ALPINE PARTICLE PHYSICS SYMPOSIUM 2023

OBERGURGL, AUSTRIA

Results from LHCb *on Lepton Flavour Universality tests in $b \to c\ell\nu$ transitions*

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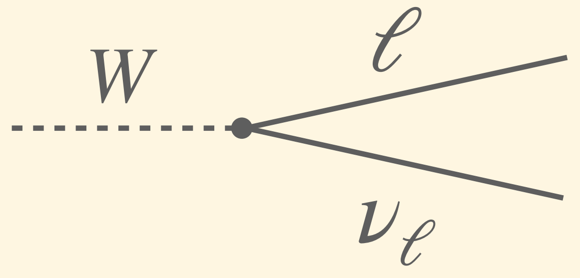
LFU: *WHO ORDERED THAT?*

Lepton Flavour Universality (LFU) := the **electroweak coupling** of bosons $(W^{\pm}, Z^0)$ to leptons is **identical**.
Yukawas y_ℓ are the only interactions **distinguishing** among leptons.



- LFU is an ***accidental*** and ***approximate*** *symmetry* of the Standard Model (SM), arising in the limit: $\mathscr{L}_{\rm SM} = \mathscr{L}^{[d\leq 4]}, \quad y_\ell \to 0.$

$$\mathscr{L}_{\rm SM} = \mathscr{L}^{d\leq 4} + \sum_{i,d} \frac{c_i^{[d]}}{\Lambda_{\rm NP}^{d-4}} O_i^{d\geq 5}$$

low-energy limit:
Lepton Flavour Universality

high-energy:
NP Operators (scalar, vector, tensor ..)

- Well motivated theoretical interest to **test the assumptions**, regardless of the tantalising experimental scenario
- Need to better **constrain** LFU in the **heavy quark** sector (b, c)

LFU IN TREE-LEVEL $b \to c\ell\nu$

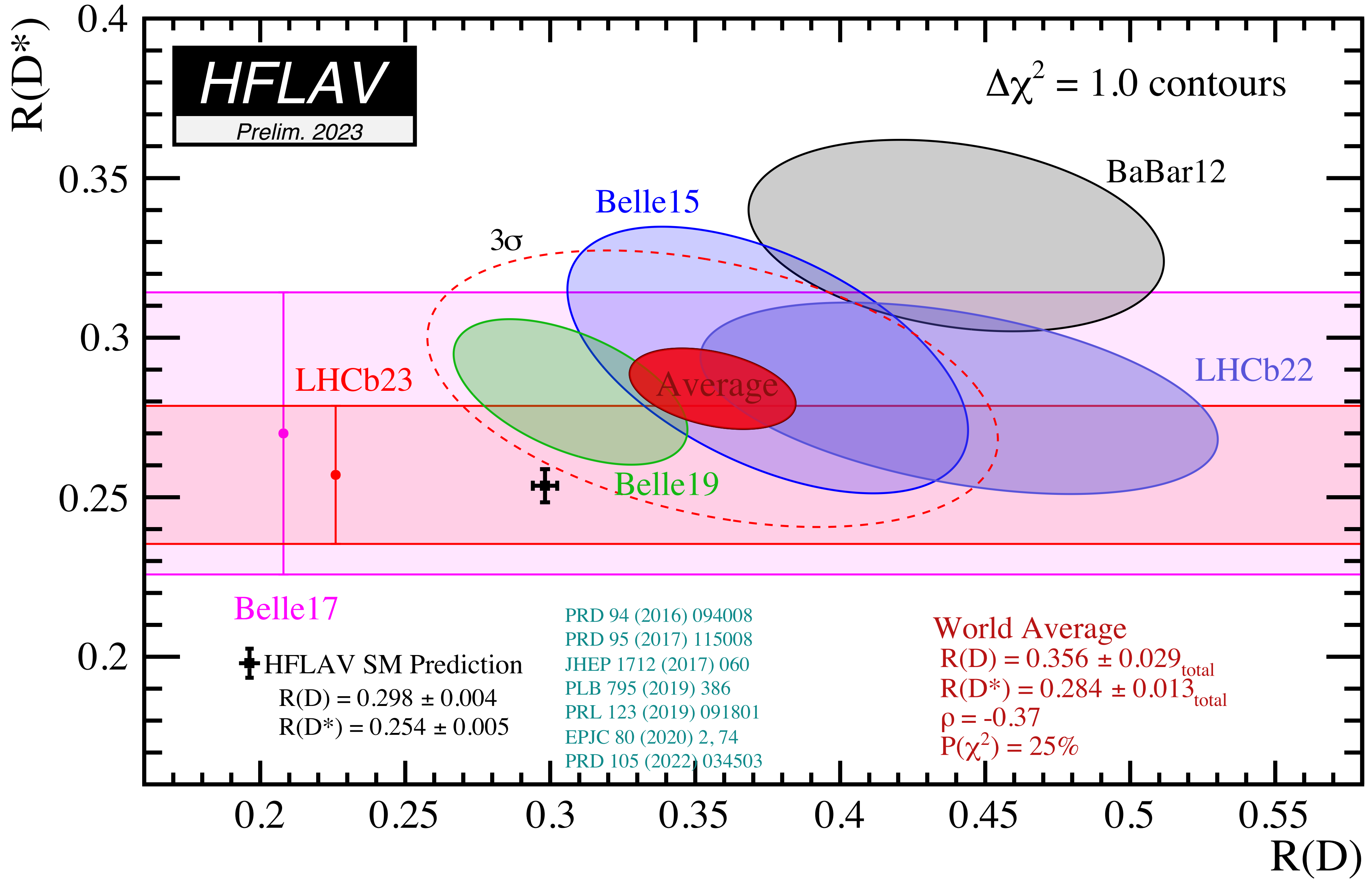
What are the *Flavour anomalies* ?

Hints for LFU **violation** in a variety of semileptonic tree-level measurements, deviating $\sim 3\,\sigma$ from the SM.

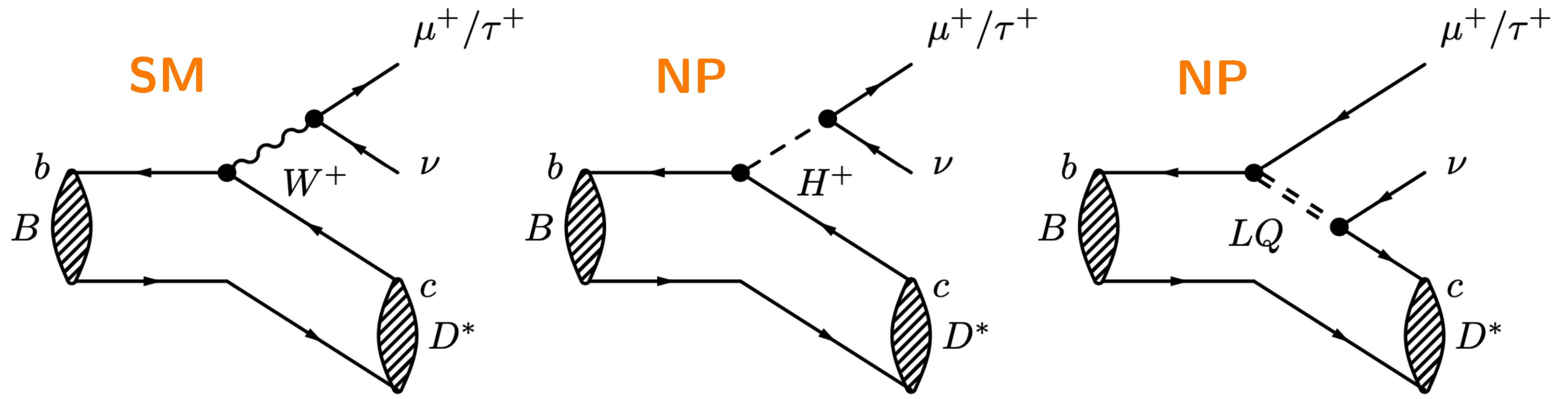
Comprehensive discussion on Flavour Anomalies at LHCb ☞ Patrizia De Simone's [talk]

- Test of LFU involving the 3rd generation of quarks and leptons ($b \to c\ell\nu$):

$$R(D^{(*)}) = \frac{\mathrm{BR}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)} \begin{array}{l} \longrightarrow \textit{signal} \\ \longrightarrow \textit{normalisation} \end{array}$$



- **Experimentally advantageous**: large yields and removal of common systematics
- **Reduced theoretical uncertainties**: most Form Factors (non-helicity suppressed) cancel out in the ratio



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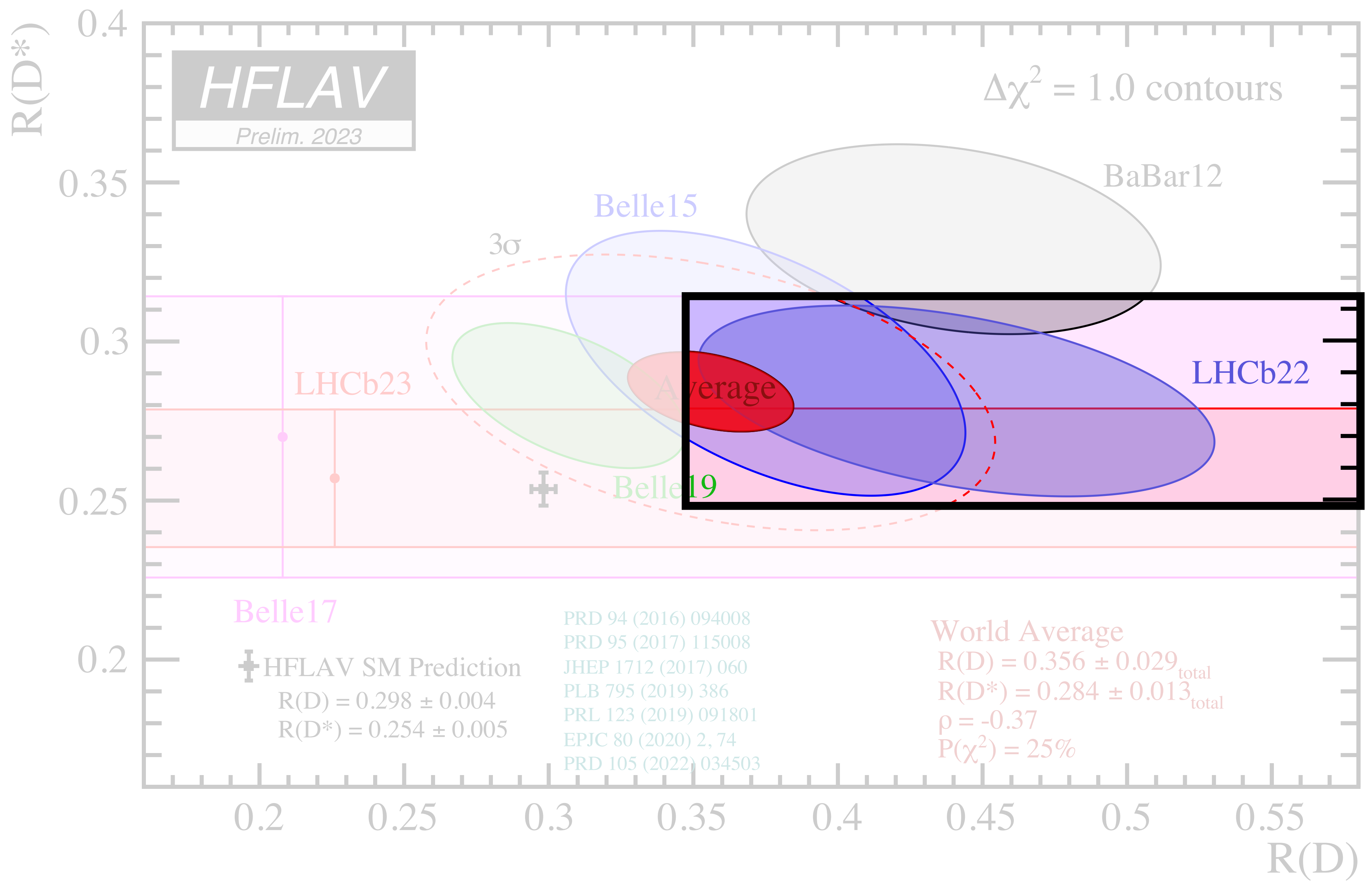


NEW LHCb MEASUREMENT

Covered in this talk:

Combined measurement of $R(D)$ and $R(D^*)$ with a muonic tau decay

Announced in Dec. 2022: [arXiv:2302.02886], to appear in PRL

COMBINED MEASUREMENT OF MUONIC R(D)-R(D*)

[arXiv:2302.02886], submitted to PRL

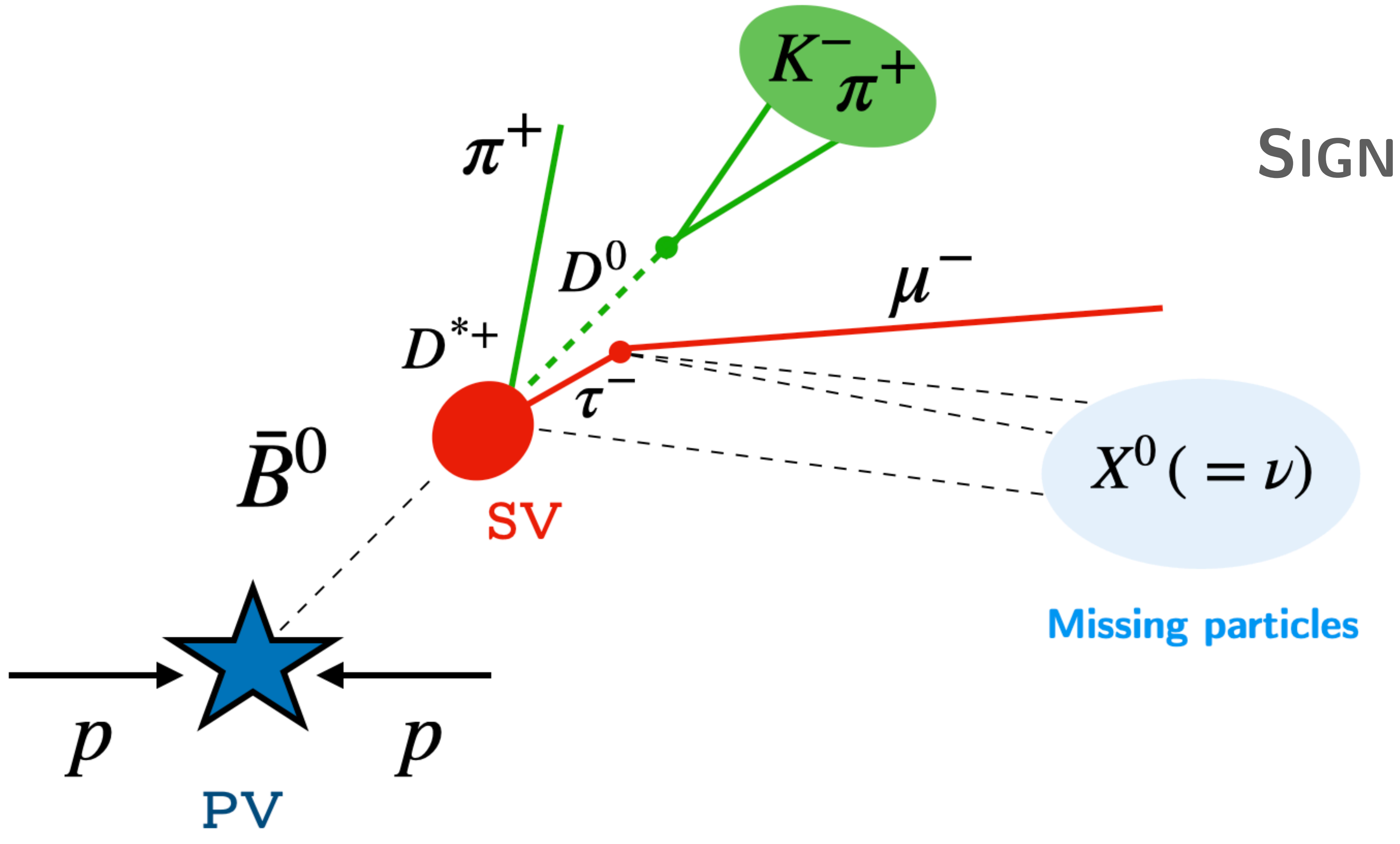
$$R(D^{(*)}) = \frac{\mathrm{BR}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)} \begin{array}{l} \longrightarrow \textit{signal} \\ \longrightarrow \textit{normalisation} \end{array}$$

- Analysis of **Run1 data**, corresponding to $3\,\mathrm{fb}^{-1}$
- **Simultaneous measurement** of $R(D)$ and $R(D^*)$
- Disjoint **signal** samples:
  - $\bar{B}^0 \to (D^{*+} \to D^0\pi^+)\,\tau^-\bar{\nu}_\tau$
  - $B^- \to (D^0 \to K^-\pi^+)\,\tau^-\bar{\nu}_\tau$, vetoing D^{*+}
- Reconstruct the **muonic decay** of the τ

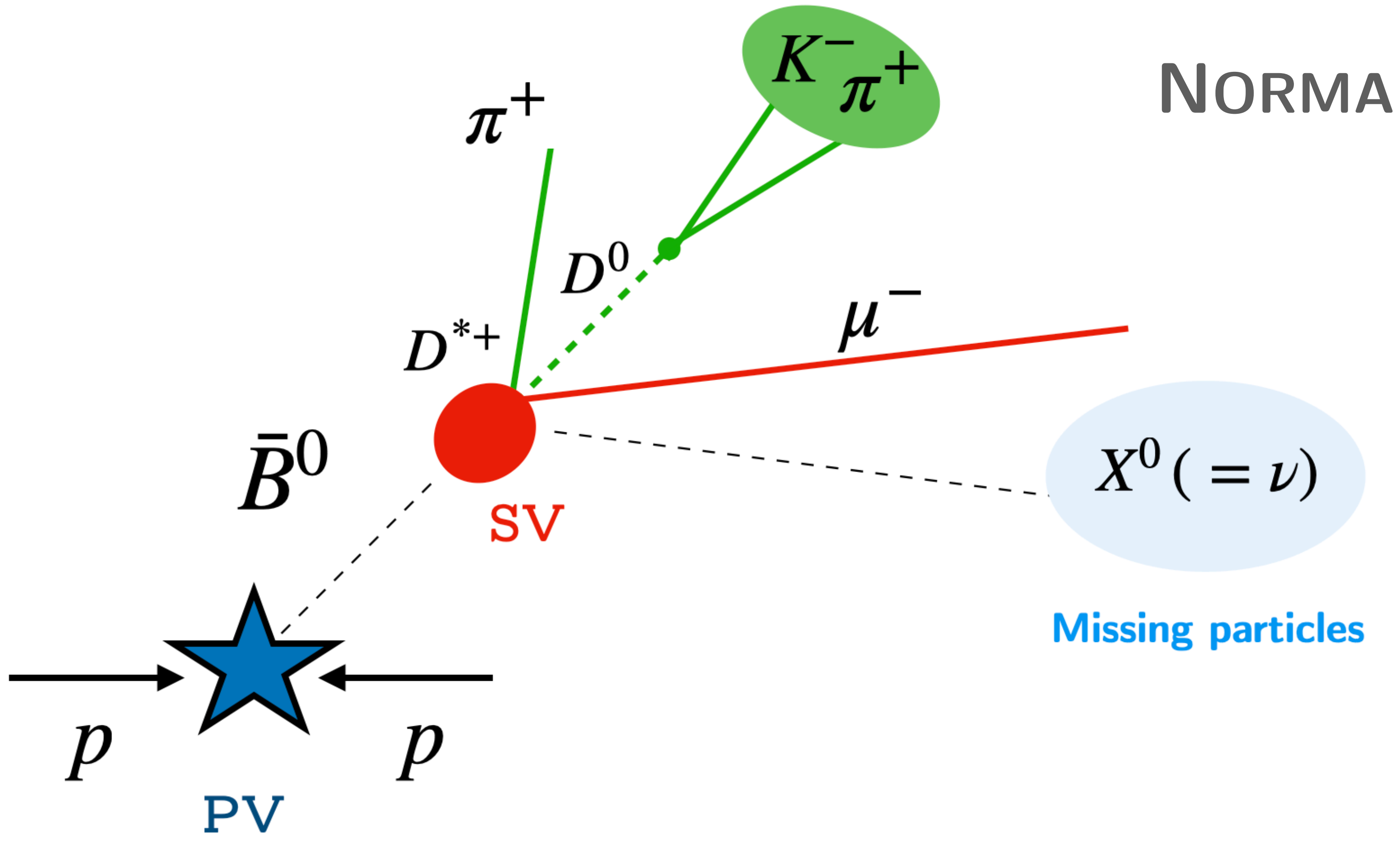
  - **Large yields**: BR $(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) \sim 17.4\,\%$

  - **Same final state** of the **normalisation** decay
- Trigger on the reconstructed D^0 part

SIGNAL MODE

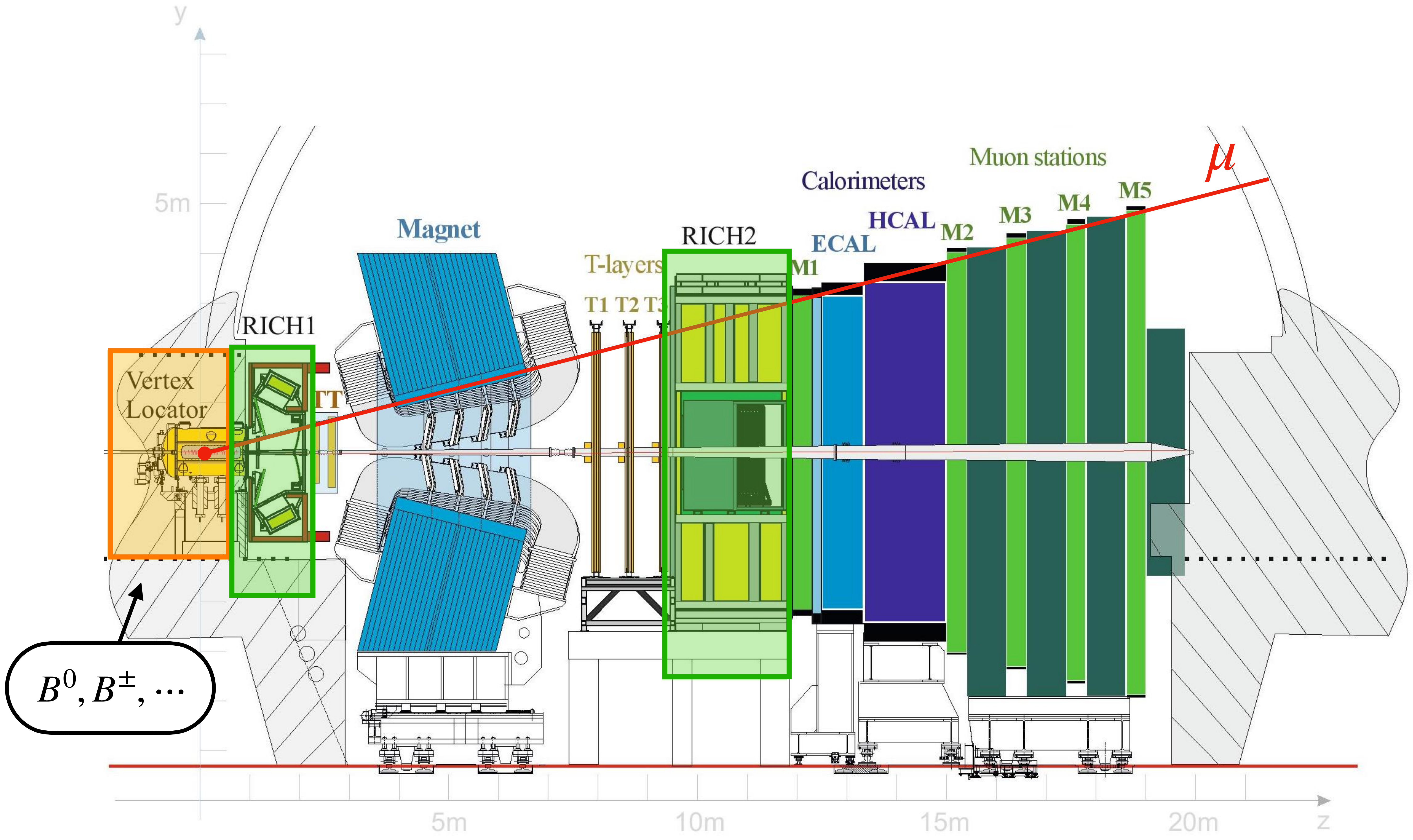


NORMALISATION MODE



MEASURING B DECAYS AT LHCb (Run1, Run2)

[LHCb-DP-2014-002]



- Ingredients to measure semi-leptonic B decays

  - Excellent ***vertex resolution***: **VELO**

  $$\sigma_{\mathrm{IP}} \simeq 15 + \frac{29}{p_{\mathrm{T}}} \mu\mathrm{m}$$

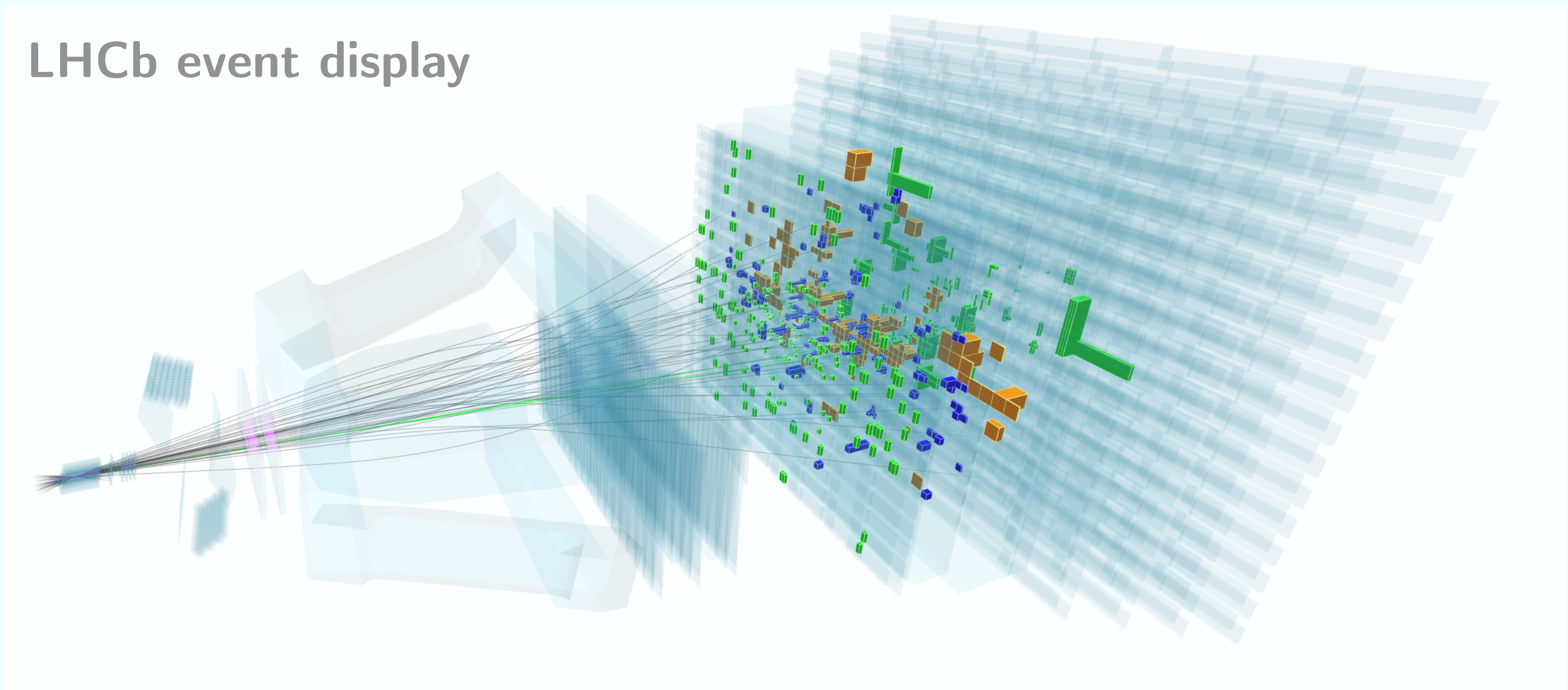
  - Particle Identification (***PID***): **RICH1**, **RICH2**

  $$\epsilon_{\mathrm{PID}}(\mu) \simeq 97\,\% \,, \quad \epsilon_{\mathrm{misID}} < 5\,\%$$

  - Good ***momentum resolution***: more than 20m of **tracking** (μ)

  $$\delta p/p \in [0.5\,\%\,, 1\%], \quad p \in [5, 200]\,\mathrm{GeV}$$

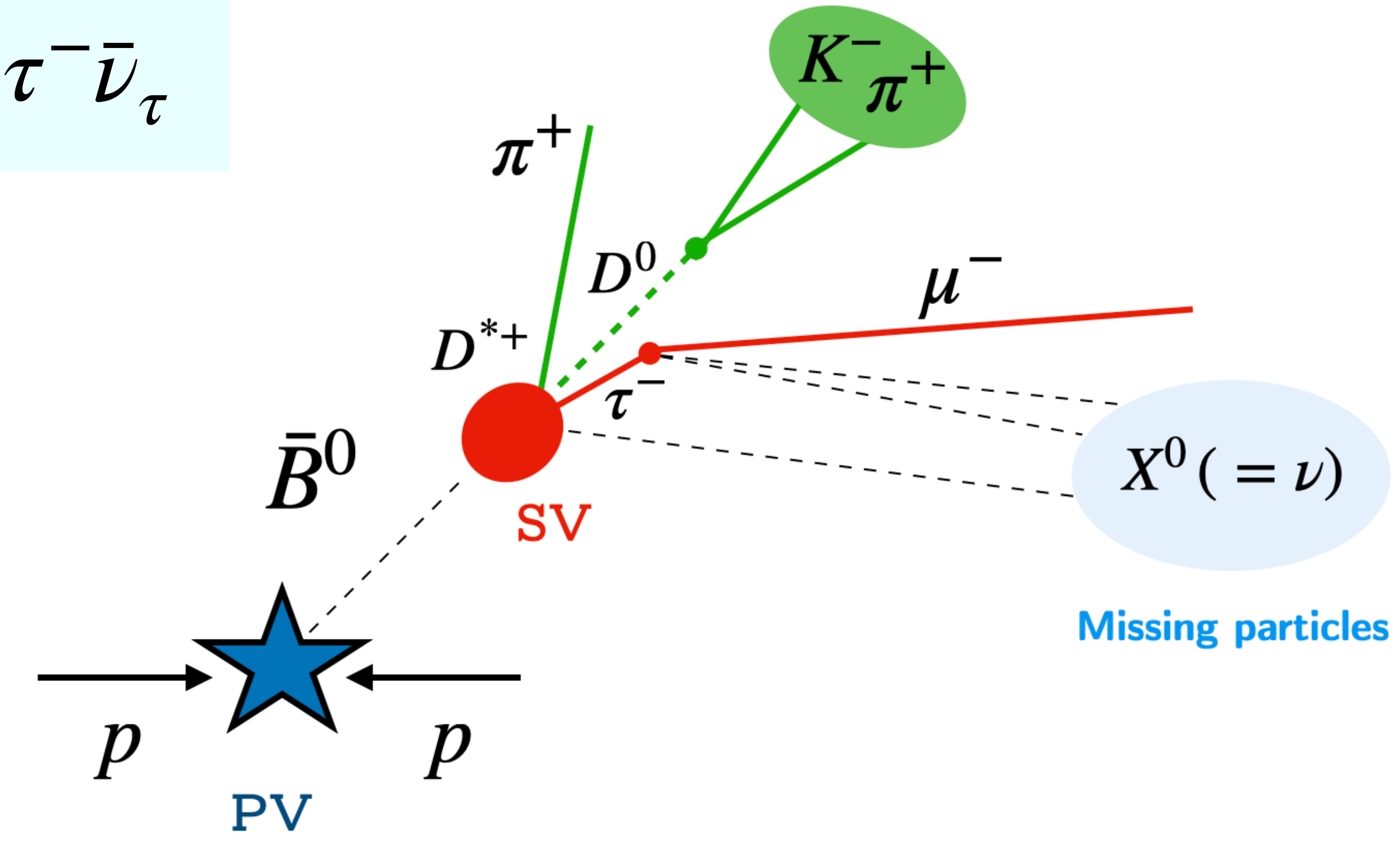
  - Flexible and efficient **Trigger**

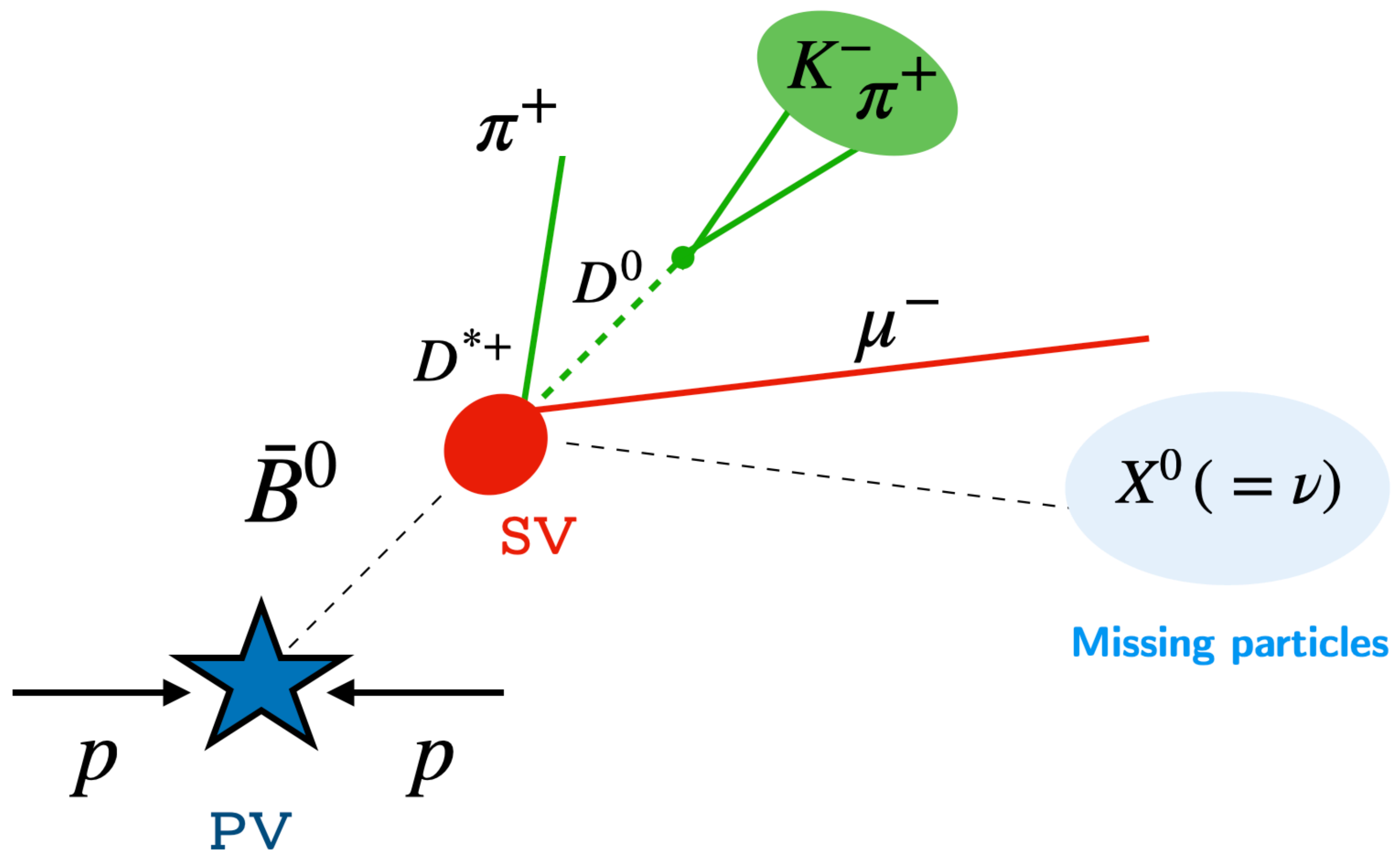


EXPERIMENTAL CHALLENGES

[arXiv:2302.02886], submitted to PRL

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





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

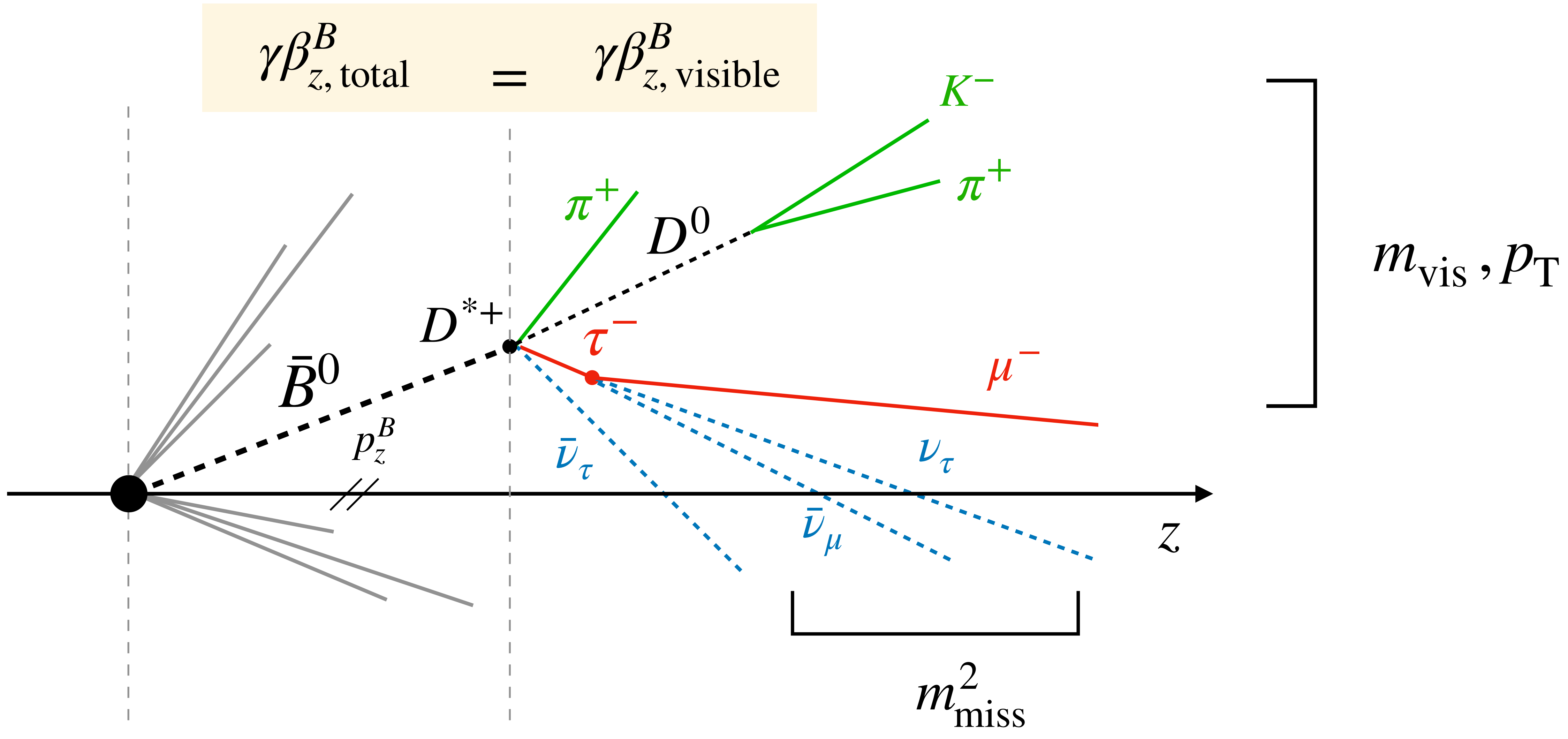
- **Missing particles** in the final state (undetected neutrinos)
  - In addition to combinatorial and mis-identified backgrounds, a plethora of **partially reconstructed backgrounds**:

$$B \to D^*\mu\nu, \quad B \to D^{**}\mu\nu, \quad B \to D^*(D \to \mu X)X \quad \cdots$$

- **Short-lived** τ, cannot reconstruct its decay vertex in the VELO
- In pp collisions the $B\bar{B}$ **centre of mass** is not fixed
  - Use the large Lorentz boost in the hadronic environment to constrain the decay kinematics

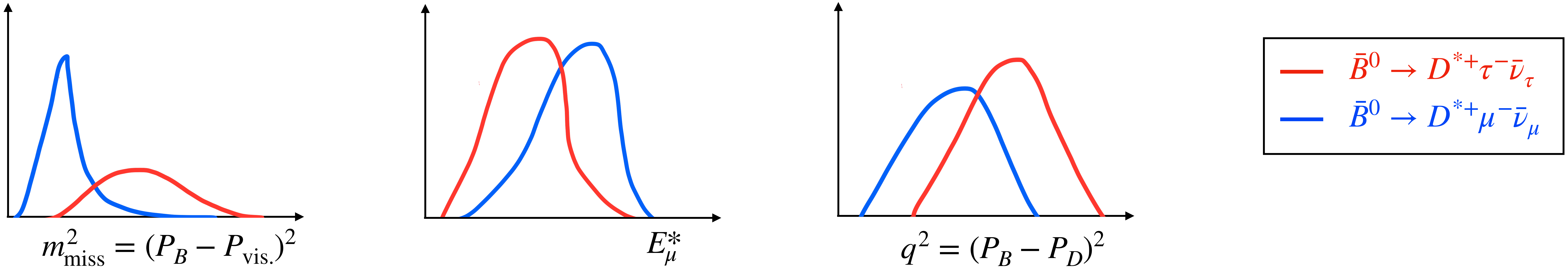
RECONSTRUCTING THE B KINEMATICS

[arXiv:2302.02886], submitted to PRL



- $p^B_\perp$: **line of flight** of the B to deduce the missing momentum
- $p^B_\parallel$: **B frame approximation**: $\gamma\beta^B_{z,\,\text{total}} = \gamma\beta^B_{z,\,\text{visible}}$
- $\dfrac{\delta p^B}{p^B} \sim 20\,\%$

- Characterise the decay via the **rest frame** quantities:



TAMING THE BACKGROUNDS

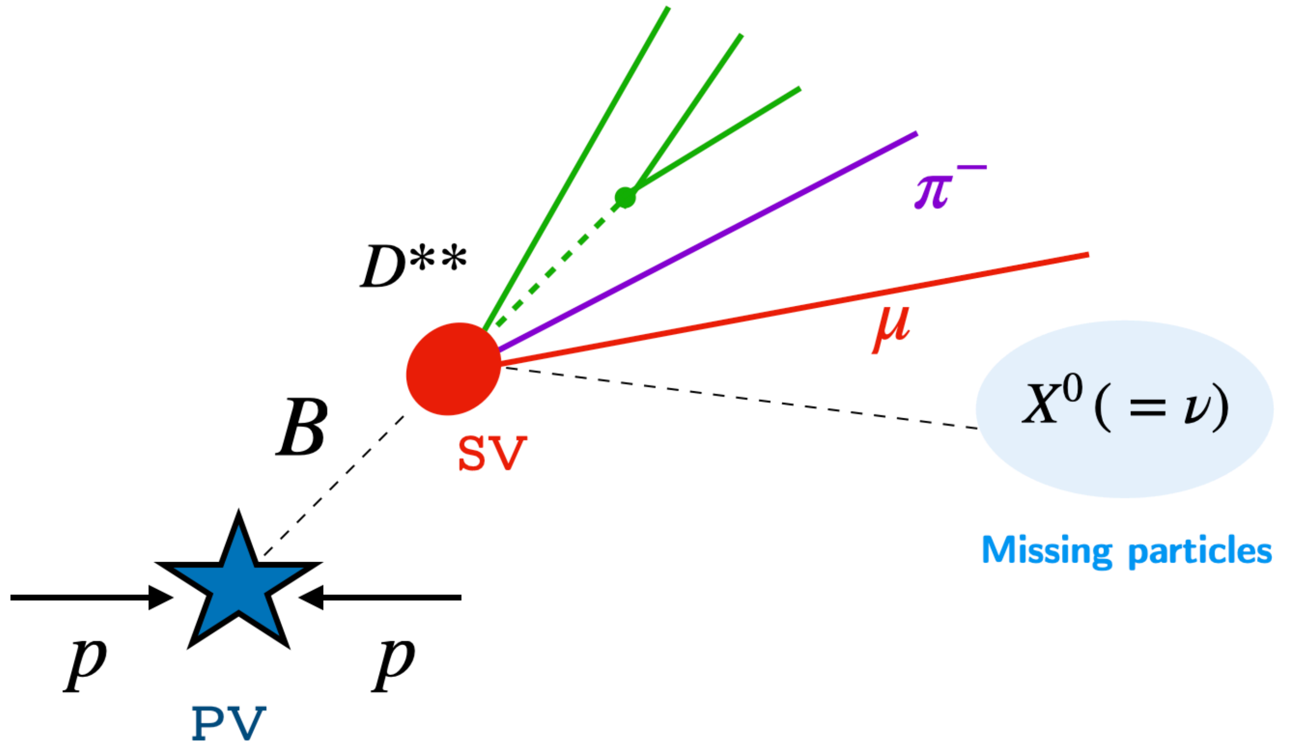
[arXiv:2302.02886], submitted to PRL

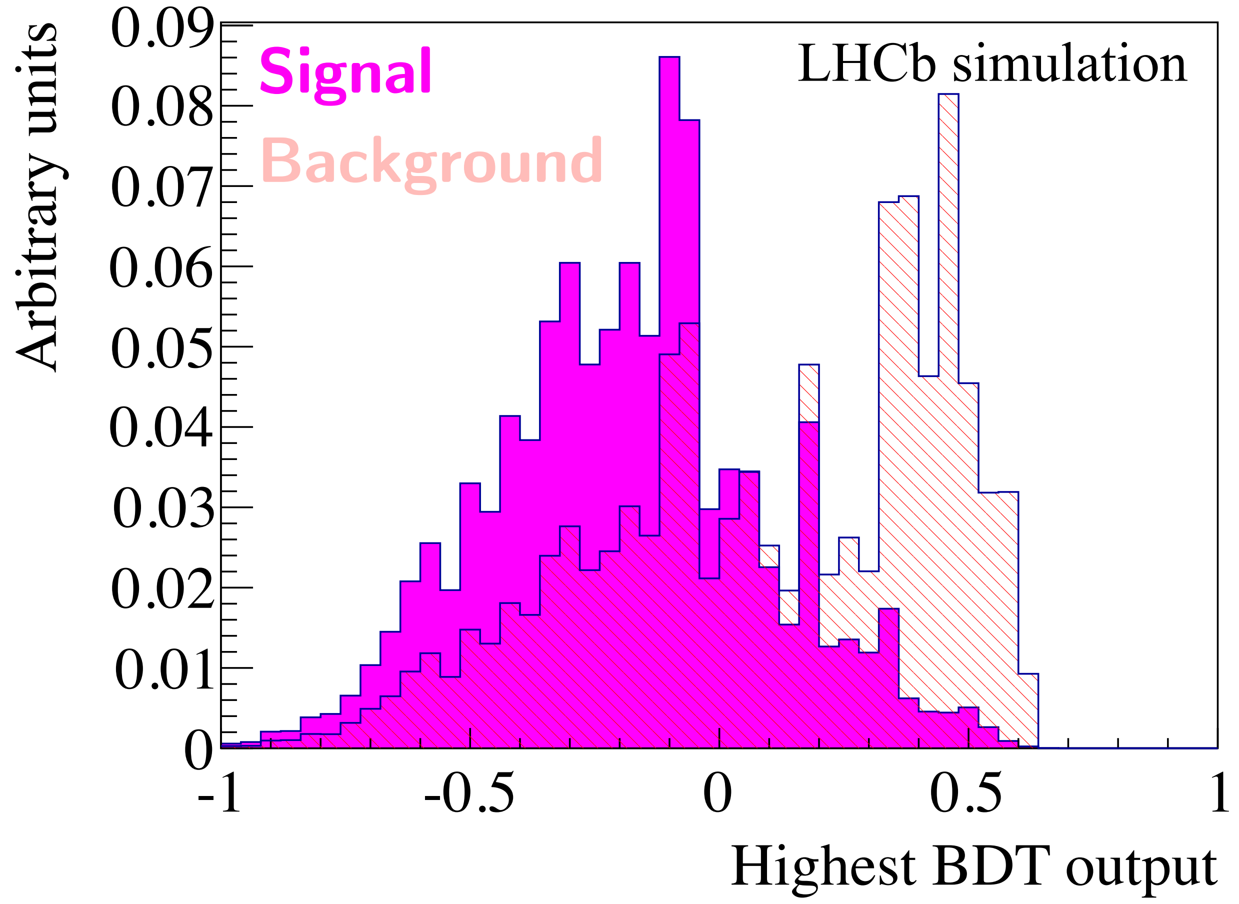
- ## CHARGED ISOLATION

  - Reject backgrounds with **additional charged** tracks (**feed down**)

$$\bar{B} \to (D^{**} \to D^{(*)}\pi^-)\,\ell\nu$$
$$\bar{B} \to (D^{**} \to D^{(*)}\pi^+\pi^-)\,\ell\nu$$
$$\bar{B} \to D^*(D \to \ell X)\,K$$

  - **MVA based** classification: probability to be associated to the PV





- ## MUONID

  - Improved muon ID classification
  - Reject backgrounds with a **hadron misidentified as muon** (data driven):

$$D^{(*)}h, \quad h \in [\pi, K, p, e, \mathrm{fake}]$$

- ## SELECTION AND VERTEX QUALITY CUTS

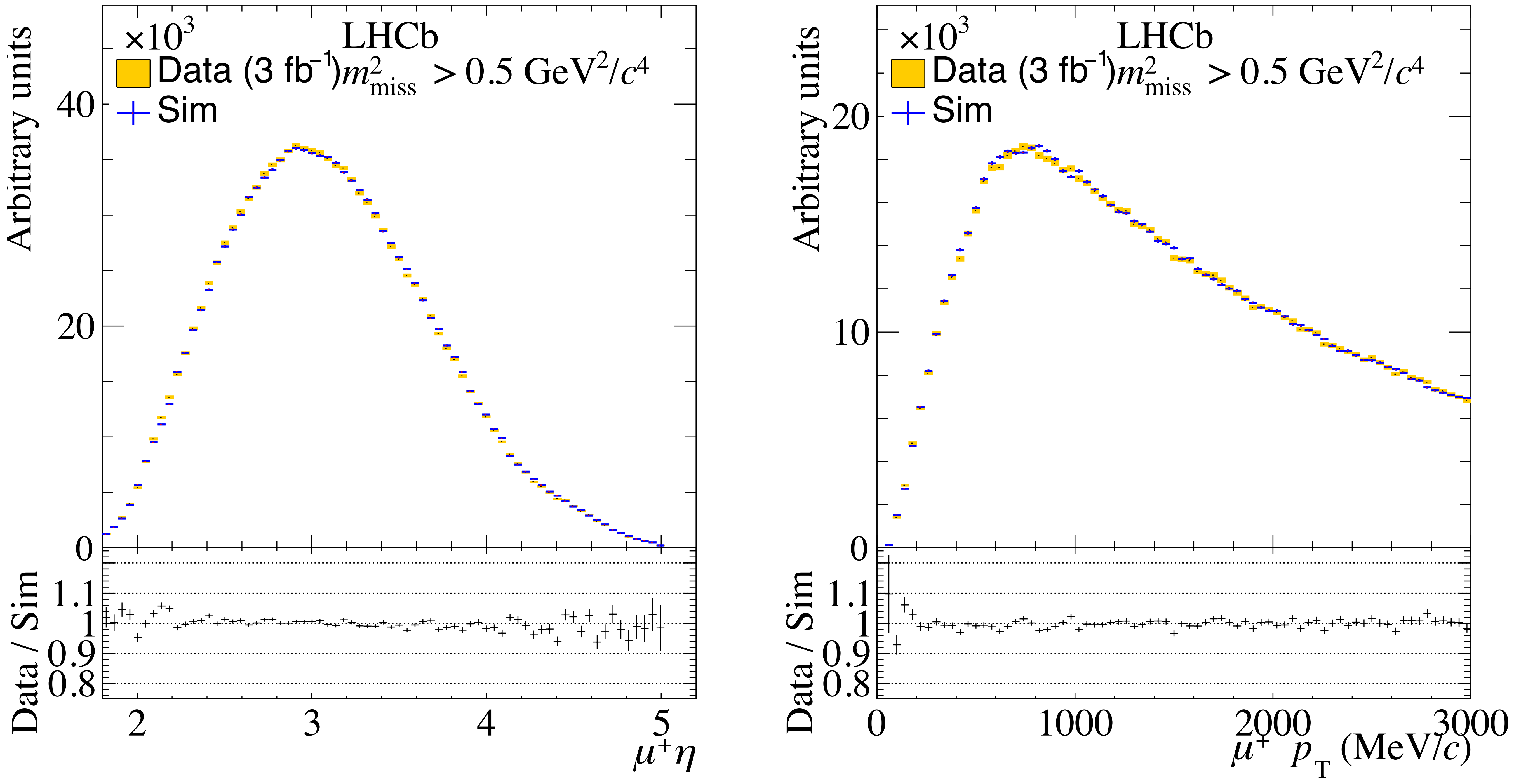
  - Reject backgrounds with a **fake** B or D^*
  - Model with **data** samples with the **same sign**

DATA/MC AGREEMENT

[arXiv:2302.02886], submitted to PRL

Much care devoted to the understanding of the **differences** between **Data** and **MC**

- Correct for **detector** and **physics effects**
  - $B \to J/\Psi\, K$ control sample:
    B production kinematics, detector occupancy, trigger
  - **Iterative strategy**: removing residual differences by reweighting on the $D^0\mu$ data
    - Use control region $m^2_{\text{miss}} < 0.4\,\text{GeV}^2$
    - Preliminary fit to compare the summed cocktail to the data



FIT STRATEGY

[arXiv:2302.02886], submitted to PRL

- **3D maximum likelihood fit**, validated with two independent fitters. Use the **rest frame** quantities:

$$m^2_{\text{miss}}, \quad E^*_\mu, \quad q^2$$

- **Simultaneous fit to 8 regions**
  - **Signal region**: $(D^0\mu)$ and $(D^{*+}\mu)$
  - 3 control regions (background enriched)

- **One pion sample** (1 extra π associated to B)

  D^{**} backgrounds

- **Two pion sample** (2 extra π associated to B)

  Heavier D^{**} states and non-resonant backgrounds

- **One Kaon sample** (1 extra K associated to B)

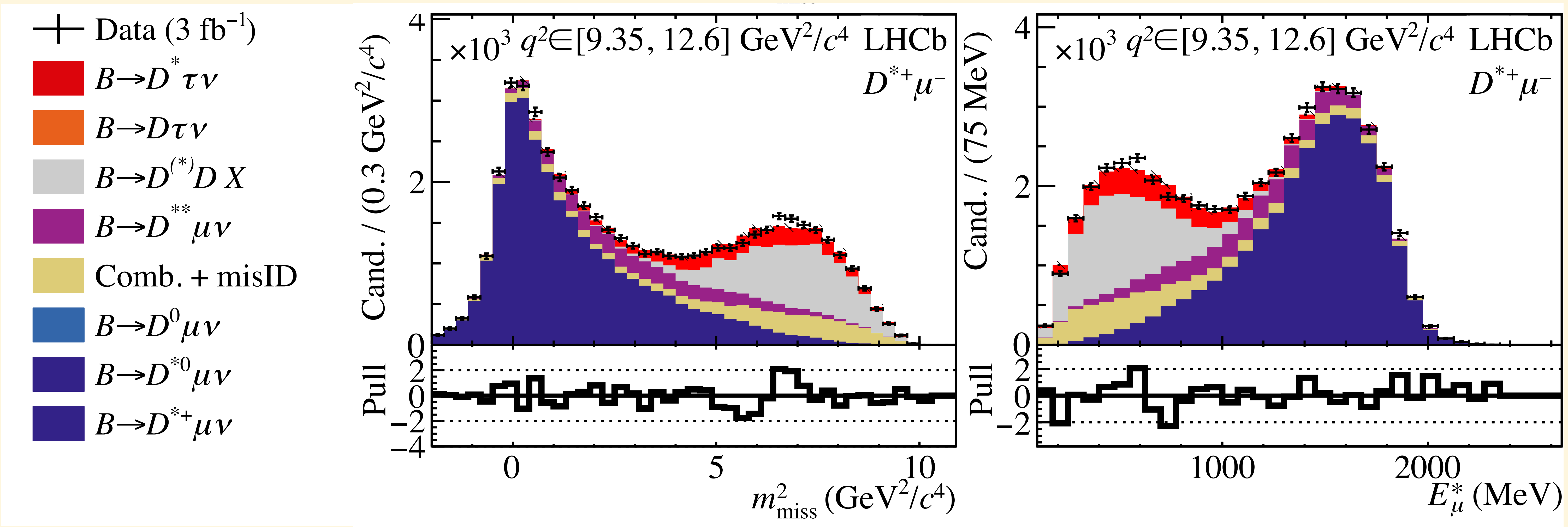
  Backgrounds $B \to D^0DX$, semi-leptonic D decay

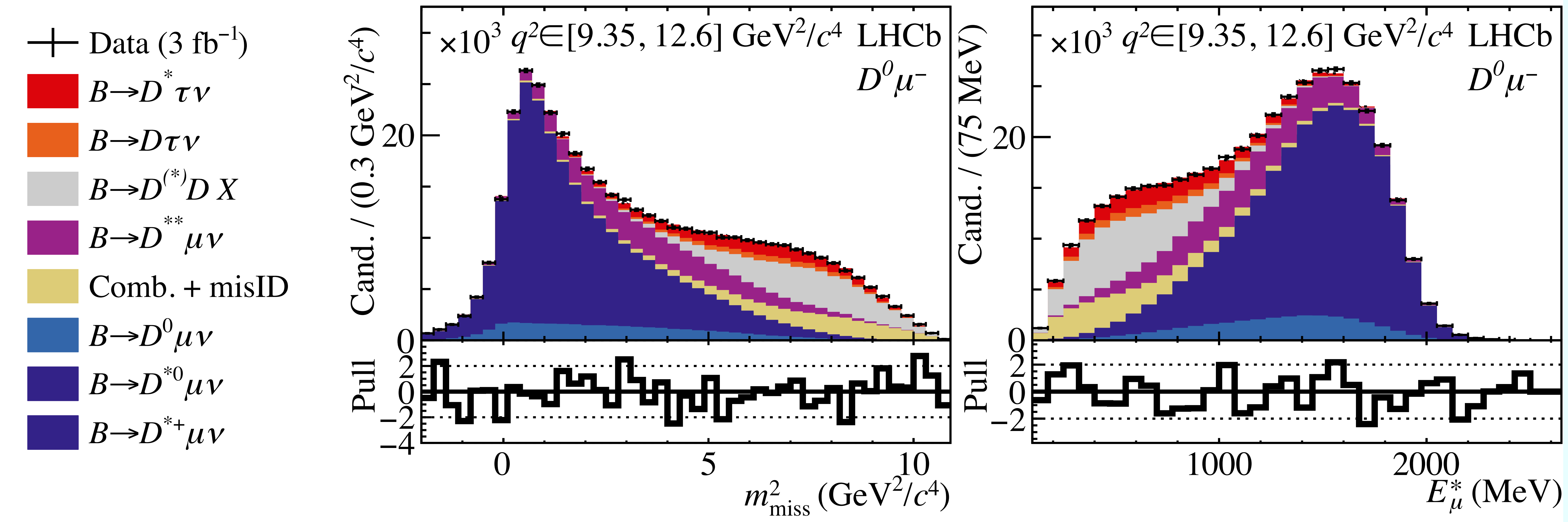
SIGNAL REGION FIT

[arXiv:2302.02886], submitted to PRL

FORM FACTORS, long distance QCD effects:

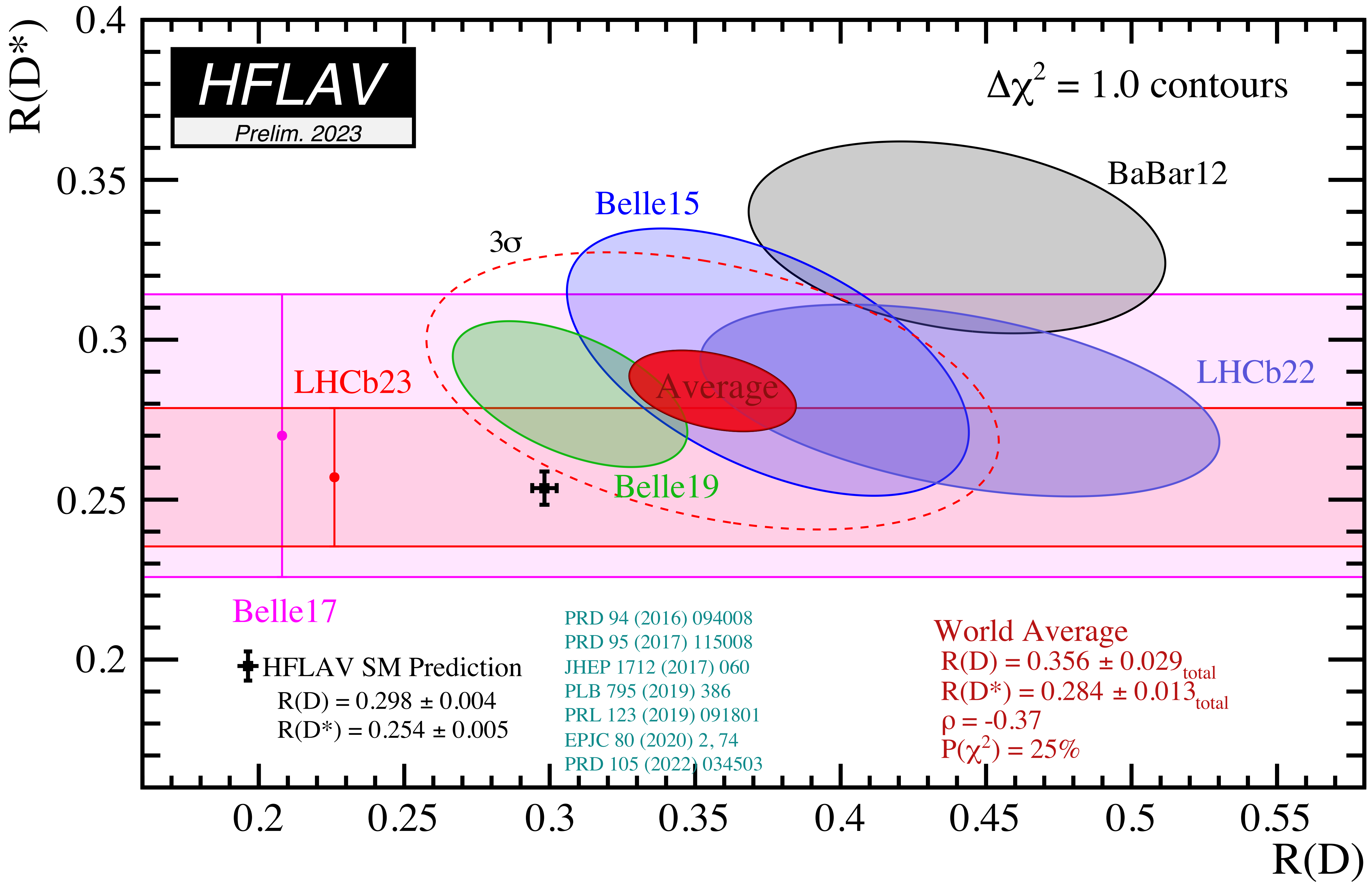
- $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$: BGL parameterisation
  [JHEP11(2017)061]
- $B^- \to D^0\ell^-\bar{\nu}_\ell$: BCL parameterisation
  [Phys. Rev. D 92, 054510]
- Theory constraint on helicity-suppressed terms. Other terms floating in the fit.





RESULT

[arXiv:2302.02886], submitted to PRL



- **First combined measurement of muonic $R(D)$ and $R(D^*)$ at a hadron collider**

$$R(D) = 0.441 \pm 0.060\,(\text{stat}) \pm 0.066\,(\text{sys})$$

$$R(D^*) = 0.281 \pm 0.018\,(\text{stat}) \pm 0.024\,(\text{sys})$$

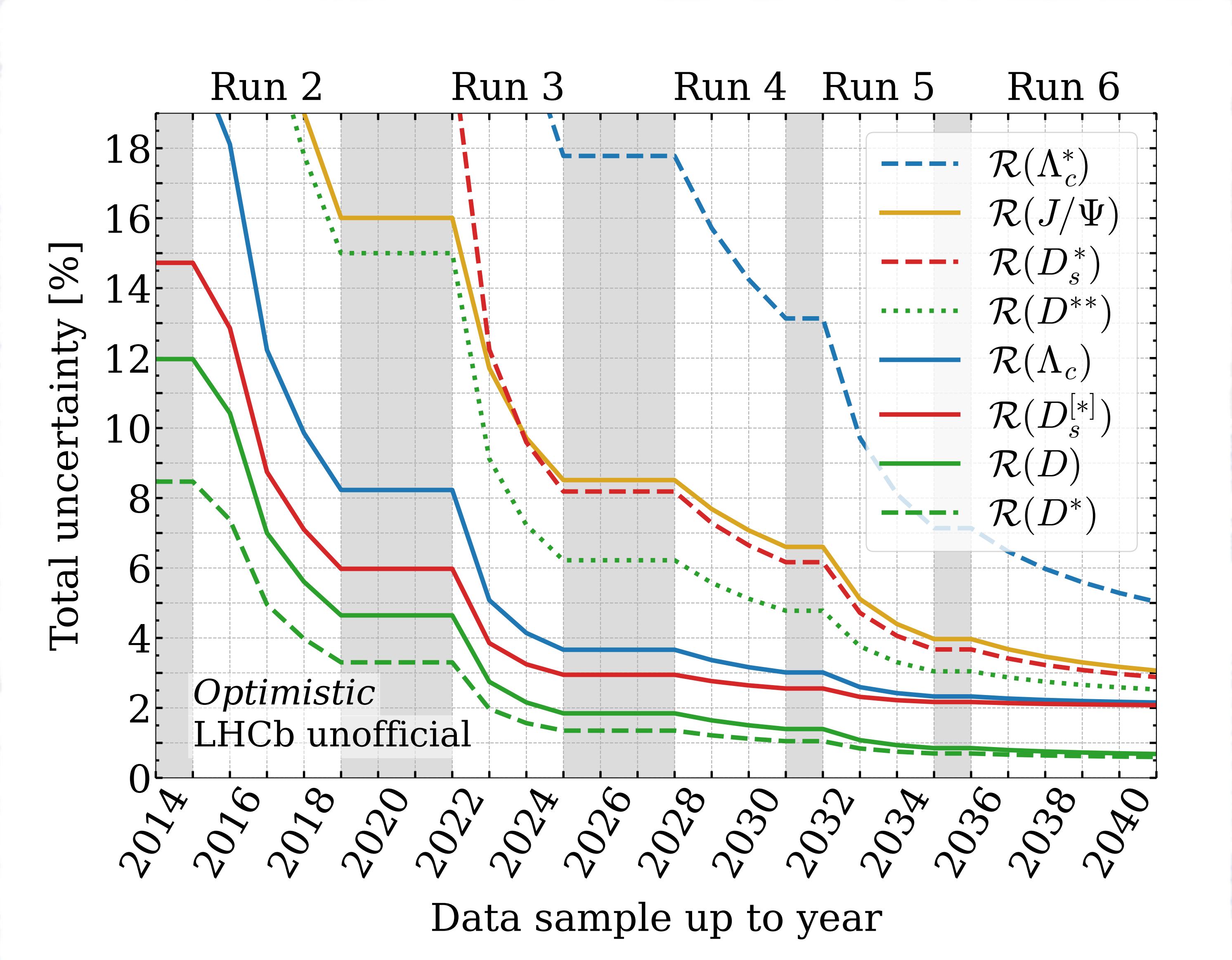
Consistent with the SM at $1.9\,\sigma$ level

- Dominant systematic uncertainty:

  - Size of MC simulated samples
  - Background modelling

SUMMARY AND OUTLOOK

- Discussed the **theoretical** and **experimental motivation** to **test LFU** in $b \to c\ell\nu$ transitions
- Presented the **new 2022 LHCb** combined $R(D)$ and $R(D^*)$ **muonic measurement:** [arXiv:2302.02886], to appear in PRL



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

FUTURE PROSPECTS

- **Update** the current measurement(s) with **more data**
  - Reduce statistical uncertainty: **yields Run2 = (4x)Run1**
- Over-constrain the problem by measuring **more final states**
- Better synergy with **theory** community
  - Measure differential distributions to improve predictions on the long distance effects (Form Factors)

Thanks for listening!