LHCb analyses and prospects for decays involving τ

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The 2024 International Workshop on the High Energy Circular Electron Positron Collider
Oct 22-27, 2024, Hangzhou

Outline

- Motivation: τ and new physics
- The LHCb detector
- Physics results involving τ from LHCb
- Challenges and prospects
- Summary

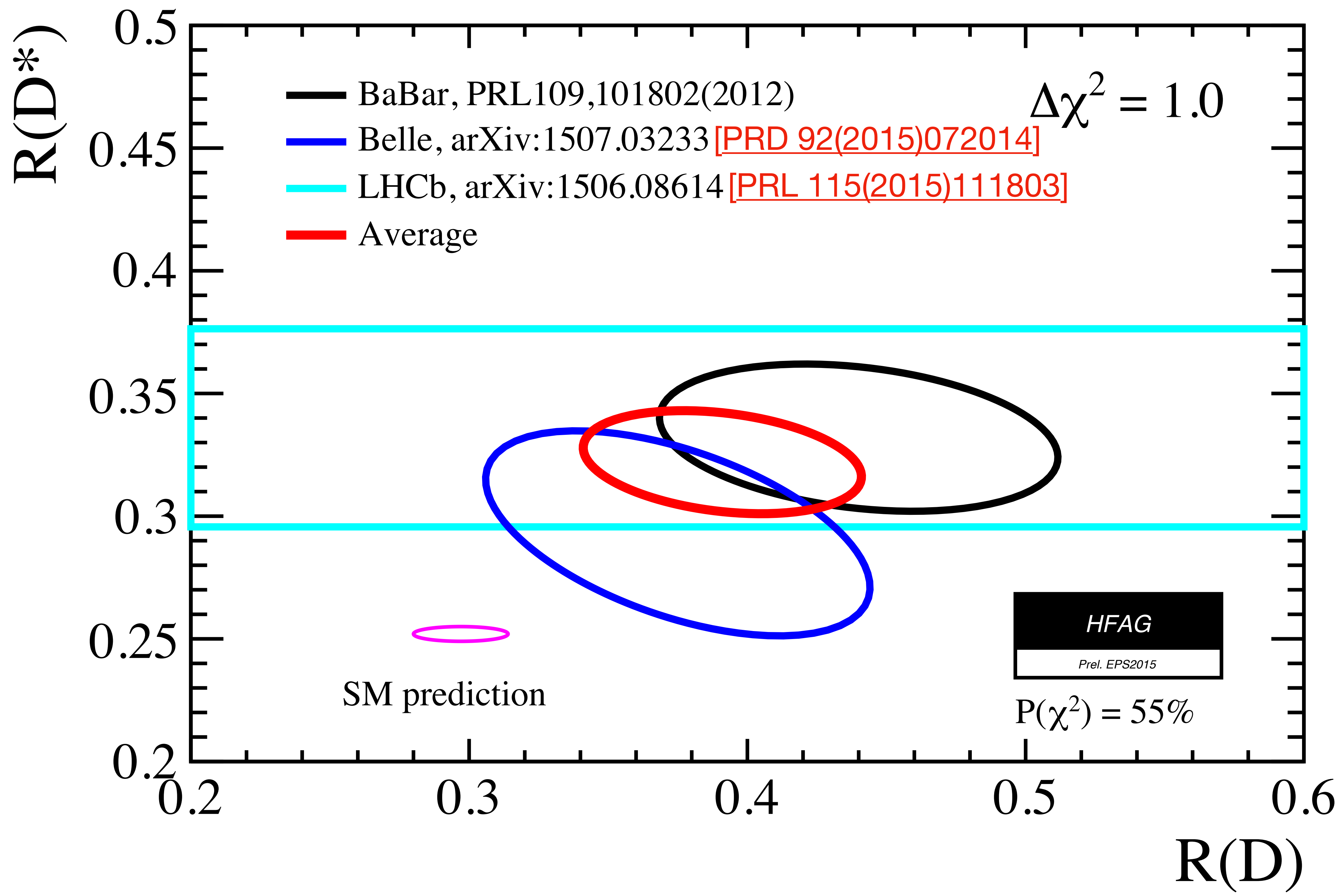
Motivation: τ and new physics

- In the same year for observation of the Higgs boson, Babar collaboration reported a 3.4σ tension for $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}(\ell = e, \mu)$$

- As an accidental symmetry in SM, lepton flavour universality expects the same coupling between gauge bosons and three charged leptons.
- Physics beyond the SM could introduce enhancement for processes involving different charged leptons, especially the heavier third generation τ-lepton.
- The tension in $R(D^{(*)})$ stimulates a lot of explorations for new physics, like LFU tests with semitauonic decays, LFV searches with rare decays…

First average for $R(D^{(*)})$ from HFLAV



LFU: lepton flavour universality
LFV: lepton flavour violation

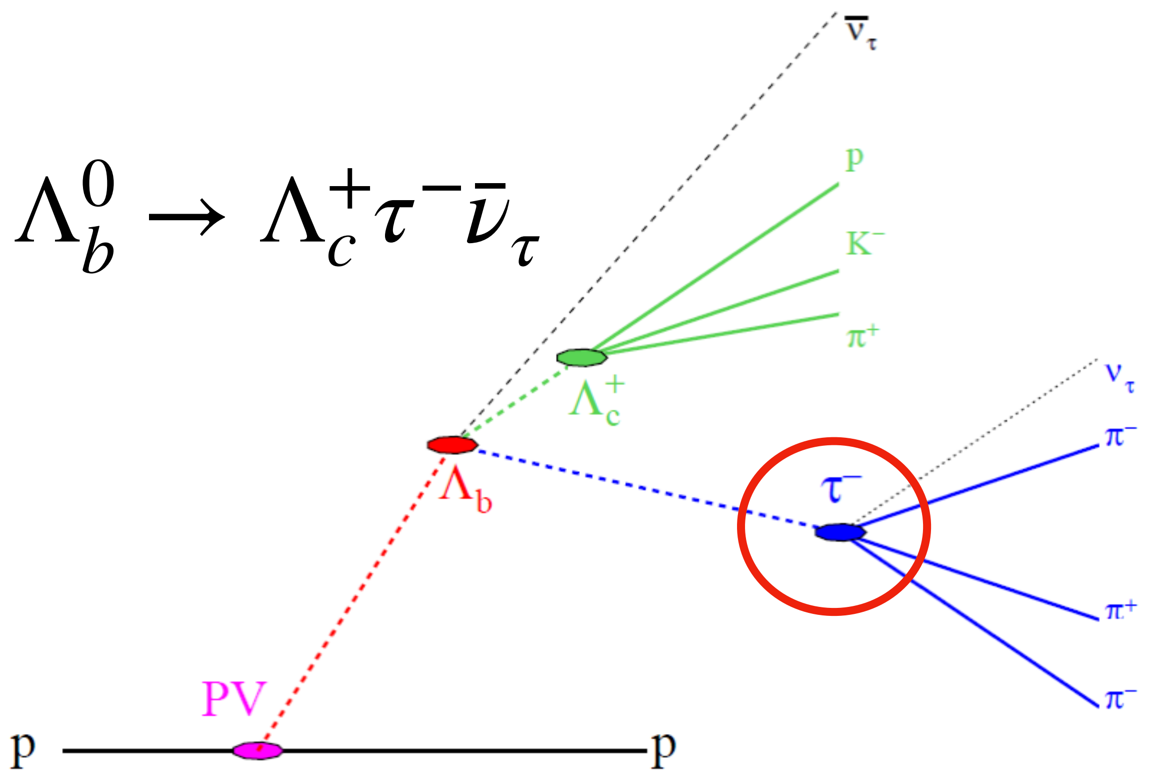
The LHCb detector (Run1&2)

Int. J. Mod. Phys. A 30(2015)153002
JINST 3(2008)S08005

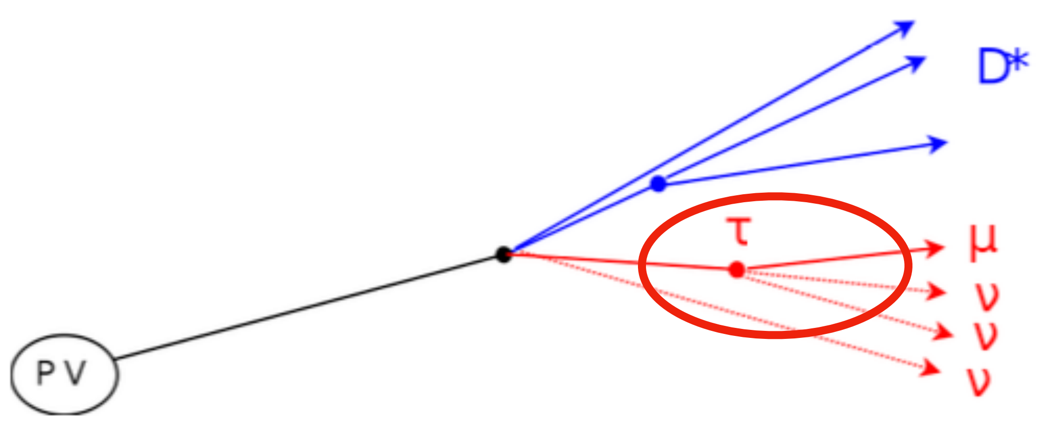
A single-arm forward spectrometer, designed for the study of heavy flavour physics

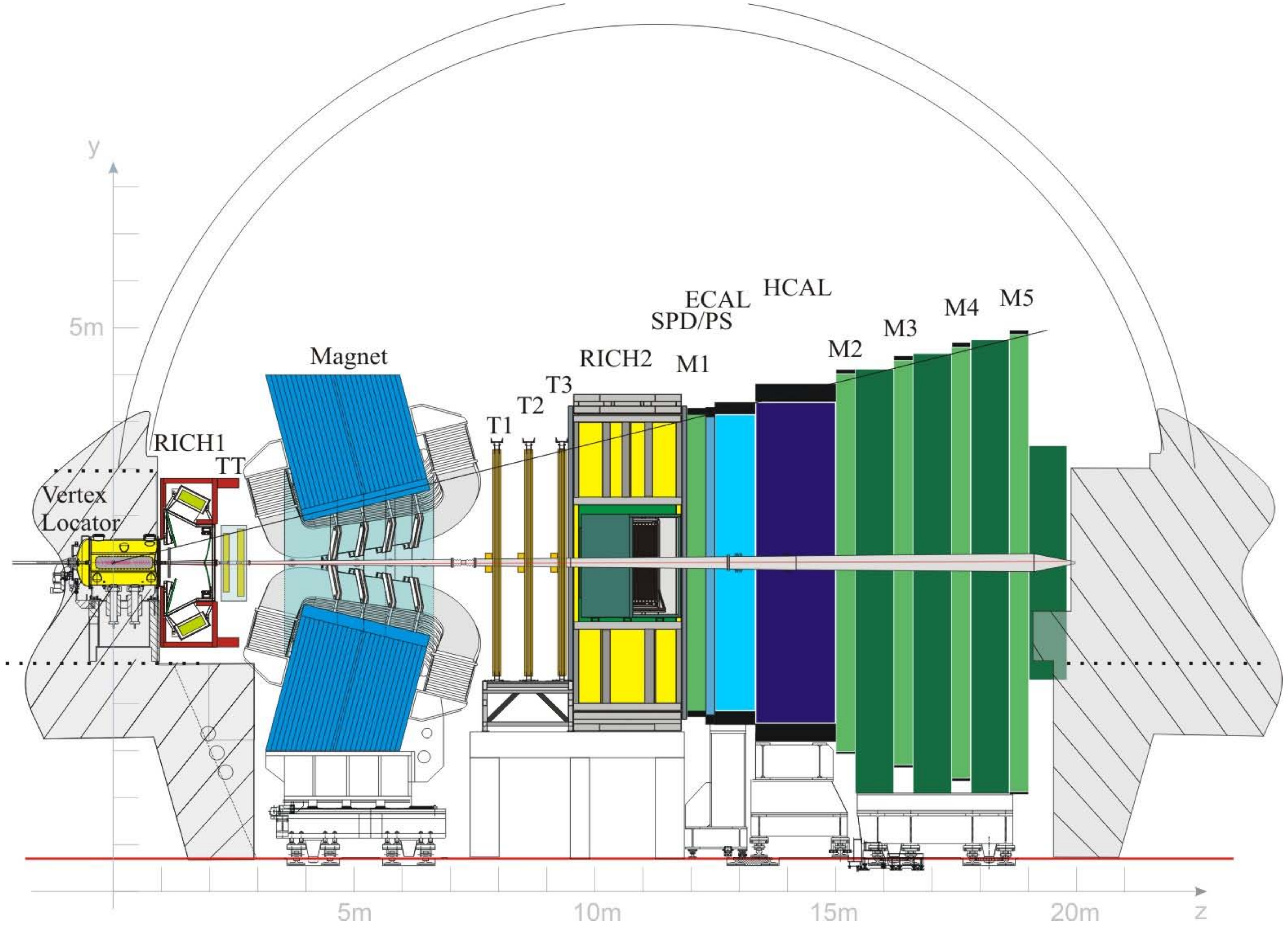
- Excellent vertex, IP and decay-time resolution
- Very good momentum resolution
- Good hadron and muon identification
- $2 < \eta < 5$ range (LHCb acceptance):
  ~$3 \times 10^4/s$ $b\bar{b}$ pairs@ 7 TeV ~x2 yield@ 13 TeV

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$



$\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$

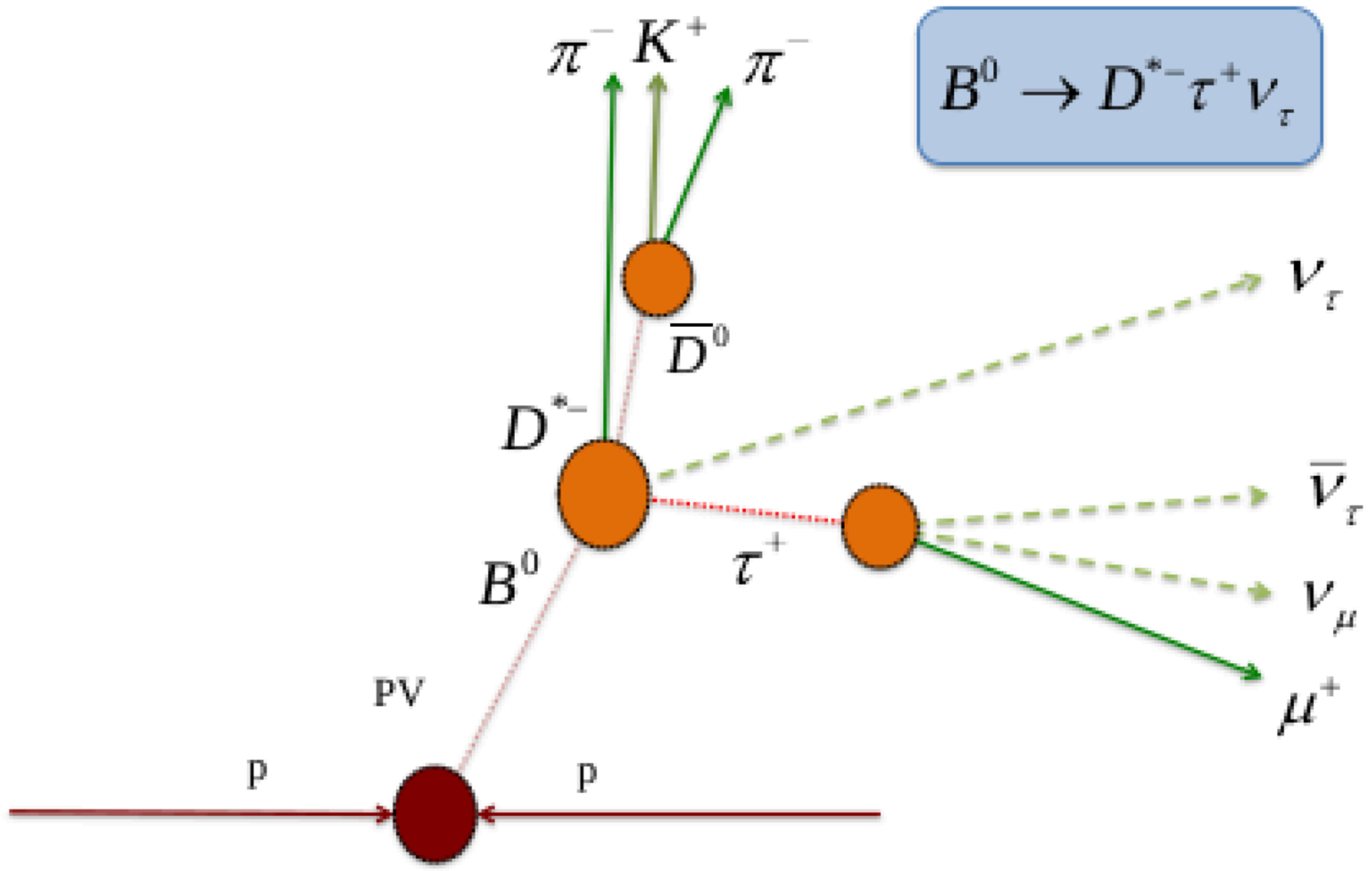




Different reconstruction methods of τ-lepton at LHCb

Muonic decays of τ

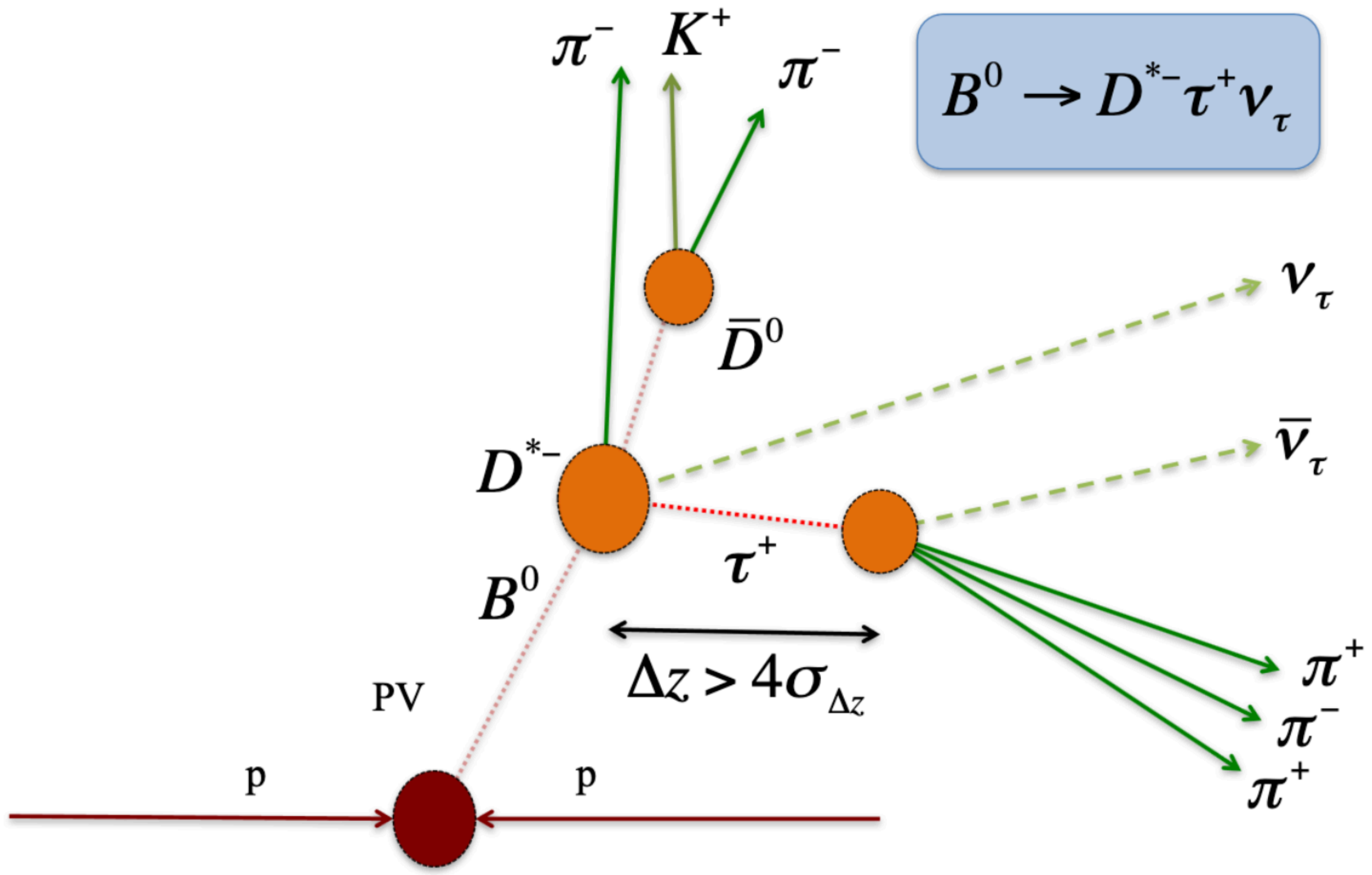
$\mathscr{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = (17.39 \pm 0.04)\,\%$



- Direct measurement of $R(X_c)$
- High statistics
- Backgrounds from D meson must be controlled well
- Sensitive to $D^{**}\mu^-\bar{\nu}_\mu$

Hadronic decays of τ

$\mathscr{B}(\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau) \sim 13.5\,\%$



- Detached τ^+ decay position to suppress dominant backgrounds
- High purity sample
- Specific dynamics of $\tau^+ \to 3\pi^\pm(\pi^0)\bar{\nu}_\tau$
- $R(X_c)$ calculation requires external inputs
- Lower statistics

LFU tests using semitauonic decays at LHCb

Muonic decays of τ

$\mathscr{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = (17.39 \pm 0.04)\,\%$

- $R(D^*)$, Run1 3fb^{-1}
  [PRL 115(2015)111803]

Supersede

- $R(D^0)$ & $R(D^*)$, Run1 3fb^{-1}
  [PRL 131(2023)111802]
- $R(D^+)$ & $R(D^{*+})$, part. Run2 2fb^{-1}
  [LHCb-PAPER-2024-007]
- $R(J/\psi)$, Run1 3fb^{-1}
  [PRL 120(2018)121801]

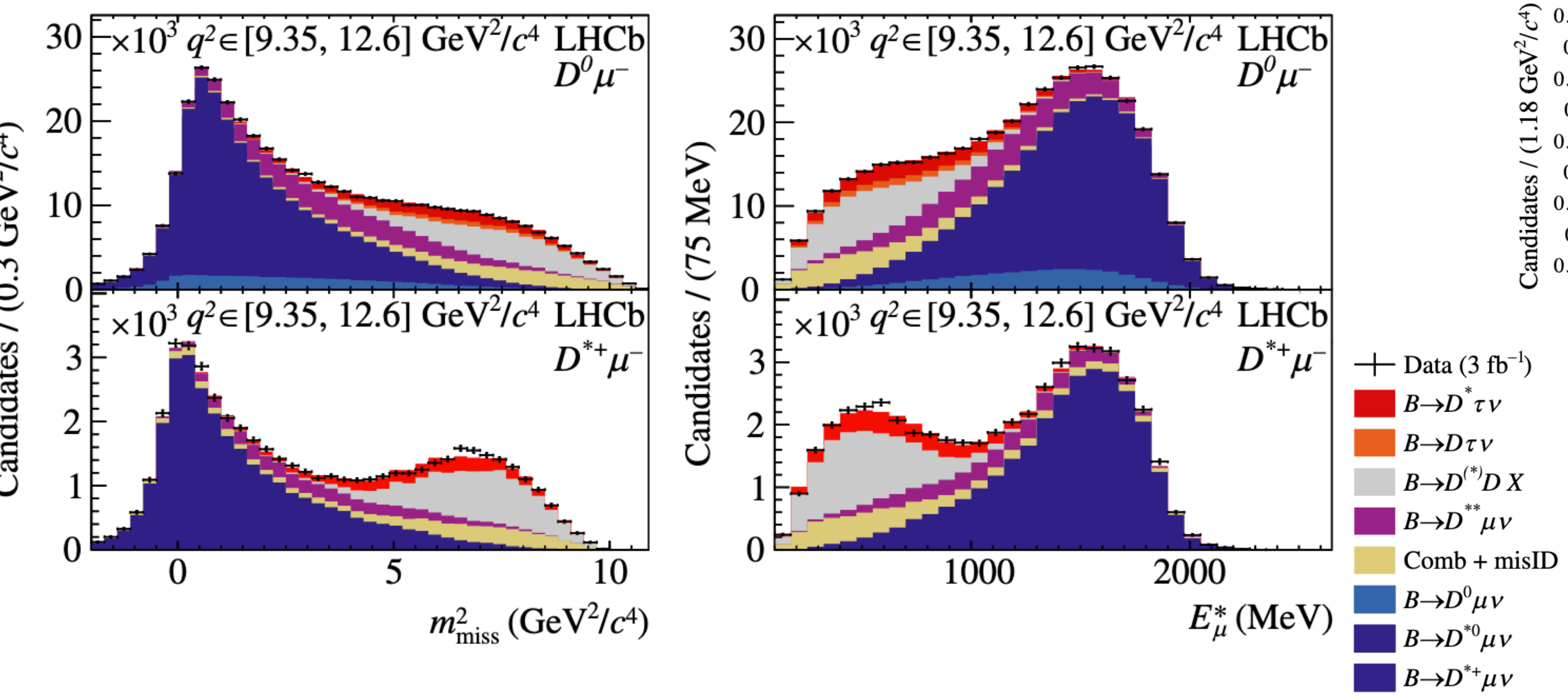
Hadronic decays of τ

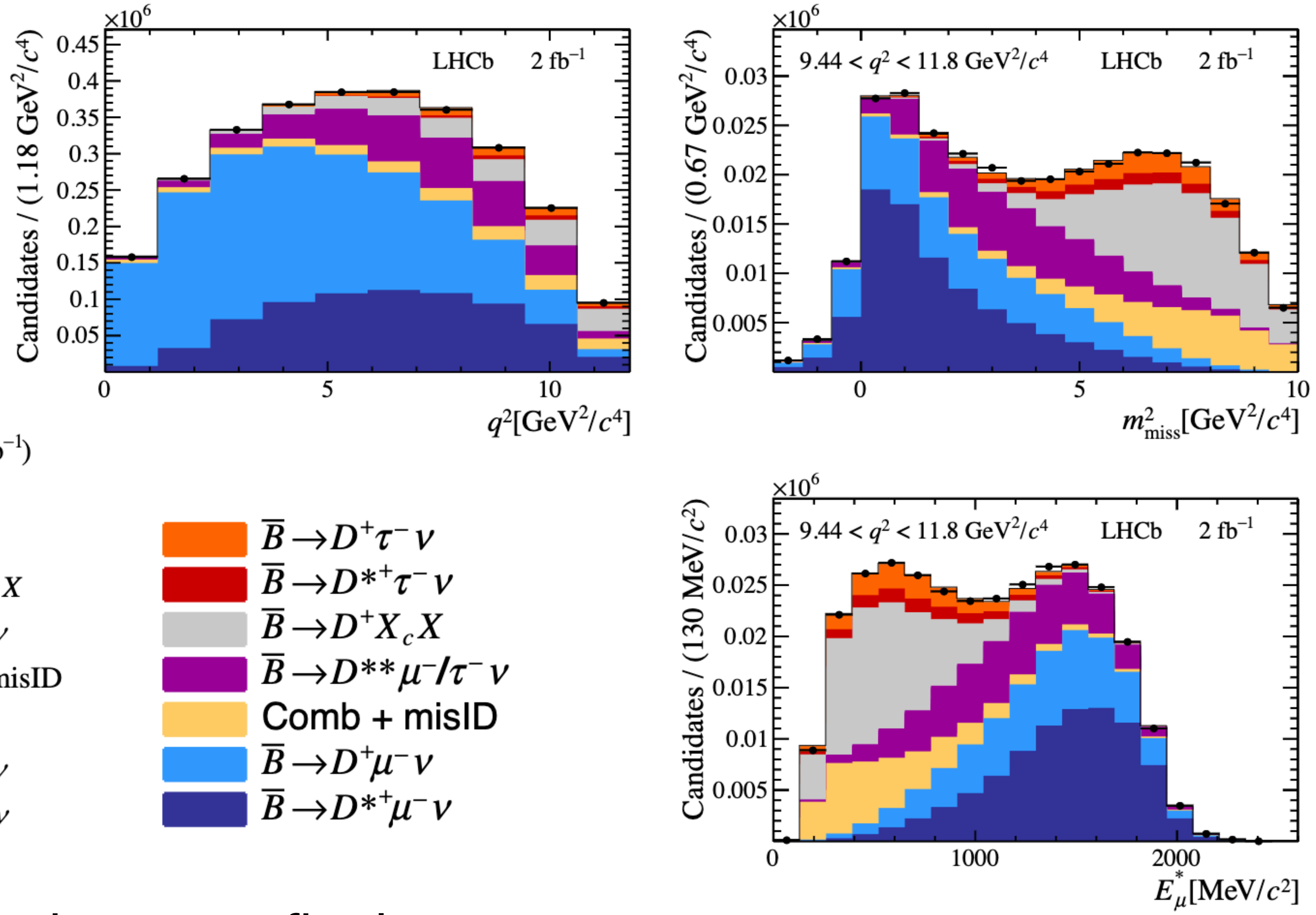
$\mathscr{B}(\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau) \sim 13.5\,\%$

- $R(D^*)$, Run1 3fb^{-1} (2018)
  [PRL 120,171802, PRD 97,072013]
- $R(D^*)$, part. Run2 2fb^{-1}
  [PRD 108(2023)012018]
  (Erratum [PRD 109(2024)119902])
- $R(\Lambda_c)$, Run1 3fb^{-1}
  [PRL 128(2022)191803]
- $F_L^{D^*}$, Run1+part. Run2 5fb^{-1} (2023)
  [LHCb-PAPER-2023-020]
- $R(D^{**})$, Run1+Run2, 9fb^{-1} *New!*
  [LHCb-PAPER-2024-037], in preparation

LFU tests using semitauonic decays at LHCb

- $R(D^0)$ & $R(D^*)$, Run1
  [PRL 131(2023)111802]
- $R(D^+)$ & $R(D^{*+})$, part. Run2
  [LHCb-PAPER-2024-007]

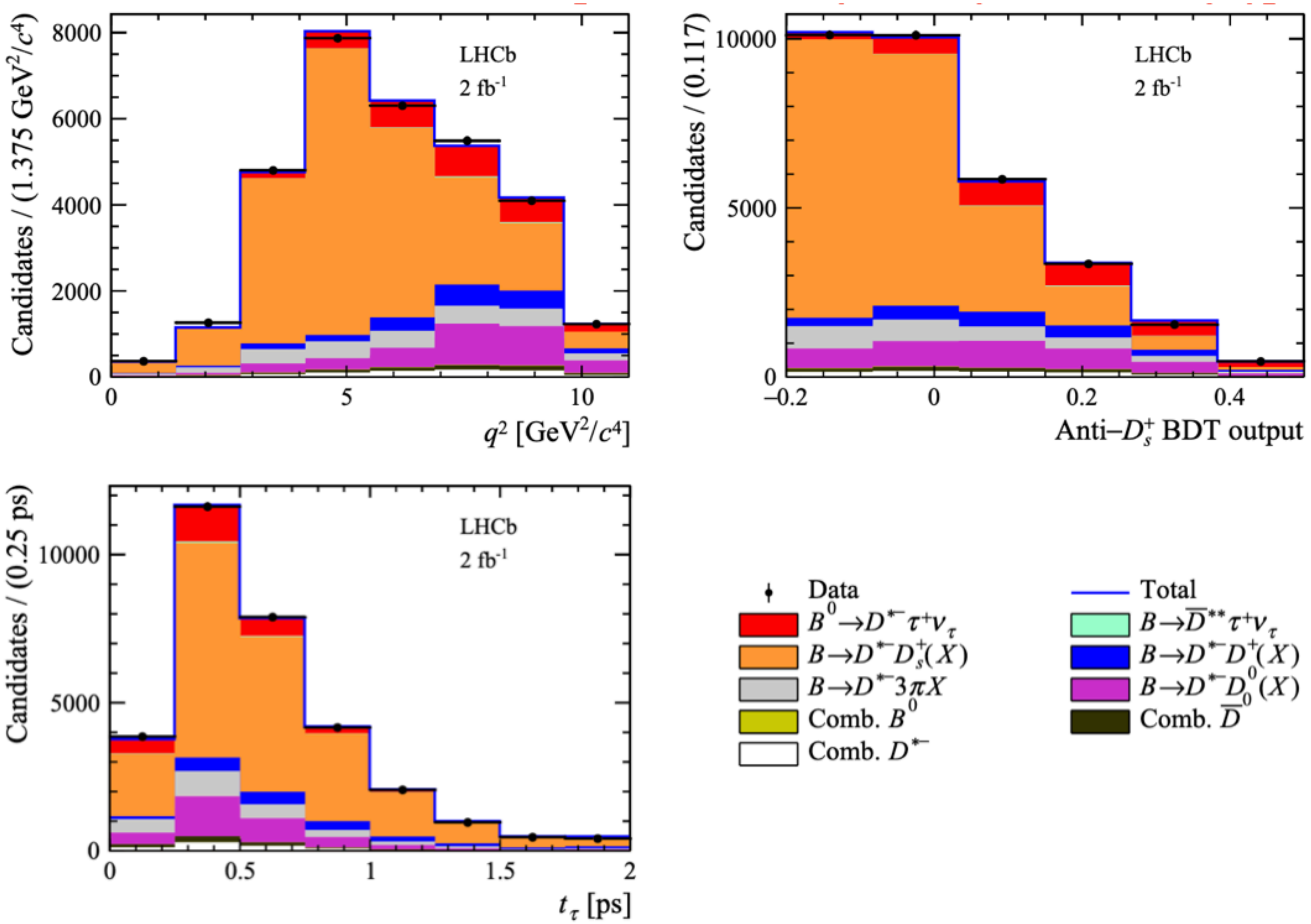




- Signal and normalisation channels have the same final states
  - τ channel will be background for μ channel
- Large statistics, low purity
- Main backgrounds from double-charm process and misID

LFU tests using semitauonic decays at LHCb

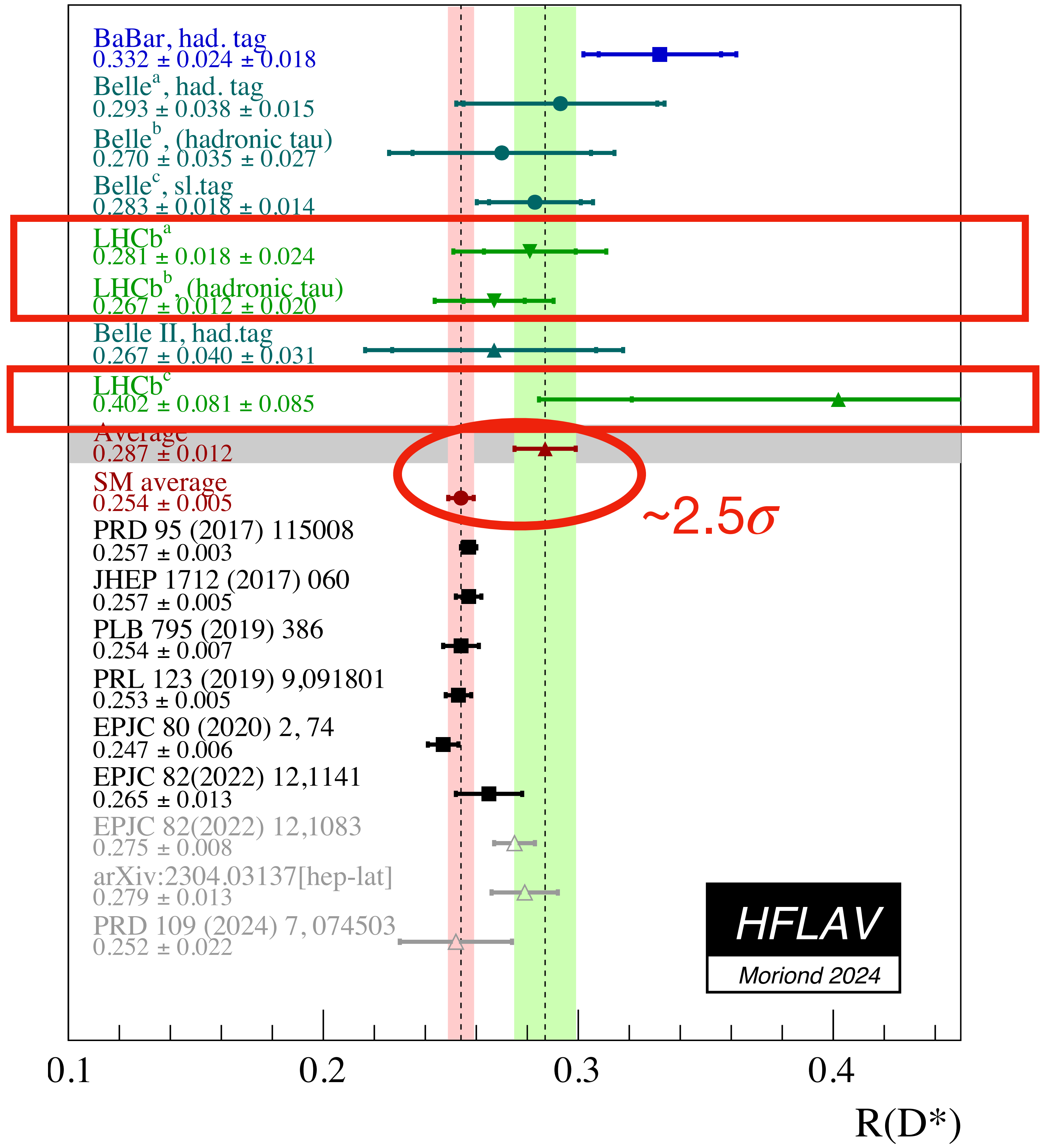
- $R(D^*)$, part. Run2
  [PRD 108(2023)012018] (Erratum [PRD 109(2024)119902])

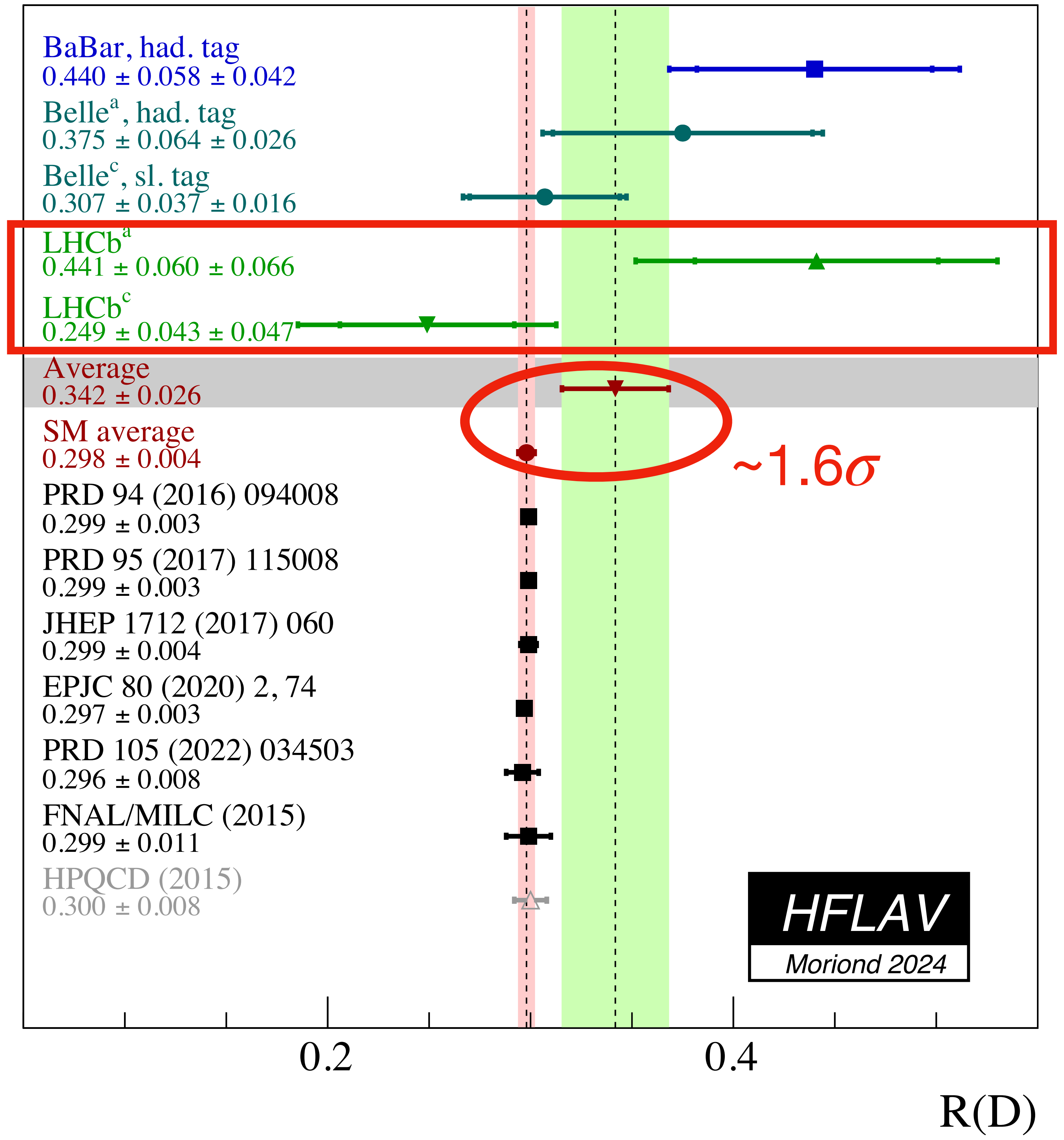


- Normalise to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$
  - External input for getting $R(D^*)$
- Lower statistics, higher purity
- Main backgrounds from $B \to D^{*-}D_s(X)$

Current $R(D) - R(D^*)$ scenario

[HFLAV2024]





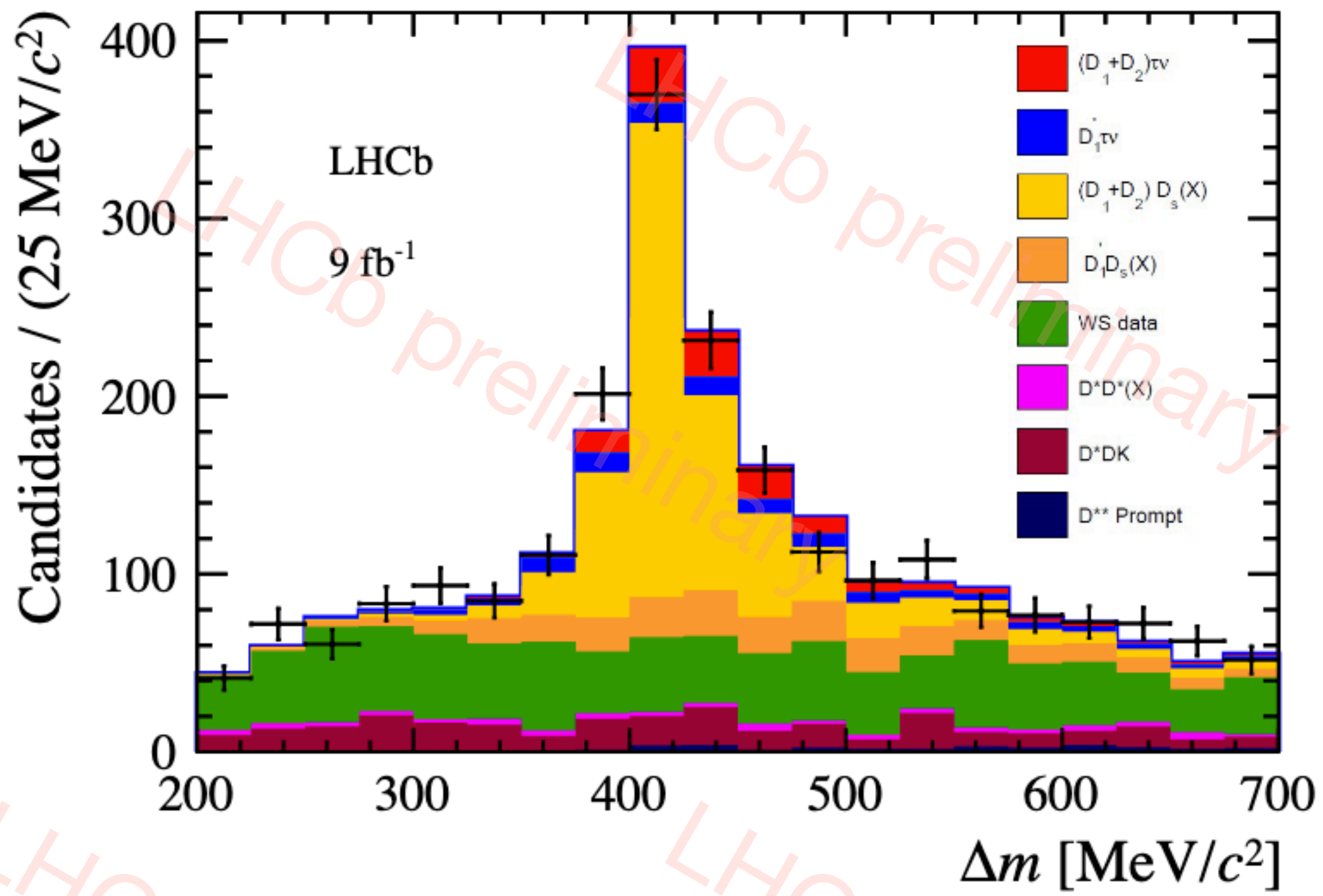
- LHCb[a]: Muonic $R(D)$ & $R(D^*)$, Run1
- LHCb[b]: Hadronic $R(D^*)$, Run1+part. Run2
- LHCb[c]: Muonic $R(D^+)$ & $R(D^{*+})$, part. Run2

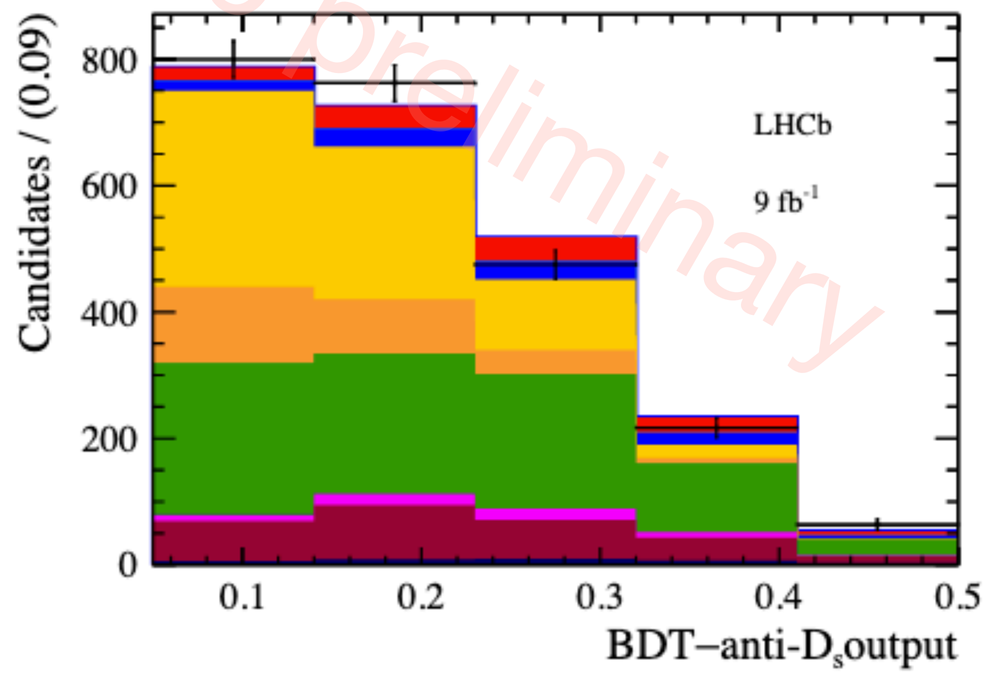
- $R(D)$ & $R(D^*)$ tension with SM: 3.3σ
- Theory predictions are quite precise ~ 1%
- Belle & Belle II results dominated by statistical uncertainty
- LHCb results have $\sigma_{syst} > \sigma_{stat}$

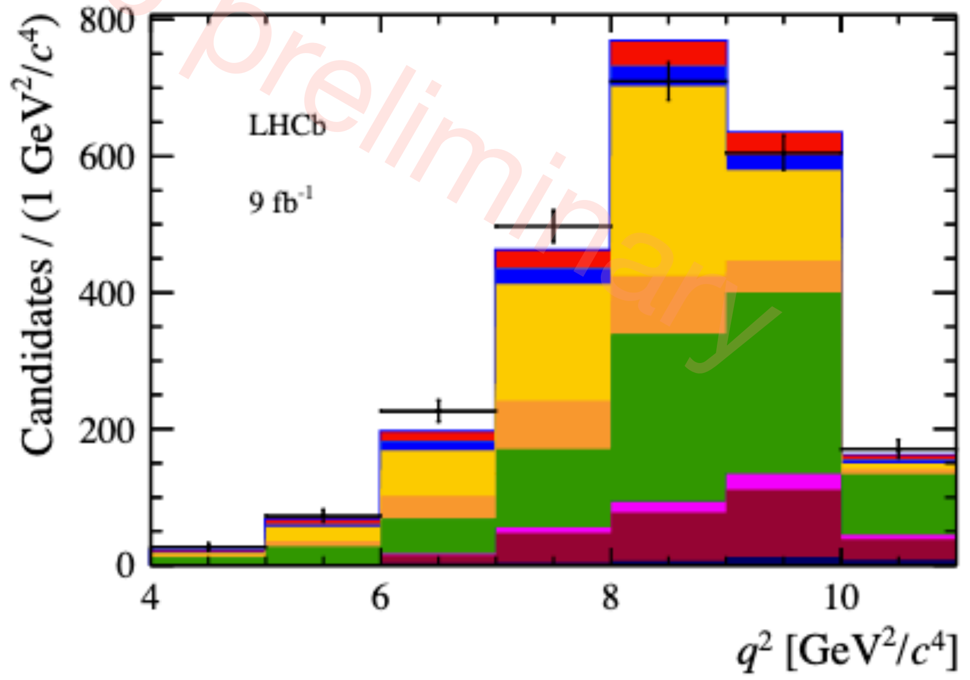
LFU tests using semitauonic decays at LHCb

New!

- $R(D^{**})$, Run1+Run2
  [LHCb-PAPER-2024-037], in preparation







$D^{**0}_{1,2}$: $D_1(2420)^0$ and $D_2^*(2460)^0$

- First evidence of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ ~3.5σ

$$\frac{\mathscr{B}(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{\mathscr{B}(B^- \to D^{**0}_{1,2}D_s^{(*)-})} = 0.19 \pm 0.05$$

- With external input of $\mathscr{B}(B^- \to D^{**0}_{1,2}(D_s^- + D_s^{*-}))$ and $\mathscr{B}(B^- \to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu)$:

$$R(D^{**0}_{1,2}) = 0.13 \pm 0.03(stat) \pm 0.01(syst) \pm 0.02(ext)$$

- Consistent with SM prediction: 0.09 ± 0.02
- Measured signal yields can be used to constrain $B \to D^{**}\tau^-\bar{\nu}_\tau$ background in $R(D^*)$ measurement

$$N_{D^{**0}_{1,2}\tau^-\bar{\nu}_\tau} = 123 \pm 23(stat) \pm 14(syst)$$
$$N_{(D^{**0}_{1,2}+D_1')\tau^-\bar{\nu}_\tau} = 220 \pm 34(stat) \pm 25(syst)$$

Rare decays involving τ at LHCb

Lepton flavour violating decays

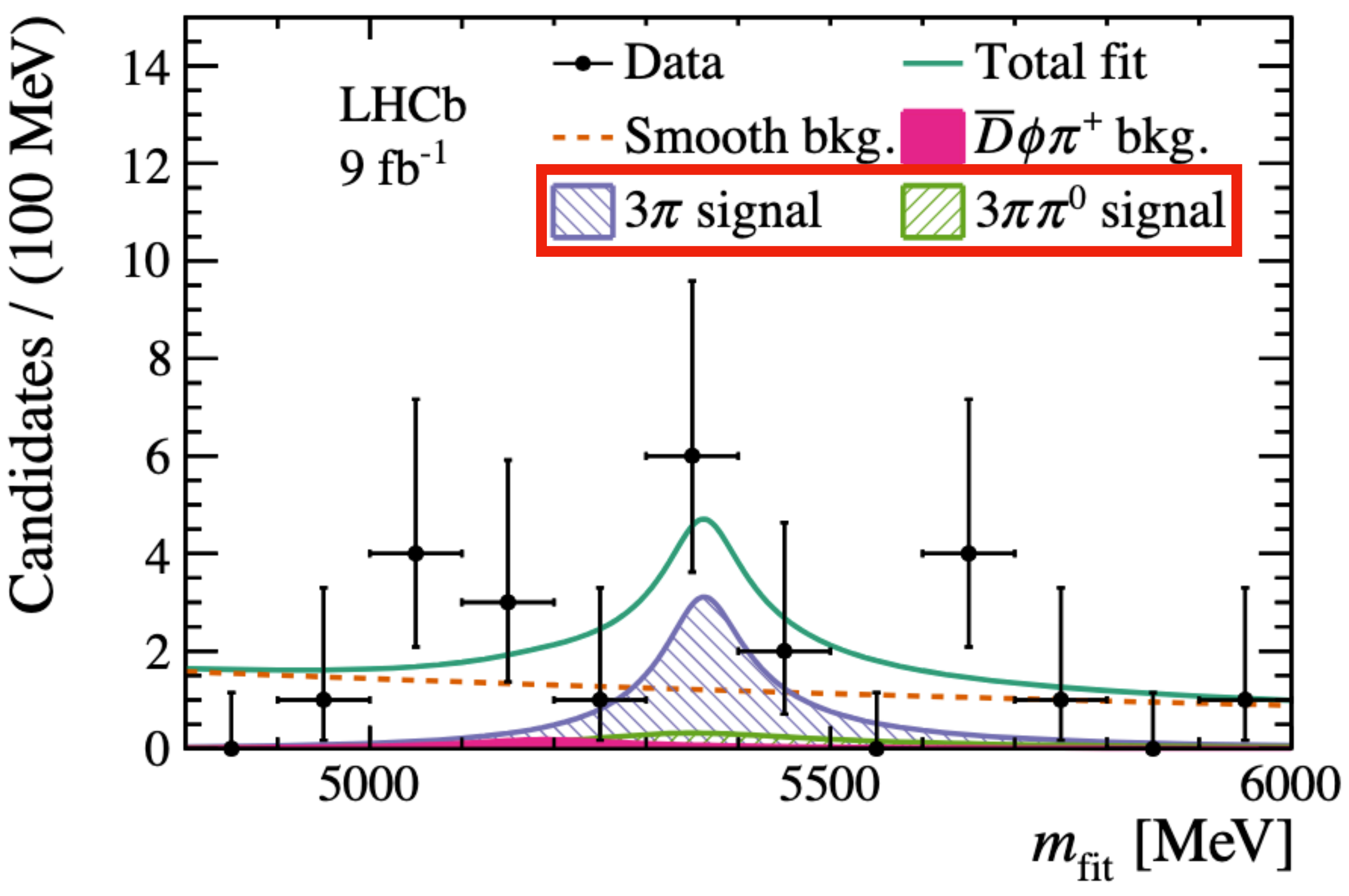
- $B_s^0 \to \phi\mu^{\pm}\tau^{\mp}$, Run1+Run2 $9\mathrm{fb}^{-1}$
  [arXiv: 2405.13103]
- $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$, Run1+Run2 $9\mathrm{fb}^{-1}$
  [JHEP 06(2023)143]
- $B^+ \to K^+\mu^-\tau^+$, Run1+Run2 $9\mathrm{fb}^{-1}$
  [JHEP 06(2020)129]
- $B_{(s)}^0 \to \tau^{\pm}\mu^{\mp}$, Run1 $3\mathrm{fb}^{-1}$
  [PRL 123(2019)211801]
- $\tau^- \to \mu^-\mu^+\mu^-$, Run1 $3\mathrm{fb}^{-1}$
  [JHEP 02(2015)121]

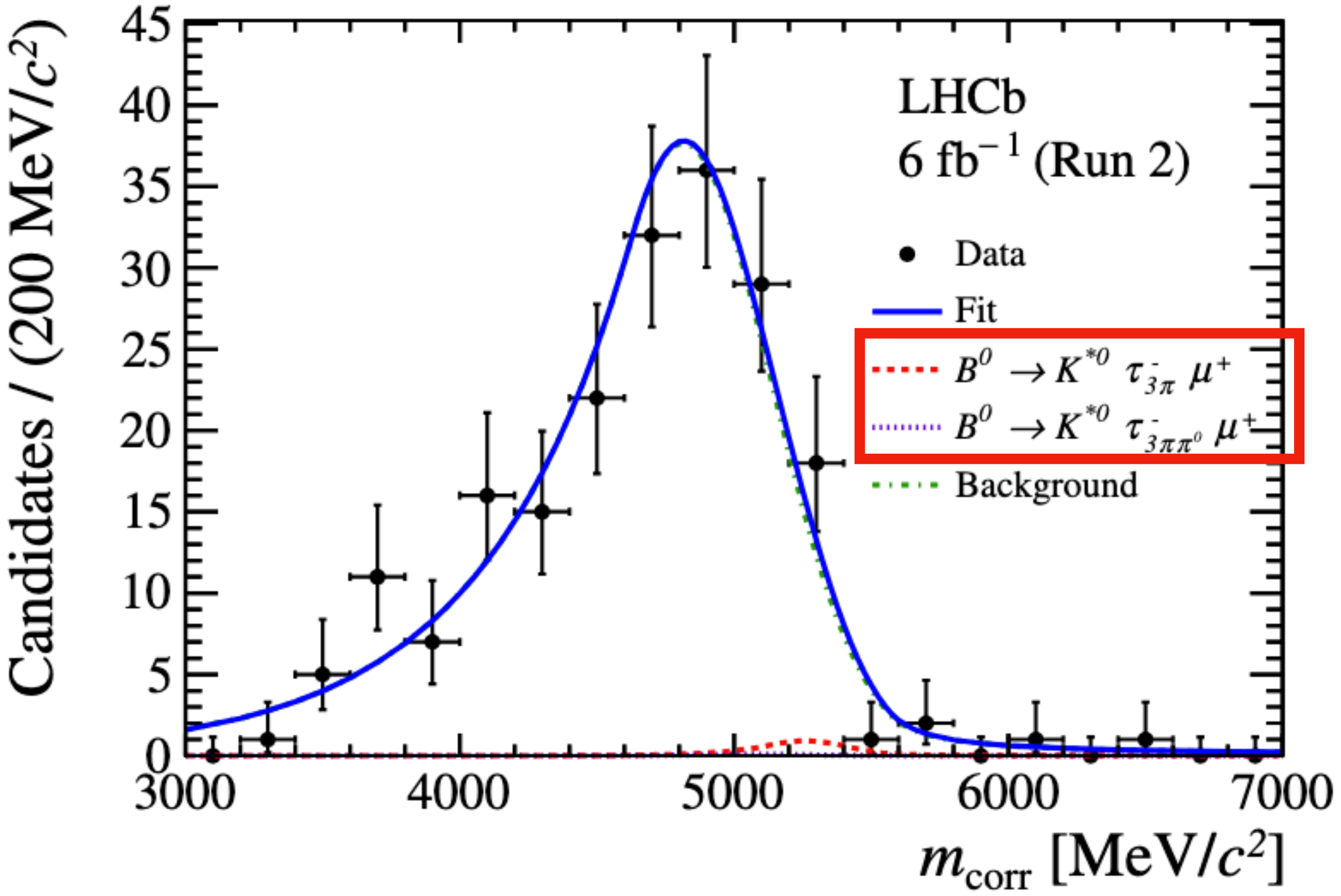
$N \to \tau^+\tau^-$ measurement

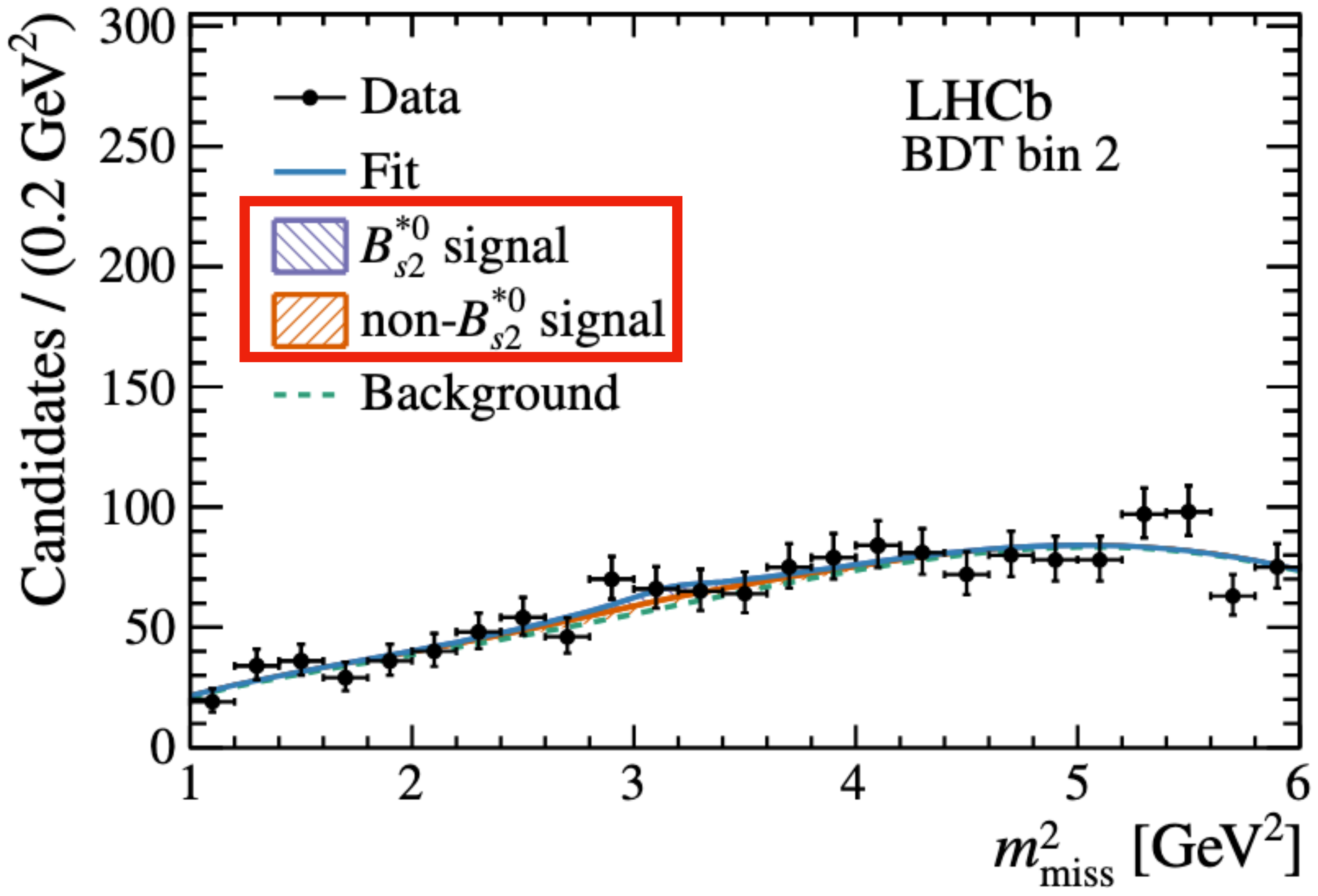
- $Z \to \tau^+\tau^-$ production, $\sqrt{s} = 7{,}8$ TeV $1{,}2\mathrm{fb}^{-1}$
  [JHEP 01(2013)111,JHEP 09(2018)159]
- $B_{(s)}^0 \to \tau^+\tau^-$, Run1 $3\mathrm{fb}^{-1}$
  [PRL 118(2017)251802]

Representative results of rare decays

- $B_s^0 \to \phi\mu^\pm\tau^\mp$, Run1+Run2
  [arXiv: 2405.13103]
- $B^0 \to K^{*0}\tau^\pm\mu^\mp$, Run1+Run2
  [JHEP 06(2023)143]
- $B^+ \to K^+\mu^-\tau^+$, Run1+Run2
  [JHEP 06(2020)129]







$\mathscr{B}(B_s^0 \to \phi\mu^\pm\tau^\mp) < 1.0 \times 10^{-5}$ at 90% CL
$< 1.1 \times 10^{-5}$ at 95% CL

$\mathscr{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$ at 90% CL
$< 1.2 \times 10^{-5}$ at 95% CL

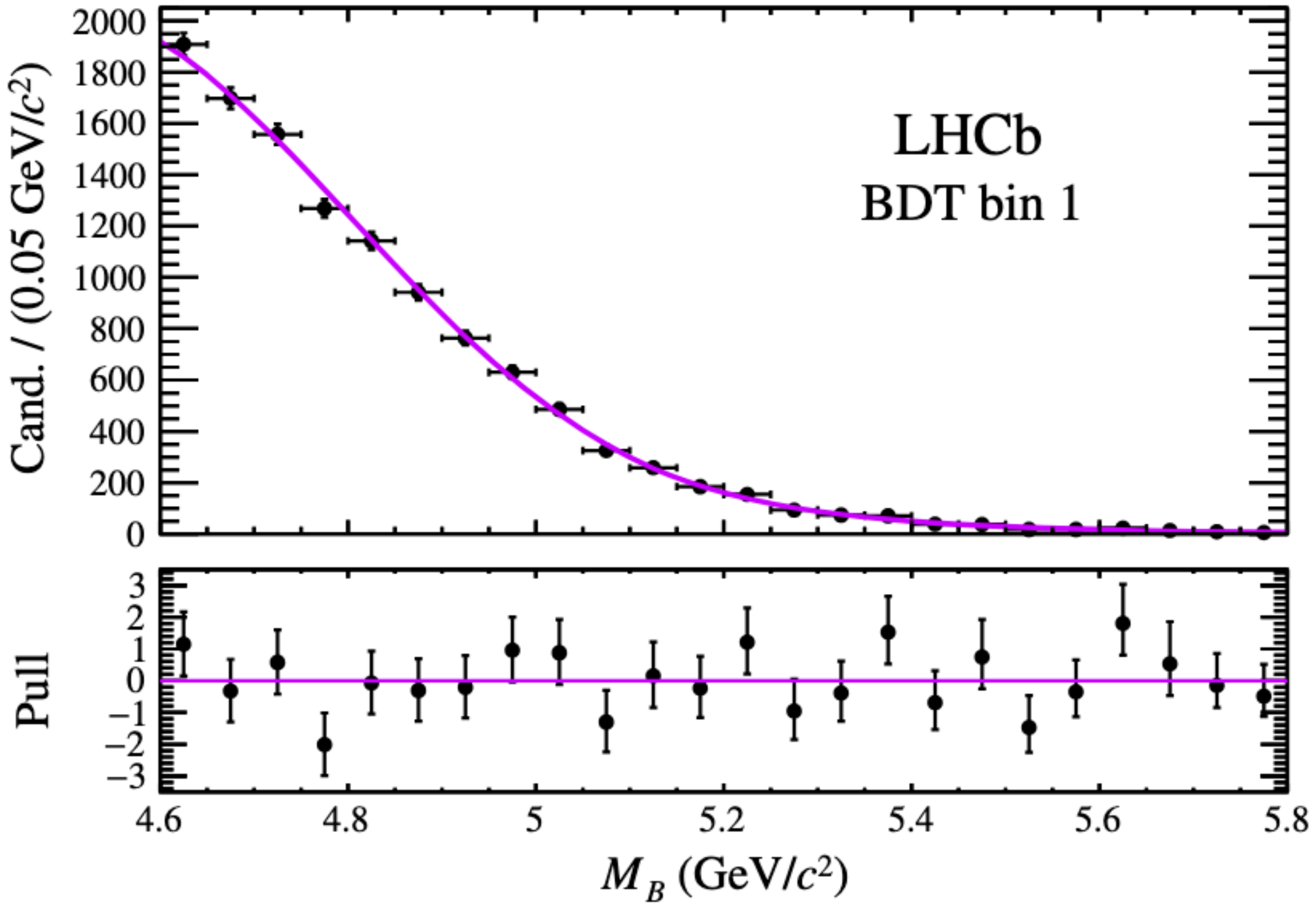
$\mathscr{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6}$ at 90% CL
$< 9.8 \times 10^{-6}$ at 95% CL

$\mathscr{B}(B^+ \to K^+\mu^-\tau^+) < 3.9 \times 10^{-5}$ at 90% CL
$< 4.5 \times 10^{-5}$ at 95% CL

Representative results of rare decays

- $B^0_{(s)} \to \tau^\pm\mu^\mp$, Run1 3fb^{-1}
[PRL 123(2019)211801]

Theory prediction with NP enhancement:
$\mathscr{B}(B^0_s \to \tau^\pm\mu^\mp)$ in $10^{-9} - 10^{-4}$

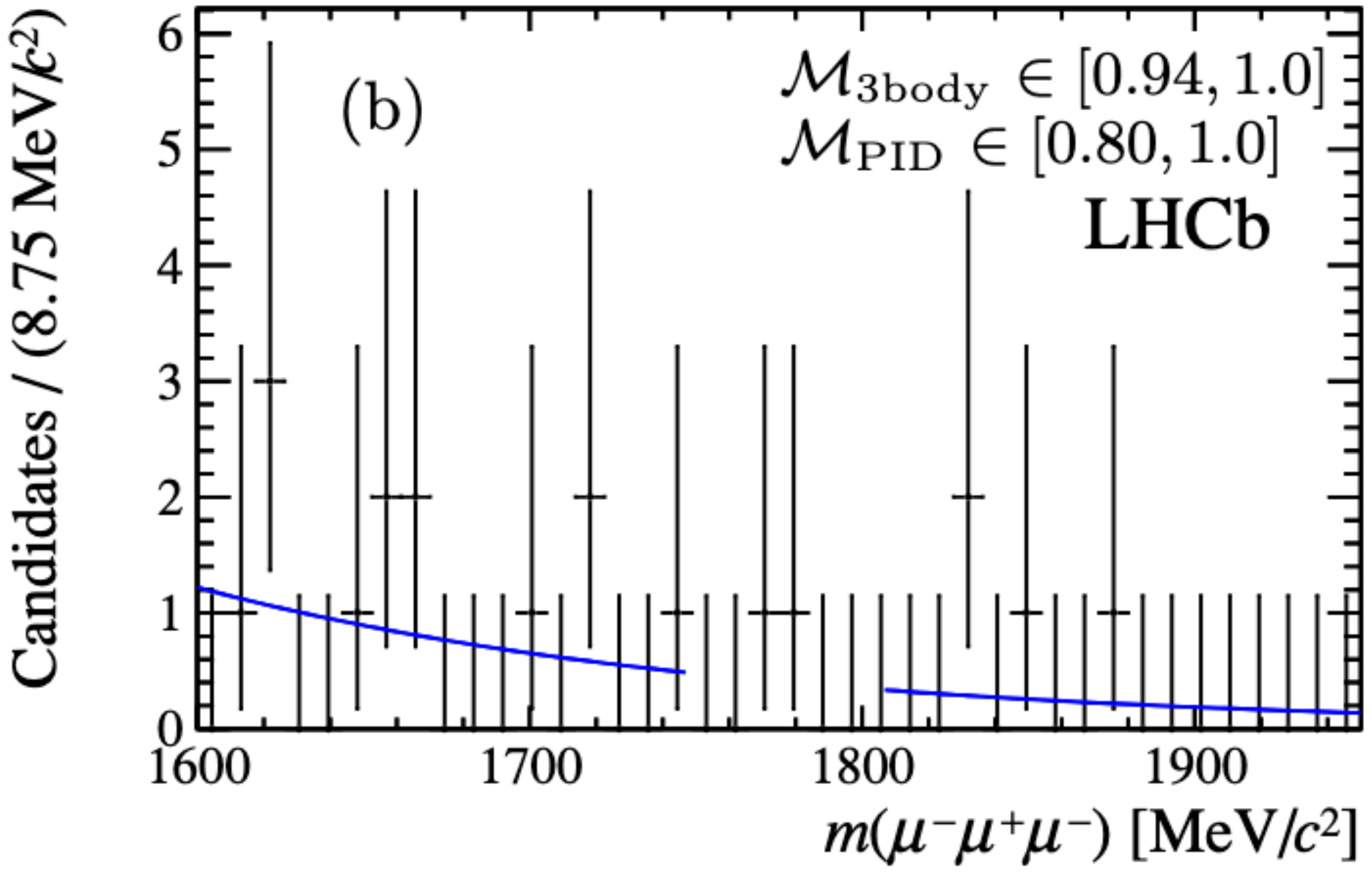


Assuming no $B^0_s \to \tau^\pm\mu^\mp$
$\mathscr{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$ at 95% CL

Assuming no $B^0 \to \tau^\pm\mu^\mp$
$\mathscr{B}(B^0_s \to \tau^\pm\tau^\mp) < 4.2 \times 10^{-5}$ at 95% CL

- $\tau^- \to \mu^-\mu^+\mu^-$, Run1 3fb^{-1}
[JHEP 02(2015)121]

Theory prediction with NP enhancement:
$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-)$ in $10^{-9} - 10^{-8}$

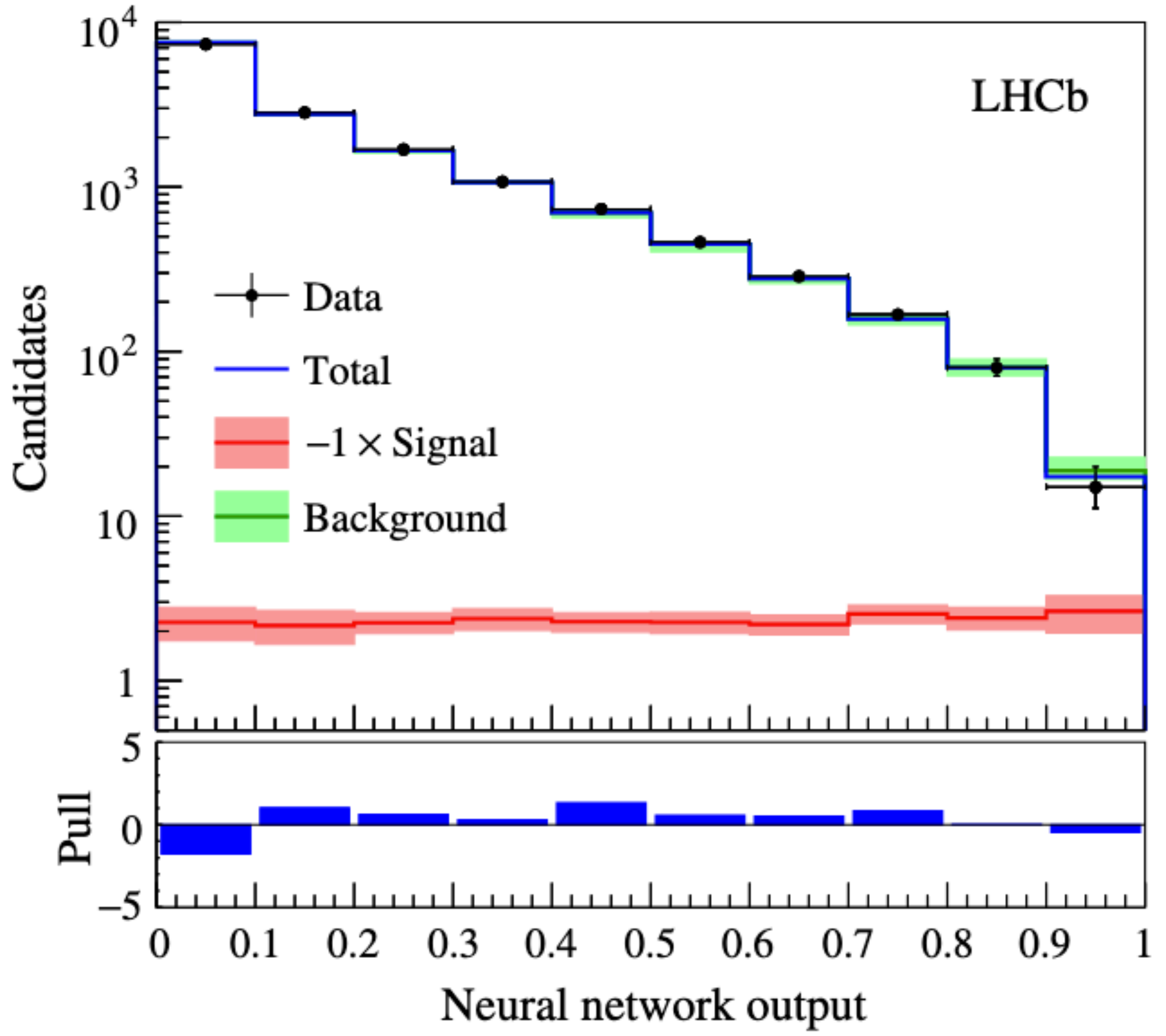


$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0 \times 10^{-8}$ at 90% CL
(1fb^{-1} at 7 TeV [PLB 724(2013)36])

This result:
$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}$ at 90% CL

- $B^0_{(s)} \to \tau^+\tau^-$, Run1 3fb^{-1}
[PRL 118(2017)251802]

Theory prediction with NP enhancement:
$\mathscr{B}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$
$\mathscr{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$



Assuming no $B^0_s \to \tau^+\tau^-$
$\mathscr{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ at 95% CL

Assuming no $B^0 \to \tau^+\tau^-$
$\mathscr{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95% CL

Challenges

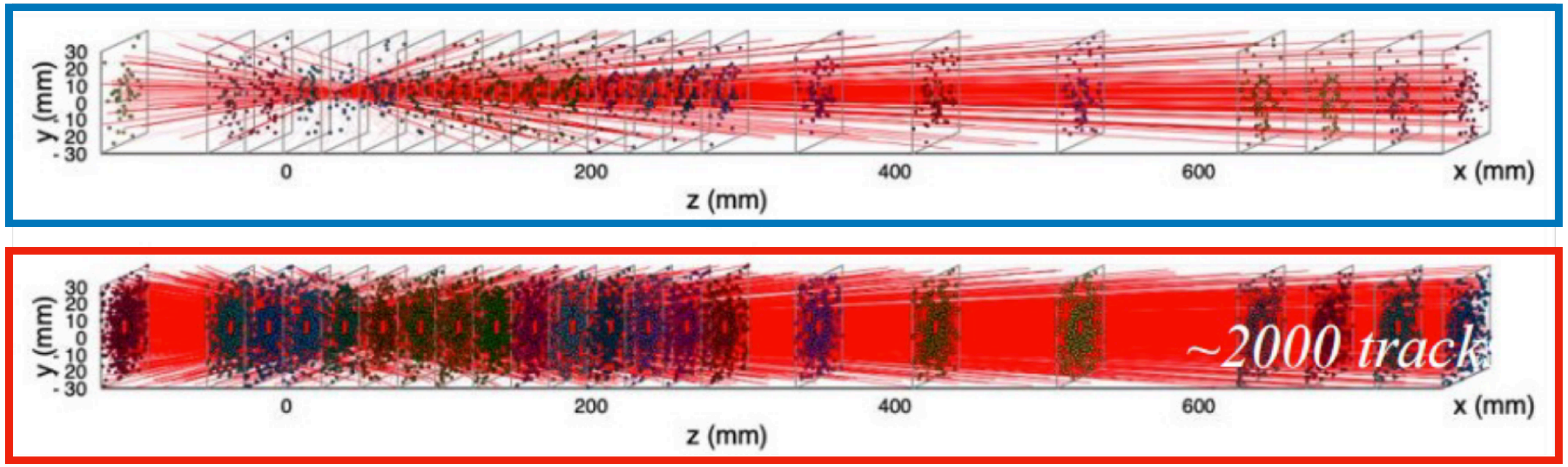
- Physics challenges
  - Theoretical challenges
    - Form factors
    - Predictions for double charm BFs, especially for excited states, which are more complicated to measure experimentally
    - Precise prediction for BFs of rare decays
  - Experimental challenges: how to handle systematics
    - Pile-up will lead to complexity of PV match
    - Increased data statistics require corresponding massive simulation events
    - Background with low BFs will become more and more significant…

Challenges

- Challenges in other aspects

  mu: average *pp* interactions per bunch crossing

  - Pile-up: mu ~ 1 for Run1&2; mu ~ 5 for Run3&4; mu ~ 40 for Run5&6
    - Reconstruction of PV
  - Detector performance
  - Computing resources
  - Lack of humanpower…



Upgrade of LHCb experiment

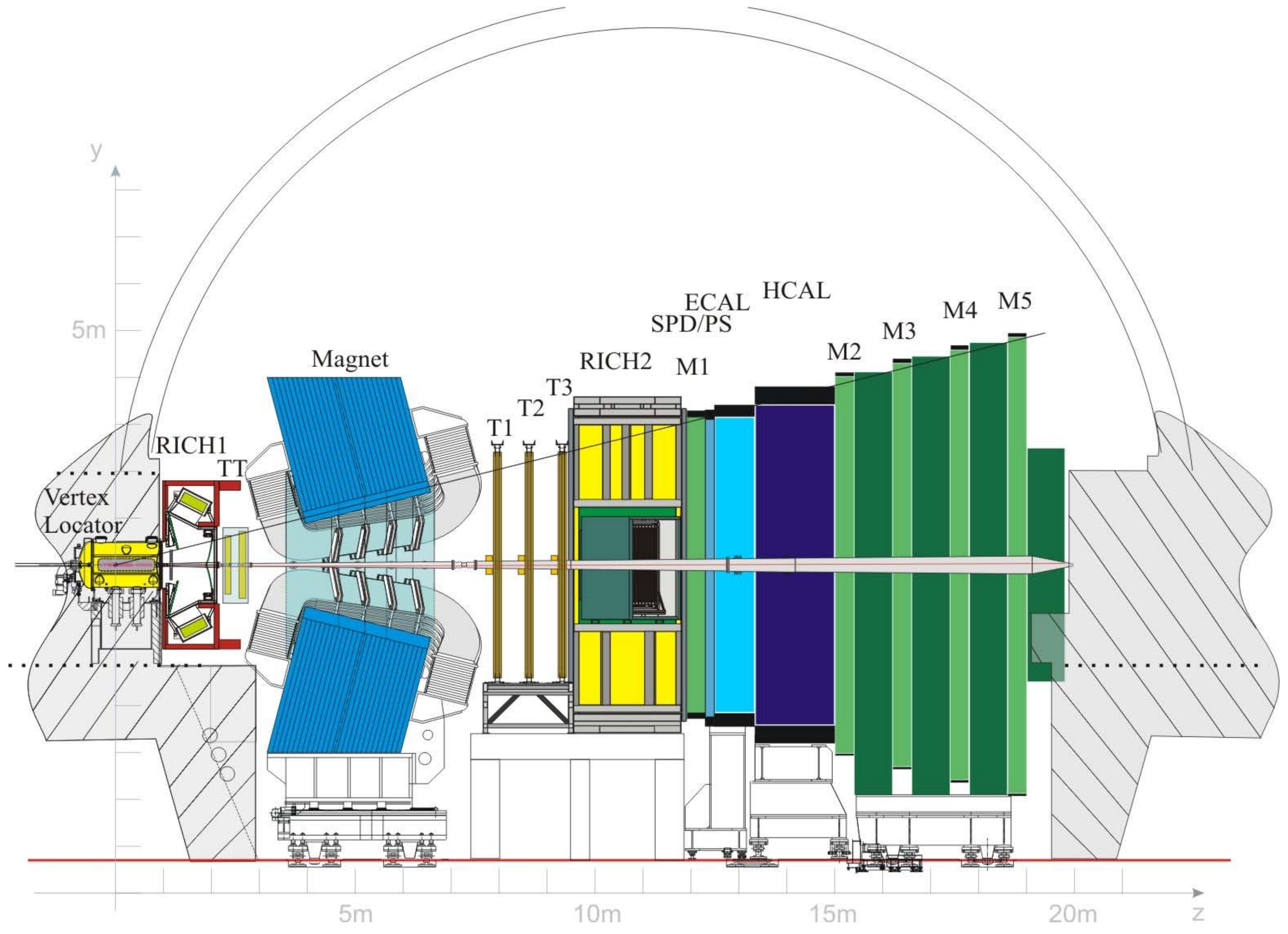
See talk from Peilian Li and Ao Xu

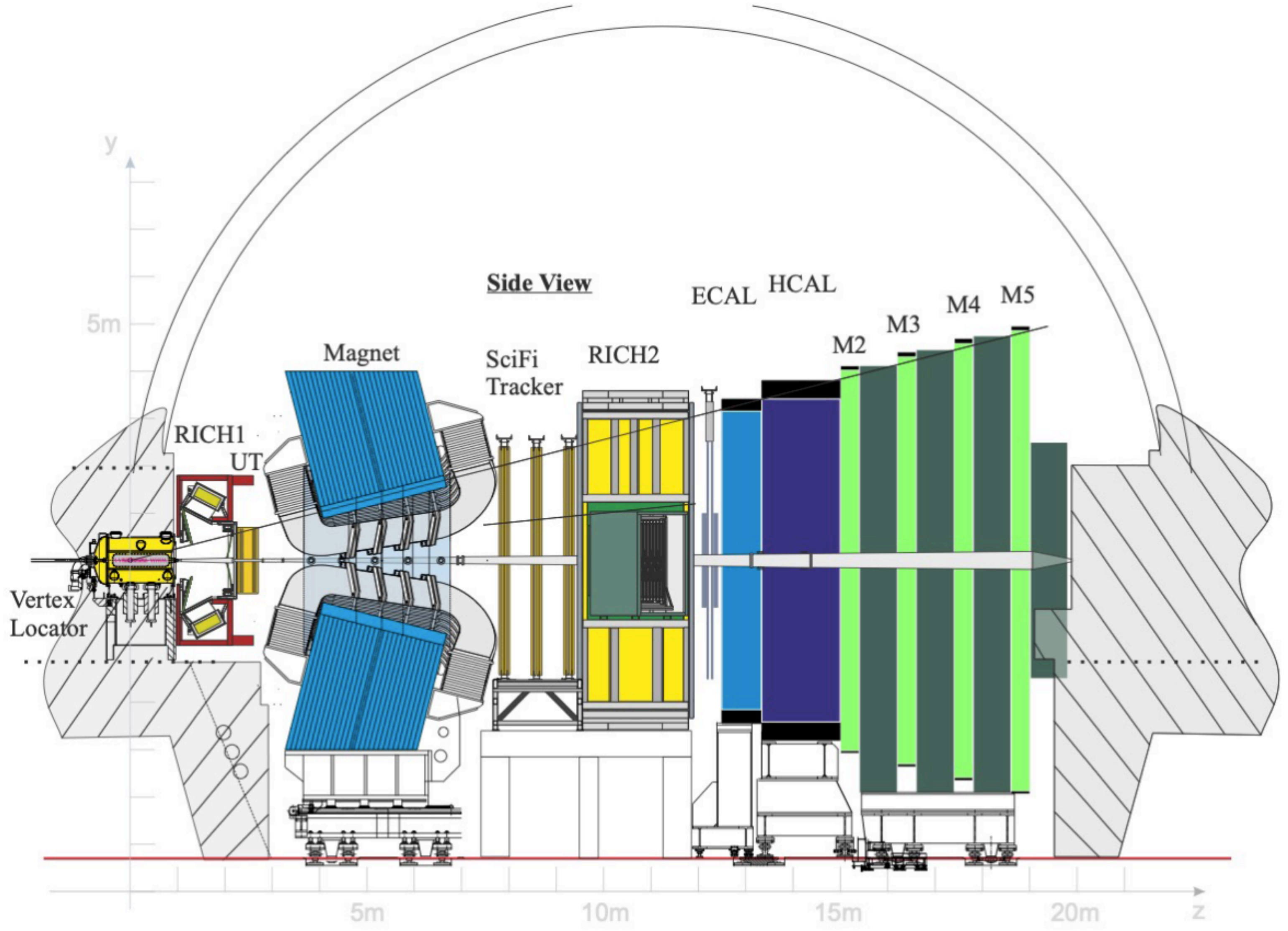
See talk from Zhiyang Yuan

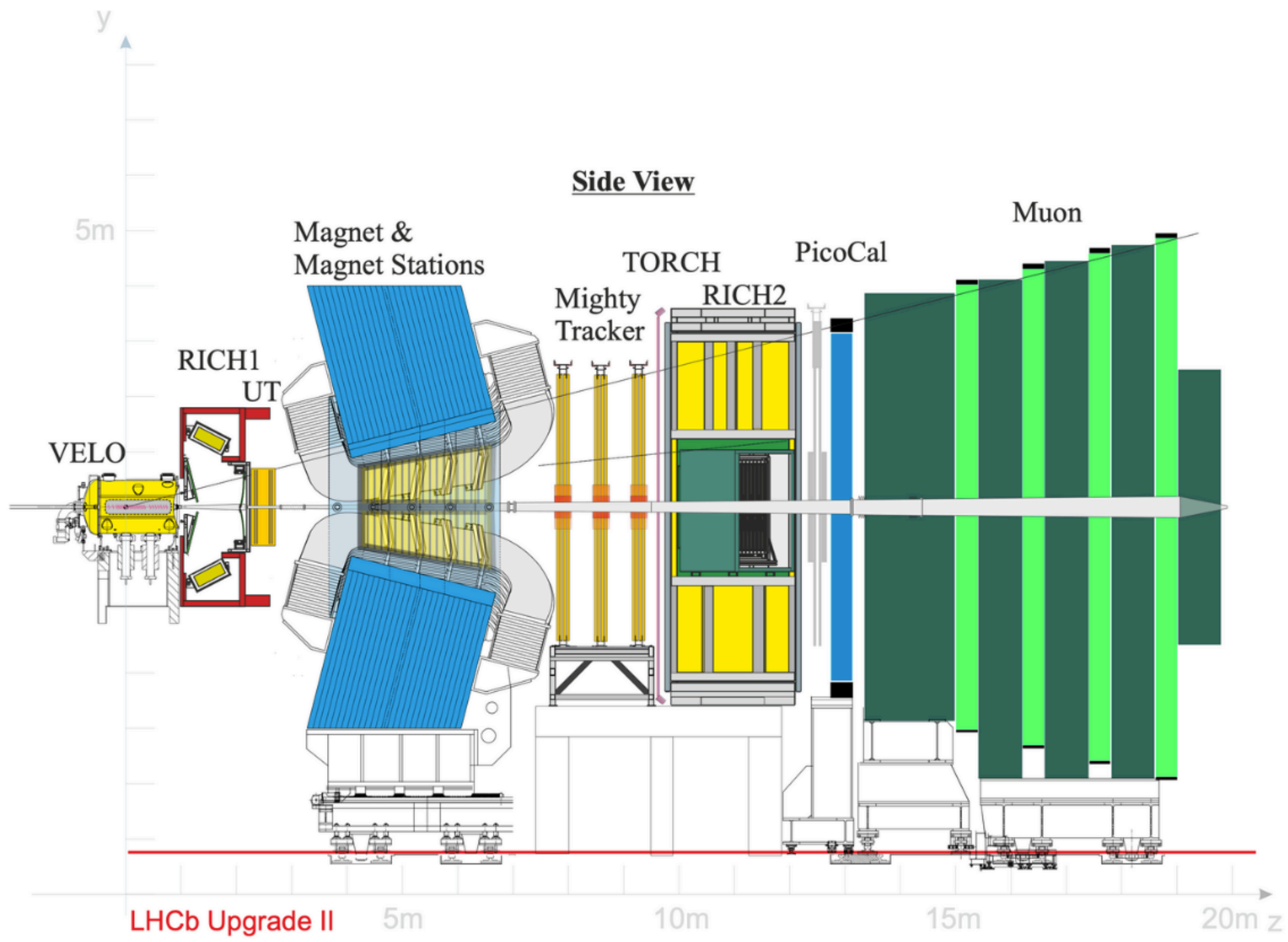
Past

Now

Future







Run1 & Run2 (2011-2018)

Run3 & Run4 (2022-2032(?))

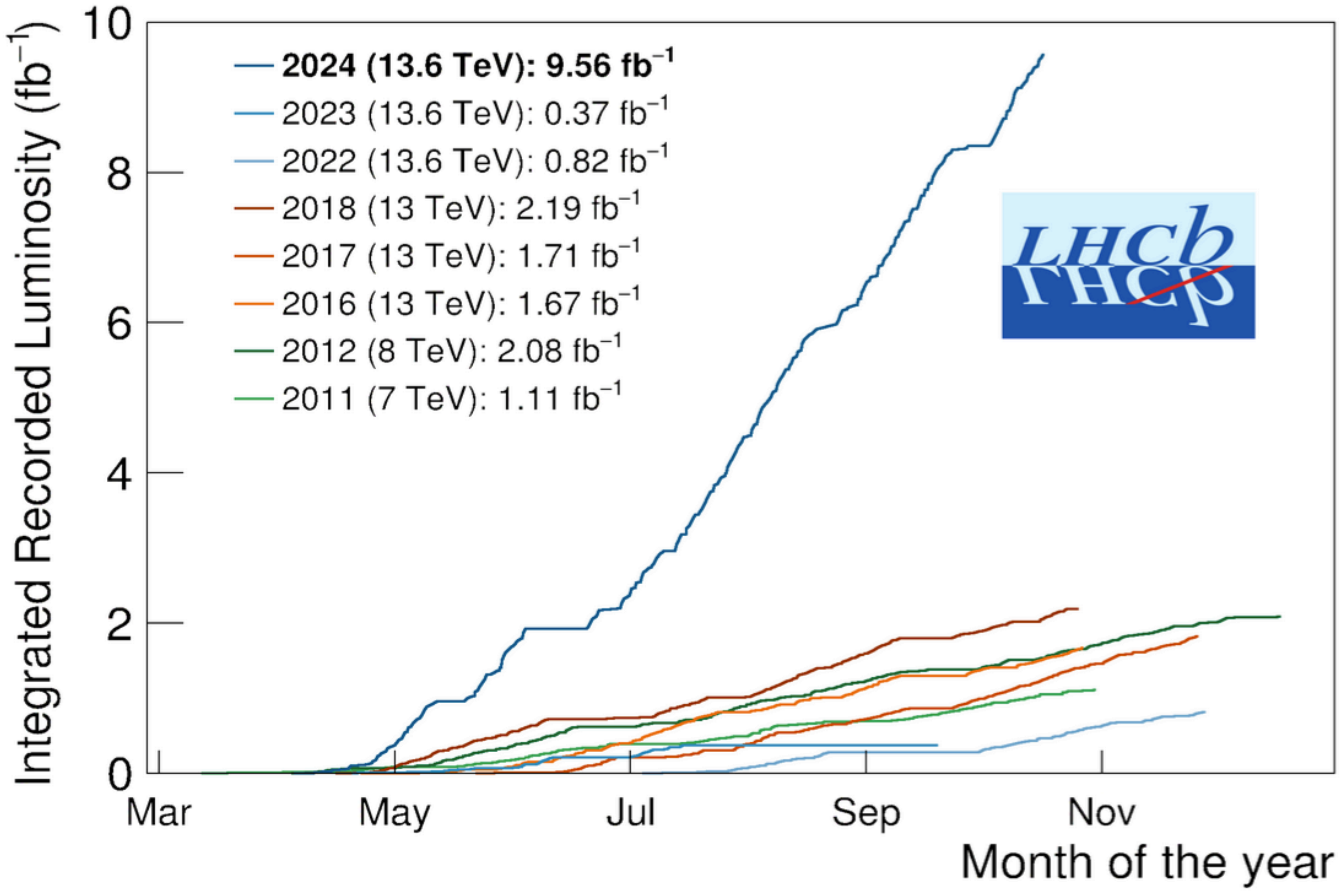
Pure software trigger

Run5 & Run6 (~2035-2040)

Timing info will be added

The goal is to collect much more data and in the meantime keep the same or even better performance than Run1&Run2

LHCb data-taking



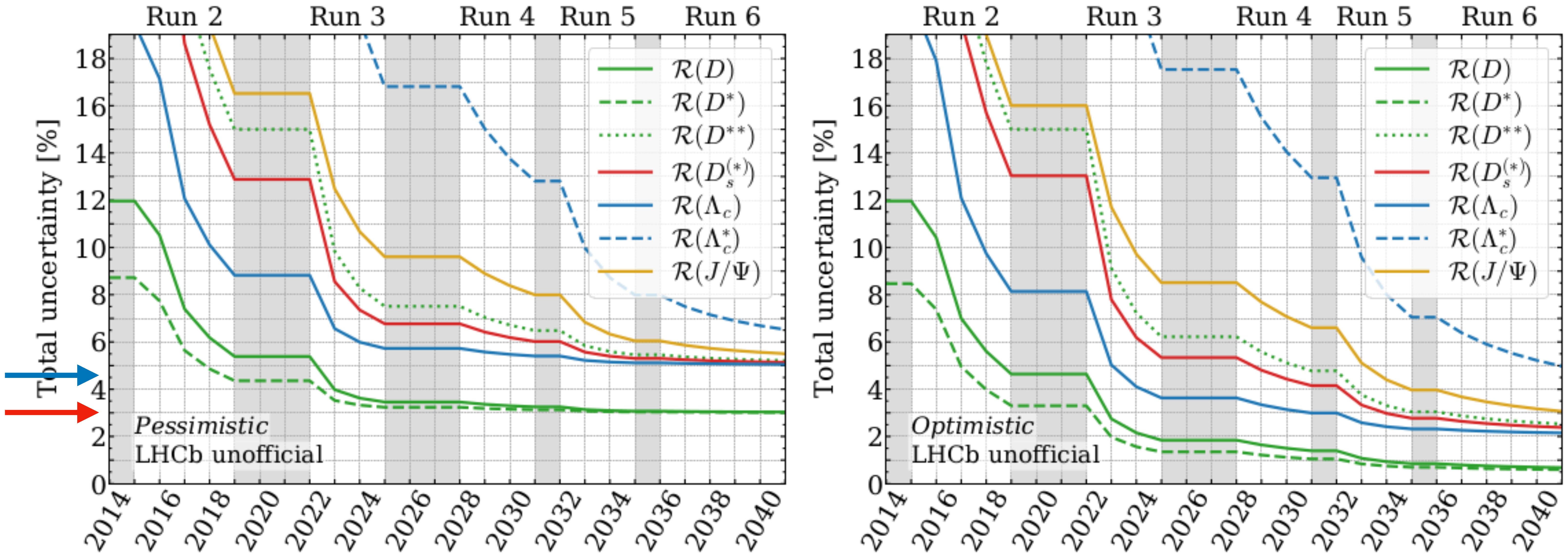
2024 > Run1+Run2 !!

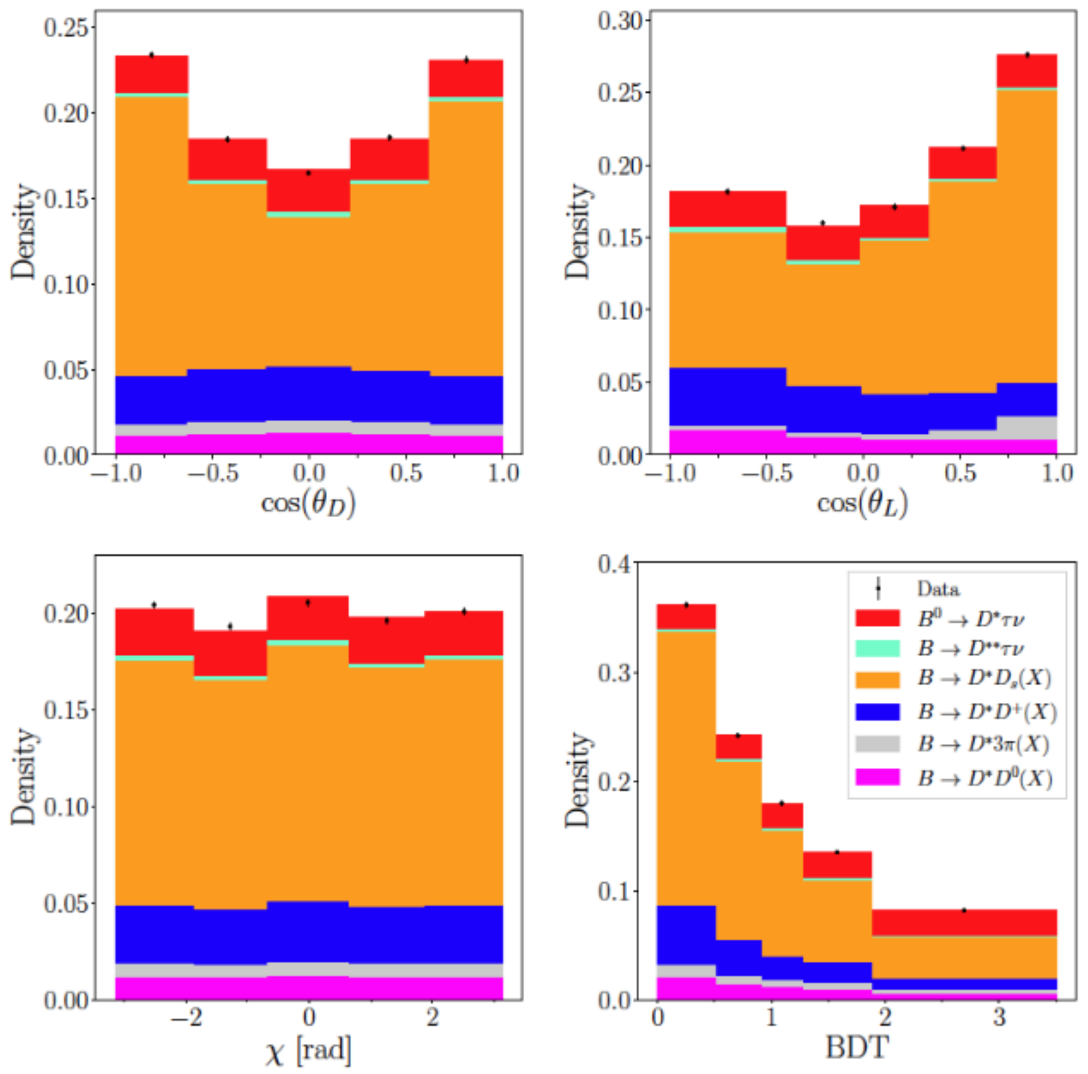
- In 2022,
  the Upstream Tracker was not installed and commissioning took long time
- In 2023,
  VELO was kept open due to a vacuum incident
- In 2024,
  VELO is back, UT is installed and working well !
- The target for end of Upgrade I(~2032): 50fb^{-1}
- The target for end of Upgrade II(~2040): 300fb^{-1}

Prospects of semitauonic decays

[Rev. Mod. Phys. 94, 015003]

- More statistics
  - Analyses including Run2 6 fb^{-1} data samples ongoing
  - Data taking in Run3
- Control of systematics
  - New technologies (fast simulation, multivariate selection…)
  - Inputs from other experiments and theorists
  - …
- Probe into various observables
  - $R(D_s^+)$, $R(\Lambda_c^+)$, $R(J/\psi)$ …
  - Polarisation measurement
  - Angular analyses





[JHEP 11(2019)133]

Prospects of angular analysis of $B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with full Run1+Run2 data sample from simulation

Prospects of rare decays involving τ

[arXiv: 1808.08865]

<Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era>

- $B^0_{(s)} \to \tau^+\tau^-$
  - $\mathscr{B}(B^0_s \to \tau^+\tau^-)$:
    Upper limit 1.3×10^{-3} (Upgrade I, 50fb^{-1}) ~ 5 times improvement
    Upper limit 5.0×10^{-4} (Upgrade II, 300fb^{-1}) ~ 2.6 times improvement
  - Inputs about resonant structure in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ from Belle II would help to reduce systematic limitation

- $B^0_{(s)} \to \tau^\pm\mu^\mp$
  - $\mathscr{B}(B^0 \to \tau^\pm\mu^\mp)$:
    Upper limit ~10^{-5} (Run1+Run2, 3fb^{-1}) ~ 5 times improvement
    Upper limit 3×10^{-6} (Upgrade II, 300fb^{-1}) ~ 3 times improvement
  - Mass reconstruction depends heavily on primary and τ vertices resolution, improvement in the tracking system required.

Prospects of rare decays involving τ

[arXiv: 1808.08865]

<Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era>

- $B \to K^{(*)}\tau^{\pm}\mu^{\mp}$
  - Sensitivity scales almost linearly with $\sqrt{\mathscr{L}}$, so for Upgrade II ($300\mathrm{fb}^{-1}$):
    - Upper limit for $\mathscr{B}(B^+ \to K^+\tau^{\pm}\mu^{\mp})$ ~ 6.2×10^{-6} at 90% CL
    - Upper limit for $\mathscr{B}(B^0 \to K^{*0}\tau^{\pm}\mu^{\mp})$ ~ 1.4×10^{-6} at 90% CL
  - P_B from reconstruction of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ or $B_{s2}^{*0} \to BK$ can give complementary info
- $\tau^- \to \mu^-\mu^+\mu^-$
  - NP theory prediction: $\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-)$ in $10^{-9} - 10^{-8}$
  - Current experimental limit: $\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.2 \times 10^{-8}$ (LHCb & B Factories)
  - LHCb during Upgrade II would probe down to $\mathcal{O}(10^{-9})$
- FCNC processes like $B \to K^{(*)}\tau^+\tau^-$, $\Lambda_b^0 \to pK^-\tau^+\tau^-$ ...
  - Analyses ongoing, hopefully results will be revealed in the near future
  - Precision expected ~ $\mathcal{O}(10^{-5}) - \mathcal{O}(10^{-3})$

Summary

- LHCb has reported a lot of physics results involving τ-lepton:
  - For LFU tests using semitauonic decays, precisions are comparable with results from B Factories
  - For rare decays, searches for LFV have pretty good sensitivity ~$\mathcal{O}(10^{-5})$
  - For both sides, LHCb also provides valuable measurements for $B_s^0, B_c^+, \Lambda_b^0 \ldots$
- With more data taken(even existing data), more results are expected:
  - Improving precision for published results: $R(X_c)$, $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$, $\mathcal{B}(B_{(s)}^0 \to \tau^\pm\mu^\mp)$...
  - Looking at other observables: $\mathcal{B}(H_b \to H_s\tau^+\tau^-)$, angular observables of $R(X_c)$...
- Many challenges ahead, but also many gains and pleasures !

Thank you for listening!