The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022 Taipei, Taiwan

2022 LHCP TAIPEI

Rare decays from B and D mesons at LHCb

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on behalf of the LHCb collaboration

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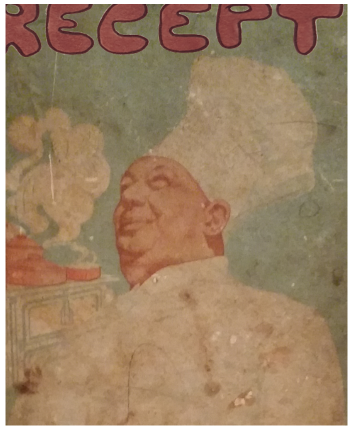


The rare decays program of LHCb

Lepton Flavour Universality (LFU)

$b \to s$ FCNC

Lepton Flavour Violation (LFV)

Rare decays

$c \to u$ FCNC

Radiative decays

Fully leptonic decays

The rare decays program of LHCb

Checkout Gabriele Simi's talk!

Lepton Flavour Universality (LFU)

Checkout Liang Sun's talk!

Lepton Flavour Violation (LFV)

$b \to s$ FCNC

Rare decays

Radiative decays

$c \to u$ FCNC

This presentation's focus!

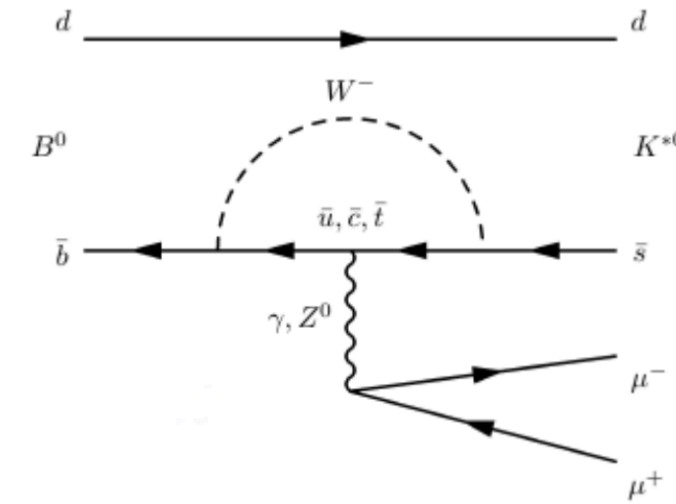
Fully leptonic decays

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

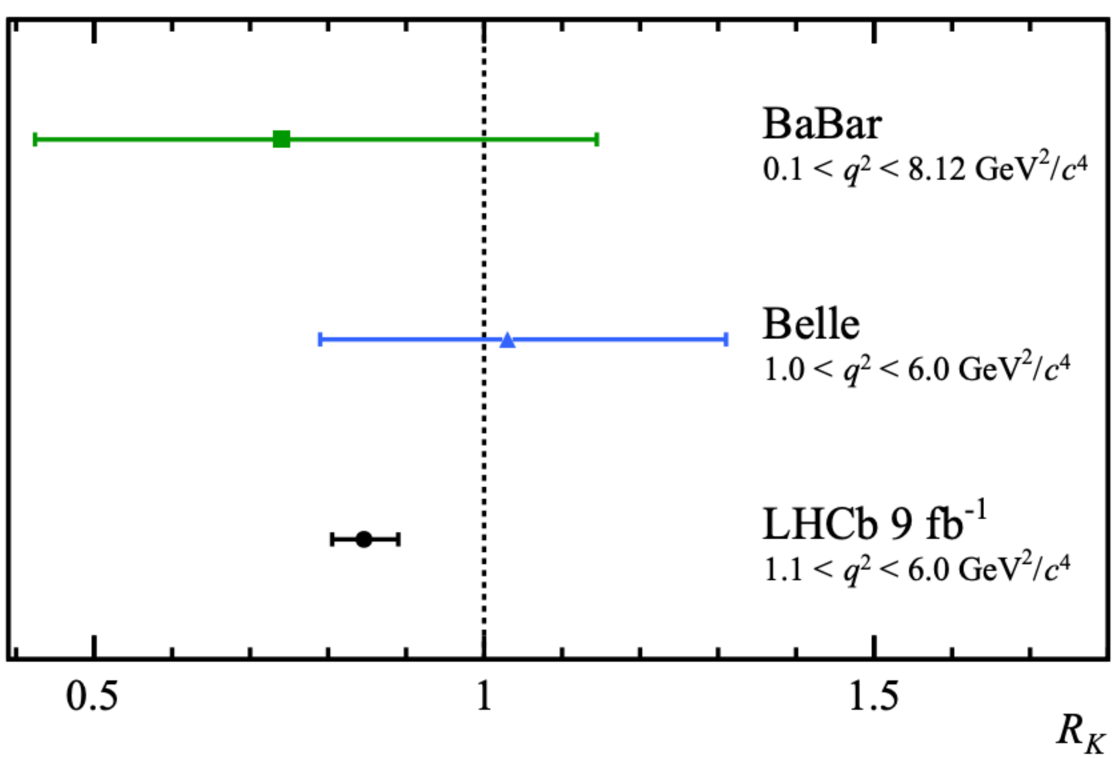
Why we care about rare B decays

- Rare B decays are excellent probes of **Flavour Changing Neutral Current (FCNC)** processes:
  - Not allowed at tree-level in the SM - very rare
  - Sensitive to indirect NP contributions
  - Theoretically clean!
- Coherent pattern of deviations from the SM in several **LFU** measurements and angular observables - hint of NP
- Could also manifest itself as **LFV**
- Complementary measurements from **radiative** and ultra rare **purely leptonic decays** offer important additional information and constraints

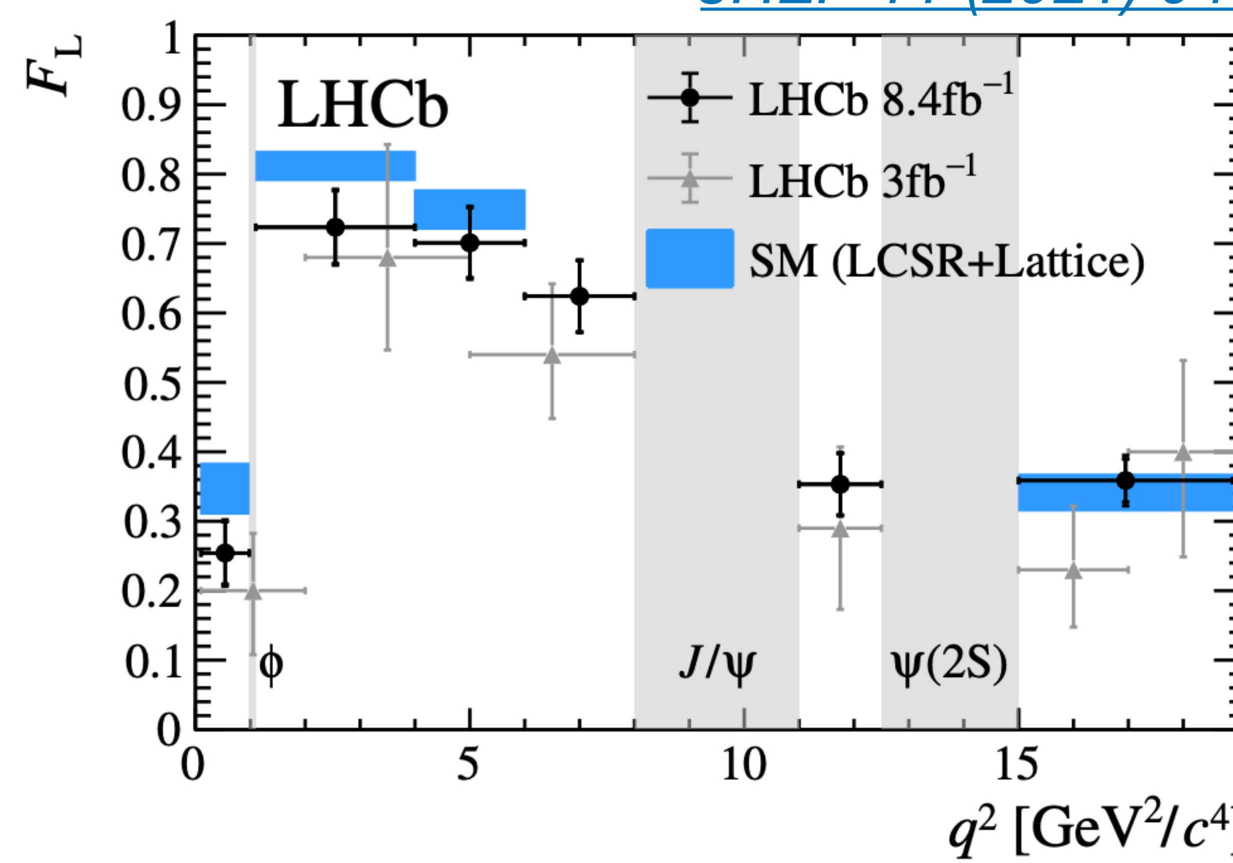
Example $b \to s\ell\ell$ FCNC



Nature Physics volume18, pages 277–282 (2022)



JHEP 11 (2021) 043



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!**

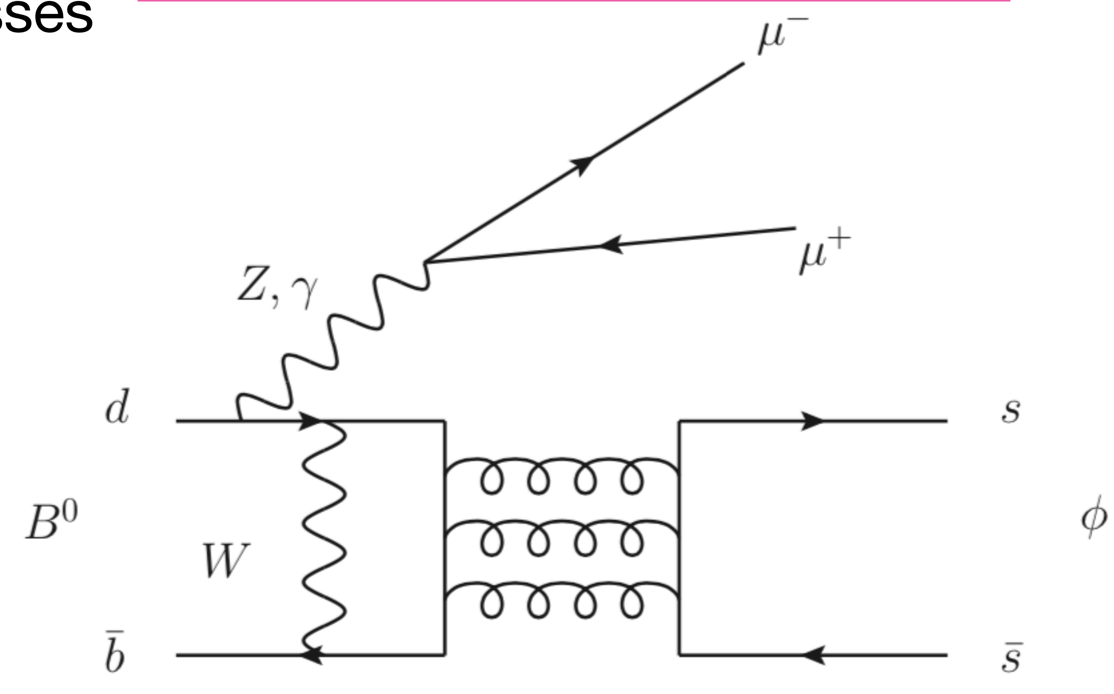
Analysis strategy:

- 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

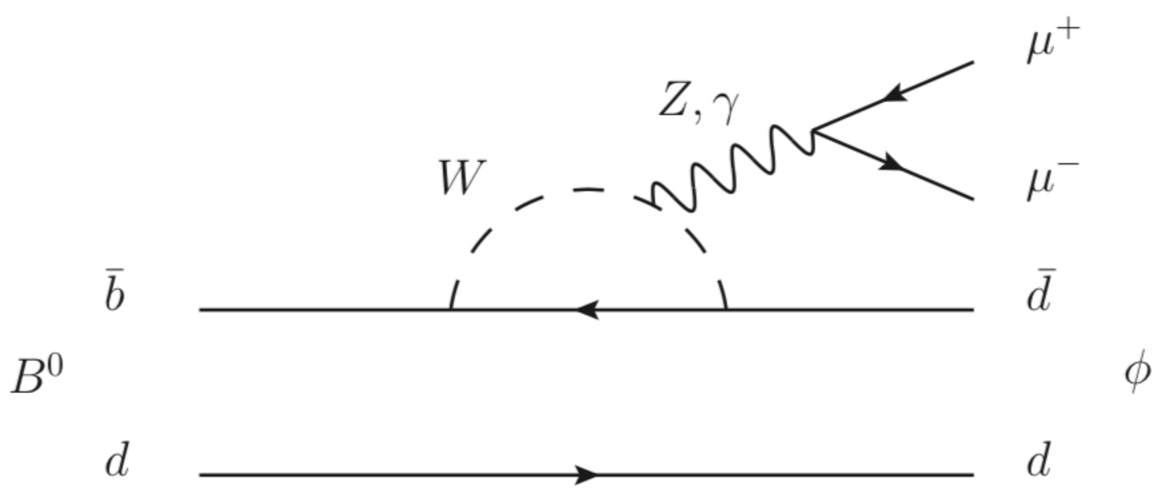
Main backgrounds:

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

Example penguin annihilation



Contribution from $\omega - \phi$ mixing



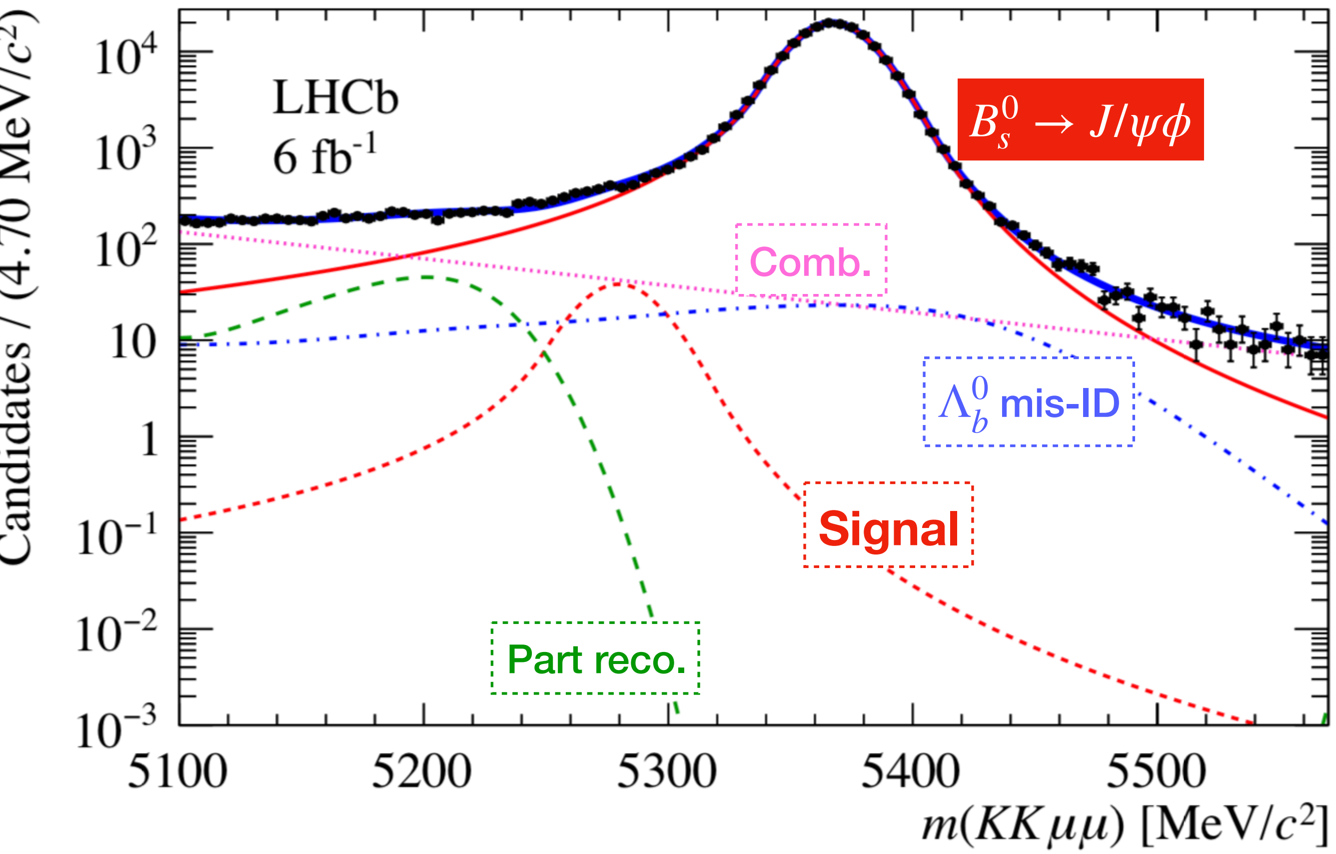
Search for the decay $B^0 \to \phi\mu^+\mu^-$

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

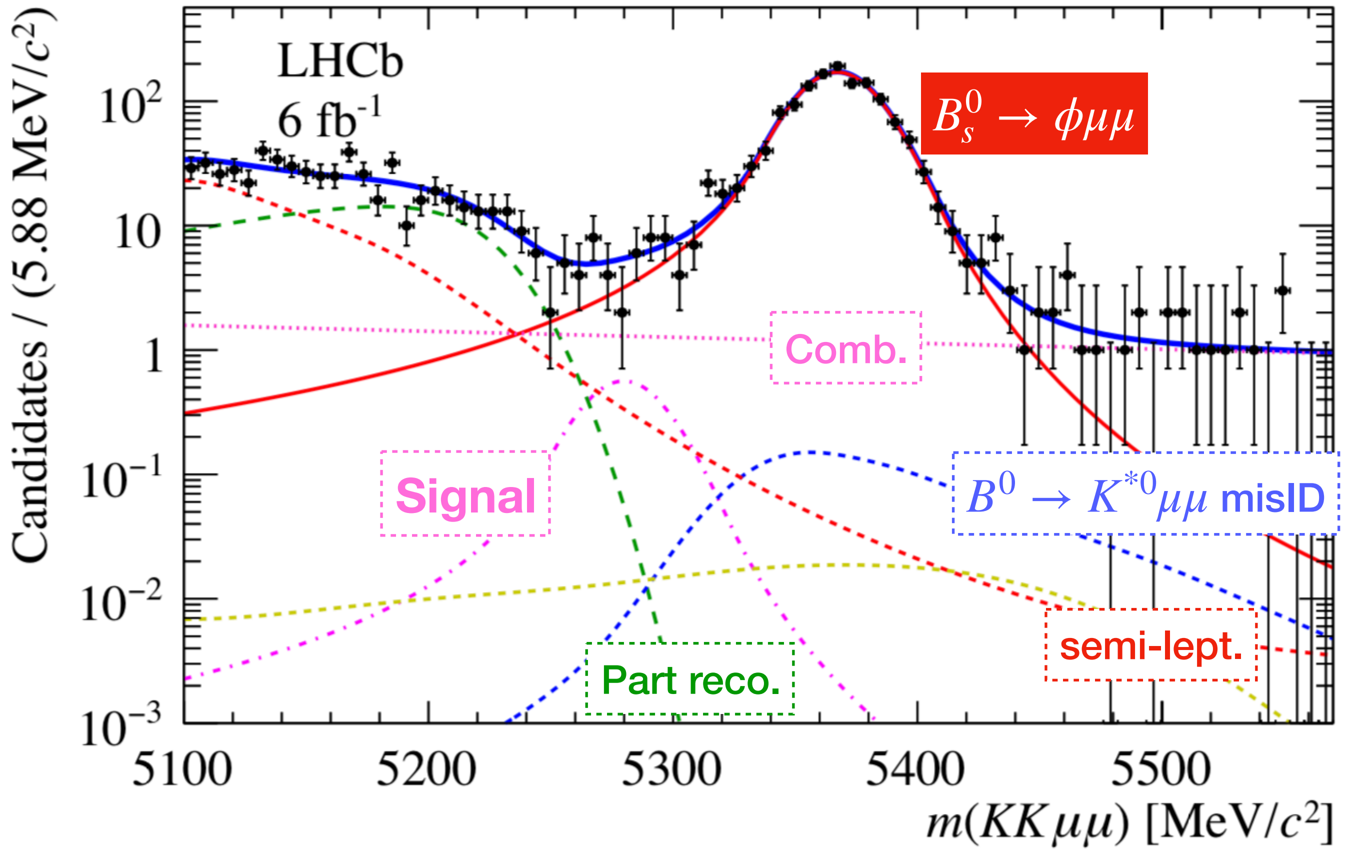
- BR($B^0 \to \phi\mu\mu$) from mass fit in range including both B^0 and B^0_s peaks
- $B^0_s \to \phi J/\psi(\to \mu^+\mu^-)$ used to train combinatorial MVA classifier + $B^0_{(s)}$ mass shape
- No signal observed → upper limit on BR

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

J/ψ mode



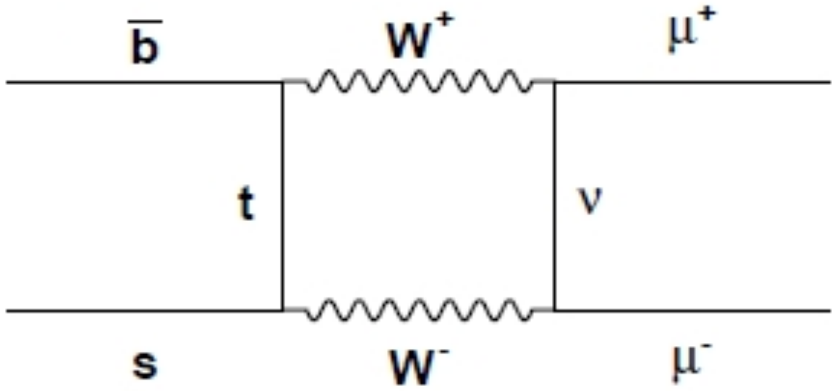
Rare mode

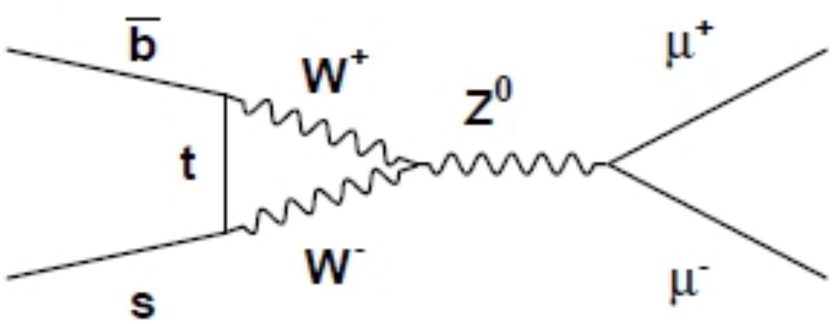


$B^0_{(s)}$ decays into two muons

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



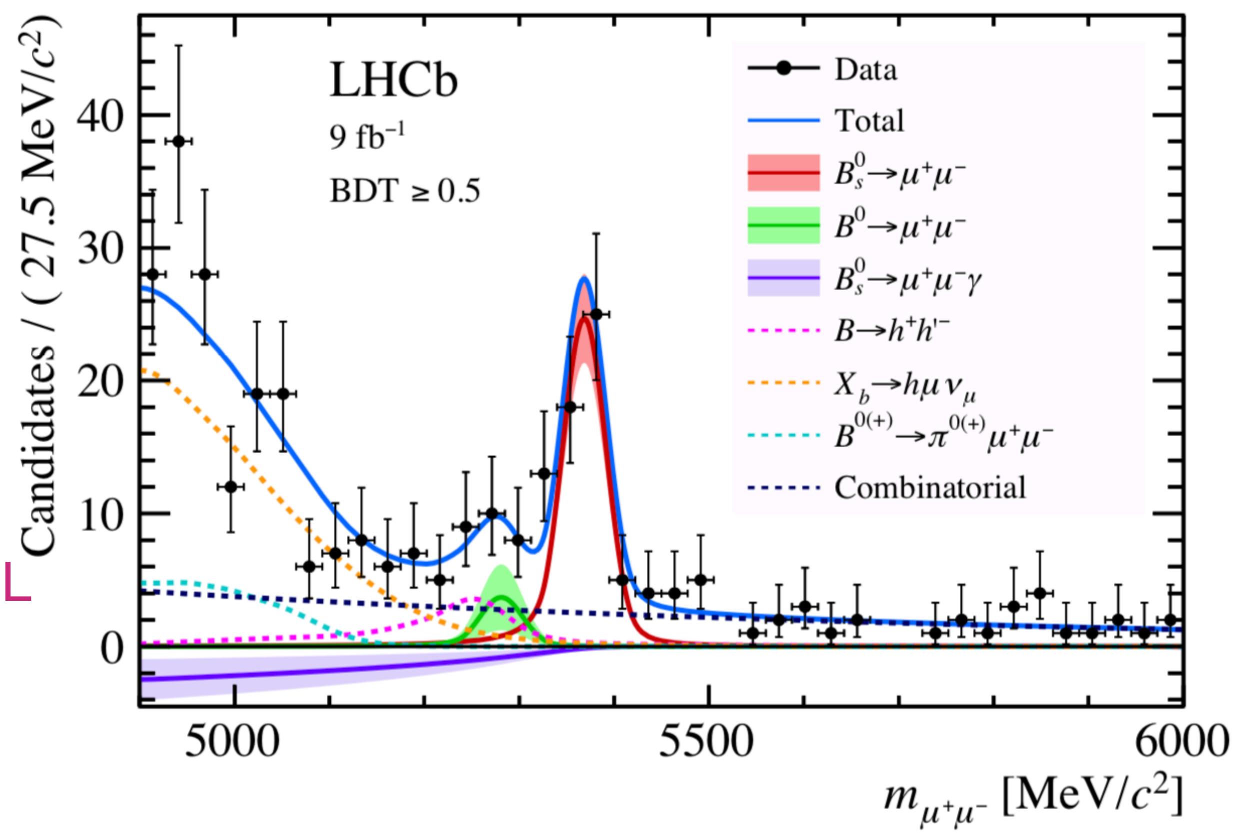


$B^0_s \to \mu^+\mu^-$ observed @ **10σ:**

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

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

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



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

Phys. Rev. Lett. 128 041801

Effective lifetime determination:

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

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

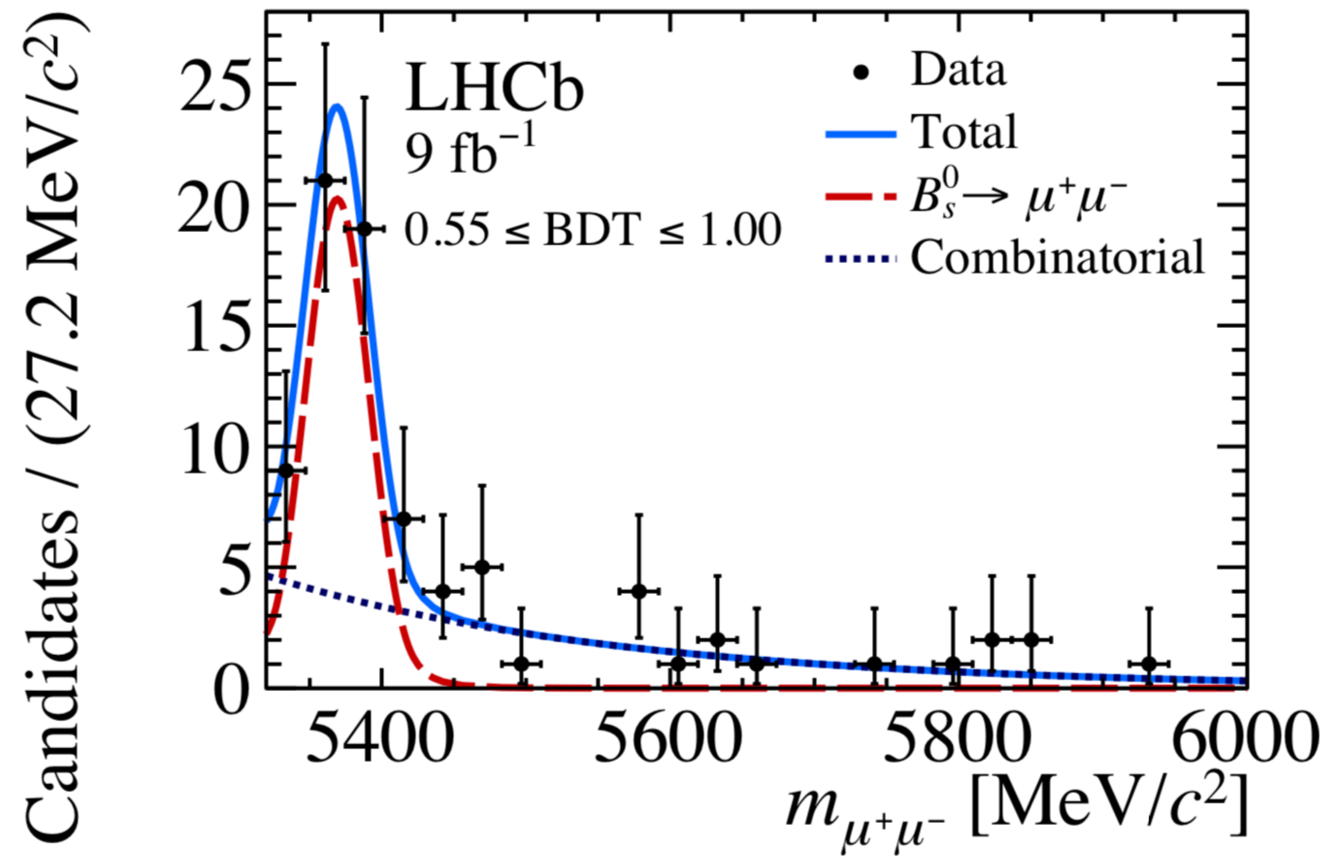
▸ $\tau_{\mu\mu}$ **sensitive to NP**

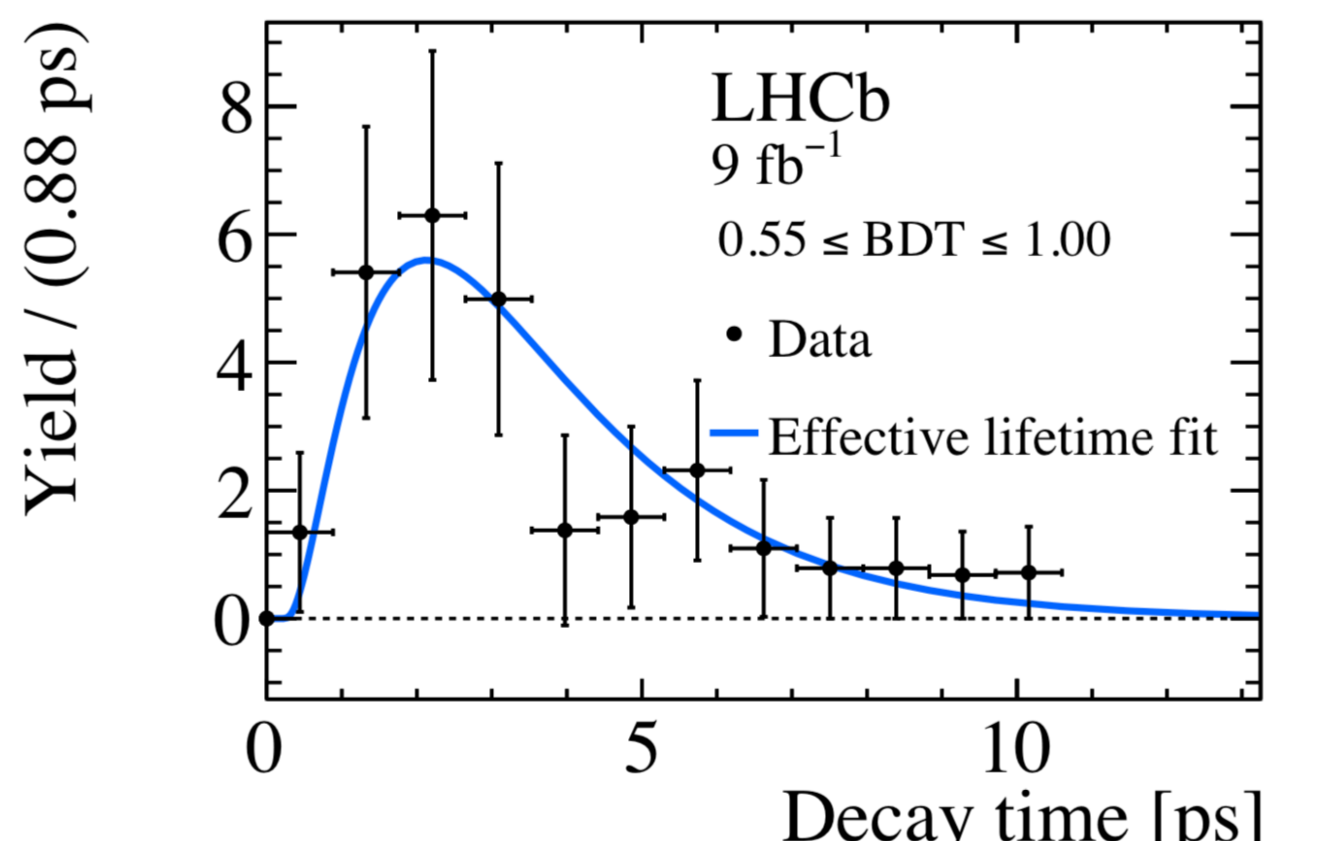
Strategy:

- 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

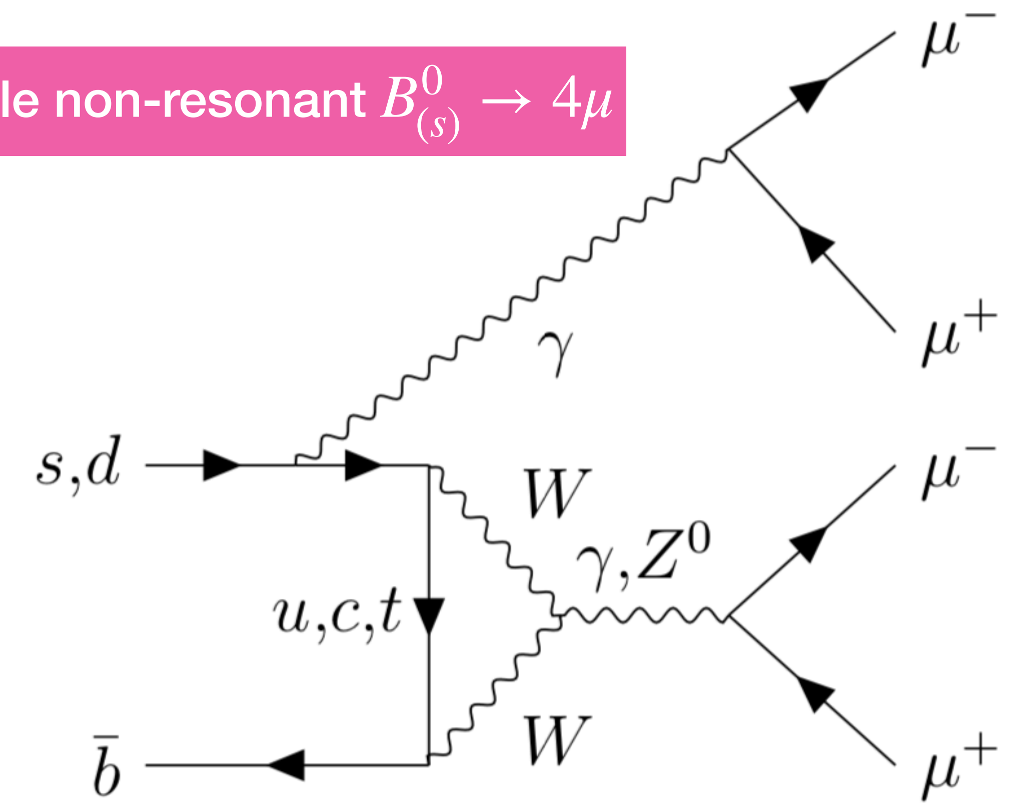
J. High Energ. Phys. 2022, 109

Extremely rare in the SM:

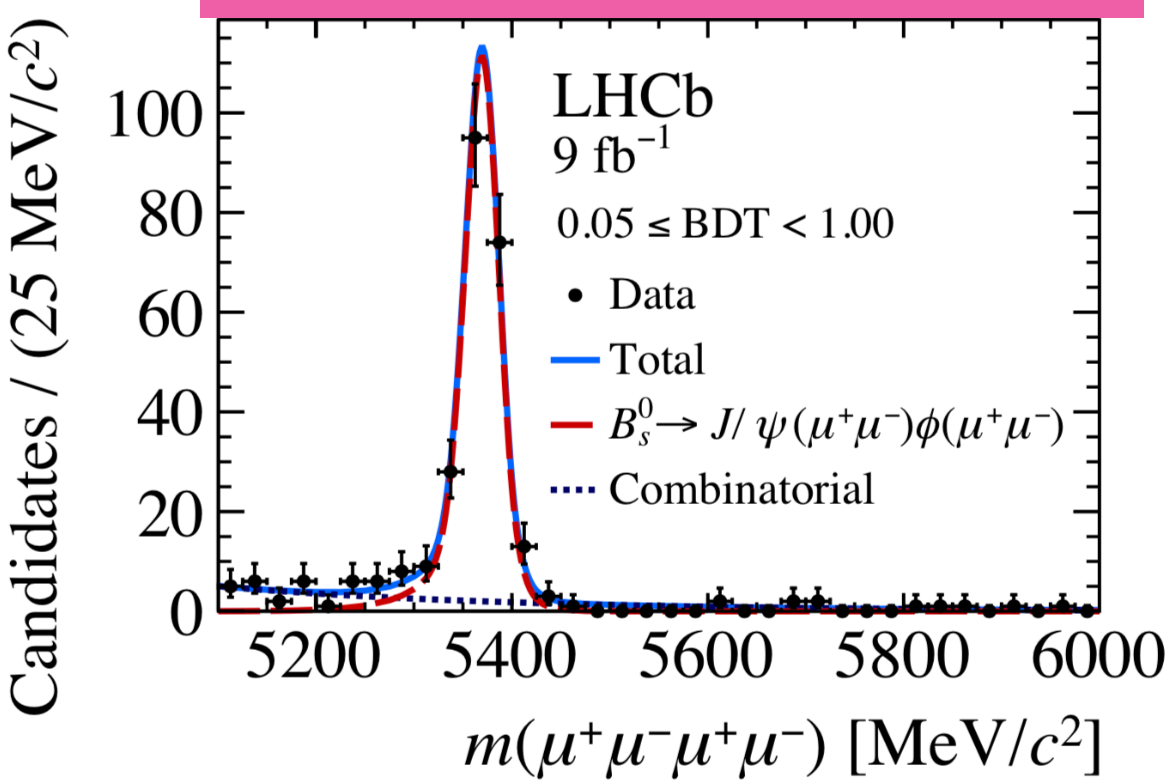
- $B^0_s : \mathcal{O}(10^{-10}), B^0 : \mathcal{O}(10^{-12})$

- 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

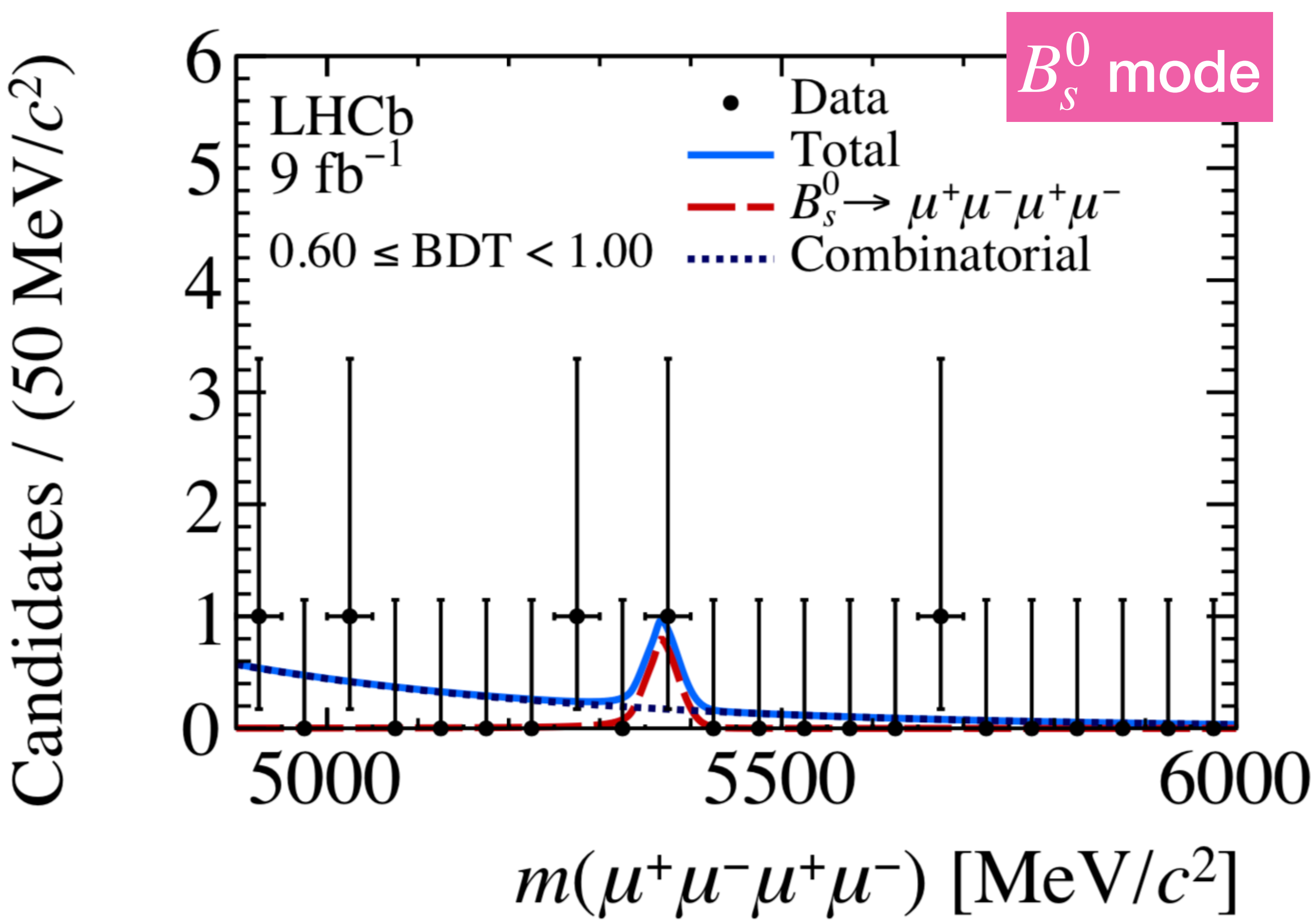


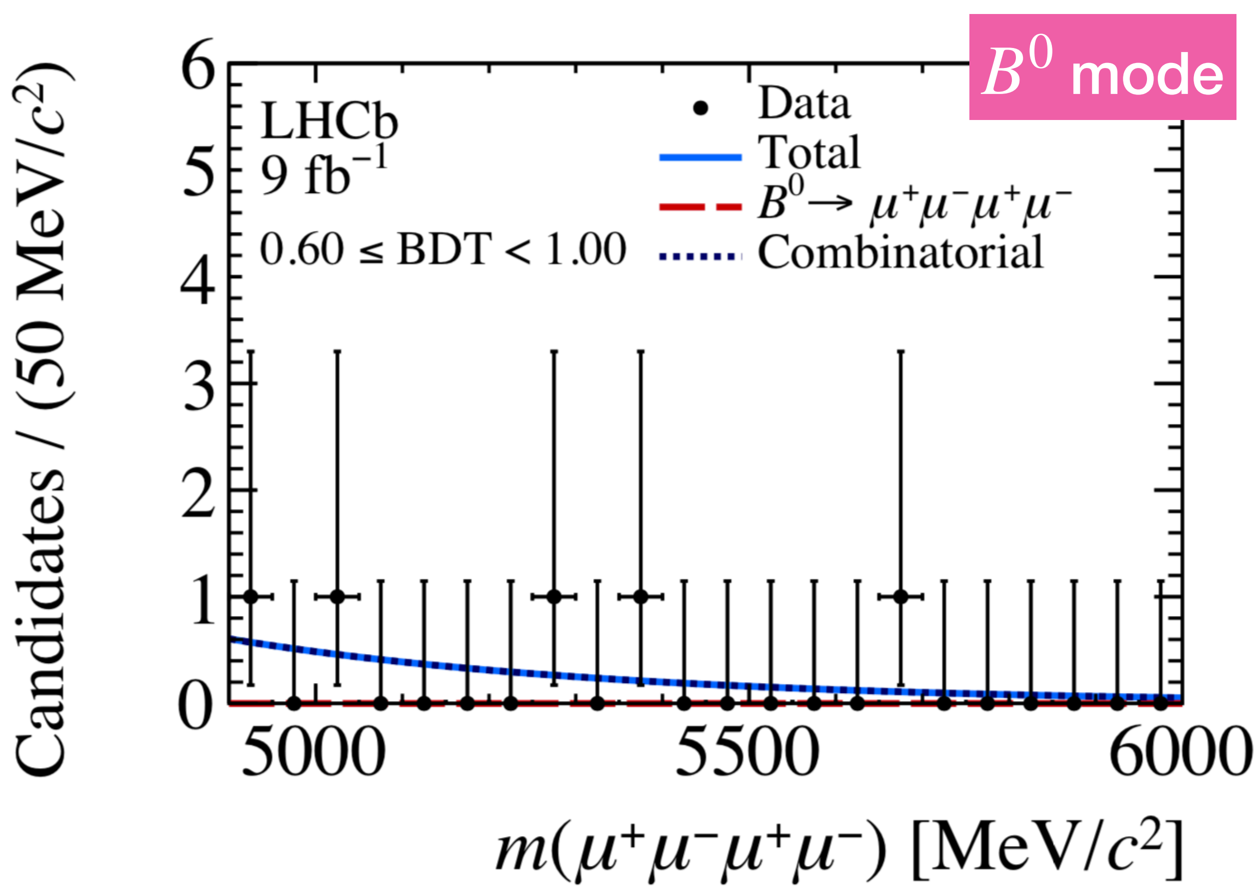
Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

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 $\Lambda_b^0 \to \Lambda\gamma$

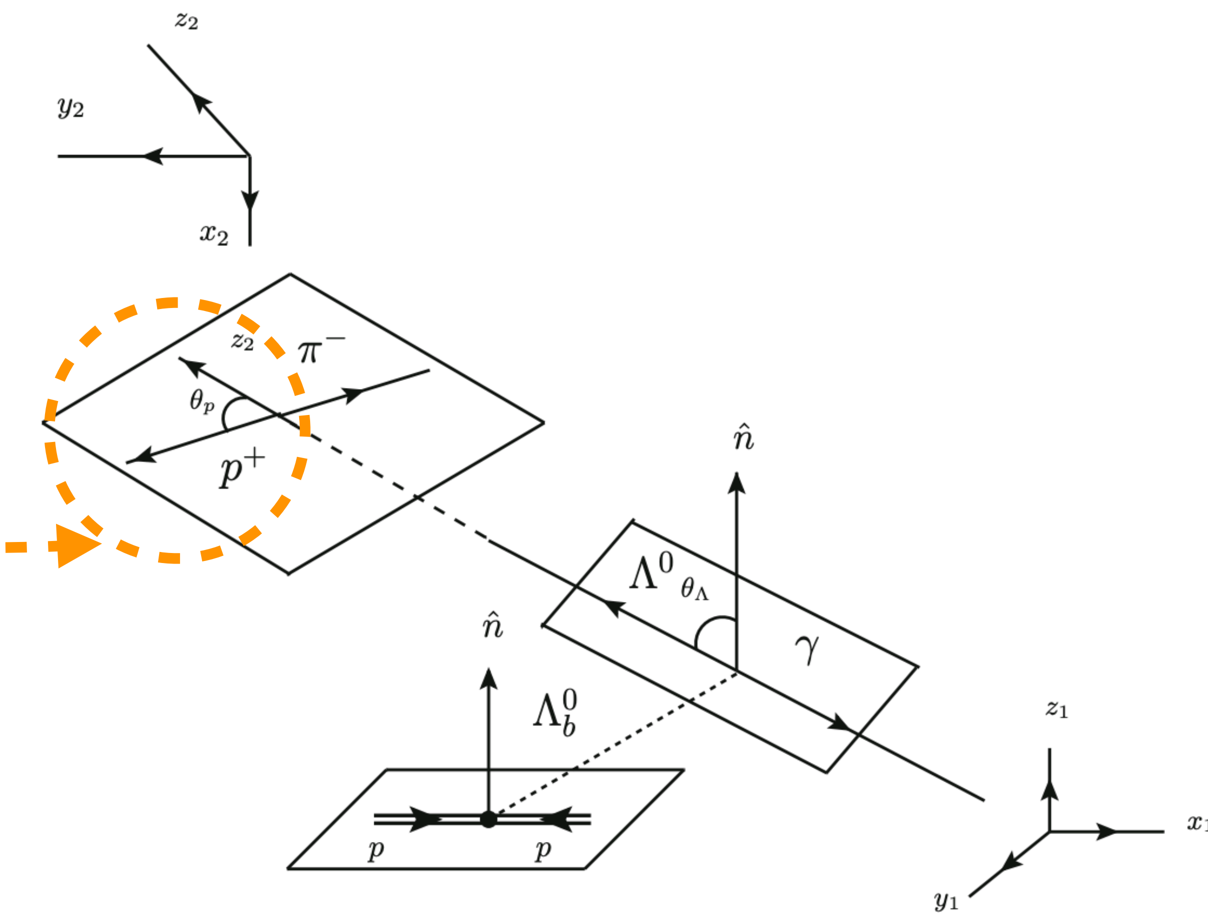
Phys. Rev. D 105, L051104

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

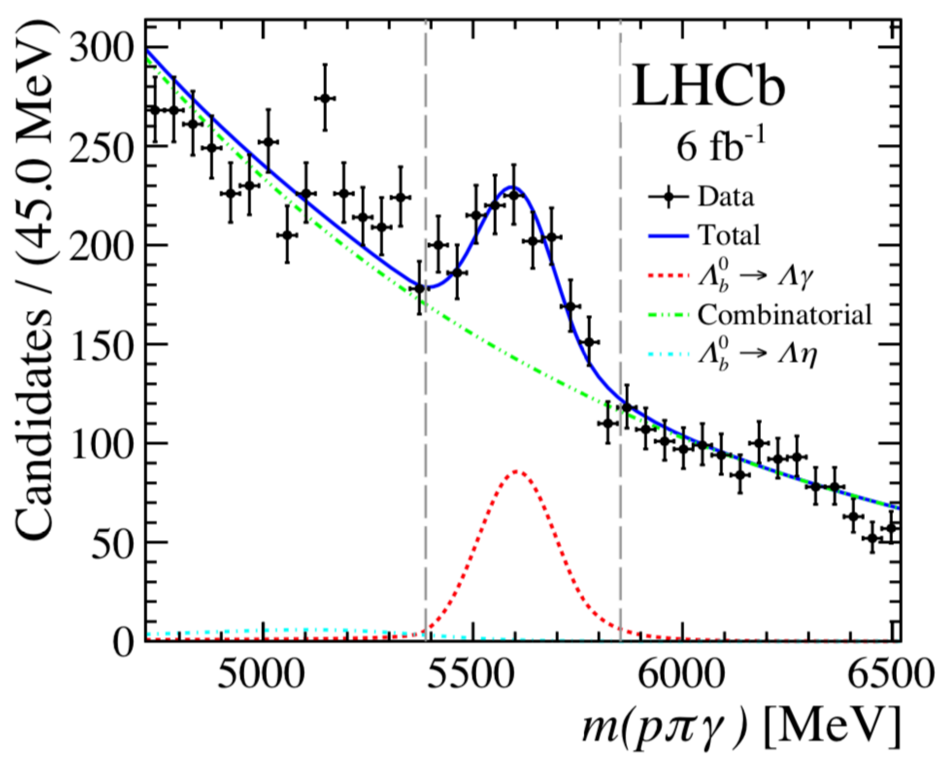
- $\Lambda_b \to \Lambda\gamma$ with $\Lambda \to p\pi$ probes helicity structure

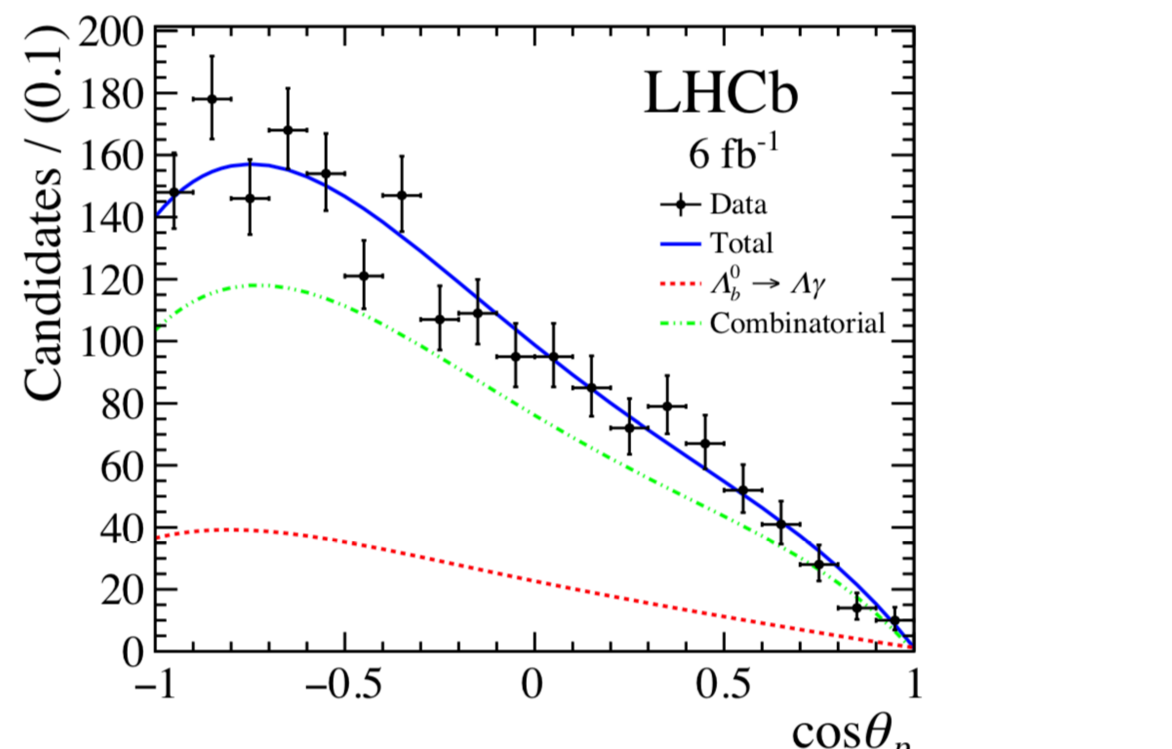
$$\frac{d\Gamma}{d(cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda cos\theta_p$$

▸ **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



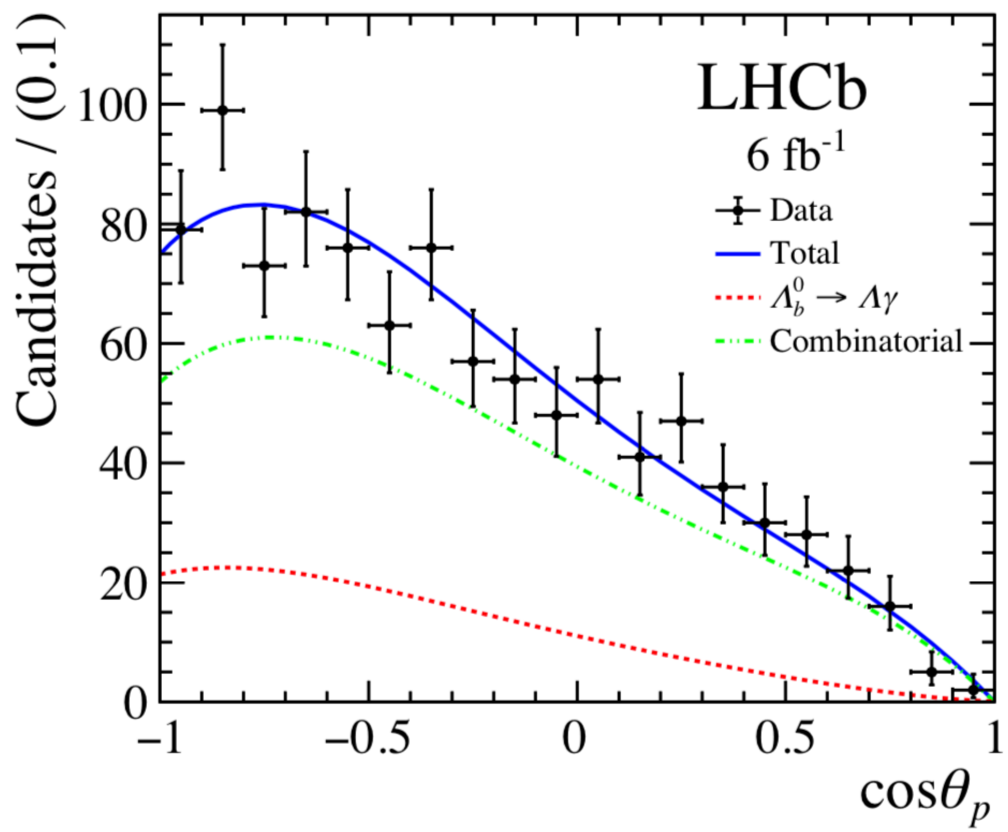


Photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

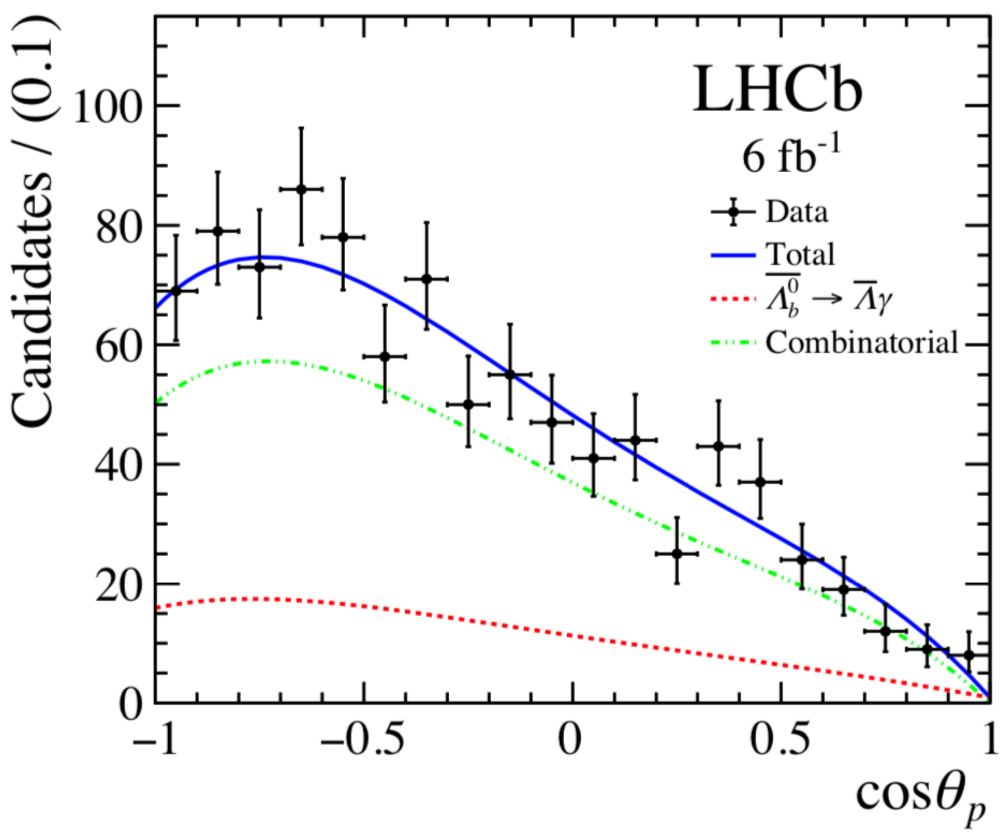
[Phys. Rev. D 105, L051104]

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

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 $\Lambda_b^0 \to \Lambda\gamma$

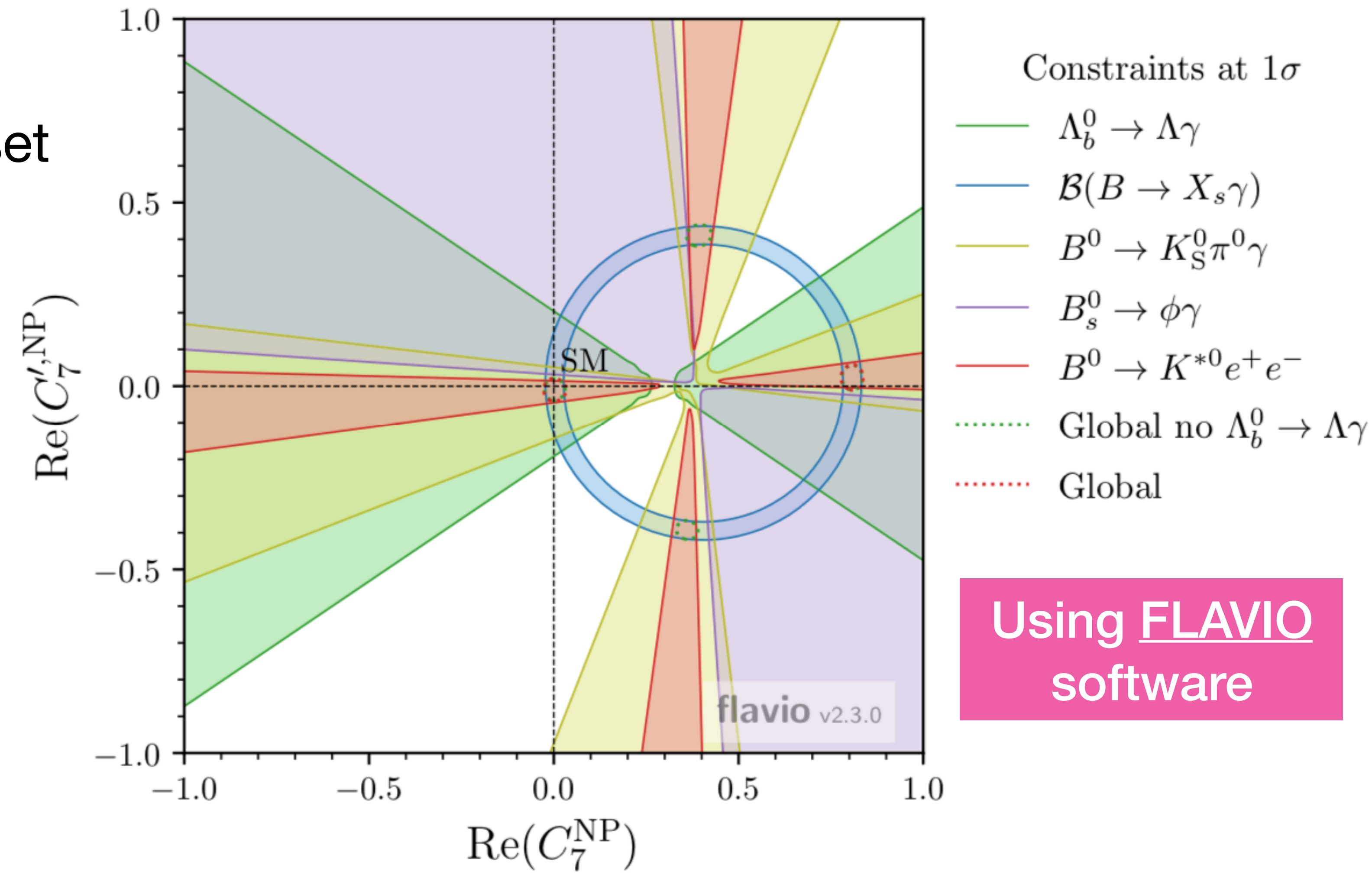
Phys. Rev. D 105, L051104

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

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

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

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

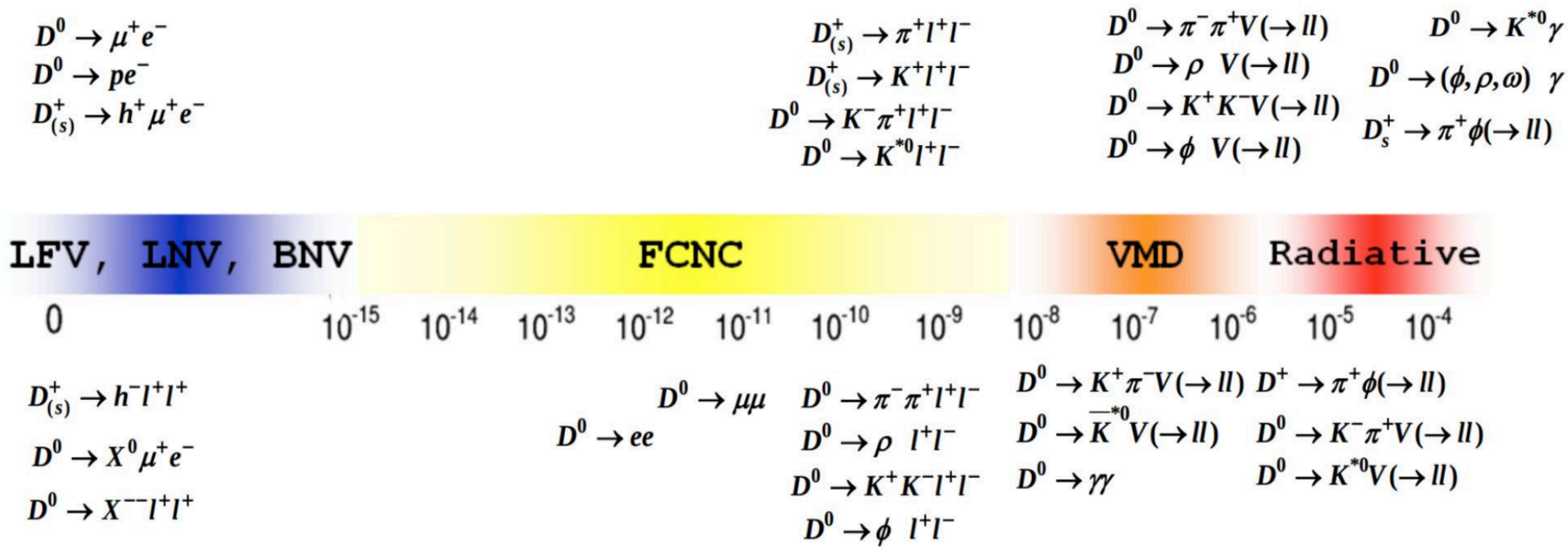


Using FLAVIO software

- 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 $C_7^{(')NP}$
- **Exclusion of previously uncovered phase-space!**

And what about rare charm?

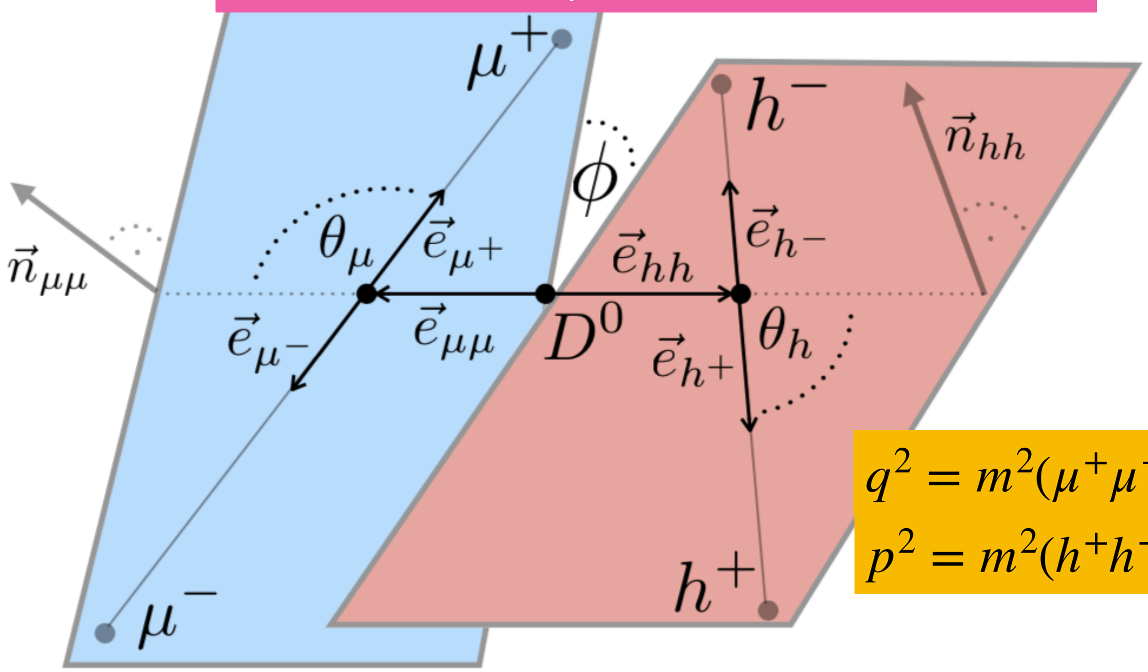
- Probing $c \to u$ type FCNC - **complementarity to B physics!**
- Charm scale not too far from Λ_{QCD} & resonant D contributions
  - Accurate theoretical predictions are challenging
  - Test SM consistency / search for NP through clean observables & null tests
- Very suppressed in the SM due to GIM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



$D^0 \to h^+h^-\mu^+\mu^-$ angular analysis

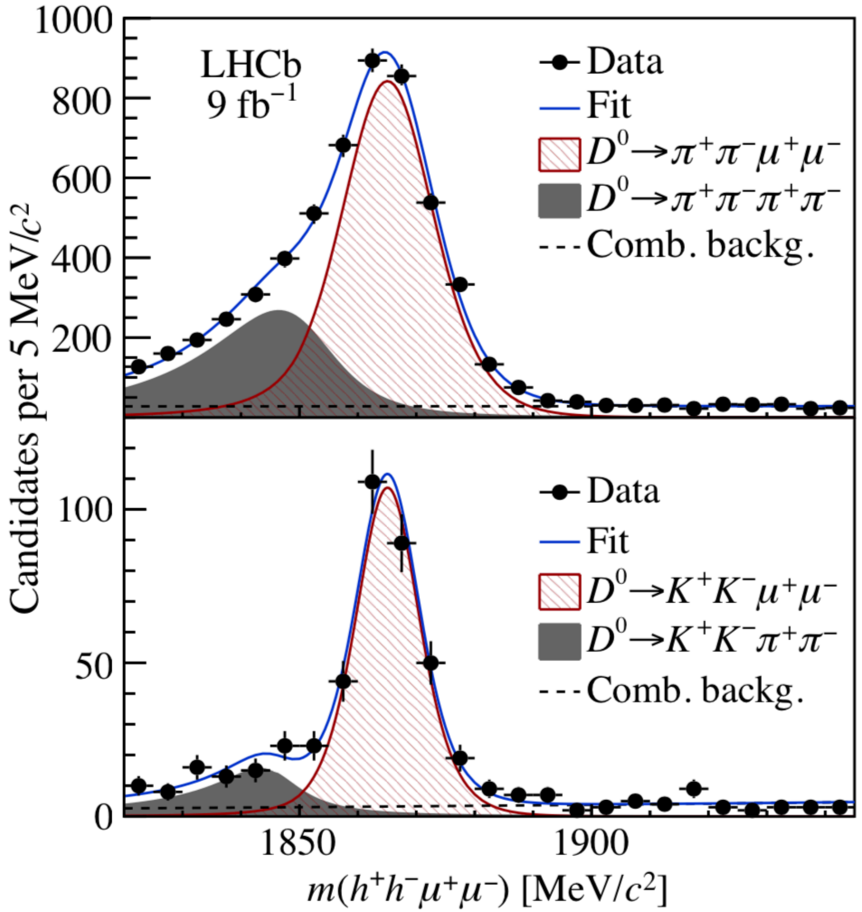
LHCB-PAPER-2021-035
arXiv:2111.03327

Kinematics described by 3 decay angles $\theta_\mu, \theta_h, \phi$ + q^2, p^2



$q^2 = m^2(\mu^+\mu^-)$
$p^2 = m^2(h^+h^-)$

- Interference from long and short distance contributions
  - $\mathscr{B} \sim \mathcal{O}(10^{-6} - 10^{-7})$
- Previously measured by LHCb but without full angular picture!
  - First observation ($h = \pi, K$) with 2012 data (2 fb^{-1}) [Phys. Rev. Lett. 119, 181805]
  - Measurement of selected angular and CP asymmetries with Run 1 + 2016 data (5 fb^{-1}) [Phys. Rev. Lett. 121, 091801]
- **First full angular analysis of a rare charm decay**
- Using full Run 1 + Run 2 dataset (9 fb^{-1}) → 3x more statistics!
- Differential decay rate described by 9 angular coefficients I_{1-9}
- Determined from the decay rate asymmetries in angular *tags*
- Measurements inclusively and in bins of q^2
  - Resonance regions ($\eta, \rho^0, \omega, \phi$) used to perform SM null-tests



$D^0 \to h^+h^-\mu^+\mu^-$ angular analysis

LHCB-PAPER-2021-035
arXiv:2111.03327

- Measurement of **CP average and asymmetries:**

$$< S_i > = \frac{1}{2}[\, < I_i > + (-) < \bar{I}_i > \,]$$

$$< A_i > = \frac{1}{2}[\, < I_i > - (+) < \bar{I}_i > \,]$$

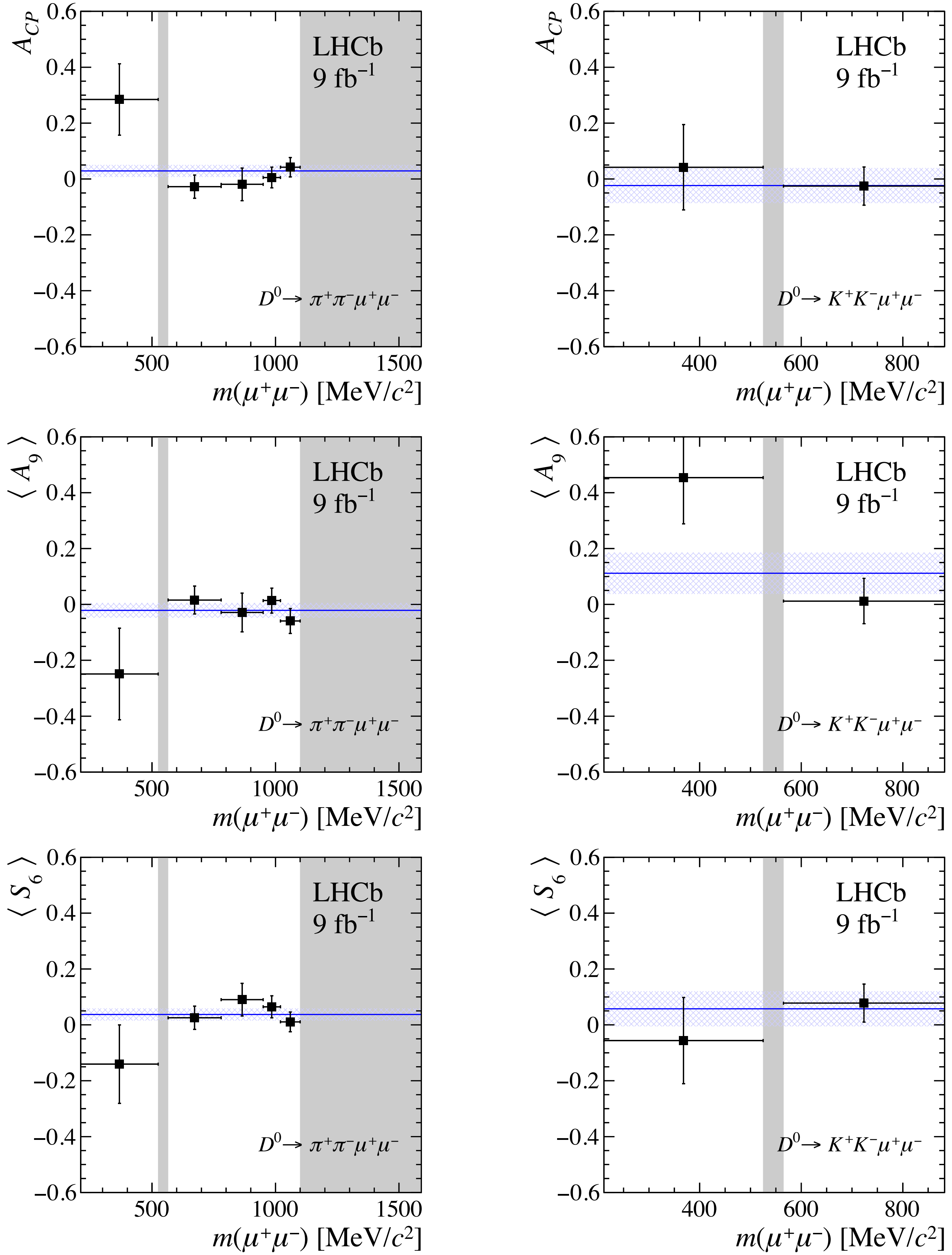
(CP odd)

- And **CP asymmetry**

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}$$

- In agreement with SM prediction:
  - 0.3σ for $D^0 \to \pi^+\pi^-\mu^+\mu^-$
  - 2.7σ for $D^0 \to K^+K^-\mu^+\mu^-$

For more details on CPV, check out Mark William's talk



Conclusions

- Rare B and D 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