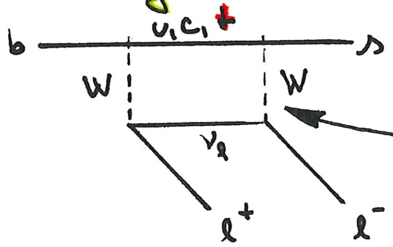
B anomalies introduction

Rare B decays

- B: b is heavy → many secondary products
  → couples from QCD ($m_b \gg \Lambda_{QCD}$) ⇒ better precision
- Rare: Forbidden at tree level
  → loops only
  → branching fraction $\sim 10^{-6}$ or less

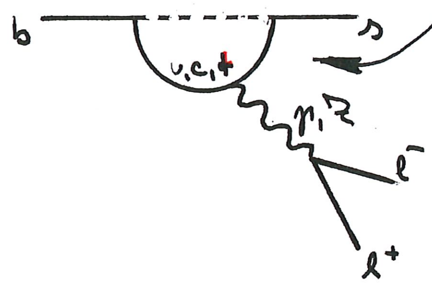
- Our goal is to find Physics Beyond the Standard Model
- b decays only weakly → we look into $b \to s\ell\ell$ transitions
  - Flavor Changing Neutral Current (FCNC)

- **Box diagram**



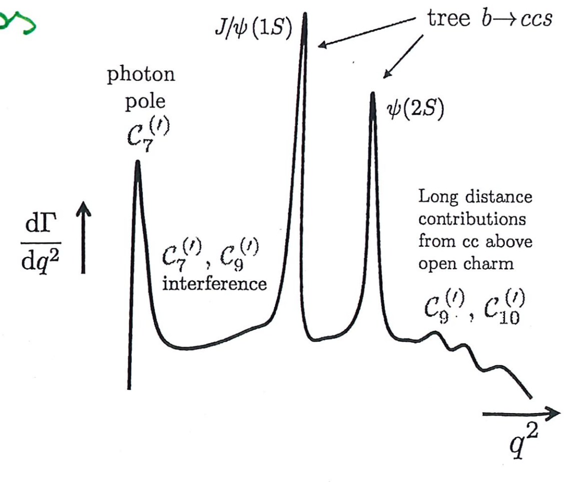
Possible contribution from NP: probing virtual particles
→ high mass reach

- **Penguin diagram**



- depending on the spectator quark: $B \to K^* \ell\ell$
  $B \to K \ell\ell$
  $B_s \to \phi \ell\ell$

- properties of these decays are measured in q^2
  q^2 = dilepton invariant mass
  - different physics in different q^2 regions

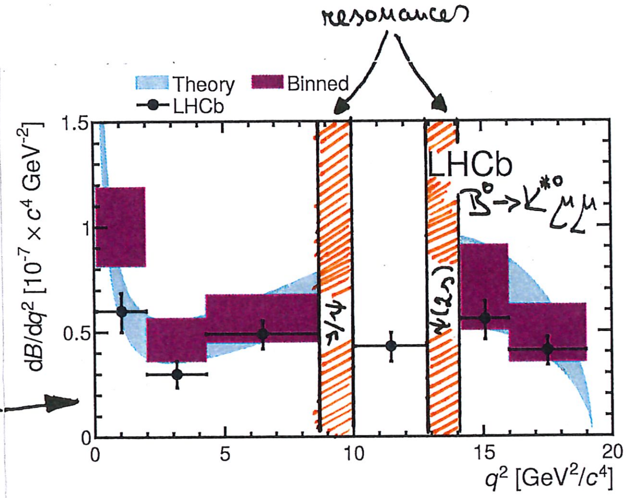


- we can measure branching fractions (BF), angular distributions and contributions from different leptons
- measured by many experiments, the most and best results from LHCb and Belle, which I will focus on

LHCb	vs	Belle
High rate (~MHz)		Low rate (~kHz)
busy events		cleaner events
all kinds of b-hadrons		$\Upsilon(4s)$
unknown event energy		$E_{event} = E_{beam}$

Branching fractions

- 1st results consistent with SM
  - BaBar hep-ex/0604007
  - LHCb 1112.3515
  - Belle 0904.0770
  - CDF 1108.0695
- e.g. LHCb result using 1 fb^{-1} (1304.6325)



- with more statistics, discrepancies start to appear:

  - high q^2 region (above $\psi(2s)$) [10^{-8}]:

$$\int \frac{dB}{dq^2} dq^2 = 6{,}7 \pm 1{,}1 \pm 0{,}4 \quad (\text{stat}, \text{sys})$$

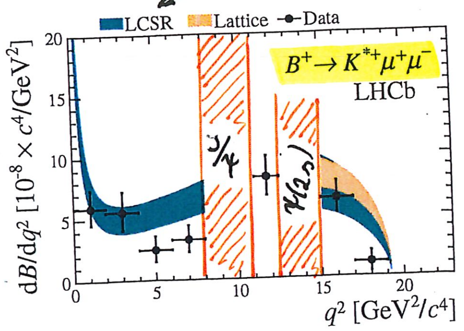
$SM_{pred} = 9{,}8 \pm 1$ ← LIGHT CONE SUM RULE

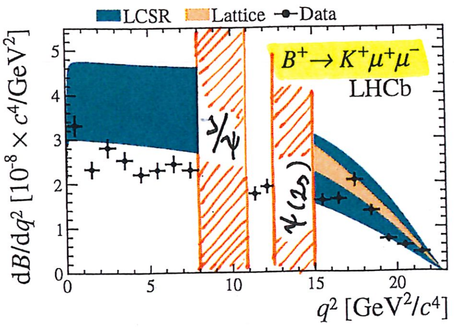
$$\int \frac{dB}{dq^2} dq^2 = 8{,}5 \pm 0{,}3 \pm 0{,}4 \quad (\text{stat}, \text{sys})$$

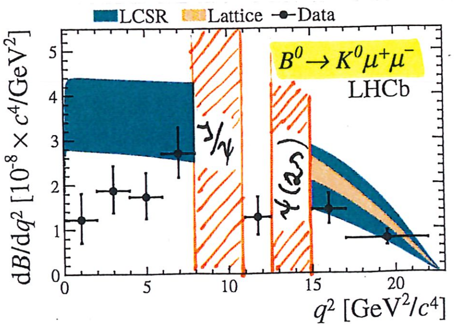
$SM_{pred} = 10{,}7 \pm 1{,}2$

$$\int \frac{dB}{dq^2} dq^2 = 15{,}8\, ^{+3{,}2}_{-2{,}9} \pm 1{,}1 \quad (\text{stat}, \text{sys})$$

$SM_{pred} = 26{,}8 \pm 3{,}6$







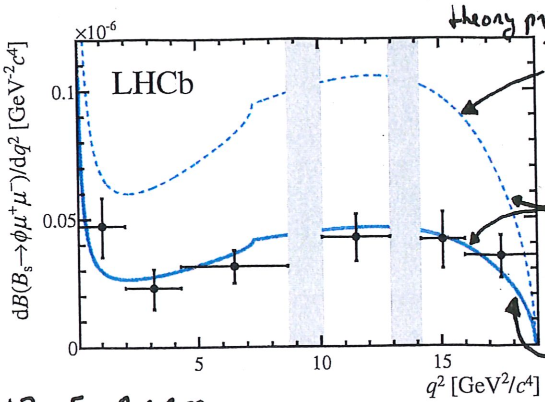
(1403.8044 (3 fb^{-1}))

→ all consistently below the SM prediction

- note that the theory uncertainties are very correlated: integrated BF has ~ same theory uncertainty, while the experimental uncertainty shrinks

- $B_s \to \phi \mu\mu$ BF follows a similar story

$1\ fb^{-1}$ ⟶ $3\ fb^{-1}$

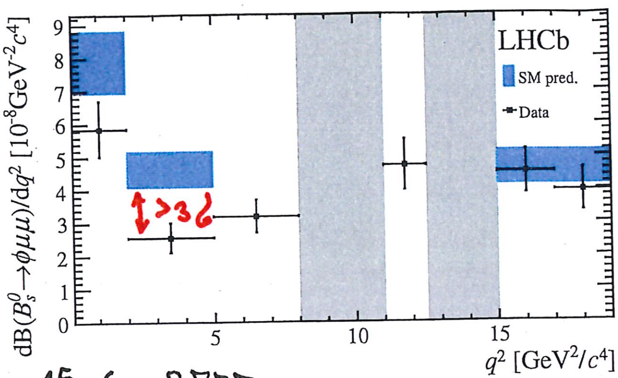


theory prediction for BF predicted by the Light Front Quark model

No errors are shown!

leading-order SM prediction scaled to the fitted BF

1305.2168



1506.08777

$$\int \frac{dB}{dq^2} dq^2 = \left(7{,}07 \,{}^{+0{,}64}_{-0{,}59}\,(\text{stat}) \pm 0{,}17\,(\text{sys}) \pm 0{,}71\,(\text{Reference chanell})\right) 10^{-7}$$

SM: $\sim 15 \cdot 10^{-7}$

$$\int \frac{dB}{dq^2} dq^2 = \left(7{,}97 \,{}^{+0{,}45}_{-0{,}43}\,(\text{stat}) \pm 0{,}22\,(\text{sys}) \pm 0{,}25\,(\text{full } q^2) \pm 0{,}6\,(\text{Reference chanell})\right) \cdot 10^{-7}$$

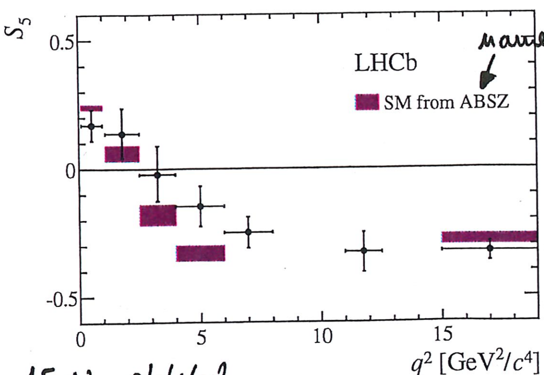
- if we measure with 2x more statistics, the discrepancy will remain $\sim 3\sigma$ due to theory uncertainties (hadronic uncertainties are the biggest)
- all experimental BF results consistently BELOW SM predictions

Angular observables

- first measurements already together with BF measurements
- we can measure form-factor independent angular observables
  → smaller theoretical uncertainties

- defined as $P_j' = \dfrac{S_j}{\sqrt{F_L(1-F_L)}}$

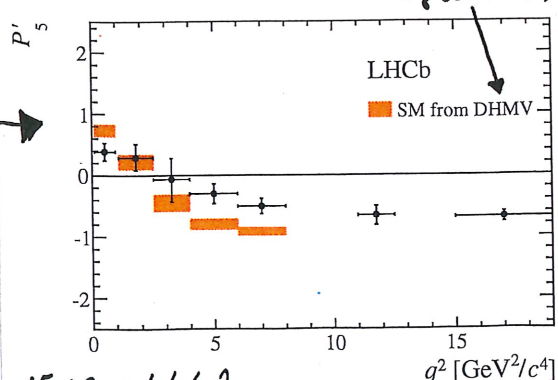
S_j ← bilinear K^* decay amplitude; F_L ← longitudinal K^* polarization



names of authors

1512.04442

⊗



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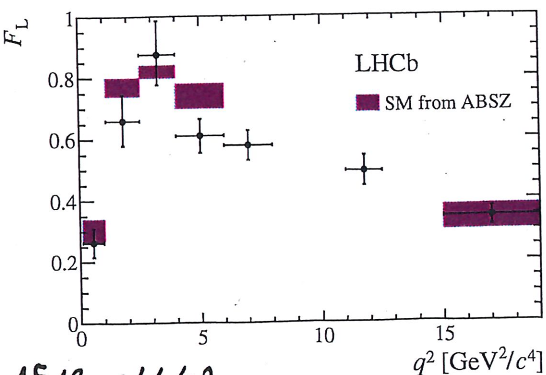
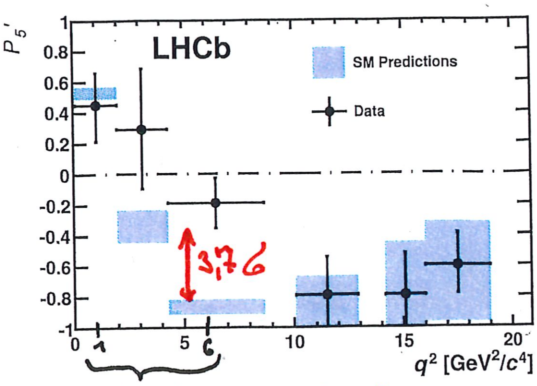
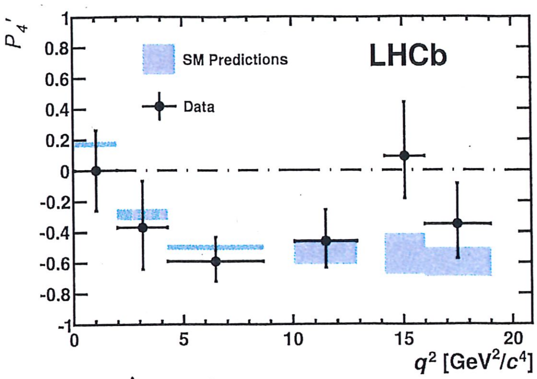


1512.04442

- first measurement of P_j' by LHCb in 2013 (1308.1707) using $1{,}0\,fb^{-1}$



if integrated, 2,5σ



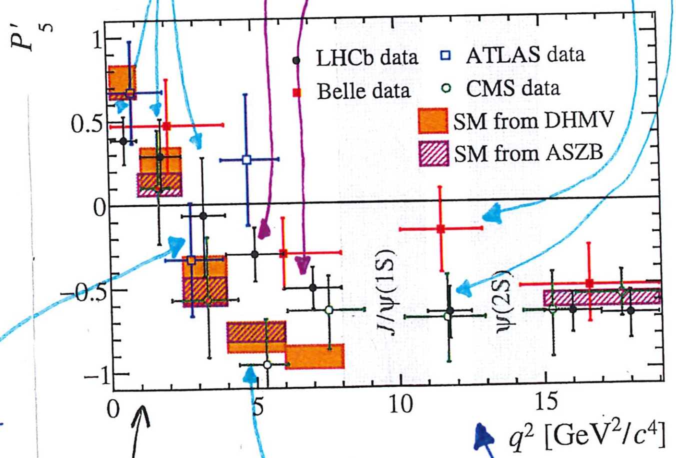
no tensions

- 1 out of 24 measurements is 3,7σ away
  - assuming they are independent measurements, statistical probability of this happening is 0,5 %

- this measurement was followed by many:
  - LHCb 1512.04442 $B^0 \to K^{0*}\mu\mu$, $3\,fb^{-1}$
  - Belle 1612.05014 $B \to K^* \ell\ell$ ← $\mu\mu, ee$; ↑ K^{0*}, K^{+*}
  - ATLAS 1805.04000 $B^0 \to K^{0*}\mu\mu$
  - CMS 1710.02846 $B^0 \to K^{0*}\mu\mu$

LHCb has larger dataset 2,8σ 3,0σ

Belle has worse statistics



similar errors, but LHC has narrower bins

compatible both with SM and LHCb!

Too large radiative tail from $B^0 \to K^* J/\psi(\mu\mu)$ for ATLAS

small excluded region, $0{,}98 < q^2 < 1{,}1$ due to $\phi(\to\mu\mu)$ pollution

- LHCb has more $P_{(5)}'$ measurements ongoing
  a, $5{,}2\,fb^{-1}$ $B^0 \to K^{0*}\mu\mu$ analysis
  b, Third lecture :)

- angular distributions were similarly measured in $B_s \to \phi\mu\mu$
  - all agrees with SM predictions

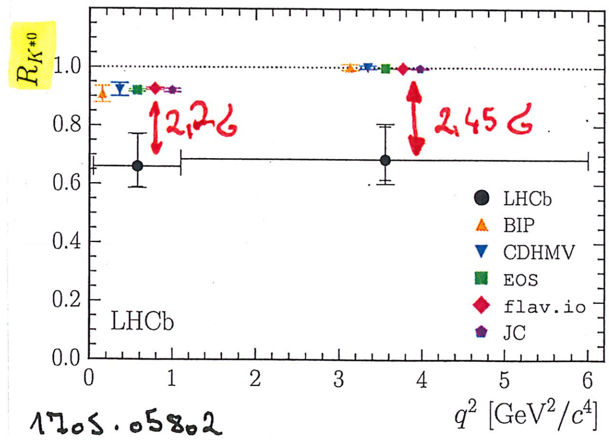
Lepton flavor universality

- we are looking into $b \to s\ell\ell$ transition
- NP can occur in the loops AND it might prefer μ or e (or τ)
  - → let's investigate ratios of $b \to s\mu\mu$ / $b \to see$
  - again, done in bins of q^2
- We define a variable R_X:

$$R_X := \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to X\mu\mu)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to Xee)}{dq^2} dq^2}$$

- R_X has very small theoretical uncertainties
  - QED contribution $\sim 10^{-2}$
  - QCD contribution $\sim 10^{-3}$ (details in 1605.07633)
    - mostly cancels out
- unfortunately, experimental uncertainties are much larger than the theory ones

- Let's have a look at R_K and R_{K^*}:



1705.05802

← q^2 range up to 6 GeV (again radiative tails, but in ee channel)

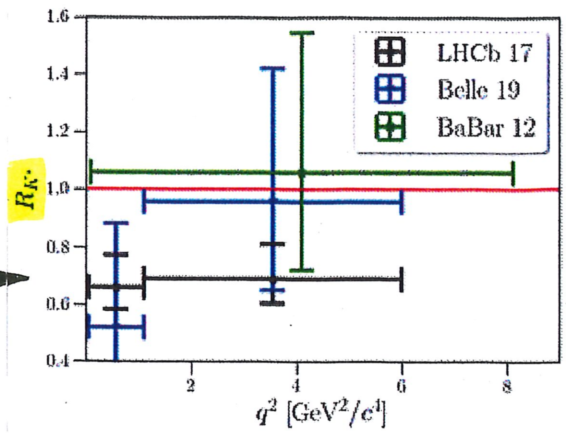
← at low q^2, $R_K^{SM} < 1$ due to the mass difference μ^-/e^-

← error-bars 95,4 % and 99,7 % CL

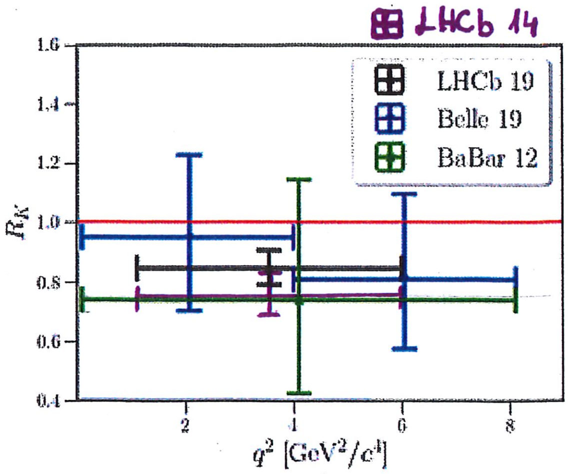
Belle also have results in $10 < q^2 < 22$ GeV

BaBar: 1204.3933
Belle: 1904.02440
LHCb: 1705.05802

LHCb has the most precise results →



- more on e^- reconstruction next week!



LHCb: 1406.6482

$3\,fb^{-1}$, $R_K = 0{,}745\,^{+0{,}090}_{-0{,}074}\,(stat) \pm 0{,}036\,(sys)$

→ 2,6 σ tension

LHCb: 1903.09252

$5\,fb^{-1}$, $R_K = 0{,}846\,^{+0{,}060}_{-0{,}054}\,(stat)\,^{+0{,}016}_{-0{,}014}\,(sys)$

→ 2,5 σ tension

- the analysis used improved reconstruction selection
- agrees with the previous $3\,fb^{-1}$ result
- when fitted separately ($3+2\,fb^{-1}$), there is a difference of 1,9 σ
  → fluctuations happen!

Belle: 1908.01848

BaBar: 1204.3933

Outlook

- there are a lot of tensions of 2-3 σ with the SM
  - most of them are in the same direction
  → consistent picture
- very attractive for theorists, but not in the expected direction
  - some SM extensions can explain all anomalies
- there are other tensions with SM outside of $b \to s\ell\ell$
  - e.g. R_{D^*}, R_D (1506.08614) or $R_{J/\psi}$ (1711.05626)
- Future measurements and theory predictions will be very exciting whether the anomalies hold or not!