Measurement of the differential distributions of $B_s^0 \to D_s^* \mu \nu_\mu$ decay with the LHCb detector

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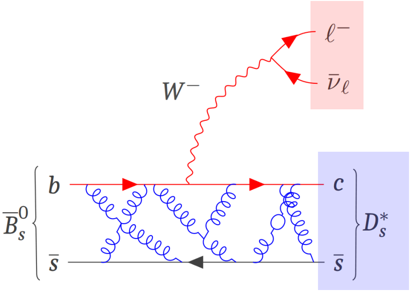
Main motivations

Lepton pair



Hadrons

$$\mathbf{B^0_s} \longrightarrow \mathbf{D^*_s}\, \mu\, \nu_\mu$$

We have tensions in V_{ub}, V_{cb} and $\mathcal{R}(D)$-$\mathcal{R}(D^*)$ measurements (see M. Di Carlo talk for instance), semileptonic decays could help us because:

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

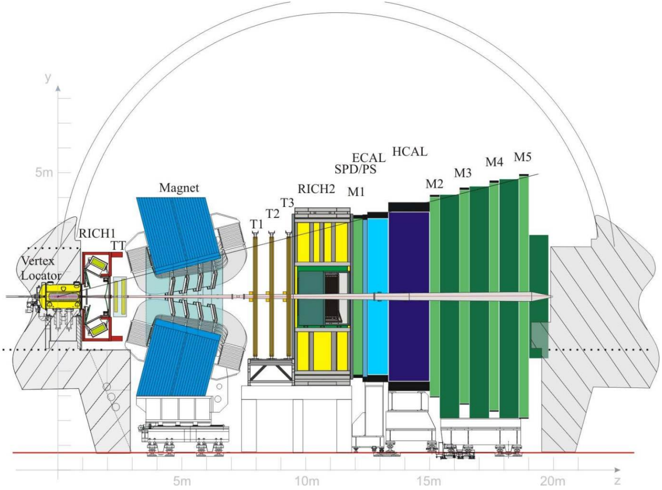
Additionally:

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

LHCb experiment

see A. Lupato talk

Goal: B-Physics, CP violation, etc.
Acceptance: $1.8 < \eta < 4.9$
Luminosity: $2 \cdot 10^{32}\, cm^{-2}\, s^{-1}$
B's/year: 10^{12}



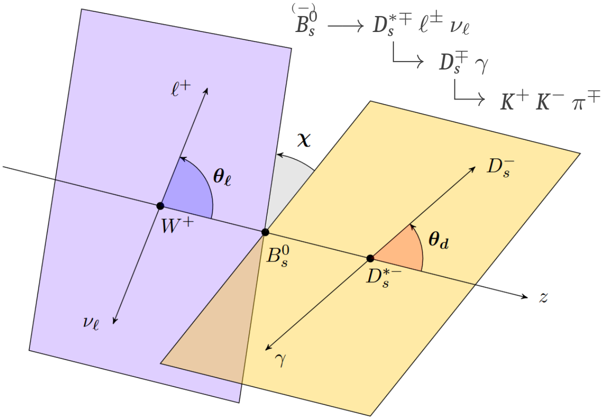
The decay kinematics

The analysis aims to measure the decay rate in the space given by the variables that describe the decay kinematics:

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

$q^2 = (p_{B_s^0} - p_{D_s^*})^2$
θ_ℓ and θ_d are helicity angles
χ angle between decay planes

We used Run 2 data, for a total of $\sim 6\ \text{fb}^{-1}$



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

The differential decay width

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

- $I_i(q^2)$ functions encapsulate the hadronic interaction: we use CLN and BGL[1] models to parametrise their expressions, or fit them with a model-independent approach
  - Modifying the $I_i(q^2)$ functions and considering a New Physics coupling constant ϵ_{NP}, different structures for NP can be implemented:

$$I_i(q^2) \quad\Longrightarrow\quad I_i(q^2, \epsilon_{NP})$$

- $\Xi_i(\theta_\ell, \theta_d, \chi)$ are known functions of the angular variables

[1] Caprini-Lellouch-Neubert and Boyd-Grinstein-Lebed

First steps of the analysis

Events selection :

- $D_s^{\pm} \to K^+K^-\pi^{\pm}$ selection, ϕ and K^* resonances
- $D_s^* \to D_s\gamma$ reconstruction, soft γ selection
- charge of the identified muon opposite to that of D_s^*

Then, background channels are rejected with:

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

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

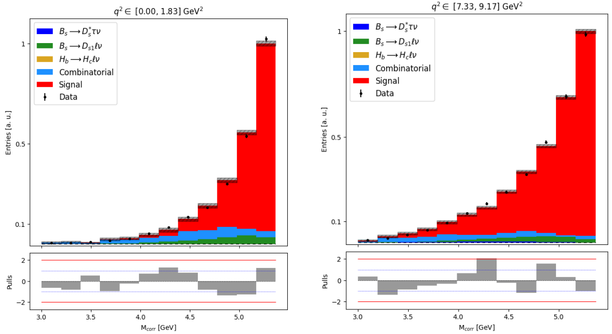
The signal yields

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

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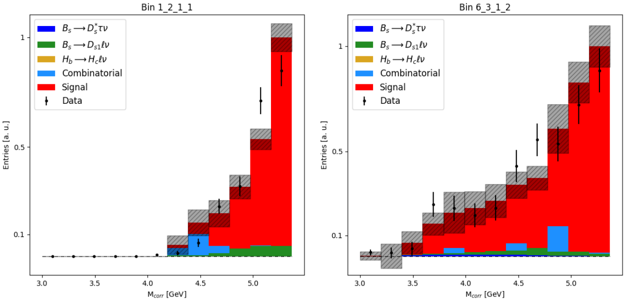

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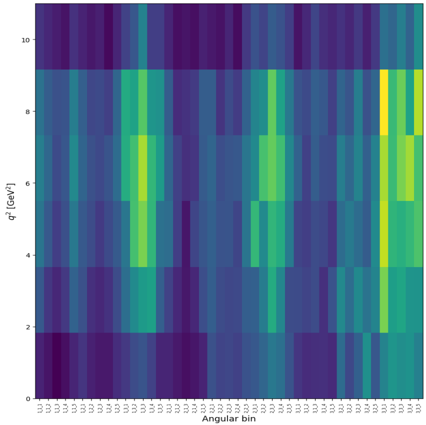
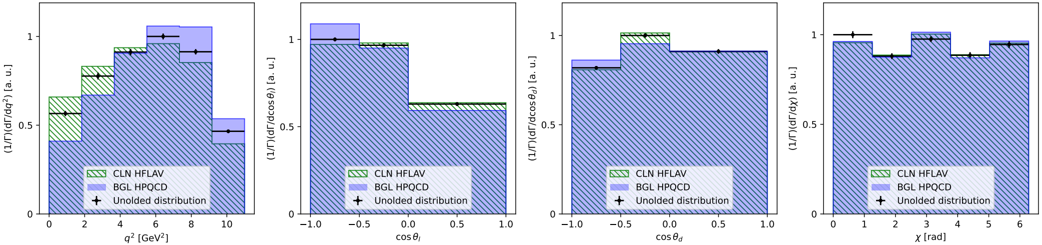
Once we extract the signal yield distribution, we can:

- Unfold the distribution with migration matrix + efficiency vector to account for detector effects
- Compare the unfolded distribution with theory/other experiments
- Use the unfolded distribution to perform a model-independent fit to extract $I_i(q^2)$ functions



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

Comparison with predictions



- Models used: HFLAV averages for CLN, HPQCD predictions for BGL
- Visible tension in some bins
- Something similar was observed comparing Belle data with HPQCD predictions, but with different binning and with $B^0 \to D^*$

Model-independent $I_i(q^2)$ determination

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

$$N^{\text{pred}}_{k,p,q,r} = \int_{\Delta q^2_k} \int_{\Delta \cos\theta_{\ell\, p}} \int_{\Delta \cos\theta_{d\, q}} \int_{\Delta\chi_r} \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_d \mathrm{d}\chi} dq^2 \overbrace{d\cos\theta_\ell d\cos\theta_d d\chi}^{d\Omega}$$

$$\propto \sum_i \int_{\Delta q^2_k} \left(1 - m^2_\mu/q^2\right)^2 |\vec{p}_{D^*_s}(q^2)|\, I_i(q^2)\, dq^2 \cdot \int_{\Delta\Omega_l} \Xi_i(\theta_\ell, \theta_d, \chi)\, d\Omega$$

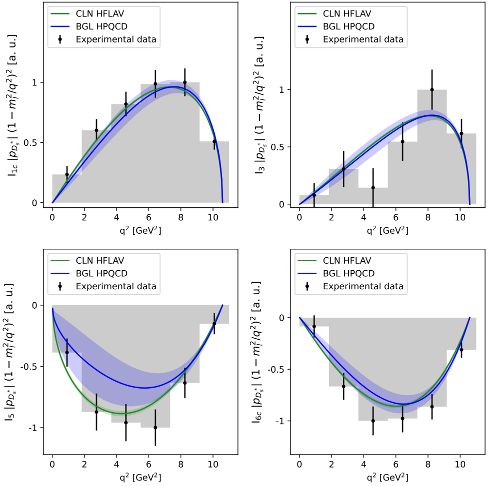
$$\propto \sum_i J_{i,k}(q^2) \cdot \zeta_{i,l}(\theta_\ell, \theta_d, \chi)$$

q^2 bins

$I_i(q^2)$ functions

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 $I_i(q^2)$ determination



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

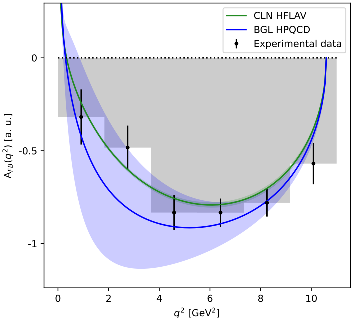
$$\propto \Big[I_{1s}\sin^2\theta_d + I_{1c}(3+\cos 2\theta_d) + I_{2s}\sin^2\theta_d\cos 2\theta_\ell$$
$$+ I_{2c}(3+\cos 2\theta_d)\cos 2\theta_\ell + I_3\sin^2\theta_d\sin^2\theta_\ell\cos 2\chi$$
$$+ I_4\sin 2\theta_d\sin 2\theta_\ell\cos\chi + I_5\sin 2\theta_d\sin\theta_\ell\cos\chi$$
$$+ I_{6s}\sin^2\theta_d\cos\theta_\ell + I_{6c}(3+\cos 2\theta_d)\cos\theta_\ell$$
$$+ I_7\sin 2\theta_d\sin\theta_\ell\sin\chi + I_8\sin 2\theta_d\sin 2\theta_\ell\sin\chi$$
$$+ I_9\sin^2\theta_d\sin^2\theta_\ell\sin 2\chi\Big]$$

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

We can build several observables to evaluate the contribution of New Physics interaction, for instance the forward-backward asymmetry:

$$\mathcal{A}_{FB}(q^2) = \left[\int_0^1 \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell} d\cos\theta_\ell - \int_{-1}^0 \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell} d\cos\theta_\ell\right] / \frac{d\Gamma}{dq^2}$$
$$= \frac{3\,(I_{6s}+4I_{6c})}{6I_{1s}+24I_{1c}-2I_{2s}-8I_{2c}}$$

$\Rightarrow$ Compute the asymmetry for each q^2 bin using the fitted $I_i(q^2)$ values



Conclusions

- This work will lead to the first measurement of $B_s^0 \to D_s^* \mu \nu_\mu$ differential distributions
  - ⋆ Computation of systematic uncertainties is ongoing, a first version of the internal Analysis Note will be published soon
- It is possible to directly test different New Physics scenarios, with both a model-dependent and a model-independent approach

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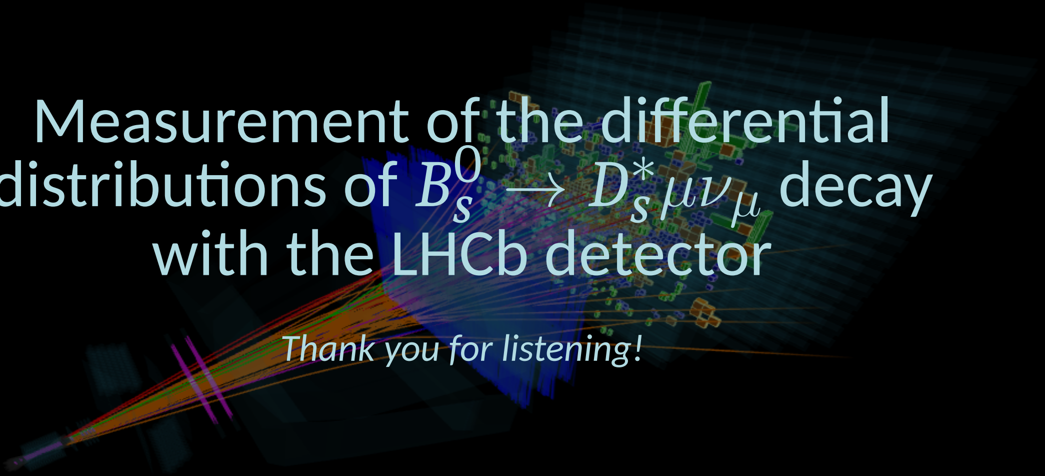


Thank you for listening!

F. Manganella - November 13^{th}, 2024

The differential width

arXiv:1801.10468

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

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

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

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

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

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

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

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

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

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

New Physics tensor

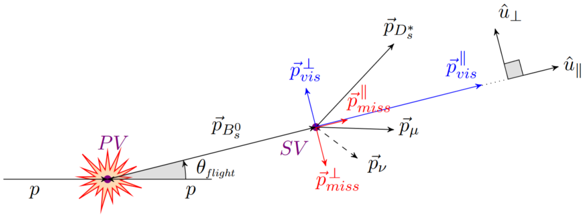
$$H'_{eff} = H^{SM}_{eff} + \frac{G_F}{\sqrt{2}} V_{cb} \left[\epsilon^{\ell}_{T} \bar{c} \sigma_{\mu\nu} (1-\gamma_5) b \bar{\ell} \sigma^{\mu\nu} (1-\gamma_5) \nu_\ell + h.c. \right] \qquad \sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$$

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

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

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

Kinematic variables reconstruction



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

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

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

$$\Downarrow$$

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

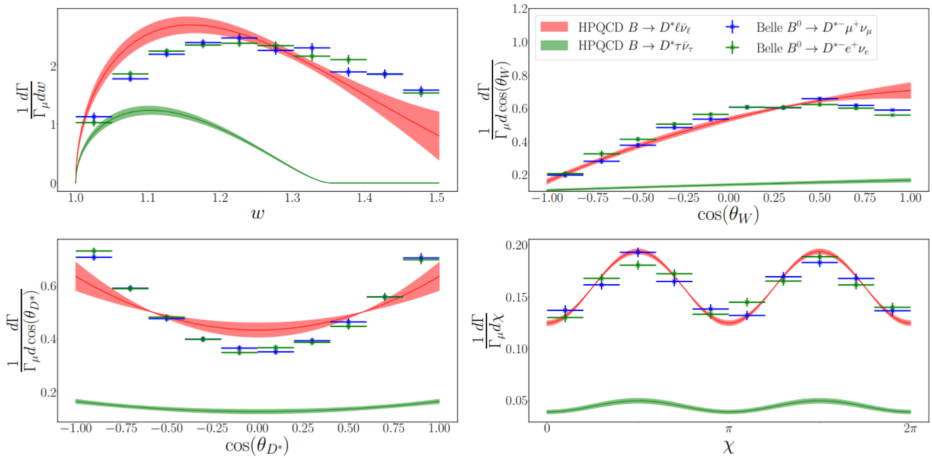
Unfolded fit

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

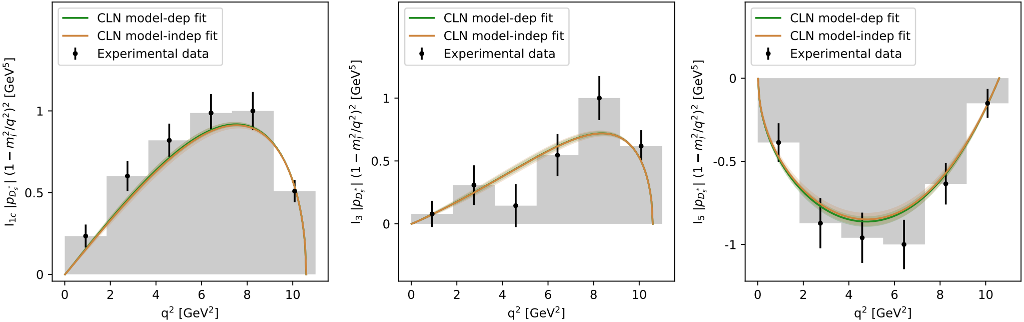
where $\vec{N}^{\text{unf}}$ is obtained using Bayesian unfolding

Belle and HPQCD

arXiv:2304.03137



CLN and BGL shapes from fitted $I_i(q^2)$ functions



Where:

- Model-dependent shape = extract model parameters from differential distribution
- Model-independent shape = extract model parameters from the fitted integrals