B-anomalies at LHCb

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On behalf of

the LHCb Collaboration

FCCP 2022

UNIVERSITY OF LIVERPOOL

Anomaly

- /əˈnɒm(ə)li/ something that deviates from what is standard, normal, or expected.

    e.g. "there are a number of anomalies in the present system“

Is there a common thread?

I rely on a number of excellent recent (21-22) presentations e.g.

- 2021: M. Patel, Planck Conference (30/6/21)
- *Talks by:* V. Gligorov; F. Blanc; L. Bian; P. Resmi; S. Schmitt; *all in* (ICHEP 2022, 6/7/22);
- F. Dordei (NuFACT, 2022, 1/8/22)
- A. Mauri (XVth Quark Confinement and Hadron Spectrum Conference, 1/8/22)
- L. Scantlebury (Rencontres de Vietnam, 16/8/22)
- C. Marin (14th Conference on Intersections and Nuclear Physics, 29/8/22)

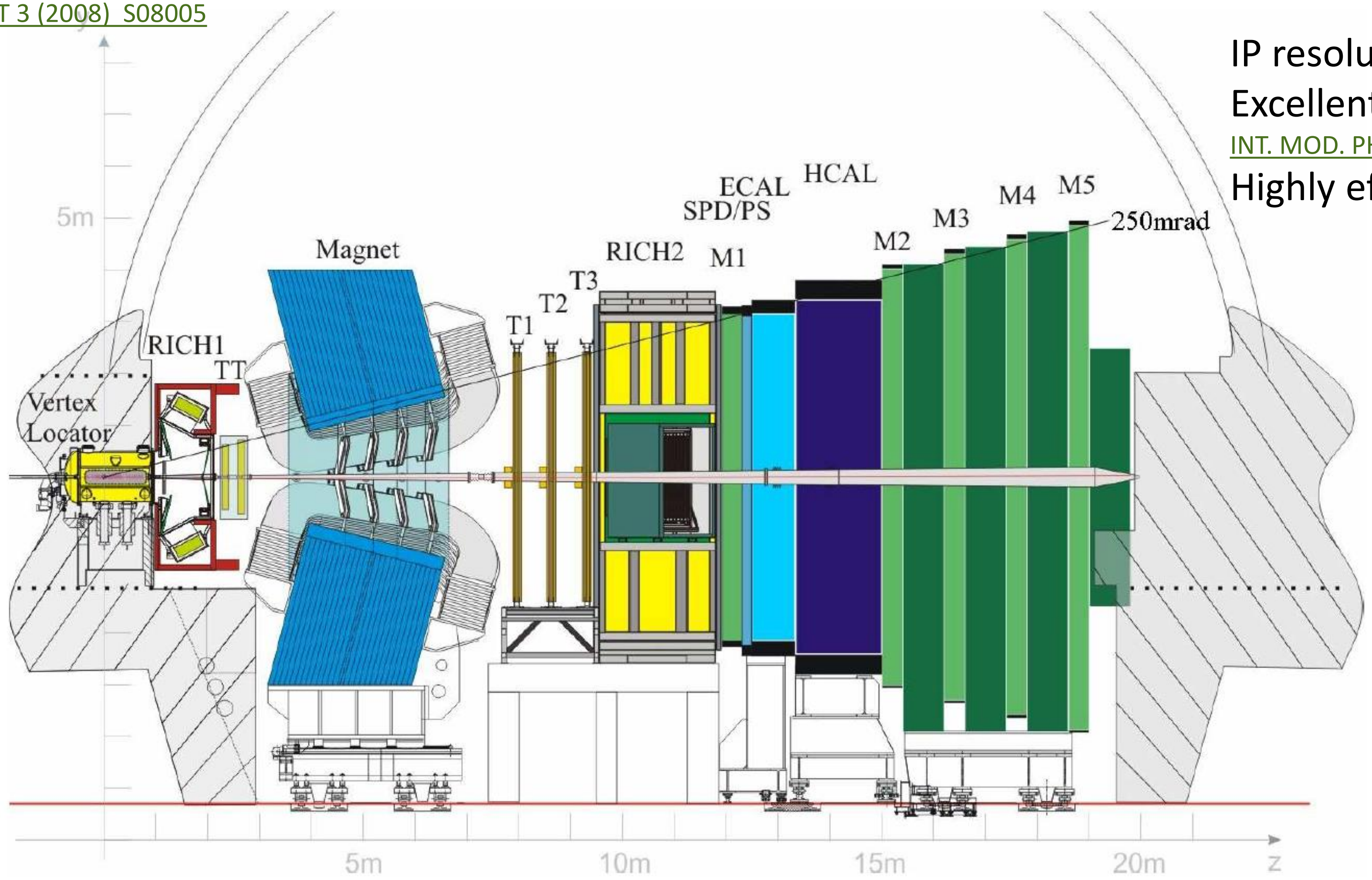
Context Here

- Huge world wide activity on flavour in lepton sector
  - Neutrinos (flavour violation)
  - CERN – LHC can study b decays
    - Future experiments such as MuonE
  - Belle
  - FNAL (g-2, ,mu2e)
  - PSI (mu3e…)
- Theory/Phenomenology…

- Probing for BSM at LHCb
  - Golden Mode
  - B-Decays (EWP)
  - Lepton Universality
    - Angular Tests $b \to s\mu\mu$
    - Ratios of Branching Fractions
      - *b→ sll (FCNC)*
      - *b → clv (CC)*
    - Ratios sensitive to 3rd Generation
  - Lepton Flavour Violation
- The Future
  - LHCb Sensitivities

Detector

JINST 3 (2008) S08005



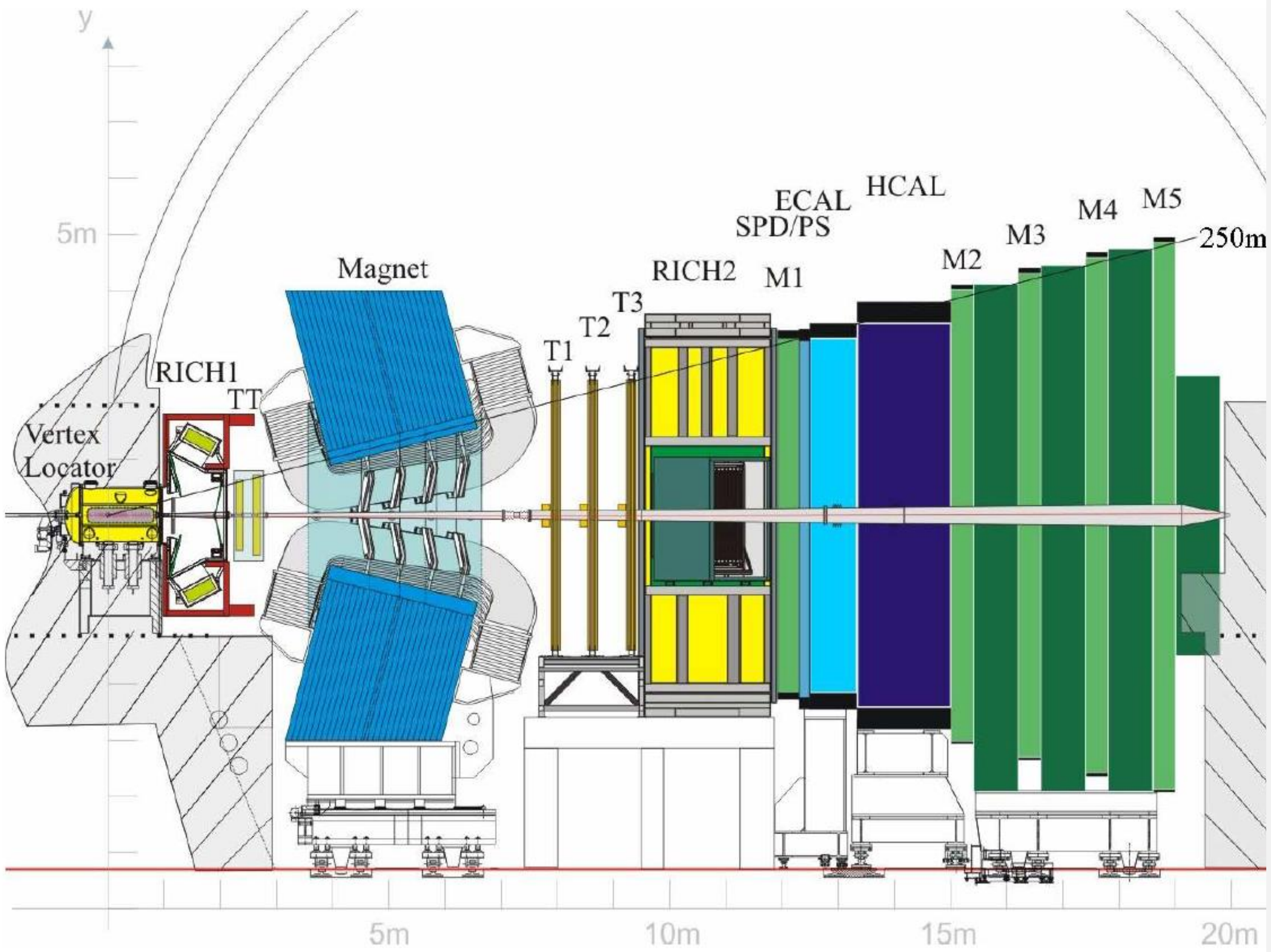
IP resolution ~ 20 μm @high P_T

Excellent vertex reconstruction

INT. MOD. PHYS A30 (2015) 1530022

Highly efficient Particle ID

Detector



Electrons

- 2012: $E_T \gtrsim$ 3 GeV trigger threshold
- Bremsstrahlung influences momentum resolution, requiring "recovery"
- ID

$$e \to e: \quad 90\%$$
$$h \to e: \quad 5\%$$

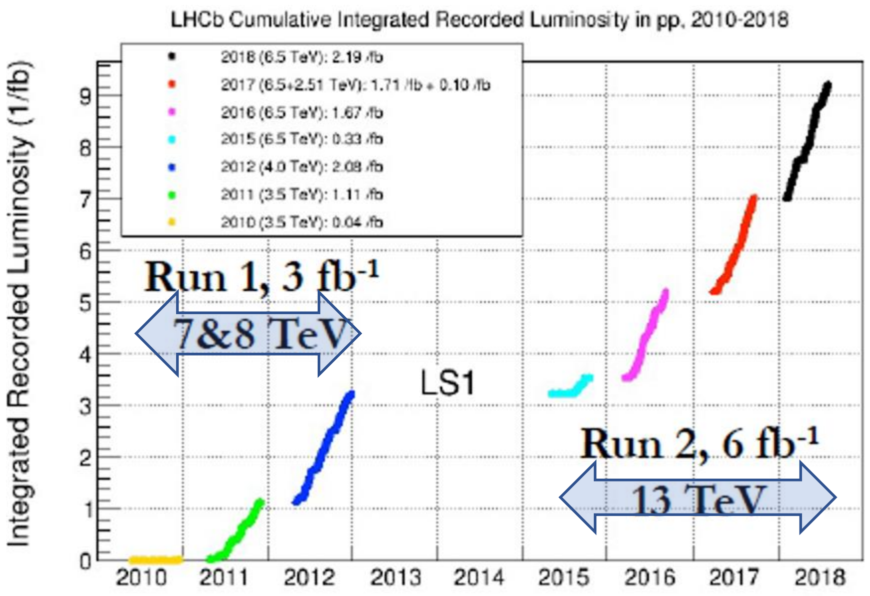
Muons

- 2012: $p_T \gtrsim$ 1.5 GeV trigger threshold (lower)
- ID

$$\mu \to \mu: \quad 97\%$$
$$\pi \to \mu: \quad 1-3\%$$

LHCb sample of B's

- 3fb^{-1} @ 70μb O (10^{11}) B's
- 6fb^{-1} @ 150μb O (10^{12}) B's



$$\sigma_{b\bar{b}}(7\ \text{TeV}) = 72.0 \pm 0.3 \pm 6.8\ \mu\text{b}$$
$$\sigma_{b\bar{b}}(13\ \text{TeV}) = 154.3 \pm 1.5 \pm 14.3\ \mu\text{b}$$

PRL 118 (2017) 052002

Introduction

Golden Mode

Semileptonic Decays

Lepton Universality

Lepton Flavour Violation

Summary

Golden Mode: Fully leptonic $B_s \to \mu^+\mu^-$

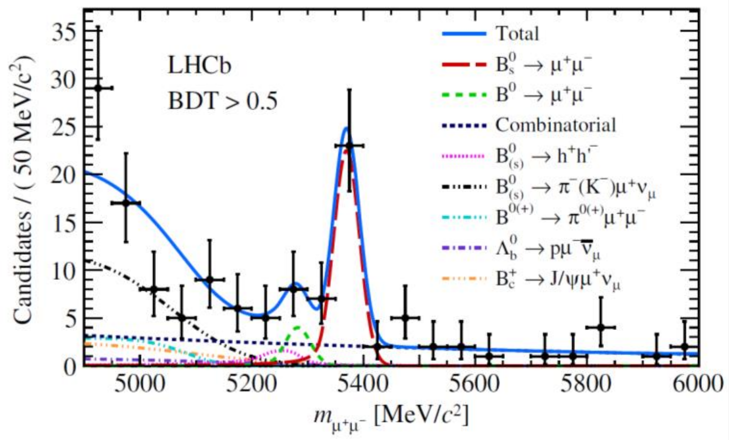
$B_s^0 \to \mu^+\mu^-$

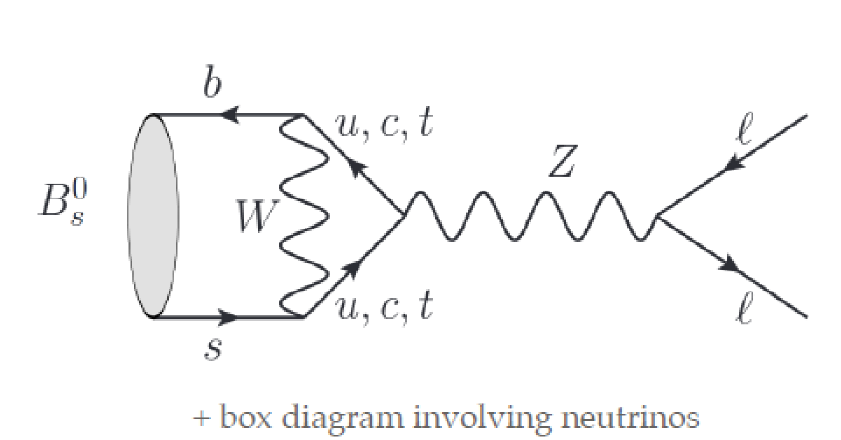
PRL 118(2017)191801

Theory

PRL 112(2014)101801

2017





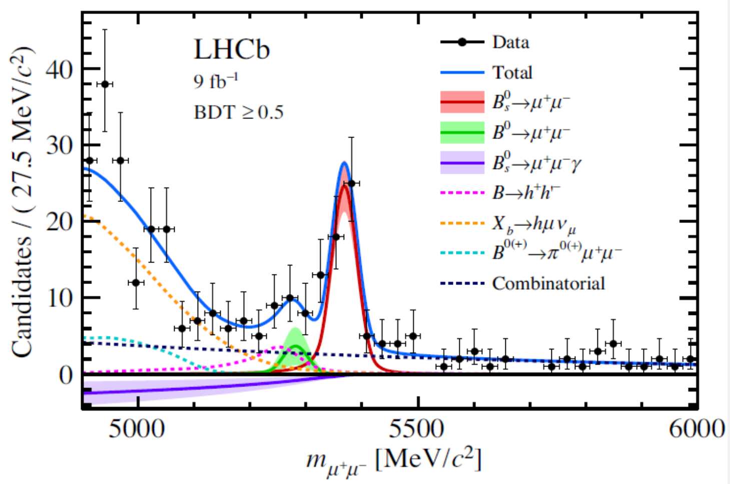
$B_s^0 \to \mu^+\mu^-$

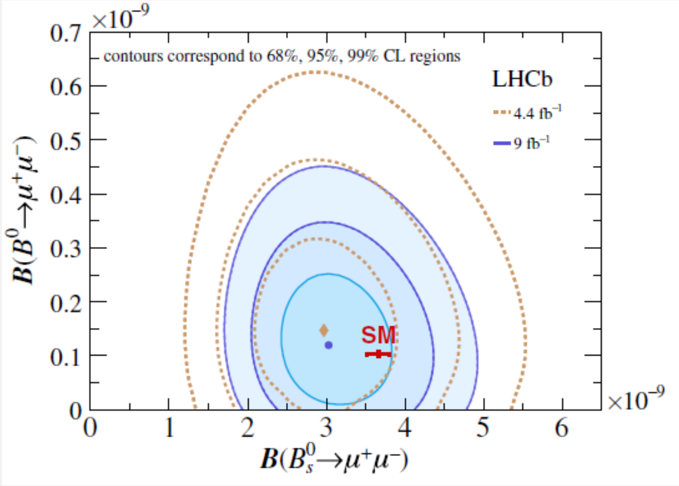
PRL 128(2022)141801

Theory

PRL 112 (2014) 041801
JHEP 10(2019) 232

2022





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PRL 118(2017)191801

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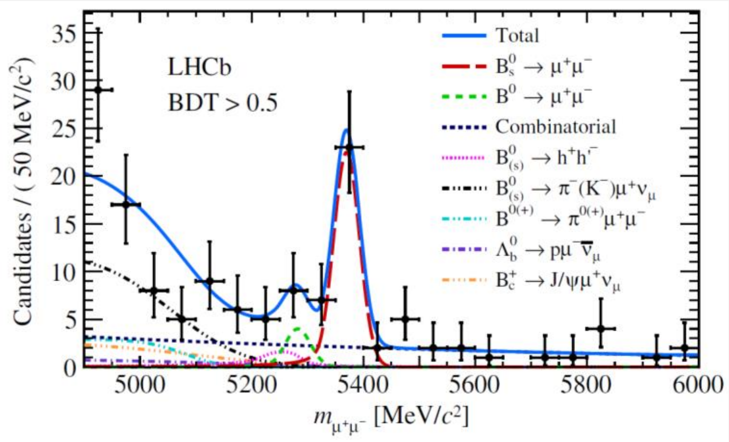
PRL 112(2014)101801

2017



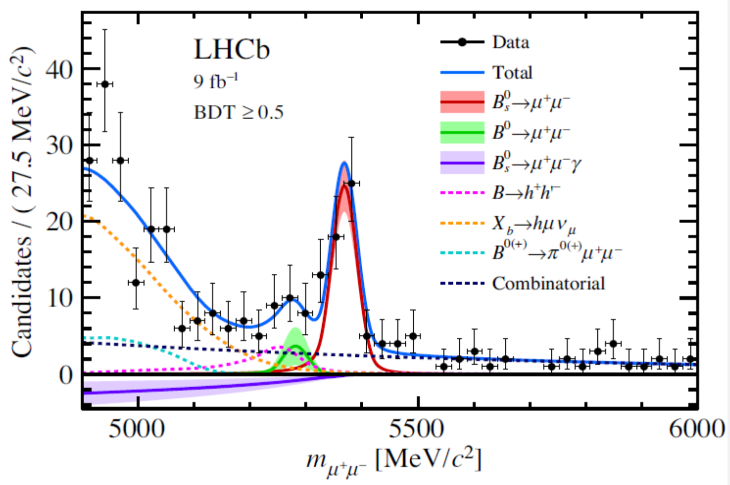
$B_s^0 \to \mu^+\mu^-$

PRL 128(2022)141801

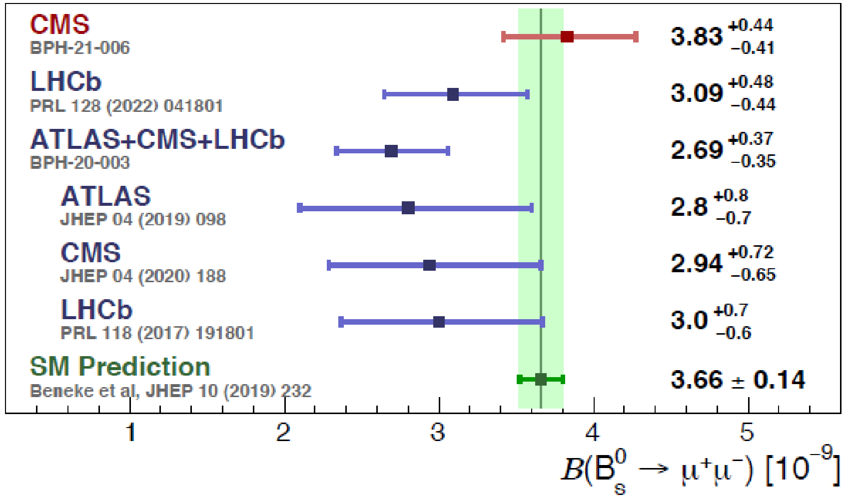
Theory

PRL 112 (2014) 041801
JHEP 10(2019) 232

2022



See CERN Seminar 26 Jul 2022

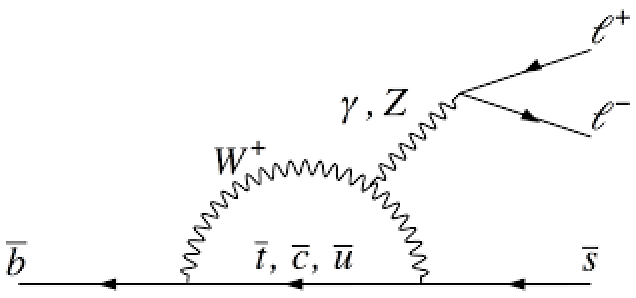


One of our most important rare decay modes shows no sign of anomaly

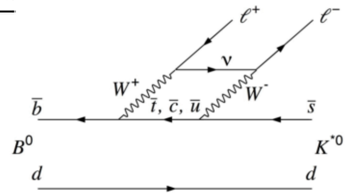
Electro-Weak Penguins

FCNC

- Sensitive to NP in Loops & high mass range
- Fundamental test of couplings to b-quarks
- Semi-leptonic decays
  - Elegant (and reasonably) and "easy" to reconstruct (p, ID, low multiplicity)
  - Hadrons in final and initial state (unlike $B_s \rightarrow \mu^+\mu^-$)



leptons
e, μ, …



Branching Fractions

- "count how many you get" – consistency with SM (i.e. theory?)
- Check as function of kinematics (e.g. q^2= inv. mass of leptons, …)
- Understand (require) hadronic corrections to interpret

"Early" and important tests

Some branching fractions (2014-2021)

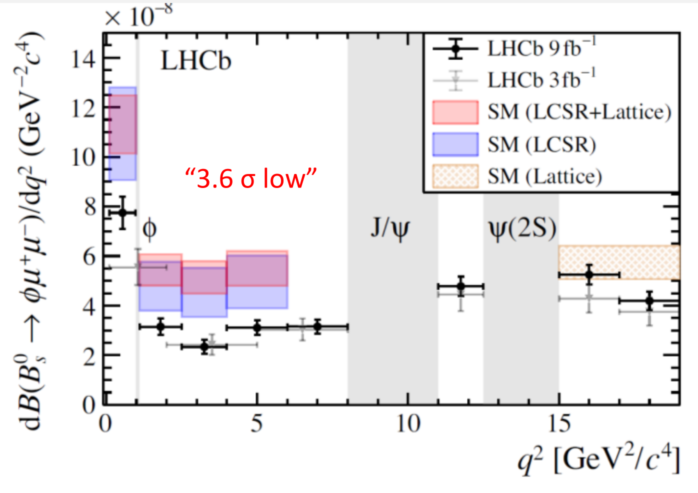
$B_s^0 \rightarrow \phi\mu^+\mu^-$

PRL 127(2021) 151801

Theory

JHEP 08(2016) 098
EPJ C 75 (2015) 382
arXiv: 1810.08132

PRL 112(2014) 212003
PoS LATTICE(2014) 212003

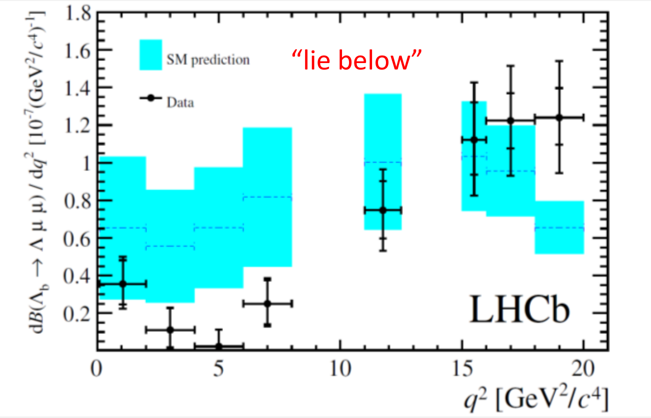


$\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$

JHEP 06(2015) 115
JHEP 09(2018) 145

Theory

PRD 87 (2013) 074502
See also
https://arxiv.org/pdf/1602.01399.pdf

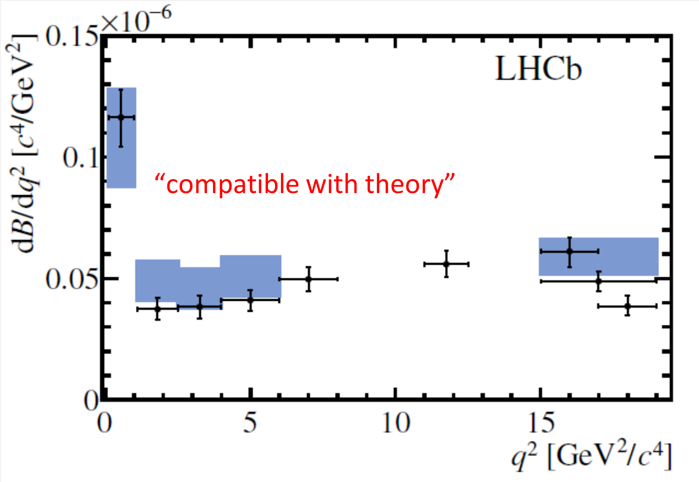


$B^0 \rightarrow K^*(892)^0\mu^+\mu^-$

JHEP11(2016)047

Theory

JHEP 10 (2013) 011
PRD 85 (2012) 034014
NP B 868 (2013) 368

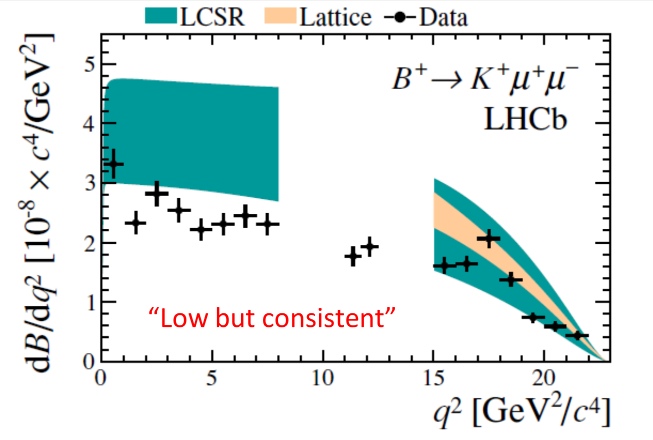


$B^+ \rightarrow K^+\mu^+\mu^-$

JHEP 06(2014) 133

Theory

JHEP 07 (2011) 067
JHEP 01 (2012) 107



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Some branching fractions (2014-2021)

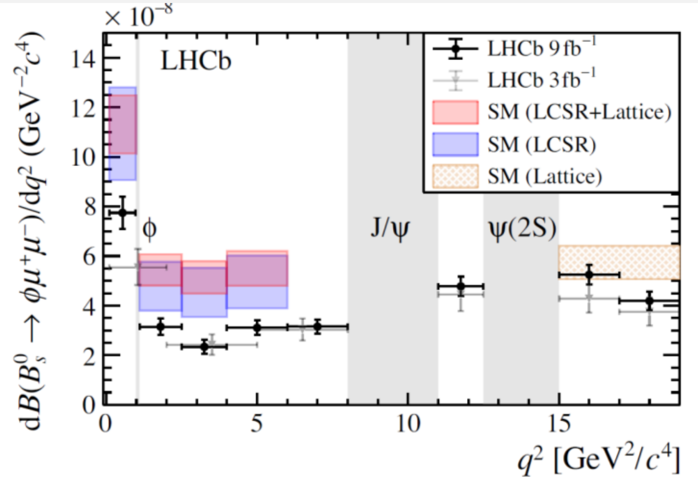
$B_s^0 \to \phi\mu^+\mu^-$

PRL 127(2021) 151801

Theory

JHEP 08(2016) 098
EPJ C 75 (2015) 382
arXiv: 1810.08132

PRL 112 (2014)

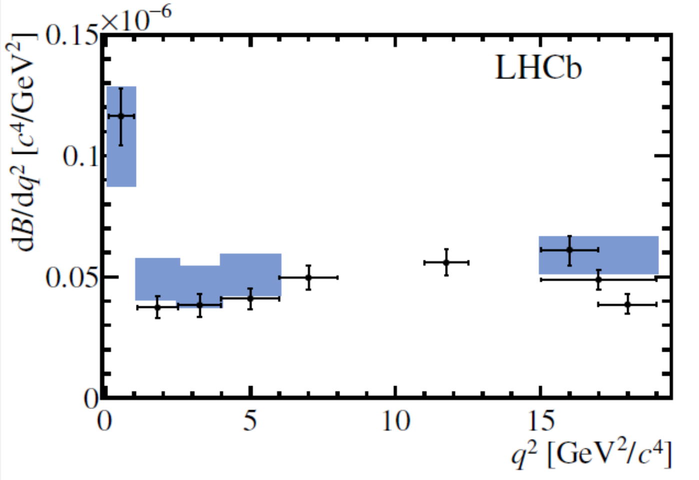


$B^0 \to K^*(892)^0\mu^+\mu^-$

JHEP11(2016)047

Theory

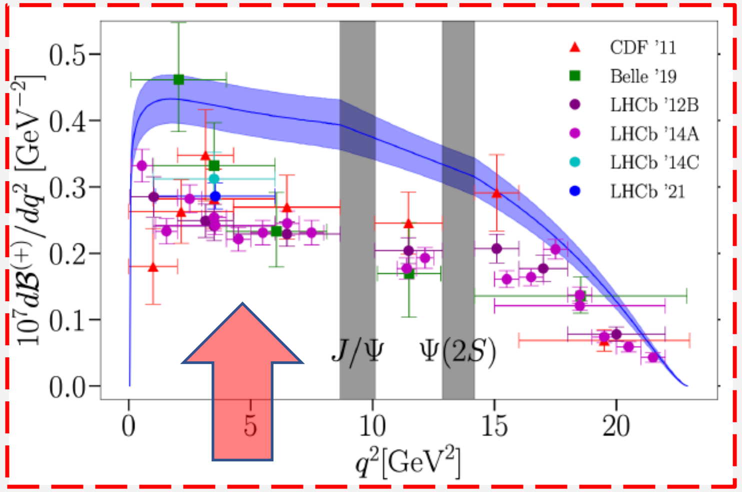
JHEP 10 (2013) 011
PRD 85 (2012) 034014
NP B 868 (2013) 368



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

Lattice perspective and Summary C. Bouchard (CIPANP 2022)

- $1.1 \le q^2/\text{GeV}^2 \le 6$: below $c\bar{c}$ resonances; improved precision and increased tension



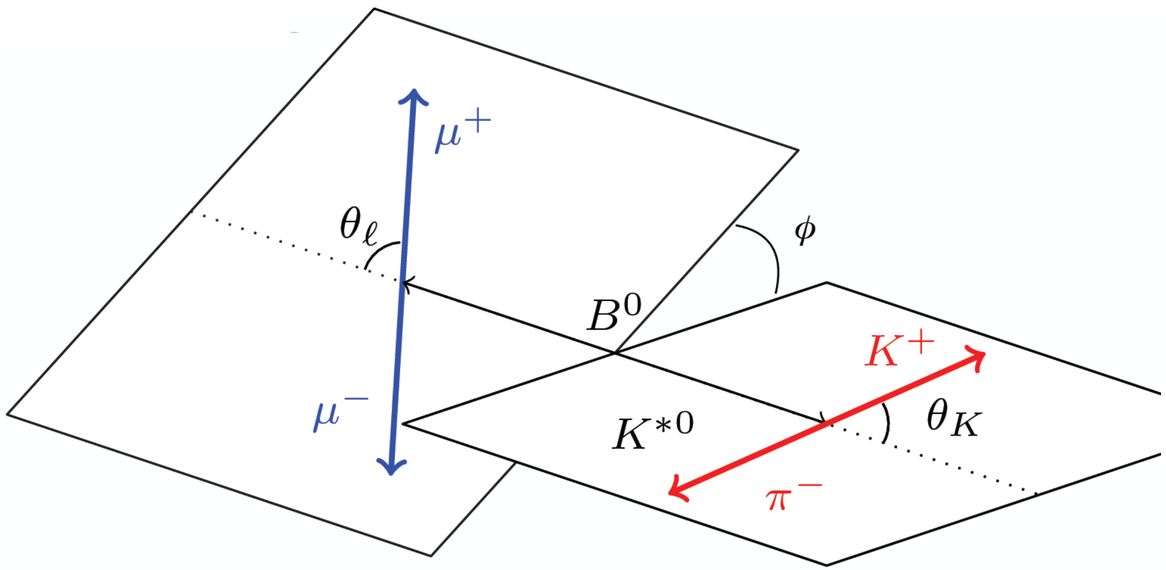
"single experiment (LHCb '14A) approaching … 5σ"

See: https://arxiv.org/pdf/2207.13371.pdf

Angular Analyses - $b \to s\ell\ell$

- Basic decay kinematics in terms of:
  - 3 angles $\theta_\ell, \theta_K, \phi$
  - Invariant mass of the lepton pair
- Cross-sections
- We can also construct optimized variables with sensitivity to NP, study as a $f(q^2)$ for example P_5'
- Acceptance needs care and large yields (differential cross-sections)

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



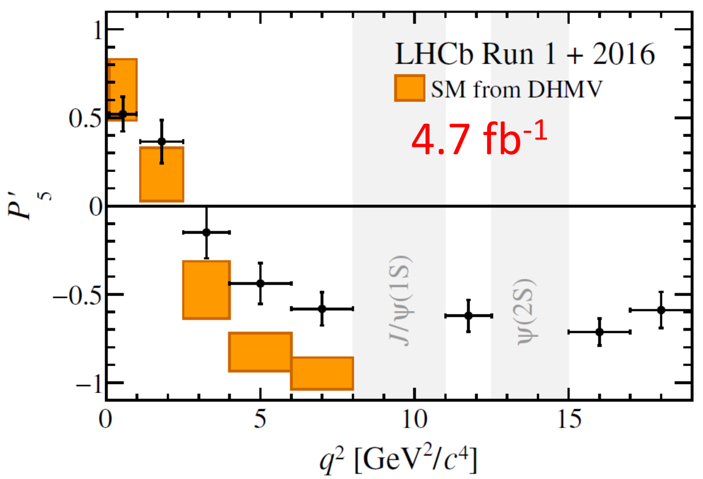
$B^0 \to K^{*0}\mu^+\mu^-$: P_5'

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

PRL 125 (2020) 011802

Theory

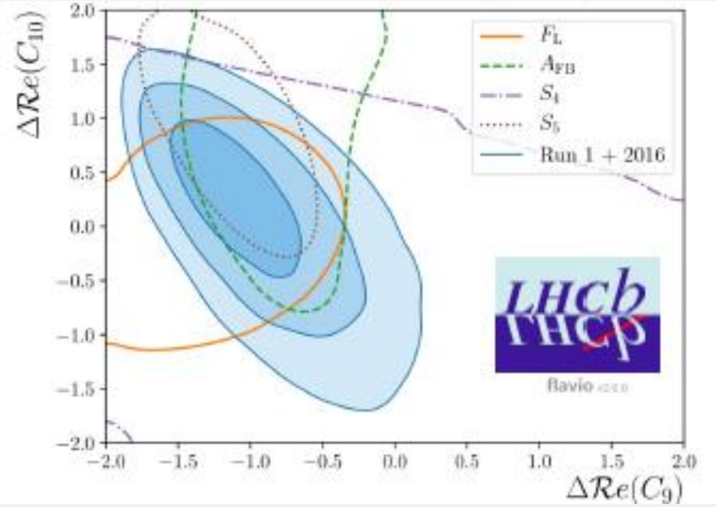
JHEP 12 (2014) 125
JHEP 09 (2010) 089.



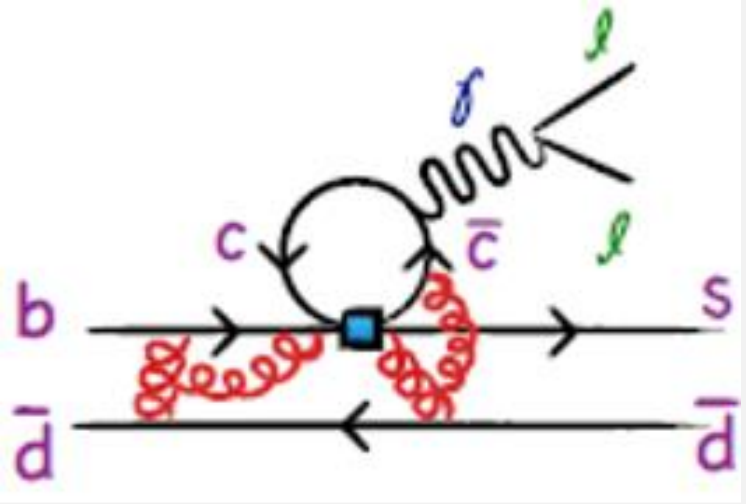
"individual measurements … largely in agreement with the SM predictions"

4600 events

2.7 - 3.3 σ preference for NP with negative $\mathcal{R}e(C_9)$



Charm loops?



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Semileptonic Decays

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Summary

$B^+ \to K^{*+}\mu^+\mu^-$: P_5'

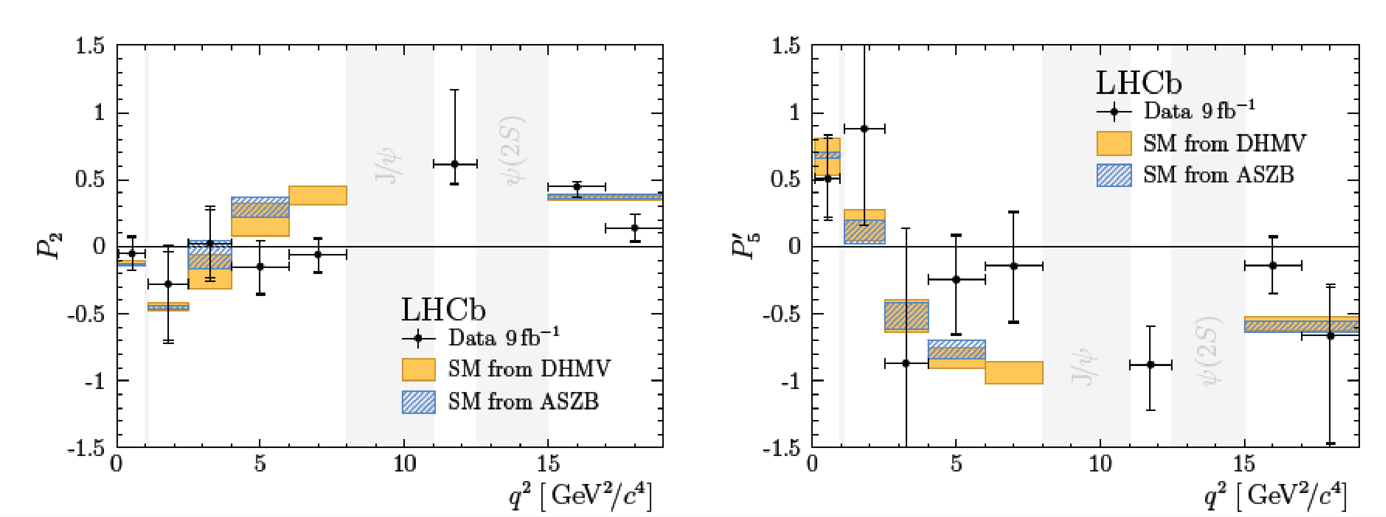
$B^+ \to K^{*+}\mu^+\mu^-$

PRL 126 (2021) 161802

Theory

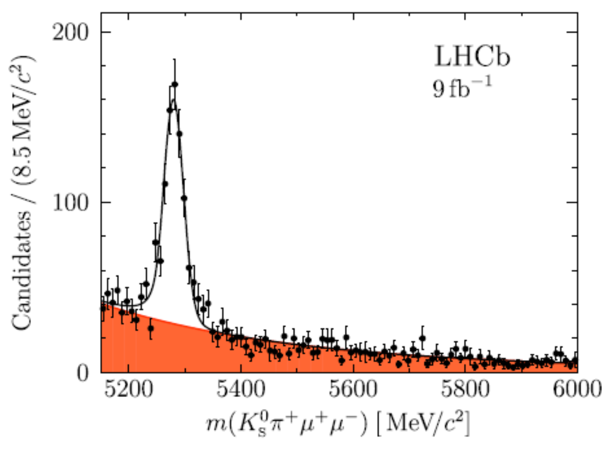
JHEP 08 (2016) 098
PRD 89 (2014) 094501
PoS LATTICE2014 (2015) 372
JHEP 06 (2016) 92

JHEP 01 (2018) 93
JHEP 09 (2010) 089
arXiv:1810.08132



~740 events

"The results confirm the global tension with respect to the SM predictions [3.1σ, $\mathcal{R}e(C_9)$ ~−1.9] "



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

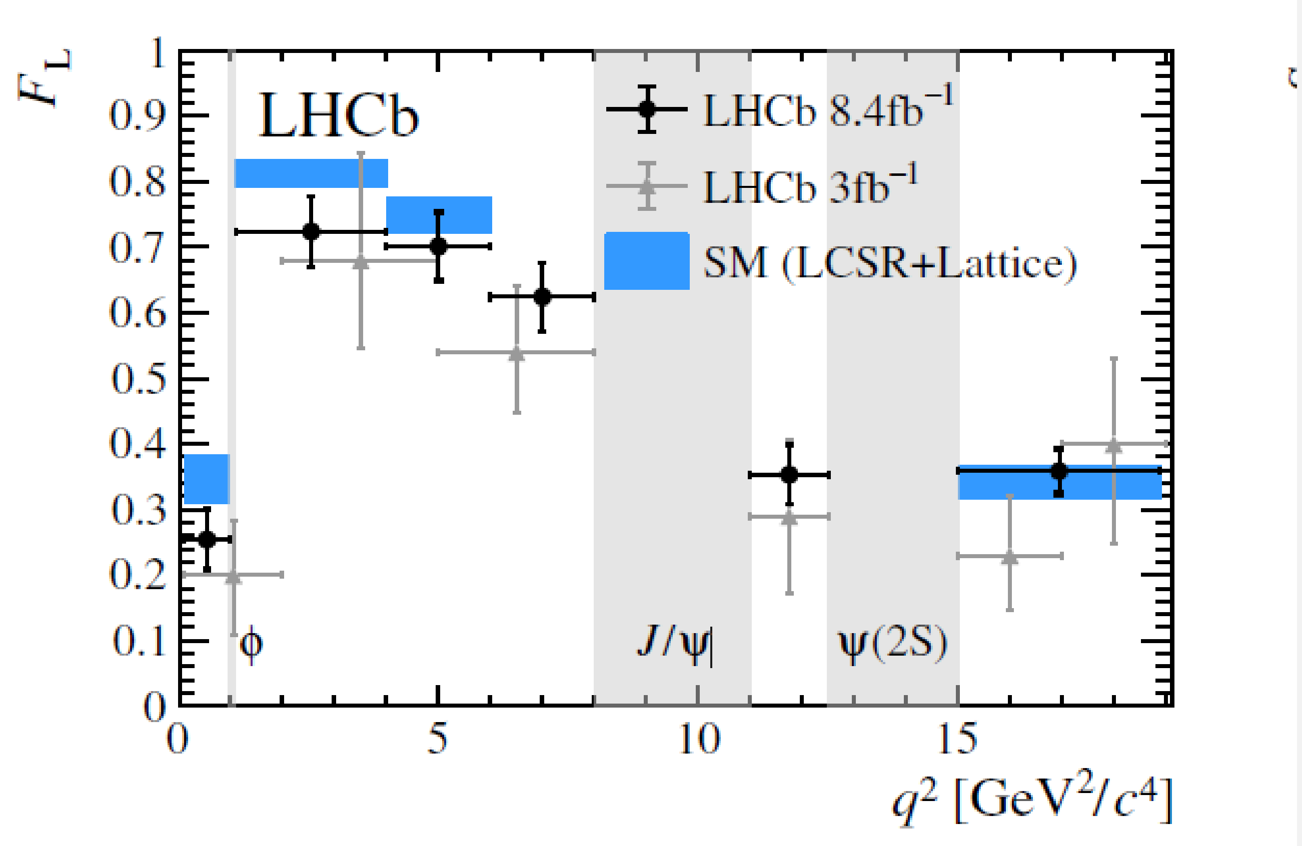
$B_s^0 \to \phi\mu^+\mu^-$

JHEP 11 (2021) 043

Theory

JHEP 08 (2016) 098
arXiv:1810.08132
PRL 112 (2014) 212003
PoS LATTICE2014 (2015) 372

~ 1900 events



Angular distributions are a key tool in our search for NP

"The results are found to be compatible with SM predictions"

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Lepton Flavour Universality: $R_H\ (b \to s\ell\ell)$

- Do electrons, muons (and taus) couple according to the SM? For electrons and muons one way has been: $R_H = \frac{Br(B \to H\mu^+\mu^-)}{Br(B \to He^+e^-)}$
- Experimentally: $R_H = \frac{Number(B \to H\mu^+\mu^-)}{Number(B \to He^+e^-)} \times \frac{\epsilon(B \to He^+e^-)}{\epsilon\,(B \to H\mu^+\mu^-)}$
- Minimize systematics using: $R_{J/\psi} = \frac{Br(B \to HJ/\psi(\mu^+\mu^-))}{Br(B \to HJ/\psi(e^+e^-))} = 1$

ratio of numbers × *ratio of efficiencies* arXiv:2103.11769

$$R_H = \left(\frac{\frac{Number(B \to H\mu^+\mu^-)}{Number(B \to HJ/\psi(\mu^+\mu^-))}}{\frac{Number(B \to He^+e^-)}{Number(B \to HJ/\psi(e^+e^-))}}\right) \times \left(\frac{\frac{\epsilon(B \to He^+e^-)}{\epsilon(B \to HJ/\psi(e^+e^-))}}{\frac{\epsilon\,(B \to H\mu^+\mu^-)}{\epsilon(B \to HJ/\psi(\mu^+\mu^-))}}\right)$$

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Theory Expectation

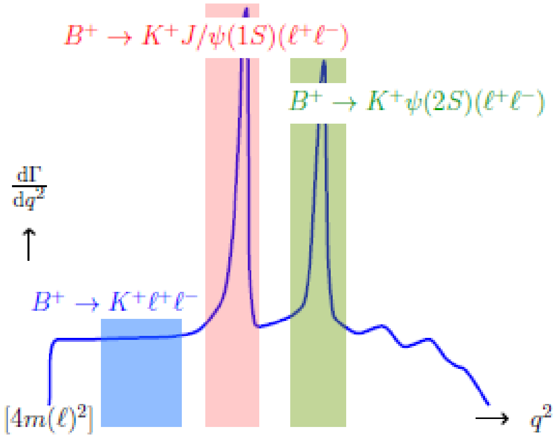
- $R_{K,\,K^*}$

$$R_H[q^2_{\min}, q^2_{\max}] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B \to He^+e^-)}{\mathrm{d}q^2}}$$

EPJ C 76 (2016) 440

"a deviation of R_K or R_{K*} from 1 exceeding the 1 % level, performed along the lines of … in the region 1 GeV^2<q^2<6 GeV^2, would be a clear signal of physics beyond the Standard Model"

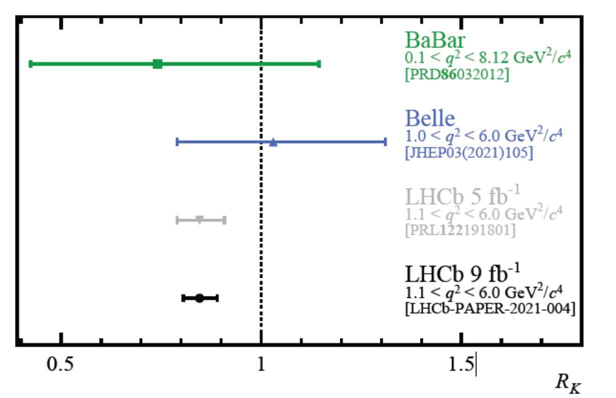
One has a series of complex measurements (and checks) to do.
Can use the 2S region for validation



R_H

R_{K^+}

Nature Phys 18 (2022) 277-282



$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$

Theory

JHEP 06 (2016) 092

JHEP 12 (2007) 040

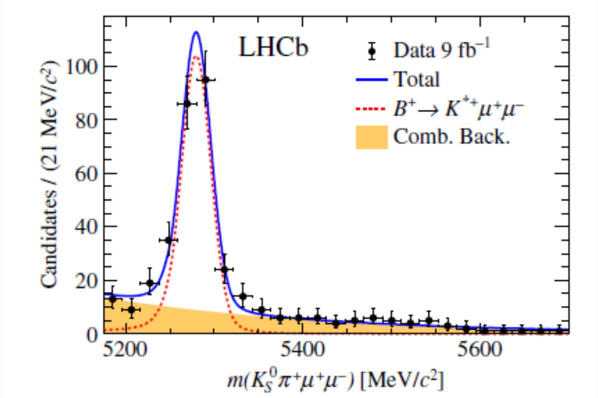
EPJ C76 (2016) 440

arXiv:1810.08132.

arXiv:1810.08132

$R_{K^{*+}}$

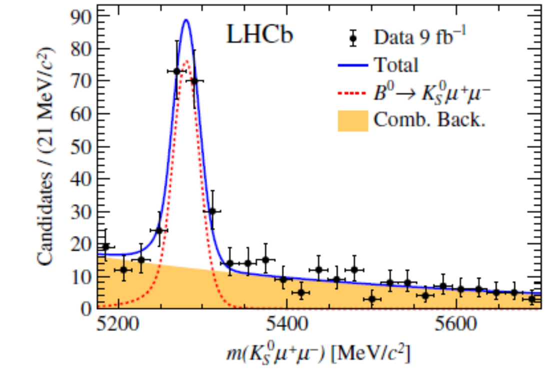
PRL 128 (2022) 191802



$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst}).$

$R_{K^0_S}$

PRL 128 (2022) 191802

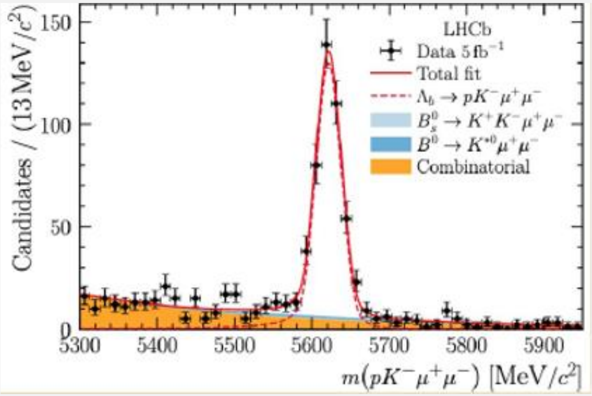


" measurements are individually consistent with the SM … "

$R_{K^0_S} = 0.66^{+0.20}_{-0.14}(\mathrm{stat})^{+0.02}_{-0.04}(\mathrm{syst}),$

R_{pK^-}

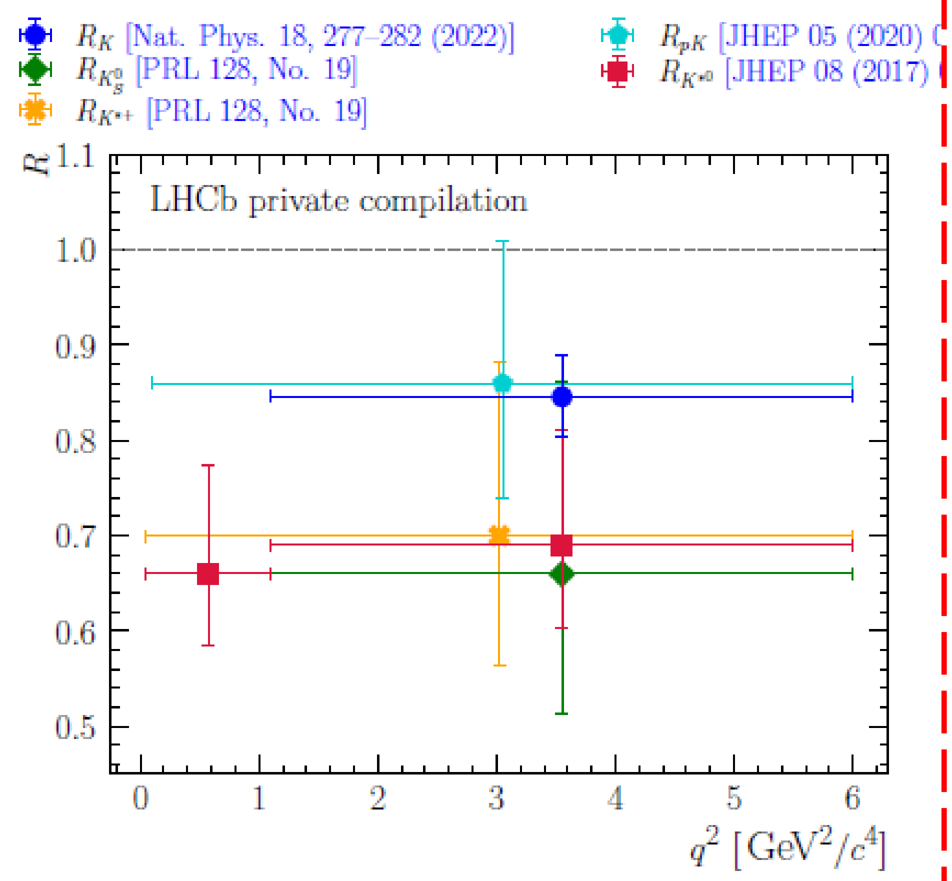
JHEP 08 (2020) 040



$R_{pK}|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86\,^{+0.14}_{-0.11} \pm 0.05,$

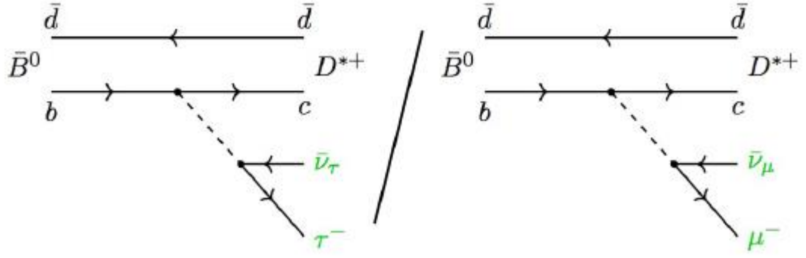
Status

- LHCb working on a unified analysis of R_K and $R_{K^{*0}}$ (isospin partners)
- Final Run 1 and Run 2 results
- Deeper understanding of the measurements
- HIGH PRIORITY for collaboration
- "*We appreciate your patience*"



Schmitt@ICHEP

Lepton Flavour Universality: $R_{H_c}\ (b \to c\ell\nu)$



- Look at 3rd Generation
- Plentiful (CC) Decays
- LFU probe

$$R_{H_c} = \frac{Br(H_b \to H_c \tau \overline{\nu_\tau})}{Br(H_b \to H_c \ell \overline{\nu_\ell})}$$

- Tau decays can be either muonic or hadronic (e.g. 3 pions)
- Neutrinos not detected (MC fits, special fitting)
- Semileptonic decays predicted at O(%) level

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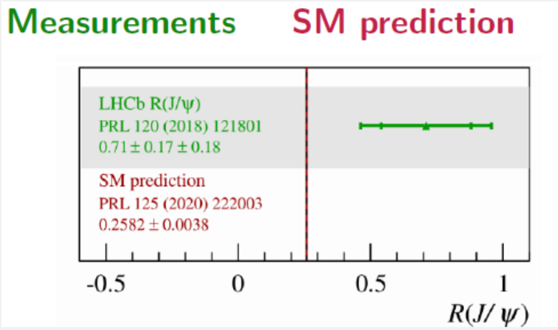
Lepton Flavour Universality: R_{H_c}

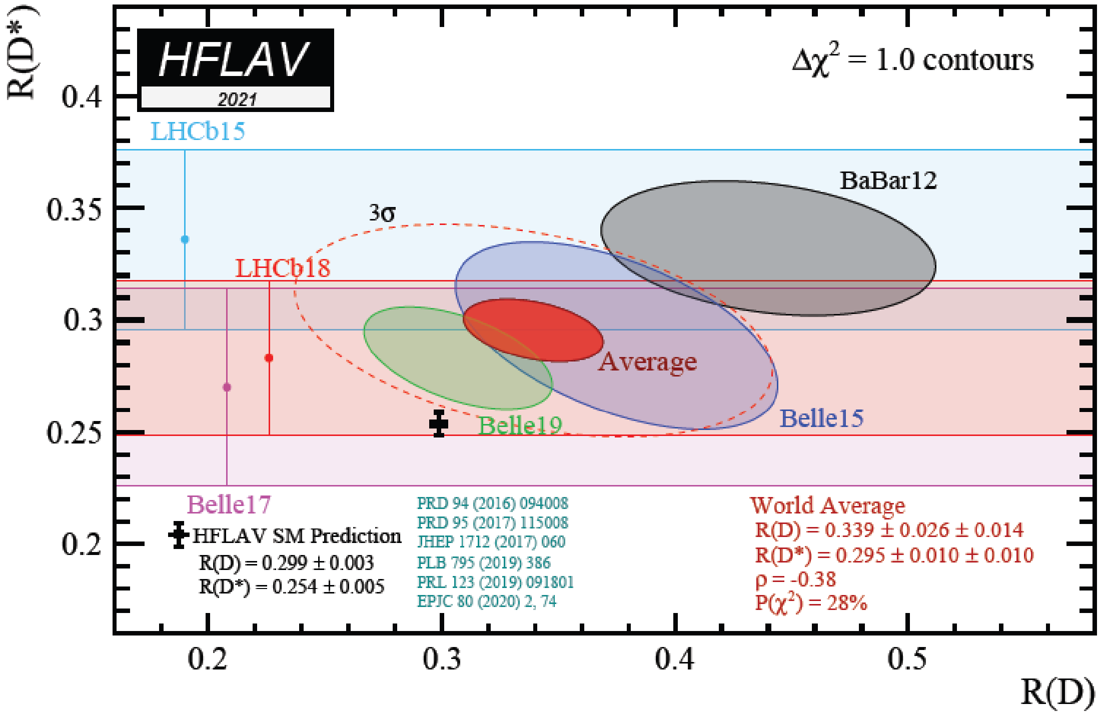
- Some results (Muonic)
  - $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ PRL 115 (2015) 111803 *(2σ from SM)*
  - $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ PRL 120 (2018) 121801 *(2σ from SM)*



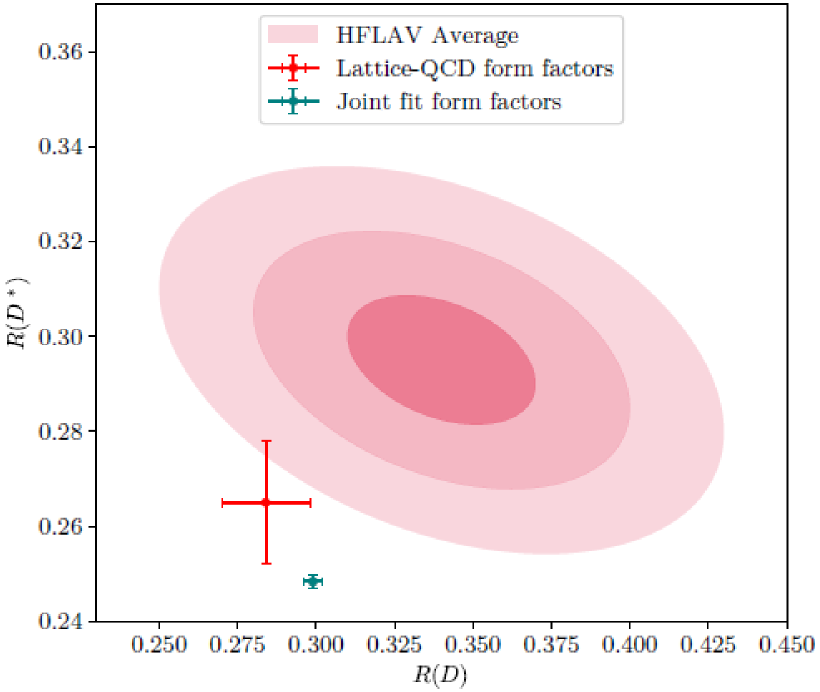
- Some results (Hadronic)
  - $R_{D^*} = 0.280 \pm 0.018 \pm 0.026 + 0.013$(ext Br) PRL 120 (2018) 171802 *(1σ from SM)*
  - new $R_{\Lambda_c} = 0.242 \pm 0.026 \pm 0.040 + 0.059$ (ext Br) PRL 128 (2022) 191803 *(1σ from SM)*

Recent fits to $R_{D^*} - R_D$

arXiv:2206.07501



arXiv:2105.14019



Lepton Flavour (Number) Violation

- LFV decays super-suppressed in SM with *Br* O(10^{-54})
  - Loops
  - Neutrino oscillations
- Evidence of LFV clearly would indicate NP
- LHCb has undertaken a programme of searching for flavour violating effects with electrons and muons as well as muons and taus.

Lepton Flavour (Number) Violation

$B^+ \to K^+ e^\pm \mu^\mp$	$< 7.0\times10^{-9}$ *	Phys. Rev. Lett. **123** (2019) no.24, 241802
$B^+ \to K^+ \mu^\pm \tau^\mp$	$< 3.9\times10^{-5}$ *	JHEP **06** (2020), 129
$B^0_{(s)} \to e^\pm \mu^\mp$	$< 1.0\times10^{-9}$ *	JHEP **03** (2018), 078
$B^0_{(s)} \to \mu^\pm \tau^\mp$	$< 3.4\times10^{-5}$ *	Phys. Rev. Lett. 123 (2019) no.21, 211801)
$B^0_{(s)} \to p \mu^-$	$< O(10^{-8})$	LHCb-paper-2022-022 (in preparation - from Dordei @NUFACT)
$B^0 \to K^{*0} \mu^\pm \tau^\mp$	$< O(10^{-5})$	LHCb-paper-2022-021
$B^0 \to K^{*0} e^\pm \mu^\mp$	$< O(10^{-8})$	LHCb-paper-2022-008 (in preparation - from Dordei @NUFACT)
$B^0_s \to \phi e^\pm \mu^\mp$	$< O(10^{-8})$	LHCb-paper-2022-008 (in preparation - from Dordei @NUFACT)

Note the tau decay modes limits https://arxiv.org/abs/2207.04005

** I have only given the higher of two numbers !*

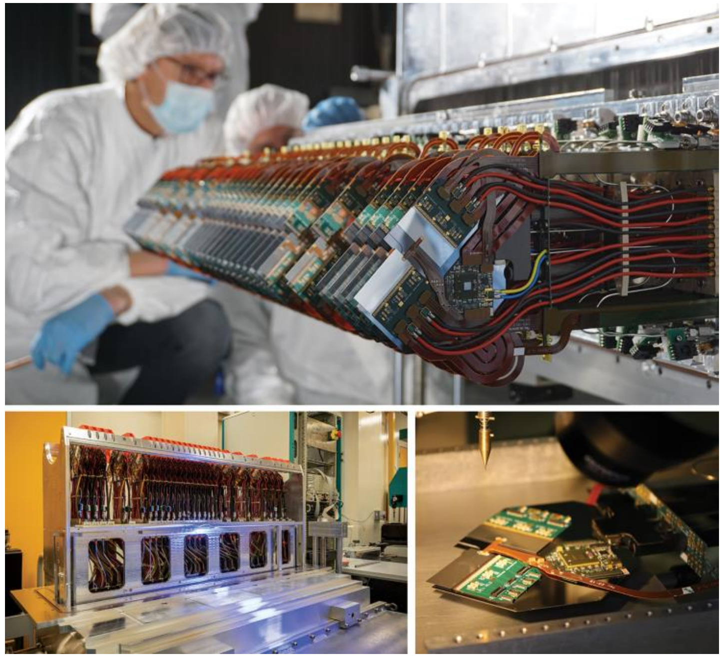
Evidence for NP from Anomalies

- LHCb opens a unique window on SM and potential BSM physics at the LHC thanks to its detector configuration
- Almost all measurements are well understood within the standard model
- The excitement in the muon sector (not least from g-2!) makes the tests we can perform especially important
- No "obvious" signature of NP in exclusive and semileptonic decays nor in tests of lepton universality and lepton flavour violation
- Global fits (not discussed here) and indications (e.g. in FCNC angular distributions) exhibit chronic tensions with SM
  - (where not done already) measurements should be done with full Run 1 & 2 data
  - Extended R_K studies a priority
- More data in Run 3 (and of course other experiments add to landscape)

Future

- Extensive and exciting Physics Programme for Run 3
  - Expand anomaly search to baryons?
- New detector capabilities (e.g. VELO) for improved performance with new 40 MHz trigger
- Example: (from Schmitt @ ICHEP22) a huge step forwards

R_X	$9\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
R_K	0.043	0.017
$R_{K^{*0}}$	0.052	0.020
R_ϕ	0.130	0.050
R_{pK}	0.105	0.041
R_π	0.302	0.117



Thanks

- To FCCP for invitation
- To my colleagues for the amazing achievement of designing, building, commissioning, operating and analysing the data from LHCb.

Backup