Lepton flavour universality tests in $b \to c l \nu$ decays at LHCb

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On behalf of LHCb Collaboration

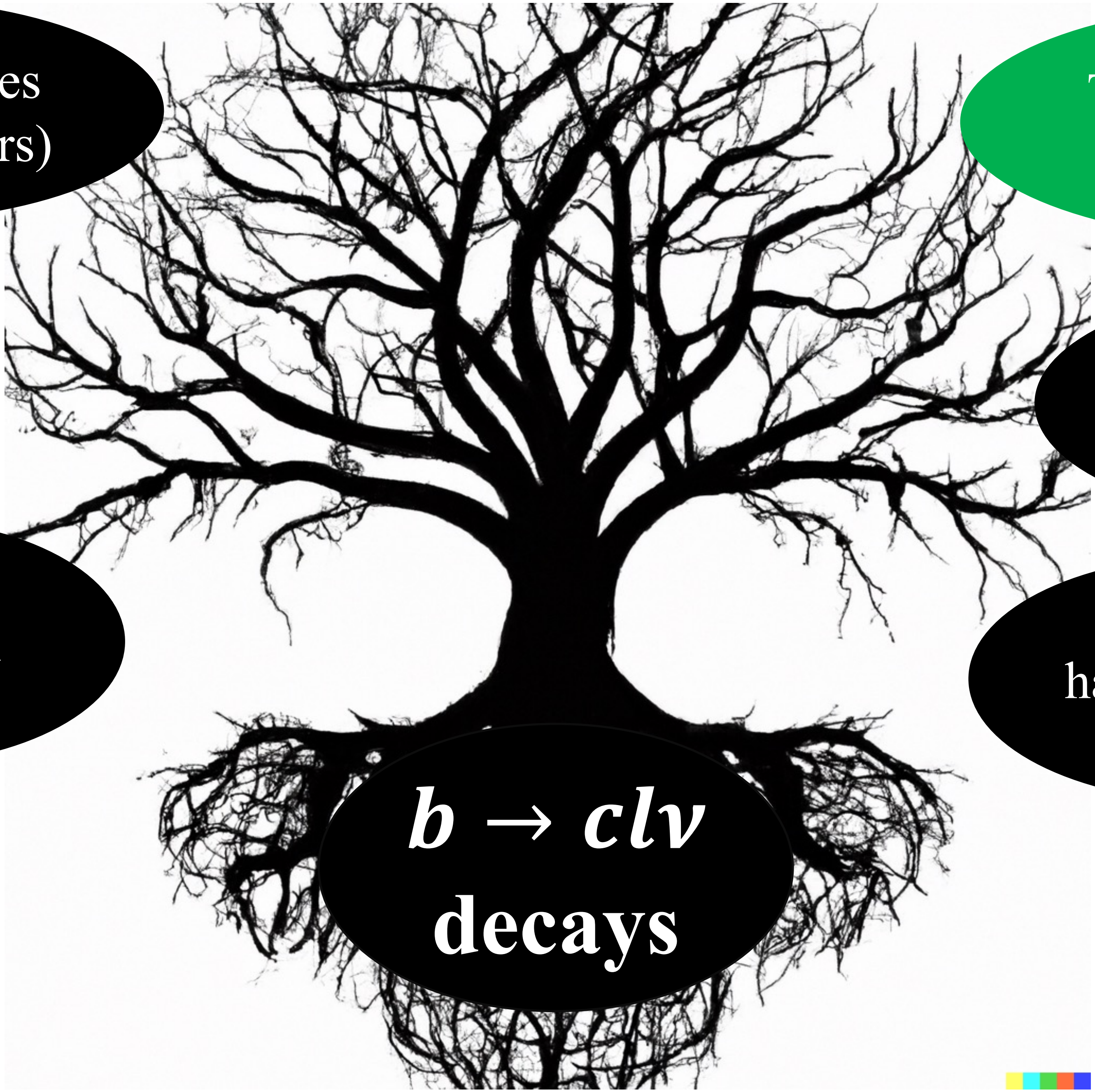
57th Recontres de Moriond EW 2023

University of Zurich UZH

Decay properties (BF, form factors)

Constrain CKM: $|V_{cb}|$

b-hadron production properties



$b \to cl\nu$ decays

Test lepton flavour universality

c-hadron decay/production properties

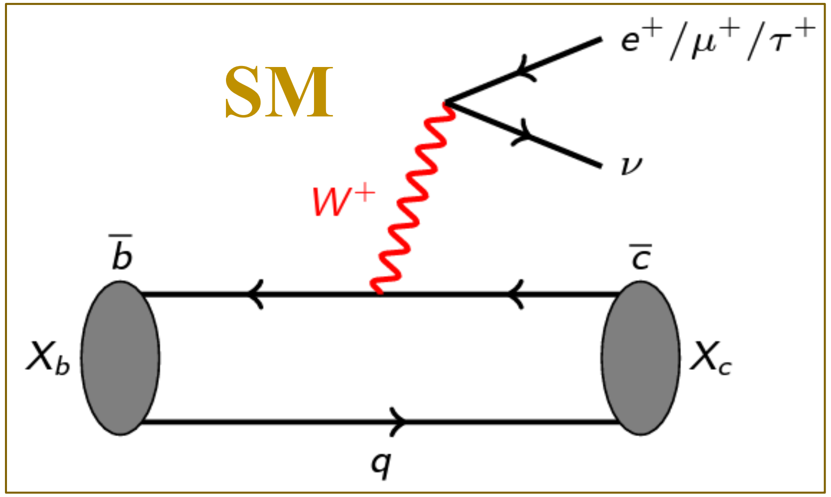
Neutral b-hadron mixing properties

Lepton Flavour Universality (LFU)

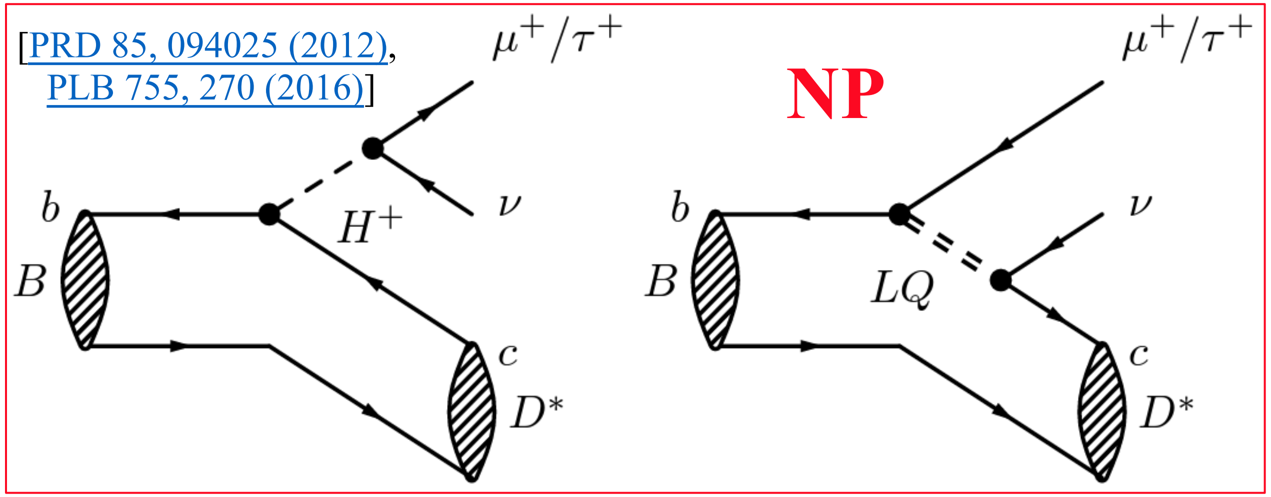
- In Standard Model, electroweak couplings to each lepton generation are identical (except Yukawa).
- Couplings affected by New Physics (NP) contributions (particularly 3rd gen. of leptons).
- Ratio of branching fraction (BF) of different lepton species ideal for testing LFU.

$$R(X_c) = \frac{BF(X_b \to X_c l \nu)}{BF(X_b \to X_c l' \nu)}$$

$$l, l' \in (e, \mu, \tau)$$



[PRD 85, 094025 (2012), PLB 755, 270 (2016)]



LFU ratio

$$R(X_c) = \frac{BF(X_b \to X_c l \nu)}{BF(X_b \to X_c l' \nu)}$$

$l, l' \in (e, \mu, \tau)$

Advantages

- **Good statistical precision:** Thanks to large b-hadron production and large BF.
- **Theoretically and experimentally "clean":** Common systematic and hadronic form factor uncertainties mostly cancel.

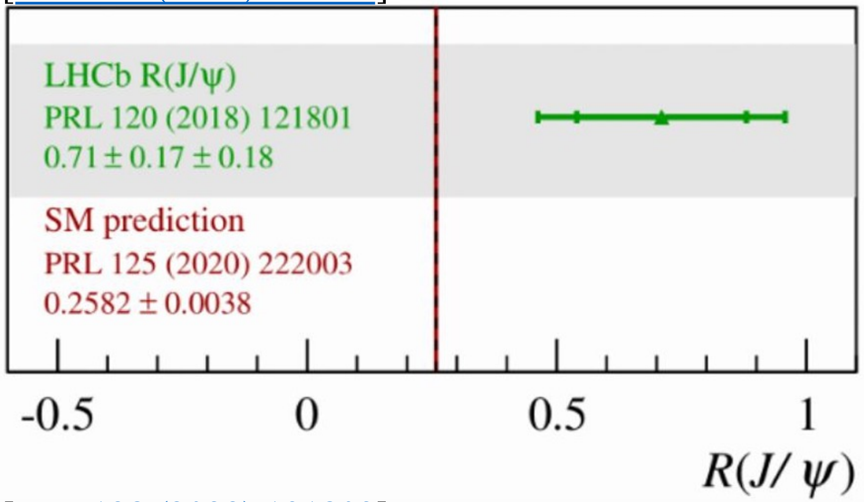
Challenges

- Missing neutrinos in the final state, affects the resolution of the observables @ LHCb.
- Large partially reconstructed background contamination.
- Large simulation samples needed for modelling signal and bkg.

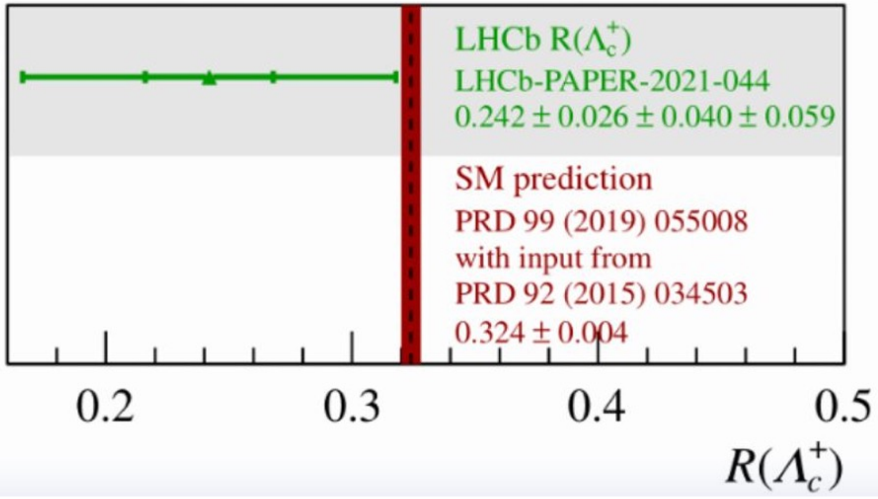
Hints of LFU

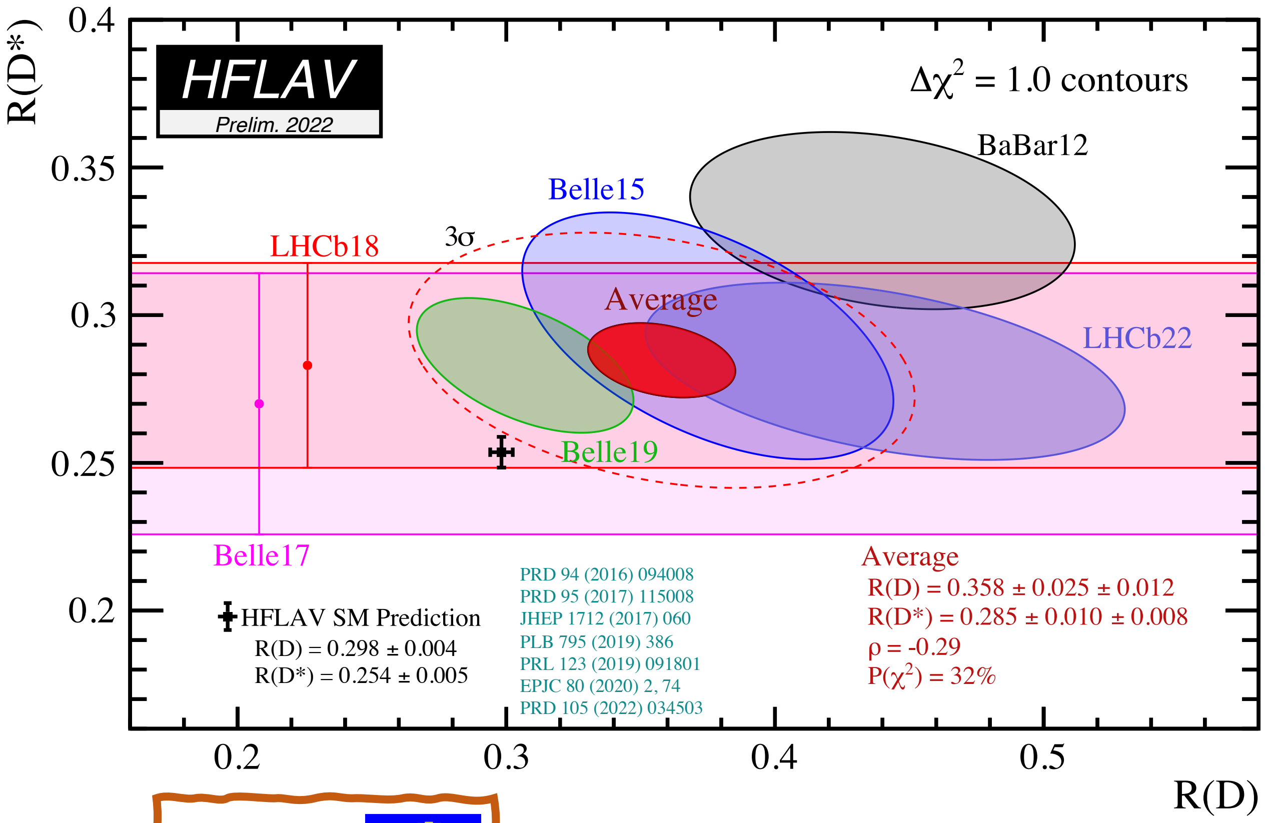
Measurements **SM prediction**

[PRL 120 (2018) 121801]



[PRL 128 (2022) 191803]





Before Dec 2022:

3.3σ tension wrt SM

Two new players from LHCb

- **Combined measurement of $R(D)$ and $R(D^*)$ with muonic τ decay.**
  - **Superseeding previous analysis (Run I data).**

Announced in December 2022
[arXiv:2302.02886]
(Submitted to PRL)

- **Measurement of $R(D^*)$ with hadronic τ decay.**
  - **Updates previous analysis using partial Run II data.**

Announced @ La Thuile
[LHCb-PAPER-2022-052]
(In-preparation)

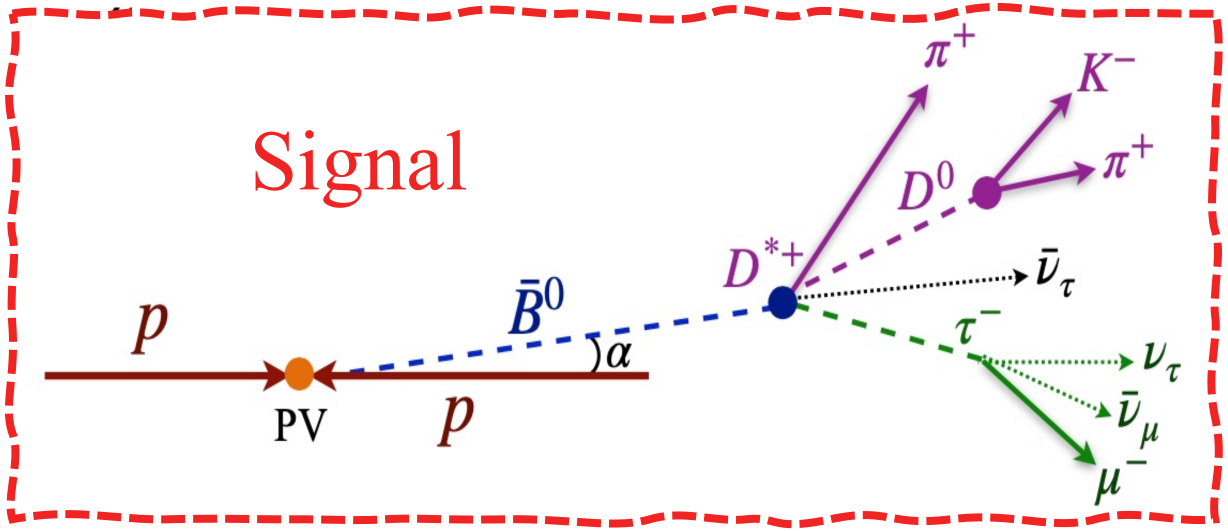
Combined measurement of $R(D^*)$ and $R(D)$

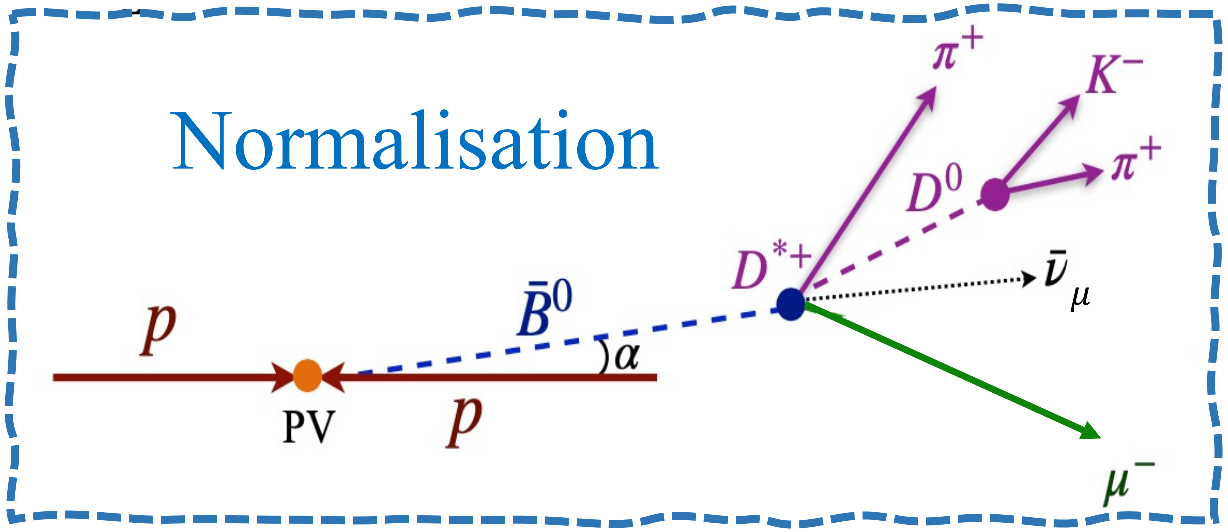
Credits: Nat Geo

Signal and normalisation

[arXiv:2302.02886]
(Submitted to PRL)

- ➢Use Run 1 ($3\ fb^{-1}$) data.
- ➢Use muonic τ decay with large BF (~17.4%).
- ➢Signal decays: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_l$, $B^- \to D^{*0}\tau^-\bar{\nu}_l$ and $B^- \to D^0\tau^-\bar{\nu}_l$.
- ➢Use two disjoint samples:
  - $[\boldsymbol{D^{*+}\mu^-}]$: Signal $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_l$.
  - $[\boldsymbol{D^0\mu^-}]$ **veto** $\boldsymbol{D^{*+}}$: All 3 signals.
- ➢Use as normalisation semi-muonic decay (~ 20 times signal).

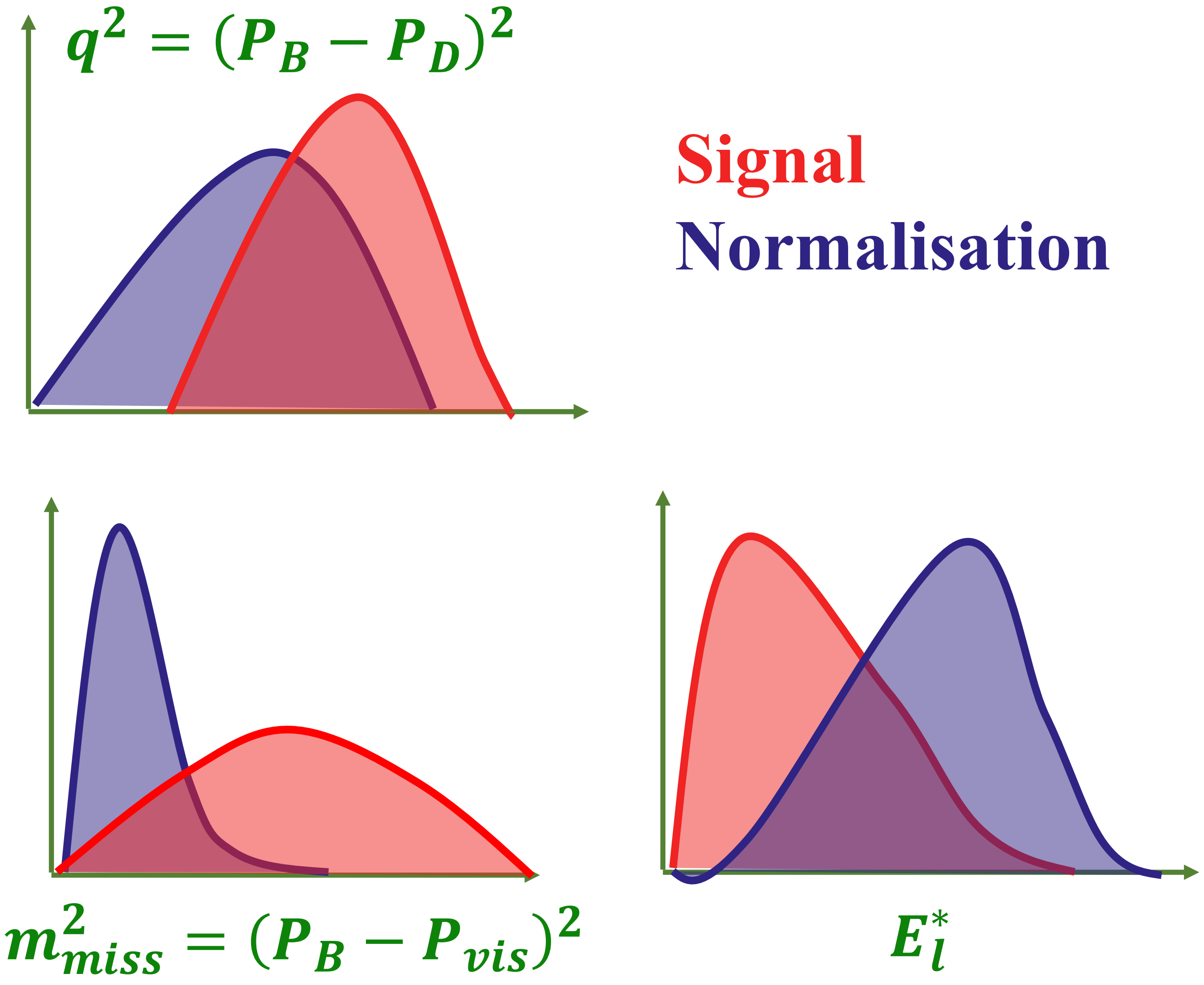




Separate signal and normalisation

[arXiv:2302.02886]
(Submitted to PRL)

- Require good separation w.r.t normalisation mode.
- For this, reconstruct B momentum (~20% resolution):
  - $p_B^{\perp}$ using **flight direction**.
  - $p_B^{\parallel}$ using **boost approx**. $p_B^{\parallel} \propto p_{vis}^{\parallel}$
- **Use discriminating variables**: q^2, m_{miss}^2 and E_l^*.

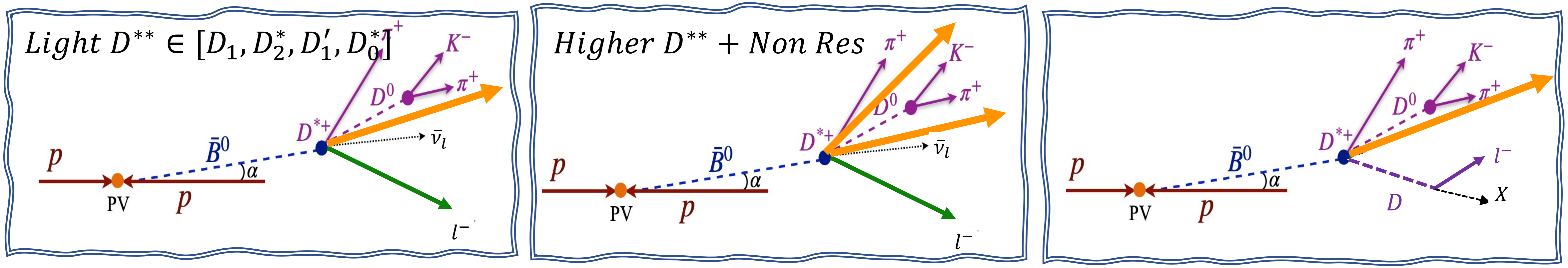


Other backgrounds

[arXiv:2302.02886]
(Submitted to PRL)

- **Feed-down bkg:** Reduced with isolation requirement (MVA based) and modelled using simulation.

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

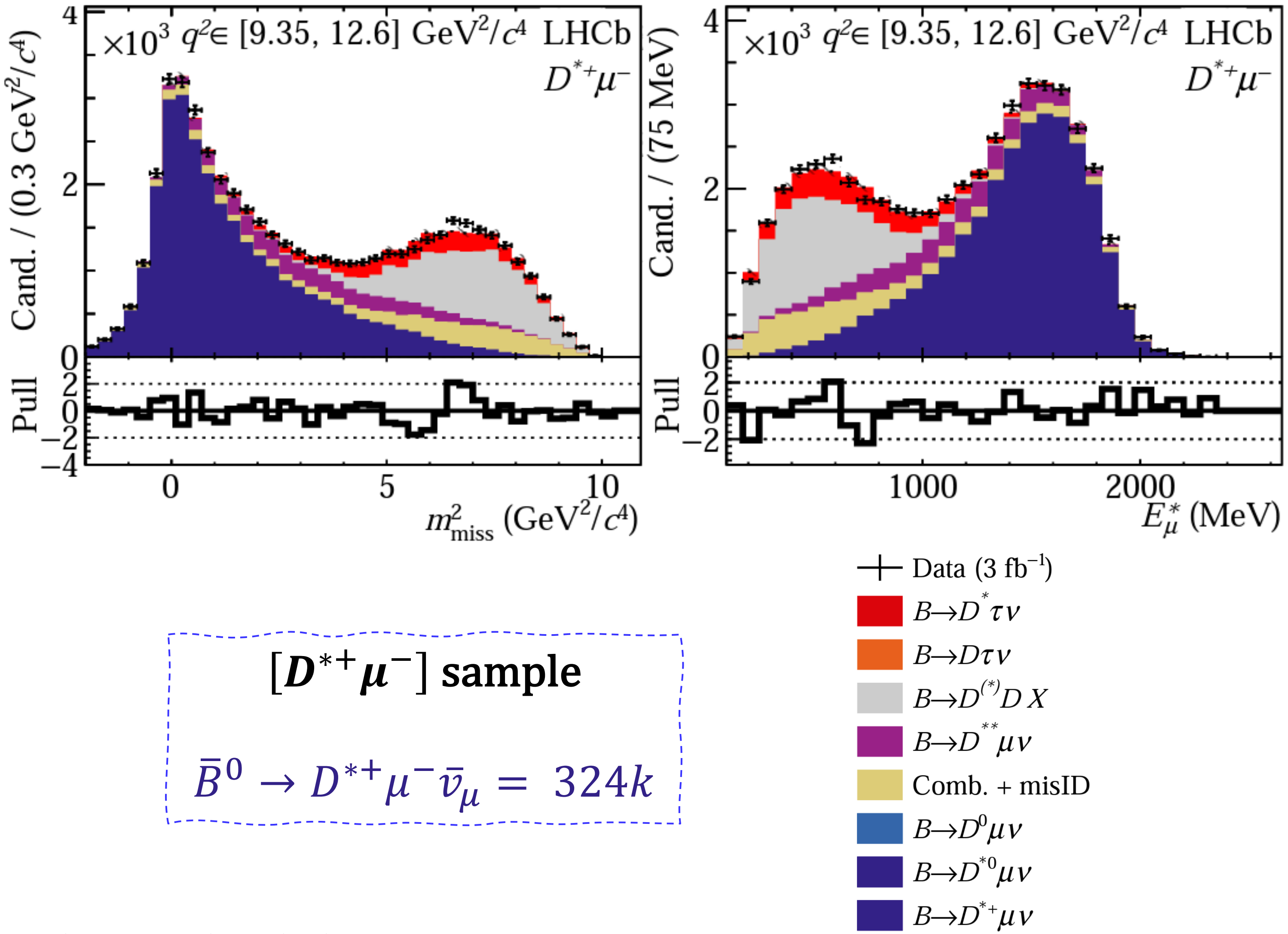


- **Misidentified $K^-/\pi^- \to \mu^-$ bkg:** Reduced with PID cuts (improved muon ID) and modelling using data ($D^{(*)}h^-$ where $h \in [K, \pi, p, e, fake]$).
- **Fake B and fake D^*bkg**: Reduced with vertex quality cuts and modelled using data ($D^{(*+)}\mu^+$ and $D^0\pi^-\mu^-$).

Fit for signal ($D^{*+}\mu^-$)

[arXiv:2302.02886]
(Submitted to PRL)

- 3D maximum likelihood template fit to q^2 (4 *bins*), m^2_{miss} and E^*_l.
- Simultaneous fit to 8 samples:
  For each $[D^{*+}\mu^-]$ and $[D^0\mu^-]$:
  - 1 signal region
  - 3 control regions enriched in bkg (using reversed isolation requirements).



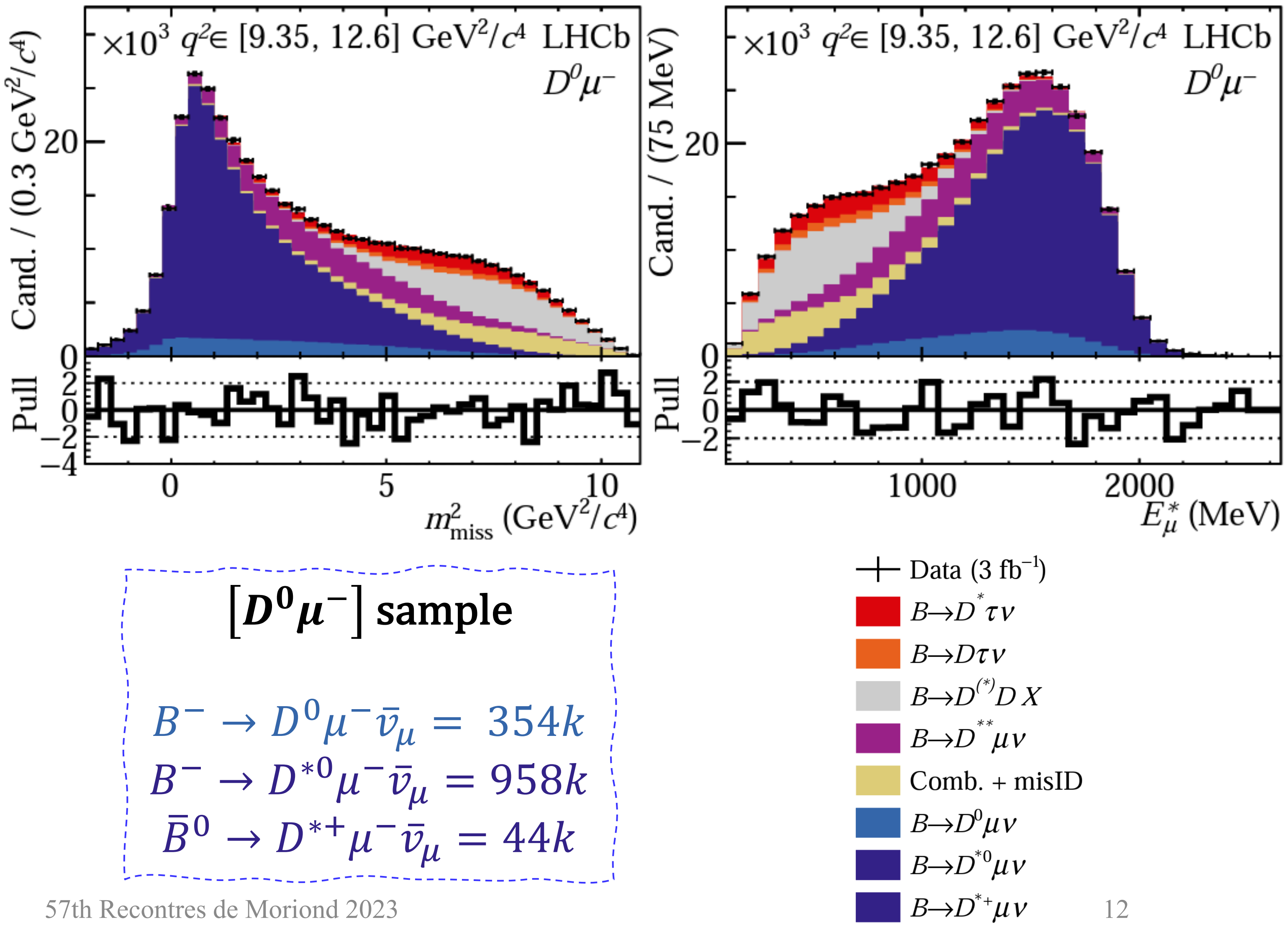
$[D^{*+}\mu^-]$ sample

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu = 324k$

Fit for signal ($D^0\mu^-$)

[arXiv:2302.02886]
(Submitted to PRL)

- ➢Form factors (FF) for signal:
  - ➢D^{*+}: BGL
    [JHEP 11 (2017) 061, JHEP 12 (2017) 060]
  - ➢D^0: BCL
    [PRD 92 (2015) 054510].
  - ➢D^{**}: Bernlochner & Ligeti
    [PRD 95 (2017) 014022]



- ➢Helicity-suppressed terms constrained and other FF param. are inferred from fit.

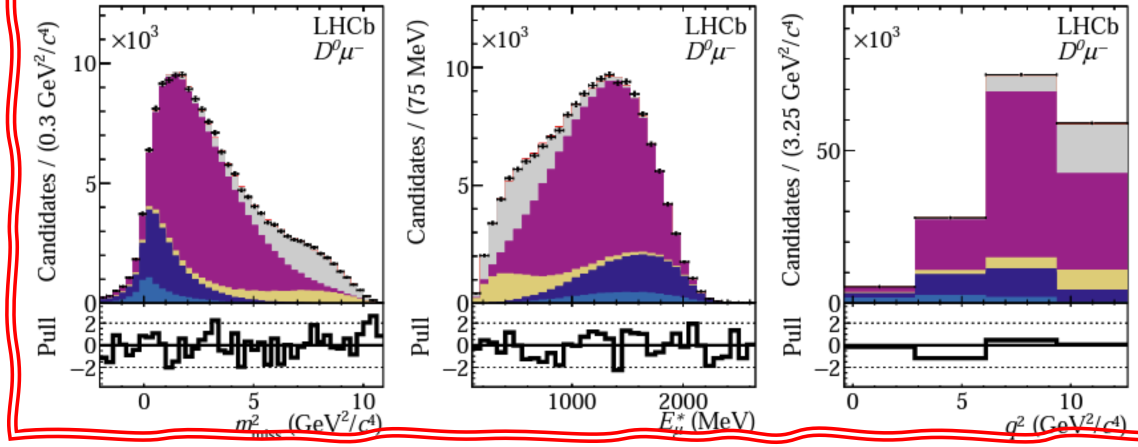
$[D^0\mu^-]$ sample

$B^- \to D^0\mu^-\bar{\nu}_\mu = 354k$
$B^- \to D^{*0}\mu^-\bar{\nu}_\mu = 958k$
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu = 44k$

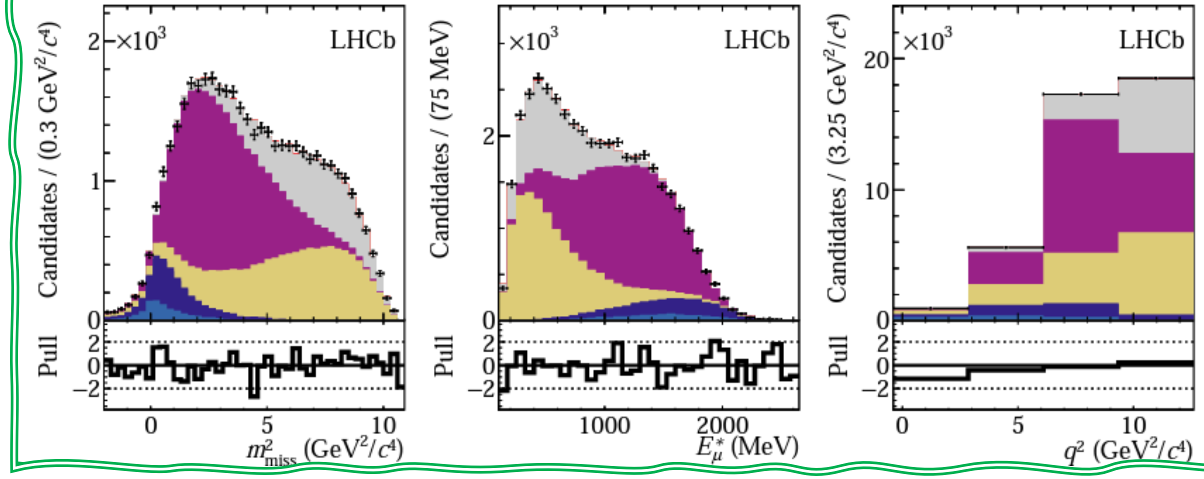
Control regions ($D^0\mu^-$)

[arXiv:2302.02886]
(Submitted to PRL)

1 extra π associated to B vertex



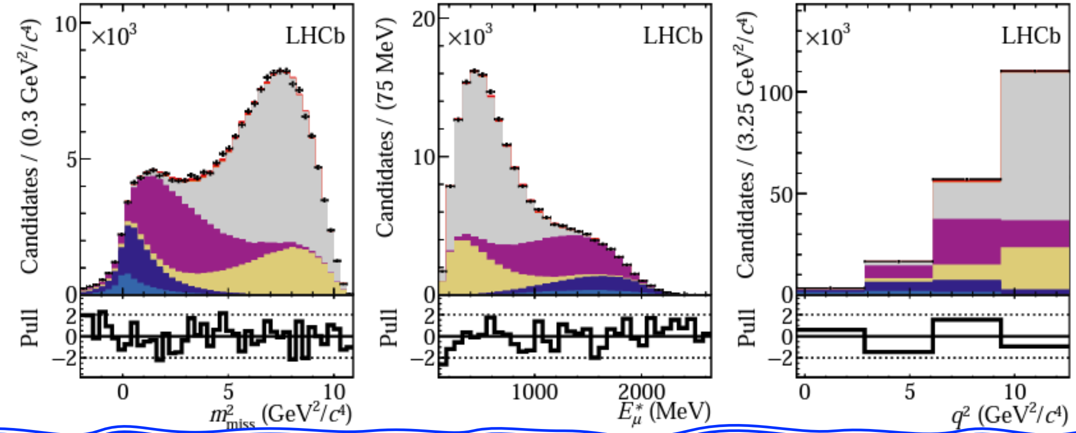
2 extra π associated to B vertex



$\bar{B}\to D^{**}(\to D^{(*)}\pi^-\pi^+)\, l^-\nu$
(control decay prop.)

$\bar{B}\to D^{**}(\to D^{(*)}\pi^-)\, l^-\nu$
(control FF parameters)

1 extra K associated to B vertex



$\bar{B}\to D^{(*)}D(\to l^-X)K^{(*)}$
(control phase space modelling)

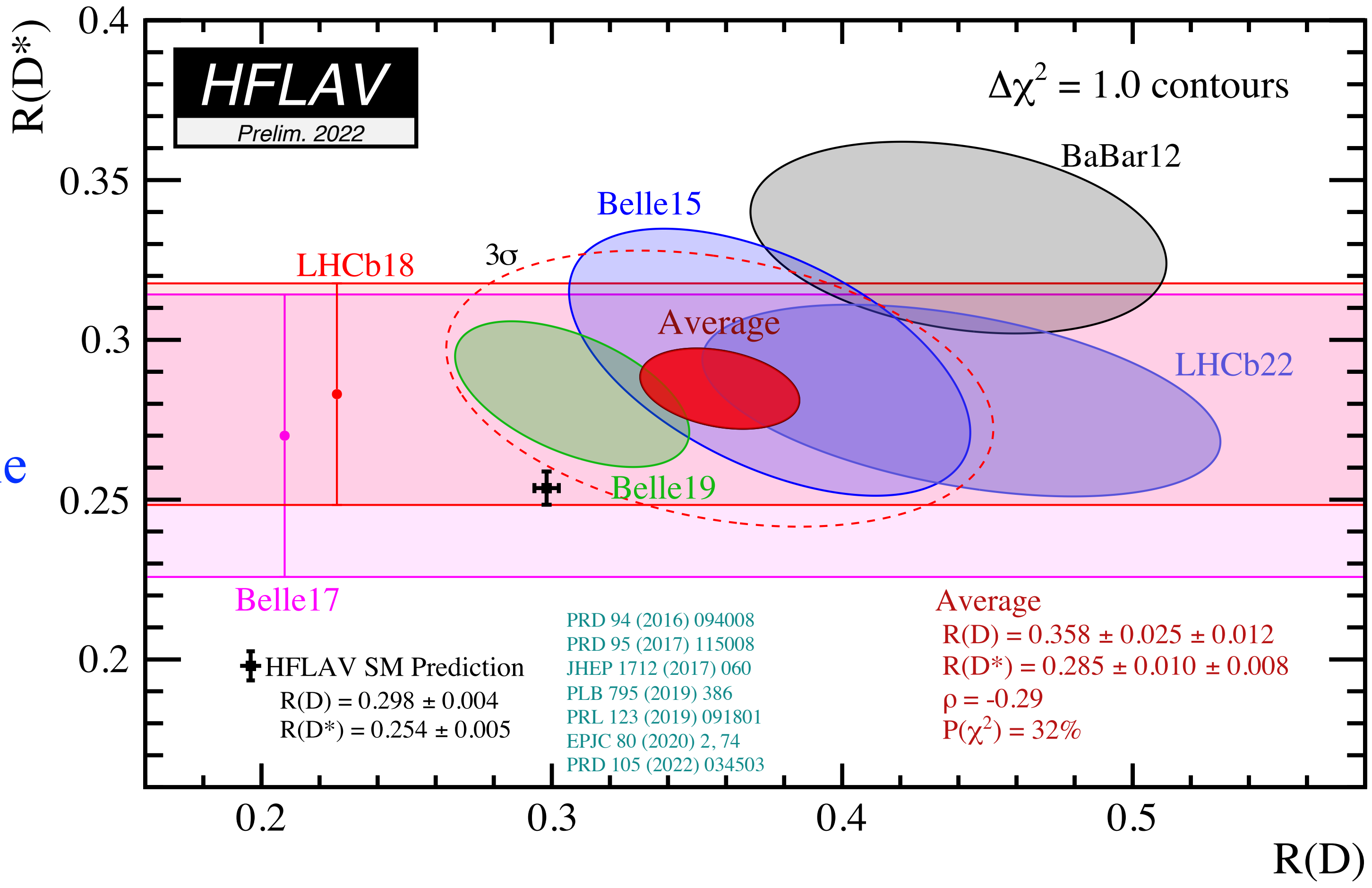
Fit result

[arXiv:2302.02886]
(Submitted to PRL)

$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$R(D) = 0.441 \pm 0.060 \pm 0.066$$
$$\rho = -0.43$$

Dominant systematics: Simulation sample size and modelling of bkg.

Current result: **1.9σ wrt SM**
WA: 3.3σ → **3.2σ wrt SM**



Measurement of $R(D^*)$ with hadronic τ decay

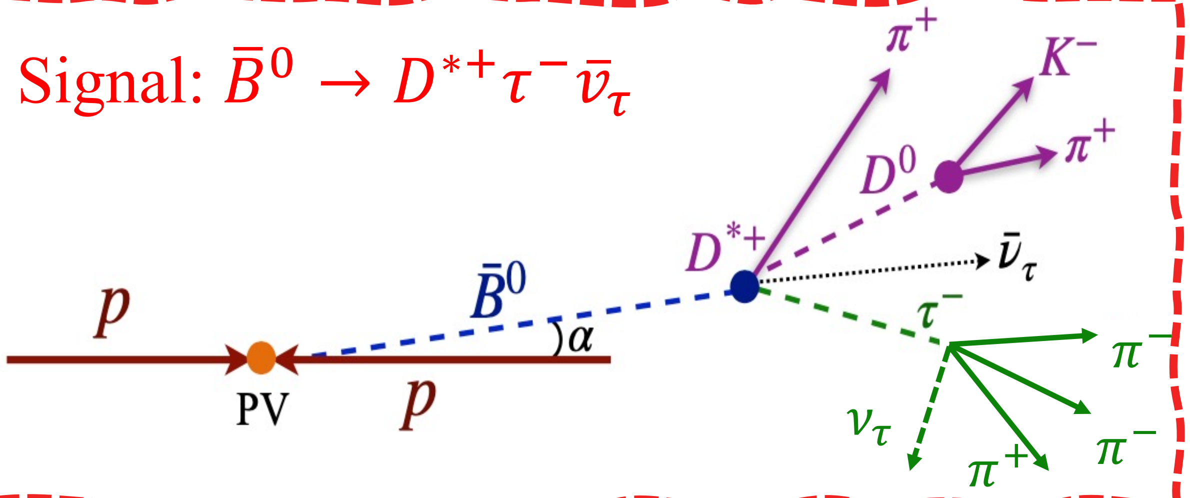
Credits: Nat Geo

Signal and normalisation

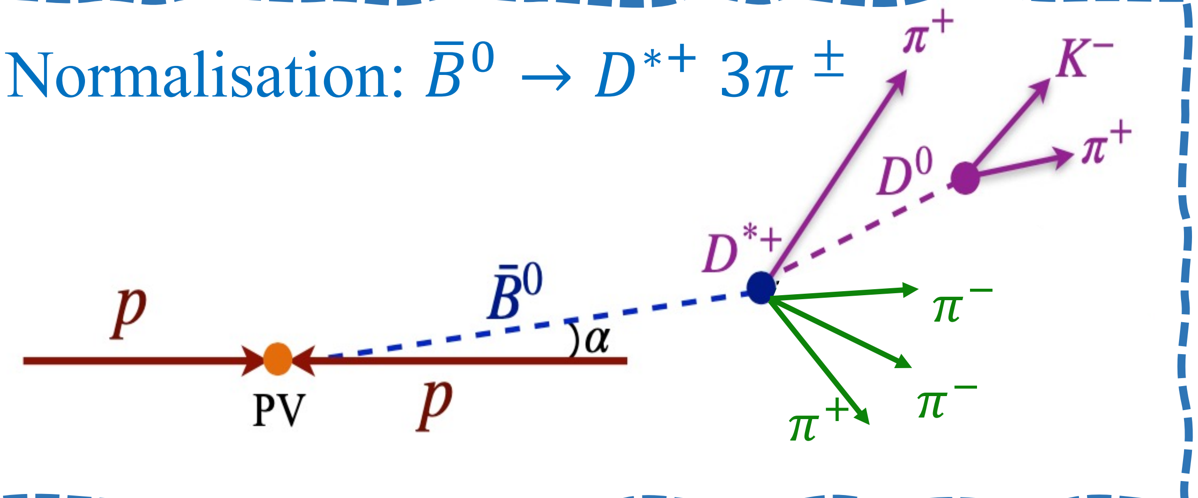
[LHCb-PAPER-2022-052]
(In-preparation)

- Use partial Run 2 ($2\ fb^{-1}$) (~1.5 times more signal than Run 1).
- Use hadronic $\tau \rightarrow 3\pi(\pi^0)$ decay with BF ~ 13.5%.
- Use as normalisation hadronic $\bar{B}^0$ decay.

Signal: $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$



Normalisation: $\bar{B}^0 \rightarrow D^{*+}\ 3\pi^{\pm}$



Measure

$$K(D^*) = \frac{BF(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)}{BF(\bar{B}^0 \rightarrow D^{*+}\ 3\pi^{\pm})}$$

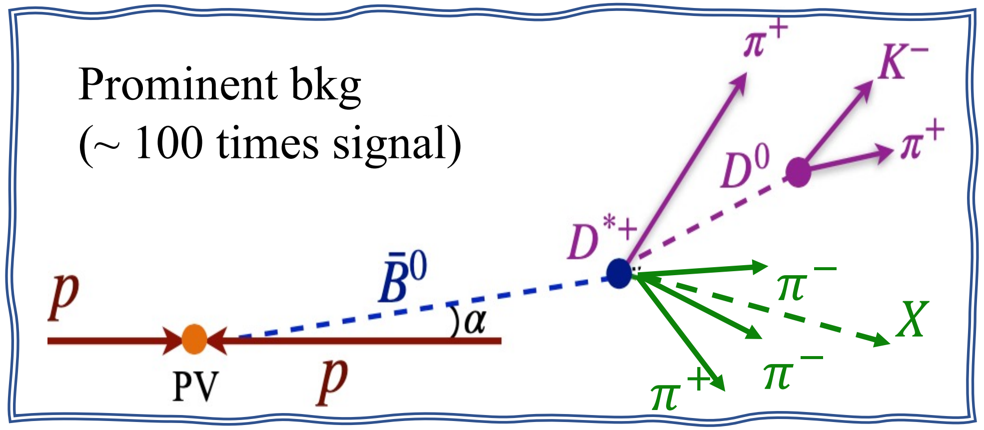
External input

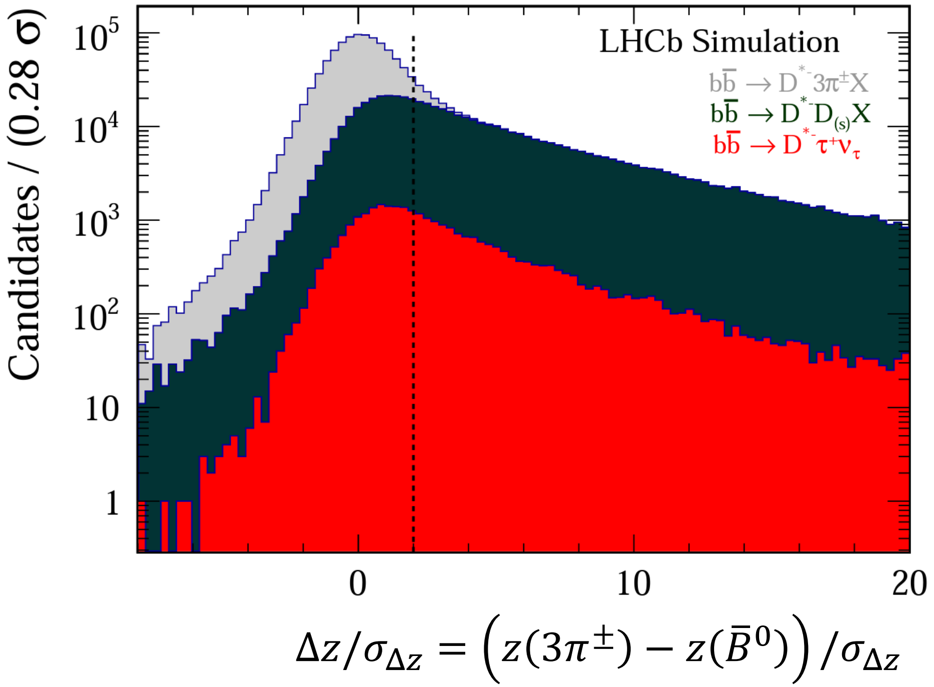
$$R(D^*) = K(D^*) \times \frac{BF(\bar{B}^0 \rightarrow D^{*+}\ 3\pi^{\pm})}{BF(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)}$$

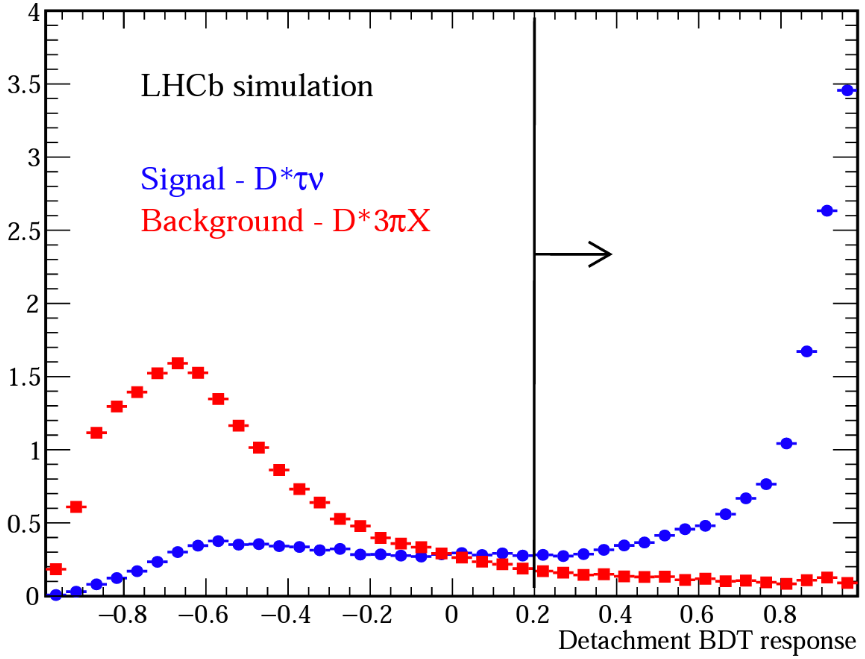
Background of $\bar{B}^0 \to D^{*+} 3\pi^{\pm} X$

[LHCb-PAPER-2022-052]
(In-preparation)

- ➢Reduce by requiring τ vertex to be downstream w.r.t. the B vertex along the beam direction + dedicated BDT classifier.
- ➢Bkg modelling using simulation.





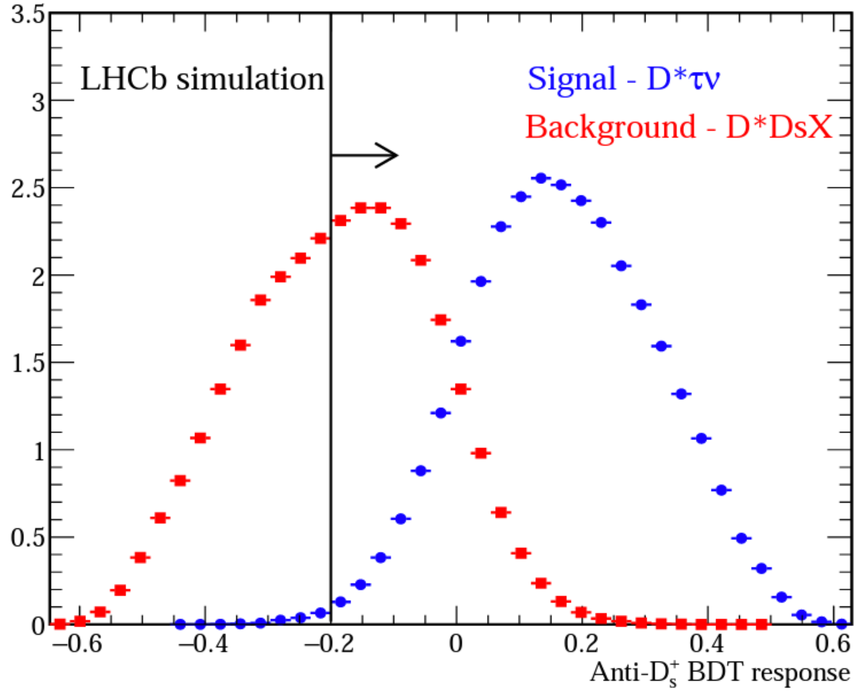


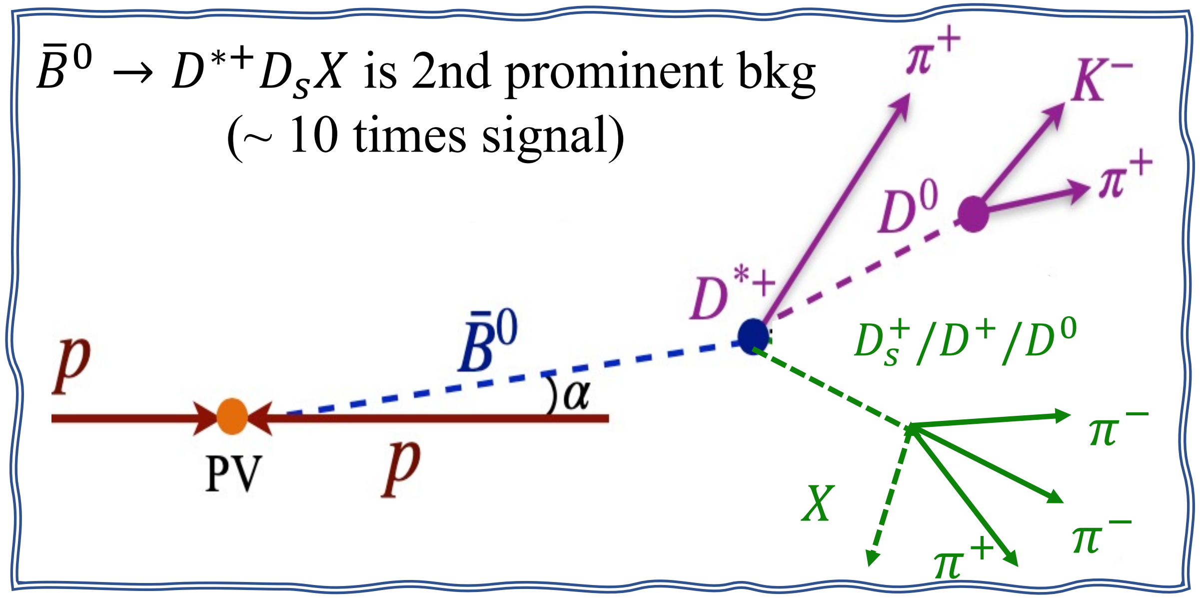
"Double charm" background

[LHCb-PAPER-2022-052]
(In-preparation)

- $\bar{B}^0 \rightarrow D^{*+} D_s(\rightarrow 3\pi^{\pm})\, X$ bkg reduced with dedicated BDT classifier based on kinematics and resonant structure.
- Other bkgs $D^+(\rightarrow K^- 2\pi^+)$ and $D^0(\rightarrow K^- 3\pi^{\pm})$ reduced using PID cuts and dedicated BDT classifiers, respectively.
- Modelled using simulations, with corrections from dedicated data control regions.

Also a fit variable

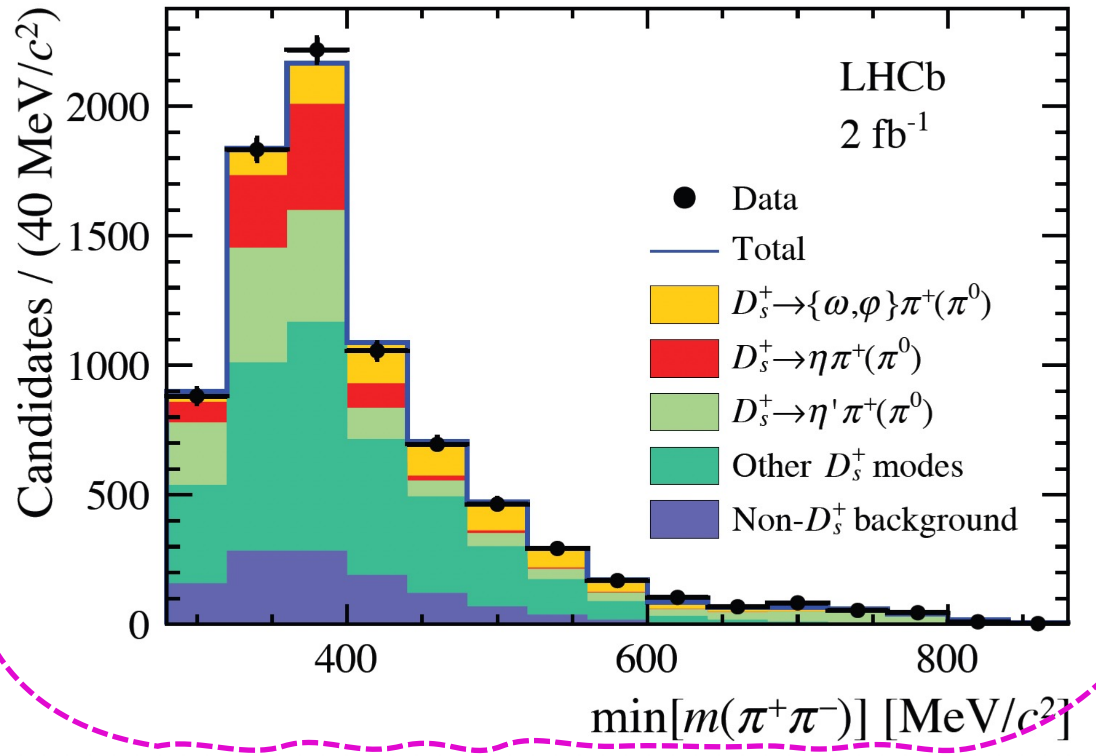




Modelling of $\bar{B}^0 \to D^{*+} D_s^+ X$ [LHCb-PAPER-2022-052] (In-preparation)

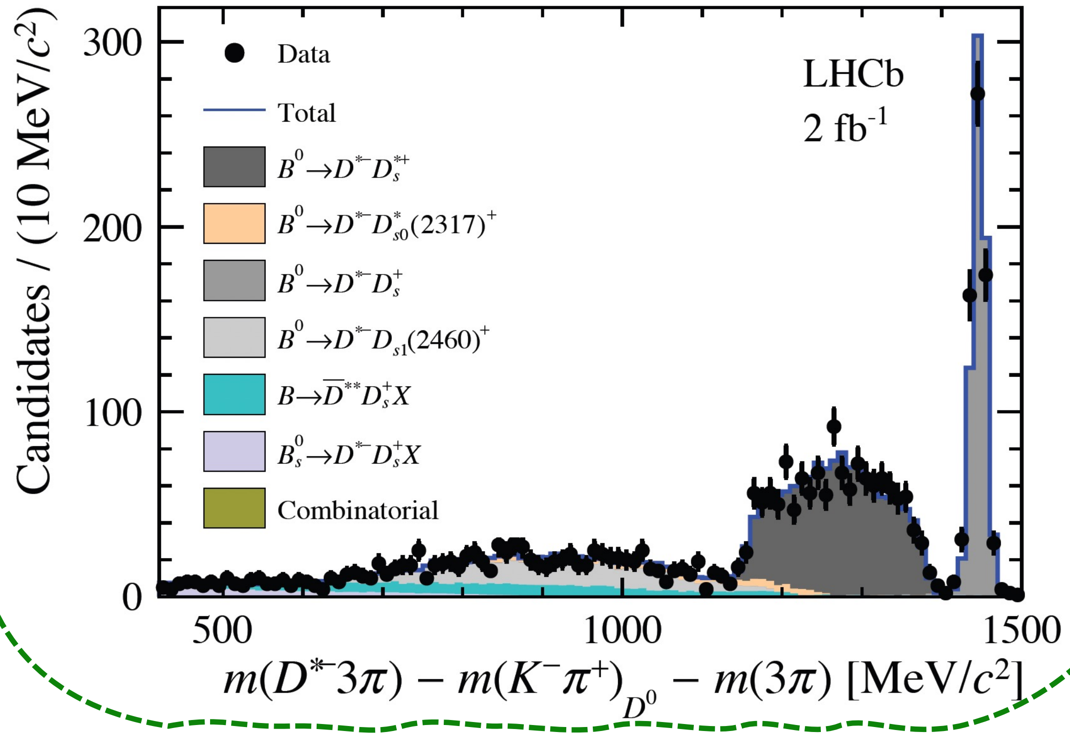
$D_s^+ \to 3\pi^\pm X$ decay modes

- Control data region: Selected by reversing D_s^+ BDT cut.
- Resonant contrb. from fit to 4 kinematic variables and MC samples corrected.



D_s^+ production modes

- Control data region: Events 20 MeV around D_s^+ mass + remove D_s^+ BDT cut.
- Fractions constrained in the signal fit.



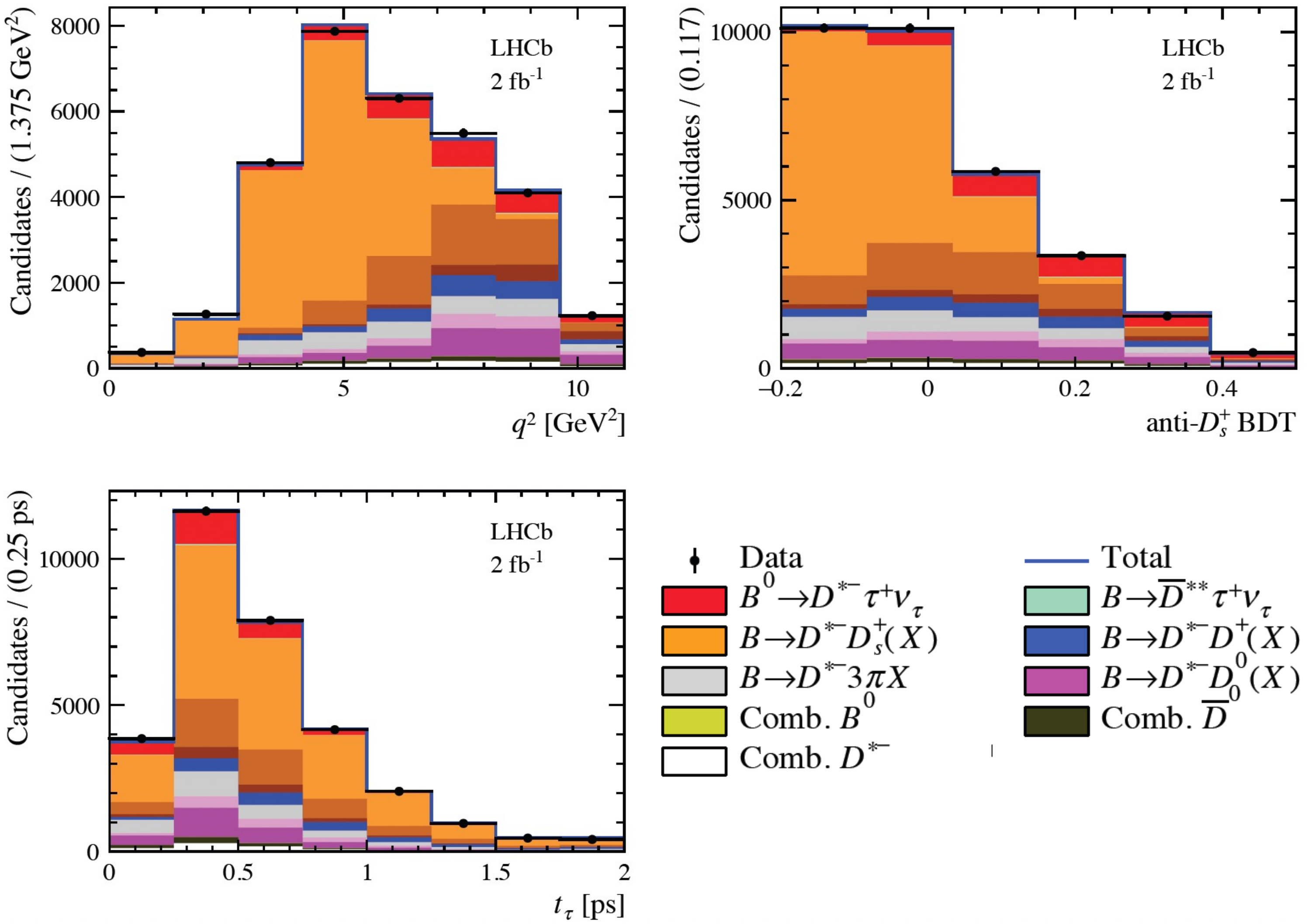
Fit for signal

[LHCb-PAPER-2022-052]
(In-preparation)

- 3D maximum likelihood template fit to q^2, anti-D_s^+ BDT output and τ lifetime.
- Form factor correction:
  - D^{*+}: CLN parametrisation
    [Nucl. Phys. B 50, 153 (1998)]
- Signal and norm. yield:

$$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\mu = 2469 \pm 154$$

$$\bar{B}^0 \to D^{*+}3\pi^\pm = 30540 \pm 182$$



Fit result

[LHCb-PAPER-2022-052]
(In-preparation)

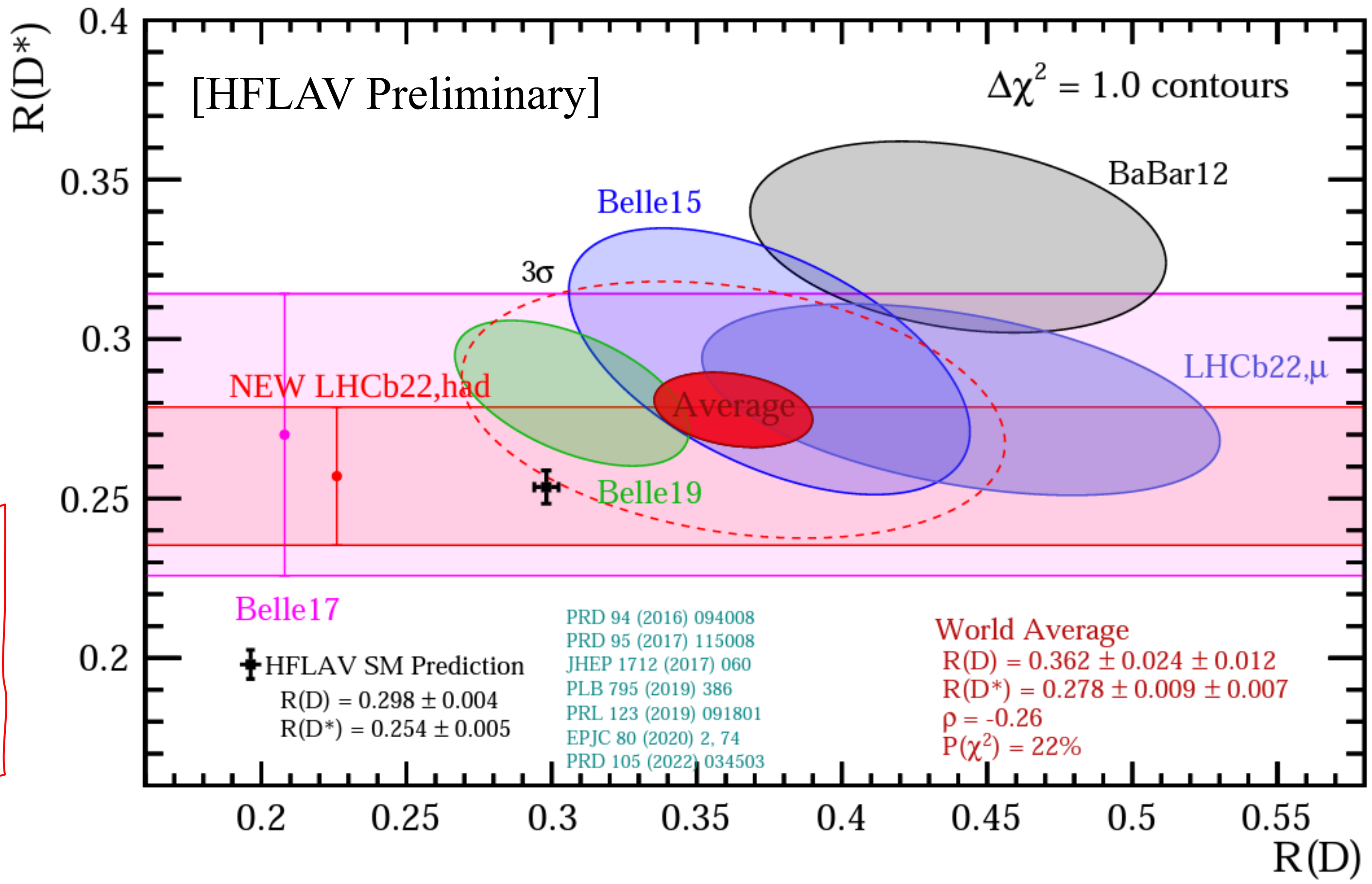
$K(D^*) = 1.700 \pm 0.101\ (stat)^{+0.105}_{-0.100}\ (syst)$

$R(D^*) = 0.247\ \pm 0.015(stat) \pm 0.015(syst)\ \pm\ 0.012(external\ input)$

Dominant systematics: Simulation sample size and modelling of bkg.

One of the most precise $R(D^*)$, when combined with Run 1 result (LHCb22, had)
$\boldsymbol{R(D^*) = 0.257\ \pm\ 0.012(stat)\ \pm 0.014\ (syst)\ \pm\ 0.012\ (ext)}$

Current result: < **1σ wrt SM**
WA: 3.2σ → **3 σ wrt SM**



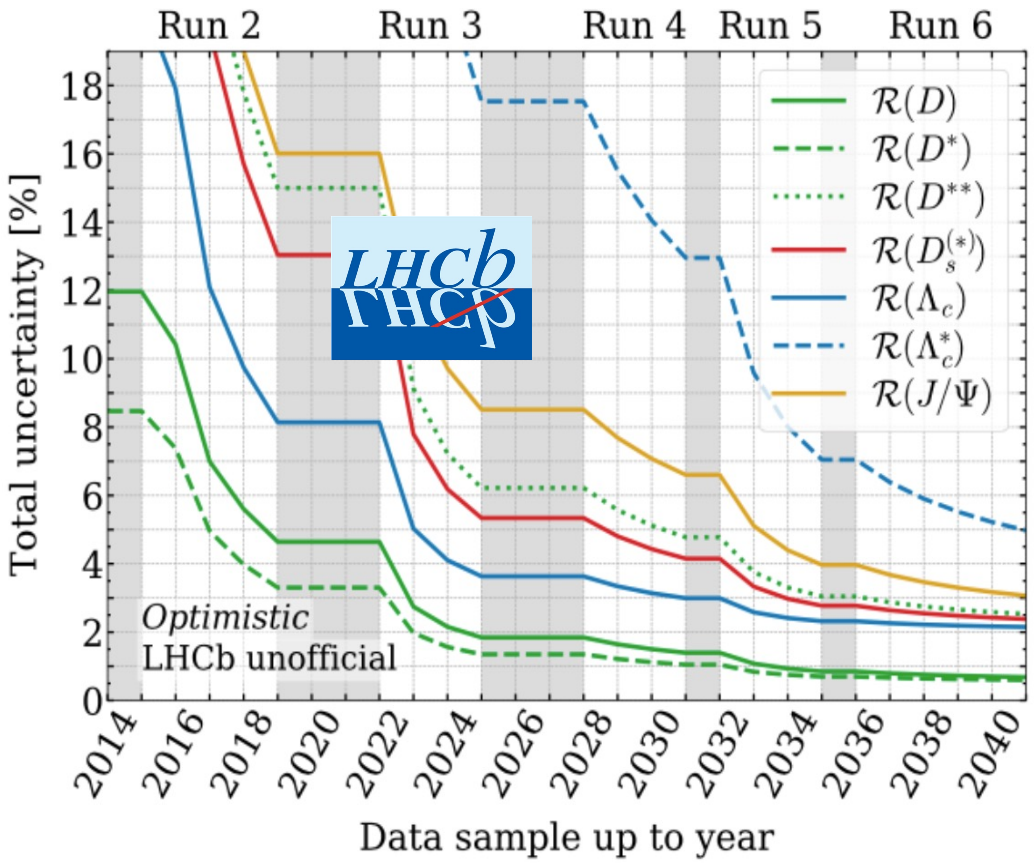
Connect to CERN seminar tomorrow!

Outlook and Summary

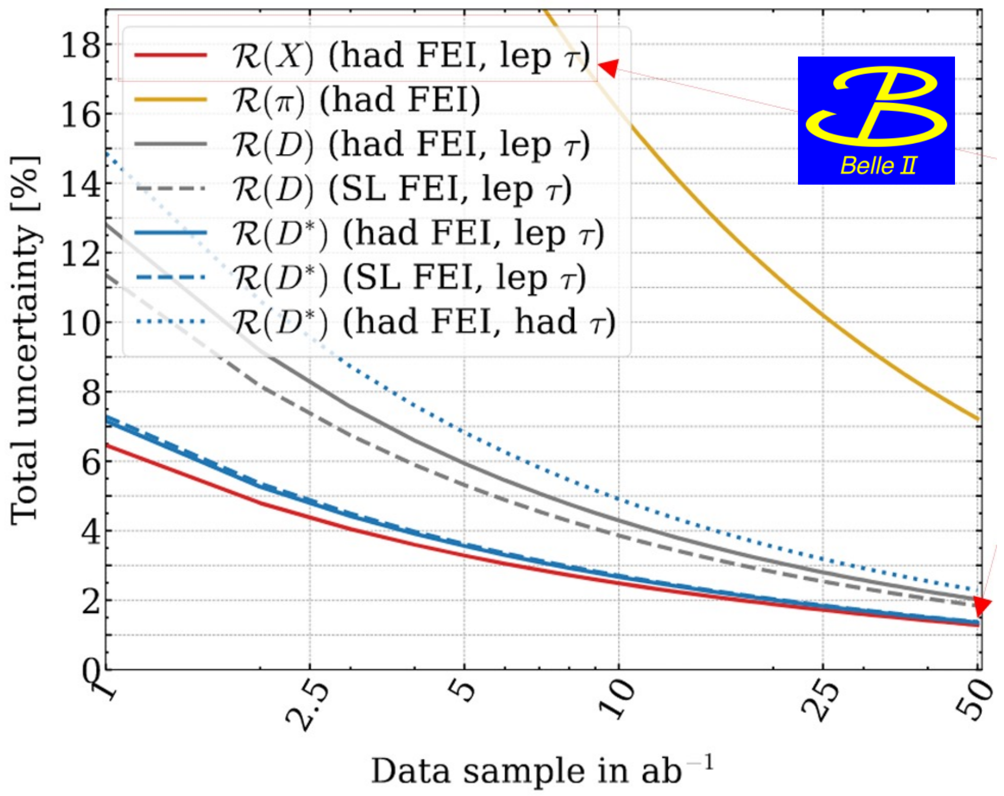
Credits: Nat Geo

Outlook

➢Many more $R(X_c)$ measurements in the pipeline e.g. $R(D^+), R(D^{*0}), R(\Lambda_c^+)$ ...

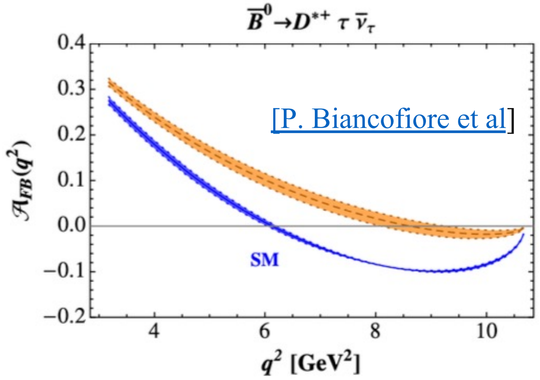


[Rev. Mod. Phys. 94, 015003 (2022)]



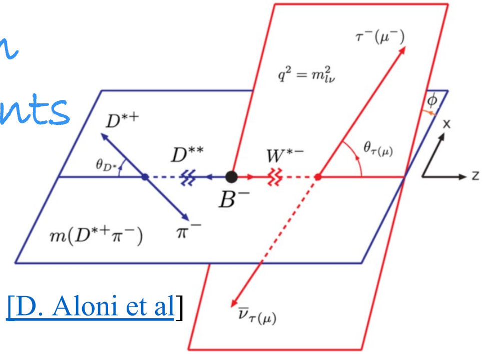
[Belle II talk @ Beyond Flavour Anamolies III]

Summary



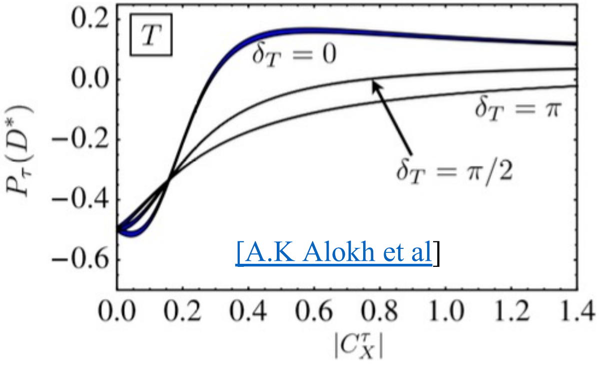
Forward-backward aysmmetries

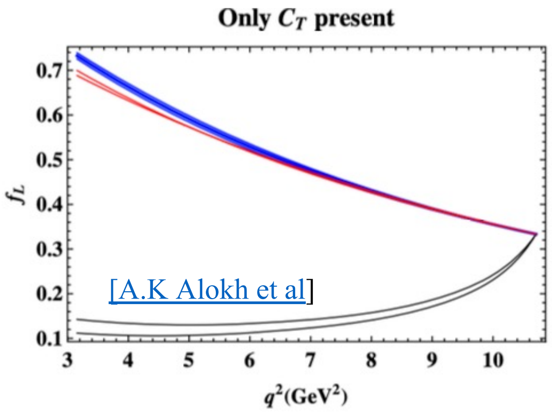
CP violation measurements



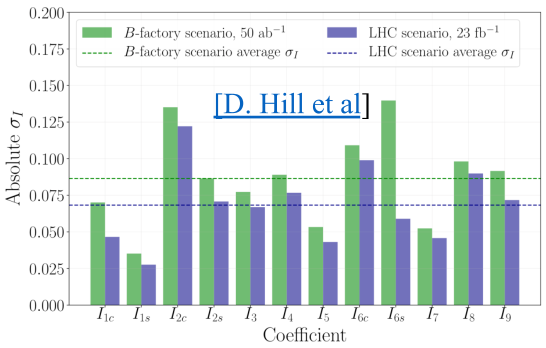
- Semileptonic charged current decays are an excellent tool to probe LFU.
- Summary and challenges of two recent LHCb results presented.
- Many possible roads to new physics…

Polarisation of involved τ lepton



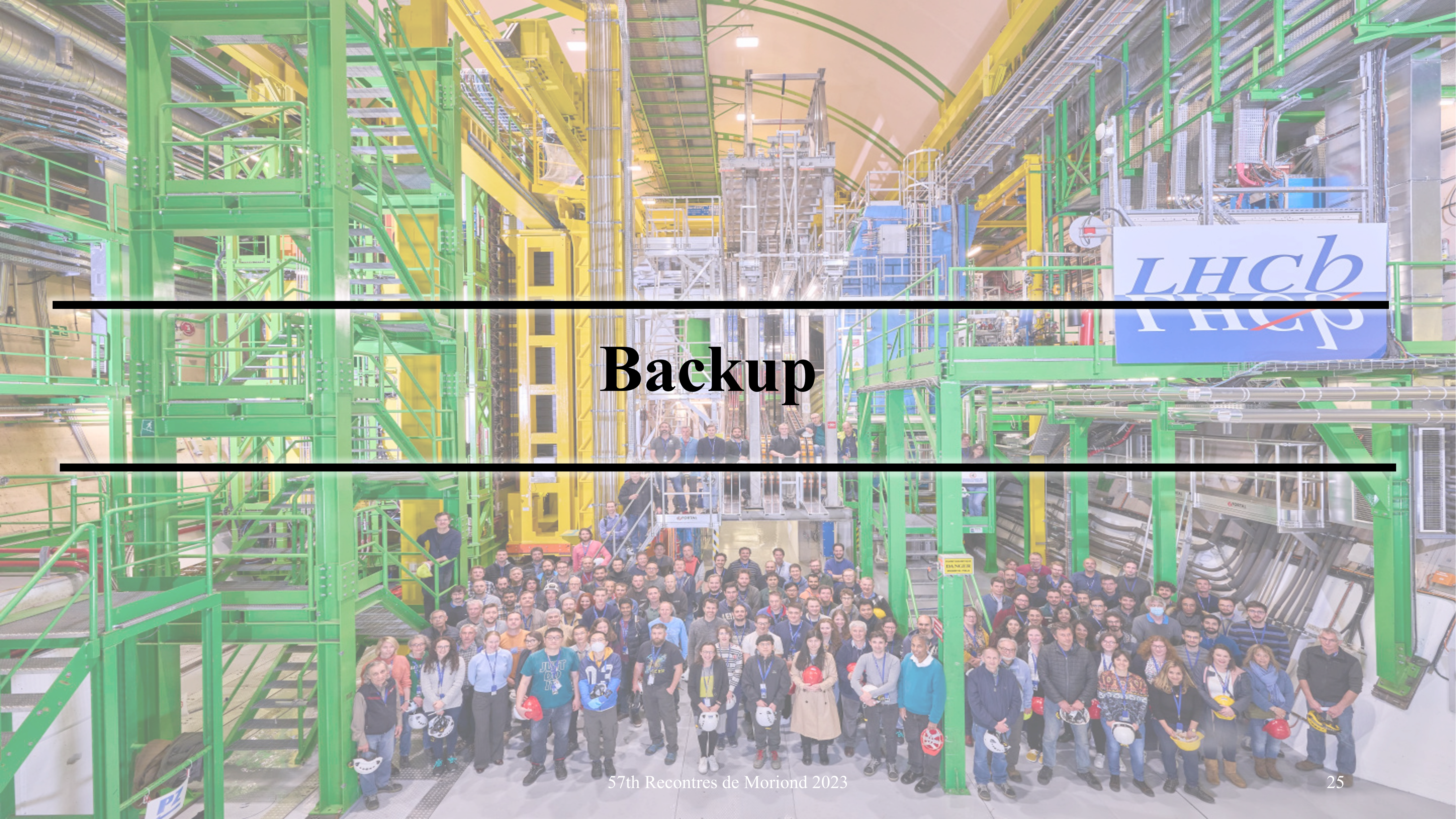


Polarization of charm hadron



Angular analysis for wilson coefficient

Backup



Systematic uncertainty

Model uncertainties (should scale with size of the control sample)

External inputs to the fit

Small multiplicative uncertainties

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	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau\ )$	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	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ 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

Relative systematic uncertainty on $\mathcal{K}(D^*)$

Compared to Run 1 analysis, the size is halved from employing fast simulation techniques [ReDecay].

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-}D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-}D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-}D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-}D^0(X)$ template shapes	1.2
$B \to D^{*-}D_s^+(X)$ template shapes	0.3
$B \to D^{*-}3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

BESIII results from $D \to 3\pi^\pm$ should help reduce this systematic in future.

Other dominant sources include signal and background modelling

Previous vs current leptonic τ

Previous

Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Current

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	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}(\overline{B} \to D^*D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	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	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ 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

Previous vs current hadronic τ

Previous

Table 7: List of the individual systematic uncertainties for the measurement of the ratio $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}3\pi)$.

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

Current

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-}D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-}D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-}D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-}D^0(X)$ template shapes	1.2
$B \to D^{*-}D_s^+(X)$ template shapes	0.3
$B \to D^{*-}3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

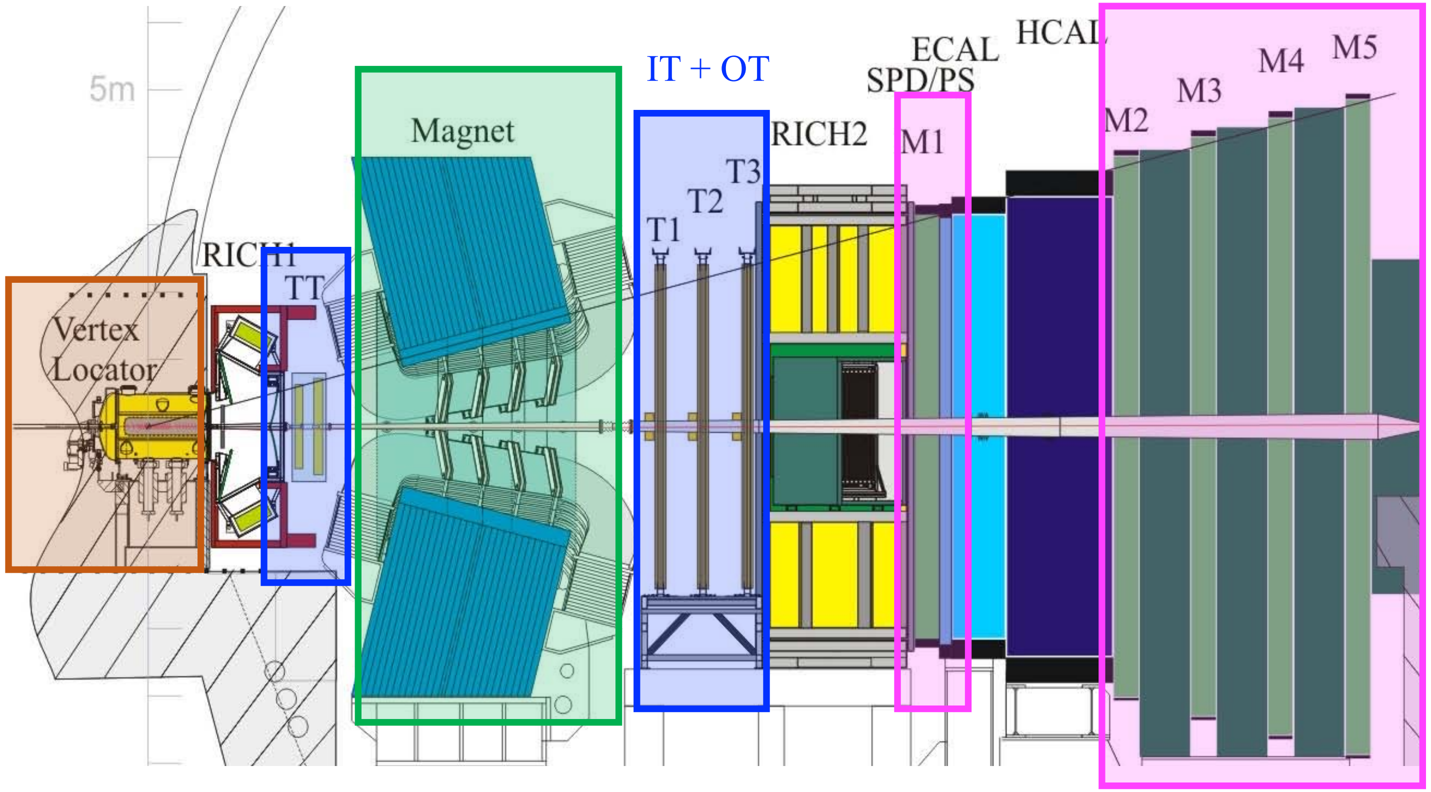
Track and Vertex reconstruction [LHCb-DP-2014-002]

Vertex locator
- 42 silicon modules provide r and ϕ coord.
- Retractable halves
- 8mm from beam in data taking

Tracking stations
- TT and IT: silicon microstrips
- OT: Straw-tube modules

Dipole magnet
- 4 Tm magnetic field
- Polarity inverted every few weeks

Muon stations
- Consists of 5 stations (M1-M5)
- MWPCs + triple GEM



- Good decay time res. $\sigma_\tau \sim 45\ fs\ wrt\ \tau_B \sim 1.5\ ps$
- Good momentum res. $\frac{\delta p}{p} \sim 0.5\% - 1\%\ (5 - 200\ GeV)$

Particle identification (PID) [LHCb-DP-2014-002]

Ring imaging Cherenkov detectors

- PID for kaons, pion and protons
- Covers a wide momentum range

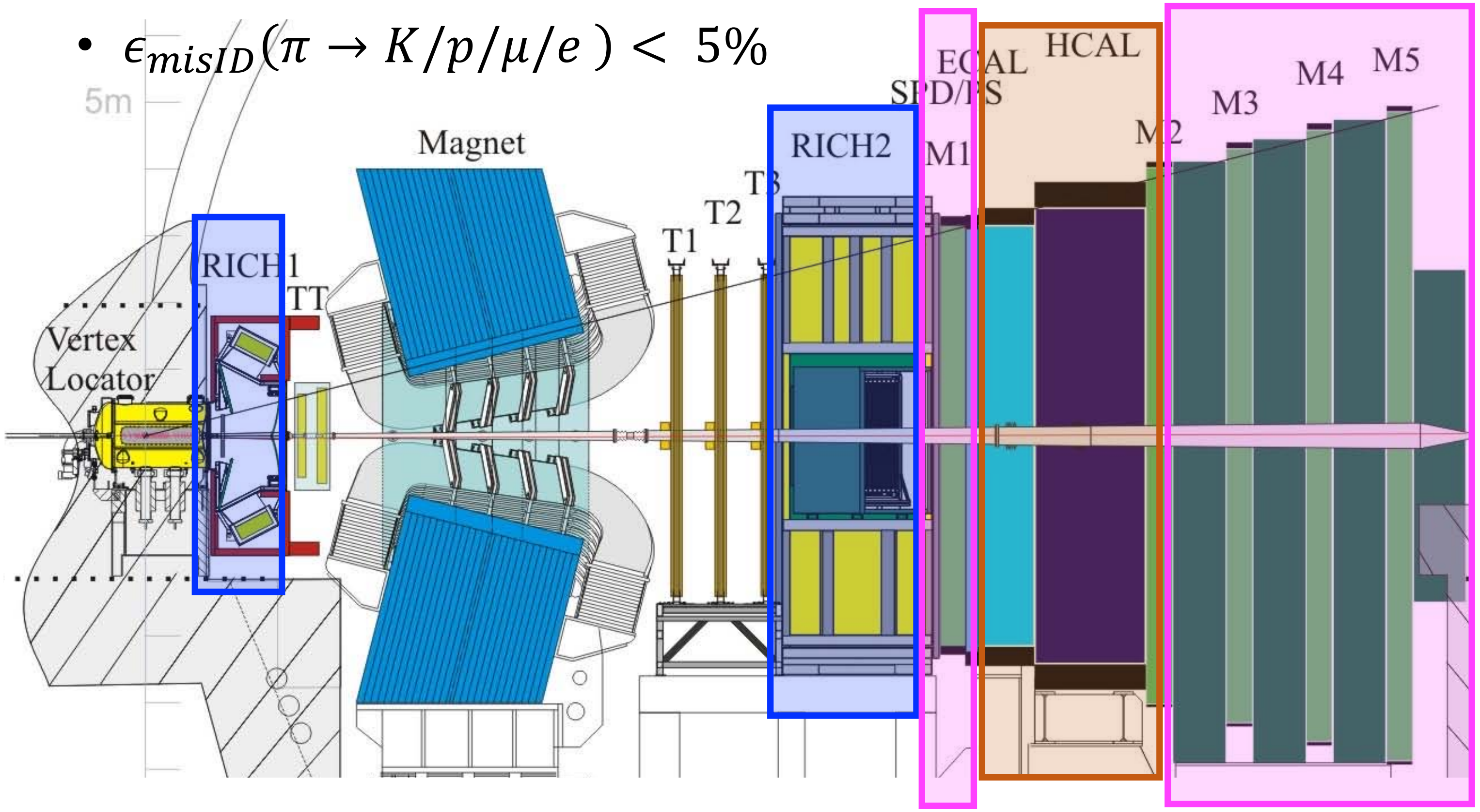
Calorimeters

- SPD,PS,ECAL,HCAL
- PID for e, γ, π^0
- Energy and position for neutral objects and trigger for e, γ

Muon stations

- 5 stations (M1-M5) have high purity PID for muons

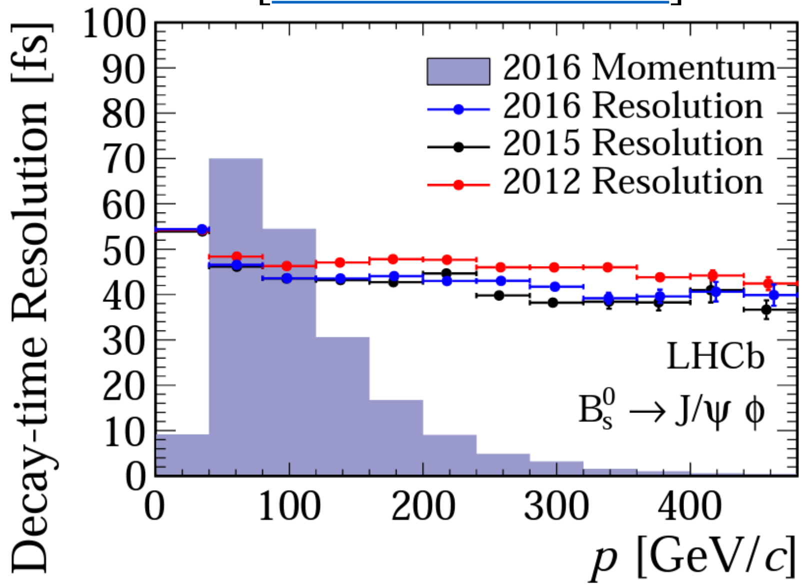
- $\epsilon_{PID}(K \rightarrow K) > 95\%$.
- $\epsilon_{misID}(\pi \rightarrow K/p/\mu/e) < 5\%$



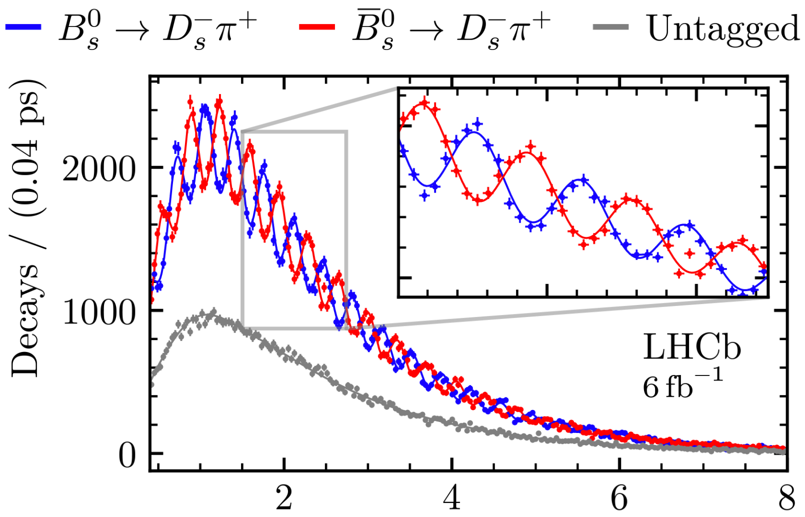
SPD: Scintillating pad detector
PS: Preshower

Vertex reconstruction

[LHCb-DP-2019-001]



Excellent vertexing in VELO! Can still reconstruct downstream decays (K_S, Λ).



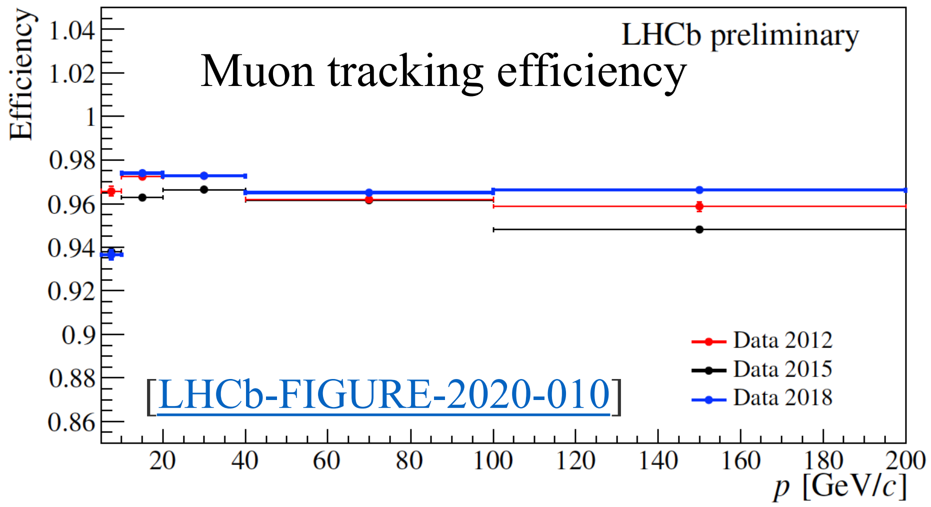
[LHCb-PAPER-2021-005]

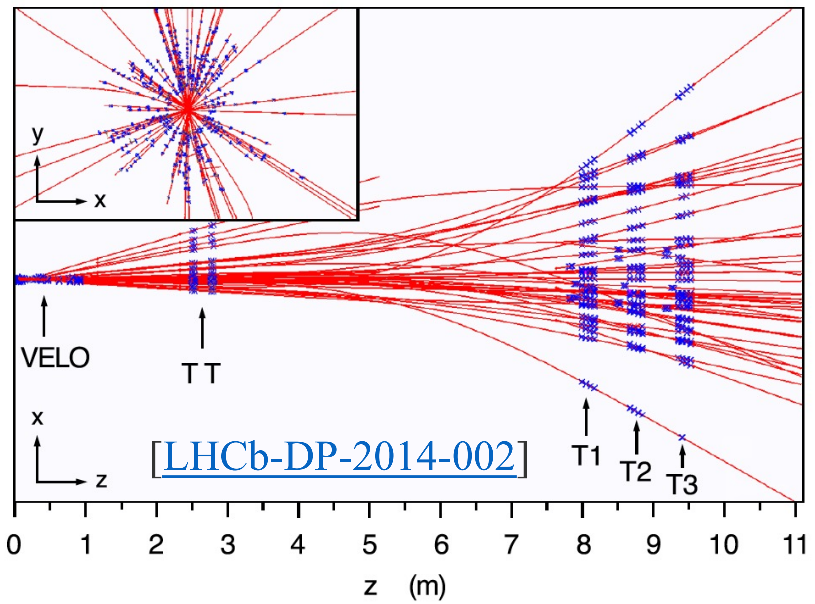
- Good resolution on **Impact Parameter** (IP) required for efficiently selecting B decays: $\sigma_{IP} \sim 20\ \mu m$ for high p_T tracks.
- Good resolution on **decay time** crucial for time-dependent CP violation analyses: $\sigma_\tau \sim 45\ fs\ wrt\ \tau_B \sim 1.5\ ps$

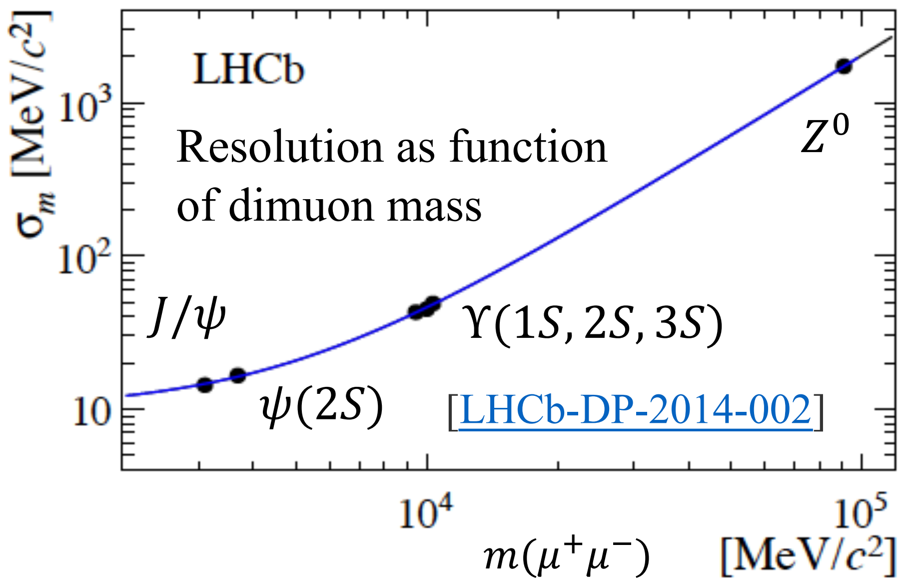
Track reconstruction

Excellent track reconstruction!

- $\epsilon(tracking) \sim 96\%$
- $\frac{\delta p}{p} \sim 0.5\% - 1\%\ (5 - 200\ GeV)$
- $\sigma(m_{J/\psi}) \sim 15\ MeV$

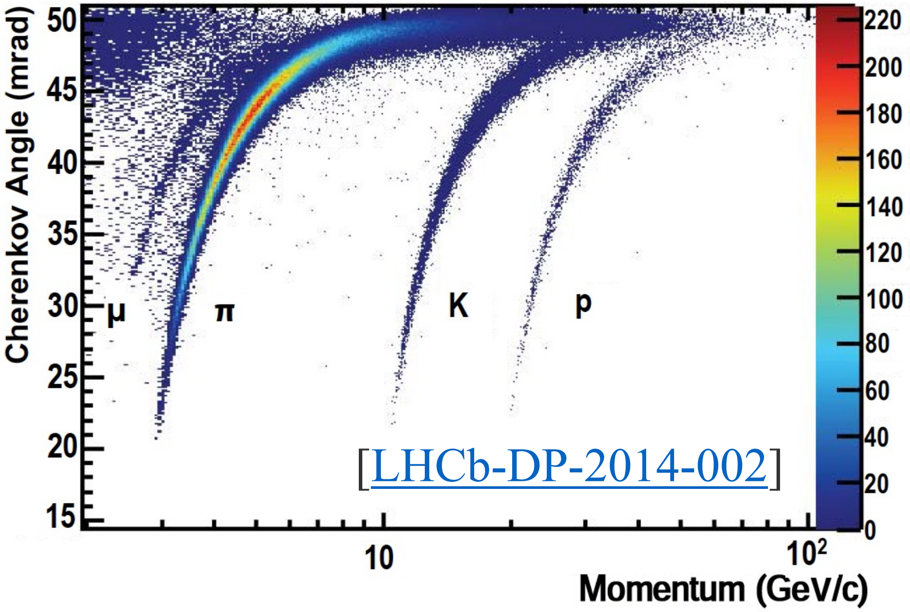


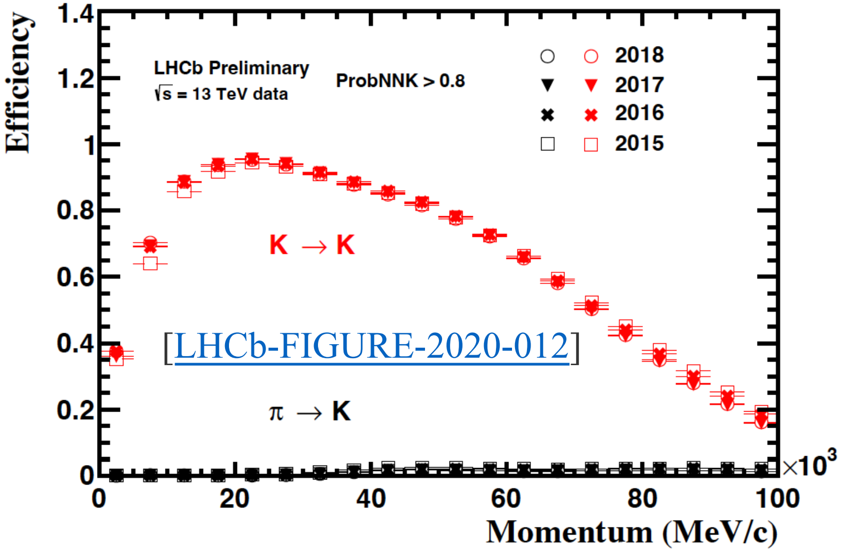


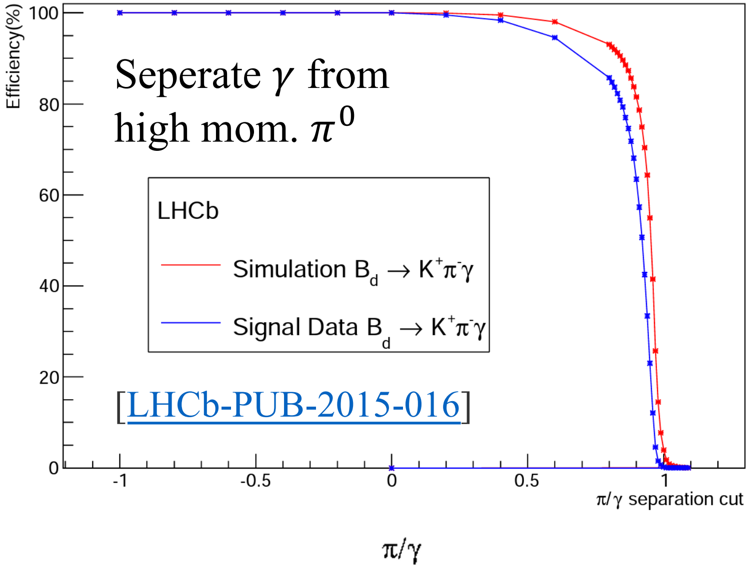


Particle identification performance

- Charged: Combine info from RICH, CALO, MUON.
  - $\epsilon_{PID}(K \rightarrow K) > 95\%$ (same for μ and lower for e)
  - $\epsilon_{misID}(\pi \rightarrow K/p/\mu/e) < 5\%$
- Neutral: Dedicated NN for identifying deuterons and separating γ from hadrons, $e^{\pm}$ and high-energy π^0s.



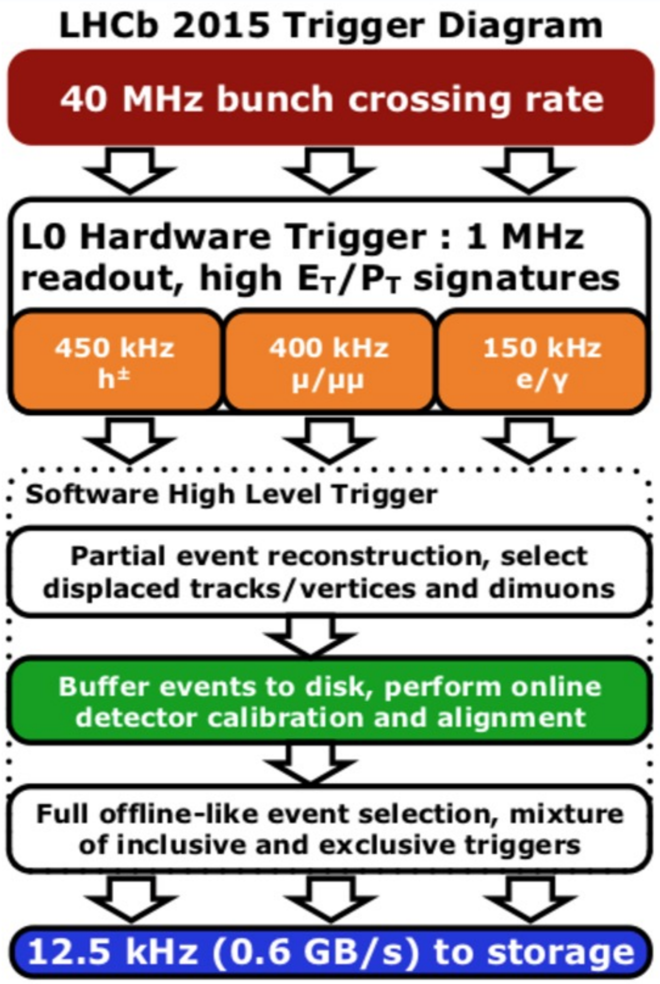




LHCb trigger (2015-2018)

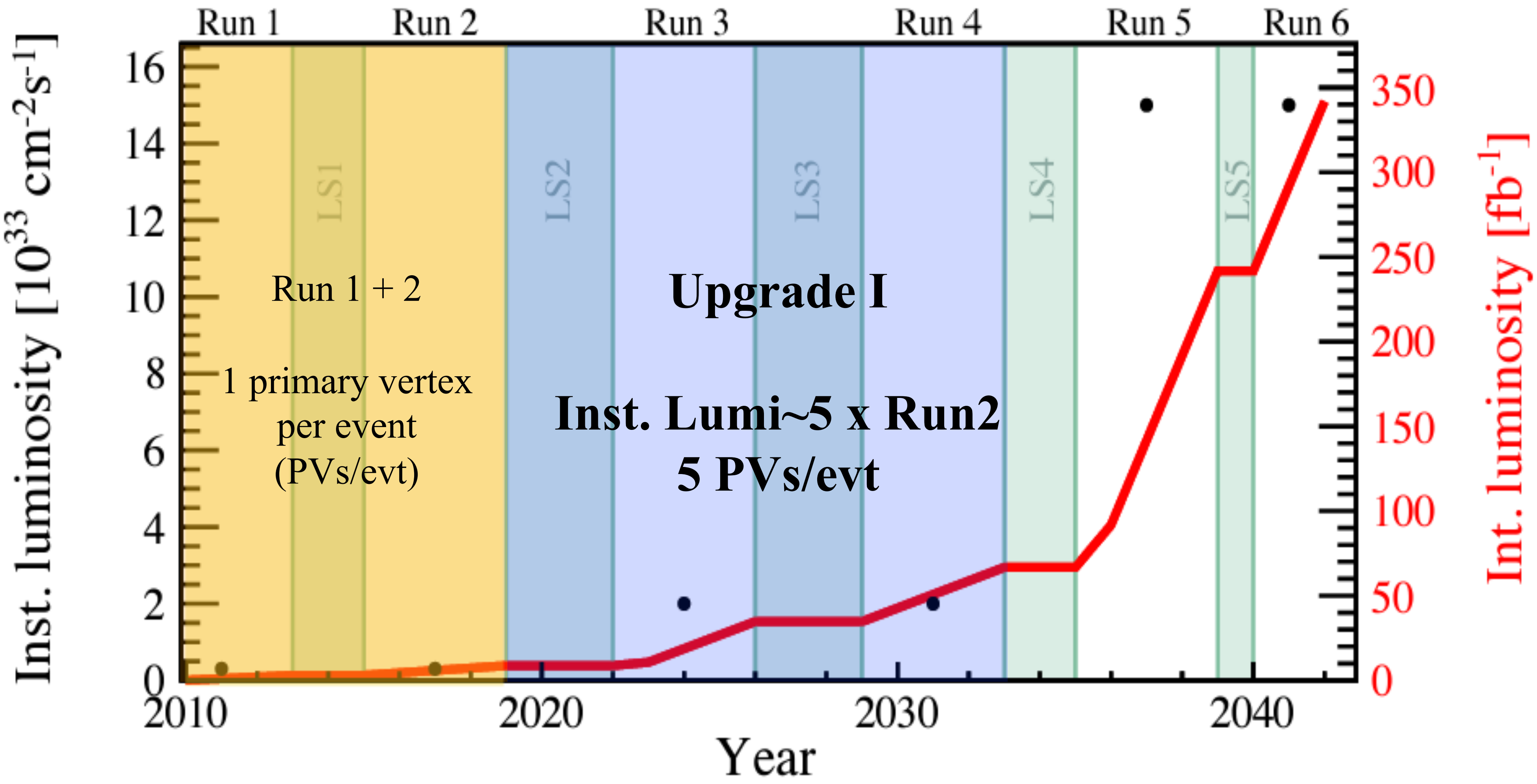
[2019 JINST 14 P04006, Comput.Phys.Commun. 208 (2016) 35-42]

- Trigger needed to **reduce storage and readout costs with good signal to background ratio**.
- Consists of three stages:
  - **L0**: Hardware, E_T/p_T thresholds.
    40 MHz → 1 MHz.
  - **HLT1**: Software, partial reconstruction,
    1 MHz → 150 kHz.
  - **HLT2**: Full event reconstruction,
    100 kHz → 12.5 kHz.

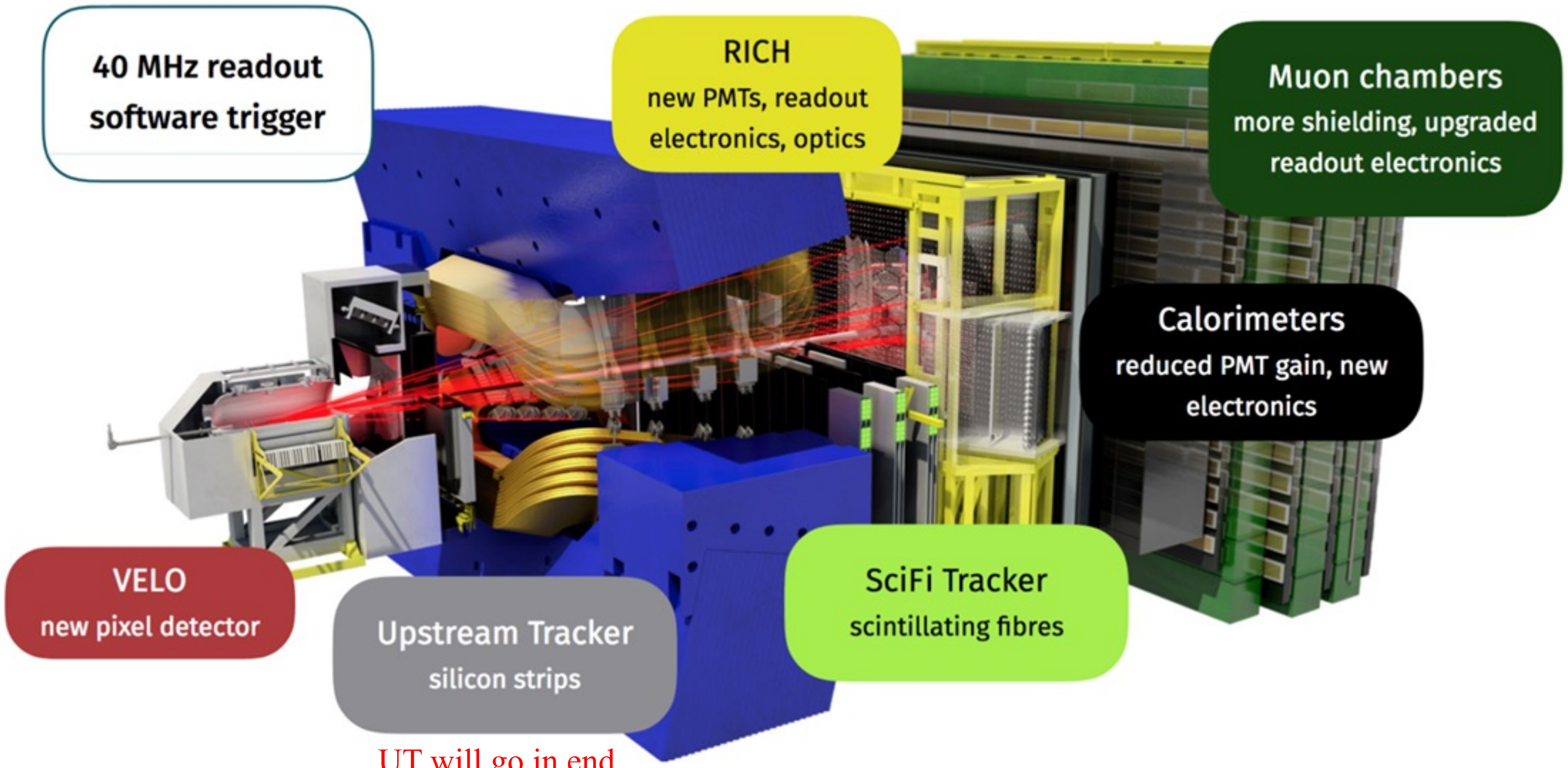


L0: Level 0 trigger
HLT: High level trigger

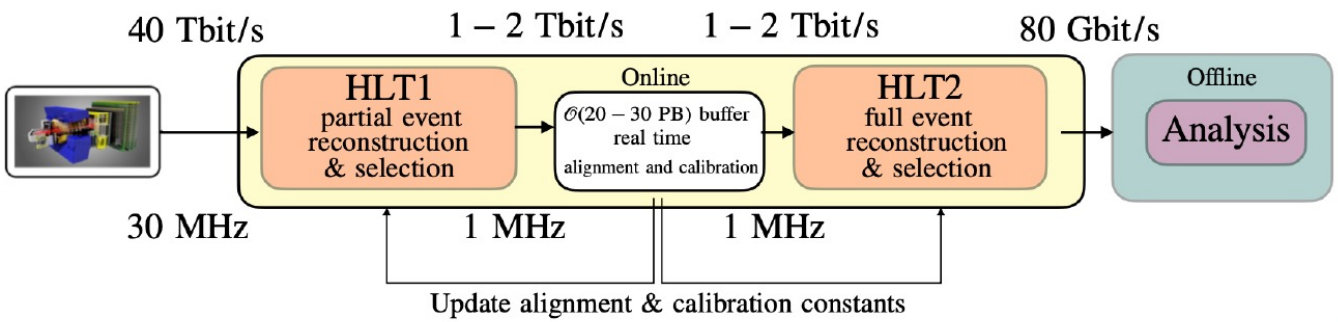
LHCb past and present



Brand new detector for 2022-2032!



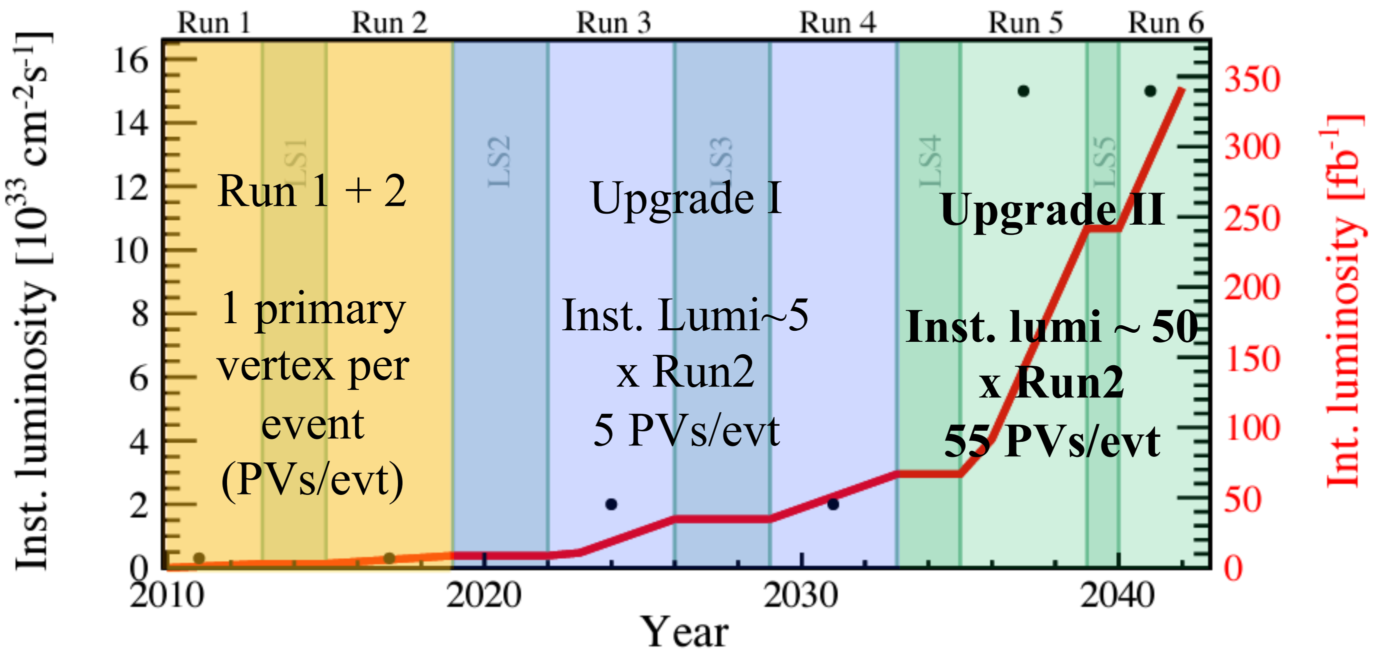
UT will go in end of this year



No hardware trigger, fully software based!

Hadronic yield $/fb^{-1}$: 2 x Run2

LHCb future (HL-LHC, 2035-2042)



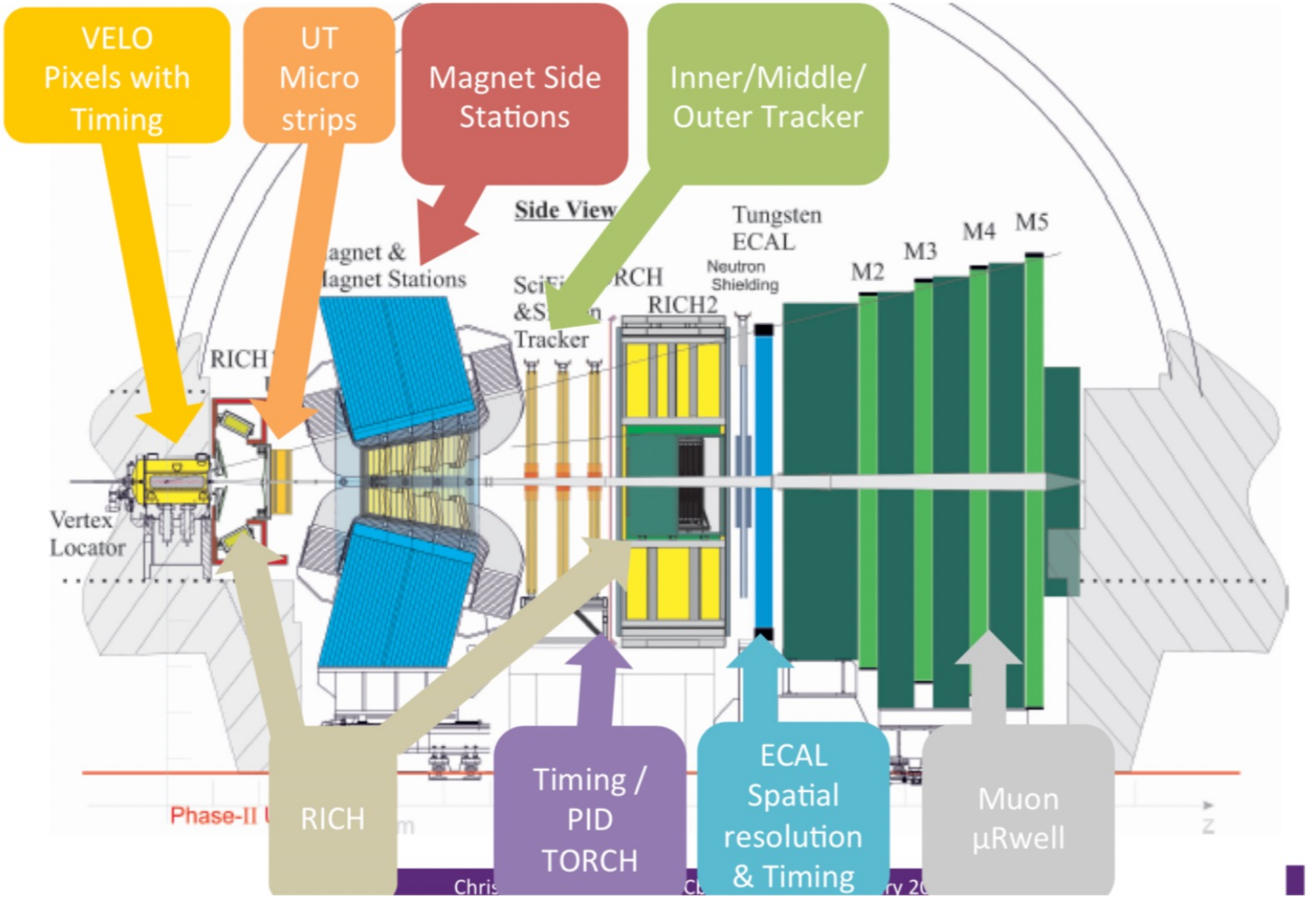
[CERN-LHCC-2021-012]

- Starting R&D phase of new technologies

bridge to future accelerators
- precision timing for tracking and PID
- extreme radiation hardness
- low-cost monolithic pixels
- cryogenic cooling (for SiPMs)

→ **LHCb welcomes new collaborators!**

Upgrade II



VELO
Pixels with
Timing
UT
Micro
strips
Magnet Side
Stations
Inner/Middle/
Outer Tracker
Side View
Tungsten
ECAL
Neutron
Shielding
M2
M3
M4
M5
RICH2
Tracker
Vertex
Locator
RICH
Timing /
PID
TORCH
ECAL
Spatial
resolution
& Timing
Muon
µRwell