Introduction to flavour experiments

In memoriam of Sheldon Stone (Feb. 14, 1946 – Oct. 6, 2021)

https://cerncourier.com/a/sheldon-stone-1946-2021/

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Outline

- Lesson 1: Introduction to flavour physics
- Lesson 2: The CKM matrix
- Lesson 3: Rare decays of heavy hadrons
- Lesson 4: Mixing and CP violation

Rare decays of B mesons

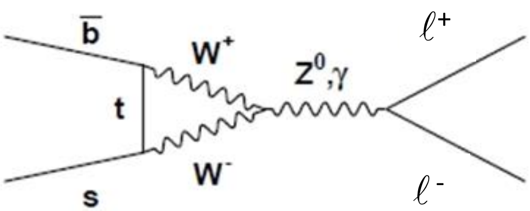
What is a rare decay?

Four-leaf clover: 1/10000, symbol of good luck

Rare decays of B mesons

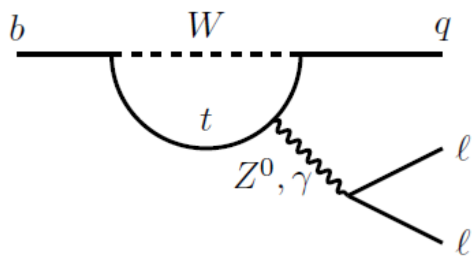
- *b→s,d* quark transitions are Flavor Changing Neutral Currents (FCNCs),
  → in the SM they only can occur through loops (*penguin and box diagrams*),
  excellent probe for physics beyond the SM

leptonic



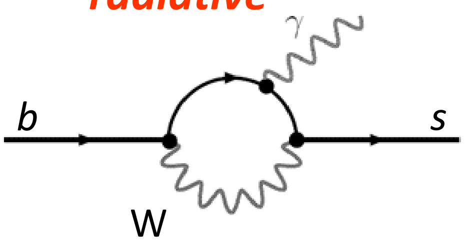
BR ~ 10^{-9}

semileptonic



BR ~ 10^{-7}

radiative



BR ~ 10^{-5}

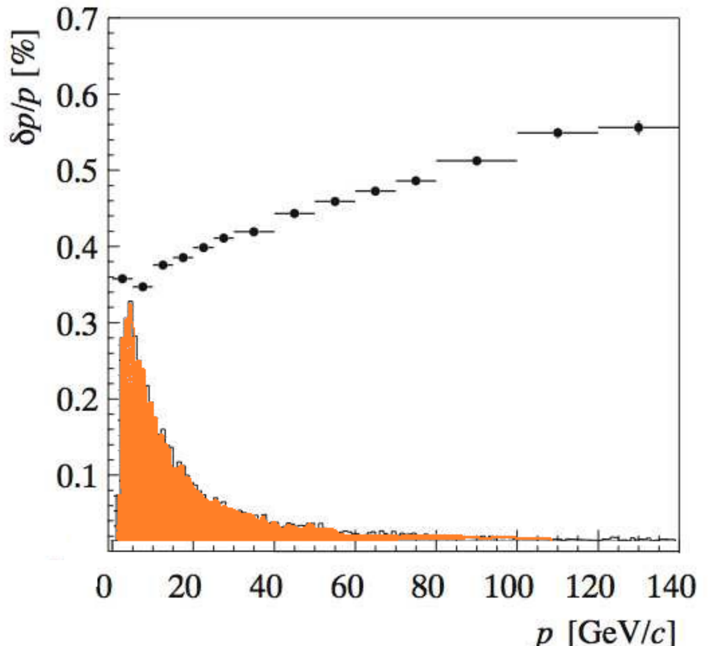
Experimentally → leptons/photons with high transverse momenta

Theoretically → observables can be calculated in terms of Wilson coefficients

Rare decays of B mesons

What do we need?

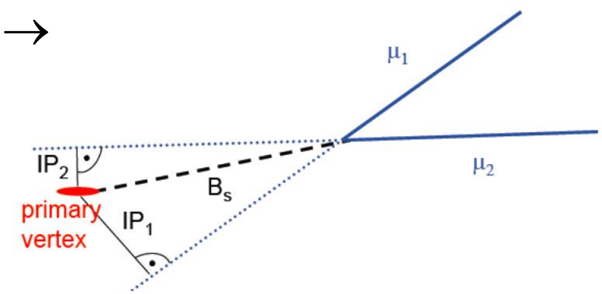
- A lot of data! → High luminosity and large b cross section (LHC experiments, BELLE II)
- High momentum and impact parameter resolutions →
  - high mass resolution
  - good signal and background separation

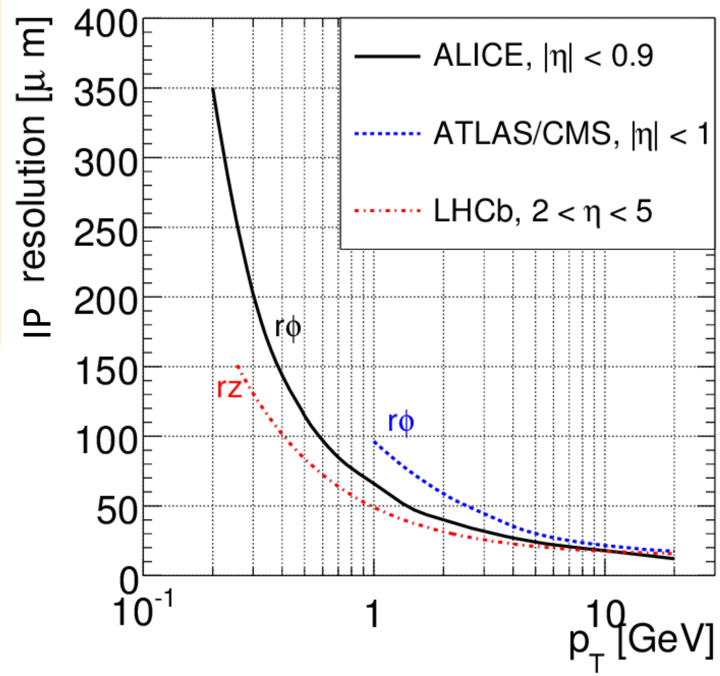


LHCb NOTE OTR-2005-014

σ_p/p

LHCb = 0.4-0.6 %
ATLAS = 5-6 %
CMS = 1-3 %
BELLE II =0.3 -2%

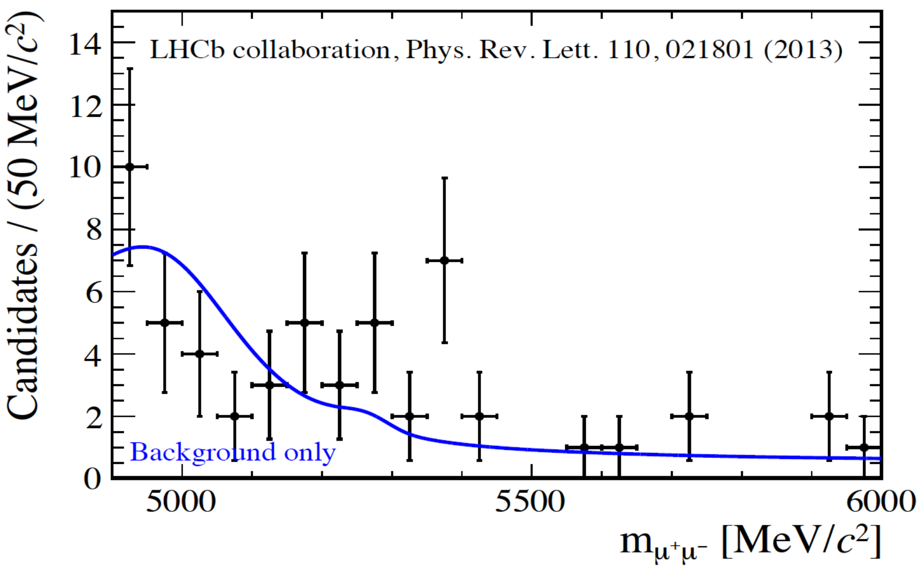


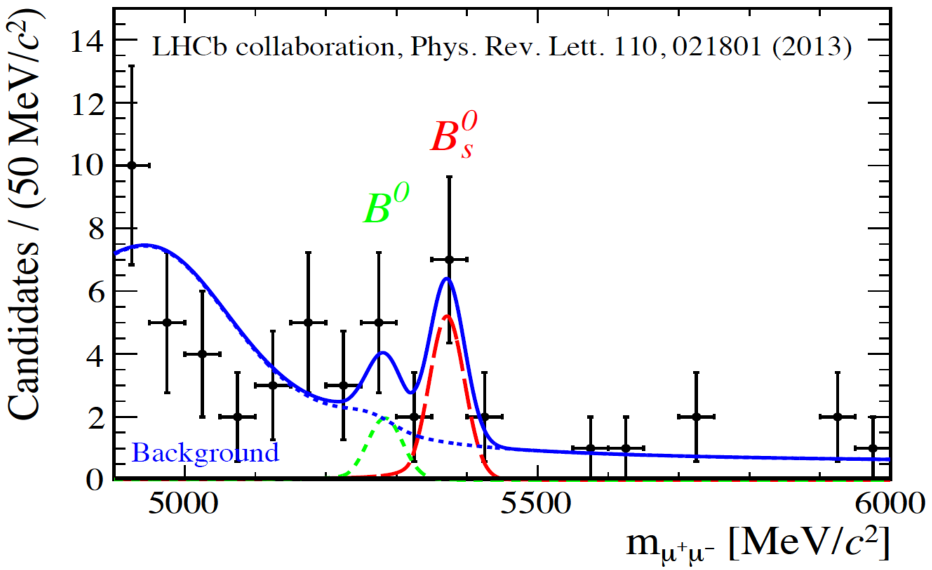


Rare decays of B mesons

Reconstructed mass resolution
σ_M ($J/\psi \rightarrow \mu^+\mu^+$)

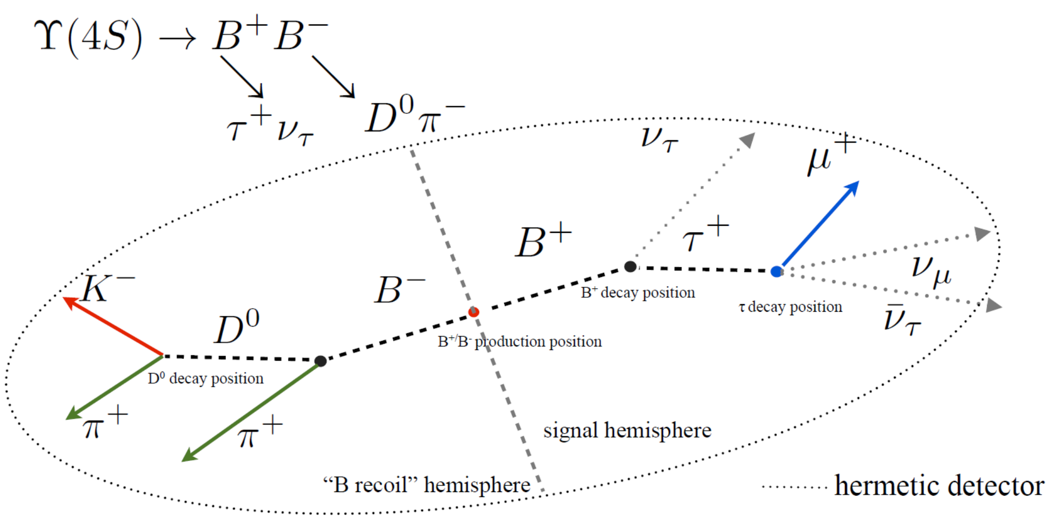
LHCb = 13 MeV
ATLAS = 71 MeV
CMS = 40 MeV
BELLE II = 4 MeV

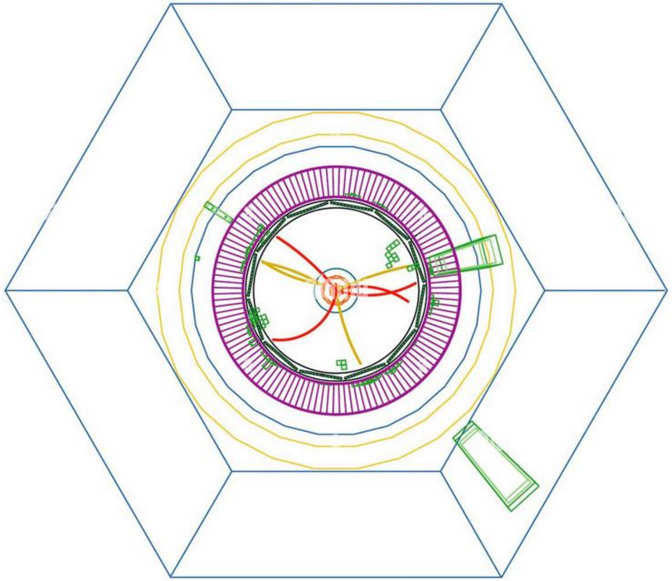




Rare decays of B mesons

How do we measure branching fractions?





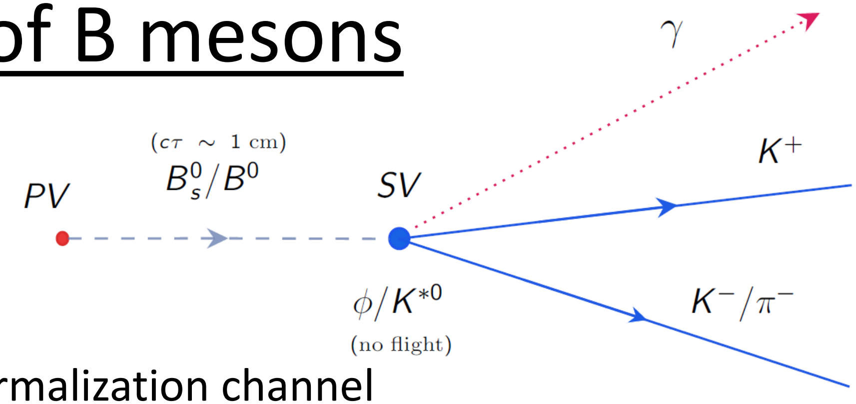
- ***Absolute branching fractions:***

→ we need to know precisely how many events are produced and reconstructed [Reconstruction efficiencies are taken from simulation and validated with data]

$$N_{B\rightarrow\tau\nu} = 2 \times N_{B\bar{B}} \times BR(B\rightarrow\tau\nu) \times BR(\tau\rightarrow\mu\nu\nu) \times \varepsilon_{rec}$$

↳ known from the B recoil hemisphere $(\sim \mathcal{L} \times \sigma_{e+e-\rightarrow\Upsilon(4S)})$

Rare decays of B mesons



- ***Relative branching fractions:***

$\rightarrow$ we need a well known and abundant normalization channel

[Ratios of efficiencies are taken from simulation and validated with data]

$$\frac{N_{B_s^0\rightarrow\phi\gamma}}{N_{B^0\rightarrow K^{*0}\gamma}} = \frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0\rightarrow\phi\gamma)}{\mathcal{B}(B^0\rightarrow K^{*0}\gamma)} \times \frac{\mathcal{B}(\phi\rightarrow KK)}{\mathcal{B}(K^*\rightarrow K\pi)} \times \frac{\epsilon_{sel}^{B_s^0\rightarrow\phi\gamma}}{\epsilon_{sel}^{B^0\rightarrow K^{*0}\gamma}}$$

f_s gives the probability of hadronization of a b quak into a B_s meson
f_d gives the probability of hadronization of a b quark into B_d meson
If we use the same data sample, $\mathcal{L}$ and $\sigma_{pp\rightarrow \text{ b quark}}$ cancel in the ratio

Efficiencies usually have different contributions, and some of they cancel in the ratio $\rightarrow$ less systematic uncertainties

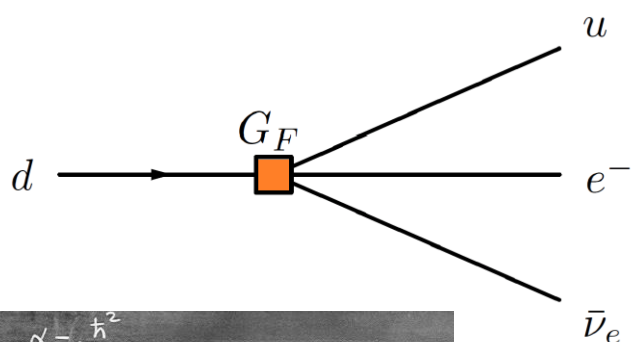
$$\epsilon_{\rm sel} = \epsilon_{\rm acc} \times \epsilon_{\rm trigger} \times \epsilon_{\rm reco} \times \epsilon_{\rm offline} \times \epsilon_{\gamma\rm PID} \times \epsilon_{tr\rm PID}$$

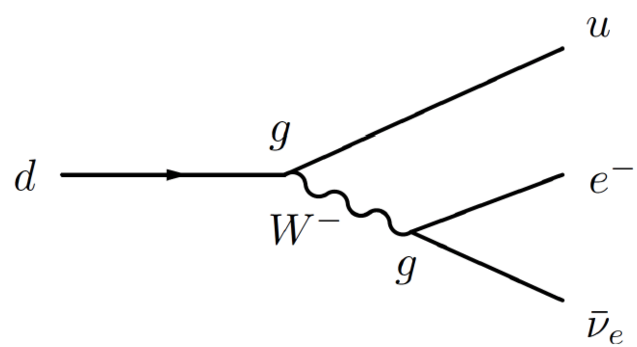
Detector geometry | event selection | event reconstruction | Background subtraction

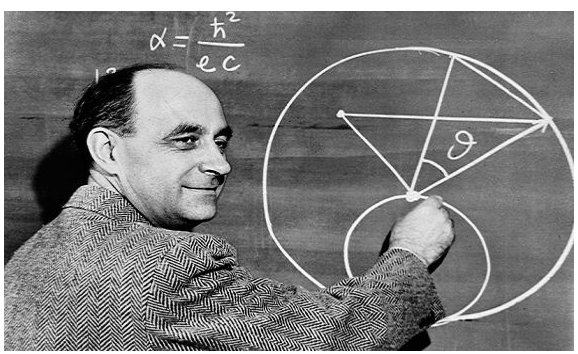
Rare decays of B mesons

How do we compute expected values?

Remind the Fermi's theory of the β decay:
We can consider the 4-point fermion vector current, coupled under Fermi's Coupling Constant G_F.







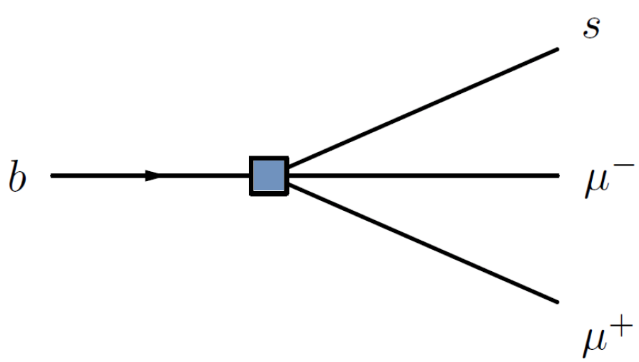
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

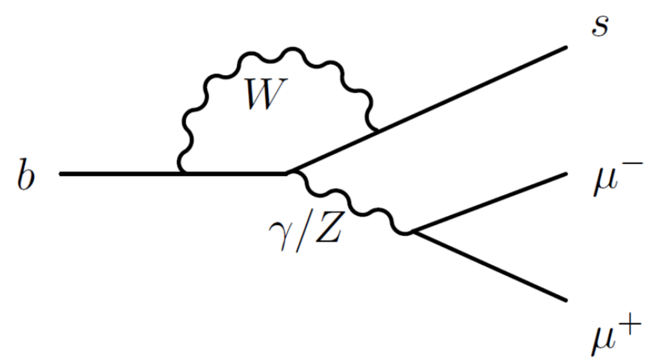
One can consider any description depending on the energy scale we are working on

Rare decays of B mesons

How do we compute expected values?

Same idea for FCNC processes:





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

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

CKM couplings

Wilson Coefficients (μ = scale)

Hadronic Matrix Elements

Rare decays of B mesons

→ OPE: a series of effective vertices multiplied by effective coupling constants ***Cᵢ***.

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 → right handed currents: suppressed in SM

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 decays of B mesons

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

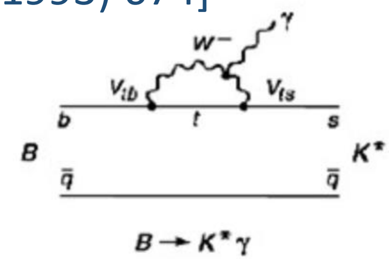
Some examples of dependences in B decays:

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \rightarrow X_s\gamma$	X		
$B \rightarrow K^*\gamma$	X		
$B \rightarrow X_s\mu^+\mu^-$	X	X	X
$B \rightarrow K\mu^+\mu^-$	X	X	X
$B \rightarrow K^*\mu^+\mu^-$	X	X	X
$B_s \rightarrow \mu^+\mu^-$			X

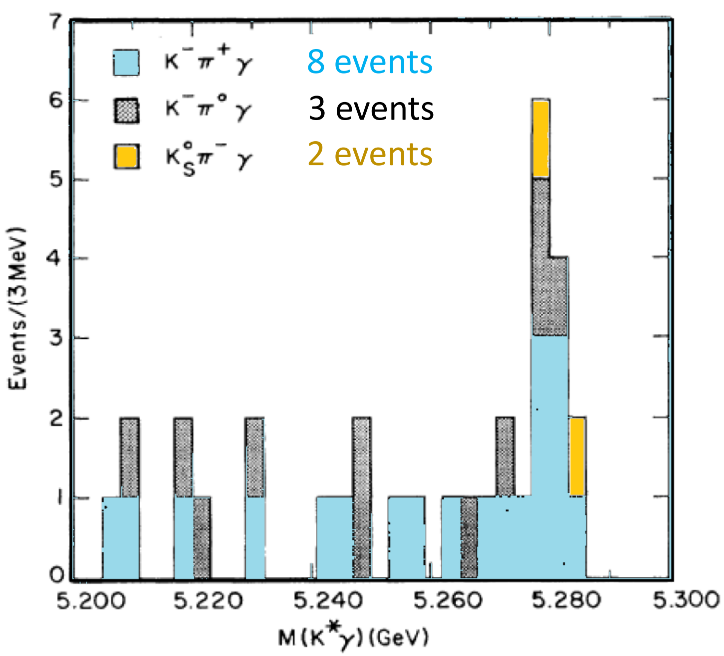
Rare decays of B mesons B→K*γ

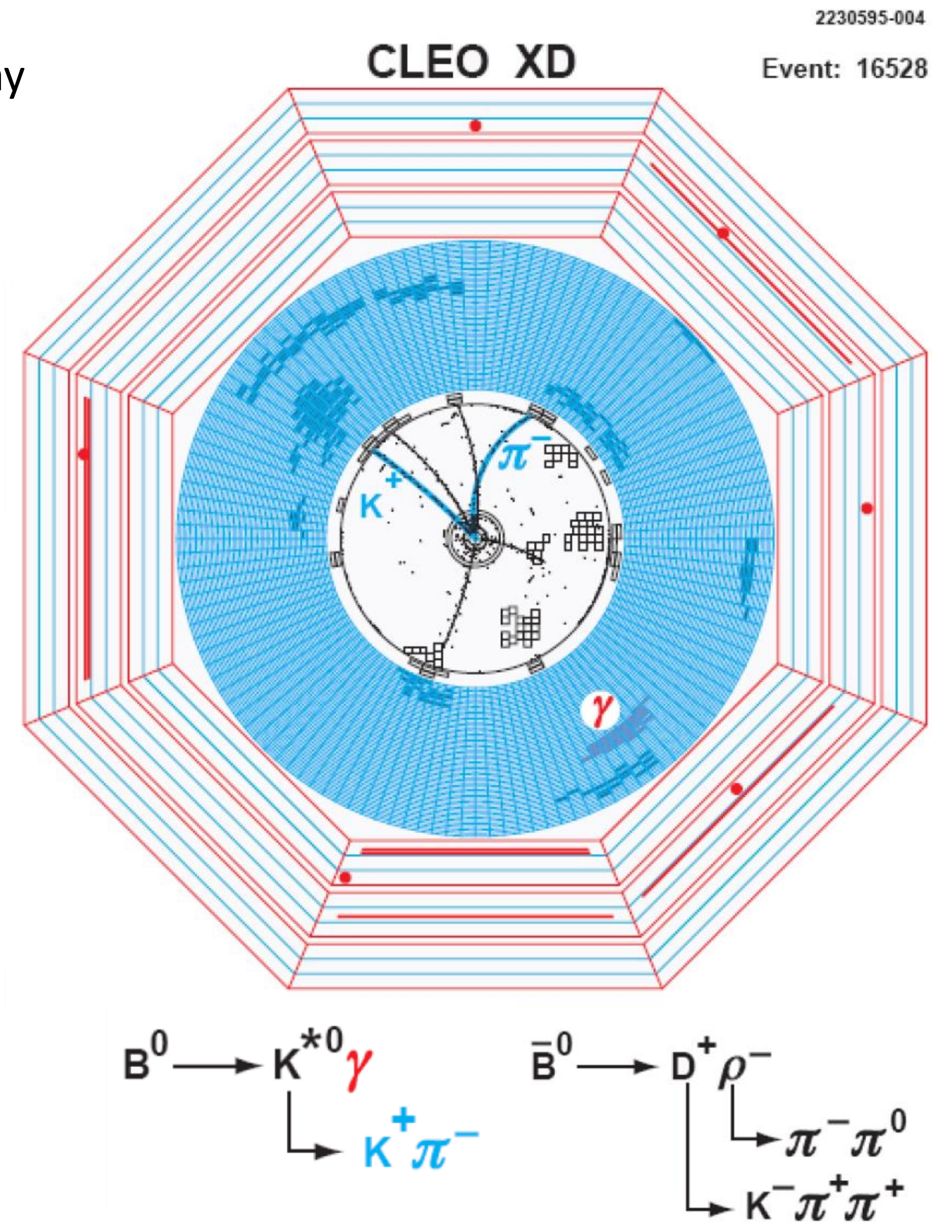
First measurement of the radiative decay B→K*γ at CLEO II at the Υ(4S)

[Phys.Rev.Lett. 71 (1993) 674]



1.5M $B\bar{B}$ events



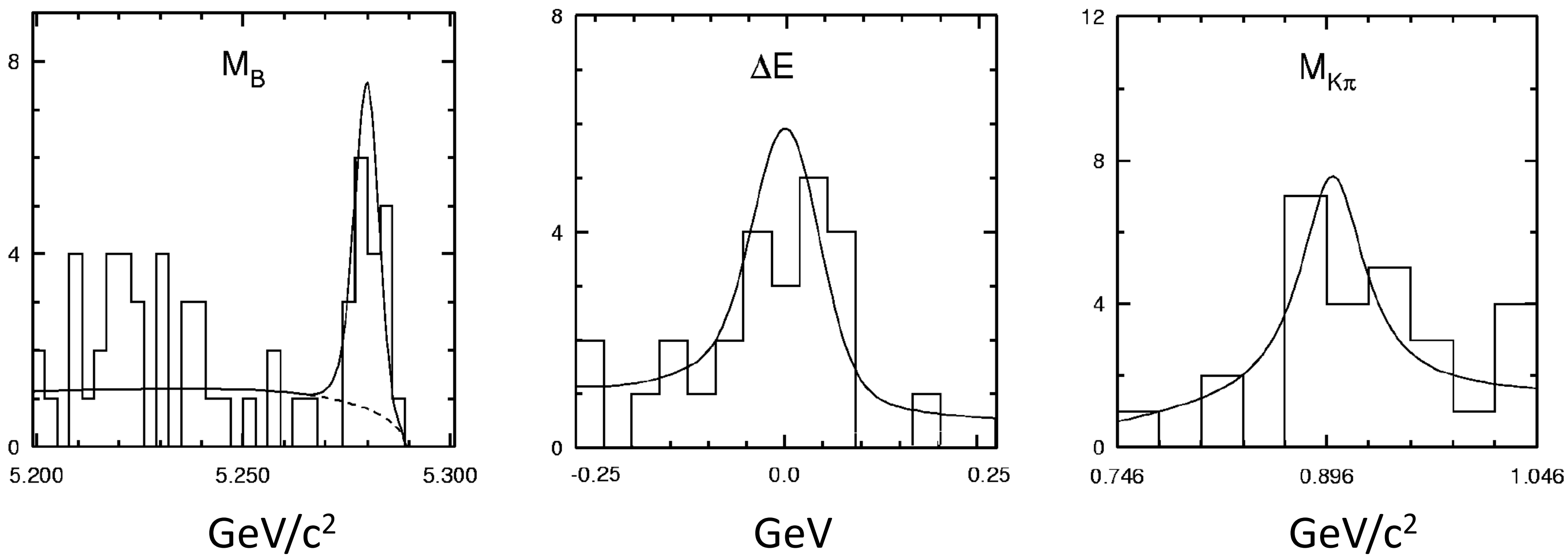


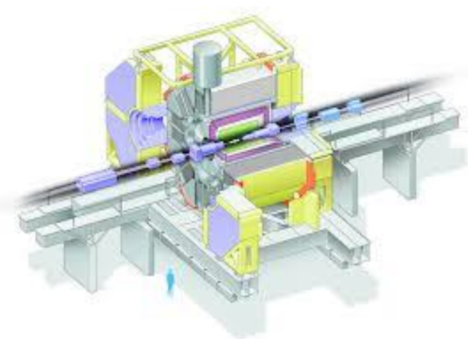
$BR(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9)\times 10^{-5}$

Rare decays of B mesons $B \to K^*\gamma$

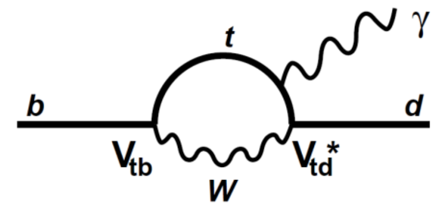
$$\Delta E = (E_{K^*} + E_\gamma) - E_{beam} \approx 0$$

$$M_B = \sqrt{E_{beam}{}^2 - (\vec{p}_{K^*} + \vec{p}_\gamma)^2}$$



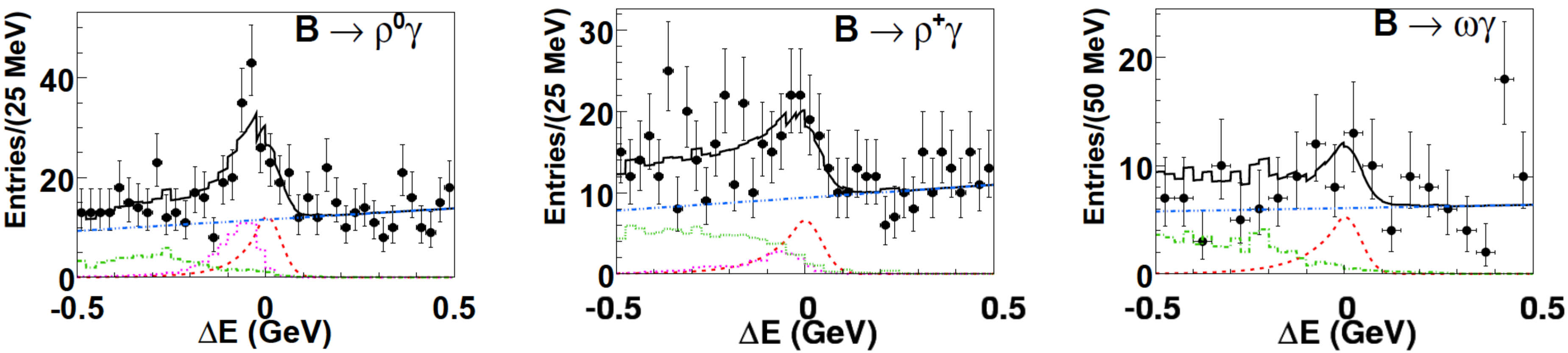


Rare decays of B mesons B→ργ



Even more suppressed: $b \to d\gamma$ at Belle (with 657 million B mesons!)

[arXiv:0804.4770 [hep-ex]]

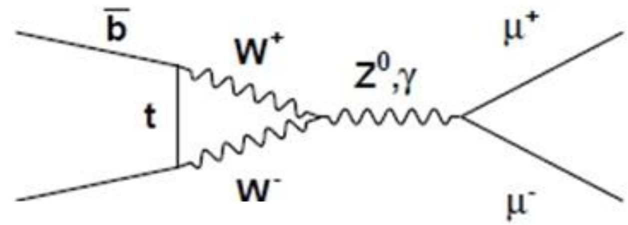


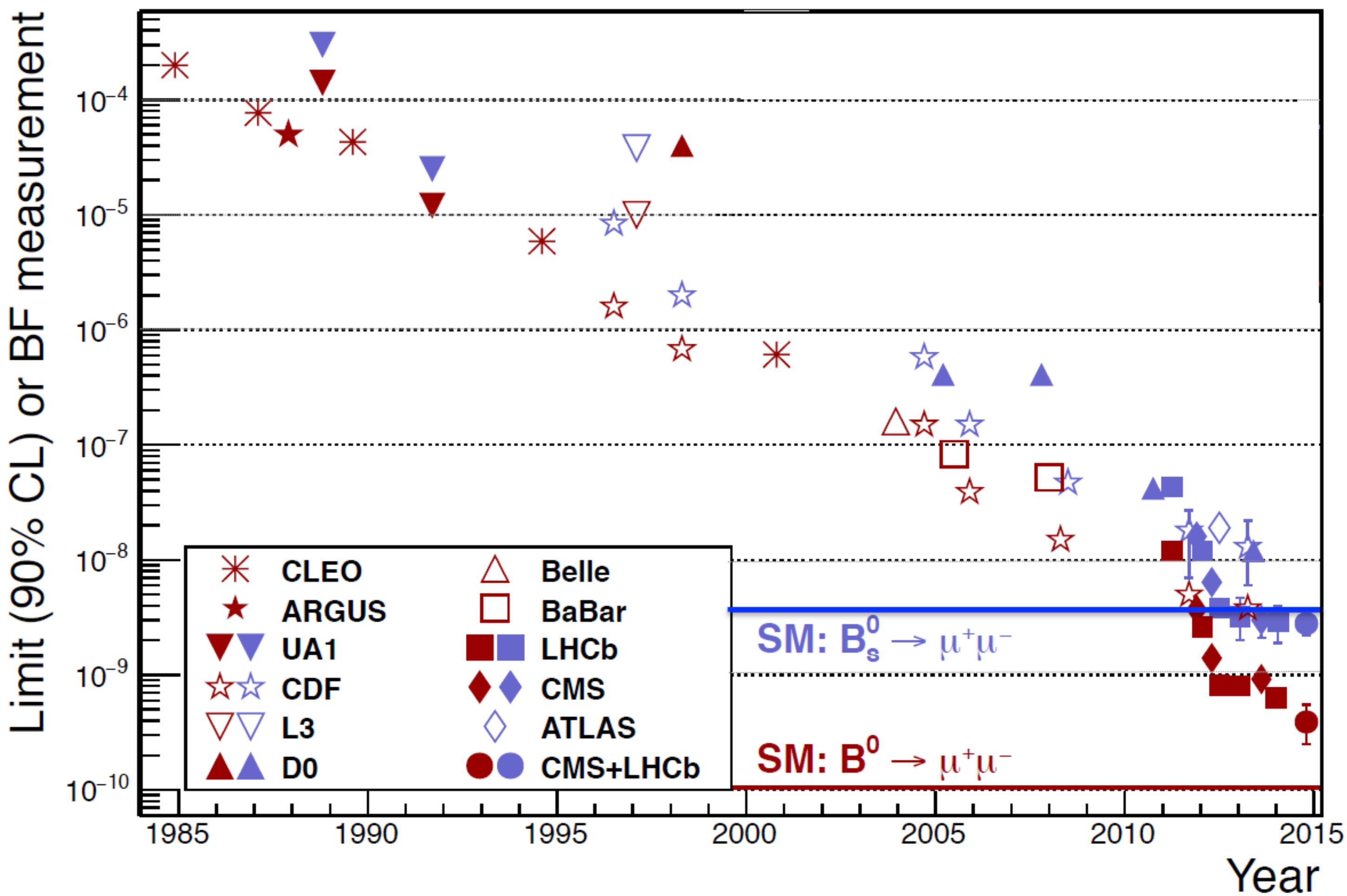
Mode	Yield	Significance	Efficiency (%)	$\mathcal{B}$ (10^{-7})
$B^+ \to \rho^+\gamma$	$45.8\,^{+15.2}_{-14.5}\,^{+2.6}_{-3.9}$	3.3	8.03 ± 0.59	$8.7\,^{+2.9}_{-2.7}\,^{+0.9}_{-1.1}$
$B^0 \to \rho^0\gamma$	$75.7\,^{+16.8}_{-16.0}\,^{+5.1}_{-6.1}$	5.0	14.81 ± 0.95	$7.8\,^{+1.7}_{-1.6}\,^{+0.9}_{-1.0}$
$B^0 \to \omega\gamma$	$17.5\,^{+8.2}_{-7.4}\,^{+1.1}_{-1.0}$	2.6	6.58 ± 0.76	$4.0\,^{+1.9}_{-1.7} \pm 1.3$

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

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

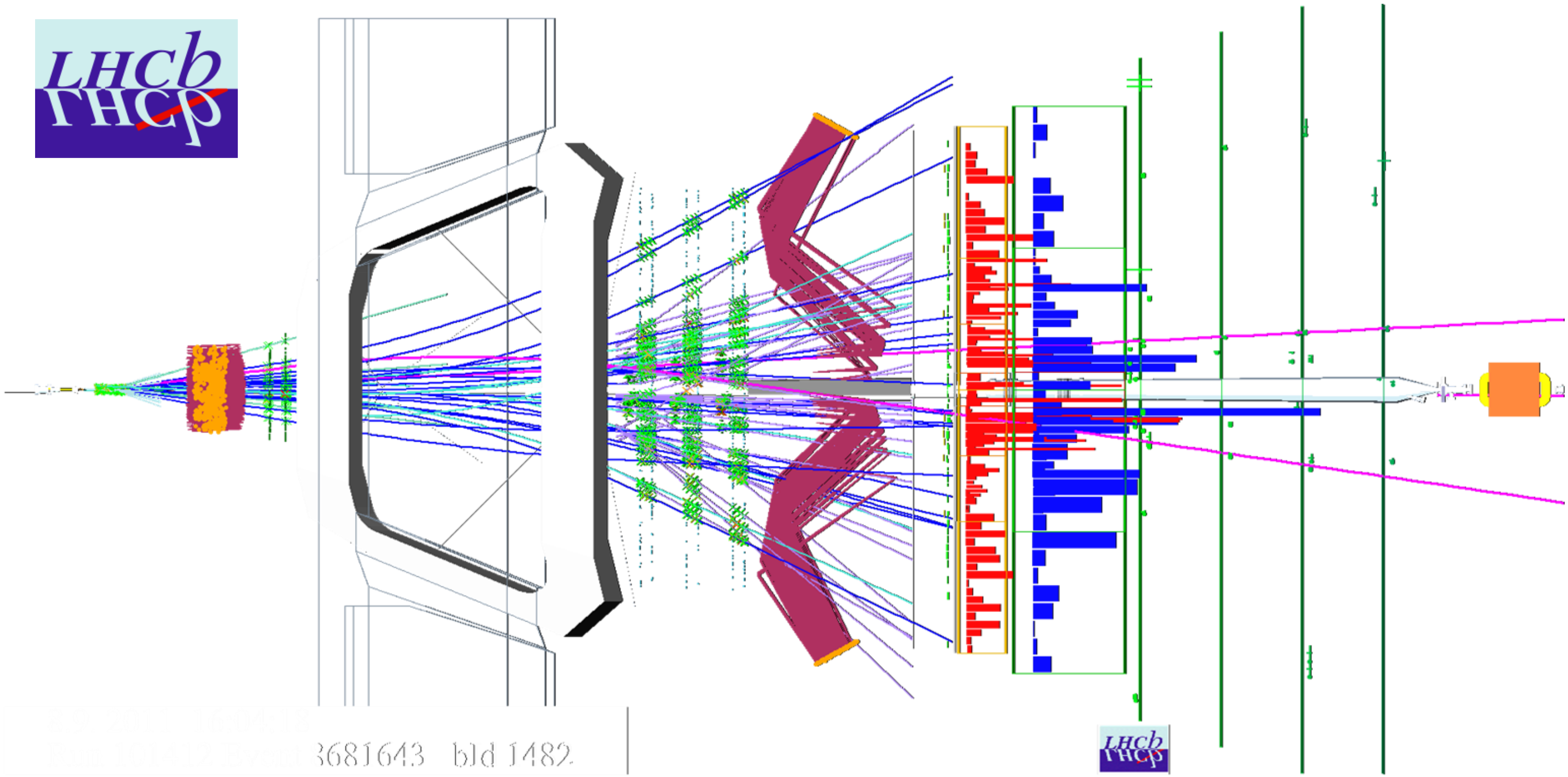
- Searched for over the last 30 years,
  observed by LHCb and CMS [Nature 522 (2015) 68]





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

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

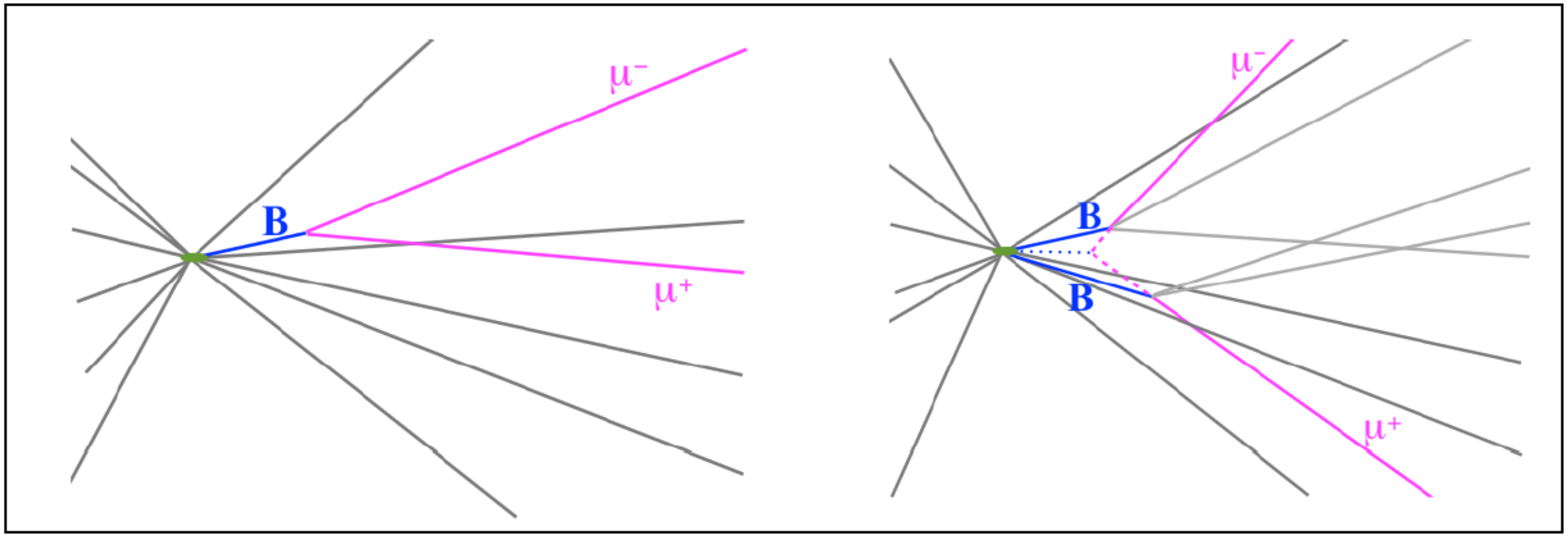


Rare decays of B mesons: $B_s \rightarrow \mu^+\mu^-$

A lot of events with two muons, very difficult to distinguish them:

- Background: BR($B \rightarrow X\mu^+$) = 10^{-1}
- Signal: BR($B_s^0 \rightarrow \mu^+\mu^-$) < 10^{-8}

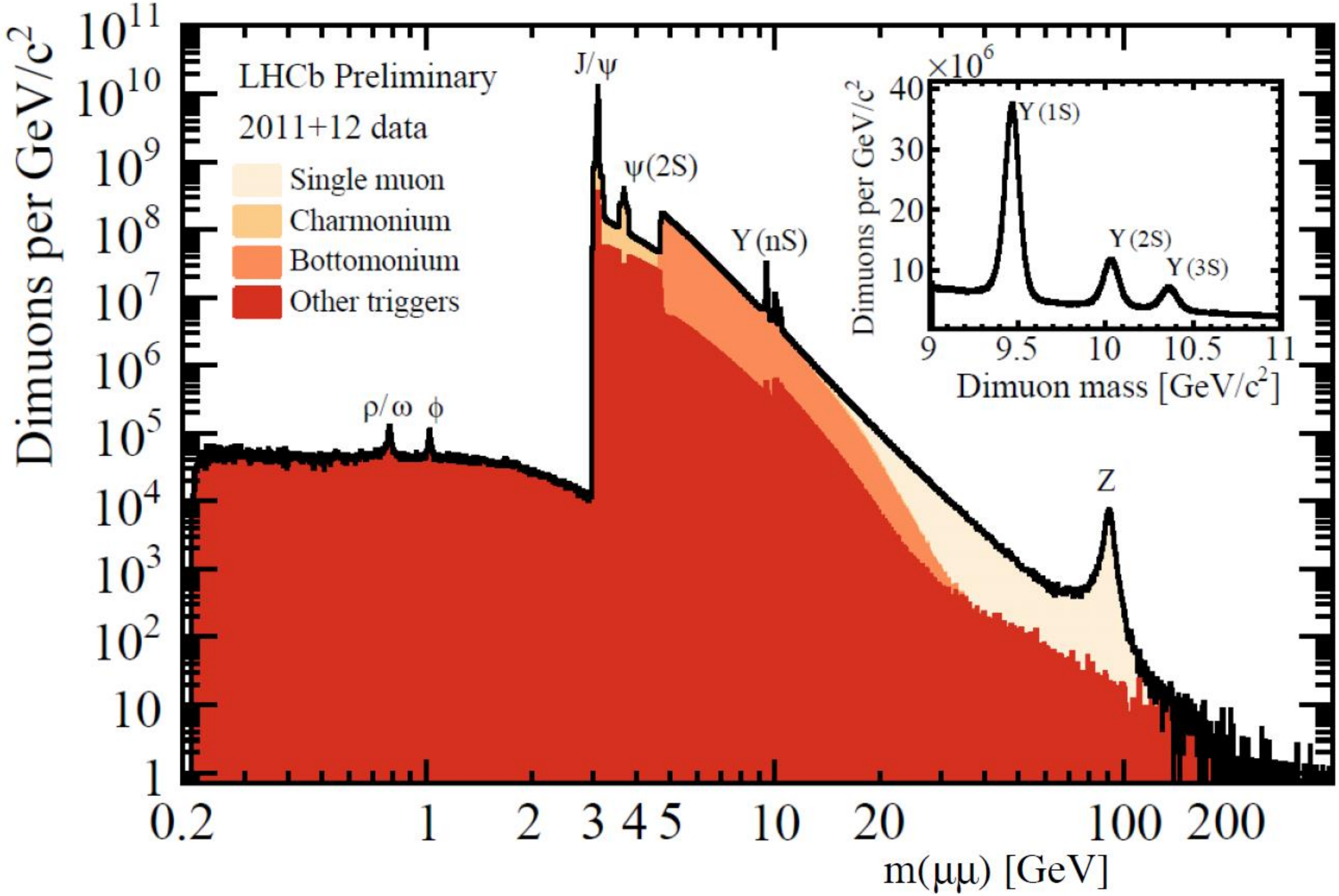
10^{12} B events produced, BR ~10^{-9}, Eff~5% → expected ~ 50 events



Thesis S.Oggero (2013)

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

And many resonances…

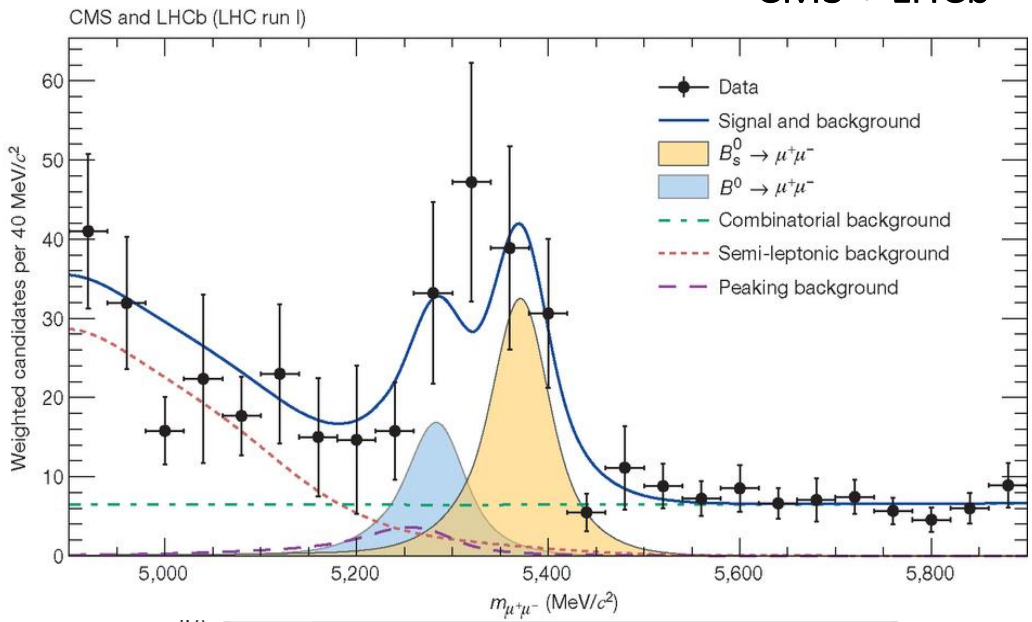


Rare decays of B mesons: $B_s \to \mu^+\mu^-$

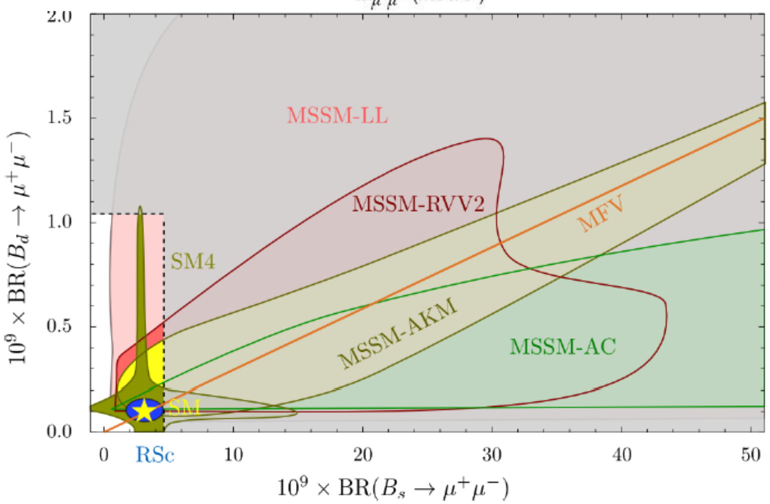
→ First evidence by LHCb and CMS in 2012!

CMS + LHCb

[Nature 522, 68–72 (2015)]



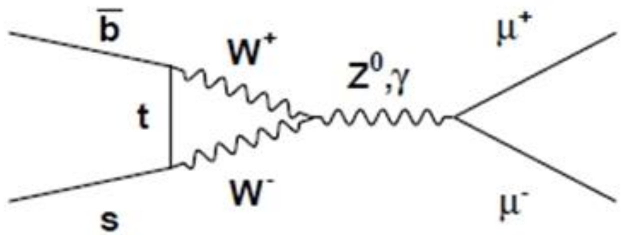
→ New Physics constraints:

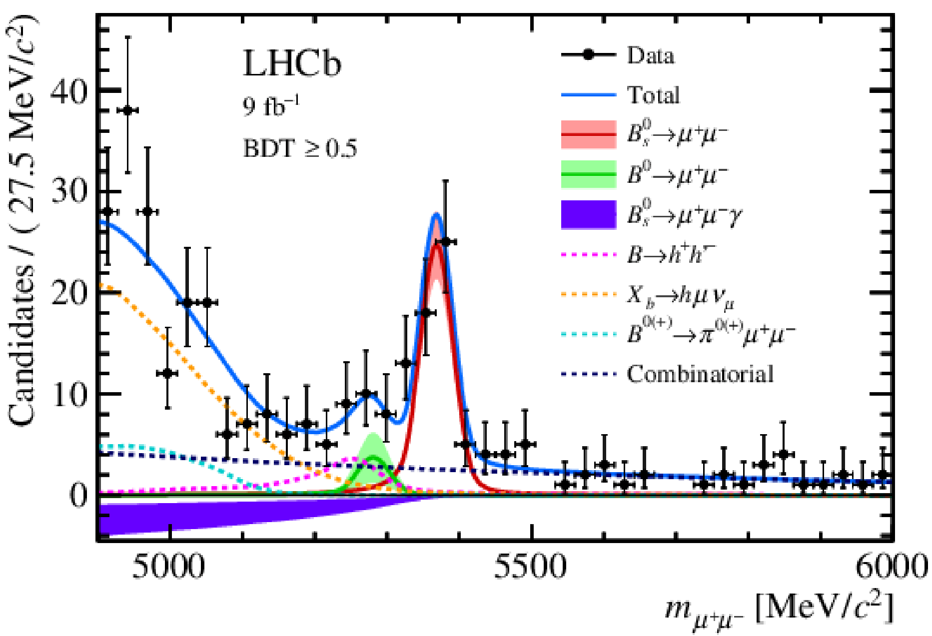


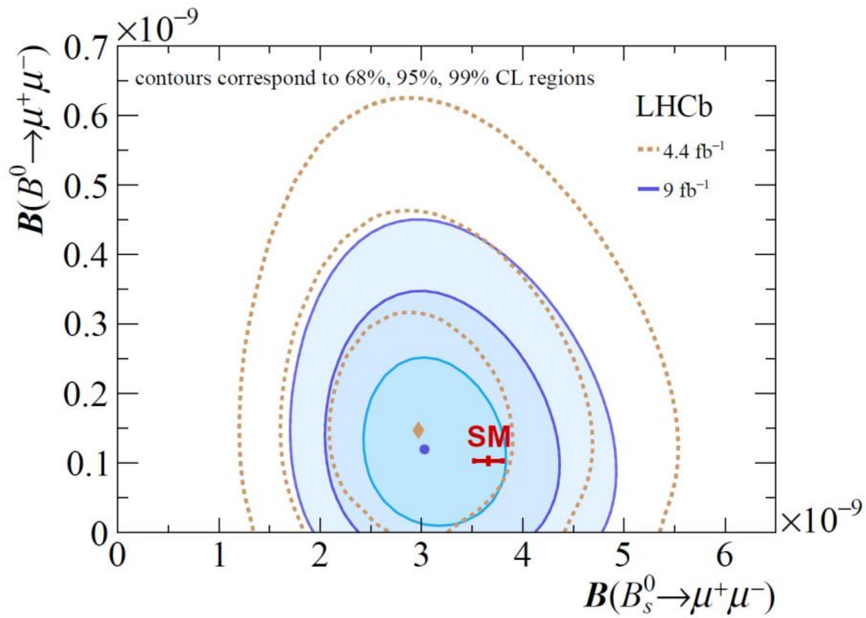
Rare decays of B mesons: $B_s \to \mu^+\mu^-$

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

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







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

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

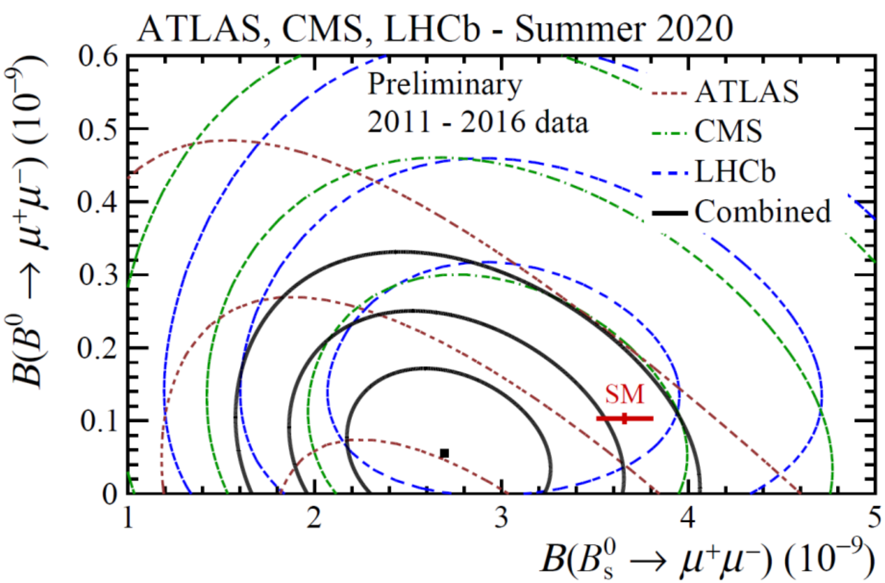
Rare decays of B mesons: $B_s \to \mu^+\mu^-$

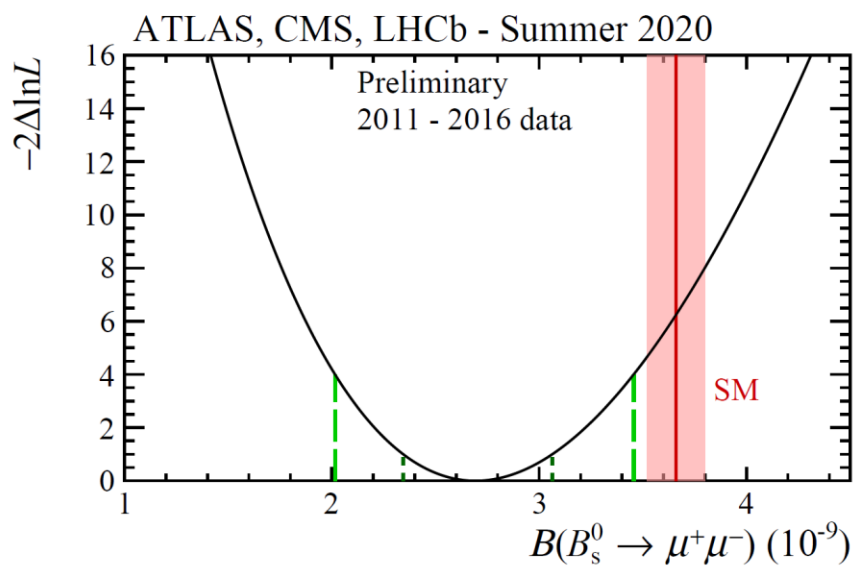
- Also measured by ATLAS and CMS (2011-2016 data), combined result*:

[CMS PAS BPH-20-003]

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

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



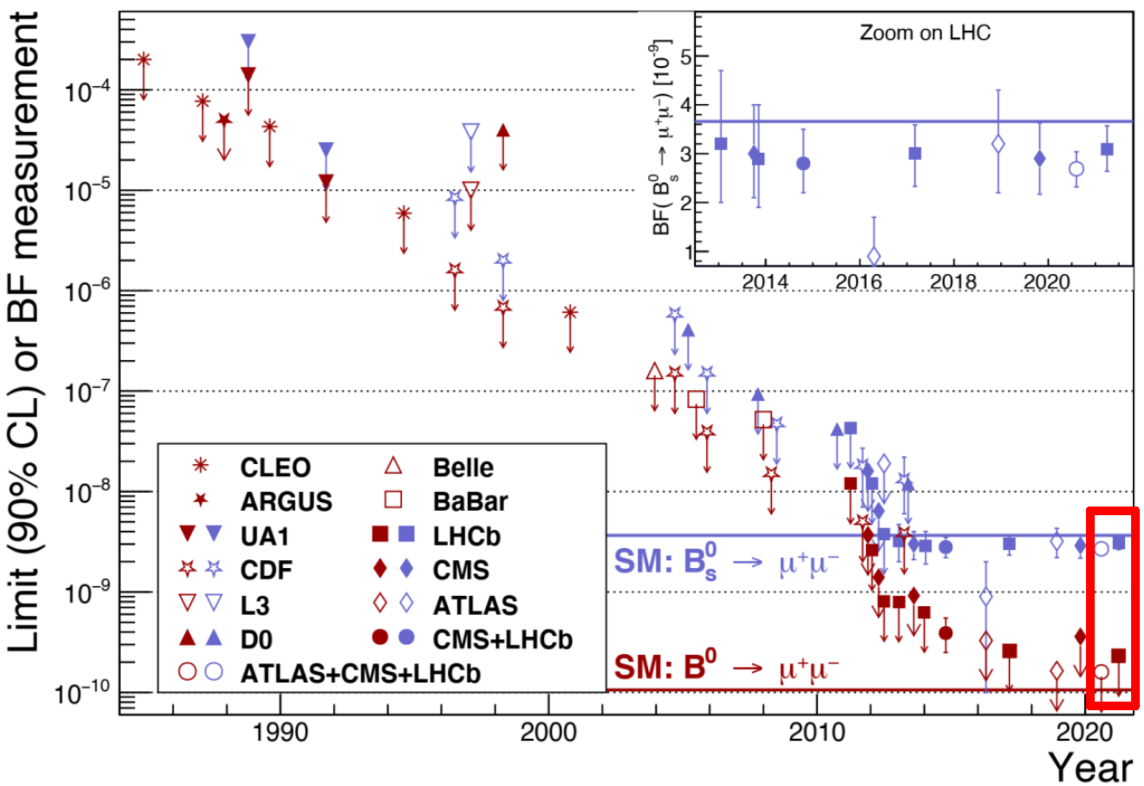


Below, but compatible with the SM at 2.1σ

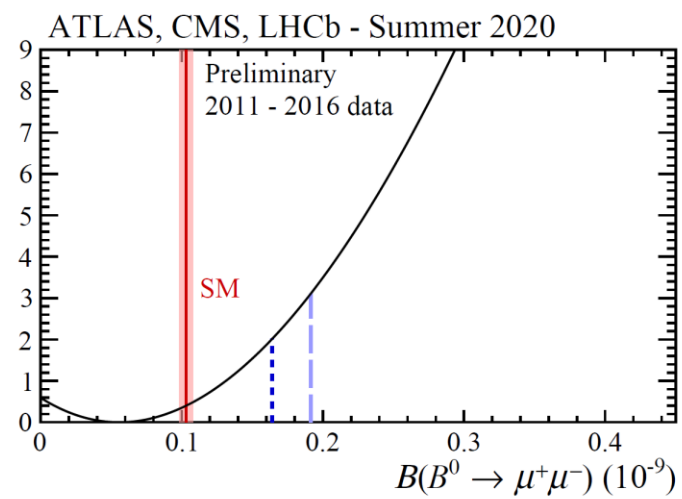
* Result from LHCb with partial statistics

Rare decays of B mesons: $B^0 \to \mu^+\mu^-$

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



[CMS PAS BPH-20-003]



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

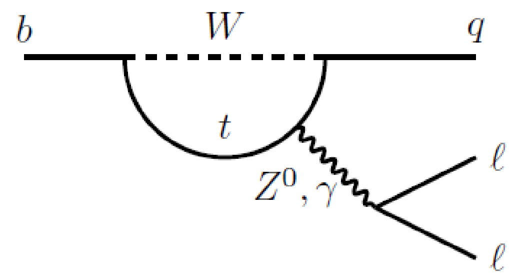
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$ *

* Result from LHCb with partial statistics

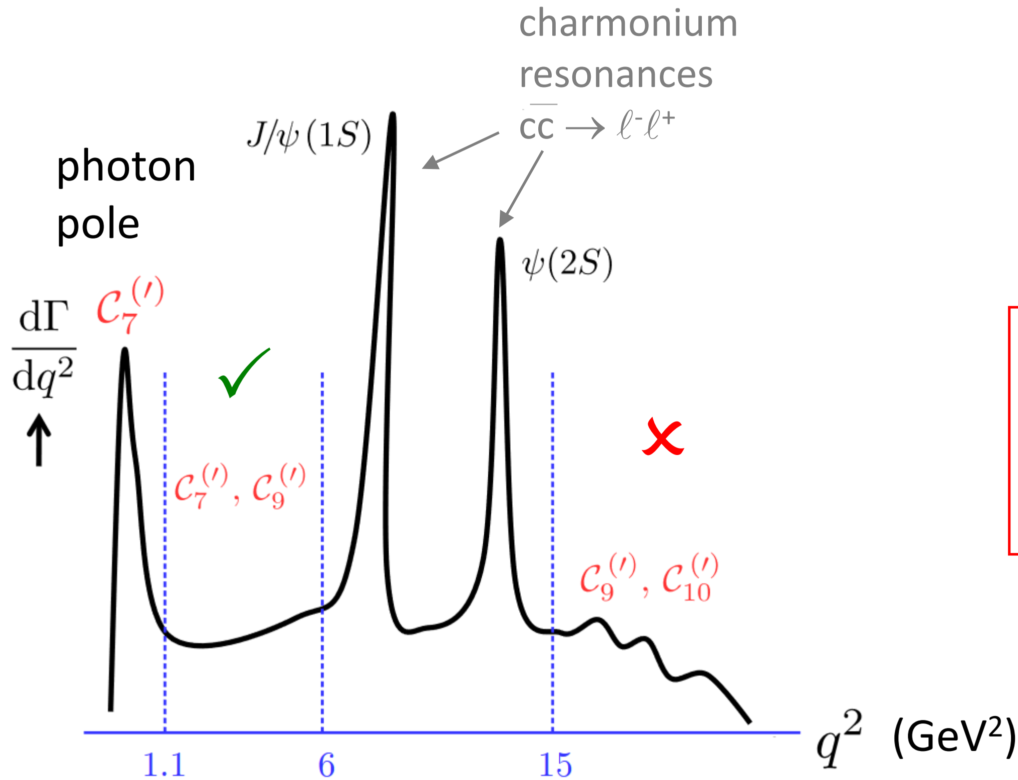
Rare decays of B mesons: $B \to h\,\mu^+\mu^-$

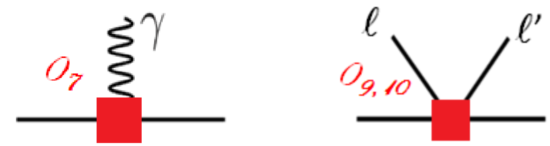
- Differential decay width: $d\Gamma/dq^2$

Each q^2 region probes different processes



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





SM values ($\mu = m_b$): $C_7 \sim -0.33$

$C_9 \sim 4.27$

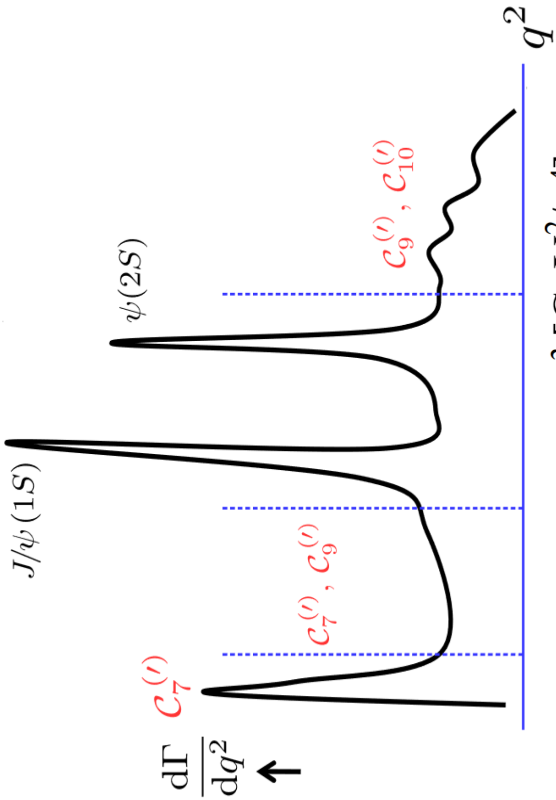
$C_{10} \sim -4.17$

(Everything else small or negligible)

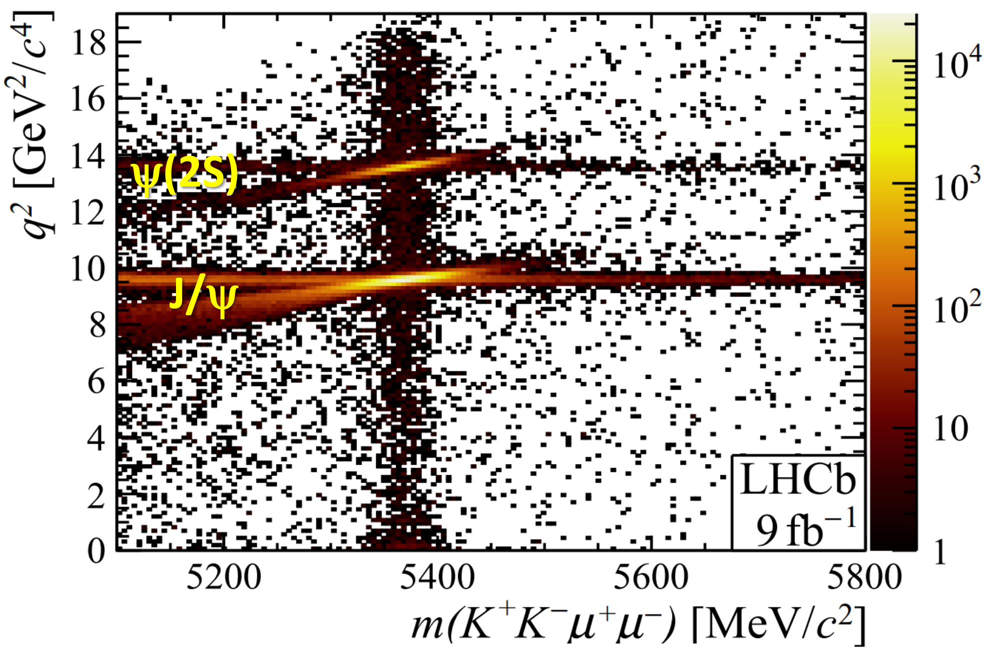
$C_i = C_i^{SM} + C_i^{NP}$

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

Rare decays of B mesons: $B \to h\, \mu^+\mu^-$

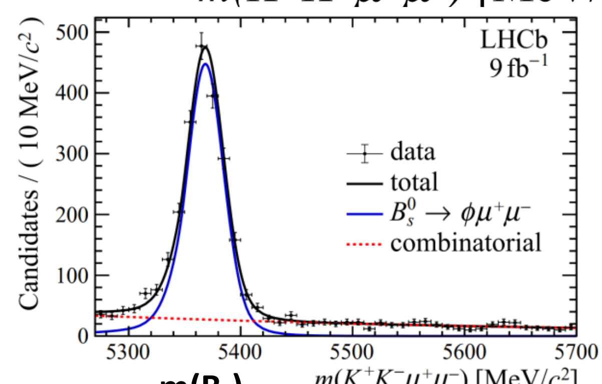


B_s mass vesus q^2 for $B_s \to \phi\mu^+\mu^-$



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

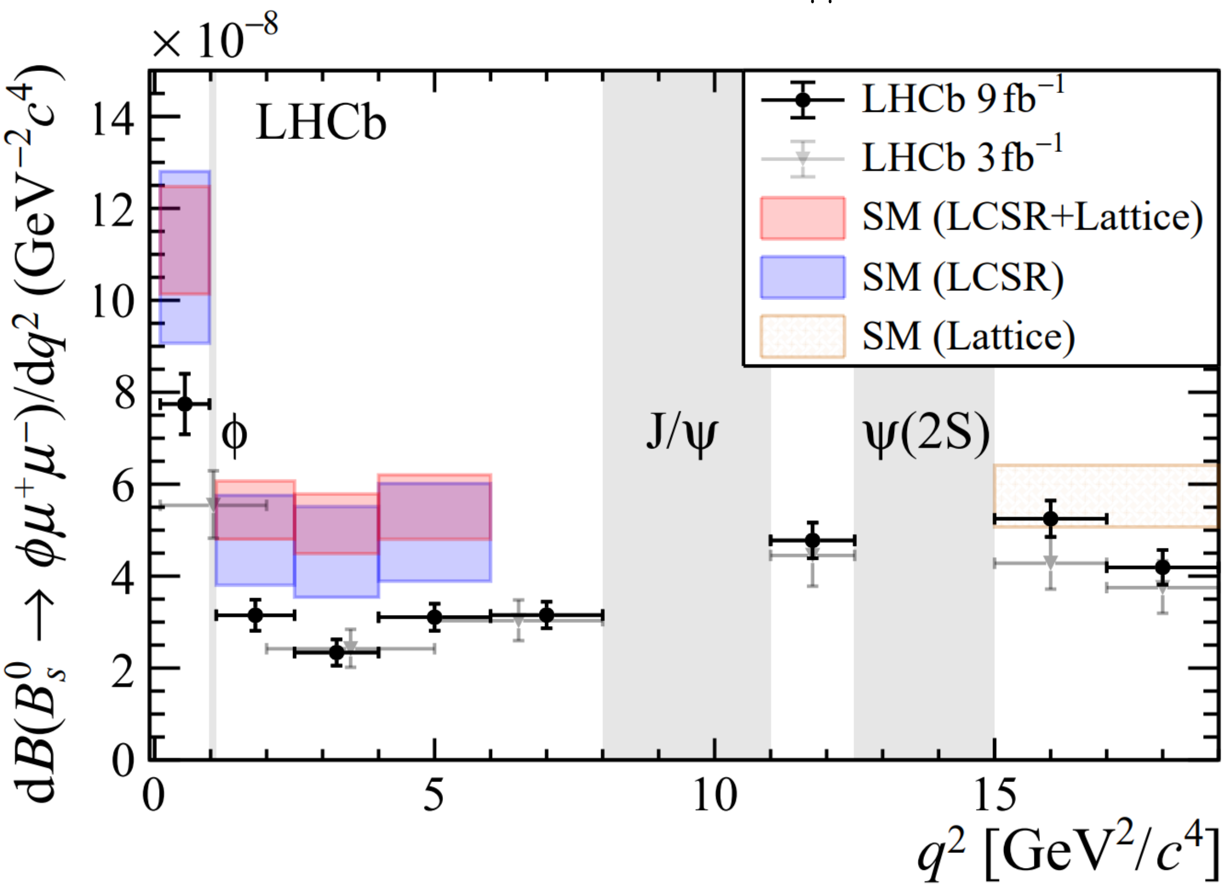
[arXiv:2105.14007]



m(B_s)

Rare decays of B mesons: $B \to h\,\mu^+\mu^-$

- Differential decay width as function of $q^2 = m^2_{\mu\mu}$



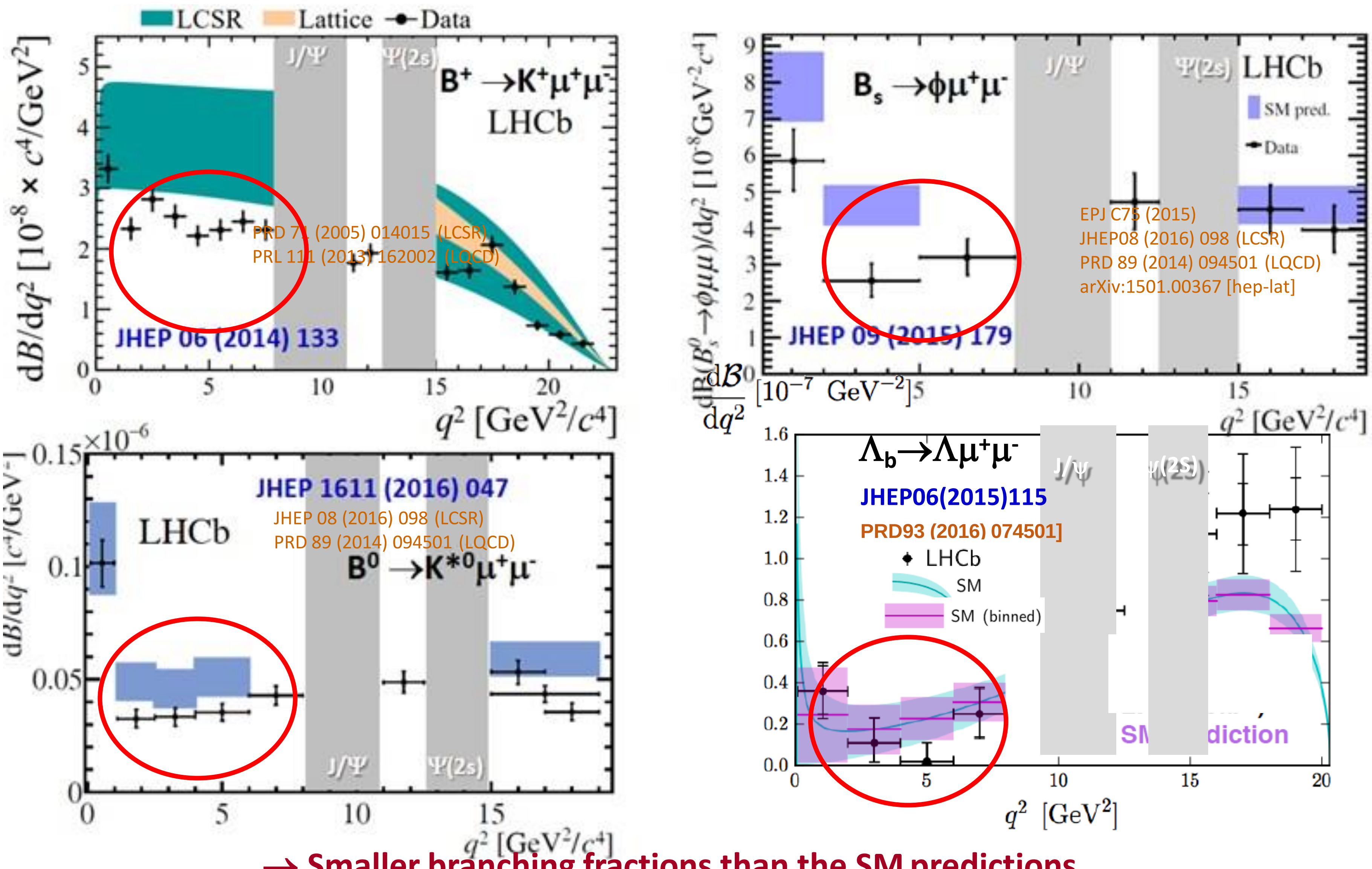
[arXiv:2105.14007]

In the q^2 region 1.1-6 GeV^2 →

3.6σ away from SM predictions

Rare decays of B mesons: $B \to h\,\mu^+\mu^-$

Results in other channels:

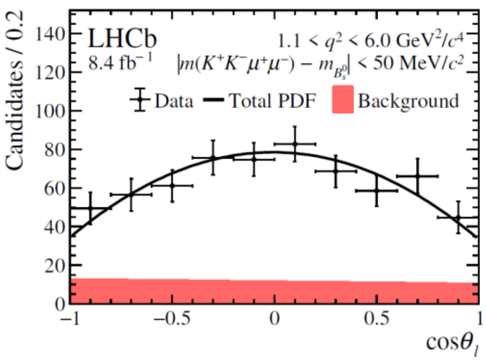


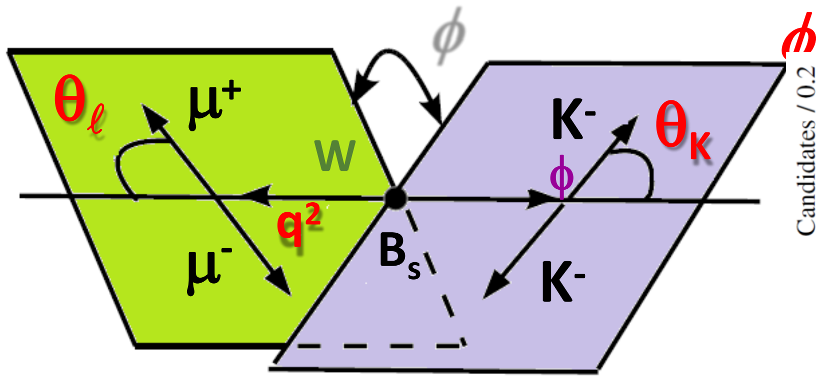
→ Smaller branching fractions than the SM predictions

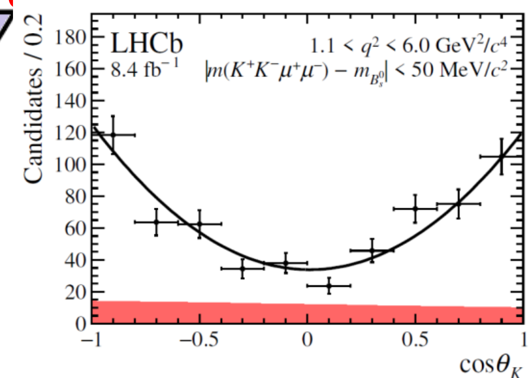
Rare decays of B mesons: $B \to h\,\mu^+\mu^-$

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

[arXiv:2107.13428]





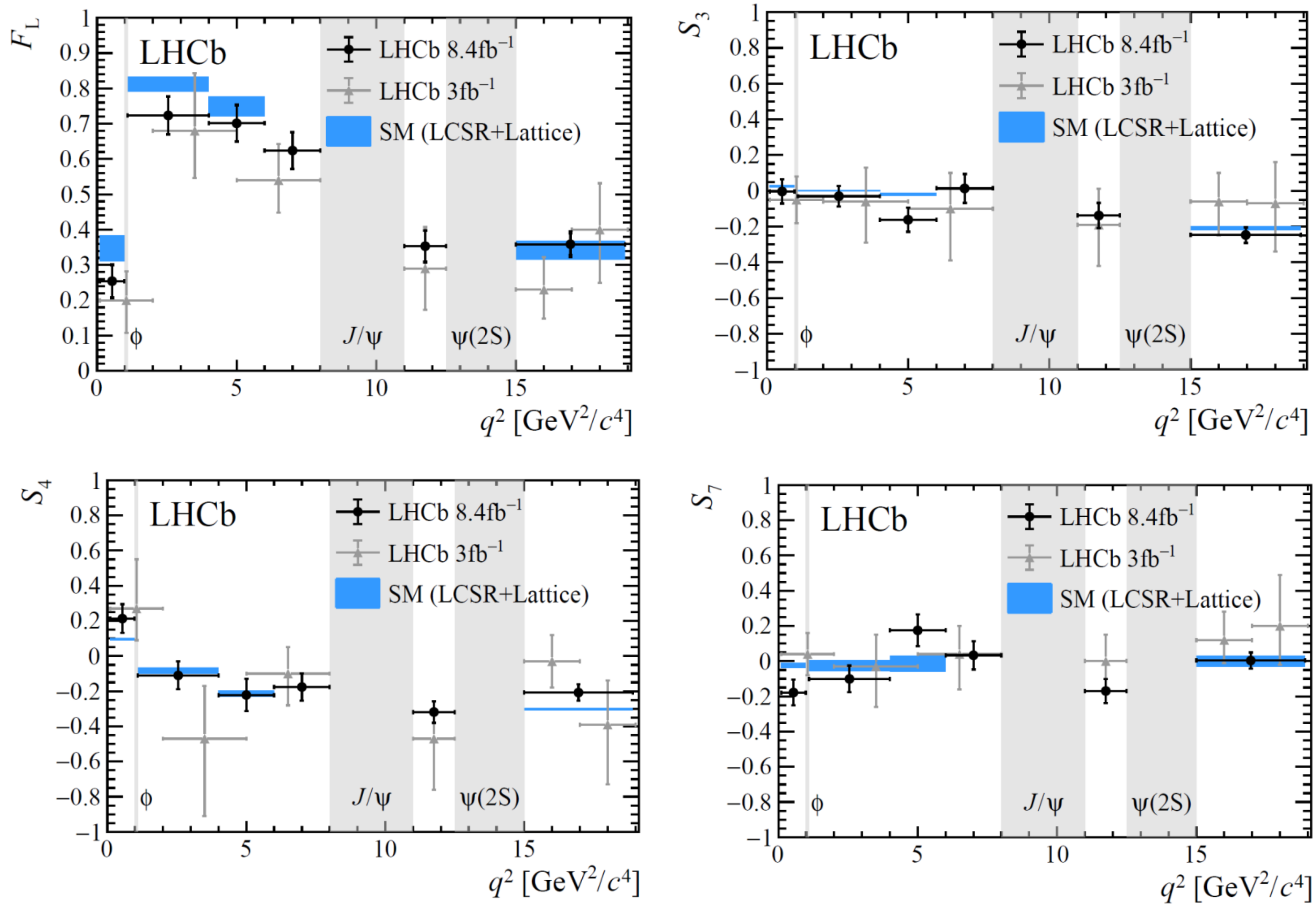


$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_l) \\
&+F_\mathrm{L}\cos^2\theta_K(1-\cos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

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

F_L , A_{FB}, S_i , A_i

Rare decays of B mesons: $B \rightarrow h\, \mu^+\mu^-$



→In general good agreement with SM, deviations less than 2σ

Rare decays of B mesons: $B \to h\,\mu^+\mu^-$

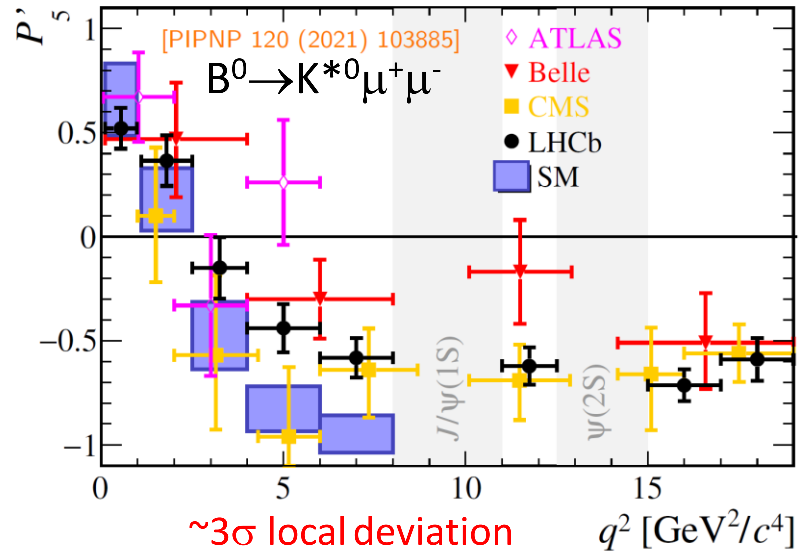
[JHEP 10 ('18) 047]
[PRL 118 ('17) 111801]
[PLB 781 ('18) 517]

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

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

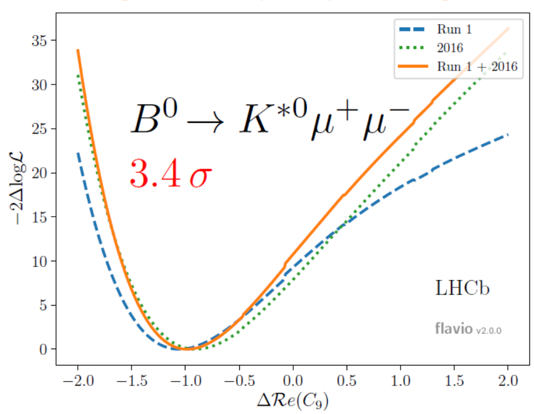
Two new analyses by LHCb with full data:

- 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]

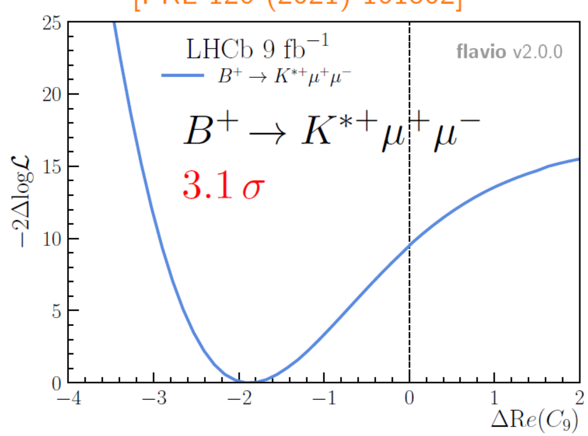


~3σ local deviation

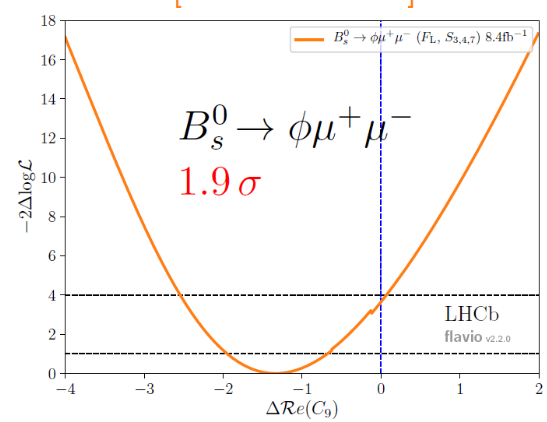
[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]



[arXiv:2107.13428]



→ Negative shift of Re(C_9) preferred over SM hypothesis at level of 2-3σ

Rare decays of B mesons: R_K

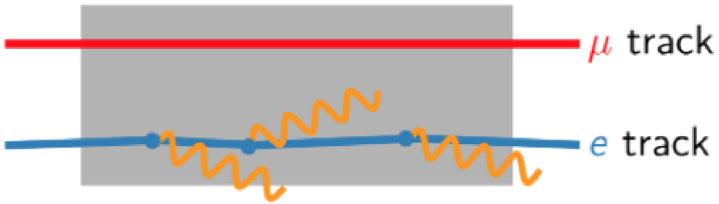
- In the SM all leptons are expected to behave in the same way

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

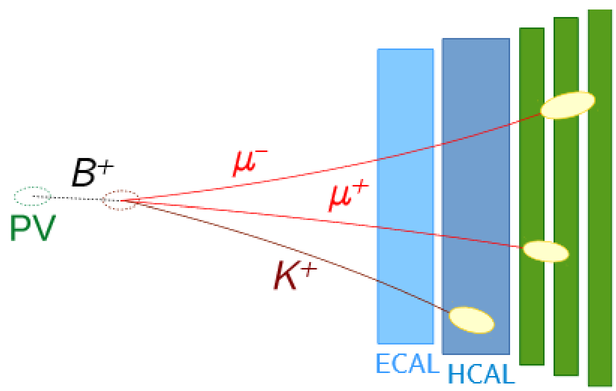


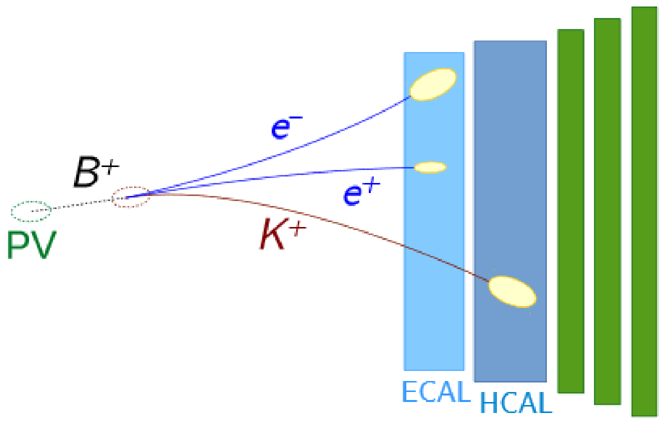
- Experimentally, we perform a double ratio to cancel systematic uncertainties

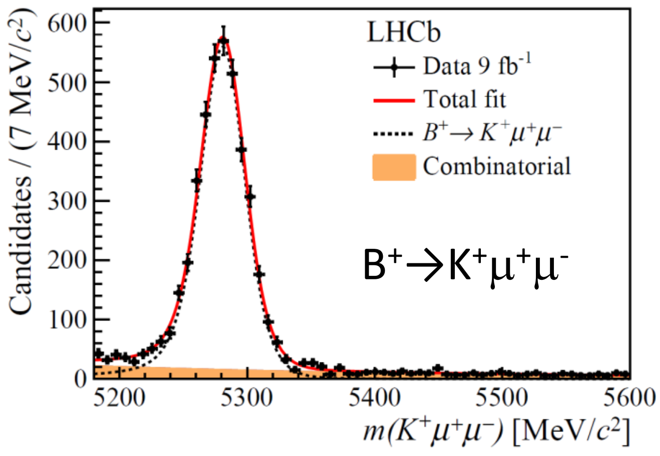
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

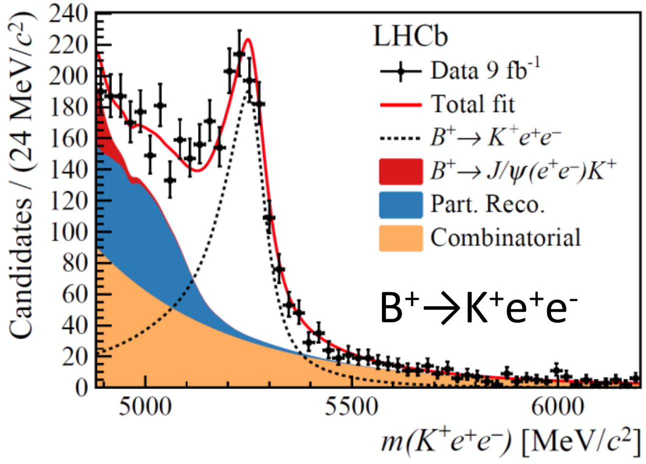
Rare decays of B mesons: R_K

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



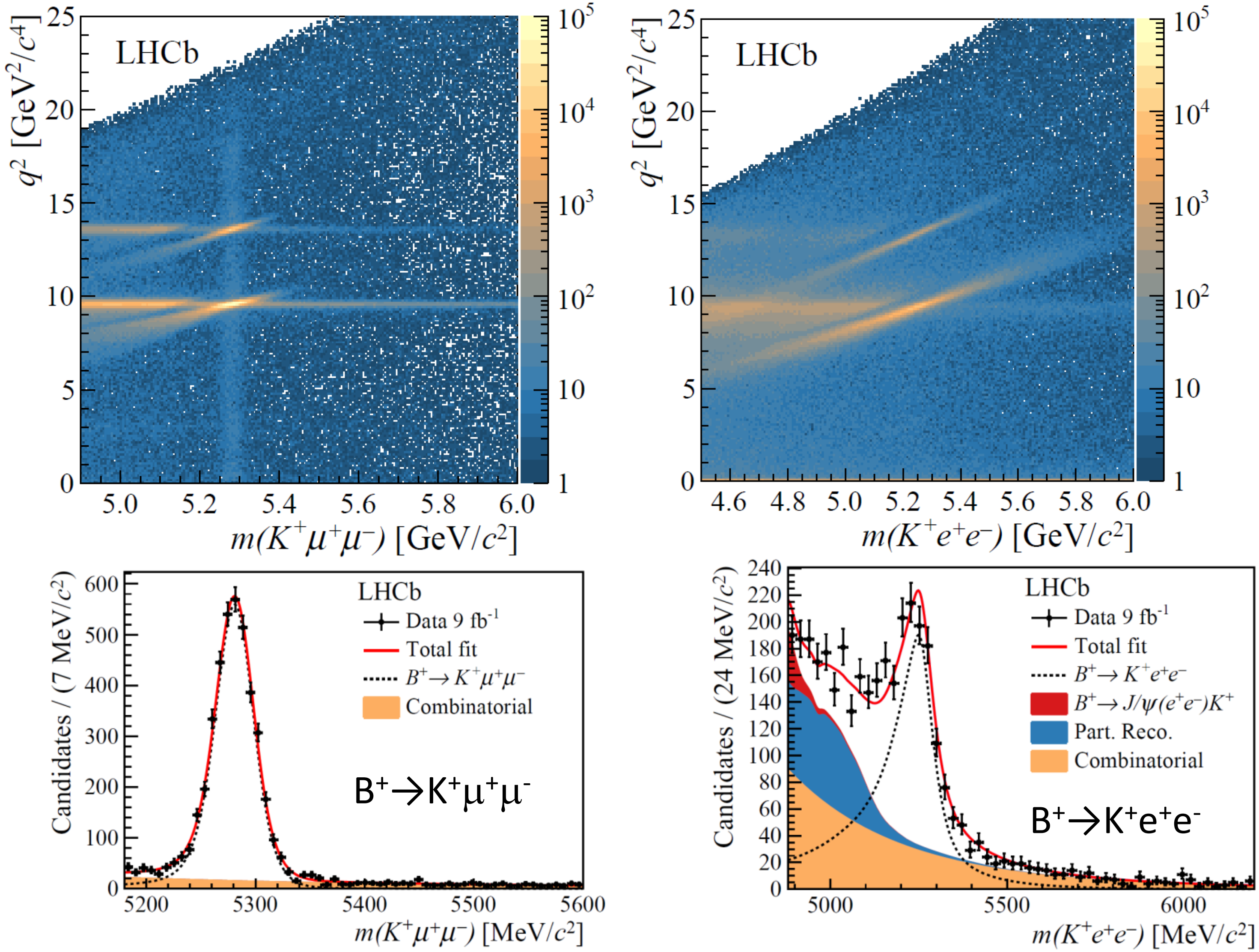






Rare decays of B mesons: R_K

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

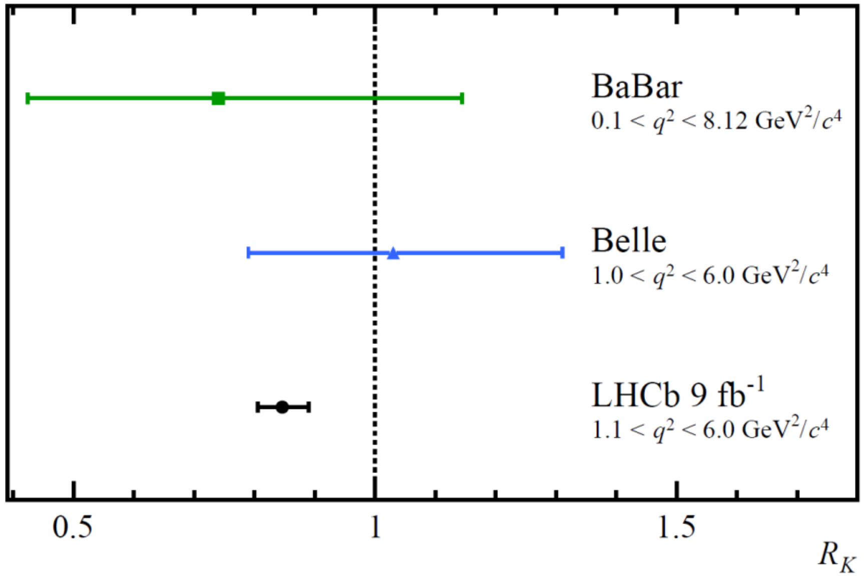


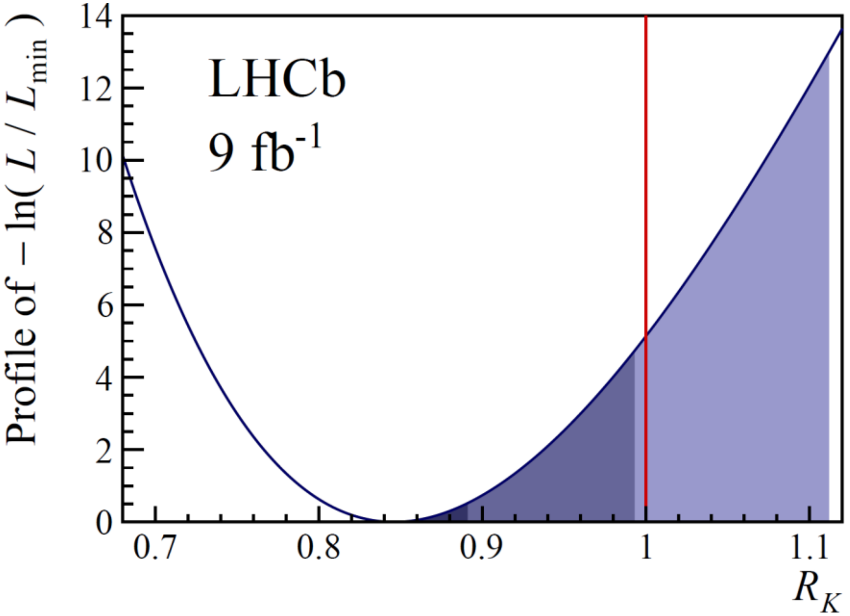
Rare decays of B mesons: R_K

Results with full LHCb data:
[arXiv:2103.11769]

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

($1\ \text{GeV}^2 < q^2 < 6\ \text{GeV}^2$)



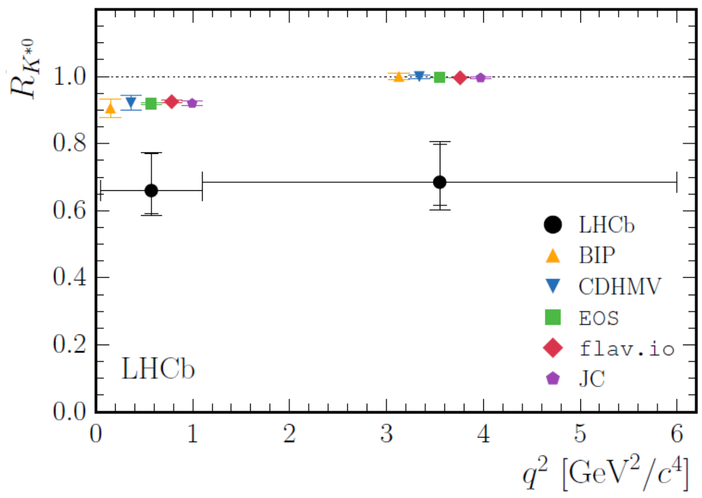


→ Deviation from SM at **3.1σ** ⇒ evidence of LFU violation

Rare decays of B mesons: R_K

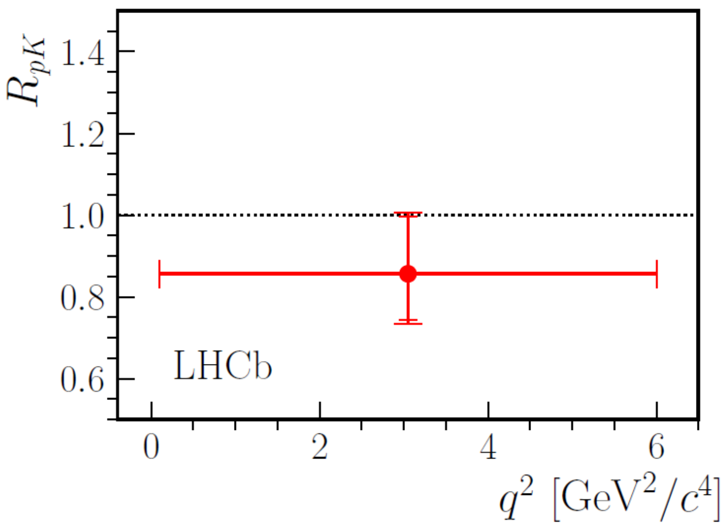
- Previous results in other channels:

➜ LHCb measurement in the $B \to K^* \mu^+ \mu^-$ channel, $\mathbf{R_{K^*}}$, with 3fb^{-1}



[JHEP 08 (2017) 055]

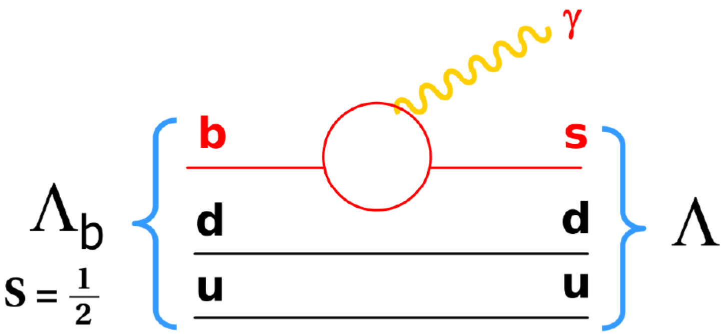
➜ LHCb measurement in the $\Lambda_b \to pK\mu^+\mu^-$ channel, $\mathbf{R_{pK}}$, with 5fb^{-1}

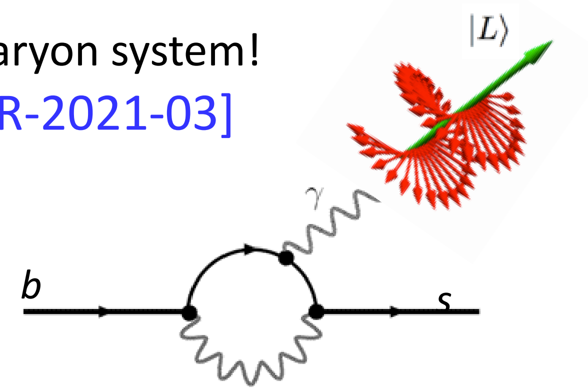


[JHEP 05 (2020) 040]

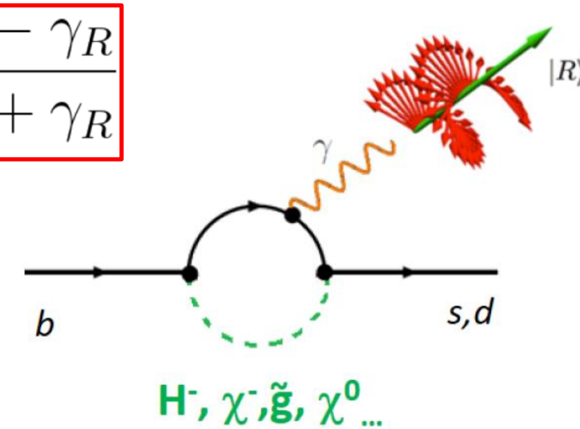
Rare decays of B mesons: b→sγ

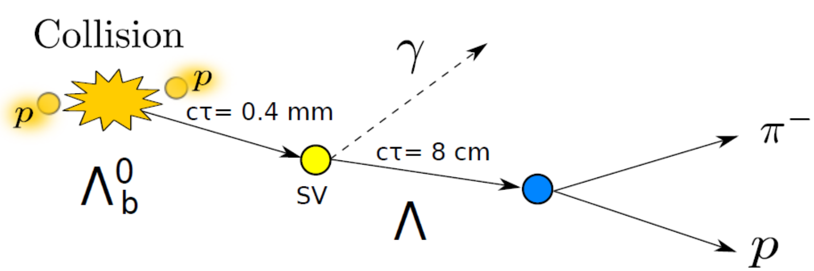
- First measurement of the **photon polarization** in a b-baryon system!
  (Expected to be left handed in the SM) [LHCb-PAPER-2021-03]





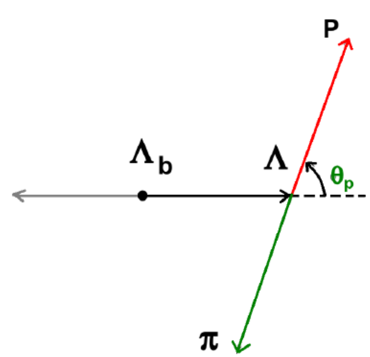
$$\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$$





Angular distribution:

$$\Gamma_{\Lambda_b} = \frac{1}{4}\left(1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p\right)$$



Rare decays of B mesons: b→sγ

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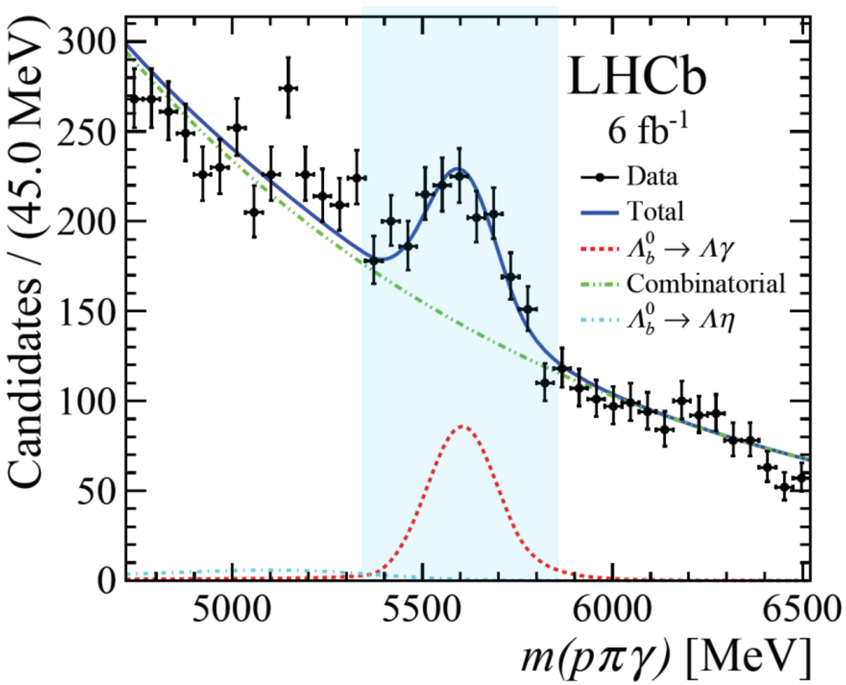
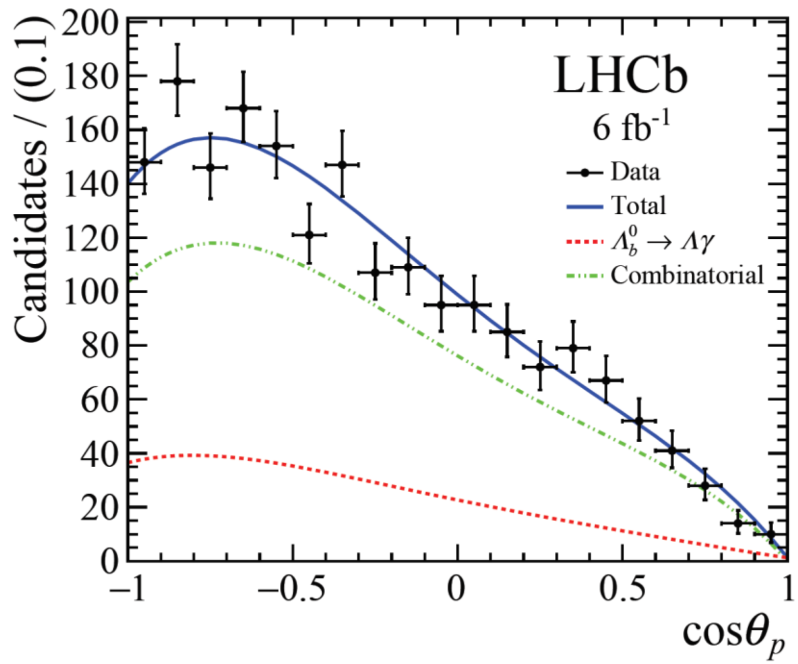
  (Expected to be left handed in the SM) [LHCb-PAPER-2021-03]



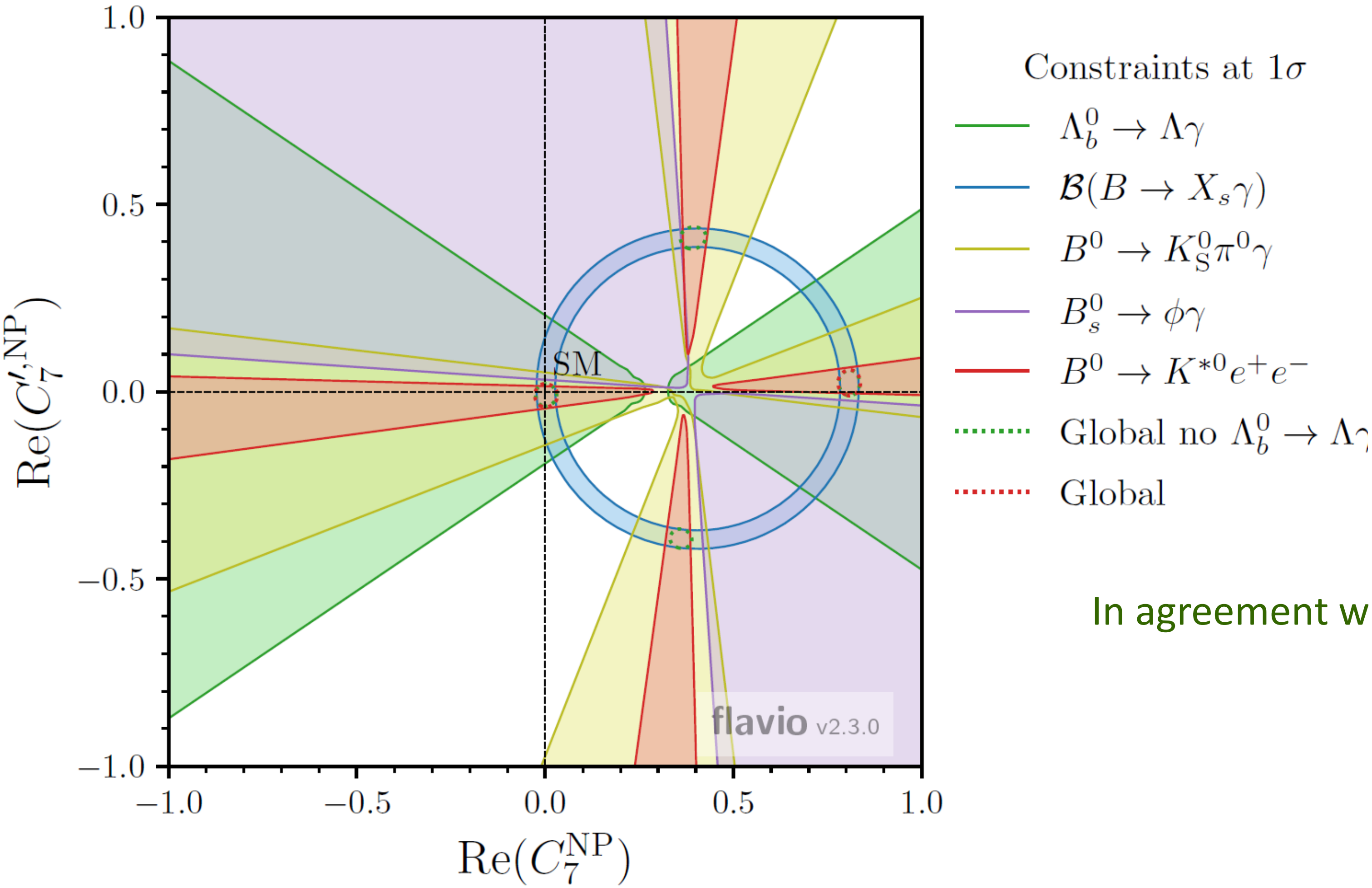


$$\alpha_\gamma = 0.82\,^{+0.17}_{-0.26}\,(\text{stat.})\,^{+0.04}_{-0.13}\,(\text{syst.})$$

In agreement with SM

Rare decays of B mesons: b→sγ

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

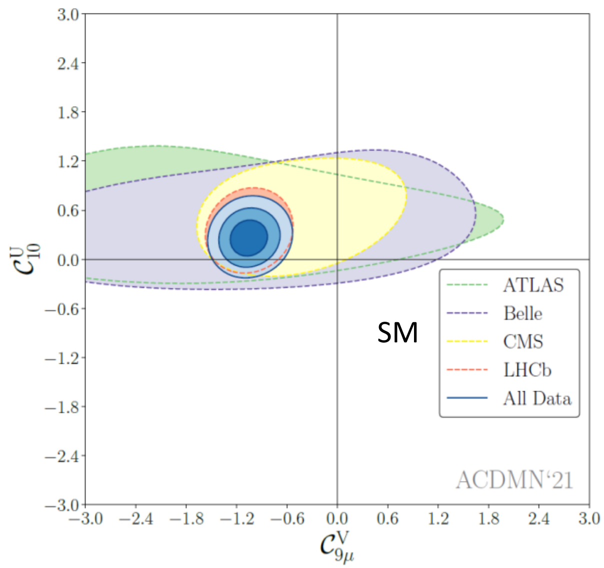


In agreement with SM

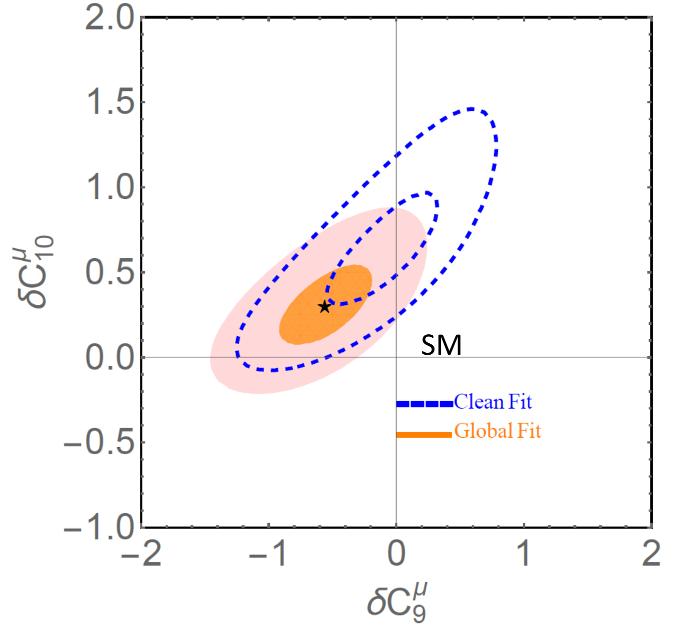
Rare decays of B mesons

Global fits (more than 100 observables)

J. Matias *et al*, arXiv:2104.08921



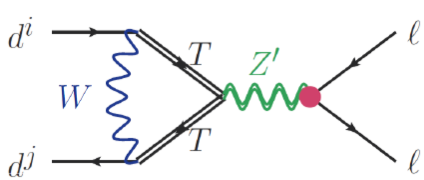
J.M. Camalich *et al*, arXiv:2103.12738

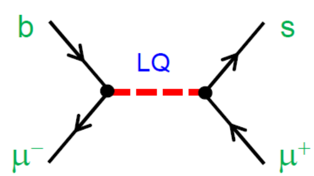


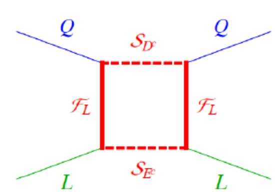
New Physics hypothesis preferred over SM by more than 4 - 5σ

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

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







Rare decays of B mesons

Just a reminder …

Particle	Indirect			Direct		
ν	β decay		1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay		1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?