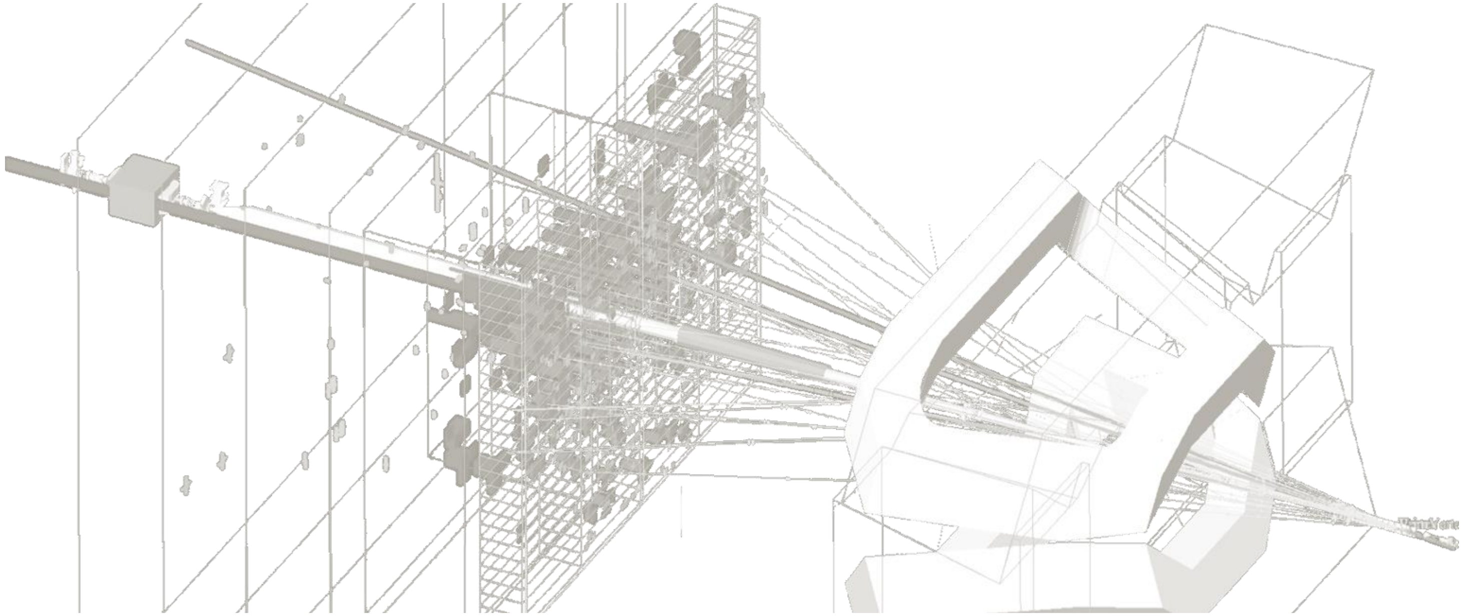


Lepton Flavor Universality tests using semileptonic b-hadron decays

42[nd] International Conference on High Energy Physics (ICHEP)

Friday July 19[th] 2024

Phoebe M Hamilton
(on behalf of the LHCb Collaboration)
(University of Maryland)

The LHCb (Run1/2) Detector

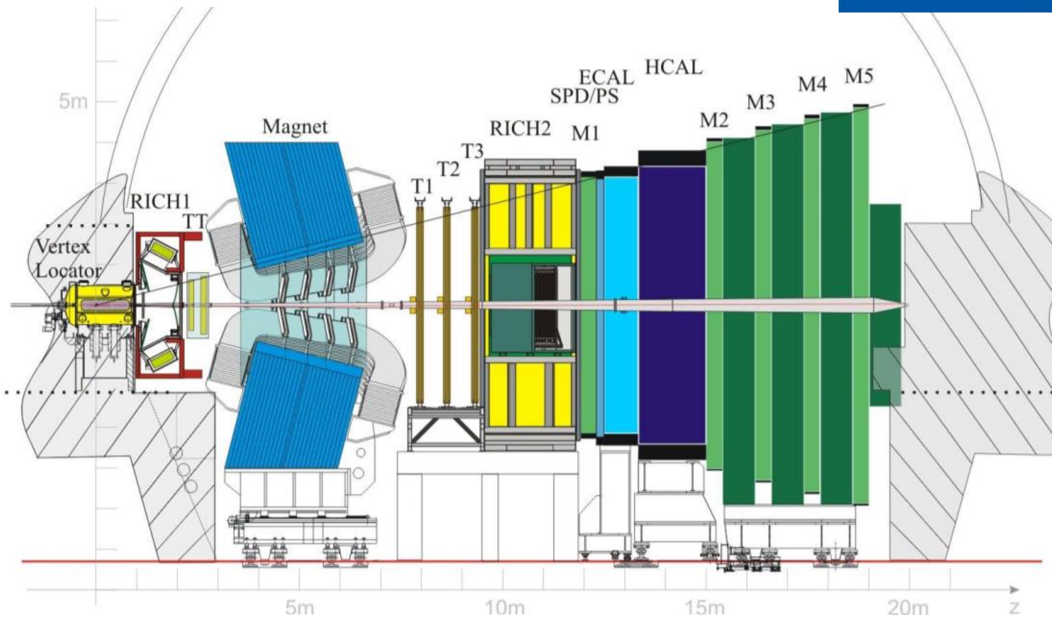
Focus on forward direction to exploit highly-boosted b quark production at LHC: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle (value!)

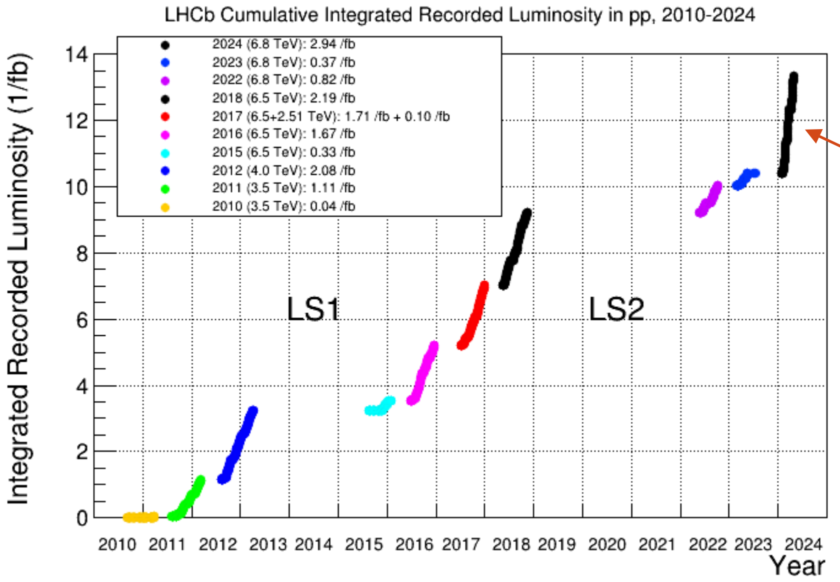
Single arm spectrometer optimized for beauty and charm physics at high η:

- Trigger: ≈ 90% efficient for dimuon channels, ~30% for all-hadronic
- Tracking: $\sigma_p/p \approx 0.4\%-0.6\%$ (p from 5 to 100 GeV), $\sigma_{IP} < 20\ \mu m$
- Vertexing: $\sigma_\tau \approx$ 45 fs for $B_s^0 \to J/\psi\phi$
- PID: 97% μ ID for 1-3% π→μ misID
- Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

Large boost of b-hadrons means *macroscopic* displacements with respect to PV

- Most backgrounds come from *other B decays* rather than underlying event





See Giulia Tuci's slides from yesterday

Lepton universality

In Standard Model (SM), charged lepton flavors are ***identical copies*** of one another

- Electroweak couplings are trivially equal for all three flavors by construction, only Higgs Yukawa couplings differentiate them
- Amplitudes for processes involving e, μ, τ must all be identical up to explicit mass dependence (phase space, fermion helicity)
- Tests of SM LFU have been performed in a number of different systems over the years
  - $Z \to \ell\ell, W \to \ell\nu, \tau \to \ell\nu\bar{\nu}, \pi \to \ell\nu, K \to \pi\ell\nu$, etc...

Universality of the EW interactions does not necessarily imply universality of physics beyond the SM

New physics preferentially coupling to the 3rd generation is usually less well-constrained, and can modify SM charged and neutral currents

- Examples: $A^0, H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks

Many LFU violating NP models are strongly constrained by direct searches, but can be tuned to evade these bounds while preserving their effect on heavy flavor observables

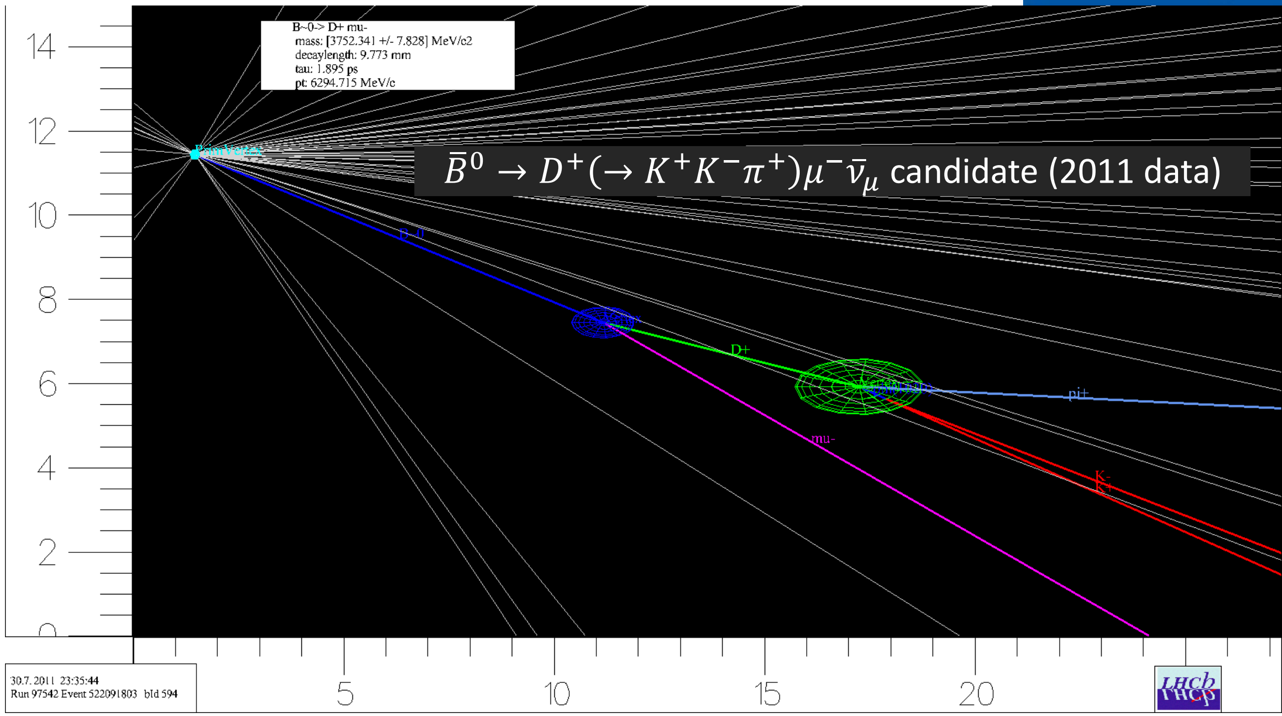
LFU in Semileptonic B decays

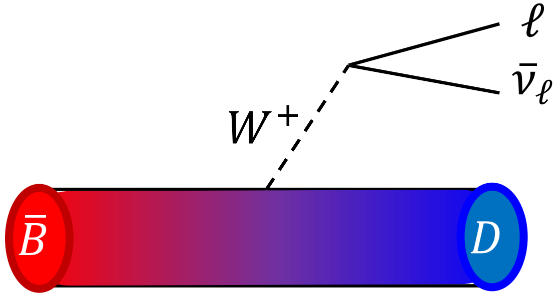
"Beta decay" of B hadrons – signature is lepton (μ or e (or τ!)) , recoiling hadronic system, and missing momentum

Theoretically well-understood in the SM

- Tree level virtual W emission – strong V-A structure
- No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
  - $\bar{B} \to W^{*\pm} D^{(*)}$ half of the decay still needs non-perturbative input

Charged lepton universality implies branching fractions for semileptonic decays to e, μ, τ differ only phase space and helicity-suppressed contributions

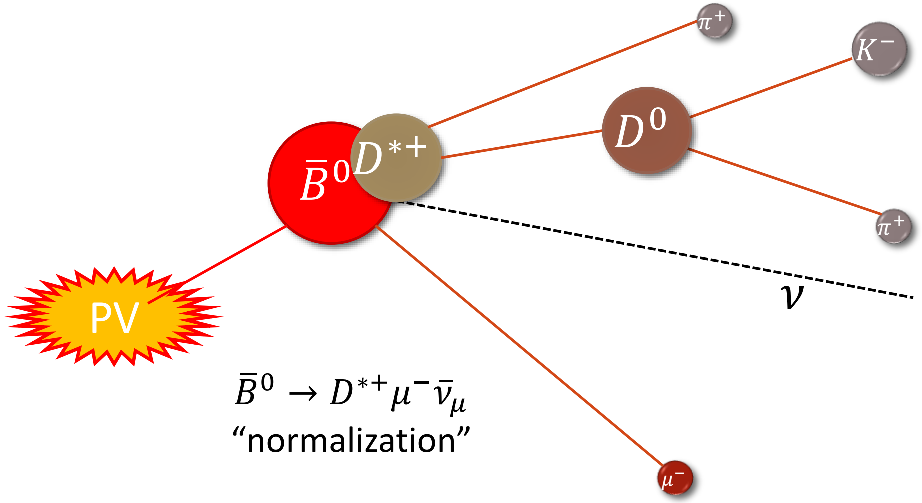




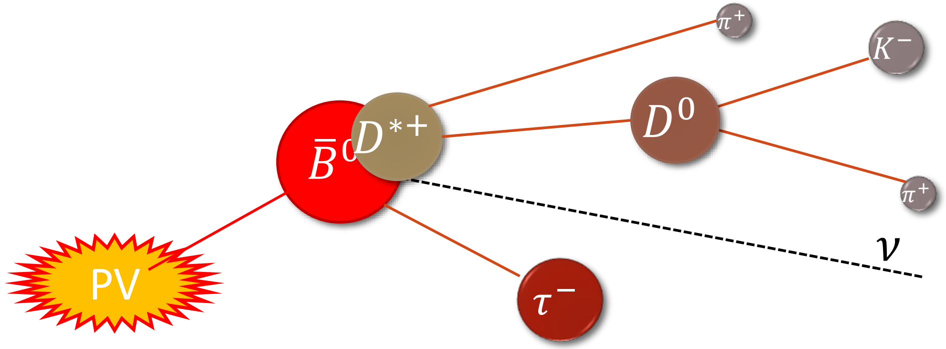
R(Dx) LFU ratios

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\ell)}$$

- Theoretically clean due to cancellation of most of the form factor uncertainty
  - Helicity-suppressed amplitudes as well as the FFs in the low q^2 normalization region don't cancel
  - SM: $R(D^*) = 0.254(5)$ HFLAV, Phys. Rev. D 107, 052008
    $R(D) = 0.298(4)$ + web updates
- $\tau^- \to \mu^-\bar{\nu}_\ell\nu_\tau$
  - Direct normalization from identical (visible) final state
  - Must disentangle from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ in fit
- $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Clear signature at LHCb: higher signal purity
  - Reliant on external measurements to get back R(D*)
- Common Challenges: missing neutrinos with poorly-constrained momentum
  - Don't know full momentum -> unknown rest frame
  - Large partially-reconstructed B backgrounds



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



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

Since ICHEP 2022

From LHCb:

- Two new measurements in $\tau^- \to \mu^- \bar{\nu}\nu$ mode
  - PRL 131, 111802(2023)
    - supersedes PRL 115, 111802(2015)
  - arXiv:2406.03387 [hep-ex] (2024)
    - new! 2016 (Run2) data
- Two new measurements in $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ mode
  - PRD 108, 012018 (2023); PRD 109, 119902(E) (2024)
    - Analysis on 2016 (Run2) data
  - arXiv:2311.05224 [hep-ex] (2023)
    - D^* polarization measurement
      - see Anna Lupato's slides from this morning
- Today: will focus on the new $\tau^- \to \mu^- \bar{\nu}\nu$ measurement(s)
  - With apologies – I wish I had time to cover more!

Submitted to PRL

CERN-EP-2024-125
LHCb-PAPER-2024-007
June 5, 2024

Measurement of the branching fraction ratios $R(D^+)$ and $R(D^{*+})$ using muonic τ decays

PHYSICAL REVIEW D **108,** 012018 (2023)

Test of lepton flavor universality using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ channels

R. Aaij *et al.**
(LHCb Collaboration)

PHYSICAL REVIEW LETTERS **131,** 111802 (2023)

Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

R. Aaij *et al.**
(LHCb Collaboration)

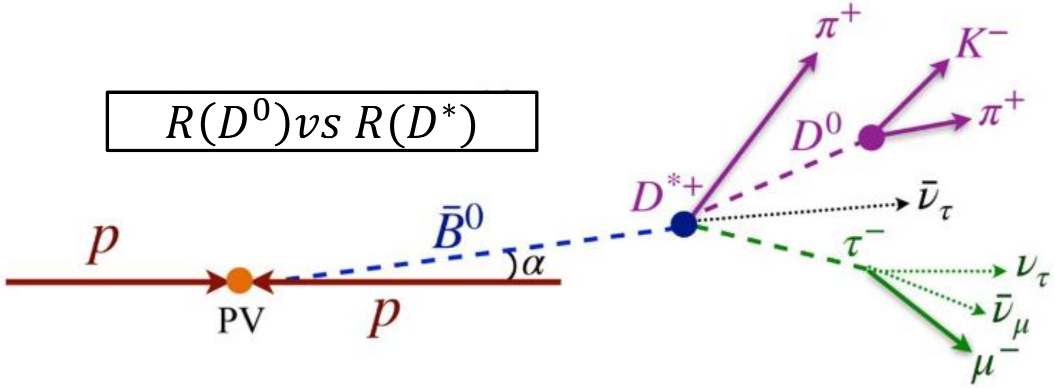
Submitted to PRD

CERN-EP-2023-225
LHCb-PAPER-2023-020
October 26, 2023

Measurement of the D^* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

A tale of two analyses

$R(D^0) vs\ R(D^*)$



2011+2012 datasets (3/fb)

- Extends and supersedes result from 2015

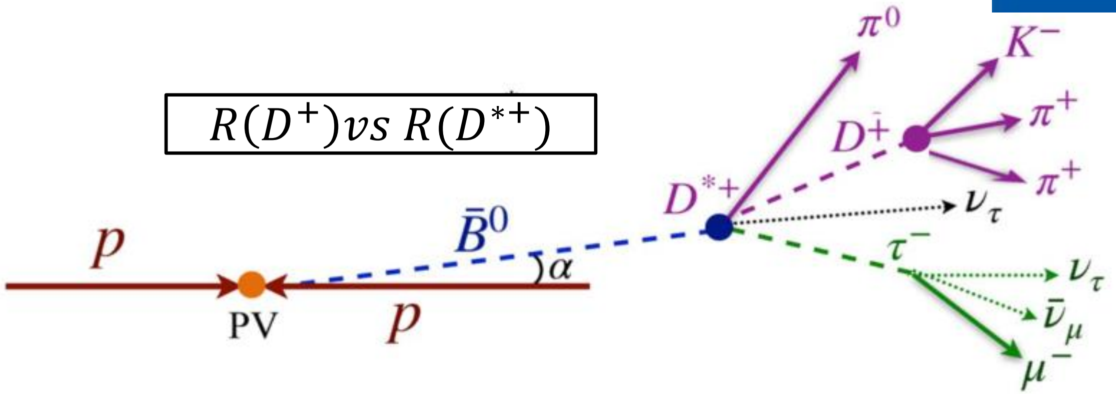
"Piggybacked" on loose $D \to K\pi$ trigger

Joint fit to $D^{*+}\mu^-$ and $D^0\mu^-$ datasets

- $D^0\mu^-$ data includes large D^* feed-down
  $B \to D^0 \ell\nu$,
  $B \to D^{*0}[\to D^0\pi^0]\ell\nu$,
  $B \to D^+[\to D^0\pi^+]\ell\nu$ with missed π^+

Custom muon selector flat in $p_T(\mu)$

$R(D^+) vs\ R(D^{*+})$



2016 dataset (2/fb)

First measurement utilizing dedicated $B \to H_c\tau[\to \mu\nu\nu]\nu$ trigger lines for Run2

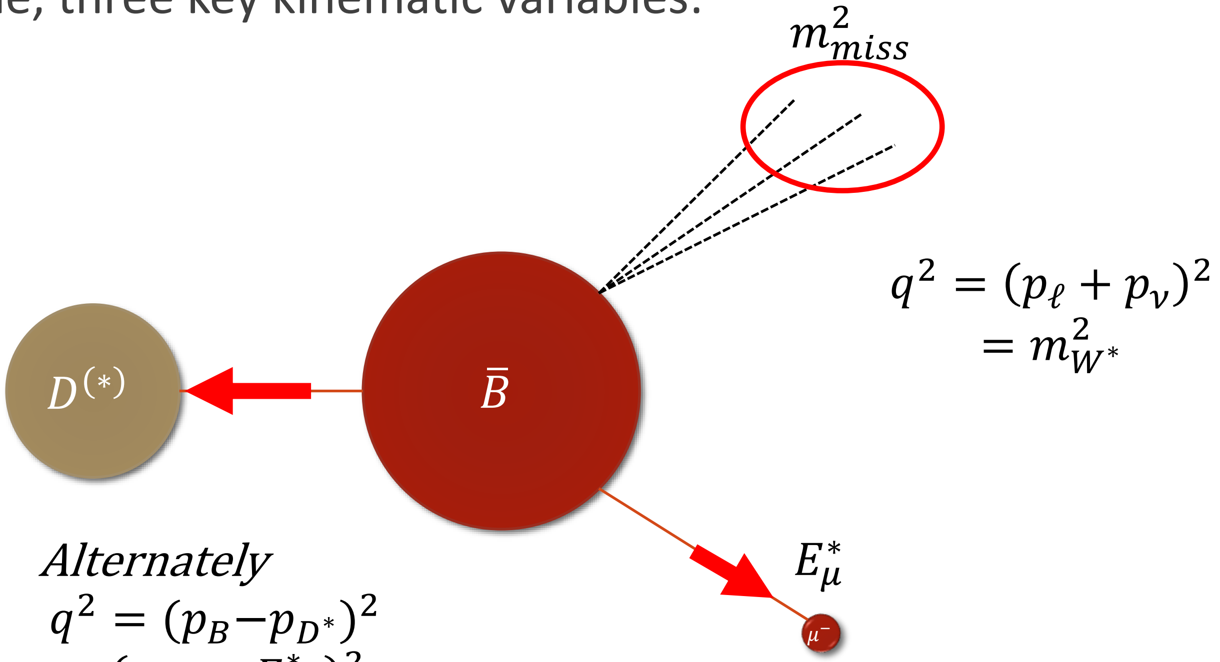
Fit to single $D^+\mu^-$ sample

- New MVA to reject events with ECAL deposits consistent with slow π^0
- Reduced feed-down from D^* since only isospin-disfavored $D^{*+} \to D^+\pi^0$ contributes
- New fast "tracker-only" simulation allows for much higher statistics templates

More traditional muon DLL selection

Distinguishing $b \to c\tau(\to \mu\nu\nu)\nu$ from $b \to c\mu\nu$

In the B rest frame, three key kinematic variables:



Alternately
$q^2 = (p_B - p_{D^*})^2$
$= (m_B - E_{D^*}^*)^2$

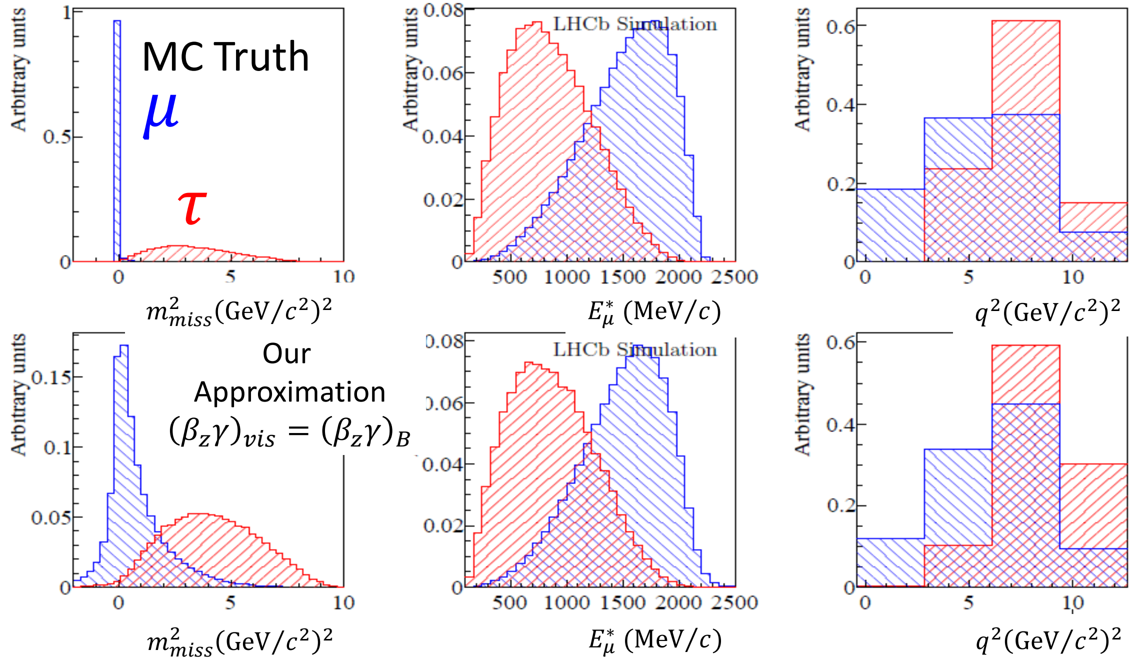
$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$	$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$
$m_{miss}^2 > 0$	$m_{miss}^2 = 0$
E_l^* spectrum is soft	E_l^* spectrum is hard
$\mathrm{m}_\tau^2 \le q^2 \le 10.6\ \mathrm{GeV}^2$	$m_\mu^2 \le q^2 \le 10.6\ \mathrm{GeV}^2$

Leptonic tau techniques

LHCb-PAPER-2015-025 supplemental
PRL 115, 111803 (2015)

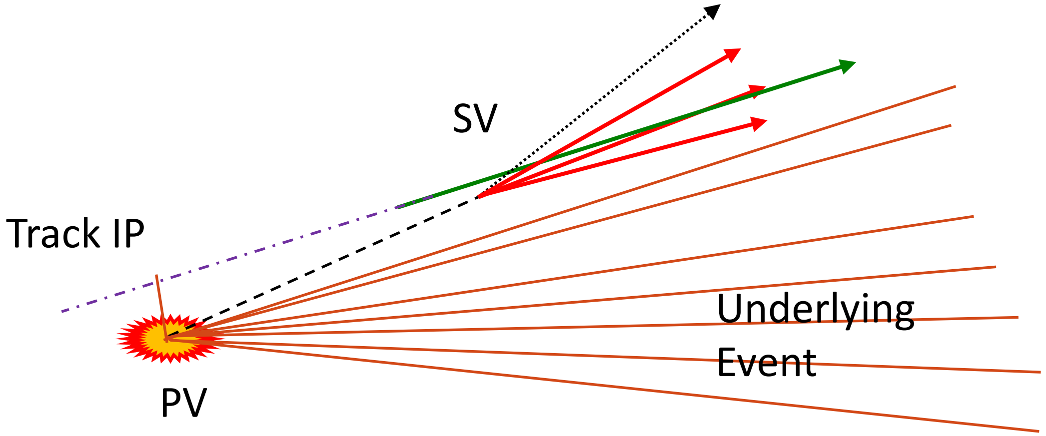
No information on initial B momentum to reconstruct the discriminating variables

- Key: Resolution on rest frame variables doesn't matter much because distributions are broad to begin with –
  well-behaved approximation still preserves differences for *fully 3D fit to* $[m_{miss}^2, E_\mu^*, q^2]$ using sim. templates
  - Approximation + knowledge of direction from PV to SV => solve for full B momentum



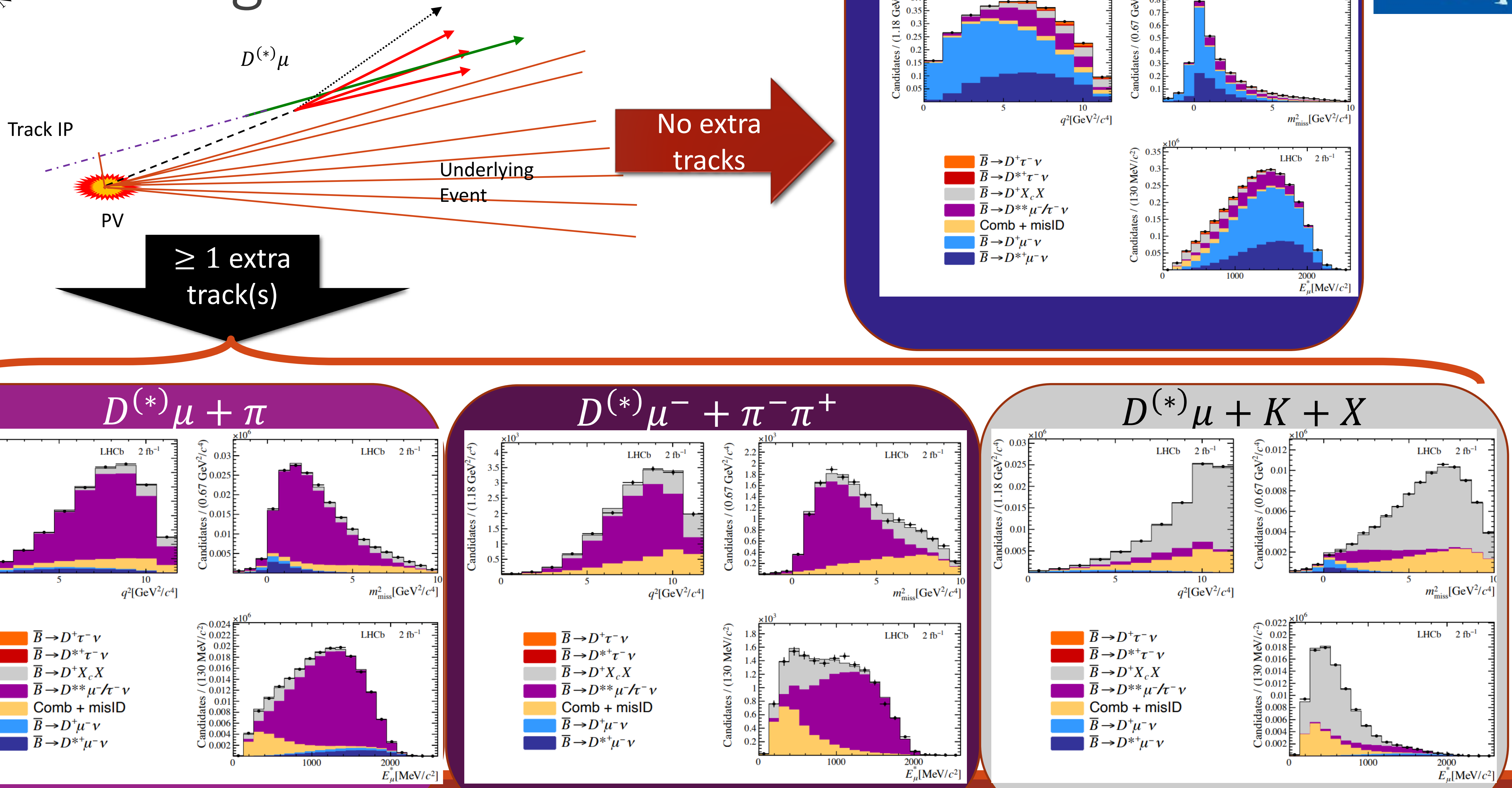
Use superb tracking system to fight huge partially-reconstructed background

- Scan over every track and compare against $D^{*+}\mu^-$ vertex with machine-learning alg.
- Allows for cleaner signal sample *and* data control samples enriched in key backgrounds



Fit Regions

LHCb-PAPER-2024-007 supplementary
arXiv:2406.03387 [hep-ex]



Results

First measurements of $R(D^0)$ and $R(D^+)$ at a hadron collider.

- Run1 analysis still dominated by MC stats due to dilution from multiple rounds of corrections
- Run2 fast simulation approach finally breaks through that limitation
- Other systematics to keep an eye on: double-charm background shape and misID modelling
  - Seeing continual improvement in unfolding procedures

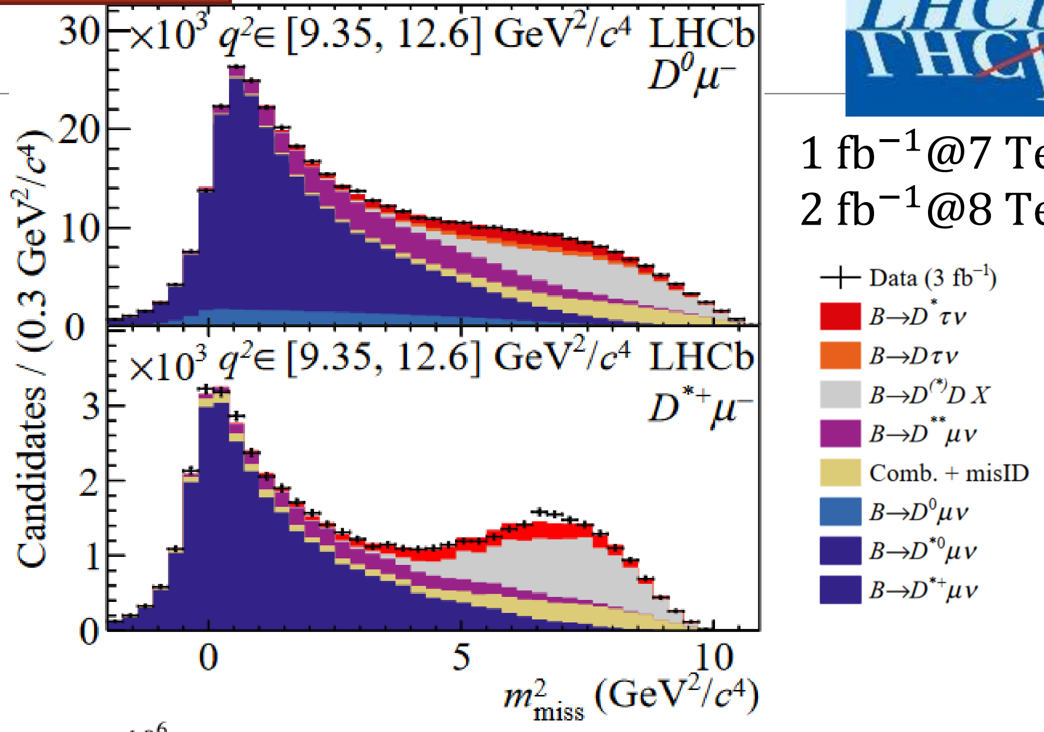
$$R(D^0) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$$
$$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.023(sys)$$
$$correlation\ coefficient = -0.43$$

$$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(sys)$$
$$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(sys)$$
$$correlation\ coefficient = -0.39$$

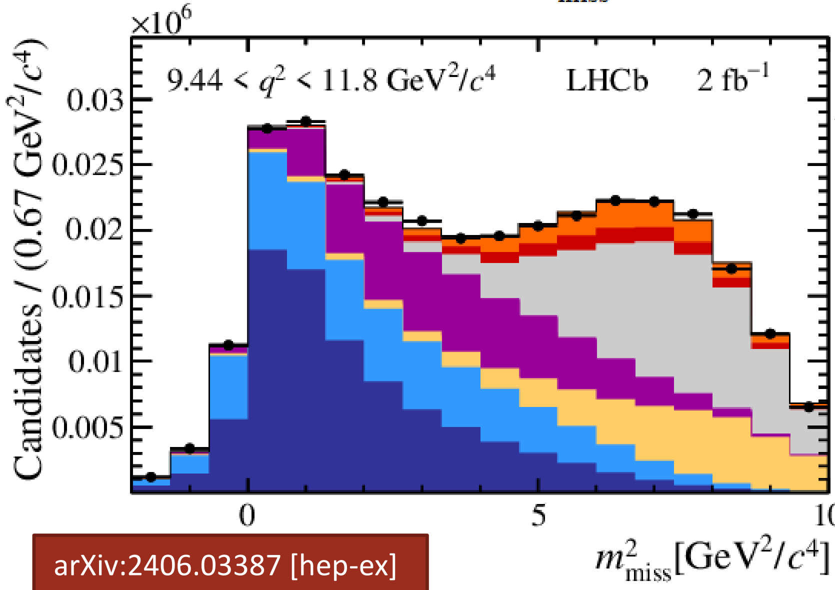
RECALL SM: $R(D^*) = 0.254(5)$
$R(D) = 0.298(4)$

PRL 131, 111802(2023)

$1\ fb^{-1}$@7 TeV
$2\ fb^{-1}$@8 TeV



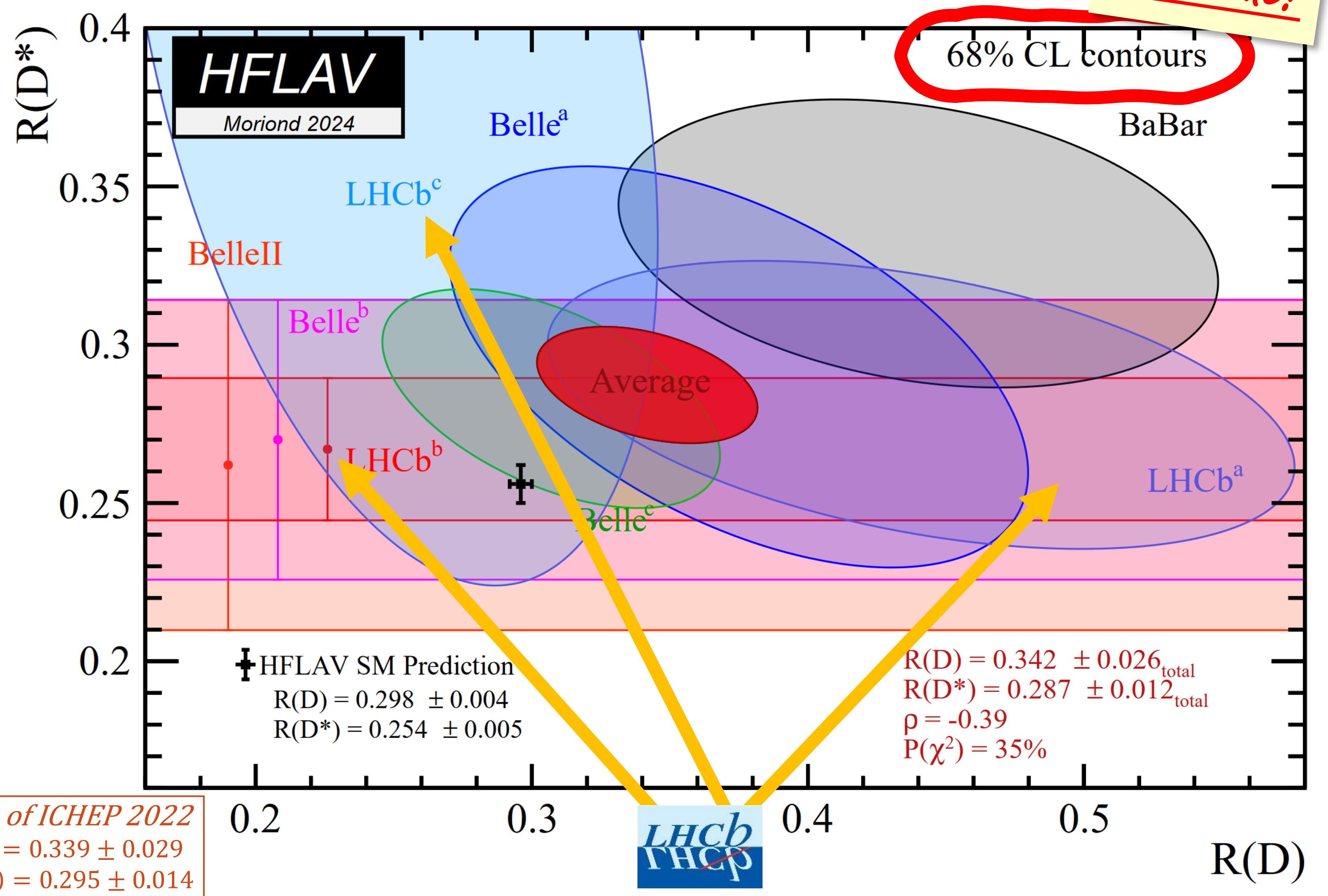
$D^+\mu^-$
13 TeV



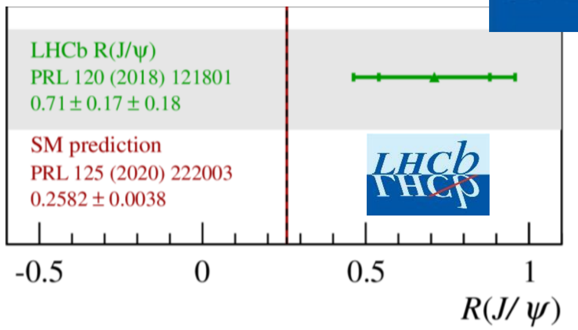
arXiv:2406.03387 [hep-ex]

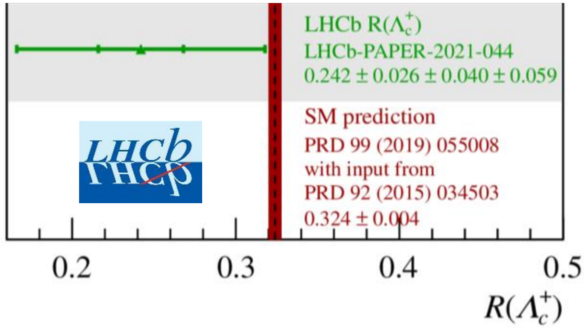
Current status

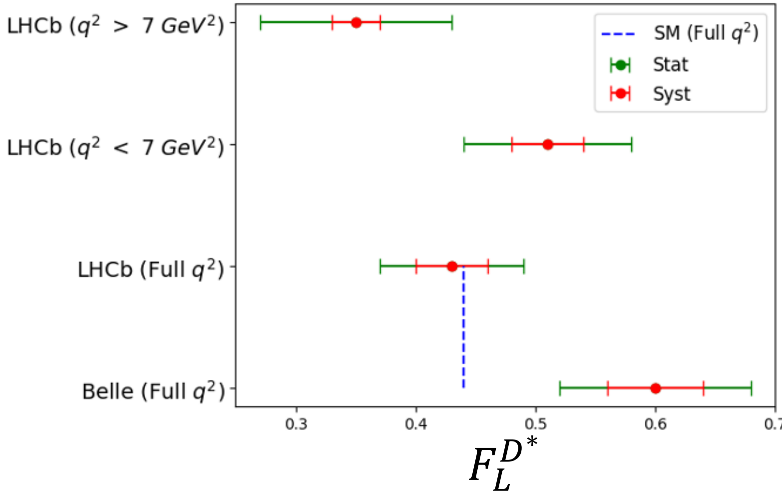
Nota bene!



c.f. as of ICHEP 2022
$R(D) = 0.339 \pm 0.029$
$R(D^{*}) = 0.295 \pm 0.014$
$\rho = -0.38$
$P(\chi^2) = 28\%$





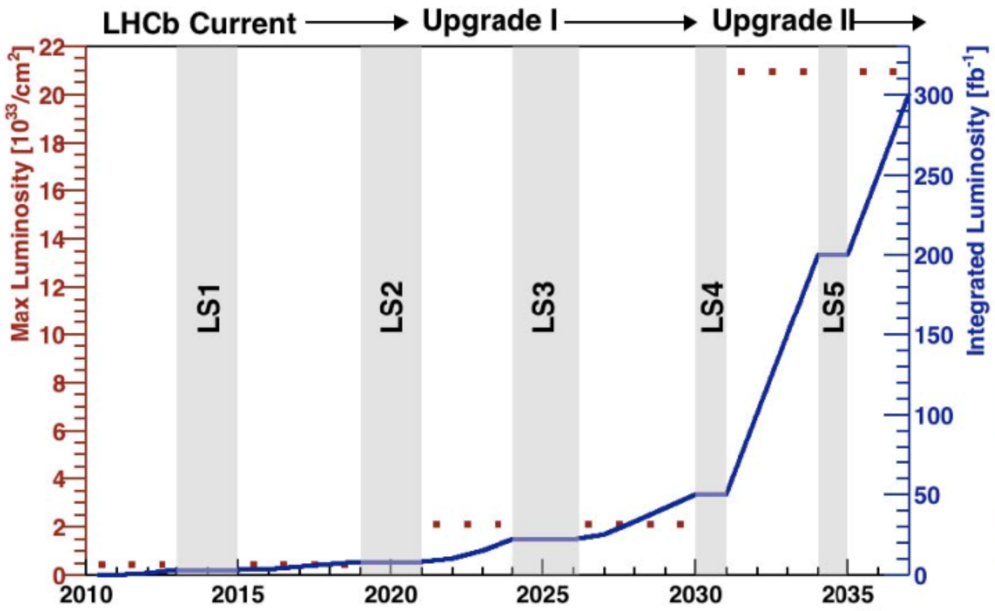


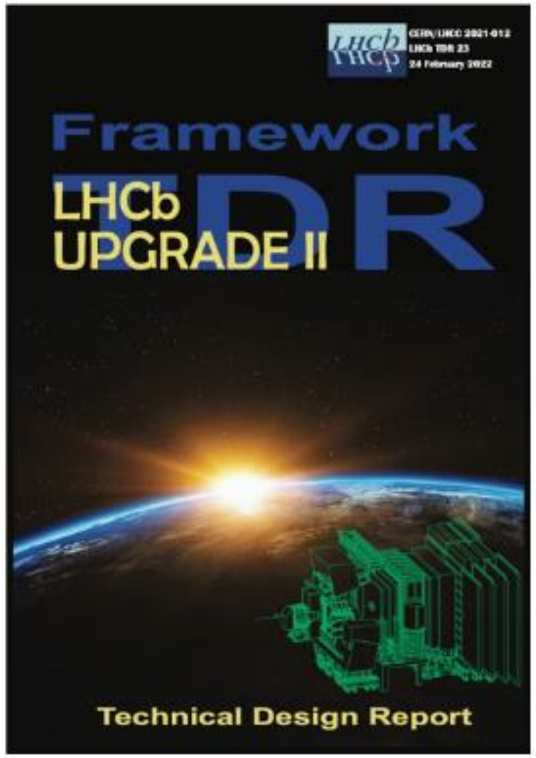
Flavor frontiers beyond LS4

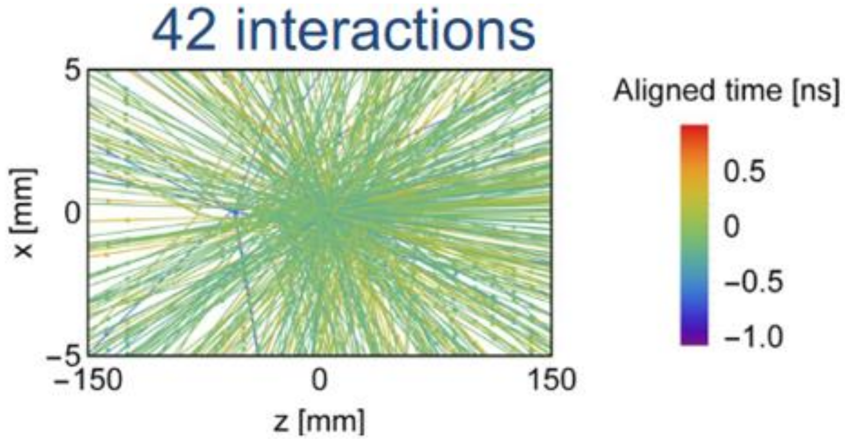
LHCb 'Upgrade II' currently under study to record 300/fb

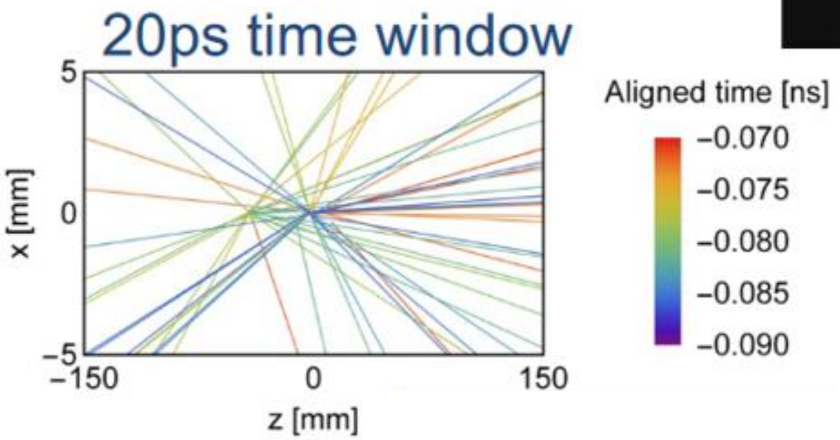
- Physics reach still limited by detector, not collider
- Maximizing reach will require coping with pileup in the forward region
  - Granularity, timing

Plans maturing rapidly, some commitments already in place









"4D" vertex finding

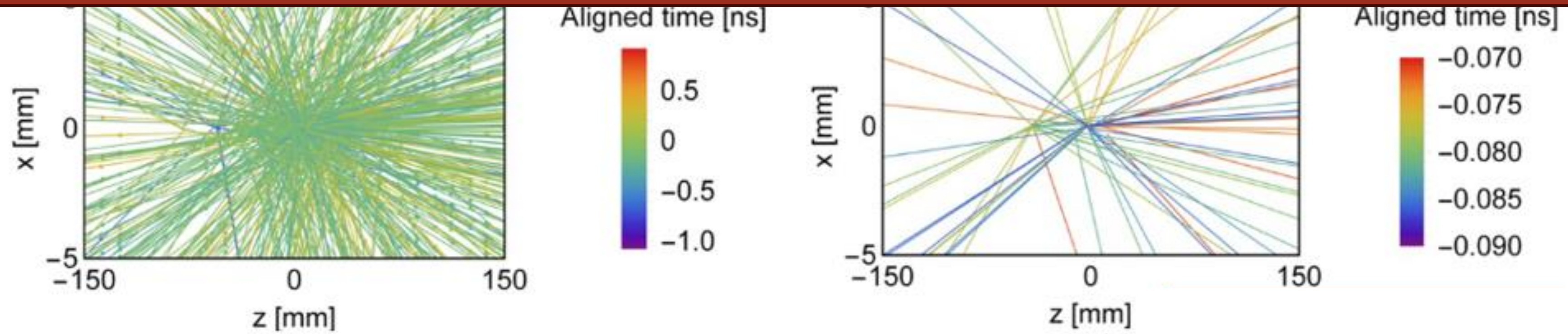
Flavor frontiers beyond LS4

LHCb 'Upgrade II' currently under study to record 300/fb

- Physics reach still limited by detector, not collider
-

Pla
cor

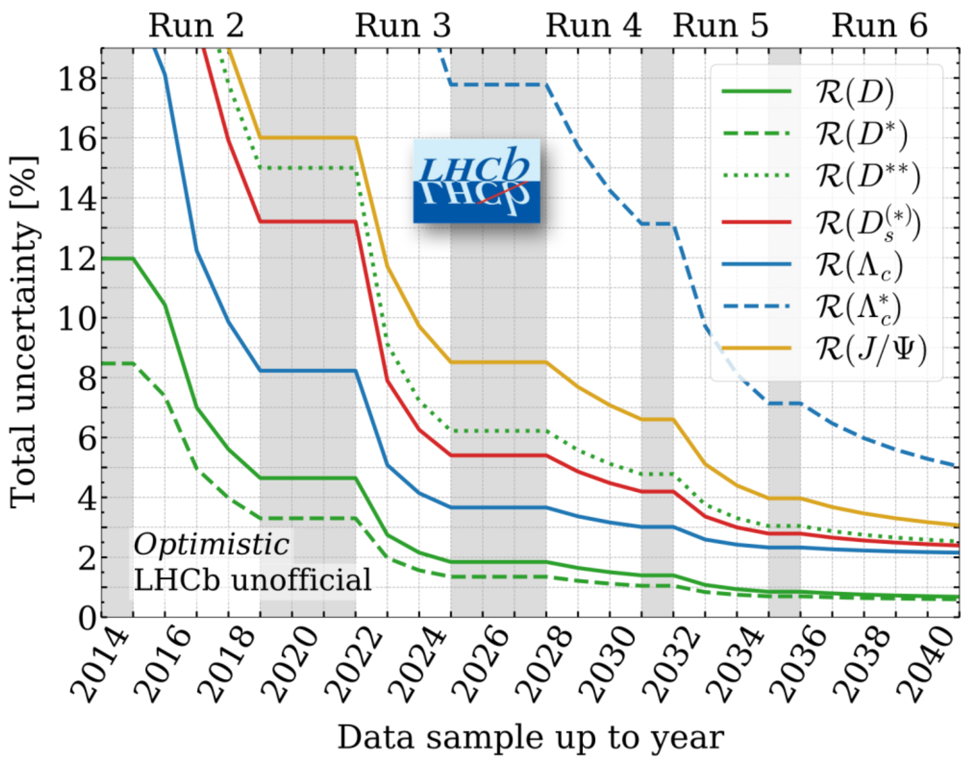
See Renato Quagliani's slides from yesterday



"4D" vertex finding

Summary

- B physics experiments are pushing lepton universality tests beyond validating the electroweak interaction, with LHCb playing a key role that will continue through the next decades
- Two new results measuring $R(D)$ vs $R(D^*)$ with $\tau \to \mu\bar{\nu}\nu$
  - First measurements of $R(D^+)$ and $R(D^0)$ at a hadron collider
  - $R(D^0)$ vs $R(D^*)$: Supersedes and extends 2015 $R(D^{*+})$ measurement
    - Improvements in modeling of all backgrounds – many lessons learned for the future
  - $R(D^+)$ vs $R(D^{*+})$: New, uses 2016 data
    - First use of dedicated trigger paths for $\bar{B} \to X_c\tau[\to \mu\bar{\nu}\nu]\bar{\nu}$ and fast simulation techniques essential for full exploitation of large (and growing) LHCb dataset
- Further progress also in $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ channels
  - Measurement of D^{*+} longitudinal polarization
- Much more to come from LHCb in these areas: higher statistics, more final states, angular observables



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

End

Syst. Tables

PRL 131, 111802(2023)

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}$ $(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}$ $(\times 10^{-2})$	Correlation
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ form factors	0.7	2.1	
$\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu$ form factors	0.8	1.2	
$\mathcal{B}\ [\bar{B} \to D^* D_s^-(\to \tau^-\bar{\nu}_\tau)X]$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}$ $(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}$ $(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\bar{B}_s^0 \to D_s^{**}\mu^-\bar{\nu}_\mu$ model uncertainty	0.6	2.4	
Baryonic backgrounds	0.7	1.2	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
Data-simulation corrections	0.4	0.8	
MisID template unfolding	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}$ $(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}$ $(\times 10^{-2})$	
Data-simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\bar{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

arXiv:2406.03387 [hep-ex]

Background classes

Bernlochner et al, PRD 85 094033 (2012)

Semileptonic feed-down backgrounds:

- $\bar{B} \to D^{**}[\to D^{(*)}\pi]\ell\bar{\nu}$
- $\bar{B} \to D^{**}[\to D^{(*)}\pi\pi]\ell\bar{\nu}$

Semileptonic cross-feed:

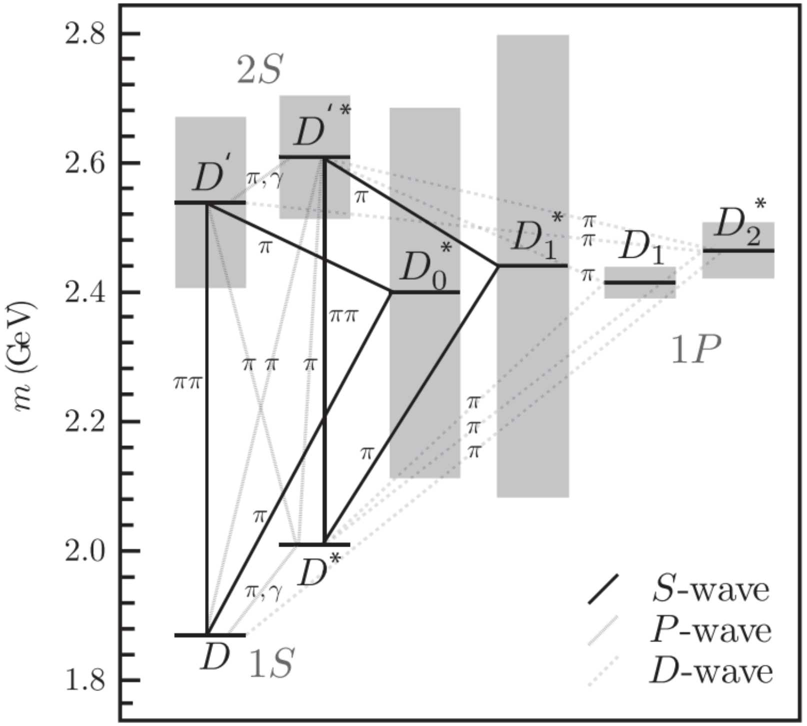
- $\bar{B}_s^0 \to D_s^{**+}[\to D^{(*)}K]\ell\bar{\nu}$

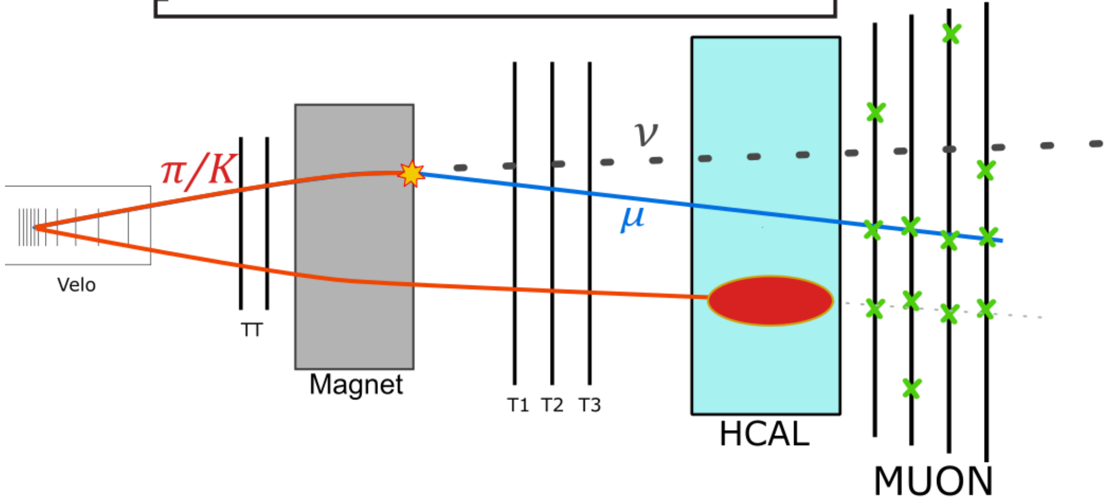
"Double-charm"

- $\bar{B} \to D^{(*)}\bar{D}_{(s)}^{(*)}[\to X\ell\bar{\nu}]$
- $\bar{B} \to D^{(*)}\bar{D}_s^{(*)}[\to \tau\bar{\nu}]$
- $\bar{B} \to D^{(*)}\bar{D}^{(*)}[\to X\ell\bar{\nu}]K$

Other "junk" backgrounds:

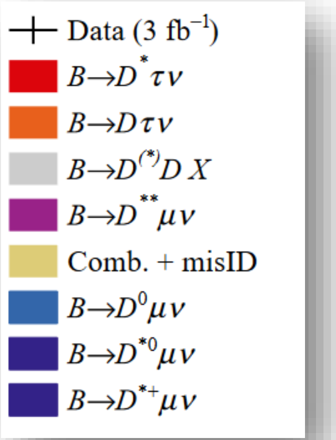
- Combinatorial background
- Fake muon background
  - Data-driven unfolding with smearing to account for decay-in-flight kinks

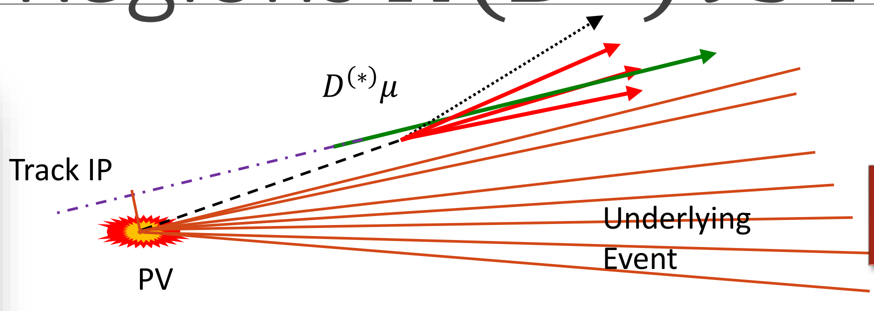




LHCb-PAPER-2022-039 supplementary

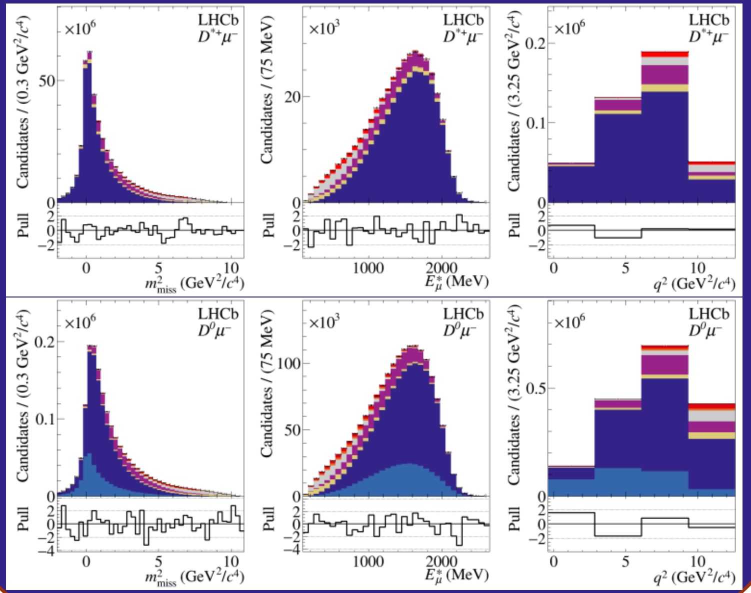
Fit Regions $R(D^0) vs R(D^*)$





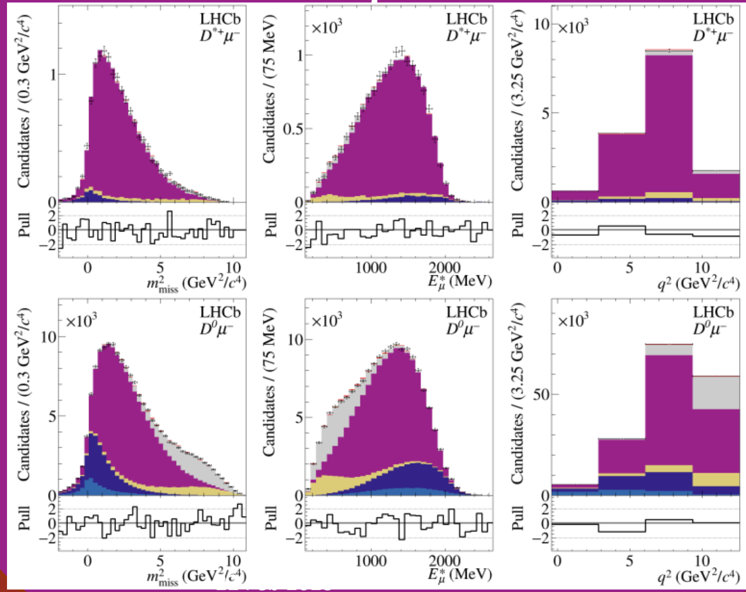
No other SV-like tracks

Isolated signal

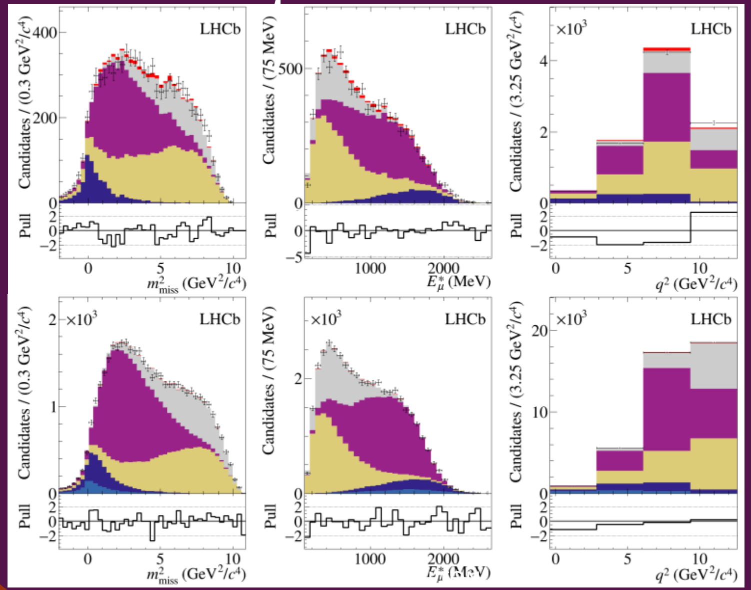


$\geq$ 1 SV-like track(s)

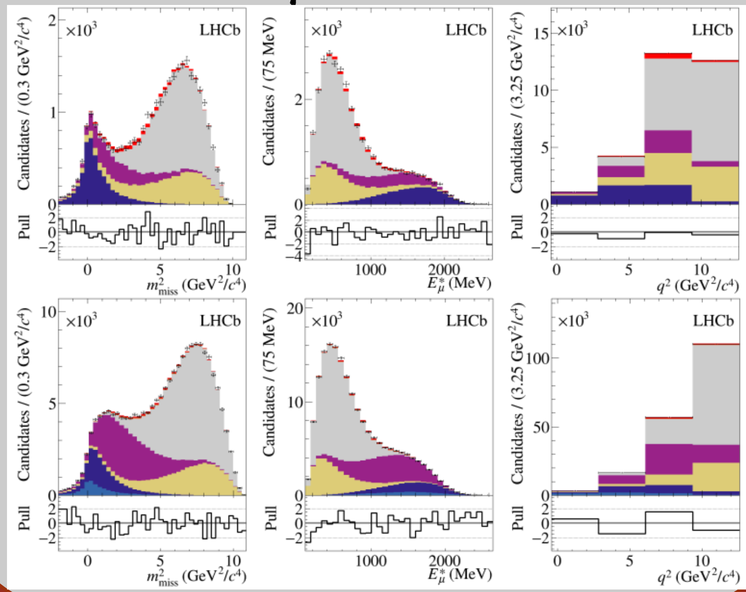
$D^{(*)}\mu + \pi$



$D^{(*)}\mu^- + \pi^-\pi^+$



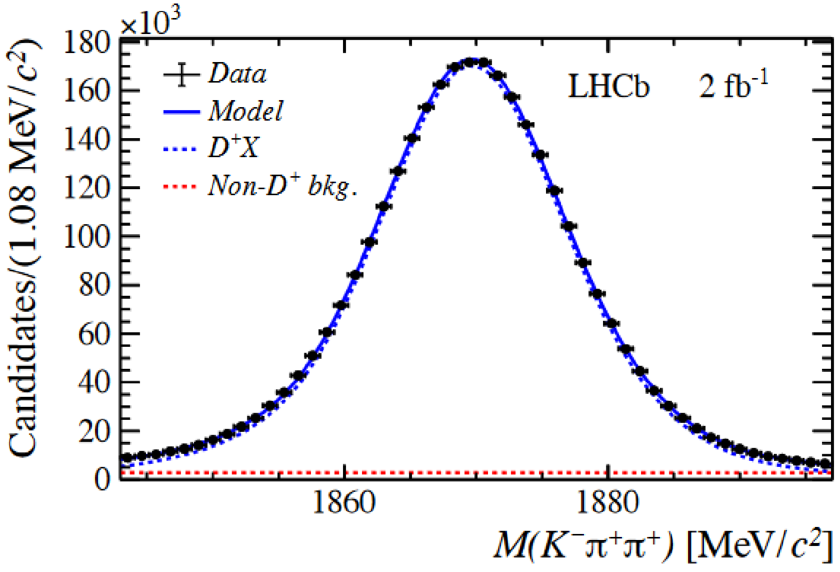
$D^{(*)}\mu + K + X$



Additional Complications $R(D^+)$

Background from random $K^-\pi^+\pi^+$ combinations is a factor of a few worse than in 2-body $D^0 \to K^-\pi^+$

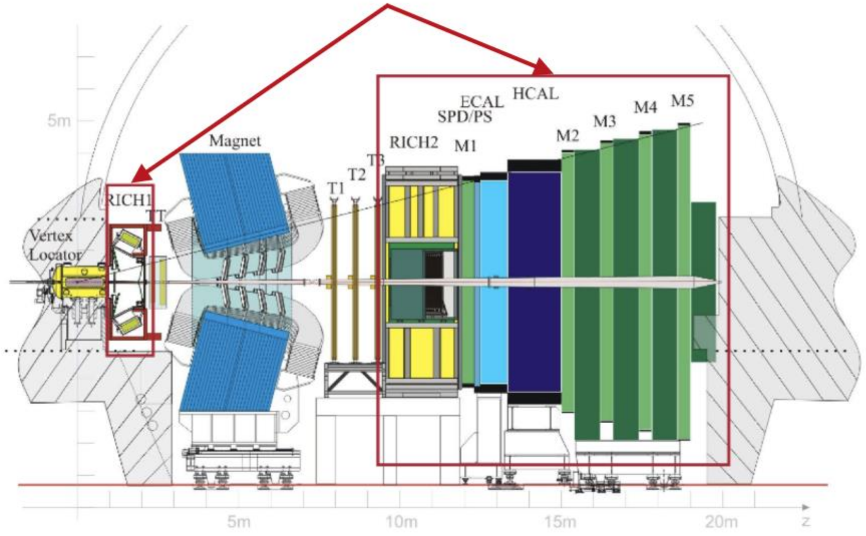
- Explicitly remove them with sWeights from fit to $m_{K\pi\pi}$
- Trade-off: likelihood fit to weighted data
  - Care must be taken with error bars!

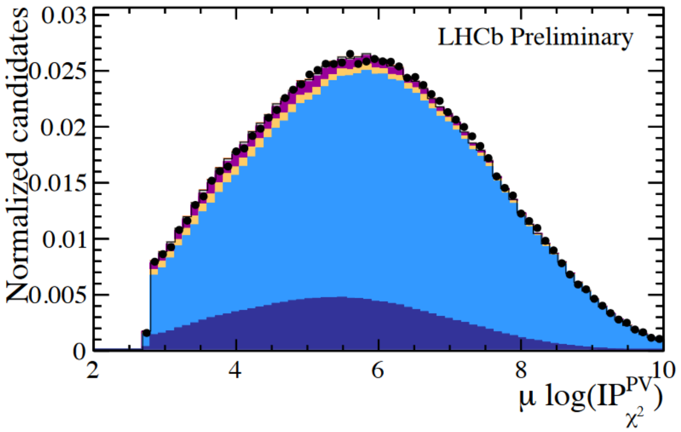


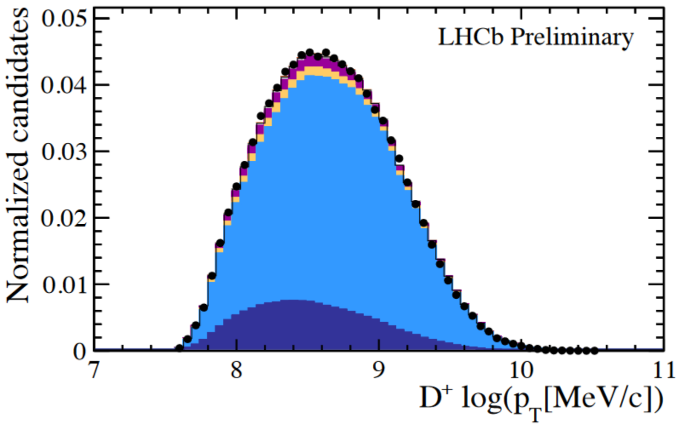
Large dataset requires large MC sample

- First such analysis to use "tracker-only" fast simulation
- Trigger emulation a challenge – for these LFU analyses the hardware trigger is unbiased on the muon -- HCAL trigger on signal hadrons or any trigger on rest of event

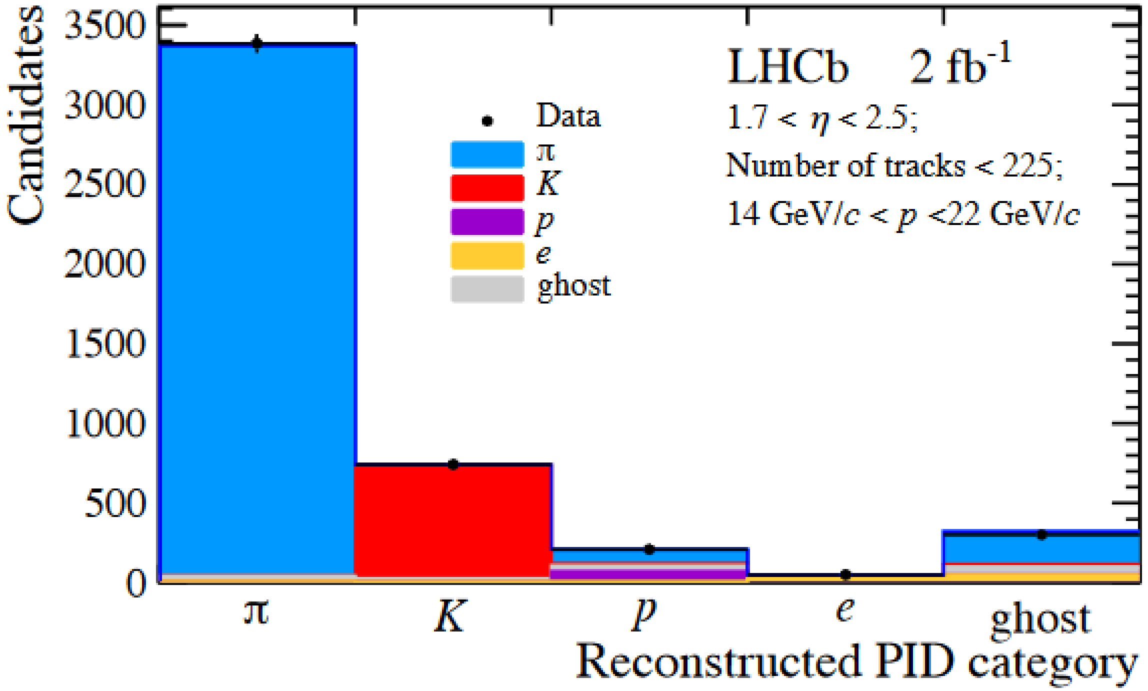
Sub-detector response turned off

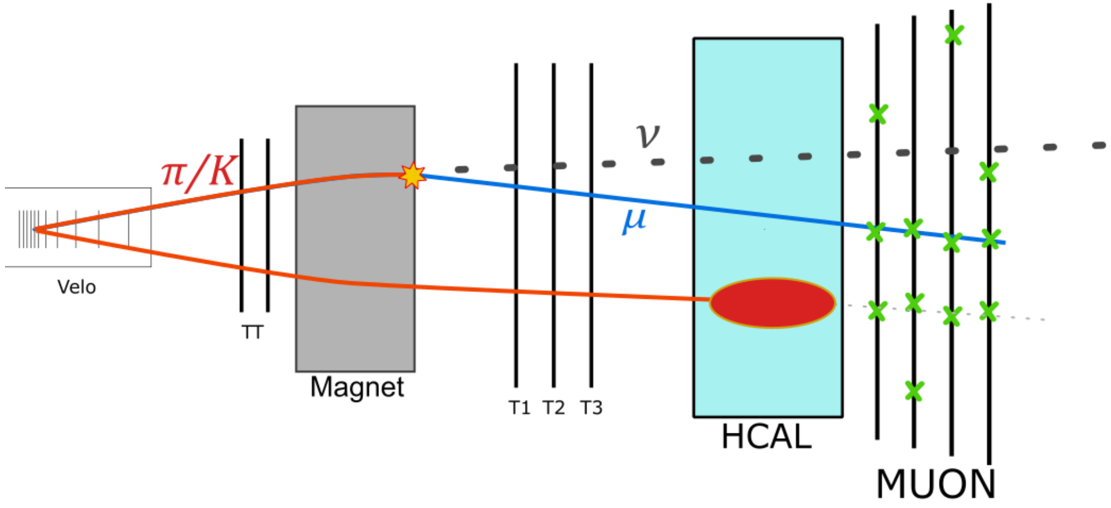






Challenge: fake muon background modelling



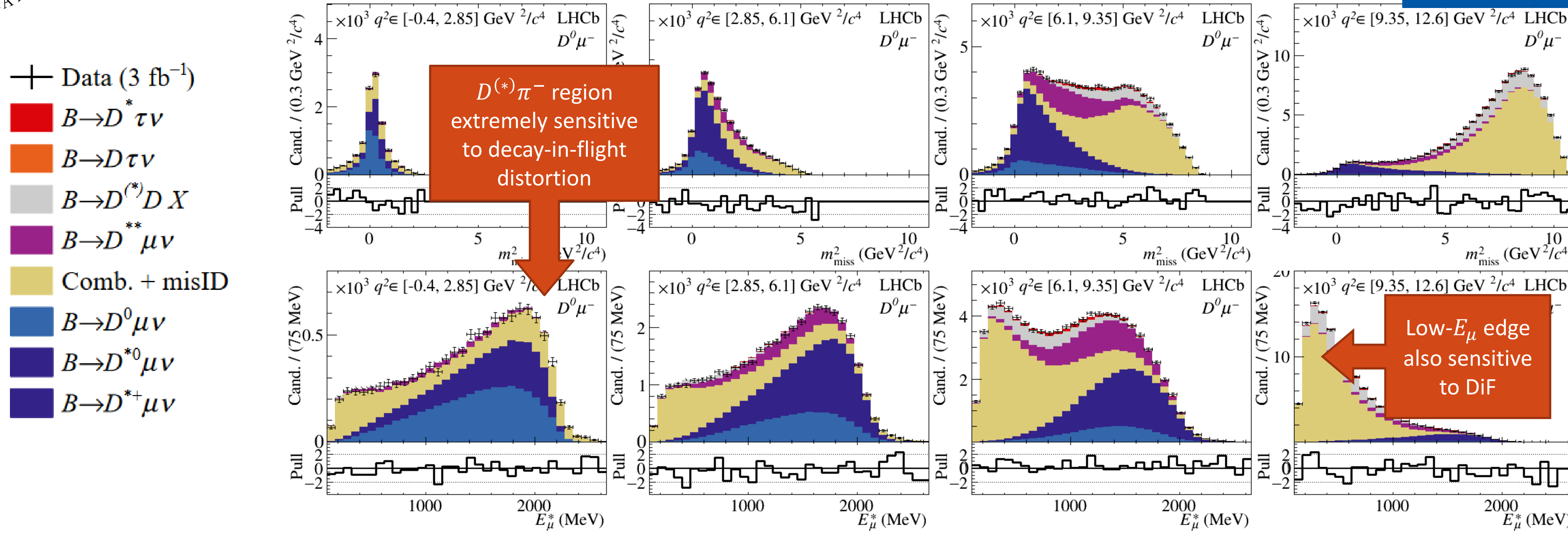


Likelihood based unfolding to build fake μ template from non-muon control sample in Run2

Also used in Run1 analysis and cross-validated with “hybrid Bayesian unfolding” pioneered in $R(J/\psi)$

MisID validation example (Run1)

LHCb-PAPER-2022-039 supplementary



Background shape validated against data *rejected* by new selection but *retained* by old