technische universität dortmund

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Experimentelle Physik V
Teilchenphysik

# Rare decays in b hadrons

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**(TU Dortmund)**

**13.3.2016**

RENCONTRES DE MORIOND
50
since 1966

# Indirect searches for New Physics

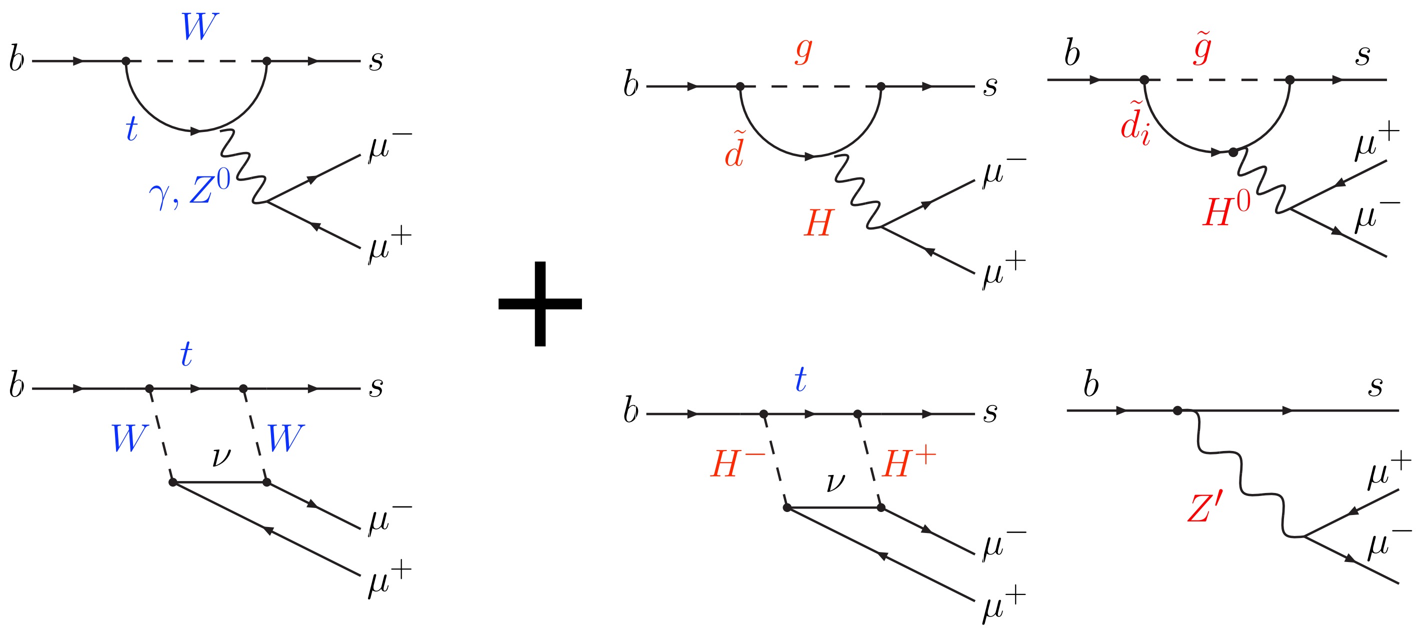
- High **energy**:
  “real” new particles can be produced and discovered via their decays
  - Discovery of the Higgs boson at the LHC → completion of the SM
  - **Tested scale : <10TeV**

- High **precision**:
  **“virtual” new particles** can be seen in quantum loops
  - Higher mass scale reachable (up to **~100TeV**)

**Direct and indirect searches are both needed, both equally important, and complement each other**

# Searches for New Physics in $b \to s\, \ell^+ \ell^-$

## Rare B decays:




- SM: Flavour changing neutral currents only at loop-level
- $b \to s\, \ell^+ \ell^-$ give a unique glimpse to higher scales: experimentally and theoretically clean

- $b \to s\, \ell^+\ell^-$ decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory, allows to extract potential New Physics amplitudes

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

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

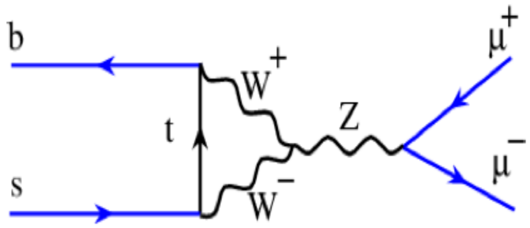
- Menu for this talk:
  - Purely leptonic decays: $B_s \to \mu^+\mu^-$
    → sensitive to $C_{S,P}$ and $C_{10}$
  - Recent measurements of $b \to s\, \ell^+\ell^-$, dominantly $B^0 \to K^* \mu^+\mu^-$
    → sensitive to $C_{7,9}$ and $C_{10}$
  - Lepton flavour universality
    → sensitive to $C^e$ vs $C^\mu$

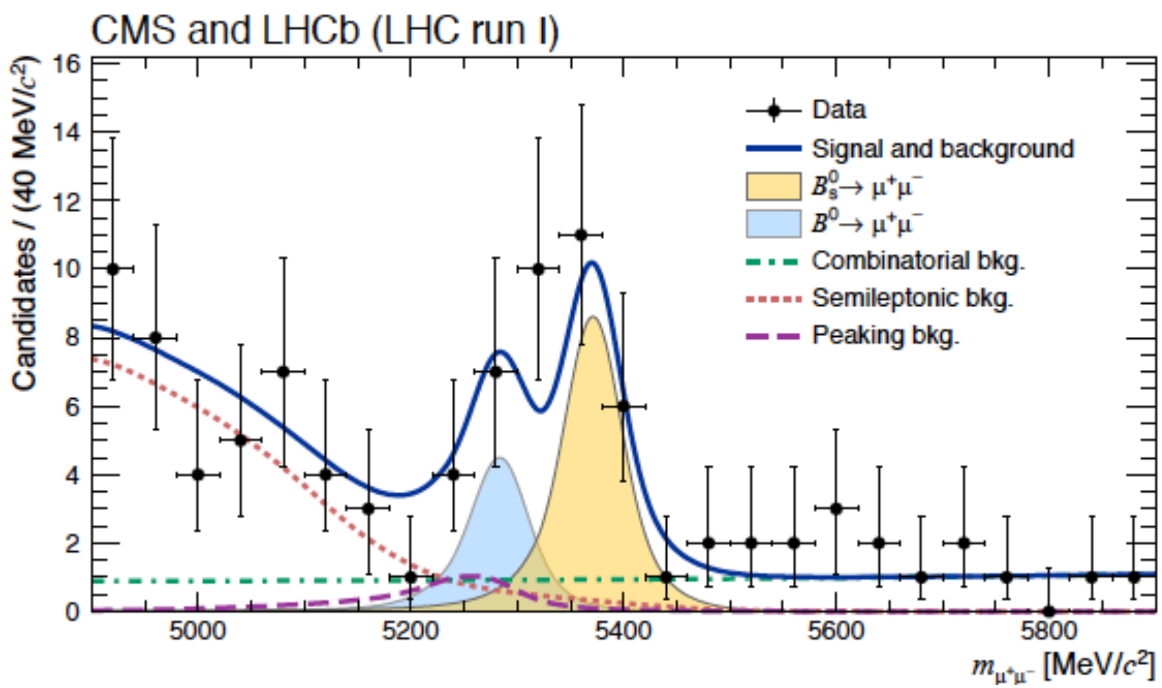
LETTER

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

OPEN
doi:10.1038/nature14474

Standard Model




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

SM: $3.66 \pm 0.23 \times 10^{-9}$

6.2σ significance → first observation

- compatible with SM at 1.2σ

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

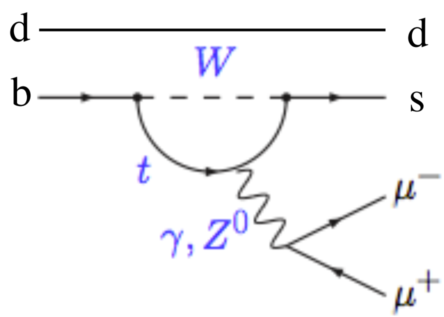
SM: $1.06 \pm 0.09 \times 10^{-10}$

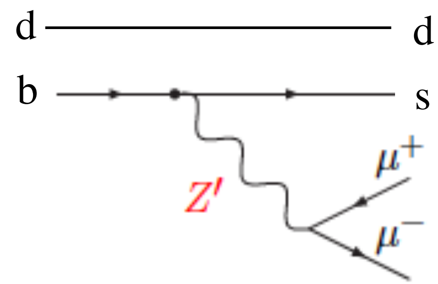
3.0σ significance → first evidence

- compatible with SM at 2.2σ

SM: Bobeth et al: PRL 112 101801 (2014)

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




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

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

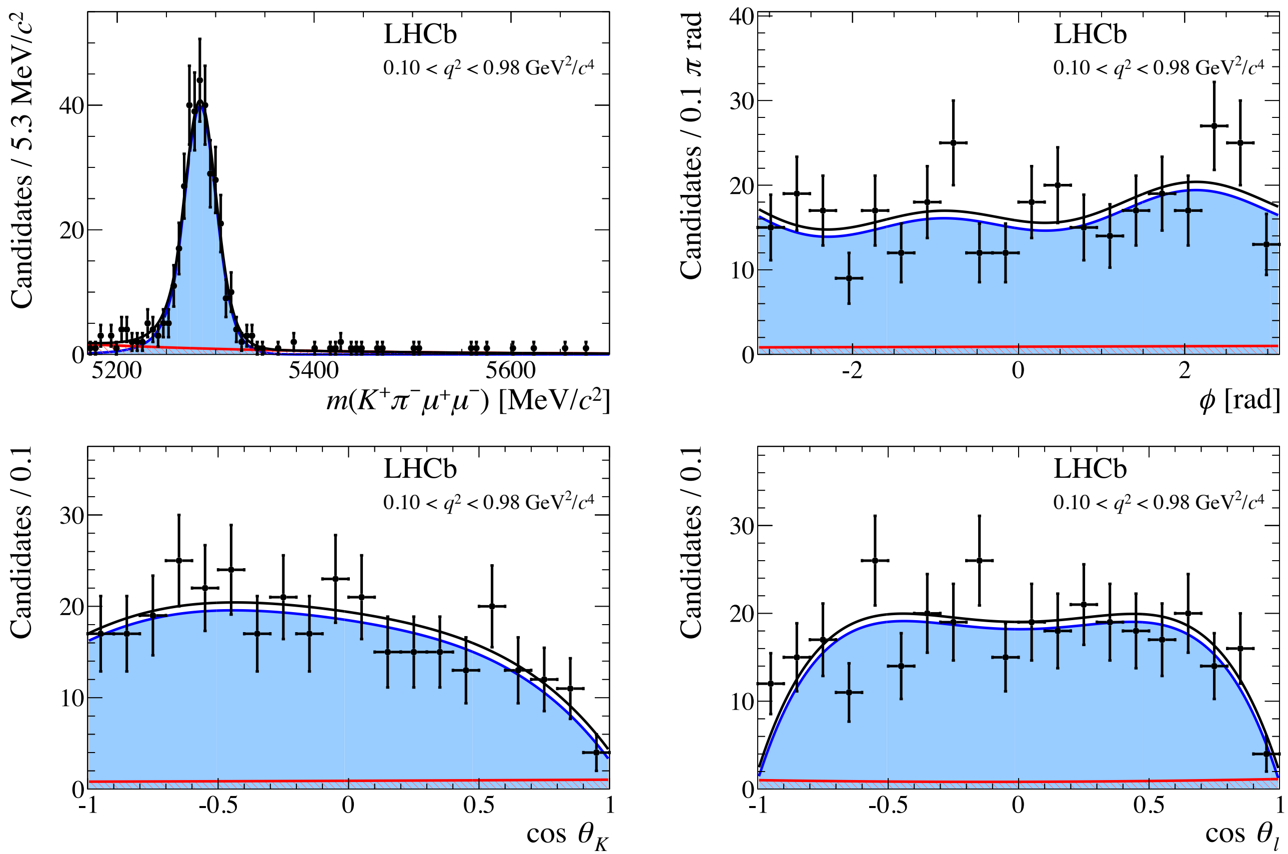
Observables depend on B→K* form factors and on short distance physics

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

- LHCb published the first full angular analysis of the decay
  - Unbinned maximum likelihood fit to $K\pi\mu\mu$ mass and three decay angles
  - Simultaneously fit $K\pi$ mass to constrain s-wave configuration
  - Efficiency modelled in four dimensions
  - Binned in $q^2 = m_{\mu\mu}^2$

JHEP02(2016)104

Example fit projections in low $q^2$ bin



- Full angular fit allows to extract:
  - CP-averaged terms and their correlations
  - CP asymmetries

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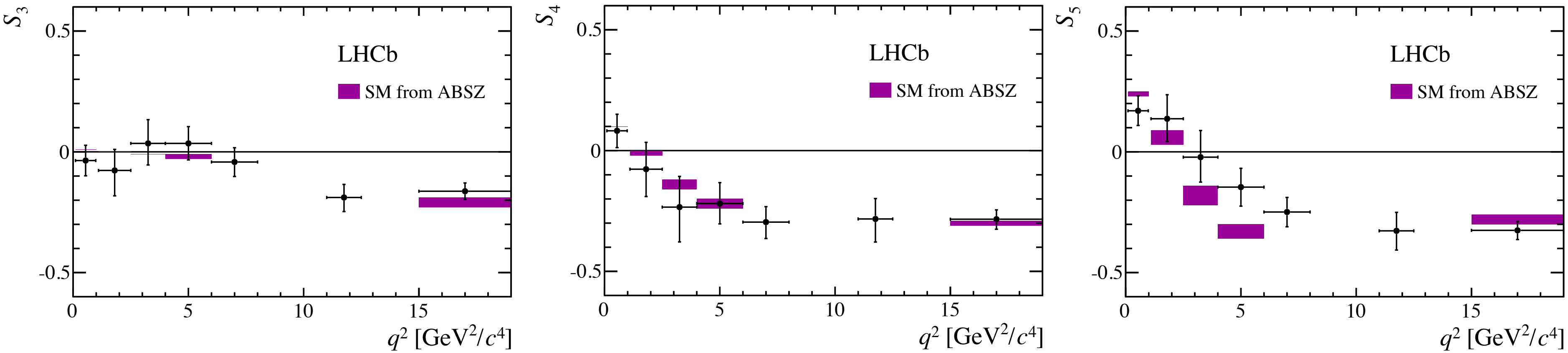
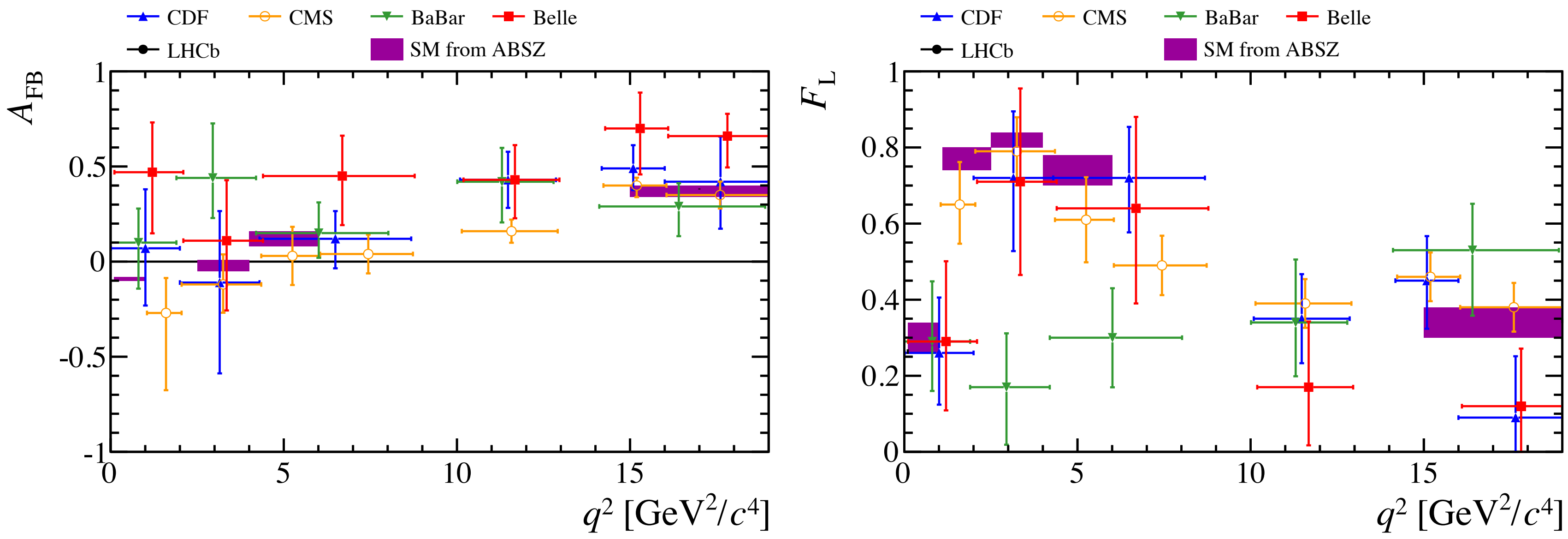



- Standard Model predictions based on

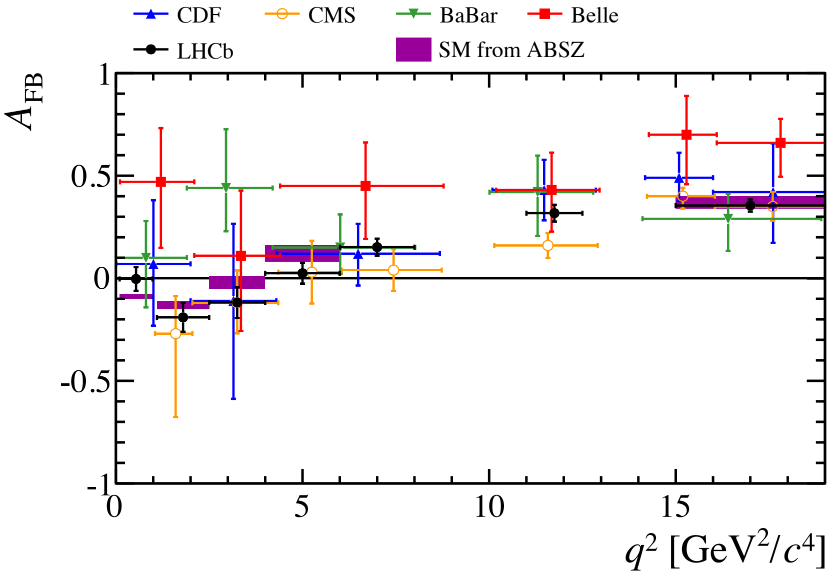
**[Altmannshofer & Straub, arXiv:1411.3161]**
**[LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]**
**[Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]**

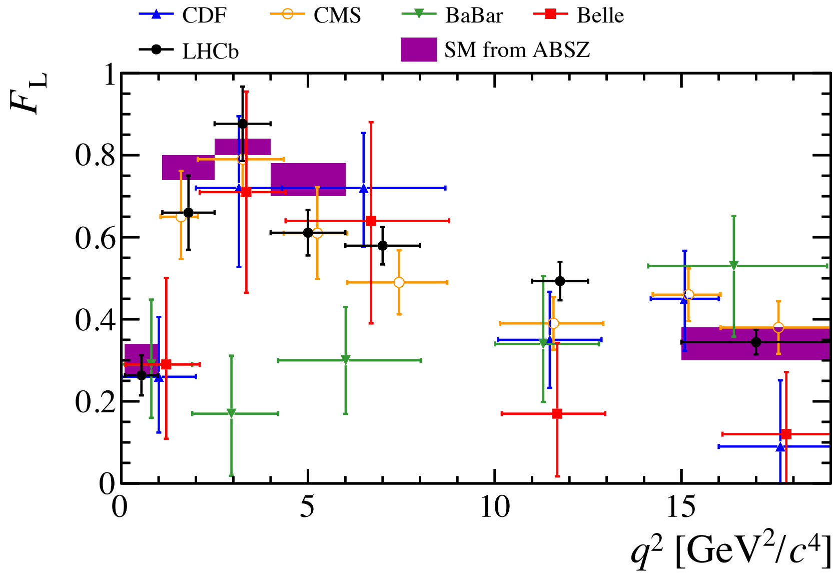
# Results




References:
LHCb [JHEP 02 (2016) 104] ,
CMS [PLB 753 (2016) 424]
BaBar [arXiv:1508.07960]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801].

# Results

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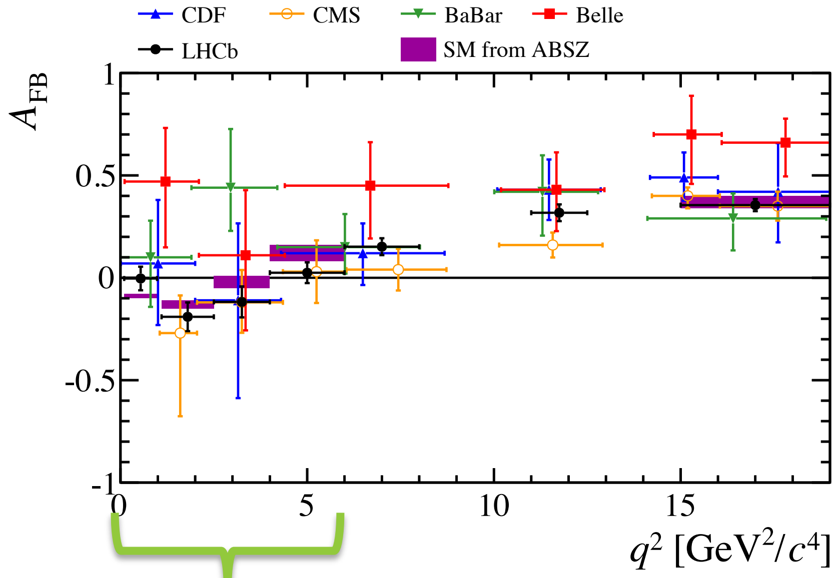
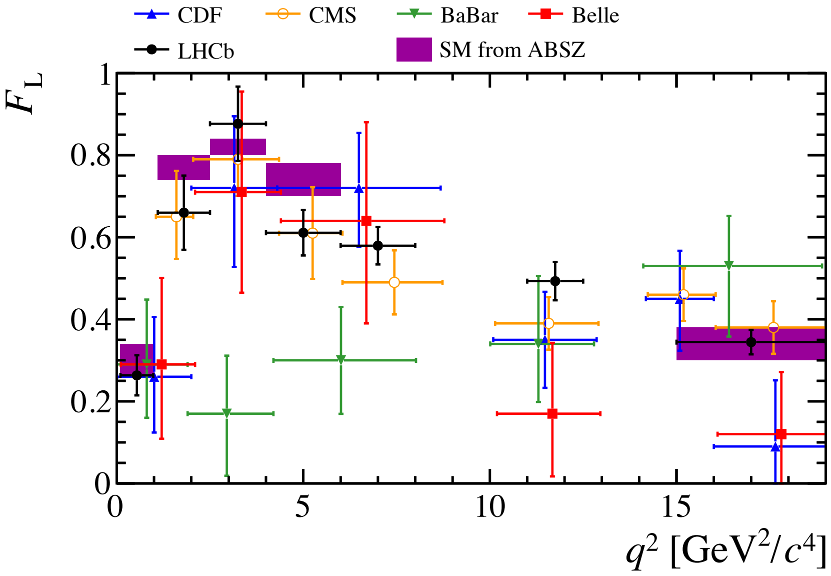
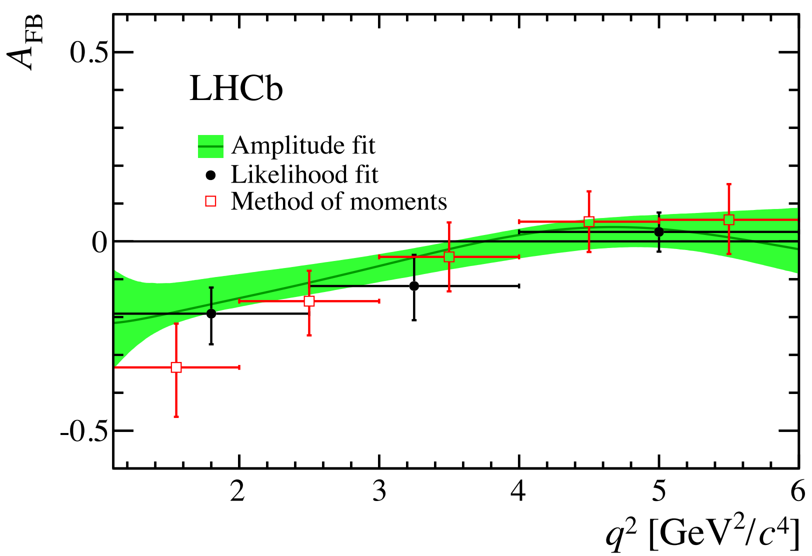



JHEP02(2016)104

- Determine zero crossing points by parameterizing the angular distribution with $q^2$ dependent decay amplitudes

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

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

$$q_0^2(S_4) < 2.65\,\mathrm{GeV}^2/c^4 \text{ at } 95\%\text{ C.L.}$$

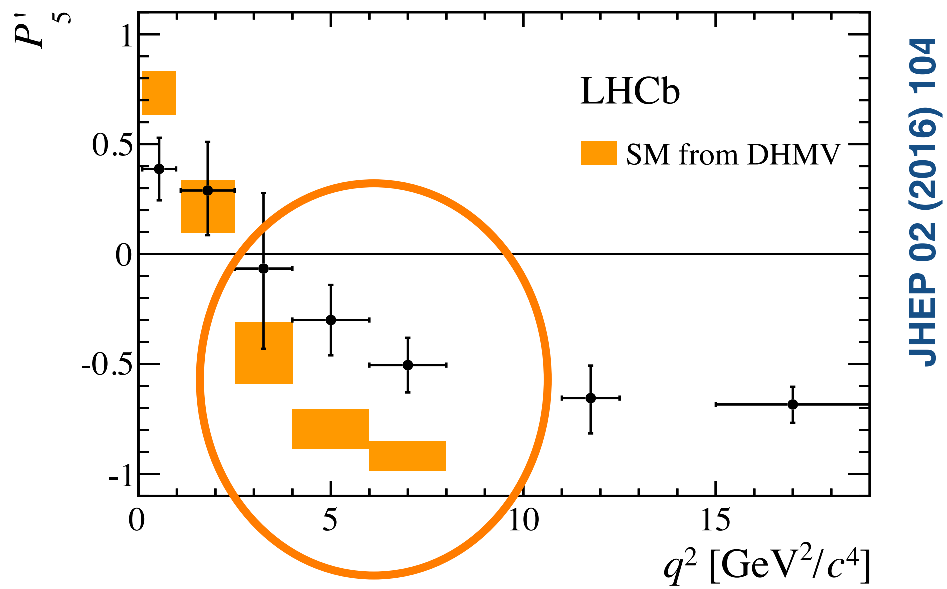
SM: $q_0{}^2(A_{FB}) \sim 3.9-4.4$ GeV$^2$/$c^4$

Bobeth, Hiller, v.Dyk, Wacker JHEP 01 (2012) 107
Beneke, Feldmann, Seidel: EPJ C41 (2005) 173
Ali, Kramer, Zhu EPJ C47 (2006) 625

# Form-factor "free" observables

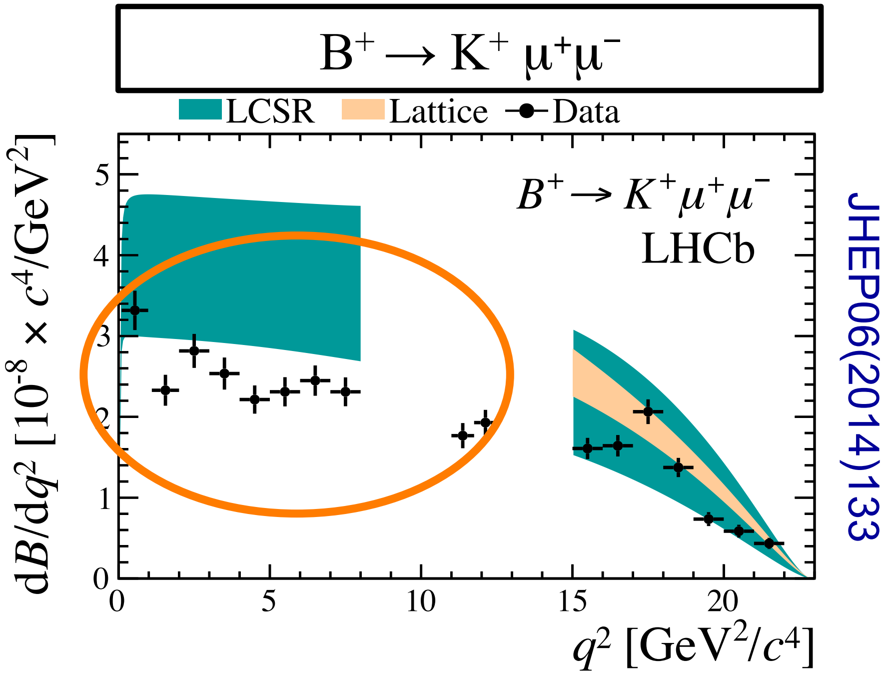
- In QCD factorization/SCET there are only two form factors
  - One associated with $A_0$ and the other with $A_{||}$ and $A_{perp}$
- Create ratios of observables with minimal dependence on form-factors, eg

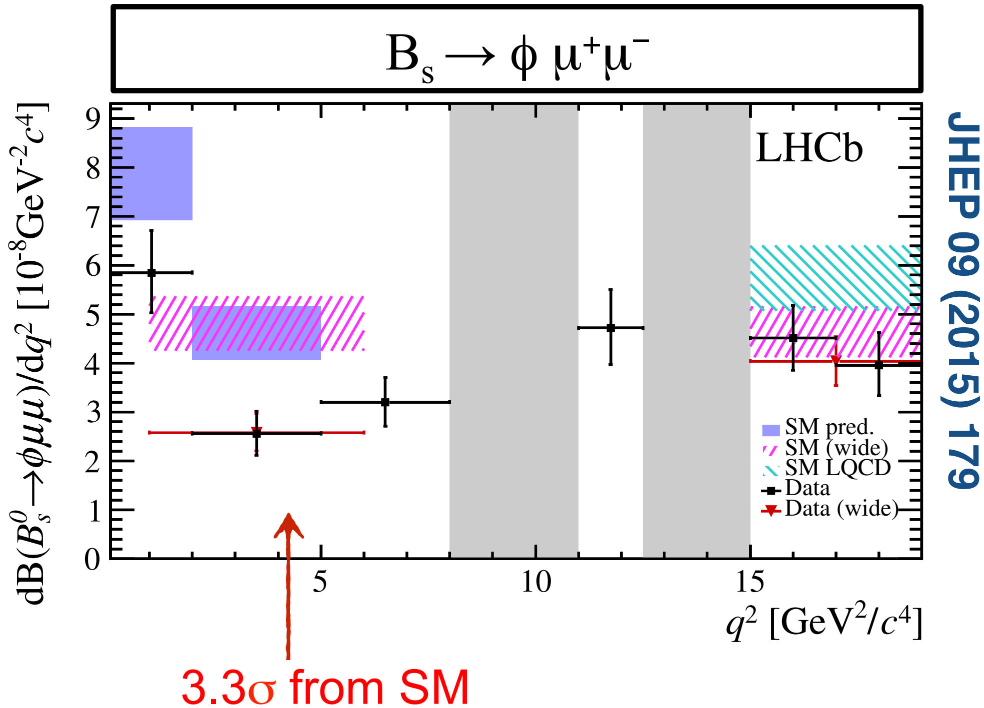
$$P'_5 = S_5/\sqrt{F_L(1-F_L)}$$




- 2013: deviation in $P_5$' seen with 1fb$^{-1}$ of data
- Full Run 1 analysis confirms effect
- If the observed anomalies are real, expect discrepancies in **other $b \rightarrow s$ decays** ..

# Branching fractions of $b \to s\,\mu^+\mu^-$



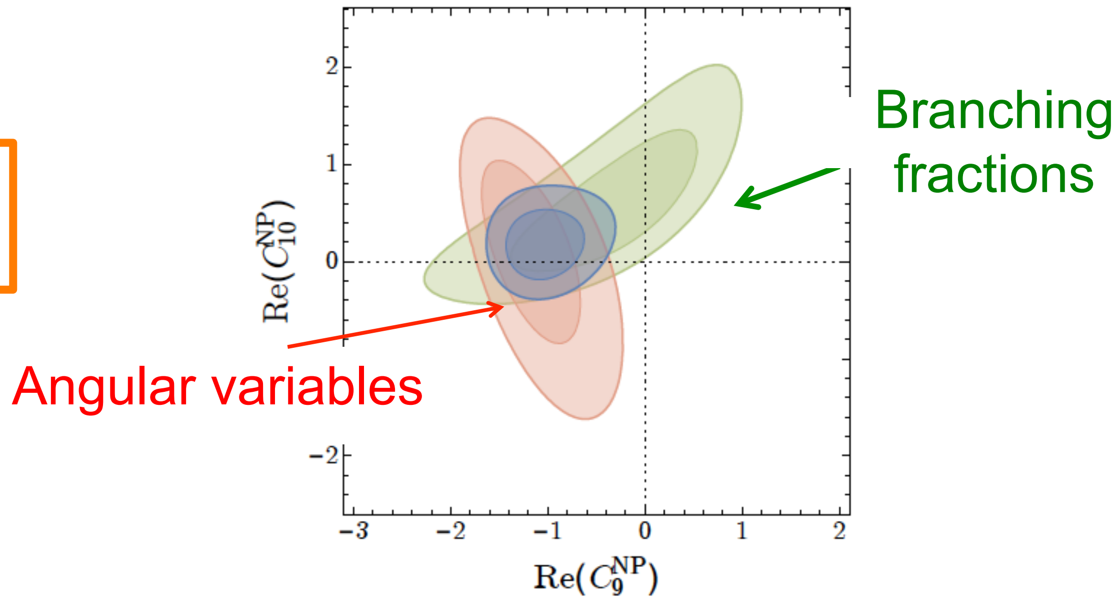

- Analysis of large class of $b \to s\,\mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - → Perform global analysis

SM predictions based on
**[Altmannshofer & Straub, arXiv:1411.3161]**
**[LCSR form-factors from Bharucha et al. arXiv:1503.05534]**
**[Lattice prediction from Horgan et al. arXiv:1310.3722]**

Effective Hamiltonian:

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

Altmannshofer & Straub, 1503.06199



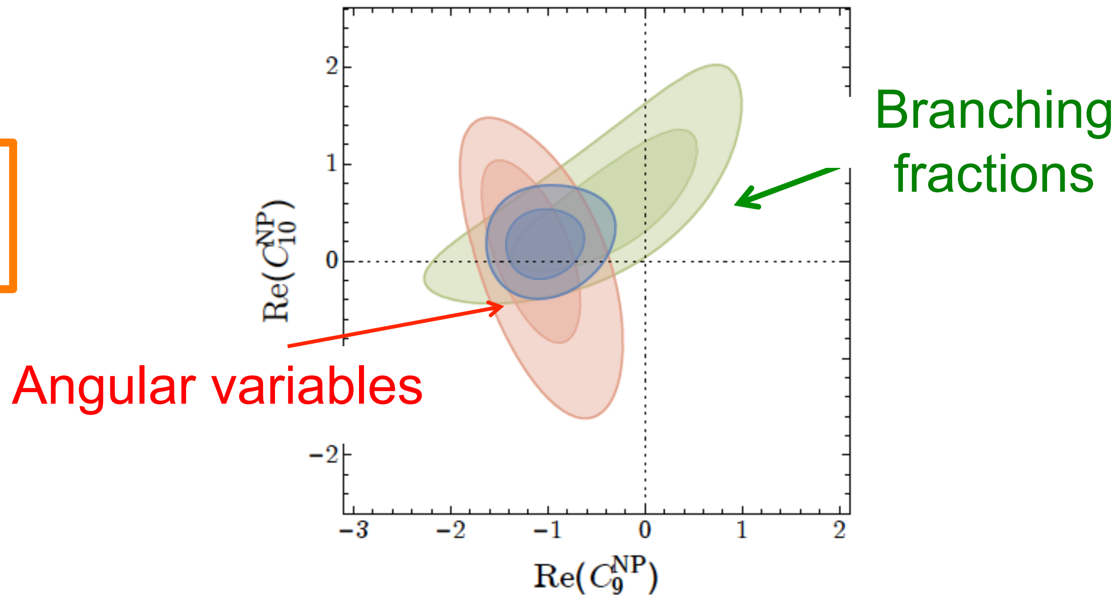

- Global fit to all $b \to s$ data prefers a deviation from the Standard Model in a vector-like interaction

# Combine all $b \to s$ data in global fit

Altmannshofer & Straub, 1503.06199

Effective Hamiltonian:

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



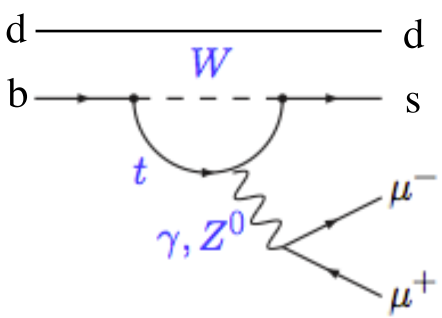

- Global fit to all $b \to s$ data prefers a deviation from the Standard Model in a vector-like interaction
- Interpretation:
  - “clearly New Physics”, or ..
  - Not well understood QCD contribution

→ Understanding needs more data and theoretical work

# Lepton universality

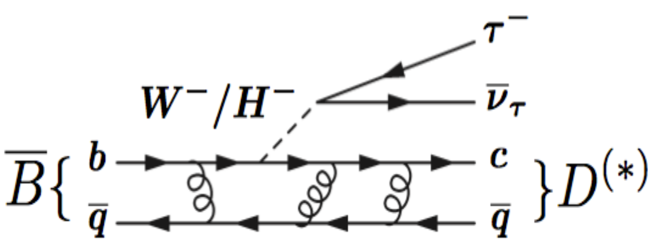
- In the SM, leptons couple universal to $W^{\pm}$ and $Z^0$
  → test this in ratios of semileptonic decays

electrons / muons




$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

tau / muons




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

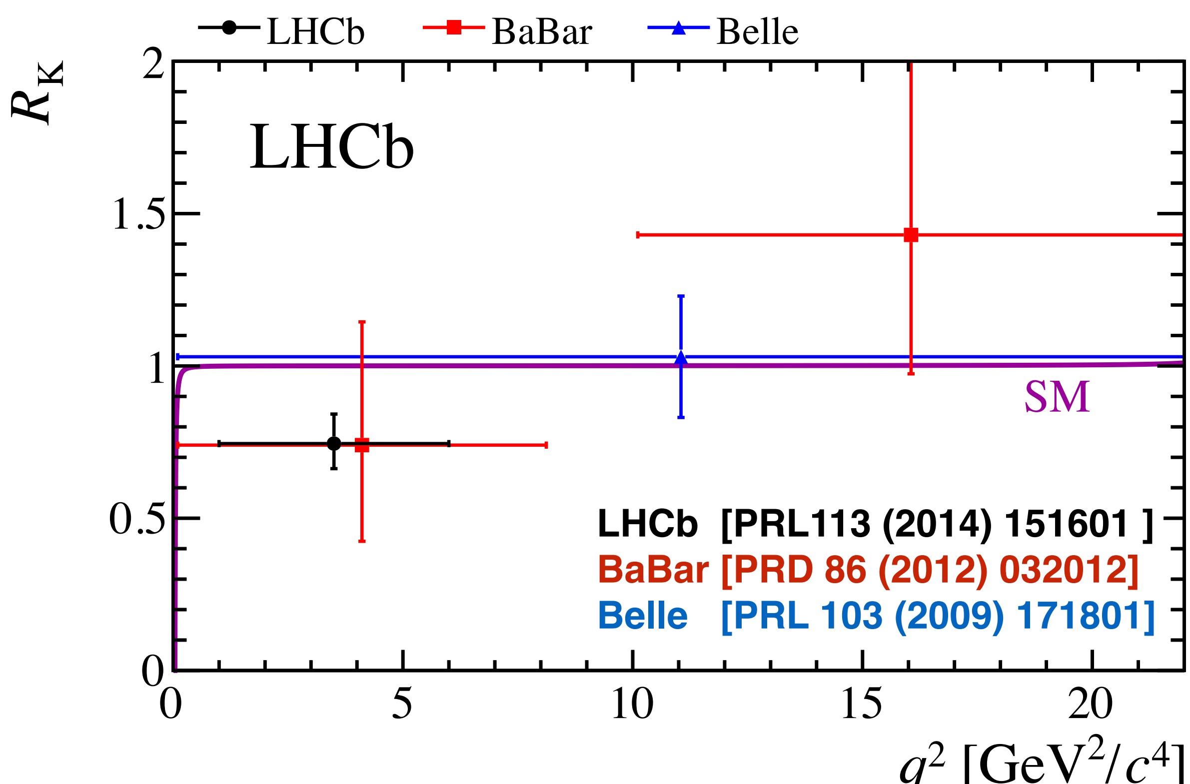
- Ratios differ from unity only by phase space
  → hadronic uncertainties cancel in the ratio

# LFU: electron vs. muon ($R_k$)

LHCb measures with $3fb^{-1}$

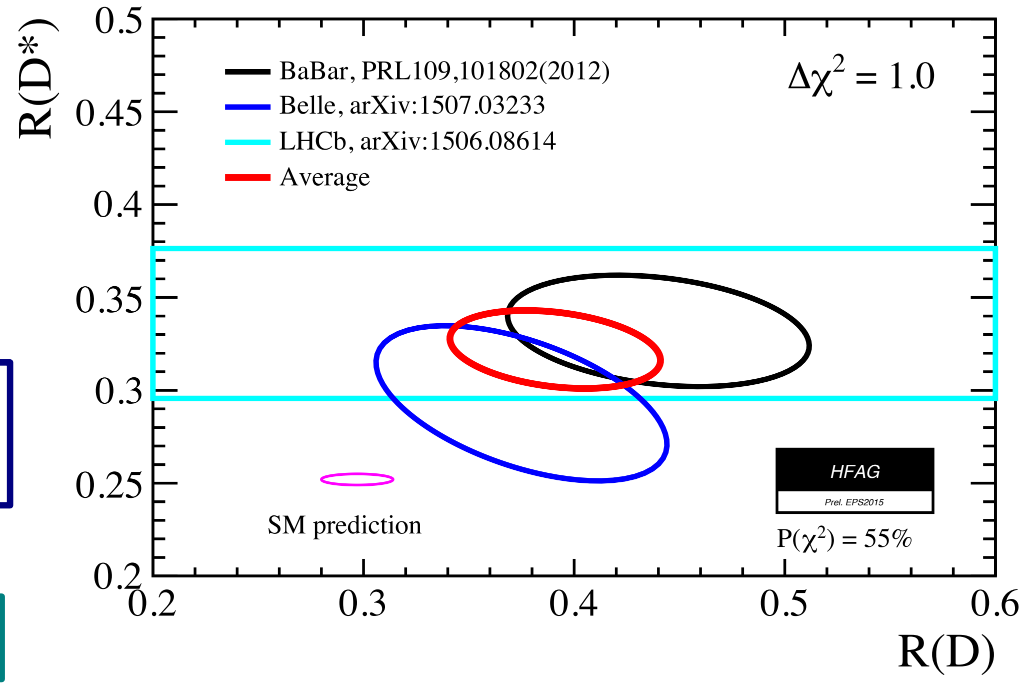
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745 \begin{array}{l} +0.090 \\ -0.074 \end{array} (stat) \pm 0.036 (syst)$$

(SM: $R_k$=1.00, consistent at 2.6σ)



# R(D) and R(D*)

$$R_{D*} = \frac{BR(B^0 \to D*^+ \tau^- \bar{\nu})}{BR(B^0 \to D*^+ \mu^- \bar{\nu})}$$




Belle

$\mathbf{R(D) = 0.375 \pm 0.064 \pm 0.026}$
$\mathbf{R(D^*) = 0.293 \pm 0.038 \pm 0.015}$

LHCb

$\mathbf{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$

PRL 115(2015)111803

- Combination is **3.9**$\sigma$ from the SM expectation:

$$R(D^*) = 0.252 \pm 0.003$$

**[Kamenik et al. Phys. Rev. D78 014003 (2008), S. Jajfer et al. Phys. Rev. D85 094025 (2012)]**

# Summary

- The Standard Model is tested in a variety of channels
  - → many measurements consistent with predictions
  - → **significant deviations in of $b \rightarrow s\, \ell^+\ell^-$ channels**
  - → **need for data to conclude**

- Interesting flavour data coming soon
  - LHCb Run 2 → tripling the dataset
  - LHCb Upgrade – record data with „Trigger-less Readout“

# Backup

LHCb

The LHCb Public results

## LHCb publications

[to restricted-access page]

PUBLICATIONS PER WORKING GROUP

FLAVOUR TAGGING

$b$-HADRONS AND QUARKONIA

$B$ DECAYS TO CHARMONIUM

DETECTOR PERFO

CHARMLESS $b$-HADRON DECAYS

QCD, ELECTROWEAK AND EXOTICA

RARE DECAYS

CHARM PHYSICS

SEMILEPTONIC $B$ DECAYS

LUMINOSITY

$B$ DECAYS TO OPEN

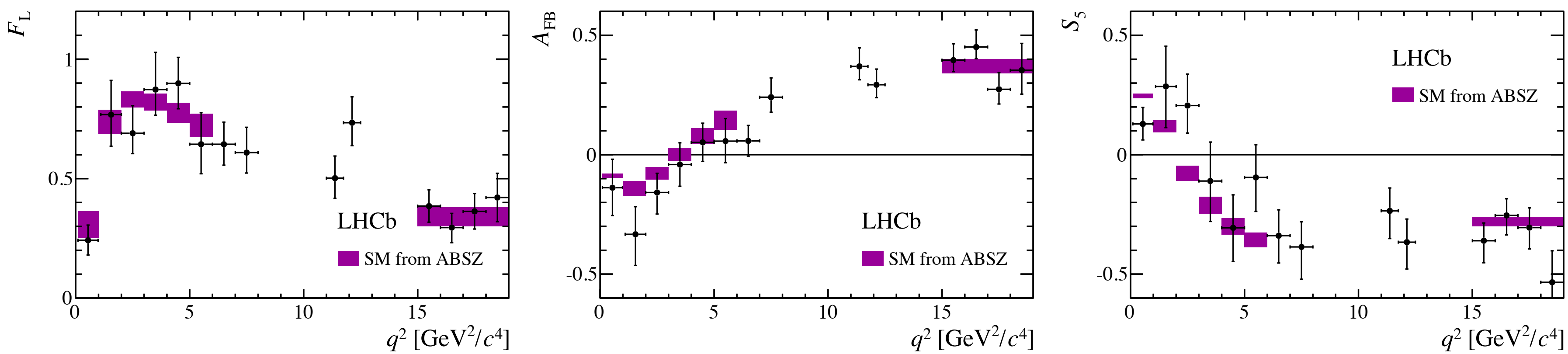
List of papers (Total of 303 papers)

| TITLE | DOCUMENT NUMBER | JOURNAL |
|---|---|---|
| Measurement of the $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ branching fractions | PAPER-2015-053 | PRD |
| A new algorithm for identifying the flavour of $B_s^0$ mesons at LHCb | PAPER-2015-056 | JINST |
| First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays and measurement of the associated coherence parameters | PAPER-2015-057 | PRL |
| Constraints on the unitarity triangle angle $\gamma$ from Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays | PAPER-2015-059 | PRL |
| Measurement of the difference of time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays | PAPER-2015-055 | PRL |
| Study of $\psi(2S)$ production and cold nuclear matter effects in $p$Pb collisions at $\sqrt{s_{NN}} = 5$ TeV | PAPER-2015-058 | JHEP |
| Observation of the $B_s^0 \to J/\psi\phi\phi$ decay | PAPER-2015-033 | JHEP |

# K*mm moment analysis

- Can also determine the angular observables using principal moments of the angular distribution:
  - ✓ Robust estimator even for small datasets (allows us to bin more finely in $q^2$).
  - x Statistically less precise than the result of the maximum likelihood fit.

**[LHCb, JHEP 02 (2016) 104]**




- SM predictions based on
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  **[LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]**
  **[Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]**

# LHCb Upgrade Projections

| | Observable | Current precision | LHCb ($5\ \text{fb}^{-1}$) | Upgrade ($50\ \text{fb}^{-1}$) | Theory uncertainty |
|---|---|---|---|---|---|
| Gluonic penguin | $S(B_s \to \phi\phi)$ | - | 0.08 | 0.02 | 0.02 |
| | $S(B_s \to K^{*0}\bar{K}^{*0})$ | - | 0.07 | 0.02 | $< 0.02$ |
| | $S(B^0 \to \phi K^0_S)$ | 0.17 | 0.15 | 0.03 | 0.02 |
| $B_s$ mixing | $2\beta_s\ (B_s \to J/\psi\phi)$ | 0.35 | 0.019 | 0.006 | $\sim 0.003$ |
| Right-handed currents | $S(B_s \to \phi\gamma)$ | - | 0.07 | 0.02 | $< 0.01$ |
| | $\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$ | - | 0.14 | 0.03 | 0.02 |
| E/W penguin | $A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$ | - | 0.14 | 0.04 | 0.05 |
| | $s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$ | - | 4% | 1% | 7% |
| Higgs penguin | $\mathcal{B}(B_s \to \mu^+\mu^-)$ | - | 30% | 8% | $< 10\%$ |
| | $\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s\to\mu^+\mu^-)}$ | - | - | $\sim 35\%$ | $\sim 5\%$ |
| Unitarity triangle angles | $\gamma\ (B \to D^{(*)}K^{(*)})$ | $\sim 20°$ | $\sim 4°$ | 0.9° | negligible |
| | $\gamma\ (B_s \to D_s K)$ | - | $\sim 7°$ | 1.5° | negligible |
| | $\beta\ (B^0 \to J/\psi\ K^0)$ | 1° | 0.5° | 0.2° | negligible |
| Charm CPV | $A_\Gamma$ | $2.5 \times 10^{-3}$ | $2 \times 10^{-4}$ | $4 \times 10^{-5}$ | - |
| | $A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$ | $4.3 \times 10^{-3}$ | $4 \times 10^{-4}$ | $8 \times 10^{-5}$ | - |

# Experimental overview of $b \to s\,(d)\,\ell^+\ell^-$

- FCNC decays $b \to s\,(d)\,\ell^+\ell^-$ : large variety of final states
  - Allows detailed test of the structure of the underlying interaction
  - Effects in one decay can be cross checked in others

| # of events | BaBar $433 fb^{-1}$ | Belle $605 fb^{-1}$ | CDF $9.6 fb^{-1}$ | LHCb 1 / 3 $fb^{-1}$ | ATLAS $5 fb^{-1}$ | CMS $5 fb^{-1}$ |
|---|---|---|---|---|---|---|
| $B^0 \to K^{*0}\,\ell^+\ell^-$ | 137±44* | 247±54* | 288±20 | 2361±56 | 466±34 | 415±29 |
| $B^+ \to K^{*+}\,\ell^+\ell^-$ | | | 24±6 | 162±16 | | |
| $B^+ \to K^+\,\ell^+\ell^-$ | 153±41* | 162±38* | 319±23 | 4746±81 | | |
| $B^0 \to K^0_s\,\ell^+\ell^-$ | | | 32±8 | 176±17 | | |
| $B_s \to \phi\,\ell^+\ell^-$ | | | 62±9 | 174±15 | | |
| $\Lambda_b \to \Lambda\,\ell^+\ell^-$ | | | 51±7 | 78±12 | | |
| $B^+ \to \pi^+\,\ell^+\ell^-$ | | limit | | 25±7 | | |

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]

LHCb
arxiv:1403.8044
+1305.2168
+1306.2577
+JHEP12(2012)125

*mixture of $B^0$ and $B^\pm$ and $\ell = e,\mu$
other experiments: $\ell = \mu$ only

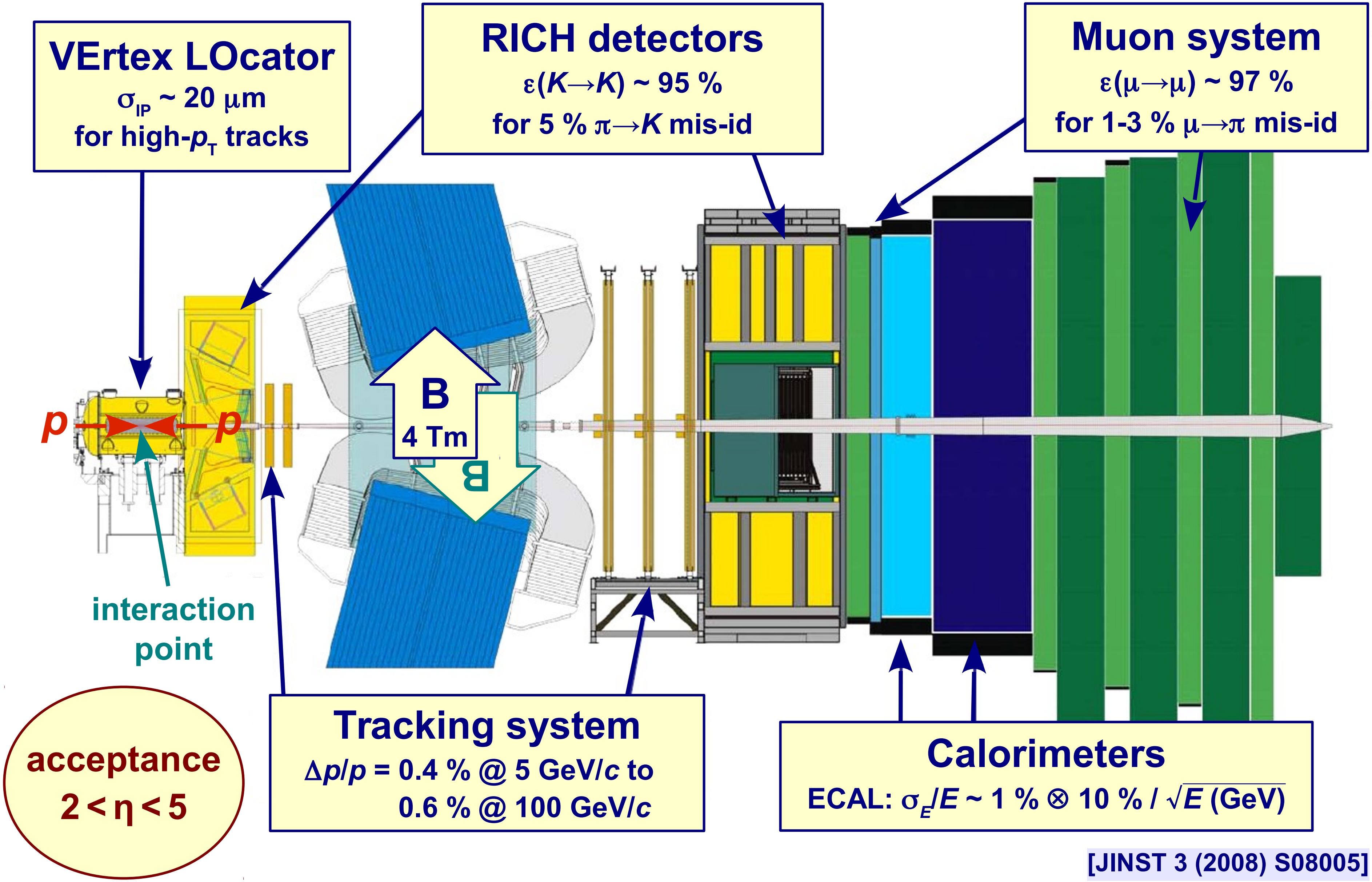
- $B_s$ System
  CPV in J/$\psi\phi$, $\phi\phi$,
  CPV in Mixing
- $B \rightarrow \mu\mu$
- CKM phase $\gamma$ in $B\rightarrow DK$
- CPV in $B_d$
- $B\rightarrow X_s$ ll (exclusive)
- $B\rightarrow X\gamma$ (exclusive)
- Charm physics
- Semi-leptonic B decays
- $\tau$ - physics: LFV
- $B\rightarrow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

"$B_s$ & charged tracks"

Important cross checks

"inclusive & neutrals "

# The LHCb experiment




[JINST 3 (2008) S08005]