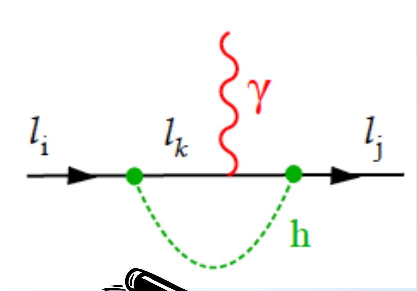
Indirect searches of NP from Flavour Physics.



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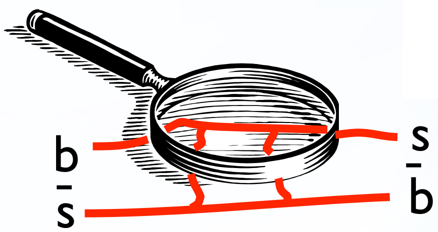
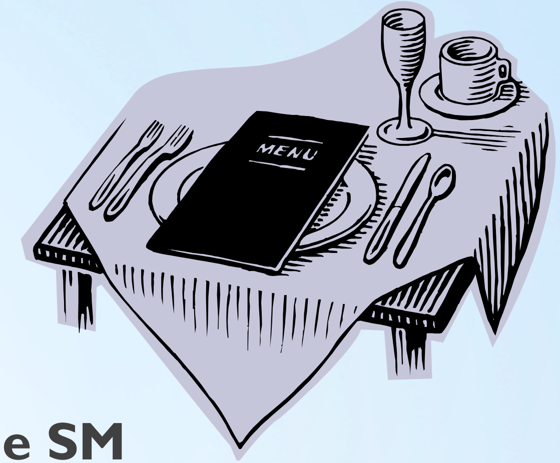
CERN, PH Department



*Plan of the lectures:

1. Introduction
2. Brief historical reminder
3. The SM flavour sector and beyond the SM
4. Status of measurements in the lepton sector
5. Status of measurements in the quark sector
   - 5.1 Tree level measurements
   - 5.2 $\Delta F2$ box measurements
   - 5.3 $\Delta F1$ EW penguin measurements
6. What do we learn about NP from flavour?
7. Take home messages.



Loops approach

If the **precision** of the measurements is high enough, we can discover NP due to the effect of "virtual" new particles in loops.

But not all loops are equal… In **"non-broken" gauge theories** like QED or QCD the "decoupling theorem" (Phys. Rev. D11 (1975) 2856) makes sure that the contributions of **heavy ($M>q^2$) new particles are not relevant**. For instance, you don't need to know about the top quark or the Higgs mass to compute the value of $\alpha(M_Z^2)$.

However, in broken gauge theories, like the weak and yukawa interactions, radiative corrections are usually proportional to Δm^2, i.e. the size of the isospin breaking.

In general, larger effects of NP expected in loops involving 3rd family in the SM.

Quantum interference: access to the imaginary phase.

Moreover, through the study of **the interference of different quantum paths** one can access not only to the magnitude of the couplings of NP, but also to their phase (for instance, by measuring CP asymmetries).

When does one have CP violation? $\Gamma(a \to b+c) \neq \Gamma(\overline{a} \to \overline{b+c})$

In terms of the two amplitudes ($A_{1,2}$) contributing to the process:

$$\Gamma(a \to b+c) = |A_1|^2 + |A_2|^2 + 2\Re(A_1 A_2^*)$$

$$\Gamma(\overline{a} \to \overline{b+c}) = |\overline{A_1}|^2 + |\overline{A_2}|^2 + 2\Re(\overline{A_1}\,\overline{A_2^*})$$

The CP asymmetry will be non-zero when

$$\Re(A_1 A_2^*) \neq \Re(\overline{A_1}\,\overline{A_2^*})$$

if the module of $A_{1,2}$ is invariant (as in the case of the SM). Therefore**, 2 phases are needed** one that changes with CP (weak phase) and another that is invariant (strong phase).

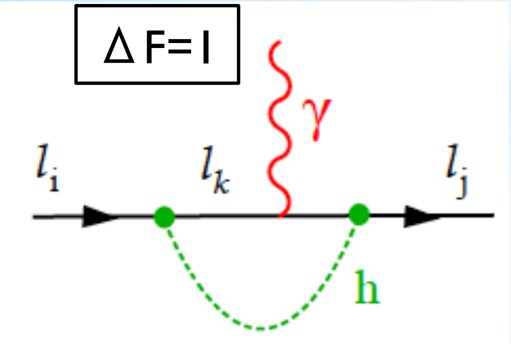
Exercise: can you show this explicitly?

The power of indirect searches

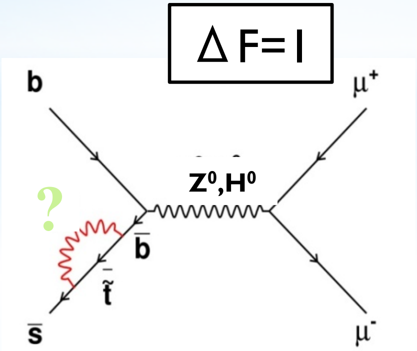
Within the SM, **only weak interactions through the Yukawa mechanism** can produce a non-zero CP asymmetry. It is indeed a big mystery why there is no CP violation observed in strong interactions (axions?).

Therefore, precision measurements of FCNC can reveal NP that may be **well above the TeV scale**, or can provide key information on the **couplings and phases** of these new particles if they are visible at the TeV scale.

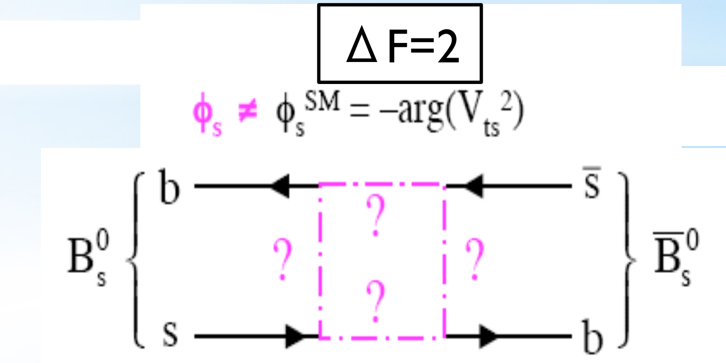
Direct and indirect searches *are both needed and equally important, complementing each other.*



$l_i \rightarrow l_j\ \gamma$ LFV radiative decay



$B_s \rightarrow \mu^+\mu^-$ Higgs "Penguin"



B_s–$\bar{B}_s$ oscillations: "Box" diagram

Status of searches for NP

So far, no significant signs for NP from direct searches at the LHC while a (the SM?) Higgs boson has been found with a mass of ~126 GeV/c^2.

Before LHC, expectations were that *"naturally"* the masses of the new particles would have to be light in order to reduce the *"fine tuning"* of the EW energy scale. Theory departments were full of advocates of supersymmetric particles appearing at the TeV energy scale.

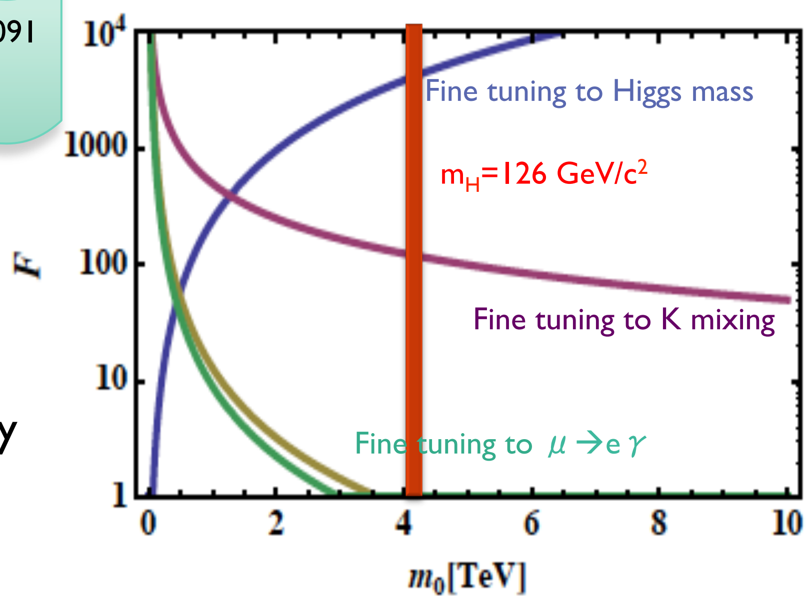
However, the absence of NP effects observed in flavour physics implies some level of *"fine tuning"* in the flavour sector. Why, if there is NP at the TeV energy scale, it does not show up in precision flavour measurements?

→ **NP FLAVOUR PROBLEM**

Non-natural solution:
→ Minimal Flavour Violation (MFV).

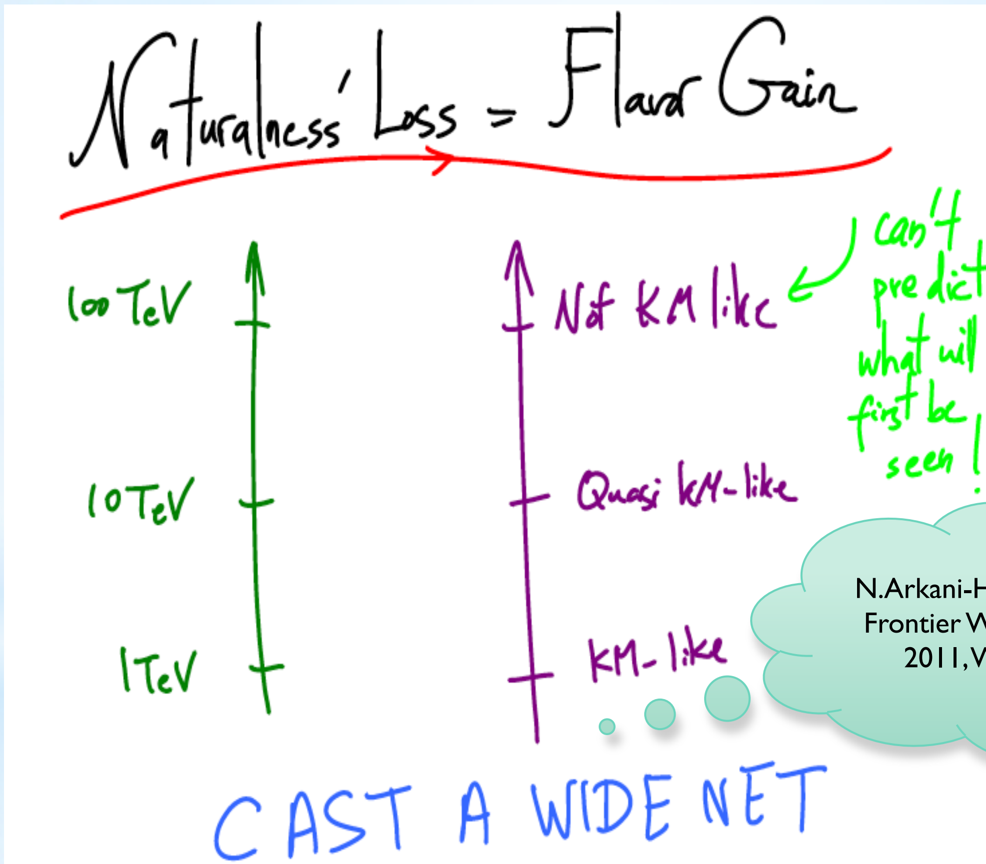
In models like CMSSM the situation now requires some level of fine-tuning in the Higgs sector, but may relax the requirements on the flavour sector!

arXiv:1205.7091
CMSSM



Status of searches for NP

As we push the energy scale of NP higher, the NP FLAVOUR PROBLEM is reduced, <u>hypothesis like MFV look less likely</u> → **chances to see NP in flavour physics have, in fact, increased** when Naturalness (in the Higgs sector) seems to be less plausible!



N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)

Brief historical reminder: flavour physics and the building up of the SM.

Strong Isospin and Strangeness

In 1932 Heisenberg introduced the concept of **Isospin** as a classification mechanism:

$$p : (I, I_z) = (1/2, +1/2) \qquad n : (I, I_z) = (1/2, -1/2)$$

$$\pi^+ : (I, I_z) = (1, +1) \quad \pi^0 : (I, I_z) = (1, 0) \quad \pi^- : (I, I_z) = (1, -1)$$

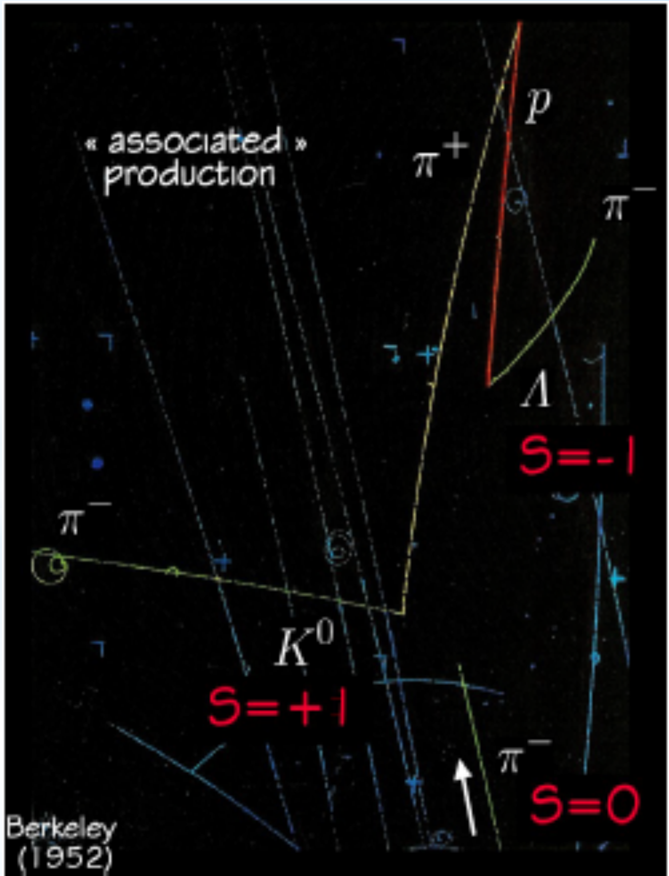
All particles in the same Isospin representation are identical if EM is switched off.

The discovery of new long-lived particles (weak decays) with very large pair production (strong production) motivated Gell-Mann(1953) and Nishijima (1955) to introduce a new quantum number:

strangeness conserved in strong interactions but not conserved in weak decays.

Therefore, particles seem to exist with **new quantum numbers! Gell-Mann/Nishijima formula:**

$$Q = I_3 + \frac{1}{2}(B + S).$$

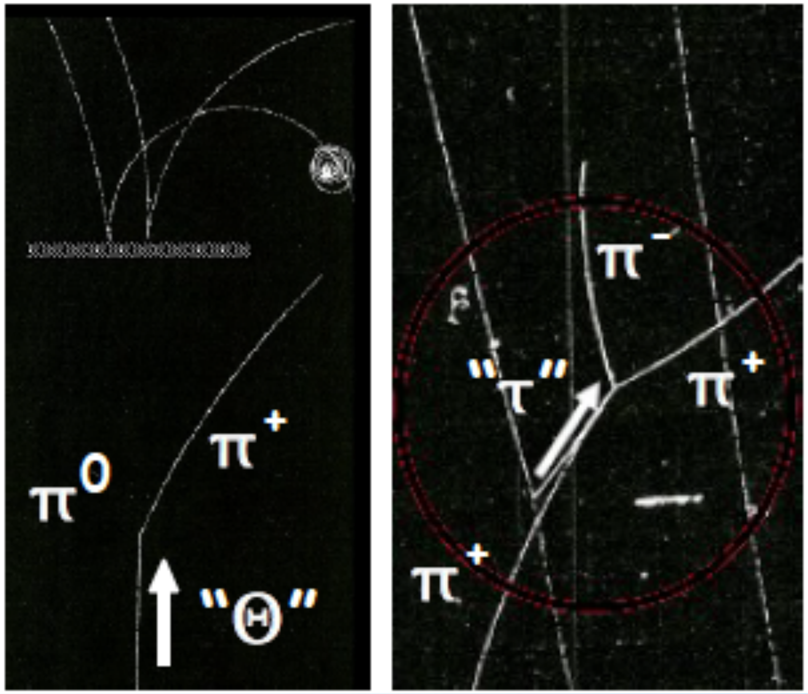


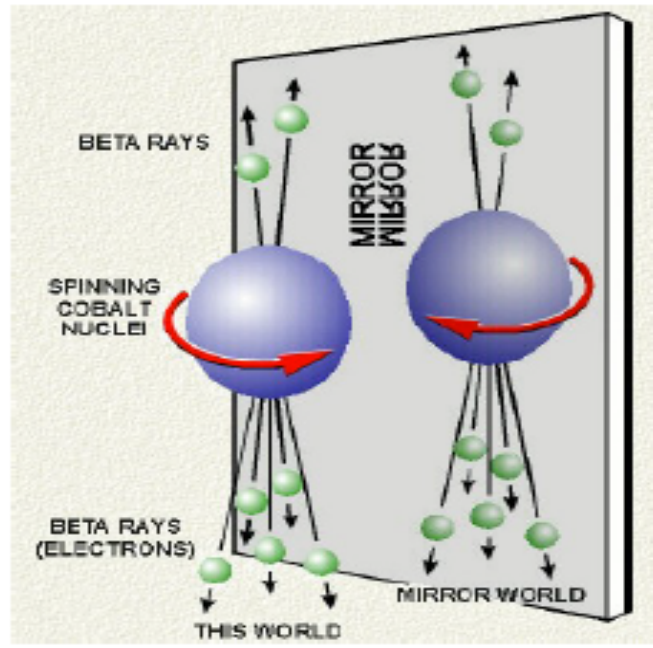
Parity Violation: V-A weak interactions

And these strange particles seem to have strange behavior: Θ/τ **puzzle**.

These “two” particles have the same mass and lifetime, but decay into $\pi^+\pi^0$ (even parity) and the other into $\pi^+\pi^-\pi^+$ (odd parity).

What if they are the same particle (K^+) but **parity is not conserved in weak interactions**?
Yang, Lee (1956): **V-A theory** *(PR 104 (1956) 254)*.



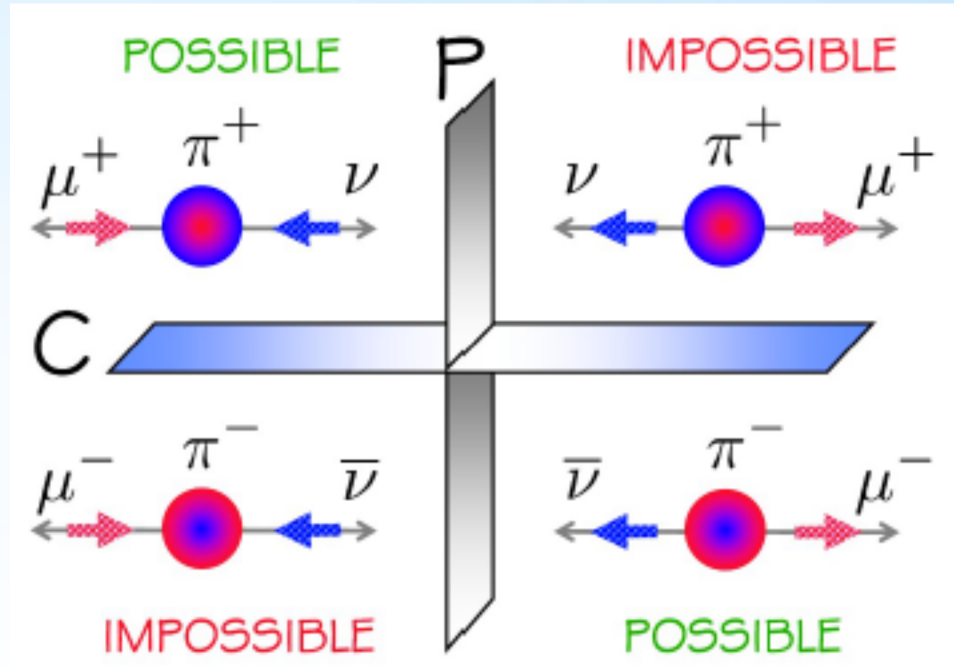


Wu et al. (1956): **direct observation of P violation**.
(PR 105 (1957) 1413)

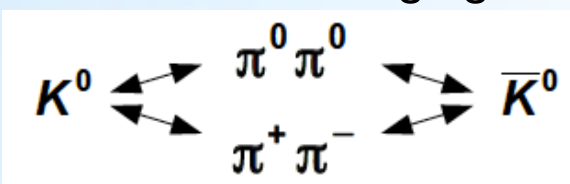
Measure angular distribution of electrons from β decays of polarized ^{60}Co. Most of the electrons are measured in the opposite direction to the spin of the ^{60}Co→ **parity is maximally violated!**

CP symmetry

Semileptonic π→ μ ν decays confirmed that parity is maximally violated, but **CP is conserved**, i.e. the measured rates for π^- to left-handed μ^- are the same than for π^+ to right-handed μ^+.



On the other hand, K^0 can mix as strangeness is not conserved. In the language of the 60s:



If CP is conserved, then one can define two states $K_{1,2}$ that are eigenstates of both the weak interactions and the CP operator:

$$|K_1\rangle = \frac{1}{\sqrt{2}} \cdot \left\{ |K^0\rangle + |\bar{K}^0\rangle \right\} \quad \Rightarrow \quad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}} \cdot \left\{ |K^0\rangle - |\bar{K}^0\rangle \right\} \quad \Rightarrow \quad CP\,|K_2\rangle = -\,|K_2\rangle$$

Gell-Mann, Pais *(PR 97 (1955) 1387))*

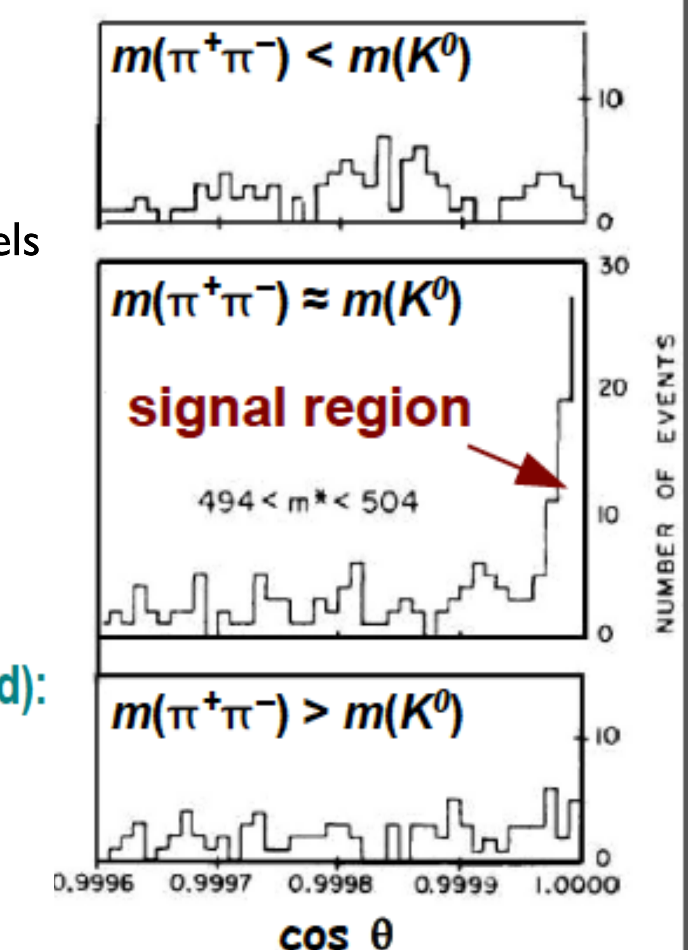
K_1 can decay into two pions while K_2 cannot. All possible decays channels for K_2 are suppressed by parity violation (semi-leptonic) or by phase space. **K_2 is expected to have a much longer lifetime than K_1 (x500).**

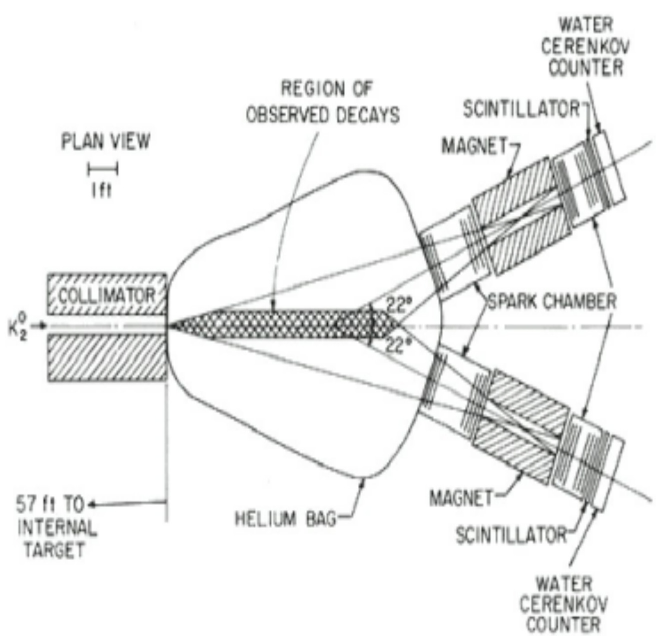
K mixing and CP violation

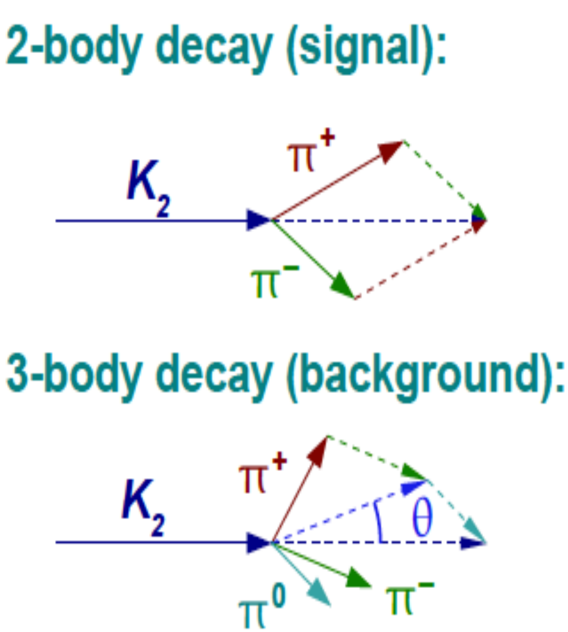
Christenson, Cronin, Fitch, Turlay (1964): **Observation of $K_2 \rightarrow \pi^+\pi^-$**. The experiment shoot protons on a target to produce K^0, after a long enough trip in a vacuum pipe, they achieved a pure K_2 beam.

Experimentally use invariant mass (energy conservation) and angle between K_2 and $\pi^+\pi^-$ (momentum conservation). Find excess of ~56 events in the signal region: **$BF(K_2 \rightarrow \pi^+\pi^-) \sim 2\times10^{-3}$ → CP violation!**

This was beyond what theory could explain then →
Superweak models

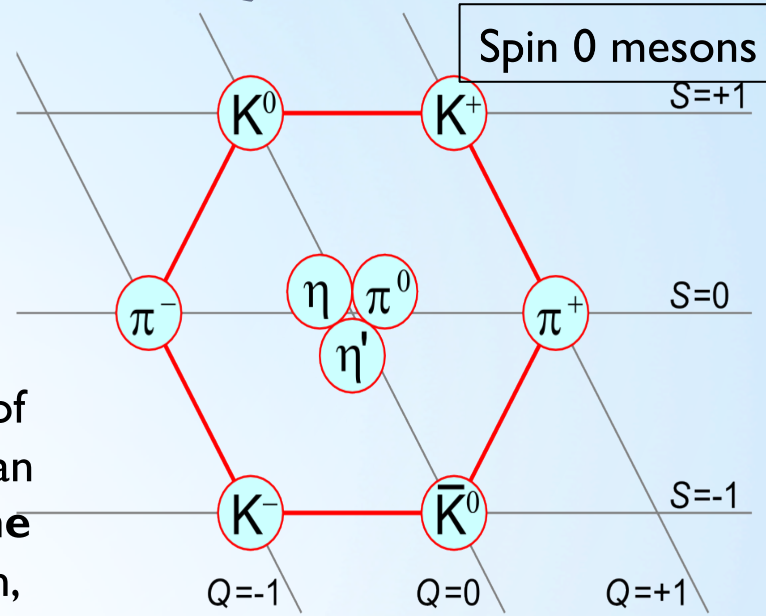




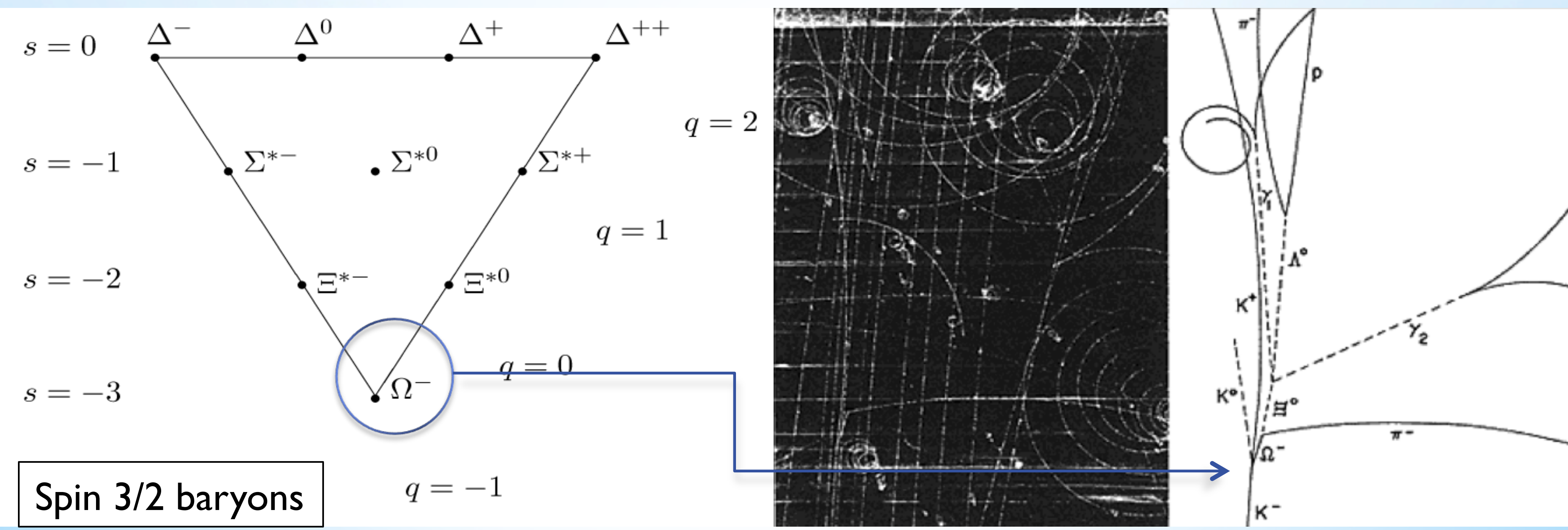


SU(3) and the Quark Model

Gell-Mann/Nishijima formula developed into the **"eightfold way"** classification: all known mesons and baryons could fit in **SU(3) representations**. Prediction of Ω⁻(sss) baryon observed in 1964 at Brookhaven (Barmes et al.).

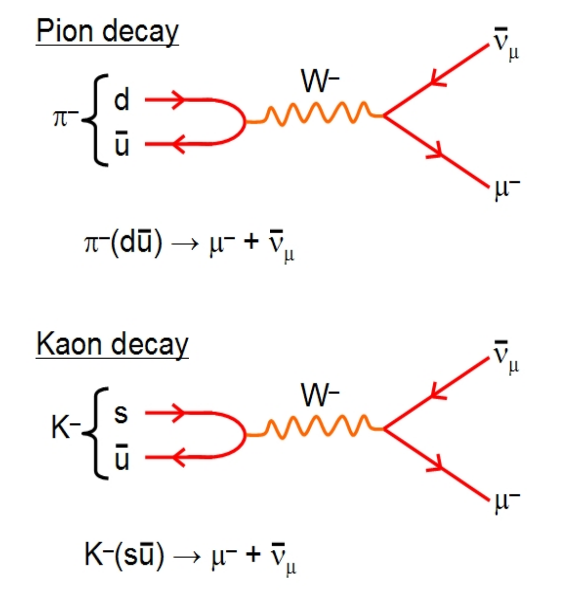


Gell-Mann, Zweig interpreted this organization in terms of **constituent quarks**. Developing previous ideas from Han and Nambu, the concept of **colour as the charge of the strong interactions** was articulated in 1973 by Bardeen, Fritzsch and Gell-Mann.



Cabibbo and GIM mechanism

Moreover, the **weak coupling did not look to be universal**: why BR($K \rightarrow \mu\nu$) << BR($\pi \rightarrow \mu\nu$) after dealing with phase space?



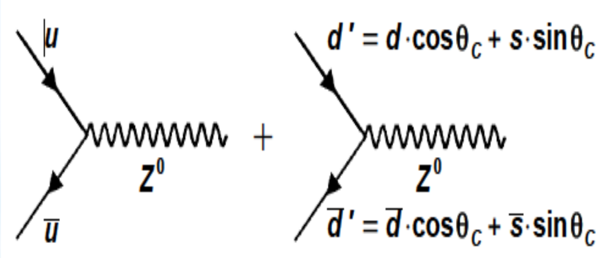
Cabibbo (1963): **weak interactions couples to a linear combination:**

(PRL 10 (1963) 531)

$$d' = \cos\theta_c \cdot d + \sin\theta_c \cdot s$$

and using todays language:

$$\frac{s \rightarrow u\,W^-}{d \rightarrow u\,W^-} = \frac{\sin^2\theta_c}{\cos^2\theta_c} \approx \frac{1}{20}$$



But, if the neutral weak currents also couples to d' **expect large FCNC**. Experimentally, however, BR($K_2 \rightarrow \mu\mu$) ~7×10^{-9}.

Glashow, Ilioupoulos and Maiani (1970). *(PRD 2 (1970) 1285)*

Assume a **new (not yet observed quark)** in SU(2) quark doublets→ **FCNC cancel at tree level!**

Exercise: can you show this explicitly?

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \text{ with } \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \cdot \begin{pmatrix} d \\ s \end{pmatrix}$$

From the Δm_K measurements, $\mathbf{m_c}$ was predicted to be **~1.5 GeV!** Gaillard and Lee (1974)

(PRD 10 (1974) 894)

CKM mechanism

Kobayashi, Maskawa (1972): If we have 3 quark generations, CP violation is allowed!

(FTP 49 (1973) 652)

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

From the **$2n^2$** parameters of the **CKM matrix** with **n families**, we can reduce by n^2 from Unitarity constraints and 2n-1 from unphysical phases, so only **$(n-1)^2$ are free**.

Therefore, while **n=2 has only one free parameter** (Cabibbo angle) and is real, **n=3 has four parameters (3 angles + 1 phase) allowing for CP violation**.

Even before finding charm (as needed for GIM to work), theorists were already requiring another quark family to be able to accommodate CP violation! Although this option was competing with Superweak models!

Charm quark

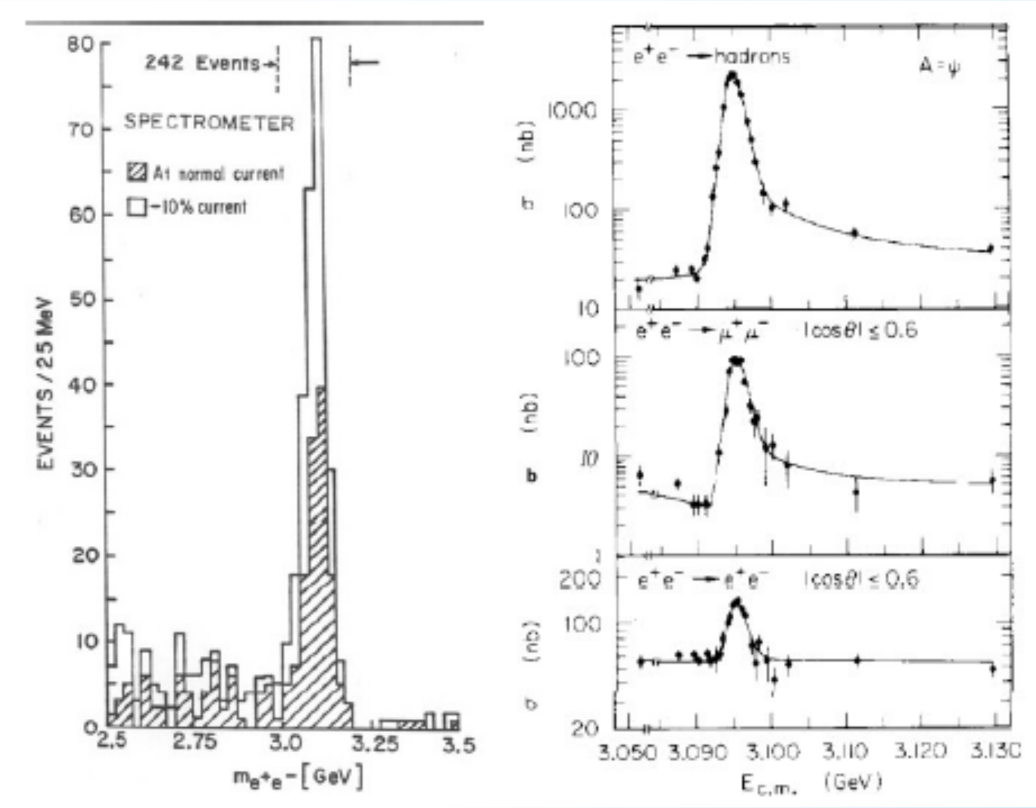
November Revolution (1974): *(PRL 33 (1974) 1404)* *(PRL 33 (1974) 1406)*

Observation of a **narrow resonance** at a mass of **3.1 GeV**, simultaneously in **proton-Be collisions at BNL** (p+Be → e^+e^-+X, **Ting et al.**) and in **$e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons at SLAC (Richter et al.)**

The new resonance, **J/ψ**, had a narrow width, therefore a **long lifetime**, excluding interpretations as a uds state.

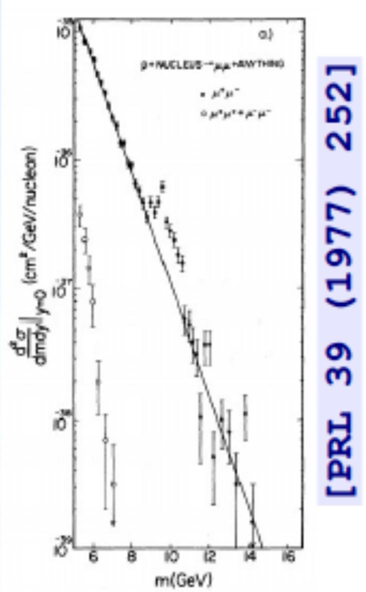
Most plausible explanation was a bound state of a **new quark (charm)** with mass **~1.5 GeV!**

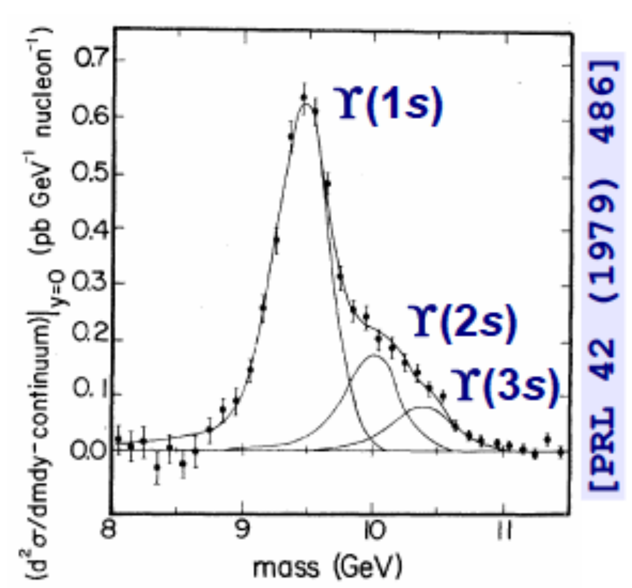
Soon after confirmed by the observation of new cc states and of open charm (D mesons).



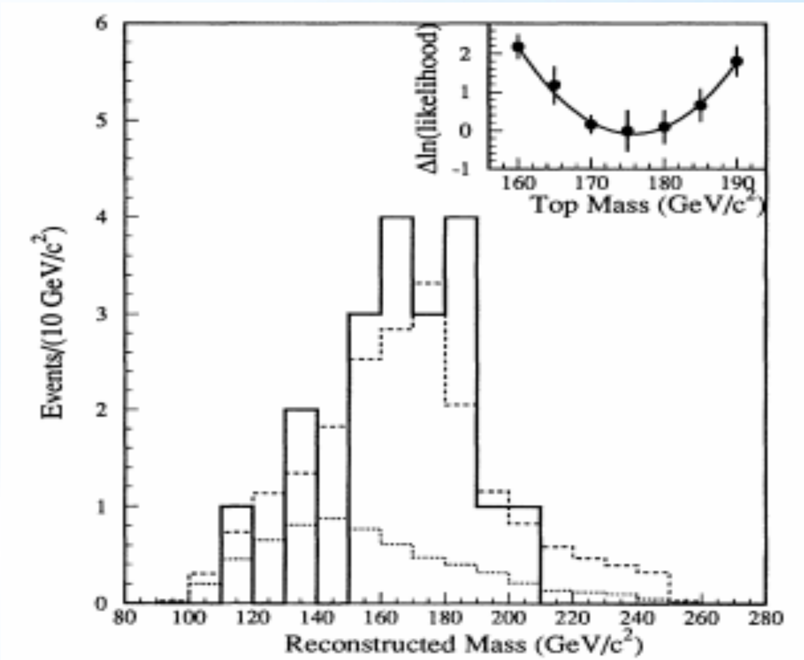
Bottom and Top quark

Lederman et al. (1977): search for bb resonances in **p+Cu → $\mu^+\mu^-$+X at Fermilab.** The observation of an excess of $\mu^+\mu^-$ pairs at 9.4-10.4 GeV invariant mass was resolved later into three resonances, interpreted as **bb states** with **m_b~4.5 GeV**.
In the 80s CLEO further confirmed this picture with the discovery of Υ (4s) and B^0 and $B^{\pm}$ mesons.





After the discovery of the b-quark, few people had any doubt of the existence of the **t-quark**. Moreover its mass was predicted to be large **(>50 GeV)** from **B-mixing measurements (ARGUS, 1987)** and between **150 and 200 GeV from LEP** precision EW measurements **in the 90s.**
CDF/D0 (1995): Observation of tt production in pp collisions **at the Tevatron**.



CDF: 175±8±10 GeV D0: 199^{+19}_{-21}±22 GeV

(PRL 74 (1995) 2626)

(PRL 74 (1995) 2632)

Leptons and neutrinos

Anderson, Neddermeyer discovered the μ with cosmic rays at Caltech in 1936. But because its mass was so close to the **Yukawa pion**, it was not recognized as a heavy electron until 1947 → **I. Rabi: "Who ordered that?".**

In 1930 Pauli proposed the existence of the **neutrino to explain Beta** decay. **In 1956 Reines and Cowan** using neutrinos from nuclear reactors, demonstrated their existence using the inverse Beta decay reaction: anti-ν p → n e^+.

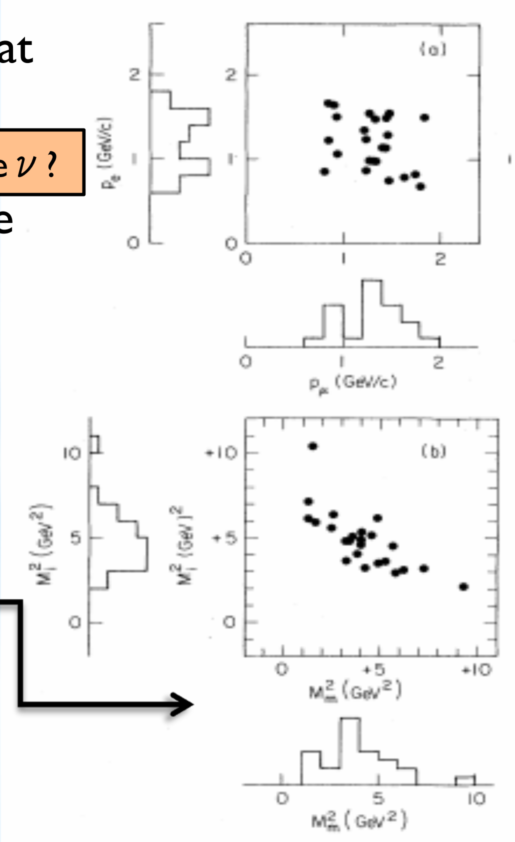
In 1962 Lederman, Schwartz and Steinberger discovered that there were at least **two kind of neutrinos** with different properties. Using $\pi \to \mu\ \nu$ decays, they observed ν interactions producing μ but no electrons in the final state. One had to conclude that the ν **in pion decays were not the same as the ones in Beta decays**!

Exercise: why can we safely neglect $\pi \to e\,\nu$?

The τ **lepton** was observed in a series of experiments between **1974-77 by Perl et al. at SLAC**. They found a number of unexplained events of the type **$e^+e^- \to e\,\mu + \geq 2$ undetected**.

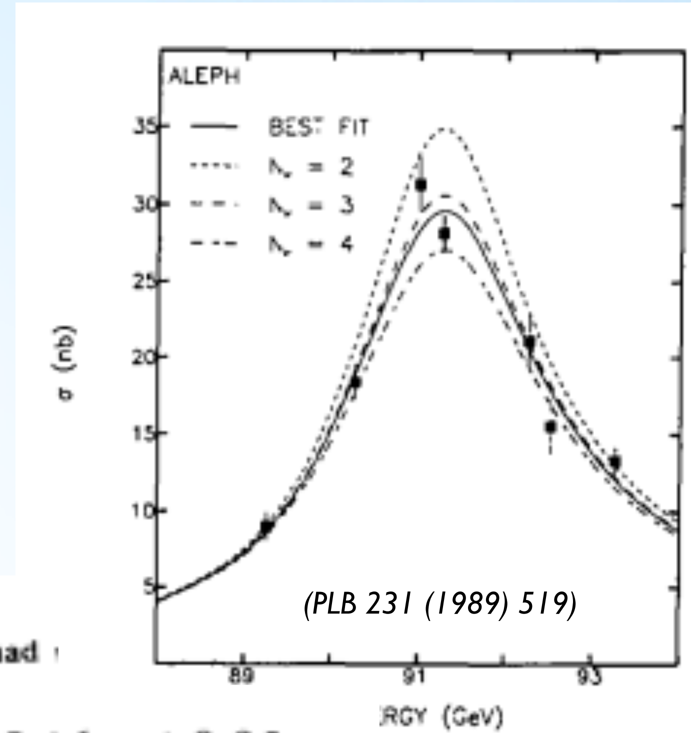
The interpretation was $e^+e^- \to \tau^+\tau^- \to e\,\mu + 4\nu$ with $m_\tau \sim 1.6\text{-}2$ GeV.

(PRL 35 (1975) 1489)



Three families also in the lepton sector

When **LEP** started producing e^+e^- collisions around the mass of the **Z boson**, there were already indications that the number of light neutrinos was three from previous experiments as well as from astrophysical arguments.



(PLB 231 (1989) 519)

In 1989 after few months since the first collisions, the LEP experiments were able to measure precisely the **total width of the Z boson:**

$$\Gamma_Z = N_\nu \Gamma_\nu + 3\Gamma_{ee} + \Gamma_{had}\,,$$

For instance, ALEPH measured: $N_\nu = 3.27 \pm 0.24_{stat} \pm 0.16_{sys} \pm 0.05_{th}\,,$

LEP measurements became very precise with more statistics, and the final number, **N_ν=2.9840±0.0082**, leaves no doubt that there are **not more than three light neutrinos**.

The third neutrino (ν_τ) was **observed in 2000 by the DONUT** Collaboration at Fermilab.

The SM flavour sector.

The SM Solution

The SM is able to accommodate all previous discussed experimental evidence with:

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i)$$

$$\Sigma_{\psi = Q_L, u_R, d_R, L_L, e_R} \Sigma_{i=1..3} \overline{\psi}_i i\not{D} \psi_i$$

$$Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R, \quad d_R, \quad L_L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R$$

The **gauge component** is the **"elegant" part**. There is **no distinction between different generations** and has a **huge degree of symmetry** (invariant under 5 independent U(3) global rotations). We only need to know α, θ_W, M_W and α_s and everything is determined by the local gauge symmetry group: $\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$.

The **Higgs component**, however, **breaks the flavour symmetry**. It is the **origin of the flavour structure** of the model and, in my view, is an ad hoc procedure. It is also the component that is **not stable to quantum corrections**. To describe this part we need a total of **14 parameters!**

The origin of masses and mixings, together with the origin of family replications is the most pressing problem of the SM.

Flavour in the SM: Yukawa Mechanism in the quark sector.

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + Y_e^{ij}\bar{L}_L^i \phi E_R^j + {\rm h.c.}$$

$$\lambda_d = {\rm diag}(y_d, y_s, y_b)\ , \quad \lambda_u = {\rm diag}(y_u, y_c, y_t)\ , \qquad y_q = \frac{m_q}{v}\ .$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u\ ,$$

The quark flavour structure within the SM is described by 6 couplings and 4 CKM parameters. In practice, is convenient to move the CKM matrix from the Yukawa sector to the weak current sector:

$U_i = \{u, c, t\}$:

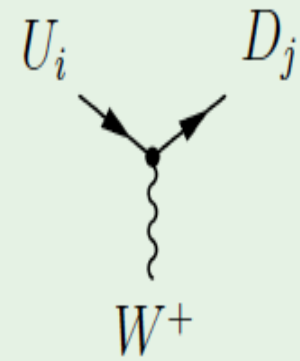
$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

$$\mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}}(\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^+_\mu$$

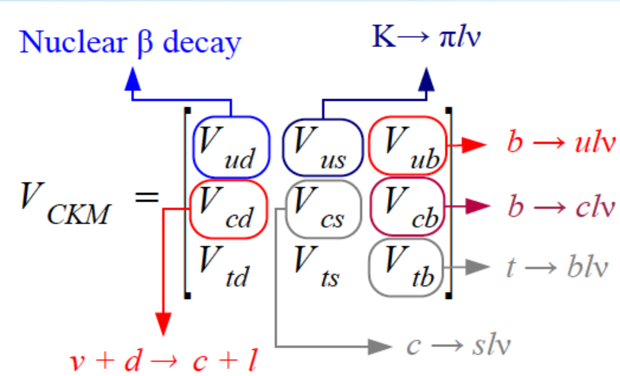
$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix



In the SM quarks are allowed to change flavour as a consequence of the Higgs mechanism to generate quark masses.

CKM at work

Using **Wolfenstein** parameterization (A, λ , ρ , η):



CKM

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho+i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

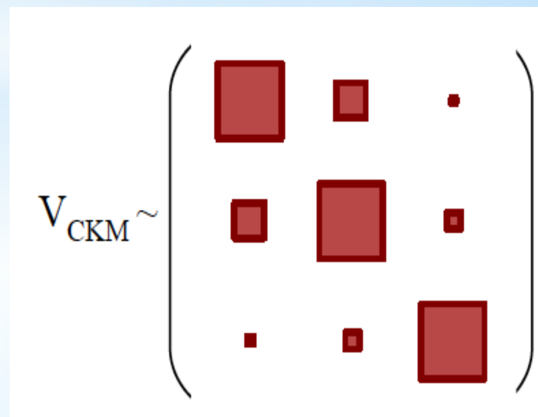
λ **= sin** θ_c **≈**V_{us} measured precisely in K semileptonic decays.

A = 0.80±0.02
λ = 0.225±0.001

In 1983 the measurements of **B mesons lifetimes** found to be **"unexpectedly" large (MAC, MARK-II),** confirm $V_{cb} < V_{us}$ → $|V_{cb}/V_{us}| \approx A\lambda$.

Moreover, the observation of **b→ul**ν decays in the 90s **(CLEO, ARGUS)** confirm $V_{ub} << V_{us}$. Therefore, experiments confirm the **CKM hierarchy.**

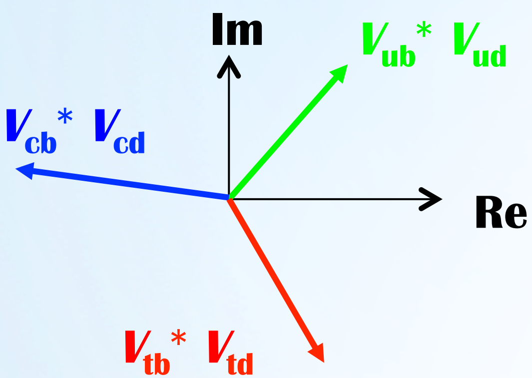
Notice that all V_{ij} **couplings** can be accessed experimentally using **tree-level decays**, with the **exception of** V_{td} **and** V_{ts} (at least until a large enough sample of top quarks is available).



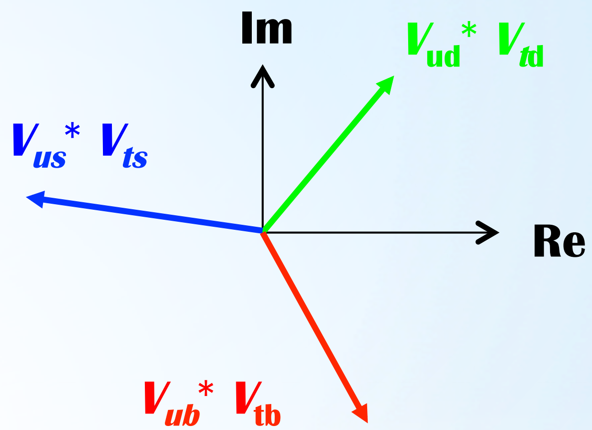
CKM Unitarity

Imposing unitarity to the CKM matrix results in six equations that can be seen as the sum of three complex numbers closing a triangle in the complex plane. Two of these triangles are relevant for the study of CP-violation in B-physics and define the angles:

1) $V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$



2) $V_{ud}^{*}V_{td} + V_{us}^{*}V_{ts} + V_{ub}^{*}V_{tb} = 0$



$$\alpha = \arg\left(\frac{-V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right),\quad \beta = \arg\left(\frac{-V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)\quad \text{and}\quad \gamma = \arg\left(\frac{-V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)\quad \Phi_s/2 = \arg\left(\frac{-V_{cb}V_{cs}^{*}}{V_{tb}V_{ts}^{*}}\right)$$

$\arg V_{td} \approx -\beta$

$\arg V_{ub} \approx -\gamma$

$\arg V_{ts} \approx -\varphi_s/2$

$\eta = 0.34 \pm 0.02$

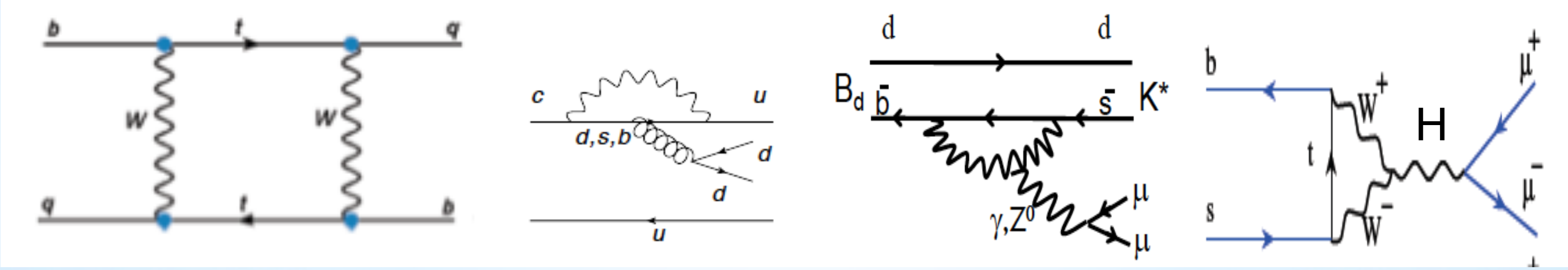
$\rho = 0.14 \pm 0.03$

$$\tan\beta \approx \frac{\eta}{1-\rho}\left(1-\frac{\lambda^2}{2}\right) \approx \tan(23.6^\circ)$$

$$\tan\gamma \approx \frac{\eta}{\rho} \approx \tan(66^\circ)$$

$$\phi_s \approx -2\eta\lambda^2 \approx -2^\circ$$

FCNC loops in the SM



Δ F=2 box　　QCD Penguin　　EW Penguin　　Higgs Penguin

*Map of Flavour transitions and type of loop processes: → **Map of these lectures!***

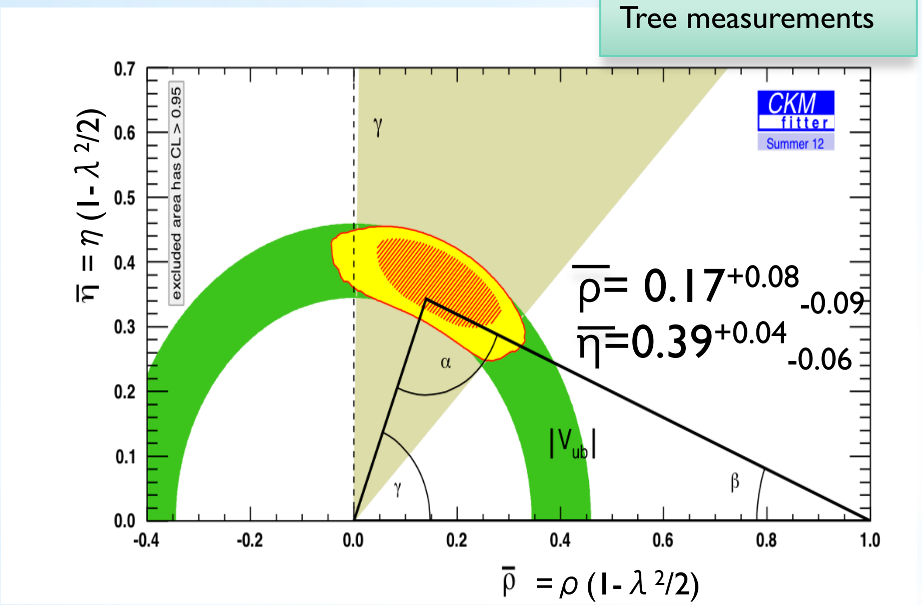
	b→s ($\lvert V_{tb}V_{ts}\rvert \alpha\ \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert \alpha\ \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert \alpha\ \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert \alpha\ \lambda^5$)
Δ F=2 box	$\Delta M_{Bs}, A_{CP}(B_s \to J/\Psi\ \Phi)$	$\Delta M_B, A_{CP}(B \to J/\Psi K)$	$\Delta M_K,\ \varepsilon_K$	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)} ll$, $B \to X_s \gamma$	$B \to \pi ll$, $B \to X \gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu\ \nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu\ \mu$	$B \to \mu\ \mu$	$K \to \mu\ \mu$	$D \to \mu\ \mu$

Tree vs loop measurements

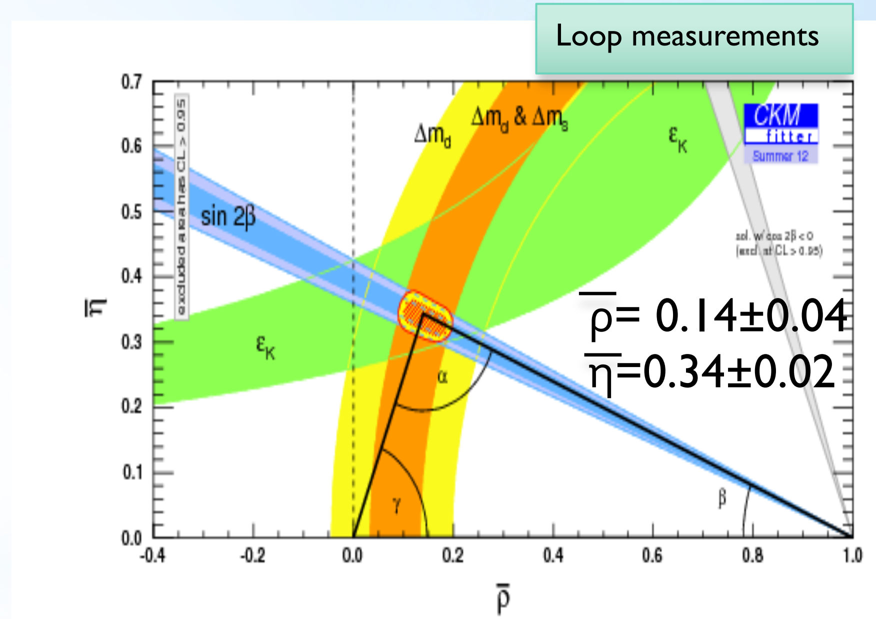
(A, λ, ρ, η) are not predicted by the SM. They need to be measured!

If we assume NP enters only at loop level, it is interesting to compare the determination of the parameters (ρ, η) from processes dominated by tree diagrams ($V_{ub}, \gamma, \ldots$) with the ones from loop diagrams ($\Delta M_d \& \Delta M_s, \beta, \varepsilon_K, \ldots$).

Tree measurements



Loop measurements



Courtesy S. Descotes-Genon on behalf of CKMfitter coll.

Need to improve the precision of the measurements at tree level to (dis-)prove the existence of NP contributions in loops.

Beyond the SM flavour sector.

Flavour in the SM: Yukawa Mechanism in the lepton sector.

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

In the SM the lepton Yukawa matrices can be diagonalized independently due to the global G_l symmetry of the Lagrangian, and therefore there are not FCNC.

$$\mathcal{G}_\ell = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

However, the discovery that ν oscillate (and ν are massive) implies that Lepton Flavour is not conserved. The level of Charged Lepton Flavour Violation depends on the mechanism to generate neutrino masses (for instance, **Seesaw mechanism**).

PMNS

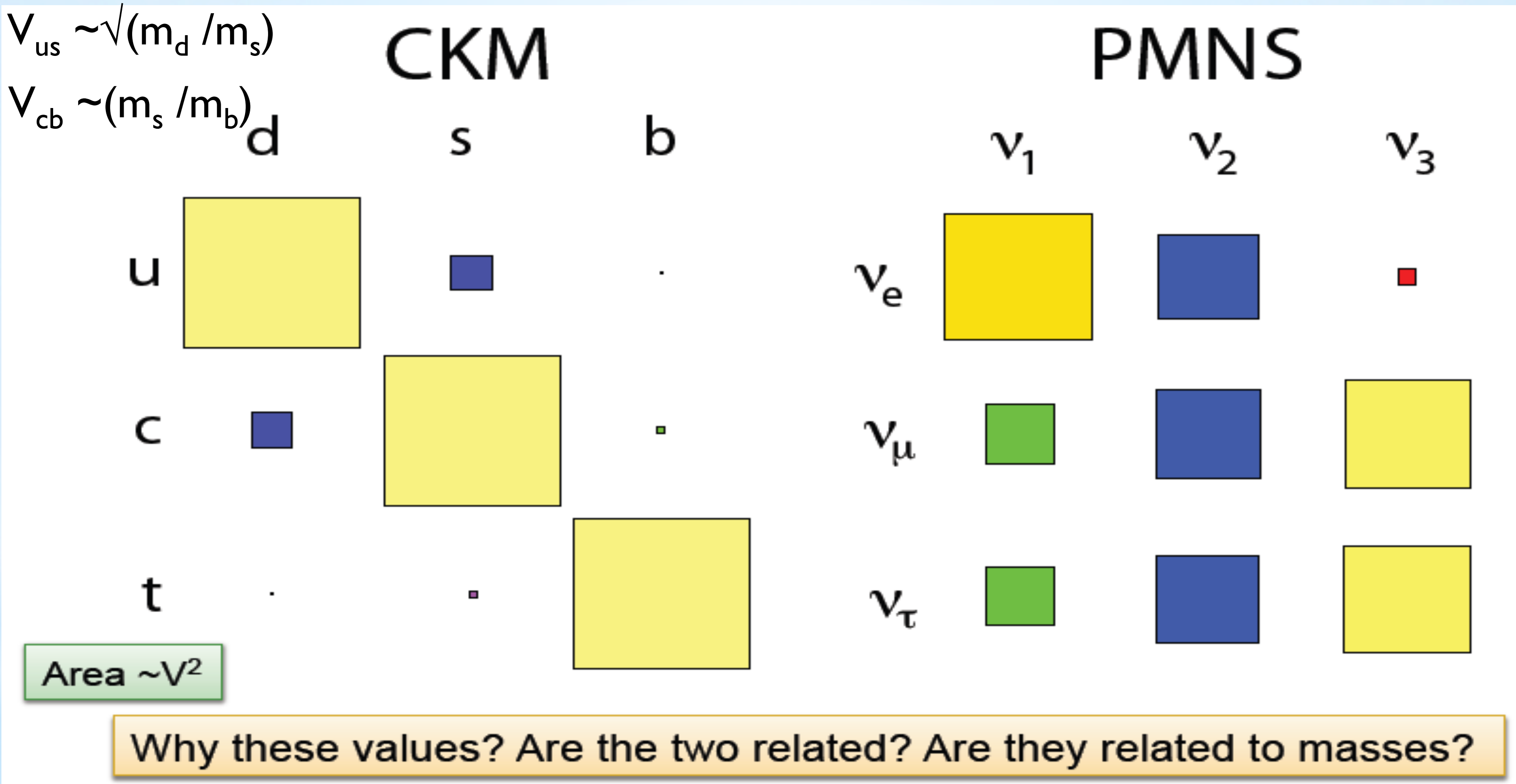
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$\theta_{12}[^\circ] = 33.36^{+0.81}_{-0.78}$$
$$\theta_{23}[^\circ] = 40.0^{+2.1}_{-1.5} \text{ or } 50.4^{+1.3}_{-1.3}$$
$$\theta_{13}[^\circ] = 8.66^{+0.44}_{-0.46}$$
$$\delta_{\rm CP}[^\circ] = 300^{+66}_{-138}$$

In general, while quark flavour changing Yukawa couplings to the Higgs are strongly suppressed by $\Delta F=2$ indirect measurements, processes like $H\rightarrow\tau\mu$ or $H\rightarrow\tau e$ are only loosely bounded (O(10%)).

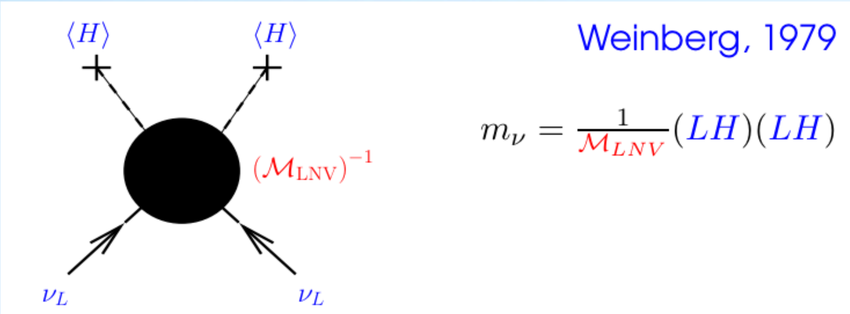
Flavour structure is not simple!

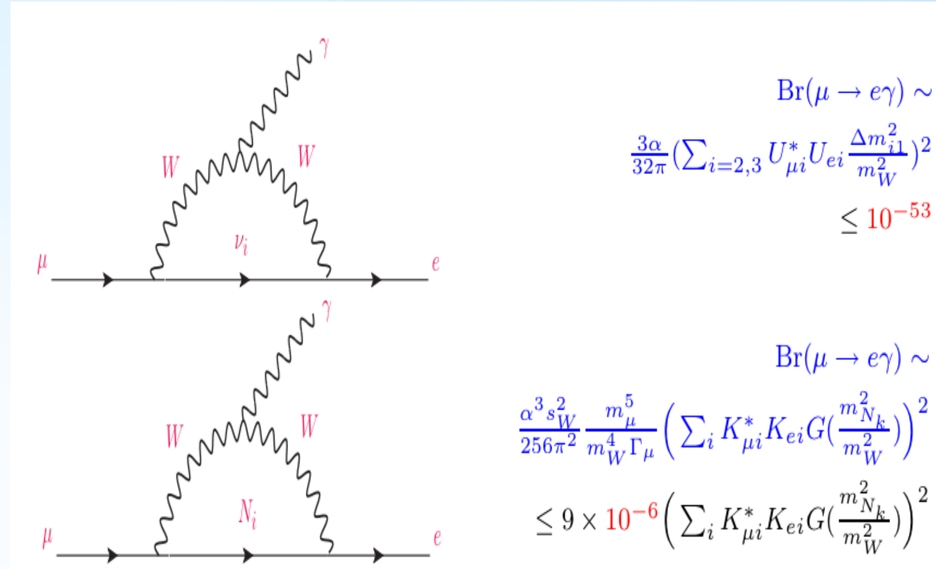
We know there are FCNC in the lepton sector (analogous to the quark sector) because we have observed neutrino oscillations. Therefore the Yukawa couplings in the lepton sector do contain also a mixing matrix.



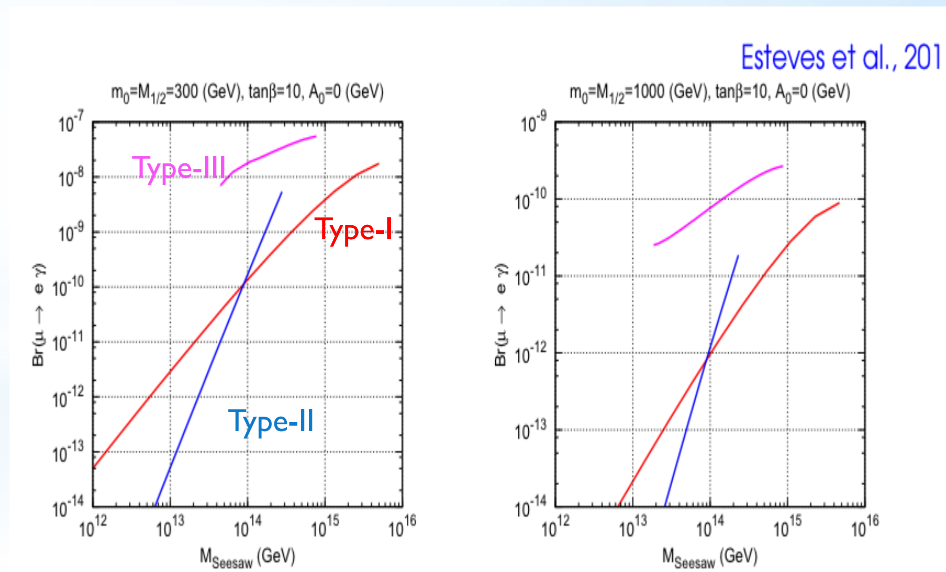
Can the seesaw mechanism explain the very different structures between quarks and leptons?

Seesaw mechanism and LFV





If neutrinos are **Dirac particles**, expect **very small** (far from experimental sens.) **LFV.**



However, if neutrinos are **Majorana particles** and something like the **Seesaw mechanism** is at work, **large values** (close to experimental sens.) are favoured.

In general, **any extension of the SM with new states at the TeV scale generates large charged LFV.**

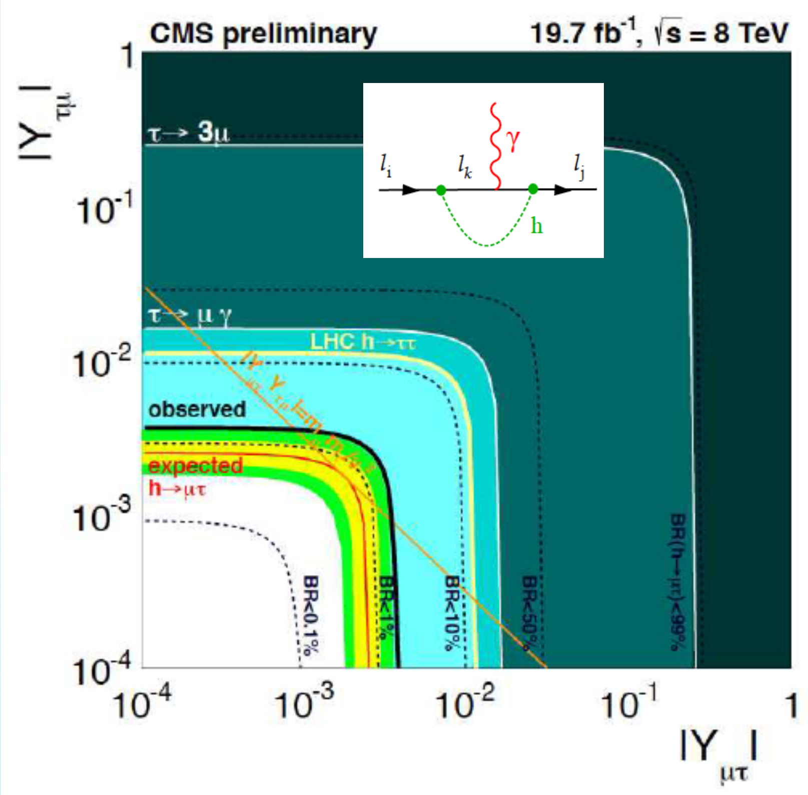
LFV and Higgs Decays

Can the seesaw mechanism explain the very different structures between quarks and leptons?

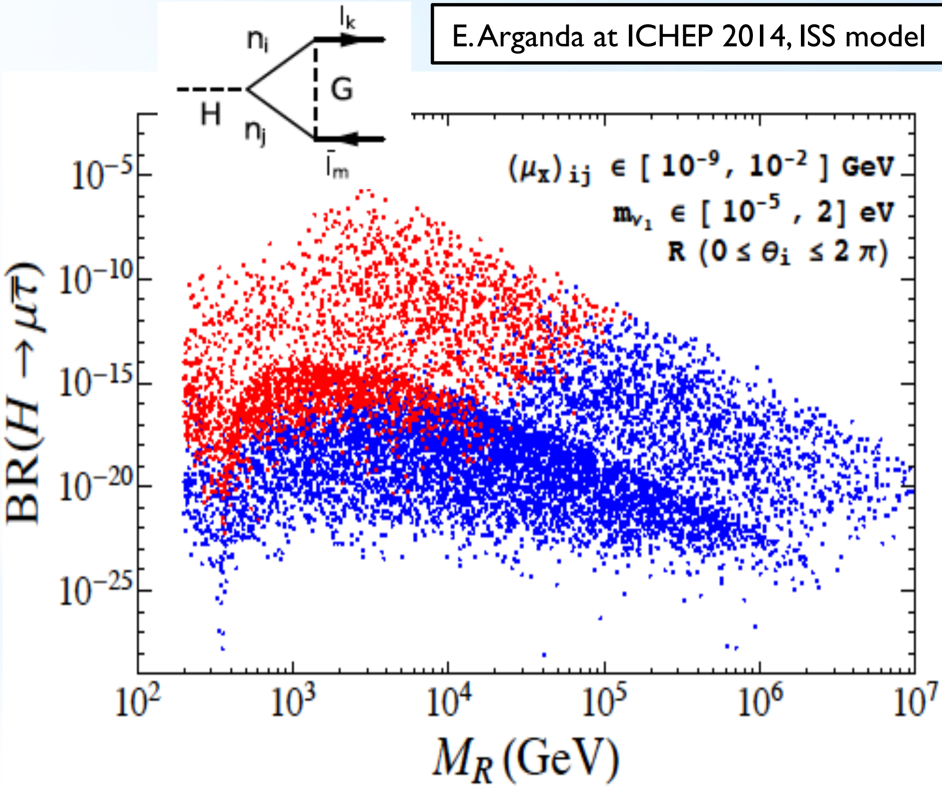
Once you start building models that predict the Yukawa couplings you have a prediction for processes like FCNC in charged lepton decays and flavour violating Higgs decays (FVHD). The interplay between neutrino measurements, FVHD and CLFV can be a very powerful constraint of the NP energy scale(s).

Examples:

G. Isidori at ICHEP 2014



E. Arganda at ICHEP 2014, ISS model



Excluded by $\mu \to e\gamma$. Allowed by all the constraints.

Flavour Beyond the SM

We know the **SM** does **not describe ν masses**, does not have **a good DM candidate** and **cannot explain the baryon asymmetry** in the Universe. Moreover, there is no explanation for the **flavour structure**, does **not include Gravity** and suffers from **fine-tuning issues in the Higgs sector.**

So, let's take the **SM as an approximation** to the true underlying theory:

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

ν masses indicate already the existence of **d=5** operators in this expansion and of very **large values of Λ** (probably related to the breaking of Lepton Number). Precision FCNC measurements in the quark sector also indicate **large values of Λ.** On the other hand, the **d=2** operators in the **Higgs sector** require a **low value of Λ** to stabilize the Higgs mass term.

The search for the scale Λ at the High Energy Frontier is complemented by the sensitivity of (c_n/Λ) of experiments at the High Intensity Frontier.

Extended Scalar Sector

Consider a two Higgs doublet model with different vacuum expected values, $\mathbf{v_1}$ and $\mathbf{v_2}$.

$$\overline{d}_{R,i}(\hat{h}^{ij}_{d,1}\,\phi_1 + \hat{h}^{ij}_{d,2}\,\phi_2)\,d_{L,j}$$

$$\hat{m}^{ij}_d = \hat{h}^{ij}_{d,1}\mathrm{v}_1 + \hat{h}^{ij}_{d,2}\mathrm{v}_2$$

In general, the diagonalization of the mass matrix will not give diagonal Yukawa couplings → **large FCNC**.

Ok, let's assume that each Higgs doublet couples only to one type of quarks, i.e. something like **SUSY** (or 2HDM type-II). But then, at some energy scale, this symmetry breaks → expect **again large FCNC**, if the SUSY scale is not far away.

Minimal Flavour Violation: at tree level the quarks and squarks are diagonalized by the same matrices → **no FCNC at tree level**, like in the SM.

At loop level, however, expect both Higgs doublets to couple to up and down sectors → expect **large FCNC at large tan** β .

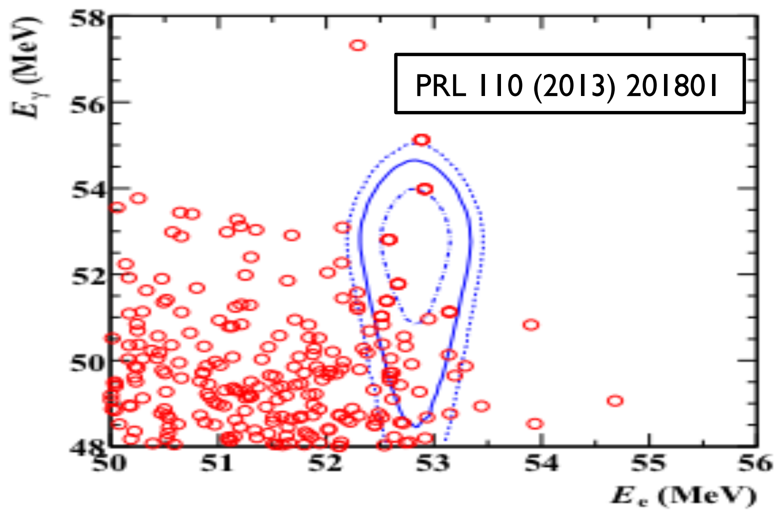
At least two indirect paths to study Higgs BSM:

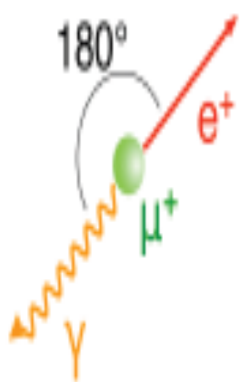
1. **Precise measurements of the Higgs boson properties.**
2. **Precise measurements of FCNC.**

Status of experimental measurements in the lepton sector.

CLFV: $\mu \rightarrow e\gamma$

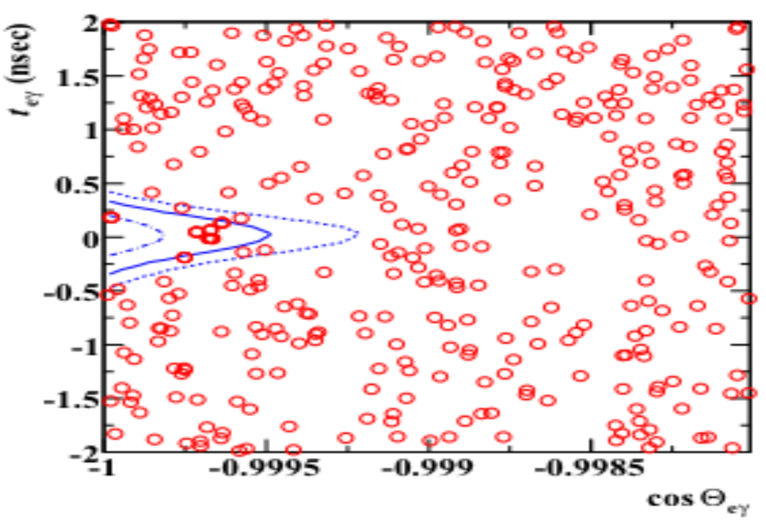
The discovery of neutrino oscillations implies CLFV at some level. Many extensions of the SM to explain neutrino masses, introduce large CLFV effects (depends on the nature of neutrinos). There is one more very important advantage w.r.t. the quark sector: **the reach for NP energy scale is not so much affected by QCD uncertainties in the SM predictions.**





The **MEG collaboration** at PSI using 3.6×10^{14} stopped muons collected in 2009-11 have achieved a sensitivity of $BR(\mu \rightarrow e\gamma)<5.7\times10^{-13}$@90%C.L.

Relevant variables $E_{\gamma,e}$ and the timing (e, γ) and cos $\theta_{e\gamma}$



$BR(\mu \rightarrow e\gamma)$	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

CLFV: $\mu \to e\gamma$

Results with Data taken until summer 2013 still to be shown. MEG upgrade expects to increase x10 sensitivity with upgraded detector (2016-2019).

Difficult to further improve with this technique due to accidental backgrounds, which should increase with beam intensity.

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T,$$

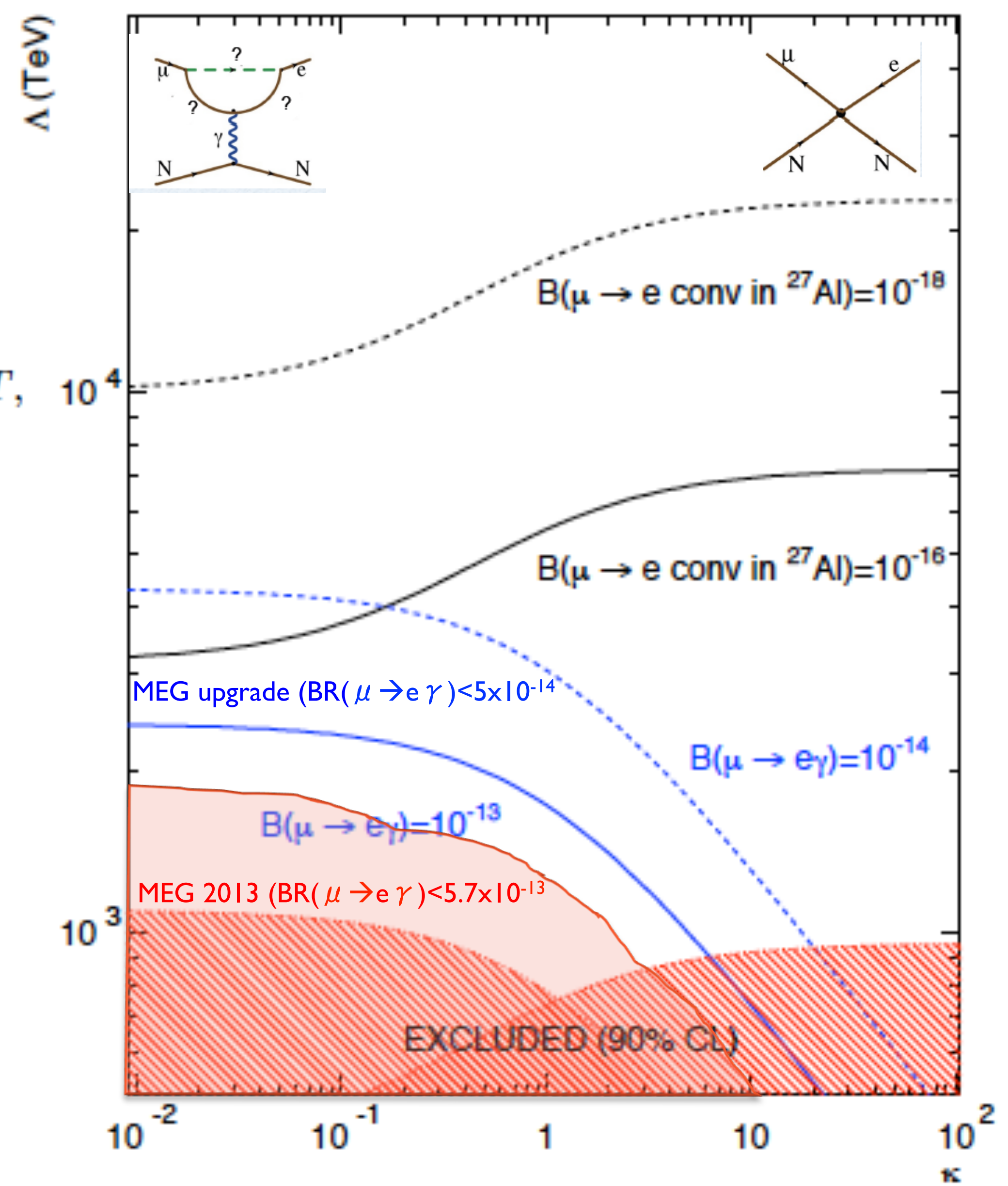
Maybe improving Δe_γ using converted photons, could overcome the lost in efficiency, and may reach to 10^{-15}.

Typically two operators contribute as function of Λ:

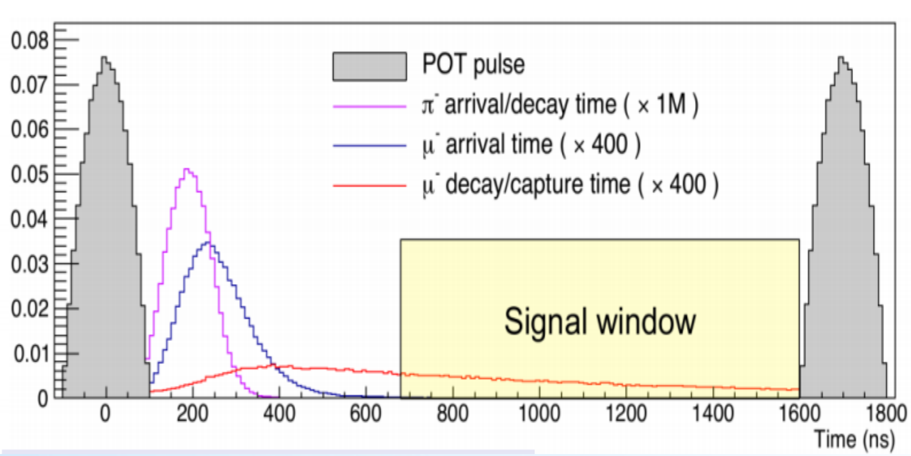
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R\gamma_\mu e_L \bar{f}\gamma^\mu f$$

And κ is the relative strength of their contribution.

Modified from A.Gouvea and P.Vogel, arXiv:1303.4097



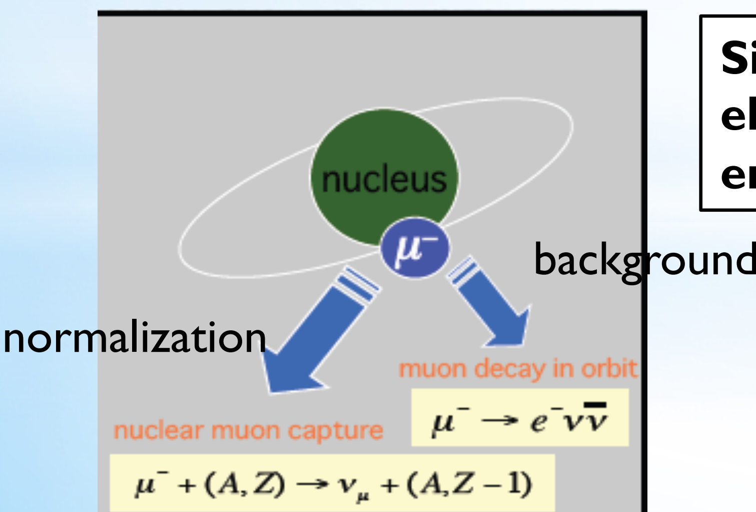
CLFV: $\mu \rightarrow eN$



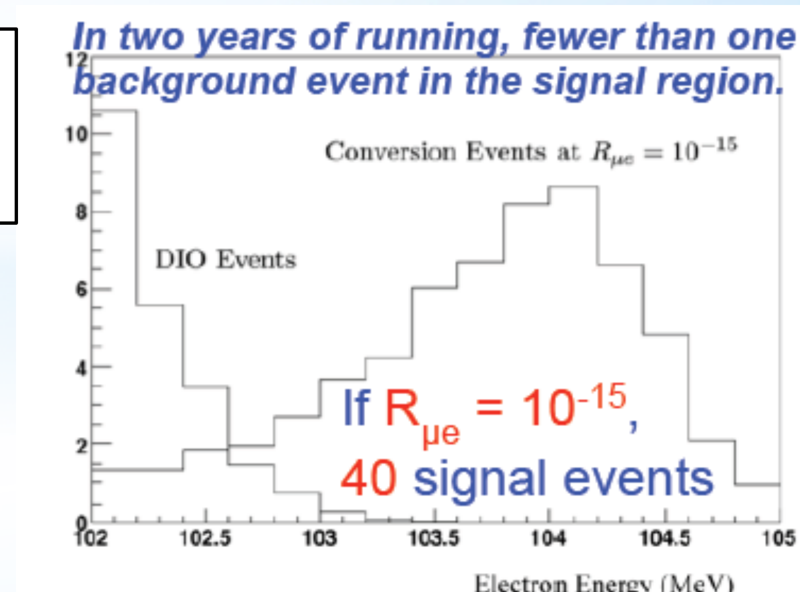
More feasible is to improve on $\mu \rightarrow eN$ conversions. Best existing limits from **SINDRUM-II at PSI**: R($\mu \rightarrow$eAu) <7x10^{-13} @90% C.L. with O(10^8) μ^-/sec and time between pulses <20ns.

Mu2e at the **booster** will use O(10^{10}) μ^-/sec and time between pulses ~1700ns, to reach R ($\mu \rightarrow$eAl) <7x10^{-17} @90% C.L. In a similar time scale, and with similar beam parameters, **COMET-II** at **JPARC's main ring** will reach similar sensitivities.

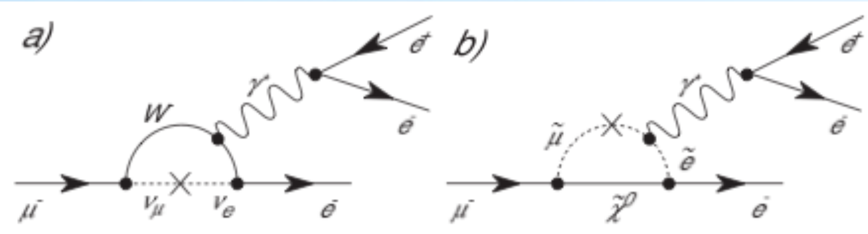
Preliminary studies show that an upgraded Mu2e and PRIME/PRISM (using Ti) at JPARC could increase x10 sensitivity of Mu2e.



Single 105 MeV electron, beyond endpoint of DIO.



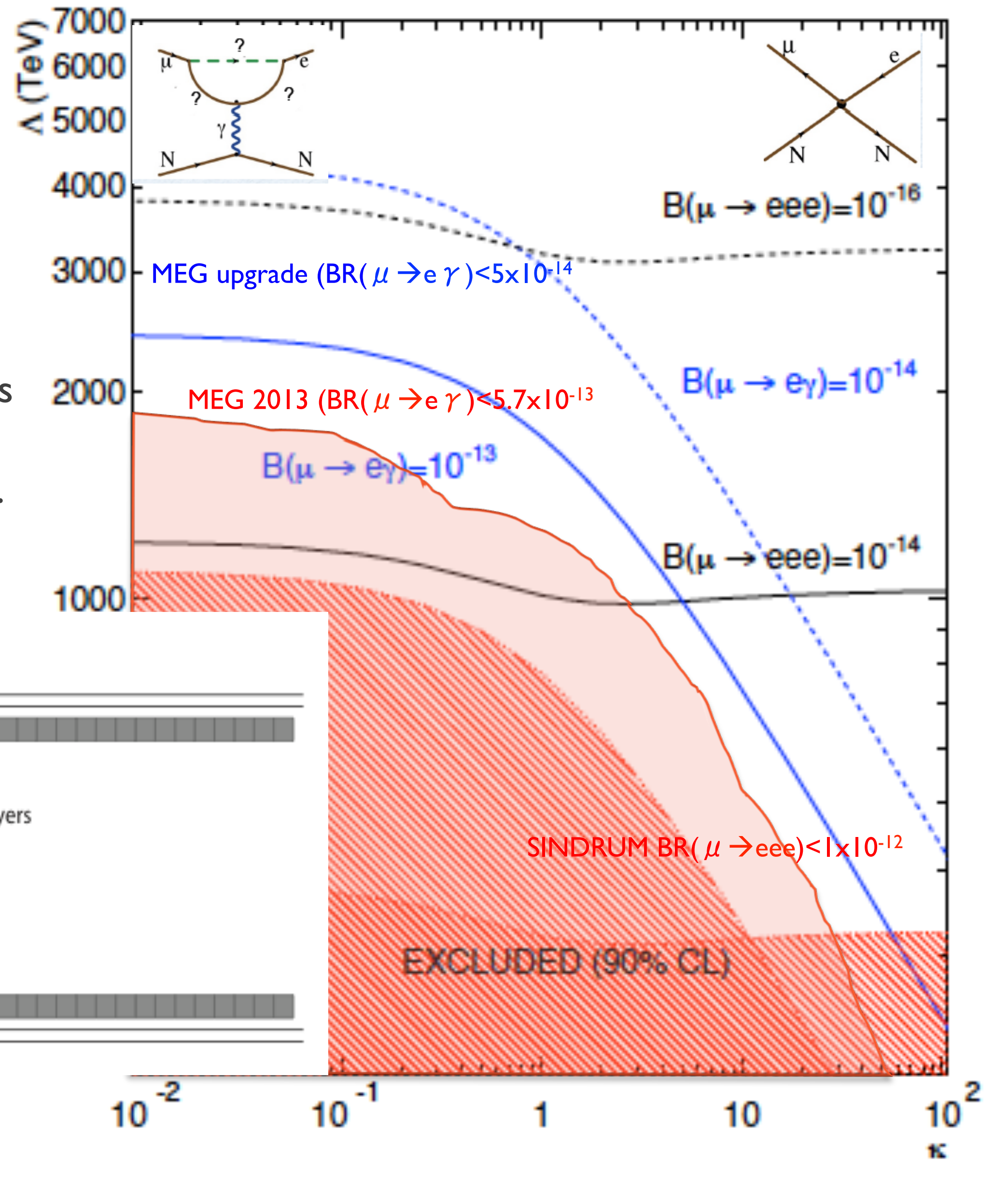
CLFV: $\mu \rightarrow eee$

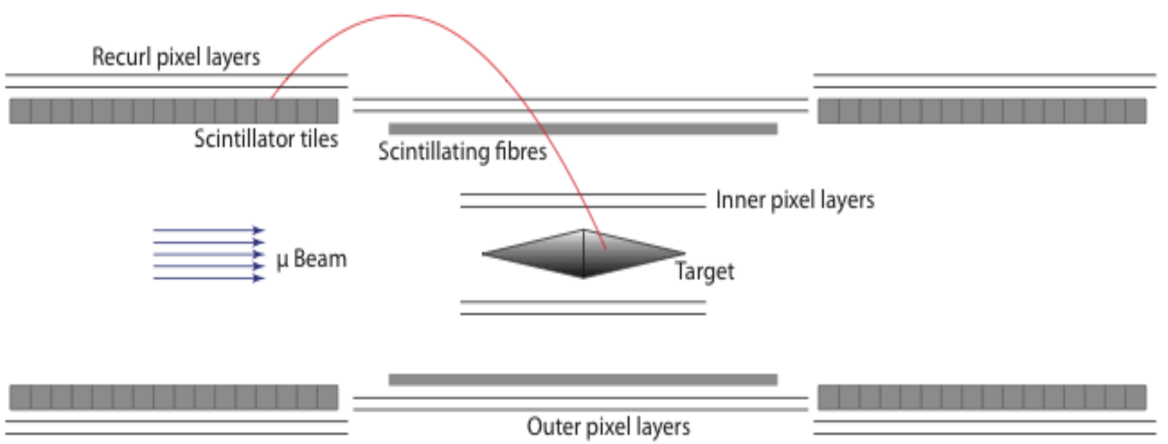


The best limit BR($\mu \rightarrow$eee)<10^{-12} is from **SINDRUM**, with essentially zero bkg.

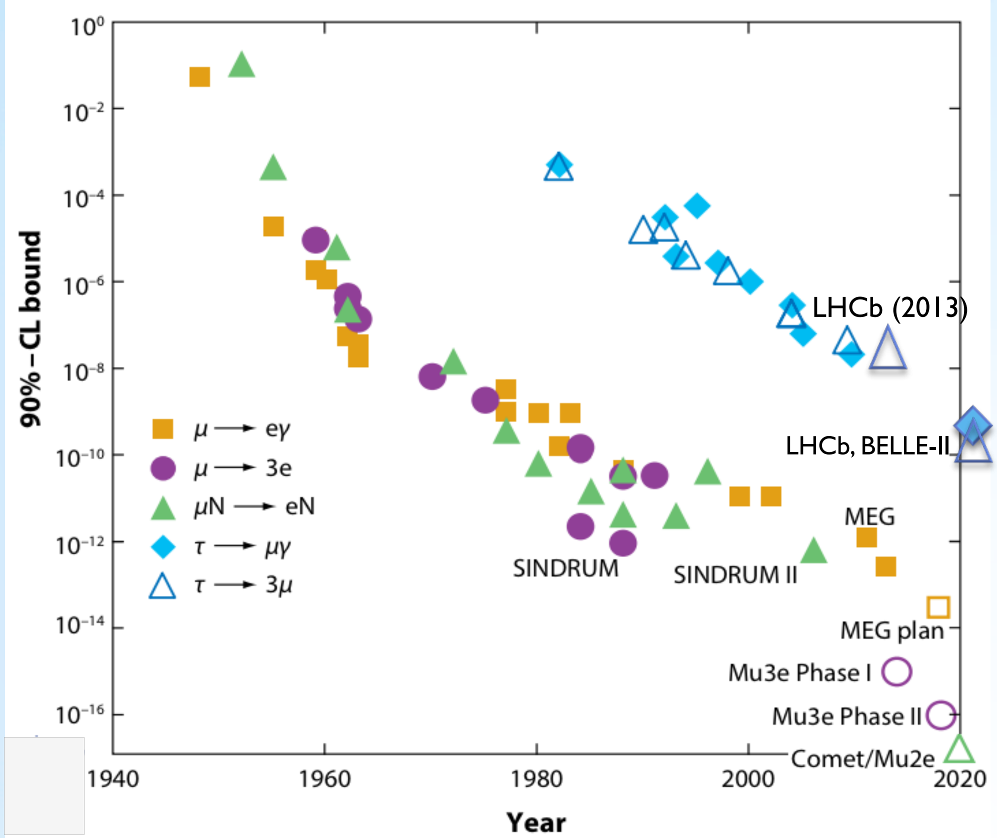
Mu3e proposal improves sensitivity to 10^{-16}, by using the proposed **HiMB line at PSI**, with rates of 2×10^{19} μ/sec DC beams. Accidental bkg are under control with excellent detector resolution. Limitation may come from $\mu \rightarrow e\nu\nu\gamma$(ee).

Modified from A.Gouvea and P.Vogel, arXiv:1303.4097





CLFV: Tau Decays



In principle τ are **more sensitive** per event than μ since mass typically decreases GIM suppression, (>500).

However, production rates at e^+e^- B-factories are not in the same league!

With ~1.4×10^9 τ events the best limits at 90% C.L. are:

arXiv:1001.3221, arXiv:1002.4550

	BR($\tau \rightarrow \mu\gamma$)	BR($\tau \rightarrow \mu\mu\mu$)
BELLE:	4.5×10^{-8}	2.1×10^{-8}
BABAR:	4.4×10^{-8}	3.3×10^{-8}

However, **at the LHC τ are copiously produced** (mainly from charm decays, $D_s \rightarrow \tau\nu$). At 7 TeV pp collisions, ~8×10^{10} τ/fb^{-1} are produced (~5×10^{14} at HL-LHC!). Recently, **LHCb** has reached similar sensitivities for BR($\tau \rightarrow \mu\mu\mu$) than B-factories using $3fb^{-1}$,

LHCb: BR($\tau \rightarrow \mu\mu\mu$)<5.6(4.6)x$10^{-8}$ at 95(90)% CL.

New at TAU 2014

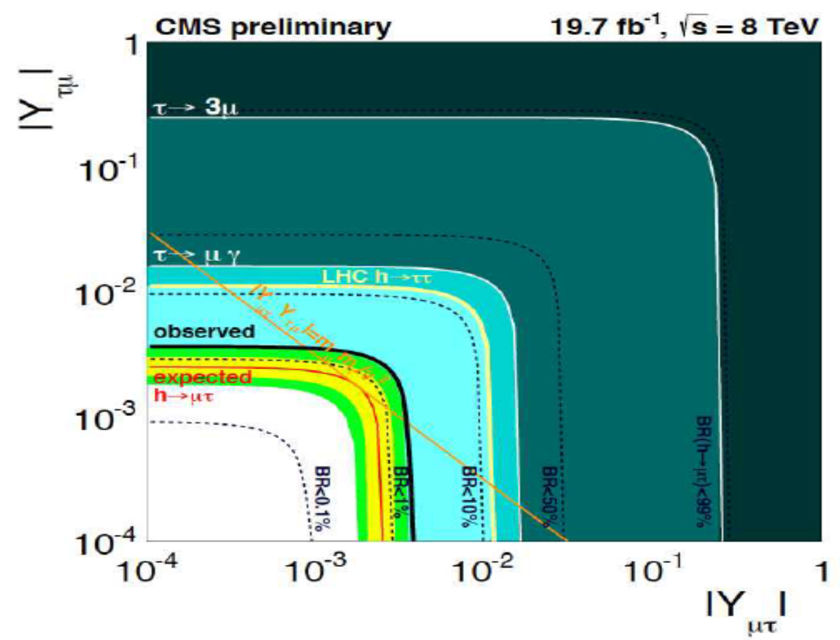
Large bkg component in the most sensitive region is ($D_s^+ \rightarrow \eta[\mu\mu\gamma]\mu\nu$).
BELLE-II and LHCb will reach similar sensitivities O(10^{-9}).

Interplay between HFVD and CLFV

In a generic approach, CMS has look for non-diagonal Yukawa couplings, and observe ~2.5 σ excess, that can be interpreted as:

$$Br(H \to \mu\tau) < 1.57\% \quad (95\%\ CL)$$

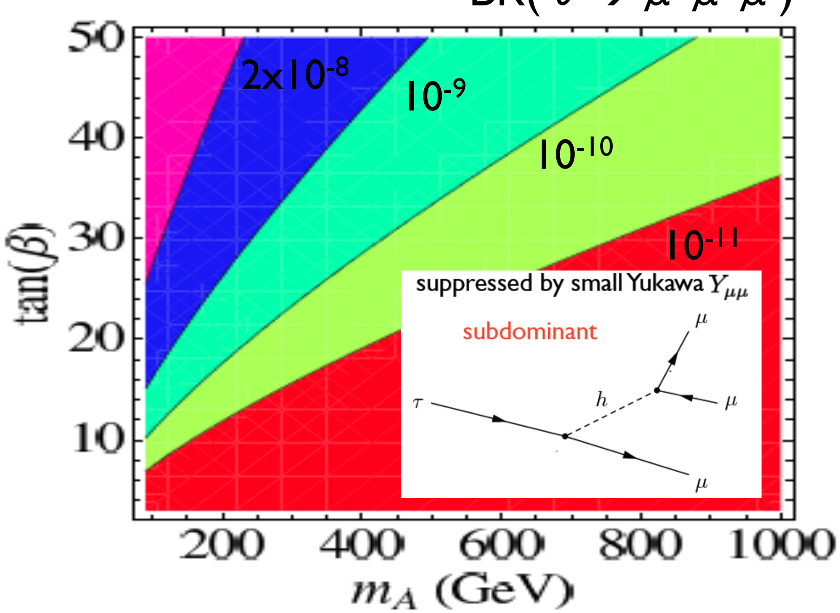
(CMS-PAS-HIG-14-005)
Expected limit: (0.75±0.38)%

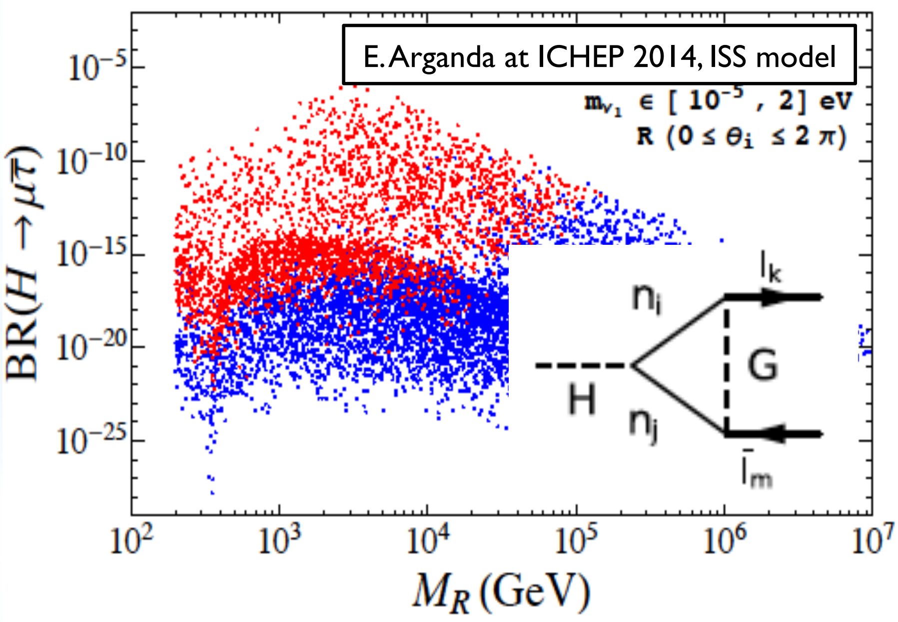


However, once a specific model to generate neutrino masses is defined (f.i. ISS), correlations between CLFV and HFVD may not be trivial.

Interplay between low energy precision measurements and precise measurements of Higgs properties.

BR($\tau \to \mu\ \mu\ \mu$)



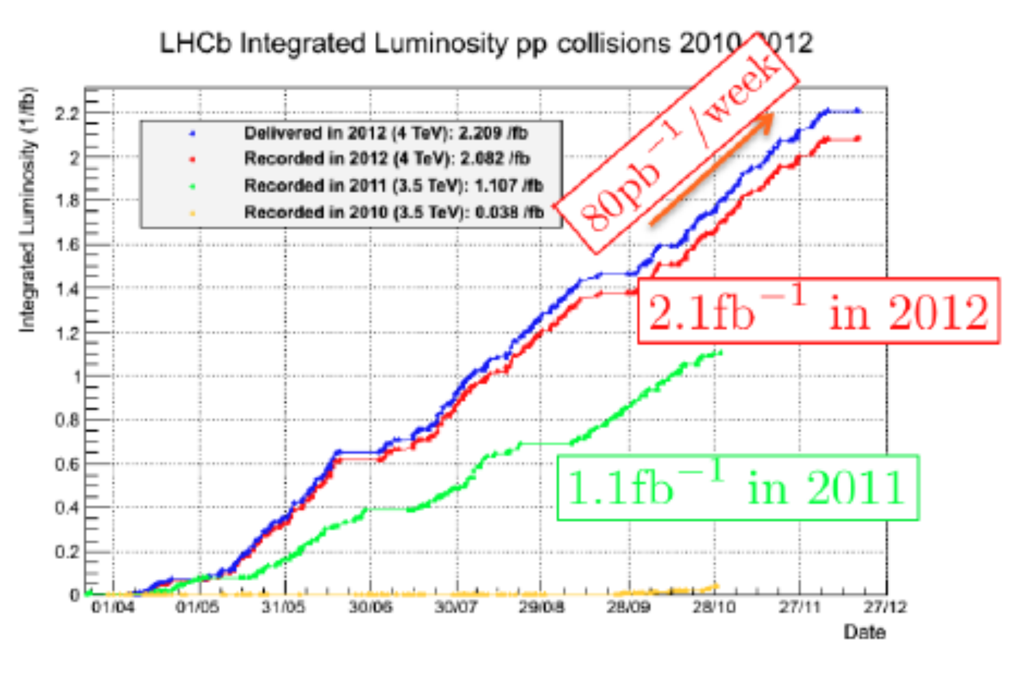


Excluded by $\mu \to e\gamma$. Allowed by all the constraints.

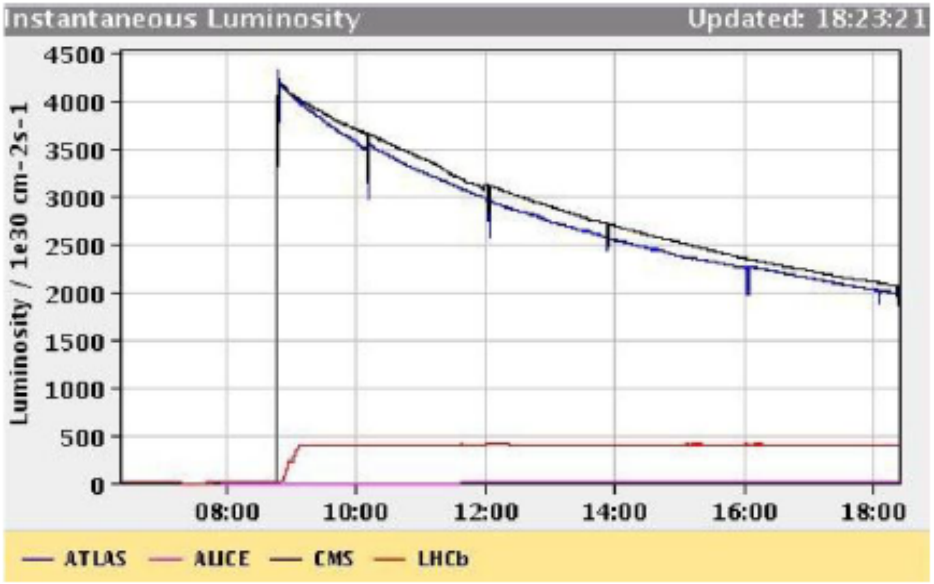
Status of experimental measurements in the quark sector.

LHC is working like a dream!

Since the first proton-proton collisions at the LHC at 7 TeV in Spring 2010, the progress has been fantastic!



In 2012 LHC delivered routinely peak luminosities of $4 \times 10^{33}/cm^2/sec$ at 8 TeV, for a total of 23/fb to **ATLAS&CMS** (6/fb in 2011 at 7 TeV).



LHCb took data at a constant luminosity $0.4 \times 10^{33}/cm^2/sec$ thanks to luminosity leveling, for a total of 2.2/fb at 8 TeV delivered (1.2/fb in 2011 at 7 TeV).

LHCb average number of visible pp collisions per bunch crossing ~2, while for ATLAS/CMS is ~20.

LHC is working like a dream!

The bb x-section was measured by LHCb at 7 and 8 TeV to be: $(284\pm53)\times10^{9}$ fb (PLB 694, 209) and $(298\pm36)\times10^{9}$ fb (arXiv:1304.6977). The cc x-section ~20 times higher! (arXiv:1302.2864)

About 40% of the b-quarks produced at the LHC fragments into $B^{\pm}$ and another 40% into B^{0}, while 10% fragments into B_s and 10% into baryons.

However at the LHC, the two b-quarks are produced incoherently → extra dilution factor in the tagging of neutral mesons.

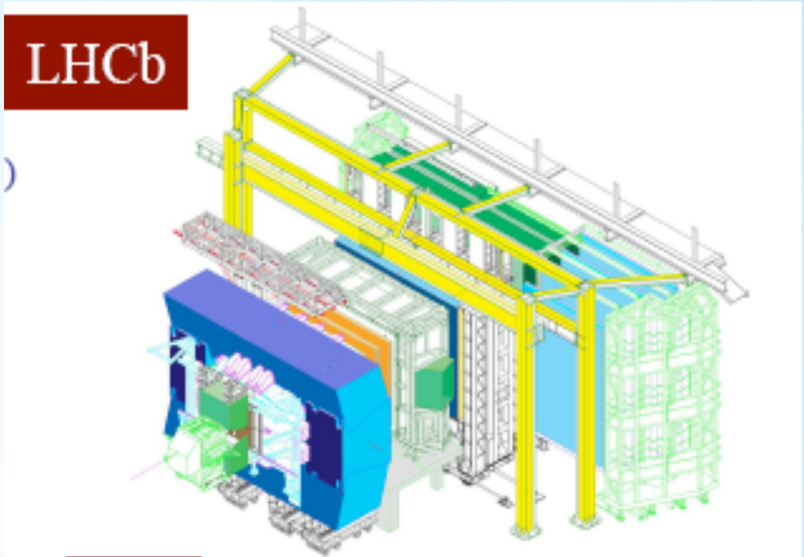
The LHCb detector acceptance ranges between ~10% for $B_s \to \mu^+\mu^-$ decays to, for instance, ~5% for $B_s \to J/\Psi[\mu^+\mu^-]\Phi[K^+K^-]$.

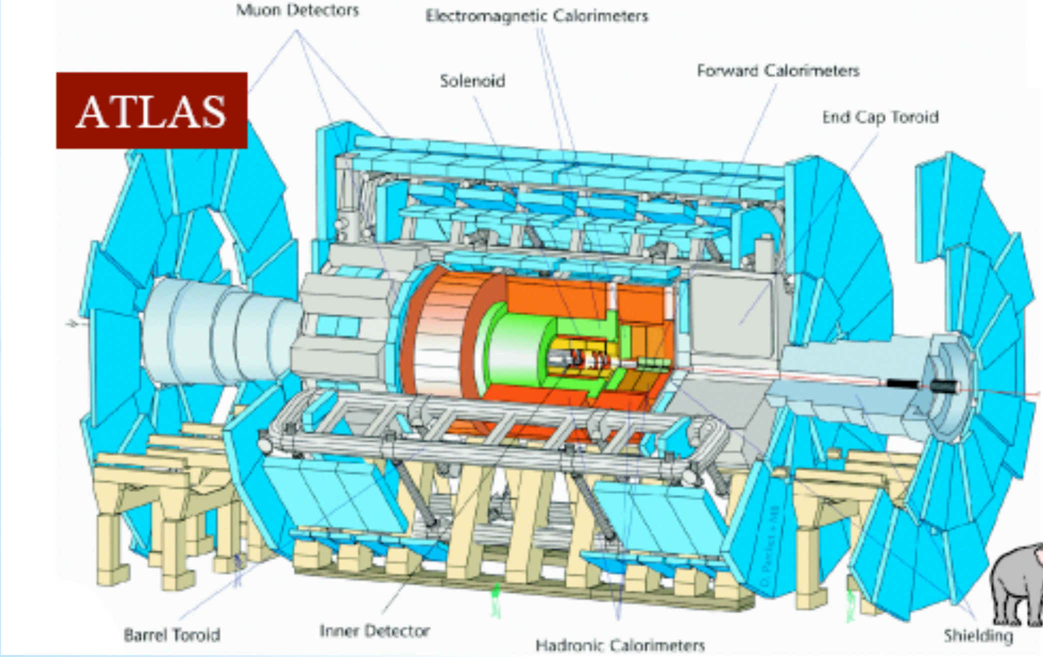
Rule of thumb:

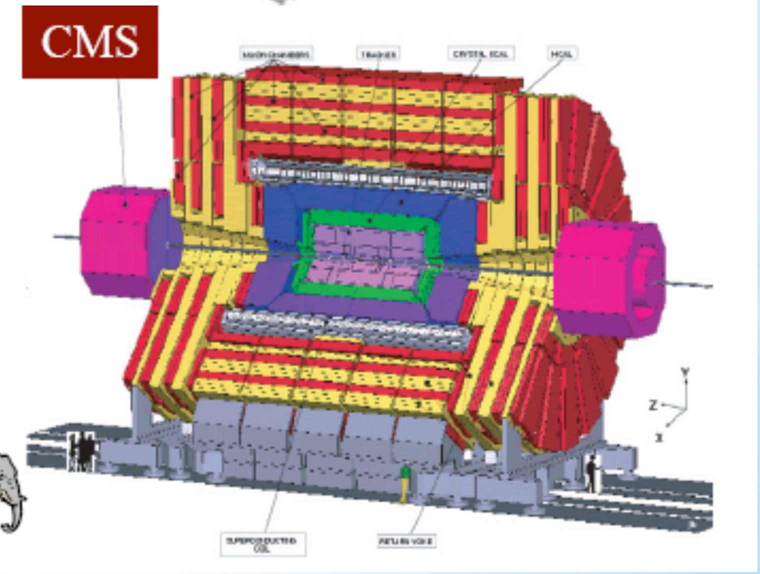
1/fb at 7TeV at LHCb is equivalent to (1k-5k)/fb at the e^+e^- B-factories before tagging for $B^0/B^{\pm}$ decays into charged particles.

LHC detectors for pp physics

- **ATLAS/CMS**
  - General purpose experiments optimized for high Pt Physics at 10^{34} cm^{-2} s^{-1}
- **LHCb**
  - Dedicated (b,c)-Physics experiment



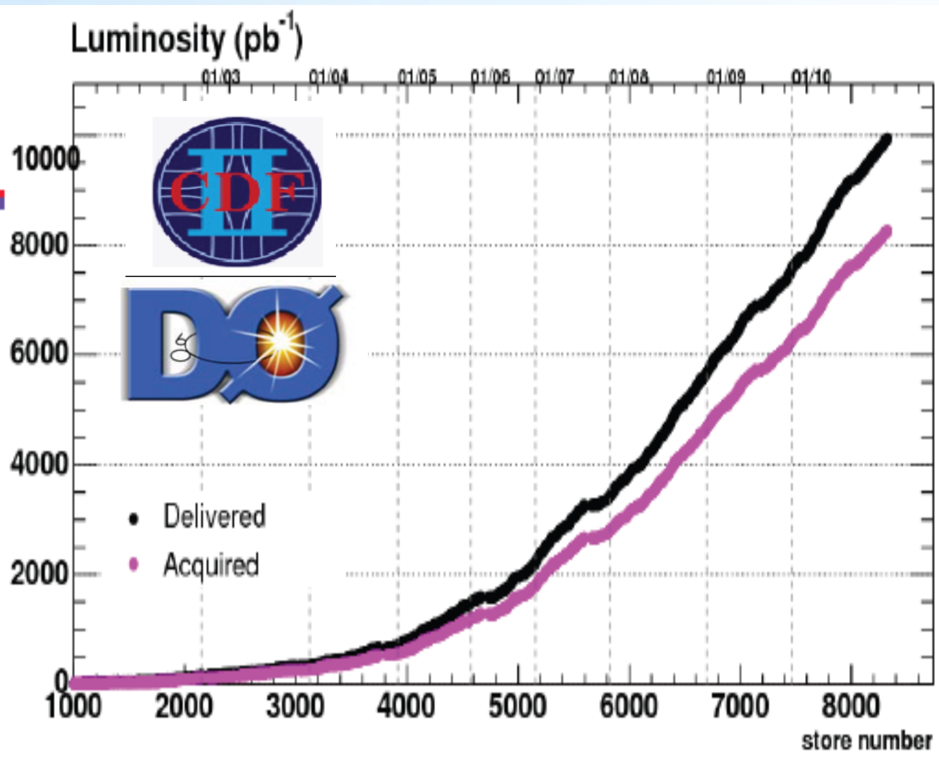


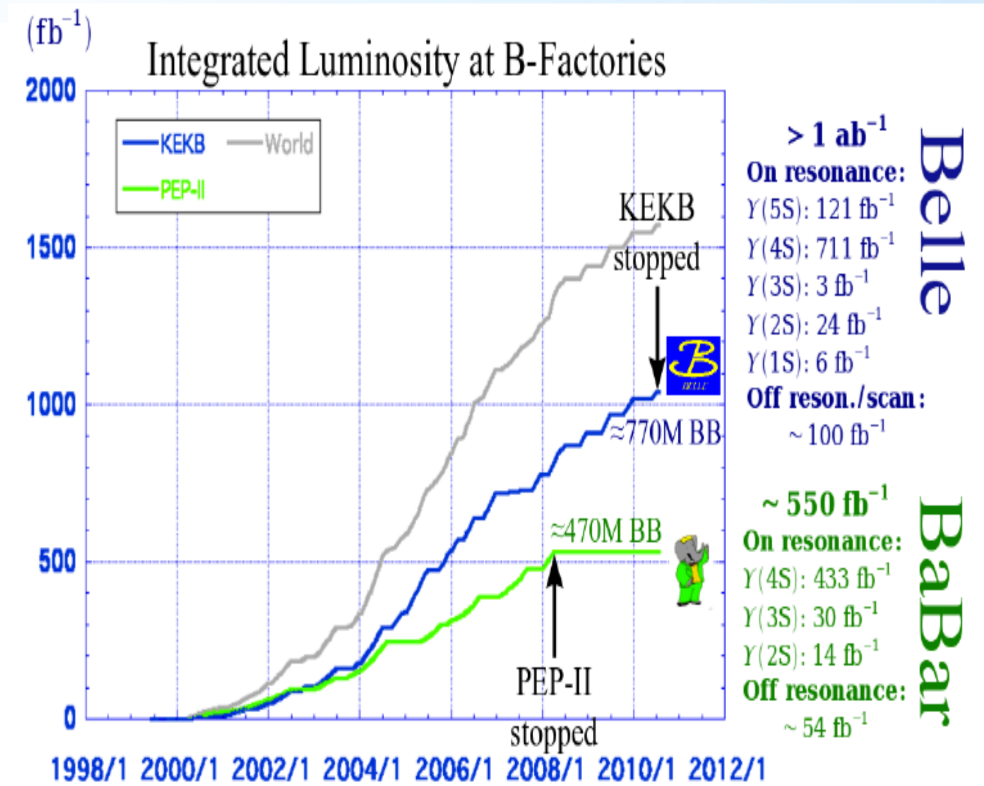


Standing on the shoulders of giants

But the path the LHC experiments have just started to walk, has been paved by the amazing performance and results from the predecessors.

CDF pioneering work with the vertex trigger in a hadron collider deserves special mention (my personal bias).





LHCb detector

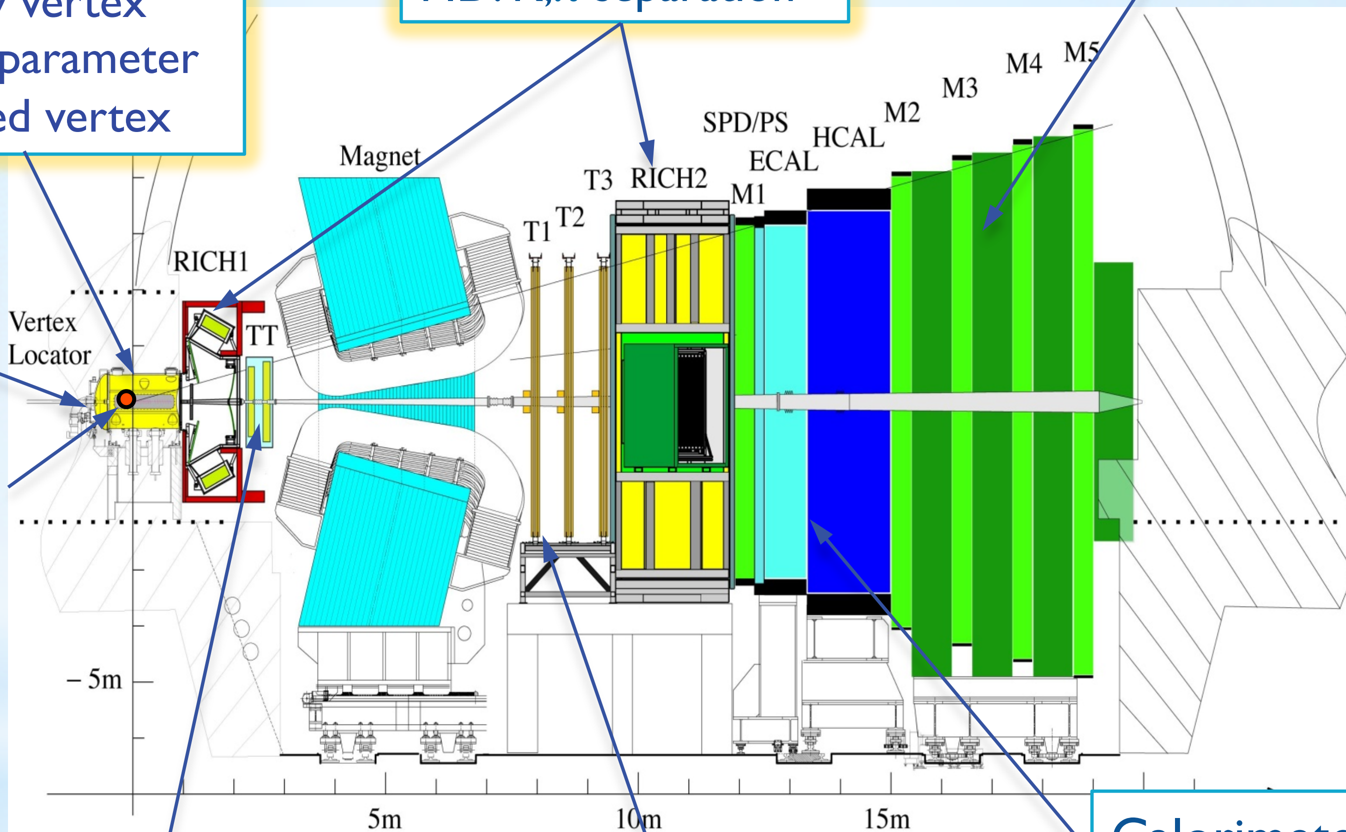
VELO:
primary vertex
impact parameter
displaced vertex

RICHES:
PID: K,π separation

Muon System

PileUp System

Interaction region

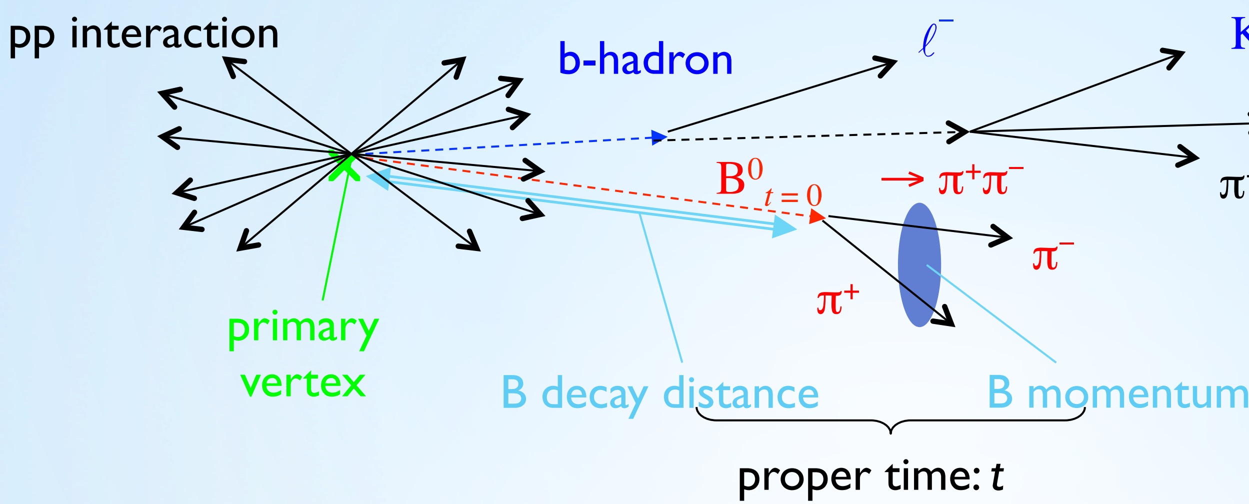


Trigger Tracker: p for trigger and K_s reco

Tracking Stations:
p of charged particles

Calorimeters:
PID: e,γ, π^0

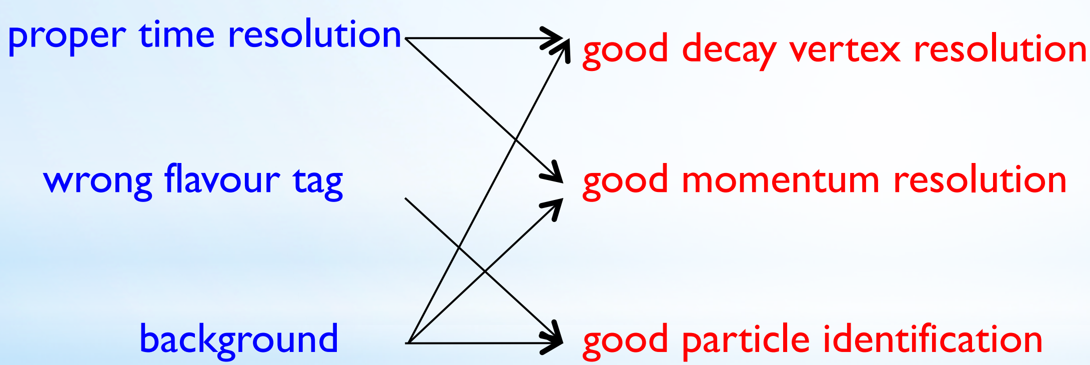
Detector requirements

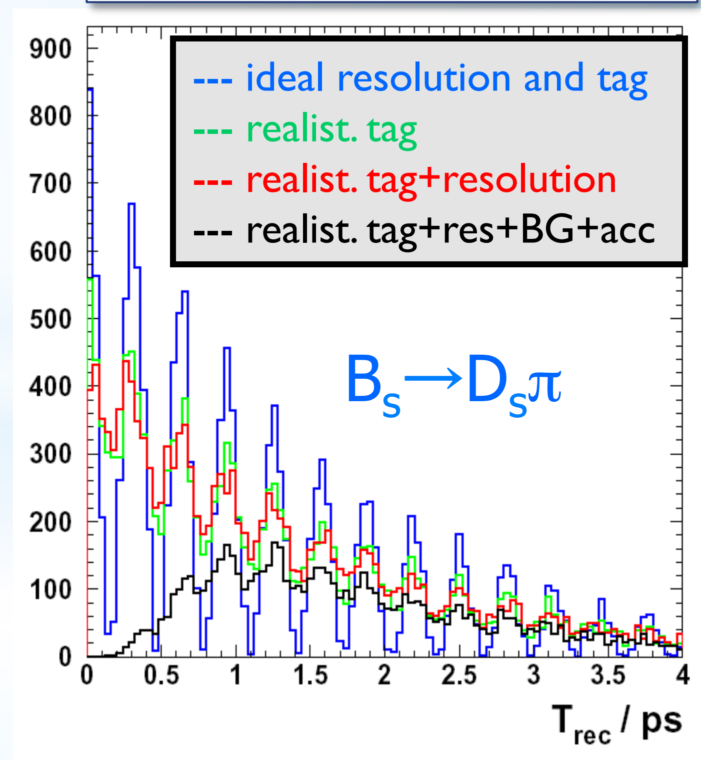


$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$$A_{CP}(t) = \frac{\eta_f \sin\phi_s \sin(\Delta m_s)t}{\cosh(\Delta\Gamma_s t/2) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s t/2)}$$

CP violating oscillation amplitudes are damped by

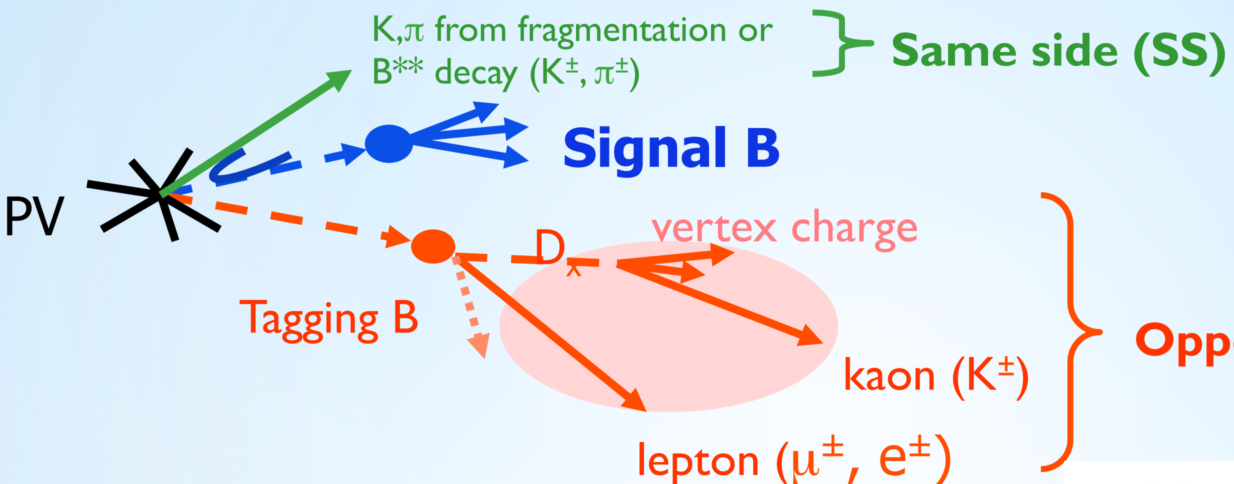


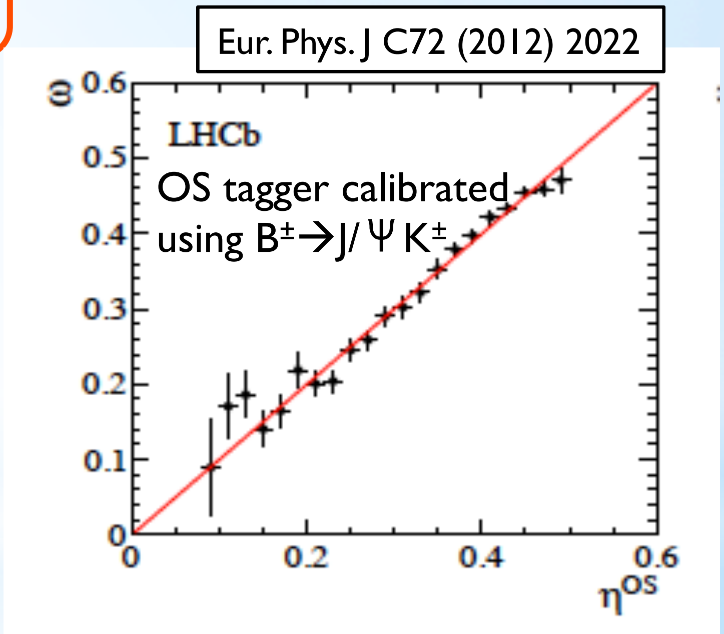


Exercise: Can you show that $A^{meas}(t) \approx D_{tag}\, D_{res}\, A(t)$
with $D_{tag} = (1-2w)$ and $D_{res} = \exp(-(\Delta m\, \sigma_t)^2/2)$.

What relative precision do you need to know these dilution factors if you want the total systematic uncertainty ≤0.01?

Flavour Tagging





Flavour tagging algorithms are not perfect!

Backgrounds in tagger selections

The *tagging B* can oscillate incoherently (unlike in B-factories):

40% $B^\pm$, 10% baryons : no oscillation ☺

40% B_d: $\Delta m_d \sim \Gamma_d \Rightarrow$ oscillated 17.5% ☺

10% B_s: $\Delta m_s >> \Gamma_s \Rightarrow$ oscillated 50% ☹

Characterization of tagging algorithms:

ε^{tag}: fraction of events with a tag

$\omega \equiv N^W/(N^W+N^R)$: wrong tag fraction

$\varepsilon^{eff} \equiv \varepsilon^{tag}(1-2\omega)^2$: effective tagging efficiency

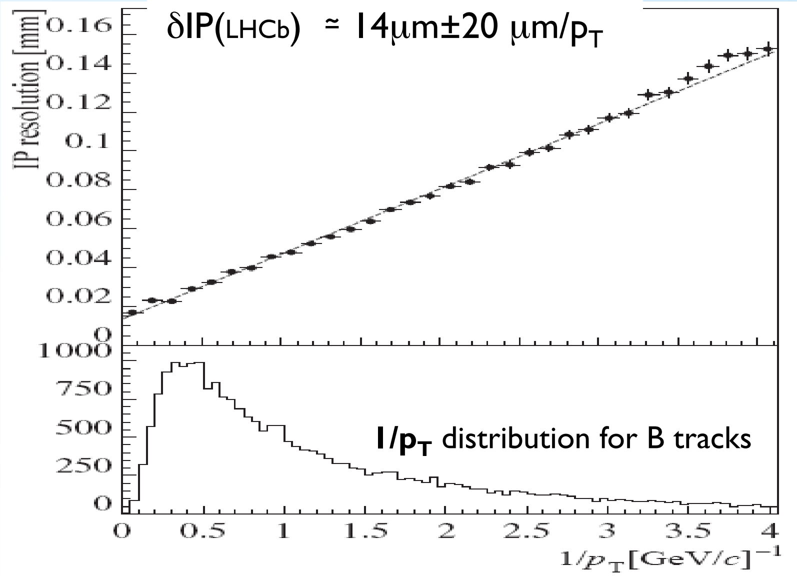
CDF/LHCb ε_{eff} ~4% for B_s
BABAR/BELLE ε_{eff} ~30% for B_d

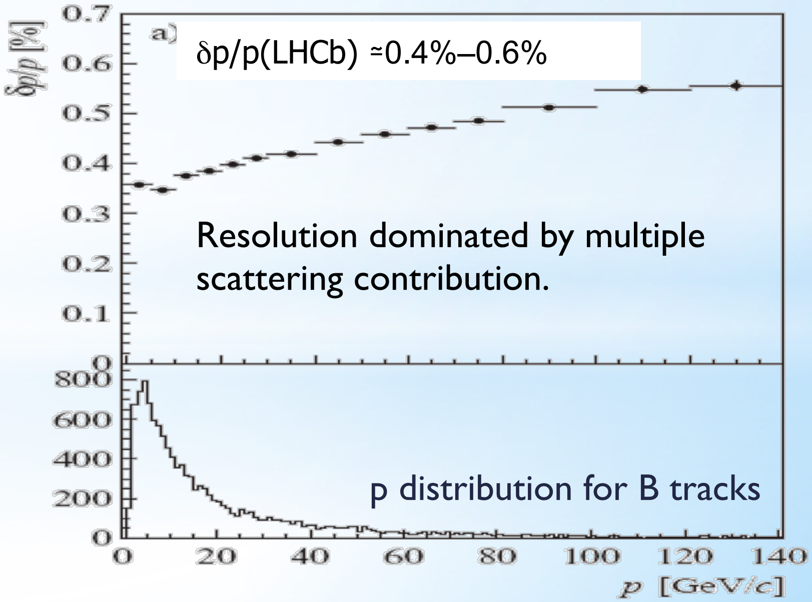
Tracking performance: Momentum and impact parameter resolution

	ATLAS Si Pixel	CMS Si Pixel	LHCb Si VELO
N channels	80 M	66 M	170 k
Size	50x400 μm (pixel)	100x150 μm (pixel)	40 μm (strip)
Distance to beam	8.8 cm	4.4 cm	0.8 cm

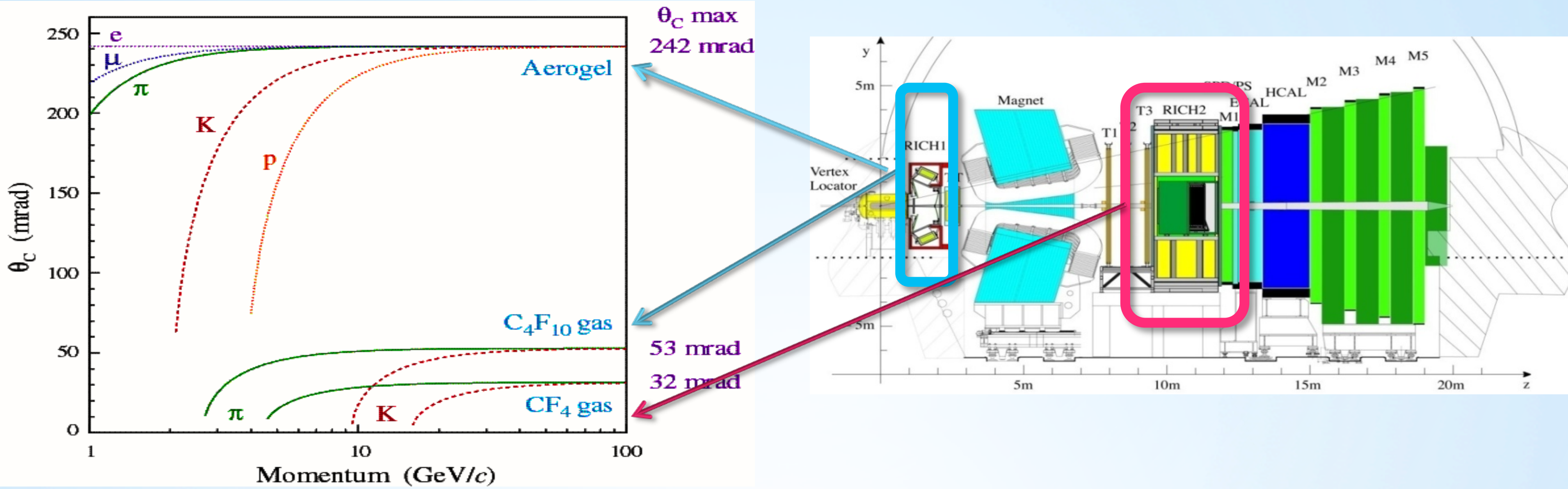
Integral Bdl: CMS/LHCb ~ 4 Tm, ATLAS ~2.5 Tm

	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	**45 fs**
Invariant Mass resolution (2-body)	80 MeV/c²	45 MeV/c²	25 MeV/c²	**22 MeV/c²**

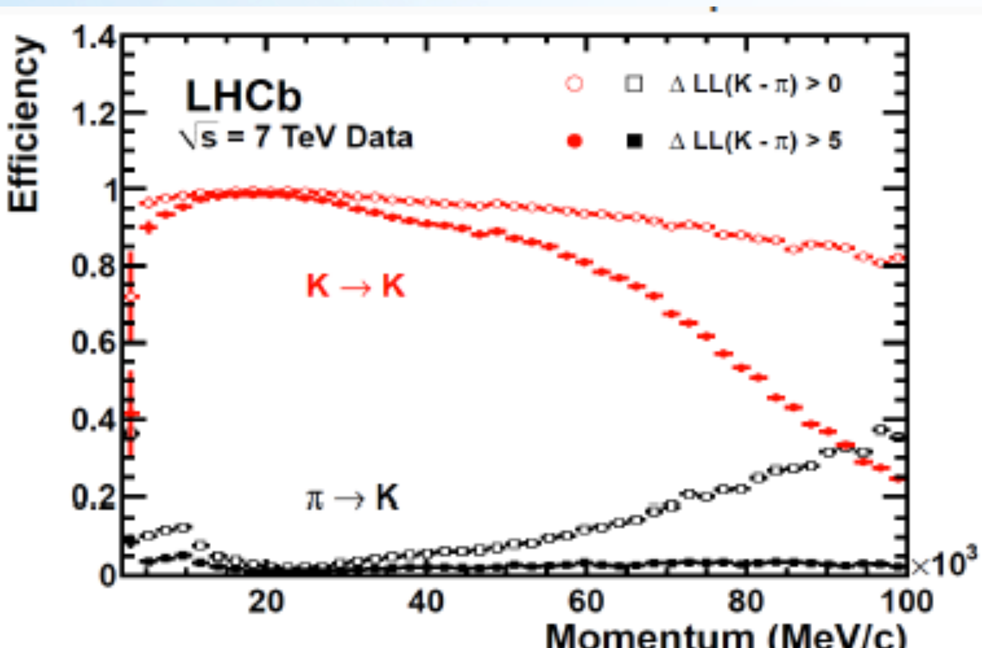


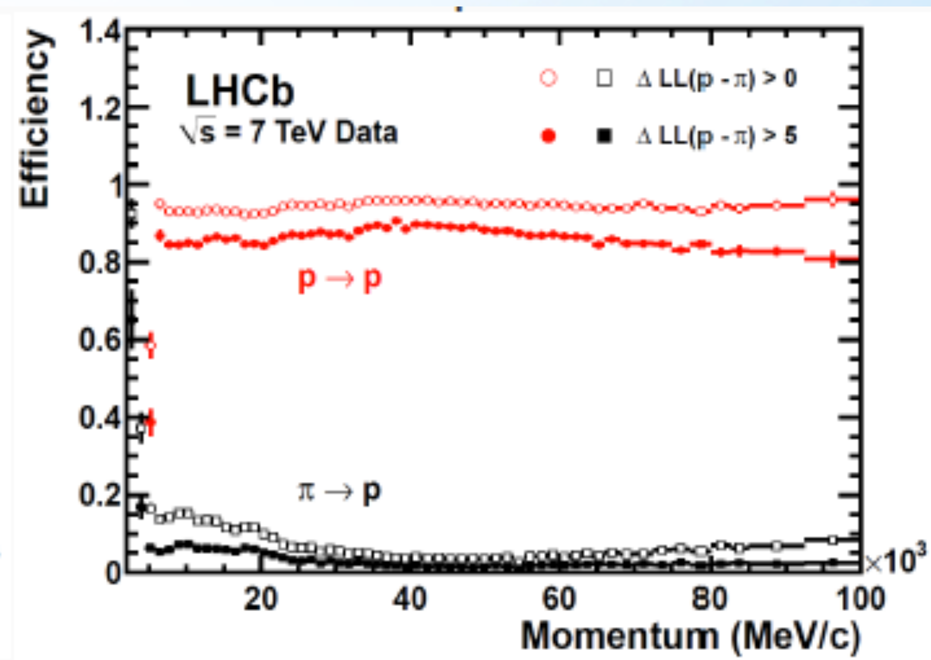


LHCb Particle Identification

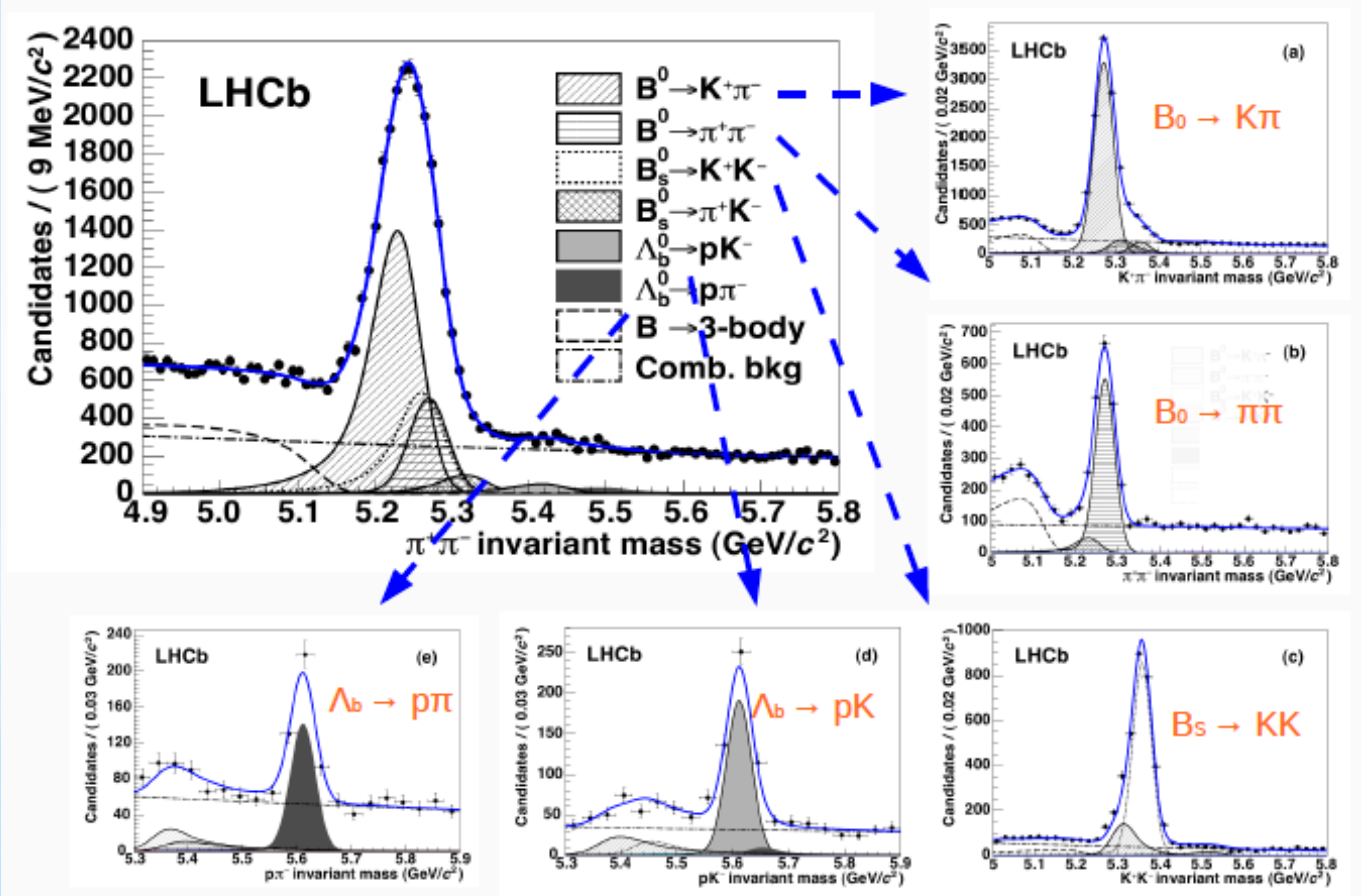


Efficiencies computed from data: pure samples of kinematically selected $K_s \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$, $D^0 \rightarrow K^+\pi^-$



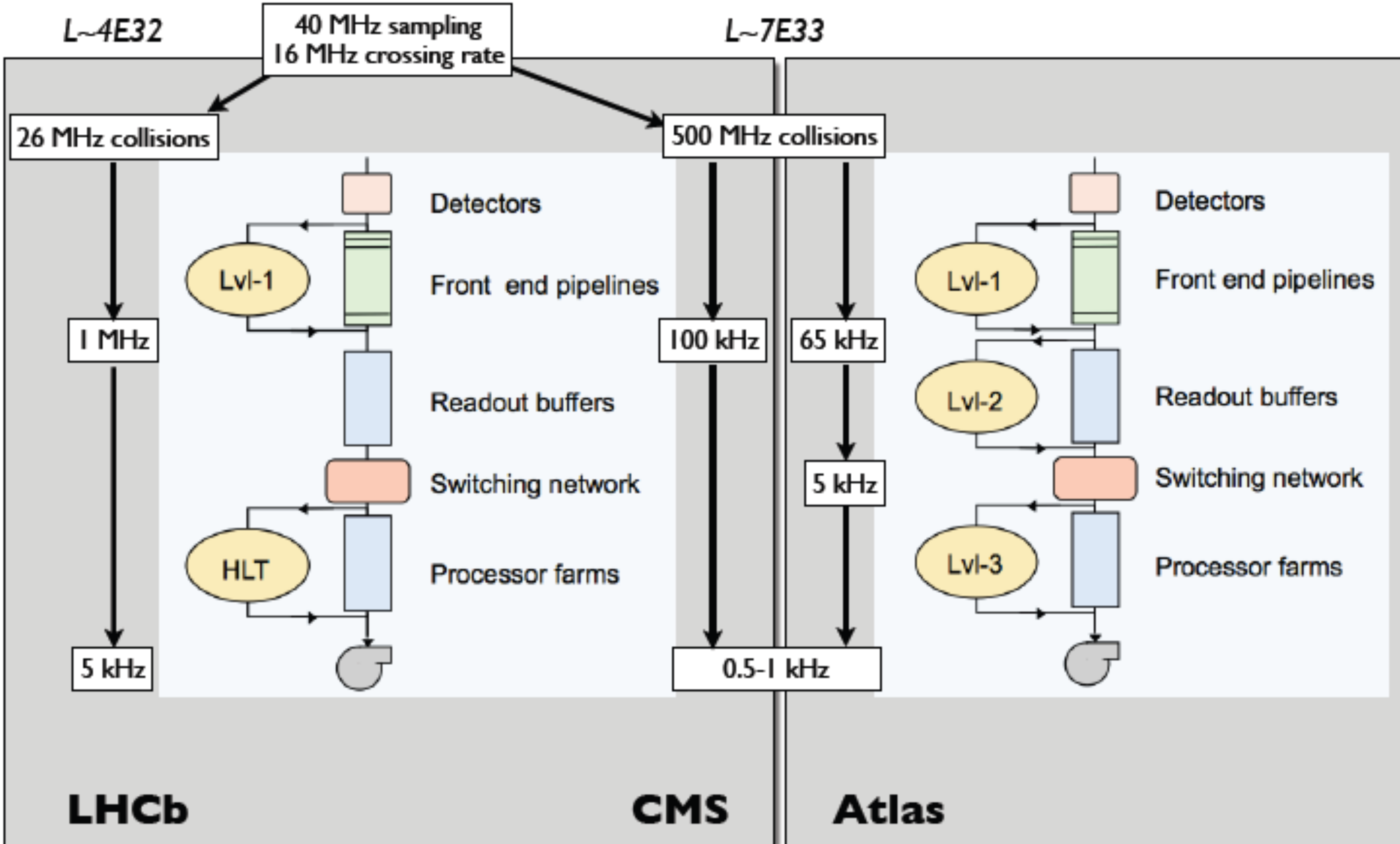


LHCb Particle Identification



JHEP10 (2012) 037

Trigger systems at LHC



LHCb Trigger System

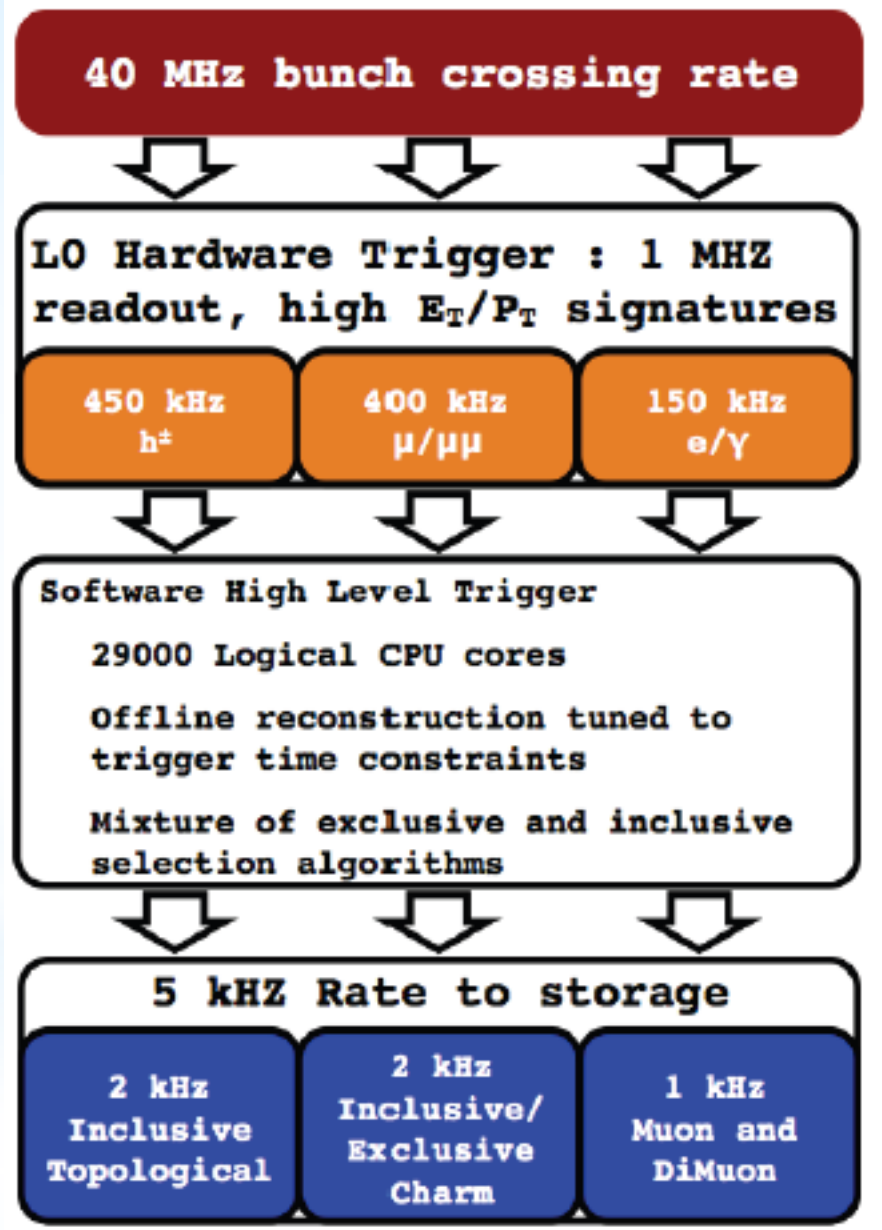
LHCb trigger output rate completely saturated by bb/cc events. However, only interested in relatively rare events (BR$<10^{-3}$) → the **LHCb trigger is what is called b-tagging** at ATLAS/CMS!

For bb an inclusive approach just works fine, but need exclusive selections for cc.

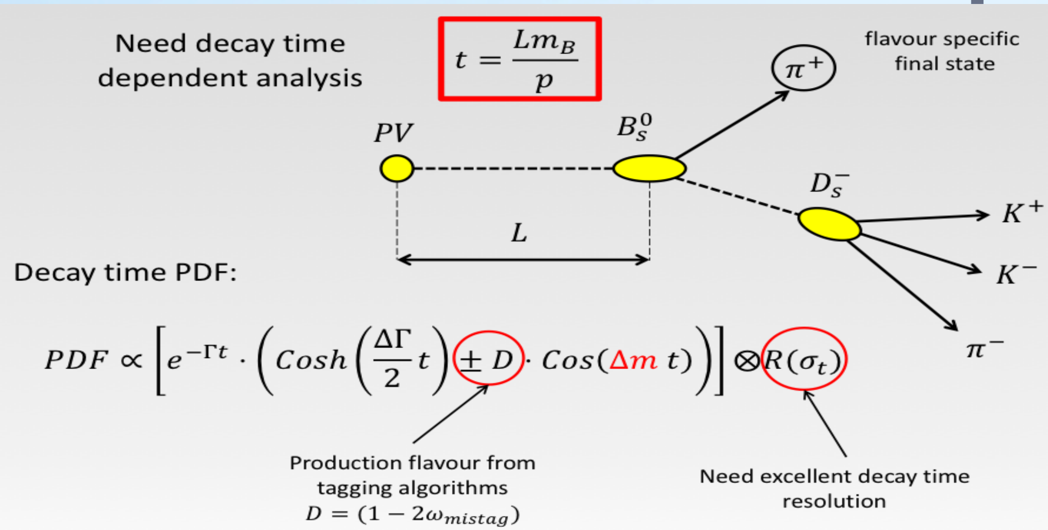
One synchronous **hardware** level, DAQ rate limited to **1 MHz.**

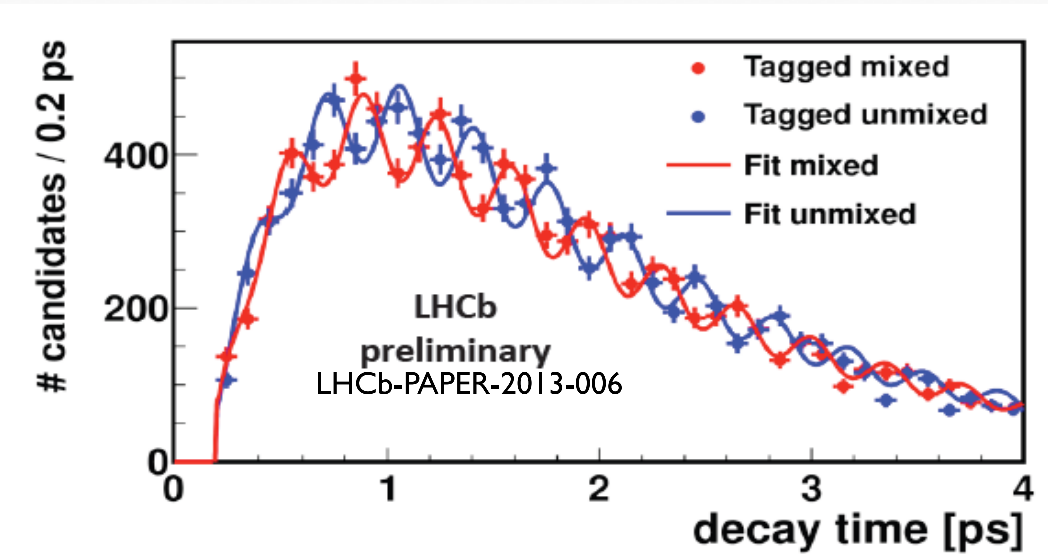
Computing farm with **software HLT.**

- First rate reduction based on track reconstruction (**~80 kHz**).
- Final inclusive/exclusive algorithms reconstruct B/D candidates (**~5 kHz**).



…and the LHCb performance is up to it!





$B_s \rightarrow D_s^- [K^-K^+\pi^-]\pi^+$

Hadron trigger **~34k candidates/fb**

Proper time resolution **~ 44 fs**
(to be compared with $2\pi^{-1} \Delta m_s^{-1}$~350 fs)

Effective tagging **~3.5%**

Δm_s = 17.768±0.023±0.006 ps^{-1}

c.f. CDF with proper time resol. ~87 fs
Δm_s = 17.77±0.10±0.07 ps^{-1}.

Precision measurements at hadron colliders are not any more a dream!

(Parenthesis)Advantages/Disadvantages of Existing Facilities

Common "past" knowledge:

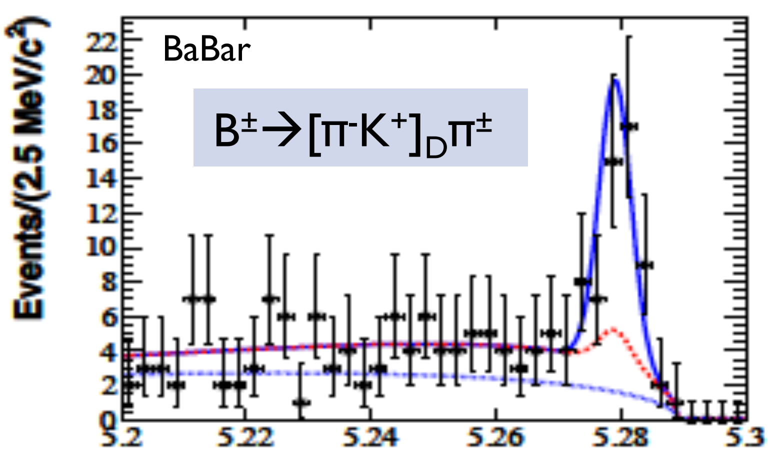
lepton colliders → precision measurements vs **hadron colliders** → discovery machines

After the achievements at the TeVatron in precision EW measurements (W mass) and B-physics results (Δm_s) and in particular the astonishing initial performance of LHCb, I think the above mantra **is over simplistic and not true**.

Lepton colliders have the advantage of a known CoM energy, better selection efficiencies and high luminosities (10^{34}-10^{36}) $cm^{-2}s$. However, at the $\Upsilon(4S)$ only $_{B(d,u)}$ mesons are produced.

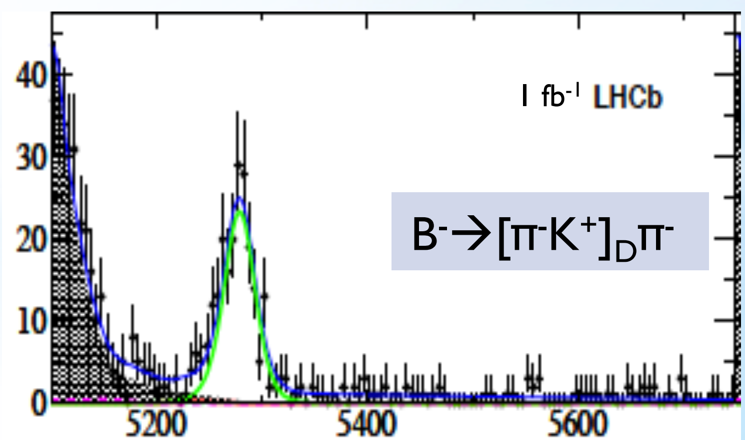
Hadron colliders have a very large cross-section ($\sigma_{bb}(LHC7) \sim 3\times10^5 \sigma_{bb}(\Upsilon(4S))$), very performing detectors and trigger system. Effective tagging efficiency is typically x10 better at lepton colliders.

arXiv:1006.4241



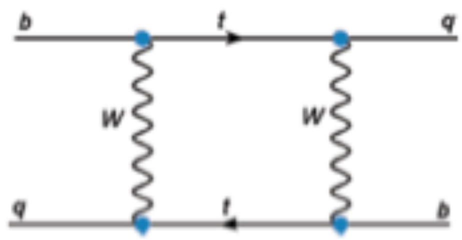
Energy-substituted mass (GeV/c²)

arXiv:1203.3662

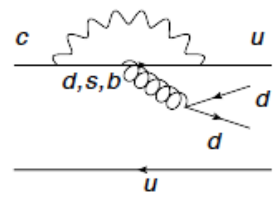


Invariant mass (MeV/c²)

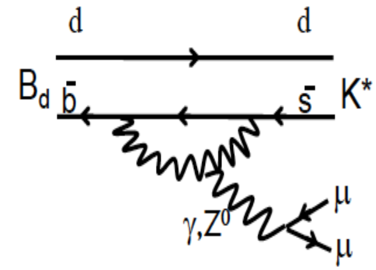
FCNC loops in the SM



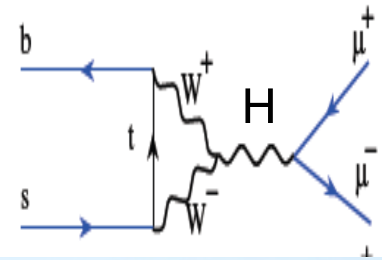
$\Delta F=2$ box



QCD Penguin



EW Penguin



Higgs Penguin

*Map of Flavour transitions and type of loop processes: → **Map of these lectures!***

	b→s ($\lvert V_{tb}V_{ts}\rvert \alpha \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert \alpha \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert \alpha \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert \alpha \lambda^5$)
$\Delta F=2$ box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi \Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)} ll$, $B \to X_s \gamma$	$B \to \pi ll$, $B \to X \gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu \nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu \mu$	$B \to \mu \mu$	$K \to \mu \mu$	$D \to \mu \mu$

Tree Level Measurements: V_{ub},V_{cb},V_{tb},arg(V_{ub})

Current status of the CKM magnitudes

$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

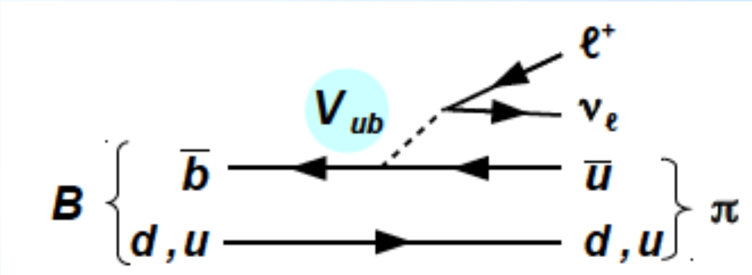
The 2x2 matrix formed by **$|V_{ud}|$,$|V_{us}|$,$|V_{cd}|$ and $|V_{cs}|$** has been measured using nucleus, pion, kaon and charm decays to be "almost" unitary. It only depends on **λ = 0.2253±0.0008.**

This sub-matrix is real up to $O(\lambda^5)$.

$|V_{ub}|$ and $|V_{cb}|$ are measured in semileptonic $B^{\pm}$ and B_d decays: inclusive and exclusive methods.

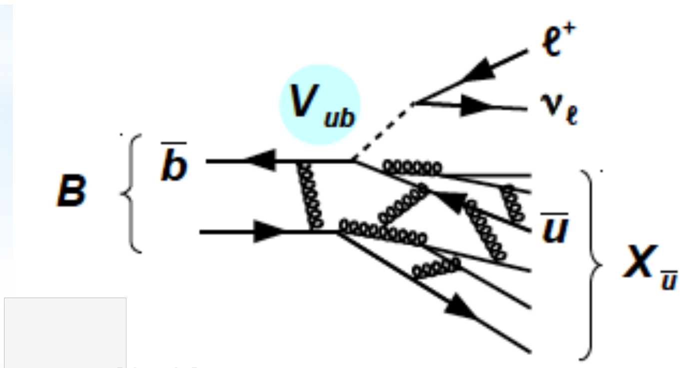
Exclusive measurements "easier" experimentally, but QCD form factors!

$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$



Inclusive measurements more robust theoretically, but need to control experimental backgrounds!

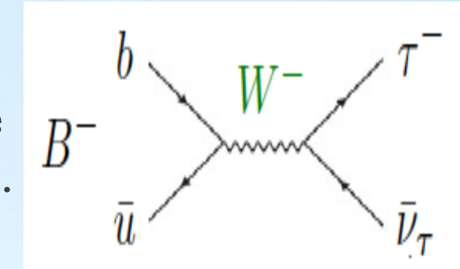
$|V_{ub}| = (4.41 \pm 0.15) \times 10^{-3}$
$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3}$

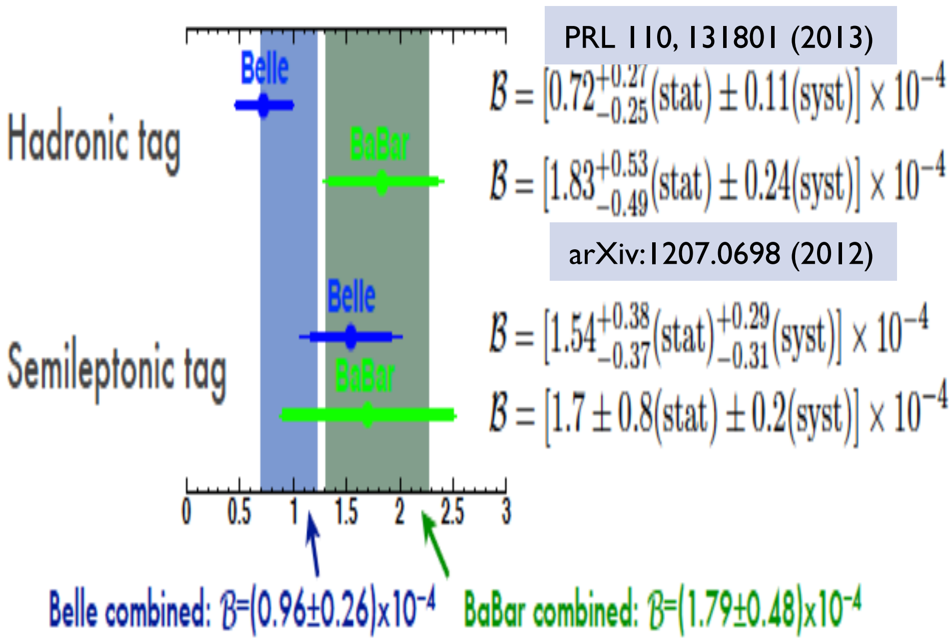


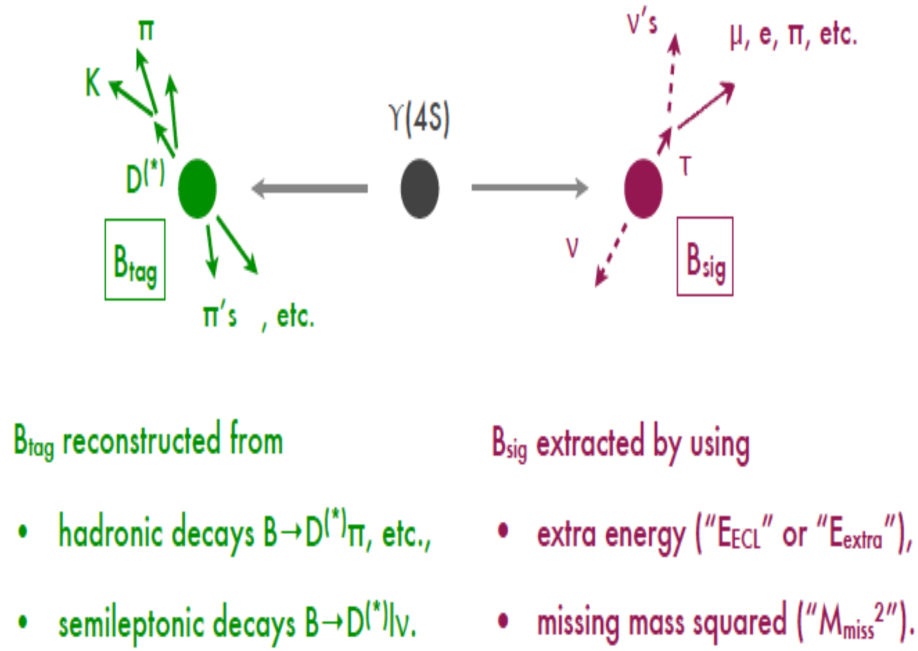
Inclusive measurements ~30% higher, with significances (2-3) σ

b→u: Charged Higgs at tree level?

For some time the measured BR($B \to \tau\nu$) was about **a factor two higher than the CKM fitted** value (3σ), in better agreement with the **inclusive V_{ub}** result. Measurement is very challenging at hadron colliders.







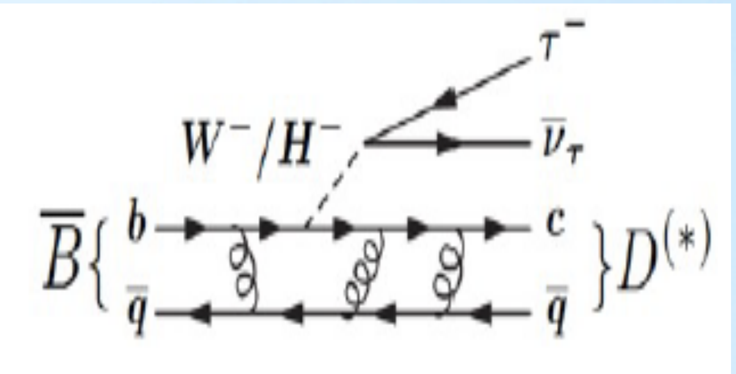
In 2012 **Belle** presented a more precise hadron tag analysis, in better agreement with the fitted CKM value:

World average BR($B \to \tau\nu$)$_{exp}$= $(1.15 \pm 0.23) \times 10^{-4}$ vs CKM fit:$(0.83 \pm 0.09) \times 10^{-4}$

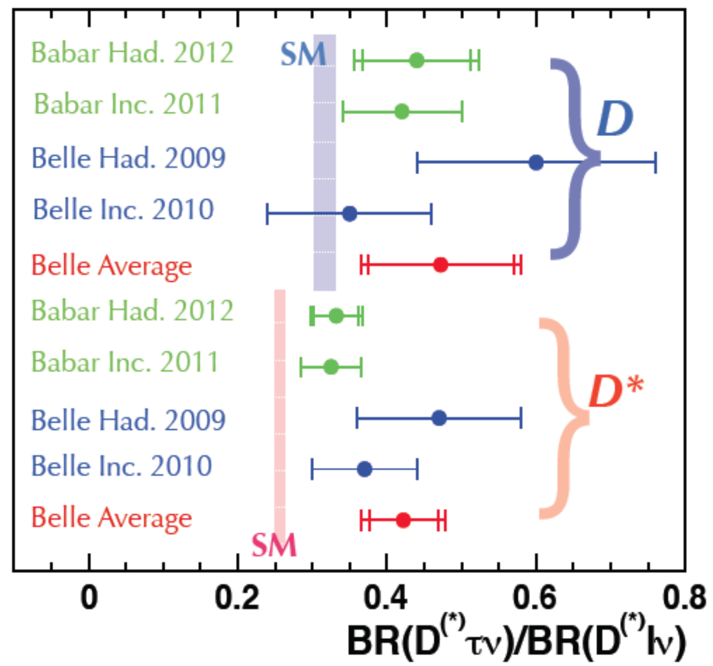
b→c: Charged Higgs at tree level?

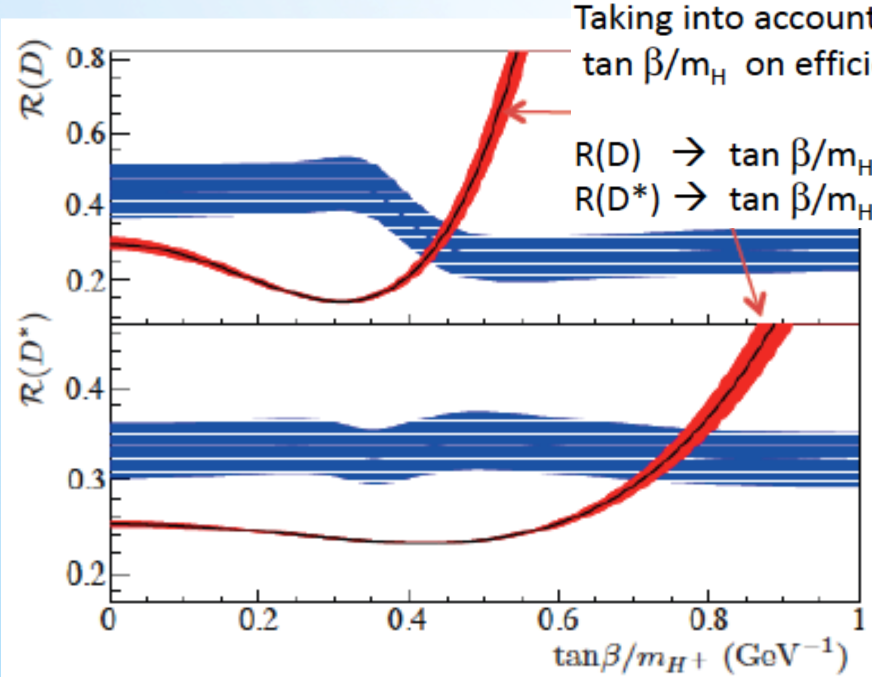
BABAR also presented in 2012 a more precise measurement of BR(B→D(*) $\tau\ \nu$)/BR(B→D(*)l ν).

Ratio cancels V_{cb} and QCD uncertainties. Combined D and D* BABAR results are **3.4 σ higher than SM**



Not obvious NP explanation. 2HDM need to be stretched to be able to explain the measured ratio at BABAR, and in any case it would be in tension with the latest measurements of BR(B→ $\tau\ \nu$).





Taking into account the effect of $\tan\beta/m_H$ on efficiency

R(D) → $\tan\beta/m_H = 0.44 \pm 0.02$
R(D*) → $\tan\beta/m_H = 0.75 \pm 0.04$

2HDM

Belle should be able to reduce the uncertainties on B→D(*) $\tau\ \nu$ soon at similar level than BABAR.

V_{ub}, V_{cb} Personal Recap.

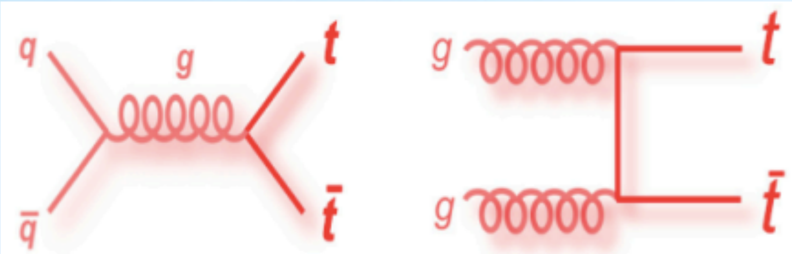
No convincing discrepancy to suggest NP at tree level in the measurements of the magnitudes of $|V_{ub}|, |V_{cb}|$.

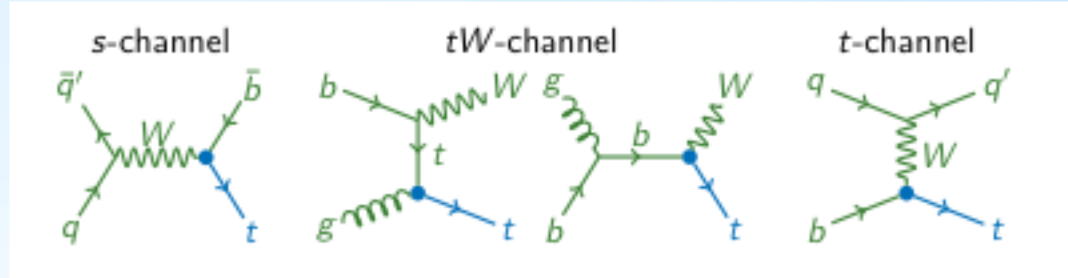
However, the internal discrepancies between V_{ub} inclusive and exclusive measurements, makes more **difficult the comparison with loop** measurements.

This is certainly one of the **most interesting improvements** that could come from the **upgrade of Belle: Belle-II.** In addition to improved measurements in tau channels.

In parallel, new experimental studies of systematic uncertainties is probably worth the effort.

V_{tb} from top decays

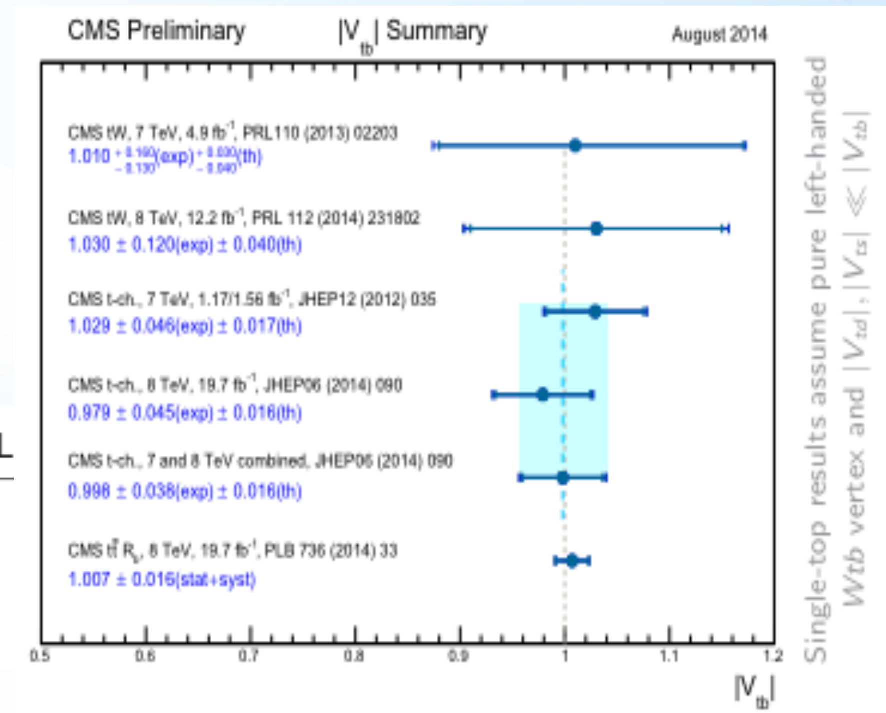




LHC has become also a top factory. **O(5M) tt pairs** produced with 20fb^{-1} at 8 TeV. Also **O(50k) single top** produced, which allows for a tree level determination of V_{tb}. All t-channels and tW-channels compatible with $|V_{tb}|=1$.

Moreover, the most precise determination is obtained by **CMS**, by measuring $\mathbf{R_b}$ (ratio of events with b-jets over q-jets) in tt dilepton channel.

$$R_b = BF(Wb)/B(Wq) = |V_{tb}|^2$$



Experiment	Type	$\|V_{tb}\|$	$\|V_{tb}\| >$ ... @ 95% C.L
CDF	$t\bar{t}$ l+jets	0.97 ± 0.05	0.89
CDF	$t\bar{t}$ ll	0.93 ± 0.04	0.85
D0	$t\bar{t}$ l+jets/ll	0.90 – 0.99	0.96
CMS	$t\bar{t}$ ll	1.007 ± 0.016	0.972

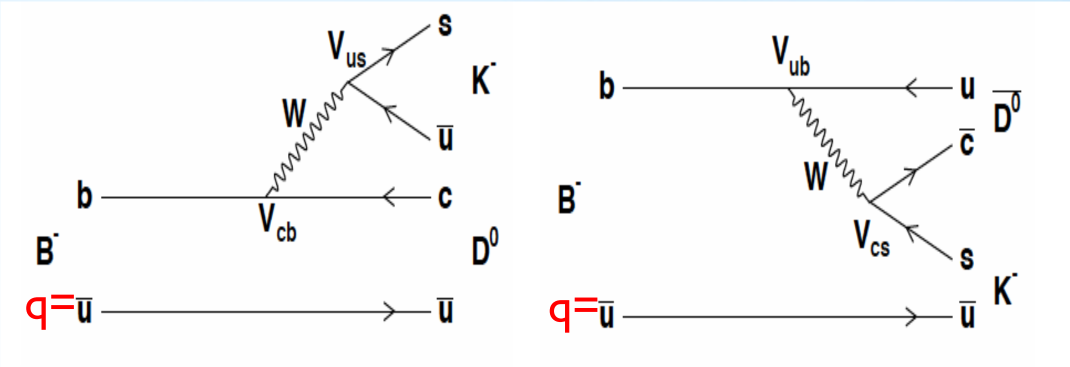
V_{ub} phase: Experimental Strategies

q=u: with D and anti-D in same final state

$B^{\pm} \rightarrow DX_s$ X_s={$K^{\pm}$, $K^{\pm}\pi\pi$, $K^{*\pm}$,…}

q=s: Time dependent CP analysis.
Inteference between B_s mixing and decay.

$B_s \rightarrow D^{\pm}_s K^{\mp}$



($|V_{cb}V_{us}| \alpha \lambda^3$)   ($|V_{ub}V_{cs}| \alpha \lambda^3$)

In the case q=u the experimental analysis is relatively simple, selecting and counting events to measure the ratios between B and anti-B decays. NP contributions to D mixing are assumed to be negligible or taken from other measurements.

However the extraction of γ requires the knowledge of the ratio of amplitudes ($r_{B(D)}$) and the difference between the strong and weak phase in B and D decays ($\delta_{B(D)}$)
→charm factories input (CLEO/BESIII).

In the case q=s, a time dependent CP analysis is needed to exploit the interference between B_s mixing and decay. NP contributions to the mixing needs to be taken from other measurements ($B_s \rightarrow J/\Psi\phi$).

V_{ub} phase: Experimental Strategies

CP modes

$$\frac{<\Gamma(B^{\pm}\to[\pi\pi]_D K^{\pm}), \Gamma(B^{\pm}\to[KK]_D K^{\pm})>}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

average of *KK* and *ππ modes*

$$\frac{\Gamma(B^-\to D_{CP}K^-) - \Gamma(B^+\to D_{CP}K^+)}{\Gamma(B^-\to D_{CP}K^-) + \Gamma(B^+\to D_{CP}K^+)}$$

$B^{\pm}\to D[KK,\pi\pi]K^{\pm}$ with D decays in CP modes *(Gronau, London, Wyler) PLB 253 (1991) 483 and PLB265 (1991) 172.*

$$R_{CP+} = 1 + r_B{}^2 + 2r_B\cos\delta_B\cos\gamma \qquad A_{CP+} = \frac{2r_B\sin\delta_B\sin\gamma}{1 + r_B{}^2 + 2r_B\cos\delta_B\cos\gamma}$$

ADS mode

$$\frac{\Gamma(B^{\pm}\to[\pi K]_D K^{\pm})}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

$$\frac{\Gamma(B^-\to D_{ADS}K^-) - \Gamma(B^+\to D_{ADS}K^+)}{\Gamma(B^-\to D_{ADS}K^-) + \Gamma(B^+\to D_{ADS}K^+)}$$

$B^{\pm}\to D[K\pi]K^{\pm}$ *(Atwood, Dunietz, Soni) PRL 78 (1997) 3257..*

$$R^{ADS} = \frac{r_B{}^2 + r_D{}^2 + 2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma} \qquad A^{ADS} = \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{r_B{}^2 + r_D{}^2 + 2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}$$

Same argument works for Dπ final states, but r_B (hence interference) is ~10 smaller.

A variation of the above methods, is when $D\to K_s h^+h^-$, *(Giri, Grossman, Soffer and Zupan,* PRD68, 054018 (2003)) .
A Dalitz analysis of the three-body decays allows for an increase in sensitivity.

V_{ub} phase: B-factories

In fact, the most precise determination of γ from B-factories is from the Dalitz analysis (**GGSZ**) of the decays $B^{\pm}\rightarrow D(K_s\pi\pi)\,K^{\pm}$.

Combining with the decays $B\rightarrow D_{CP}X_s$ (**GLW**) and the decays $B\rightarrow D(K^{+}\pi^{-}(\pi^{0}))X_s$ (**ADS**):

$$\text{BABAR: } \gamma = 69\,^{+17}_{-16}\,^{\circ} \quad (r_B(DK)=0.092\pm0.013)$$

$$\text{Belle : } \gamma = 68\,^{+15}_{-14}\,^{\circ} \quad (r_B(DK)=0.112\pm0.015)$$

CKMFITTER (BABAR+Belle) combination: $\gamma = 66 \pm 12^{\circ}$
to be compared with $\gamma = 66.4^{+1.3}_{-2.5}{}^{\circ}$ from loops measurements.

Example from Belle:

for B→DK:

$r_B = 0.168^{+0.063}_{-0.064}$

$r_B = 0.108^{+0.045}_{-0.023}$

$r_B = 0.104^{+0.020}_{-0.021}$

$\mathbf{r_B = 0.112^{+0.014}_{-0.015}}$

GGSZ

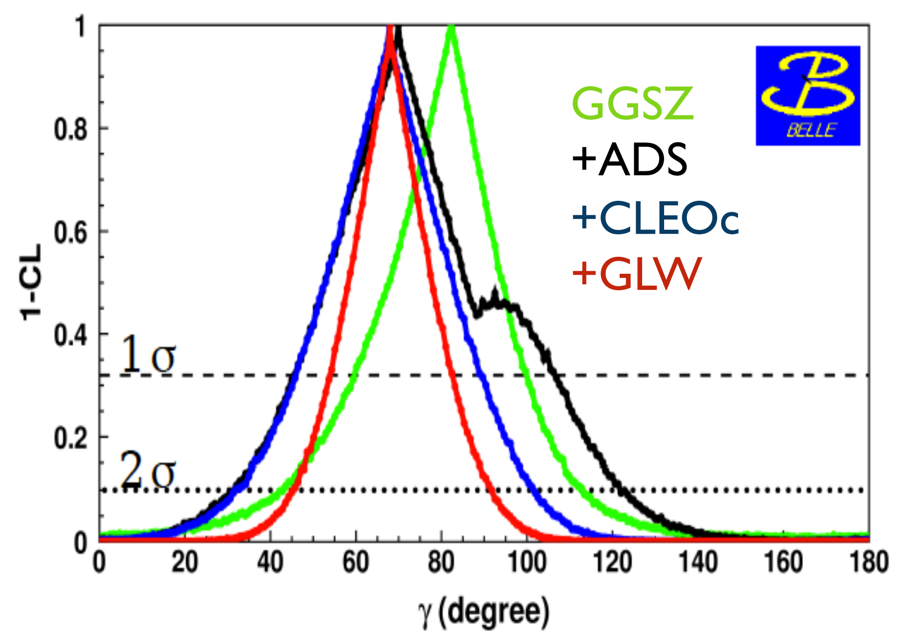
$\gamma = [82\,^{+18}_{-23}]^{\circ}$

GGSZ+ADS

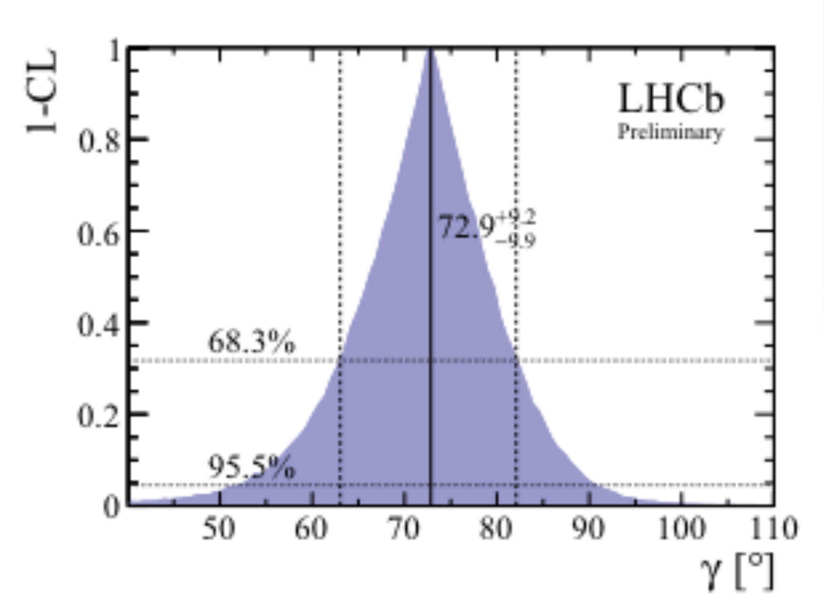
$\gamma = [70\,^{+37}_{-24}]^{\circ}$

GGSZ+ADS+δ_D

$\gamma = [68 \pm 22]^{\circ}$



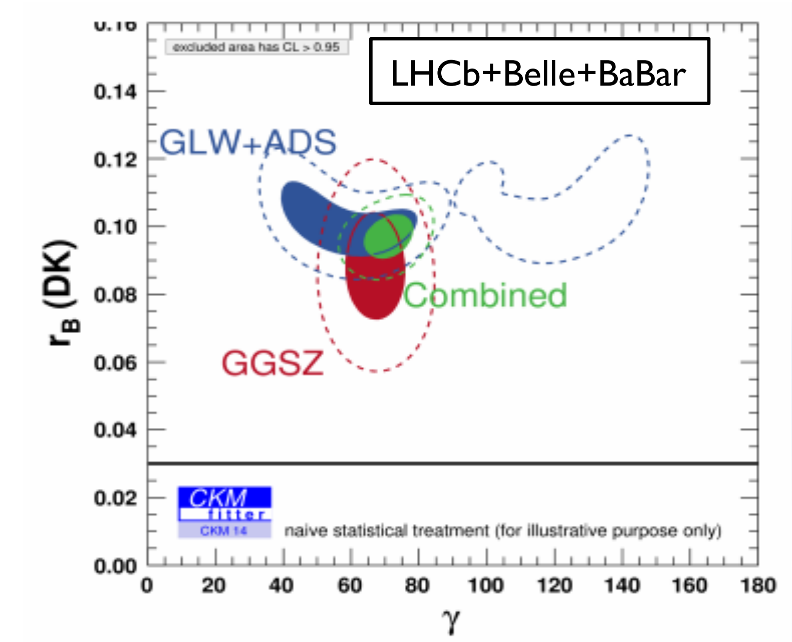
V_{ub} phase: LHCb combination



LHCb preliminary combination, includes B→DK and B_s→D_sK:

γ = **$72.9^{+9.2}_{-9.9}$°** (r_B(DK)=0.091±0.008)

$$\tan\gamma \approx \frac{\eta}{\rho}$$



Excellent internal compatibility of GGSZ and GLW/ADS. Expect **±6°** when all RUN-I data is analyzed.

LHCb and B-factories tree level measurements are in **good agreement.** LHCb has reach better sensitivity than combination of B-factories.

Both LHCb and B-factories agree with the indirect determination from loop measurements:

γ (tree)= $73.2^{+6.3}_{-7.0}$° vs γ (loop)= $66.4^{+1.3}_{-2.5}$°

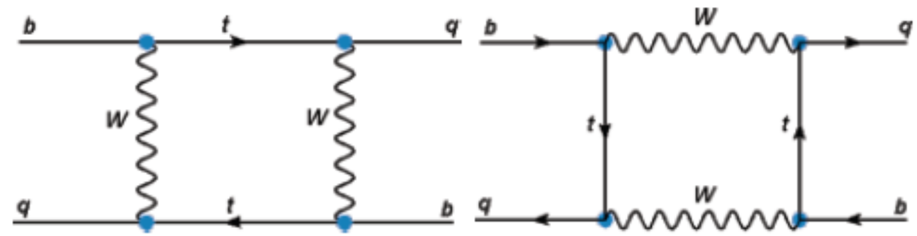
(r_B(DK)=0.097±0.006)

ΔF=2 Box Measurements

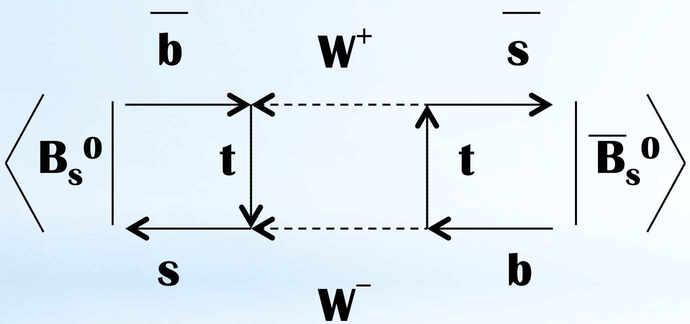
Mixing theory

dispersive   absorptive

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$



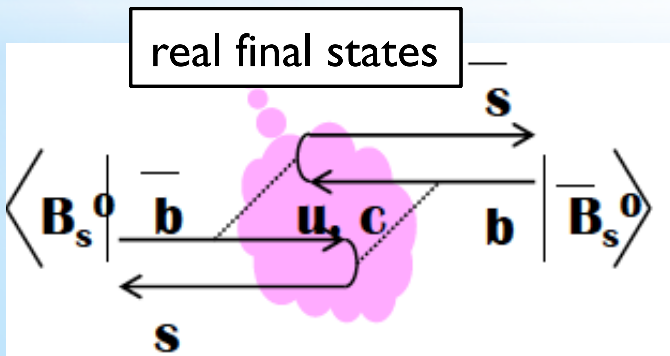
In principle one expects NP to affect the dispersive part, i.e. new heavy particles ($M>q^2$) contributing virtually to the box diagram. The absorptive part is dominated by the production of real light particles ($M<q^2$).



Dispersive part: M_{12}

$\Delta m_q = 2|M_{12}| \propto B_s f_s^2 |V_{tq}|^2\ |V_{tb}|^2 \rightarrow \Delta m_d \ll \Delta m_s$

$\arg M_{12} = \arg (V_{tq}^* V_{tb})^2 + \pi = \varphi_q + \pi$



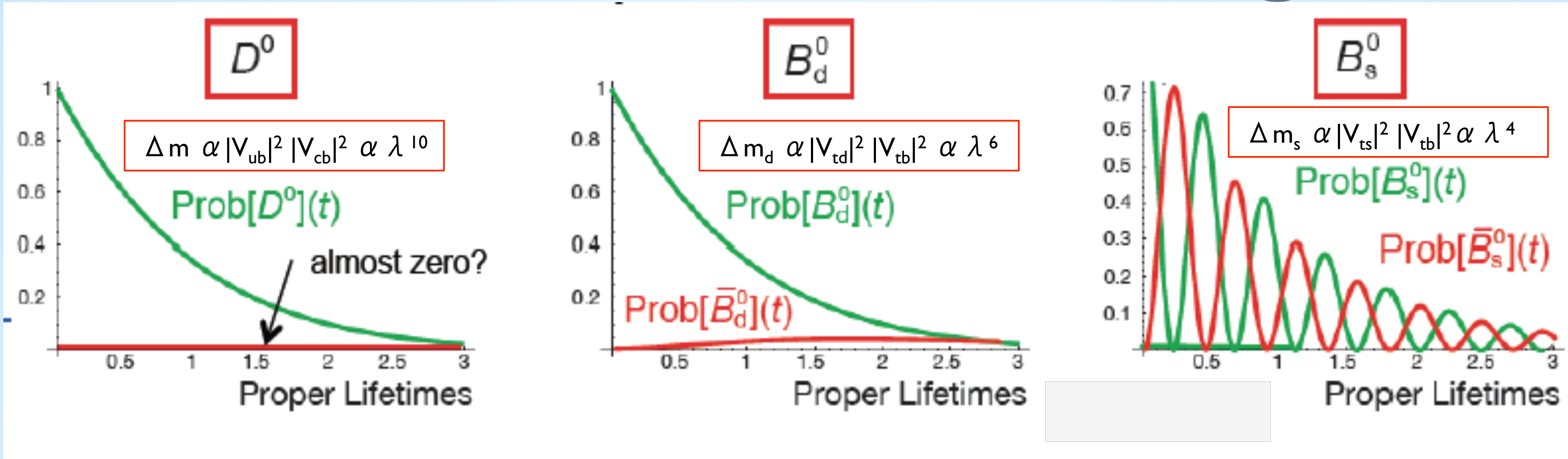
Absorptive part: Γ_{12}

$$\Delta\Gamma = 2\,|\Gamma_{12}| \qquad \frac{\Delta\Gamma}{\Delta m} = \frac{3\pi m_b^2}{2 m_W^2 S(x_t)} \approx 5\times 10^{-3}$$

$\Delta\Gamma_d \propto 0.004\times\Gamma_d$

$\Delta\Gamma_s \propto 0.1\times\Gamma_s$

Mixing theory



The oscillation frequency is given by $\Delta M_q \sim 2|M^q_{12}|$.

The width difference by $\Delta\Gamma_q \sim 2|\Gamma^q_{12}|\cos(\varphi_q)$ with $\varphi_q = \arg(-M^q_{12}/\Gamma^q_{12})$.

Expect very small CP violation in the oscillation, or equivalently very small values for flavour-specific CP asymmetries:

$$a^q_{fs} = |\Gamma^q_{12}/M^q_{12}|\sin(\varphi_q)$$

Best chance to see SM-level CP asymmetries in the interference between mixing and decay.

How can we measure the V_{ub}, V_{td} and V_{ts} phases?

B^0 system

$\bar{B}^0 \to \bar{B}^0$ $\quad b \to \bar{c}+cs$: $V_{cb}V_{cs}^* \propto e^{i\,0}$

$\bar{B}^0 \to B^0$: $M_{12} \propto e^{2i\beta}$ $\quad \bar{b} \to \bar{c}+\bar{c}s$: $V_{cb}^*\,V_{cs} \propto e^{i\,0}$

$\to J/\psi\, K_S$

$A_{CP}(t) \propto \sin 2\beta \times \sin \Delta mt$

$\bar{B}^0 \to \bar{B}^0$ $\quad b \to \bar{c}+ud$: $V_{cb}V_{cd}^* \propto e^{i\,0}$

$\bar{B}^0 \to B^0$: $M_{12} \propto e^{2i\beta}$ $\quad \bar{b} \to \bar{u}+\bar{c}d$: $V_{ub}^*\,V_{cd} \propto e^{i\gamma}$

$\to D^{(*)+}\,\pi^-$

$$r_B \approx \frac{A\lambda^2}{A\lambda^4\sqrt{\rho^2+\eta^2}}$$

$A_{CP}(t) \propto \sin(2\beta+\gamma) \times \sin \Delta mt$

B_s system

$\bar{B}_s^0 \to \bar{B}_s^0$ $\quad b \to \bar{c}+cs$: $V_{cb}V_{cs}^* \propto e^{i\,0}$

$\bar{B}_s^0 \to B_s^0$: $M_{12} \propto e^{I\varphi_s}$ $\quad \bar{b} \to \bar{c}+\bar{c}s$: $V_{cb}^*\,V_{cs} \propto e^{i\,0}$

$\to J/\psi\,\phi(\eta)$

$A_{CP}(t) \propto \sin\varphi_s \times \sin \Delta mt$

$\bar{B}_s^0 \to \bar{B}_s^0$ $\quad b \to \bar{c}+us$: $V_{cb}V_{us}^* \propto e^{i\,0}$

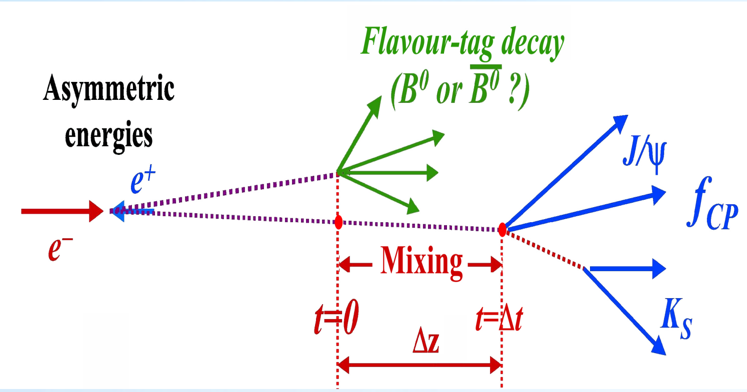
$\bar{B}_s^0 \to B_s^0$: $M_{12} \propto e^{I\varphi_s}$ $\quad \bar{b} \to \bar{u}+\bar{c}s$: $V_{ub}^*V_{cs} \propto e^{i\gamma}$

$\to D_s^+\,K^-$

$$r_B \approx \frac{A\lambda^3}{A\lambda^3\sqrt{\rho^2+\eta^2}}$$

$A_{CP}(t) \propto \sin(\varphi_s+\gamma) \times \sin \Delta mt$

ΔF=2 box in b→d transitions



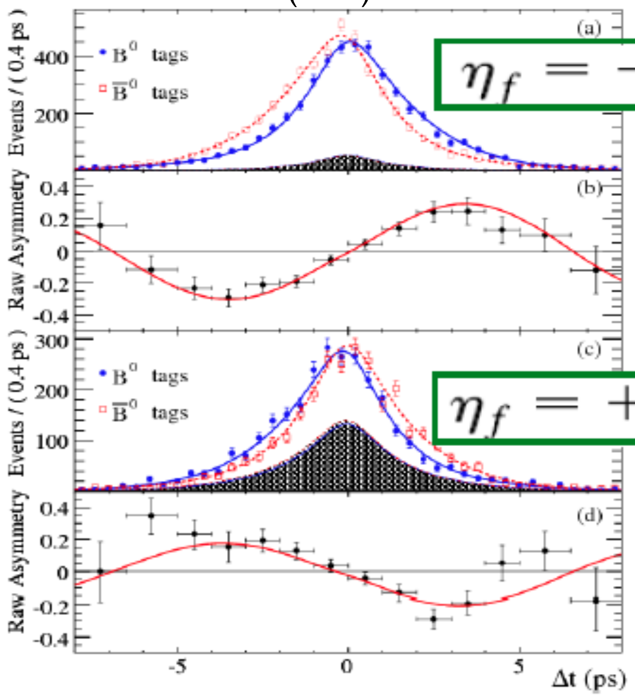
NP phases contributing to the dispersive part (M^q_{12}) should contribute to the measurements of the time dependent CP asymmetry in B→J/ψ K_s and/or B_s→J/Ψ Φ.

The CP asymmetry as a function of the lifetime distribution of tagged events shows an oscillation pattern. The frequency of these oscillations determine M_{12} while the amplitude is proportional to arg(M_{12}).

B→J/ψ K_s(K_L)

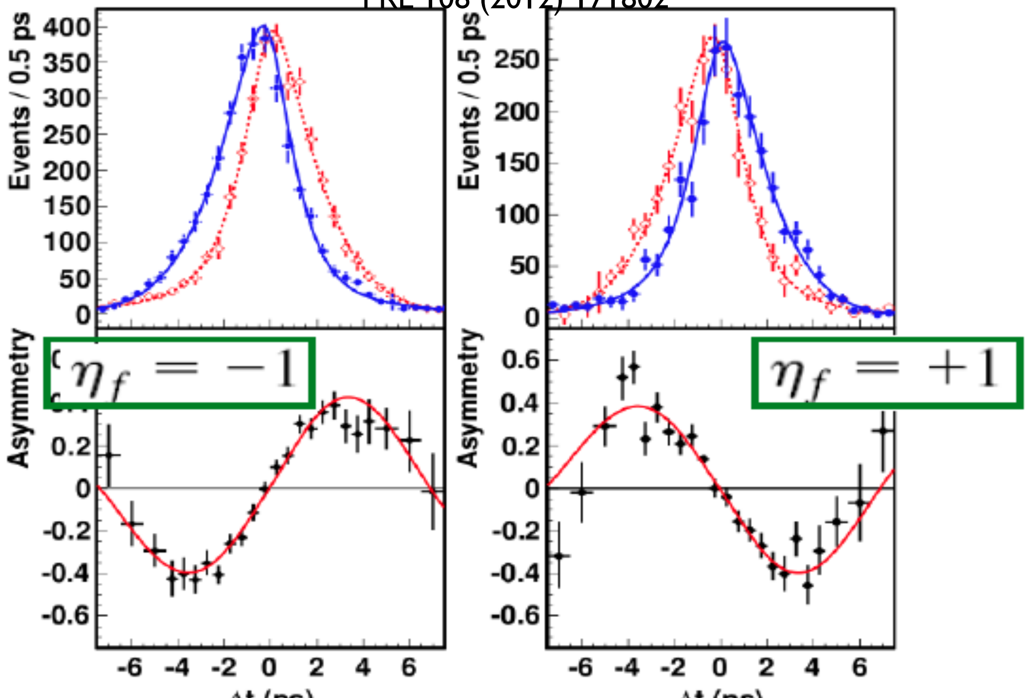
BABAR

PRD 79 (2009) 072009



BELLE

PRL 108 (2012) 171802



Δ F=2 box in b→d transitions

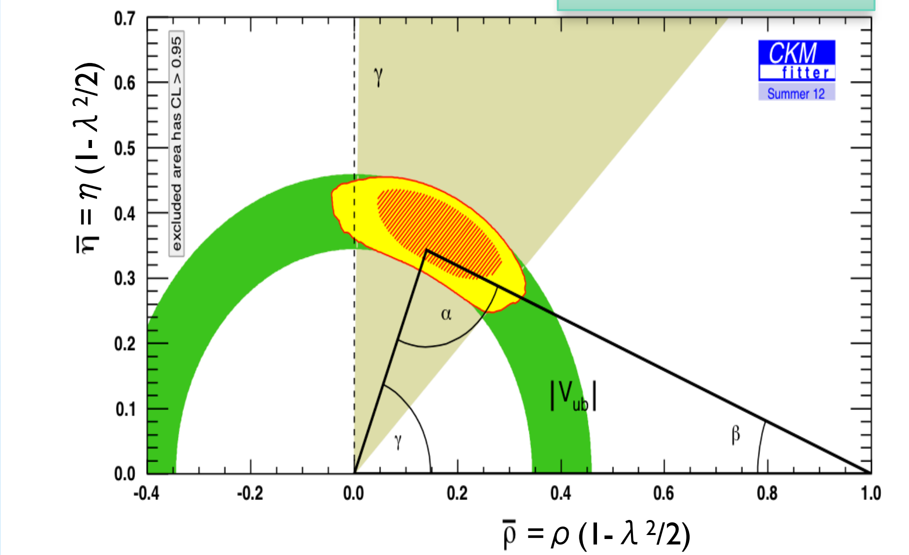
CKMFITTER (BABAR+Belle) combination:

$$\tan\beta \approx \frac{\eta}{1-\rho} \qquad \beta = 21.38^{+0.79}_{-0.77}{}^\circ$$

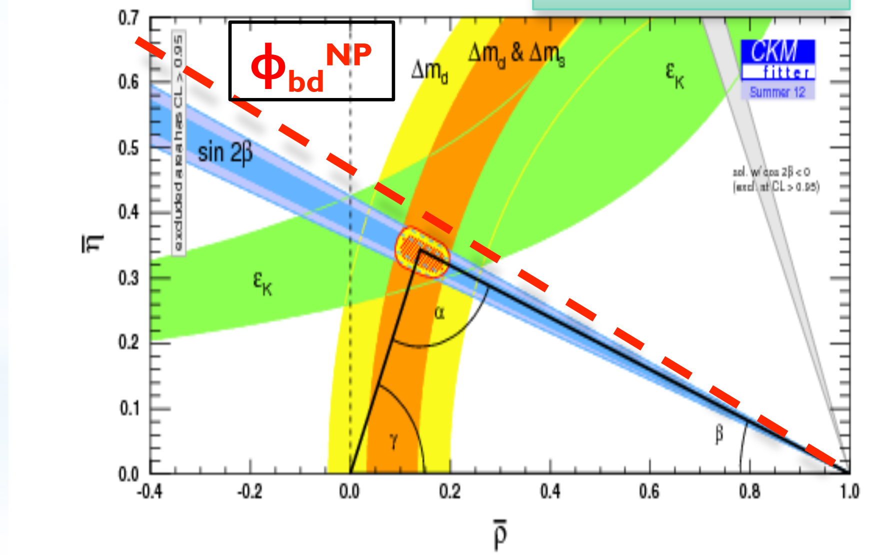
Which can be compared with the indirect determination using "tree measurements": β = **24.9+0.8-1.9°**

If we assume the SM, then the phase of V_{td} is known better than 4% from b→d transitions in box diagrams. However, NP must be contributing to some level! Therefore, the precise measurement of β is in fact, a precise measurement of (β + ϕ_{bd}^{NP}).

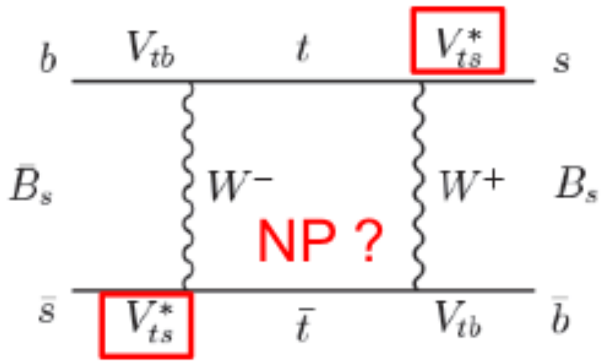
Tree measurements



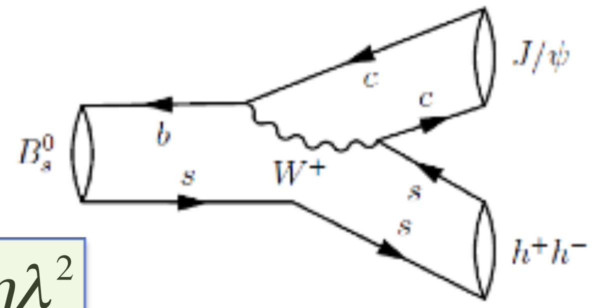
Loop measurements



$\Delta F=2$ box in b→s transitions: CP asymmetries in $B_s \to J/\Psi\ \Phi$



$$\phi_s \approx -2\eta\lambda^2$$

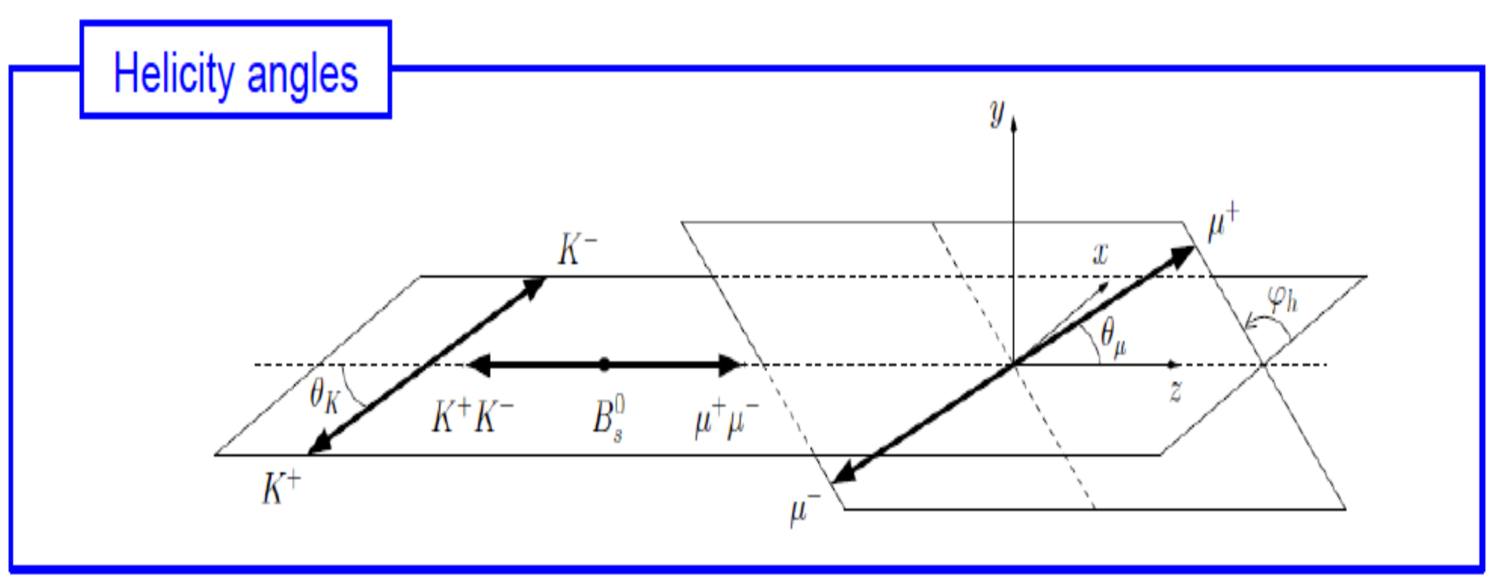


+ small penguin pollution

$$\phi_D^{SM} = -2\arg\left(V_{cs}V_{cb}^*\right) \approx 0$$

Sensitivity to the phase in the box diagram, through the interference between mixing and decay.

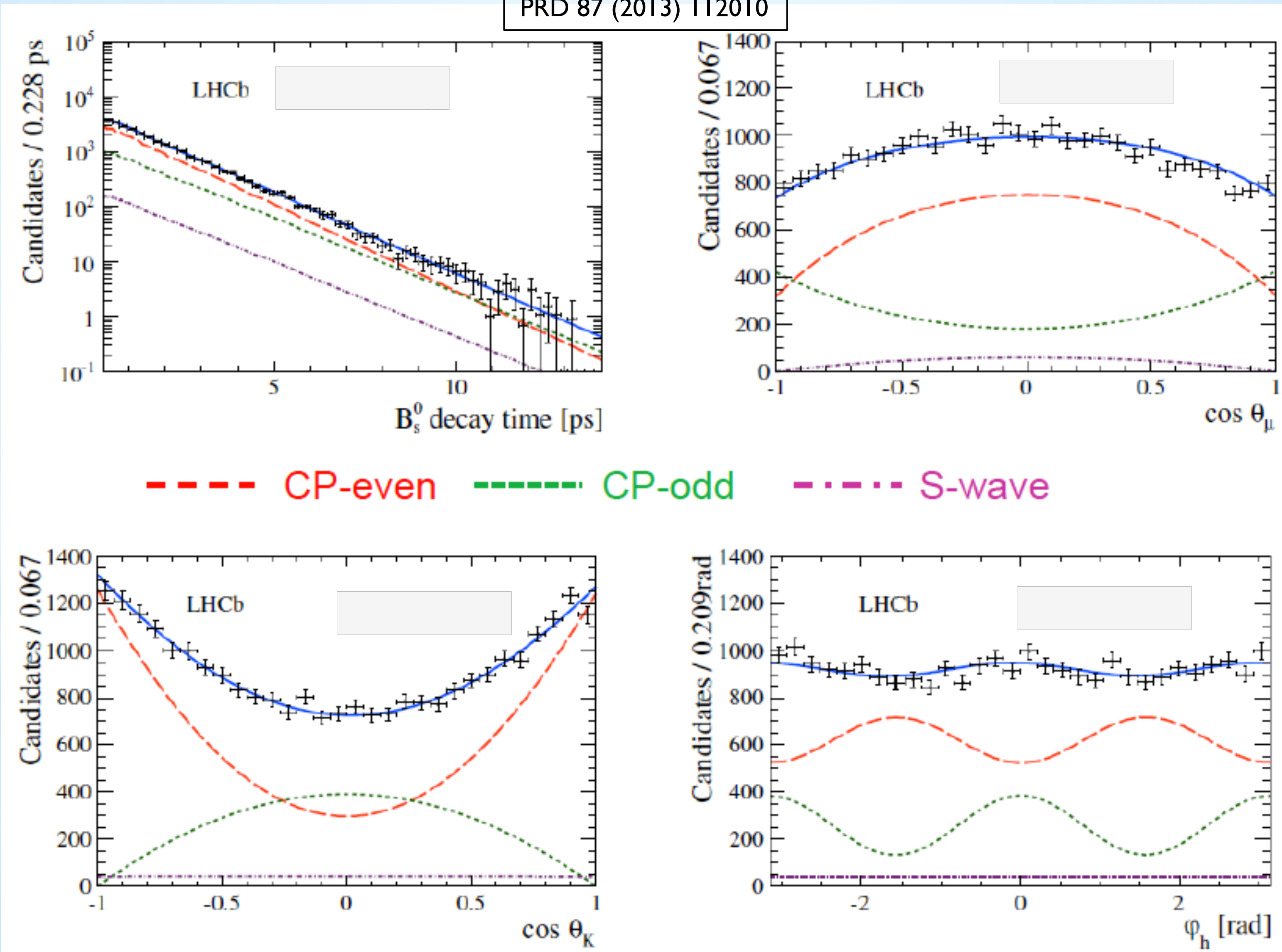
Angular analysis is needed in $B_s \to J/\Psi\ \Phi$ decays, to disentangle statistically the CP-even and CP-odd components. Use the helicity frame to define the angles: $\theta_K, \theta_\mu, \phi_h$.



∆F=2 box in b→s transitions

LHCb flavour tagging improved with the inclusion of Kaon Same Side Tag: **εD^2 = (3.13 ± 0.23)%**

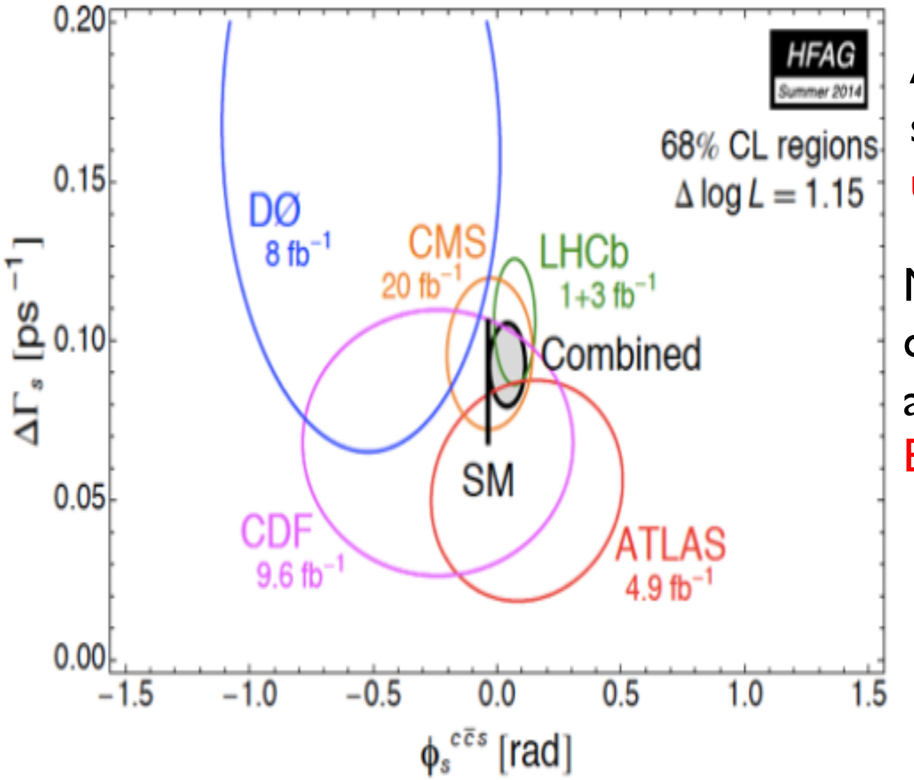
PRD 87 (2013) 112010



Δ F=2 box in b→s transitions

The result of the LHCb angular analysis of $B_s \to J/\Psi\, \Phi$ decays with 1fb^{-1} *(PRD 87 (2013) 112010)* combined with the new results using 3fb^{-1} $B_s \to J/\Psi\, \pi\pi$ decays (arXiv:1405.4140) gives:

Φ_s(LHCb) = 0.070 ±0.054(stat)±0.011(syst)



This result can be compared with the indirect determination: **Φ_s = -0.036±0.002.**

Although, there has been **impressive progress** since the initial measurements at CDF/D0, the uncertainty needs to be further reduced.

Meanwhile, other LHC experiments have started contributing. ATLAS tagged analysis with 5fb^{-1} and recently CMS tagged analysis with 20fb^{-1} of $B_s \to J/\Psi\, \Phi$ decays gives:

CMS-PAS-BPH-13-012

Φ_s(CMS) = -0.03 ±0.11(stat)±0.03(syst)

arXiv:1407.1796

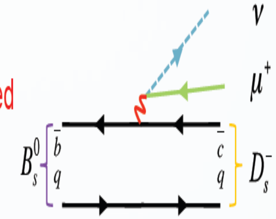
Φ_s(ATLAS) = 0.12 ±0.25(stat)±0.11(syst)

D0 flavour specific asymmetries

Could it be that we have large NP effects in the absorptive part?

$a^q_{fs} = |\Gamma^q_{12}/M^q_{12}| \sin(\varphi_q)$

$B_q^0 \rightarrow D_q^- \mu^+ \nu_\mu$: Allowed



$\bar{B}_q^0 \rightarrow D_q^- \mu^+ \nu_\mu$: Not allowed directly

$$a_{SL}^q = \frac{\Gamma(\bar{B}(t) \rightarrow f) - \Gamma(B(t) \rightarrow \bar{f})}{\Gamma(\bar{B}(t) \rightarrow f) + \Gamma(B(t) \rightarrow \bar{f})} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

D0 inclusive measurement of the dimuon asymmetry is interpreted as a linear combination of $a_{SL}(B_d)$ and $a_{SL}(B_s)$. **No production asymmetry** at pp colliders. **Detector asymmetry** controlled by switching magnet polarity.

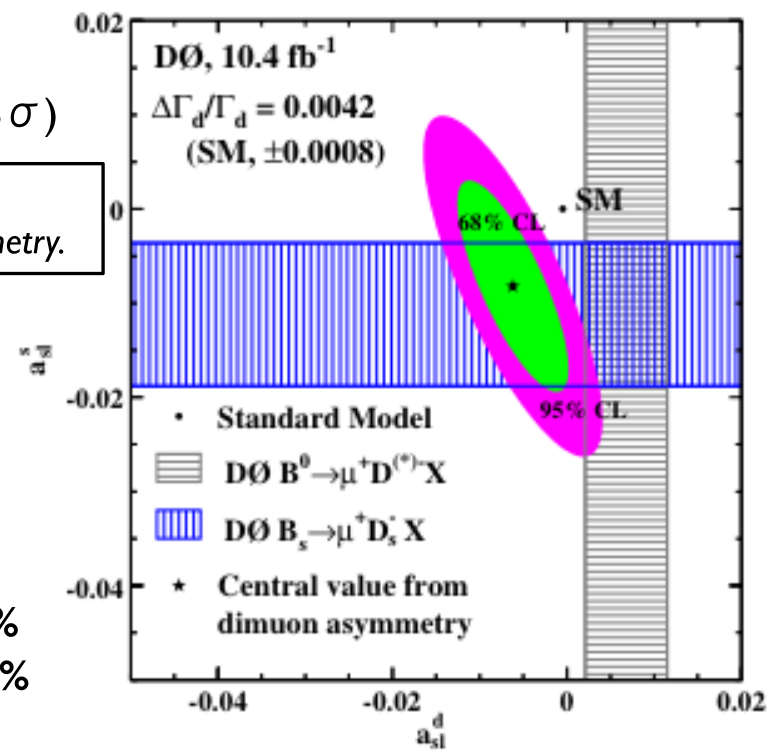
D0 Dimuon: $\mathbf{A^b_{SL}}$**= (-0.496±0.153(stat)±0.072(syst))**% (2.8 σ)

Phys. Rev. D89, 012002 (2014)

Systematic uncertainty drastically reduced by assuming the bkg from the single-muon asymmetry.

and fitting the data in **bins of IP**:

$a_{SL}(B_d)$ = (-0.62±0.42)% , **$a_{SL}(B_s)$ = (-0.86±0.74)%**



Moreover, D0 has also measured:

Using $B_d \rightarrow \mu^+ D^{(*)-}$: **$a_{SL}(B_d)$ = (0.68±0.45(stat)±0.14(syst))%**

Using $B_s \rightarrow \mu^+ D_s^-$: **$a_{SL}(B_s)$ = (-1.12±0.74(stat)±0.17(syst))%**

LHCb flavour specific asymmetries

LHCb cannot really follow the same inclusive approach due to the relatively large production asymmetry O(1%).

However, LHCb has been able to have the **most accurate measurements** of the flavour specific asymmetries:

$$A_{\rm meas} = \frac{\Gamma(D_s^-\mu^+) - \Gamma(D_s^+\mu^-)}{\Gamma(D_s^-\mu^+) + \Gamma(D_s^+\mu^-)} = \frac{a_{\rm sl}^s}{2} + A_{\rm D} - \left(A_{\rm P} + \frac{a_{\rm sl}^s}{2}\right) \underbrace{\frac{\int e^{\Gamma_s t}\cos(\Delta m_s t)\epsilon(t)dt}{\int e^{\Gamma_s t}\cosh(\Delta\Gamma_s t/2)\epsilon(t)dt}}_{\sim 10^{-4}}$$

A_D=(0.07±0.14)%

Phys.Lett. B728 (2014) 607.

LHCb (1fb^{-1})($B_s \to D_s[\Phi\pi]\,\mu\,\nu$ X):
$a_{SL}(B_s)$ = (-0.06±0.50(stat) ±0.36(syst))%

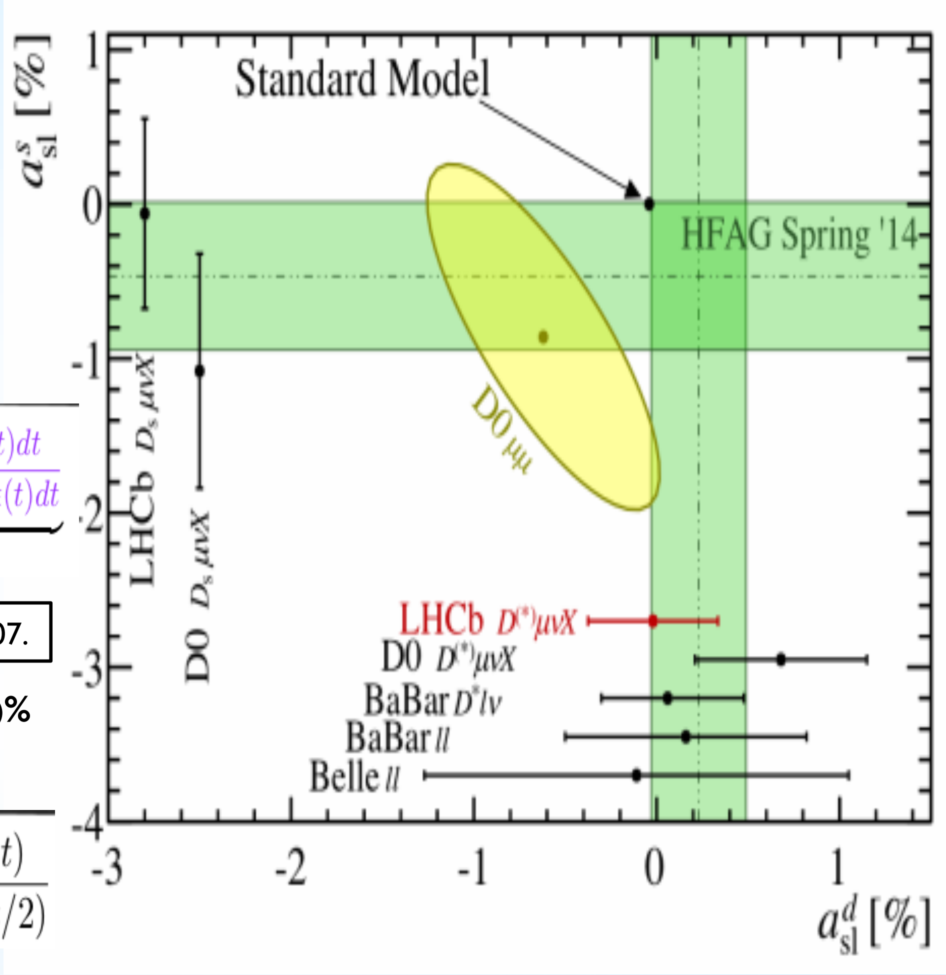
$$A_{\rm meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a_{\rm sl}^d}{2} + A_{\rm D} - \left(A_{\rm P} + \frac{a_{\rm sl}^d}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

A_D=(1.15±0.11)%

A_P=(-0.5±0.2)%

LHCb (3fb^{-1})($B_d \to D^{(*)}\,\mu\,\nu$ X):
$a_{SL}(B_d)$ = (-0.02±0.19(stat) ±0.30(syst))%

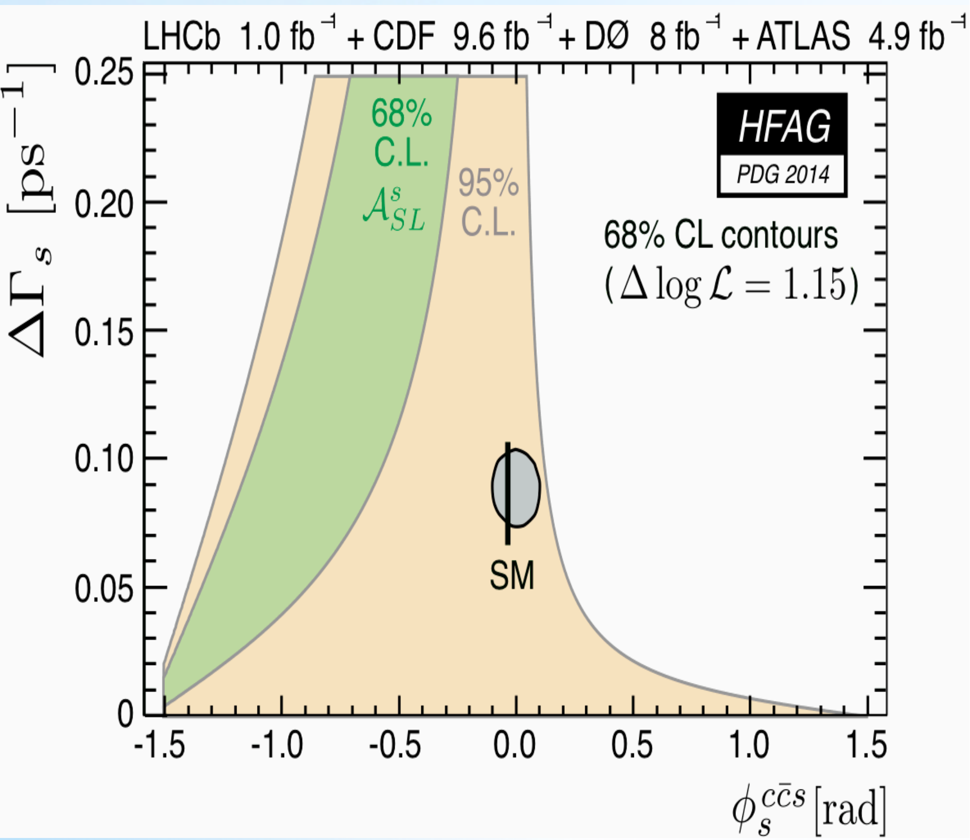
Preliminary CKM2014

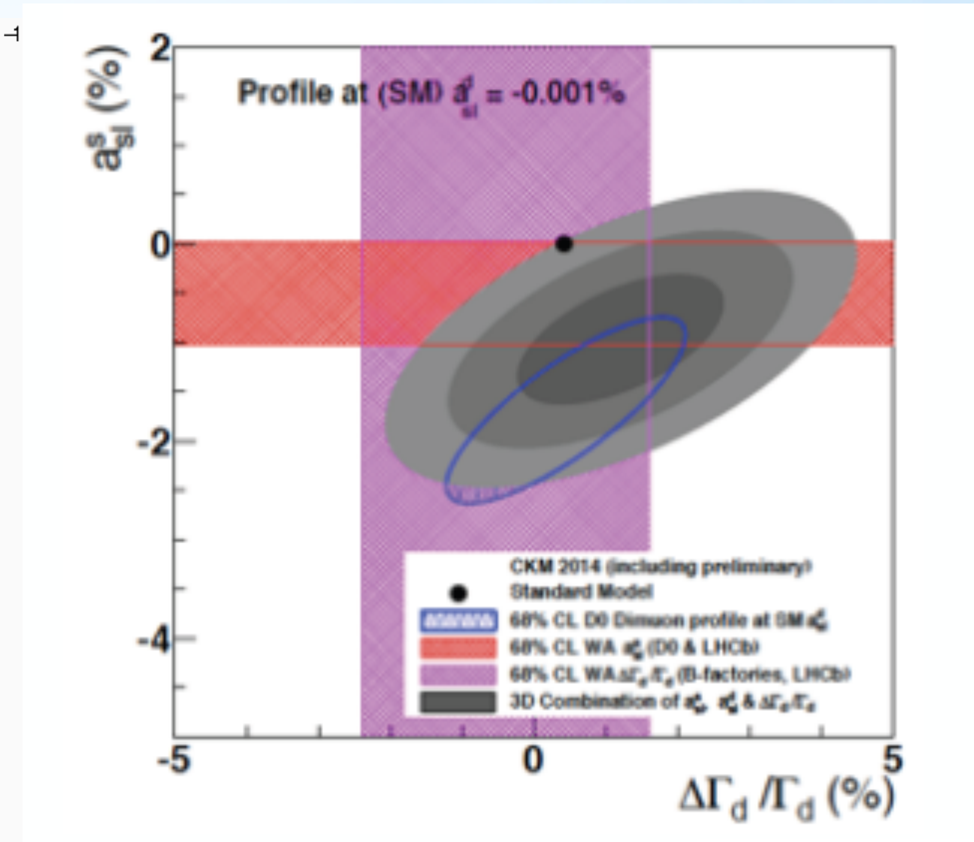


Interpretation of D0 dimuon asymmetry

LHCb needs to add more channels and more data to be able to conclude.

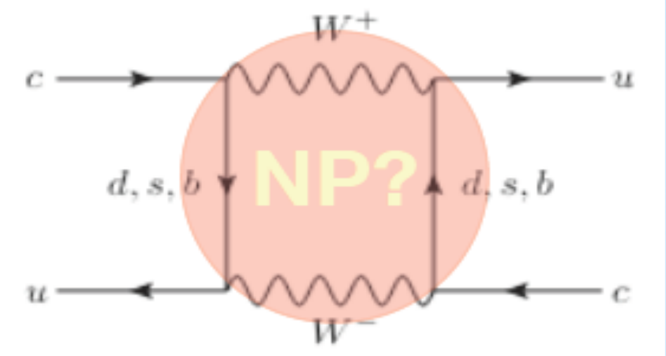
There is already a clear tension between D0 $a_{SL}(B_s)$ and the measurements of ($\Delta\Gamma_s, \Phi_s$).
However the D0 discrepancy with the SM is reduced if $\Delta\Gamma_d$ is fitted to the data rather than fixed to the SM value.





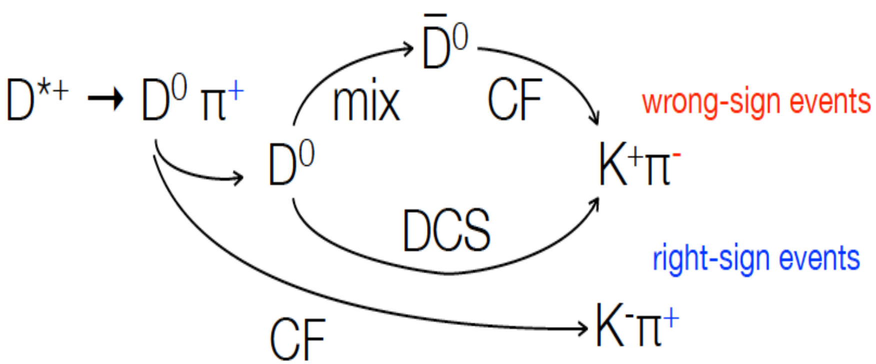
Δ F=2 box in c→u transitions: charm mixing

$$x = \frac{\Delta M}{\Gamma} = \frac{M_H - M_L}{(\Gamma_H + \Gamma_L)/2}, \qquad y = \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)}$$



In Charm mixing absorptive part dominant, therefore large theoretical uncertainties in the SM prediction. Charm mixing has been confirmed combining BaBar, Belle and CDF.

However, no observation (>5 σ) by a single experiment until 2013!



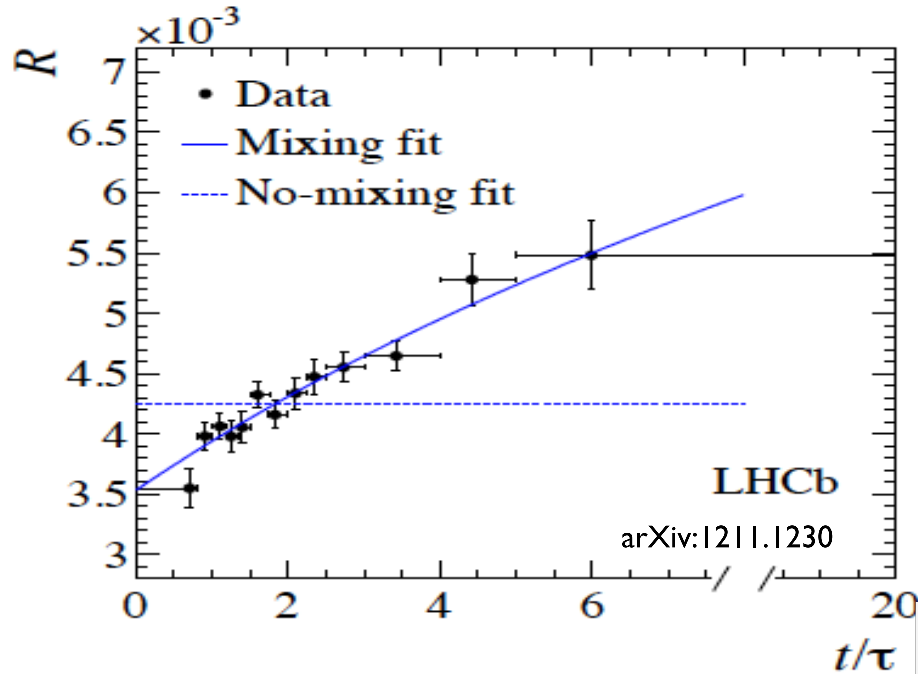
Assuming |x|,|y|<<1 and no CPV:

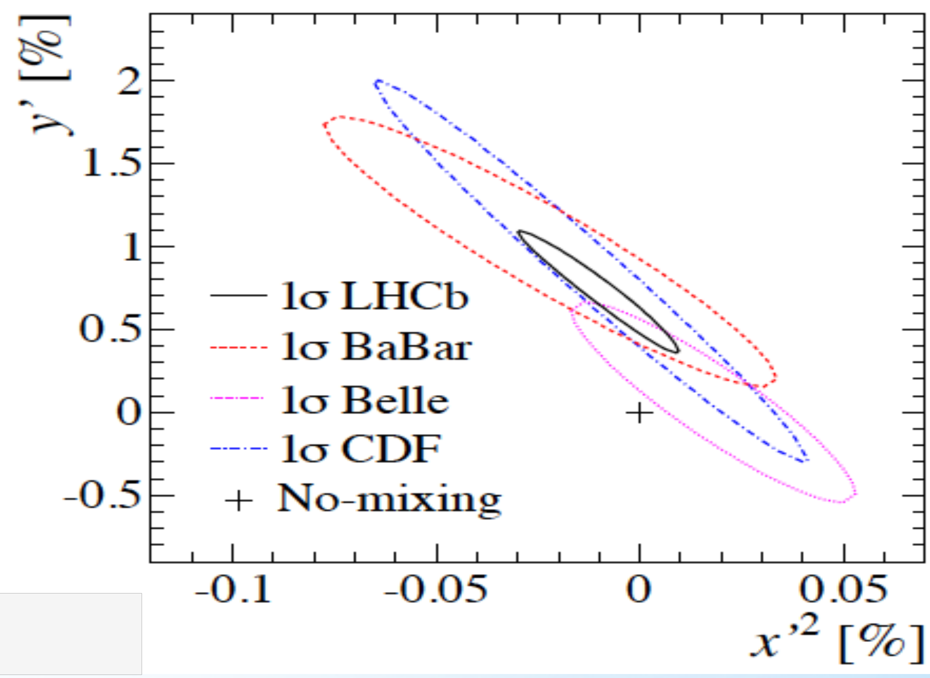
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2$$

$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

ΔF=2 box in c→u transitions: charm mixing

LHCb strategy similar than CDF: use ratio of WS to RS events as a function of time in D*→Dπ events. Charge of soft pion tags the D^0 flavour.





No mixing hypothesis excluded at 9.1 σ by LHCb.

Latest HFAG averages (LHCb, B-factories, Tevatron, CLEO):

$$x = \left(0.41^{+0.14}_{-0.15}\right)\ \%$$

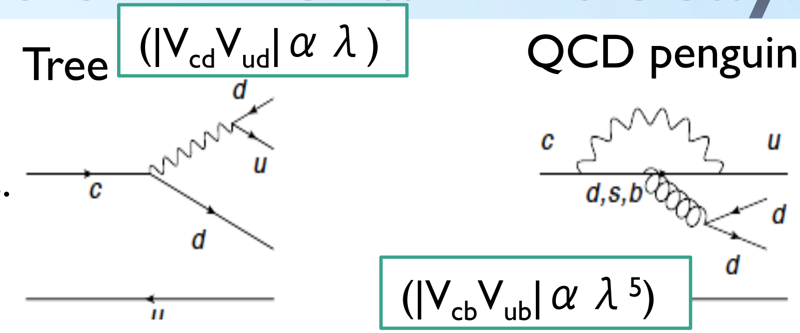
$$y = \left(0.63^{+0.07}_{-0.08}\right)\ \%$$

CP violation in charm decays

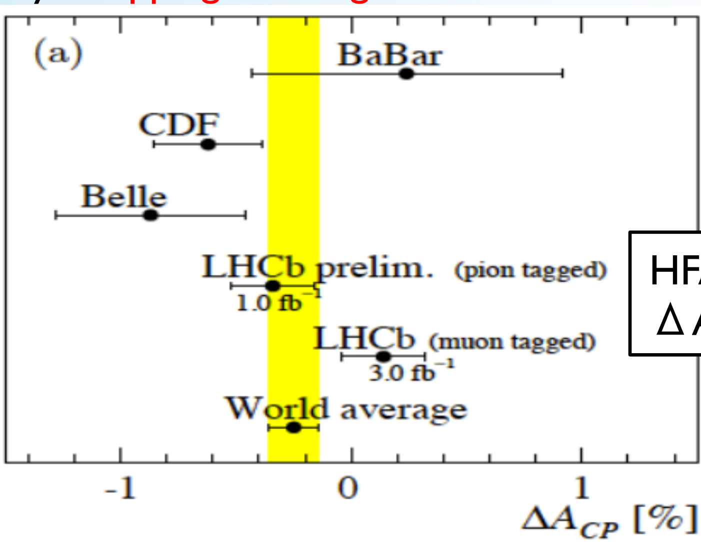
$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \simeq A_f^d + \frac{\langle t \rangle}{\tau_D} A_\Gamma$$

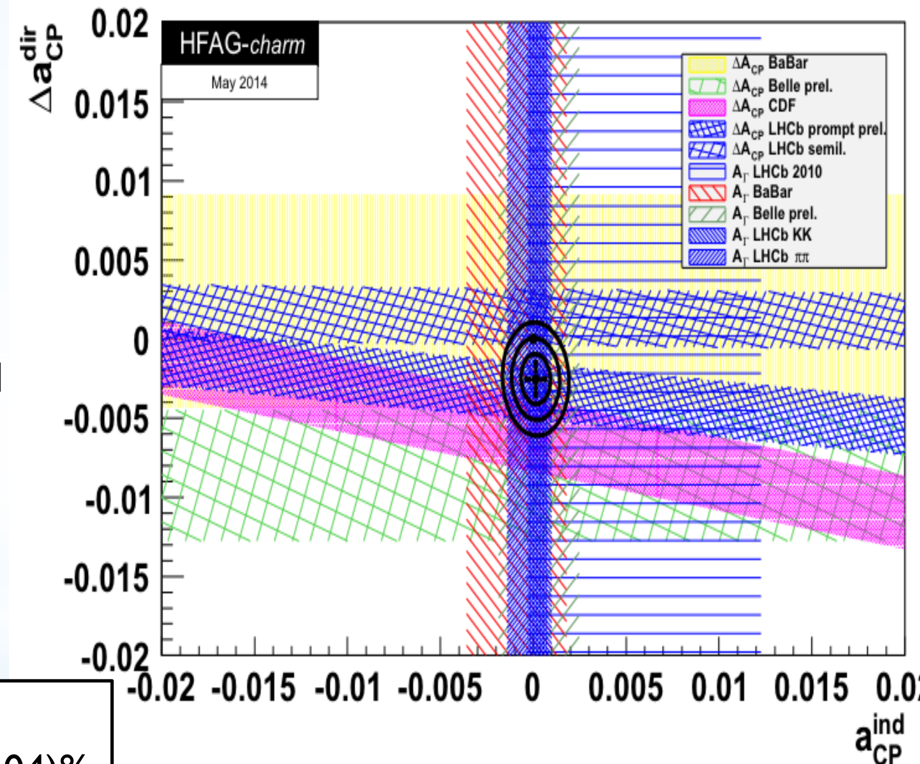
Time integrated A_{CP} has both direct and indirect components.

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) \simeq A_{KK}^d - A_{\pi\pi}^d + \frac{\Delta \langle t \rangle}{\tau_D} A_\Gamma$$



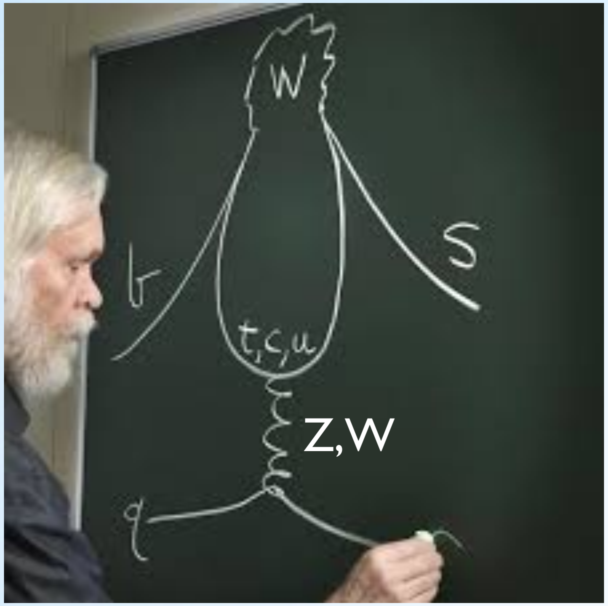
ΔA_{CP} cancels detector and production asymmetries to first order. The SM, and most NP models, predict opposite sign for KK and ππ. Use of U-spin and QCD factorization leads to ΔA_{CP}~4 Penguin/Tree ~0.04%. **$D^{*\pm} \to D^0 [h^+h^-] \pi^\pm$** pion's charge determines the flavour of D^0. Alternatively, using **$B \to D \mu \nu$** decays the muon's charge determines the flavour. Most of the systematics cancel in the subtraction, and are controlled by swapping the magnetic field.





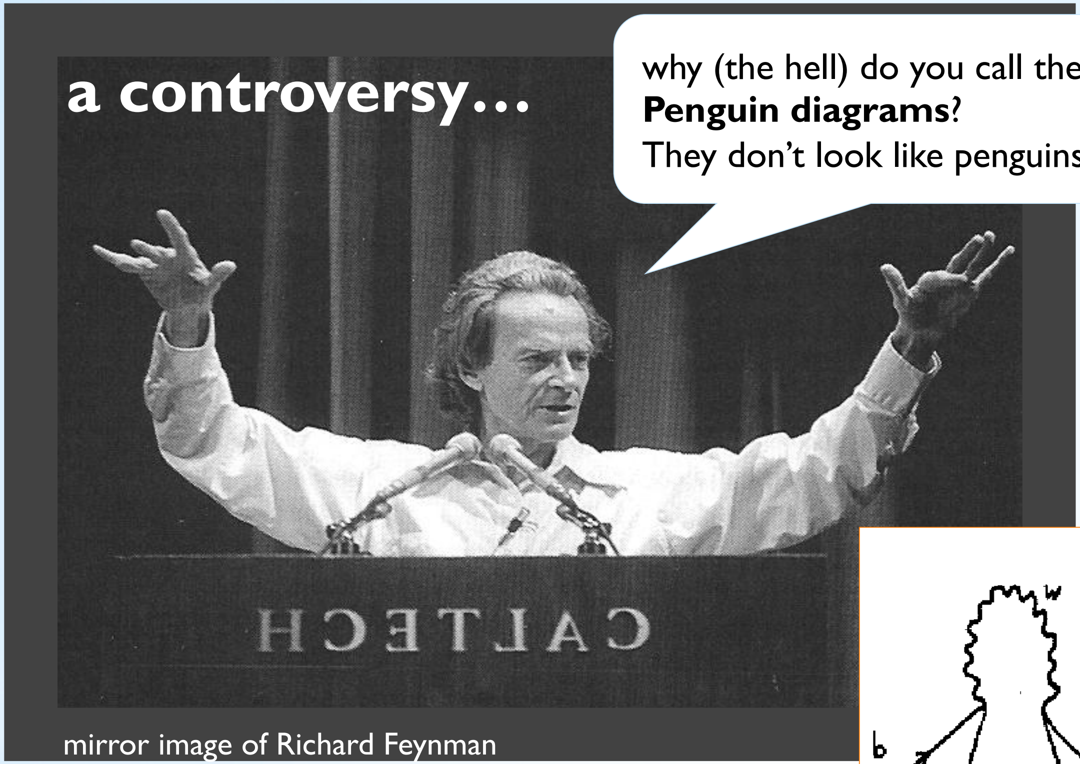
HFAG:
ΔA_{CP}=(-0.253±0.104)%

No significant evidence for CP violation. Effects O(%) are out of the game.



ΔF=1 EW Penguins

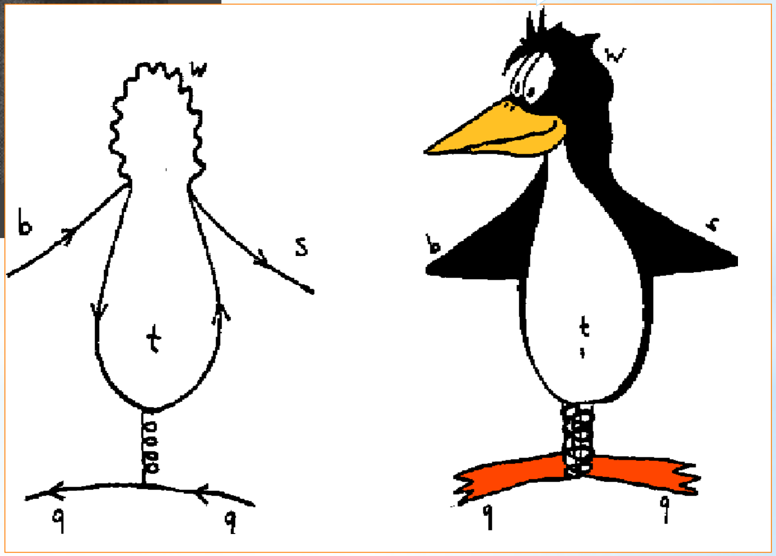
Why Penguins?



mirror image of Richard Feynman

why (the hell) do you call these **Penguin diagrams**? They don't look like penguins!

I've never seen a **Feynman diagram** that looks like **you** ☺

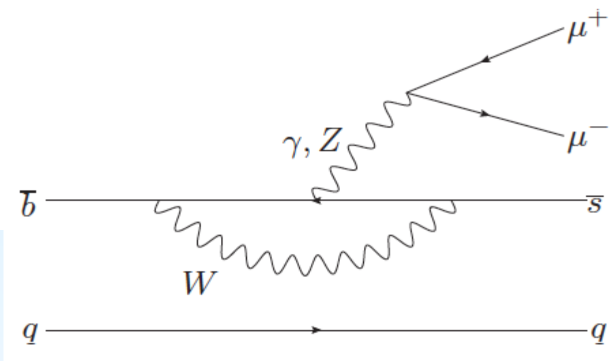


Taken from A. Hoecker Summer Student lectures at CERN (2006)

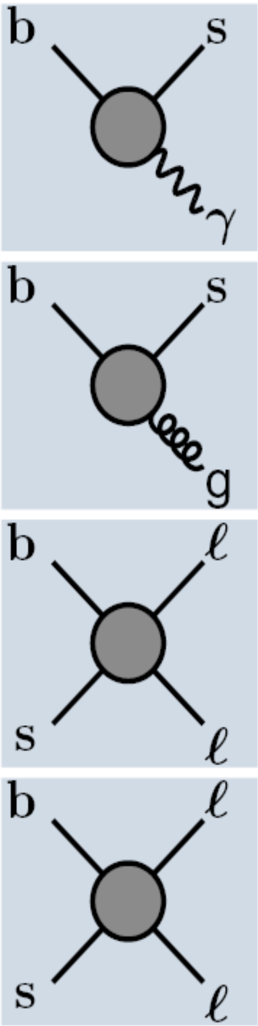
For the wikipedia version of the history, see: http://en.wikipedia.org/wiki/Penguin_diagram

Δ F=1 EW penguins in b→s transitions: Theoretical framework

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.}$$



$\mathcal{O}_{7\gamma}$, $\mathcal{O}_{8g}$, $\mathcal{O}_{9\ell,10\ell}$, $\mathcal{O}_{S,P}$



Describe b→s transitions by an effective Hamiltonian.

Long distance effects absorbed in the definition of the operators O_i, while the interesting short distance can be computed perturbatively in the Wilson coefficients C_i.

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$

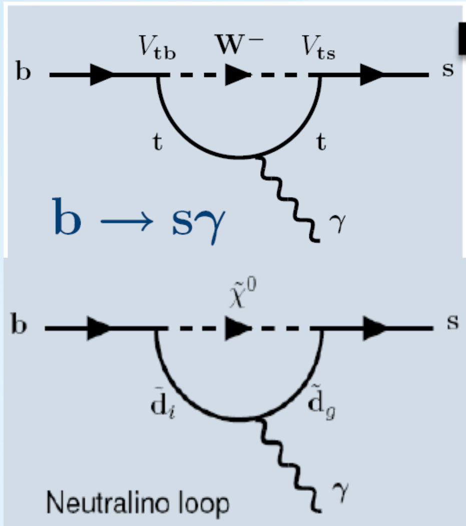
$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,,$$

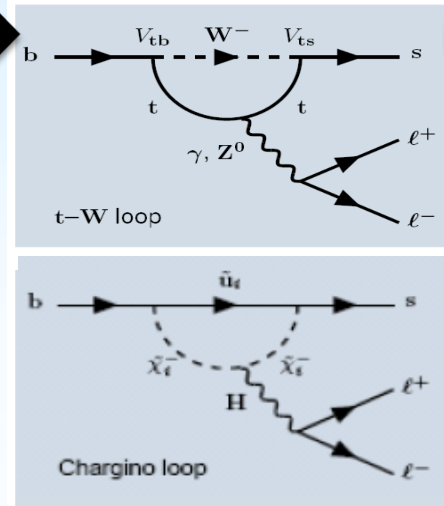
Three impersonations of the EW penguin in B decays

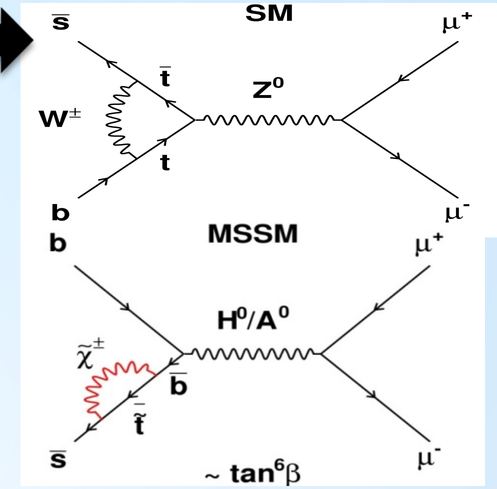
α_{QED} suppression → helicity suppression

SM

MSSM



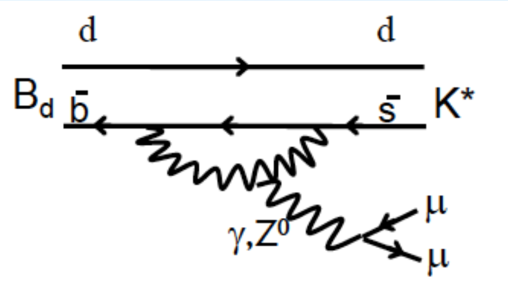




	Relevant Operators	*BR*(SM)	*BR* exp	
$B_s \to \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5\pm0.4)\cdot10^{-5}$ LHCb: arXiv:1209.0313	γ polarization
$B^0 \to K^* \mu^+\mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$		$(1.16\pm0.19)\cdot10^{-6}$ LHCb: arXiv:1205.3422	angular distributions
$B_s \to \mu^+\mu^-$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$	$(3.6\pm0.2)\cdot10^{-9}$ helicity suppressed	$(2.8^{+0.7}_{-0.6})\cdot10^{-9}$ LHCb&CMS: PRL 111 (2013) 101804-05	BR

ΔF=1 EW penguins in b→s transitions: B→K*$\mu\mu$ angular analysis

b→s ($|V_{tb}V_{ts}| \alpha\ \lambda^2$)

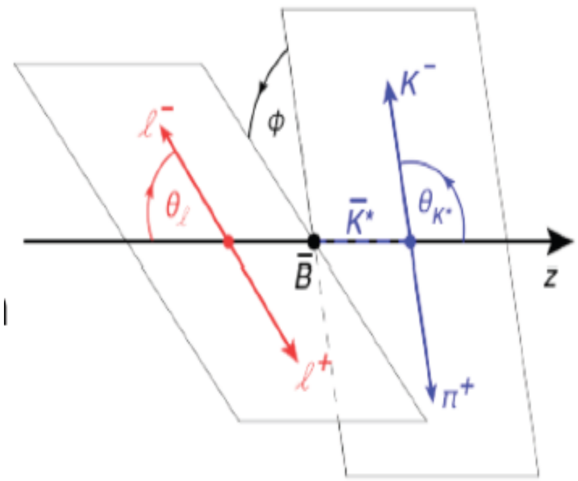


B→K*$\mu\mu$ is the golden mode to test new vector(-axial) couplings in b→s transitions.

K*→Kπ is self tagged, hence angular analysis ideal to test helicity structure.

Sensitivity to O_7, O_9 and O_{10} and their primed counterparts.
Folding technique (Φ→Φ+π) for Φ<0, reduces the number of parameters to fit to four.

$$\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} \propto F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\phi + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\phi$$

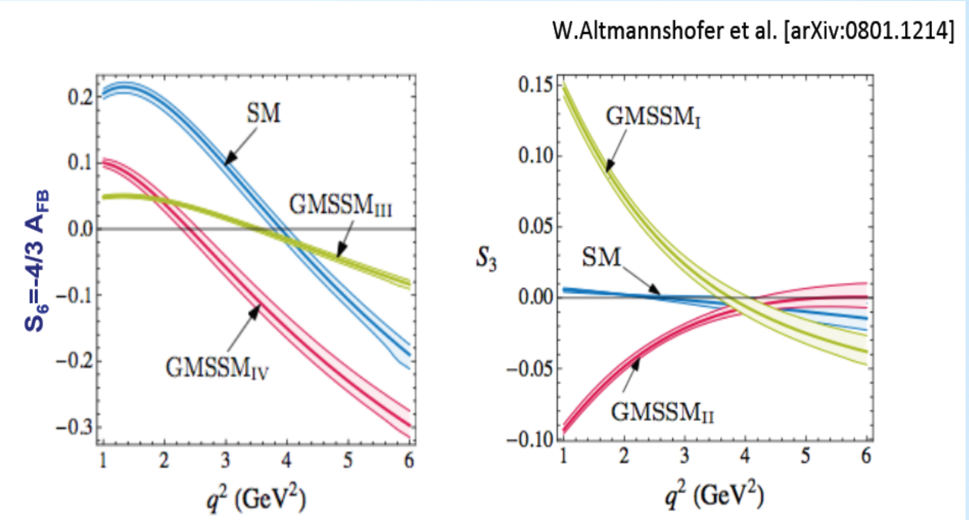


Results from **B-factories and CDF** very much limited by the statistical uncertainty. **LHCb** already has with 1 fb^{-1} published the largest sample (~900 candidates). ATLAS/CMS not far behind.

Hadronic uncertainties under reasonable control for:

- **F_L:** Fraction of K* longitudinal polarization.
- **S_6=-4/3A_{FB}**: Forward-Backward asymmetry of the lepton.
- **$S_3\ \alpha\ A^2_T(1-F_L)$**: Asymmetry in K* transverse polarization.

A_{FB} zero crossing point particularly well predicted within the SM.



Moreover, the dependence with form factors can be further reduced with a redefinition of observables:

$$A_T^{(2)} = \frac{2S_3}{(1-F_L)}$$
$$A_T^{Re} = \frac{S_6}{(1-F_L)}$$
$$P'_4 = \frac{S_4}{\sqrt{(1-F_L)F_L}}$$
$$P'_5 = \frac{S_5}{\sqrt{(1-F_L)F_L}}$$
$$P'_6 = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$
$$P'_8 = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P'_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P'_6\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P'_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

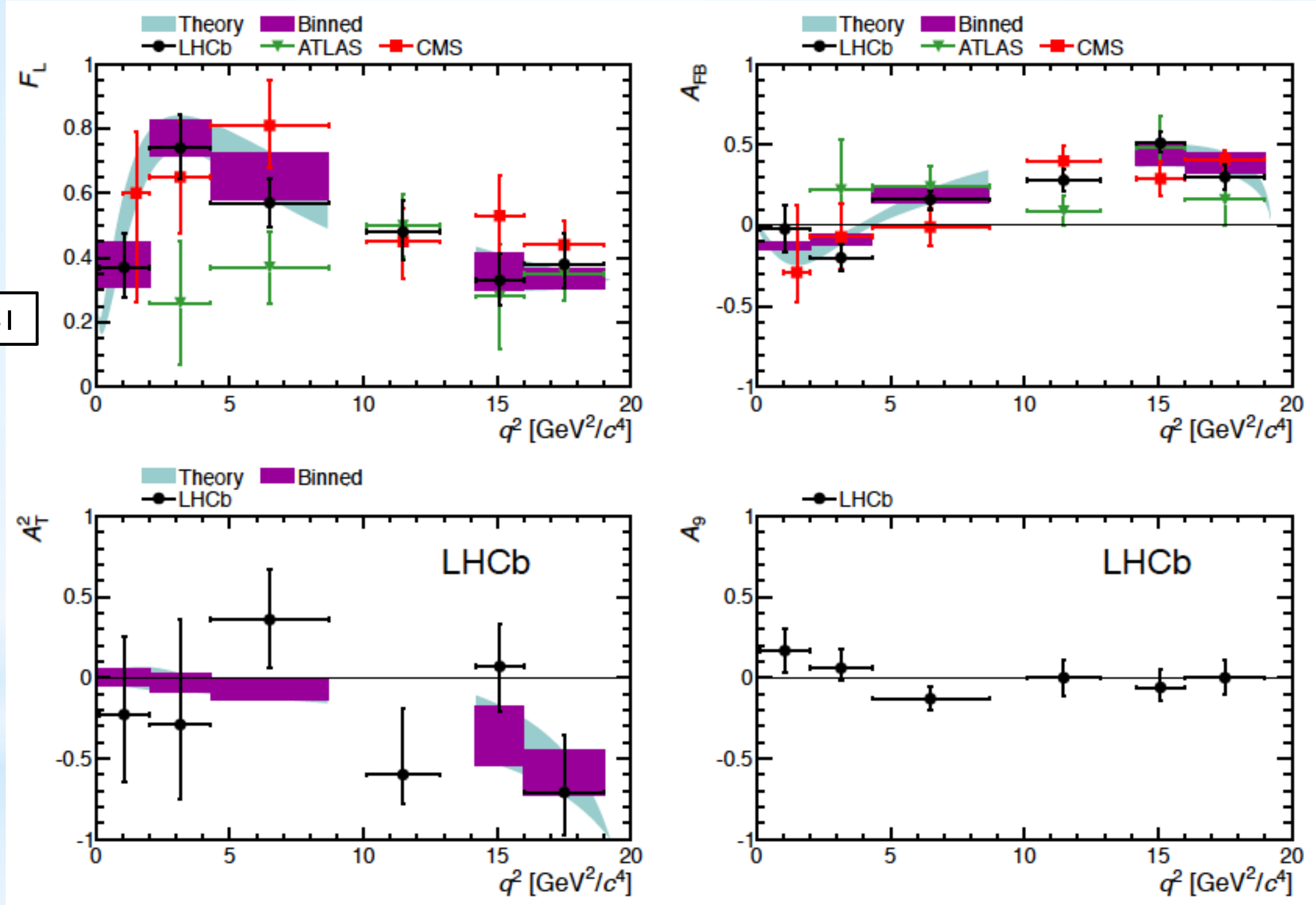
$B \to K^* \mu\mu$ Angular Analysis Results

Also ATLAS and CMS with ~400 candidates with 5 fb^{-1} start to contribute to this analysis. They are particularly competitive at large q^2.

LHCb: JHEP 1308 (2013) 131

CMS: PLB 727 (2013) 77

ATLAS-CONF-2013-038



LHC experiments have already surpassed the precision from B-factories and Tevatron. LHCb is the most precise. **Within uncertainties observables are consistent with the SM.**

B→K* μ μ Angular Analysis Results

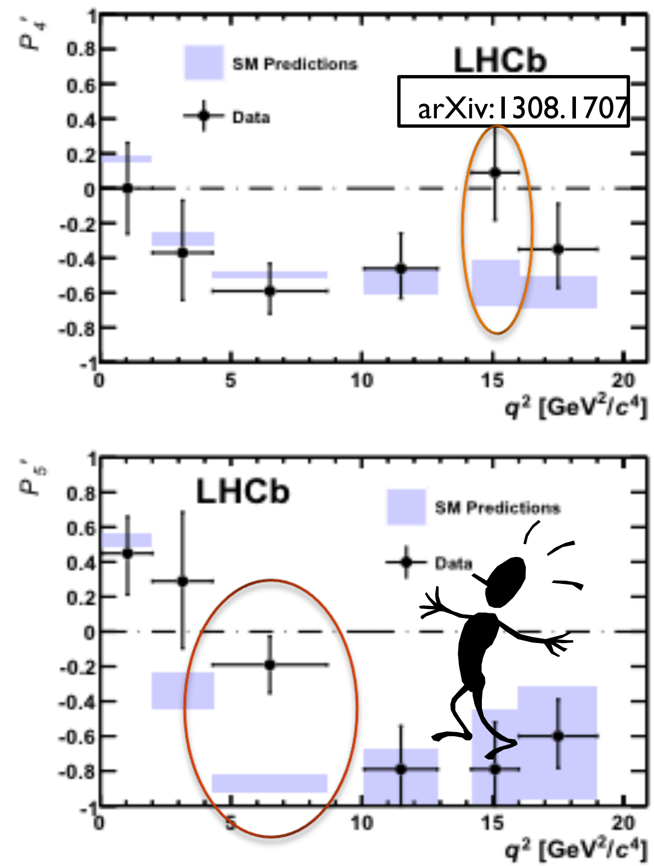
Other folding techniques, can give access to the rest of observables.

$$P'_4,\ S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_5,\ S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_6,\ S_7: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_8,\ S_8: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$



Most of measurements in good agreement with SM predictions. Only a hint of disagreement in P'_5 at low q^2. With more luminosity a full angular analysis (no folding) will allow to exploit the full statistical power of the data.

Comments on P'$_5$ significance

SM predictions for P'$_5$ differ significantly between different authors.

Nevertheless, NP contributing to C_9 could provide a better fit to the data, and still be compatible with other measurements.

The increase in sensitivity of the analysis with 3 fb^{-1} could already be tale-telling.

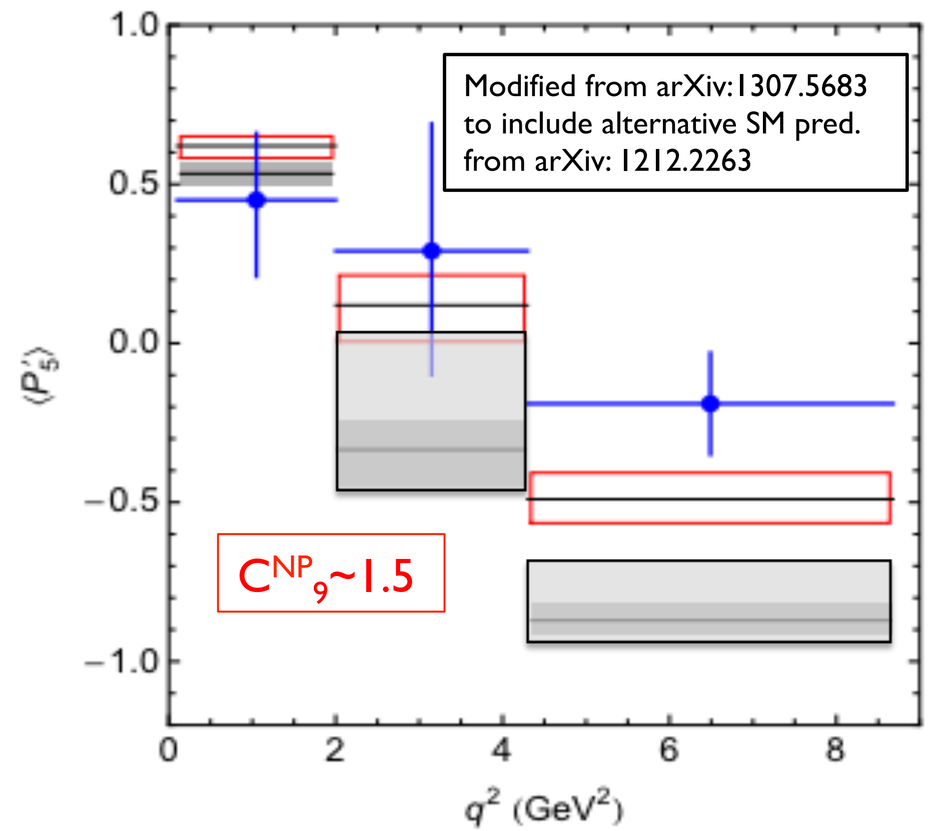
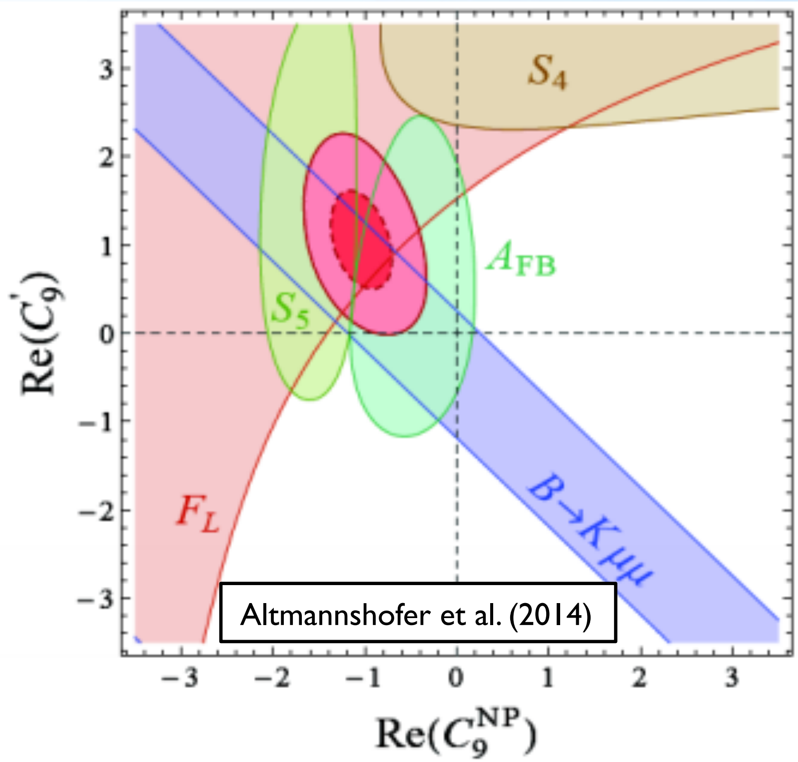


FIG. 4: Improvement in the q^2-dependence of P'_5 in the illustrative case $C_9^{NP} = C_{9'}^{NP} = -1.5$ (and NP contributions to the other Wilson coefficients set to zero).

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

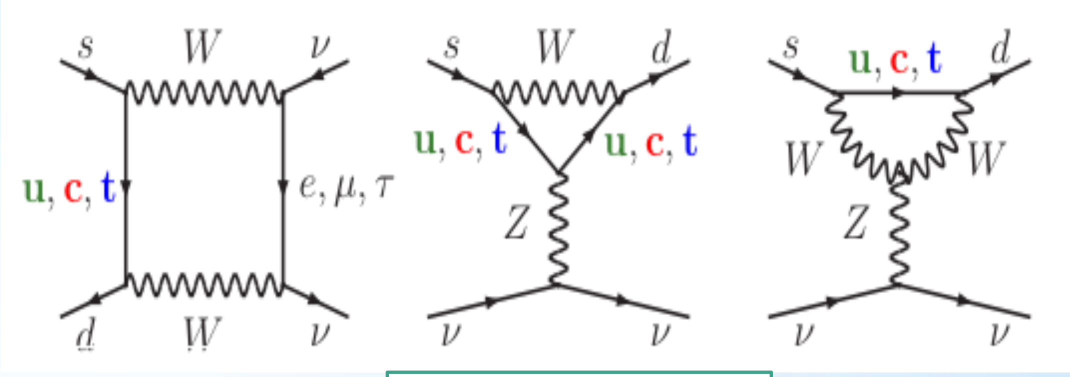
$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell),$$



ΔF=1 EW penguins in s→d transitions: $K^{0(+)}\to\pi^{0(+)}\nu\nu$

$K^{0(+)}\to\pi^{0(+)}\nu\nu$ are certainly the "cleanest" Kaon decays (not long distance pollution affecting lepton modes, dominated by a single operator) and provide sensitivity to $|V_{td}|$.

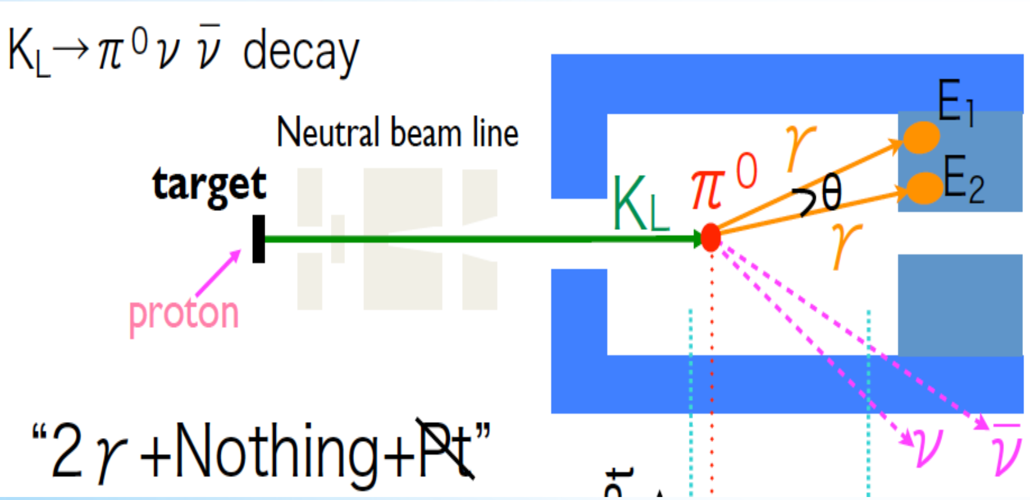
$BR_{TH}(K^+\to\pi^+\nu\nu) = (7.8\pm0.8)\times10^{-11}$,
$BR_{TH}(K^0\to\pi^0\nu\nu) = (2.4\pm0.4)\times10^{-11}$



s→d ($|V_{ts}V_{td}|\ \alpha\ \lambda^5$)

both uncertainties are expected to be below 10% ultimately. The charged(neutral) mode is sensitive to CP-conserving(violating) NP.

BNL E787/E949 have observed 7 $K^+\to\pi^+\nu\nu$ candidates → **$BR=(17\pm11)\times10^{-11}$**
KEK E391 had no $K^0\to\pi^0\nu\nu$ candidates → **$BR<2.6\times10^{-8}$ @90% C.L.**



New at CKM2014: KOTO (KEK) show results after 100h run at 10% power design (interrupted by JPARC irradiation accident May 2013). Restart data taking in 2015.

Observe 1 event for 0.36±0.16 bkg

Already similar sensitivity than E391!
Next run expect x20 improvement.

ΔF=1EW penguins in s→d transitions: $K^{0(+)} \to \pi^{0(+)} \nu \nu$

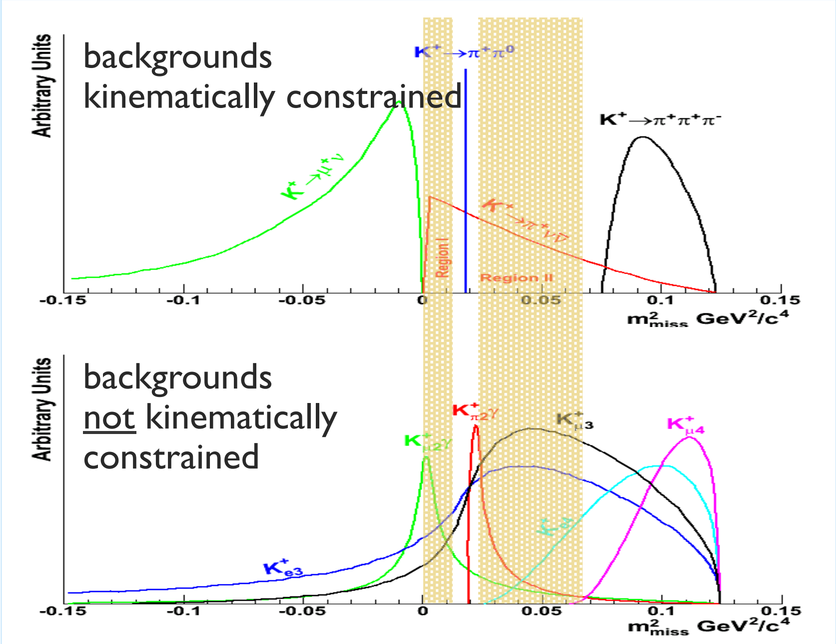
NA62 at CERN starts pilot run in **October 2014**, and data taking 2015-17, using the technique of decay in flight.

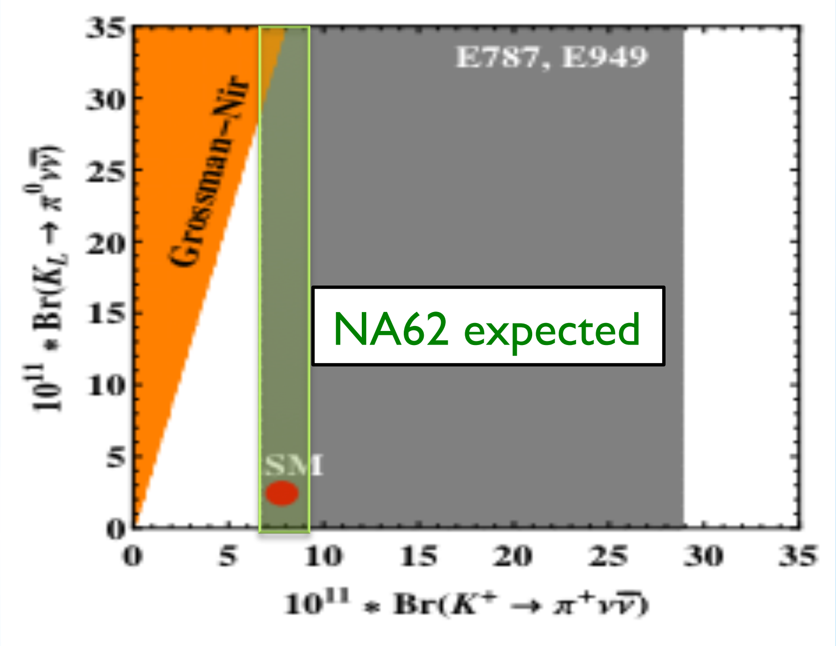
4.5×10^{12} Kaon decays per year (10% of the produced K decay in 60m fiducial volume). Total rate 750 MHz (only 6% due to K).

Expect to decrease the **experimental uncertainty to ~10% on BR($K^+ \to \pi^+ \nu \nu$), with O(100) SM events and <10 bkg.**

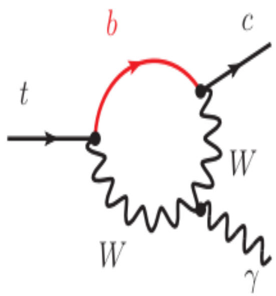
After the LS2 **(2018)**, if a factor 10^8 π^0 rejection has been achieved, NA62 plans to attempt to measure the **neutral mode** (upgrades in the beam, target and detector would be needed).

KOTO-2 has the potential to even go further in precision.





$\Delta F=1$ EW penguins $t \to c,u$ transitions: top decays



$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{M_W^2}V_{tb}V_{cb}^*$$

$$\Rightarrow \mathrm{Br}(t \to c\gamma)_{\mathrm{SM}} \simeq 5 \times 10^{-14}$$

Like in charm decays, FCNC heavily suppressed within the SM. Unlike charm decays, top FCNC are much less affected by long distance effects!

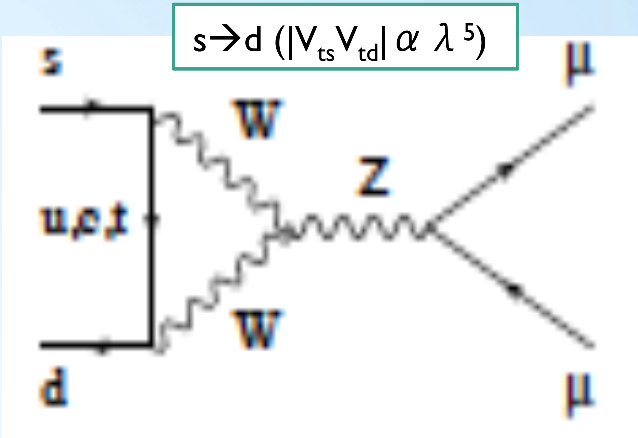
$Br(t\to u\gamma) < 1.61\times10^{-4}$	8 TeV, 19.1 fb^{-1}	CMS PAS TOP-14-003
$Br(t\to c\gamma) < 1.82\times10^{-3}$		
$Br(t\to ug) < 3.55\times10^{-4}$	7 TeV, 5 fb^{-1}	CMS PAS TOP-14-007
$Br(t\to cg) < 3.44\times10^{-3}$		
$Br(t\to qZ) < 5\times10^{-4}$	7 TeV, 5 fb^{-1} 8 TeV, 19.7 fb^{-1}	PRL 112 (2014) 171802

However, indirect limits from B and D decays, are in general one order of magnitude more stringent. With **O(100) fb^{-1}** ATLAS and CMS will be able to access the interesting region of sensitivity.

ΔF=1 Higgs penguins in s→d transitions: K→ $\mu^+ \mu^-$

The pure leptonic decays of **K,D and B** mesons are a particular interesting case of EW penguin.

The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to new (pseudo-)scalar interactions →**Higgs penguins!**



BR($K_L \to \mu\mu$)=(6.84±0.11)x10^{-9} (BNL E871, PRL84 (2000)) measured to be in agreement with SM, but completely dominated by absorptive (long distance) contributions. In the case of $K_s \to \mu\mu$ the absorptive part is calculated to be 5x10^{-12} as it is proportional to Im($V_{td}V_{ts}$). NP enhancement up to 10^{-11} is possible.

The best existing limits on $K_s \to ll$ at 90% C.L. are:

BR($K_s \to \mu\mu$)<3.2x10^{-7} (PLB44 (1973))
BR($K_s \to ee$) <9x10^{-9} (KLOE, PLB672 (2009))

In particular a measurement of BR($K_s \to \mu\mu$) of O(10^{-10}-10^{-11}) would be a clear indication of NP in the dispersive part, and would increase the interest of a precise measurement of $K^+ \to \pi^+ \nu\nu$.

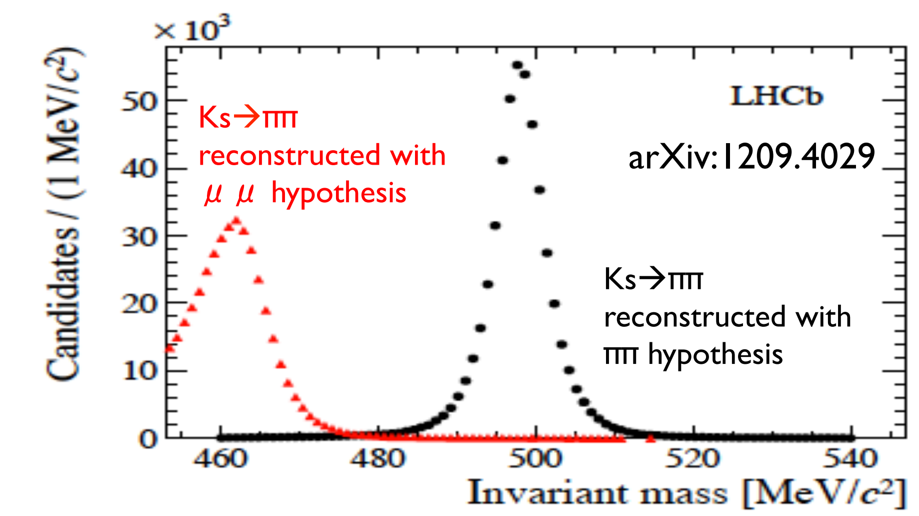
Δ F=1 Higgs penguins in s→d transitions: K→ $\mu^+\mu^-$

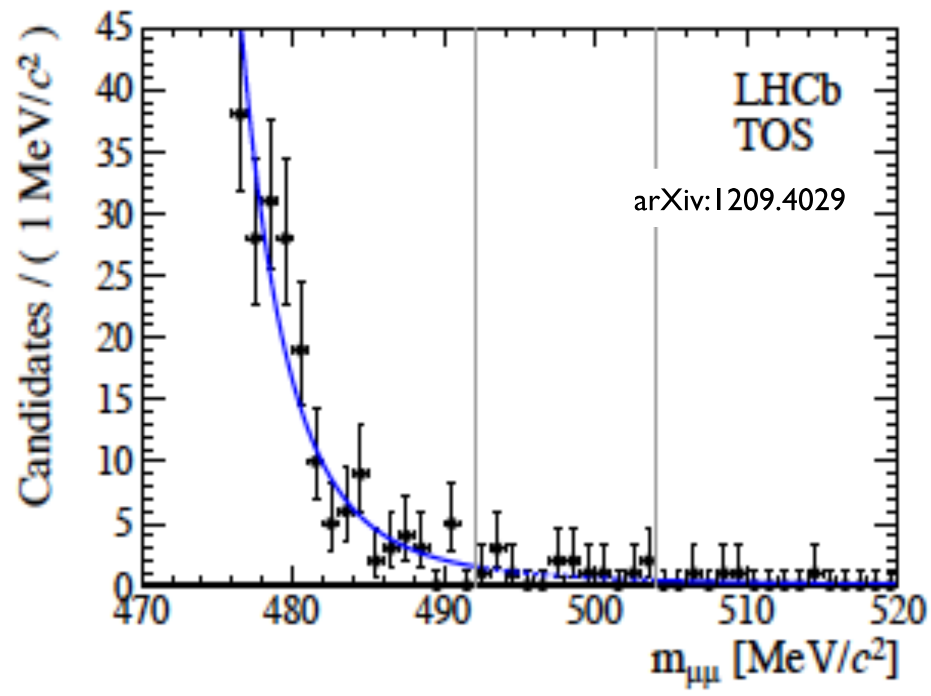
LHC produces 10^{13} K_s per fb^{-1} in the LHCb acceptance. Trigger was not optimized for this search in 2011.

Excellent LHCb invariant mass resolution critical to reduce peaking bkg.

Mass distribution compatible with bkg hypothesis:

BR(K_s→ $\mu\mu$)<11(9)x10^{-9} at 95(90)% C.L.
x30 improvement w.r.t. previous limit!

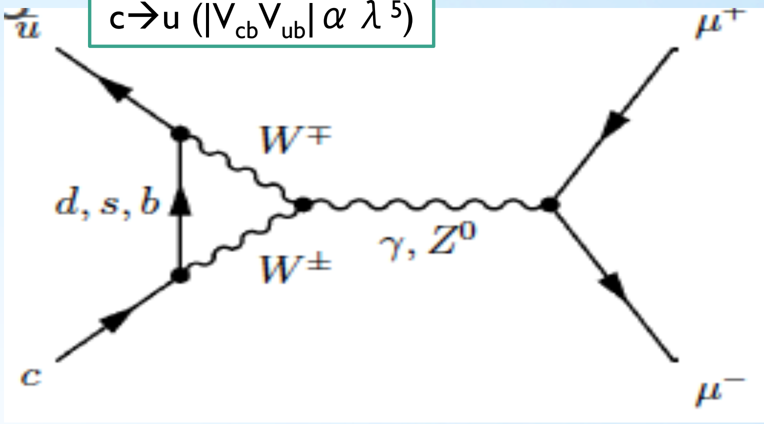




Excellent prospects to reach the interesting region ~10^{-11} with the LHCb upgrade.
Complement NA62 physics program.

ΔF=1 Higgs penguins in c→u transitions: D→ $\mu^+\mu^-$

c→u ($|V_{cb}V_{ub}|\ \alpha\ \lambda^5$)



Charm decays are **complementary** to B and K decays, because in the **loops** the relevant quarks **are down-type** rather than up-type.

Short distance contribution to **D→ $\mu\ \mu$** decays is **O(10^{-18})** within the SM.

Long distance contributions could be indeed much larger, but they are limited to be **below 6×10^{-11}** from the existing **limits on D→ $\gamma\ \gamma$**:

$$\mathcal{BR}^{(\gamma\gamma)}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5} \mathcal{BR}(D^0 \to \gamma\gamma)$$ Phys.Rev. D66 (2002) 014009

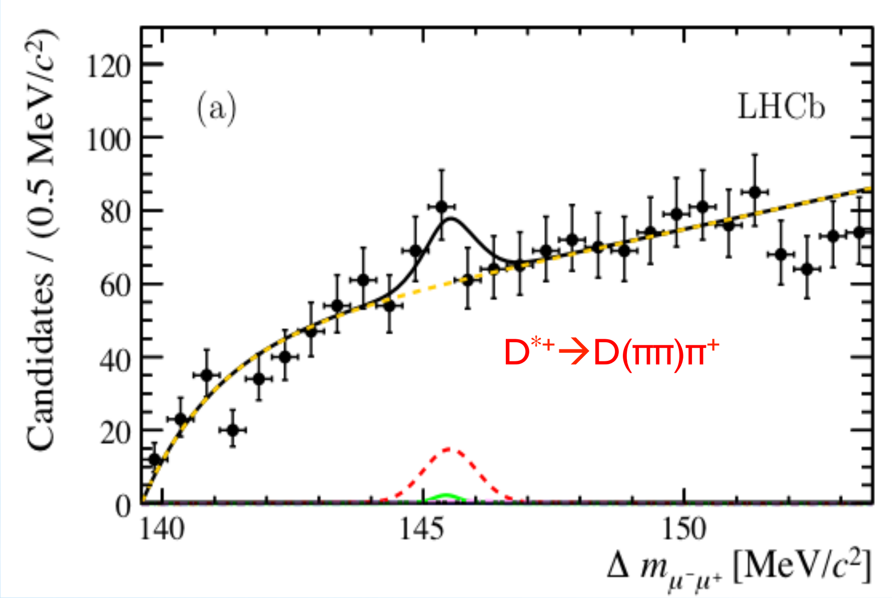
BABAR result BR(D→ $\gamma\ \gamma$ <2.2×10^{-6} @90% C.L.) Phys. Rev. D85 (2012) 091107

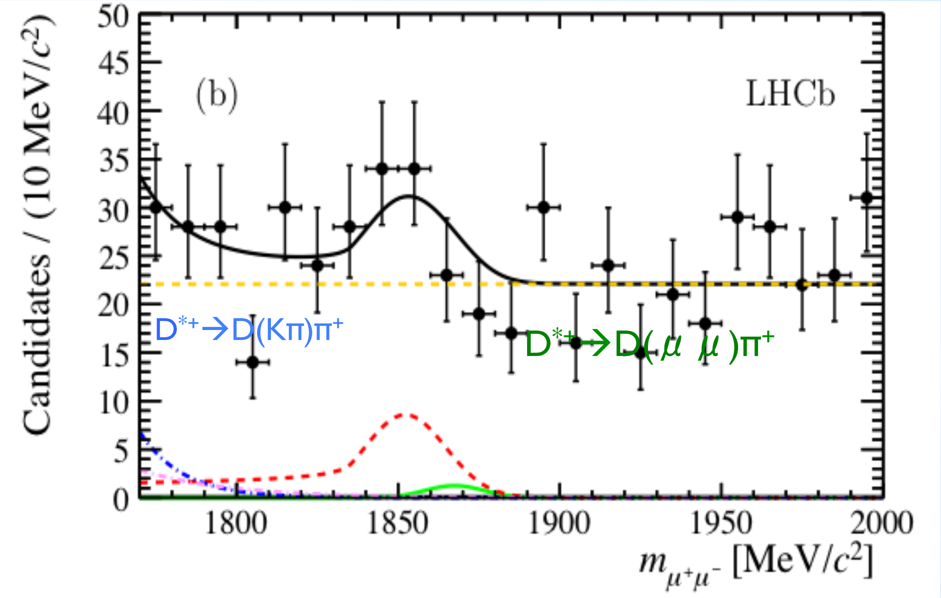
Charm decays complement K and B mesons decays.

ΔF=1 Higgs penguins in c→u transitions: D→ $\mu^+\mu^-$

Use D^{*+}→Dπ^+ tagged events to decrease combinatorial background. Experimental control of the peaking background is crucial (D→ππ).
Best existing limit before 2012 was from **Belle, <1.4x10^{-7}@90%C.L.**

LHCb,0.9 fb^{-1}: <6.2x10^{-9}@90%C.L. Phys. Lett. B725 (2013) 15. *(factor ~20 improvement)*
CMS, 0.09 fb^{-1} : <5.4x10^{-7}@90%C.L. CMS-PAS-BPH-11-017



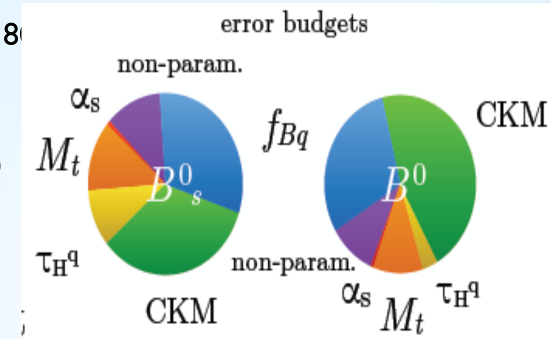


BABAR update for summer 2012 show a slight excess of candidates (8 observed, 3.9±0.6 bkg) which was interpreted as a **two-sided 90% C.L. limit, [6,81]x10^{-8}, in tension with LHCb results.**

ΔF=1 Higgs penguins in b→d,s transitions: B decays

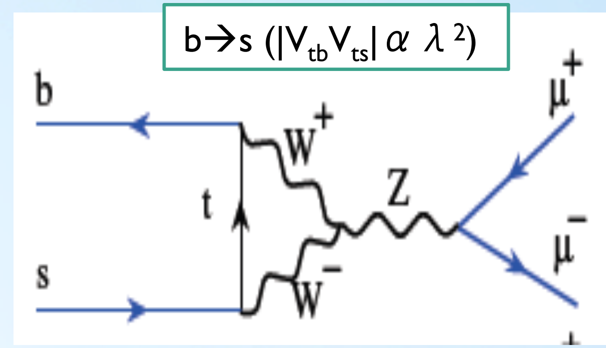
These decays are well predicted theoretically, and experimentally are exceptionally clean. Within the SM, the time-integrated predicted values are:

PRL 112 (2014) 1018



$BR_{SM}(B_s \to \mu\,\mu) = (3.66\pm0.23)\times10^{-9}$

$BR_{SM}(B \to \mu\,\mu) = (1.06\pm0.09)\times10^{-10}$

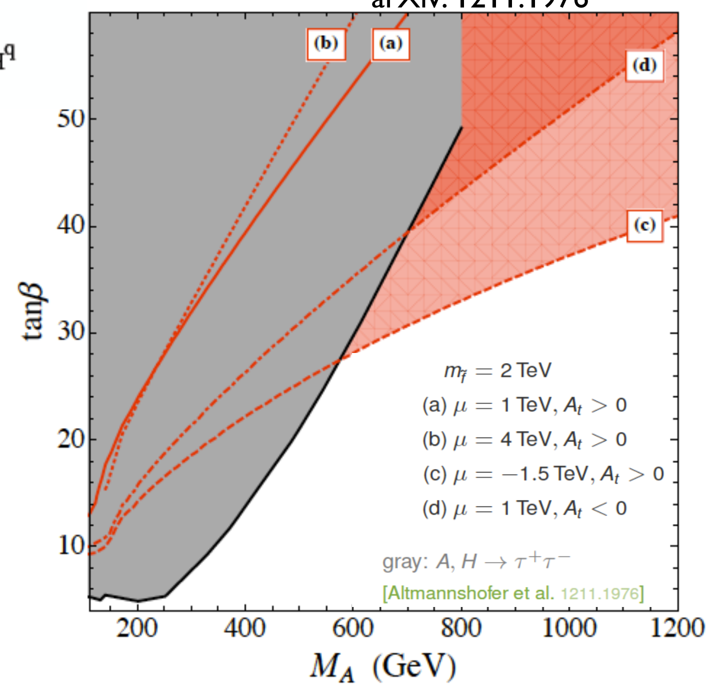


$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3 \sin^4\theta_W} |V_{tb}^* V_{tq}|^2 \tau_{Bq} M_{Bq}^3 f_{Bq}^2 \sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}} \times$$

$$\times \left\{ M_{Bq}^2 \left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)\left(\frac{C_S - \mu_q C_S'}{1+\mu_q}\right)^2 + \left[M_{Bq}\left(\frac{C_P - \mu_q C_P'}{1+\mu_q}\right) + \frac{2m_\mu}{M_{Bq}}(C_A - C_A')\right]^2 \right\}$$

with $\mu_q = m_q/m_b \ll 1$ and $m_\mu/m_B \ll 1$. Hence if $C_{S,P}$ are of the same order of magnitude than C_A they dominate by far.

arXiv: 1211.1976



$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{1/\Gamma_H^s}\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}\sqrt{1-\frac{4m_\mu^2}{M_{B_d}^2}}}{M_{B_s}\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}} = 0.0295^{+0.0028}_{-0.0025}$$

Superb test for new (pseudo-)scalar contributions. Within the MSSM this BR is proportional to $\tan^6\beta / M_A^4$

ΔF=1 Higgs penguins in b→d,s transitions: B decays

Main difficulty of the analysis is large ratio B/S.

Assuming the SM BR then after the trigger and selection, CDF expects ~0.26 $B_s \to \mu\mu$ signal events/fb, ATLAS ~0.4, CMS ~0.8 while LHCb ~12 (6 with BDT>0.5).

The background is estimated from the mass sidebands. **LHCb** is using the signal pdf shape from control channels. All experiments normalize to a known B decay.

In the B_s mass window the background is completely dominated by combinations of real muons

(main handle is the invariant mass resolution: *a factor two better invariant mass resolution is equivalent to a factor two increase in luminosity*).

	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	**45 fs**
Invariant Mass resolution (2-body)	80 MeV/c^2	45 MeV/c^2	25 MeV/c^2	**22 MeV/c^2**

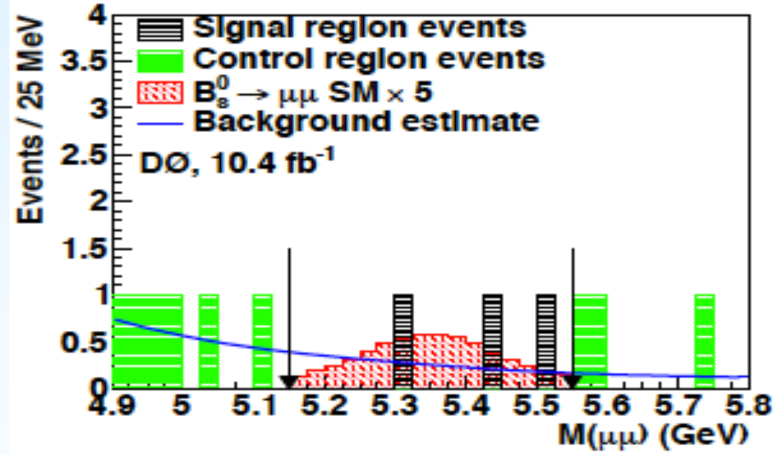
Therefore, for equal analyses strategies:

~1/fb at LHCb is equivalent to ~10/fb at CMS, ~20/fb at ATLAS/CDF.

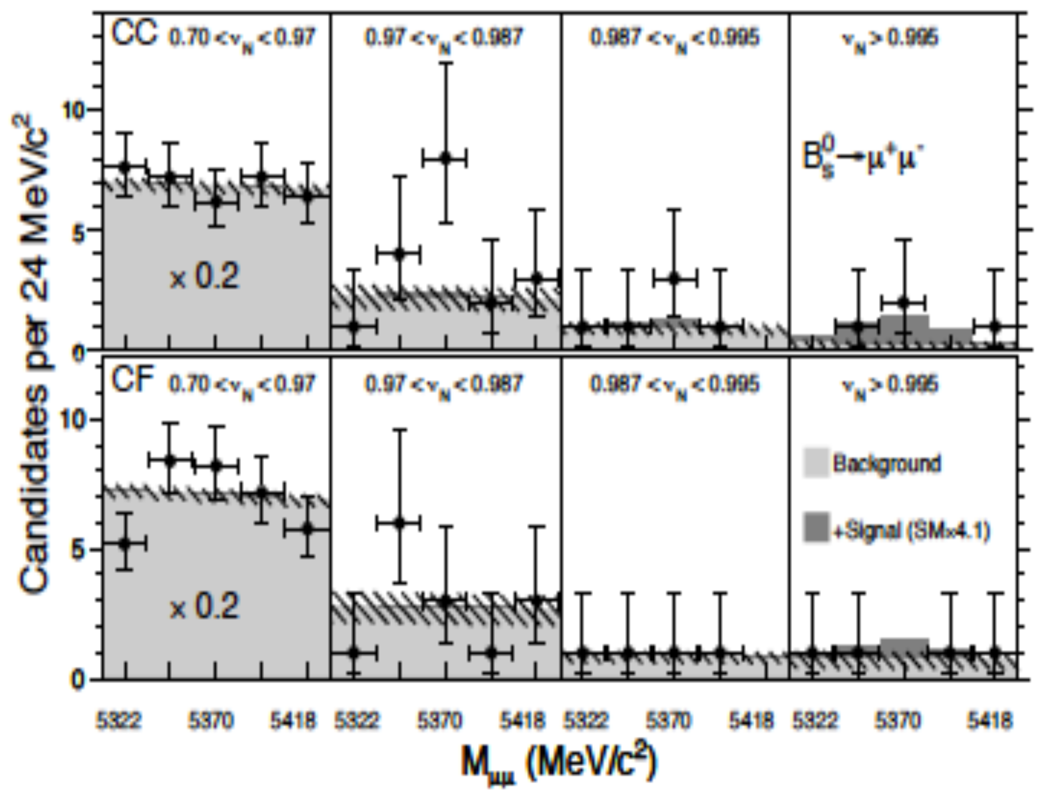
$\Delta F=1$ Higgs penguins in b→d,s transitions: Tevatron Results

D0: $10.4\ \mathrm{fb}^{-1}$ [arXiv:1301.4507]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 15 \cdot 10^{-9} \text{ @ } 95\ \%\ \text{C.L.}$$



CDF analysis strategy very similar than LHCb: Use multivariate PDF and invariant mass distribution. Small excess observed over the background-only hypothesis in the B_s mass window (p-value = 0.9%).



CDF: $10\ \mathrm{fb}^{-1}$ [PRD 87, 072003 (2013)]

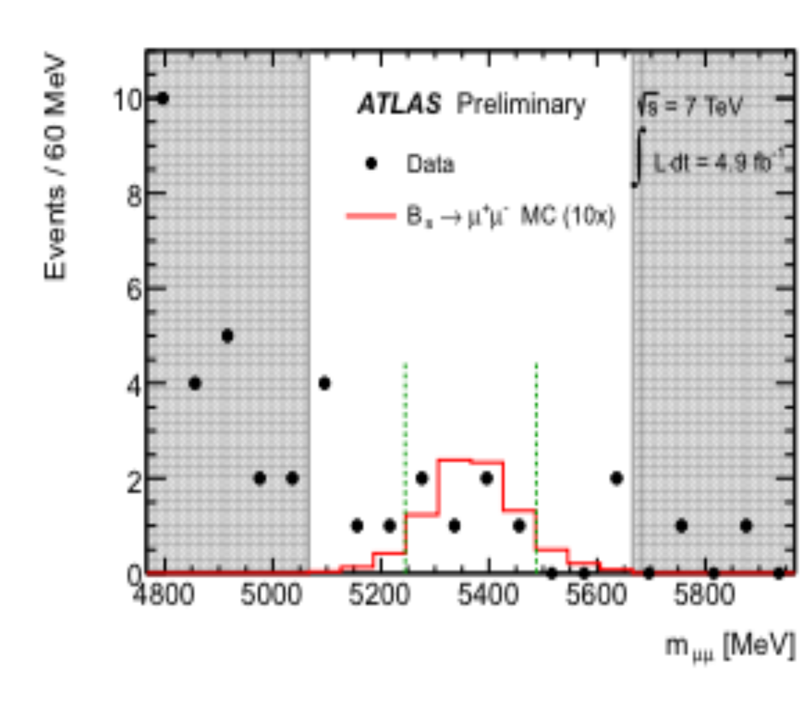
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \in [0.8, 34] \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \cdot 10^{-9}$$
@ 95 % C.L.

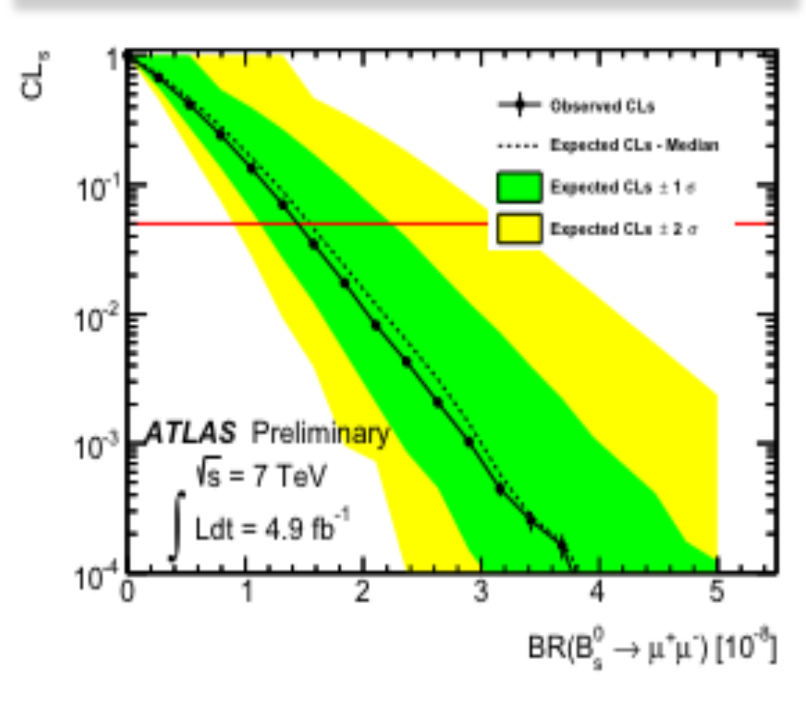
Δ F=1 Higgs penguins in b→d,s transitions: ATLAS Results

Both ATLAS and CMS divide the data sample in bins of η to take into account the invariant mass resolution dependence. **ATLAS** with **4.9 fb^{-1}** observes 6 candidates in the mass window, compatible with 6.8 expected from the sidebands background.

ATLAS-CONF-2013-076

BR($B_s \to \mu^+\mu^-$)< 15x10^{-9} @95% C.L.





$\Delta F=1$ Higgs penguins in b→d,s transitions: CMS Results

CMS and LHCb invariant mass resolution allows for simultaneous fit of B_d and B_s.

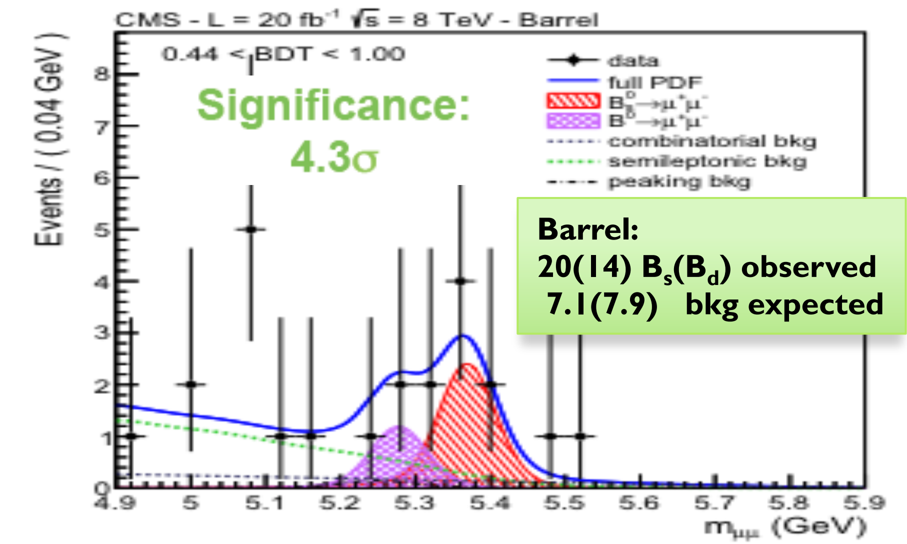
PRL 111 (2013) 101804

With **25fb^{-1}** analyzed by summer 2013, CMS expects to have 4.8 σ evidence for $B_s \rightarrow \mu^+\mu^-$ decays over the null hypothesis assuming the SM.

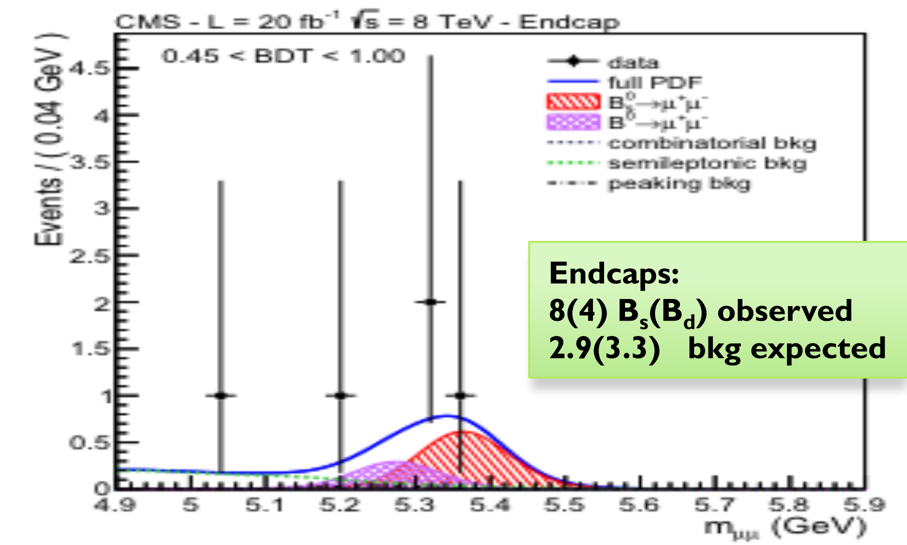
		$\varepsilon_{tot}[10^{-2}]$	N^{exp}_{signal}	N^{exp}_{total}	N_{obs}
7 TeV	B^0 barrel	0.33 ± 0.03	0.27 ± 0.03	1.3 ± 0.8	3
	B^0_s barrel	0.30 ± 0.04	2.97 ± 0.44	3.6 ± 0.6	4
	B^0 end cap	0.20 ± 0.02	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s end cap	0.20 ± 0.02	1.28 ± 0.19	2.6 ± 0.5	4
8 TeV	B^0 barrel	0.24 ± 0.02	1.00 ± 0.10	7.9 ± 3.0	11
	B^0_s barrel	0.23 ± 0.03	11.46 ± 1.72	17.9 ± 2.8	16
	B^0 end cap	0.10 ± 0.01	0.30 ± 0.03	2.2 ± 0.8	3
	B^0_s end cap	0.09 ± 0.01	3.56 ± 0.53	5.1 ± 0.7	4

Final sensitivity, by further dividing these samples in 12 categories:

$BR(B_s \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ (4.3 σ)
$BR(B_d \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ (2.0 σ)



Barrel:
20(14) $B_s(B_d)$ observed
7.1(7.9) bkg expected



Endcaps:
8(4) $B_s(B_d)$ observed
2.9(3.3) bkg expected

ΔF=1 Higgs penguins in b→d,s transitions: LHCb Results

LHCb had already shown evidence of **$BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ (3.5σ)** by Autumn 2012 using 2.1 fb^{-1}.

With **3fb^{-1}** analyzed by summer 2013, LHCb expects to have 5.0σ evidence for $B_s \to \mu^+\mu^-$ decays over the null hypothesis assuming the SM.

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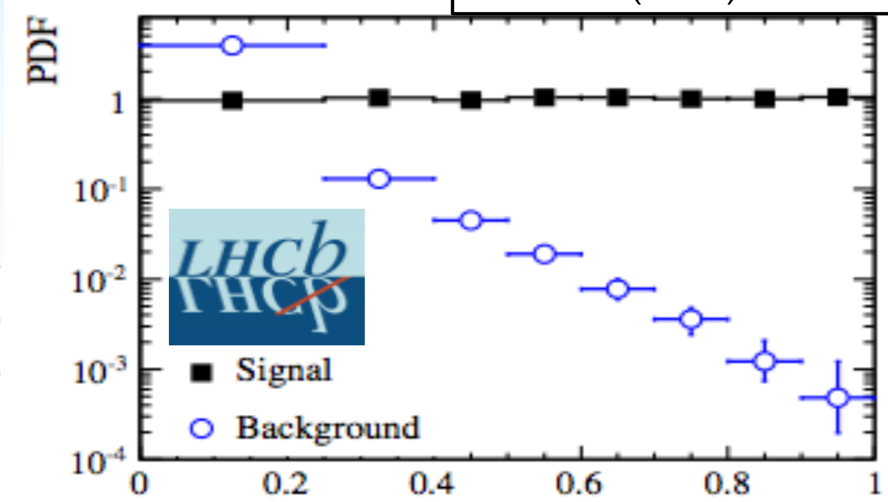
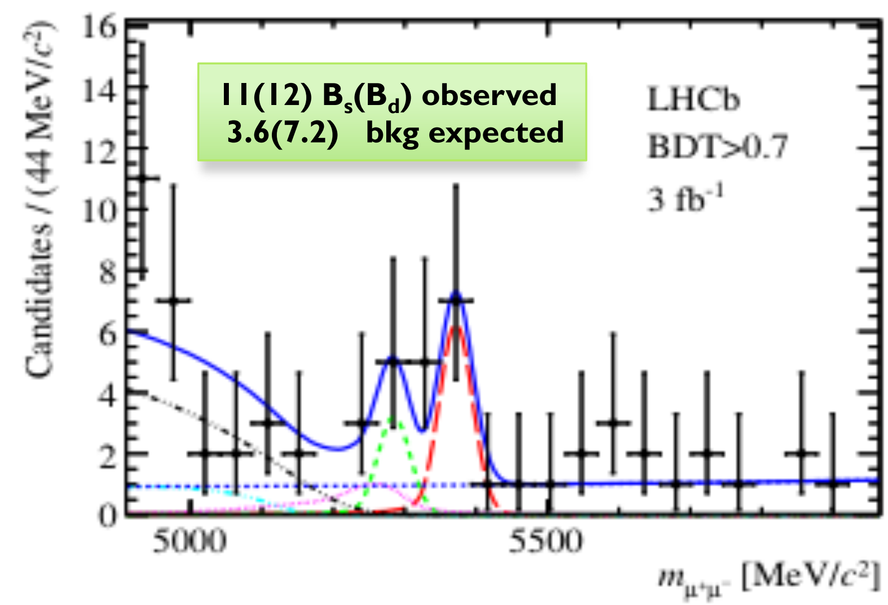


B_s

Invariant mass [MeV/c^2]		BDT 0.5 – 0.6	0.6 – 0.7	0.7 – 0.8	0.8 – 0.9	0.9 – 1.0
5311 – 5431	Exp. comb. bkg	$11.9^{+1.5}_{-1.4}$	$4.77^{+1.11}_{-0.95}$	$2.17^{+0.79}_{-0.65}$	$0.79^{+0.48}_{-0.34}$	$0.29^{+0.32}_{-0.18}$
	Exp. peak. bkg	$0.148^{+0.048}_{-0.040}$	$0.147^{+0.047}_{-0.040}$	$0.140^{+0.045}_{-0.038}$	$0.130^{+0.042}_{-0.035}$	$0.111^{+0.035}_{-0.030}$
	Exp. signal	$3.75^{+0.47}_{-0.43}$	$3.76^{+0.47}_{-0.43}$	$3.61^{+0.46}_{-0.42}$	$3.68^{+0.46}_{-0.42}$	$3.79^{+0.46}_{-0.42}$
	Observed	16	13	5	4	2

B_d

Invariant mass [MeV/c^2]		BDT 0.5 – 0.6	0.6 – 0.7	0.7 – 0.8	0.8 – 0.9	0.9 – 1.0
5224 – 5344	Exp. comb. bkg	$12.8^{+1.7}_{-1.5}$	$4.9^{+1.2}_{-1.1}$	$2.14^{+0.88}_{-0.70}$	$0.82^{+0.53}_{-0.37}$	$0.29^{+0.35}_{-0.19}$
	Exp. peak. bkg	$0.88^{+0.29}_{-0.21}$	$0.88^{+0.28}_{-0.21}$	$0.83^{+0.27}_{-0.20}$	$0.77^{+0.25}_{-0.18}$	$0.66^{+0.21}_{-0.16}$
	Exp. Cross-feed	$0.590^{+0.078}_{-0.070}$	$0.591^{+0.076}_{-0.070}$	$0.567^{+0.077}_{-0.069}$	$0.579^{+0.076}_{-0.069}$	$0.595^{+0.077}_{-0.069}$
	Exp. signal	$0.424^{+0.050}_{-0.047}$	$0.425^{+0.050}_{-0.047}$	$0.408^{+0.050}_{-0.047}$	$0.416^{+0.049}_{-0.046}$	$0.428^{+0.050}_{-0.046}$
	Observed	16	7	3	6	3



$BR(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$ (4.0σ)
$BR(B_d \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10}$ (2.0σ)

CMS & LHCb Combination

Simultaneous fit to CMS and LHCb data presented at CKM2014 for the first time.

Assuming SM expect **7.6 σ** sensitivity for B_s and **0.8 σ** for B_d.

$BR(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ (6.2 σ)
$BR(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ (3.2 σ)

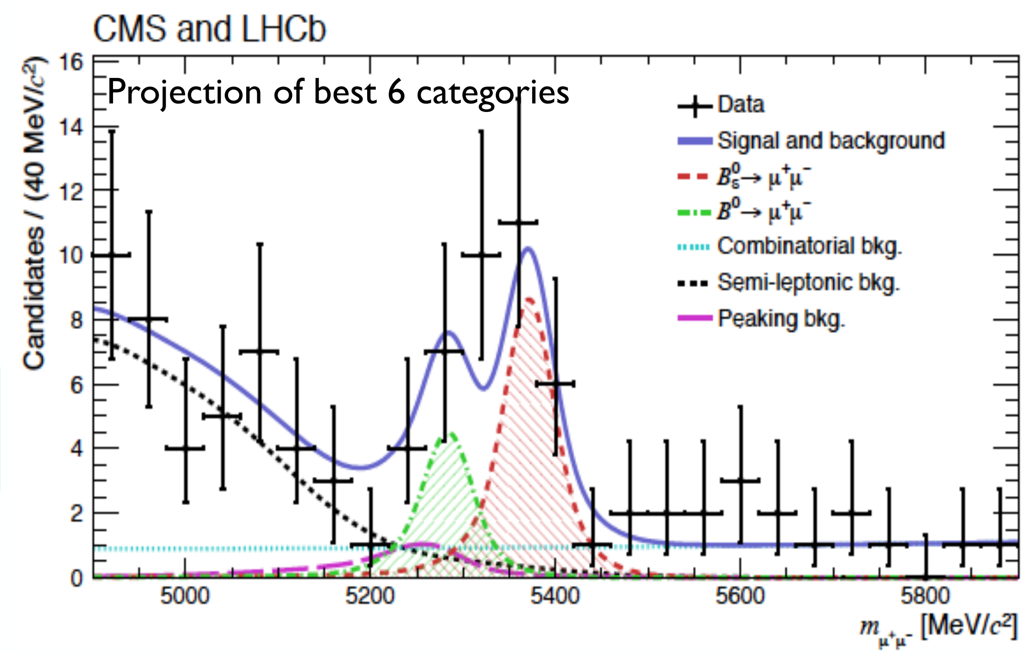
The measured BRs are compatible with the SM predictions:

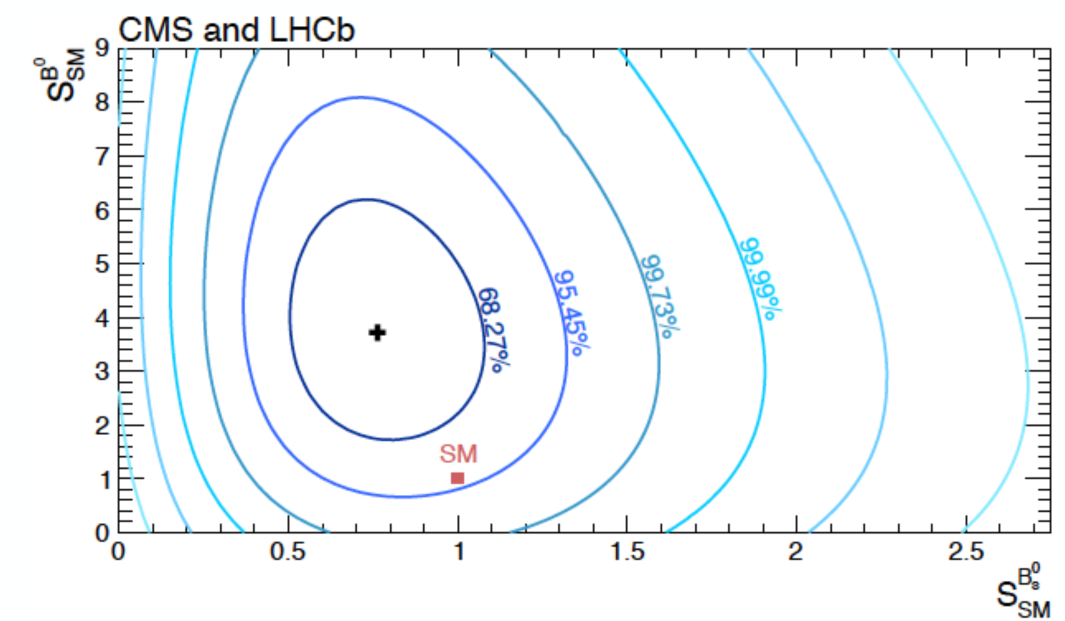
$S_{SM}(B_s) = 0.76^{+0.20}_{-0.18}$ (-1.2 σ)
$S_{SM}(B_d) = 3.7^{+1.6}_{-1.4}$ (+2.2 σ)

and its ratio, a clean test of MFV, is measured to be:

$R = 0.14^{+0.08}_{-0.06}$ (+2.3 σ)

(including TH uncertainty).



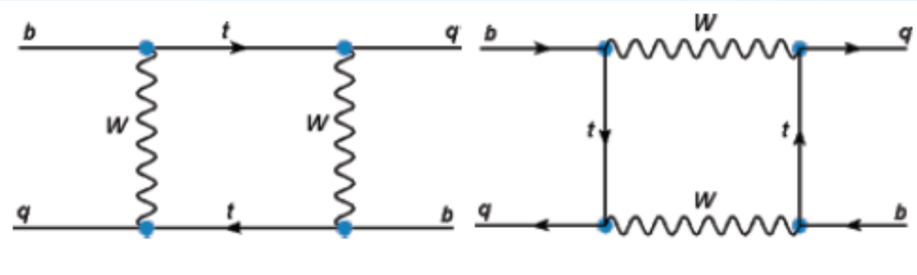


What do we learn about NP from flavour measurements?

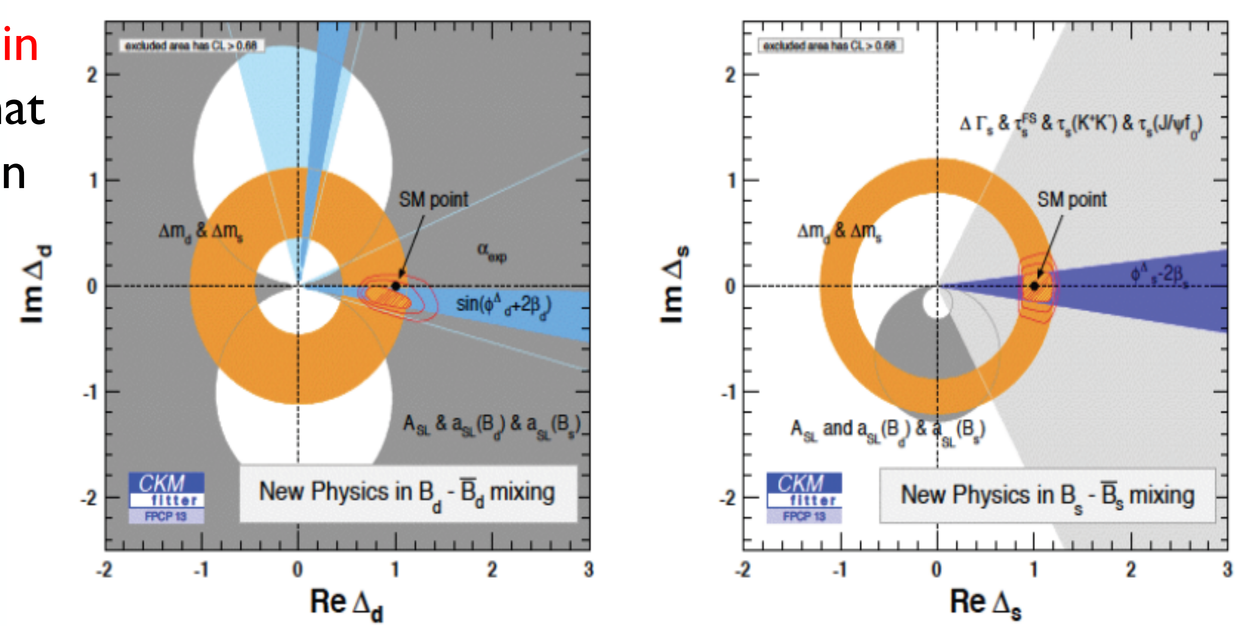
ΔF=2 box in b→q transitions: Implications

$$\langle B_q^0 | M_{12}^{SM+NP} | \overline{B}_q^0 \rangle \equiv \Delta_q^{NP} . \langle B_q^0 | M_{12}^{SM} | \overline{B}_q^0 \rangle$$

$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\ \mathrm{Im}(\Delta_q) = |\Delta_q| e^{i\phi^{\Delta_q}}$$



No significant evidence of NP in B_d or B_s mixing . Remember that what is named SM prediction in these plots, is in fact the determination from other measurements (tree level).



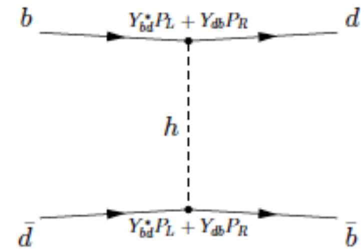
New CP phases in dispersive contribution to box diagrams constrained @95%CL to be <12% (<20%) for B_d(B_s).

Need to increase precision to disentangle NP phases of few percent in B_d and B_s mixing

Δ F=2 box: Yukawa couplings constraints

Roni Harnik at
LHCb-TH workshop
(14-16) October 2013

Meson Mixing



- Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j / v^2$
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\lvert Y_{uc} Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$	
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\lvert Y_{db} Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$	
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\lvert Y_{sb} Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$	
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	8×10^{-9}
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

Upper values expected for "natural" models

"Natural" models are constrained!

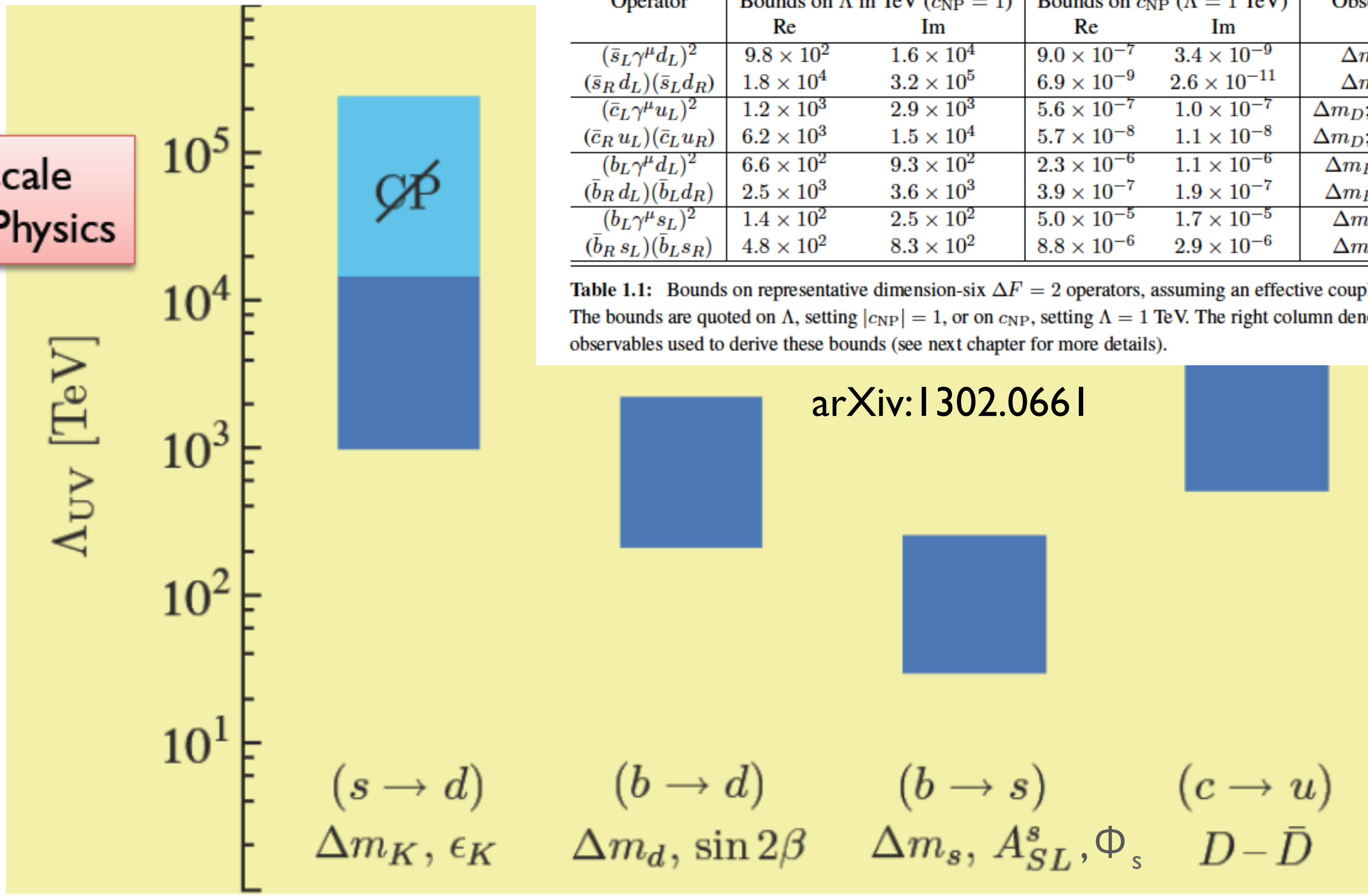
Δ F=2 box implications

Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} (Λ = 1 TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\|q/p\|,\phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|,\phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Table 1.1: Bounds on representative dimension-six $\Delta F=2$ operators, assuming an effective coupling c_{NP}/Λ^2. The bounds are quoted on Λ, setting $|c_{NP}|=1$, or on c_{NP}, setting $\Lambda = 1$ TeV. The right column denotes the main observables used to derive these bounds (see next chapter for more details).

arXiv:1302.0661

Mass scale of New Physics



CP violation in K system

Oscillations and CPV in B_d system

Oscillations and CPV in B_s system

Oscillations in D system

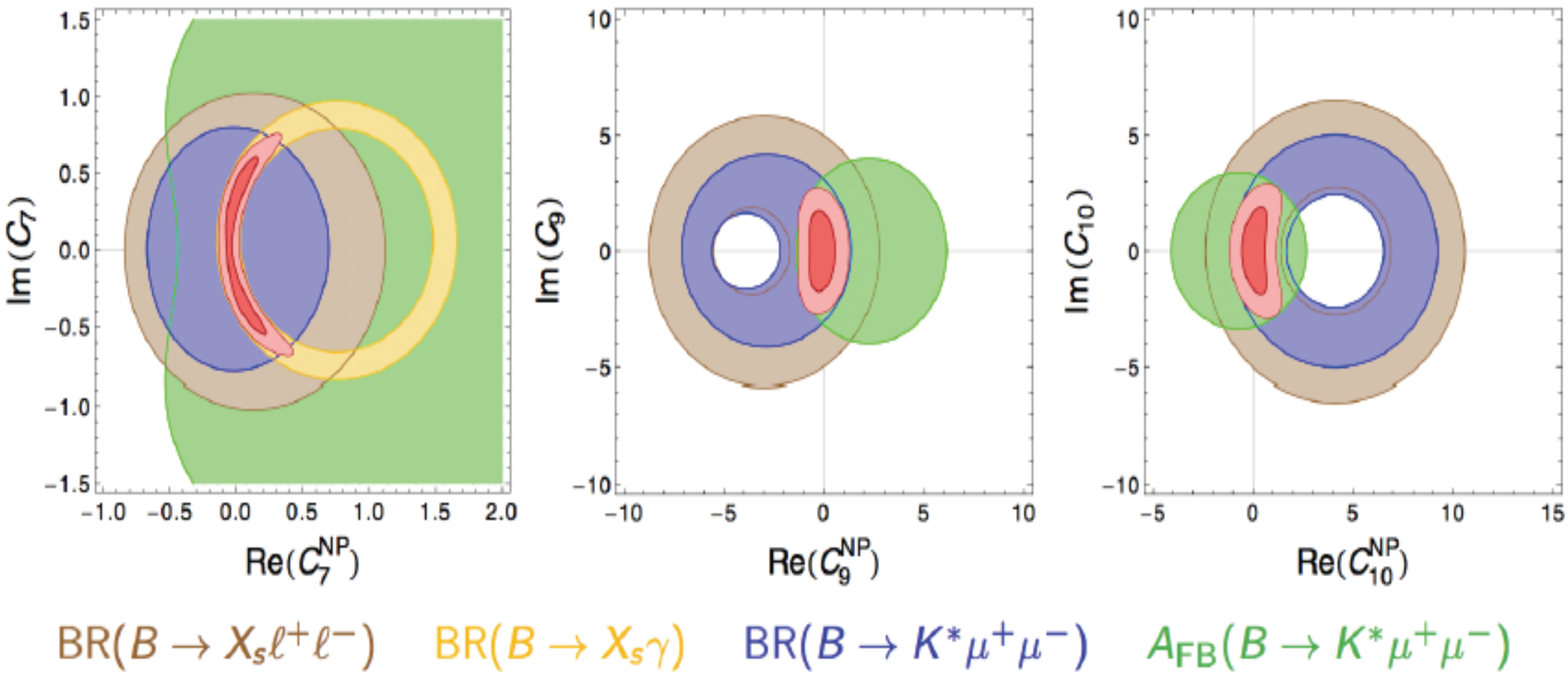
Δ F=1 EW penguins in b→s transitions: Implications

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell),$$

arXiv:1111.1257

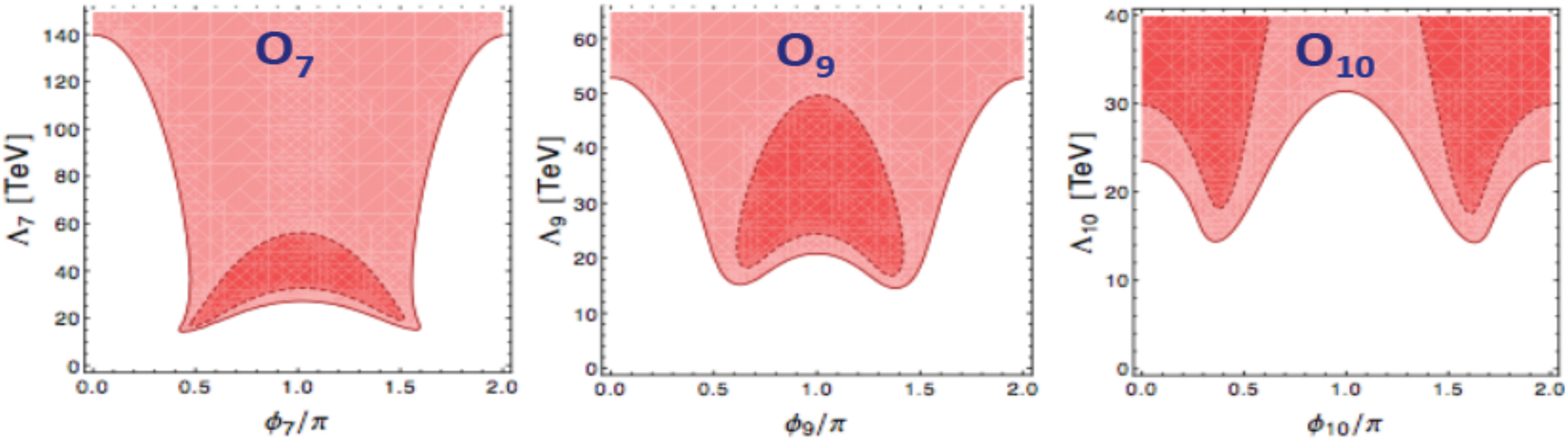


Δ F=1 EW penguins in b→s transitions: Implications

Tree level flavour violation

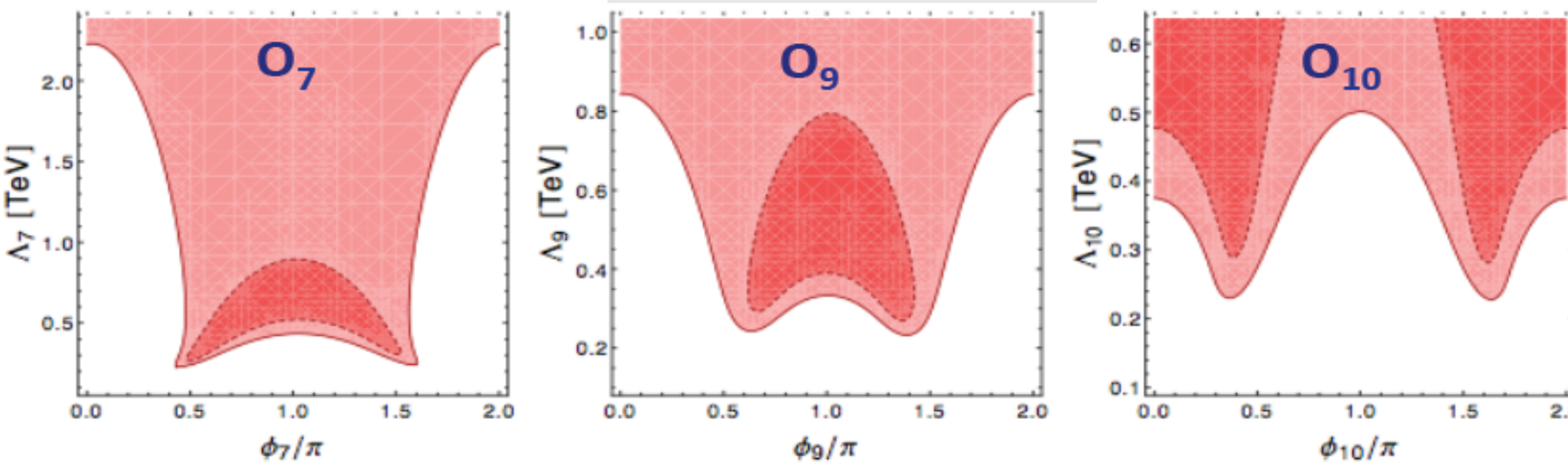
$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

D. Straub, arXiv:1111.1257, JHEP 1202:106



Loop level CKM-like flavour violation

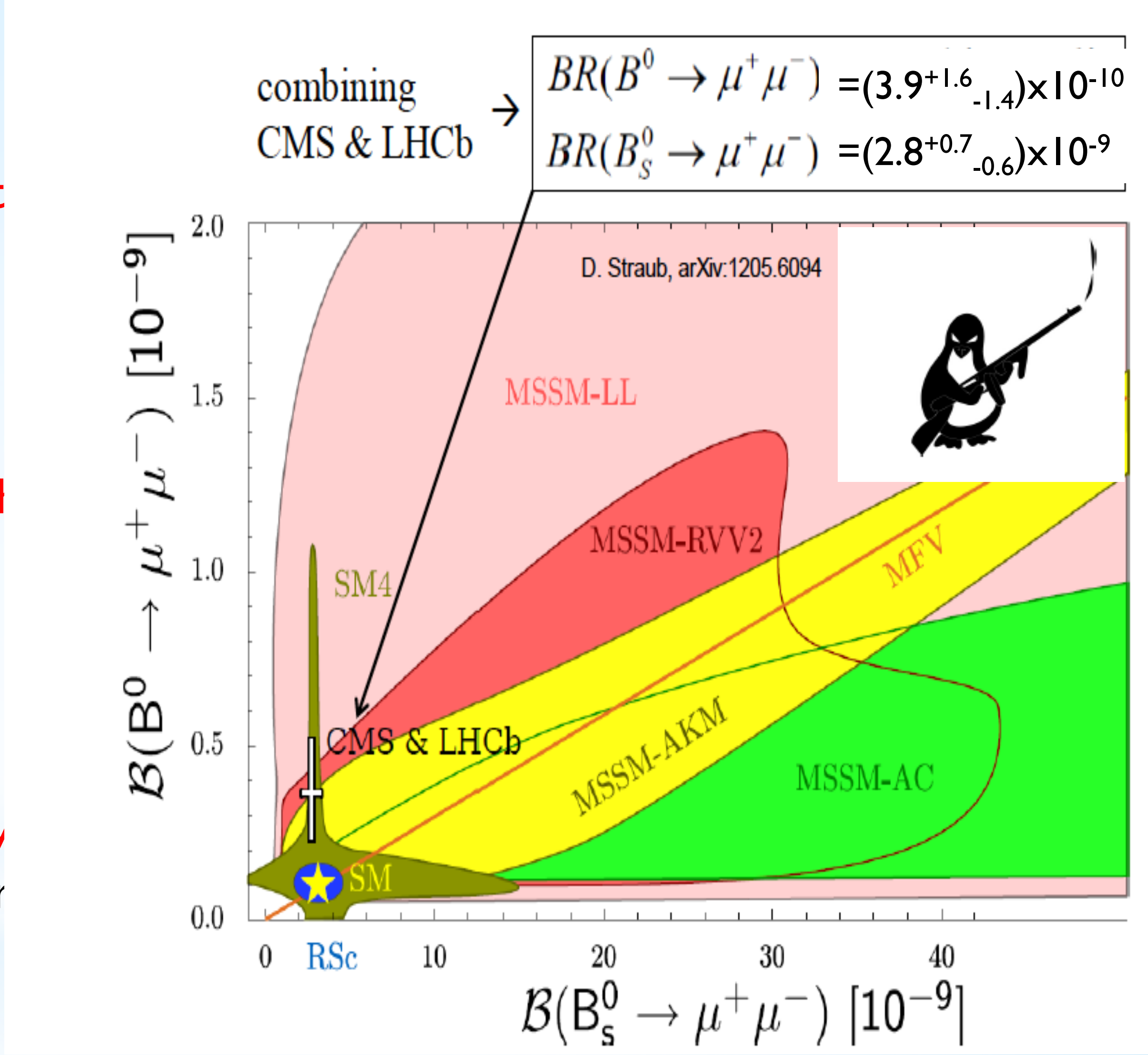
$$\mathscr{L} = \mathscr{L}_{\text{SM}} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$



Latest results on $B_{(s)} \to \mu^+ \mu^-$ strongly constraint the paramet space for many NP models, complementing direct searches from ATLAS/CMS.

In particular, large tan β with ligh pseudo-scalar Higgs in CMSSM strongly disfavored.

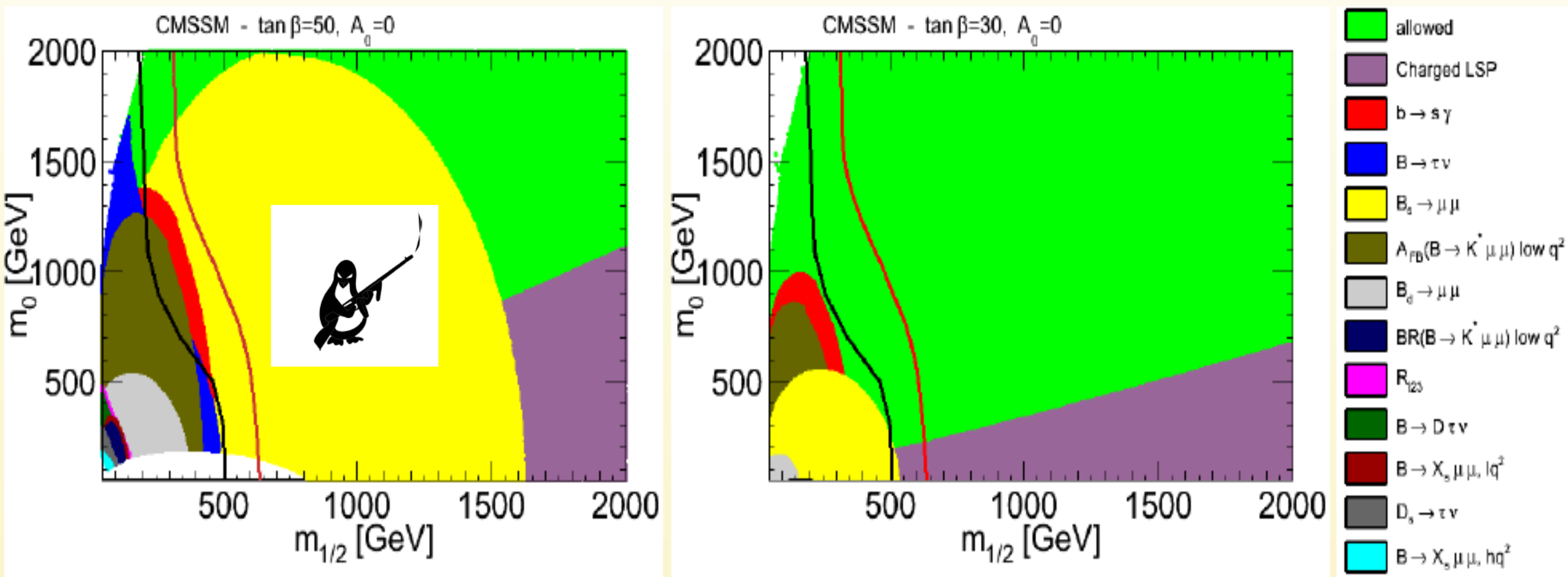
The precision achieved now is such that $B_{(s)} \to \mu^+ \mu^-$ sensitivity to (Z, γ) penguin cannot longer be considered sub-leading.



Δ F=1 EW penguins implications within CMSSM

Take the example of CMSSM… Flavour constraints are much more effective than direct searches at large tan β !

N. Mahmoudi, arXiv:1205.3099



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

Wrap up

Take home messages

Indirect measurements (loops approach) are not limited by the energy of the collisions, but by the precision of the measurements.

Historically, indirect measurements in the flavour sector have been crucial to build the SM.

The discovery of a non-zero mixing matrix in the lepton sector, makes the study of charged lepton flavour violation a priority → **What's the origin of neutrinos mass?**

Precision measurements in FCNC in the quark sector show no sign of NP at the (10-20)% level in $\Delta F=2$ processes → **What's the flavour structure of NP?**

Search for rare decays in $\Delta F=1$ quark processes show also no evidence of NP → **What's the energy scale of NP?**

Take home messages.

Interest in precision flavour measurements is stronger than ever. In some sense it would have been very "unnatural" to find NP at LHC from direct searches with the SM CKM structure.

There is a priory as many good reasons to find NP by measuring precisely the couplings of the new scalar boson, as by precision measurements in the flavour sector!

The search is not over.

LFV experiments with **muon decays** around the world will be providing interesting results in the next 10 years. **NA62/KOTO** have just started collecting first data. **LHCb upgrade** plans to collect ~50 fb^{-1} with a factor ~2 increase in bb and cc cross-section. **ATLAS/CMS** plan to collect ~300 fb^{-1} and **Belle-II** plans to collect ~50 ab^{-1} before HL-LHC era.

We don't know yet what is the scale of NP→ cast a wide net!

Don’t give up yet!