Tests of Lepton Flavor Universality in tree-level B Meson Decays at LHCb

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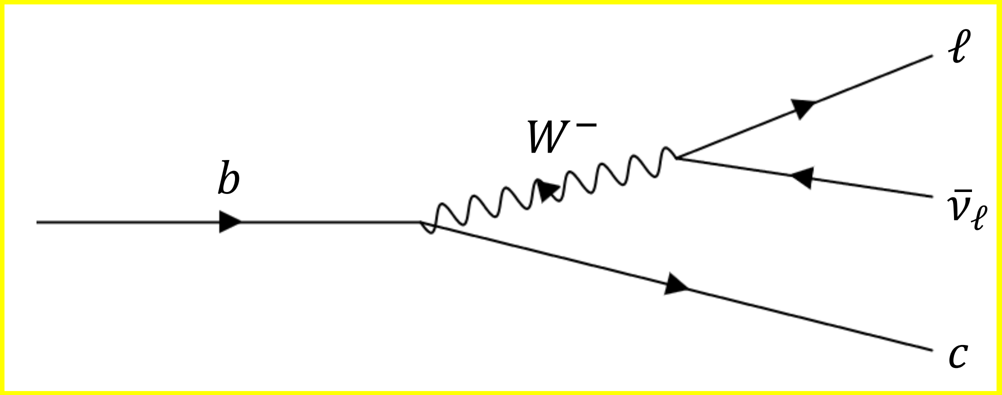
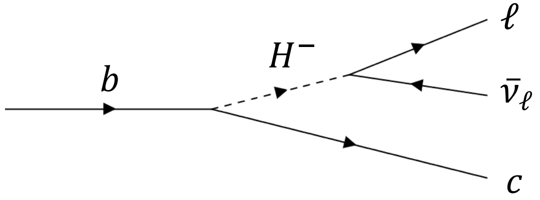
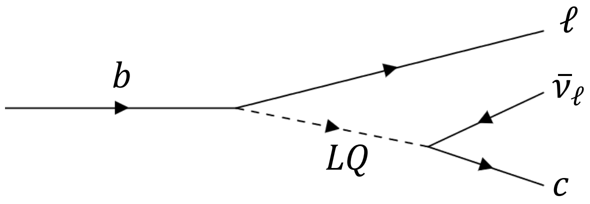
Lepton Flavor Universality

- SM electroweak couplings identical between lepton generations, only broken by Higgs Yukawa → differences driven by m_ℓ
  - Deviations from LFU provide signatures of new physics
- $b \to c\tau\bar{\nu}_\tau$
  - $\mathrm{BF}(B \to D^{(*)} l\bar{\nu}_\ell)$ ~ 0.1
  - Theoretically fairly clean
  - Very sensitive to NP because of third-generation fermions
- Experimental observables
  - Angular distributions
  - LFU ratios of BFs

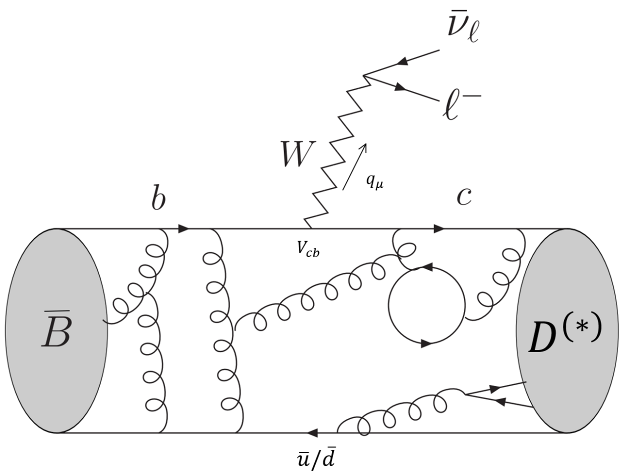


+ ?





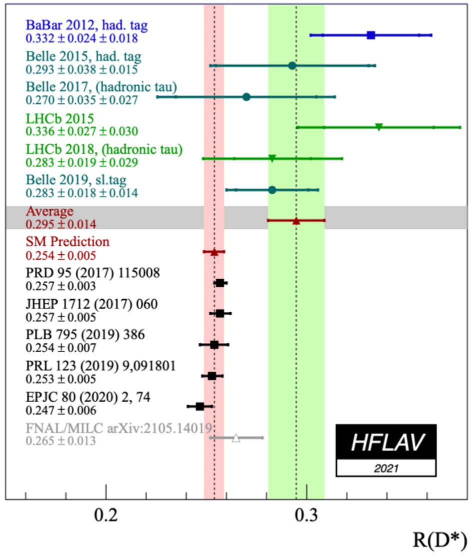
BF Ratio Measurements Make for Clean Observables

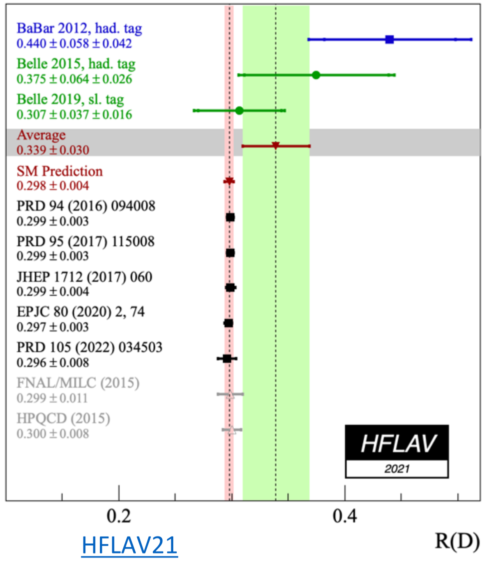


$$\frac{d\Gamma(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} \propto \begin{array}{l} |V_{cb}|^2 \\ f(q^2, m_\ell) \to \text{hadronic effects/form factors} \end{array}$$

$$R(D^{(*)}) = \frac{\int_{m_\tau^2}^{(m_B - m_{D^{(*)}})^2} dq^2 \frac{d\Gamma(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{dq^2}}{\int_{m_\mu^2}^{(m_B - m_{D^{(*)}})^2} dq^2 \frac{d\Gamma(\bar{B}\to D^{(*)}\mu\bar{\nu}_\mu)}{dq^2}} = \frac{\Gamma(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{\Gamma(\bar{B}\to D^{(*)}\mu\bar{\nu}_\mu)}$$

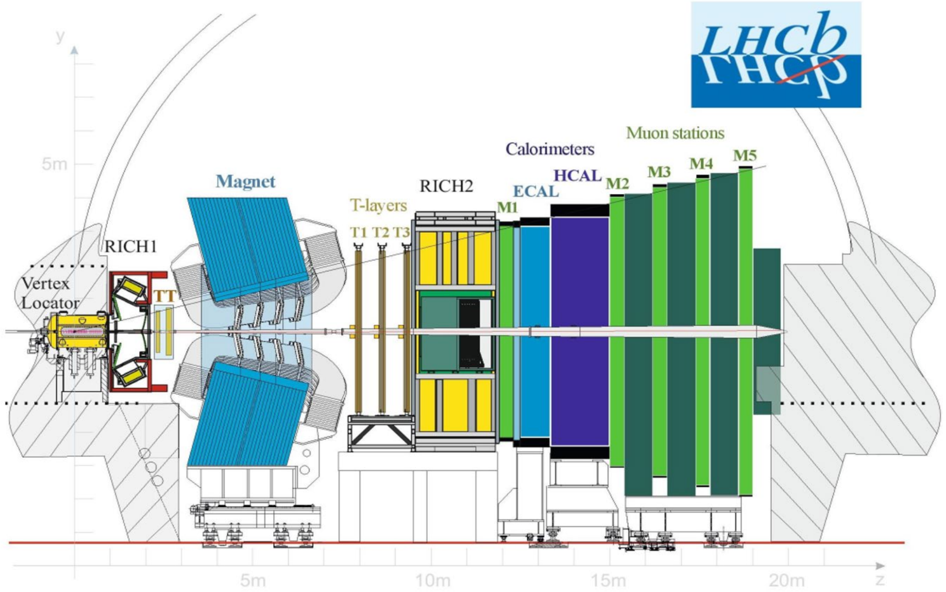
- Dominant theory uncertainties on $\Gamma(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$ due to V_{cb}, hadronic FFs
  - Mostly cancel in ratio!
- Experimental systematic uncertainties reduced via ratios of efficiencies



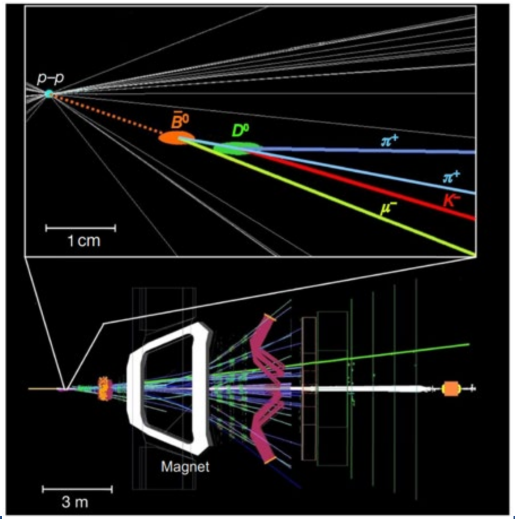


HFLAV21

LHCb



Nature **546**, 227–233 (2017)



	Run 1	Run 2
Completion date	2012	2018
Center-of-mass energy	7/8 TeV	13 TeV
$b\bar{b}$ cross section [nb]	$(3.0/3.4)\times10^5$	5.6×10^5
Integrated luminosity [fb^{-1}]	3	6
B^0 mesons [10^9]	170	580
B^+ mesons [10^9]	170	580
B_s mesons [10^9]	40	140
Λ_b baryons [10^9]	90	300
B_c mesons [10^9]	1.3	4.4

- Forward detector, but captures 25% $b\bar{b}$
  - Mostly $gg \to b\bar{b}$
  - $B^{0,+}$ and B_c, B_s, Λ_b
- Strengths:
  - **Vertexing**: VELO 8.2 mm from PV, resolution $< 300\ \mu m$
  - **Tracking**: 95% charged tracks ($p > 5$ GeV) reconstructed, $< 1\%$ resolution
  - **PID**: approx. 97% for e, μ, 3% π^+ mis-ID, good separation between π^+, K^+, p
- Challenging environment

Reconstructing p_B at LHCb

No tagging methods available → take advantage of **large boost**

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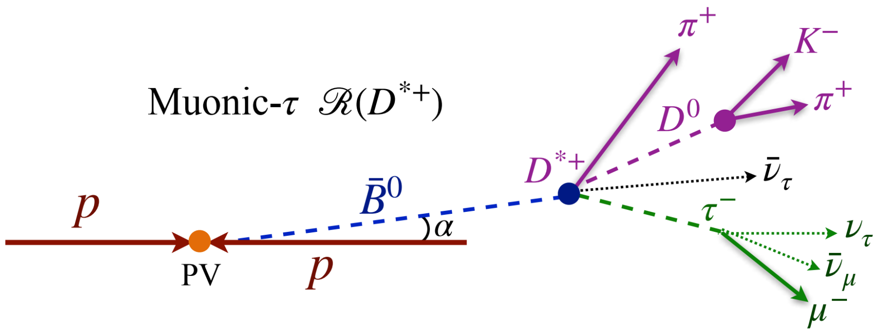

$p_B^z/m_B \approx p_{D^*\mu}^z/m_{D^*\mu}$

Muonic $\tau \rightarrow \mu\nu_\tau\bar{\nu}_\mu$: rest frame approximation

- Pros: larger BF, same visible final states for μ/τ
  - Direct measurement of $R\left(D^{(*)}\right) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{1}{\mathrm{BF}(\tau\rightarrow\mu\nu_\tau\bar{\nu}_\mu)}$
- Con: 3 missing neutrinos
  - Worse resolution, more backgrounds

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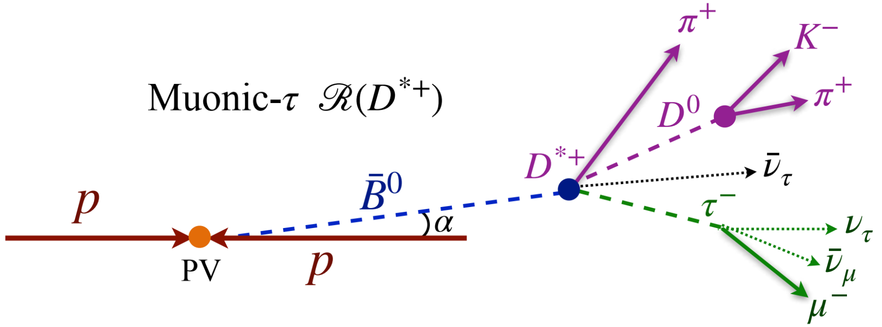

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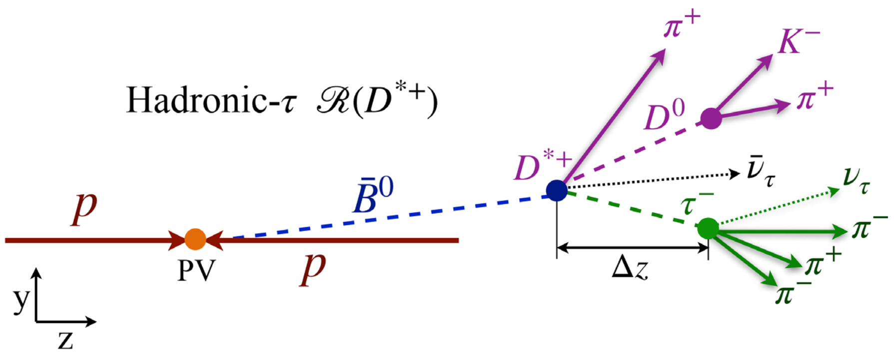


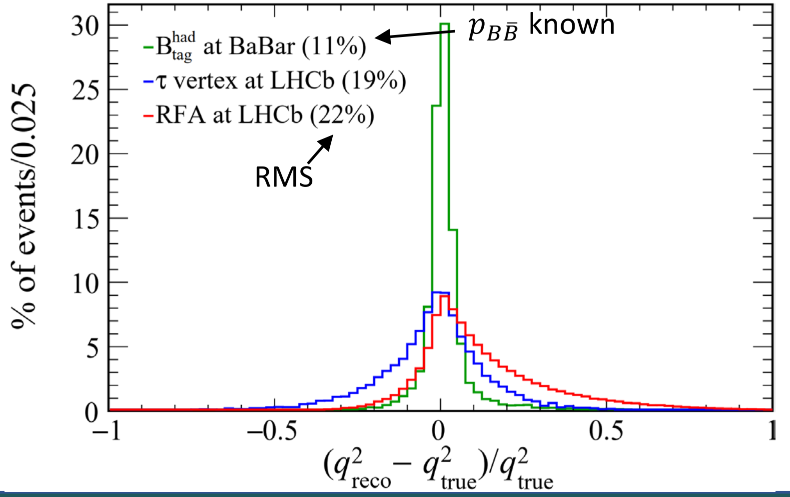
$\hat{\boldsymbol{p}}_\tau \approx \hat{\boldsymbol{p}}_{\pi\pi\pi}$

Hadronic $\tau \to \pi^-\pi^+\pi^-\nu_\tau$: τ vertex reconstruction

- Pros: better resolution, purity
- Con: requires external BF to cancel σ in $R(D^{(*)})$

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

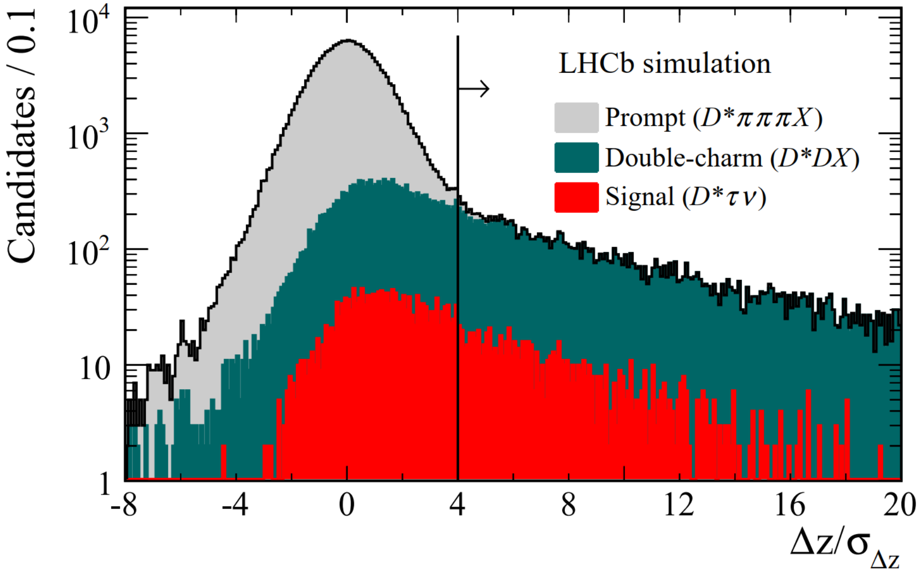
Resolution for $p_{B_{sig}}$ Estimates (Simulated)



Hadronic τ: $R(D^*)$

- Run 1: 7/8 TeV 3 fb^{-1} collected 2011/12, Run 2: 13 TeV 2 fb^{-1} collected 2015/16
- $\tau \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$, $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$
- $R(D^*) = \frac{\Gamma(\bar{B}\to D^{*+}\tau\bar{\nu})}{\Gamma(\bar{B}\to D^{*+}\pi^-\pi^+\pi^-)} \frac{\Gamma(\bar{B}\to D^{*+}\mu\bar{\nu})}{\Gamma(\bar{B}\to D^{*+}\pi^-\pi^+\pi^-)}$

  external, *irreducible* σ

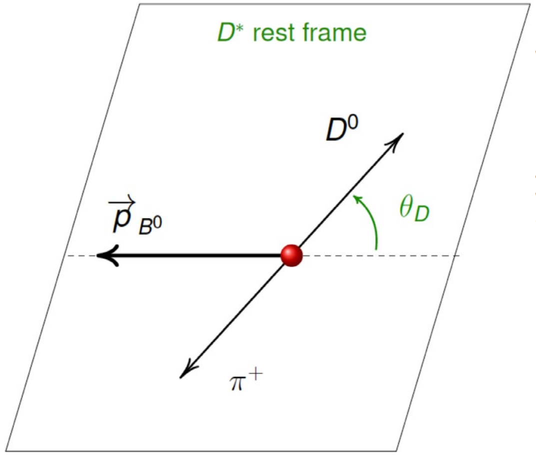


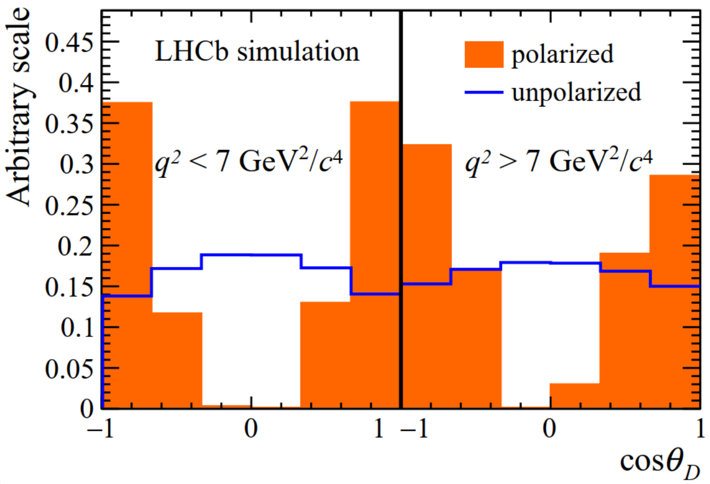
- Separate $B \to D^*3\pi(X)$ by τ flight distance
- Run 1: $R(D^*) = 0.291 \pm 0.019$ (stat) ± 0.026 (sys) ± 0.013 (ext) Phys. Rev. D **97** (2018) 072013
  Run 2: $R(D^*) = 0.247 \pm 0.015$ (stat) ± 0.015 (sys) ± 0.012 (ext) Phys. Rev. D 108 (2023) 012018
  - Most precise $R(D^*)$
  - Major systematics scale with more data/MC but need other measurements for σ_{ext}

Hadronic τ: $F_L^{D^*}$

- Run 1: 7/8 TeV 3 fb^{-1} collected 2011/12, Run 2: 13 TeV 2 fb^{-1} collected 2015/16
- $\tau \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$, $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$

$$F_L^{D^*}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma/dq^2}$$





- Signal yields split into unpolarized/polarized
  - Modeled by MC
- Results consistent with SM and Belle results, dominant systematic is MC stats:
  - $q^2 < 7$: $F_L^{D^*} = 0.51 \pm 0.07(\text{stat}) \pm 0.03(\text{sys})$
  - $q^2 > 7$: $F_L^{D^*} = 0.35 \pm 0.08(\text{stat}) \pm 0.02(\text{sys})$
  - Average over q^2: $F_L^{D^*} = 0.43 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})$

Submitted to Phys. Rev. D

Muonic τ Analyses: $R(D^{*,0})$, $R(D^{*,+})$

- $R(D^{*,0})$ Run 1: 7/8 TeV 3 fb^{-1} collected in 2011/12
- $R(D^{*,+})$ Run 2: 13 TeV 2 fb^{-1} collected in 2015/16
- Reconstruct as $\tau \rightarrow \mu\nu_\tau\bar{\nu}_\mu$,
  - $R(D^{*,0})$: $D^{*+} \rightarrow D^0\pi^+_{slow}$, $D^0 \rightarrow K^-\pi^+$
  - $R(D^{*,+})$: $D^{*+} \rightarrow D^+\pi^0$, $D^+ \rightarrow K^-\pi^+\pi^+$
    - $D^+ \rightarrow K^-\pi^+\pi^+ \approx 10\%$ vs $D^0 \rightarrow K^-\pi^+ \approx 4\%$
    - D^* feed-down significantly reduced
      - $D^{*0} \rightarrow D^+\pi^-$ is kinematically forbidden
      - BDT trained to reject additional π^0 to reduce $D^{*+} \rightarrow D^+\pi^0$ → Prioritize $R(D^+)$

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- Susceptible to partially reconstructed backgrounds
  - Excited $1P$ (and higher) $\boldsymbol{D^{**}}$: Measure FFs in (control) data
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- Susceptible to partially reconstructed backgrounds
  - Excited $1P$ (and higher) $\boldsymbol{D}^{**}$: Measure FFs in (control) data
  - Double charm: Find $\boldsymbol{DD}$ shape corrections in control regions
- BDT developed to identify extra charged tracks not isolated from B decay
  - With PID info, used to define control samples that fix bkg modeling

Signal Sample
(No extra tracks from B)
$D^{(*)}\mu^-$

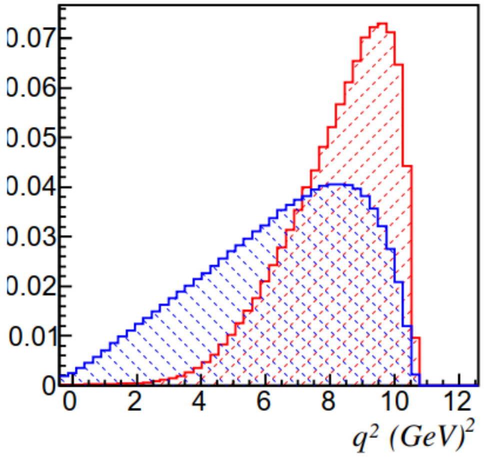
1 Extra π Sample
(Enriched in D^{**})
$D^{(*)}\mu^-\pi^-$

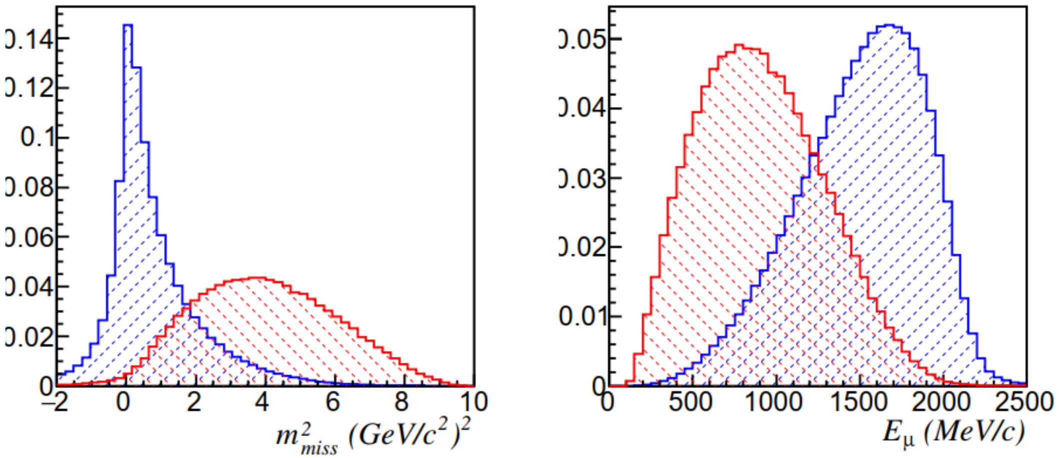
2 Extra π Sample
(Enriched in D^{**}_H)
$D^{(*)}\mu^-\pi^+\pi^-$

1 Extra K Sample
(Enriched in DD)
$D^{(*)}\mu^-K^\pm$

Muonic τ Analyses: $R(D^{*,0})$, $R(D^{*,+})$

- Yields from multidimensional maximum likelihood template fits (signal and control) to data
  - MC templates: signal, normalization, partially reconstructed bkg
  - Data templates: μ and π_{slow} combinatorial, misidentified μ
  - Discriminating variables:
    - $q^2 = (p_B - p_{D^{(*)}})^2$
    - $m_{miss}^2 = (p_B - (p_{D^{(*)}} + p_\mu))^2$ ← visible
    - E_μ^* (B rest frame)





Rest frame approx. kinematics for simulated reconstructed $D^*\mu$ signal vs normalization

Muonic τ Results: $R(D^{*,0})$, $R(D^{*,+})$

Run 1 Muonic $R(D^{*,0})$

$R(D^0) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{sys})$

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

Run 2 Muonic $R(D^{*,+})$

$R(D^0) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{sys})$

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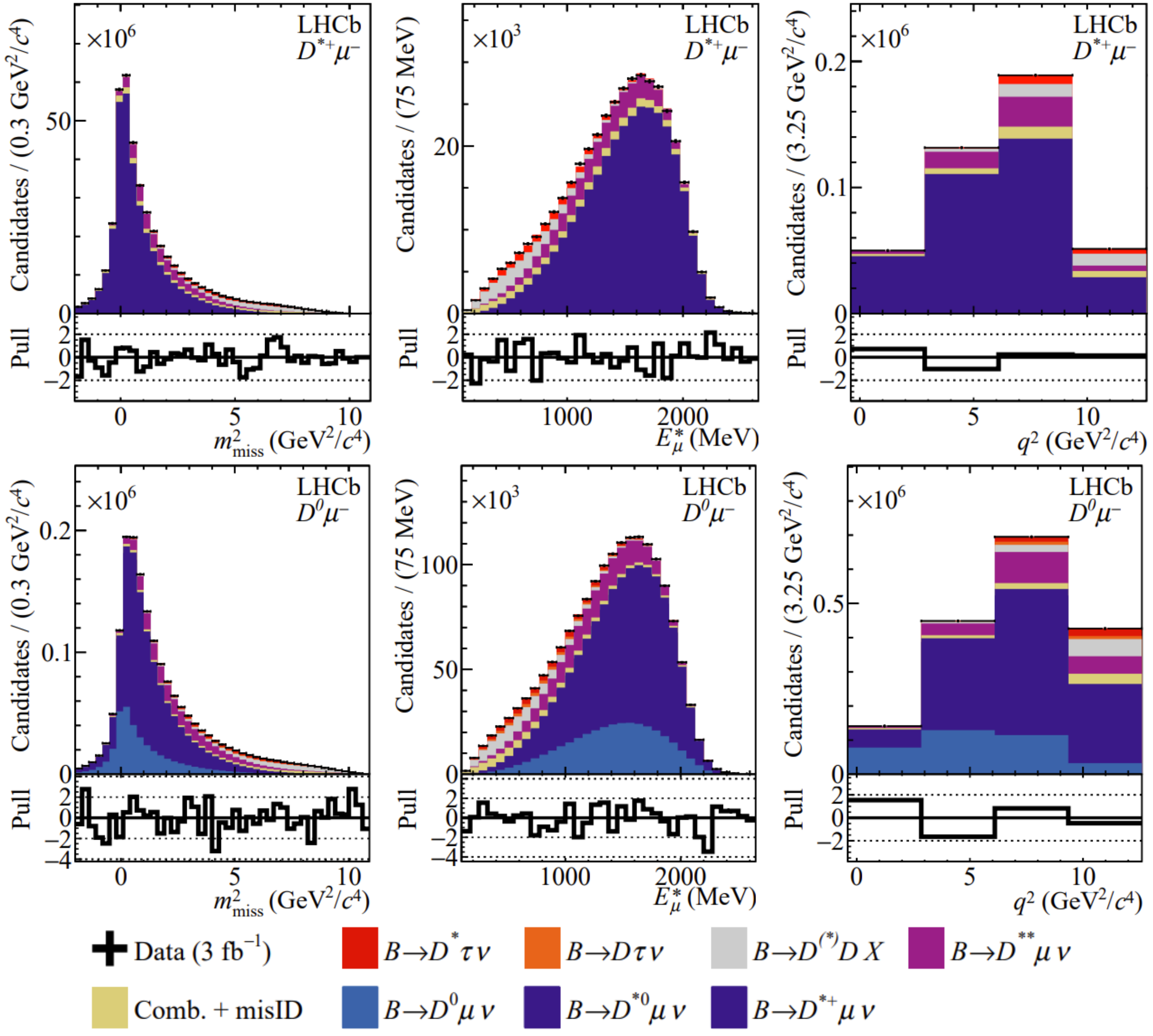
- Main **systematics** due to DD modeling, FFs, size of simulated samples: all *scale with data*



PRL 131 (2023) 111802

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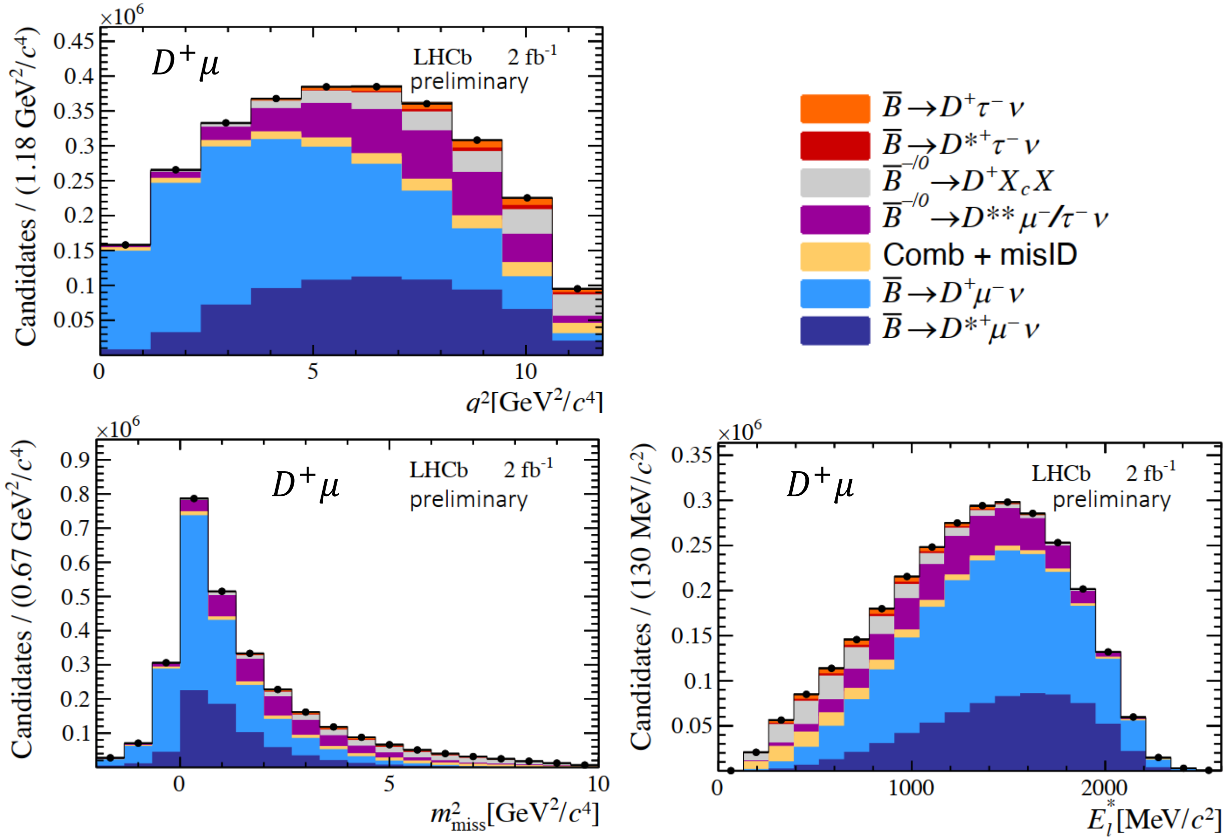

LHCb-PAPER-2024-007

Current Status of $R(D^{(*)})$

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Run 1,2 Hadronic $R(D^{*,+})$

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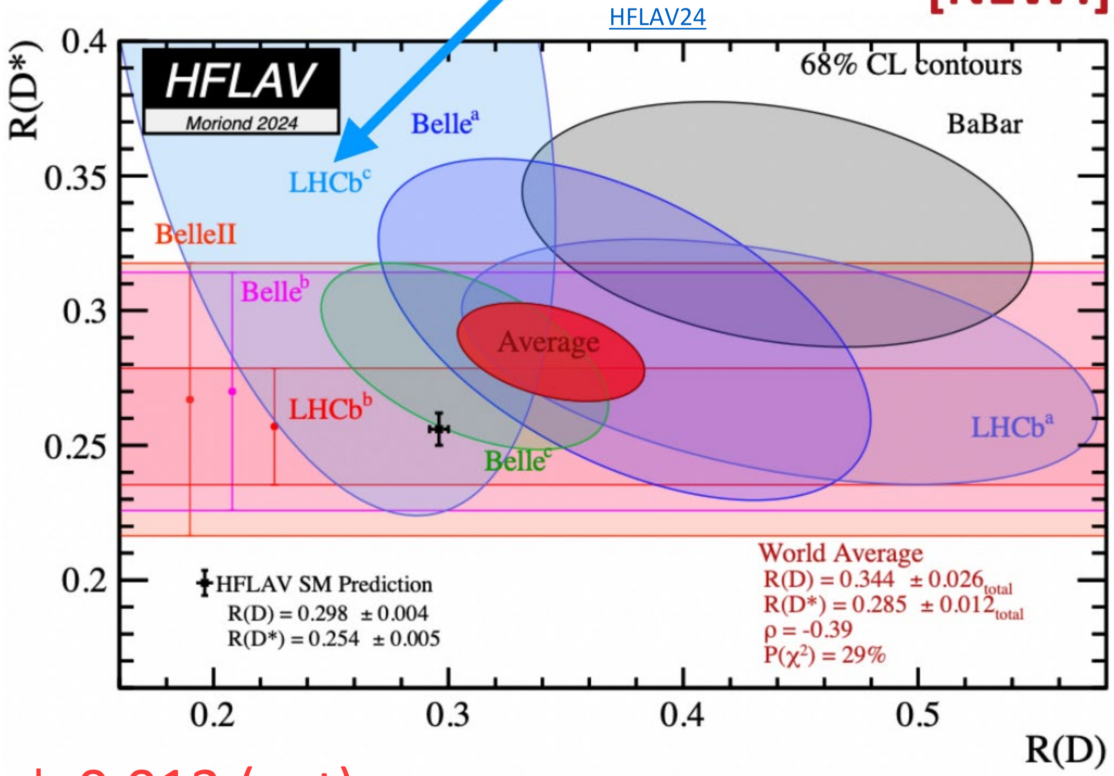
[LHCb preliminary]

[NEW!]



Current tension

3.17σ

Future of LFUV at LHCb

- Anomalies for $b \to c\tau\bar{\nu}_\tau$ remain, but to confirm anomalies and constrain NP, beyond $R(D^{(*)})$:
  - Different decay channels
    - $R(J/\psi)$ with $B_c \to J/\psi[\to \mu\mu]\tau[\to \mu\bar{\nu}_\mu\nu_\tau]\bar{\nu}_\tau$
      - Run 1 → 1.8σ tension, Run 2 ongoing
    - $\Lambda_b \to \Lambda_c\tau\nu$, $B^0 \to D^{**}\tau\nu$, $B_s \to D_s^{(*)}\tau\nu$
  - Different measurements
    - Angular analysis of $B^0 \to D^* l\nu$
    - Kinematic distributions

	Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2012	2018	2031	2041
Center-of-mass energy	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	$(3.0/3.4)\times 10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	3	6	40	300
B^0 mesons [10^9]	170	580	4,200	32,000
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B_s mesons [10^9]	40	140	1,000	7,600
Λ_b baryons [10^9]	90	300	2,200	16,000
B_c mesons [10^9]	1.3	4.4	32	240

- Collider upgrades → expect $\sim 100x$ more data
  - Computing will pose a major challenge
    - Places great importance on fast sim
      - $R(D^{*,+})$: first analysis to use tracker-only simulation
        - 8x faster MC, 40% less storage
  - Many systematics driven by data, could get $\sigma_{R(D^{(*)})} \sim 3\%$

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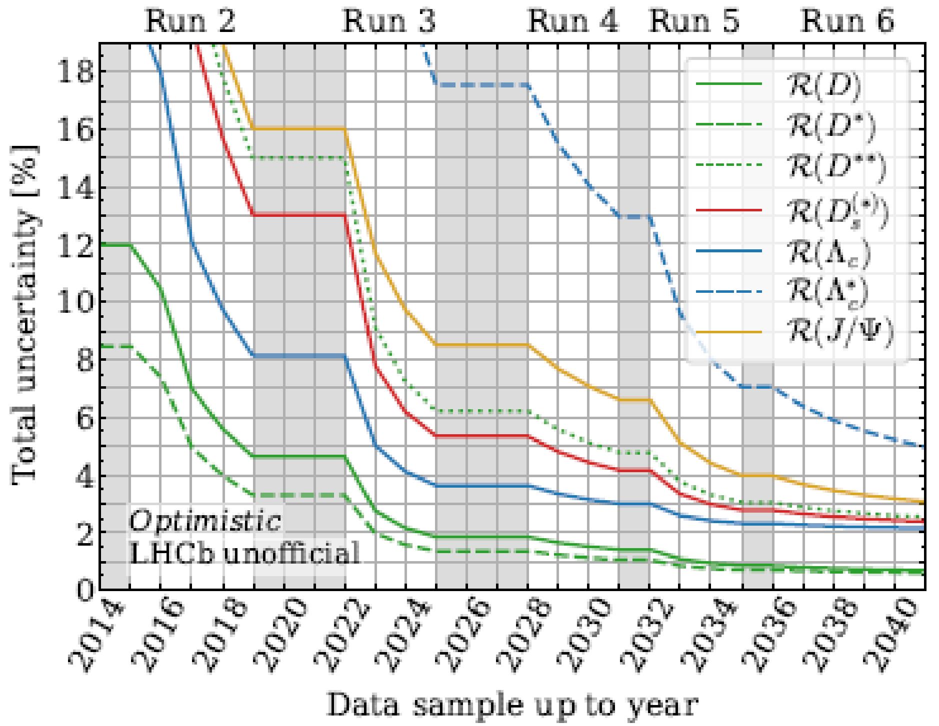


Many exciting results to come!

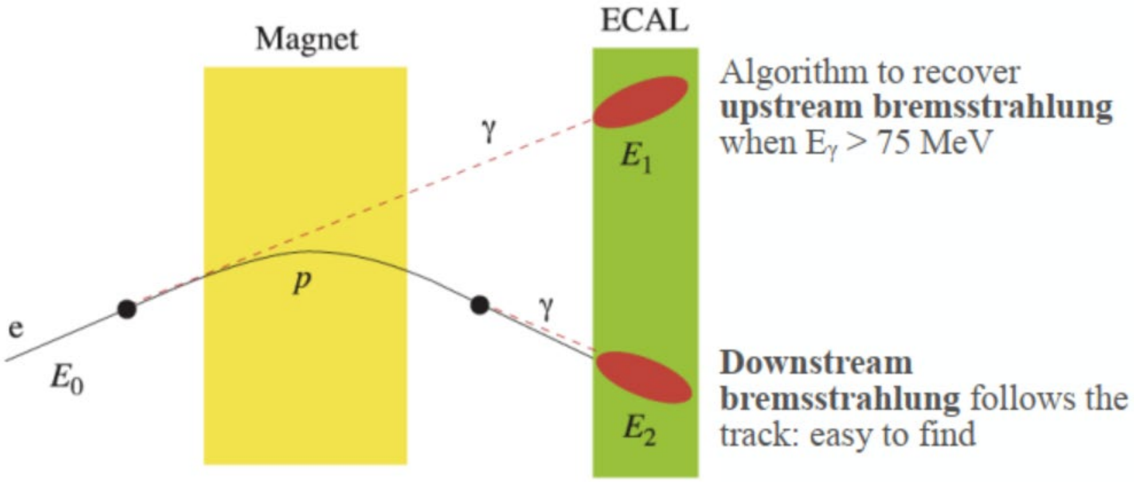
Stay tuned

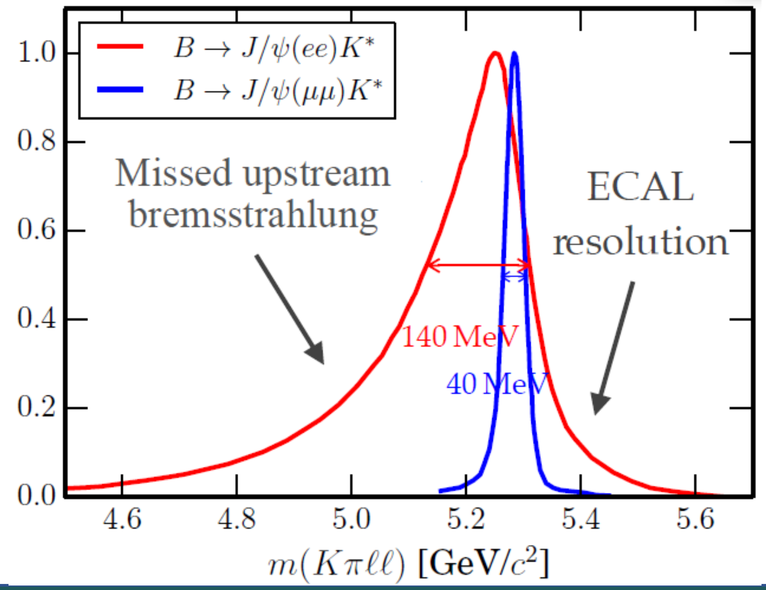
Thank you!

Backup

e, Neutral Reconstruction at LHCb

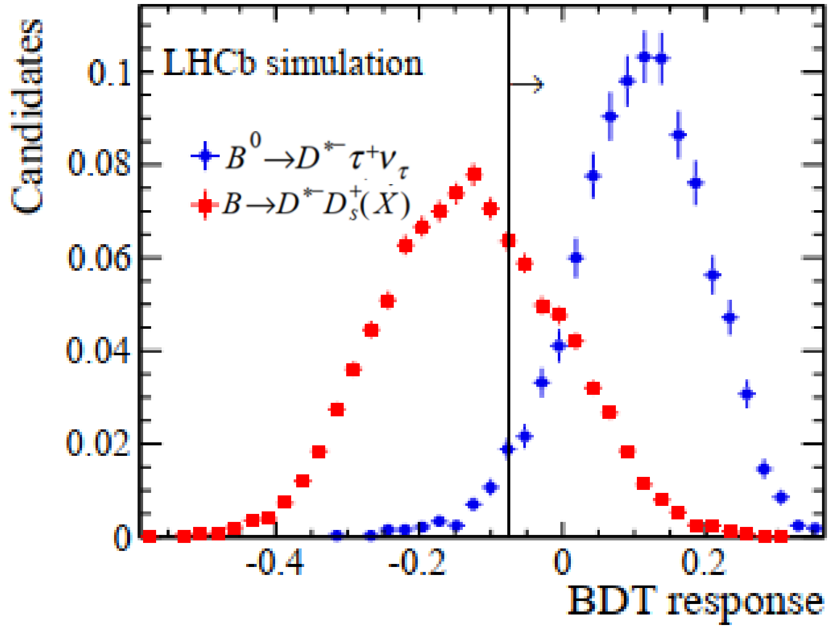
- At LHCb, e reconstruction very difficult
  - Lots of material → lots of brem.
  - Relatively low calorimeter granularity
  - Results in e:
    - Worse mass resolution
    - More difficult to trigger on
  - Inspires e.g. the measurement of $R(K^{(*)}) = \frac{\Gamma(B\to K^{(*)}\mu^-\mu^+)}{\Gamma(B\to K^{(*)}e^-e^+)}$ as a double ratio involving $B \to K^{(*)}J/\psi(\to l^-l^+)$, $R(K^{(*)}) = \frac{\Gamma(B\to K^{(*)}\mu^-\mu^+)}{\Gamma(B\to K^{(*)}J/\psi[\to\mu^-\mu^+])}\frac{\Gamma(B\to K^{(*)}J/\psi[\to e^-e^+])}{\Gamma(B\to K^{(*)}e^-e^+)}$ in order to cancel uncertainties due to electrons in the second ratio
- Neutral particle reconstruction also difficult, mainly because of low calorimeter granularity





Handling Double Charm Bkg for Hadronic τ

- After cutting out $B \to D^* 3\pi X$, remaining bkg dominated by double-charm
  - BFs not well-measured, and $D_s \to 3\pi X$ kinematics closely resemble signal
    - $D_s \to 3\pi X$ often accompanied by more neutral particles → rejected by a neutral isolation BDT, "anti-D_s BDT"
      - Includes input variables related to energy of neutral particles deposited in calorimeters in cones around the 3π direction
    - Make use of different resonant structure between $\tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ vs $D_s \to 3\pi X$
      - Perform separate fit in control sample with low anti-D_s BDT score to correct corresponding simulation
    - Control samples used to correct decay fractions and yields of double charm



Phys. Rev. D 108 (2023) 012018

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    - Control samples used to correct decay fractions and yields of double charm

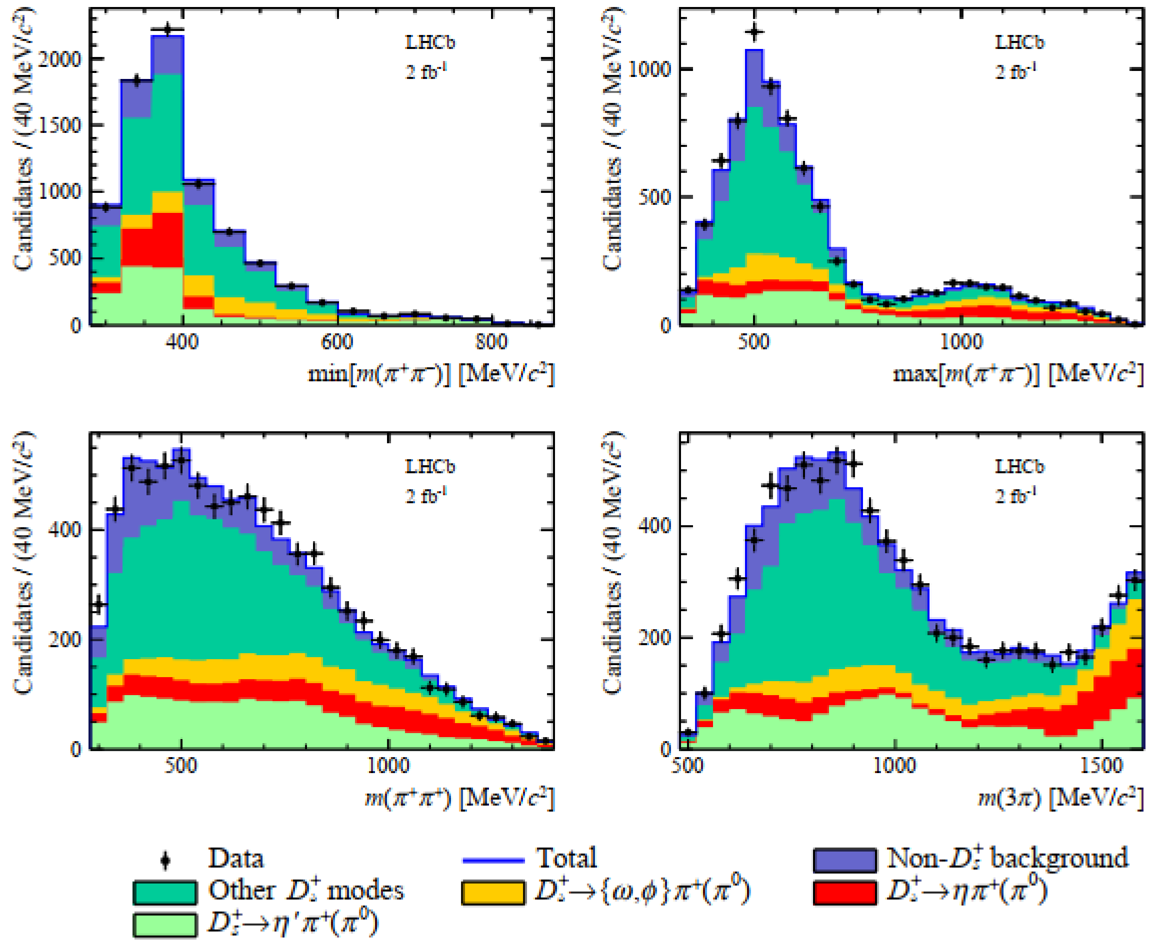
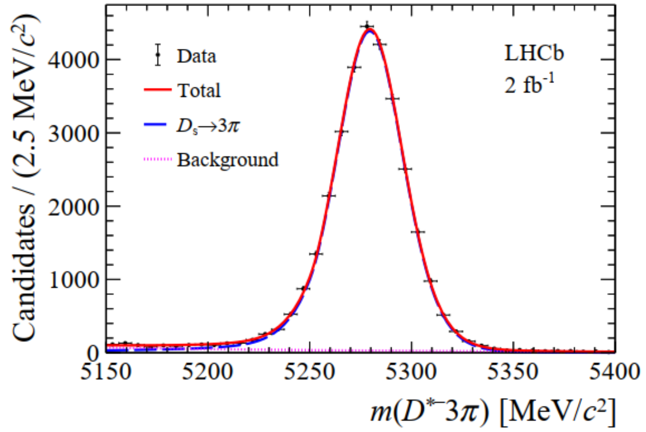


Figure 1: Projections of the $D_s^+ \to 3\pi X$ components for the variables: $\min[m(\pi^+\pi^-)]$, $\max[m(\pi^+\pi^-)]$, $m(\pi^+\pi^+)$ and $m(3\pi)$ in the fit to the control data samples.

Run 1,2 Hadronic $R(D^*)$: Fit and Results

- Signal fit variables: q^2, t_τ, anti-D_s BDT
  - t_τ useful to distinguish from double charm since τ lifetime is 3x longer than D
- Normalization yield found from unbinned fit to $m(D^* 3\pi)$
  - Sample reverses 3π detachment selection



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- Run 1: $R(D^*) = 0.291 \pm 0.019$ (stat) ± 0.026 (sys) ± 0.013 (ext)
  Run 2: $R(D^*) = 0.247 \pm 0.015$ (stat) ± 0.015 (sys) ± 0.012 (ext)
  - Most precise $R(D^*)$
  - Major systematics can be scaled down with more data + MC but external σ needs other measurements (Belle II)

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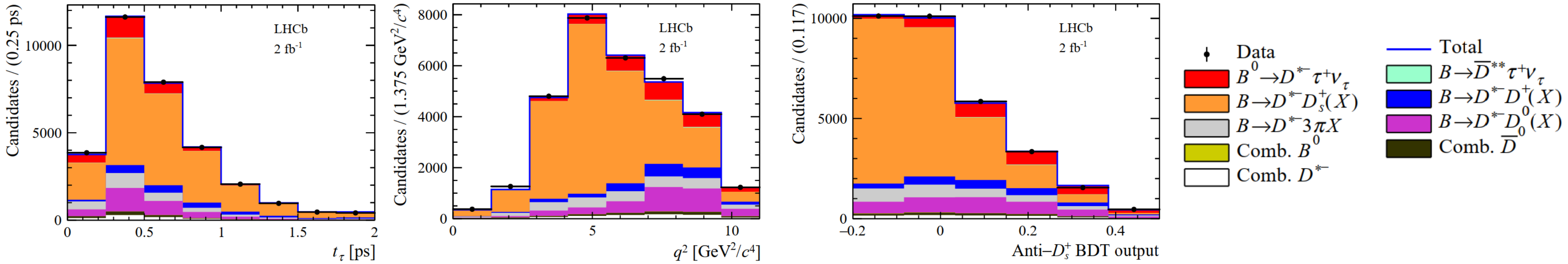
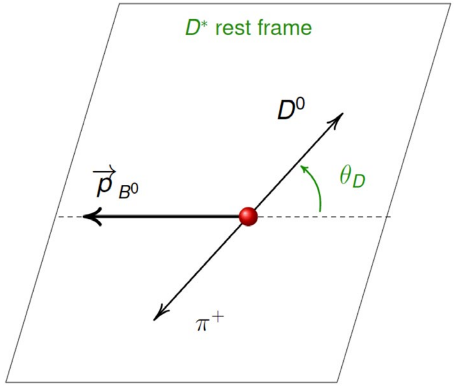


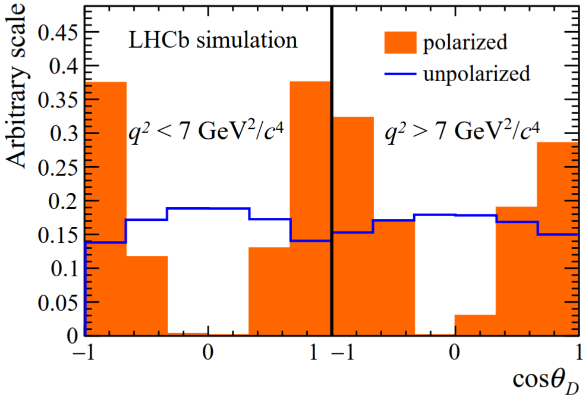
Run 1+2 D^* Polarization

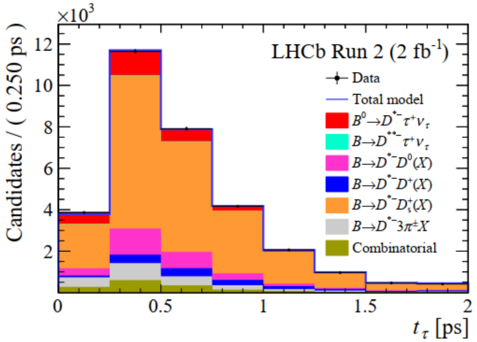


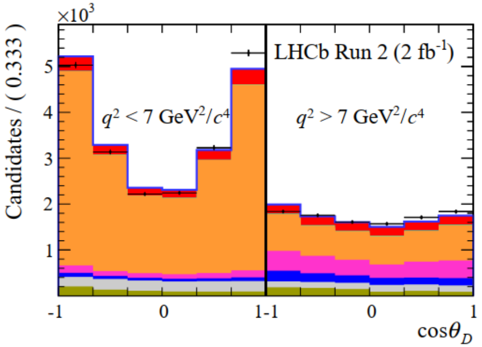
Unpolarized signal fraction — Polarized signal fraction

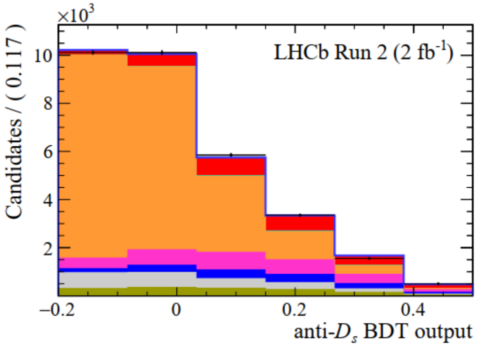
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

$$F_L^{D^*}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma/dq^2} = \frac{a_{\theta_D} + c_{\theta_D}}{3a_{\theta_D} + c_{\theta_D}}$$









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- Run 1+2 combined: separate fits, combined in result
- Background rejection and separation almost identical to hadronic $R(D^*)$, but fit to $\cos(\theta_D)$ in low/high q^2
  - Signal template split into polarized and unpolarized
    - Relative amount floated in the fit
- Results are consistent with SM and Belle results, dominant systematic is MC stats:
  - $q^2 < 7$: $F_L^{D^*} = 0.51 \pm 0.07(\text{stat}) \pm 0.03(\text{sys})$
  - $q^2 > 7$: $F_L^{D^*} = 0.35 \pm 0.08(\text{stat}) \pm 0.02(\text{sys})$
  - Average over q^2: $F_L^{D^*} = 0.43 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})$

Systematic Uncertainties for Hadronic τ

- $R(D^*)$

Source	systematic uncertainty (%)
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

- $F_L^{D^*}$

Source	low-q^2	high-q^2	whole q^2 range
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
Limited template statistics	0.027	0.017	0.019
Fraction of signal $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\nu_\tau$ decays	0.001	0.001	0.001
Fraction of D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s^+ decay model	0.008	0.009	0.009
Shape of $\cos\theta_D$ template in $D^{*-}D_s^+$ decays	0.002	0.001	0.002
Shape of $\cos\theta_D$ template in $D^{*-}D_s^{*+}$ decays	0.007	0.002	0.004
Shape of $\cos\theta_D$ template in $D^{*-}D_s^+X$ decays	0.007	0.006	0.007
Shape of $\cos\theta_D$ template in $D^{*-}D^+X$ decays	0.002	0.002	0.003
Shape of $\cos\theta_D$ template in $D^{*-}D^0X$ decays	0.002	0.002	0.003
$F_L^{D^*}$ integration method	-	-	0.002
Total	0.036	0.023	0.029

FFs (with Parametrizations for Muonic τ)

- Theoretical FF measurements use combination of lattice (small recoil), QCD sum rules/light cone sum rules (large recoil)
- Muonic $R(D^{*,+})$ first to use HAMMER/RooHammerModel to implement FF reweighting and template $\pm 1\sigma$ variations
  - HAMMER (Helicity Amplitude Module for Matrix Element Reweighting) an example of software that helps meet computing challenges: already difficult to generate enough MC to fit assuming SM, and would be prohibitively difficult to re-generate MC for every NP scenario

$R(D^{*,0})$ Run 1 FF parametrizations (values floated in fit)
$B \to D$: BCL PRD 92 (2015) 054510
$B \to D^*$: BGL PRD 94 (2016) 094008
$B \to D^{**}$: BLR PRD 95 (2017) 014022

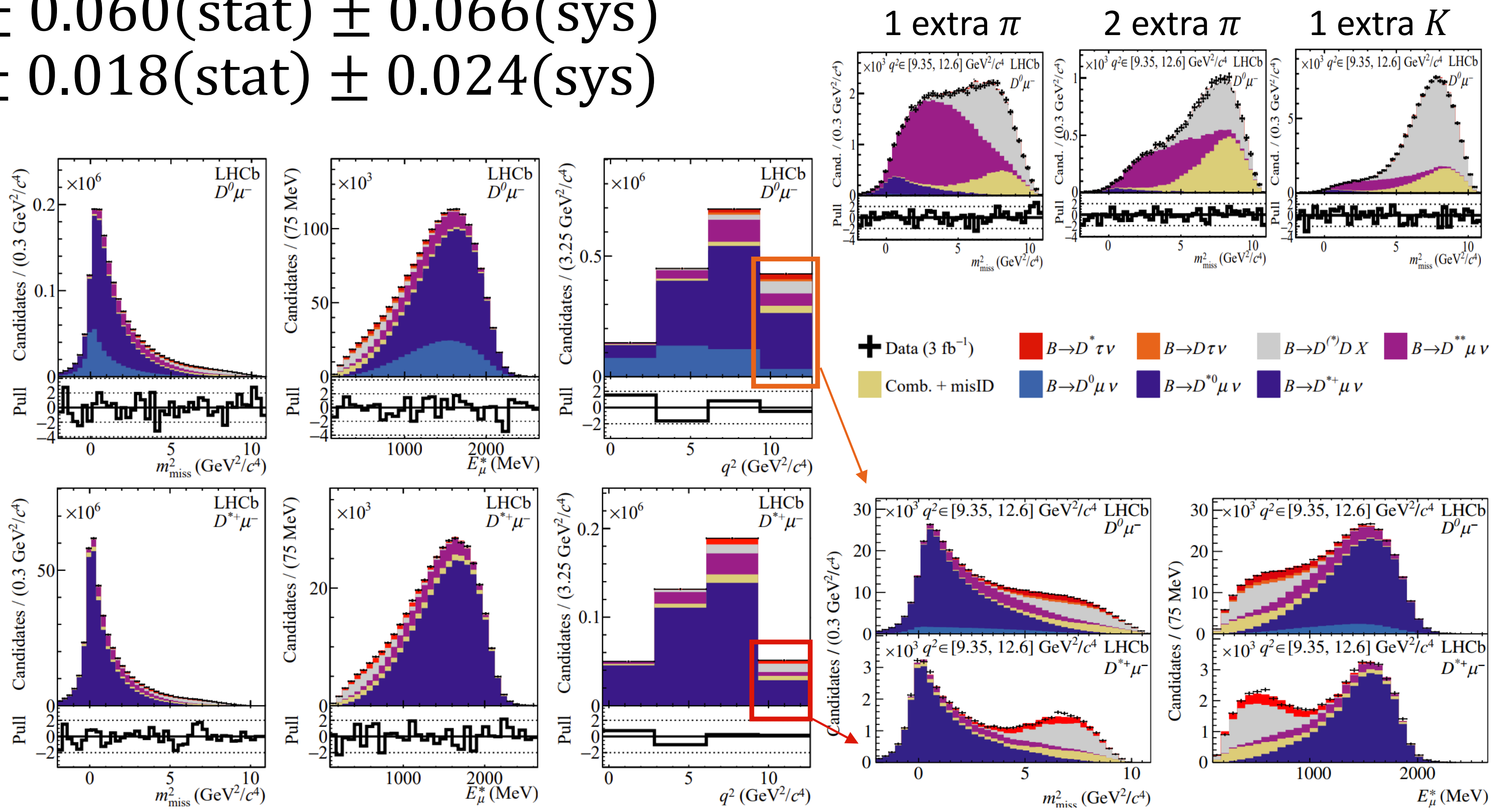
$R(D^{*,+})$ Run 2 FF parametrizations (values floated in fit)
$B \to D$: BGL PRD 94 (2016) 094008
$B \to D^*$: BGL Eur. Phys. J. C 82, 1141 (2022)
$B \to D^{**}$: BLR PRD 95 (2017) 014022

Run 1 Muonic $R(D^{*,0})$: Results

$$R(D^0) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{sys})$$
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.024(\text{sys})$$

- 2 fitters used for added consistency check
- Main systematics due to DD modeling, FFs, size of simulated samples
  - Scale with data

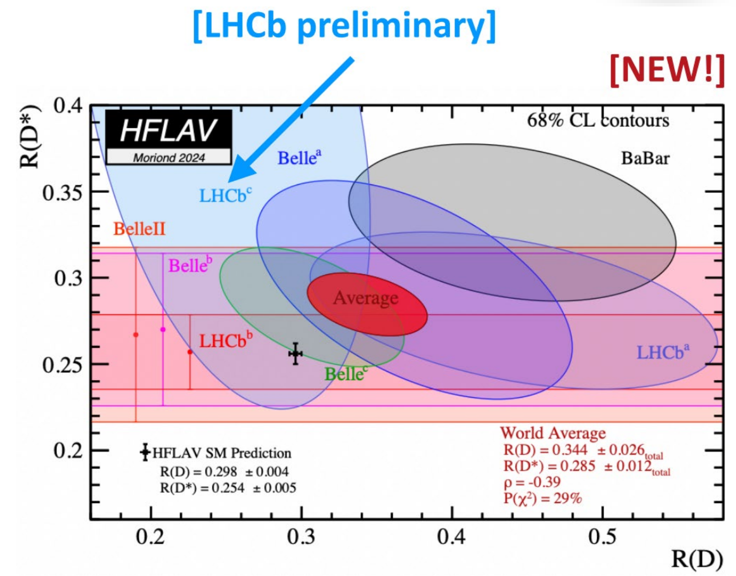
Good agreement in control samples too!

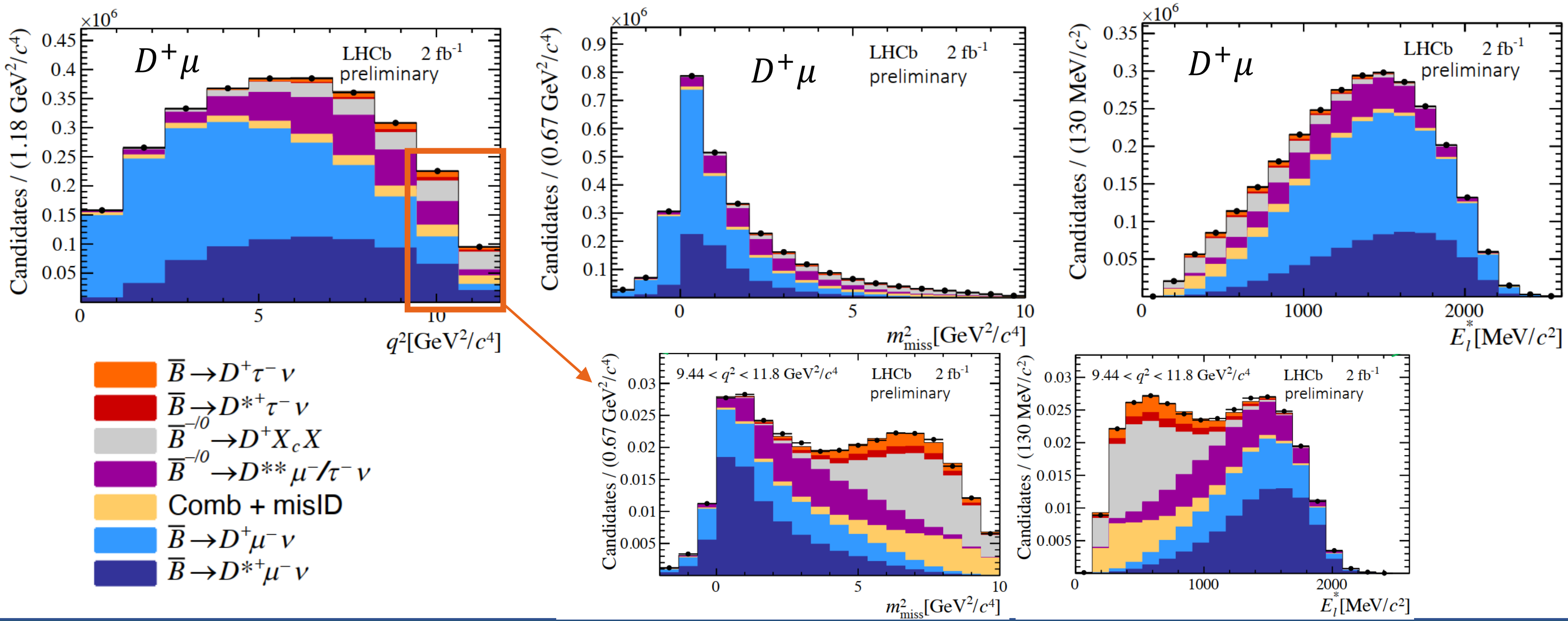


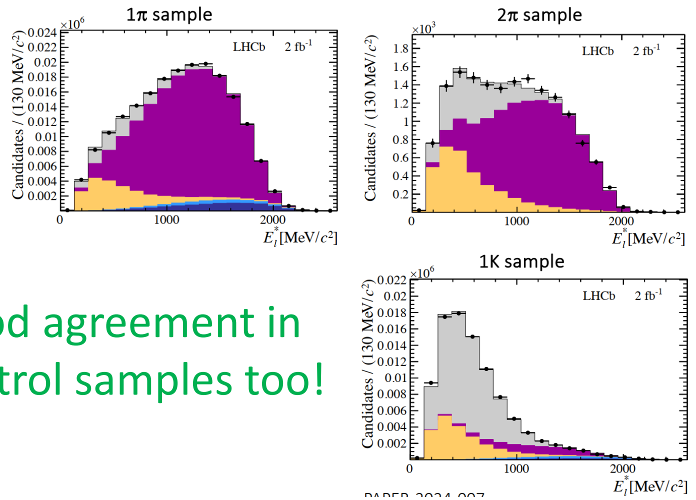
Run 2 Muonic $R(D^{*,+})$: Results

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

- Similar to $R(D^{*,0})$, main systematics due to DD modeling, FFs, size of simulated samples







Good agreement in control samples too!

Systematic Uncertainties for Muonic τ

- $R(D^{*+,0})$

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}$ $(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}$ $(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
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
Total uncertainty	3.0	8.9

- $R(D^{(*)+})$

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^*)$
Form factors	0.023	0.035
$B \to D^{**}$	0.024	0.025
$B \to D^+X_cX$	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