technische universität
dortmund

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

LHCb

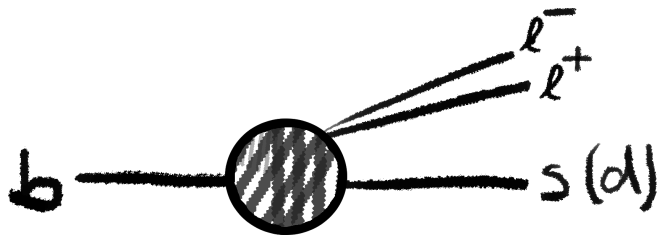
Rare b and c decays at LHCb

Maximilian Schlupp
on behalf of the LHCb collaboration,

HQL, 26th May 2016
Blacksburg VA

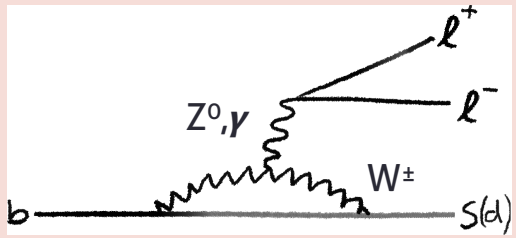
The $b \to s l^+ l^-$ system

- Today's focus: $b \to s l^+ l^-$ decays



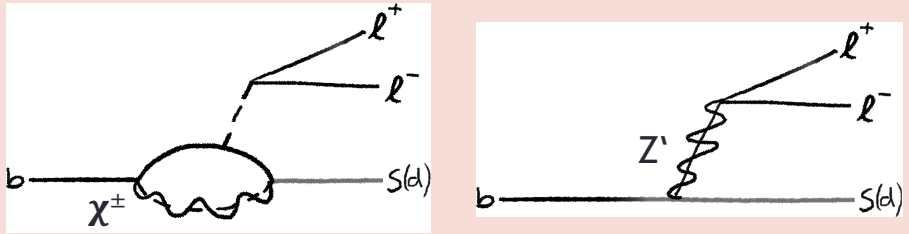
- Standard model: Flavor changing neutral currents (FCNC) forbidden on tree-level

SM



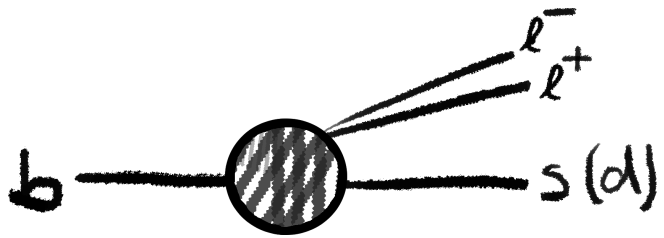
- New heavy particles can contribute virtually to the tree or loop-level
  - ➔ Can modify branching fractions and angular observables

BSM



The b→sl⁺l⁻ system

- Today's focus: b→sl⁺l⁻ decays



- Model independent description: effective field theory

$$\mathcal{H}_{eff} \propto G_F \; V_{tb}V_{ts}^* \sum_i C_i \; \mathcal{O}_i$$

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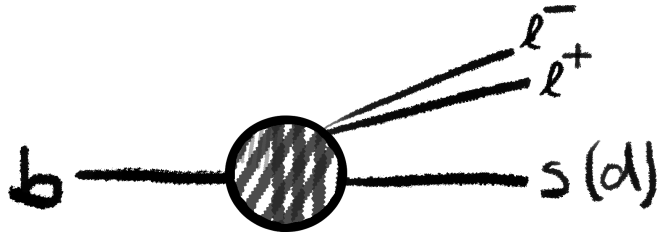

- Model independent description: effective field theory

Effective couplings (*Wilson coefficients*)

$$\mathcal{H}_{eff} \propto G_F \; V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local Operators

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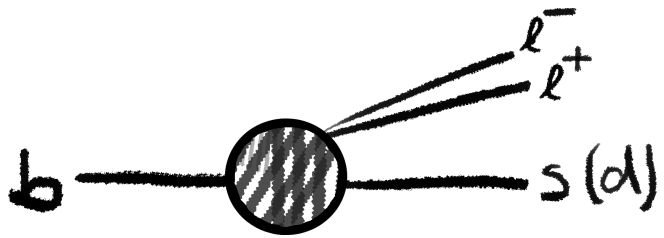

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$$\mathcal{H}_{eff} \propto G_F \; V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local Operators

"New Physics" contributions:

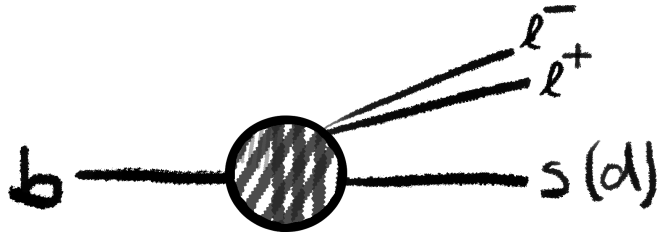
NP coupling

$$\Delta\mathcal{H}^{NP} \propto \frac{\epsilon}{\Lambda_{NP}^2} \mathcal{O}_i$$

NP scale

The b→sl⁺l⁻ system

- Today's focus: b→sl⁺l⁻ decays



- Model independent description: effective field theory

The b→sl⁺l⁻ system provides an excellent laboratory for precision tests of the SM

Effective couplings (*Wilson coefficients*)

$$\mathcal{H}_{eff} \propto G_F \, V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local Operators

"New Physics" contributions:

$$\Delta\mathcal{H}^{NP} \propto \frac{\epsilon}{\Lambda_{NP}^2} \mathcal{O}_i$$

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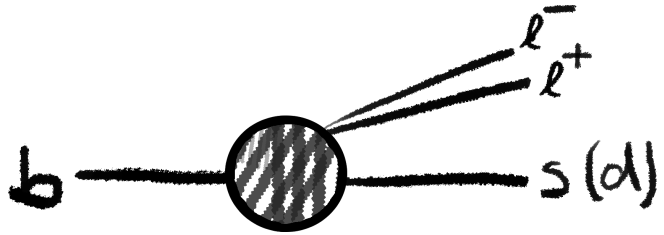

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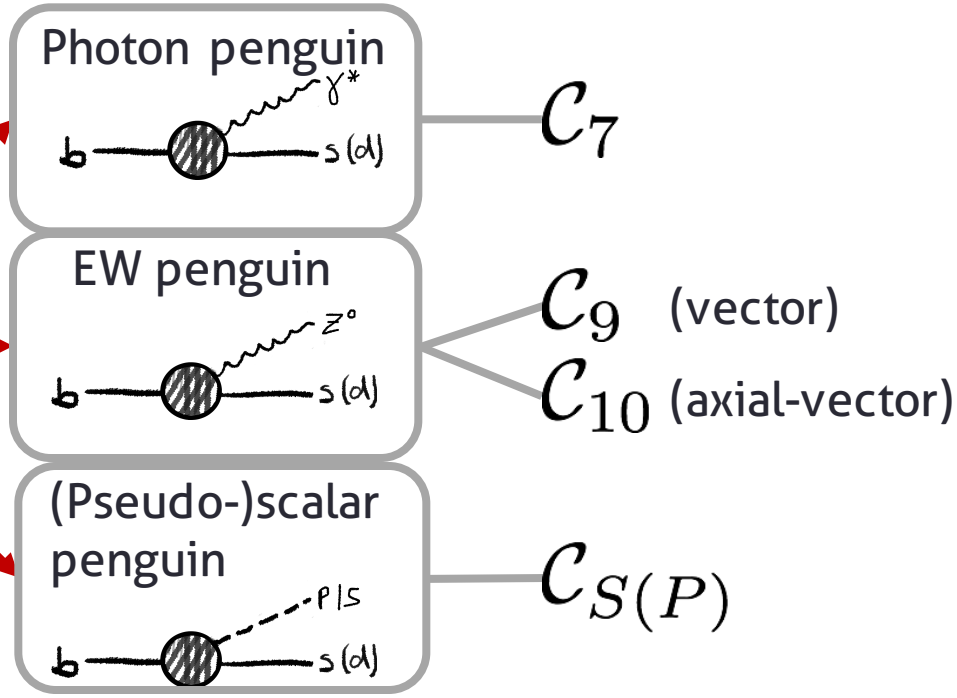

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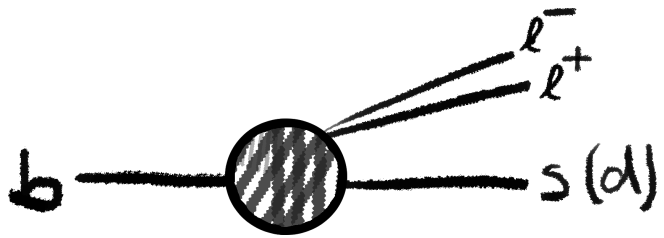

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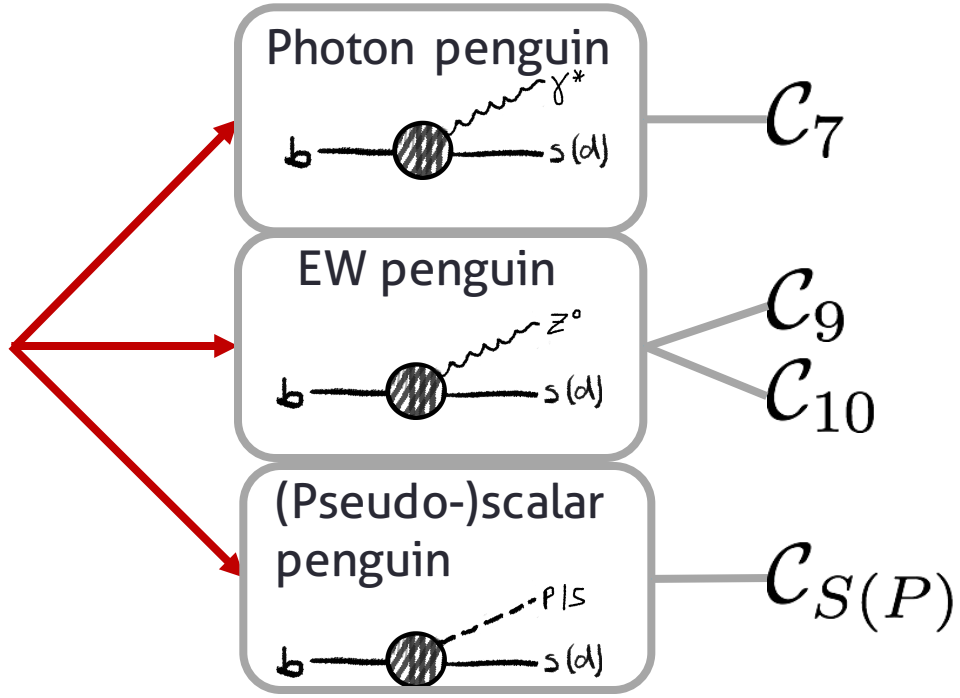


	$B \to X_s \; l^+l^-$	$B^0_{(s)} \to l^+l^-$
Photon penguin	✓	✗
EW penguin	✓	✗
	✓	✓
(Pseudo-)scalar penguin	✓	✓

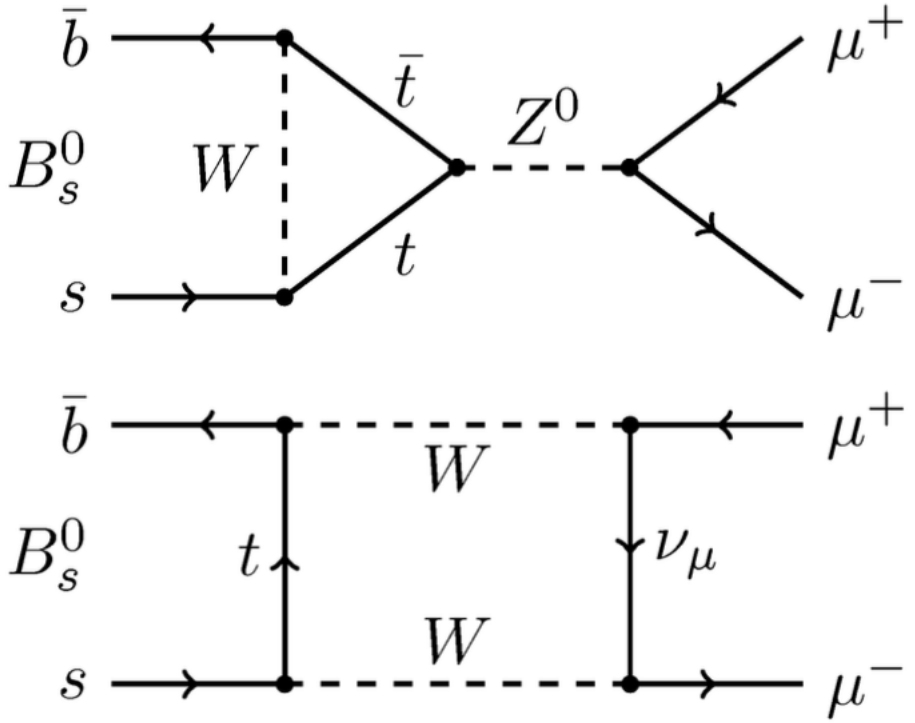
LETTER

First observation of $B_s^0 \to \mu^+\mu^-$

OPEN
Nature 522, 68-72 (2015)

- Extremely rare b-hadron decay
  - Flavour changing neutral current
  - Helicity suppressed
- Purely leptonic: experimentally & theoretically clean
- SM prediction [Bobeth et al, PRL 112 (2014) 101801]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$



- New physics sensitivity w.r.t. SM axial-vector current:
  - Possible new scalar or pseudoscalar contributions

$$\mathcal{B} \propto \left(1 - \frac{4m_\mu^2}{M_B^2}\right) |\mathcal{C}_S - \mathcal{C}'_S|^2 + \left|(\mathcal{C}_P - \mathcal{C}'_P) + \frac{2m_\mu}{M_B^2}(\mathcal{C}_{10} - \mathcal{C}'_{10})\right|^2$$

LETTER

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OPEN
Nature 522, 68-72 (2015)

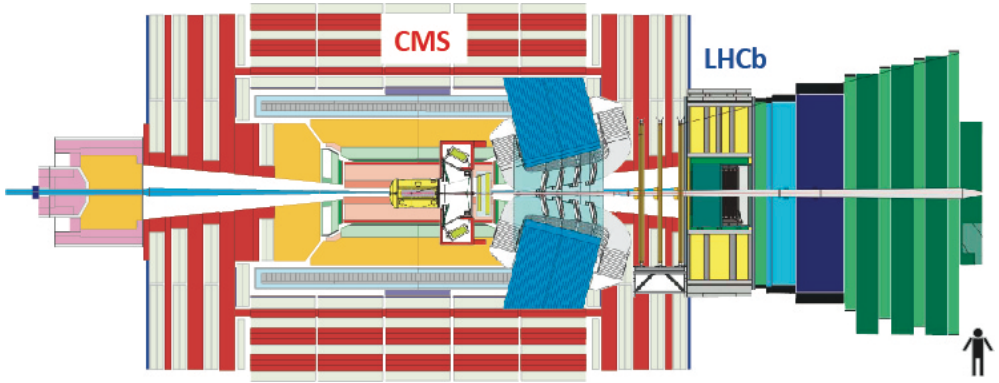
- First joined analysis of LHC data by two experiments
  - Simultaneous fit to LHCb and CMS data
- First observation of $B_s^0 \to \mu^+\mu^-$
  - 6.2σ significance (expected 7.2σ)

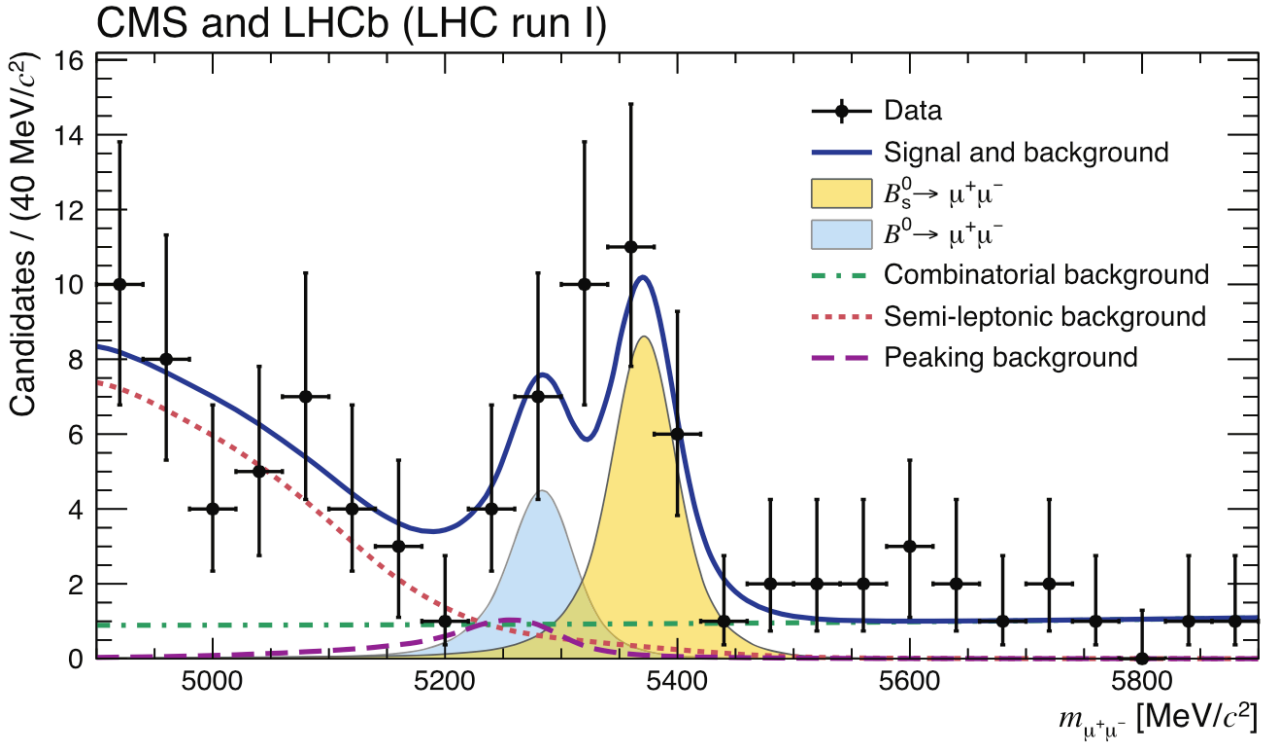
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

- First evidence of $B^0 \to \mu^+\mu^-$
  - 3.0σ significance (expected 0.8σ)

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

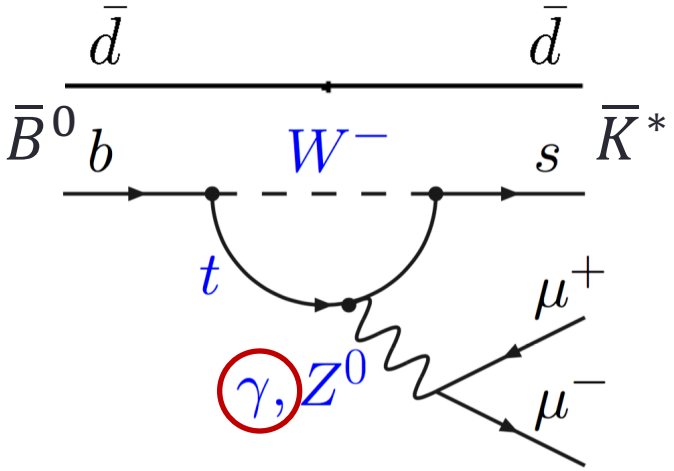
ATLAS result: Jaroslav, after the coffee

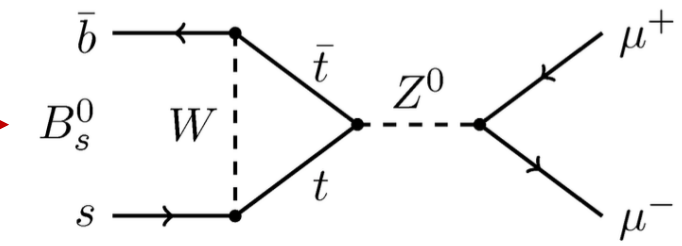




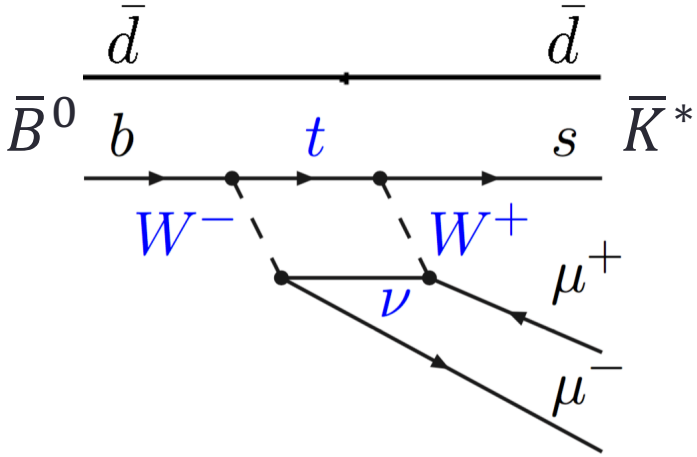
Angular analysis of $B^0 \to K^*\mu^-\mu^+$

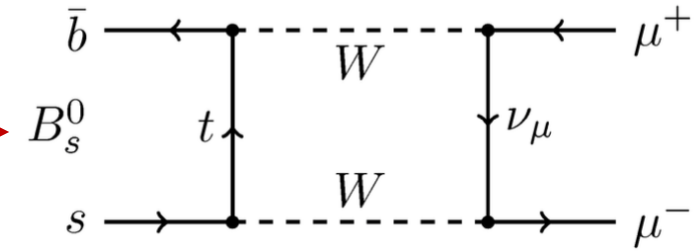
- Additional outgoing particle
  - No helicity suppression
  - Allows vector contributions (esp. photon) instead of only axial-vector
  - ➔ Sensitive to C_7, C_9, C_{10}





- Full angular analysis of $B^0 \to K^*\mu^-\mu^+$ decays

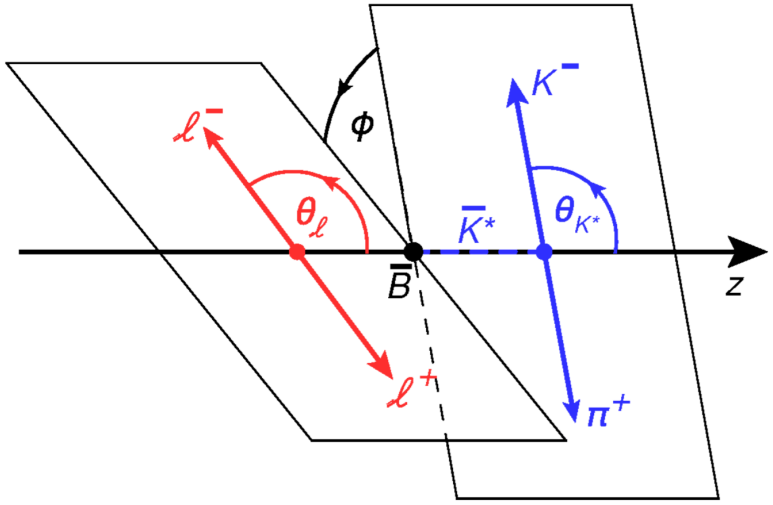




Angular analysis of $B^0 \to K^*\mu^-\mu^+$

- Full angular analysis of $B^0 \to K^*\mu^-\mu^+$ decays
  - Parametrize decay in helicity angles $\vec{\Omega} = (\theta_l, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

→ Full 4D angular acceptance



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

Angular analysis of $B^0 \to K^*\mu^-\mu^+$

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→ Full 4D angular acceptance

→ Set of coefficients F_L, A_{FB}, S_i depending on Wilson coefficients $\mathcal{C}_7$, $\mathcal{C}_9$, $\mathcal{C}_{10}$ and **$B^0 \to K^*$ form factors**

→ Measure in bins of q^2

Fraction of longitudinal polarisation of the K^*

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
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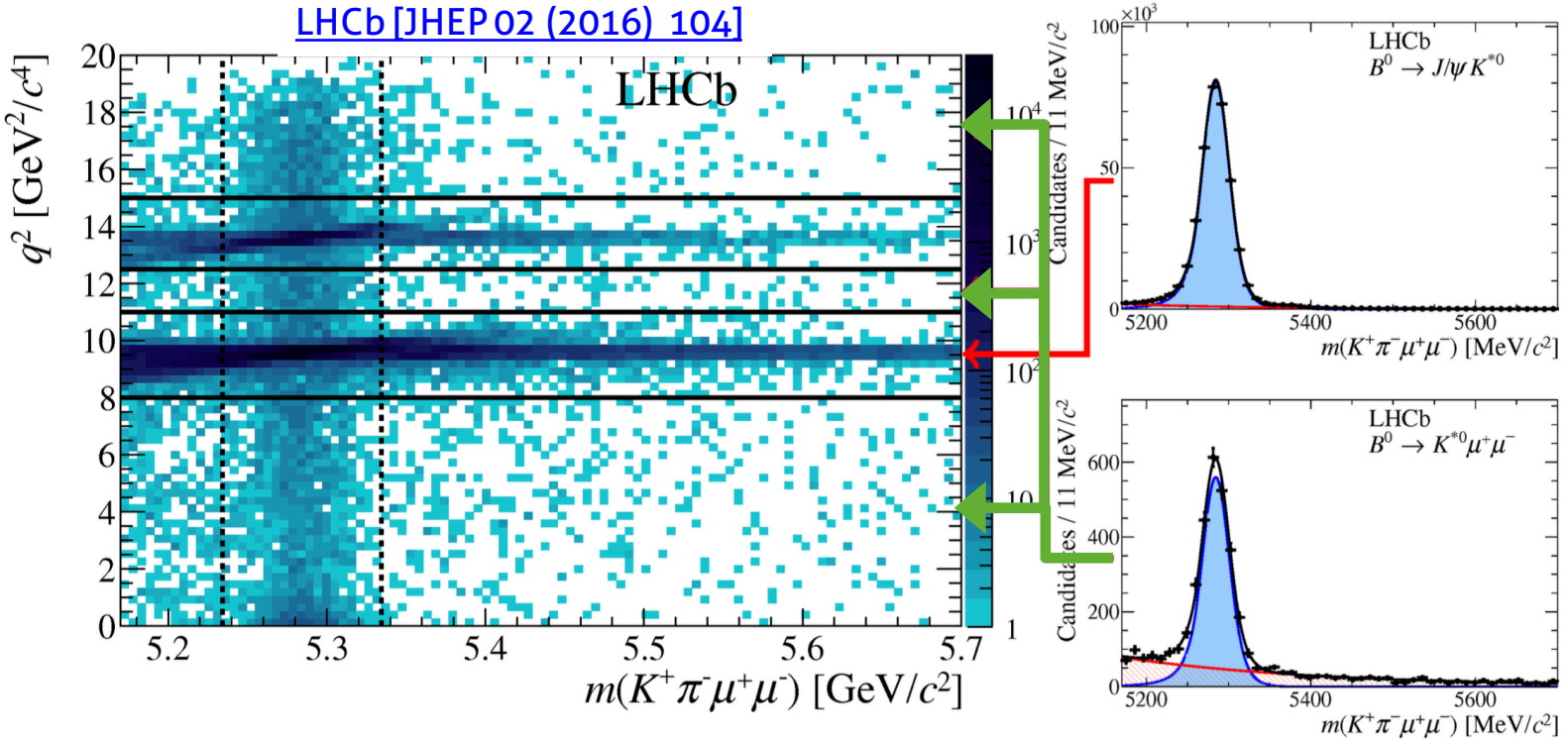
Forward-backward asymmetry of dilepton system

Angular analysis of $B^0 \to K^*\mu^-\mu^+$

- Use Kπμμ invariant mass as discriminating variable
  - Veto charmonium resonances in q^2 region

LHCb [JHEP 02 (2016) 104]



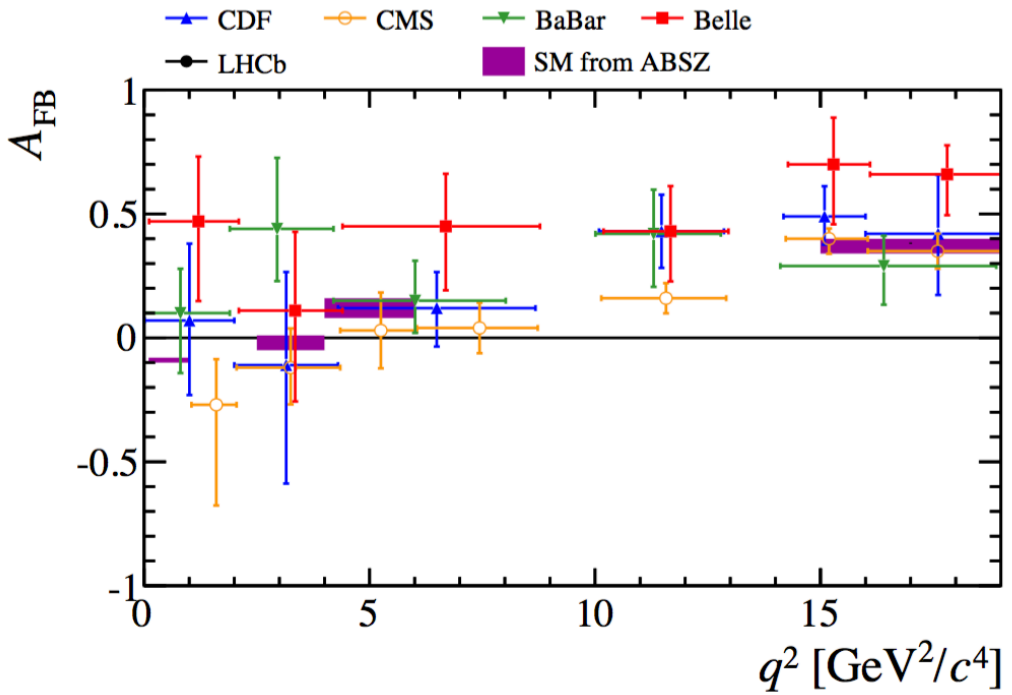
Control channel: $B^0 \to J/\psi K^*$
About 350k events

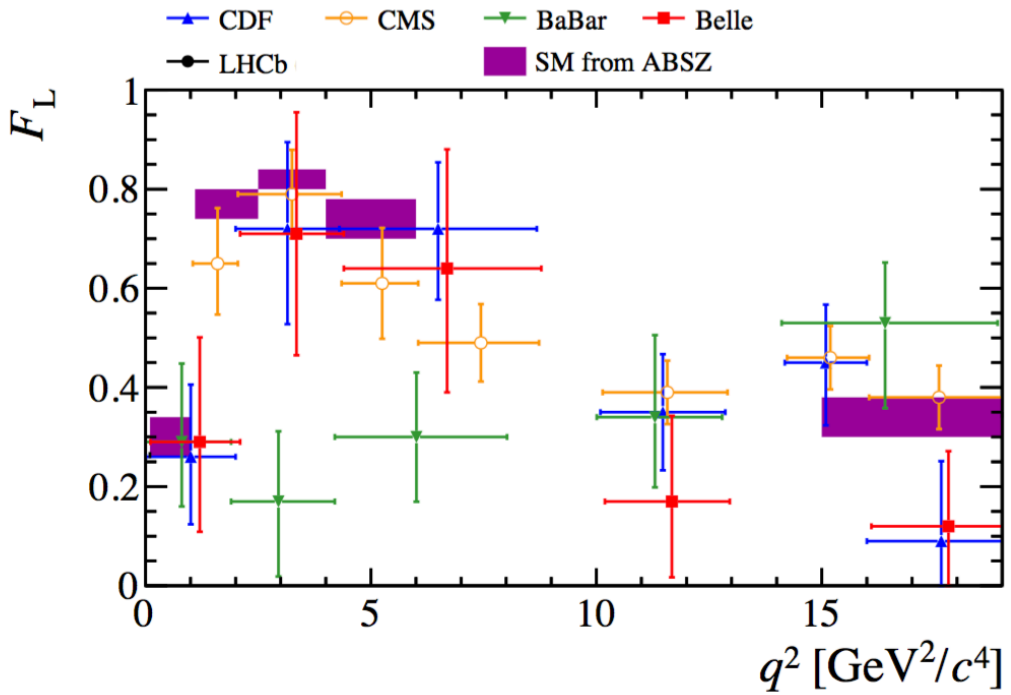
Signal channel: $B^0 \to K^*\mu^-\mu^+$
About 2400 events in Full LHC Run 1 data

- Unbinned maximum likelihood fit to Kπμμ mass and three decay angles
  - Fit Kπ mass simultaneously to constrain S-wave contribution

Angular analysis of $B^0 \to K^* \mu^- \mu^+$

- First measurement of the full set of angular observables





LHCb [JHEP 02 (2016) 104]
CMS [PLB 753 (2016) 424]
BaBar [PRD 93 (2016) 052015]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801]

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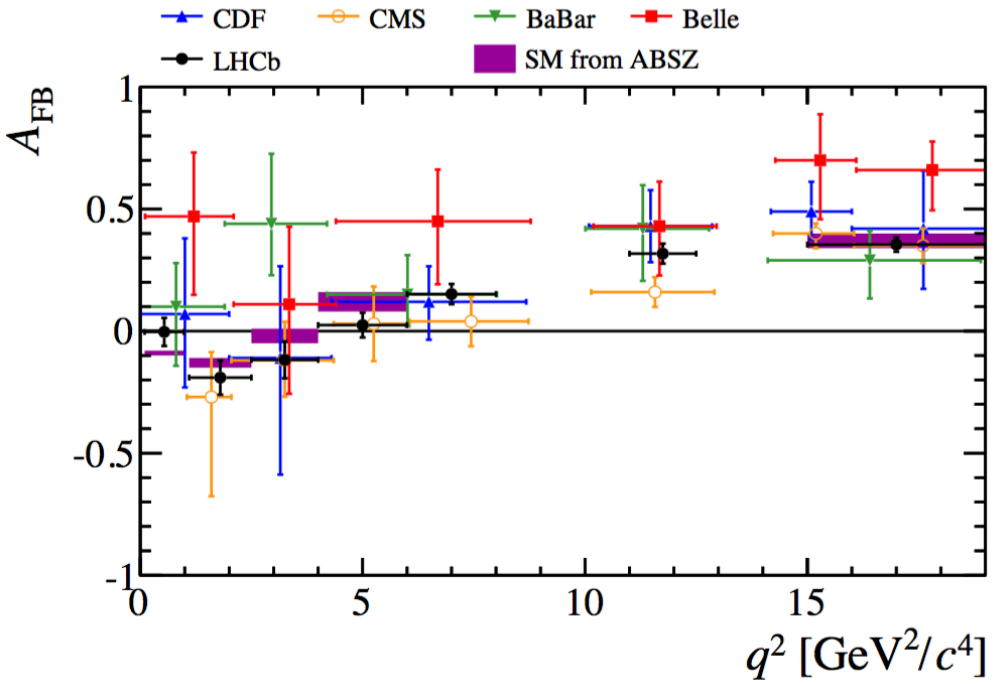

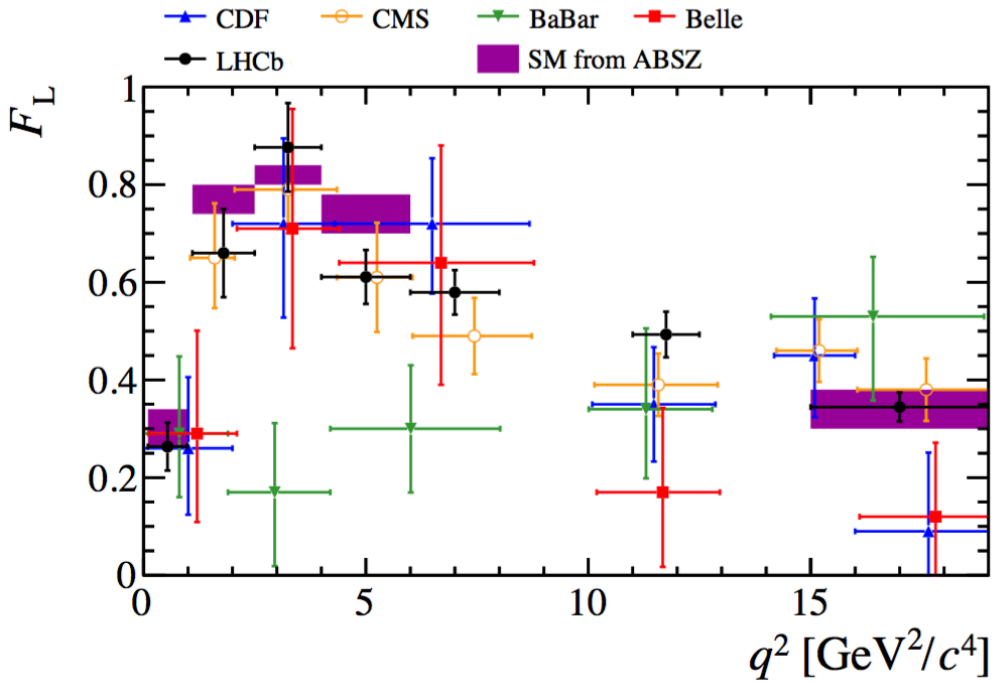

- Disentangle form factor from short distance physics effects?
  - → Create ratio of observables with minimal form factor dependence, e.g. [S. Descotes-Genon et al., JHEP 12 (2014) 125]

$$P_5' = S_5 / \sqrt{F_L (1 - F_L)}$$

LHCb [JHEP 02 (2016) 104]
CMS [PLB 753 (2016) 424]
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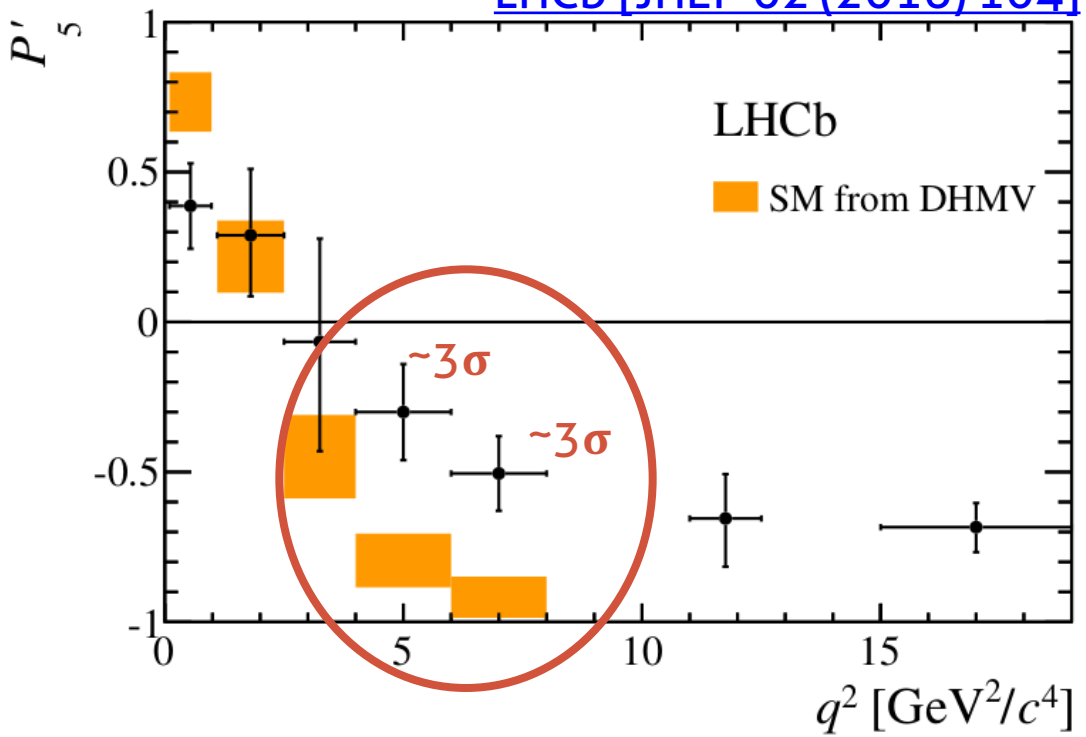
Angular analysis of $B^0 \to K^* \mu^- \mu^+$

- Less form factor dependent variable

$$P_5' = S_5 / \sqrt{F_L (1 - F_L)}$$

- Local discrepancy of ~3σ in two q^2 bins
- Global analysis of the $B^0 \to K^* \mu^- \mu^+$ decay topology finds tension of 3.4σ w.r.t. the SM
- Full LHC Run 1 data confirms tension in P'_5 from LHCb 1/fb measurement
- If tensions are due to "real" physical effects
  ➔ observe discrepancies in other b→s decays

LHCb [JHEP 02 (2016) 104]

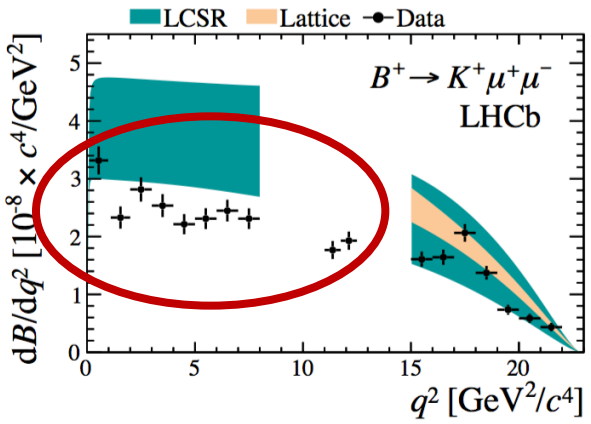


SM: [S. Descotes-Genon et al., JHEP 12 (2014) 125]

Angular analysis of $B^0 \to K^* \mu^- \mu^+$

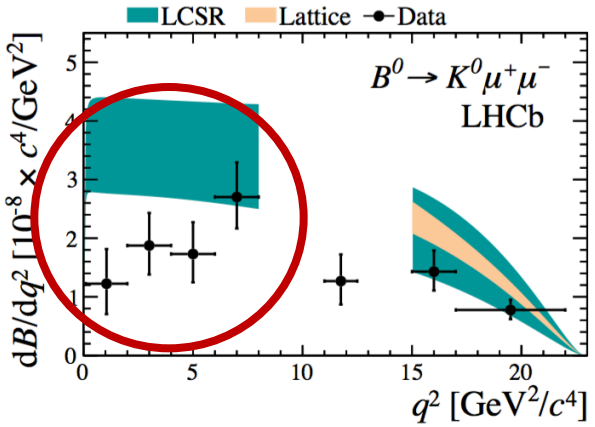
$B^+ \to K^+ \mu^+ \mu^-$

JHEP 06 (2014) 133



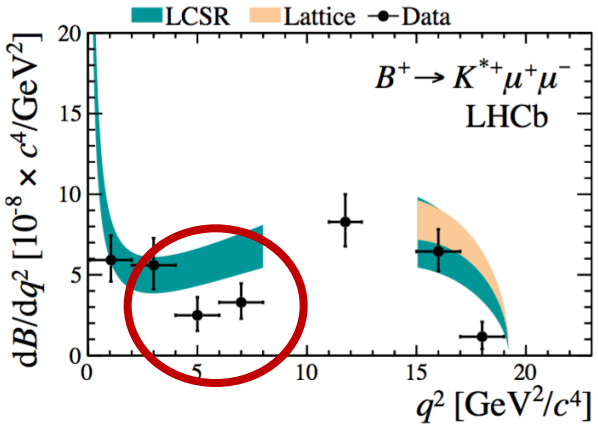
$B^0 \to K^0 \mu^+ \mu^-$

JHEP 06 (2014) 133



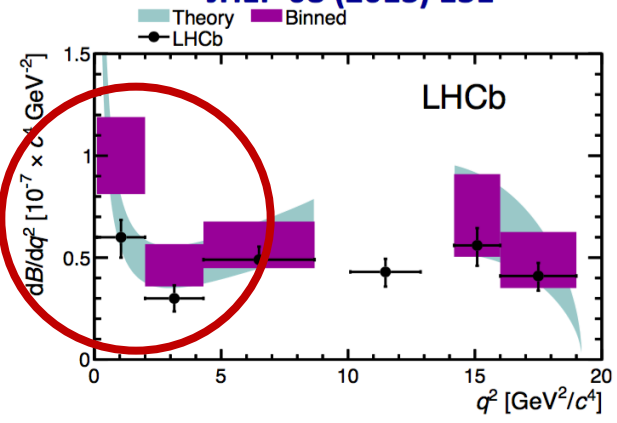
$B^+ \to K^{*+} \mu^+ \mu^-$

JHEP 06 (2014) 133



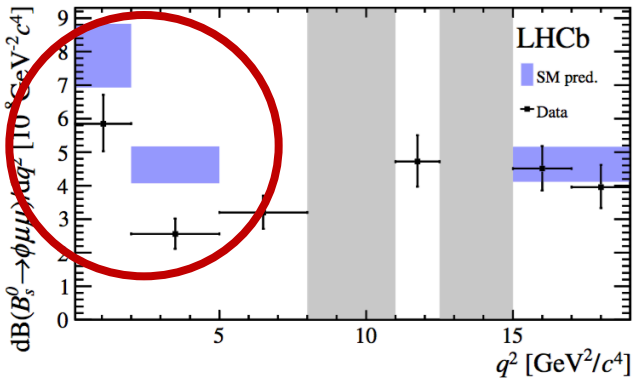
$B^0 \to K^{*0} \mu^+ \mu^-$

JHEP 08 (2013) 131



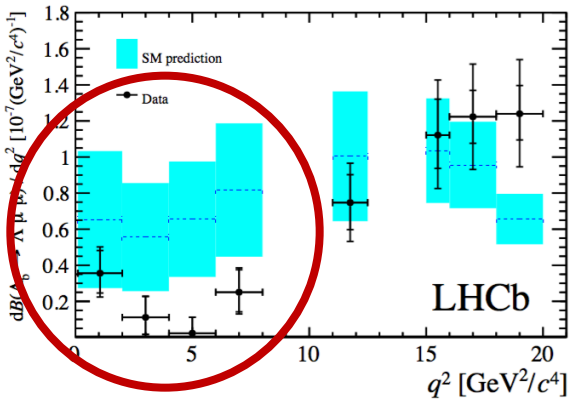
$B_s \to \phi \mu^+ \mu^-$

JHEP 09 (2015) 179



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

JHEP 06 (2015) 115



- Large class of possible b→s transitions
- Several "tensions", but individually not significant

What can we learn from the "big picture"???

→ Perform global analysis

Global fit to combined b→s observables

- Combined b→s data: 88 measurements by 6 experiments
  - $B^0 \to K^* \mu^- \mu^+$
  - $B_s^0 \to \mu^- \mu^+$
  - $B \to X_s \mu^- \mu^+$
  - $B \to X_s \gamma$

- Separate SM from "new physics" (NP) effects

$$\mathcal{H}_{eff} \propto \sum_i \left(C_i^{SM} + C_i^{NP} \right) \mathcal{O}_i$$

Global fit to combined b→s observables

- Combined b→s data: 88 measurements by 6 experiments
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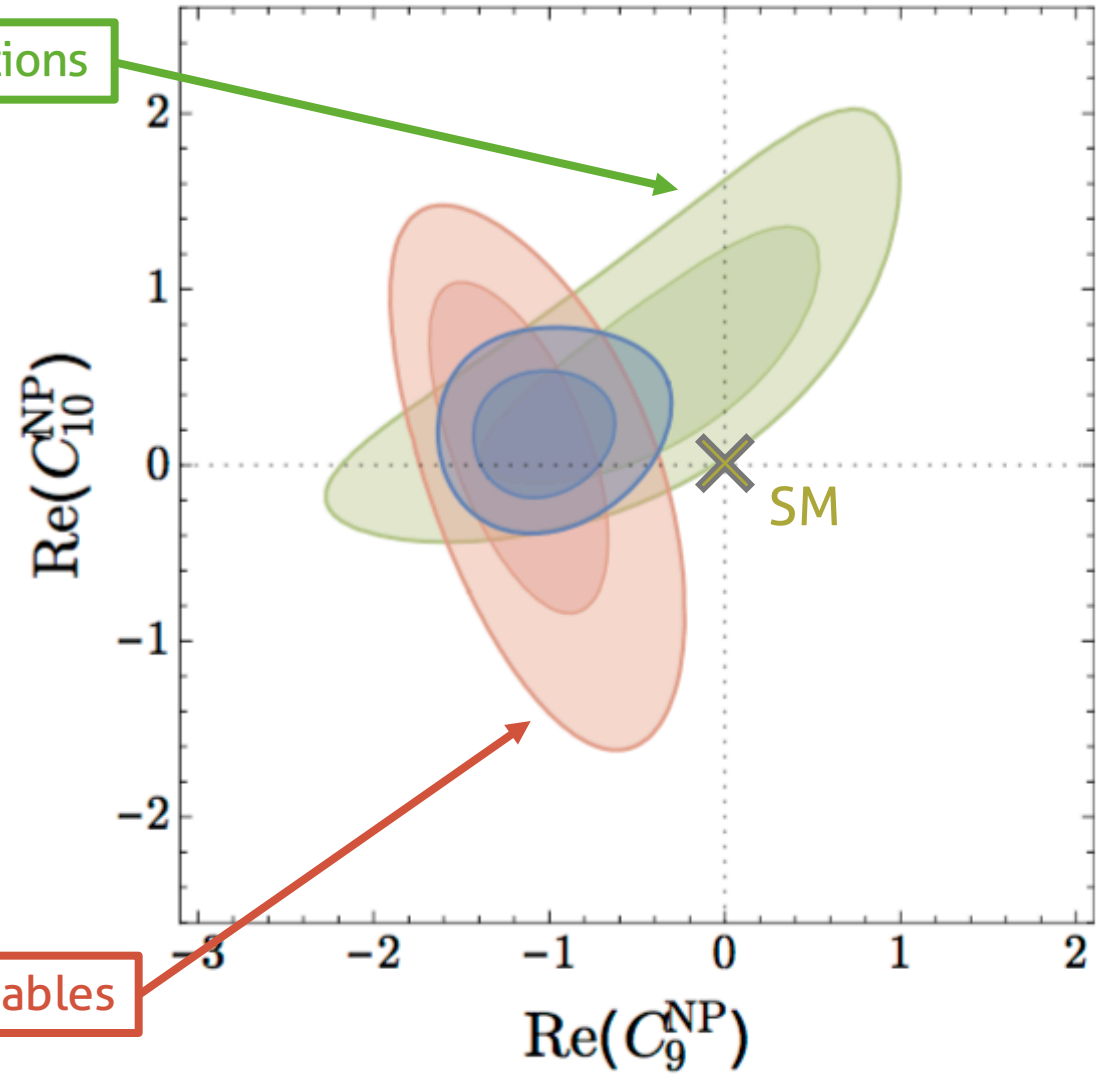
[Altmannshofer, Straub, arXiv:1503.06199]

- Separate SM from "new physics" (NP) effects

$$\mathcal{H}_{eff} \propto \sum_i \left(\mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}\right) \mathcal{O}_i$$

Global fit favours non-SM vector-like contribution (3–5σ)

[Descotes-Genon et al., arXiv:1510.04239]



Global fit to combined b→s observables

- Combined b→s data: 88 measurements
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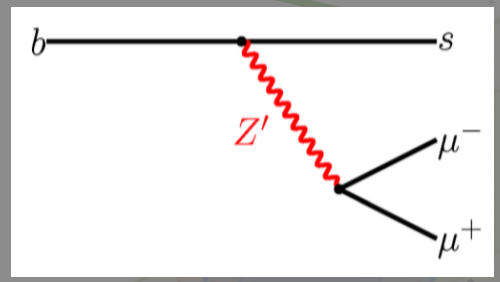
  - $B \to X_s \mu^- \mu^+$
  - $B \to X_s \gamma$
- Separate SM from "new physics" (NP) effects

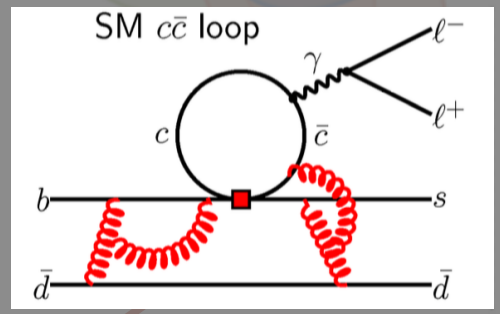
$$\mathcal{H}_{eff} = \sum_i \left(C_i^{SM} + C_i^{NP}\right) O_i$$

[Altmannshofer, Straub, arXiv:1503.06199]

What can cause this??

- "Clearly new Physics"?
- Not well-known QCD contributions?



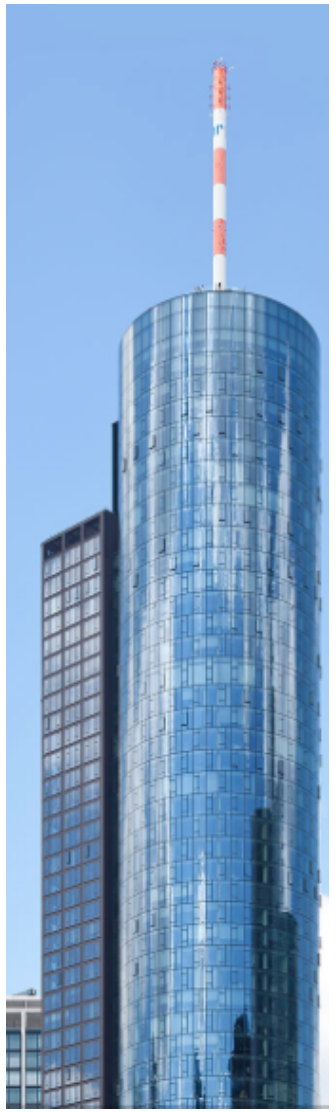


Global fit favours non-SM vector-like contribution

➔ **More data & theoretical work necessary**

Rare charm decays

CHARM

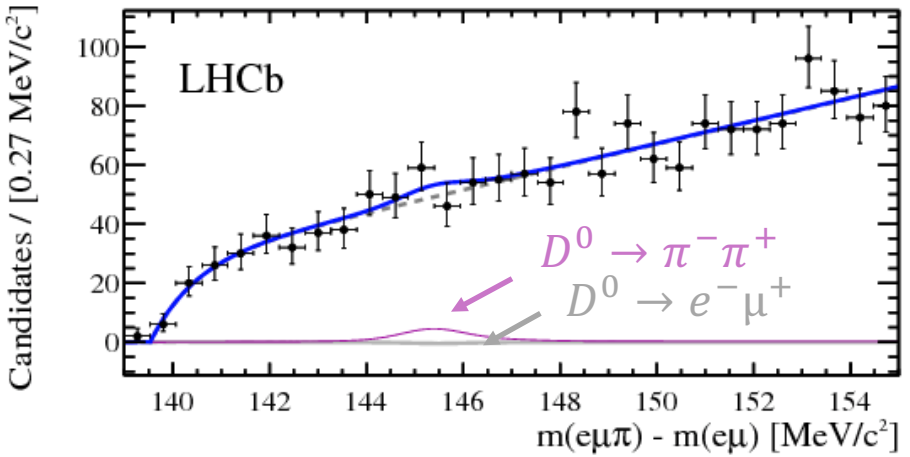


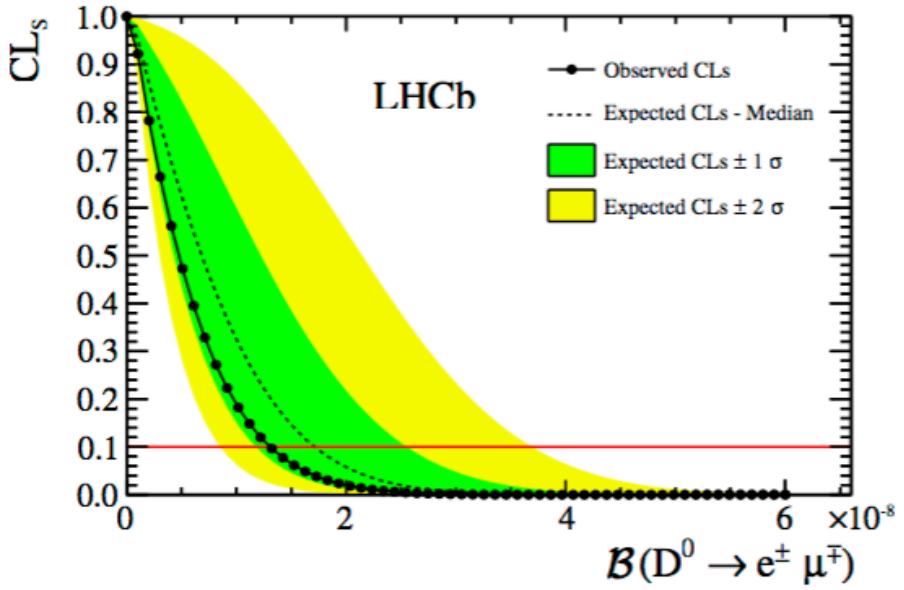
Search for $D^0 \to e^-\mu^+$ decays

- The observation of lepton-flavor violation would be a striking evidence for "new physics"
- Search for lepton-flavor violation in the charm-sector
  - In RPV SUSY: O(≲10^{-6}) [Burdman et al., PRD **66** (2002) 014009]
- Exploit small Δm in $D^{*+} \to D^0\pi^+$ decays to suppress background
- Challenge: mis-identified $D^0 \to \pi^-\pi^+$ background
- Simultaneous fit to Δm and m($e^+\mu^-$) in three bins of a multivariate classifier
  - No signal found → limit (CLs method)

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

[LHCb, PLB 754 (2016) 167]





Summary

- The rich and flavorful observables in rare b and c decays provide an excellent laboratory to test the SM

- Several interesting anomalies observed in the $b \to s l^+ l^-$ system
  - More data & theoretical work is needed to conclude

- Additional deviations in lepton-flavor universality tests observed

  → **Talk by Anna Lupato, tomorrow, 10.55 am**

- Interesting flavor data is coming
  - LHCb Run 2 → tripling the dataset
  - But also competition is good for the business

Most stringent limits

$D^0 \to \mu^+\mu^-$	$< 6.2 \times 10^{-9}$
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$< 5.5 \times 10^{-7}$
$D^+ \to \pi^+\mu^+\mu^-$	$< 7.3 \times 10^{-8}$
$D_s^+ \to \pi^+\mu^+\mu^-$	$< 4.1 \times 10^{-7}$

LHCb, PLB 725 (2013) 15
LHCb, PLB 728 (2014) 234
LHCb, PLB 724 (2013) 203

Summary

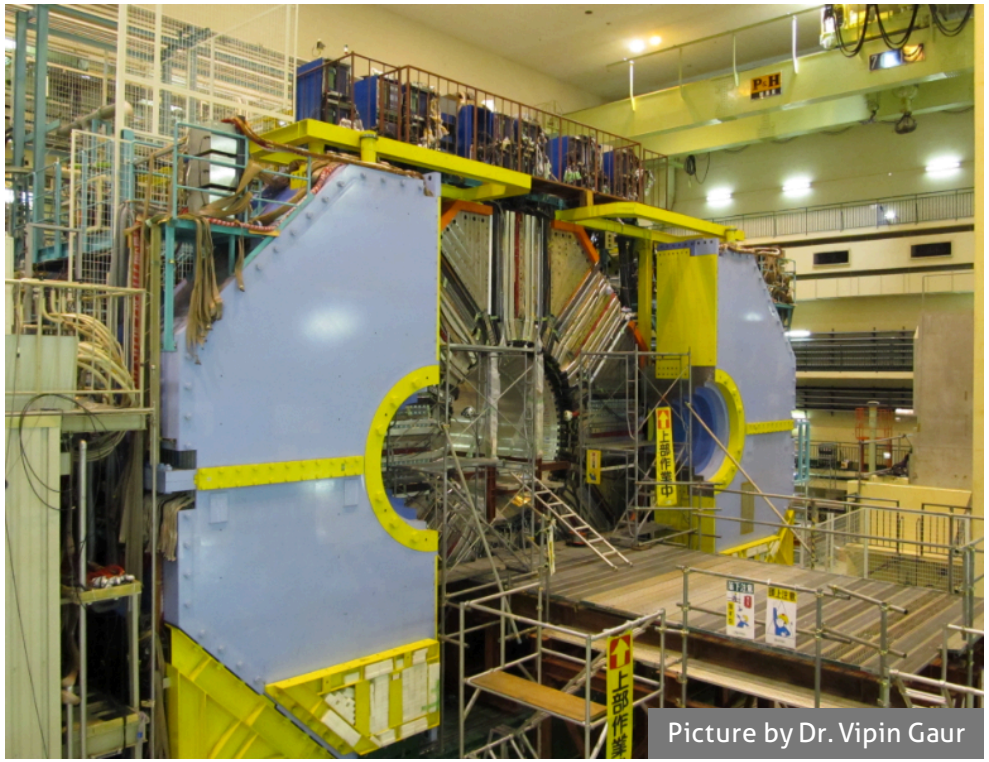
Congratulation to our colleagues of SuperKEKB & Belle2!

Belle2 Collaboration @belle2collab · Mar 2

The SuperKEKB accelerator has achieved the “first turns” of positron and electron beams! kek.jp/en/NewsRoom/Re…

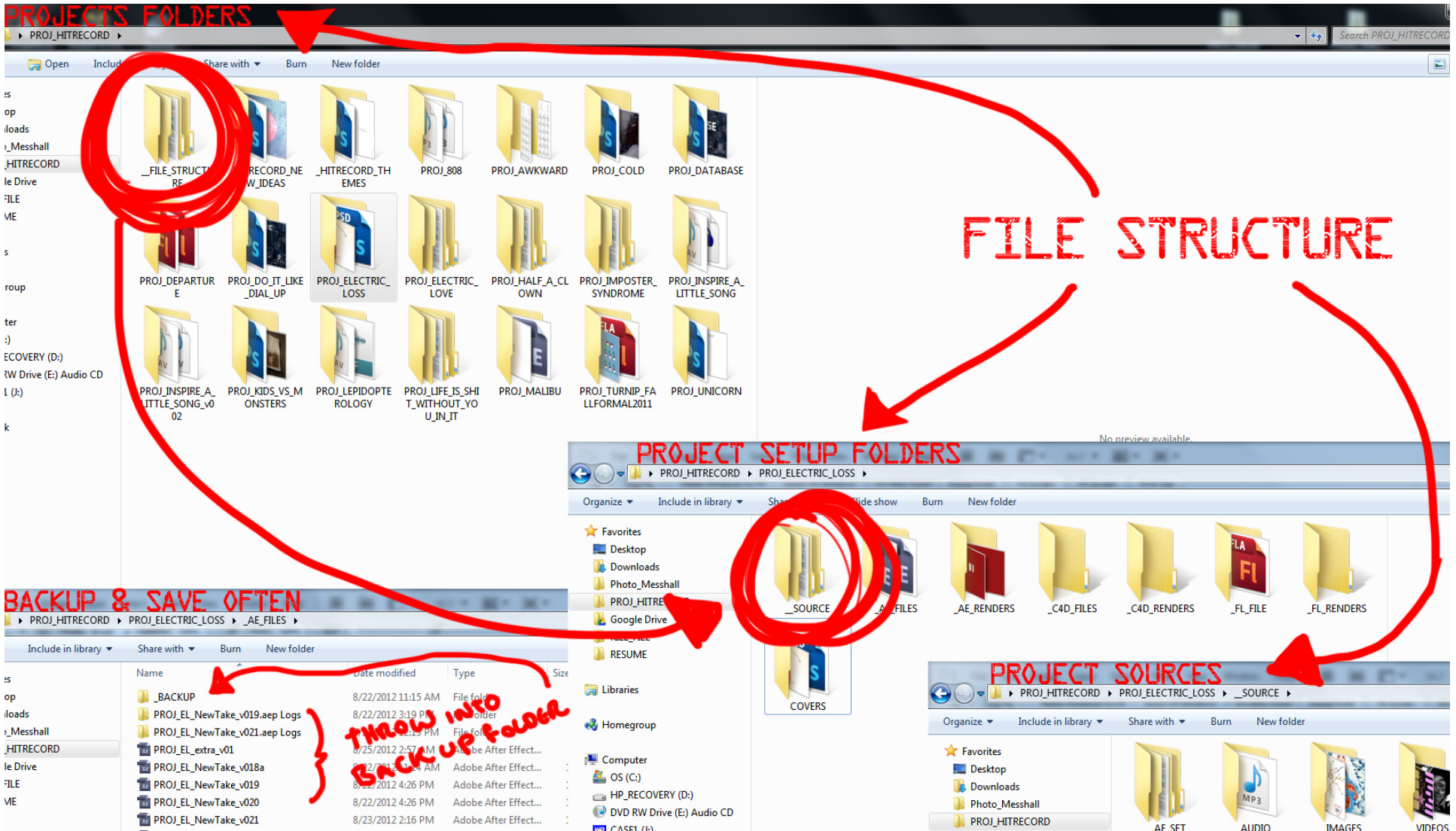
18 13

There are decades of fascinating flavor-physics to come!



Picture by Dr. Vipin Gaur

Backup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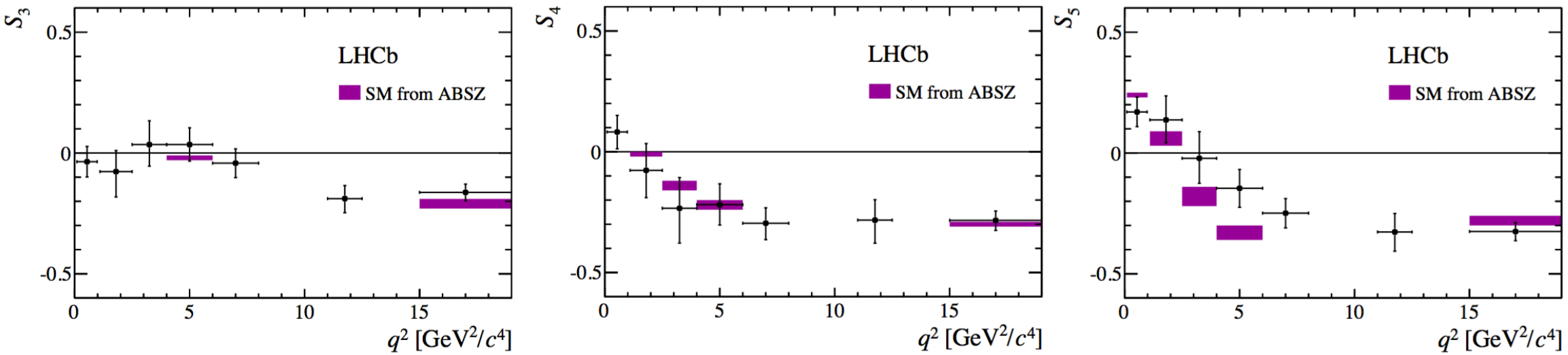
Angular analysis of $B^0 \to K^* \mu^- \mu^+$

- First full angular analysis: measurement of the full set of CP-averaged & CP-asymmetry observables...

JHEP02(2016)104



- SM predictions:
  - [Altmannshofer & Straub, EPJC 75 (2015) 382]
  - [LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]
  - [Lattice form-factors from Horgan, Liu, Meinel & Wingate, PoS LATTICE2014 (2015) 372]

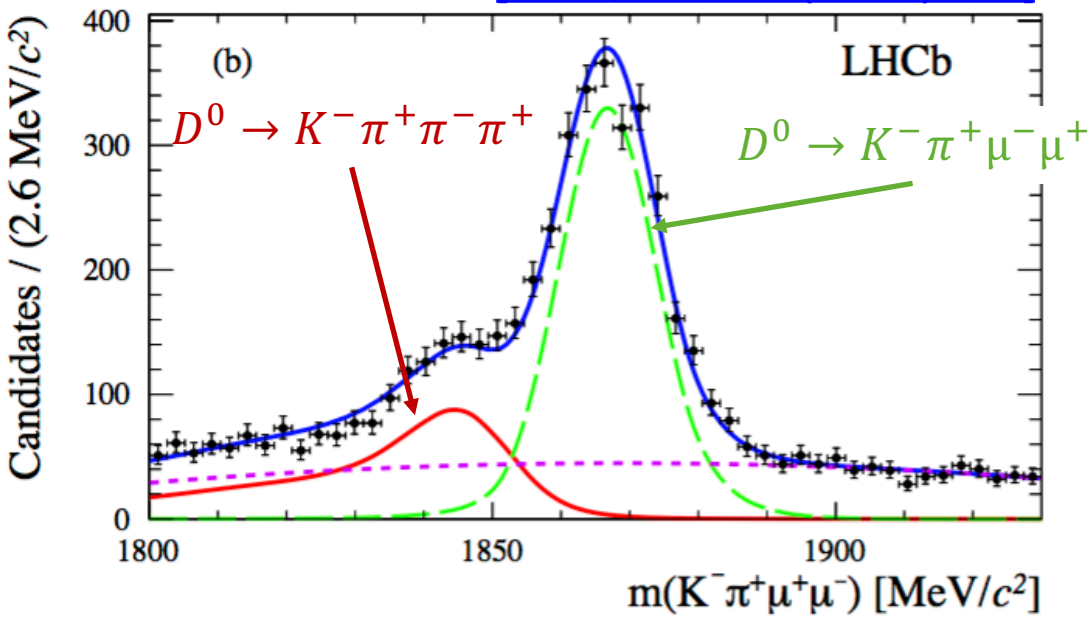
First observation of $D^0 \to K^-\pi^+\mu^-\mu^+$

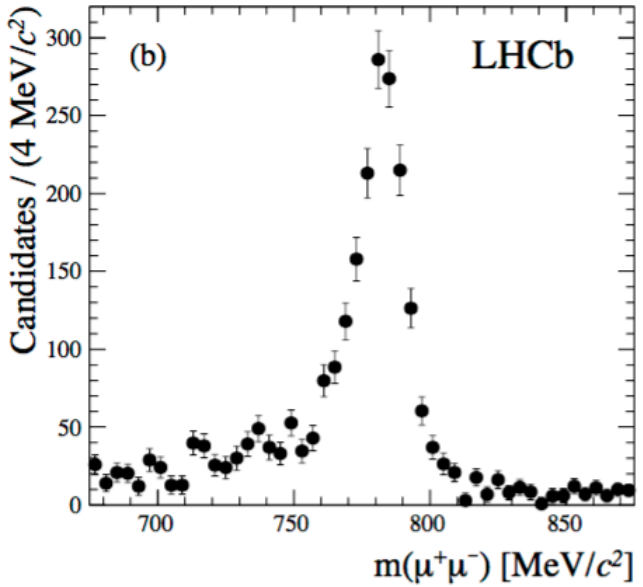
- Similar analyses possible in the charm-sector
  - E.g.: c→u FCNCs
    - $D^0 \to \pi^-\pi^+\mu^-\mu^+$
    - $D^0 \to K^-K^+\mu^-\mu^+$
- Important reference channel is $D^0 \to K^-\pi^+\mu^-\mu^+$
- First measurement of the branching fraction of $D^0 \to K^-\pi^+\mu^-\mu^+$ decays in the q² region around the ***ρ/ω*** resonances

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12(\text{stat}) \pm 0.40(\text{syst})) \times 10^{-6}$$

- First step towards c→u FCNCs measurements

[LHCb, PLB 757 (2016) 558]





LHCb & Belle II—Healthy interplay

- B_s System
  CPV in $J/\psi\phi$, $\phi\phi$,
  CPV in Mixing
- $B \to \mu\mu$
- CKM phase γ in $B \to DK$
- CPV in B_d
- $B \to X_s$ ll (exclusive)
- $B \to X\gamma$ (exclusive)
- Charm physics
- Semi-leptonic B decays
- τ - physics: LFV
- $B \to D, D^* \tau\nu$
- $B \to X_s$ ll (inclusive)
- $B \to X\gamma$ (inclusive)
- $B \to \tau\nu, \mu\nu$
- $B \to K^*\nu\nu, B \to \nu\nu$

"B_s & charged tracks"

Important cross checks

"inclusive & neutrals "