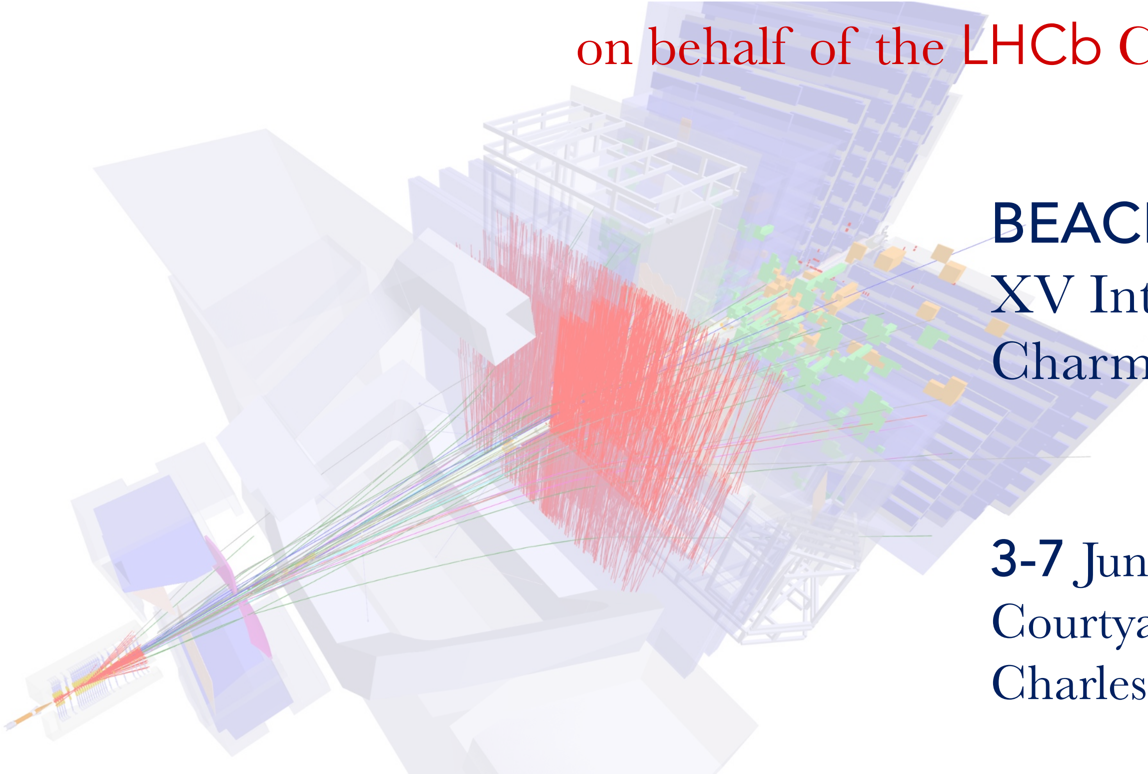


LFU tests in semileptonic decays at LHCb

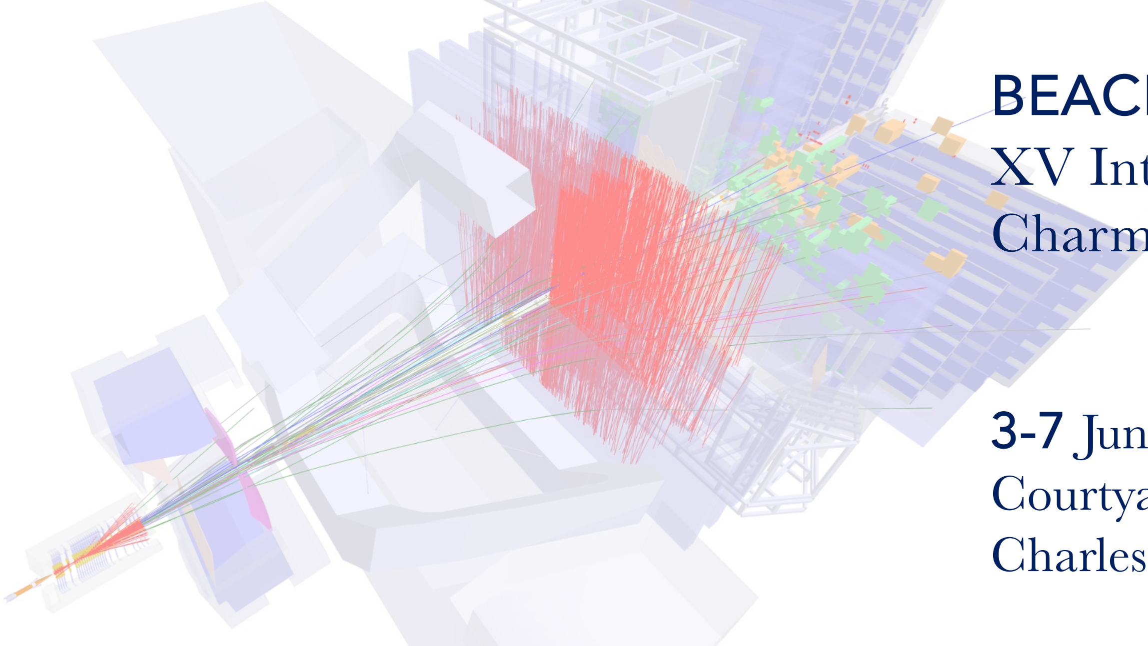
P. de Simone (LNF-INFN),
on behalf of the LHCb Collaboration

BEACH 2024
XV International Conference on Beauty,
Charm, Hyperons in Hadronic Interactions

3-7 June, 2024
Courtyard Charleston Historic District
Charleston, SC, USA

LFU tests in semileptonic decays at LHCb

- introduction
- detection of B semileptonic decays at LHCb
- $R(D^+)$ and $R(D^{*+})$
- D^{*-} longitudinal polarization in $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$



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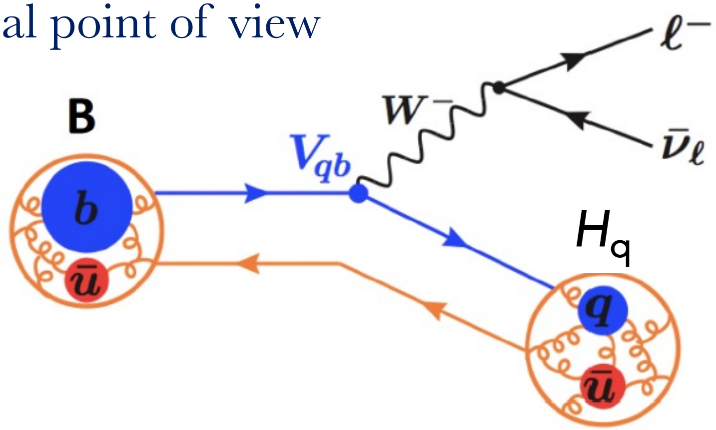
tree level semileptonic b→cℓν$_\ell$ transitions

✓ semileptonic decays are clean channels from a theoretical point of view

$$\mathcal{M}(B \to H_q \ell^- \overline{\nu}) = -i \frac{G_F}{\sqrt{2}} V_{qb} L^\mu H_\mu$$



✓ factorization of the hadronic and leptonic currents ➔ no final state interactions

b→cℓν$_\ell$ transitions are an open portal for many studies to test the Standard Model and search for effect of possible New Physics:

✓ determination of the CKM matrix elements V_{ub} and V_{cb}

✓ test of Lepton Flavour Universality comparing rate production for different kind of leptons in the final states

✓ sensitivity to NP also through kinematics of the final state particles

→ **brand new LHCb results in this talk**

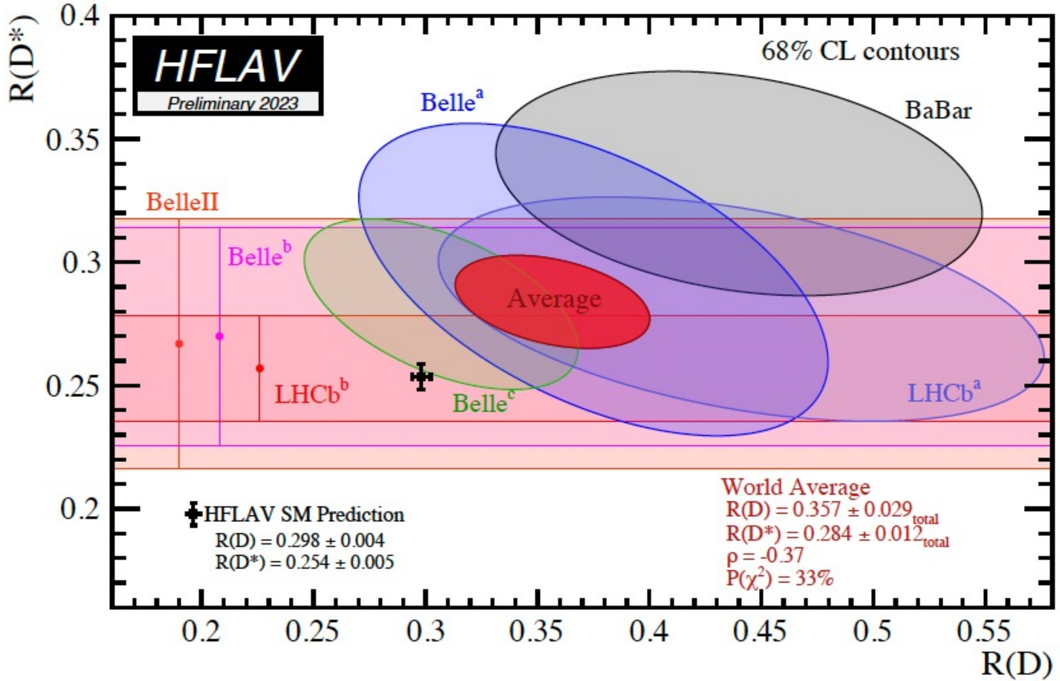
test of LFU in tree level semileptonic $b \to c\tau\nu_\tau$ transitions

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau\nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu\nu_\mu)}$$

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s \ldots$$
$$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \ldots$$

- ✓ hadronic uncertainties mostly cancel in the ratio
- ✓ reduced experimental systematic uncertainties in ratios of efficiencies

- ✓ most precise measurements from $B \to D^{(*)} \ell\nu_\ell$ decays
- ✓ HFLAV 2023 ➔ the deviation w.r.t. the SM stays at 3.3σ level for the combination of R(D)-R(D*)



more measurements are strongly motivated

- ✓ to further improve R(D)-R(D*) precision
- ✓ to extend the physics program
  - ✓ R(Hc)
  - ✓ angular analysis of $b \to c\ell\nu_\ell$ decays

$b \to c\tau\nu_\tau$ transitions at LHCb

Run 1: 2010-11	~**1.1** fb^{-1}	at 7 TeV
2012	~**2.1** fb^{-1}	at 8 TeV
Run 2: 2015-18	~**6.** fb^{-1}	at 13 TeV

leptonic τ decays

✓ R(D^{*+})
Run 1 data sample, 3 fb^{-1}
[PRL 115, 111803]

✓ R(D^0) and R(D^{*+})
Run 1 data sample, 3 fb^{-1}
[PRL 131, 111802]

✓ R(D^+) and R(D^{*+})
Run 2 data sample, 2 fb^{-1}
[LHCb-PAPER-2024-007, in preparation]

this talk

✓ R(J/ψ)
Run 1 data sample, 3 fb^{-1}
[PRL 120, 121801]

hadronic τ decays

✓ R(D^{*+})
Run 1 data sample, 3 fb^{-1}
[PRL 120, 171802]

✓ R(D^{*+})
Run 2 data sample, 2 fb^{-1}
[PRD 108, 012018]

✓ R(Λ_c^+)
Run 1 data sample, 3 fb^{-1}
[PRL 128, 191803]

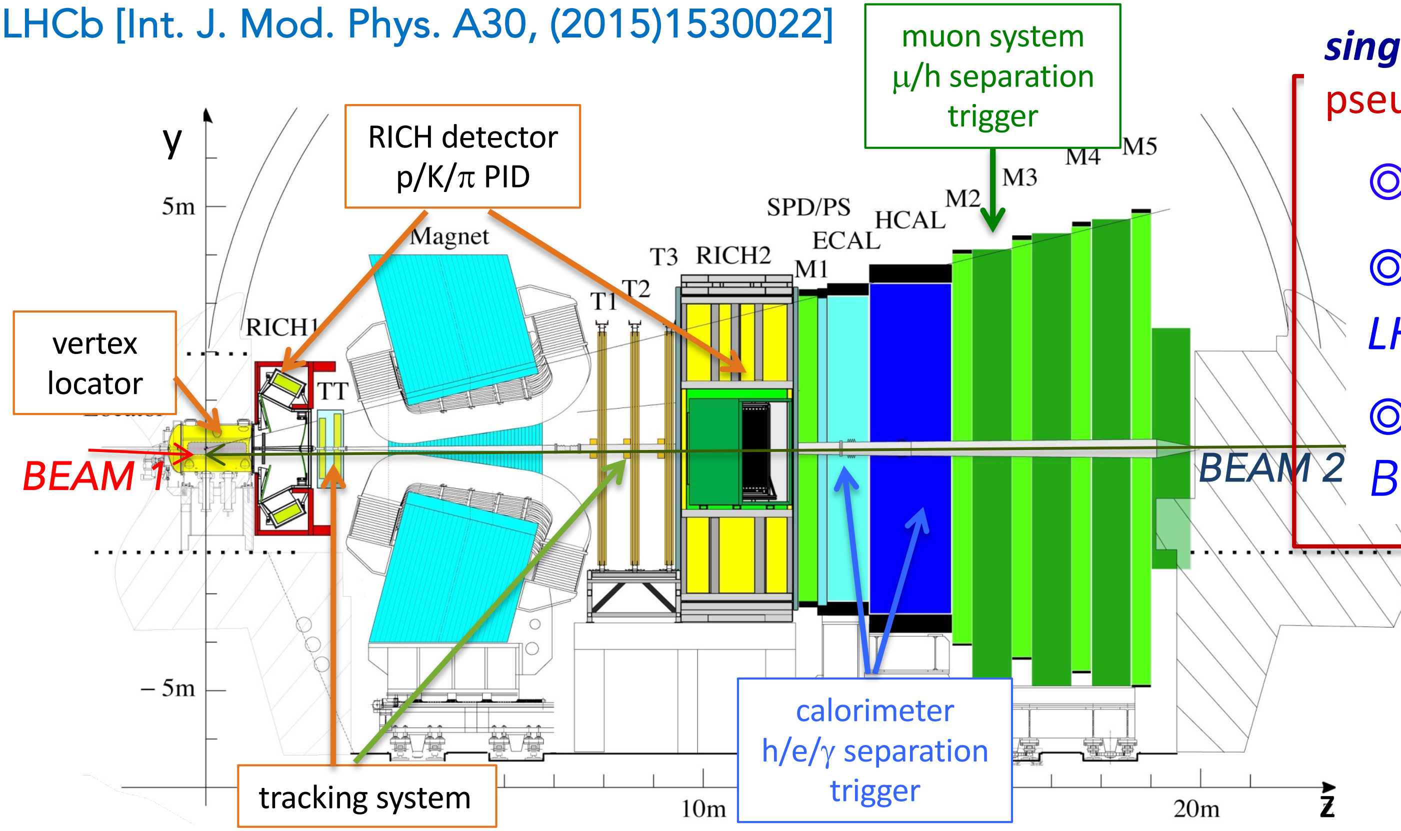
this talk

✓ D^{*+} F_L
Run 1 & Run 2 data sample, 5 fb^{-1}
[arXiv:2311.05224]

detection of B semileptonic decays at LHCb

detection of B semileptonic decays at LHCb

LHCb [Int. J. Mod. Phys. A30, (2015)1530022]



muon system
μ/h separation
trigger

RICH detector
p/K/π PID

vertex
locator

tracking system

calorimeter
h/e/γ separation
trigger

single-arm forward spectrometer

pseudorapidity range ➔ $2 < \eta < 5$

◎ σ_{bb}~500 μb

◎ *~ 25% of bb-bar pairs in LHCb acceptance*

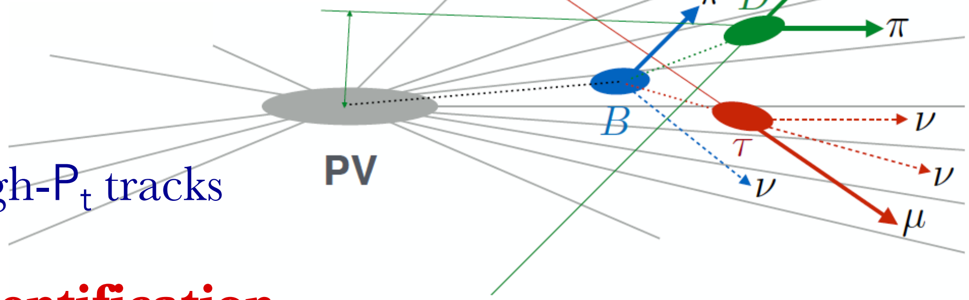
◎ *large boost → B mesons fly ~1 cm*

precise tracking → excellent resolutions

✓ decay time resolution ~ 45 fs

✓ Impact Parameter resolution ~ 20 μm for high-P_t tracks

✓ $\Delta p/p$ ~ 0.5% at 5 GeV

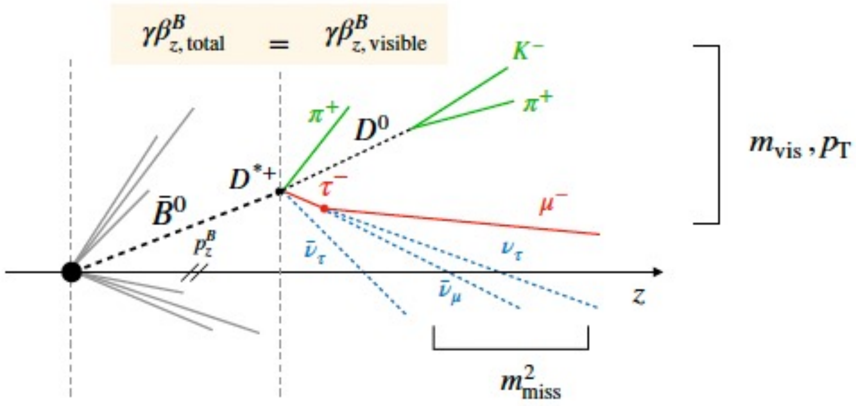


excellent particle IDentification

✓ π/K separation over 2-100 GeV, ε_K~90% for ~5% (π→K) misID

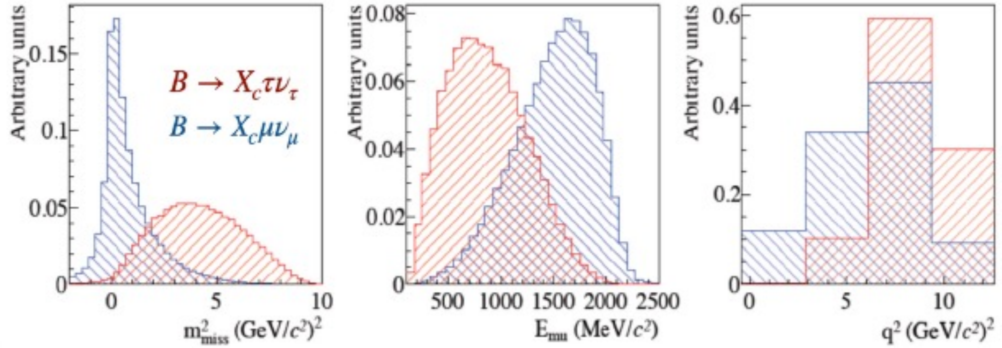
✓ powerful muon ID, ε_μ~97% for 1-3% π→μ misID

B semileptonic decays: common methods and tools



✓ missing neutrinos ➔ no narrow peak to fit

- use B flight direction to measure transverse component of missing momentum
- longitudinal component approximated with boost of the **visible final state** $\gamma\beta^B_{z,\text{total}} = \gamma\beta^B_{z,\text{visible}}$ to access rest frame kinematics ➔ ~20% resolution on B momentum



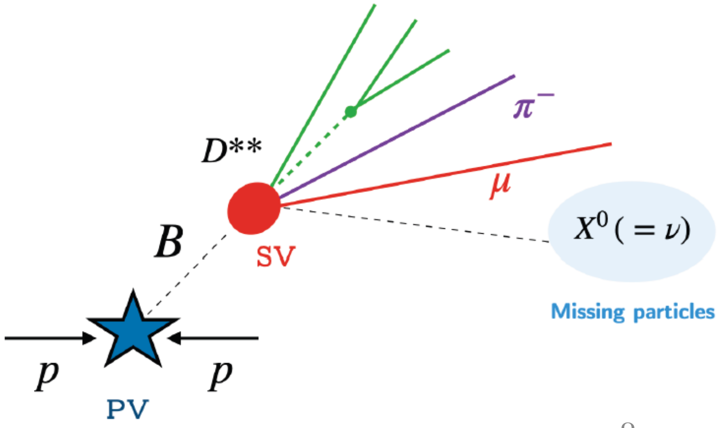
$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$

E^*_μ muon energy in B rest frame

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

✓ large backgrounds from partially reconstructed B decays $B \to D^{**}\mu\nu$, $B \to (D \to X\mu)D^*X$ with many unknowns (form factors, decay rate, etc.)

- require isolated D vertex ➔ multivariate classifiers



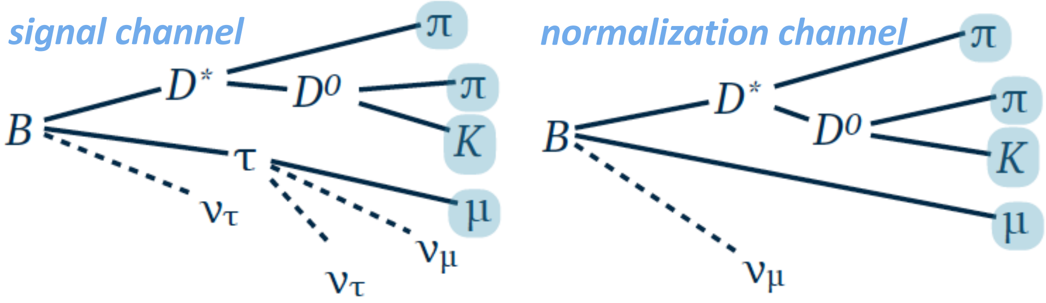
B semileptonic decays: τ reconstruction

leptonic decays

Mode	BF (%)
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.82 ± 0.04
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.39 ± 0.04

eνν channel only at B factories

✓ semitauonic and semimuonic channels have same visible final states



✓ part of systematic cancels in the ratio

✓ higher statistic but larger background

hadronic decays

Mode	BF (%)
$\tau^- \to \pi^- \pi^0 \nu_\tau$	25.49 ± 0.09
$\tau^- \to \pi^- \nu_\tau$	10.82 ± 0.05
$\tau^- \to 3\pi^\mp \nu_\tau$	9.31 ± 0.05
$\tau^- \to 3\pi^\mp \pi^0 \nu_\tau$	4.62 ± 0.05

1-prong channels only at B factories
3-prongs channels only at LHCb

✓ final states are not the same

✓ systematic do not cancel in the ratio between signal and normalization channels

➔ at LHCb measure with respect to another decay with similar final state: B→D*πππ

✓ higher purity sample but lower statistic
  - ○ no charged leptons in the final state
  - ○ reconstructable τ decay vertex

R(D^+) and R(D^{*+})

[LHCb-PAPER-2024-007, in preparation,

LHCb preliminary]

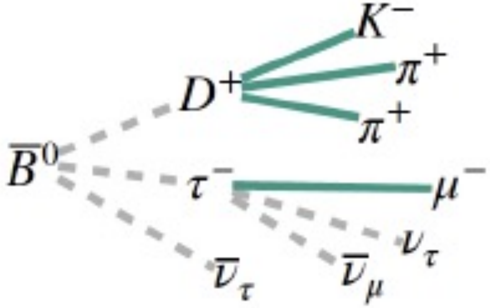
$R(D^{+(*)})$ from $\overline{B}^0 \to D^{+(*)}\tau^-\overline{\nu}_\tau$

✓ first LHCb measurement using D^+ ground state
✓ fully leptonic $\tau \to \mu\, \nu_\mu \nu_\tau$ and $D^+ \to K^-\pi^+\pi^+$ decays

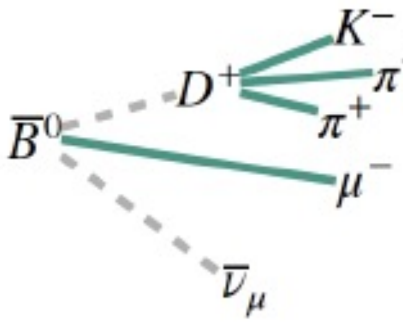
✓ partial Run 2 data sample: 2 fb^{-1} at $\sqrt{s}$ = 13 TeV

✓ primary goal is to measure $R(D^+)$
✓ feed-down from unreconstructed $D^{*+} \to D^+\pi^0/\gamma$ gives access to $R(D^{*+})$ in the same visible final $K\pi\pi\mu$ final state with 4 charged tracks

signal channel



normalization channel



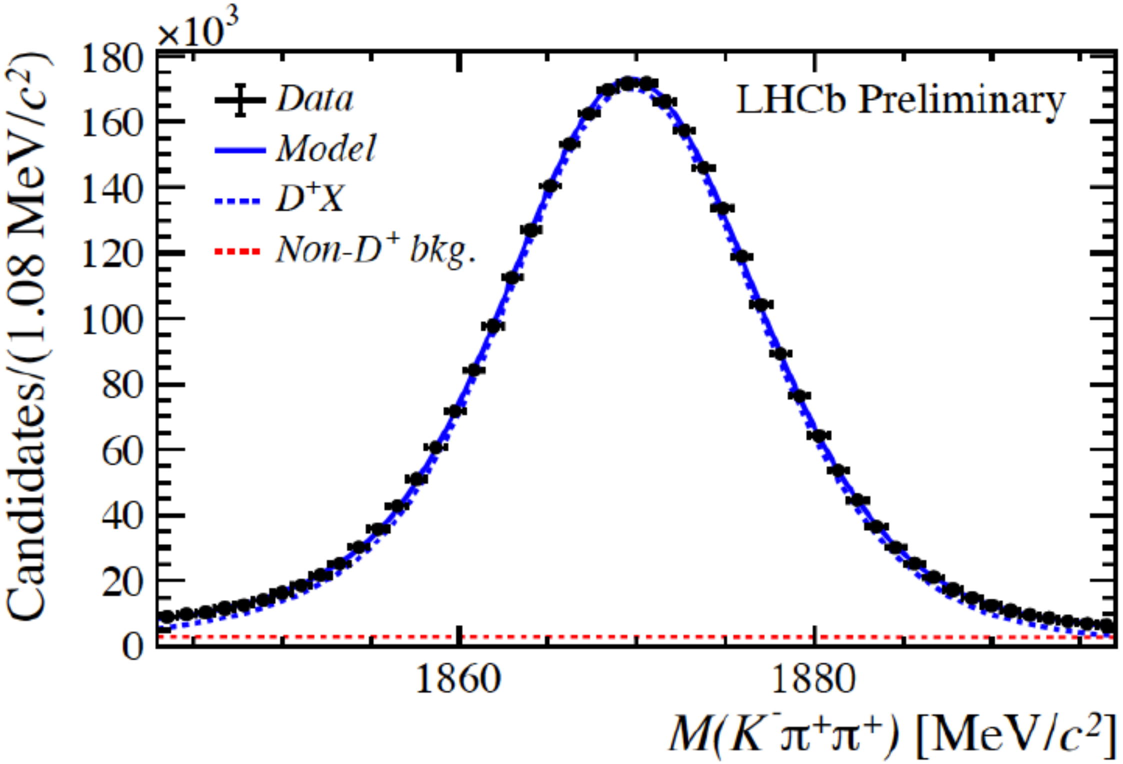
$$R\left(D^{+(*)}\right) = \frac{\mathcal{B}(\bar{B}^o \to D^{+(*)}\, \tau^- \nu_\tau)}{\mathcal{B}(\bar{B}^o \to D^{+(*)}\, \mu^- \nu_\mu)} = \frac{\epsilon_\mu^{D^{+(*)}}}{\epsilon_\tau^{D^{+(*)}}} \frac{N_\tau^{D^{+(*)}}}{N_\mu^{D^{+(*)}}} \frac{1}{\mathcal{B}(\tau^- \to \mu^- \nu_\tau \nu_\mu)}$$

✓ yield ratio determined from fit to data
✓ efficiency ratio determined from simulation
✓ only external input $\mathcal{B}(\tau \to \mu\nu\nu)$

data sample selection

- ✓ particle ID, kinematic and topologic requirements on $(K^-\pi^+\pi^+)\mu$

- ✓ BDT to remove fake D^+ candidates from accidental tracks combinations
- ✓ residual D^+ background removed with *sPlot* technique *[NIM A555 (2005) 356]*



- ✓ **neutral** BDT trained to discriminate between $B^0 \rightarrow D^+\tau^-\nu_\tau$ and $B^0 \rightarrow D^{+*}\tau^-\nu_\tau$ ➔ uses neutral calorimeter objects in a cone around D^+ direction and reconstructed π^0 consistent with $D^{*+} \rightarrow D^+\pi^0$

strategy to measure the signal yields

✓ **final charged track isolation BDT to split the data sample into:**

- ○ ***signal sample*** $D^+\mu^-$
  and 3 more ***control samples,*** with enhanced sensitivity to background components

- ○ 1π ***sample*** $D^+\mu^-\pi^-$ feed-down from 1P D^{**} states: $B \to D^{**}[D^+X]\mu\,\nu$
  $B \to D^{**}[D^+X]\tau[\mu\nu\nu]\,\nu$

- ○ 2π ***sample*** $D^+\mu^-\pi^+\pi^-$ feed-down from higher-mass D^{**} states

- ○ 1K ***sample*** $D^+\mu^-K^-$ double-charm $B \to D^+H_c[\mu\nu X]X'$

✓ **simultaneous 3D binned fit to the 4 samples using the discriminating variables:**

$m^2_{miss} = (p_B - p_D - p_\mu)^2$,E^*_μ , $q^2 = (p_B - p_D)^2$

fit components (1)

✓ **signal, normalization and physics background templates from** MC

- **main physics background**

$B \to D^{**}$

1. fractions of 1P state varied in the fit
2. higher D^{**} mass states shape also varied

double-charm

1. fractions and shapes varied in the fit

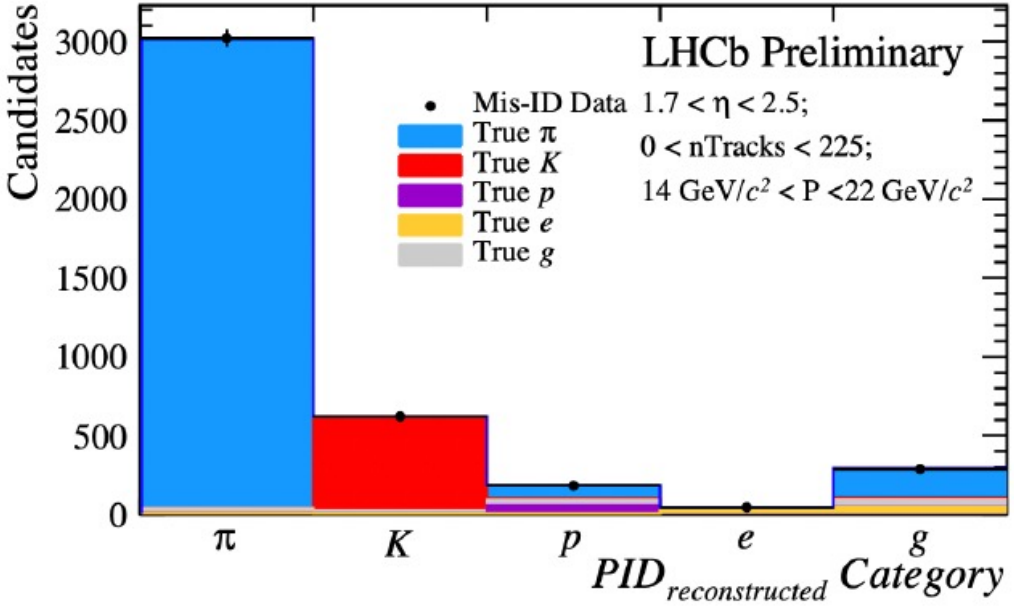
- **form factor parametrization**

$B \to D^{+}$: BGL *[PRD 94 (2016) 094008]*
$B \to D^{*}$: BGL *[Eur. Phys. J. C 82, 1141 (2022)]*
$B \to D^{**}$: BLR *[PRD 95 (2017) 014022]*
💥 this is the first analysis that uses HAMMER *[Eur. Phys. J. C. 80 (2020) 883]*
implemented in RooHammerModel *[JINST 17 (2022)T04006]* ➔
form factor parameters varied in the template fit with external constraints

fit components (2)

✓ **data based templates**

- μ **mis-identified background** from fake-μ control sample D^+h^-
h = [π, K, p, e, g(fake tracks)]

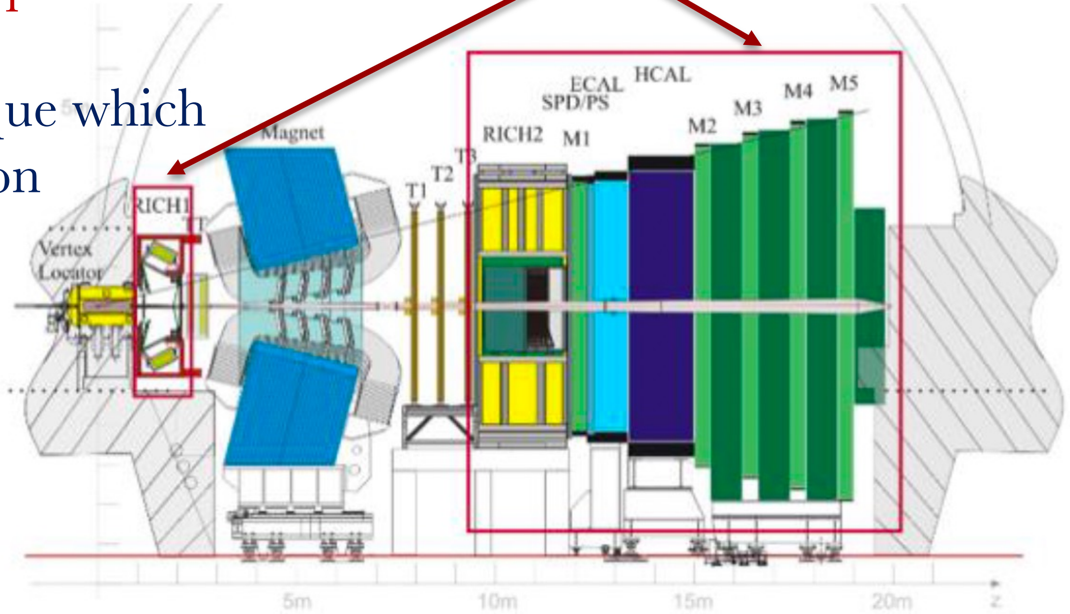


exception ➔ template for fake tracks (g) from MC

- **combinatorial background** from same charge $D^+\mu^+$ data sample

tracker-only simulation

1. size of simulated sample can limit the final precision
2. heavy reliance on binned MC templates



sub-detectors response turned off

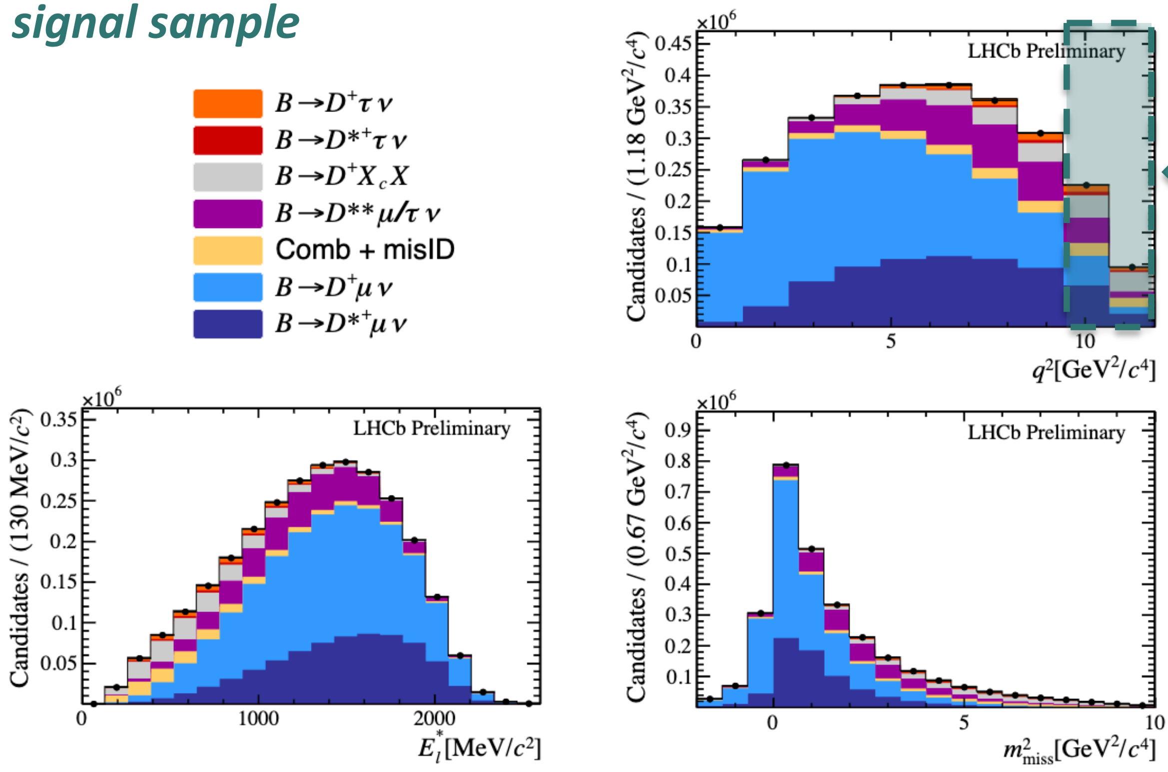
- ○ **new fast simulation** technique which turns off RICH photon propagation and Calo showers
- ○ 8 times faster and 40% less disk space
- ○ enable to produce large amount of simulation sample

- ○ emulate effects of the missing detectors at analysis level
- ○ PID and tracking efficiencies from data control samples
- ○ final tuning of MC templates with data/simulation corrections:
  B kinematics, multiplicity,
  QED effects *[PRL 120 (2018)261804]*, …

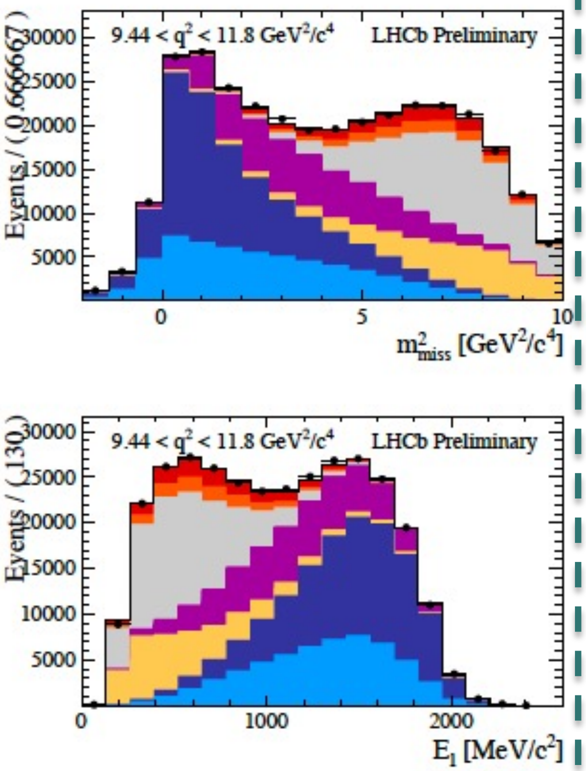
final excellent data/simulation agreement

fit results

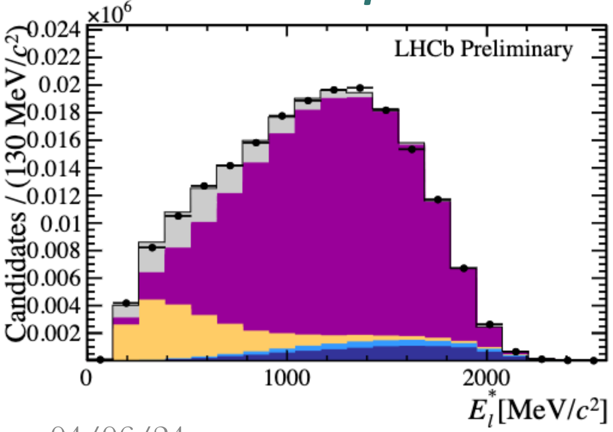
signal sample



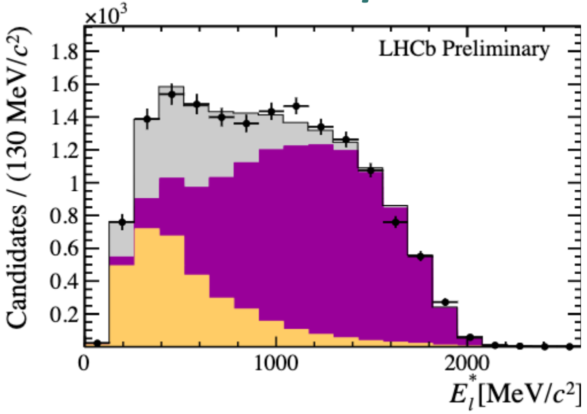
zoom in high q^2 bins



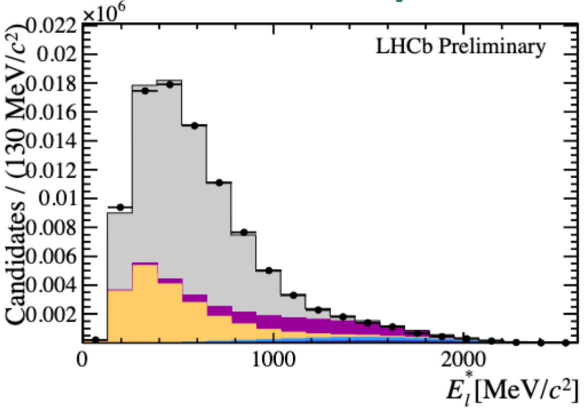
1π sample



2π sample



1K sample



R(D$^+$) and R(D^{*+}) results

LHCb ***preliminary***

$R(D^+) = 0.249 \pm 0.043_{stat} \pm 0.047_{syst}$

$R(D^{*+}) = 0.402 \pm 0.081_{stat} \pm 0.085_{syst}$

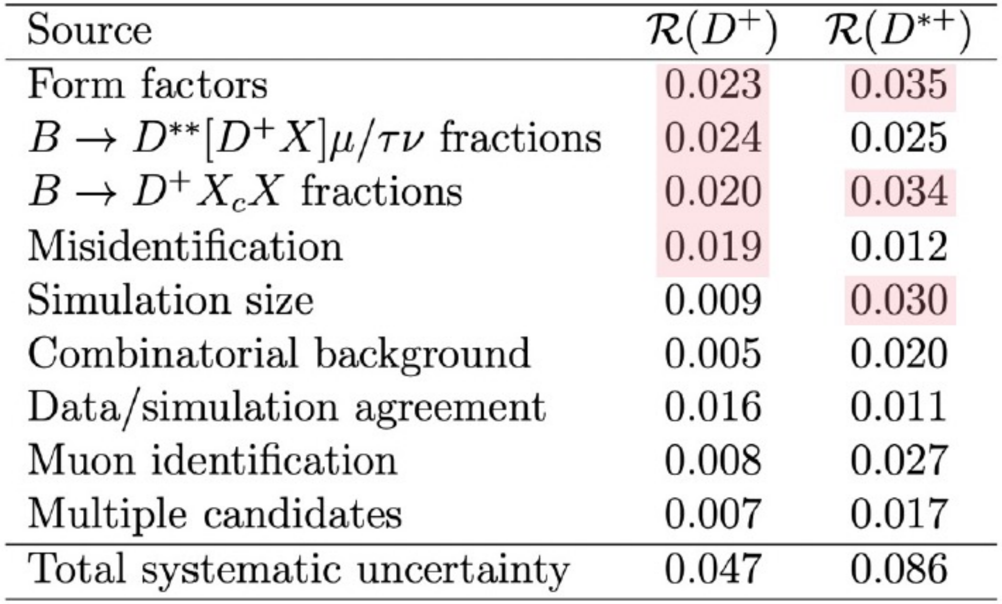
correlation coefficient $\rho = -0.39$

compatible with SM at 0.78σ

signal yields :
$N_\tau^D \sim 35000$
$N_\tau^{D^*} \sim 29000$

$$R\left(D^{+(*)}\right) = \boxed{\frac{\epsilon_\mu^{D^{+(*)}}}{\epsilon_\tau^{D^{+(*)}}}} \frac{N_\tau^{D^{+(*)}}}{N_\mu^{D^{+(*)}}} \frac{1}{\mathcal{B}(\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu)}$$

systematic uncertainties



Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$B \to D^+X_cX$ fractions	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	0.086

systematic uncertainty on ratio of efficiencies very subdominat

main systematic uncertainties are from form-factors parametrisation and background modelling

$R(D^+)$ and $R(D^{*+})$ results

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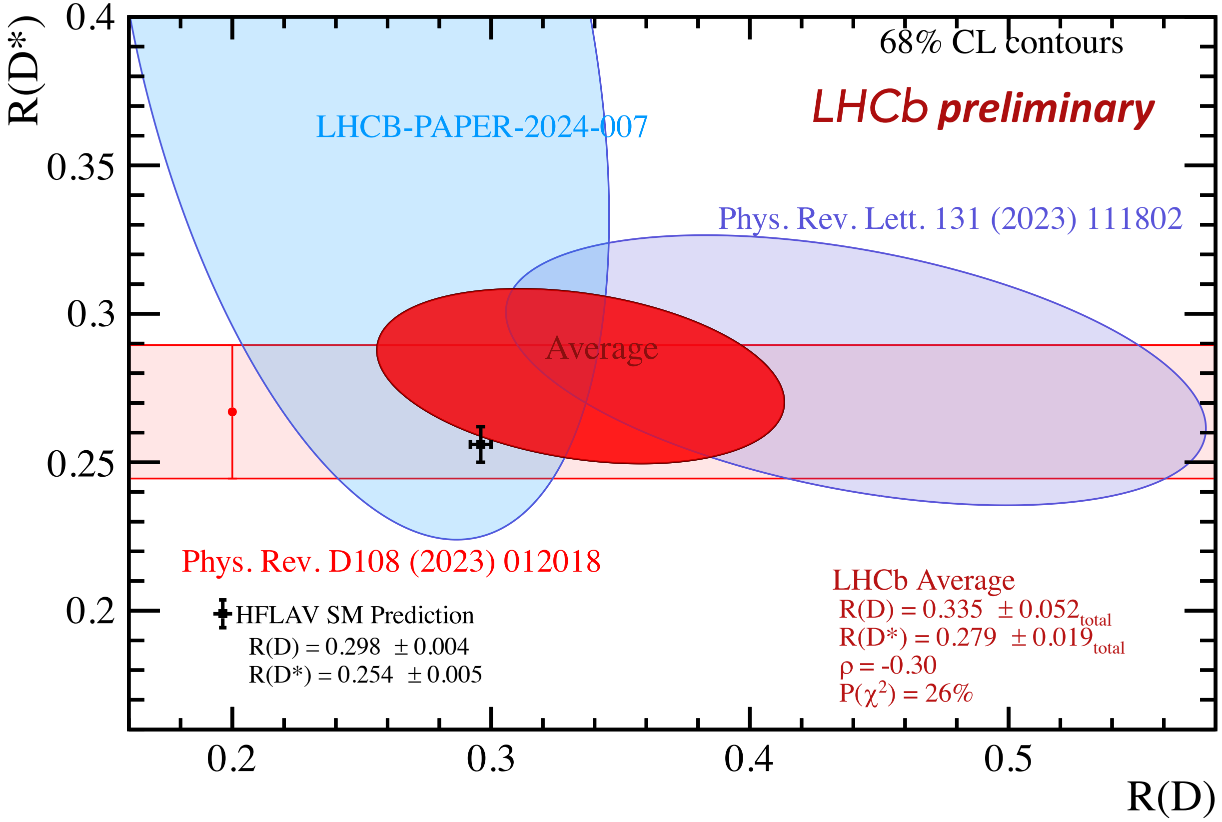


LHCb combination:

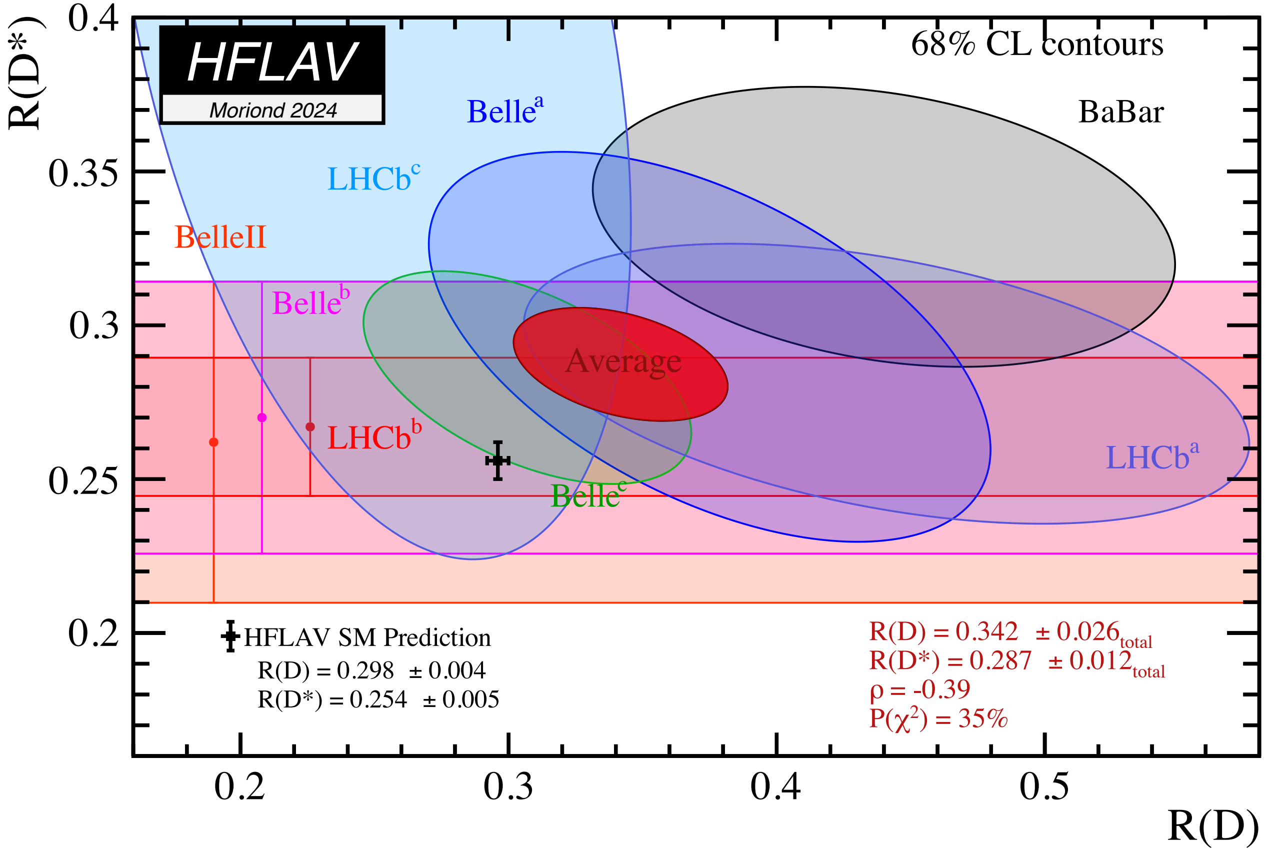
$R(D^*) = 0.279 \pm 0.01$

$R(D) = 0.335 \pm 0.052$

$\rho = -0.30$

new R(D) - R(D*) world average

including this new result *[LHCb-PAPER-2024-007 in preparation]*
the world average becomes ➔ R(D*) = 0.287 ± 0.012; R(D) = 0.342 ± 0.026



the deviation w.r.t. the SM stays at 3.31σ level for the combination of R(D)-R(D*)

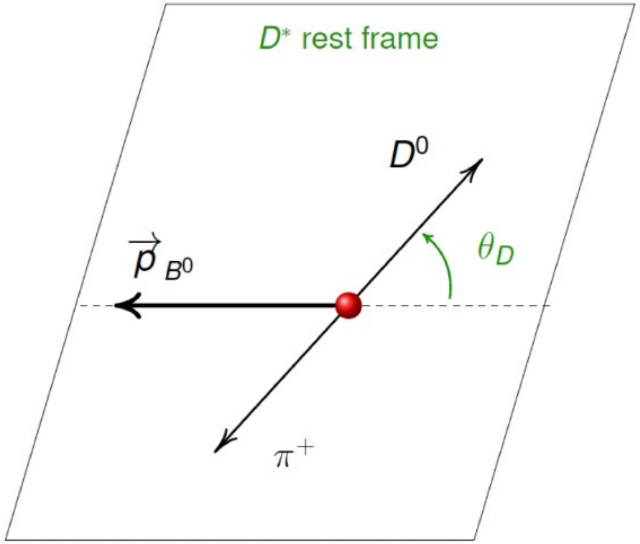
note that this plot has been updated on the 20th of May 2024 to include:
the updated R(D*) measurement from Belle II *[arXiv:2401.02840]* (updated w.r.t. the result presented at Lepton Photon 2023) and the updated R(D*) measurement by LHCb *[will appear soon as arXiv:2305.01463v2]* (updated w.r.t. *[PRD 108, 012018]*)

D^{*-} longitudinal polarization in $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$

[arXiv:2311.05224]

longitudinal D^* polarization fraction $F_L^{D^*}$

✓ studies of kinematic and angular distributions, such as $F_L^{D^*}$, can provide additional sensitivity to NP: can test presence of new mediators and different spin structures



✓ **first** LHCb **angular analysis on** $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ **with** $\tau \rightarrow 3\pi^\pm(\pi^0)\nu_\tau$

✓ the value of $F_L^{D^*}$ is extracted from the angular distribution of the $D^{*-} \rightarrow D^0\pi^-$

unpolarized signal fraction

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

polarized signal fraction

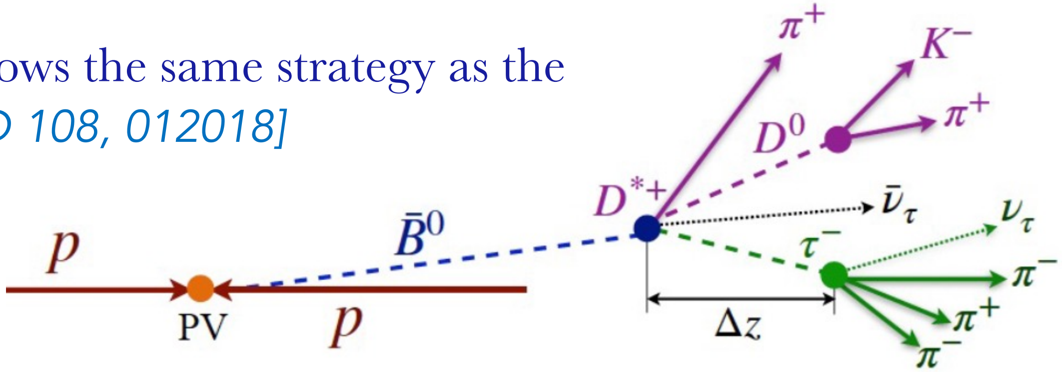
$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

the presence of new mediators impacts the polarisation fraction

✓ data sample ~5 fb^{-1} at $\sqrt{s}$ = 7 - 8 TeV (Run 1) and 13 TeV (Run 2)

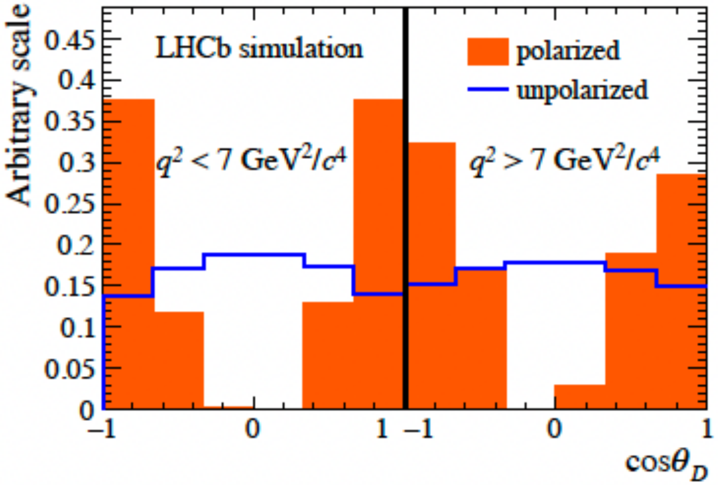
D^* polarization $F_L^{D^*}$ measurement

- ✓ selection of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ decays follows the same strategy as the R(D^*) measurements *[PRL 120, 171802] [PRD 108, 012018]*



just few highlights

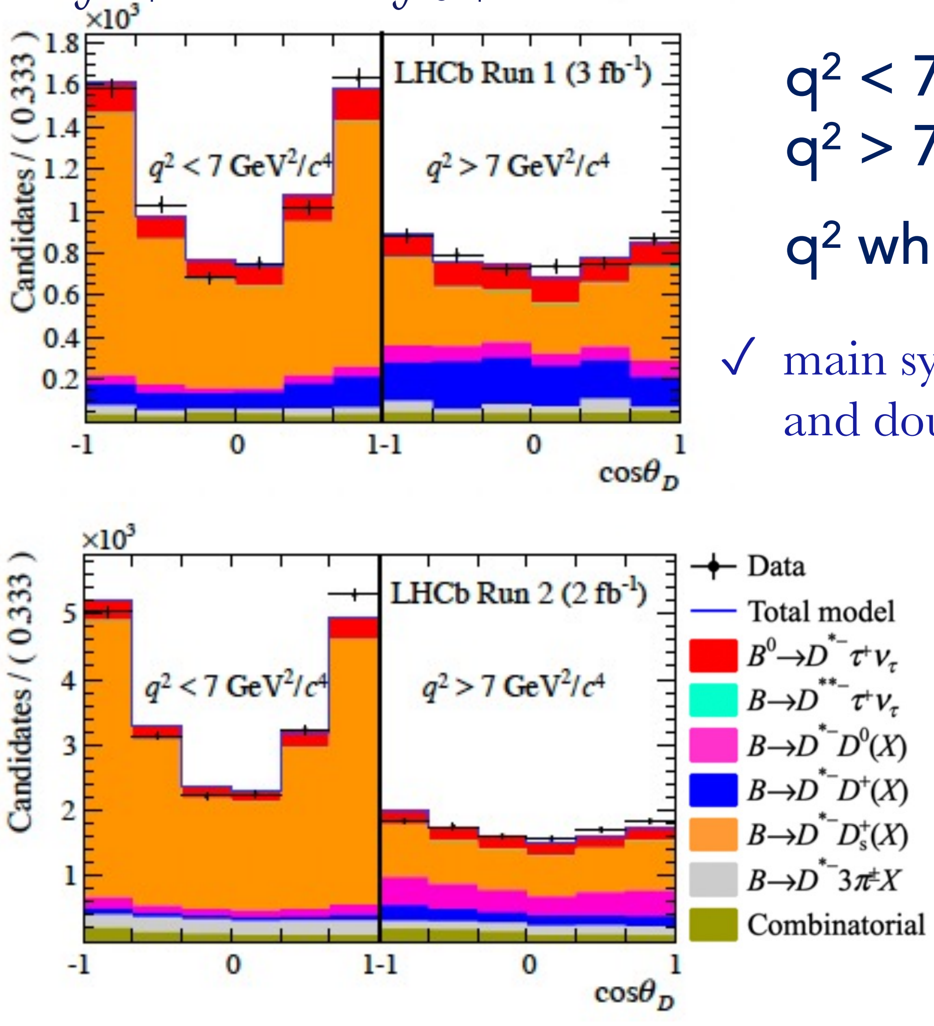
- ✓ signal candidates are built based on the **6 final-state charged tracks** ➔ tracks/vertex quality, particle identification and mass constraints
- ✓ the requirement of a 3π vertex to be downstream w.r.t. the B vertex along the beam direction suppresses the main background $D^*3\pi X$ (~100 × signal)
- ✓ BDT classifier based on kinematic and resonant structure to remove the largest contributor of the double charm background $B \rightarrow D^* D_s(3\pi X)X$ (~10 × signal): anti-D_s BDT



- ✓ 4D binned template fit
  - ○ simultaneous on two q^2 bins ($\lesssim 7\ \mathrm{GeV}^2/c^4$)
  - ○ $\cos\theta_D$
  - ○ τ decay time
  - ○ anti-D_s BDT output
- ✓ two MC signal templates: **polarized** and **unpolarized**

D* polarization F_L^{D*} result

$f_{\text{low } q2} = 0.36 \pm 0.07$ $f_{\text{high } q2} = 0.01 \pm 0.08$



- ✓ F_L^{D*} determined from the observed fractions of polarized signal at low and high q^2 regions

$q^2 < 7\ \text{GeV}^2/c^4$: $0.51 \pm 0.07_{\text{stat}} \pm 0.03_{\text{syst}}$
$q^2 > 7\ \text{GeV}^2/c^4$: $0.35 \pm 0.08_{\text{stat}} \pm 0.02_{\text{syst}}$

q^2 whole range : $0.43 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}}$

- ✓ main systematic from MC template, FF parametrization, and double charm background modelling

Compatible with previous Belle measurement:

$F_L^{D*} = 0.60 \pm 0.08 \pm 0.04$ [arXiv:1903.03102]

Compatible with SM:

$F_L^{D*} = 0.441 \pm 0.006$ [PRD 98 (2018) 095018]
$F_L^{D*} = 0.457 \pm 0.010$ [Eur. Phys. J. C 79, 268 (2019)]
$F_L^{D*} = 0.467 \pm 0.009$ [Eur. Phys. J. C 80, 347 (2020)]
$F_L^{D*} = 0.422 \pm 0.010$ [arXiv:2310.03680]
$F_L^{D*}[q^2 < 7GeV^2/c^4] = 0.495 \pm 0.017$ [arXiv:2310.03680]
$F_L^{D*}[q^2 > 7GeV^2/c^4] = 0.383 \pm 0.006$ [arXiv:2310.03680]

outlook

tree level semileptonic $b \rightarrow c\tau\nu_\tau$ transitions

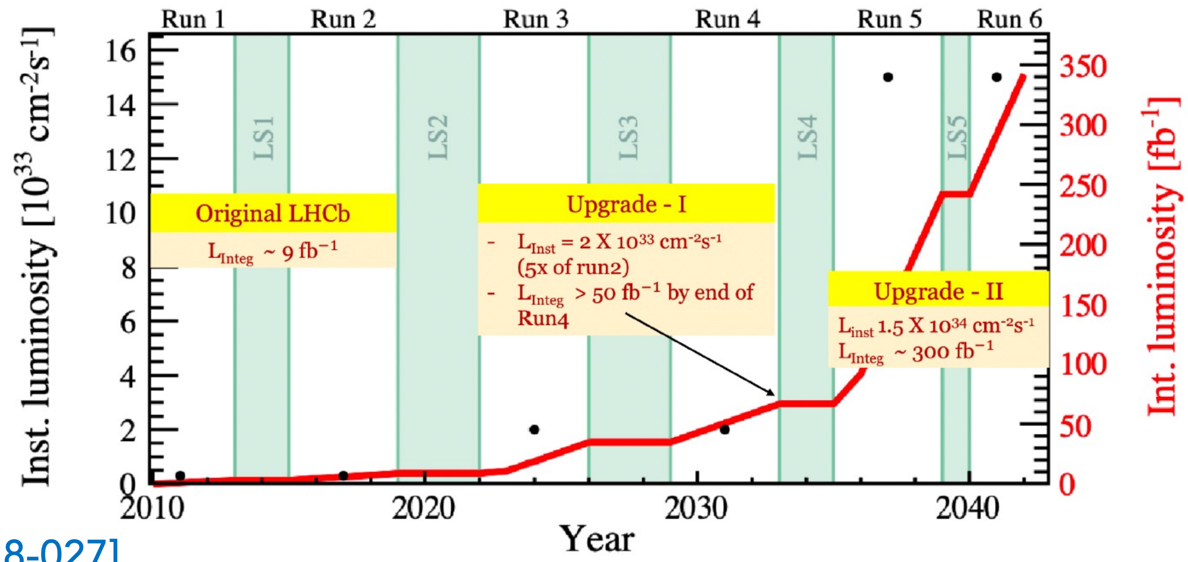
✓ *adding full Run 2 dataset*

✓ *many new measurements underway : $R(D_s^*)$ muonic, $R(\Lambda_c)$ muonic, B^0 decays to other charm mesons selecting different D decay channels*

✓ *several angular analysis are ongoing*
$B^0 \rightarrow D^*\mu\nu$, $B^0 \rightarrow D^*\tau\nu$, $\Lambda_b \rightarrow \Lambda_c\mu\nu$, $B_s \rightarrow D_s\mu\nu$, …
to provide new tests and constraints of possible physics beyond SM

✓ Run3 ***data taking is underway with an improved detector***
qualified to accumulate 50 fb^{-1}
[LHCb-TDR{13,14,15,66}]

✓ *to take full advantage of the* HL-LHC, $\mathcal{L}$ *up to* 1.5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$
➔ *major upgrade of the detector to collect up to* 300 fb^{-1}
[CERN/LHCC 2021-012, CERN/LHCC 2018-027]



✓ ***larger data samples and improved model descriptions will help to control systematic uncertainties***

conclusions

- new simultaneous $R(D^+)$ and $R(D^{+*})$ measurement using the muonic τ decay with partial Run 2 dataset
  - compatible with the SM at 0.78 σ level
- global picture unchanged for $R(D)$-$R(D^*)$ combination
  - overall tension with SM at the 3.17 σ level

- first angular analysis of charged-current semitauonic decays, measuring $F_L^{D^*}$ in $B^0 \to D^* \tau \nu$
  - better precision than Belle measurement, compatible with it and with the SM

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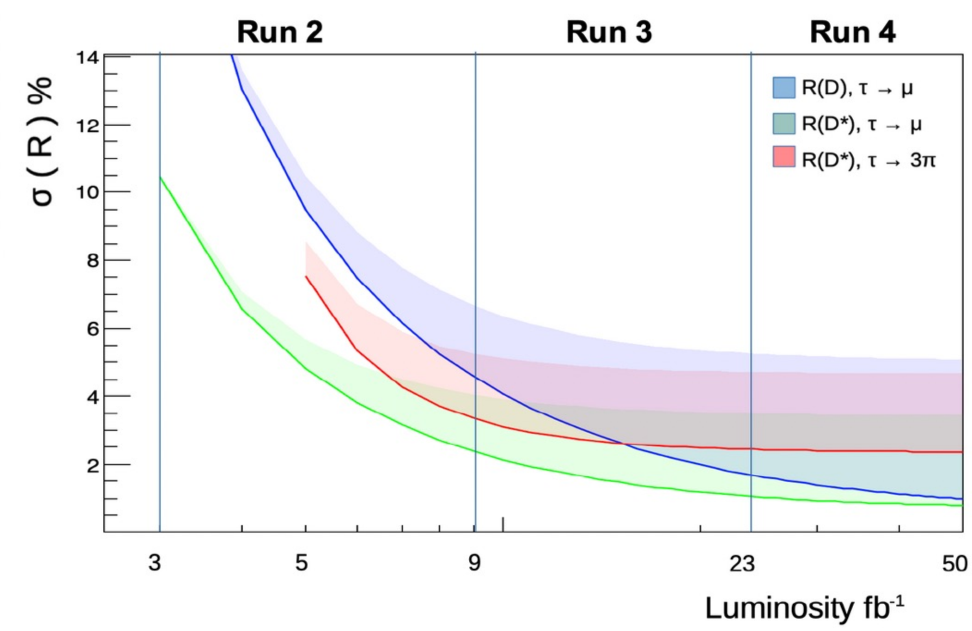
Thank you
for your attention !

spares

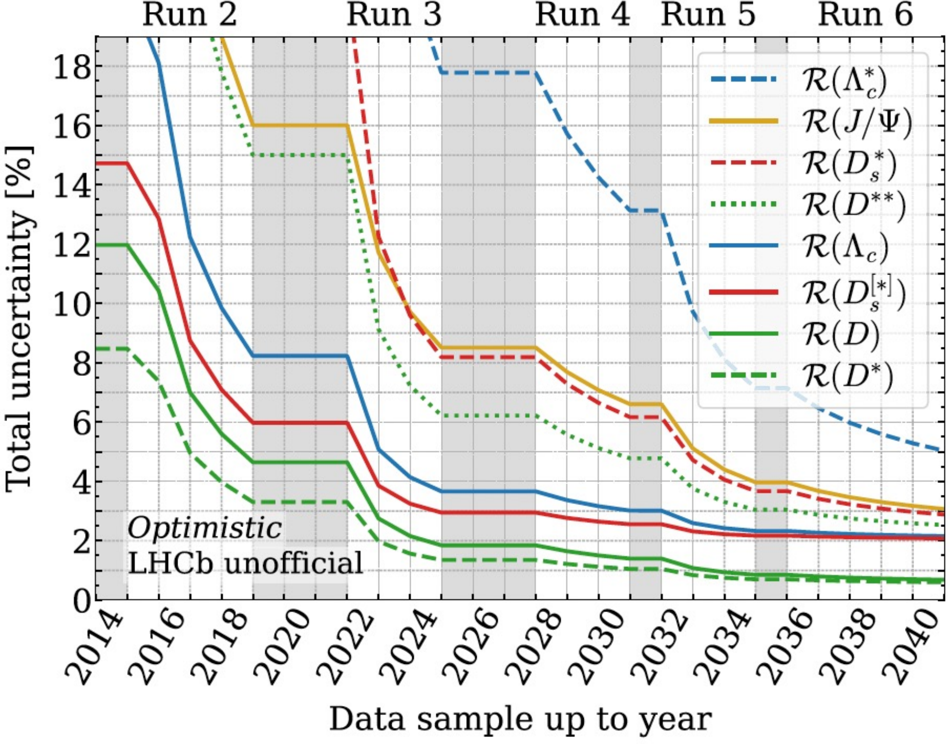
projections on R(H$_c$) measurements



the bands represent the degree of optimism/pessimism in our ability to reduce systematics

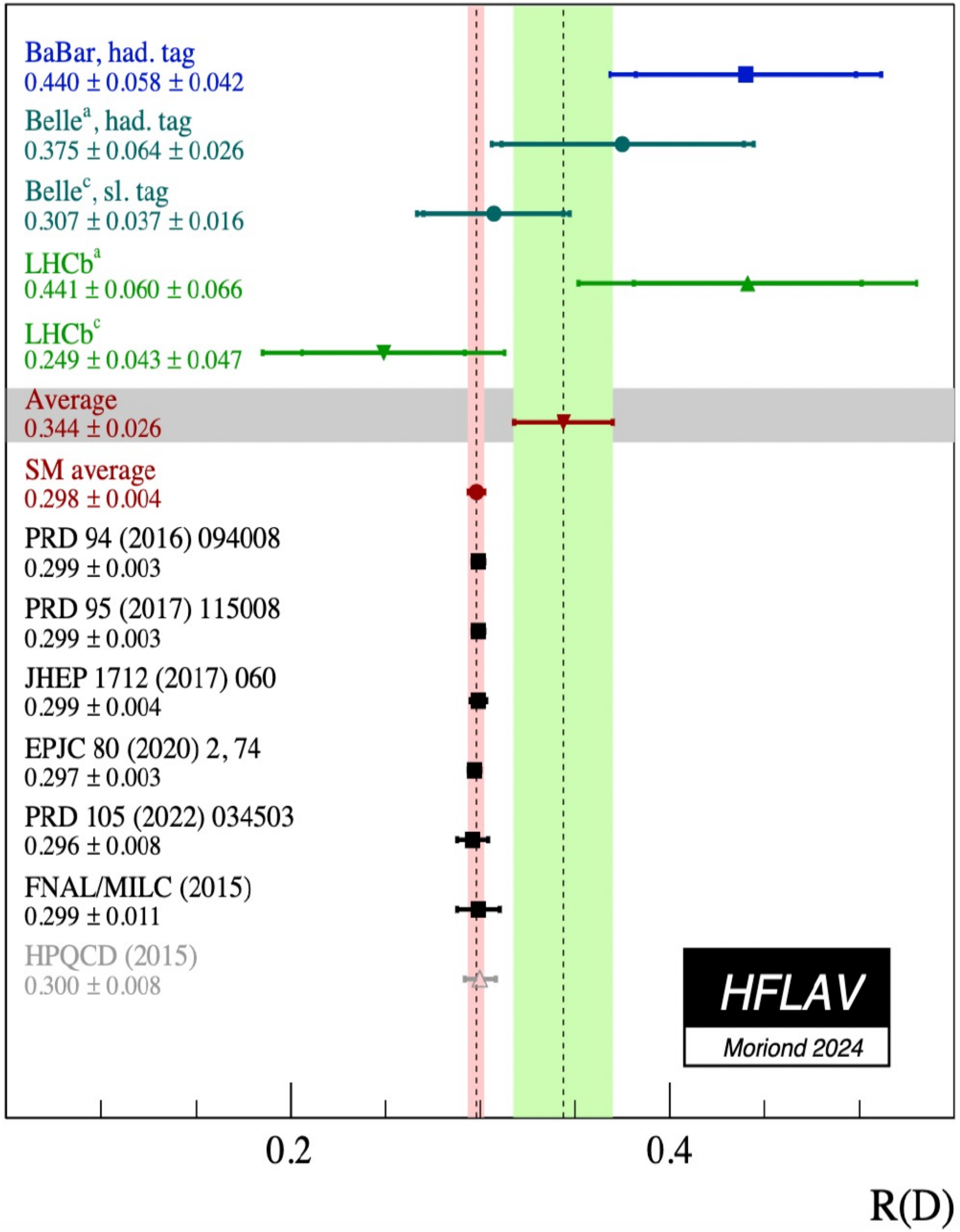
projections on other ongoing analyses in LHCb

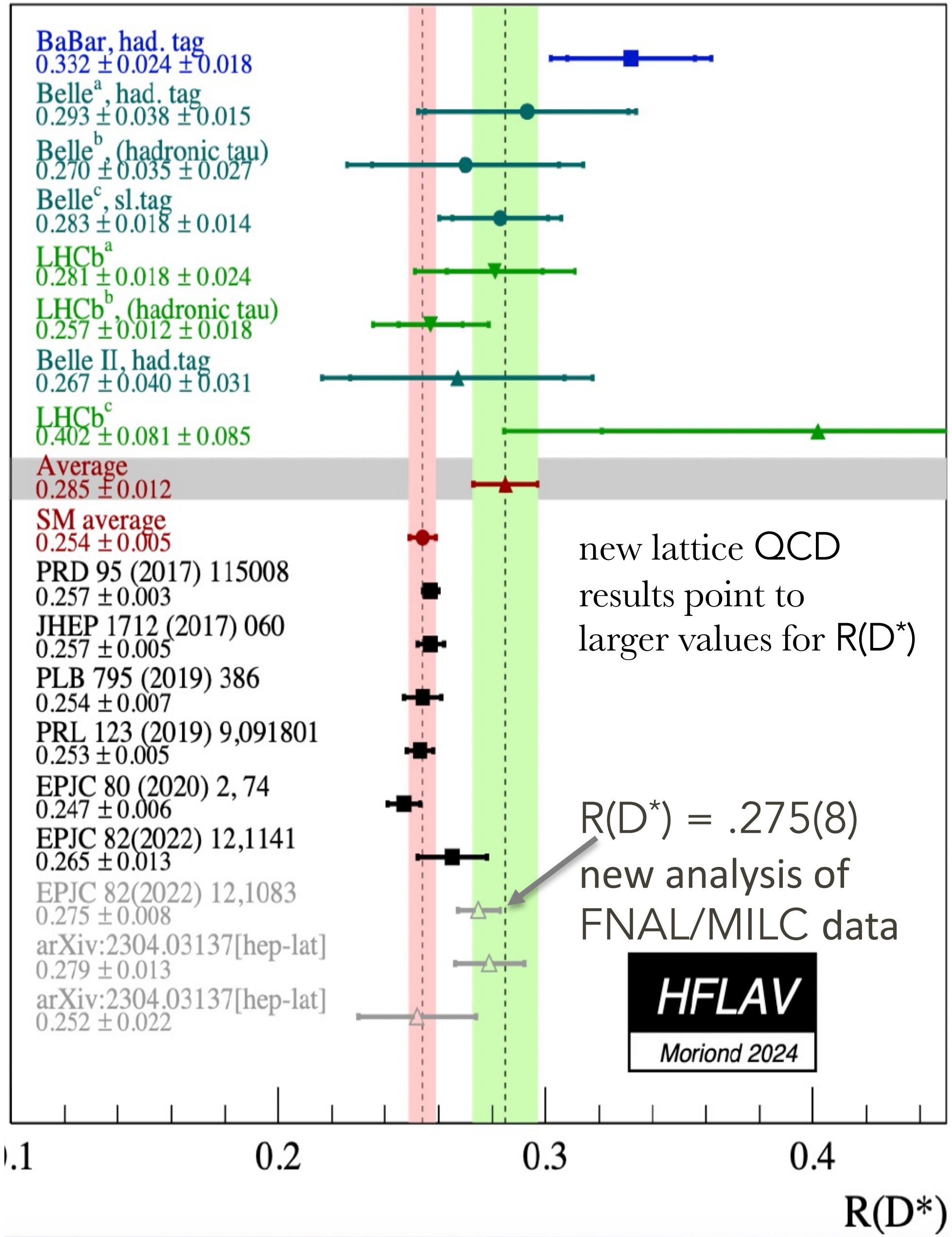
[Rev.Mod.Phys. 94 (2022) 015003]



crucial cross check with other decay modes

status of R(D) and R(D*)





new lattice QCD results point to larger values for R(D*)

R(D*) = .275(8)
new analysis of FNAL/MILC data

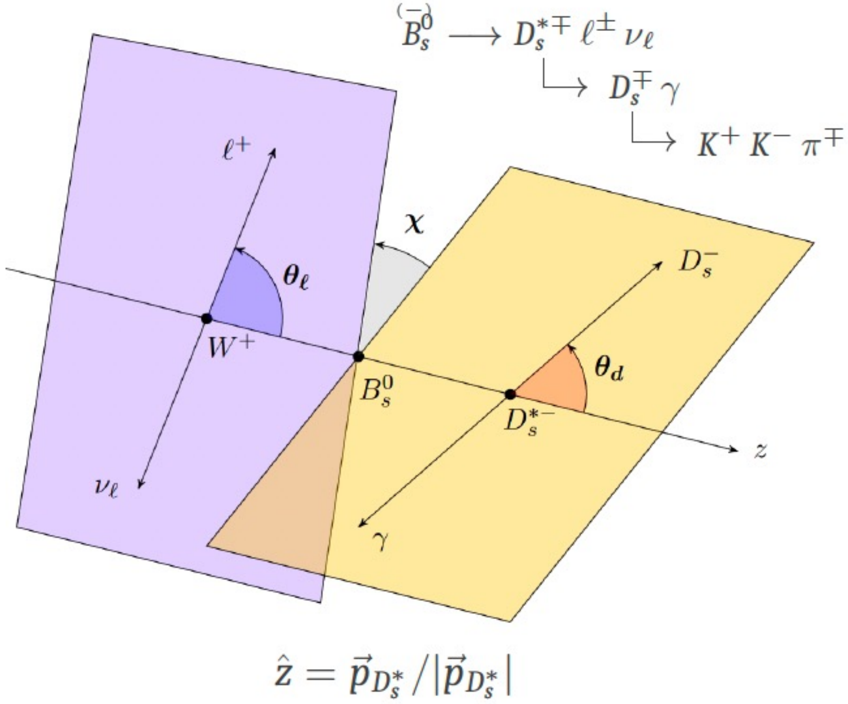
beyond R(H_c) : going differential

✓ angular analyses with semitauonic and semimuonic to probe spin structure of physics beyond SM

✓ even in case R(H_c) is SM-like, it will put strong constraints on NP models

$$\frac{d^4(B^0 \to D^*\ell^+\nu_\ell)}{dq^2\, d\cos^2\theta_\ell\, d\cos\theta_{D^*}\, d\chi} \propto |V_{cb}|^2 \sum_i \boxed{\mathcal{H}_i(q^2)} f_i(\theta_\ell, \theta_{D^*}, \chi)$$

✓ $\mathcal{H}_i$ sensitive to New Physic and Form Factors many observables can be derived by $\mathcal{H}_i$



Recent literature (non-exhaustive list):

D.Hill et al. JHEP 11 (2019) 133

V. Dedu, A.Poluektov JHEP 07 (2023) 063

B. Bhattacharya et al. JHEP 05 (2019) 191

C.Bobeth et al. EPJ.C 81 (2021) 11, 984

M. Fedele et al. ArXiv;2305.15457

Z. Huang et al. PRD 105 (2022) 1, 013010

B. Bhattacharya et al. JHEP 07 (2020) 07, 194

M. Ivanov et al. PRD 95 (2017) 3, 036021

D. Becirevic et al. NPB 946 (2019) 114707

O. Colangelo, F.DeFazio, JHEP 06 (2018) 082

R(D$^{(*)}$) with $\tau \to \mu \bar{\nu}_\mu \nu_\tau$

PRL 131, 111802]

$$R\left(D^{(*)}\right) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

where D$^{(*)}$ stands for a D^0, a D^{*+} or a D^{*0}

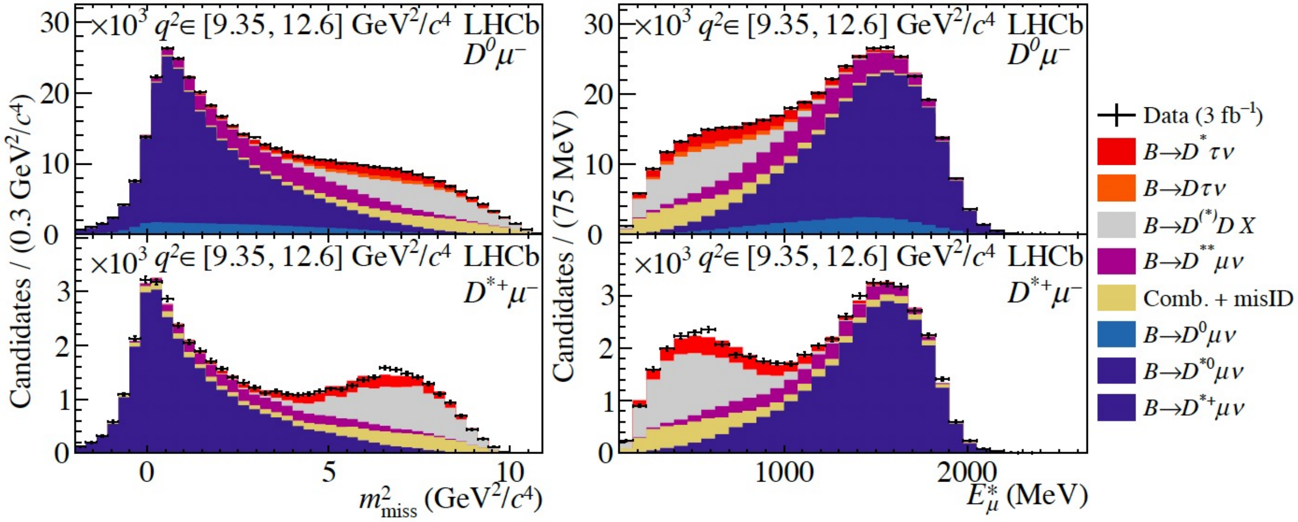
✓ select D$^0\mu^-$ and D$^{*+}\mu^-$ candidates with D$^0 \to K^-\pi^+$, D$^{*+} \to D^0(K^-\pi^+)\pi^+$

signal and normalization decay chains with identical visible final states, many uncertainties cancel on R(D$^{(*)}$)

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using muonic $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

3D template fit to

- ▶ $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- ▶ $m^2_{\text{miss}} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- ▶ E^*_μ energy of μ



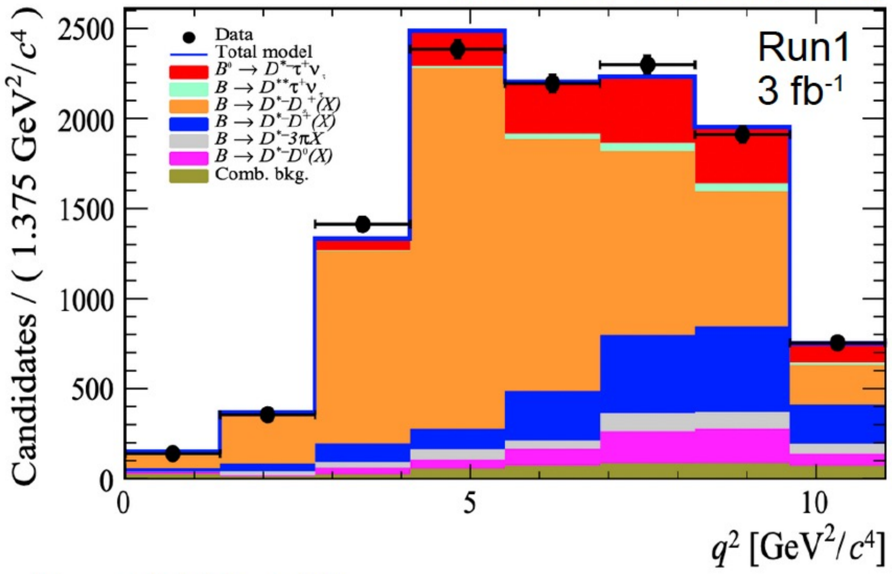
$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$

$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

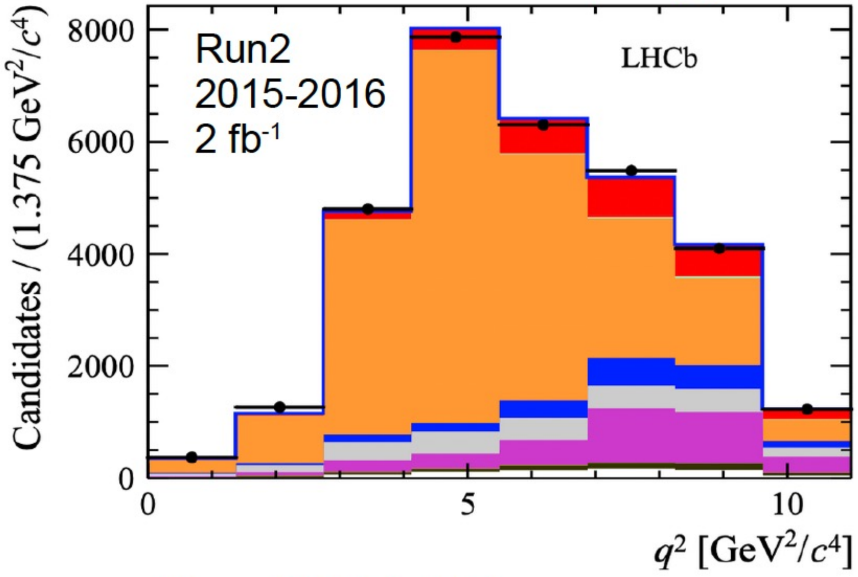
Agreement with SM at 1.9σ

R(D*) with $\tau \to 3\pi^\pm(\pi^0)\nu_\tau$

PRL 120, 171802 (2018)



PRD 108(2023)1,012018



N $_{\text{sig}}$=1296 ± 86

N $_{\text{sig}}$=2469 ± 154

$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13\,(\text{stat}) \pm 0.18\,(\text{syst})$$

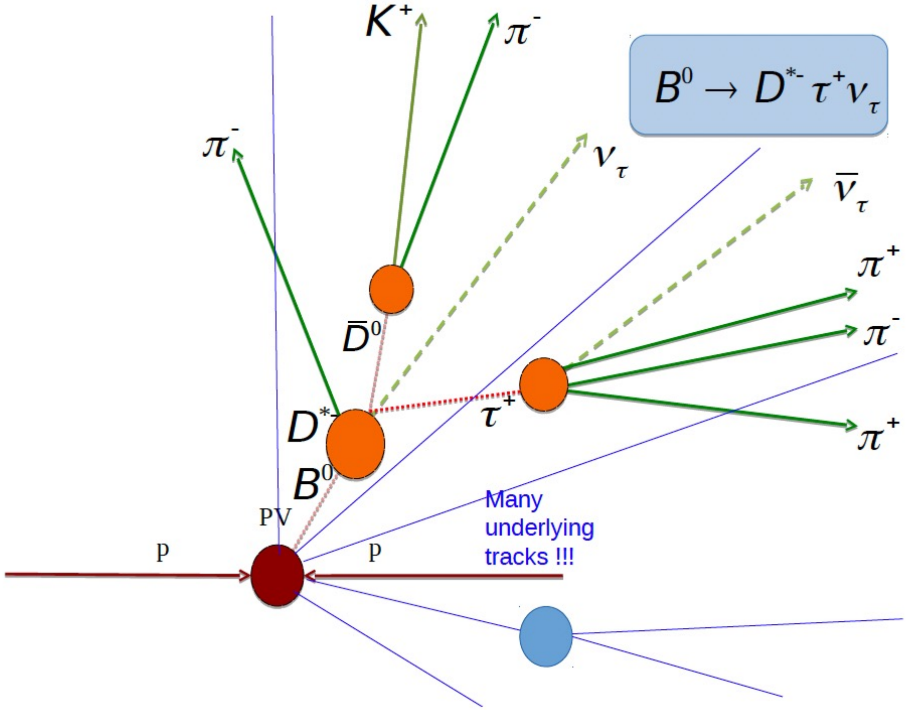
10%

$$\mathcal{K}(D^{*-}) = 1.70 \pm 0.10(\text{stat})^{+0.11}_{-0.10}(\text{syst})$$

6%

MC size is the single dominant systematic (4.1%) → Reduced to 2% using fast MC ReDecay, EPJC 78, 1009 (2018)

R(D*) with $\tau \rightarrow 3\pi^{\pm}(\pi^{0})\nu_{\tau}$: ReDecay



[EPJC **78**, 1009 (2018)]

❶ Generate 1 complete event: signal + underlying event

❷ Re-generate the B decay 100 times and merge each with the underlying event

❸ Repeat ❶ and ❷ N times

→ Factor $\mathcal{O}(10)$ faster simulation

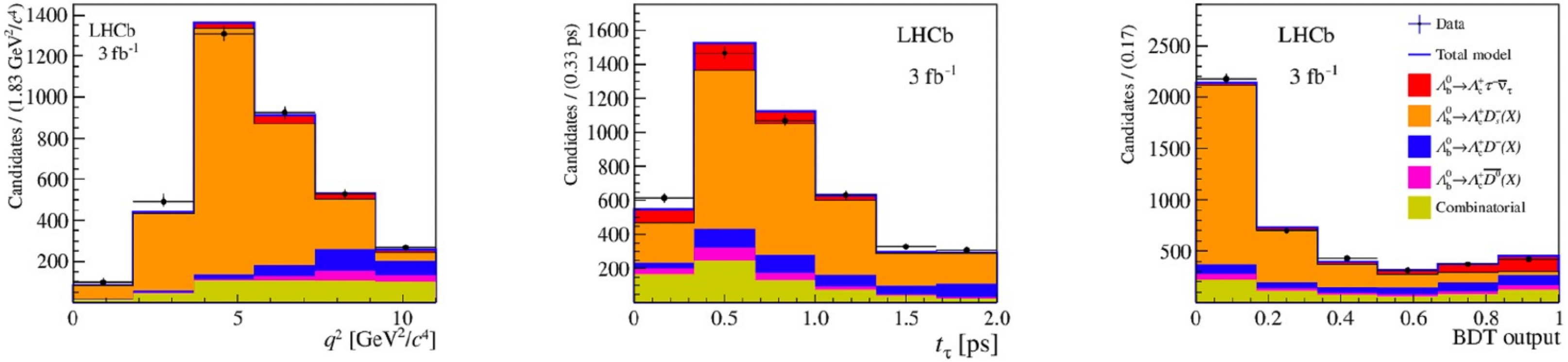
$R(\Lambda_c)$ with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$

[PRL 128 (2022) 191803]

- First LFU test in a baryonic $b \to c\ell\nu_\ell$ decay with Run 1 data using hadronic $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Normalisation channel $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} \qquad R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \underbrace{\left\{ \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \right\}}_{\text{ext. input}}$$

- 3D template fit to extract signal yield



$$\mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$$

$$R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$

Agreement within 1.0σ to SM

R(D*) and R(J/ψ) with $\tau \to \mu\nu\nu$ at LHCb

***LHCb** [PRL 115 (2015) 111803]*

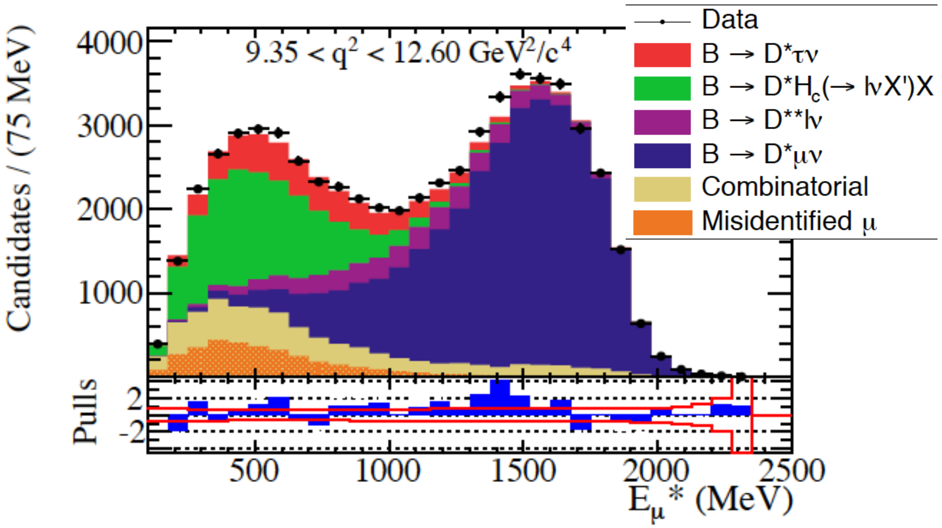
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

using $D^{*-} \to D^0(\to K^+\pi^-)\,\pi^-$

visible final state ➔ $\pi\,(K\pi)\,\mu$

large backgrounds from partially reco B decays

➔ MVA techniques based on μ isolation



$R(D^*) = 0.336 \pm 0.027_{stat} \pm 0.030_{syst}$

1.9 σ above Standard Model

***LHCb** [PRL 120 (2018) 121801]*

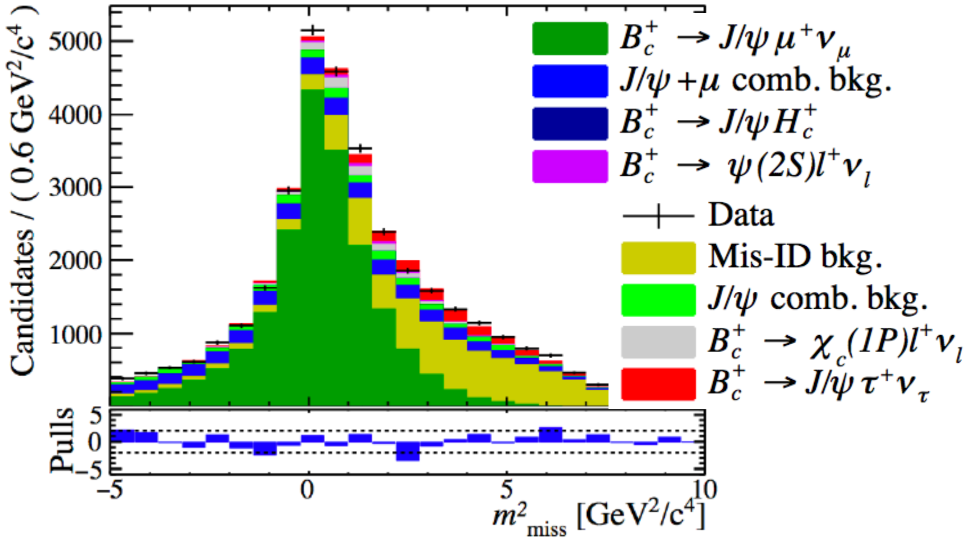
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)}$$

using $J/\psi \to \mu^+\mu^-$

visible final state ➔ $(\mu\mu)\mu$

shorter B_c decay time helps to discriminate

large background from lighter b hadrons



$R(J/\psi) = 0.71 \pm 0.17_{stat} \pm 0.18_{syst}$

~ 2. σ above Standard Model

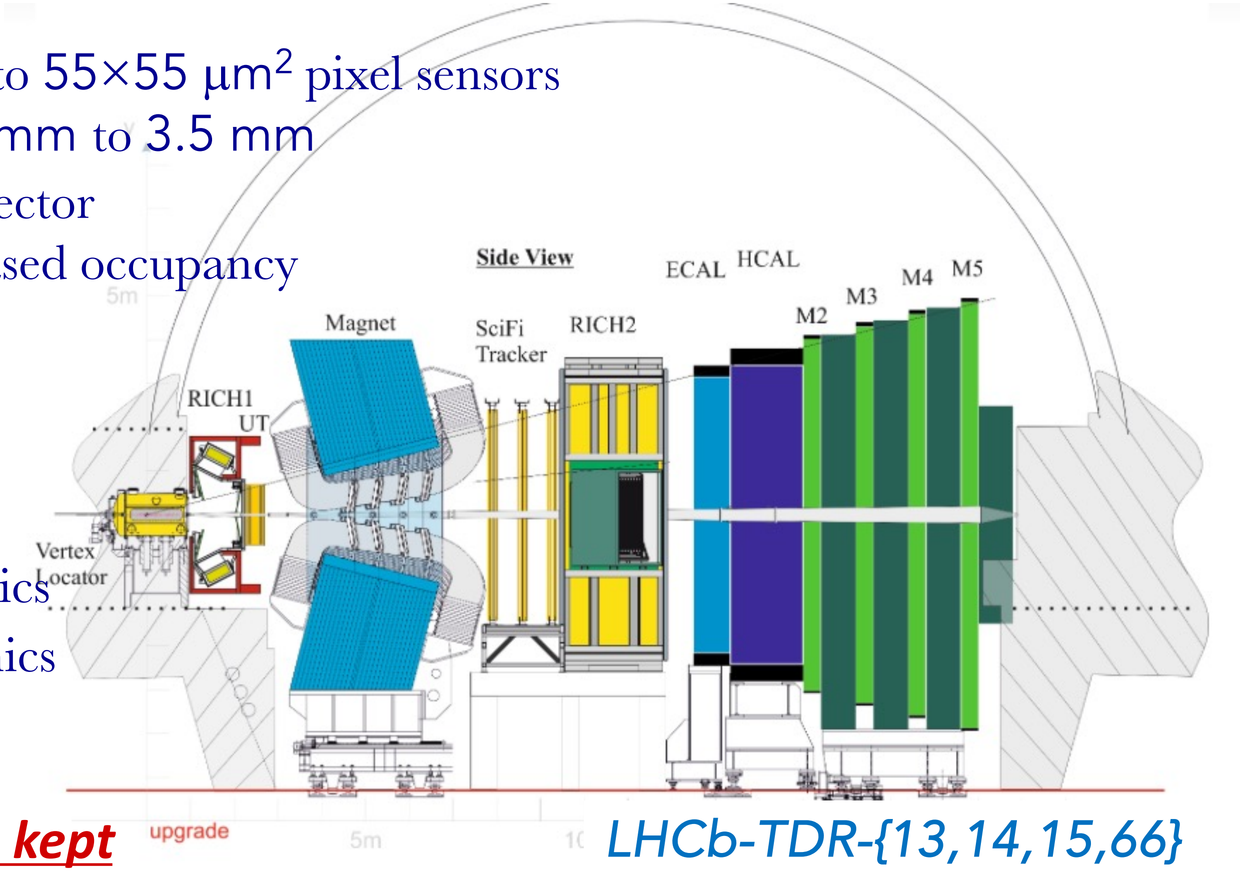
Run 1 data sample, **about 3 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV**

the LHCb upgrade

- restarted data taking at $\mathcal{L}$ up to 2×10^{33} cm^{-2}s^{-1} (x5 $\mathcal{L}$ Run 2)
- upgrade detector qualified to accumulate 50 fb^{-1} ➔

upgrade all sub-detector electronics to 40 MHz readout

make all trigger decision in software and some new detectors



VELO from microstrip sensors (R,ϕ) to 55×55 μm^2 pixel sensors
closer to the beam, from 5.5 mm to 3.5 mm

Upstream Tracker silicon strip detector
adapt segmentation to increased occupancy

SciFi Tracker 3 stations of X-U-V-X
scintillating fibre planes

PID new photodetectors for RICH1
and RICH2

Calorimetry new readout electronics

Muon System new readout electronics

➔ ***less than 10% of all channels kept***

LHCb-TDR-{13,14,15,66}