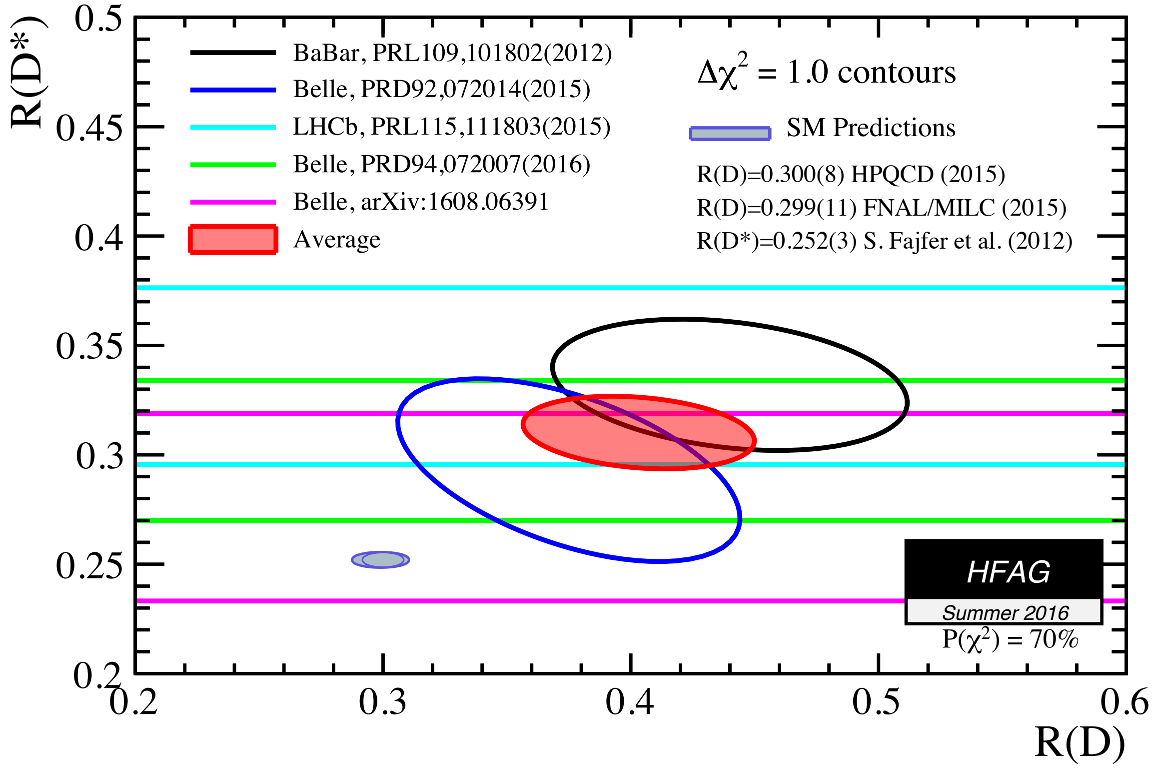
Rare B and strange decays

Siim Tolk
on behalf of the LHCb collaboration

Moriond EW
2017

Serious tensions in **Lepton Flavour Universality** tests

arXiv:1612.07233

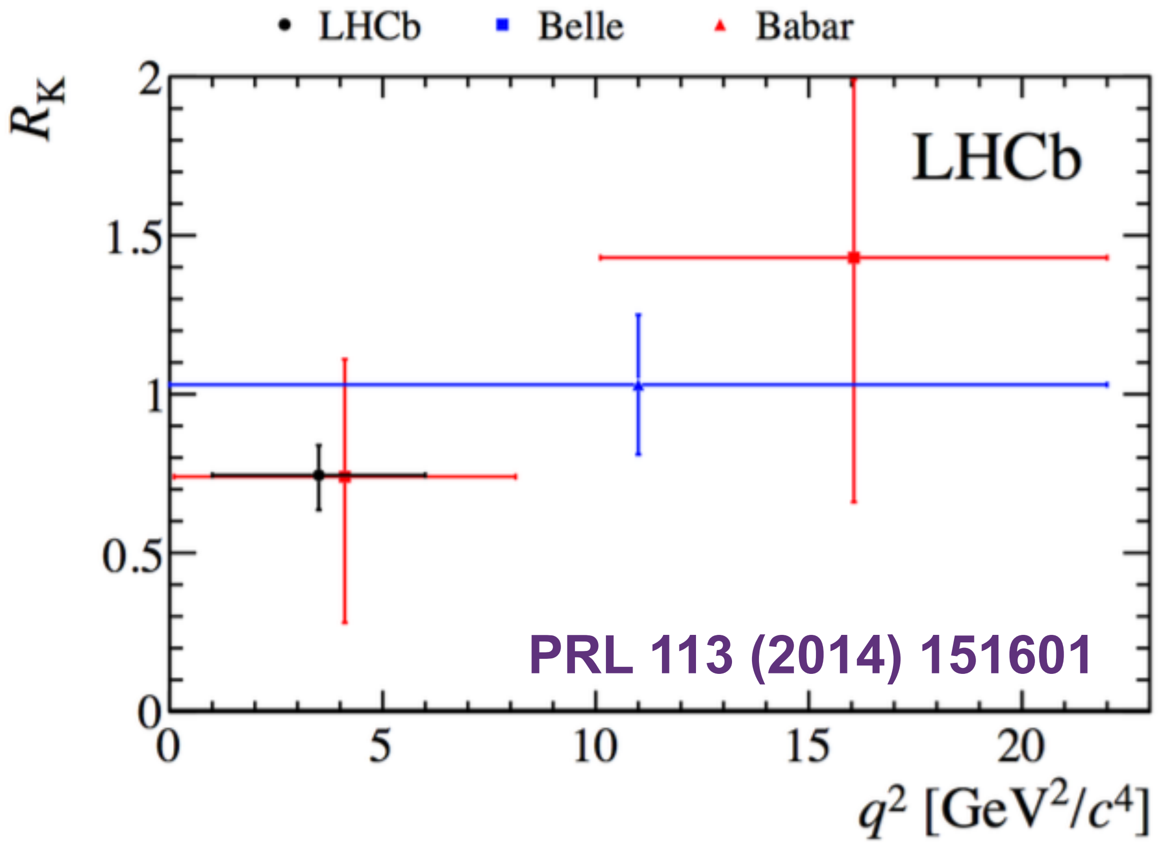


Semi-leptonic decays

Tree level (3'rd/2'nd generation)

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

➽ **SM compatibility: 3.9σ**
➽ New Physics competing with SM at tree level?



PRL 113 (2014) 151601

Rare decays

Loop level (2'nd/1'st generation)

$$\mathcal{R}(K) \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

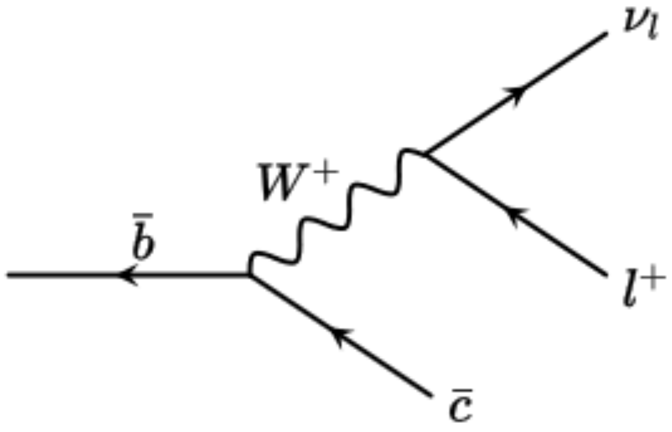
➽ **SM compatibility 2.6σ**
➽ New Physics at loop level?

➽ Could be a manifestation of the same NP (~TeV leptoquarks)

Phys. Rev. Lett. 116, 141802 (2016)

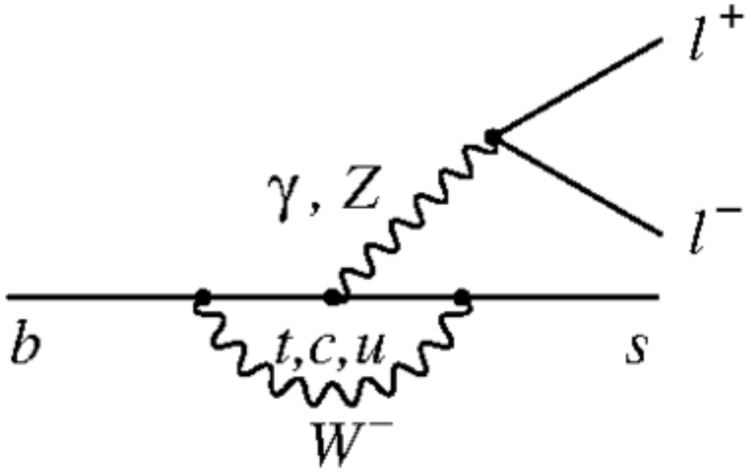
Rare decays in the Standard Model (SM)

Tree level CC



$$\mathcal{M}_{CC} \sim G_F V_{ij} U^*_{kl}$$

The SM FCNC



$$\mathcal{M}_{FCNC} \sim G_F \frac{\alpha}{4\pi} \sum_k V_{ki} V^*_{kj} \frac{m_k^2}{M_W^2}$$

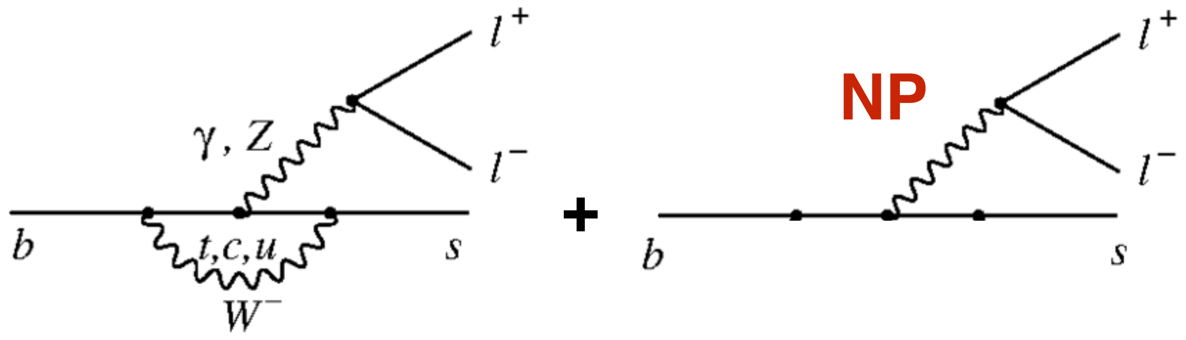
☛ **GIM**, **loop**, **CKM**, …
(branching fractions ≤ 10^{-6})

…+ **helicity** $(m_\mu / M_B)^2 \sim 10^{-4}$
(branching fractions ≤ 10^{-9})

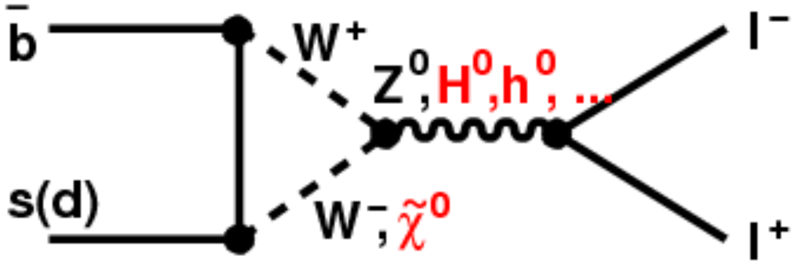
- ➽ involve flavour changing up-up or down-down type quark transitions (**FCNC**)
- ➽ In SM: **suppressed by multiple mechanisms**:
  only allowed at loop level (**GIM**), must involve an **off-diagonal CKM element** and (possibly) **helicity** suppressed:

Rare decays are sensitive to heavy New Physics (NP)

NP at tree level



NP at loop level



☛ $B_s \to \mu^+\mu^-$ sensitive to Z’s up to 160TeV or new scalars up to 1000TeV

JHEP 1411 (2014) 121

☛ In $B_s \to \mu^+\mu^-$ (pseudo)scalars can bypass the helicity suppression

☛ Two Higgs Doublet model effects ~ $\tan(\beta)^3$

$$\mathcal{M}_{FCNC} \sim G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi}\left(C^{SM} + \underbrace{\boxed{\frac{4\pi}{\alpha}\frac{1}{V_{tb}V_{ts}^*}}}_{\sim 200^2} \frac{g_{sb}^2 g_{ll}^2}{\underset{\uparrow}{M^2}}\right) \times (\bar{s} \otimes \bar{l}l)$$

☛ $M_{NP} \sim 10^2$ TeV

☛ Indirect NP signs are expected to precede the direct evidence.

The **theoretical description** of the rare hadron decays

Excellent review: [arXiv:1606.00916]

- processes over a **wide energy range:**

0.2GeV……4GeV……80GeV…… ~ 100 TeV ?

Λ_{QCD}	Λ_b	Λ_{EW}	Λ_{NP}
(non-perturbative regime)	(b mass)	(W mass)	(new physics scale)

- described by the **effective field theory** and **operator product expansion**:

dim-6 operators

$$A(B \to f) = \langle f|\mathcal{H}_{eff}|B\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_{CKM}\ \underline{C_i(\mu_b)}\ \underline{\langle f|\mathcal{Q}_i(\mu_b)|B\rangle}$$

Wilson coefficients (perturbative)

Hadronic matrix el. (include non-perturbative QCD)

Leptonic modes

$$\langle ll|j_{ll}\cdot j_{qq}|B_q\rangle = \langle ll|j_{ll}|0\rangle \cdot \underline{f_{Bq}}$$

Lattice QCD

Semi-leptonic modes:

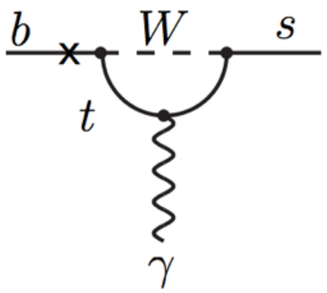
$$\langle llM|j_{ll}\cdot j_{qq}|B\rangle = \langle ll|j_{ll}|0\rangle \cdot \underline{F(q^2)} + \underline{C_{non-fact}}$$

corrections

Lattice QCD (large q^2)
Light Cone Sum Rules (small q^2)

The operators relevant for the rare B decays:

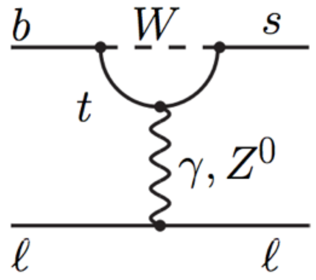
Excellent review: **[arXiv:1606.00916]**



Electromagnetic penguin

$$\mathcal{Q}_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu P_{R(L)}} b) F^{\mu\nu}$$

$b \to s l^+ l^-$

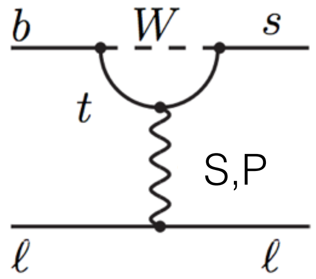


Semi-leptonic vector current

Semi-leptonic A-V current

$$\mathcal{Q}_9^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu l)$$

$$\mathcal{Q}_{10}^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu \gamma_5 l)$$



Scalar

Pseudo-scalar

$$\mathcal{Q}_S^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}_{L(R)} b_{R(L)})(\bar{l} l)$$

$$\mathcal{Q}_P^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}_{L(R)} b_{R(L)})(\bar{l}\gamma_5 l)$$

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

*four quark operators $Q_{1\ldots6}$ only contribute through operator mixing.

➽ New Physics can
- ☛ alter the SM operator contributions (Wilson coefficients)
- ☛ enter through new operators (right-handed Q's, $Q_{S,P}$)

Electromagnetic and semi-leptonic Wilson coefficients: $C_{7,}$ C_9 and C_{10}

Wilson coefficients are measured in **global b→ sl$^+$l$^-$(γ) analysis**

Excellent review: **[arXiv:1606.00916]**

☛ No evidence for right-handed FCNC ($C'_i = 0$) and $C_{(7,9,10)}$ signs [-,+,-] agree with the predictions (pre LHC discussion)

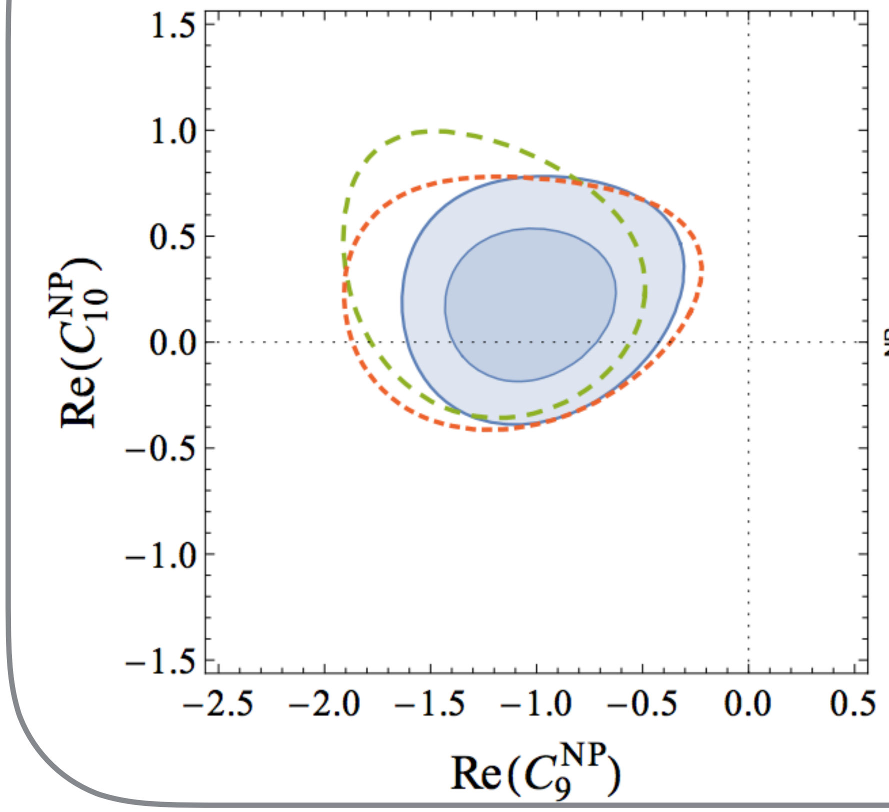
☛ There are tensions w.r.t SM (up to 4σ)

☛ Tensions are **driven** by **$B^0 \to K^* \mu^+ \mu^-$ angular observables** and by several **exclusive b→sl$^+$l$^-$ branching fraction** measurements; supported by R(K).

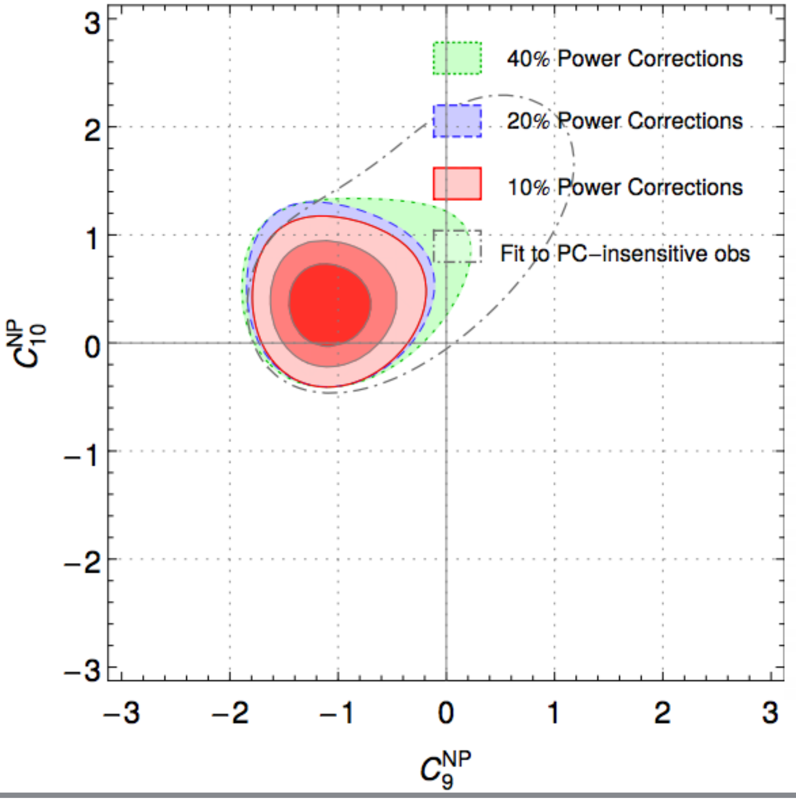
☛ **Tensions are relieved** by (NP effects?):

$$[(C_9)^\mu_s]^{NP} \approx -1.1 \quad \text{or} \quad [(C_9)^\mu_s]^{NP} = -[(C_{10})^\mu_s]^{NP} \approx -0.5$$

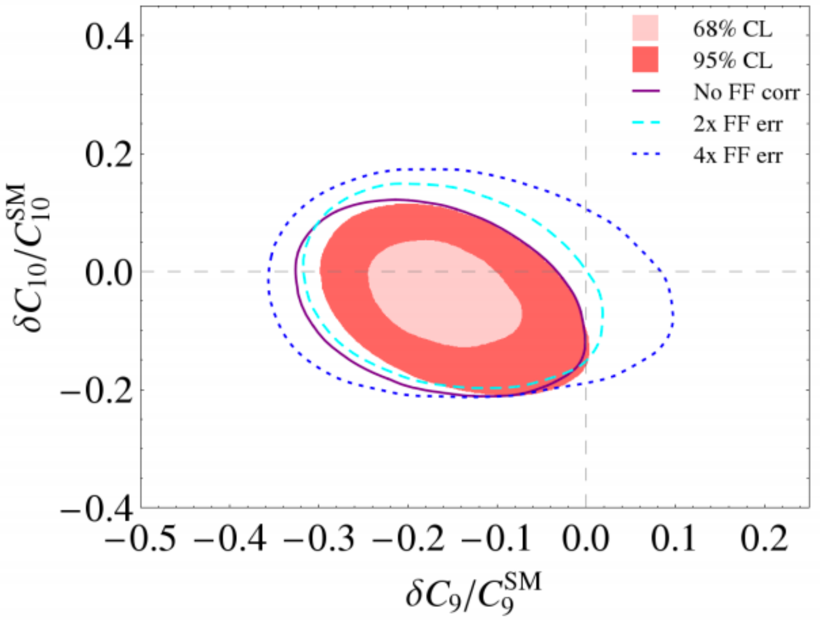
Altmannshofer, Straub **[Eur.Phys.J.C75(8)(2015)382]**



Descotes-Genon, Hofer, Matias, Virto **[JHEP 06 (2016) 092]**



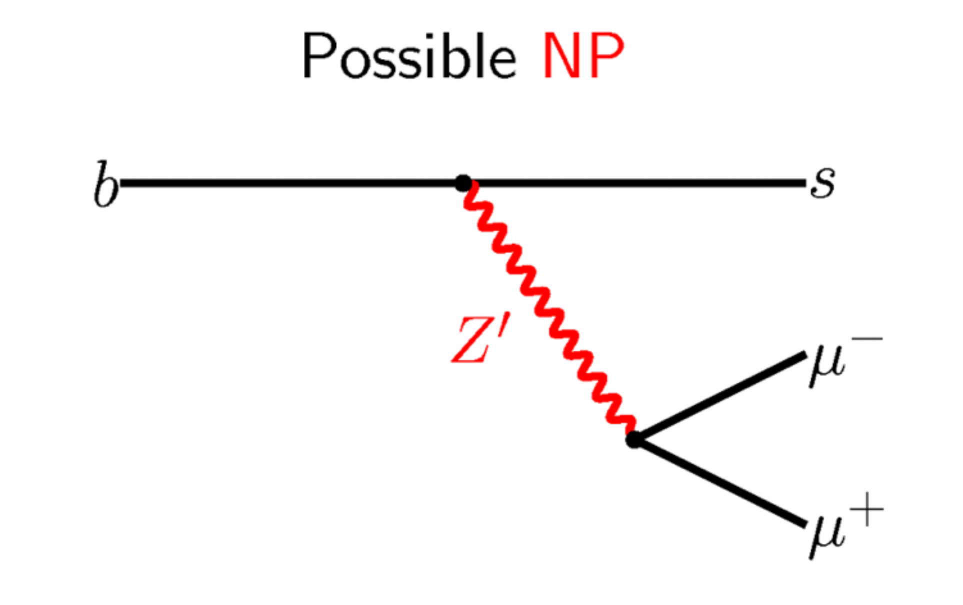
Hurth, Mahmoudi, Neshatpour **[arXiv:1603.00865]**



Understanding the origin of the tensions

Excellent review: **[arXiv:1606.00916]**

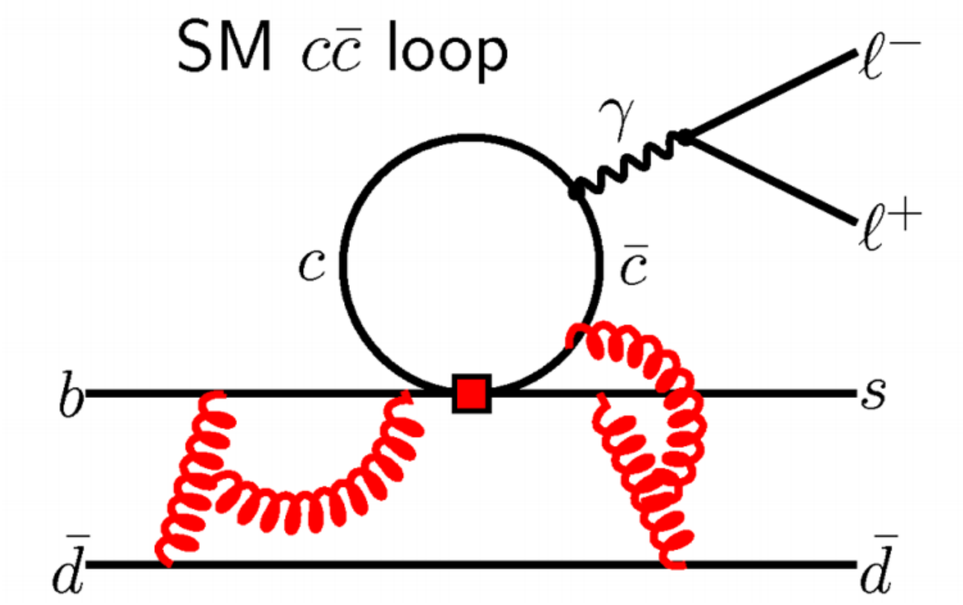
Z’, leptoquarks,…



$$C_9 + C_9^{NP}$$

or

Hadronic SM effects



$$C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2)$$

Large long-distance charm resonance effects far from the resonances on the q^2 plane.

NEW!

➽ **Measure the resonance effects in C_9 in an inclusive analysis:**

$$B^+ \to K^+\mu^+\mu^- \;+\; B^+ \to K^+ X_{c\bar{c}}(\to \mu^+\mu^-)$$

Measuring **resonance effects in C₉**

[arXiv:1612.06764]
submitted to EPJC

NEW!

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

- The differential decay rate depends on the Wilson coefficients:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2\right.$$
$$\left. + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2) + 2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

fix C₇ to the SM value (small)

- Parametrise resonance effects:

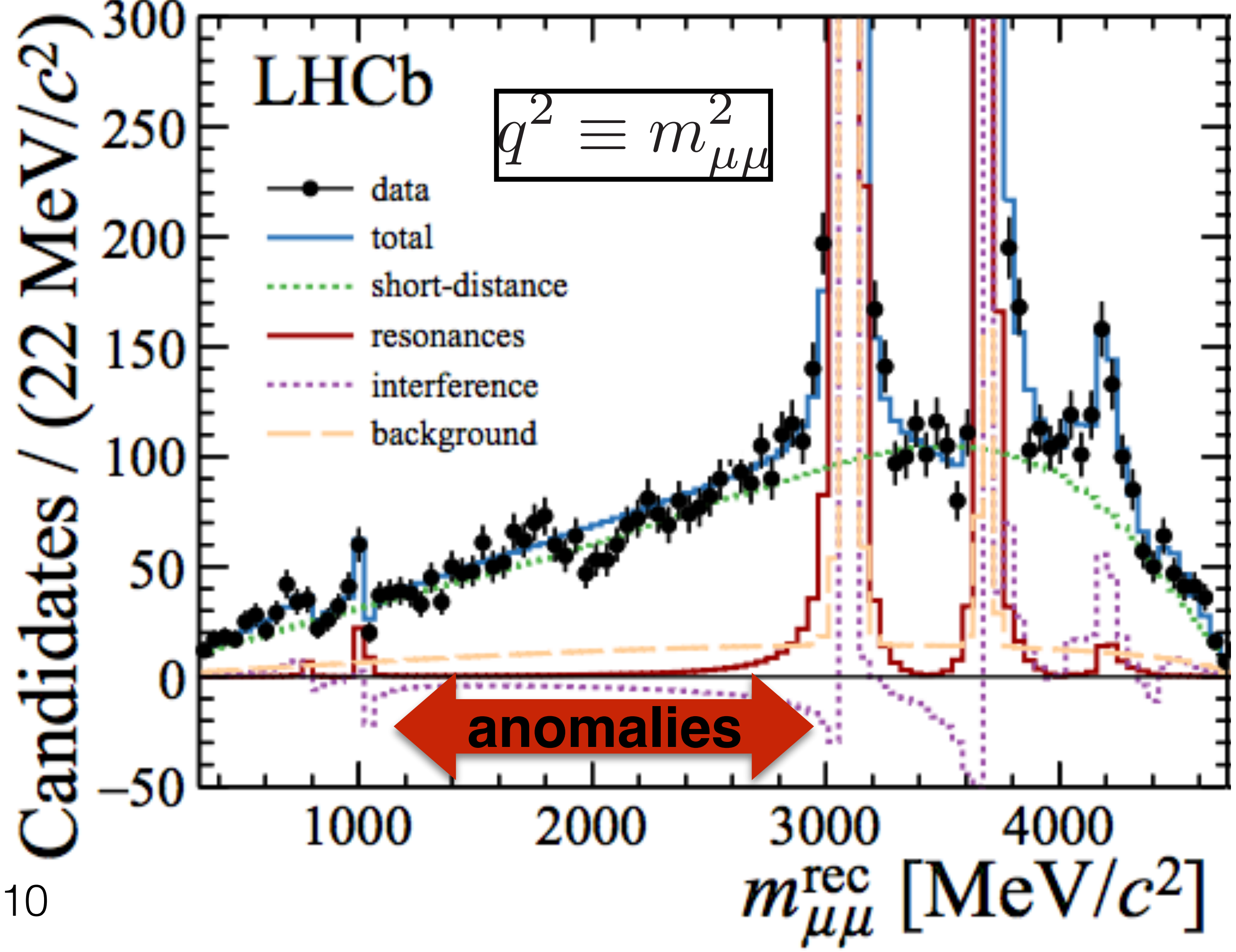
$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + \sum_j \eta_j \underline{e^{i\delta_j}}\, \underline{A_j^{\text{res}}(q^2)}$$

relative phase to C₉

Breit-Wigner/ Flatté Φ(3770)

Resonance	$\psi(2S)$
$\rho(770)$	$\psi(3770)$
$\omega(782)$	$\psi(4040)$
$\phi(1020)$	$\psi(4160)$
J/ψ	$\psi(4415)$

Phase: neg. neg.



Measuring resonance effects in C_9

[arXiv:1612.06764]
submitted to EPJC

NEW!

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

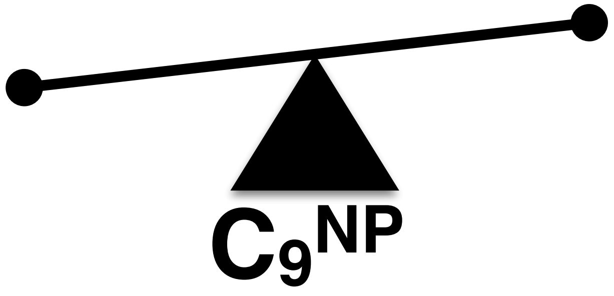
- The **short-distance branching fraction** agrees with the previous (exclusive) result:

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.29 \pm 0.07\,(\text{stat}) \pm 0.21\,(\text{syst})) \times 10^{-7}$$ **old**

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$ **new**

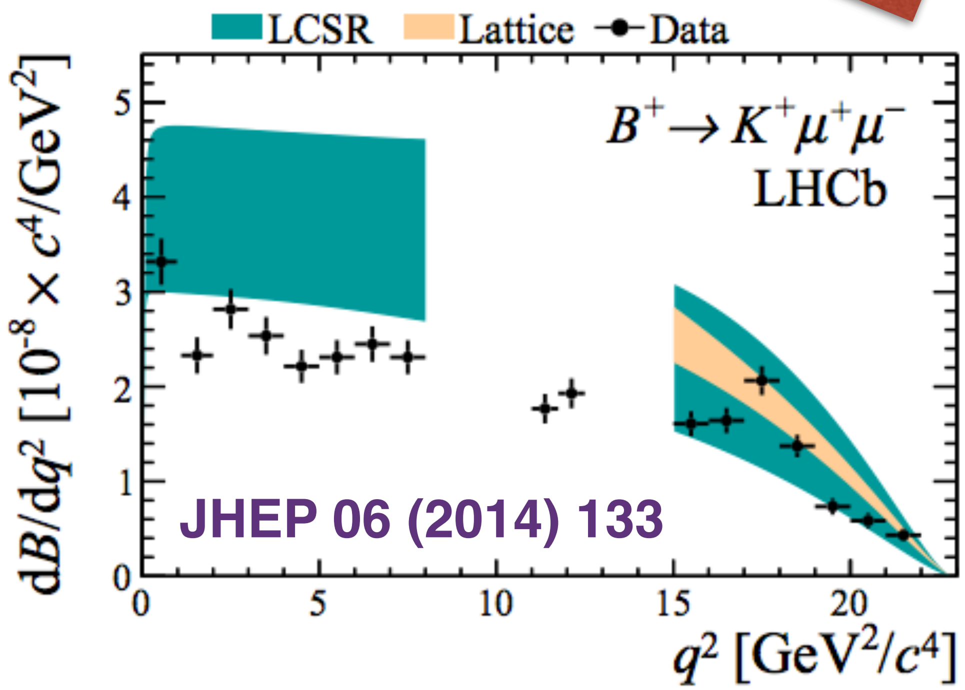
- 1D (C_9,C_{10}=SM) fit: **C_9<SM** (as the global fits)

- 2D (C_9,C_{10}) fit: **C_9>SM** C_{10}<SM (as **[JHEP06(2015)115]**)

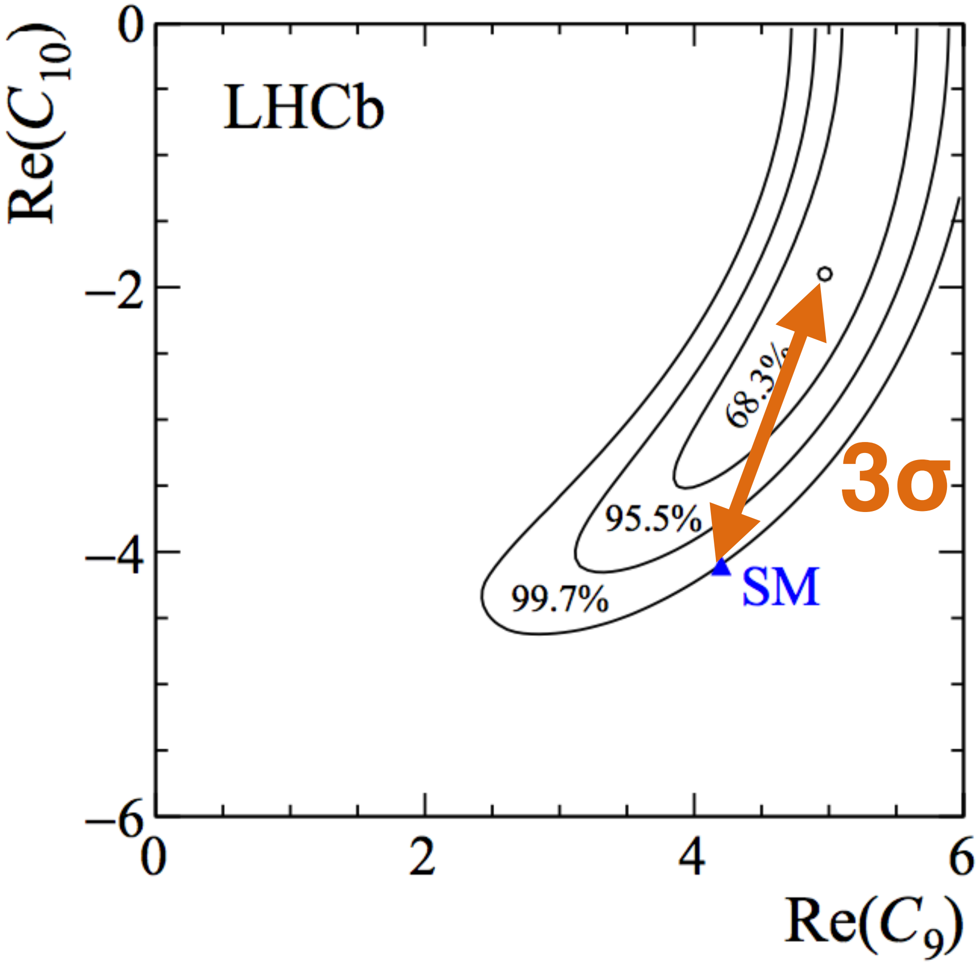


- The main conclusion: contributions from J/ψ and ψ(2S) are contained around their (narrow) resonances.

- Inclusive **$B^0 \to K^*\mu^+\mu^-$** analysis will follow



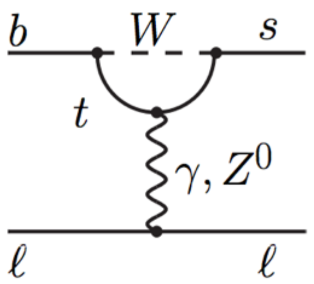
JHEP 06 (2014) 133



Scalar and pseudoscalar Willson cofficients: C_S and C_P

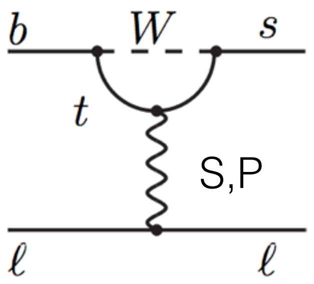
Coefficients C_{10}, C_S and C_P in fully leptonic B decays

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



Semi-leptonic
A-V current

$$\mathcal{Q}_{10}^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu\gamma_5 l)$$



Scalar

$$\mathcal{Q}_{S}^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{s}_{L(R)} b_{R(L)})(\bar{l} l)$$

Pseudo-scalar

$$\mathcal{Q}_{P}^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{s}_{L(R)} b_{R(L)})(\bar{l}\gamma_5 l)$$

- Only **C_{10}** contributes in the Standard Model
- NP sensitivity in **C_S** and **C_P** is larger than in C_{10} (no helicity suppression)
  (K*mumu sensitivity to C_S is lower than initially expected)
- Very precise Standard Model predictions (limited by CKM and B decay constant):

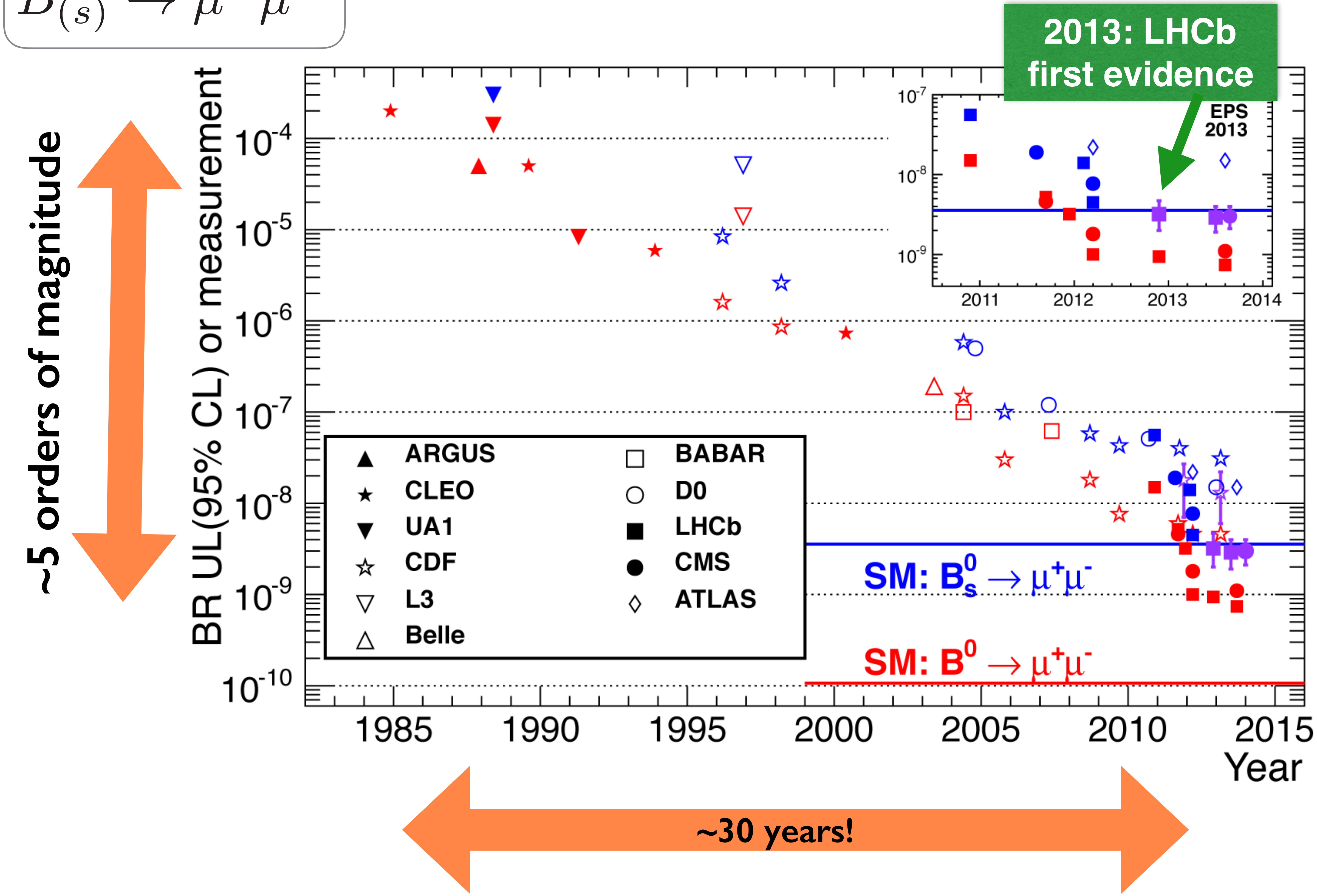
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.59 \pm 0.18) \times 10^{-9}$$

Rel. Unc. from 6.4% -> 5%
Phys. Rev. Lett. 112, 101801 (2014)
updated in arXiv:1702.05498

How long does it take to find a **three-in-a-billion** decay?

$B_{(s)} \to \mu^+\mu^-$

Phys. Rev. Lett. 110, 021801 (2013)



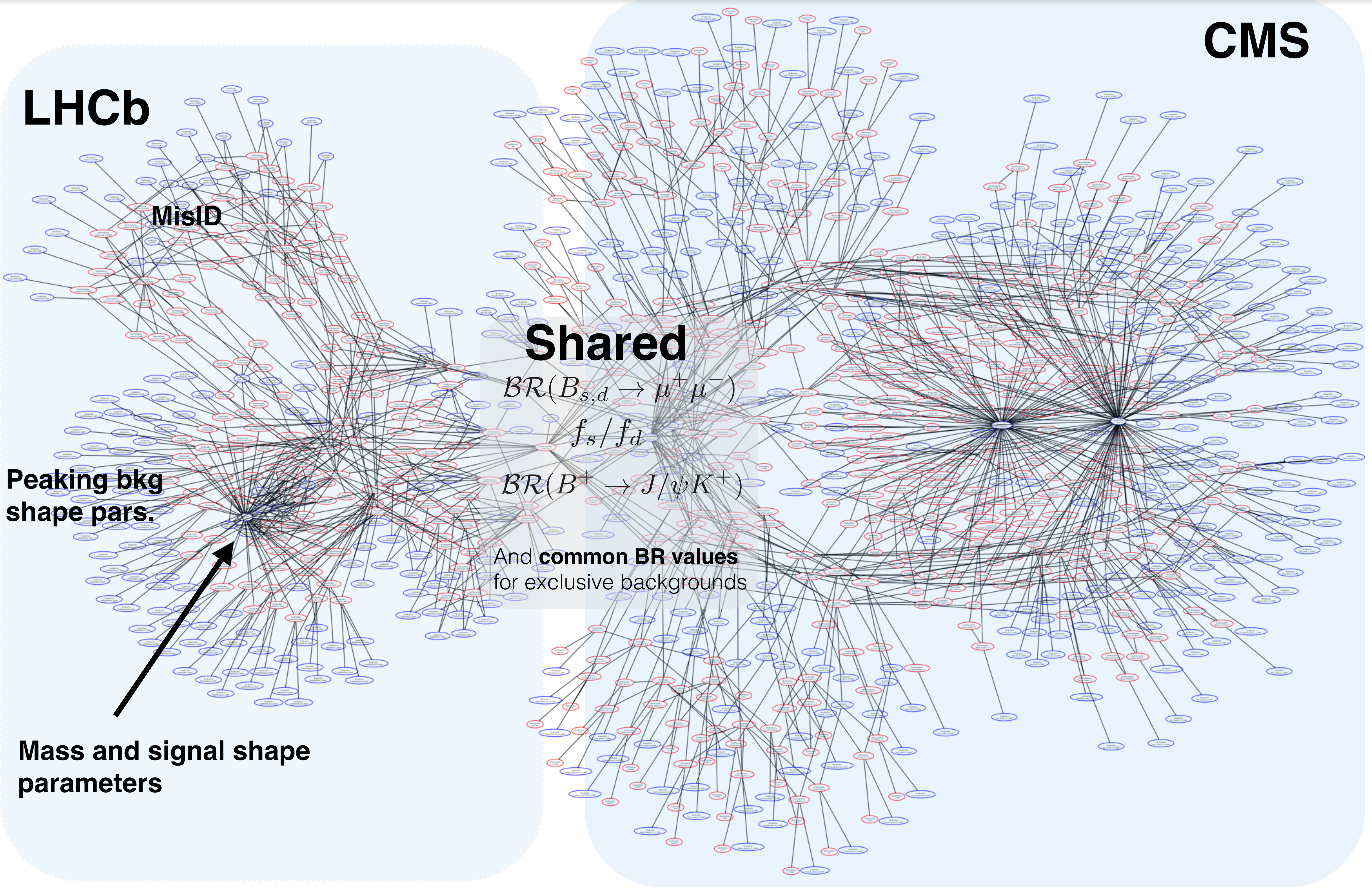
2013: LHCb first evidence

~5 orders of magnitude

~30 years!

Combined CMS and LHCb Run 1 analysis

Nature 522, 68-72 (04 June 2015)



LHCb

CMS

MisID

Peaking bkg shape pars.

Mass and signal shape parameters

Shared

$\mathcal{BR}(B_{s,d} \to \mu^+\mu^-)$

f_s/f_d

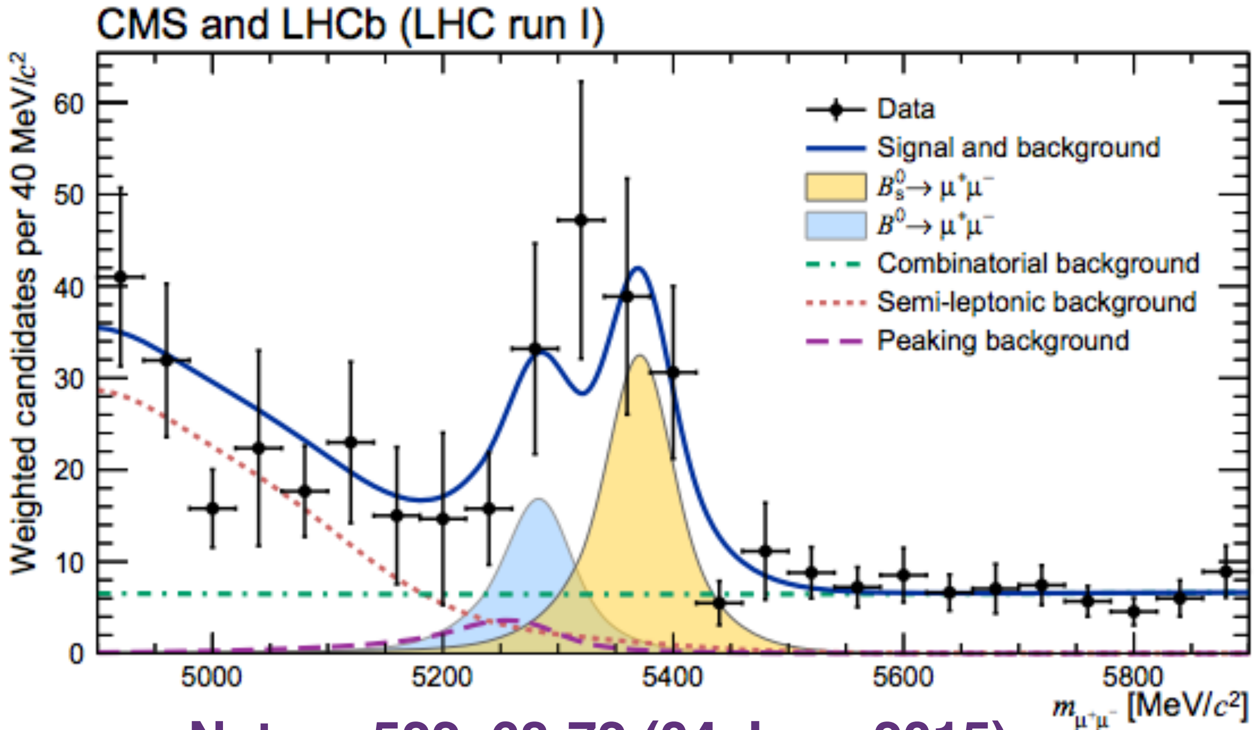
$\mathcal{BR}(B^+ \to J/\psi K^+)$

And **common BR values** for exclusive backgrounds

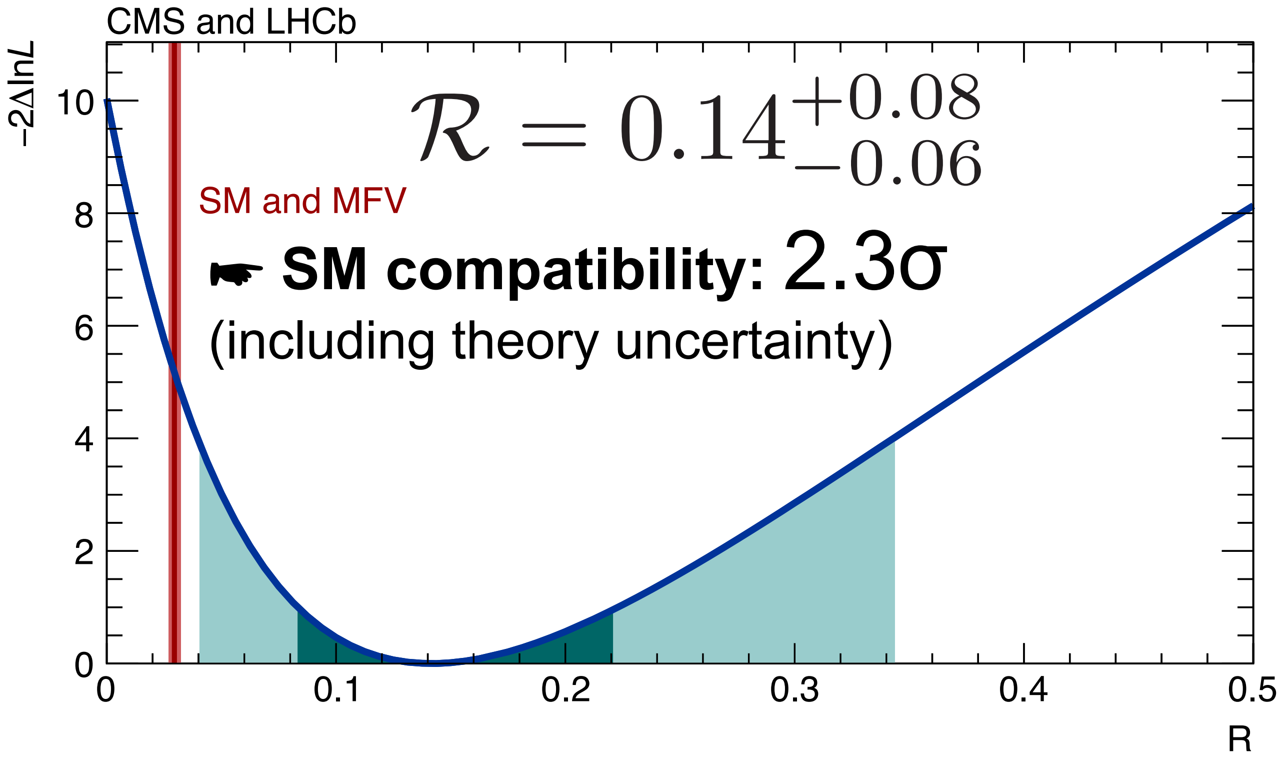
First observation in Run 1

Nature 522, 68-72 (04 June 2015)

$$B_{(s)} \to \mu^+\mu^-$$



Nature 522, 68-72 (04 June 2015)



$$\mathcal{R} = 0.14^{+0.08}_{-0.06}$$

☛ **SM compatibility:** 2.3σ (including theory uncertainty)

- **The fitted central values**

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

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

- **The combined significances** (w.r.t. the null hypothesis, using Wilk's theorem)

6.2σ obs. (expected 7.2σ in SM)

3.2σ obs. (expected 0.8σ in SM)

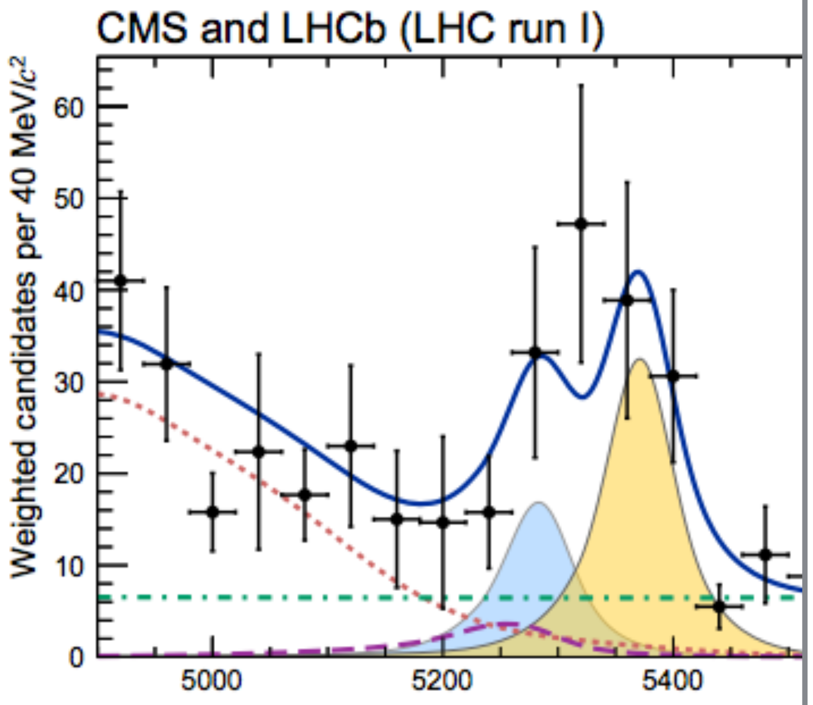
*Cross-checked with Feldman-Cousins: 3.0σ (official significance)

- The first **observation** of **$B_s \to \mu\mu$** decay and the first **evidence** of **$B_d \to \mu\mu$** **(unexpected!)**

First observation in Run 1

Nature 522, 68-72 (04 June 2015)

$$B_{(s)} \to \mu^+\mu^-$$

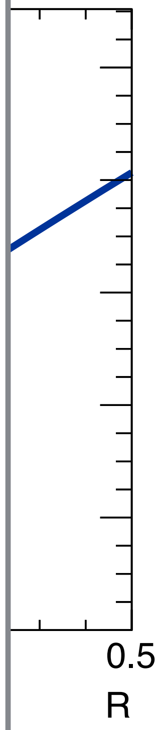


Nature 522, 68-72 (04 Ju

- The fitted central v

$$\mathcal{BR}(B_s \to \mu^+\mu^-) =$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.$$



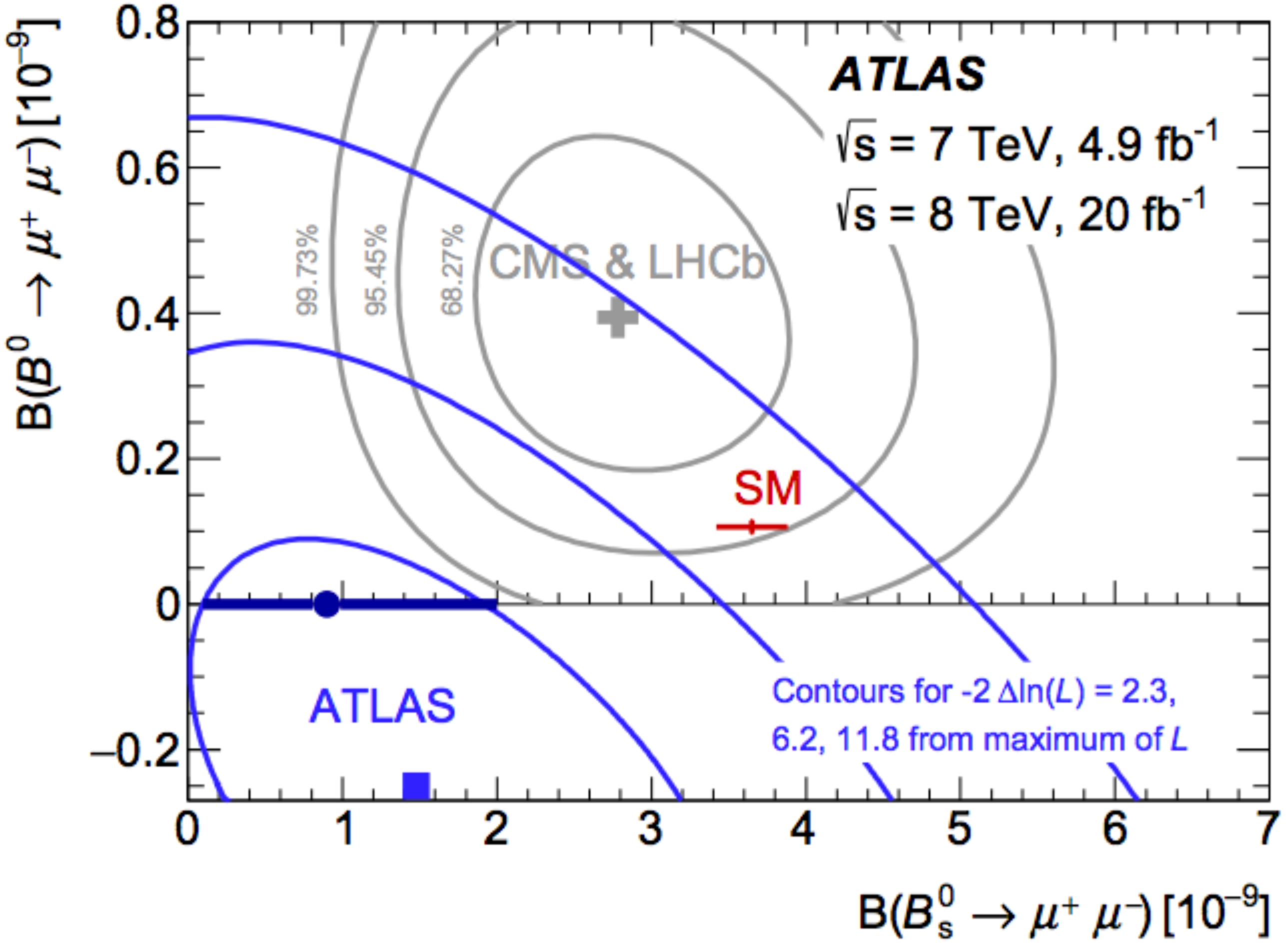
em)

Cross-checked with Feldman-Cousins:

3.0σ (official significance)

- The first **observation** of **B_s→μμ** decay and the first **evidence** of **B_d→μμ (unexpected!)**

ATLAS' Run1 results are compatible



Eur.Phys.J. C76 (2016) no.9, 513

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}\ (2\sigma)$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) < 4.2 \times 10^{-10} (95\% CL)$$

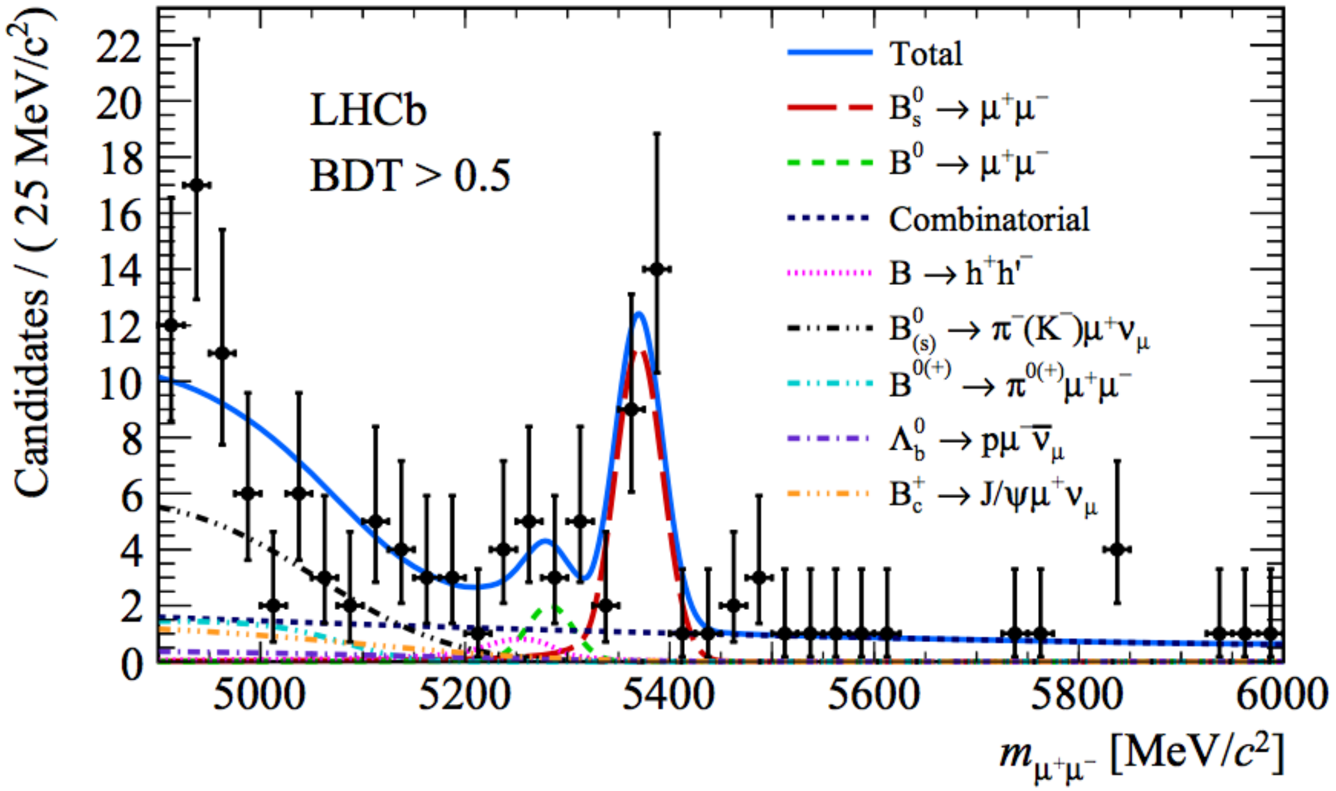
First results from Run 2 (LHCb Run1 + Run2)

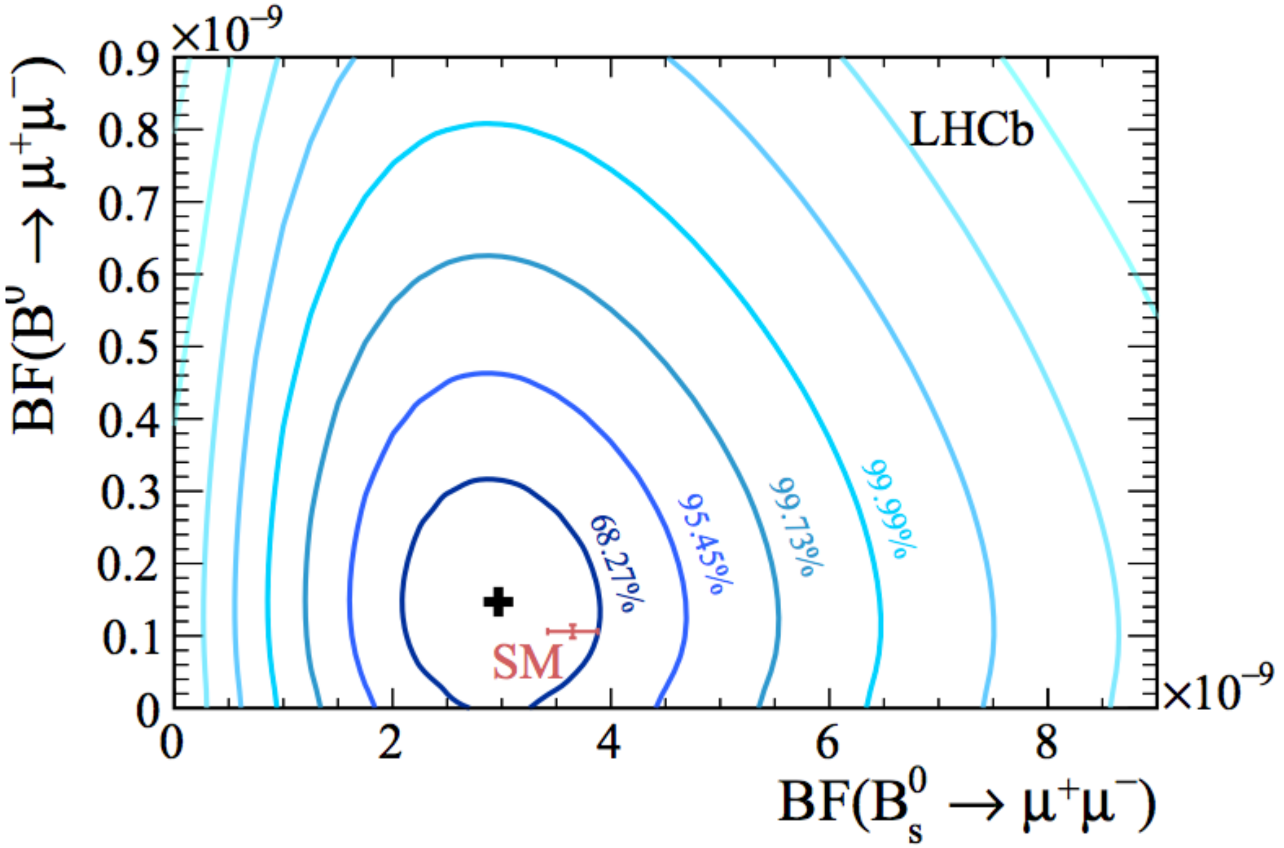
see M.Mulder's talk @ YSF4

NEW!

arXiv:1703.05747
Submitted to PRL

$B_{(s)} \to \mu^+\mu^-$





- **LHCb Run1 data (3fb^{-1}) + 2015 (0.33fb^{-1}) + 2016 (1.4fb^{-1})**
- Several **improvements** compared to the old analysis:
  - better di-hadron background rejection (50%)
  - exclusive background estimates validated on data
  - new isolation variables with improved geometry
- The most precise results up to date;
the **first single experiment** **$B_s \to \mu\mu$ observation**

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

$$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

$B_s \to \mu\mu$ (7.8σ) and $B_d \to \mu\mu$ (1.6σ)

First interpretations of the Run 2 $B_s \to \mu^+\mu^-$ results

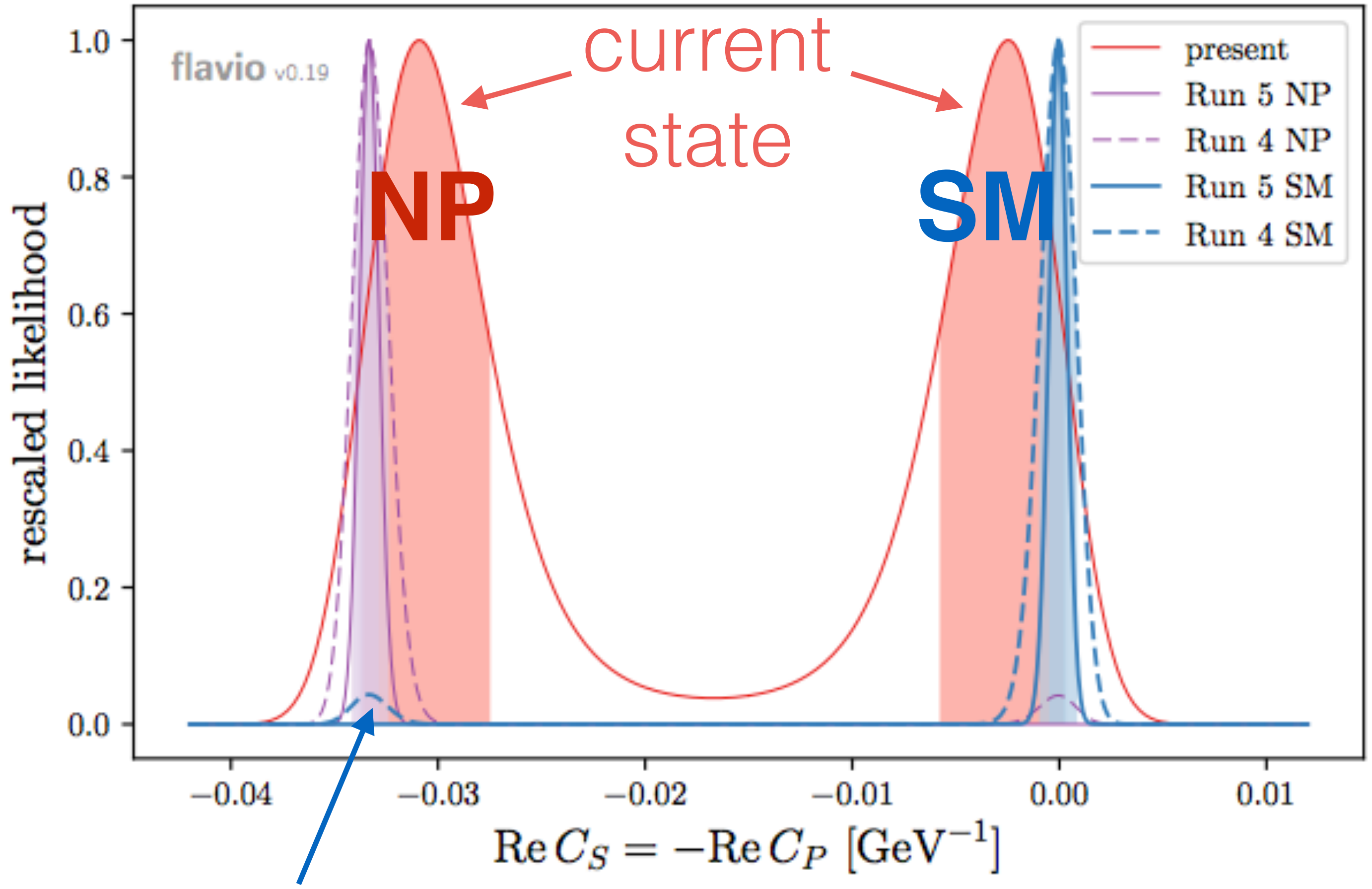
NEW!

arXiv:1703.05747
Submitted to PRL

$$B_{(s)} \to \mu^+\mu^-$$

- Fit for $C_S = -C_P$ (MFV NP e.g. MSSM)

arXiv:1702.05498



- **Ambiguity can be solved** by measuring the **mass-eigenstate-rate asymmetry**:

$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^{\mathrm{H}} \to \mu^+\mu^-) - \Gamma(B_s^{\mathrm{L}} \to \mu^+\mu^-)}{\Gamma(B_s^{\mathrm{H}} \to \mu^+\mu^-) + \Gamma(B_s^{\mathrm{L}} \to \mu^+\mu^-)}$$

Range: **NP [-1.....+1] SM**

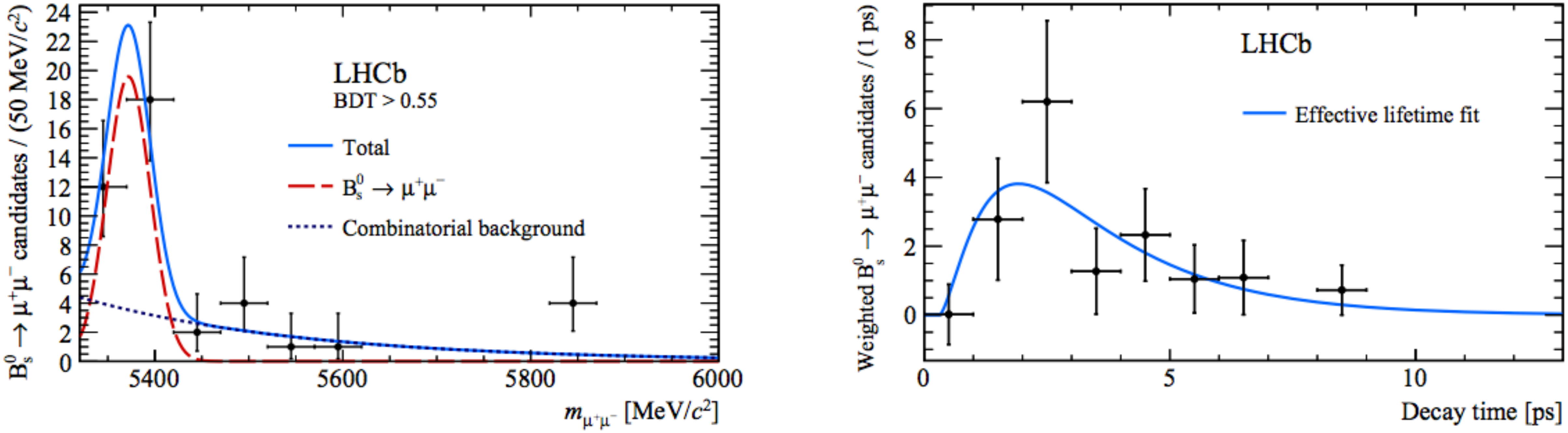
First **effective $B_s \to \mu^+\mu^-$ lifetime** measurement

NEW!

arXiv:1703.05747
Submitted to PRL

$$B_{(s)} \to \mu^+\mu^-$$

- **Mass-eigenstate-rate asymmetry** can be determined from the **$B_s \to \mu\mu$** effective lifetime:



$$\tau(B_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 ps$$

(stat) (syst)

- Compatible with the SM: $\tau(B_s \to \mu^+\mu^-)^{SM} = (1.615 \pm 0.010) ps$
- Proof of concept measurement (no attempt to extract $A_{\Delta\Gamma}$ yet)
- Result consistent with the $A_{\Delta\Gamma}$ = +1(-1) at 1.0σ (1.4σ)

Other **di-lepton decays**

Other di-lepton decays searches

NEW!
Updated results

$B_{(s)} \to \tau^+\tau^-$

- **More abundant than muon mode**

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

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

- Only existing limit is on B_0 mode:

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \quad \text{@ } 90\% \text{ C.L.}$$

Phys.Rev.Lett.96:241802,2006

Bobeth et al, PRL 112 (2014), 101801

- Implications from LFU tests: R_K,$R(D^{(*)})$ ☛ **O(10^3) boost to the BF**?

arXiv:1505.05164

- LHCb analyses Run 1 data (3fb^{-1}) for the **hadronic τ-modes**

$$\mathcal{B}(\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\bar{\nu}_\tau) = (9.31 \pm 0.05)\%$$

..and select the intermediate resonances:

$$\tau^- \to a_1^-(1260)\nu_\tau \to \rho^0(770)\pi^-\nu_\tau$$

- Results with an **updated τ→3body decay model:**

$$\boxed{\begin{array}{l}\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ @ } 95\% CL \\ \mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ @ } 95\% CL\end{array}}$$

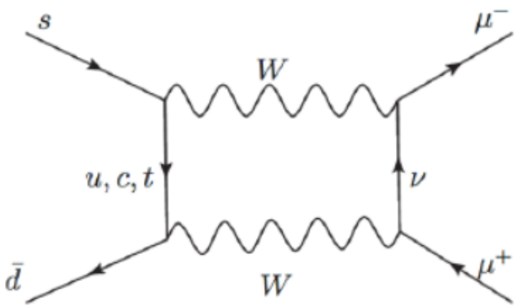
arXiv:1703.02508
Submitted to PRL

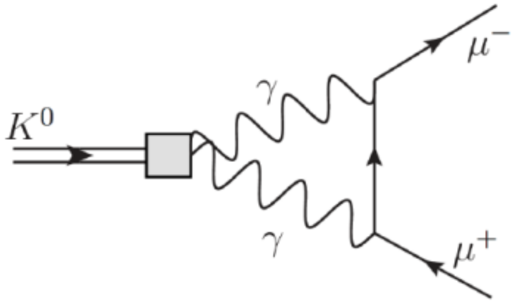
(assuming one of the other B mode)

Other di-lepton decays searches

PRELIMINARY (KAON2016)

$$K_S \to \mu^+\mu^-$$





- Not measured yet…SM expectation: JHEP 0401 (2004) 009

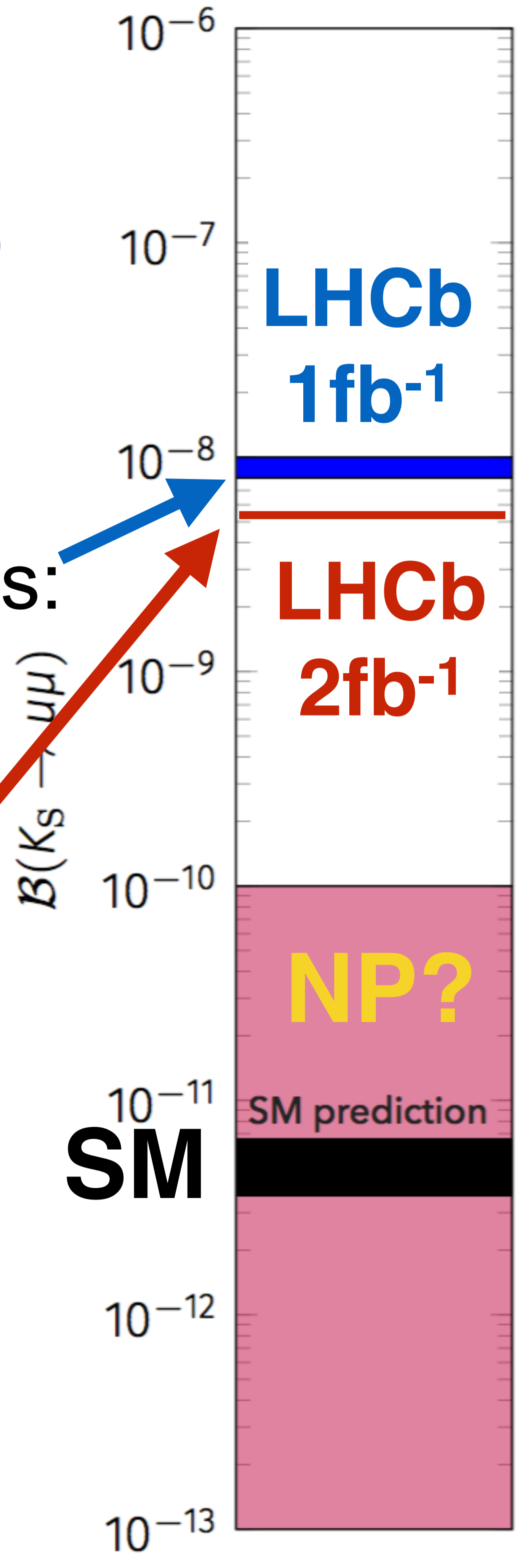
$$\mathcal{B}(K_S \to \mu^+\mu^-)^{SM} = (5.0 \pm 1.5) \times 10^{-12}$$

- LHCb 1fb^{-1} analysis improves previous limit by ~30 times: JHEP 01 (2013) 090

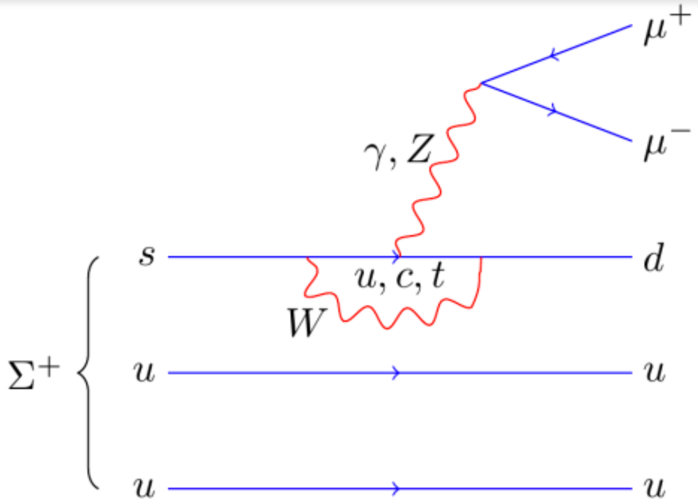
- LHCb 2fb^{-1} analysis:

$$\mathcal{B}(K_S \to \mu^+\mu^-) < 6.9 \times 10^{-9} \text{ @ } 95\% CL$$

Update: KAON2016 result has been revised with a new signal classifier and trigger selection.
Paper with improve will follow (soon)



(Pseudo)scalar resonance searches

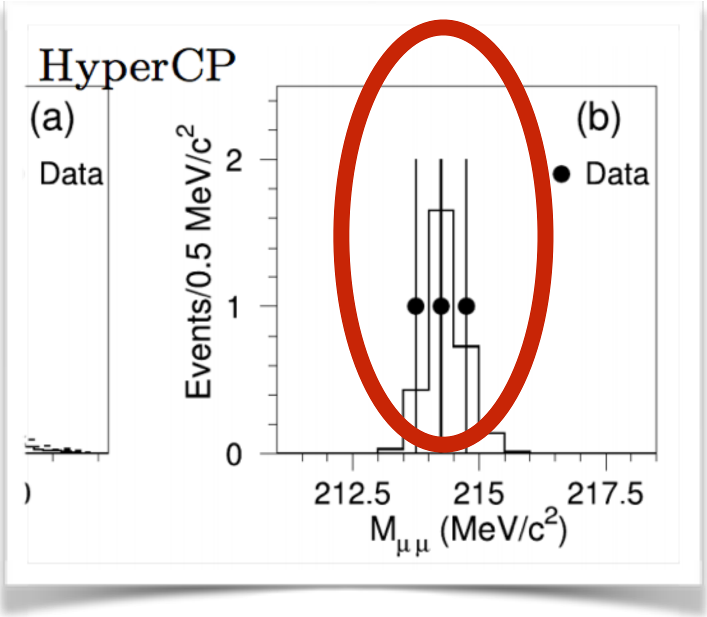


- **In 2005 HyperCP**: Measured $\Sigma^+ \to p\mu^+\mu^-$
  PRL 94 (2005) 021801

$$\mathcal{B}(\Sigma^+ \to p^+\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$$

- **..which agrees to the SM predictions**
  Phys.Rev. D72 (2005) 074003

- …could the di-muon mass be pointing to a new **intermediate P→$\mu^+\mu^-$ resonance at 214 MeV/c²?**

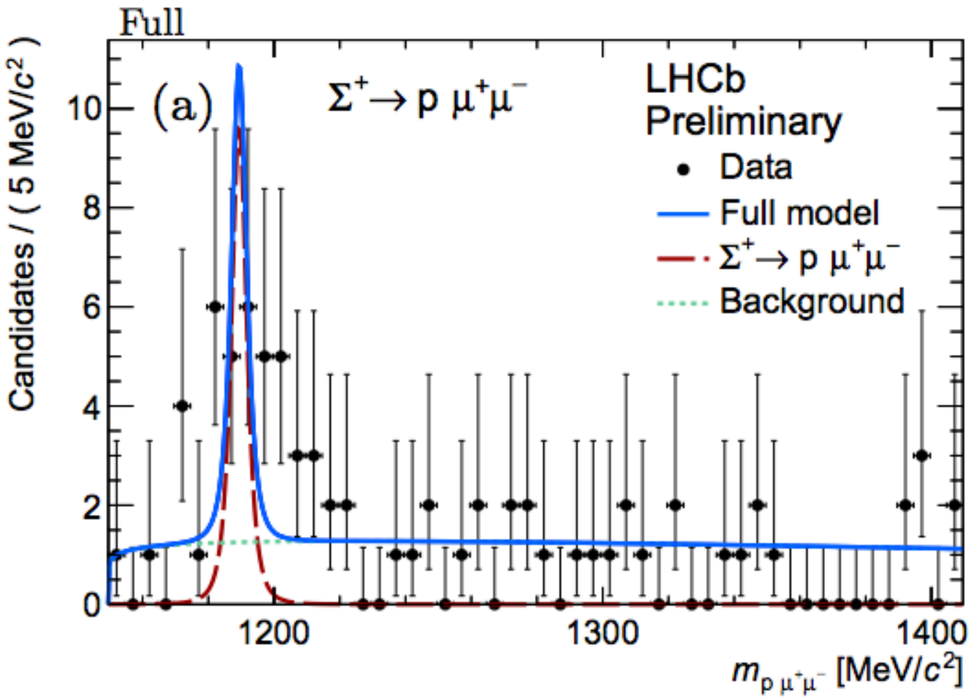


Direct P-resonance searches in LHCb

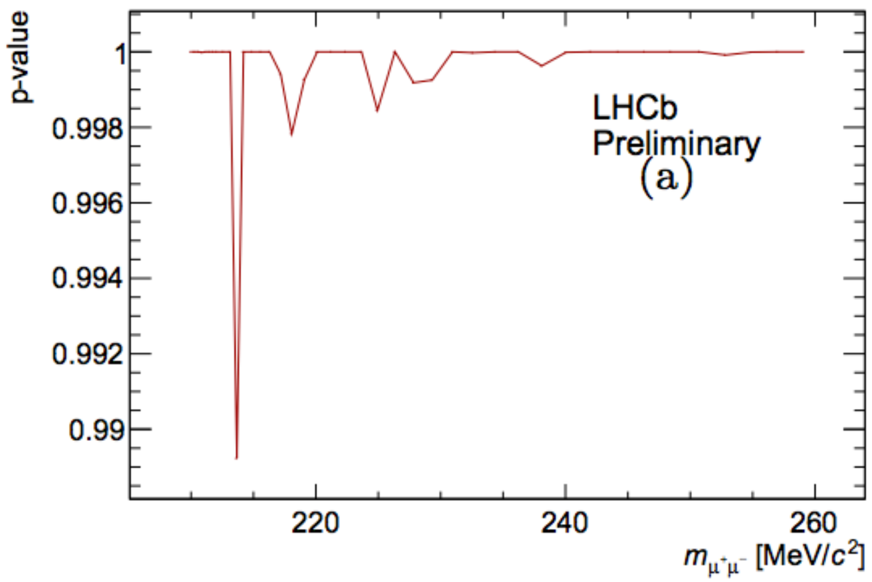
Preliminary

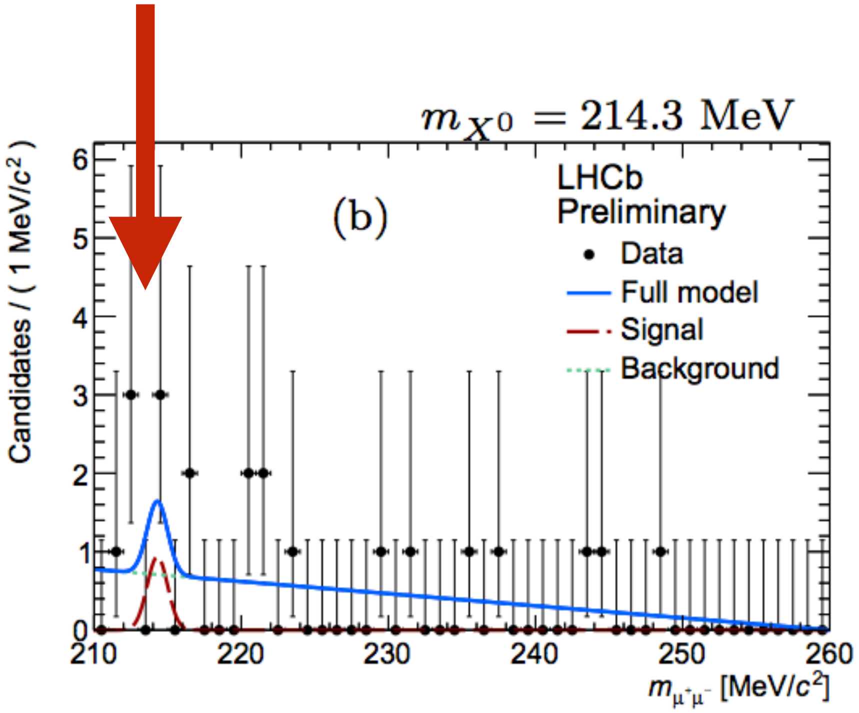
LHCb-CONF-2016-013

$$\Sigma^+ \to p\mu^+\mu^-$$



- **The decay is confirmed:**
  13 candidates (4σ) in LHCb Run 1 data
- **No evidence for a di-muon resonance**
  - example fit around 214MeV
    (fit: 1.6(1.9) candidates)





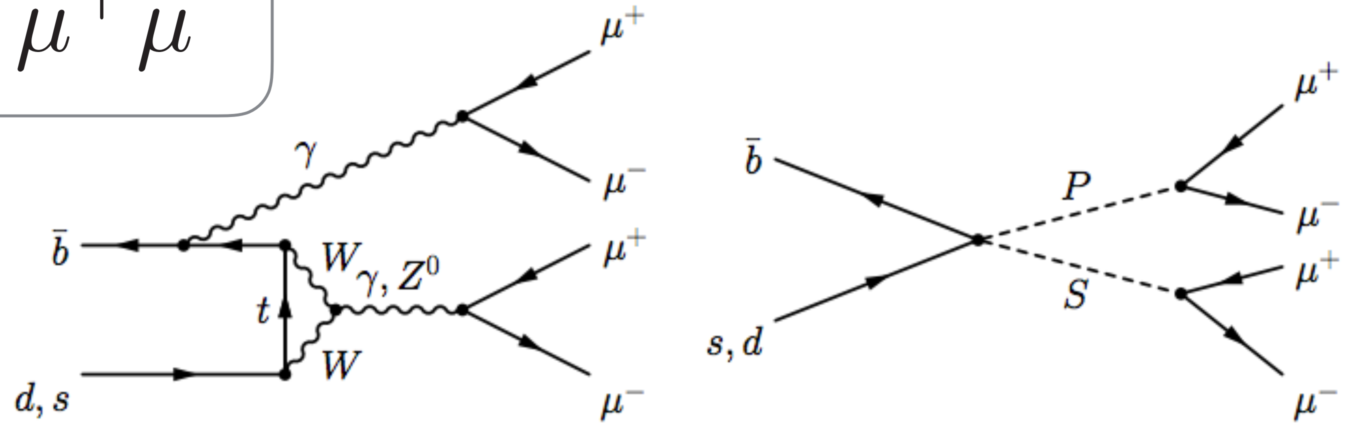
- **Branching ratio results will follow in a paper** (precision at HyperCP level)

Indirect P(S)-resonance searches in LHCb

NEW!

JHEP 03 (2017) 001

$$B_{(s)} \to \mu^+\mu^-\mu^+\mu^-$$



- Very low **non-resonant SM predictions: $3.5*10^{-11}$**
  Phys.Lett. B556 (2003) 169-176
- Sensitive to **intermediate resonances** (MSSM sgoldsino's, P(S)→$\mu^+\mu^-$)
- New analysis includes many improvements to the analysis (normalisation, multivariate selection) and an additional 2fb^{-1} of Run 1 data.
- **New improved upper limits with the full 3fb^{-1} Run 1 data:**

Mode	1 fb^{-1}	3 fb^{-1}	f
$B_s^0 \to \mu^+\mu^-\mu^+\mu^-$	$< 1.6 \times 10^{-8}$	$< 2.5 \times 10^{-9}$	6.4
$B^0 \to \mu^+\mu^-\mu^+\mu^-$	$< 6.6 \times 10^{-9}$	$< 6.9 \times 10^{-10}$	9.5
$B_s^0 \to S(\mu^+\mu^-)P(\mu^+\mu^-)$	$< 1.6 \times 10^{-8}$	$< 2.2 \times 10^{-9}$	7.3
$B^0 \to S(\mu^+\mu^-)P(\mu^+\mu^-)$	$< 6.3 \times 10^{-9}$	$< 6.0 \times 10^{-10}$	10.5

(for the S/P scenario, assume short lived m(S) of 2.6GeV and m(P) of 214.3MeV)

Summary

➽ See all the LHCb results

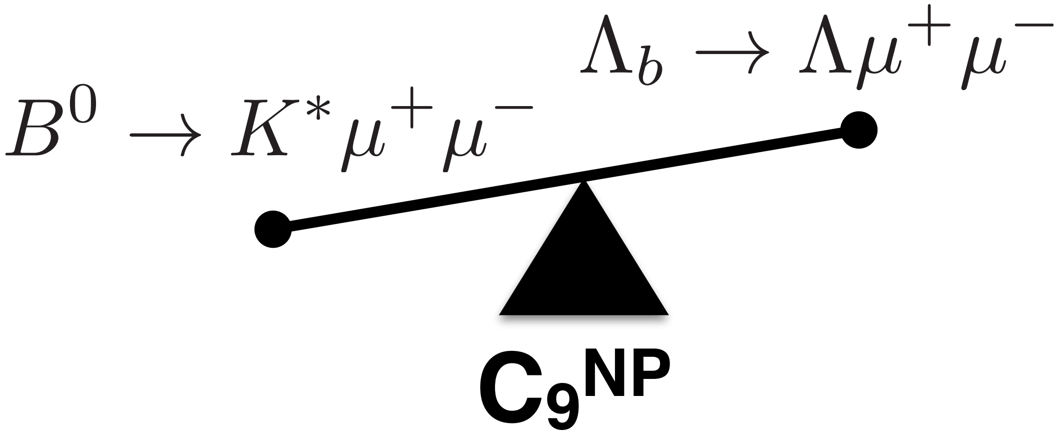
- **Tensions in semi-leptonic Wilson coefficients are well established by several independent global (b-sl^+l^-) fits.**
  - ☛ resonance contributions to C_9 not likely to be the cause: effects contained to the narrow resonance regions (inclusive **$B^+ \rightarrow K^+\mu^+\mu^-$** analysis).
- The LHCb Run1+2 $B^0_{(s)} \rightarrow \mu^+\mu^-$ analysis shows a SM like $B_s \rightarrow \mu^+\mu^-$ at 7.8σ; $B_d \rightarrow \mu^+\mu^-$ excess is not confirmed.
- (Pseudo)scalar contributions ambiguities can be solved by an **effective $B^0_s \rightarrow \mu^+\mu^-$ lifetime** measurement. First (statistics limited) results available.
- No large NP effects seen in other rare leptonic modes: $B^0_{(s)} \rightarrow \tau^+\tau^-$, $B^0_{(s)} \rightarrow \mu^+\mu^-\mu^+\mu^-$ or $K_S \rightarrow \mu^+\mu^-$. LHCb sets new strong new limits.
- $\Sigma^+ \rightarrow p\mu^+\mu^-$ confirmed, alas no sign of a pseudoscalar di-muon resonance.
- **Serious tensions in** (several) **LFU tests**:
  R($D^{(*)}$) (third/second generation) ~ 3.9σ
  R(K) (second/first generation) ~ 2.6σ

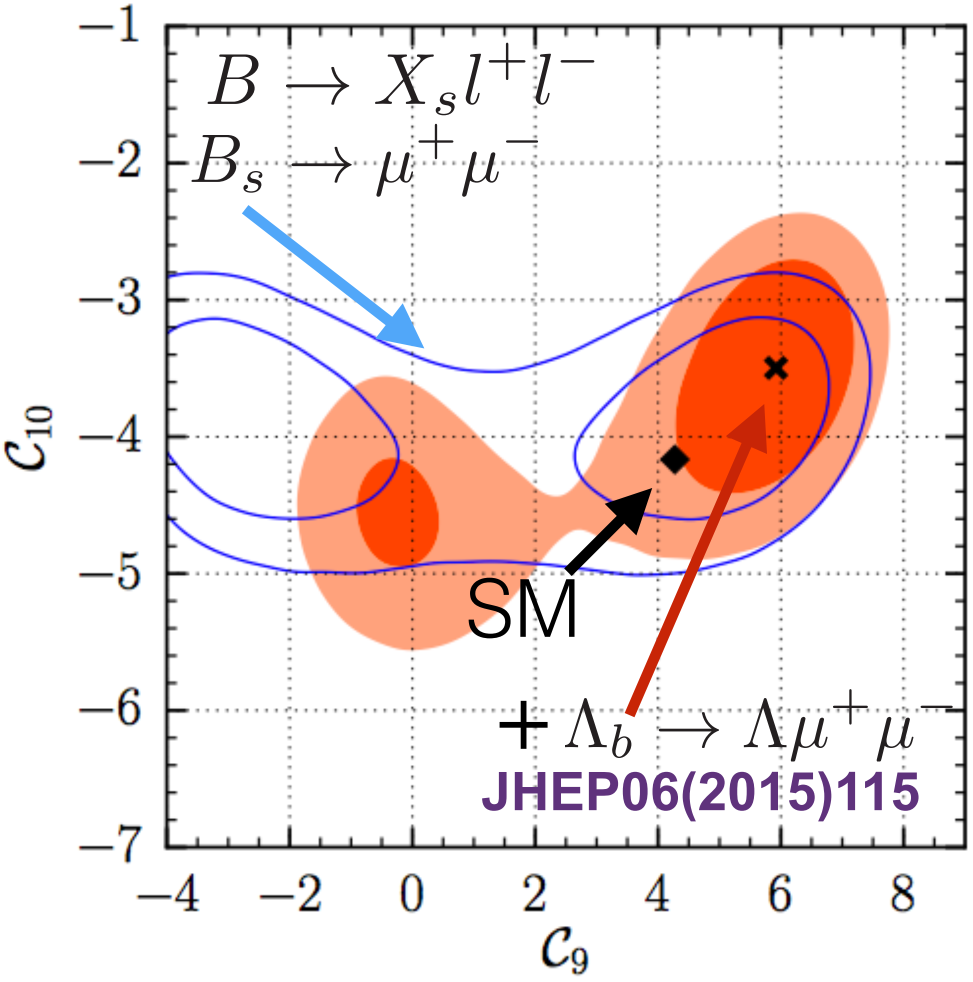
The Wil sis:

➽ A (simpler) global fit including $\Lambda_b \to \Lambda\mu^+\mu^-$ shows a mild **opposite effect on C9**:

Note the different setup:

- ☛ no K*mm, excl. b→sl+l-
- ☛ fit both $C_{9,10}$.
- ☛ no constraint on C_9=-C_{10}





JHEP06(2015)115

arXiv:1603.02974

Excellent review: **[arXiv:1606.00916]**

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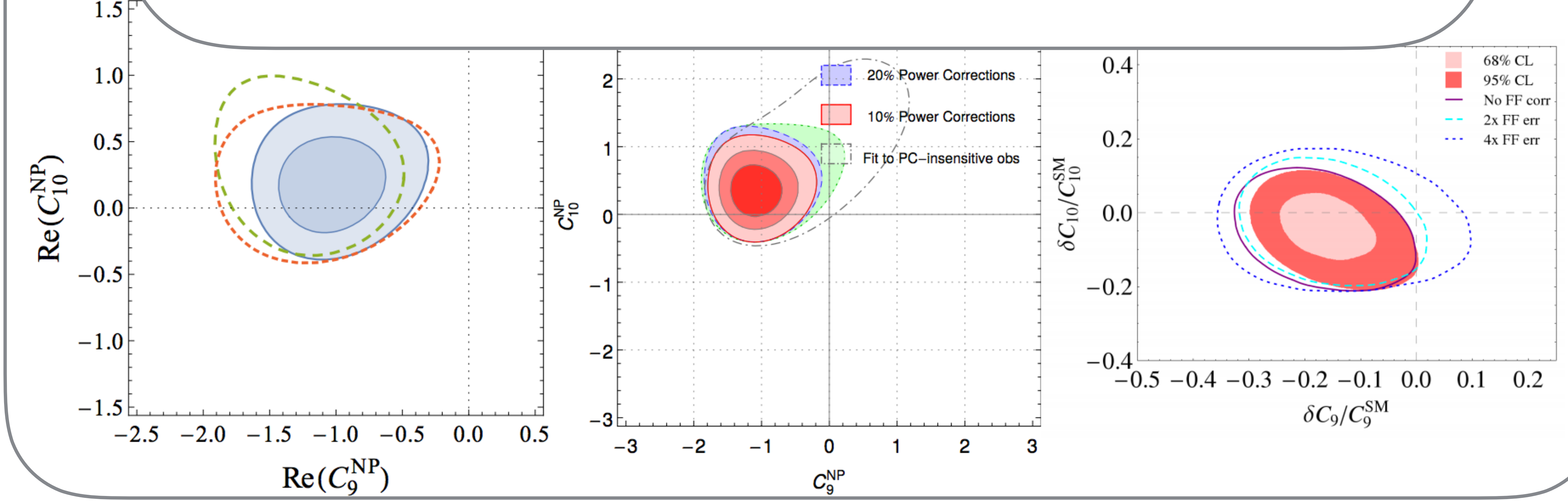


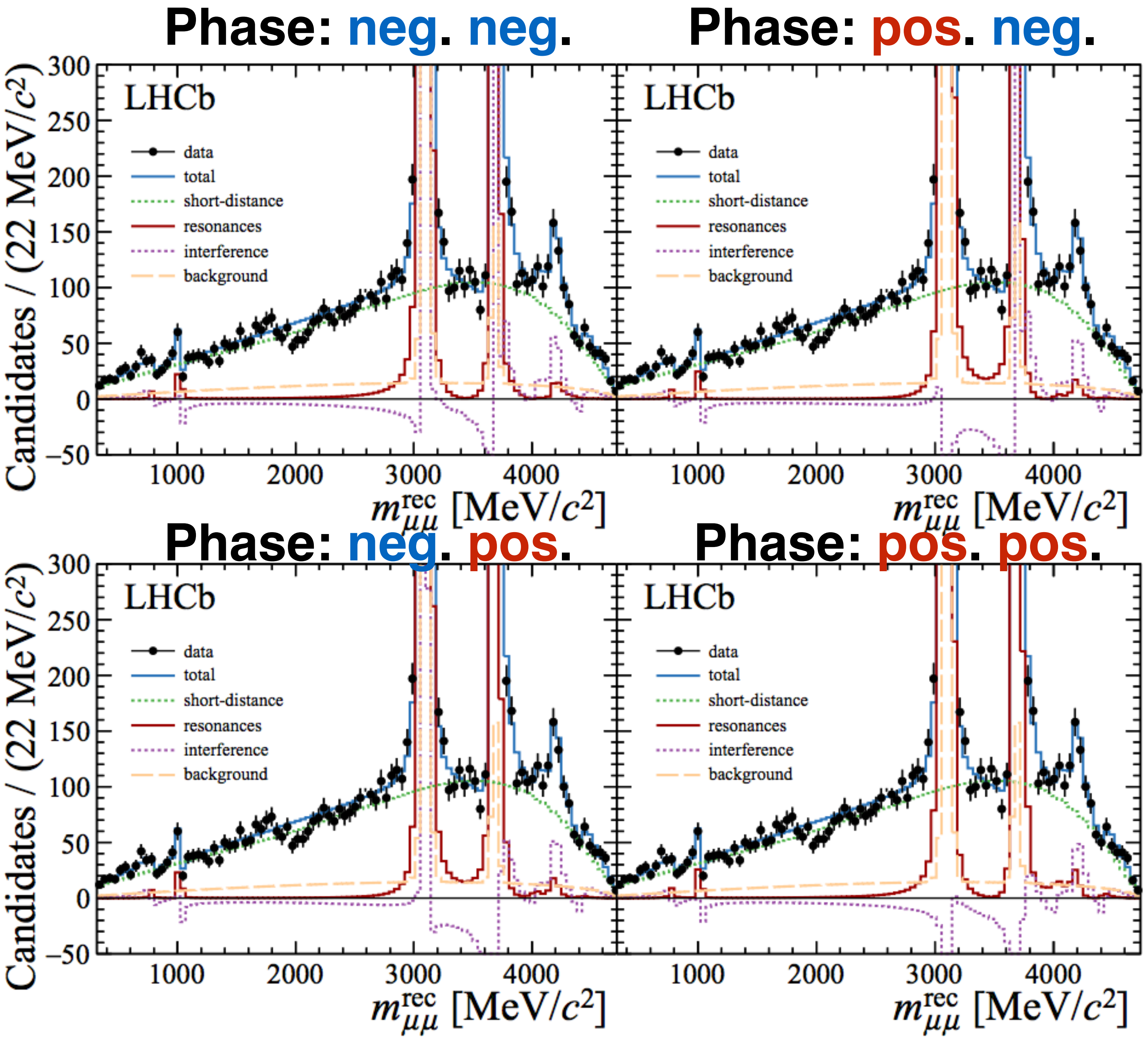
Measuring **resonance effects in C_9**

[arXiv:1612.06764]
submitted to EPJC

NEW!

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

- Four degenerate Jpsi and psi2S phase sign choices:



Phase: neg. neg.

Phase: pos. neg.

Phase: neg. pos.

Phase: pos. pos.

Coefficients C_{10}, C_S and C_P in fully leptonic B decays

$$B_{(s)} \to \mu^+\mu^-$$

- Only C_{10} contributes in the Standard Model
- NP sensitivity in C_S and C_P is larger than in C_{10} (no helicity suppression)
  (K*mumu sensitivity to C_S is lower than initially expected)

$$\frac{\mathrm{BR}(B_q \to \ell^+\ell^-)}{\mathrm{BR}(B_q \to \ell^+\ell^-)_{\mathrm{SM}}} = \frac{|S|^2\left(1-\frac{4m_\ell^2}{m_{B_q}^2}\right)+|P|^2}{|C_{10}^{\mathrm{SM}}|^2}$$

SM: S=0

SM: P=1

$$S = \frac{m_{B_q}^2}{2m_\ell}\left[(C_S)_q^\ell - (C'_S)_q^\ell\right] \quad P = \left[(C_{10})_q^\ell - (C'_{10})_q^\ell\right] + \frac{m_{B_q}^2}{2m_\ell}\left[(C_P)_q^\ell - (C'_P)_q^\ell\right]$$

- Very precise Standard Model predictions (limited by CKM and B decay constant):

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.59 \pm 0.18) \times 10^{-9}$$

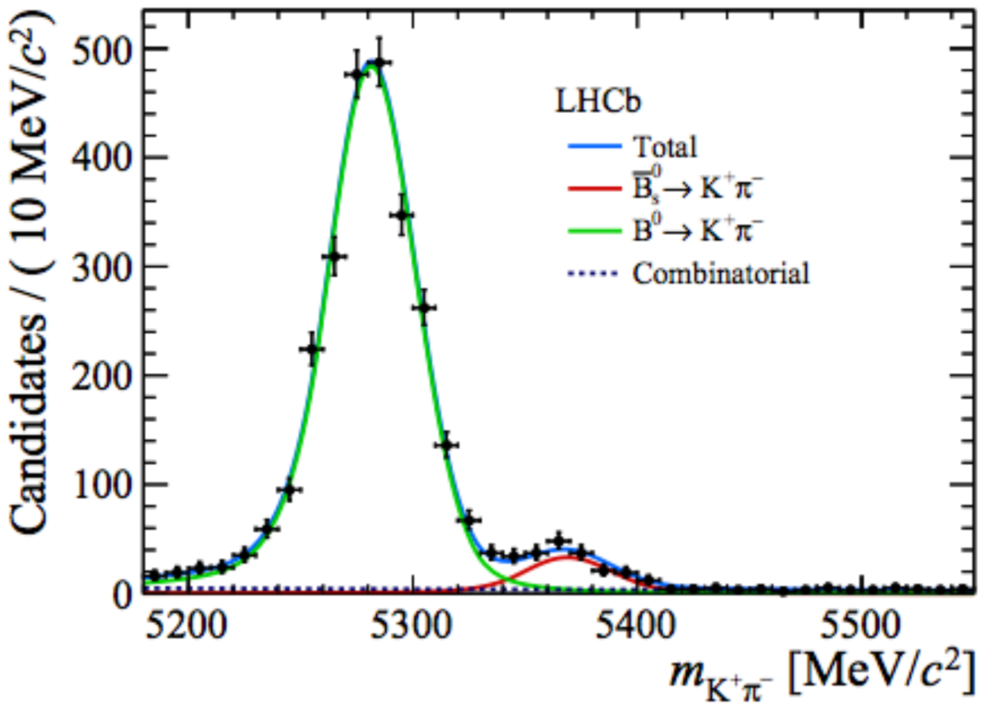
Rel. Unc. from 6.4% -> 5%

Phys. Rev. Lett. 112, 101801 (2014)

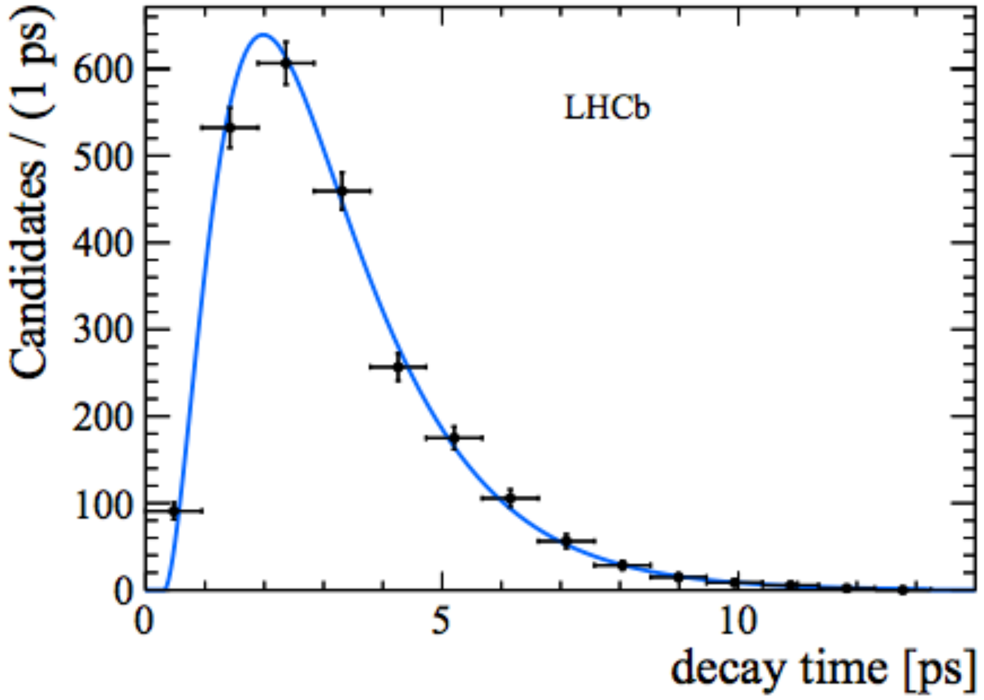
updated in arXiv:1702.05498

Effective lifetime analysis strategy confirmation on $B_d \to K^+\pi^-$

$B_{(s)} \to \mu^+\mu^-$



The use of simulated events to determine the decay-time acceptance function is validated by measuring the effective lifetime of $B^0 \to K^+\pi^-$ decays selected in data

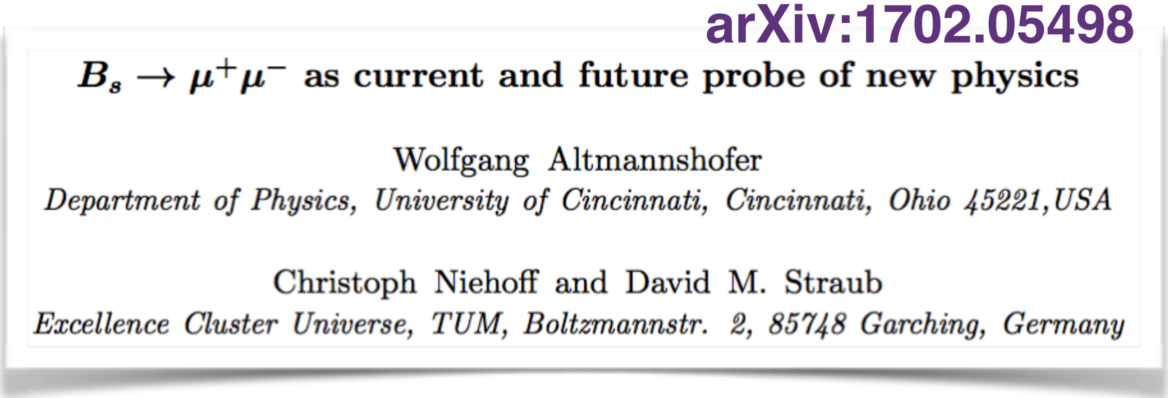


The measured $B^0 \to K^+\pi^-$ effective lifetime is 1.52 ± 0.03 ps, where the uncertainty is statistical only. The statistical unc. in assigned as a systematic to the effective **$B_s \to \mu\mu$** lifetime measurement.

MSSM with MFV (present)

$B_{(s)} \to \mu^+\mu^-$

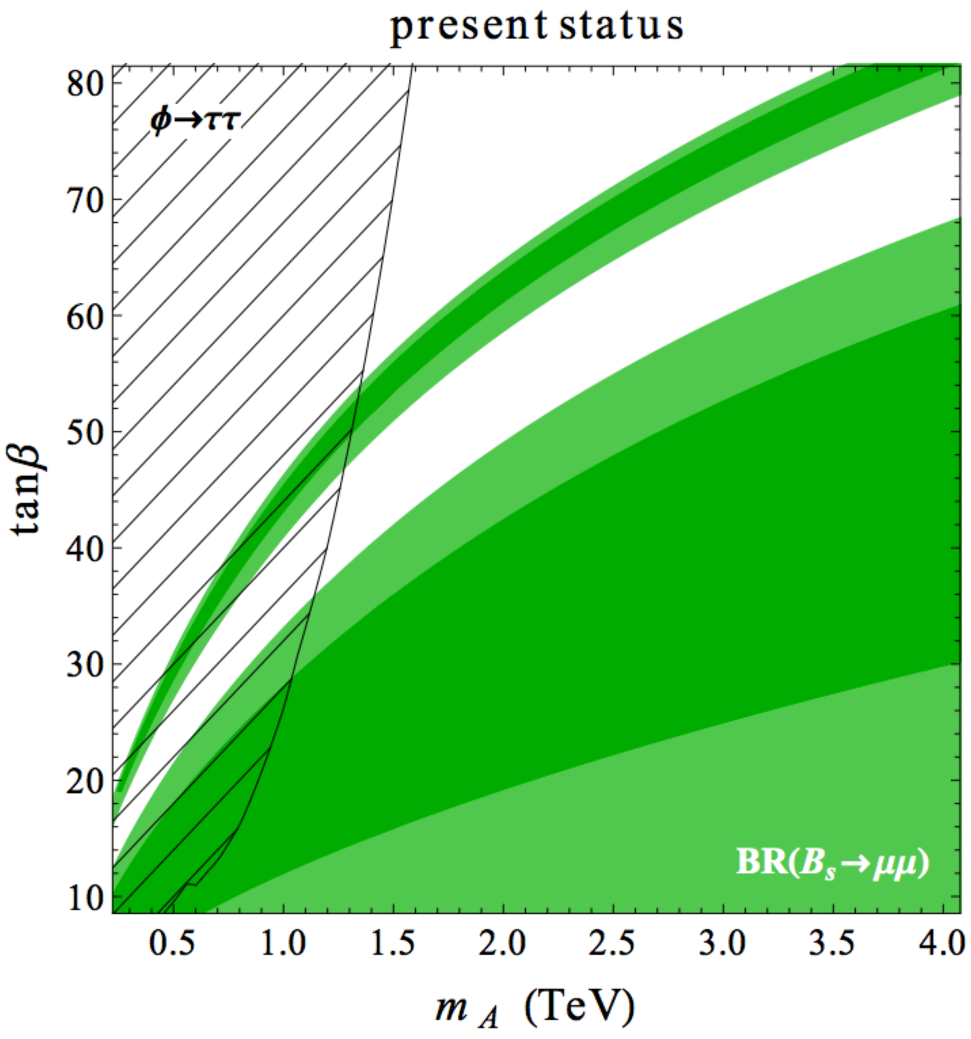
arXiv:1702.05498



$B_s \to \mu^+\mu^-$ as current and future probe of new physics

Wolfgang Altmannshofer
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221,USA

Christoph Niehoff and David M. Straub
Excellence Cluster Universe, TUM, Boltzmannstr. 2, 85748 Garching, Germany



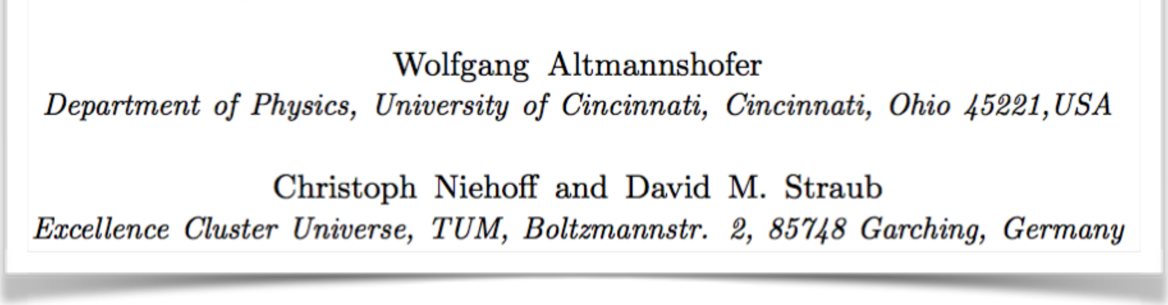
Green=allowed

FIG. 5. Current constraints in the m_A - $\tan\beta$ plane in the MSSM scenario discussed in the text. The dark and light green shaded regions are *allowed* by the $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$ measurements at the 1σ and 2σ level. The black hatched region is *excluded* by direct searches for $\tau^+\tau^-$ resonances. Throughout the plot the light Higgs mass is $m_h = 125$ GeV.

MSSM with MFV (projections)

$$B_{(s)} \to \mu^+\mu^-$$

arXiv:1702.05498



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$$\sigma_{\rm exp}(B_s \to \mu^+\mu^-) = 0.19\,, \quad \sigma_{\rm exp}(A_{\Delta\Gamma}) = 0.8\,, \quad \text{for } 50 \text{ fb}^{-1} \quad (\text{“Run 4”}),$$
$$\sigma_{\rm exp}(B_s \to \mu^+\mu^-) = 0.08\,, \quad \sigma_{\rm exp}(A_{\Delta\Gamma}) = 0.3\,, \quad \text{for } 300 \text{ fb}^{-1} \quad (\text{“Run 5”}).$$

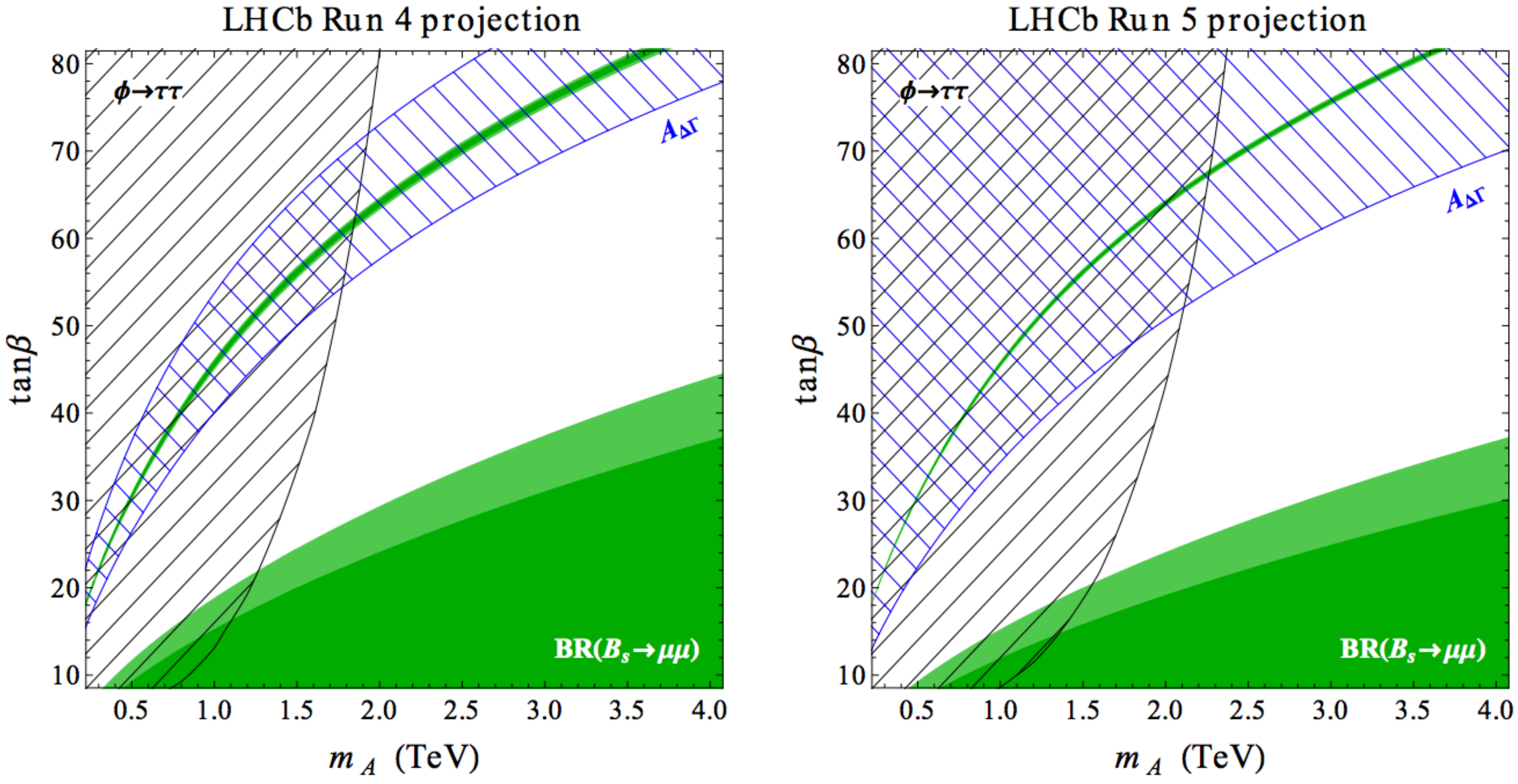


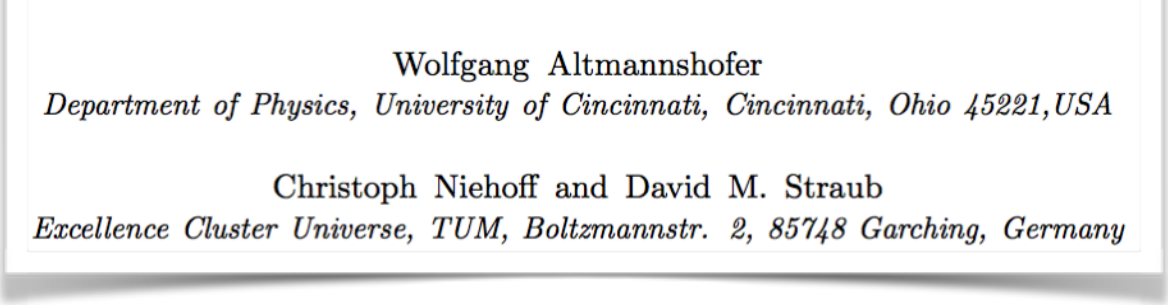
FIG. 6. Expected sensitivities in the m_A - $\tan\beta$ plane in the MSSM scenario discussed in the text. Left: integrated luminosities of 50 fb^{-1} at LHCb and 300 fb^{-1} at CMS and ATLAS. Right: integrated luminosities of 300 fb^{-1} at LHCb and 3000 fb^{-1} at CMS and ATLAS. The dark and light green shaded regions will be *allowed* by the expected $\overline{\rm BR}(B_s \to \mu^+\mu^-)$ sensitivity at the 1σ and 2σ level, assuming the SM rate. The black hatched region could be *excluded* by direct searches for $\tau^+\tau^-$ resonances assuming no non-standard signal. The blue hatched region can be covered by measurements of the mass-eigenstate rate asymmetry $A_{\Delta\Gamma}$. In both plots the light Higgs mass is $m_h = 125$ GeV.

Green=allowed

Leptoquarks

$$B_{(s)} \to \mu^+\mu^-$$

arXiv:1702.05498



$B_s \to \mu^+\mu^-$ as current and future probe of new physics

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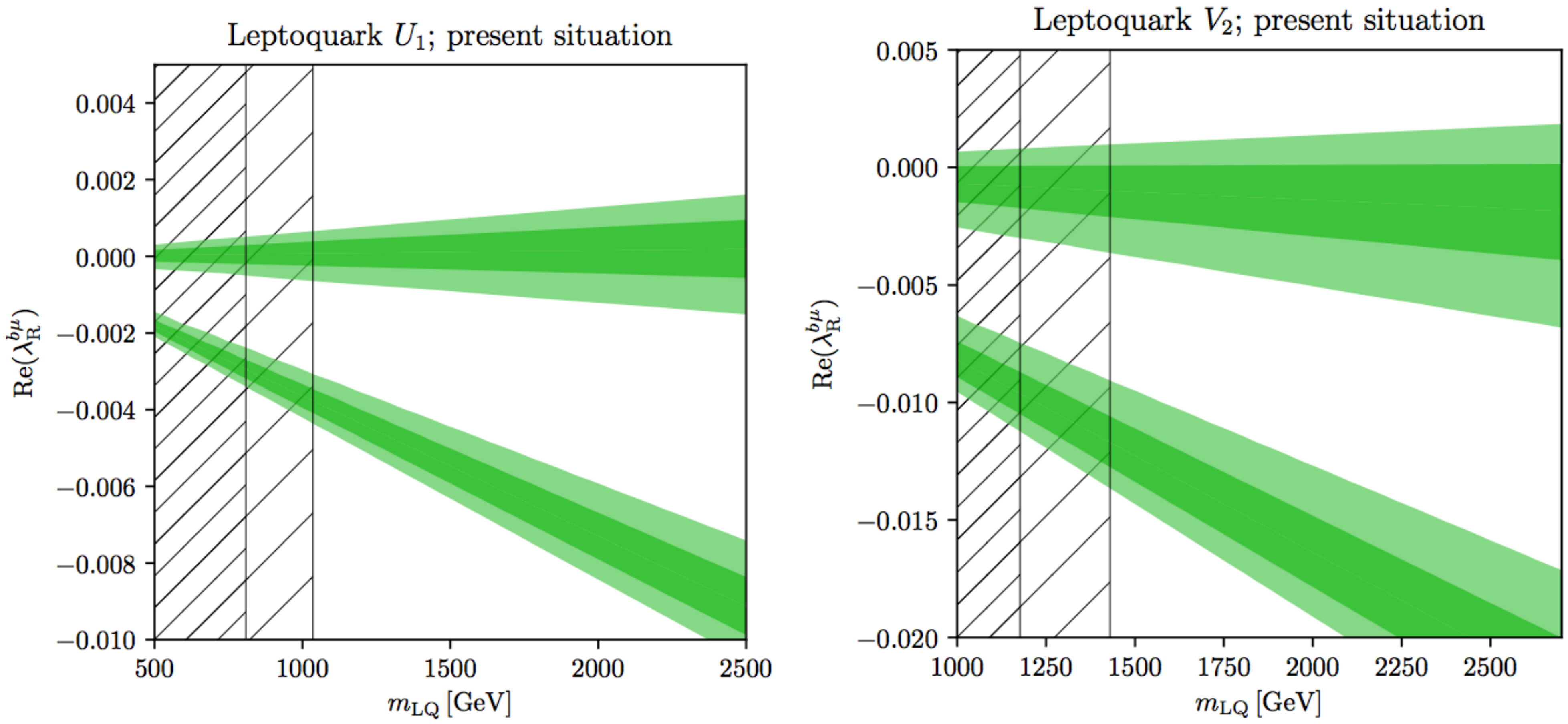
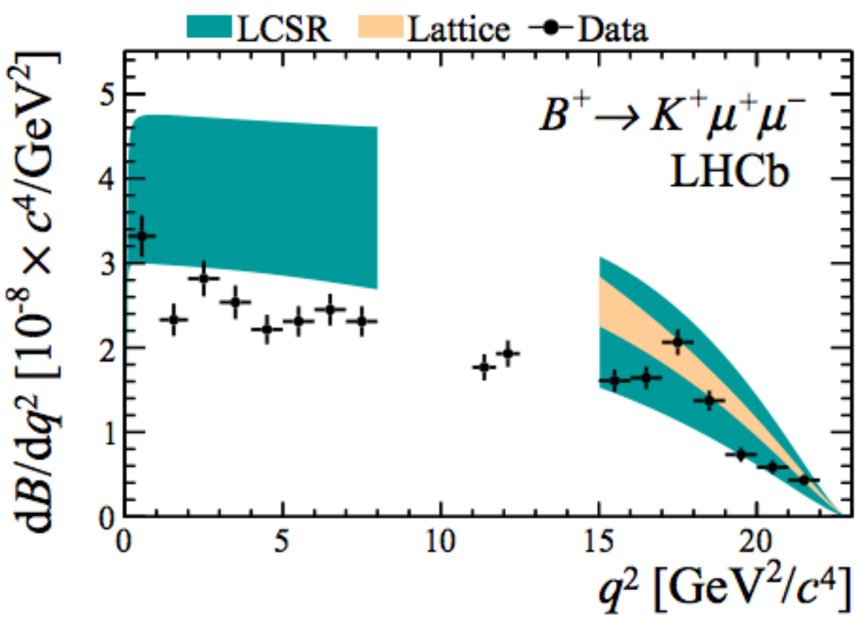
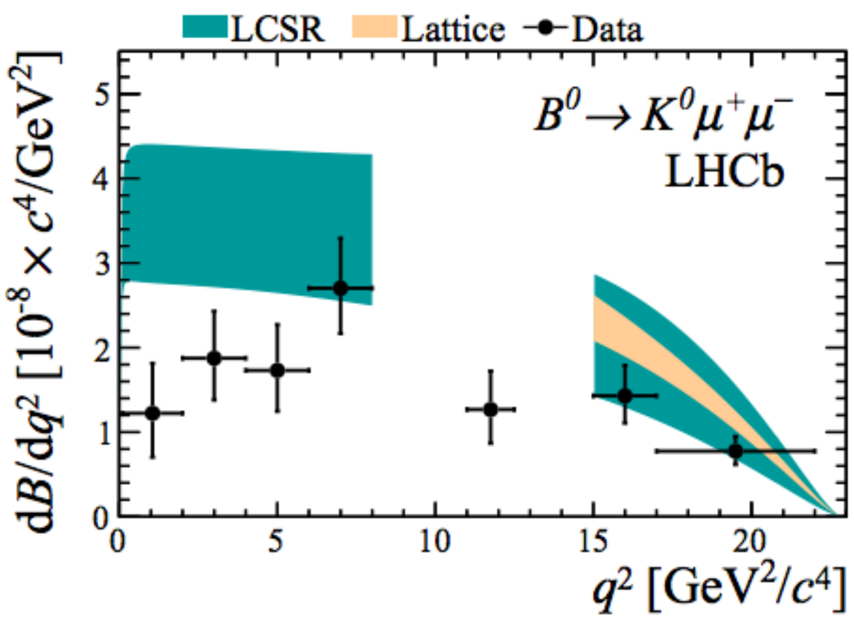


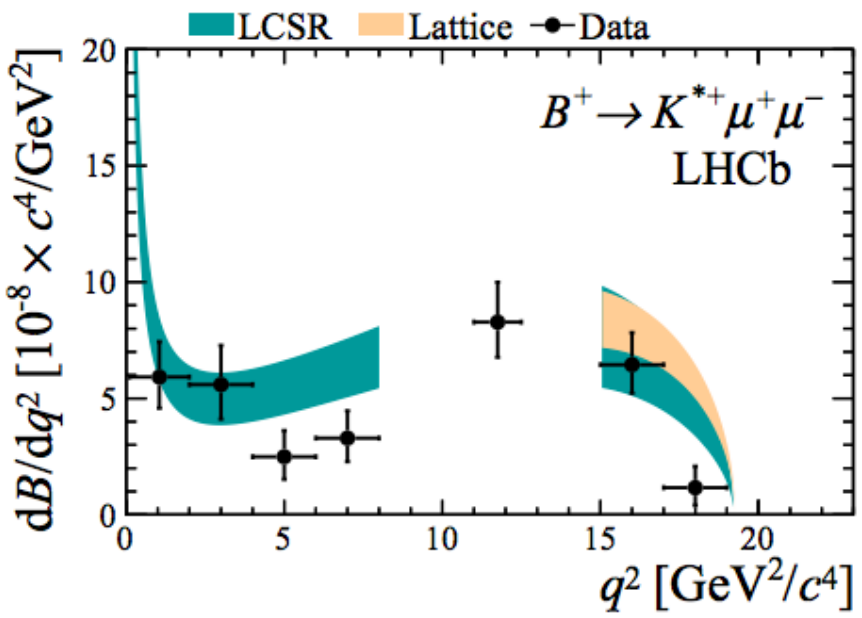
Green=allowed

FIG. 7. The currently allowed parameter regions in the mass vs. coupling plane for the LQs U_1 (*left*) and V_2 (*right*) in the scenarios (43) and (44). Inside the dark and light green bands, the present value of the experimental branching ratio (13) is reproduced at 1 and 2σ, respectively. The black //-hatched regions show the exclusions from present direct searches. The more densely hatched region corresponds to minimal LQ production, while the more coarsely hatched region is for YM-like production.

Lower than predicted **differential b-sll branching fractions**:







JHEP 06 (2014) 133

Decay mode	Measurement
$B^+ \to K^+\mu^+\mu^-$	$8.5 \pm 0.3 \pm 0.4$
$B^0 \to K^0\mu^+\mu^-$	$6.7 \pm 1.1 \pm 0.4$
$B^+ \to K^{*+}\mu^+\mu^-$	$15.8\ ^{+3.2}_{-2.9} \pm 1.1$

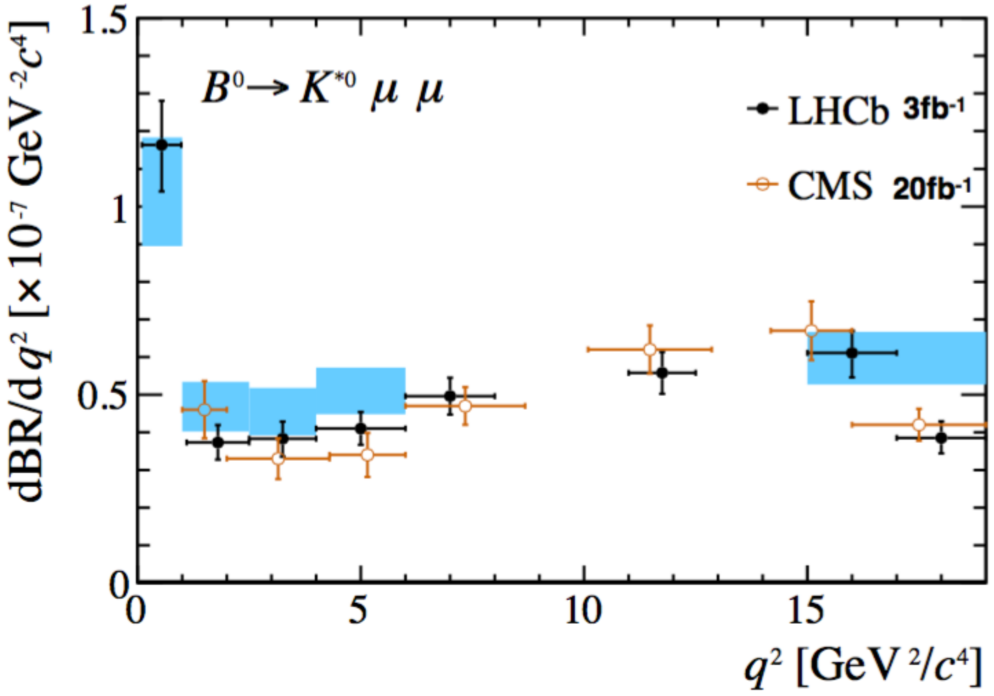
Individual B decays to leptons

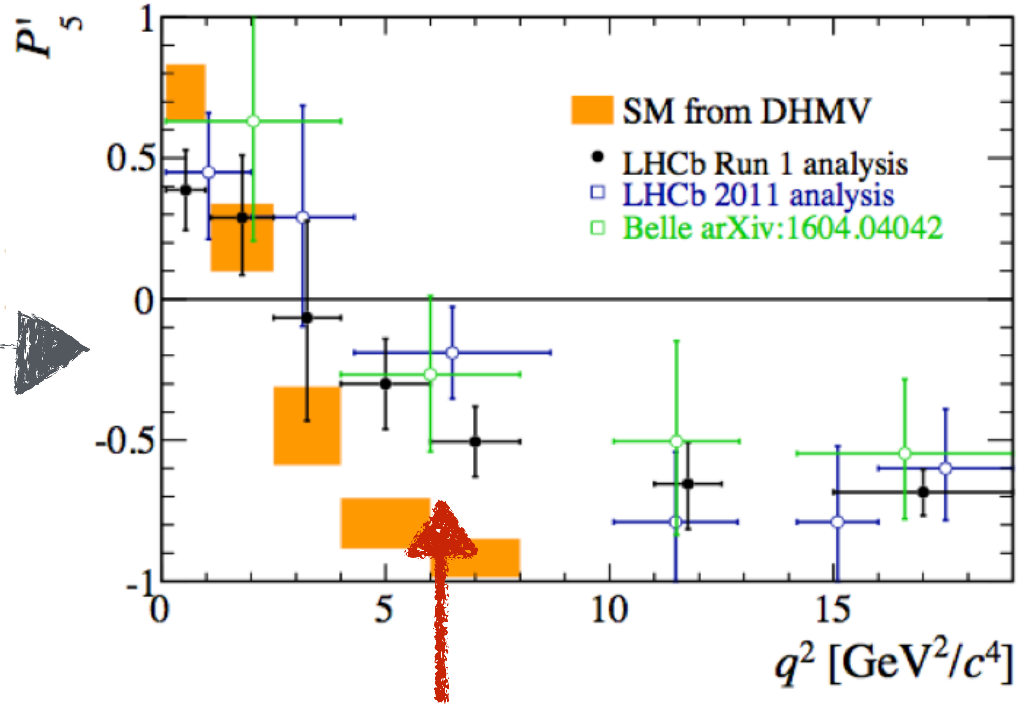
$$B^0 \to K^* \mu^+ \mu^-$$

- Measured **BF lower** than predicted by SM (though predictions have large uncertainties)

LHCb: arXiv:1606.04731, CMS: PLB 753 (2016) 424
SM: JHEP 01 (2012) 107 , PRL111 (2013) 162002, EPJC (2015) 75 382

- **Angular distributions** sensitive to NP effects
- 3 angles and di-lepton mass squared mapped to **optimised variables** to reduced form factor dependencies
- Significant local **tension in** one of the variables **P’$_5$**





Global fit at **3.4σ** from SM predictions

$$B^0 \to K^* e^+ e^-$$

- Very challenging (statistics, resolution, trigger)
- Simplified angular analysis performed (in agreement with SM)

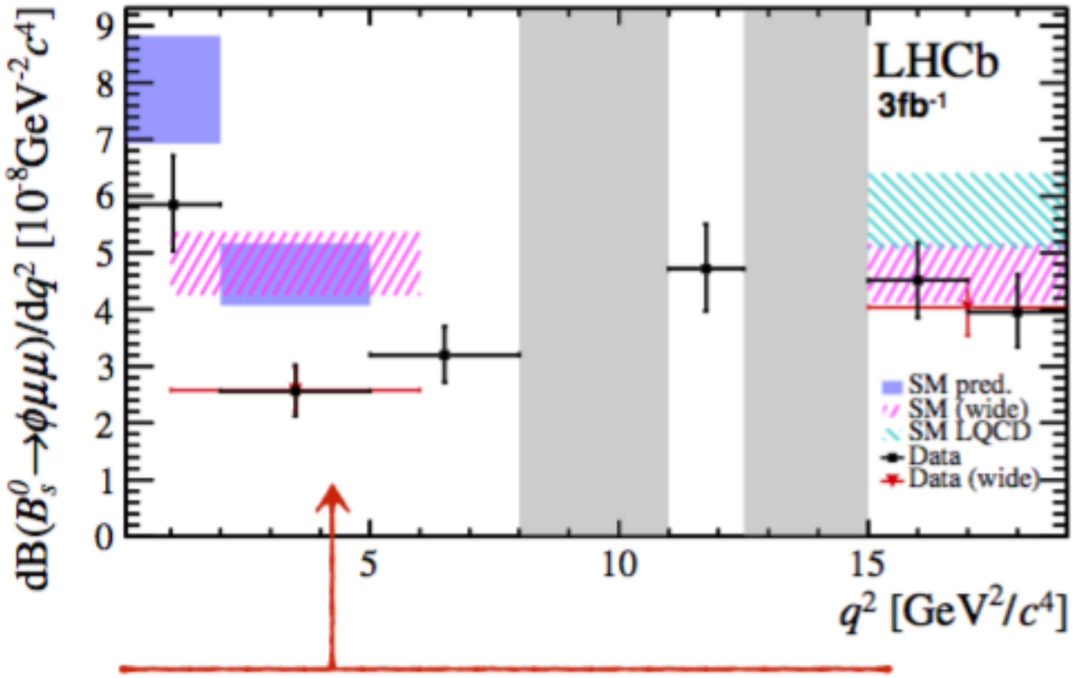
LHCb: LHCb-PAPER-2014-066,
SM: PRD 93 (2016) 014028

Individual B decays to leptons

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

- **Narrow ϕ resonance simplifies selection**
- **Lower BF** than predicted in the SM
- Only CP averaged **angular observables** accessible (e.g. no P’$_5$), latter **in agreement**

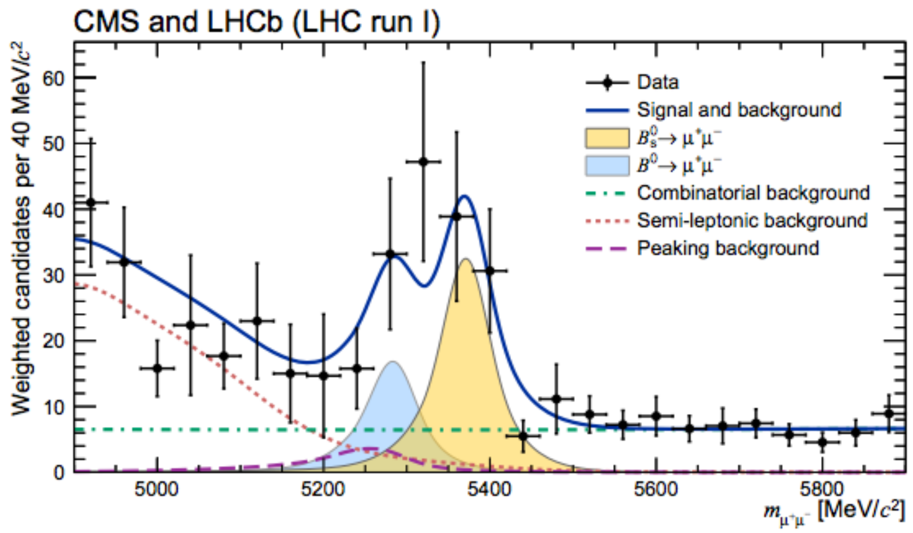
LHCb: JHEP 09 (2015) 179,
SM: EPJC (2015) 75 382, arXiv:1503.05534,
PRD 89 (2014) 094501



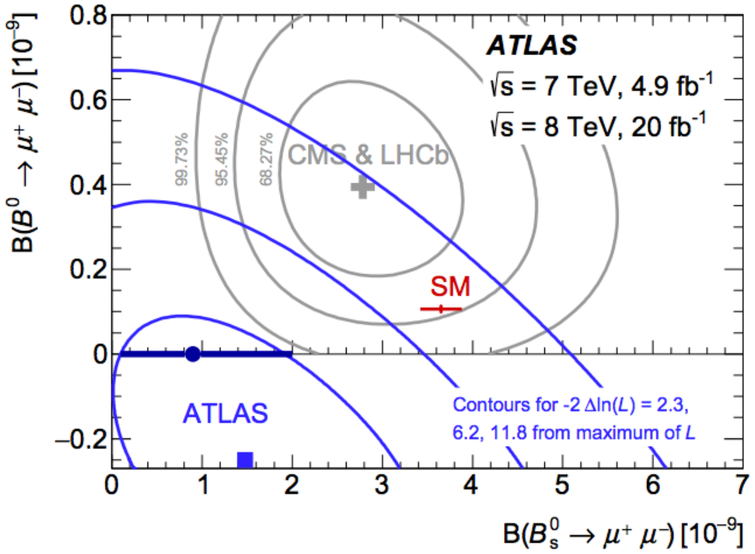
In a wide bin from 1 < q^2 < 6 GeV^2/c^4, the data is >3σ from the SM prediction

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

➤ **Similar (lower BF) trend** seen in other **b→sμ$^+$μ$^-$** processes
Compatibility with the SM 1.2σ for B_s (and 2.2σ for B^0)



Nature 522, 68-72 (04 June 2015)



arXiv:1604.04263

Historical success of the effective approach

- Effective approach has historically played a crucial role in **understanding the underlying theory from both direct and indirect measurements**:
  - ➤ **1933**: First model for the weak decays. Same coupling for the beta decay and muon decay suggested **underlying structure (V-A)**
  - ➤ **1960**'s: Predicting **charm** to make **GIM** work and explain missing FCNC.
  - ➤ **1970**'s: Predict lower bounds on **Z and W masses** from muon lifetime (motivate SPS)
  - ➤ **2010**'s: **Lepton Flavour Universality Violation? Z'? Leptoquarks?**