Artwork adapted from Sandbox Studio, Chicago with Ana Kova

LHCb indirect searches for physics BSM

2 July 2022 - SUSY - Ioannina

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Alexander von Humboldt
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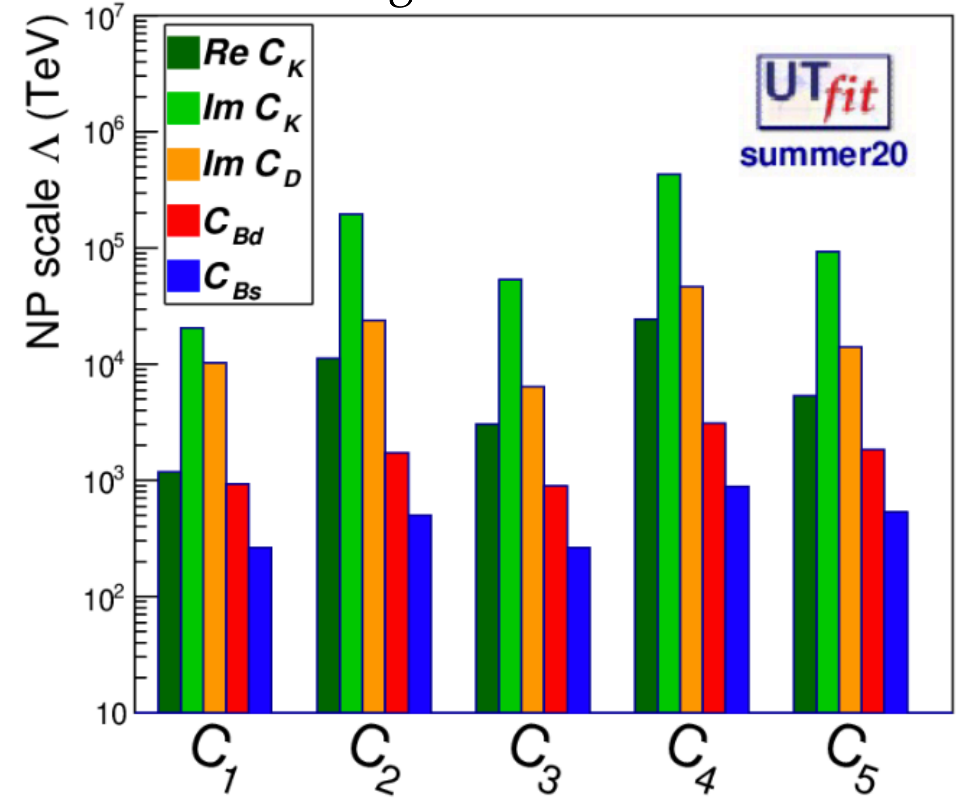
Indirect searches in quark flavour

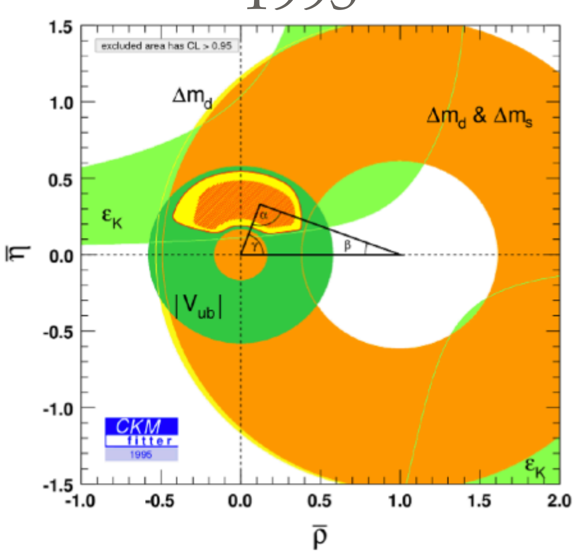
- Quark flavour-changing processes
  → indirect probe of BSM physics
- Shaping the BSM landscape up to high energies
  - e.g. Minimal Flavour Violation hypothesis
- Trying to address the flavour puzzle
  - Yukawas not controlled by any SM symmetry

Reach for generic flavour structure

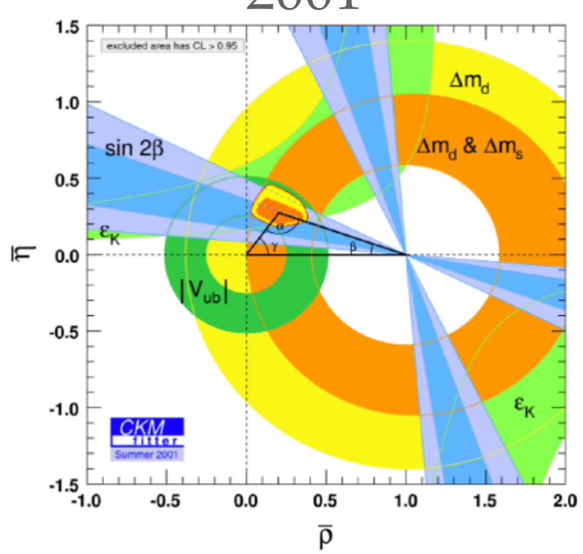


See Marcella's talk and JHEP 0803:049,2008

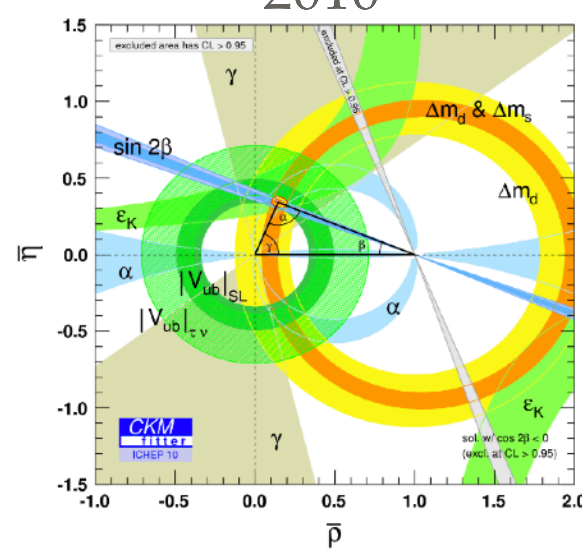
1995



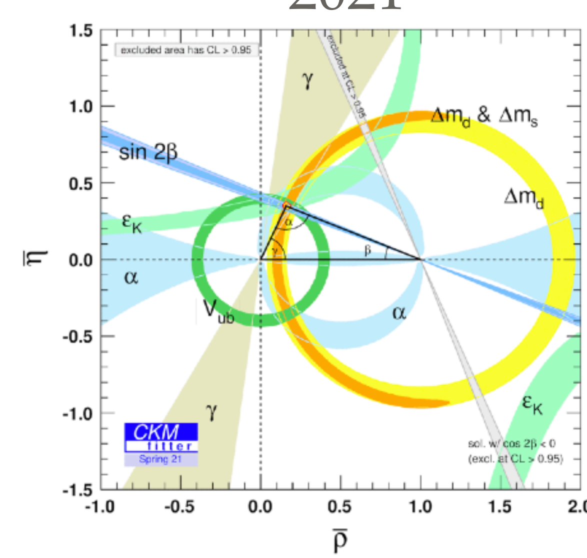
2001



2010



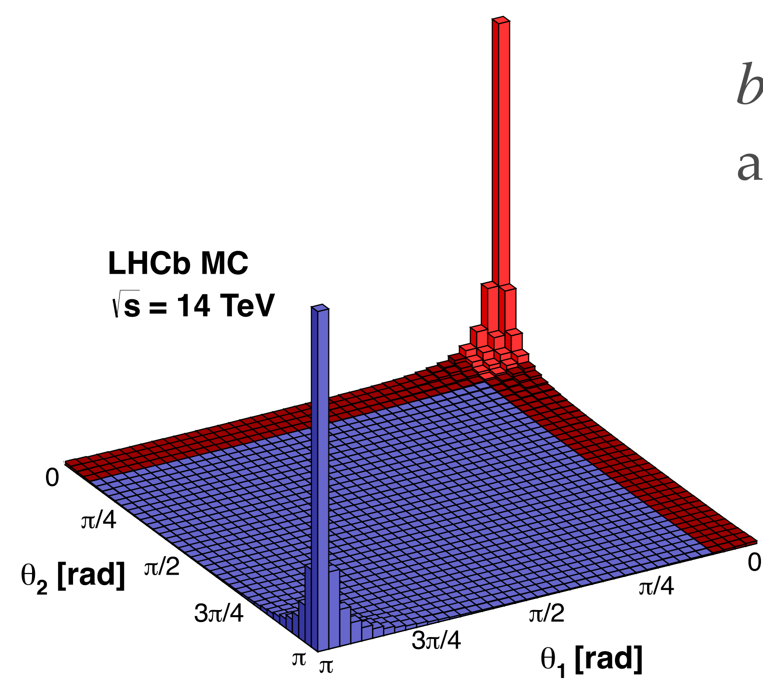
2021



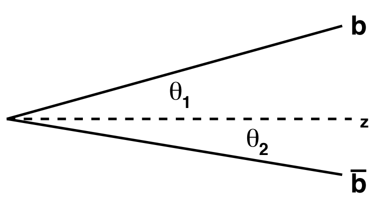
The LHCb experiment

b physics at the LHC

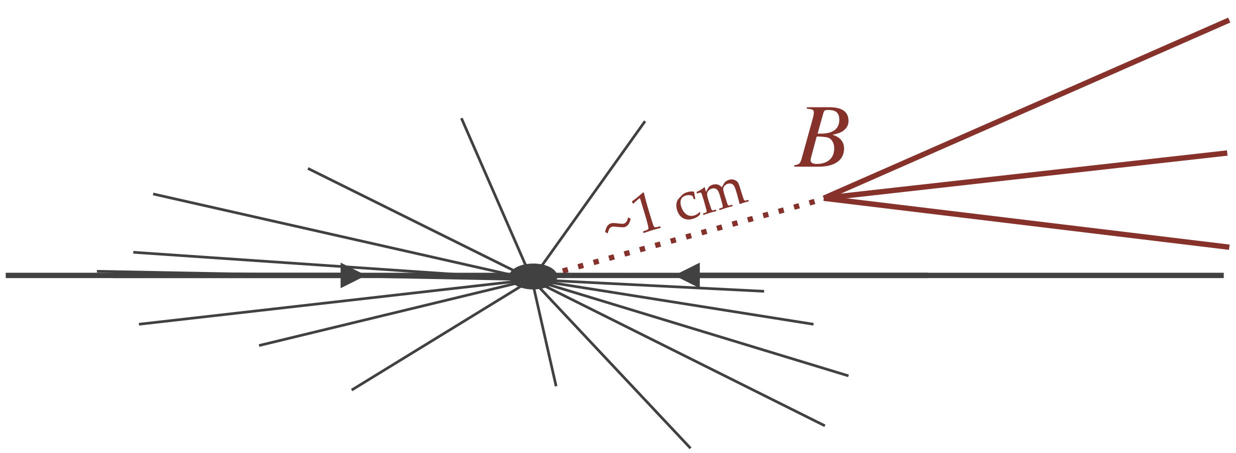
- $\sigma(pp \to b\bar{b}X)^{13\ \text{TeV}} \simeq 0.5\ \text{mb}$
  $\mathscr{L}^{\text{LHC}} \simeq 10^{34}\ \text{cm}^{-2}s^{-1}$ $\Longrightarrow$ **rate = 5 MHz**
- $\sigma(\text{inelastic}) \simeq 200 \times \sigma(b\bar{b}X)$



$b\bar{b}$ production angles θ_1, θ_2



- $b\bar{b}$ produced at small angle
- ...high detector occupancy
- Large boost $\beta\gamma \simeq 20$
  $\to$ displaced vertex ~1cm



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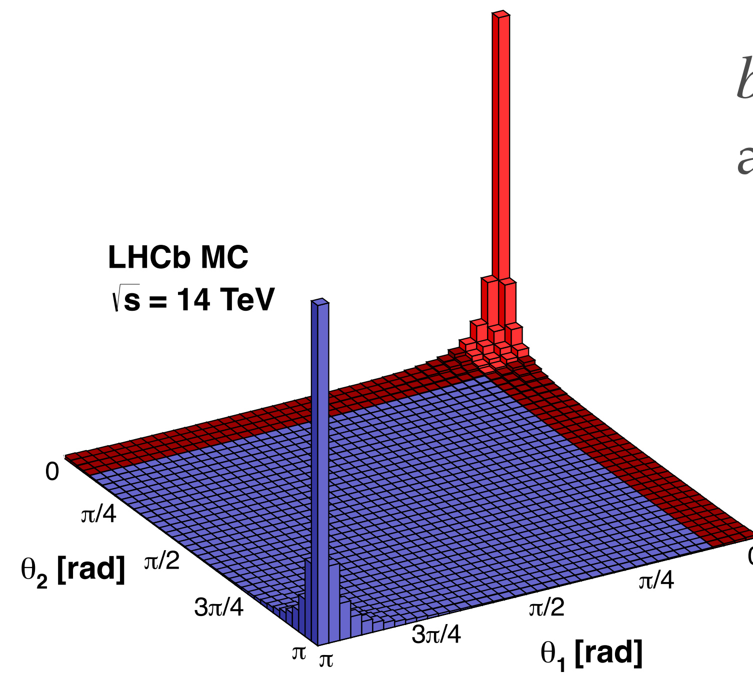
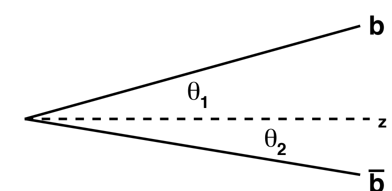
$\Longrightarrow$ **rate = 5 MHz**

- $\sigma(\mathrm{inelastic}) \simeq 200 \times \sigma(b\bar{b}X)$

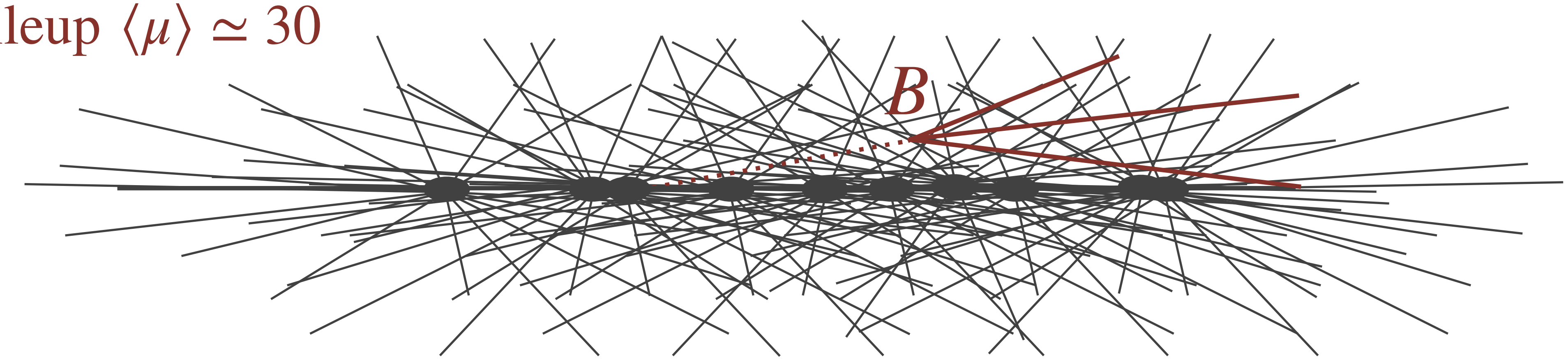
$b\bar{b}$ production angles $\theta_1,\ \theta_2$





- $b\bar{b}$ produced at small angle
- …high detector occupancy

- Large boost $\beta\gamma \simeq 20$
  $\rightarrow$ displaced vertex ~1cm
- …but pileup $\langle\mu\rangle \simeq 30$



Int.J.Mod.Phys. A 30, 1530022 (2015)

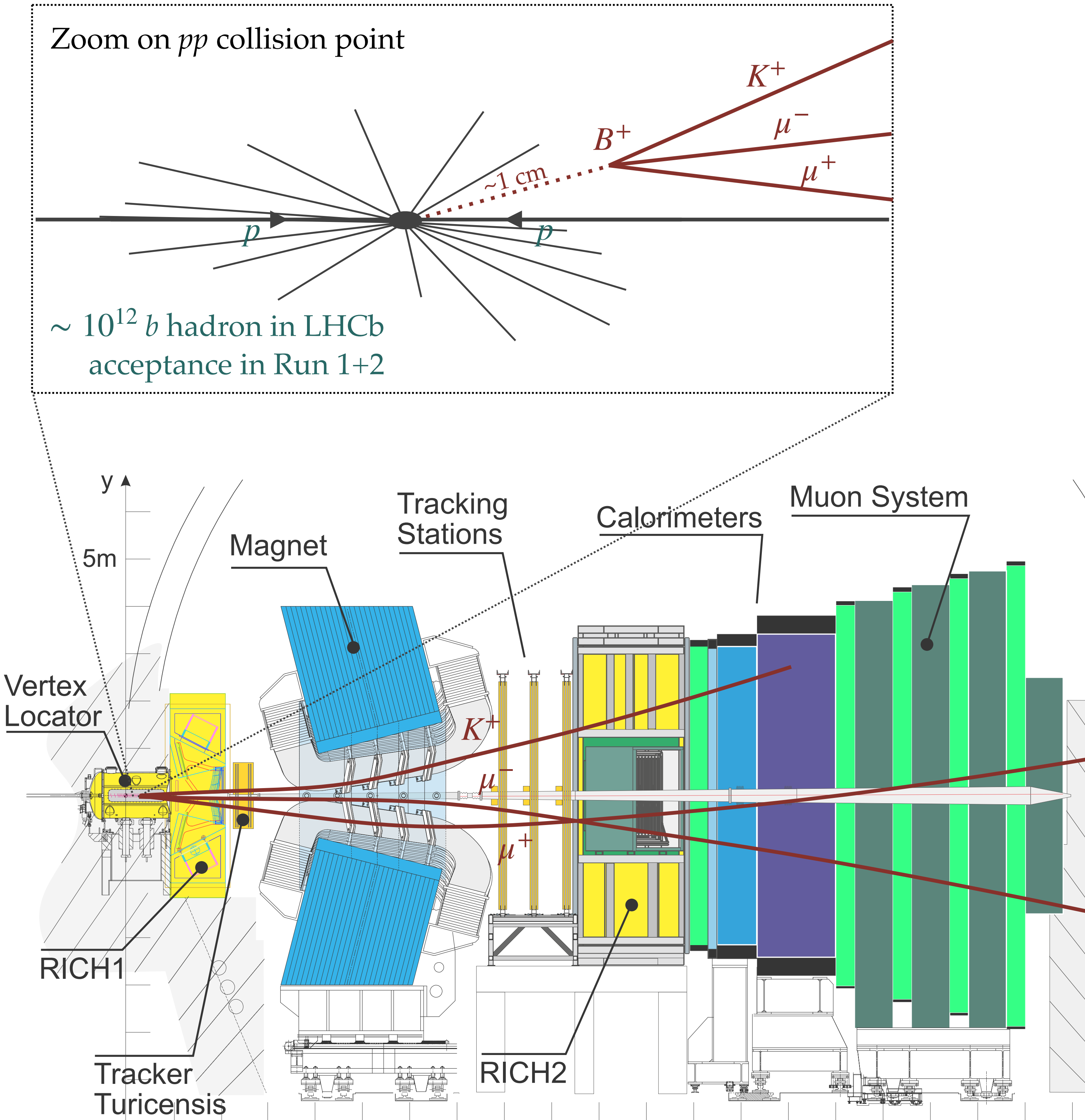
The LHCb experiment

LHCb detector design

- Lower luminosity for $\langle \mu \rangle \simeq 1$
  $\mathscr{L}^{\text{LHCb}} \simeq 3.5 \times 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
  $\rightarrow 10^{12}$ b hadrons in LHCb acceptance in Run 1+2
- Covers forward region of pp collisions ($2 < \eta < 5$)

- Displaced vertex identification
- Low-p_{T} triggers (few GeV)
- Dipole magnet with very precise tracking detectors $\sigma_p/p \sim 0.5\,\%$
- Particle ID with calorimeters, muon system and Cherenkov detectors (RICH)

A broad physics program in the LHC forward region



Flavour physics at LHCb

Selected world-best measurements from LHCb

Beauty

- Mixing in both B_d and B_s:
  $\Delta m_d = 0.5062 \pm 0.0019 \pm 0.0010\ \mathrm{ps}^{-1}$ [1]
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \mathrm{ps}^{-1}$ [2]
- CKM angle $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$ [3]
- CPV phase in B_s system
  $\phi_s = -0.083 \pm 0.041 \pm 0.006$ rad [4]
- Electroweak FCNC in $b \to s$ -> more later

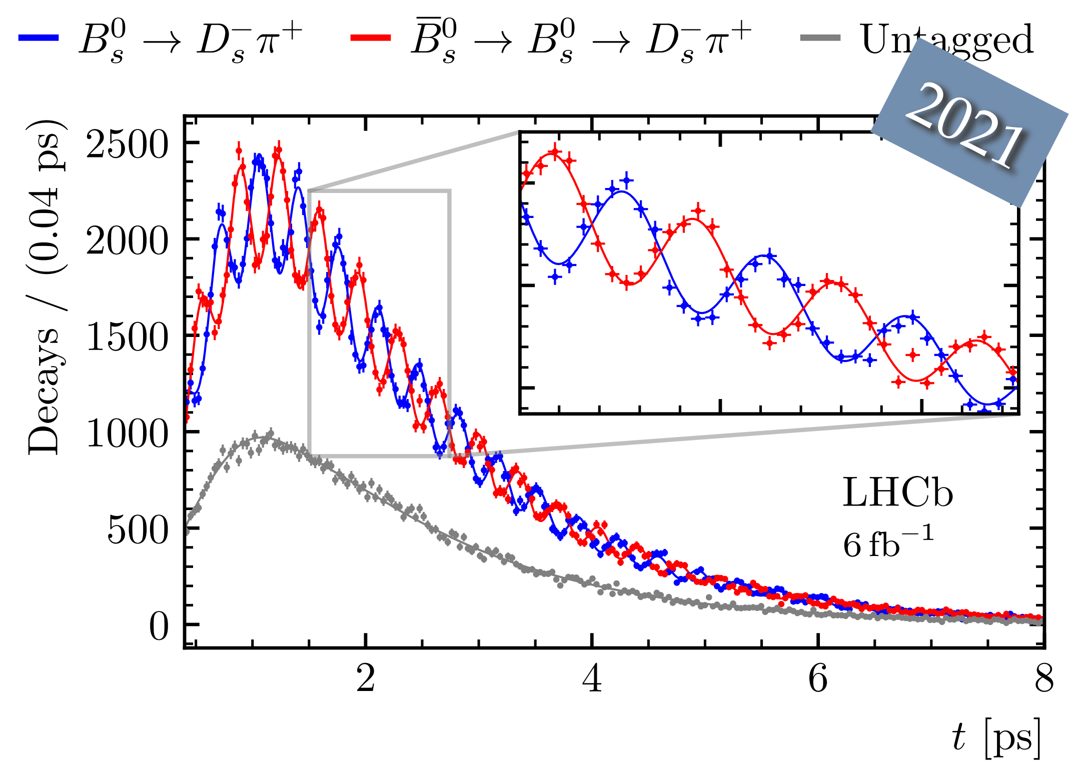
Charm

- CP violation and Δm **firstly observed** by LHCb
  $\rightarrow$ direct $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [5]
  $\rightarrow$ $x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$ [6]

Strange

- $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 2.1 \times 10^{-10}$ at 90% CL [7]

Nature Physics 18, (2022) 1-5



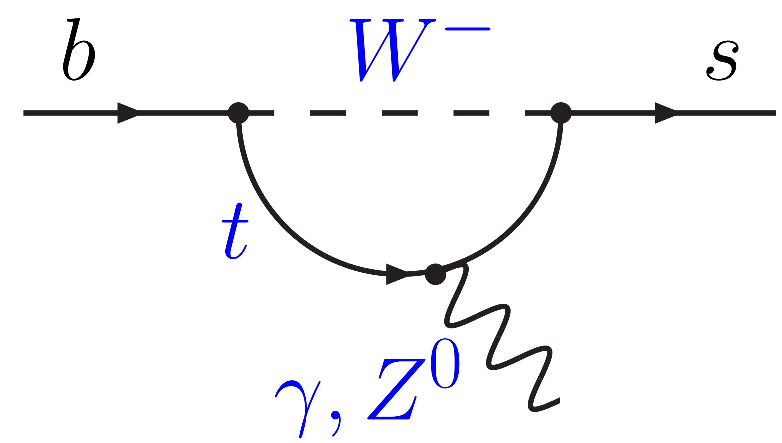
References:
[1] HFLAV average of 4 LHCb analyses
[2] Nature Physics 18, (2022) 1-5
[3] JHEP 12 (2021) 141
[4] Phys. Rev. D 105, 092013
[5] Phys. Rev. Lett. 122 (2019) 211803
[6] Phys. Rev. Lett. 127, (2021) 111801
[7] Phys. Rev. Lett. 125, (2020) 231801

More details on:

Electroweak FCNC in $b \to s$

Electroweak FCNC in $b \to s$

- Electroweak $b \to s$ transitions
  - Suppressed by loop, V_{CKM} and GIM $\to$ decay rates of order 10^{-6} or less
  - Tiny BSM contributions can enter at the same order as SM amplitude
  - Sensitive to SUSY even if MFV



$b \to s\gamma,\ b \to s\ell^+\ell^-,\ B_s \to \ell^+\ell^-$

- Excellent experimental probe
  - No neutrinos involved!
  - Several complementary observables
  - Several complementary decay channels

→ Branching ratios, angular analyses, SM symmetry tests

- Radiative $b \to s\gamma$
- Leptonic $B_{(s)} \to \mu^+\mu^-$
- Semileptonic $b \to s\ell^+\ell^-$

	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
◉ Radiative $b \to s\gamma$	✓			
◉ Leptonic $B_{(s)} \to \mu^+\mu^-$			✓	✓
◉ Semileptonic $b \to s\ell^+\ell^-$	✓	✓	✓	✓

EFT below EW scale (LEFT):

$$\mathcal{H}_{\text{eff}} = \frac{1}{(34\ \text{TeV})^2} \sum_i C_i O_i$$

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{\mathrm{R(L)}}b)F^{\mu\nu}$$ dipole ($b \to s\gamma$)

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}}b)(\bar{\ell}\gamma^\mu\ell)$$ vector

$$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$ axial-vector

$$O_S^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{R(L)}}b)(\bar{\ell}\ell)$$ scalar

$$O_P^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{R(L)}}b)(\bar{\ell}\gamma_5\ell)$$ pseudo-scalar

Radiative $b \to s\gamma$

Left handed $C_7 = C_7^{SM} + C_7^{NP}$

- $\mathcal{B}(B \to X_s\gamma) \propto C_7^2 + C_7'^2$
  - 5% precise prediction [1]
  - 5% precise from B-factories [2]
  - Very hard at LHCb
- $\mathrm{Im}(C_7)$ measured with A_{CP}
  - $B \to K_S\pi^0\gamma$ at B-factories [2]
  - Tagged time-dep. analysis of $B_s \to \phi\gamma$ at LHCb [3]

Right handed $C_7' = C_7'^{NP}$

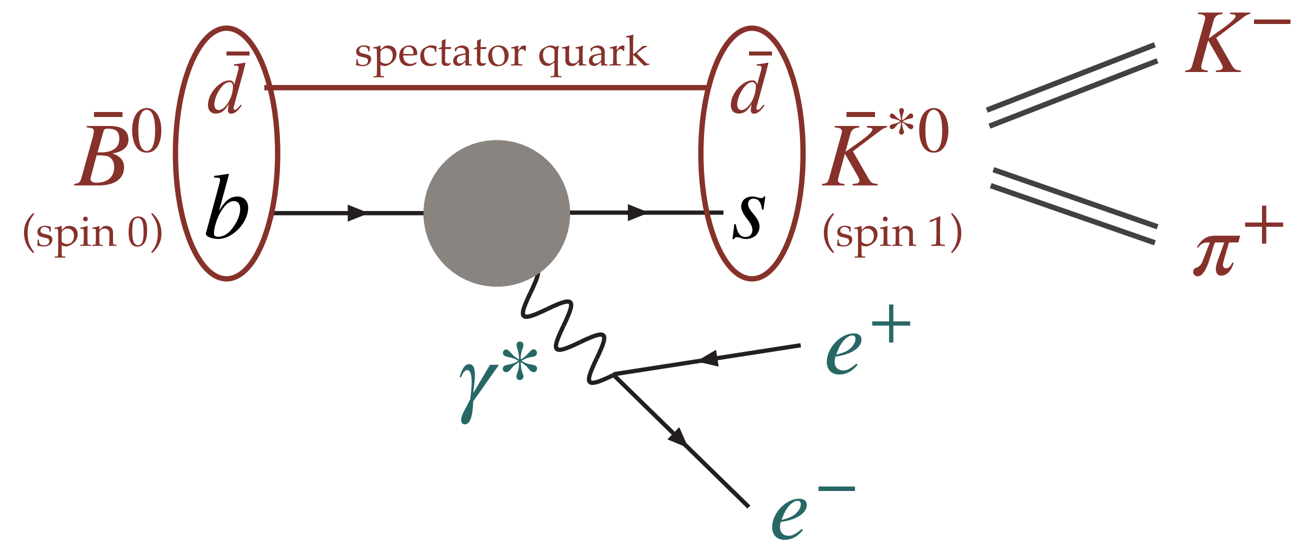
- Mixing-induced CPV in $B \to K_S\pi^0\gamma$ at B-factories [2]
- $\Delta\Gamma_s$ induced rate asymmetry in $B_s \to \phi\gamma$ at LHCb [3]
- Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb [4]
- Transverse asymmetries in $B^0 \to K^*e^+e^-$ at LHCb [5]

-> the most sensitive

[1] M. Misiak et al JHEP 06(2020)175
[2] HFLAV average of BaBar and Belle
[3] LHCb PRL 123 (2019) 081802
[4] LHCb PRD 105 (2022) L051104
[5] LHCb JHEP 12 (2020) 081

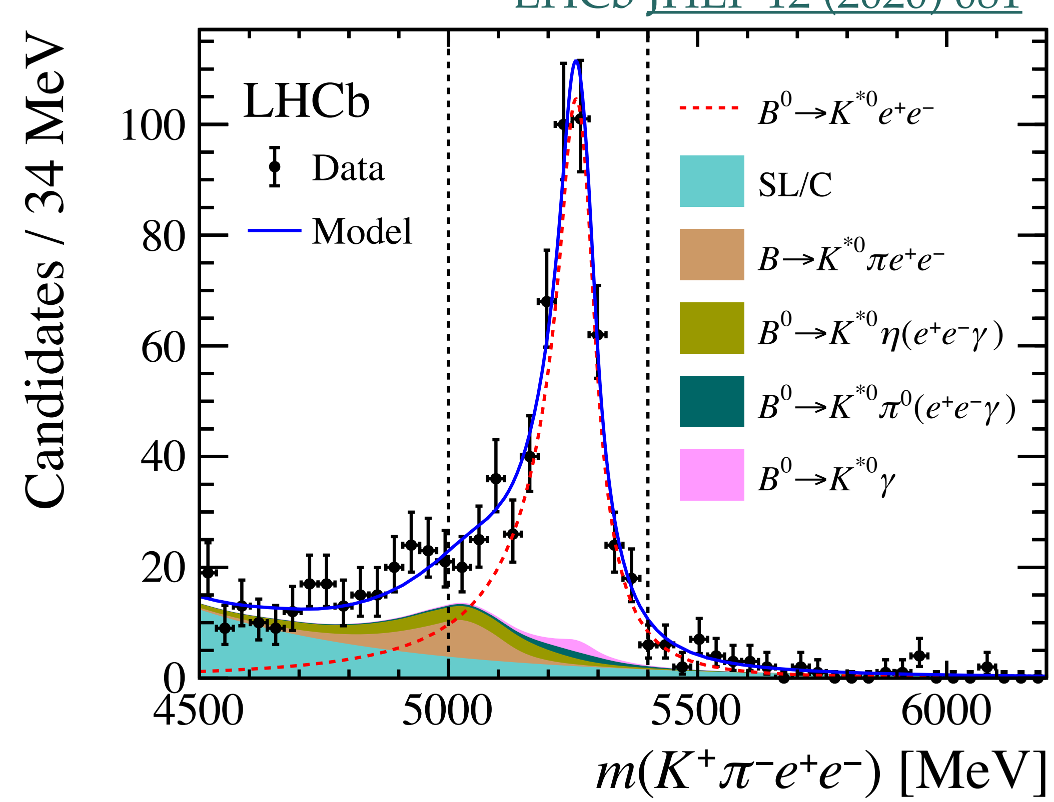
$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$

- ✓ Use $\gamma^* \to e^+ e^-$ to measure photon polarisation!
- ✓ Get nice $K^- \pi^+ e^- e^+$ final state
- ◉ Rate lower by $\alpha_{\text{e.m.}}$



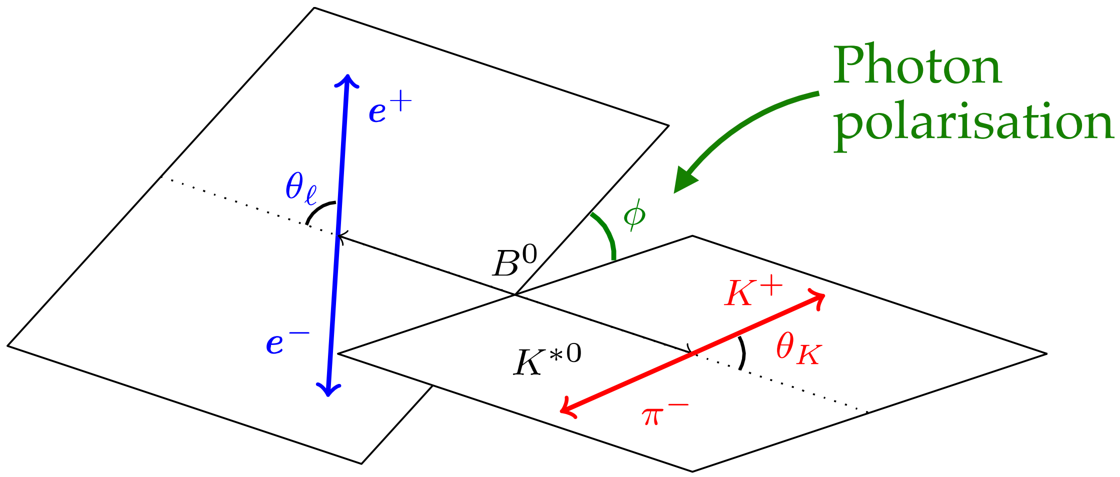
- ✓ About 500 events with LHCb dataset despite BR $\sim 2 \times 10^{-7}$

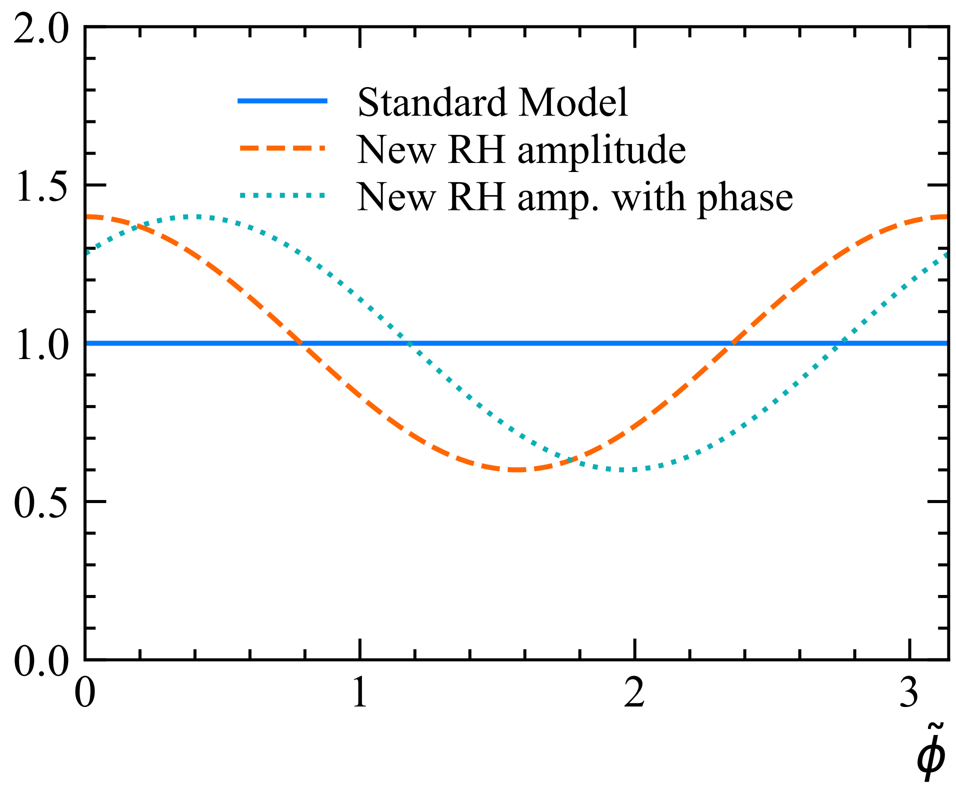
LHCb JHEP 12 (2020) 081



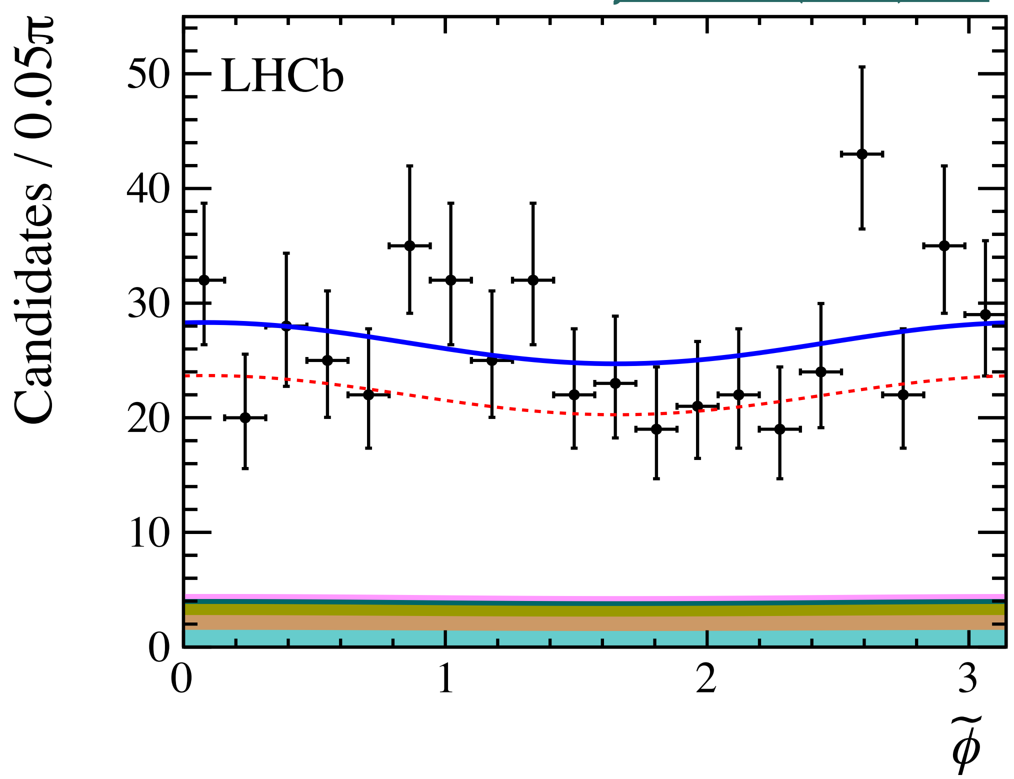
$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$

- $B^0 \to K^+\pi^- e^+ e^-$ described by 3 angles
- Photon polarisation measured with ϕ
  - $\cos 2\phi$ or $\sin 2\phi$ modulation would signal right-handed contribution



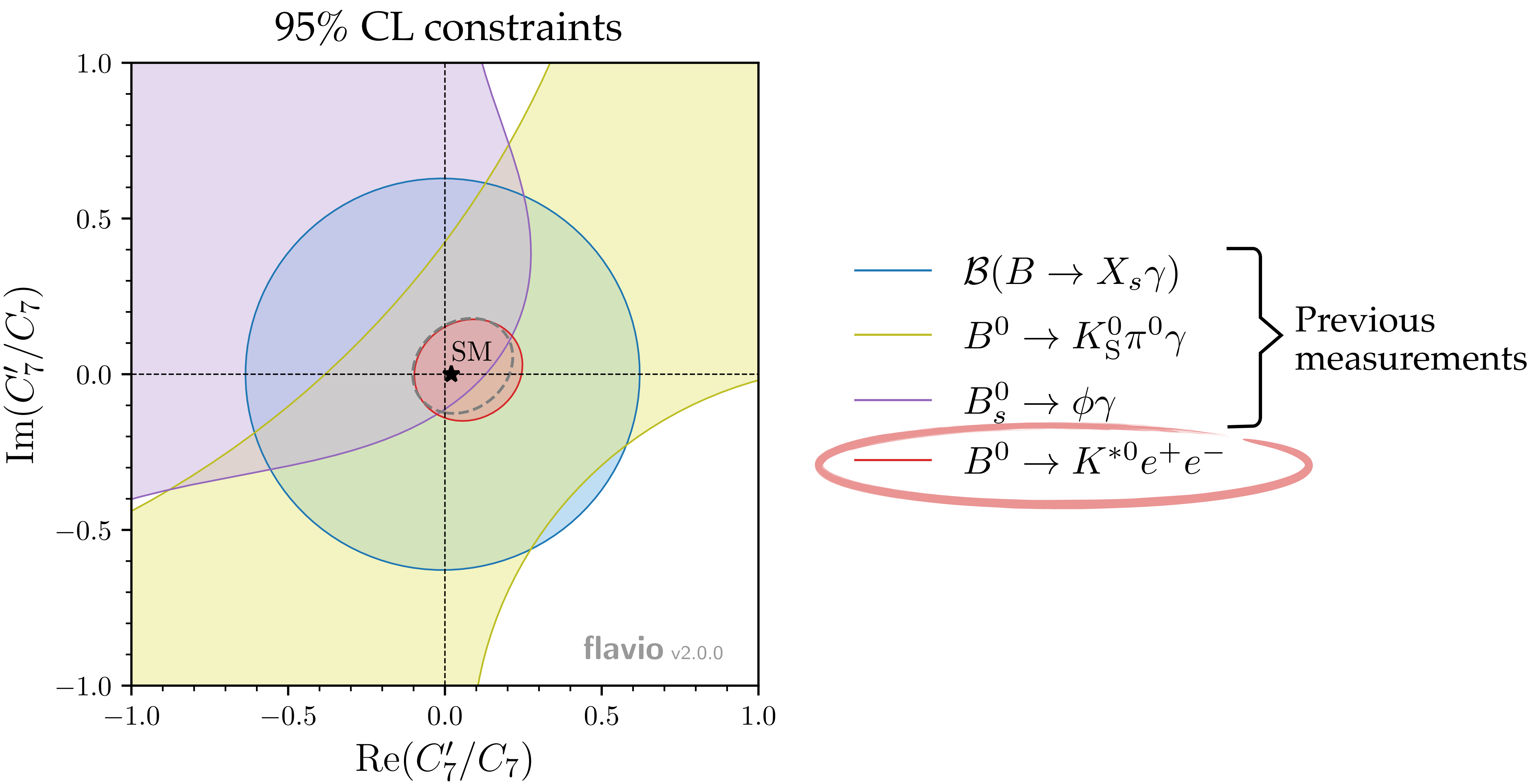


LHCb JHEP 12 (2020) 081



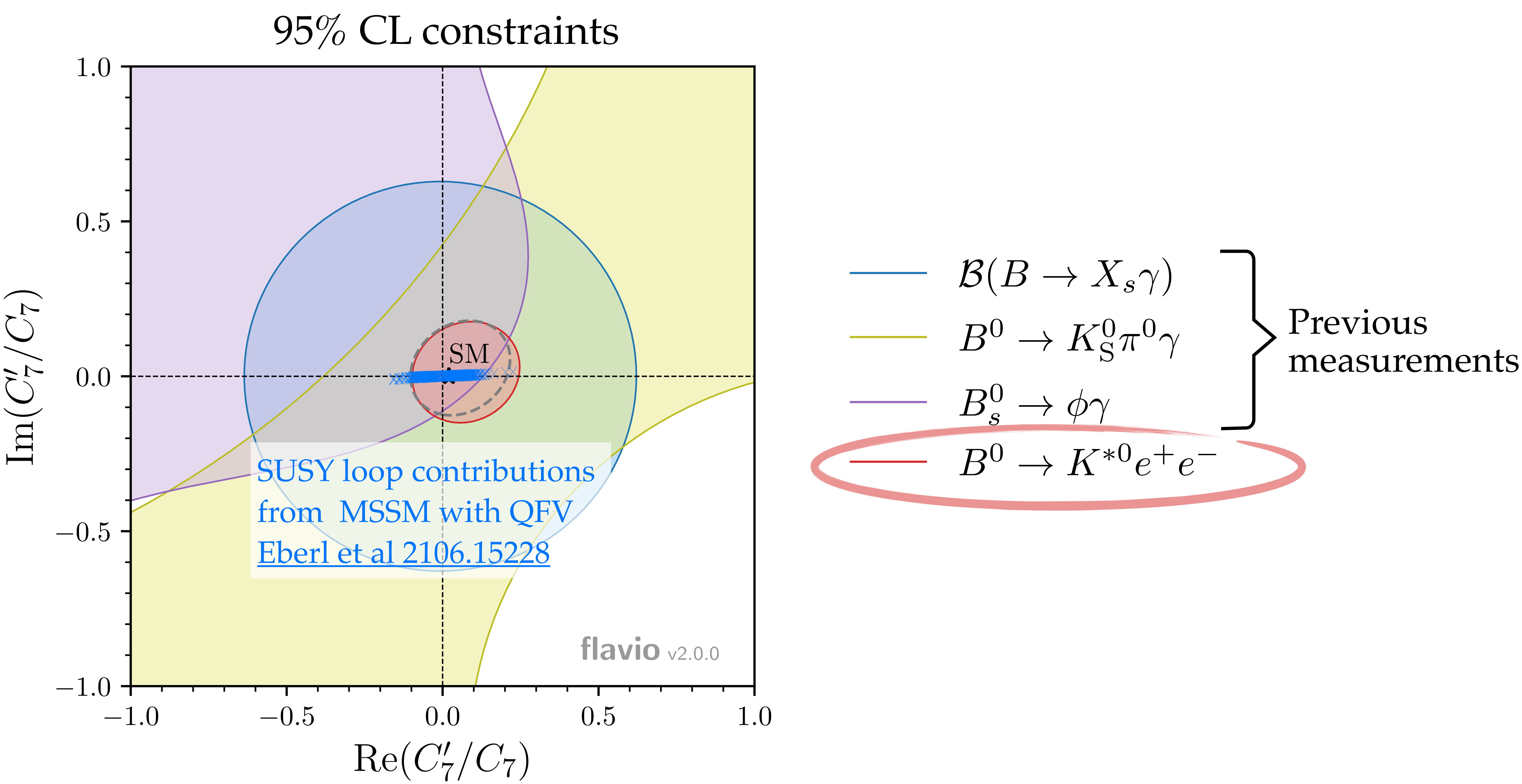
$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$

LHCb JHEP 12 (2020) 081



$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$

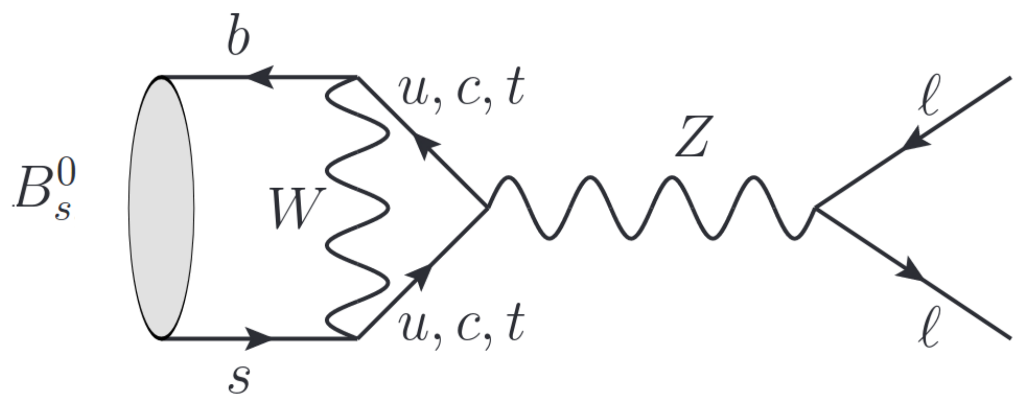
LHCb [JHEP 12 (2020) 081]



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

- A golden flavour physics channel
  - Very rare 10^{-9} BR (helicity suppression)
  - Precise 4% BR prediction (fully leptonic)

Beneke et al. JHEP 10 (2019) 232
Kozachuk et al., PRD 97 (2018) 053007



+ box diagram involving neutrinos

- Searched since the 80's and firstly observed in 2014 by LHCb+CMS (Nature 522 (2015) 68)

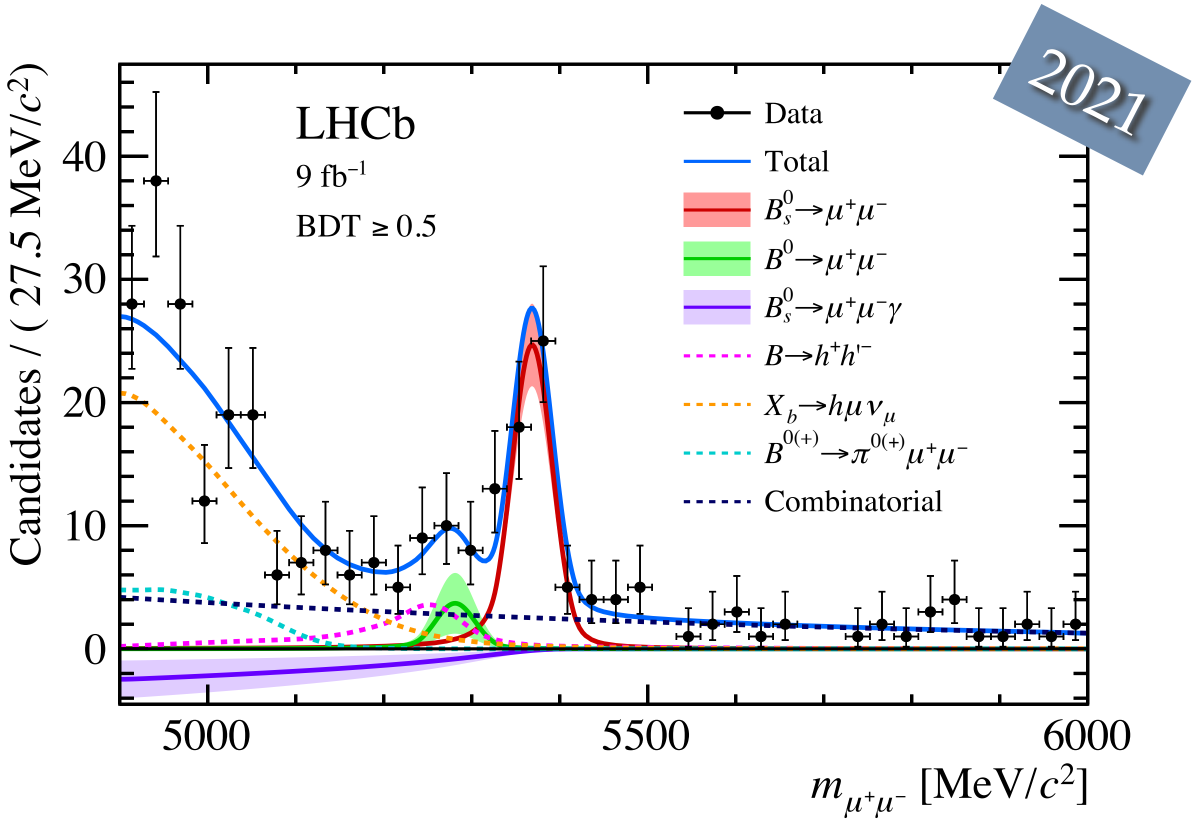
Leptonic $B_s \to \mu^+\mu^-$

LHCb PRD 105(2022)012010 PRL 128(2022)041801

- Now measurement with LHCb Run 1+2 reached 16% uncertainty:

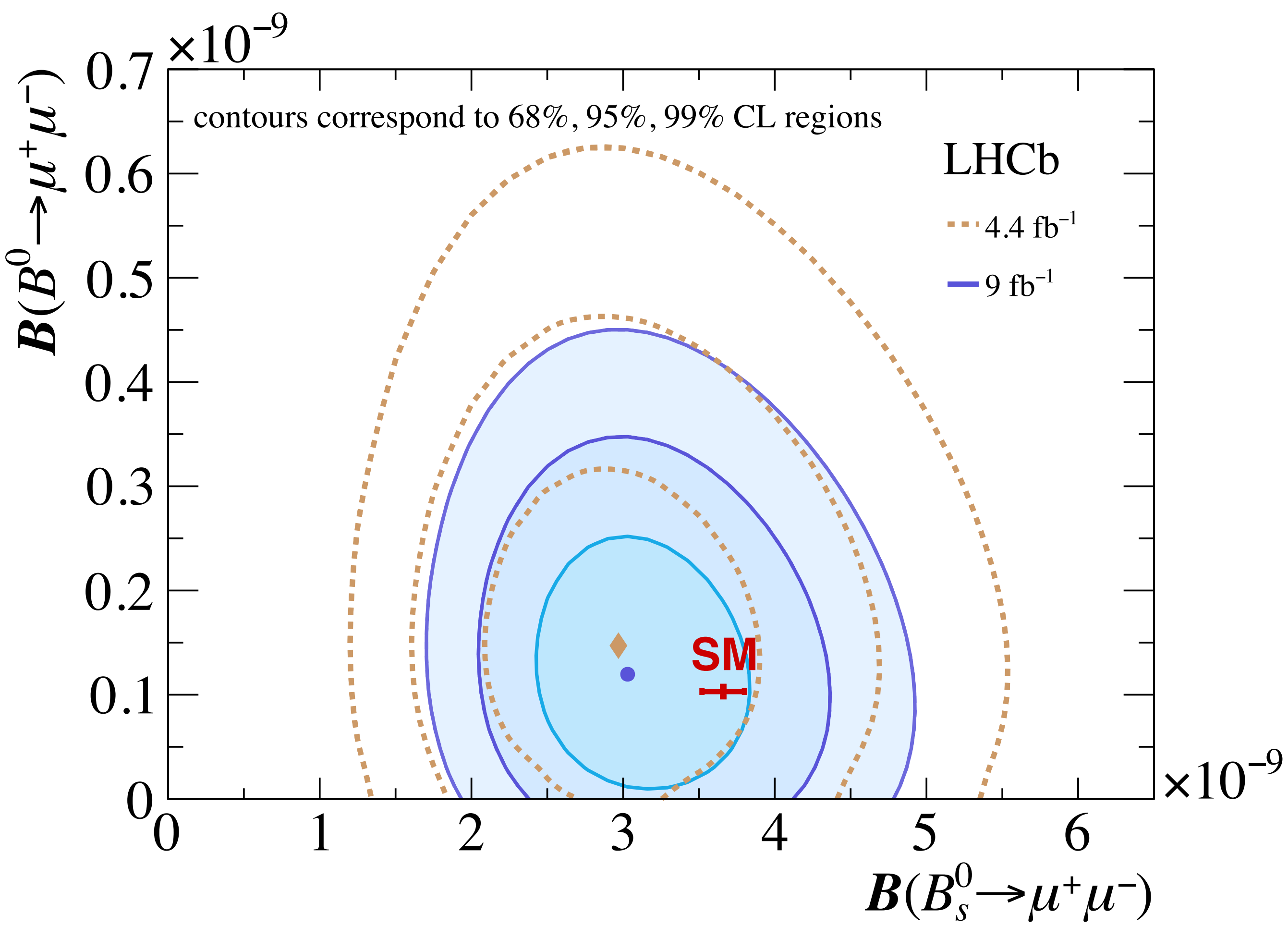
  $$BR(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

- Contribution from MFV MSSM $\propto t_\beta^6/m_A^4$
- Expect 10% precision when we will combine with **upcoming** ATLAS+CMS Run 2



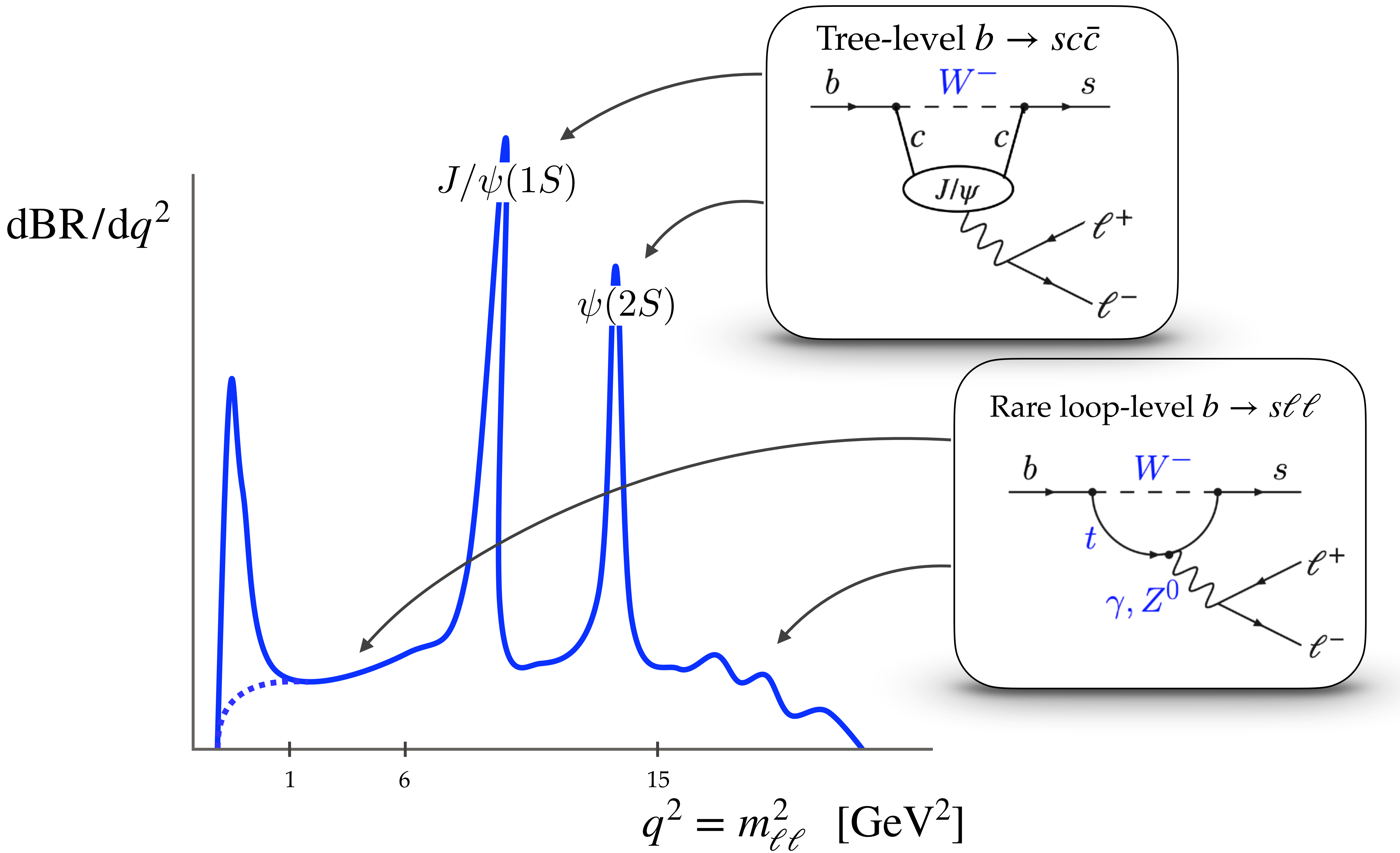
Leptonic $B_{(s)} \to \mu^+\mu^-$

LHCb PRD 105(2022)012010 PRL 128(2022)041801



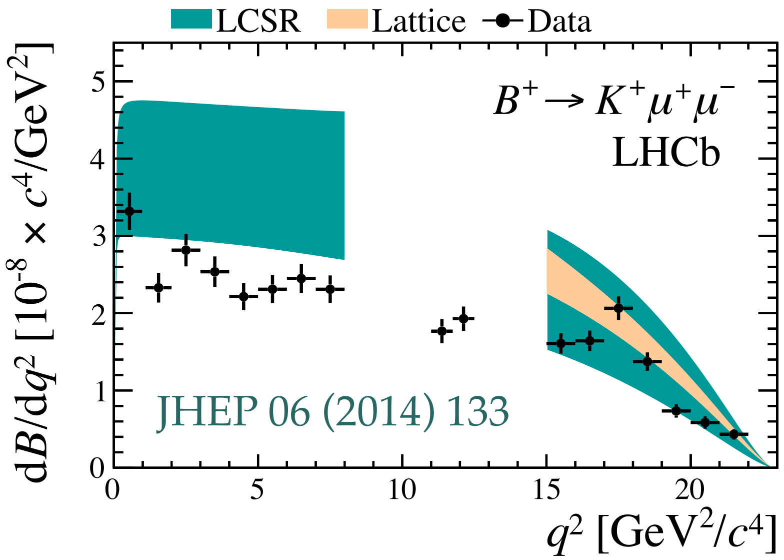
- $BR(B_d \to \mu^+\mu^-) < 2.6 \times 10^{-10}$
- Testing the MFV paradigm
- Excellent agreement with SM

Semileptonic $b \to s\ell\ell$

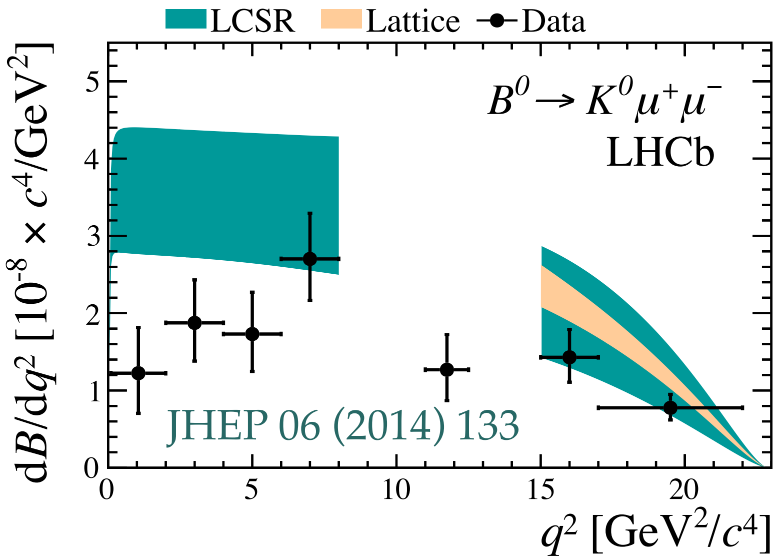


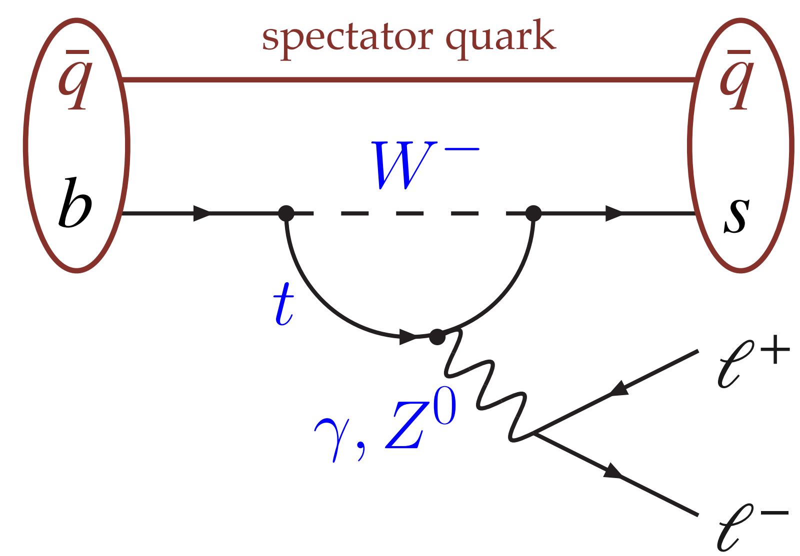
Branching ratios

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

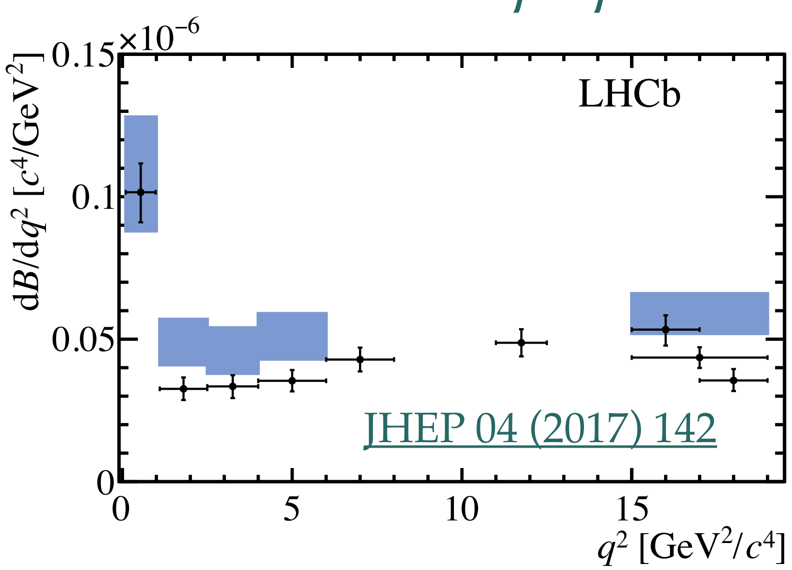


$B^0 \to K^0\mu^+\mu^-$

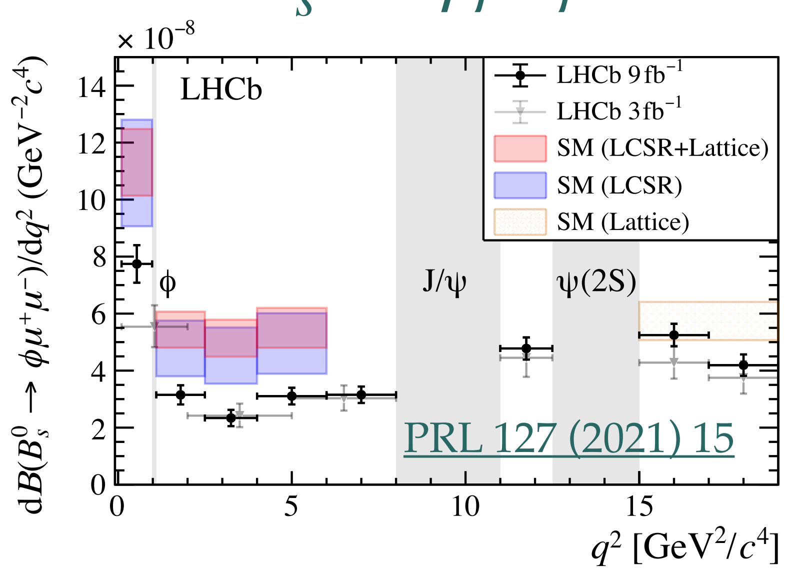




$B^0 \to K^{*0}\mu^+\mu^-$



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



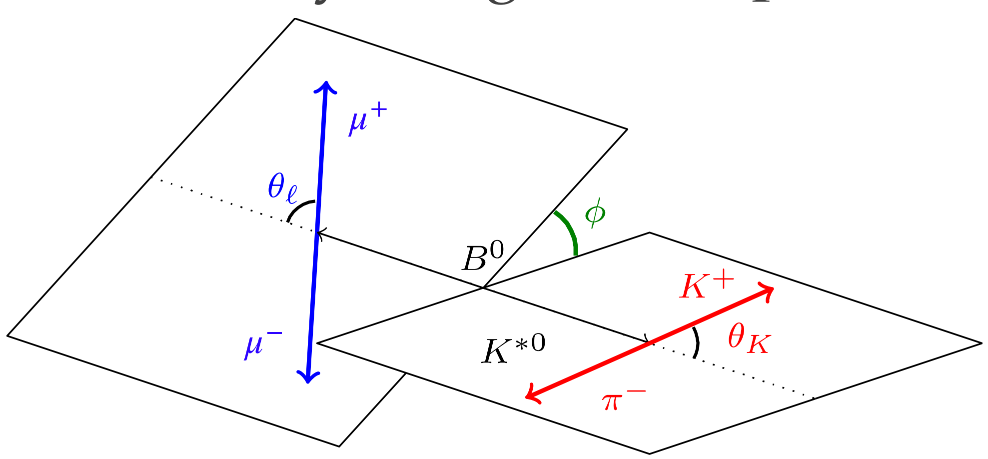
dB/dq^2 in exclusive $b \to s\mu\mu$ seems to undershoot SM

- Theory uncertainties ~20-30% (hadronic form factors)
- Coherent undershooting, but predictions uncertainties are correlated

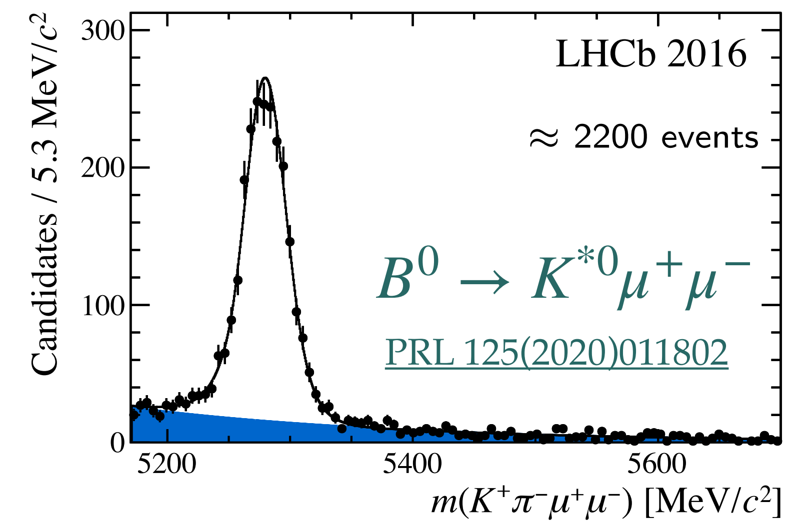
Angular analyses

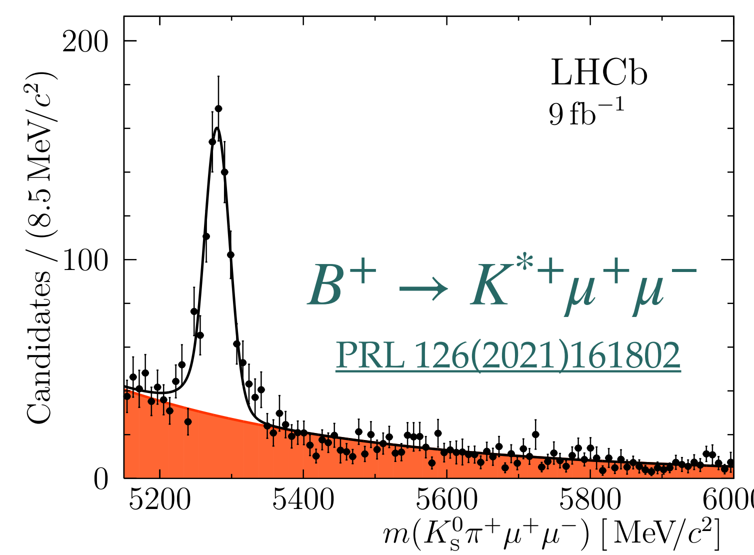
spin-1 hadron

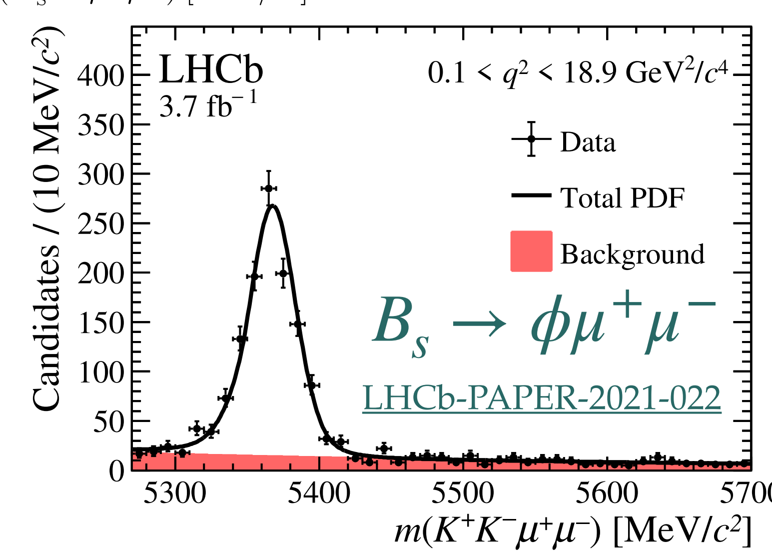
- $B \to V\mu^+\mu^-$ 4-body decay has rich kinematic structure to be studied
- Described by 3 angles and q^2



- Recent results:
  - $B^0 \to K^{*0}\mu^+\mu^-$with 6/fb (~4600 events)
  - $B^+ \to K^{*+}\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi\mu^+\mu^-$ with 9/fb (~1900 events)



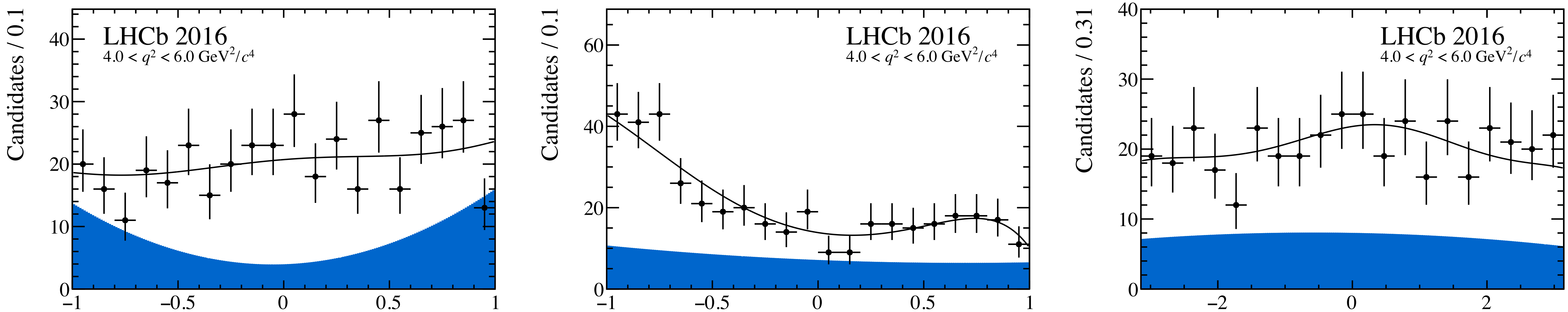




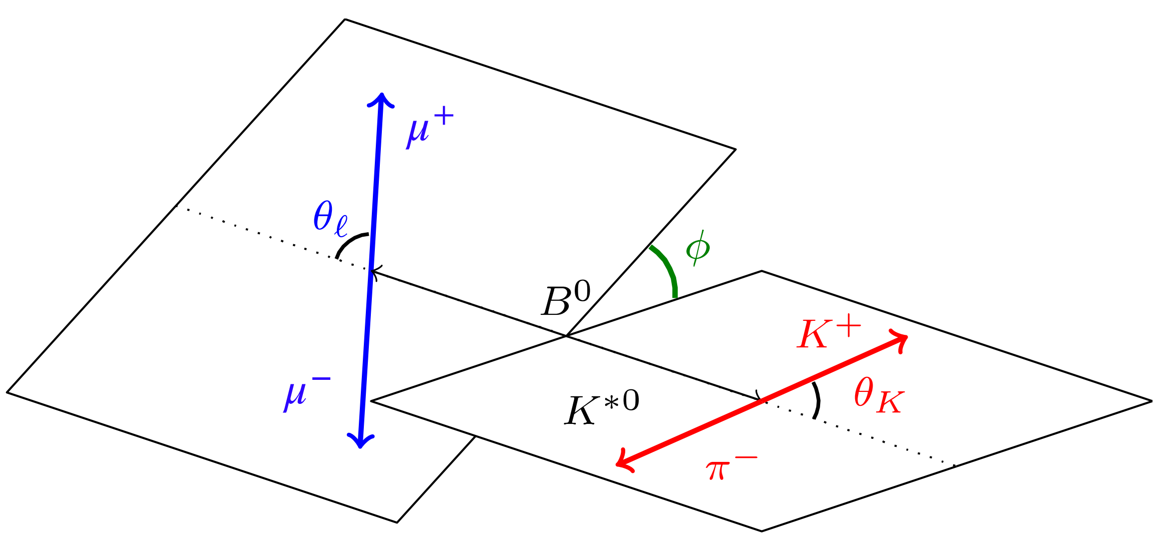
Angular analyses

PRL 125(2020)011802

$B^0 \to K^*\mu^+\mu^-$ in $4.0 < q^2 < 6.0$ GeV^2



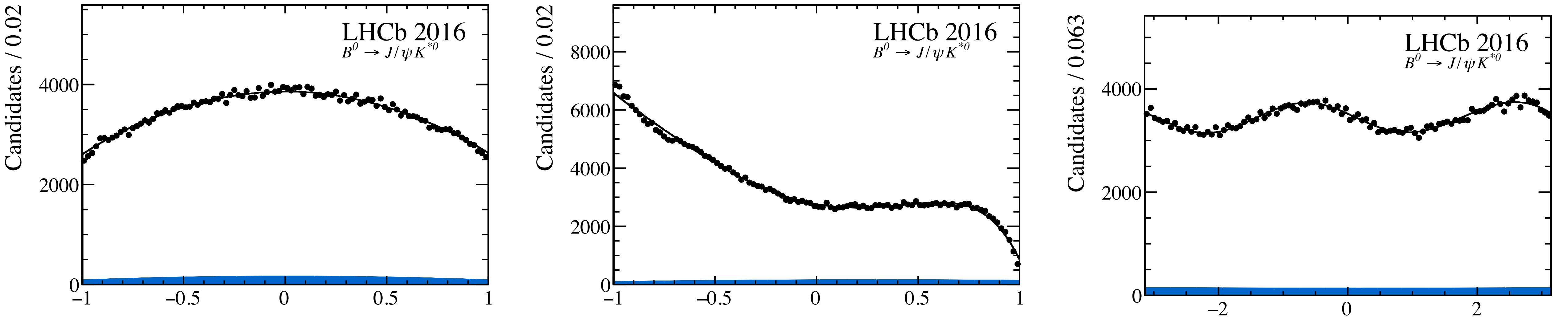
$\cos\theta_\ell$ $\cos\theta_K$ ϕ



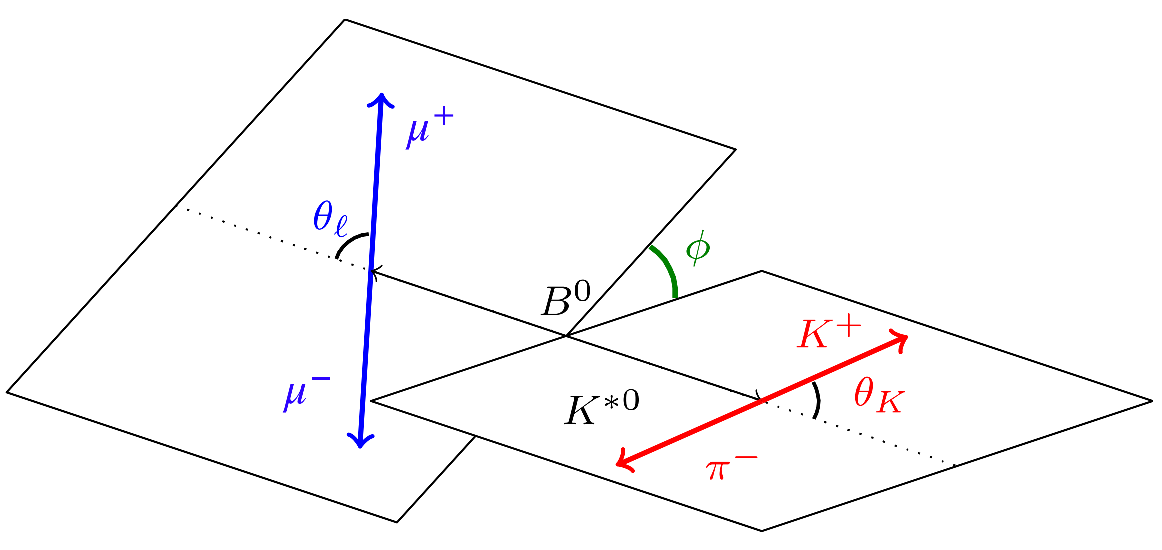
Angular analyses

[PRL 125(2020)011802](PRL 125(2020)011802)

$B^0 \to K^* J/\psi(\mu^+\mu^-)$ control channel



$\cos\theta_\ell$ $\cos\theta_K$ ϕ

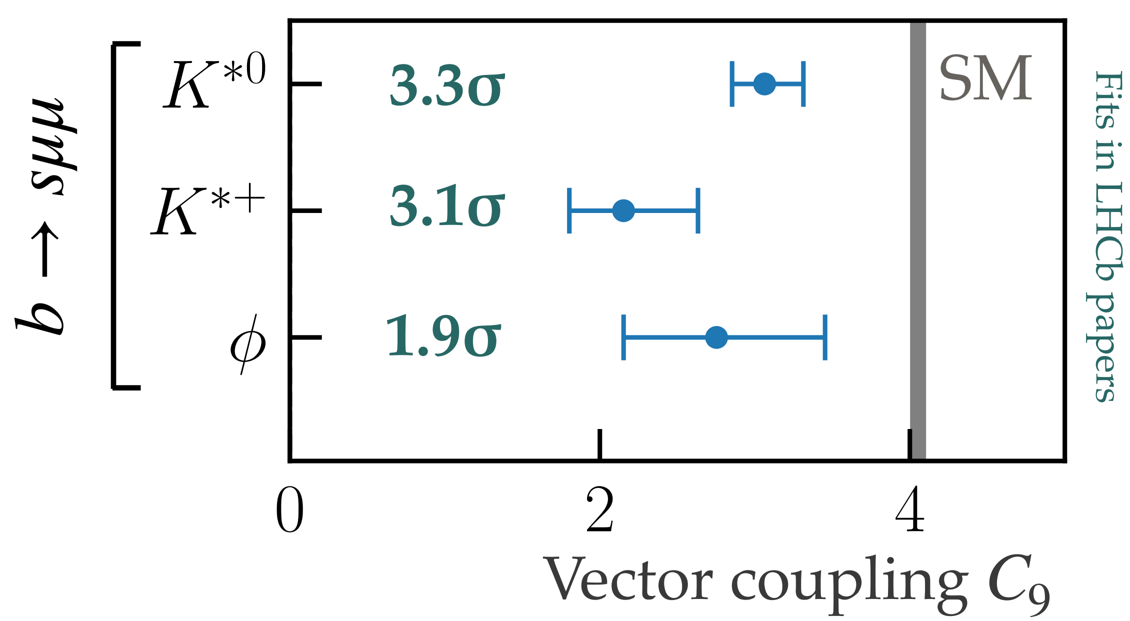


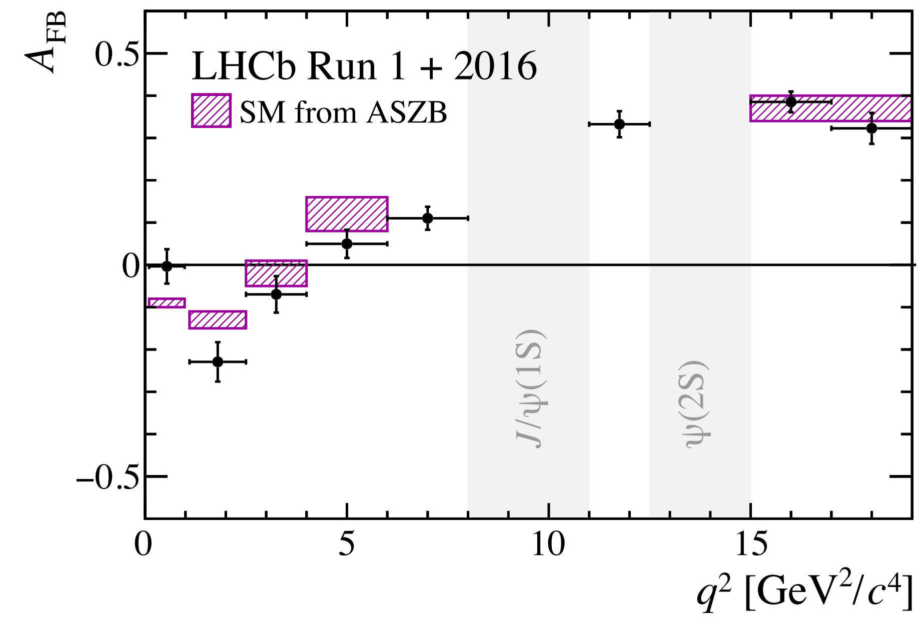
Angular analyses

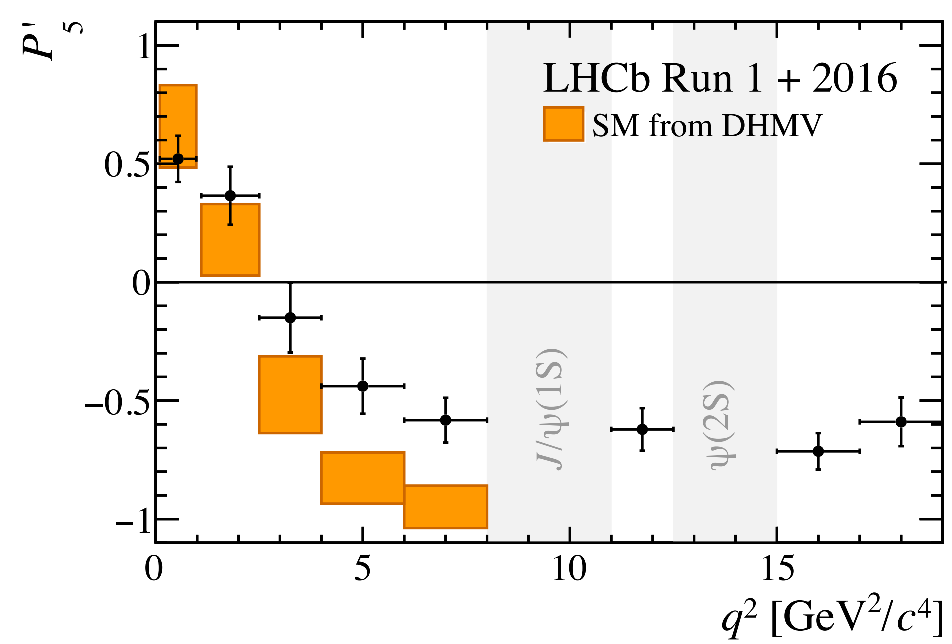
PRL 125(2020)011802

- Measure many angular observables in q^2 bins
- SM predictions are challenging, but uncertainties are smaller than for BR's
- Optimised observables where hadronic uncertainties cancel out at 1st order (e.g. P_5')

- Some deviations at >2σ level observed
- Deviations are **coherent** and **significant** when interpreted as modified vector coupling C_9





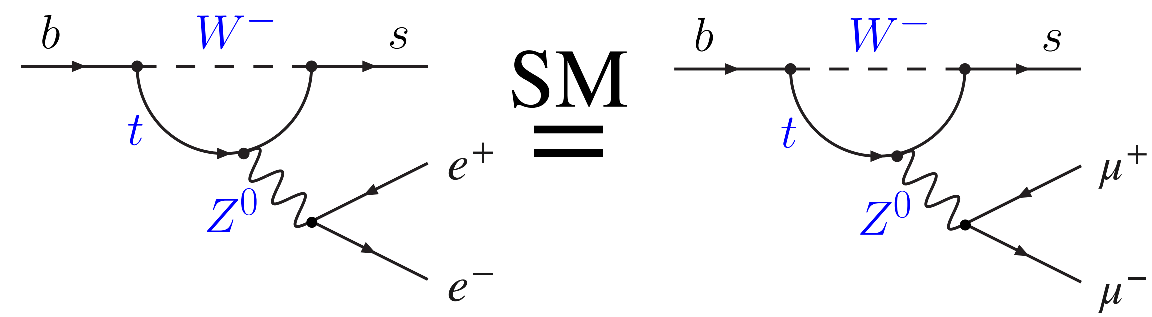


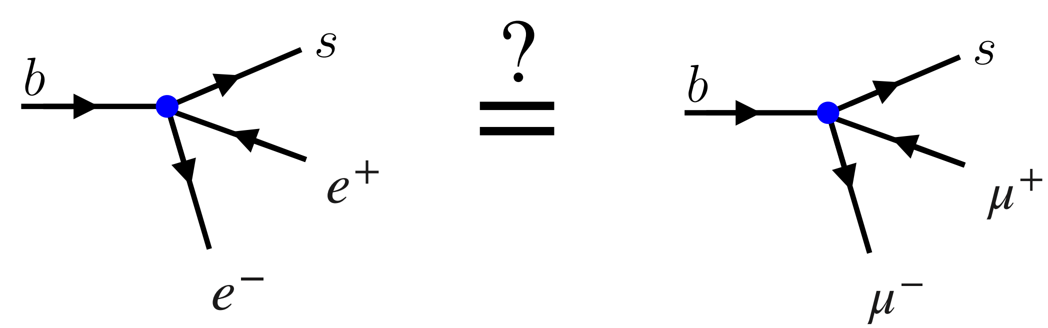
SM prections from:

Bharucha et al arXiv:1503.05534
Altmannshofer et al arXiv:1411.3161

Descotes-Genon et al arXiv:1407.8526
Khodjamirian et al arXiv:1006.4945

LU tests in $b \to s\ell^+\ell^-$





- $b \to s\ell^+\ell^-$ is lepton universal in the SM
  $\to$ can identify LU violating NP contribution

  Hiller & Kruger arXiv:hep-ph/0310219

- Predictions are uncontroversial and very precise
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED corrections

  Bordone et al arXiv:1605.07633

- Main challenge at LHCb is e/μ differences in the detector response

$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s \mu^+\mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+e^-\right)} \overset{\mathrm{SM}}{=} 1.00 \pm 0.01$$

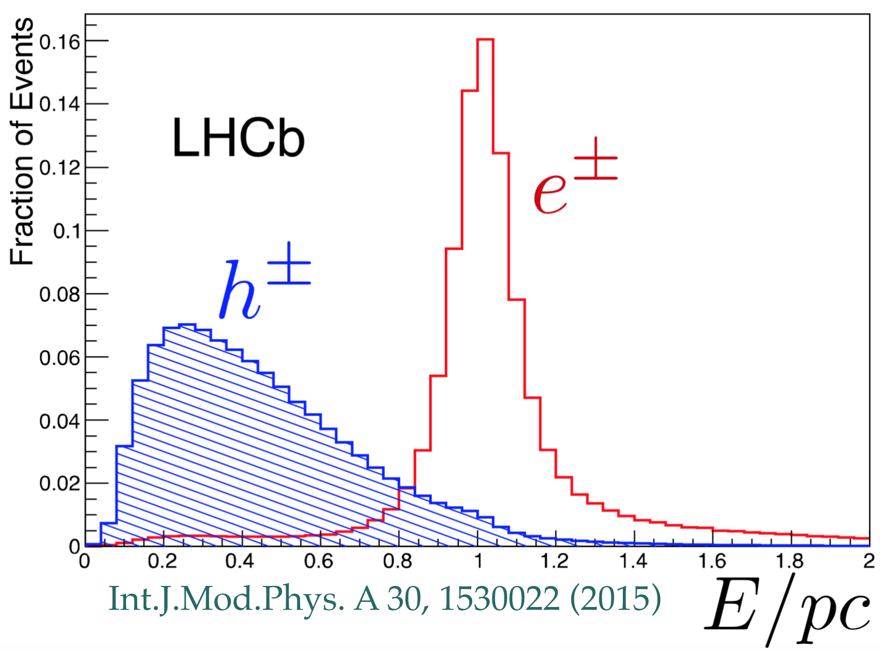
Electrons at LHCb

- Efficiency bottleneck at hardware trigger:
  - $p_T(\mu^{\pm}) > 1.5 - 1.8$ GeV
  - $E_T(e^{\pm}) > 2.5 - 3.0$ GeV
- Electron ID based on ECAL and tracking (harder and slower than μ ID)

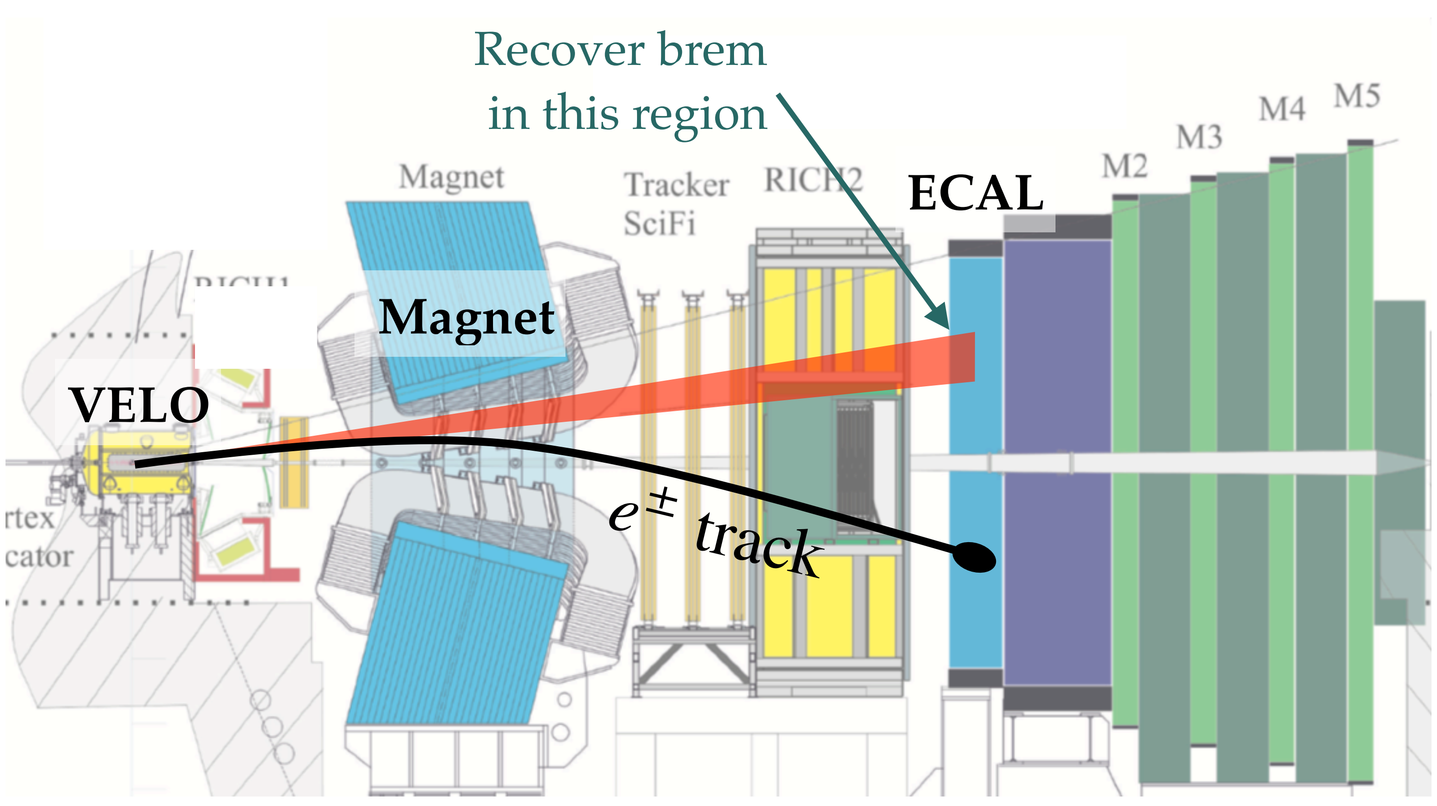
$$\frac{\epsilon(B^+ \to K^+\mu^+\mu^-)}{\epsilon(B^+ \to K^+e^+e^-)} \simeq 2.8$$

- Measurement of $p(e^{\pm})$ affected by bremsstrahlung emission before magnet
- Bremsstrahlung photon recovery procedure has limited efficiency

Electron ID



Int.J.Mod.Phys. A 30, 1530022 (2015)

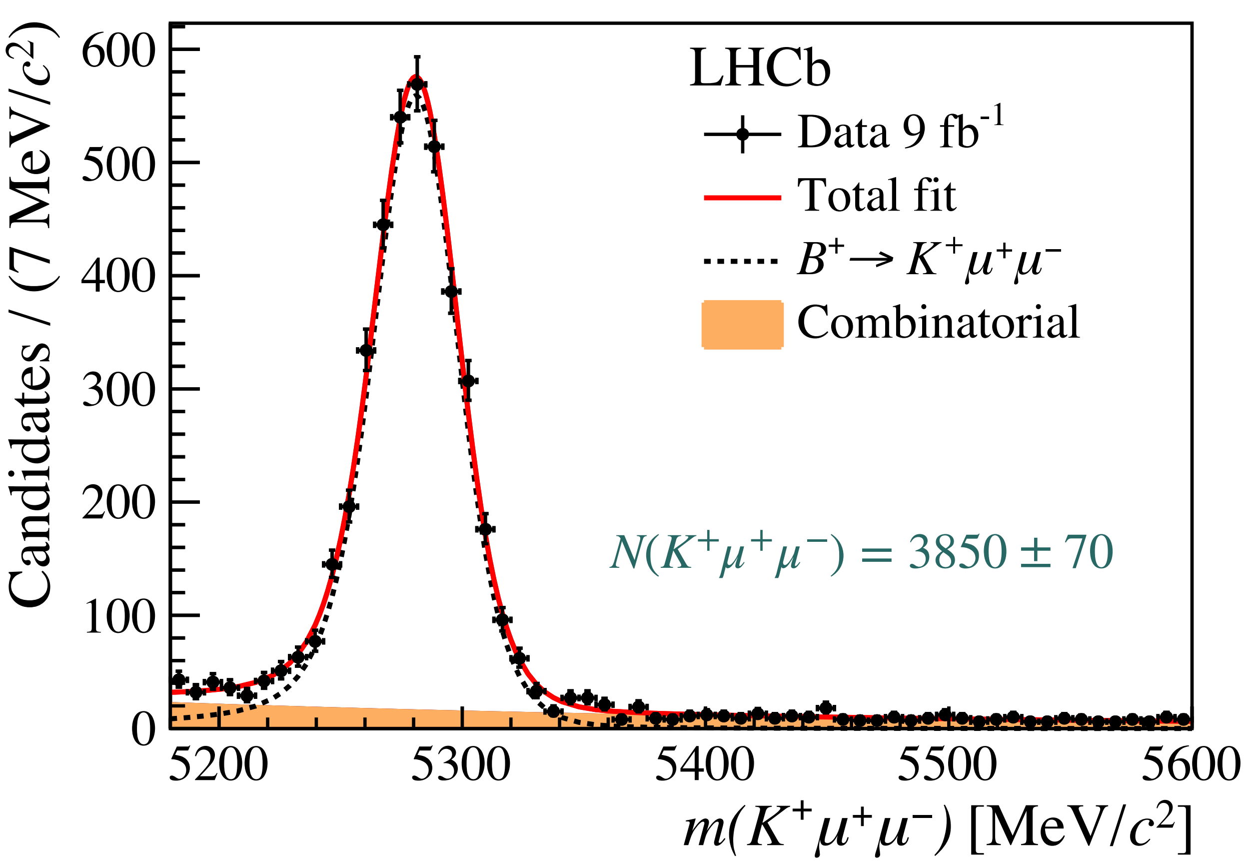


Int.J.Mod.Phys. A 30, 1530022 (2015)

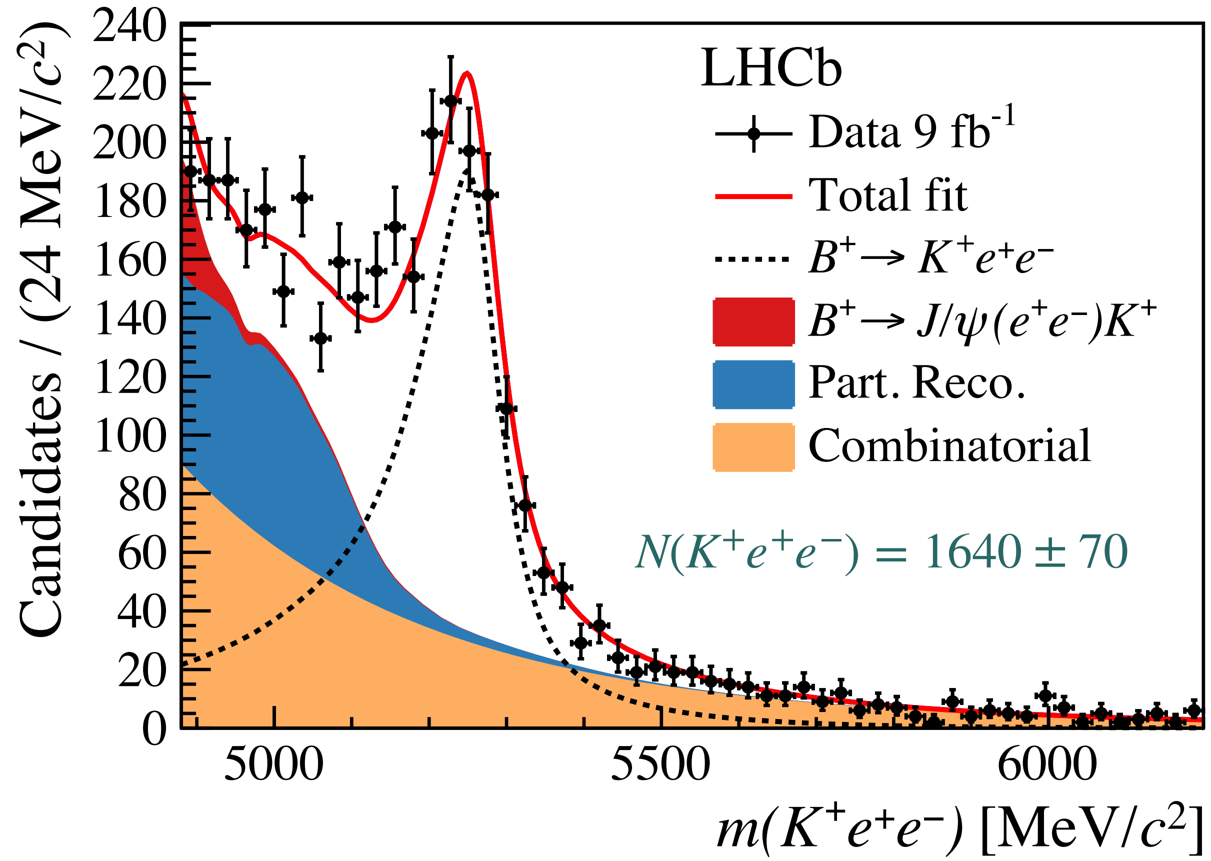
Electrons at LHCb

LHCb Nature Physics 18, (2022) 277-282

Muons



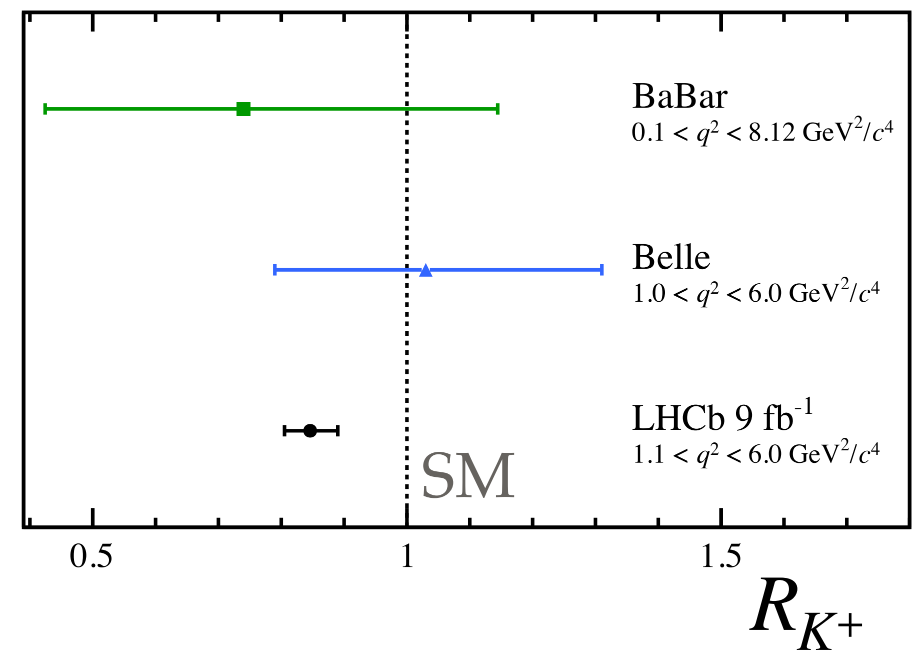
Electrons



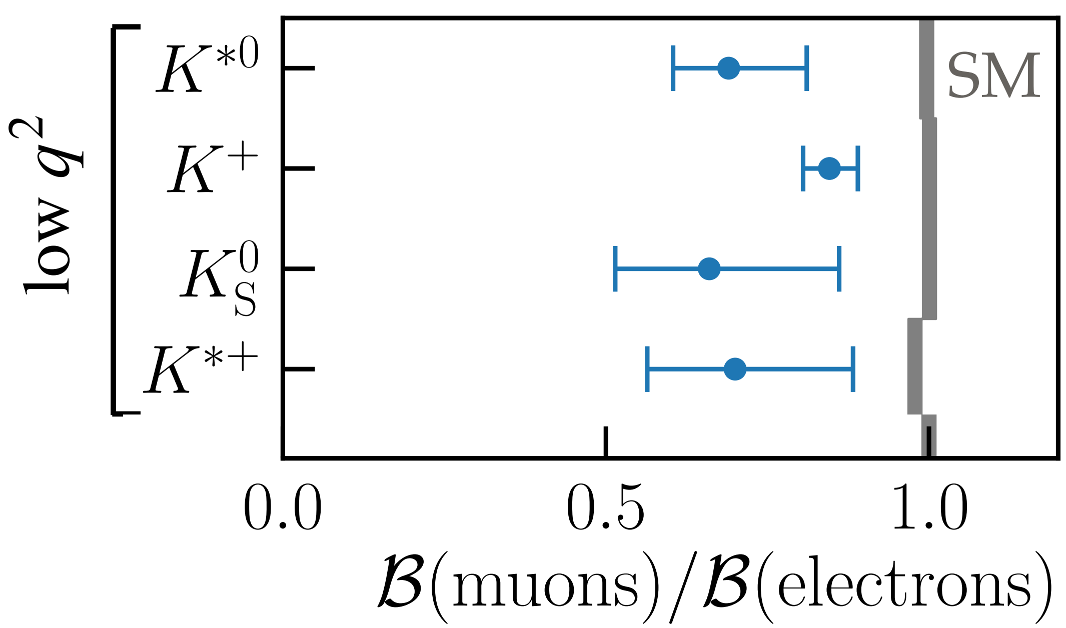
LU tests in $b \to s\ell^+\ell^-$

- Results much more precise than previous experiments
- Measured in several $b \to s\ell\ell$ decay channels
- If confirmed, it would be a clear sign of physics beyond the SM
- Hints of LU violation in charged current $b \to c\ell\nu$ could be connected $\to$ LHCb working to improve precision on $R(D)$ and $R(D^*)$

LHCb Nature Physics 18, (2022) 277-282



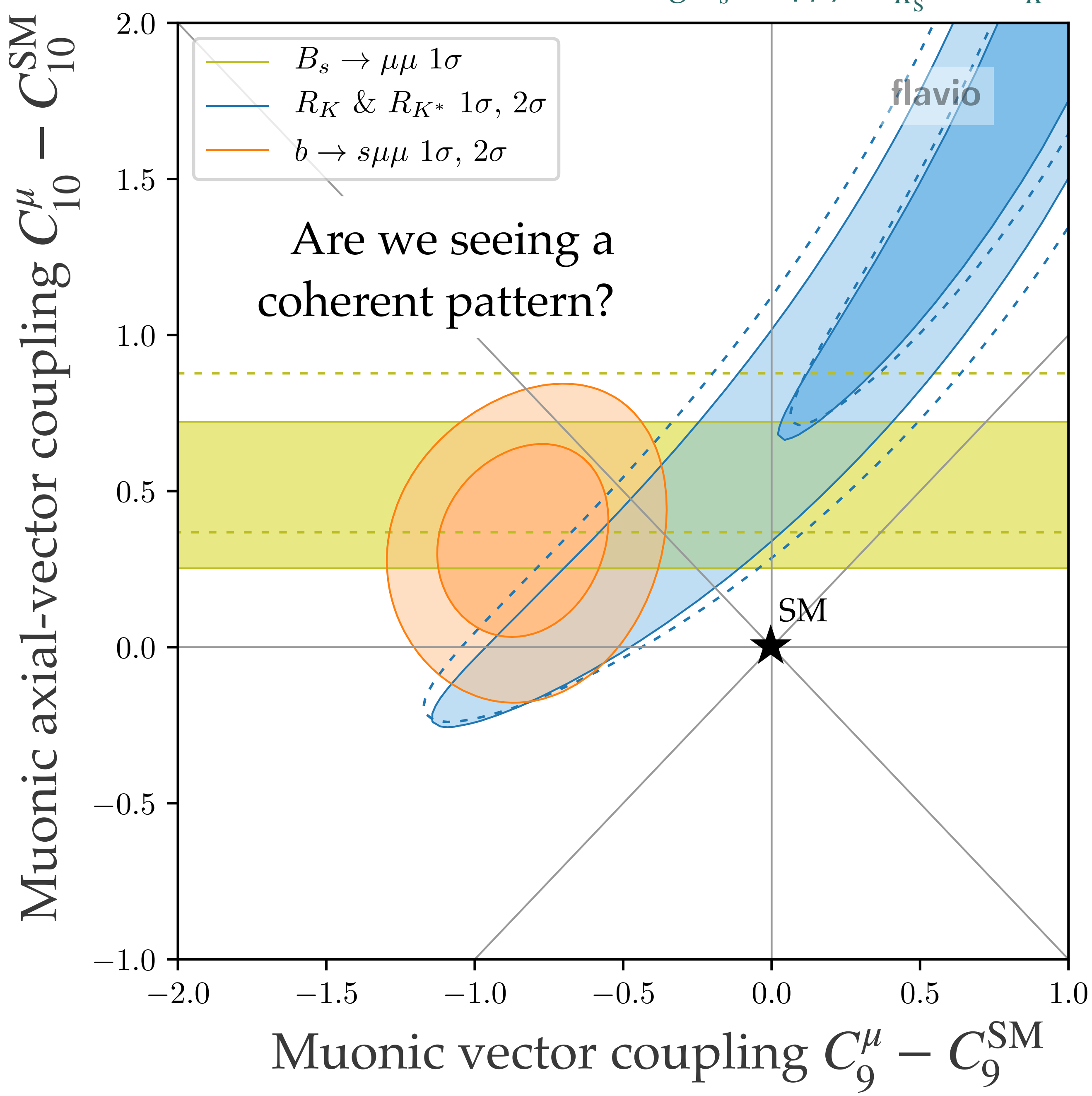
Personal compilation of results



Effective theory interpretation

- Fit couplings to **all** $b \to s\ell\ell$ results
  - Model with modified left-handed coupling to muons $C_L^\mu = C_9^\mu - C_{10}^\mu$ fits better than SM by **>5σ**
    Review talk from 20/10/2021
  - Generic lepton-dependent short-distance contribution fits better than SM by **>4σ**
    G.Isidori et al, PLB822(2021)136644

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370
Not including $B_s \to \phi\mu\mu$, $R_{K^0_S}$ and $R_{K^{*+}}$



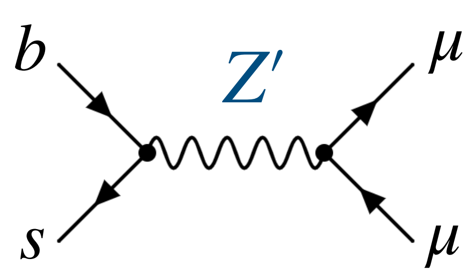
Connection to high energy

$$\frac{g_{\rm NP}}{\Lambda_{\rm NP}} \sim \frac{1}{30\ \rm TeV}$$

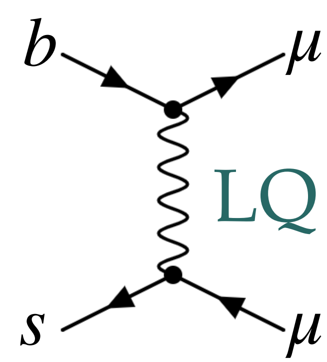
$\rightarrow$ Could be out of reach for the LHC if $g_{NP} \simeq 1$

- Talk from Kostas on Monday
- Important to leave no stone unturned at the LHC

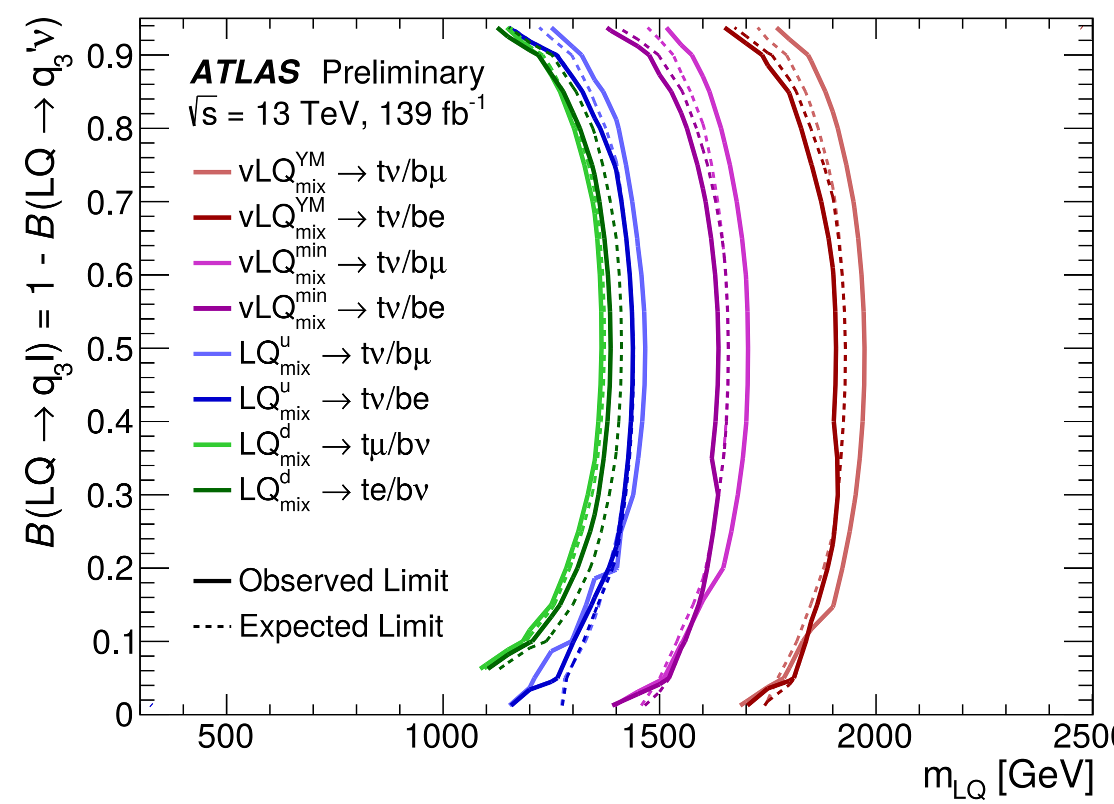
Tree level candidates:



or



ATLAS-CONF-2022-009



- Several models addressing these anomalies (and others) at SUSY2022!

A wide $b \to s\ell^+\ell^-$ program

- $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^*\mu^+\mu^-$
  - **More sophisticated** analyses possible with O(10k) events
  - Aim to get a handle on theory uncertainties ($c\bar{c}$)
- **Angular LU test** with $B^0 \to K^*\ell^+\ell^-$
  - Common explanation of $b \to s\mu\mu$ and LU anomalies implies LU breaking in the angular observables
- Lots of potential in Λ_b decays

CERN-LHCC-2018-027

R_X precision	9fb^{-1}
~~R_K~~	~~0.043~~
$R_{K^{*0}}$	0.052
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302
~~$R_{K^0_S}$~~	~~0.26~~
~~$R_{K^{*+}}$~~	~~0.22~~

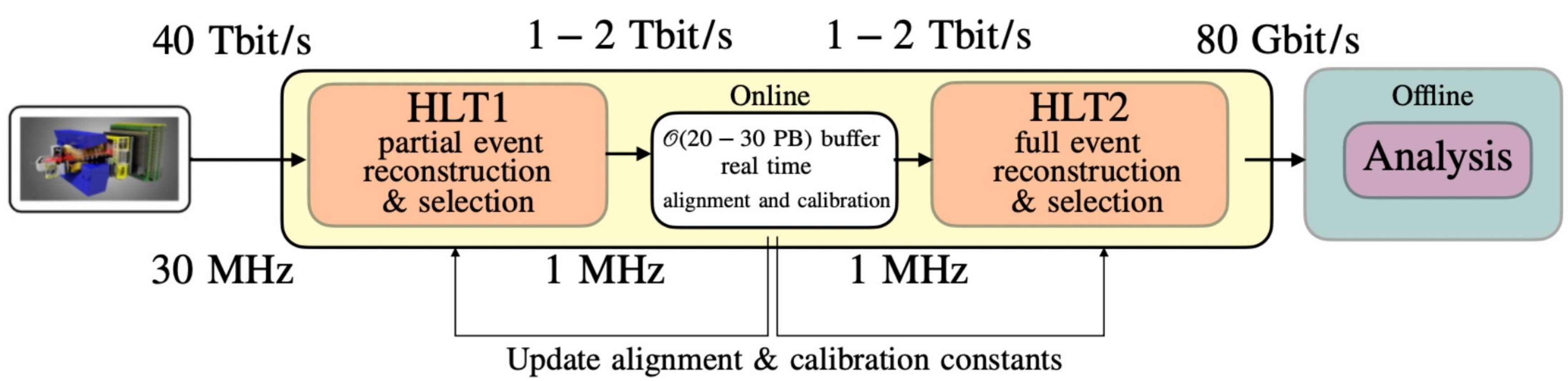
+ we are exploring high q^2

S.Glashow et al Phys.Rev.Lett. 114 (2015) 091801

- LFU violation implies LFV
  $\to$ several LFV searches: $e^+\mu^-$, $\mu^+\tau^-$

LHCb Upgrade I

- Upgraded detector for Runs 3 and 4 (TDR)
  - Readout electronics and several subdetectors upgraded
  - Can run at 5x higher luminosity
  - Full-software trigger using GPUs

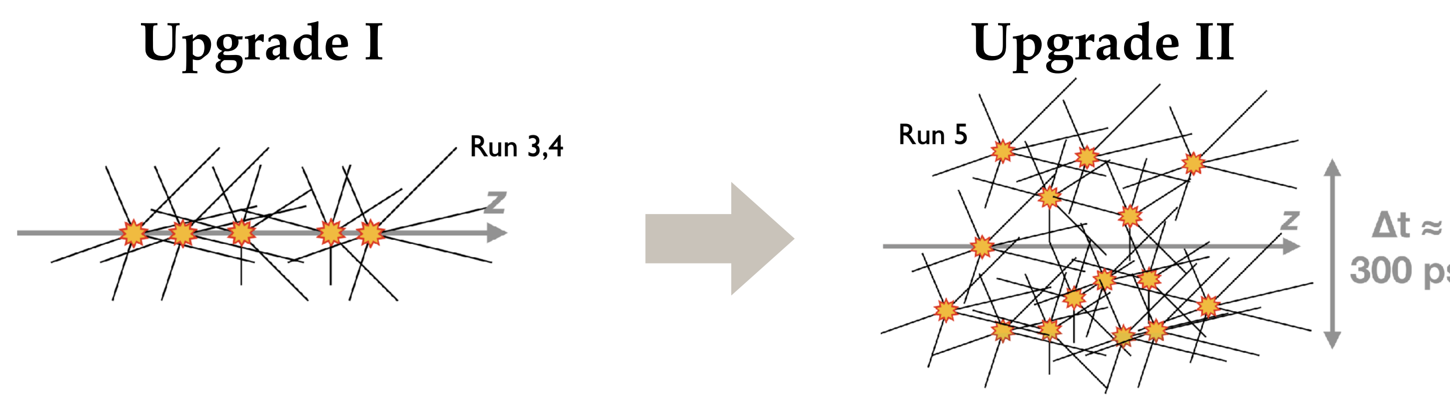


- Most measurements will directly profit from the higher statistical precision (about factor 3 with Run 3 only)

LHCb Upgrade II

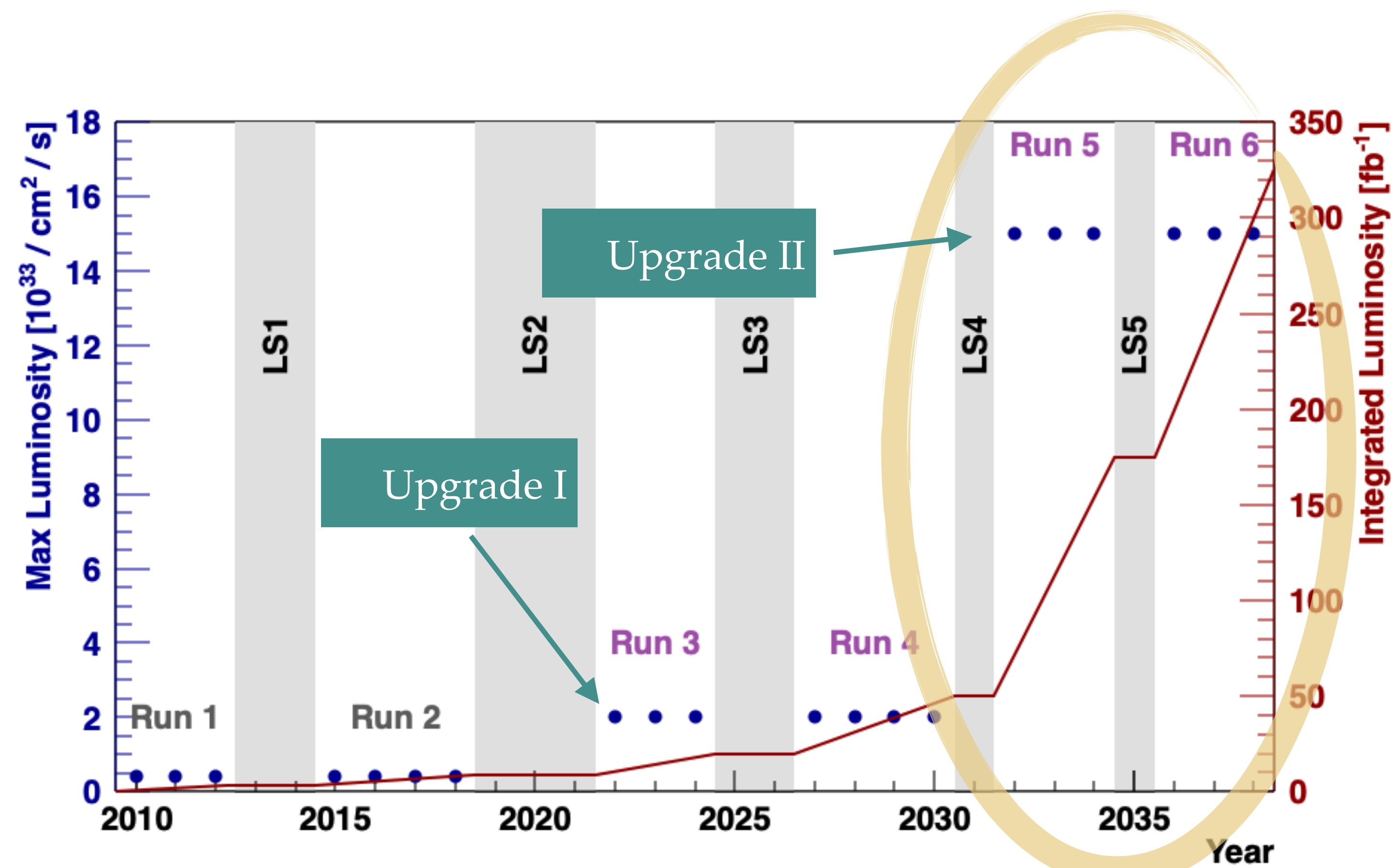
LHCB-PUB-2018-009

- LHCb **Upgrade II** to run at 10x luminosity of Upgrade I



- Potentially the only flavour facility in the world on this timescale
- **Driven by detector developments**: granularity, material budget, radiation hardness, timing, RTA

- Upgrade II sensitivity:
  - Angle γ with 0.35° precision
  - CPV ϕ_s with 4 mrad precision
  - R_K with 0.7% precision
  - $\dfrac{B_d \to \mu\mu}{B_s \to \mu\mu}$ with 10% precision
- **Double reach in NP energy scale Λ_{NP}**



See ICHEP talk by Federico

Conclusions

- Indirect effects often anticipated discoveries in HEP
  - Several leading measurements in precision quark-flavour physics coming from LHCb
  - Provided brief review of electroweak $b \to s$

→ "Discovery commences with the awareness of anomaly"
Thomas Kuhn

- LHCb performance in Runs 1-2 vindicated the detector design and motivated upgrades I and II to run at much higher luminosity

- Tantalising anomalies in $b \to s\ell\ell$ decays
  - LHCb can clarify the situation with complementary measurements and the upcoming upgrade data
  - Inputs from ATLAS, CMS and Belle II are extremely valuable and eagerly anticipated

→ "Extraordinary claims require extraordinary evidence"
Carl Sagan

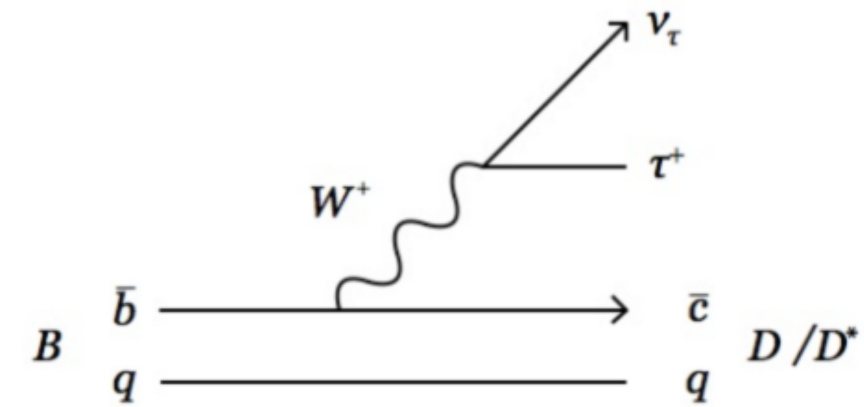
BACKUP

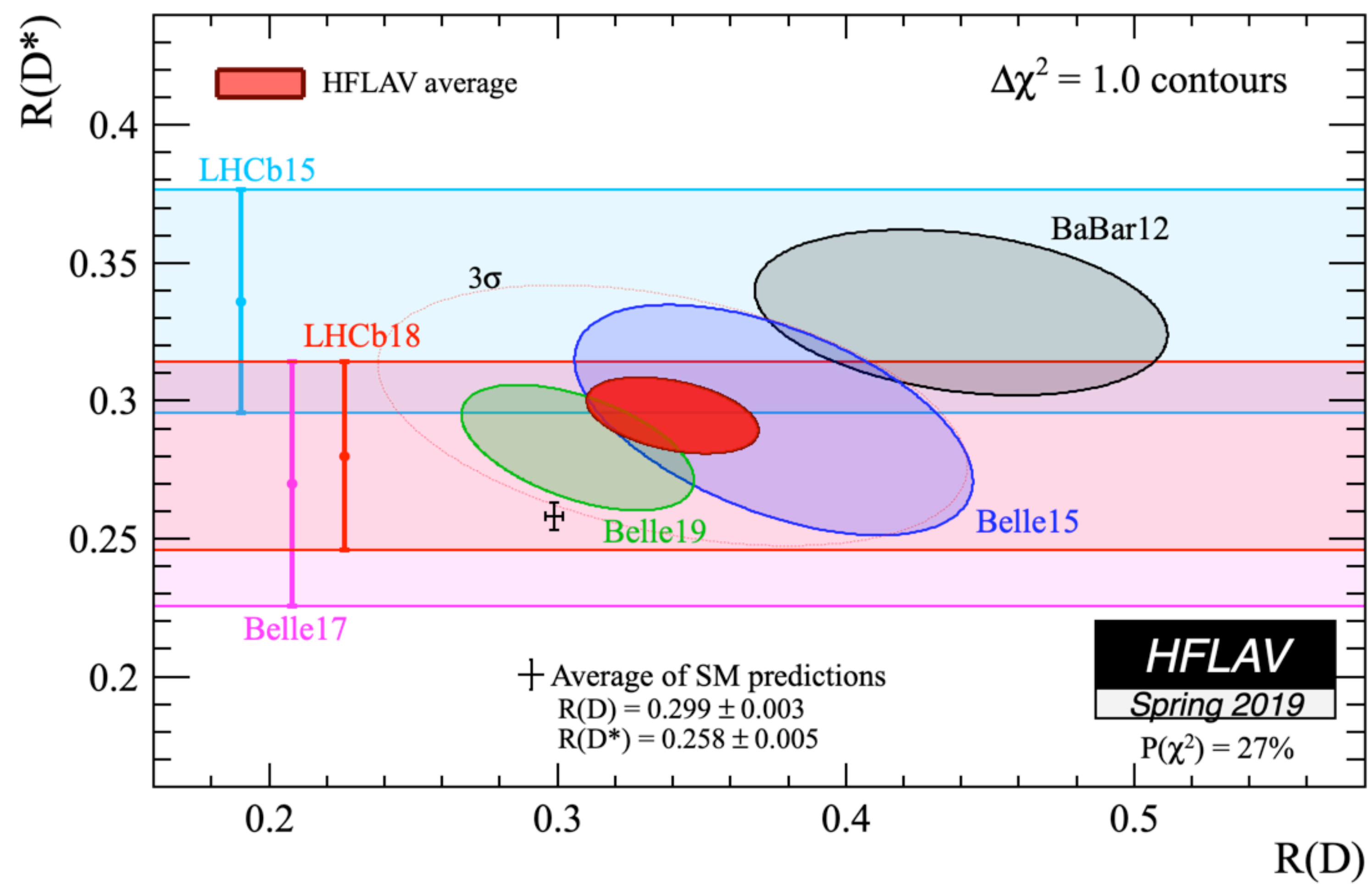
LU in tree-level B decays

- LFU has been tested intree-level $b \to c\ell\nu$ transitions
  - Comparing τ decay to $\ell = \mu(,e)$

$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$

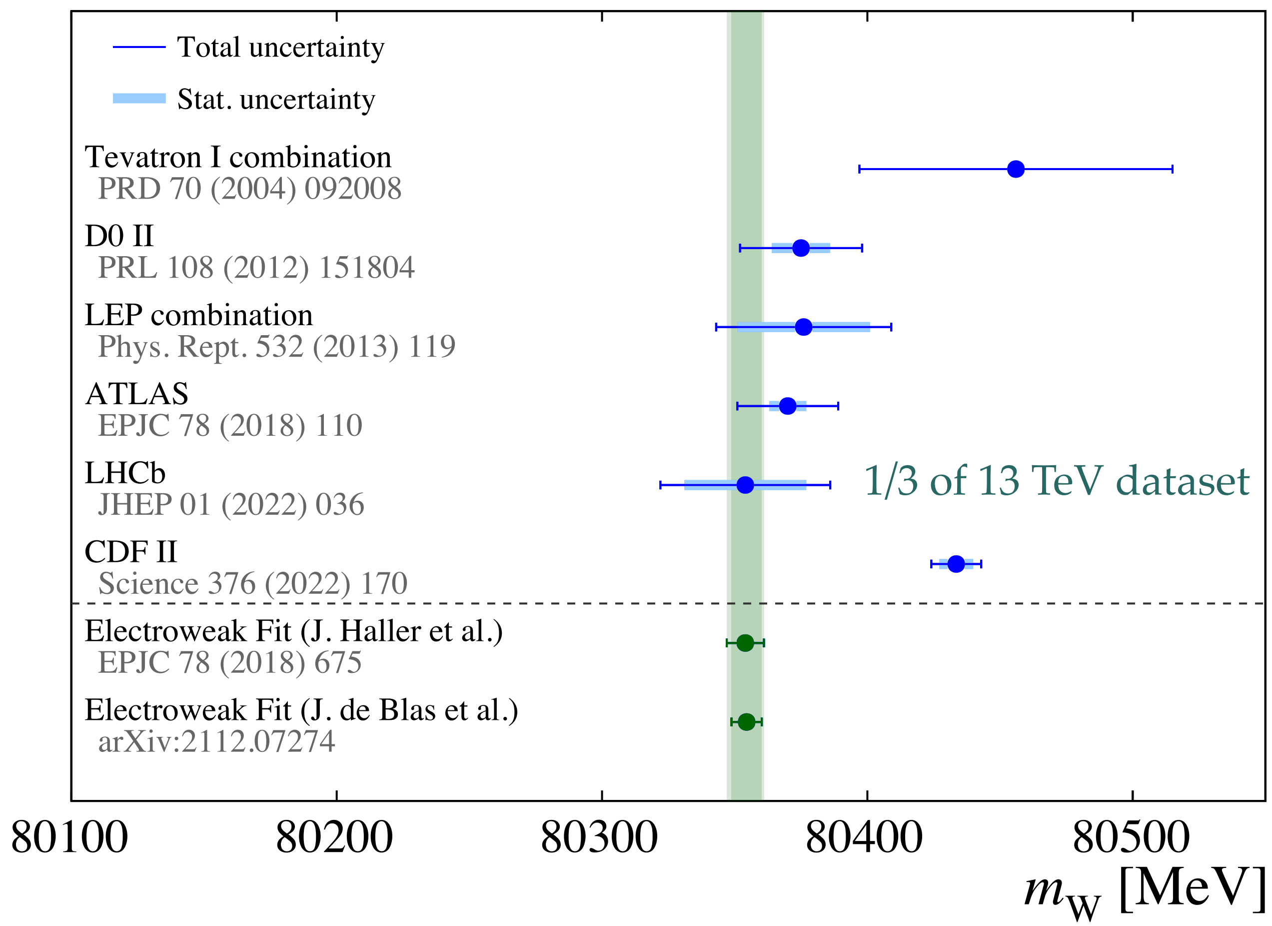
- LHCb, Belle and BaBar have comparable sensitivity
  - Measurements complicated by missing neutrino(s)
  - **Combined** result deviates about 3σ from the SM
- LHCb working on combined measurement of $R(D)$ and $R(D^*)$





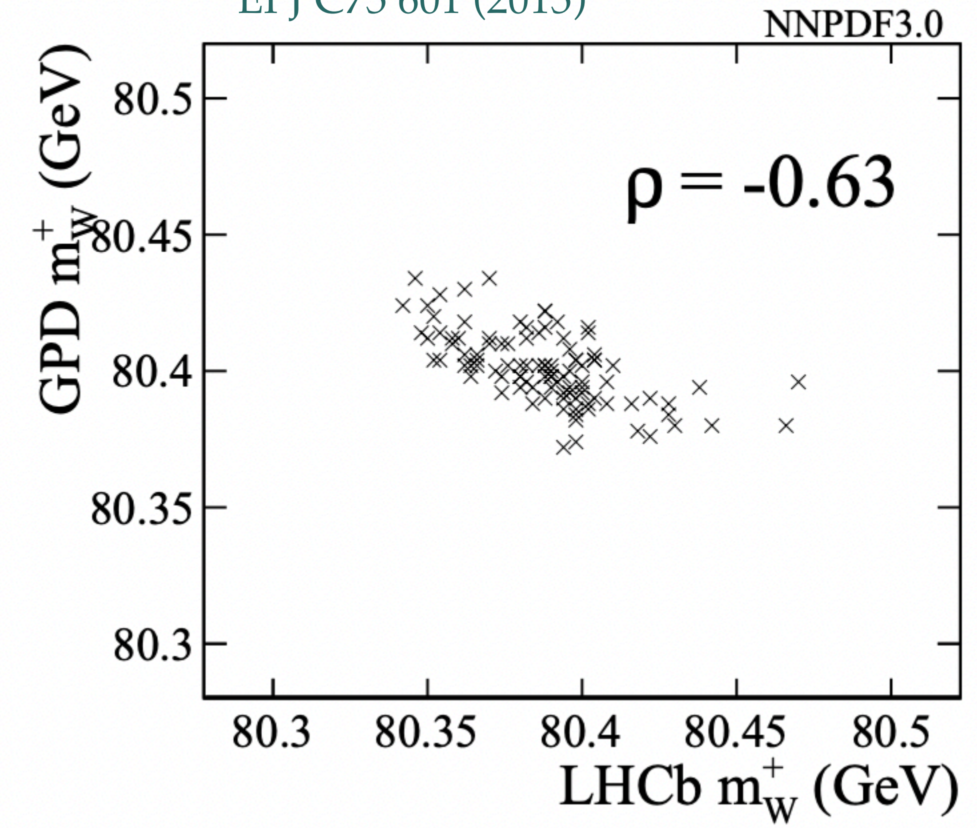
Measuring m_W at LHCb

LHCB-FIGURE-2022-003



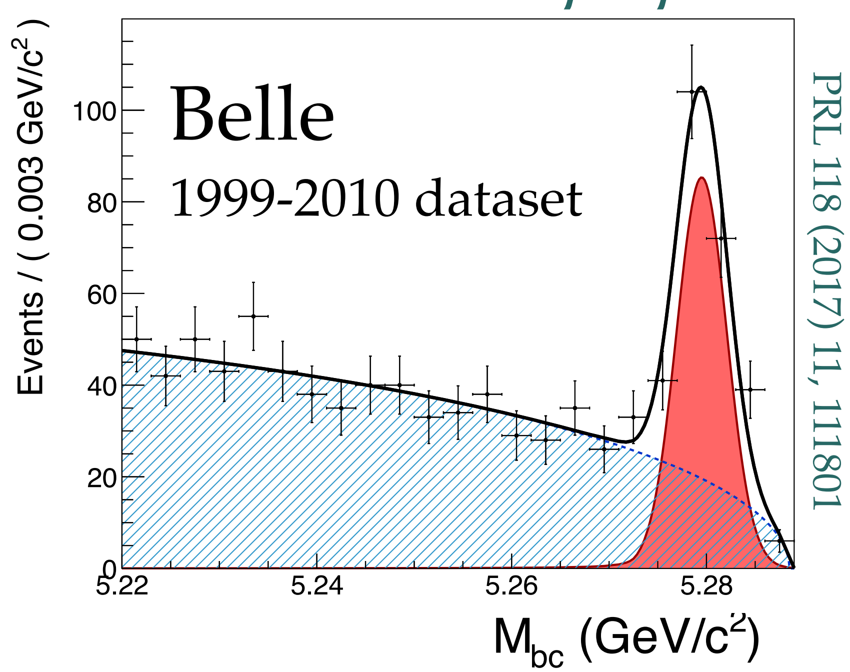
Expect anticorrelated PDF uncertainties!

EPJ C75 601 (2015)

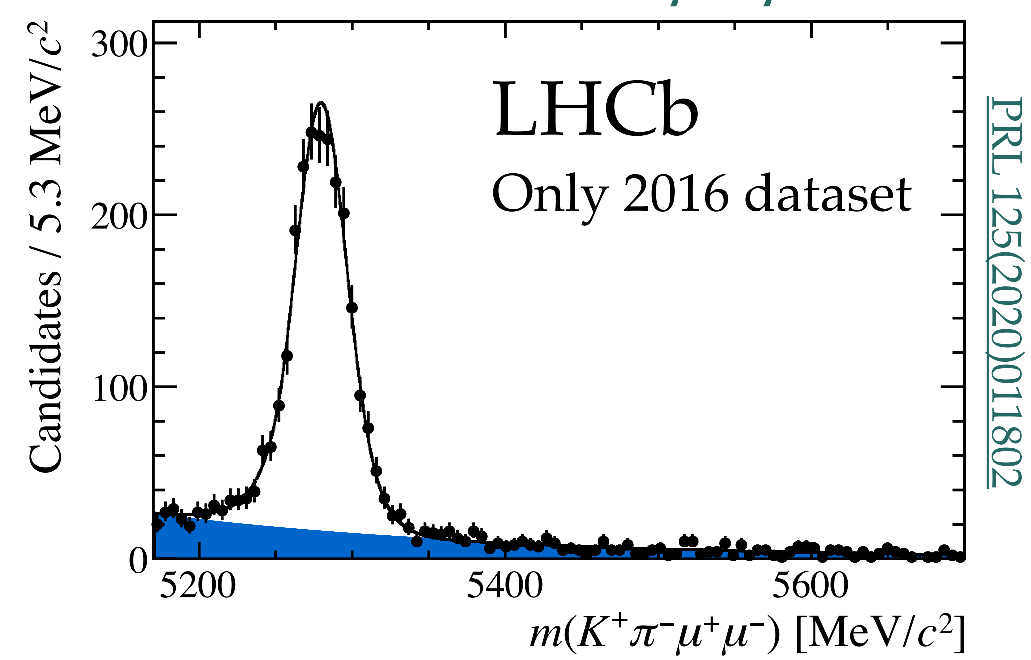


Entering the precision era

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



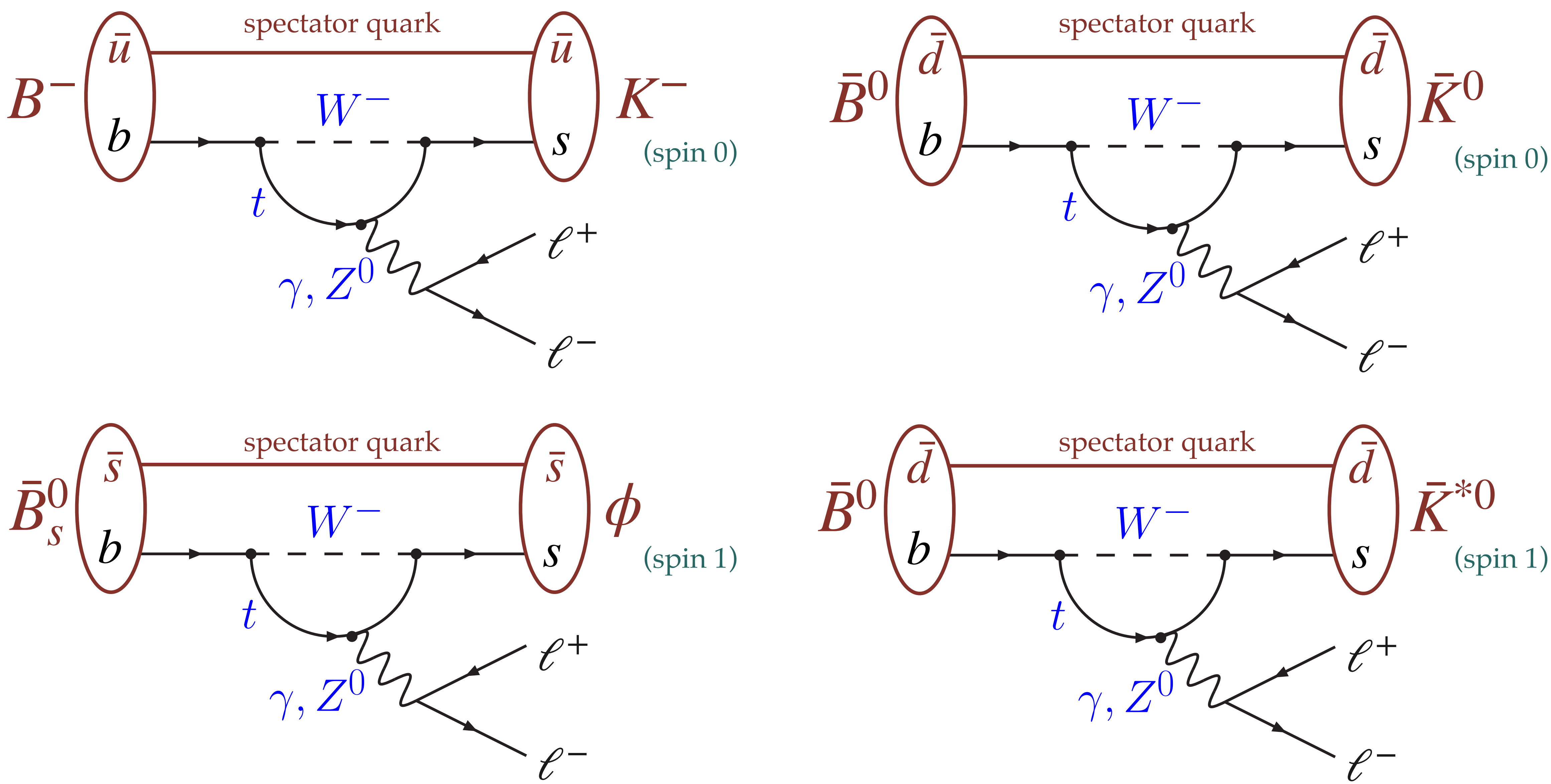
$B^0 \to K^+\pi^-\mu^+\mu^-$



- LHCb best at heavy-flavour decays with **charged final state**
  - ➡ e.g. collected in one year $10\times$ more $B \to K^+\pi^-\mu^+\mu^-$ decays than the Belle experiment collected in 10 years

$\to$ we just entered the precision era of $b \to s\ell\ell$

Hadronisation in $b \to s\ell\ell$

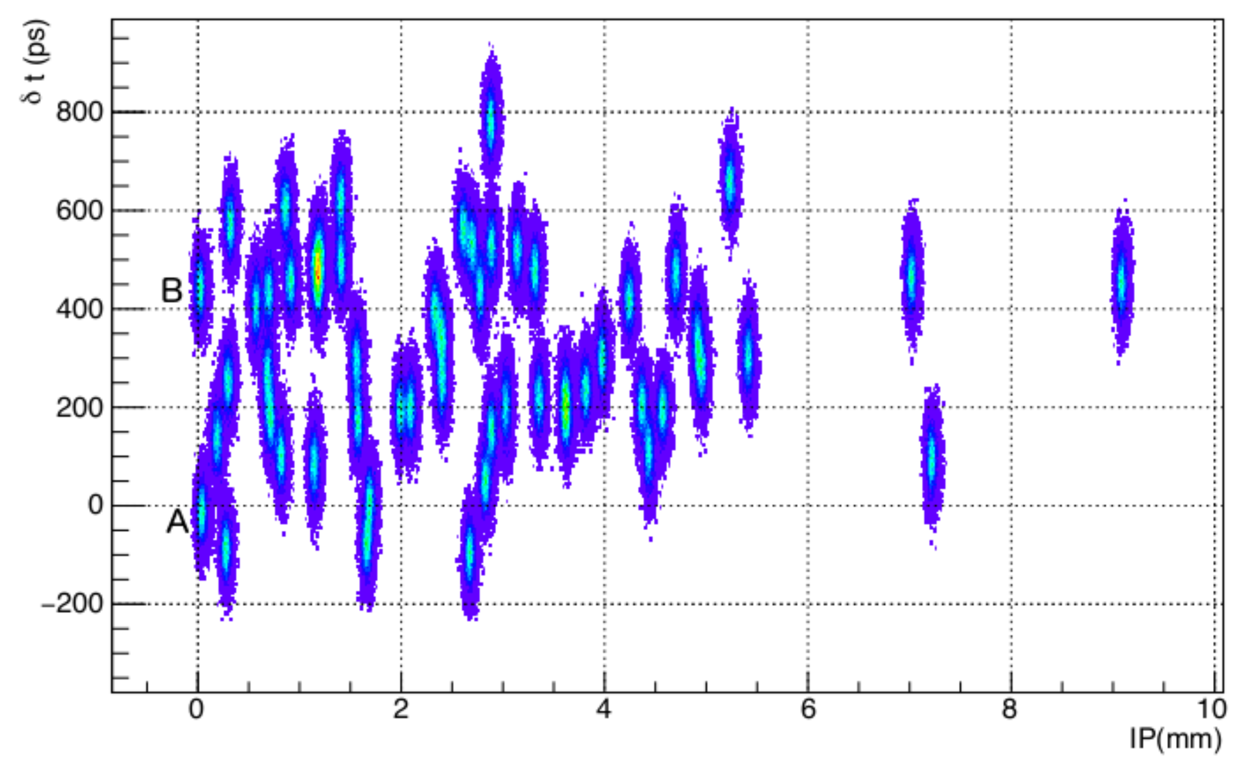


- Several decays, depending on spectator quark and spin-parity
- Opportunity to study $b \to s\ell\ell$ in various systems
- QCD makes theoretical predictions more challenging

LHCb Upgrade II

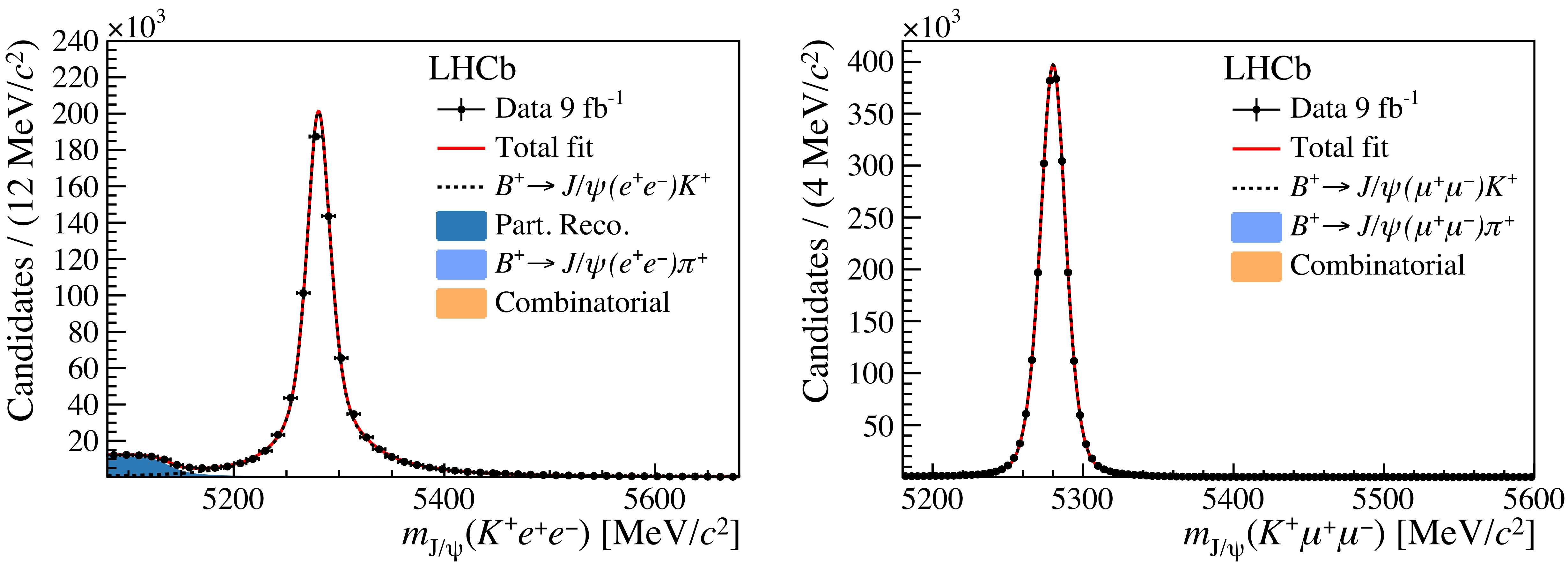
- Plan to crank up luminosity by another factor 10 in Run 5-6 (2030s)
  - Aim at collecting 300/fb by 2040
- Need to deal with the collision pile-up of about 50
  - Higher granularity
  - Lower material budget
  - Better radiation hardness
  - Tracking detectors with precise timing (200ps/hit in VELO, 20-50ps in ECAL)
  - Hardware accelerators for online reconstruction

Timing is crucial to find origin vertex of *B* decay



Control channel

LHCb arXiv:2103.11769

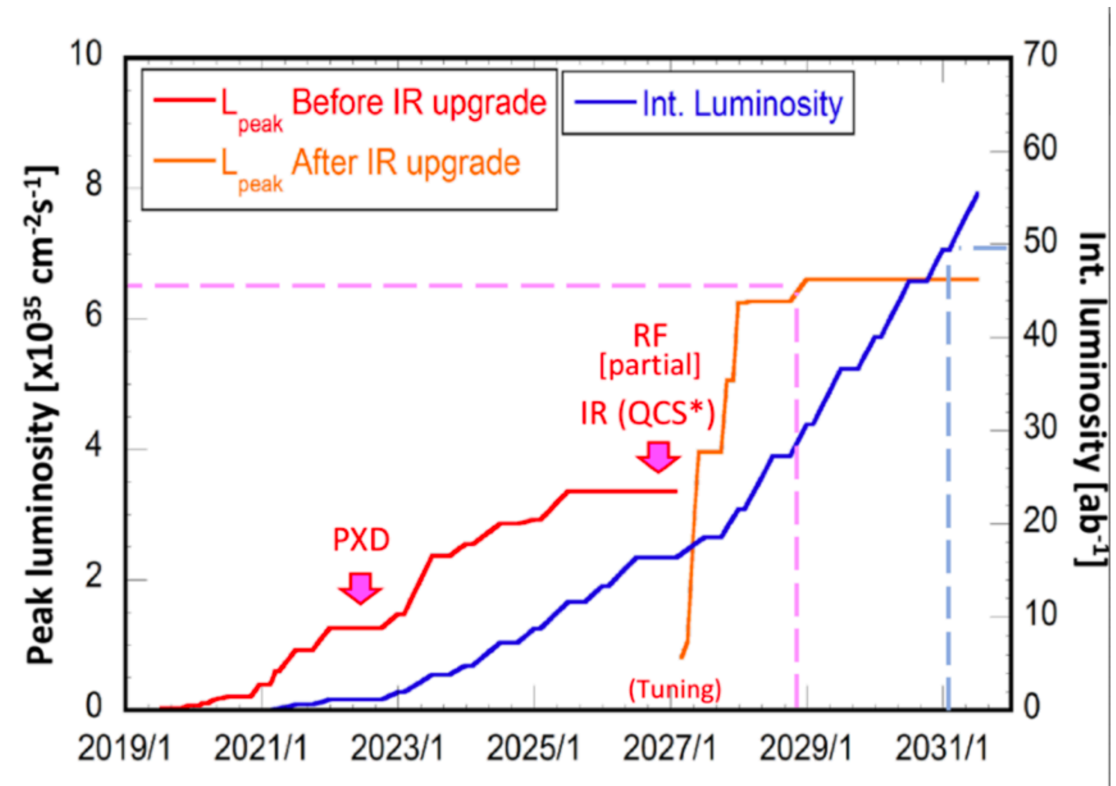


- $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ decays are known to respect LU at 0.4% level
- Define R_K as double ratio with control channel

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi\,(\mu^+ \mu^-))} \frac{\mathcal{B}(B^+ \to K^+ J/\psi\,(e^+ e^-))}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

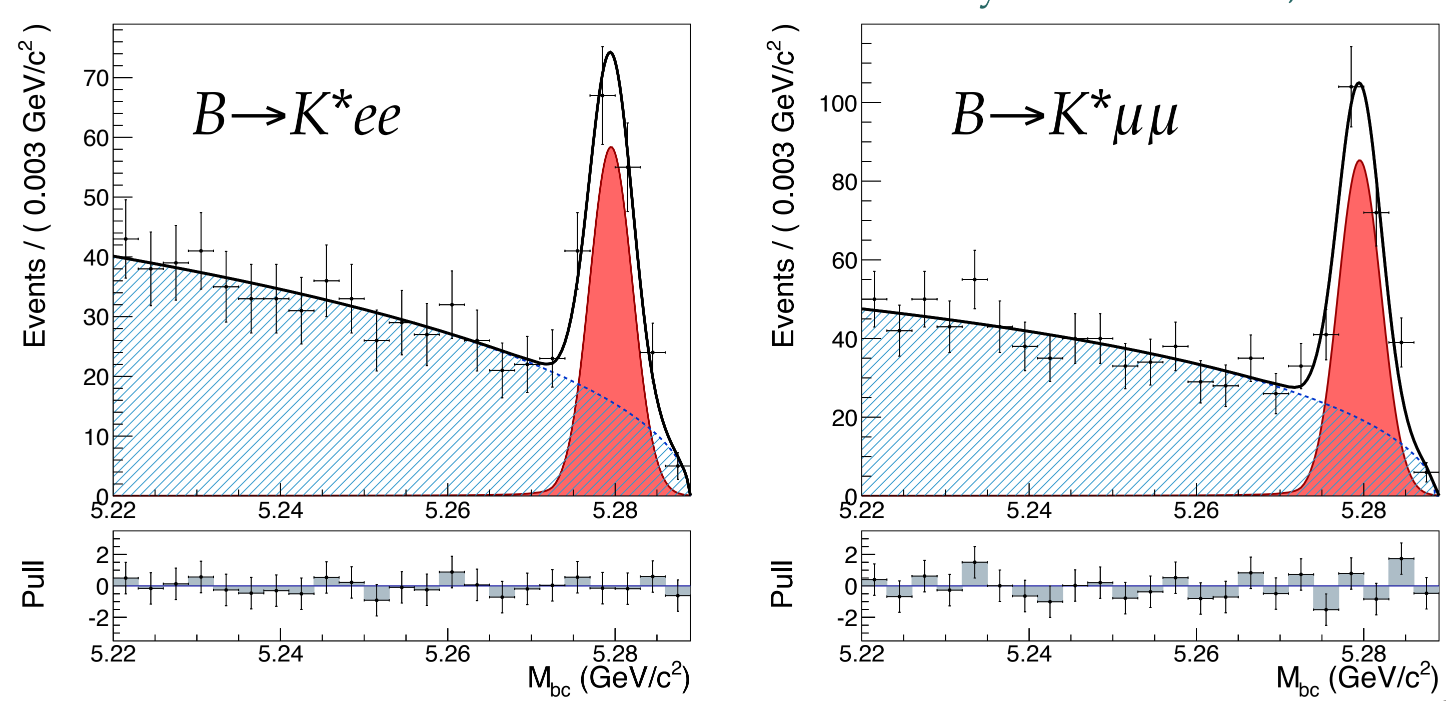
Few words on Belle II

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Much cleaner than LHC environment
  - Cross-section $\mathcal{O}$(nb): need huge luminosity
- Belle II is ramping up
  - Aim at collecting 50 ab^{-1} around 2031
  - Not as much stat as LHCb in charged modes:
    $K^+\mu\mu$: 1 fb^{-1} LHCb $\simeq$ 2.5 ab^{-1} Belle II
    $K^+e^+e^-$: 1 fb^{-1} LHCb $\simeq$ 1 ab^{-1} Belle II
- But Belle II can measure channels with neutral hadrons and neutrinos → great complementarity
- \+ Essential validation of the anomalies from experiment with very different environment and challenges



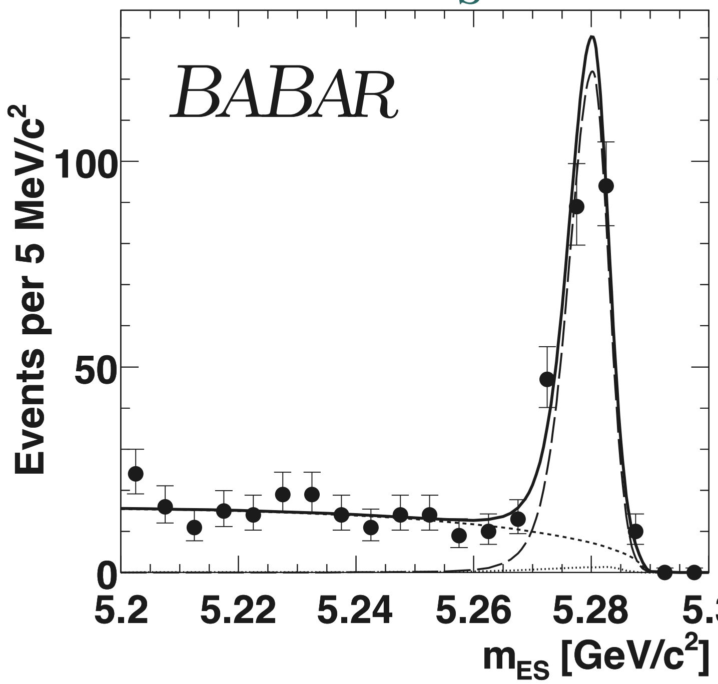
Belle: Phys. Rev. Lett. 118, 111801

Response to muons and electrons is very similar!



LHCb vs B-factories

$B^0 \to K_S^0 \pi^0 \gamma$



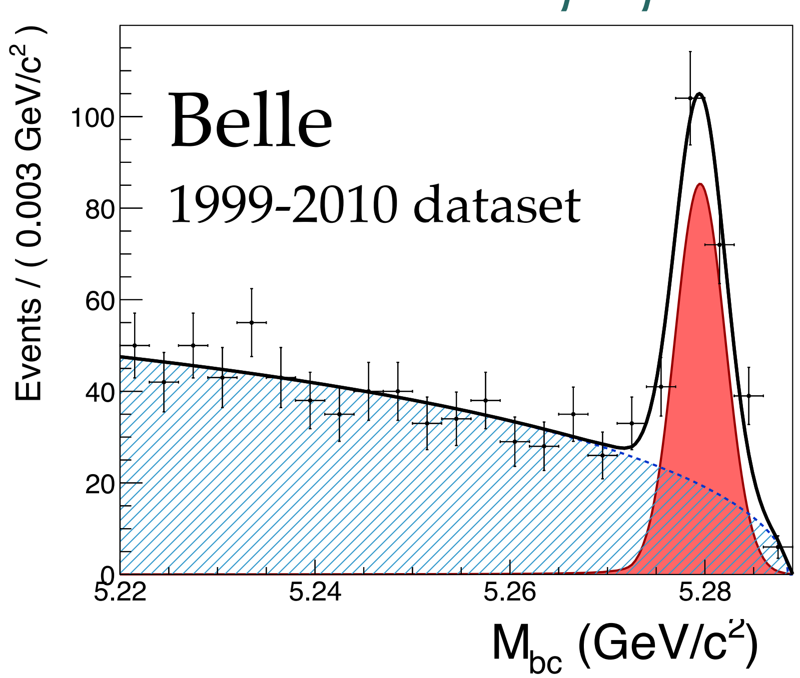
Phys.Rev. D78 (2008) 071102

$B^0 \to K_S^0 \pi^0 \gamma$

Impossible at LHCb

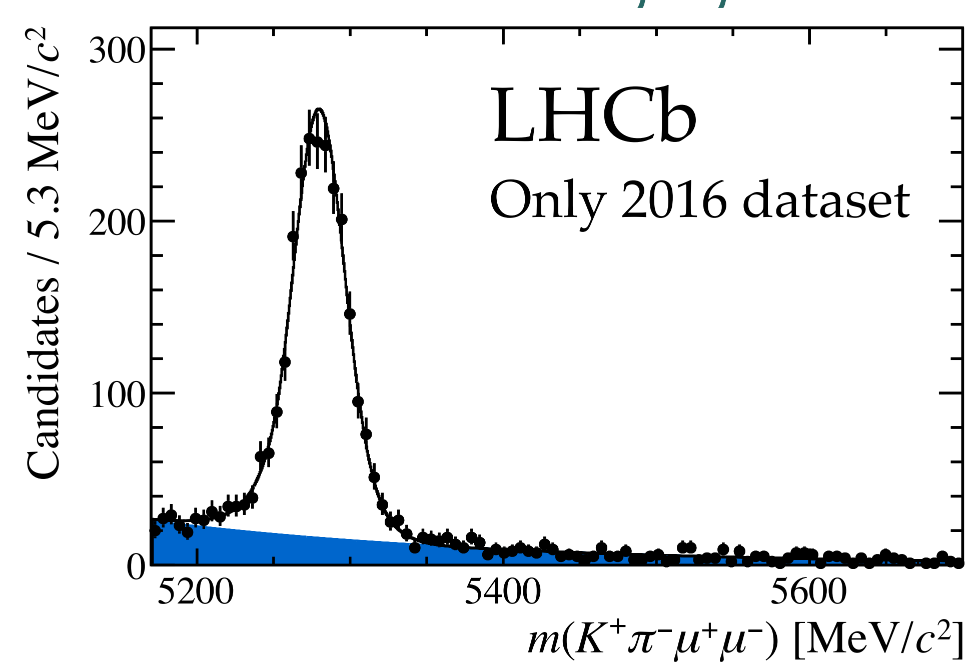
→ Belle II experiment
(50× Belle luminosity)

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



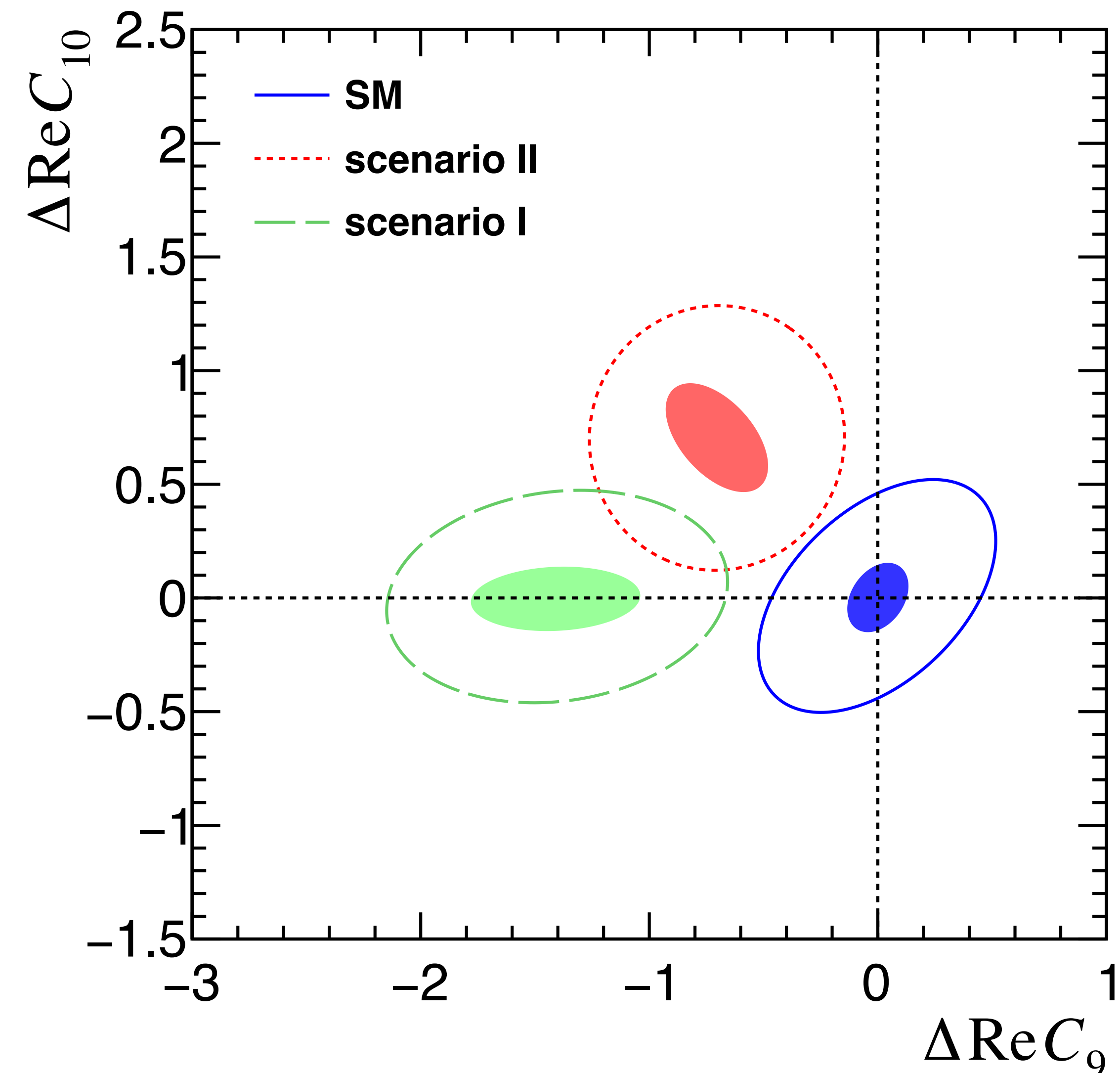
PRL 118 (2017) 11, 111801

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



Rare decays in Upgrade II

- $B_{(s)} \to \mu\mu$, LFU tests and LFV searches will directly profit from the higher statistics
- Withh 400k events, the $B^0 \to K^*\mu\mu$ angular analysis will enter a new precision era, where sophisticated amplitude analyses will allow to disentangle NP and SM effects
- If anomalies are confirmed:
  - The Upgrade II will allow to precisely pin down their structure and possibly discover related effects in $b \to d\ell\ell$, $b \to se\mu$
- If anomalies are not confirmed:
  - The Upgrade II will give a unique chance to probe NP effects at an energy scale about twice as large as the current one



LU tests at LHCb

- Previous LU tests:

- $B^0 \to K^{*0}\ell^+\ell^-$ with 3 fb^{-1}

  $R_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$ in $[0.045,1.1]$ GeV^2

  $R_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst})$ in $[1.1,6.0]$ GeV^2

  → **2.2-2.5σ deviation from SM per bin**

  LHCb arXiv:2103.11769

- $\Lambda_b \to pK^-\ell^+\ell^-$ with 4.7 fb^{-1}

  $R_{pK^-} = 0.86^{+0.14}_{-0.11}(\text{stat}) \pm 0.05(\text{syst})$ in $[0.1,6.0]$ GeV^2

  → **agrees with SM at <1σ**

  LHCb, JHEP 05 (2020) 040

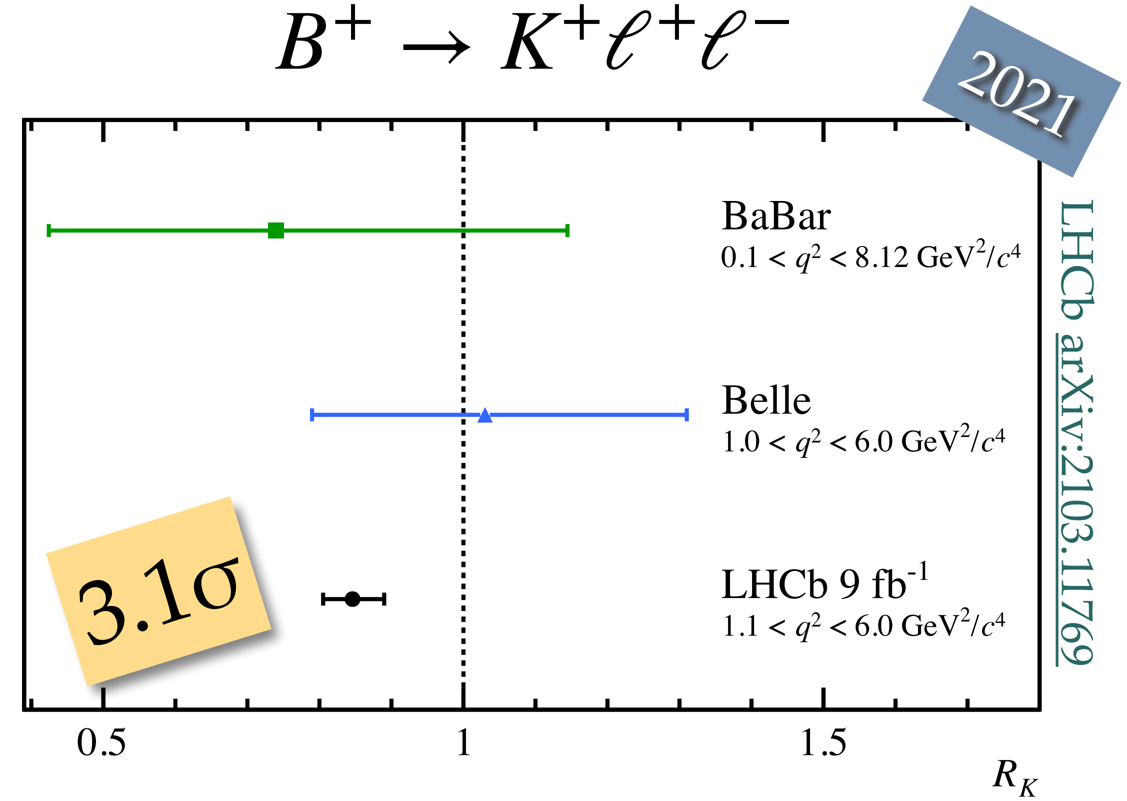
- $B^+ \to K^+\ell^+\ell^-$ with 9 fb^{-1}

  $R_{K^+} = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst})$ in $[1.1,6.0]$ GeV^2

  → **3.1σ deviation from the SM**

  LHCb, JHEP 08 (2017) 055

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



- **New tests of isospin partners of R_{K^+} and $R_{K^{*0}}$ with 9 fb^{-1}**

$$R^{-1}_{K^0_S} = 1.51^{+0.40}_{-0.35}(\text{ stat. })^{+0.09}_{-0.04}(\text{ syst. })$$

$$R^{-1}_{K^{*+}} = 1.44^{+0.32}_{-0.29}(\text{ stat. })^{+0.09}_{-0.06}(\text{syst.})$$

LHCb arXiv:2110.09501