HINTS FOR NEW PHENOMENA IN RARE AND FORBIDDEN DECAYS

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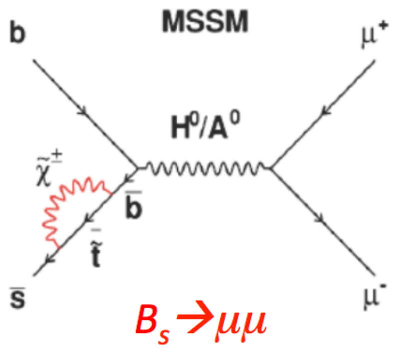
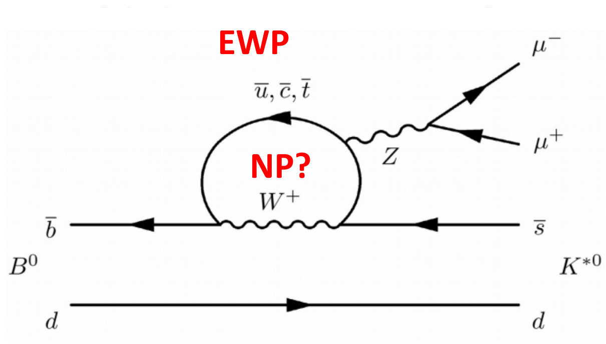
(LPNHE-CNRS/IN2P3)
on behalf of the LHCb collaboration
(with close results from ATLAS, CMS and B-factories)

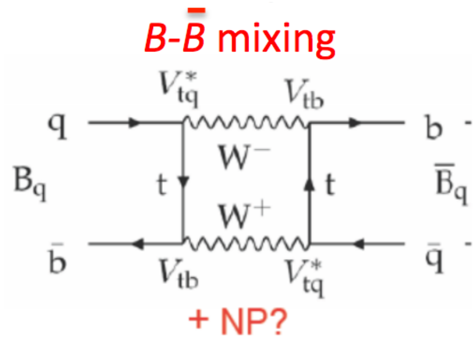
IPA: Interplay between Particle and Astrophysics
LAL Orsay, 5-9 September 2016

INDIRECT SEARCHES FOR NEW PHYSICS

- Indirect effects of new physics can be searched for measuring low energy processes like b-hadron decays.







- New particles in the loop or tree level processes could enhance/suppress decay rates, introduce new sources of CP violation, modify angular distributions.

- Particles in loops are virtual, so mass scales even higher than the current collider energies can be probed (complementary approach).

- Experimental measurements of decays for which precise theoretical predictions exists are performed in order to validate or infirm the SM.

- The pattern of deviations can guide towards NP.

THE POWER OF RARE AND FORBIDDEN DECAYS

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- **Rare hadron decays** are powerful probe of New Physics:

  - they mainly proceed via loop diagrams only;
  - they are suppressed in the SM, so more sensitive to NP;
  - there is a rich phenomenology, and many precise SM predictions.

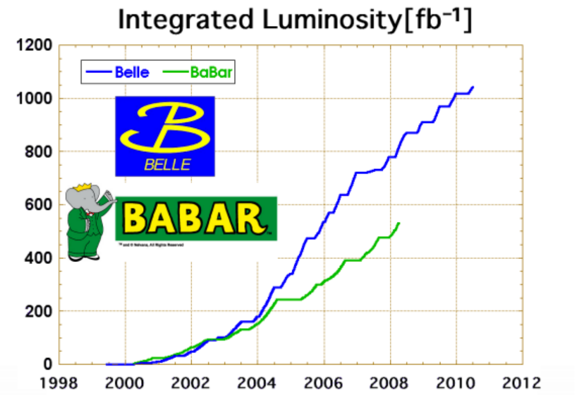
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

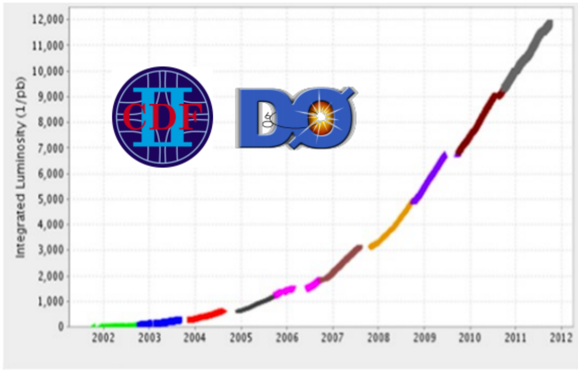
i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

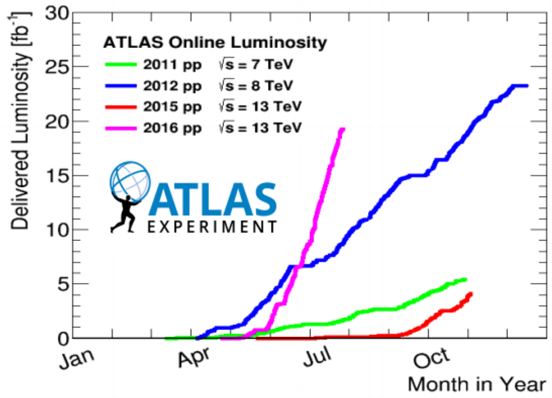
Operators Oi: non-perturbative long-distance effects
Wilson coefficients Ci: perturbative short-distance effects

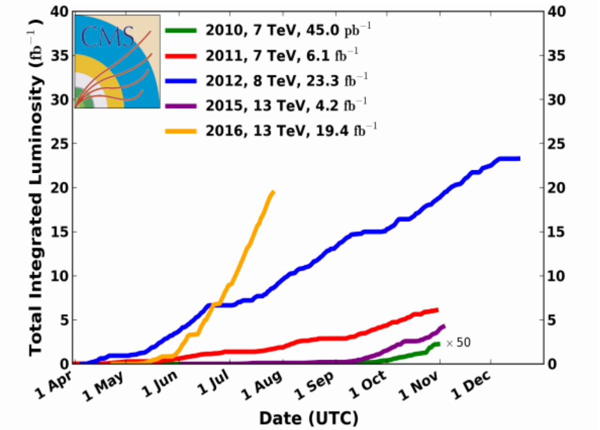
- **Forbidden decays** provides null tests of the SM (LFV, LNV processes).

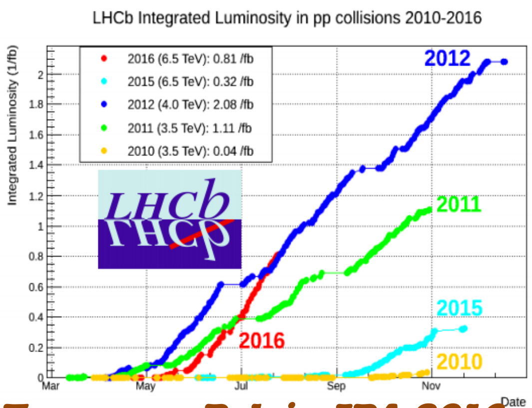
A LOT OF LUMINOSITY COLLECTED…











Lots of events need to be collected to study rare processes:

intensity frontier!

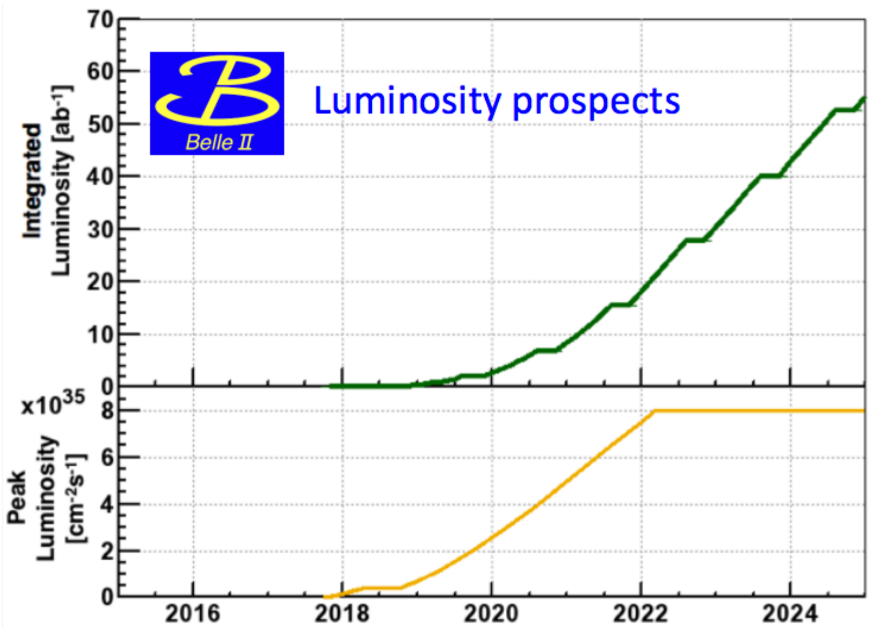
Experiment	$\int\mathcal{L}\,dt$ [fb^{-1}]	σ_{beauty} [μb]	End of life
BaBar	530 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2008
Belle	1040 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2010
CDF/D0	12 (total)	100 [$p\bar{p}$ at 2 TeV]	2011
ATLAS/CMS	55 (so far)	250-500 [pp at 7-13 TeV]	> 2030
LHCb*	4.2 (so far)	250-500 [pp at 7-13 TeV]	> 2030

* Forward detector optimised for beauty and charm physics with levelled luminosity to limit pileup effects

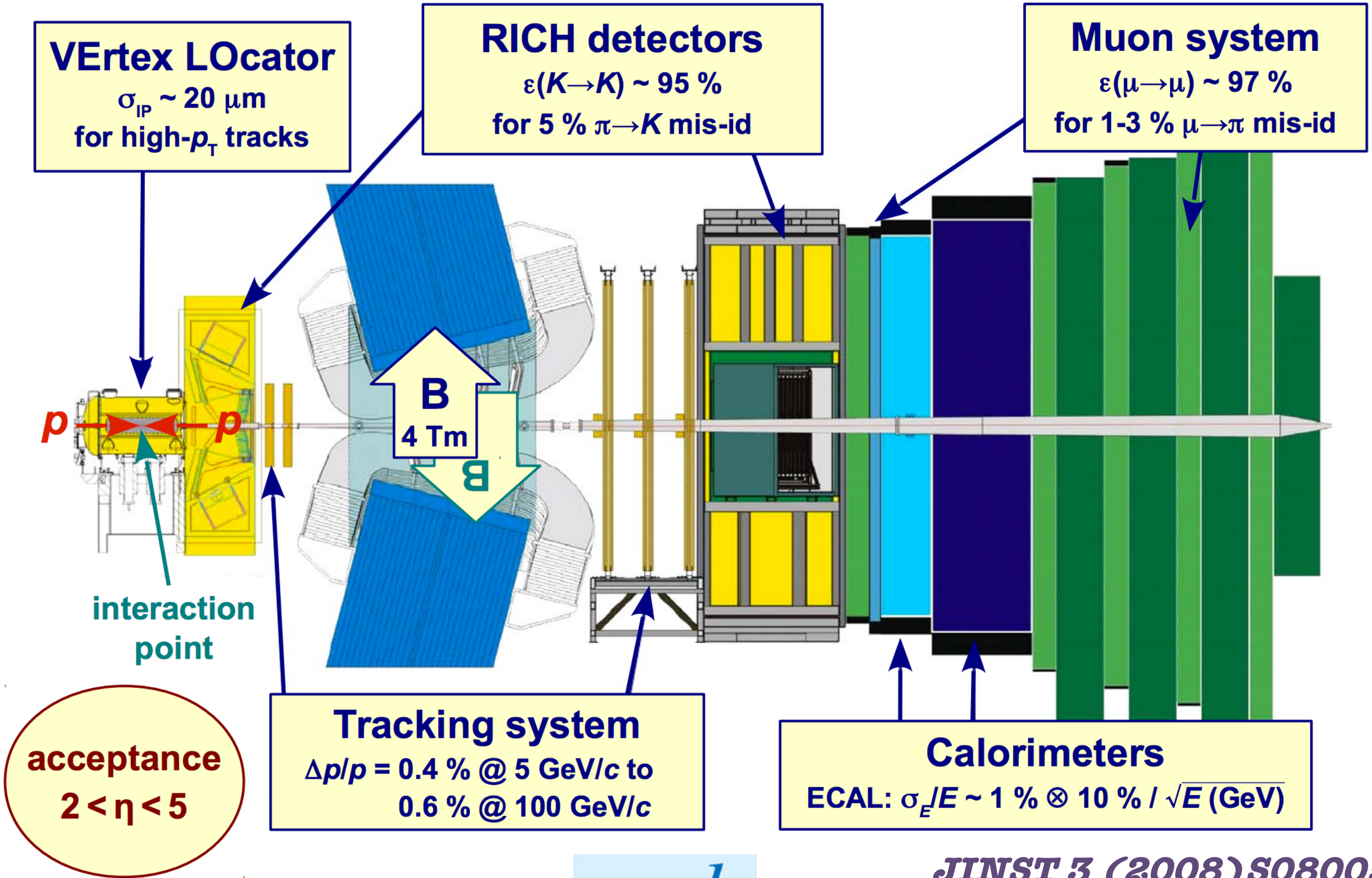
...AND MORE LUMINOSITY TO COME!

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2x10^{34}$ $cm^{-2}s^{-1}$



A FLAVOUR PHYSICS DETECTOR: LHCb

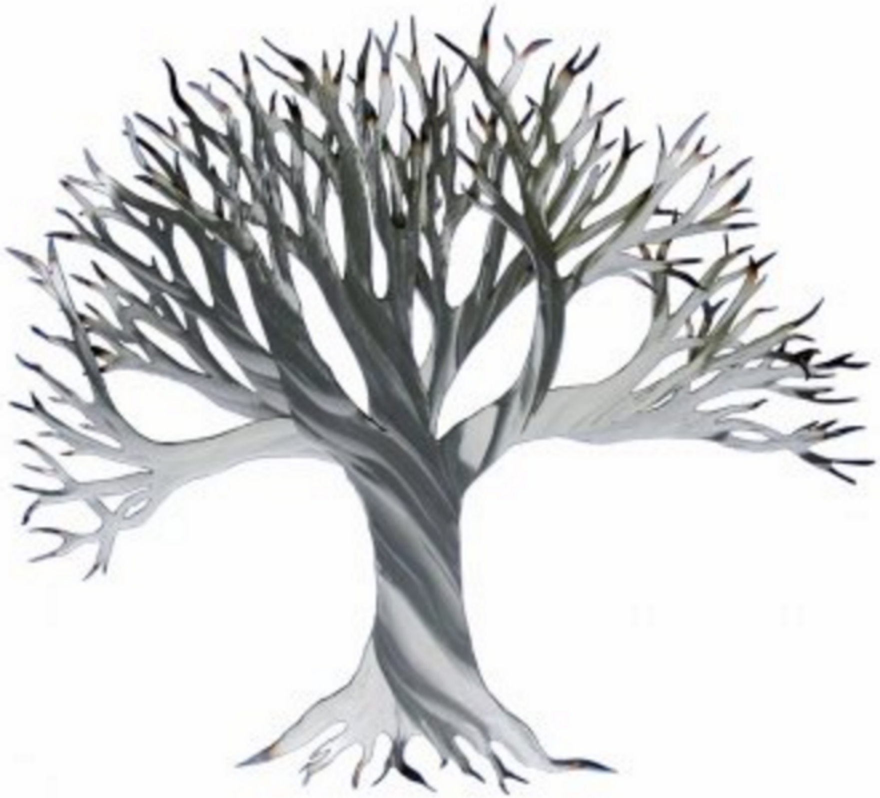


JINST 3 (2008) S08005

OUTLINE OF THE TALK

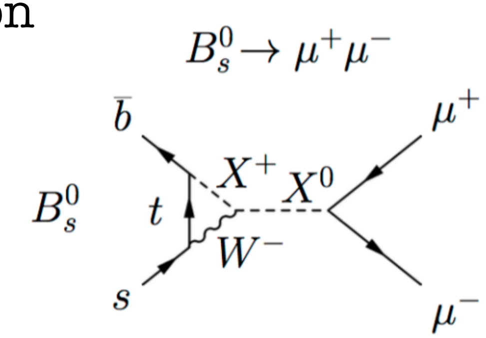
- ***BRANCHING FRACTIONS MEASUREMENTS***
- ***ANGULAR ANALYSES***
- ***LEPTON FLAVOR UNIVERSALITY TESTS***
- ***CHARGED LEPTON FLAVOR VIOLATING SEARCHES***

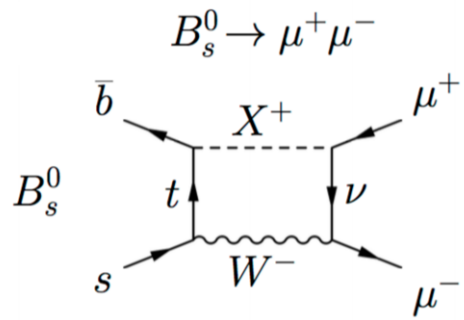
BRANCHING FRACTIONS



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

- $B_{(s,d)}$->$\mu\mu$ is a FCNC b->$s(d)$ transition
- Proceeds through loop diagrams
- Additionally helicity suppressed in the SM
- Sensitive to models with extended Higgs sector and large tanβ

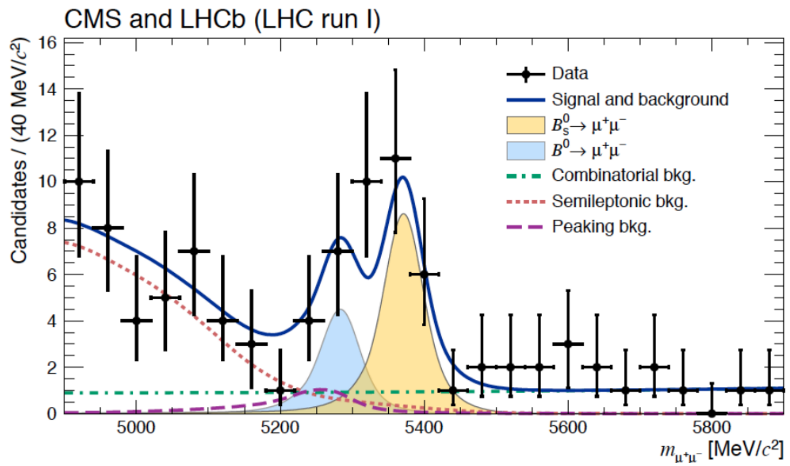




- The combined Run1 datasets from CMS and LHCb yields to the first observation of B_s->$\mu\mu$ with 6.2σ significance

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

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



- Results are compatible with the SM at 1.2σ

Nature 522 (2015) 68

- For B_d->$\mu\mu$ there is an excess at 3σ, compatible with the SM at 2.2σ.

$B_s \rightarrow \mu\mu$: ATLAS ENTERS THE GAME

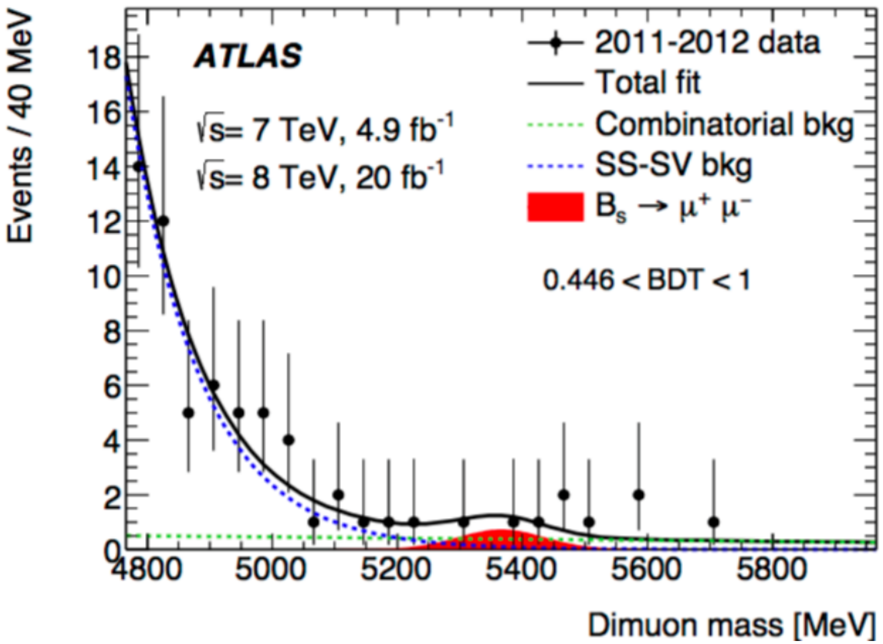
Recently ATLAS published their searches with Run1 dataset:

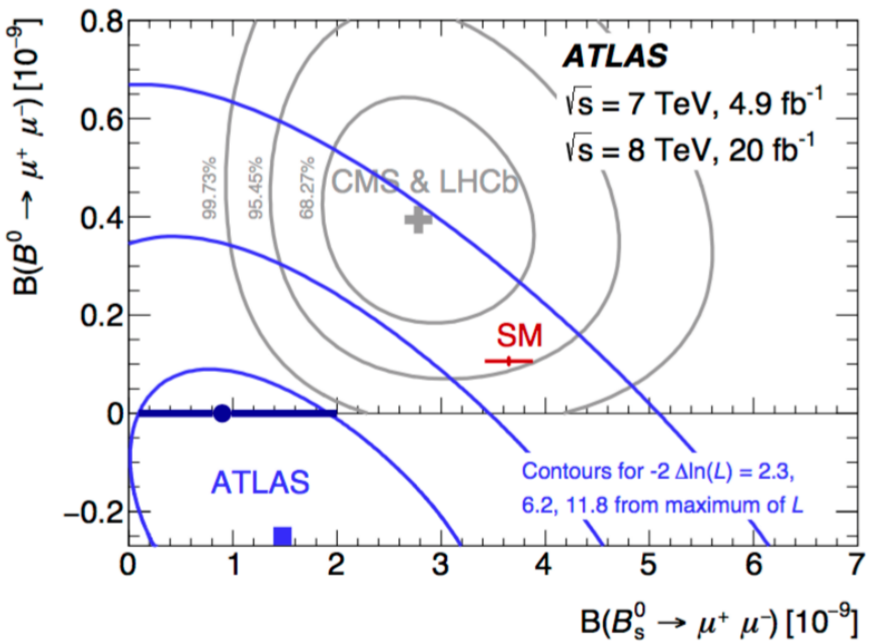
- No significant signal
- Uncertainty at the level of the CMS and LHCb
- Limit compatible with the SM with a *p-value* of 4.8%

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

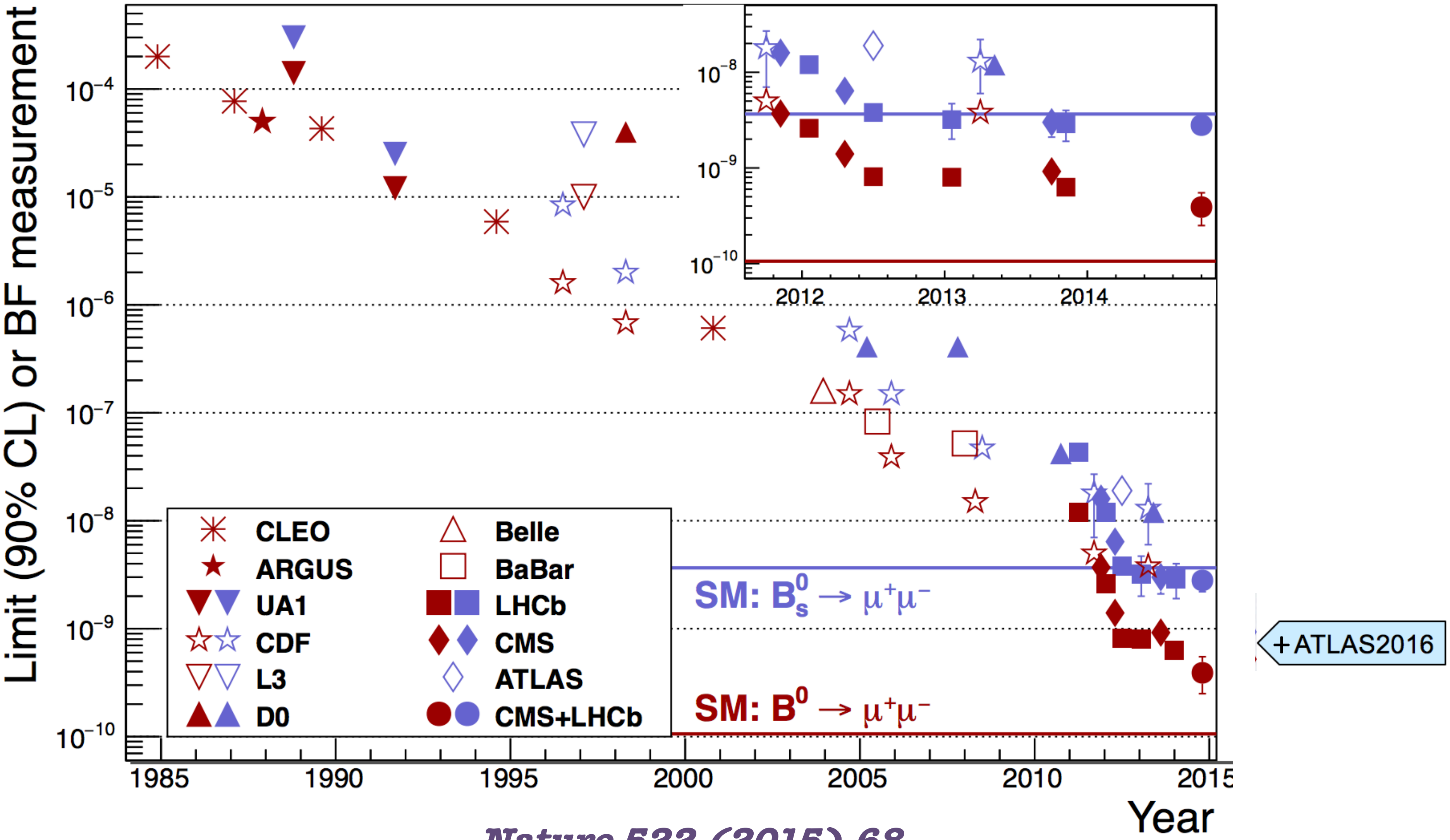
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95\% CL)}$$

arXiv:1604.04263





A 30 YEARS SEARCH....



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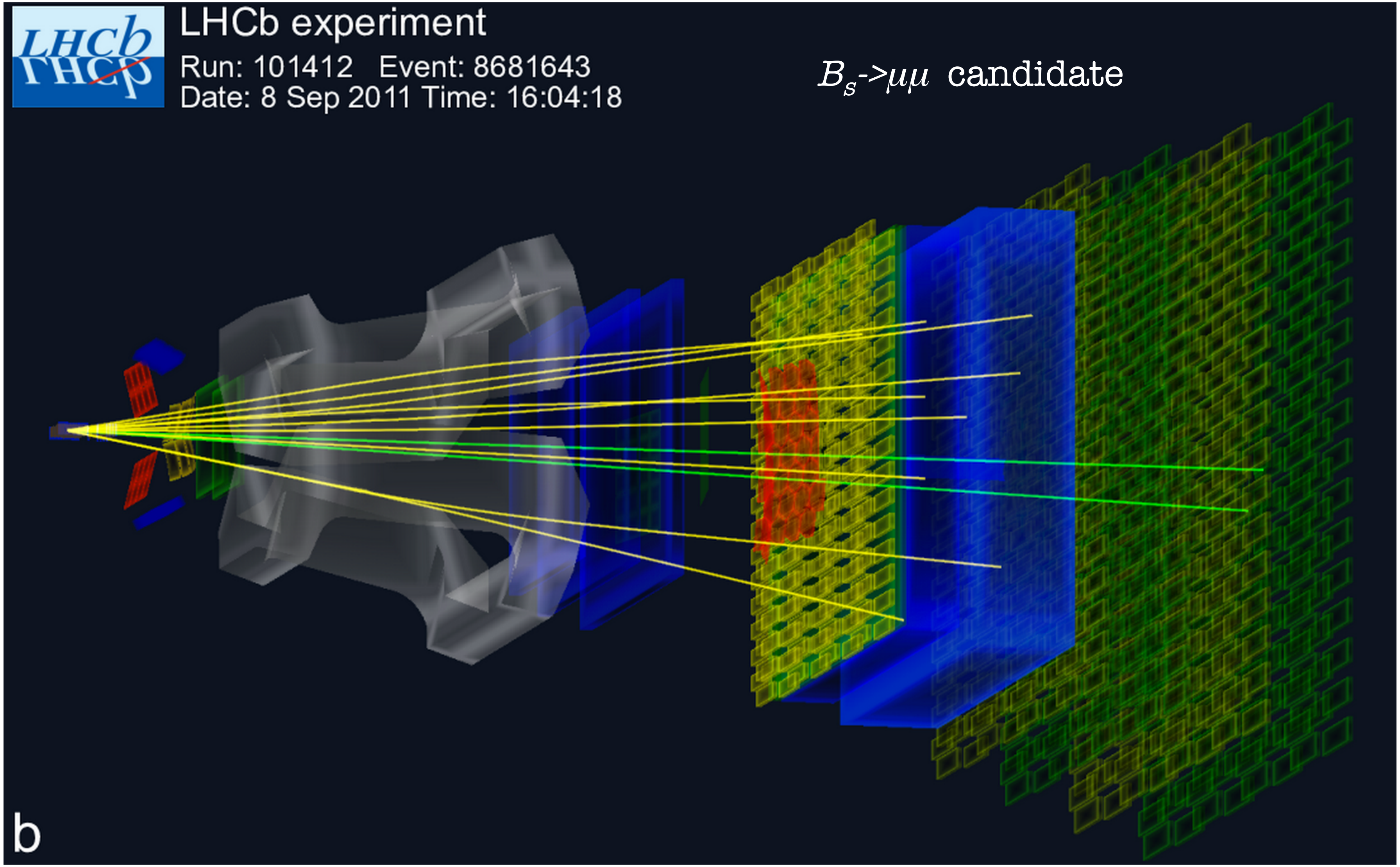
...AND WE FINALLY SEE IT!



b->sll BRANCHING FRACTIONS

- Measured *BR* are consistently lower than the SM predictions, despite large error from the form factors
- Theory uncertainties are correlated across the q^2

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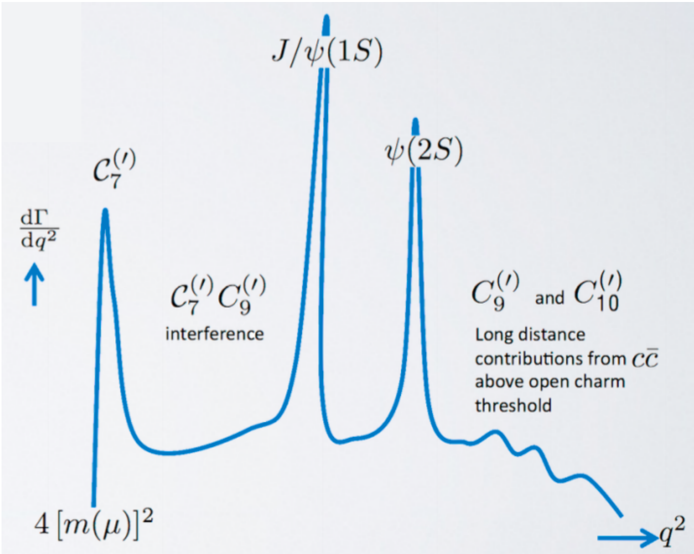
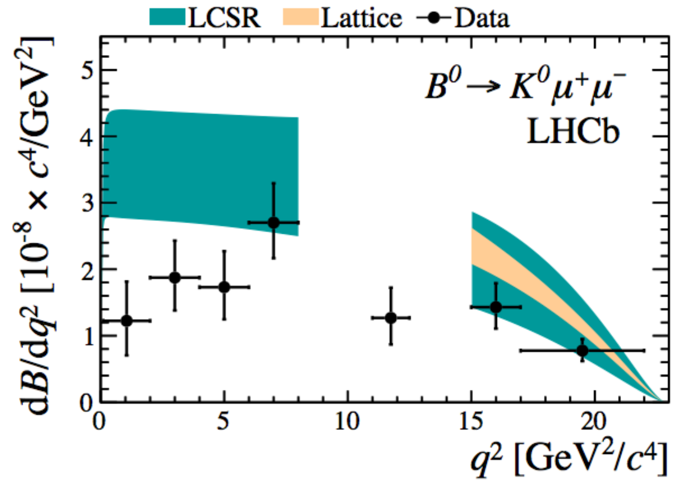
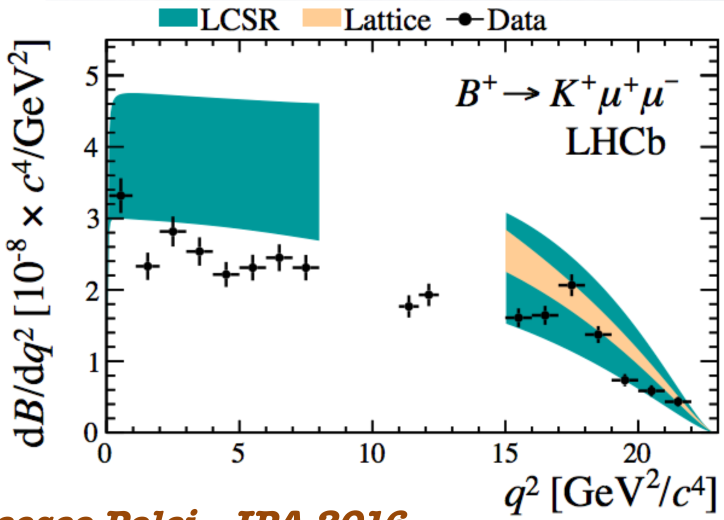
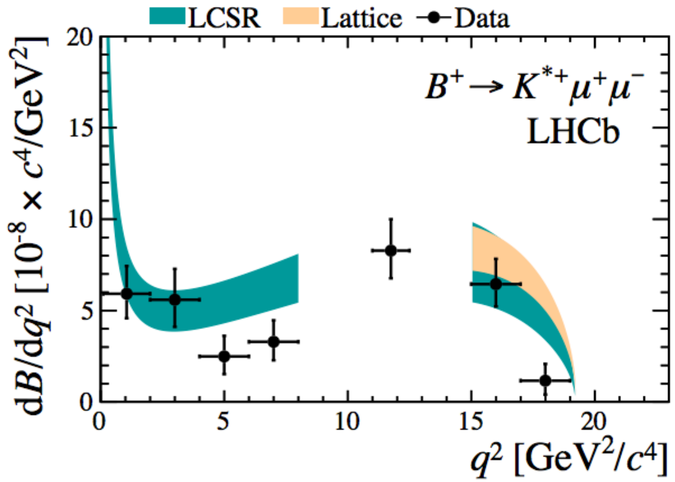


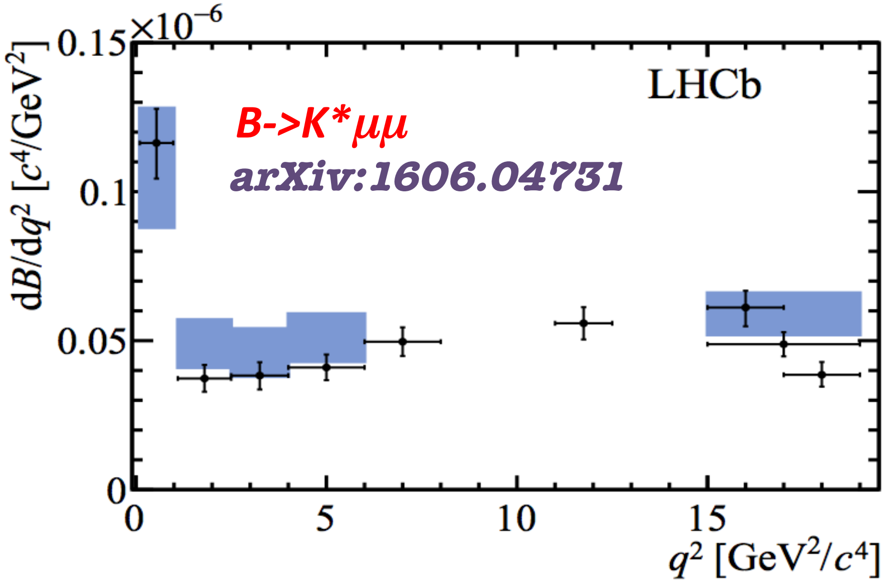


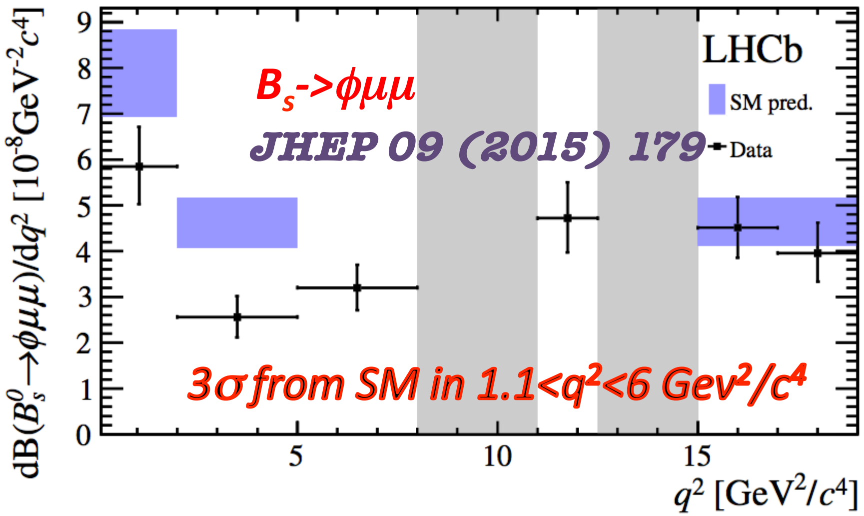


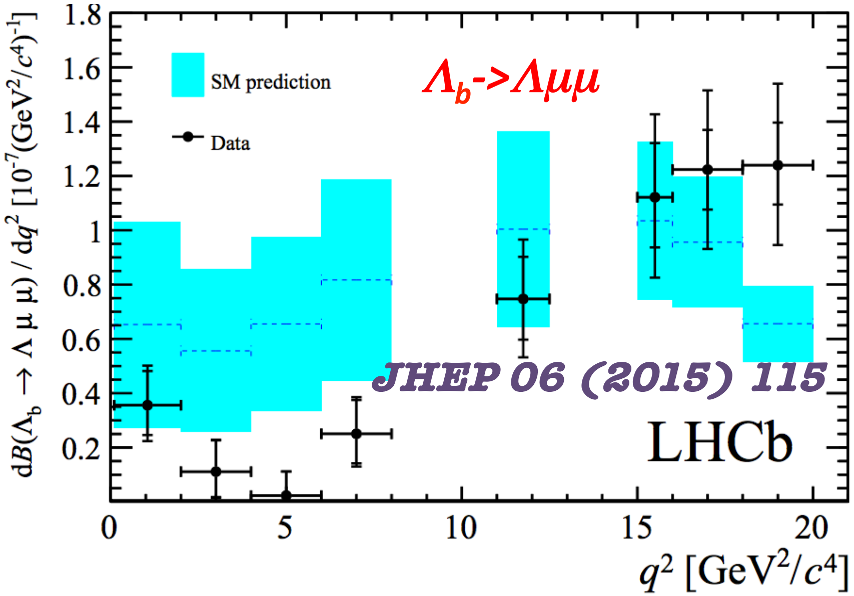


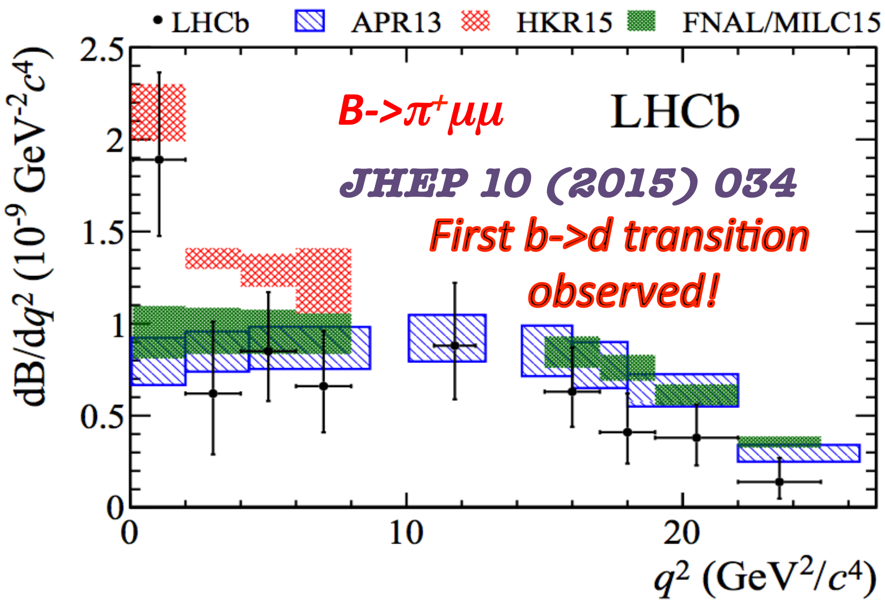
LCSR: Bobeth et al [JHEP07(2011)067]
Lattice: Bouchard et al [1310.3207] and Horgan et al [PRL112,212003(2014)]

b->s(d)ll BRANCHING FRACTIONS

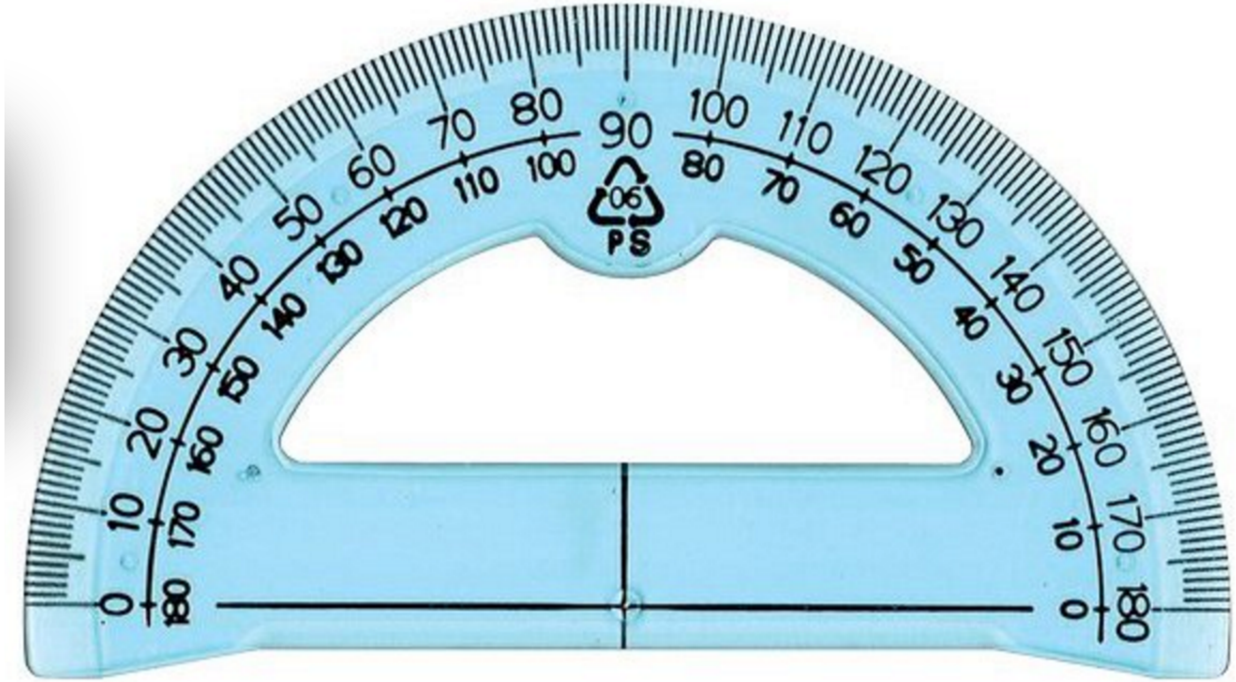








ANGULAR ANALYSES

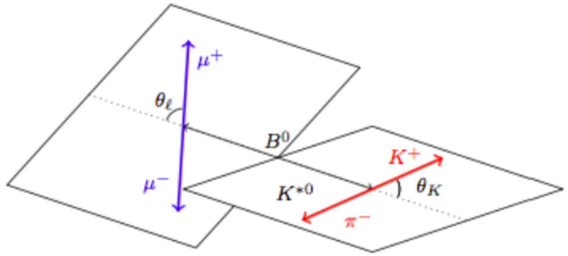


THE PRINCIPLE OF ANGULAR ANALYSES

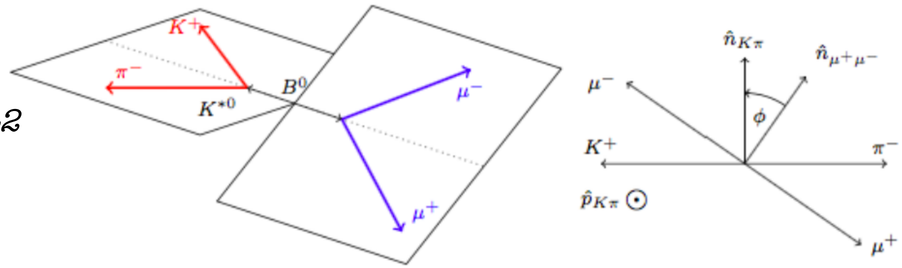
- Angular analyses are complex, but a rich framework to measure a variety of observables, sensitive to different sources of new physics depending on q^2

- Decays with four particles in the final state are described by:
  - three angles in the helicity basis;
  - the di-lepton invariant mass squared q^2

- Observables depend on Wilson coefficients (underlying short-distance physics) and form-factors (hadronic matrix elements)



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

Example: ***B->K*μμ***

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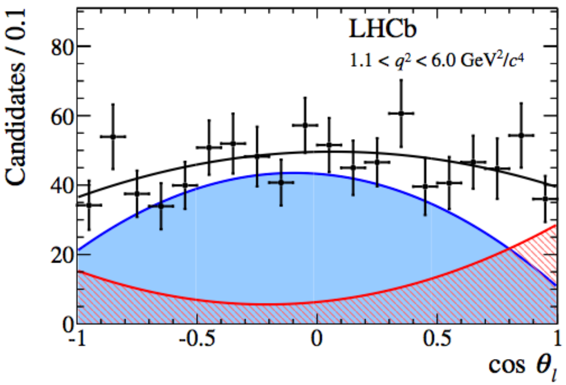
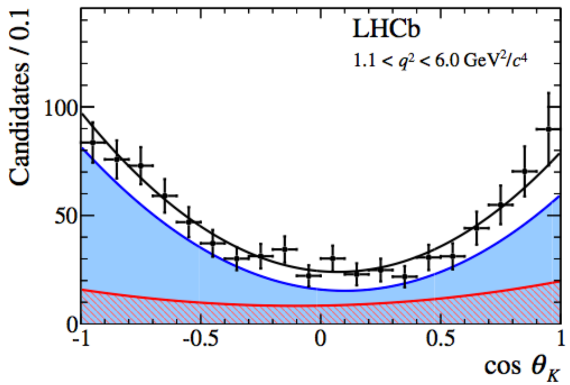
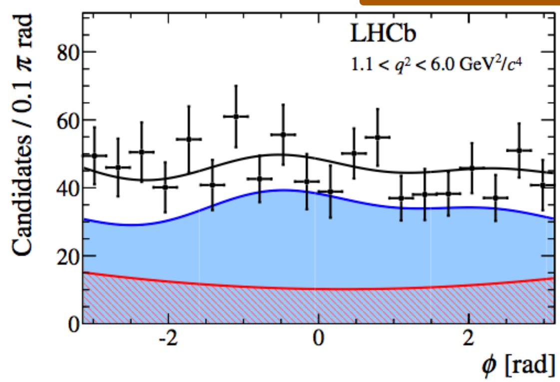






B→ $K^*\mu\mu$ ANGULAR ANALYSIS

Full angular distribution described by eight independent observables:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

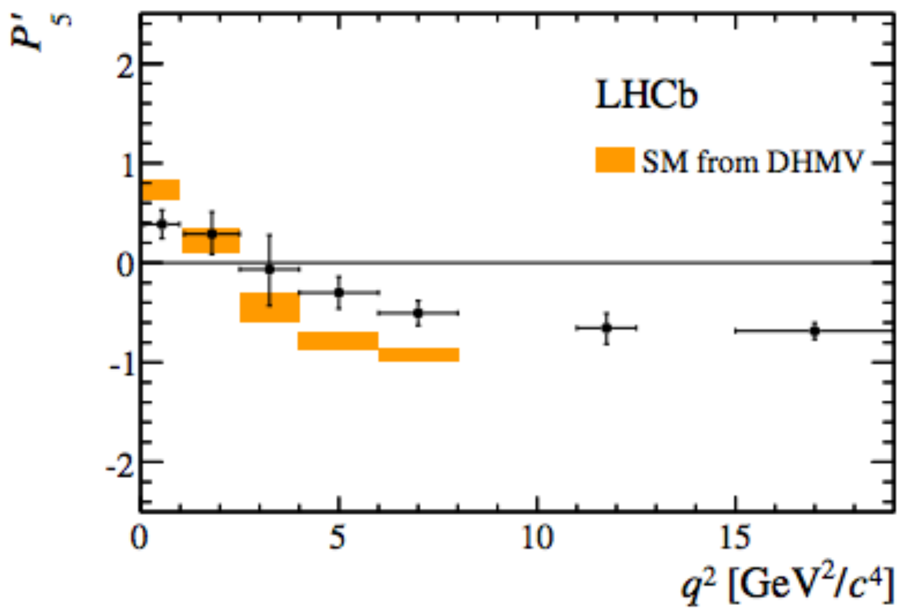
Observables (A_{FB}, F_L and S_j) are function of the Wilson coefficients

A cleaner set of observables, where hadronic form factor uncertainties cancels at the leading order, can be defined (*JHEP 1305(2013)137*), ex:

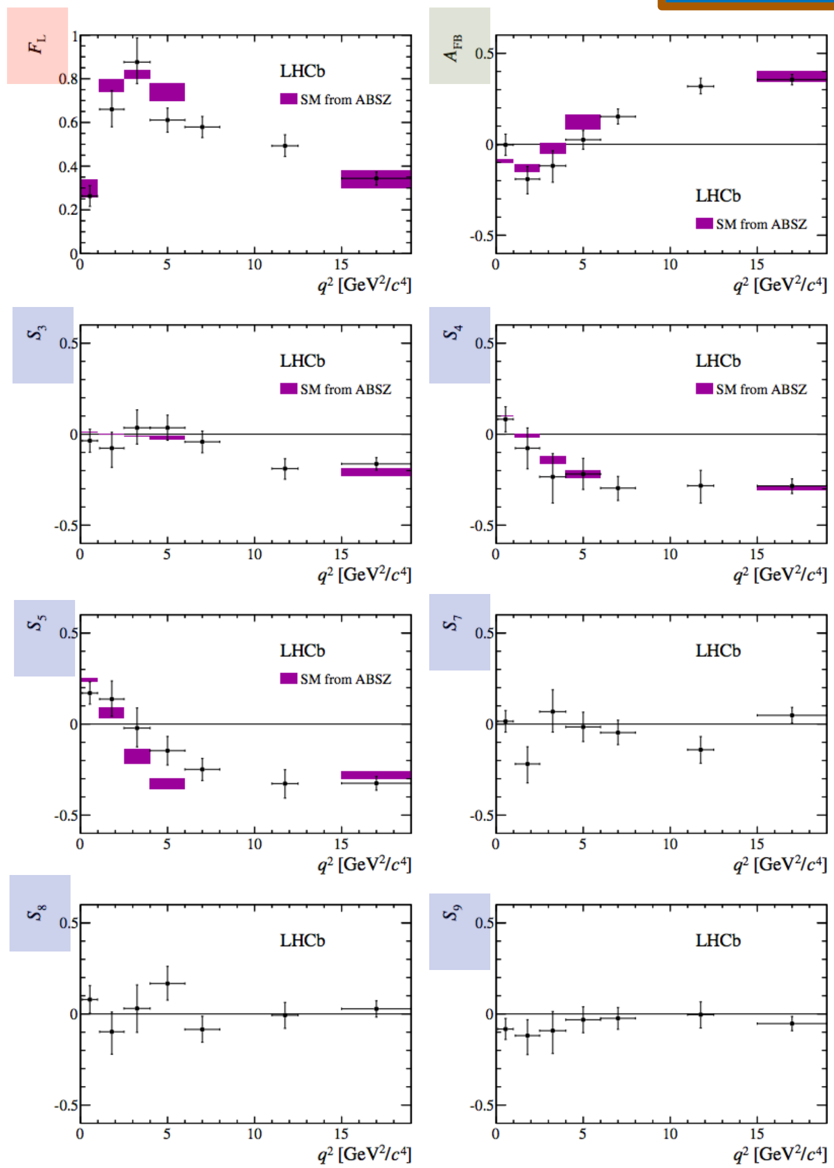
$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

LHCb performed the first full angular analysis of $B \to K^*\mu\mu$, using Run1 (3 fb^{-1})

- full set of CP-averaged angular terms
- full set of CP-asymmetries
- correlation matrix published
- form-factor independent ratios of observables measured (P')



Puzzling discrepancy of about 3.4 σ



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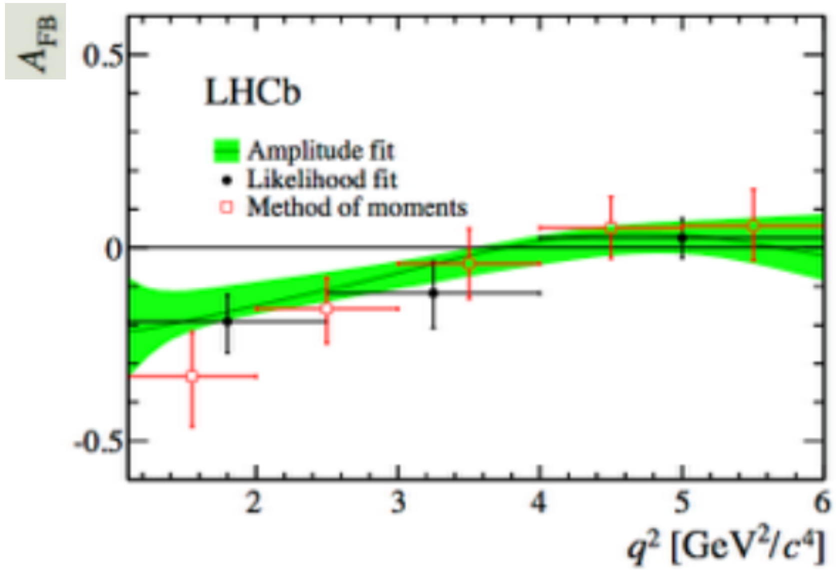
Additional measurement of the zero-crossing point, parameterizing the angular distribution with q^2 dependent decay amplitudes



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$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ CL}$$

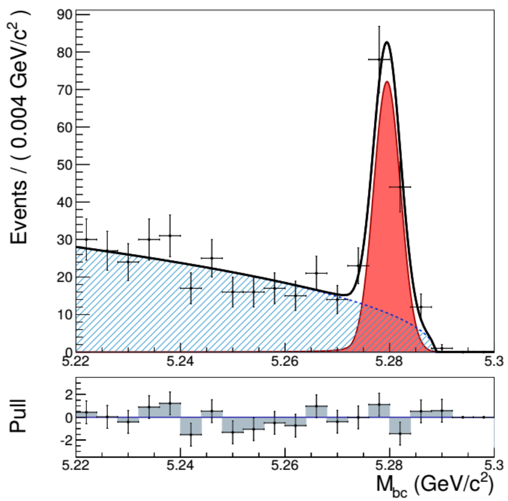
$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ CL}$$

$$\text{SM: } q_0^2(A_{\mathrm{FB}}) \sim [3.9, 4.4]\,\mathrm{GeV}^2/c^4$$

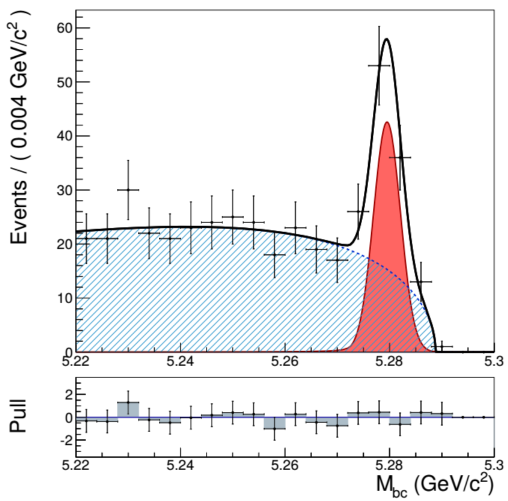
[JHEP 01 (2012) 107, EPJ C41 (2005) 173, EPJ C47 (2006) 625]

Folding technique:

- not enough statistics to perform eight-dimensional fit
- use symmetries of *sin* and *cos* to cancel terms
- reduce number of free paramters to 3: F_L, S_3 and S_i or P_i'



(a)$B^0 \to K^*(892)^0\mu^+\mu^-$



(b)$B^0 \to K^*(892)^0 e^+ e^-$

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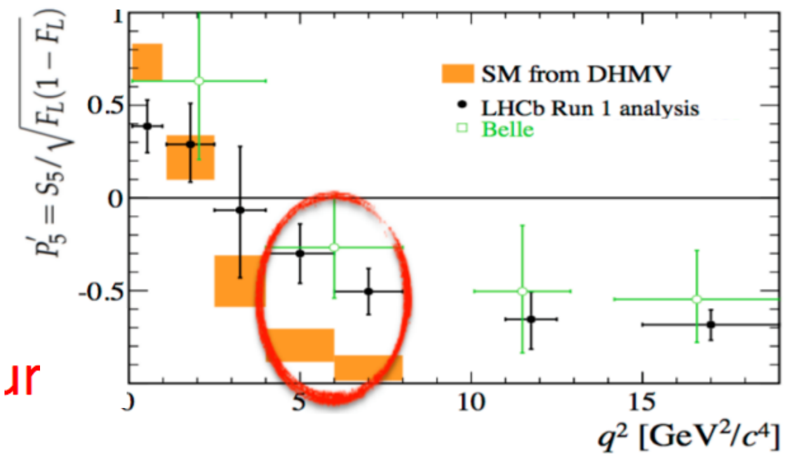
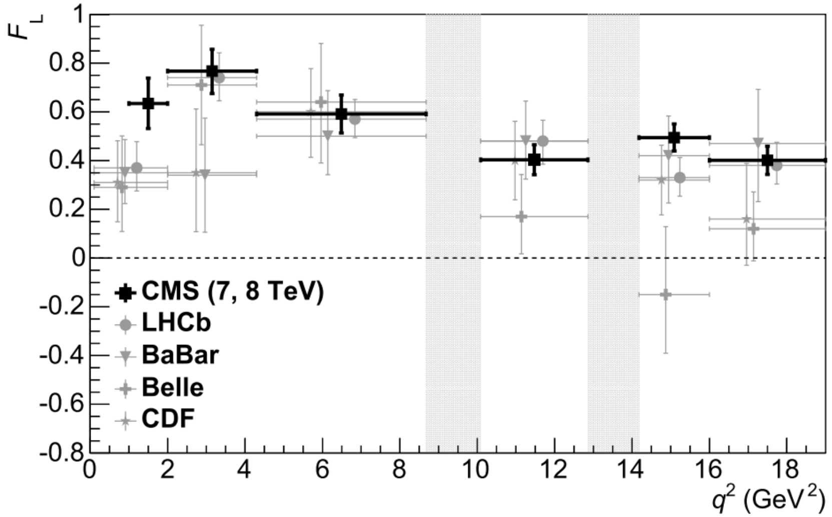
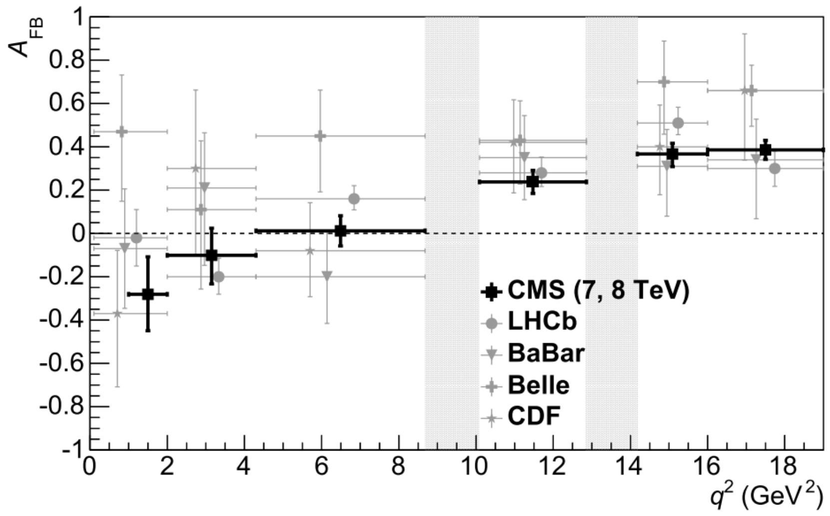
arXiv:1604.04042

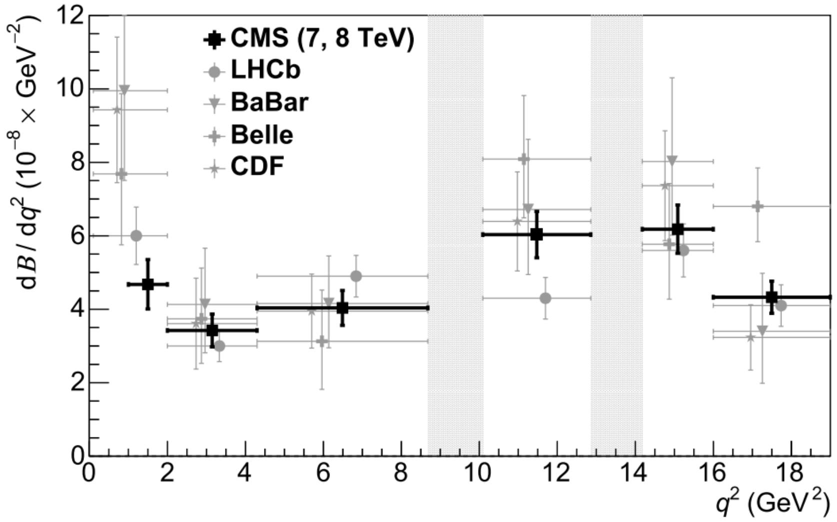


- Could be a genuine NP effect!
- Or a statistical effect: more data needed!
- Or a QCD effect not fully understood (charm loops, e.g JHEP 06 (2016) 116)

CMS $B \rightarrow K^*\mu\mu$ ANGULAR ANALYSIS







Phys. Lett. B 753, 424 (2016)

- Folding technique.
- Consistent with other results.

- BaBar: Phys. Rev. D 86 (2012) 032012,
- Belle: *Phys. Rev. Lett.* ***103*** *(2009) 171801*
- CDF: *Phys. Rev. Lett.* ***108*** *(2012) 081807*
  Phys. Rev. Lett. 106 (2011) 161801
- LHCb (3 fb^{-1}): JHEP 08 (2013) 131

OTHER CHANNELS EXPLORED

- $B_s \to \phi\mu\mu$ is very clean experimentally!
- Final state not self-tagging: less observables

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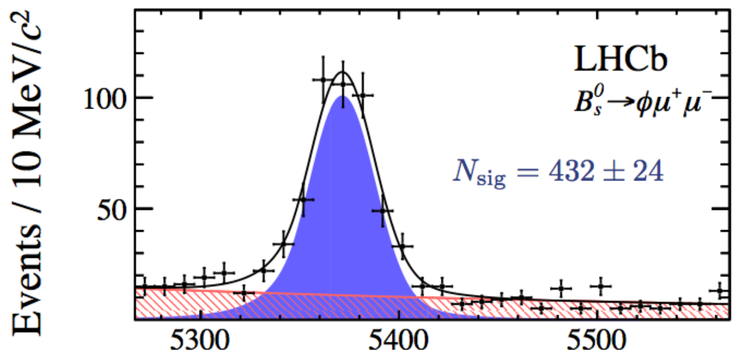

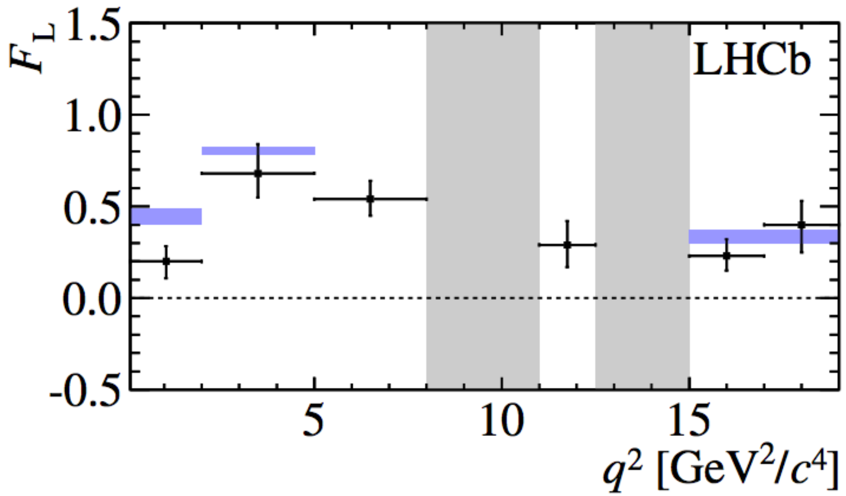

- $\Lambda_b \to \Lambda\mu\mu$ gives access to different combinations of Wilson coefficients
- More statistics needed

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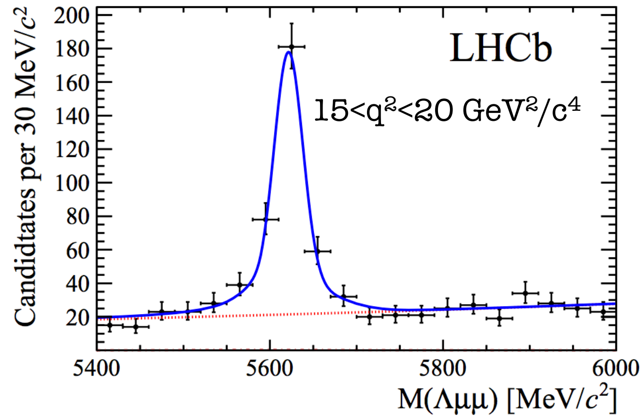
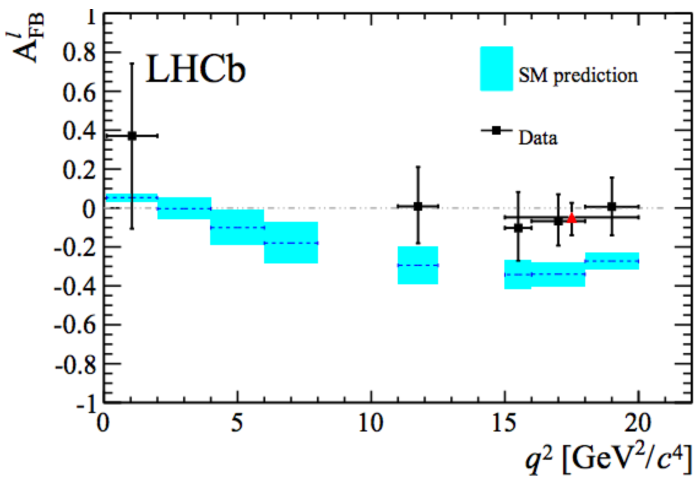
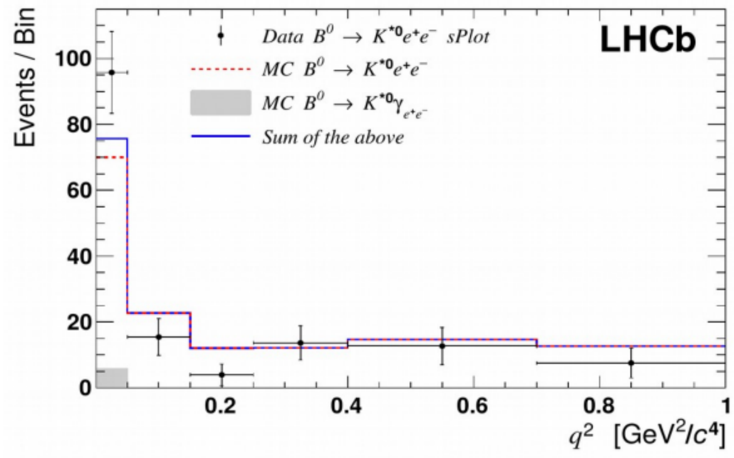
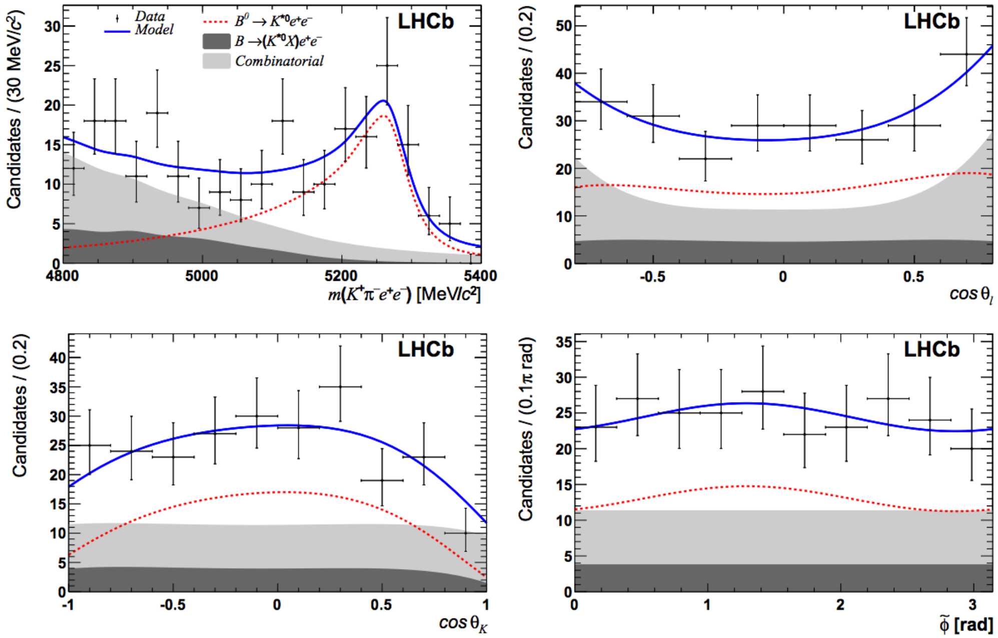




B→ K*ee SAME GAME WITH THE ELECTRONS!

- Experimentally challenging for trigger and bremsstrahlung effects.
- Explore lower q^2 region. Higher sensitivity to C_7 (photon polarization).
- Lower yields than muon channel.
- Results in agreement with SM.





$$
\begin{aligned}
F_L &= 0.16 \pm 0.06 \pm 0.03 \\
A_T^{Re} &= 0.10 \pm 0.18 \pm 0.05 \\
A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\
A_T^{Im} &= 0.14 \pm 0.22 \pm 0.05
\end{aligned}
$$

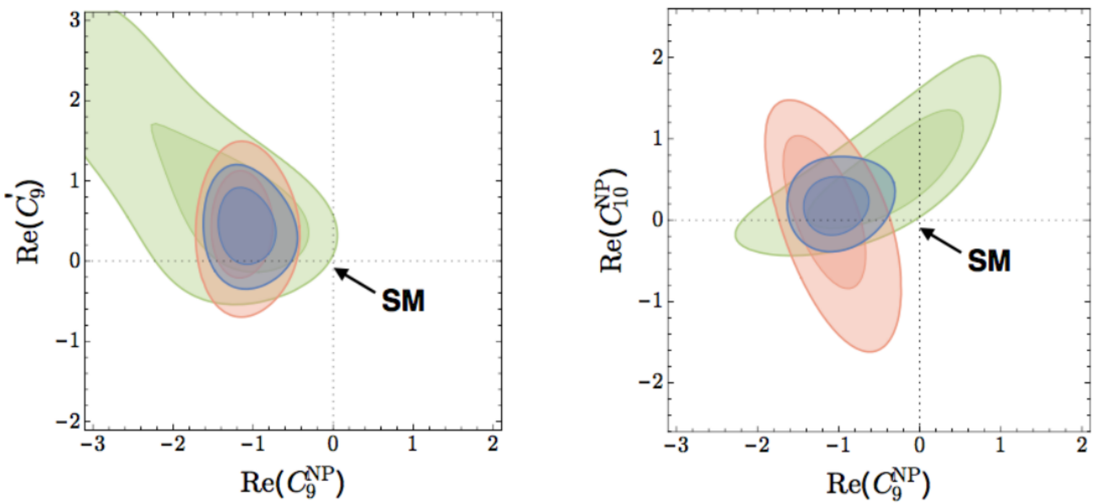
JHEP 04 (2015)064

GLOBAL FITS

Several global fits of *b->s* data have been performed (e.g. **arXiv:1503.06199**, **arXiv:1510.04239**, **arXiv:1512.07157**)

About 80 observables from 6 experiments, including *b->μμ*, *b->sll* and *b->sγ*

All fits require and additional contribution with respect to the SM predictions, preferring a non zero $C_9^{NP} \neq 0$ at ~4σ



arXiv:1503.06199

branching fractions, angular observables and combination

Possible interpretations:

- NP scenarios from new *Z'* vector with mass of few TeV
- QCD effects
- statistical fluctuation

LEPTON FLAVOUR UNIVERSALITY TESTS

THE R_K MEASUREMENT

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{{\rm d}q^2}{\rm d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\Gamma[B^+ \to K^+e^+e^-]}{{\rm d}q^2}{\rm d}q^2}$$

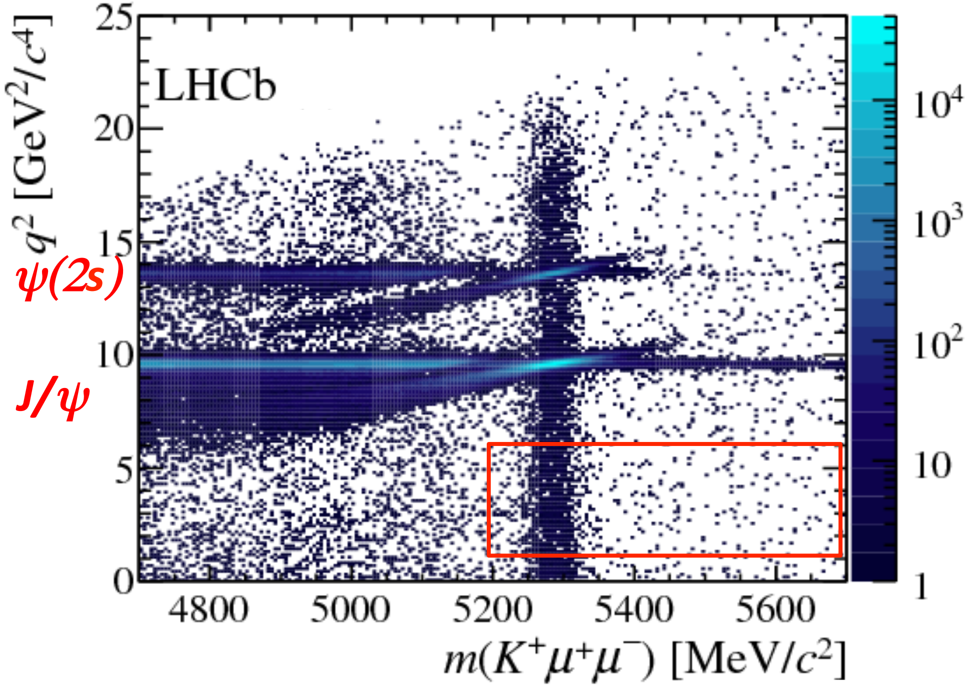
- Expected to be 1 in the Standard Model (lepton flavor universality)
- Theoretical uncertainty ~10^{-3}
- Excellent and theoretically robust test of the SM!

R_K : THE DATASET

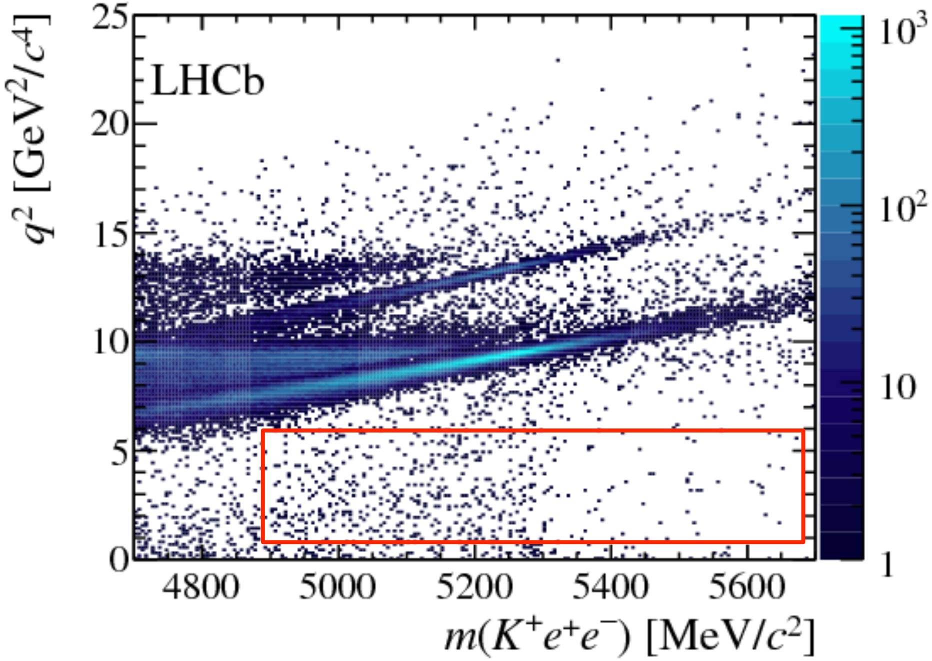
- Experimentally challenging for trigger/ tracking reconstruction differences between muons and electrons, bremsstrahlung effects…
- Use the double ratio of the rare to the J/ψ channel to reduce systematics:

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$

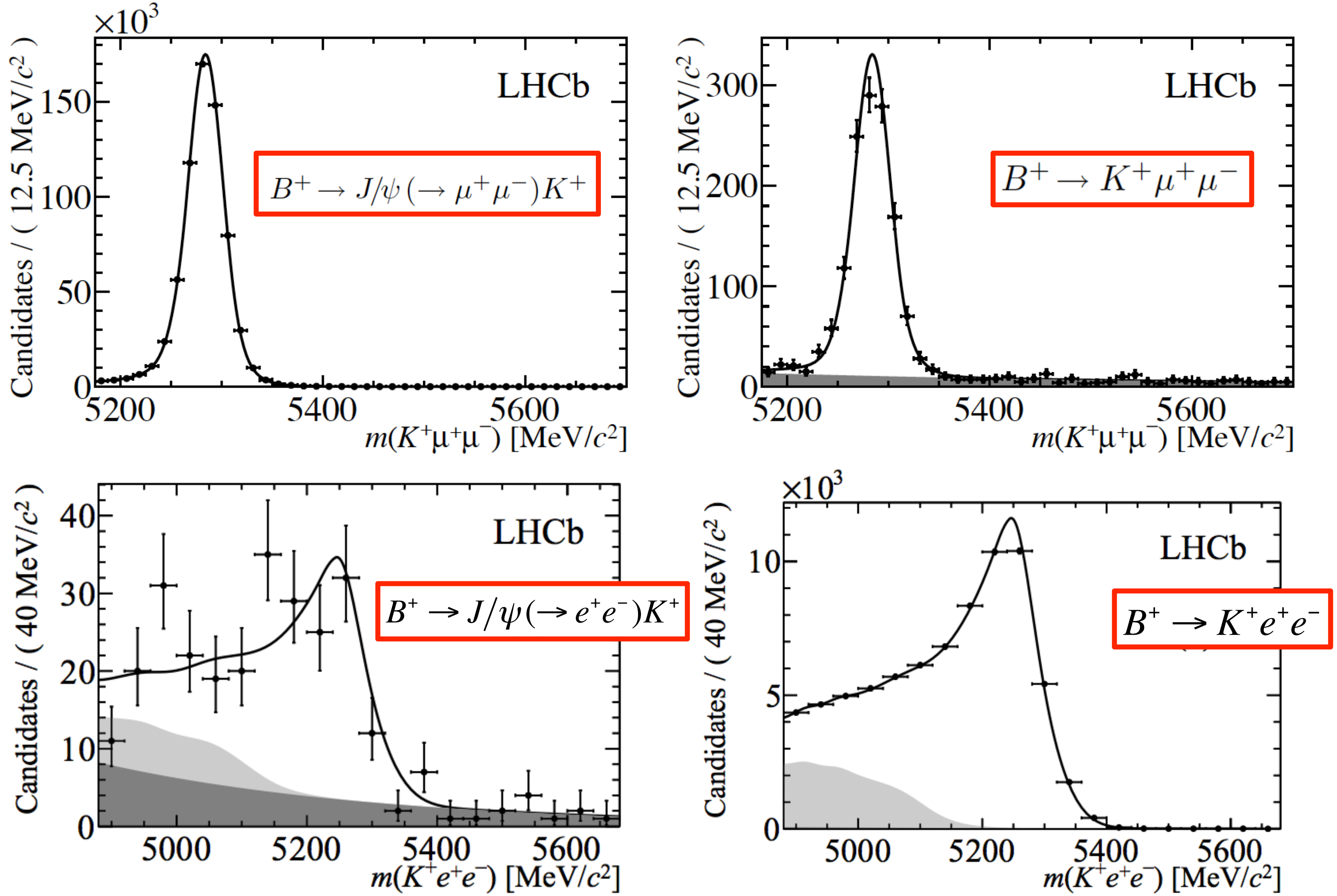
Muon channel



Electron channel

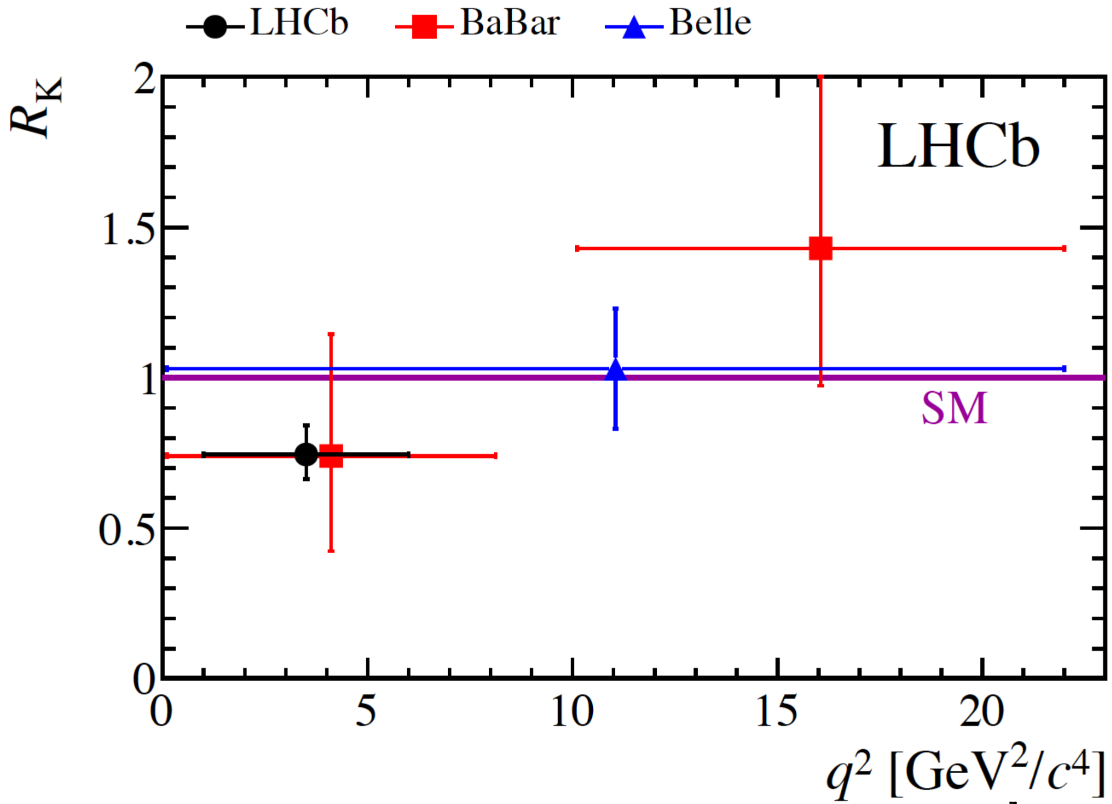


- Muon final states has excellent resolution and is very clean
- Electron final states suffers from bremsstrahlung effects



PRL 113, 151601 (2014)

R_K : RESULTS



PRL 103 (2009) 171801

PRD 86 (2012) 032012

PRL 113 (2014) 151601

- LHCb analysis on the whole run1 dataset: 3 fb^{-1}, in the q^2 range [1, 6] GeV^2/c^4

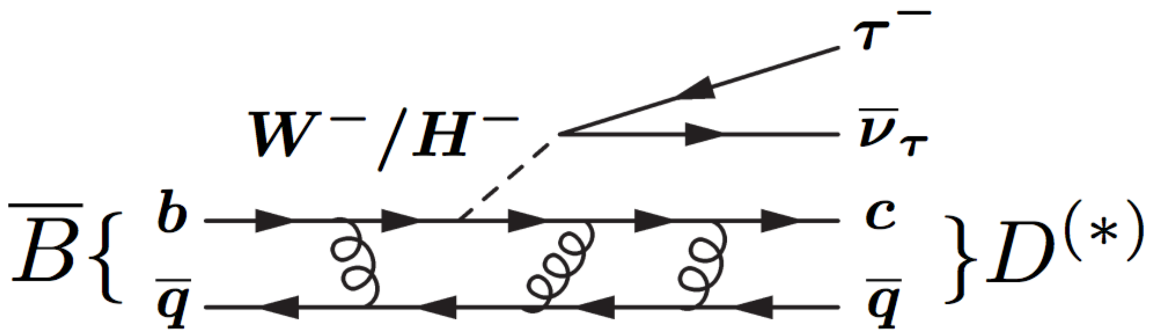
$$R_K = 0.745\ ^{+0.090}_{-0.074}\ \text{(stat)} \pm 0.036\ \text{(syst)}$$

- **Compatible with Standard Model at 2.6 σ**
- Consistent with decay rates deviations if NP do not couple with electrons
- More data coming with run2 (and maybe some improvements in the analysis): measurement in the other bins, more *R, etc…*

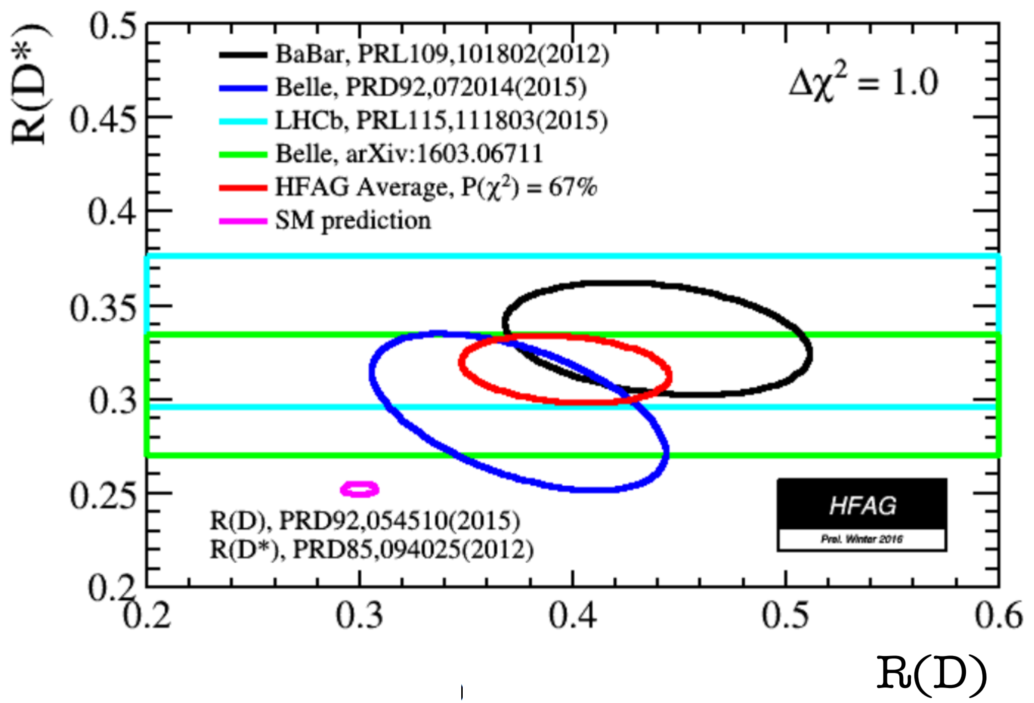
THE R_{D^*} MEASUREMENT

$$R_{D^*} = \frac{\Gamma(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu_\tau})}{\Gamma(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu_\mu})}$$

- In the Standard Model (lepton flavor universality), the mass of the lepton is the only difference between the two decays
- Theoretical uncertainty ~2% for D^* mode
- Sensitive to charged Higgs or non minimal flavor violating couplings favoring the tau



- ***R(D*) = 0.336 ± 0.027 (stat) ± 0.030 (syst)*** *PRL 115, 111803 (2015)*
- First measurement at an hadron collider
- In agreement with past B factories measurements
- **2.1σ larger than Standard Model expectation**
- Combining also B factories results on R(D), 4σ discrepancy observed
- Reduction of systematic error expected with more data coming



LHCb can additionally perform measurements with other b hadrons (B_s, B_c, Λ_b).

Belle performed the first measurement using semileptonic tag:

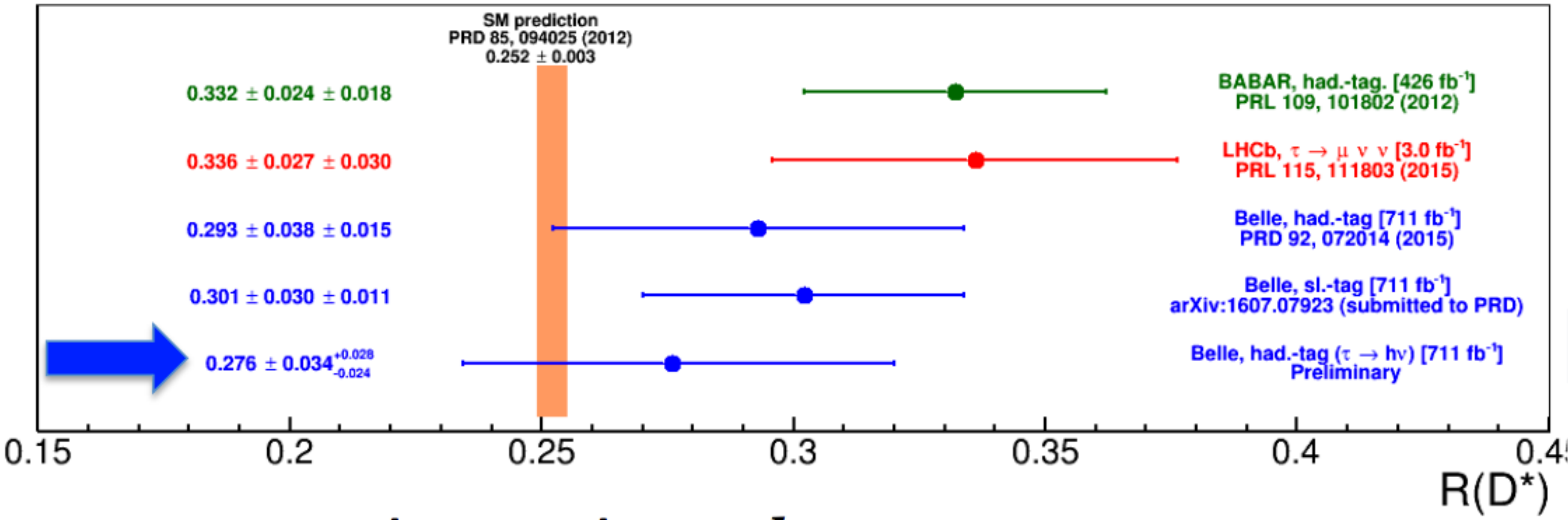
- $\mathcal{R}(D^*) = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst})$

arXiv:1607.07923 (submitted to PRD)

and updated the result of hadronic tag, providing additionally the first measurement of the τ polarization in these decays:

- $\mathcal{R}(D^*) = 0.276 \pm 0.034(\text{stat})^{+0.029}_{-0.026}(\text{syst})$
- $\mathcal{P}_\tau = -0.44 \pm 0.47(\text{stat})^{+0.20}_{-0.17}(\text{syst})$

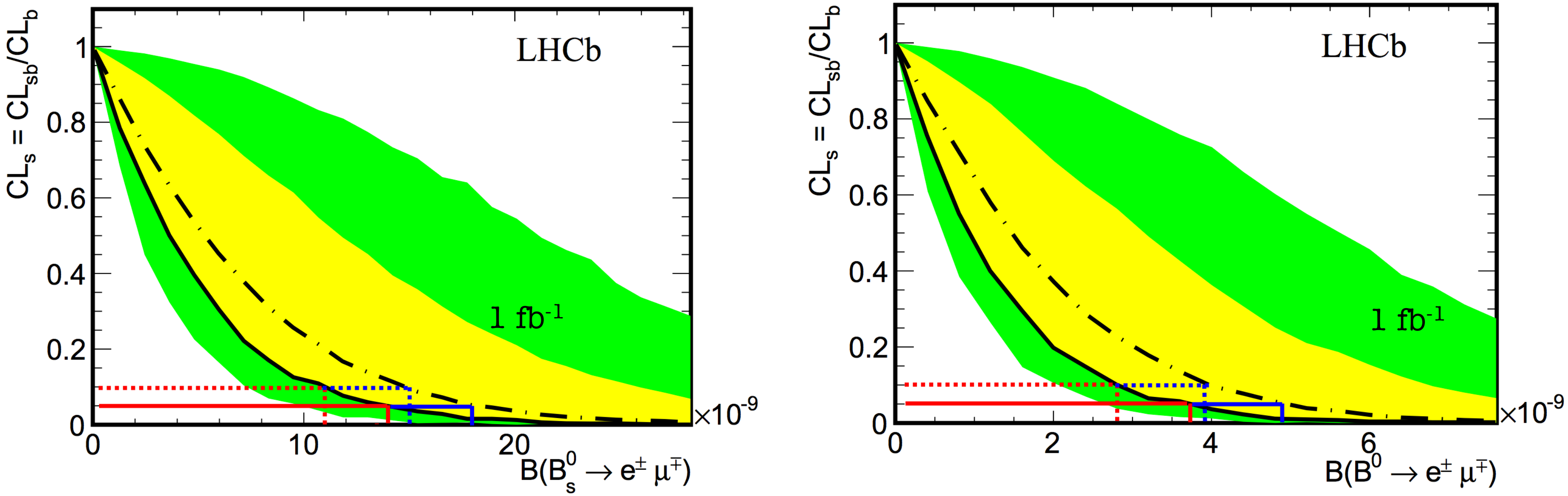
Preliminary
hadronic tag $\tau \rightarrow h\nu$



CHARGED LEPTON FLAVOUR VIOLATION SEARCHES

B→ e μ

PLB 111 (2013) 141801



Mode	Limit	90 % C.L.	95 % C.L.
$B_s^0 \to e^\pm\mu^\mp$	Expected	1.5×10^{-8}	1.8×10^{-8}
	Observed	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm\mu^\mp$	Expected	3.8×10^{-9}	4.8×10^{-9}
	Observed	2.8×10^{-9}	3.7×10^{-9}

Limits on Pati-Salam leptoquark model:

- *$M_{LQ}(B_s$->eμ)>101 TeV/c^2 @95%CL*
- *$M_{LQ}(B_d$->eμ)>126 TeV/c^2 @95%CL*

OTHER INTERESTING B cLFV DECAYS

BABAR

Phys. Rev. D73 (2006) 092001

$$\mathcal{B}(B^+ \to K^+ e^\pm \mu^\mp) < 9,1 \times 10^{-8}$$

$$\mathcal{B}(B^+ \to K^+ e^\pm \tau^\mp) < 3,0 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+ \tau^\pm \mu^\mp) < 4,8 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^*(892)^+ e^\pm \mu^\mp) < 1,4 \times 10^{-6}$$

$$\mathcal{B}(B \to K^*(892)^0 e^\pm \mu^\mp) < 5,8 \times 10^{-7}$$

$$\mathcal{B}(B \to K e^\pm \mu^\mp) < 2,7 \times 10^{-7}$$

Work is ongoing to perform these searches in LHCb.

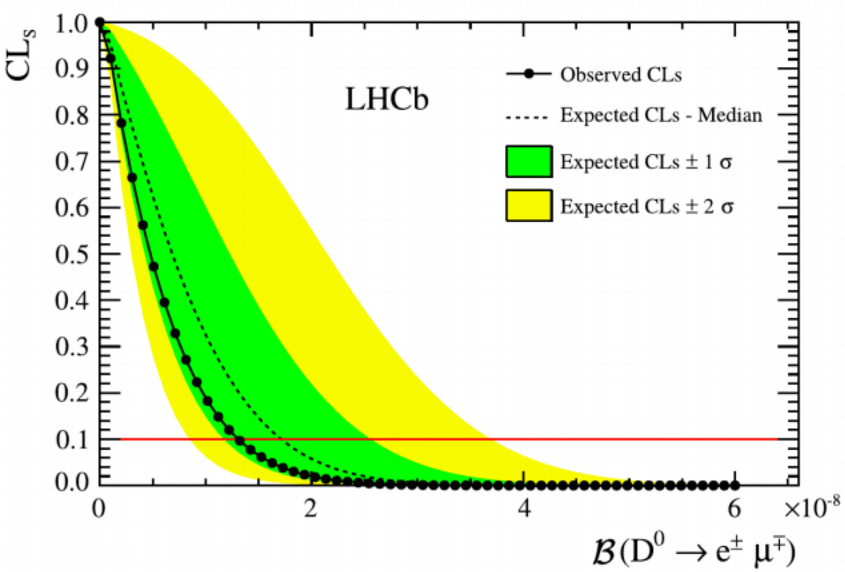
$D \rightarrow e\,\mu$

PLB 754 (2016) 167

New world best limit!

$BF(D^0 \to e\mu) < 1.3(1.6) \times 10^{-8}$

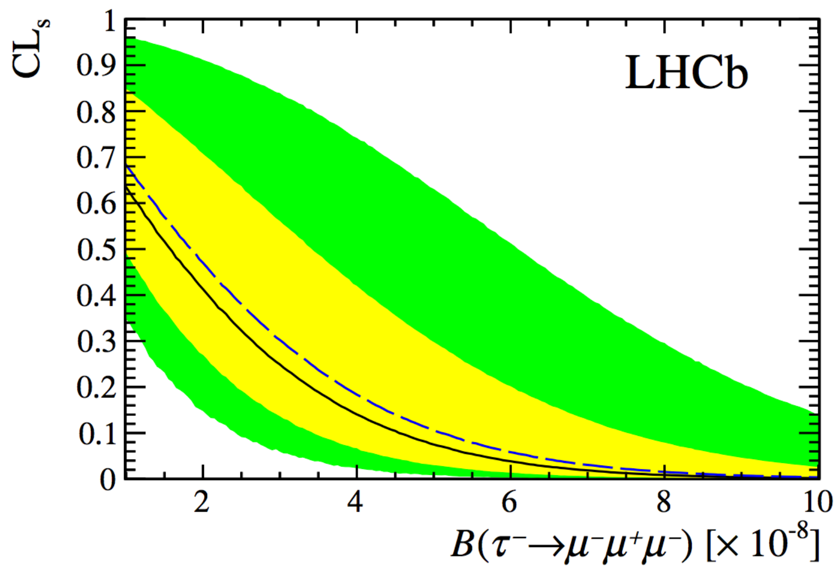
at 90(95)%CL



$\tau^- \rightarrow \mu^-\mu^+\mu^-$

JHEP 02 (2015) 121

Belle: $B(\tau^- \rightarrow \mu^-\mu^+\mu^-) < 2.1\times10^{-8}$ @ 90% CL
BaBar: $B(\tau^- \rightarrow \mu^-\mu^+\mu^-) < 3.3\times10^{-8}$ @ 90% CL
LHCb: $B(\tau^- \rightarrow \mu^-\mu^+\mu^-) < 4.6\times10^{-8}$ @ 90% CL



CONCLUSION

- Flavour physics has a strong potential for unveiling new physics phenomena.

- The indirect searches, complementary to direct search, are providing important constraints to the theories and interesting puzzles to solve.

- Some tensions are appearing in different channels and analyses, potentially interpretable in a coherent way.

- There is a clear and long flavor research program ahead, both at LHC and Belle II…

…and considering the ongoing tensions, maybe we are not so far from catching the cat hiding among the penguins….