Recent searches for new physics and rare decays at LHCb

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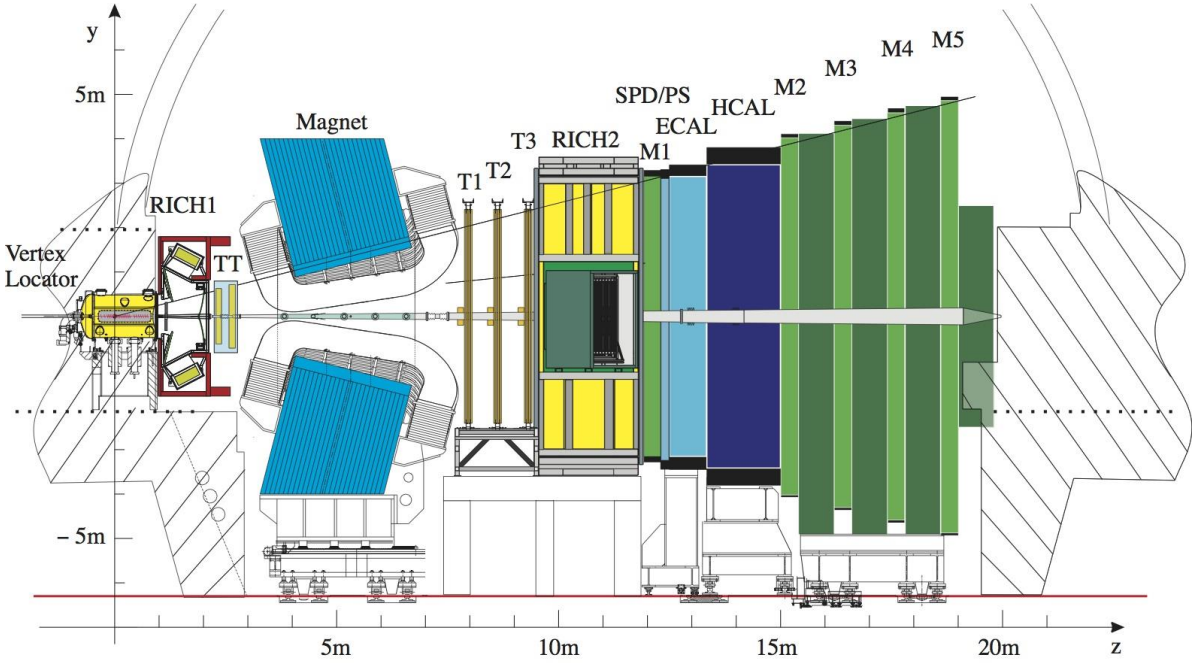
第八届中国LHC物理研讨会
2022年11月23-27日

Outline

- Rare decays
  - Flavor changing charged current (FCCC)
  - Lepton-favour violating
  - Baryon- and lepton-number violating
  - Rare B meson charmless baryonic decays

LHCb experiment

LHCb collaboration： 19 counties, 87 institutes, 1507 members

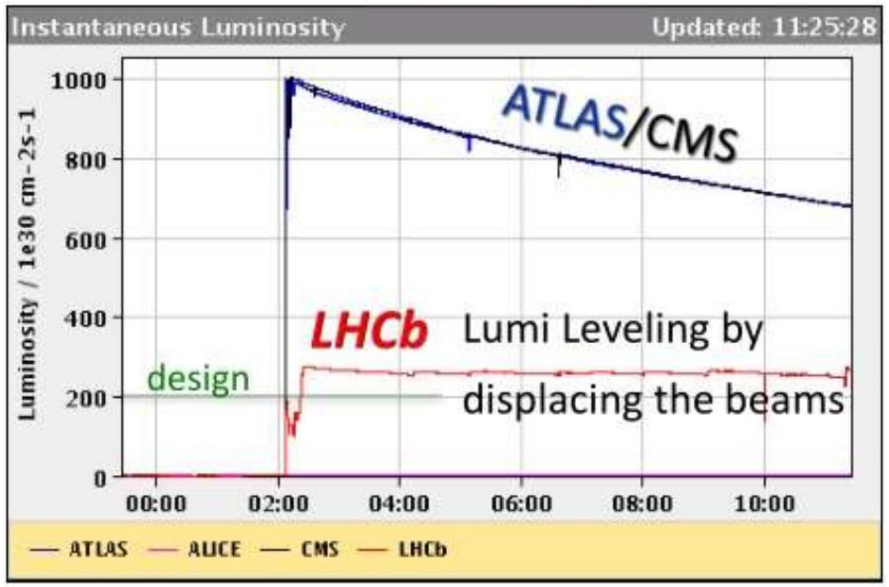


中国单位：
清华大学
华中师范大学
中国科学院大学
武汉大学
高能物理研究所
华南师范大学
湖南大学
北京大学
兰州大学

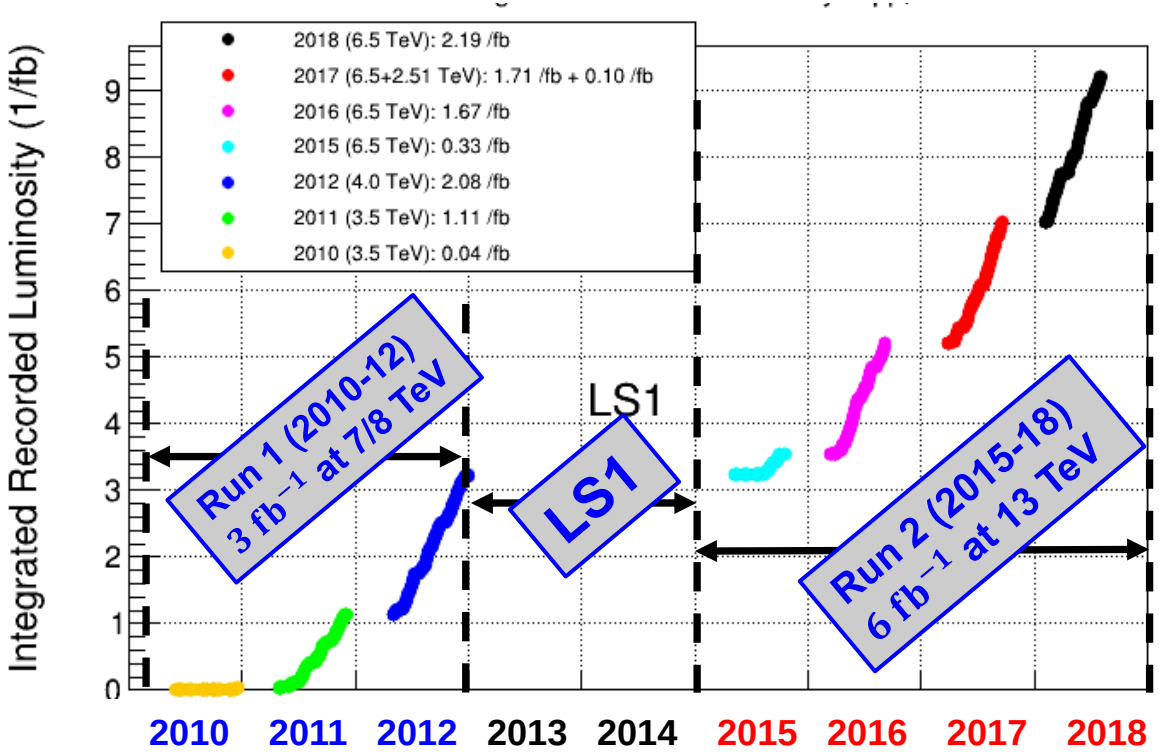
- Understand matter-antimatter imbalance (CP violation)
- Search for new physics (Rare decays)
- Explore and understand QCD (Hadron properties, exotic hadrons)

LHCb data samples

Luminosity levelling $L \sim 3 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$



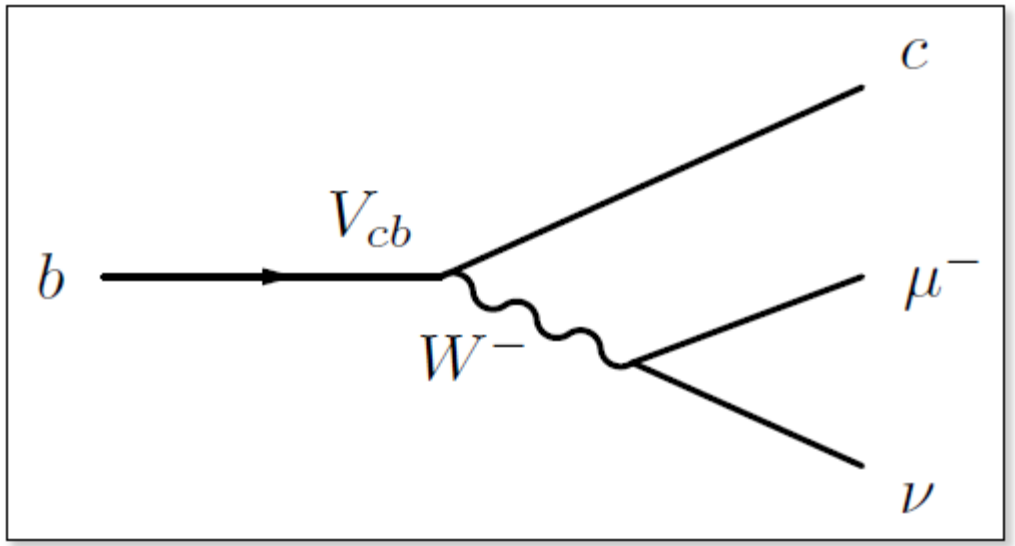
Run-I: 3 fb^{-1}, Run-II: 6 fb^{-1}



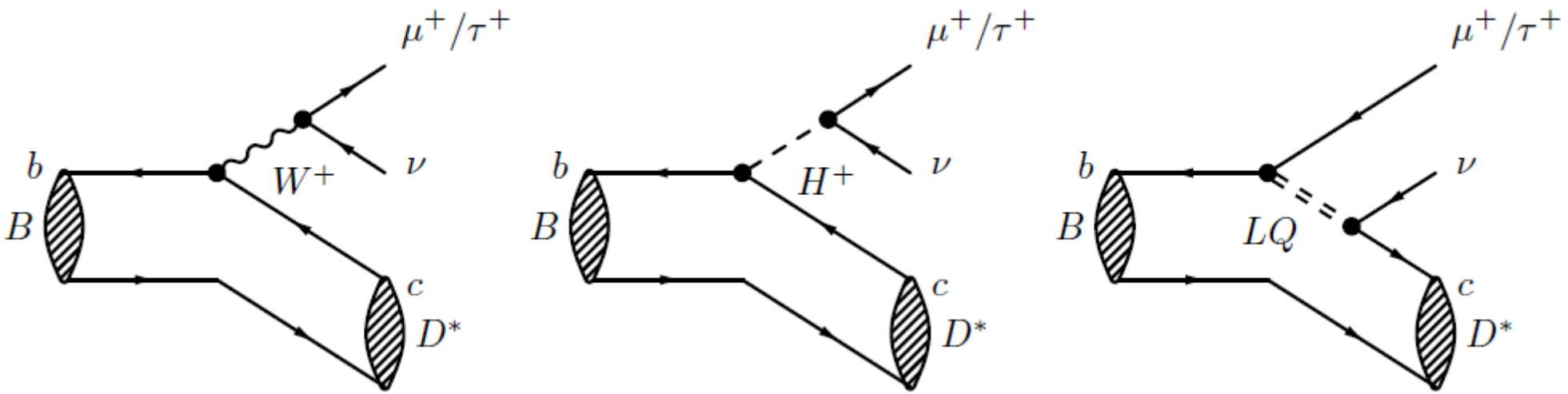
Large $b\bar{b}$ and $c\bar{c}$ production cross sections:

$\sigma(b\bar{b}X) \sim 0.5\% \times \sigma_{pp}^{\mathrm{inelas}},\ \sigma(c\bar{c}X) \sim 10\% \times \sigma_{pp}^{\mathrm{inelas}}$

FCC $b \to c l^- \nu$ decays

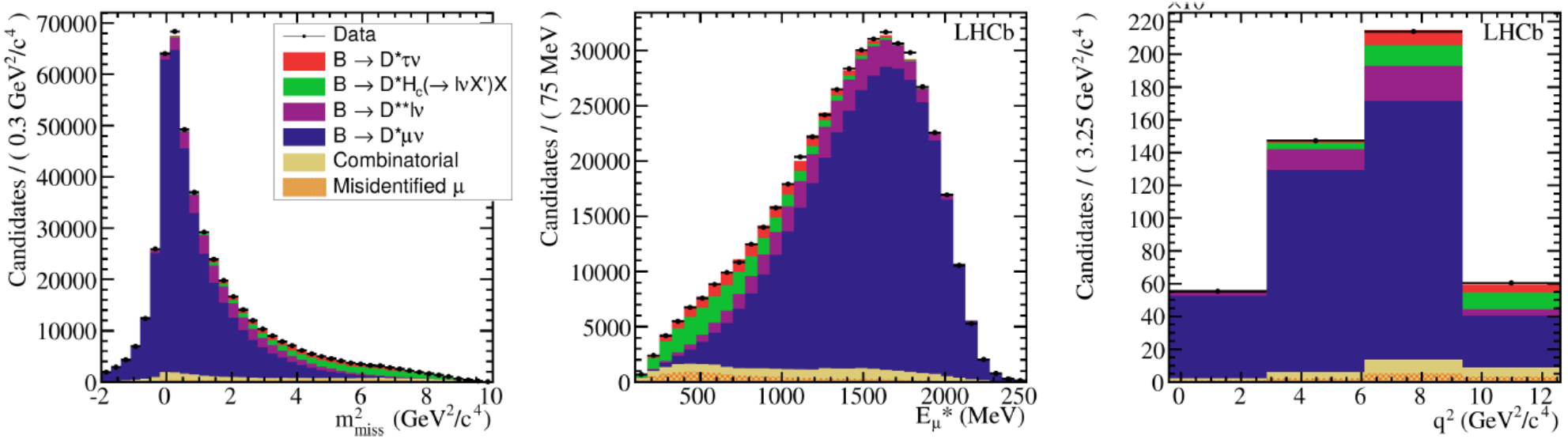


$B \to D^{(*)}\tau^{-}\bar{\nu}_{\tau}$



- In the SM, the only difference between $B \to D^{(*)}\tau^{-}\bar{\nu}_{\tau}$ and $B \to D^{(*)}\mu^{-}\bar{\nu}_{\mu}$ is the mass of the lepton
- Rate $R\left(D^{(*)}\right) = \mathcal{B}(B \to D^{(*)}\tau^{-}\bar{\nu}_{\tau})/\mathcal{B}(B \to D^{(*)}\mu^{-}\bar{\nu}_{\mu})$ is sensitive to e.g charged Higgs, leptoquarks

R(D*) vs R(D) in 2015 with Run 1 data

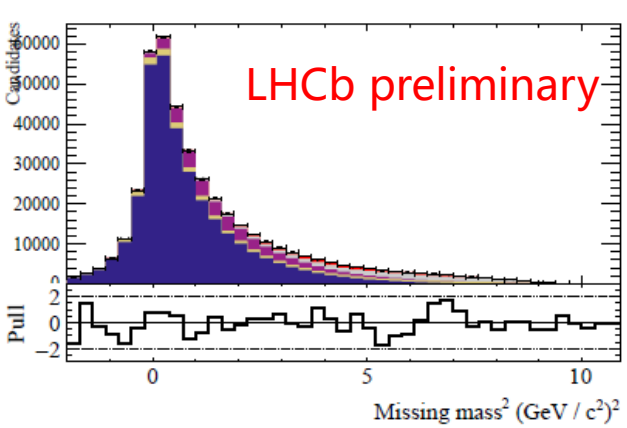


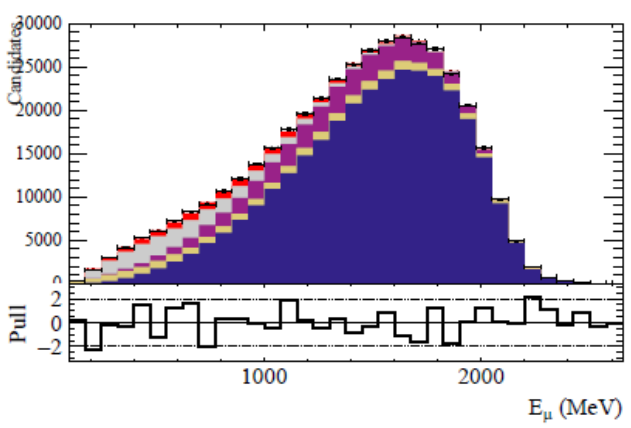
Phys. Rev. Lett. 115 (2015) 111803

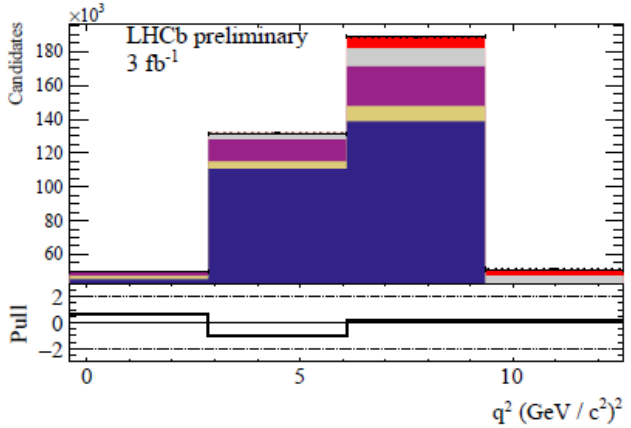
- Measure $R(D^*)$ with Run 1 $D^{*+}\mu^-$ data
- Three dimesional template fit in $m^2_{missing}$(left) E_μ(middle), and q^2(right)
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters
  - Shape variations for all major backgrounds controlled using data samples
  - Histogram statistics included via Barlow-Beeston "lite"

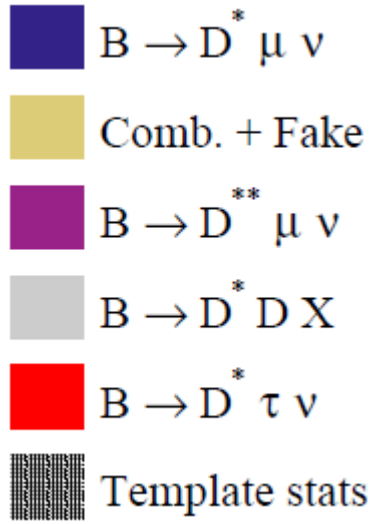
New measurement of R(D*) vs R(D)

- Simultaneously measure $R(D^*)$ and $R(D)$ with Run 1 $D^{*+}\mu^-$ and $D^0\mu^-$ data
  - Higher branching fractions and higher efficiency $D^0\mu^-$ sample ~5 larger $D^{*+}\mu^-$ sample





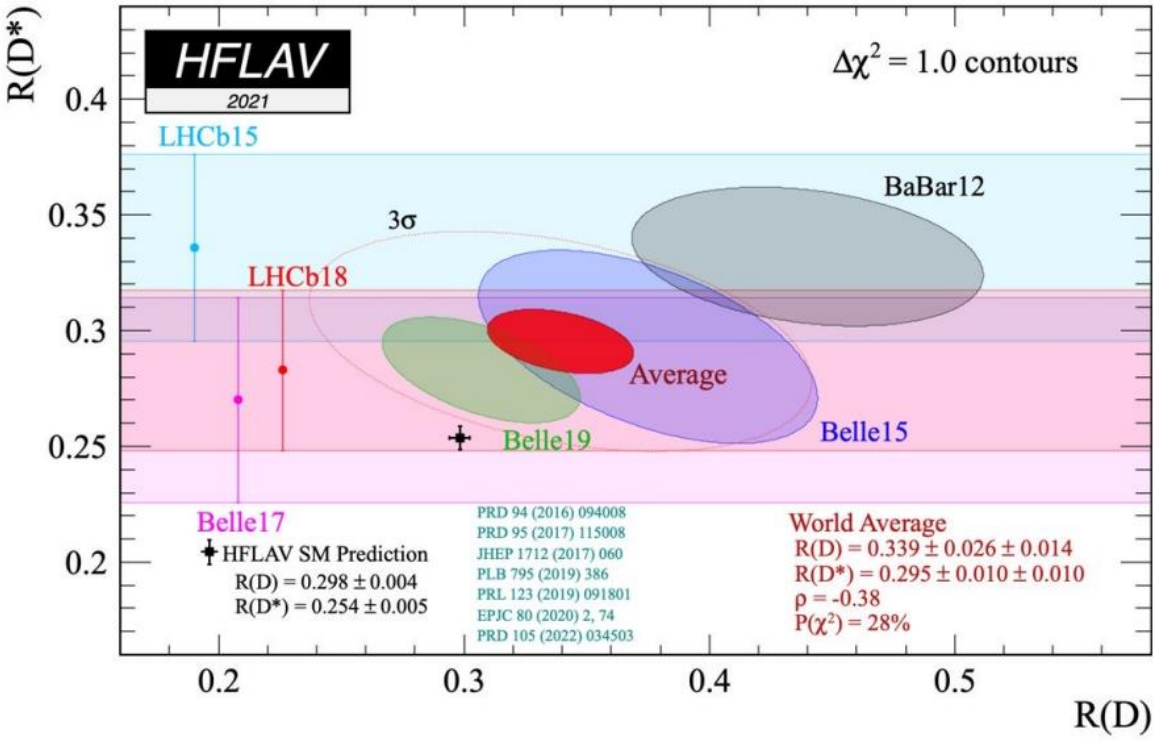


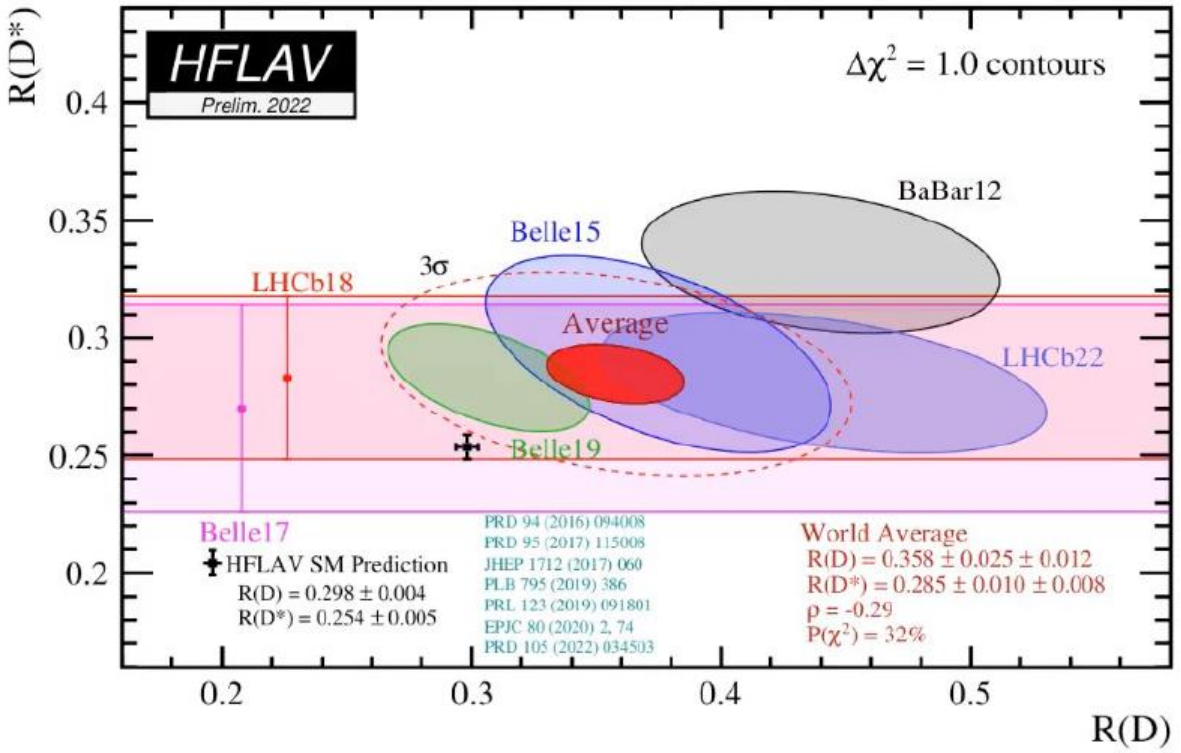


- New $D^{*+}\mu^-$ sample $R(D^*)$, 1.6σ agreement with our previous result
- $R(D^*) = 0.281 \pm 0.018 \pm 0.024$
- $R(D) = 0.441 \pm 0.060 \pm 0.066$
- $\rho = -0.43$
- 1.9σ agreement with SM

LHCb-PAPER-2022-039

New measurement of R(D*) vs R(D)





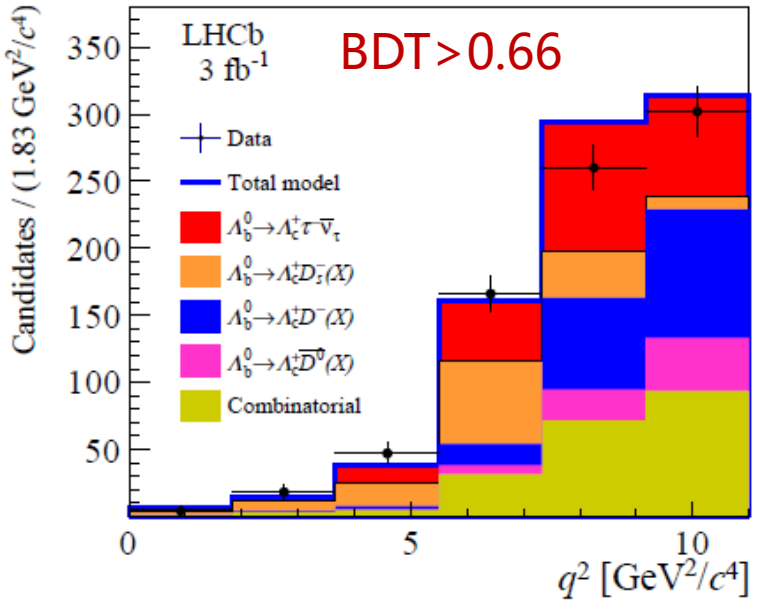
- Slightly lower R(D), slightly higher R(D), reduced correlation
- World average 3.3σ to 3.2σ agreement with SM
- Excellent overall agreement between measurements

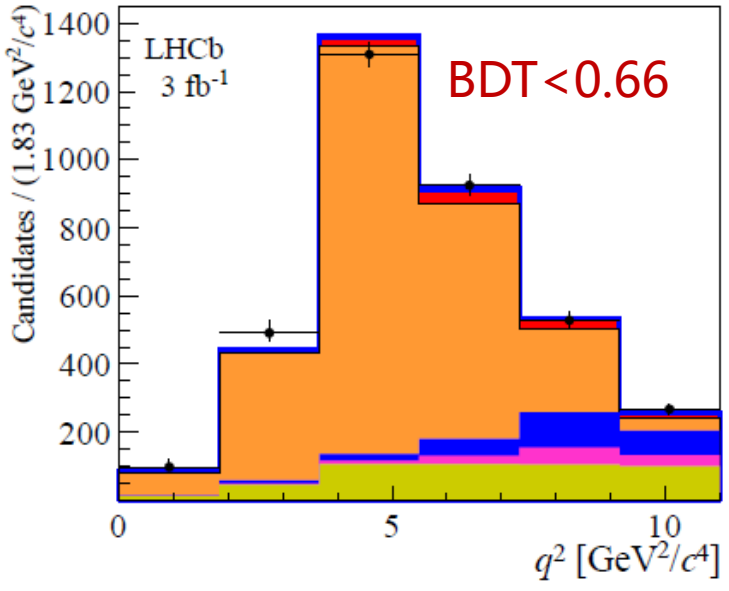
https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

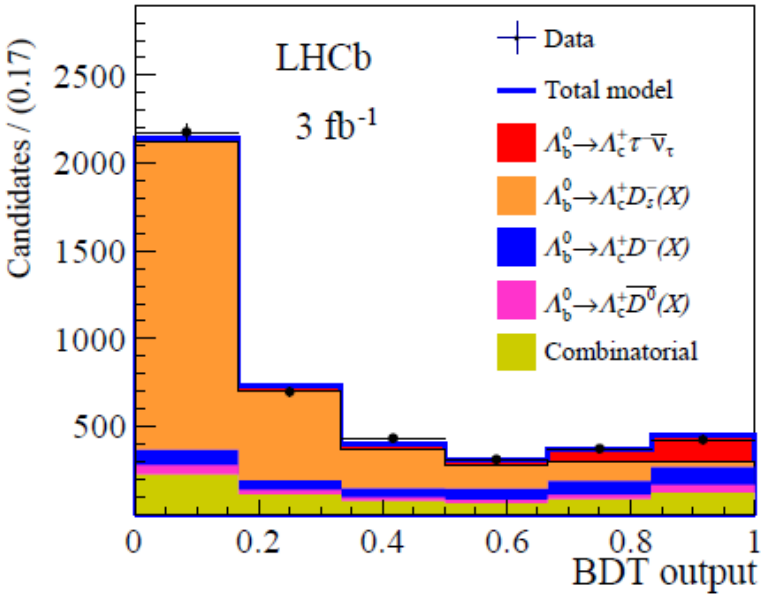
First observation of $\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with Run 1 data

- $R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)} = 0.324 \pm 0.004$ provide a sensitive probe of SM extensions

Phys. Rev. D99 (2019) 055008







- $\Lambda_b \to \Lambda_c^+ 3\pi$ as normalization channel arXiv:2201.03497
- $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ or $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$
- $\mathcal{B}(\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$, $\sigma(6.1)$
- $R(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$
- Agreement with the standard model prediction

Lepton-favour violating

$$B^0 \to K^{*0}\mu^{\pm}e^{\mp}, B_s^0 \to \phi\mu^{\pm}e^{\mp}, B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$$

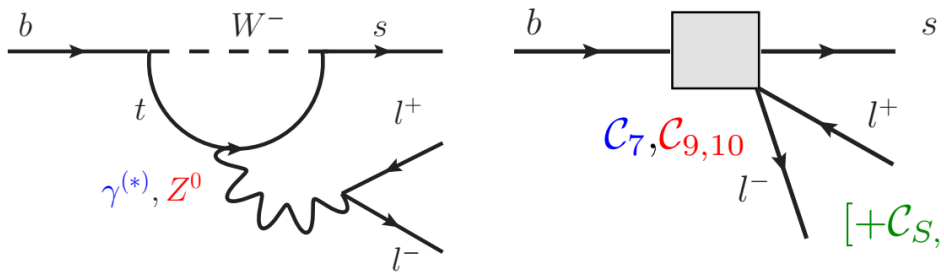
$b \to s l^+ l^-$ decays

➢ $b \to s l^+ l^-$ decays described by effective Hamiltonian

$$H = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + \frac{K}{\Lambda_{NP}^2} O_j^{(6)}$$

New physics can affect Wilson coefficients C_i or add new operators O_j

➢ Sensitivity to Wilson coefficients

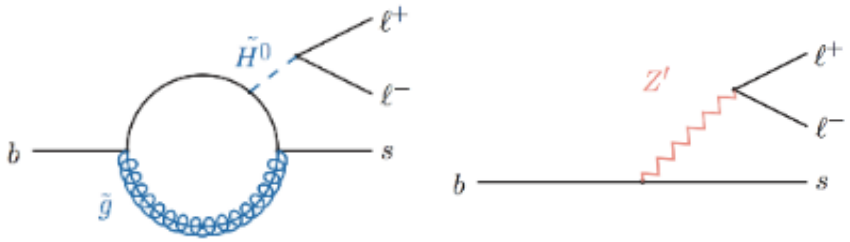


- $B^0_{(s)} \to l^+ l^-$ $[C_{10}, C_S, C_P]$
- $b \to s l^+ l^-$ $[C_7, C_9, C_{10}]$

7: photon penguin; 9,10: EW penguin; S,P: (pseudo-) scalar penguin

➢ Theoretically clean probes of NP

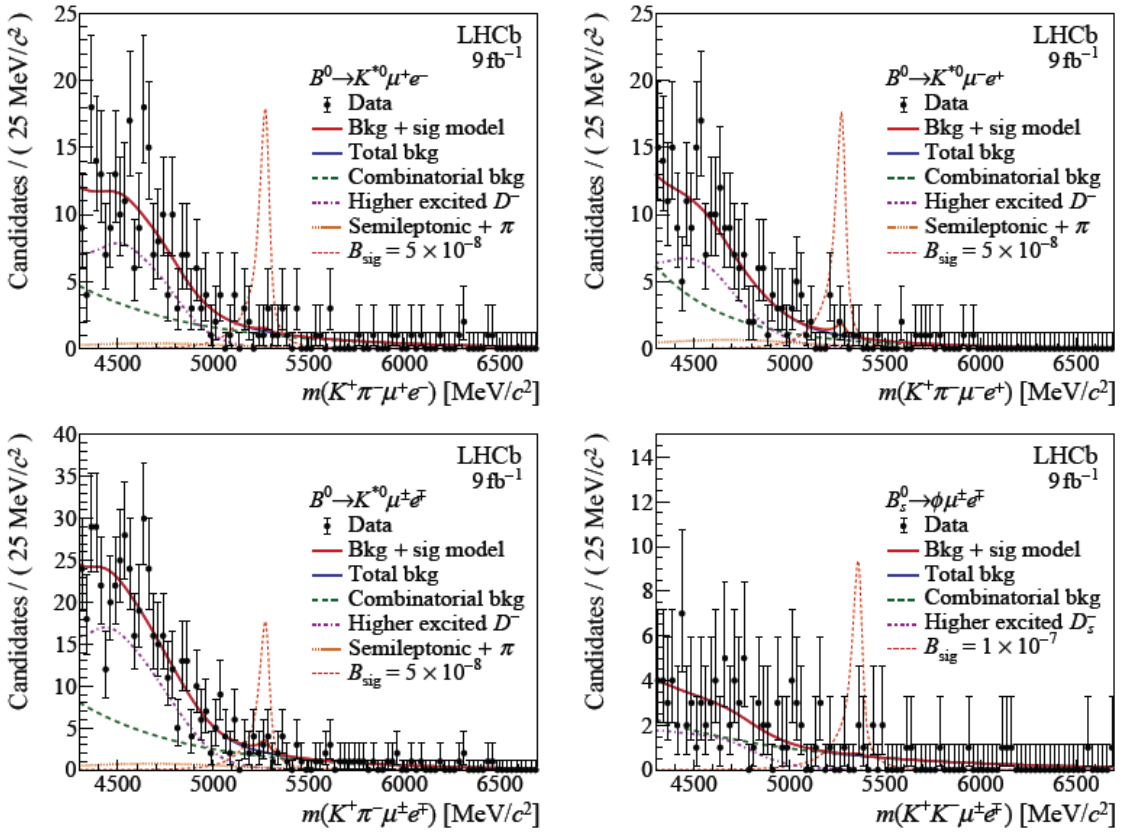
- Pure leptonic decays
- Special angular observables
- Ratio between $e/\mu/\tau$



Search for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$ with Run 1&2 data

- Forbidden or strongly suppressed in the SM
- Sensitive to new heavy particles beyond the SM

- $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}$ and $B^0 \to J/\psi(\to \mu^+\mu^-)\phi$ as normalization channel
- No significant signals are observed
- The world's most stringent limits
- Limits are reported for scalar and left-handed lepton-favour violating New Physics scenarios



$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (6.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9}\ (7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1 \times 10^{-9}\ (11.7 \times 10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 16.0 \times 10^{-9}\ (19.8 \times 10^{-9})$$

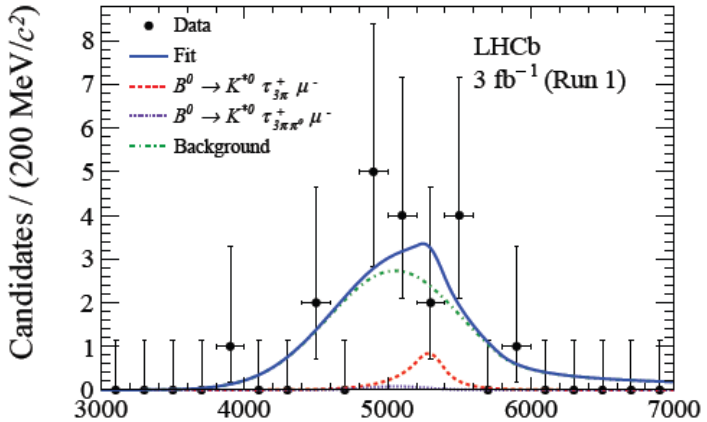
arXiv:2207.04005

Mode	Left-handed	Scalar
$B^0 \to K^{*0}\mu^+e^-$	6.7 (8.3)	8.4 (10.2)
$B^0 \to K^{*0}\mu^-e^+$	8.0 (9.5)	9.9 (11.5)
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$	12.0 (13.9)	14.7 (17.0)
$B_s^0 \to \phi\mu^{\pm}e^{\mp}$	16.5 (20.5)	18.8 (23.1)

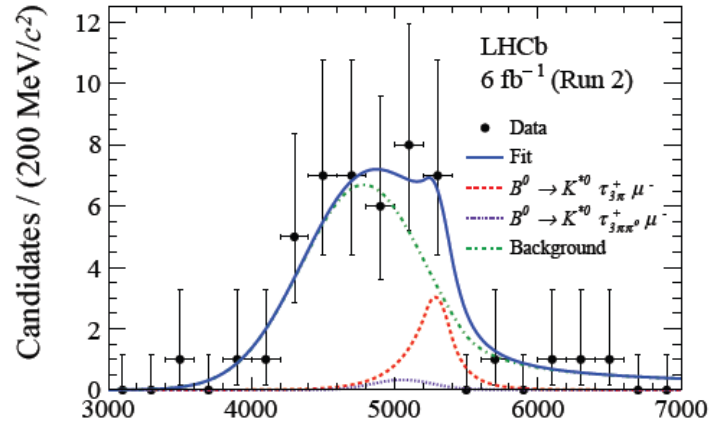
Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ with Run 1&2 data

- $B^0 \to D^- D_s^+$ as normalization channel
- $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ or $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$
- No significant signals are observed
- $\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$ @90%(95%) CL
- $\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6}$ @90%(95%) CL
- The most stringent upper limits on $b \to s\tau\mu$ transitions.

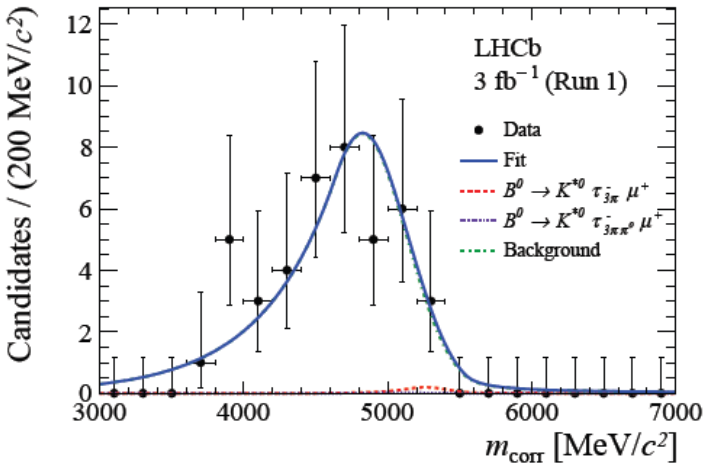
arXiv:2209.09846



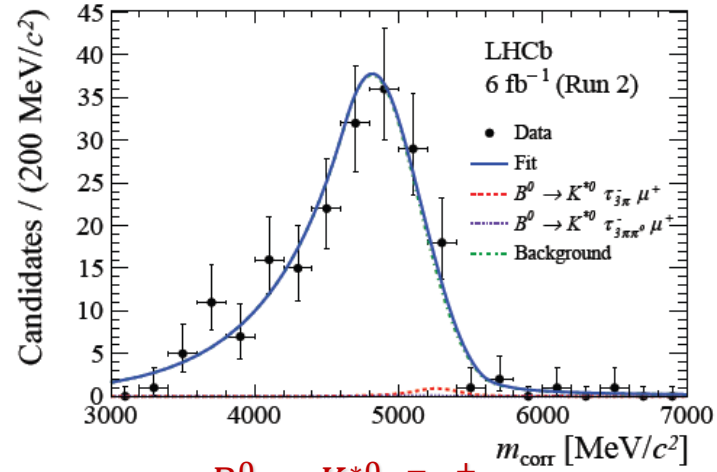
$B^0 \to K^{*0}\tau^+\mu^-$



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



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



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

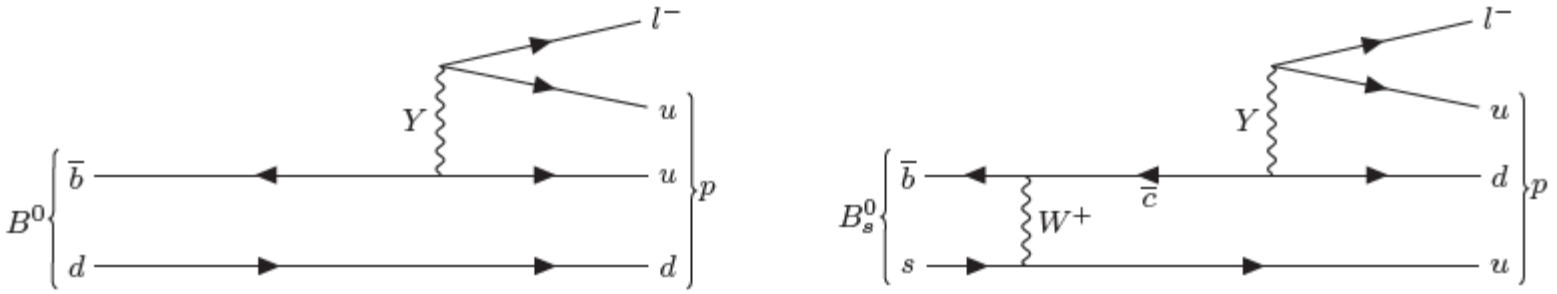
The corrected mass $m_{\rm corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}} + p_\perp$

Baryon- and lepton-number violating

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

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

- **Fact:** Matter anti-matter asymmetry in the Universe
- **Solution**: baryon number must be violated
- **SM predict**: $\mathcal{B}(\bar{b} \to uul^-) < 2.4 \times 10^{-27}$ Phys. Rev. D72 (2005) 095001



Hypothetical Feynman diagrams of $B^0 \to pl^-$ mediated by a hypothetical Y boson. arXiv:2210.10412

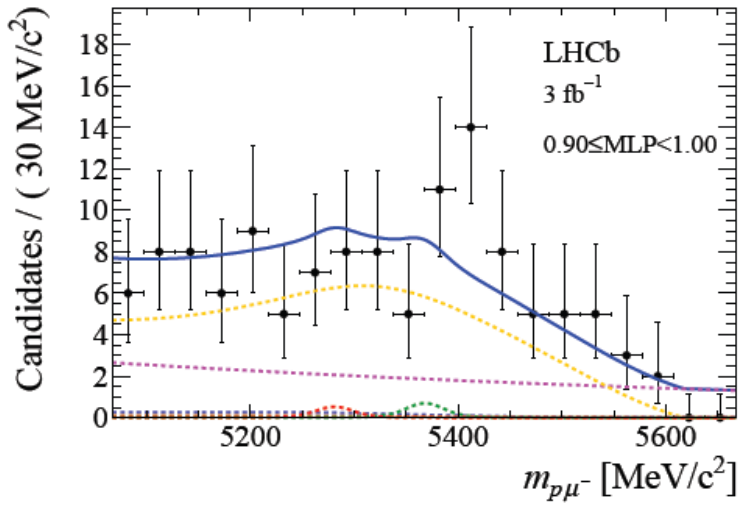
Jike's parallel talk for details

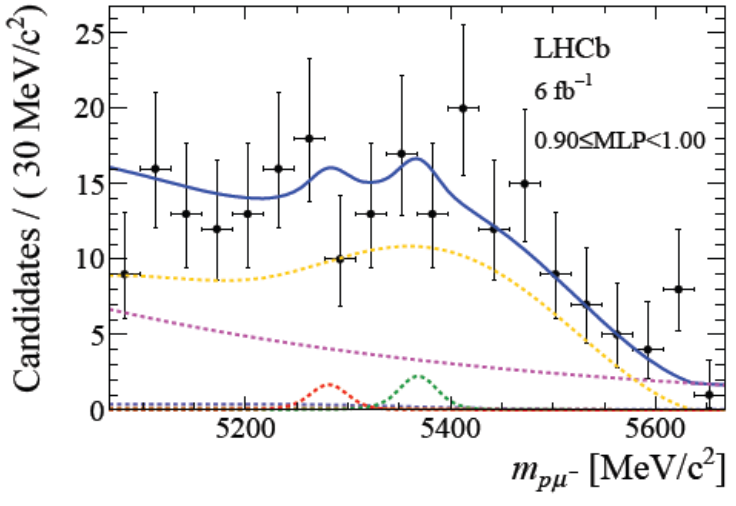
第八届中国LHC物理研讨会 The 8th China LHC Physics Workshop (CLHCP2022) (23-November 27, 2022): Parallel Session: HF/HI/QCD · Indico of IHEP (Indico)

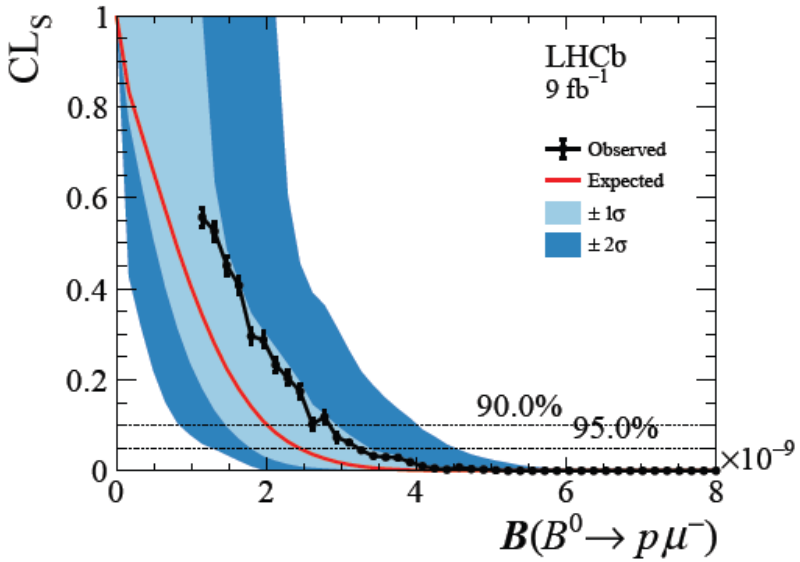
Search for $B^0_{(s)} \to p\mu^-$ with Run 1&2 data

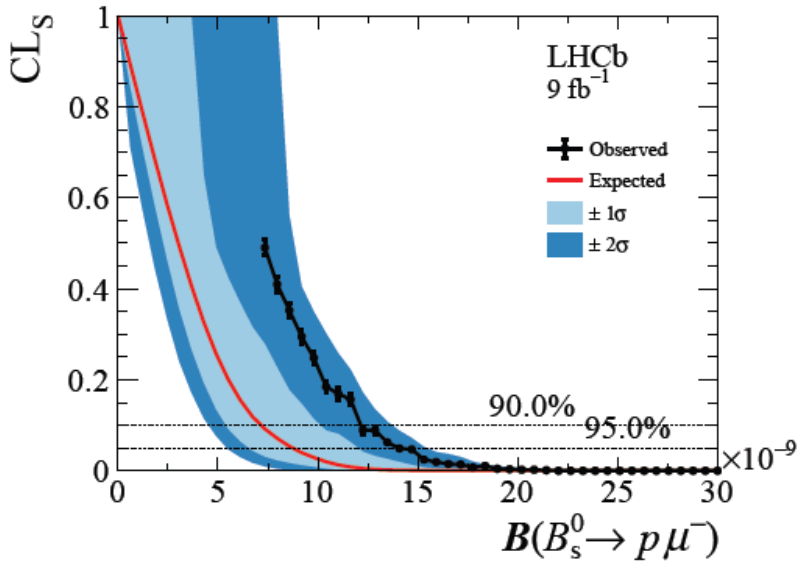
(by LHCb-China members)

- $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ as normalization channel
- No significant signals are observed
- $\mathcal{B}(B^0 \to p\bar{p}) < 2.6(3.1) \times 10^{-9}$@90%(95%) CL
- $\mathcal{B}(B^0_s \to p\bar{p}) < 12.1(14.0) \times 10^{-9}$@90%(95%) CL
- The first upper limits on these decays









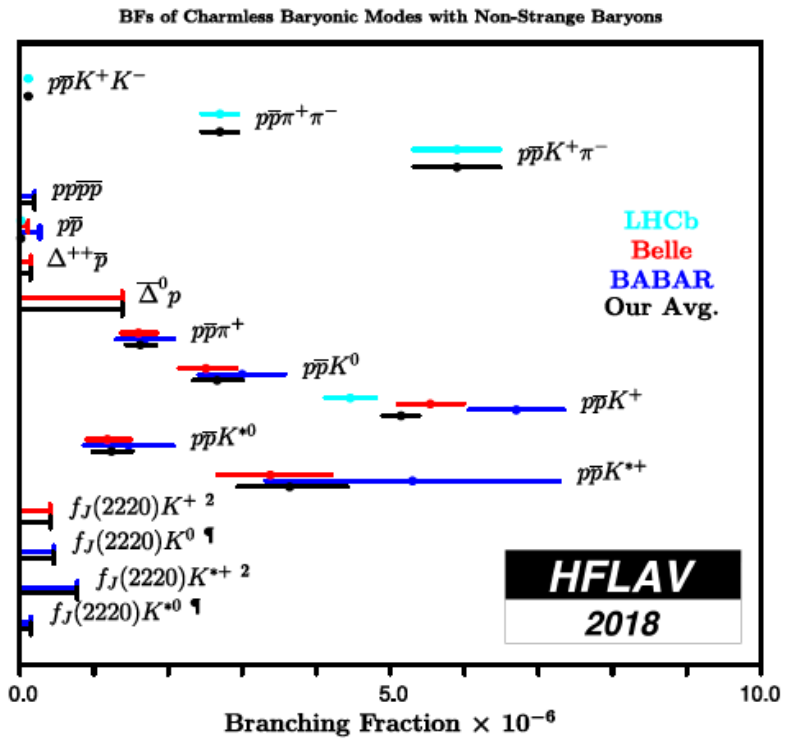
arXiv:2210.10412

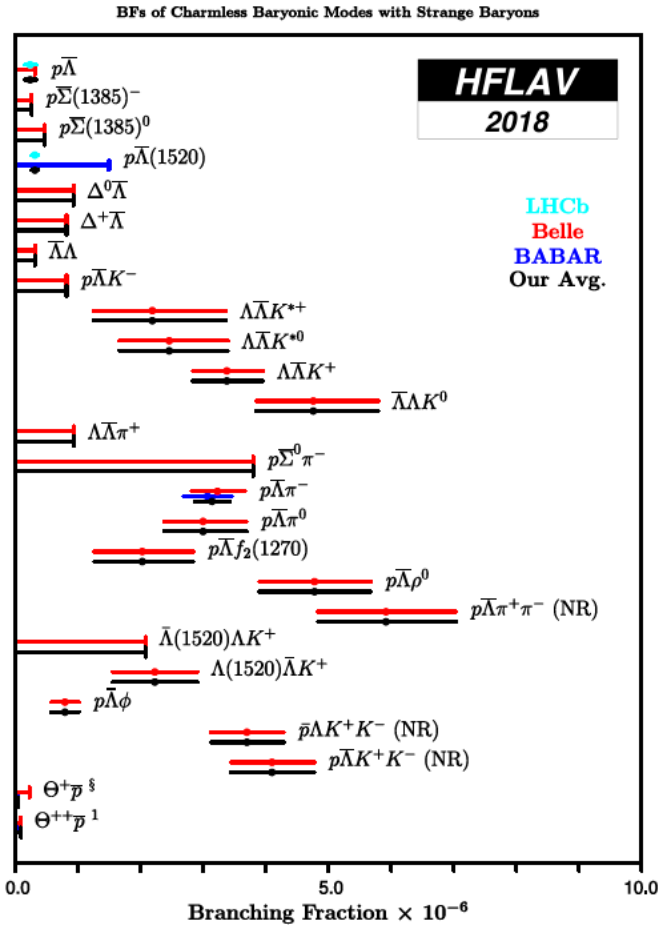
Rare B meson charmless baryonic decay

$$B_s^0 \to p\bar{p},\ B_{(s)}^0 \to p\bar{p}p\bar{p}$$

The charmless baryonic decays of B

- Two-body baryonic decays suppressed with respect to multibody decays
- The decays of B mesons into multiple baryon final states are still far from being fully understood



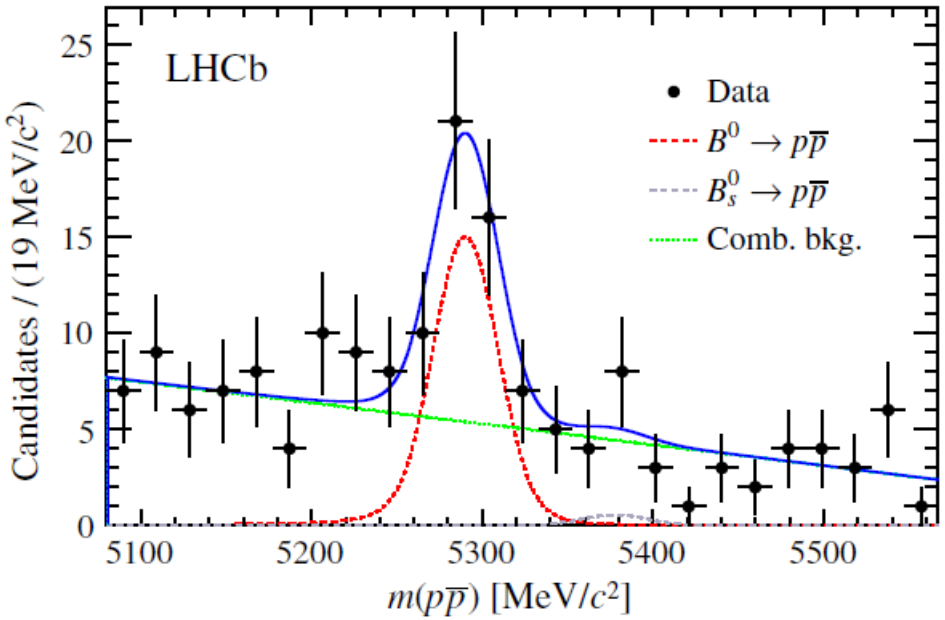


Charmless baryonic $B^+$and B^0 modes branching fractions reported by HFLAV

Search for $B^0_{(s)} \to p\bar{p}$

- First observation of $B^0 \to p\bar{p}$ with Run 1 data

PRL 119, 232001 (2017)



- $\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$
- $\mathcal{B}(B^0_s \to p\bar{p}) < 1.5 \times 10^{-8}$@90% CL
- Some predictions expect $B^0_s \to p\bar{p}$ to be further suppressed (no penguin-level gluon-exchange and annihilation contributions)
  [PRD 89, 056003 (2014), PRD 95, 096004 (2017)]
- Other predictions expect $B^0_s \to p\bar{p}$ rates similar to that of $B^0 \to p\bar{p}$ (penguin-level gluon-exchange and annihilation contributions can't be neglected)
  [JHEP2004, 035 (2020)]

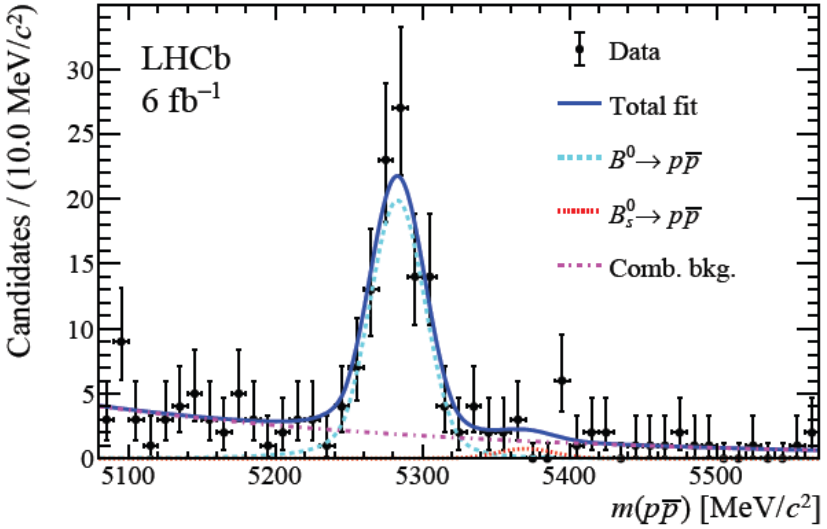
- Updated search for $B^0_s \to p\bar{p}$ decay is needed

Search for $B_s^0 \to p\bar{p}$ with Run 2 data

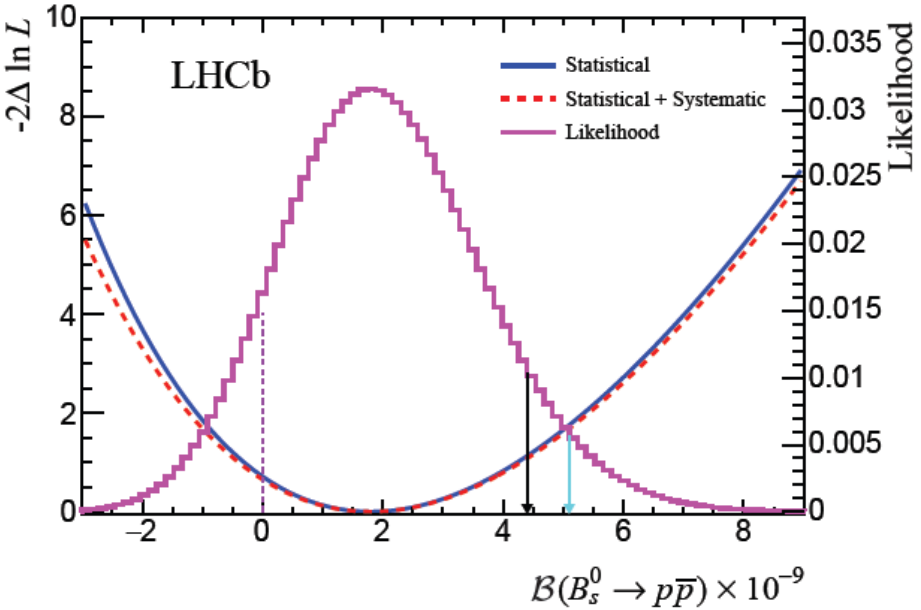
(by LHCb-China members)

arXiv:2206.06673, accepted by PRD

- $N(B^0 \to p\bar{p}) = 98 \pm 11(16.2\sigma)$
- $N(B_s^0 \to p\bar{p}) = 4 \pm 5(0.9\sigma)$
- $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+\pi^-$ as normalization channel
- $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8}$
  Consistent with Run 1



- Improved Upper Limit on $B_s^0 \to p\bar{p}$ by factor 3
  - $\mathcal{B}(B_s^0 \to p\bar{p}) < 1.5 \times 10^{-8}$@90% CL (RUN-I)
  - $\mathcal{B}(B_s^0 \to p\bar{p}) < 4.5(5.1) \times 10^{-9}$@90%(95%) CL (RUN-II)



Jike's parallel talk for details

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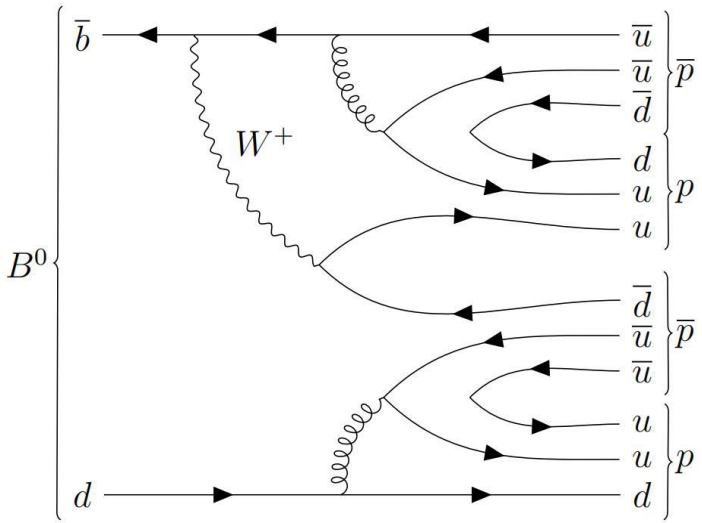
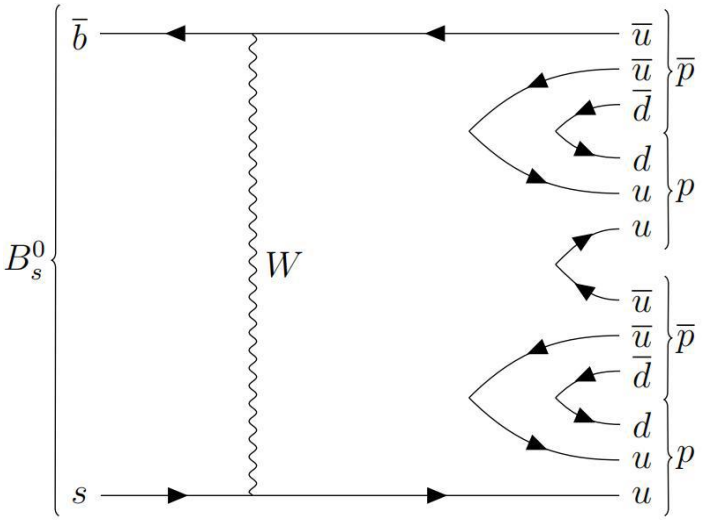
Search for $B^0_{(s)} \to p\bar{p}p\bar{p}$

- B meson decay to 4-baryon mode was never observed
  - $B^0 \to pppp$ (2.9σ) **Phys. Rev. D 98, 071102 (2018)**

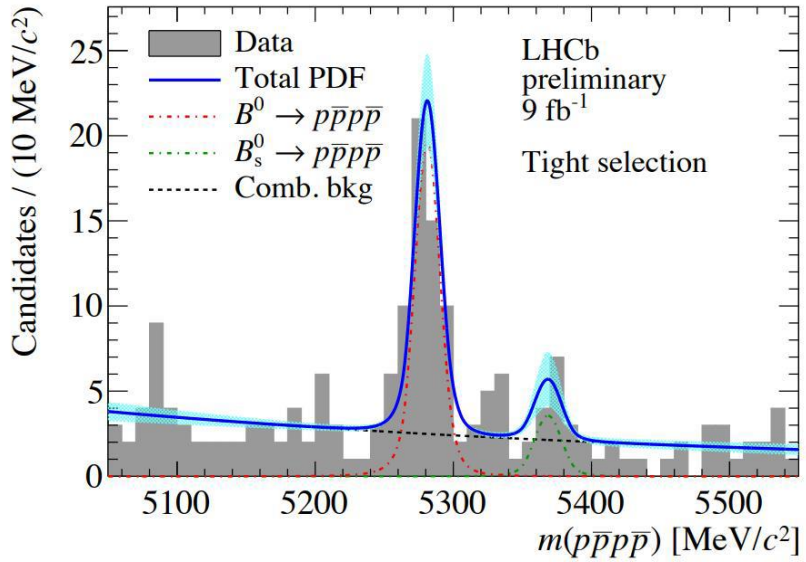
- $B_s \to pppp$ (**no study reported**) is expected to be further suppressed with respect to B^0
  - Hadronisation fraction f_s/f_d~25%, and $\left|\frac{V_{us}}{V_{ud}}\right|^2$ ~5%



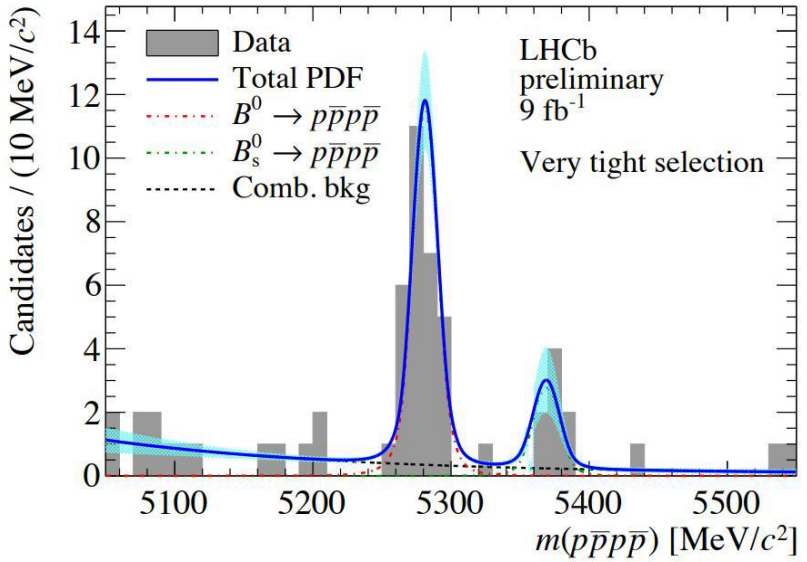


Search for $B^0_{(s)} \to p\bar{p}p\bar{p}$ with Run 1&2 data

Tight selection



Very tight selection



$\mathbf{N(B^0 \to p\bar{p}p\bar{p}) = 48 \pm 8}$

Significance: > 9σ

$\mathbf{N(B^0_s \to p\bar{p}p\bar{p}) = 7 \pm 3}$

Significance: 4σ

Haoqiang's parallel talk for details

第八届中国LHC物理研讨会 The 8th China LHC Physics Workshop (CLHCP2022) (23-November 27, 2022): Parallel Session: HF/HI/QCD · Indico of IHEP (Indico)

- $B^0 \to J/\psi(\to p\bar{p})K^{*0}(\to K^+\pi^-)$ and $B^0_s \to J/\psi(\to p\bar{p})\phi(\to K^+K^-)$ as normalization channel
- $\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$
- $\mathcal{B}(B^0_s \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$
- $B^0_s \to p\bar{p}p\bar{p}$ channel is not expected to be Cabibo suppressed: $\left|\frac{V_{us}}{V_{ud}}\right|^2 \sim 5\%$
- Expect more theoretical explanations

Summary and prospects

- **There is no sign of beyond the SM source yet**
  - FCCC: $R(D^*)$, $R(D)$, $\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$
  - Lepton-favour violating: $B^0 \to K^{*0} \mu^\pm e^\mp$, $B_s^0 \to \phi \mu^\pm e^\mp$, $B^0 \to K^{*0} \tau^\pm \mu^\mp$
  - Baryon- and lepton-number violating: $B^0 \to p\mu^-$
  - Rare B meson charmless baryonic decay: $B_s^0 \to p\bar{p}$, $B_{(s)}^0 \to p\bar{p}p\bar{p}$

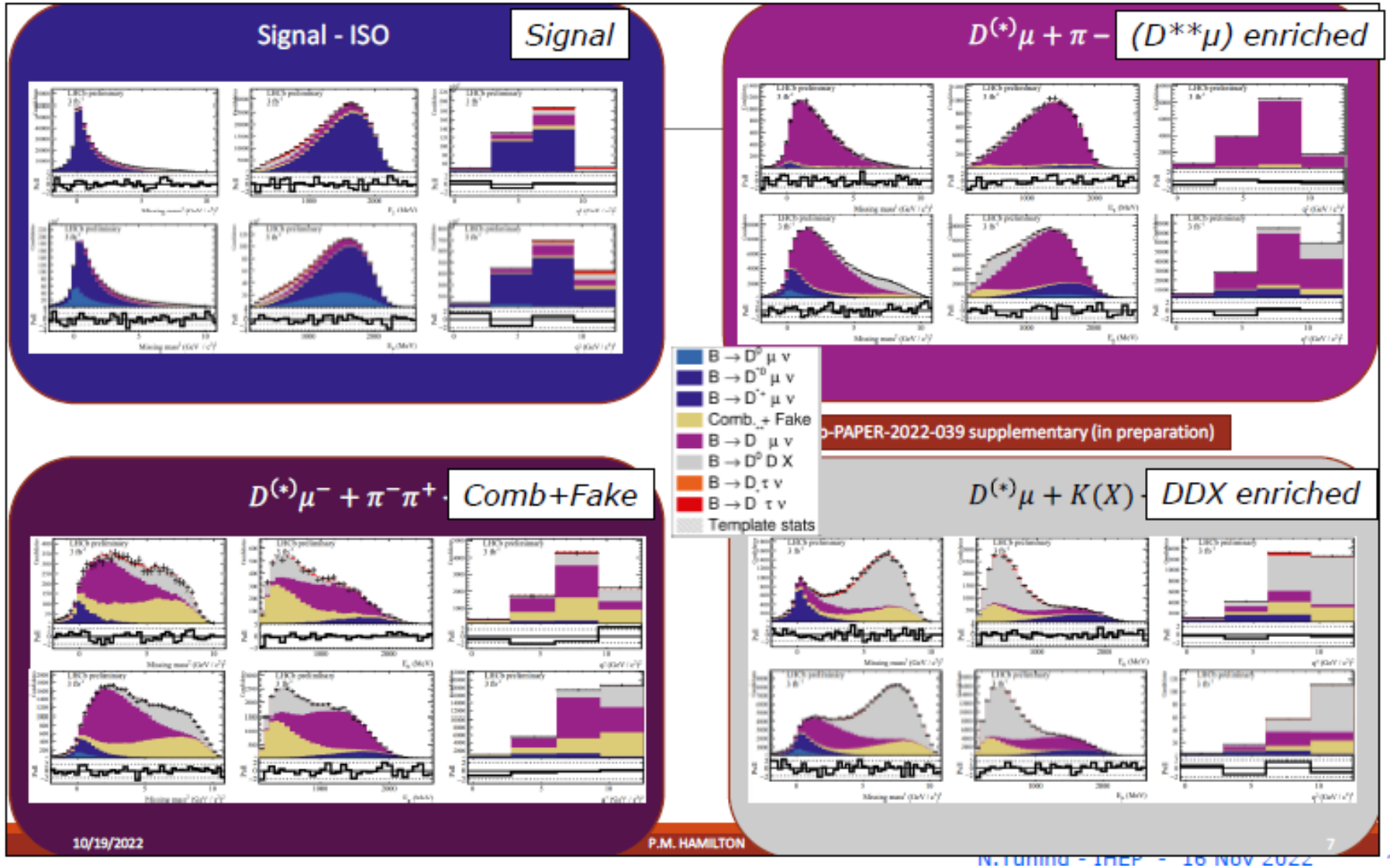
- **Opportunities with Run 3&4 (50 $\mathbf{fb^{-1}}$)**
  - Higher precision in rare decay measurements: $B_{s/d}^0 \to \mu^+\mu^-$, angular distributions and LFU tests in $b \to s l^+ l^-$ decays, …
  - Wider scope for exploitation: LFU tests in $b \to d l^+ l^-$ decays, CPV in baryon decays, CPV in rare decays,…

LHCb-China team is currently focusing on rare decay measurements

Backup

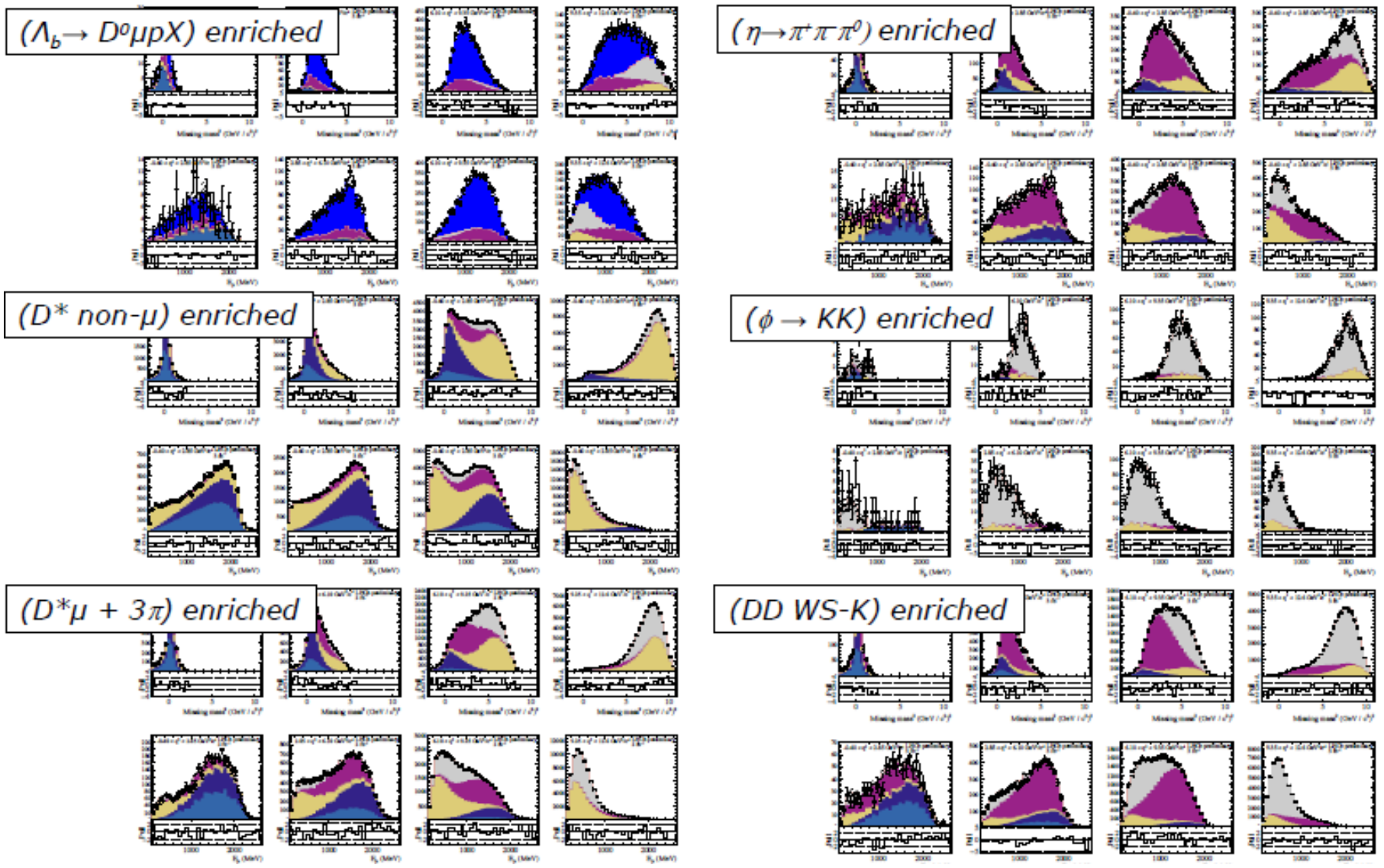
Measurement of R(D*) vs R(D)

- Fit Simultaneous 3D-fit to 8 samples (and in 4 q2 bins…) :



Measurement of R(D*) vs R(D)

- Fit was checked on specific subsamples:



$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$