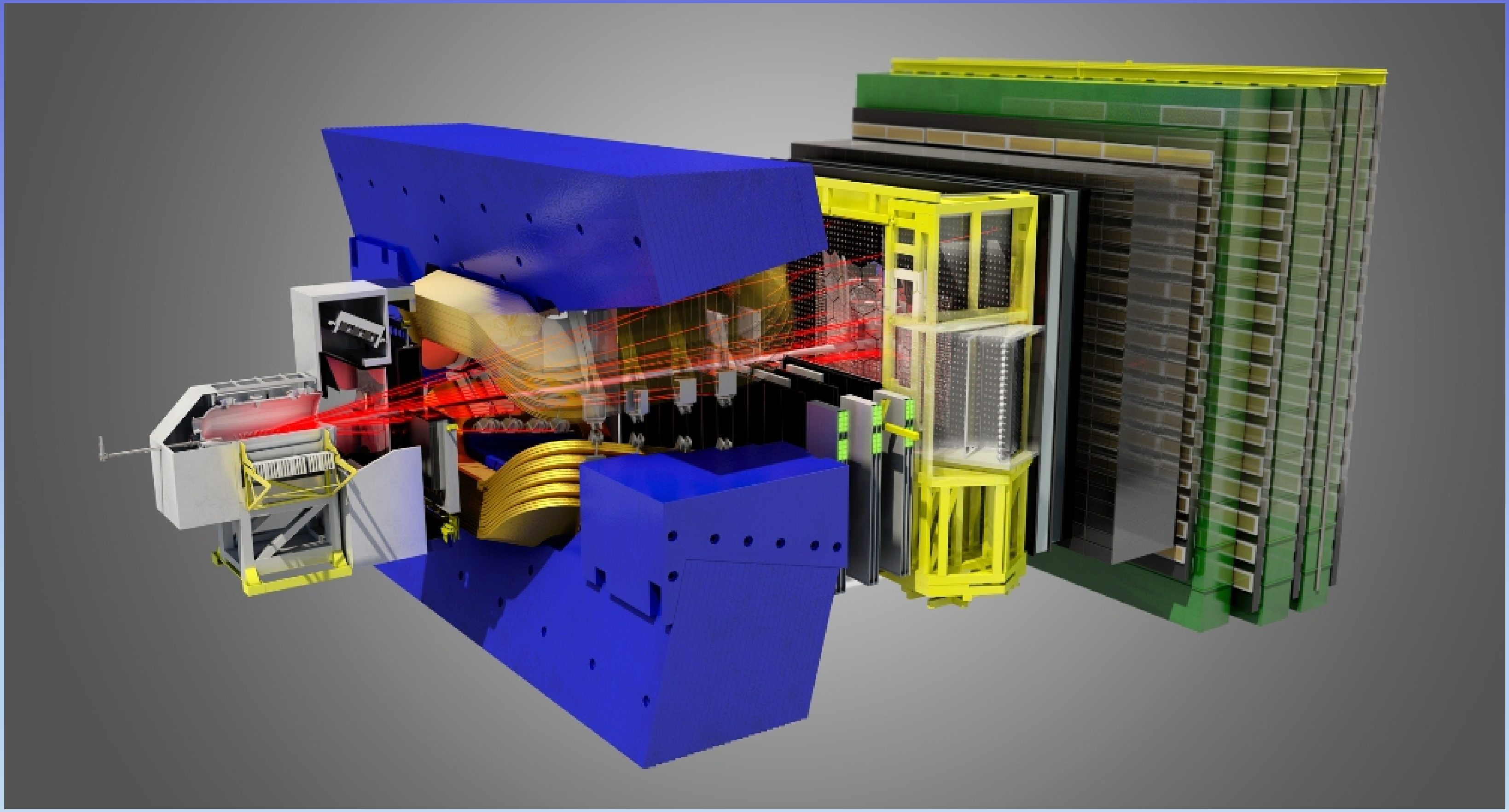
Taller de Altas Energías (TAE 2016)
2016, 04 -17 September, Benasque, Spain

LHCb Physics



Arantza Oyanguren (IFIC – CSIC/UV)

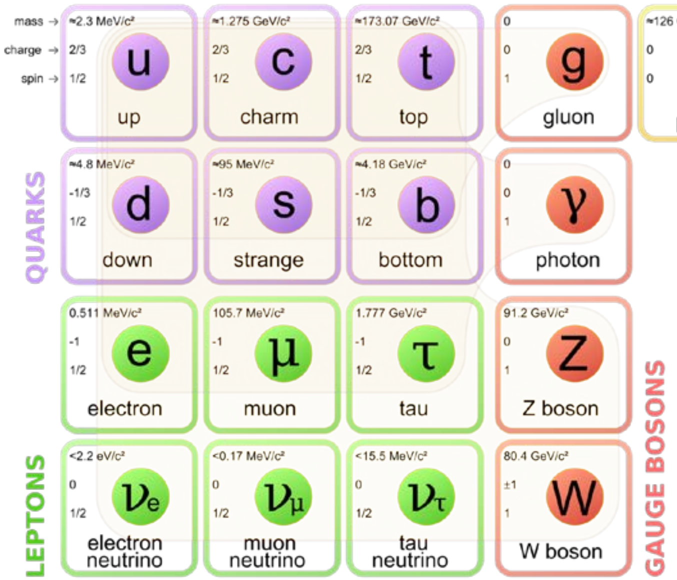
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Outline

- Introduction
- The LHCb experiment
- The CKM matrix
- B mixing and CP violation
- Rare decays of B mesons
- Pentaquarks
- Future plans

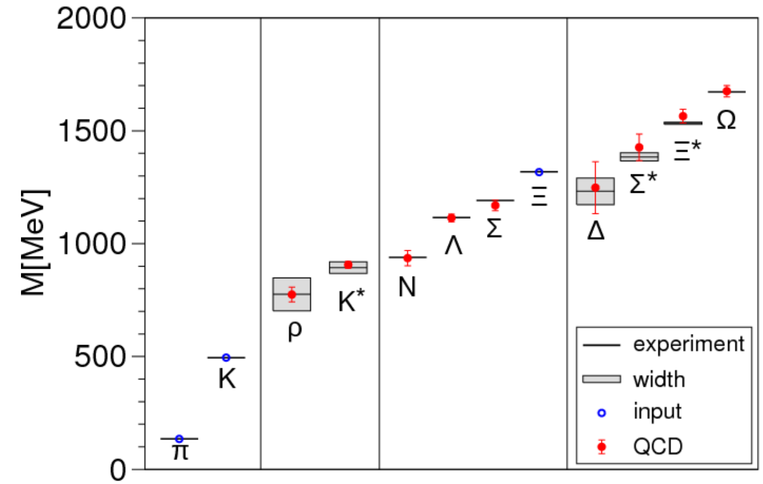
Introduction

Our Standard Model of Particle Physics:

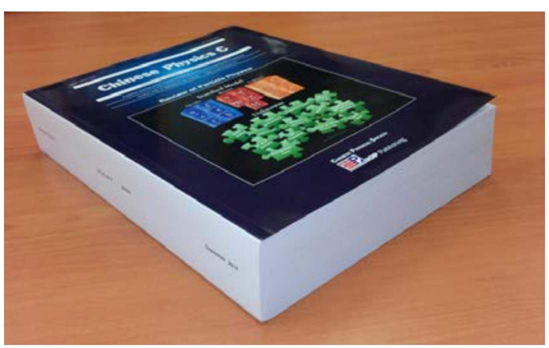


+ antiparticles

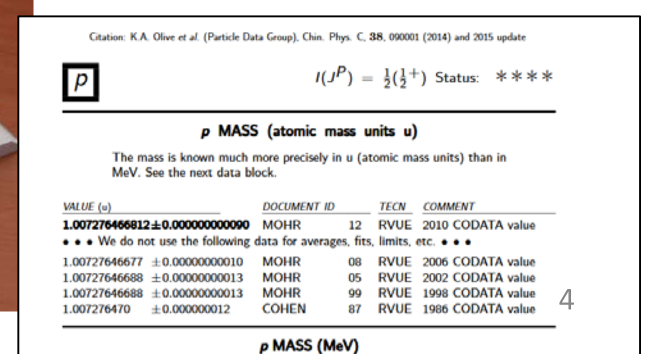
Hadrons:



Particle Data Book (PDG):



1675 pages!!



Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

$\boxed{p}$ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS (atomic mass units u)

The mass is known much more precisely in u (atomic mass units) than in MeV. See the next data block.

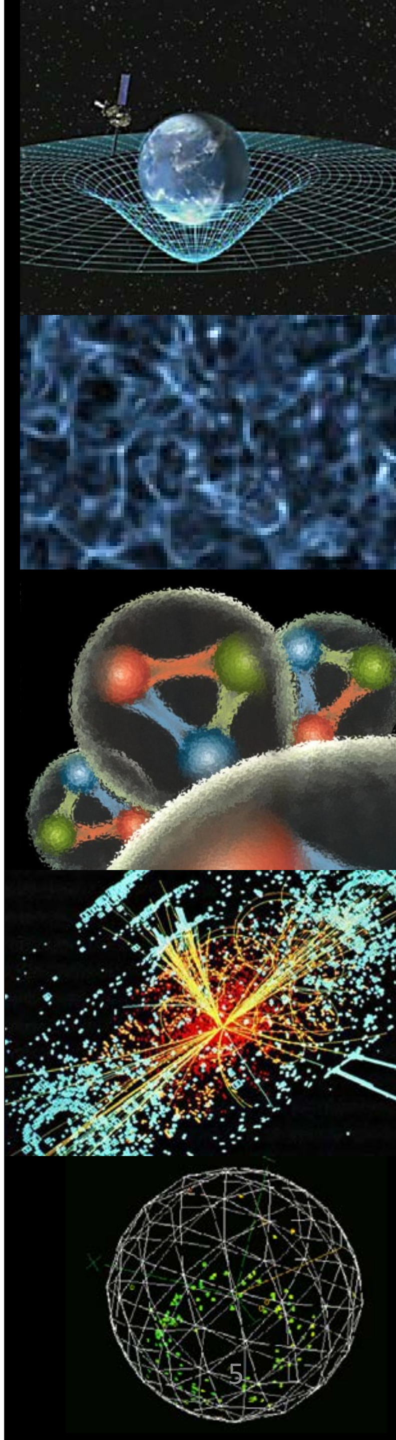
VALUE (u)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.007276466812±0.000000000090	MOHR	12	RVUE	2010 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00727646677 ±0.00000000010	MOHR	08	RVUE	2006 CODATA value
1.00727646688 ±0.00000000013	MOHR	05	RVUE	2002 CODATA value
1.00727646688 ±0.00000000013	MOHR	99	RVUE	1998 CODATA value
1.007276470 ±0.000000012	COHEN	87	RVUE	1986 CODATA value

p MASS (MeV)

Introduction

The problems of our Standard Model …

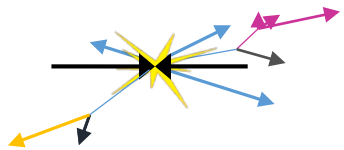
- Quantum Theory of Gravity
- Inflation
- Quark/lepton generation masses: compositeness?
  Substructure? Strings?
  Common sub-elements quarks and leptons?
  Why three families?
- Matter-Antimatter asymmetry
  CPV in SM (K, B) + Big Bang ?
- Cosmological constant (dark energy …)
- Dark matter
- Higgs & EW symmetry breaking? Forces Unification?
- Neutrinos (mass?, hierarchy?...)



Introduction

Looking for New Physics…

Direct searches:

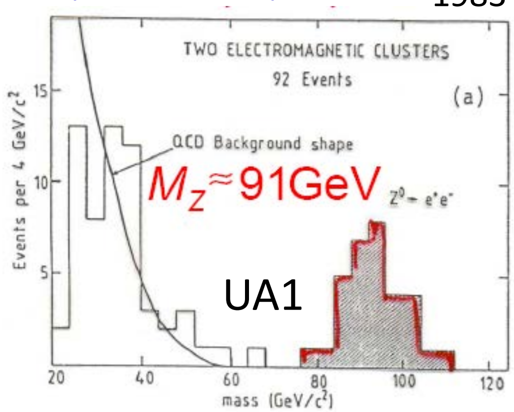


$$E^2 = m^2c^4 + p^2c^2$$

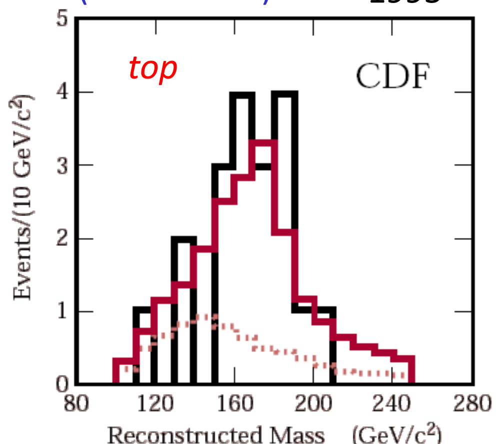
High energy

$\rightarrow$ **particles created *on-shell*: *Evidence in mass plots***

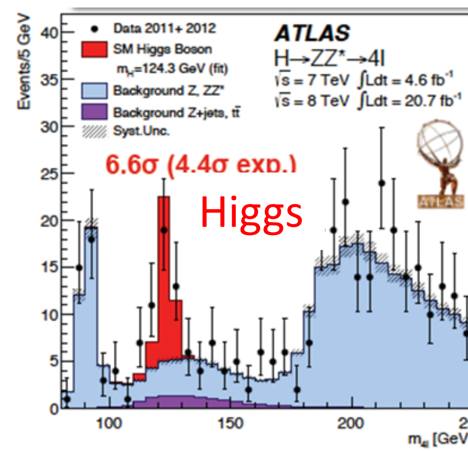
($\sqrt{s}$= 546 GeV) 1983



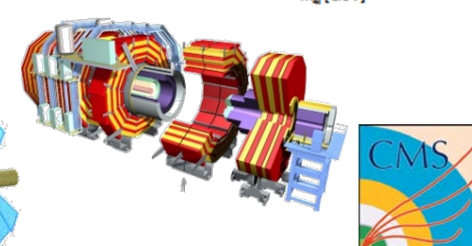
($\sqrt{s}$= 1.9 TeV) 1995



($\sqrt{s}$= 7 TeV) 2012



Higgs discovery, 2012

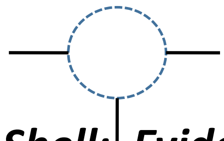


Introduction

Looking for New Physics…

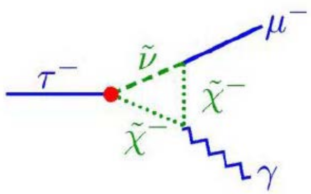
<u>Indirect searches</u>**:**

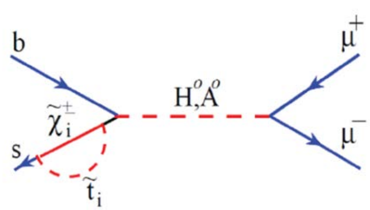
High precision

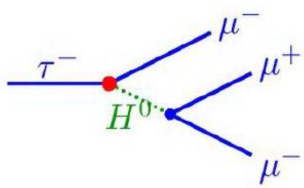


$\rightarrow$ **particles created *off-Shell:* *Evidence in quantum effects (loops)***

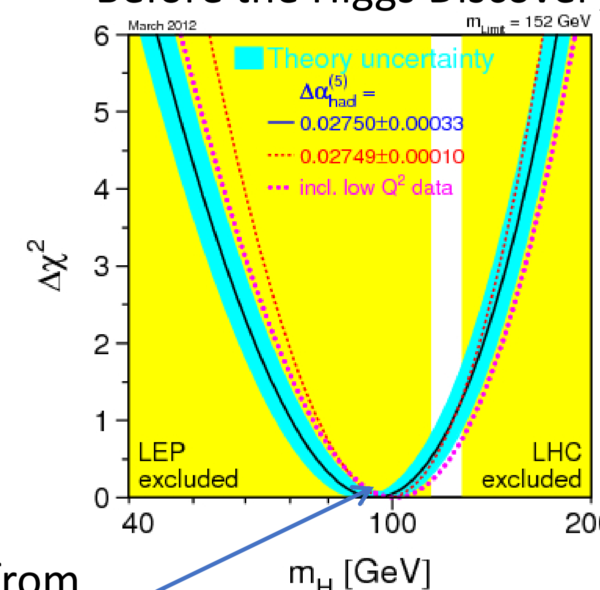
(BR's, asymmetries…)



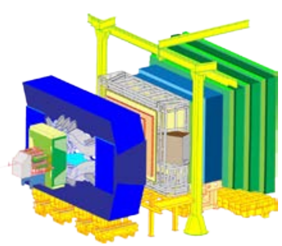




Before the Higgs Discovery…

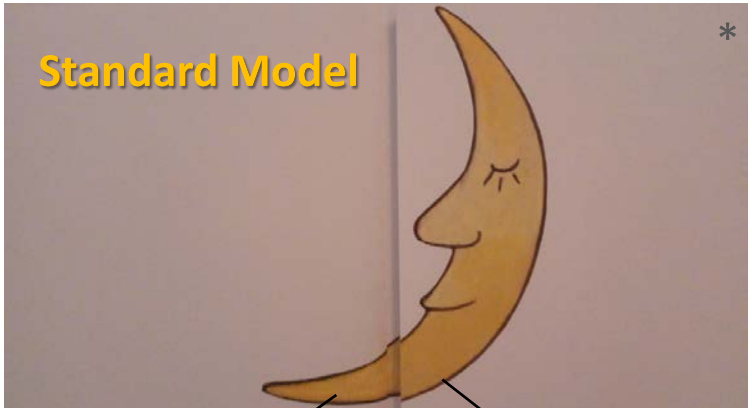


Predicted from electroweak measurements



LHCb

Introduction

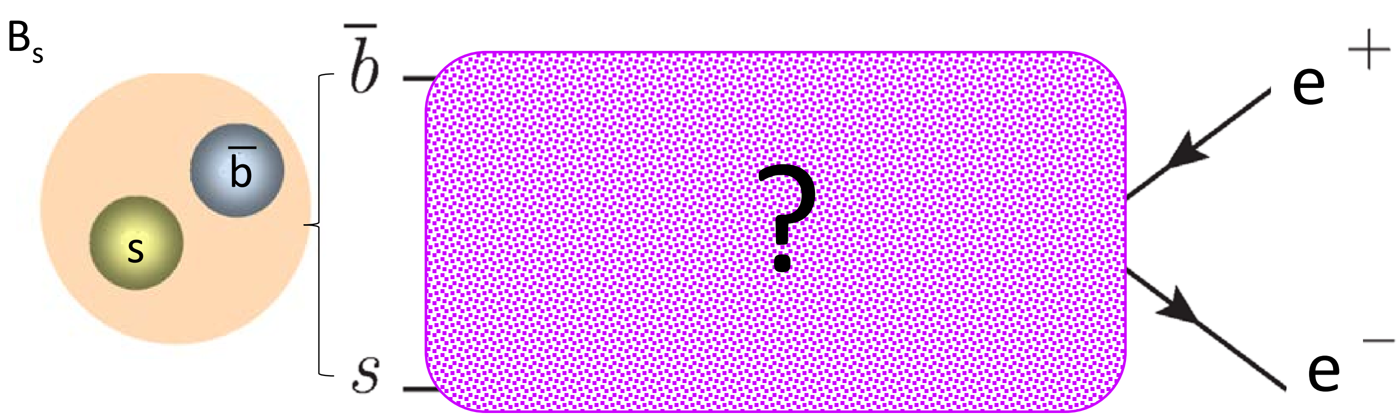


What we see

What we think it is

What it is

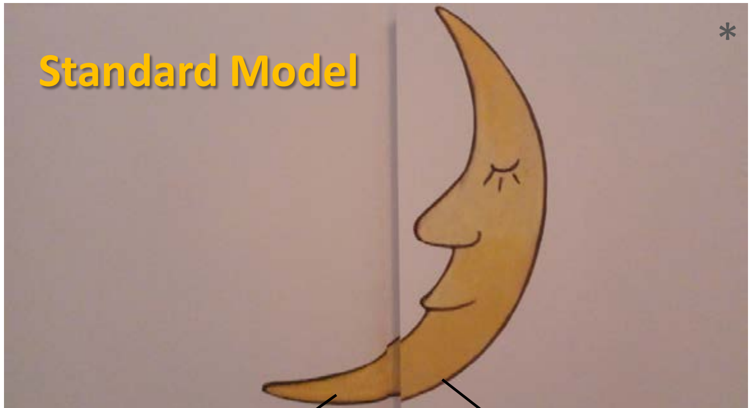
It can be tested by studying quantum effects:



Number of particles produced,
angular distributions,
origin point in the detector…

* ¡Oh!, Josse Goffin

Introduction

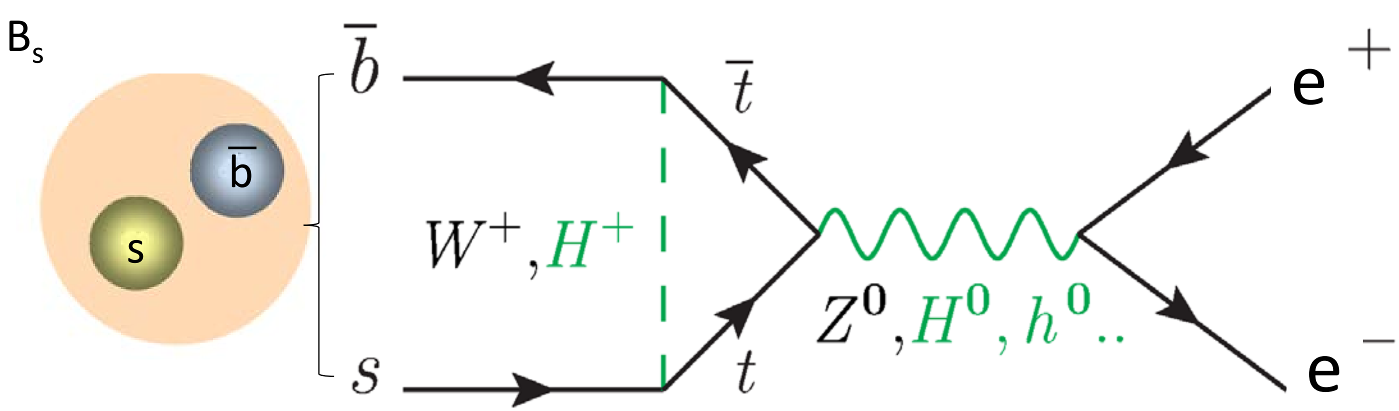


What we see

What we think it is

What it is

It can be tested by studying quantum effects:

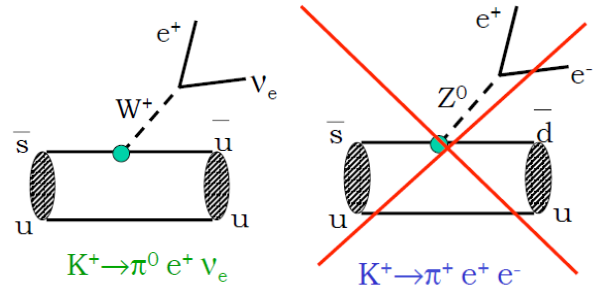


Number of particles produced,
angular distributions,
origin point in the detector…

New Particles

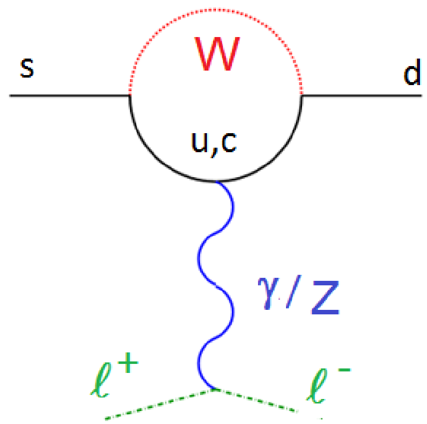
* ¡Oh!, Josse Goffin

Introduction



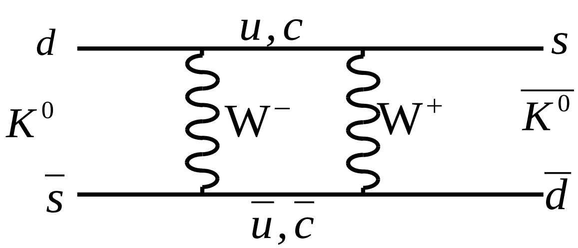
- The GIM mechanism:

In 1970's Glashow, Iliopoulos and Maini describe the mechanism by which flavour-changing neutral currents (FCNCs) are suppressed, and predicted the existence of the c quark



- Gaillard, Lee and Rosner :

$m_c \sim 1.5$ GeV from kaon mixing



$$\Delta m_K = \frac{G_F^2}{4\pi} m_K f_K^2 m_c^2 \cos^2\theta_c \sin^2\theta_c$$

- 1974 c quark discovered (B. Richter at SLAC and S. Ting at BNL)

2 DECEMBER 1974
EW LETTERS

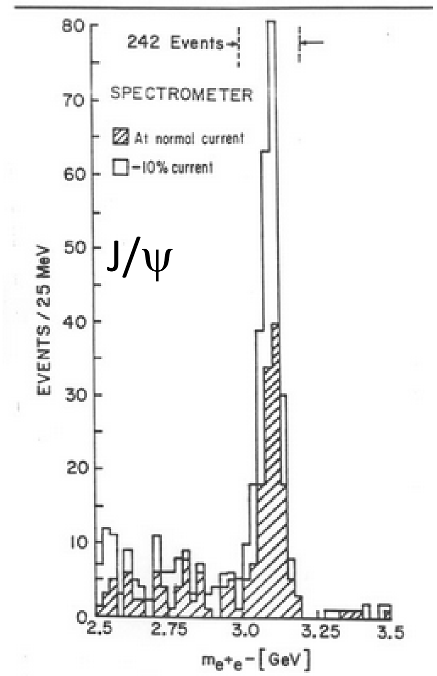
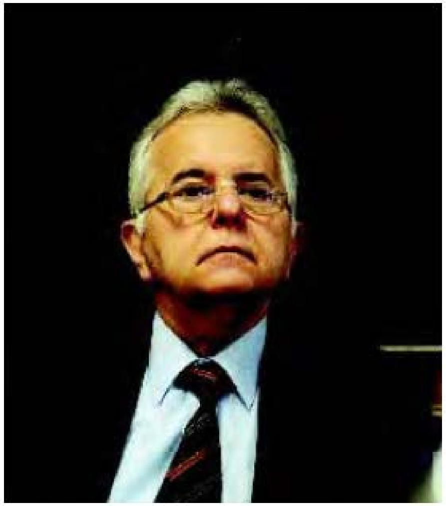


FIG. 2. Mass spectrum showing the existence of J. ...sults from two spectrometer settings are plotted ...wing that the peak is independent of spectrometer ...rents. The run at reduced current was taken two ...nths later than the normal run.

Introduction

- The CKM mechanism:



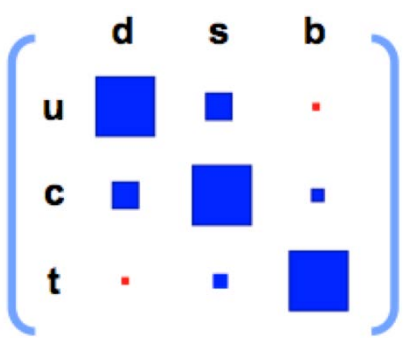
2008

Cabibbo

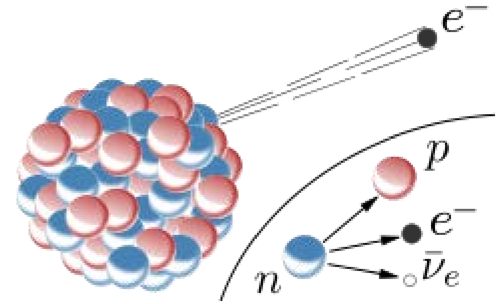
Kobayashi

Maskawa

$V_{CKM} =$

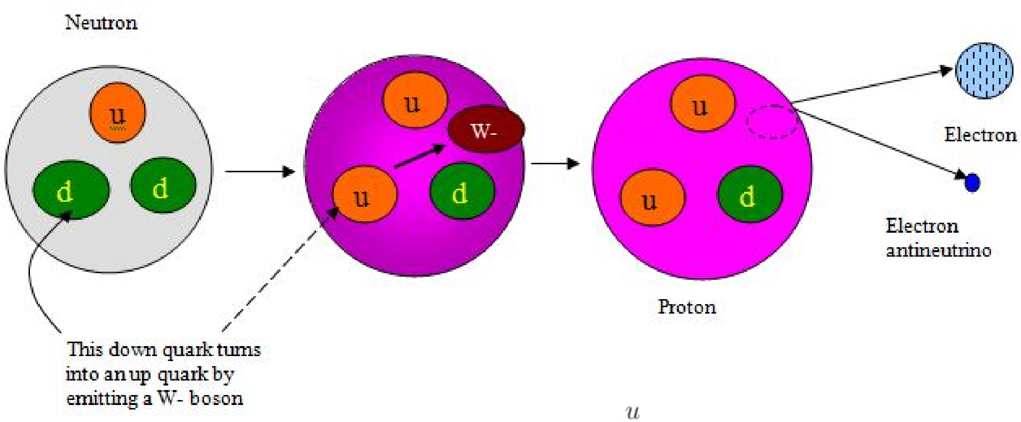


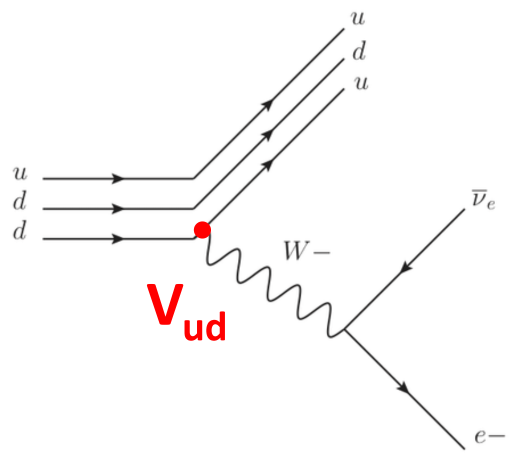
Introduction



Example: β -decay (very well known)

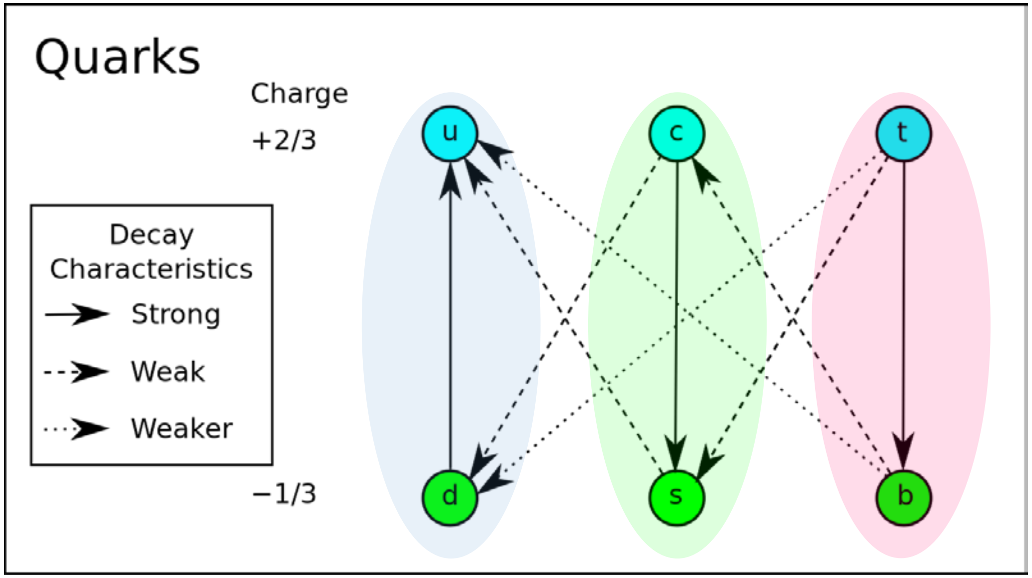
$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \overline{\nu}_e $$

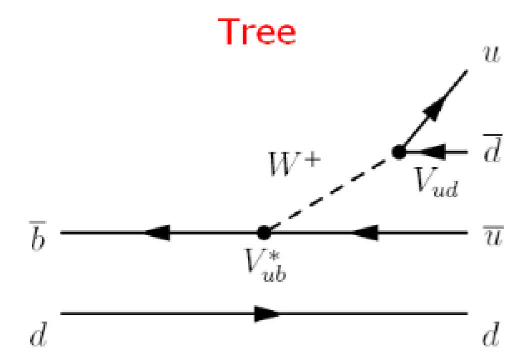


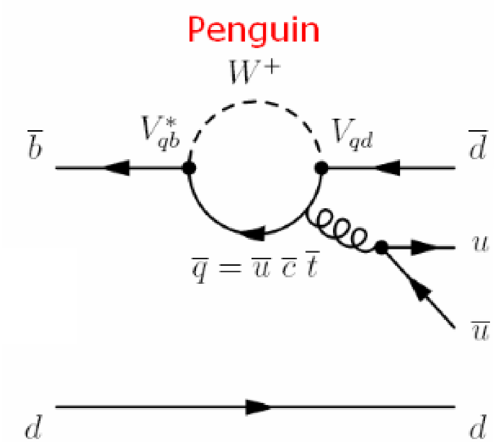


(V_{ud} is large ~ 0.97)

Introduction







$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix},$$

- Transitions between the same family are favored
- Some of them are very rare (ex: V_{ub})
- Need to change charge: FCNC not allowed at tree level, need to proceed via loop diagrams (CKM suppressed)
- If a transition occurs with larger probability than expected $\rightarrow$ **New Particle** (i.e. New Physics)

Introduction

In summary:

- We understand that the Standard Model cannot be the ultimate theory

  It should be a low-energy effective theory of a more fundamental theory at a higher energy scale (TeV range)

  Hierarchy problem: New Physics required to cancel radiative corrections to the Higgs mass but leave the electroweak predictions from the SM unaffected

- Flavour structure:
  $\rightarrow$ provide the suppression mechanism for FCNC processes already observed.
  $\rightarrow$ need to measure the flavour structure to distinguish between the NP models.

- The physics performed at LHCb (flavour physics) goes hand-in-hand with direct searches (ATLAS and CMS).

Introduction

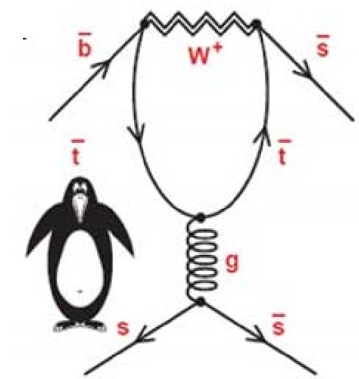
The b of LHCb…

- Heaviest quark that forms hadronic bound states (m~4.7 GeV)
- Must decay outside the 3rd family
  - All decays are CKM suppressed
  - Long lifetime (~1.6 ps)
- High mass: many accessible final states

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

(all Br's are small)

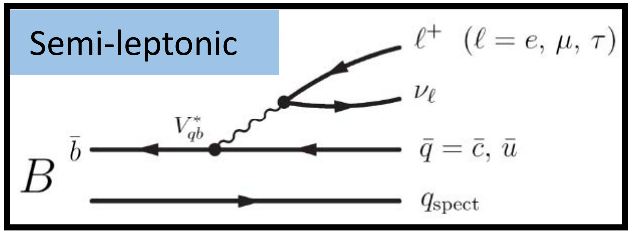
- Dominant decay process: "tree" $b \to c$ transition
- Very suppressed "tree" $b \to u$ transition
- FCNC: "penguin" $b \to$ s,d transition

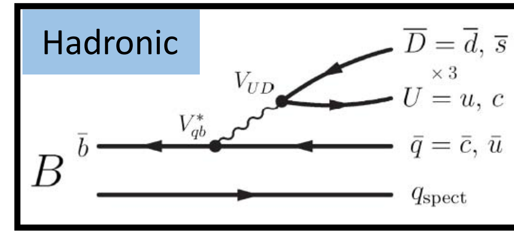


- Flavour oscillations ($b \to t$ "box" diagram)
- CP violation – expect large CP asymmetries in some B decays

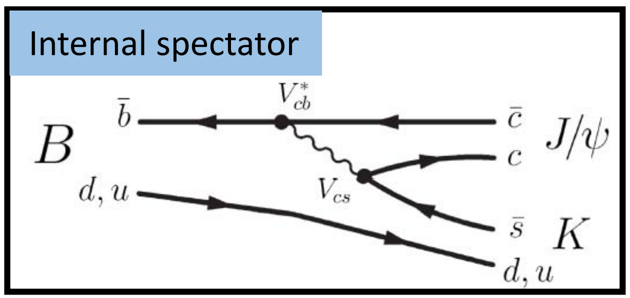
Introduction

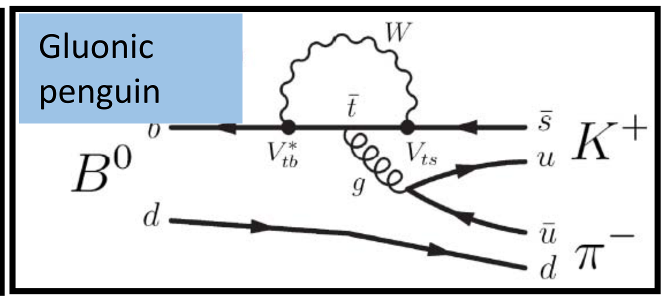
Dominant tree decays:

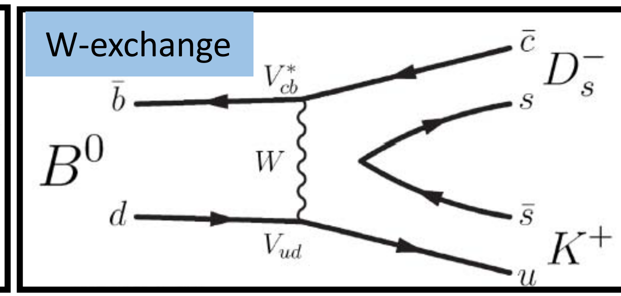




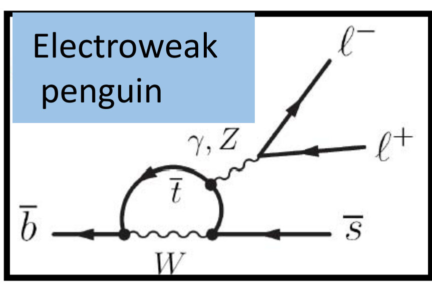
Rare hadronic decays

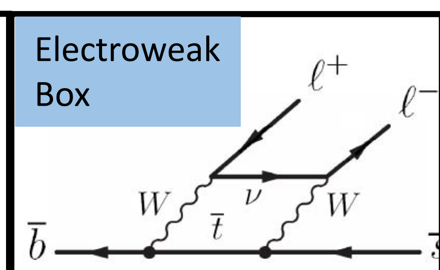


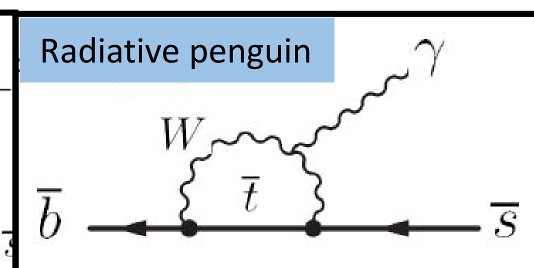


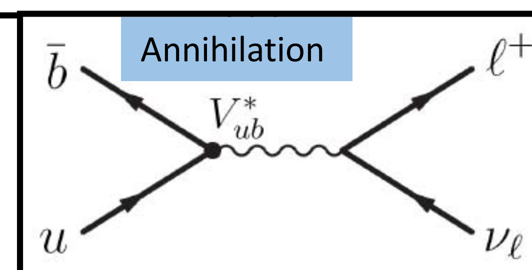


Radiative and leptonic decays









Introduction

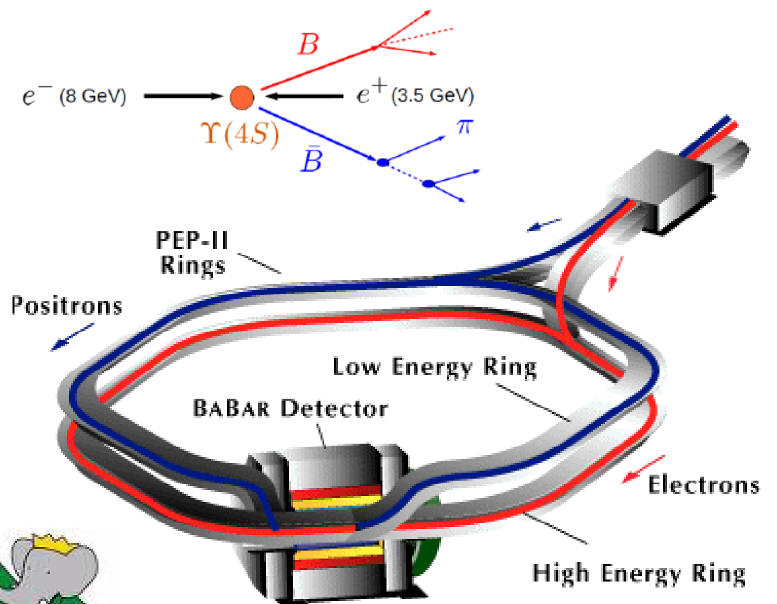
(1999 - 2008 / 2010)

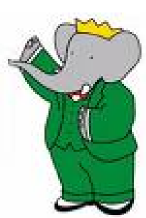
* First measurement of CPV in the B system
* High precision CKM matrix
* Discovery of η_b

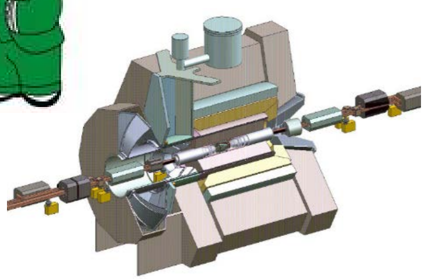
The precesors of LHCb, key in flavour physics:

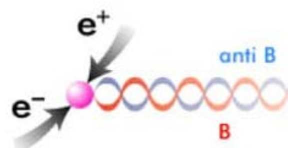
The b-factories: Belle at KEK (Japan) and BaBar at PEP-II (California)

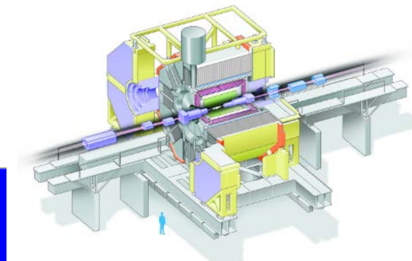
Asymmetric e+ e- colliders working at the Υ(4S) energy.

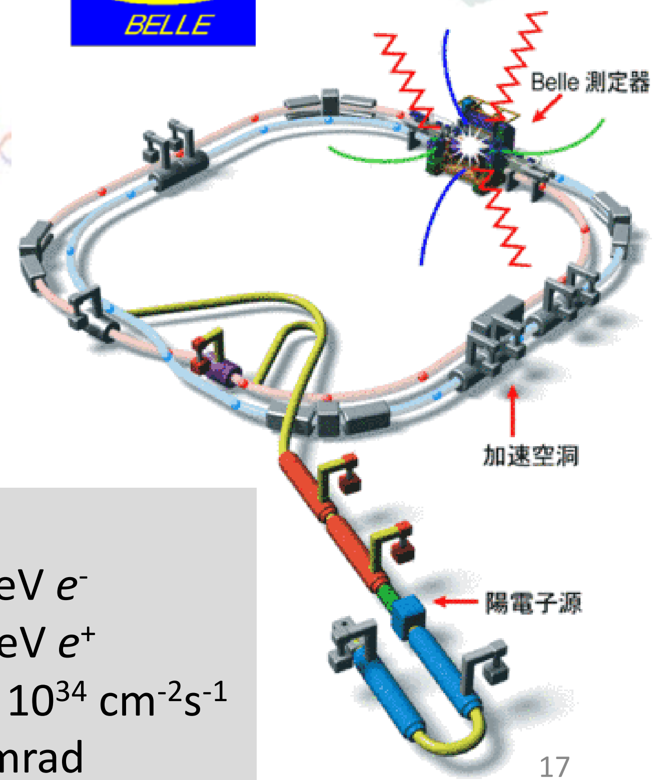












PEP-II /KEK-B

High Energy Ring : 9.0 / 8.0 GeV e^-

Low Energy Ring : 3.1 / 3.5 GeV e^+

Design luminosity : 3 x 10^{33} / 10^{34} cm^{-2}s^{-1}

Beam crossing angle : 0 / 22 mrad

Introduction

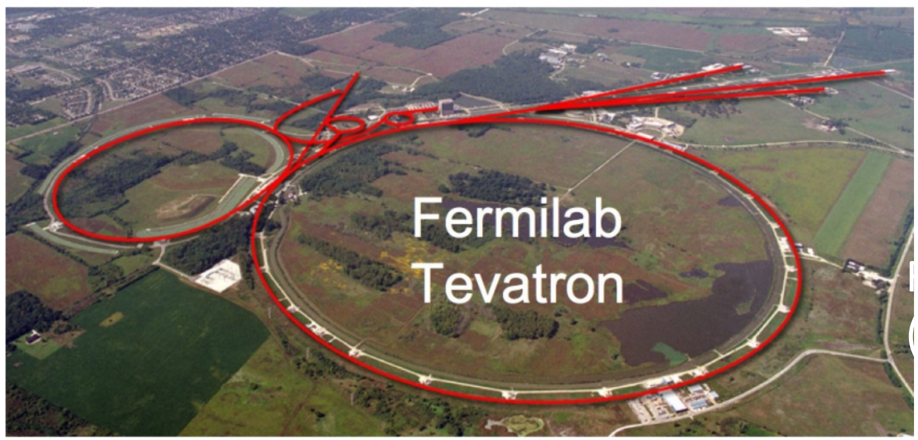
(1987- 2011)

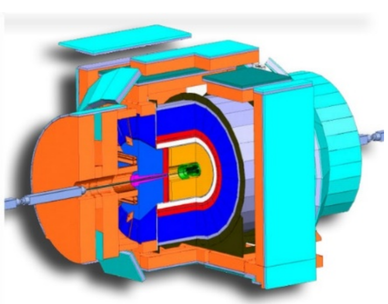
* Discovery of the top quark
* First measurement of B_s oscillations
* Discovery of the Ξ_b baryon

<u>The precesors of LHCb, key in flavour physics</u>

The Tevatron at Fermilab (Illinois): CDF and D0

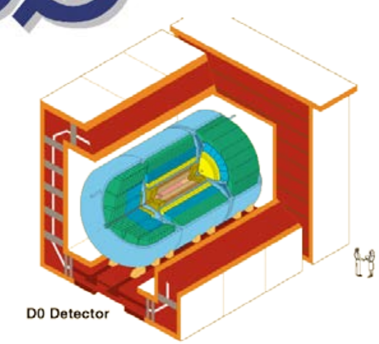
$p\bar{p}$ collider working at cm of mass energy of 1.96 TeV.





TEVATRON

Superconducting $p\bar{p}$ ring
Energy : 1 TeV/beam
Detectors: CDF, D0
Luminosity: 10^{32} $cm^{-2}s^{-1}$
Physics: W, Z,Top Production
Higgs searches
B physics



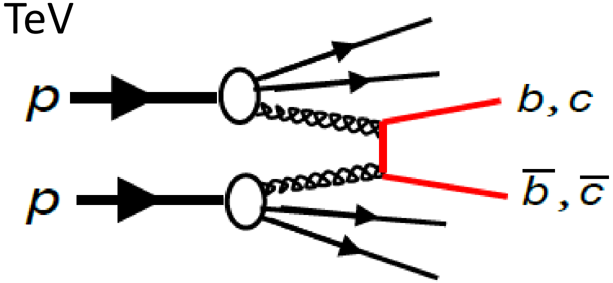
The LHCb experiment

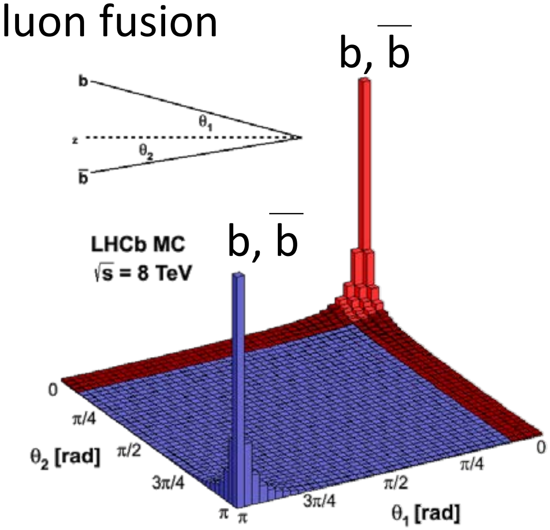
The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion

  ~250 μb @ √s=7 TeV

  ~500 μb @ √s=14 TeV





The b quarks hadronize in B, B_s, $B^*_{(s)}$, b-baryons…

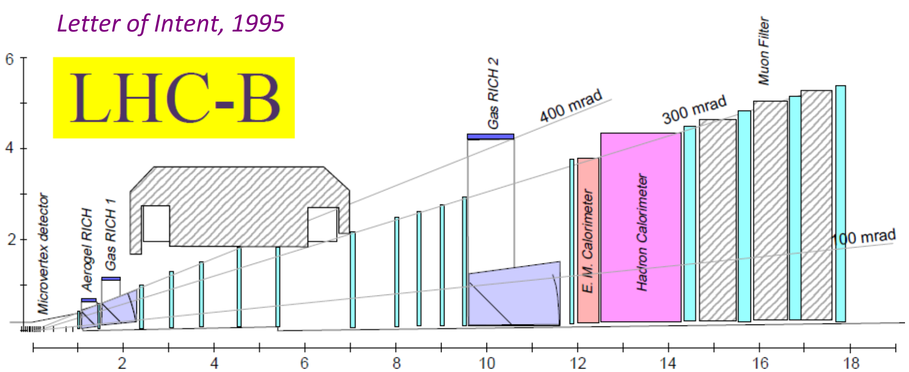
→ average B meson momentum ~ 80 GeV

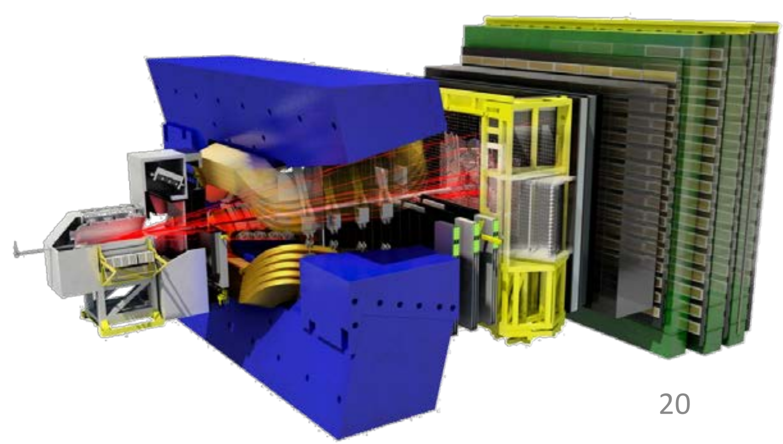
- The LHCb idea: to build a single-arm forward spectrometer:

  ~ 4% of the solid angle (2 < η < 5),

  ~30% of the *b* hadron production

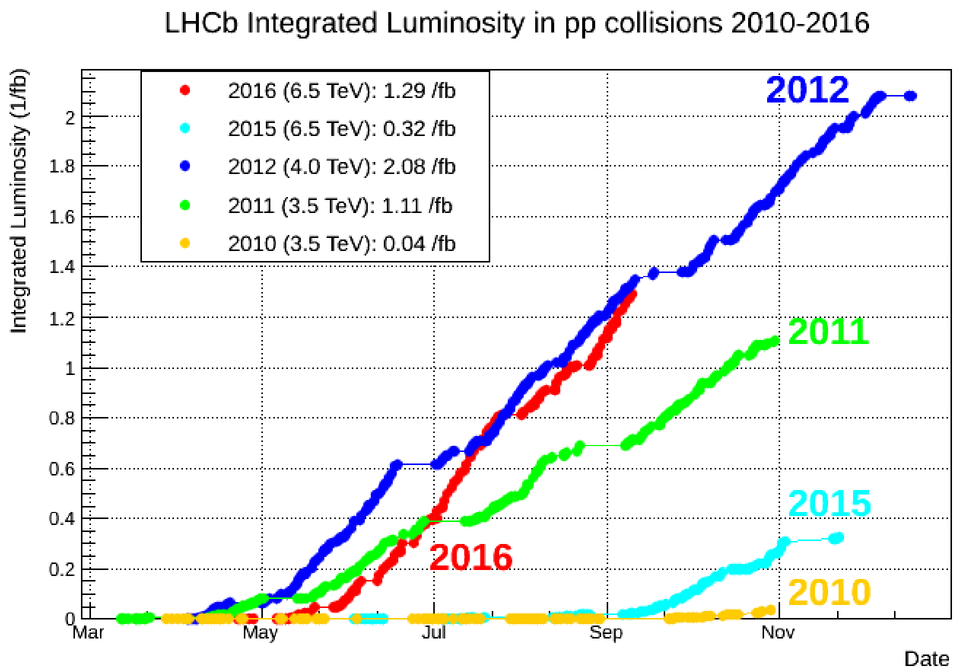
Letter of Intent, 1995





The LHCb experiment

- Very good performance: **3 fb^{-1}** accumulated in Run1 at 7 TeV, working well for Run2 at 13TeV, expected **5 fb^{-1}**

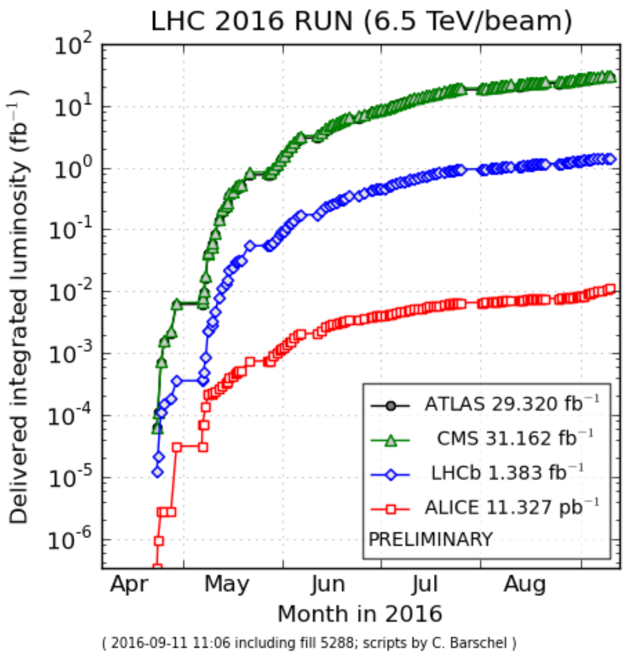


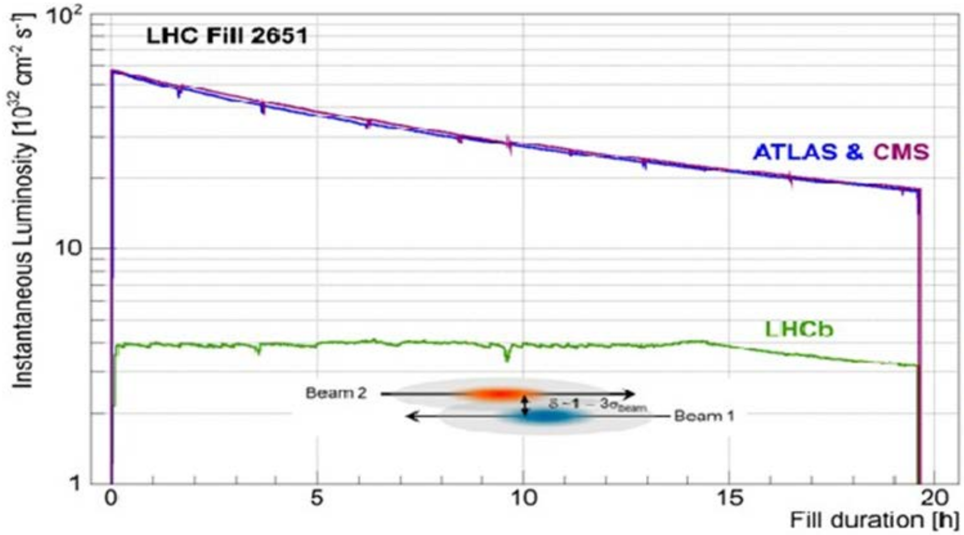
In terms of b-hadrons: $N=\int \mathcal{L}\sigma$

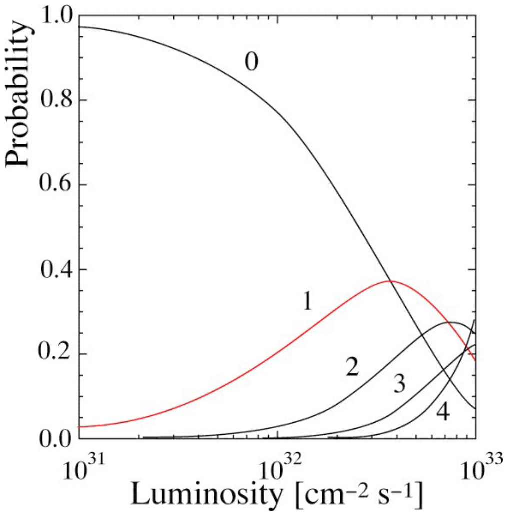
$\rightarrow$ σ ~ 500 μb at 13TeV, x 30% (due to the acceptance) = 150 μb
$\rightarrow$ $b\bar{b}$ pairs produced in *1 inverse femtobarn* (N/fb^{-1}) = 10^{15} * 150 x 10^{-6}

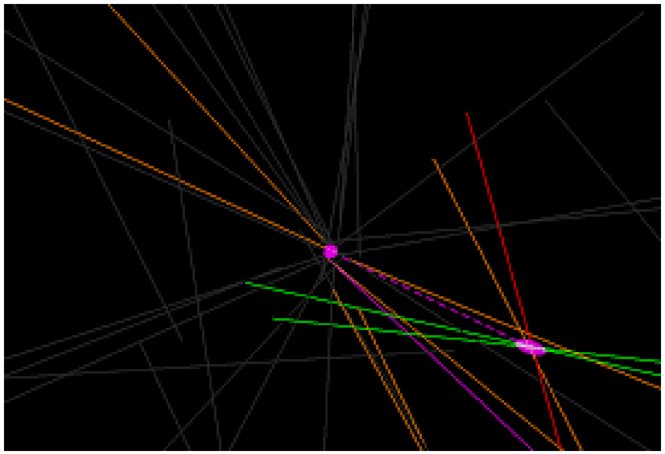
~ 1.5 x 10^{11}

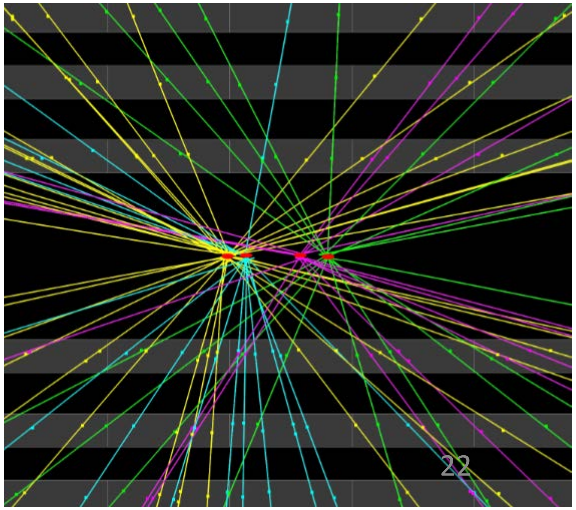
The LHCb experiment





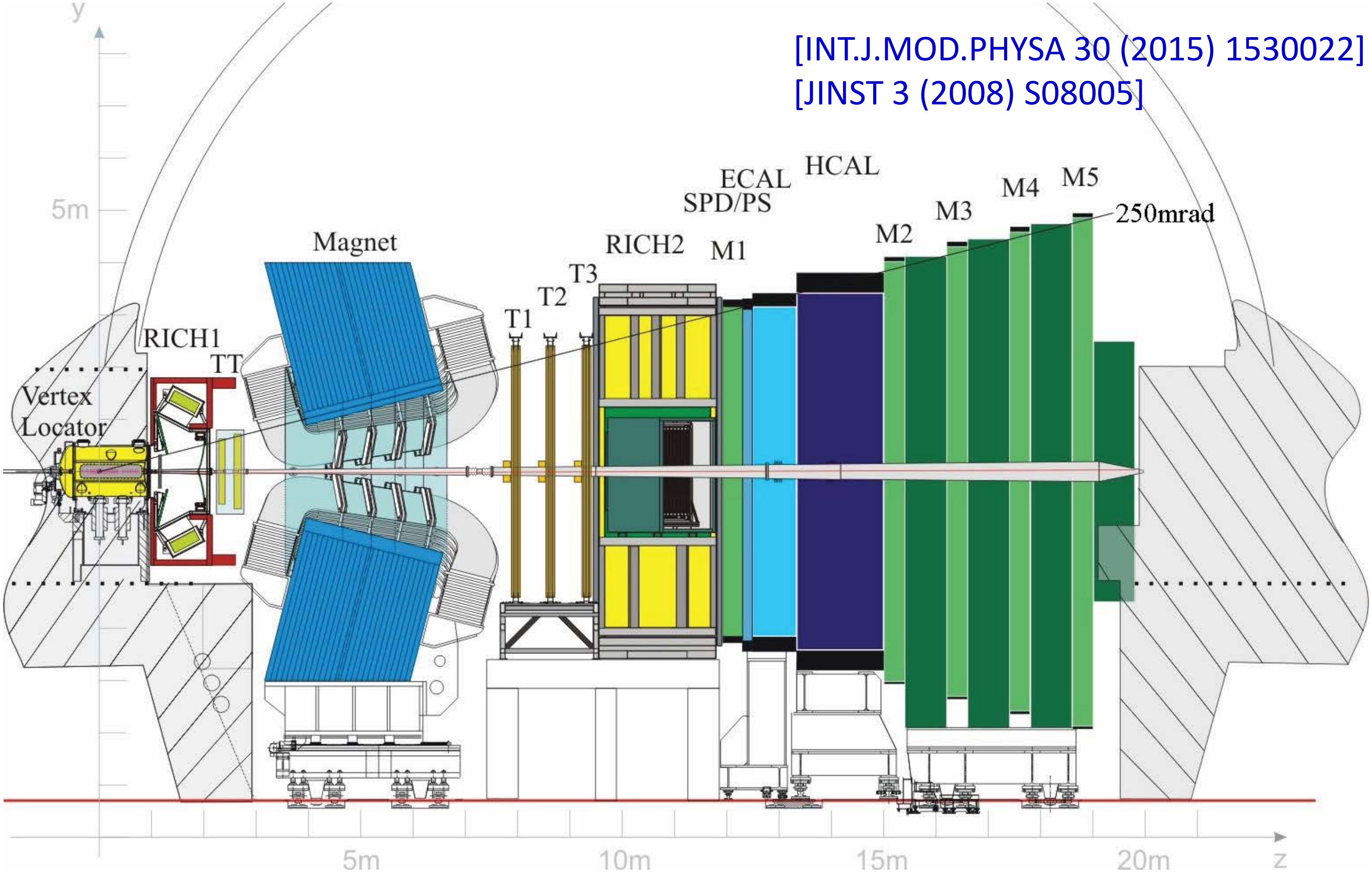






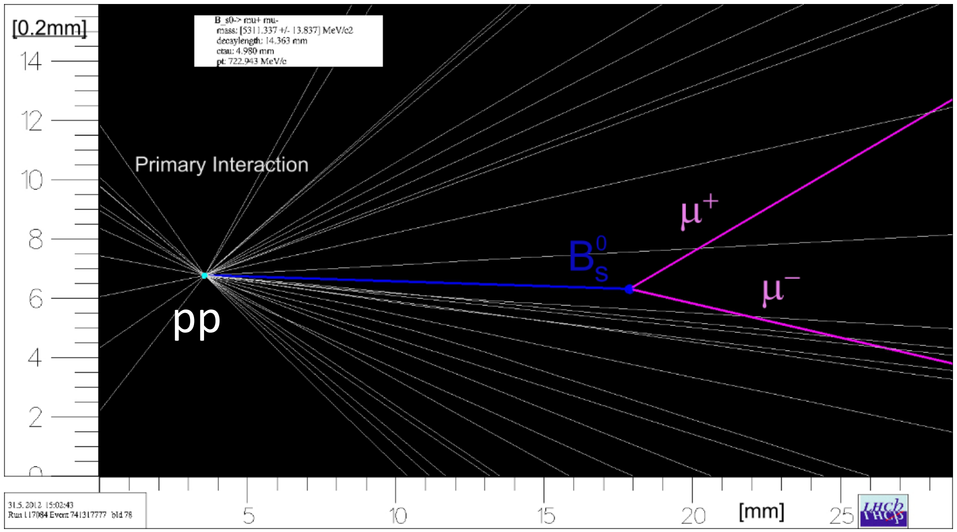
The LHCb experiment

[INT.J.MOD.PHYSA 30 (2015) 1530022]
[JINST 3 (2008) S08005]



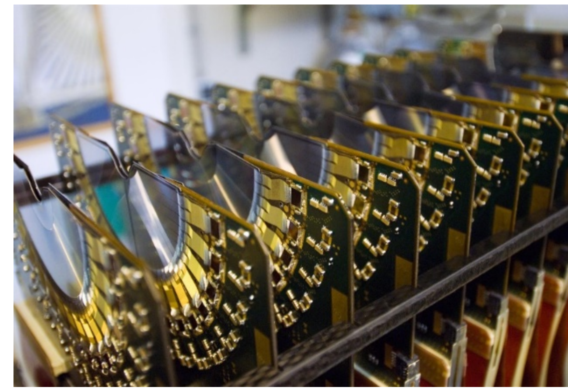
The LHCb experiment

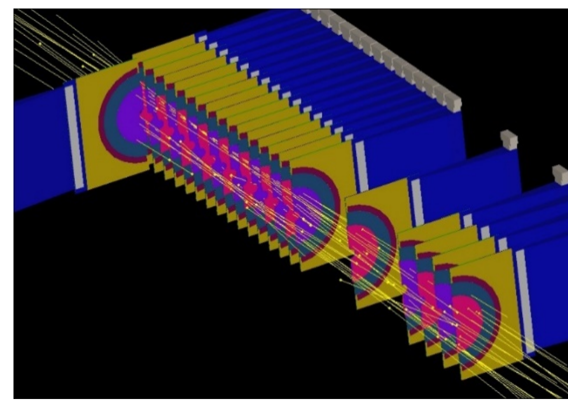
What do we need?



- To reconstruct production and decay vertices
  - $\rightarrow$ Good decay vertex resolution
  - $\rightarrow$ Good impact parameter resolution
- To reconstruct the particle trajectory
  - $\rightarrow$ Good momentum resolution

Vertex detector (VELO)

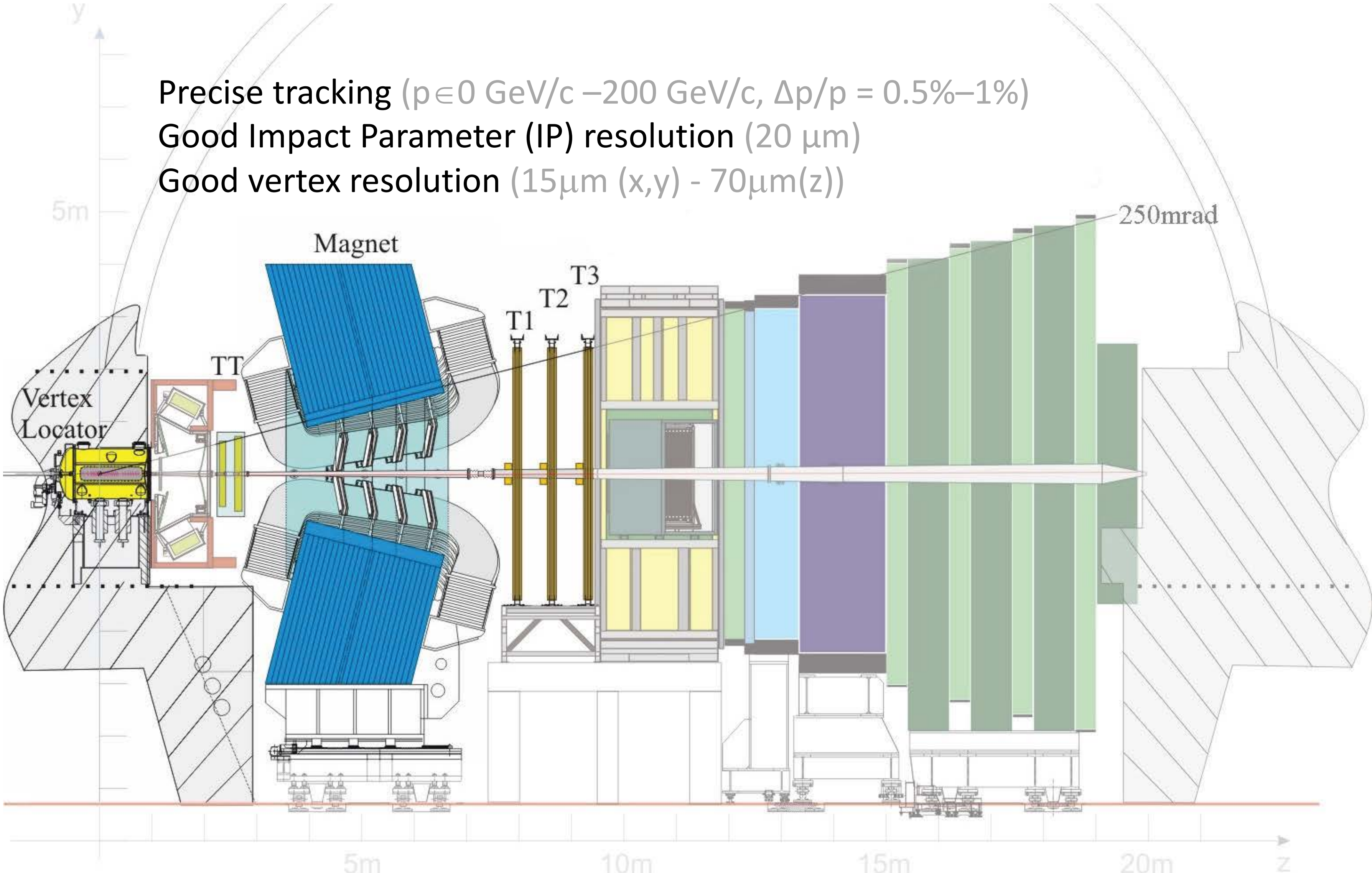




: How long will a Λ_b baryon be travelling in the detector before decaying? ($\beta\gamma$ ~100)

The LHCb experiment

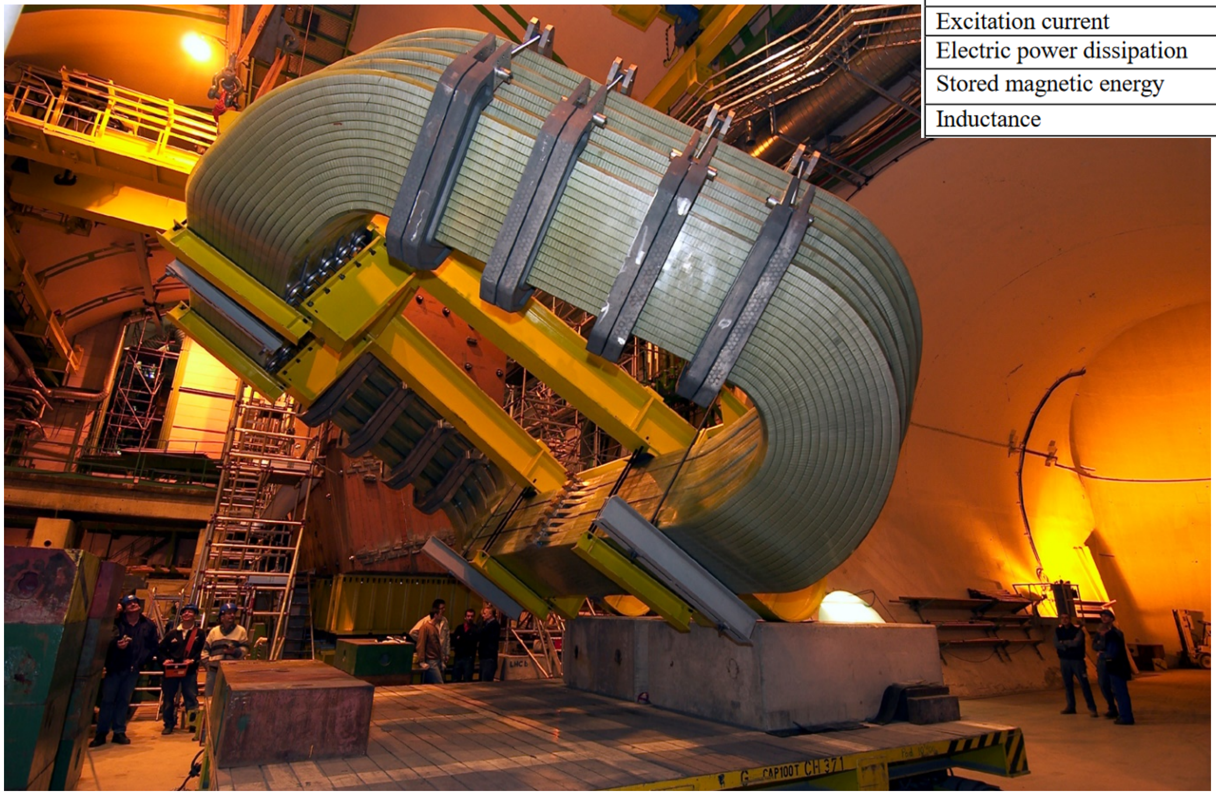
Precise tracking (p∈0 GeV/c –200 GeV/c, Δp/p = 0.5%–1%)
Good Impact Parameter (IP) resolution (20 μm)
Good vertex resolution (15μm (x,y) - 70μm(z))

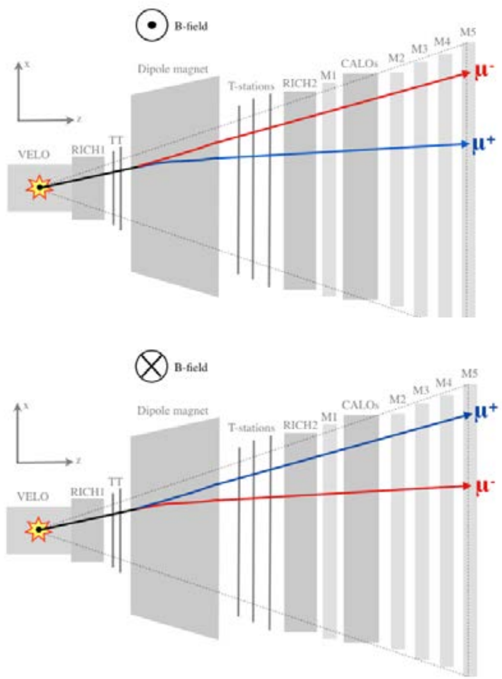


The LHCb experiment

The LHCb magnet:

Magnetic Parameters	
Bending power	$\int B\,dl = 4$ Tm (10 m track length)
Non-uniformity of $\int B\,dl$	$\leq \pm$ 5% in acceptance (hor.: ±300 mrad, vert.: ±250 mrad)
Excitation current	NI = 2 x 1.3 MA
Electric power dissipation	P_e = 4.2 MW
Stored magnetic energy	$W_m \approx 32$ MJ
Inductance	$L \approx 2$ H





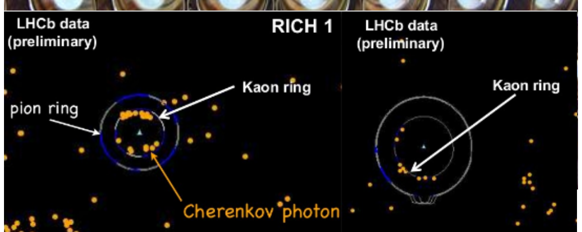
→ Inversion of polarity to study detector asymmetries

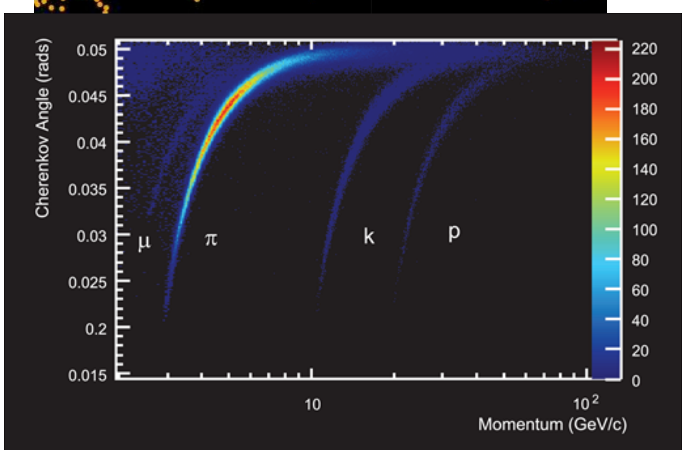
The LHCb experiment

- To recognize the type of particles

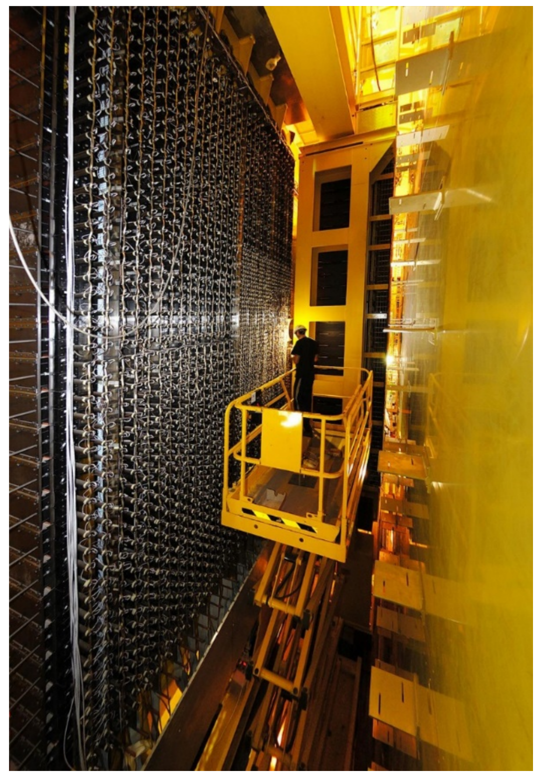
$\rightarrow$ Good particle identification systems (PID)

Cherenkov detectors (RICH)

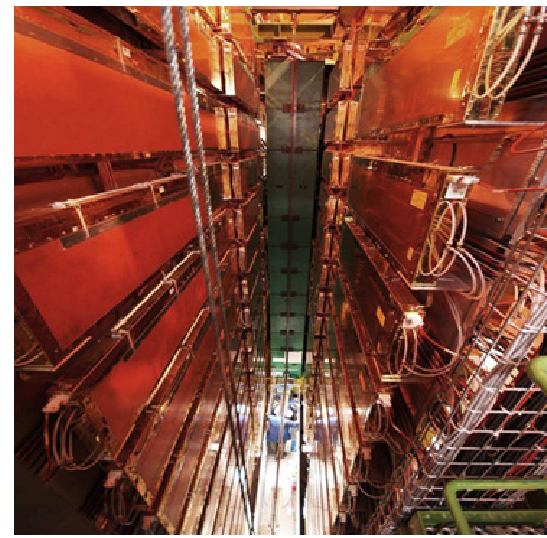


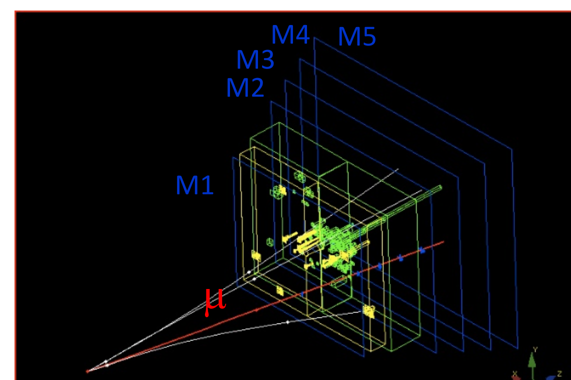


Calorimeters (ECAL, HCAL)



Muon chambers



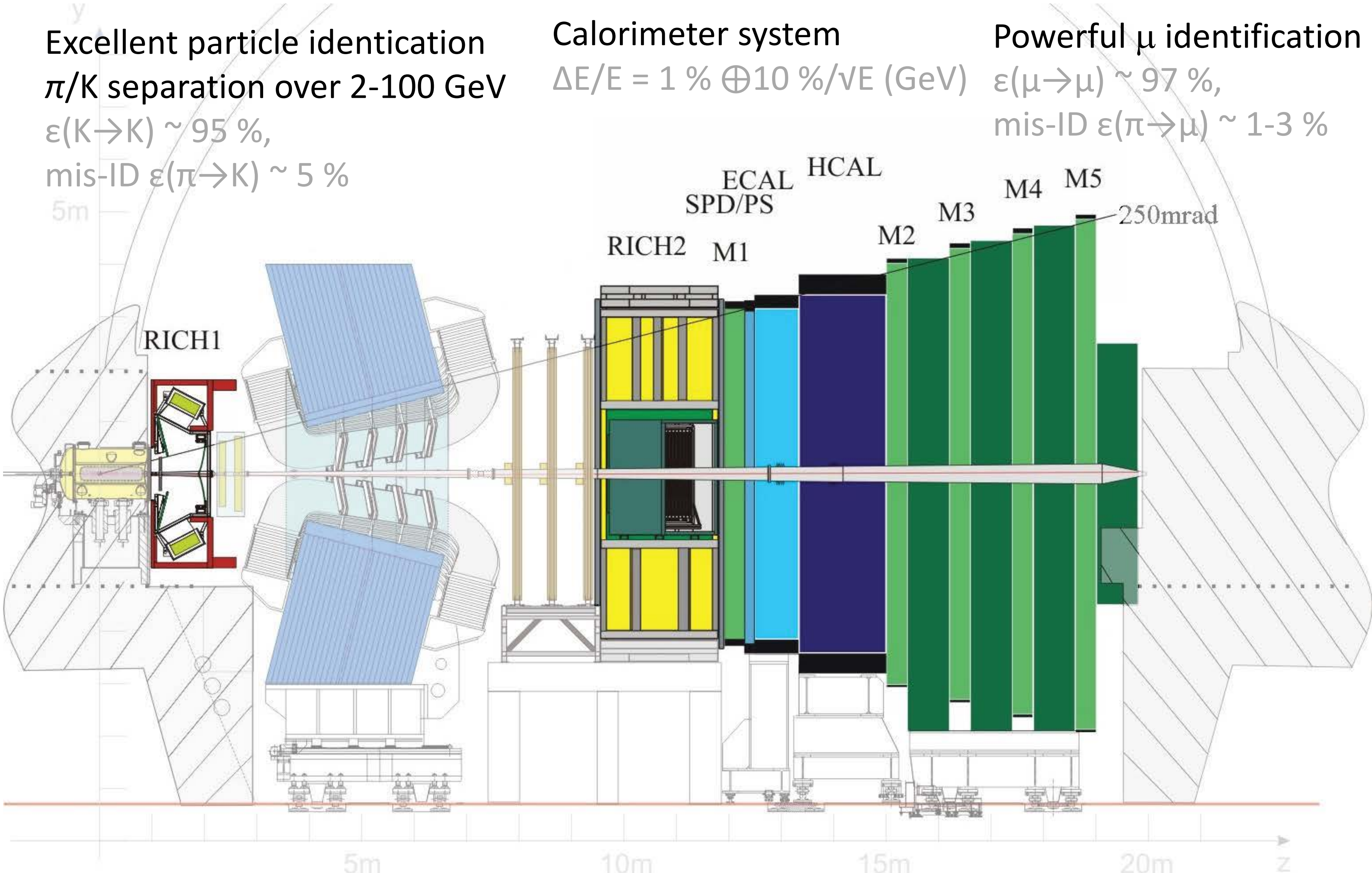


The LHCb experiment

Excellent particle identication
π/K separation over 2-100 GeV
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

Calorimeter system
ΔE/E = 1 % ⊕10 %/√E (GeV)

Powerful μ identification
ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %



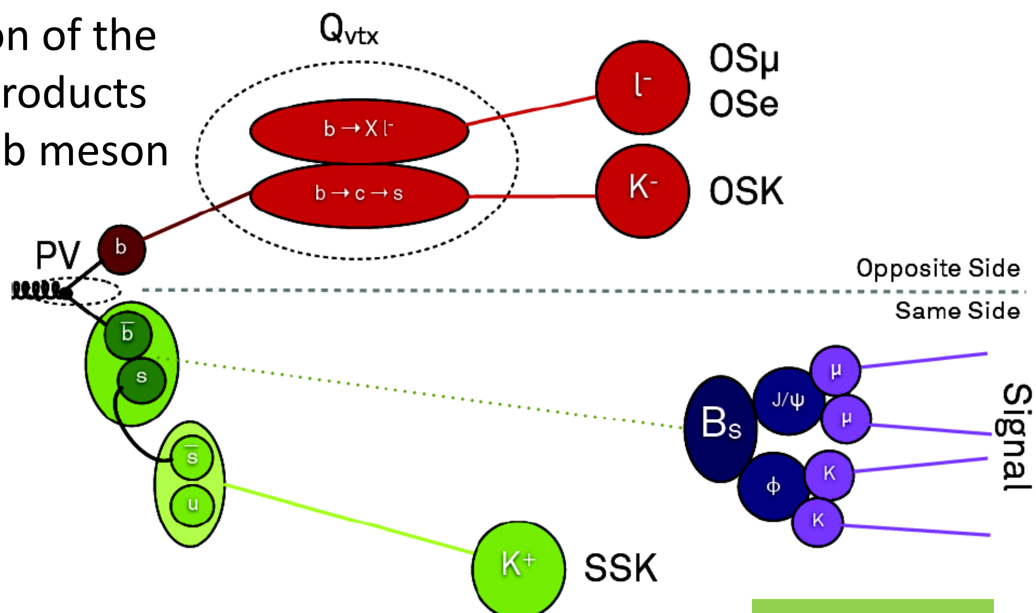
The LHCb experiment

- B mesons oscillates between particle and antiparticle $B^0 \rightarrow \overline{B}^0$
- We need to know the flavour of the particle at the production point

Flavour tagging

Use different algorithms that make use of the characteristics of the fragmentation of the b quark, the charge of the decay products or the charge related to the other b meson produced in pp $\rightarrow$ X $b\overline{b}$

Opposite side



Same side

Tagging efficiency ε_{tag} : fraction of events with a flavour tag decision

Wrong-tag fraction ω:
fraction of tagged events for which tagging decision is wrong

Figure of merit: *effective tagging power*

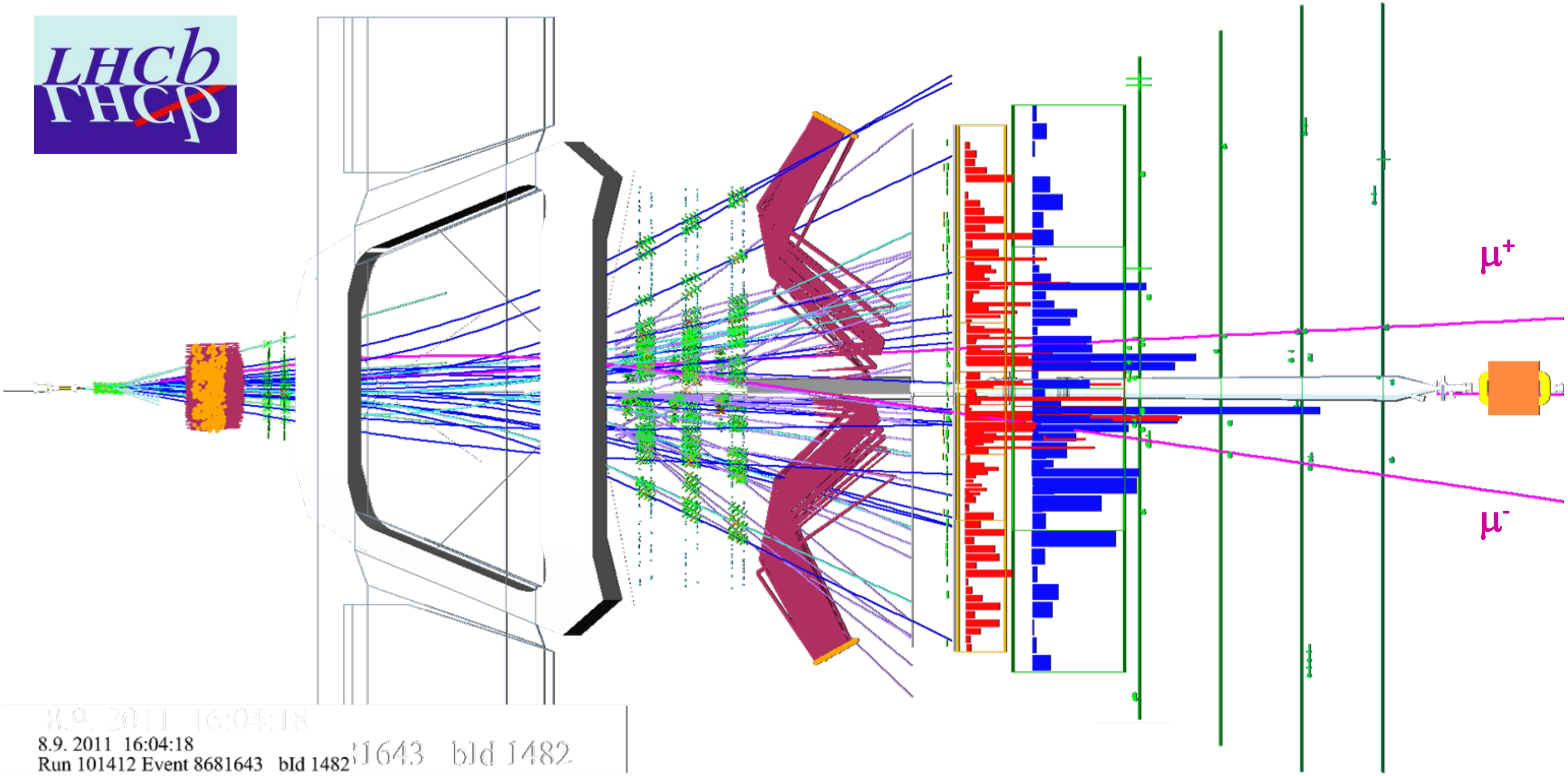
$$\boldsymbol{\varepsilon_{eff} = \varepsilon_{tag} D^2 = \varepsilon_{tag} (1 - 2\omega)^2}$$

$\boxed{N_{evts} \times \varepsilon_{tag}(1-2\omega)^2}$

$D^2 \equiv$ dilution factor

The LHCb experiment

$B_s \rightarrow \mu^+\mu^-$ event



The LHCb experiment

- Comparison between facilities:

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s^0 (10%), Λ_b^0 (10%), others (< 1%)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

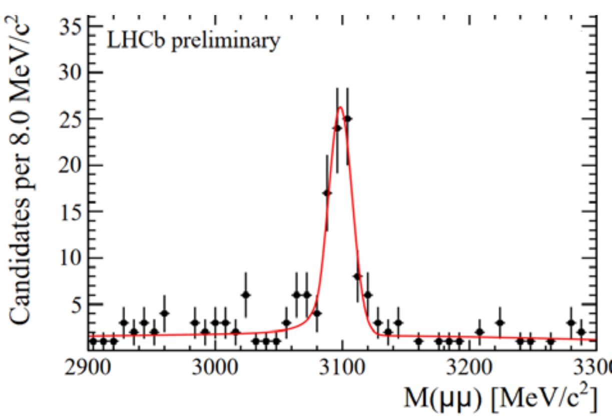
: Which is the maximum momentum of the pion in the B $\to \pi\ell\nu$ decay in the lab frame in BaBar at PEP-II and LHCb at LHC experiments ?

The LHCb experiment

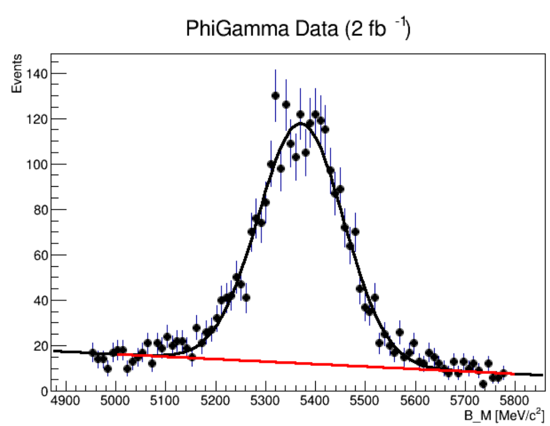
What do we measure?

Examples of observables:

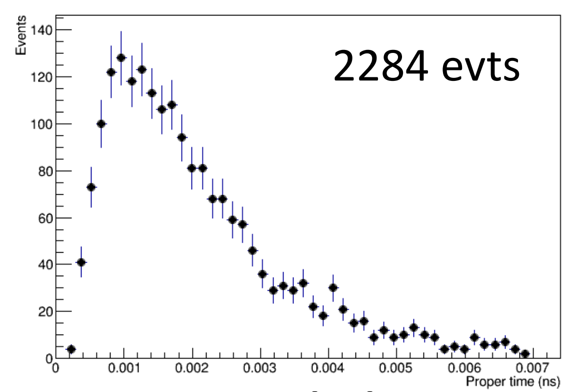
- Invariant masses: from momentum and PID hypothesis of the detected particles
- Decay times: from distance between the origin and decay vertices (and using information of the particle momentum)
- Angular distributions: from directions of the decay products (momentum, vertices)
- Branching fractions: from the mass distributions, counting the number of events
- Time dependent asymmetries (needed flavour tagging!)
- Ratios of observables: cancellation of systematic uncertainties



$M_{J/\psi}$ (MeV)



M_{Bs}(MeV) ($\phi\gamma$)

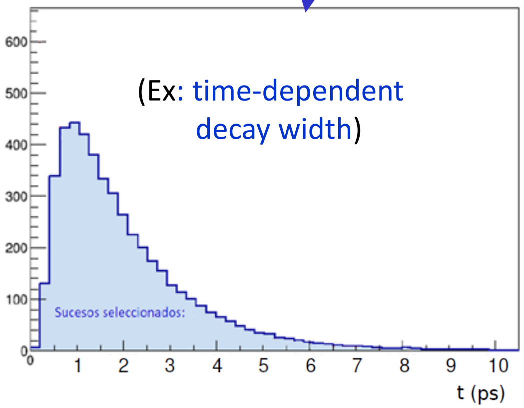


t(ns)

The LHCb experiment

Including experimental effects:

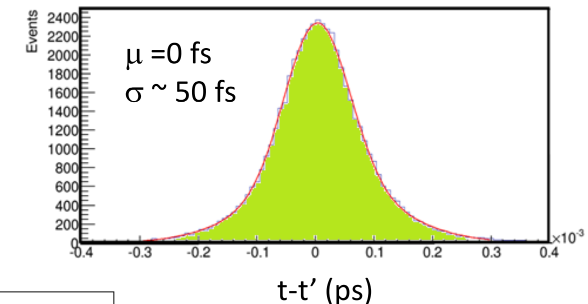
$\boxed{\text{Observable}(X')} = \boxed{\text{Physics }(X, P)} \cdot \boxed{\text{Acceptance}(X)} \times \boxed{\text{Resolution }(X,X')}$

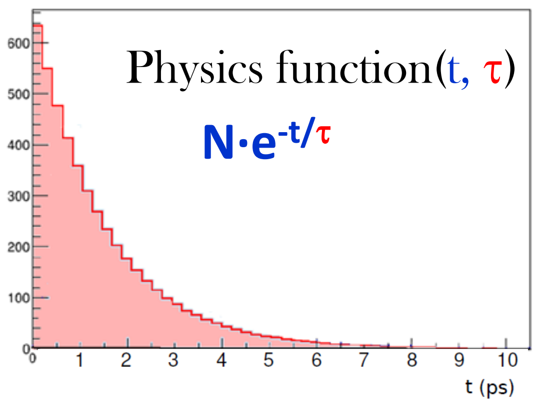


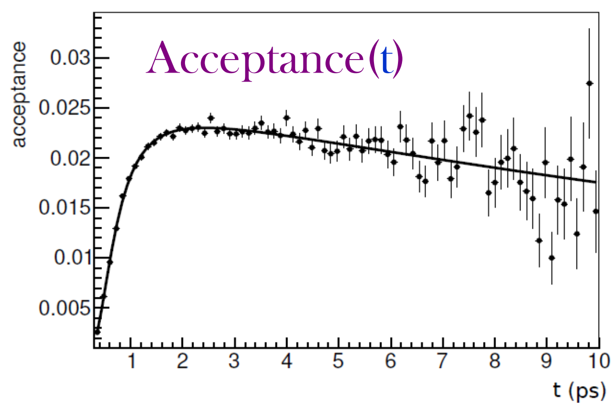
Efficiency dependent of X

$$\frac{\#\text{ detected }(X)}{\#\text{ produced }(X)}$$

R(t,t')







- One can use MC simulations to study the acceptance and resolution functions
- Better: Use control samples from data (similar to the signal channel) to extract them

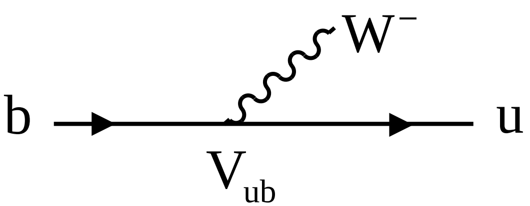
The CKM matrix

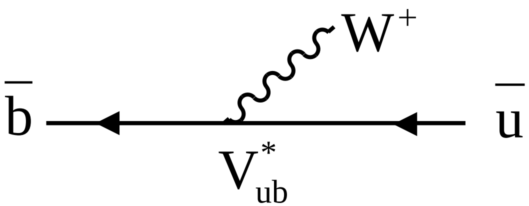
The CKM matrix V_{CKM} describes rotation for quarks between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

Quarks
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Antiquarks
$$\begin{pmatrix} \overline{d}' \\ \overline{s}' \\ \overline{b}' \end{pmatrix} = \begin{pmatrix} V_{ud}^* & V_{us}^* & V_{ub}^* \\ V_{cd}^* & V_{cs}^* & V_{cb}^* \\ V_{td}^* & V_{ts}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} \overline{d} \\ \overline{s} \\ \overline{b} \end{pmatrix}$$

V_{ij} governs the transition from quark j to quark i





CP violation due to complex phases of CKM matrix elements

The CKM matrix

- The CKM matrix is complex and unitary $\hat{V}^{+}_{CKM}\hat{V}_{CKM} = 1$
- 4 independent parameters
  - $\rightarrow$ Fundamental constants of the Standard Model
  - $\rightarrow$ Must be determined from experiment

- **Standard parametrization (PDG):**
  - 3 angles: $\theta_{12}, \theta_{23}, \theta_{13}$ and 1 phase δ

$$V_{CKM} = R_{23} \times R_{13} \times R_{12}$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$$

The CKM matrix

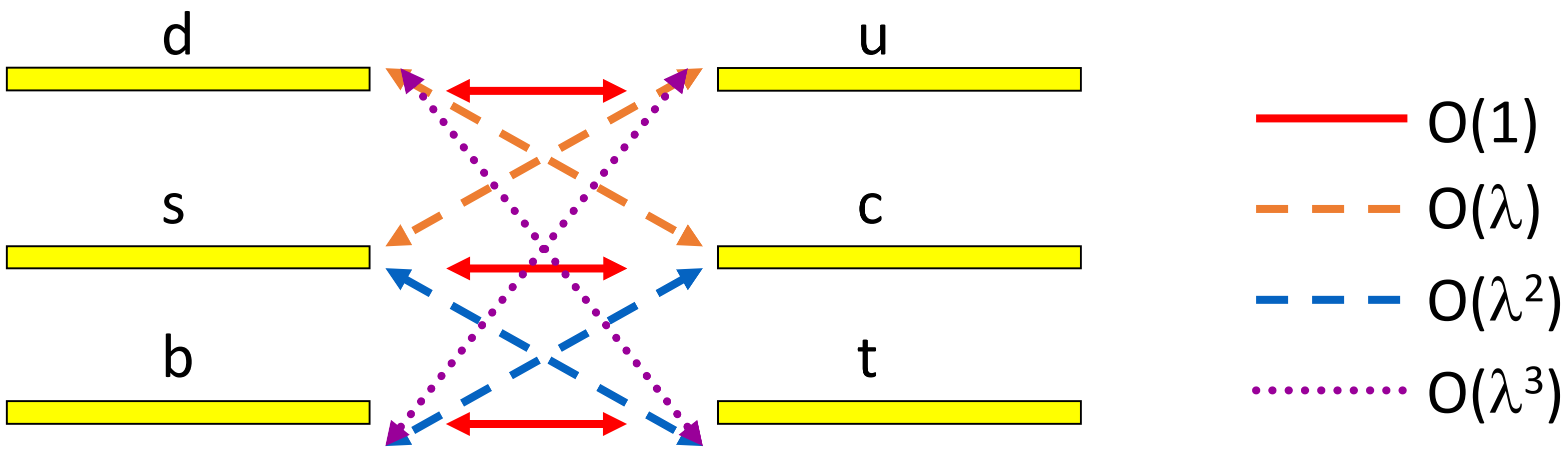
- **Wolfenstein parameterization:** $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{23} \sim 0.004$

- Perturbative, reflects the hierarchy of the matrix elements in terms of λ

$$\lambda = sin\,\theta_{12} \approx 0.23$$

- The four parameters are defined as:

$$\lambda = s_{12} \quad A = \frac{s_{23}}{s_{12}^2} \quad \rho = \frac{s_{13}\cos\delta}{s_{12}s_{23}} \quad \eta = \frac{s_{13}\sin\delta}{s_{12}s_{23}}$$



The CKM matrix

Wolfenstein parameterization to O(λ^3):

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

(but next-to leading order corrections in λ may be important at LHC)

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5\left(1/2-\rho-i\eta\right) & 1-\lambda^2/2-\lambda^4/8\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$$(\bar{\rho},\bar{\eta}) \equiv (1-\lambda^2/2)(\rho,\eta)$$

The CKM matrix

- CP Violation in the Standard Model:

  - Requirements for CP violation

$$\left(m_t^2 - m_c^2\right)\left(m_t^2 - m_u^2\right)\left(m_c^2 - m_u^2\right)$$
$$\times\left(m_b^2 - m_s^2\right)\left(m_b^2 - m_d^2\right)\left(m_s^2 - m_d^2\right)\times J_{CP} \neq 0$$

$$J_{CP} = \left|\mathrm{Im}\left\{ V_{i\alpha} V_{j\beta} V_{i\beta}^{*} V_{j\alpha}^{*} \right\}\right| \quad (i \neq j, \alpha \neq \beta)$$

  - *Jarlskog* invariant:

$$J_{CP} = s_{12} s_{13} s_{23} c_{12} c_{23} c_{13} \sin\delta = \lambda^6 A^2 \eta = O\left(10^{-5}\right)$$

$\rightarrow$ CP violation is small in the Standard Model

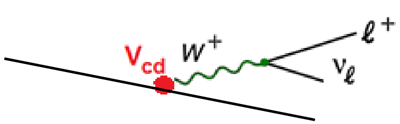
(and cannot explain the observed baryon asymmetry of the Universe)

The CKM matrix

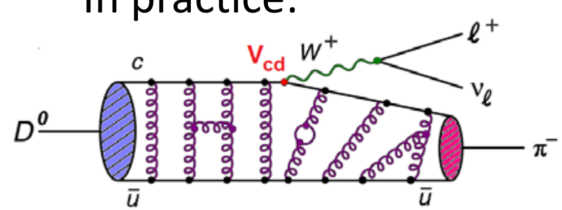
- PDG 2014:

$$
\begin{pmatrix}
\begin{array}{c} 0.97425 \pm 0.00022 \\ \text{superallowed } 0^+ \to 0^+ \ \beta \text{ decays} \end{array} & \begin{array}{c} 0.2253 \pm 0.0008 \\ \text{semileptonic / leptonic kaon decays hadronic} \\ \text{tau decays} \end{array} & \begin{array}{c} (4.13 \pm 0.49) \times 10^{-3} \\ \text{semileptonic / leptonic B decays} \end{array} \\
\begin{array}{c} 0.225 \pm 0.008 \\ \text{semileptonic charm decays} \\ \text{charm production in neutrino beams} \end{array} & \begin{array}{c} 0.986 \pm 0.016 \\ \text{semileptonic / leptonic charm decays} \end{array} & \begin{array}{c} (41.1 \pm 1.3) \times 10^{-3} \\ \text{semileptonic B decays} \end{array} \\
\begin{array}{c} (8.4 \pm 0.6) \times 10^{-3} \\ B_d \text{ oscillations} \end{array} & \begin{array}{c} (40.0 \pm 2.7) \times 10^{-3} \\ B_s \text{ oscillations} \end{array} & \begin{array}{c} 1.021 \pm 0.032 \\ \text{single top production} \end{array}
\end{pmatrix}
$$

In theory:



In practice:



$\rightarrow$ Need theory to describe QCD effects (lattice QCD)

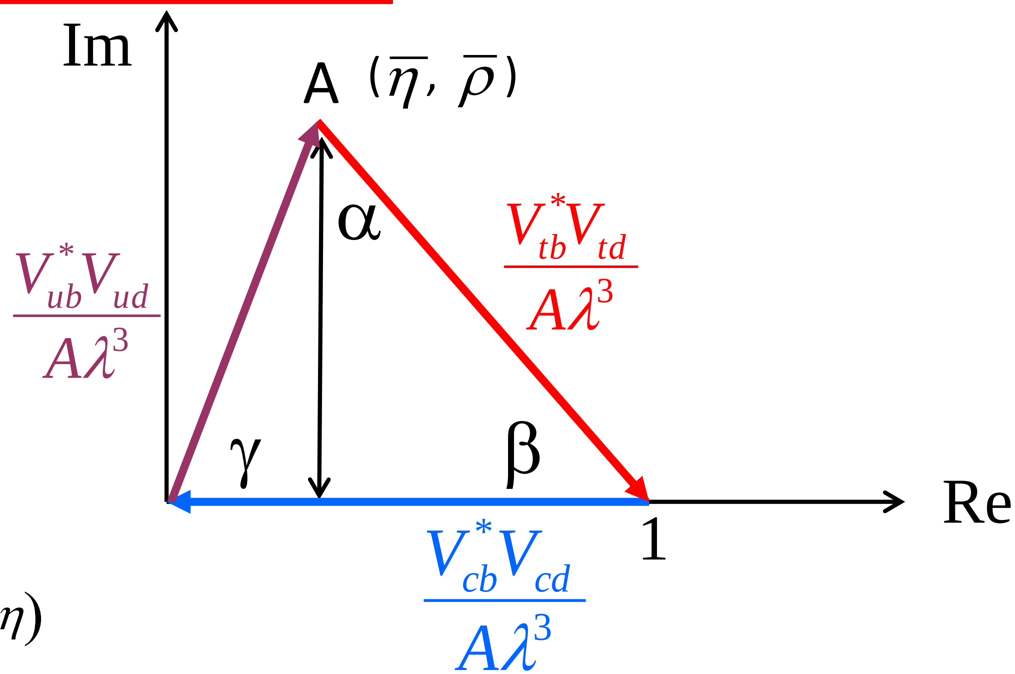
: How well is satisfied unitarity from the measured CKMs?

The CKM matrix

The Unitarity Triangle → CKM is unitary:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix}^{*} = \mathrm{I}$$

$$\boxed{V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0}$$



$$(\overline{\rho}, \overline{\eta}) \equiv (1 - \lambda^{2}/2)(\rho, \eta)$$

$$\boxed{\gamma \equiv \arg\left[-\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}\right] = \tan^{-1}\frac{\eta}{\rho} \sim 70^{o}}$$

$$\boxed{\beta \equiv \arg\left[-\frac{V_{cb}^{*}V_{cd}}{V_{tb}^{*}V_{td}}\right] = \tan^{-1}\frac{\overline{\eta}}{1-\overline{\rho}} \sim 21^{o}}$$

$$\boxed{\alpha \equiv \pi - \beta - \gamma}$$

The CKM matrix

The Unitarity Triangle

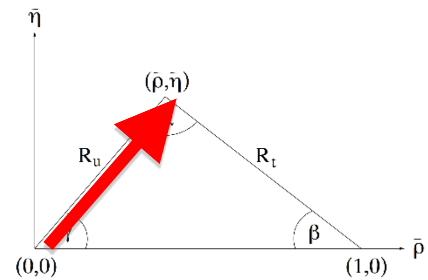
The idea: try to measure as many flavour observables as possible

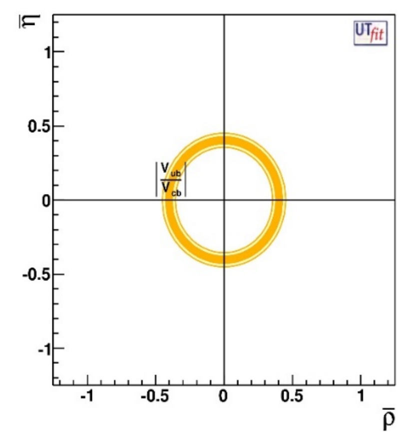
overconstraint the unitarity triangle

Ex: Measuring the $b \to u\, \ell\nu$ vs the $b \to c\, \ell\nu$ transition

$$\frac{\Gamma(b \to u \ell \nu)}{\Gamma(b \to c \ell \nu)} \sim \left|\frac{V_{ub}}{V_{cb}}\right|^2 \sim \frac{1}{50}$$

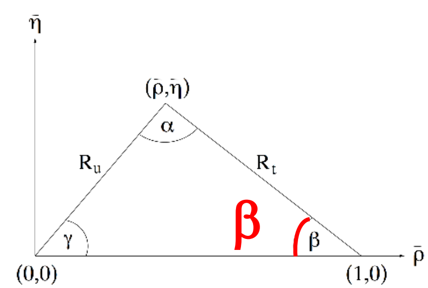
$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\lambda^2/2}\sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

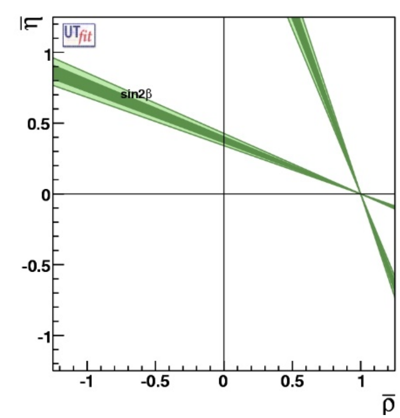




Ex: Measuring time-dependent asymmetries in $b \to c\bar{c}\, s$ decays
(effect from interference of mixing and decay)

$$\beta = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}}$$

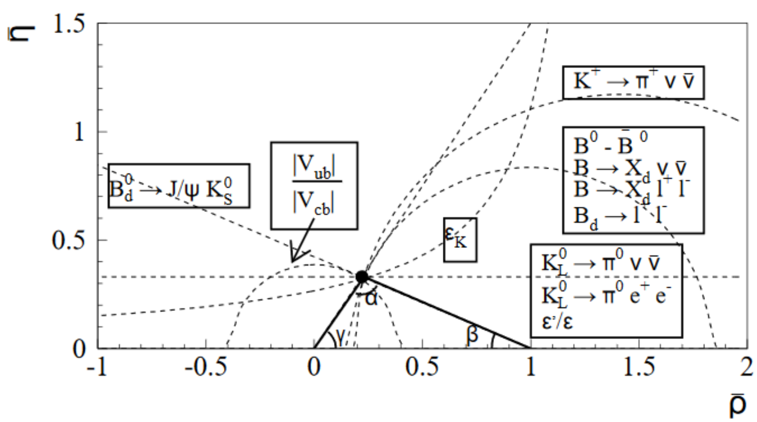


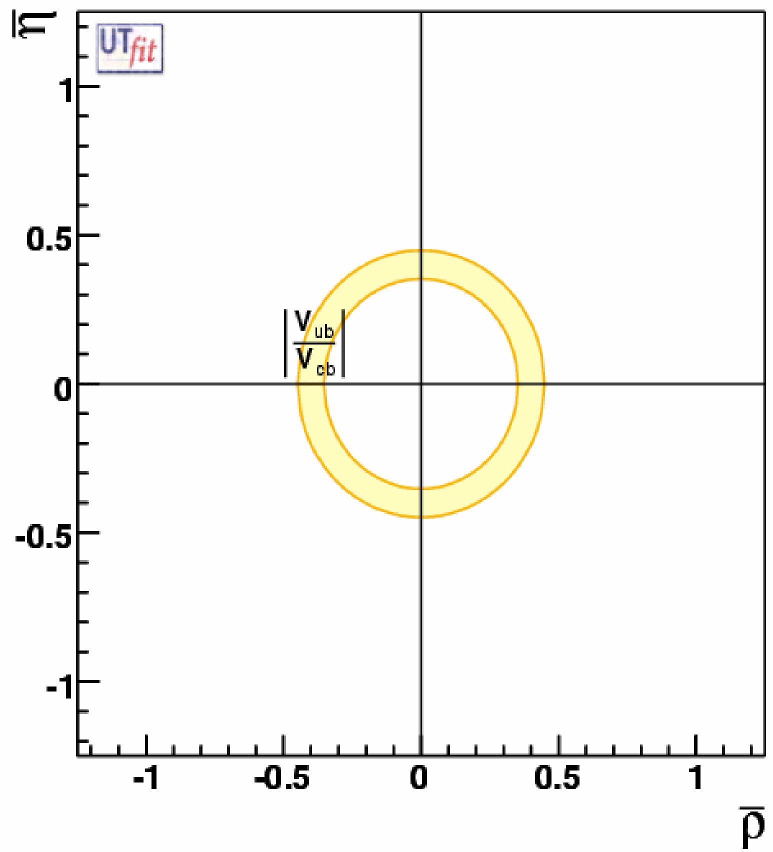


The CKM matrix

The Unitarity Triangle

The idea: try to measure as many flavour observables as possible
overconstraint the unitarity triangle



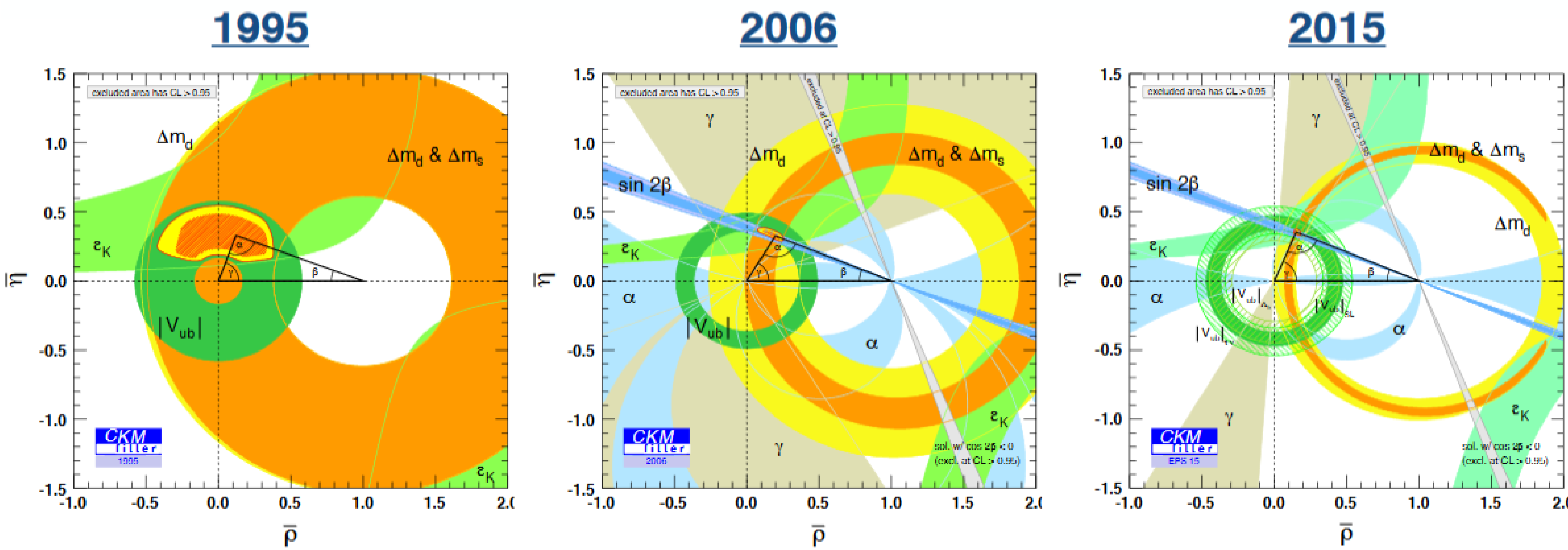


- If all measurements meet in the same apex$\rightarrow$ good understanding of the flavour structure of the SM

- If not $\rightarrow$ New Physics

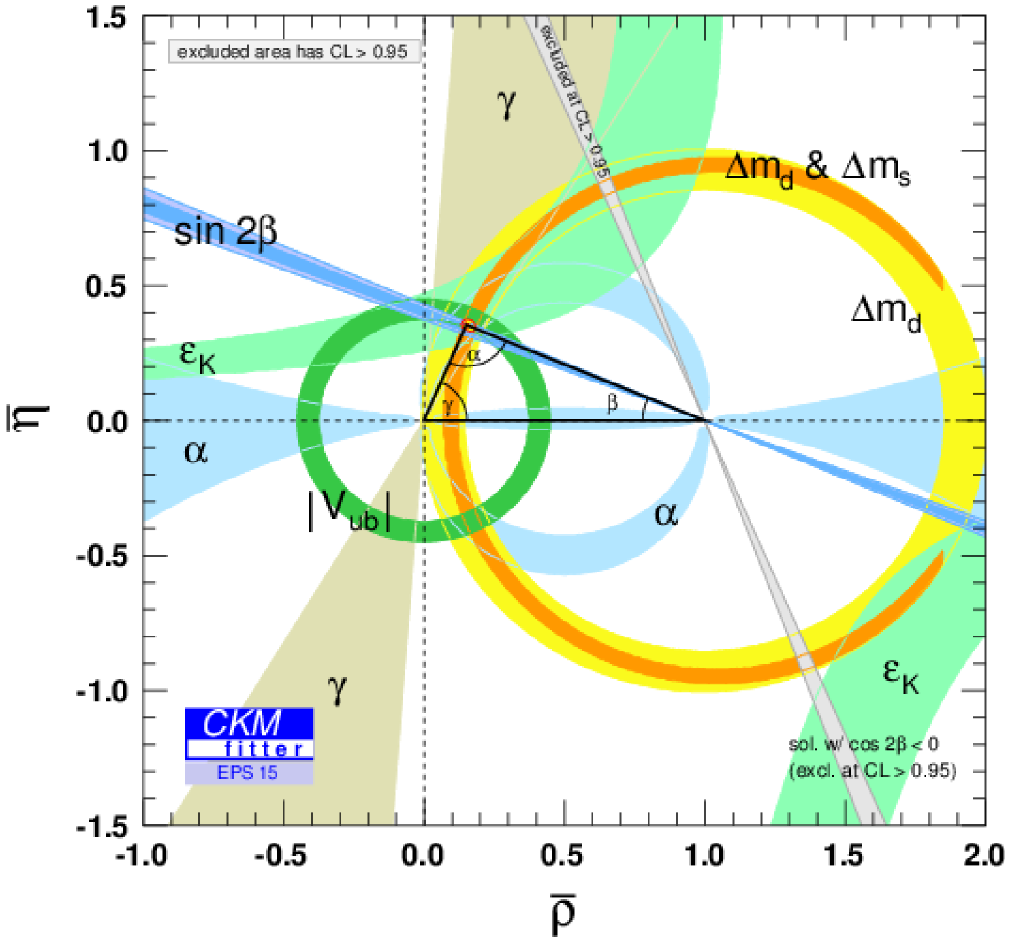
The CKM matrix

The Unitarity Triangle



- Precision measurements of CKM elements (fundamental parameters!)
- Measure all angles and sides in many different ways and look for inconsistencies → quantum effects from new particles
- Compare tree level processes (new physics is not expected) with loop processes sensitive to new particles
- With more precision the new physics scale has to be higher.

The CKM matrix



$$\bar{\rho} = 0.132 \pm 0.020$$
$$\bar{\eta} = 0.358 \pm 0.012$$

- Good agreement between the experimental measurements

- Validation of Standard Model in the flavour sector

- Few discrepancies ("tensions")

- Understanding from QCD is crucial

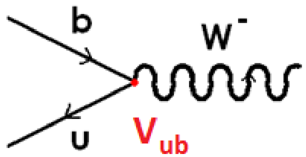
- Still room for New Physics, need more precision!

http://ckmfitter.in2p3.fr/

http://www.utfit.org/UTfit/

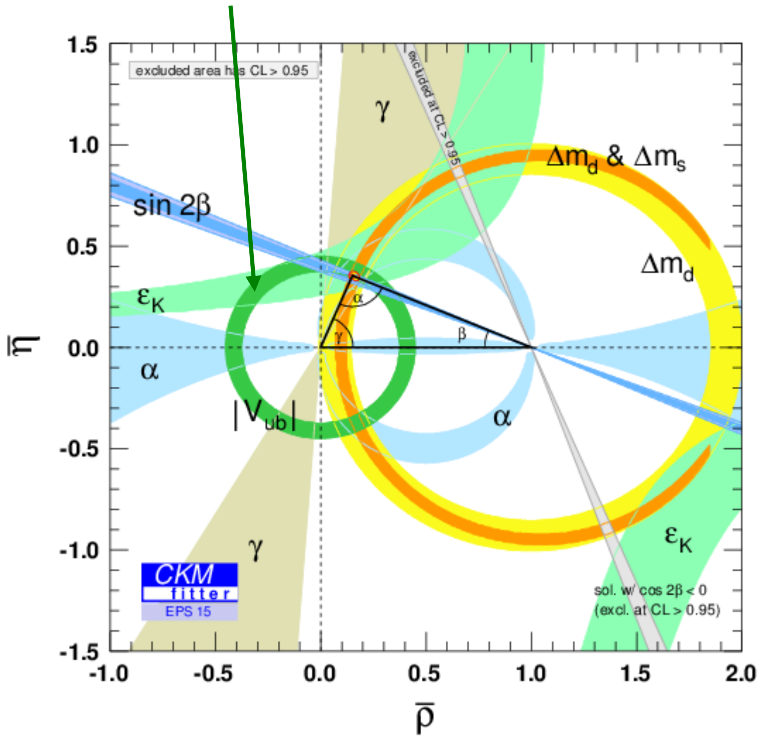
The CKM matrix

- Measuring the CKM matrix element V_{ub} at LHCb:

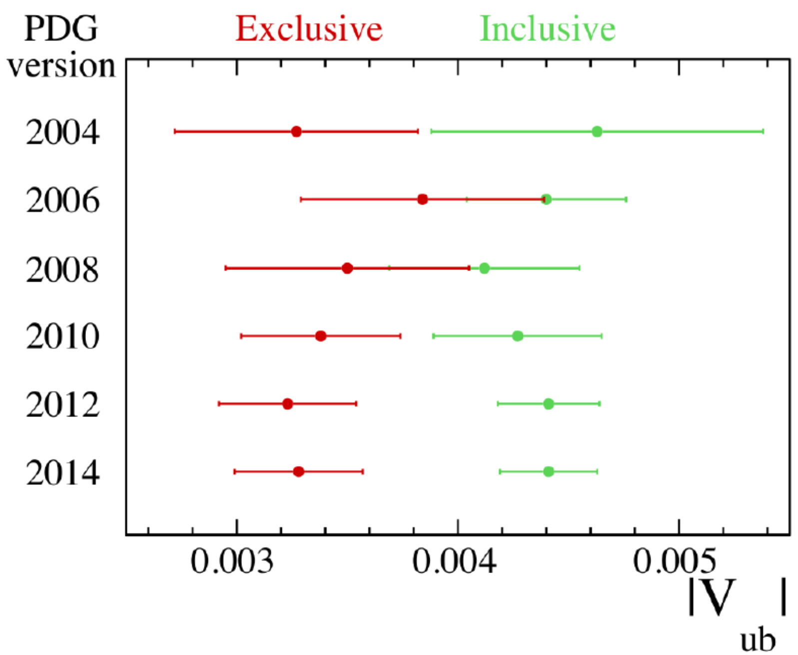


Key constraint in the flavour picture since it is extracted from decays at tree-level

(No loops $\rightarrow$ no New Physics expected, it's a reference to be compared with)



Discrepancy between ways of measuring this element during years:



Exclusive: from specific channels: $B \rightarrow \pi \ell \nu$, $B \rightarrow \rho \ell \nu$ …

Inclusive: from total rate $B \rightarrow X_u \ell \nu$

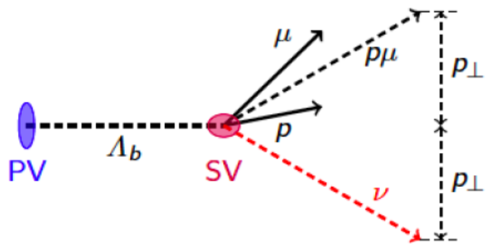
The CKM matrix

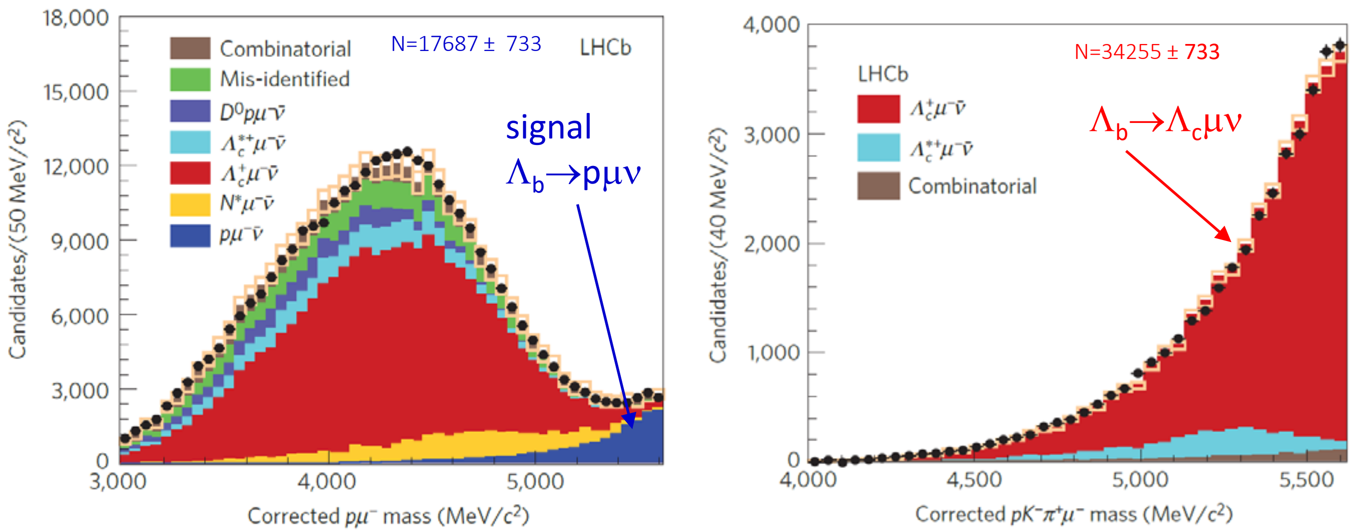
At LHCb very challenging due to the missing neutrino:

Using semileptonic decays of b-baryons:

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2}$$ x Ratio of form factors ← (5% accuracy from LQCD)

- Use information from displaced vertex
- Select high q^2 region (theory more precise)
- Corrected mass: $m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$





[Nature Physics 10 (2015) 1038]

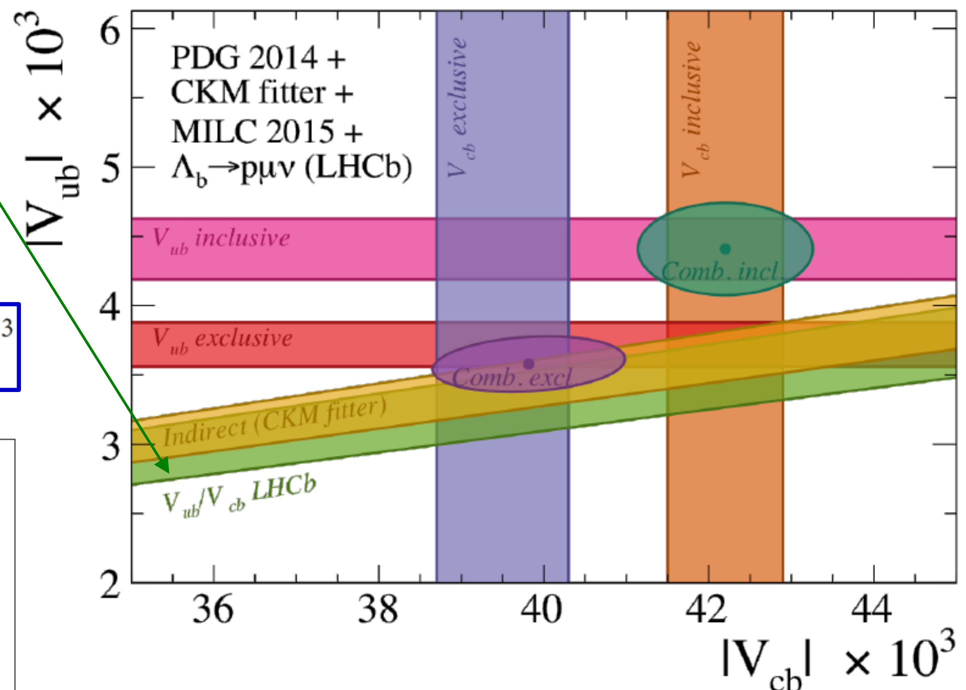
The CKM matrix

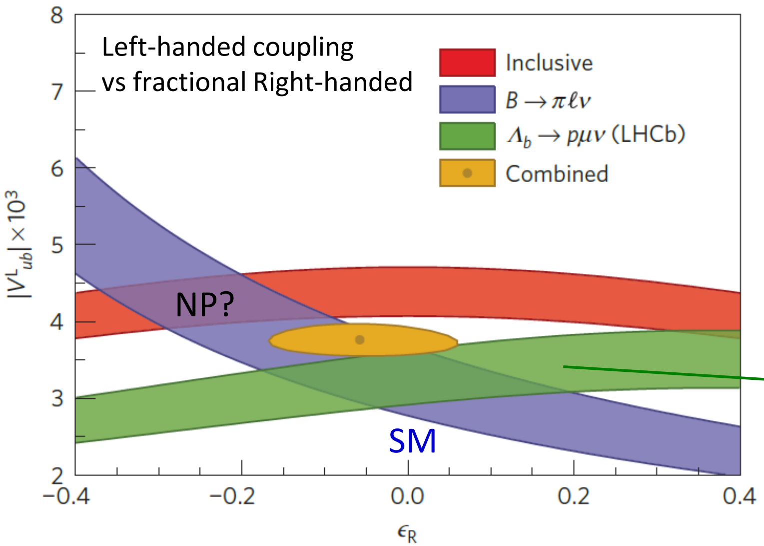
[Nature Physics 10 (2015) 1038]

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

Using the world average from exclusive V_{cb}:

$$\boxed{|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}}$$





Disfavours New Phyiscs models with Right-handed currents

B mixing and CP violation

Mixing of neutral B mesons governed by

$$i\frac{\partial}{\partial t}\begin{pmatrix}a\\b\end{pmatrix} = H\begin{pmatrix}a\\b\end{pmatrix} = \begin{pmatrix} M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix}$$

Mass eigenstates:

$$\left|B_{L,H}\right\rangle = p\left|B^0\right\rangle \pm q\left|\overline{B^0}\right\rangle$$

p and q represent the amount of state mixing

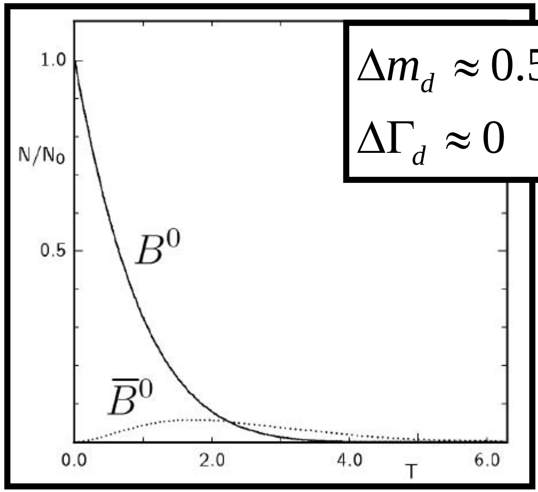
$$|p|^2+|q|^2=1$$

$$|q/p|=1$$

$$\frac{q}{p}=\sqrt{\frac{M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*}}{M_{12}-\frac{i}{2}\Gamma_{12}}}$$

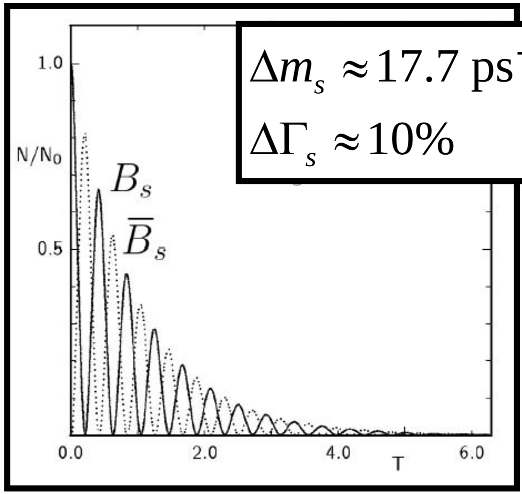
$$\Delta m = m_H - m_L = 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|$$



$\Delta m_d \approx 0.505\ \mathrm{ps}^{-1}$

$\Delta\Gamma_d \approx 0$



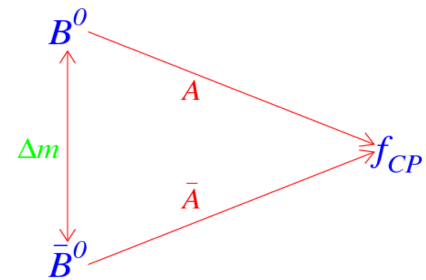
$\Delta m_s \approx 17.7\ \mathrm{ps}^{-1}$

$\Delta\Gamma_s \approx 10\%$

B mixing and CP violation

Decay amplitudes of flavour states decaying to the same final state f

$$A_f = \langle f | H | B^0 \rangle \quad \overline{A_f} = \langle f | H | \overline{B^0} \rangle$$



One can define $\lambda_f = \dfrac{q}{p} \dfrac{\overline{A_f}}{A_f}$

$$\tau \equiv 1/\Gamma$$
$$x \equiv \Delta m/\Gamma$$
$$y \equiv \Delta\Gamma/2\Gamma$$

Time dependence of decay rate for initially pure flavour states:

$$\boxed{\begin{aligned}\Gamma_f &\equiv \left|\langle f | H | B^0(t) \rangle\right|^2 = \frac{1+|\lambda_f|^2}{2} |A_f|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau + C_f \cos xt/\tau - S_f \sin xt/\tau\right] \\ \overline{\Gamma}_f &\equiv \left|\langle f | H | \overline{B}^0(t) \rangle\right|^2 = \frac{1+|\lambda_f|^2}{2} \left|\frac{p}{q} A_f\right|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau - C_f \cos xt/\tau + S_f \sin xt/\tau\right]\end{aligned}}$$

$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_{\Delta f}^2 + S_f^2 + C_f^2 = 1$$

B mixing and CP violation

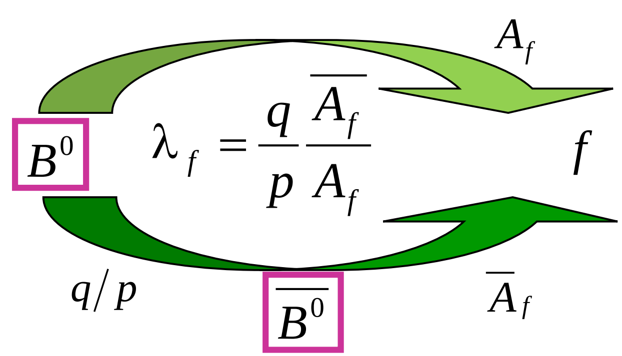
CP Violation $\rightarrow\ \Gamma_f \neq \overline{\Gamma}_f$

Three types:

- **CPV in Decay:** $B^0 \rightarrow f \quad \neq \quad \overline{B^0} \rightarrow \overline{f}$ $\qquad \boxed{\left|\dfrac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1}$
- **CPV in Mixing:** $B^0 \rightarrow \overline{B^0} \quad \neq \quad \overline{B^0} \rightarrow B^0$ $\qquad \boxed{\left|\dfrac{q}{p}\right| \neq 1} \quad \boxed{\mathrm{Im}\left\{\Gamma_{12}^{*} M_{12}\right\} \neq 0}$
- **CPV in Interference between mixing and decay:**

$$\boxed{\left|\lambda_f\right| = 1, \quad \mathrm{Im}\left\{\lambda_f\right\} \neq 0}$$

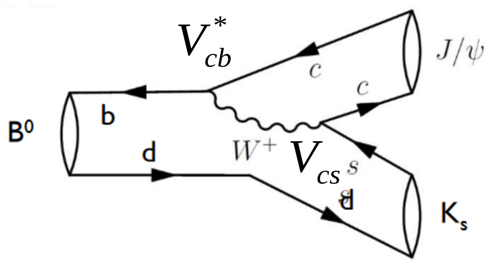
$$\boxed{A_f^{CP}(t) = \frac{\Gamma_f(t) - \overline{\Gamma}_f(t)}{\Gamma_f(t) + \overline{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}}$$

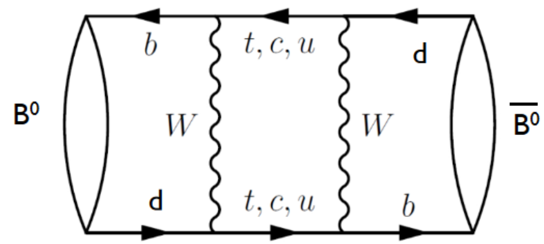


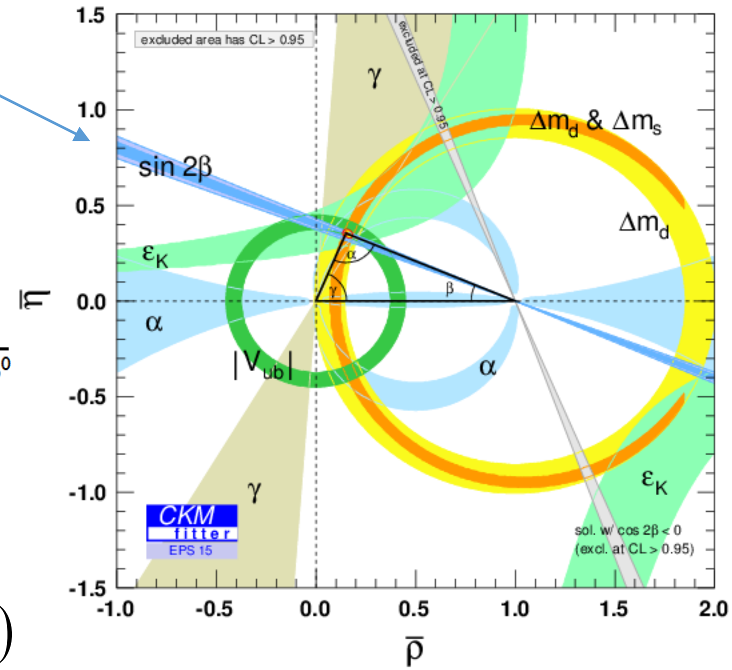
B mixing and CP violation

Measuring the β angle of the CKM triangle

Golden channel: $B^0 \to J/\psi\, K^0$







$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \overline{\Gamma}_f(t)}{\Gamma_f(t) + \overline{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}$$

$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}$$

$$\sim -C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

$$\mathrm{Im}\{\lambda_f\} = \mathrm{Im}\{-e^{-2i\beta}\} = \sin 2\beta$$

C_f ~0 in the SM

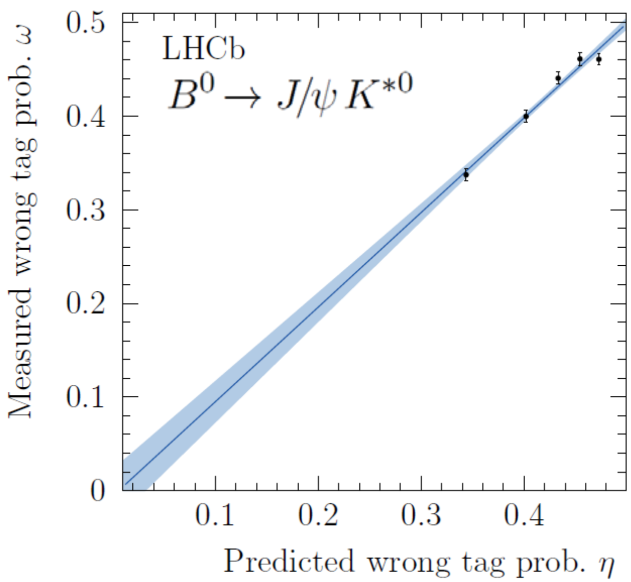
$$\boxed{A_f^{CP}(t) \sim \sin 2\beta \sin(\Delta m t)}$$

B mixing and CP violation

Count number of tagged signal events reconstructed as function of time

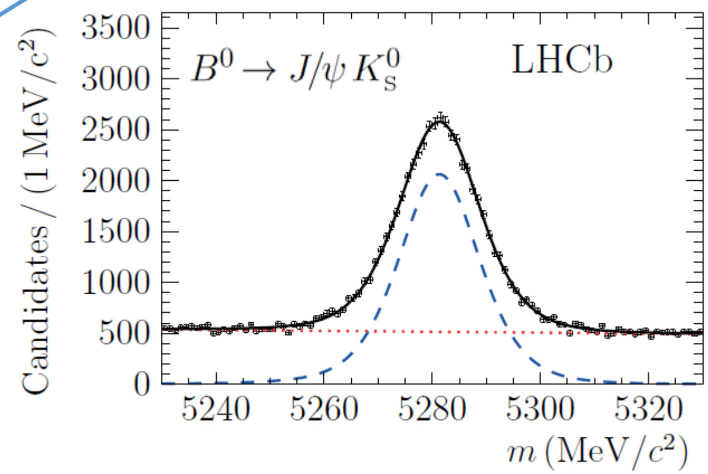
$$A_{CP}(t) = \frac{N\left(B_{tag} = B^0\right) - N\left(B_{tag} = \overline{B}^0\right)}{N\left(B_{tag} = B^0\right) + N\left(B_{tag} = \overline{B}^0\right)} \approx \pm\{(1-2\omega)\times \sin 2\beta \times \sin(\Delta m \Delta t)\} \otimes \mathrm{R}(\Delta t)$$

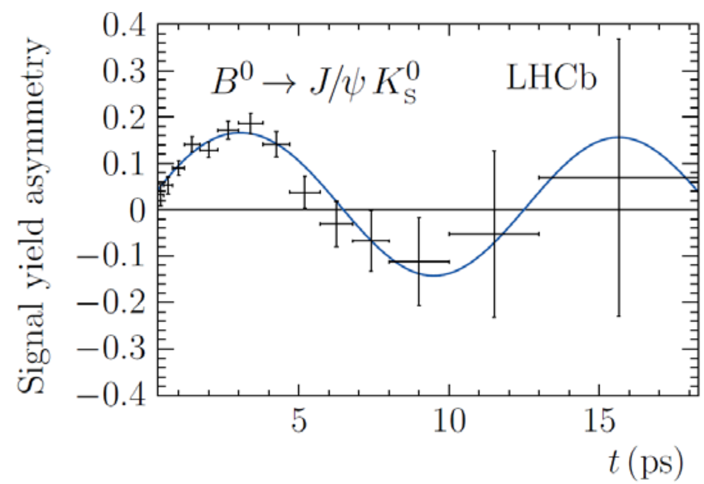
Flavour mistag calibrated using a control sample flavour specific ($K^{*0} \to K^-\pi^+$)



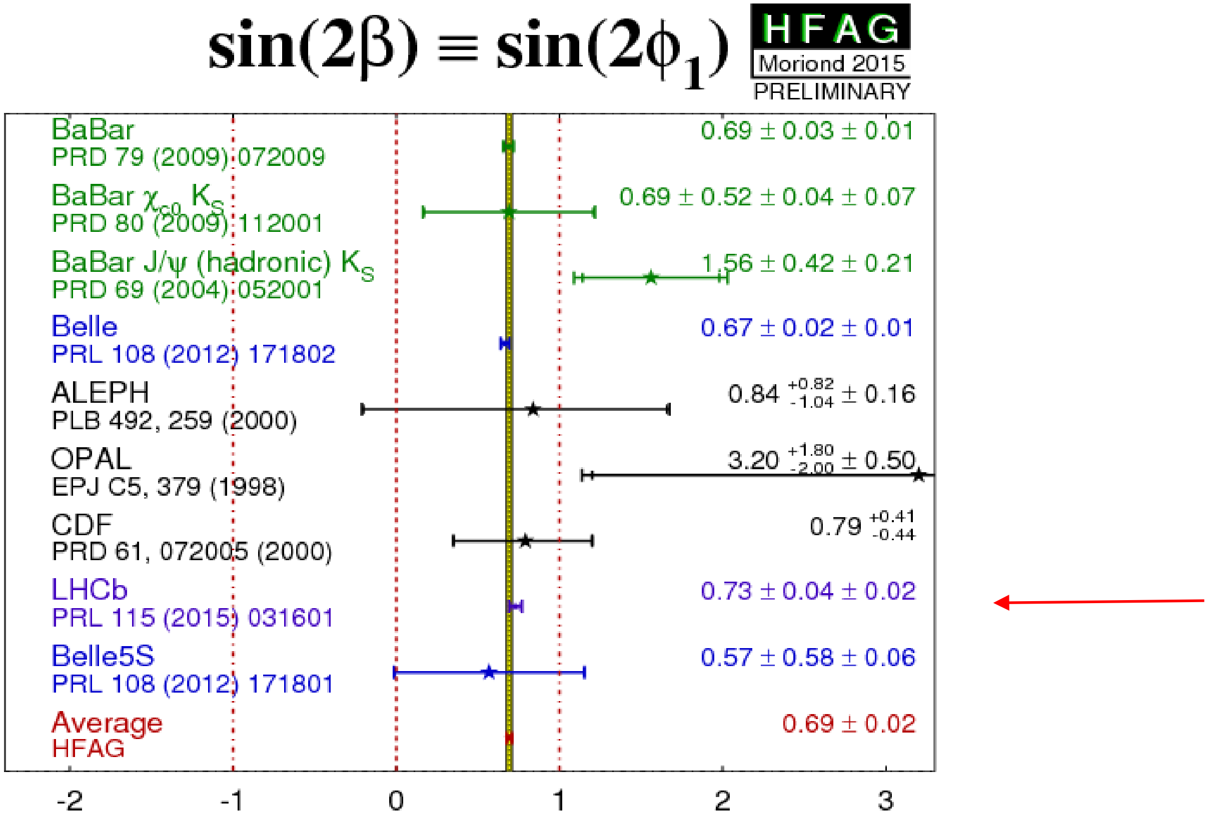
$$\omega = (35.62 \pm 0.12)\,\%$$

$$\varepsilon_{\rm tag} = (36.54 \pm 0.14)\,\%$$





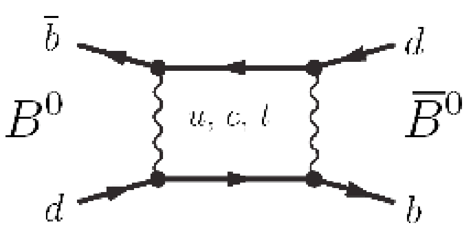
B mixing and CP violation

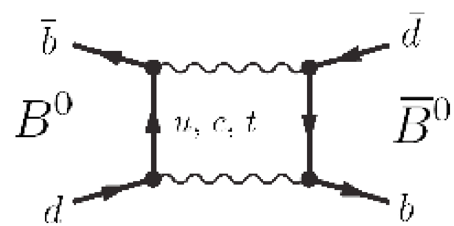


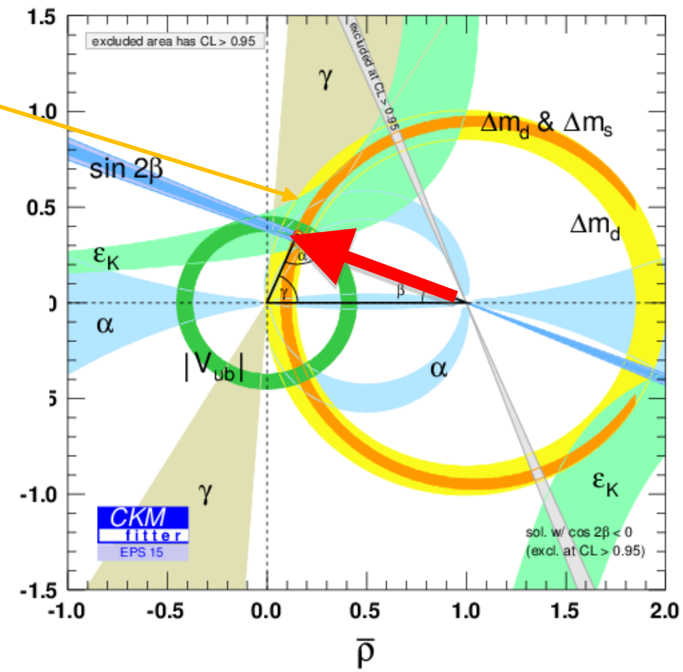
B mixing and CP violation

Measuring the other side of the CKM triangle

- Through the mass difference Δm_d, Δm_s in the box diagrams:





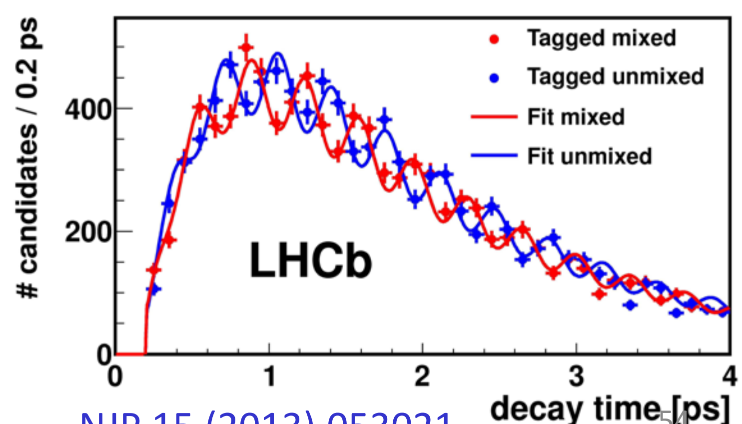


The time-dependent asymmetry A(t) of $B_{d,s}$ events that changed flavour (mixed) or not (unmixed) is:

$$\boxed{A_{mix}(t)\,\frac{N^{unmix}(t)-N^{mix}(t)}{N^{unmix}(t)+N^{mix}(t)} = \cos\Delta mt}$$

with experimental effects:

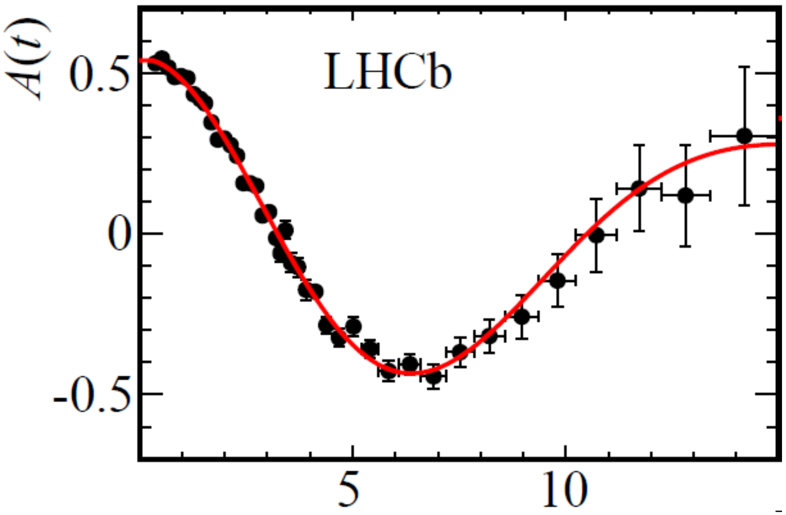
$$=\{(1-2\omega)\times\cos\Delta m\Delta t\}\otimes R(\Delta t)$$



NJP 15 (2013) 053021

B mixing and CP violation

Measuring the other side of the CKM triangle



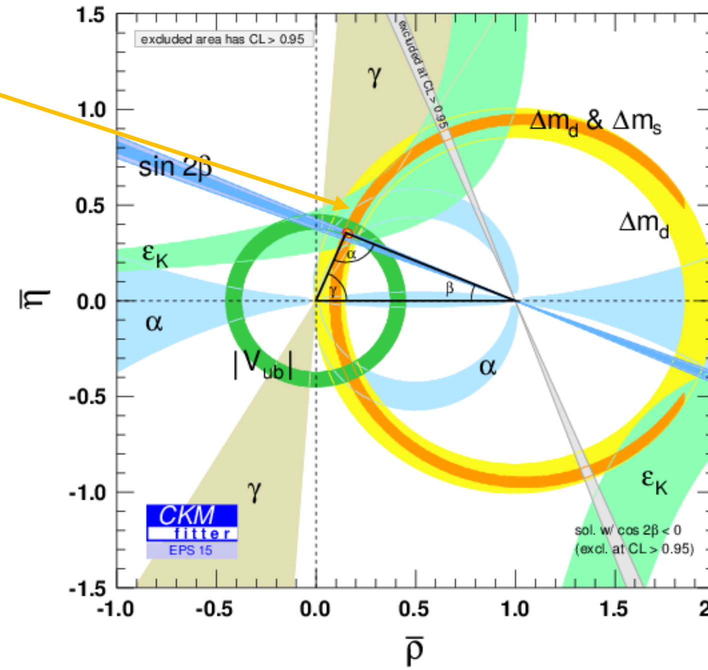
t(ps)

(best tagging category)

[EPJ C (2016) 76]

$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$

$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$



$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

error from theory

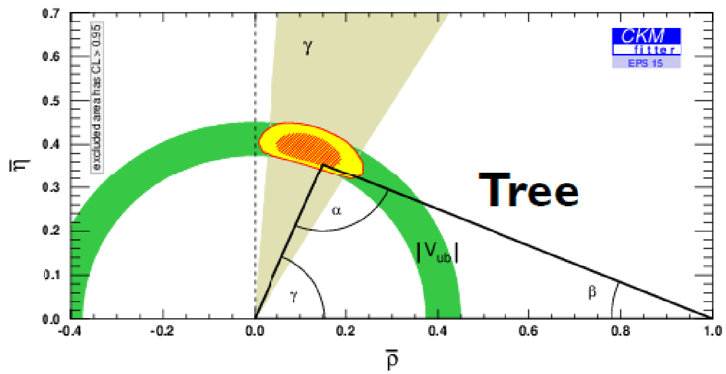
$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

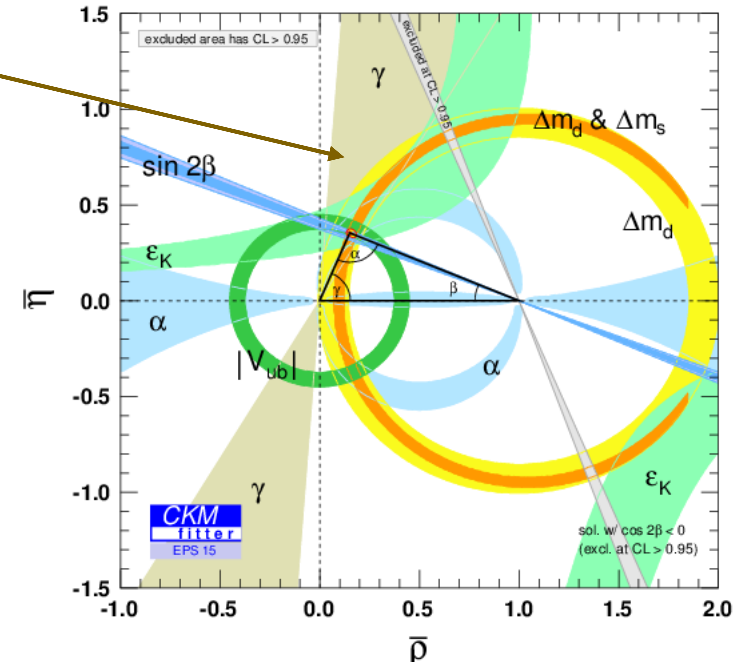
Q : Could you infer the top mass from the measured Δm_d?

B mixing and CP violation

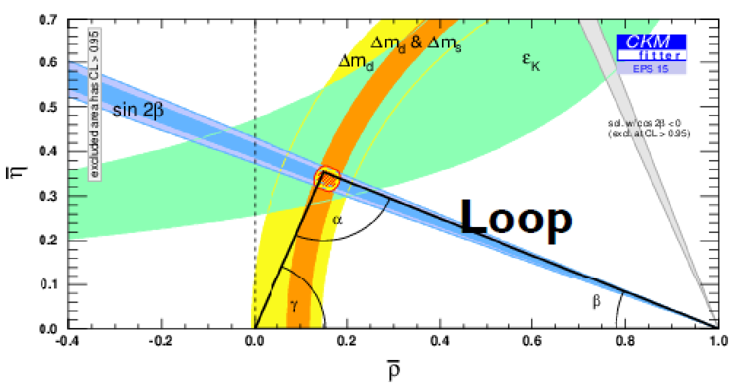
Measuring the γ angle of the CKM triangle

Key to determine the apex from tree level processes, with V_{ub} is the "reference clock"

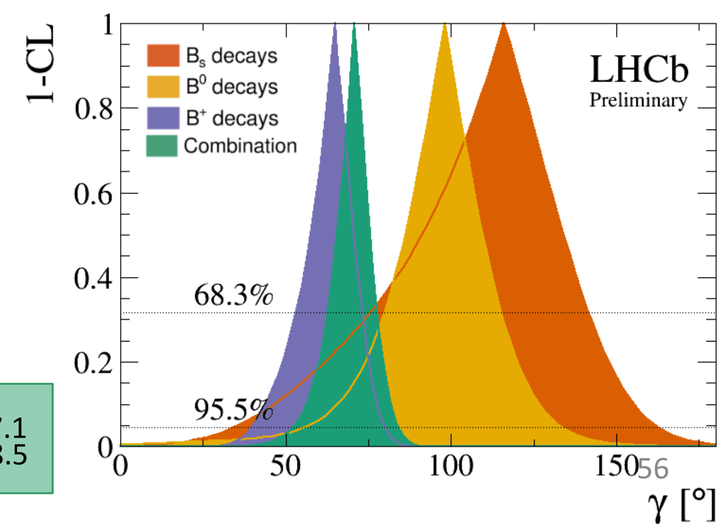




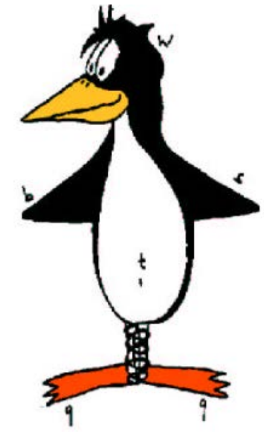
To be compared with constraints from loop processes:



$\gamma = 70.9^{+7.1}_{-8.5}$

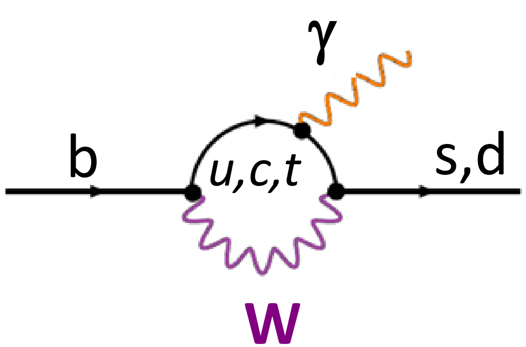


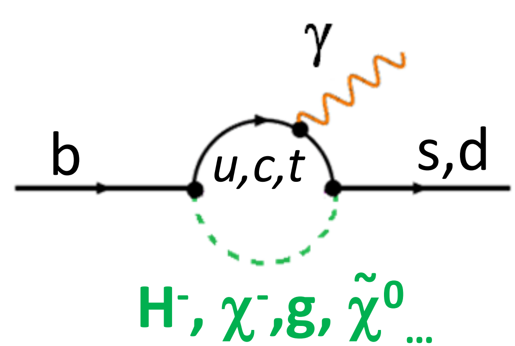
Rare decays



Rare decays:

- Processes very suppressed, go through loop diagrams
- Branching fractions $10^{-5} – 10^{-10}$
- Highly sensitive to New Physics: if one finds more events than expected $\rightarrow$ new particles in the loop
- If leptons or photons in the final states, very clear experimental signatures

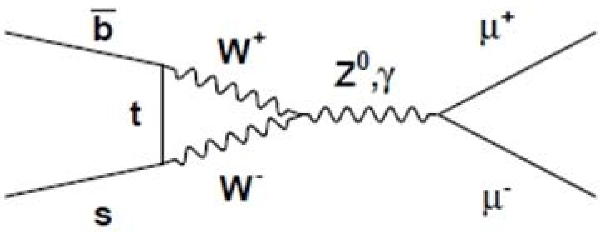




Rare decays

One of the most relevant channels:

$\boxed{B_s \to \mu^+\mu^-}$

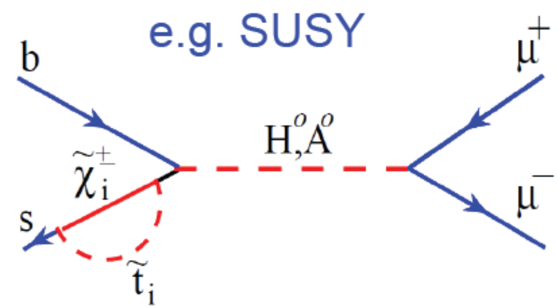


→ FCNC + helicity supressed → **Very Rare decay**:

→ Standard Model prediction:

[PRL 112 101801 (2014)]

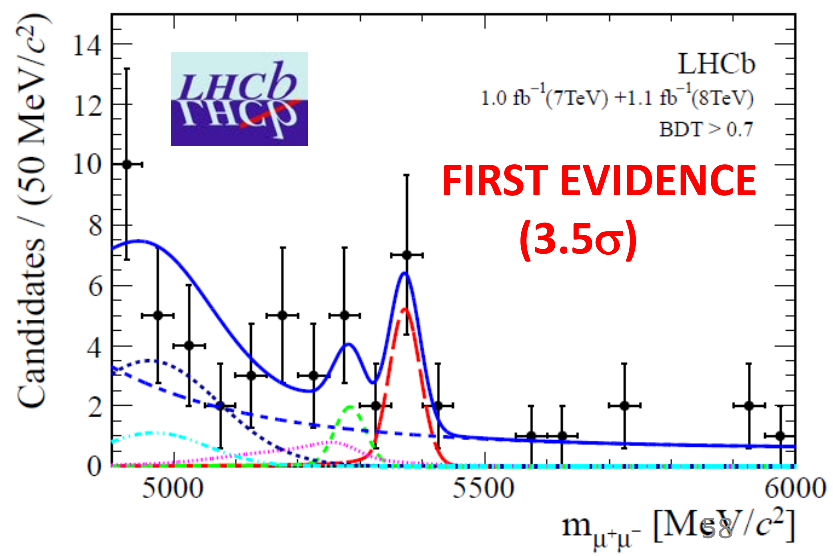
$$\mathcal{B}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$



→ Enhanced by New Physics models (e.g. SUSY ~ $tg^6\beta/m^4_A$)

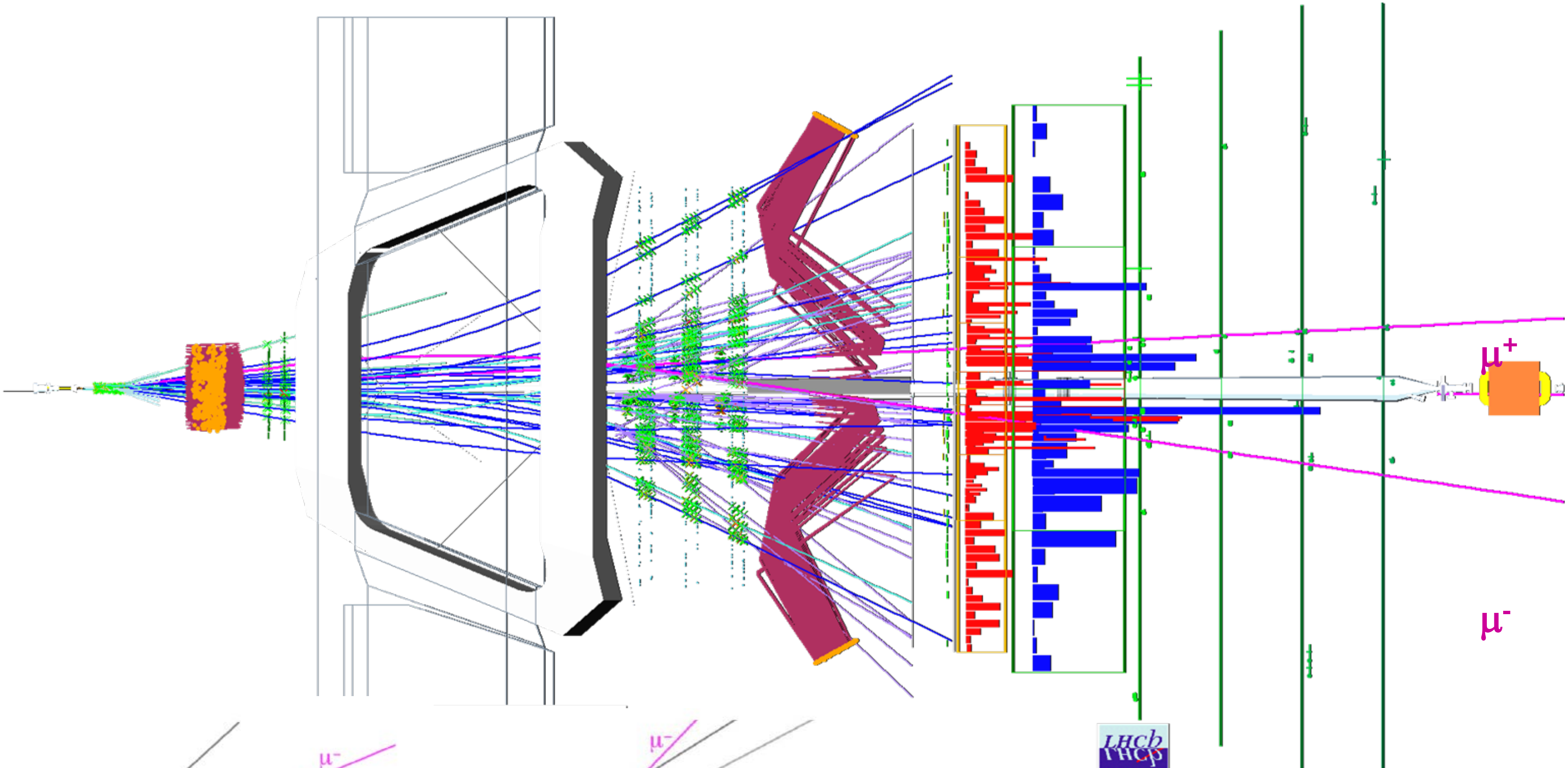
→ First evidence by LHCb in 2012!

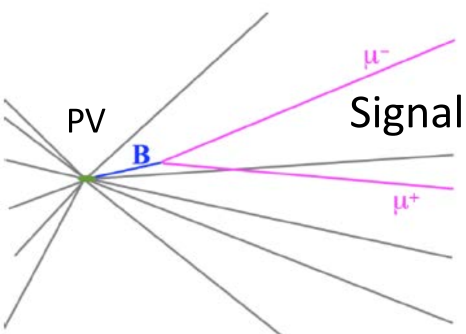
[LHCb, PRL110 (2013)021801] (2fb^{-1})

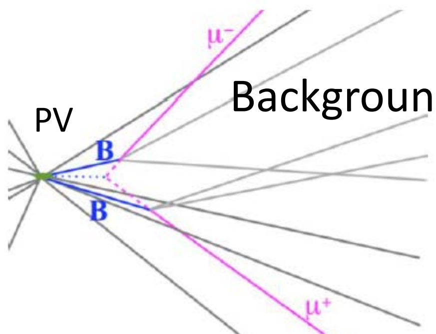


Rare decays

$B_s \to \mu^+\mu^-$ event

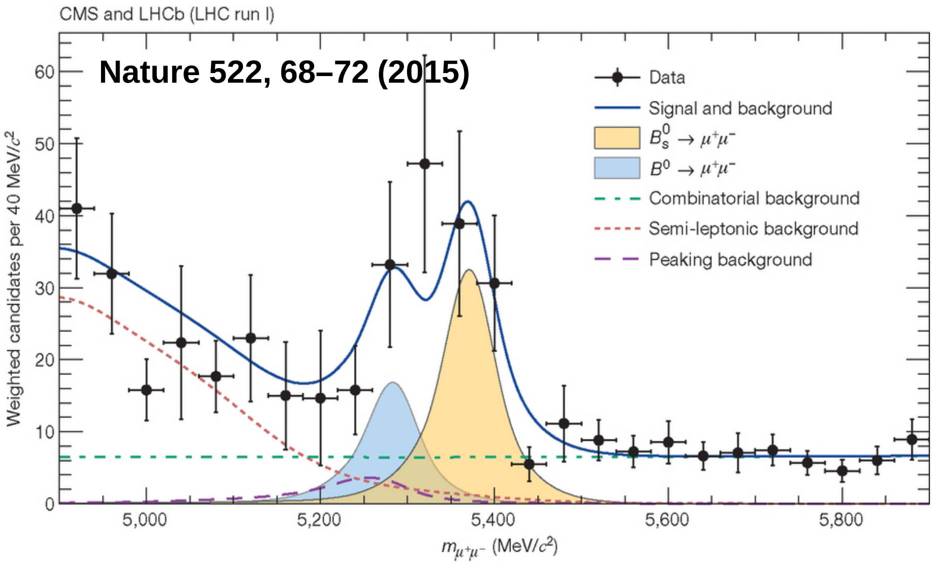






CMS + LHCb

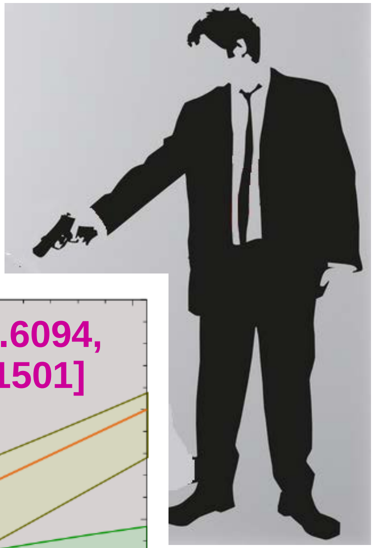
Rare decays

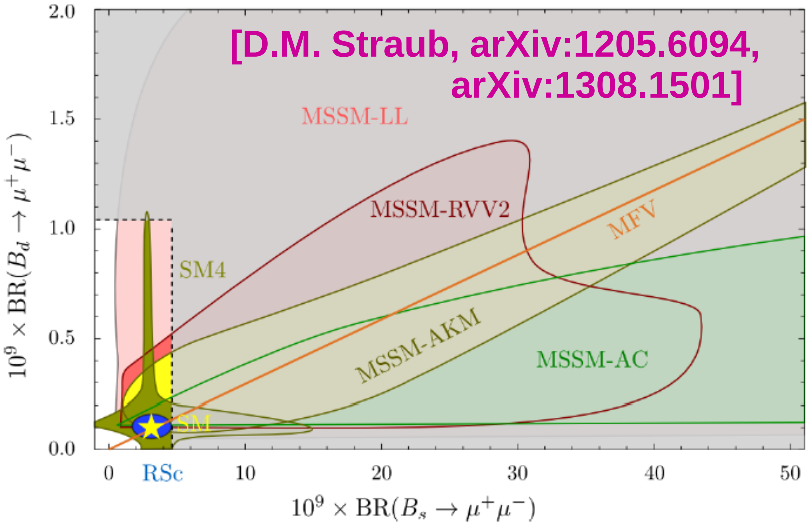


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$ **6.2σ**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$ **3.2σ**

- Known as "the New Physics killer":

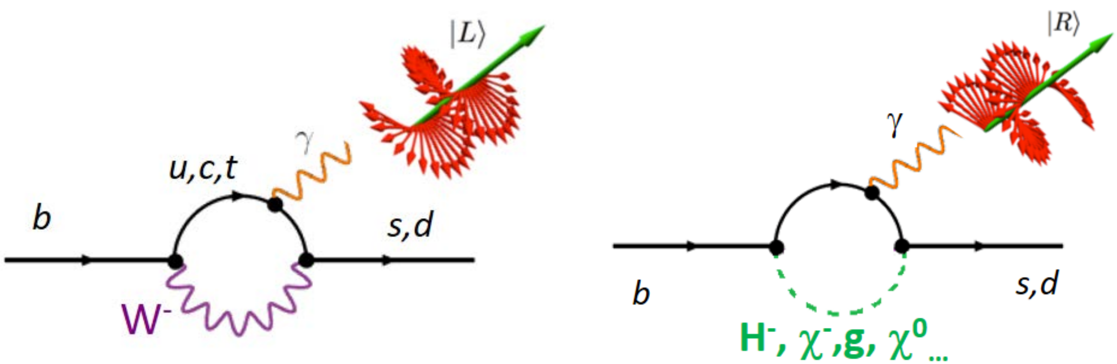




Rare decays

Probing the spin structure of the photon: $\boxed{B_s \rightarrow \phi\gamma}$

- In the Standard Model photons emitted in $b \rightarrow s\gamma$ transitions are left-handed polarized
- New particles in the loop could add right-handed contributions



- The polarization of the photon can be inferred from the time evolution of the B_s decay

$$\Gamma_{B_s^0}(t) = |A|^2 e^{-\Gamma_s t} \left(\cosh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}^{\Delta} \sinh \frac{\Delta\Gamma_s t}{2}\right)$$

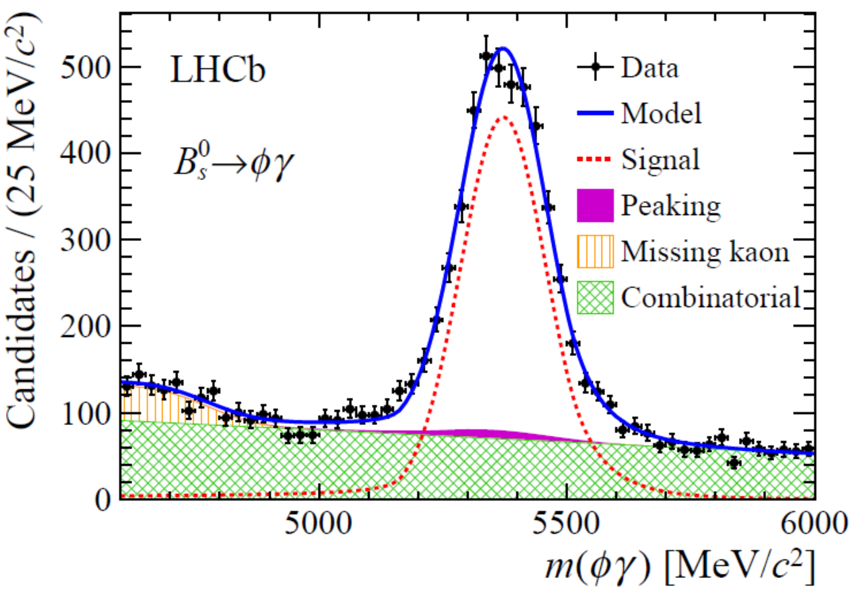
Related to the ratio of right to left handed amplitudes

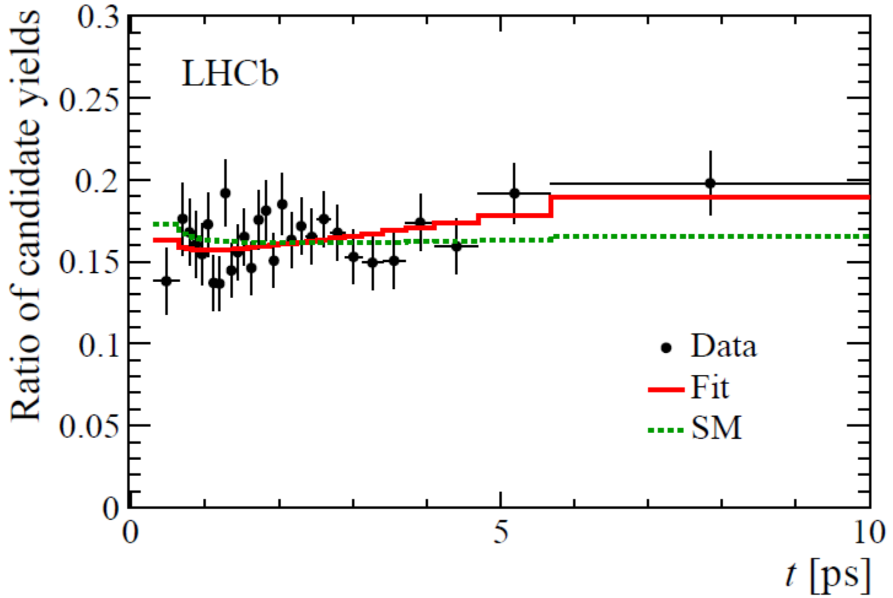
$$\mathcal{A}^{\Delta}_{SM} = 0.047\,^{+0.029}_{-0.025}$$

Rare decays

This sensitivity comes from the effect of the mixing of $B_s \to \phi\gamma$ and $\overline{B}_s \to \phi\gamma$ with $\phi \to K^+K^-$

Use a control channel with no sensitivity to the photon polarization (ex: a flavor specific channel $B \to K^*\gamma$, with $K^* \to K^-\pi^+$)

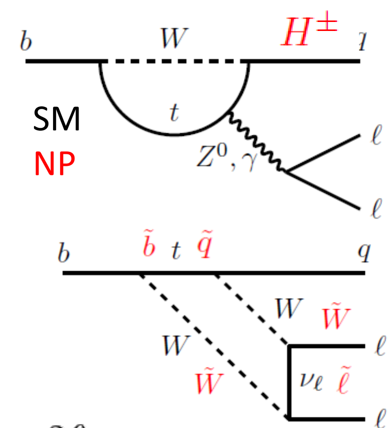




$$\boxed{\mathcal{A}^{\Delta} = -0.98 \, {}^{+0.46}_{-0.52} \, {}^{+0.23}_{-0.20}}$$

[LHCb, arXiv:1609.02032]

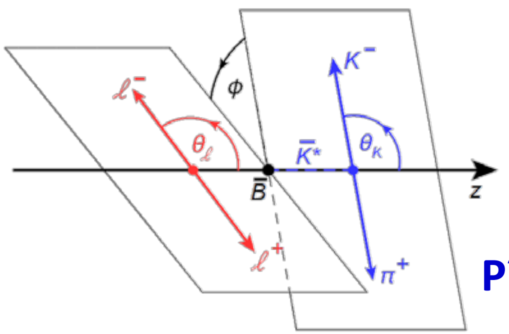
Rare decays



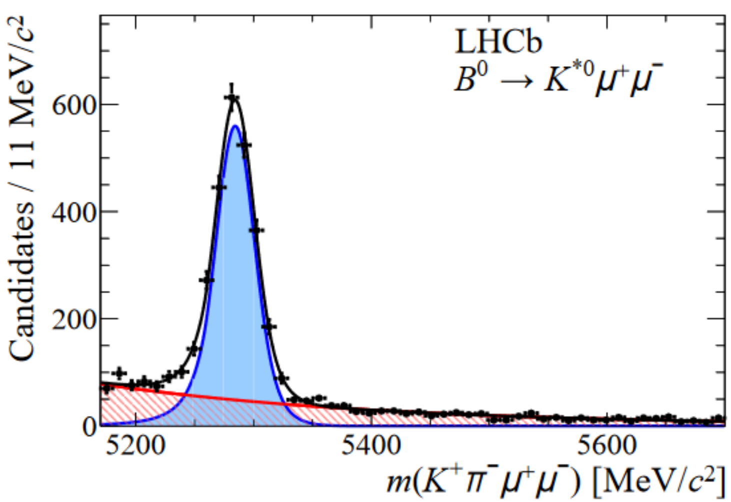
Some tensions / anomalies with the SM:

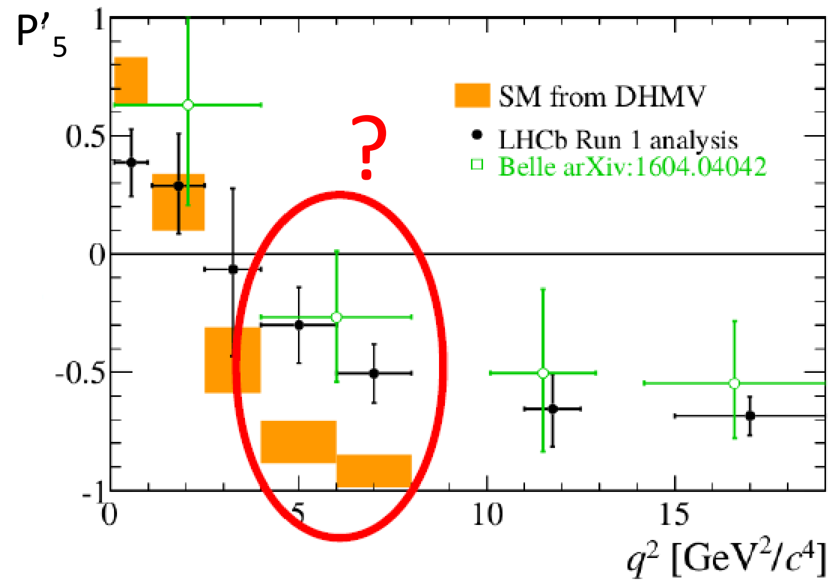
- **P'$_5$**: an angular observable in the $B \to K^* \mu^+ \mu^-$ decay channel

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos 2\theta_\ell$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



$P'_5 = S_5 / \sqrt{F_L(1-F_L)}$





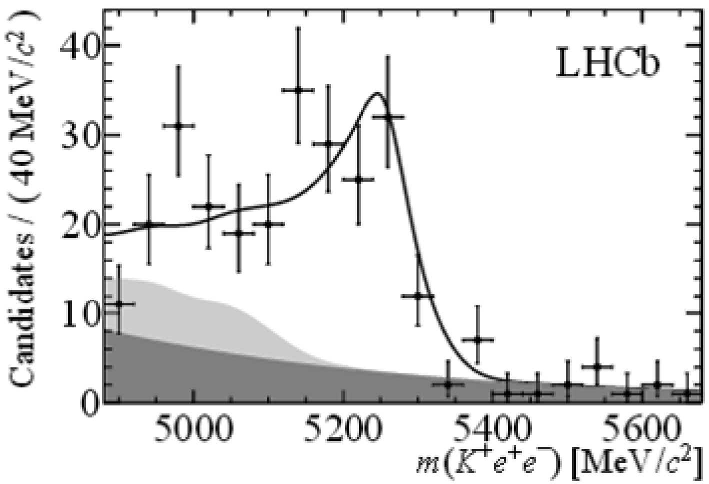
JHEP 02 (2016) 104

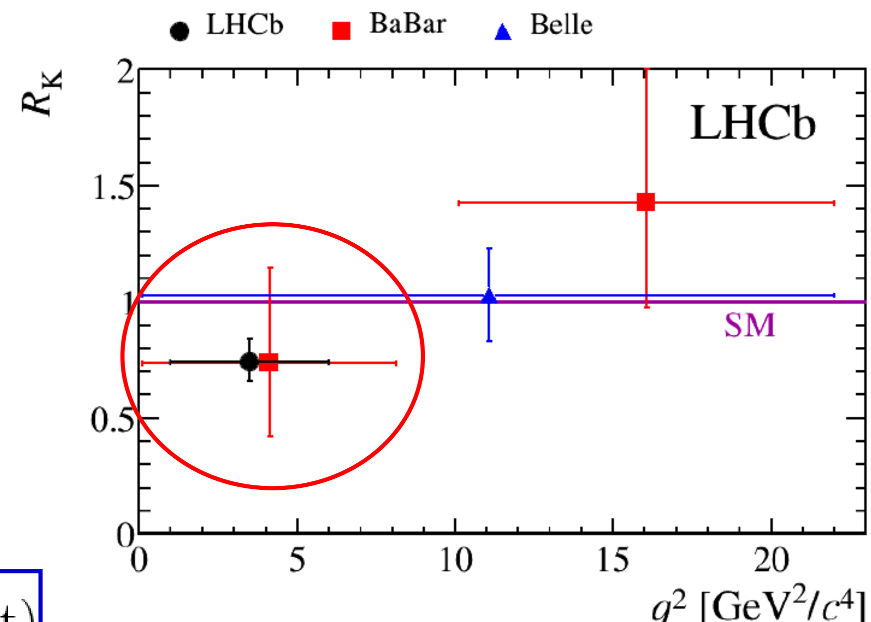
Rare decays

- **R_K :** in the SM all leptons are expected to behave in the same way.

For instance,

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1.000 + O(m_\mu^2/m_b^2) \text{ (SM)}$$





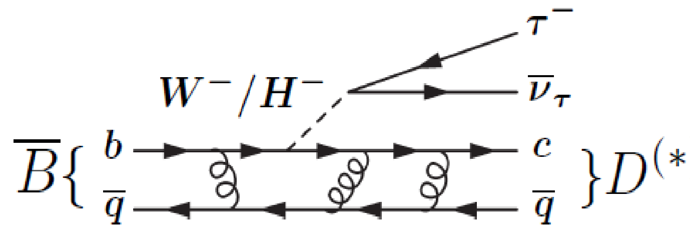
$$\boxed{R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})}$$

New Z' bosons??

$\rightarrow$ Consistent (but lower) than the SM at **2.6σ**

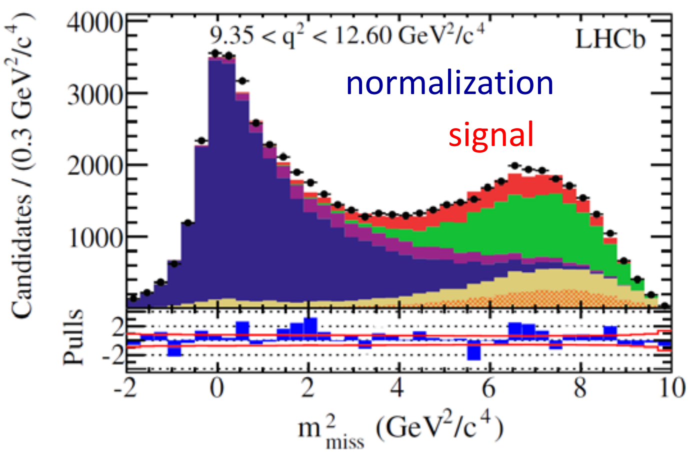
[PRL 113 (2014) 151601]

Rare decays

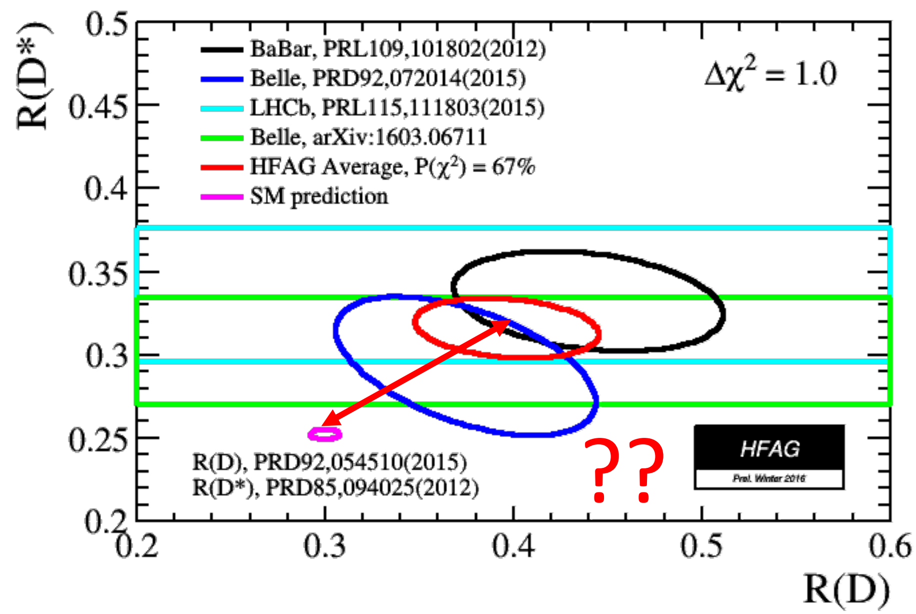


- **R_{D*}**: Other test with leptons, theory precise (V_{cb} and form factors cancel)

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$



$m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$



$$\boxed{\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})}$$

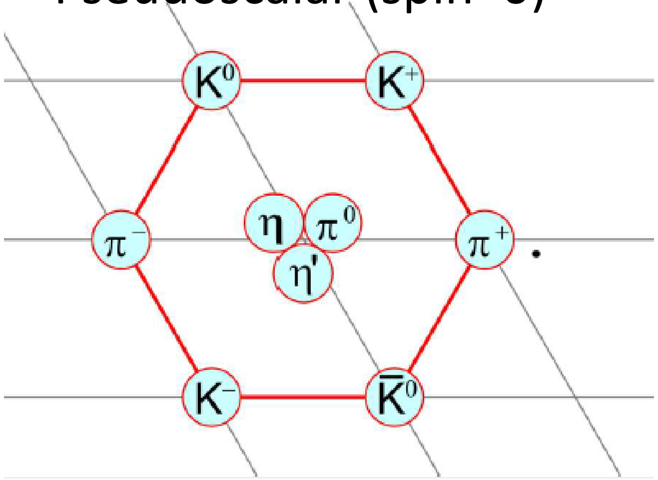
[PRL 115 (2015) 111803]

The Quark Model

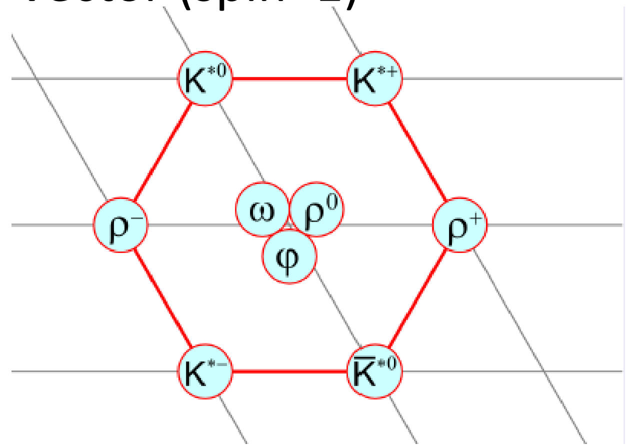
Pentaquarks

Meson multiplets:

Pseudoscalar (spin=0)

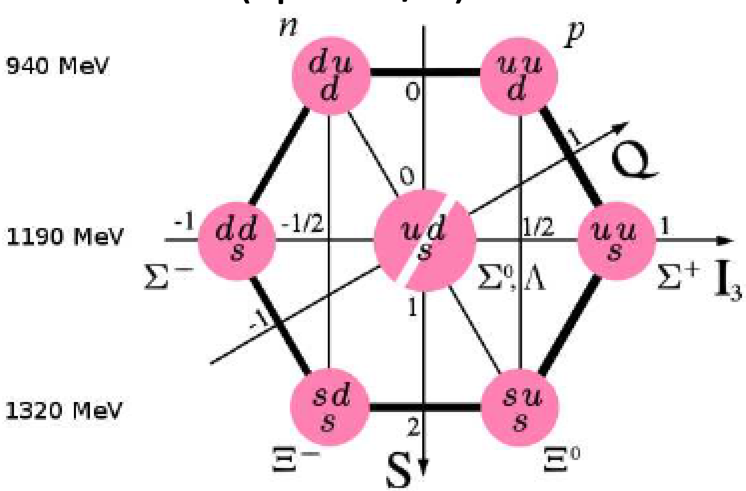


Vector (spin=1)

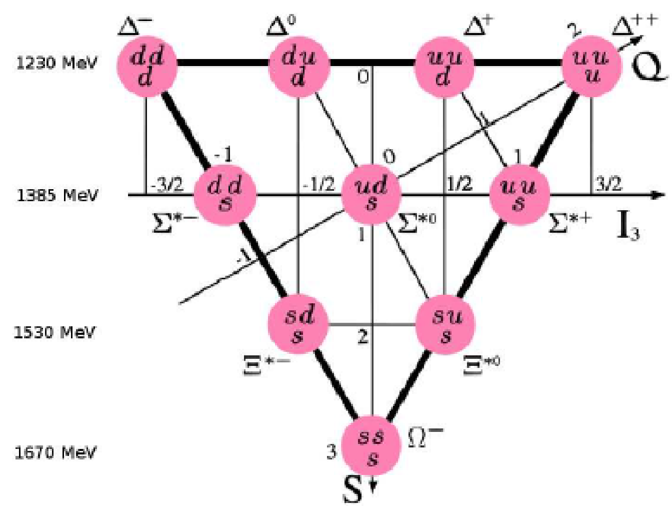


Baryon multiplets:

Octet (spin=1/2)

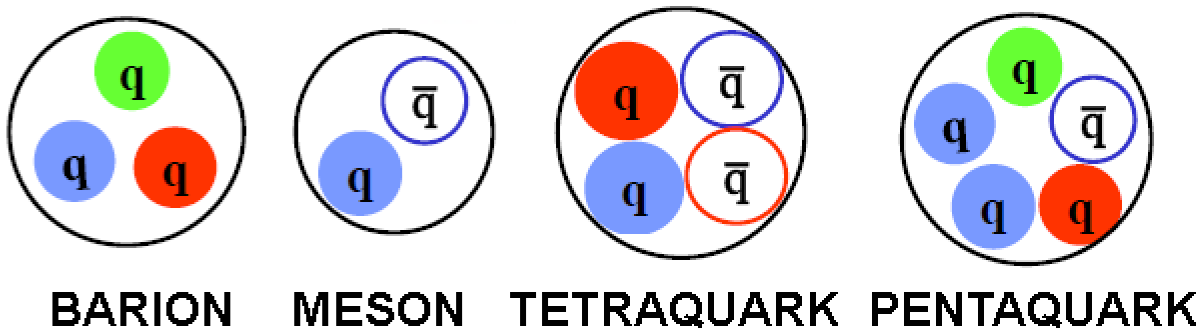


Decuplet (spin=3/2)



Pentaquarks

• There are several possibilities for combining quarks with color into colorless hadrons, as predicted from the origin of the Quark Model [M. Gell-Mann, PL8 (1964) 214]

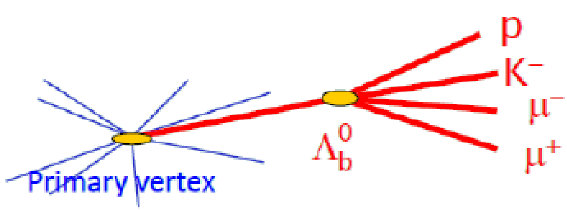


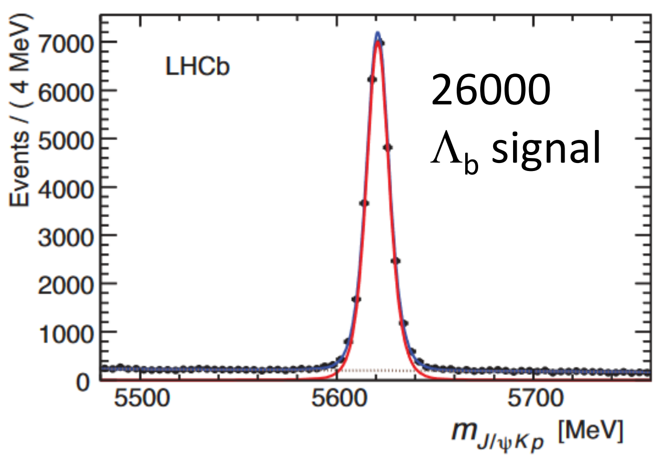
$qq\bar{q}\bar{q}$ and $qqqq\bar{q}$ states predicted

Several of these states have been announced since 1970, but have disappeared with time and new data analysis…

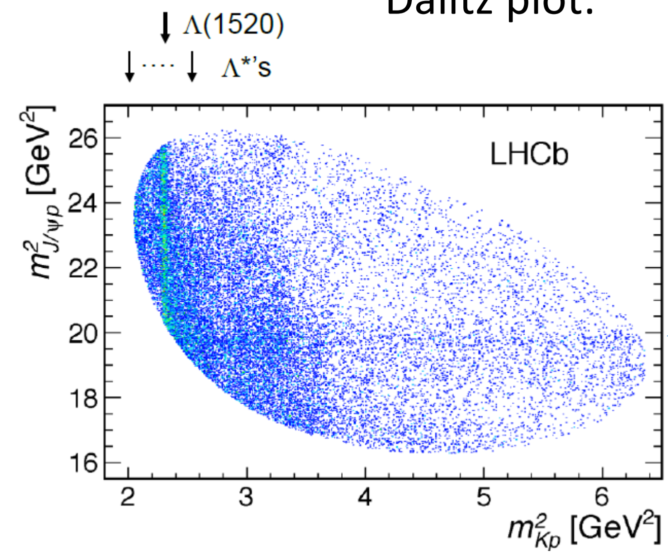
Pentaquarks

$\Lambda_b \to J/\psi\ p\ K$ observed for first time at LHCb: very clear signal

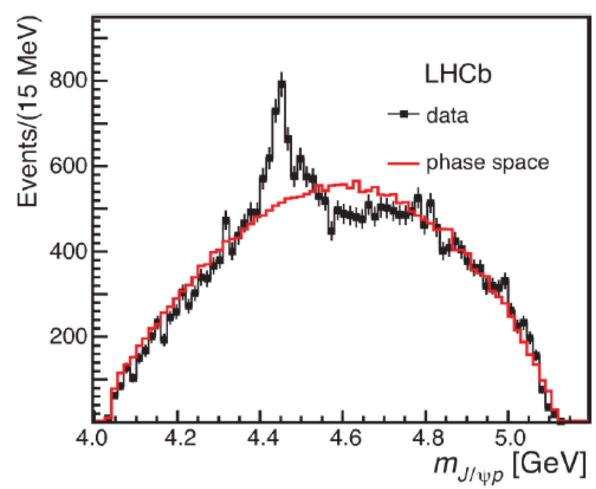




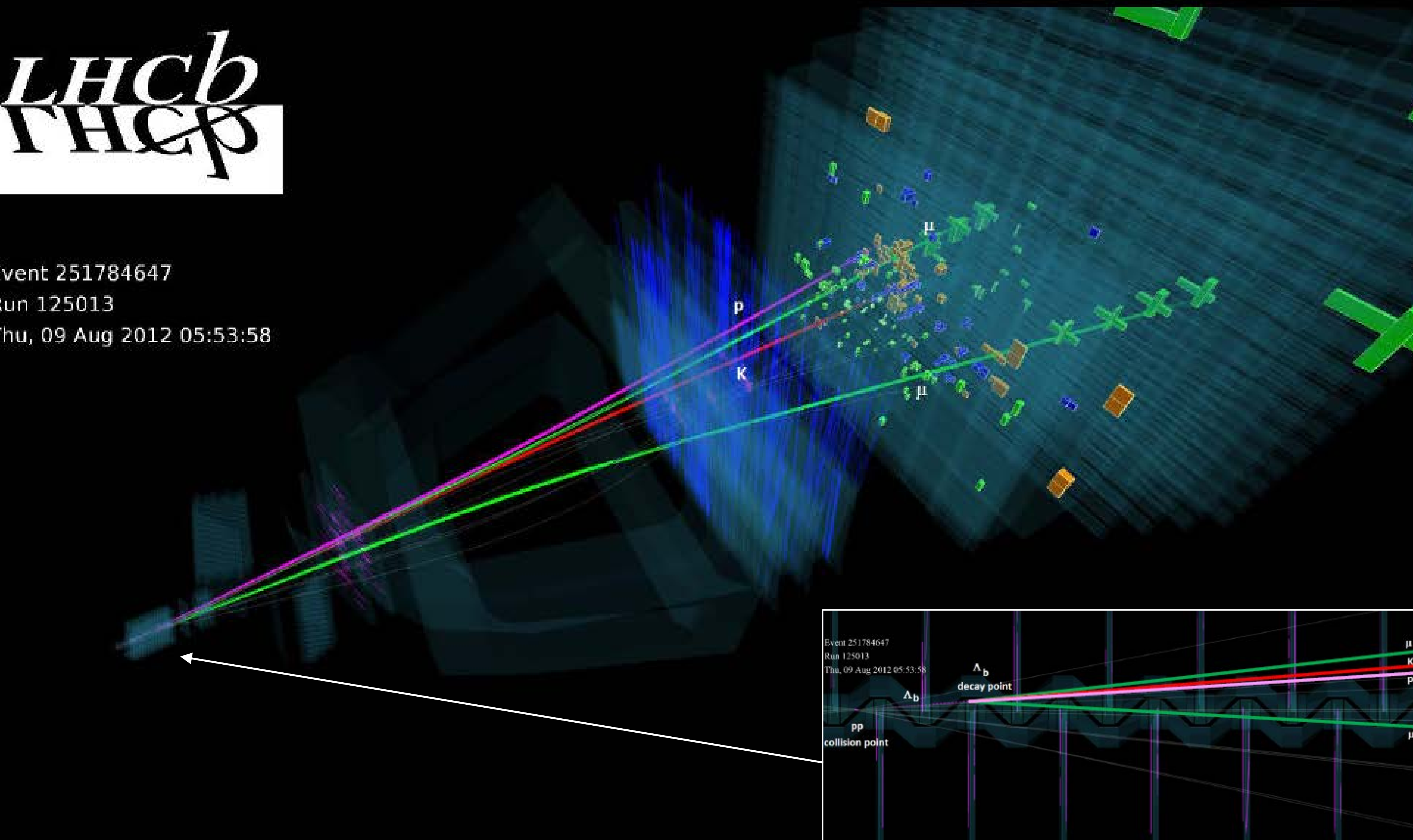
Dalitz plot:



?

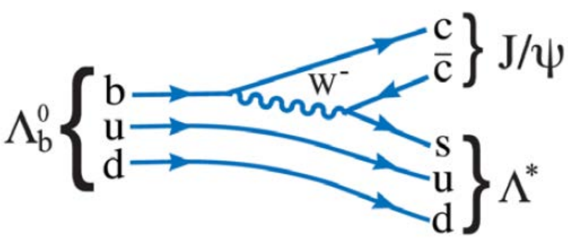


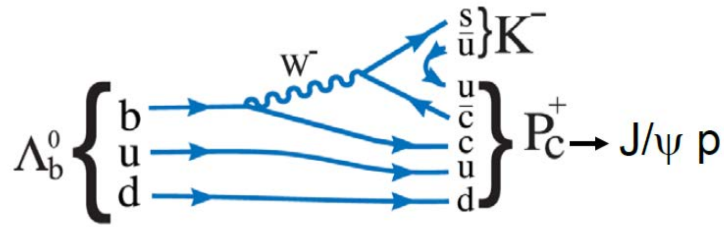
$\Lambda_b^0 \rightarrow J/\psi\ p\ K^-$ candidate



Pentaquarks

Considering a pentaquark P_c^+, and two interfering processes:

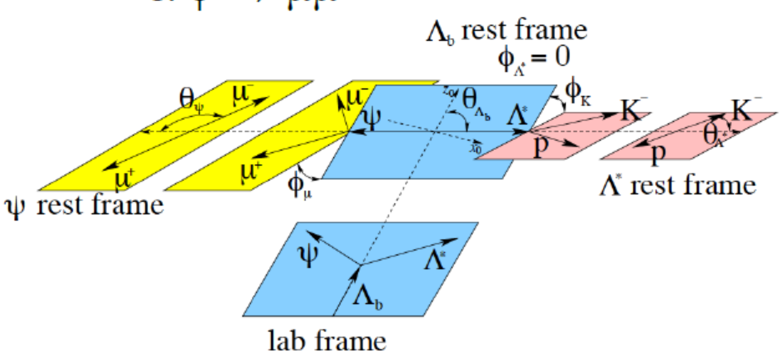




$\Lambda_b^0 \rightarrow J/\psi\ \Lambda^*$

$\Lambda^* \rightarrow p\ K^-$

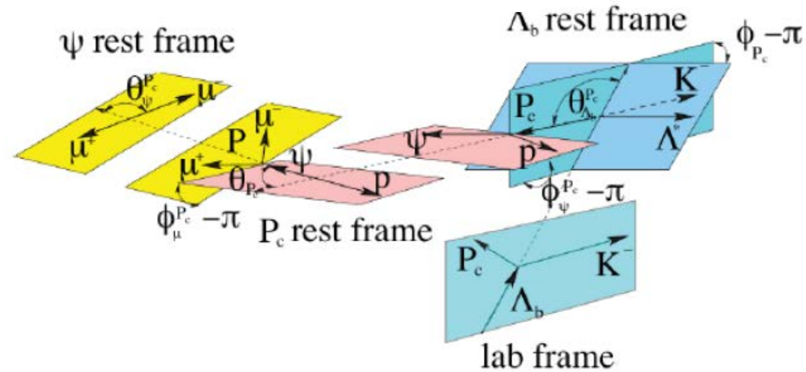
$J/\psi \rightarrow \mu\mu$



$\Lambda_b^0 \rightarrow P_C^+\ K^-$

$P_C^+ \rightarrow J/\psi\ p$

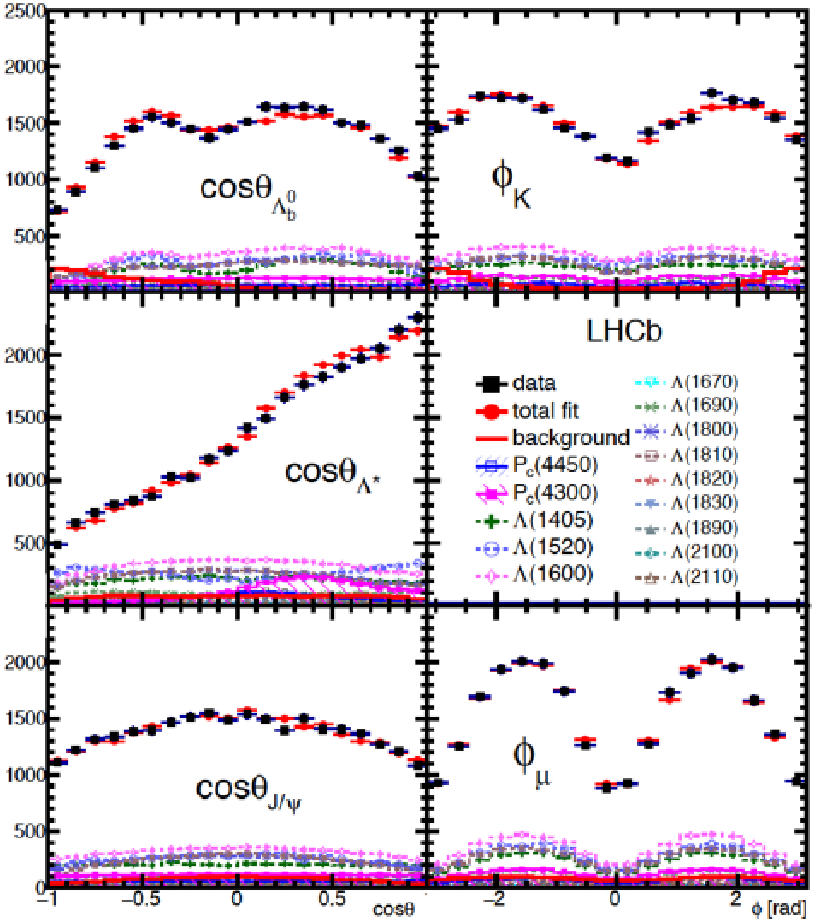
$J/\psi \rightarrow \mu\mu$



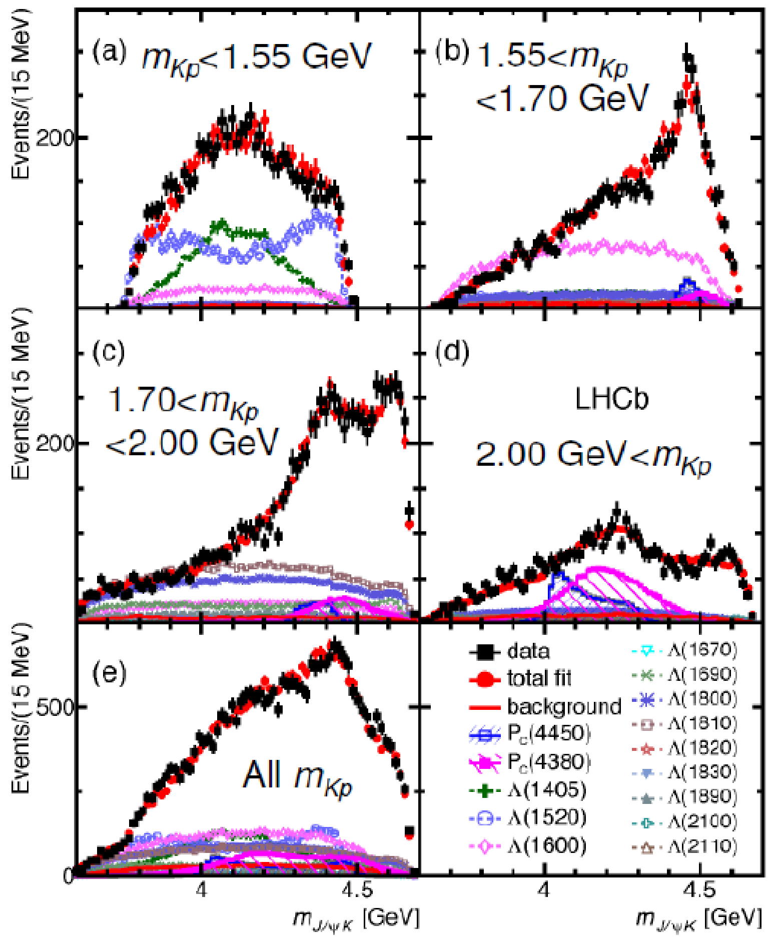
5 angles: fit $\theta_{\Lambda b}$, ϕ_K, $\theta_{J/\psi}$, $\theta_{\Lambda*}$, ϕ_μ distributions

Pentaquarks

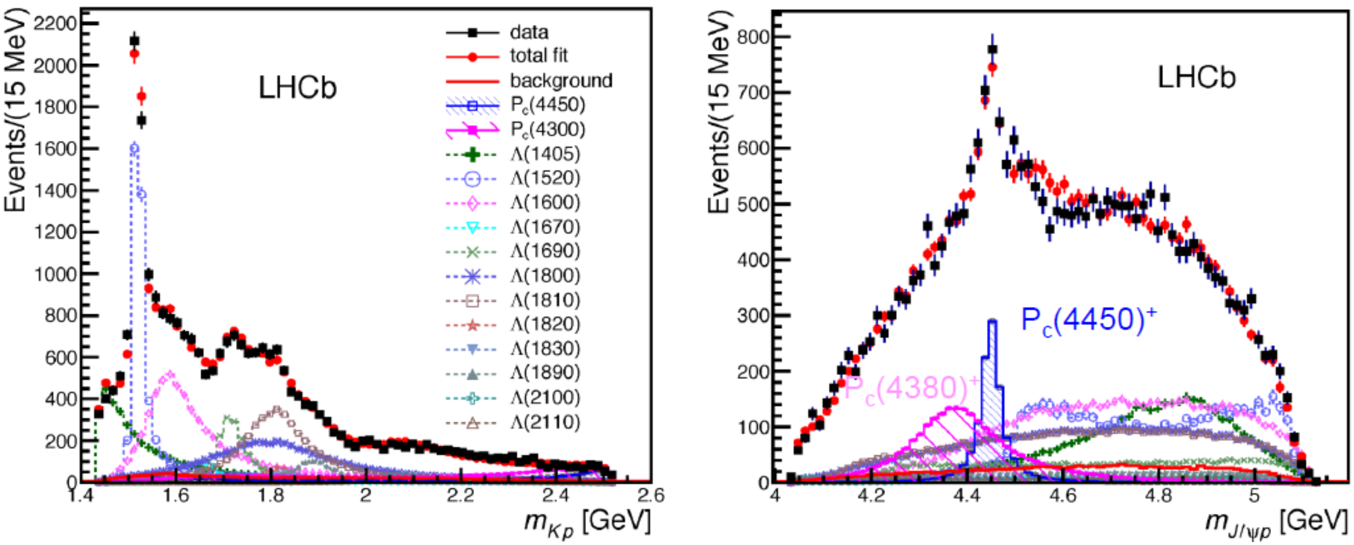
Angular analysis:



Fit in different Λ^* regions:



Pentaquarks



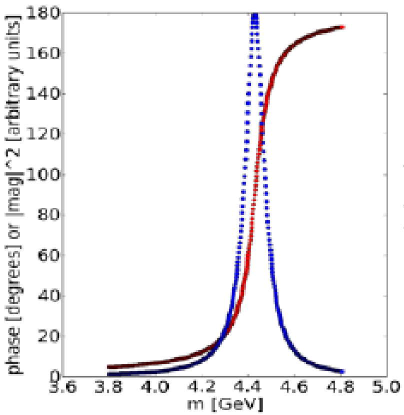
PRL 115, 072001

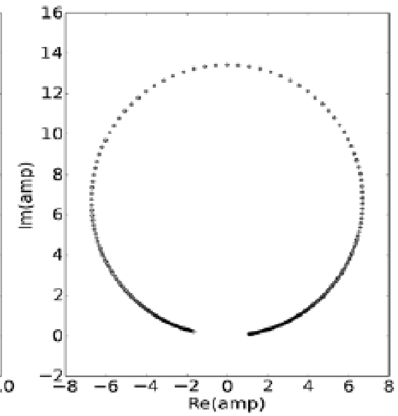
State	Mass (MeV)	Width (MeV)	J^P
$P_c(4380)+$	4380 ± 8 ± 29	205 ± 18 ± 86	$3/2^-$
$P_c(4450)+$	4449.8 ± 1.7 ± 2.5	39 ± 5 ± 19	$5/2^+$

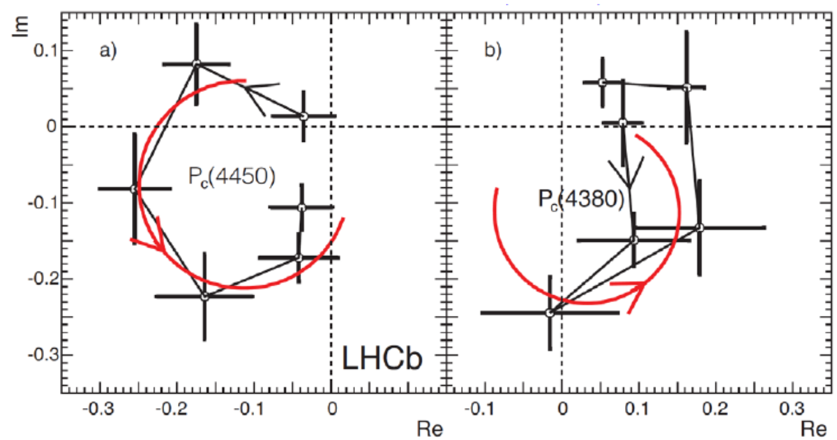
Pentaquarks

Is it a resonance? (change phase over the mass distribution?)

Argand diagram



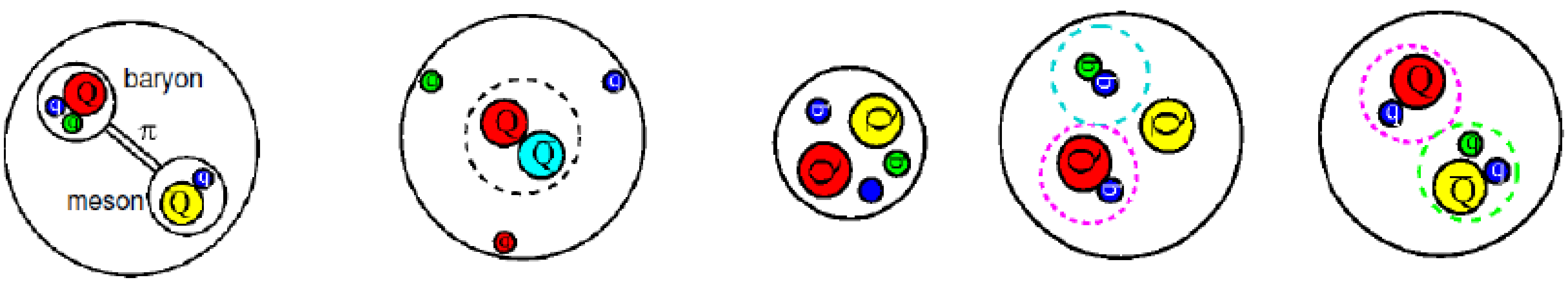




Yes !

?

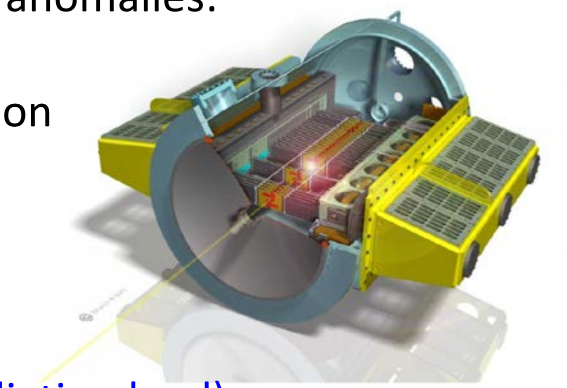
250 citations!, many models trying to explain it:



Future plans

The LHCb Upgrade:

- At present we did not find evidence for New Phyiscs, but a few anomalies:
  Standard Model deviations are expected to be small
- Most of the measurements are limited by the statisticall precision



- Increase the luminosity from $4x10^{32}$ up to $2\times10^{33} cm^{-2}s^{-1}$
- Fully flexible & efficient software trigger up to 40 MHz input
- Record 20 –100 kHz data
- Upgrade VELO and Tracker (adapt to higher occupancy and radiation load)

	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Remember that we have 10^{11} $b\bar{b}$ pairs/fb !

(At Belle II: 10^9 $B\bar{B}$ pairs/ab)

Future plans

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \rightarrow \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B \rightarrow \tau\nu$, $D\tau\mu$,
- $B \rightarrow K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

On-going

Belle II