# Experiment - Rare decays

## Test the Standard Model with meson decays


FSP LHCb
Erforschung von Universum und Materie

Heisenberg-Programm
Deutsche Forschungsgemeinschaft DFG

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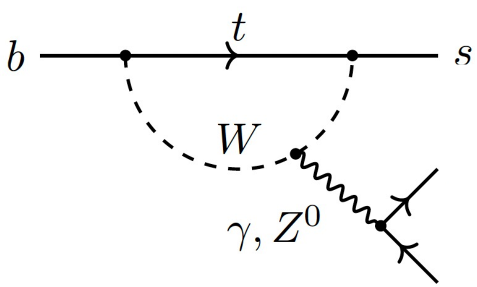
# Content

- Rare decays:
  - leptonic
  - $b \to s\, \ell^+ \ell^-$
  - Radiative decays

# Testing $b \to s\, \ell^+\ell^-$ transitions

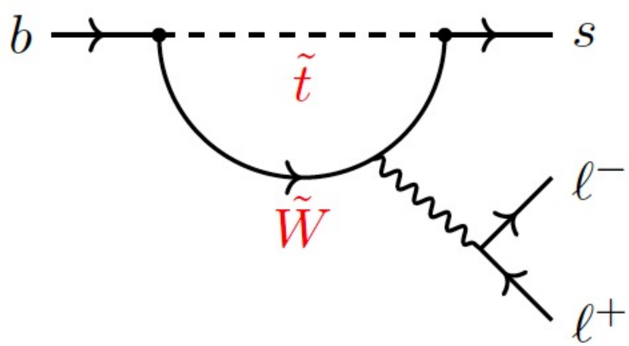
$b \to s\ell\ell$ decays in the SM



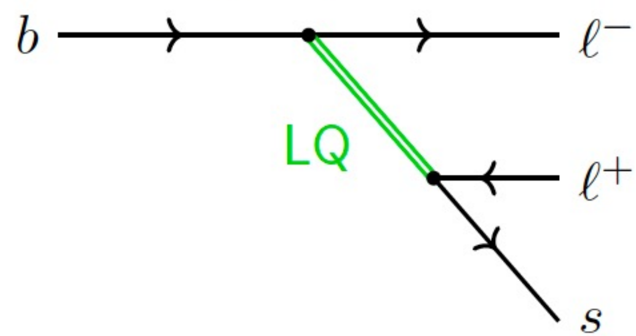

## $\to s\ell\ell$ decays in the SM

## Possible contributions from NP

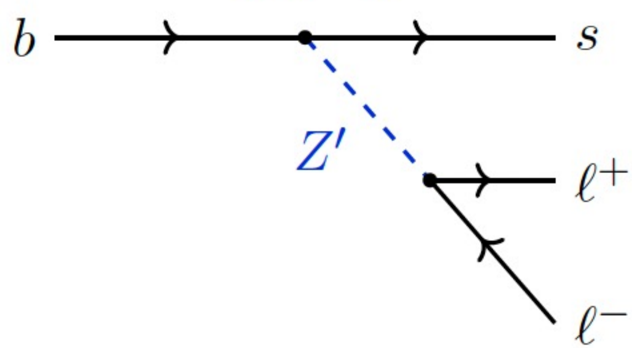
Supersymmetry




Leptoquarks

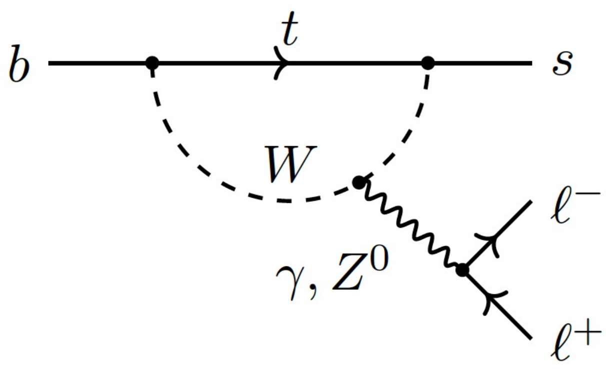



New heavy gauge bosons



# Testing $b \to s \ell^+\ell^-$ transitions

## $b \to s \mu^+\mu^-$ base diagram




- Purely leptonic
  - "add nothing"

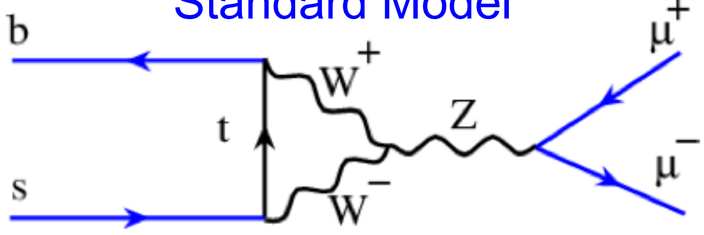
- Semileptonic
  - add d quark as spectator
    → $B^0 \to K^{*0} \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \to \phi \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \to K^+ \mu^+\mu^-$

## Theory prediction: Standard Model

| decay | SM |
|---|---|
| $B_s \rightarrow \mu^+\mu^-$ | $3.66 \pm 0.14 \times 10^{-9}$ |
| $B^0 \rightarrow \mu^+\mu^-$ | $1.1 \pm 0.1 \times 10^{-10}$ |

SM: Bobeth, Stamou et al: PRL112(2014)101801
Beneke et al, JHEP10(2019)232
Mixing effects: Fleischer et al, PRL109(2012)041801

Standard Model

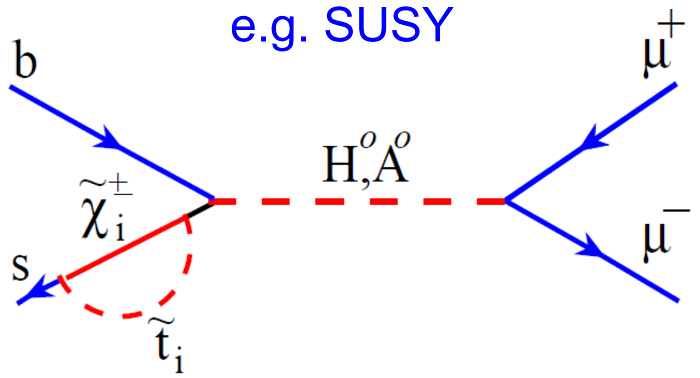



Left handed couplings
→ helicity suppressed

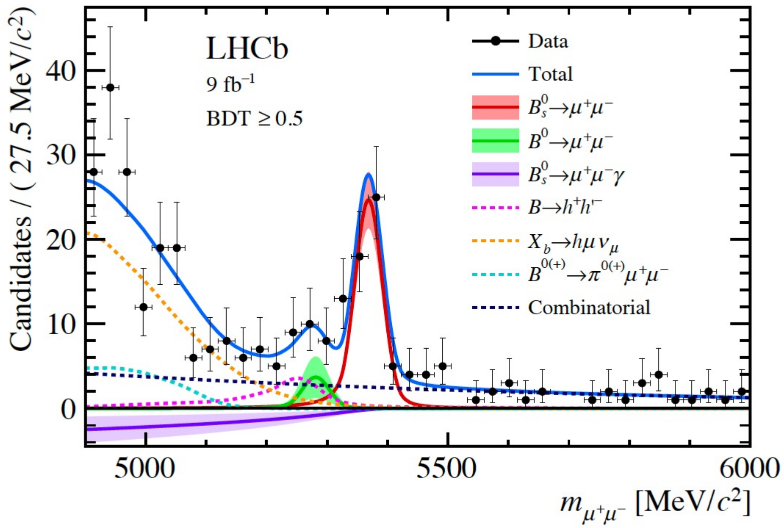
## Discovery channel for New Phenomena

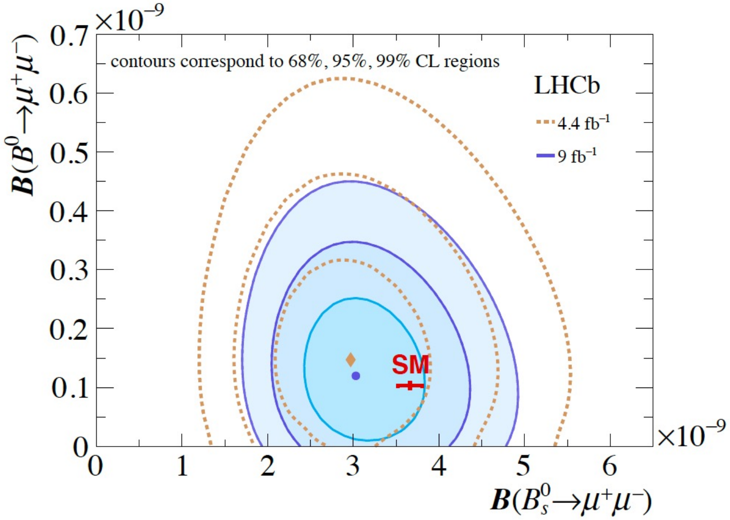
➔ Very **sensitive to an extended scalar sector**
(e.g. extended Higgs sectors, SUSY, etc.)

e.g. SUSY



[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]



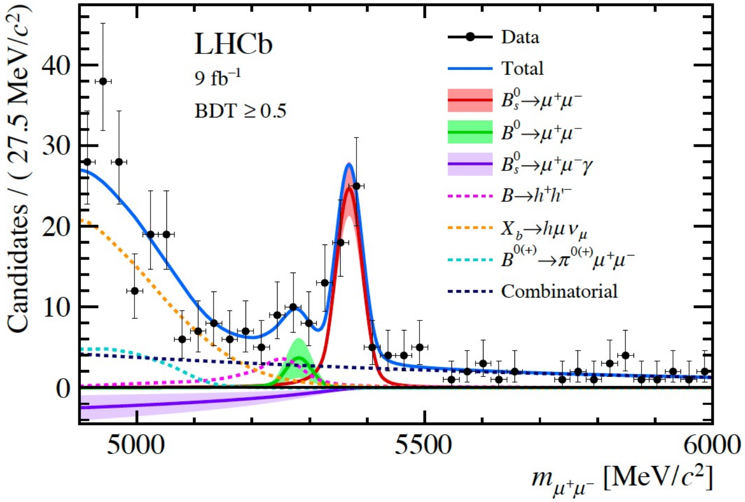




- Recent LHCb measurement [PRL 128 (2022) 041801] [PRD 105 (2022) 012010]

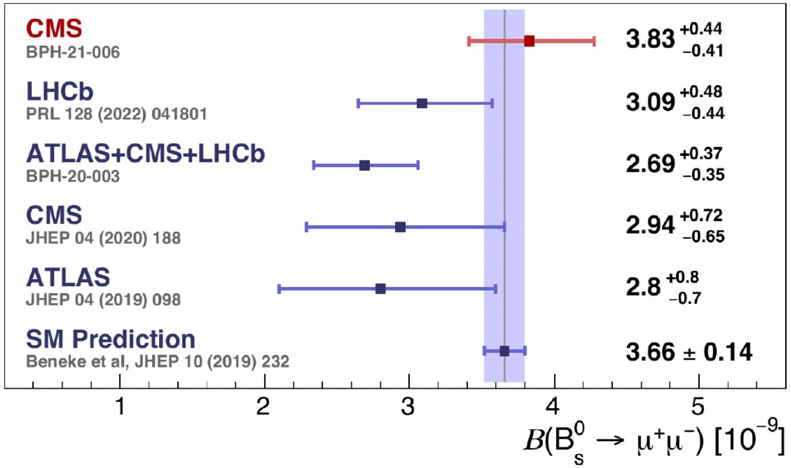
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46\,+0.15}_{-0.43\,-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10} \quad (\mathcal{B} < 2.6 \times 10^{-10} \text{ @ } 95\%\,\text{CL})$$

# Golden channel: $B_{s,d} \to \mu^+\mu^-$ from LHCb .. and CMS

[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]




[CMS-PAS-BPH-21-006]




- New precise CMS measurement moves average further to SM [CMS-PAS-BPH-21-006]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.83^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.37^{+0.75}_{-0.67}{}^{+0.08}_{-0.09}) \times 10^{-10} \quad (\mathcal{B} < 1.9 \times 10^{-10} \text{ @ } 95\% \text{ CL})$$

- Precision approaches 10%

- Chapeau to our CMS colleagues. Inspires hard work for LHCb

# Effective lifetime

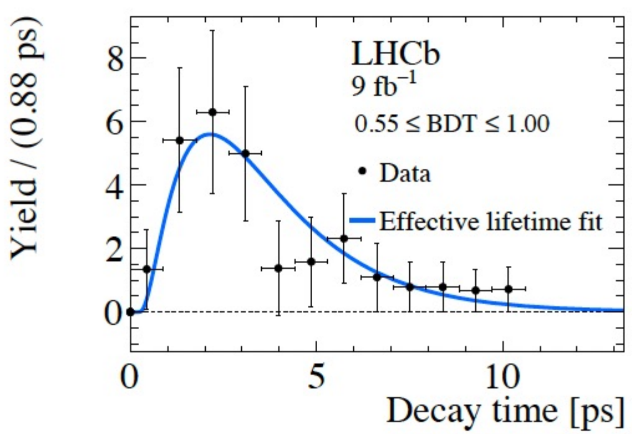
- The decay time distribution gives access to complementary information related to $B_s^0$-$\overline{B}_s^0$ mixing.
- The SM predicted *effective lifetime* is equal to that of the heavy $B_s^0$ mass eigenstate: [PRL 109 (2012) 041801]

[PTEP 2022 (2022) 083C01]

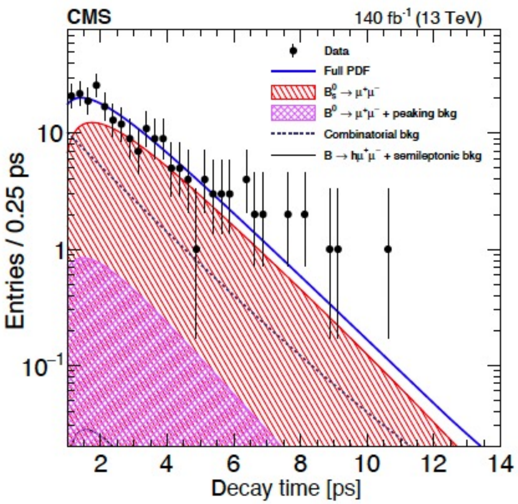
$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\Gamma(B_s^0(t)\to\mu^+\mu^-)\,dt}{\int_0^\infty \Gamma(B_s^0(t)\to\mu^+\mu^-)\,dt} \stackrel{\text{SM}}{=} \tau_H = 1.624 \pm 0.009$$

[PRD 105 (2022) 012010]

(Bkg. subtracted)




[arXiv:2212.10311]



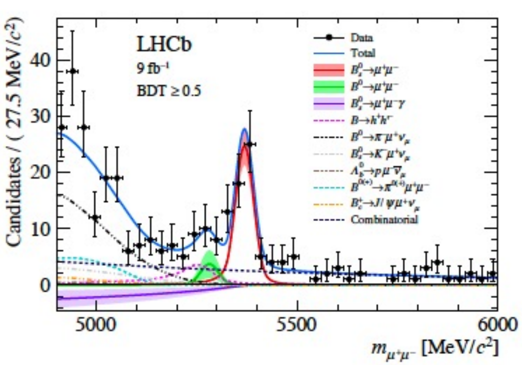

Results are consistent with SM expectation of $\tau_{\mu^+\mu^-} = \tau_H$ at $1.5\sigma$ (LHCb) and $1\sigma$ (CMS).

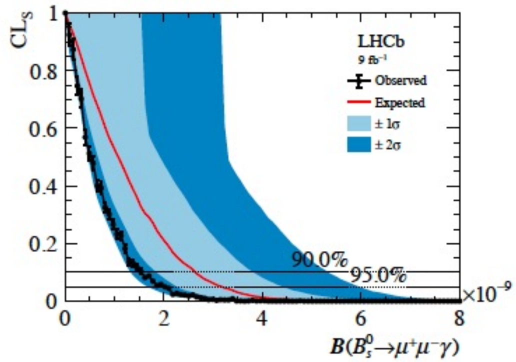
**LHCb**: $\tau_{\mu^+\mu^-} = \mathbf{2.07 \pm 0.29}$ (stat.) $\pm$ **0.03** (syst.) ps

**CMS**: $\tau_{\mu^+\mu^-} = \mathbf{1.83^{+0.23}_{-0.20}}$ (stat.)$^{+0.04}_{-0.04}$ (syst.) ps

## $B_s^0 \to \mu^+\mu^-\gamma$ [PRD 105 (2022) 012010]

ISR contribution in high $q^2$ region.



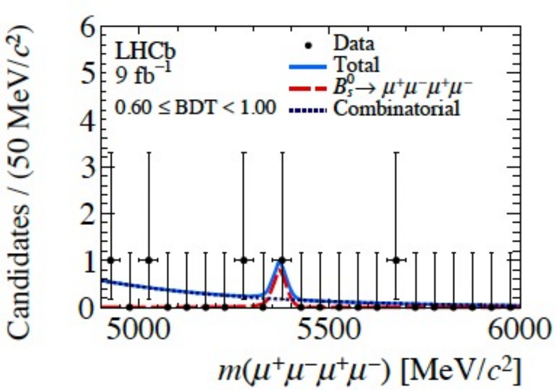

Issues: SM prediction

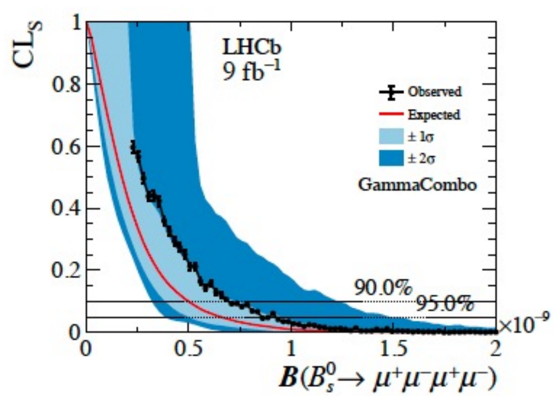
LHCb: $B \to \mu\mu\gamma\ \ no\ \gamma$

Reconstructed photon in progress

## $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ [JHEP 03 (2022) 109]

fully non-resonant.

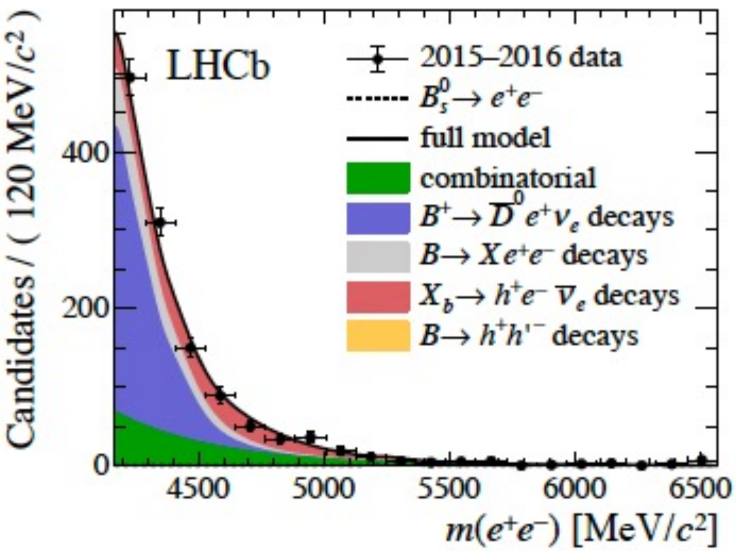


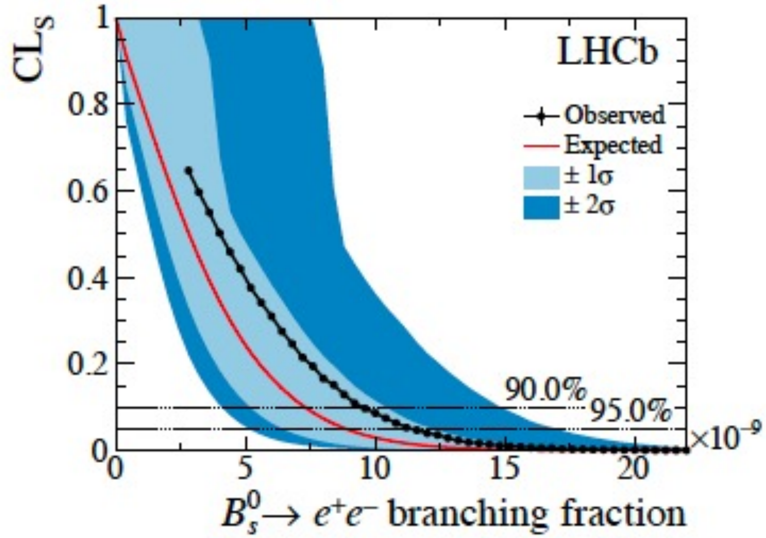




Search for light scalars

motivation for more studies in four leptons

$\boldsymbol{B_s^0 \to e^+e^-}$
[PRL 124 (2020) 211802]

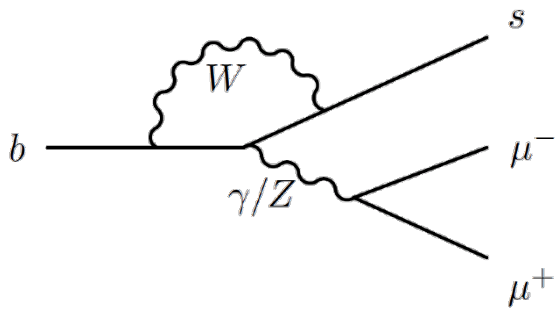


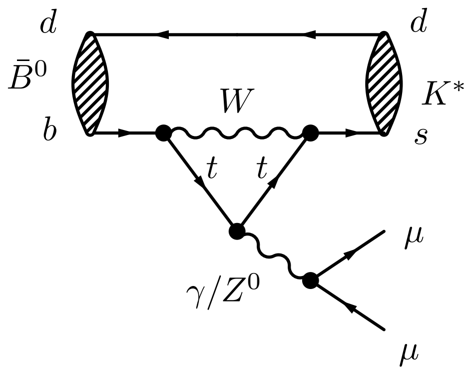




„Just bad muons?“
Increased helicity suppression makes $B \to e^+e^-$ a clean Null test

Similarly for LFV decays (not discussed here)

## $b \to s\ \mu^+\mu^-$ base diagram

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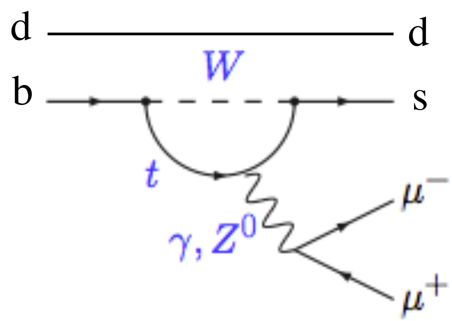
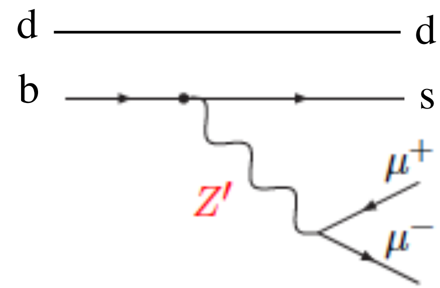
# Angular analysis of $B^0 \to K^{*0} \mu^+\mu^-$




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

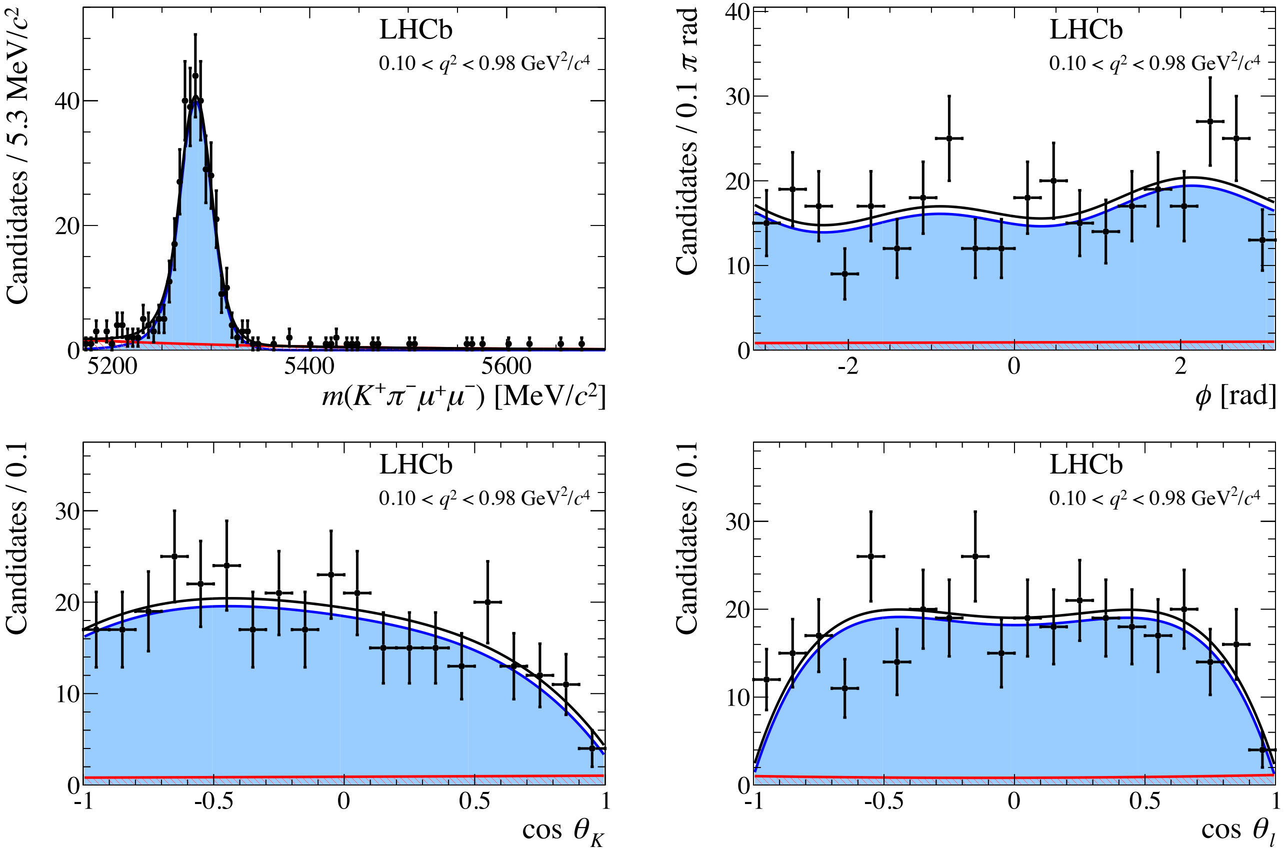
fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

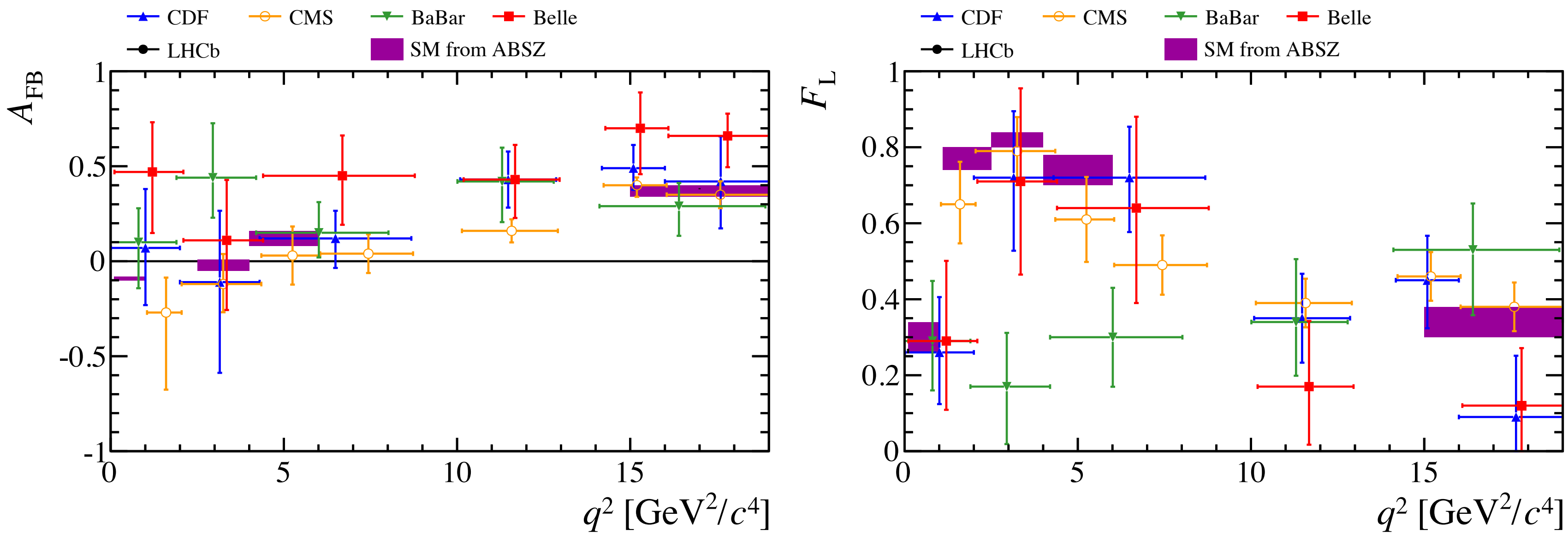
Observables depend on B→K* form factors and on short distance physics

- 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 $q^2 = m_{\mu\mu}^2$

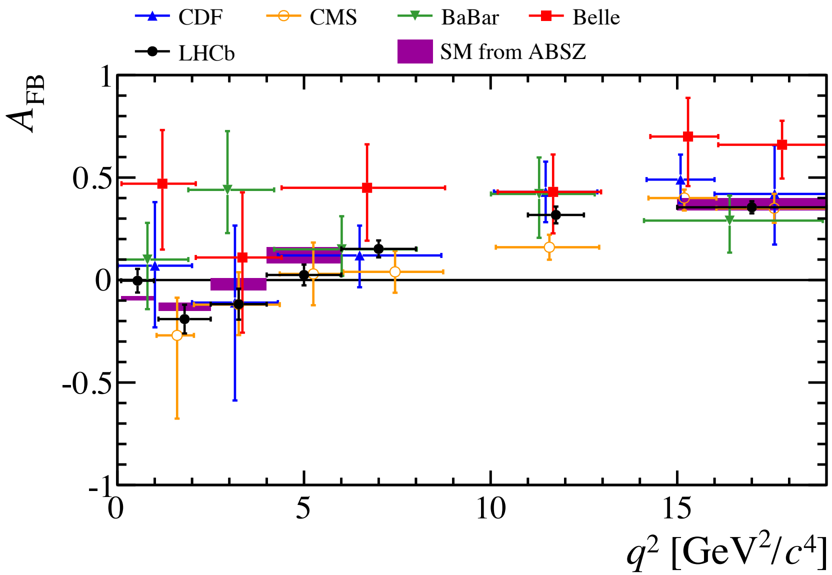
Example fit projections in low $q^2$ bin

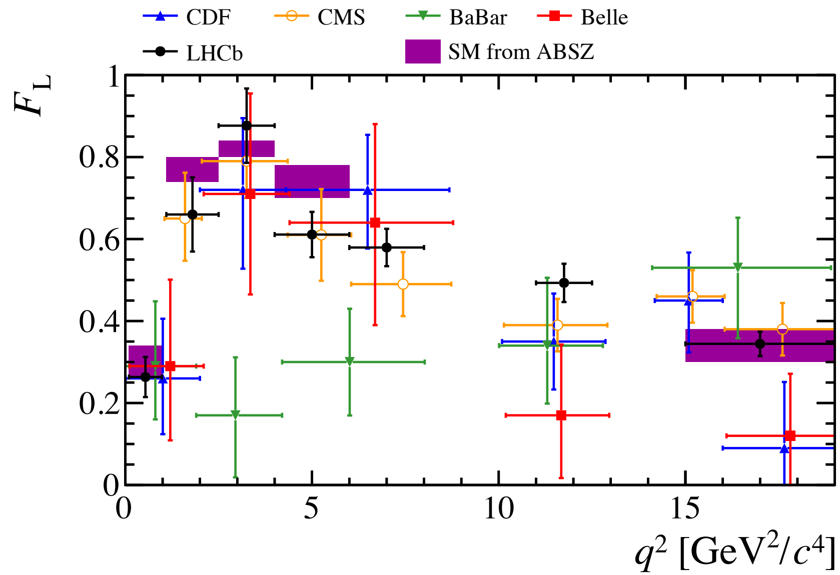


# Results




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].




- Situation unclear. Clean up by smarter observables

$P_i^{(\prime)}$ **basis**

***Reparameterise the fit to obtain optimised observables:***

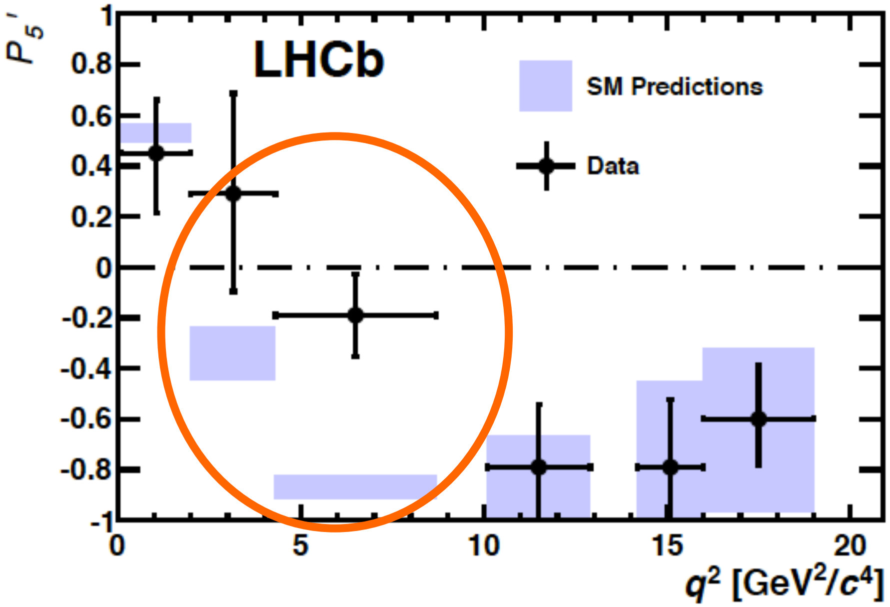
*form factor uncertainties cancel at first order*

**JHEP 12 (2014) 125, JHEP 09 (2010) 089**

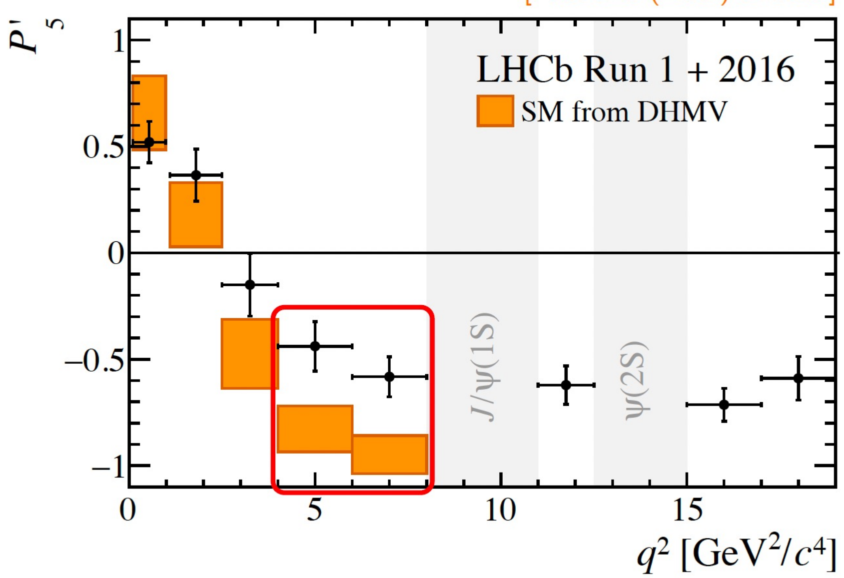
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.Rev.Lett. 111 (2013) 191801




[PRL 125 (2020) 011802]



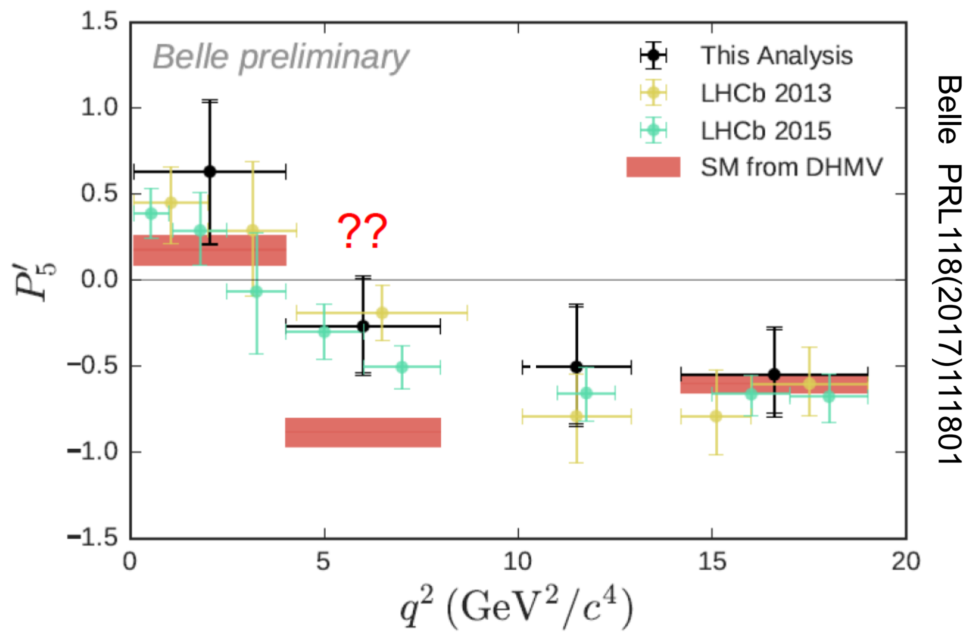

- Full Run 1 analysis confirms effect
  Run 2 update coming

# Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys. …

## Belle still has a word to say




Lower statistical power, but very consistent

[LHCb, JHEP 02 (2016) 104]

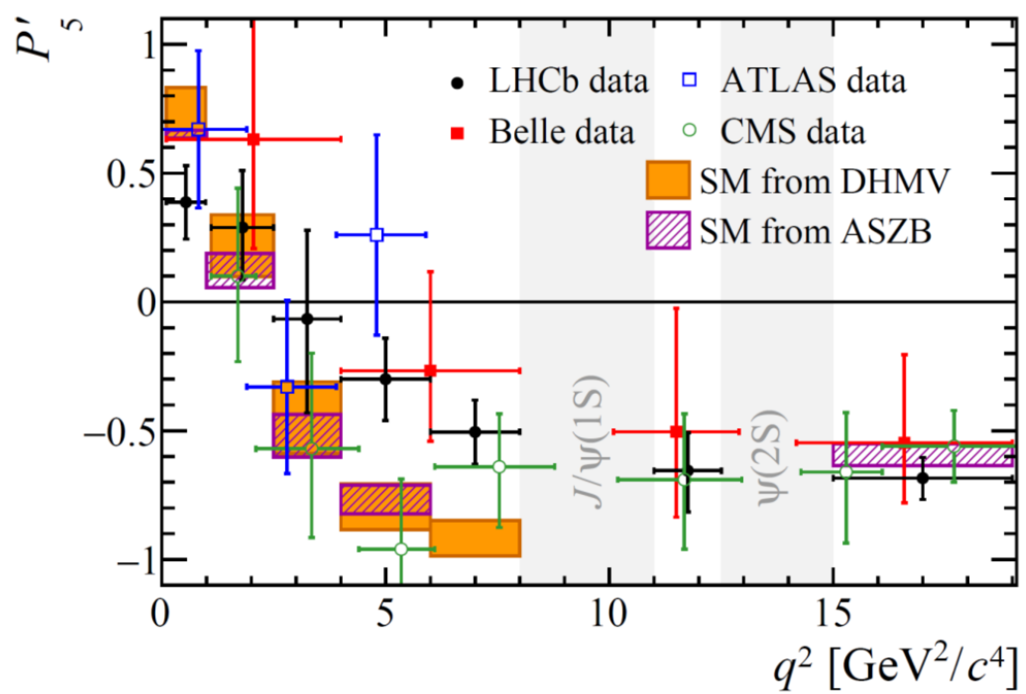
- Full Run …

# Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays

LHCb, Phys.

.. and ATLAS and CMS



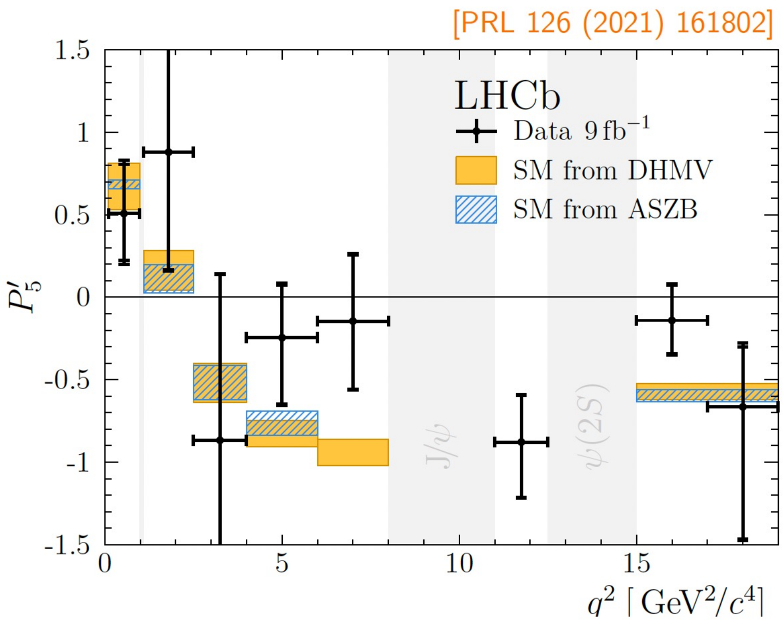

[ATLAS-CONF-2017-023, CMS-PAS-BPH-15-007]

[LHCb, JHEP 02 (2016) 104]

- Full Rur

Situation unclear…. If real, expect discrepancies in **other $b \to s$ decays** ..

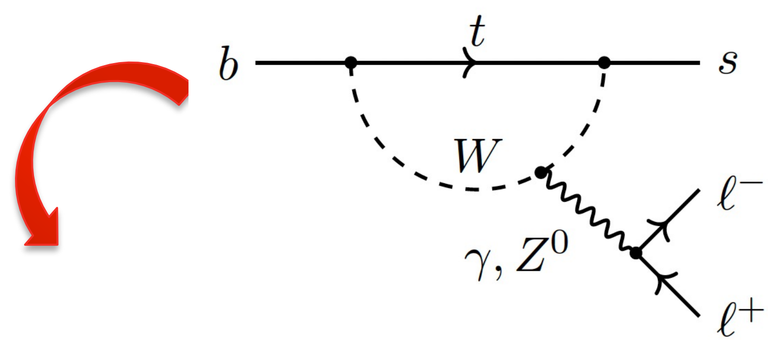
# Puzzling deviations: $B^+ \to K^{*+} \mu^+\mu^-$



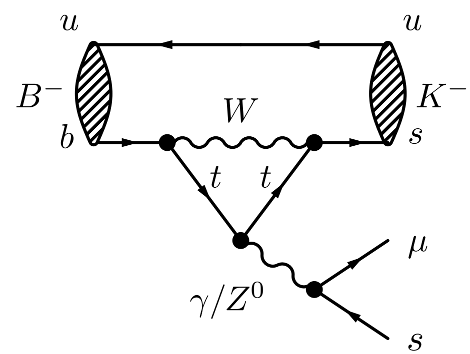

- Recent LHCb measurement using Run 1+2 data [PRL 126 (2021) 161802]
- Global tension corresponding to 3.1$\sigma$, consistent with $B^0 \to K^{*0} \mu^+\mu^-$

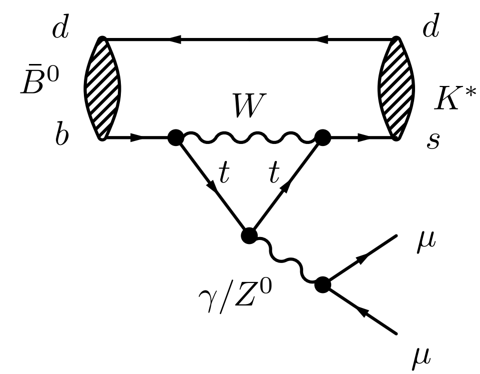
# Other b → s $\mu^+\mu^-$ decays

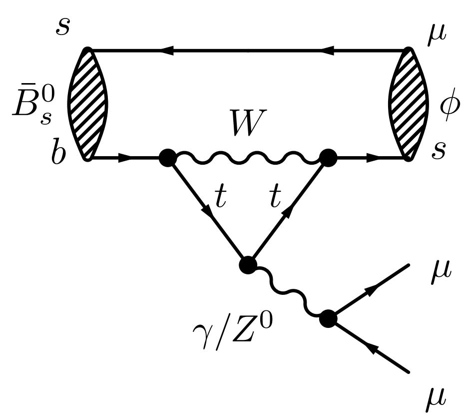
- Decay modes with same effective Feynman diagram accessible
  → different spectator quarks

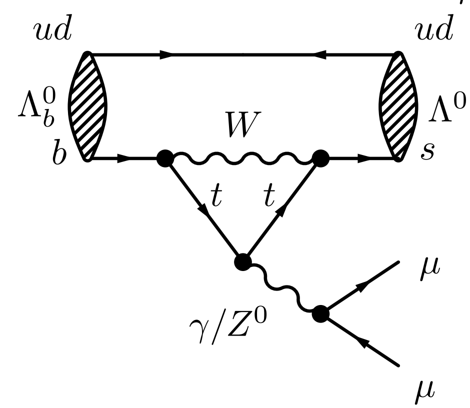



- Test for same new effects
  → expect suppressed branching fractions

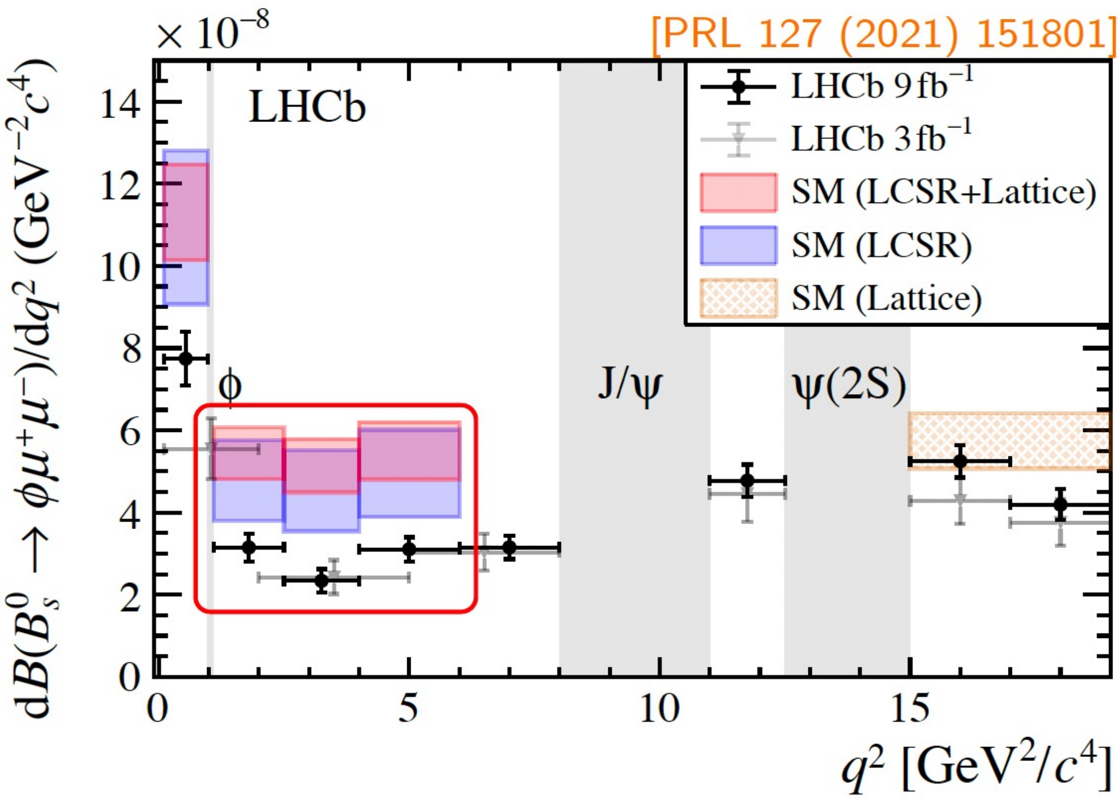


# BR of $B_s \to \phi\mu^+\mu^-$



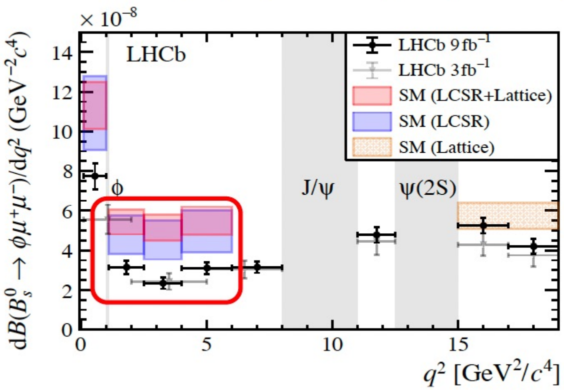

SM LCSR
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 8]

SM LCSR+Lattice
[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

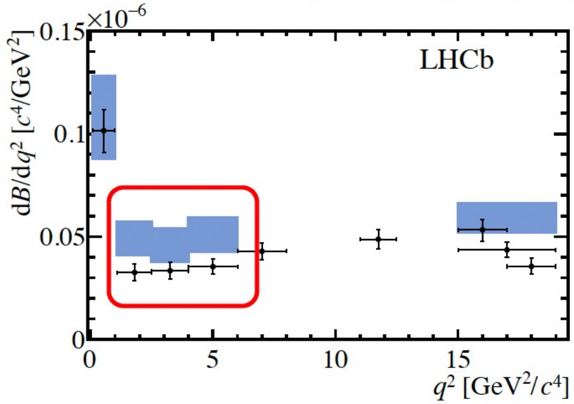
- Recent LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4) = (2.88 \pm 0.21) 10^{-8}\,\text{GeV}^2/c^4$
- Tension with SM at $3.6\,\sigma$ (LCSR+Lattice) and $1.8\,\sigma$ (LCSR only)

# $b \to s\, \ell^+ \ell^-$ branching fraction measurements

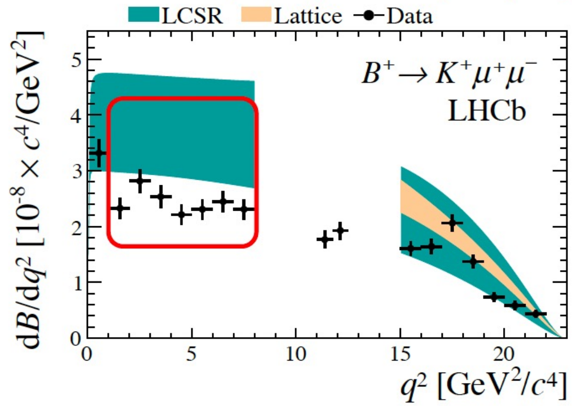
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



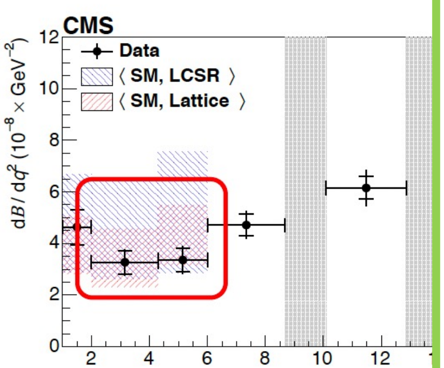

LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]




LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]

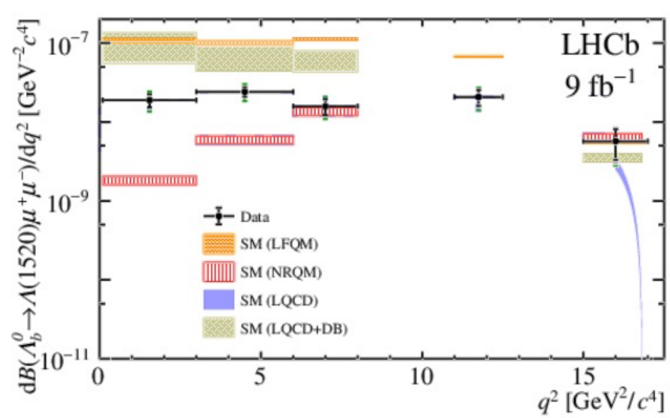



CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753

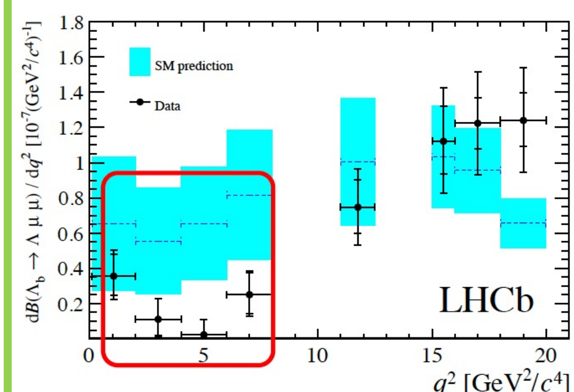



$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

arXiv:2302.08262




LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]

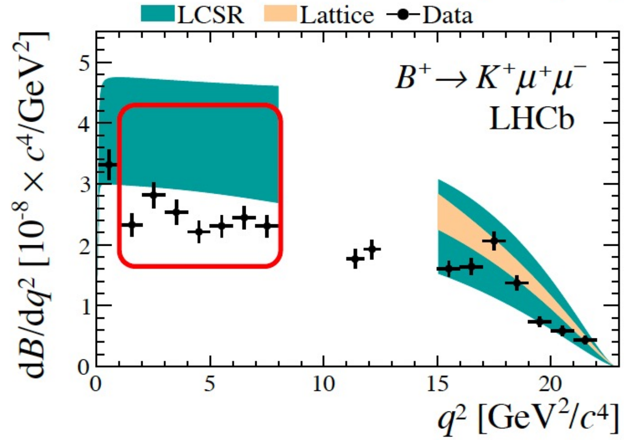



- Data consist … icularly at low $q^2$)
- Tensions at … t sizeable had. uncertainties

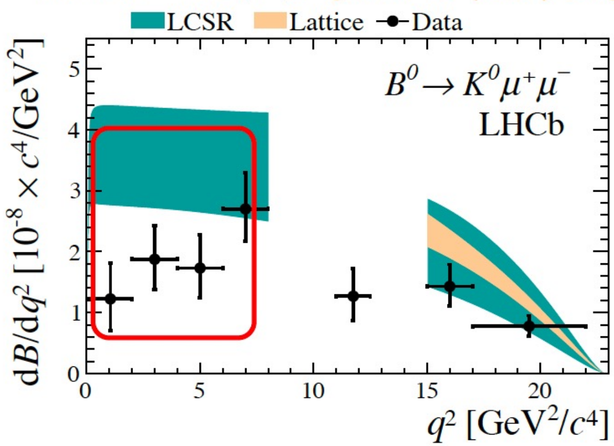
# $b \to s\,\ell^+\ell^-$ branching fraction measurements

- Recent developments on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, arXiv:2207.13371]

LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]

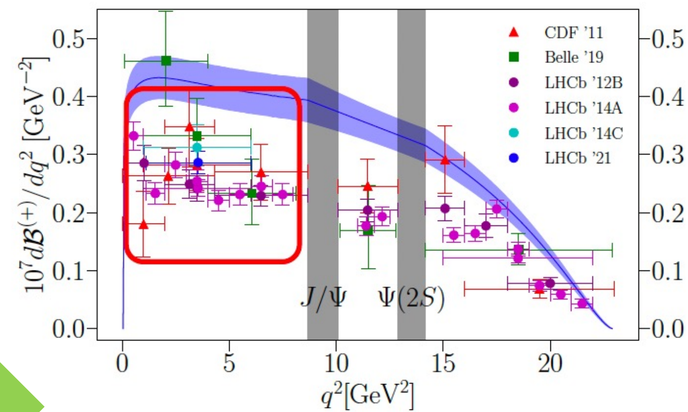



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]

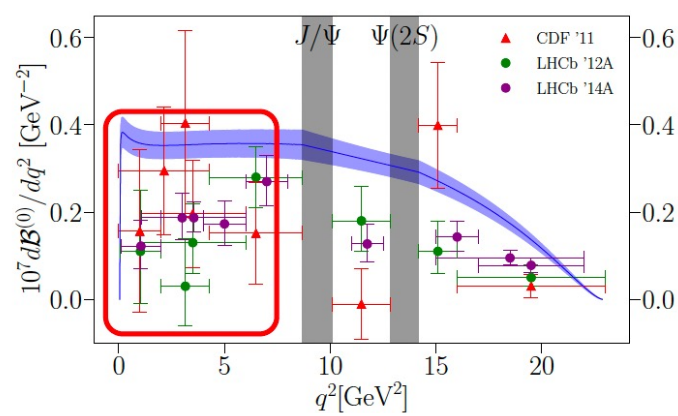



TH developments

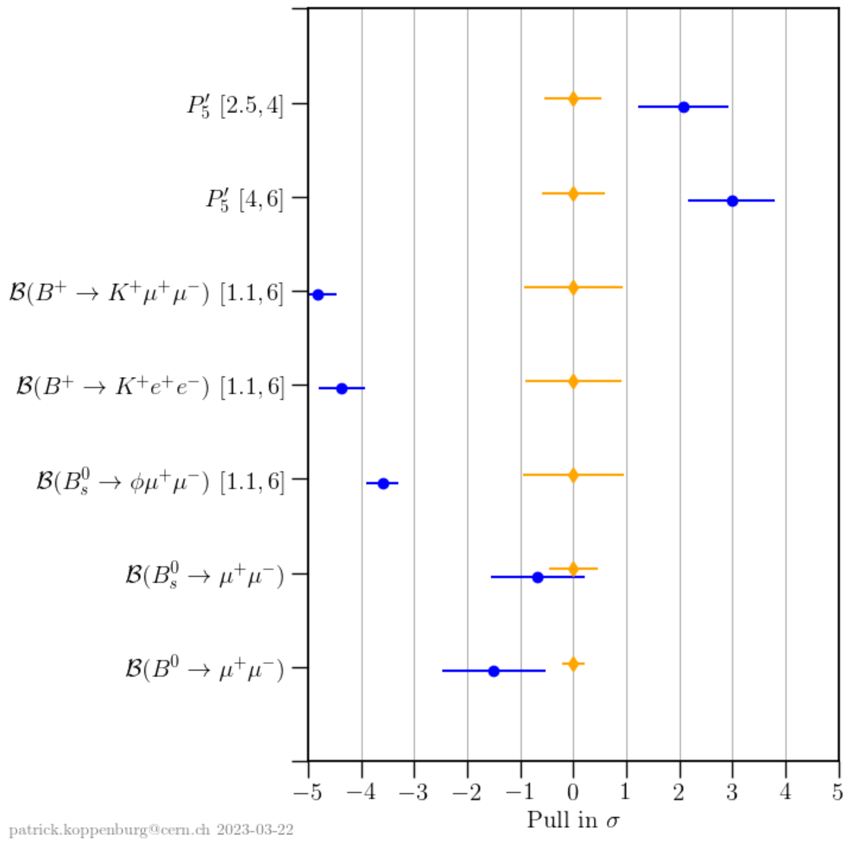
Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]




Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]



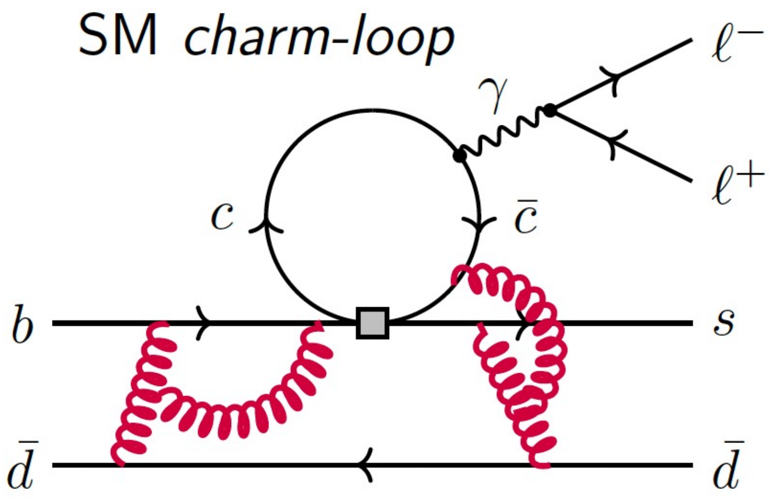
# Branching fractions of $b \to s\, \mu^+\mu^-$

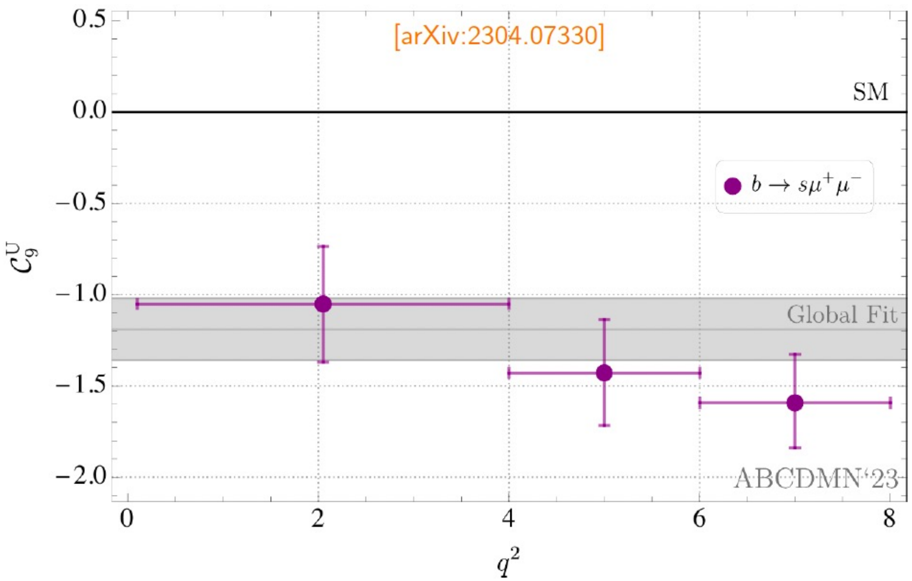



- Analysis of large class of $b \to s,d\ \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    **→ intriguing hint or theoretical issue in prediction?**

**→ TH developments needed as well as more measurements**

# QCD or something (even) more interesting?




- Disentangling hadr. contributions requires work from theory and experiment
- Progress on theory side:
  - Form-factors are systematically improved on the lattice [PRD 107 (2023) 1]
  - Recent more precise estimation of charm-loop effect [JHEP 09 (2022) 133]
- Exploit $q^2$-dependence:
  - charm-loop rises towards $c\bar{c}$-resonances
  - NP $q^2$-independent
- $q^2$-unbinned approaches to better exloit data [JHEP 11 (2017) 176]
  Different $c\bar{c}$-loop parameterisations pursued [EPJC 78 (2018) 453] [JHEP 10 (2019) 236] [EPJC 80 (2020) 12] [JHEP 09 (2022) 133]

# Radiative decays

- LHCb has measured these observables in a time-dependent tagged analysis of $B_s^0 \to \phi\gamma$.
- Results are in agreement with the SM predictions [PLB 664 (2008) 174-179].
- No evidence for enhancement of right-handed photons.

**Photon polarisation and $CPV$ in $B_s^0 \to \phi\gamma$**

**LHCb results**: [PRL 123 (2019) 8, 081802]

$$A^{\Delta}_{\phi\gamma} = -0.67^{+0.37}_{-0.41}\ (\text{stat.}) \pm 0.17\ (\text{syst.})$$

$$C_{\phi\gamma} = 0.11 \pm 0.29\ (\text{stat.}) \pm 0.11\ (\text{syst.})$$

$$S_{\phi\gamma} = 0.43 \pm 0.30\ (\text{stat.}) \pm 0.11\ (\text{syst.})$$

# Virtual photon polarization in $B^0 \to K^{*0} e^+ e^-$

- At low $q^2$, the $B^0 \to K^{*0} e^+ e^-$ decay is dominated by virtual photon contributions from $\mathcal{C}_7^{(\prime)}$.
- The angular distribution at very low $q^2$ simplifies to four observables: $F_L$, $A_T^{Re} \equiv 2P_2$, $A_T^{(2)} \equiv P_1$, $A_T^{Im} \equiv -2P_3^{CP}$.
- $A_T^{(2)}$ and $A_T^{Im}$ are sensitive to the virtual photon polarisation.

**Angular observables in $B^0 \to K^{*0} e^+ e^-$**

**LHCb results** for $q^2 \in [0.0008, 0.257]\ \mathrm{GeV}^2/c^4$:

$$F_L = 0.044 \pm 0.026\ (\mathrm{stat.}) \pm 0.014\ (\mathrm{syst.})$$

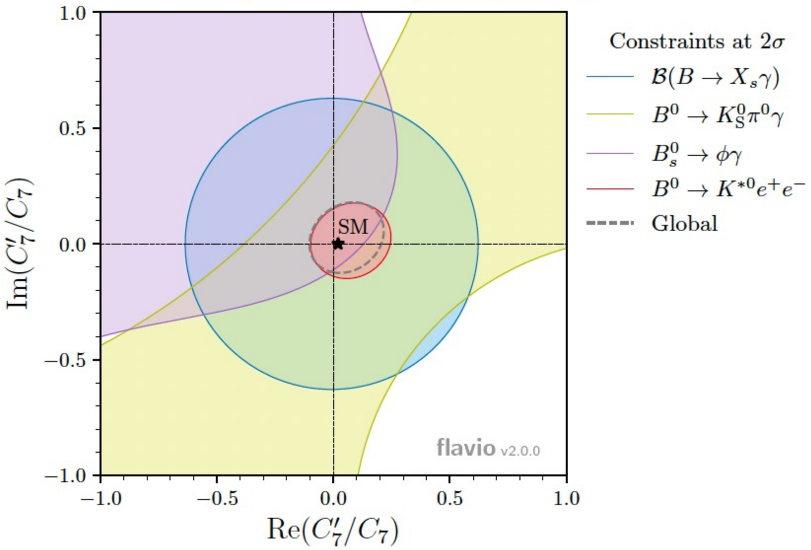
$$A_T^{Re} = -0.06 \pm 0.08\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{syst.})$$

$$A_T^{(2)} = +0.11 \pm 0.10\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{syst.})$$

$$A_T^{Im} = +0.02 \pm 0.10\ (\mathrm{stat.}) \pm 0.01\ (\mathrm{syst.})$$

- Compatible with Standard Model predictions.
- Currently the strongest constraints on contributions from right-handed photons.

[JHEP 12 (2020) 081]



## Photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

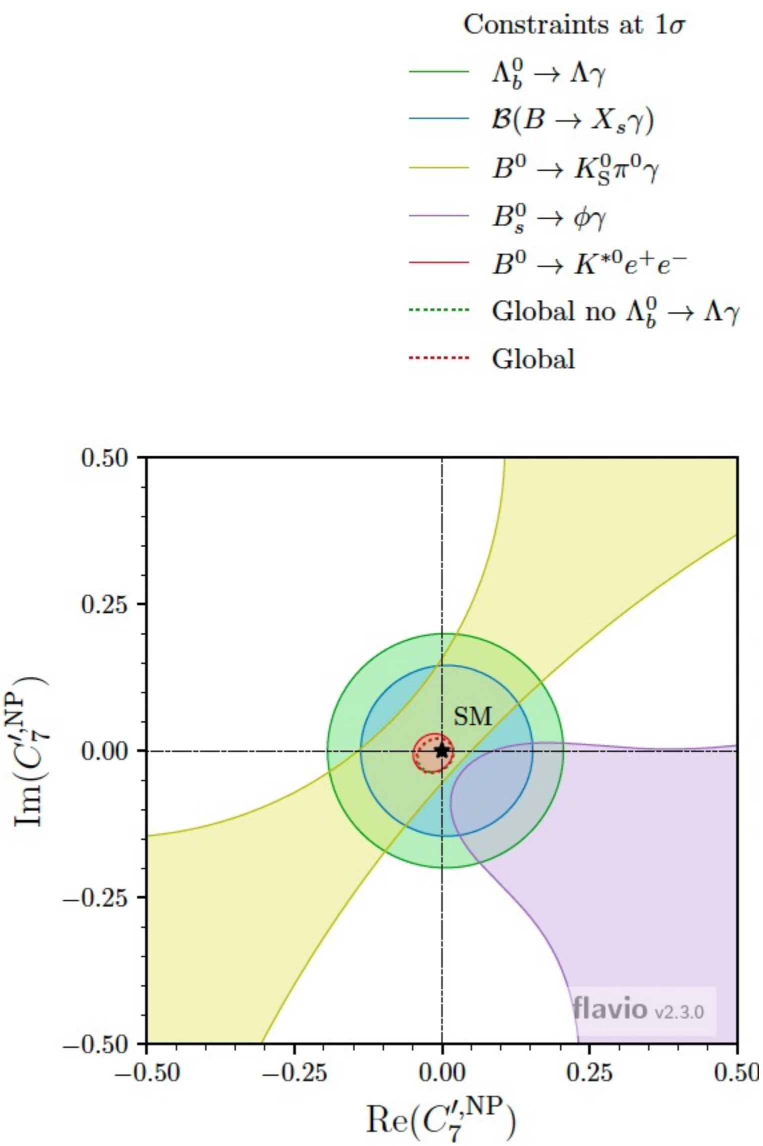
**LHCb results** [PRD 105 (2022) 5, L051104]:

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})$$

$$\alpha_\gamma^- > 0.56\ (0.44)\ \text{at}\ 90\%\ (95\%)\ \text{C.L.} \qquad (\Lambda_b^0)$$

$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}\,(\text{stat.})^{+0.16}_{-0.09}(\text{syst.}) \qquad (\overline{\Lambda}_b^0)$$

- Consistent at $1\sigma$ with SM prediction of 1 for $\alpha_\gamma$.
- Consistent with *CP* symmetry, $\alpha_\gamma^- = -\alpha_\gamma^+$.

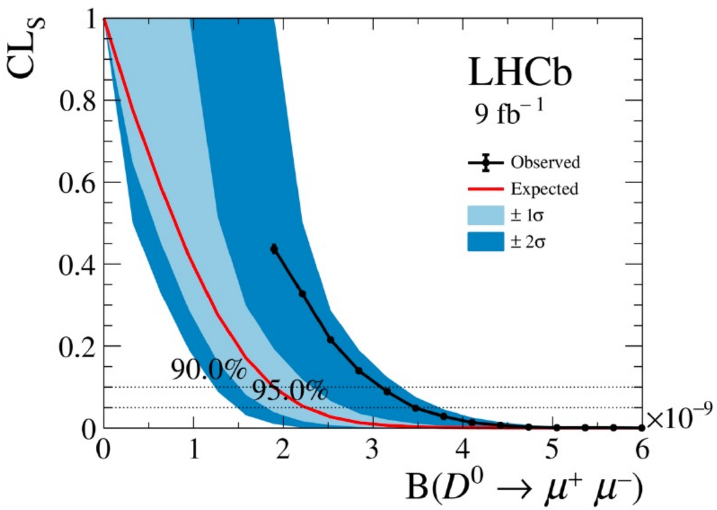



Can we think of observables (eg utilizing the spin) to make the Baryon more than a bad meson?

# No slide on rare D, K, ..

$\mathcal{B}(D^0 \to \mu^-\mu^+) < 3.1(3.5) \times 10^{-9}$ at 90 (95)% C

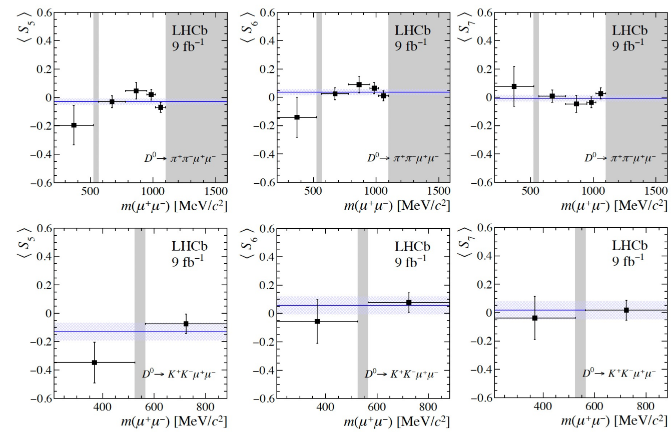
PAPER-2022-029, arXiv:2212.11203




*"Angular analysis of $D^0 \to \pi^-\pi^+\mu^+\mu^-$ and $D^0 \to K^-K^+\mu^+\mu^-$ decays and search for CP violation"*

LHCb-PAPER-2021-035
arXiv:2111.03327

- shown examples: SM null tests $\langle S_{5,6,7}\rangle$ [$\langle S_6\rangle \sim A_{FB}$]




agreement with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

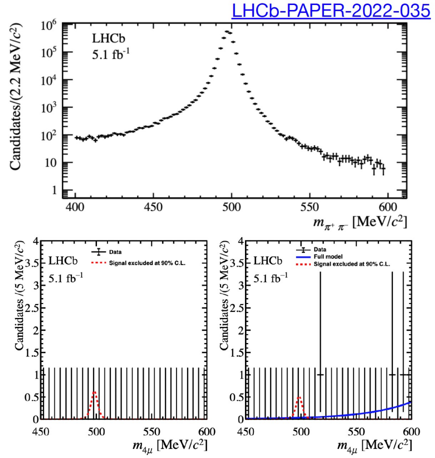
$K^0_{S/L} \to \mu^+\mu^-\mu^+\mu^-$

- Abundant normalisation yield
- 90% C.L. by integrating positive side of profile likelihood

$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9},$$

- Modelling of trigger efficiency is leading systematic

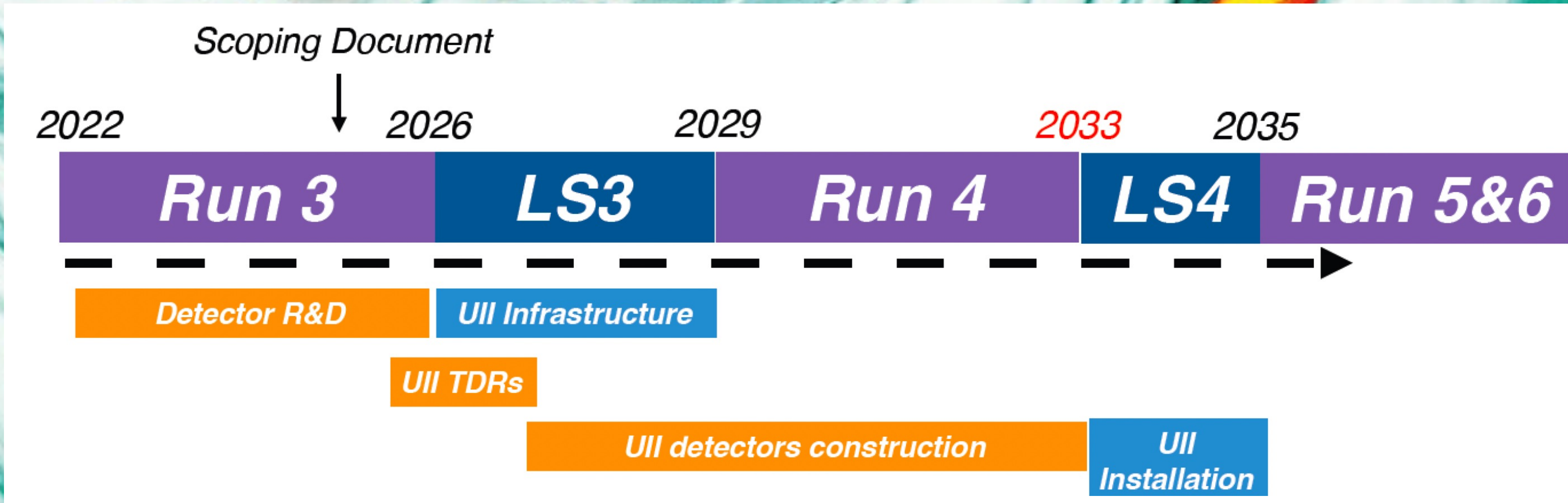
LHCb-PAPER-2022-035




Also here, we have a nice dataset on tape.

Funny ideas welcome .

# Quo vadis ?

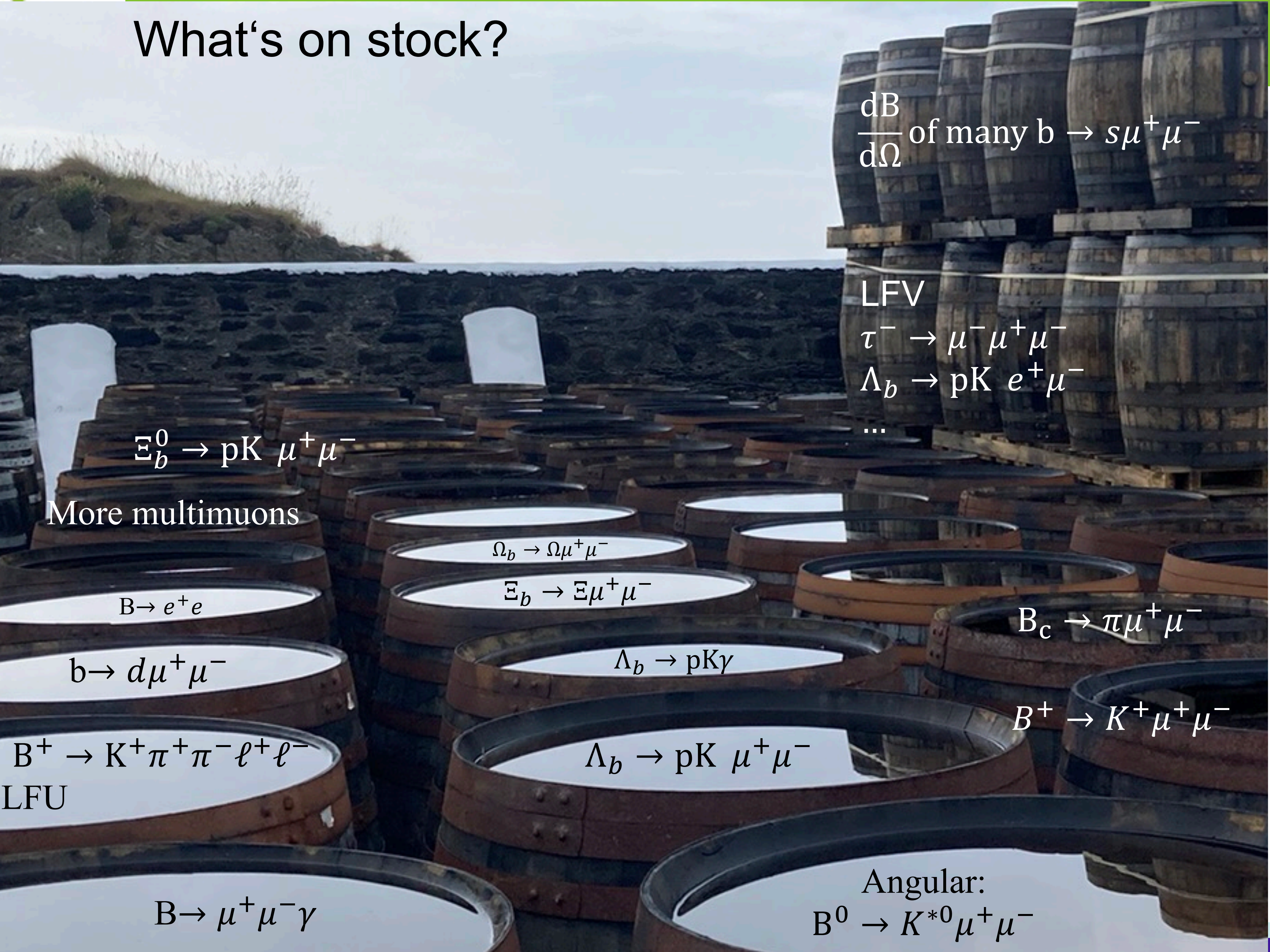



Some work to do before the harvest of Run 3 begins


Concerning rare decays,
now is a very good time for ideas
to exploit the
Run 1 and 2 dataset

E.g.
$B \to \rho\mu\mu, \Lambda_b \to \Lambda^*(pK)\,\mu\,\mu\,,$
$B^+ \to K\pi\pi\,\ell\ell,\, \Xi_b^0 \to \Lambda\mu\mu, \ldots$
(my ideas, what are yours?)

# What‘s on stock?



# One symbol summary