Rare leptonic B decays

Siim Tolk
on behalf of the LHCb collaboration

UNIVERSITY OF CAMBRIDGE

SUSY
Mumbai 2017

A broad and versatile physics programme

- CP violation in B decays
- New Physics searches at high energy scales
    - In rare beauty and charm decays
- Understanding QCD
    - Heavy flavour production, hadron spectroscopy (pentaquark states, bc states), unique fixed target programme
- Quark Gluon Plasma studies:
    - Rich heavy ion programs (production at p-Pb/Pb-p, fixed target p/pB-Ne)

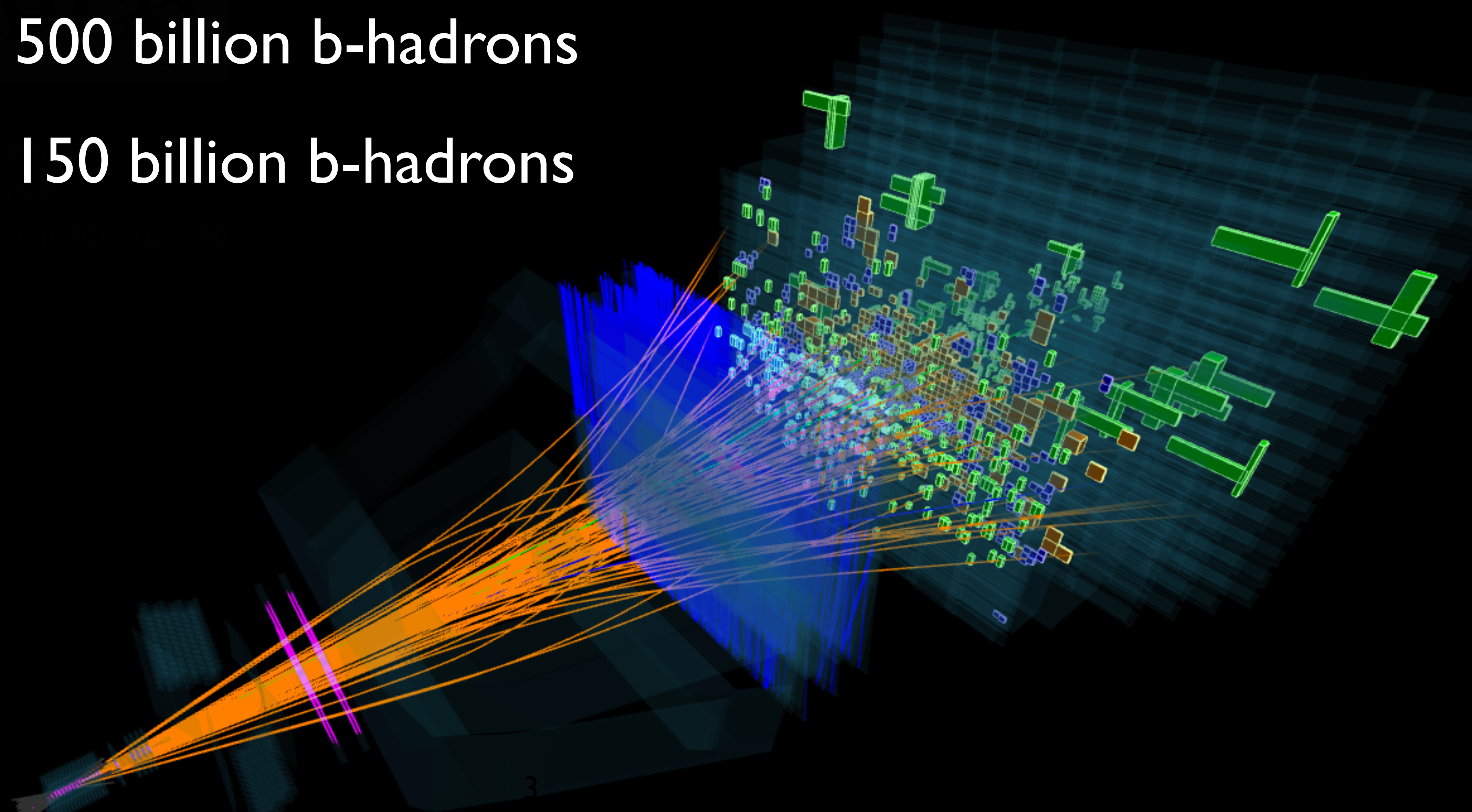
[ALL LHCB PUBLICATIONS]

LHCb is designed for B-physics

- Built in the high b-hadron production cross section region $2<\eta<5$

[PRL 118, 052002 (2017)]

  - $\sigma(pp \rightarrow bb)^{LHCb}$ @ 13TeV ~155μb
  - Run I: 500 billion b-hadrons
  - Run II: 1150 billion b-hadrons



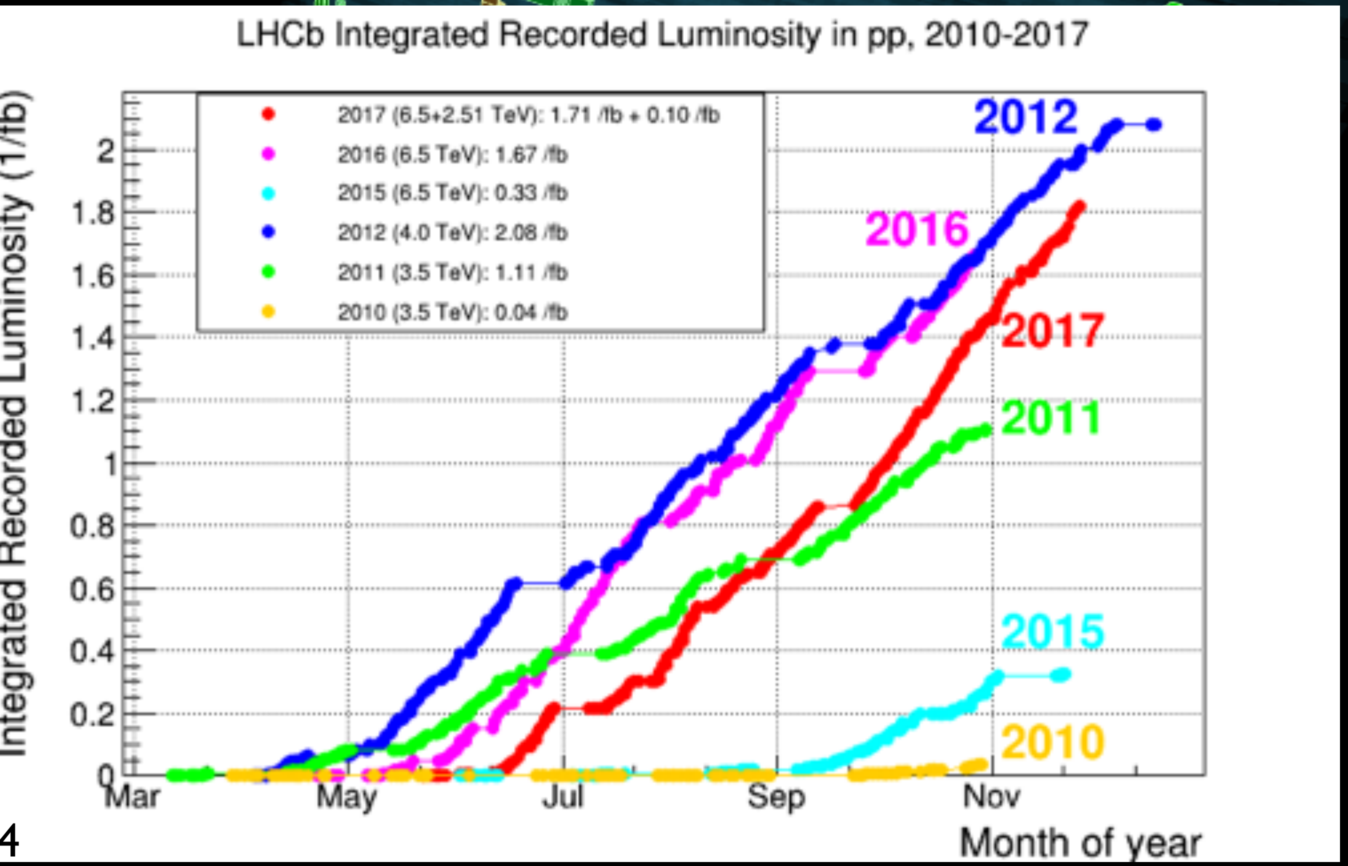
LHCb is designed for B-physics

- Built in the high b-hadron production cross section region $2<\eta<5$

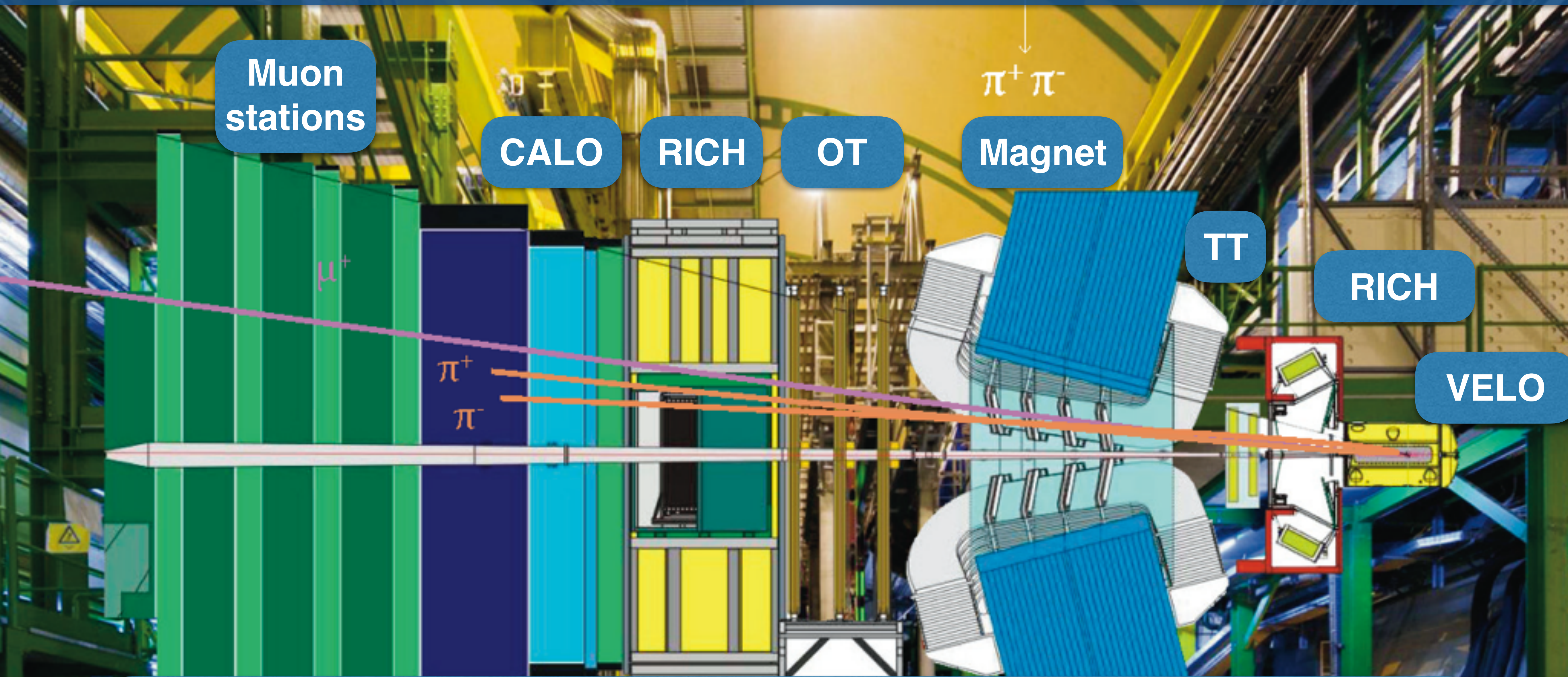
[PRL 118, 052002 (2017)]

  - $\sigma(pp\rightarrow bb)^{LHCb}$ @ 13TeV ~155μb
  - Run I: 500 billion b-hadrons
  - Run II: 1150 billion b-hadrons

- LHCb recorded **$3fb^{-1}$ in RunI** and **$3.7fb^{-1}$ in Run II.**
- High efficiency in 2017 (~91.4%)



LHCb detector @ LHC



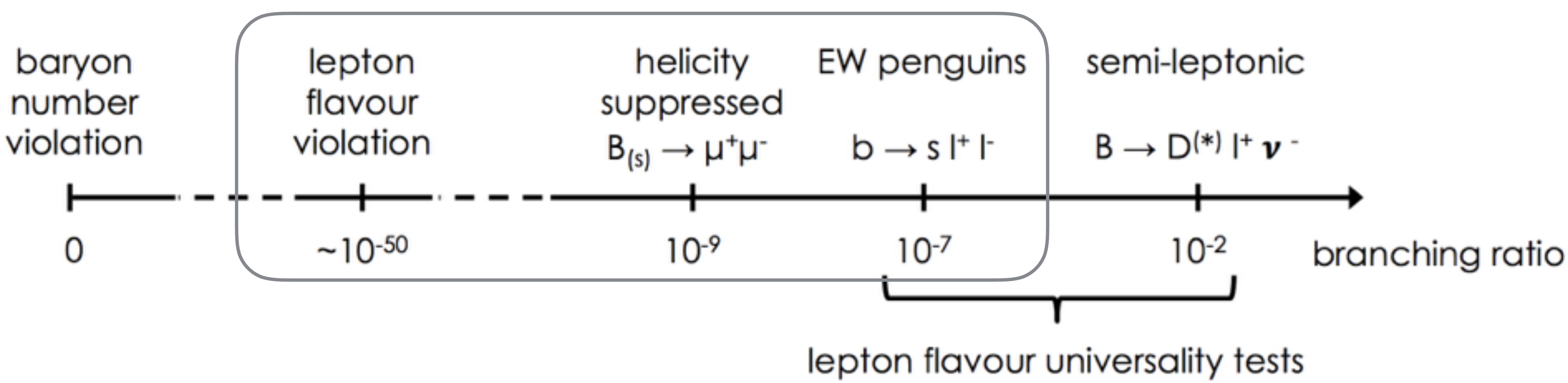
- **Clean collision environment** (μ ~1.6) and high boost (γ~20)
- **Good mass resolution** (~23 MeV for $B \to \mu^+\mu^-$)

Excellent charged hadron identification, vertexing, high trigger and tracking efficiencies (>~90%) also in the low p_T range.

The large sample of precisely reconstructed B-decays is a true **goldmine** for New Physics searches.

Expose New Physics effects where the Standard Model is suppressed

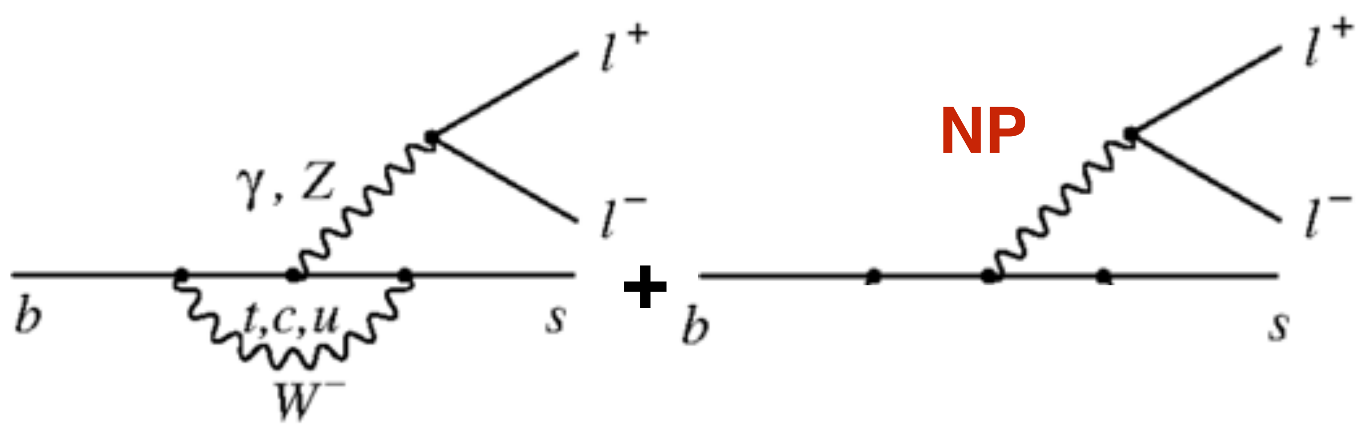
- $b \to sll$ and $b \to dll$ transitions are rare in the SM
  No tree level contributions
  (GIM, CKM, possibly helicity suppressed)

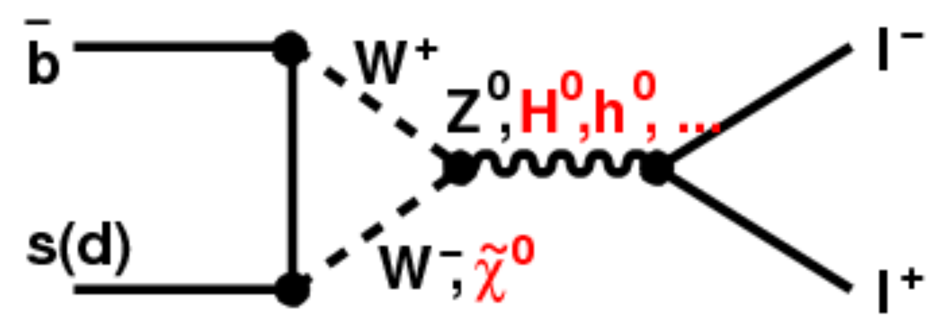


Expose New Physics effects where the Standard Model is suppressed

- New Physics can (in principle) enter at both tree and loop level:

NP at tree level | **NP at loop level**



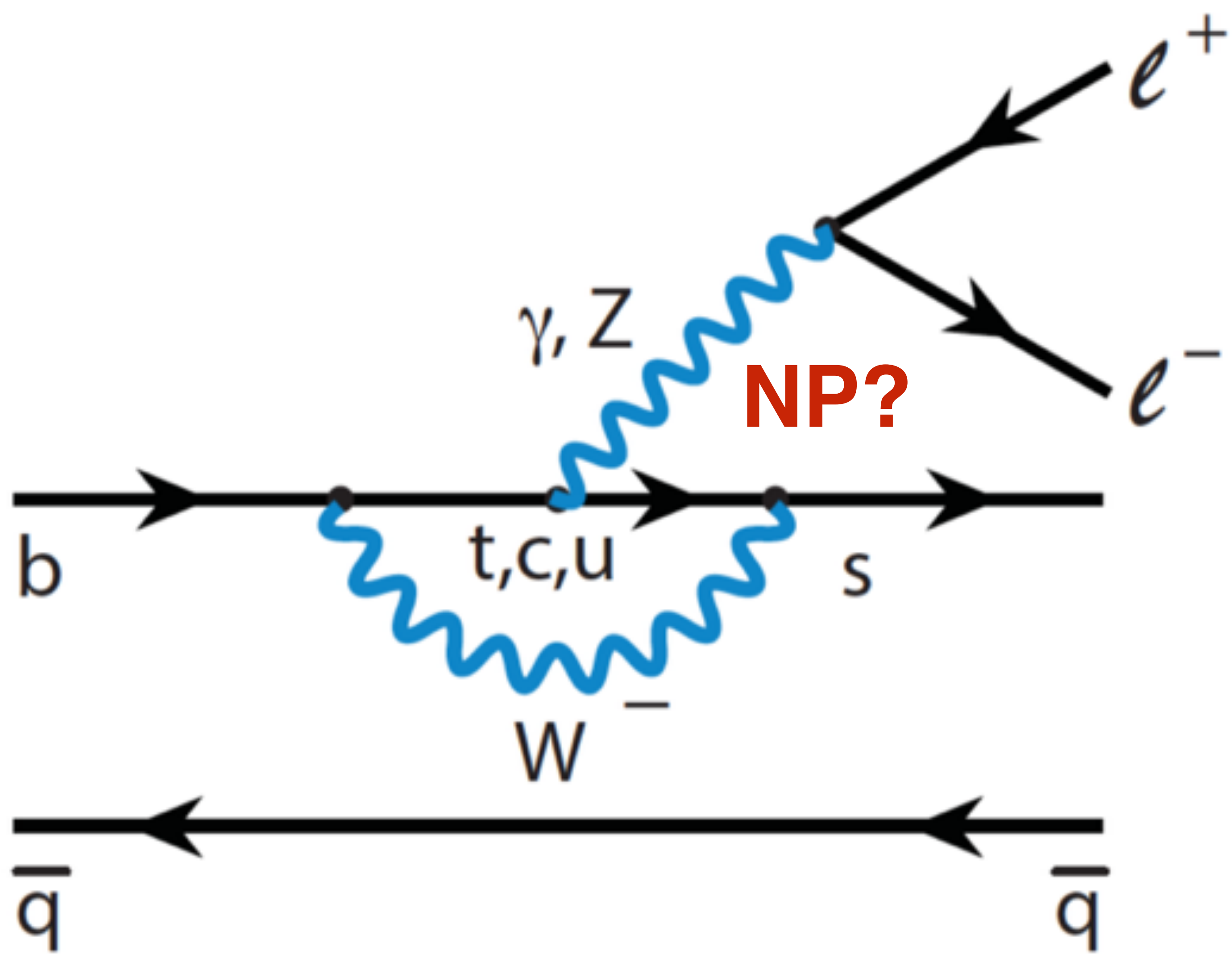


$B_s \to \mu^+\mu^-$ sensitive to Z's up to ~150TeV or new scalars up to 1000TeV **[A.Buras et al, JHEP 1411 (2014) 121]**

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

A strong case for indirect searches

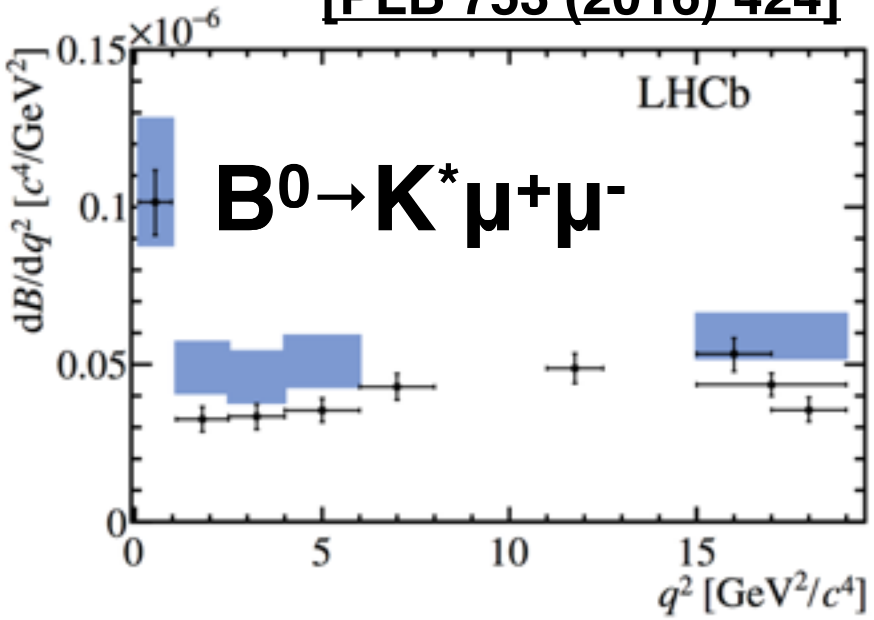
- Indirect searches are sensitive to higher energy scales (~100TeV)
- Historically, indirect searches have led the way in shaping the Standard Model (e.g. charm predicted 4 years before the direct proof)
- Complementary to (but no substitute for) the comprehensive direct NP search programmes



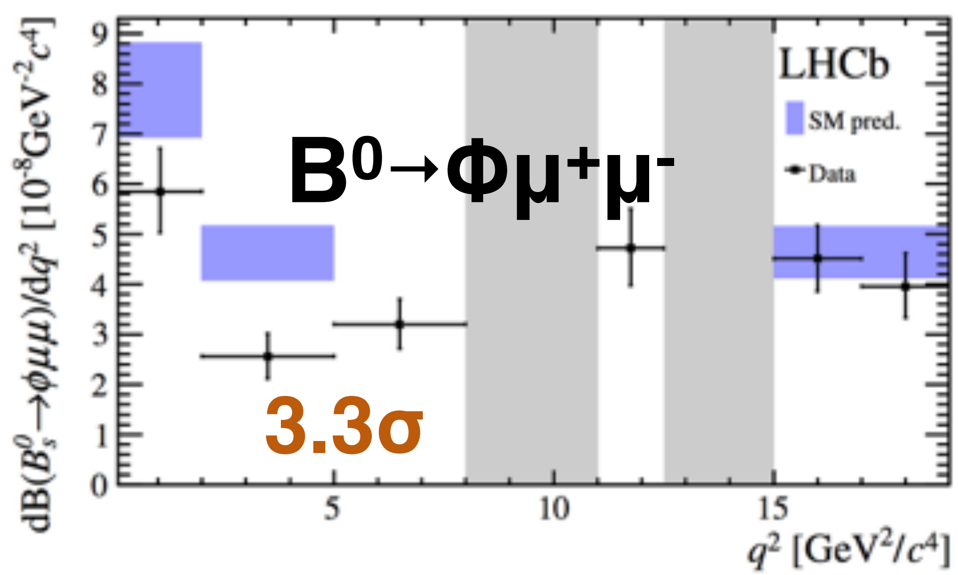
- For several reasons, rare decays involving **b→sll transitions** have emerged as possibly the most interesting phenomena in particle physics..

First: exclusive $b \to s\mu^+\mu^-$ branching fractions

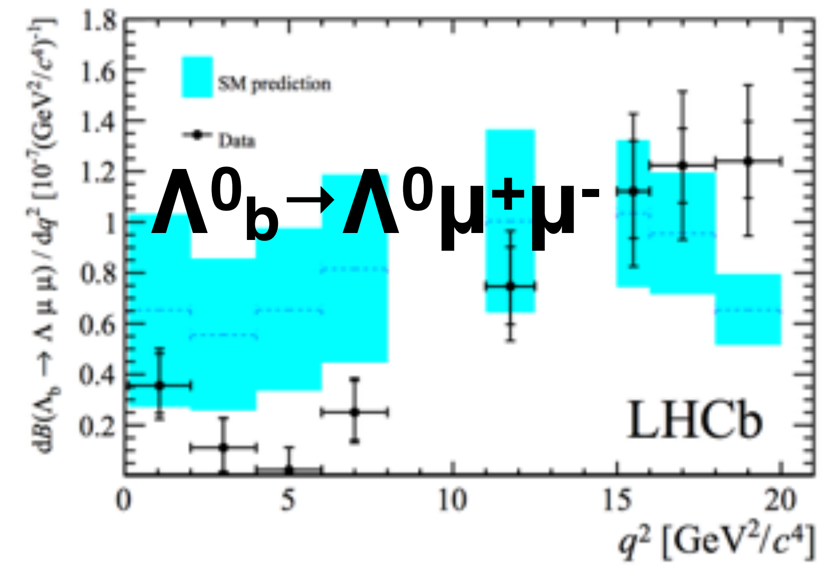
[JHEP 04 (2017) 142]
[PLB 753 (2016) 424]



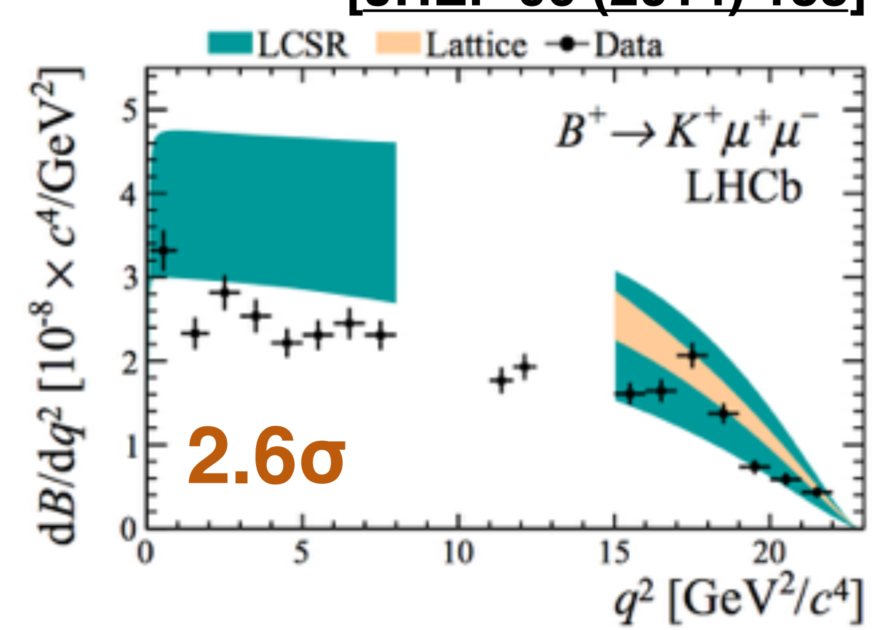
[JHEP 09 (2015) 179]



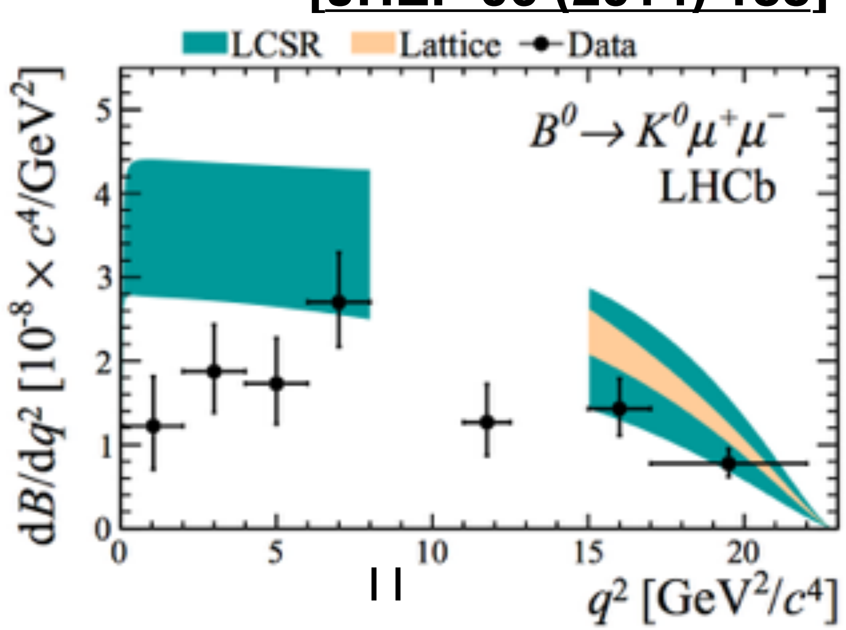
[JHEP 06 (2015) 115]



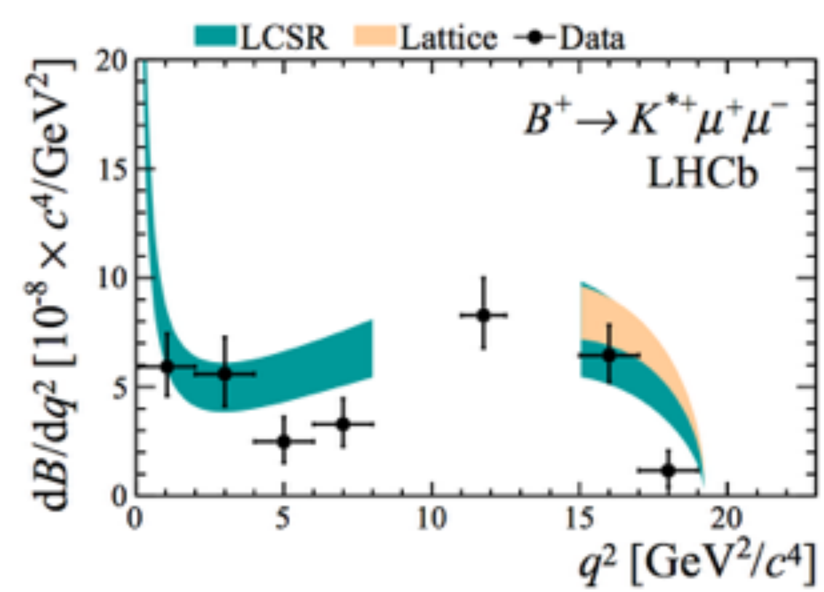
[JHEP 06 (2014) 133]



[JHEP 06 (2014) 133]

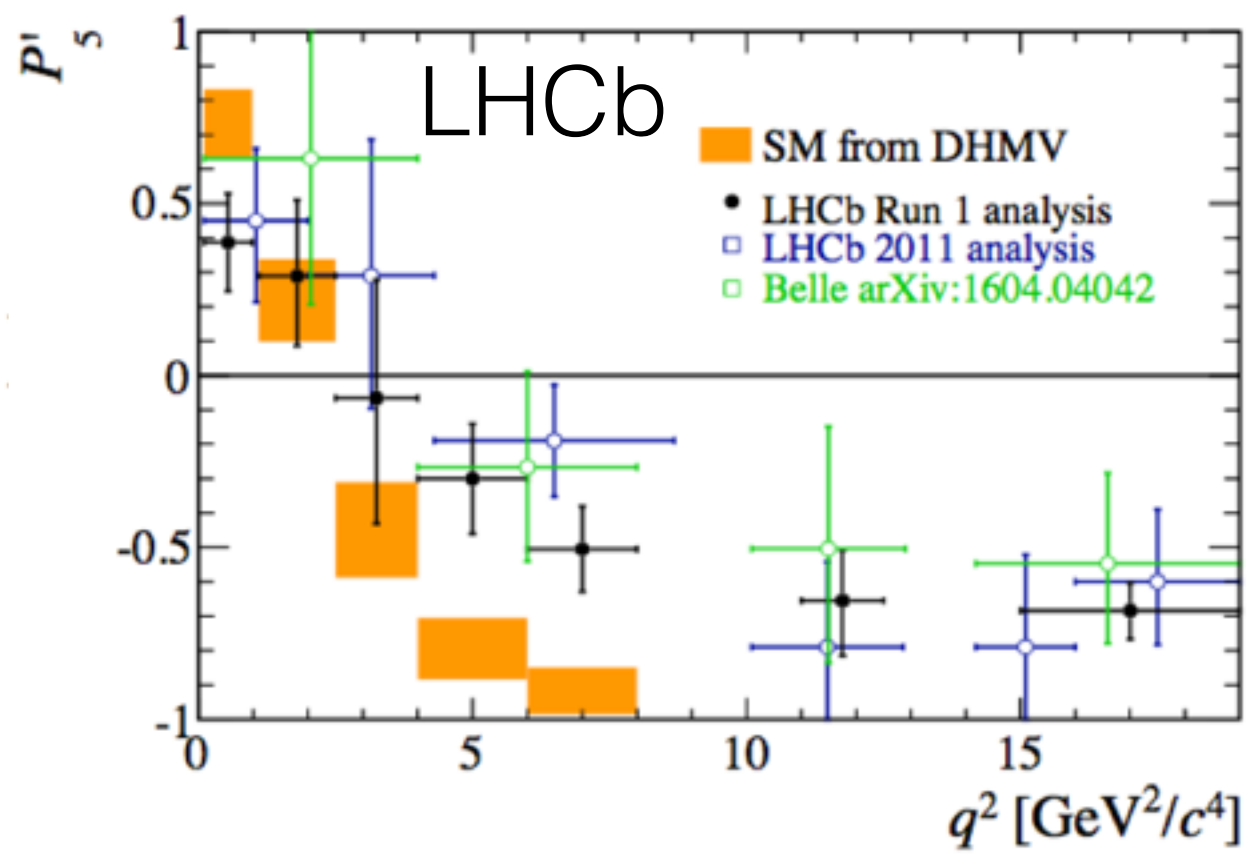


[JHEP 06 (2014) 133]

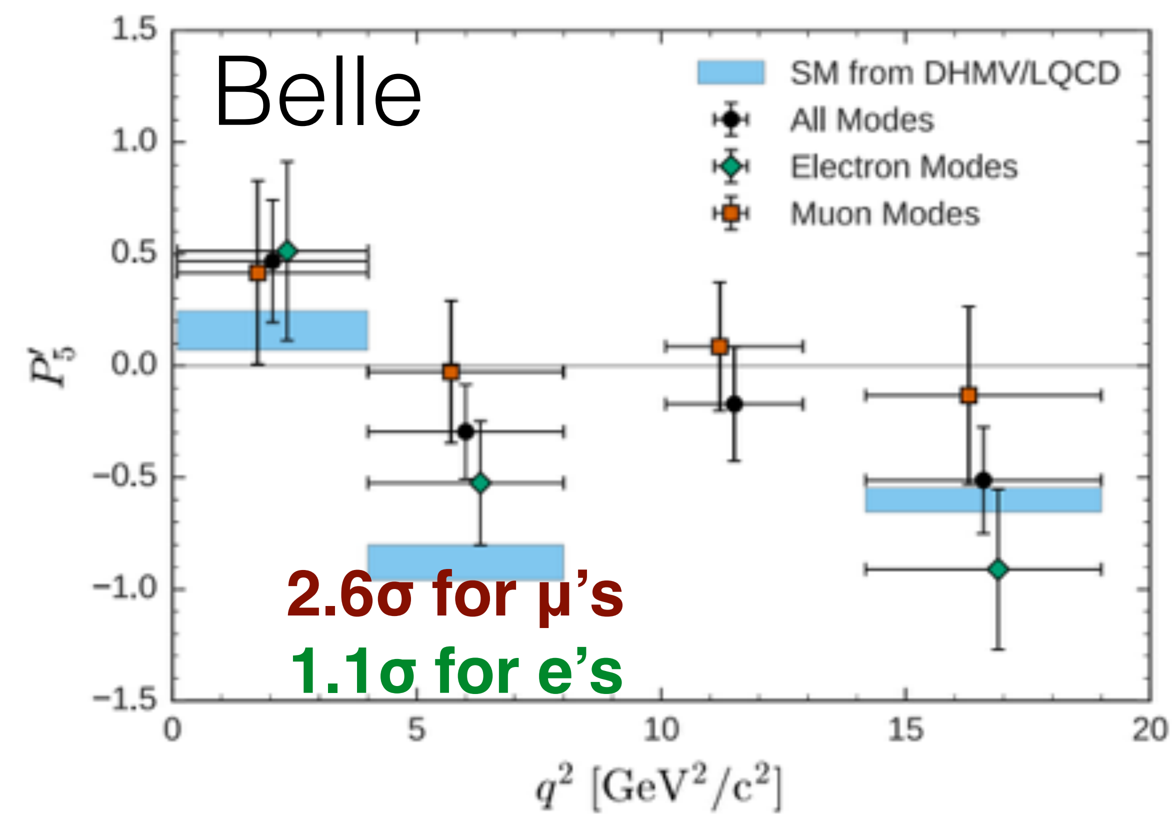


Second: tensions in $b \to s l^+ l^-$ angular observables

$B^0 \to K^* \mu^+ \mu^-$ [JHEP 02 (2016) 104]



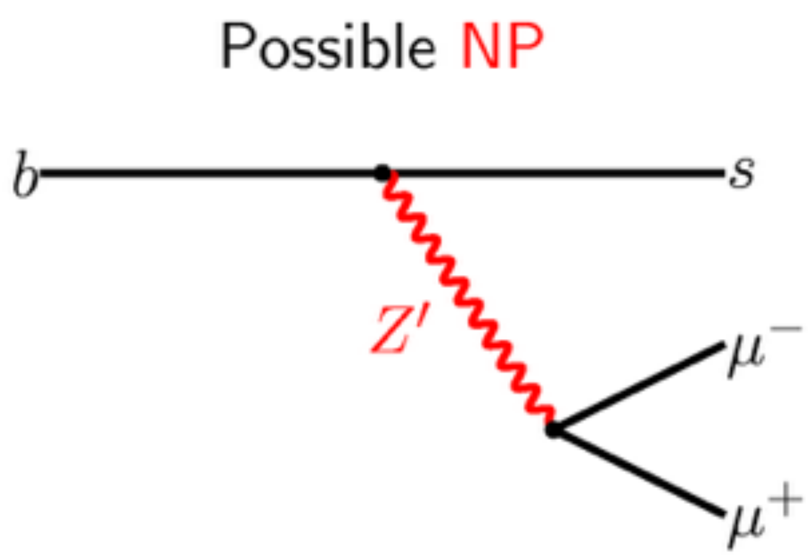
[PRL 118 (2017) 111801]



- Theoretically clean angular parameter P_5' diverges from the predictions (3.4σ)
- The tension is larger for muons

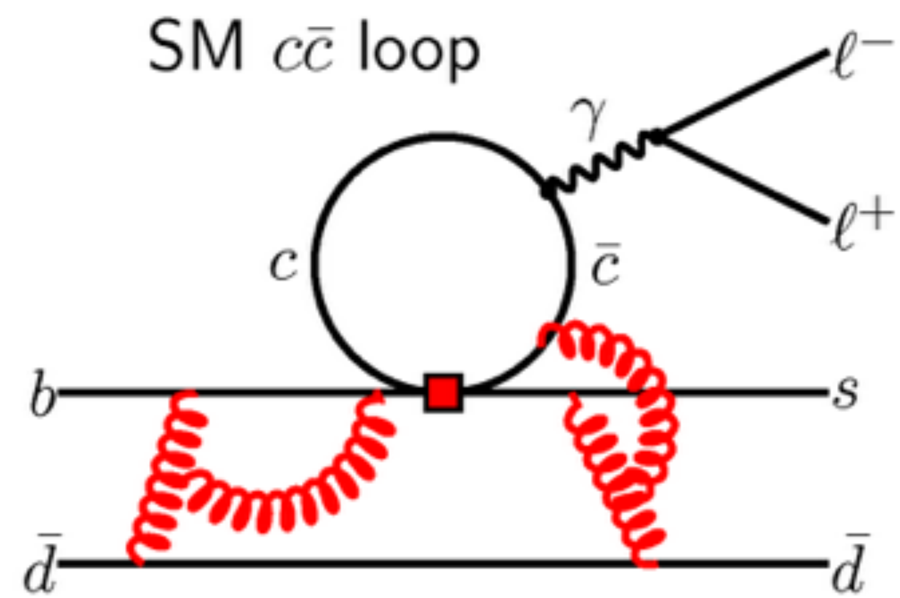
New Physics is not the only possible explanation to these effects:

Z', leptoquarks,…



$$C_9 + C_9^{NP}$$

Hadronic SM effects



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

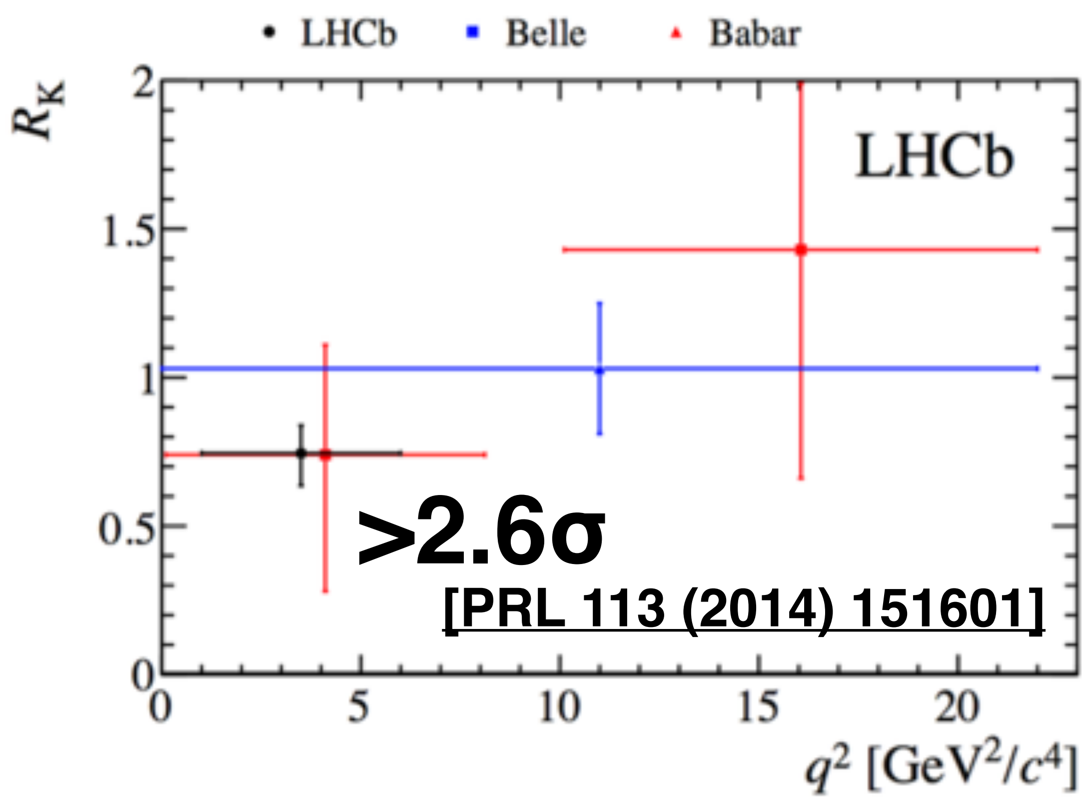
Long-distance charm resonance effects far from the resonances on the q^2 plane.

But…if it were due to hadronic effects..

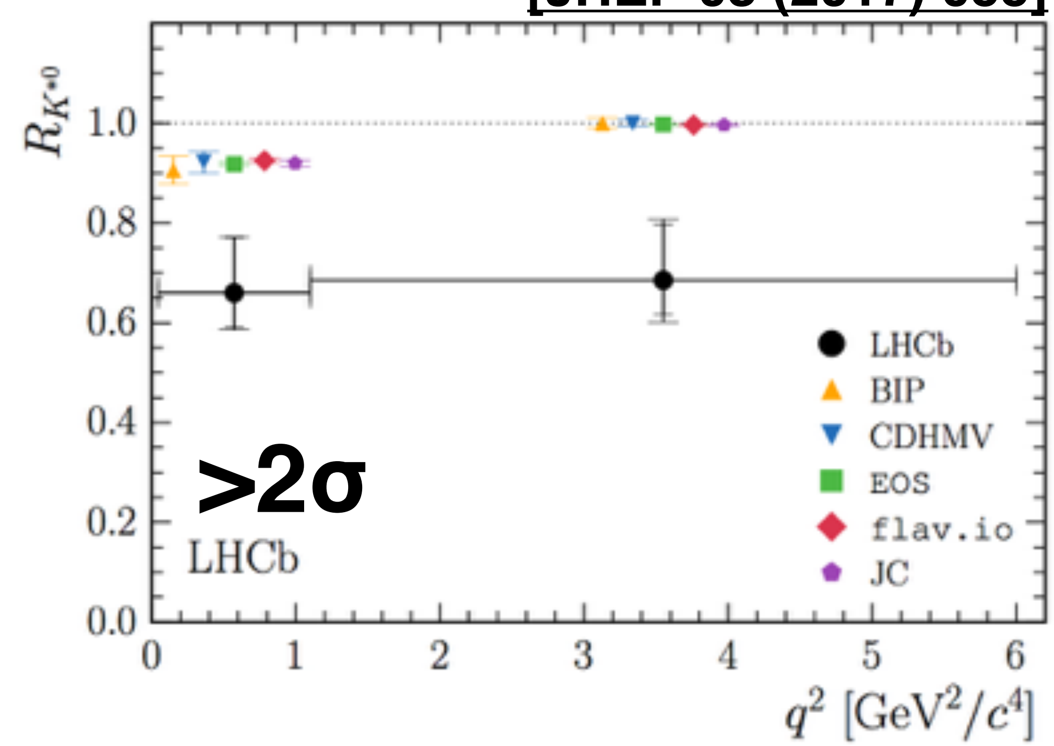
..then we should see no deviations from the SM in the **ratios of b→sll branching fraction.**

Third: tensions in ratios: $b \rightarrow s\mu^+\mu^-$ / $b \rightarrow s e^+ e^-$

- The measured muon and electron mode ratios are lower than predicted in the SM (LFU)



[JHEP 08 (2017) 055]

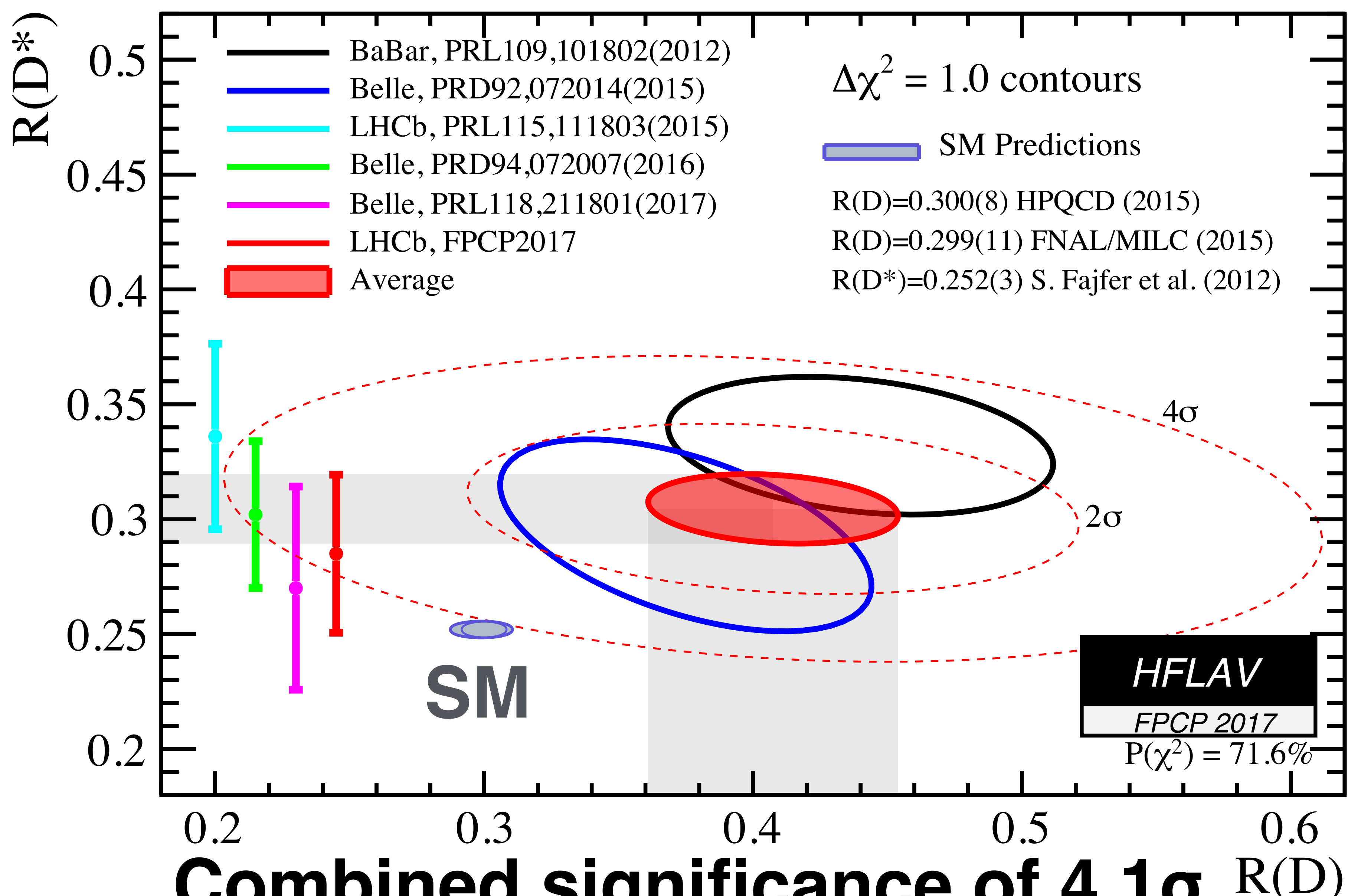


$$\mathcal{R}(K) \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$\mathcal{R}(K^*) \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

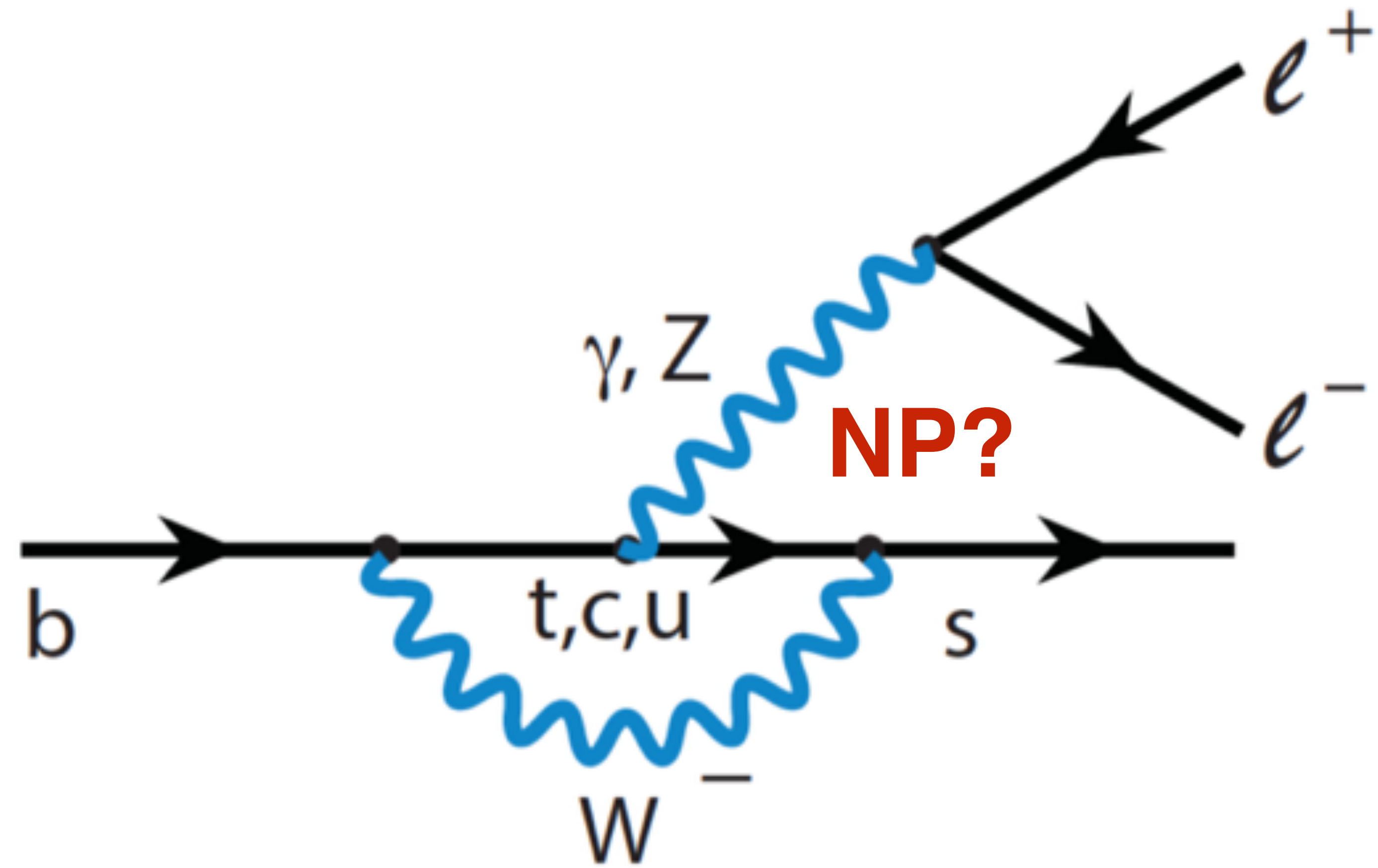
…a footnote: LFU divergencies are also seen in the semi-leptonic B decays via b→cl⁺l⁻ transitions:

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



Combined significance of 4.1σ

What can fully leptonic B-decays add?



All B-decays include 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)

and can be described by the **effective field theory** and **operator product expansion** by splitting the scale at b mass (μ_b):

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

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:

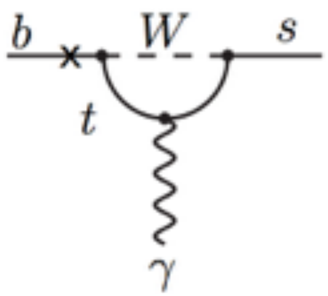
$$\langle llM|j_{ll} \cdot j_{qq}|B\rangle = \langle ll|j_{ll}|0\rangle \cdot \underline{F(q^2)} + \underline{C_{non-fact}}$$

corrections

Lattice QCD (large q^2)

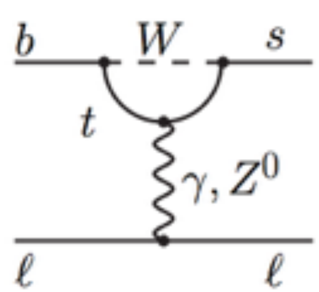
Light Cone Sum Rules (small q^2)

The A-V semi-leptonic current (O_{10}) contributes to both semi-leptonic and fully leptonic B-decays:



Electromagnetic penguin

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



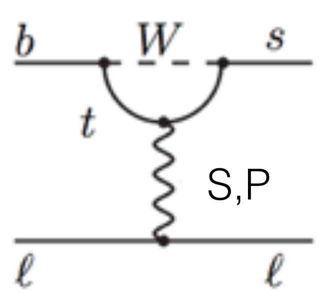
Semi-leptonic vector current

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

Semi-leptonic A-V current

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

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



Scalar

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

Pseudo-scalar

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

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

*In SM only O_{10} contributes to the leptonic modes, Higgs contribution via O_S is negligible

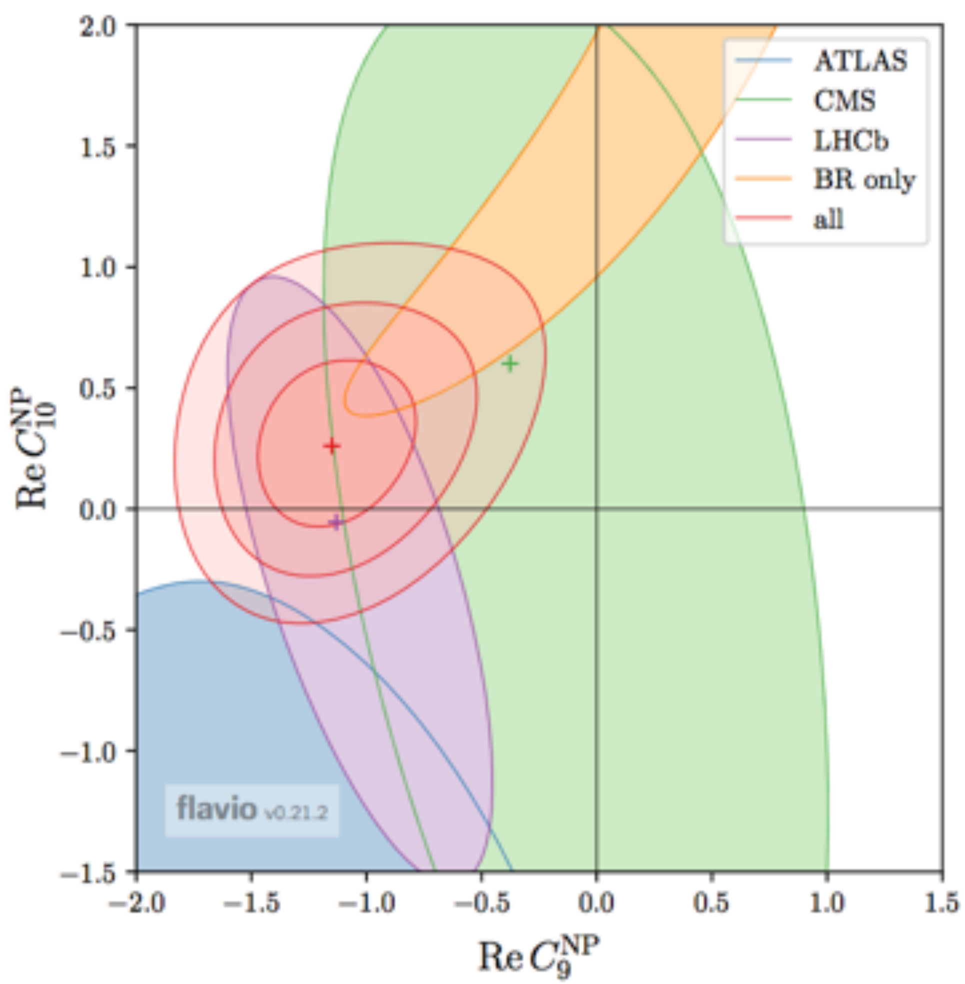
➽ New Physics can

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

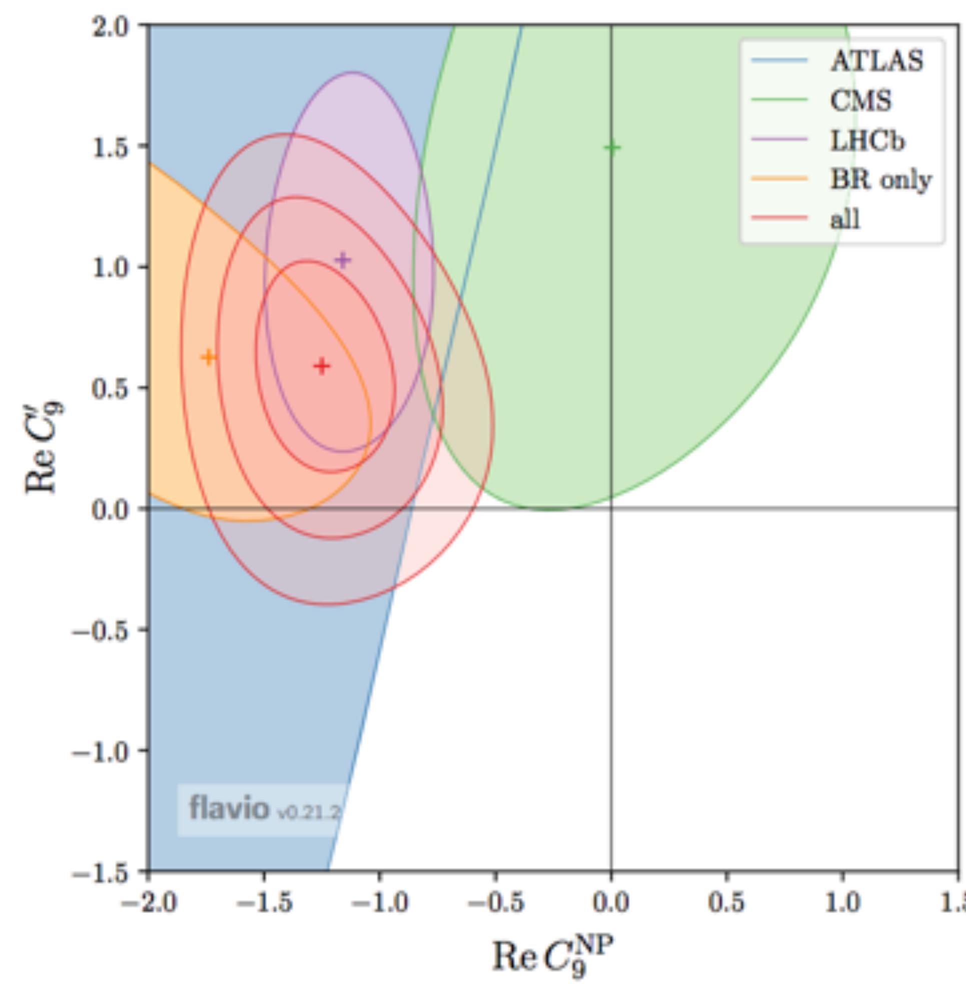
The Wilson coefficients are determined from global $b \to sl^+l^-(\gamma)$ analysis, which point to

- tensions at 4-5σ level w.r.t SM in left-handed muon couplings
- two favoured (model independent) solutions to the tensions:

a) $C_9^{NP} = -C^{NP}_{10}$



b) $C_9^{NP} < 0$



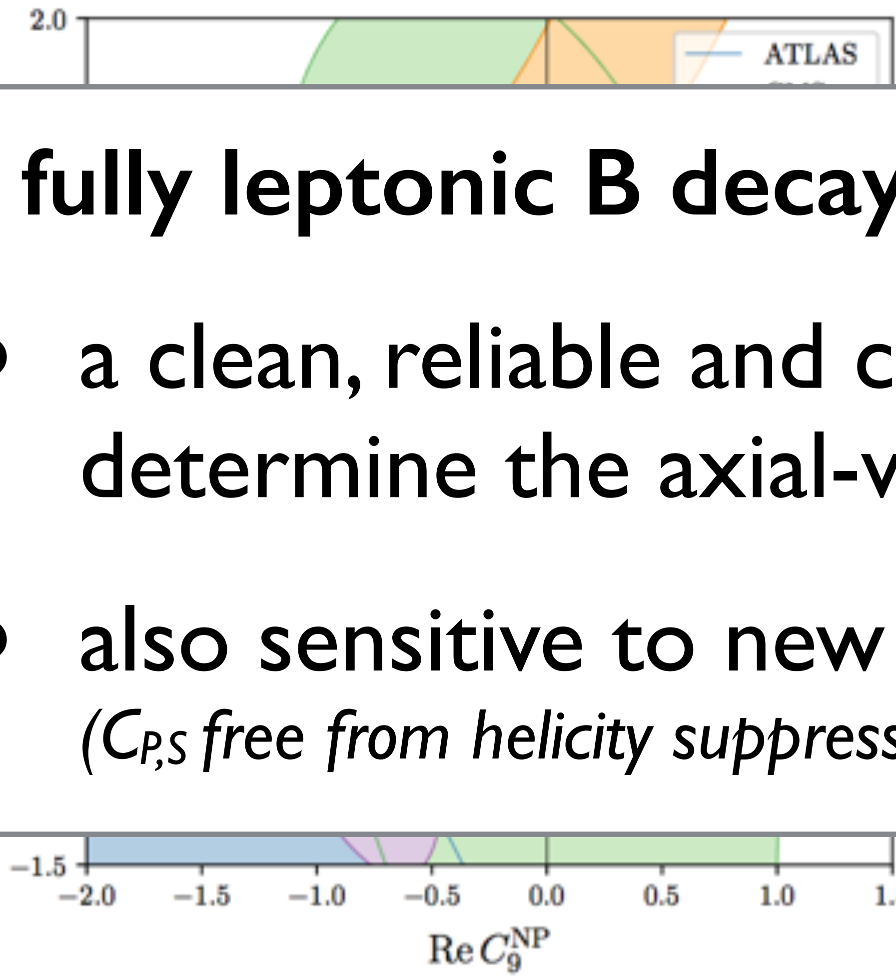
Altmannshofer et al [EPJC (2017) 77:377], Capdevilaa et al [PSI-PR-17-05]

(~90 measurements e.g. in Descotes-Genon, Hofer, Matias, Virto [JHEP 06 (2016) 092], Altmannshofer, Straub [EPJC 75(8) (2015) 382], Hurth, Mahmoudi, Neshatpour [arXiv:1603.00865]

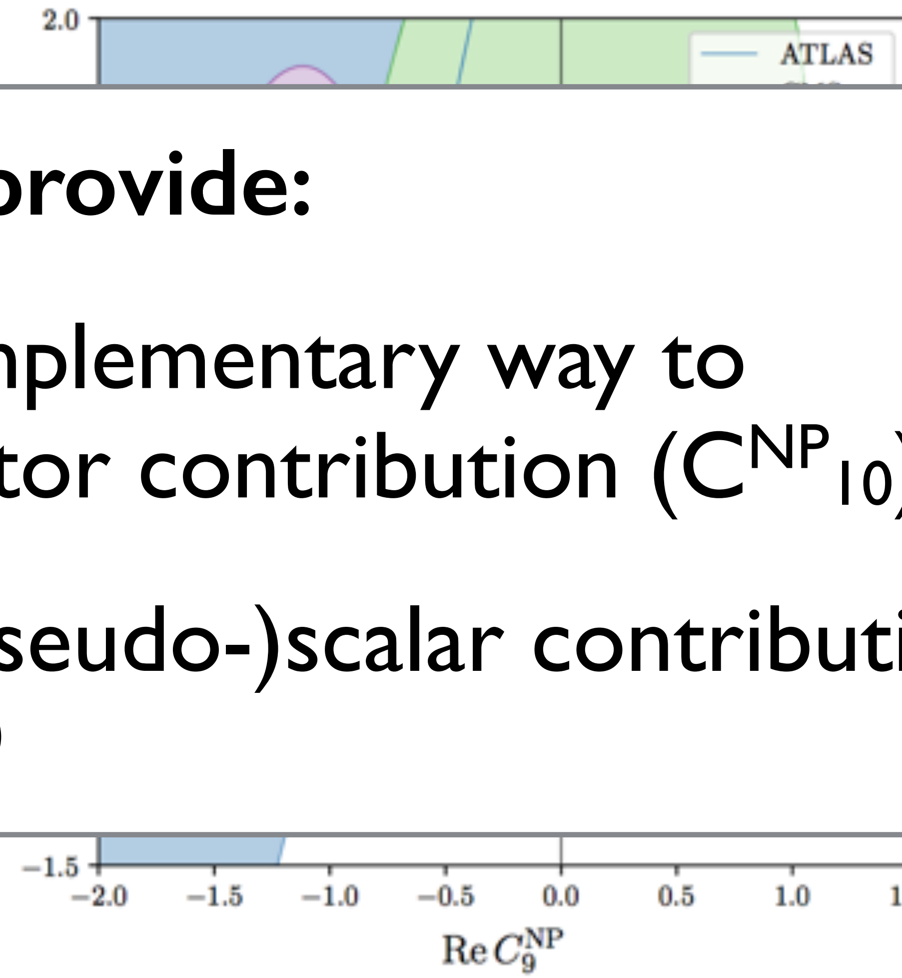
The Wilson coefficients are determined from global $b \to s l^+ l^- (\gamma)$ analysis, which point to

- tensions at 4-5σ level w.r.t SM in left-handed muon couplings
- two favoured (model independent) solutions to the tensions:

a) $C_9^{NP} = -C^{NP}_{10}$



b) $C_9^{NP} < 0$



Rare fully leptonic B decays provide:

- a clean, reliable and complementary way to determine the axial-vector contribution (C^{NP}_{10})
- also sensitive to new (pseudo-)scalar contributions
  ($C_{P,S}$ free from helicity suppression)

(~90 measurements e.g. in Descotes-Genon, Hofer, Matias, Virto [JHEP 06 (2016) 092], Altmannshofer, Straub [EPJC 75(8) (2015) 382], Hurth, Mahmoudi, Neshatpour [arXiv:1603.00865]

The experimental success story of

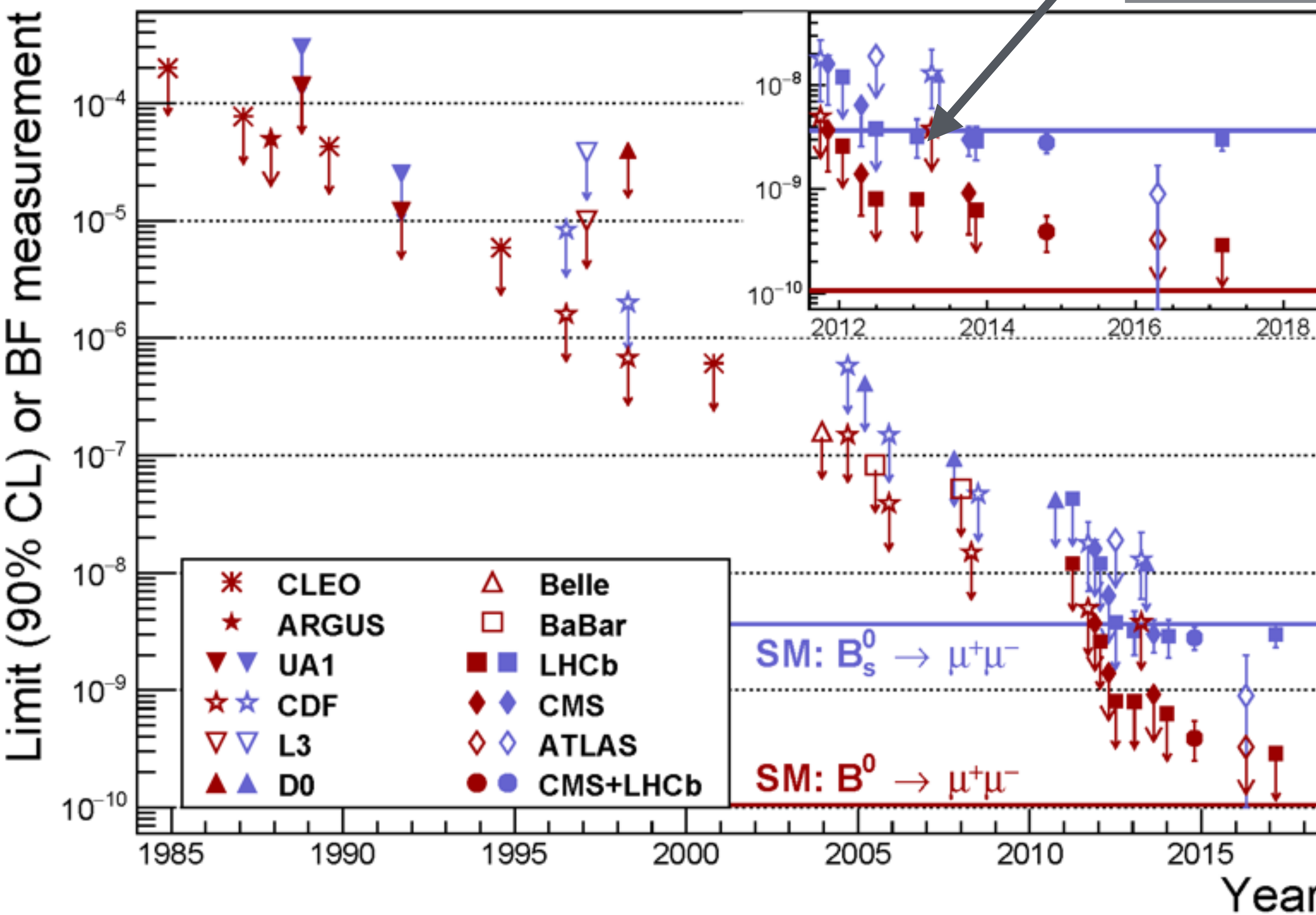
$$B^0_{(s)} \to \mu^+ \mu^-$$

One of the most important indirect New Physics probes at the LHC.

Persistence that paid off after 30 years

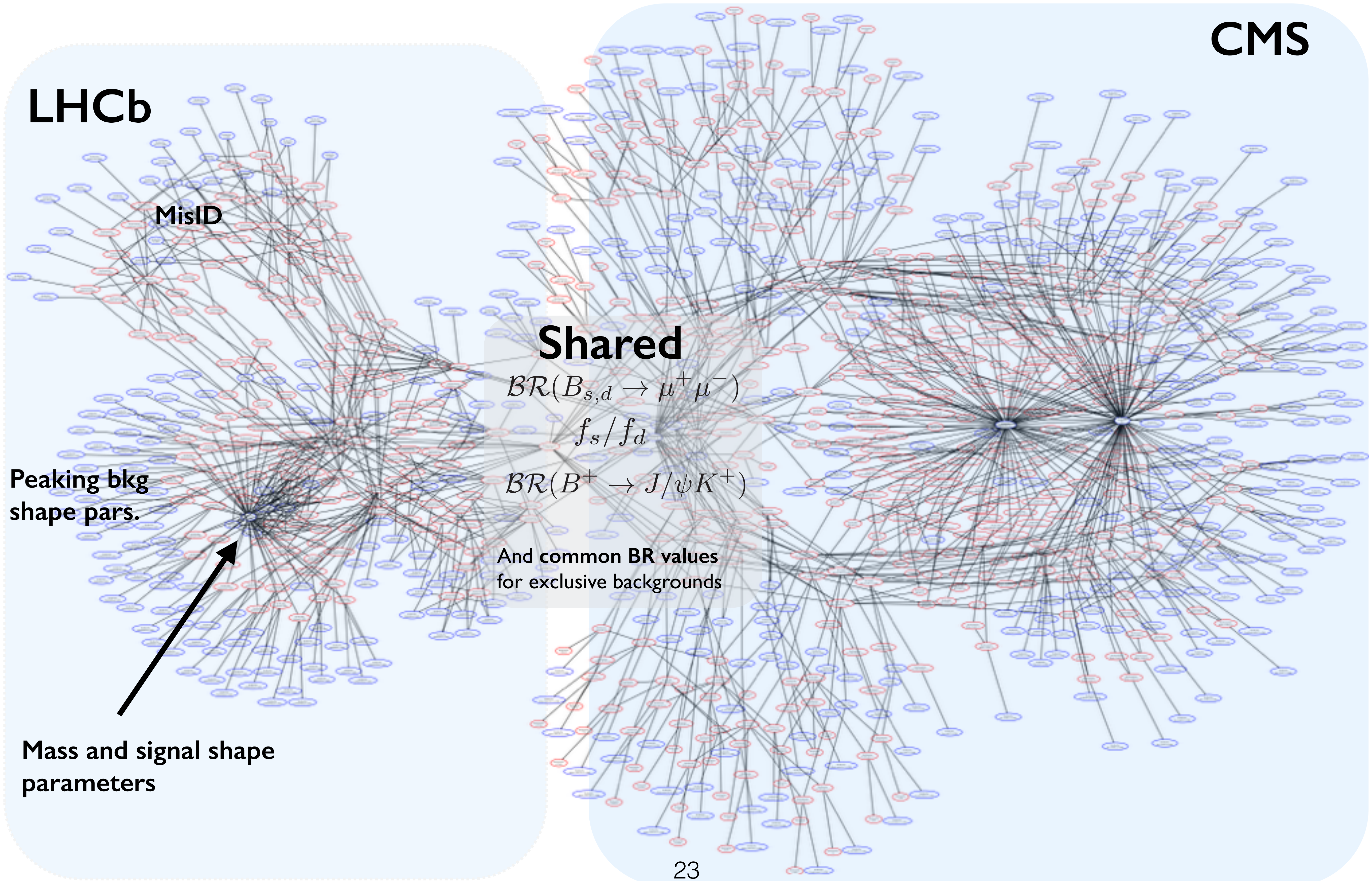
[PRL 110, 021801 (2013)]

2013: first evidence seen by LHCb



[Nature 522, 68-72 (04 June 2015)]

The combined Run 1 $B^0_{(s)} \to \mu^+\mu^-$ analysis models

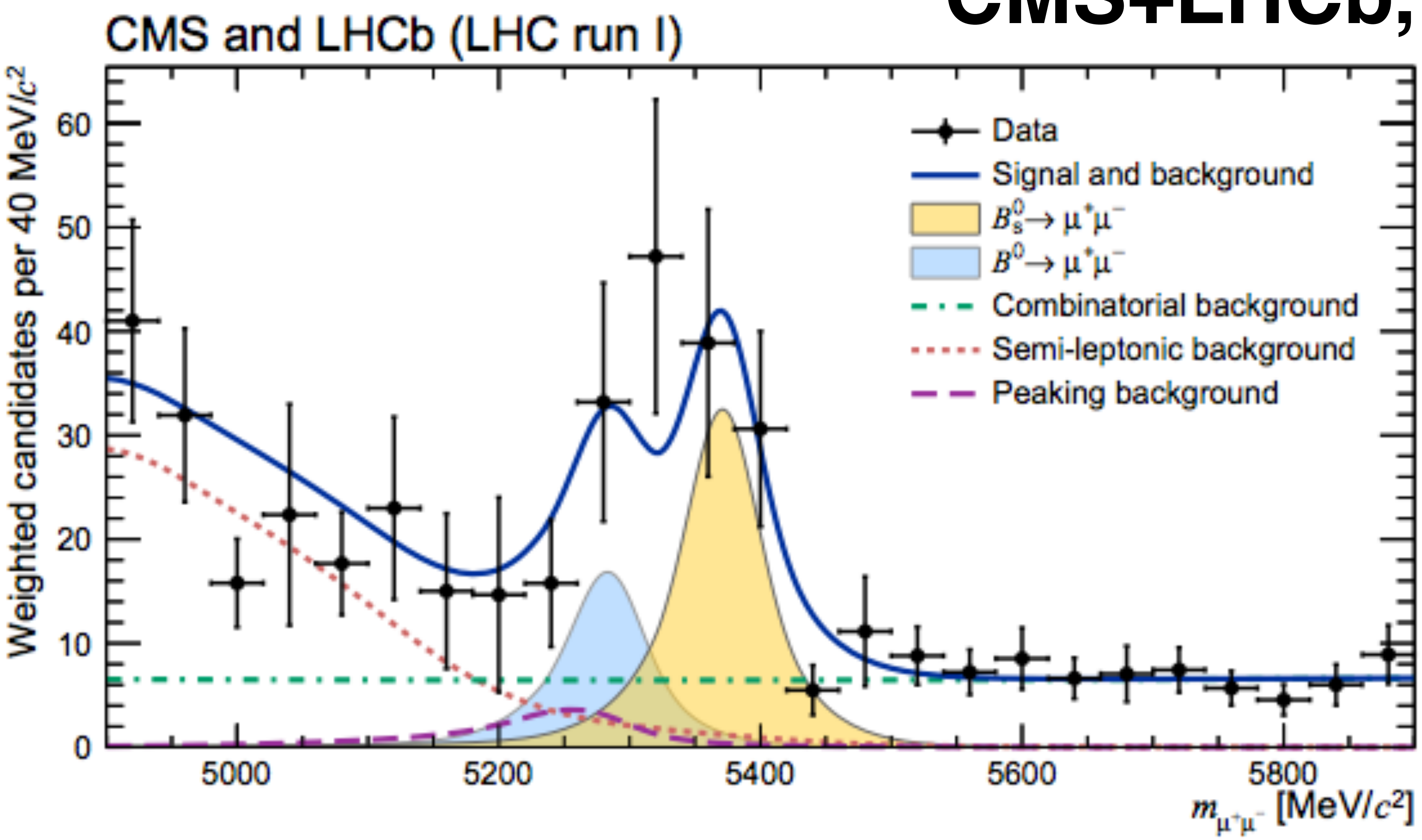


2015

[Nature 522, 68-72 (04 June 2015)]

The first observation of $B_s \to \mu\mu$ decay and the first evidence of $B_d \to \mu\mu$:

CMS+LHCb, Run I



➽ **The fitted central BF values**

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$ **6.2σ obs.** (expected 7.2σ in SM)

$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$ **3.2σ obs.** (expected 0.8σ in SM)

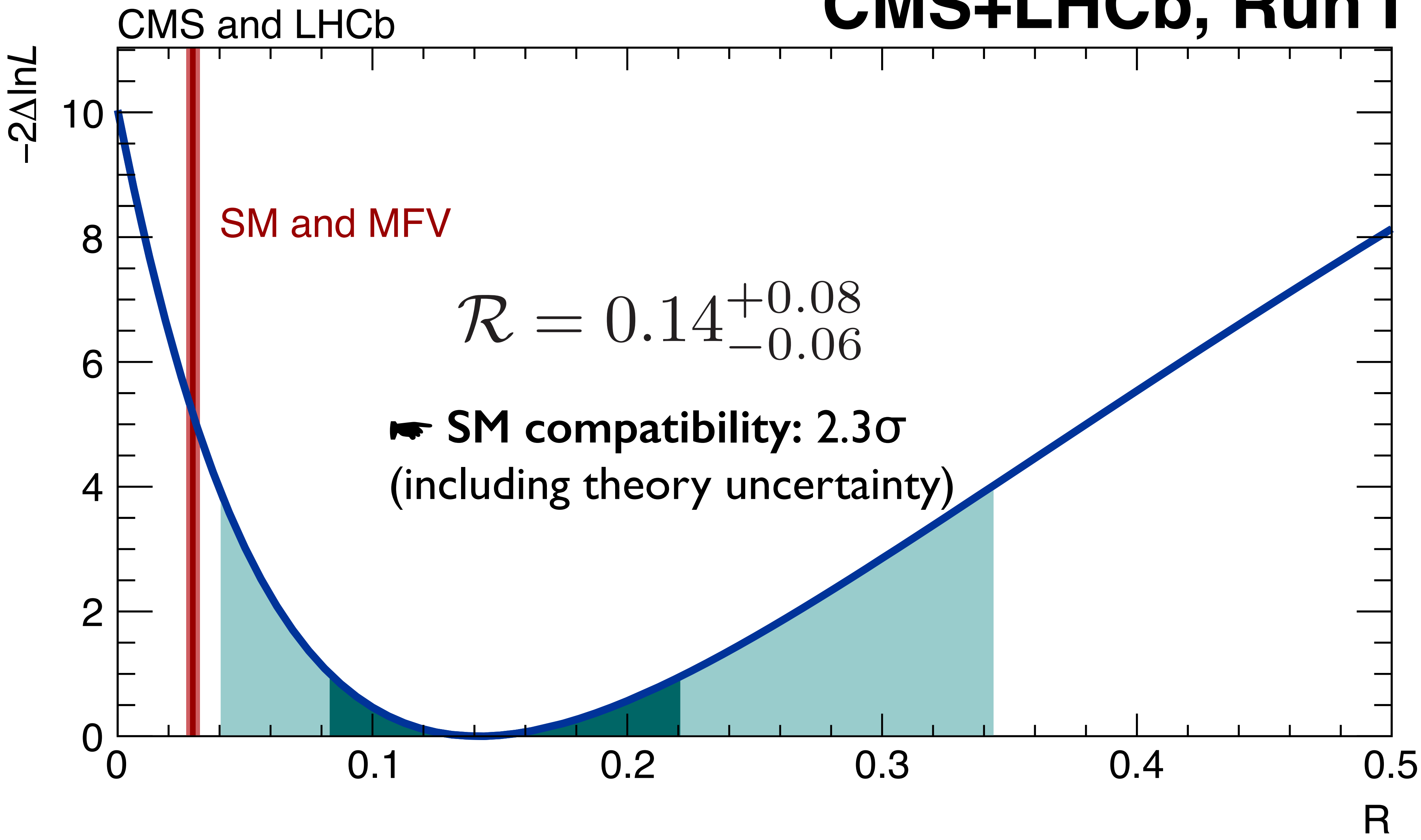
*Cross-checked with Feldman-Cousins:
3.0σ (official significance)

2015

[Nature 522, 68-72 (04 June 2015)]

The ratio R = BF($B_d \to \mu\mu$) / BF($B_s \to \mu\mu$) is a precise test of minimal flavour violation (MFV):

CMS+LHCb, Run I



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

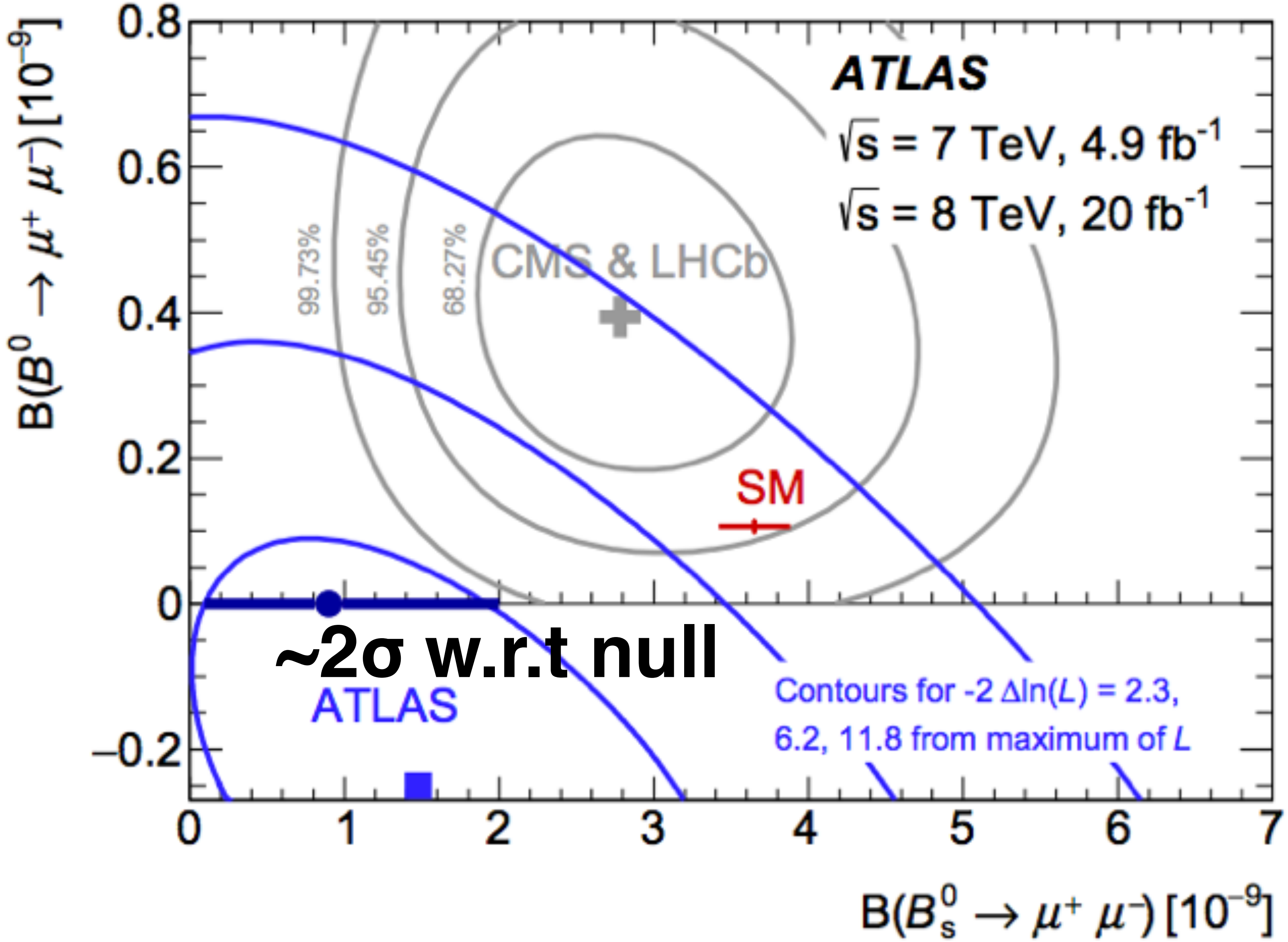
☛ **SM compatibility:** 2.3σ
(including theory uncertainty)

2016

[EPJC 76 (2016) no.9, 513]

Run 1 results from ATLAS are in agreement.

$B_s \to \mu\mu$ excess at 2σ:



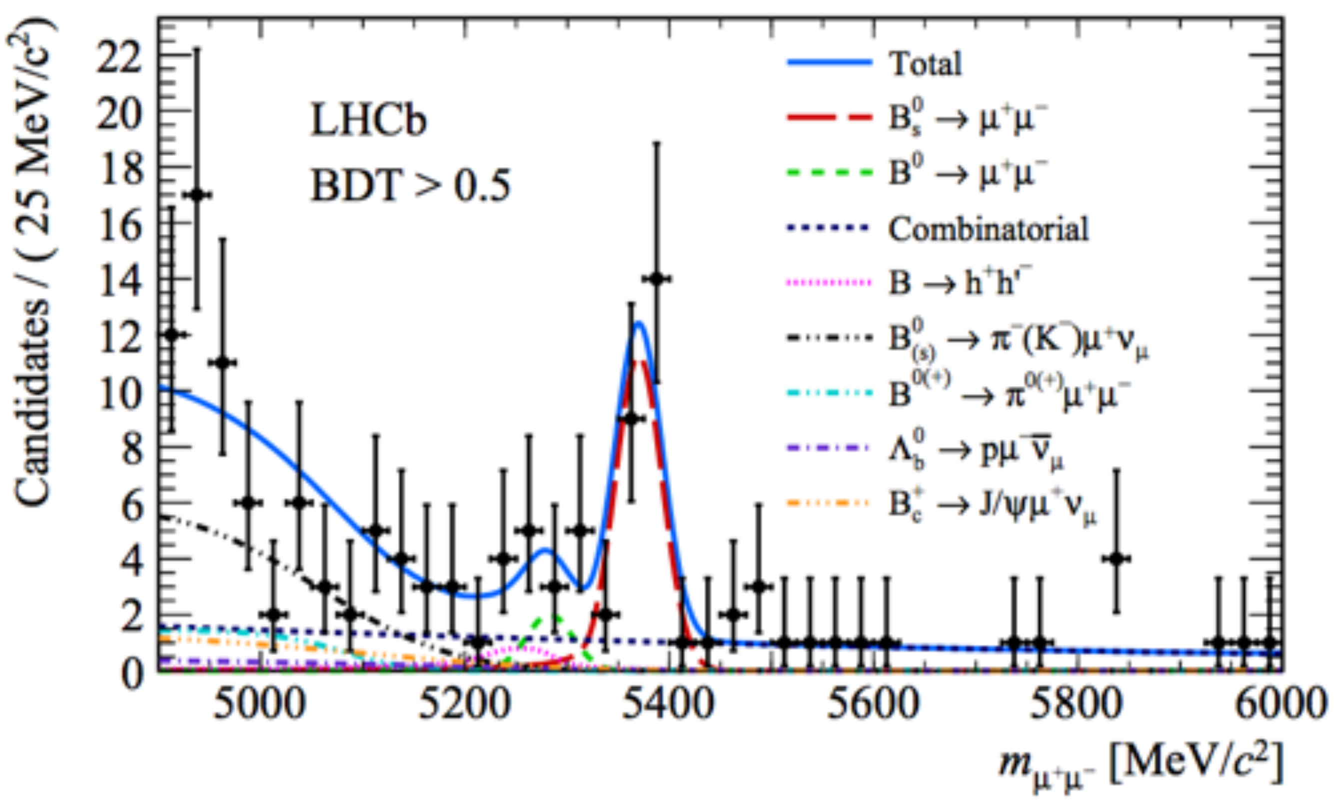
$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}\ (2\sigma)$$

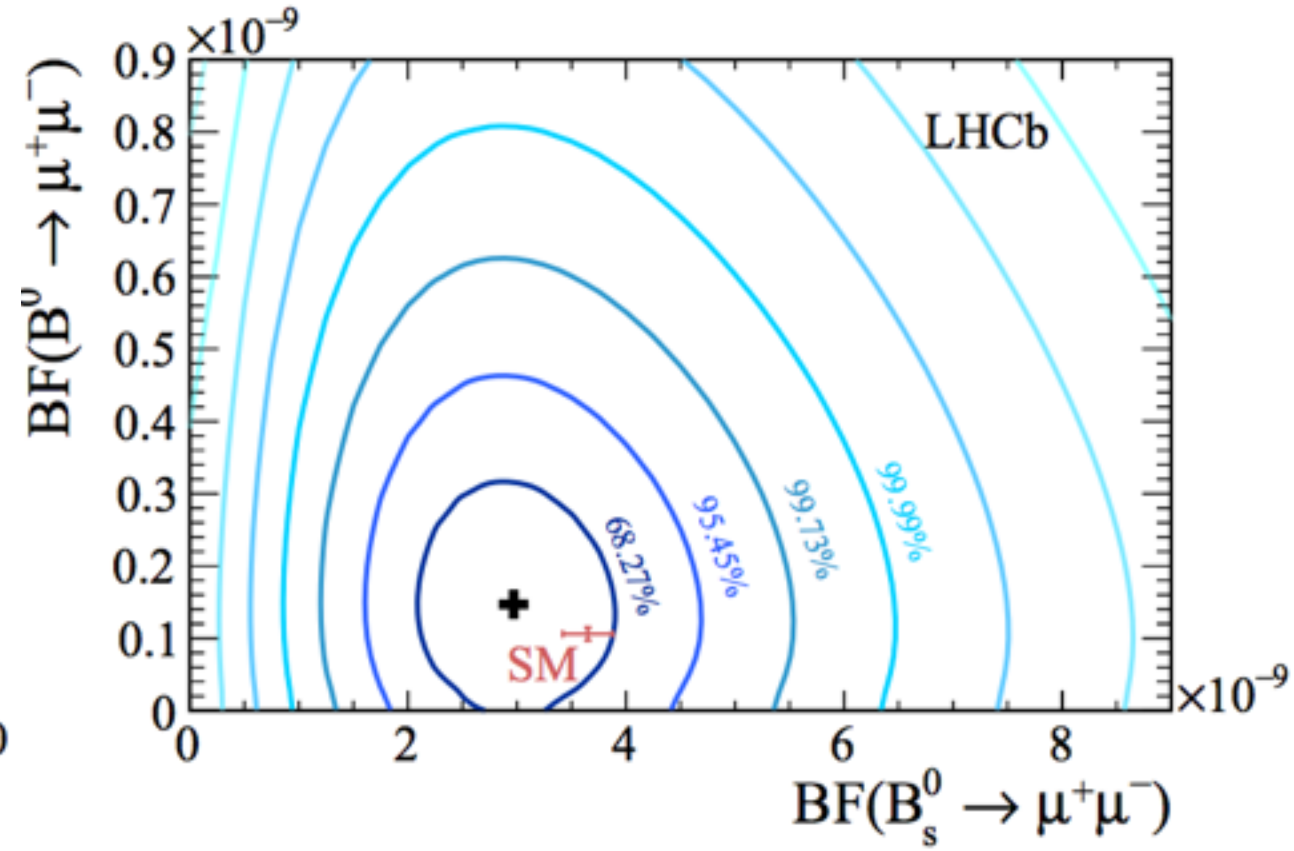
$$\mathcal{BR}(B_d \to \mu^+\mu^-) < 4.2 \times 10^{-10} (95\% CL)$$

2017!

[PRL 118, 191801 (2017)]

In Run II, LHCb observes $B_s \to \mu^+\mu^-$ independently with 7.8σ:





- **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 improve BDT

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

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

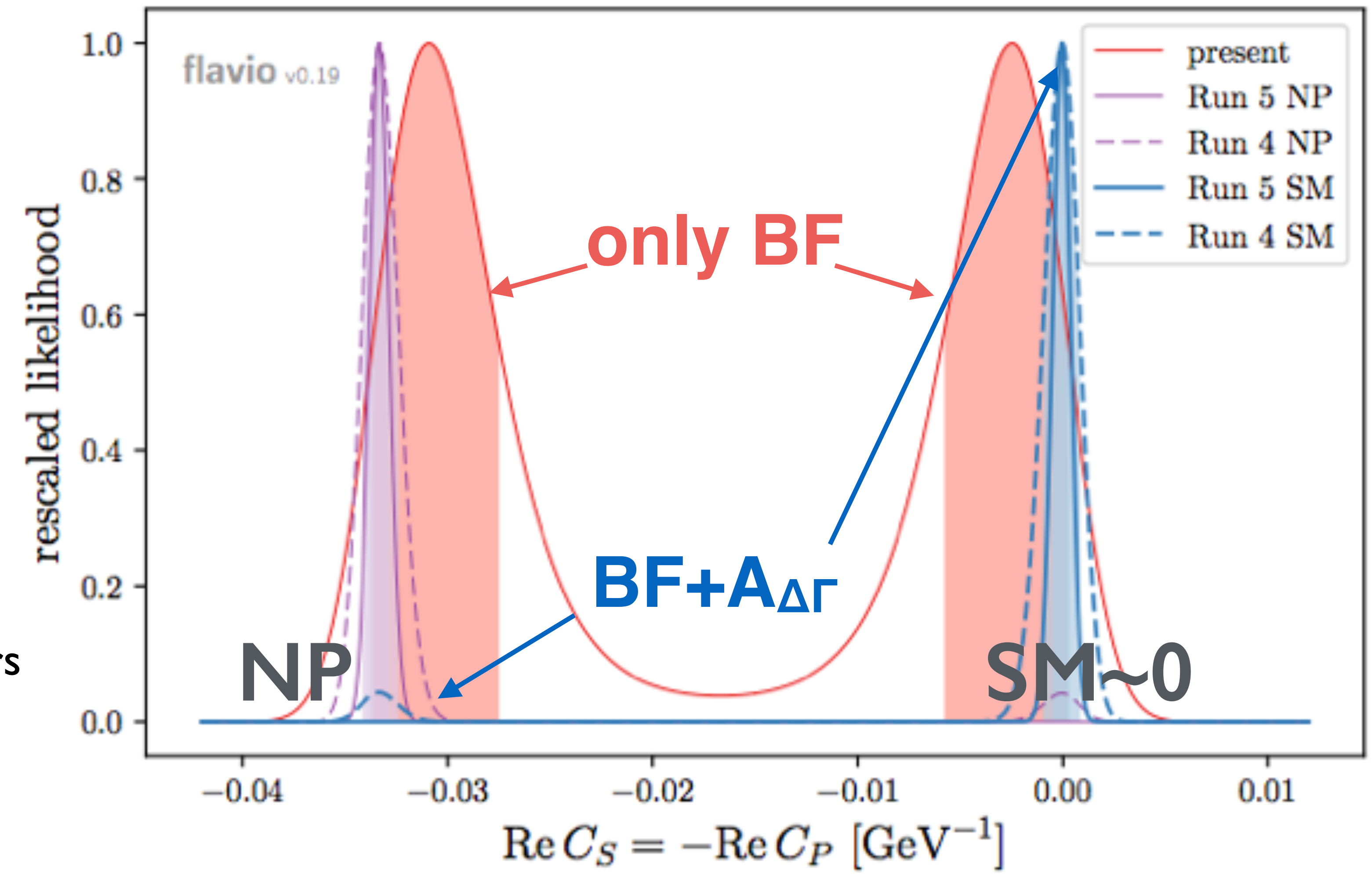
$B_s \to \mu\mu$ (7.8σ) and $B_d \to \mu\mu$ (1.6σ)

- **The most precise results up to date, first single experiment $B_s \to \mu\mu$ observation.**

$B_s \to \mu^+\mu^-$ is sensitive to new physics even if its branching ratio is not.

for example..

Altmannshofer et al
[JHEP 05 (2017) 076]



MFV NP: new (pseudo-)scalars (MSSM, two-leptoquark scenarios)

- Measured BF alone leads to ambiguity: e.g. $C_S = -C_P$ equally likely to the SM solution ($C_S = C_P = 0$)
- **Mass-eigenstate-rate asymmetry** ($A_{\Delta\Gamma}$) can solve the ambiguity:

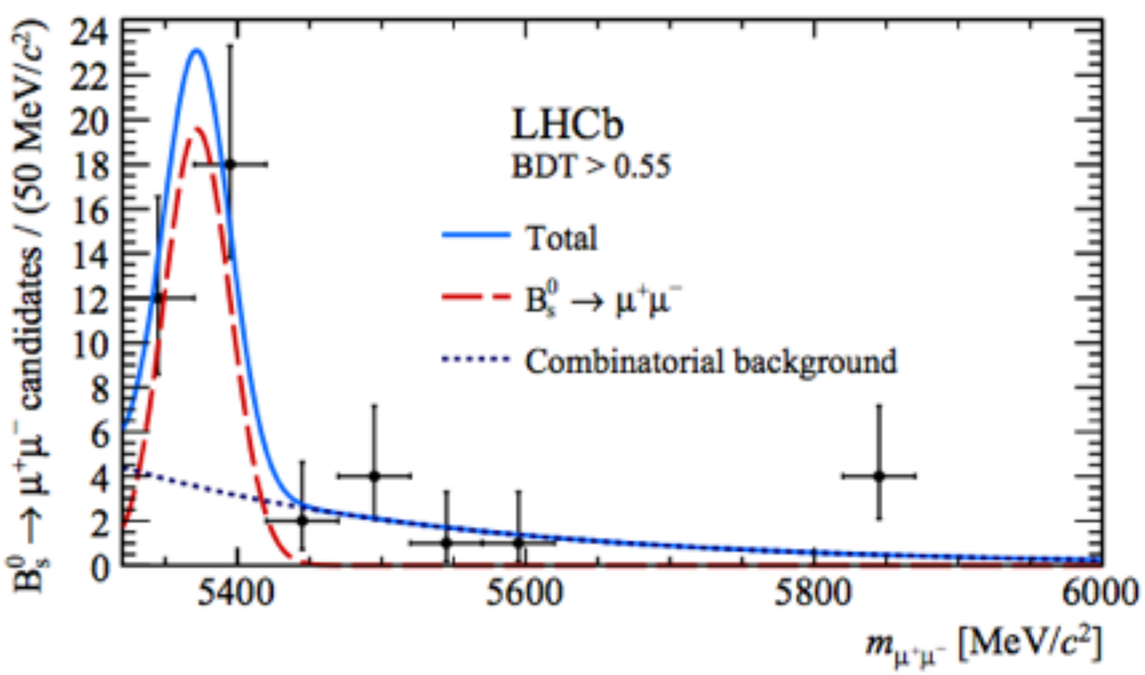
$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^{\mathrm{H}} \to \mu^+\mu^-) - \Gamma(B_s^{\mathrm{L}} \to \mu^+\mu^-)}{\Gamma(B_s^{\mathrm{H}} \to \mu^+\mu^-) + \Gamma(B_s^{\mathrm{L}} \to \mu^+\mu^-)}$$

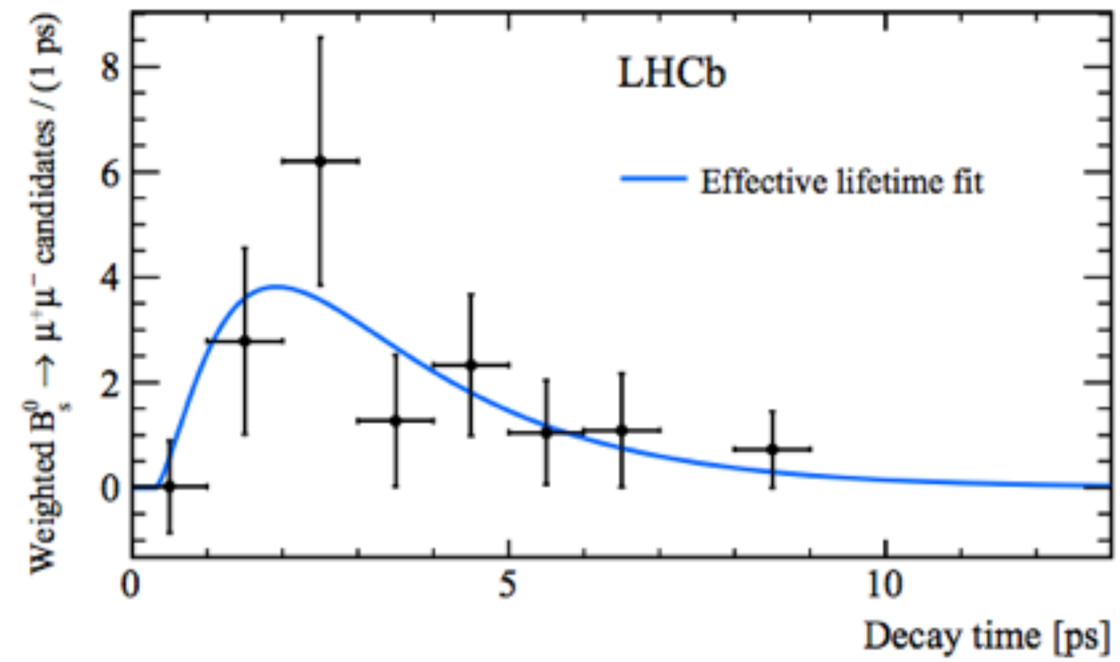
SM: $A_{\Delta\Gamma} = +1$

LHCb goes beyond the counting: the first effective lifetime measurement

- $A_{\Delta\Gamma}$ can be determined from **the effective $B_s \to \mu\mu$ lifetime:**

[PRL 118, 191801 (2017)]

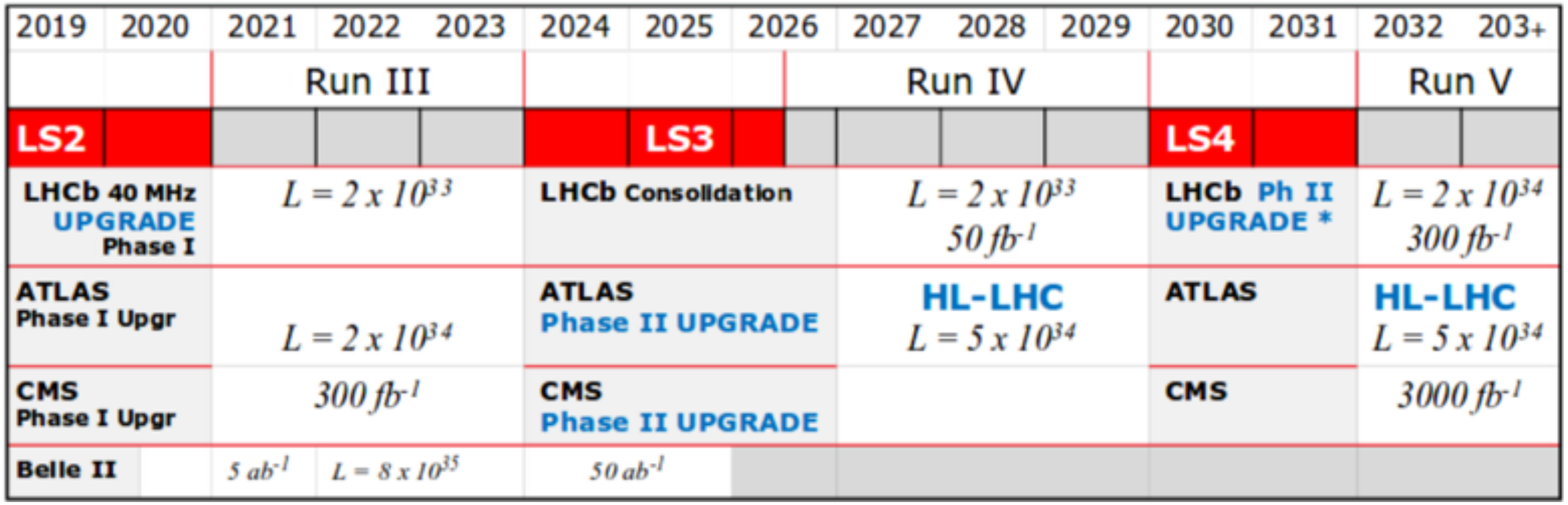




$$\tau(B_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 ps$$
(stat) (syst)

- Compatible with the SM: $\tau(B_s \to \mu^+\mu^-)^{SM} = (1.615 \pm 0.010) ps$
- **First** (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)

Goals for both before and after the upgrade(s)



- Improve the $BF(B_s \to \mu\mu)$ to constrain NP in $C_{10,S,P}$
- Measure $B^0 \to \mu\mu$ and test MFV in the BF ratio
  - If very lucky, could see evidence as early as 2019 (expect ~20 SM candidates after Run 2, ~60 together with Run 3)
- Determine the $A_{\Delta\Gamma}$ to probe the hidden New Physics effects in C_S and C_P
  - First discriminating $A_{\Delta\Gamma}$ measurement expected after Run 3 with ~35% rel. precision (~20%,<10% uncertainty after Run 4,5)

Other $B \rightarrow l^+l^-$ modes

Other $B \to l^+ l^-$ modes

- $B_{(s)} \to e^+ e^-$ heavily helicity suppressed (~10^{-13}) in the SM and experimentally difficult

- $B_{(s)} \to \tau^+ \tau^-$ challenging experimentally, but also affected the least by the helicity suppression:
  - $BF_{SM}(B_s \to \tau^+ \tau^-) = 7.7(5) \times 10^{-7}$ **Bobeth et al [PRL 96:241802 (2014)]**
  - previous limit only for B^0
    $BF(B^0 \to \tau^+ \tau^-) < 4.1 \times 10^{-3}$ @ 90%CL BaBar **Aubert et al [PRL 96:241802 (2006)]**
  - LFU tensions R(D), R(D*) could imply a $O(10^3)$ boost (Z', leptoquarks, 2HDM,..) **Alonso et al [1505.05164]**

$B_{(s)} \to \tau^+\tau^-$ search in Run I data

[PRL 118, 251802 (2017)]

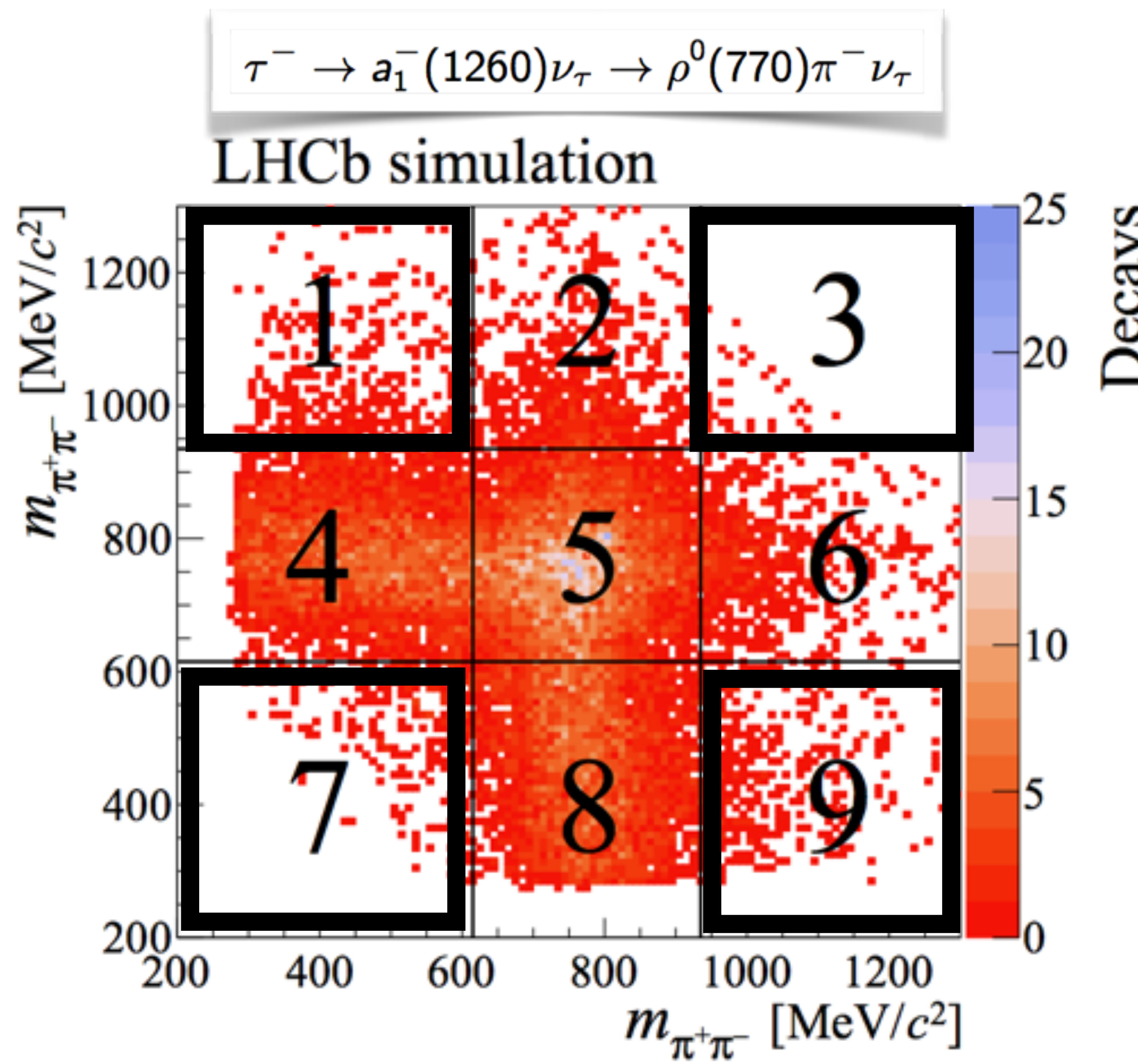
- LHCb analyses Run1 data ($3fb^{-1}$) for the **hadronic τ-modes:** BF($\tau \to \pi\pi\pi\nu$) = 9.31(5)%
- Two final state neutrinos render B-mass useless for signal/background (and B^0/B_s) separation
- Instead use the intermediate $\rho^0(770) \to \pi^+\pi^-$ resonance of the predominant decay chain:

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

$B_{(s)} \to \tau^+\tau^-$ search in Run I data

PRL 118, 251802 (2017)

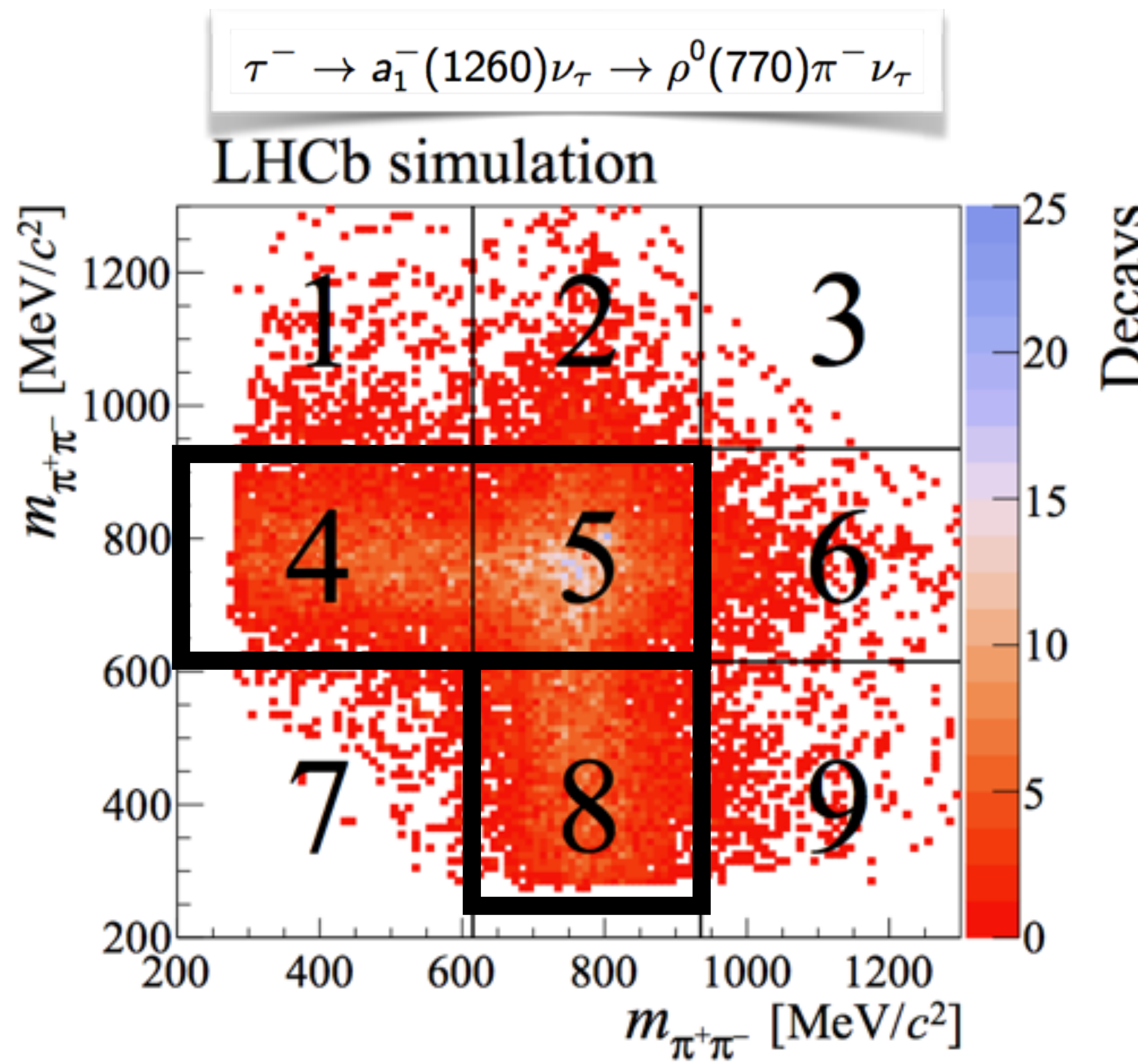
- **Optimise the selection, train NN: one-τ in 1-3-7-9** (13% N_{Sig})
- Background model from: one-τ in 4-5-8 and other in one-τ 4-8 (58% N_{Sig})
- Signal region: both τ's in 5 (16% N_{Sig})



$B_{(s)} \to \tau^+\tau^-$ search in Run I data

PRL 118, 251802 (2017)

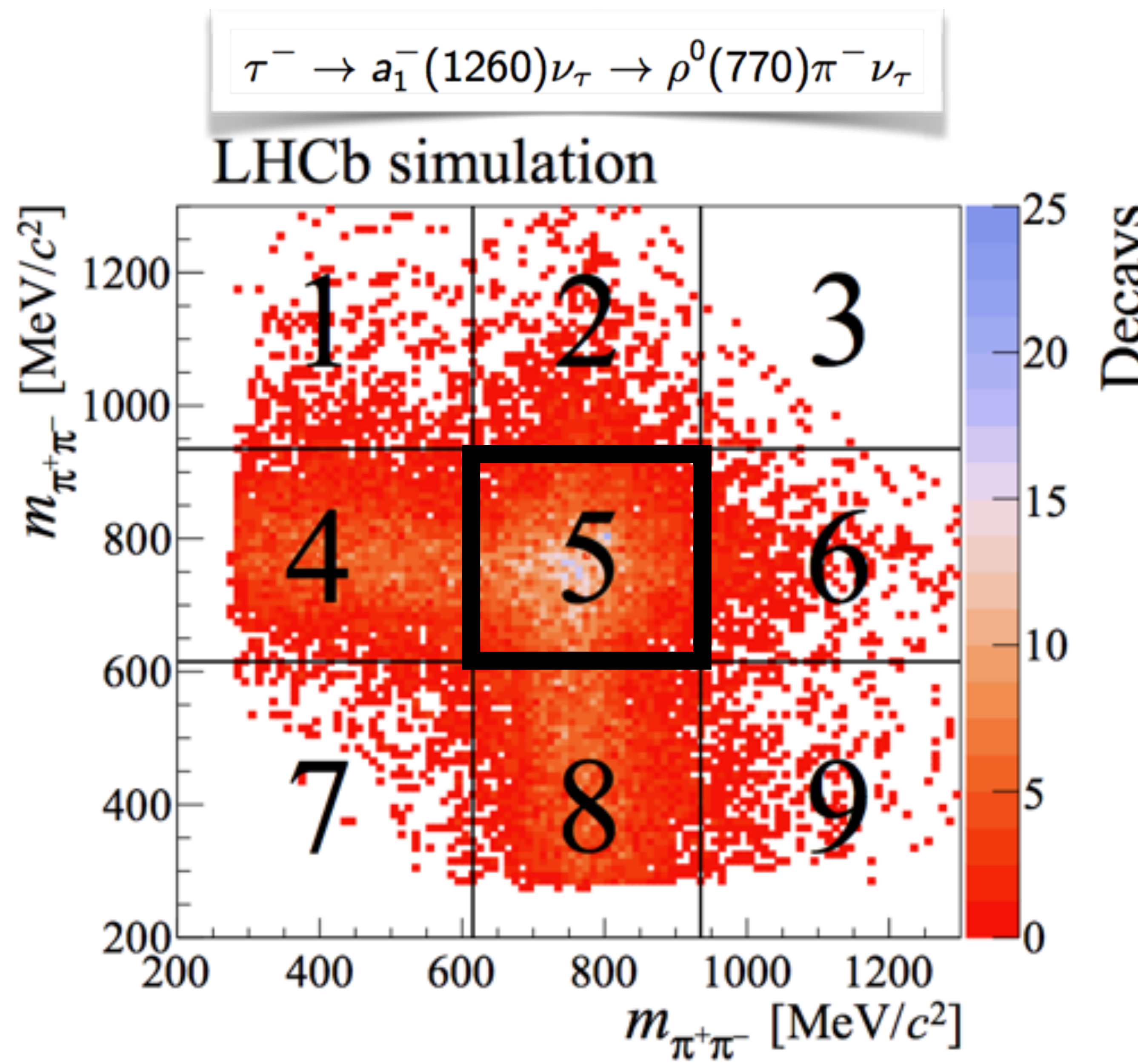
- Optimise the selection, train NN: one-τ in 1-3-7-9 (13% N_{Sig})
- **Background model from: one-τ in 4-5-8 and other in one-τ 4-8** (58% N_{Sig})
- Signal region: both τ's in 5 (16% N_{Sig})



$B_{(s)} \to \tau^+\tau^-$ search in Run I data

PRL 118, 251802 (2017)

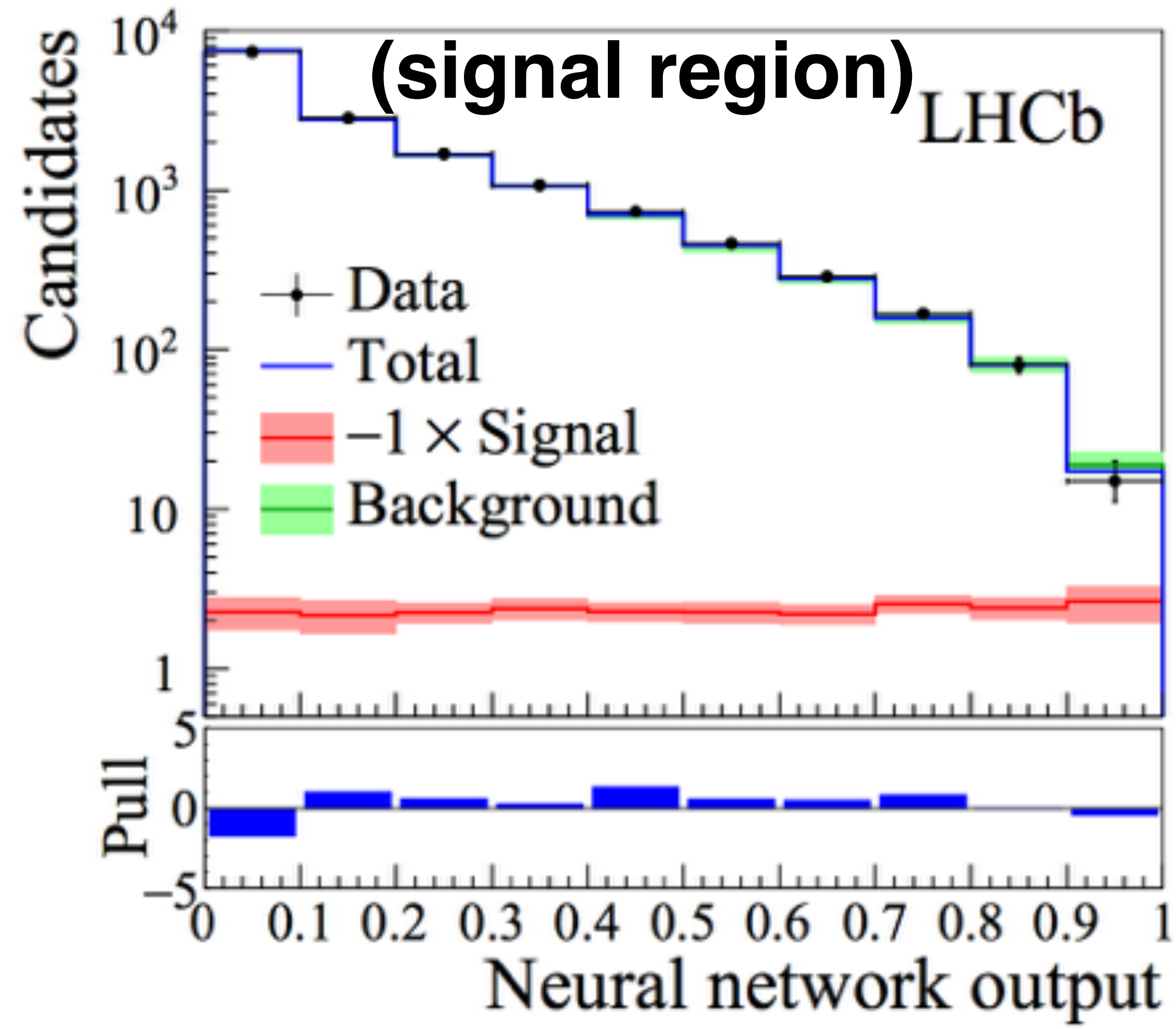
- Optimise the selection, train NN: one-τ in 1-3-7-9 (13% N_{Sig})
- Background model from: one-τ in 4-5-8 and other in one-τ 4-8 (58% N_{Sig})
- **Signal region: both τ's in 5** (16% N_{Sig})



$B_{(s)} \to \tau^+\tau^-$ search in Run I data

PRL 118, 251802 (2017)

- The separate signal from the background using a neural-net
  - 29 discriminating variables (geom., kin., iso.,τ params.)
  - Signal MC distributions calibrated on the normalisation modes
- Normalise the BF to $B_0 \to D^-D^+_s$ (where $D \to 3h$):

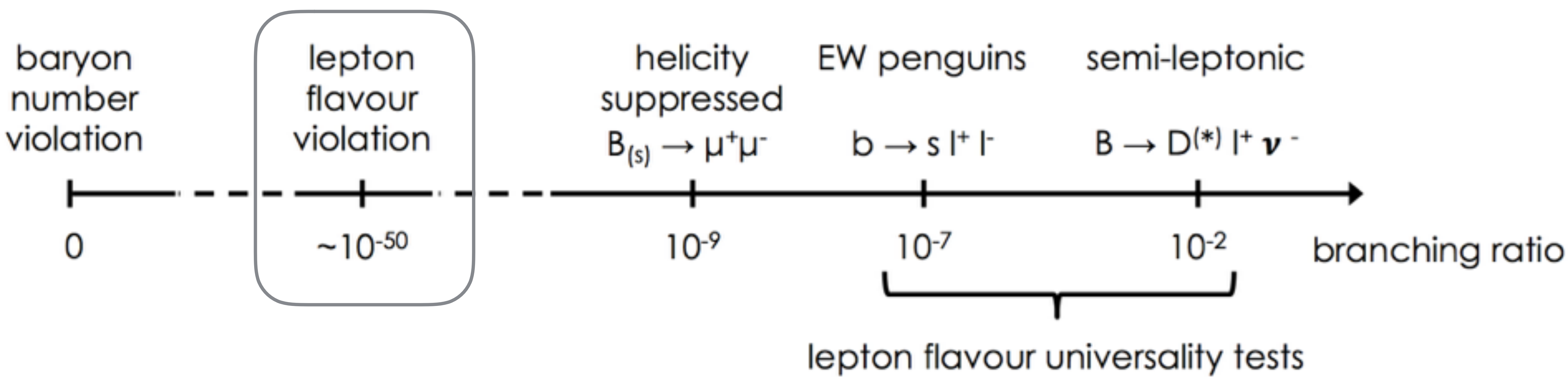


$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ @ } 95\%CL$$
$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ @ } 95\%CL$$

(assuming one or the other B mode)

PRL 118, 251802 (2017)

Leptonic B decays have more to offer..

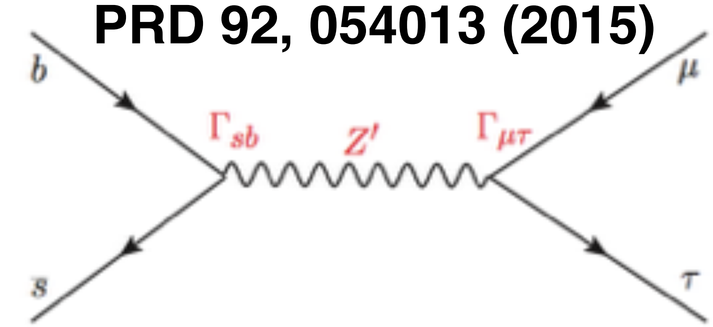


Fully leptonic $B \rightarrow l_x^+ l_y^-$ decays are practically non-existent in the SM

Lepton flavour violation searches in LHCb

- Especially interesting in the light of the recent lepton non-universality hints: $R(K^{(*)})$, $R(D^{(*)})$.
- A large number of modes (SUSY, Z', leptoquark, Pati-Salam,..) could enhance
  - $BF(B_{(s)} \to \tau^+ \mu^-) \sim O(10^{-8})$ in generic Z'
  - $BF(B_{(s)} \to e^+ \mu^-) \sim O(10^{-11})$

PRD 92, 054013 (2015)



- Existing limits:
  - $BF(B^0 \to \tau^+ \mu^-) < 2.2 \times 10^{-5}$ @90% BaBar
  - $BF(B^0 \to e^+ \mu^-) < 3.7 \times 10^{-9}$ @95% LHCb 1fb^{-1}
  - $BF(B_s \to e^+ \mu^-) < 1.4 \times 10^{-8}$ @95% LHCb 1fb^{-1}

PRD 77, 091104 (2008)

PRL 111 (2013) 141801

New!

$B_{(s)} \to e^+\mu^-$ search in Run I data

arXiv:1710.04111
submitted to JHEP

- Analyse full Run I sample ($3 fb^{-1}$) with improved selection (esp. BDT)
- Similar to $B_{(s)} \to \mu^+\mu^-$, yet more challenging
  - Bremsstrahlung correction to the e-momentum
- Selected $e^+\mu^-$ candidates in $m_{e\mu} \in [4.9, 5.85]$ GeV/c^2
  - contaminated by combinatorial background
  - sample split in two depending on the nr. of recovered photons: a) $e+0\gamma$ and b) $e+n\gamma$

New!

$B_{(s)} \to e^+\mu^-$ search in Run I data

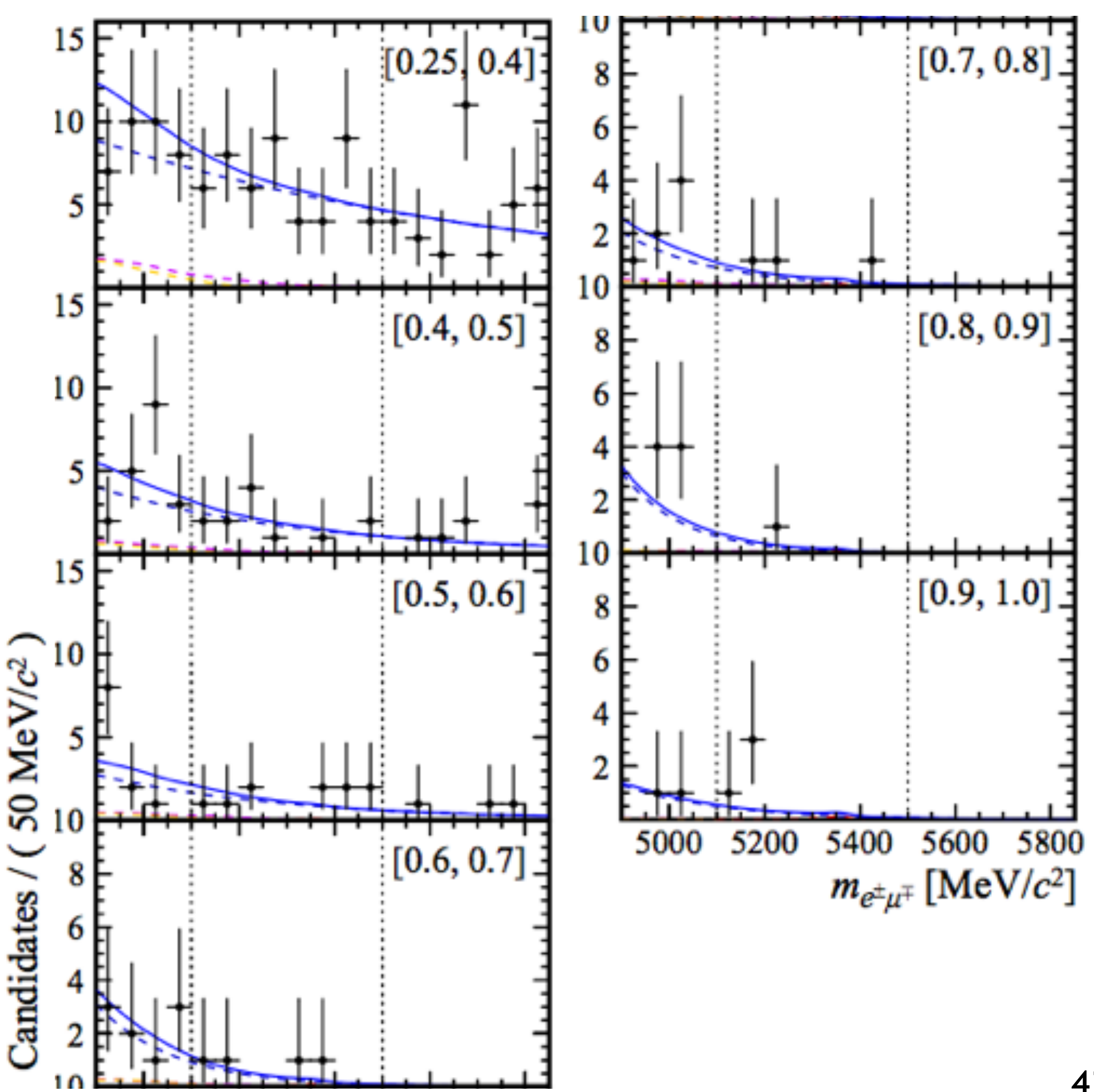
arXiv:1710.04111
submitted to JHEP

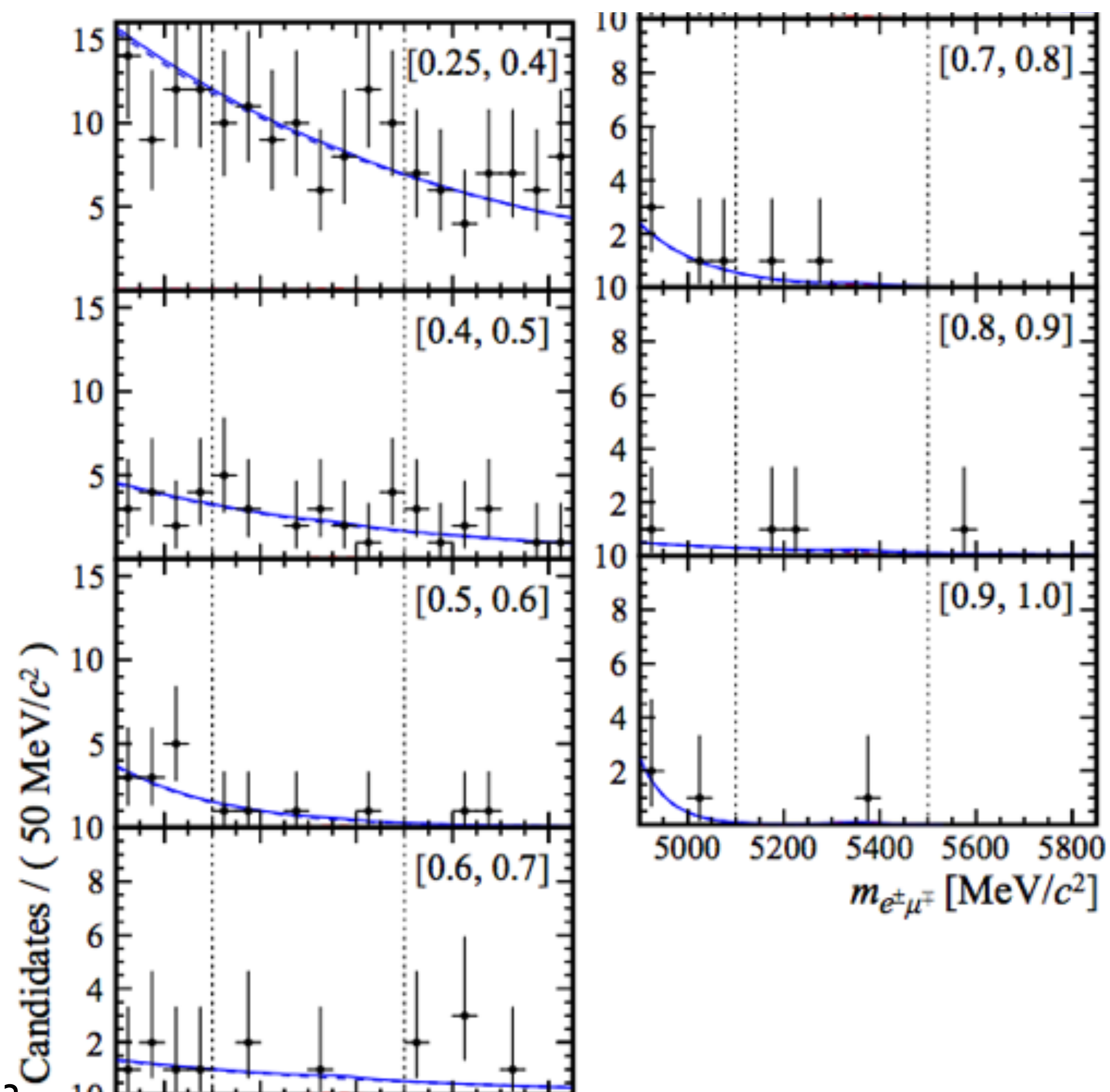
- The combinatorial is suppressed using a multivariate classifier (BDT):
  - trained on $B_{(s)} \to e^+\mu^-$ MC and same sign $e^{+/-}\mu^{+/-}$ data
  - signal response calibrated on $B^0 \to K^+\pi^-$ data (accounting for Bremsstrahlung)
- Simultaneous fit on 2x7 BDT bins. Model:
  - Signal+mis-identified bkg.($B \to hh$, $B \to hl\nu$) +combinatorial bkg.
  - individual for both bremsstrahlung categories

No $B_{(s)} \rightarrow e^+\mu^-$ signal in Run I data

arXiv:1710.04111
submitted to JHEP

- a) No Bremsstrahlung
- b) Bremsstrahlung





New!

$B_{(s)} \to e^+\mu^-$ search in Run I data

arXiv:1710.04111
submitted to JHEP

- LHCb sets the most stringent limits up to date:

channel	expected	observed
$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp)$	$3.9\,(5.0) \times 10^{-9}$	$5.4\,(6.3) \times 10^{-9}$
$\mathcal{B}(B^0 \to e^\pm\mu^\mp)$	$0.9\,(1.2) \times 10^{-9}$	$1.0\,(1.3) \times 10^{-9}$

- The limit on $B_s \to e^+\mu^-$ is set assuming only B_{Heavy} decays (as in SM).
  - B_{Light}: $BF(B_s \to e^+\mu^-) < 6.0(7.2)\times10^{-9}$ @90(95)%CL

Rare leptonic B-decays at the end of 2017

- B-decays have provided us with some of the most interesting puzzles in particle physics:
  - global W. coefficient analysis show a coherent picture
  - anomalies either in **vector (C_9)** OR in both **vector and axial-vector currents (C_9, C_{10})**

- Fully leptonic B-decays can **constrain the axial-vector contributions (C_{10})**
  - SM like BF($B_s \to \mu^+\mu^-$) excludes very large contributions to $C_{10,S,P}$, but not yet precise enough to distinguish btw. $C^{NP}_{10}+C^{NP}_9$ and C^{NP}_9 alone scenarios.
- Only beginning to tap into $B_{(s)} \to \mu^+\mu^-$
  - Effective $B_s \to \mu^+\mu^-$ lifetime will help to expose/ exclude $C_{S,P}$ contributions invisible to the BF alone (first LHCb results on Run1+Run2 are out, $A_{\Delta\Gamma}$ accessible in Run 3)
  - $B_d \to \mu^+\mu^-$ could enter the game soon (2019? but most likely in Run 3)

- In the light of the recent LFU tensions **other leptonic B modes are as important:**
    - LHCb sets best/first $B_{(s)} \rightarrow \tau^+\tau^-$ limits on Run 1 data at $O(10^{-3})$
    - LHCb sets best $B_{(s)} \rightarrow e^+\mu^-$ limits on Run 1 data at $O(10^{-9})$

Back-up

Historical success of the 'effective' approach

- The 'effective' model independent 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. Similar coupling in the beta decay and muon decay suggested **an underlying structure (V-A)**
  ➤ **1960**'s: Motivated **charm** prediction to make **GIM** work and explain missing FCNC.
  ➤ **1970**'s: In predicting lower bounds on **Z and W masses** from muon lifetime (motivate SPS)
  ➤ **2010**'s: **Lepton Flavour Universality Violation? Z'? Leptoquarks?**

$B \to \mu\mu$ future in numbers

Unofficial crude back-of-the-envelope Standard Model yield estimates based on the Run 1 performance:

Assuming SM and Run1 performance (raw est.)	**Run1**	**+Run 2 (2019)**	**+Run3 (2024)**	**+Run4 (2030)**	**+Run 5** (assume 30% have good S/B)
Lumi (fb^{-1})	3	5,3	15	15	250
$N(B_s \to \mu^+\mu^-)$	35	155	0.5k	0.9k	2.7k
$N(B_d \to \mu^+\mu^-)$	4	20	60	0.1k	0.3k
$\sigma_{Relative}(BF(B_s \to \mu^+\mu^-))$	40%	20%	15%	13%	~10%
$\sigma_{Relative}(A_{\Delta\Gamma})$	-	115%	35%	20%	<10%

Rare di-lepton modes

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

[Phys. Rev. Lett. 112, 101801 (2014)]
with updated **top mass**
[http://arxiv.org/abs/1403.4427]

➤ Precise Standard Model predictions for individual modes:

$$\mathcal{BR}(B_s \to \mu^+\mu^-)^{<t><CP>} = 3.66 \pm 0.23 \times 10^{-9} \text{ (6.4\% unc.)}$$
$$\mathcal{BR}(B_d \to \mu^+\mu^-)^{<t><CP>} = 1.06 \pm 0.09 \times 10^{-10} \text{ (8.5\% unc.)}$$

$B_s^0 \to \mu^+\mu^-$	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$B^0 \to \mu^+\mu^-$	f_{B_d}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

➤ Even more precise Standard Model predictions for the ratio (MVF test):

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{1/\Gamma_H^s}\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}\sqrt{1-\frac{4m_\mu^2}{M_{B_d}^2}}}{M_{B_s}\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}} = 0.0295^{+0.0028(8.7\%)}_{-0.0025(7.7\%)}$$

Error budget of R:
- 8% from V_{td}/V_{ts}
- 3.7% from f_{Bd}/f_{Bs}
- 1.4% from B_s lifetime

- Top mass, Wilson coefficients, and V_{tb} cancel in theory predictions
- Experimental side: no need for the normalisation

Nature 522, 68-72 (04 June 2015)

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

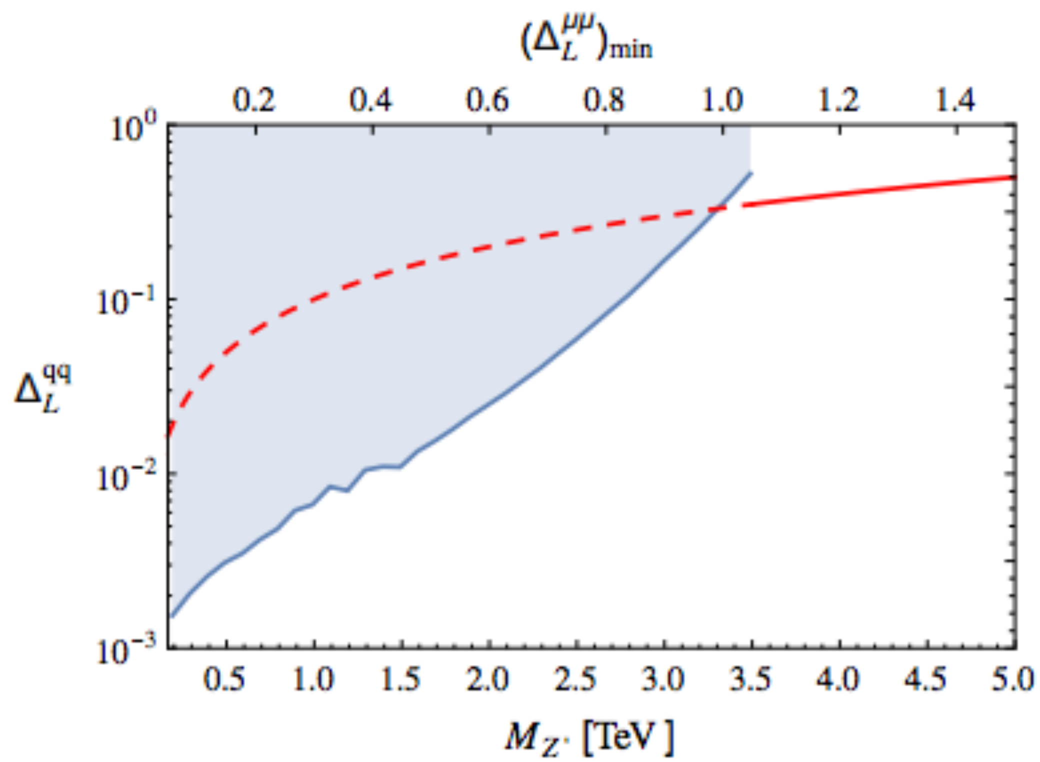
$$S = \frac{m_{B_q}^2}{2m_\ell}\left[(C_S)_q^\ell - (C'_S)_q^\ell\right] \quad P = \left[(C_{10})_q^\ell - (C'_{10})_q^\ell\right] + \frac{m_{B_q}^2}{2m_\ell}\left[(C_P)_q^\ell - (C'_P)_q^\ell\right]$$

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

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

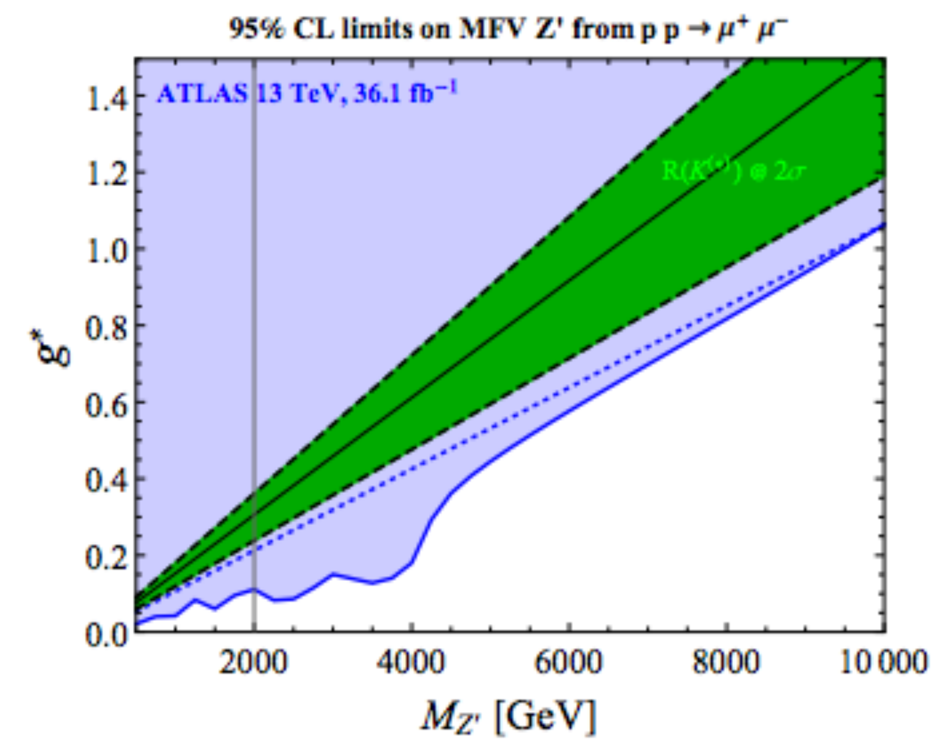
Rel. Unc. from 6.4% -> 5%
Phys. Rev. Lett. 112, 101801 (2014)
updated in arXiv:1702.05498

Dimuon constraints: two examples



Altmannshofer and Straub 1411.3161

- For $M_{Z'} \lesssim 3.5$ TeV, coupling to light quarks must be suppressed



Greljo and Marzocca 1704.09015

- MFV-like coupling to quarks is already excluded

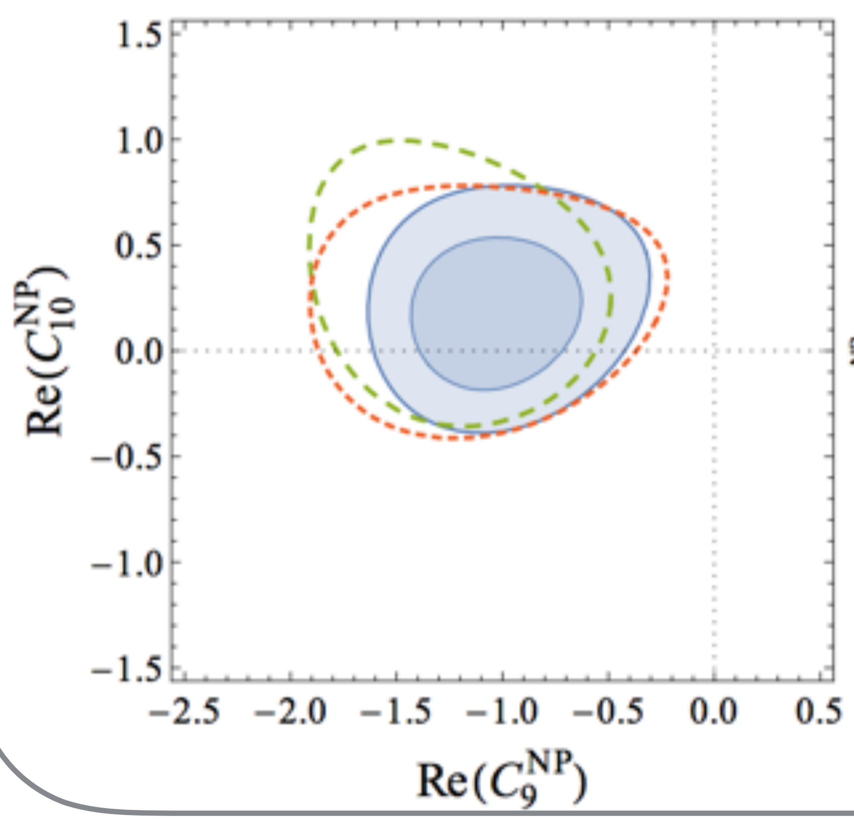
Wilson coefficients are measured in **global b→ sl⁺l⁻(γ) analysis**

- 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 $b \to s l^+ l^-$ branching fraction** measurements; supported by R(K).
- **Tensions are relieved** by (NP effects?):

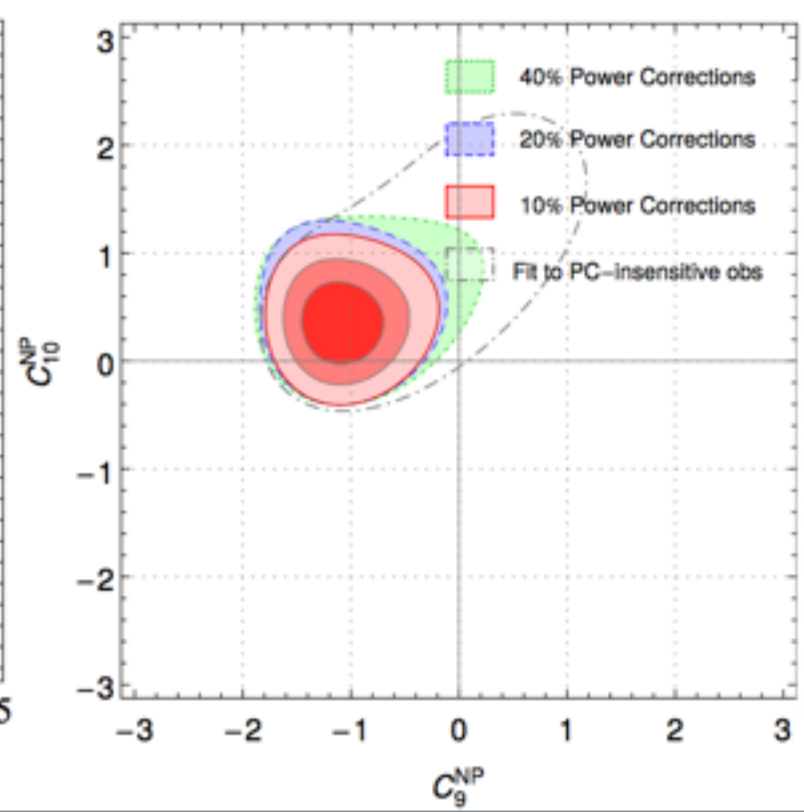
$$[(C_9)^\mu_s]^{NP} \approx -1.1 \quad \text{or} \quad [(C_9)^\mu_s]^{NP} = -[(C_{10})^\mu_s]^{NP} \approx -0.5$$

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

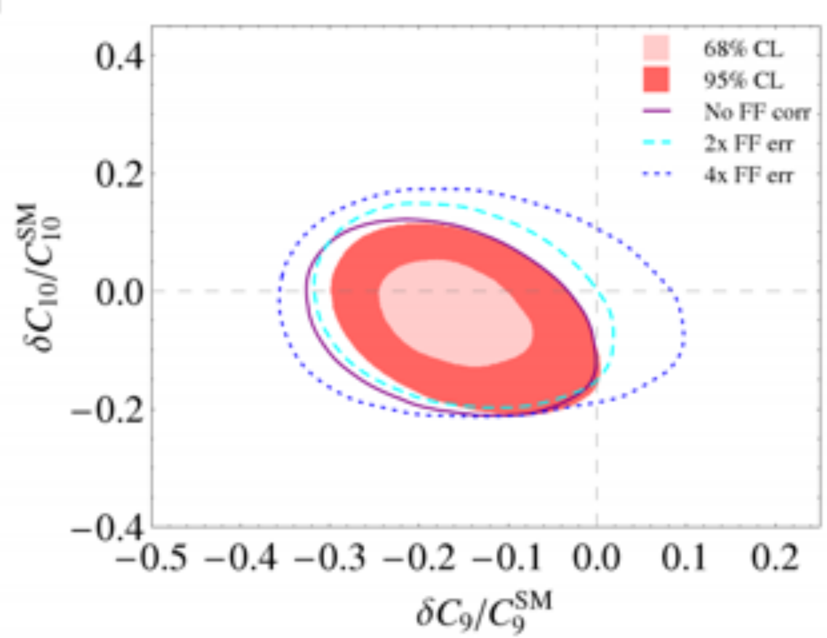
Altmannshofer, Straub **[Eur.Phys.J.C75(8)(2015)382]**



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



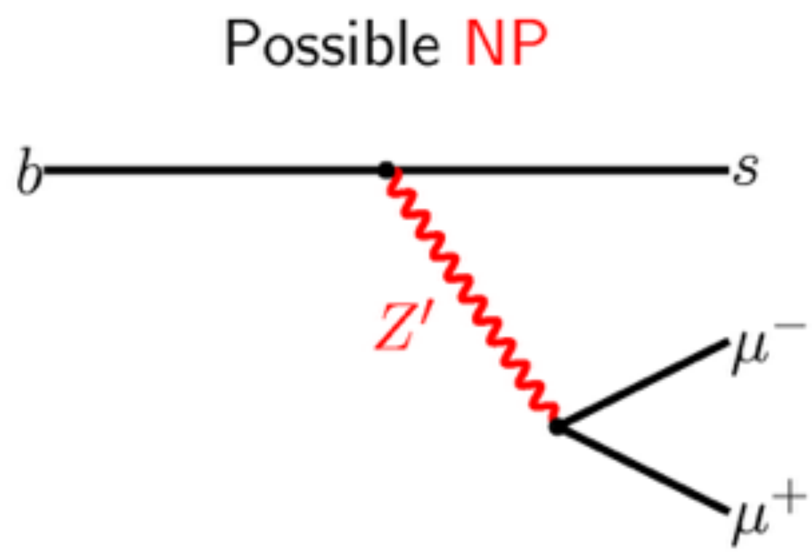
Hurth, Mahmoudi, Neshatpour **[arXiv:1603.00865]**



Understanding **the origin** of the tensions

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

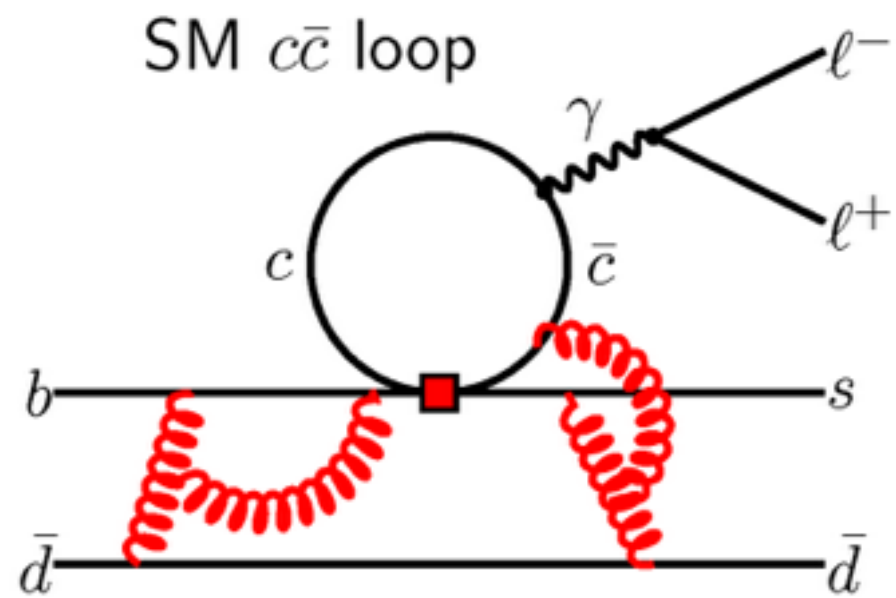
Z', leptoquarks,…



$$C_9 + C_9^{NP}$$

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 C_9

[arXiv:1612.06764] submitted to EPJC

NEW!

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

➽ The differential decay rate depends on the Wilson coefficients:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |\mathbf{k}|\beta \left\{ \frac{2}{3}|\mathbf{k}|^2\beta^2 \left|\mathcal{C}_{10} f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2 - m_K^2)^2}{q^2 m_B^2} \left|\mathcal{C}_{10} f_0(q^2)\right|^2 + |\mathbf{k}|^2 \left[1 - \frac{1}{3}\beta^2\right] \left|\mathcal{C}_9 f_+(q^2) + 2\mathcal{C}_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2)\right|^2 \right\},$$

fix C_7 to the SM value (small)

☛ Parametrise resonance effects:

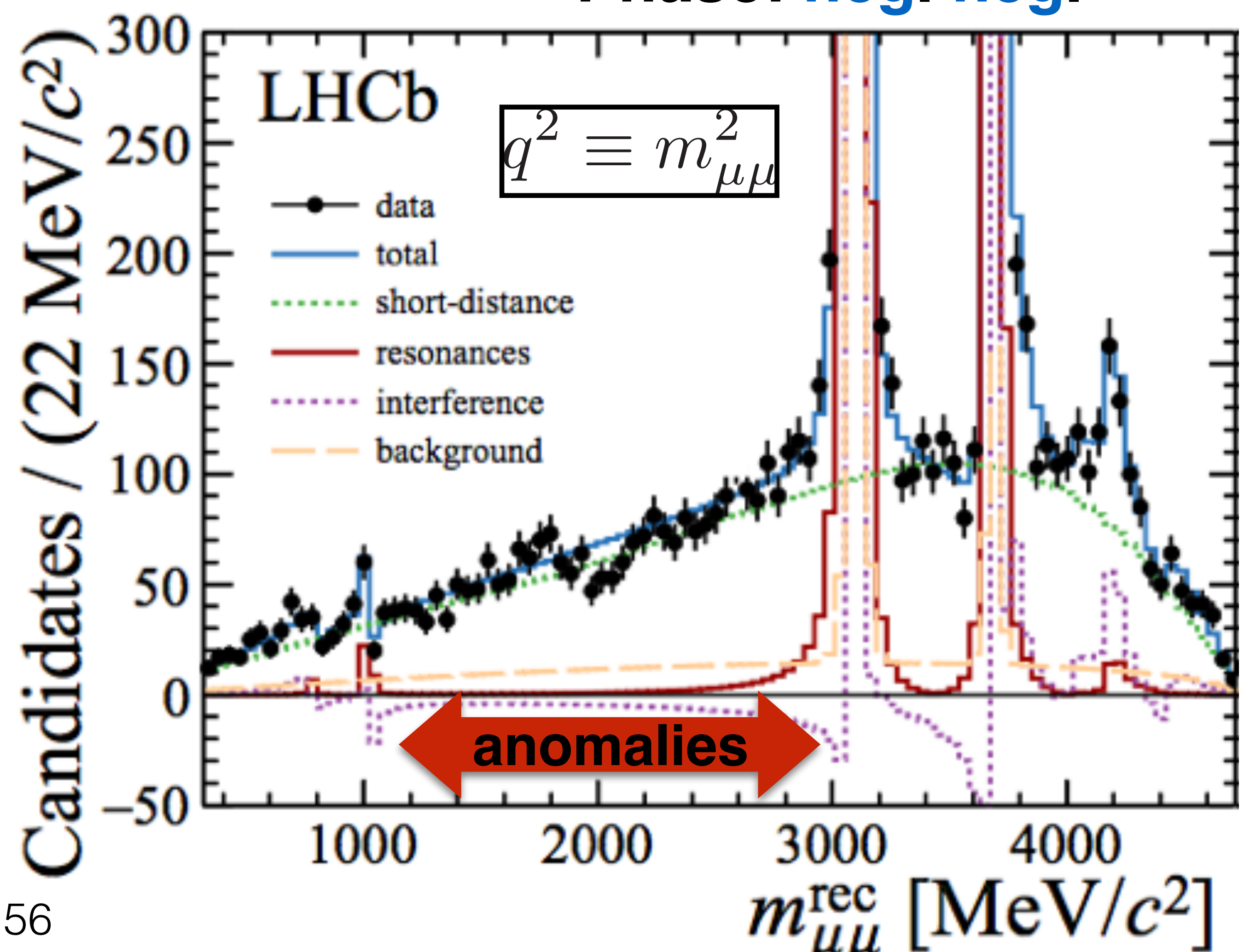
$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2)$$

relative phase to C_9

Breit-Wigner/ Flatté Φ(3770)

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

Phase: neg. neg.



Measuring **resonance effects in C_9**

[arXiv:1612.06764]
submitted to EPJC

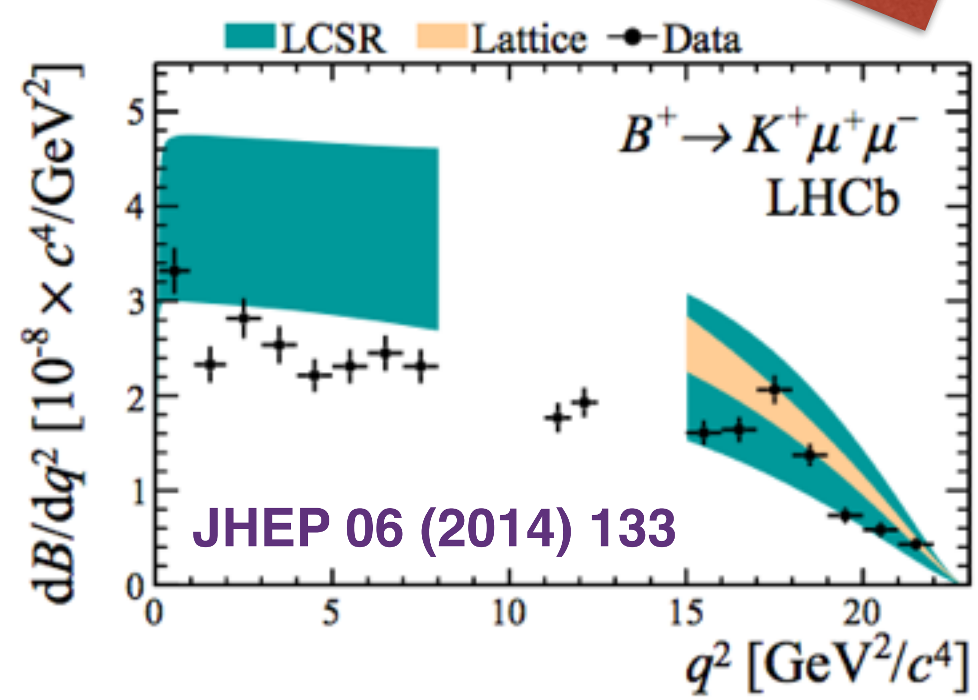
NEW!

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

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

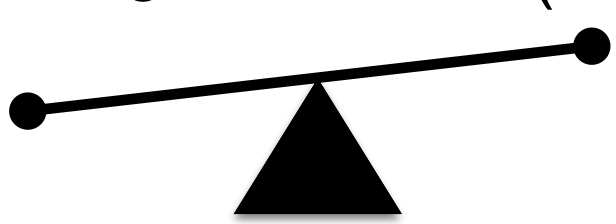
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.29 \pm 0.07\,(\text{stat}) \pm 0.21\,(\text{syst})) \times 10^{-7}$$ **old**

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

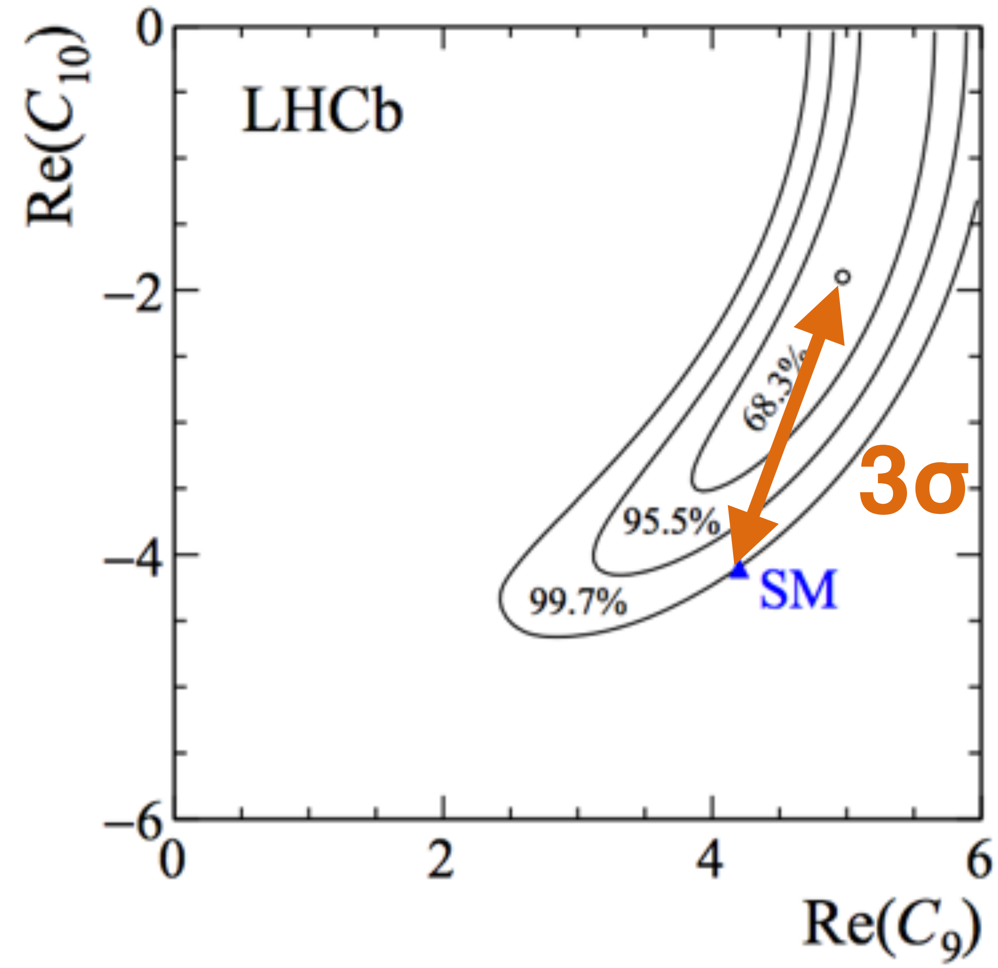


- 1D (C_9, C_{10}=SM) fit: **C_9<SM** (as the global fits)

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



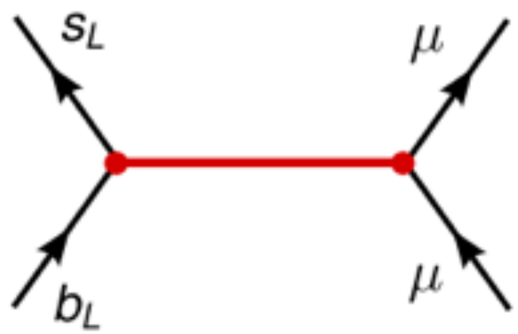
C_9^{NP}



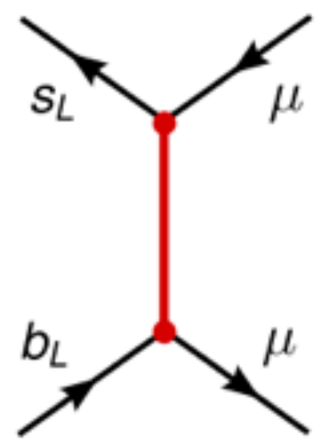
- The main conclusion: contributions from J/ψ and ψ(2S) are contained around their (narrow) resonances.

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

Possible New Physics

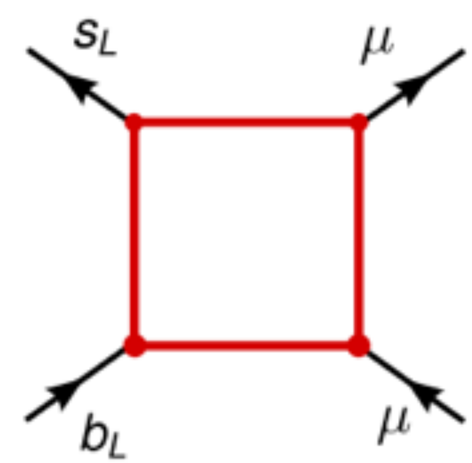


- Z'
- $SU(2)_L$ singlet or triplet



- Leptoquark
- Spin 0 or 1

Talk by I. Nisandzic, B. Grinaios



- New scalars/vectors, also leptoquarks possible