FSP LHCb
Erforschung von Universum und Materie

Bundesministerium für Forschung, Technologie und Raumfahrt

dortmund university

color meets flavor

Wilson coefficient measurement with $B^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ angular analyses

Tobias Knospe

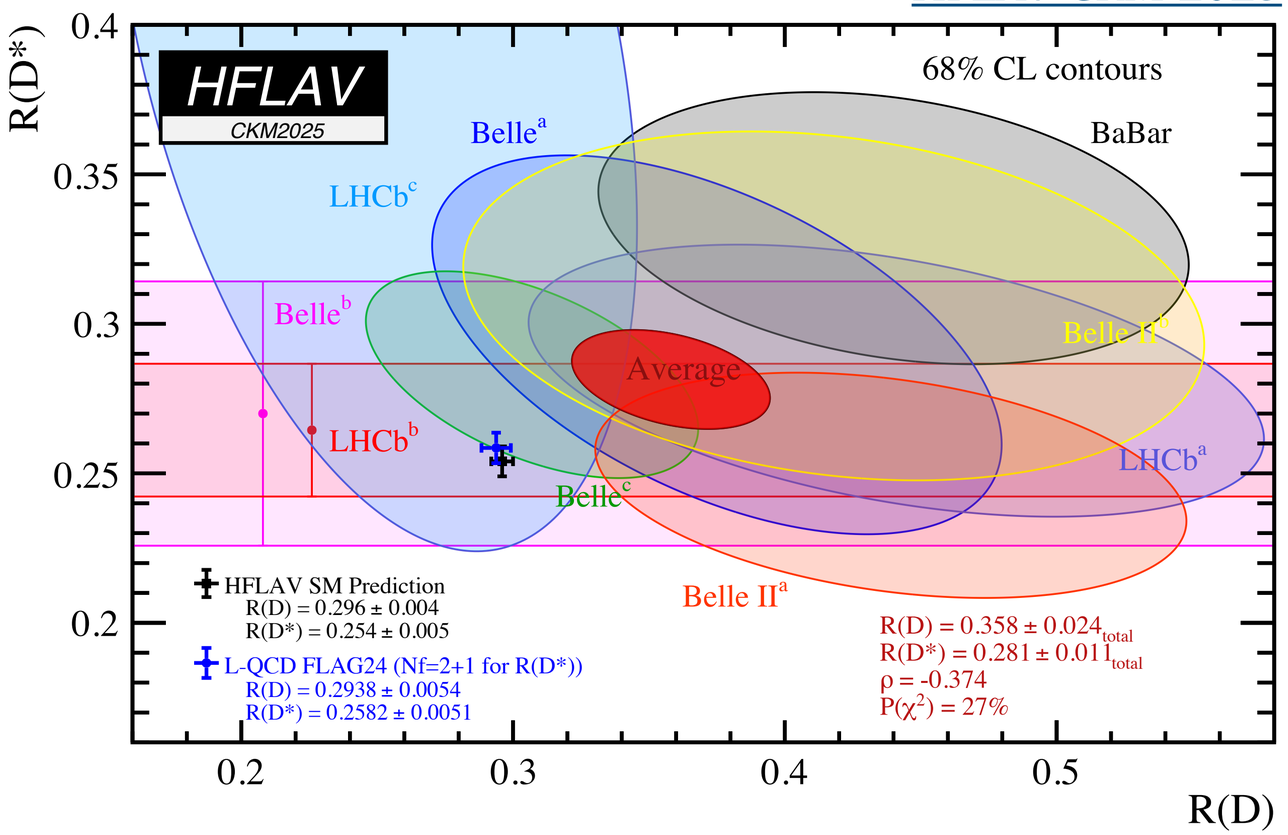
Motivation

- Semileptonic B decays provide test bench for **Lepton Flavour Universality**
- Ratios of branching fractions is one choice to test LFU:

$$R(D^{(*)}) = \frac{BF(B^0 \to D^{(*)}\tau\nu)}{BF(B^0 \to D^{(*)}\mu\nu)}$$

- **3.8σ tension** in $R(D)$ and $R(D^*)$ measurement with SM prediction
- Measuring angular distributions is a sensitive **test for New Physics**

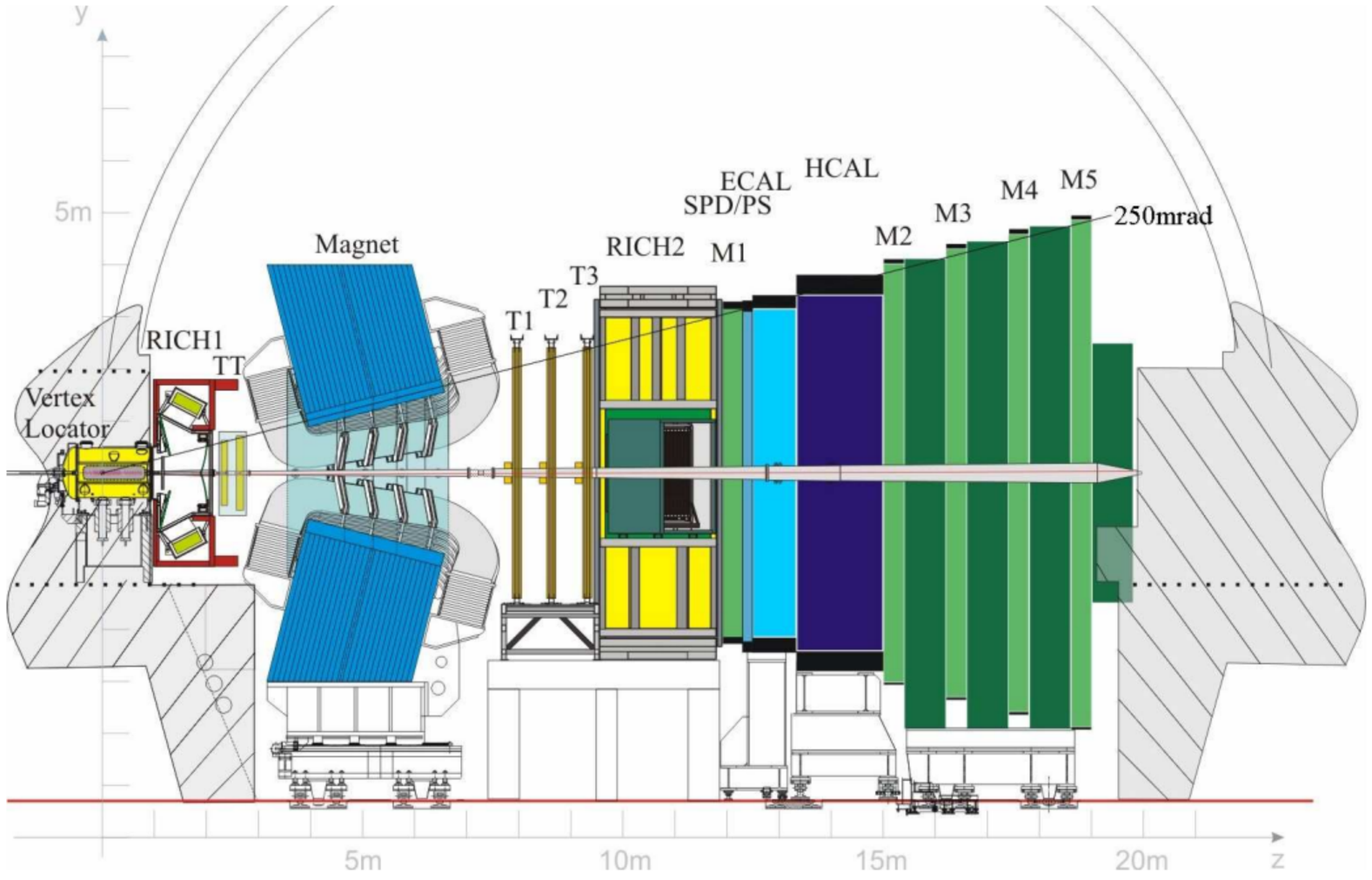
HFLAV CKM 2025



LHCb Detector

JINST 3 S08005 (2008)

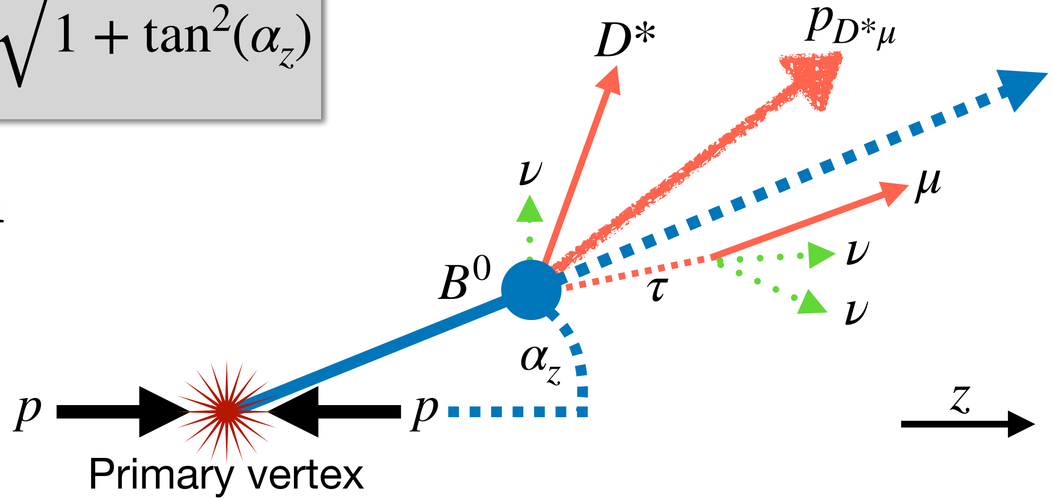
- Single-arm forward spectrometer
  - Covering forward region ($\eta \in 2-5$)
- **Proton-proton** collisions at $\sqrt{s} = 13\,\text{TeV}$
- Optimised for B**-meson** reconstruction



Challenges at LHCb

- Missing momentum from neutrinos
  - No simple B rest frame reconstruction
  - Resolution degradation
  - Large backgrounds

- B rest frame approximation: $$|p_B| = \frac{m_B}{m_{D^*\mu}} p^z_{D^*\mu} \sqrt{1 + \tan^2(\alpha_z)}$$
  - Combined with B meson flight direction



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- Full quadratic equation:
  one neutrino → two-fold ambiguity
  JHEP 2012 21 (2017)

$$p^{\pm} = p^{\parallel}_{D^*\mu} - a \pm \sqrt{r}$$

$$a = \frac{p^{\parallel}_{D^*\mu}(m^2 - m^2_{D^*\mu} - 2(p^{\perp}_{D^*\mu})^2)}{2((p^{\perp}_{D^*\mu})^2 - E^2_{vis})}$$

$$r = \frac{E^{\parallel}_{D^*\mu}(m^2 - m^2_{D^*\mu} - 2(p^{\perp}_{D^*\mu})^2)}{4((p^{\perp}_{D^*\mu})^2 - E^2_{vis})^2} + \frac{(E_{D^*\mu}p^{\perp}_{D^*\mu})^2}{(p^{\perp}_{D^*\mu})^2 - E^2_{vis}}$$

  - Selecting random solution
  - Linear regression arxiv:1611.08522v2

Challenges at LHCb

- Missing momentum from neutrinos
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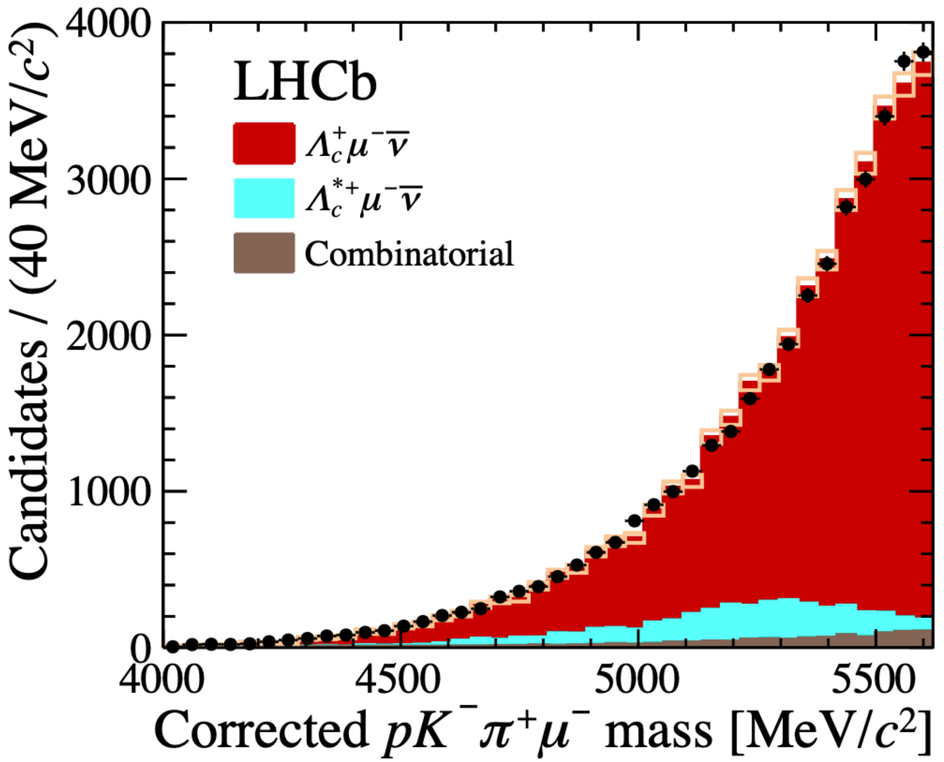
  - Resolution degradation
  - Large backgrounds

- Broad signal distributions
  - Reconstructed distributions are significantly smeared
  - No peaking signal structure



Nat. Phys. 11 (2015) 743-747

Challenges at LHCb

- Missing momentum from neutrinos
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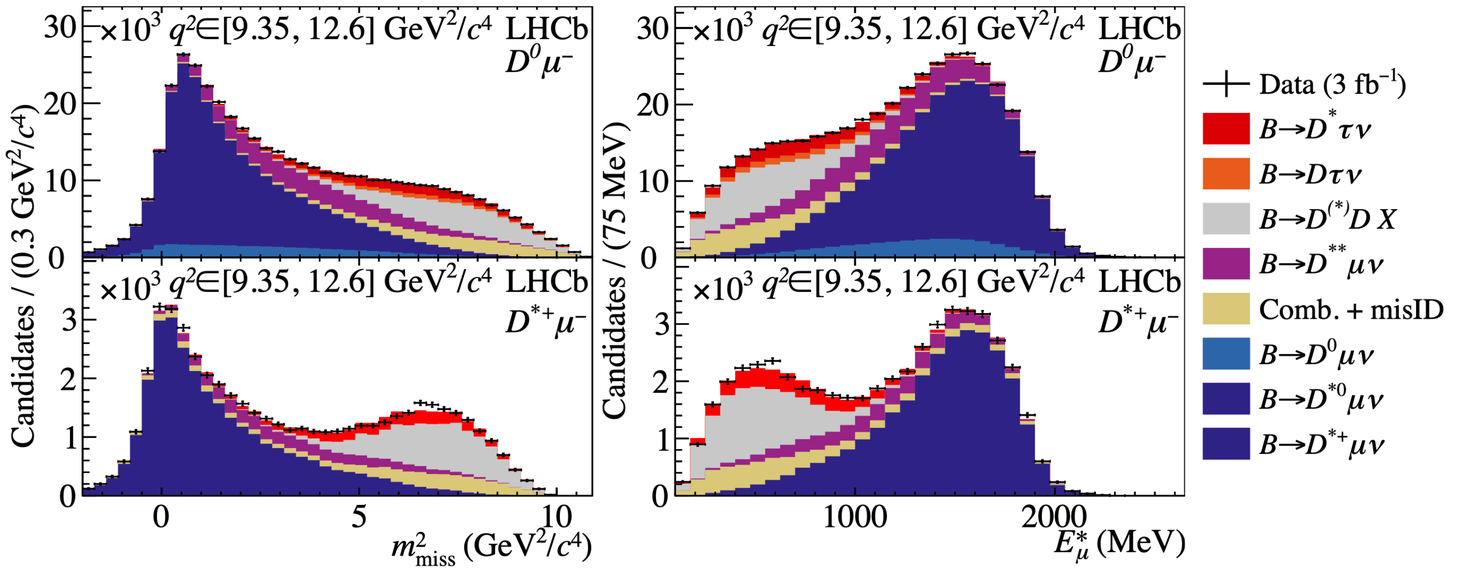
- Background contamination from underconstrained kinematics
  - Must be modelled precisely



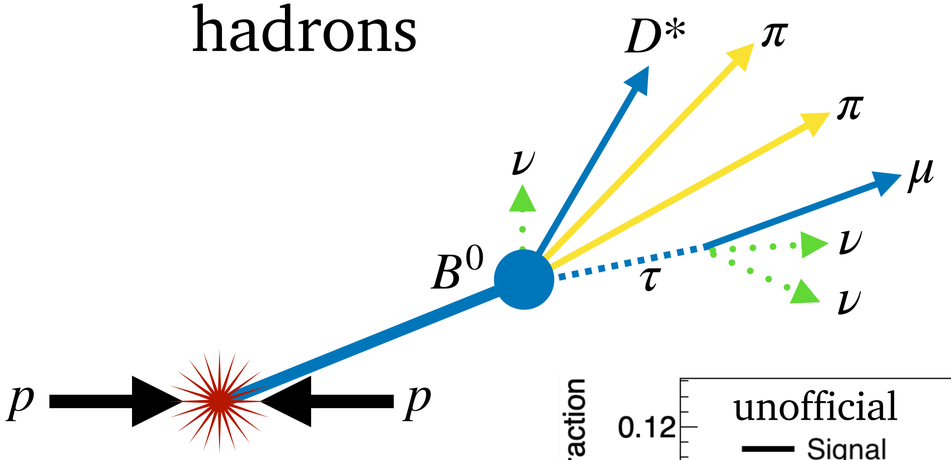
PRL 131 (2023) 111802

Backgrounds

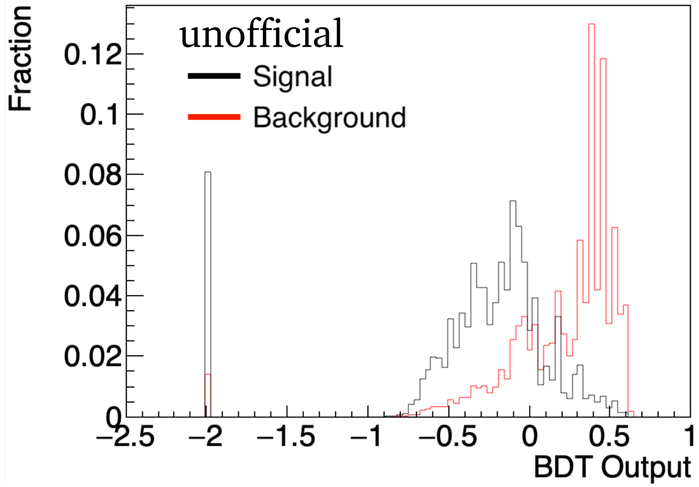
- Usually modelled with simulation
  - Decays to heavier charmed hadrons
    $B \to D^{**}(\to D^{*}\pi\pi)\ell\nu$
  - Double charm backgrounds
    $B \to D^{*}H_c X$

- Data derived
  - Misidentified hadrons
  - Combinatorial backgrounds

- Use of charged and neutral isolation
  - Classification of heavier charm hadrons

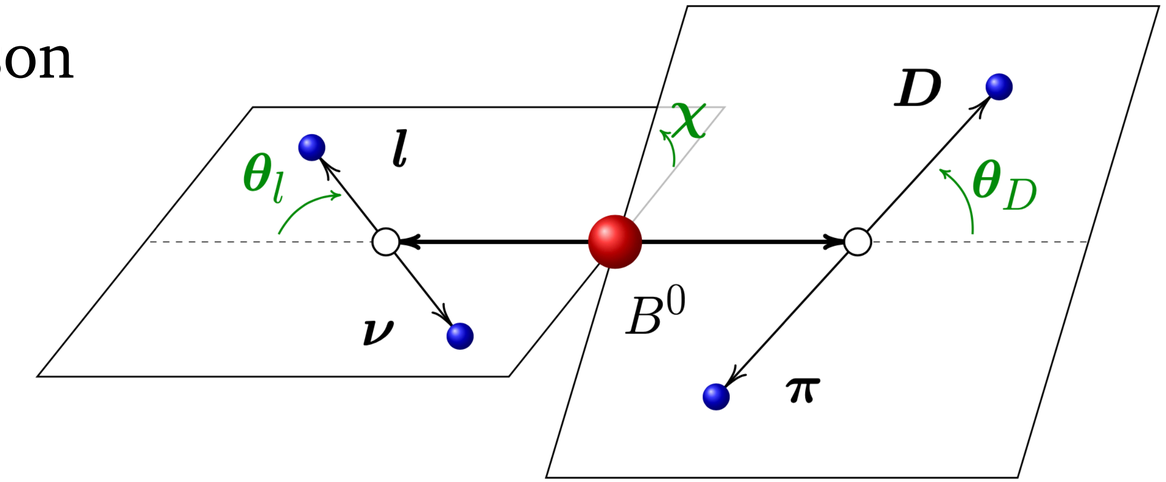


[PRL 120 (2018) 121801]
[PRL 128 (2022) 191803]
[PRL 131 (2023) 111802]



Angular Analysis

- θ_l: Angle between the **lepton** and the B meson in the lepton system rest frame
- θ_D: Angle between the D **meson** and the B meson in the D^* rest frame
- χ: Angle between the two decay planes



- $q^2 = \left(p_B - p_{D^*}\right)^2$
  - Momentum transfer onto the **lepton system**
- $m^2_{miss} = \left(p_B - p_{D^*} - p_l\right)^2$
  - **Missing energy** from the neutrino

- **5D template** fit to: $\cos\theta_l, \cos\theta_D, \chi, q^2, m^2_{miss}$
- θ_l, θ_d, χ and q^2 **enter directly** in the differential decay rate $d\Gamma$
- $m^2_{miss} \rightarrow$ **background rejection**

Hadronic Form Factors

- Measurement of decay rate → access to NP Wilson coefficients
  - Semi-leptonic final state → non-perturbative low-energy QCD effects enter decay rate

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2} = \frac{G_F^2|V_{cb}^2||\eta_{EW}|^2|\vec{p}|^2q^2}{96\pi^3 m_{B0}^2}\left(1-\frac{m_\ell^2}{q^2}\right)\times\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1-\frac{m_\ell}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

$$H_0 = \frac{\mathcal{F}_1(w)}{m_B\sqrt{1+r^2+2wr}}$$
$$H_\pm = f(w) \mp m_B m_{D^*}\sqrt{w^2-1}g(w)$$
$$H_t = m_B\frac{\sqrt{r}(1+r)\sqrt{w^2-1}}{\sqrt{1+r^2-2wr}}\mathcal{F}_2(w)$$
with $r = m_{D^*}/m_B$

- Helicity amplitudes $H_0, H_\pm, H_t$ need approximation
  - Constrain long distance hadronic effects (form factors) and short distance Wilson coefficients
- Many parameterisation available, using different assumptions
  - BGL PRL 74 4603 (1995), BLPR PRD 95, 115008 (2017), CLN Nucl. Phys. B 530 1 (1998), …

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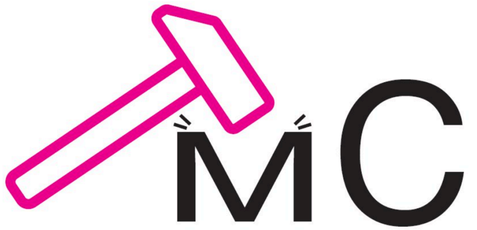
HAMMER arXiv:2002.00020

- Tool for **reweighting simulated events** to different New Physics scenarios and/or form factor parameterisations
- **Generating NP samples** without running full simulation chain



Helicity Amplitude Module
for Matrix Element Reweighting

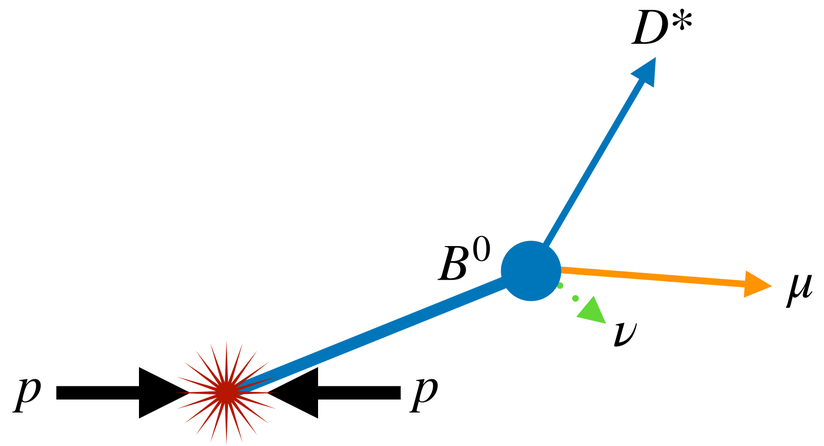
Weight ω_i is calculated for each event i:

$$\omega_i = \frac{\Gamma^i_{old}}{\Gamma^i_{new}} \frac{d^n\Gamma^i_{new}/dx}{d^n\Gamma^i_{old}/dx}$$

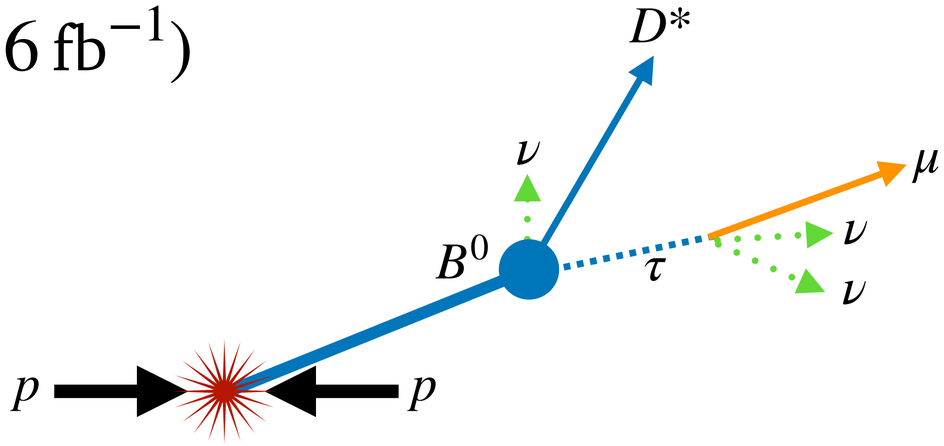
were Γ^i_{old} is the decay rate for the model implemented in the simulation,
Γ^i_{new} is the decay rate for the updated model

$B^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ Angular Analyses

- $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ with LHCb Run 1 data ($3\,\text{fb}^{-1}$)
  - Hadronic form factor parameters
    - CLN(SM), BGL(SM), BLPR
  - NP Wilson coefficients (5 scenarios)

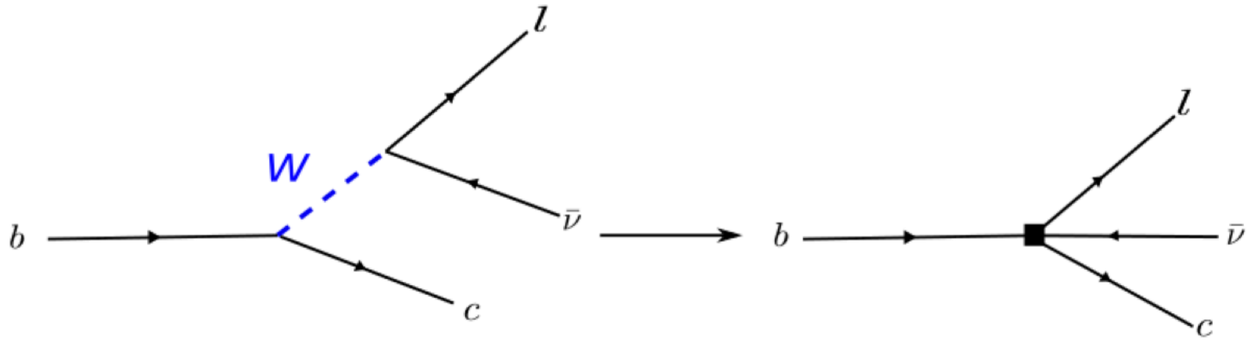


- $B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ with LHCb Run 2 (2016) data ($1.6\,\text{fb}^{-1}$)
  - Hadronic form factor parameters
    - BGL(SM), BLPR
  - NP Wilson coefficients (1* scenario)



New Physics

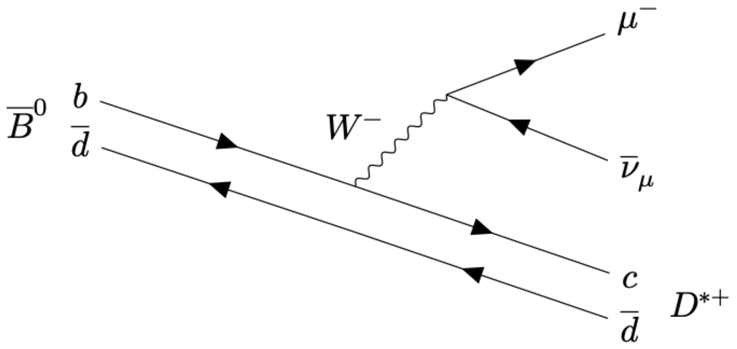
- Effective Field Theory (EFT) approach
  - Heavy intermediate particles are integrated out
  - Effective 4-fermion couplings



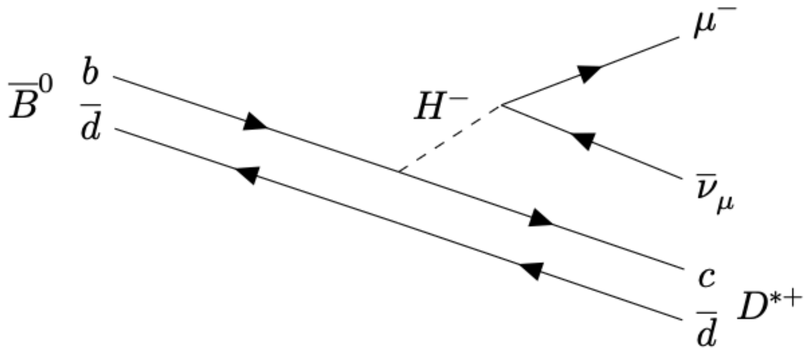
$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \sum C_i O_i \quad \text{,with } C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

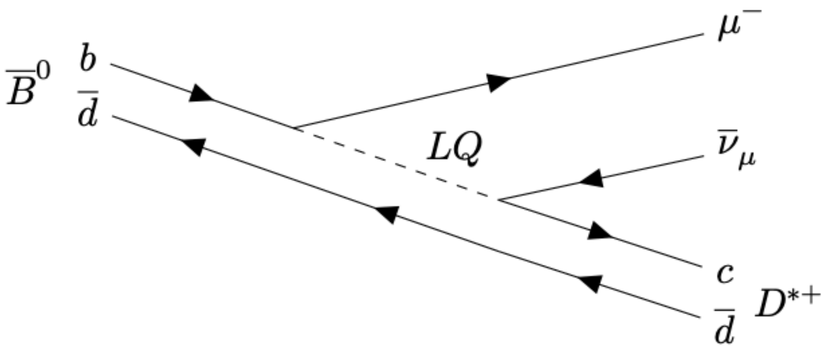
- Wilson coefficients C_i describe NP contribution
- Wilson operators O_i describe spin structure

Standard Model



New Physics





$B^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ Angular Analyses

- Reparameterisation in multi-parameter scenarios [EPJC 81 984 (2021)](#)
  - ~~$C_S = S_{qRlL} + S_{qLlL}$~~ , $C_P = S_{qRlL} - S_{qLlL}$
    $C_V = V_{qRlL} + V_{qLlL}$, $C_A = V_{qRlL} - V_{qLlL}$
  - Fix one imaginary part since overall phase is not observable

- $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ (5 scenarios)
  - 3 Single WC fits: S_{LL} , V_{RL} , T_{LL}
  - $\mathfrak{R}(S_{LL})$, $\mathfrak{R}(V_{RL})$, $\mathfrak{R}(T_{LL})$
  - C_P , V_{RL} , $\mathfrak{R}(T_{LL})$
    (with T_{LL} positive)

- $B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ (1* scenario)
  - $\mathfrak{R}(C_P)$, $\mathfrak{R}(C_V)$, $\mathfrak{R}(C_A)$, $\mathfrak{R}(T_{LL})$

NP currents in HAMMER

Current	C_i	O_i
SM	1	$[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu]$
Vector	V_{qLlL}	$[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu]$
	V_{qRlL}	$[\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_L \nu]$
	V_{qLlR}	$[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_R \nu]$
	V_{qRlR}	$[\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_R \nu]$
Scalar	S_{qLlL}	$[\bar{c}P_L b][\bar{\ell}P_L \nu]$
	S_{qRlL}	$[\bar{c}P_R b][\bar{\ell}P_L \nu]$
	S_{qLlR}	$[\bar{c}P_L b][\bar{\ell}P_R \nu]$
	S_{qRlR}	$[\bar{c}P_R b][\bar{\ell}P_R \nu]$
Tensor	T_{qLlL}	$[\bar{c}\sigma^{\mu\nu} P_L b][\bar{\ell}\sigma_{\mu\nu} P_L \nu]$
	T_{qRlR}	$[\bar{c}\sigma^{\mu\nu} P_R b][\bar{\ell}\sigma_{\mu\nu} P_R \nu]$

Common Analysis Strategy

- Selection and neutrino reconstruction
- Correct for data/simulation-differences
- Signal, normalisation and D^{**} backgrounds are **reweighted using HAMMER**
- Produce **5D fit templates** ($\cos\theta_l$, $\cos\theta_d$, χ, q^2 and m^2_{miss})
  - Signal and most background **shapes from simulation**
  - **MisID** and **Combinatorial** shapes are **data derived**

- Binned templated maximum likelihood fit with RooFit interfaced with HAMMER
  - Extract **hadronic form factors** and **Wilson coefficients** (blinded)
    - NP only modelled in the **signal channel** (maximally LFU violating)

Data/Simulation Correction

- Signal and most background shapes are modelled with Monte Carlo simulation
- Simulation can be improved by reweighting mismodelled parameters

1. Initial reweighting of B production kinematics
2. Reweighting of final state particle kinematics
3. Corrections to the soft pion from the $D^{*+} \to D^0 \pi^+$ decay
4. Account for different simulation versions

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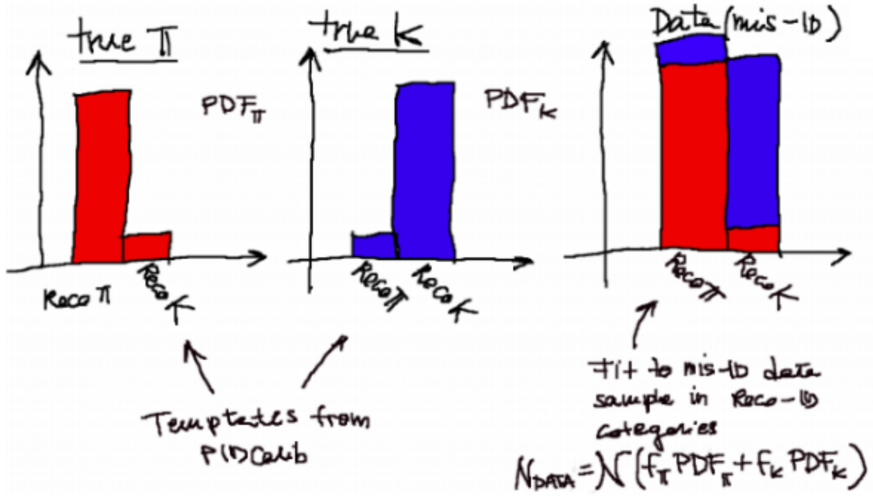
Data Derived Backgrounds

- **MisID**
  - sample of $B \to D^* h^{\pm}$ with **same selection** as the signal except **inversed muon ID** requirements
  - PID information is used to decompose the sample in 5 categories (π, K, p, e, g)
  - Yields are measured for all categories using PID efficiencies
- **Combinatorial**
  - Same sign combinations of D^* and μ
  - Fake D^* from D^0 combined with a wrong sign π



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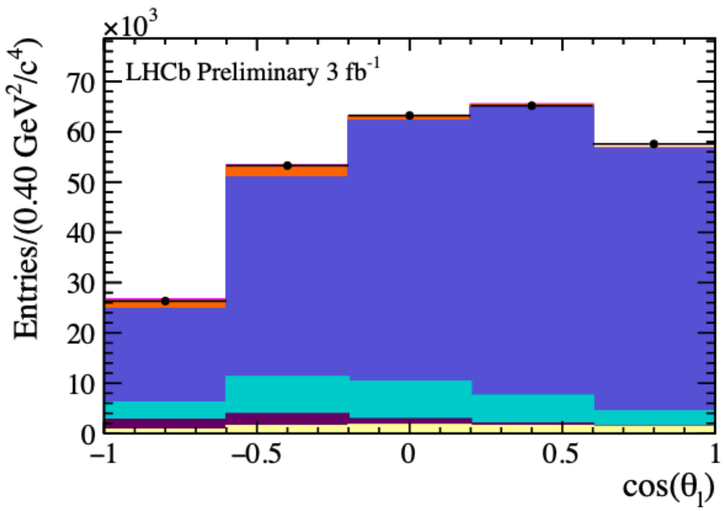
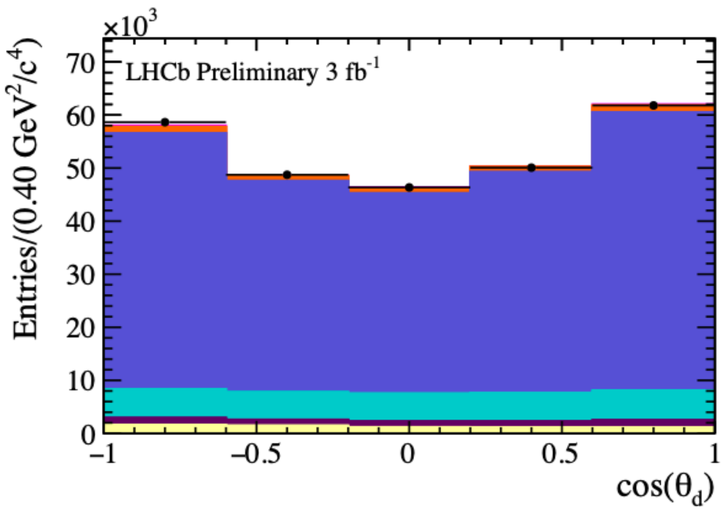
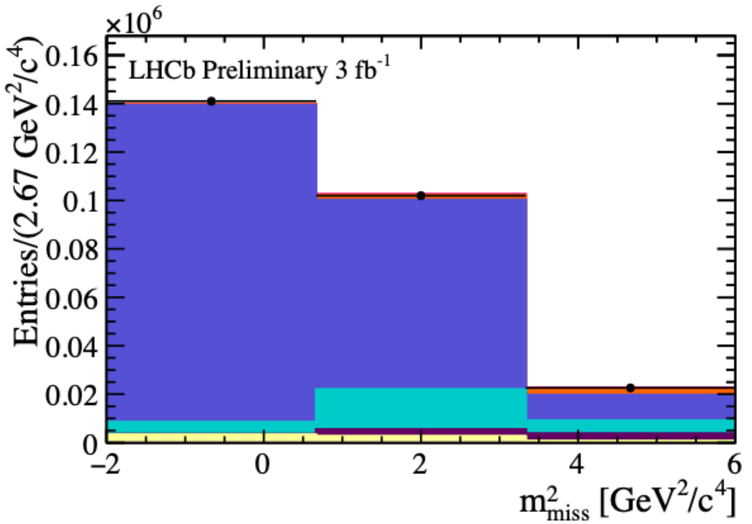
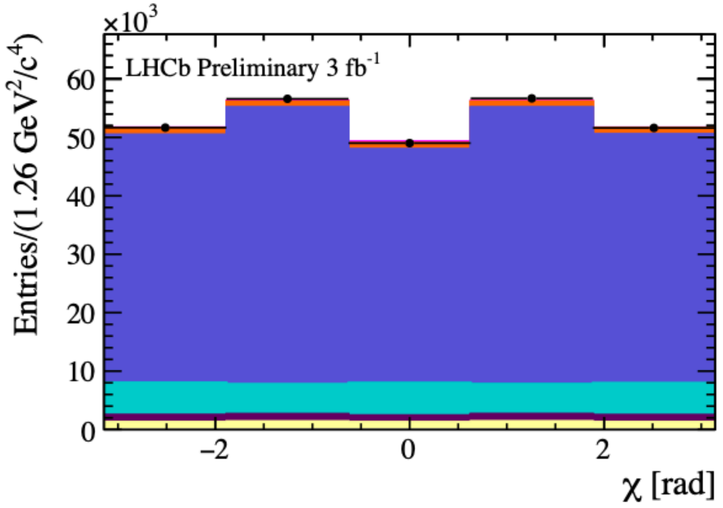
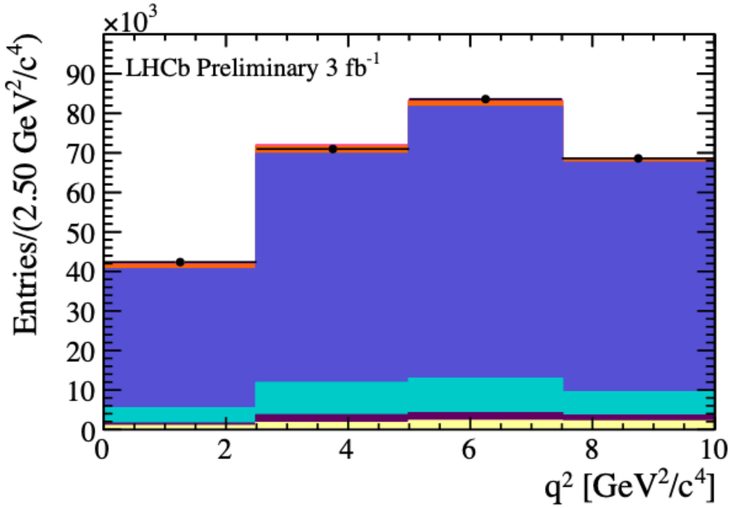
$B^0 \to D^*\mu\nu$ Angular Analysis

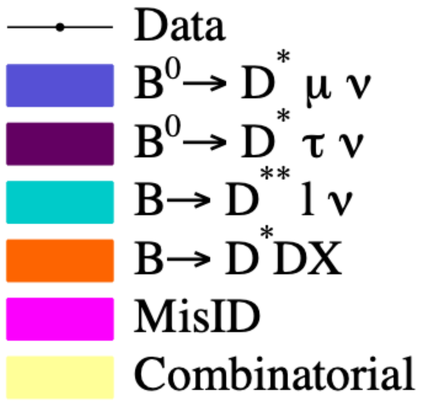












LHCb-CONF-2026-001

$B^0 \to D^*\mu\nu$ — Systematic uncertainties

- **Data/MC correction**
  - Simulation is reweighted to account for differences in PID and kinematic distributions
    - Data is fitted with a second iteration of weights generation
- **BGL series truncation**
  - Model that minimises the Bayesian Information Criterion (BIC)

$$\mathrm{BIC} = \chi^2 + k\ln(n)$$

Fit quality χ^2, sample size n, number of parameters k

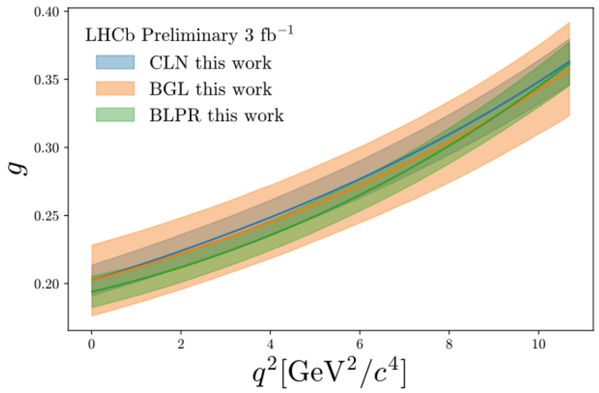
    - Maximum residual of the two next best models is assigned as systematic uncertainty
- **Simulation sample size**
  - Fitting with bootstrapped samples

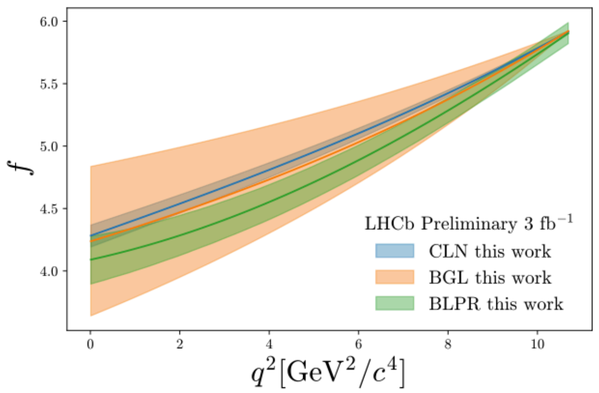
$B^0 \to D^*\mu\nu$ — Systematic Uncertainties

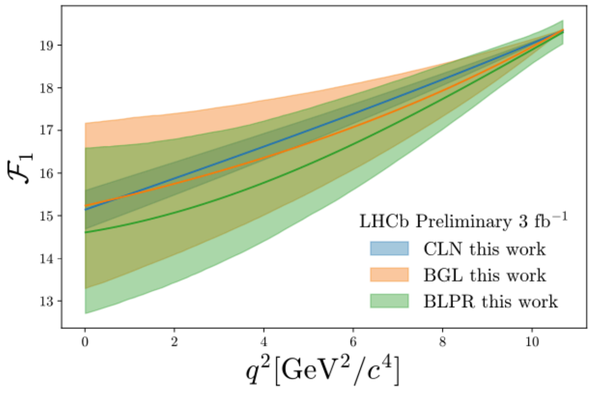
- **NP from backgrounds**
  - NP is injected in $B \to D^*\tau\nu$ template
- **MisID shape**
  - Shape variation is expected due to pion and kaon decays in flight
    - Effect is estimated from simulation
  - Ghost misID efficiency is poorly modeled in simulation
    - Efficiency is varied within its uncertainty
- **Modelling of double charm and D^{**} higher excited states**
  - Use alternative shapes in the fit model PRL 131 (2023) 111802
- **Coulomb corrections**
  - Applying weights according to reference arXiv:1803.05881v3
- **Fixed parameters in the fit model**
  - Pseudodata fitted with alternative model

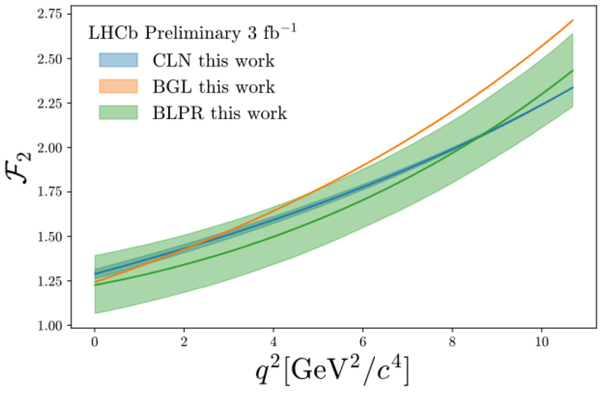
$B^0 \to D^*\mu\nu$ — SM Measurement

	CLN			BGL					BLPR				
Systematic source	R_1	R_2	ρ^2	a_0	a_1	b_1	c_1	c_2	$\bar{\rho}^2_*$	$\chi_2(1)$	$\chi_2'(1)$	$\eta(1)$	$\eta(1)'$
Simulation sample size	0.013	0.012	0.016	<0.001	0.019	0.004	0.001	0.022	0.024	0.087	0.15	0.10	0.42
Simulation corrections	0.047	0.029	0.018	0.002	0.010	0.030	0.004	0.005	0.025	0.27	0.15	0.34	0.18
BGL truncation	–	–	–	<0.001	0.017	0.006	<0.001	0.004	–	–	–	–	–
Fixed d_i parameters	–	–	–	<0.001	0.005	<0.001	<0.001	0.009	–	–	–	–	–
Fixed b_0 parameter	–	–	–	<0.001	0.003	<0.001	<0.001	0.004	–	–	–	–	–
Fixed R_0 parameter	0.001	0.001	0.003	–	–	–	–	–	–	–	–	–	–
Fixed χ_3' parameter	–	–	–	–	–	–	–	–	<0.001	0.034	0.016	0.018	0.090
MisID model	0.004	0.001	0.001	<0.001	0.016	<0.001	<0.001	0.010	0.001	0.018	0.003	0.032	0.005
Physics bkg. model	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.002	0.002	0.006
Coulomb correction	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.002	0.005	0.006
Total systematic	0.049	0.031	0.030	0.002	0.031	0.031	0.007	0.026	0.04	0.29	0.21	0.36	0.47
Stat. uncertainty	0.032	0.014	0.020	0.001	0.022	0.004	0.001	0.026	0.03	0.12	0.18	0.14	0.52



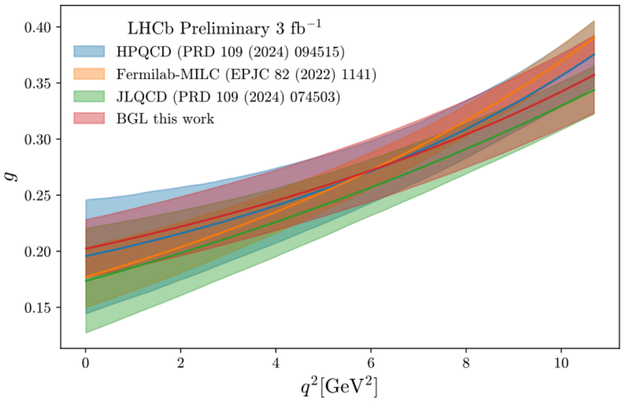


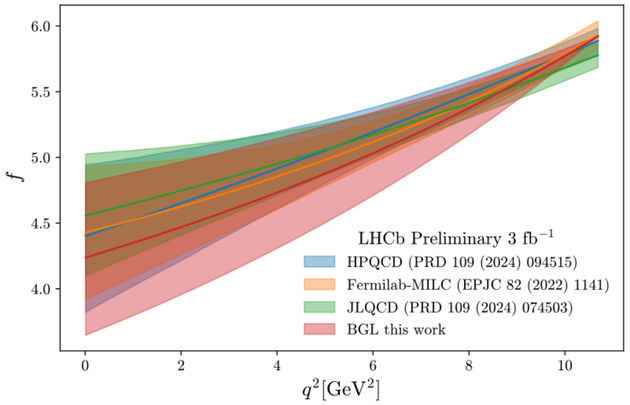


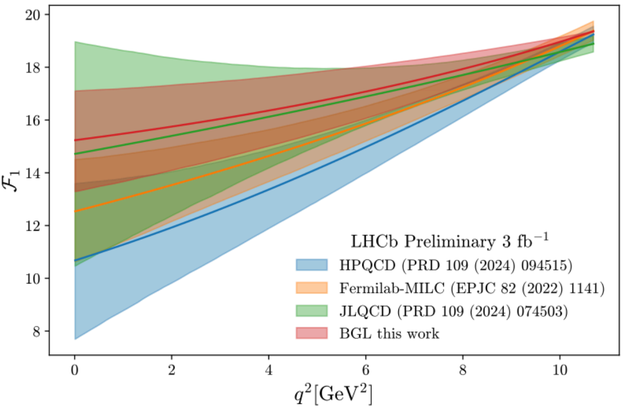


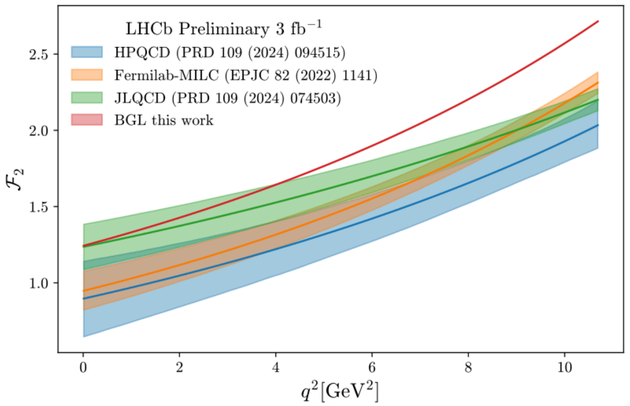
$B^0 \to D^*\mu\nu$ — SM Measurement

- Comparison with **lattice QCD** calculations

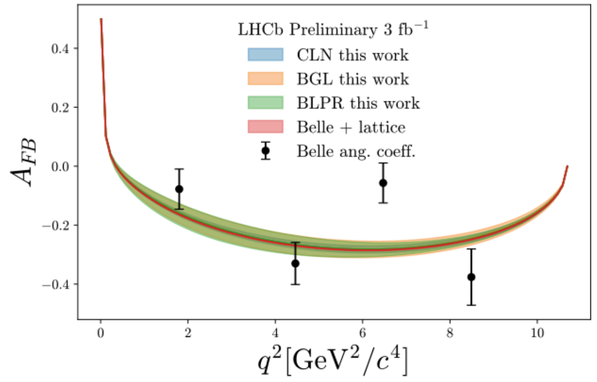


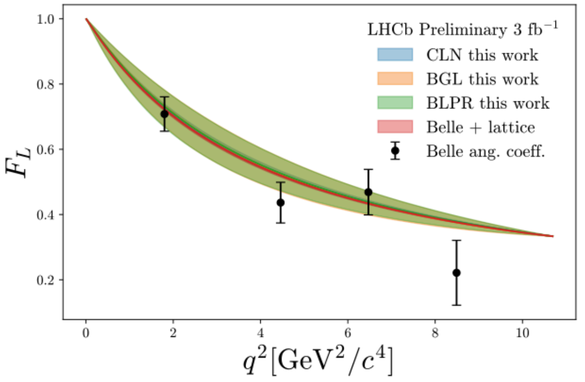


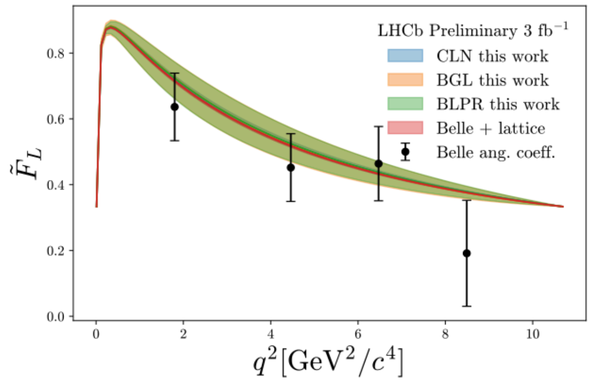




- Forward-backward asymmetry (A_{FB})
- Longitudinal muon polarisation ($\tilde{F}_L$)
- Longitudinal D^* polarisation (F_L)







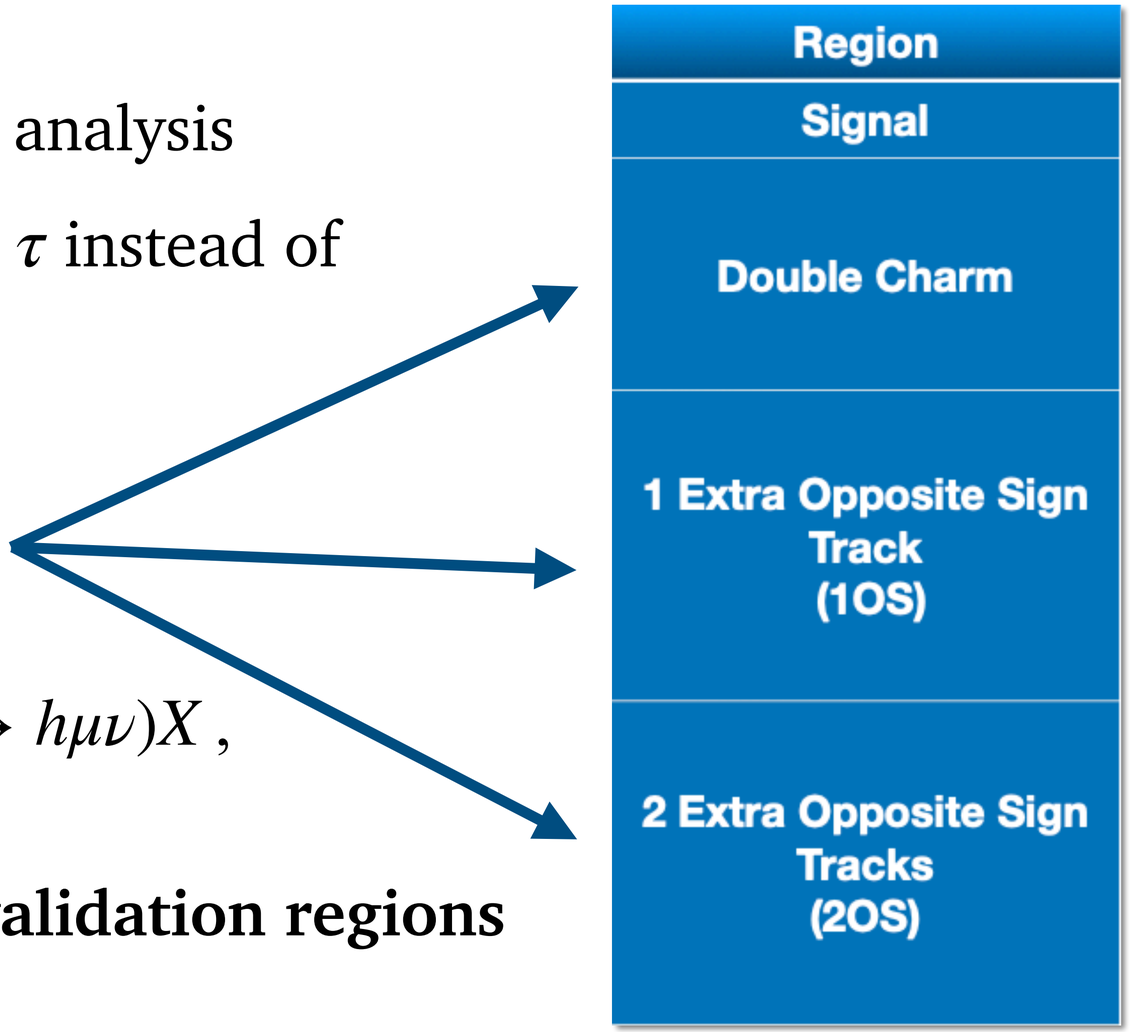
$B^0 \to D^*\mu\nu$ — NP Measurement

- Publication of **NP scenarios follows** soon:
  - 3 Single WC fits: S_{LL} , V_{RL} , T_{LL}
  - $\mathfrak{R}(S_{LL})$, $\mathfrak{R}(V_{RL})$, $\mathfrak{R}(T_{LL})$
  - C_P , V_{RL} , $\mathfrak{R}(T_{LL})$ (with T_{LL} positive)

- In all NP scenarios the **WCs are measured together with the hadronic form factor** parameters

$B^0 \to D^*\tau\nu$ Angular Analysis

- **Independent** from the $B^0 \to D^*\mu\nu$ angular analysis
- **Different data set** and **selection** (enriching τ instead of rejecting them)
- Backgrounds need much more control
  - Simultaneous fit with **3 control regions** enriched with specific backgrounds
  - **Additional form factors** for $B \to D(D \to h\mu\nu)X$, $B \to (D^{**} \to D^*\pi\pi)\mu\nu$, MisID
  - Background templates are studied in **6 validation regions**



$B^0 \to D^*\tau\nu$ — Systematic Uncertainties

- Analysis is still **work in progress** in LHCb
  - **Systematic uncertainty sources** similar to the $B \to D^*\mu\nu$ angular analysis
    - Additional sources due to template modelling
- Publication is planned for:
  - $R(D^*)$ in SM scenario
  - NP scenario with:
    - $\mathfrak{R}(C_P)$, $\mathfrak{R}(C_V)$, $\mathfrak{R}(C_A)$, $\mathfrak{R}(T_{LL})$

- Simulation sample size
- Data/MC corrections
- MisID shape
- Coulomb corrections
- Fixed parameters in the fit model
  - Additionally:
  - Combinatorial modelling
  - Vertex resolution smearing
  - Fake D* removal
  - B_s to D_s** FFs

Outlook

- Measurement of **hadronic form factors**
  - Improved modelling of QCD effects
  - BLPR just once measured outside Belle (II)
- Precise **Wilson coefficient measurement** will give insight into the observed tension

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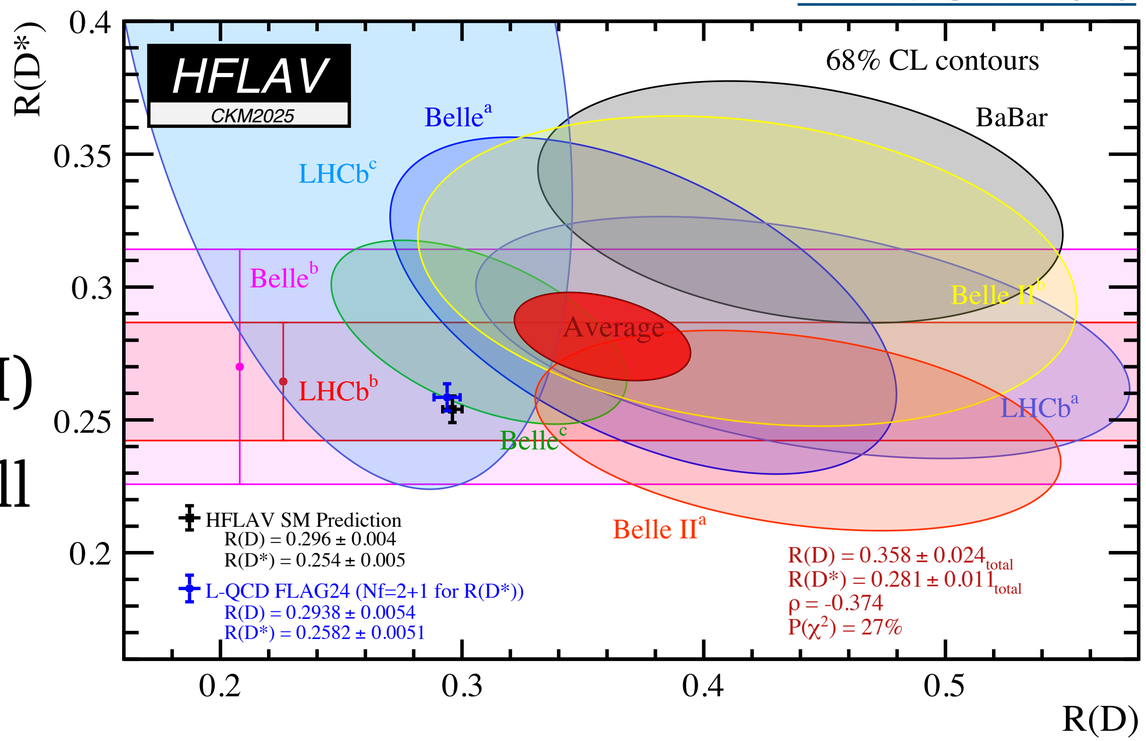

Back-Up

Complete Differential Decay Width

$$\frac{\mathrm{d}^5\Gamma}{\mathrm{d}q^2\mathrm{d}m_{D^*}\mathrm{d}\cos\theta_D\mathrm{d}\cos\theta_l\mathrm{d}\chi} = \frac{1}{128(2\pi)^6 m_B^2}|q|\left(1-\frac{m_l^2}{q^2}\right)\frac{|\hat{p}_D|}{m_{D^*}}|M(B^0\to D^* l\nu_l)|^2,$$

$$\begin{aligned}
|M(B^0\to D^* l\nu_l)|^2 = N|gD^*D\pi|^2|\hat{p}_D|^2|B\tilde{W}_{D^*}|^2 \times \Big[&(|H_+|^2+|H_-|^2)\\
&\left(1+\cos^2\theta_l+\frac{m_l^2}{q^2}\sin^2\theta_l\right)\sin^2\theta_D + 2(|H_+|^2-|H_-|^2)\cos\theta_l\sin^2\theta_D\\
&+4|H_0|^2\left(1+\frac{m_l^2}{q^2}\right)\sin^2\theta_l\sin^2\theta_D + 4|H_t|^2\frac{m_l^2}{q^2}\cos^2\theta_D\\
&-2\beta_l^2(\mathrm{Re}(H_+H_0^*)\cos 2\chi + \mathrm{Im}(H_+H_0^*-H_-H_0^*)\sin 2\chi)\sin^2\theta_l\sin^2\theta_D\\
&-\beta_l^2\left(\mathrm{Re}\left(H_+H_0^*+H_-H_0^*-\frac{m_l^2}{q^2}(H_+H_t^*+H_-H_t^*)\right)\cos\chi\right.\\
&\left.+\mathrm{Im}\left(H_+H_0^*+H_-H_0^*-\frac{m_l^2}{q^2}(H_+H_t^*-H_-H_t^*)\right)\sin\chi\right)\sin\theta_l\sin^2\theta_D\\
&+8\mathrm{Re}(H_0H_t^*)\frac{m_l^2}{q^2}\cos\theta_l\cos^2\theta_D\Big],
\end{aligned}$$

$B^0 \to D^* \mu \nu$ — Correlations

CLN parametrisation

		Statistical correlations			
			R_1	R_2	ρ^2
R_1	1.303 ± 0.032 (stat) ± 0.049 (syst)	R_1	1.000	0.66	-0.61
R_2	0.859 ± 0.014 (stat) ± 0.031 (syst)	R_2		1.000	-0.77
ρ^2	1.211 ± 0.020 (stat) ± 0.030 (syst)	ρ^2			1.000

BGL parametrisation

		Statistical correlations					
			a_0	a_1	b_1	c_1	c_2
a_0	0.026 ± 0.001 (stat) ± 0.002 (syst)	a_0	1.000	-0.91	0.50	0.35	-0.27
a_1	-0.039 ± 0.022 (stat) ± 0.031 (syst)	a_1		1.000	-0.56	-0.23	0.15
b_1	-0.008 $\pm$ 0.004 (stat) $\pm$ 0.031 (syst)	b_1			1.000	0.58	-0.48
c_1	-0.001 ± 0.001 (stat) ± 0.007 (syst)	c_1				1.000	-0.97
c_2	0.019 ± 0.026 (stat) ± 0.026 (syst)	c_2					1.000

BLPR parametrisation

		Statistical correlations					
			$\bar{\rho}^2_*$	$\chi_2(1)$	$\chi_2'(1)$	$\eta(1)$	$\eta(1)'$
$\bar{\rho}^2_*$	1.28 ± 0.03 (stat) ± 0.04 (syst)	$\bar{\rho}^2_*$	1.000	-0.28	-0.68	-0.27	0.83
$\chi_2(1)$	-0.11 ± 0.12 (stat) ± 0.29 (syst)	$\chi_2(1)$		1.000	0.11	-0.68	-0.33
$\chi_2'(1)$	0.38 ± 0.18 (stat) ± 0.20 (syst)	$\chi_2'(1)$			1.000	0.32	-0.85
$\eta(1)$	0.43 ± 0.14 (stat) ± 0.36 (syst)	$\eta(1)$				1.000	-0.38
$\eta(1)'$	-0.52 ± 0.52 (stat) ± 0.47 (syst)	$\eta(1)'$					1.000