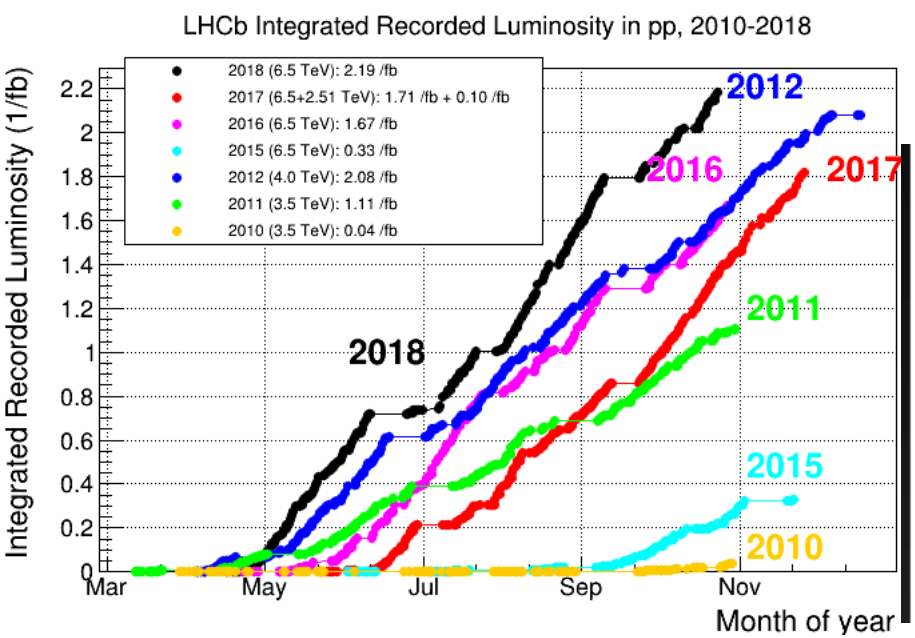
LHCb status and outlook

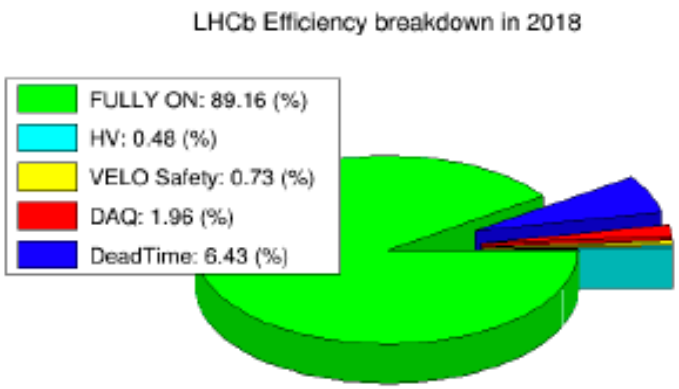
Marina Artuso
Syracuse University

Highlights of current and planned physics program

LHCb is moving to the next chapter!

- We are currently completing our Run II data set and at the last stride towards the construction of what is essentially a NEW LHCb detector





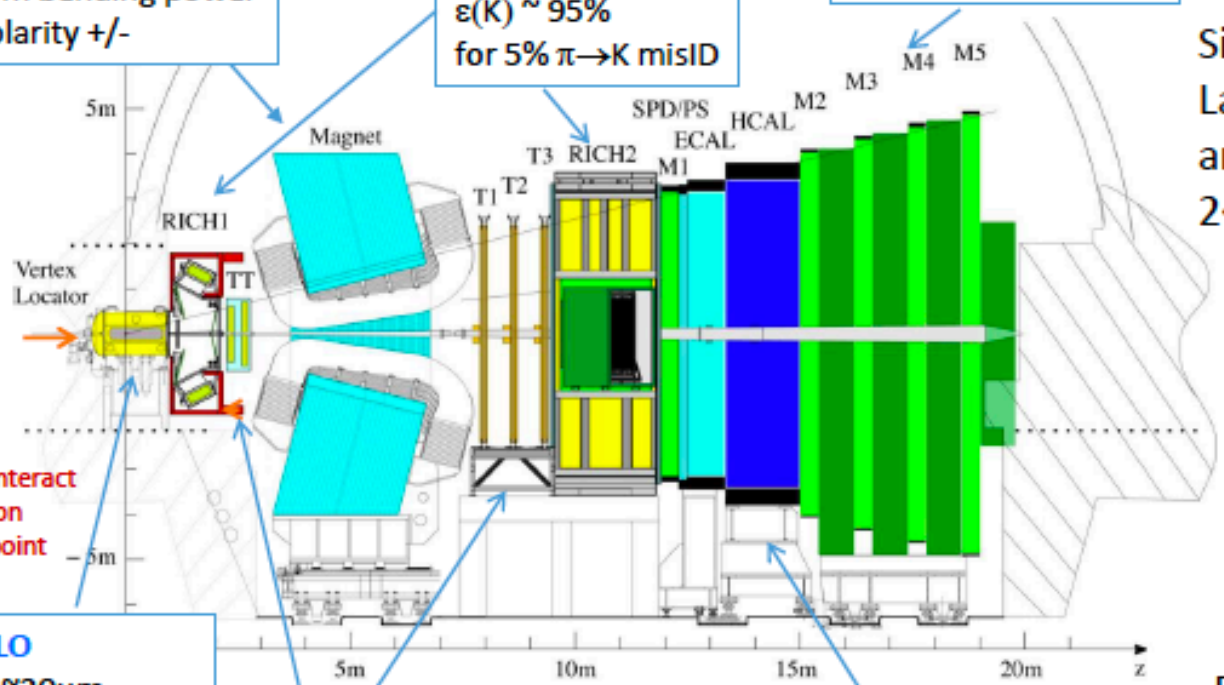
LHCb detector

JINST 3(2008) S08005
IJMPA 30 (2015) 1530022

Dipole magnet
4Tm bending power
Polarity +/-

RICh detectors
$\varepsilon(K) \sim 95\%$
for 5% $\pi \to K$ misID

MUON system
$\varepsilon(\mu) \sim 97\%$
for 1-3% $\pi \to \mu$ misID

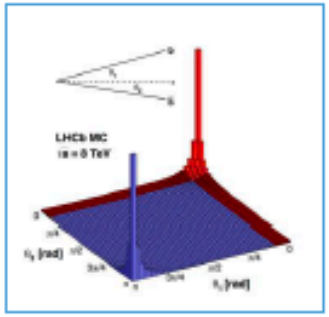


VELO
$\sigma_{IP} \sim 20\mu m$
(high p^T tracks)

TRACKING Systems
$\Delta p/p = 0.5 - 0.8\%$
(20-100 GeV)

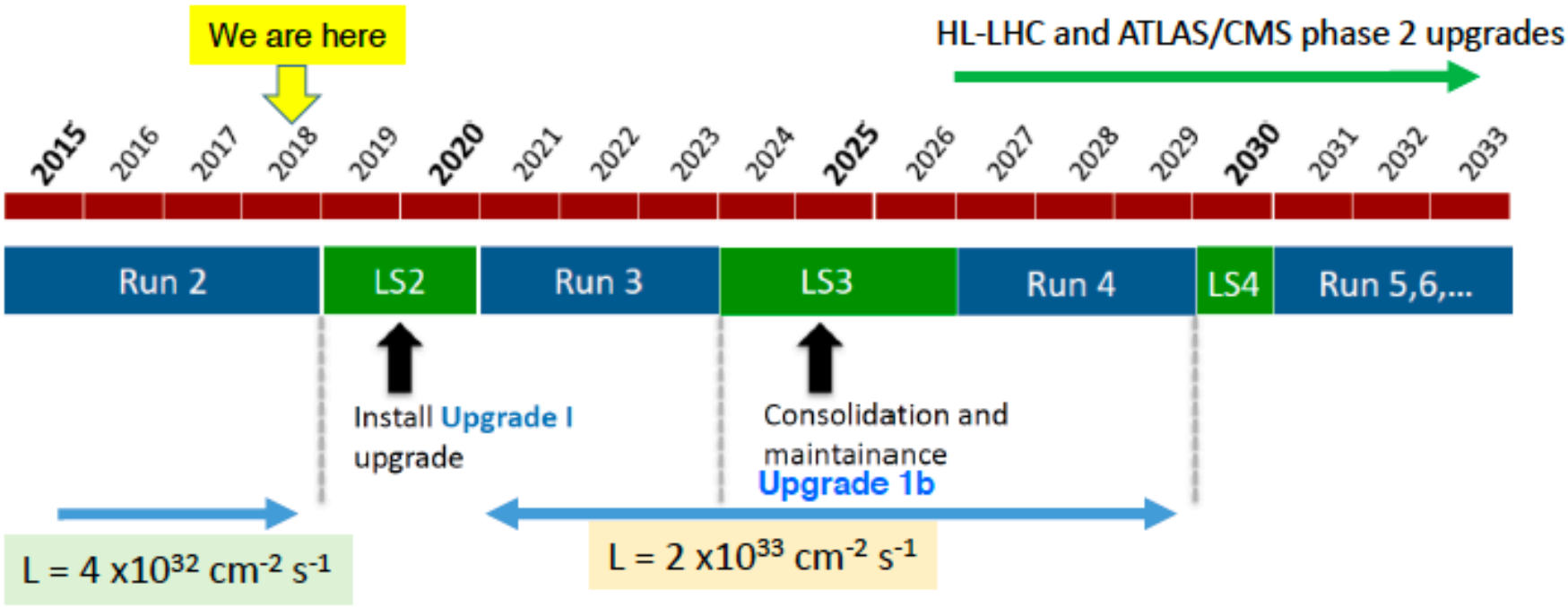
CALORIMETERS
ECAL: $\sigma_E/E \sim 1\% \oplus 10\%/\sqrt{E}$

Single arm spectrometer:
Large acceptance for $b\bar{b}$ and $c\bar{c}$ in forward region
$2<n<5$



Precision tracking and vertexing
Excellent PID systems
Efficient leptonic and hadronic trigger

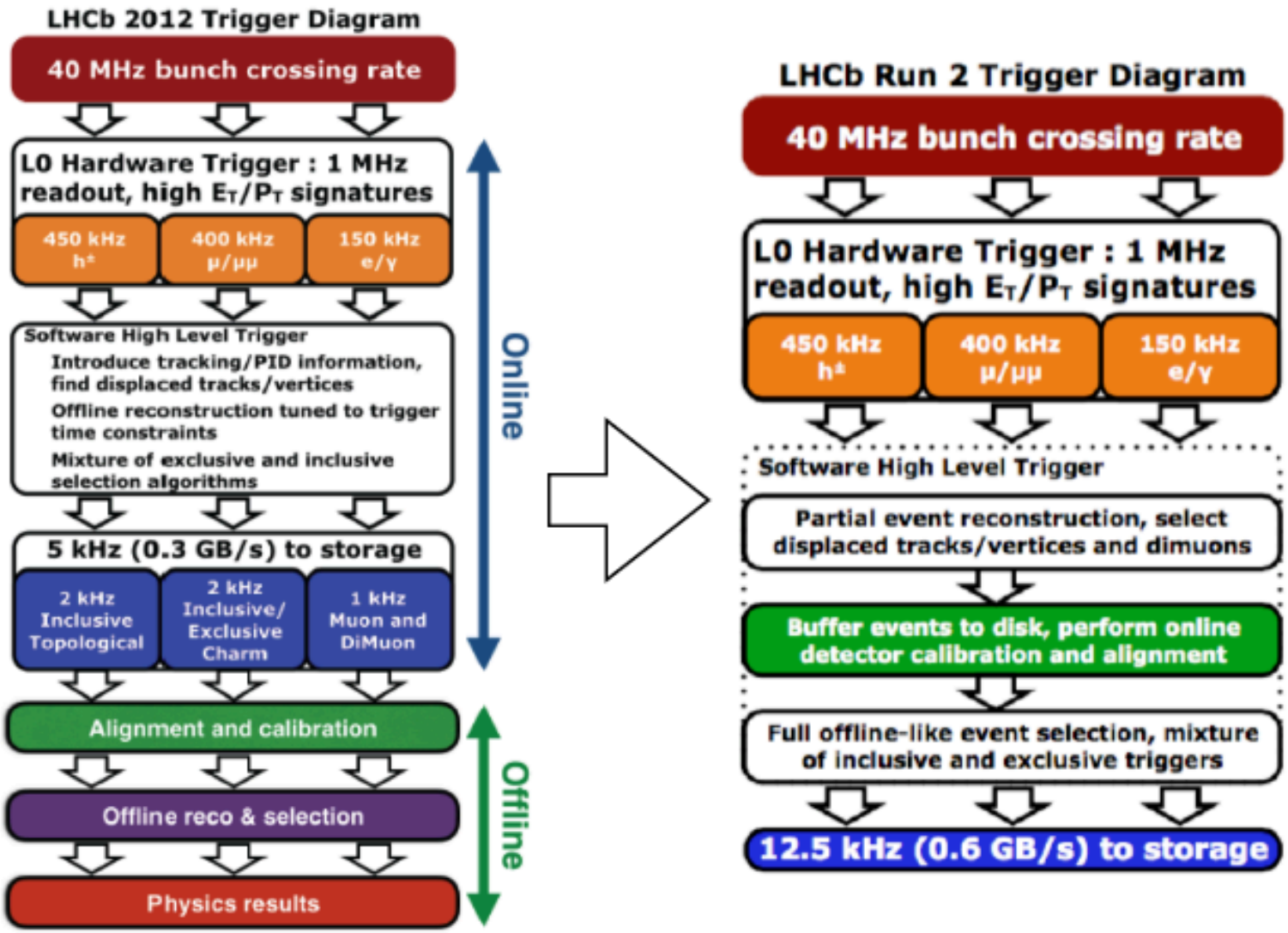
At the dawn of a new chapter!



Upgrade I in construction

- will allow to run at 5 x current instant luminosity
- aim to collect 50 fb^{-1} by LS4
- detector consolidation and modest enhancement foreseen in LS3 (start of HL-LHC)

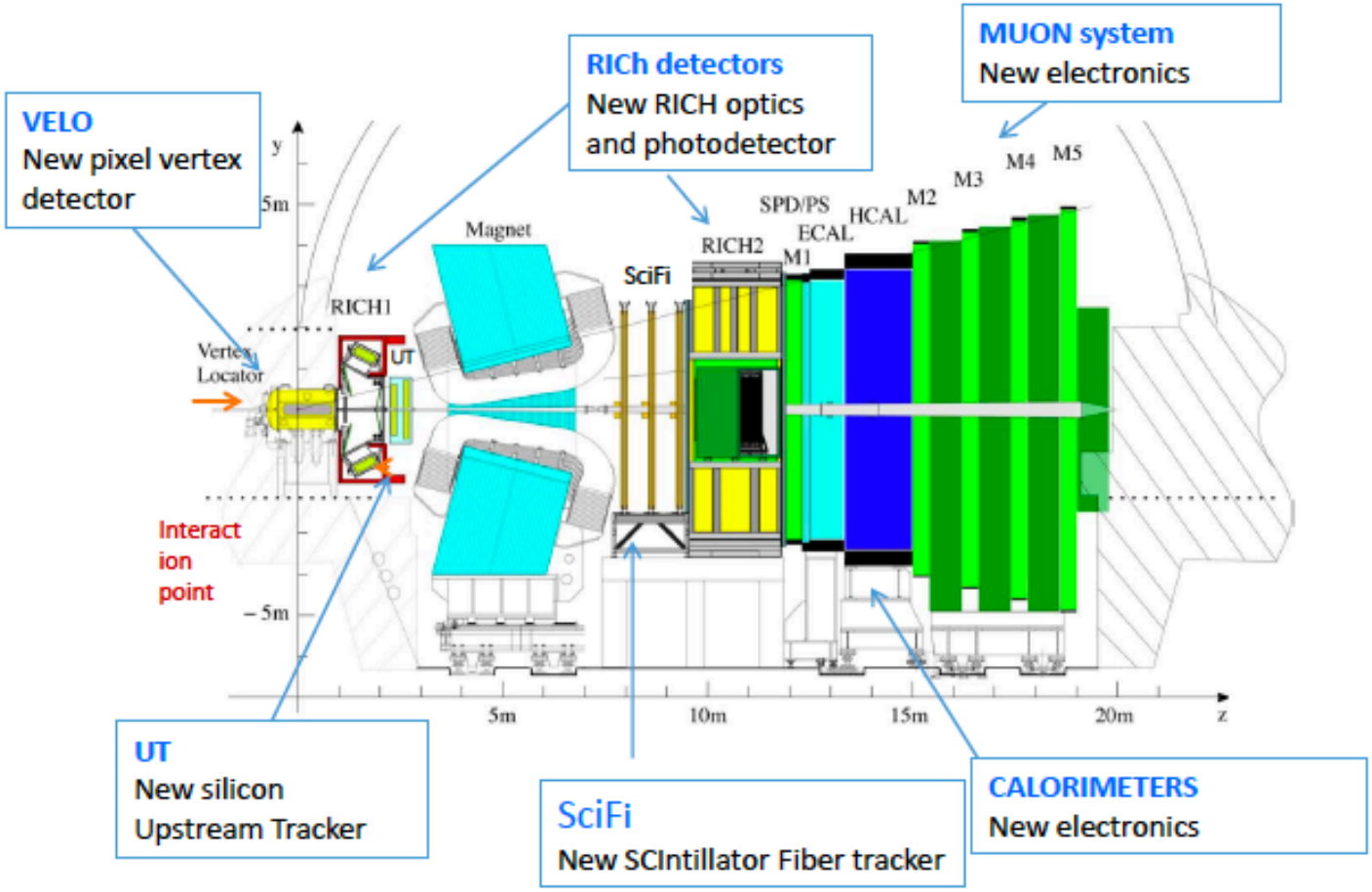
The LHCb Trigger



Run 1 Run 2

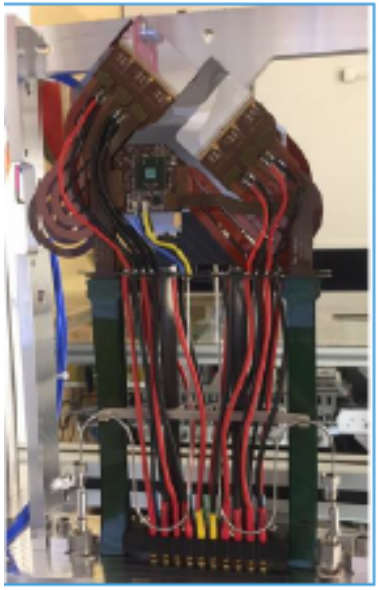
The LHCb Upgrade Phase I

All sub-detectors read-out at 40 MHz for a fully software trigger



Getting ready for the finish line!

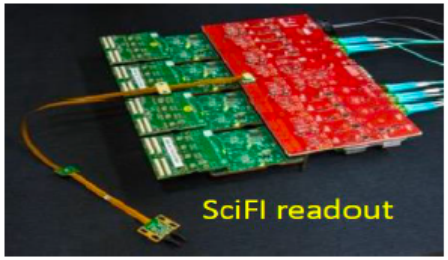
Velo module



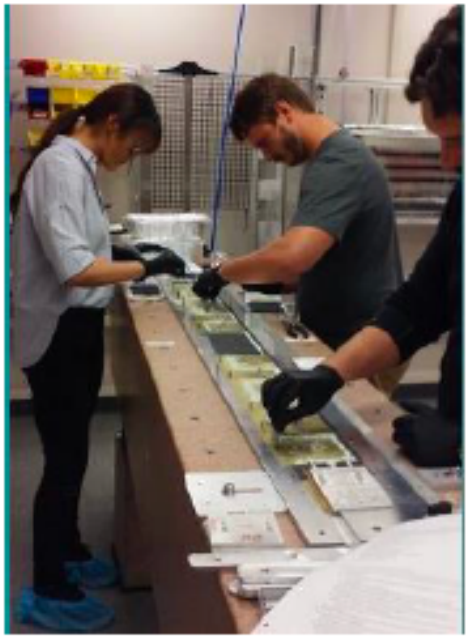
UT sensor

RICH MAMPT under test

SciFi Module

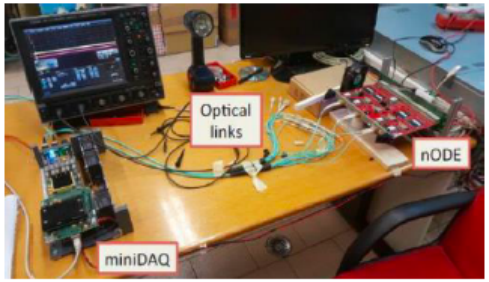


UT staves constructions



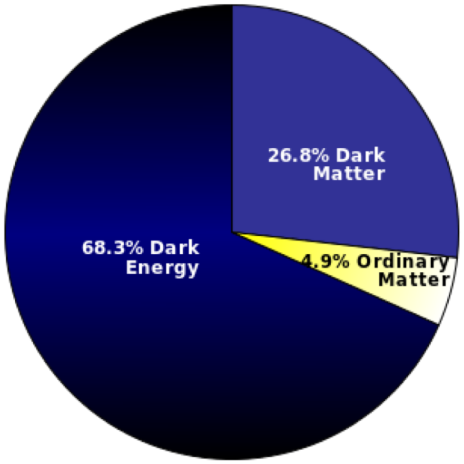
Calorimeter electronics

Test of muon electronics



The big questions

What is the universe made of?

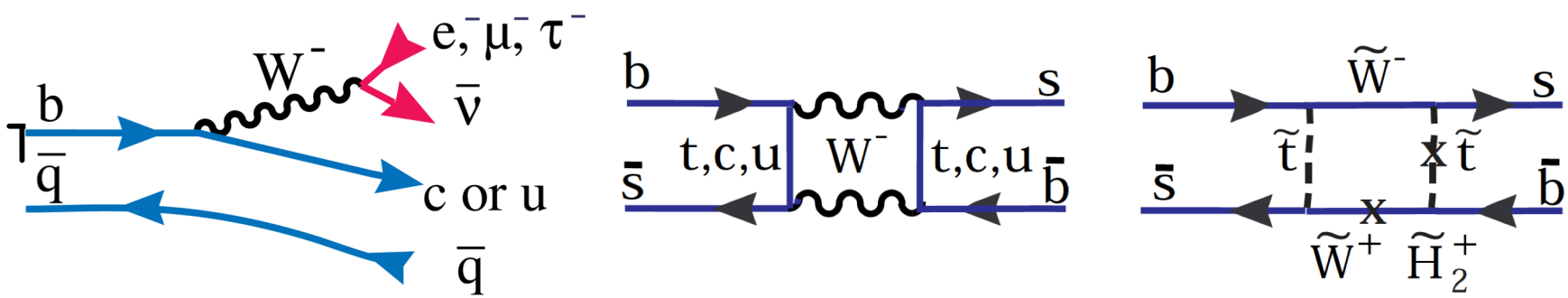


- ❑ Baryon asymmetry of the universe
- ❑ Hierarchy Problem: We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections
- ❑ Gravity at "elementary particle level" scale

⇒ Search for "new physics" answering these questions in a coherent manner

Flavor physics as a probe for new physics

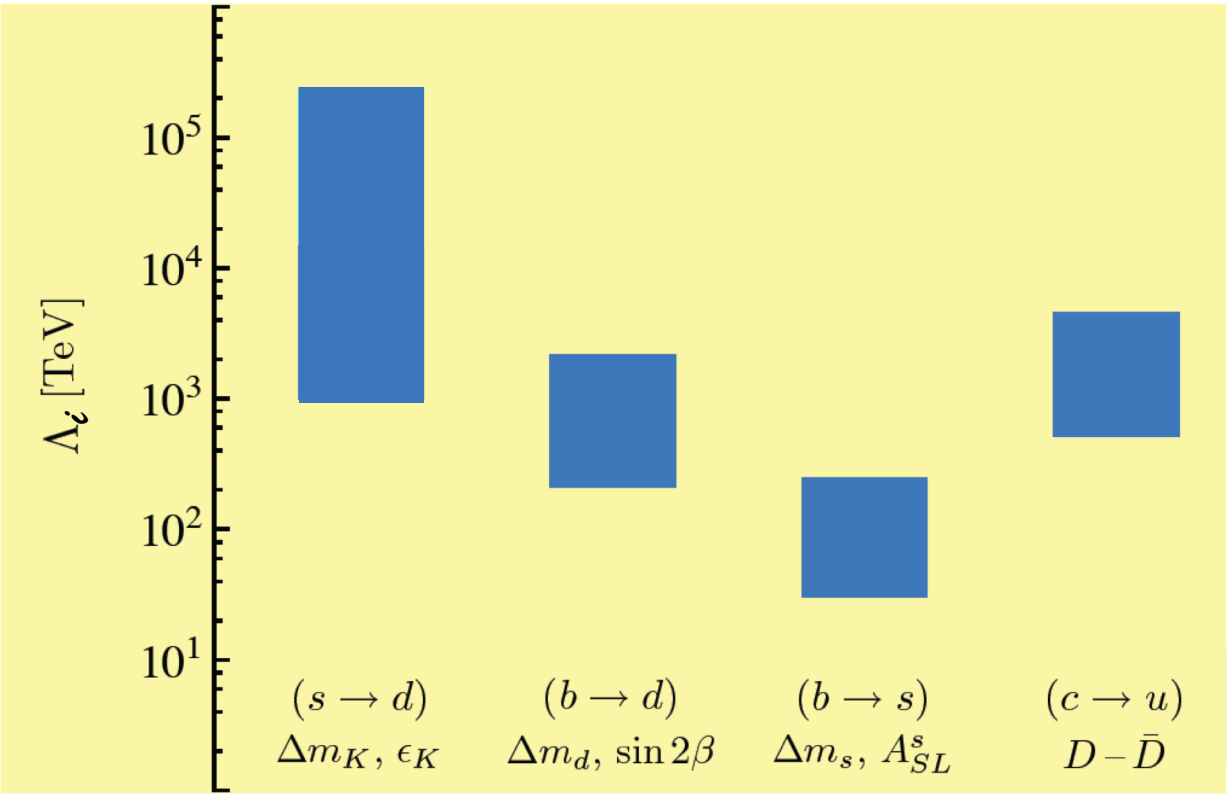
- Flavor physics = study of the interactions that distinguish the 3 generations of fermions
  - In Standard Model Yukawa couplings
- New physics manifestations in flavor physics = new couplings or new forces



Flavor as a High Mass Probe

$$L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$

- Already excluded ranges



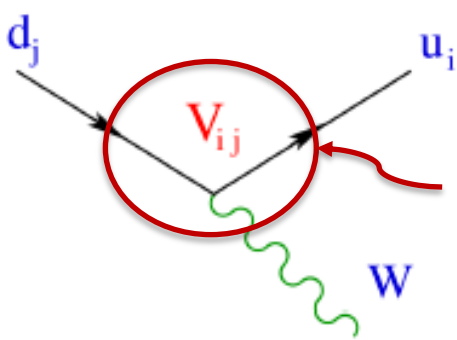
Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

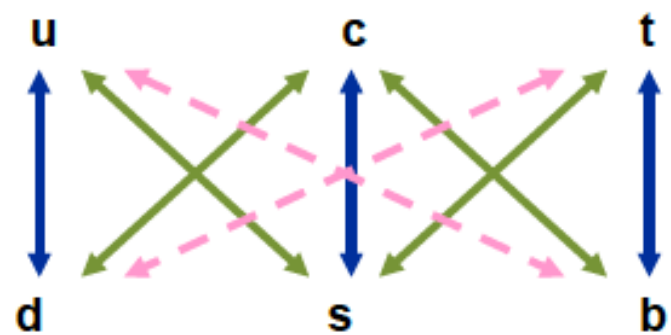
See: Isidori, Nir & Perez arXiv:1002.0900;

The unitarity triangles

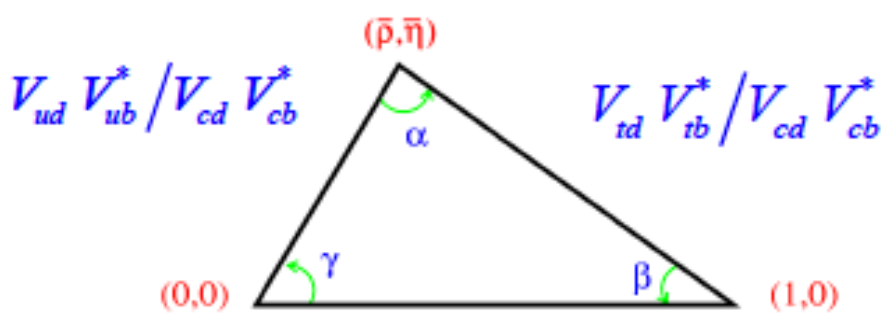
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.}$$



Cabibbo-Kobayashi-Maskawa (CKM) Matrix



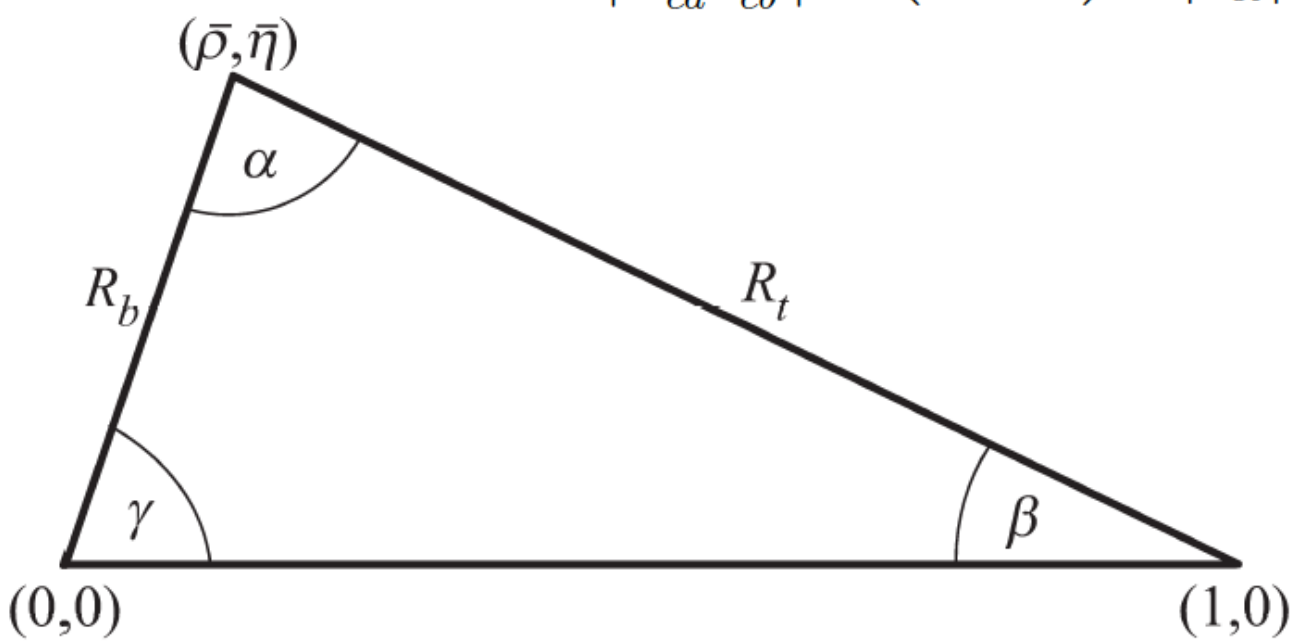
Visualization of Standard Model test as unitarity triangles



The reference unitarity triangle

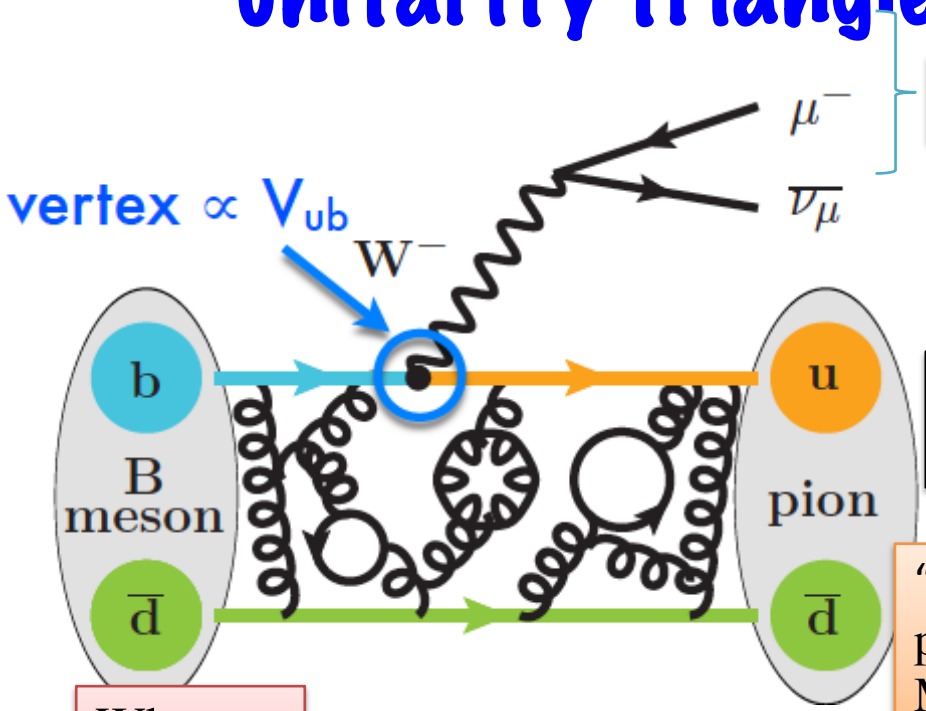
- R_b, γ should establish the SM foundation (tree level processes)
- γ extracted from loop-level processes provides another SM check

$$R_b = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\frac{|V_{ub}|}{|V_{cb}|}$$



Measuring the sides of the standard unitarity triangle

Illustration focused on V_{ub}, change $u \rightarrow c$ for V_{cb}.



$q^2=m^2(\mu\nu)$

"exclusive" study a specific final state

"inclusive" study an inclusive property of the decay (E_μ, M_{had},q^2)

Experimental observables

What we want to know

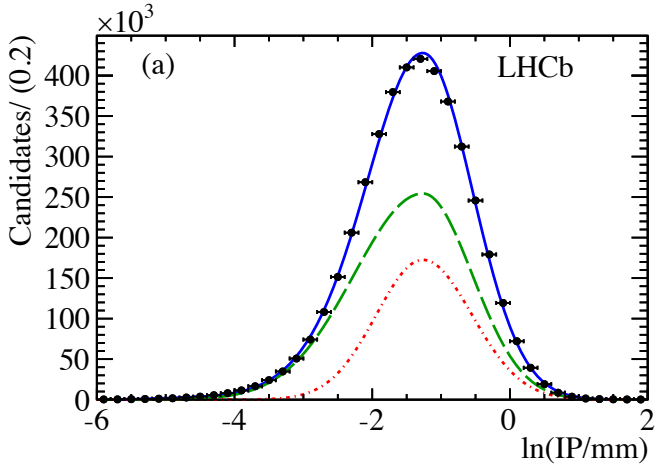
Lattice QCD,LC sum rules, HQE..

$(\Gamma, d\Gamma/dq^2 ... = |V_{ub}|^2 x$ (Hadronic matrix element) x (known factors)

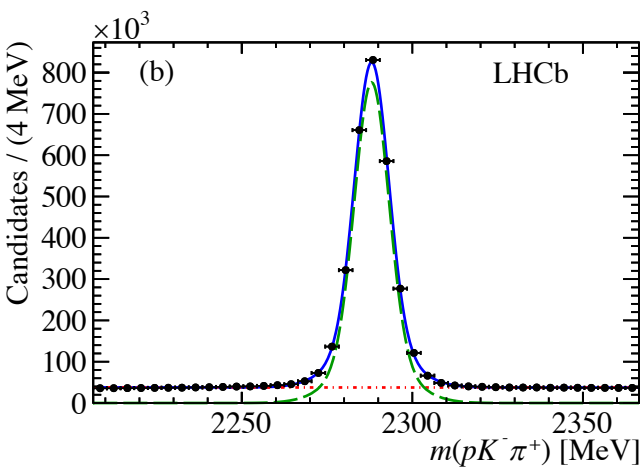
LHCb-PAPER-2017-016

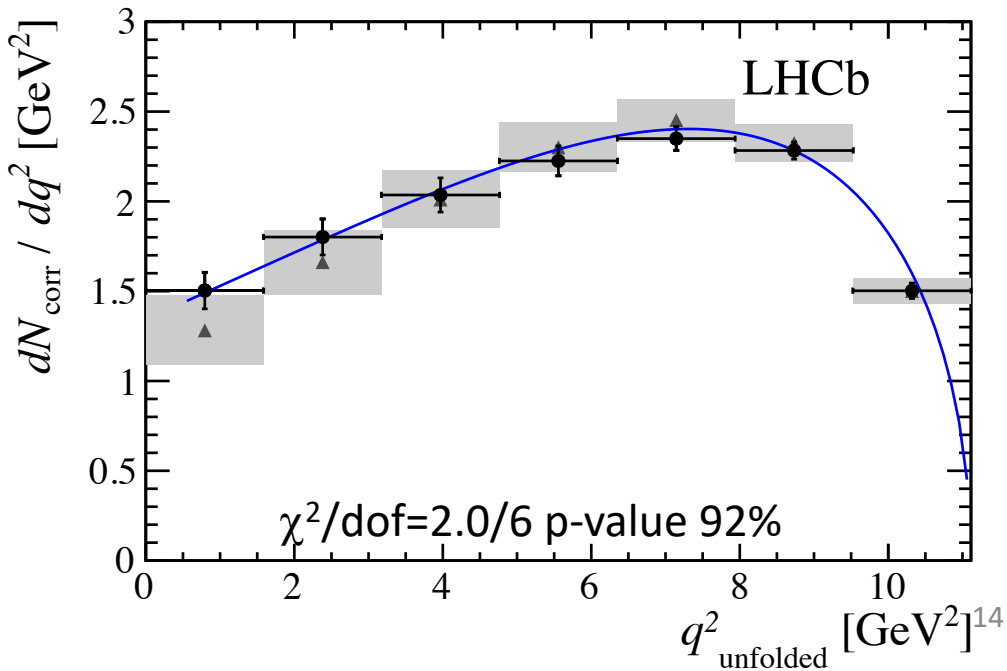
Validation of HQE and lattice calculations

See S. Ely's talk



LHCb measurement of the shape of the differential decay width in $\Lambda_b \to \Lambda_c \mu \nu_m$ semileptonic decays & comparison with lattice QCD predictions [Meinel, Detmold & Lehner, arXiv:1504.01421] and HQET static approximation, more sophisticated fit to the data by Ligeti et al [arxiv:1808.09464] up to order Λ^2/m_c^2

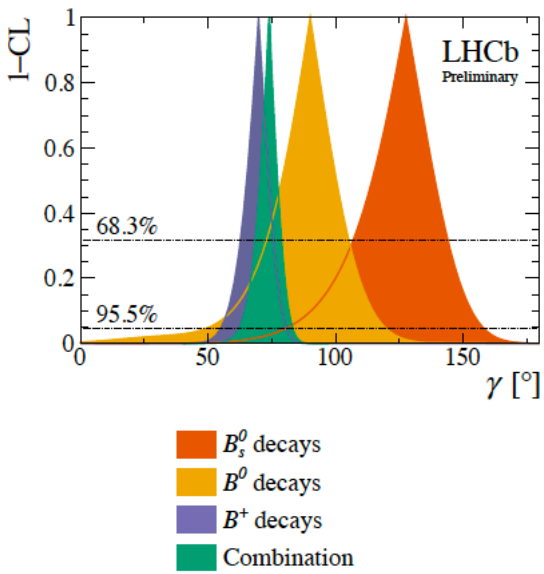




The angle γ from tree level processes

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

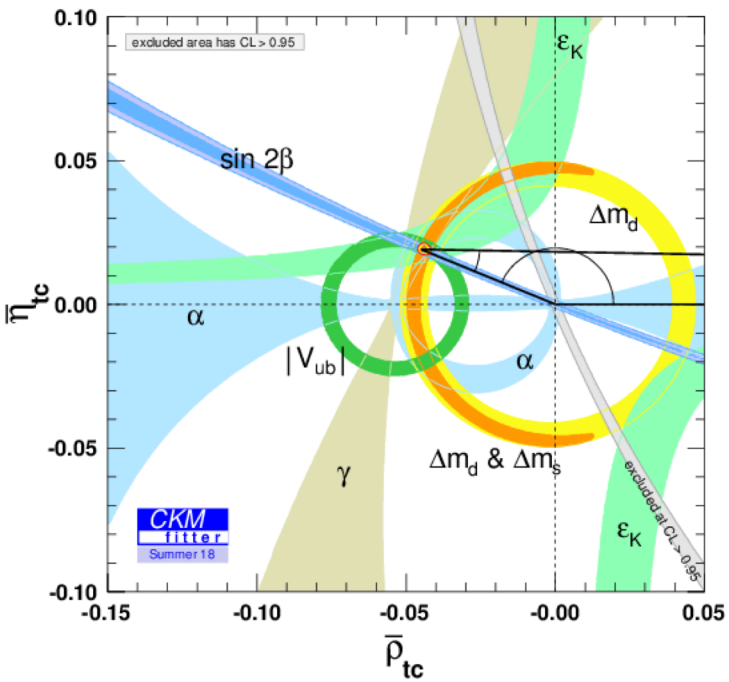
† Run 1 corresponds to an integrated luminosity of $3\,\mathrm{fb}^{-1}$ taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of $2\,\mathrm{fb}^{-1}$ taken at a centre-of-mass energy of 13 TeV.

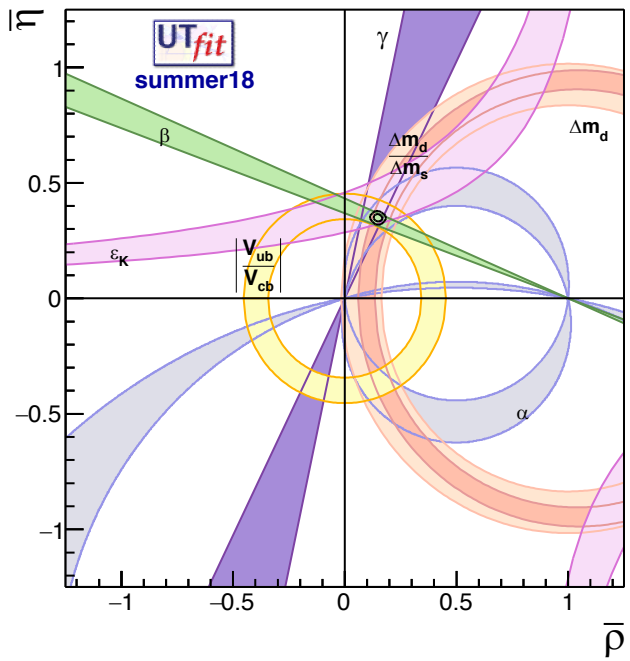


- LHCb γ combination yields $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ [LHCb-CONF-2018-002]
- Dominating the world average $\gamma = (73.5^{+4.2}_{-5.1})^\circ$ [HFLAV winter 2018]
- Slight tension with loop-determination $\gamma = (65.6^{+1.0}_{-3.4})^\circ$ [CKMfitter 2018]
- 3–4° precision with full Run 2, 1.5° with $23\,\mathrm{fb}^{-1}$, 0.35° with Upgrade II

The standard triangle – after ~30 years

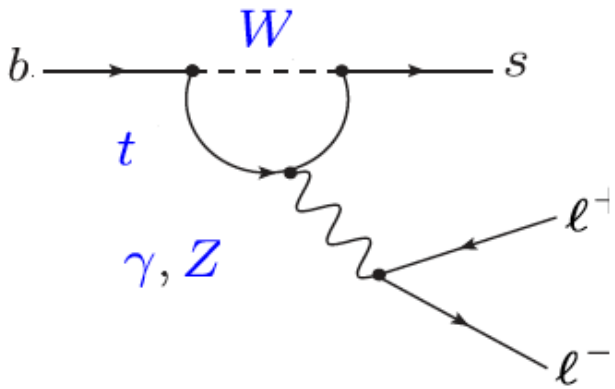
CLEO,LEP, BaBar, Belle, LHCb

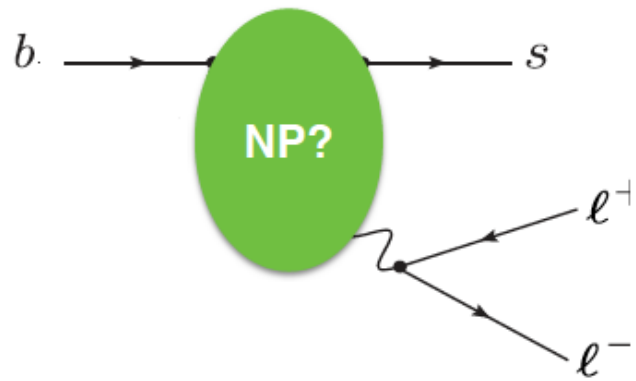




Looks like a triumph of the Standard Model, room for new physics at 10%-15% level

Rare decays and generic searches for new physics





Rare decays are described by an effective Hamiltonian expressed in terms of an operator product expansion:

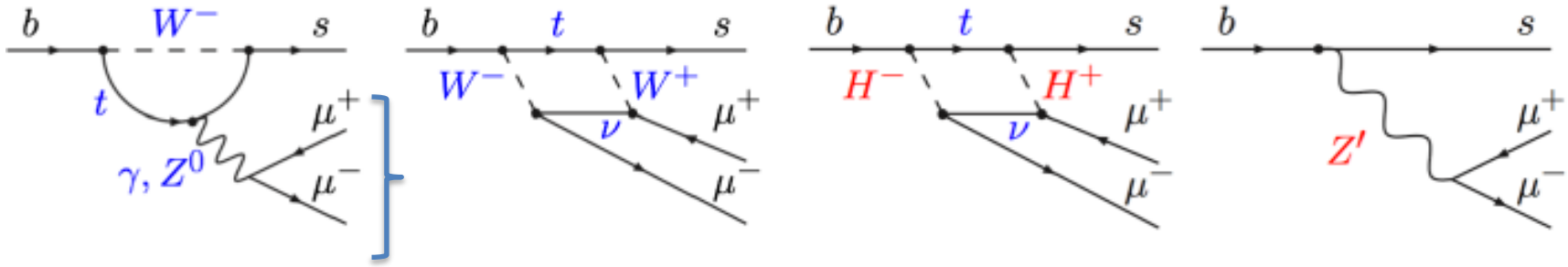
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

How can we pin down new physics contributions?

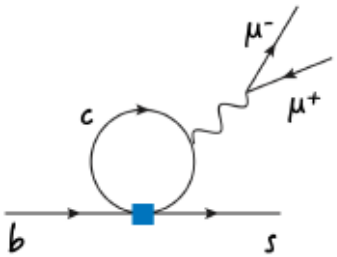
Operator	$B_{d,s} \to X_{s,d}\, \mu\mu$	$B_{s,d} \to \mu\mu$	$B \to X_{s,d}\, \gamma$
O_7	√		√
O_9	√		
O_{10}	√	√	
$O_{S,P}$		√	

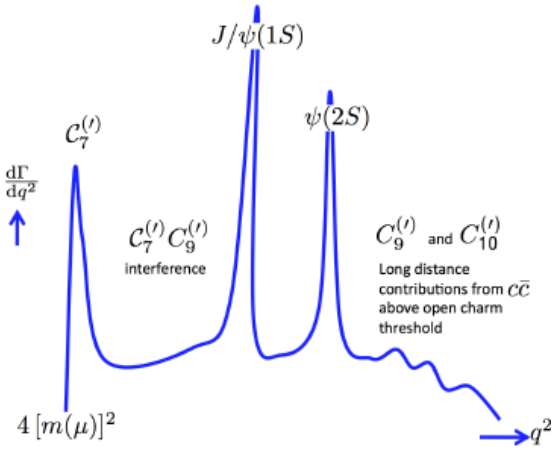
$b \to s(d)\, \ell^+\ell^-$



Invariant mass squared = q^2

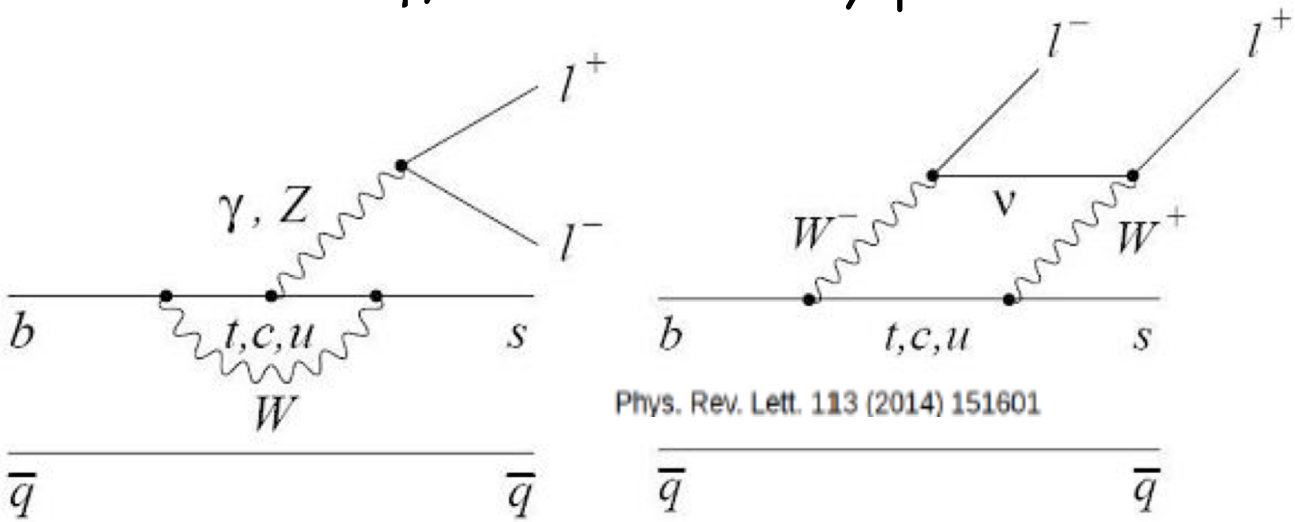
VETO charmonium resonances, where hadronic physics makes things complicated





$B \to K^{(*)} \ell^+ \ell^-$

- Similar to $K^*\gamma$, but more decay paths

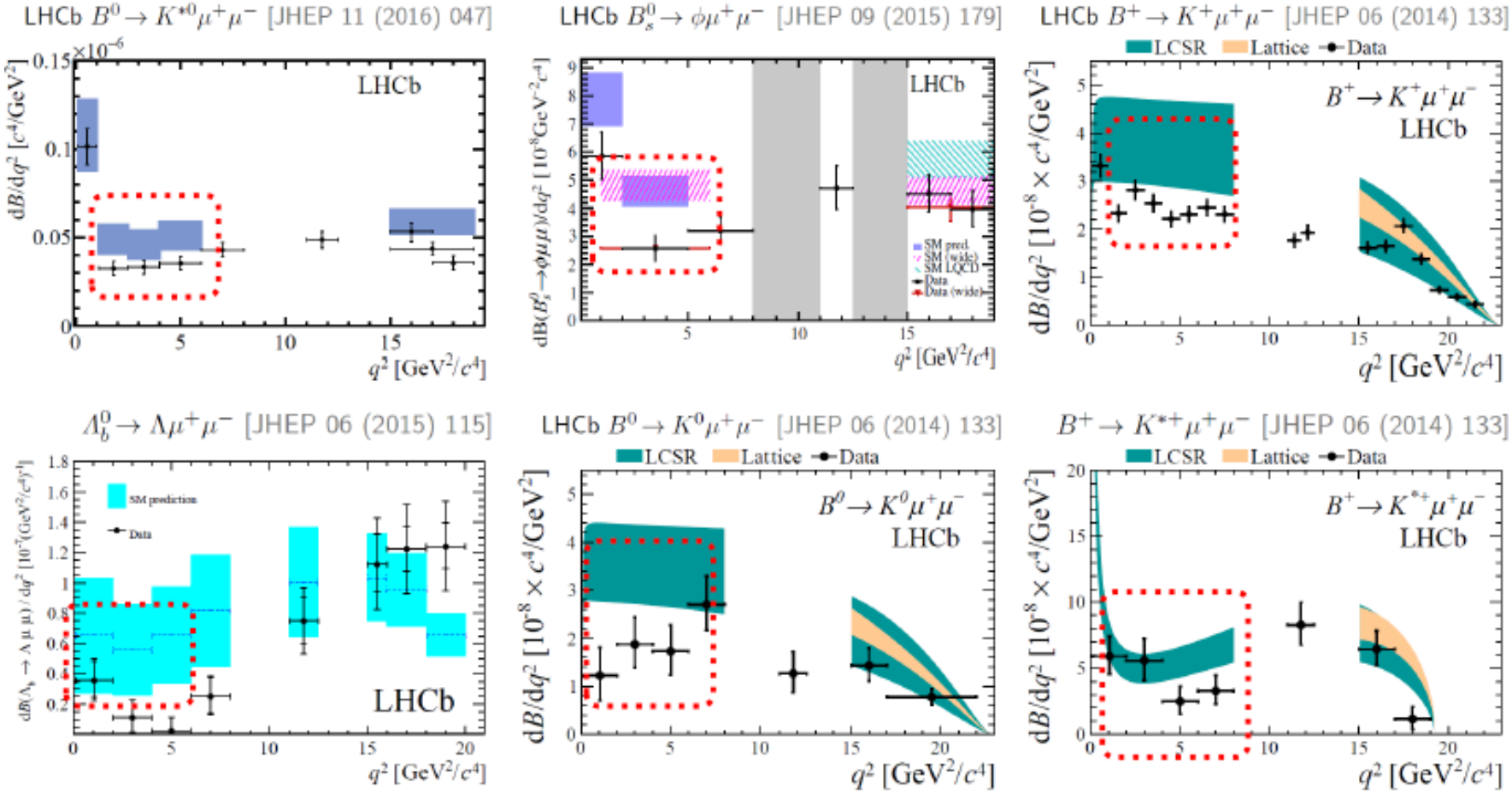


Phys. Rev. Lett. 113 (2014) 151601

+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM
- Not all the variables are equal! The never ending struggle to tame strong interaction effects!

Branching fractions

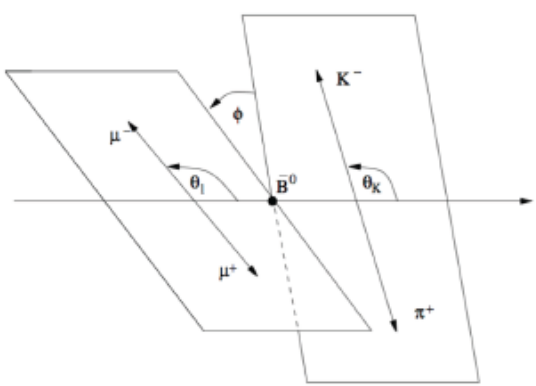


Branching fractions are generally lower than theoretical expectations, SM predictions have uncertainties associated with hadronic effects

Angular distributions in $B \to K^{(*)} \ell^+ \ell^-$

Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects

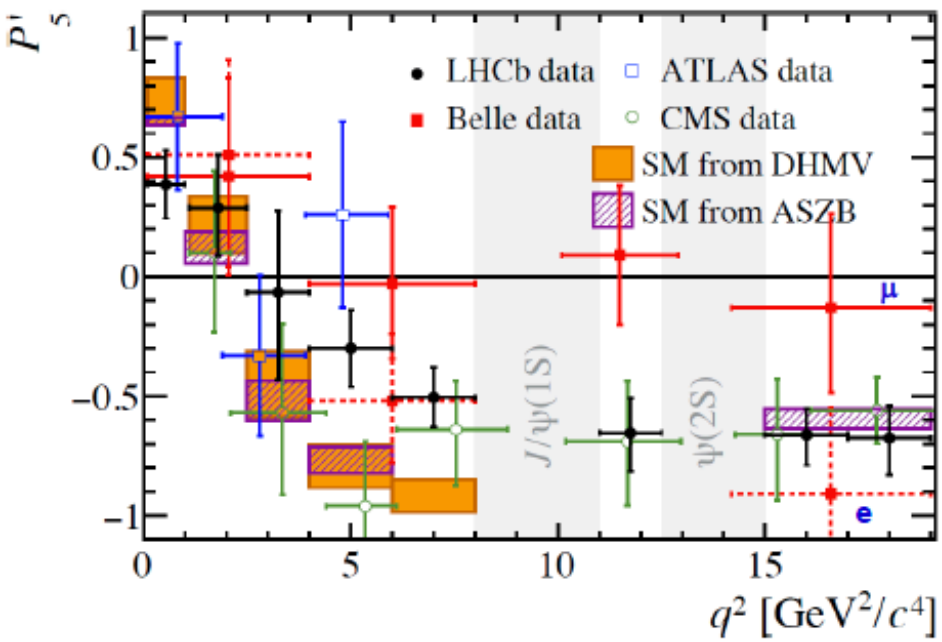
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



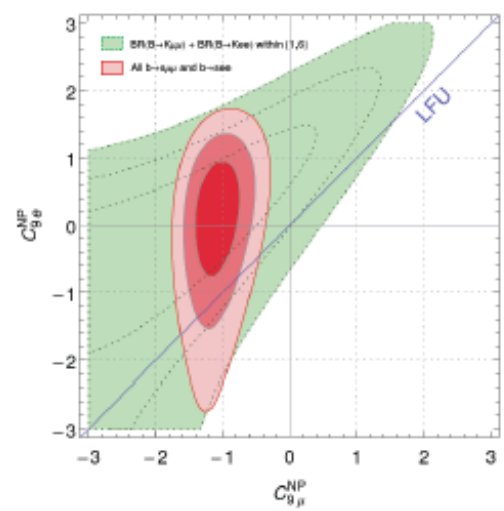
The P'_5 anomaly in the decay $B \to K^{(*)}\mu^+\mu^-$

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

Less sensitive to hadronic uncertainties. However precise and well defined uncertainty assessment needed.



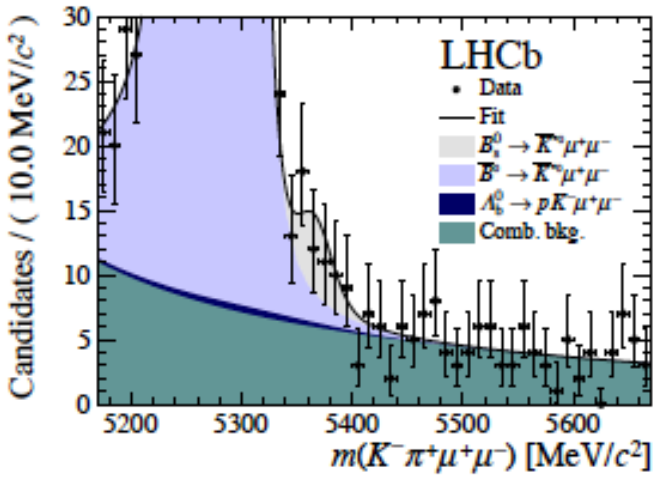
Descotes-Genon et al, 1510.04239



$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

Exploring new modes: $b \to d l^+ l^-$

- First evidence for the decay $B_s^0 \to K^{*0}\mu^+\mu^-$ [JHEP 07 (2018) 020]:
  - Extremely challenging due to $B^0 \to K^{*0}\mu^+\mu^-$ contamination
  - Distinguishable thanks to LHCb high momentum resolution



- Using 4.6 fb^{-1} data (2011-2016): 3.4σ significance

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{norm})) \times 10^{-8}$$

Lepton universality in $B \to K^{(*)}\ell^+\ell^-$

- Study the double ratio

LHCb paper 2017-013

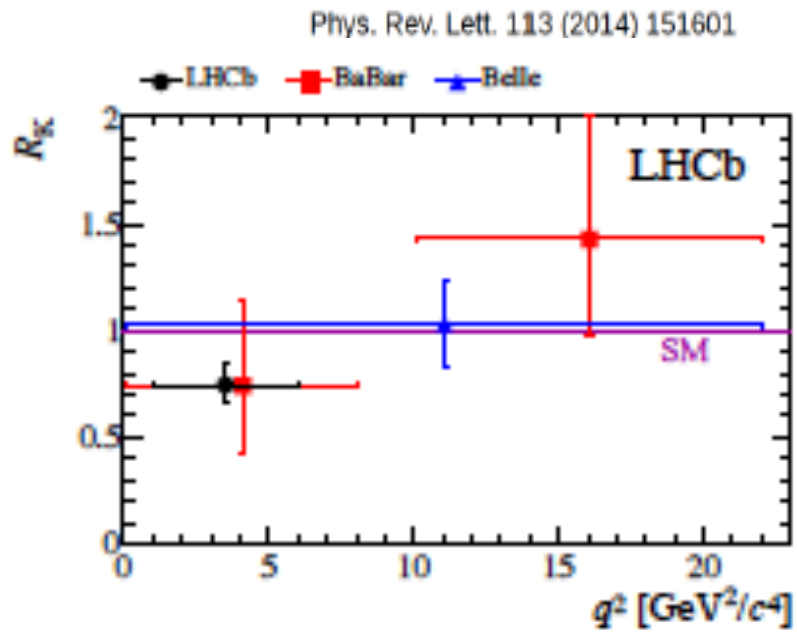
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- Double ratio ensures that measurement is robust against systematic effects
- Measurement of control channels

$$R_{J\psi} = \frac{B(B^0 \to J/\psi\mu^+\mu^-)}{B(B^0 \to J/\psi e^+e^-)} = 1.06 \pm 0.006[\text{stat}] \pm 0.045[\text{sys}]$$

LFU violation in $B \to K\ell^+\ell^-$

$$R_K = \frac{Br(B \to K\mu^+\mu^-)}{Br(B \to Ke^+e^-)}$$



In the first bin

$$R_K = 0.75^{+0.090}_{-0.074} \pm 0.036$$

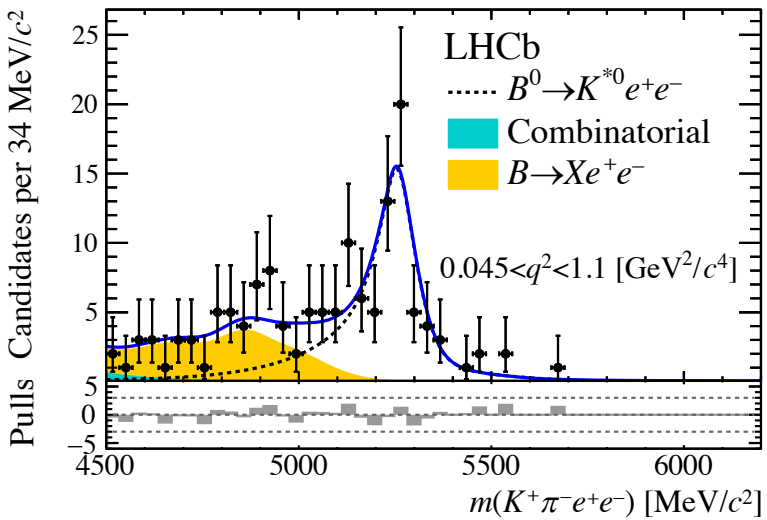
Actually measured:

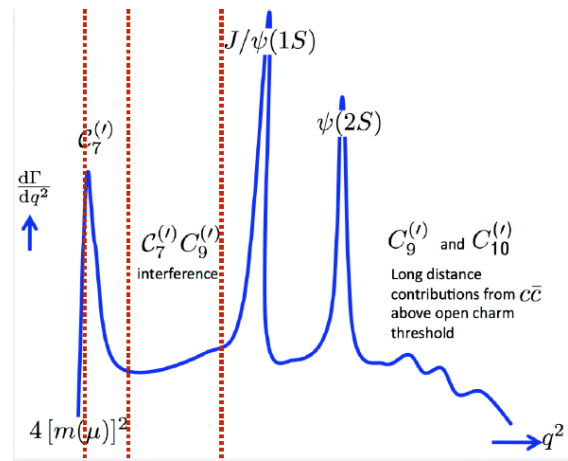
$$R_K \equiv \frac{\mathcal{B}\left(B^- \to K^-\mu^+\mu^-\right) / \mathcal{B}\left(B^- \to K^- J/\psi, J/\psi \to \mu^+\mu^-\right)}{\mathcal{B}\left(B^- \to K^- e^+e^-\right) / \mathcal{B}\left(B^- \to K^- J/\psi, J/\psi \to e^+e^-\right)}$$

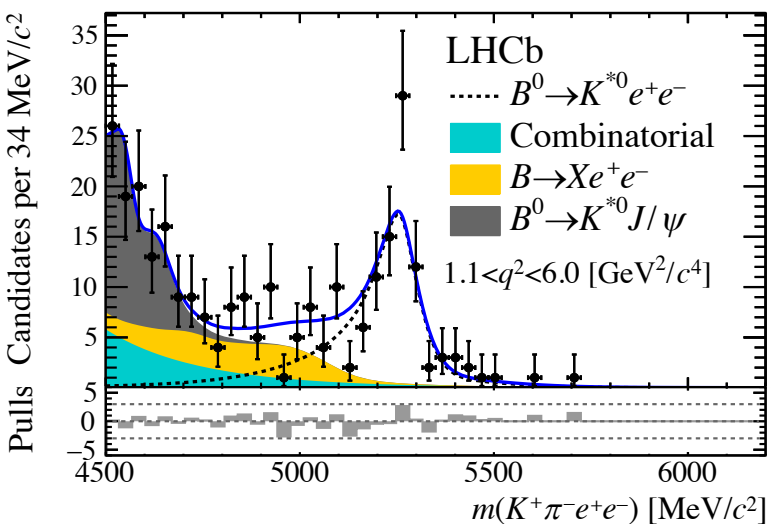
Di-electron branching fraction consistent with SM

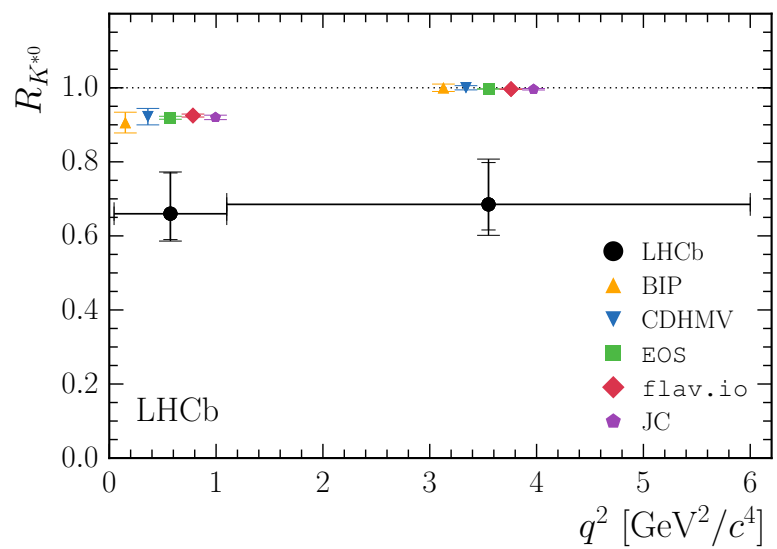
$B \to K^* \mu^+ \mu^- / B \to K^* e^+ e^-$

LHCb, JHEP 08 (2017) 055

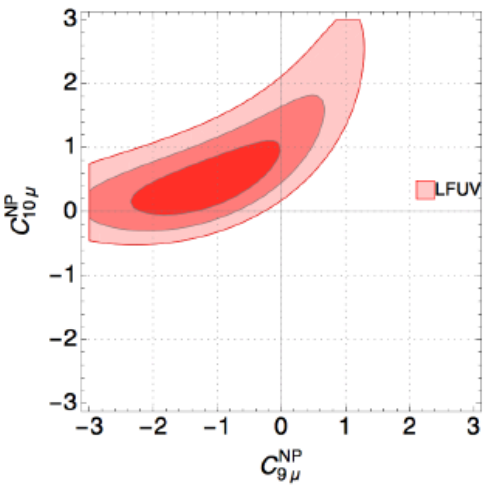




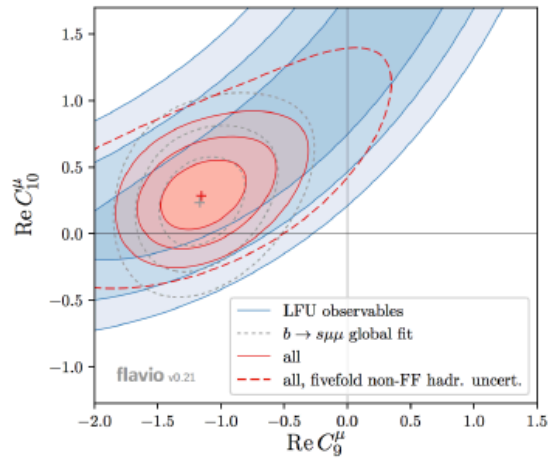




Global analyses of $b \to s\ell^+\ell^-$ (including LFU observables)



[JHEP 01 (2018) 093]

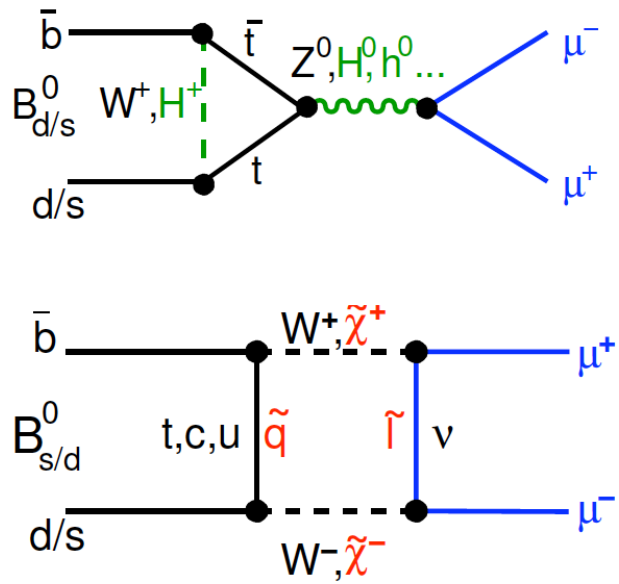


[PRD 96 (2017) 055008]

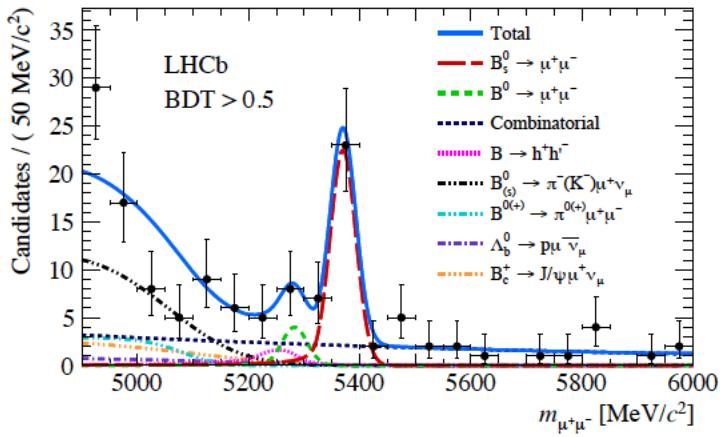
- LFU violation observations may be accommodated by a BSM violation consistent with the other $b \to s\ell^+\ell^-$ tensions
- Best explanation seems to be new physics in di-muon channel via $C_9^{\mu}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

$B \to \ell^+\ell^-$

- Excellent probes of new physics:
  - CKM suppressed, loop suppressed, and helicity suppressed
  - Powerful probes of new scalar and pseudoscalar interactions

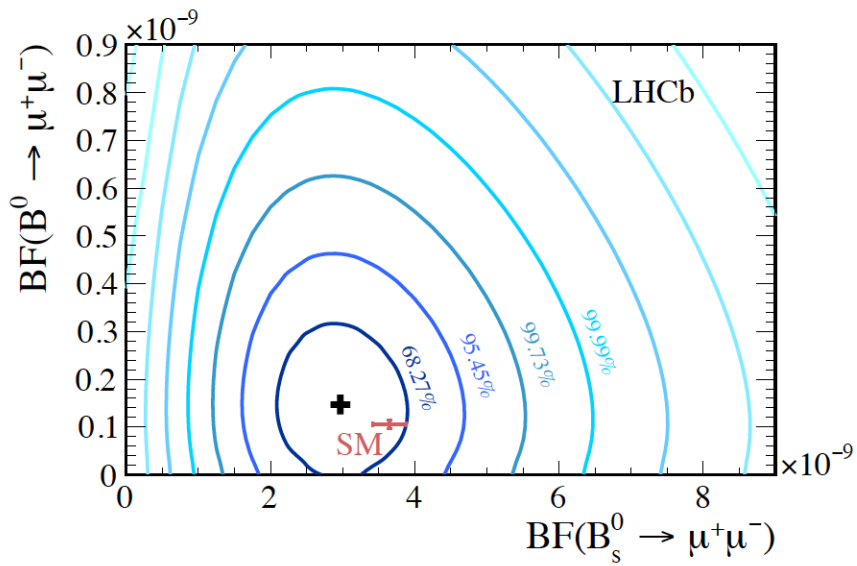


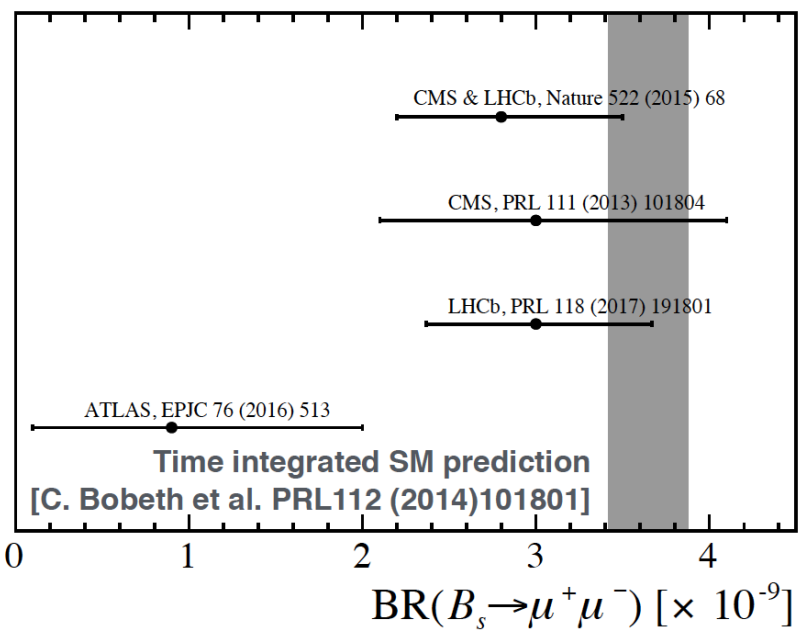
$B_s \to \mu^+\mu^-$



$$B(B_s \to \mu^+\mu^-) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad 95\%CL$$

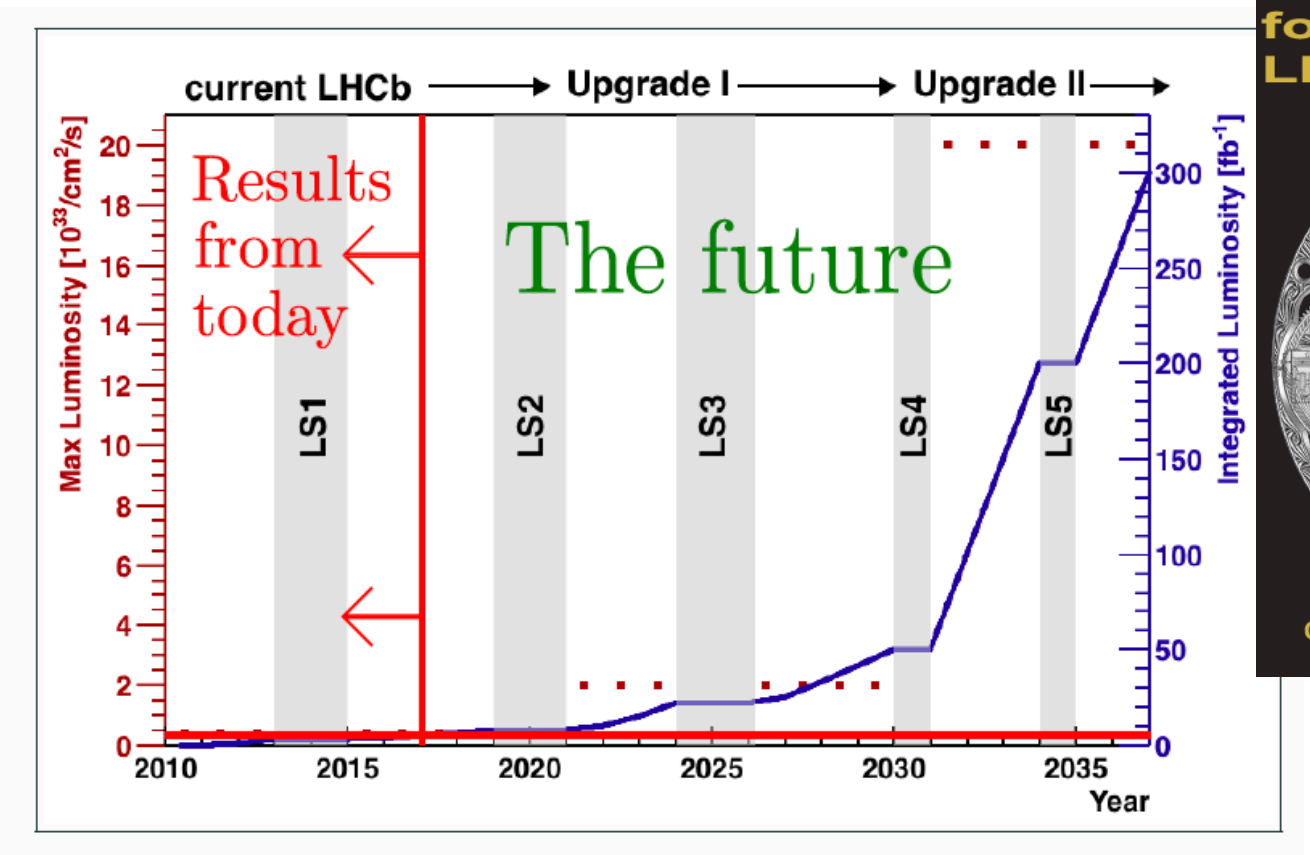




Theoretical uncertainty ~6%

What is next?

LHCb-PUB-2018-009



Summary and outlook

- The CKM triangles are providing a wonderful validation of the SM, but subtle new physics effects may be still revealed
- Tantalizing tensions in EW penguin decays have surfaced
- Study of $B \to \ell^+\ell^-$ is broadening its scope beyond branching fraction measurement
- Precise calculations of the hadronic matrix element are key to the success of this experimental program
- LHCb has just a vibrant program both in terms of physics analysis and instrumental improvement to pursue this exciting physics

Summary and outlook II

Antonio Pich at Implications of LHCb measurements and future prospects

- **Flavour Structure and** $\not{C}\not{P}$ are major pending questions
- **Related to SSB** → **Scalar Sector** (Higgs)
- Important **cosmological implications** (Baryogenesis)
- Sensitive to **New Physics:** **Flavour Anomalies!**

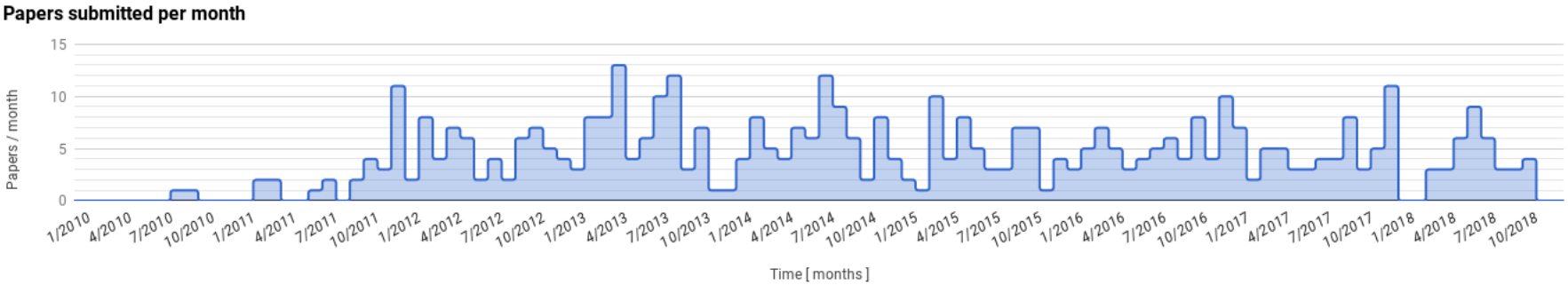
Intriguing signals **(most anomalies related to 3rd family)**

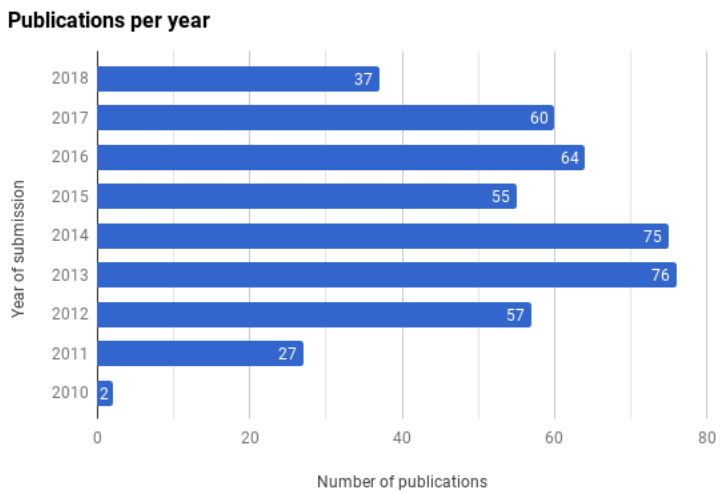
Many questions. Higher statistics & better systematics (QCD) needed

Eagerly awaiting new experimental results

Back-up information will follow

THE END


Papers submitted per month
Papers / month
15
10
5
0
1/2010
4/2010
7/2010
10/2010
1/2011
4/2011
7/2011
10/2011
1/2012
4/2012
7/2012
10/2012
1/2013
4/2013
7/2013
10/2013
1/2014
4/2014
7/2014
10/2014
1/2015
4/2015
7/2015
10/2015
1/2016
4/2016
7/2016
10/2016
1/2017
4/2017
7/2017
10/2017
1/2018
4/2018
7/2018
10/2018
Time [months]


Publications per year
Year of submission
2018
2017
2016
2015
2014
2013
2012
2011
2010
37
60
64
55
75
76
57
27
2
0
20
40
60
80
Number of publications

Eur. Phys. J. C 73 (2013) 2373

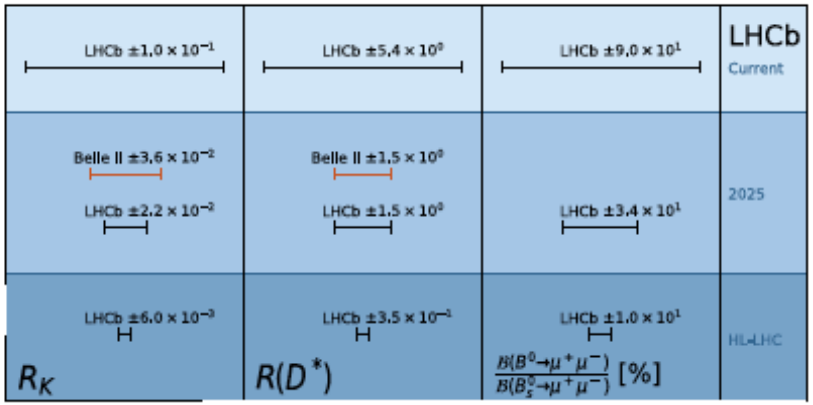
Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb^{-1} by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision (in 2012)	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

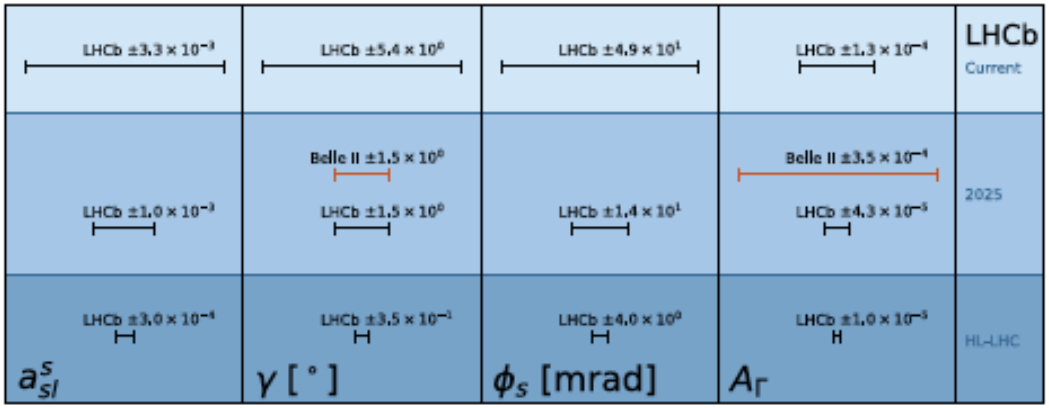
Upgrade II – physics case examples

Physics Case – Rare Decays

- Wide range of $b \rightarrow s l^+ l^-/d l^+ l^-$ observables
- 10 % precision on $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$

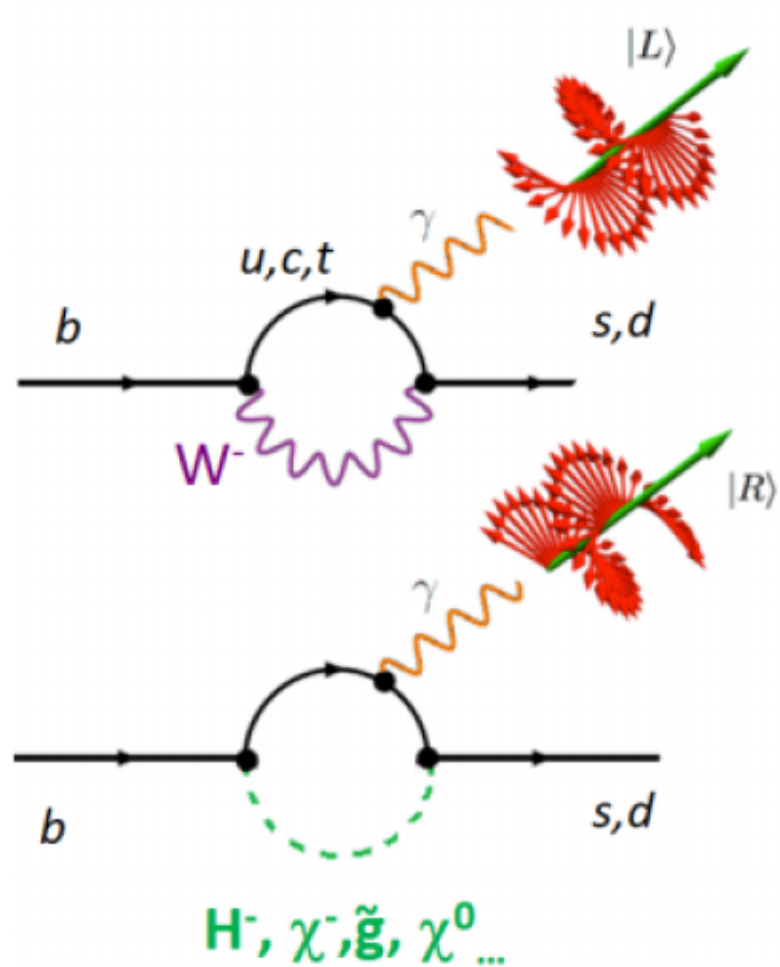


- γ: 0.4°
- ϕ_s: 3 mrad
- Charm CPV: $O(10^{-5})$



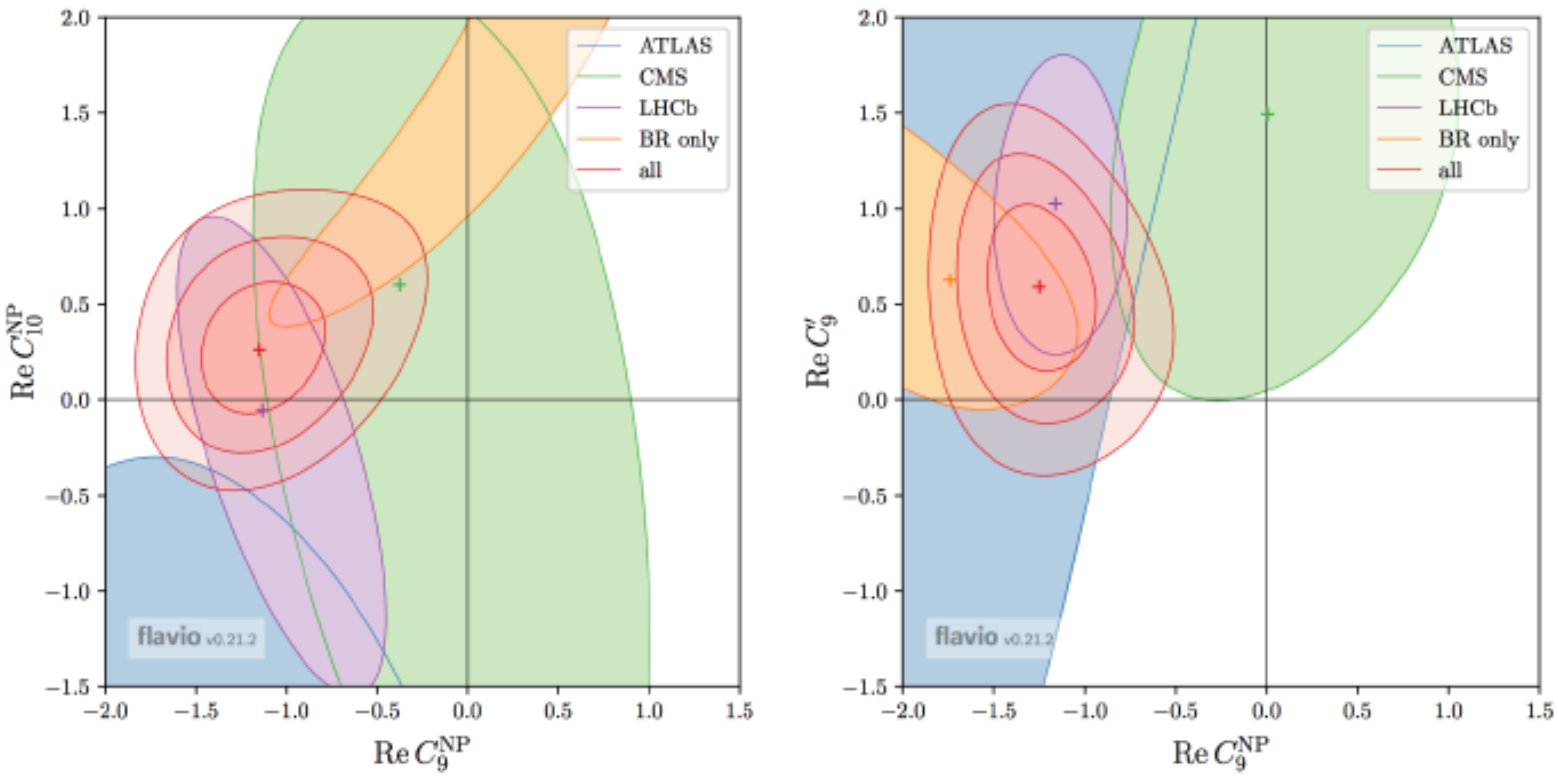
Radiative B decays

- The branching fraction $B(b \to s\gamma)$ is consistent with the Standard Model & is a powerful constraint of new physics scenarios
- Sensitive to the O_7 operators
- CP violation and photon polarization add sensitivity to NP



Global fits – Angular observables and branching fractions

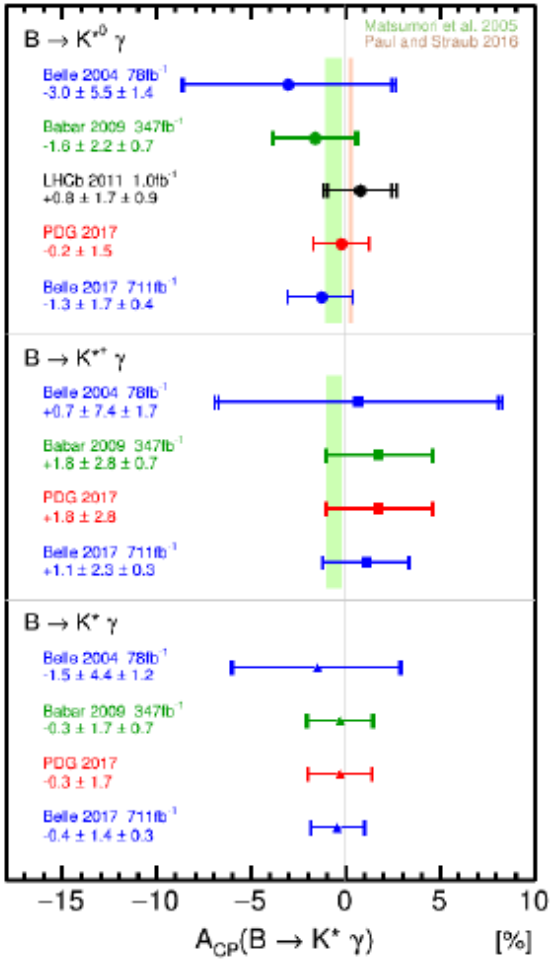
W. Altmannshofer et al EPJC 77(2017)377



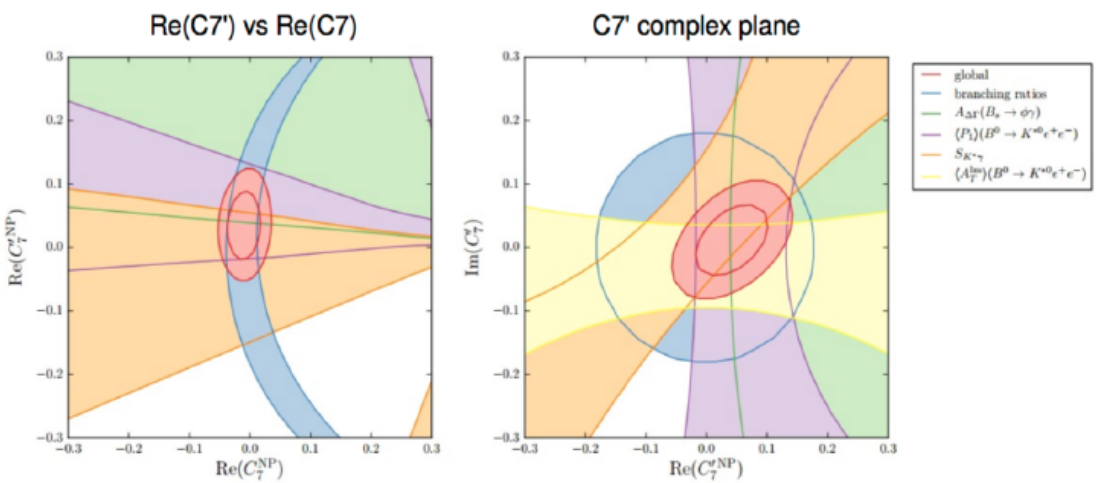
C_9^{NP} proposed as the the most likely explanation

Radiative B decays

- Sensitive to the O_7 operators
- CP violation and photon polarization add sensitivity to NP



Paul, A. & Straub, D.M. J. High Energ. Phys. (2017) 2017: 27



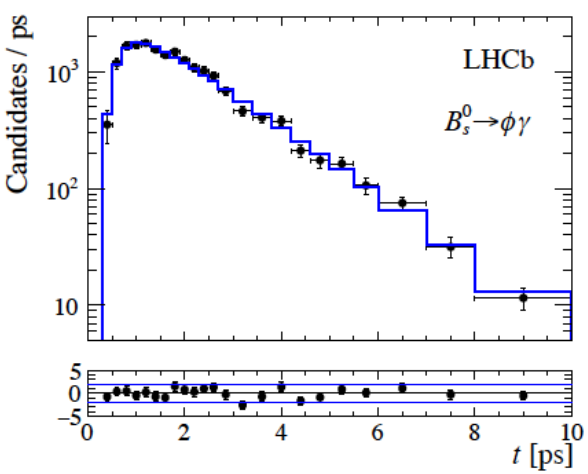
Photon polarization in $B_s \to \phi\gamma$

PHYS. REV. LETT. 118, 021801 (2017)

- First measurement of the photon polarisation in $B_s^0 \to \phi\gamma$.
  - Time-dependent decay rate is sensitive to photon polarisation:

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta} sinh(\Delta\Gamma_s t/2)\right]$$

  - SM prediction: $\mathcal{A}^{\Delta} = 0.047^{+0.029}_{-0.025}$ [PRB 664 (2008) 174]

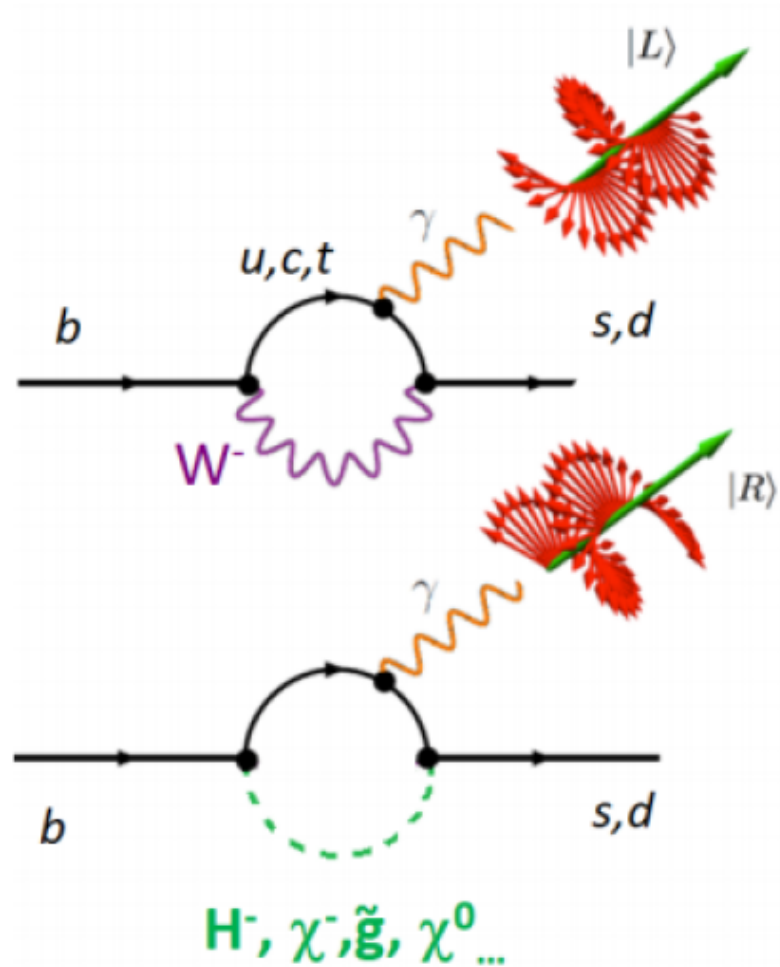


Compatible with the SM at 2.6σ

$$\mathcal{A}^{\Delta} = -0.98^{+0.46}_{-0.52}(stat.)^{+0.23}_{-0.20}(syst.)$$

Radiative B decays

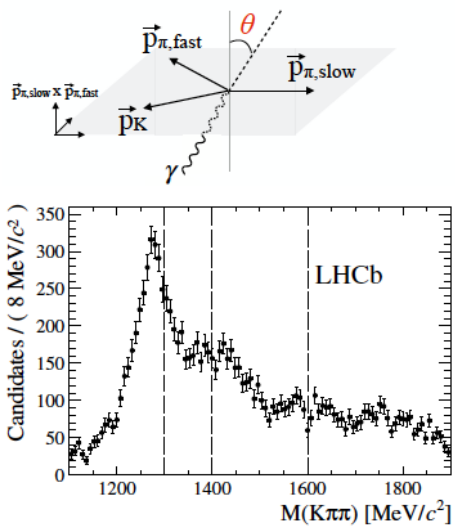
- The branching fraction $B(b \to s\gamma)$ is consistent with the Standard Model & is a powerful constraint of new physics scenarios
- Sensitive to the O_7 operators
- CP violation and photon polarization add sensitivity to NP

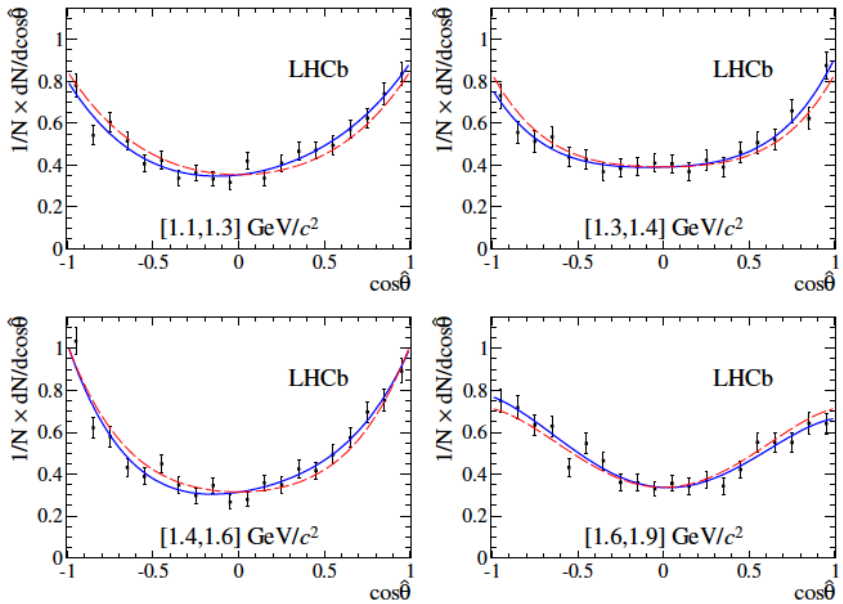


Photon polarization in $B \to K^*\gamma$

PHYS. REV. LETT. 112, 161801 (2014)

- First observation of photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$:

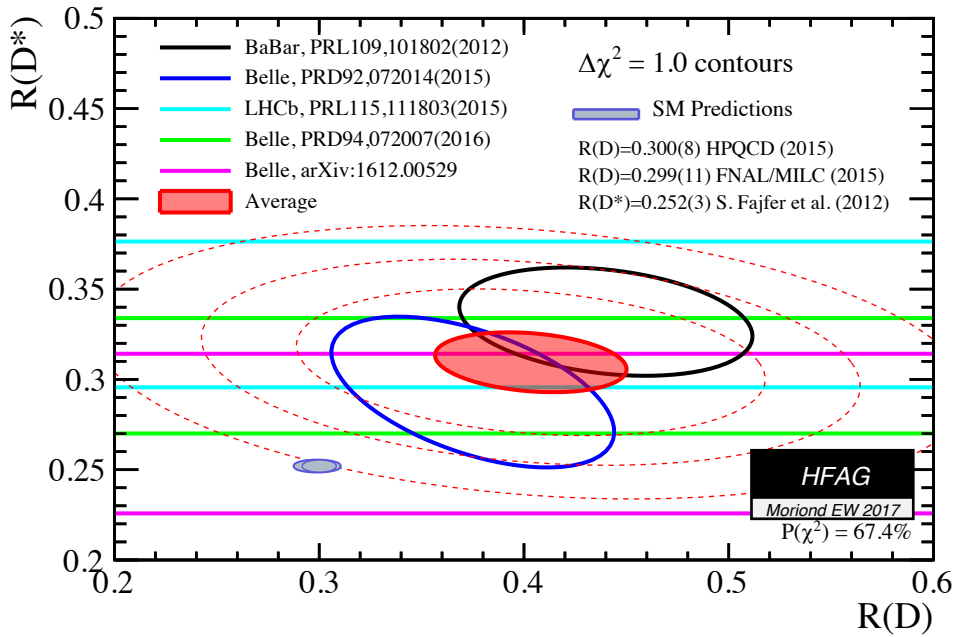




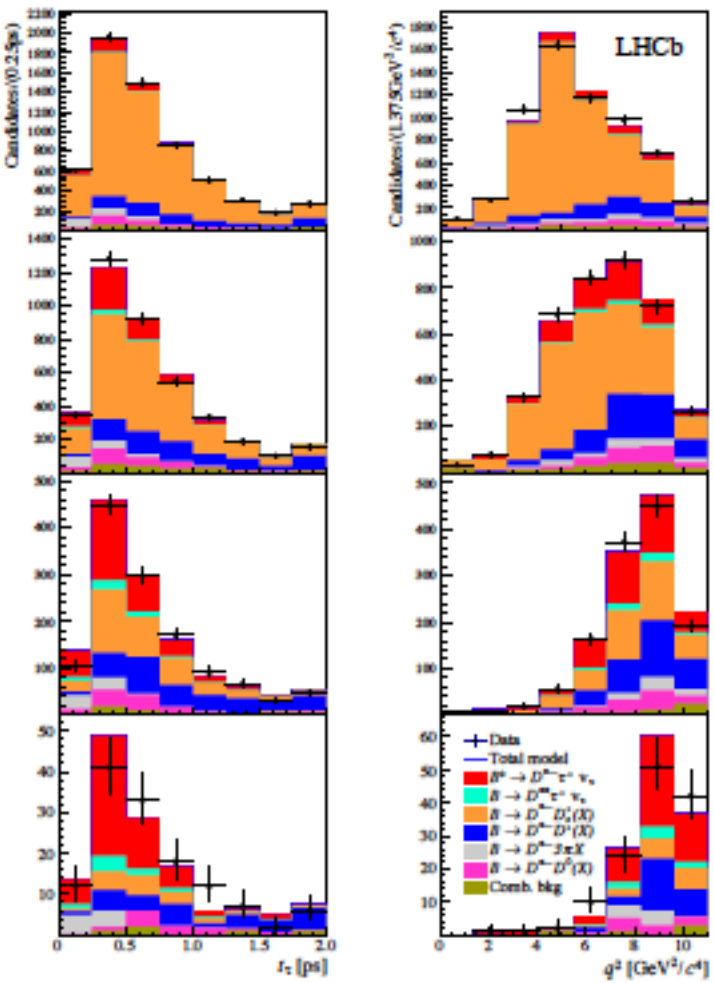
- Exact value of the polarisation depends on hadronic content
  $\to$ full amplitude analysis ongoing.

Lepton flavor violation in $B \to D^{(*)}\tau\nu$

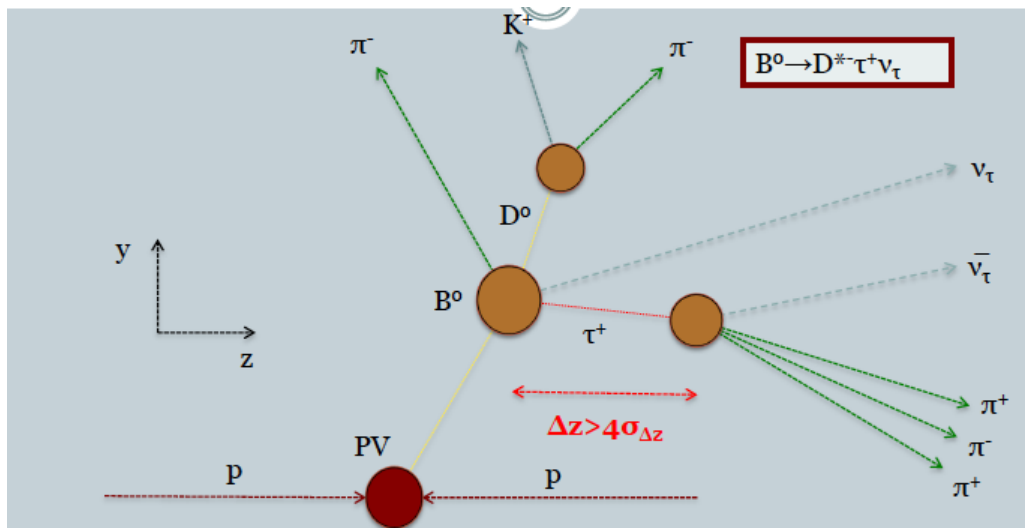
- First reported by BaBar [PRL109, 101802 (2012)], 4 more measurements by BaBar, Belle & LHCb
- Combined RD and RD* fit about 3.9σ from SM predictions



Lepton flavor violation in $B \to D^* \tau \nu$ ($\tau \to 3\pi(\pi^0)$)



LHCb-PAPER-2017-017



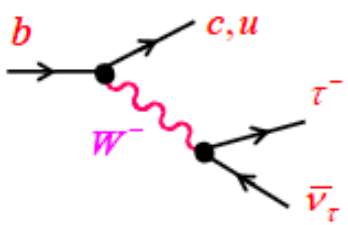
$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.39 \pm 0.09\,(\text{stat}) \pm 0.12\,(\text{syst}) \pm 0.06\,(\text{ext})) \times 10^{-2}$$

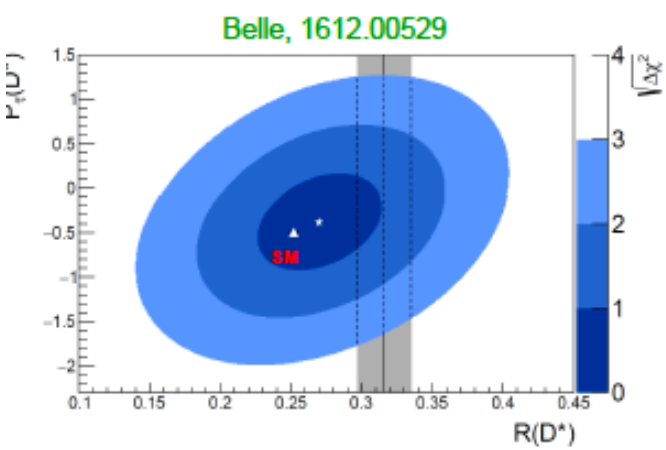
Current status

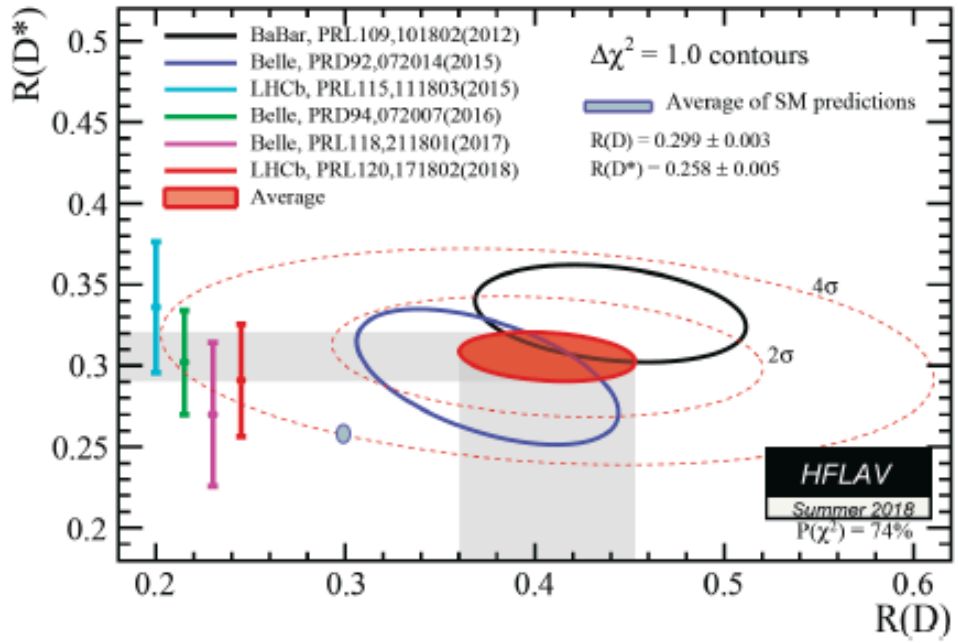
Flavour Anomaly

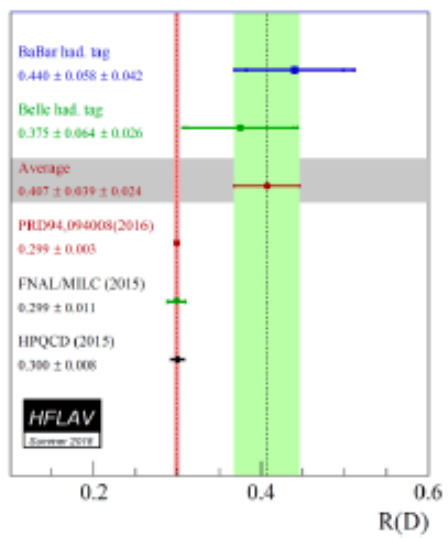
3.8 σ discrepancy

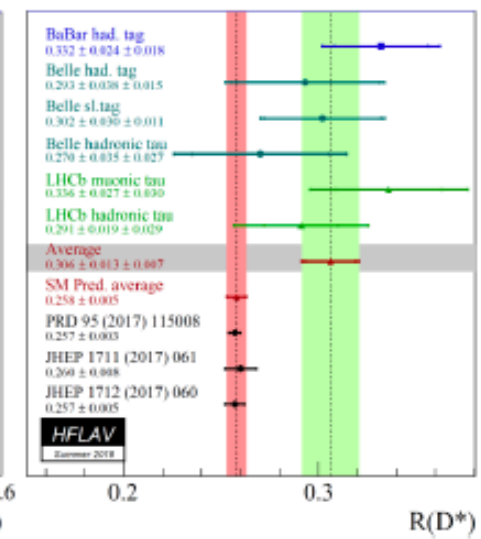
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}\,(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{Br}\,(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$







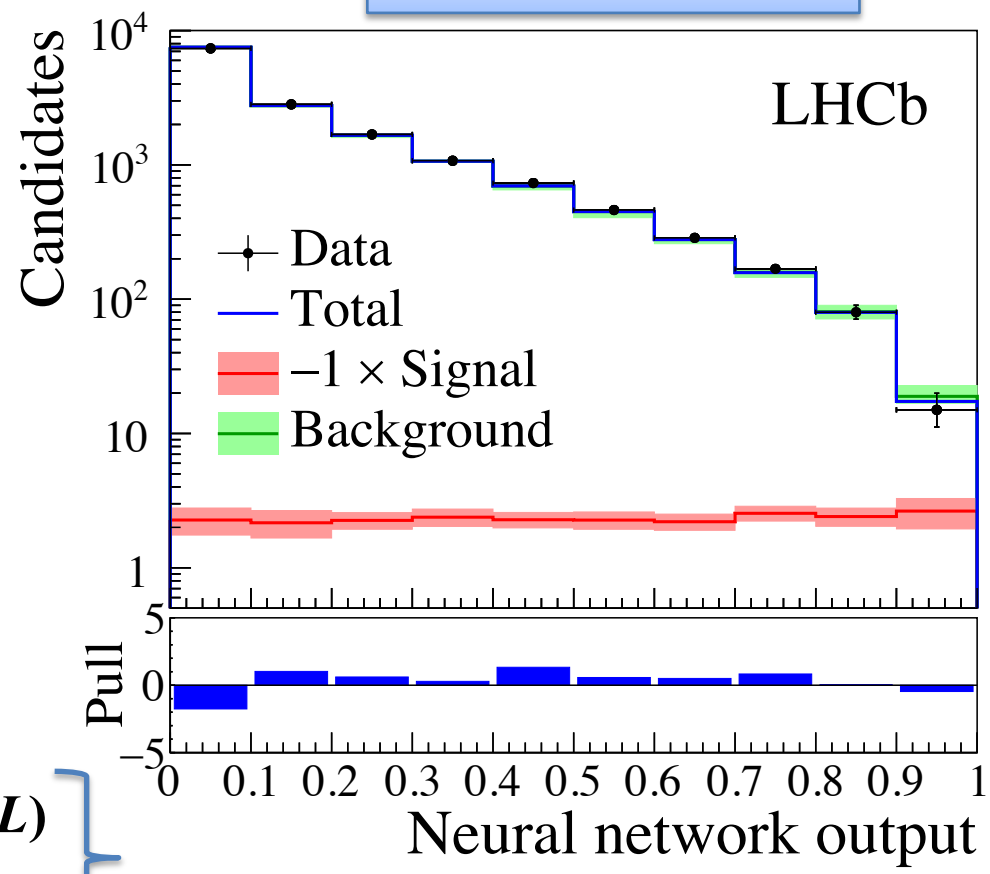




$B(s,d) \to \tau^+\tau^-$

- Based on $3fb^{-1}$ (run 1)
- Use $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$ decay
- Presence of 2 undetected ν make this analysis challenging
- Use neural net to discriminate signal from background

PRL 118 (2017) 251802



$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad (95\%CL)$$

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \quad (95\%CL)$$

Assuming no contribution from the other channel

Effective lifetime

PRL 118(2017)191801

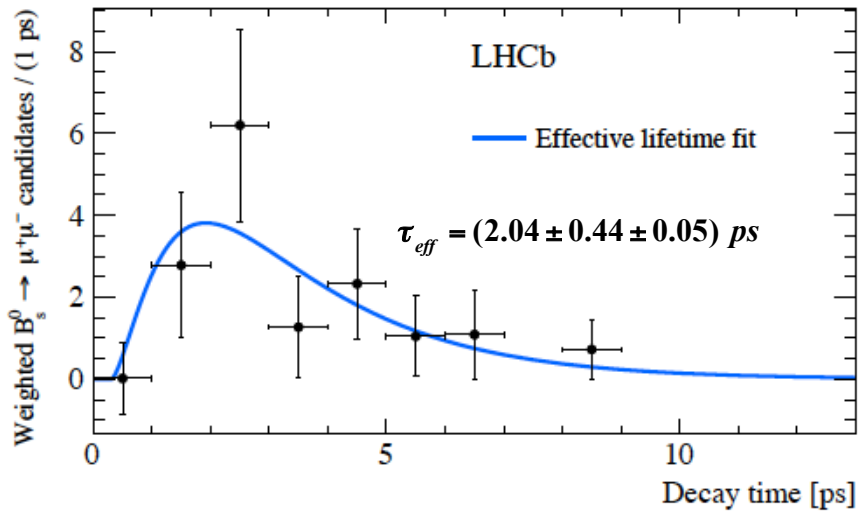
- The $\mathcal{A}_{\Delta\Gamma}$ parameter modifies the effective lifetime of the decay:

$$\tau_{eff} = \frac{\tau_{B_S}}{1-y_s^2}\left(\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right)$$

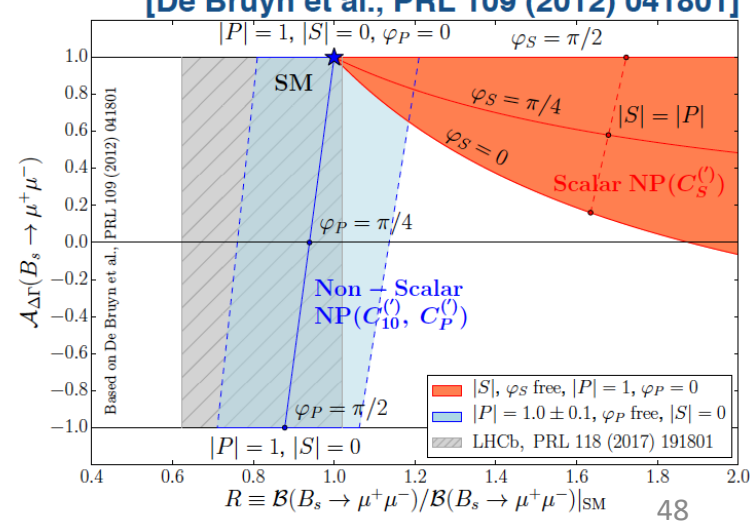
$$y_s = \tau_{B_S}\frac{\Delta\Gamma}{2}$$

- Not yet sensitive to $\mathcal{A}_{\Delta\Gamma}$ that provides separation between scalar and pseudoscalar NP contributions

- Good prospects for run 3&4

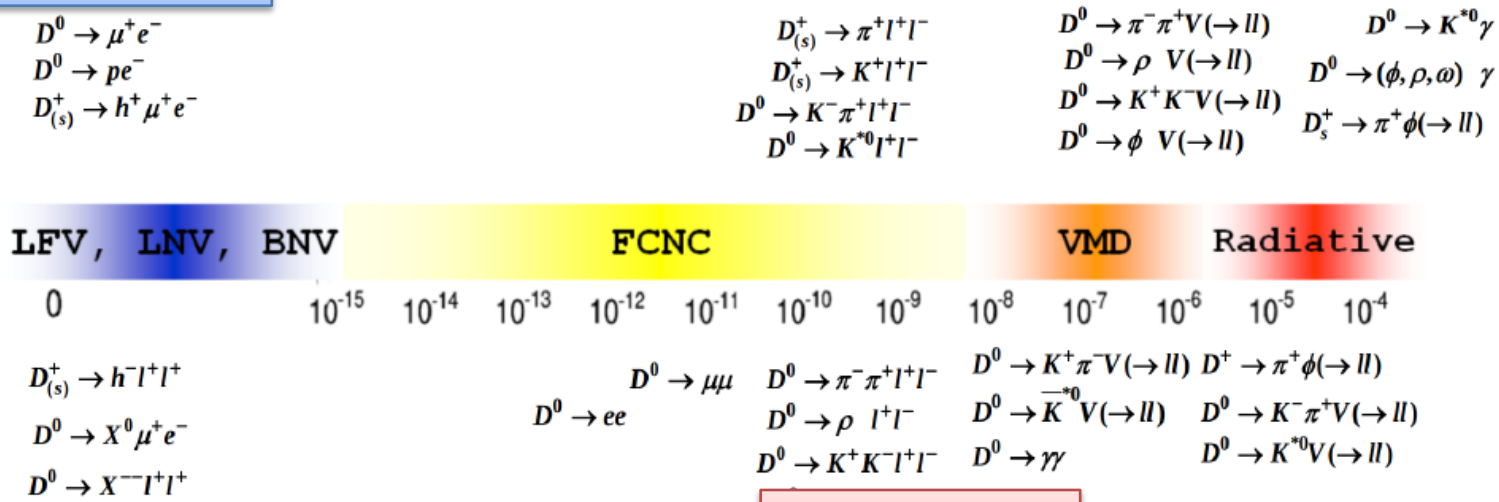


[De Bruyn et al., PRL 109 (2012) 041801]

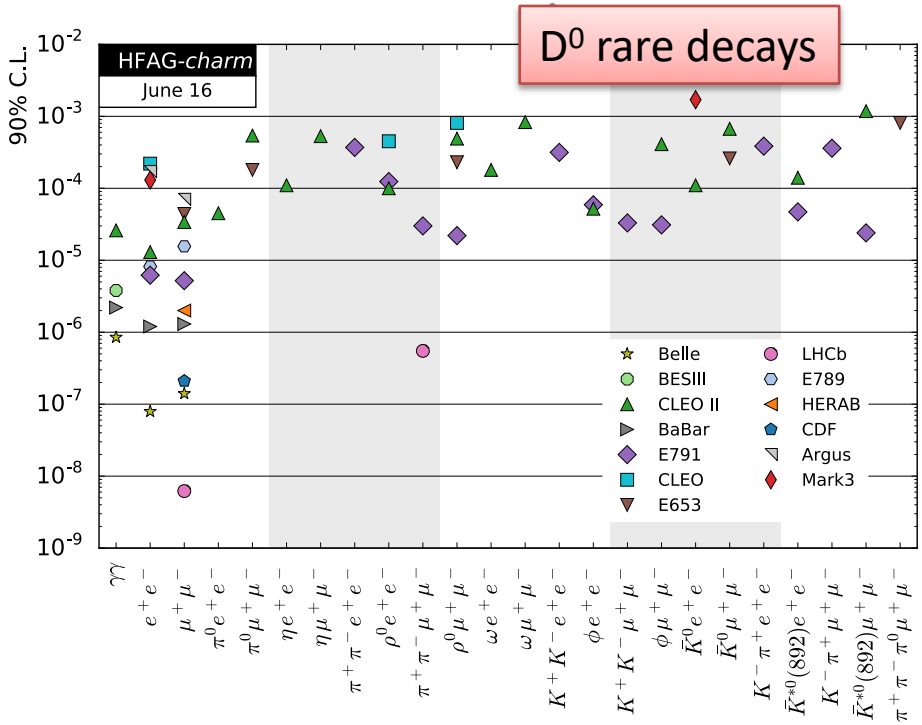


Rare charm decays

J. Prisciandaro FPCP 2017



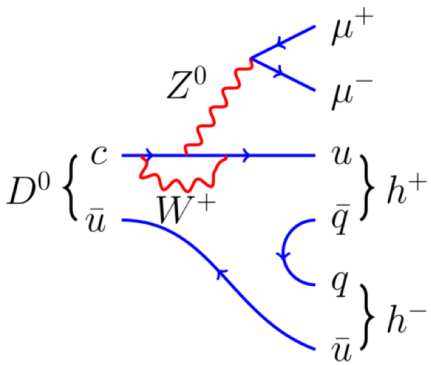
D^0 rare decays



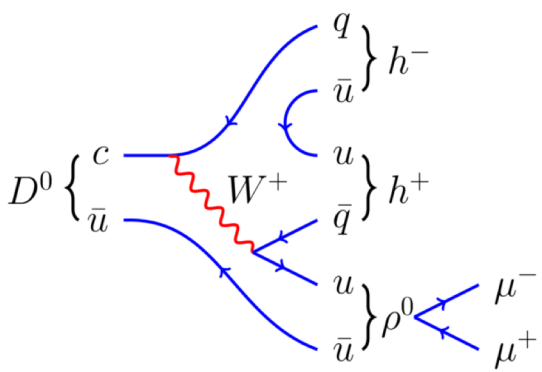
$D^0 \to K^+K^-(\pi^+\pi^-)\mu^+\mu^-$

New!

LHCb-PAPER-2017-019



Short distance

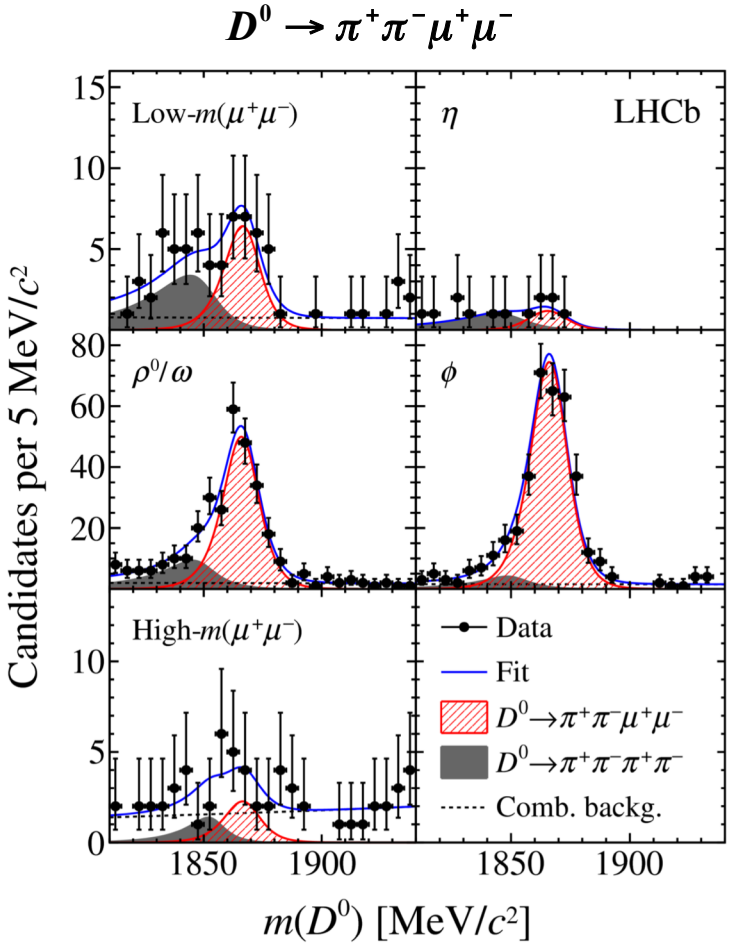


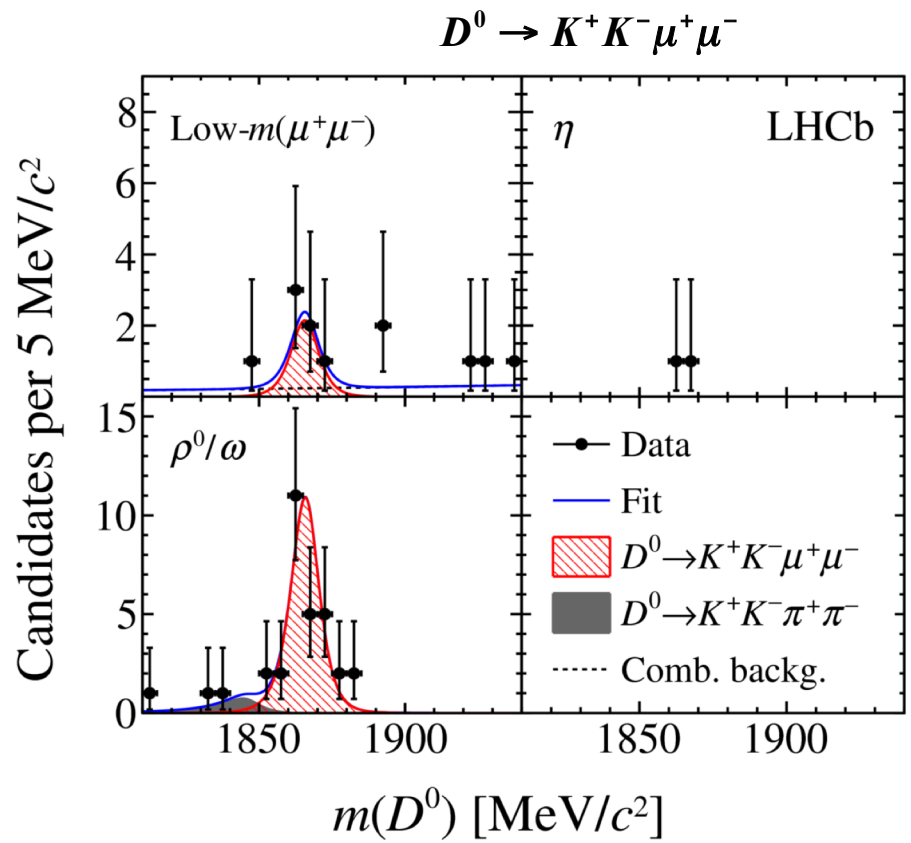
Long distance

- Short distance SM branching fraction expectations highly suppressed
  - [$\mathcal{O}(10^{-9})$- arXiV:1101.6053]
- Long distance contributions can increase BF to $\mathcal{O}(10^{-6})$ [arXiV:0706.1133]
- Resonances affect all dimuon invariant mass spectrum but more prominent in low-mass resonance regions

Results

LHCb-PAPER-2017-019



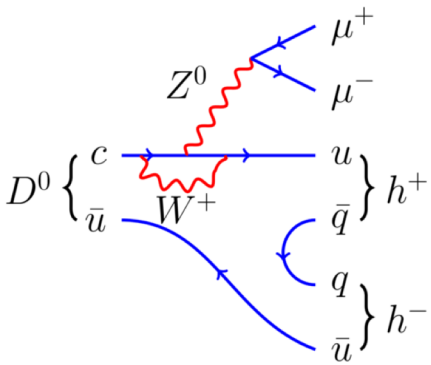


$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

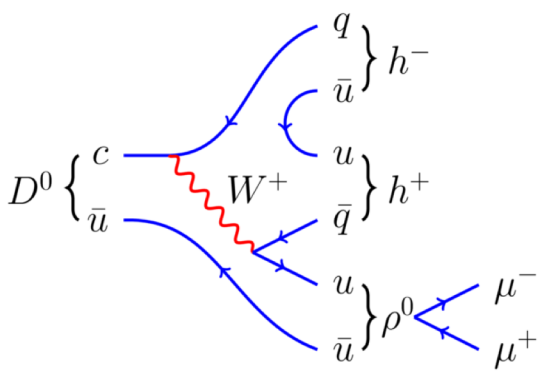
$D^0 \to K^+K^-(\pi^+\pi^-)\mu^+\mu^-$

New!

LHCb-PAPER-2017-019



Short distance

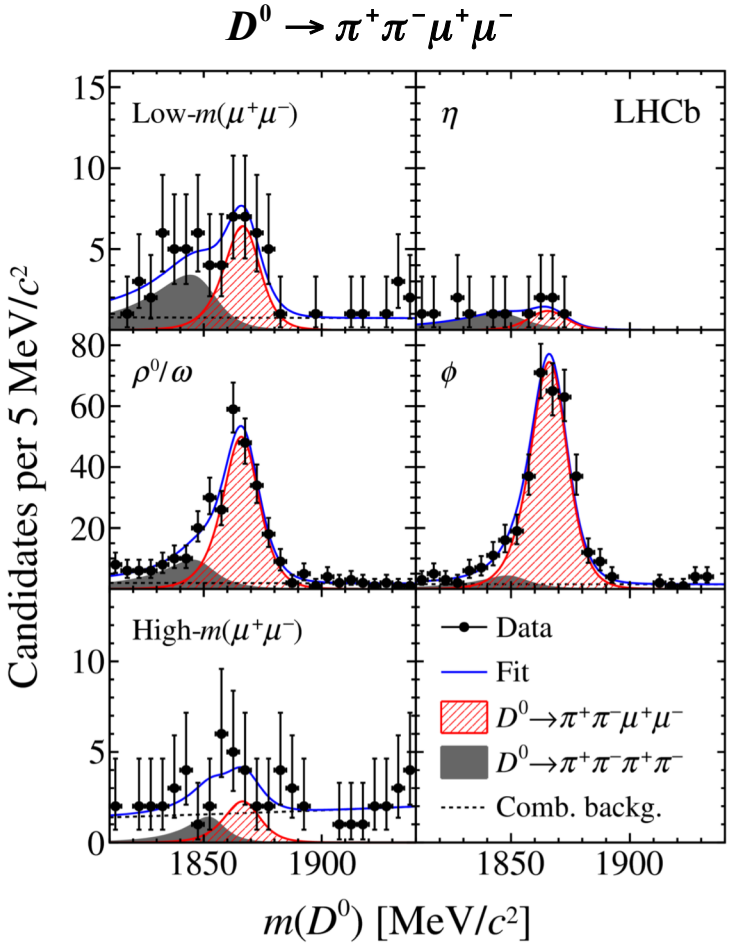


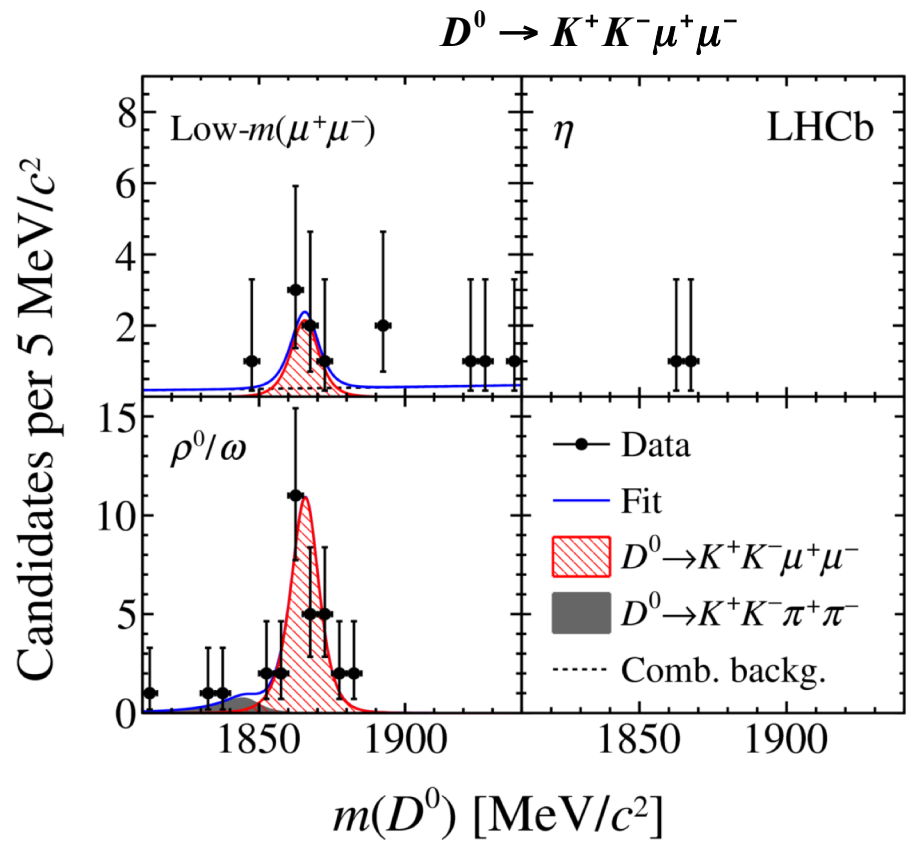
Long distance

- Short distance SM branching fraction expectations highly suppressed
  - [$\mathcal{O}(10^{-9})$- arXiV:1101.6053]
- Long distance contributions can increase BF to $\mathcal{O}(10^{-6})$ [arXiV:0706.1133]
- Resonances affect all dimuon invariant mass spectrum but more prominent in low-mass resonance regions

Results

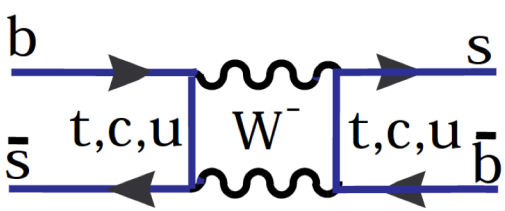
LHCb-PAPER-2017-019

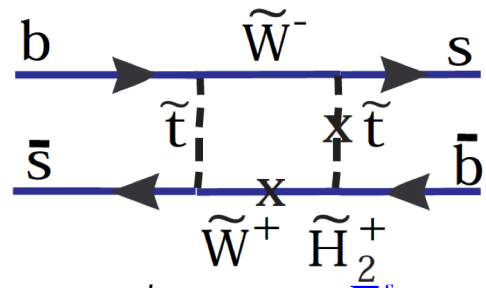




$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

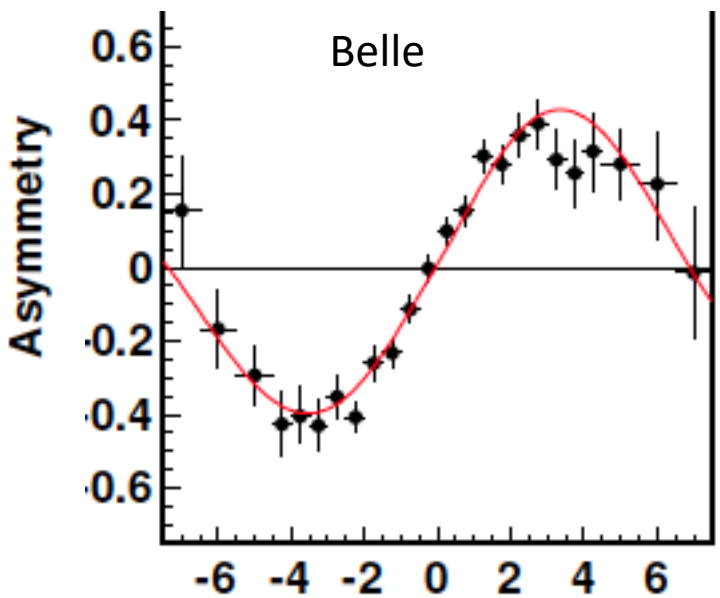
B mixing and CP violation





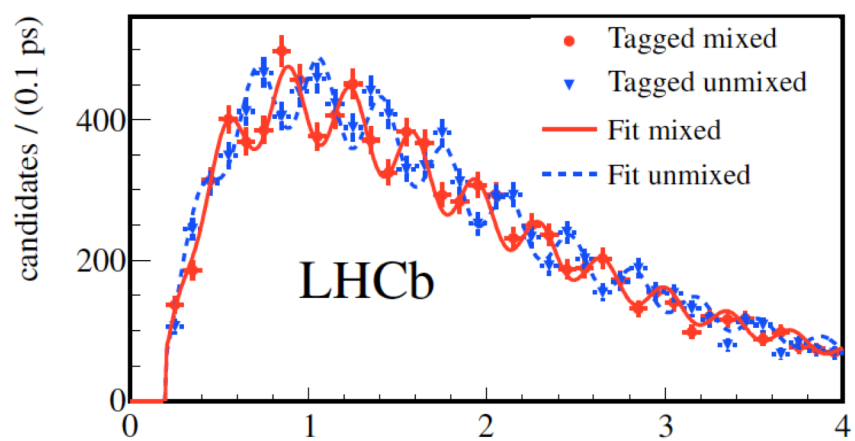
Time evolution of Flavor Eigenstates

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}^s - i\frac{\Gamma_{11}^s}{2} & M_{12}^s - i\frac{\Gamma_{12}^s}{2} \\ M_{12}^{s*} - i\frac{\Gamma_{12}^{s*}}{2} & M_{22}^s - i\frac{\Gamma_{22}^s}{2} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$



PDG 2012

$$\Delta m_d = 0.507 \pm 0.004 \ \ \mathrm{ps}^{-1}$$

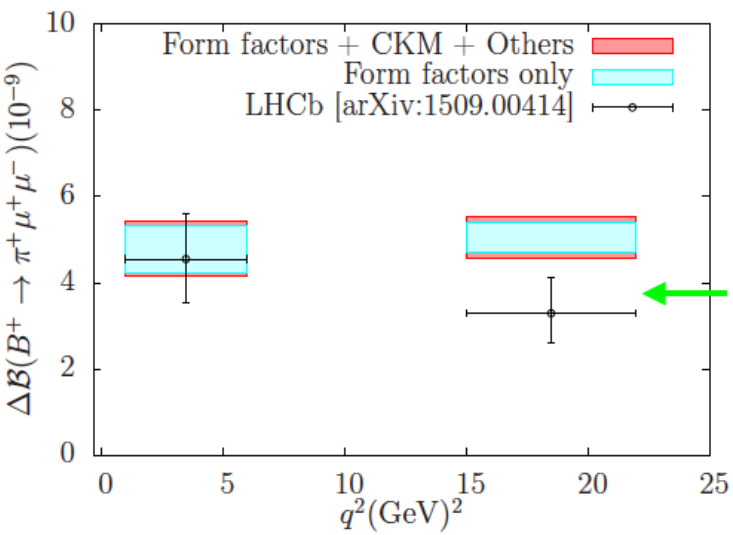


$$\Delta m_s = 17.768 \pm 0.023 \ (\mathrm{stat}) \pm 0.006 \ (\mathrm{syst}) \ \mathrm{ps}^{-1}$$

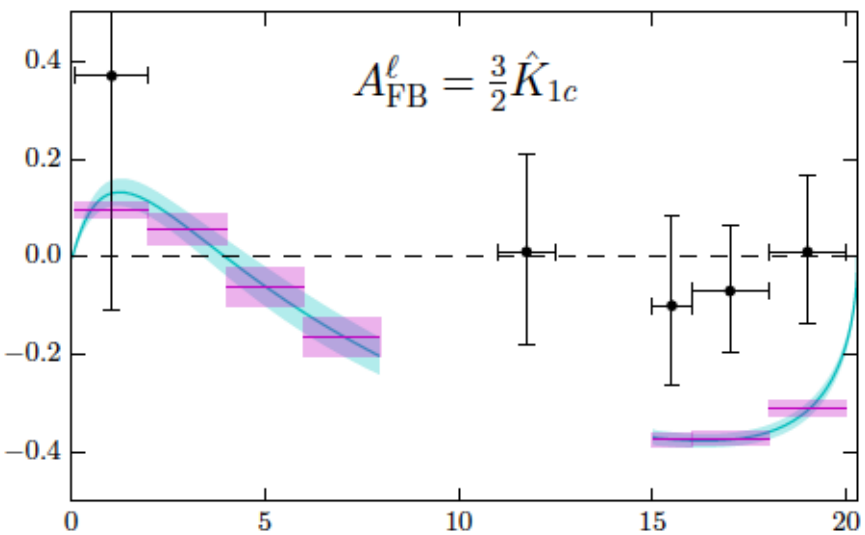
Other flavor-changing neutral current "tensions"

LHCb [arXiV:1509.00414]

FNAL/MILC:1510.02349



2σ tension

LHCb [arXiV:1503.07138]

Detmold, Lehner, Meinel: 1602.01399