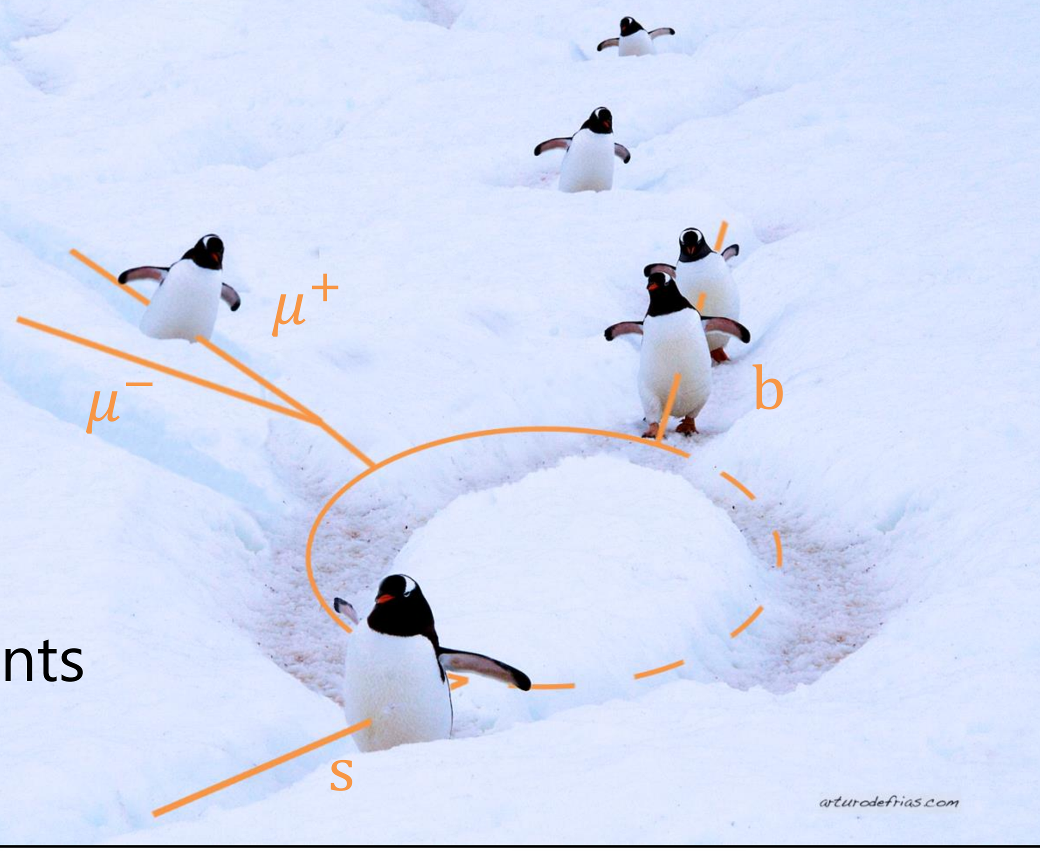
Electroweak penguin B decays

Thomas Nikodem

on behalf of the
LHCb collaboration

including results
from other experiments



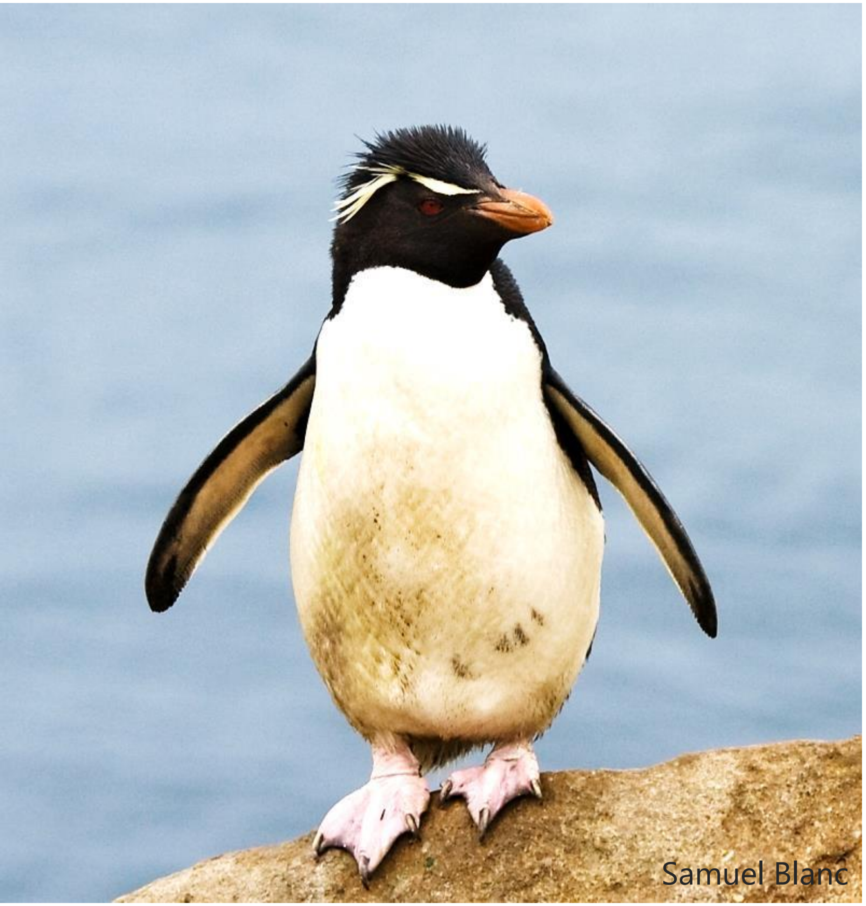
LHCb

erc
European Research Council
Established by the European Commission

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

PHYSIKALISCHES INSTITUT

Outline



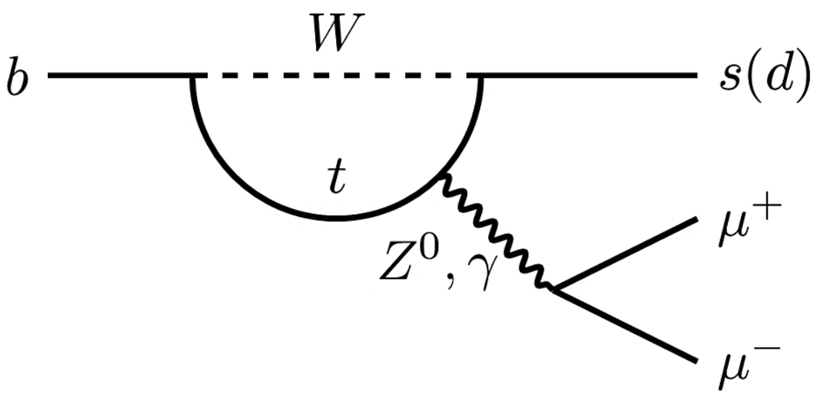
1) Theory

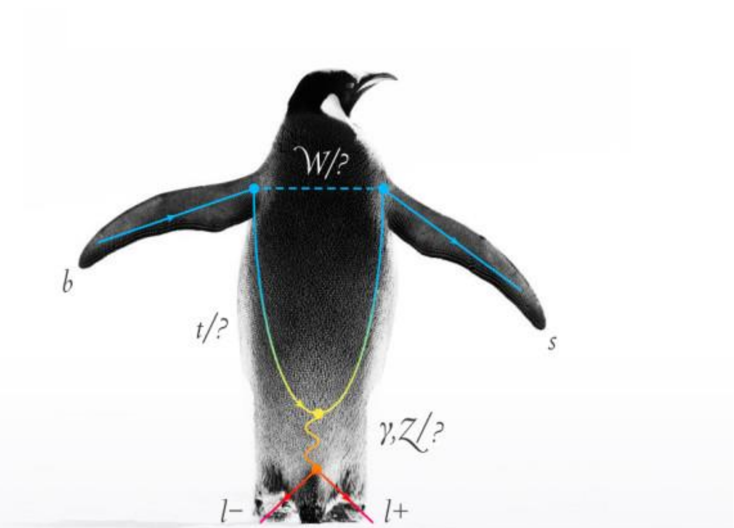
2) Measurements

3) Interpretation

What is a penguin?

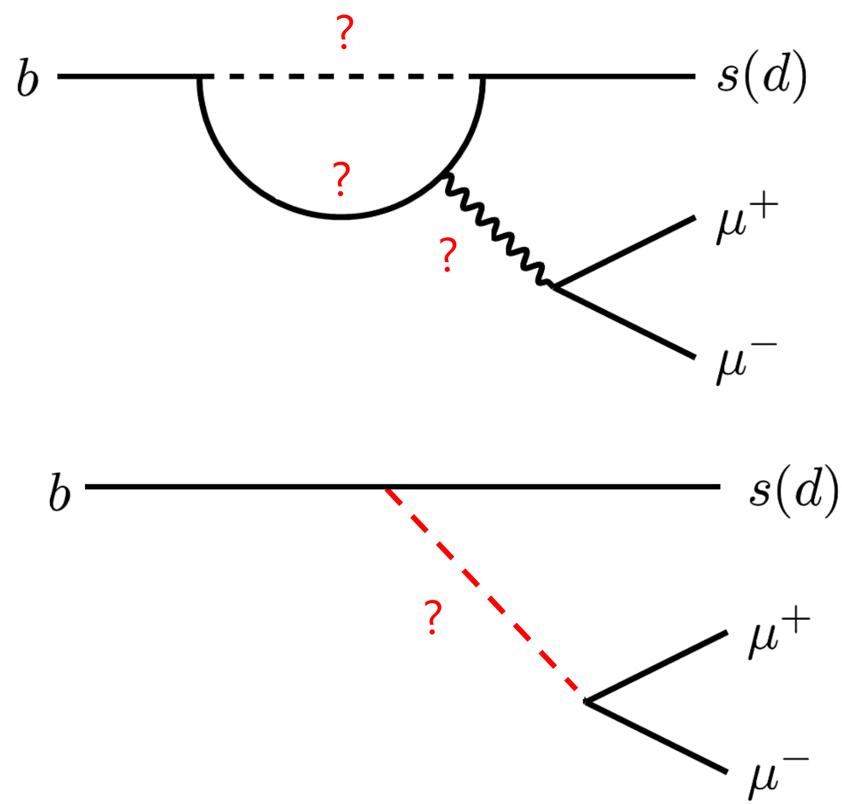
Standard Model Penguin





quantamagazine.org

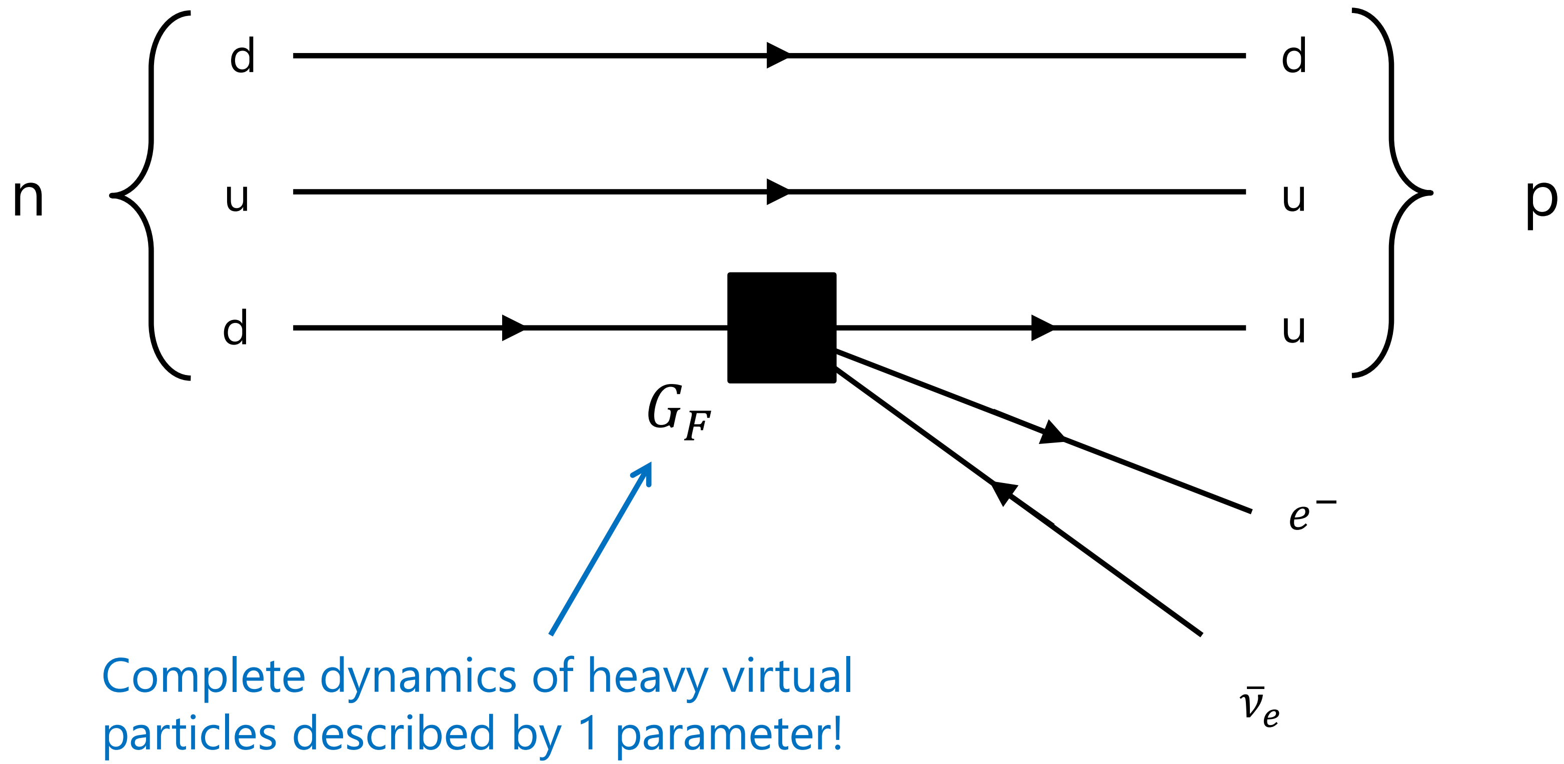
New Physics



→ Indirect search for new heavy particles

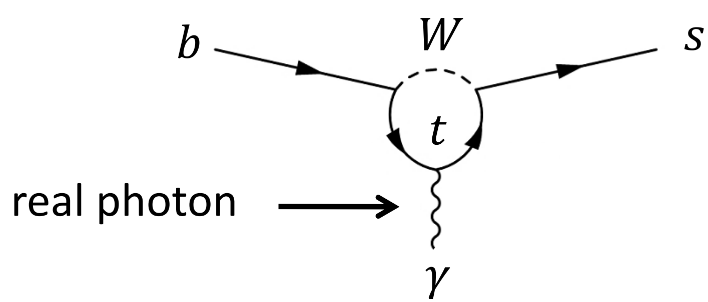
Fermi's theory of Beta Decay

- Beta decay described by 4-point interaction with coupling strength G_F :

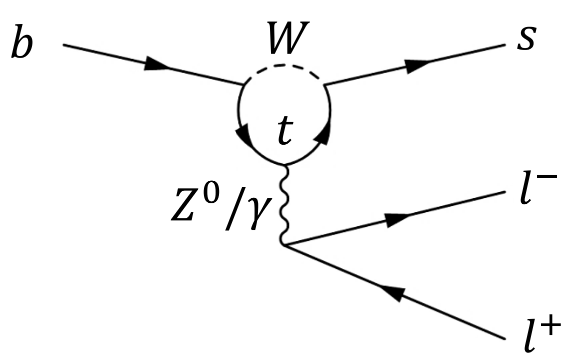


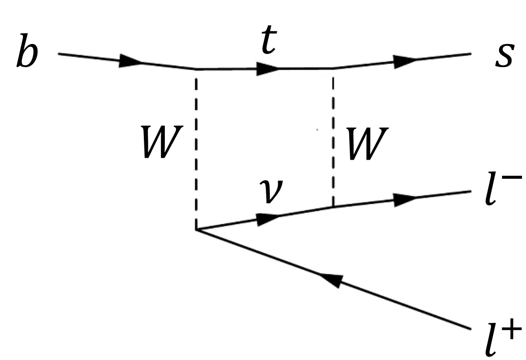
Effective operators

- Effective operators correspond to different physical processes, i.e.:
  - Photon penguin O_7:



  - Electroweak penguin O_9, O_{10}:





Effective description

- Effective Hamiltonian for b-s transition (leading contribution):

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

Coupling Strength C_i = Wilson coefficient
→ Sensitive to New Physics

i = 1, 2	Tree
i = 3-6, 8	Gluon penguin
i = 7	Photon penguin
i = 9, 10	Electroweak penguin
i = S, P	Scalar/Pseudoscalar penguin

- Decays sensitive to different Wilson coefficients:

$B \to X_s \gamma$	C_7
$B \to (X_s, K^*) l^+ l^-$	C_7, C_9, C_{10}
$B \to \mu^+ \mu^-$	C_{10}, C_S, C_P

Observables

- Most basic and possible with least statistics: **Branching Ratio**

☹ But: Large theoretical uncertainties due to hadronical part
(form factors)

☺ In **ratio** measurements many uncertainties (theoretical and experimental) cancel:

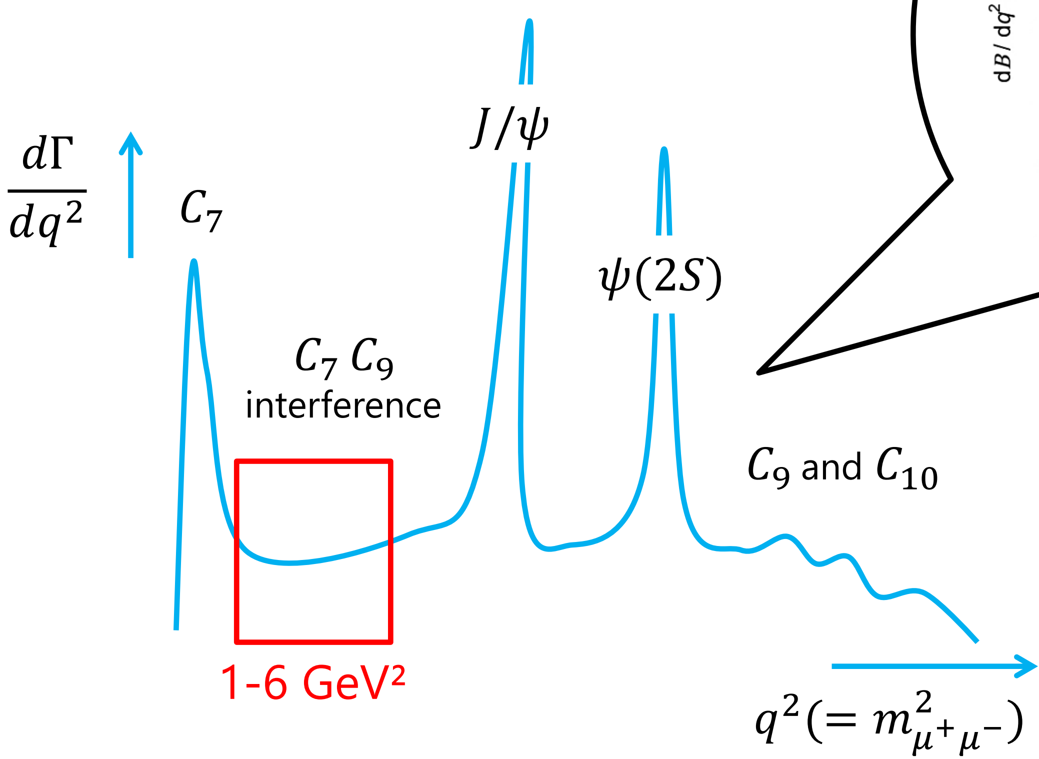
→ Ratio of different decays

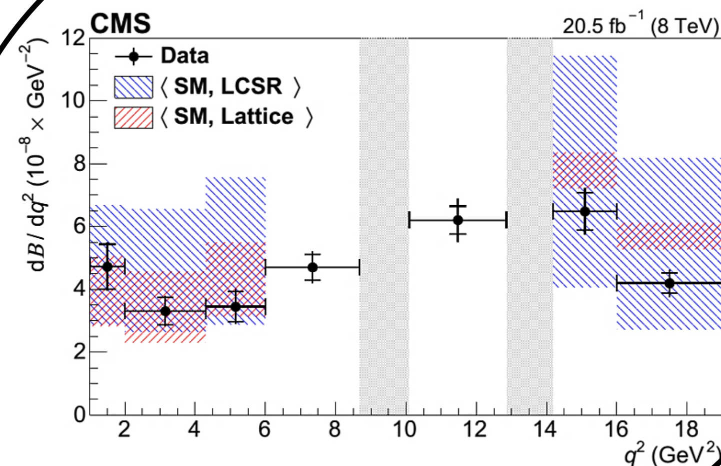
→ Ratio of different phase space regions
→ **angular** measurements (forward-backward asymmetry)

q² dependence

Results look like:

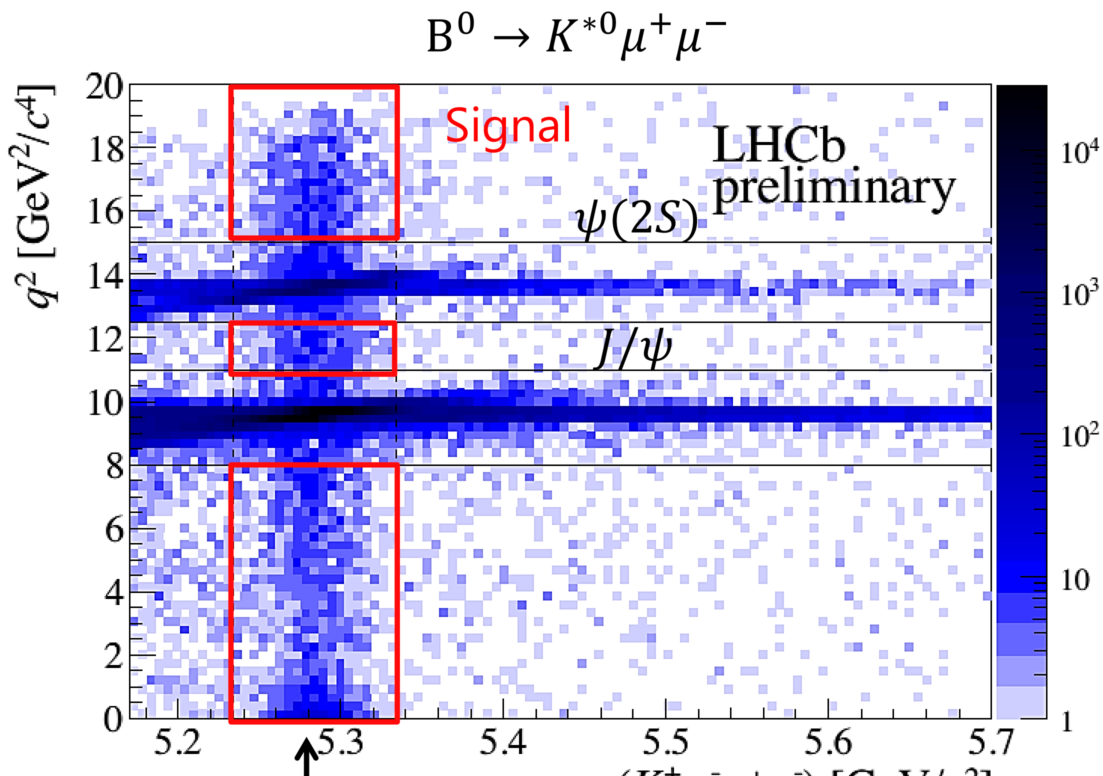
$B^0 \to K^{*0}\mu^+\mu^-$

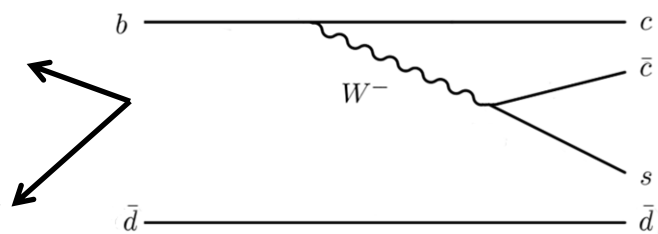




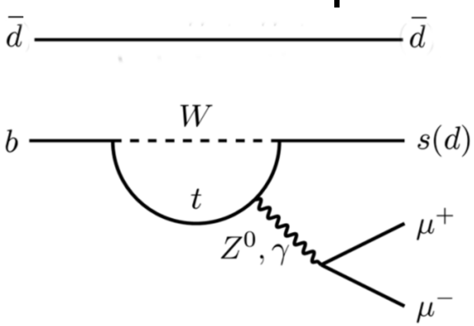
arXiv:1507.08126

Charmonium Resonances





Tree level decay:
~100 times more events than signal decay



Rare decay:
≈ 3000 signal candidates

Recent measurements

Branching Ratio

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$ (LHCb, Mar 14)

$B^0 \to K^{*0}\mu^+\mu^-$ (CMS, Jul 15)

$B_s^0 \to \phi\,\mu^+\mu^-$ (LHCb, Jun 15)

$B^+ \to \pi^+\mu^+\mu^-$ (LHCb, Sep 15)

$\Lambda_b^0 \to \Lambda\,\mu^+\mu^-$ (LHCb, Mar 15)

$B_{(s)}^0 \to \mu^+\mu^-$ (CMS+LHCb, Jun 15)

CP asymmetry

$B^+ \to \pi^+\mu^+\mu^-$ (LHCb, Sep 15)

Isospin asymmetry

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$ (LHCb, Mar 14)

Lepton universality

$B^+ \to K^+l^+l^-$ (LHCb, Jun 14)

$b \to (s/d)(\mu^+\mu^-/e^+e^-)$

Angular

$B^0 \to K^{*0}l^+l^-$ (LHCb, Jan 15
LHCb, Mar 15
CMS, Jul 15
BaBar, Aug 15)

$B^+ \to K^{*+}l^+l^-$ (BaBar, Aug 15)

$B_s^0 \to \phi\,\mu^+\mu^-$ (LHCb, Jun 15)

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ (LHCb, Mar 15)

Recent measurements

Branching Ratio

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$ (LHCb, Mar 14)

$B^0 \to K^{*0}\mu^+\mu^-$ (CMS, Jul 15)

$B_s^0 \to \phi\,\mu^+\mu^-$ (LHCb, Jun 15)

$B^+ \to \pi^+\mu^+\mu^-$ (LHCb, Sep 15)

$\Lambda_b^0 \to \Lambda\,\mu^+\mu^-$ (LHCb, Mar 15)

$B_{(s)}^0 \to \mu^+\mu^-$ (CMS+LHCb, Jun 15)

CP asymmetry

$B^+ \to \pi^+\mu^+\mu^-$ (LHCb, Sep 15)

Isospin asymmetry

$B^{0,+} \to K^{0,+,*+}\mu^+\mu^-$ (LHCb, Mar 14)

Lepton universality

$B^+ \to K^+ l^+ l^-$ (LHCb, Jun 14)

>2σ deviation from SM prediction

Angular

$B^0 \to K^{*0} l^+ l^-$ (LHCb, Jan 15; LHCb, Mar 15; CMS, Jul 15; BaBar, Aug 15)

$B^+ \to K^{*+} l^+ l^-$ (BaBar, Aug 15)

$B_s^0 \to \phi\,\mu^+\mu^-$ (LHCb, Jun 15)

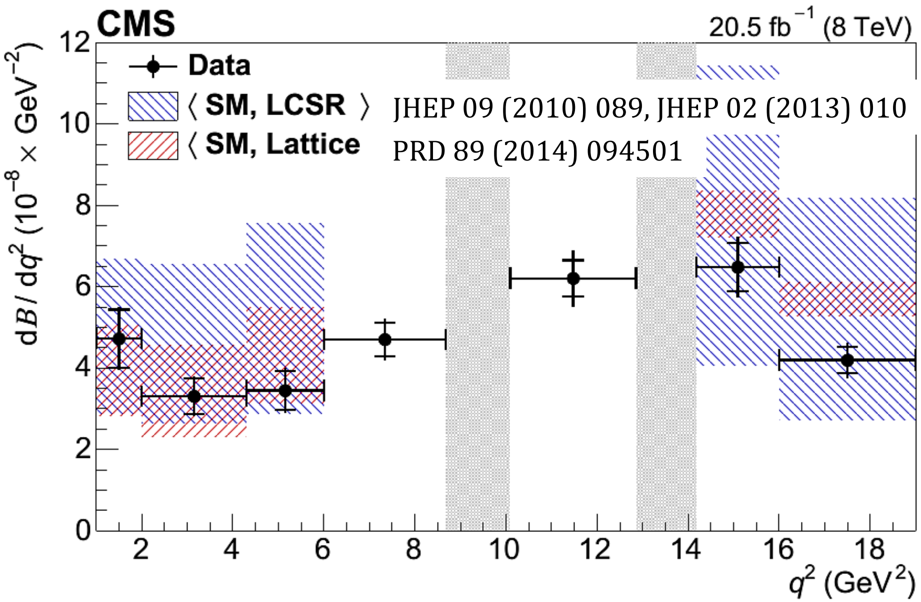
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ (LHCb, Mar 15)

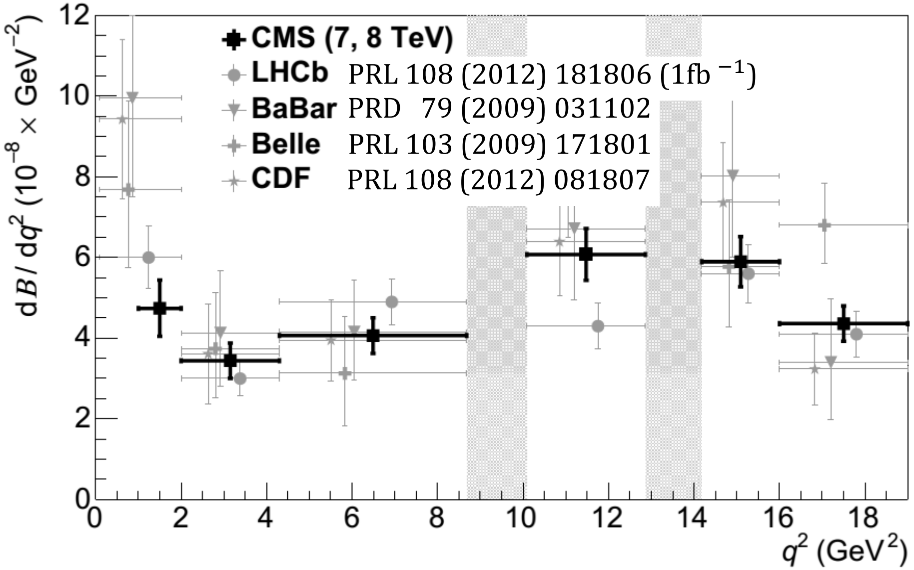
Branching Ratio

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

CMS, arXiv:1507.08126

transition: b-s
spectator: d





- Compatible to SM predictions
- Compatible to previous results
- 8TeV update from LHCb soon

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

LHCb, JHEP 06 (2014) 133

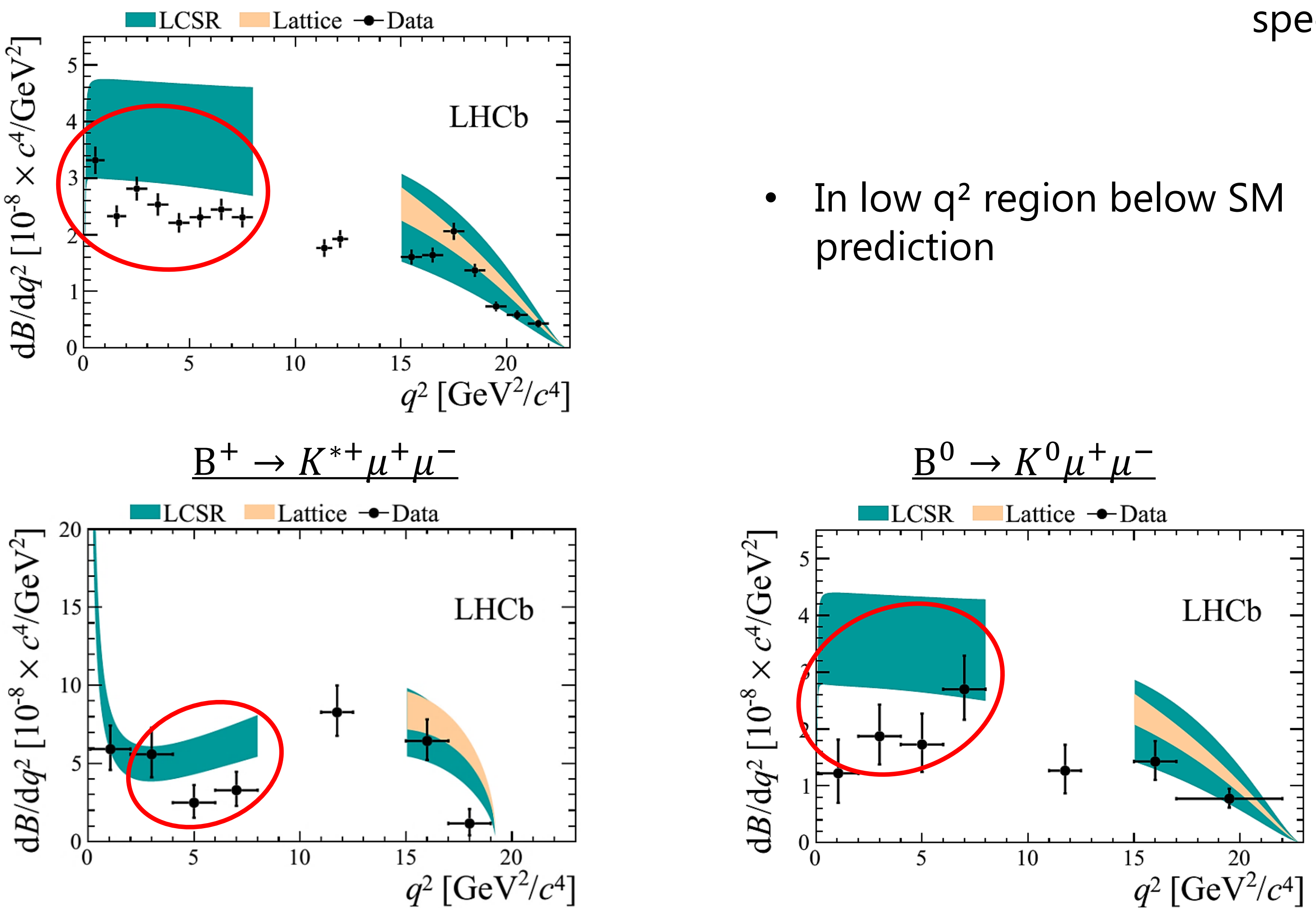
transition: b-s
spectator: u,d

- In low q² region below SM prediction

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

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

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

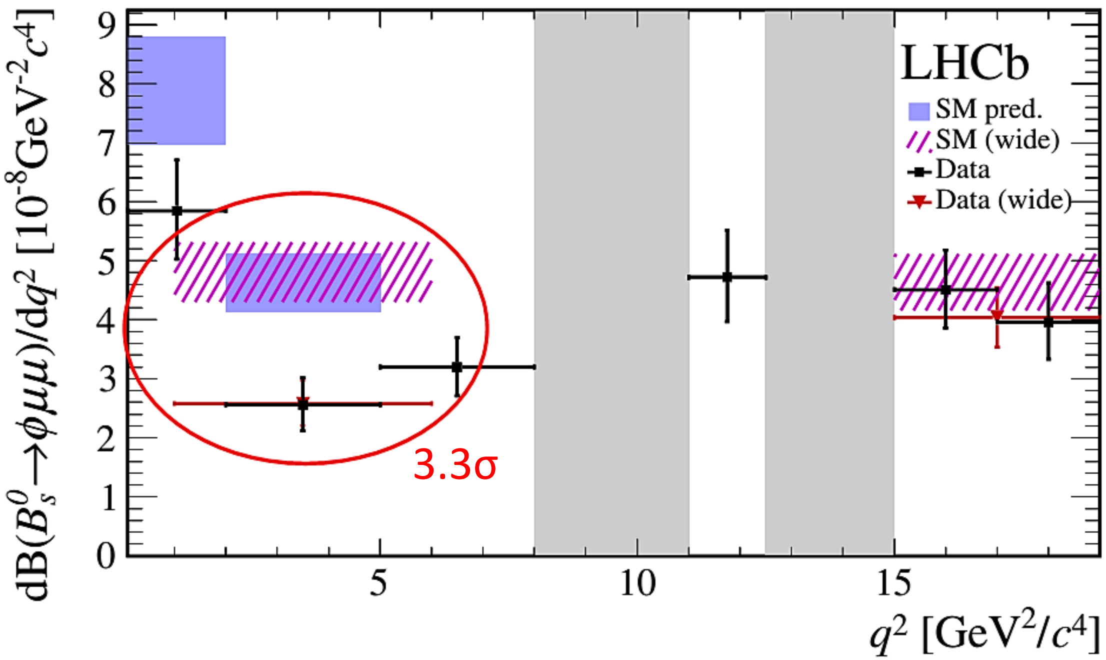


SM: JHEP 01 (2012) 107

BR of $B_s^0 \to \phi\mu^+\mu^-$

LHCb, arXiv:1506.08777

transition: b-s
spectator: s

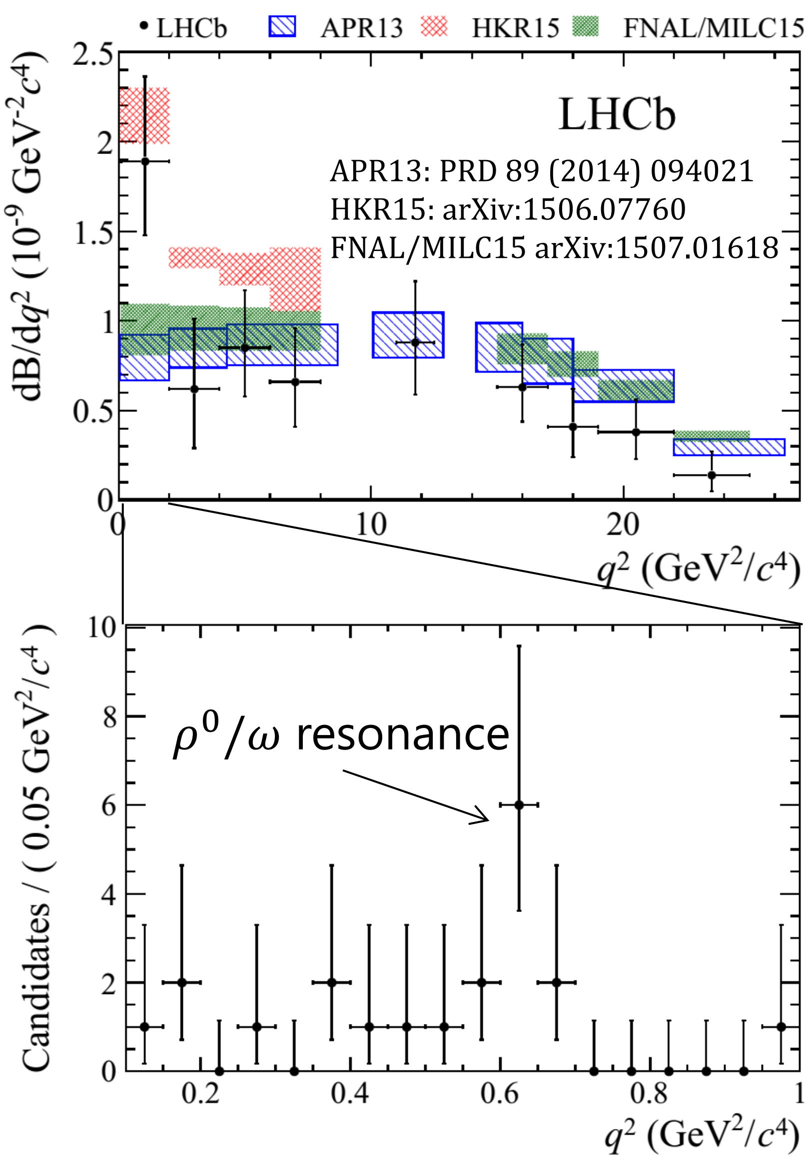


SM (wide): Altmannshofer, Straub, arXiv:1411.3161

- Narrow ϕ resonance:
  → clean signal
- In low q^2 region below SM

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

LHCb, arXiv:1509.00414

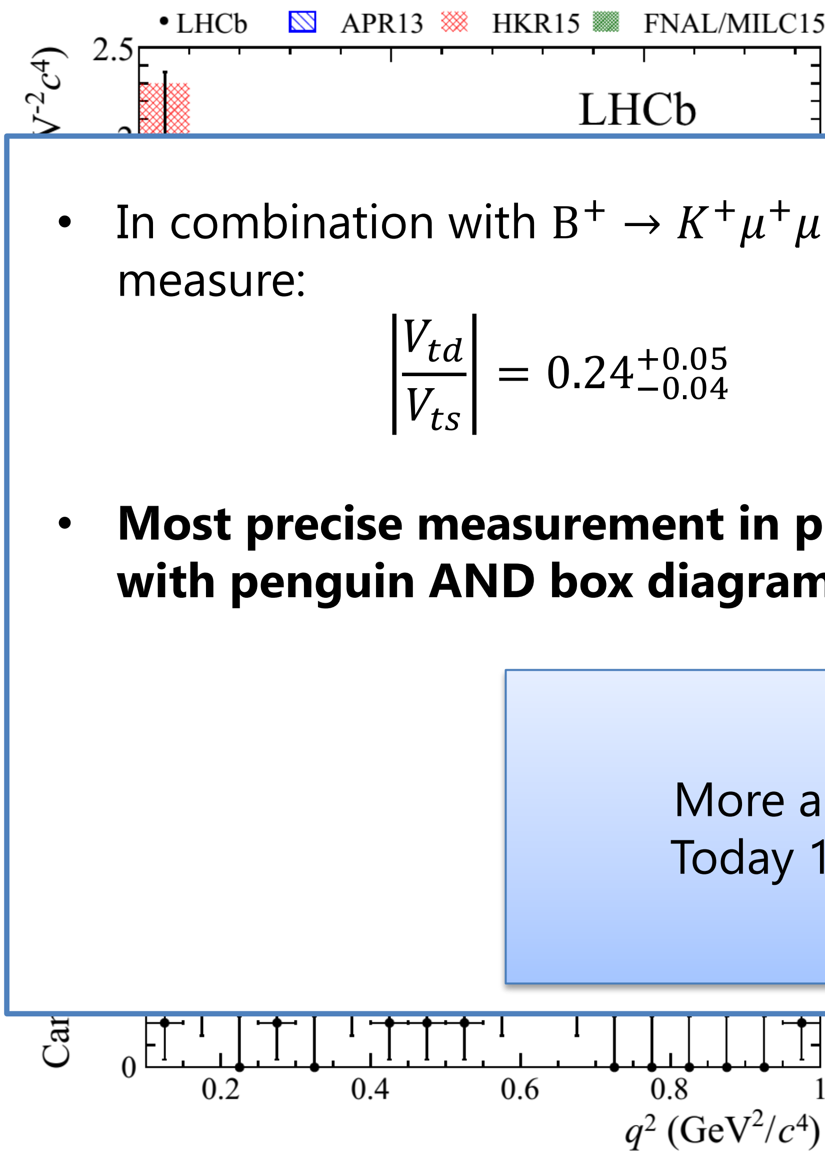


transition: b-d
spectator: u

- ρ^0/ω resonance clearly visible
- Only in HKR15 calculation low q² resonances taken into account
- Agreement with SM, however again everywhere slightly below

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

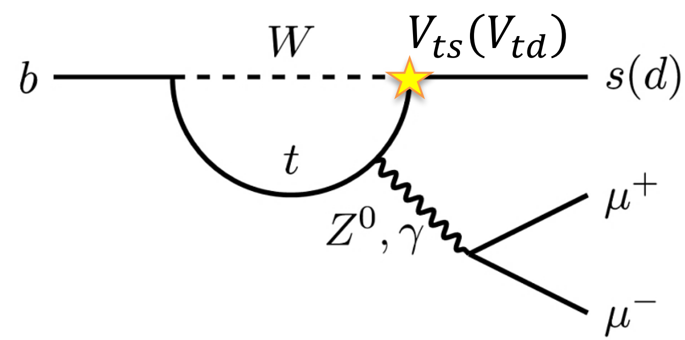
LHCb, arXiv:1509.00414



transition: b-d
spectator: u

- In combination with $B^+ \to K^+\mu^+\mu^-$ measure:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}$$



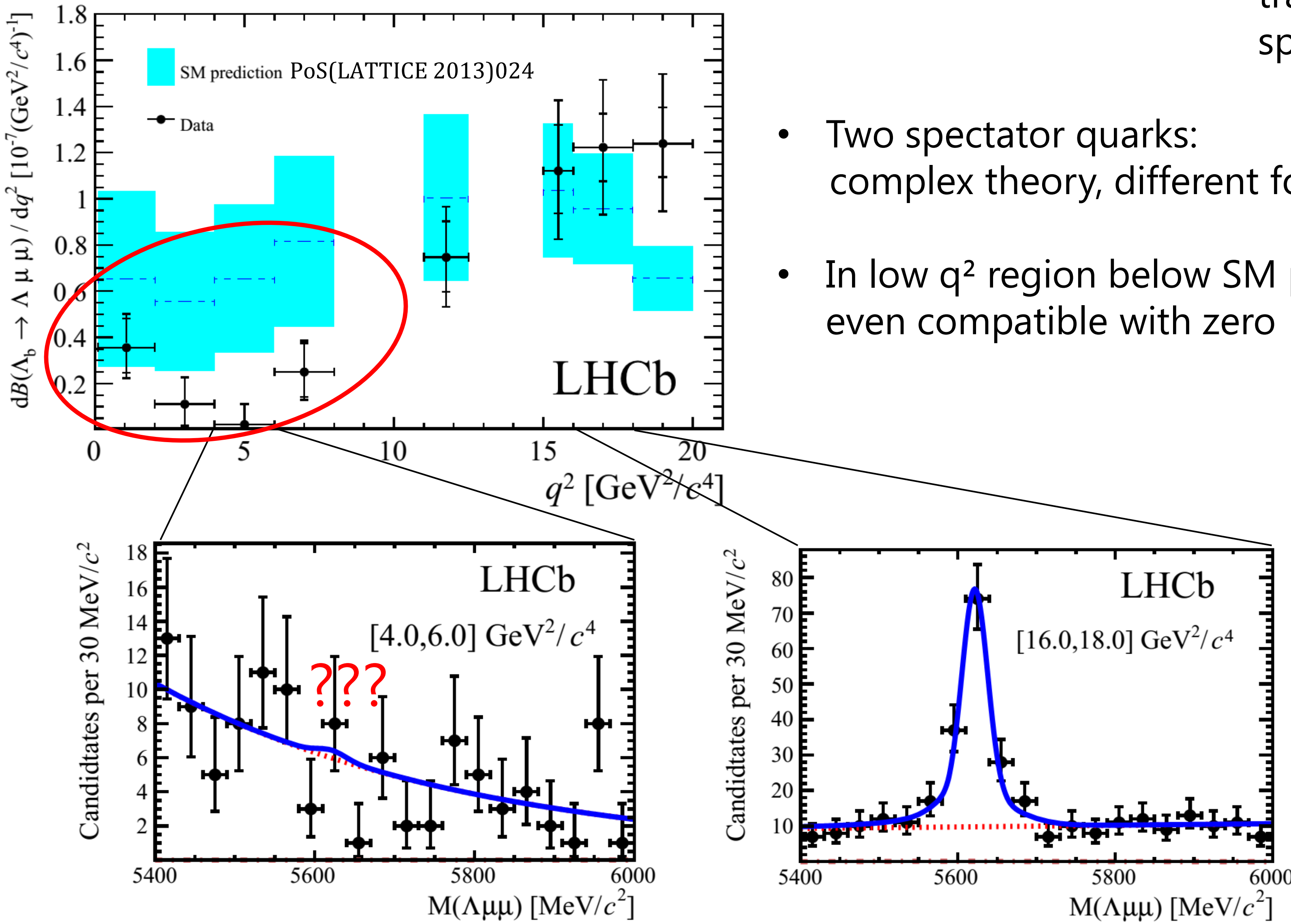
- **Most precise measurement in process with penguin AND box diagrams**

More about CKM angles:
Today 11:40, James Libby

BR of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

LHCb, JHEP 06 (2015) 115

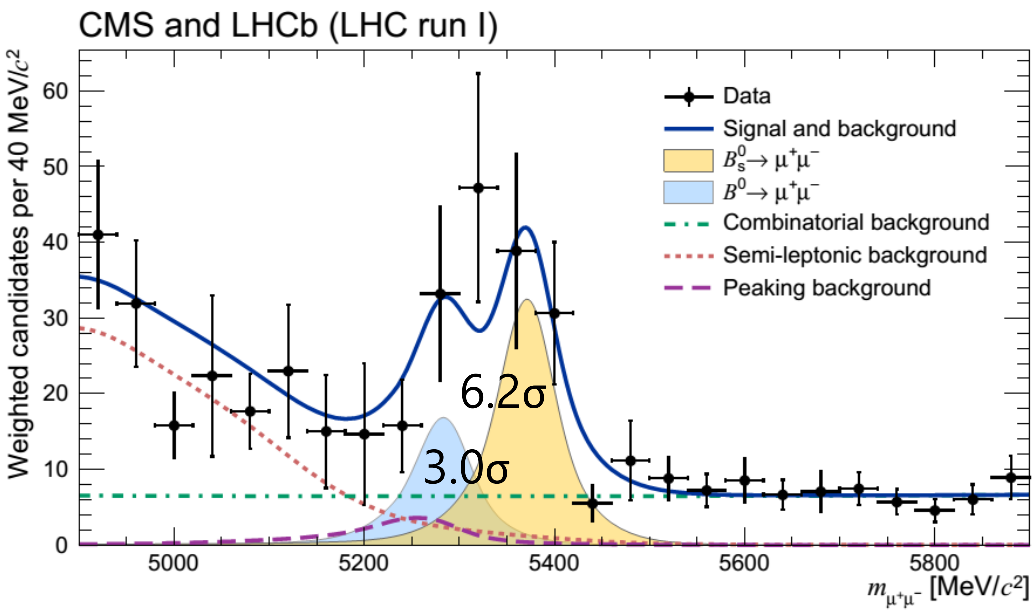
transition: b-s
spectator: u+d



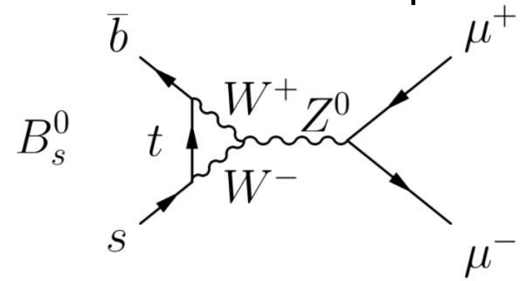
- Two spectator quarks: complex theory, different form factors
- In low q^2 region below SM predictions, even compatible with zero

BR of $B^0_{s,d} \to \mu^+\mu^-$

CMS+LHCb, Nature 522, 68-72 (June 2015)



transition: b-s,d
spectator: -



- b-s(d) transition without spectator quark
- sensitive to other C_i then decays presented until now

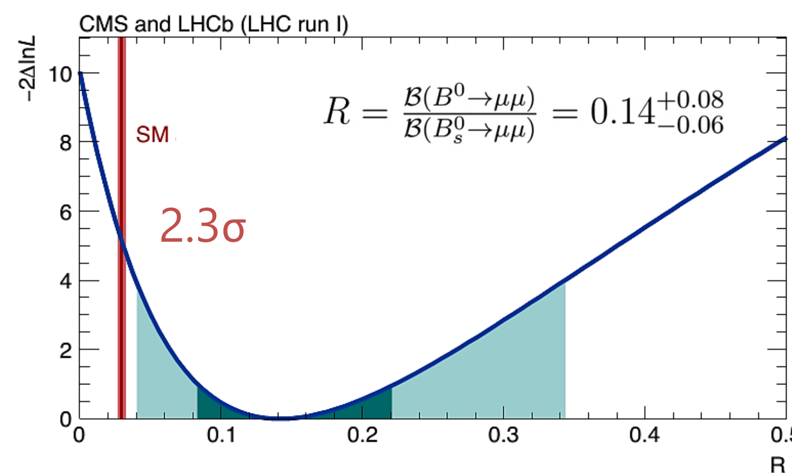
SM: PRL 112(2014) 101801

$$\mathrm{BR}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \cdot 10^{-9}$$
$$\mathrm{BR}(B^0_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \cdot 10^{-10}$$

Measured (CMS+LHCb,7+8TeV)

$$\mathrm{BR}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$$
$$\mathrm{BR}(B^0_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$$

Ratio:



BR ratio and asymmetry

Lepton Universality

LHCb, PRL 113, 151601 (2014)

transition: b-s
spectator: u

- Ratio of Branching ratios:

$$\mathbf{R_K} = \frac{\mathbf{BR(B_u^+ \rightarrow K^+ \mu^+ \mu^-)}}{\mathbf{BR(B_u^+ \rightarrow K^+ e^+ e^-)}}$$

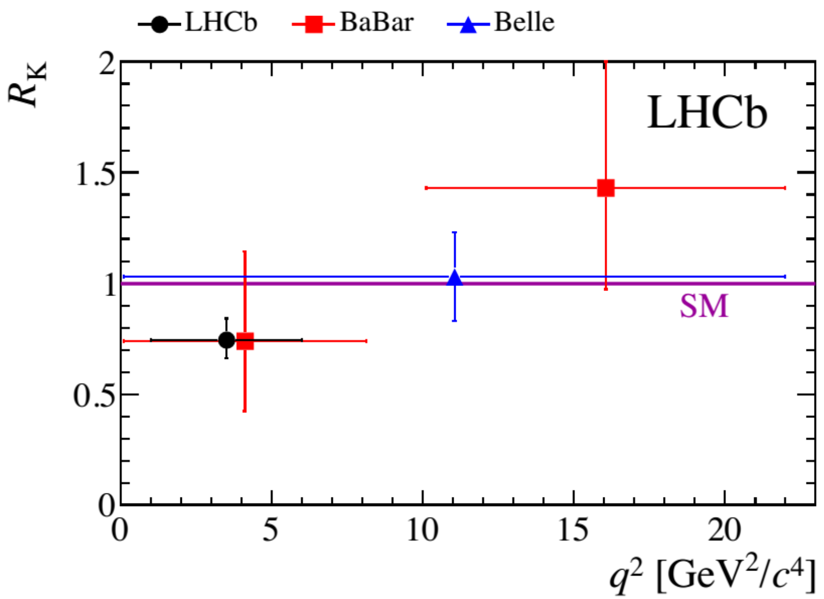
- Very precise Standard Model prediction:

$$\mathbf{R_K = 1.00030^{+0.00010}_{-0.00007}}$$

- Measurement from LHCb in q^2 1-6 GeV^2:

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

→ 2.6σ from SM prediction

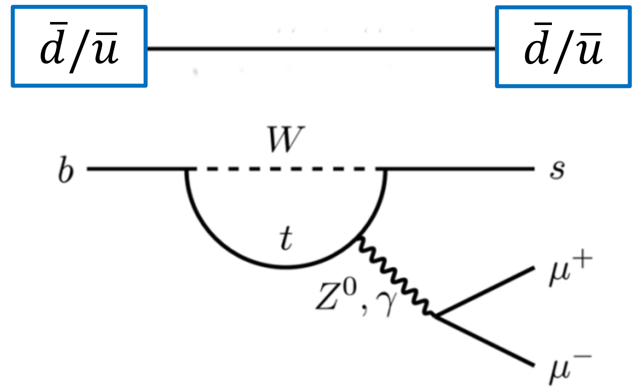


SM	Bobeth et al. arXiv:0709.4174
BaBar	PR D86 (2012) 032012
Belle	PRL 103 (2009) 171801

Isospin asymmetry

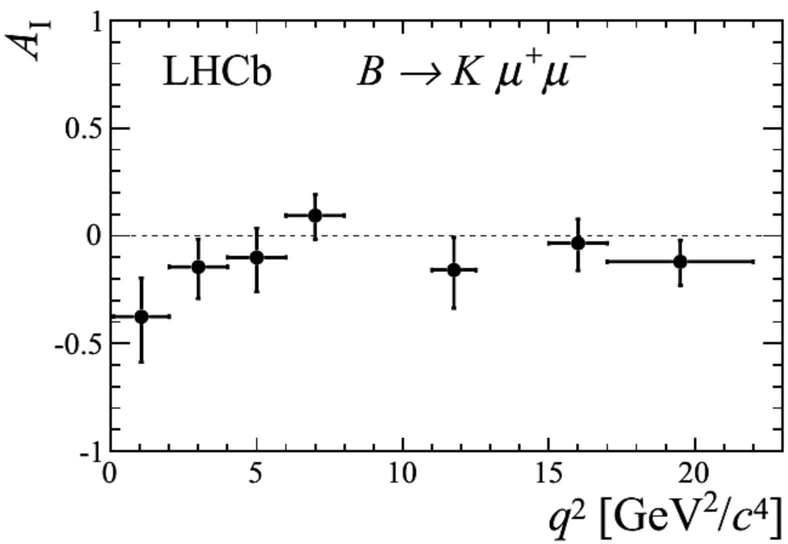
LHCb, JHEP 06 (2014) 133

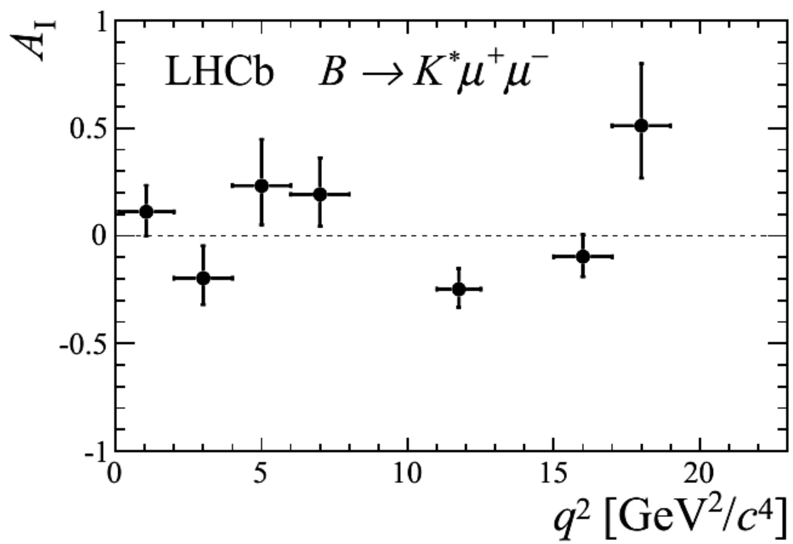
- Test effect of charge of spectator quark
- Consistent with SM



transition: b-s
spectator: u,d

$$A_I\left(B \to K^{(*)}\mu^+\mu^-\right) = \frac{\Gamma\left(B^0 \to K^{(*)0}\mu^+\mu^-\right) - \Gamma\left(B^+ \to K^{(*)+}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{(*)0}\mu^+\mu^-\right) + \Gamma\left(B^+ \to K^{(*)+}\mu^+\mu^-\right)}$$





SM=O(1%)

CP asymmetry

LHCb, arXiv:1509.00414

transition: b-d
spectator: u

$$A_{CP}(B \to \pi\mu^+\mu^-) = \frac{\Gamma(B^- \to \pi^-\mu^+\mu^-) - \Gamma(B^+ \to \pi^+\mu^+\mu^-)}{\Gamma(B^- \to \pi^-\mu^+\mu^-) + \Gamma(B^+ \to \pi^+\mu^+\mu^-)}$$

- Sensitive to interference effects

- Measured in q^2 1-6 GeV^2:

$$A_{CP}(B \to \pi\mu^+\mu^-) = -0.11 \pm 0.12(\text{stat.}) \pm 0.01(\text{syst.})$$

- SM prediction (Hambrock et al., arXiv:1506.07760):

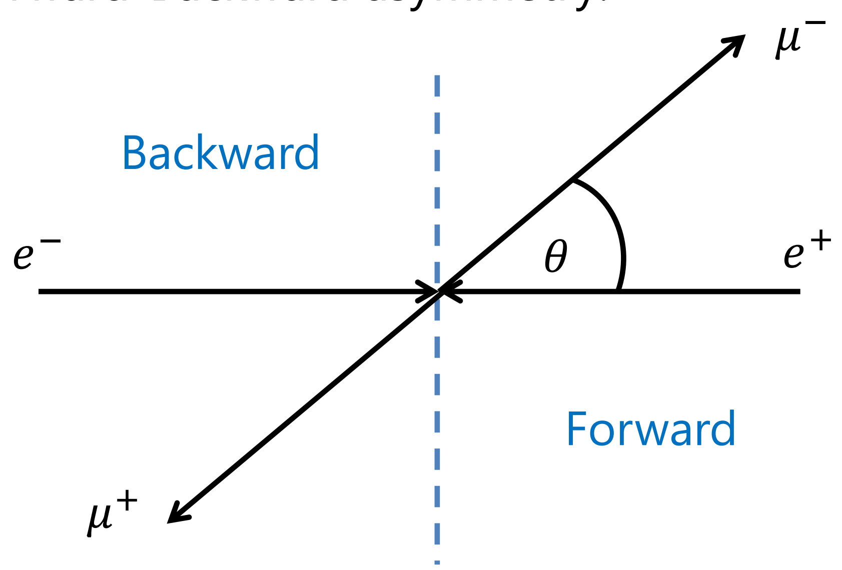
$$A_{CP}(B \to \pi\mu^+\mu^-) = -0.14^{+0.04}_{-0.03}$$

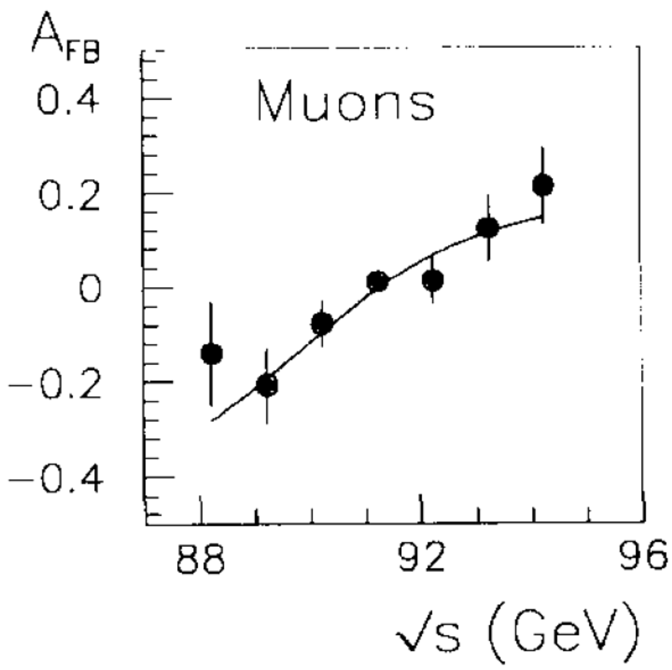
→ Consistent with SM

Angular measurements

Past: $e^+e^- \to \mu^+\mu^-$ @ LEP

- Forward-Backward asymmetry:





DELPHI, Nuclear Physics B 367 (1991) 511-574

- by counting:

$$A_{FB} = \frac{N_{forward} - N_{backward}}{N_{forward} + N_{backward}}$$

- by Maximum Likelihood fit:

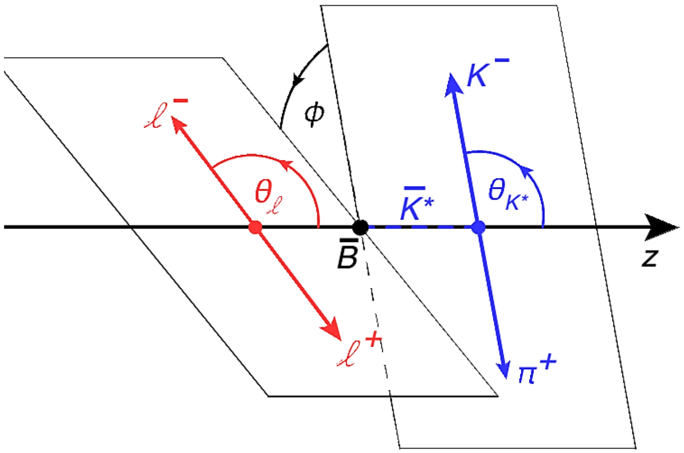
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$$

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

- Decay fully described by three angles θ_K, θ_l , ϕ and q²
- Normalized differential decay rate:

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

Decay angles:



F_L: fraction of longitudinal polarization of K*

S_i: angular observables

Attention:
Different definitions!

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

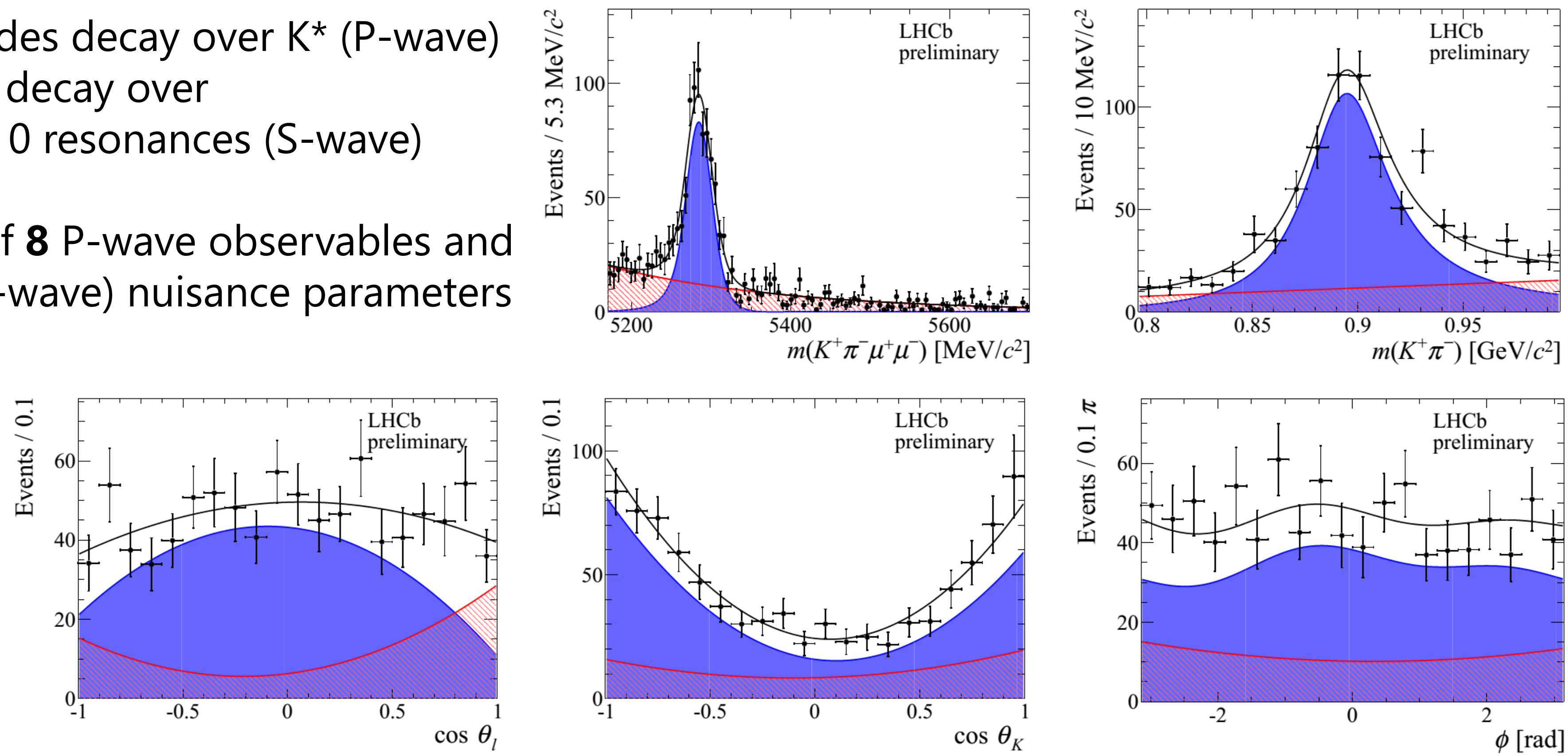
LHCb-CONF-2015-002

4D+1D Maximum Likelihood Fit to $m(K\pi\mu\mu), m(K\pi)$, 3 angles

Besides decay over K* (P-wave) also decay over spin 0 resonances (S-wave)

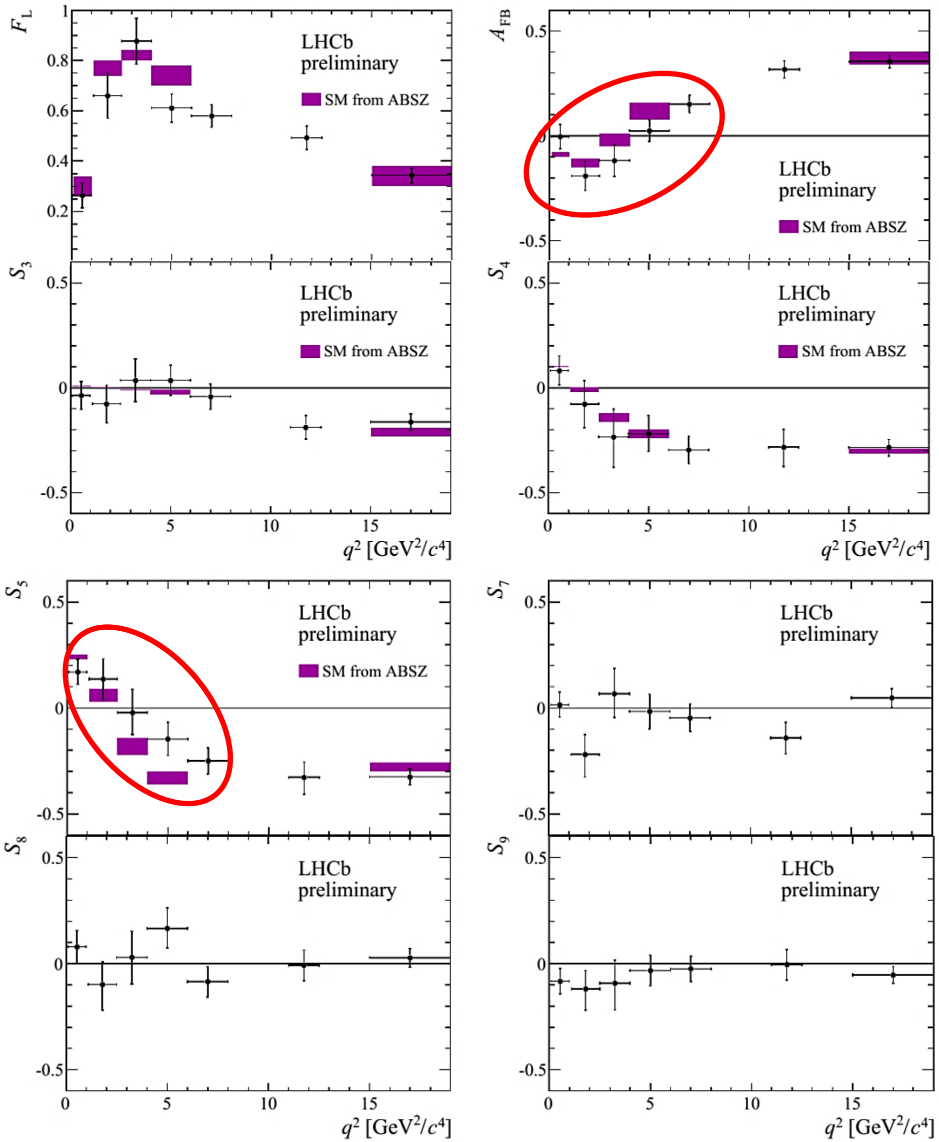
Fit of **8** P-wave observables and **6** (S-wave) nuisance parameters

Fit projections in q² bin 1.1-6 GeV²
Blue: signal
Red: combinatorial background



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

transition: b-s
spectator: d

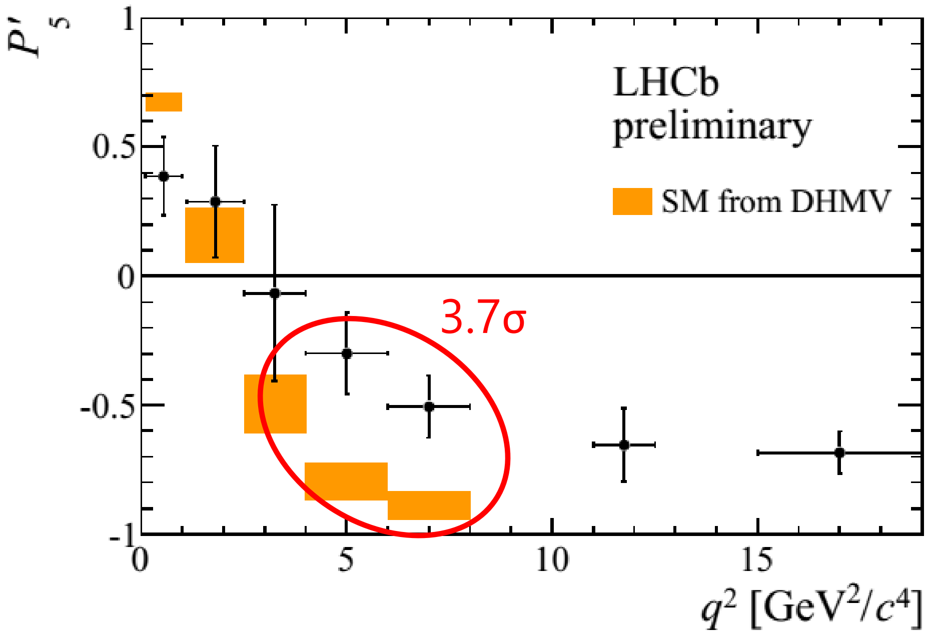


- In general good agreement with SM prediction
- In A_{FB} and S_5 in lower q² region below/above predictions

SM: Aoife Bharucha, Straub, Zwicky, arXiv:1503.05534

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

transition: b-s
spectator: d



- Also fit different observable:

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

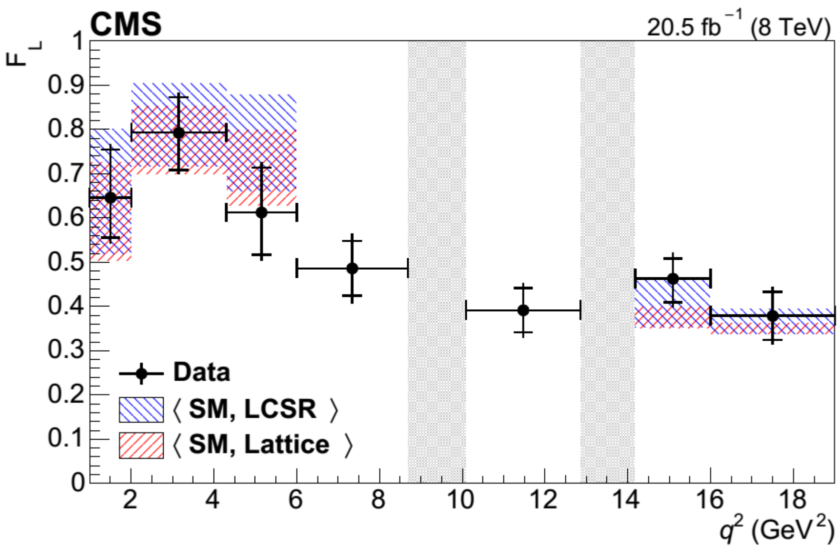
- form factor uncertainties cancel out to a certain extent
  -> more precise SM prediction

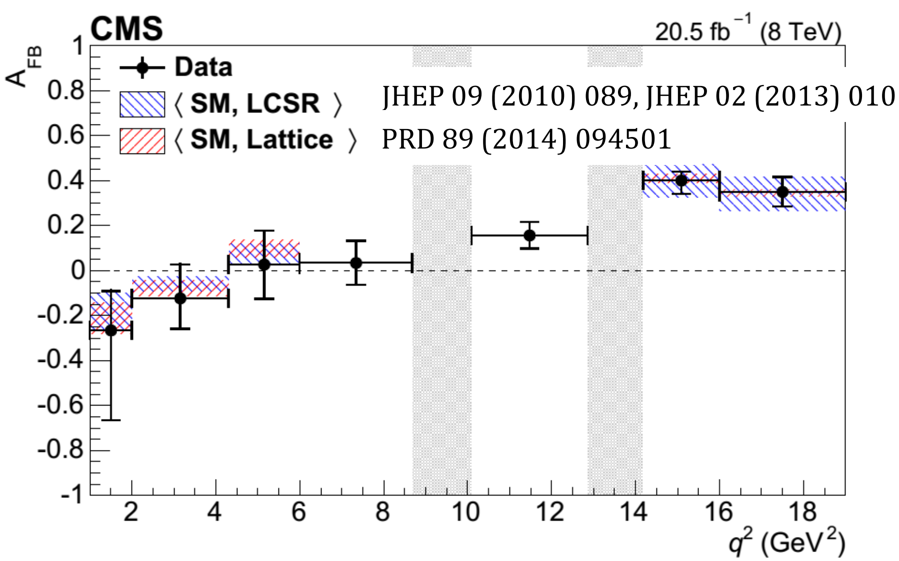
- In lower q² region 3.7σ deviation to SM observed

SM: Descotes-Genon, Hofer, Matias, Virto JHEP 1412 (2014) 125

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

CMS, arXiv:1507.08126





transition: b-s
spectator: d

- fit 2D angular distribution θ_K, θ_l
- fit S-wave contribution
- in good agreement with SM and measurement by LHCb
- Full angular analysis on its way!

Angular $B^{0,+} \rightarrow K^{*0,*+} l^+ l^-$

BaBar, arXiv:1508.07960

transition: b-s
spectator: u,d

q² 1-6 GeV²

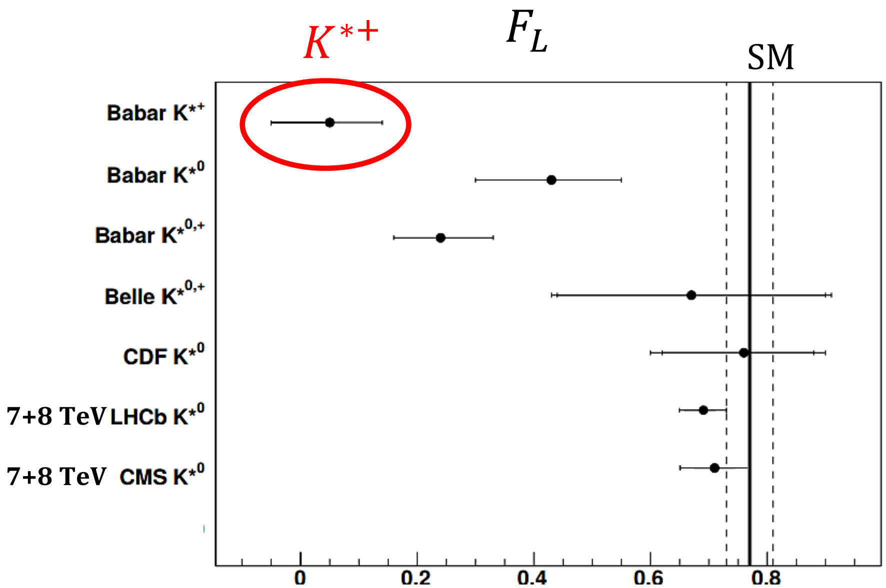


fig modified from 1508.07960

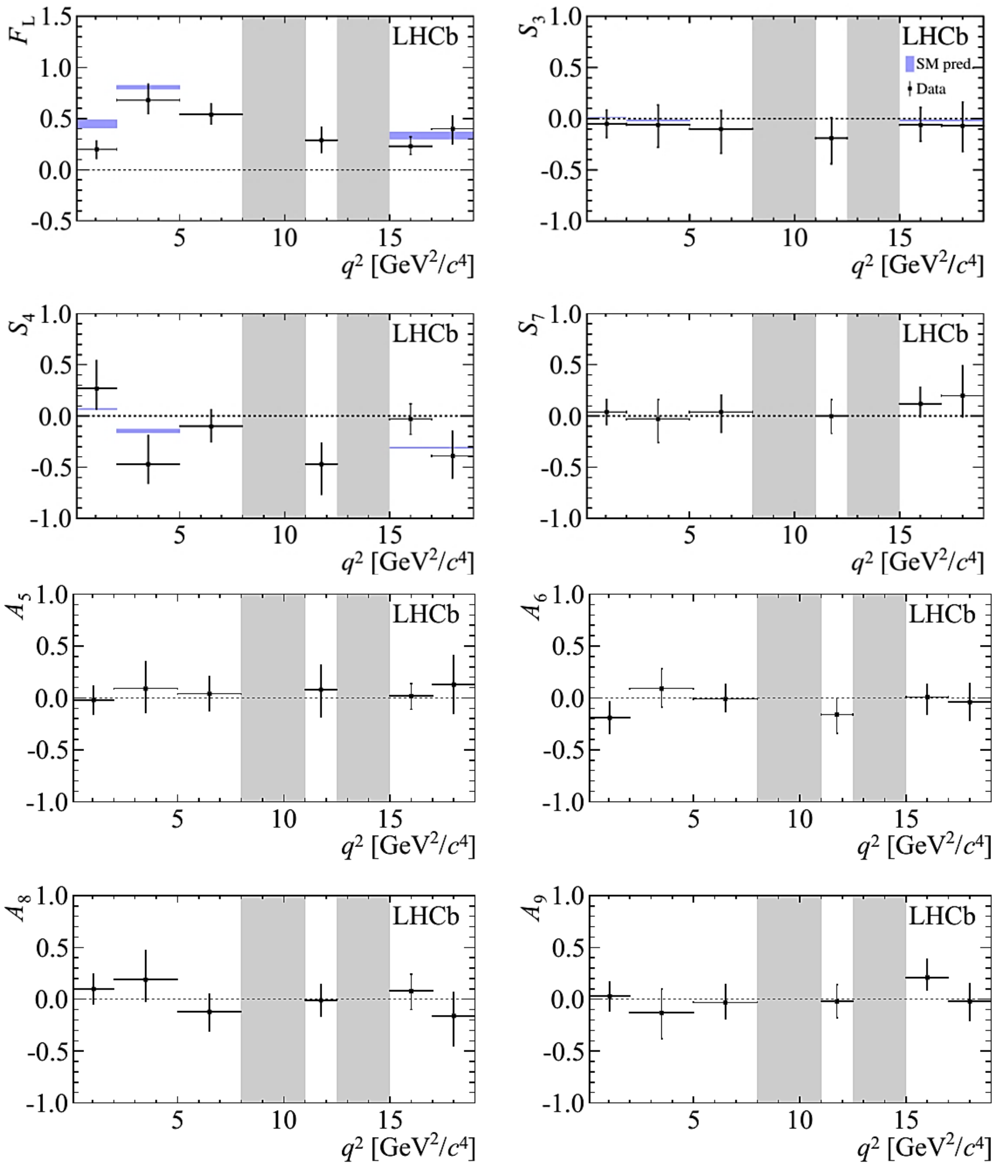
- Studying in total 5 channels
- Subsequent fits of 1D projections of θ_K, θ_l (→ study F_L , A_{FB})
- **First angular analysis of $B^+ \rightarrow K^{*+} l^+ l^-$**
- At low q²: F_L of $B^+ \rightarrow K^{*+} l^+ l^-$ below SM.

→Otherwise consistent with SM

SM:	Altmannshofer et. al. JHEP 0901, 019 (2009)
Belle	PRL 103, 171801 (2009)
CDF	PRL 108, 081807 (2012)
ATLAS	ATLAS-CONF-2013-038

Angular $B_s^0 \to \phi\mu^+\mu^-$

LHCb, arXiv:1506.08777



transition: b-s
spectator: s

- Described very similar to $B_d^0 \to K^{*0}\mu^+\mu^-$
- However, decay not self-tagging
- Measure instead T-odd asymmetries $A_{5,6,8,9}$
- **Measurement of A_5 and A_8 for $b \to sll$ for first time**

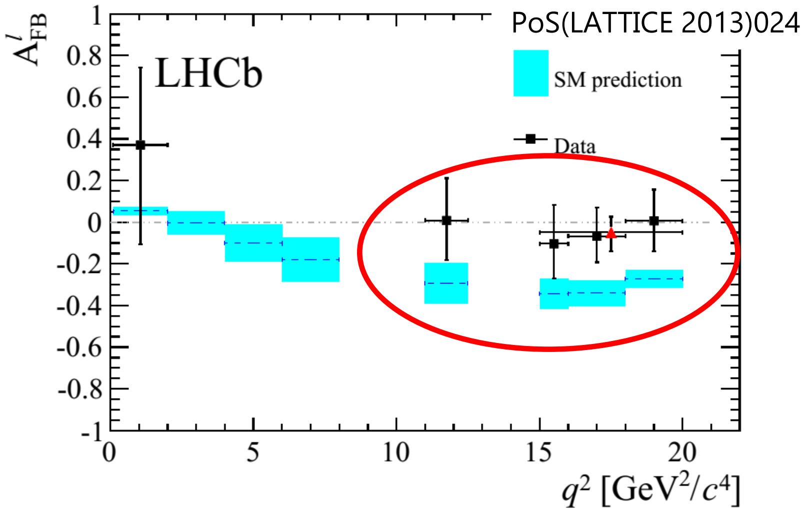
→ Consistent with SM

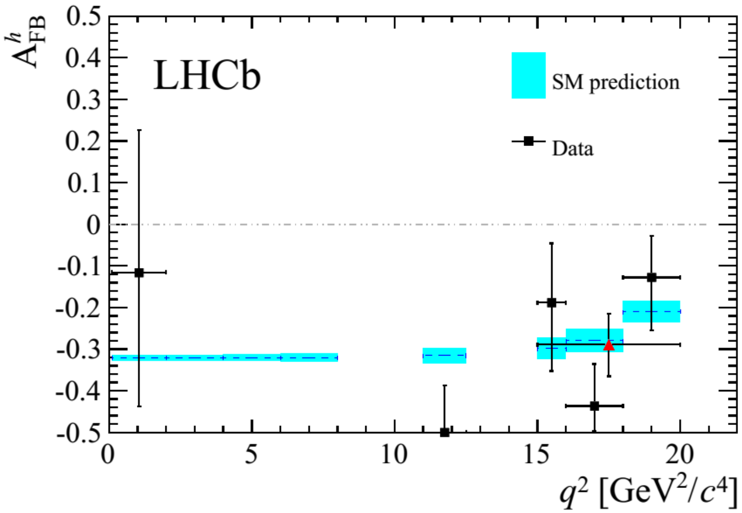
SM: Bharucha, Straub Zwicky, arXiv:1503.05534

Angular: $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

LHCb, JHEP 06 (2015) 115

transition: b-s
spectator: u+d



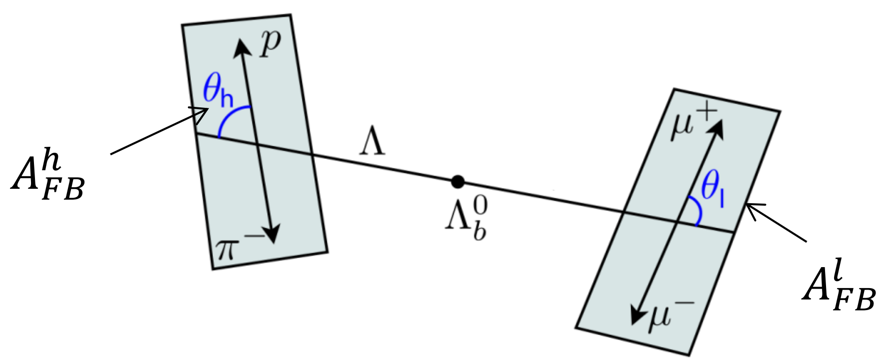


- As proton has spin, measure two forward-backward asymmetries:

  A^l_{FB} same as in $B_d^0 \to K^{*0}\mu^+\mu^-$

  A^h_{FB} in hadronic part

- At high q² A^l_{FB} above SM prediction



Summary

- Several 2-3σ deviations
- 2.6σ deviation for lepton universality
- Most striking:

  at low q², sensitive to
  $C_7 - C_9$ interference

On the path to New Physics?

Crivellin, D'Ambrosio, Heeck
Phys. Rev. D 91, 075006 (2015)

Descotes-Genon, Hofer, Matias, Virto
arXiv:1503.03328

Altmannshofer, Straub
EPJC (2015) 75: 382

Beaujean, Bobeth, van Dyk
EPJC 74 (2014) 2897

Hurth, Mahmoudi
JHEP 1404 (2014) 097

...

Combined Fit

Altmannshofer, Straub, EPJC (2015) 75: 382

- Wilson coefficients determined in χ^2 fit of observables:

91 measurements,
18 different observables

Decay Channels:

$B^{(+)} \to K^{(*)} l^+ l^-$
$B_s \to \phi\, \mu^+ \mu^-$
$B_{(s)} \to \mu^+ \mu^-$

$B \to X_s l^+ l^-$
$B \to X_s \gamma$
$B \to K^* \gamma$

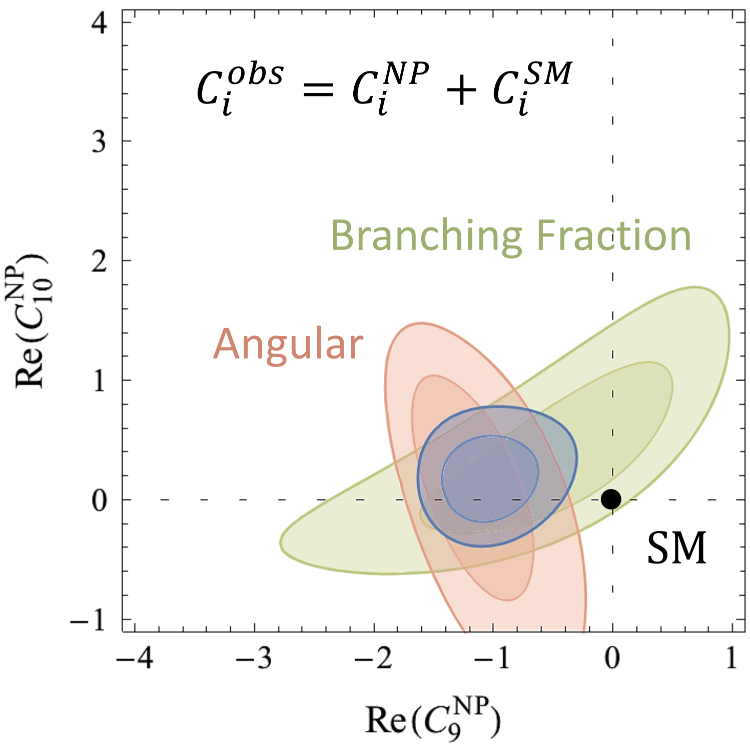
presented today

Not presented today:

- Measured by BaBar, Belle and CLEO
- In agreement with SM, important to constrain physics!

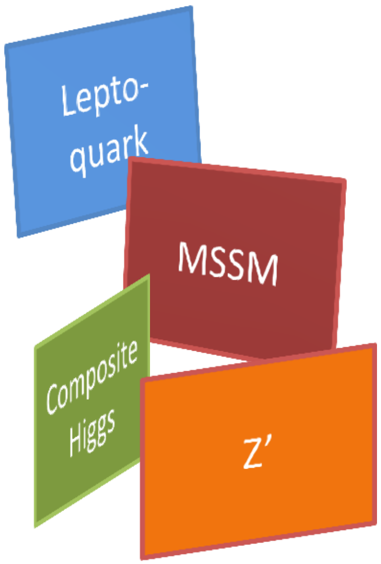
Combined Fit: Results

Altmannshofer, Straub, EPJC (2015) 75: 382

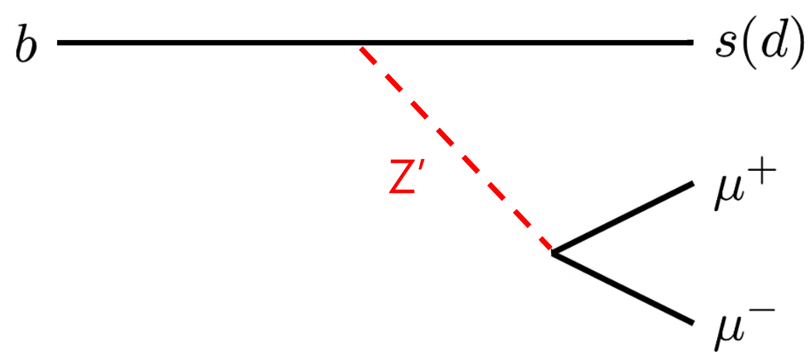


New Physics preferred over Standard Model: 3.7σ

One of the New Physics Models : Z′



b-s(d) transition at tree level:



Constrained by:

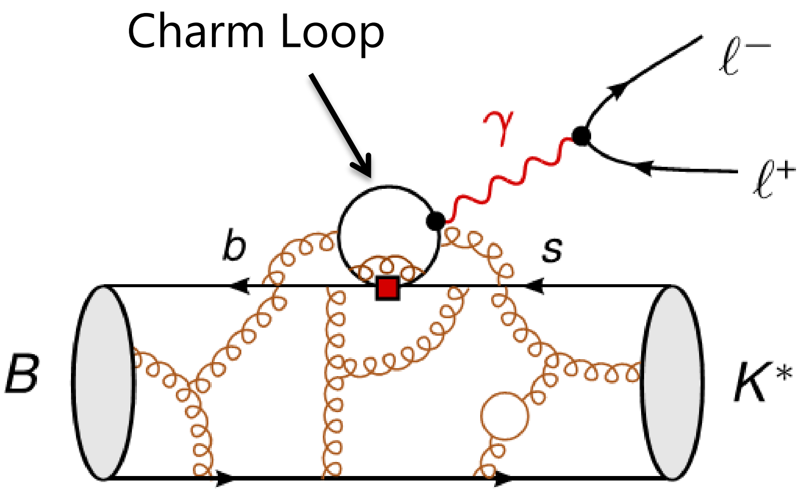
- Dilepton/Dijet production measurements at ATLAS and CMS
- B_s mixing
- ....

→ Z′ mass at least O(TeV)

Exclusion limits depend on coupling

Especially, if Z′ couples differently to muons and electrons **still** allowed!

Underestimated Theory Uncertainties?

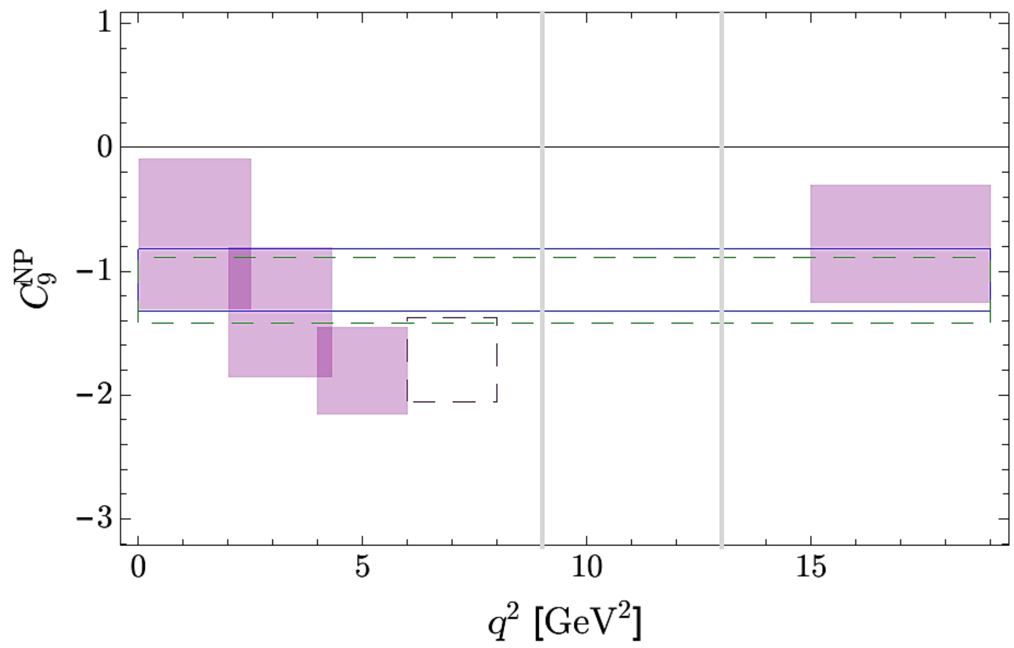


Straub, Moriond EW, 2015

- Charm Loop could mimic effect of C_9^{NP}, both: vector like coupling
- Cannot explain deviation from lepton universality
- Hadronic effects expected to be q^2 dependent!

q² dependence of fit

Altmannshofer, Straub, arXiv:1503.06199



- New Physics expected to be q² independent

→ No final answer possible yet …

The Future

More precise theory

- hadronic uncertainties

  …

More observables/decays

- asymmetries
- flavour violating decays: $B \to K\mu e$

  …

More statistics

- LHCb: $\mathbf{8fb^{-1}}$ by 2019, $\mathbf{50fb^{-1}}$ by 2030
- CMS/ATLAS: $\mathbf{100fb^{-1}}$ by 2019, $\mathbf{300fb^{-1}}$ by 2023
- Belle II: $\mathbf{50ab^{-1}}$ by 2024

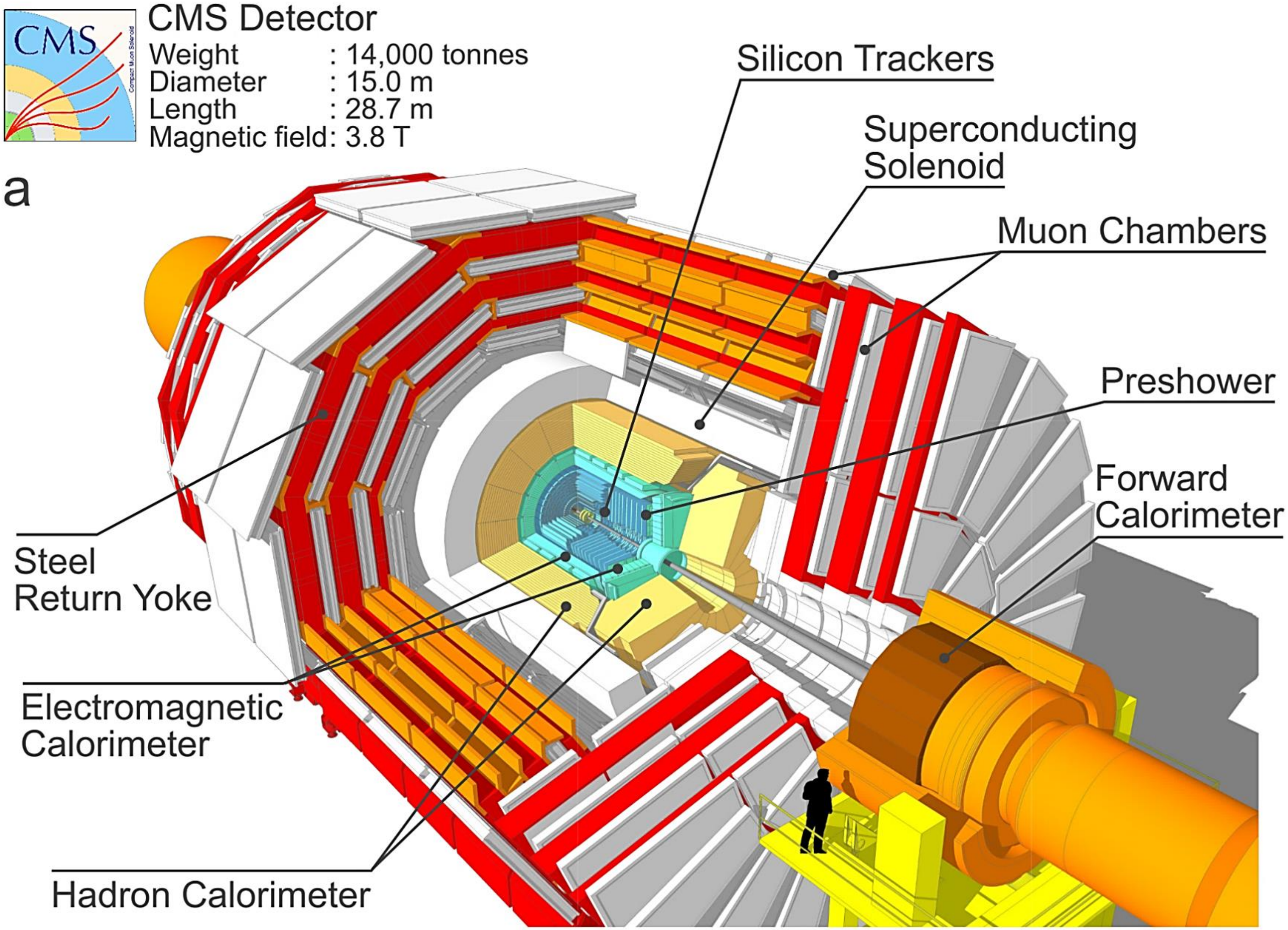
  …

Conclusion

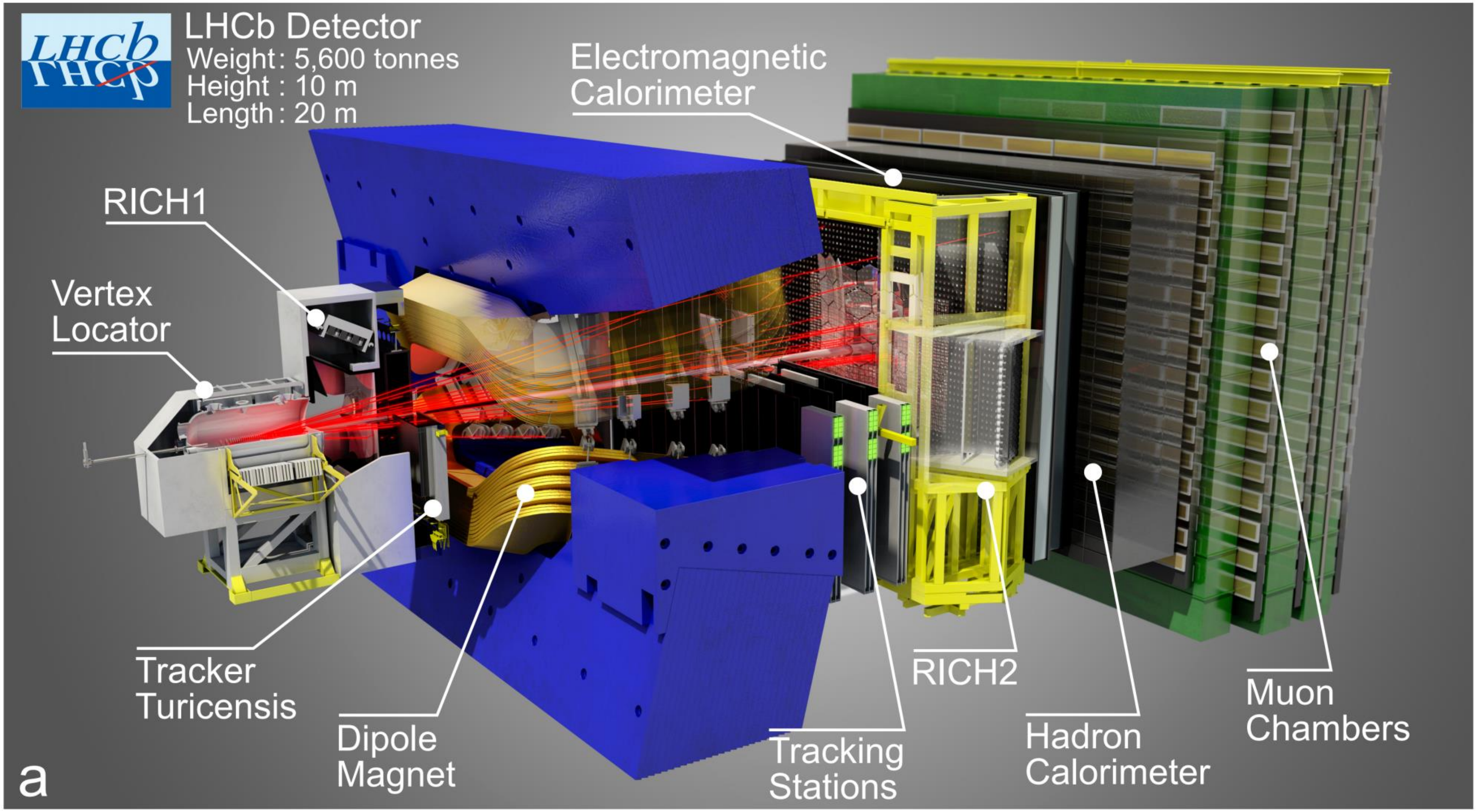
Measurement	**Compatible with SM**
Angular	
Branching Ratio	
CP asymmetry	
Isospin asymmetry	
Lepton universality	

BACKUP

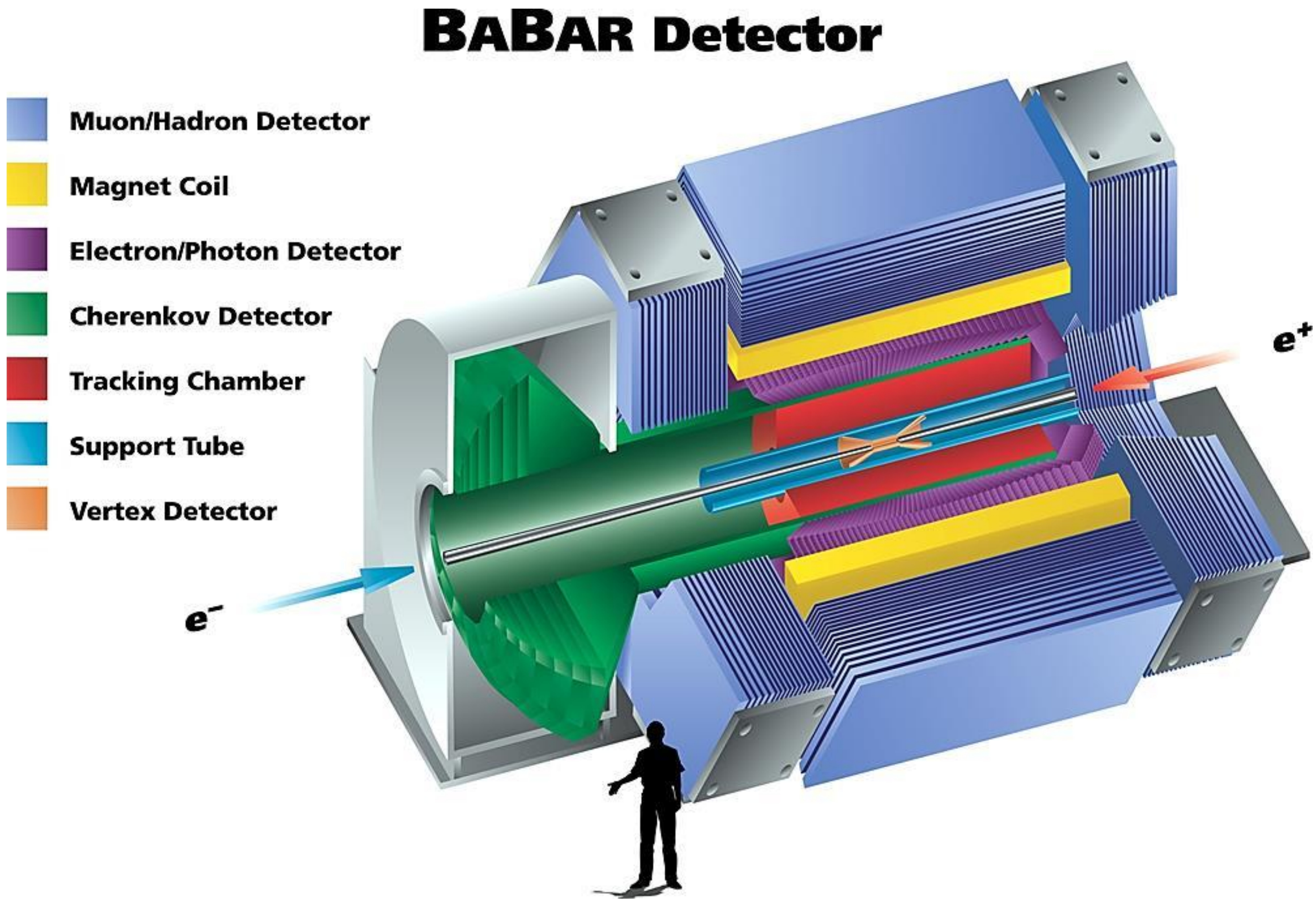
CMS Detector



LHCb detector



BaBar detector



Relations

Altmannshofer, Straub, EPJ C73 (2013) 2646

2.2. Preliminary considerations

Before turning to the numerical analysis, it is instructive to make some analytical considerations as to which Wilson coefficients have to be modified to explain the tensions in the data. An immediate observation is that all three tensions occur in CP-averaged observables, so there is no need to invoke non-standard CP violation, i.e. the Wilson coefficients can be kept real.

To get an analytical understanding of the dependence of the relevant observables on the Wilson coefficients, we can derive approximate expressions, valid for small NP contributions, neglecting interference terms between NP effects in different coefficients. We find[4]

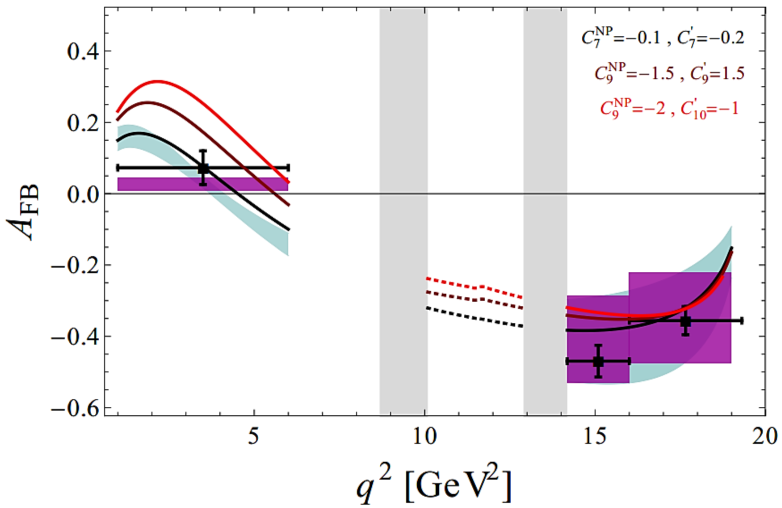
$$\langle F_L \rangle_{[1,6]} \simeq +0.77 + 0.25\, C_7^{\rm NP} + 0.05\, C_9^{\rm NP} - 0.04\, C_9' + 0.04\, C_{10}' \,, \qquad (4)$$

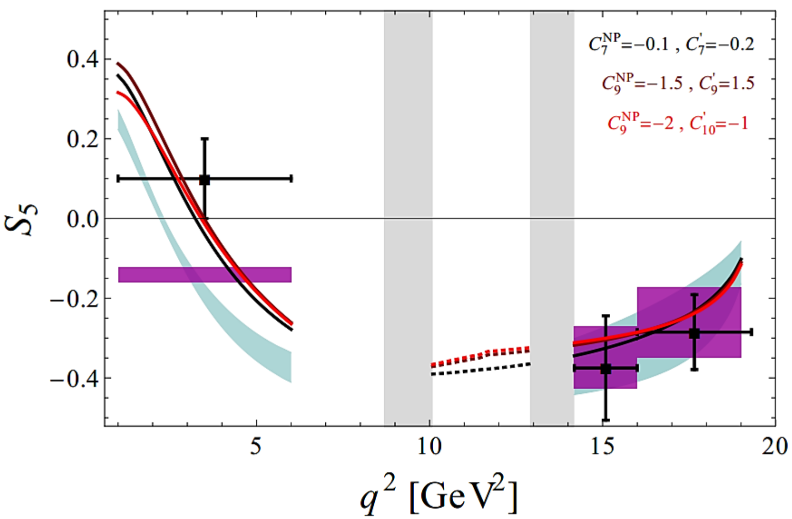
$$\langle S_4 \rangle_{[14.18,16]} \simeq +0.29 - 0.02\, C_9' + 0.03\, C_{10}' \,, \qquad (5)$$

$$\langle S_5 \rangle_{[1,6]} \simeq -0.14 - 0.59\, C_7^{\rm NP} - 0.49\, C_7' - 0.09\, C_9^{\rm NP} - 0.03\, C_9' + 0.10\, C_{10}' \,. \qquad (6)$$

Relations

Altmannshofer, Straub, EPJ C73 (2013) 2646





Branching Ratio measurement: Usual Strategy

- In each q² bin extract number of signal candidates with Maximum Likelihood Fit to $K\mu^+\mu^-$ invariant mass .
- Differential Branching Ratio:

$$\frac{dBR}{dq^2} = \frac{N(B \to K\mu^+\mu^-)}{N(B \to J/\psi(\to \mu^+\mu^-)K)} \cdot \frac{\varepsilon(B \to J/\psi(\to \mu^+\mu^-)K)}{\varepsilon(B \to K\mu^+\mu^-)} \cdot \frac{BR(B \to J/\psi K)BR(J/\psi \to \mu^+\mu^-)}{q^2_{max} - q^2_{min}}$$

Normalize to control channel

Relative reconstruction and selection efficiency from simulation

Branching Ratio of normalization channel from PDG

Angular Observables

Differential Decay Rate

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

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

CP-averaged

$$S_i = (I_j + \bar{I_j})/(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2})$$

Asymmetry

$$A_i = (I_j - \bar{I_j})/(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2})$$

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