Study of semitauonic decays at Belle and Belle II

Mateusz Kaleta, Karol Adamczyk, Andrzej Bożek, Maria Różańska

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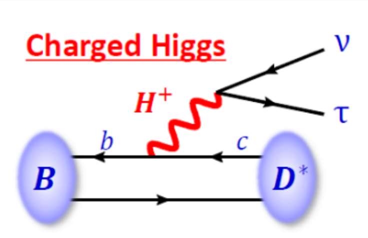
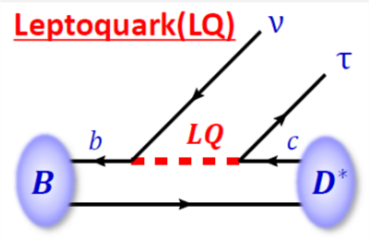
Introduction

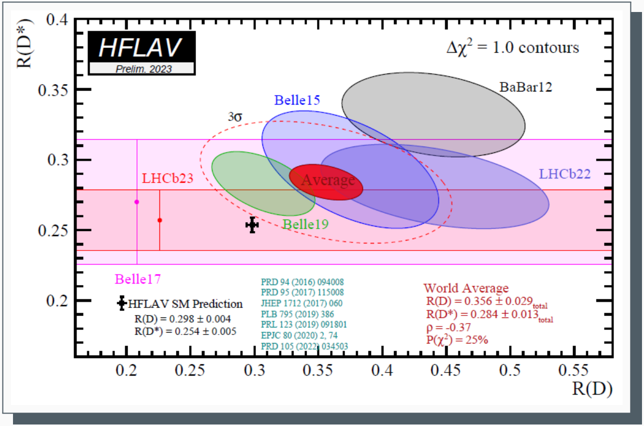
Motivation

- $B \to D^{(*)}\tau\nu$ decays are sensitive to new amplitudes at tree-level, heavy lepton in the final state
- Large number of observables: $R(D^{(*)})$, polarisations τ i D^*, q^2 distributions,
- Good theoretical tools; precise SM predictions, small hadronic uncertainties.





Current measurements: branching ratios



$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu\right)}$$

SM predictions

$R(D) = 0.298 \pm 0.004$

$R(D^*) = 0.254 \pm 0.005$

Exp. averages

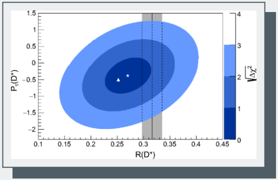
$R(D) = 0.356 \pm 0.029$

$R(D^*) = 0.284 \pm 0.013$

Combined $R(D)$ and $R(D^*)$ in tension with SM prediction at 3σ level.

Current measurements: angular characteristics

τ polarisation at Belle



$B \to \bar{D}^* \tau^+ \nu_\tau$

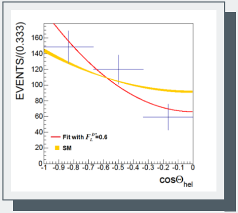
$\tau^- \to \pi^- \nu_\tau,\ \rho^- \nu_\tau$

$P_\tau = -0.38 \pm 0.51\,(stat) \pm 0.20\,(syst)$

Consistent with SM prediction at 0.6σ

[PRL118 211801 (2017), PRD97 012004 (2018)] (Belle Collaboration)

D^* polarisation at Belle



$B^0 \to D^{*-} \tau^+ \nu_\tau$

$\tau^+ \to \ell^+ \nu_\ell \bar{\nu}_\tau,\ \tau^+ \to \pi^+ \bar{\nu}_\tau$

$F_L(D^*) =$

$0.60 \pm 0.08\,(stat) \pm 0.04\,(syst)$

Results consistent with SM prediction at $1.6\sigma - 1.8\sigma$

Karol Adamczyk. PhD thesis, [arXiv:1903.03102] (Belle Collaboration)

Recent D^* polarisation at LHCb (2023)

$B^0 \to D^{*-} \tau^+ \nu_\tau$

$\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \nu_\tau$

$F_L(D^*) =$

$0.43 \pm 0.06\,(stat) \pm 0.03\,(syst)$

Compatible with SM predictions and with Belle results.

[arXiv:2311.05224v1] (LHCb Collaboration)

Goal of this analysis

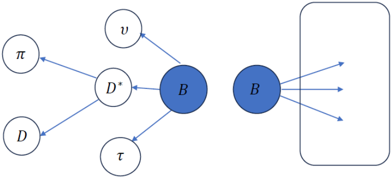
Main goal

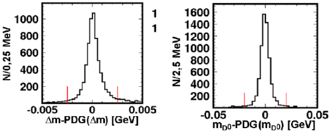
- Enhancing experimental constraints on $B \to \bar{D}^* \tau \nu_\tau$ by precise measurements of angular observables.
- Focusing on $F_L(D^*)$.

Specific goals

- **Model-independent corrections for acceptance effects**
- Increase stastistics w.r.t. previous Belle analysis:
  - combined analysis of Belle and Belle II data
  - adding charged B channel: $B^+ \to D^* \tau \nu$
  - including more D decay channels in the analysis
- Perform measurements in several q^2 bins

Analysis strategy: reconstruction





1 **Reconstruct Bsig candidates**
A clean signature from {D*, ℓ/h} pairs

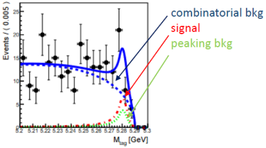
2 **Combine remaining tracks and clusters to form inclusive tag**
ROE cuts/MVA to improve S/B, tag quality and momentum resolution

3 **Analize signal sidebands to constrain peaking backgrounds**

4 **Extract signal by 1D fit to M_{tag} in ΔE_{tag} signal region**

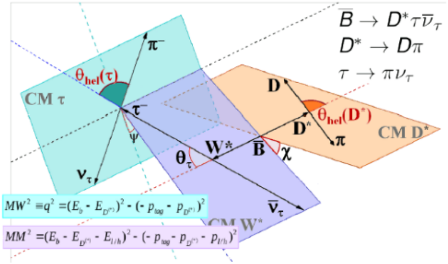
$$M_{tag} = \sqrt{E_{beam}^2 - \mathbf{p}_{tag}^2}$$

$$\Delta E_{tag} = E_{tag} - E_{beam}$$



[arXiv:1903.03102]

Analysis strategy: polarimeters



$q^2 \equiv M_W^2$ - effective mass squared of the $\tau\nu$ system

θ_τ - angle between τ&B in W^* rest frame

χ - angle between the $\tau\nu$ and D^* decay planes

$\theta_{\rm hel}(D^*)$ - angle between D&B in D^* rest frame

$\theta_{\rm hel}(\tau)$ - angle between π& direction opposite to W^* in τ rest frame

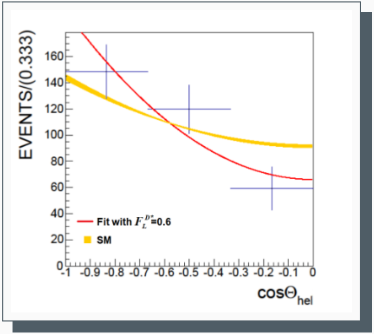
$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

$\alpha = 1.0$ for $\tau \to \pi\nu$; $\alpha = 0.45$ for $\tau \to \rho\nu$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$

M_W^2 and $\cos\theta_{\rm hel}(\tau)$, $\cos\theta_{\rm hel}(D^*)$ can be reconstructed at B-factories with hadronic decays of $B_{\rm tag}$

Improvements w.r.t. previous Belle analysis



[arXiv:1903.03102]

- $cos\theta_{hel} > 0$ region excluded from the analysis due to large drop in D^* reconstruction efficiency

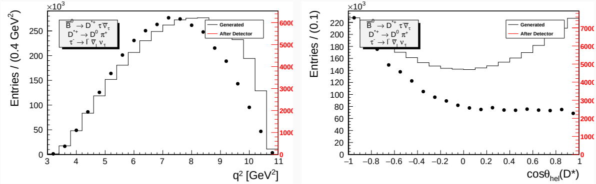
- The signal yields obtained in the bins of $cos\theta_{hel}$ were re-weighted with the following scale factors (s_l) to correct for acceptance variations.
- Correction factors s_l extracted from MC **assuming Standard Model decay dynamics**

$cos\theta_{hel}$	s
$(-1, -0.67)$	0.98 ± 0.01
$(-0.67, -0.33)$	0.96 ± 0.01
$(-0.33, 0)$	1.08 ± 0.01

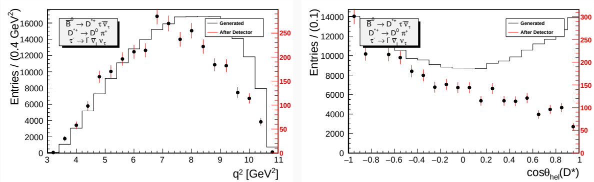
- In this work we want to apply model-independent corrections for acceptance effects

Acceptance effects (1)

Belle



Belle II



Generated (black) vs. reconstructed* (red) q^2 and $cos\theta_{hel}(D^*)$ distributions for Belle (top) and Belle II (bottom).

*True kinematics is used for reconstructed events.

Decay channel: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$

$D^{*+} \to D^0\pi^+$

$\tau^- \to \ell\bar{\nu}_\ell\nu_\tau$

Generated models:

1. **Belle: Produced locally with BSTD generator assuming SM decay dynamics (Backup)**
2. **Belle II: Centrally produced $B^0 \to X_c\tau\nu$ dsa**

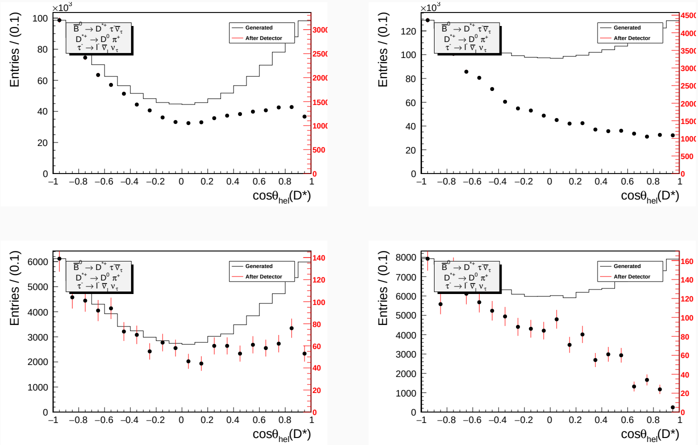
Acceptance effects (2)

$cos\theta_{hel}(D^*)$ distributions for low- (left) and high q^2 (right), for Belle (top) and Belle II (bottom)

$q^2 \leq 7GeV^2$ $q^2 > 7GeV^2$

Belle

Belle II

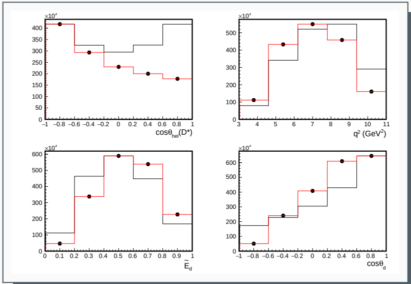


Idea:

1. Pick four variables that characterize the decay and can be reconstructed experimentally. Construct 4D histograms (generated and reconstructed) in these variables:

   - $cos\theta_{hel}(D^*)$ - cosine helicity angle D^*
   - q^2 - four-momentum transfer squared
   - $\tilde{E}_d$ - normalised τ daughter energy
   - $\cos\theta_d$ - τ daughter polar angle

*τ daughter azimuthal angle was also considered, but it was shown that it can be integrated out due to flat acceptance in that variable (Backup).



1D projections of 4D histograms: generated (black) and reconstructed* (red). Each variable was divided in 5 equidistant bins. Plot generated for Belle geometry, with BSTD generator and Standard Model decay dynamics (Backup)

*True kinematics is used for reconstructed events.

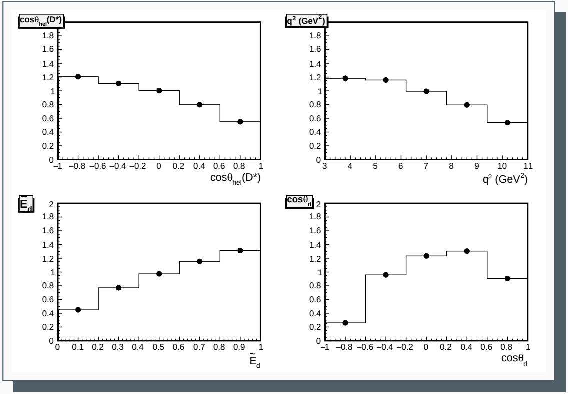
Efficiency map (2)

2. Create a 4D efficiency map by dividing reconstructed histograms by generated ones.

$$w_{ijkl} = \frac{N^{rec}_{ijkl}}{N^{gen}_{ijkl}} \frac{N^{gen}_{total}}{N^{rec}_{total}}$$

N_{ijkl} - number of events per bin

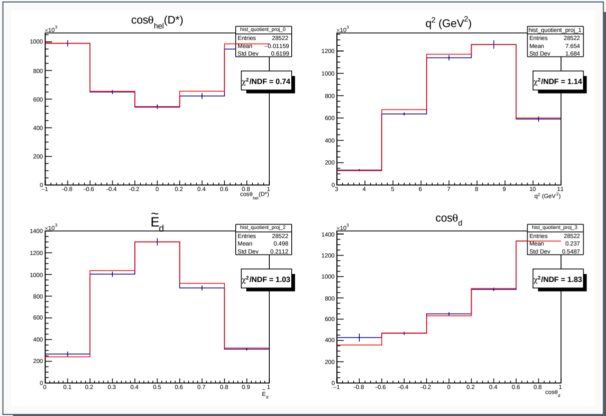
N_{tot} - total number of events



1D projections of 4D efficiency map.

Reweighting

3. Reweight reconstructed distributions using w_{ijkl} to recovered generated observables.



Generated (red) and reconstructed + reweghted distributions (blue). Plots made on independent sample generated with non-SM decay dynamics (2HDM, Backup).

Next steps

- So far detector resolution not considered in the analysis (true kinematics used for reconstructed events)

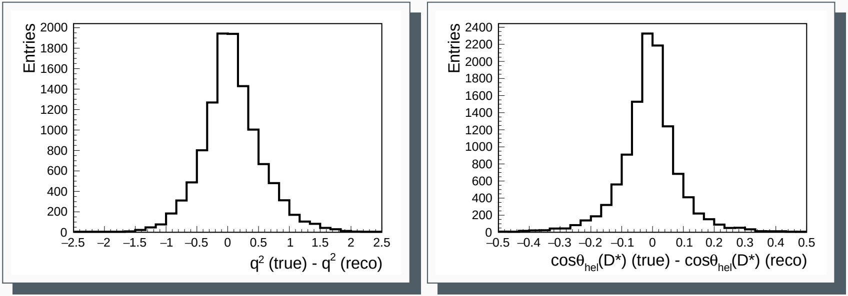


Figure: Distributions (true - reconstructed) of q^2 and $cos\theta_{hel}(D^*)$. Plot generated for Belle geometry, with BSTD generator and Standard Model decay dynamics. $M_{tag} > 5.27GeV$.

Summary

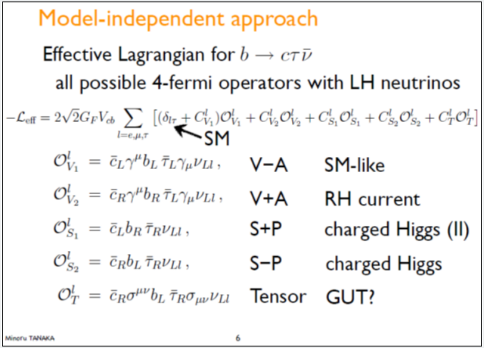
- We started working on updated $F_L(D^*)$ measurement at Belle and Belle II
- Studies on signal MC show the measurement is challenging due to large acceptance effects in $cos\theta_{hel}(D^*)$ (for both Belle and Belle II geometries)
- We plan to apply model-independent acceptance corrections not considered previously

Appendix

Monte Carlo samples: Belle

B Semi-Tauonic Generator (BSTD)

Confluence page



Calculations based on: [M. Tanaka, R. Watanabe. Phys. Rev. D 87, 034028]

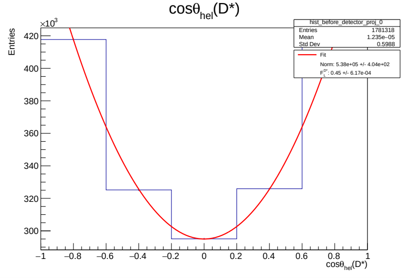
Generated samples

10^7 events generated with two models:

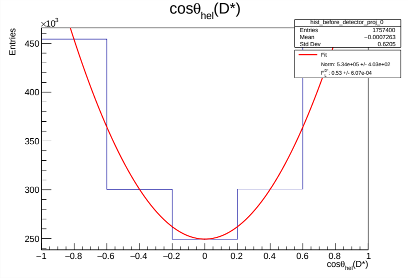
- Standard Model: $C_i = 0$
- 2HDM: $C_{S1} = -3.7$

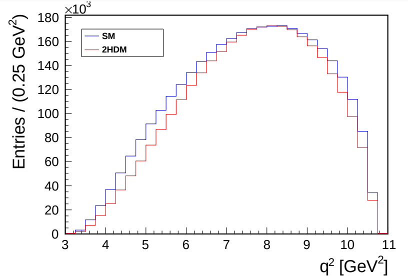
Decfiles available here.

$cos\theta_{hel}(D^*)$ (SM)



$cos\theta_{hel}(D^*)$ (2HDM)





Generated q^2 and $cos\theta_{hel}(D^*)$ distributions for two models: SM and 2HDM.

$F_L(D^*)_{SM} = 0.45$

$F_L(D^*)_{2HDM} = 0.53$

τ daughter azimuthal angle: acceptance

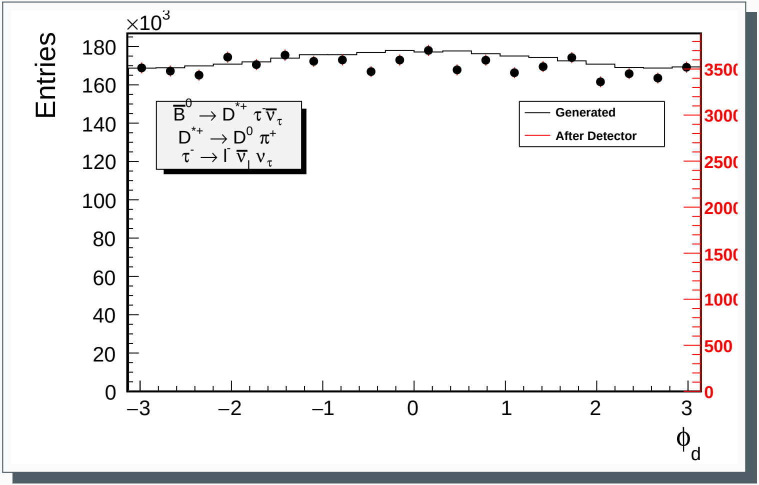


Figure: Generated and reconstructed distribution of τ daughter azimuthal angle. Plot generated for Belle geometry, with BSTD generator and Standard Model decay dynamics.

Selections

Charged PID

Belle:

- e^- : $eIDBelle > 0.6 \wedge muIDBelle < 0.98 \wedge atcPIDBelle(3,2) < 0.98$
- μ^- : $muIDBelle > 0.6 \wedge eIDBelle < 0.98 \wedge atcPIDBelle(3,2) < 0.98$
- K^+ : $atcPIDBelle(3,2) > 0.6 \wedge muIDBelle < 0.98 \wedge eIDBelle < 0.98$
- p^+ : $atcPIDBelle(4,2) > 0.6 \wedge atcPIDBelle(4,3) > 0.6 \wedge muIDBelle < 0.98 \wedge eIDBelle < 0.98$

Belle 2:

- e^- : $electronID > 0.6 \wedge muonID < 0.98$
- μ^- : $muonID > 0.6 \wedge electronID < 0.98$
- K^+ : $kaonID > 0.6 \wedge muonID < 0.98$
- p^+ : $protonID > 0.6$

ROE selection

- $E > 100MeV$, for $cos\theta < 0.50$
- $E > 160MeV$, for $cos\theta \in [0.50, 0.60]$
- $E > 180MeV$, for $cos\theta \in [0.60, 0.70]$
- $E > 200MeV$, for $cos\theta > 0.70$