B physics
(summary)

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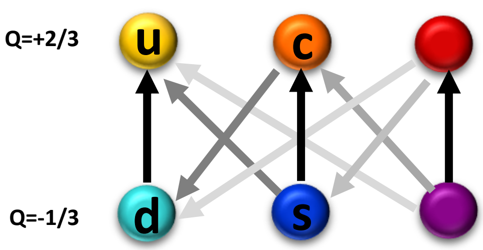
Outline

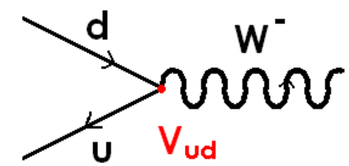
- Introduction
- The beauty experiments
- Rare B decays
- Semileptonic B decays
- CKM and CP Violation
- Spectroscopy
- The future

Introduction

- In the Standard Model of Particle Physics, transitions between different quarks are governed by the CKM mechanism:

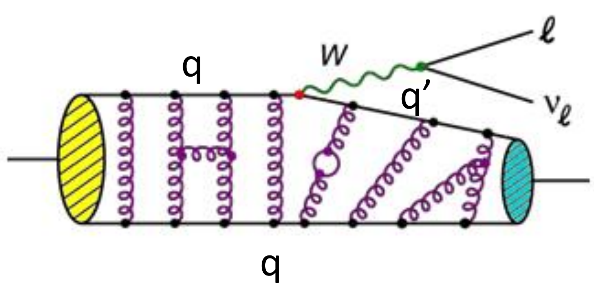


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$



- The amplitude of a hadron decay process can be described using Effective Field Theories: Operator Product Expansion (OPE)

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$



CKM couplings

Wilson Coefficients (μ = scale)

Hadronic Matrix Elements

Introduction

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

CKM couplings

Wilson Coefficients (μ = scale)

Hadronic Matrix Elements

$\rightarrow$ OPE: a series of effective vertices multiplied by effective coupling constants C_i.

Electroweak scale ~ $1/M_W$

New Physics scale ~ $1/\mathbf{M}_{NP}$

$C_i = C_i^{SM} + C_i^{NP}$

$C'_i = C'^{SM}_i + C'^{NP}_i$

Primed $C'_i \rightarrow$ right handed currents: suppressed in SM

Why B decays?

- The b-quark is the heaviest quark forming hadronic bound states (m~4.7 GeV)
- Must decay outside the 3rd family
  - $\rightarrow$ Long lifetime (~1.6 ps)
  - $\rightarrow$ Many accessible decay channels (small BR's)

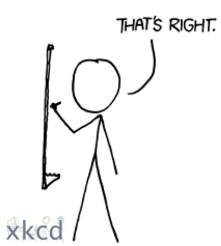
Good for experimentalists!

- Type of processes:


Dominant: $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed)

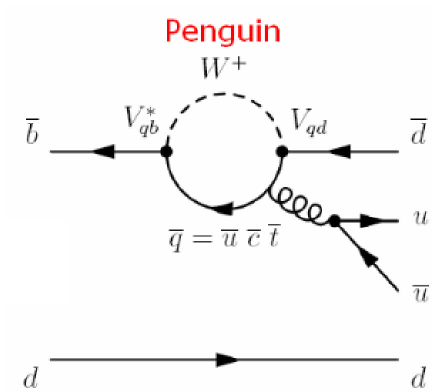

Rare: Flavour Changing Neutral Current (FCNC): $b \rightarrow s,d$


Flavour oscillations and CP violation



Ideal place to probe New Physics effects!

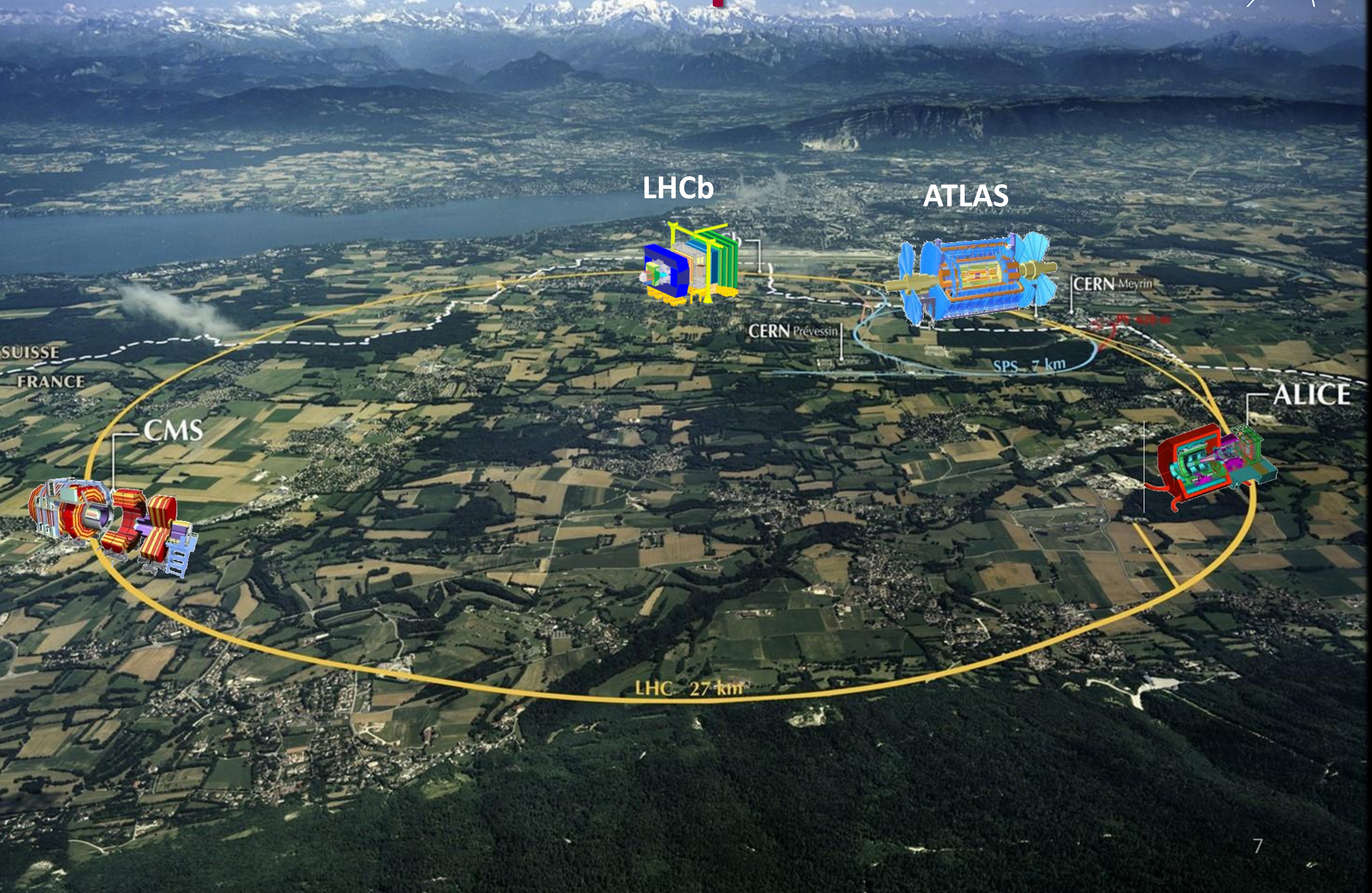
Good for theorists!



The beauty experiments

GOLDEN EAGLE
(*Aquila Chrysaetos*)
2 m wingspan
4-7 kg weight

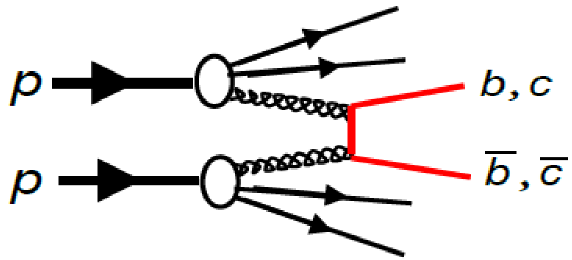
The LHC experiments

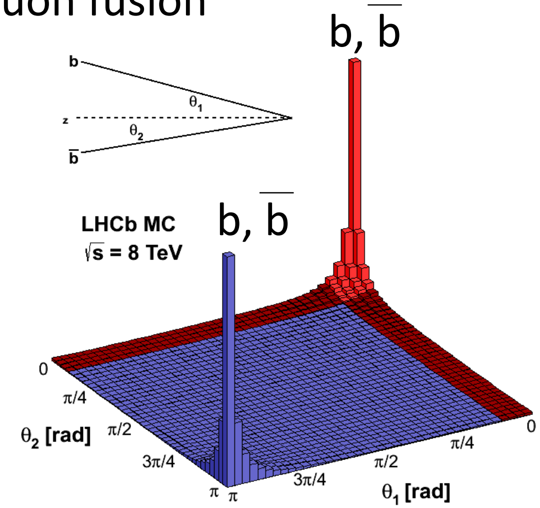


The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  ~ 300 μb @ √s=7 TeV
  ~ 600 μb @ √s=13 TeV

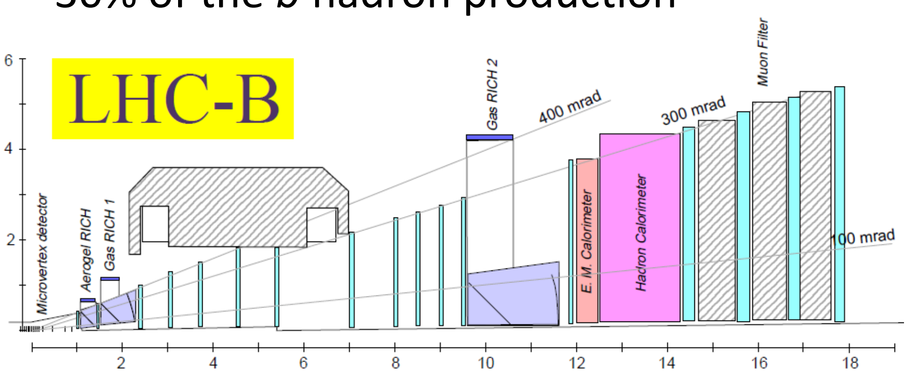
  [PRL 118 (2017) 052002]
  [JHEP 02 (2021) 023]



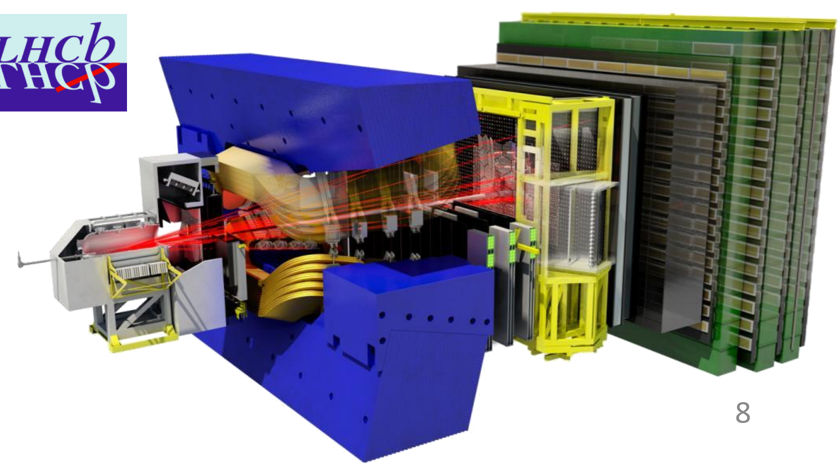


The b quarks hadronize in B, B_s, $B^*_{(s)}$, b-baryons…
→ average B meson momentum ~ 80 GeV

- The LHCb idea: to build a single-arm forward spectrometer:
  ~ 4% of the solid angle ($2 < \eta < 5$),
  ~30% of the b hadron production



Letter of Intent, 1995



The LHC experiments

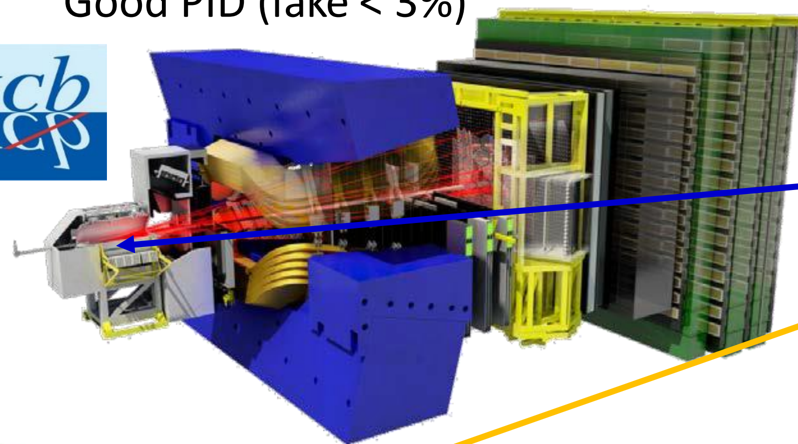
LHCb,
ATLAS & CMS

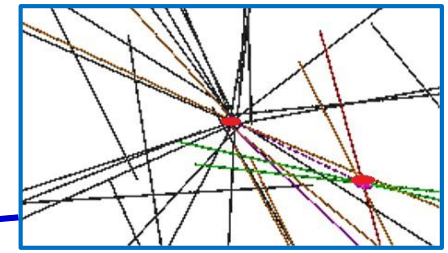
$2<\eta<5$

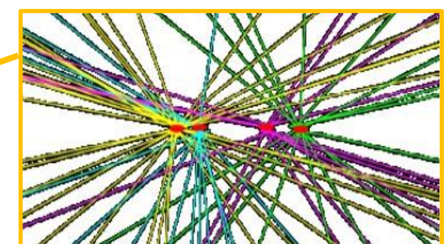
$\sigma_P \sim 0.5\text{-}1\%$

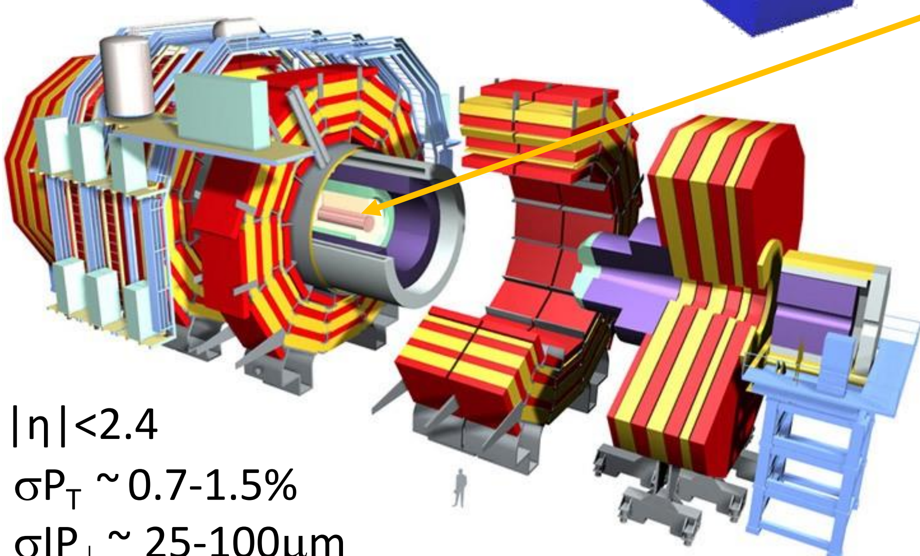
$\sigma IP_\perp \sim 15\text{-}50\ \mu m$

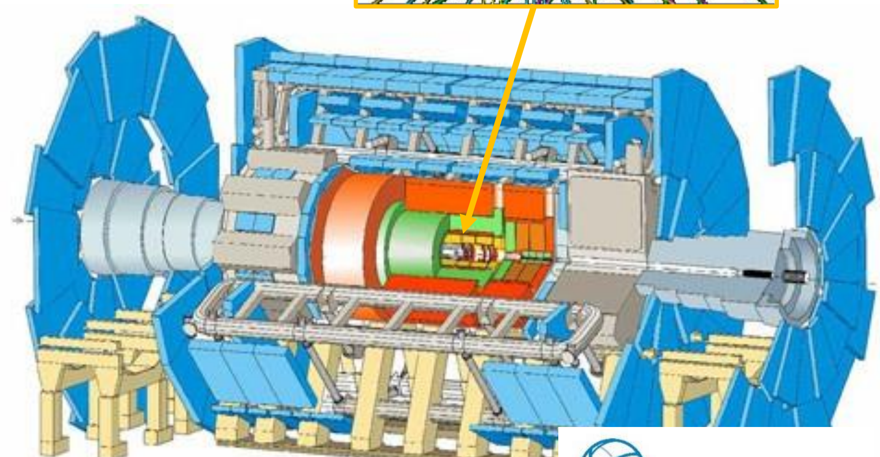
Good PID (fake < 3%)











$|\eta|<2.4$

$\sigma P_T \sim 0.7\text{-}1.5\%$

$\sigma IP_\perp \sim 25\text{-}100\mu m$

Very good PID (fake < 0.1%)

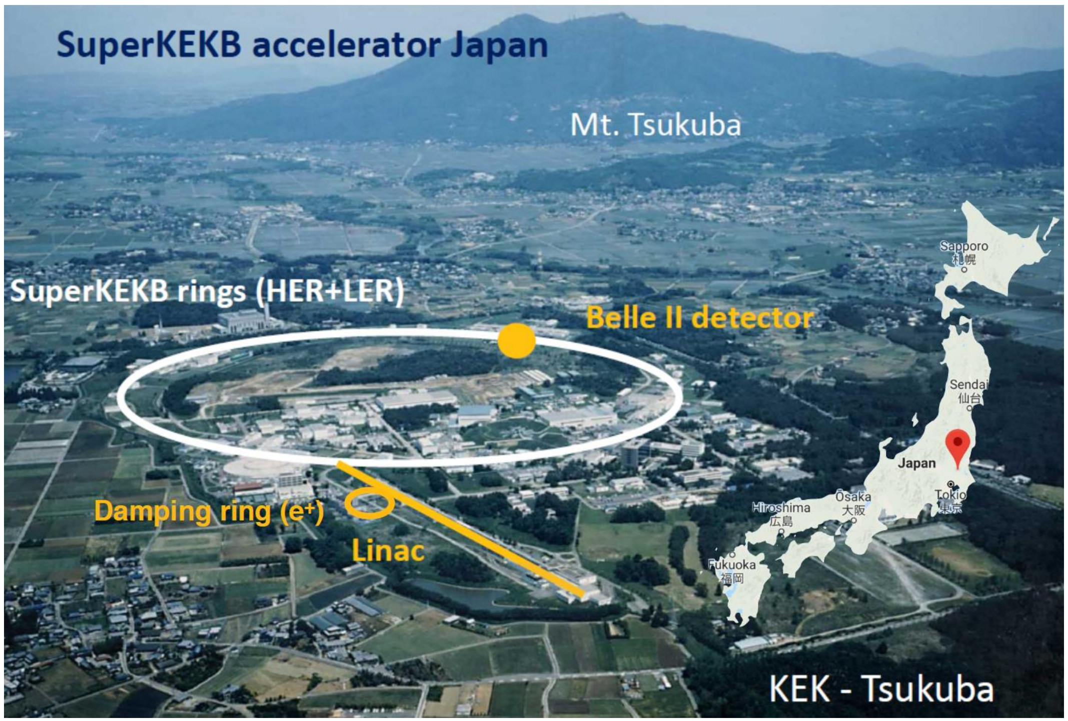
$|\eta|<2.5$

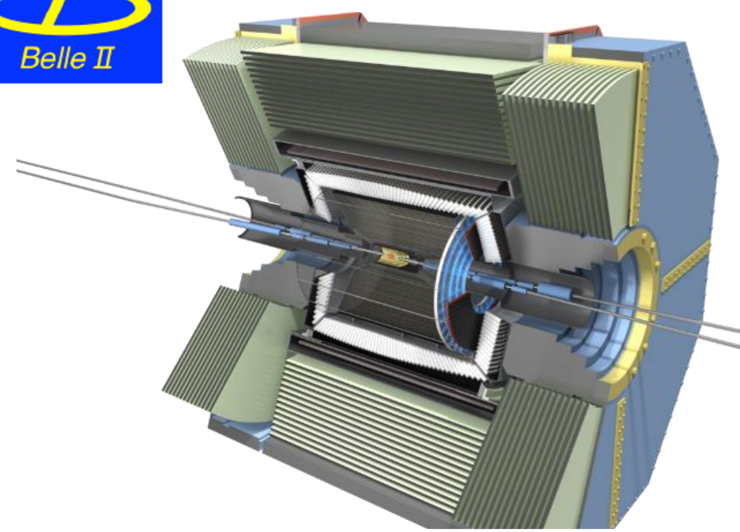
$\sigma P_T \sim 1.3\text{-}3.8\%$

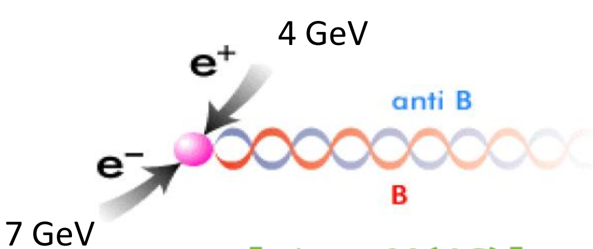
$\sigma IP_\perp \sim 25\text{-}100\mu m$

The Belle-II experiment

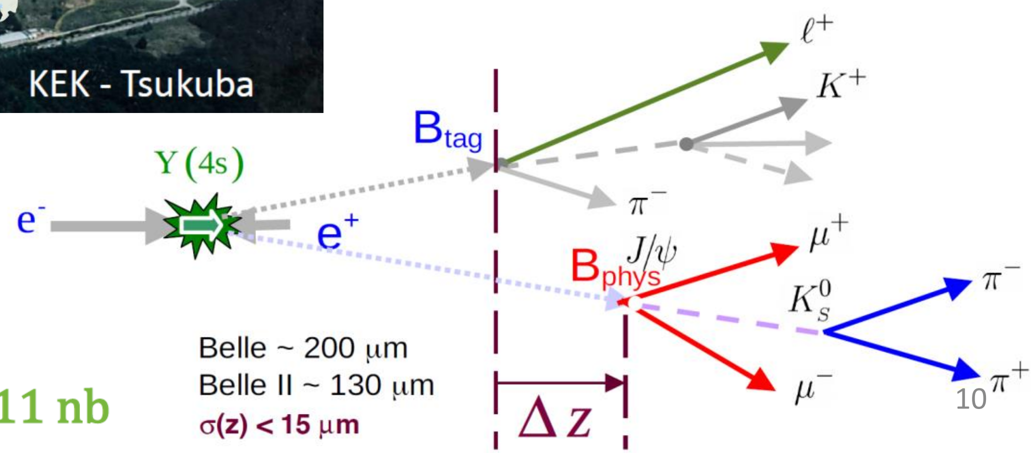
- Upgrade of the KEK e^+e^- asymmetric accelerator and the Belle experiment, working at the $\Upsilon(4S)$ (10.54 GeV)







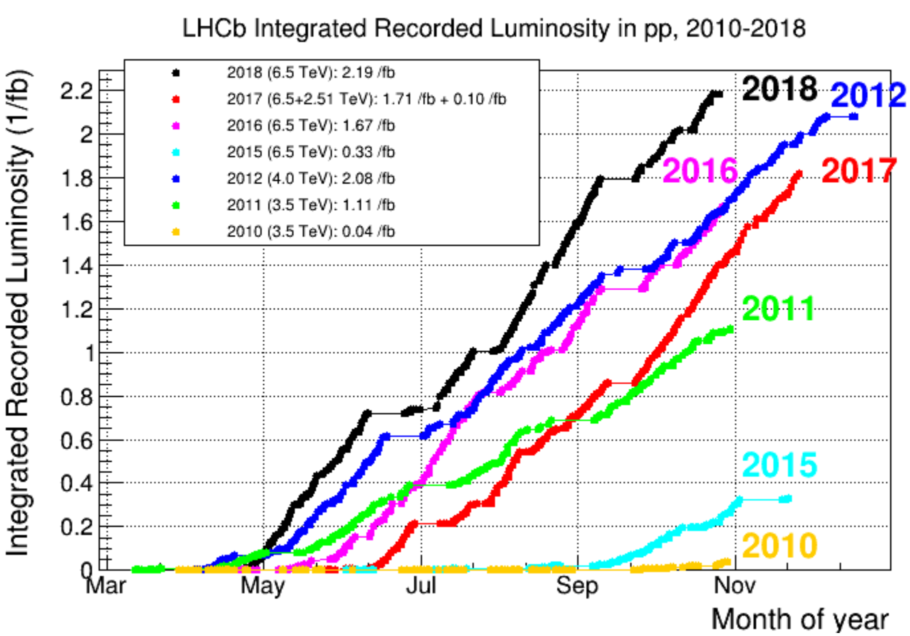
$\sigma\,[e^+e^- \to \Upsilon(4S)] = 1.11$ nb

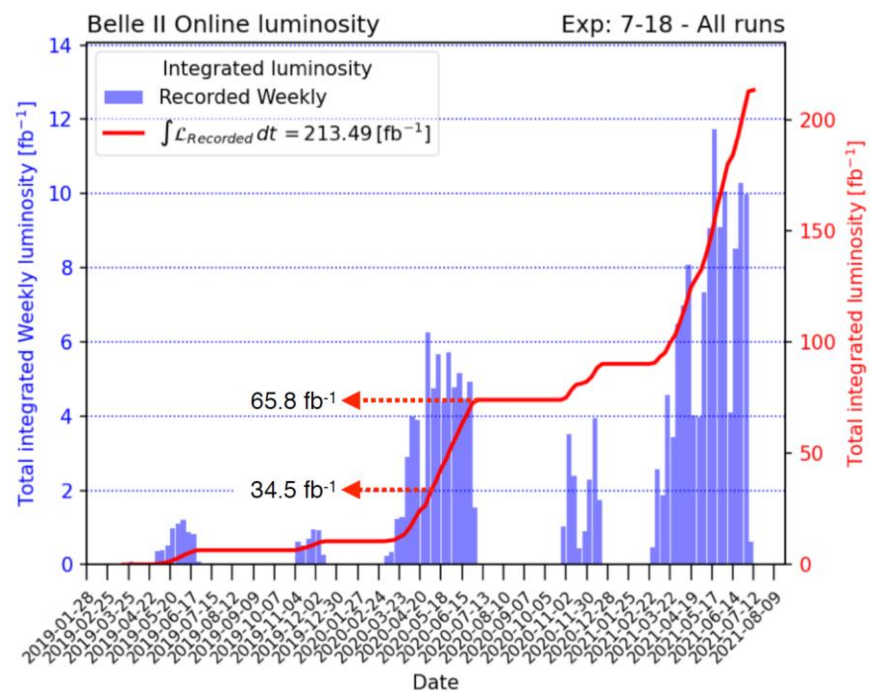


The experimental data

3 (Run1) + 6 (Run2) fb^{-1}
(2011 - 2018)

213 fb^{-1}
(2019 - 2021)



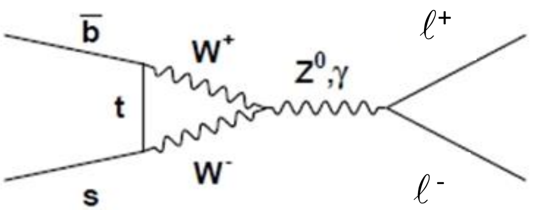


Rare B decays

Rare B decays

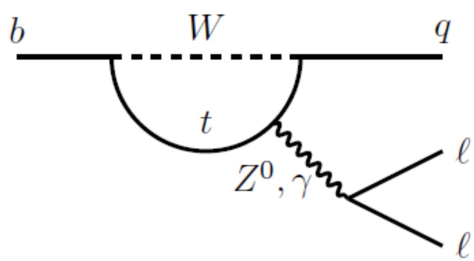
- $b \to s,d$ quark transitions are Flavor Changing Neutral Currents (FCNCs),
  $\to$ in the SM they only can occur through loops (*penguin and box diagrams*), excellent probe for physics beyond the SM

leptonic



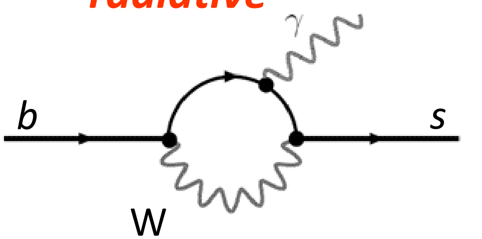
BR ~ 10^{-9}

semileptonic



BR ~ 10^{-7}

radiative



BR ~ 10^{-5}

Experimentally $\to$ leptons/photons with high transverse momenta

Theoretically $\to$ observables can be calculated in terms of Wilson coefficients

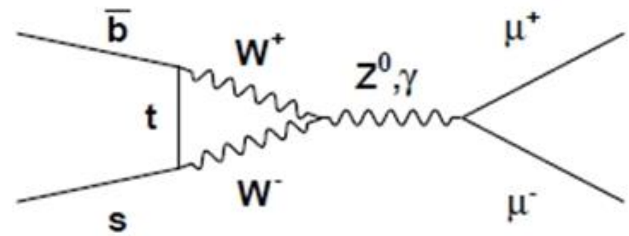
Ex: $\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2$

Hadronic uncertainties in decay constants or form factors

Rare B decays: $B_s \to \mu^+\mu^-$

NEW '21

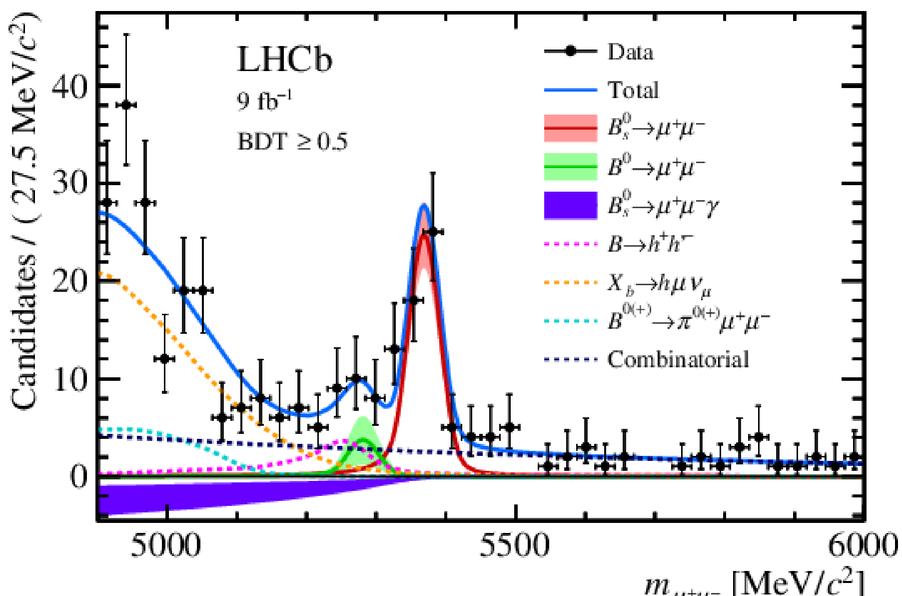
- Very rare decay: FCNC and helicity suppressed
  BR_{SM} = 3.66(14) x 10^{-9}

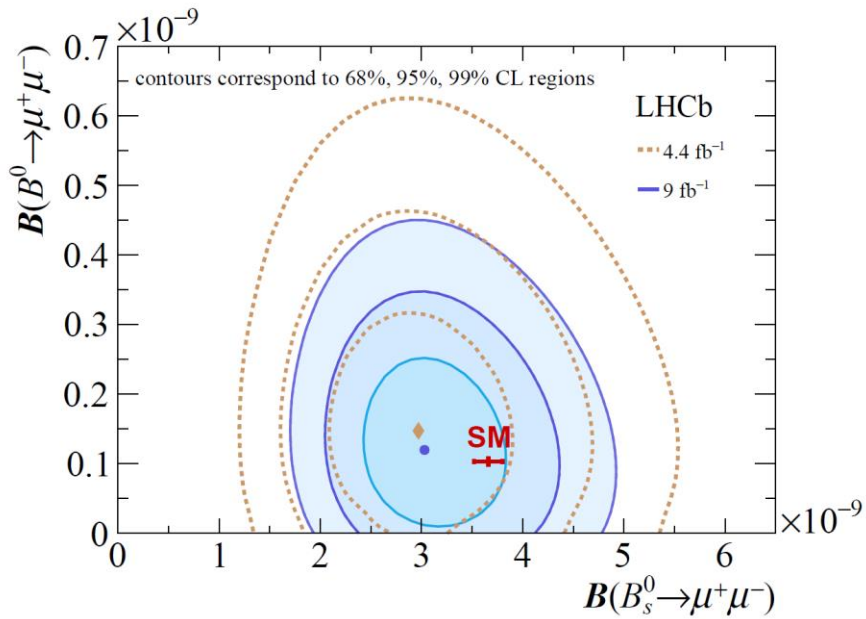


- Searched for over the last 30 years,
  observed by LHCb and CMS [Nature 522 (2015) 68]

- New results by LHCb (Run1+Run2 = 9fb^{-1}):

[arXiv:2108.09283 and 2108.09284v2 [hep-ex]]





$$\boxed{\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}}$$

$$\boxed{\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}}$$

$$\boxed{\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}}$$

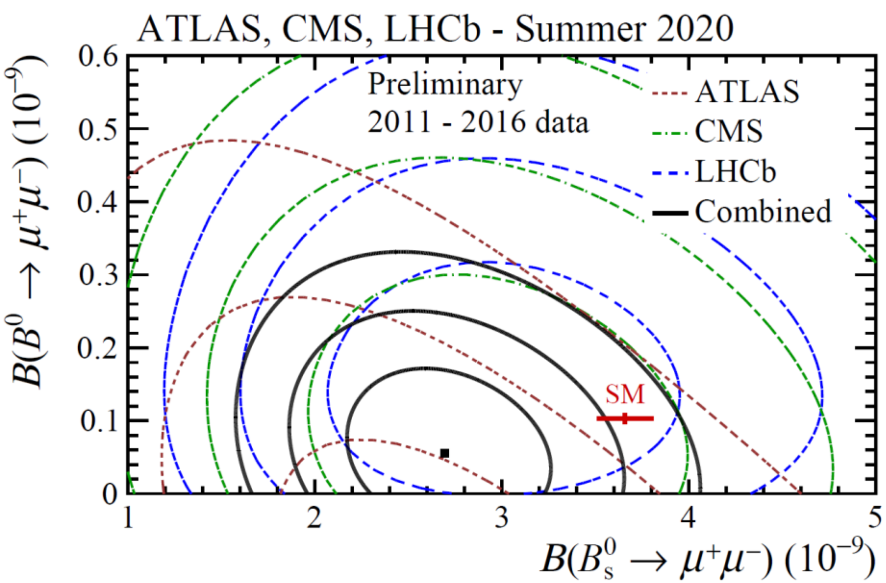
Rare B decays: $B_s \to \mu^+\mu^-$

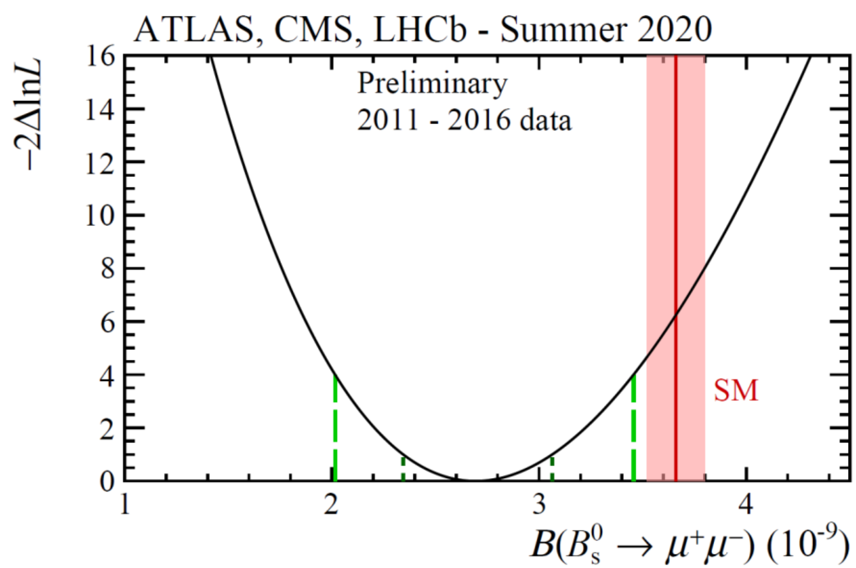
- Also measured by ATLAS and CMS (2011-2016 data), combined result*:

[CMS PAS BPH-20-003]

ATLAS [JHEP04(2019)098]
CMS [JHEP04(2020)188]
LHCb [PRL118(2017)191801]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.69\,^{+0.37}_{-0.35}\right) \times 10^{-9}$$ *



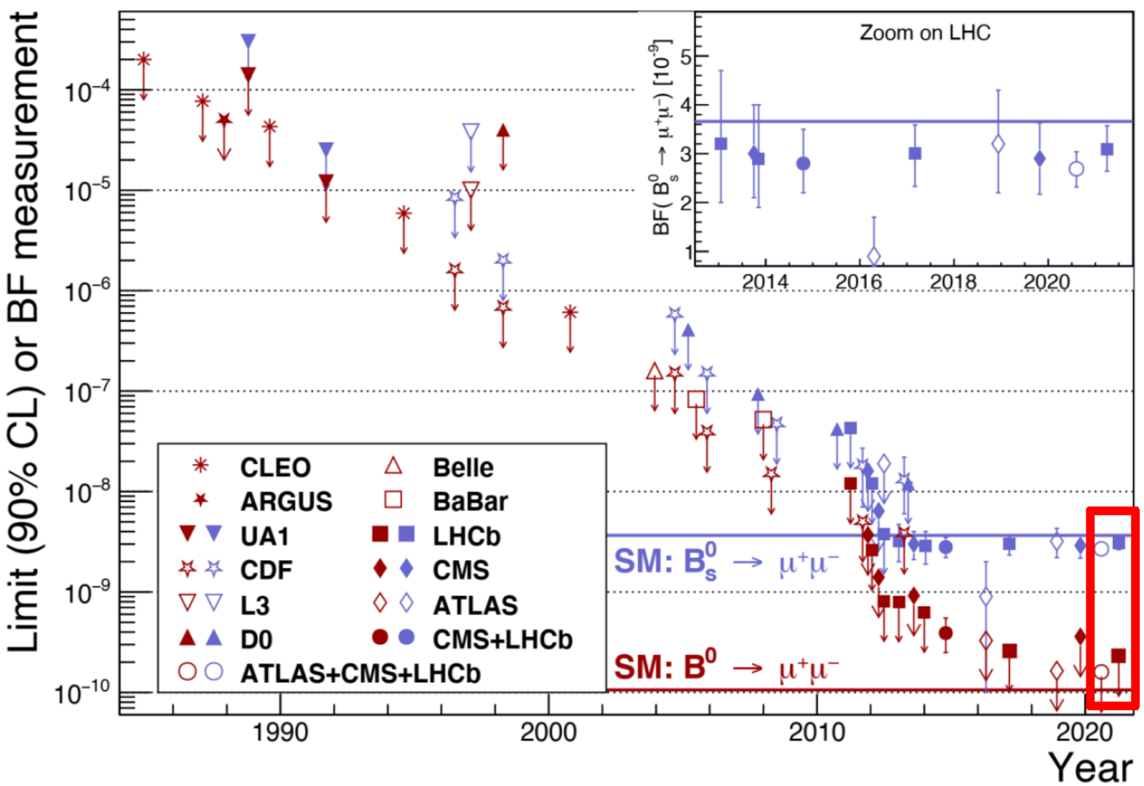


Below, but compatible with the SM at 2.1σ

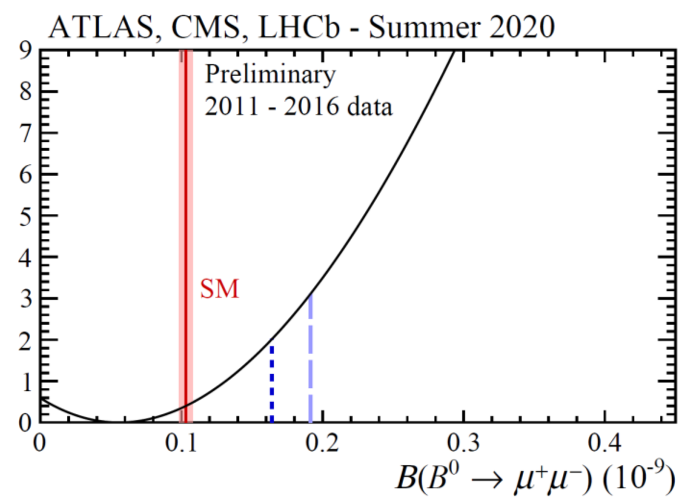
* Result from LHCb with partial statistics

Rare B decays: $B_d \to \mu^+\mu^-$

- Even more rare! ($BR_{SM} \sim 10^{-10}$), still not observed:



[CMS PAS BPH-20-003]



ATLAS [JHEP04(2019)098]
CMS [JHEP04(2020)188]
LHCb [PRL118(2017)191801]

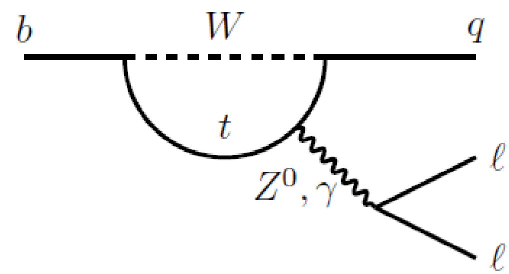
$$\boxed{\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}}$$ *

* Result from LHCb with partial statistics

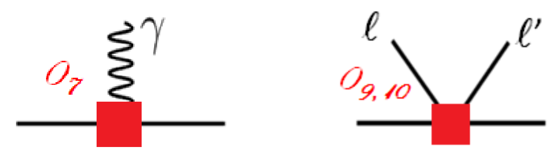
Rare B decays: $B_s \to \phi\mu^+\mu^-$

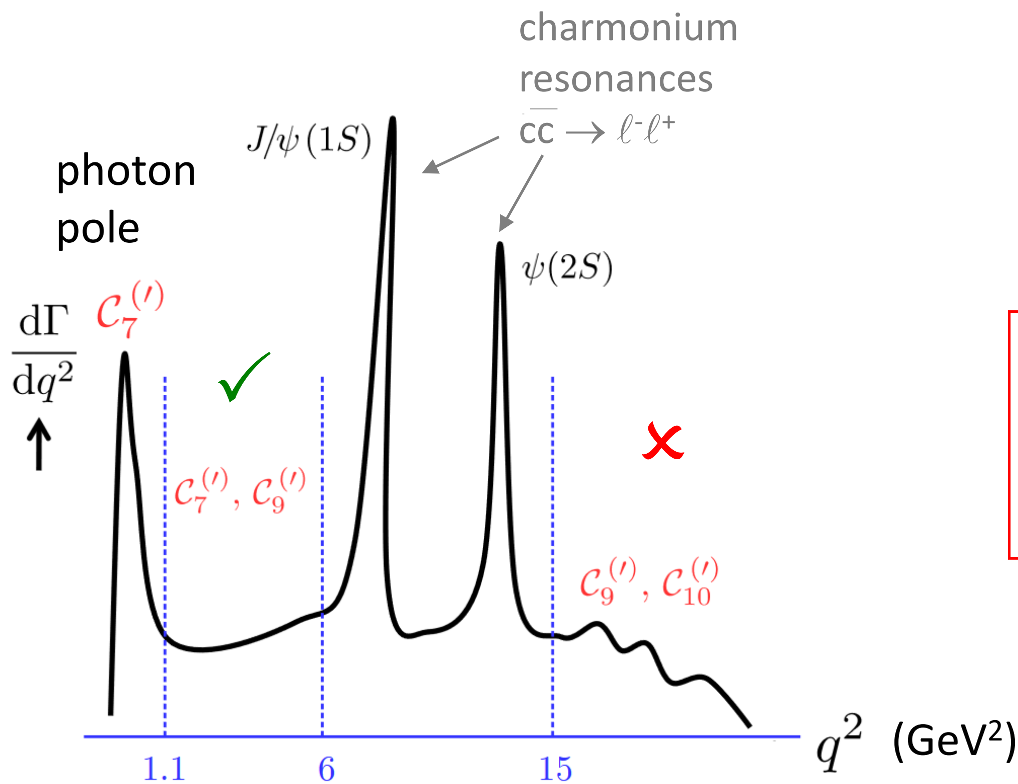
- Differential decay width: $d\Gamma/dq^2$

Each q^2 region probes different processes



$q^2 = (p_{\ell^+} + p_{\ell^-})^2$





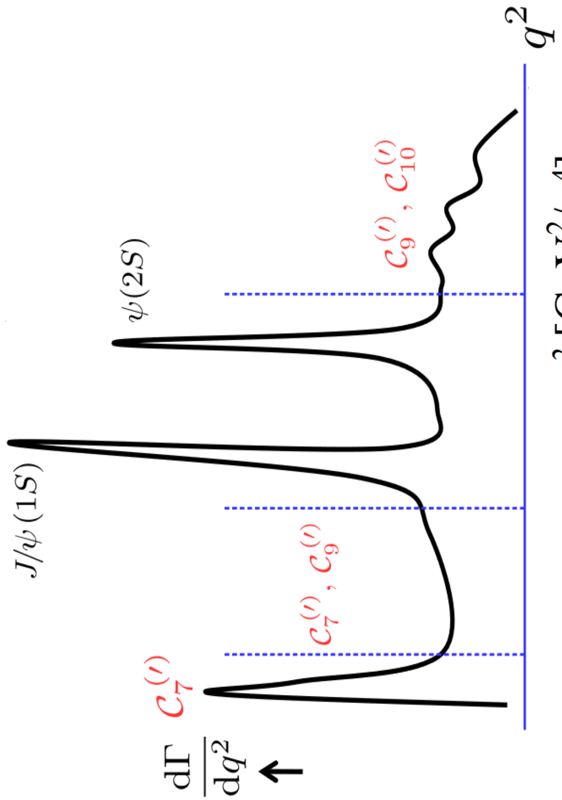
SM values (μ=m_b): C_7 ~ - 0.33
C_9 ~ 4.27
C_{10} ~ - 4.17

(Everything else small or negligible)

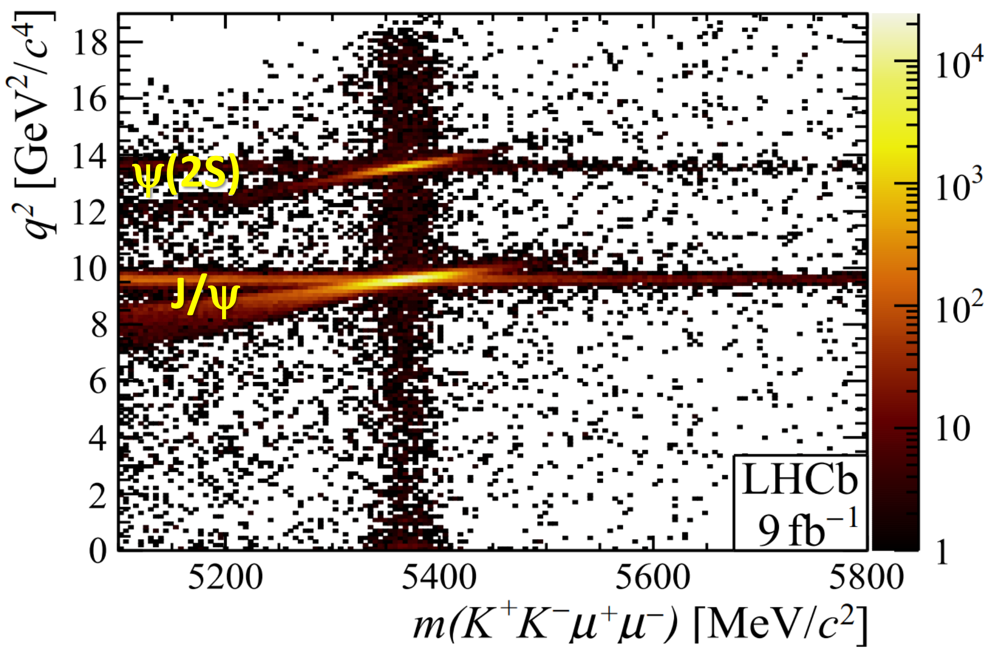
$C_i = C_i^{SM} + C_i^{NP}$

(Primed $C'_i \to$ right handed currents: suppressed in SM)

Rare B decays: $B_s \to \phi\mu^+\mu^-$

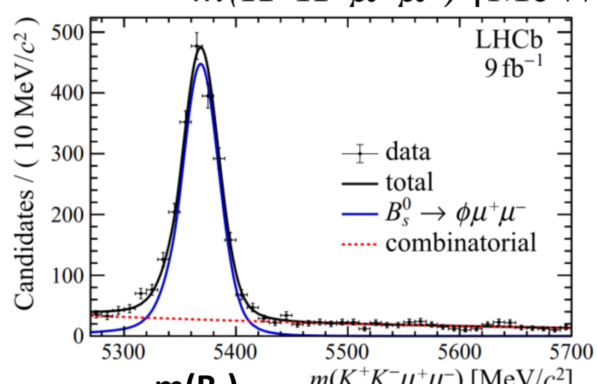


B_s mass vesus q^2 for $B_s \to \phi\mu^+\mu^-$



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

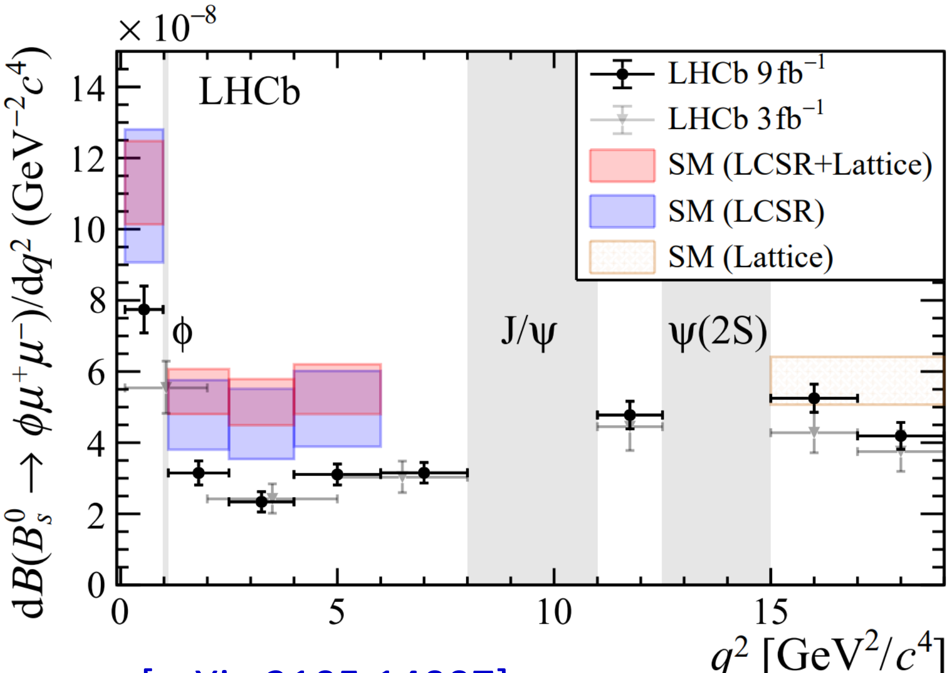
[arXiv:2105.14007]



m(B_s)

Rare B decays: $B_s \rightarrow \phi\mu^+\mu^-$

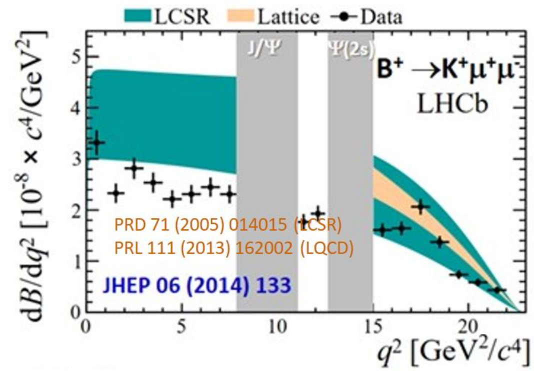
NEW '21

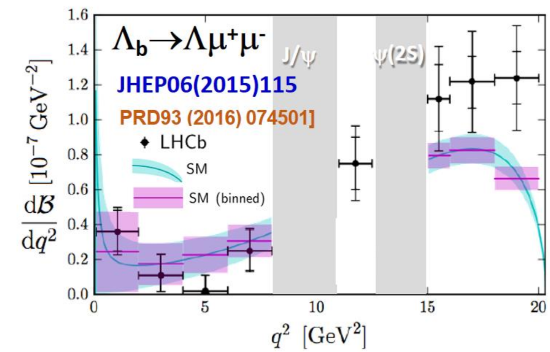


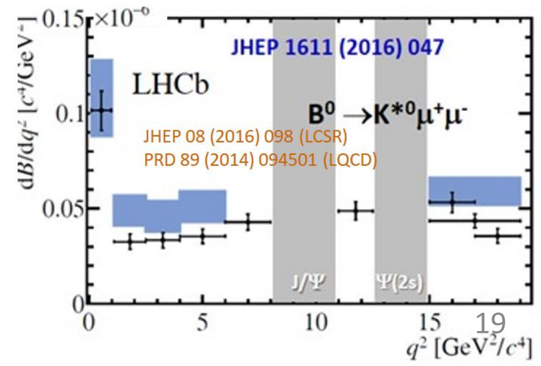
[arXiv:2105.14007]

In the q^2 region 1.1-6 GeV^2 →
3.6σ away from SM predictions

Results in other channels:



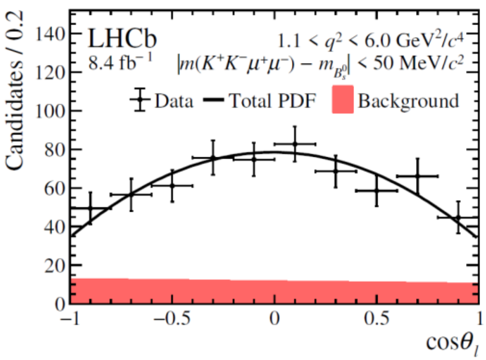


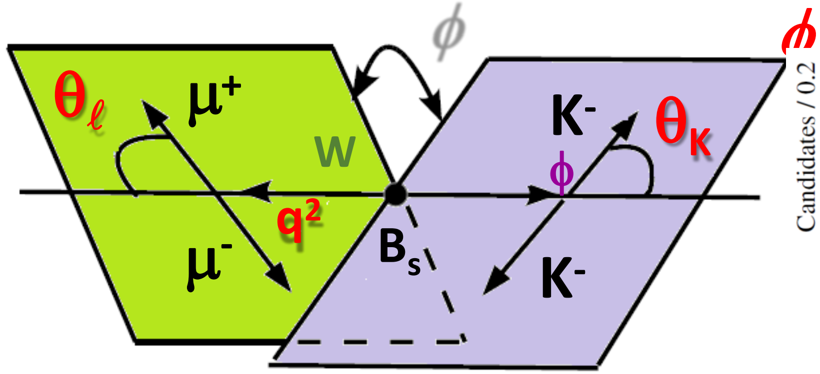


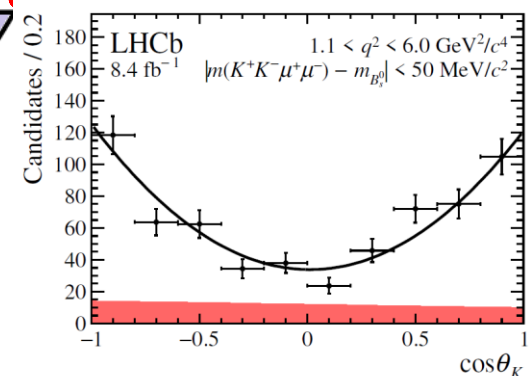
Rare B decays: $B_s \to \phi\mu^+\mu^-$

- Angular distribution in $B_s \to \phi \ell^- \ell^+$: it depends on q^2 and three angles

[arXiv:2107.13428]







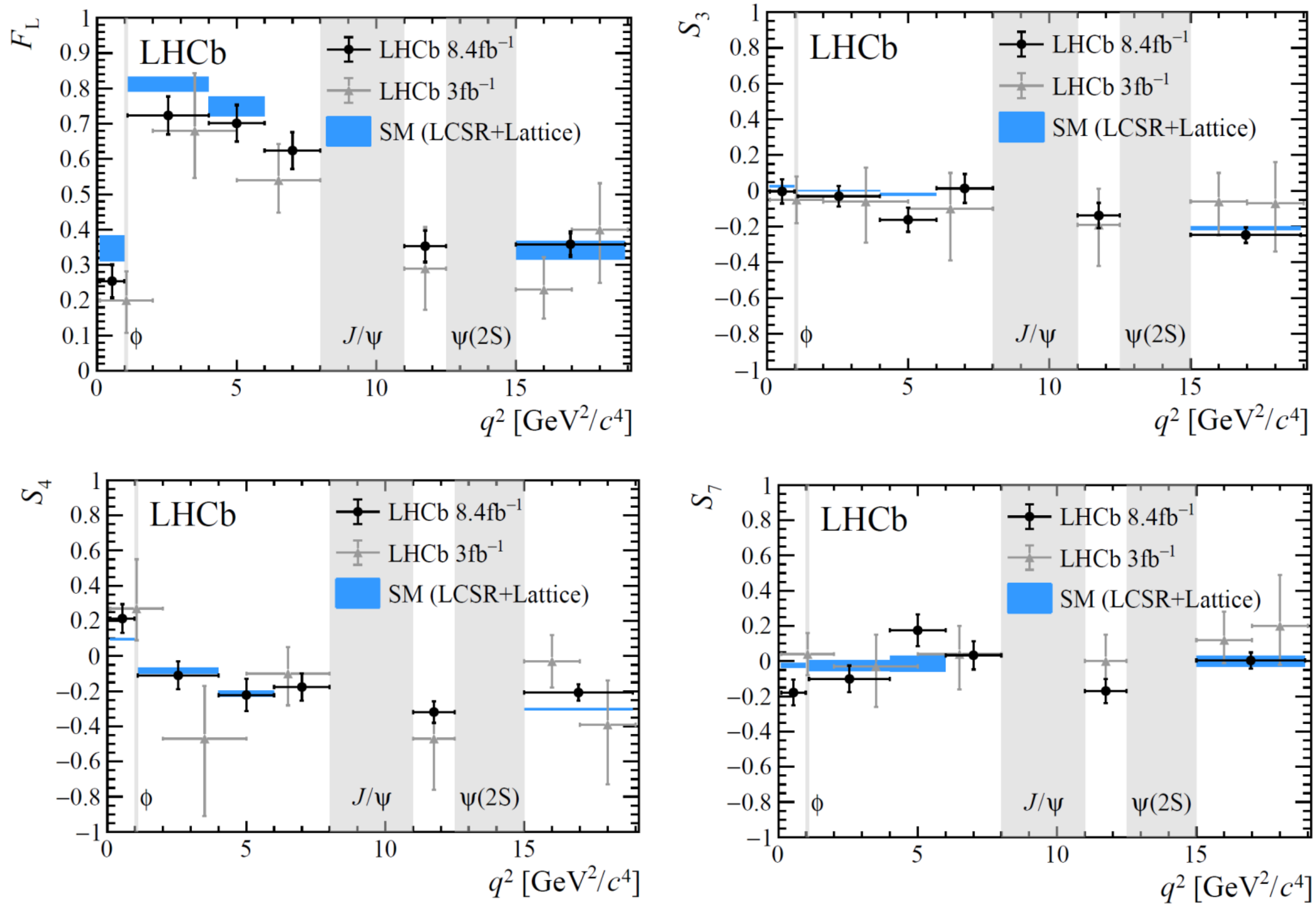
$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_l)\\
&+F_\mathrm{L}\cos^2\theta_K(1-\cos 2\theta_l)+S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi\\
&+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi+A_5\sin 2\theta_K\sin\theta_l\cos\phi\\
&+\tfrac{4}{3}A_\mathrm{FB}^{CP}\sin^2\theta_K\cos\theta_l+S_7\sin 2\theta_K\sin\theta_l\sin\phi\\
&+A_8\sin 2\theta_K\sin 2\theta_l\sin\phi+A_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
\end{aligned}
$$

$\rightarrow$ Function of observables related to CP-averages and asymmetries:

F_L, A_{FB}, S_i, A_i

Rare B decays: $B_s \to \phi\mu^+\mu^-$

NEW '21



→In general good agreement with SM (no P_5' observable here), deviations less than 2σ

Rare B decays: B→K*μ+μ-

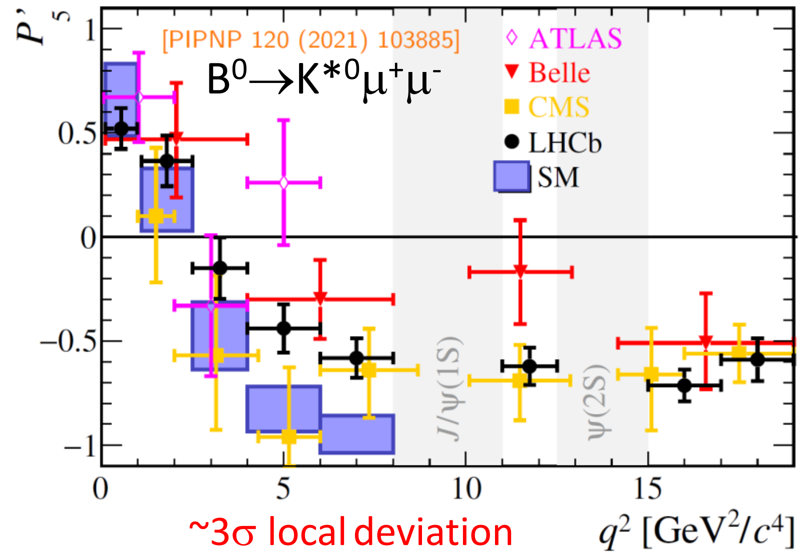
- "Optimized observables", with form factor cancellations
  [JHEP 05 (2013) 137]

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

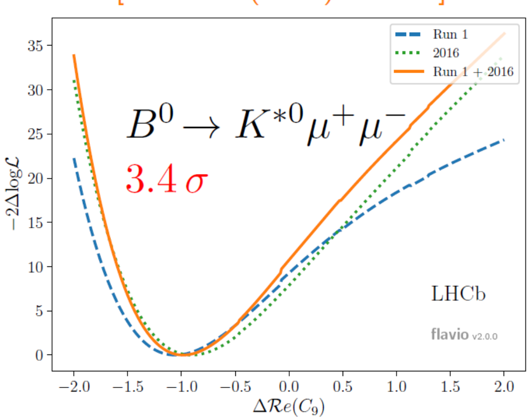
Two new analyses by LHCb with full data:

- Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$
  [PRL 126 (2021) 161802]
- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
  [PRL 125 (2020) 011802]

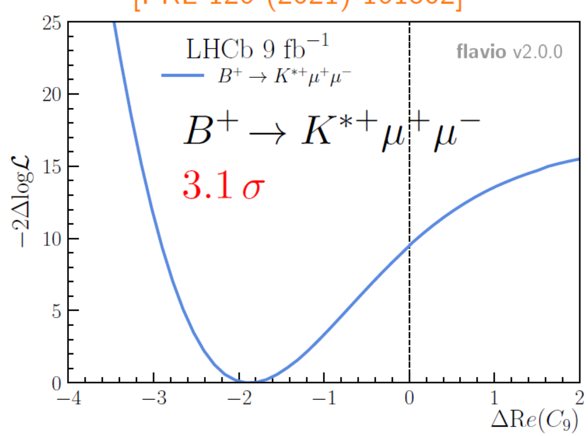
[JHEP 10 ('18) 047]
[PRL 118 ('17) 111801]
[PLB 781 ('18) 517]



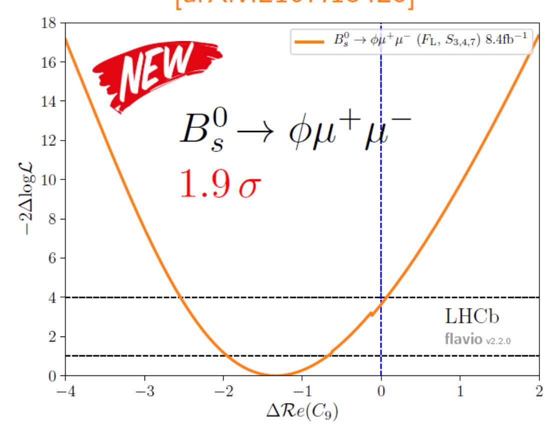
[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]



[arXiv:2107.13428]



→ Negative shift of $\mathrm{Re}(C_9)$ preferred over SM hypothesis at level of 2-3σ

Rare B decays: R_K

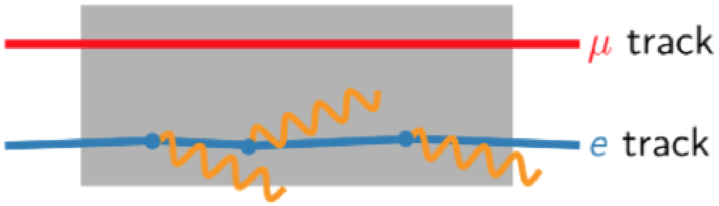
- In the SM all leptons are expected to behave in the same way

Test of lepton universality:

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

- Precise theory prediction due to cancellation of hadronic form factor uncertainties

- Challenge: bremsstrahlung by electrons

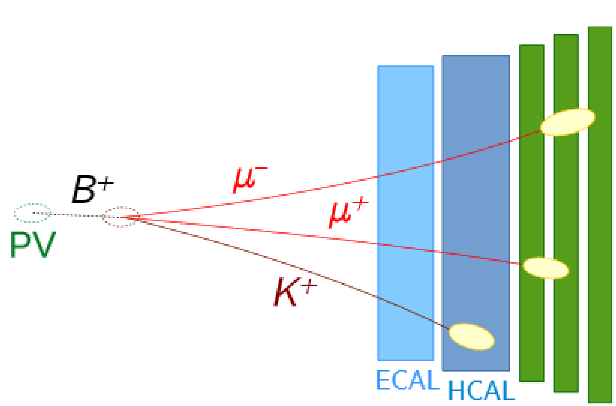


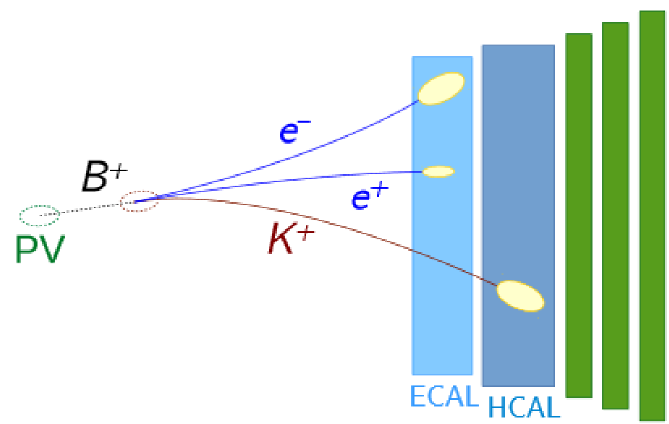
- Experimentally, we perform a double ratio to cancel systematic uncertainties

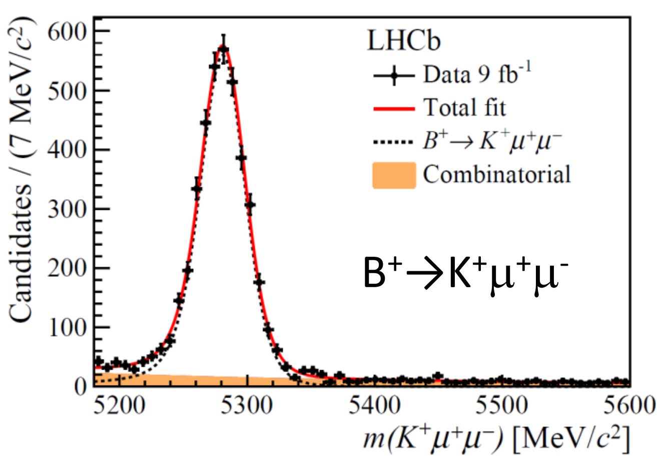
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

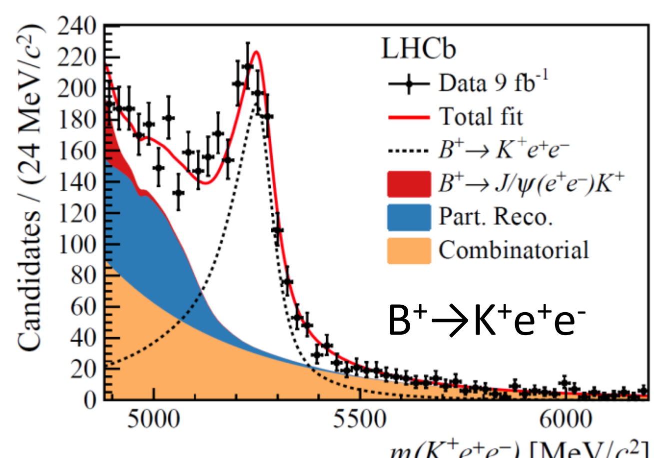
Rare B decays: R_K

Reconstructed B mass for $B^+ \to K^+\ell^+\ell^-$ (muons vs electrons) [arXiv:2103.11769]





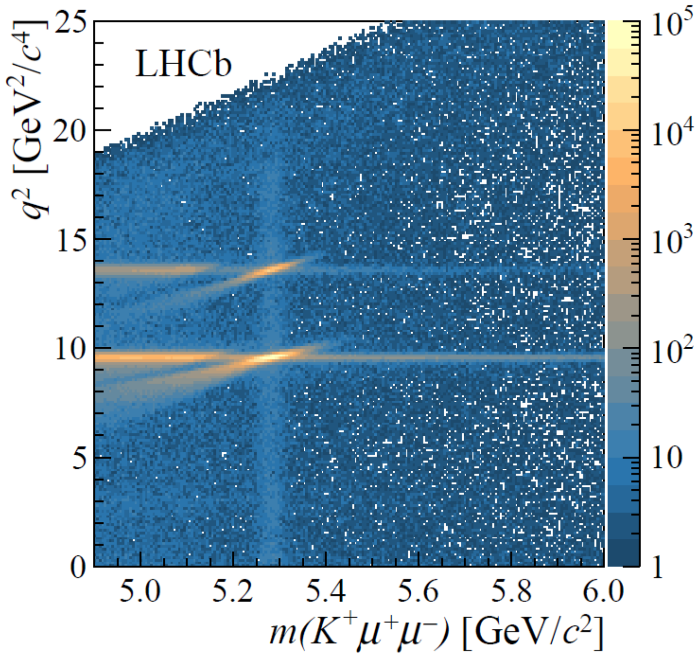


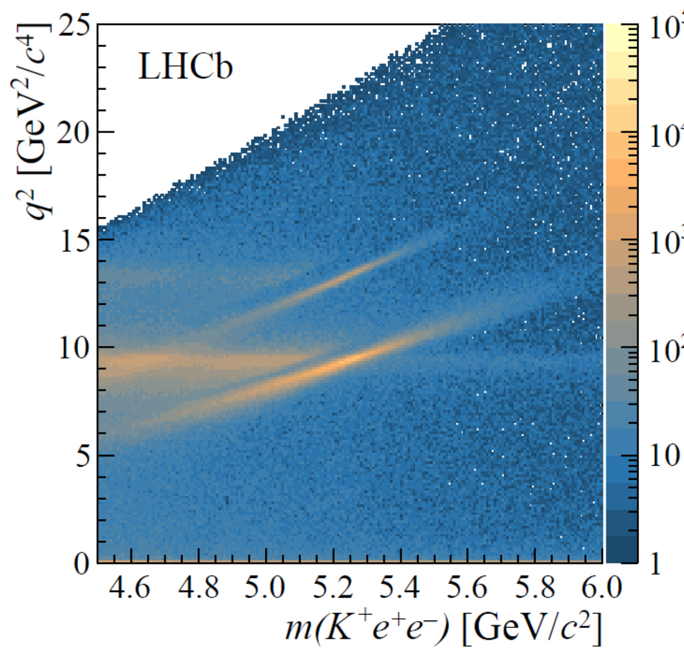


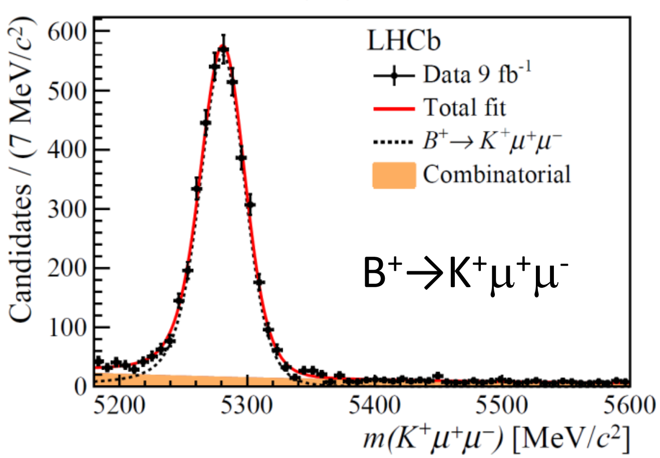
Rare B decays: R_K

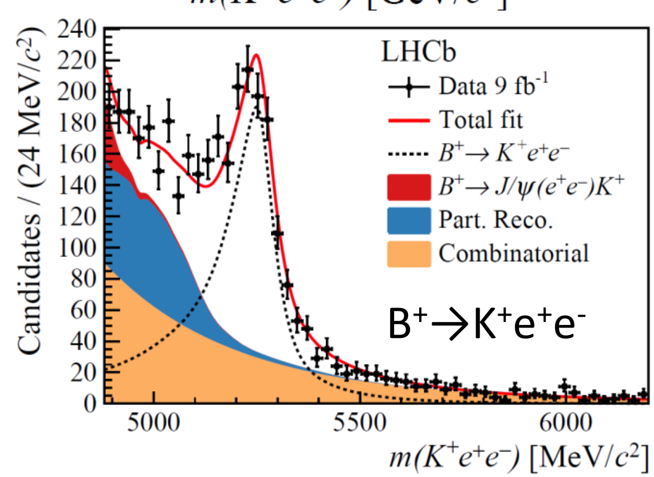
Reconstructed B mas for $B^+ \to K^+ \ell^+ \ell^-$ (muons vs electrons)

[arXiv:2103.11769]







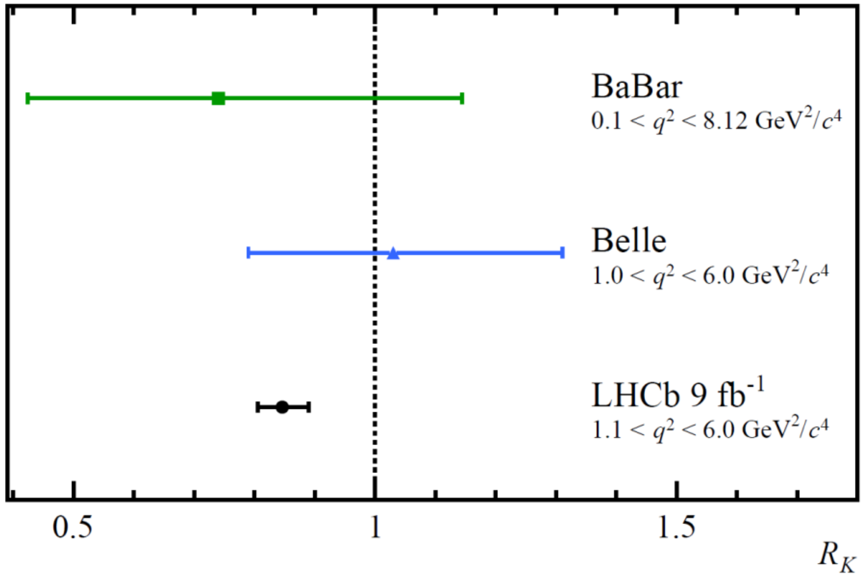


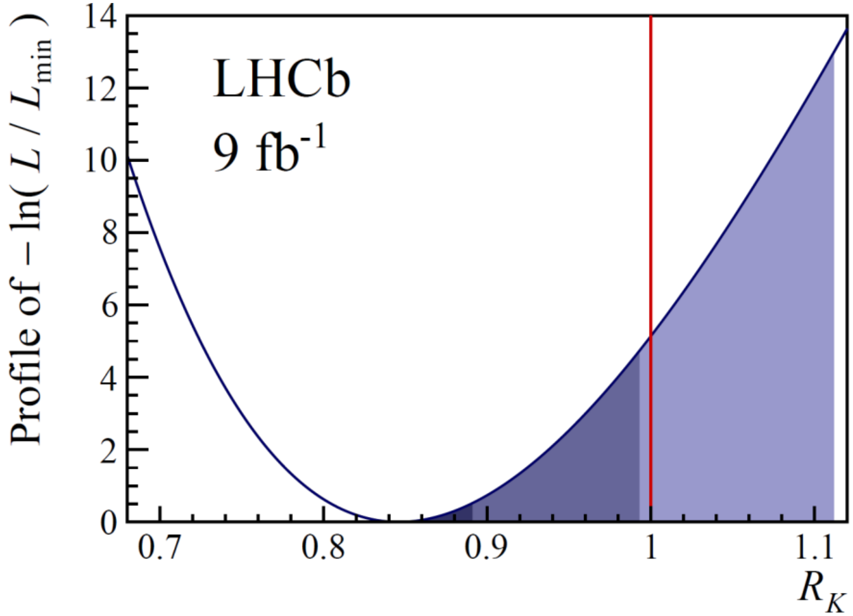
Rare B decays: R_K

Results with full LHCb data:
[arXiv:2103.11769]

$$R_K = 0.846\,^{+\,0.044}_{-\,0.041}$$

(1 GeV^2 < q^2 < 6 GeV^2)





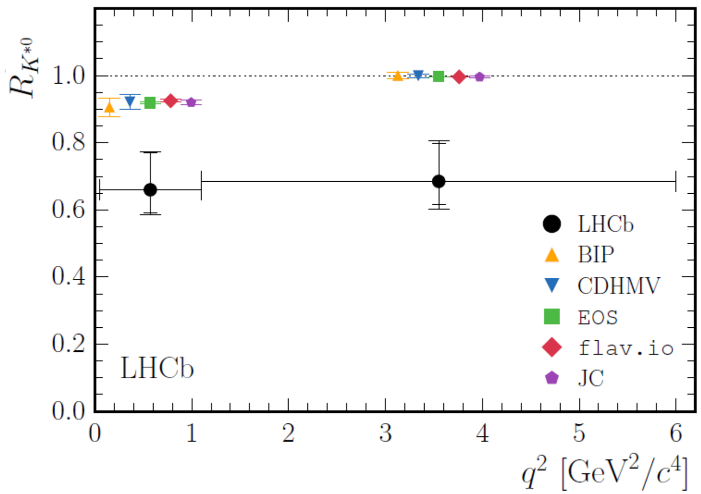
→ Deviation from SM at **3.1σ** ⇒ evidence of LFU violation

(submitted to *Nature Physics*)

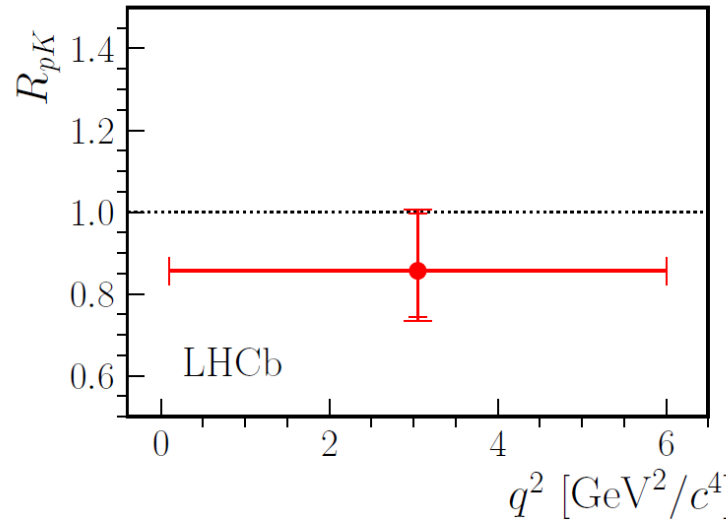
Rare B decays: R_K

- Previous results in other channels:

➔ LHCb measurement in the $B \to K^* \mu^+ \mu^-$ channel, $\mathbf{R_{K^*}}$, with $3 fb^{-1}$ [JHEP 08 (2017) 055]

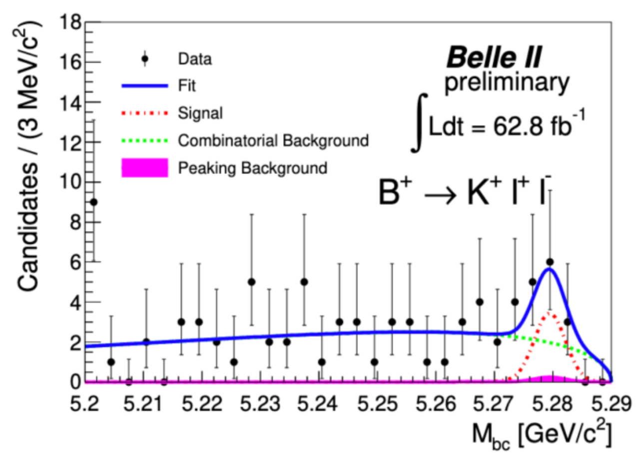


➔ LHCb measurement in the $\Lambda_b \to pK\mu^+\mu^-$ channel, $\mathbf{R_{pK}}$, with $5 fb^{-1}$ [JHEP 05 (2020) 040]



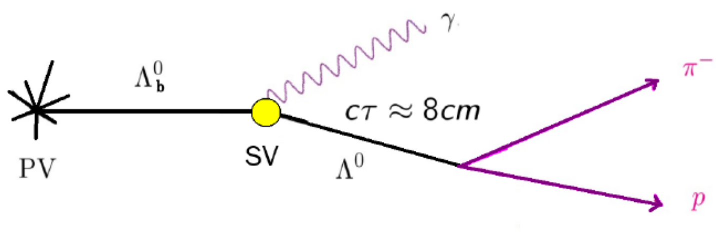
- Ongoing R_X analyses with full stat.

- And Belle II entering in the game… [BELLE2-NOTE-PL-2020-014]

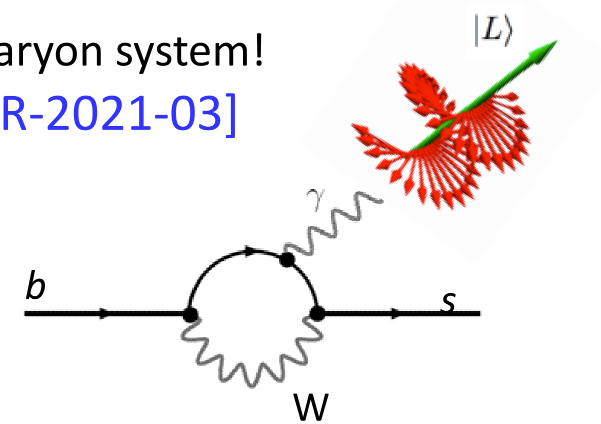


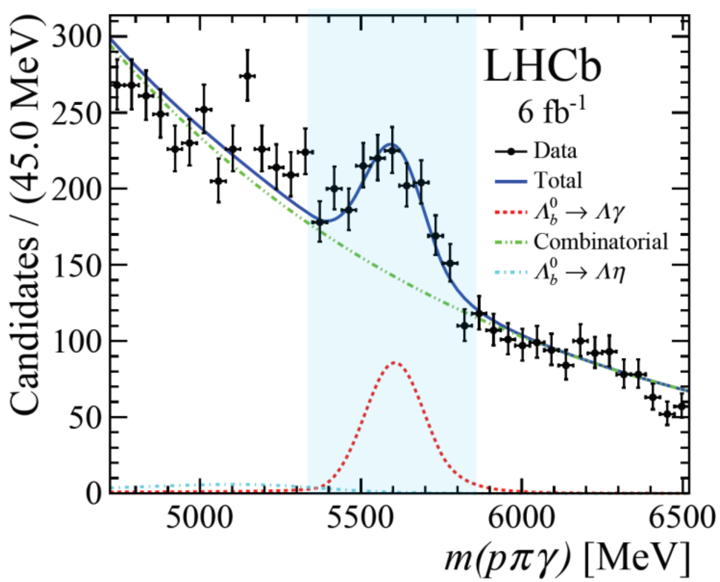
Rare B decays: $\Lambda_b \rightarrow \Lambda\gamma$

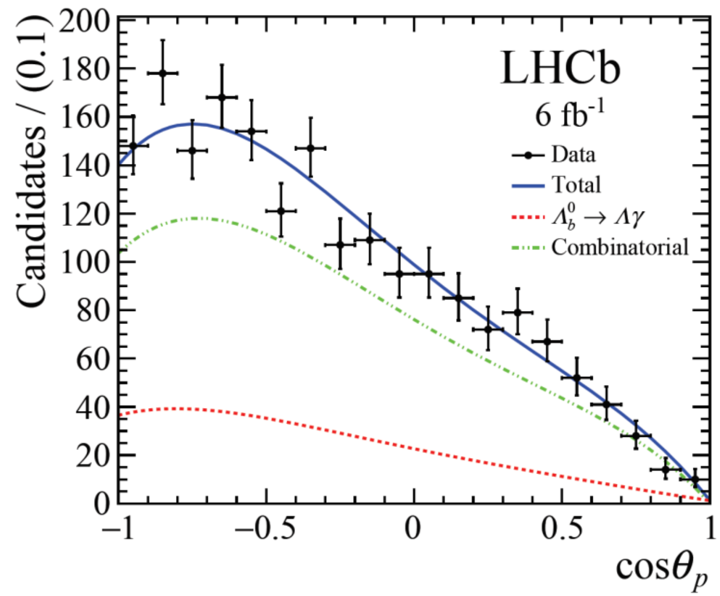
- First measurement of the **photon polarization** in a b-baryon system!
  (Expected to be left handed in the SM) [LHCb-PAPER-2021-03]



$$\boxed{\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}}$$







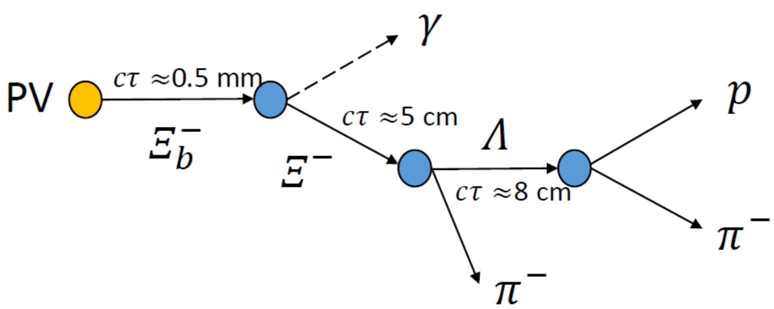
$$\boxed{\alpha_\gamma = 0.82\,^{+0.17}_{-0.26}\ (\text{stat.})\,^{+0.04}_{-0.13}\ (\text{syst.})}$$

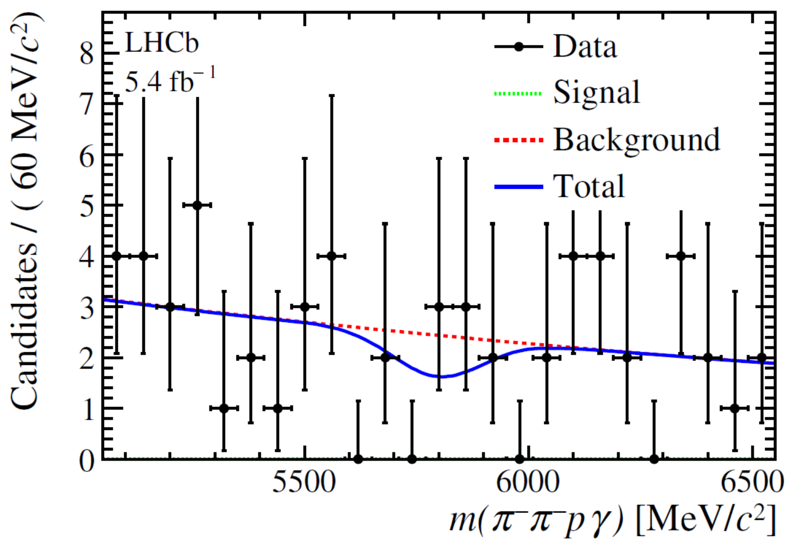
In agreement with SM

Rare B decays: $\Xi_b \rightarrow \Xi\gamma$

NEW '21

- Search for other channels: $\Xi_b \rightarrow \Xi^- \gamma$:

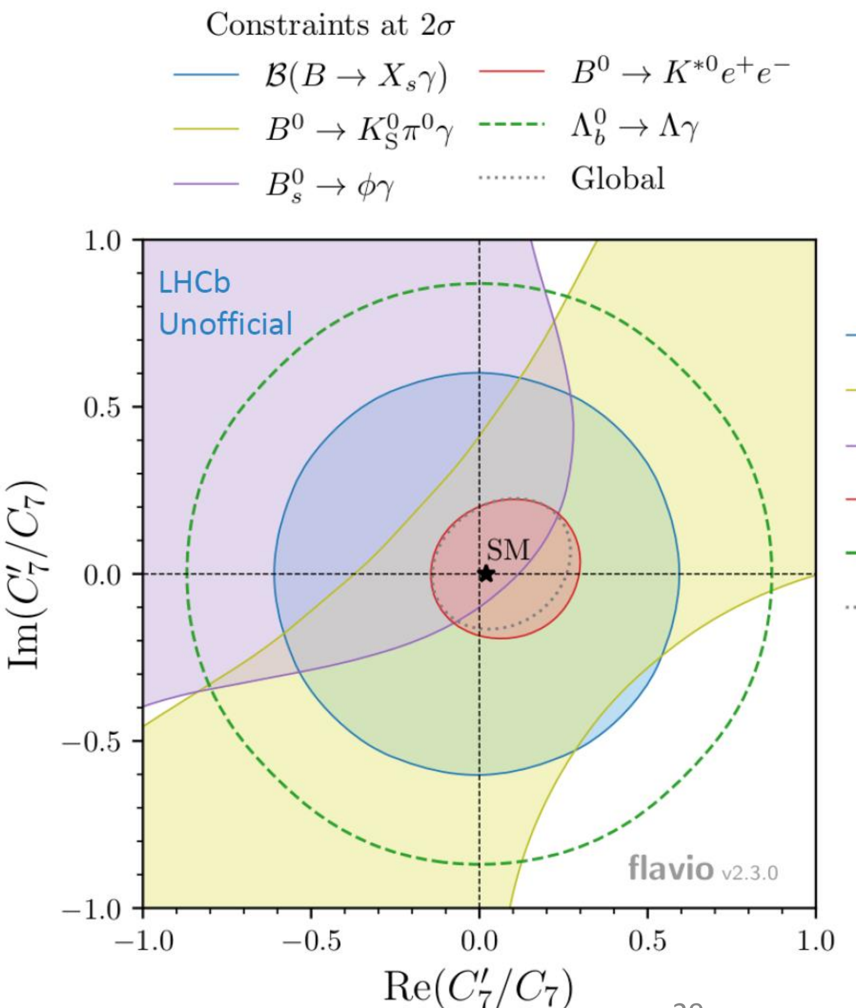




$$\boxed{\mathcal{B}(\Xi_b^- \rightarrow \Xi^-\gamma) < 1.3 \times 10^{-4} \text{ at } 95\% \text{ CL}}$$

[arXiv: 2108.07678]

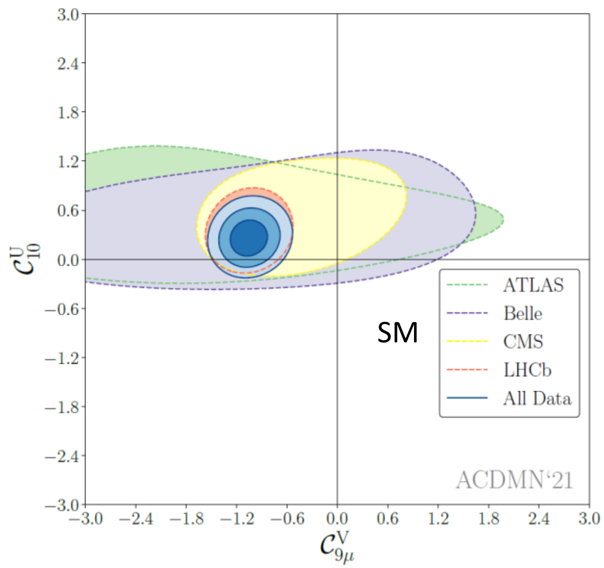
- Constraints from radiative (C7$^{(\prime)}$):



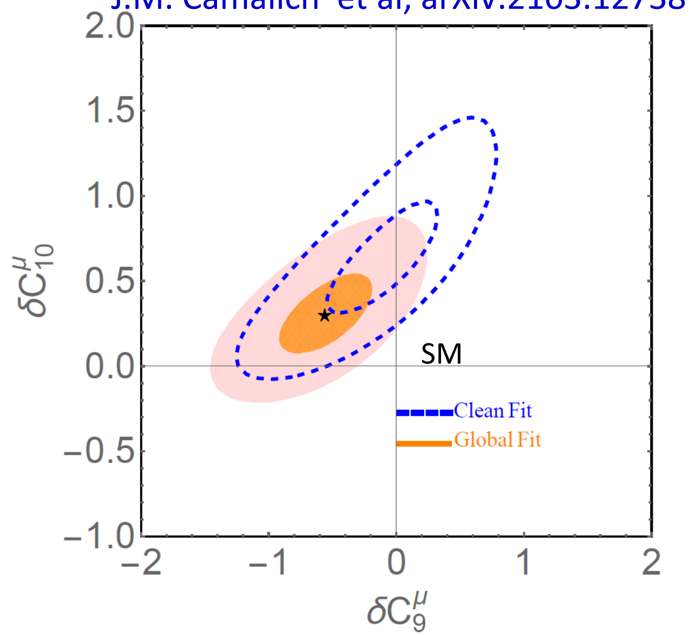
Rare B decays

Global fits (more than 100 observables)

J. Matias et al, arXiv:2104.08921



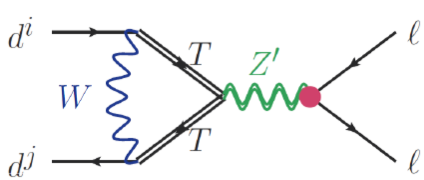
J.M. Camalich et al, arXiv:2103.12738

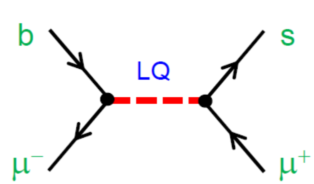


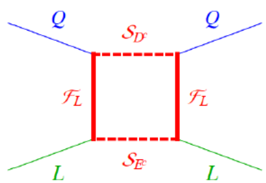
New Physics hypothesis preferred over SM by more than 4 - 5σ

Main effect on the $C_{9\mu}$ coefficient: **4.27^{SM}** -1.1^{NP}

Triggered models with Z', leptoquarks (LQ), new fermions and scalars….







Semileptonic B decays

GRIFFON VULTURE

(Gyps Fulvus)

2.6 m wingspan

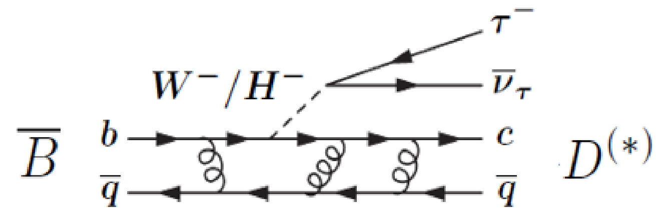
7-10 kg weight

Semileptonic B decays: $R_{D,}R_{D*}$

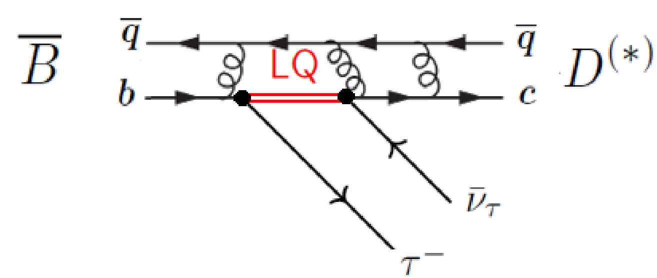
- **Another test of lepton universality** (now at tree level):

Ratio of semi-tauonic and semi-muonic branching fractions:

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



Sensitive to charged Higgs bosons and leptoquarks



SM predictions very precise : (V_{cb} and form factors (partially) cancel)

$R(D)_{SM}=0.299 \pm 0.003$

$R(D^*)_{SM}=0.252 \pm 0.003$

Based on HQET form factors:
[H. Na *et al.*, PRD 92 (2015) 054510]
[Fajfer, Kamenic, Nišandižć: PRD85 (2012) 094025]
and experimental measurements (HFLAV)
[D.Bigi, Gambino, PRD 94 (2016) 094008]

Semileptonic B decays

BaBar measured an excess of $B^0 \to D^{(*)}\tau^-\nu_\tau$ (**3σ away from SM!**) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

LHCb:

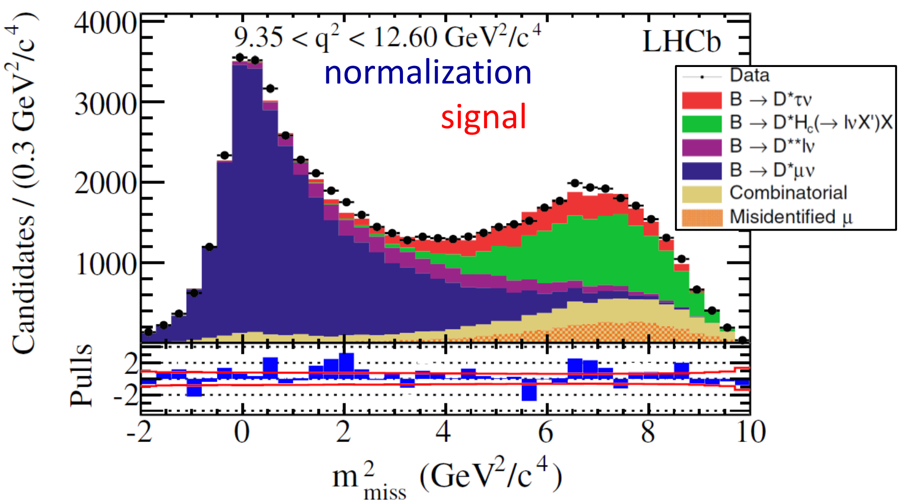
R(D*)
- $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ [PRL 115 (2015) 111803]
- $B^0 \to D^{*-}\tau^+\nu$, with $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$ [PRL 120 (2018) 171802]

R(J/ψ)
- $B^+_c \to J/\psi\ {}^-\tau^+\nu$, with with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ [PRL 120 (2018) 121801]

- Using $\boxed{\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau}$

Information from the missing mass squared $m_{miss}^2=(P_B-P_{D*}-P_\mu)^2$ and muon energy

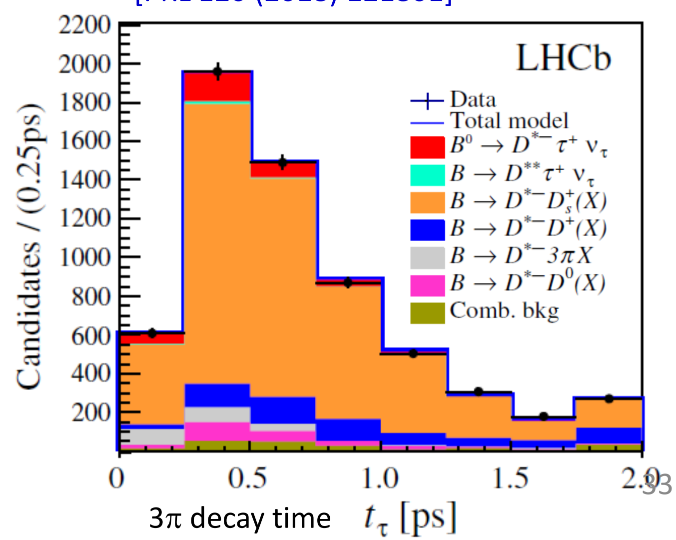
[PRL 115 (2015) 111803]



- Using $\boxed{\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau}$

Information from the position of the pions. Normalized to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

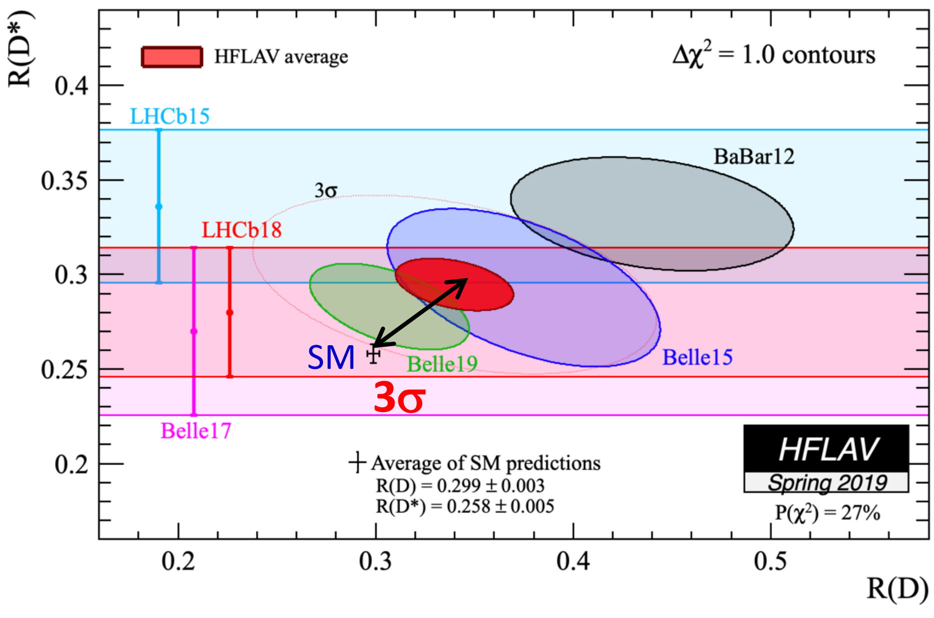
[PRL 120 (2018) 121801]

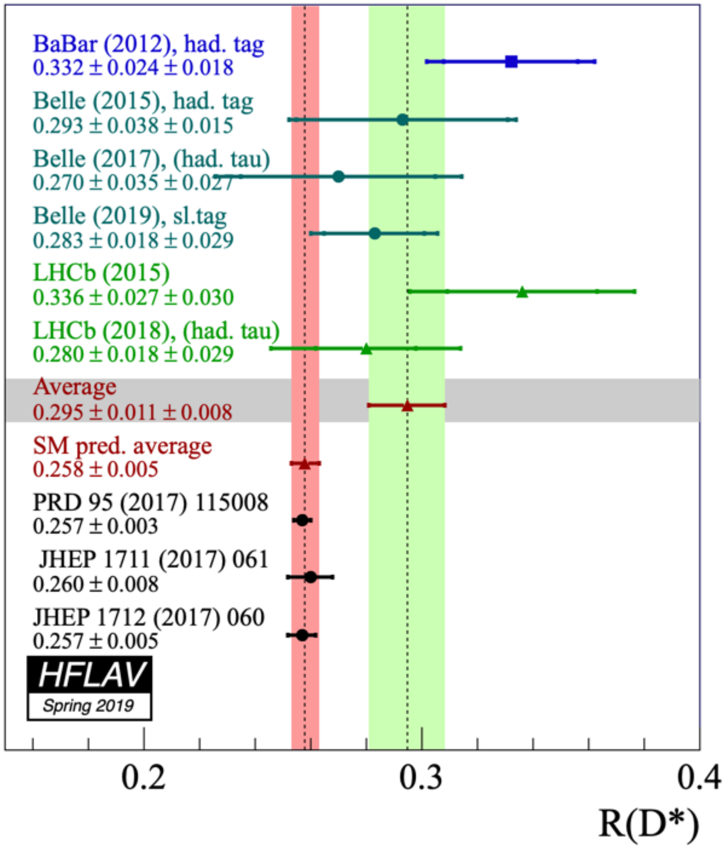


Semileptonic B decays

- Last results from Belle using semileptonic tags (D and D*ν) [PRL 124, (2020) 161803]

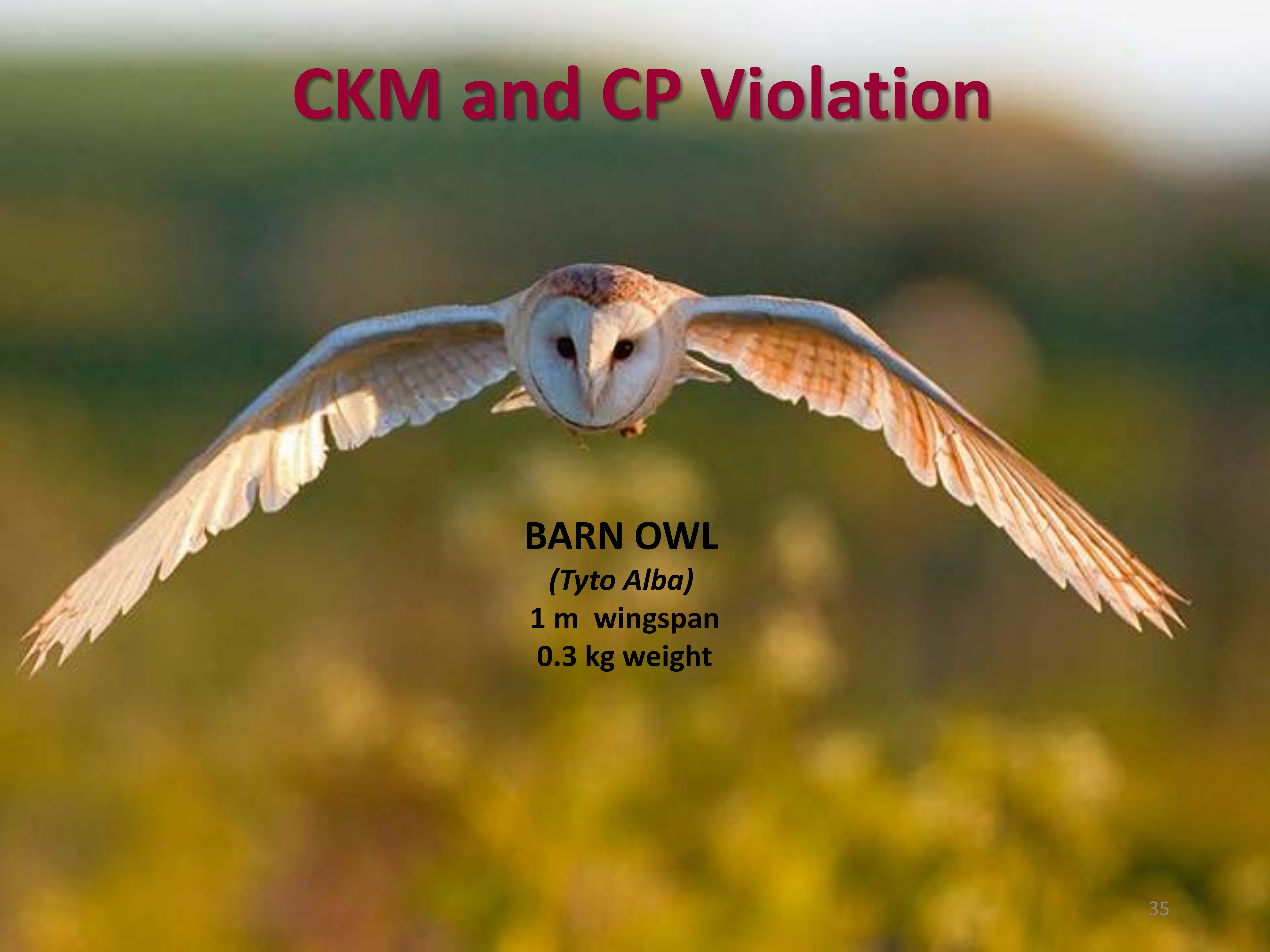
• Present global picture of R_D and R_{D^*}





→ Average: 3σ deviation from SM

CKM and CP Violation



BARN OWL

(Tyto Alba)

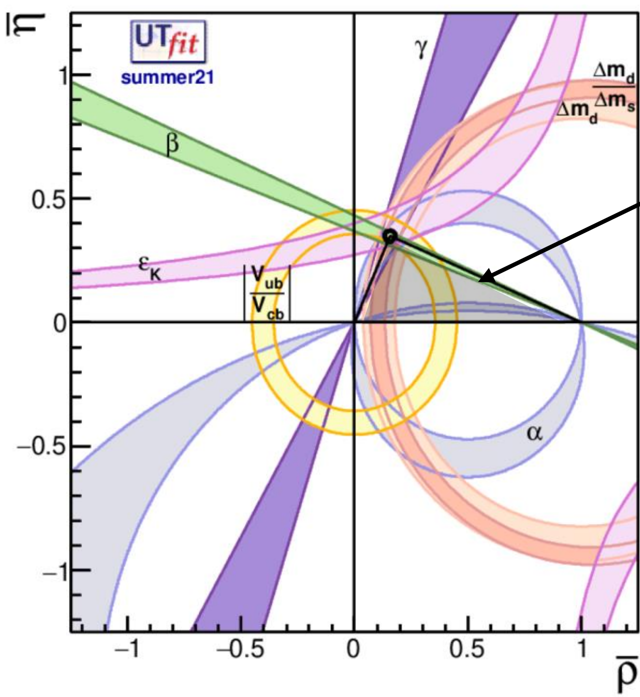
1 m wingspan

0.3 kg weight

CKM and CP Violation

- The CKM matrix can be parameterized in terms of 4 fundamental parameters:

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



- Flavour observables can be expressed as function of these parameters:

Unitary Triangle

➜ Very high level of precision (few %)
➜ No inconsistencies

$\bar\rho = 0.157 \pm 0.012$
$\bar\eta = 0.350 \pm 0.010$

NEW '21

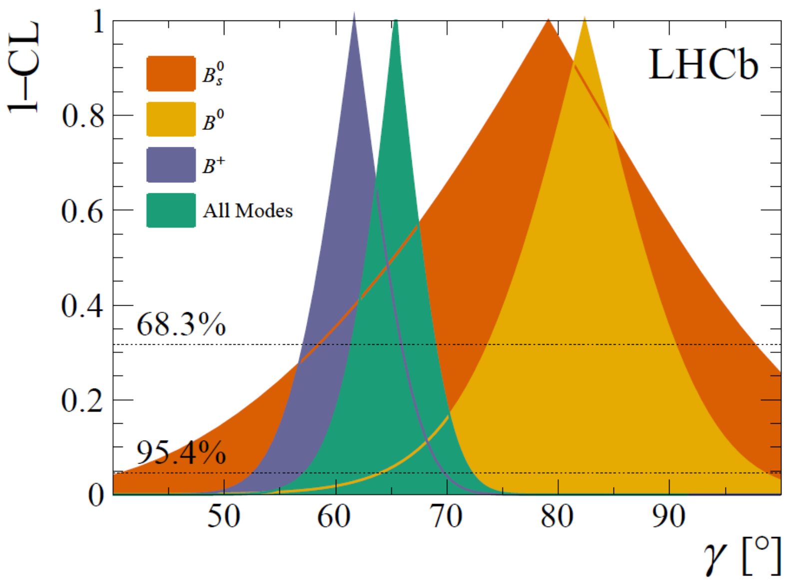
CKM and CP Violation

NEW '21

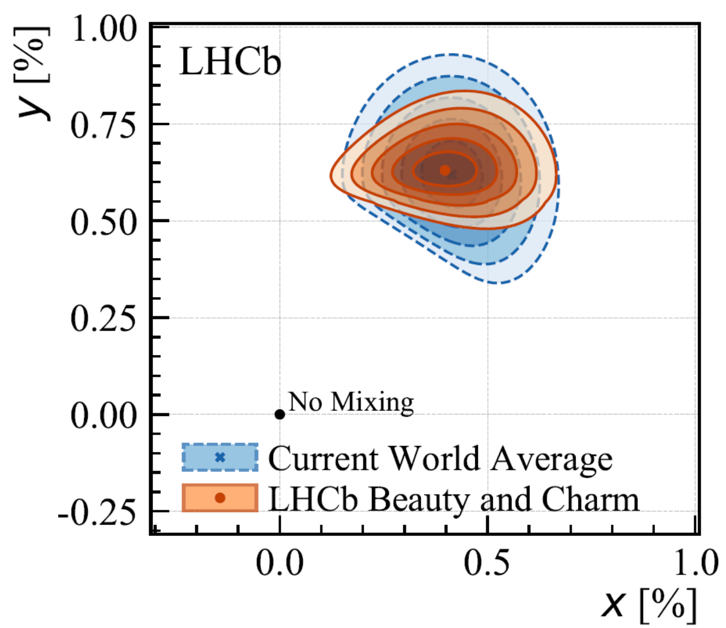
- New measurement of the γ angle at LHCb:
  [LHCb-CONF-2021-001]

$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

Fit to 151 observables, 52 parameters
Run1+Run2 data (frequentist).



Charm mixing parameters also measured:



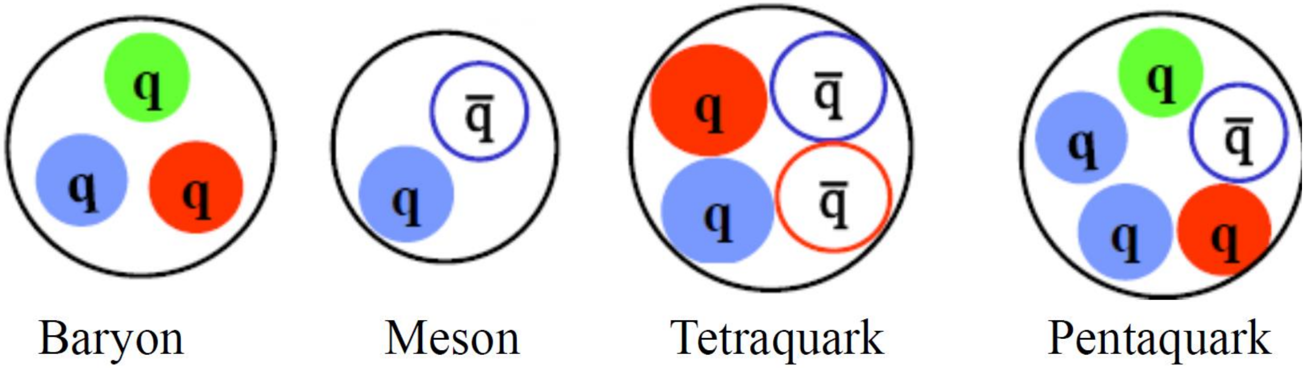
$$\boxed{\gamma = (65.4^{+3.8}_{-4.2})^\circ}$$

The most precise determination from a single experiment!

Spectroscopy

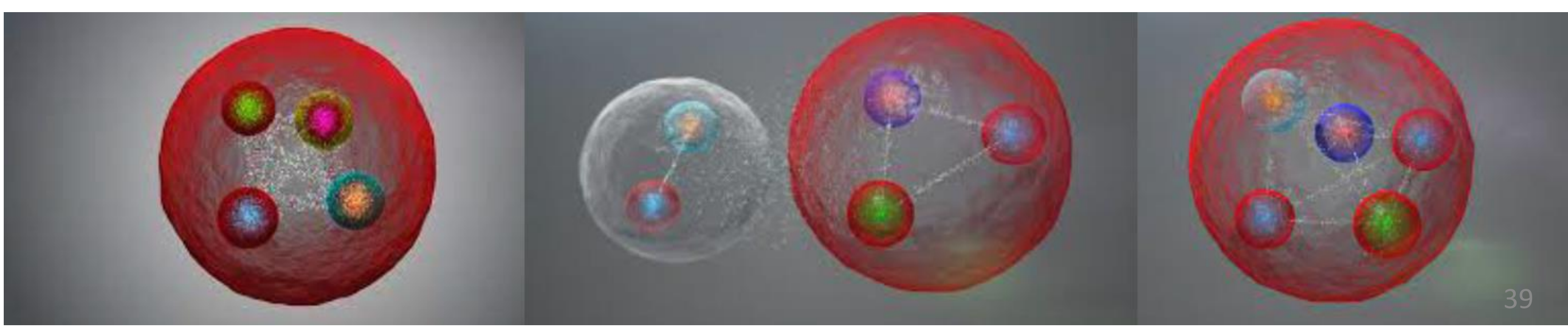
Spectroscopy

• 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]



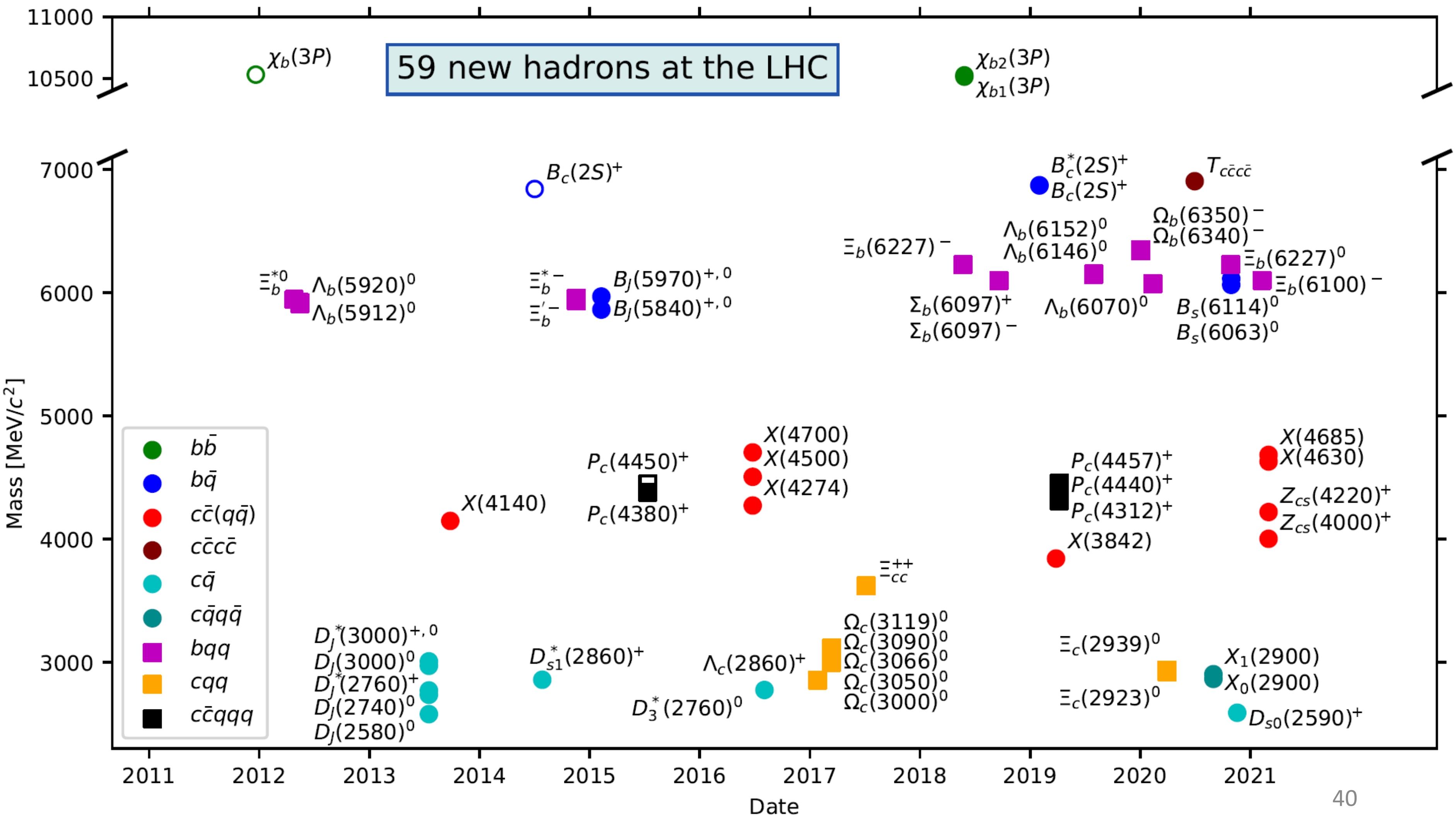
• Several of these states have been announced since 1970, but have disappeared with time and new data analysis…

• Important for our understanding of the matter structure and QCD!



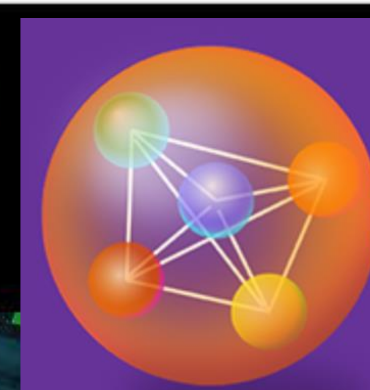
Spectroscopy

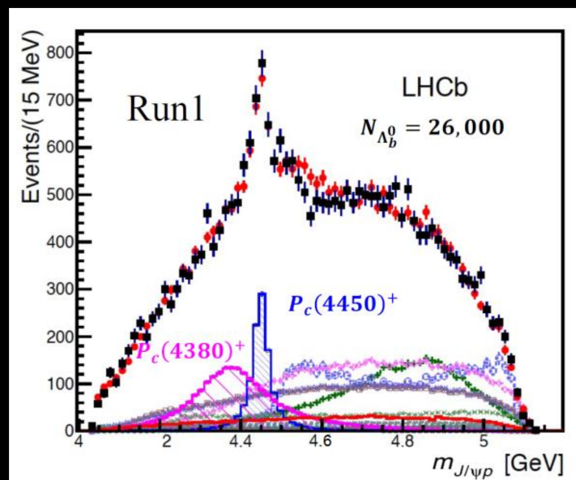
- More than 50 new hadrons discovered in the last decade, most of them by LHCb:



Spectroscopy

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





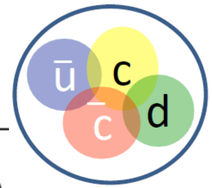
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58

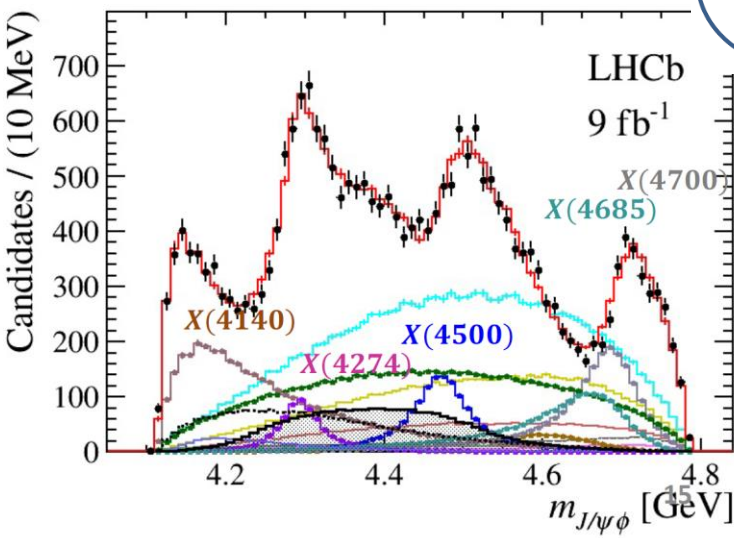
Observation of J/ψp Resonances Consistent with Pentaquark States

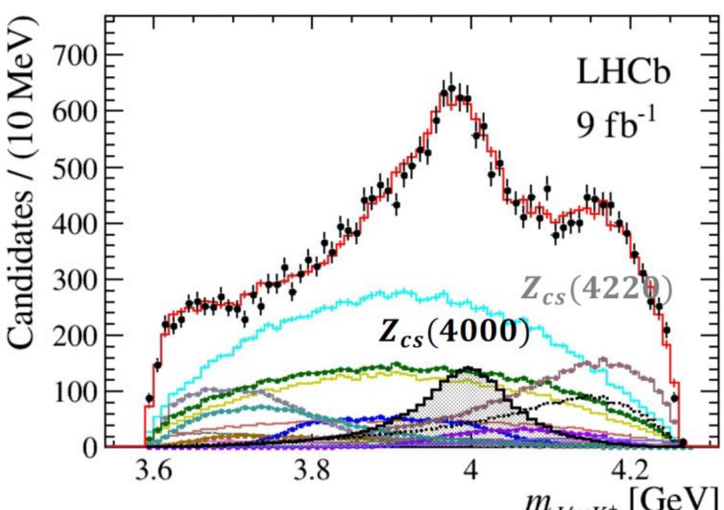
[PRL 115 (2015) 072001] **1263 citations !**

Spectroscopy

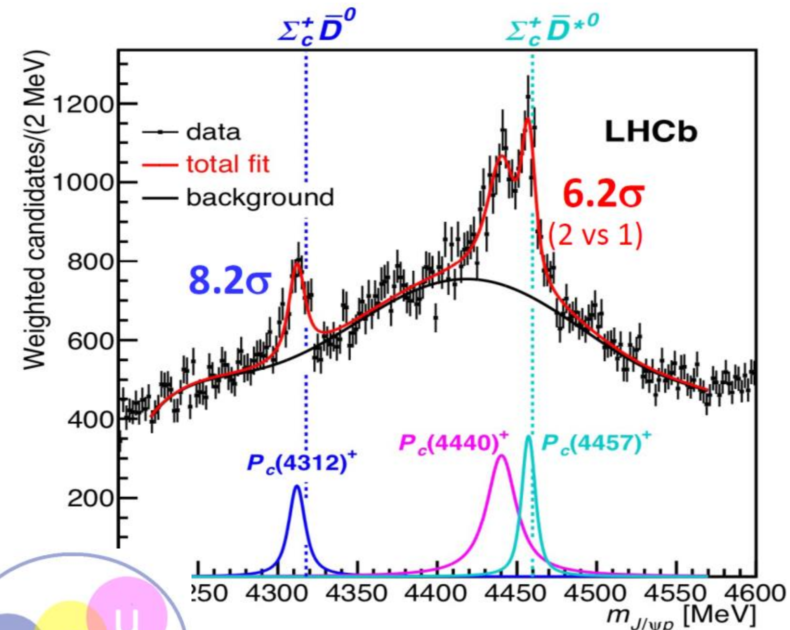
- *Hidden-charm* tetraquarks
  [PRL 127 (2021) 082001]

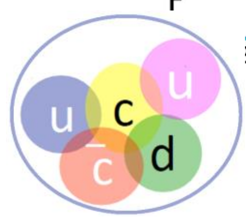


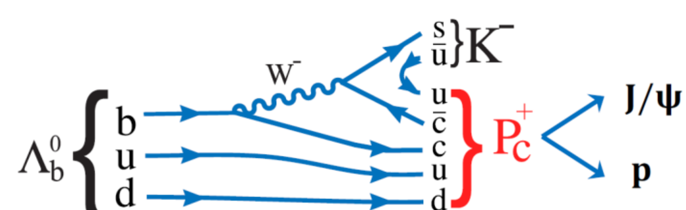




- *Hidden-charm* pentaquarks:
  [PRL 122 (2019) 222001]



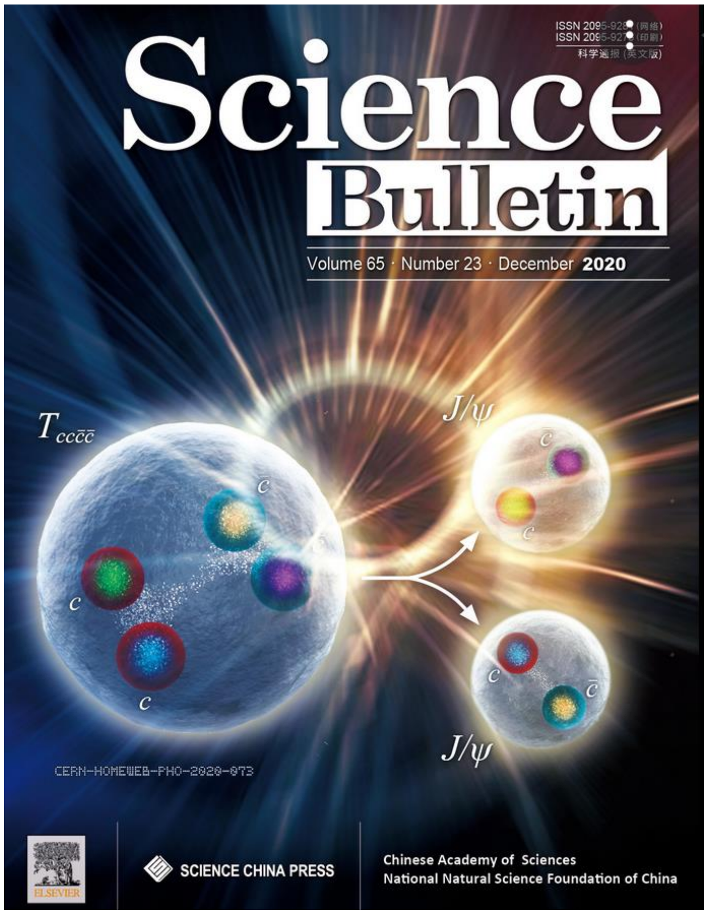




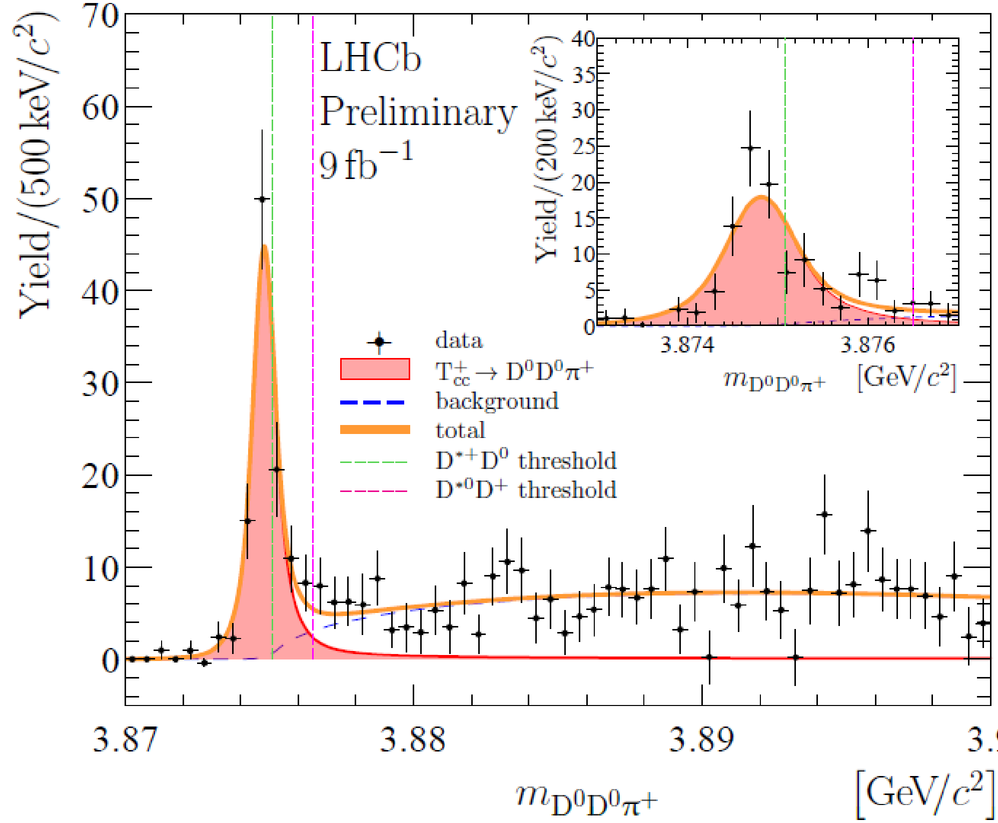
Spectroscopy

NEW '21

- Doubly-charmed tetraquark T^{+}_{cc} !



[LHCb-PAPER-2021-031]



$$m_{BW} - m_{D^{*+}} - m_{D^0} = -273 \pm 61 \pm 5^{+11}_{-14}\ \mathrm{keV}/c^2$$

$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\ \mathrm{keV}$$

CERN seminar next week:
https://indico.cern.ch/event/1065144/

The future

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	203+
				Run III						Run IV				Run V	
	LS2						LS3					LS4			
	LHCb 40 MHz **UPGRADE I**			$L = 2 \times 10^{33}$		**LHCb Consolidate: UPGRADE Ib**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$		**LHCb UPGRADE II**		$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
	ATLAS Phase I Upgr			$L = 2 \times 10^{34}$ $300\ fb^{-1}$		**ATLAS Phase II UPGRADE**				**HL-LHC** $L = 5 \times 10^{34}$				**HL-LHC** $L = 5 \times 10^{34}$ $3000\ fb^{-1}$	
	CMS Phase I Upgr					**CMS Phase II UPGRADE**									
	Belle II				$5\ ab^{-1}$		$L = 6 \times 10^{35}$				$50\ ab^{-1}$				


SciFi installation

- New detector
- Full software trigger (30MHz)
- Event reconstruction on GPU cards
- + Turbo dedicated trigger scheme
- Installation and commissioning ongoing

- Analysis of Belle II with $5\ ab^{-1}$ will start to be competitive with LHCb

The future

My message:

→ **B Physics can be the key for new physics in the coming years**

→ **Great contribution from the Spanish LHCb community and from theorists!**

→ **Missing Spanish ATLAS and CMS**

Thanks!