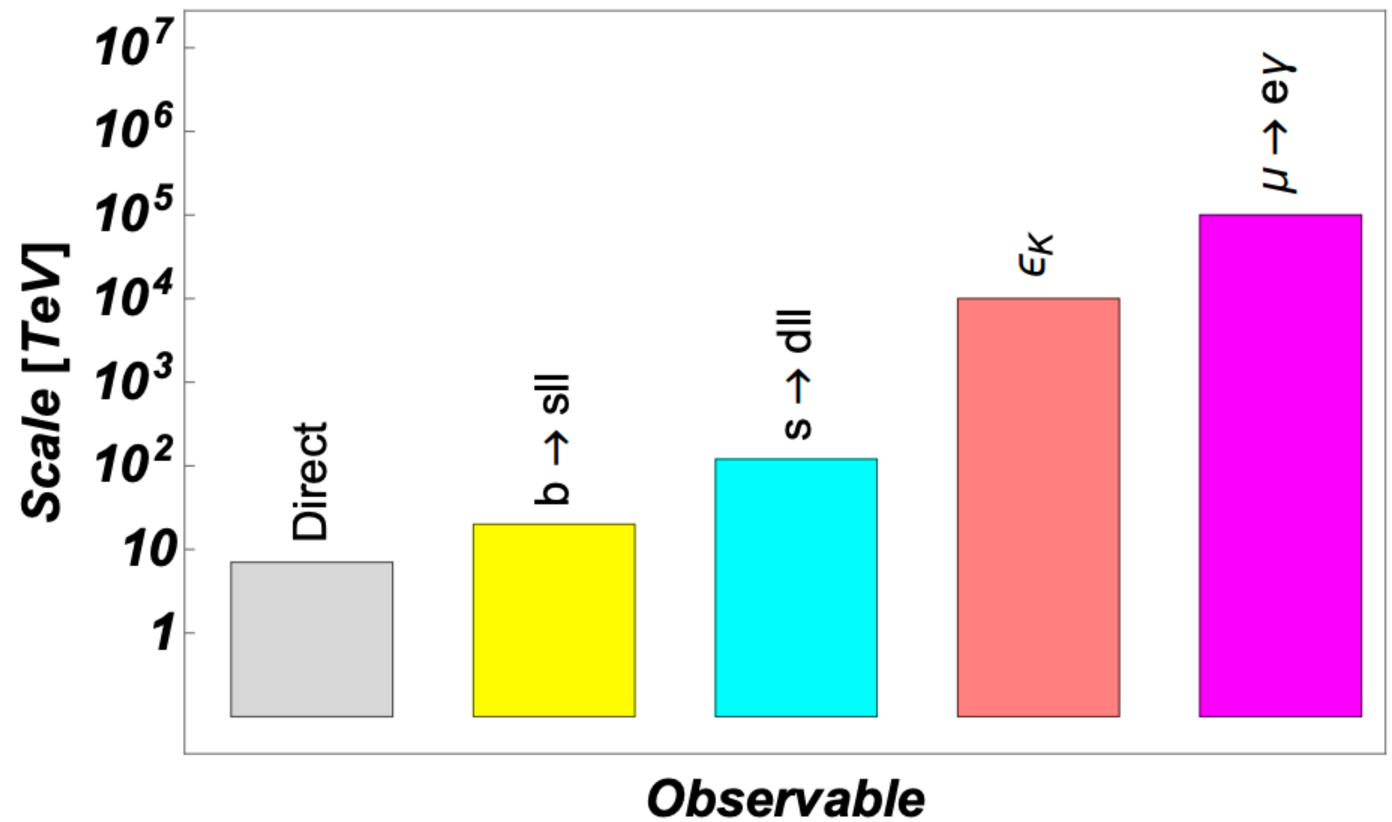
Rare and BSM decays at LHCb, and prospects

Christina Agapopoulou - CERN
on behalf of the LHCb collaboration

Why rare flavour physics decays?



- **Indirect searches:** Precise determination of SM properties can reveal discrepancies w.r.t. theory prediction - New Physics (NP) could be the culprit

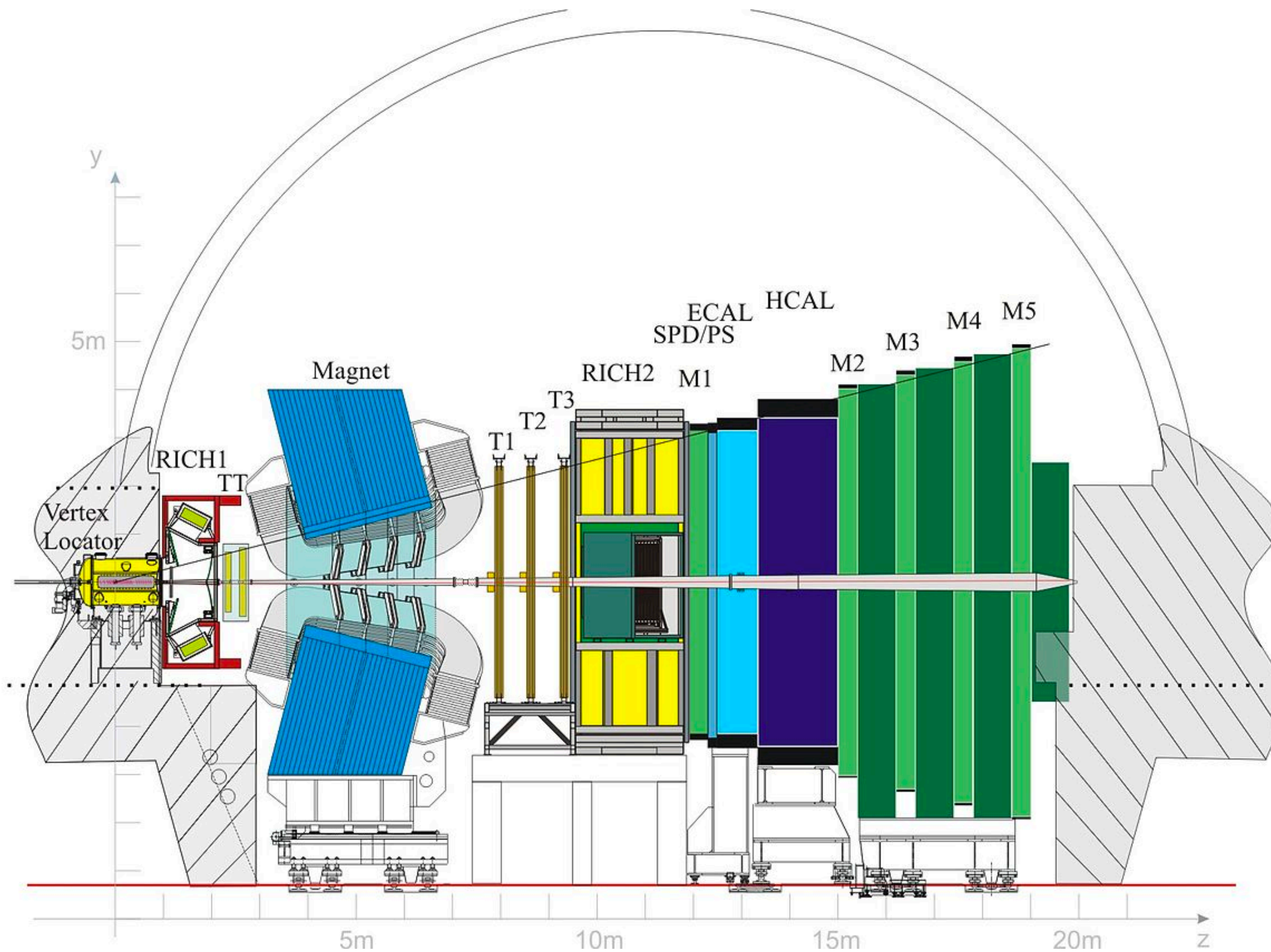
- Rare decays (suppressed in the SM by GIM, CKM etc) can have large sensitivity to high energy NP scales

- Heavy flavour (B, Charm and Kaon decays) has a rich spectrum of rare & forbidden decays, in a very interesting energy regime

- Complementary to the direct search regime

The LHCb experiment

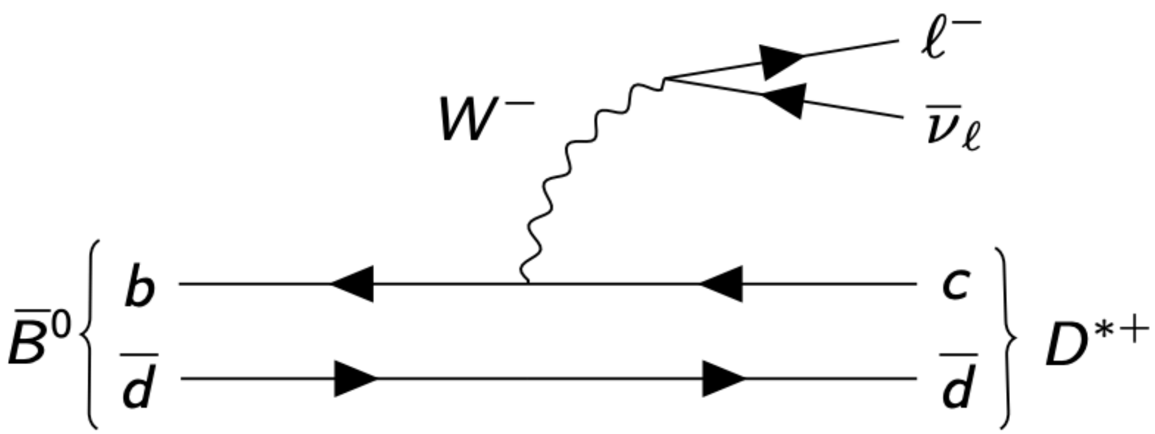
- Forward arm spectrometer ($2 < \eta < 5$) optimised for the study of heavy flavour
- High precision vertexing & tracking systems
- Complemented with excellent PID
- Collected 9 fb^{-1} of physics-worthy data in Run 1 (2011-2012) and Run 2 (2015-2018)
- Currently commissioning it's first large upgrade



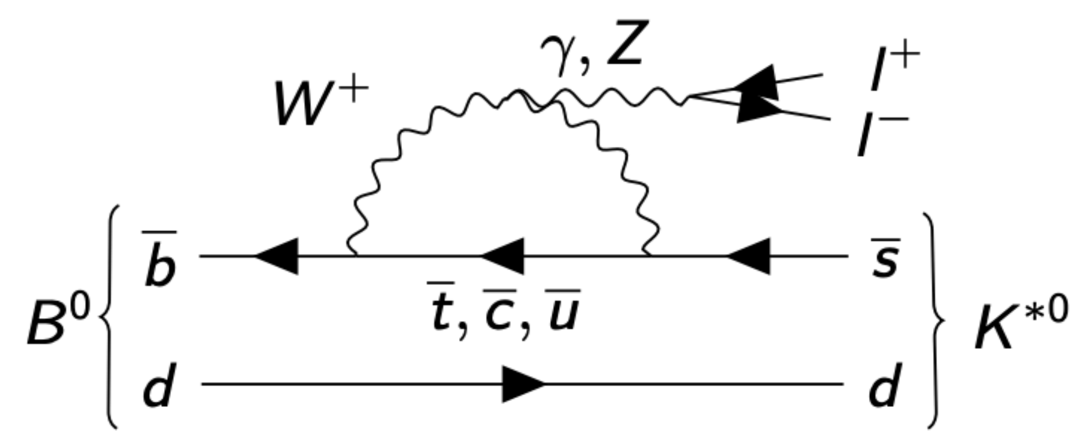
Disclaimer: not a complete overview, heavily focusing on recent results

Flavour Changing Currents

Charged



Neutral



Flavour Changing Charged Currents (FCCC)

- Tree-level semi-leptonic decays
- BR ~ 10%
- Neutrinos (missing energy) in the final state

Flavour Changing Neutral Currents (FCNC)

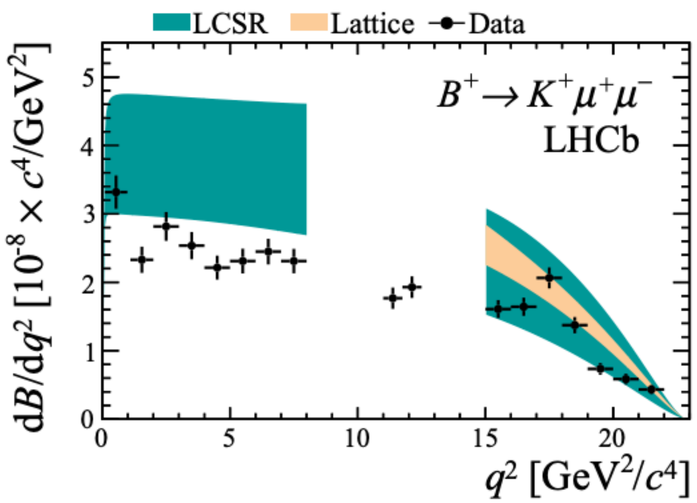
- Not allowed at tree-level in the SM **- very rare**
- Mediated by loops (penguins, box diagrams)
- BR < 10^{-6}

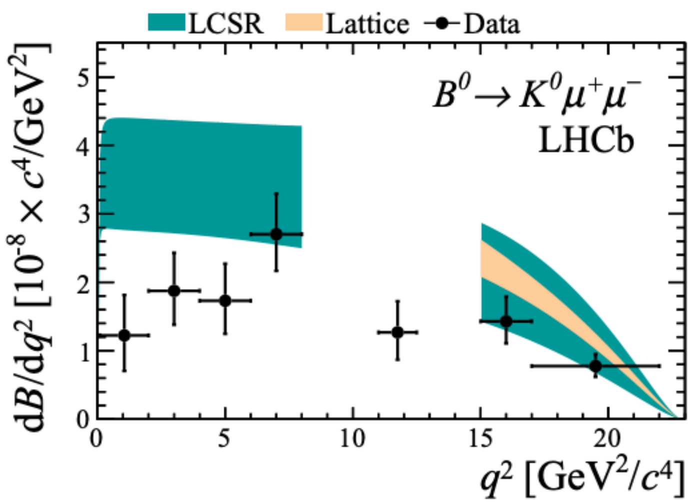
Observables

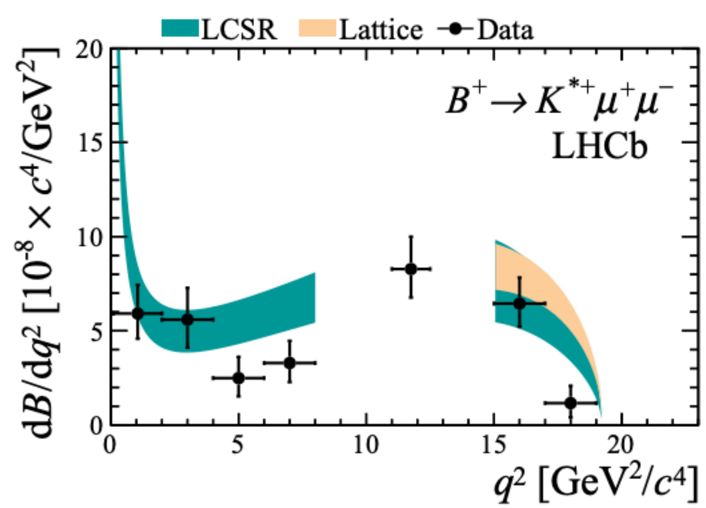
- **Differential branching fractions:**
  - i.e. let’s count how often we see the decay!
  - Large theory uncertainties on hadronic component (non-perturbative regime)

$b \to s\mu^+\mu^-$ differential branching ratios

- Various $b \to s\mu^+\mu^-$ differential BRs measured by LHCb in the last years:

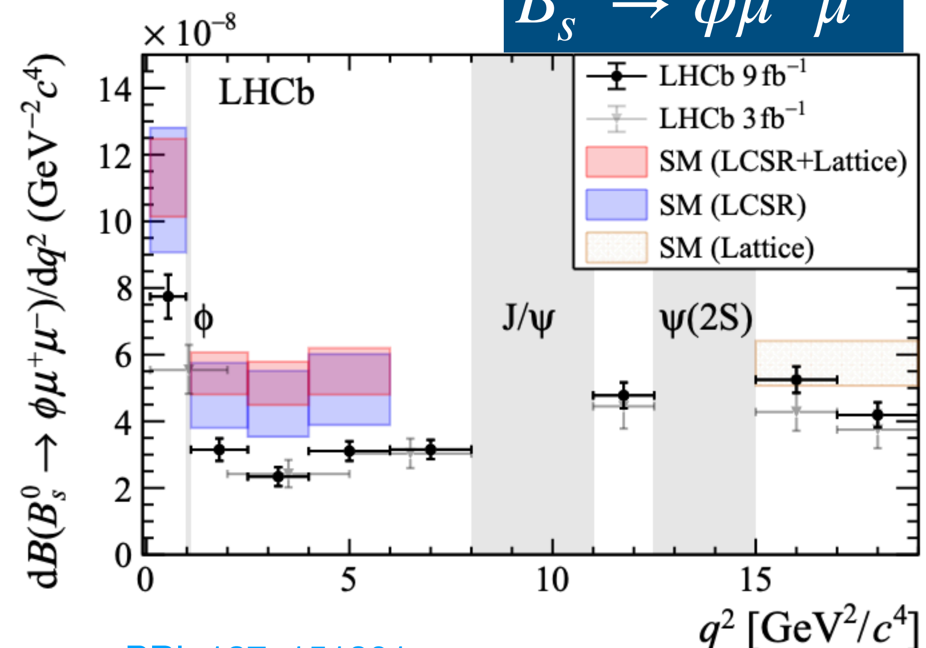






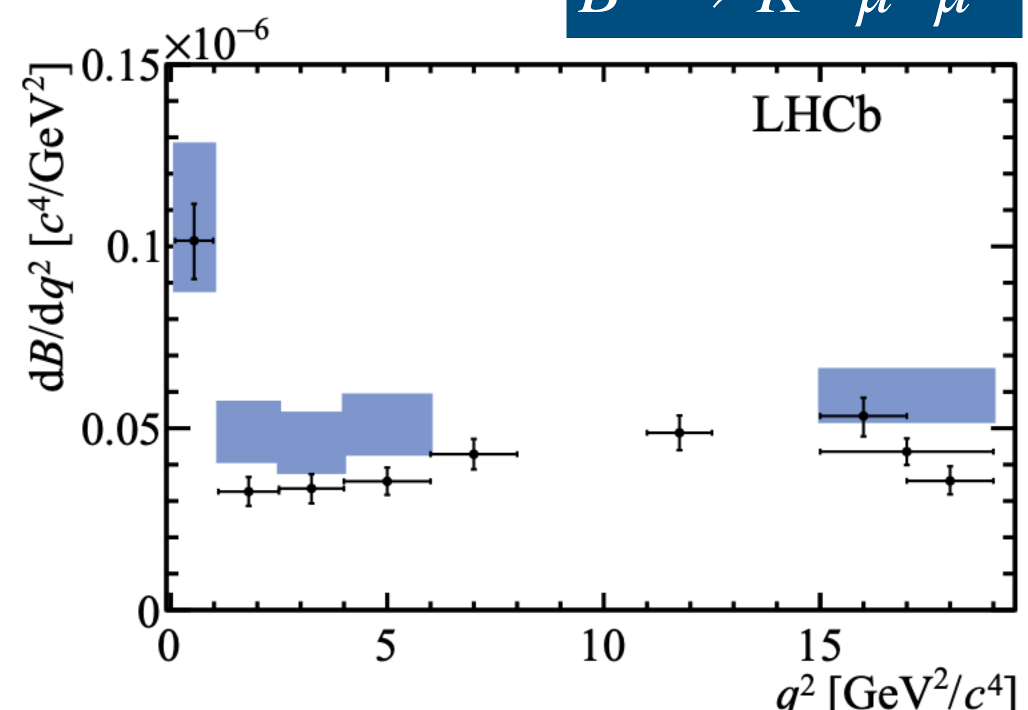
JHEP 06 (2014) 133

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



PRL 127, 151801

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

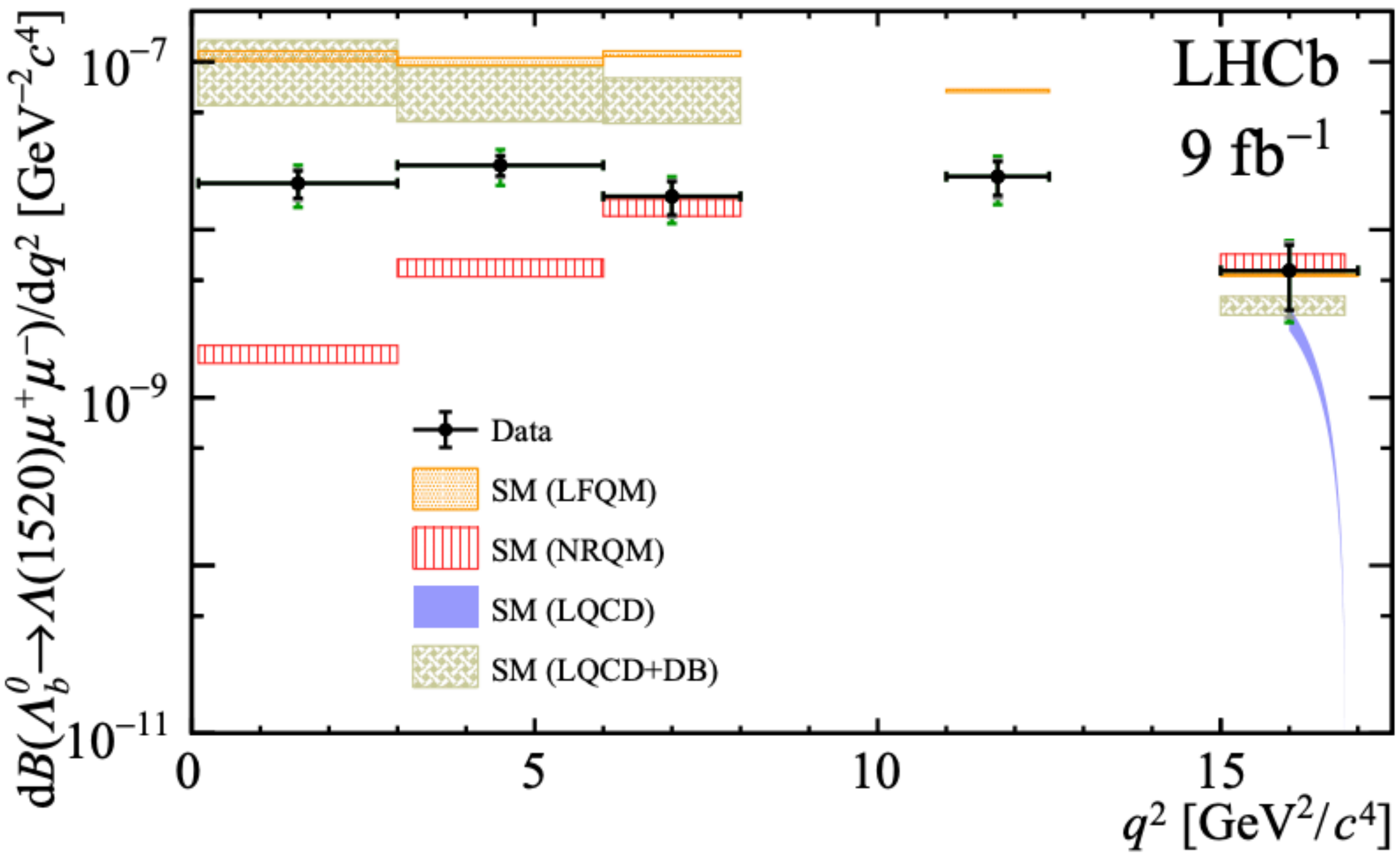


JHEP 11 (2016) 047 JHEP 04 (2017) 142

- Coherent trend for measured BRs < SM prediction
- But large theory uncertainties from form factors

$b \to s\mu^+\mu^-$ differential branching ratios

- Recent result from LHCb: first measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ BR in bins of q^2 [arXiv:2302.08262]



[arXiv:2302.08262]

- Good agreement with SM prediction at high-q^2
- At low q^2, significant variation among the different theoretical predictions
- First measurement with excited $\Lambda(1520)$, could provide complementary information

Observables

SM theoretical uncertainties

- **Differential branching fractions:**
  - i.e. let’s count how often we see the decay!
  - Large theory uncertainties on hadronic component (non-perturbative regime)

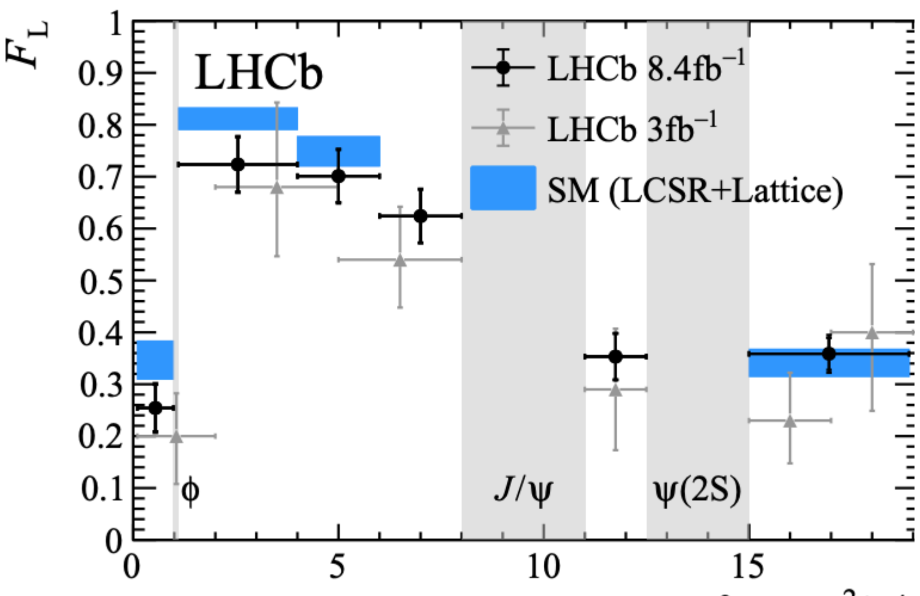
- **Angular measurements:**
  - Choice of angular basis can help mitigate form factor theory uncertainties
  - Access to asymmetries and polarisation measurements

Angular measurements

Access to various observables:

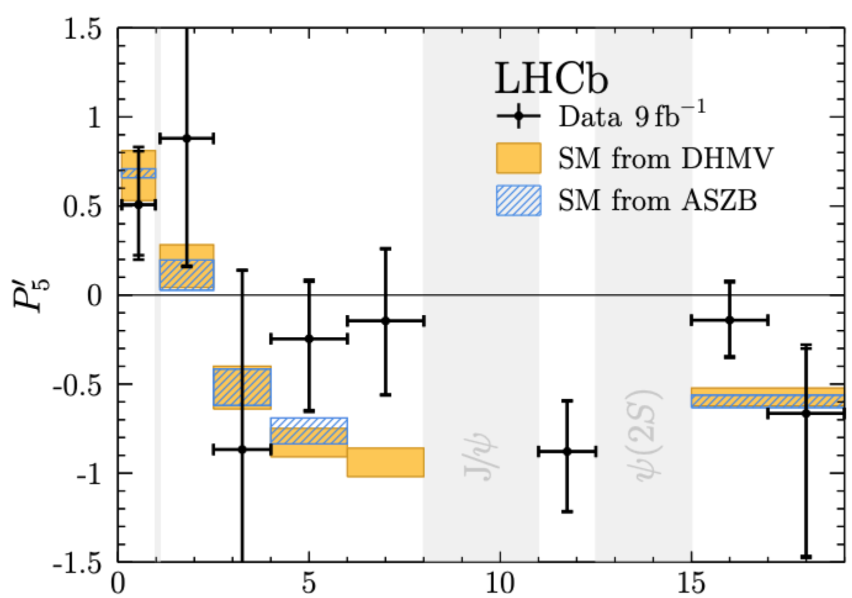
- Forward-backward asymmetry A_{FB}
- Longitudinal polarisation F_L
- Set of "clean" observables P_i to minimise hadronic uncertainties [JHEP 01 (2013), 48]

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



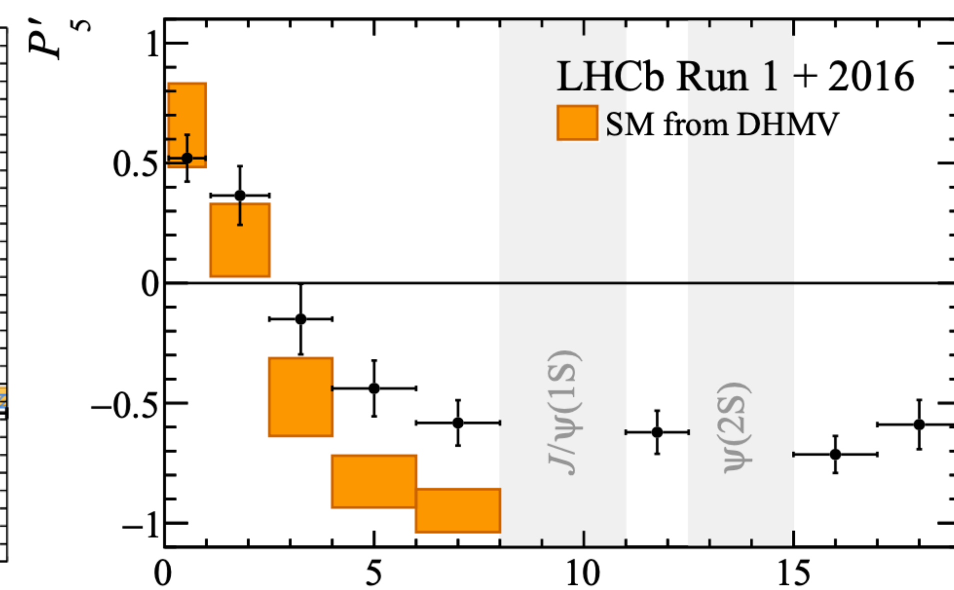
JHEP 11 (2021) 043

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



Phys.Rev.Lett. 126 (2021)

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



Phys.Rev.Lett. 125 (2020)

Tension seen in P_5' in various modes and in certain q^2 bins

- Real NP effect or contribution from charm loops?

Observables

- **Differential branching fractions:**
  - i.e. let's count how often we see the decay!
  - Large theory uncertainties on hadronic component (non-perturbative regime)
- **Angular measurements:**
  - Choice of angular basis can help mitigate form factor theory uncertainties
  - Access to asymmetries and polarisation measurements
- **Relative Branching Ratios (LFU):**
  - Between two lepton flavours (e.x. e vs μ)
  - Hadronic uncertainties cancel*
  - Also cancellation of various systematic uncertainties
  - Very precise, but sensitive only to non-universal BSM models

**only in the SM*

Observables

SM theoretical uncertainties

- **Differential branching fractions:**
  - i.e. let's count how often we see the decay!
  - Large theory uncertainties on hadronic component (non-perturbative regime)

- **Angular measurements:**
  - Choice of angular basis can help mitigate form factor theory uncertainties
  - Access to asymmetries and polarisation measurements

Very attractive measurements, both theoretically and experimentally!

- **Relative Branching Ratios (LFU):**
  - Between two lepton flavours (e.x. e vs mu)
  - Hadronic uncertainties cancel*
  - Also cancellation of various systematic uncertainties
  - Very precise, but sensitive only to non-universal BSM models

**only in the SM, and not considering long distance contributions*

LFU tests in $b \to s\ell\ell$ decays

- Measurements of branching fraction ratio R_X:

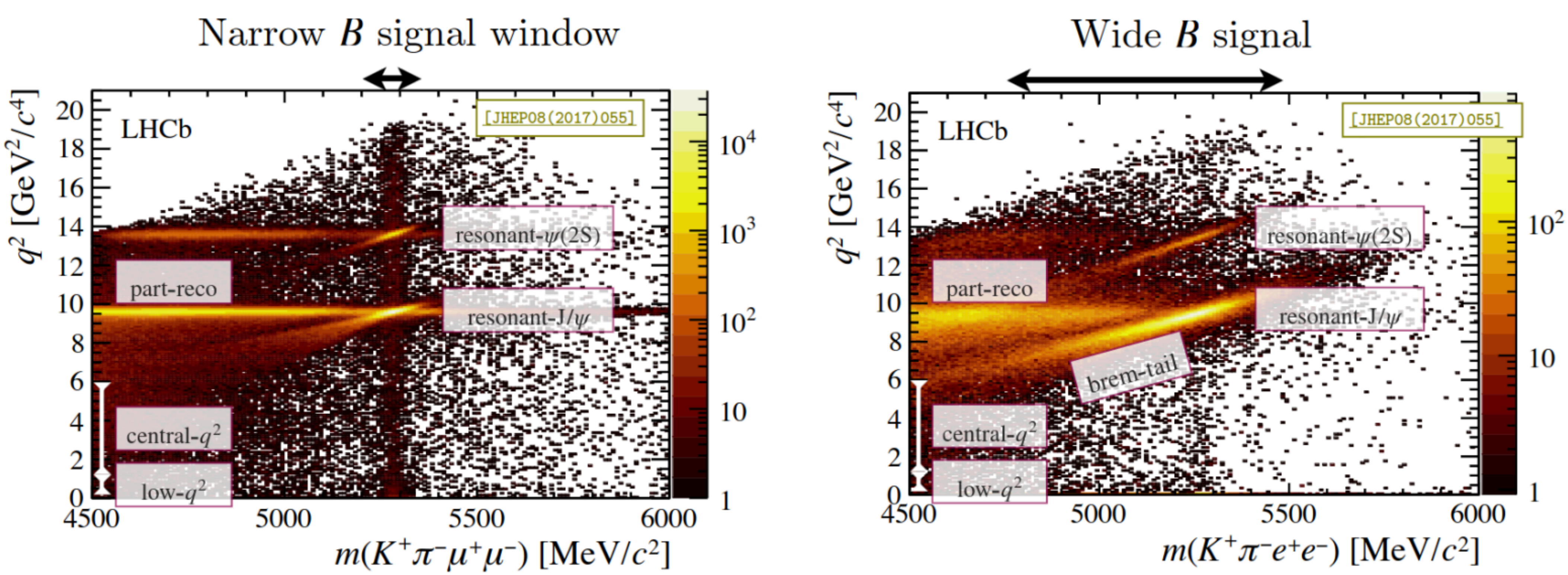
$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_1^+\ell_1^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_2^+\ell_2^-)}{dq^2} dq^2}$$

e.x $H_b = B^0$

e **vs** μ

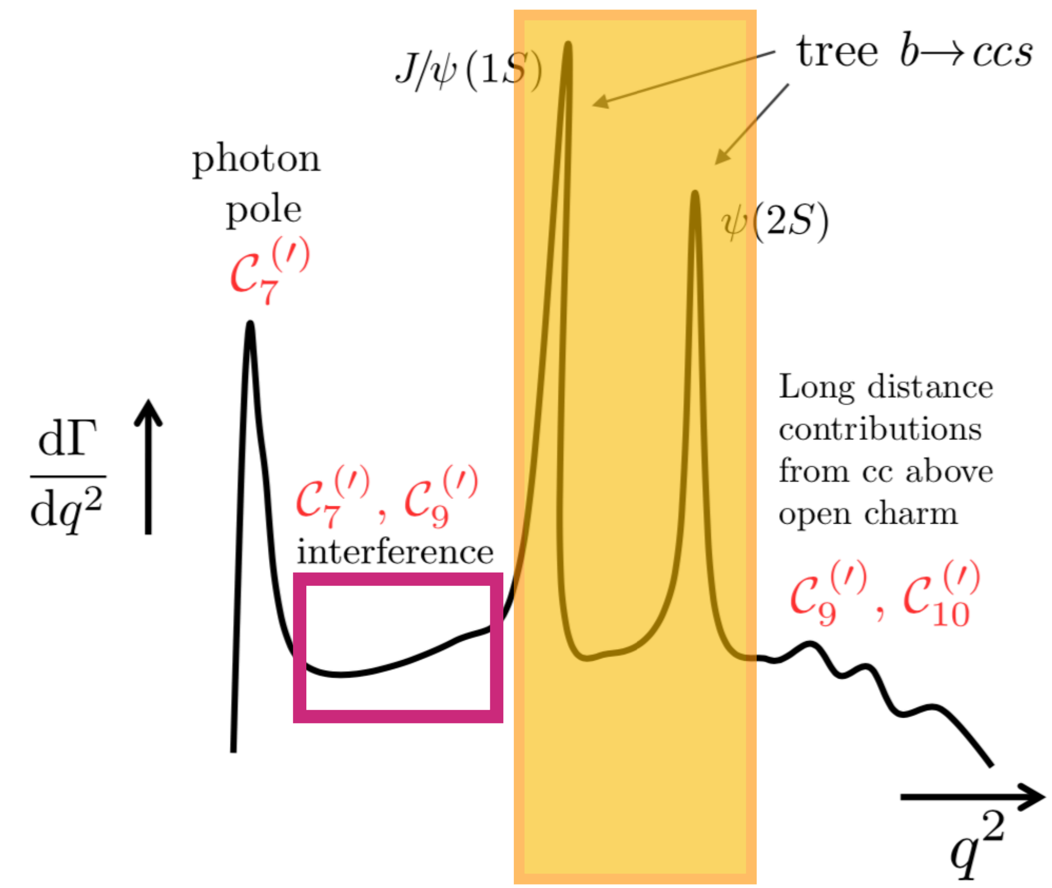
$$R_{K^{*0}} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}e^+e^-)}{dq^2} dq^2}$$

- Experimental challenges:
  - Different detector response for electrons than for muons
  - Background modelling
  - Corrections to simulation



LFU tests in $b \to s\ell\ell$ decays

- Measurement of LFU in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays with 9 fb-1 of the LHCb dataset (Run 1 +2)) [arXiv:2212.09153] [arXiv:2212.09152]

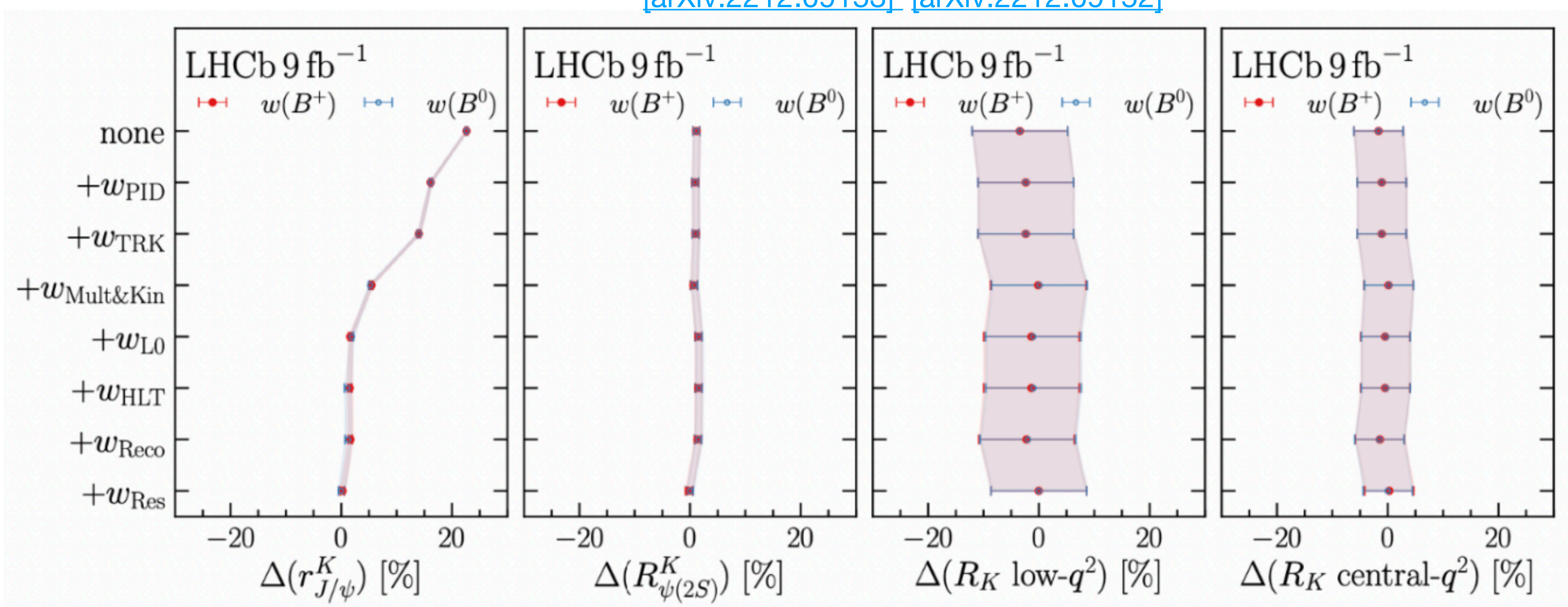


- In two $q^2 = m(\ell,\ell)^2$ bins, $c\bar{c}$ resonances used as normalisation modes

- Control of electron vs muon experimental differences a major challenge
  - measurement performed as double ratio with resonant mode to cancel out systematics

- Single electron/muon ratio of normalisation mode $r(J/\psi)$ used as validation (dominated by SM therefore needs to be unity)

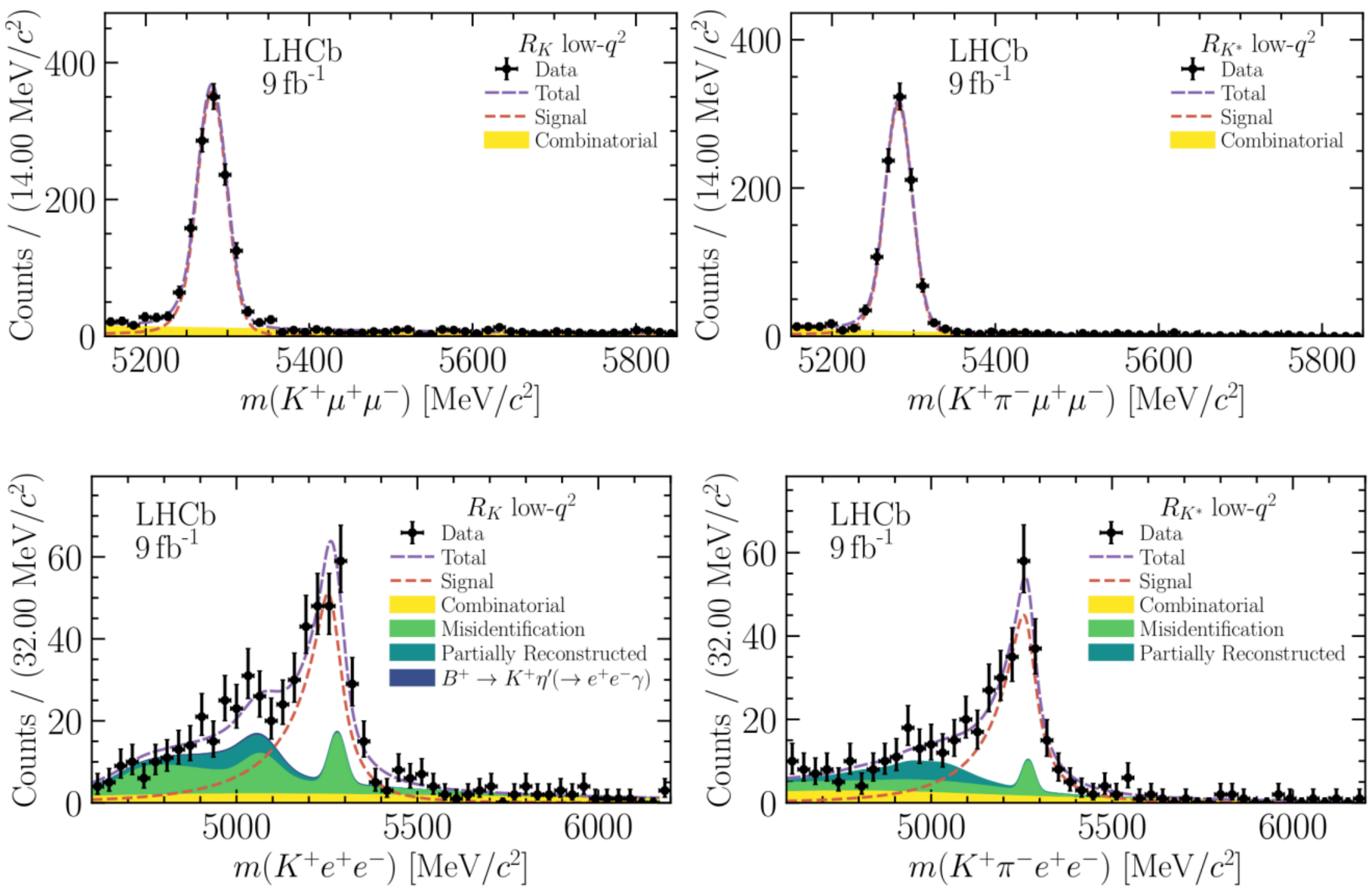
[arXiv:2212.09153] [arXiv:2212.09152]



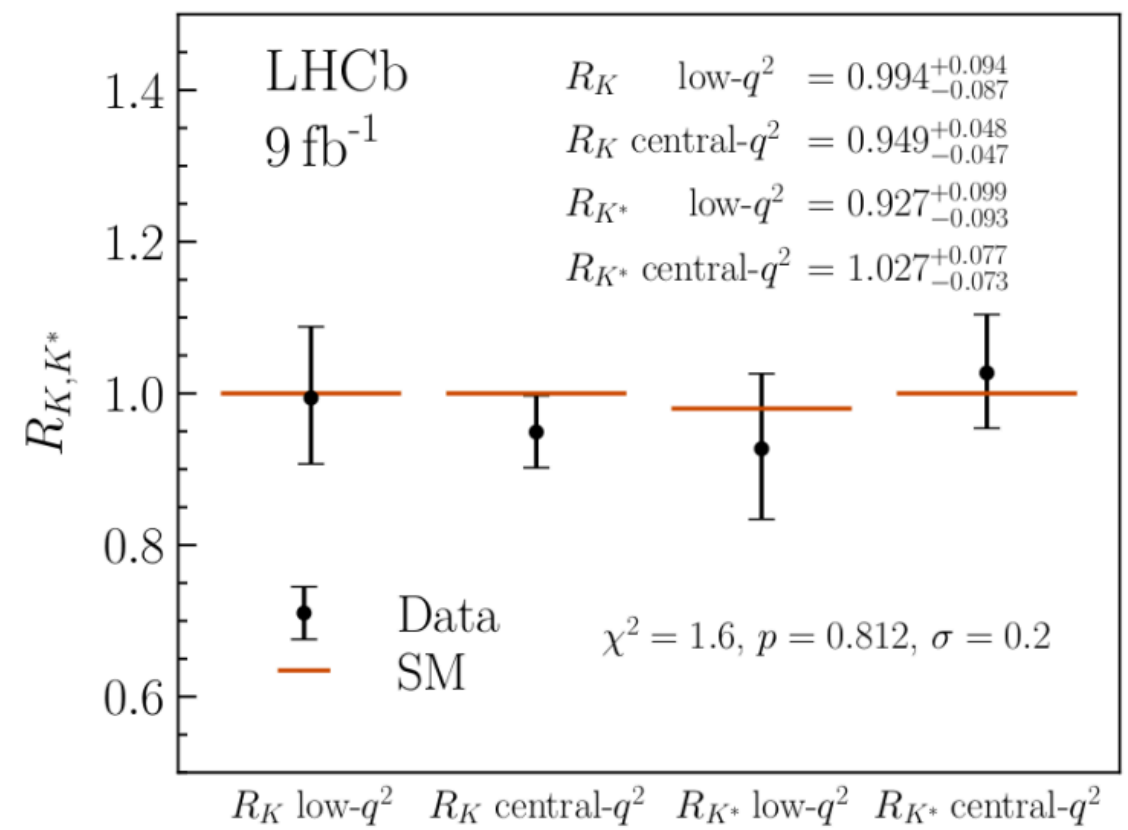
LFU tests in $b \to s\ell\ell$ decays

Both R_K and R_{K*} compatible with the SM

[arXiv:2212.09153] [arXiv:2212.09152]



[arXiv:2212.09153] [arXiv:2212.09152]



Improvements with respect to previous publication [Nat. Phys. 18, 277-282 (2022)]**:**

- Simultaneous fit & increased statistics
- Better understanding of $h \to e$ misID backgrounds:
  - Tigher PID requirements on electron modes
  - Residual misID component included in the fit

LFU tests in $b \to c\ell\nu$ decays

- Measurements of branching fraction ratio $R(H_c)$:

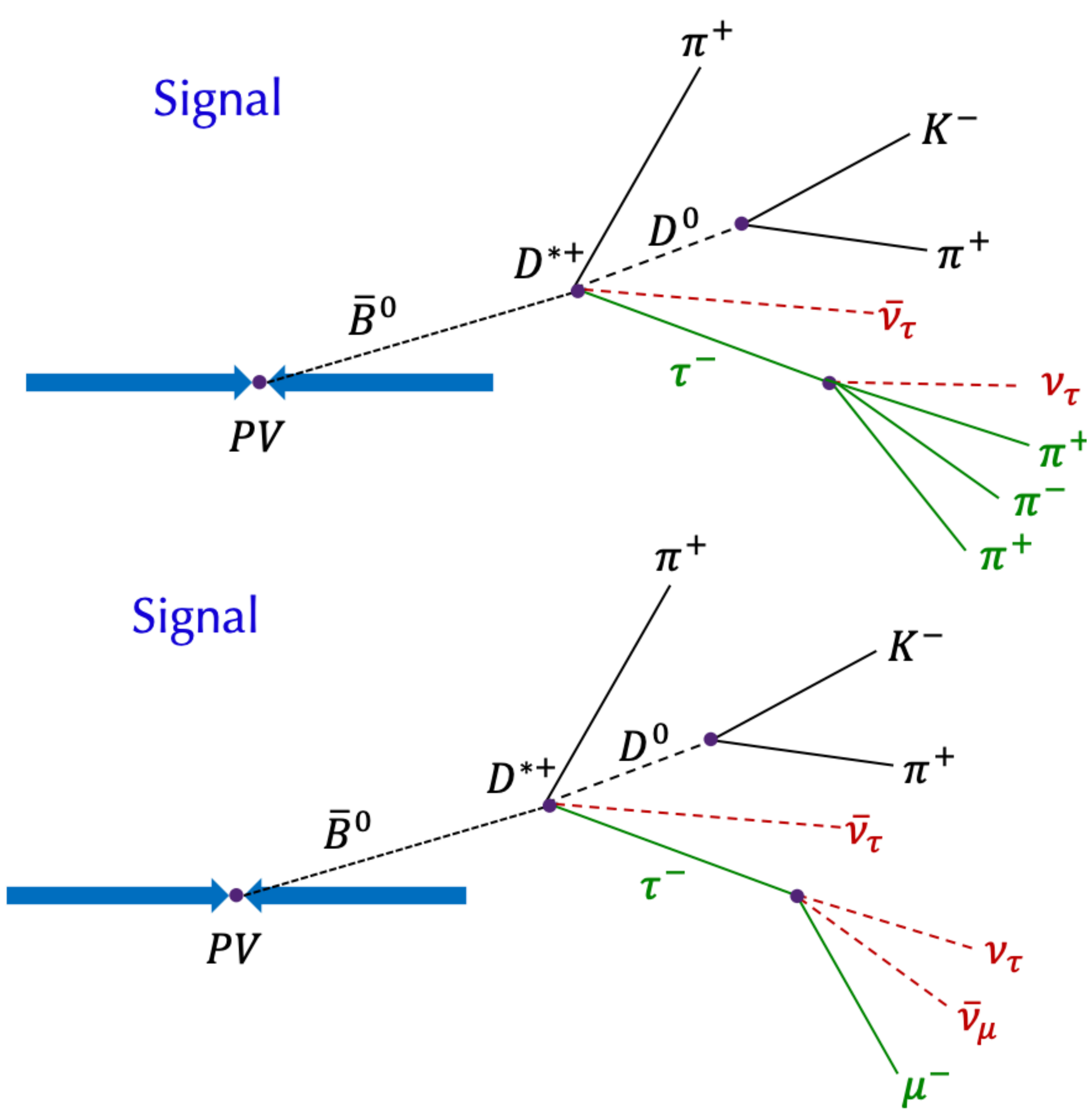
$$R(H_c) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}{dq^2} dq^2}$$

with $H_c = D^{*+}, D^0, D^+ \ldots \quad and\ \ell = e, \mu$

- Taus reconstructed in two ways in LHCb:
  - Hadronic: $\tau^+ \to \pi^+\pi^+\pi^-(\pi^0)\bar{\nu}_\tau$
  - Muonic: $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

- **Semileptonic decays challenging at LHCb:**
  - Missing energy due to presence of neutrinos
  - Tau reconstruction challenging
  - Large backgrounds -> precise simulation needed for modelling and calibrations
  - Template fits needed to extract signal yields

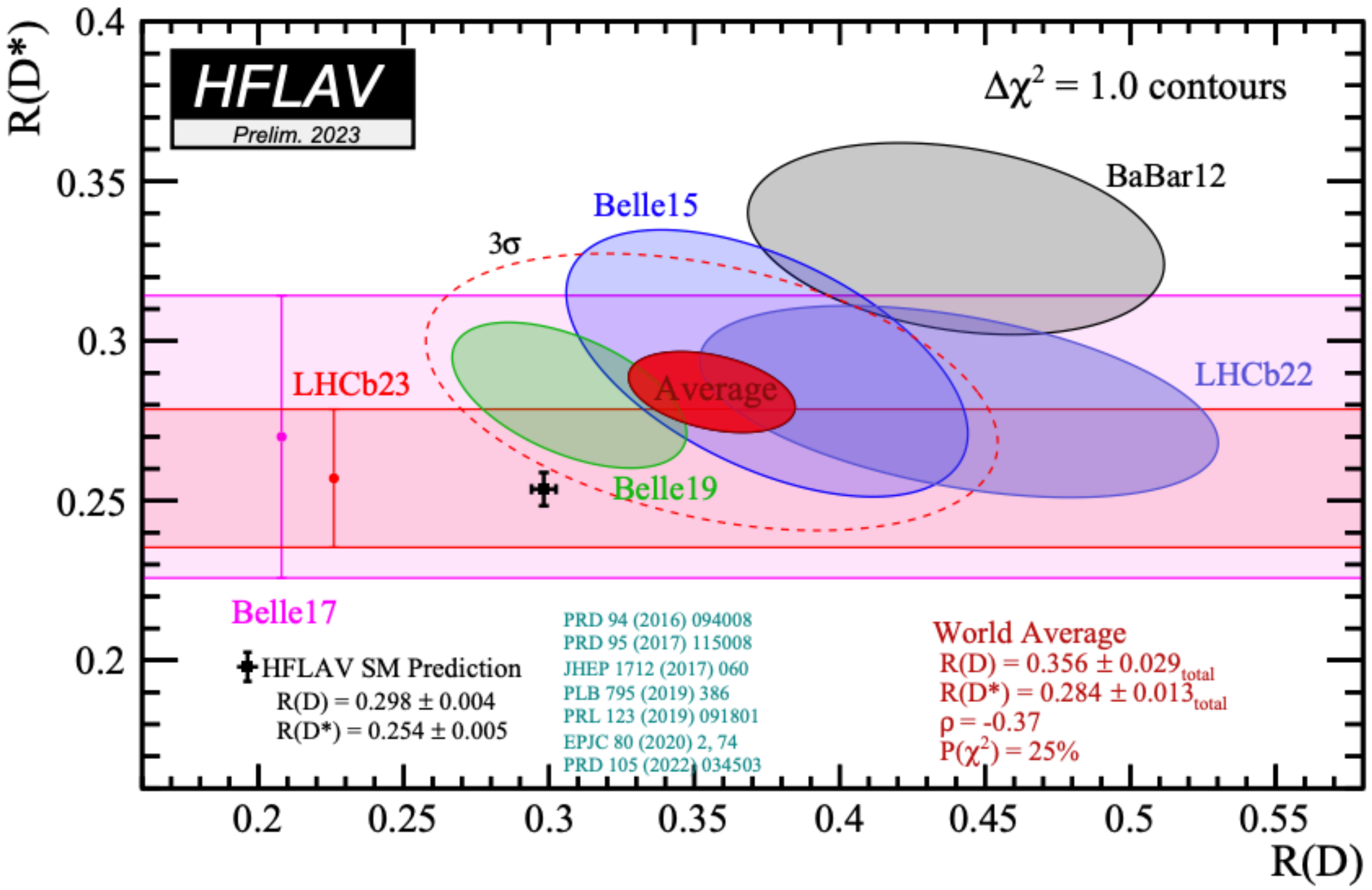
  - **But, large available statistics and many complementary modes**



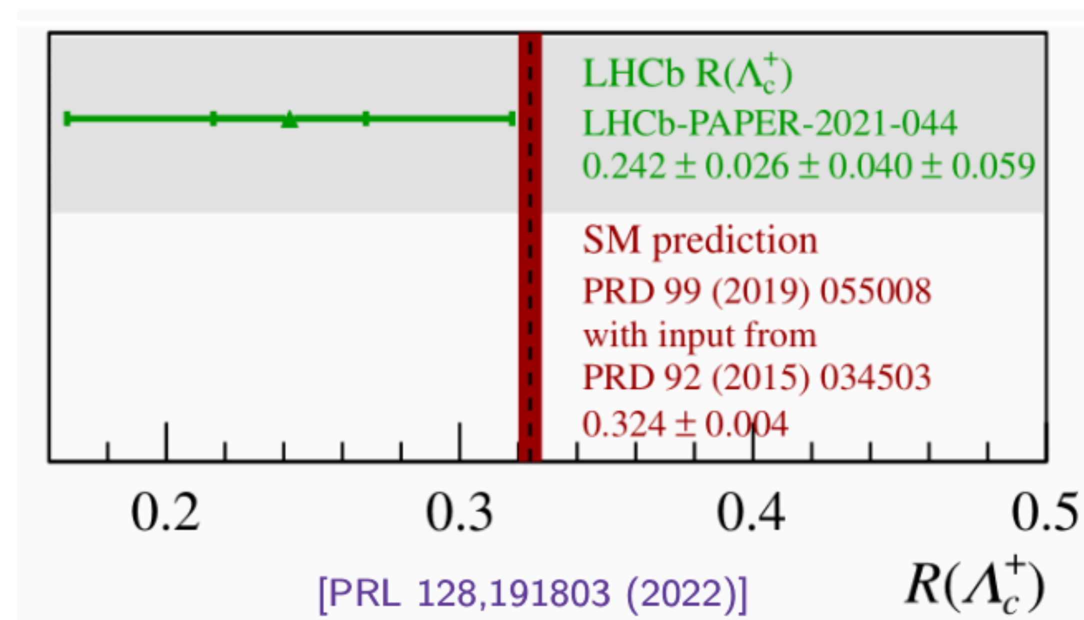
LFU tests in $b \to c\ell\nu$ decays

Two recent LHCb measurements of $R(D^{(*)})$ in the hadronic and muonic modes, **1-1.9σ agreement with the SM**

$B \to D^{(*)}\ell\nu$



$\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$ (3 fb^{-1})

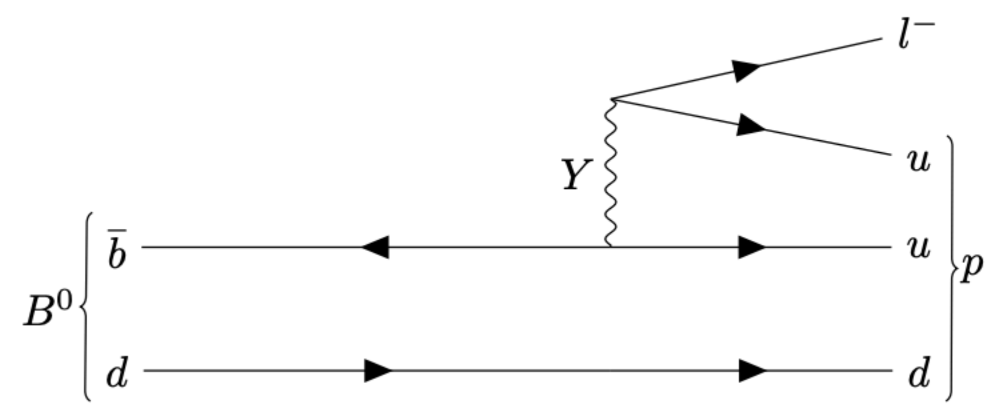


First LFU test in baryonic semileptonic decays which provide complementary information, **consistent with the SM prediction**

Forbidden processes

- **Search for $B^0_{(s)} \to p\mu^-$ decays** [arXiv:2210.10412]**:**
  - Lepton and Baryon number violating - from proton decay limit < 10^{-27}
  - First search of this decay using Run 1 + 2 dataset
  - Semileptonic decays are dominant bkg. source
  - Obtained upper limits: O($10^{-8} - 10^{-9}$)

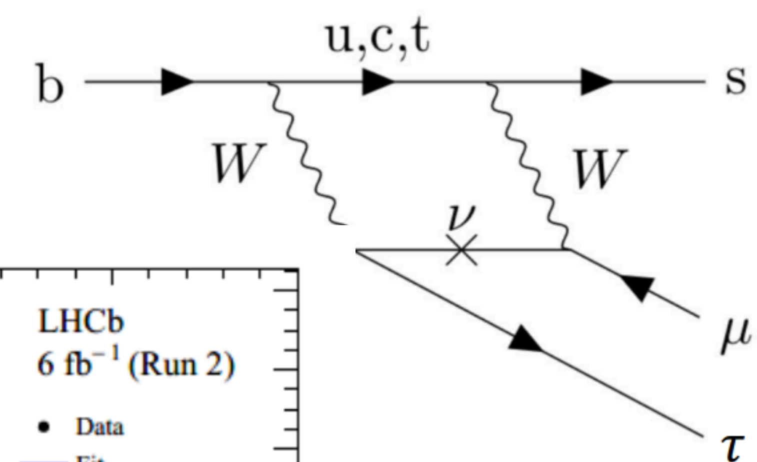
Hypothetical BSM $B^0_{(s)} \to p\mu^-$ diagram

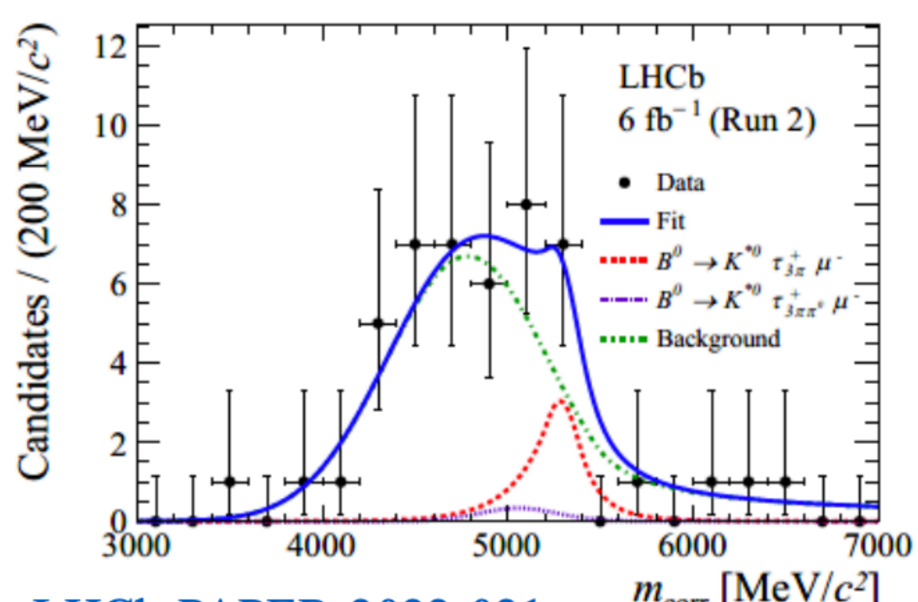


arXiv:2210.10412

- **Search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$ decays** [arXiv:2209.09846]**:**
  - Lepton flavour violating decay - only possible in the SM through neutrino oscillations
  - First search of this decay using Run 1 + 2 dataset
  - Fit to corrected mass to account for missing momentum perpendicular to B flight direction
  - Obtained upper limits: O($10^{-5} - 10^{-6}$)

Contribution with neutrino oscillation

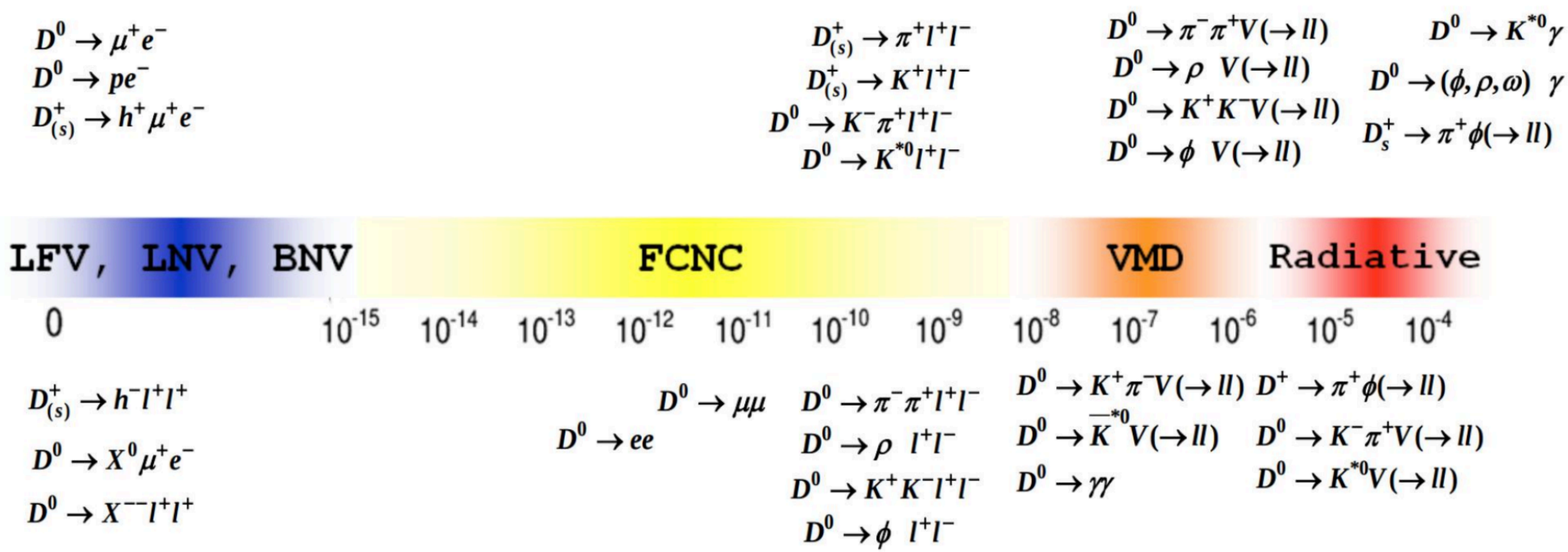




LHCb-PAPER-2022-021

And what about rare charm?

- Probing $c \to u$ type FCNC - **complementarity to B physics!**
- Charm scale not too far from Λ_{QCD} & resonant D contributions
  - Accurate theoretical predictions are challenging
  - Test SM consistency / search for NP through clean observables & null tests
- Very suppressed in the SM due to GIM and CKM suppressions
  - Rich spectrum of channels from forbidden and ultra-rare to less rare / resonant
- So far, LHCb has observed important muon modes - next step is the electrons!

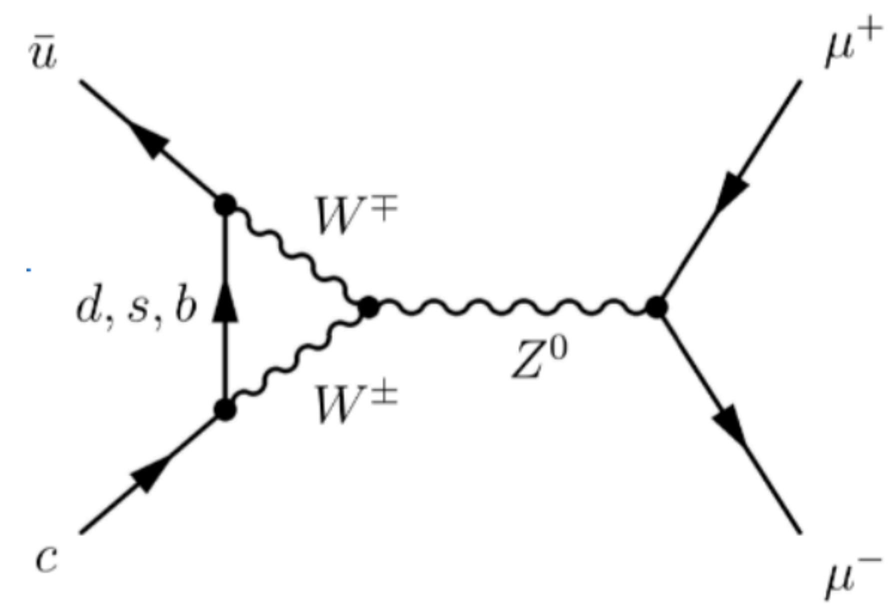


Search for $D^0 \to \mu^+\mu^-$

[arXiv:2212.11203]

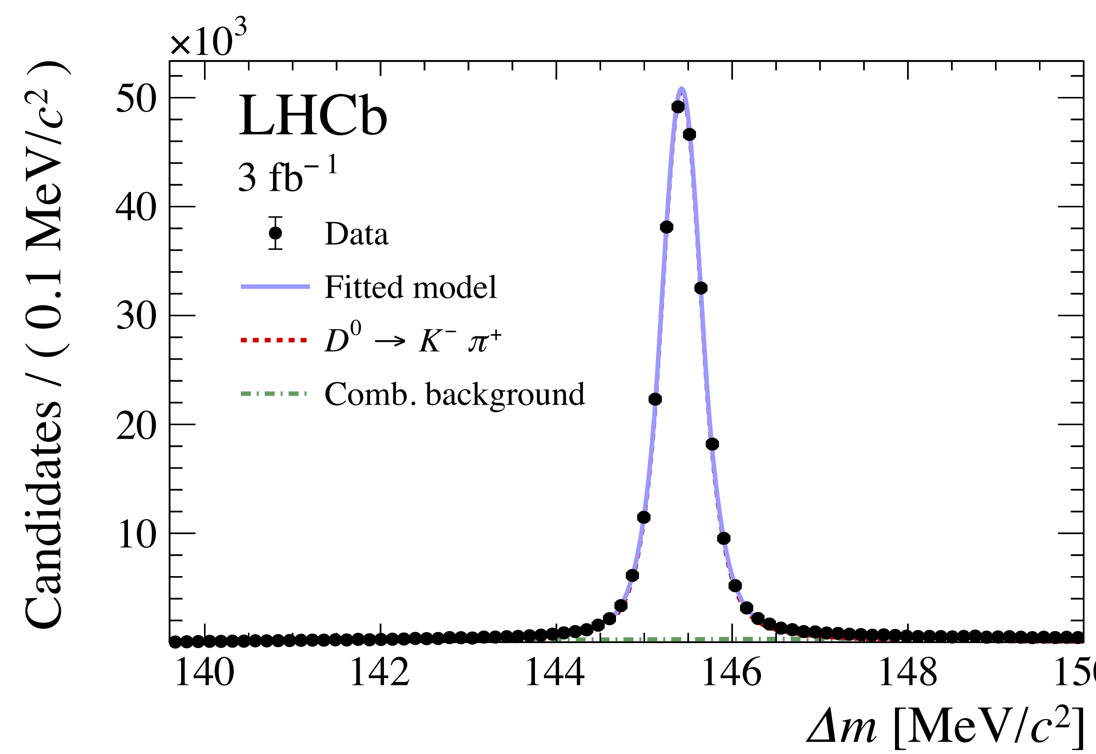
- FCNC with GIM and helicity suppression - never been observed
- Interference from long and short distance contributions in the SM
  - $\mathscr{B} \sim \mathcal{O}(10^{-11})$ [Phys. Rev. D 93, 074001]
- Previous limit by LHCb (1 fb^{-1}):
  - $B(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ at 90% CL [PLB 2013 06 37]

Z-penguin contribution in the SM



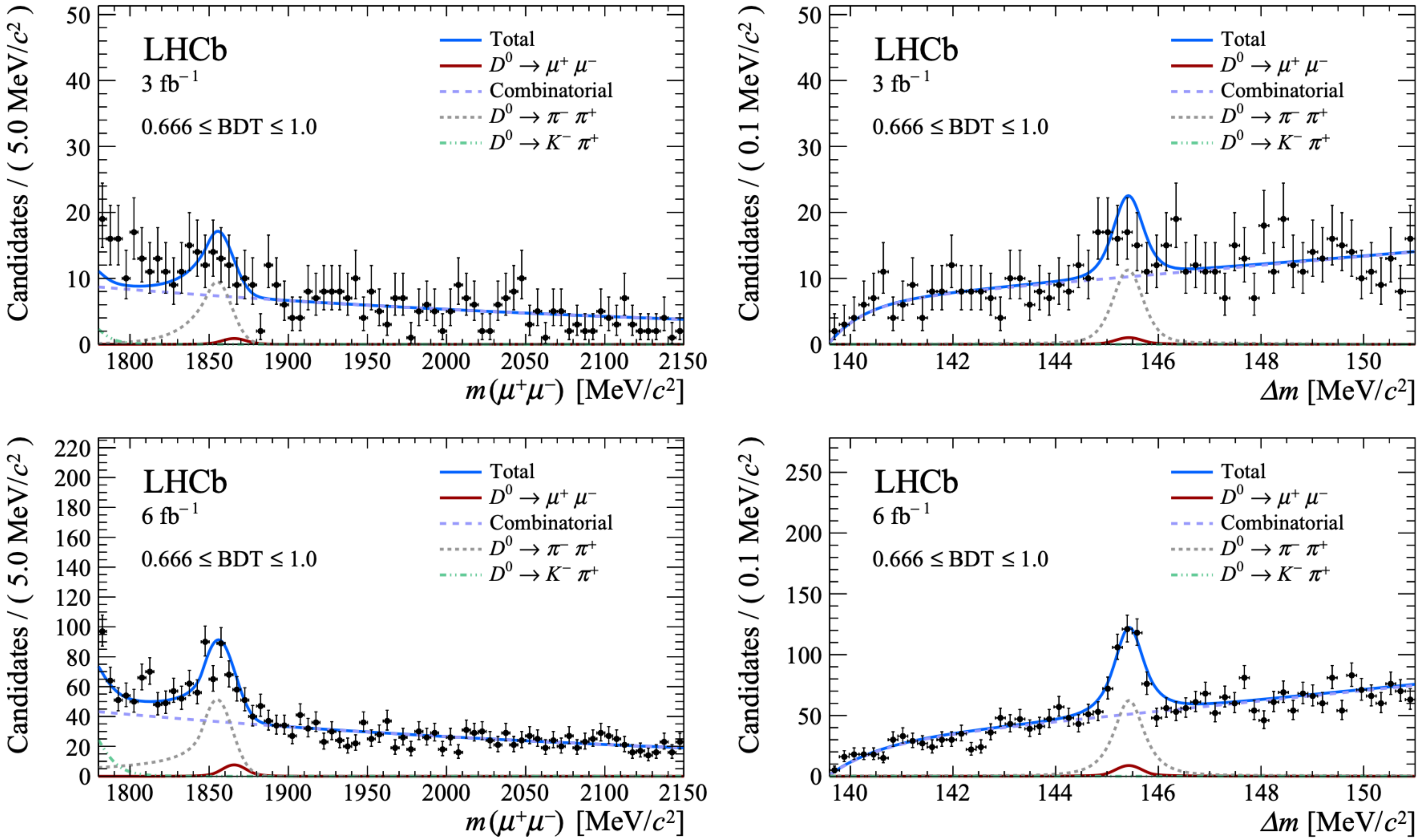
- **Analysis strategy:**
  - D^0 from reconstructed $D^{*+} \to D^0\pi^+$ tagged decays
  - Rare mode normalised to $D^{*+} \to D^0(\to h^-\pi^+)\pi^+$
  - MisID suppressed using PID info, BDT to mitigate combinatorial background
  - ML fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$ in 3 intervals

Normalisation mode fit



Search for $D^0 \to \mu^+\mu^-$

Signal mode fit for the most sensitive BDT interval [arXiv:2212.11203]



$$B(D^0 \to \mu^+\mu^-) < 2.94(3.25) \times 10^{-9}$$ at 90% CL

Improvement by x2 w.r.t. previous result

Most stringent limit of FCNC on the charm sector

Rare decays in the future of LHCb

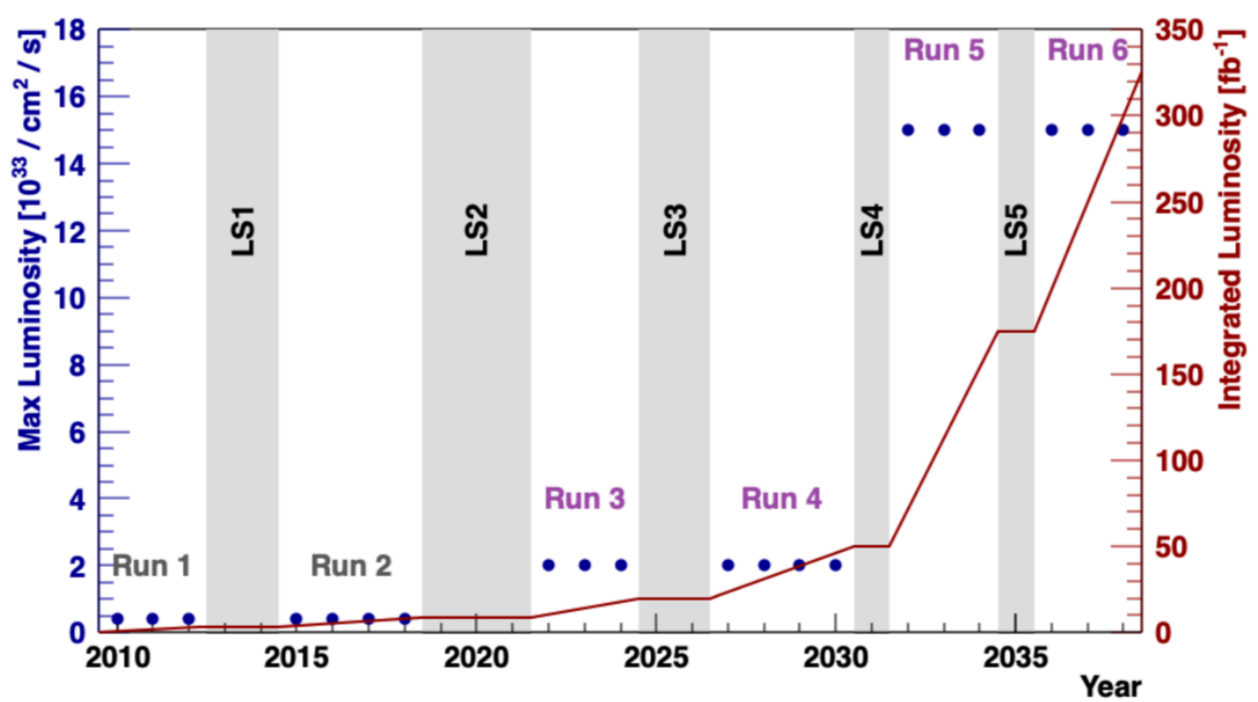
The LHCb upgrade program

U1: from 2022 - 2030

- x5 increase in inst. luminosity (4×10^{32} -> $2 \times 10^{33}\ cm^{-2}s^{-1}$)
- Integrated luminosity at the end: 50 fb^{-1}
- Majority of sub-detectors upgraded, **hardware trigger stage completely removed!**
- **Being commissioned right now**

U2: from 2032 - 2040

- x7 increase in inst. luminosity ($2 \times 10^{33} \rightarrow 1.5 \times 10^{34}\ cm^{-2}s^{-1}$)
- 300 fb^{-1} after 10 years
- Expecting to run with x7 pile-up, detector upgrades to withstand radiation and occupancy challenges (radiation hard materials, precise timing information)

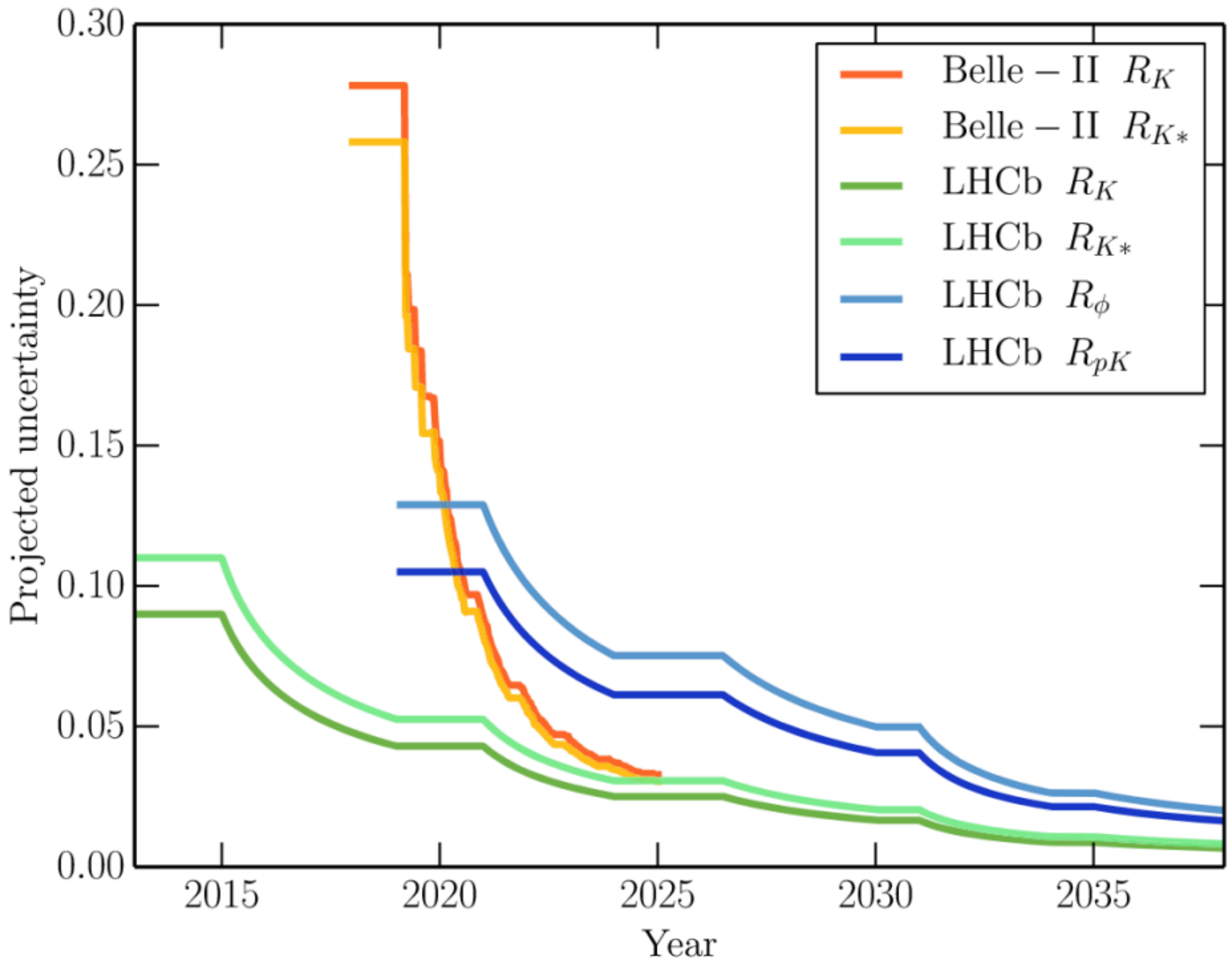


Prospects

- **Run 3 & beyond will improve the sensitivity thanks to the luminosity increase**
  - Especially for analyses that were previously limited by statistical uncertainties

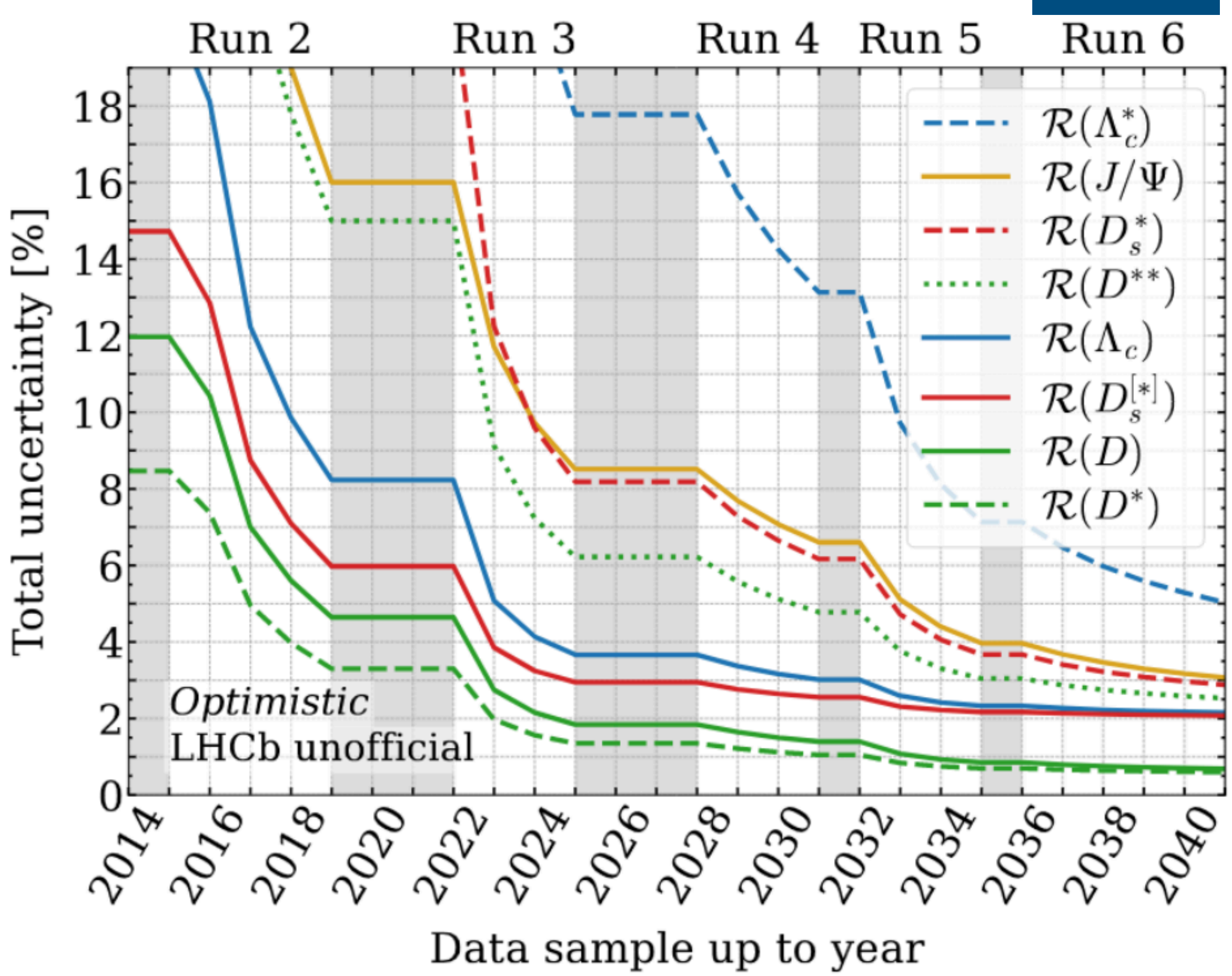
J. Phys. G: Nucl. Part. Phys. 46 023001

FCNC



Rev. Mod. Phys. 94, 015003 (2022)

FCCC



- **Novel approaches in reconstruction and trigger are being deployed right now**
  - Targeting more challenging signatures (electrons, taus)

Conclusions

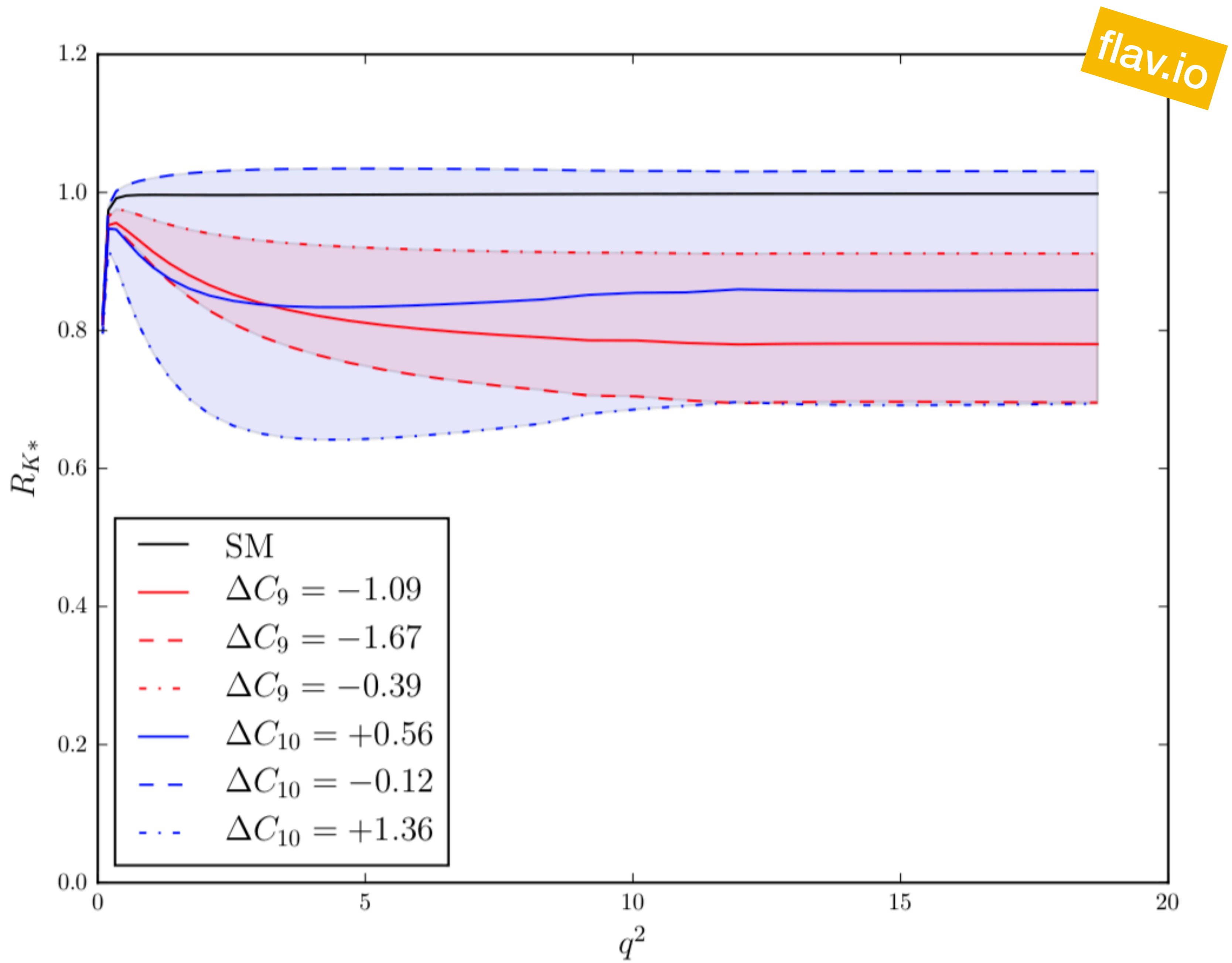
- Rare heavy flavour decays are unique indirect probes for New Physics
- LHCb continues to be a world-leading precision measurement experiment
- New results with the first 2 Runs keep coming out, AND
- A whole new run with a fully upgraded detector is starting now…
- So stay tuned for more exciting results!

Thank you for your attention!

Backup

Why Lepton Flavour Universality?

- Several BSM scenarios show dependence of R_X ratios on q^2
- Example: different C_9, C_{10} dependence of R_{K^*} between mid- and high-q^2



Electrons and muons at LHCb

- Electrons and muons interact in significantly different ways with the LHCb detector
- Understanding these differences is essential for correctly interpreting LFU ratio measurements

Muon reconstruction:

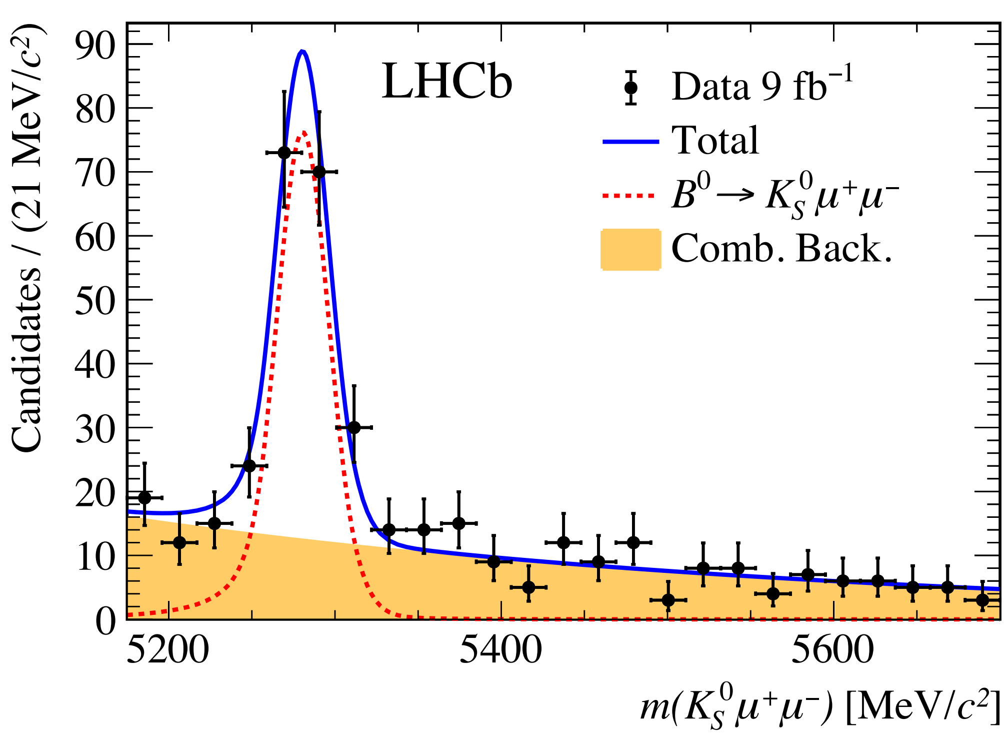
- Hits from muon stations matched to extrapolated tracks
- Momentum measured from the bending of the track

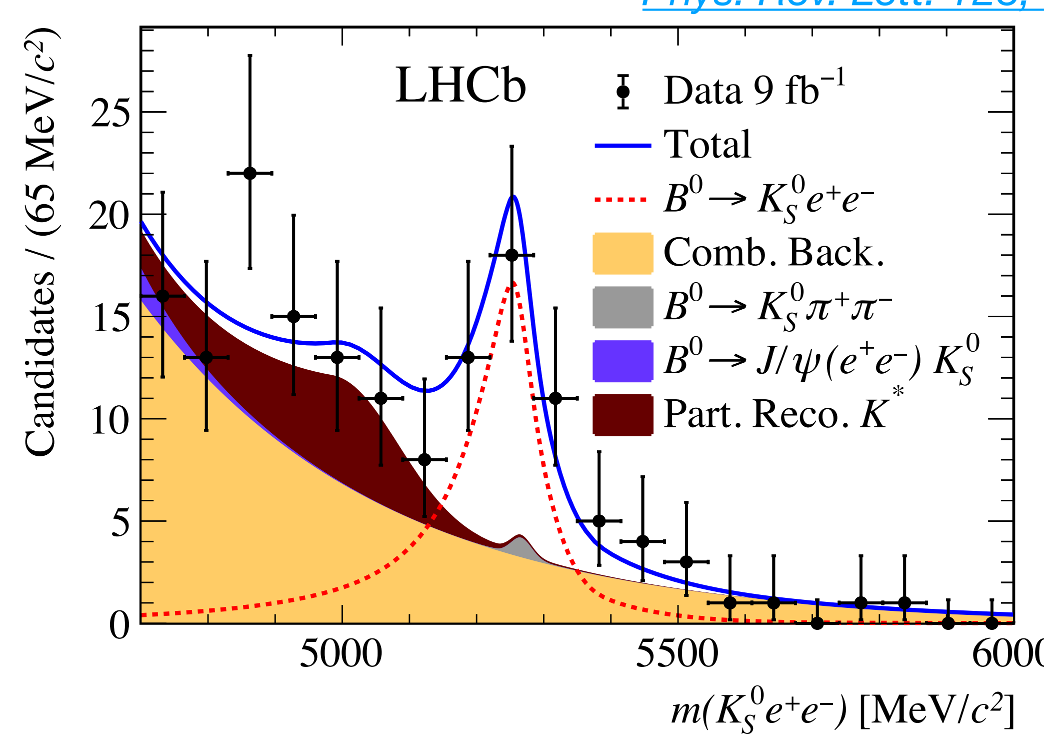
Electron reconstruction:

- Tracks matched to ECAL clusters
- Electrons often emit Bremstrahlung in LHCb
- Momentum measured from the bending of the track + Brem photons

Two main differences:
Recovery procedure of Brem photons not perfect
ECAL has higher occupancy than Muon System → higher hardware trigger thresholds

Phys. Rev. Lett. 128, 191802





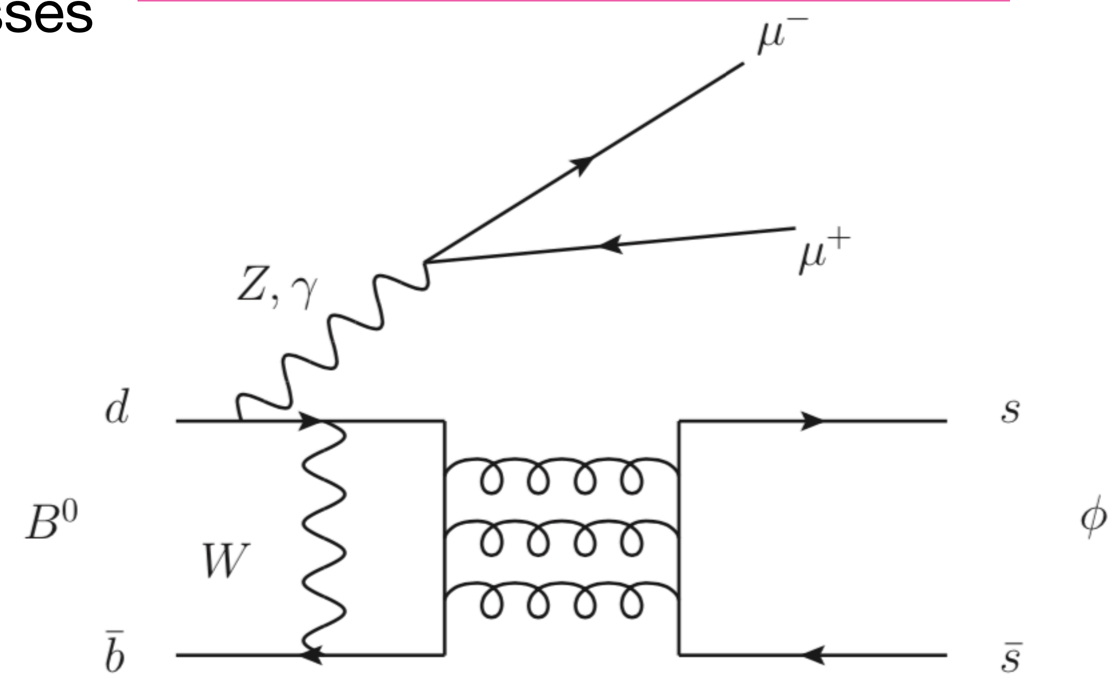
Search for the decay $B^0 \to \phi\mu^+\mu^-$

J. High Energ. Phys. 2022, 67 (2022)

Motivation:

- Ultra-rare color-suppressed penguin annihilation processes $\mathcal{O}(10^{-12})$
- $\omega - \phi$ mixing brings expected SM $\mathcal{B} \sim \mathcal{O}(10^{-11} - 10^{-10})$
- **Sensitive to NP contributions!**

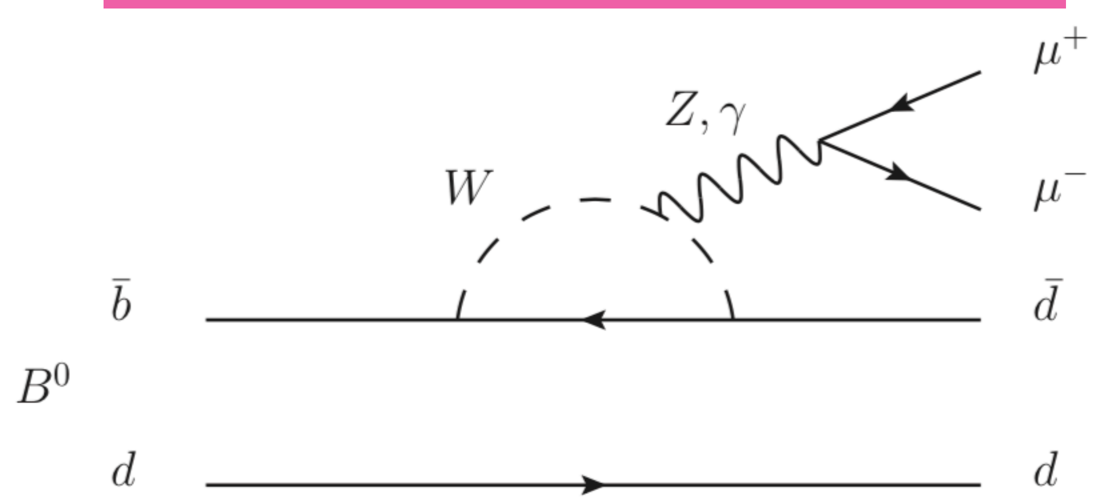
Example penguin annihilation



Analysis strategy:

- Full Run 1 + Run 2 LHCb dataset (9 fb^{-1})
- ϕ, J/ψ, $\psi(2S)$ q^2 regions excluded
- $B_s^0 \to \phi\mu^+\mu^-$ used as normalisation channel

Contribution from $\omega - \phi$ mixing



Main backgrounds:

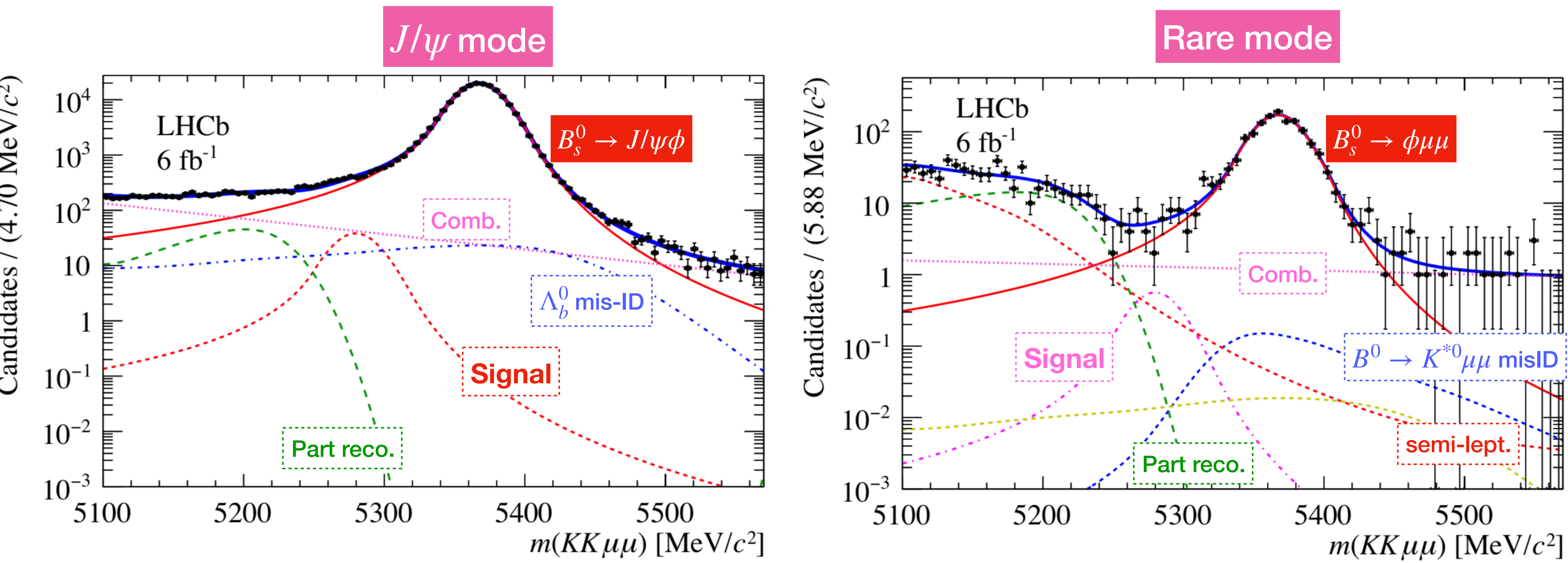
- Peaking decays with mis-ID
- Semileptonic $B_s^0 \to D_s^-(\to \phi\mu^-\bar{\nu})\mu^+\nu$
- Combinatorial
- Partially reconstructed

Search for the decay $B^0 \to \phi\mu^+\mu^-$

J. High Energ. Phys. 2022, 67 (2022)

- BR($B^0 \to \phi\mu\mu$) from mass fit in range including both B^0 and B_s^0 peaks
- $B_s^0 \to \phi J/\psi(\to \mu^+\mu^-)$ used to train combinatorial MVA classifier + $B_{(s)}^0$ mass shape
- No signal observed → upper limit on BR

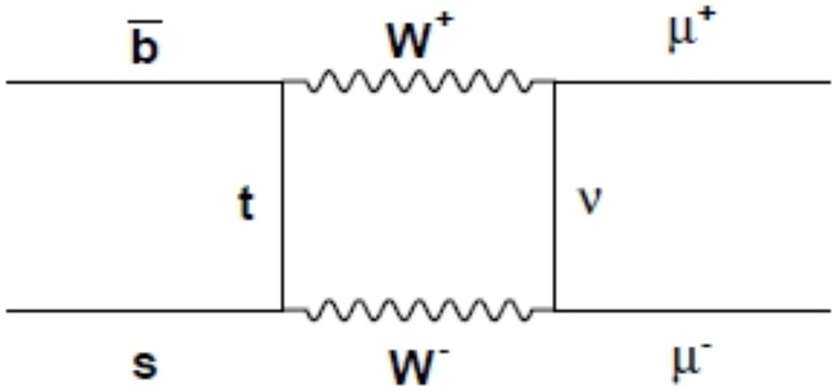
$$\mathcal{B}(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9} \text{ at a } 90\% \text{ CL}$$

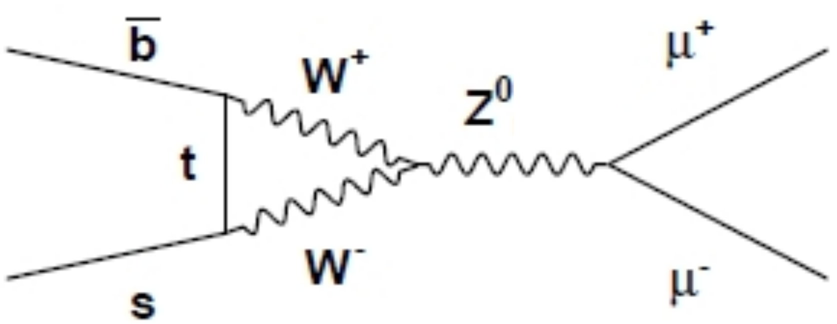


$B^0_{(s)}$ decays into two muons

Phys. Rev. Lett. 128 041801

- Loop level, helicity & CKM suppressed → **very rare!**
- Analysis supersedes previous LHCb result *[Phys. Rev. Lett. 118, 191801]*
  - Full Run 1 + Run 2
  - First search for $B^0 \to \mu^+\mu^-\gamma$



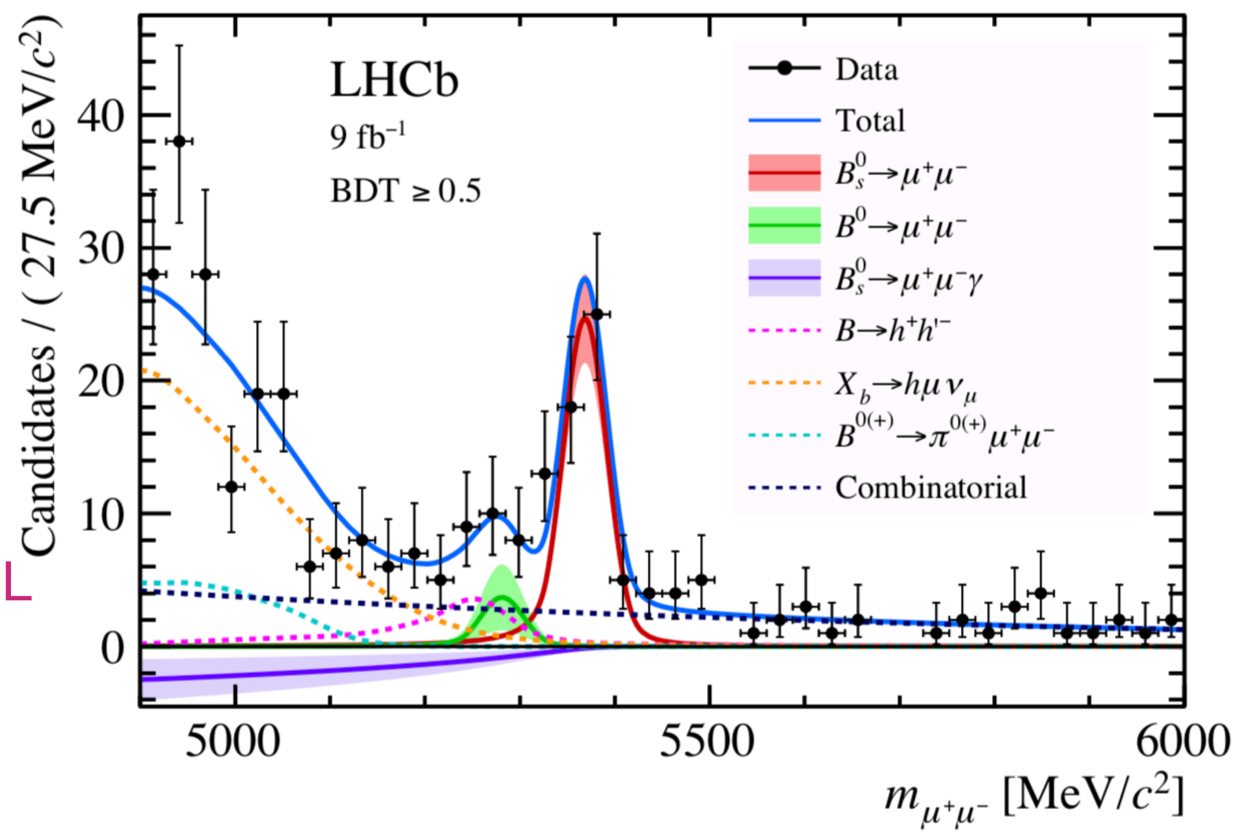


$B^0_s \to \mu^+\mu^-$ observed @ **10σ:**

- $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$

$B^0 \to \mu^+\mu^-$ & $B^0 \to \mu^+\mu^-\gamma$ not significant → **limits on the BR:**

- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 90% CL
- $\mathcal{B}(B^0 \to \mu^+\mu^-\gamma)^{m(\mu\mu)>4.9GeV/c^2} < 2.0 \times 10^{-9}$ at 90% CL



$B^0_{(s)}$ decays into two muons

Phys. Rev. Lett. 128 041801

Effective lifetime determination:

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}(1 + 2A^{\mu\mu}_{\Delta\Gamma_s} y_s + y_s^2)}{(1 - y_s^2)(1 + A^{\mu\mu}_{\Delta\Gamma_s} y_s)}$$

- In the SM, only $B^0_s \to \mu\mu$ only from heavy eigenstate ($A^{\mu\mu}_{\Delta\Gamma_s}$ = 1)

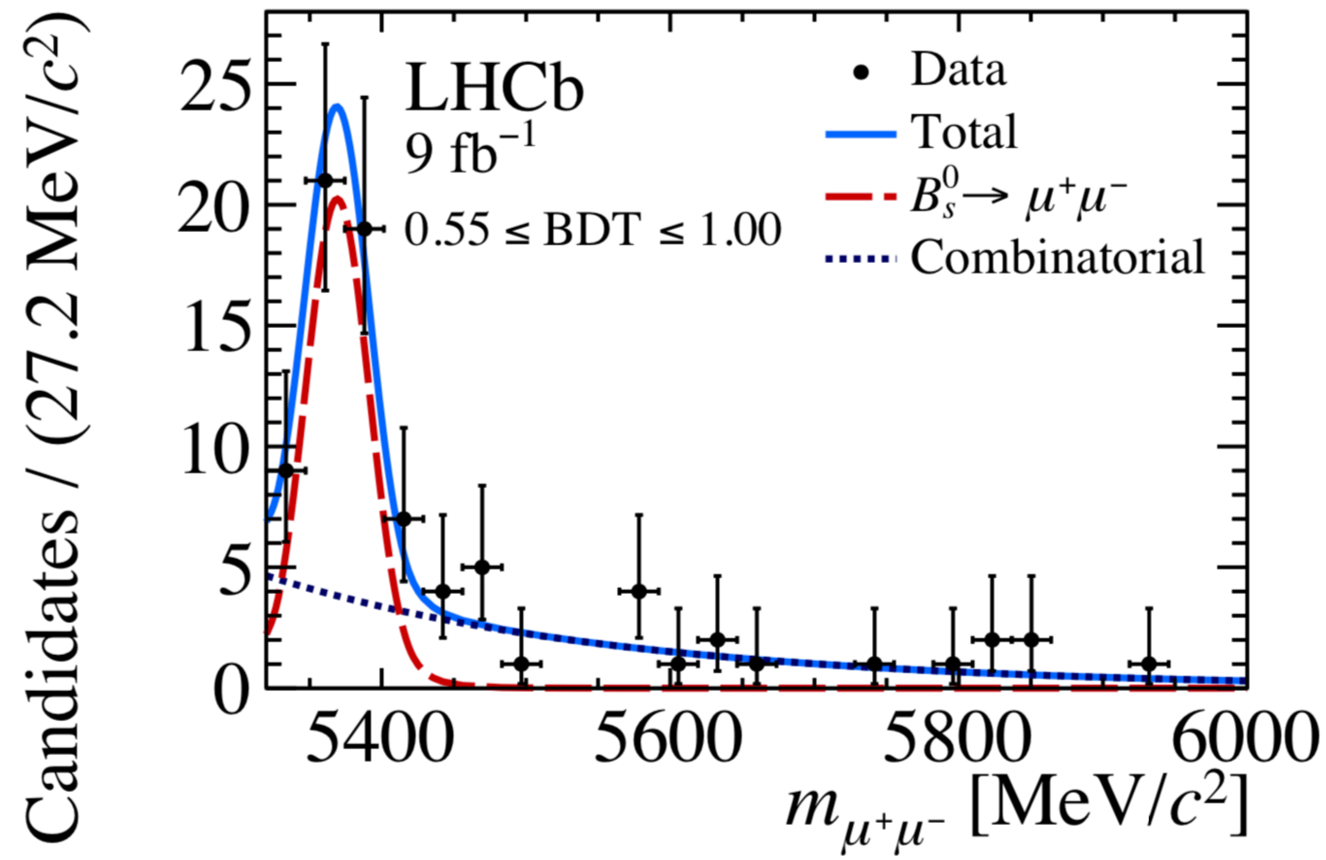
▸ **$\tau_{\mu\mu}$ sensitive to NP**

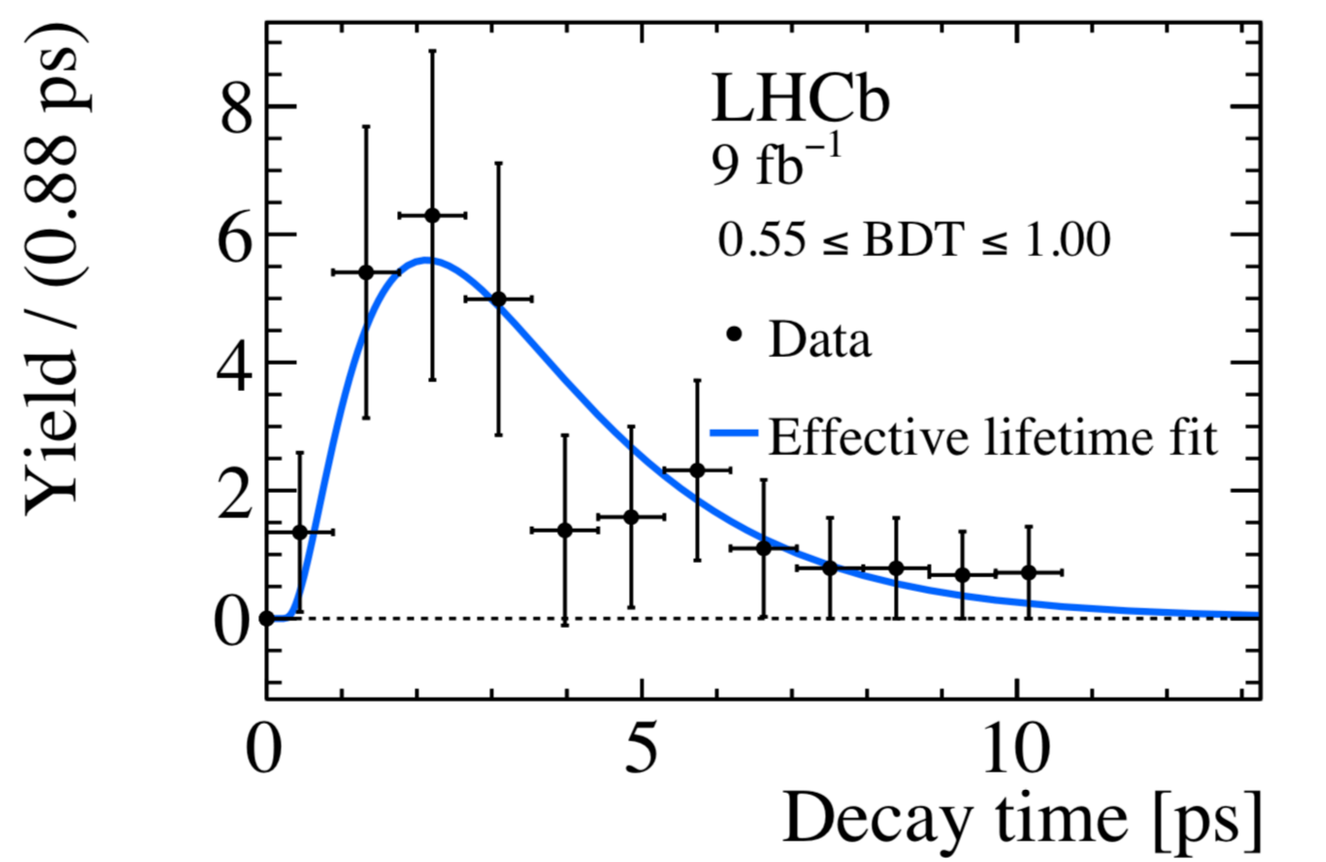
Strategy:

- Fit in reduced mass window to remove mis-ID backgrounds
- Tighter trigger for better modelling of efficiency dependence on $\tau_{\mu\mu}$
- Background-subtracted $\tau_{\mu\mu}$ distributions from *sPlot* technique

$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03\ ps$$

Consistent with $A^{\mu\mu}_{\Delta\Gamma_s}$ = 1 at 1.5σ





Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

J. High Energ. Phys. 2022, 109

Extremely rare in the SM:

- $B^0_s : \mathcal{O}(10^{-10}), B^0 : \mathcal{O}(10^{-12})$

- Full Run 1 + Run 2 dataset

- Search for **6 signal modes:**
  - Non-resonant decays: $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
  - Tree level resonant $b \to c$ transitions: $B^0_{(s)} \to J/\psi(\to \mu^+\mu^-)\mu^+\mu^-$
  - BSM light scalar resonances ($m_a \sim 1\ GeV$) $B^0_{(s)} \to a(\to \mu^+\mu^-)a(\to \mu^+\mu^-)$

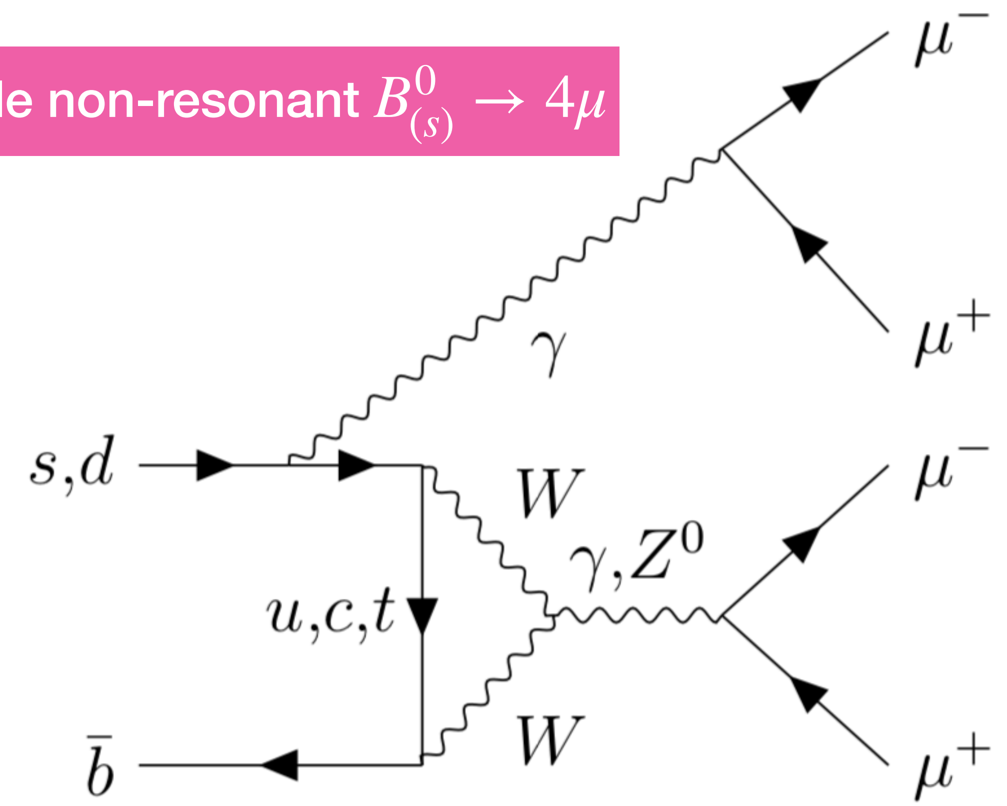
- $B^0_s \to J/\psi(\to \mu\mu)\phi(\to \mu\mu)$ used as a **normalisation channel**

- Combinatorial background suppressed by BDT

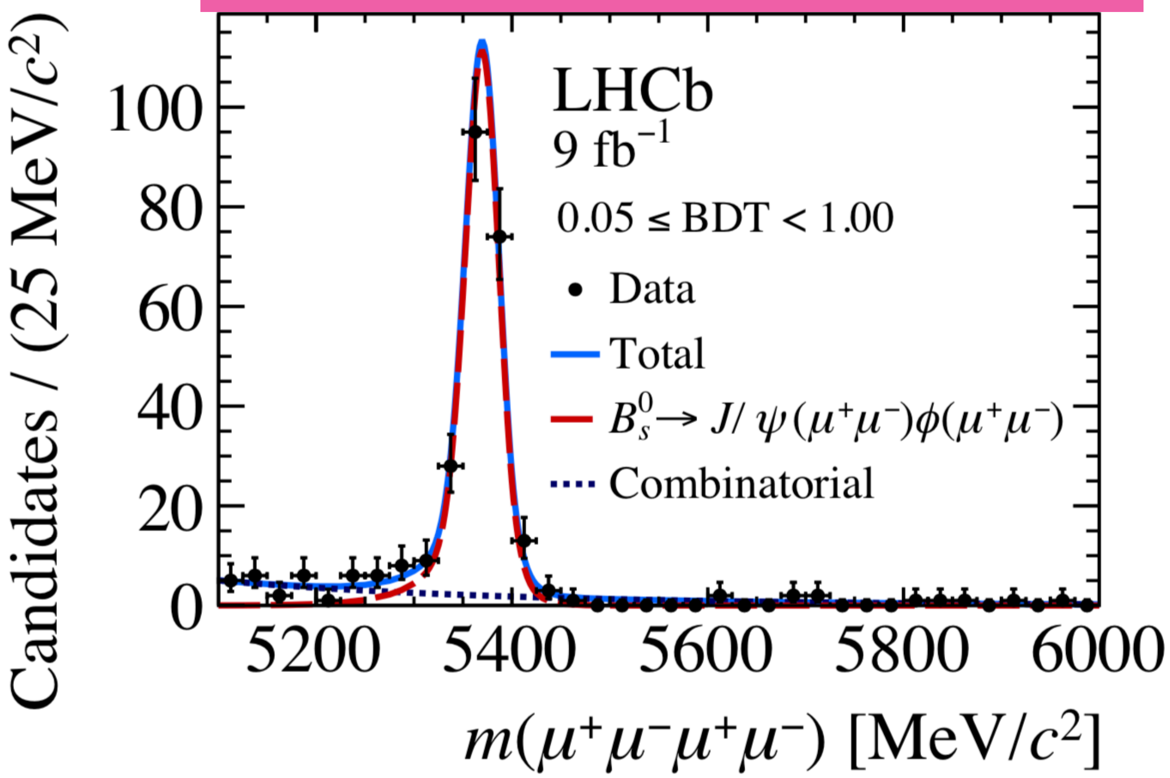
- Tight Particle Identification requirements for $h \to \mu$ mis-identification background

- Results extracted from maximum-likelihood fits to the 4-body mass spectra

Example non-resonant $B^0_{(s)} \to 4\mu$



Mass fit of the normalisation channel

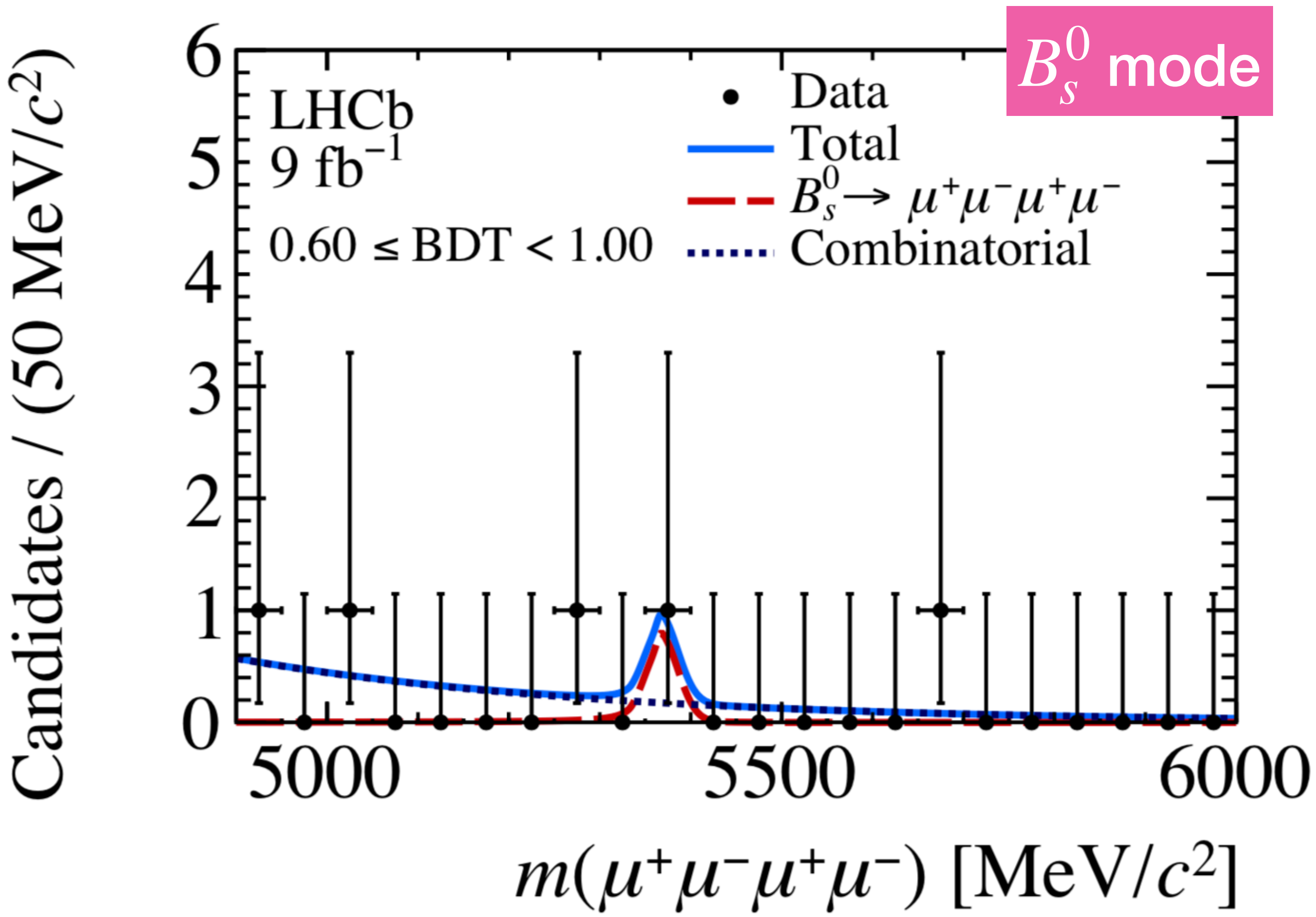


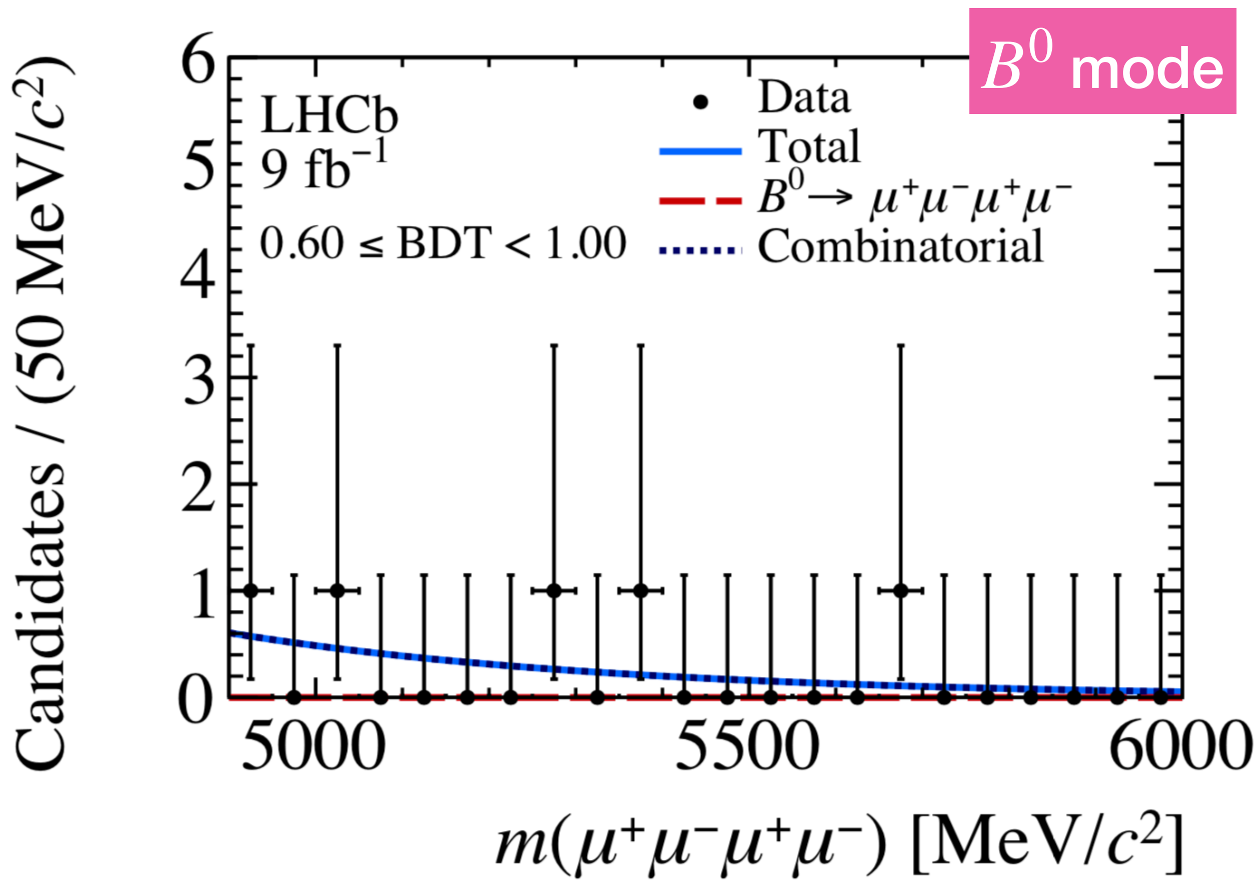
Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

J. High Energ. Phys. 2022, 109

No significant signal observed → most stringent limits to date!

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 8.6 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 1.8 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 5.8 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 2.3 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 2.6 \times 10^{-9},$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 1.0 \times 10^{-9}.$$





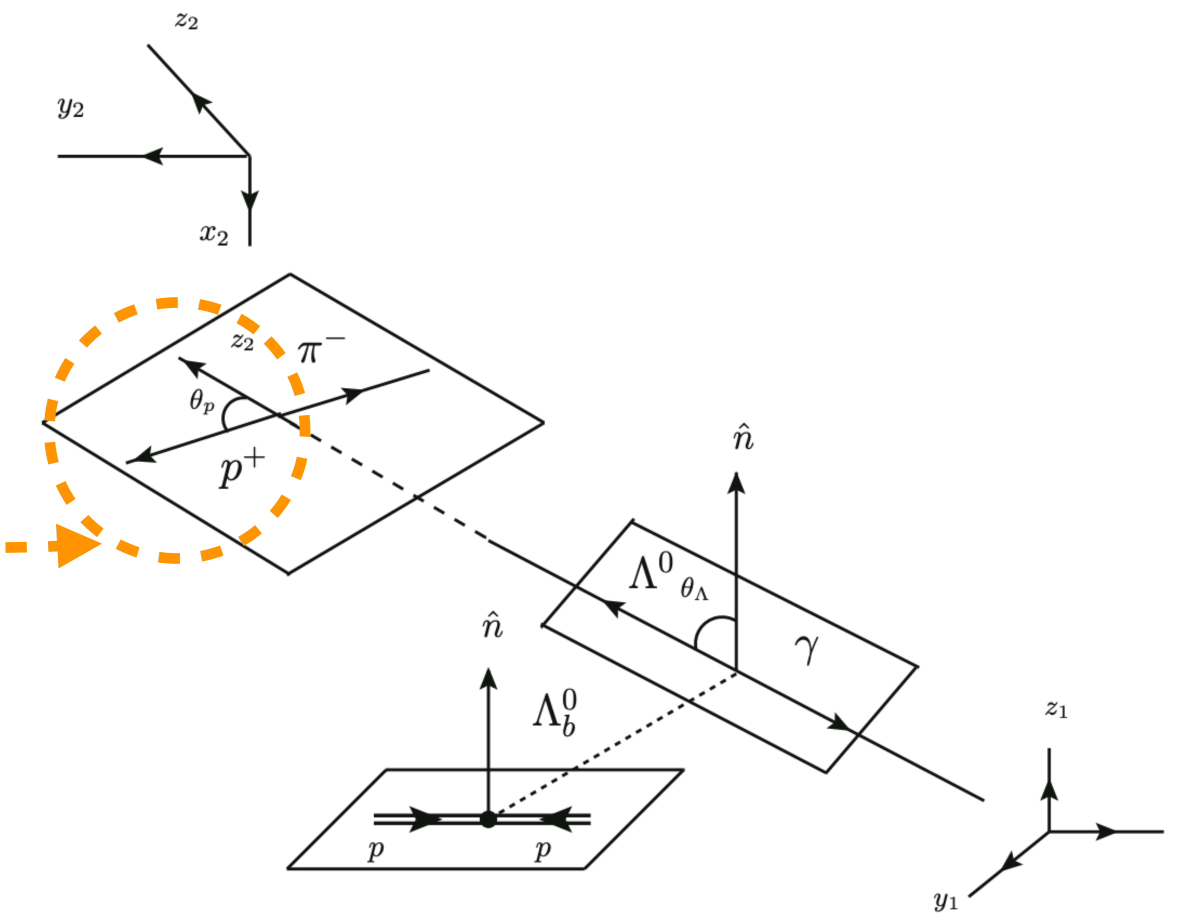
Photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

[Phys. Rev. D 105, L051104]

$b \to s\gamma$ (FCNC): γ mostly **left-handed** in SM

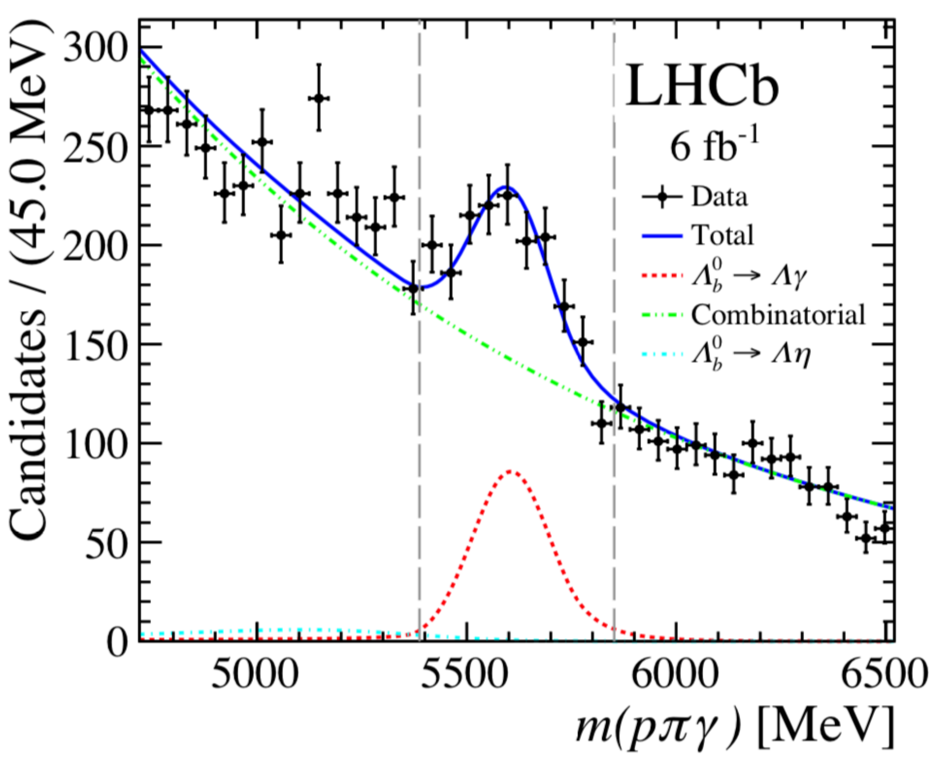
- $\Lambda_b \to \Lambda\gamma$ with $\Lambda \to p\pi$ probes helicity structure

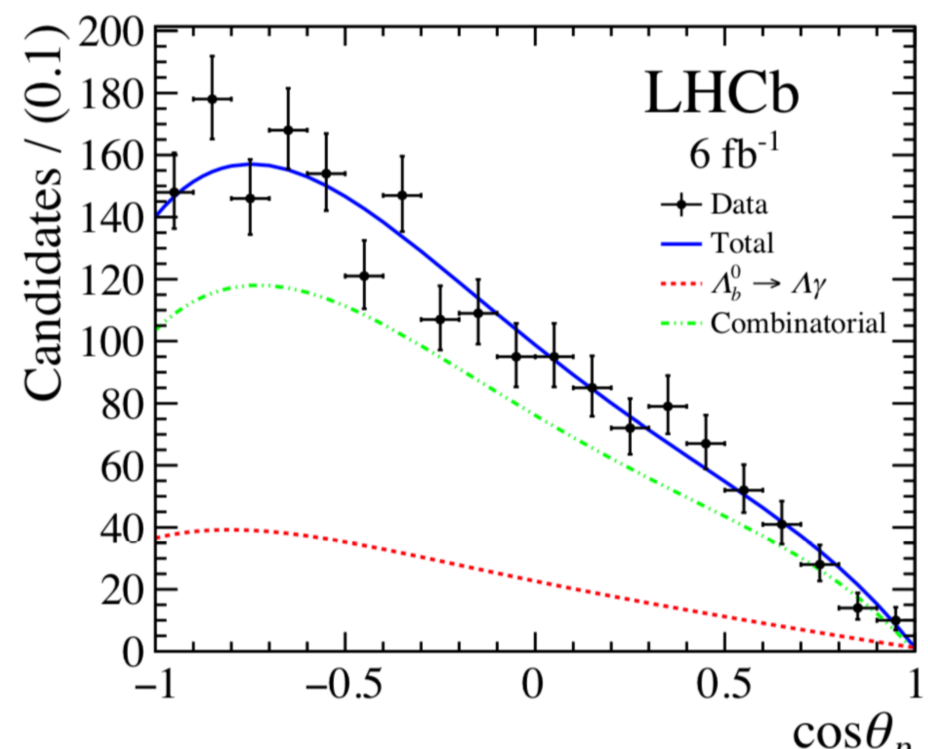
$$\frac{d\Gamma}{d(cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda cos\theta_p$$



▸ **Measure α_γ from proton angular distribution!**

- Analysis performed with full Run 2 data (6 fb^{-1})
- α_Λ from BESIII [Nature Phys. 15 (2019) 631]
- BDT to mitigate combinatorial background, small $\Lambda_b \to \Lambda\eta(\to \gamma\gamma)$ included in the fit



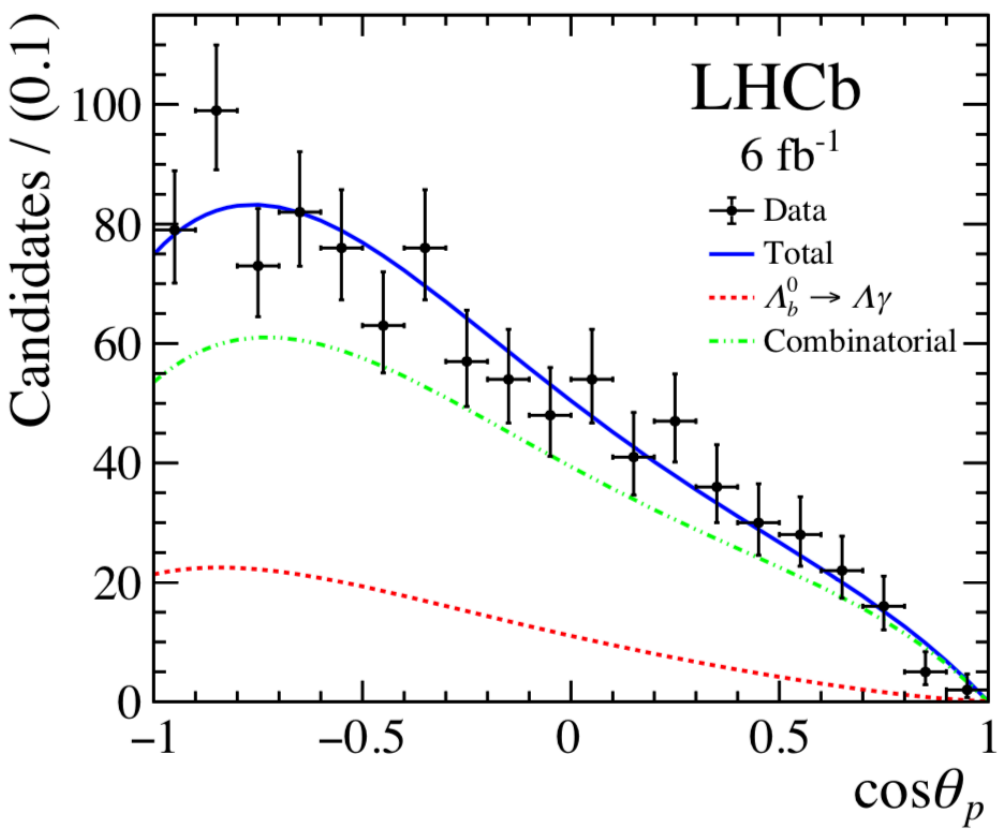


Photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

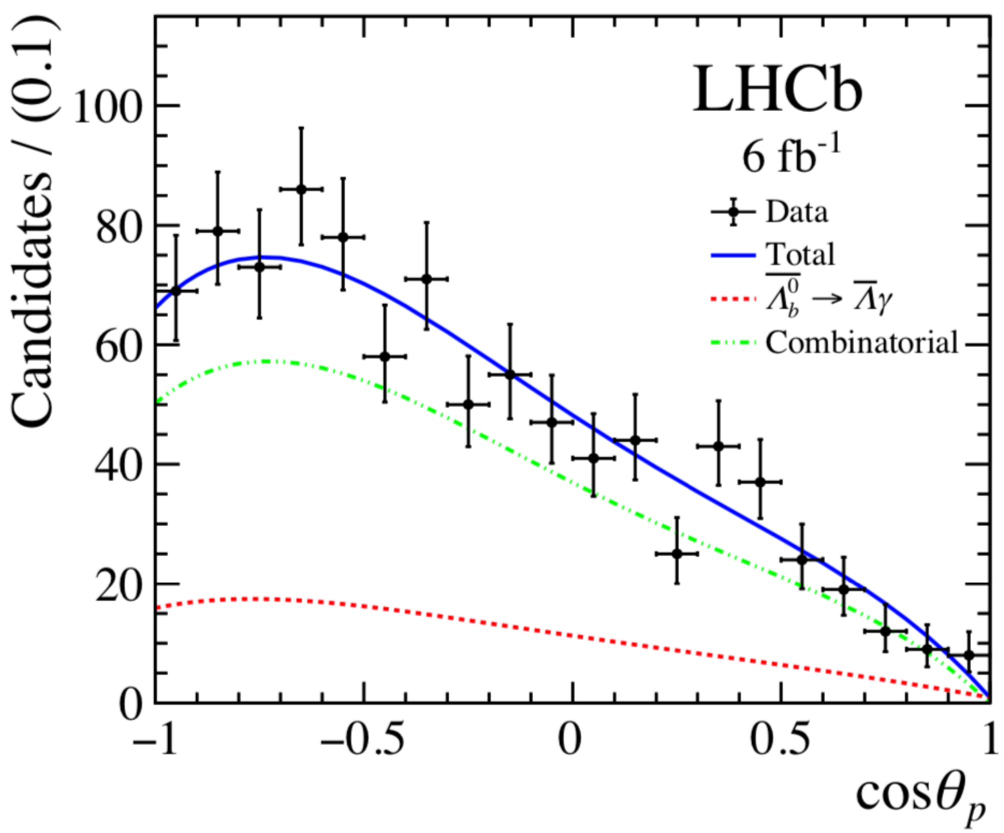
Phys. Rev. D 105, L051104

$$\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$$

Data are split to Λ_b^0 and $\bar{\Lambda}_b^0$ to study CP violation



$$\alpha_\gamma^- = 1.26 \pm 0.42 \pm 0.20$$



$$\alpha_\gamma^- = -0.55 \pm 0.32 \pm 0.16$$

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

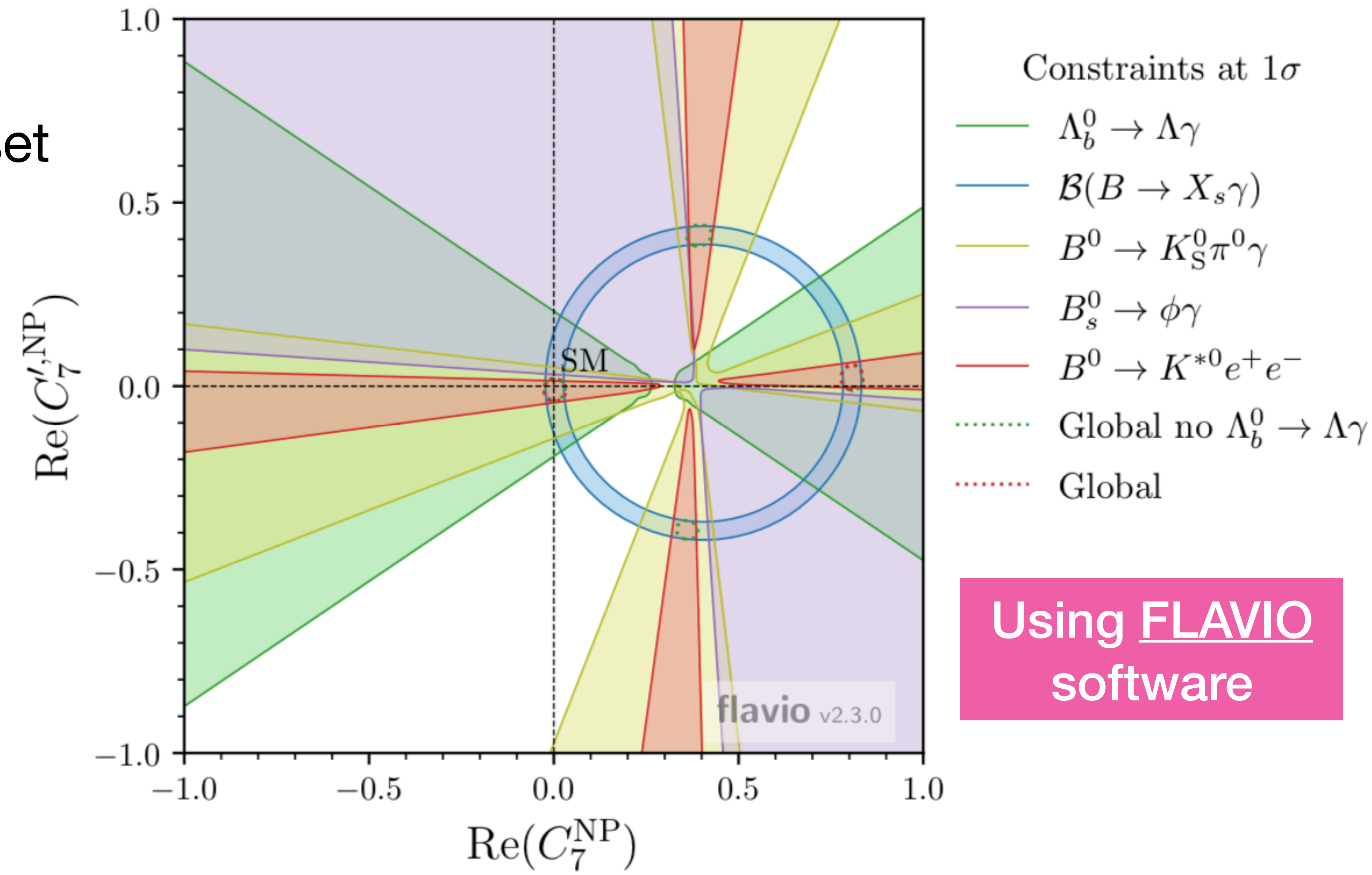
Phys. Rev. D 105, L051104

Feldman-Cousins technique used to set confidence intervals within the [-1,1] polarisation physical limits

$$\alpha_\gamma^- > 0.56\ (0.44)\ at\ 90\,\%\,(95\%)\ CL$$

$$\alpha_\gamma^+ = -\,0.56^{+0.36}_{-0.33}\ (stat.)^{+0.16}_{-0.09}\ (syst.)$$

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



Using FLAVIO software

- First measurement of photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$ decays
- Consistent with CP symmetry and SM prediction at 1σ
- Can be used to place constraints on real and imaginary parts of Wilson coefficients $C_7^{(\prime)NP}$
- **Exclusion of previously uncovered phase-space!**