Differential measurements with FCCC at LHCb

Implications of LHCb measurements and future prospects 2023

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on behalf of the LHCb Collaboration

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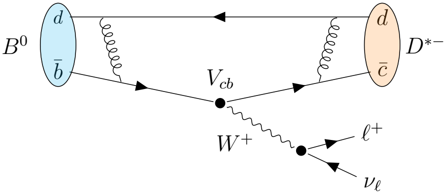
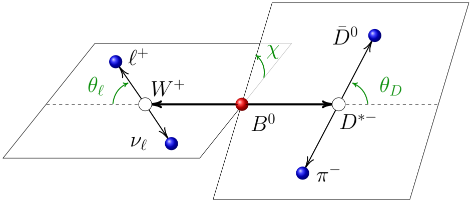
Angular analyses of semileptonic b-hadron decays

- Differential decay rate can be written as:

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

- q^2: squared invariant mass of the $\tau\nu_\tau$ system $\equiv (p_B - p_{D^*})^2$
- $\mathcal{H}_i$: electroweak couplings & QCD form-factors
- f_i: helicity angles distributions, sensitive to New Physics hadronic effects





Angular analyses are good candidates for New Physics search providing complementary information to Lepton Flavour Universality tests (see Florian's talk)

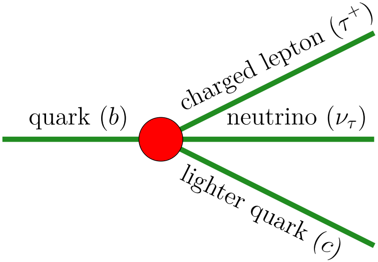
New Physics

- New Physics effects can be described by an effective Hamiltonian consisting in operators with unknown coupling constants

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum_i \mathcal{C}_i \mathcal{O}_i$$

- $\mathcal{O}_i$: effective operators (scalar, vector, tensor)
- $\mathcal{C}_i$: Wilson Coefficients (WC) describing the New Physics effects

$$\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$



- Hammer tool can be used to reweight simulated samples obtaining dynamic templates (Eur. Phys. J. **C80** 883 (2020))

- Different strategies can be considered:
  - Measure directly WC parameters
  - Measure angular coefficients (amplitudes & q^2 dependence) which relate to the WC

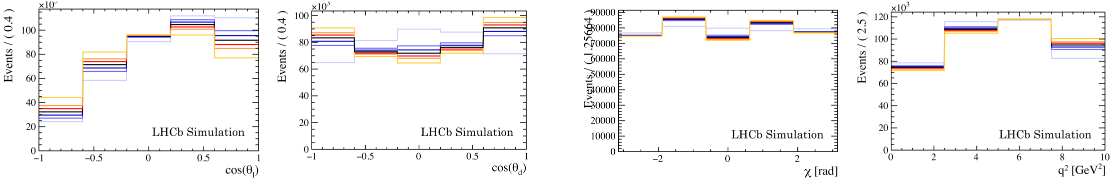
Hammer tool (Eur. Phys. J. C80 883 (2020))

- Vary the amplitude of a simulated sample from the generation model to another one of interest
- A per-event weight is determined according to the FF and WC values of the two models
- New model templates are obtained by contracting the weights tensor

$$\omega_i = \frac{\Gamma_{gen}}{\Gamma_{new}} \frac{\mathrm{d}^n\Gamma_{new}/\mathrm{d}x}{\mathrm{d}^n\Gamma_{gen}/\mathrm{d}x}$$

- Γ_{gen}: decay rate for the model used to generate the simulated sample
- Γ_{new}: decay rate according to the NP model of interest

- $B^0 \to D^{*-}\mu^+\nu_\mu$, varying $V_{qR\ell L}$ in (-0.5, -0.2, -0.1, 0., 0.1, 0.2, 0.5) [Hammer manual]



$F_L^{D^*}$ measurement in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

Longitudinal D^* polarization

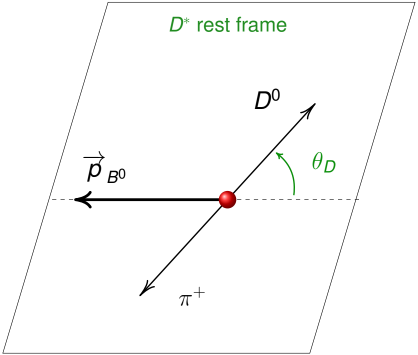
- Measurement of the longitudinal D^* polarization can provide complementary information to $R(D^*)$, showing NP contribution even if $R(D^*)$ is found compatible with SM expectation

- The differential decay rate can be expressed as 2° polynomial in $\cos\theta_D$:

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

- D^* longitudinal polarization fraction as function of $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$:

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



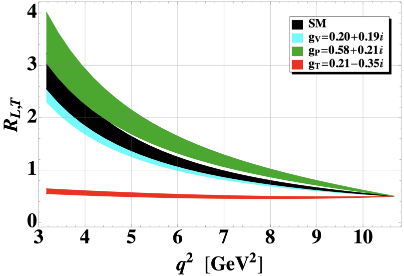
- State of art is determined by Belle results:

$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

arXiv:1903.03102

Expected value of F_l^D

- $F_L^{D^*}$ value within the SM scenario has been predicted with different methods
- The most recent theoretical predictions are:
  - 0.441 ± 0.006 [Phys. Rev. **D98**, 095018 (2018)] *Z.-R. Huang, Y. Li, C.-D. Lu, M. A. Paracha, C. Wang*
  - 0.457 ± 0.010 [EPJ **C79** 268 (2019)] *S. Bhattacharya, S. Nandi, S. K. Patra*
- Predictions for NP scenarios can be found in arXiv:1907.02257
  D. Becirevic, M. Fedele, I. Nisandzic, A. Tayduganovd



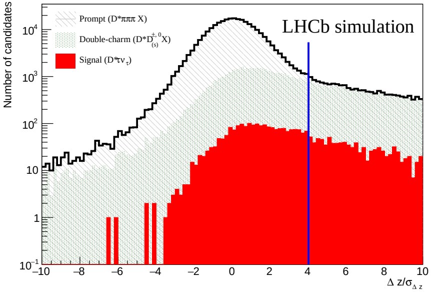
arXiv:1907.02257

- Expected dependence of $R_{L,T}$ as function of q^2 for three NP models

$$R_{L,T}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

$$F_L^{D^*}(q^2) = \frac{R_{L,T}(q^2)}{1 + R_{L,T}(q^2)}$$

- Analysis performed using hadronic τ decays
- Same strategy used in the $R(D^*)$ hadronic
- Simultaneous fit on 2011-12 (Run 1) and 2015-16 (Run 2) data



[Phys. Rev. D 97, 072013 (2018)]

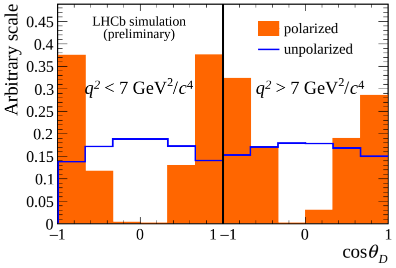
- Advantages of hadronic the decay mode:
  - only 1 neutrino in the τ decay: $\Longrightarrow$ event kinematic is properly reconstructed
  - good purity $\Longrightarrow$ strong background rejection

Initially dominant backgrounds

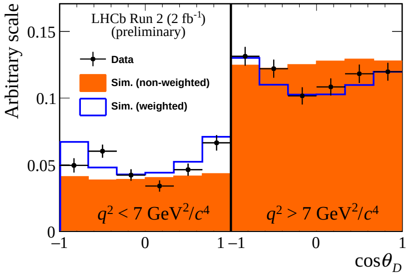
- Prompt decay $B \to D^{*-}3\pi^{\pm}X$
  - 3π system from the B meson
  - $\sim 100\times$ signal decays
  - requiring a 3π vertex detached by the B vertex along the beam axis $(\Delta_z/\sigma_{\Delta_z} > 4)$
  - additional BDT in Run 2 to reach Run 1 rejection level: > 99.9%
- Double charm $B \to D^{*-}D^{+,0}_{(s)}X$ decays
  - signal like topology
  - detached vertex due to non-negligible lifetime
  - rejected through isolation algorithm and dedicated MVA classifiers

Signal & background description [LHCB-PAPER-2023-020] (in preparation)

- $F_L^{D^*}$ determined in two q^2 regions: $\lessgtr 7\ \mathrm{GeV}^2/c^4$
- $F_L^{D^*}$ is extracted from $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$, determined splitting the signal sample in:
  - **unpolarized** $\Longrightarrow N_{sig}^{unpol} \propto a_{\theta_D}(q^2)$
  - **polarized** $\Longrightarrow N_{sig}^{pol} \propto c_{\theta_D}(q^2)$
- $\cos\theta_D$ signal distribution corrected for reconstruction effect



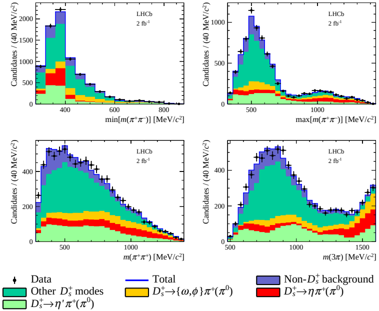
- $D^{*-}DX$ background templates determined from simulation
- Assuming no $F_L^{D^*}$ dependence on the D meson decay mode
- $\cos\theta_D$ distribution corrected through fully reconstructed control samples:
  - $D_s \to 3\pi^\pm$
  - $D^+ \to K^- 2\pi^+$
  - $D^0 \to 3\pi^\pm K^-$



Modelling of D_s in $B \to D^{*-} D_s(X)$ decays

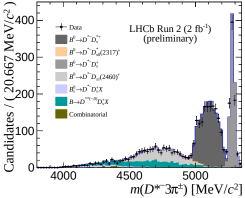
Decays of D_s [Phys. Rev. **D108**, 012018 (2023)]

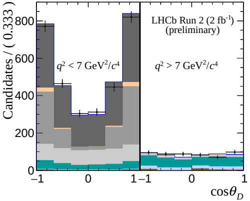
- $D_s \to 3\pi^{\pm} X$ branching fractions are not well known or correctly simulated
- Data sample selected using D_s BDT output
- Simultaneous fit to: $\min[m(\pi^+\pi^-)]$, $\max[m(\pi^+\pi^-)]$, $m(\pi^+\pi^+)$, $m(3\pi)$
- D_s fractions used to correct simulation



Production of D_s [LHCb-PAPER-2023-020] (in preparation)

- D_s meson arises from $B \to D^{*-} D_s^{+(*,**)} X$
- Poor knowledge on their relative fractions
- Enriched data sample of $D^{*-} D_s X$ decays reconstructed from $D_s \to 3\pi^{\pm}$ mode
- Fraction with respect the $D^* D_s^{*+}$ channel determined through a fit to the $m(D^{*-}3\pi)$
- Values are used to constrain the various component in the final fit





Extrapolation of $F_L^{D^*}$ on simulated sample (III)

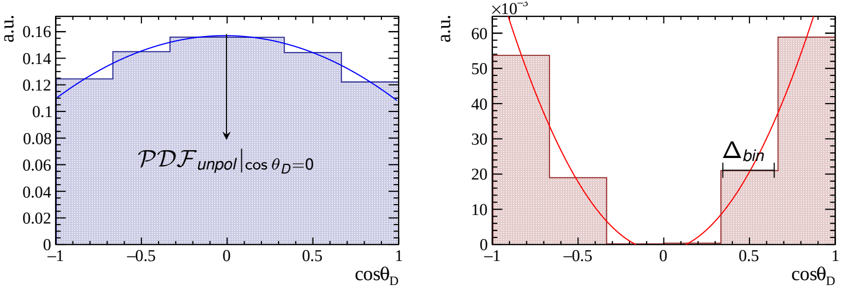
- $F_L^{D^*}$ can be determined using the equations in slide 6

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

- a_{θ_D} and c_{θ_D} are directly related to the polarized and unpolarized yield

$$a_{\theta_D}(q^2) = N^{unpol} \cdot \mathcal{PDF}_{unpol}|_{\cos\theta_D = 0}, \qquad c_{\theta_D}(q^2) = \frac{3}{2} N^{pol} \Delta_{bin}$$

signal $\cos\theta_D$ distribution



Signal fit results [LHCb-PAPER-2023-020] (in preparation)

- Signal yields from a 4D-binned template fit:
  - τ^+ lifetime (first row)
  - q^2 & $\cos\theta_D$ (second row)
  - anti-D_s BDT output (third row)
- Fit performed simultaneously on Run 1 and Run 2
- Results are integrated over Run 1 and Run 2

$F_L^{D^*}$ value extracted for the 3 q^2 region

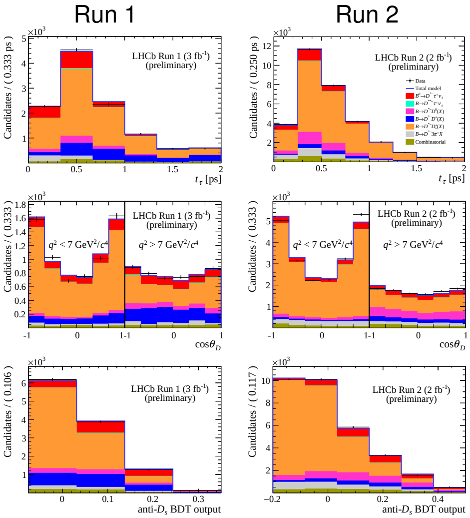
$$q^2 < 7\,\mathrm{GeV}^2/c^4 : \quad 0.51 \pm 0.07(stat) \pm 0.03(syst)$$

$$q^2 > 7\,\mathrm{GeV}^2/c^4 : \quad 0.35 \pm 0.08(stat) \pm 0.02(syst)$$

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

- All values are found to be compatible with the SM within 1σ
  - expected value in the integrated region ~ 0.44

[Phys. Rev. **D98**, 095018 (2018), EPJ **C79** 268 (2019)]



Systematic uncertainties [LHCb-PAPER-2023-020] (in preparation)

Source	low q^2	high q^2	integrated
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
TemplateSize	0.027	0.017	0.019
$\tau^+ \to 3\pi^\pm\pi^0$ fraction	0.001	0.001	0.001
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
$\cos\theta_D$ $D^{*-}D_s$	0.002	0.001	0.002
$\cos\theta_D$ $D^{*-}D_s^{*+}$	0.007	0.002	0.004
$\cos\theta_D$ $D^{*-}D_sX$	0.007	0.006	0.007
$\cos\theta_D$ $D^{*-}D^+X$	0.002	0.002	0.003
$\cos\theta_D$ $D^{*-}D^0X$	0.002	0.002	0.003
$F_L^{D^*}$ integrated	-	-	0.002
Total	0.036	0.023	0.029

Dominant source of systematic are:

- Limited size of the simulation samples
- Form factor parameterization
- Modelling of the D_s
- $\cos\theta_D$ shape in $D^{*-}D_sX$ backgrounds
- Bin migration
- Signal acceptance
- Form factor model

Future updates on the $F_L^{D^*}$ measurement

- $F_L^{D^*}$ measurement performed using Run1 and first part of Run2 data

$$F_l(D^*) = 0.43 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst})$$

- Plan is to update the $F_L^{D^*}$ value in parallel with the $R(D^*)$ measurement in hadronic τ channel.
- Expected statistical uncertainties for future updates: (optimistic scenario)

	Run1 + (2015+2016)	Run1 + Run2	Run1 + Run2 + Run3
Luminosity	5 fb^{-1}	9 fb^{-1}	30 fb^{-1}
Statistical uncertainty	0.061	$\sim$ 0.046	$\sim$ 0.025

- Some of the dominant systematic uncertainties should also decrease:
  - $\cos\theta_D$ shape in $D^* D$ backgrounds
  - D_s decay model

$B^0 \to D^* \mu \nu_\mu$ angular analysis

- Extract directly WC & FF parameters from fit to data
- Shape analysis only
  $\Longrightarrow$ no attempt to measure $|V_{cb}|$ because of loser sensitivity to yield changes

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_l d\chi} \propto \Big[I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+ (I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D)\cos 2\theta_l$$
$$+ (I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D)\cos\theta_l$$
$$+ (I_3\cos 2\chi + I_9\sin 2\chi)\sin^2\theta_l\sin^2\theta_D$$
$$+ (I_4\cos\chi + I_8\sin\chi)\sin 2\theta_l\sin 2\theta_D$$
$$+ (I_5\cos\chi + I_7\sin\chi)\sin\theta_l\sin 2\theta_D \Big],$$

- Full description using the three helicity angles
- Measure the 12 angular coefficients

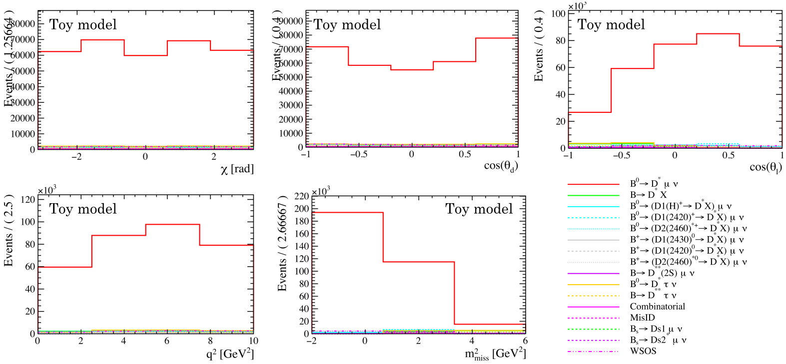
Main background contributions

- $B^0 \to D^* \tau \nu_\tau$: no NP accounted for in the fit
- $B \to D^{**} \mu \nu_\mu$: modelled with the BLPR FF parameterization PRD 97 075011 (2018)
- Semileptonic decays to heavier charmed hadrons
- MisID and combinatorial (data driven)

Dominant systematic uncertainties

- MisID background shape
- NP contribution from $B^0 \to D^* \tau \nu_\tau$
- data/simulation differences
- simulated samples size

- SM fit using different FF parametrization:
  - BGL [Phys. Rev. Lett. **74** 4603 (1995)]
  - CLN [Nucl. Phys. **B530** 1 (1998)]
  - BLPR [Phys. Rev. **D97** 075011 (2018)]
- Statistical precision comparable (Run1 only) to latest B-factory measurements: (Phys. Rev. **D100** 052007 (2019), Phys. Rev. Lett. **123** 091801 (2019))



$B^0 \to D^* \mu \nu_\mu$ angular analysis (III)

- Ideally WC determined by means of a fit to data without any assumption about the the NP structure ... (EPJ **C80** 883 (2020))
- ... but is easier to search for specific NP models (e.g. Bhattacharya et. al. JHEP **05**, 191 (2019))
- Studied different NP scenarios (plan to report fit results for each)

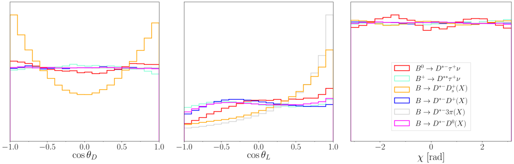
WC floating in fit \ Expected (stat - Run1) uncertainty on WC	VqRlL	VqLlL	SqRlL (SqLlL)	TqLlL
VqRlL	$\mathcal{Im}$ $\mathcal{O}(10^{-2})$ $\mathcal{Re}$ $\mathcal{O}(10^{-2})$			
VqLlL		$\mathcal{Im}$ $\mathcal{O}(10^{-1})$ $\mathcal{Re}$ —		
SqRlL (SqLlL)			$\mathcal{Im}$ $\mathcal{O}(10^{-1})$ $\mathcal{Re}$ $\mathcal{O}(10^{-1})$	
TqLlL				$\mathcal{Im}$ $\mathcal{O}(10^{-3})$ $\mathcal{Re}$ $\mathcal{O}(10^{-3})$
VqRlL+VqLlL+ SqRlL+ TqLlL	$\mathcal{Im}$ $\mathcal{O}(10^{-2})$ $\mathcal{Re}$ $\mathcal{O}(10^{-2})$	$\mathcal{Im}$ $\mathcal{O}(10^{0})$ $\mathcal{Re}$ —	$\mathcal{Im}$ $\mathcal{O}(10^{-1})$ $\mathcal{Re}$ $\mathcal{O}(10^{-1})$	$\mathcal{Im}$ $\mathcal{O}(10^{-3})$ $\mathcal{Re}$ $\mathcal{O}(10^{-2})$

Uncertainties increase, generally within same order of magnitude, fits less stable →

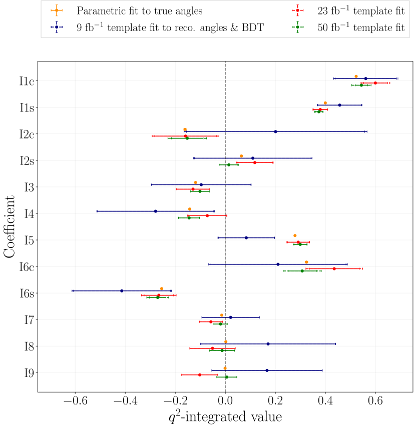
$B^0 \to D^{(*)}\tau\nu_\tau$ angular analysis

- Ideally shape + rate analysis: $R(D)$ vs $R(D^*)$ determination simultaneous to WC
- Sensitivity studies need to include the full set of backgrounds

- Better angular resolutions with 3-prong hadronic τ decays JHEP **11**, 133 (2019)
- Lower statistics than muonic case
- Large backgrounds
- External input for $R(D)$ & $R(D^*)$

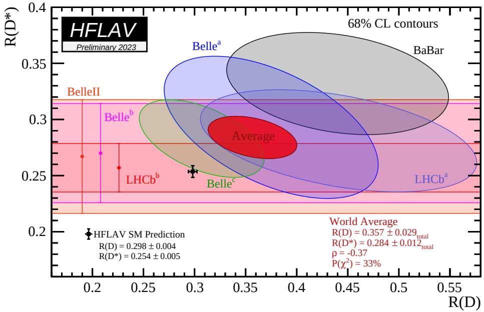


[JHEP **11**, 133 (2019)]



Conclusions

- **First measurement of $F_L^{D^*}$** with hadronic τ decays
  - smallest statistical uncertainty and performed in two q^2 bins
- $F_L^{D^*}$ compatible with the SM expectation
- **Combined** $R(D) - R(D^*)$ is still a $\mathbf{3.2}\sigma$ tension from the SM
- Full picture to be given by ongoing differential measurements



More to come!

- $R(D^*)$ hadronic & $F_L^{D^*}$ with full Run 1 & Run 2
- Many LFU analysis: $R(D^0)$, $R(D^+)$, $R(D_s)$, $R(D^*)_e$
- Full angular analysis to determine spin and structure of NP
- LHCb Upgrade era has started:

  $\Longrightarrow$ **exciting time ahead!**

Thank you for your attention!

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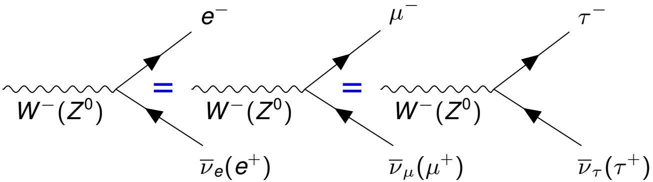
Backup

Lepton Flavour Universality

- Within the Standard Model (SM), the weak interactions towards three generations of leptons are identical



- New physics (NP) may be more sensitive to the 3rd family
- Three typical candidates for NP:
  - **leptoquarks** PRD 94, 115021, ...
  - **two Higgs doublet models** PRL 116, 081801, ...
  - **Heavy vector bosons**, e.g. W' JHEP 07 (2015) 142 1506.01705, ...
- Need to cancel for theoretical uncertainties:

$\Longrightarrow$ measure ratios of $\mathcal{B}$

Charged current $b \to c\ell\nu_\ell$

- Main contribution:
  tree level diagrams

$$R(X_c) \equiv \frac{\mathcal{B}(X_b \to X_c\tau^+\nu_\tau)}{\mathcal{B}(X_b \to X_c\ell^+\nu_\ell)}$$

$$X_b = B^{0,+}_{(s,c)}, \Lambda^0_b, \qquad \ell = \mu, e,$$
$$X_c = D^{(*)}_{(s)}, J/\psi, \Lambda^+_c$$

Neutral transition $b \to s\ell\ell$

- Main contribution:
  penguin or box diagrams

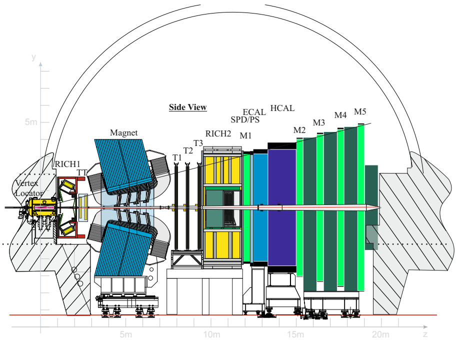
$$R(X_s) \equiv \frac{\mathcal{B}(X_b \to X_s\mu^+\mu^-)}{\mathcal{B}(X_b \to X_s e^+ e^-)}$$

(X_b, X_s) = (B^0, K^{*0}) or (B^+, K^+)

The Large Hadron Collider beauty (LHCb) Experiment

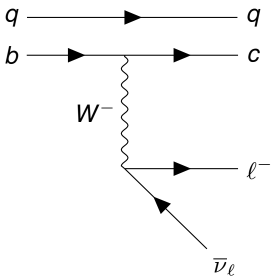
- LHCb detector is a single-arm forward spectrometer optimized for b and c hadron physics
  - pseudorapidity range: [2,5] $\Longrightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Longrightarrow \approx 3$ fb^{-1}
  - Run2 (2015-2018) $\Longrightarrow \approx 6$ fb^{-1}

- Excellent performances [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**: $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100$ GeV/c)
  - **Impact Parameter (IP) resolution**: $\sigma_{IP} \approx 20\ \mu m$ (at high p_T)
  - **Decay time resolution**: $\sigma_t \approx 50\ fs$
  - **Particle Identification (PID)**: $\varepsilon(K) \approx 95\%, \pi$ mis-ID $\approx 5\%$ ($p < 100$ GeV/c) $\varepsilon(\mu) \approx 97\%, \pi$ mis-ID $\approx$ 1-3%



Semileptonic decays at LHCb

- Tree level $\Longrightarrow$ abundant
- Theoretically clean
  - factorize hadron and lepton current
  - hadron current described by form-factors
- Experimentally tricky due to ≥ 1 missing ν_ℓ



Advantages

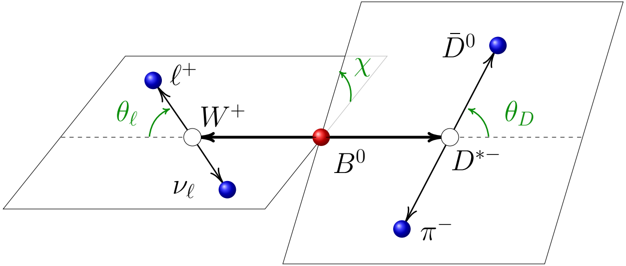
- Large H_b production
- Produce B^+, B^0, B_s^0, B_c^+, Λ_b^0, etc.
- Boosted H_b
- Efficient tracking $\Longrightarrow$ isolation

Challenges

- No beam-energy constraint
- Significant backgrounds (combinatorial + partially reco)
- Reliance on simulation
  - large samples are required

Helicity angles definition

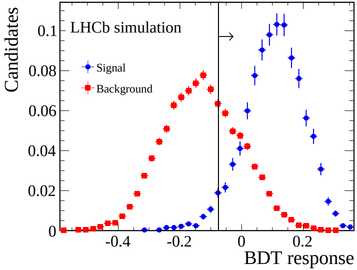
- θ_ℓ, θ_D and χ helicity angles enter directly in decay rate
- They provide (with $q^2 \equiv (p_{H_b} - p_{H_c})^2$) the highest sensitivity to New Physics effects



- θ_ℓ: angle between the direction of the lepton and the direction opposite the H_b meson in the virtual W rest frame
- θ_D: angle between the direction of the $H^0{}_c$ meson and the direction opposite the H_b meson in the $H^0{}_c$ rest frame
- χ: angle between the plane formed by H_c decay and the W decay in the H_b meson rest frame

Description of the anti-D_s BDT

- A dedicated BDT has been trained to suppress the abundant $B \to D^* D_s X$ background
- Trained performed separately for Run 1 and Run 2 data
- Signal described via simulated $B^0 \to D^{*-}\tau^+\nu_\tau$ decays, corrected for data/MC differences
- Background described using simulated sample of $B \to D^* D_s X$ decays, where the D_s decays in 3π
- Output used in final fit to control $D^* D_s X$ background



[Phys. Rev. D 97, 072013]

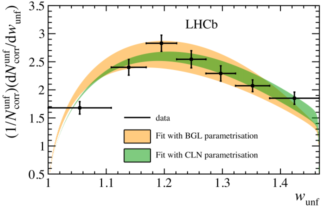
Input features

- Output of the isolation algorithms
- Momenta, masses and quality of the reconstruction of the decay chain under the signal and background hypotheses
- Masses of oppositely charged pion pairs
- Energy and the flight distance in the transverse plane of the 3π system
- Mass of the total system

Differential measurement of $B_s \to D_s^* \mu\nu_\mu$ JHEP12(2020)144

- Measurement of the shape of the $B_s \to D_s^* \mu\nu_\mu$ decay rate
- Fully reconstruct $D_s^* \to D_s\gamma$ with $D_s \to KK\pi$
- Considering two FF schemes: BGL (PRL 74 4603 (1995)) and CLN (Nucl. Phys. B530 1 (1998))
- Signal yield measured in bins of hadronic recoil parameter

$$w = v_{B_s} \cdot v_{D_s^*}$$



CLN fit	
Unfolded fit	$\rho^2 = 1.16 \pm 0.05 \pm 0.07$
Unfolded fit with massless leptons	$\rho^2 = 1.17 \pm 0.05 \pm 0.07$
Folded fit	$\rho^2 = 1.14 \pm 0.04 \pm 0.07$
BGL fit	
Unfolded fit	$a_1^f = -0.005 \pm 0.034 \pm 0.046$ $a_2^f = 1.00^{+0.00}_{-0.19}{}^{+0.00}_{-0.38}$
Folded fit	$a_1^f = 0.039 \pm 0.029 \pm 0.046$ $a_2^f = 1.00^{+0.00}_{-0.13}{}^{+0.00}_{-0.34}$