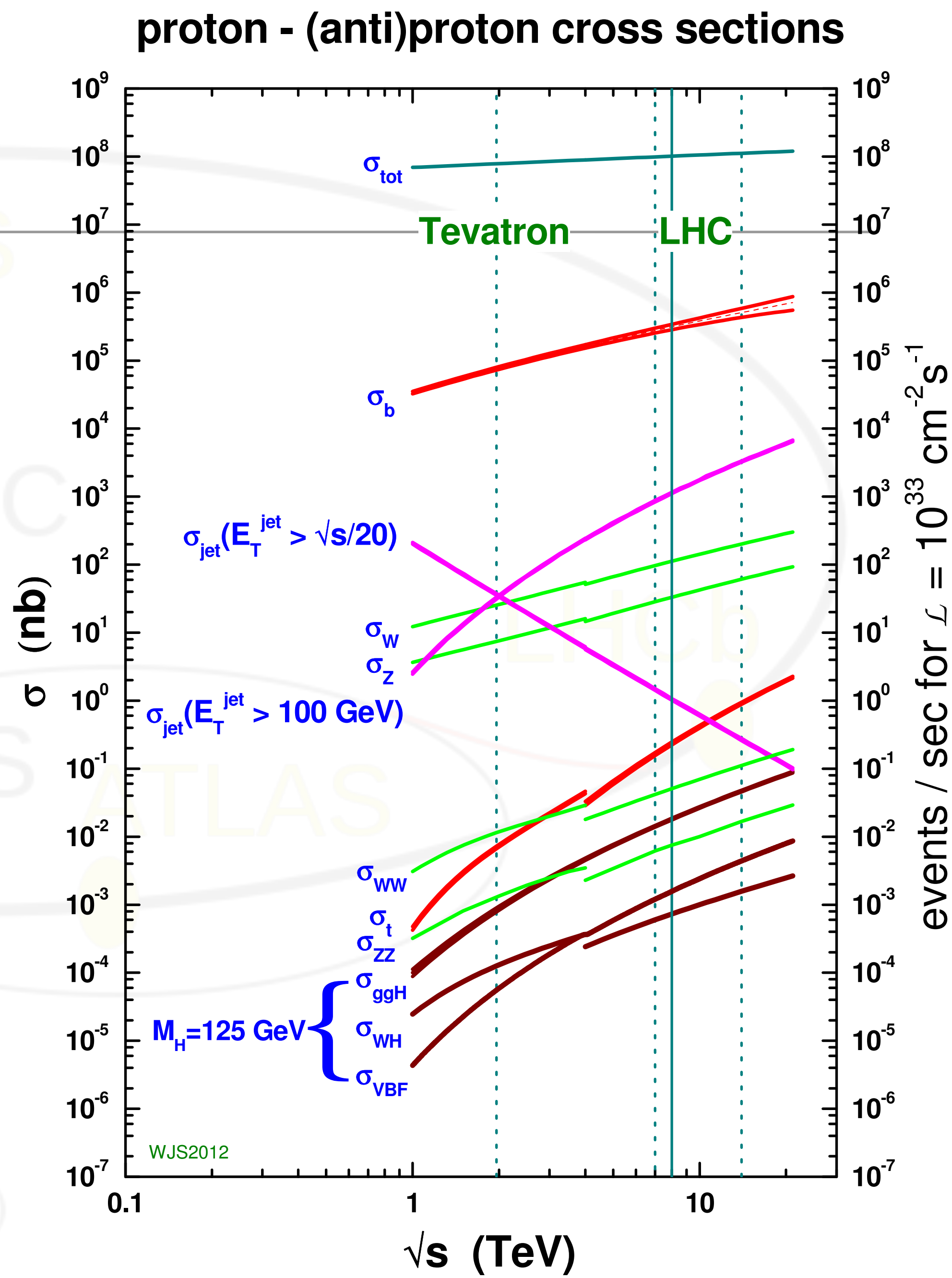
Rare B decays

Jonas Rademacker (University of Bristol, UK, LHCb)

Flavour physics at the LHC

- Huge b cross section, even huger (20×) charm cross section.
- All types of b hadrons, like $B^0=(\bar{b},d)$, $B^+=(\bar{b},u)$, $B_s=(\bar{b},s)$, $B_c=(\bar{b},c)$, $\Lambda_b=(ud\bar{b})$, … and c-hadrons like $D^0=(c,\bar{d})$, $D^+=(c,\bar{d})$, $D_s=(c,\bar{s})$, $\Lambda_c=(cdu)$, …
- The world's largest heavy flavour samples, and a dedicated flavour physics detector (LHCb).
- Best place to do heavy flavour physics, today.

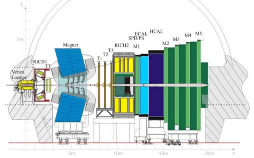


Eur.Phys.J. C63 (2009) 189-285

http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

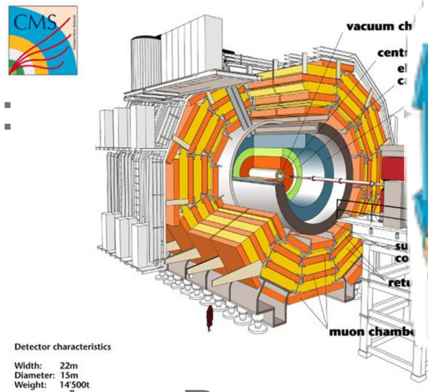
Heavy flavour physics at the LHC

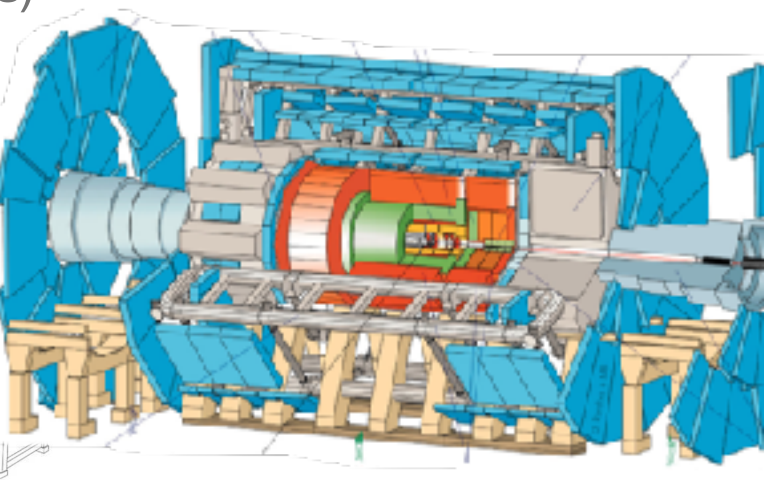
- LHCb: Dedicated flavour physics experiment at the LHC:
  - Optimised geometry
  - RICH particle ID (K/π separation)
  - Most precise vertexing at LHC
  - Dedicated heavy flavour trigger (incl B→hadrons)
  - Best mass resolution at LHC (for heavy flavour).



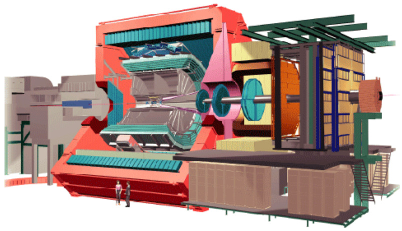
small & mighty

- ATLAS, CMS' heavy flavour skills:
  - good μ coverage,
  - efficient di-muon trigger,
  - maximal luminosity.
  - Good at rare dimuon decays such as $B_{(s)} \to \mu\mu$.





- ALICE: Cleanly reconstructs heavy flavour decays, focussed on using this to study quark-gluon plasma.



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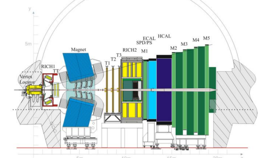
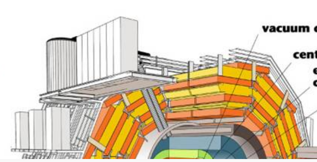
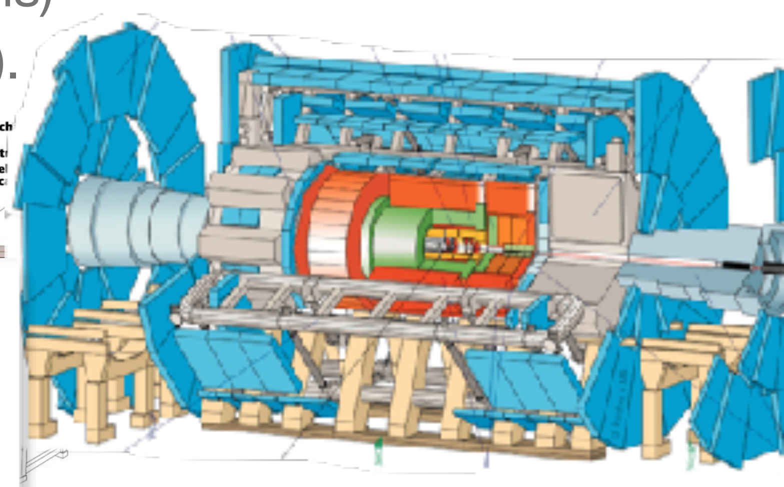


small & mighty



- ATLAS, CMS' heavy flavour skills:



Decays with μμ like B→μμ or B→J/ψX, J/ψ→μμ

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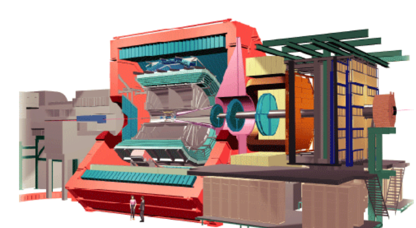
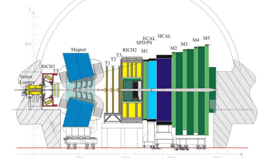


Heavy flavour physics at the LHC

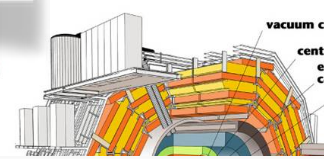
- LHCb: Dedicated flavour physics experiment at the LHC:

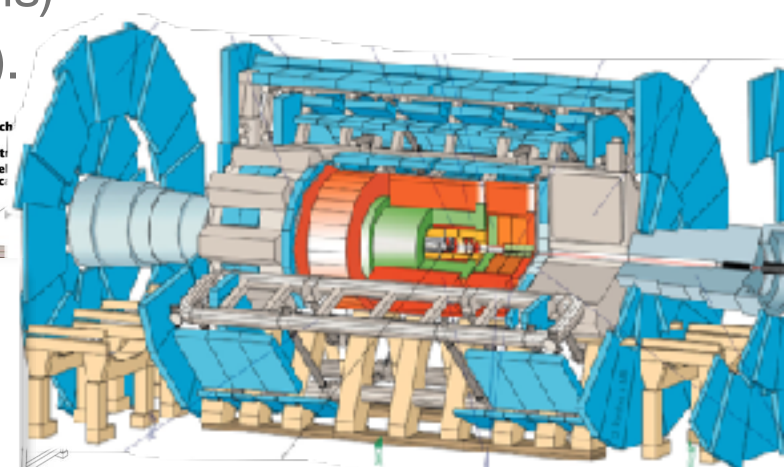
B, D, Λ_b,…→Anything
(except decays with lots of neutrals, that's for BELLE II)



small & mighty

cl B→hadrons)
eavy flavour).





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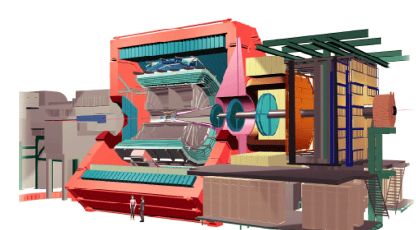
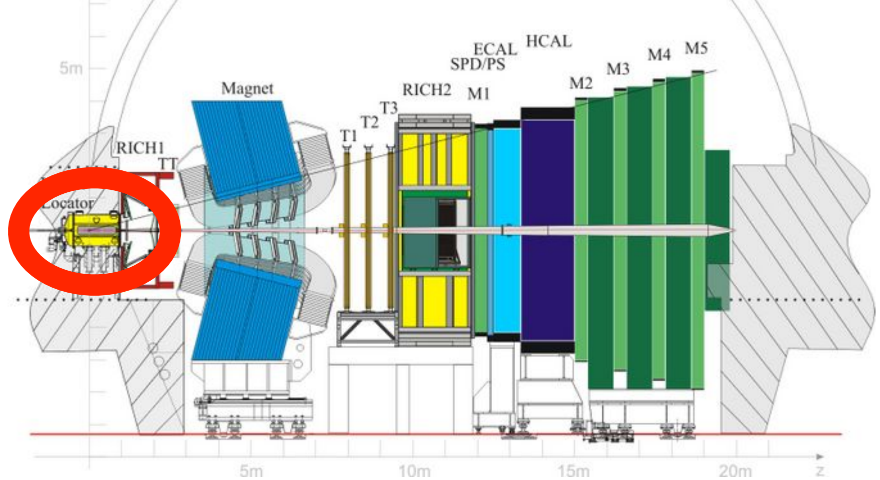
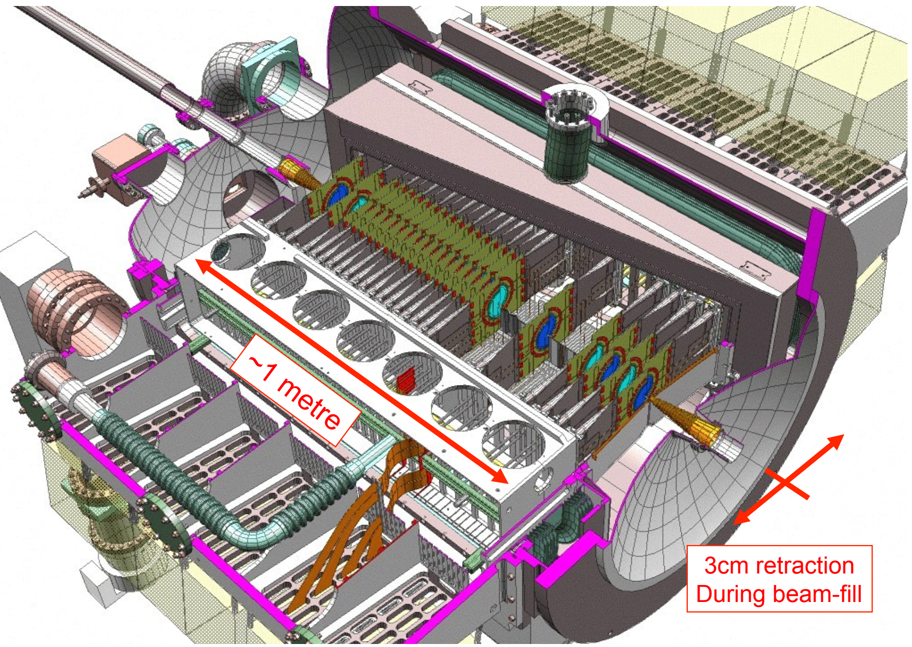
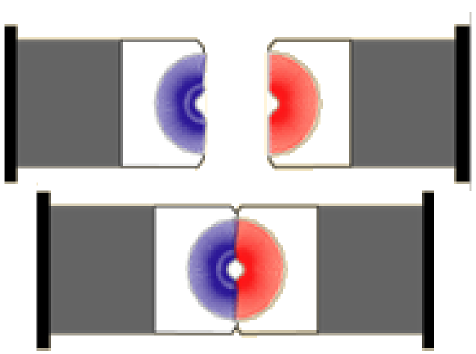
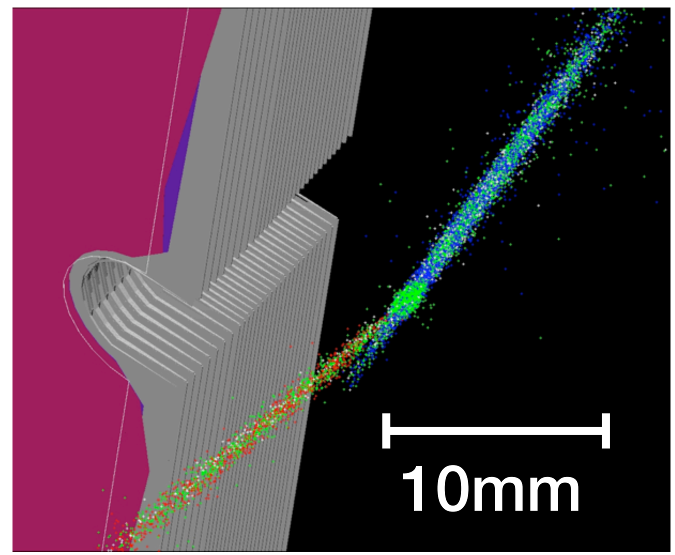


Vertex Locator (VELO)







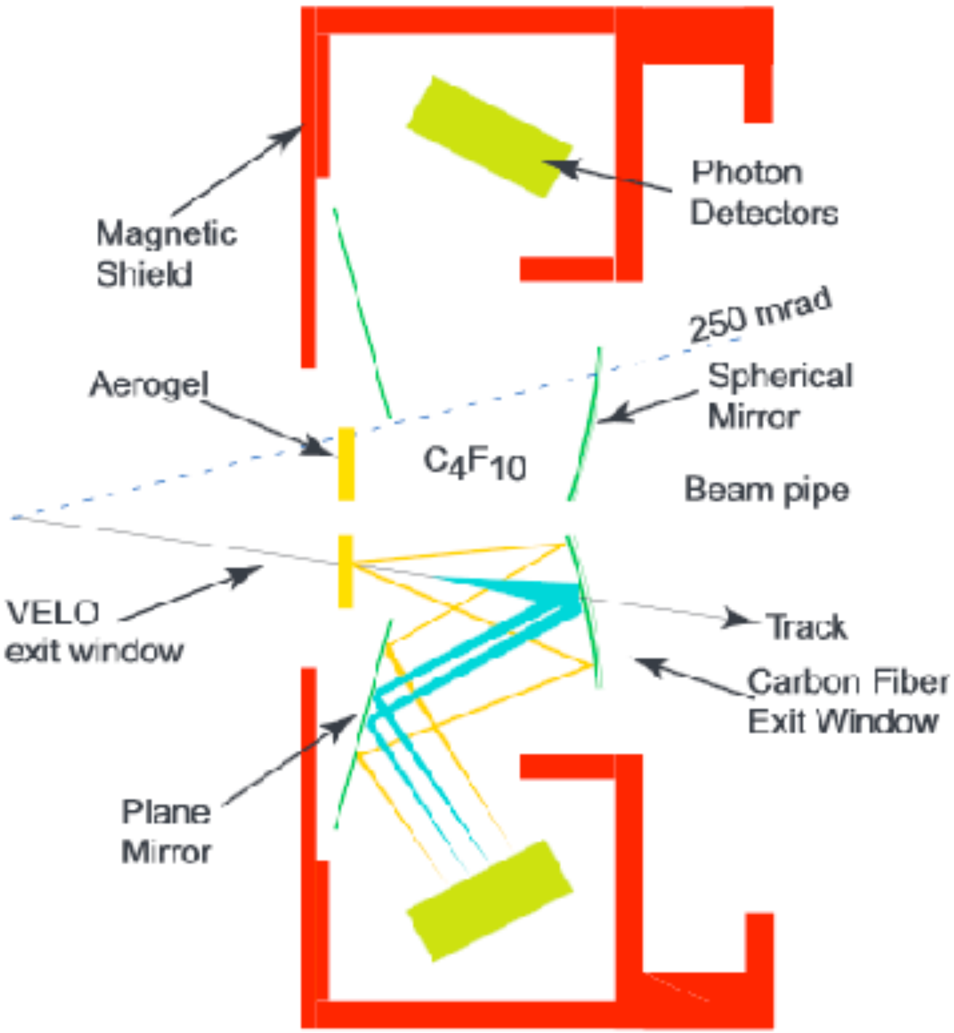


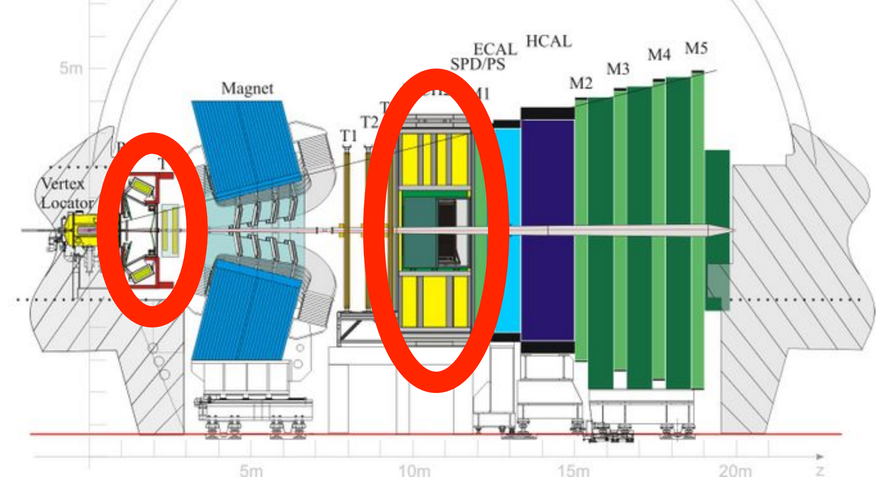
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

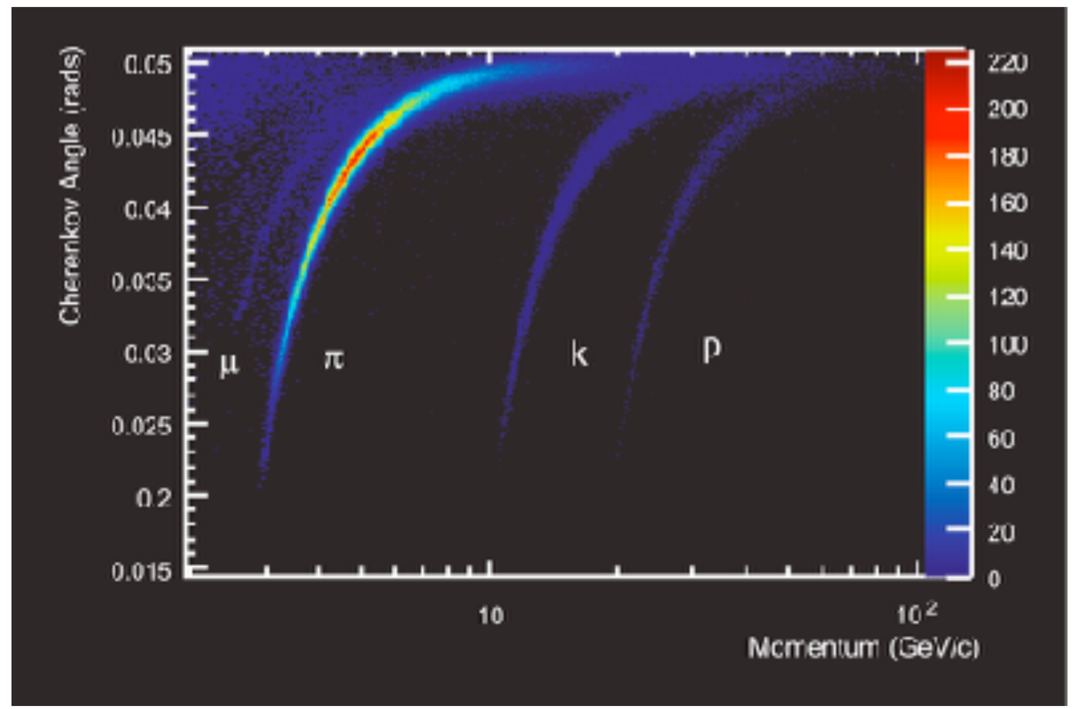
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

Locates B-meson decays to ~10 μm

Ring Imaging CHerenkov Detector (RICH)

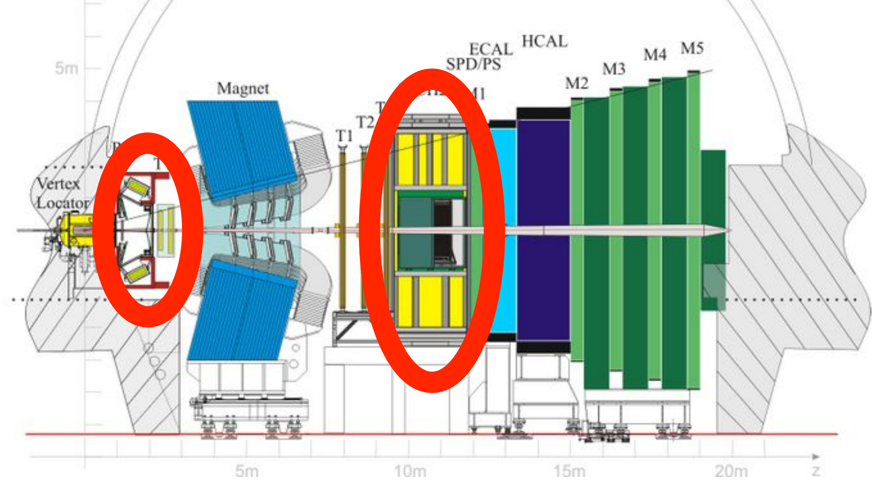


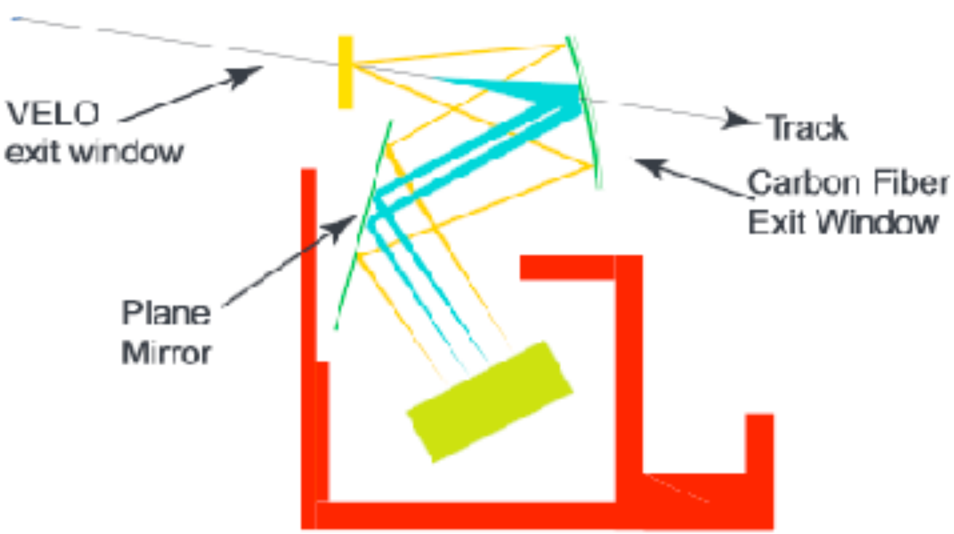


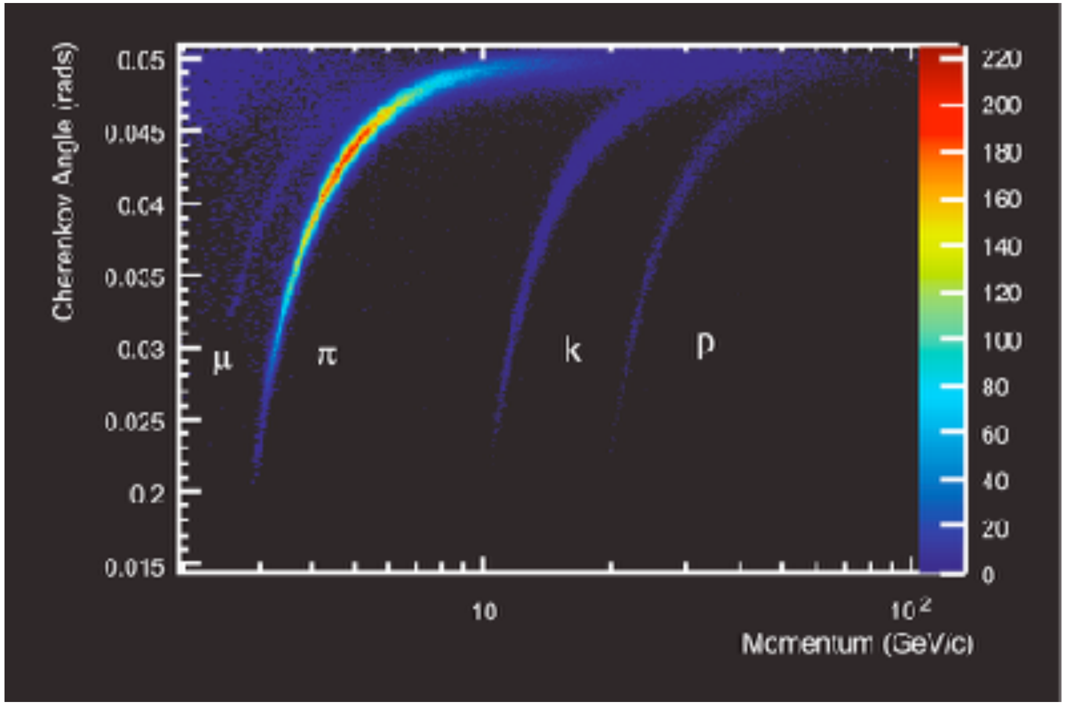


published in and on title page of: EPJ C 73:2431 (2013)

Ring Imaging CHerenkov Detector (RICH)







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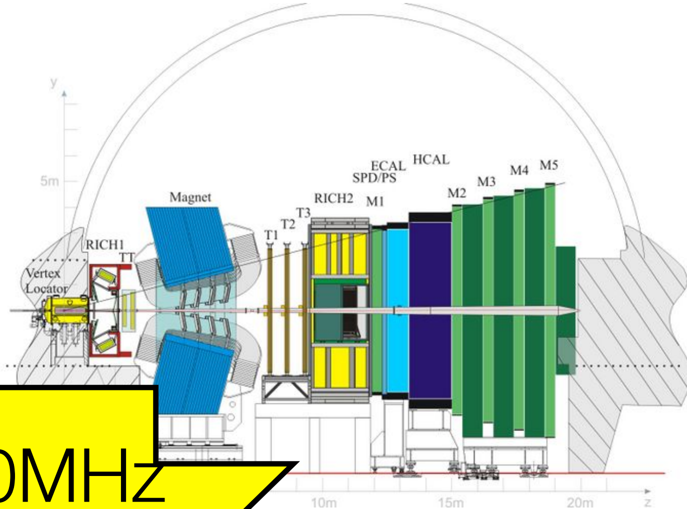
LHC… Run 1



40MHz bunch crossing

L0 hardware trigger

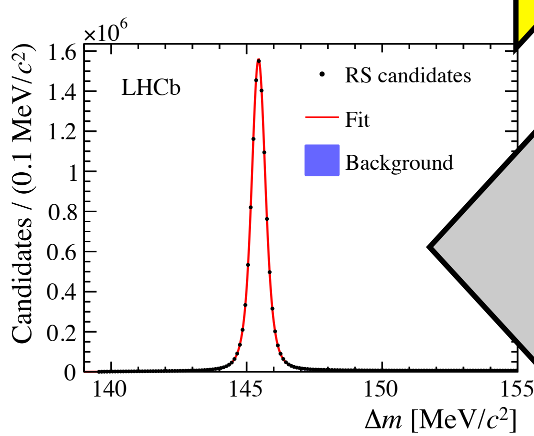
1MHz

Software trigger

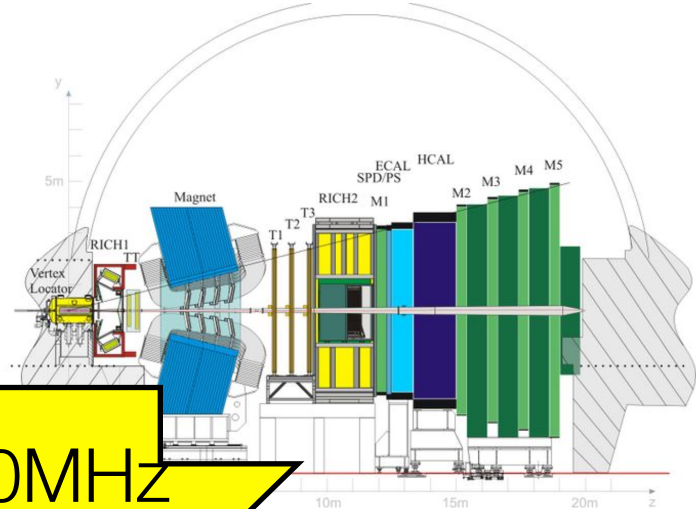
5kHz

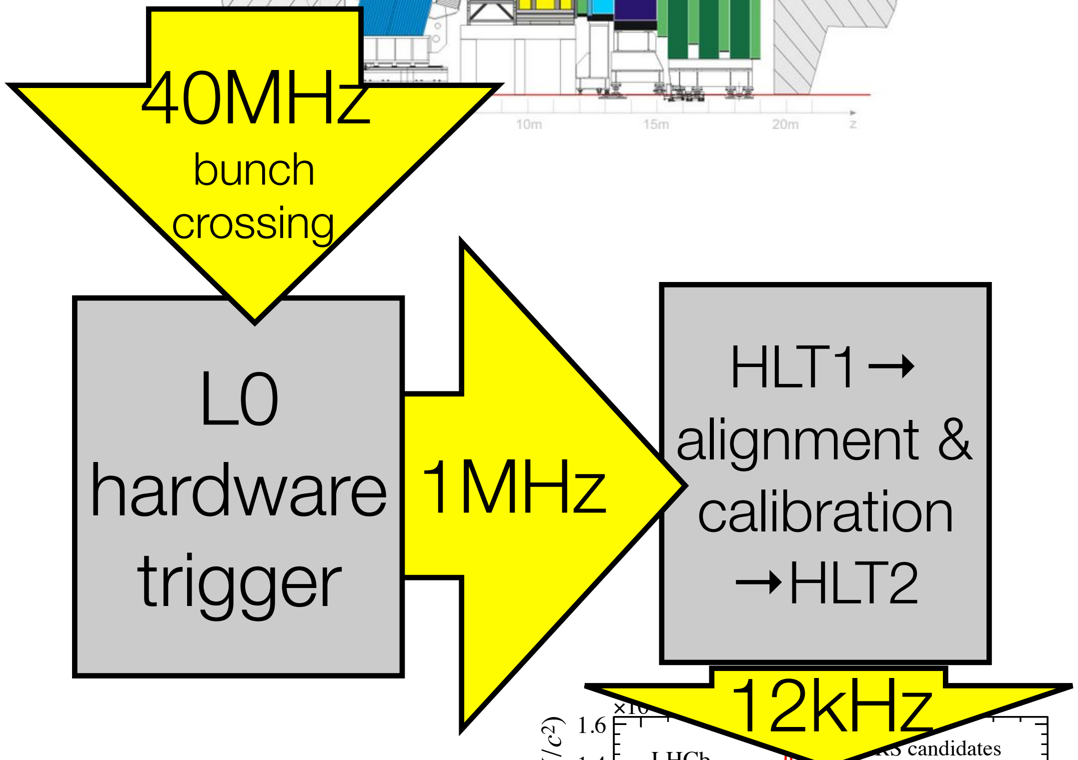
Alignment & calibration

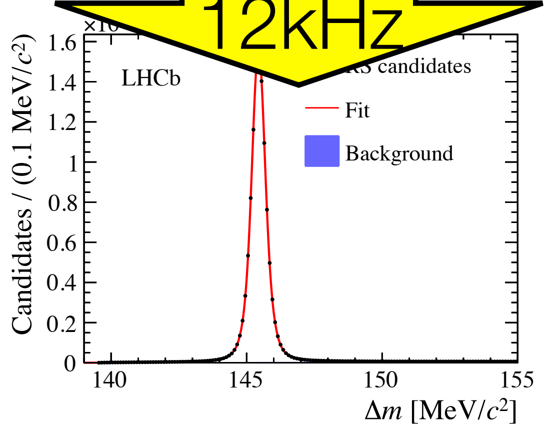
Offline reconstruction



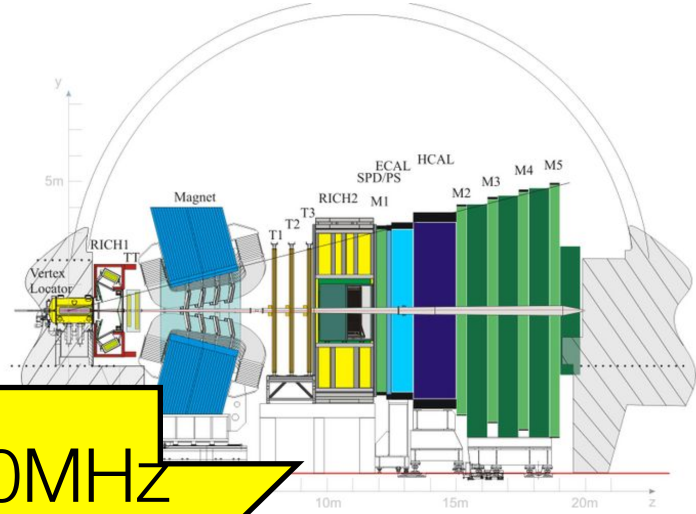
LH Run 2 (started summer 2015)







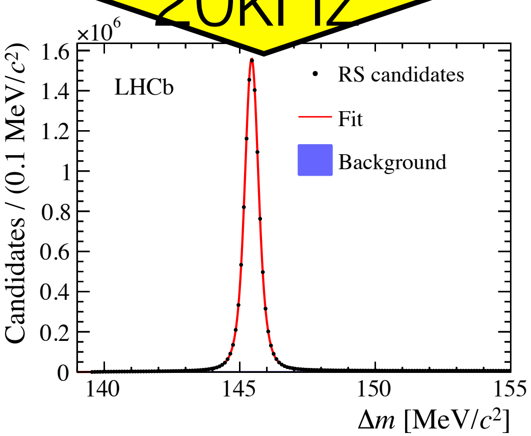
LHC upgrade (data taking in 2020)



40MHz
bunch crossing

Full event reconstruction/ selection by trigger

20kHz



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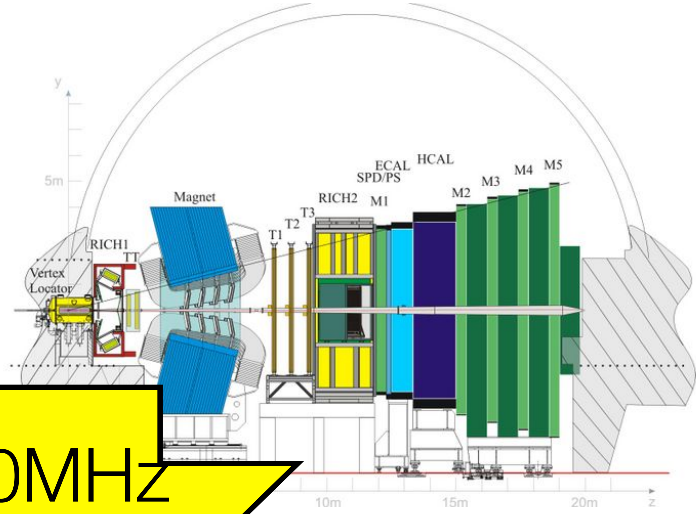

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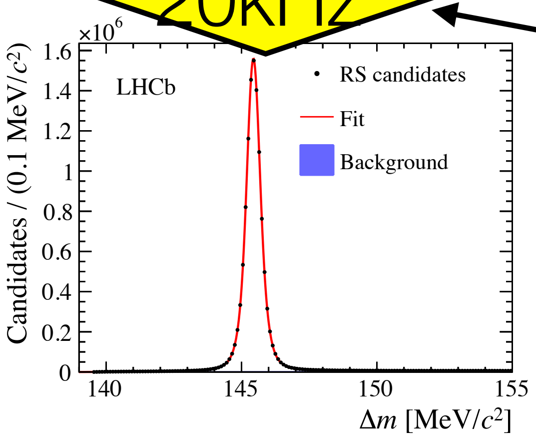
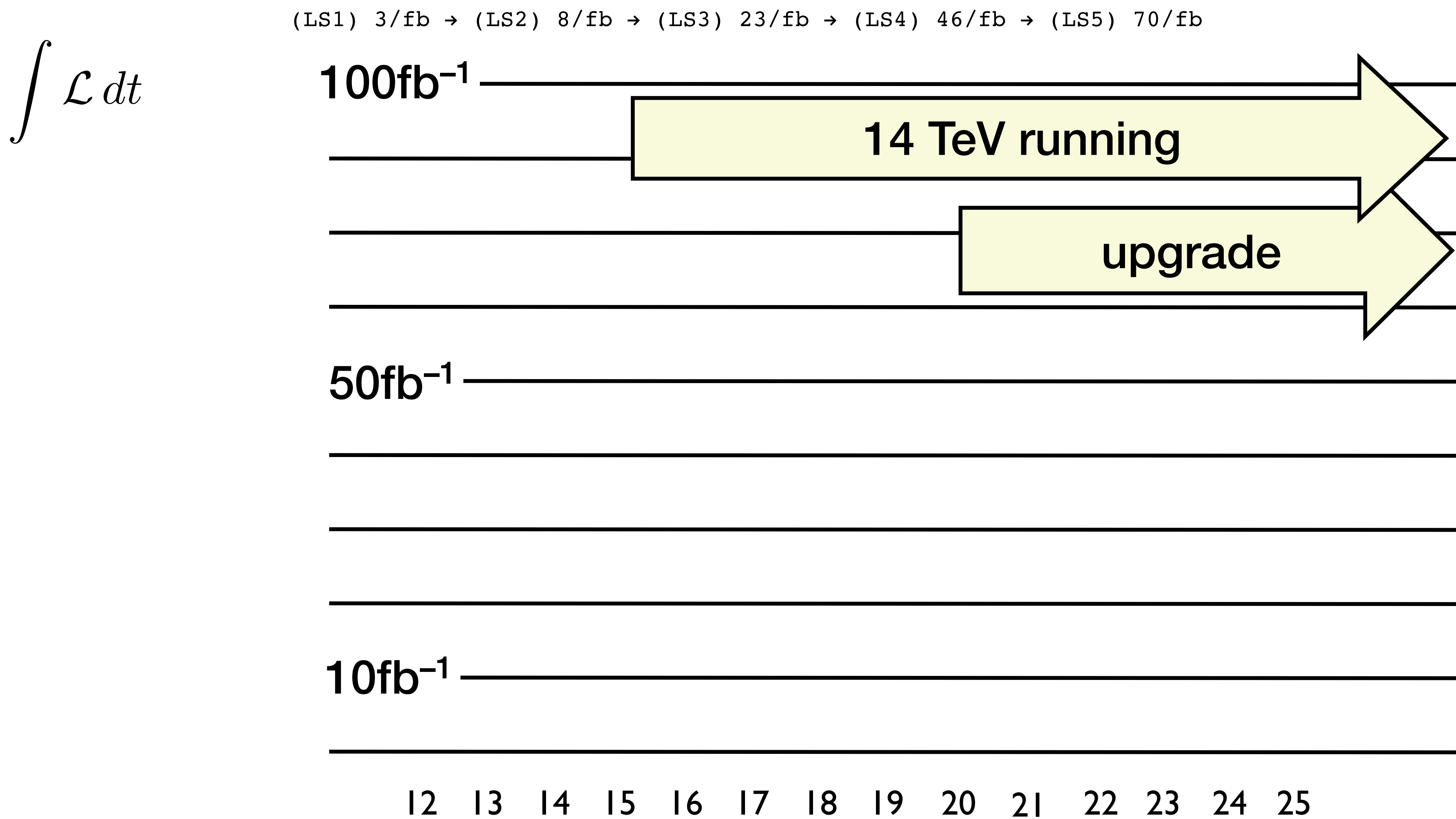


Not just *more* kHz.

Also ***better*** kHz

(higher signal fraction / benefit depends on mode)

LHCb event yields in the future (rough estimates)



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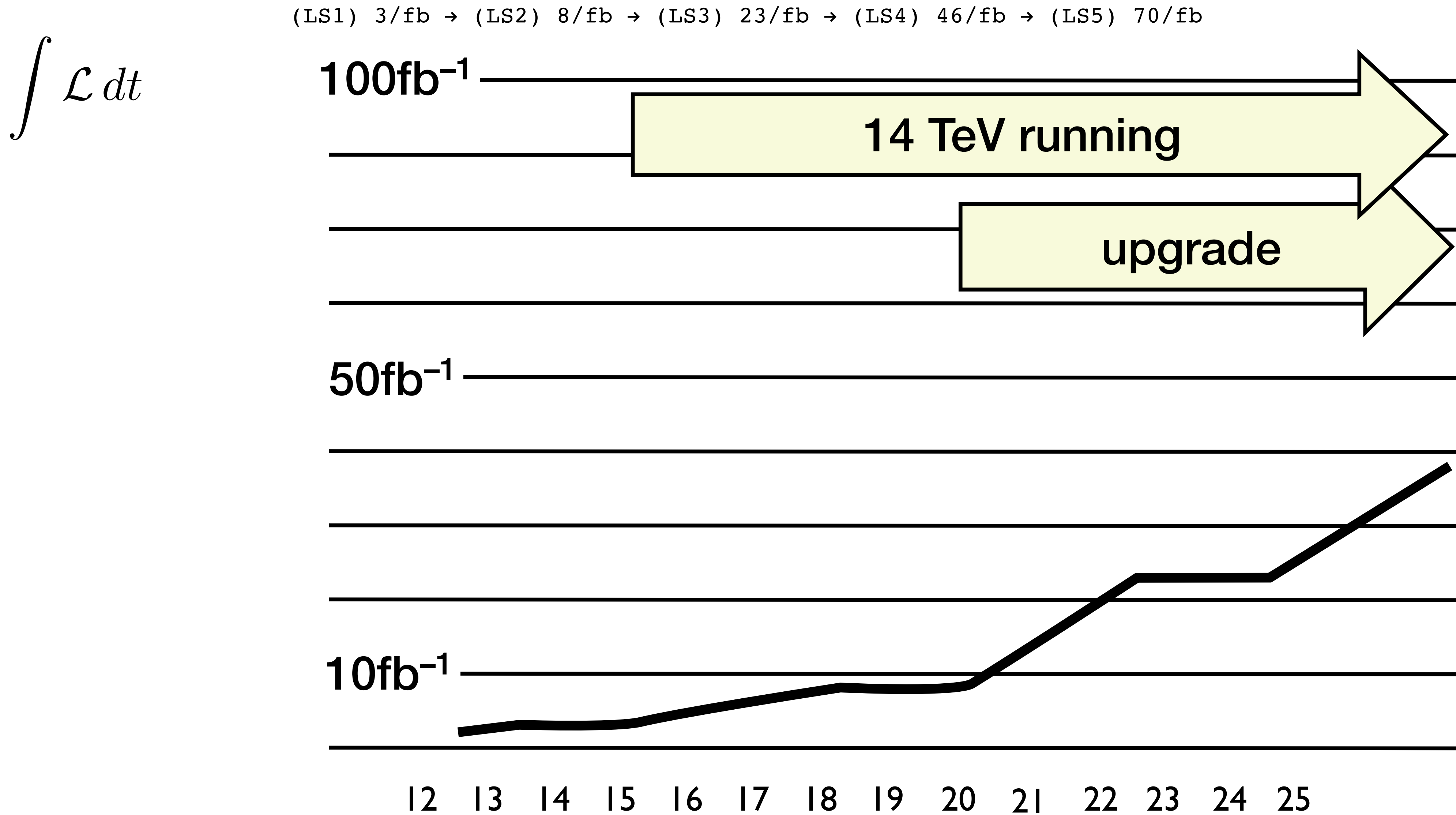

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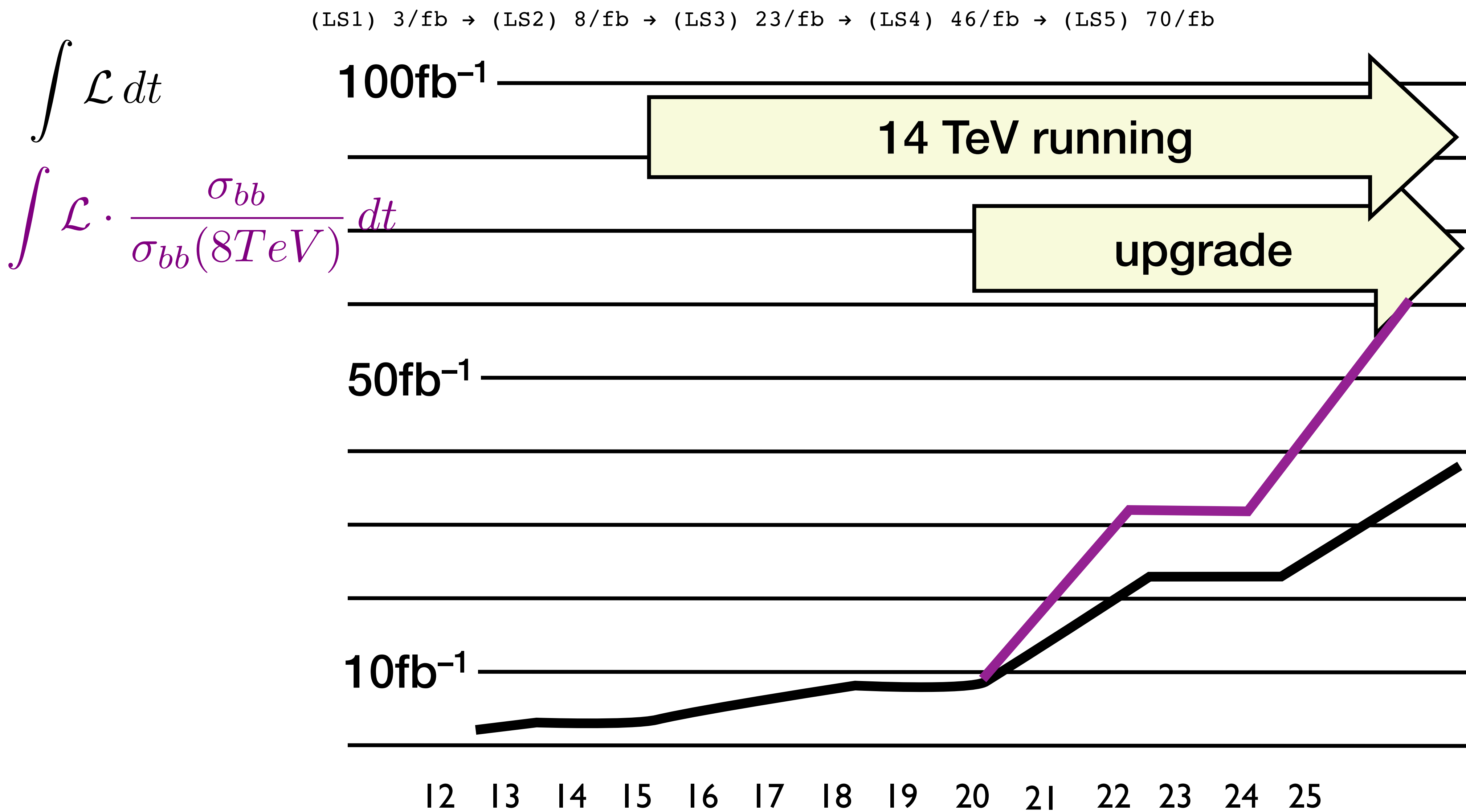


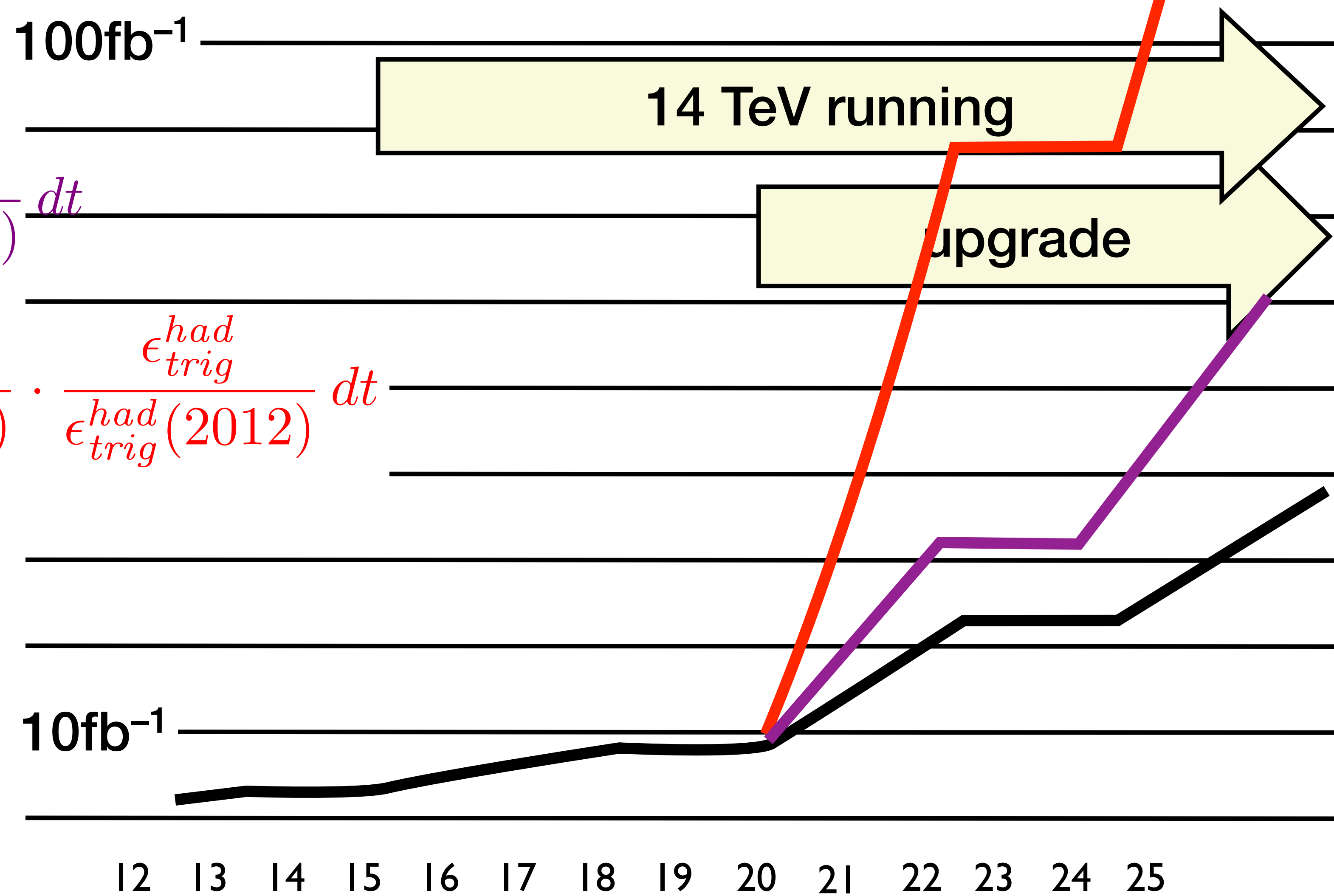
LHCb event yields in the future (rough estimates)

(LS1) 3/fb → (LS2) 8/fb → (LS3) 23/fb → (LS4) 46/fb → (LS5) 70/fb

$$\int \mathcal{L}\, dt$$

$$\int \mathcal{L} \cdot \frac{\sigma_{bb}}{\sigma_{bb}(8TeV)}\, dt$$

$$\int \mathcal{L} \cdot \frac{\sigma_{bb}}{\sigma_{bb}(8TeV)} \cdot \frac{\epsilon_{trig}^{had}}{\epsilon_{trig}^{had}(2012)}\, dt$$



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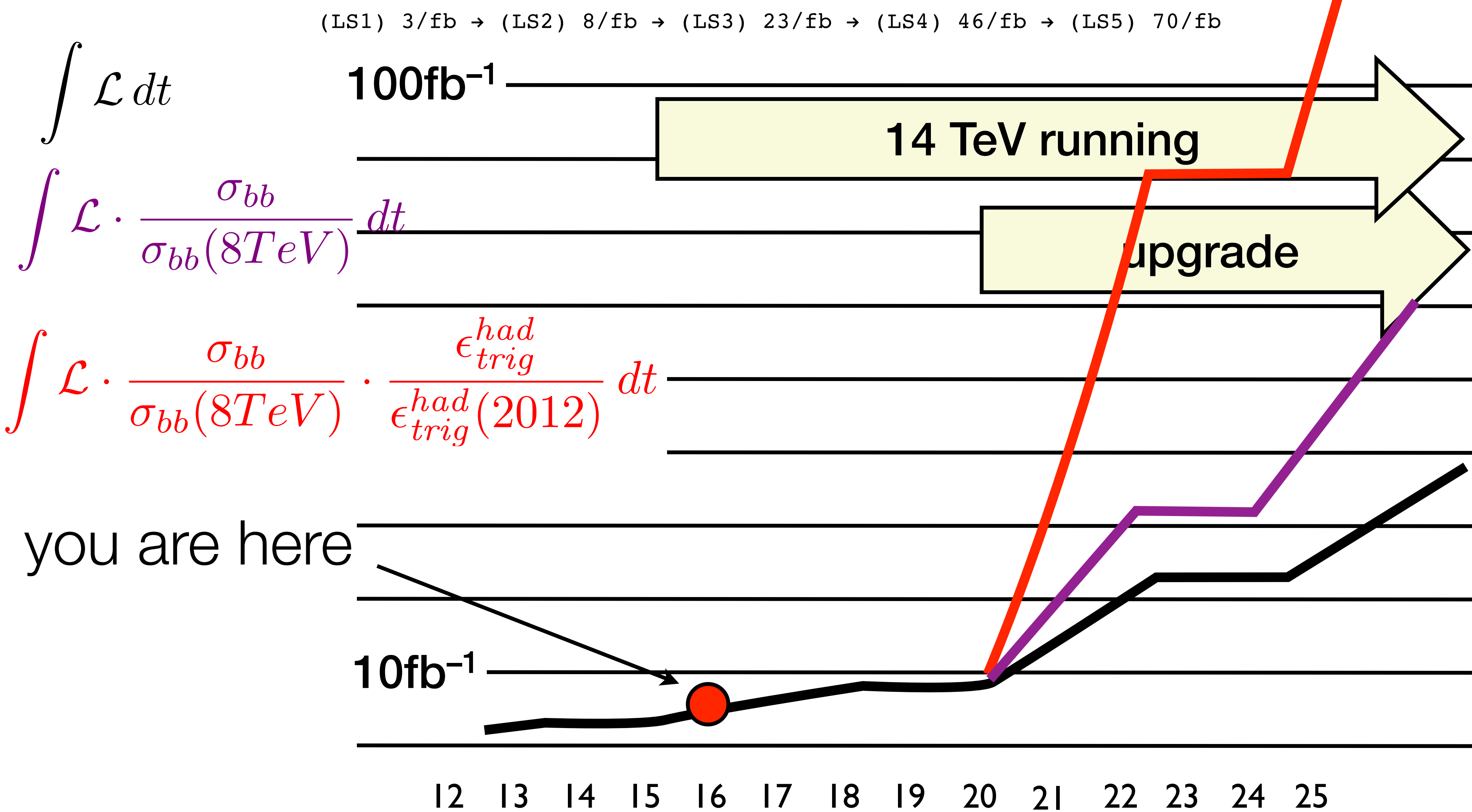
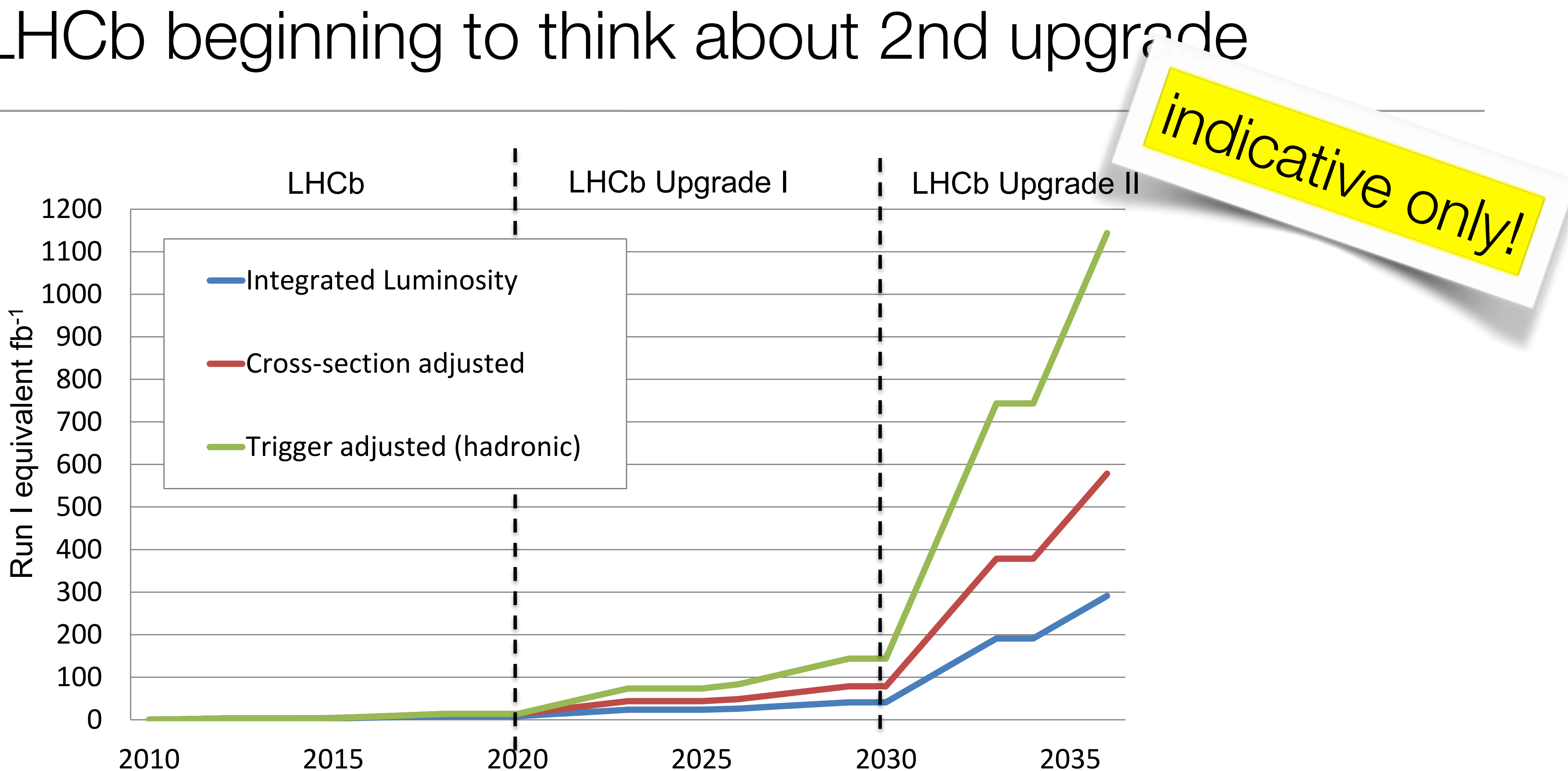
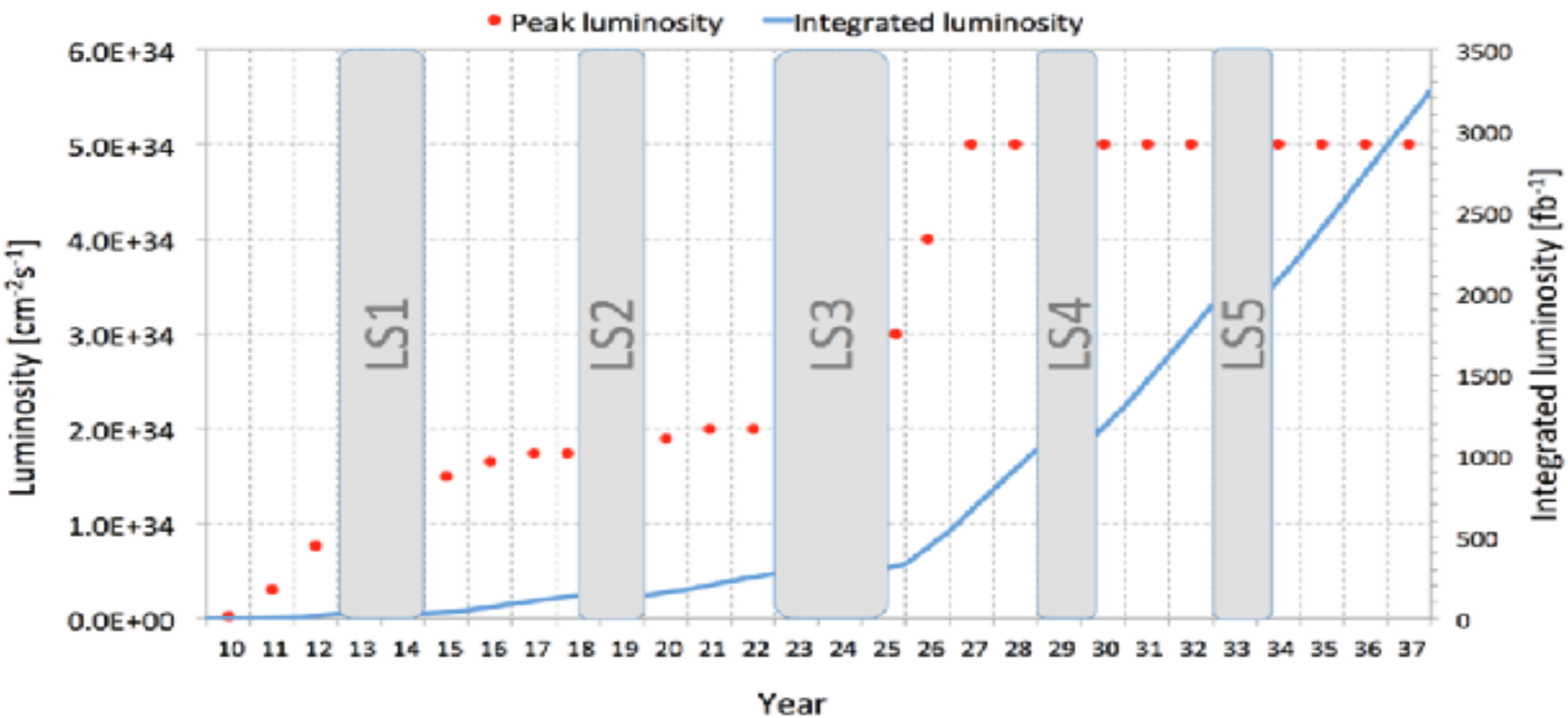


LHCb beginning to think about 2nd upgrade

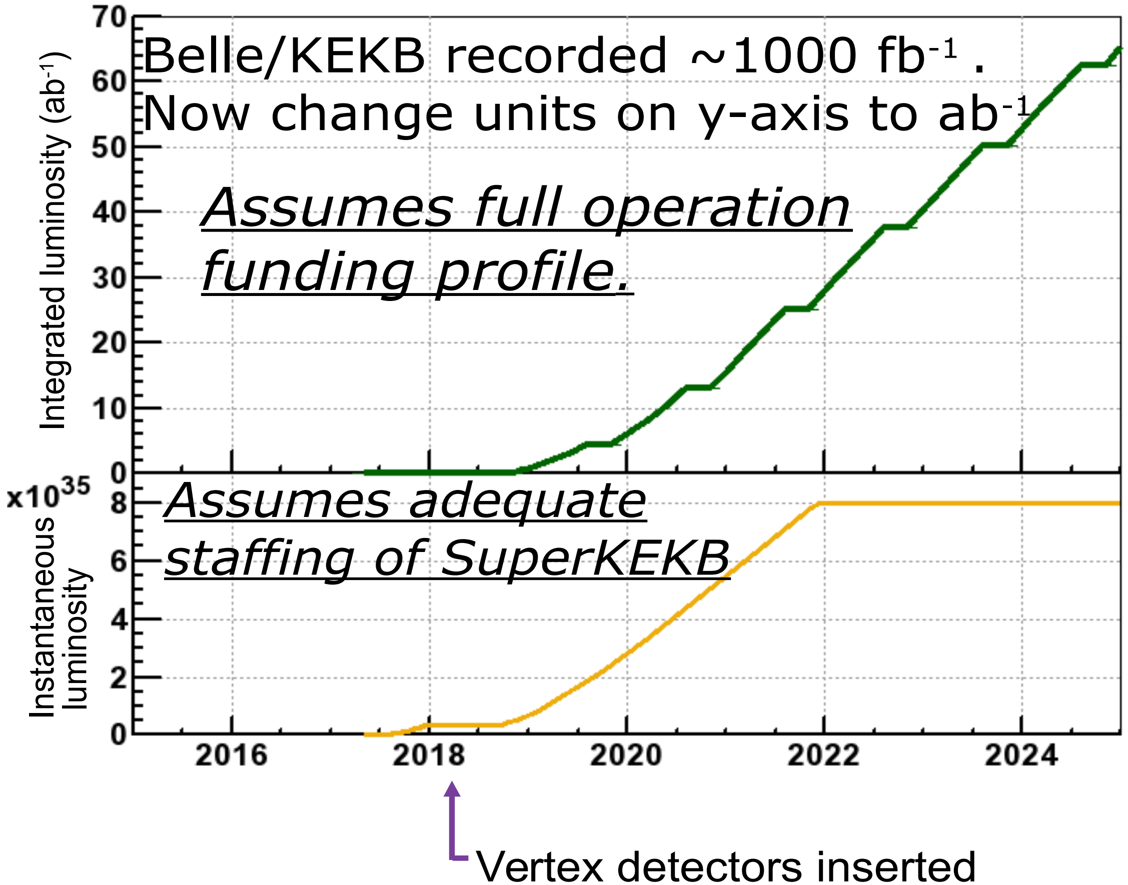


	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
LHCb	3 fb^{-1}	8 fb^{-1}	⟶	50 fb^{-1}	*300 fb^{-1}

LHC lumi projections

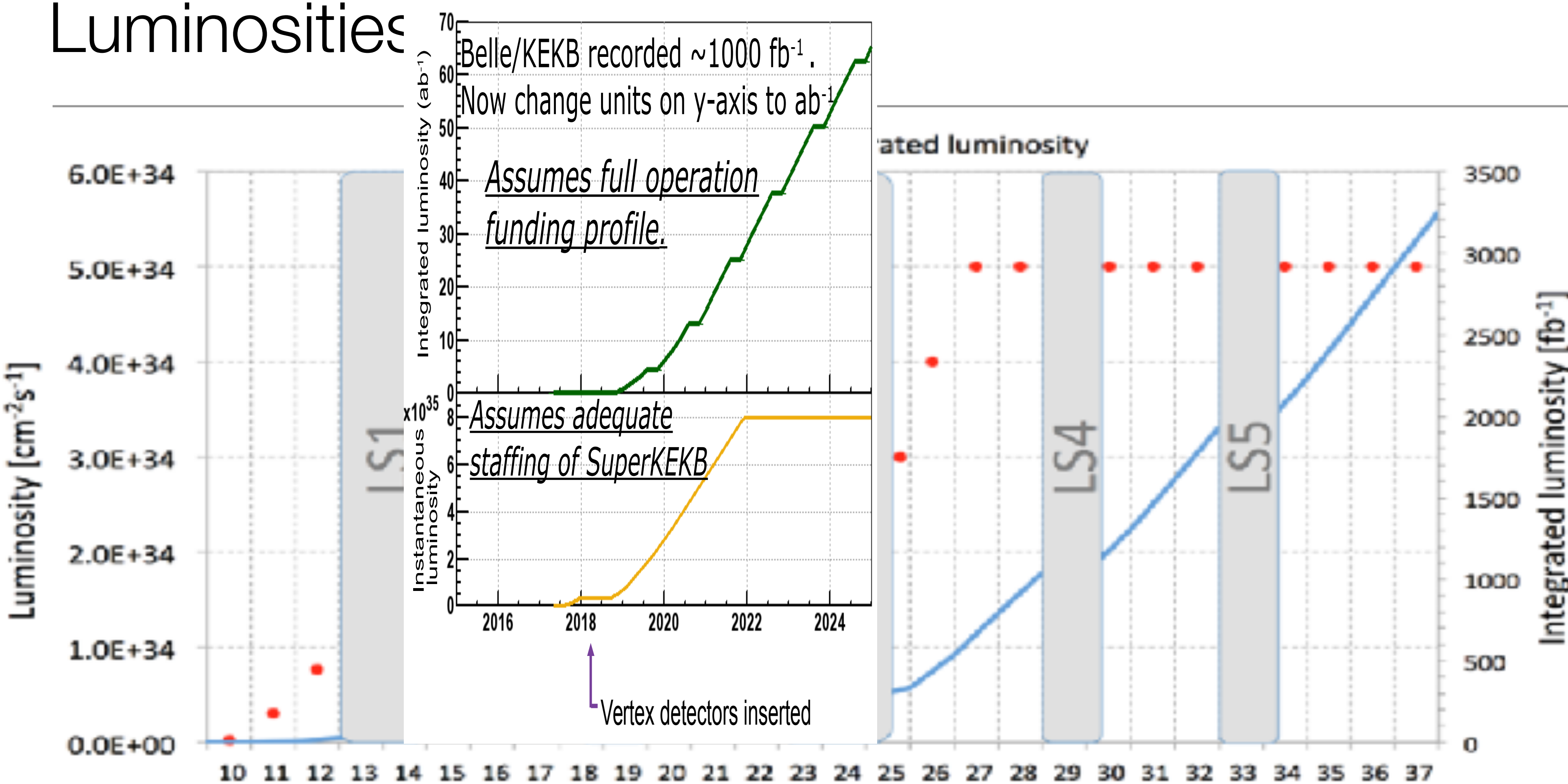


BELLE II lumi projections



M.V. Purohit, Aspen, Jan 2016

Luminosities



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Electroweak & radiative penguins

- Probe FCNC. Their suppression is an "accidental symmetry" of the SM, no fundamental reason for suppression in NP.

This illustration is based on a single example diagram. There are several others in the SM— and quite possibly beyond —that contribute to these decays (and not all apply to all three decays in the same way as the Z, γ penguin does).

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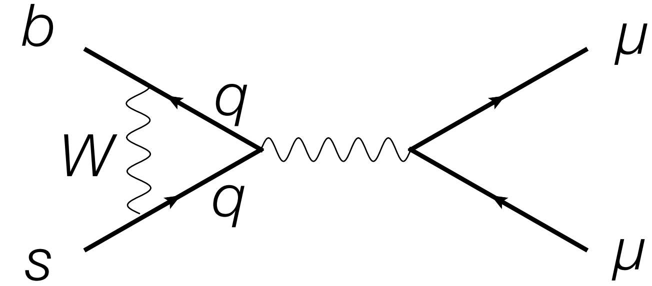
- $B_{(s,d)} \to \mu\mu$



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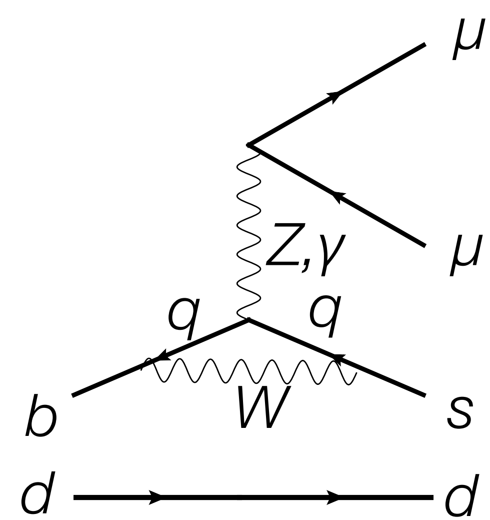
- $B \to K^{*}\mu\mu$, $B \to \phi\mu\mu$



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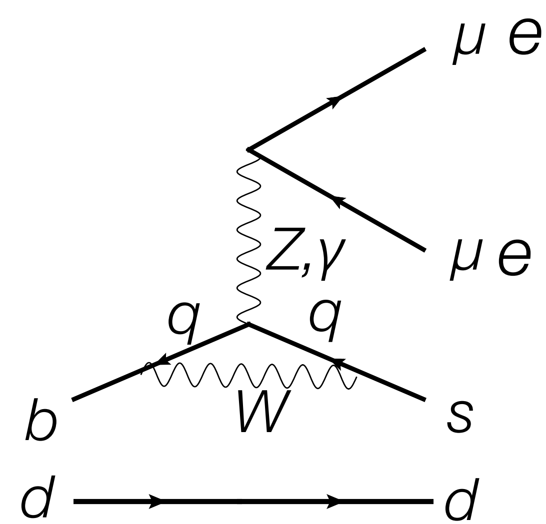
- $B \to K\mu\mu / B \to Kee$



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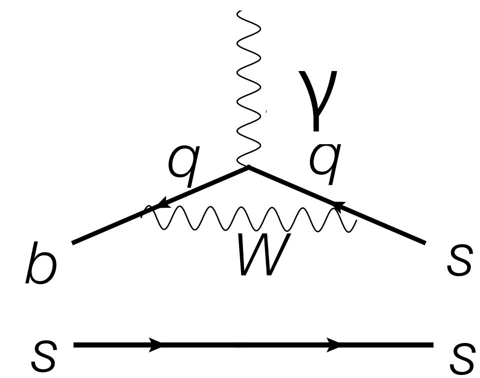
- $B_s \to \phi\gamma$



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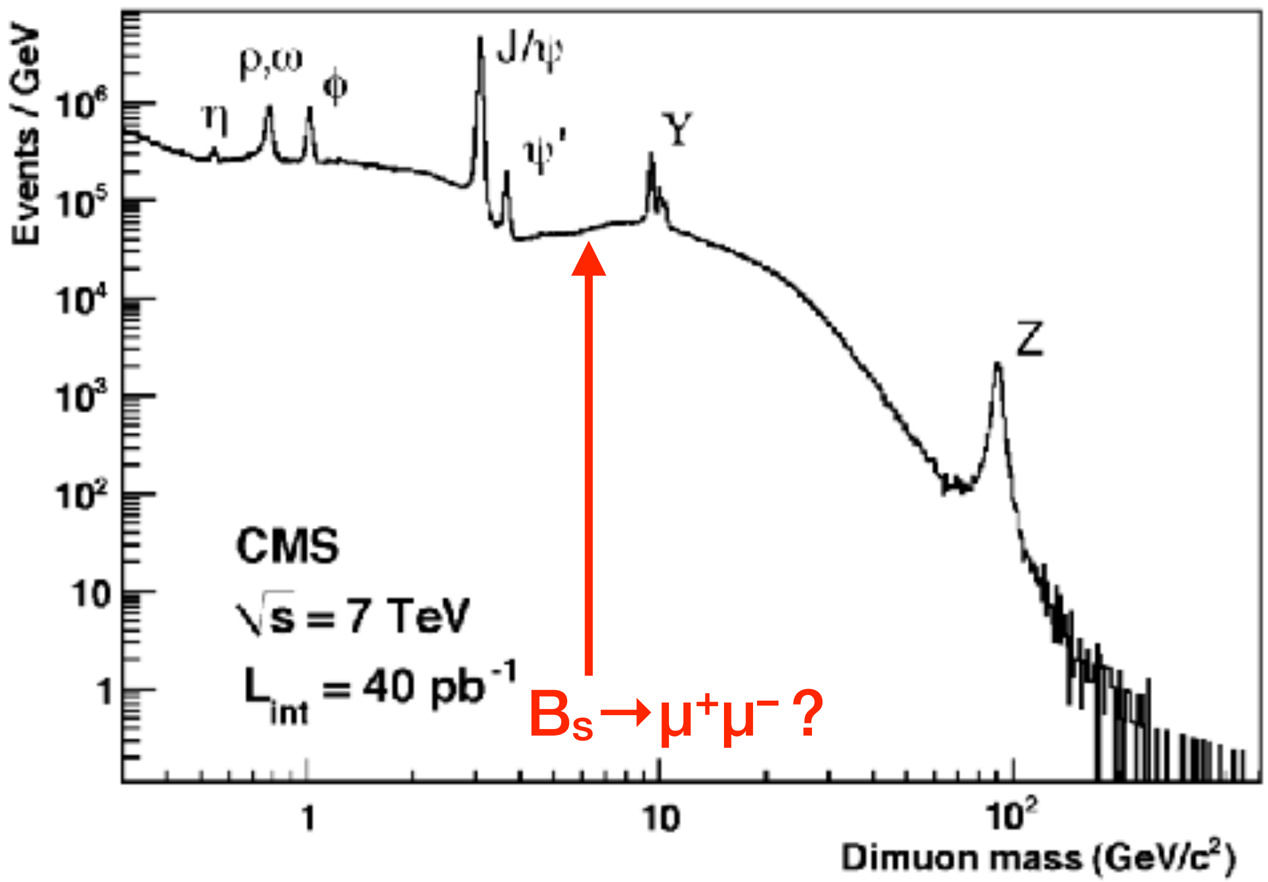
Electroweak and radiative Penguins and Wilson Coefficients

Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_{\mu}\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_5\gamma_{\mu}\ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$	(✓)	✓	

$B_{(s)} \to \mu\mu$

- Helicity-suppressed FCNC - very rare in SM!
- SM prediction [1]*:
  $BF(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \cdot 10^{-9}$
  $BF(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \cdot 10^{-10}$
- Large enhancements in many once popular SUSY models, $\propto \tan^6\beta$

Di-muon spectrum at CMS

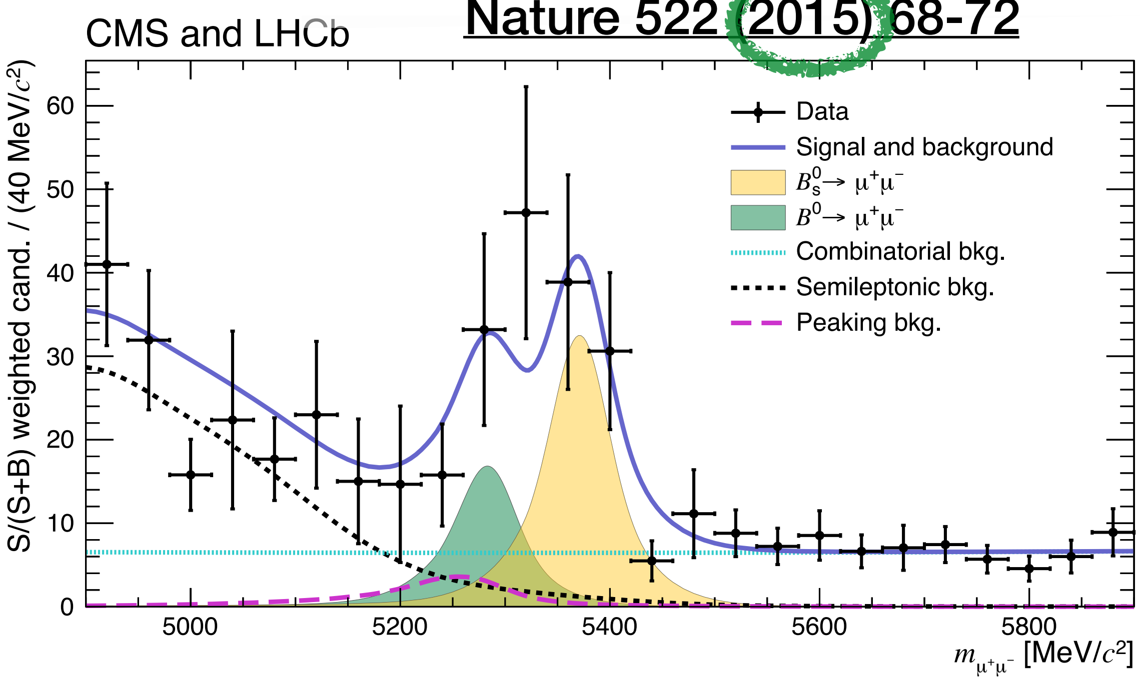


[1] PRL 112, 101801 (2014)
*) this BF refers to the time-integrated value, which differs from the one at t=0 due to the lifetime difference between the two B_s mass eigenstates. See Phys. Rev. D 86, 014027 (2012).

$B_{(s)} \rightarrow \mu\mu$

Combination of CMS & LHCb data

Nature 522 (2015) 68-72



$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

$B_{(s)} \to \mu\mu$

Combination of CMS & LHCb data

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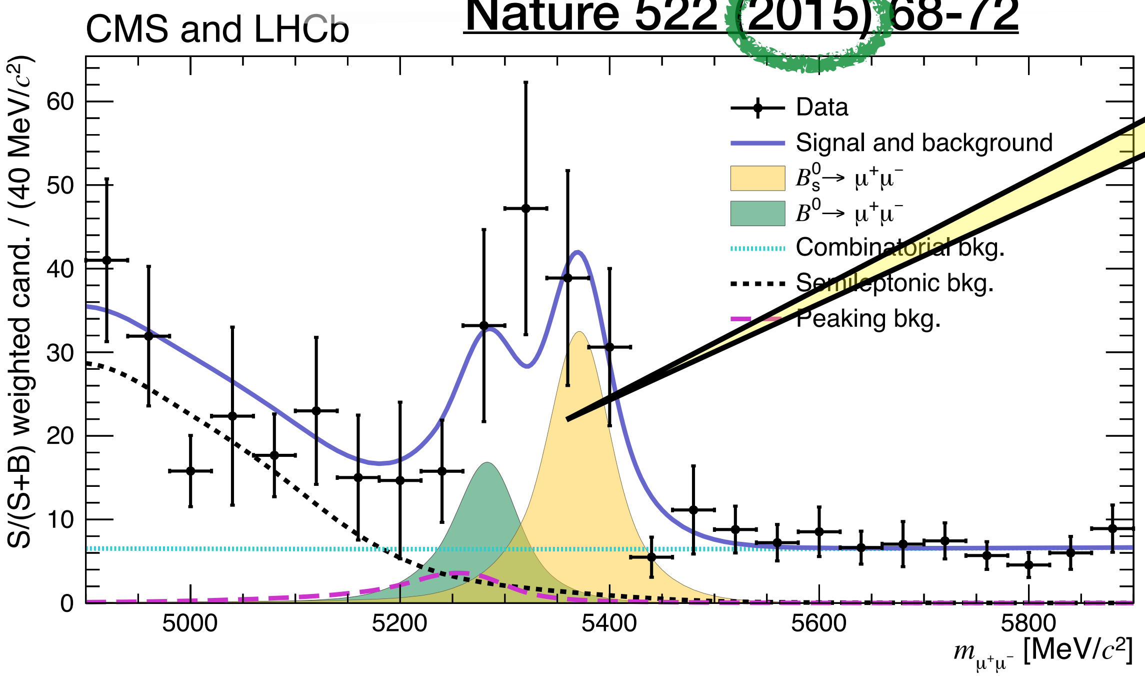

6.2σ (1st) observation (expected for SM: 7.2σ)

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$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

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Combination of CMS & LHCb data

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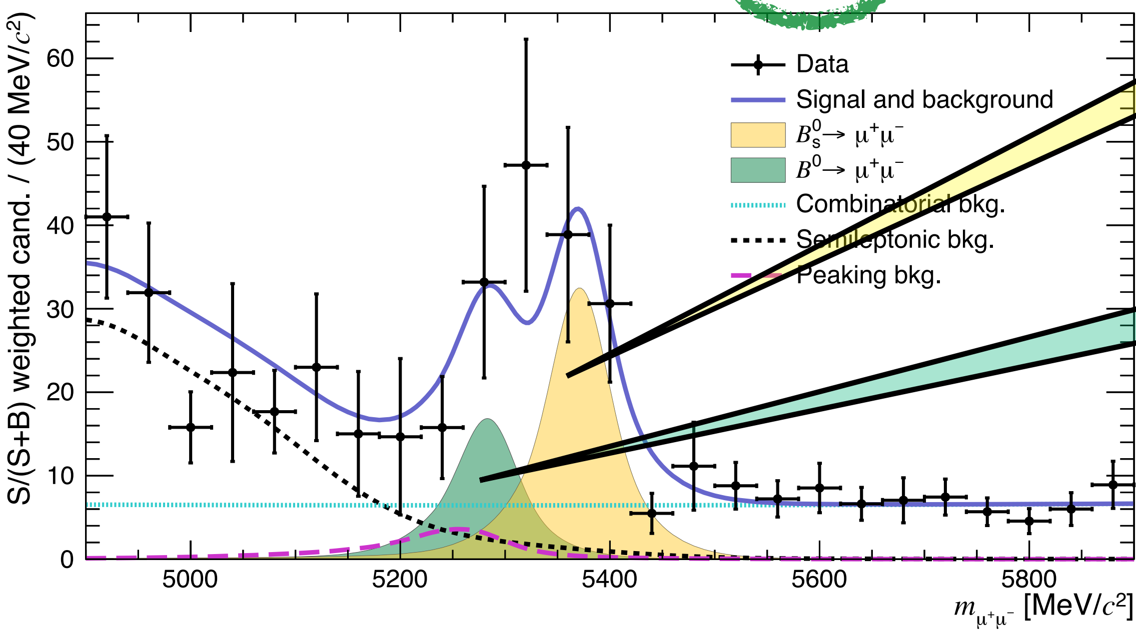


6.2σ (1^{st}) observation
(expected for SM: 7.2σ)

3.0σ (1^{st}) evidence
(expected for SM: 0.8σ)

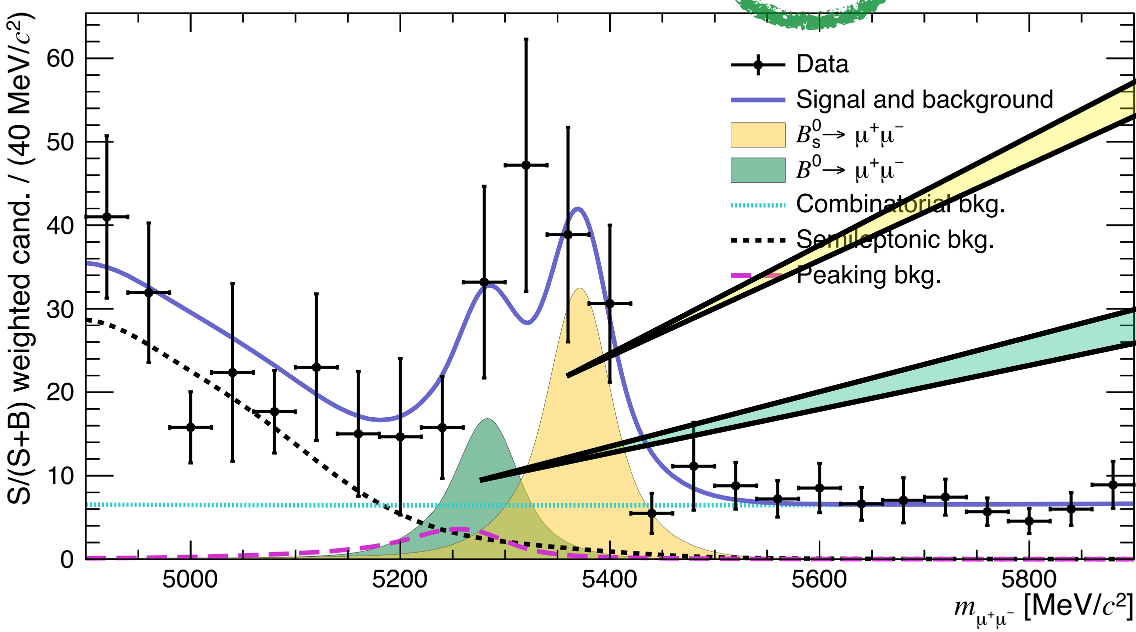
$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

$B_{(s)} \rightarrow \mu\mu$

Combination of CMS & LHCb data

Nature 522 (2015) 68-72



6.2σ (1st) observation
(expected for SM: 7.2σ)

3.0σ (1st) evidence
(expected for SM: 0.8σ)

$$\mathcal{BR}(B_s \rightarrow \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{BR}(B_d \rightarrow \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

Recent ATLAS result

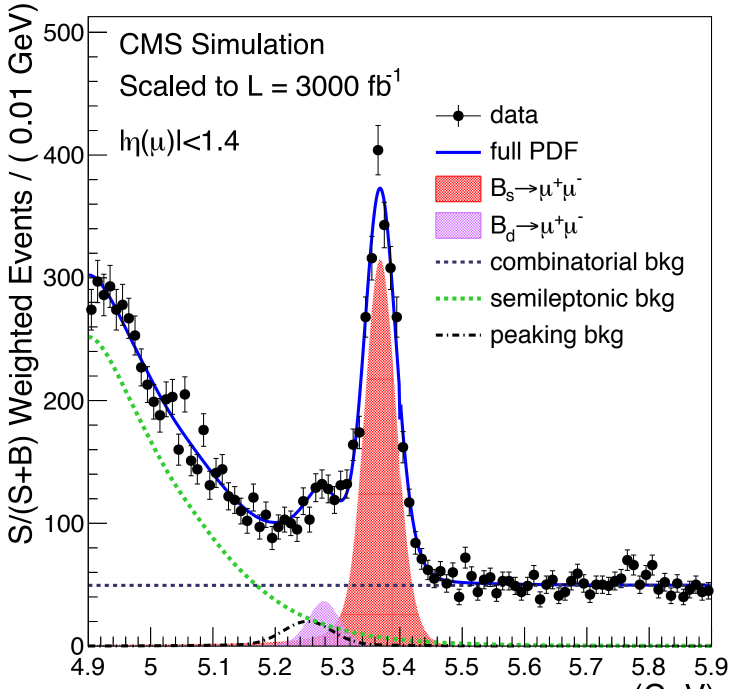
$$\mathcal{BR}(B^0_s \rightarrow \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$$

$$\mathcal{BR}(B^0_d \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10}$$

EPJ C76 (2016) no.9, 513

$B_{(s)} \to \mu\mu$ prospects

	CMS	LHCb (50fb-1)	LHCb (300fb-1)
$N(B_d)$	271	40	240
$N(B_s)$	2250	400	2400



CMS with $3ab^{-1}$, $\sigma(f_s/f_d)=5\%$, $\sigma(BR(B^{\pm} \to J/\psi K^{\pm}))=3\%$

$\sigma(B_s) = 11\%$

$\sigma(B_d) = 18\%$

$R_{s/d} = 21\%$

CMS estimates based on detailed studies in CMS PAS FTR-14-015, LHCb estimates on rather simplistic scaling for numbers in PRL111, 101805 (2013).

f_s/f_d error budget LHCb

uncorrelated errors

Source	Semileptonic (%)	Hadronic(%)
Statistical	3.0	1.7
SU(3) breaking and form factors	-	8.8
Bin dependent uncertainty	1.0	-
Semileptonic decay model	3.0	-
Backgrounds	2.0	-
Tracking efficiency	2.0	-
$\mathcal{B}(\overline{B}_s^0 \to D^0 K^+ X \mu \bar{\nu}_\mu)$	$^{+4.1}_{-1.1}$	-
$\mathcal{B}((B^-/\overline{B}^0) \to D_s^+ K X \mu \bar{\nu}_\mu)$	2.0	-
Detector acceptance and reconstruction	-	0.7
Hardware trigger efficiency	-	2.0
Offline selection	-	1.1
Boosted decision tree cut	-	1.0
Particle identification	1.5	1.5
Combinatorial background	-	1.0
Signal shape (tails)	-	0.6
Signal shape (core)	-	1.0
Total	$^{+7.1}_{-5.9}$	± 9.6

correlated errors

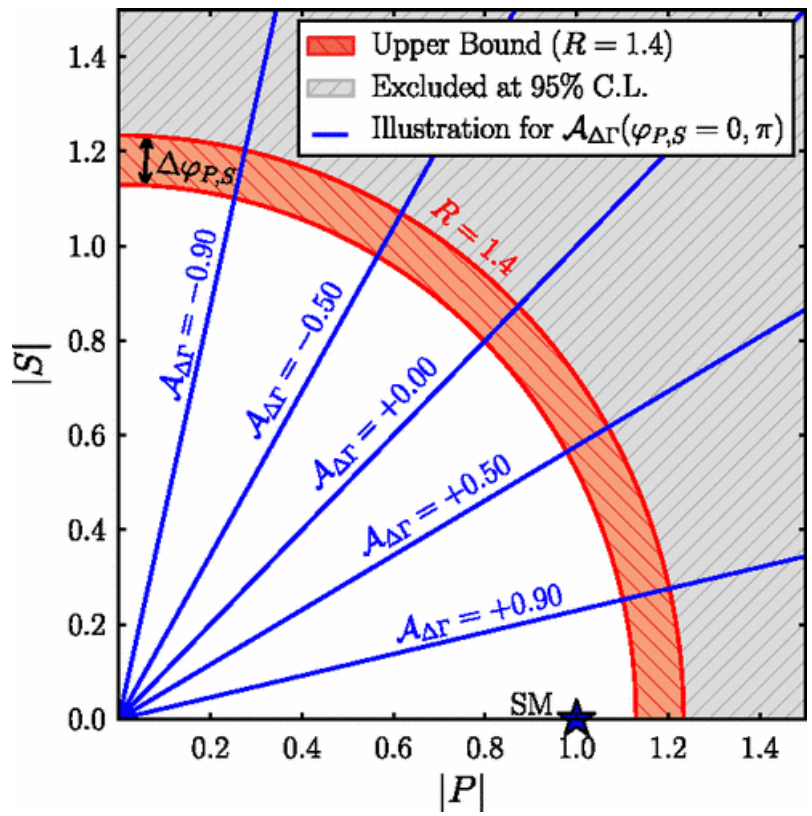
Source	Uncertainty (%)
$\mathcal{B}(D^- \to K^+ \pi^- \pi^-)$	2.2
$\mathcal{B}(D_s^- \to K^+ K^- \pi^-)$	2.5
Lifetime ratio	0.9
Total	3.4

LHCb-CONF-2013-011

$B_{(s)} \to \mu\mu$ prospects: lifetime difference

- Future datasets will give access to more observables than "just" BF
- Effective lifetime can distinguish scalar vs pseudoscalar/vector contributions.
- Need $\sigma(\tau_{\mu\mu}) \approx 2.5\%$ for 5σ separation between $A_{\Delta\Gamma}=\pm 1$
  LHCb upgrade (50/fb): $\sigma(\tau_{\mu\mu}) \approx 5\%$
  LHCb upgrade² (300/fb): $\sigma(\tau_{\mu\mu}) \approx 2\%$

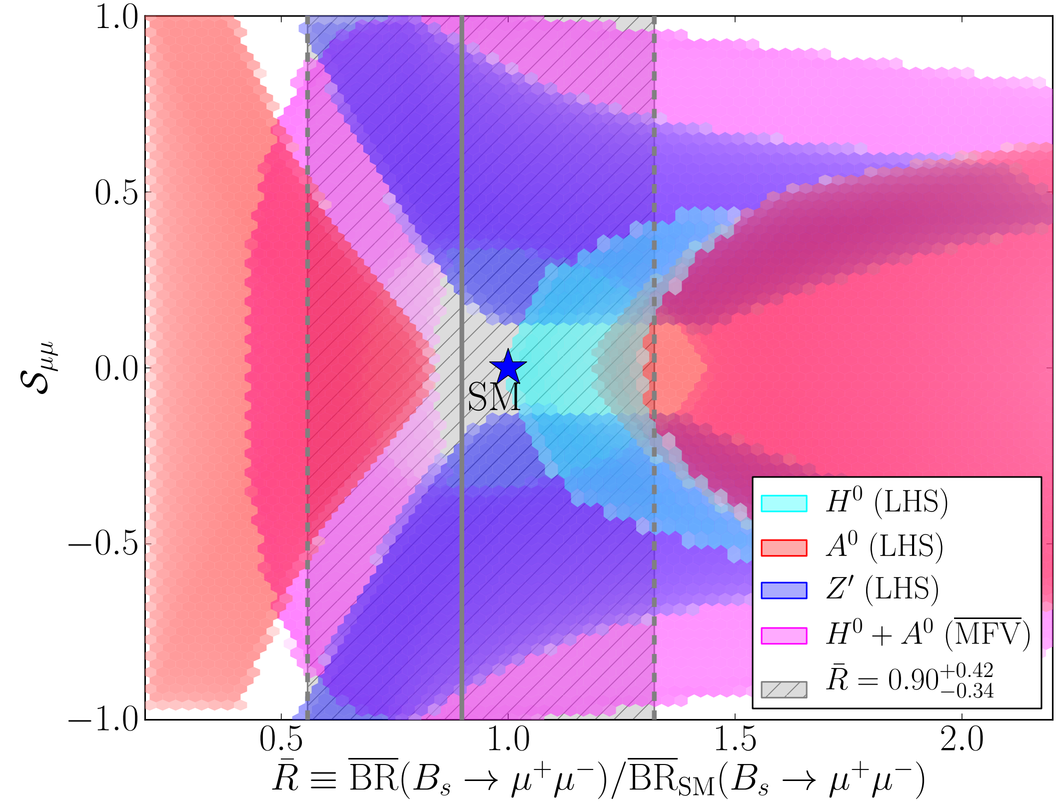
De Bruyn et al PRL109 (2012) 041801



All estimates are guesstimates!

$B_{(s)} \rightarrow \mu\mu$ prospects: time-dependent CPV, $S_{\mu\mu}$

- Making several assumptions, including effective tagging efficiency $\varepsilon D^2 = 4\%$
- … and extrapolating from S_{KK},
- … get: $S_{\mu\mu} \approx 0.3$ at LHCb upgrade[2], i.e. 300/fb.



All estimates are guesstimates!

Buras et al JHEP 1307 (2013) 77

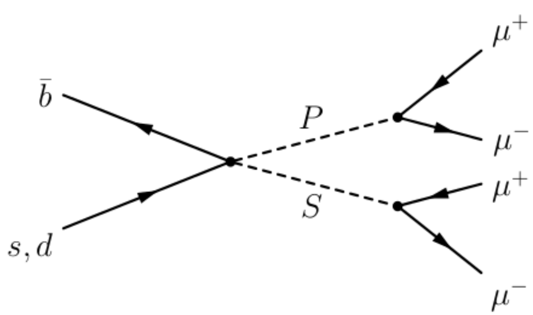
$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

- Excess of events in the low-dimuon-mass range found by HyperCP for $\Sigma^+ \to p\mu^+\mu^-$ [PRL 94 (2005) 021801] (more on this later in the talk)
- Potentially pointing towards new resonance $X[\mu\mu]$, $M(X) \approx 214\,\text{MeV}/c^2$

NEW!

LHCb-PAPER-2016-043

- $\mathcal{B}_{SM}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) \sim \mathcal{O}(10^{-11})$ (non-resonant) [PLB 556 (2003) 169]
- Sensitive to scalar (S) and pseudo-scalar (P) sgoldstinos:
  BF up to $\mathcal{O}(10^{-4})/(10^{-7})$ for B^0_s/B^0 [PRD 85, 077701 (2012)]
- Search for non-resonant $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ with $3\,\text{fb}^{-1}$



$\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-9}$

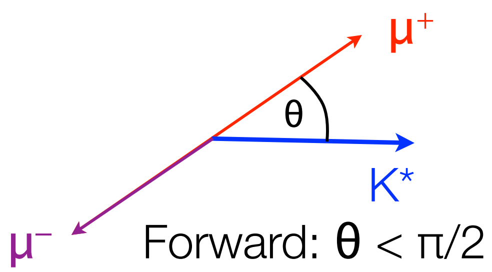
Sensitivity of few 10^{-10} possible with $300\,\text{fb}^{-1}$

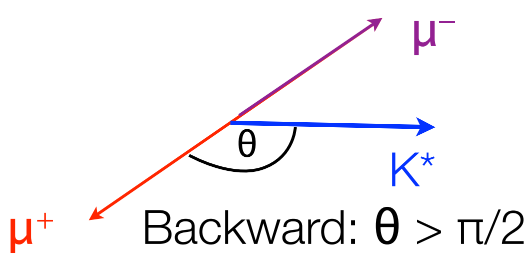
Veronika Chobanova at LHCb implications workshop

$B \to K^* \mu^+ \mu^-$: Forward-backward asymmetry in 2013

- Forward-backward asymmetry as function of $q^2 = m^2(\mu\mu)$

CMS: Physics Letters B 727 (2013) 77–100
LHCb: JHEP 1308 (2013) 131
Theory: Phys.Rev. D87 (2013) 034016





- Good agreement with SM.

- First measurement of zero-crossing point: $q_0^2 = 4.9 \pm 0.9$ GeV^2/c^4

B→K*μ⁺μ⁻: Forward-backward asymmetry in 2013

- Forward-backward asymmetry as function of $q^2 = m^2(\mu\mu)$

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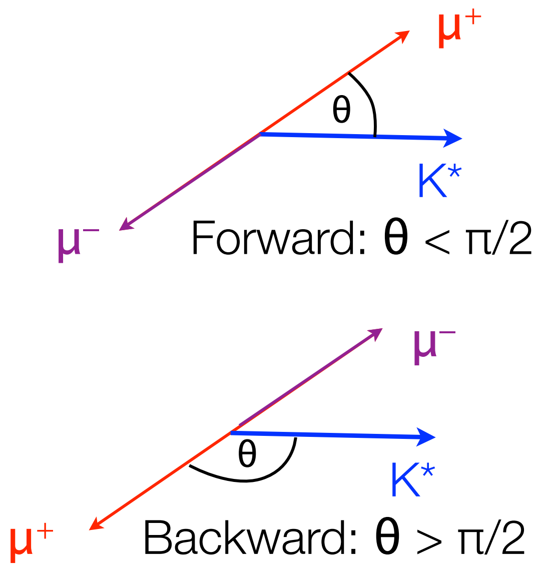
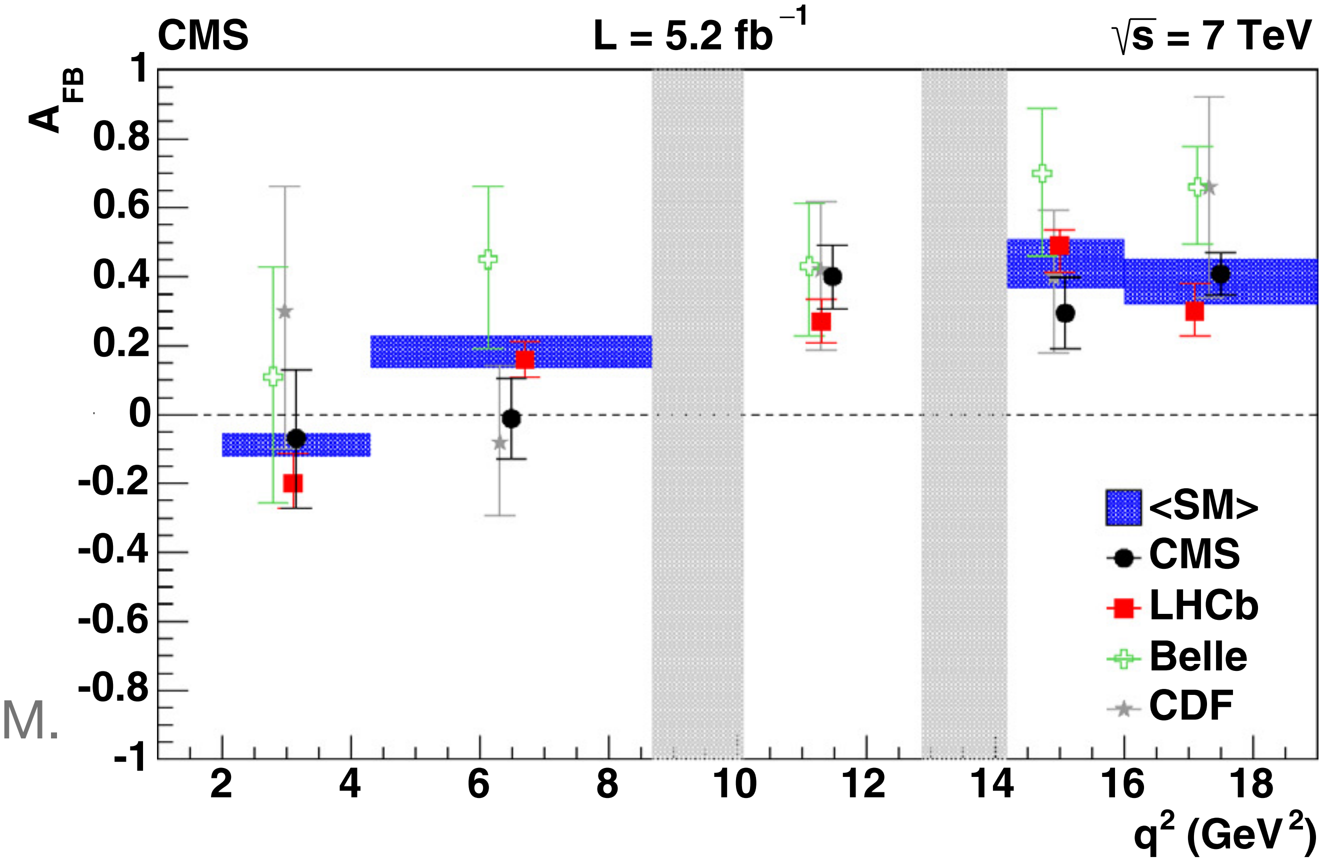
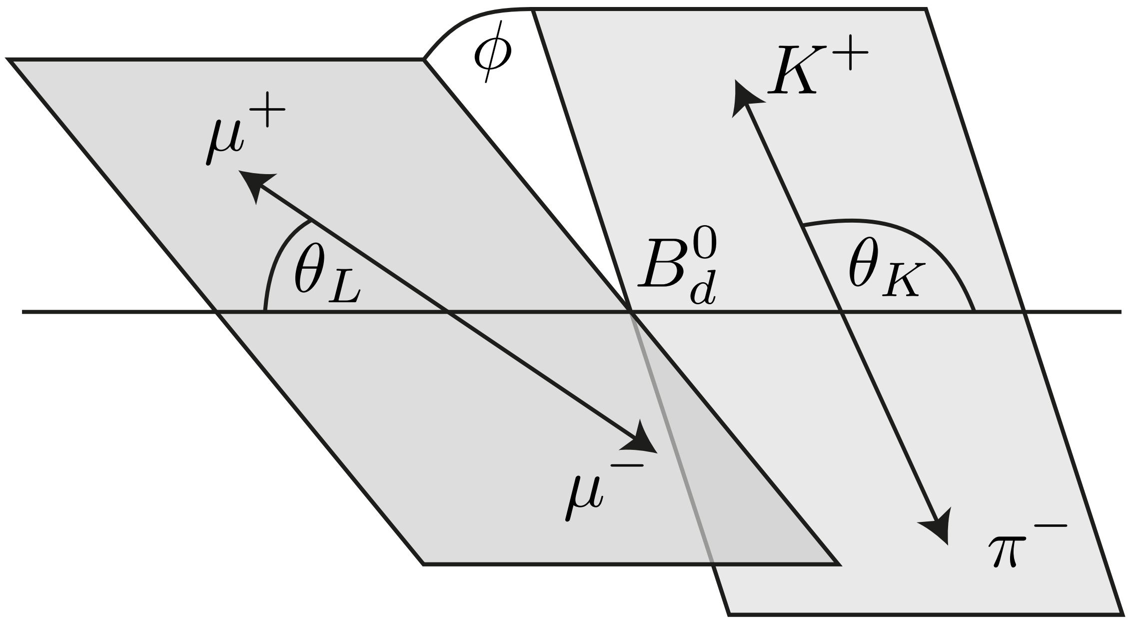




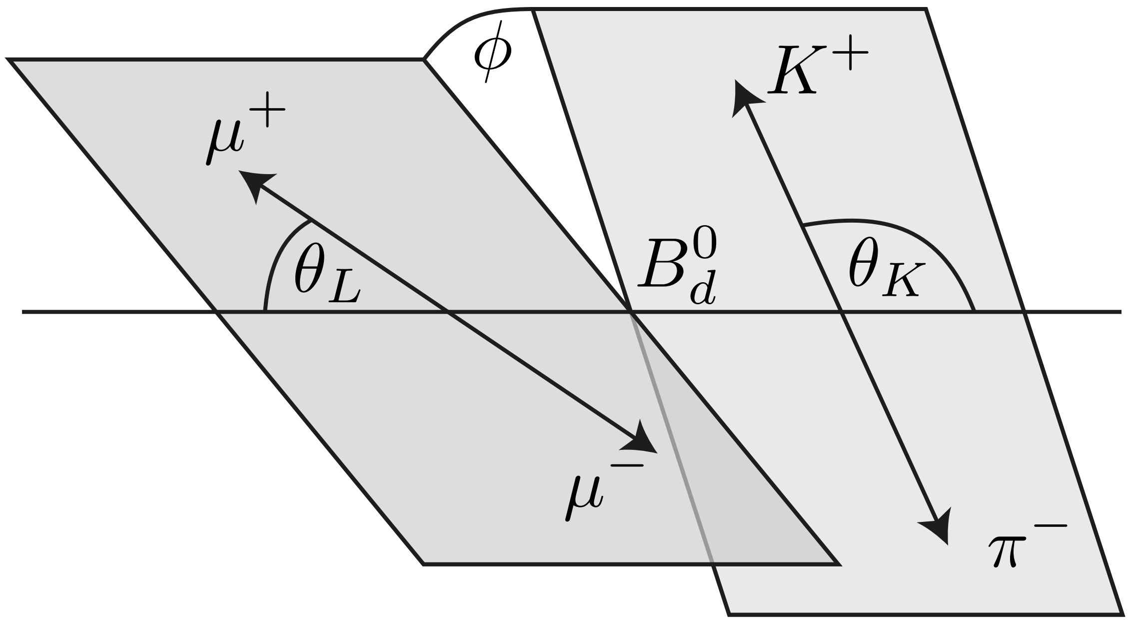
- Good agreement with SM.
- First measurement of zero-crossing point: $q_0^2 = 4.9 \pm 0.9\ \mathrm{GeV}^2/c^4$

$B \to K^* \mu^+ \mu^-$: full angular analysis (and P'5)



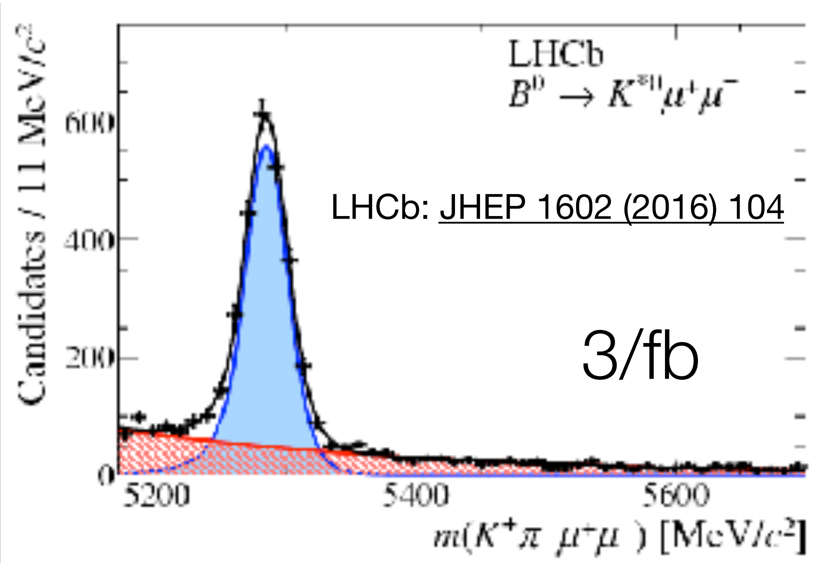
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos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

B→K*μ⁺μ⁻: full angular analysis (and P'5)



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

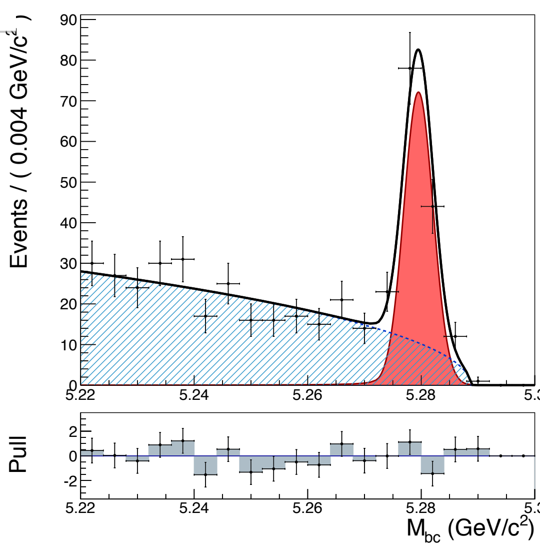
2015/16 $B \to K^* \mu^+ \mu^-$ and $B \to K^* e^+ e^-$ datasets



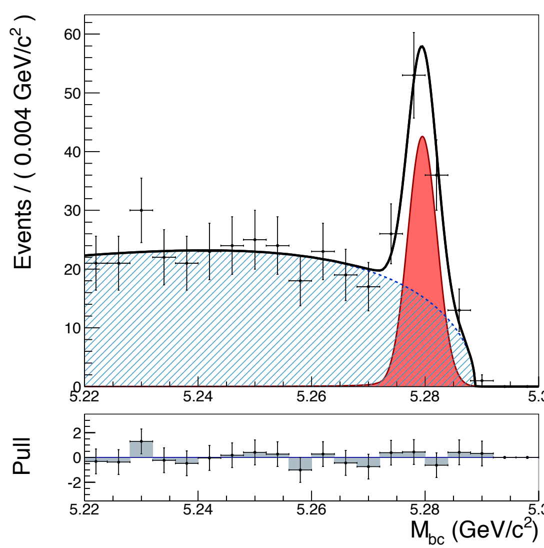
LHCb: JHEP 1602 (2016) 104

3/fb

BELLE $B \to K^* \mu^+ \mu^-$



BELLE $B \to K^* e^+ e^-$



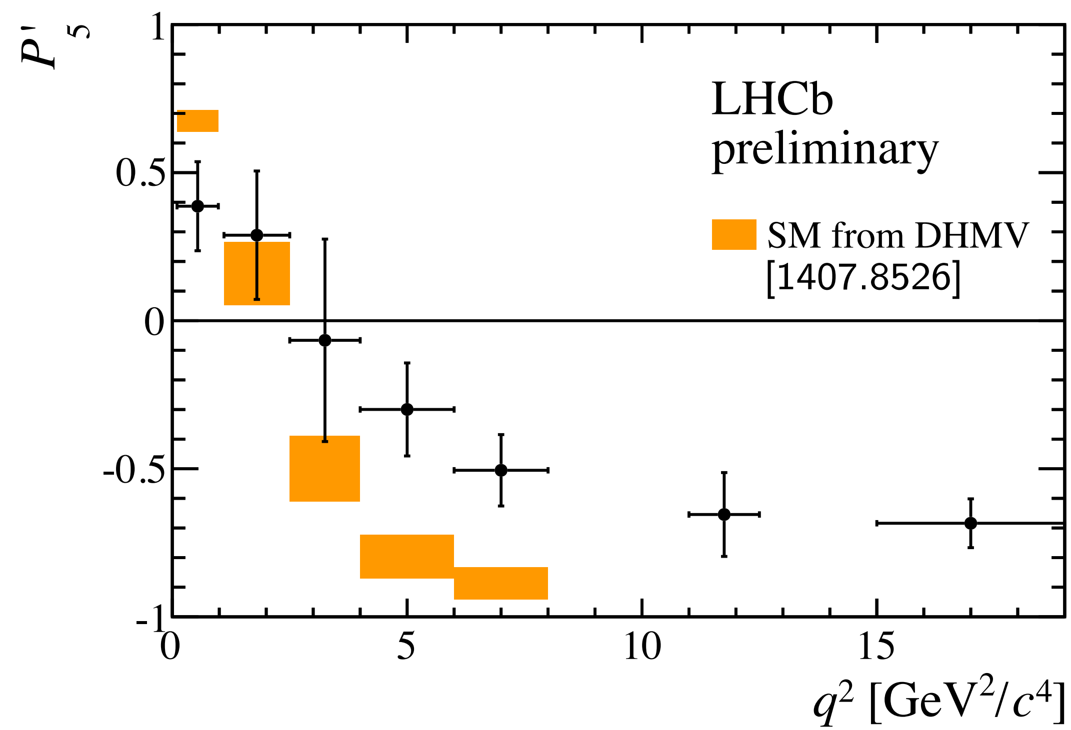
BELLE: arXiv:1604.04042 (2016)

$B \to K^* \mu^+ \mu^-$, $B \to K^* e^+ e^-$, P’5

LHCb: JHEP 1602 (2016) 104

Theory: JHEP 05 (2013) 137

- Might seem an abstract variable. It is chosen because it is less sensitive to (difficult to calculate) form factors.
- 3.4 σ global significance.
- Including related decays, evidence for New Physics at > 4σ.
- SM ruled out at 99.997% CL?



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LHCb: JHEP 1602 (2016) 104

Theory: JHEP 05 (2013) 137

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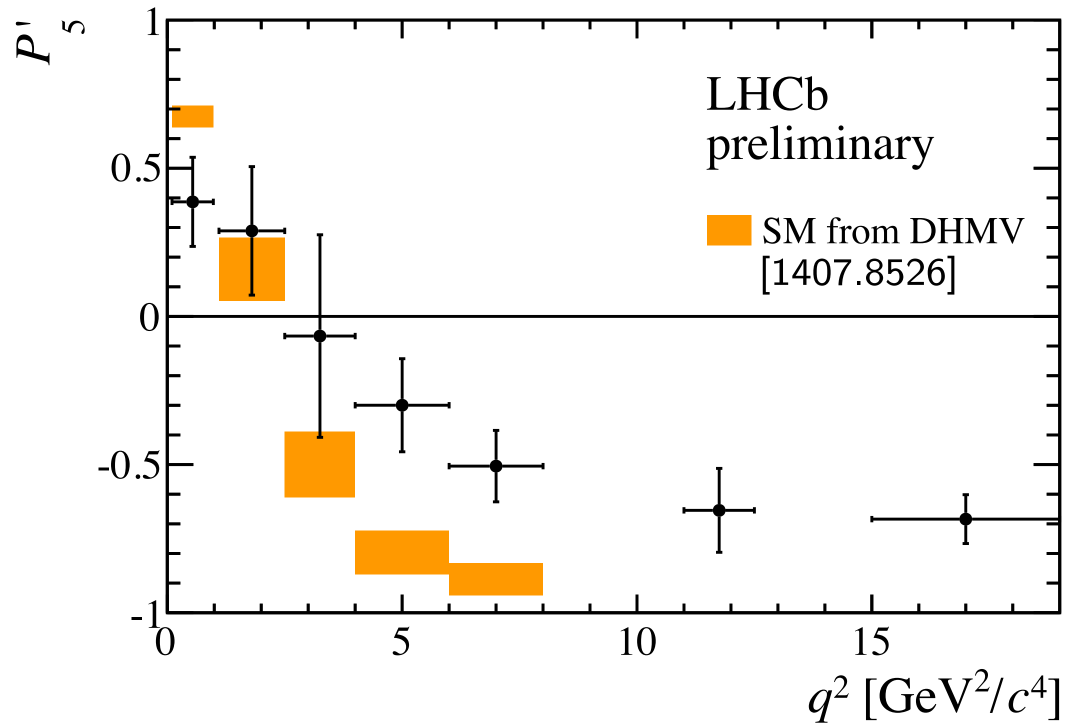

!!!

$B \to K^* \mu^+ \mu^-$, P'5

BELLE: arXiv:1604.04042 (2016)
LHCb: JHEP 1602 (2016) 104
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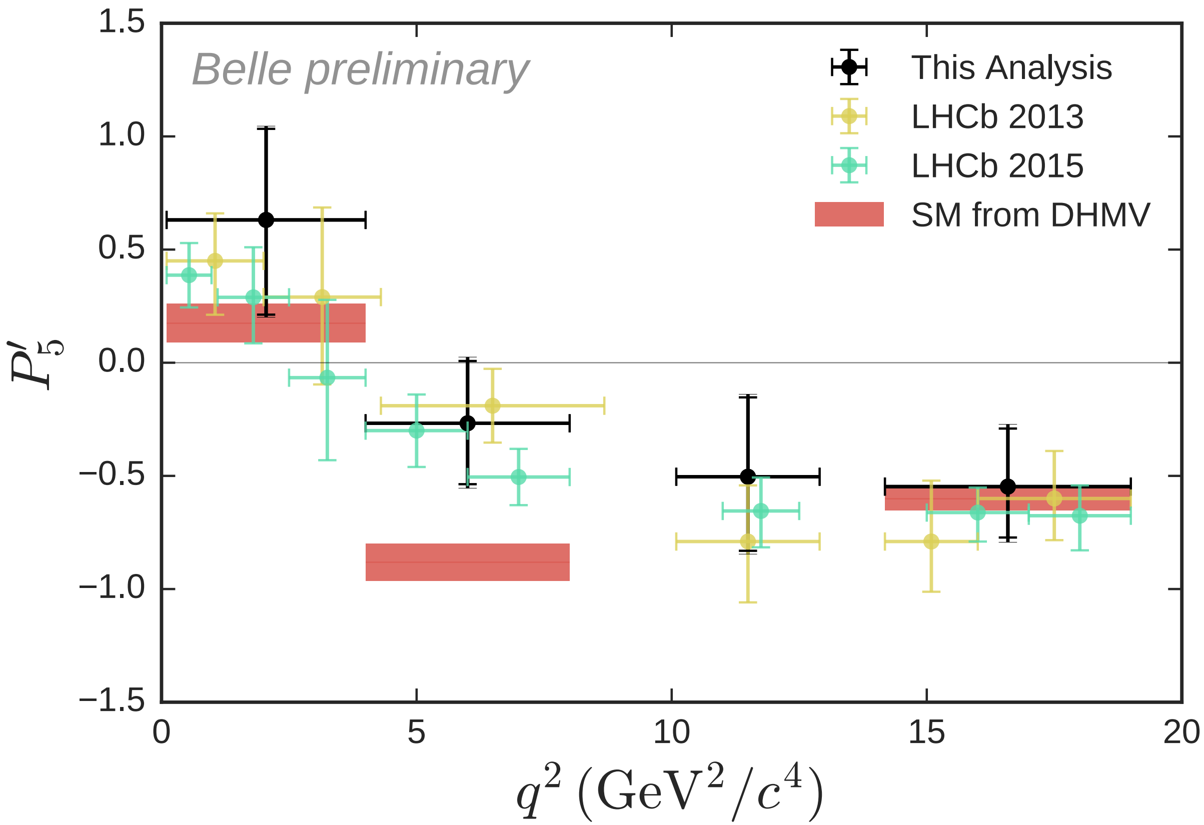
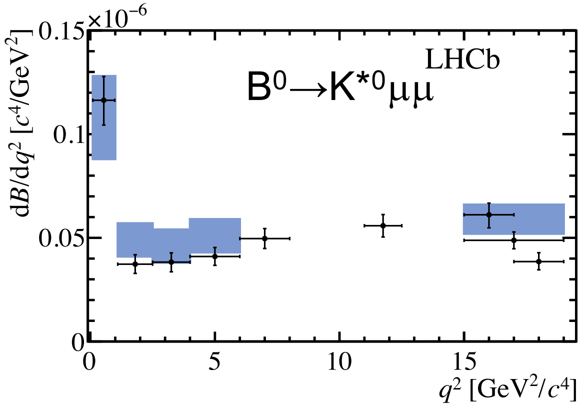
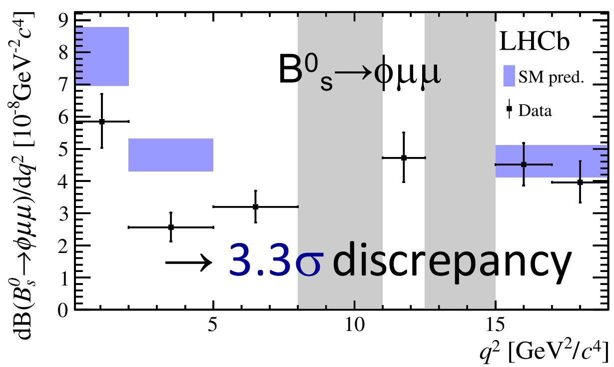
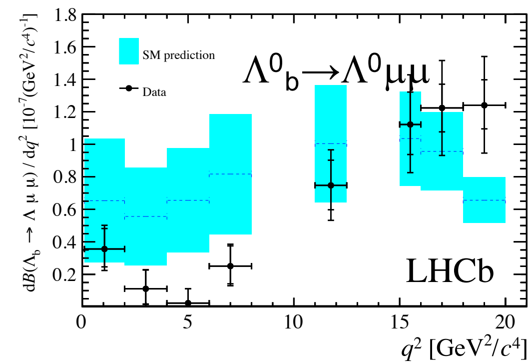


!!!

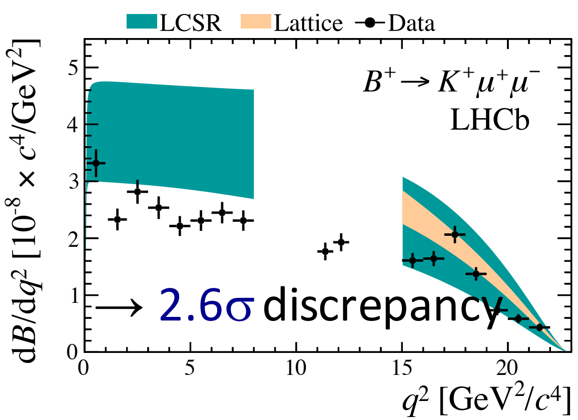
Differential BFs as function of q^2

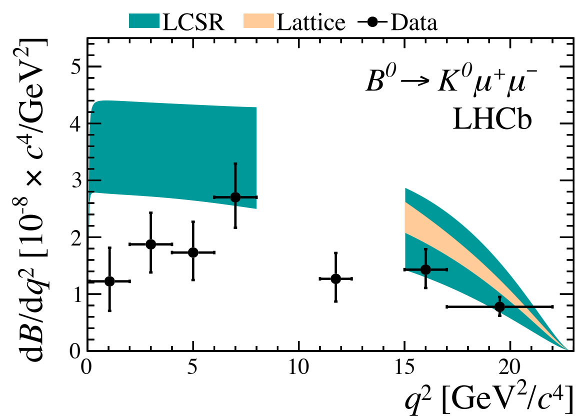


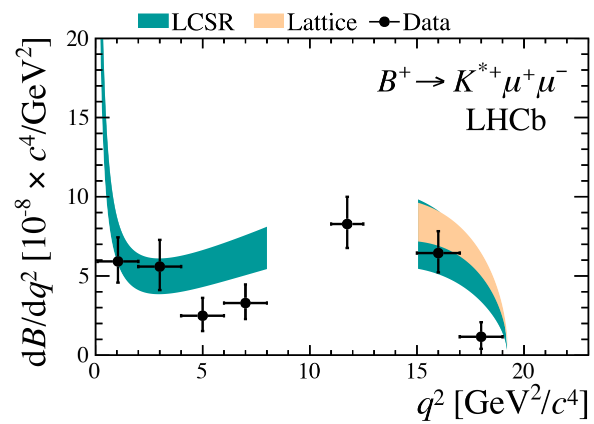




[arXiv:1606.04731] [JHEP 09 (2015) 179] [JHEP 06 (2015) 115]



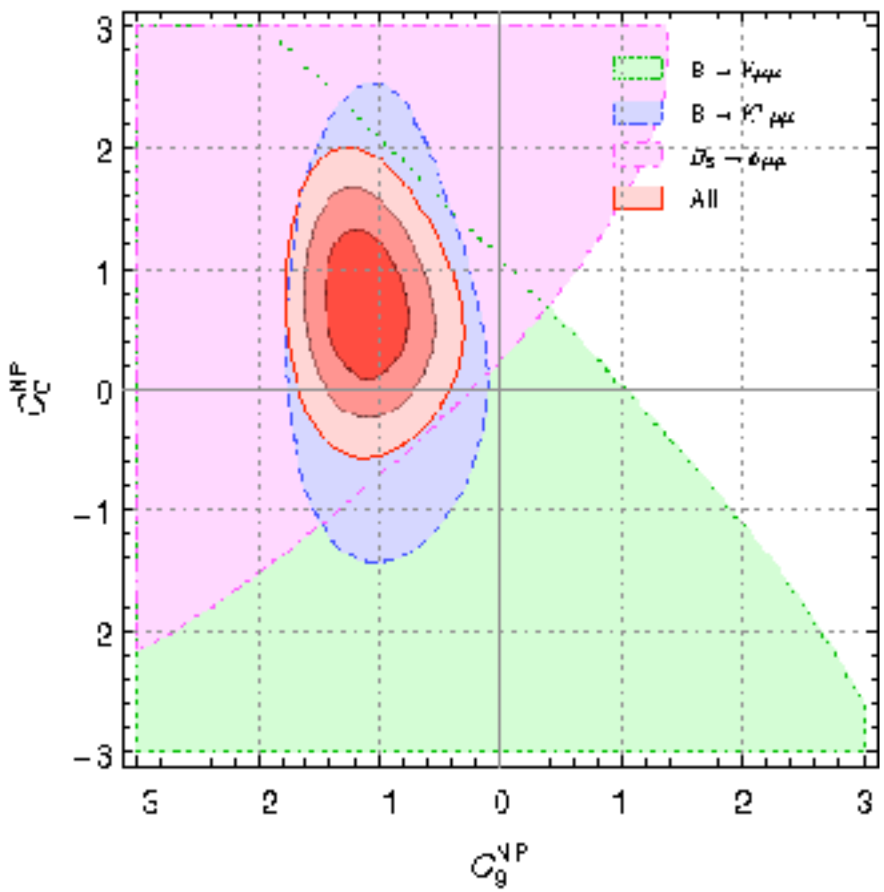




[JHEP 06 (2014) 133]

Interpretation of B→K*μ+μ− et al.

JHEP 1606 (2016) 092



… many other interpretations:

Buttazzo et al [1604.03940], Bauer et al [PRL116,141802(2016)], Crivellin et al [PRL114,151801(2015)], Altmannshofer et al [PRD89(2014)095033]...

>4σ deviation from SM

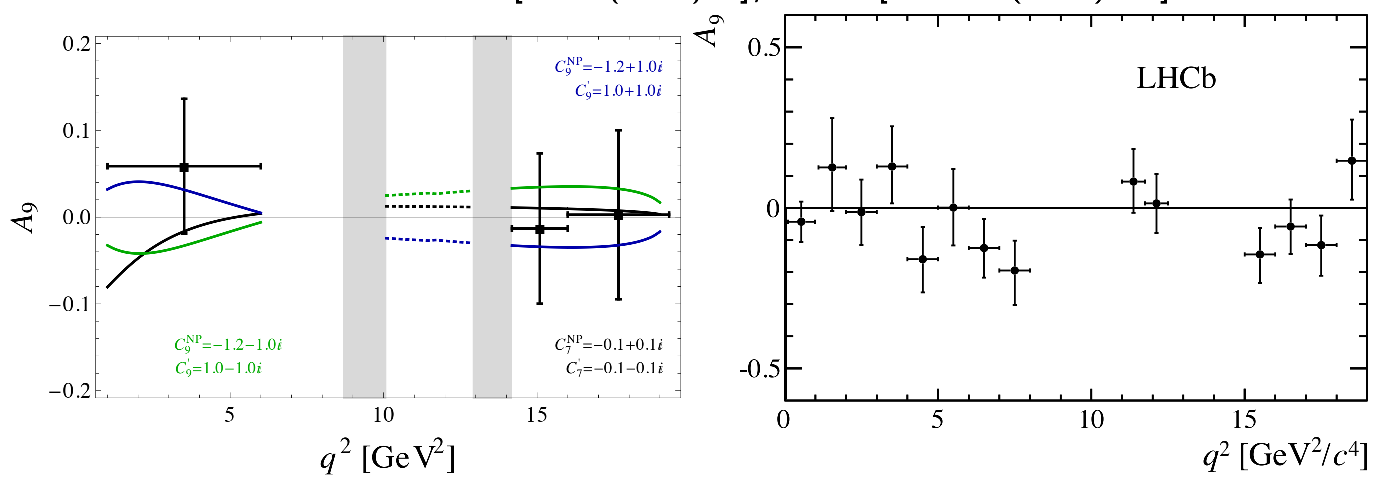
(or is it just 4σ from our ability to calculate QCD effects?)

Imaginary contributions to C_9 and C_{10}

- We have measured complete set of CP asymmetric observables LHCb [JHEP02(2016)104]

  $\rightarrow$ Sensitive to imaginary NP contributions

Altmannshofer et al [EPJC(2013)73], LHCb [JHEP02(2016)104]

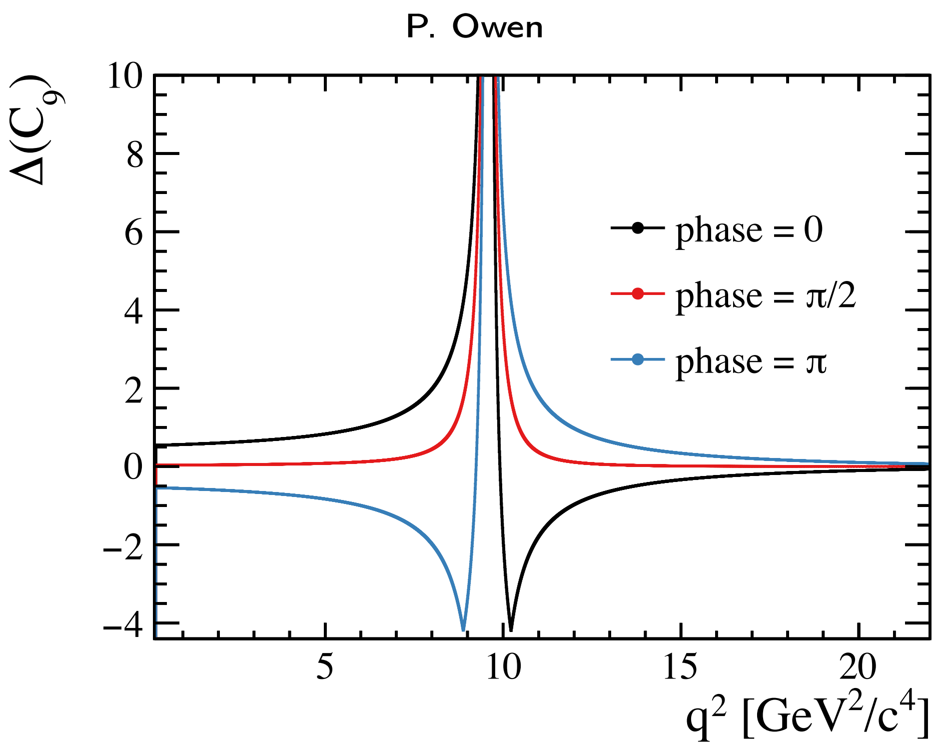


- With 300fb^{-1} collected by Run 5, LHCb could have ~500,000 $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  - More than entire Run 1 $B^0 \rightarrow J/\psi K^{*0}$ sample!
- Uncertainties in plots shrink by $\sim \times 10$ assumptions about systs

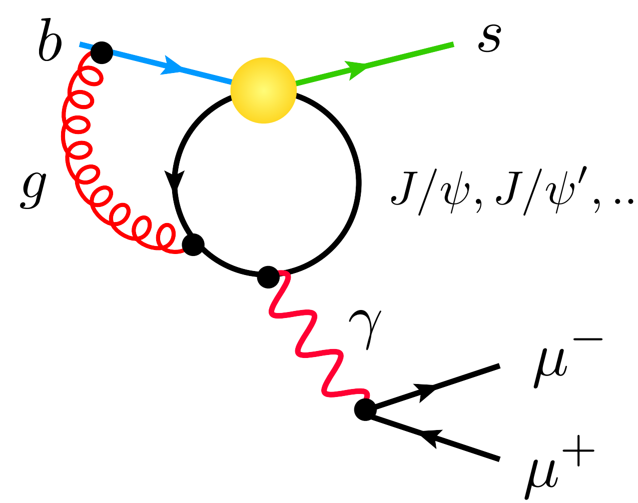
  $\rightarrow$ Sensitive to NP contributions of order shown

Is it QCD?

$$C_9^{eff} = C_9 + Y(q^2)$$



Y(q²) summarise effects of bsqq operators, where main issue is J/ψ.



Is it QCD?

$$C_9^{eff} = C_9 + Y(q^2)$$

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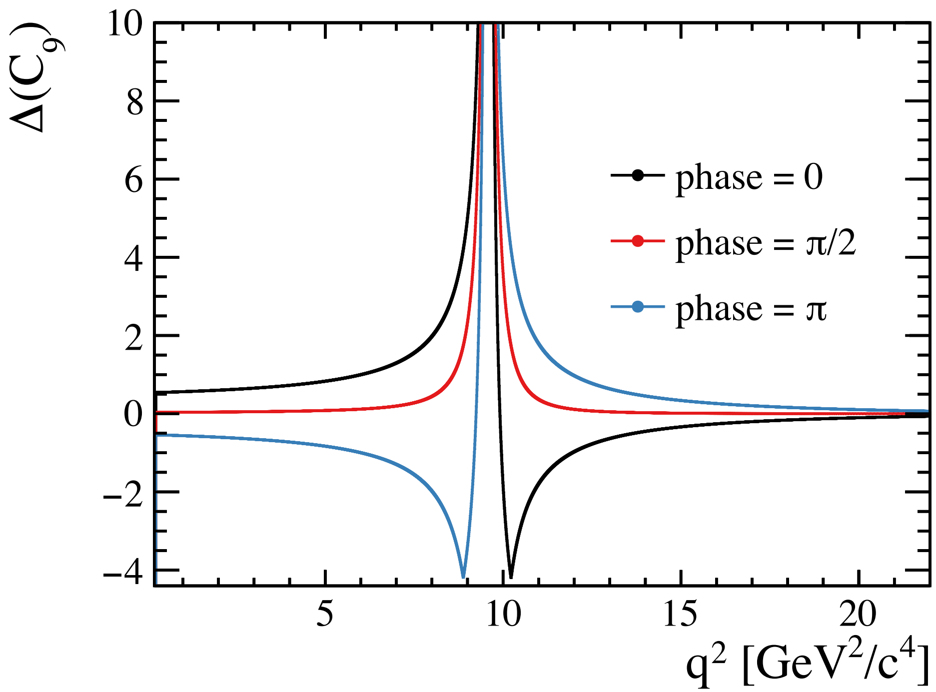
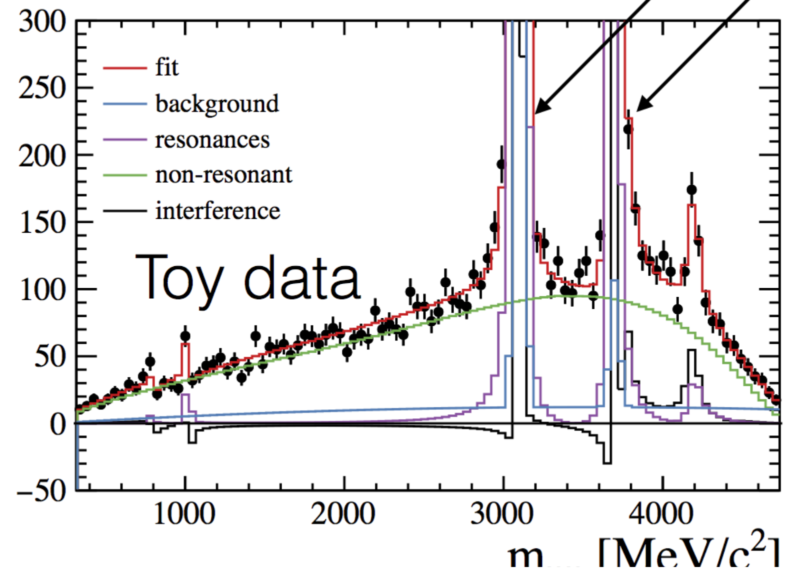
P. Owen



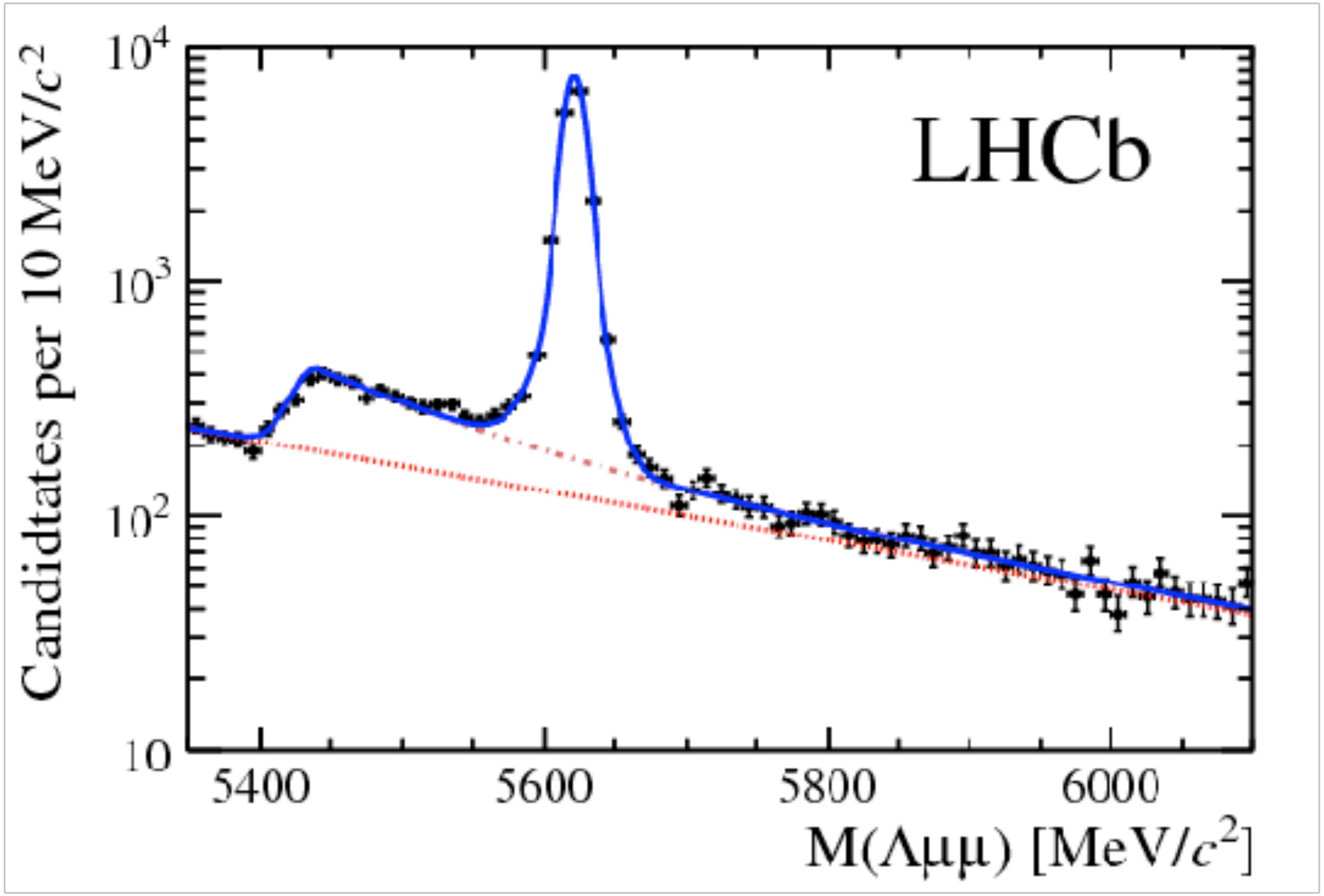
Wide due to resolution



$\Lambda_b \to \Lambda\mu^+\mu^-$ at LHCb

JHEP 1506 (2015) 115

(decay mode first observed by CDF, 24±5 events PRL 107, 201802 (2011))



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JHEP 1506 (2015) 115

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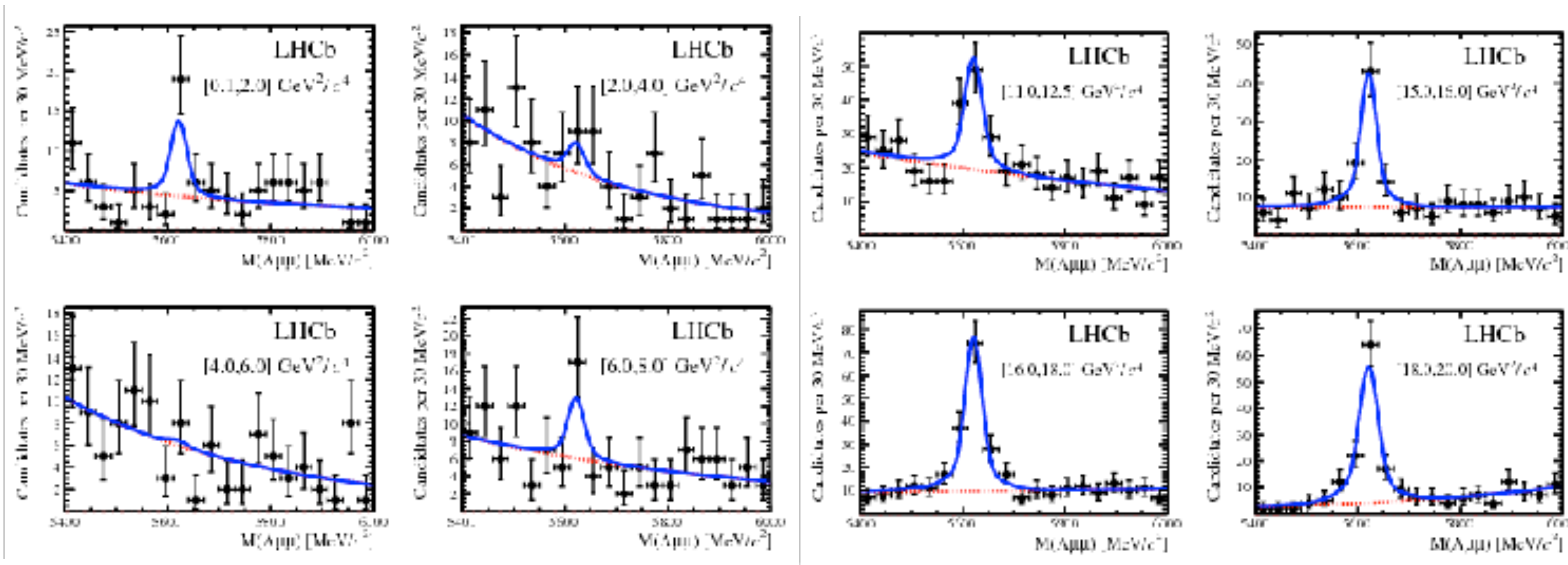

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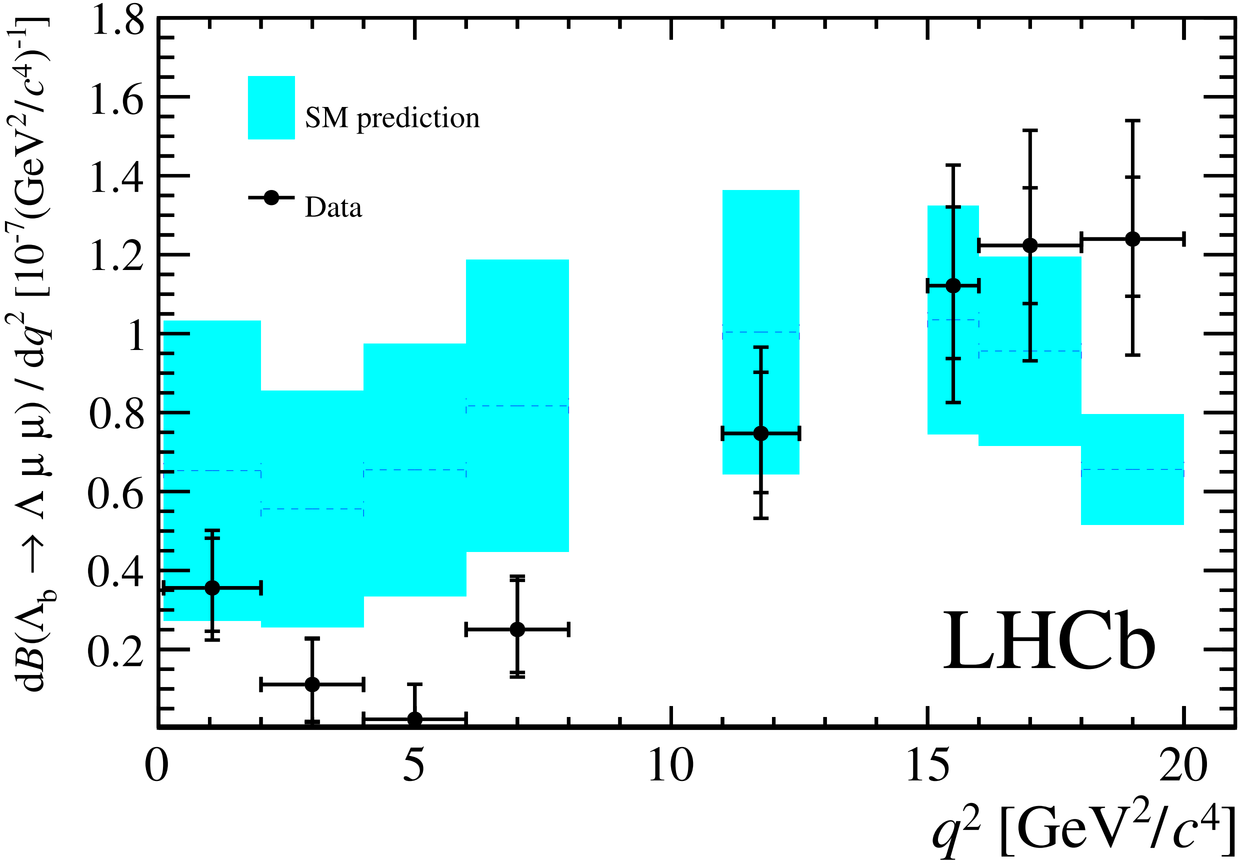
JHEP 1506 (2015) 115



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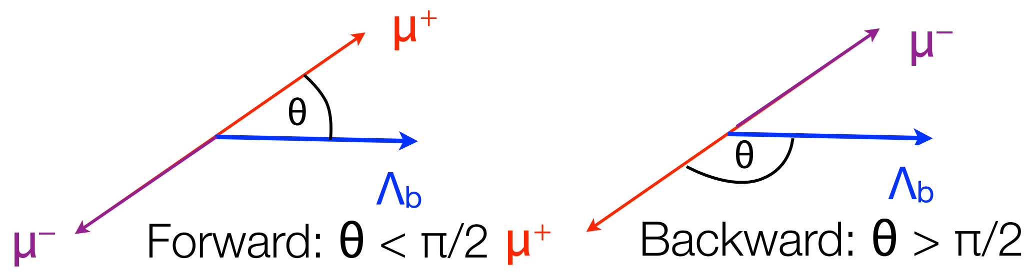
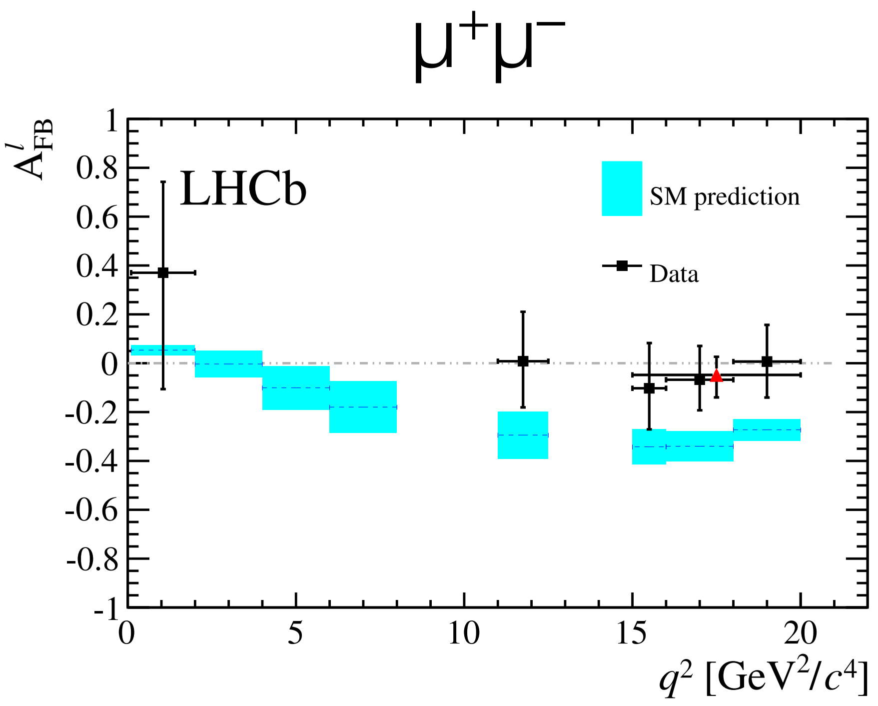
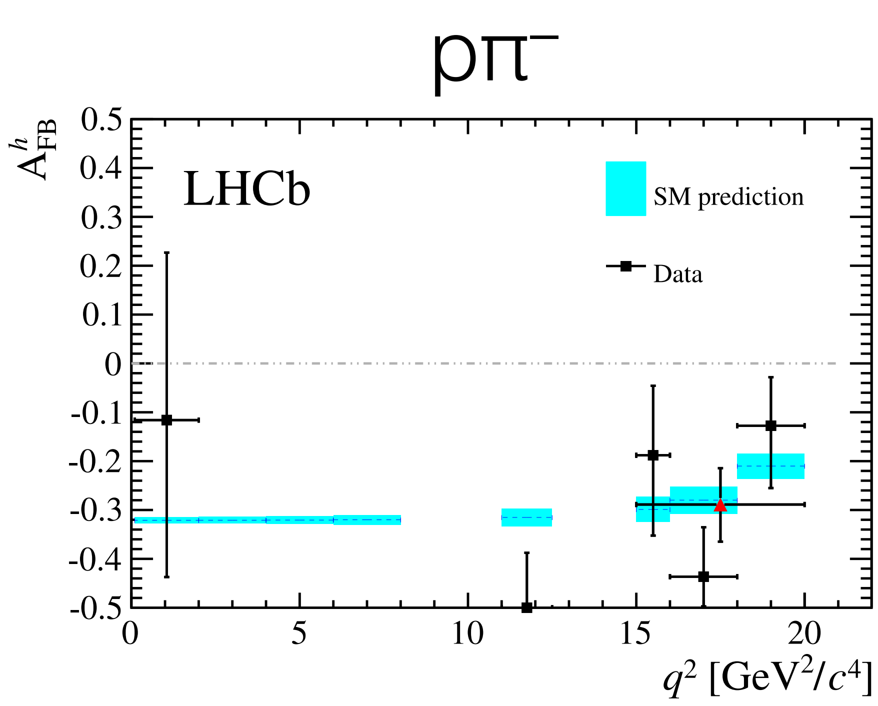
JHEP 1506 (2015) 115

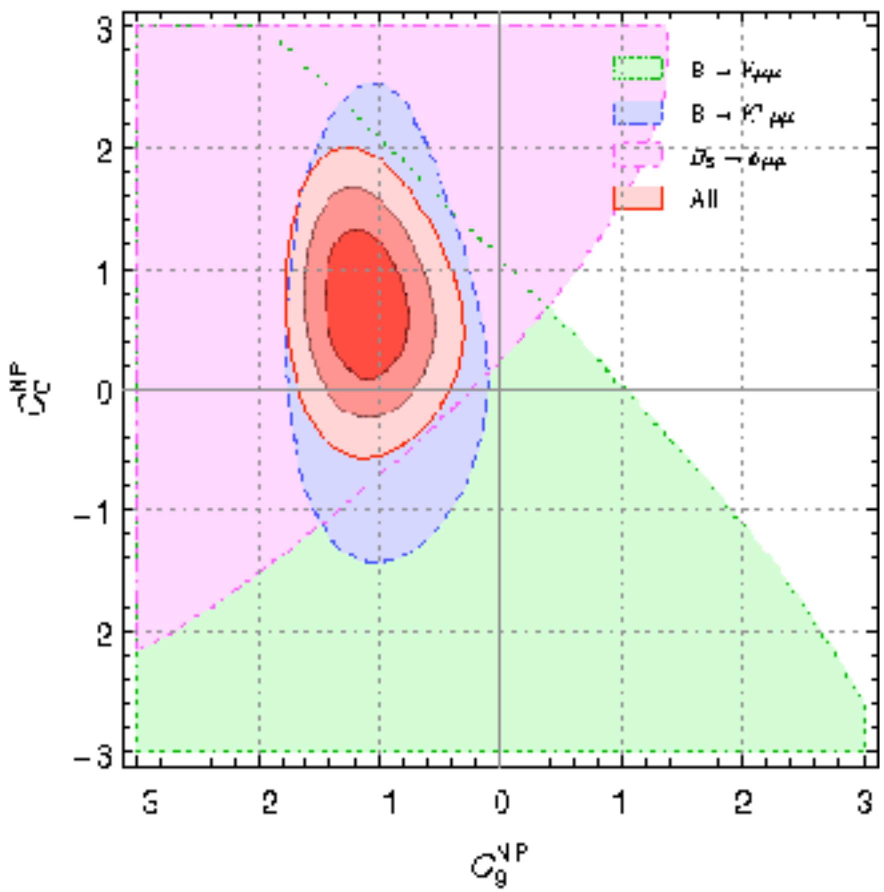




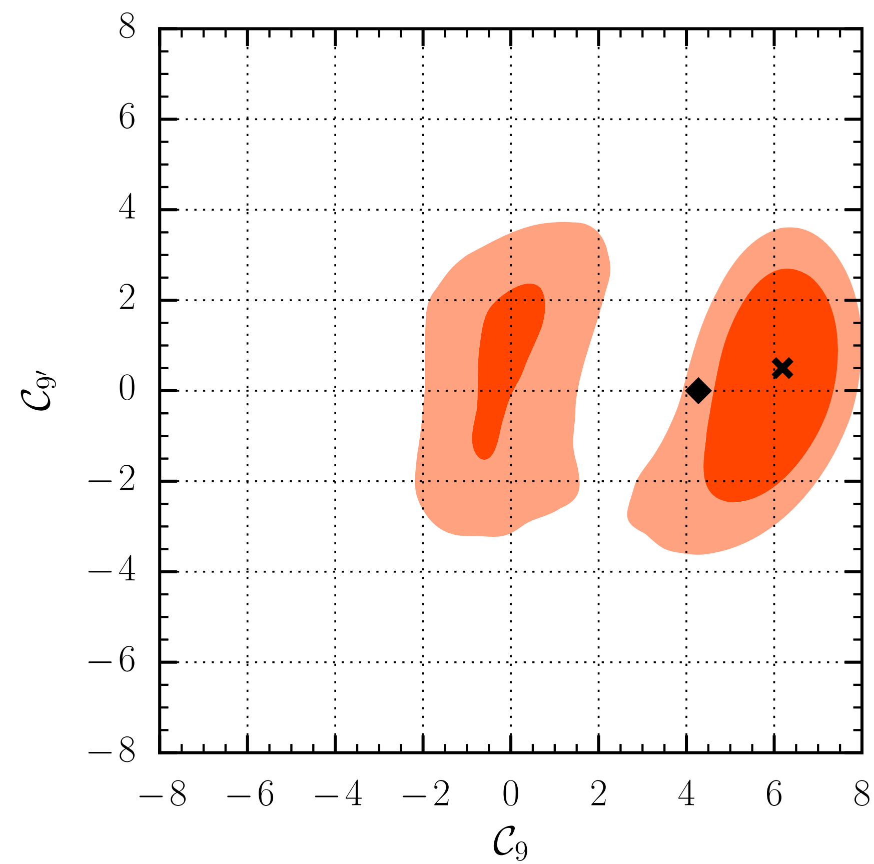


Interpretation of $B \to K^* \mu^+ \mu^-$ et al.

JHEP 1606 (2016) 092
PRD94 (2016) no.1, 013007



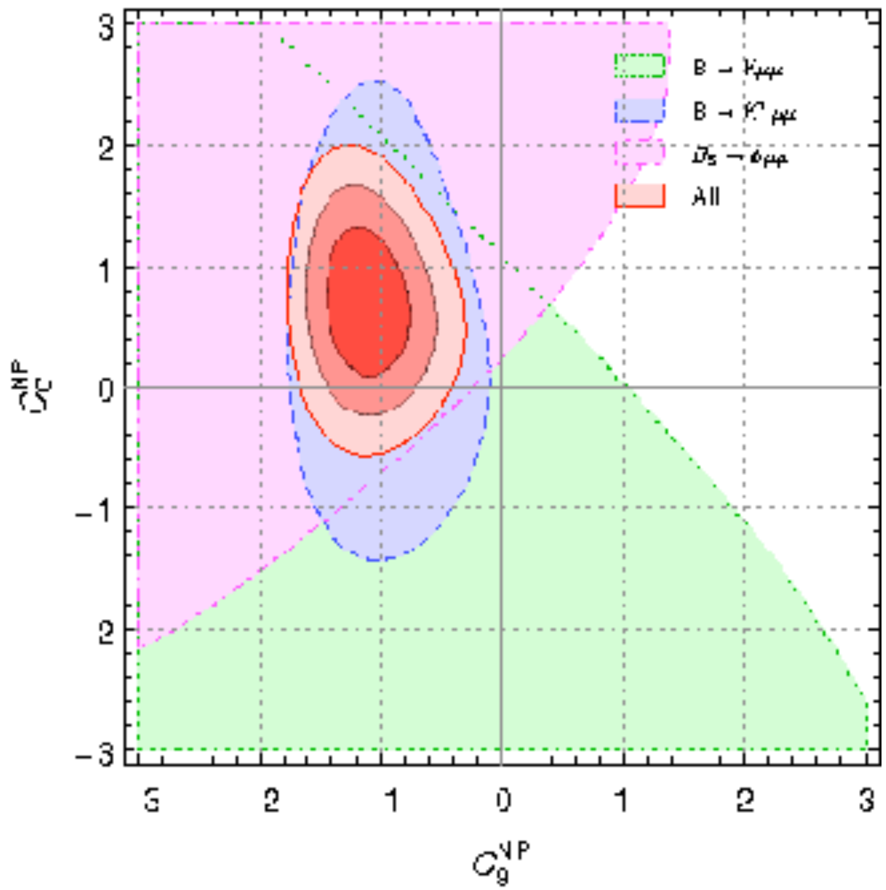
full q^2 range



high q^2 only

Interpretation of B→K*μ⁺μ⁻ et al.

JHEP 1606 (2016) 092



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JHEP 1606 (2016) 092
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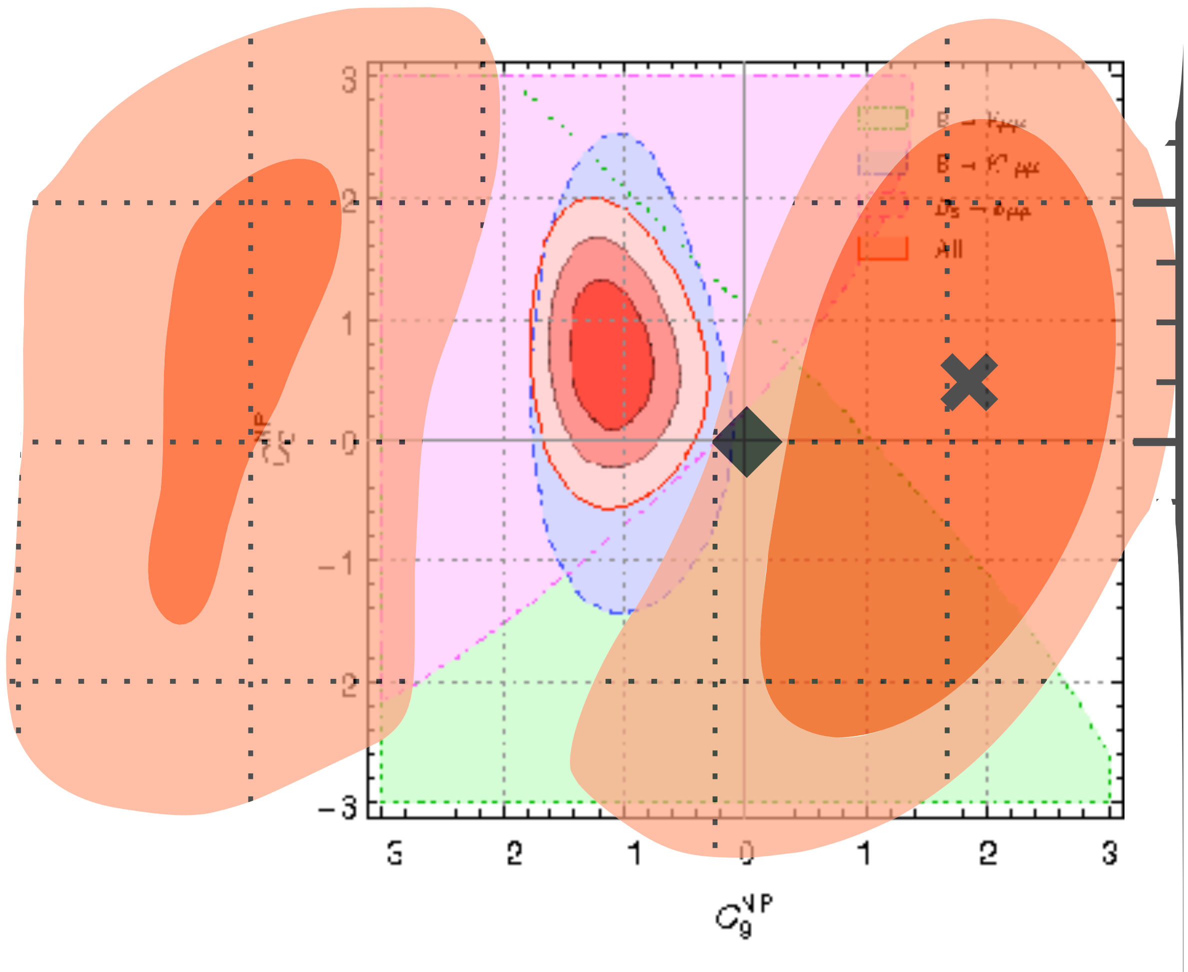


Health warning: overlaying plots using result from different q^2 ranges as input.

Prospects

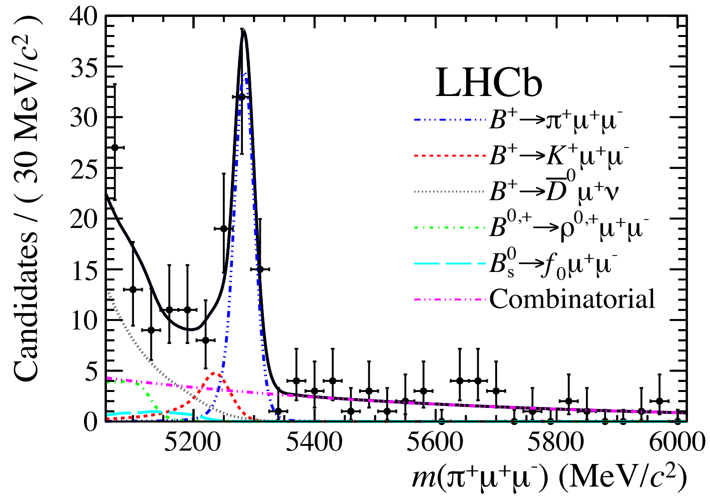
B->K*μμ in $1<q^2<6$ GeV region

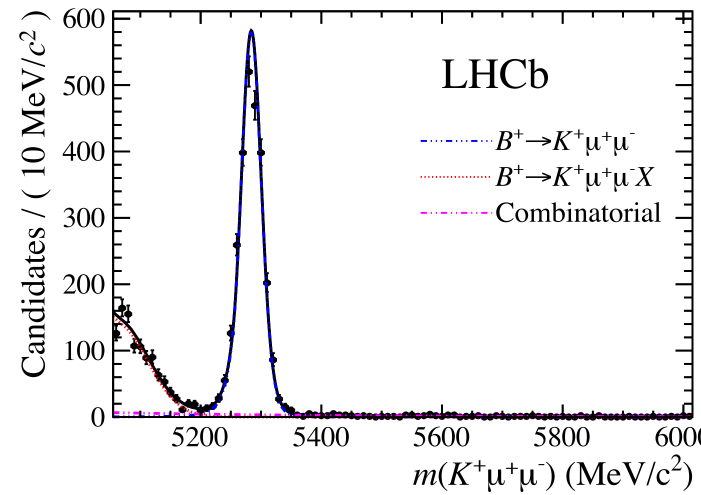
	Run 1	Run 1-3(4)	Run 1-5
LHCb JHEP 02 (2016) 104	600	20,000	120,000*
CMS Phys. Lett. B 753 (2016) 424	300	10,000	100,000

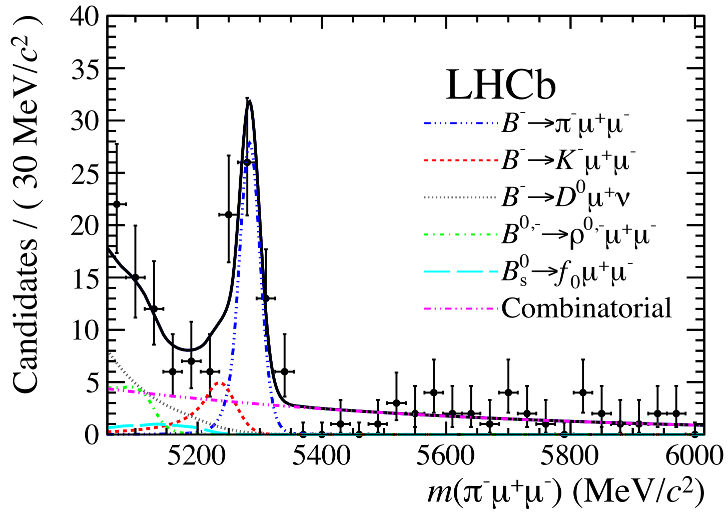
* Assuming LHCb gets 300fb^{-1}

$B^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$

JHEP 1510 (2015) 034







$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}$$

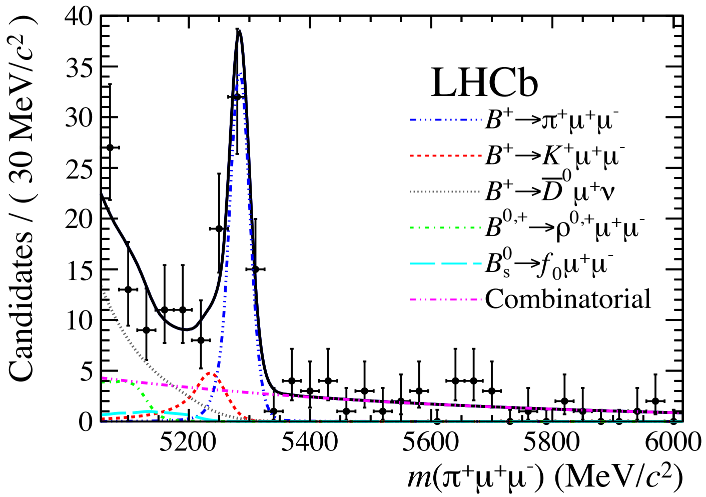
$$|V_{td}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}$$

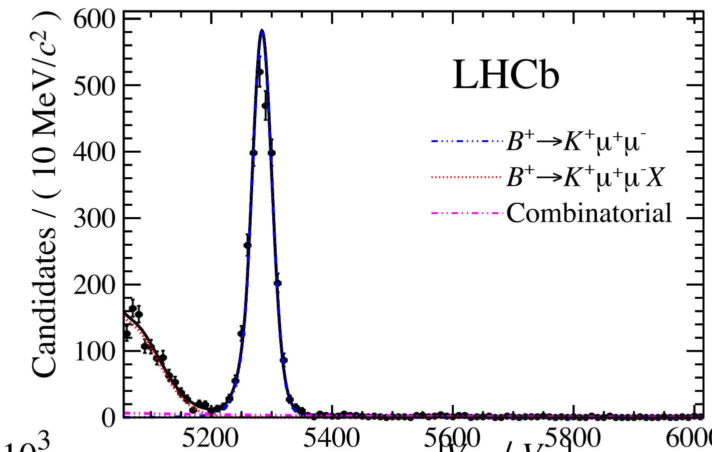
$$|V_{ts}| = 3.2^{+0.4}_{-0.4} \times 10^{-2}$$

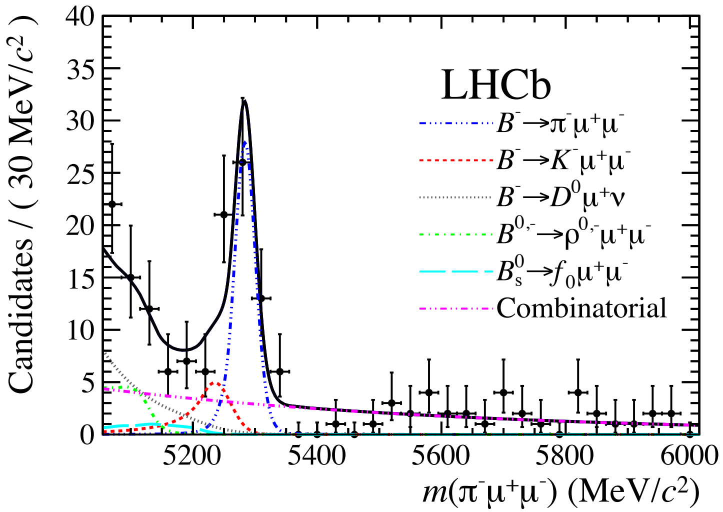
$$\mathcal{A}_{CP}(B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = -0.11 \pm 0.12\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst})$$

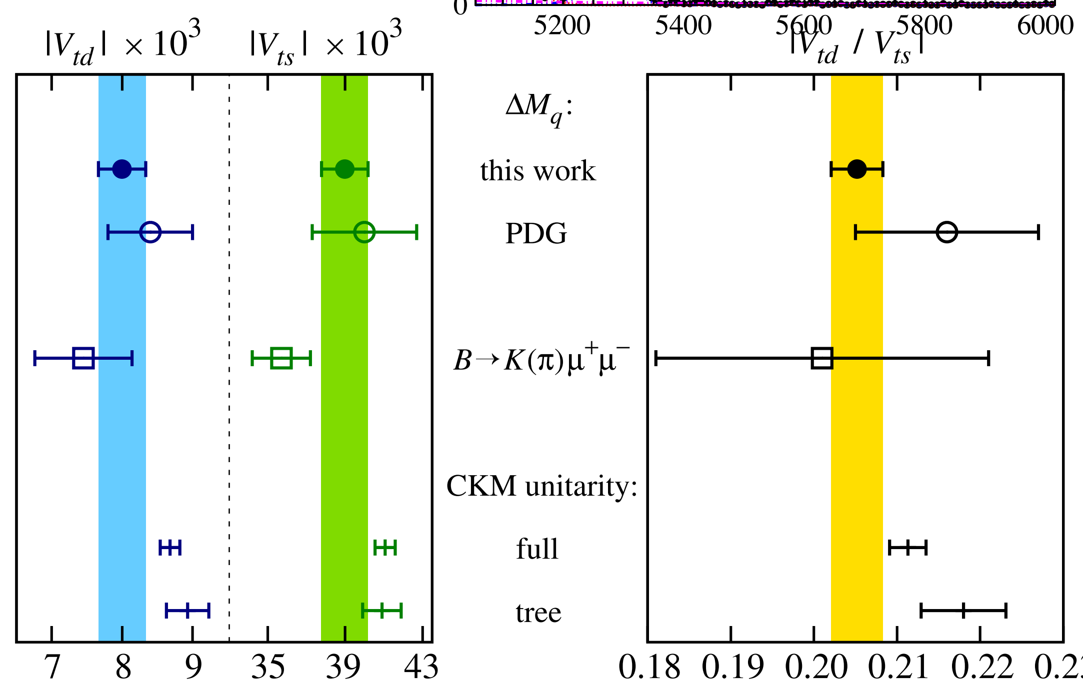
$B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

JHEP 1510 (2015) 034





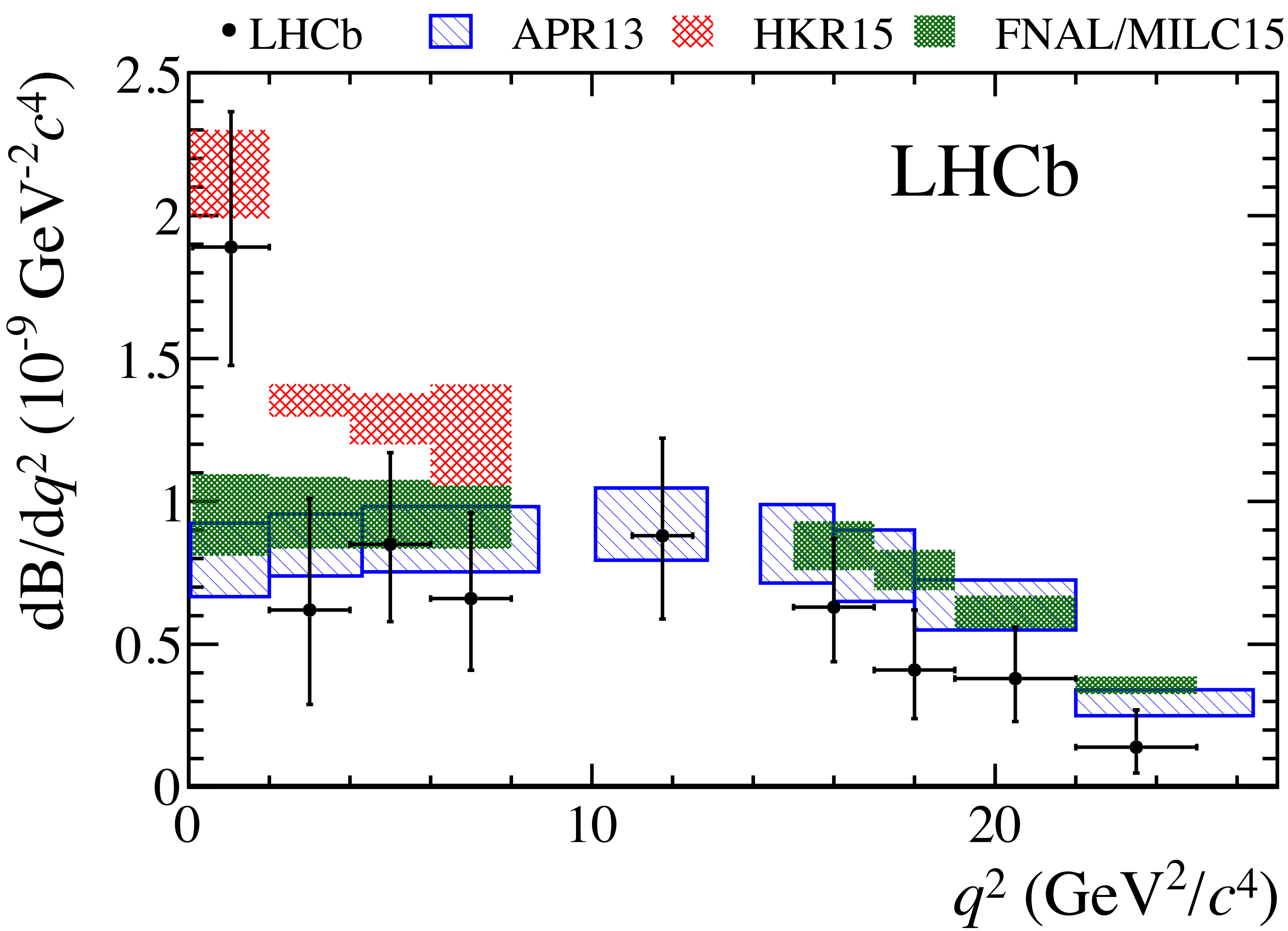




PRD93 (2016) no.11, 113016

$B^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$

JHEP 1510 (2015) 034

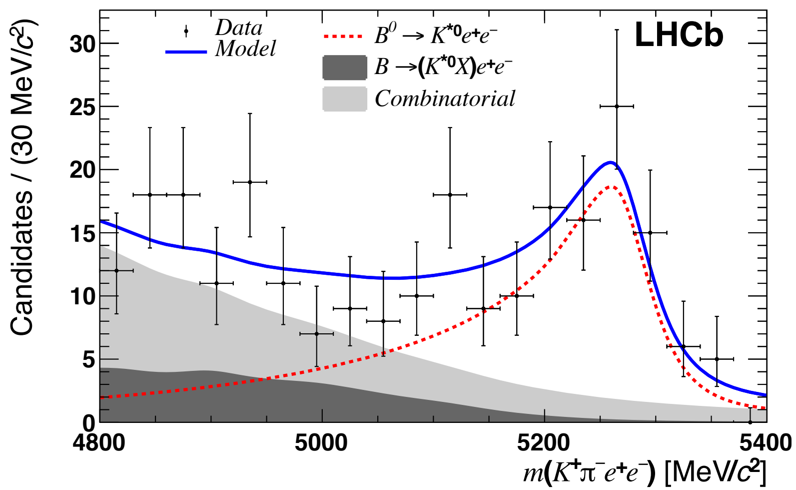


upgrade will allow precision tests in b→dll comparable to current b→sll

$B \to K^* ee$

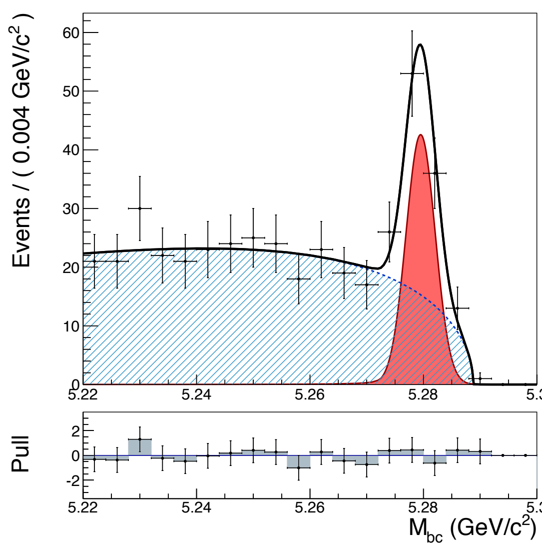
Particularly sensitive to photon polarisation, esp at low q^2.

LHCb for
$q^2 \in [0.0004, 1] GeV^2$



JHEP 1504 (2015) 064

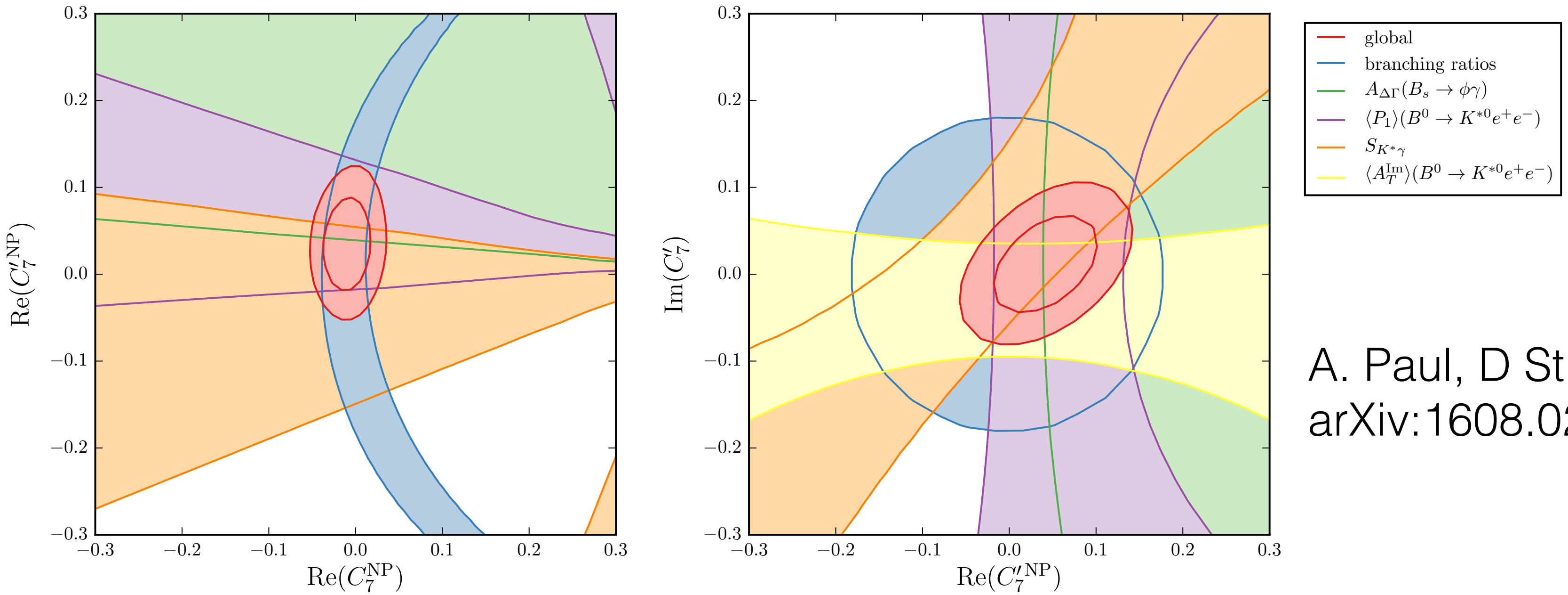
BELLE



arXiv:1604.04042 (2016)

B→K*ee

Particularly sensitive to C_7, esp Im(C_7')



A. Paul, D Straub, arXiv:1608.02556

With 3fb-1, LHCb's K*ee is already most constraining on RH plot. Belle 2 will have 50 times more data - with 300fb-1, LHCb would have 200 times more.

- Going to 300fb-1 would significantly improve constraints if can keep electron reconstruction/trigger efficiency.

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B→K(*)$\bar{\nu}\nu$ at BELLE II?

	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40	< 15	20%
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [10^{-6}]	< 55	< 21	30%

Lepton Universality with loop decays

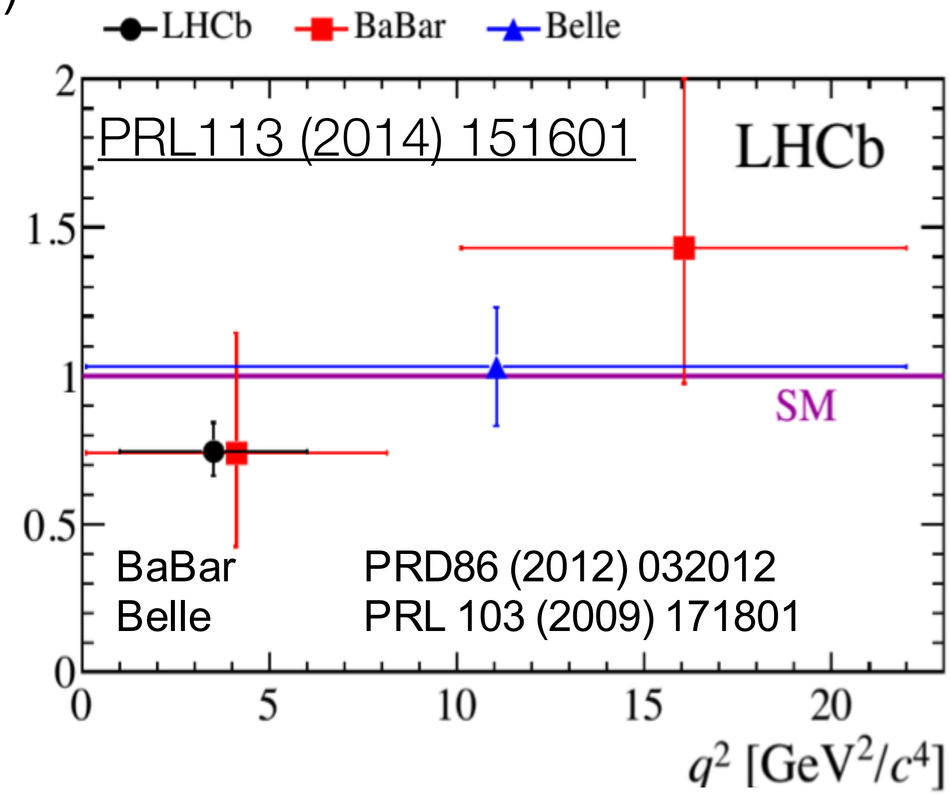
$R_K \equiv BR(B^+ \to K^+\mu\mu)/BR(B^+ \to K^+ee)$

$R_K^{SM} = 1.0003 \pm 1$

LHCb finds in $q^2 \in [1,6] GeV^2$

$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat})^{+0.036}_{-0.036}(\mathrm{syst})$

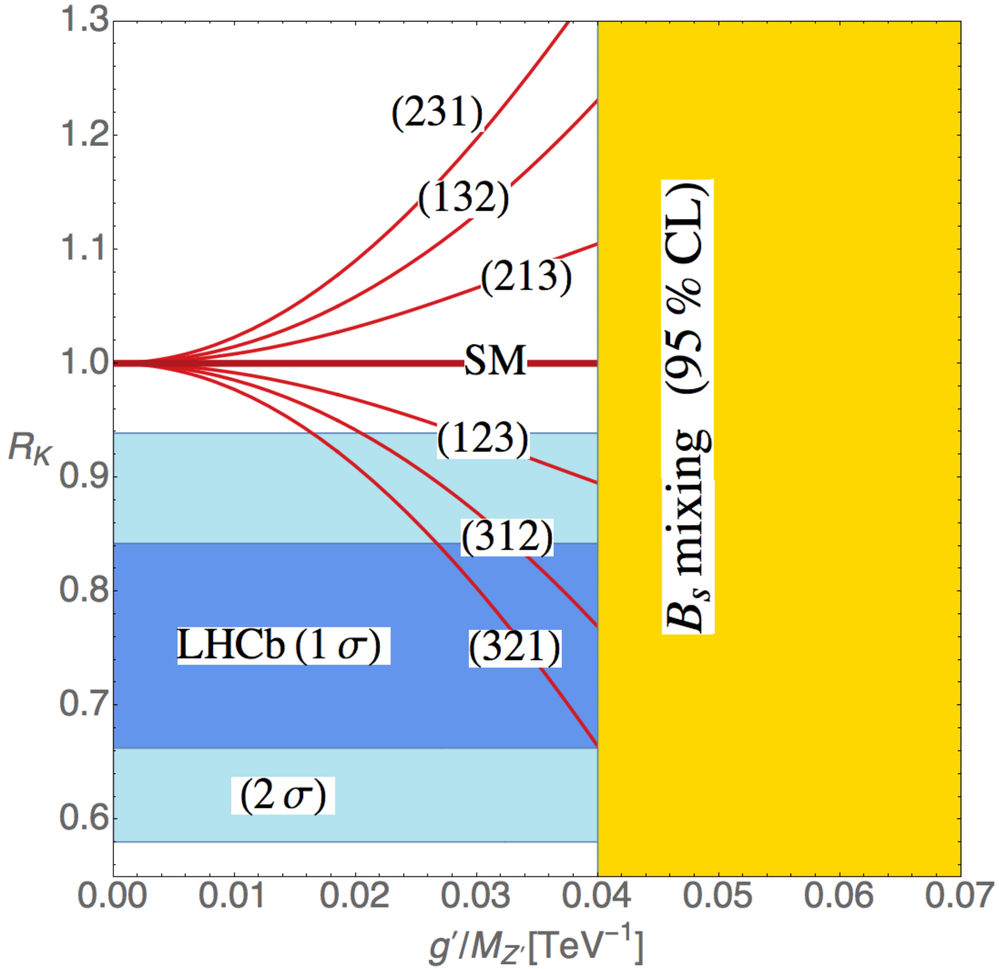
2.6σ from SM



Several theorists have pointed out this is consistent with $\Delta C_9^{ee}=0$, $\Delta C_9^{\mu\mu}=-1$ (latter consistent with $B^0 \to K^{*0}\mu\mu$) – work on-going to add range of other measurements e.g. R_{K^*}, R_ϕ,.. angular analysis $K^{*0}ee$

Model with new gauge sector with non-universal lepton charges.

models labelled by U'(1) charges of (e, μ, τ)



A. Celis, J. Fuentes-Martin, M. Jung, H. Serodio, Phys.Rev. D92 (2015) no.1, 015007

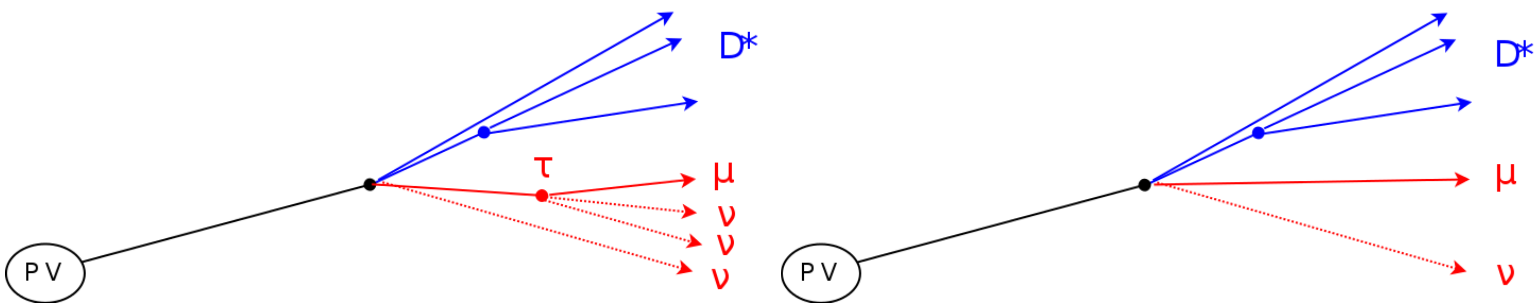
Martin Jung @ Moriond e/w 2016, arXiv:1606.09191

Not rare, but related: LU tests in trees

$$R_{D^{(*)}} = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\mu\overline{\nu}_\mu)}$$

R(D*) at LHCb

$B \to D^* \tau \nu$ $\qquad$ $B \to D^* \mu \nu$

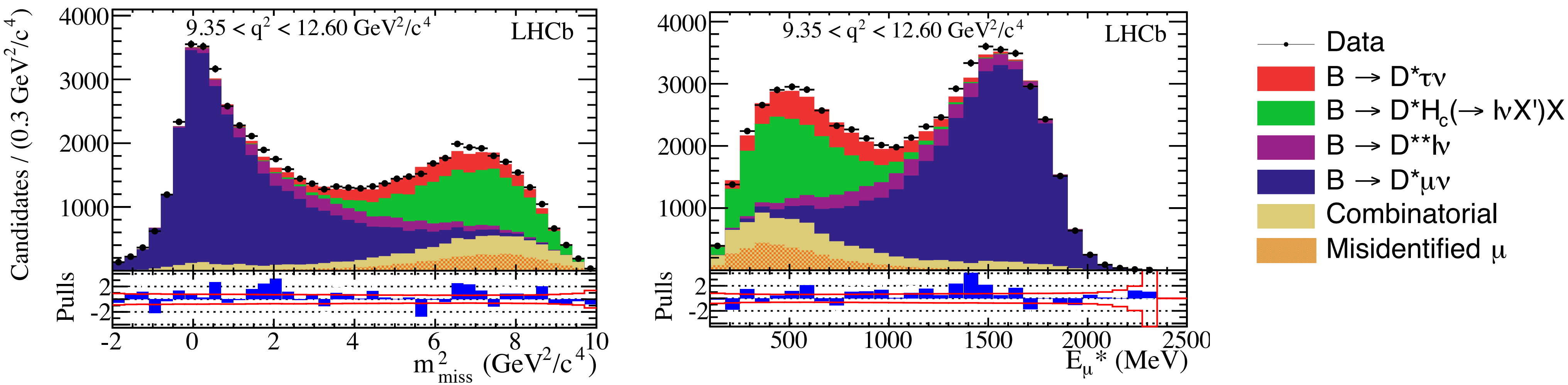


- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\to$ use approximation to access rest frame kinematics
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$18% resolution on B momentum, long tail on high side
- Can then calculate rest frame quantities - $m^2_{missing}$, E_μ, q^2

PRL 115 (2015) no.11, 111803

Lepton (non?) Universality - R(D*) @ LHCb

PRL 113 (2014) 151601



$$R(D^*) \equiv \Gamma(B^+ \to D^*\tau\nu) / \Gamma(B^+ \to D^*\mu\nu) = 0.252 \pm 0.003 \text{ in SM}$$

At LHCb: $R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$

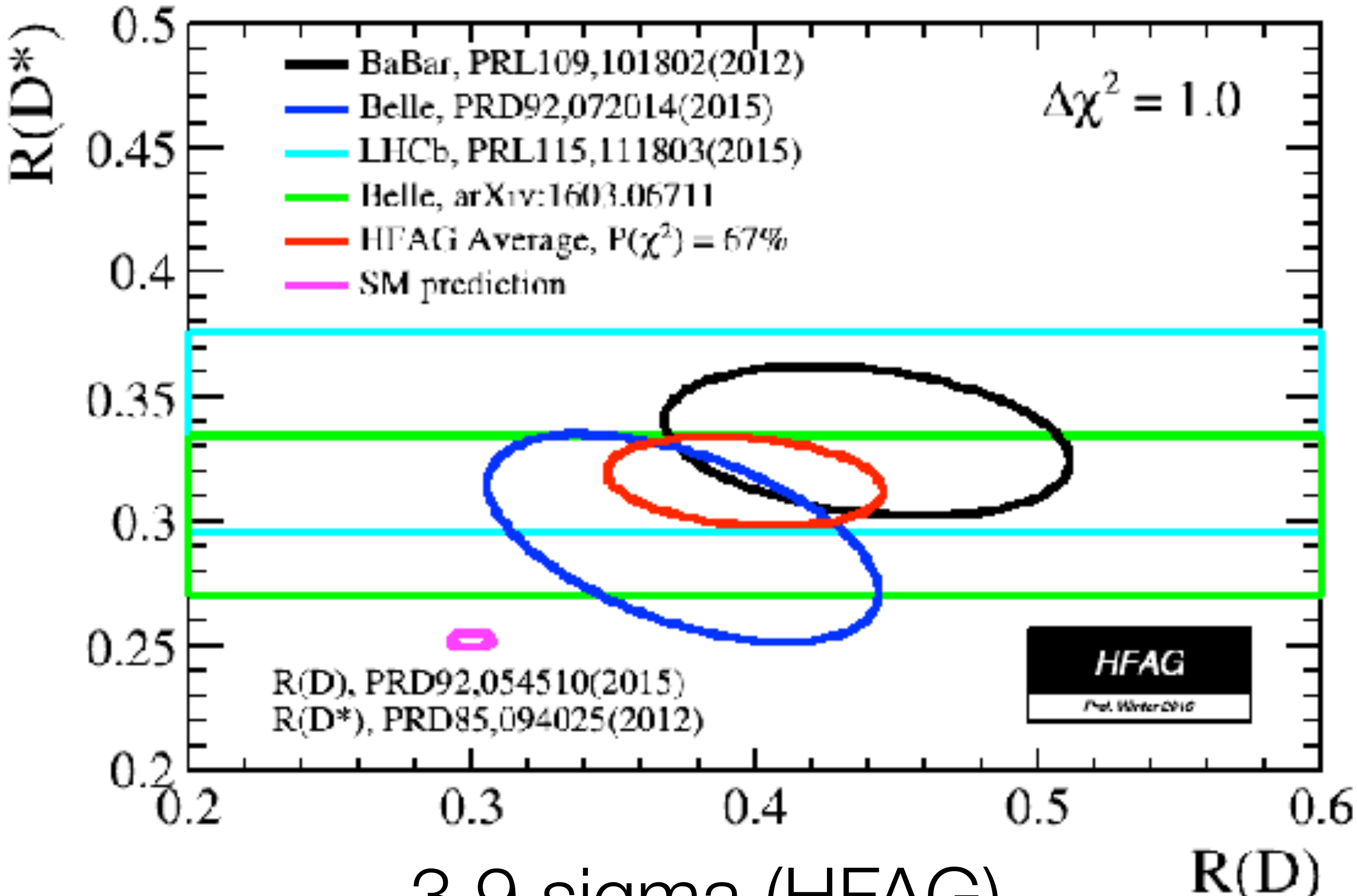
Note: LHCb can do neutrals!

For R(D*) SM prediction see PRD85 (2012) 094025

PRL 115 (2015) no.11, 111803

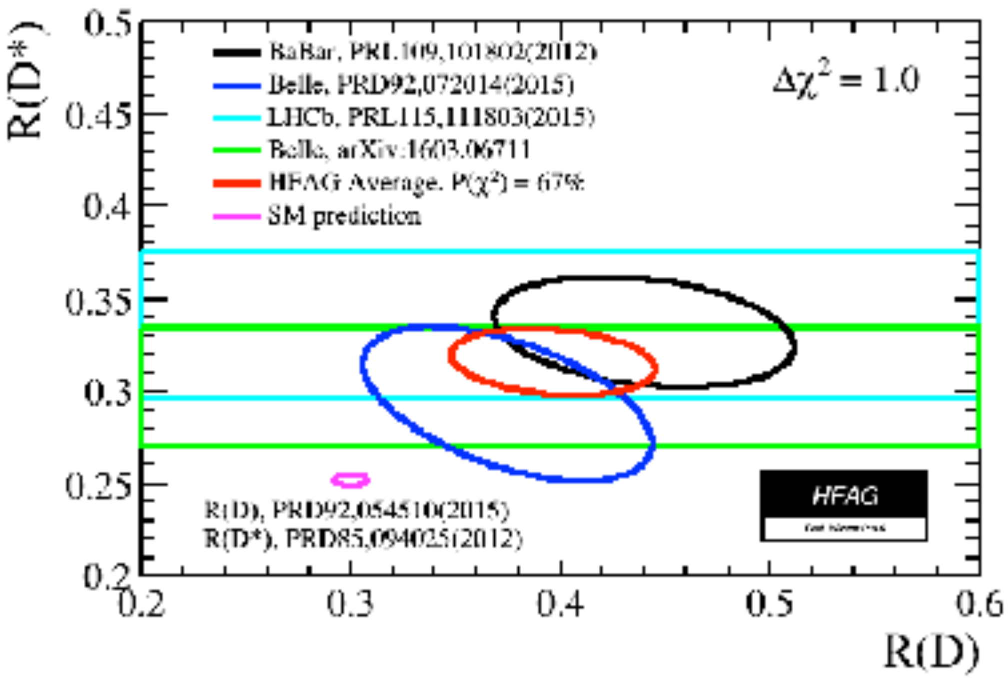
Lepton (non?) Universality - R(D*) and R_K

PRL 113 (2014) 151601



3.9 sigma (HFAG)

Lepton (non?) Universality - R(D*) and R_K

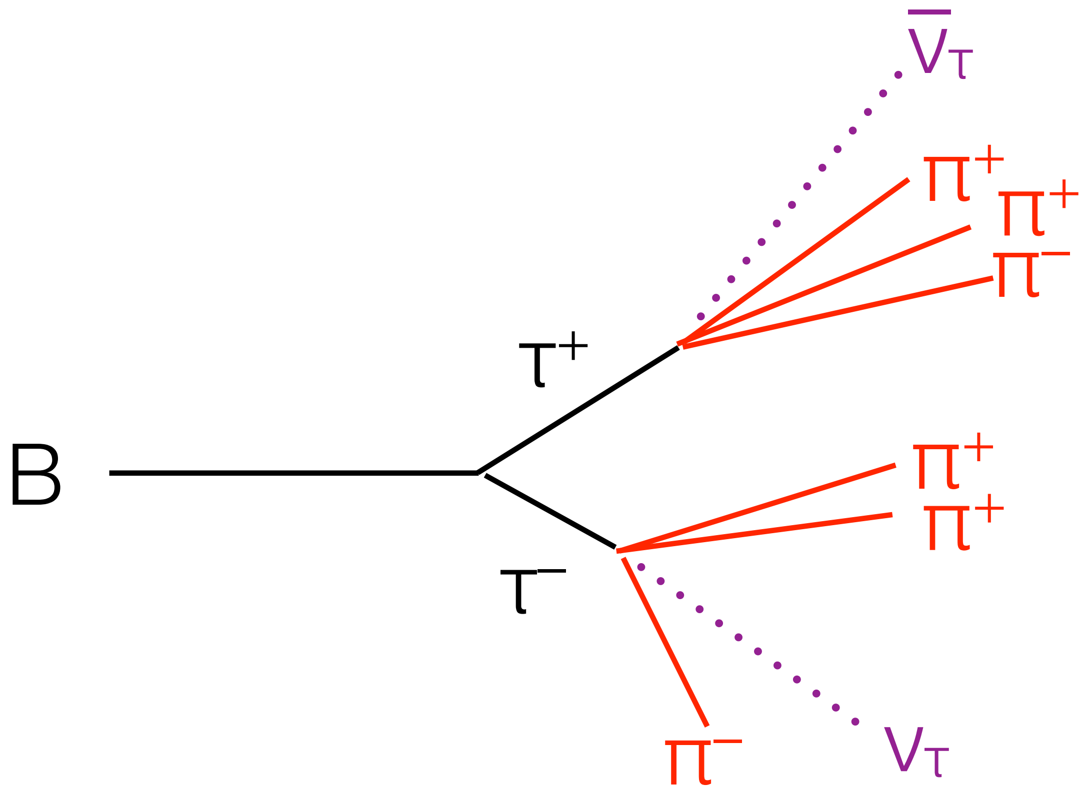


3.9 sigma (HFAG)

	R(D)	R(D*)
BaBar	0.44±0.06±0.04	0.33±0.02±0.02
BELLE	0.38±0.6±0.03	0.30±0.03±0.01 preliminary
LHCb		0.34±0.03±0.03
Aver	0.388±0.047	0.321±0.021
SM	0.300±0.008	0.252±0.005

BaBar: Phys.Rev.Lett. 109,101802 (2012) [arXiv:1205.5442 [hep-ex]] Phys.Rev.D 88, 072012 (2013) [arXiv:1303.0571]
BELLE: Phys.Rev.D 92, 072014 (2015) [arXiv:1507.03233 [hep-ex]], Preliminary at Moriond EW 2016 [arXiv:1603.06711 [hep-ex]]
LHCb: Phys.Rev.Lett.115,111803 (2015) [arXiv:1506.08614 [hep-ex]]
SM prediction: Phys.Rev.D 92, 054410 (2015) arXiv:1505.03925 [hep-lat], S.Fajfer, J.F.Kamenik, and I.Nisandzic, Phys.Rev.D85(2012) 094025 arXiv:1203.2654 [hep-ex]

$B \to \tau^+\tau^-$ @ LHCb



Reconstruction method: A. Mordà, Alessandro; G. Mancinel (dir.) CERN-THESIS-2015-264

$B \to \tau^+\tau^-$

SM predictions [PRL 112, 101801 (2014)]

$\mathcal{B}_{SM}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$

$\mathcal{B}_{SM}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$

BaBar PRL 96 (2006) 241802

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3}$ @90% CL

LHCb limits on $B^0_{(s)} \to \tau^+\tau^-$

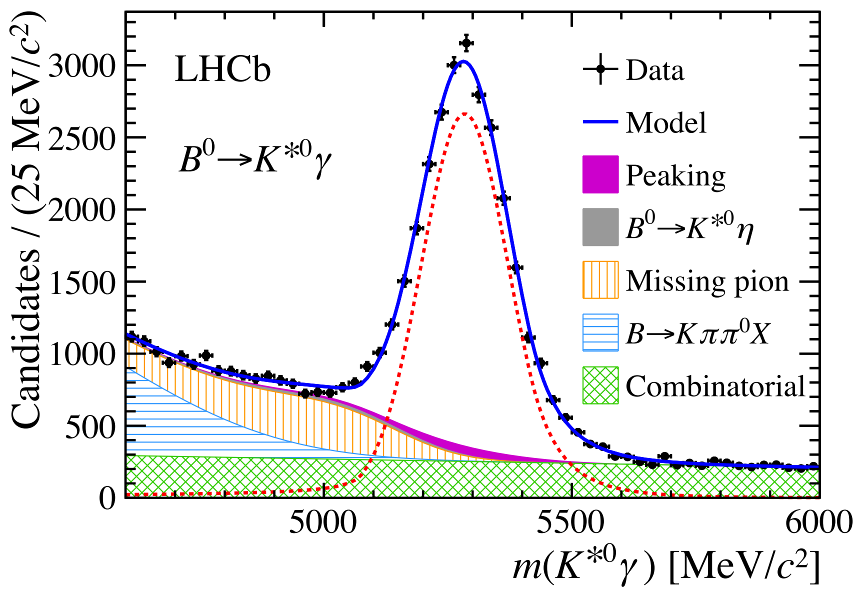
	$\mathcal{B}(B^0)$ (95% CL)	$\mathcal{B}(B^0_s)$ (95% CL)
Run I	1.3×10^{-3}	3.0×10^{-3}
$8\ fb^{-1}$	0.6×10^{-3}	1.4×10^{-3}
$50\ fb^{-1}$	0.2×10^{-3}	0.5×10^{-3}
$300\ fb^{-1}$	0.1×10^{-3}	0.2×10^{-3}

LHCb-CONF-2016-011

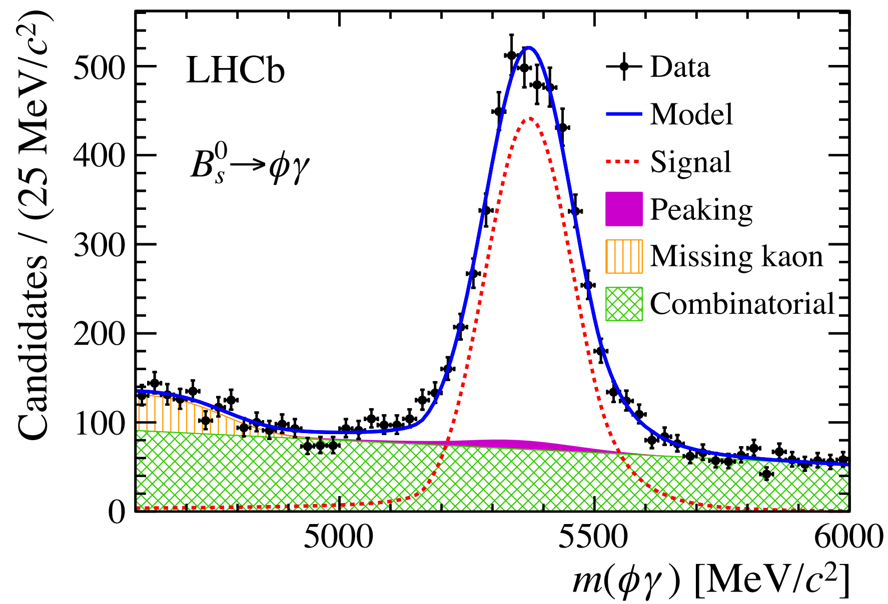
$B_s \to \phi\gamma$ at LHCb

arXiv:1609.02032 (2016)

control mode



signal mode



sensitive to

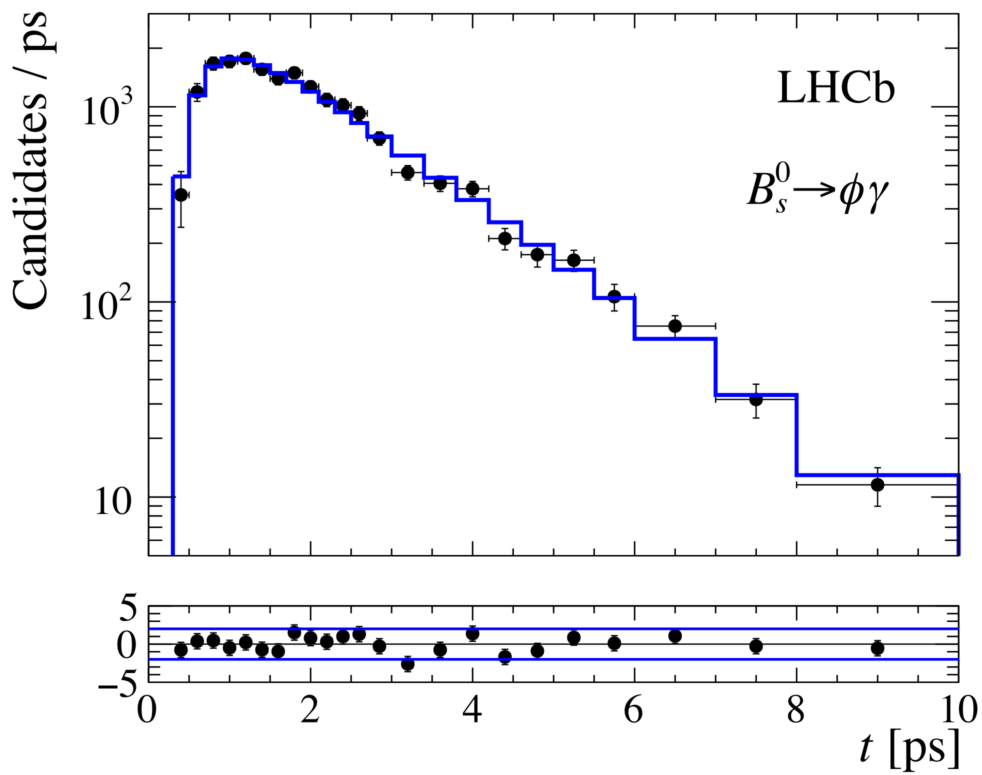
$$A^{\Delta\Gamma} \sim \frac{|\mathcal{A}(B_s \to \phi\gamma_L)|}{|\mathcal{A}(B_s \to \phi\gamma_R)|} \cos\phi_s$$

$B_s \to \phi\gamma$ at LHCb

arXiv:1609.02032 (2016)

untagged time-dependent rate

$$\Gamma(B_s + \overline{B}_s)(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - A^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right]$$



to extract

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

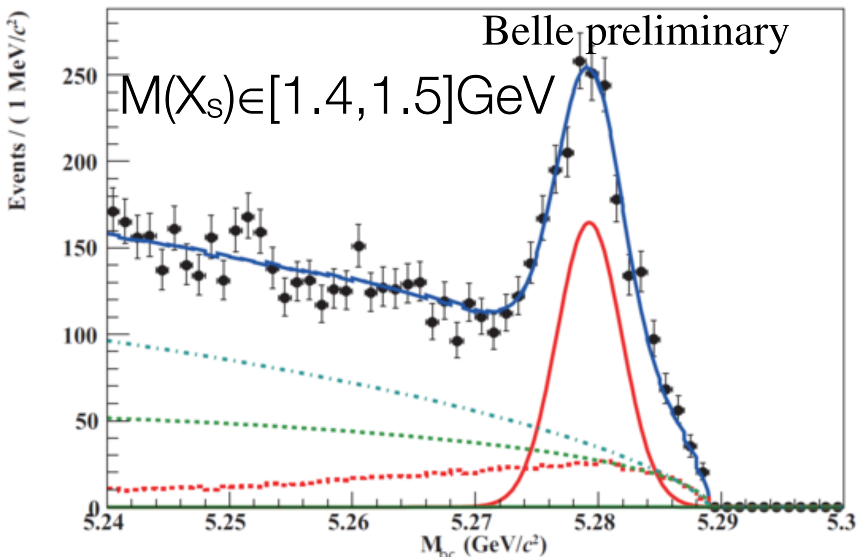
compare to

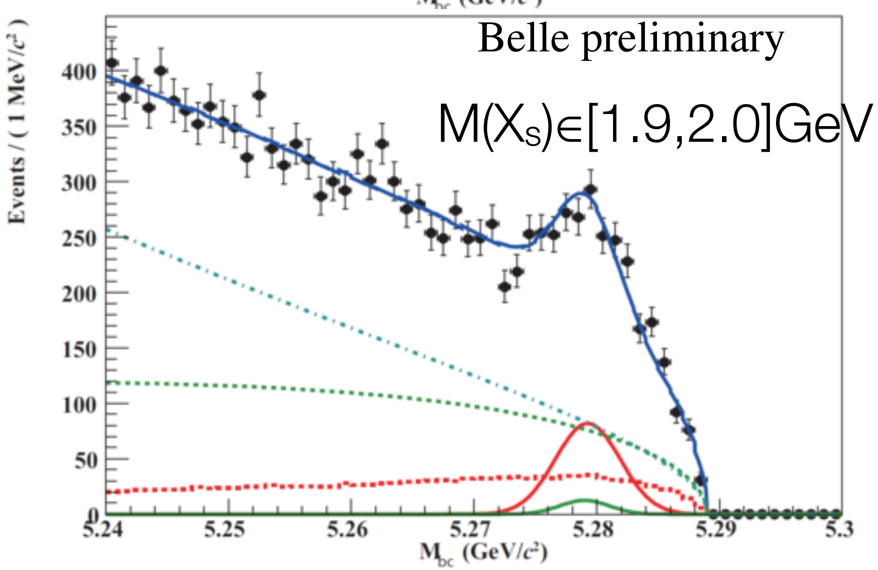
$$A^{\Delta\Gamma}(SM) = 0.047^{+0.029}_{-0.025}$$

F. Muheim, Y. Xie, R. Zwicky PLB664 (2008) 174-179

B→X(s,d)γ at BELLE

Nucl.Part.Phys.Proc. 273-275 (2016) 1354-1357





$\mathcal{B}(B \to X_s\gamma)$ for $E^*_\gamma > 1.6$ GeV

BELLE	$(3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$
prev WA	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
theory*	$(3.15 \pm 0.23) \times 10^{-4}$

*)Nucl.Phys. B764 (2007) 62-82

LHCb prospects

channel	Run 1	Run 2	Run 3,4 ($50 fb^{-1}$)
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_S\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4,700	17,500	150,000
$\Lambda_b \to \Lambda\mu^+\mu^-$	370	1500	10,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$ (low q^2)	150	550	5,000
$B_s \to \phi\gamma$	4,000	15,000	150,000

Naively scaling with luminosity and linear scaling of $\sigma_{b\bar{b}}$ with $\sqrt{s}$

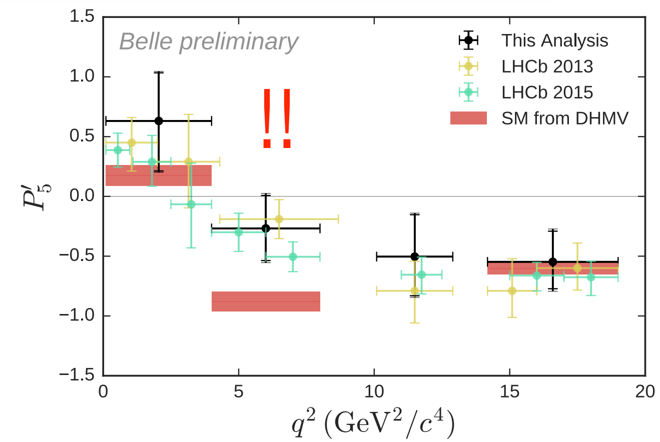
For some channels, yields at LHCb already larger than B-factory yields in normalisation mode B→JψK*. Limits precision in BF measurements, BELLE II could help, here. Also relevant for high precision area: isospin violations, see M. Jung at PLB753 (2016) 187-190.

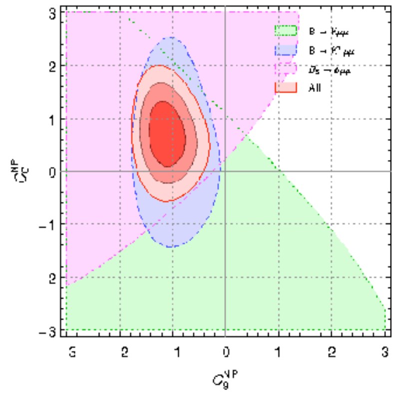
BELLE II

Missing E decays	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	96(1 ± 27%) [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7 [59]	20%	7%
	$R(B \to D\tau\nu)$	0.440(1 ± 16.5%) [29]†	5.2%	3.4%
	$R(B \to D^{*}\tau\nu)^{\dagger}$	0.332(1 ± 9.0%) [29]†	2.9%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ $[10^{-6}]$	< 40 [31]	< 15	20%
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ $[10^{-6}]$	< 55 [31]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	2.2 ± 4.0 ± 0.8 [60]	1	0.5
	$S(B \to K_S^0\pi^0\gamma)$	−0.10 ± 0.31 ± 0.07[20]	0.11	0.035
	$S(B \to \rho\gamma)$	−0.83 ± 0.65 ± 0.18 [21]	0.23	0.07
	C_7/C_9 $(B \to X_s\ell\ell)$	~20% [37]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7 [40]	0.3	−
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	−	< 2 [42]‡	−

Conclusions

- Rare decays are powerful probes of BSM physics. Deviations from SM observed in multiple channels - individually maybe not that large, but all consistently pointing to BSM contributions to C_9. Have we seen a flavour-changing, lepton universality violating Z'?





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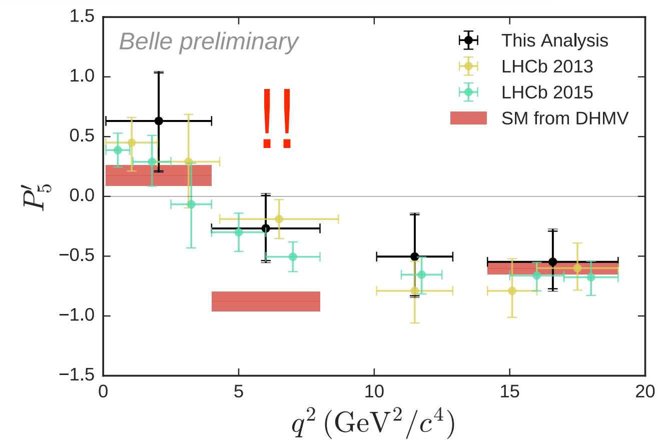
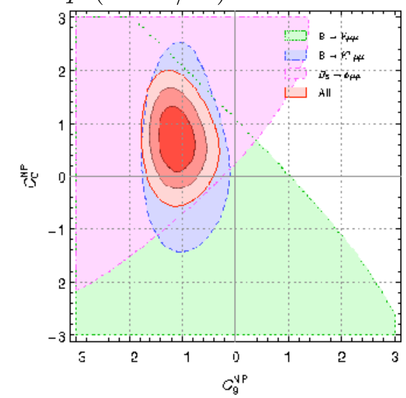




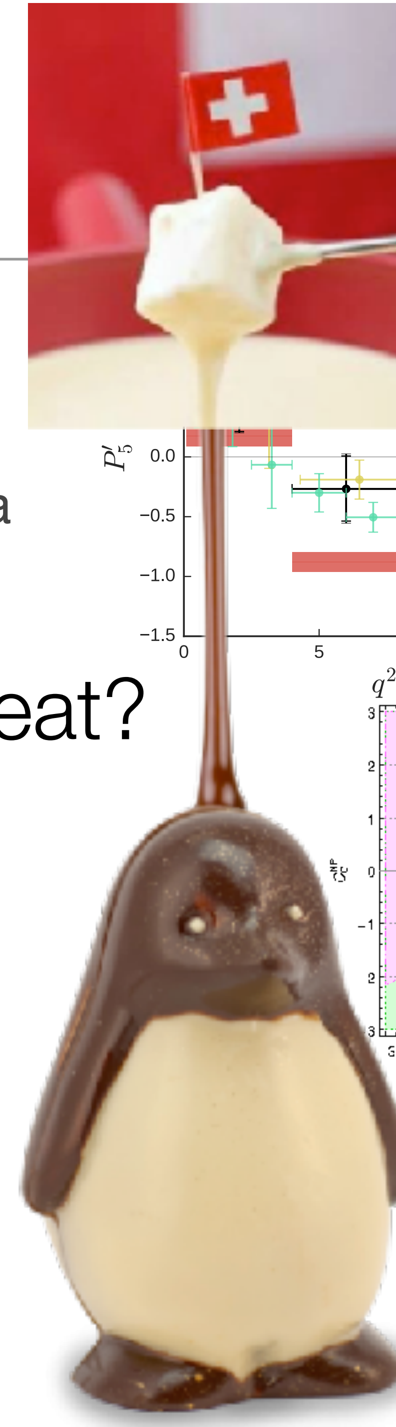
Trick?

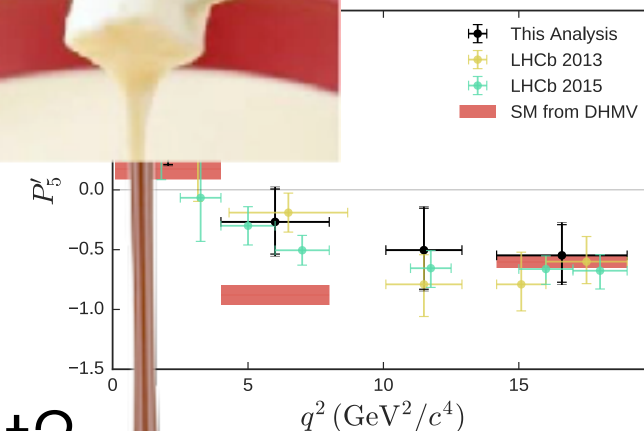
Conclusions

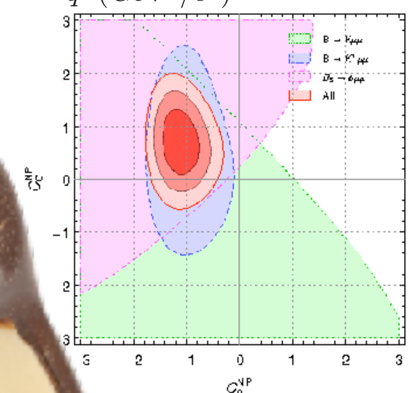
- Rare decays are powerful probes of BSM physics. Deviations from SM observed in multiple channels - individually maybe not that large, but all consistently pointing to BSM contributions to C_9. Have we seen a flavour-changing, lepton universality violating Z'?

Trick?

Or Treat?

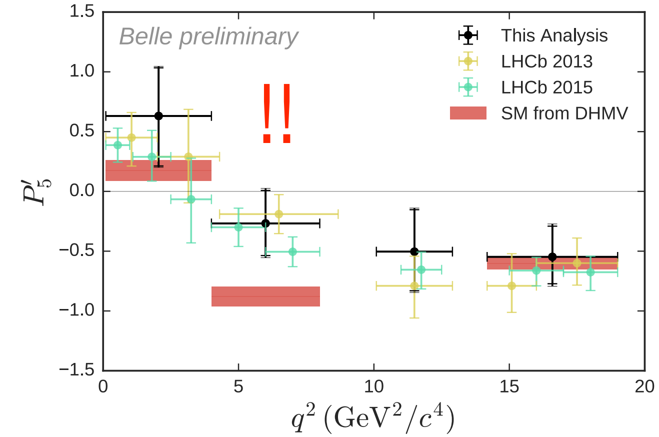






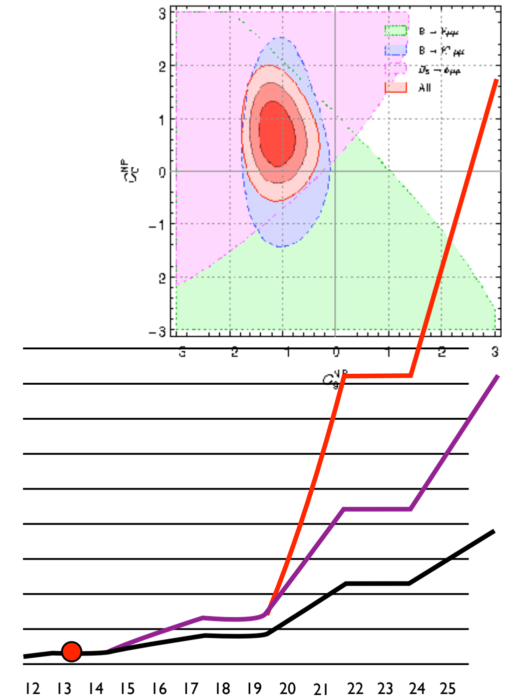
Conclusions

- Rare decays are powerful probes of BSM physics. Deviations from SM observed in multiple channels - individually maybe not that large, but all consistently pointing to BSM contributions to C_9. Have we seen a flavour-changing, lepton universality violating Z'?



- High luminosity is key to answer this question. And the control of hadronic effects.

- LHCb has shown that precision flavour physics works at a hadron machine. LHCb, upgrade, and upgade^2 will have unbeatable statistics in charged modes. Di-muon channels also accessible to ATLAS/CMS.



- BELLE II benefits from e+e– environment, and will especially shine in inclusive modes and modes with many neutrals, as well as absolute BF measurements.

Credits

- Many thanks go to
  - Flavio Archilli
  - Marc-Olivier Bettler
  - Veronika Chobanova
  - Kostas Petridis
  - Patrick Owen
- From whom I copied many slides and received a many helpful comments.

Backup

Bs->mumu lifetime formalism

$$\langle\Gamma(B_s(t)\to f)\rangle \equiv \Gamma(B_s^0(t)\to f)+\Gamma(\bar{B}_s^0(t)\to f) = R_{\rm H}^f e^{-\Gamma_{\rm H}^{(s)}t}+R_{\rm L}^f e^{-\Gamma_{\rm L}^{(s)}t},$$

$$\mathcal{A}_{\Delta\Gamma}^f \equiv \frac{R_{\rm H}^f - R_{\rm L}^f}{R_{\rm H}^f + R_{\rm L}^f}$$

$$\tau_f \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t)\to f)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t)\to f)\rangle\,dt} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2\,\mathcal{A}_{\Delta\Gamma}^f y_s + y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^f y_s}\right]$$

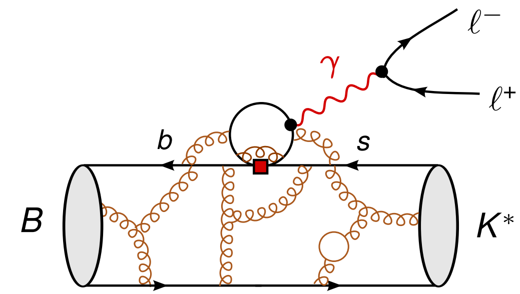
$$\mathcal{A}_{\Delta\Gamma}\,y_s = \frac{(1-y_s^2)\tau_{\mu^+\mu^-}-(1+y_s^2)\tau_{B_s}}{2\tau_{B_s}-(1-y_s^2)\tau_{\mu^+\mu^-}}$$

$$C_\lambda \equiv \frac{1-|\xi_\lambda|^2}{1+|\xi_\lambda|^2} = -\eta_\lambda\left[\frac{2|PS|\cos(\varphi_P-\varphi_S)}{|P|^2+|S|^2}\right]$$

$$S_\lambda \equiv \frac{2\,{\rm Im}\,\xi_\lambda}{1+|\xi_\lambda|^2} = \frac{|P|^2\sin 2\varphi_P - |S|^2\sin 2\varphi_S}{|P|^2+|S|^2}$$

$$\mathcal{A}_{\Delta\Gamma}^\lambda \equiv \frac{2\,{\rm Re}\,\xi_\lambda}{1+|\xi_\lambda|^2} = \frac{|P|^2\cos 2\varphi_P - |S|^2\cos 2\varphi_S}{|P|^2+|S|^2}.$$

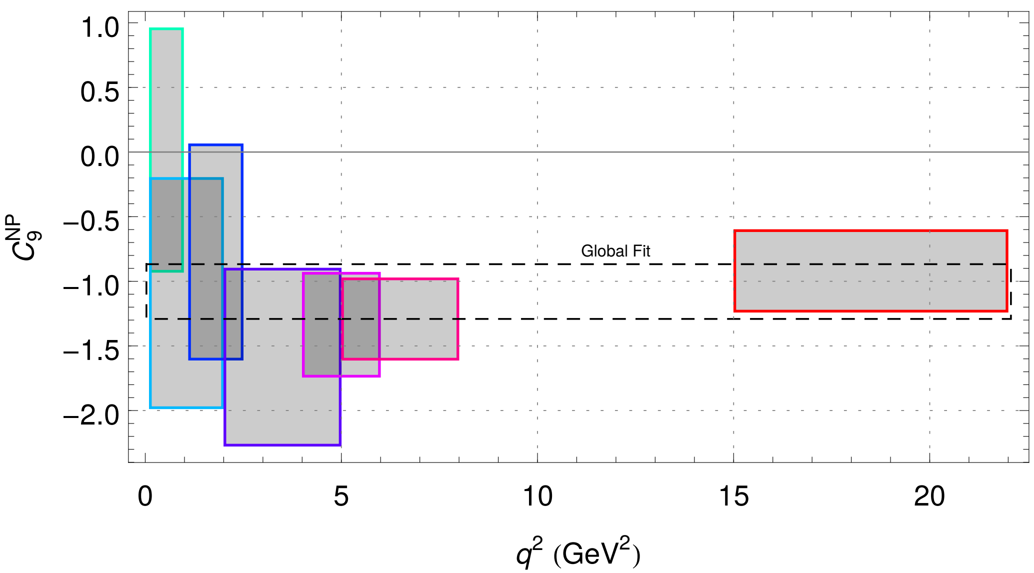
Charm loop contribution?



- The $\mathbf{O_{1,2}}$ operator has a component that could mimic a new physics effect in $\mathbf{C_9}$ through $c\bar{c}$ loop
- Effect can be parameterised as function of three helicity amplitudes $\mathbf{h_{+-0}}$
- Absorb effect of these amplitudes into a helicity dependent shift in $\mathbf{C_9}$,

  $\mathbf{C_9^{SM} + \Delta C_9^{+-0}(q^2)}$ cf. $\mathbf{C_9^{SM} + \Delta C_9^{NP}}$ ($!= \Delta C_9^{NP}(q^2)$)

  Look for $\mathbf{q^2}$ and helicity dependence of apparent shift in $\mathbf{C}_9$

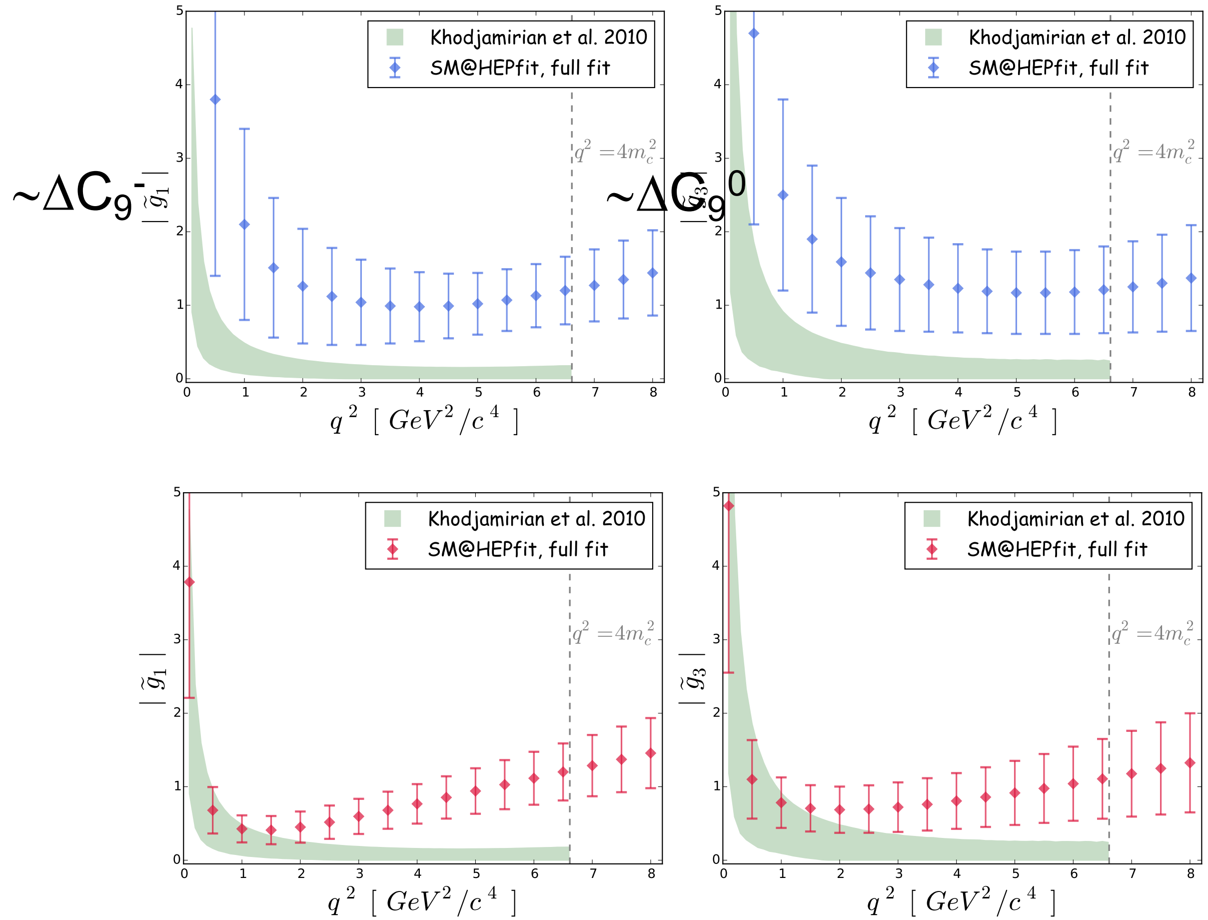


[arXiv:1510.04239]

Boxes are the 1σ errors

Charm loop contribution?

- Bayesian fit assuming polynomial form for $\mathbf{h_{+-0}}$ [arXiv:1512.07157]

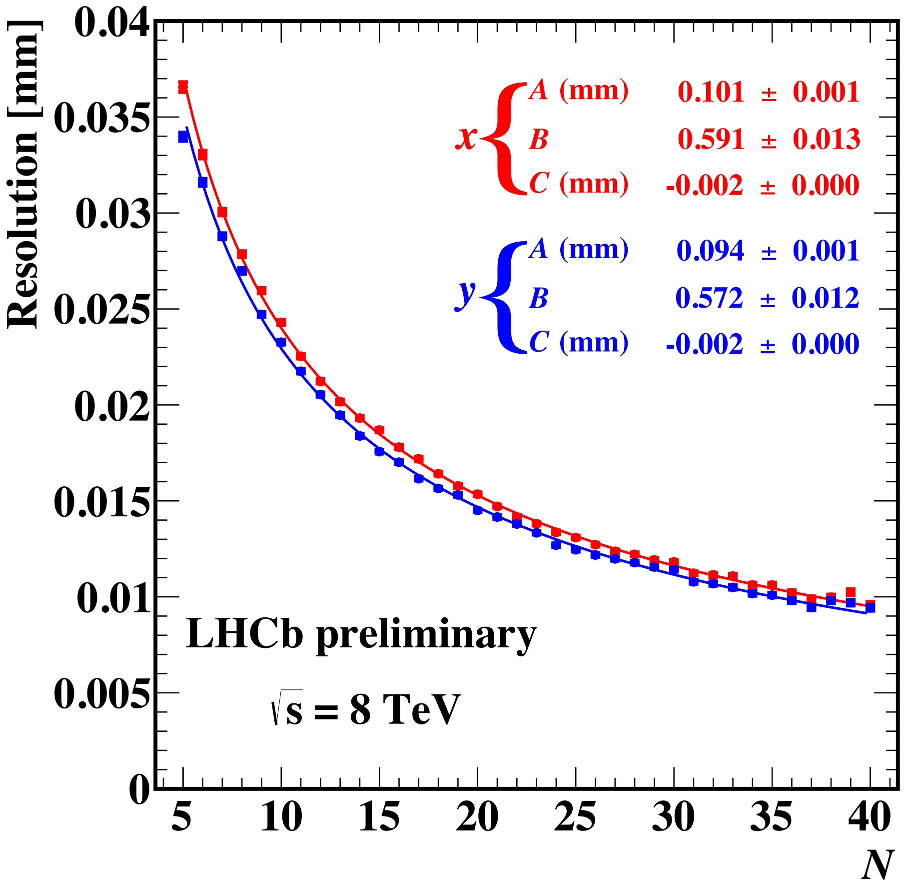


- Assumes small ΔC_9^x for small q^2 – true in SM, but not for NP

VELO

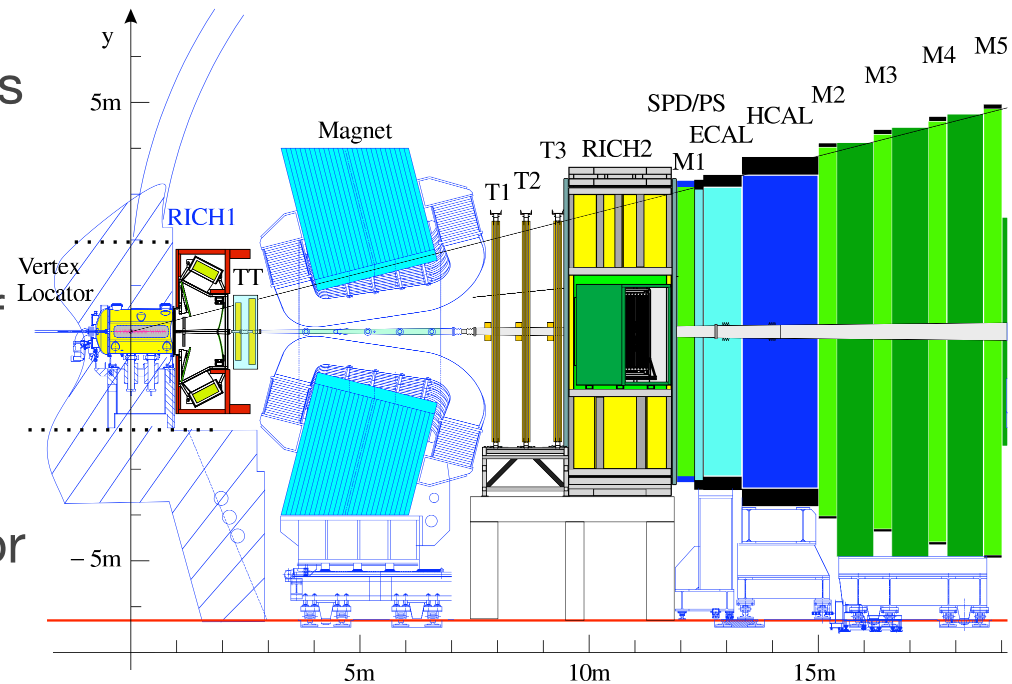
- The VELO gives LHCb the best vertex resolution at the LHC.
- This is crucial for our trigger, that selects B decays based on their characteristic detached vertices. LHCb is the only experiment at the LHC whose B trigger can efficiently select fully hadronic B decays.
- Also important time-dependent measurements (see later).

Vertex resolution (vs number of tracks)



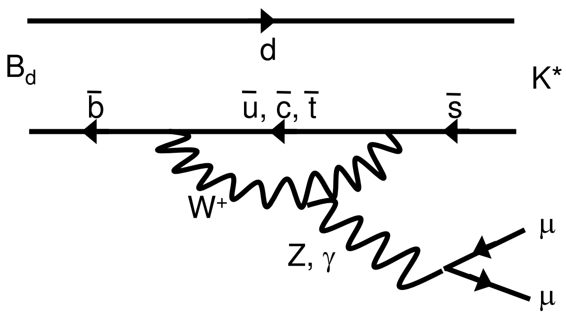
LHCb

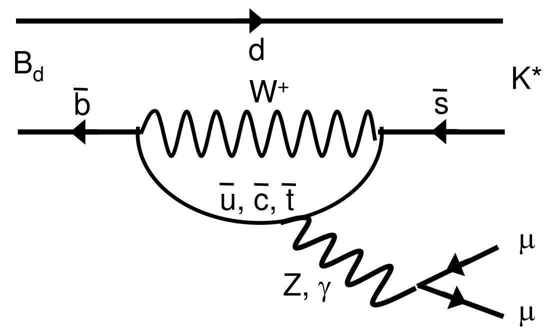
- ca 100,000 b-bbar pairs per second at 14 TeV. Produce all types of B-hadrons (B_d, B_s, $B^{\pm}$, B_c, Λ_b,...). Even more c-cbar pairs for charm physics.
- Special geometry to capture as many of them as possible.
- Vertex detector INSIDE the beampipe for extra precision
- Ring Imaging Cherenkov detector (RICH) that provides particle identification.
- Trigger on displaced vertices - captures all types of B decays.

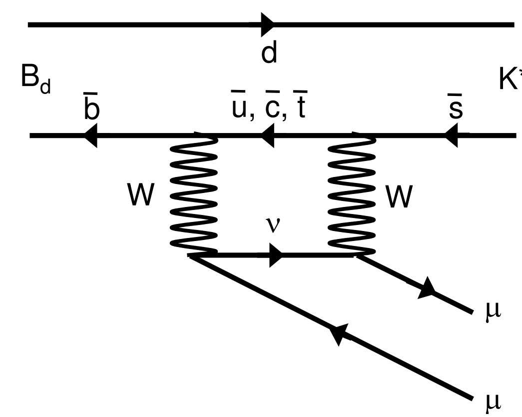


B→K*μ⁺μ⁻

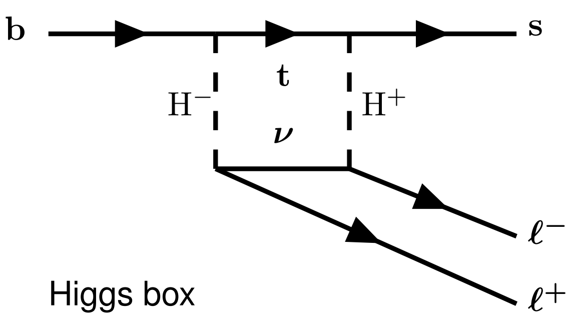
FCNC, rare in the SM (BR ~10^{-6})



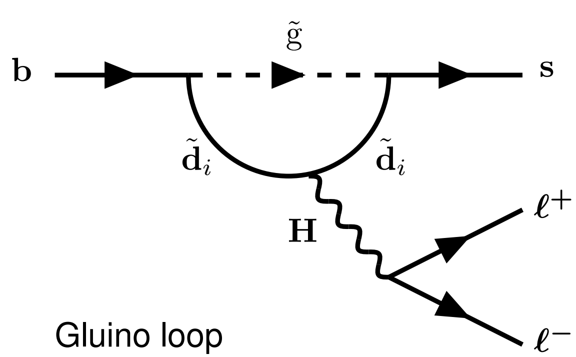




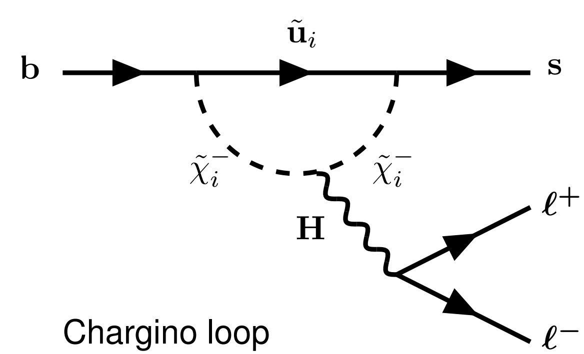
sensitive to New Physics in loops, e.g.



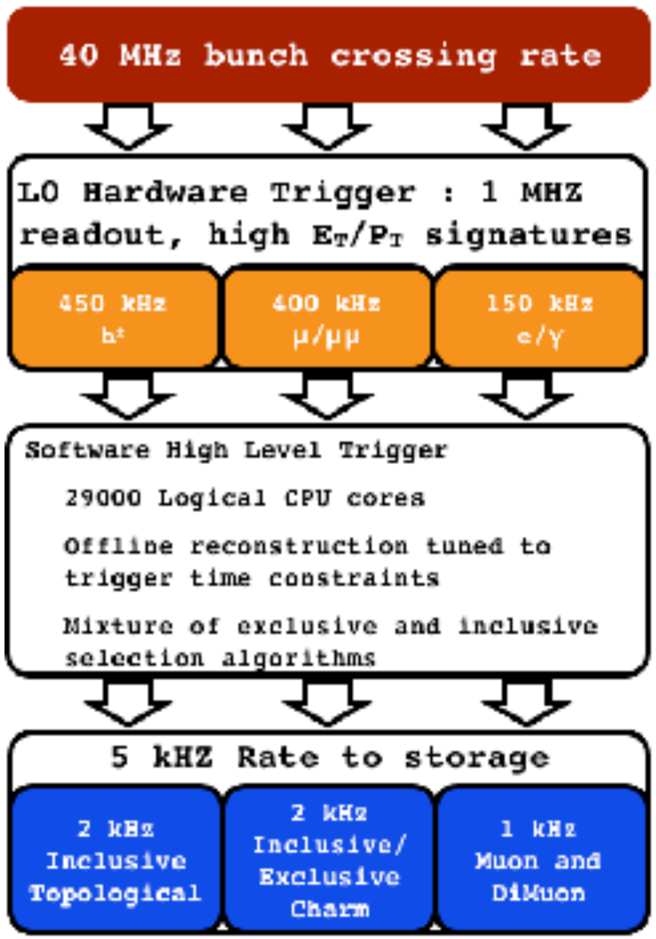
Higgs box

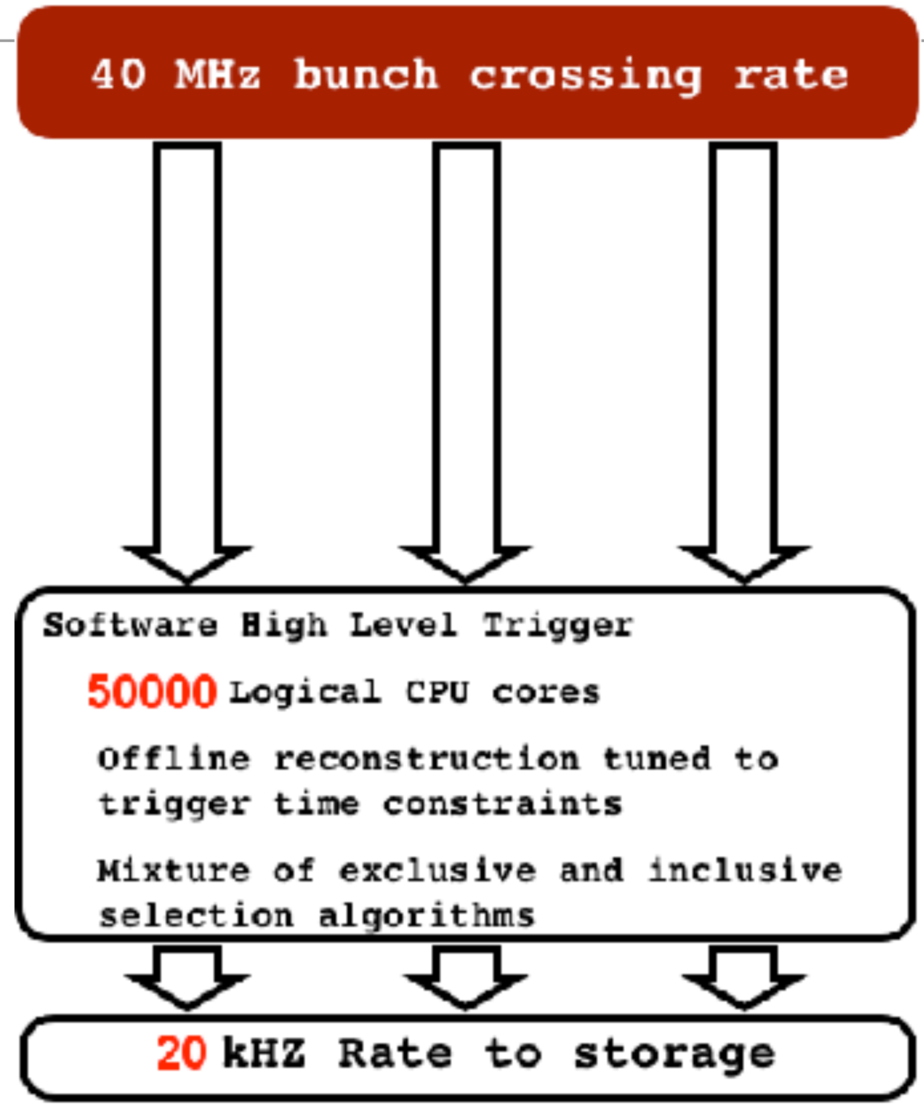


Gluino loop



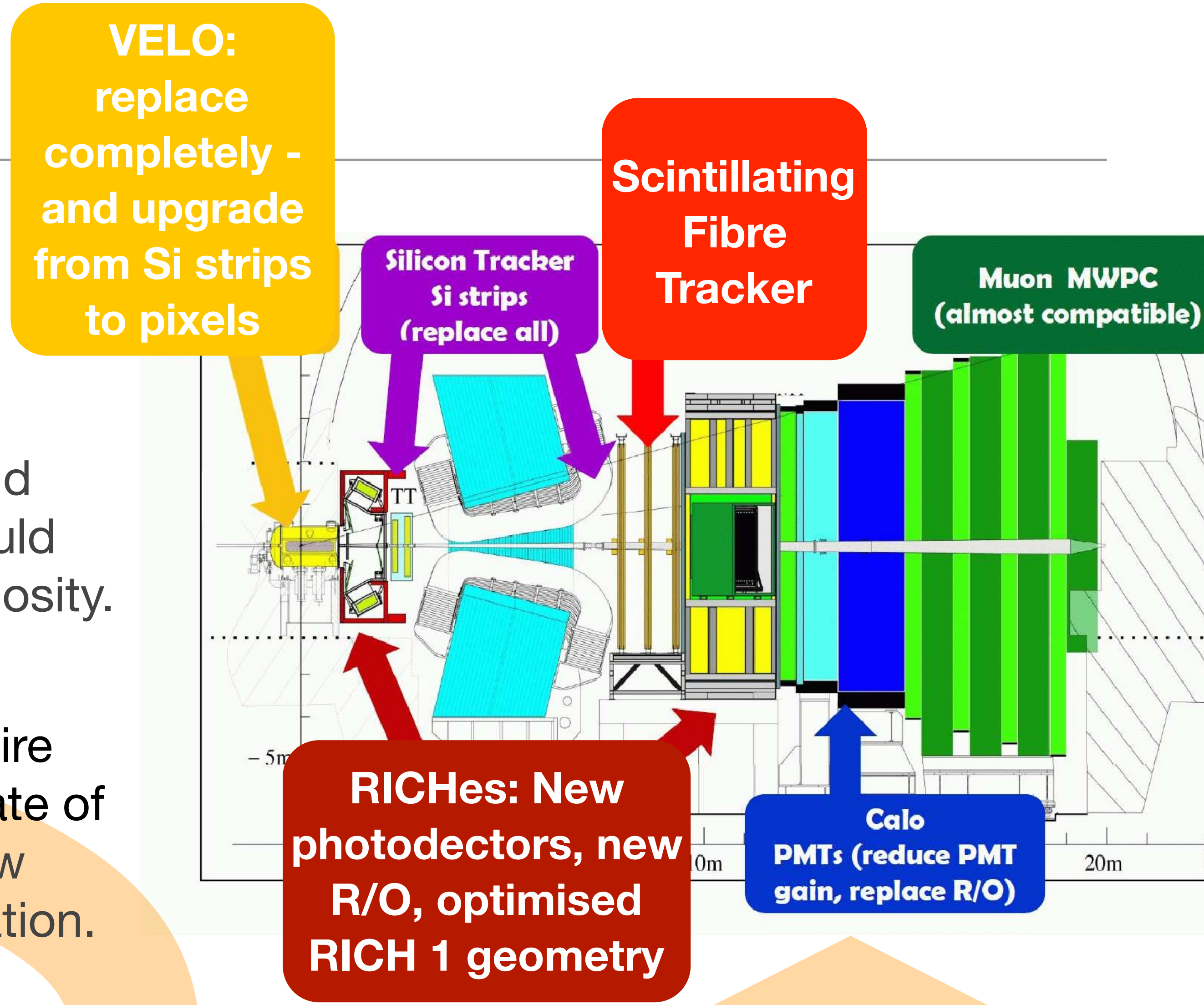
Chargino loop


40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures
450 kHz
h±
400 kHz
μ/μμ
150 kHz
e/γ
Software High Level Trigger
29000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
5 kHZ Rate to storage
2 kHz Inclusive Topological
2 kHz Inclusive/ Exclusive Charm
1 kHz Muon and DiMuon


40 MHz bunch crossing rate
Software High Level Trigger
50000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
20 kHZ Rate to storage

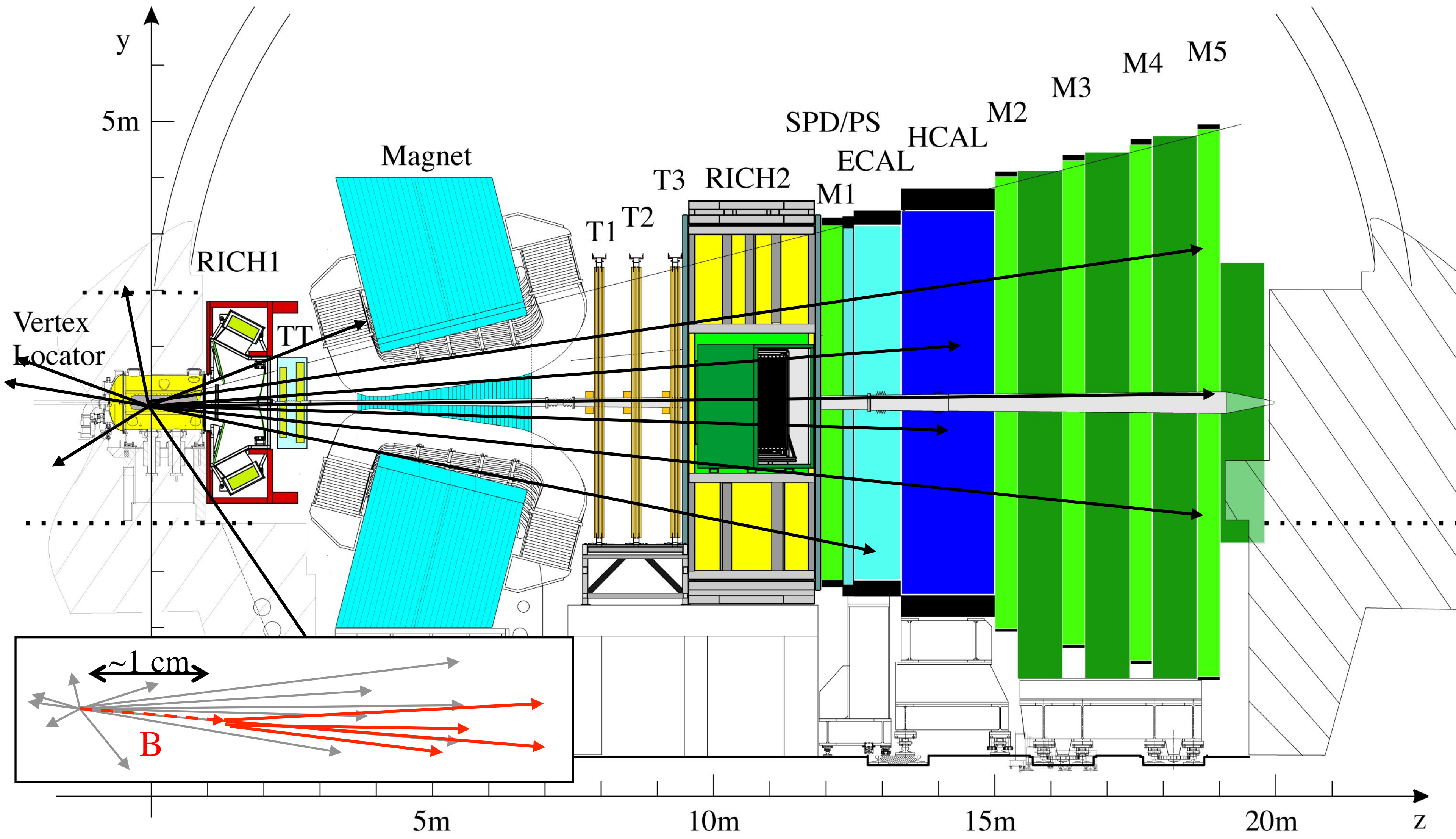
The LHCb upgrade

- Higher luminosity ⟹ higher precision ⟹ better NP reach.
- Trigger is at the heart of the upgrade. Current trigger would “choke”, the signal yields would not increase in line with luminosity.
- For upgrade, read out the entire detector at bunch-crossing rate of 40MHz, fully customisable s/w trigger, with full event information.
- Doubles the trigger efficiency for hadronic modes. Most flexible/ customisable trigger at the LHC.



Replace all electronics

The LHCb Detector



(not really rare, but I feel belongs here, anyway)

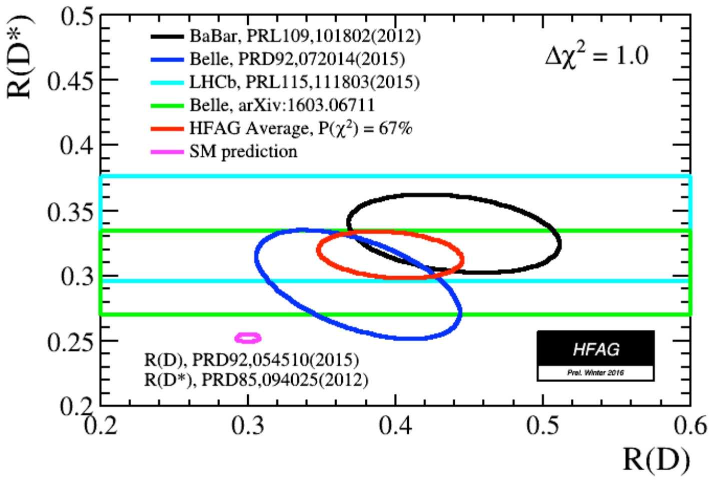
Lepton universality with tree decays

- An anomalous effect is seen in the ratio of **tree-level** branching fractions

  $R_D{}^* = B(B^0 \to D^{*+}\tau\nu)/B(B^0 \to D^{*+}\mu\nu)$

- At LHCb reconstruct the tauonic decay through $\tau \to \mu\nu\nu$, final state has three neutrinos!

- Confirms effect seen in R_D, R_{D^*} at BaBar/Belle, including latest Belle hadronic result from ICHEP combined significance now 4σ



- LHCb measurement of (R_D, R_{D^*}) in preparation. Also working on hadronic τ decay. Will also perform measurements with other b-hadrons e.g. B_s, B_c and Λ_b

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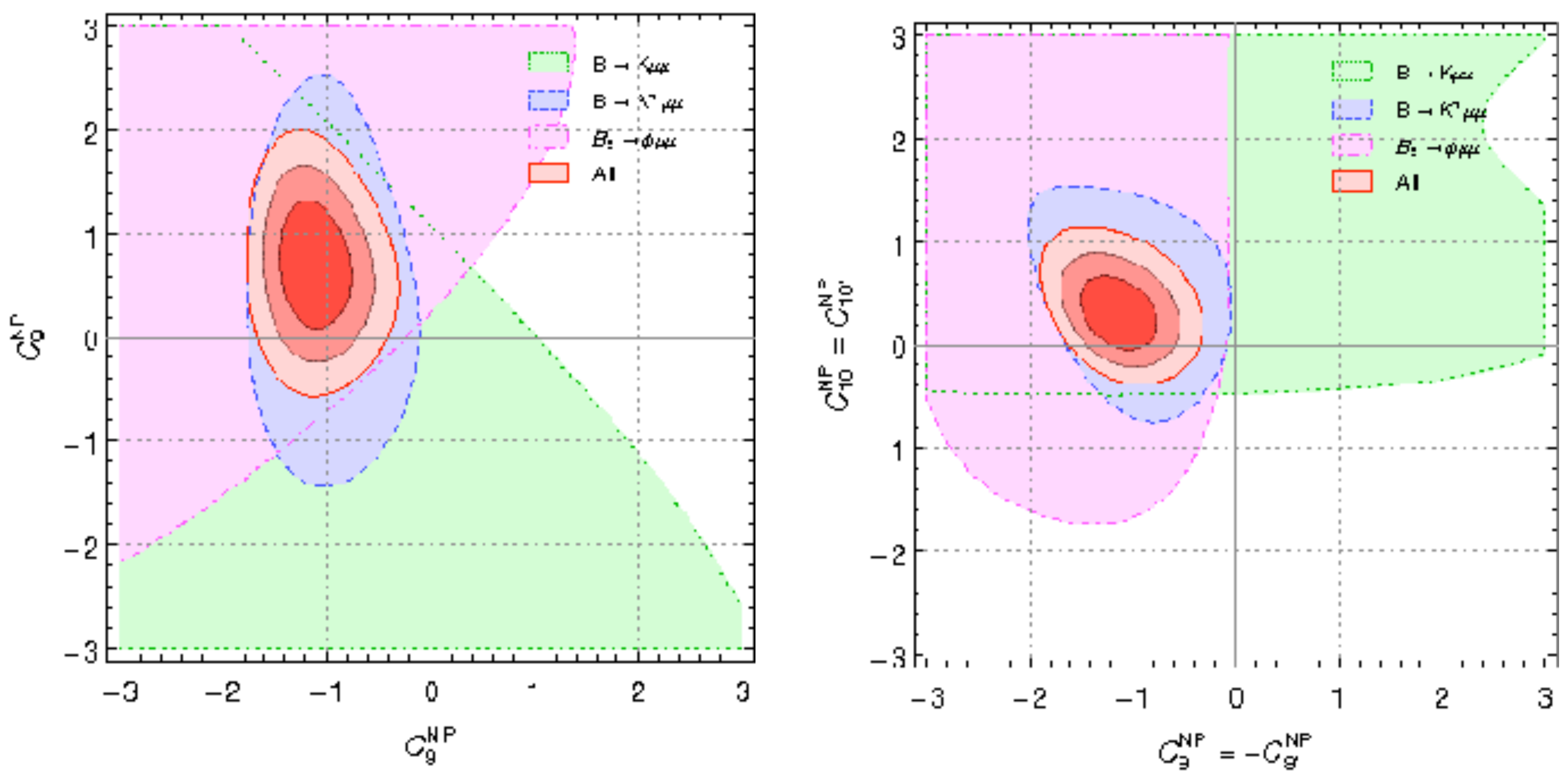
Interpretation of B→K*μ⁺μ⁻ et al.

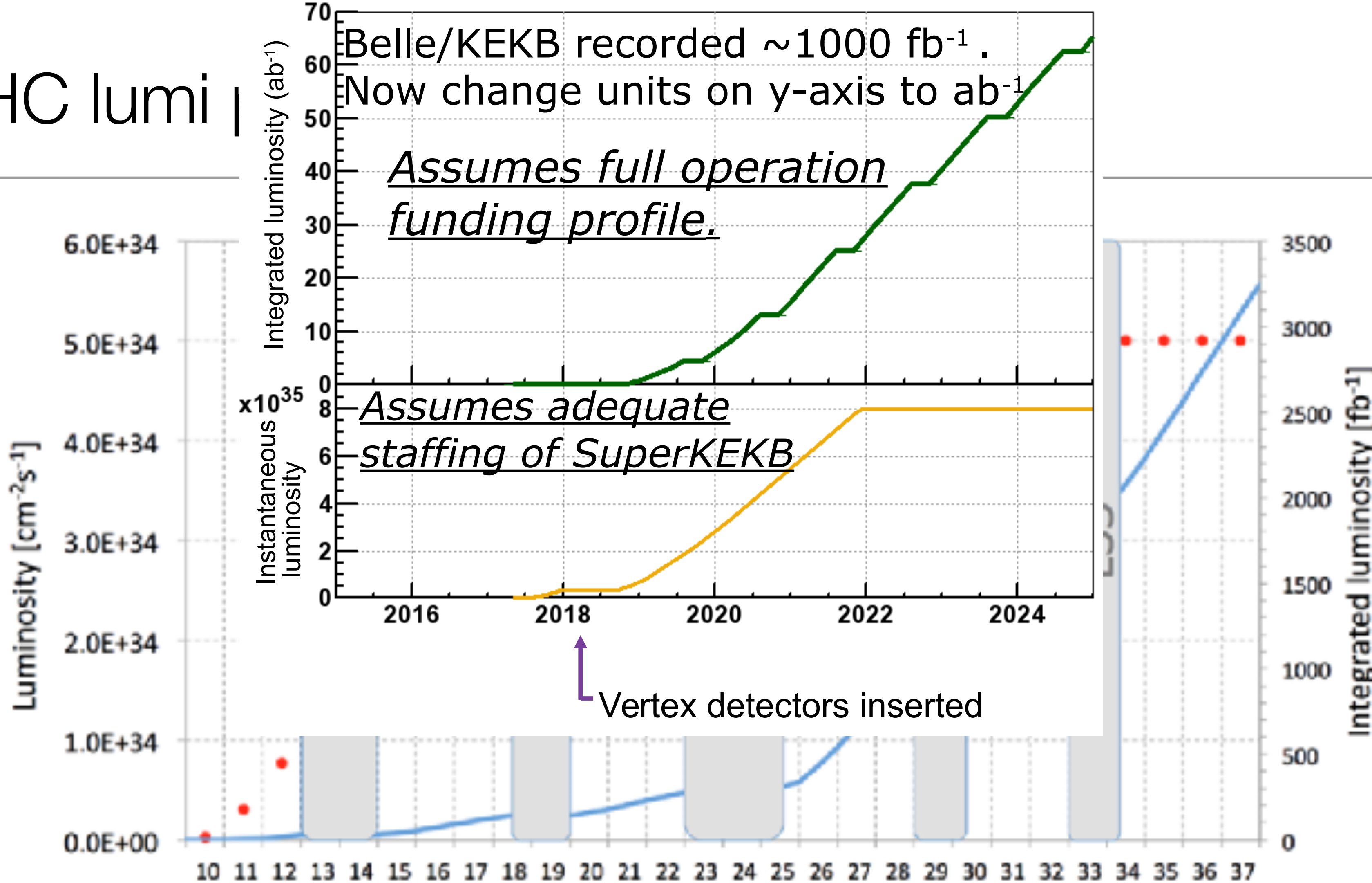
JHEP 1606 (2016) 092



>4σ deviation from SM

(or is it just 4σ from our ability to calculate QCD effects?)

LHC lumi p

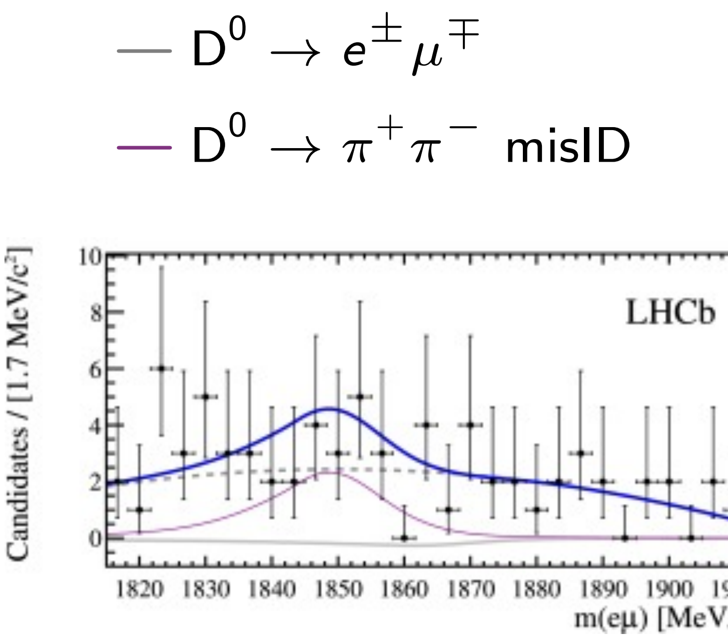


	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
LHCb	3 fb^{-1}	8 fb^{-1}	⟶	50 fb^{-1}	*300 fb^{-1}

Mode	$8\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$D^0 \to \mu^+\mu^-$	fewer 10^{-9}	few 10^{-10}	fewer 10^{-10}
$D^0 \to e^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	fewer 10^{-8}	few 10^{-9}	fewer 10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	fewer 10^{-7}	few 10^{-8}	fewer 10^{-8}
$D^0 \to hh\mu^+\mu^-$	fewer 10^{-7}	few 10^{-8}	fewer 10^{-8}

LHCb PLB 754 (2016) 167

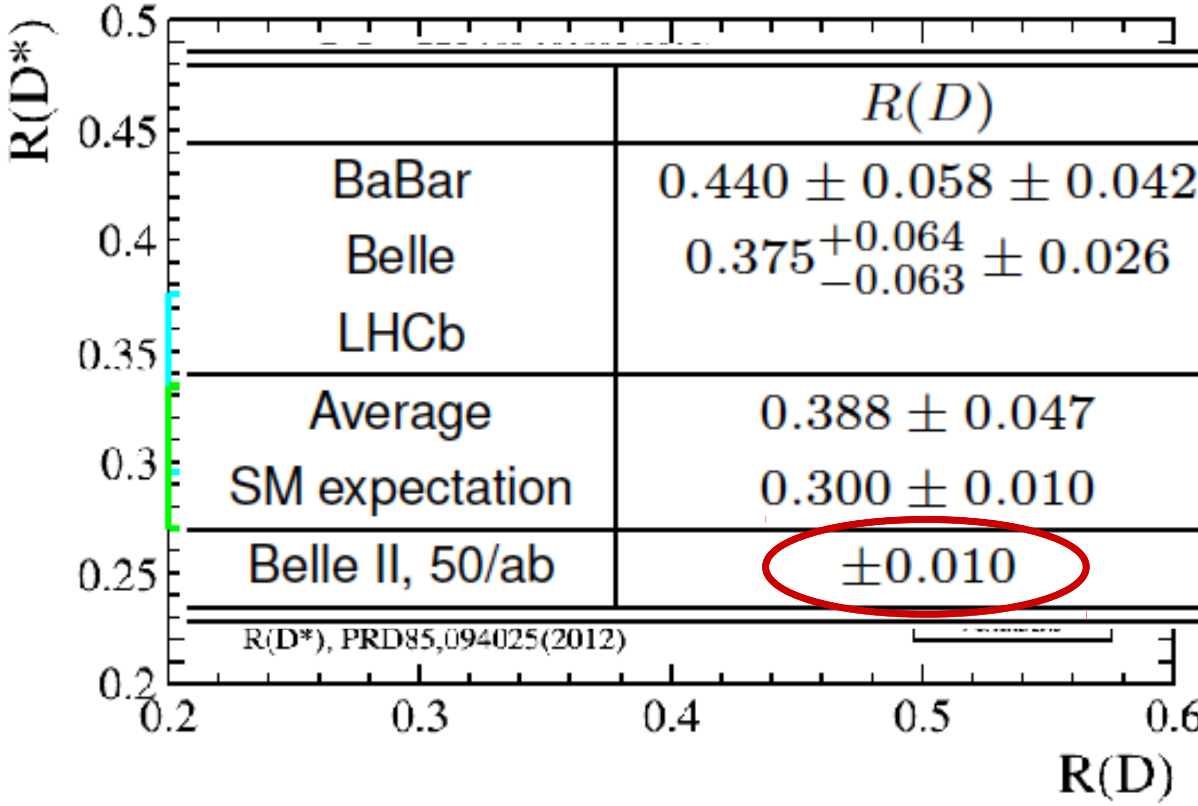
- Large LFV expected in numerous NP models (SUSY, Extra Dimension, Little Higgs)
- Previous result Belle [PRD 81, 091102(R) (2010)]
  $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 2.6 \times 10^{-7}$ at 90% CL
- LHCb with $3\,fb^{-1}$,
  $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8}$ at 90% CL



Lepton (non?) Universality - R(D*) and R_K

PRL 115 (2015) no.11, 111803

PRL 113 (2014) 151601



	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005

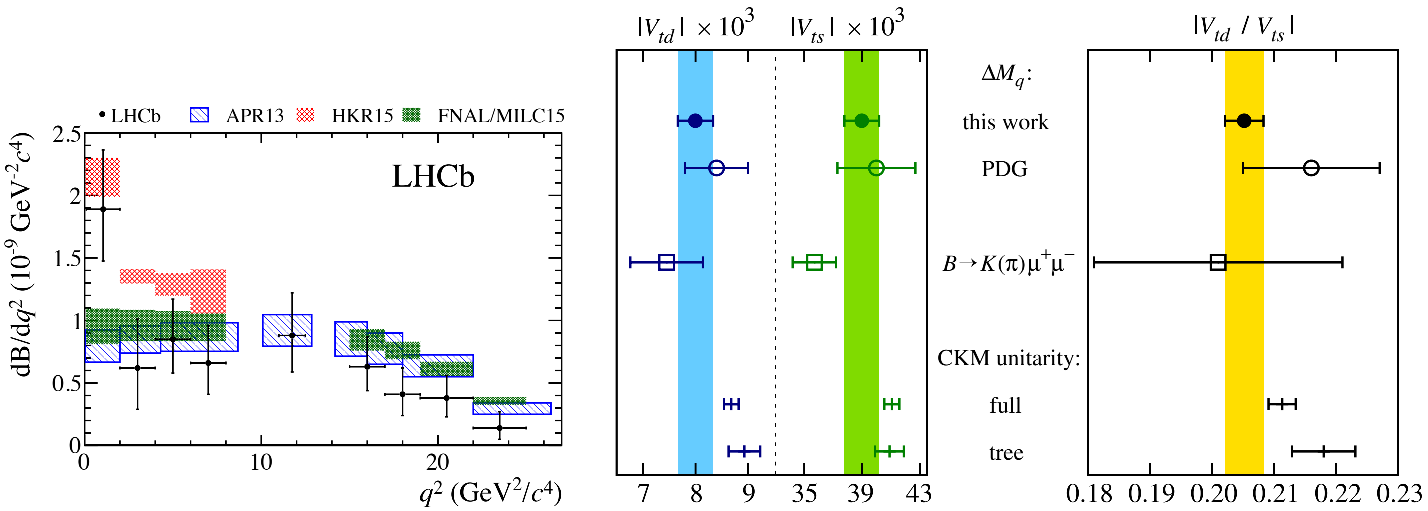
3.9 sigma (HFAG)

For R(D*) SM prediction see PRD85 (2012) 094025

$B^+ \to \pi^+\mu^+\mu^-$ differential branching fraction

- Very relevant if tensions persist $\to$ test MFV nature of new physics
- Latest lattice results enable further precision tests of CKM paradigm
  Buras,Blanke[1602.04020], FNAL/MILC[1602.03560]
- Current measurement from penguin decays of $|V_{td}/V_{ts}| = 0.201 \pm 0.020$
  FNAL/MILC[PRD93,034005(2016)]

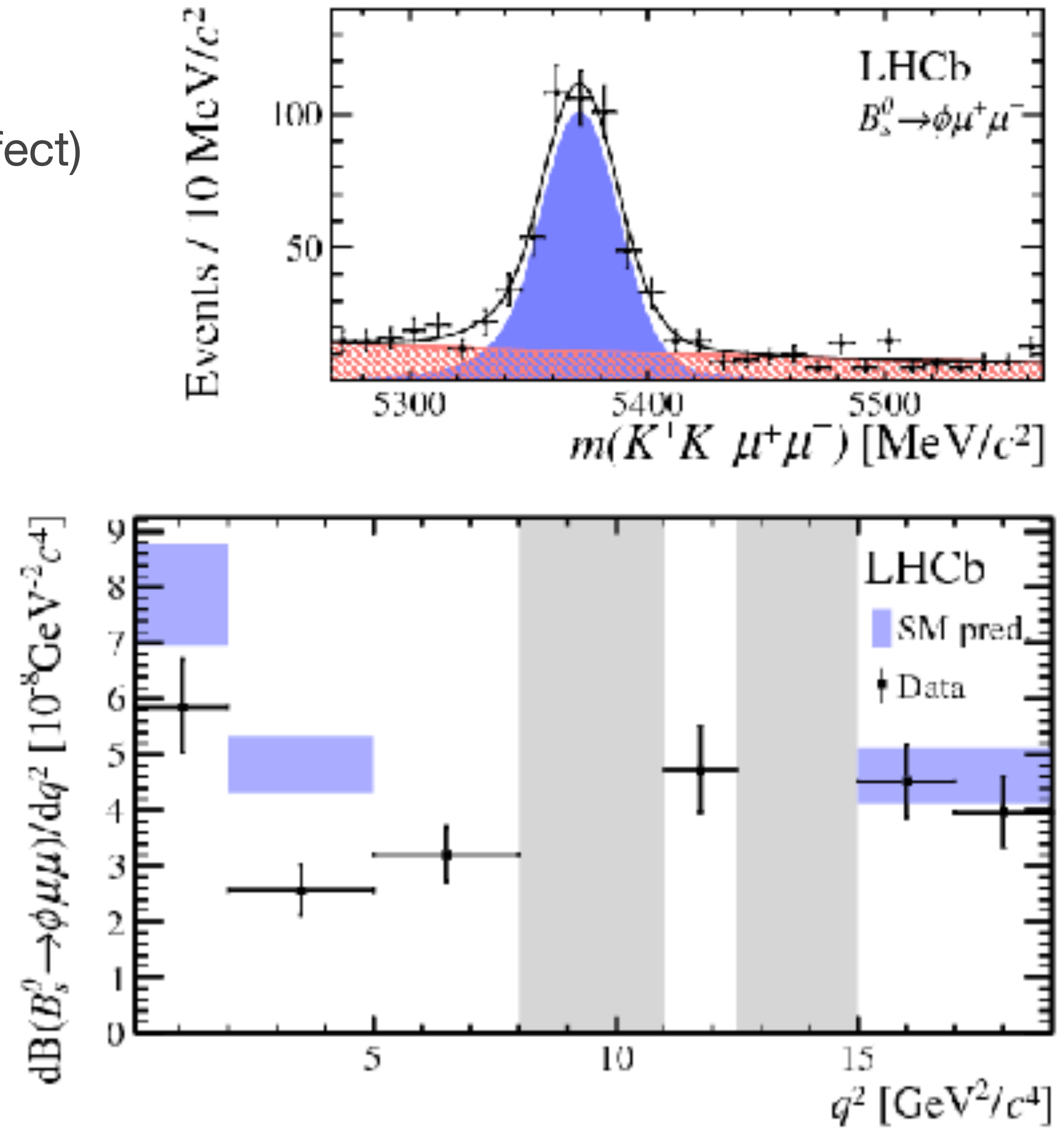
LHCb [JHEP10(2015)034] FNAL/MILC[1602.03560], FNAL/MILC[PRD93,034005(2016)]



B→ϕμ⁺μ⁻:

JHEP 1509 (2015) 179

- 3.4 σ local significance.
  (But don't forget the look-elsewhere effect)



B→φμ⁺μ⁻:

JHEP 1509 (2015) 179

- 3.4 σ local significance.
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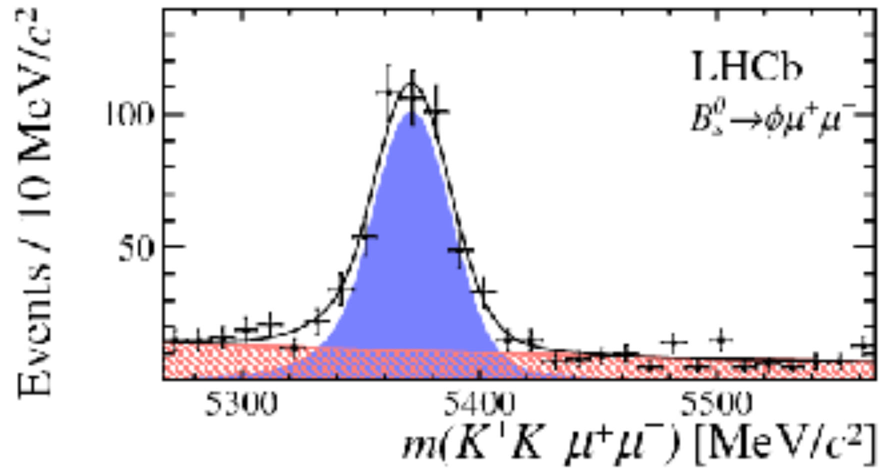

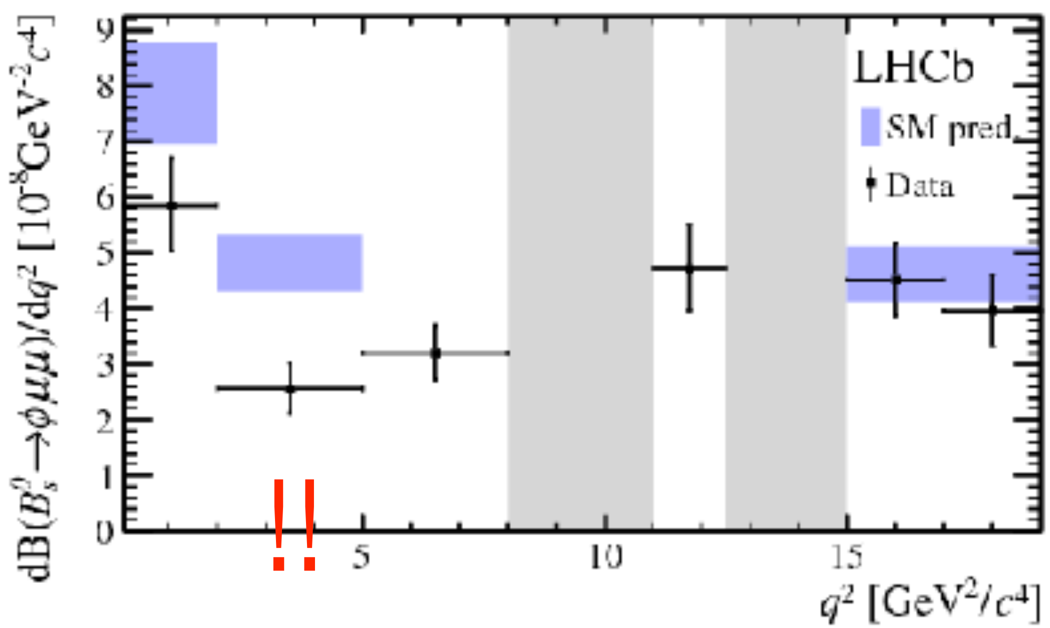

$B_{(s)} \to \mu\mu$ prospects

LHCb prospects for B decays calculated assuming

- same efficiency and signal-to-background ratio
- $\sigma_{b\bar{b}}(14\,\text{TeV}) \approx 2\sigma_{b\bar{b}}(7\,\text{TeV})$
- LHCb upgrade collects $50\,\text{fb}^{-1}$ and $300\,\text{fb}^{-1}$ at LHC-HL
- CMS collects $3\,\text{ab}^{-1}$
- Systematics: 5% f_s/f_d, 3% $B^+ \to J/\psi K^+$ (normalisation channel)

	$\sigma\left(\mathcal{B}(B_s^0 \to \mu^+\mu^-)\right)$	$\sigma\left(\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)}\right)$	
LHCb Run I	1×10^{-9}	80%	[Nature 522 (2015) 68]
LHCb $8\,\text{fb}^{-1}$	0.49×10^{-9}	39%	
LHCb $50\,\text{fb}^{-1}$	0.25×10^{-9}	16%	
LHCb $300\,\text{fb}^{-1}$	0.19×10^{-9}	8%	
CMS $3\,\text{ab}^{-1}$ (barrel)	$^{1}0.3 \times 10^{-9}$	21%	[CMS-PAS-FTR-14-015]
Theory	0.3×10^{-9}	5%	[PRL 112, 101801 (2014)]

B->K*ee

Particularly sensitive to photon polarisation, esp at low q^2.

LHCb for $q^2 \in [0.0004, 1] GeV^2$