$B \to D^* l \nu$: How to make the most out o upcoming measurement

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Beyond the flavour Anomalies 20

Ro
Centro Congressi Sapien

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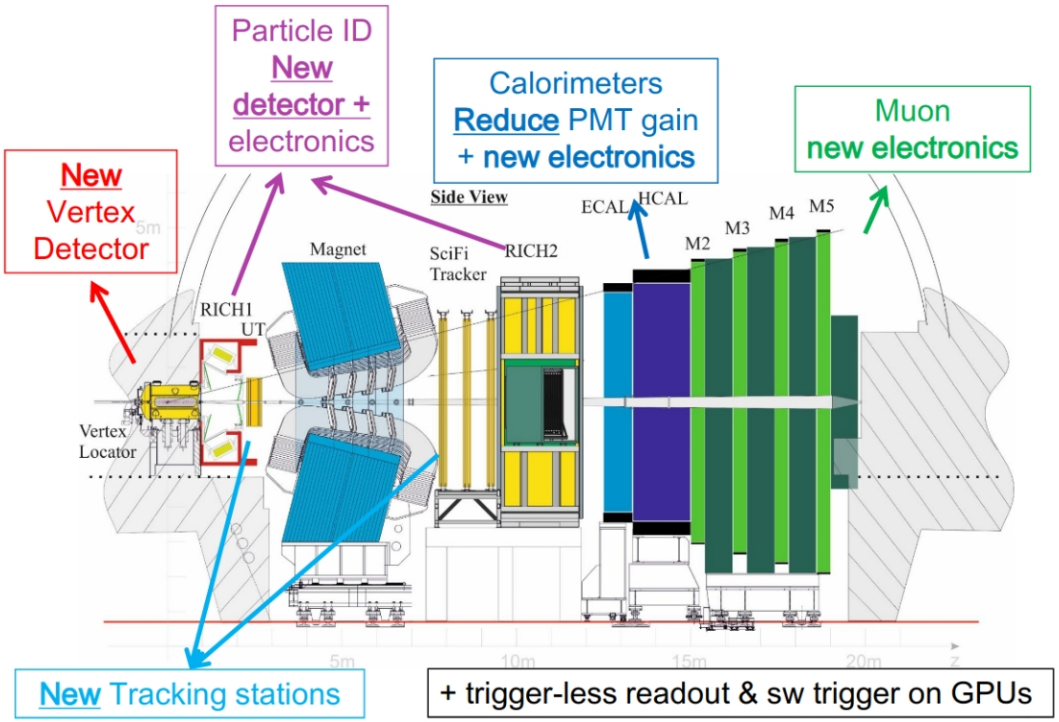
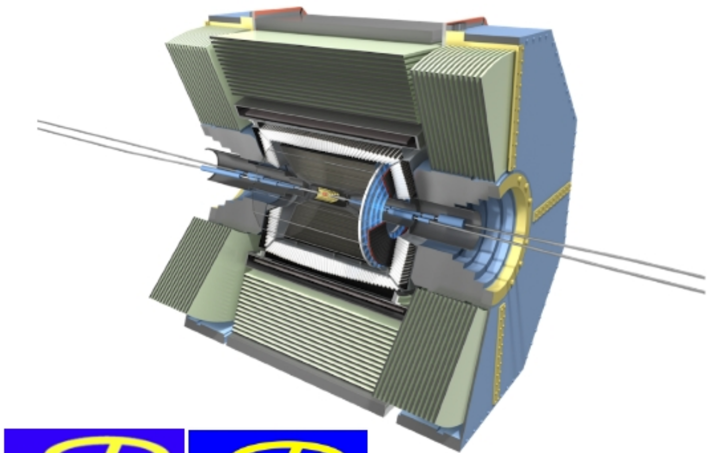
LHCb and Belle,Belle2





BELLE

Belle II

- LHCb
- Spectrometer in the forward direction (2<η<5)
- Excellent vertexing, tracking and particle identification
- Most backgrounds come from other *B* decays rather than underlying event
- Production of all types of *b* and *c* hadrons

Run1: 3 fb^{-1} @ √s =7-8 TeV
Run2: 6 fb^{-1}@ √s =13 TeV

- Belle/Belle2
- Constrained kinematics
- Easy to cross-feed tracks due to low CM momentum of B mesons
- Electrons ad good as muons

~10^9 Υ(4S) per ab^{-1}

Outline

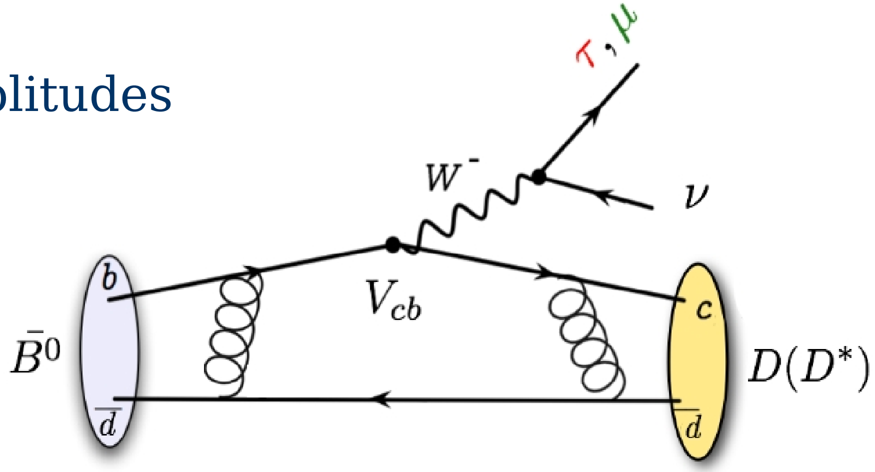
- $B \to D^* l\nu$ what we measure
- Case study: Belle recent measurements
- LHCb: some ongoing analyses
- Semitauonics

Opportunities with B→D*lν decays

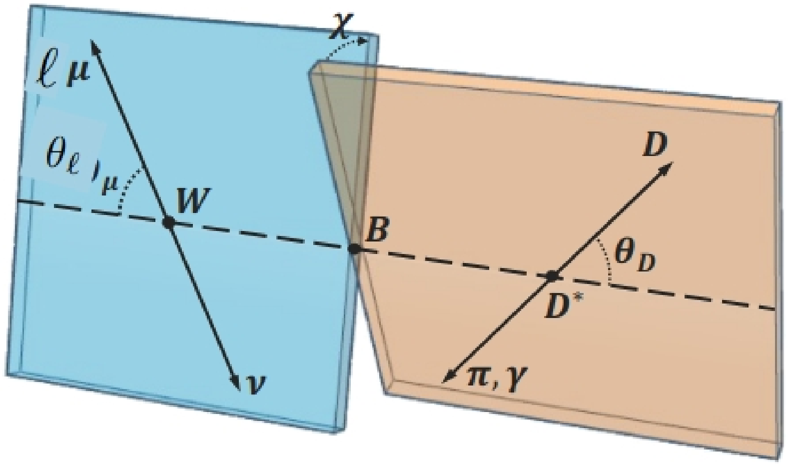
$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

Electroweak coupling + Form factors
Sensitive to new physics

- $\mathcal{H}_i(q^2)$ depend on combinations of helicity amplitudes
  - Form factors determination
  - New Physics searches
- Angles provide observables sensitive to NP:
  - F-B asymmetry
  - Longitudinal polarization
  - ...
  - Complementary to LFU



- Transition form factor measurements
- LFU test
- V_{cb}

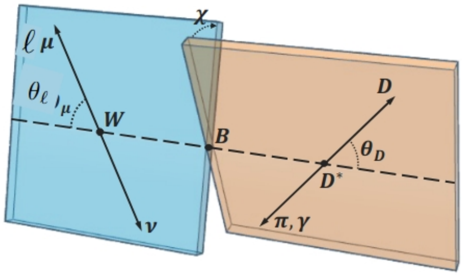


Angular coefficients

$$\frac{d^4\Gamma(B\to D^*\mu\nu)}{dw\,d\cos\theta_\mu\,d\cos\theta_D\,d\chi}=\frac{3m_B^3m_{D^*}^2G_F^2}{16(4\pi)^4}\eta_{EW}^2|V_{cb}|^2|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2 \qquad |\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2=\sum_i^6\mathcal{H}_i(w)k_i(\theta_\mu,\theta_D,\chi)$$

For massless leptons

i	$\mathcal{H}_i(w)$	$k_i(\theta_\mu,\theta_D,\chi)$	
		$D^*\to D\gamma$	$D^*\to D\pi^0$
1	H_+^2	$\frac{1}{2}(1+\cos^2\theta_D)(1-\cos\theta_\mu)^2$	$\sin^2\theta_D(1-\cos\theta_\mu)^2$
2	H_-^2	$\frac{1}{2}(1+\cos^2\theta_D)(1+\cos\theta_\mu)^2$	$\sin^2\theta_D(1+\cos\theta_\mu)^2$
3	H_0^2	$2\sin^2\theta_D\sin^2\theta_\mu$	$4\cos^2\theta_D\sin^2\theta_\mu$
4	H_+H_-	$\sin^2\theta_D\sin^2\theta_\mu\cos2\chi$	$-2\sin^2\theta_D\sin^2\theta_\mu\cos2\chi$
5	H_+H_0	$\sin2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$	$-2\sin2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$
6	H_-H_0	$-\sin2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$	$2\sin2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$

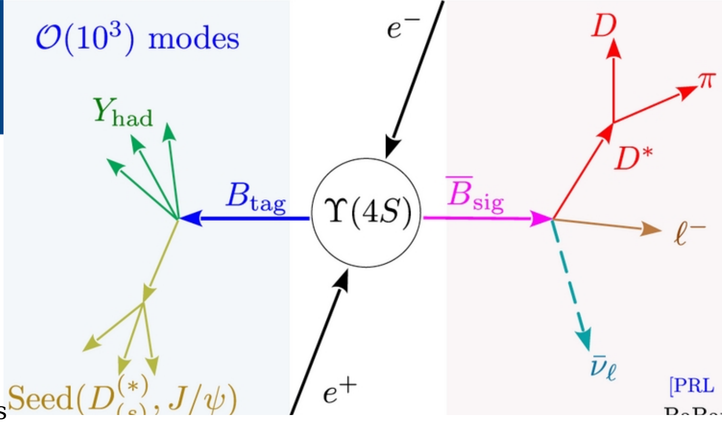


- The q^2 dependence parametrized using CLN or BGL. The differential rate can also be expressed in terms of combination of 12 angular terms $I_i(q^2)$ (or J_i) that include both SM and NP effects
  - [JHEP 12 (2020) 144]

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

- The q^2 dependence is determined by the form factors. Various parametrizations available: CLN (obsolete), BGL, BCL, BLPR

B-Factories analyses (recent)



B Tagged analysis:

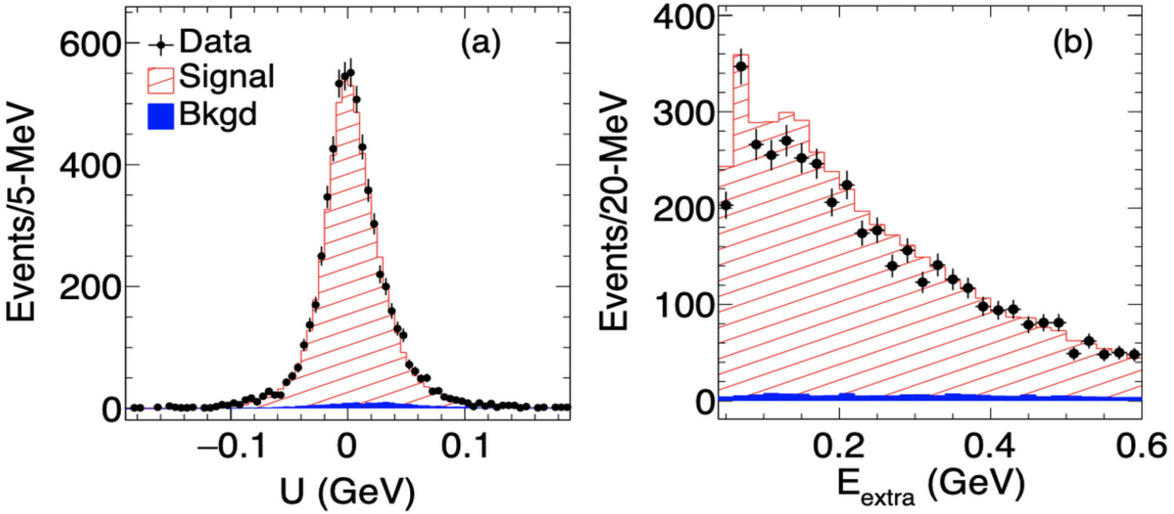
Belle Phys.Rev.D 108 (2023) 1, 012002
Belle Phys.Rev.Lett 133 (2024) 13, 131801
Belle II Phys.Rev.D 108 (2023) 9, 9

Low efficiency
Calibration of absolute efficiency is hard

Clean sample + kinematic constraints →
Suited for precise angular analysis

BaBar Phys.Rev.Lett 123 (2019) 091801 (first unbinned analysis)

U=E$_{\rm miss}$ – P$_{\rm miss}$

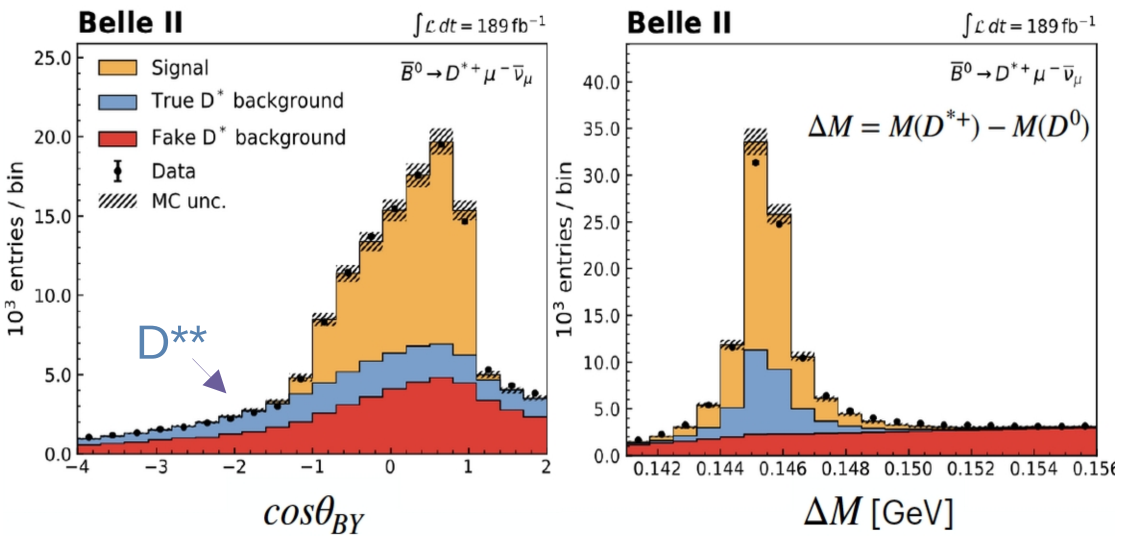


B untagged analyses

Belle Phys. Rev. D 100 (2019) 052007
Belle II Phys.Rev.D 108 (2023) 092013

High efficiency compensate for low resolution of approximated kinematics

$$cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$



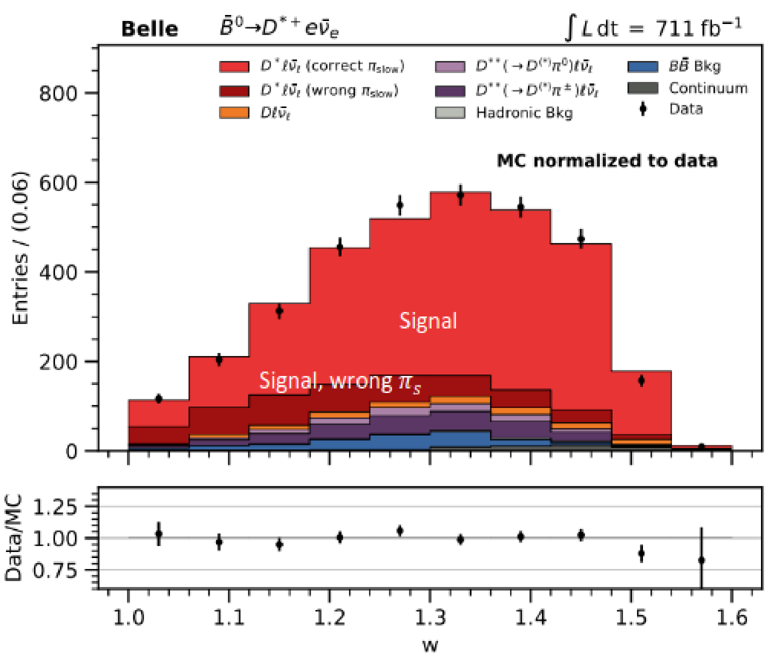
Differential analysis @ Belle

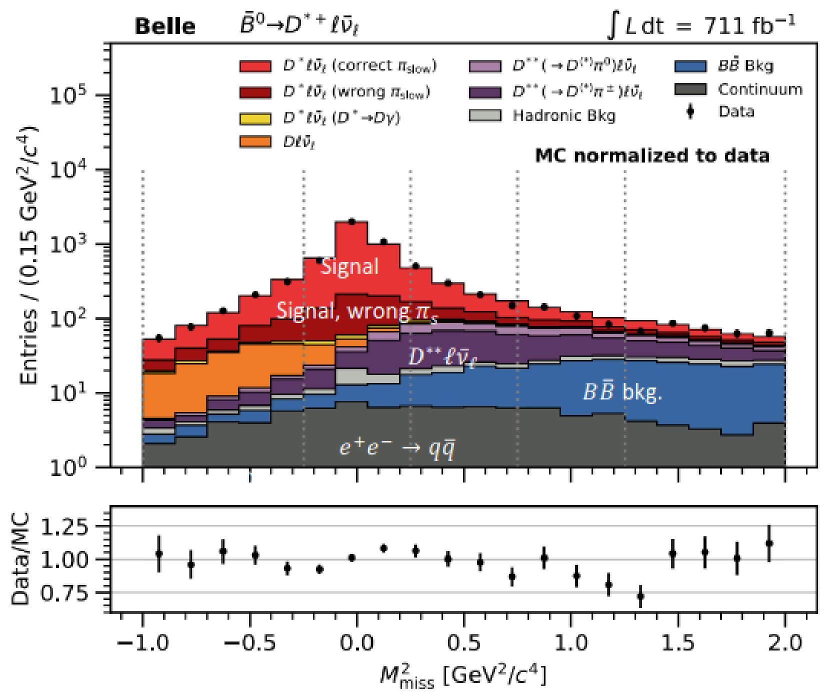
Phys.Rev.D 108 (2023) 1, 012002
Phys.Rev.Lett 133 (2024) 13, 131801

- Belle: 711 fb^{-1} @ Υ(4s) with hadronic tag-side reconstruction
- Same dataset and selection for two different analysis
  - Measure the marginal distributions of the 4D differential decay rate
  - Measure the angular coefficients $J(w)$ in bins of w

Strategy

- signal extraction in bins of kinematic variables
- unfolding for resolution and correct for the acceptance





- Background subtraction in independent variable to reduce model dependency

$$M^2_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{D^*} - p_\ell)^2.$$

Differential analysis @ Belle

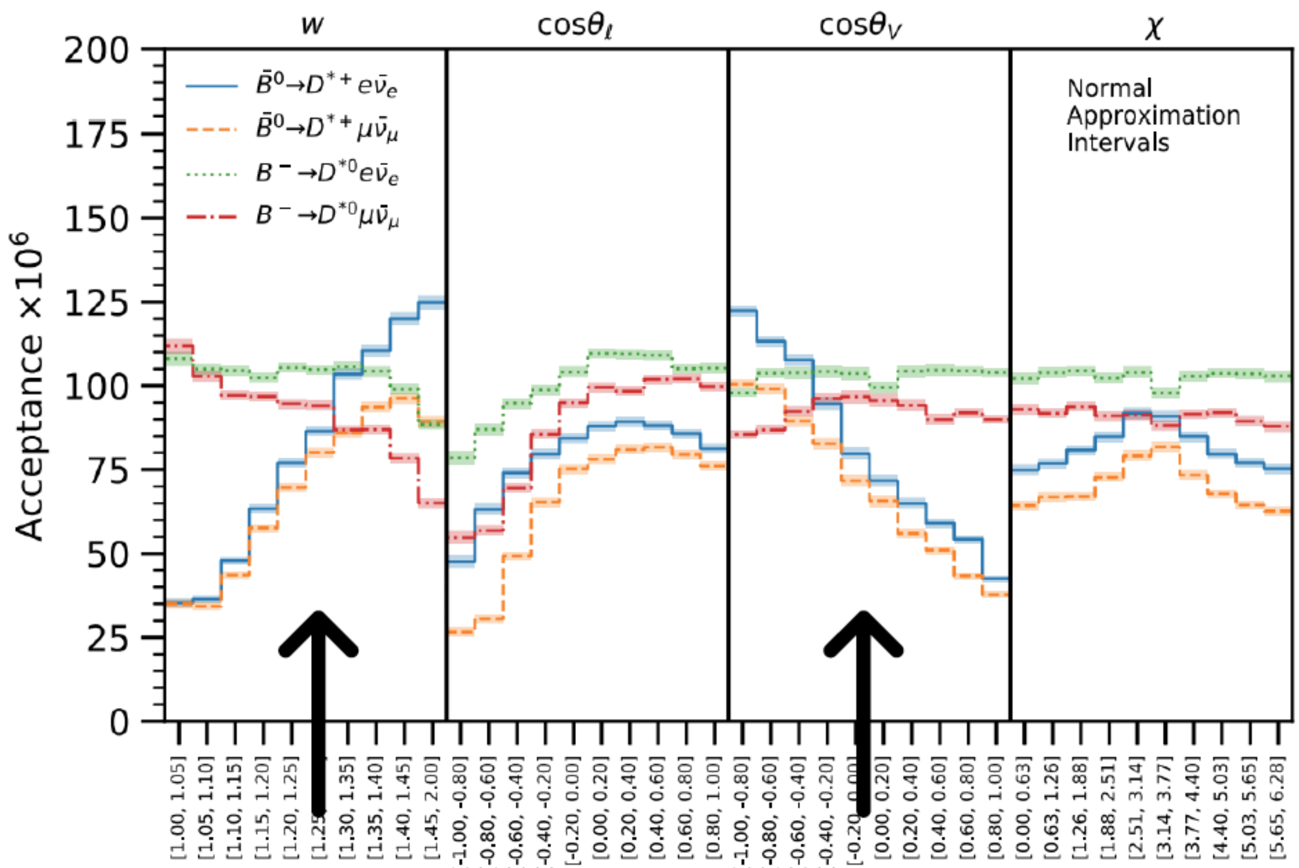
Phys.Rev.D 108 (2023) 1, 012002
Phys.Rev.Lett 133 (2024) 13, 131801

First time Belle consider neutral slow pions

- larger kinematic coverage
- but more mis-identified pions and worse resolution

$$\bar{B}^0 \to D^{*+}(\to D^0\pi_s^+, D^+\pi_s^0)$$

$$B^- \to D^{*0}(\to D^0\pi_s^0)\ell\bar{\nu}_\ell$$

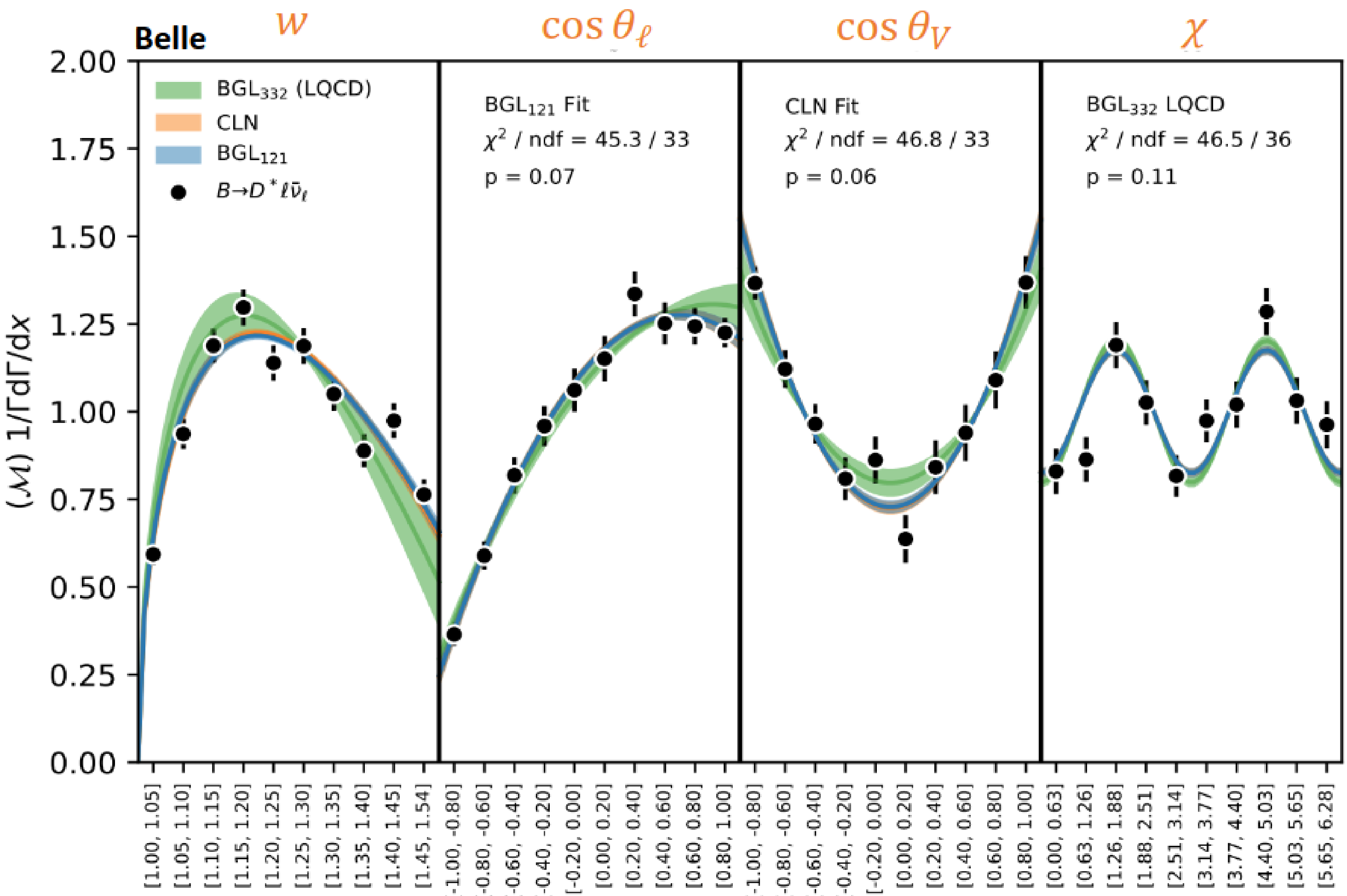


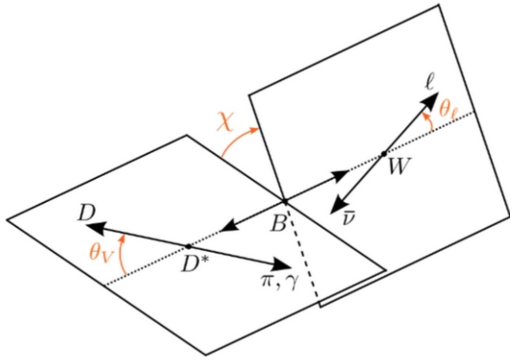
Difference in the efficiency shape is caused by the slow pion reconstruction efficiency

Differential shape of exclusive B→D*μν

Phys.Rev.D 108 (2023) 1, 012002

- Marginalized distributions + full covariance matrix
- Data well described by BGL and CLN parametrizations

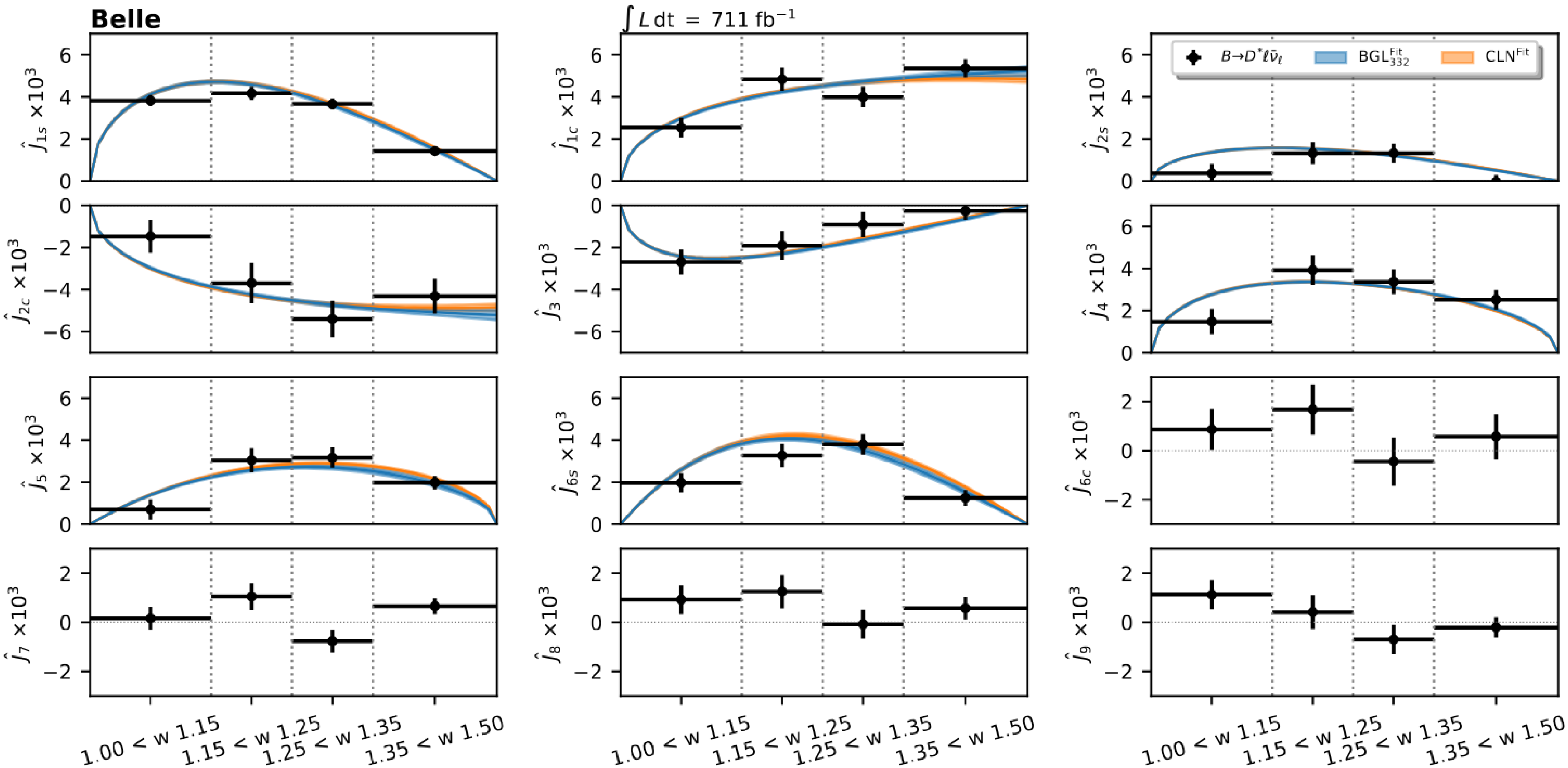




Differential distributions

- Measurement of the 12 angular coefficients in 4 bin of w

Phys.Rev.Lett 133 (2024) 13, 131801

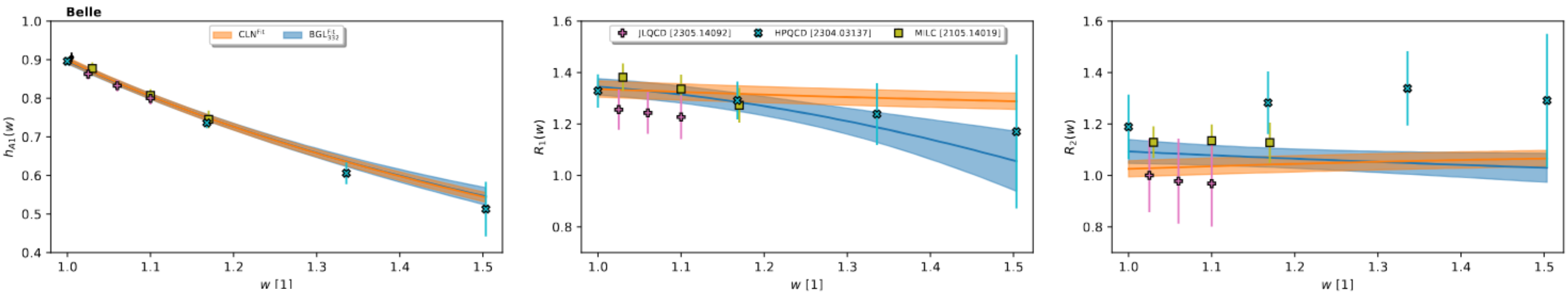


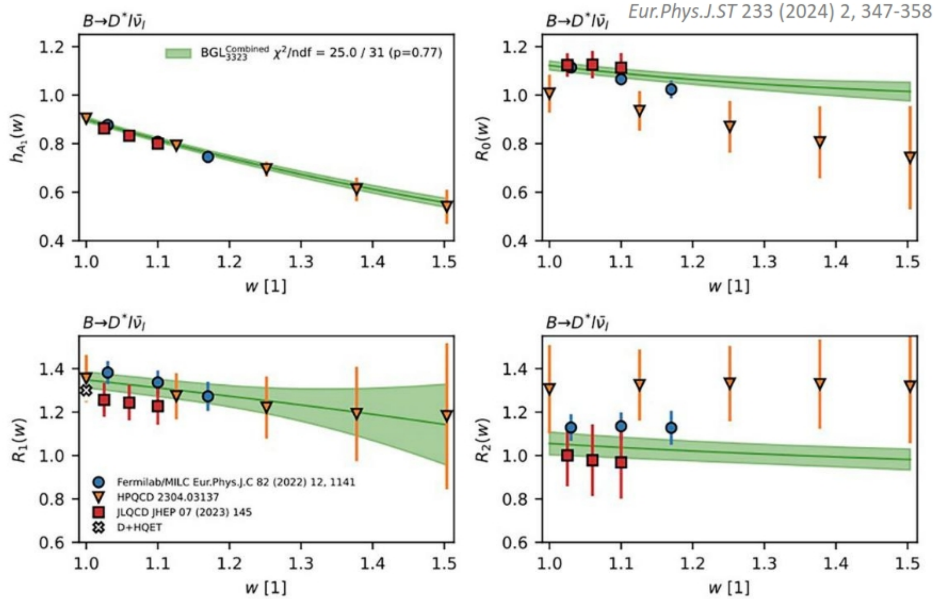
Informations available in HepData

Form Factor of $B \to D^* \mu \nu$ and $|V_{cb}|$ extration

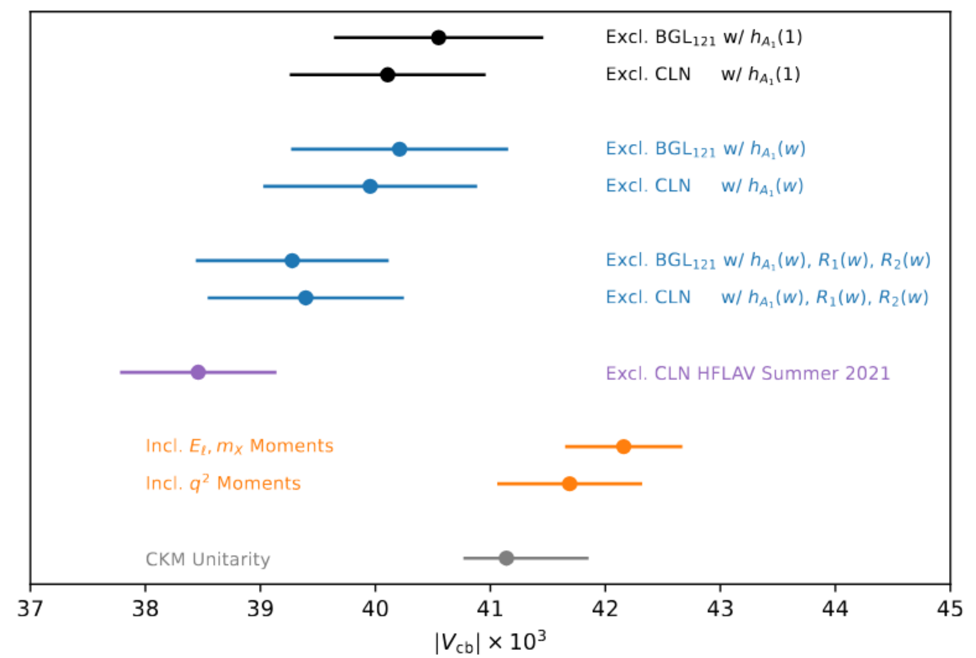
Shape measurements

[arXiv:2301.07529]





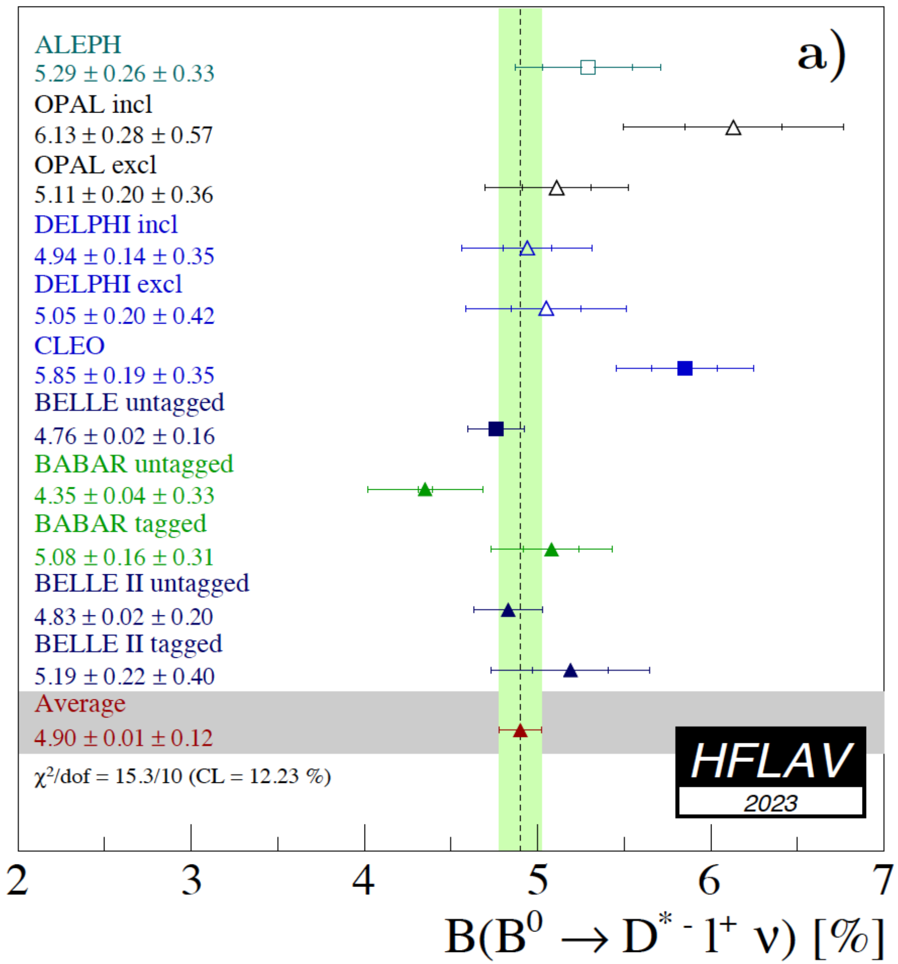
Eur.Phys.J.ST 233 (2024) 2, 347-358

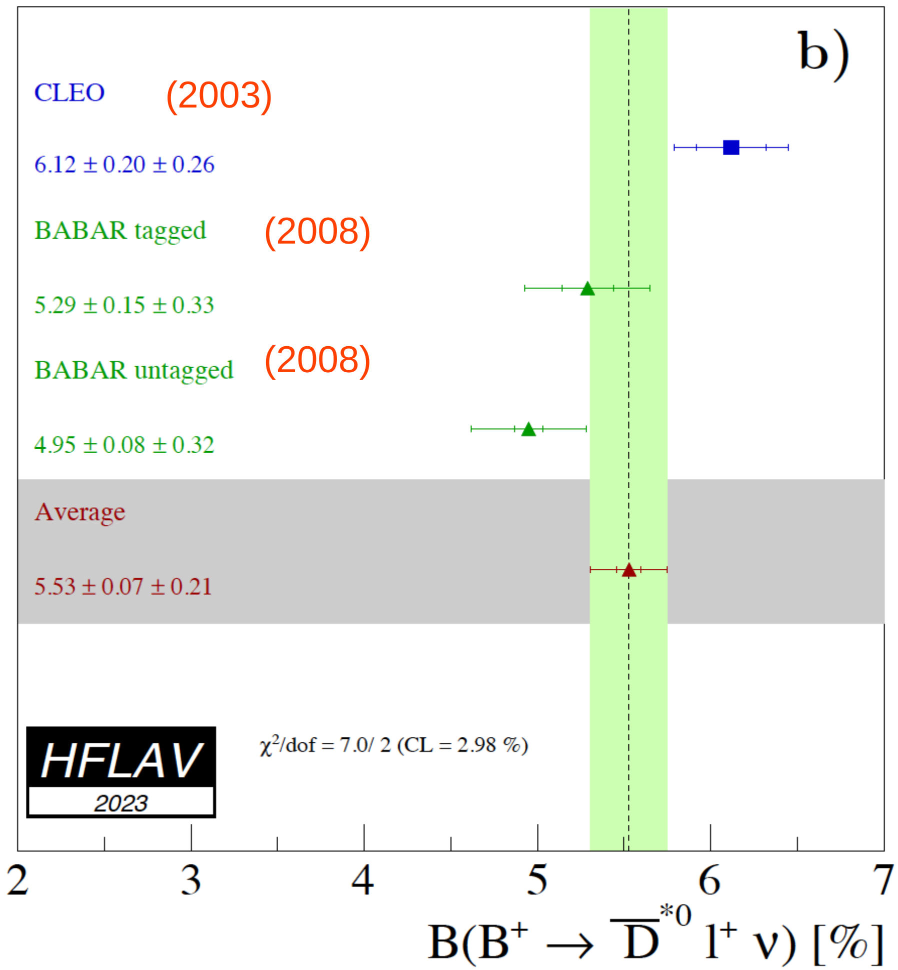


Measured shapes + LQCD inputs +
BF from HFLAV2021

$$|V_{cb}| = \sqrt{\frac{\mathcal{B}}{\Gamma' \tau_B}}$$

Branching fractions $B \to D^*\mu\nu$





Significant systematics common to the various measurements
- Slow pion efficiency
- Background from $B \to D^{**}$
- f_{00}/f_{+-}

Simultaneous analysis of $B \to D$ and $B \to D^*$
Ongoing analysis @ BelleII: no soft pion and independent from f_{00}

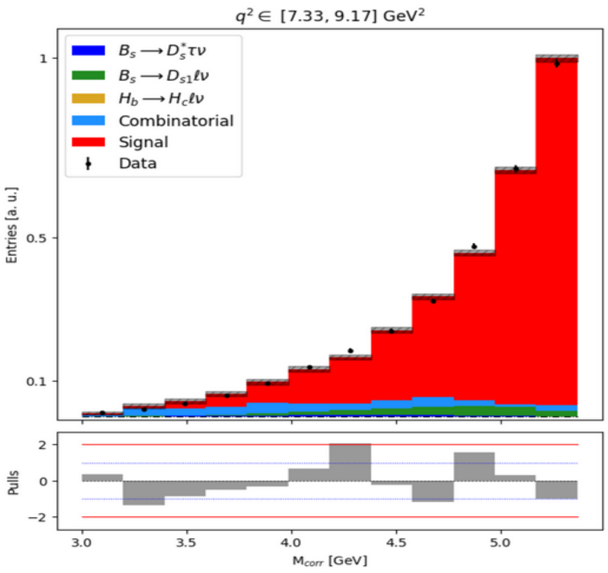
Differential distribution for $B_s \to D_s^* \mu\nu$ decays

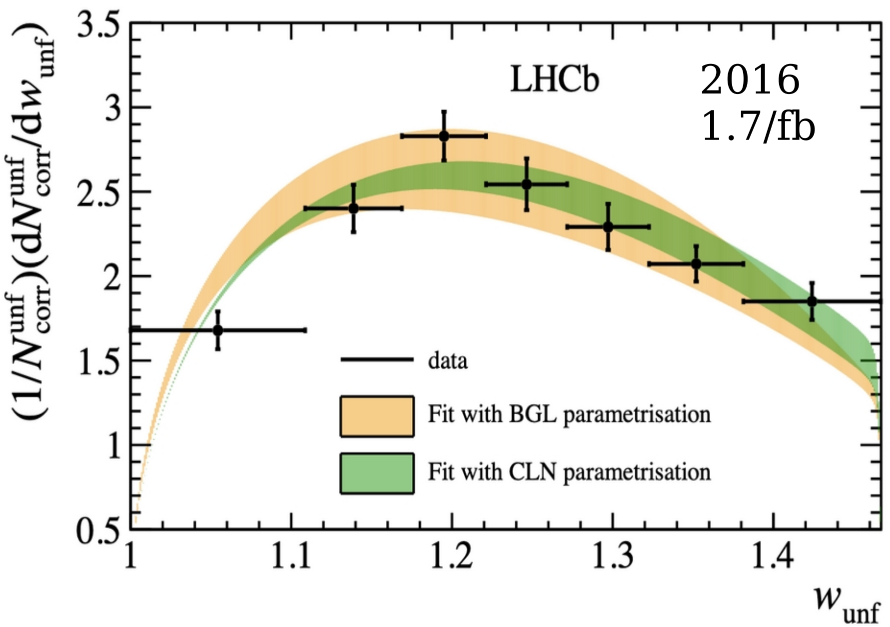
- B-hadron momentum magnitude not known
- B-direction precisely determined by PV and Decay Vertex
  - Kinematic determined with a 2-fold ambiguity
  - Corrected mass to extract signal yield

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

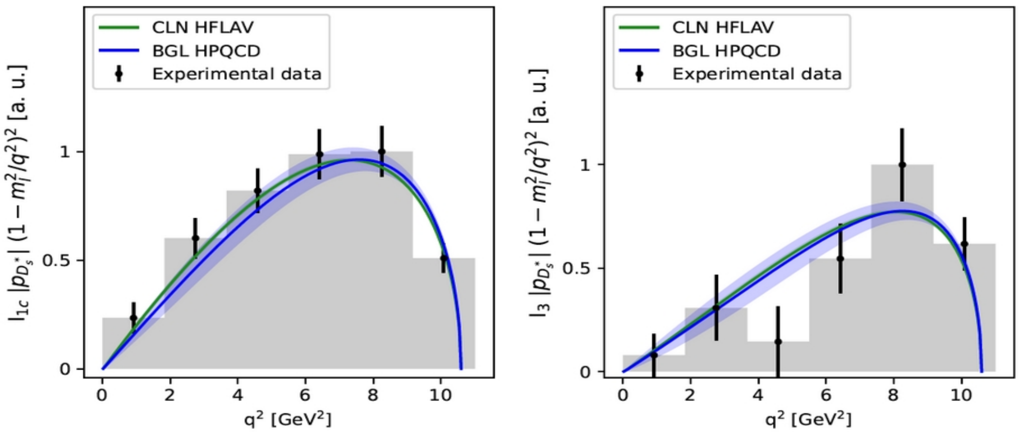
- Published the unfolded and efficiency corrected w spectrum

JHEP12(2020)144





Ongoing: determination of the J angular coefficients in 6 bins of q^2



New Physics searches using B→D*μν decays

- Measure directly Wilson Coefficients: flexible to use NP model or be model independent
  - Extract directly Wilson Coefficients and FF parameters from fit to data. First sensitive estimated B. Mitreska [CERN-THESIS-2022-105]

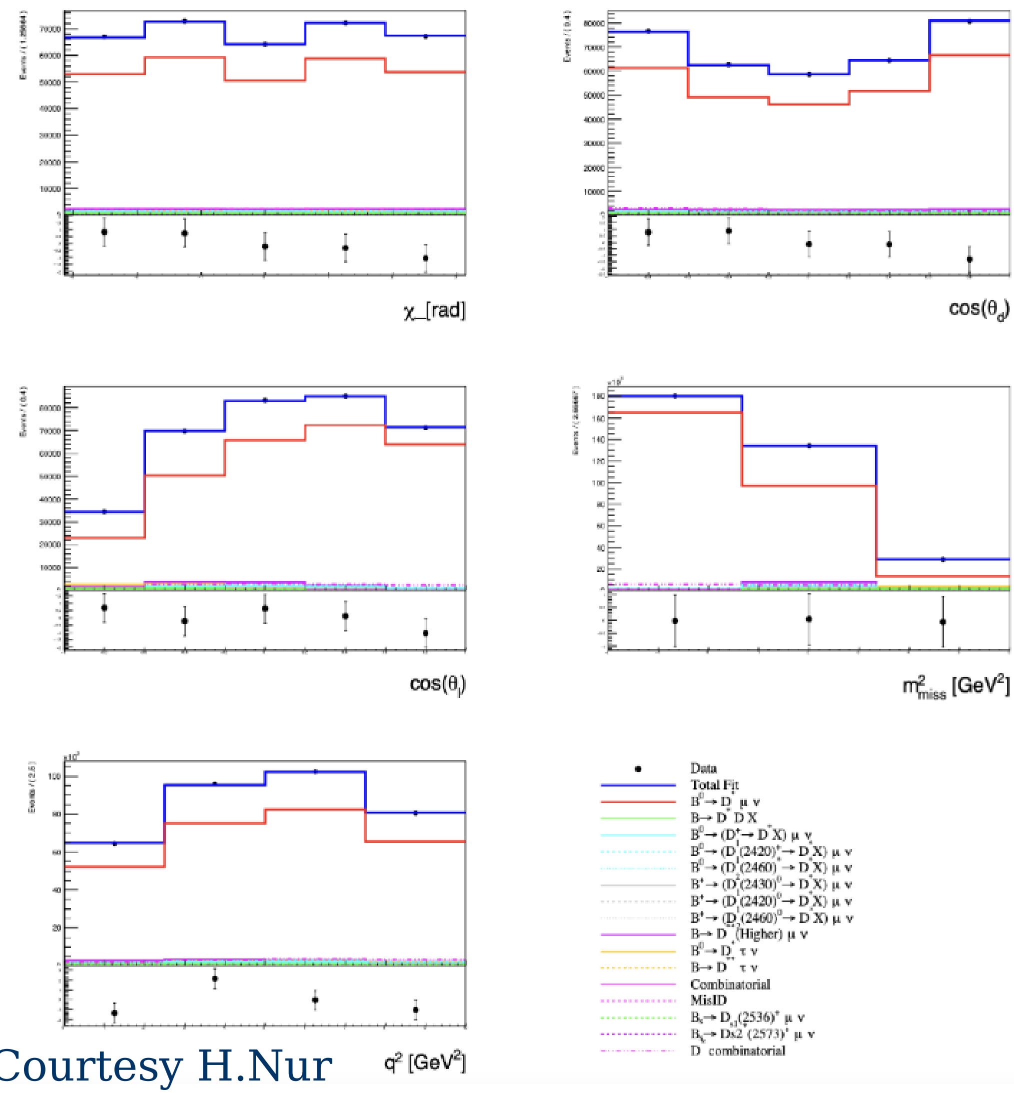
Wilson coefficients

$$C_i = C_i^{SM} + C_i^{NP}$$

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

- New Physics search strategies:
- Fit in 5D (includes M_{corr} to account for model dependence in the signal yields extraction)
- Model the New Physics effects in the fitting template using the HAMMER tool [Eur. Phys. J. C 80, 883 (2020)] to reweight MC event and obtain dynamically the templates
- Folding-in the experimental resolution and acceptance
- Shape analysis: no attempt to measure $|V_{cb}|$

- Ongoing measurement to provide differential spectra unfolded
  - High precision q^2 spectrum (and angular shapes)



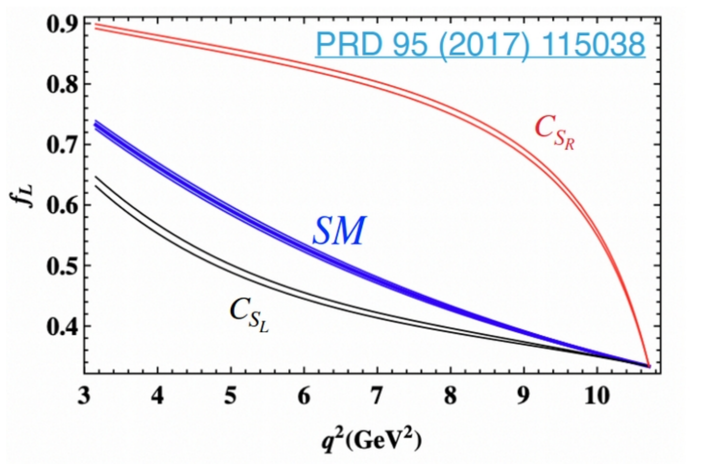
Courtesy H.Nur

Longitudinal D* polarization: beyond the LFU

[arXiv:2311.05224]

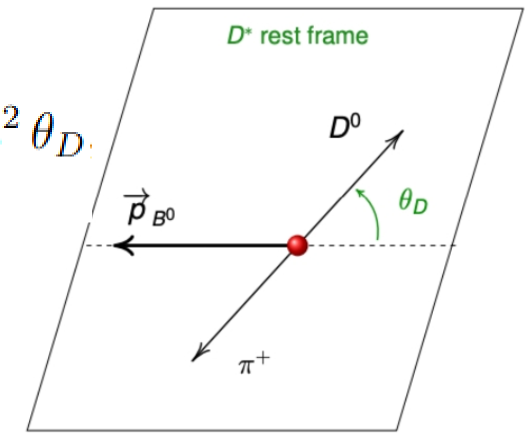
- New physics can strongly affect the D^* longitudinal polarization $F_L^{D^*}$ also if LFU ratios align with the SM prediction [arXiv:1907.02257]

- Measured by Belle: 0.60 ± 0.08 ±0.04 [arXiv:1903.03102]



- The differential decays rate of $D^* \to D^0 \pi$ can be expressed as

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



- $F_L^{D^*}$ can be calculated as

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

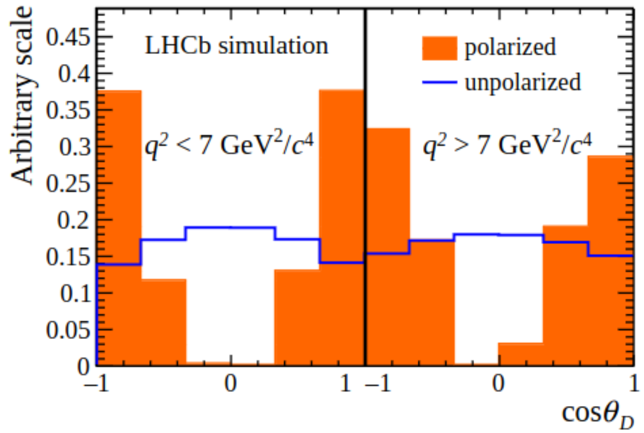
where

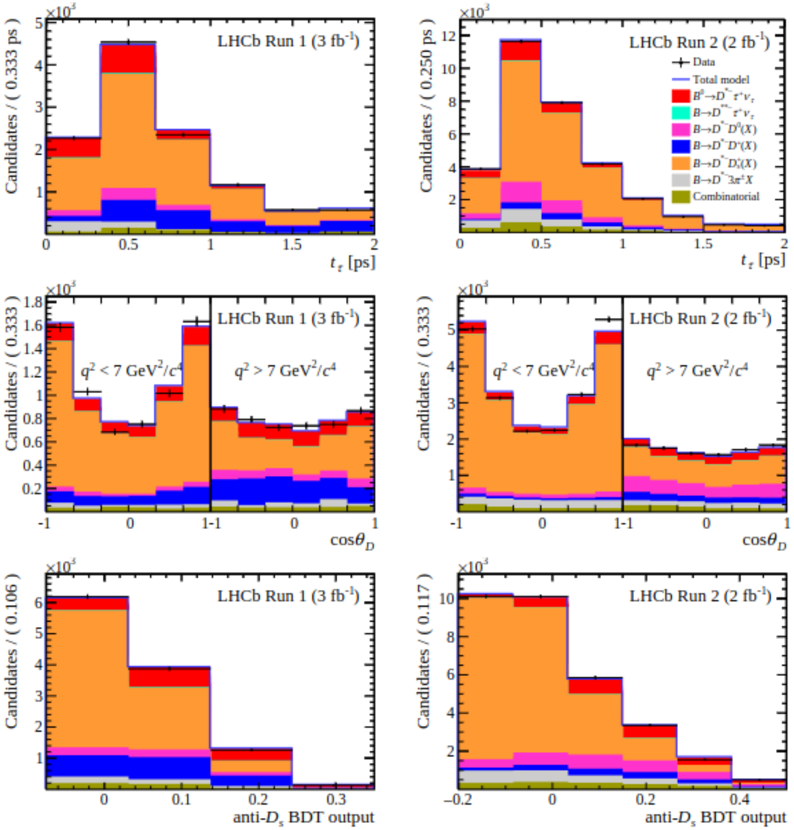
  - a_θ and c_θ are linear combinations of the angular coefficients

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

Longitudinal D^* polarization: template fit

- $F_L^{D^*}$ determined in two q^2 regions: $q^2 > 7\,\mathrm{GeV}^2/c^4$, $q^2 < 7\,\mathrm{GeV}^2/c^4$
- $F_L^{D^*}$ is extracted from a_θ and c_θ determined by splitting the simulated signal template in
  - $N_{\mathrm{unpolarized}} \propto a_\theta$
  - $N_{\mathrm{polarized}} \propto c_\theta$
- 4D template fit:
  - τ lifetime
  - q^2
  - $\cos\theta_D$
  - Anti-D_s BDT output
- Background treatment similar to R(D*) [PRD 108 012018]
- Simultaneous fit to Run1 and Run2
- Dominant sources of systematic uncertainties:
  - limited size of simulations samples;
  - form factors parametrization;
  - double charm background modelling;





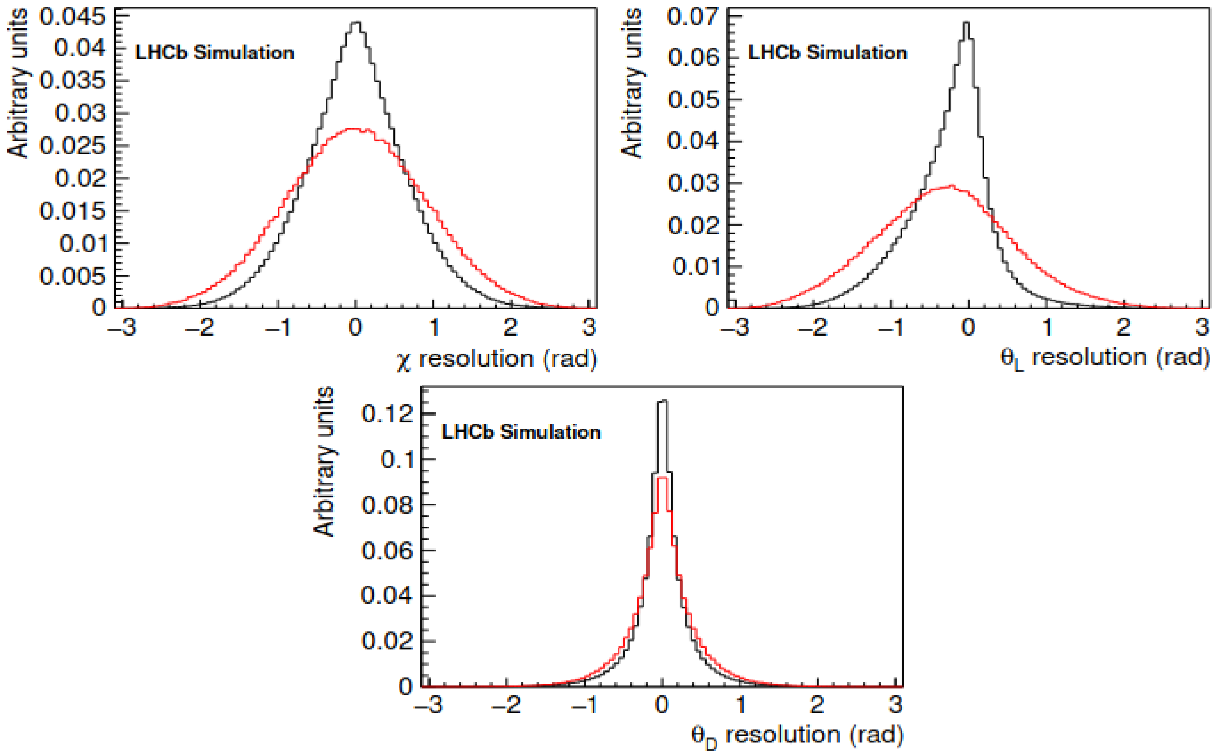
[arXiv:2311.05224]

Extending differential decays: towards Upgrade II

[arXiv:2311.05224]

- Possibility to describe the fully differential decay rate thanks to LHCb capability of resolving the three angles

$B \to D^* \mu\nu$
$B \to D^* \tau\nu$



- However, broad resolutions demand very large sample to extract the underlying physics
- Measure the 12 angular coefficients integrated in q^2 following a novel approach [JHEP 11(2019) 133]
  - Ongoing feasibility study with $B \to D^* \mu\nu$

Conclusions

- **Paramount to provide enough information (HepData) so the data can be re-used and re-interpreted**
  - Different form factor inputs (LQCD/LCSR), different assumptions, series truncation…
- **Various existing measurements already provide informations for re-interpretation**
  - Healthy to analyze the same data using different approaches
  - Other analysis are ongoing from both LHCb and Belle II
- **Crucial to perform ancillary measurements**
  - $B \to D^{**}$, both BF and Form Factors
    - Multi-pion production, other decay modes non considered?
  - $B \to DDX$: background to LHCb measurements, large uncertainty
- DO not forget about other B-hadrons accessible at LHC

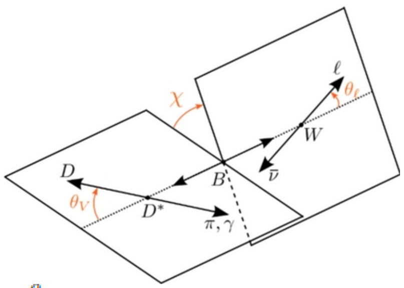
Backup

Differential analysis

- Belle: 711 fb[-1] @ Υ(4s) with hadronic tag-side reconstruction

[arXiv:2310.20286]

- $$\frac{\mathrm{d}\Gamma(\bar{B}\to D^*\ell\bar{\nu}_\ell)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\mathrm{V}\,\mathrm{d}\chi} = \frac{2G_\mathrm{F}^2\eta_\mathrm{EW}^2|V_\mathrm{cb}|^2 m_B^4 m_{\mathrm{D}^*}}{2\pi^4} \times \Big(J_{1s}\sin^2\theta_\mathrm{V} + J_{1c}\cos^2\theta_\mathrm{V} + (J_{2s}\sin^2\theta_\mathrm{V} + J_{2c}\cos^2\theta_\mathrm{V})\cos 2\theta_\ell + J_3\sin^2\theta_\mathrm{V}\sin^2\theta_\ell\cos 2\chi + J_4\sin 2\theta_\mathrm{V}\sin 2\theta_\ell\cos\chi + J_5\sin 2\theta_\mathrm{V}\sin\theta_\ell\cos\chi + (J_{6s}\sin^2\theta_\mathrm{V} + J_{6c}\cos^2\theta_\mathrm{V})\cos\theta_\ell + J_7\sin 2\theta_\mathrm{V}\sin\theta_\ell\sin\chi + J_8\sin 2\theta_\mathrm{V}\sin 2\theta_\ell\sin\chi + J_9\sin^2\theta_\mathrm{V}\sin^2\theta_\ell\sin 2\chi \Big).$$

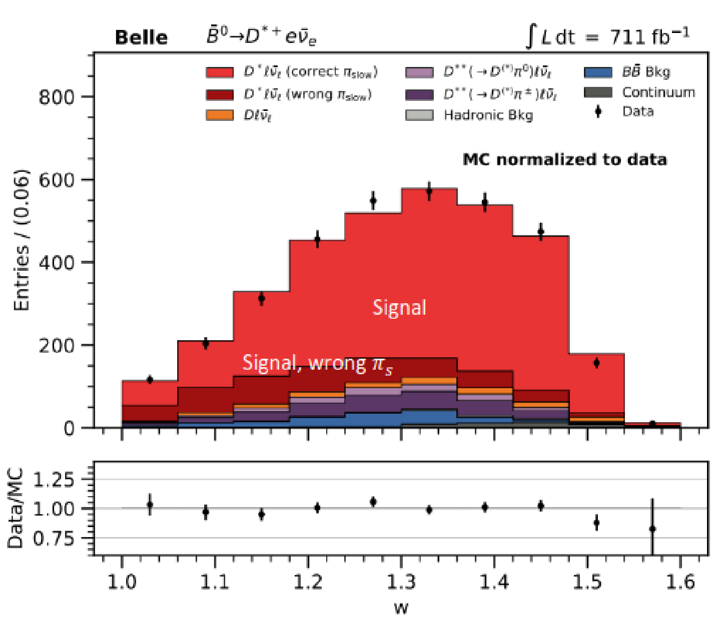


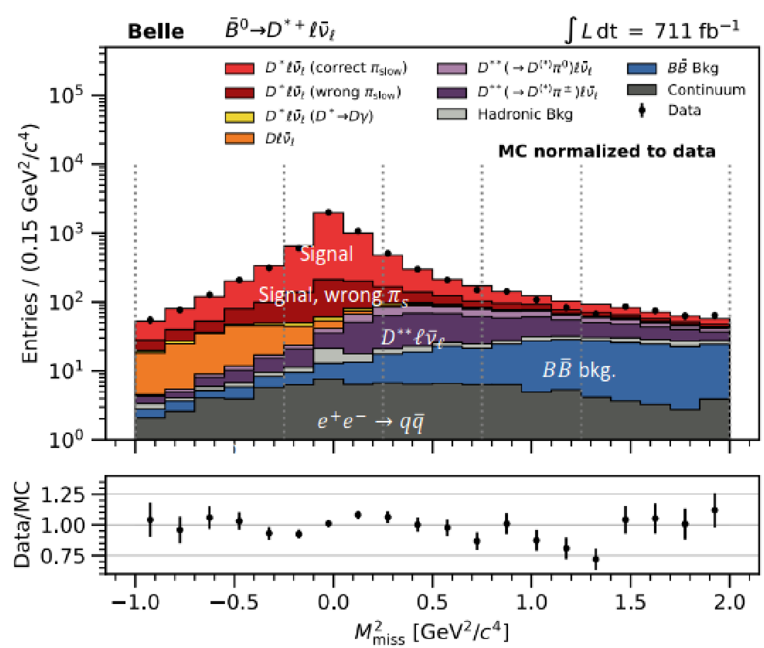
- Measurement of the angular coefficients in 4 bin of w

$$\bar{J}_i = \frac{1}{N_i}\sum_{j=1}^{8}\sum_{k,l=1}^{4} \eta_{i,j}^{\chi}\eta_{i,k}^{\theta_\ell}\eta_{i,l}^{\theta_V} R_{jkl}$$

- Signal yields in bin of angles, w, decay modes determined by

$$M_\mathrm{miss}^2 = (p_{e^+e^-} - p_\mathrm{tag} - p_{D^*} - p_\ell)^2.$$





- Background subtraction in independent variable to reduce model dependency

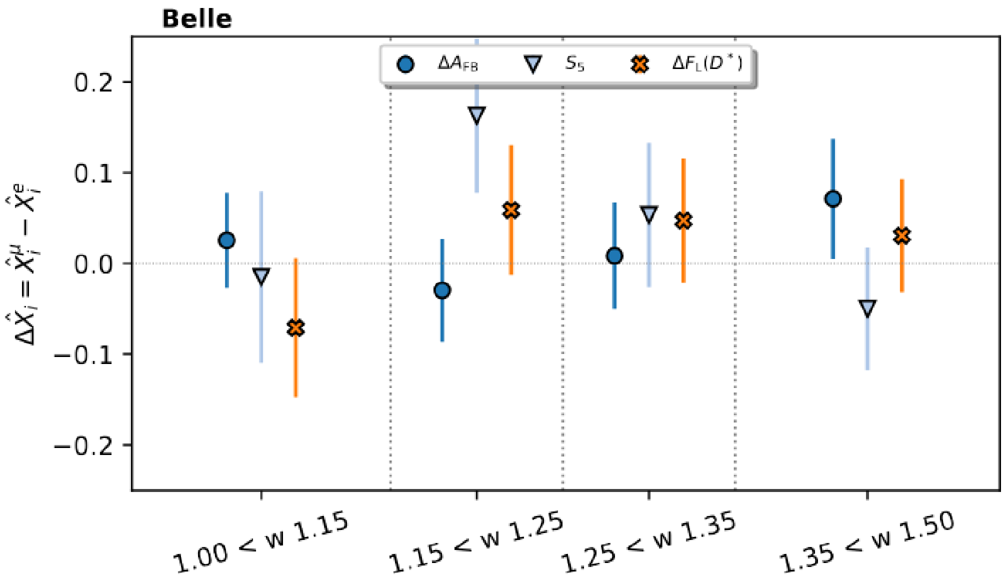
LFU observables of B→D*μν

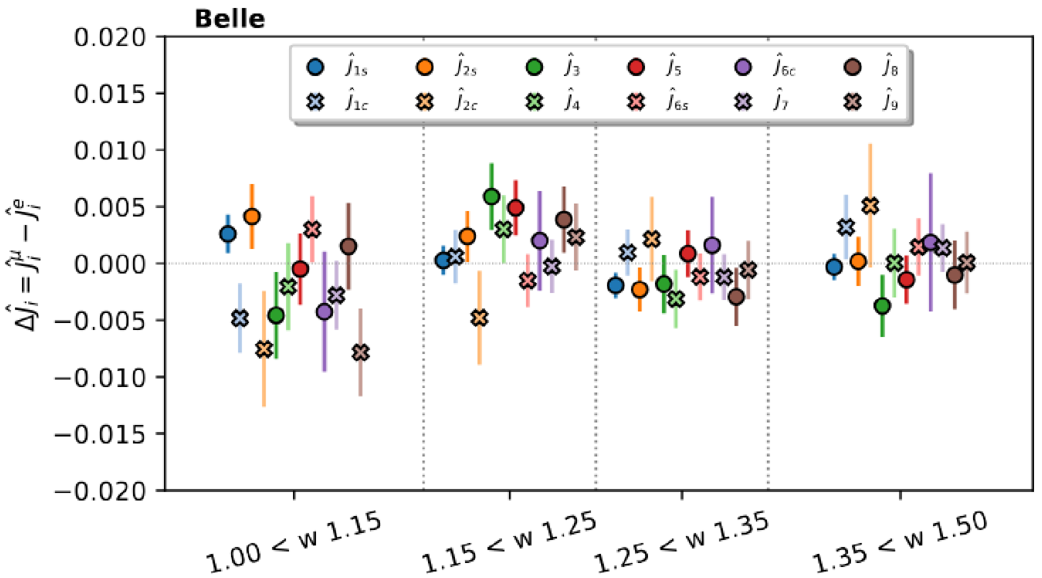
[arXiv:2311.05224]

- To test LFU between electrons and muons
- $\Delta A_{\mathrm{FB}} = A^{\mu}_{\mathrm{FB}} - A^{e}_{\mathrm{FB}}$
- No significant deviation observed

$$\Delta X = X^{\mu} - X^{e}$$

Observable	χ^2 / ndf	p-value
ΔA_{FB}	1.7 / 4	0.79
$\Delta F_{\mathrm{L}}(D^*)$	2.3 / 4	0.67
$\Delta \hat{J}_{1s}$	5.3 / 4	0.26
$\Delta \hat{J}_{1c}$	4.2 / 4	0.38
$\Delta \hat{J}_{2s}$	4.6 / 4	0.33
$\Delta \hat{J}_{2c}$	5.0 / 4	0.28
$\Delta \hat{J}_{3}$	7.4 / 4	0.12
$\Delta \hat{J}_{4}$	2.5 / 4	0.64
$\Delta \hat{J}_{5}$	4.8 / 4	0.31
$\Delta \hat{J}_{6s}$	2.1 / 4	0.72
$\Delta \hat{J}_{6c}$	1.1 / 4	0.89
$\Delta \hat{J}_{7}$	1.6 / 4	0.81
$\Delta \hat{J}_{8}$	3.3 / 4	0.51
$\Delta \hat{J}_{9}$	4.6 / 4	0.33
$\Delta \hat{J}_{i}$	41 / 48	0.76





Results

$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) : (4.922 \pm 0.023(stat) \pm 0.220(syst))\,\%$

Compatible with the current WA: $(4.97 \pm 0.12)\,\%$

$|V_{cb}|_{BGL} = (40.57 \pm 0.31(stat) \pm 0.95(syst) \pm 0.58(th)) \cdot 10^{-3}$

Compatible with the exclusive (inclusive) WA: 1.5σ (1.3σ)

$|V_{cb}|_{CLN} = (40.13 \pm 0.27(stat) \pm 0.93(syst) \pm 0.58(th)) \cdot 10^{-3}$

Compatible with the exclusive (inclusive) WA: 1.1σ (1.6σ)

Use FNAL/MILC lattice QCD data at zero recoil ($w = 1$) for normalisation. BGL truncated using nested hypothesis test: BGL(1,2,2).

LFU test by comparing separated results for electrons and muons:

$R_{e/\mu} = 0.998 \pm 0.009(stat) \pm 0.020(syst)$

$\Delta A_{FB} = (-17 \pm 16(stat) \pm 16(syst)) \cdot 10^{-3}$

$\Delta F_L = (0.006 \pm 0.007(stat) \pm 0.005(syst)) \cdot 10^{-3}$

No deviations observed from the SM.

Dominant systematic sources:

1) slow-pion reconstruction efficiency → 1.5% on $|V_{cb}|$

2) $f_{+0} = \dfrac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)}$ → 1.3% on $|V_{cb}|$

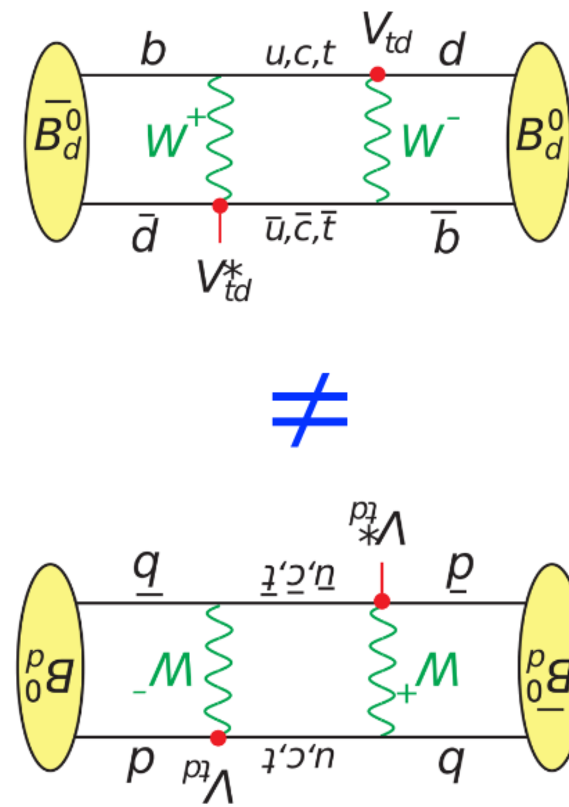
aslq

- Cpv

[M. Grabalso thesis]

CPV in mixing

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$



New physics sensitive in the loop.

Explore the flavour-specific decays $B^0 \to D^{(*)-}\mu^+ X$ and $B^0_s \to D^{(*)-}\mu^+ X$ i.e. μ charge identifies B flavour at decay.

Explore asymmetry in untagged decays i.e. no need to determine the B flavour at production.

Longitudinal D^* polarization: results

- Results integrated over run1 and run2

$$F_L^{D^*}(q^2 < 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.51 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

$$F_L^{D^*}(q^2 > 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.35 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

$$F_L^{D^*}(\text{whole } q^2 \text{ range}) = 0.43 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

- All results are found compatible with the SM within 1σ

- Compatible with previous Belle result [arXiv:1903.03102]

$$F_L^{D^*} = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$

- Compatible with SM prediction
- Plan to increase the number of bins of the fit
- Plan is to update the $F_L^{D^*}$ value in parallel with the $R(D^*)$ measurement in hadronic τ channel.