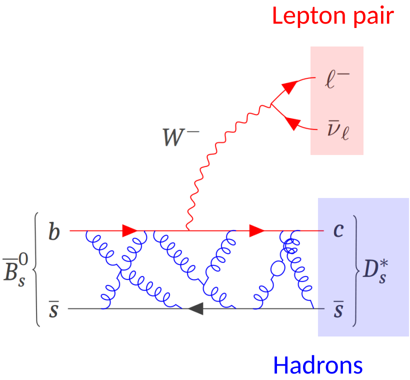
Measurements of the differential distributions of $B_s^0 \to D_s^* \mu \nu_\mu$ decays at LHCb

A feasibility study

Federico Manganella, on behalf of LHCb Collaboration
University & INFN Roma Tor Vergata

SM@LHC 2024, YSF
Rome - May 8th, 2024

Main motivations



$$\mathbf{B_s^0} \longrightarrow \mathbf{D_s^*}\,\mu\,\nu_\mu$$

We have tensions in V_{ub}, V_{cb} and $\mathcal{R}(D)$-$\mathcal{R}(D^*)$ measurements, semileptonic decays could help us because:

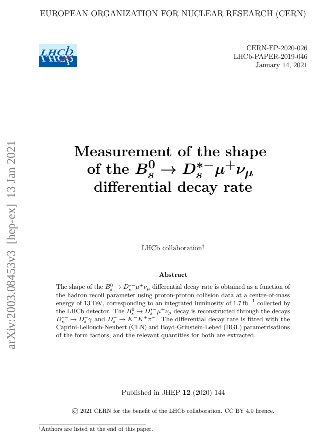
- tree-level diagram, EW and QCD
- sensitivity to New Physics

Additionally:

- simpler theoretical computations with respect to B^0 and B^+ (due to s quark)

Main motivations

- Previous analysis, see JHEP12(2020)144, published four years ago
- That was a 1-d analysis $\Rightarrow$ this is a full angular analysis



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-026
LHCb-PAPER-2019-046
January 14, 2021

arXiv:2003.08453v3 [hep-ex] 13 Jan 2021

Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate

LHCb collaboration†

Abstract

The shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate is obtained as a function of the hadron recoil parameter using proton-proton collision data at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1} collected by the LHCb detector. The $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decay is reconstructed through the decays $D_s^{*-} \to D_s^-\gamma$ and $D_s^- \to K^-K^+\pi^-$. The differential decay rate is fitted with the Caprini-Lellouch-Neubert (CLN) and Boyd-Grinstein-Lebed (BGL) parametrisations of the form factors, and the relevant quantities for both are extracted.

Published in JHEP **12** (2020) 144

© 2021 CERN for the benefit of the LHCb collaboration. CC BY 4.0 licence.

†Authors are listed at the end of this paper.

The decay kinematics

These processes are fully described by four variables:

$q^2, \theta_\ell, \theta_d, \chi$

$q^2 = (p_{B_s^0} - p_{D_s^*})^2$

θ_ℓ and θ_d are helicity angles

χ angle between decay planes

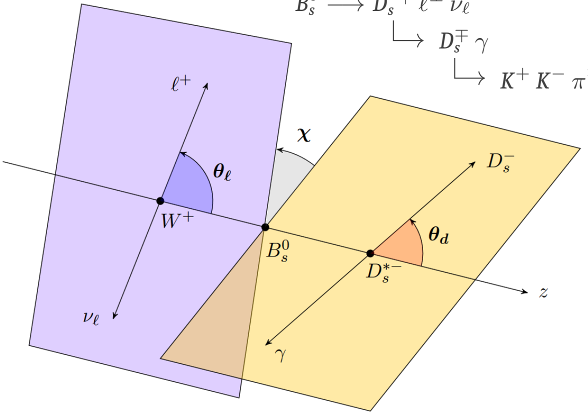
$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_d d\chi} \propto \sum_{i=1s,\ldots} I_i(q^2)\,\Xi_i(\theta_\ell, \theta_d, \chi)$$

Hadronic interaction (models) + NP

$\overset{(-)}{B_s^0} \longrightarrow D_s^{*\mp}\,\ell^\pm\,\nu_\ell$

$\hookrightarrow D_s^\mp\,\gamma$

$\hookrightarrow K^+ K^- \pi^\mp$



$\hat{z} = \vec{p}_{D_s^*} / |\vec{p}_{D_s^*}|$

First steps of the analysis

The events are selected:

- lepton and hadron with opposite charges
- $D_s^\pm \to K^+K^-\pi^\pm$ selection, ϕ and K^* resonances
- $D_s^* \to D_s\gamma$ reconstruction, soft γ selection

Then, backgrounds are rejected with:

- ${}_s\mathcal{P}lot$ to evaluate combinatorial background for the photon emitted by D_s^*
- cut on dedicated variable to suppress the doubly-charmed decays ($H_b \to H_c D_s^*$)

Templates
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$
$B_s^0 \to D_s^{*-}\tau^+\nu_\tau$
$B_s^0 \to D_{s1}\mu\nu_\mu$
$B_s^0 \to D_{s1}\tau\nu_\tau$
$B^0 \to D_s^{*+}D^{(*-)}$
$B_s^0 \to D_s^{*+}D_s^{(*-)}$
$B^+ \to D_s^{*+}\overline{D}^{*0}$
$\Lambda_b \to D_s^{*-}\Lambda_c^{(*+)}$
Combinatorial + misID

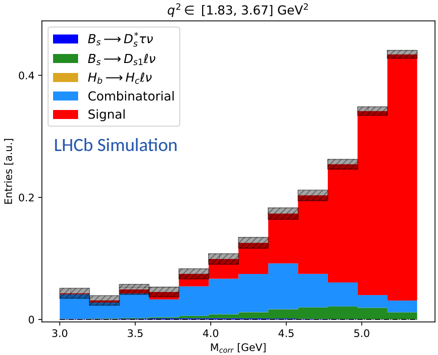
Number of signal events

Extract signal yields using

$$M_{\text{corr}} = \sqrt{m^2_{D_s^* \mu} + |p^{\perp}_{miss}|^2} + |p^{\perp}_{miss}|$$

Template binned fit over 4-d space, extrapolation in two steps:

- Simultaneous fit over q^2 bins, integrating the angles
- Second fit over all bins, fixing background templates



Variable	Bin Edges	Bins
q^2 [GeV^2]	0. 1.83 3.67 5.5 7.33 9.17 11.	6
$\cos\theta_\ell$	-1. -0.5 0. 1.	3
$\cos\theta_d$	-1. -0.5 0. 1	3
χ [rad]	0. 1.26 2.51 3.77 5.03 6.28	5

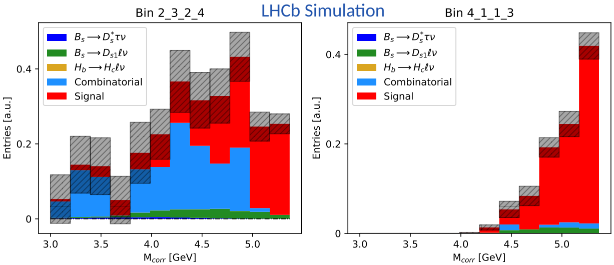
Number of signal events

Extract signal yields using

$$M_{\text{corr}} = \sqrt{m^2_{D_s^*\mu} + |p^{\perp}_{miss}|^2} + |p^{\perp}_{miss}|$$

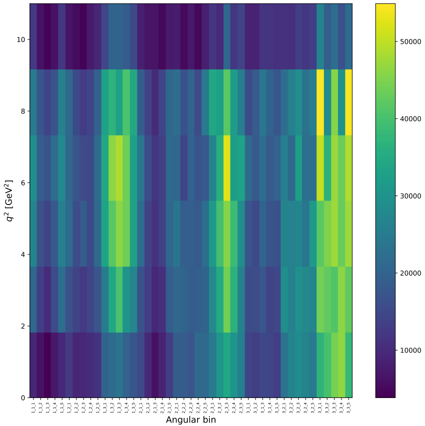
Template binned fit over 4-d space, extrapolation in two steps:

- Simultaneous fit over q^2 bins, integrating the angles
- Second fit over all bins, fixing background templates



Variable	Bin Edges	Bins
q^2 [GeV^2]	0. 1.83 3.67 5.5 7.33 9.17 11.	6
$\cos\theta_\ell$	-1. -0.5 0. 1.	3
$\cos\theta_d$	-1. -0.5 0. 1	3
χ [rad]	0. 1.26 2.51 3.77 5.03 6.28	5

Signal yields distribution



Angular bin: $\cos\theta_\ell\_\cos\theta_d\_\chi$

- Create migration matrix + efficiency vector to account for detector effects
- Fit CLN/BGL parameters using folded and unfolded distributions
- Compare the unfolded distribution with theory/other experiments
- Use the unfolded distribution to perform a model-independent fit

Model-independent approach

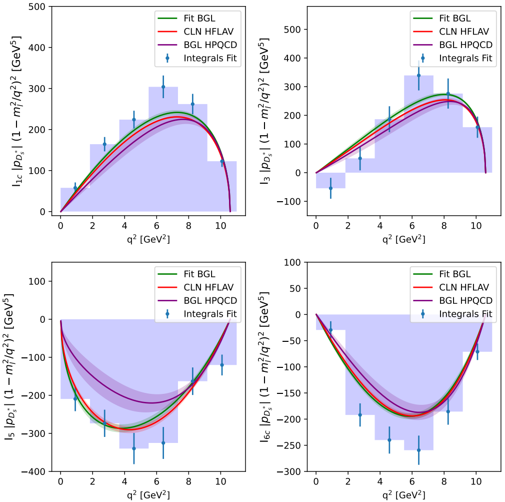
We can explicitly fit the $I_i(q^2)$ functions integrated over the q^2 bins, without any assumption on the hadronic model:

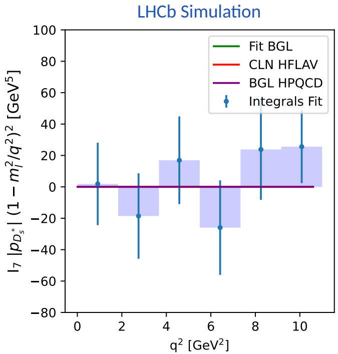
$$N_{k,l}^{\text{pred}} \propto \sum_i \int_{\Delta q_k^{2,true}} \left(1 - m_\mu^2/q^2\right)^2 |\vec{p}_{D_s^*}(q^2)| I_i(q^2)\, dq^2 \cdot \int_{\Delta\Omega_l^{true}} \Xi_i(\theta_\ell, \theta_d, \chi)\, d\Omega$$

$$\propto \sum_i J_{i,k}(q^2) \cdot \zeta_{i,l}(\theta_\ell, \theta_d, \chi)$$

where $\zeta_{i,l}(\theta_\ell, \theta_d, \chi)$ are analytically computable. We have $\sim 6 \times 10$ free parameters. After the fit we can extract CLN/BGL parameters from the $J_i(q^2)$ shapes.

Model-independent approach





We could extract information about NP, because we expect some $I_i(q^2)$ functions to be zero in SM picture.

Final thoughts

- In terms of statistics Simulations $\geq$ Dataset, hence we expect to be able to perform this analysis with data successfully
- First measurement of $B_s^0 \to D_s^* \mu\nu_\mu$ differential distributions
- It is possible to directly test different New Physics scenarios, with both a model-dependent and a model-independent approach

Measurements of the differential distributions of $B_s^0 \to D_s^* \mu \nu_\mu$ decays at LHCb

Thank you for listening!

The differential width

arXiv:1801.10468

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_d d\chi} = \mathcal{K}(q^2)\sum_i I_i(q^2)\Xi_i(\theta_\ell,\theta_d,\chi)$$

$I_i(q^2) = I_i(q^2; H_0, H_\pm, H_t)$
and H_i are written using
CLN/BGL models

$$= \mathcal{N}_\gamma |\vec{p}_{D_s^*}(q^2)| \left(1-\frac{m_\mu^2}{q^2}\right)^2 \cdot \Big[I_{1s}\sin^2\theta_d + I_{1c}(3+\cos 2\theta_d)$$
$$+ I_{2s}\sin^2\theta_d\cos 2\theta_\ell + I_{2c}(3+\cos 2\theta_d)\cos 2\theta_\ell$$
$$+ I_3\sin^2\theta_d\sin^2\theta_\ell\cos 2\chi + I_4\sin 2\theta_d\sin 2\theta_\ell\cos\chi + I_5\sin 2\theta_d\sin\theta_\ell\cos\chi$$
$$+ I_{6s}\sin^2\theta_d\cos\theta_\ell + I_{6c}(3+\cos 2\theta_d)\cos\theta_\ell$$
$$+ I_7\sin 2\theta_d\sin\theta_\ell\sin\chi + I_8\sin 2\theta_d\sin 2\theta_\ell\sin\chi + I_9\sin^2\theta_d\sin^2\theta_\ell\sin 2\chi\Big]$$

$$\mathcal{N}_\gamma = \frac{3G_F^2|V_{cb}|^2\mathcal{B}(D_s^*\to D_s\gamma)}{128(2\pi)^4 m_{B_s^0}^2} \qquad |\vec{p}_{D_s^*}(q^2)| = \frac{\lambda^{1/2}(m_{B_s^0}^2, m_{D_s^*}^2, q^2)}{2\sqrt{q^2}} \qquad \lambda(x,y,z) = x^2+y^2+z^2-2xy-2xz-2yz$$

CLN model

$$H_0 = \frac{(m_{B_s^0} + m_{D_s^*})^2 \lambda^{1/2}(m_{B_s^0}^2, m_{D_s^*}^2, q^2) A_1(q^2) - \lambda(m_{B_s^0}^2, m_{D_s^*}^2, q^2) A_2(q^2)}{2 m_{D_s^*}(m_{B_s^0} + m_{D_s^*})\sqrt{q^2}}$$

$$H_\pm = \frac{(m_{B_s^0} + m_{D_s^*})^2 A_1(q^2) \mp \lambda^{1/2}(m_{B_s^0}^2, m_{D_s^*}^2, q^2) V(q^2)}{m_{B_s^0} + m_{D_s^*}}$$

$$H_t = -\frac{\lambda^{1/2}(m_{B_s^0}^2, m_{D_s^*}^2, q^2)}{\sqrt{q^2}} A_0(q^2) \qquad w = \frac{m_{B_s^0}^2 + m_{D_s^*}^2 - q^2}{2 m_{B_s^0} m_{D_s^*}}$$

$$V(w) = \frac{R_1(w)}{R^*} h_{A_1}(w)$$

$$A_0(w) = \frac{R_0(w)}{R^*} h_{A_1}(w)$$

$$A_1(w) = \frac{w+1}{2} R^* h_{A_1}(w)$$

$$A_2(w) = \frac{R_2(w)}{R^*} h_{A_1}(w)$$

$$h_{A_1}(w) = h_{A_1}(1)[1 - 8\rho^2 z(w) + (53\rho^2 - 15) z(w)^2 - (231\rho^2 - 91) z(w)^3]$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

BGL model

$$H_0(w) = \frac{\mathcal{F}_1(w)}{\sqrt{q^2}}$$

$$H_\pm(w) = f(w) \mp m_{B_s^0} m_{D_s^*} \sqrt{w^2-1}\, g(w)$$

$$H_t(w) = m_{B_s^0} \frac{\sqrt{r}(1+r)\sqrt{w^2-1}}{\sqrt{1+r^2-2wr}} \mathcal{F}_2(w)$$

$$z(w) = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w-1}+\sqrt{2}}$$

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{N} a_n^f z^n \qquad \mathcal{F}_1(z) = \frac{1}{P_{1+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{N} a_n^{\mathcal{F}_1} z^n$$

$$g(z) = \frac{1}{P_{1-}(z)\phi_g(z)} \sum_{n=0}^{N} a_n^g z^n \qquad \mathcal{F}_2(z) = \frac{\sqrt{r}}{(1+r)P_{0-}(z)\phi_{\mathcal{F}_2}(z)} \sum_{n=0}^{N} a_n^{\mathcal{F}_2} z^n$$

New Physics tensor

$$H'_{eff} = H^{SM}_{eff} + \frac{G_F}{\sqrt{2}} V_{cb} \left[\epsilon^{\ell}_T \bar{c} \sigma_{\mu\nu} (1-\gamma_5) b \bar{\ell} \sigma^{\mu\nu} (1-\gamma_5) \nu_\ell + h.c. \right]$$

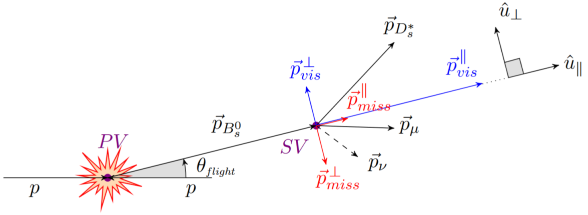
$$\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$$

$$\mathcal{A}(B^0_s \to D^*_s \ell \nu_\ell) = \frac{G_F}{\sqrt{2}} V_{cb} \left[H^{SM}_\mu L^{\mu,SM} + \epsilon^\ell_T H^{NP}_{\mu\nu} L^{\mu\nu,NP} \right]$$

$$H^j_m = \langle D^*_s(p_{D^*_s}, \epsilon_m) | \bar{c} \mathcal{O}^j (1-\gamma_5) b | B^0_s(p_{B^0_s}) \rangle \qquad L^j = \bar{\ell} \mathcal{O}^j (1-\gamma_5) \nu_\ell$$

$$\Rightarrow \quad H^{NP}_m = H^{NP}_m(T_0, T_1, T_2) \qquad I^{NP}_j = I^{NP}_j(H^{NP}_m)$$

Kinematic variables reconstruction



$$p_\pm = p_{vis}^{\parallel} - a \pm \sqrt{r}$$

$$a = \frac{\left(m_{B_s^0}^2 - m_{vis}^2 - 2(p_{vis}^{\perp})^2\right) \cdot p_{vis}^{\parallel}}{2 \cdot \left((p_{vis}^{\parallel})^2 - E_{vis}^2\right)}$$

$$r = \frac{\left(m_{B_s^0}^2 - m_{vis}^2 - 2(p_{vis}^{\perp})^2\right) \cdot E_{vis}^2}{4 \cdot \left((p_{vis}^{\parallel})^2 - E_{vis}^2\right)^2} + \frac{(E_{vis} \cdot p_{vis}^{\perp})^2}{(p_{vis}^{\parallel})^2 - E_{vis}^2}$$

$$\Downarrow$$

We assume there is only one missing particle in the final state and that $m_{B_s^0}$ is known (see JHEP02(2017)021)

$\Rightarrow$ Two fold ambiguity

Regression algorithm gives a rough estimate of $p_{B_s^0}$, we resolve the ambiguity using

$$\Delta_\pm = (p_{reg} - p_\pm)$$

Two symmetric approaches

Folded fit

$$\chi^2 = \left(\vec{N}^{\text{meas}} - \vec{N}^{\text{pred}}\right)^T \frac{1}{C(N^{\text{meas}})} \left(\vec{N}^{\text{meas}} - \vec{N}^{\text{pred}}\right)$$

where $N_i^{\text{pred}} = k \cdot \sum_{j=1}^{t} m_{ij} \cdot (\Delta\Gamma(\vec{p}) \cdot \mathcal{E})_j$ $\quad (\Delta\Gamma(\vec{p}) \cdot \mathcal{E})_j = \Delta\Gamma_j(\vec{p}) \cdot \mathcal{E}_j$

$\Delta\Gamma =$ expected yields distribution $\quad \vec{p} =$ CLN/BGL parameters

Unfolded fit

$$\chi^2 = \left(\vec{N}^{\text{unf}}/\mathcal{E} - k \cdot \Delta\Gamma(\vec{p})\right)^T \frac{1}{C(N^{\text{unf}})} \left(\vec{N}^{\text{unf}}/\mathcal{E} - k \cdot \Delta\Gamma(\vec{p})\right)$$

where $\vec{N}^{\text{unf}}$ is obtained using Bayesian unfolding

Expected true yields

$$\Delta\Gamma_j(\vec{p}) = \iint_{\Delta_j^{true}} \frac{d^4\Gamma}{dq^2 d\Omega}(\vec{p})\, dq^2 d\Omega$$

$$= \mathcal{N}_\gamma \int_{\Delta q_a^{2,true}} \int_{\Delta\Omega_b^{true}} \left(1 - \frac{m_\mu^2}{q^2}\right)^2 \sum_i |\vec{p}_{D_s^*}(q^2)| I_i(q^2)\, \Xi_i(\theta_\ell, \theta_d, \chi)\, dq^2 d\Omega$$

$$= \mathcal{N}_\gamma \sum_i \int_{\Delta q_a^{2,true}} \left(1 - \frac{m_\mu^2}{q^2}\right)^2 |\vec{p}_{D_s^*}(q^2)| I_i(q^2)\, dq^2 \int_{\Delta\Omega_b^{true}} \Xi_i(\theta_\ell, \theta_d, \chi)\, d\Omega$$

The integrals over the angular space are easy to compute, while the integrals over q^2 are computed using Bode's rule (or Simpson's 3/8 rule).

Belle and HPQCD

arXiv:2304.03137