Study of semitauonic decays at Belle and Belle II

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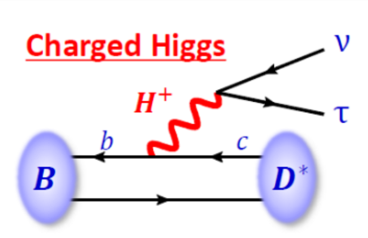
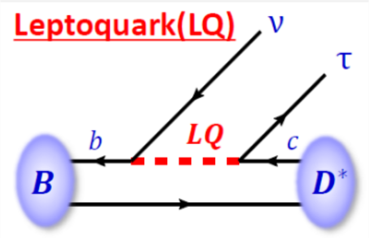
Introduction

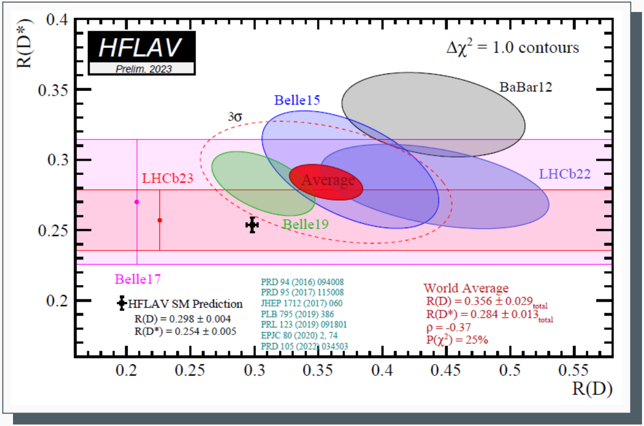
Motivation

- $B \to D^{(*)}\tau\nu$ 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



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

SM predictions

$R(D) = 0.298 \pm 0.004$

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

Exp. averages

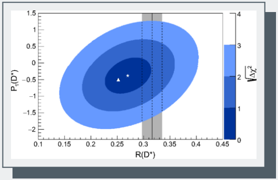
$R(D) = 0.356 \pm 0.029$

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

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

Current measurements: angular characteristics

τ polarisation at Belle



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

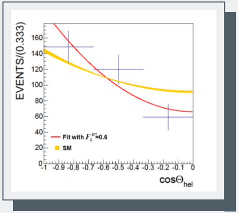
$\tau^- \to \pi^- \nu_\tau,\ \rho^- \nu_\tau$

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

Consistent with SM prediction at 0.6σ

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

D^* polarisation at Belle



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

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

$\mathrm{F}_L(D^*) =$

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

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

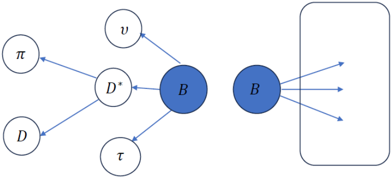
Main goal

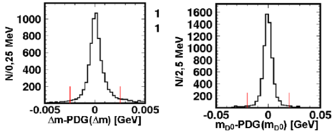
- Enhancing experimental constraints on $B \to \bar{D}^* \tau \nu_\tau$ by precise measurements of angular observables.
- Focusing on $F_L(D^*)$.

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

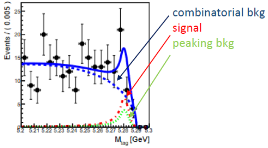
2. **Combine remaining tracks and clusters to form inclusive tag**
   ROE cuts/MVA to improve S/B, tag quality and momentum resolution

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

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

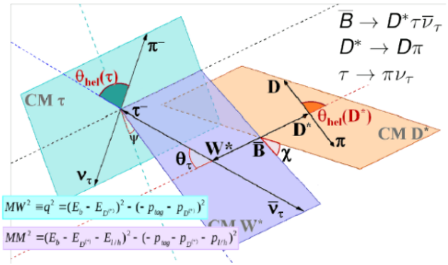
$$M_{tag} = \sqrt{E^2_{beam} - \mathbf{p}^2_{tag}}$$

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



[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

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

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

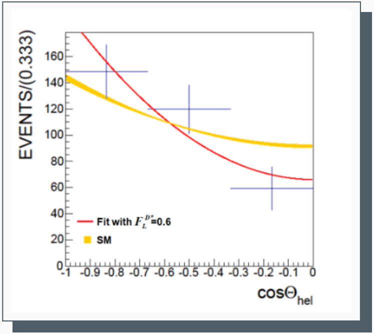
$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

$$\alpha = 1.0 \text{ for } \tau \to \pi\nu; \quad \alpha = 0.45 \text{ for } \tau \to \rho\nu$$

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

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

Improvements w.r.t. previous Belle analysis



[arXiv:1903.03102]

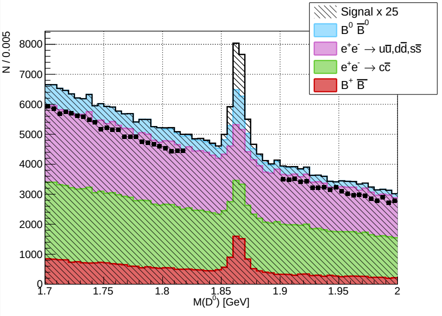
- $cos\theta_{hel} > 0$ region excluded from the analysis due to large drop in D^* reconstruction efficiency

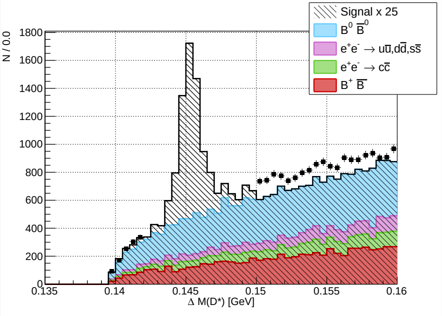
- The signal yields obtained in the bins of $cos\theta_{hel}$ were re-weighted with the following scale factors (s_l) to correct for acceptance variations.
- Correction factors s_l extracted from MC **assuming Standard Model decay dynamics**

$cos\theta_{hel}$	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

Signal-side D^* reconstruction





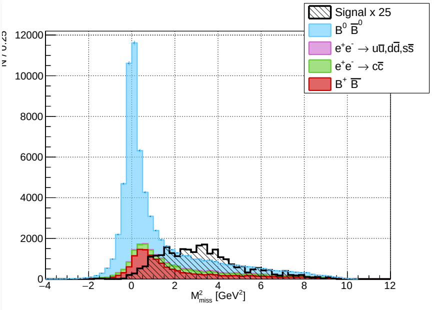
Results on Belle dataset:

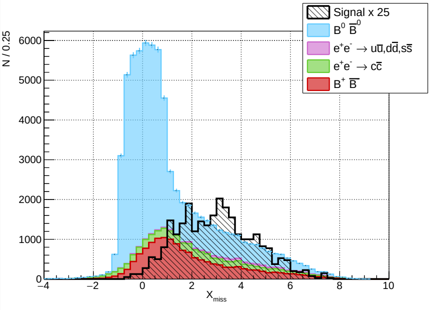
Decay channel: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$

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

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

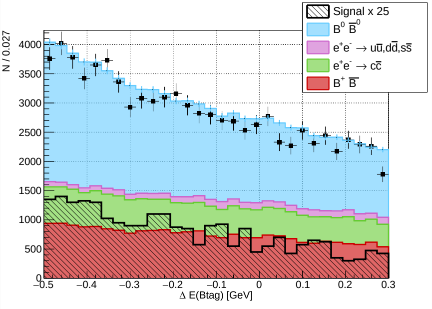
Signal-side characteristics

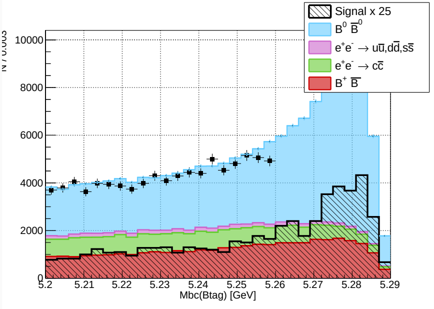




$$M^2_{miss} = (p_B - p_{vis})^2$$

$$X_{miss} = \frac{|\mathbf{p}_{\mathbf{miss}}| - |\mathbf{p}_{\mathbf{vis}}|}{\sqrt{E^2_{beam} - m^2_B}}$$





$$M_{bc} = \sqrt{E_{beam}^2 - |\mathbf{p_B}|^2}$$

$$\Delta E = E_B - E_{beam}$$

Resolution

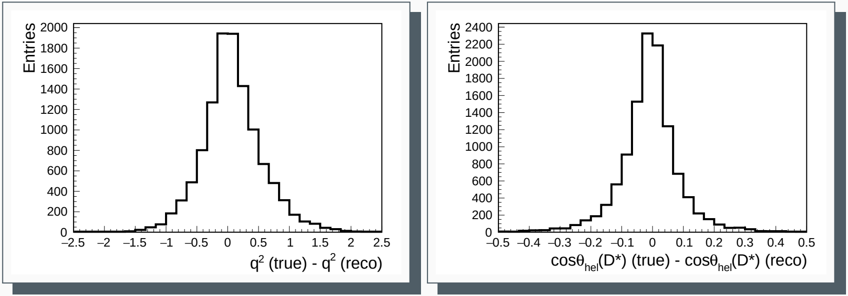
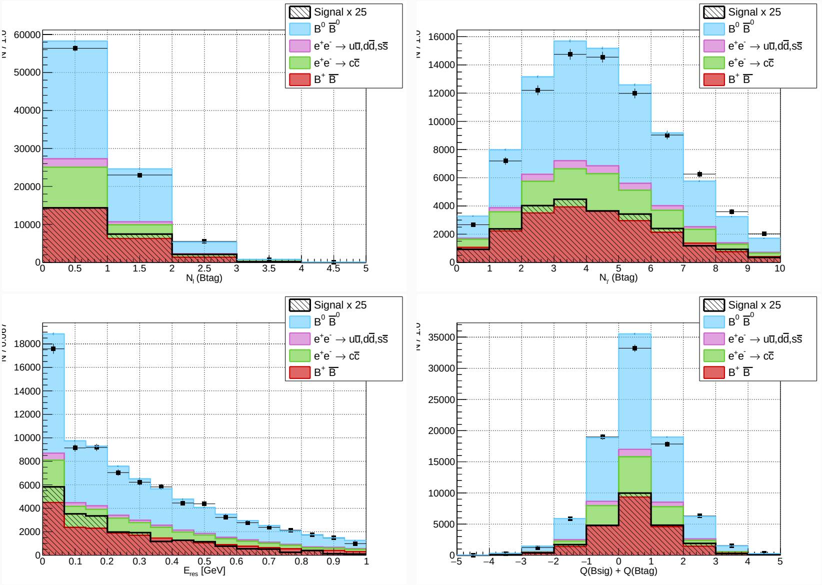


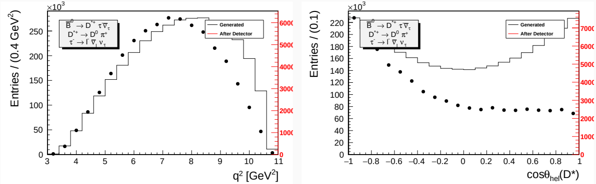
Figure: Distributions (true - reconstructed) of q^2 and $cos\theta_{hel}(D^*)$. Plot generated for Belle geometry, with BSTD generator and Standard Model decay dynamics. $M_{tag} > 5.27GeV$.

Reconstruction: additional variables

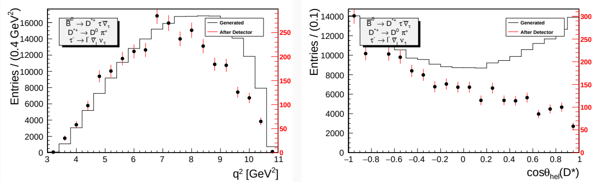


Acceptance corrections

Belle



Belle II



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

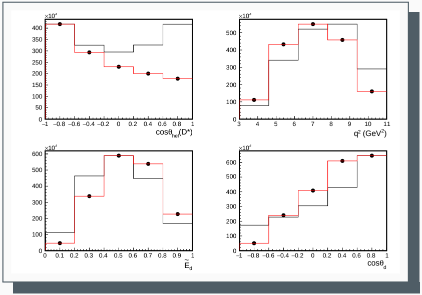
*True kinematics is used for reconstructed events.

Efficiency map (1)

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.

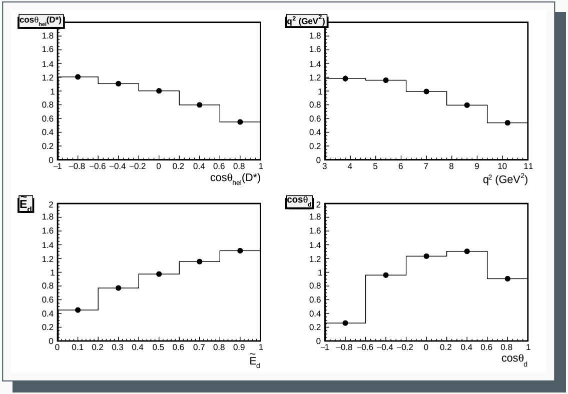
Efficiency map (2)

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

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

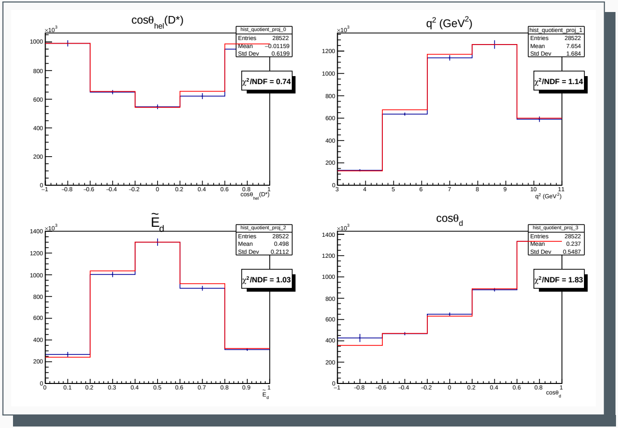
N_{ijkl} - number of events per bin

N_{tot} - total number of events



1D projections of 4D efficiency map.

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).

Summary

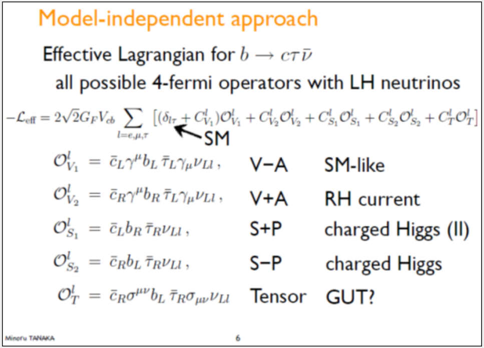
- We are working on updated $F_L(D^*)$ measurement at Belle and Belle II
- The work on reconstruction, crosfeeds and background calibration is ongoing
- Studies on signal MC show the measurement is challenging due to large acceptance effects in $cos\theta_{hel}(D^*)$
- We plan to apply model-independent 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

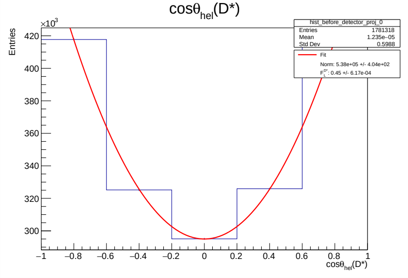
10^7 events generated with two models:

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

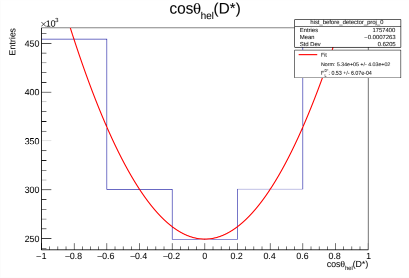
Decfiles available here.

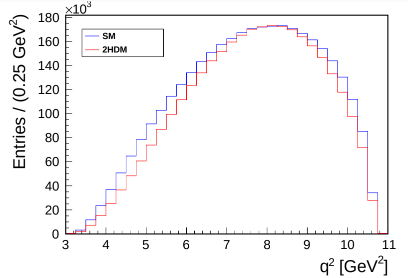
Monte Carlo samples: Belle

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



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





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

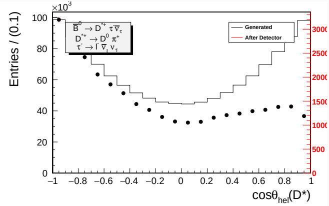
$F_L(D^*)_{SM} = 0.45$

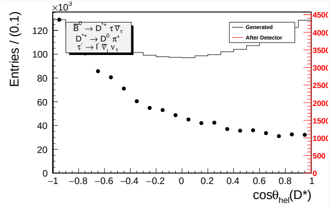
$F_L(D^*)_{2HDM} = 0.53$

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

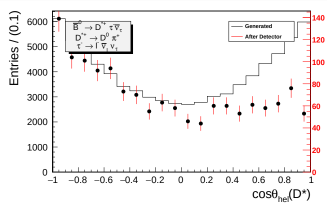
$q^2 \leq 7GeV^2$ | $q^2 > 7GeV^2$

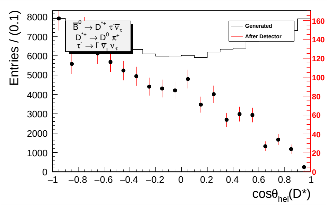
Belle





Belle II





τ daughter azimuthal angle: acceptance

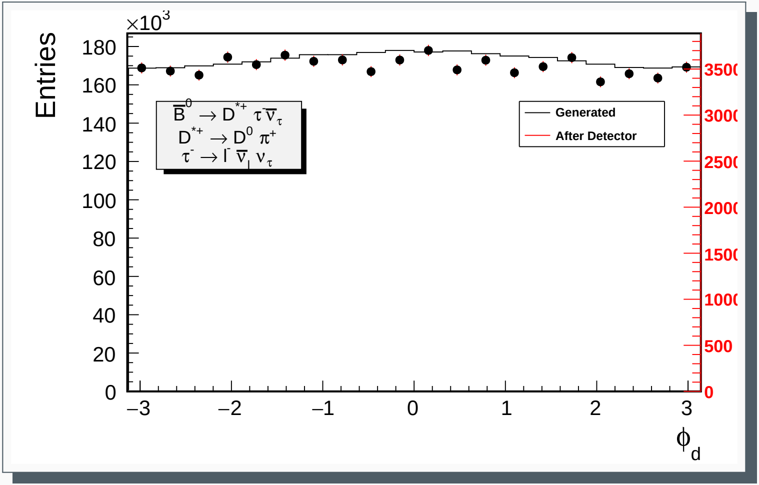


Figure: Generated and reconstructed distribution of τ daughter azimuthal angle. Plot generated for Belle geometry, with BSTD generator and Standard Model decay dynamics.

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 $cos\theta > 0.70$