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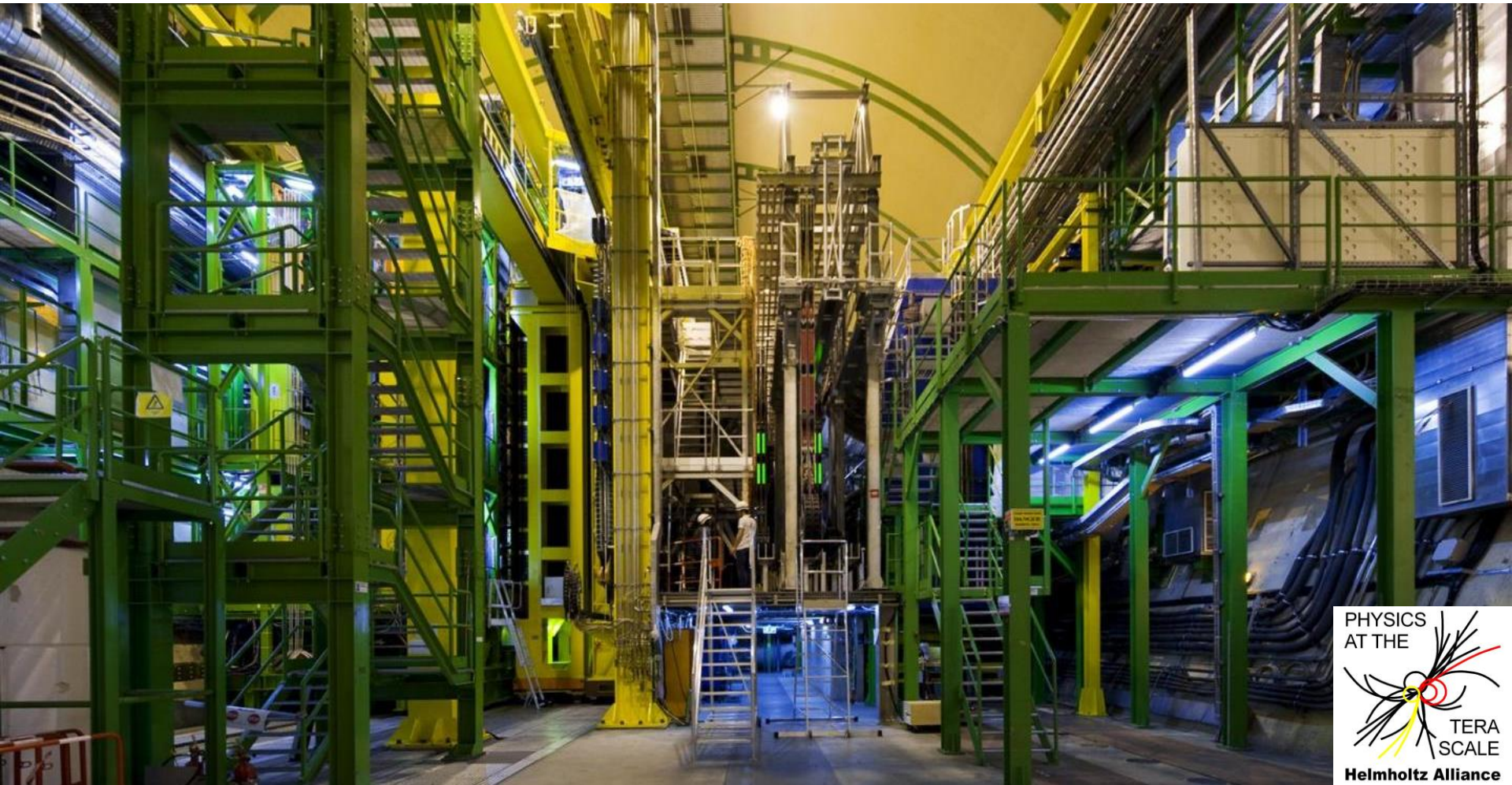
Federal Ministry
of Education
and Research

Rare decays at LHCb

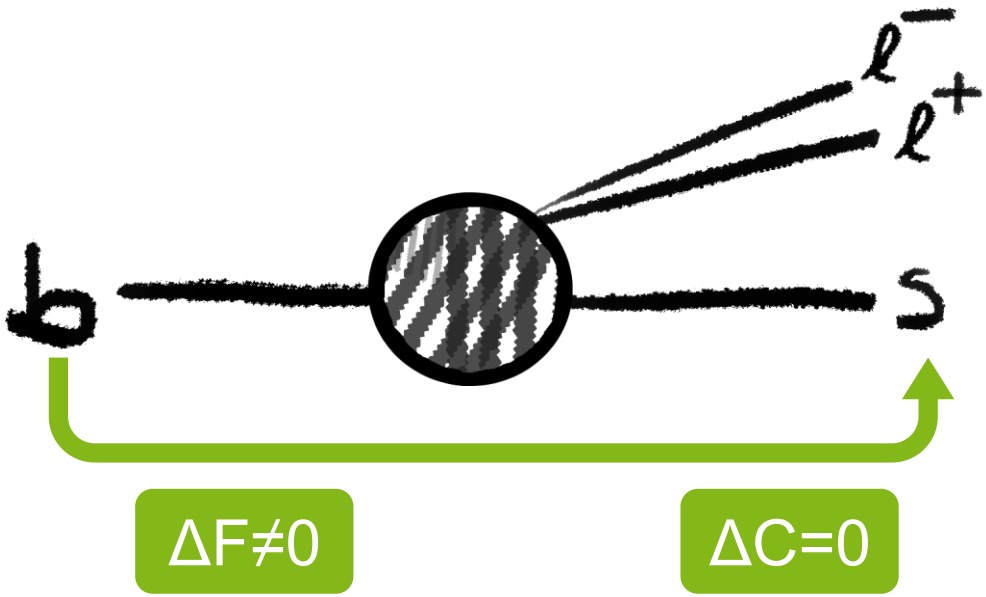
Maximilian Schlupp

Physics at the Terascale, Hamburg 18. Nov 2015

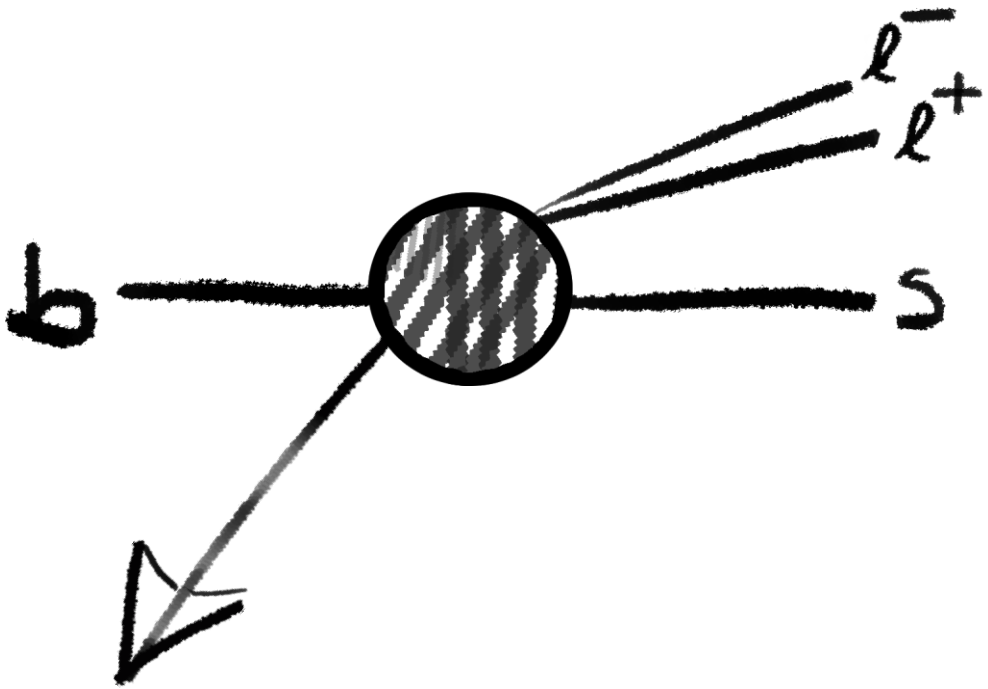


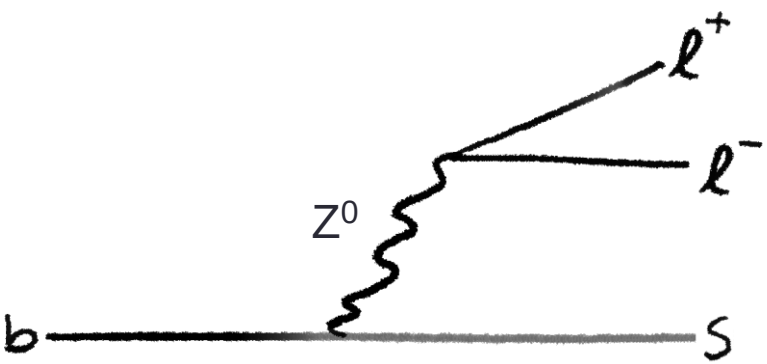
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Rare FCNC beauty decays



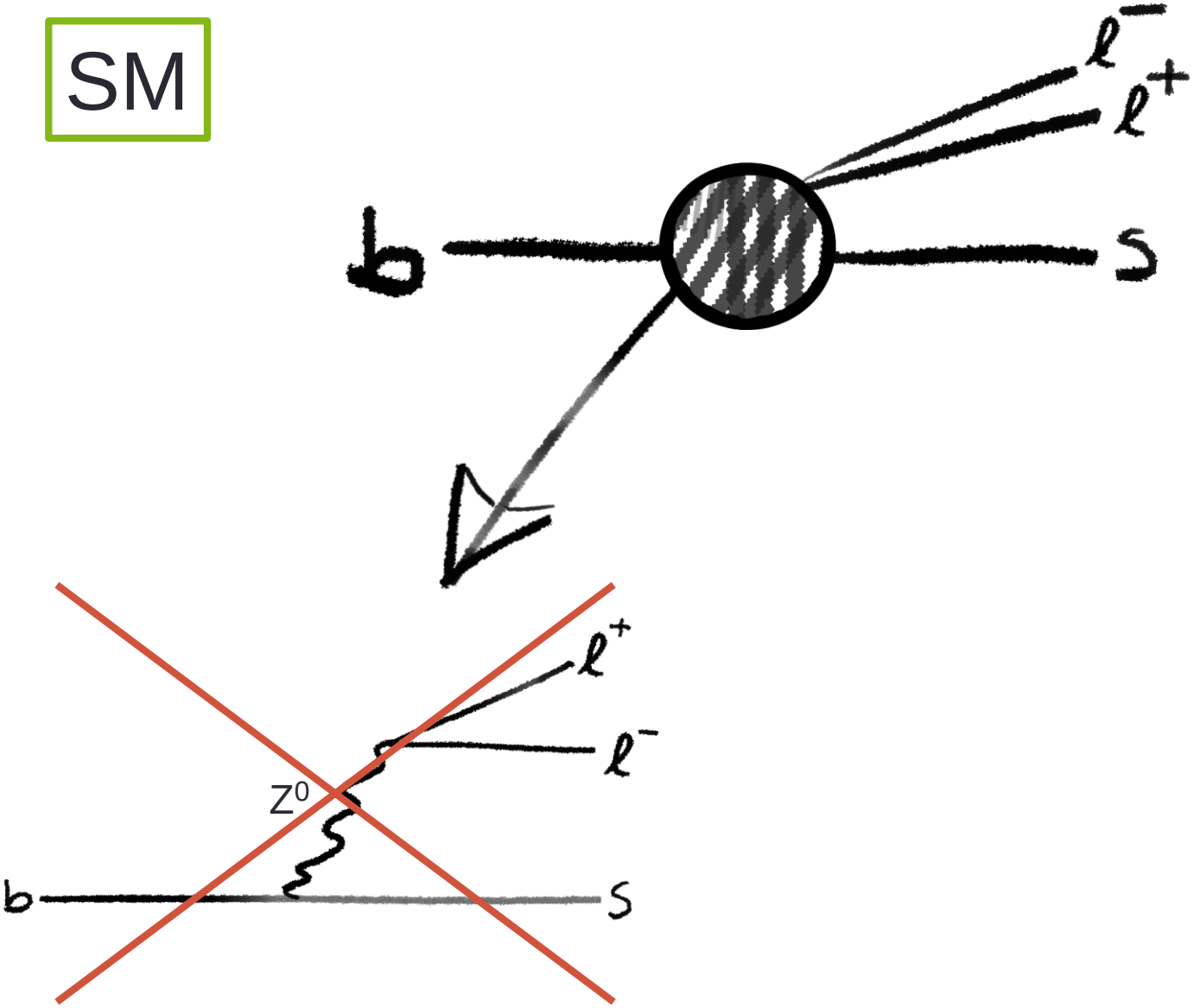
Rare FCNC beauty decays





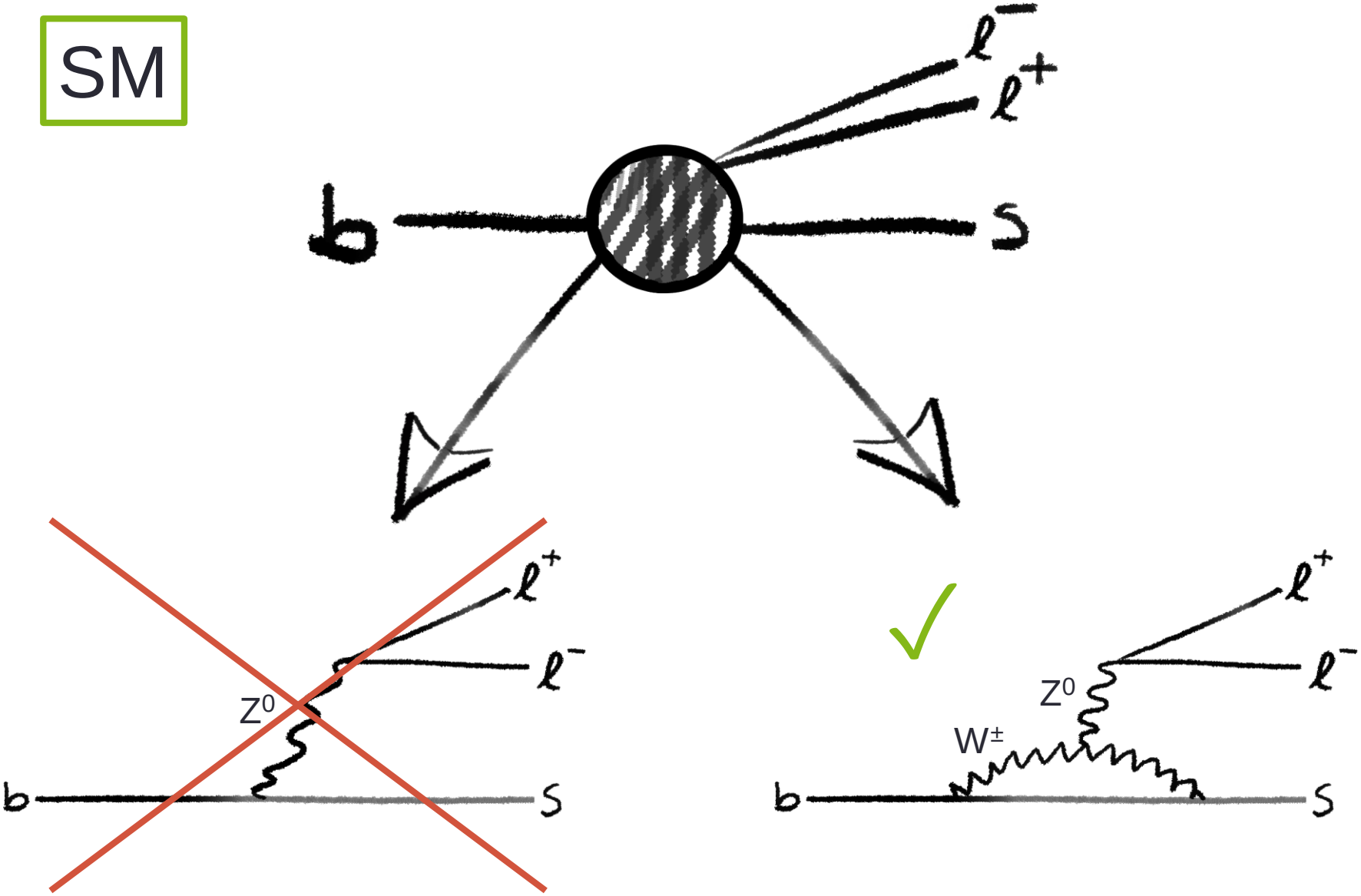
Rare FCNC beauty decays

SM



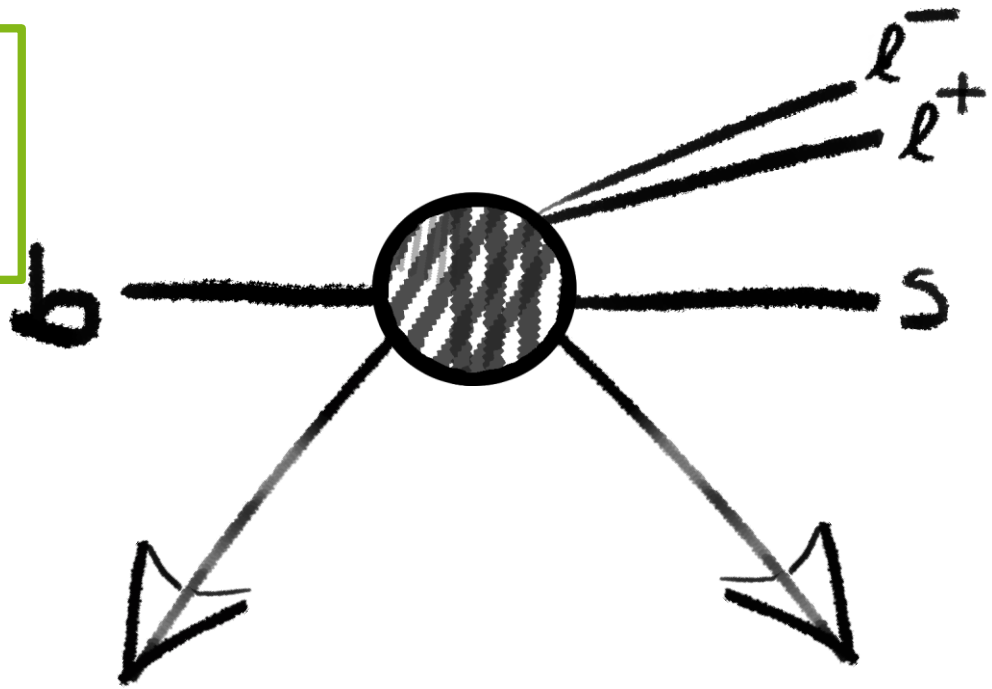
Rare FCNC beauty decays

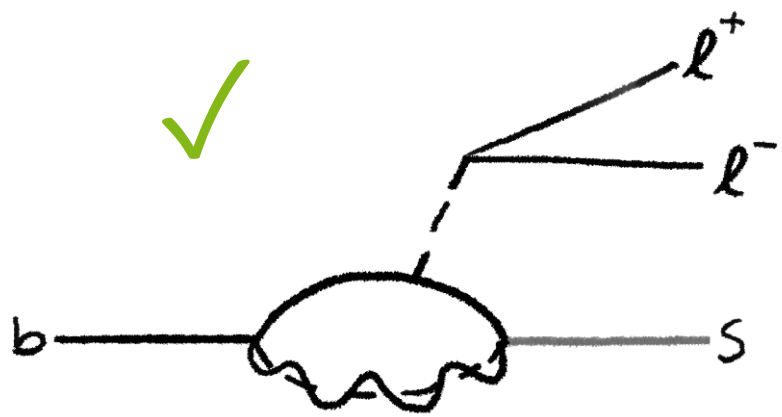
SM



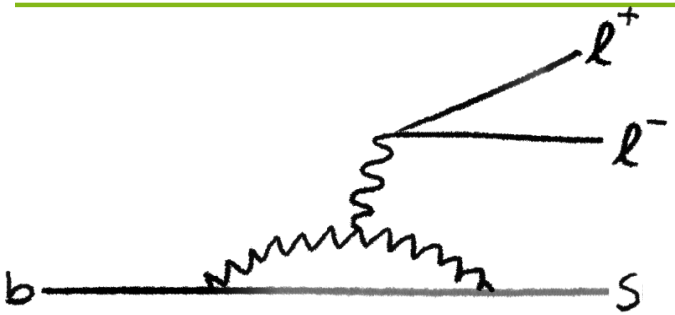
Rare FCNC beauty decays

beyond the SM

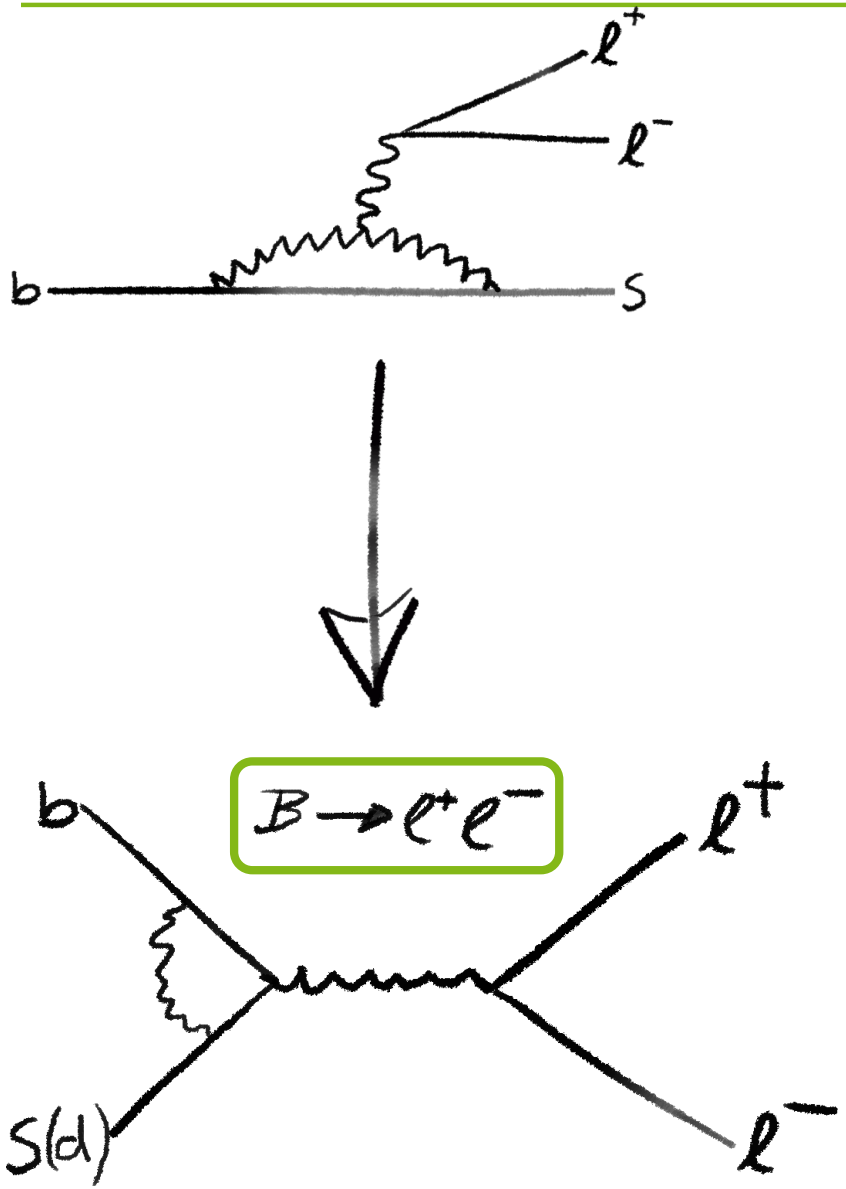




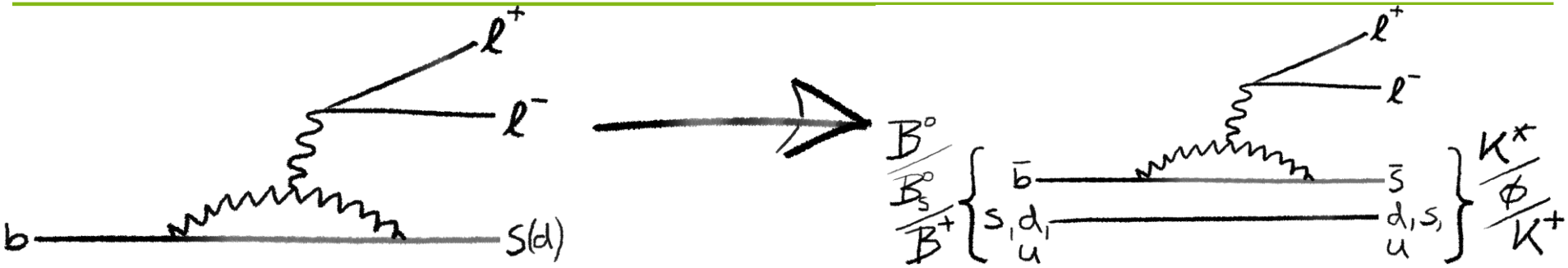
Measuring rare FCNC beauty decays

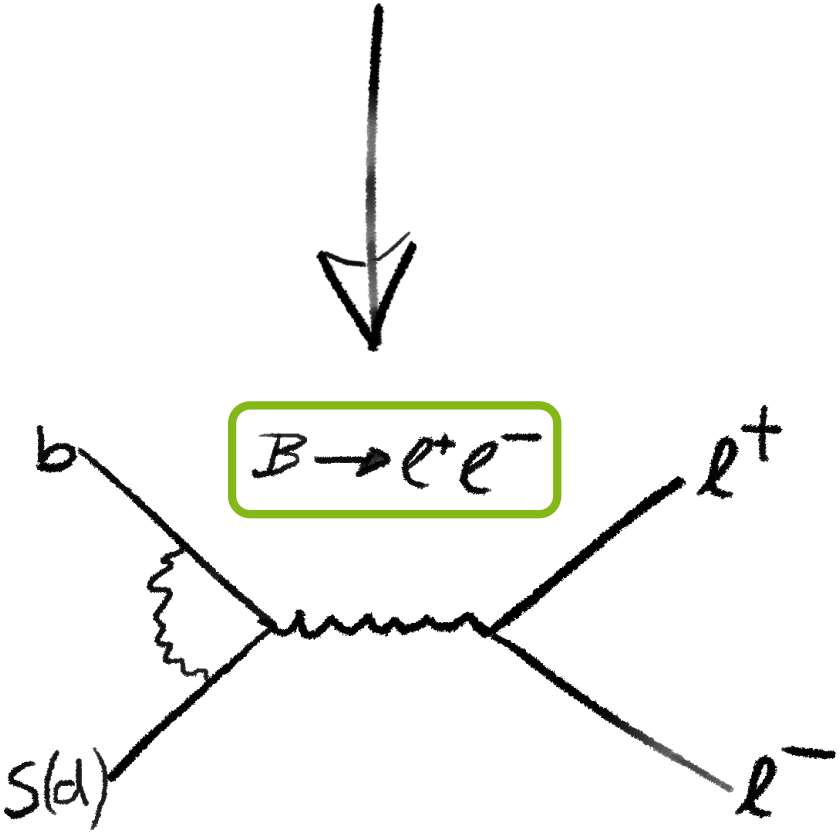


Measuring rare FCNC beauty decays

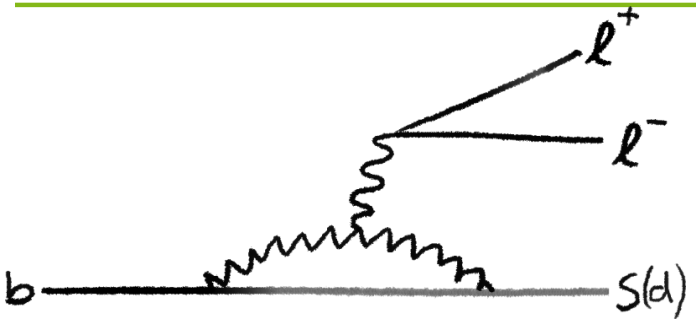


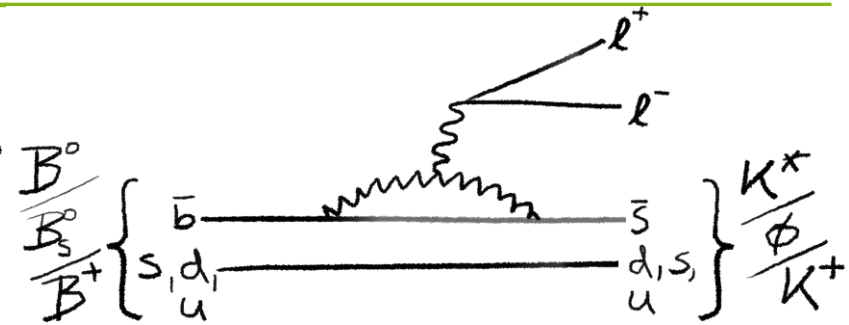
Measuring rare FCNC beauty decays

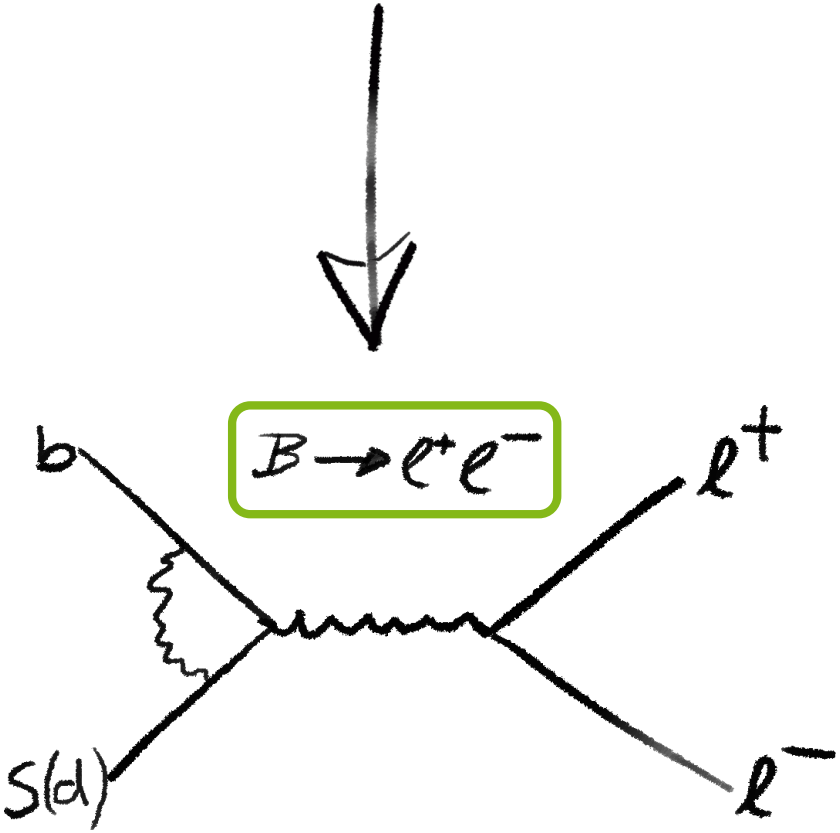




Measuring rare FCNC beauty decays



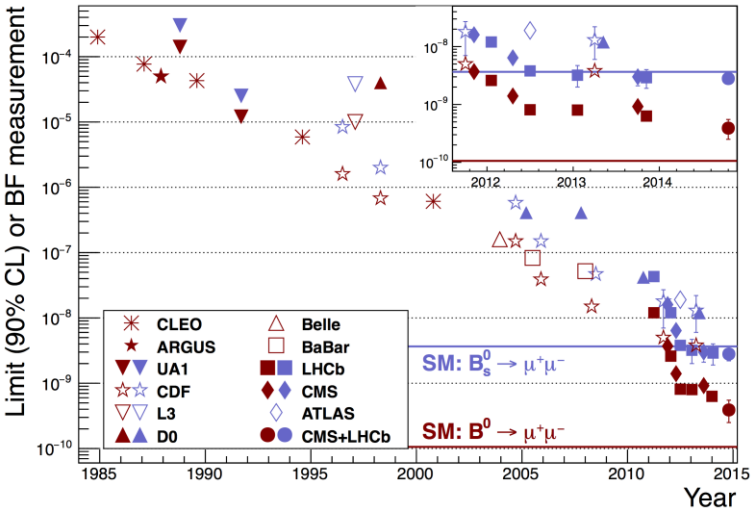


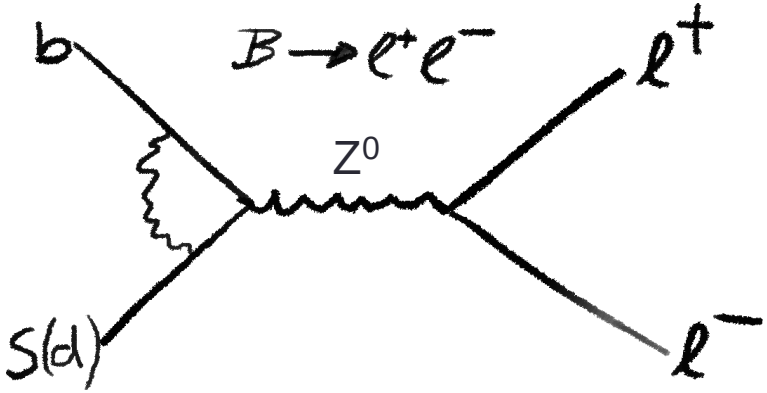


Outline:

- $B \to \mu^+\mu^-$
- $B^- \to K^-l^+l^-$
- $B^0 \to K^*\mu^+\mu^-$
- $B_s \to \phi\mu^+\mu^-$

$B \rightarrow \mu^+\mu^-$





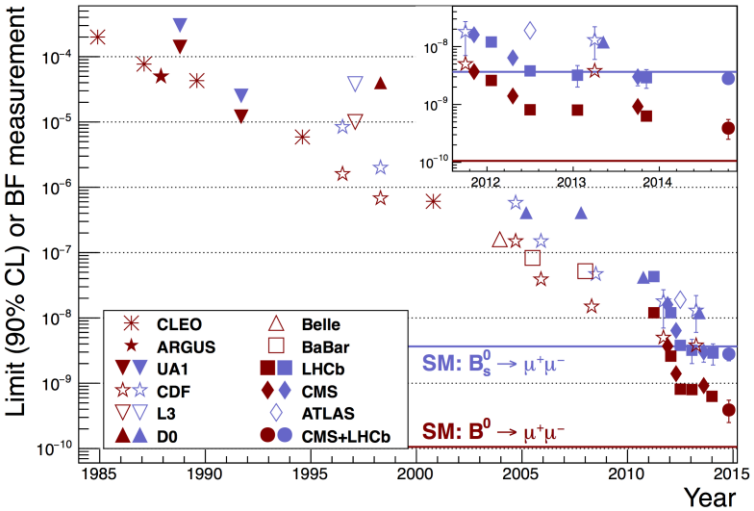
- Helicity suppressed in the SM
- Very clean: theoretically and experimentally

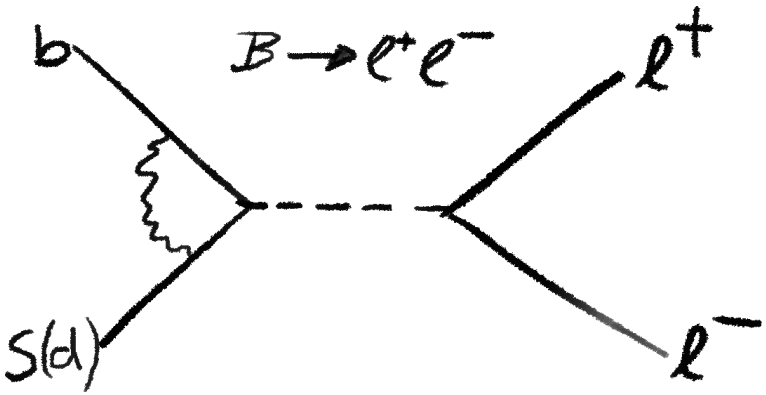
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$ [Bobeth et al., PRL 112(2014) 101801]*

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

*updated with latest top quark mass measurement (Tevatron & LHC) arXiv:1403.4427 [hep-ex]

B→μ⁺μ⁻





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$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

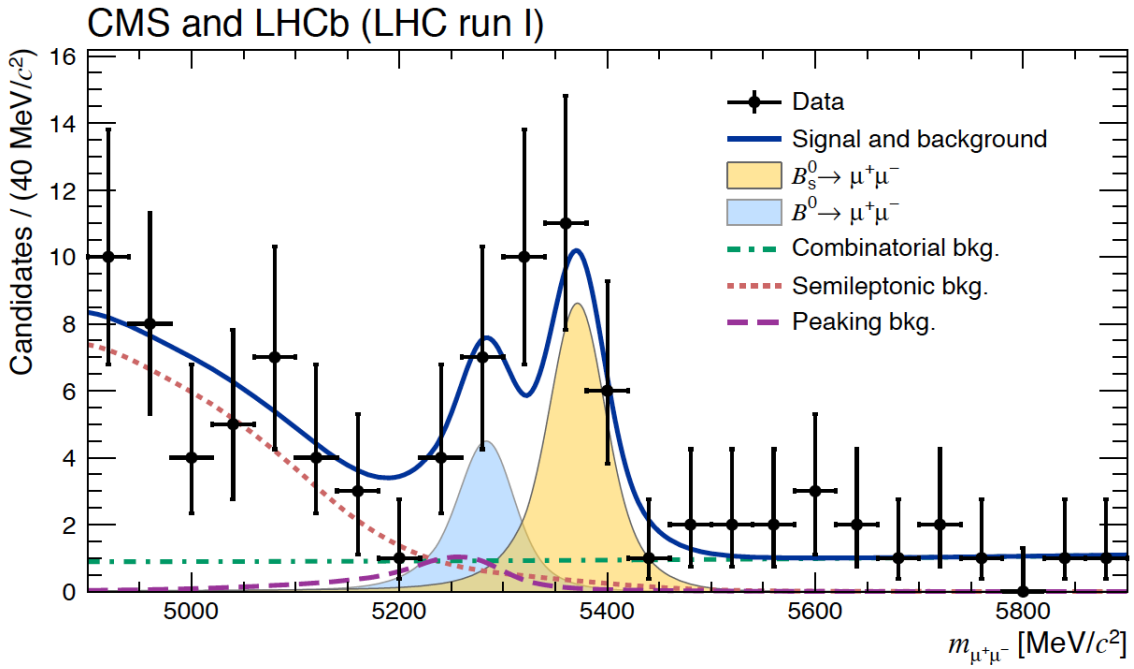
- Highly sensitive to models beyond the SM, esp. with an enhanced (pseudo-)scalars sector

*updated with latest top quark mass measurement (Tevatron & LHC) arXiv:1403.4427 [hep-ex]

[Nature 522, (2015) 68−72]

B→μ⁺μ⁻ at the LHC

- Perform most precise LHC measurement of B→ μ⁺μ⁻ branching fractions
- Combination of LHCb & CMS analyses
- Simultaneous fit to the LHCb & CMS datasets



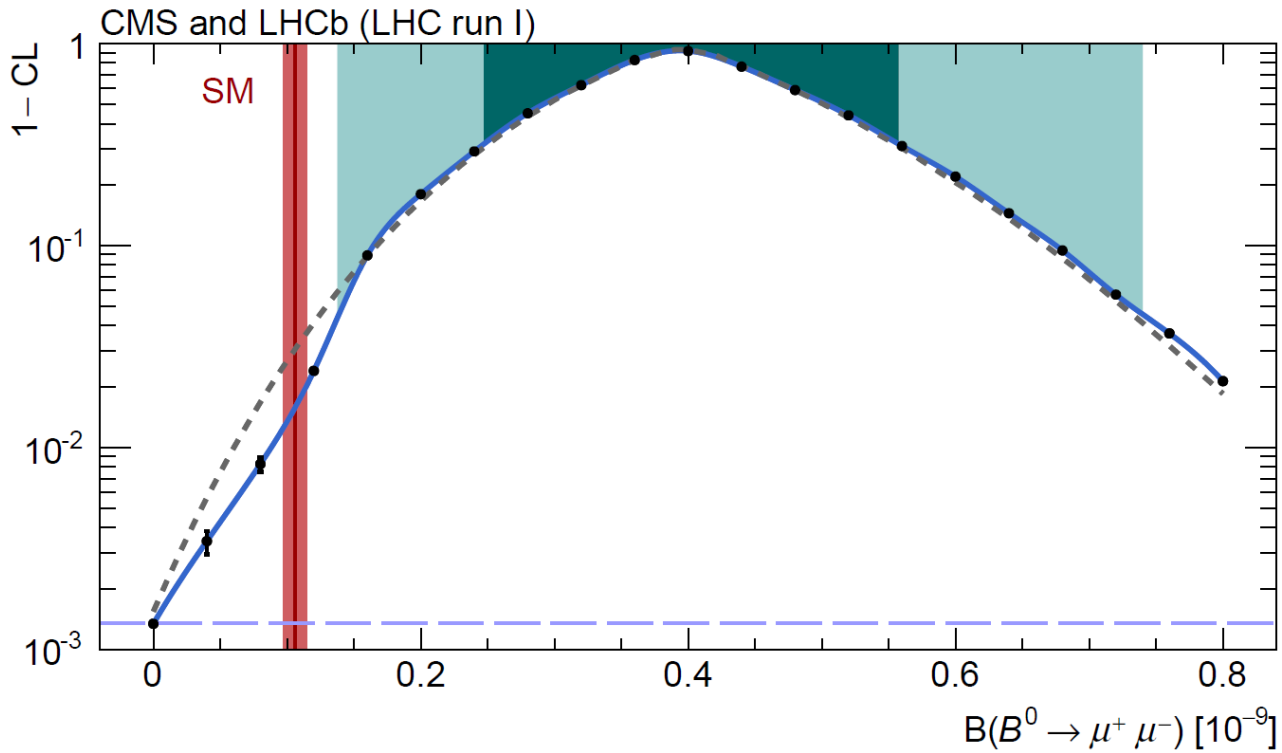
$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$
$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right)_{\mathrm{SM}} = 3.66 \pm 0.23 \times 10^{-9}$$

$$\mathcal{B}\left(B_d^0 \to \mu^+\mu^-\right) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$
$$\mathcal{B}\left(B_d^0 \to \mu^+\mu^-\right)_{\mathrm{SM}} = 1.06 \pm 0.09 \times 10^{-10}$$

[Nature 522, (2015) 68−72]

$B \rightarrow \mu^+\mu^-$ at the LHC

- Statistical interpretation: Feldman-Cousins based method
- $O(10^5)$ CPU hours



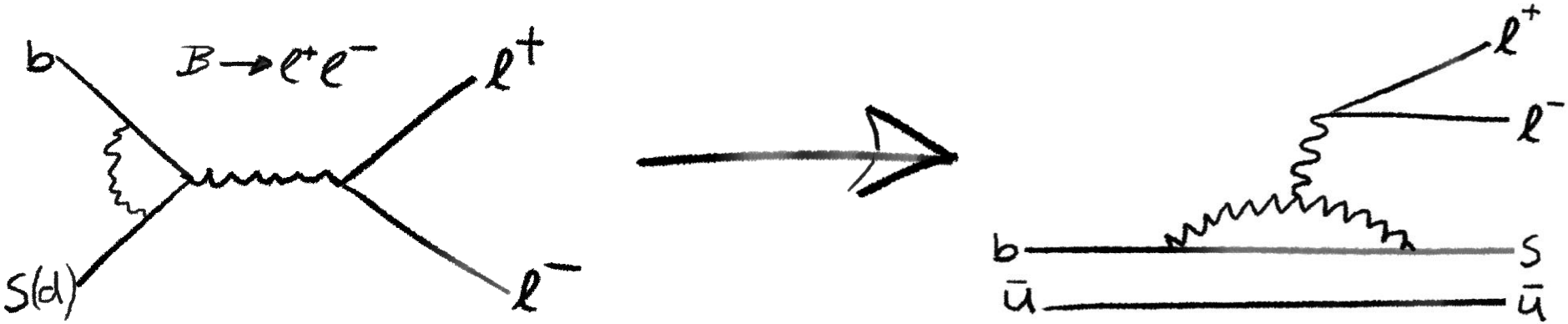
3.0σ for $B^0 \rightarrow \mu^+\mu^-$
First evidence

BF 2.2σ above the SM

6.2σ for $B^0_s \rightarrow \mu^+\mu^-$
First obervation

BF 1.2σ below the SM

[PRL 113, (2014) 151601] Lepton universality in $B^+ \to K^+ l^- l^+$



- Lepton universality is a fundamental test of the SM

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

$$\boxed{1 \pm \mathcal{O}(\lesssim 10^{-3})}$$ (SM)

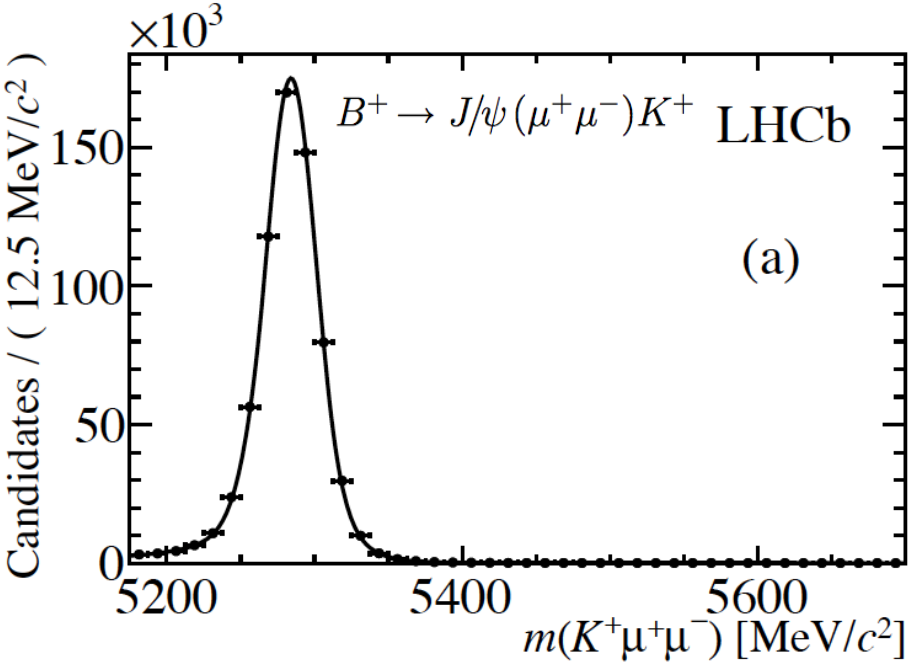
Bobeth, Hiller, Piranishvili [JHEP 12 (2007) 040]

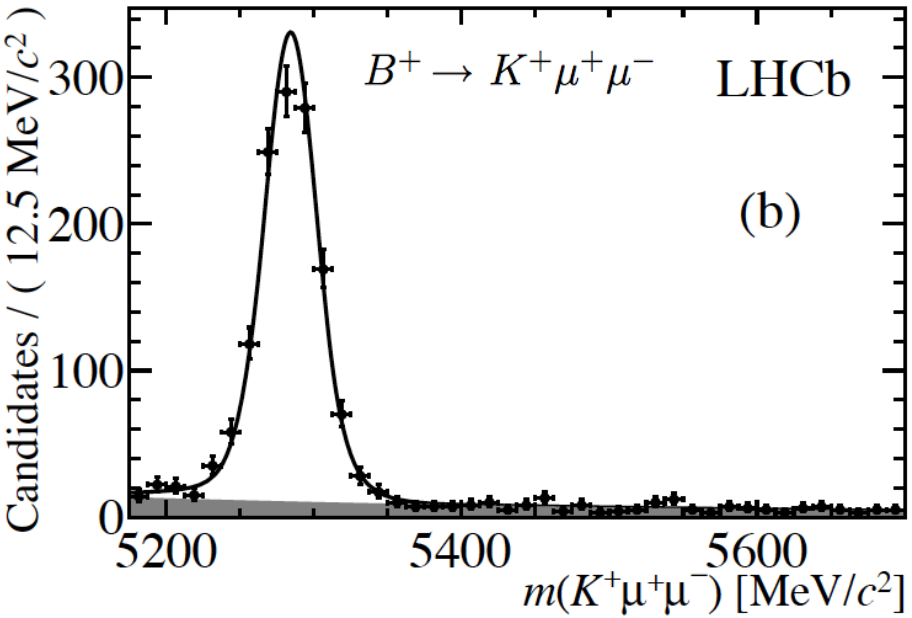
- $q^2 = m(l^+ l^-)$

[PRL 113, (2014) 151601] Lepton universality in $B^+ \rightarrow K^+ l^- l^+$

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

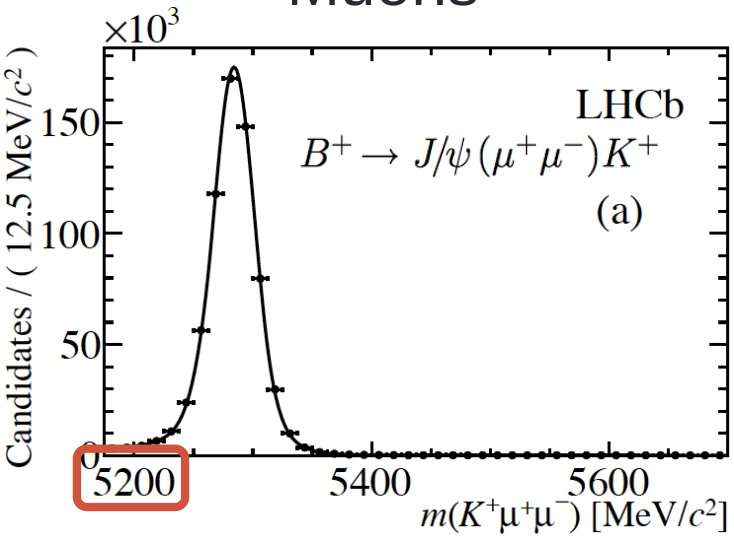
- Muon channels ✓



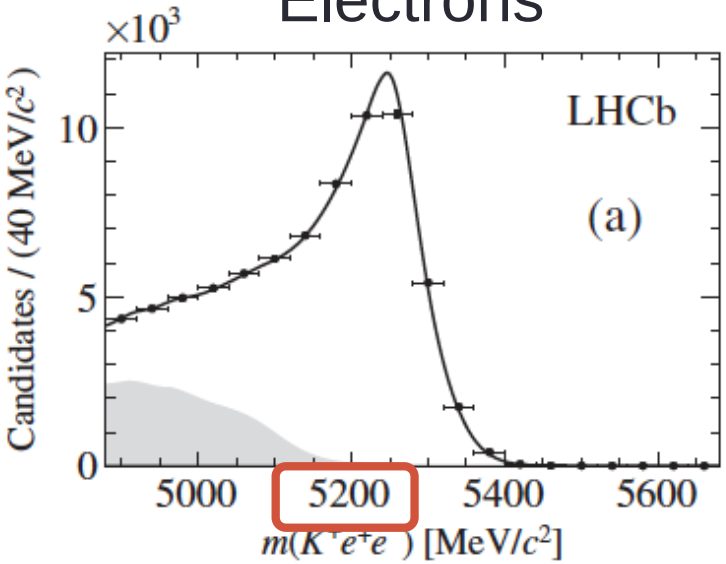


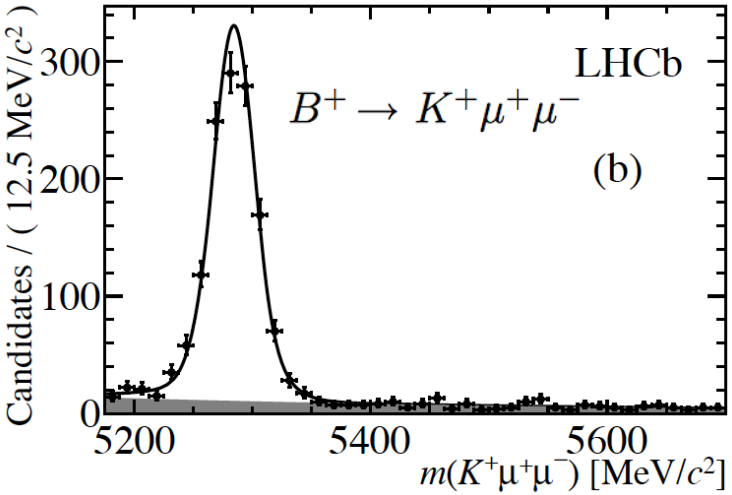
[PRL 113, (2014) 151601] Lepton universality in $B^+ \rightarrow K^+ l^- l^+$

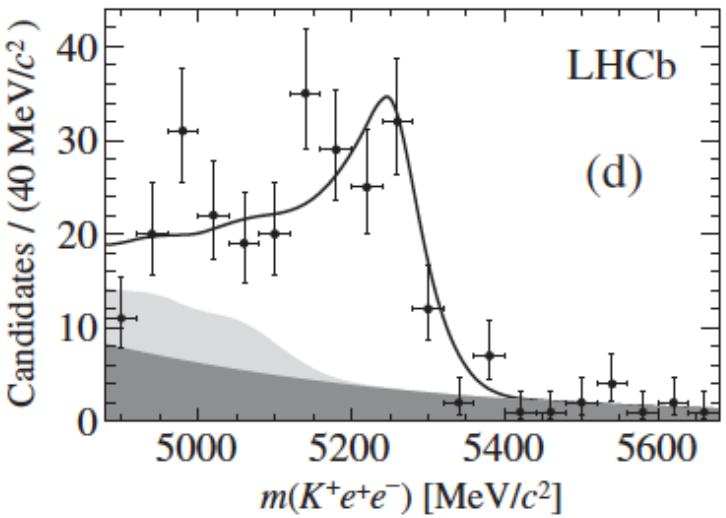
Muons



Electrons

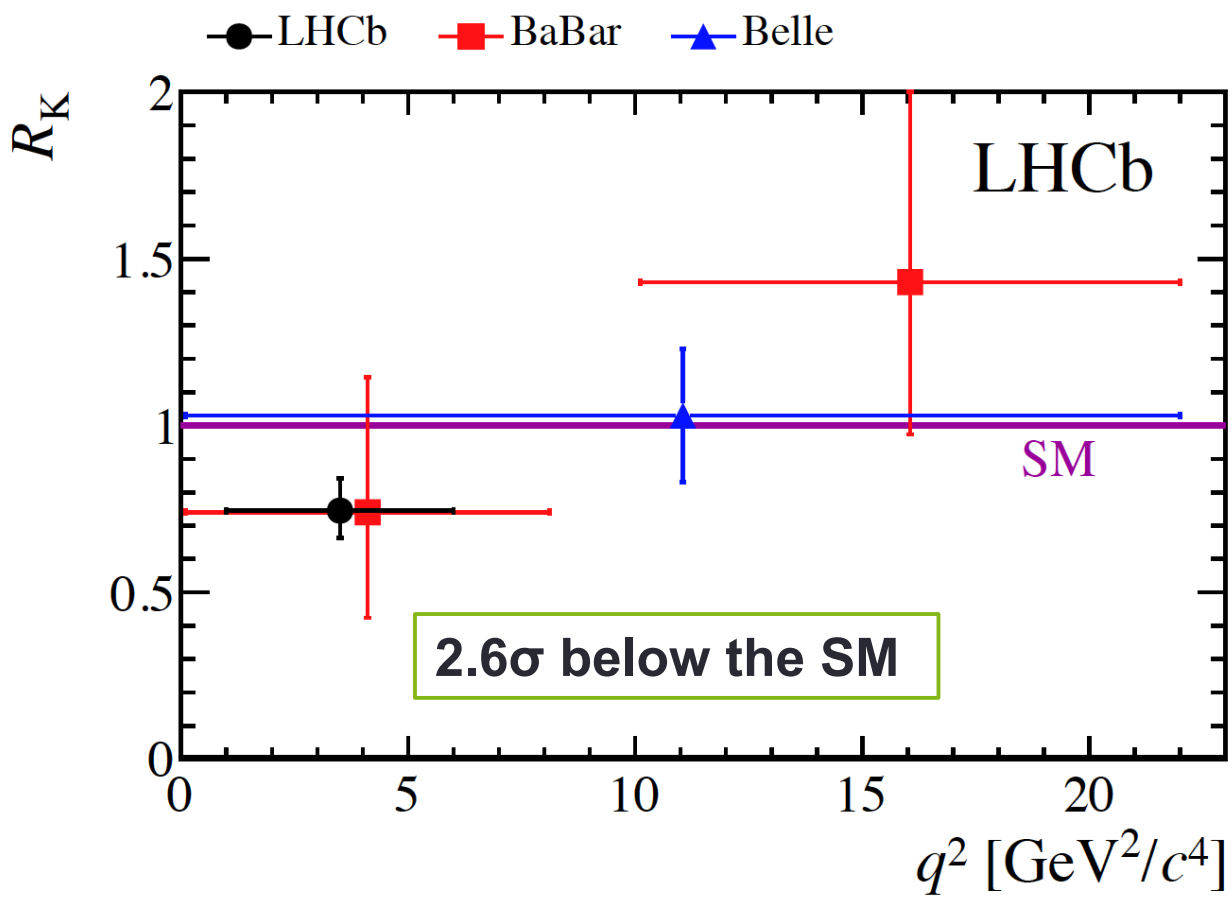






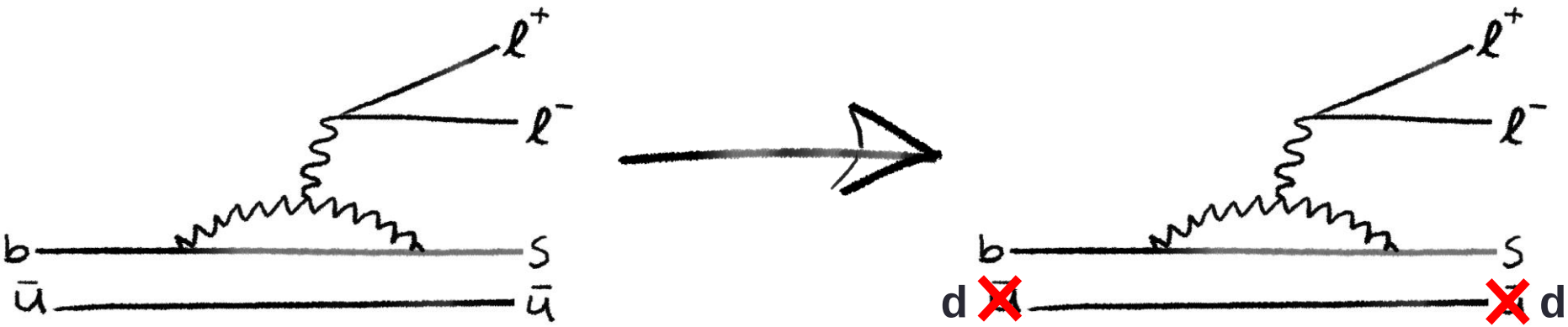
[PRL 113, (2014) 151601] Lepton universality in $B^+ \rightarrow K^+ l^- l^+$

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



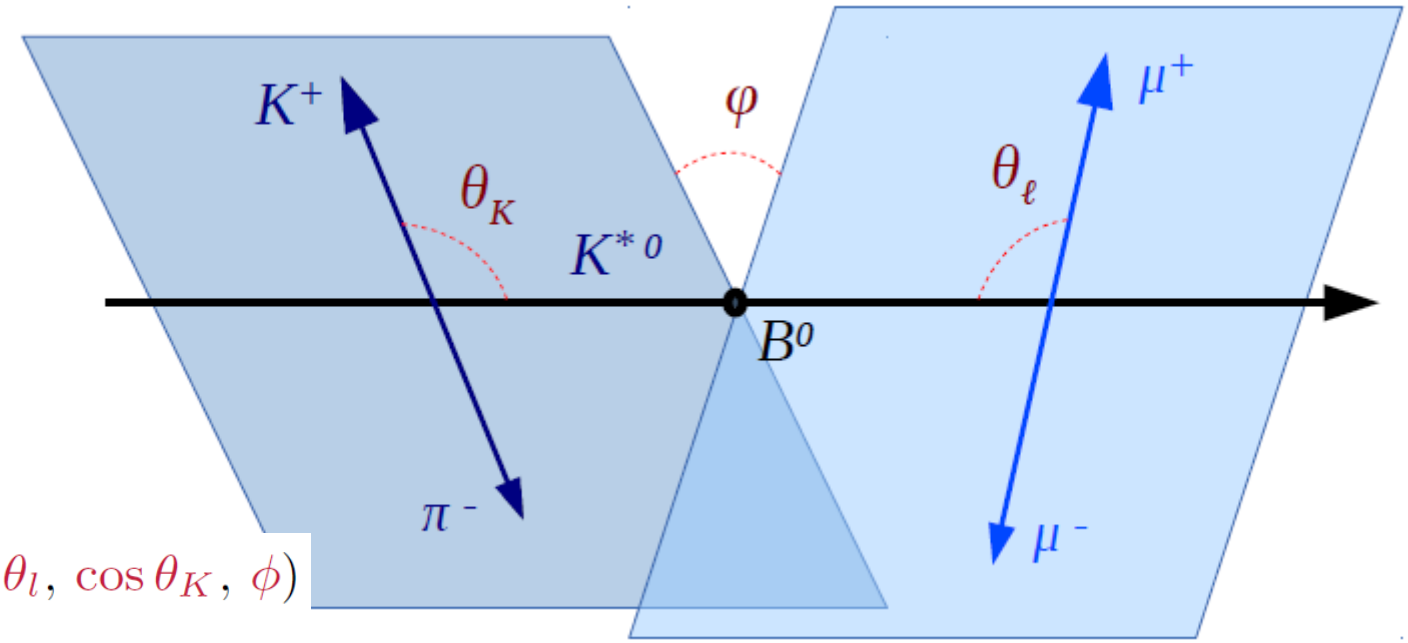
[LHCb-PAPER-2015-051]

$B^0 \rightarrow K^{*0}\mu^+\mu^-$



- Peudoscalar to vector/vector transition
- Full angular analysis

$B^0 \rightarrow K^{*0}\mu^+\mu^-$



$\vec{\Omega} = (\cos\theta_l,\ \cos\theta_K,\ \phi)$

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_j I_j(q^2) f_j(\vec{\Omega})$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_j \bar{I}_j(q^2) f_j(\vec{\Omega})$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2} \right)$$

$$A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2} \right)$$

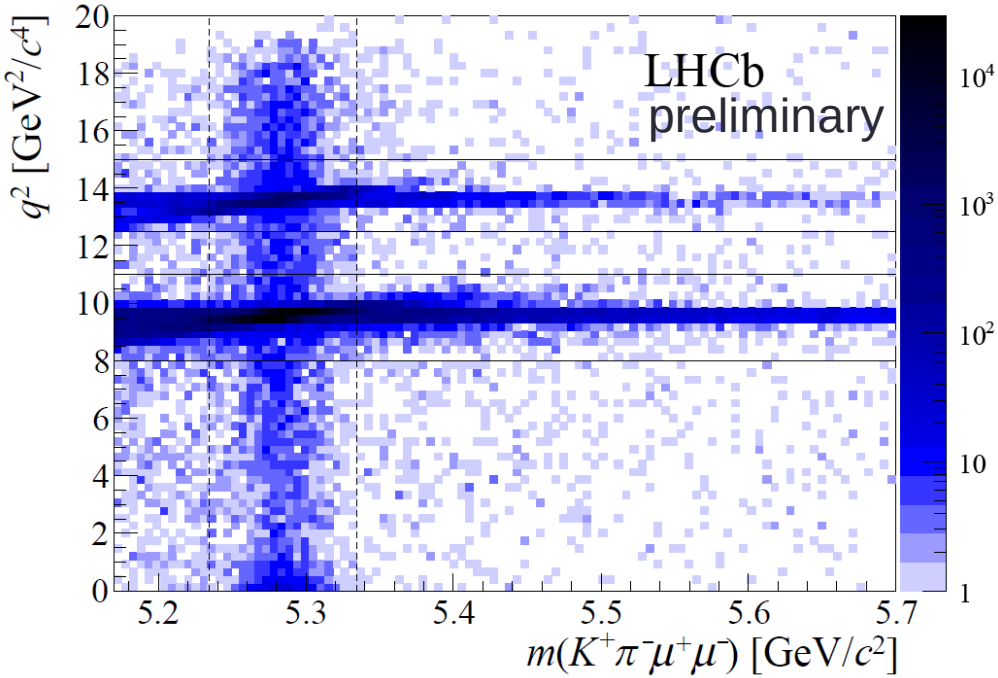
- Divide out form factor uncertainties (to leading order): $S_j \rightarrow P'_j$
- Anomalie found in P'_5 with $1fb^{-1}$ LHCb data, confirmed in CONF note with $3fb^{-1}$
- Now the paper is going to be submitted with
  - Likelihood fit (expected highest sensitivity)
  - Methods of moments (more robust → finer binning)
    - No angular fit, but using orthogonal relations of f_j
  - Amplitude fit (zero crossing points, not covered)

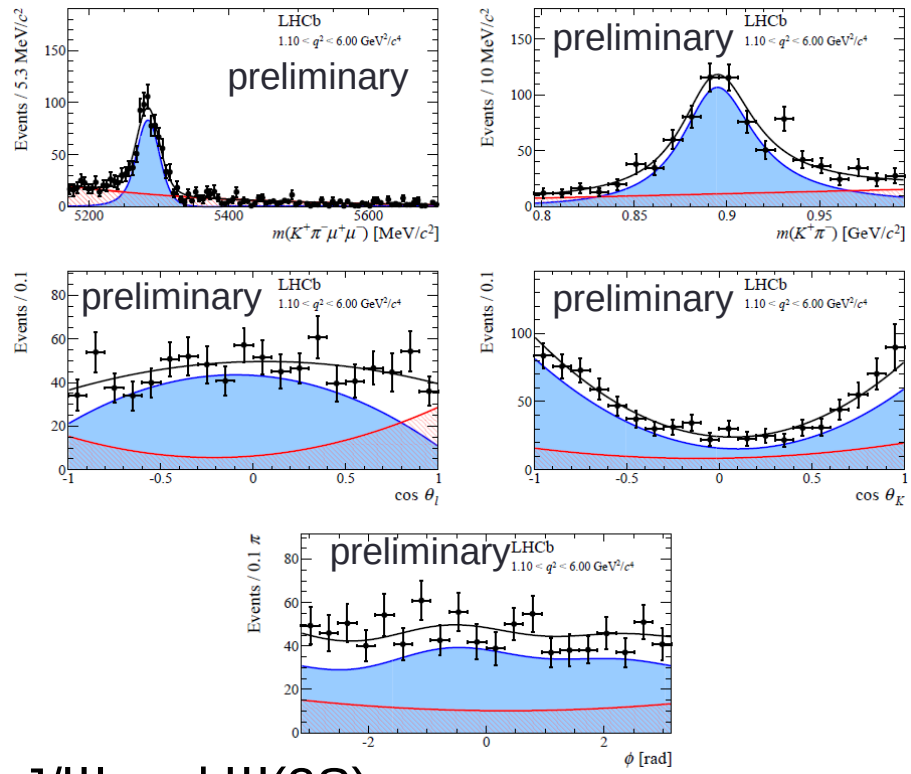
$$\int f_i(\vec{\Omega}) f_j(\vec{\Omega}) \mathrm{d}\vec{\Omega} = \lambda_i \delta_{ij}$$

- But first one needs some data…

[LHCb-PAPER-2015-051]

$B^0 \rightarrow K^{*0}\mu^+\mu^-$



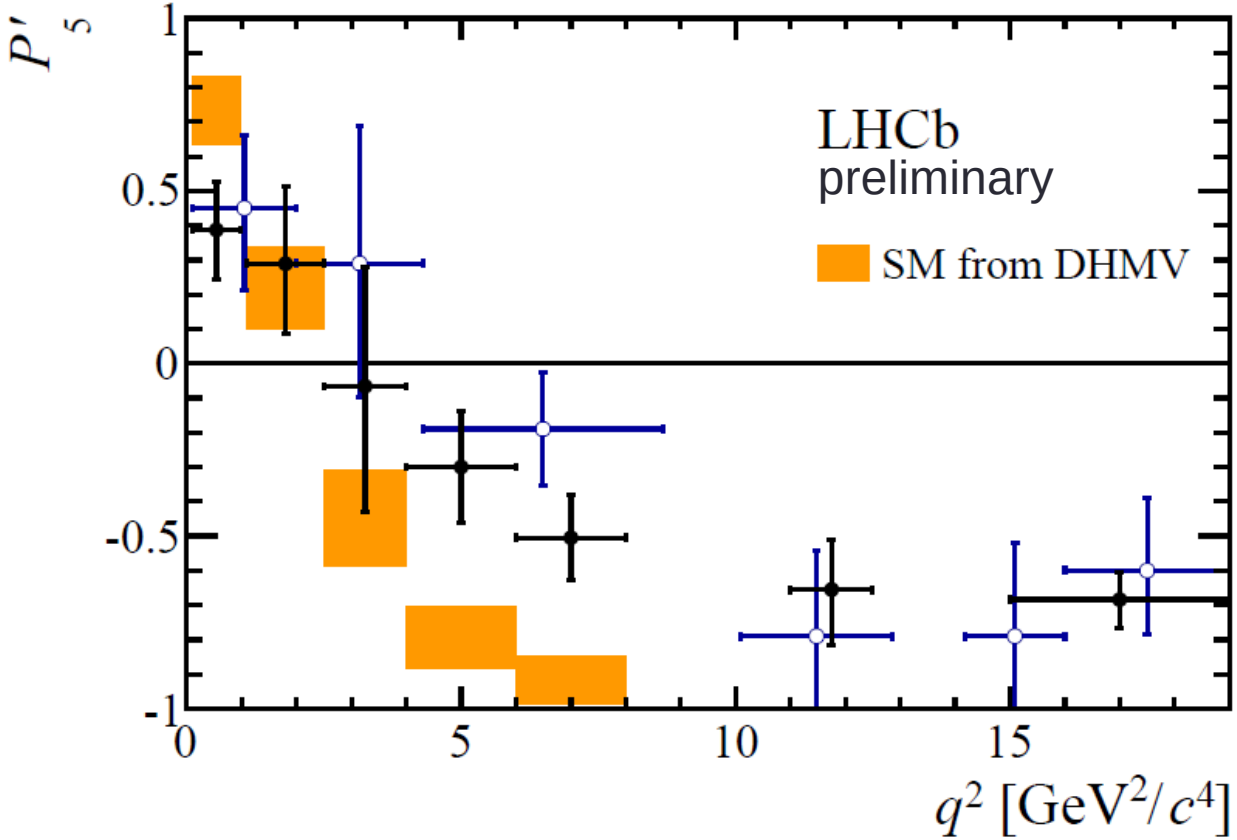


- Clear signal B^0 mass range, excluding J/Ψ and Ψ(2S)
- 2398 ± 57 single candidates (624 ± 30 in q^2=[1.1,6] GeV^2/c^4) (150 at Belle)
- Full 4-D correllated acceptance function (q^2, decay angles)
- Account for scalar component in $K^+\pi^-$

[LHCb-PAPER-2015-051]

$B^0 \rightarrow K^{*0}\mu^+\mu^-$

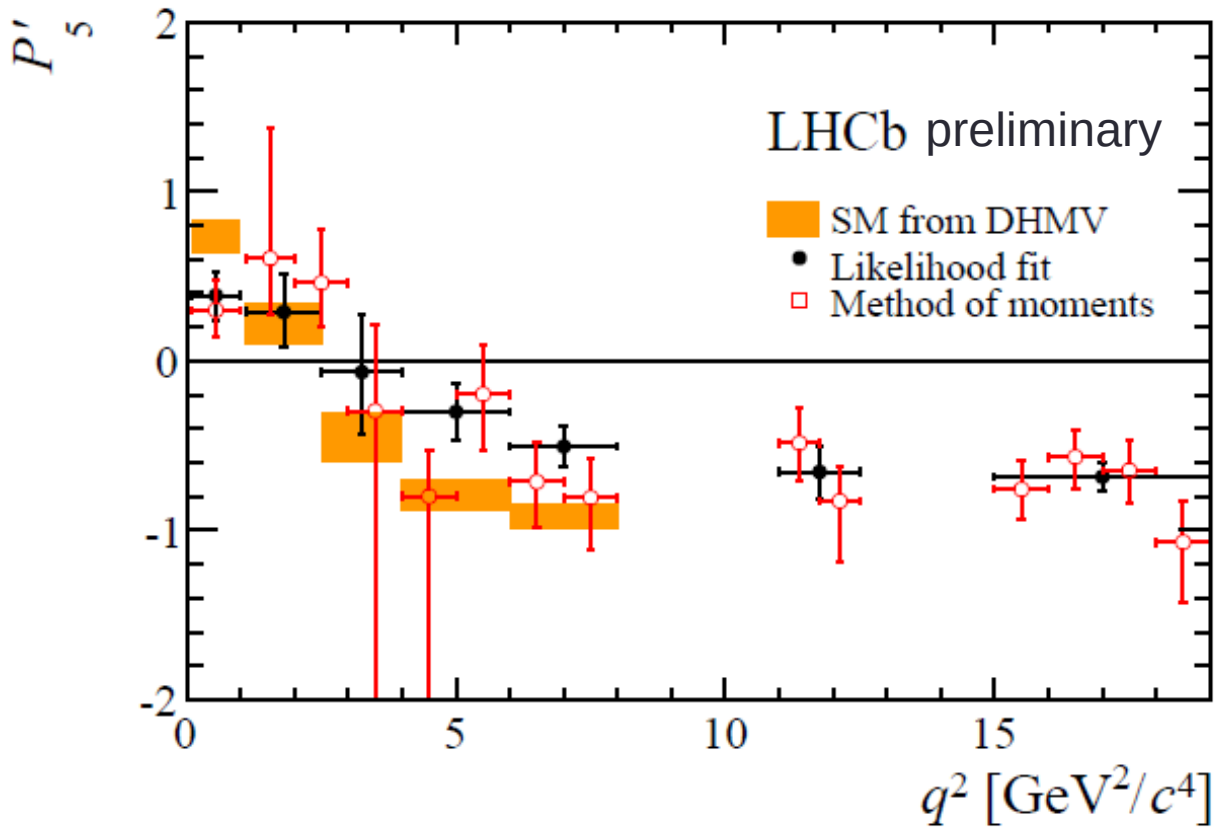
(SM) Descotes-Genon, Hofer, Matias, Virto, [JHEP12(2014)125]



- Tension with **global** SM best fit point 3.4σ

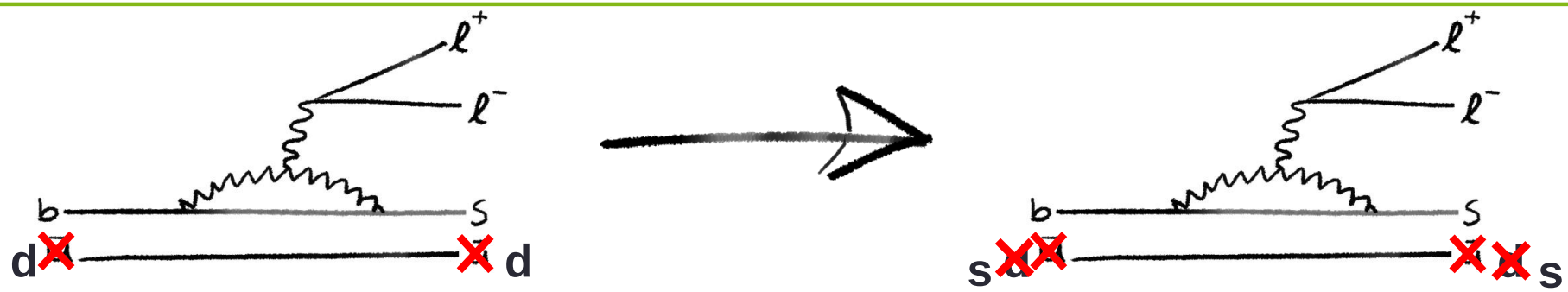
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

Comparison between Likelihood and methods of moments approach



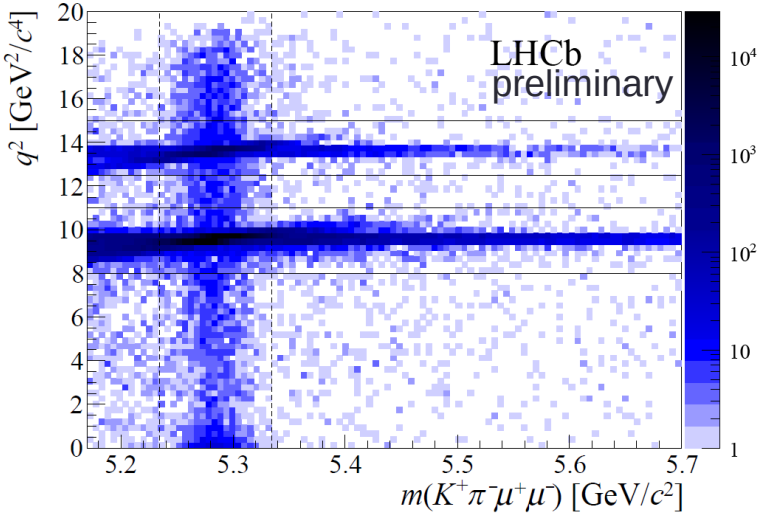
[JHEP09(2015)179]

$B_s \rightarrow \Phi \mu^+ \mu^-$

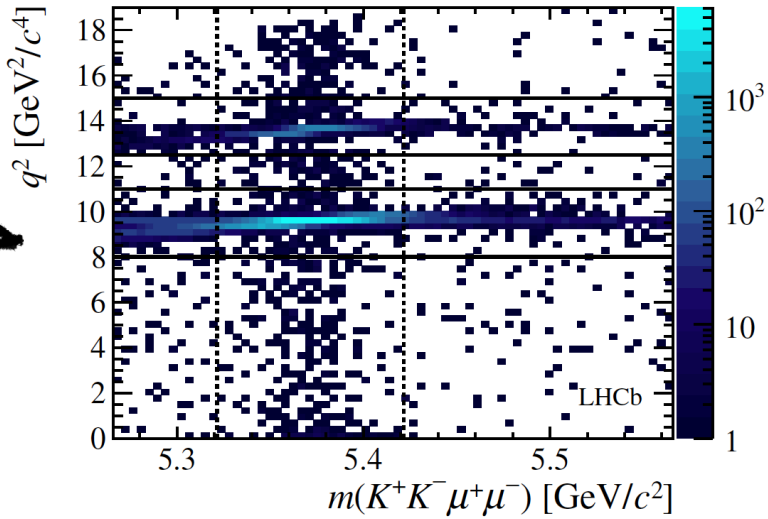


- Pseudoscalar to vector/vector
- Similar to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

2398 ± 57 single candidates



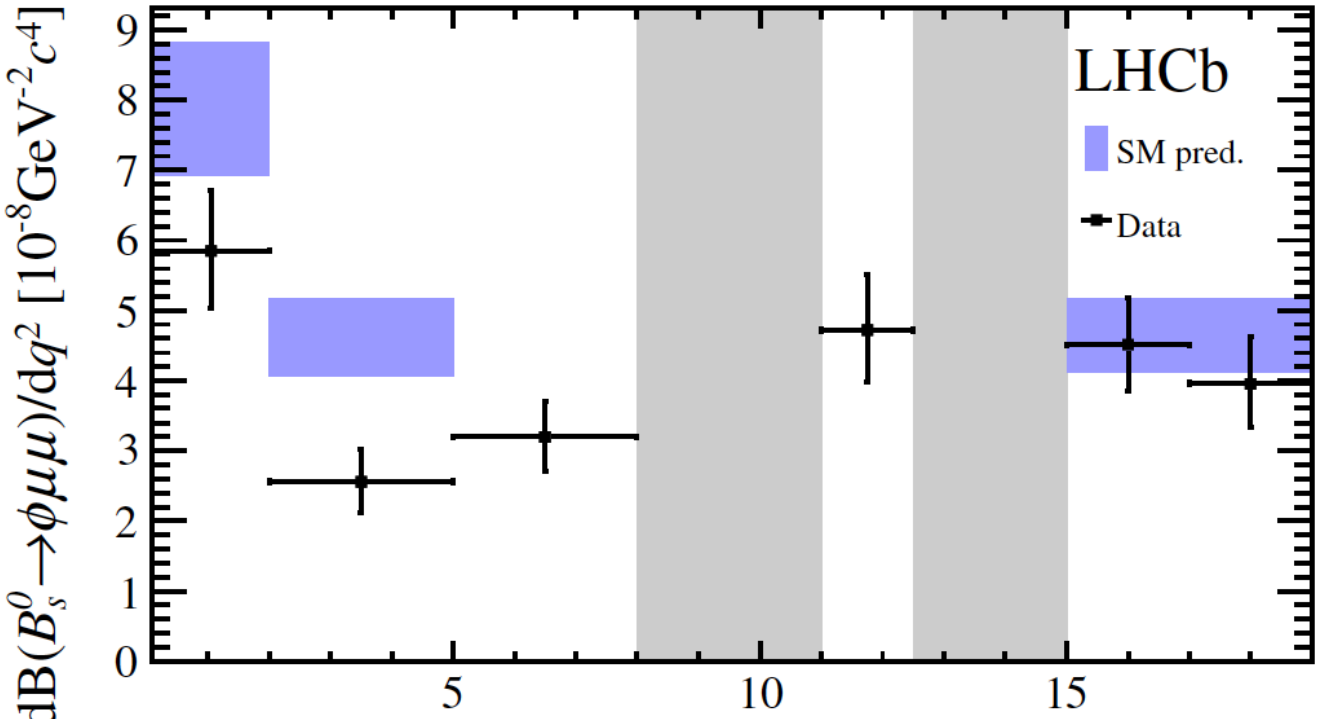
432 ± 24 single candidates



[JHEP09(2015)179]

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

- Most angular observables are consistent with zero

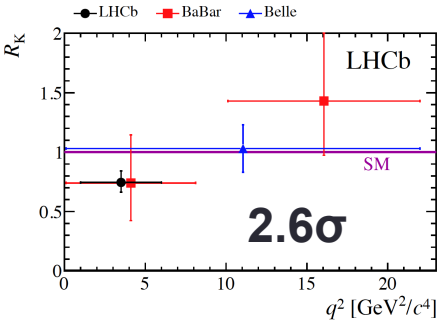


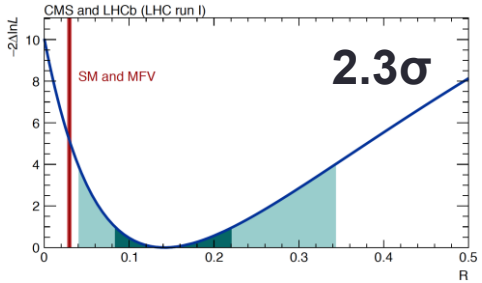
(SM)
Altmannshofer, Straub, [Eur.Phys.J.C75(2015)382]
Bharucha, Straub, Zwicky, [arXiv:1503.05534]

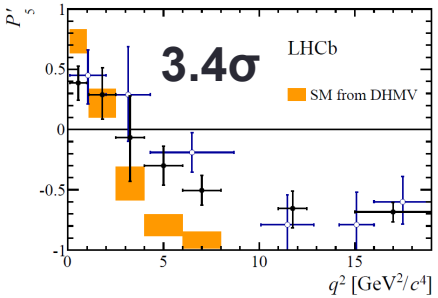
- 3.3σ Sigma below the SM in the low q^2 regime

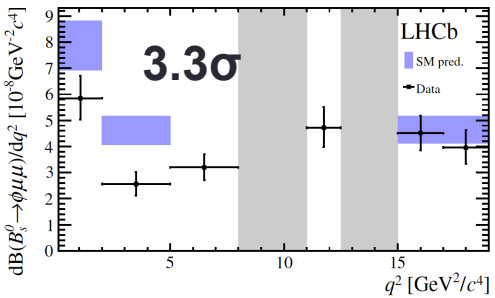
Summary

- During LHC Run I a list of anomalies popped up in b→s(d)l^+l^- transitions









- Many possible explanations from theory

- Necessity for communication between experimentalists and theorists
  - Nice examples are the LHCb implication workshops (last: Nov 2015)

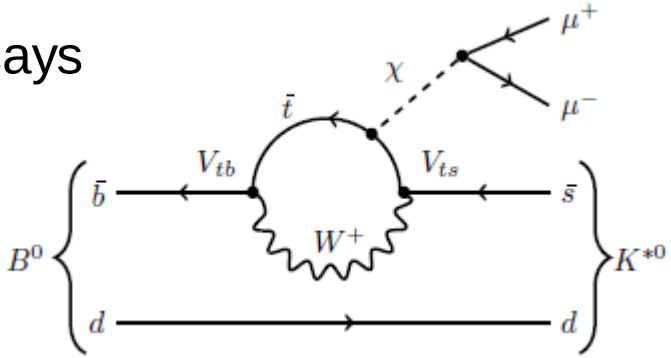
- b→s(d)l^+l^- remains of prime interest in Run II

Thanks to the Physics at the Terascale alliance for organising the workshop and support

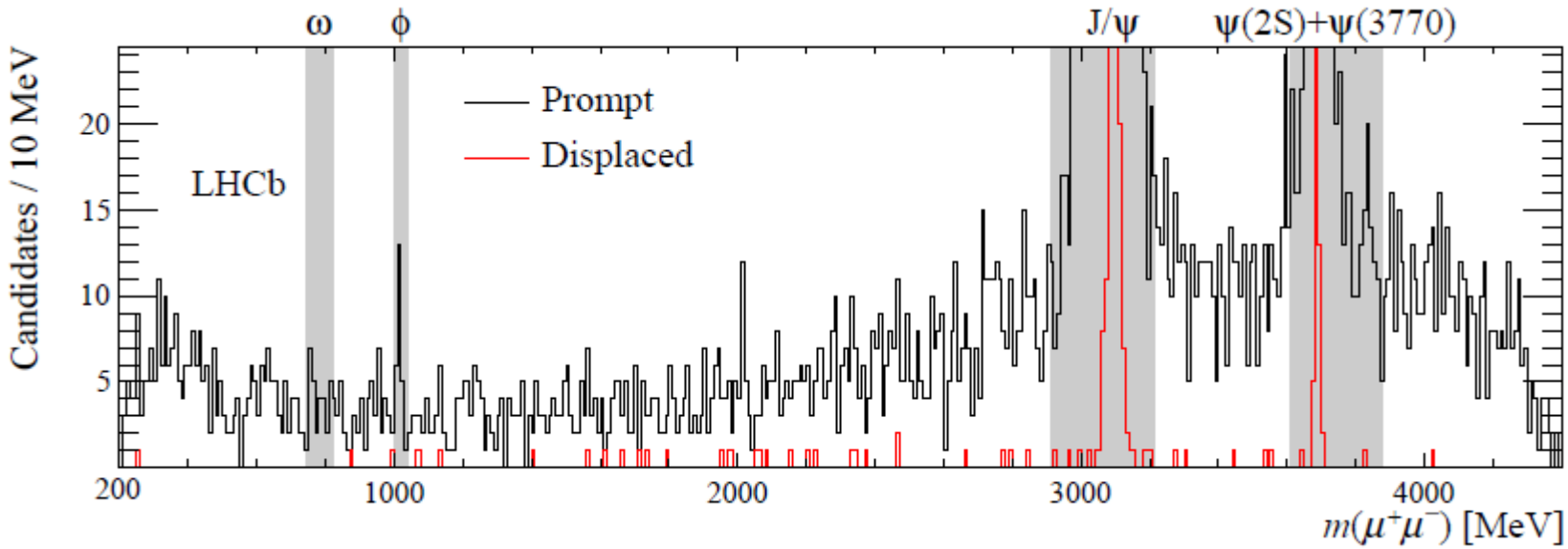
An extra slide

- Search for low mass bosons in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays

  [PRL115(2015)161802]



- High interest for light scalars $m(\chi) < 2\text{GeV}/c^2$



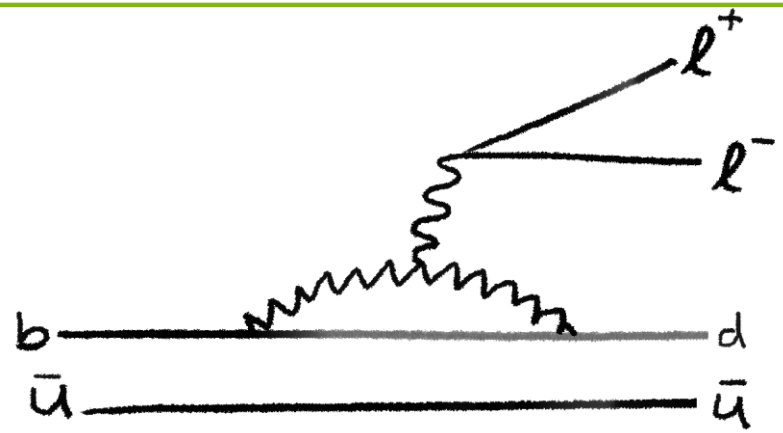
- No significant signal is found → stringent limits on axion, inflaton models

[JHEP 10 (2015) 034]

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

- First observed by the LHCb collaboration [JHEP 06 (2014) 125]

$$\mathcal{B}(B^- \to \pi^- \mu^+ \mu^-) = (2.3 \pm 0.6) \times 10^{-8}$$



- Differential branching fraction ($q^2=m^2(\mu\mu)$)

$$\frac{d\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)}{dq^2}$$

- Non-zero direct CP asymmetry predicted in the SM

$$\mathcal{A}^{CP} = -\frac{\mathcal{N}(B^+ \to \pi^+ \mu^+ \mu^-) - \mathcal{N}(B^- \to \pi^- \mu^+ \mu^-)}{\mathcal{N}(B^+ \to \pi^+ \mu^+ \mu^-) + \mathcal{N}(B^- \to \pi^- \mu^+ \mu^-)} + \mathcal{A}^{\text{Detection}} + \mathcal{A}^{\text{Production}}$$

$$\mathcal{A}^{CP} = -0.143^{+0.035}_{-0.029}$$

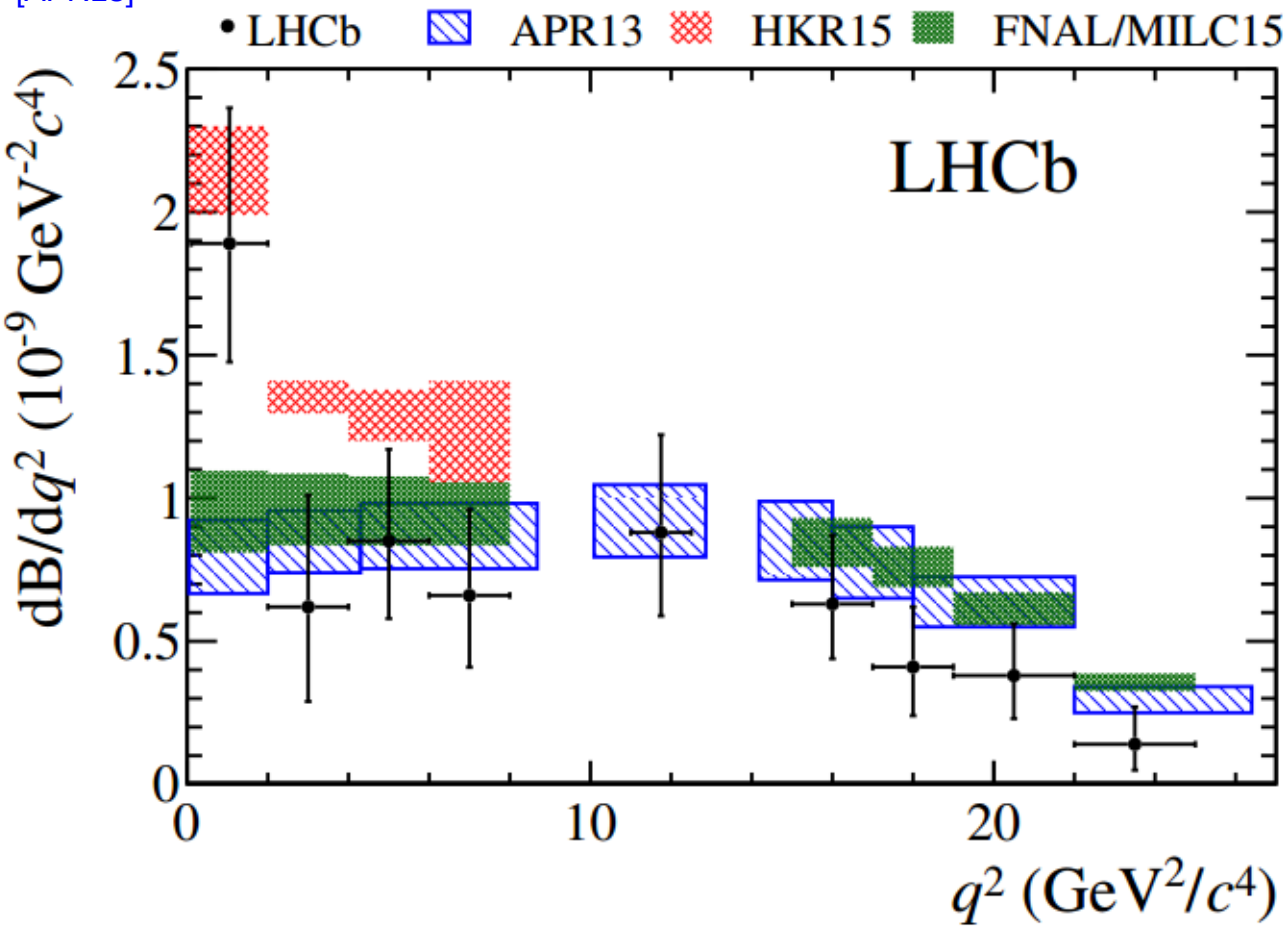
Hambrock, Khodjamirian, Rusov
[PRD 92 (2015) 074020]

[JHEP 10 (2015) 034]

$B^- \rightarrow \pi^- \mu^+ \mu^-$ branching fraction

$$\mathcal{B}(B^- \to \pi^- \mu^+ \mu^-) = (1.83 \pm 0.24) \times 10^{-8}$$
$$\mathcal{B}(B^- \to \pi^- \mu^+ \mu^-)_{\rm SM} = (1.88^{+0.32}_{-0.31}) \times 10^{-8}$$

[APR13]



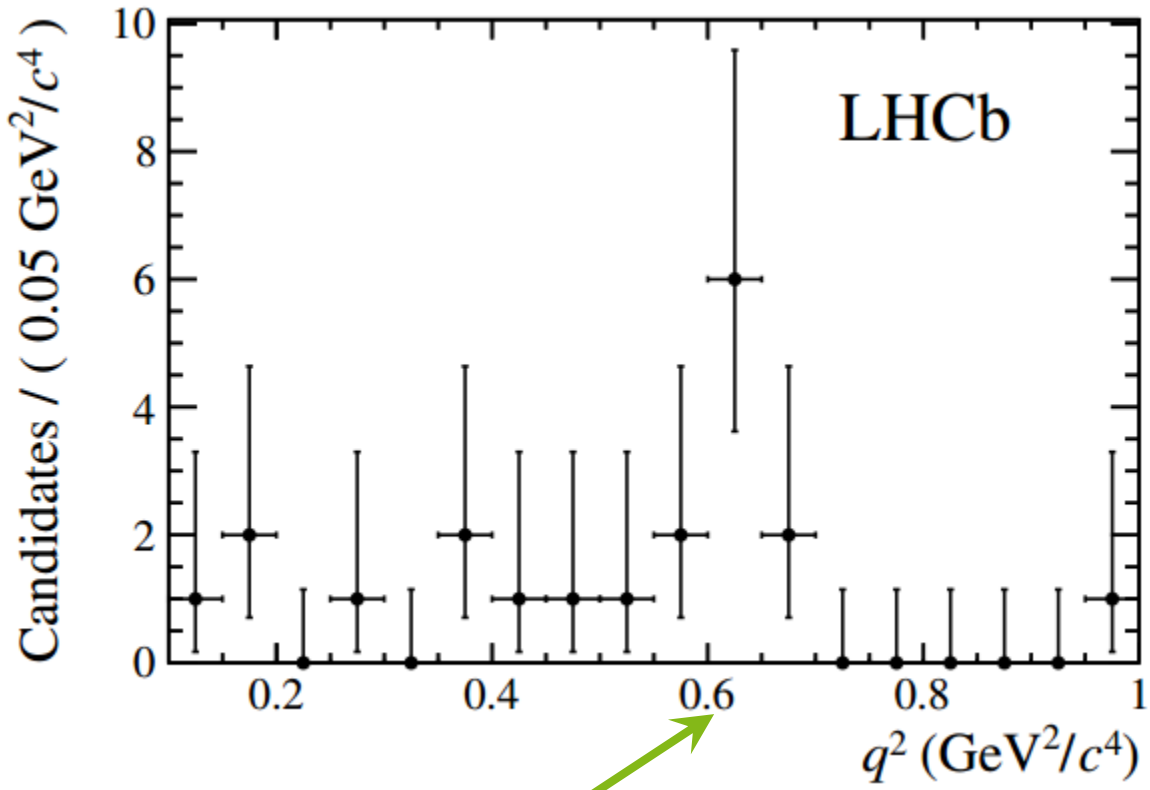
a) Ali, Parkhomenko, Rusov [PRD 89 (2014) 094021]

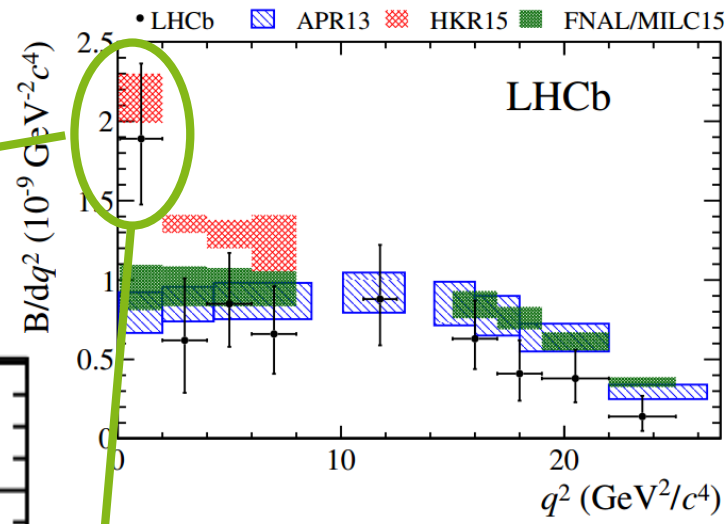
b) Hambrock, Khodjamirian, Rusov [PRD 92 (2015) 074020]

c) FNAL lattice / MILC collaboration [PRL 115 (2015) 152002]

[JHEP 10 (2015) 034]

$B^- \rightarrow \pi^- \mu^+ \mu^-$ branching fraction





ρ/ω

a) Ali, Parkhomenko, Rusov [PRD 89 (2014) 094021]

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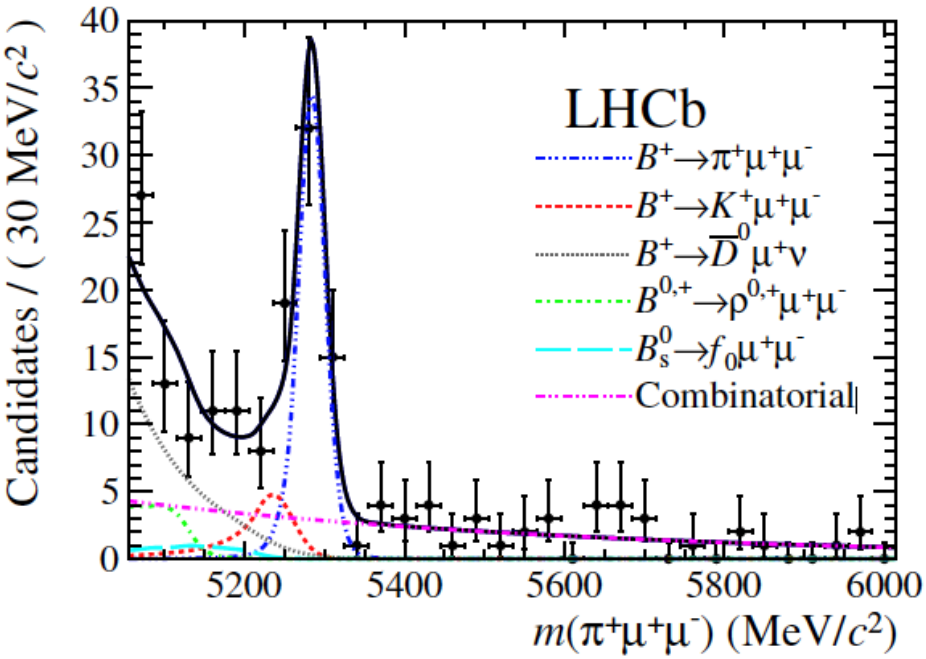
c) FNAL lattice / MILC collaboration [PRL 115 (2015) 152002]

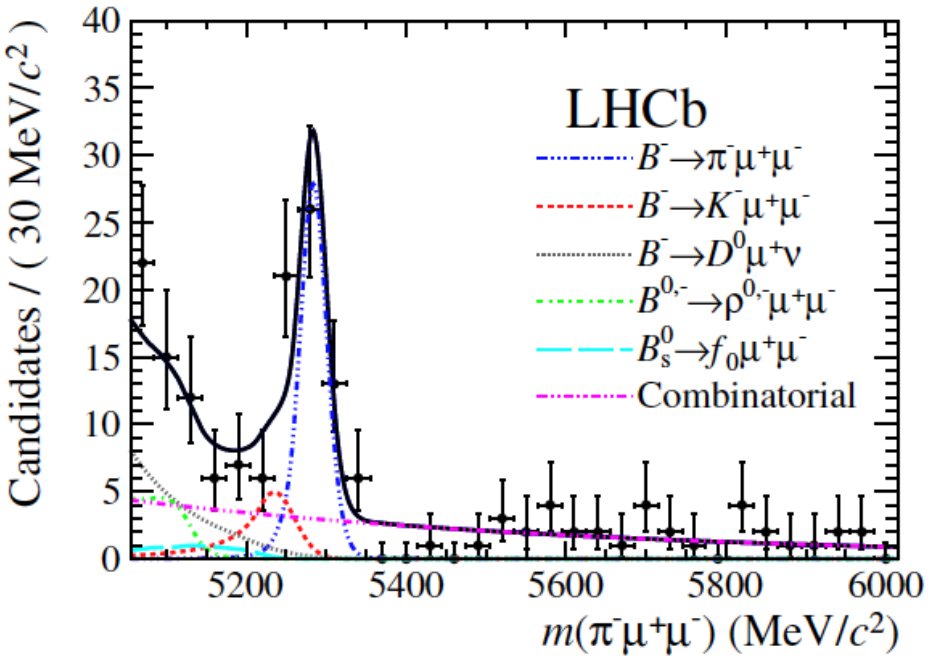
[JHEP 10 (2015) 034]

$B^- \to \pi^- \mu^+ \mu^-$ CP asymmetry

- negligible detection & production asymmetry

$$\mathcal{A}^{CP} = -\frac{\mathcal{N}(B^+ \to \pi^+ \mu^+ \mu^-) - \mathcal{N}(B^- \to \pi^- \mu^+ \mu^-)}{\mathcal{N}(B^+ \to \pi^+ \mu^+ \mu^-) + \mathcal{N}(B^- \to \pi^- \mu^+ \mu^-)}$$





$$\boxed{\mathcal{A}^{CP} = -0.11 \pm 0.12}$$

$$\mathcal{A}^{CP} = -0.143^{+0.035}_{-0.029} \quad \text{(SM)}$$