Search for new physics in semitauonic B decays at B factories

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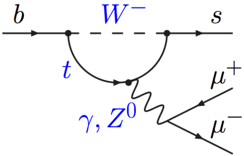
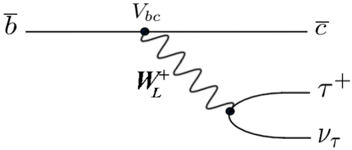
Outline

1. Hints of anomalies and NP scenarios in semileptonic B decays
2. Polarization measurements in semitauonic B decays
3. Summary and prospects

Experimental puzzles at semileptonic B decays

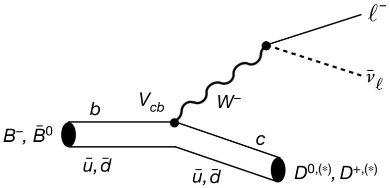


- Hint of violation of LFU in $R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)} \mu^- \mu^+)}{\Gamma(B \to K^{(*)} e^- e^+)}$ (LHCb) ($R_{K^{(*)}}$ puzzle)
- Tension in $B \to K^* \mu^+ \mu^-$ angular observables
- Rare decays with good signatures can be measured precisely by LHCb



- Measurements by different experiment (BaBar, Belle, LHCb) favor larger than expected $R(D^{(*)}) = \frac{\mathcal{B}(B \to \bar{D}^{(*)} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D}^{(*)} \ell^+ \nu_\ell)}$ ($R_{D^{(*)}}$ puzzle)
- measurements of differential observables in semitauonic B decays with high precision on Belle II data
- methodology for new measurments can be prototyped and developed on Belle data

Semitauonic B decays



Arithmetic average of SM predictions from HFLAV:

$$R(D^*)^{\rm SM} = \frac{\mathcal{B}(B \to \bar{D}^* \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D}^* \ell^+ \nu_\ell)} = 0.258 \pm 0.005$$

$$R(D)^{\rm SM} = \frac{\mathcal{B}(B \to \bar{D} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D} \ell^+ \nu_\ell)} = 0.299 \pm 0.003$$

New Physics scenarios

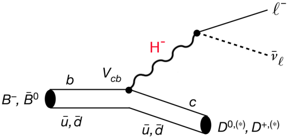
charged Higgs

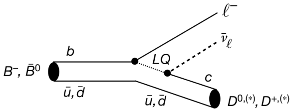
Leptoquarks

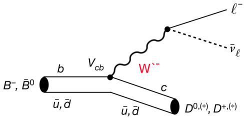
R, q^2, angular distributions affected

new vector boson W'^-

changes in R, not in the kinematics







Experimental techniques @ B factories

Tagging techniques

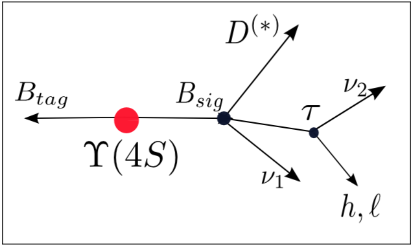
efficiency ↑ ↓ purity

- Inclusive
  $B \to$ *hadrons* (inclusive modes)
  $\epsilon \approx O(1\%)$
  A. Matyja: PRL **99**, 191807, (2007),
  A. Bozek: PRD **82**, 072005, (2010)
- Semileptonic
  $B \to D^{(*)}\ell\nu_\ell$
  $\epsilon \approx O(0.3\%)$
  Y. Sato: PRD **94**, 072007, (2016)
  G. Caria: PRL **124**, 161803, (2020)
- Hadronic
  $B \to$ *hadrons* (exclusive modes)
  $\epsilon \approx O(0.1\%)$
  M. Huschle: PRD **92**, 072014, (2015),
  S. Hirose: PRL **118**, 211801, (2017)

Contribution of Belle group from Kraków:
BF measurments

First observation of $B^0 \to D^{*-}\tau^+\nu_\tau$ Decay at Belle
PRL **99**, 191807, (2007).

Observation of $B^+ \to \overline{D}^{*0}\tau^+\nu_\tau$ and evidence for $B^+ \to \overline{D}^0\tau^+\nu_\tau$ at Belle
PRD **82**, 072005, (2010).

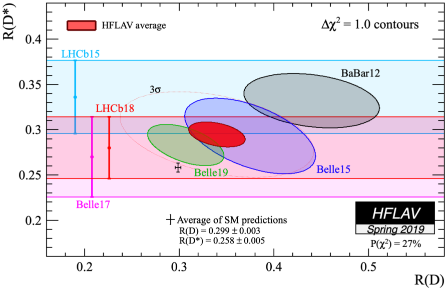


- at least 2 neutrinos in final state $\to$ exclusive production of $B\overline{B}$ pairs at B factories; kinematical constrains from beam energy; $B_{\rm tag}$direction;

Experimental situation

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

$\ell = e, \mu$: normalization



HFLAV

$R_D = 0.340 \pm 0.027_{stat} \pm 0.013_{syst}$
$R_{D^*} =$
$0.295 \pm 0.011_{stat} \pm 0.008_{syst}$

deviation from SM:
$\sim 1.4\sigma$ for $R(D)$

$\sim 2.5\sigma$ for $R(D^*)$

$\sim 3.08\sigma$ tension between SM and combined $R(D^{(*)})$ by BaBar, Belle and LHCb

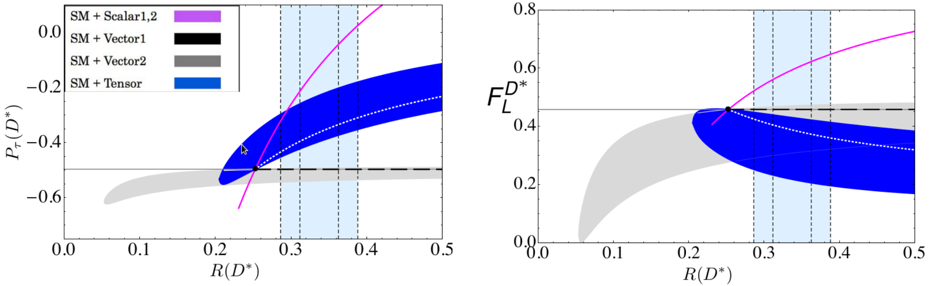
$\rightarrow$ other observables not fully explored yet

Another observables

in semitauonic B decays D^* and τ polarizations sensitive probes of various NP scenarios

example of theoretical predictions for $\overline{B} \to D^* \tau \overline{\nu}$

M. Tanaka and R. Watanabe, Phys. Rev. D **87**, 034028 (2013)



$$P_\tau = \frac{\Gamma(\lambda_\tau = +1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = +1/2) + \Gamma(\lambda_\tau = -1/2)}$$

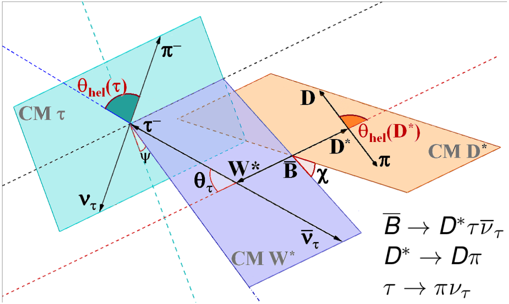
$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$$

$F_L^{D^*}$: fraction of longitudinal polarization of D^*

SM: $P_\tau(D^*) \approx -0.5$

SM: $F_L^{D^*} = 0.46 \pm 0.03$

Kinematic variables describing $B \to D^{(*)}\tau\nu$



$\overline{B} \to D^*\tau\overline{\nu}_\tau$

$D^* \to D\pi$

$\tau \to \pi\nu_\tau$

$q^2 \equiv M_W^2$ - 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 $\tau \to \pi\nu$; $\quad \alpha = 0.45$ for $\tau \to \rho\nu$

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

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

First measurement of τ polarization in $B \to D^* \tau \nu$

PRL. **118**, 211801 (2017); done by Nagoya group (S. Hirose, T. Ijima)

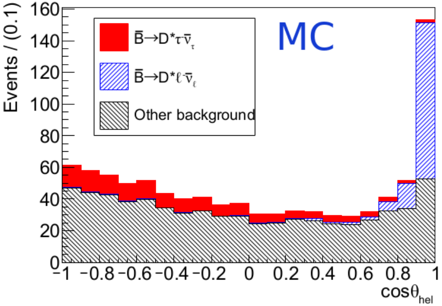
sample divided into two bins of $cos\theta_{\rm hel}$:
I: $-1 < cos\theta_{\rm hel} < 0$;
II: $0 < cos\theta_{\rm hel} < 0.8$ (for $\tau \to \pi\nu$)

both $\bar{B}^0$ and B^- decays are used

$$P_\tau = \frac{2}{\alpha} \frac{\Gamma_{cos\theta_{\rm hel}>0} - \Gamma_{cos\theta_{\rm hel}<0}}{\Gamma_{cos\theta_{\rm hel}>0} + \Gamma_{cos\theta_{\rm hel}<0}}$$

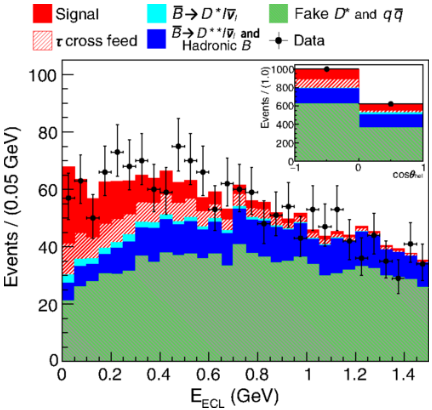
Experimental challenges

- only 2 body τ decays: $\tau \to \pi\nu, \rho\nu$
- distribution of $\cos\theta_{hel}(\tau)$ is modified by:
  - cross-feeds from other τ decays (contribute mainly in the region of $\cos\theta_{hel}(\tau) < 0$)
  - peaking background (concentrated around $\cos\theta_{hel}(\tau) \approx 1$)
- corrections for detector effects: acceptance, asymmetric $\cos\theta_{\rm hel}$ bins, crosstalks between different τ decays
- for $\tau \to \pi(\rho)\nu$ modes combinatorial background from poorly known hadronic B decays



Results

PRL **118**, 211801 (2017); done by Nagoya group (S. Hirose, T. Ijima)



contributions from Kraków group:
- deliver analytical derivation of formulas
- find the bug and validate MC generator (BSTD), which caused omitting interference terms

dominant systematics:
- hadronic B decays composition ($^{+0.13}_{-0.10}$, $^{+7.6\%}_{-6.8\%}$)
- MC stat. for PDF shapes

$$P_\tau(D^*) = -0.38 \pm \mathbf{0.51(stat.)}\ ^{+0.21}_{-0.16}(syst.)$$

- first measurement of $P_\tau(D^*)$; the result excludes $P_\tau(D^*) > +0.5$ at 90% C.L.

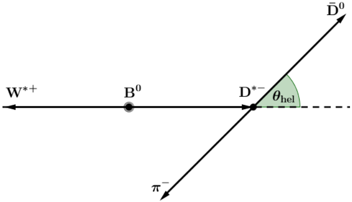
D^* polarization studies

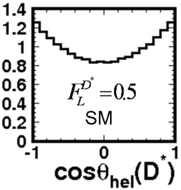
done by Kraków group

$R(D^{(*)})$ systematically above the SM expectations, surprisingly large effect for $R(D^*)$ then for $R(D)$ $\Rightarrow$ D* polarization measurement

Measure $F_L^{D^*}$ from fit to $\cos\theta_{\rm hel}(D^*)$ distribution:

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





In comparison to τ polarization:

- all τ decays are useful $\rightarrow$ larger statistic
- less affected by cross-feeds between different τ decays

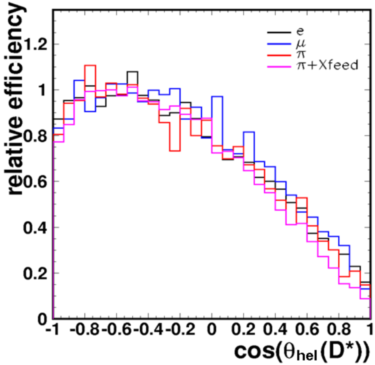
theoretical papers on D^* polarization studies:

- Z.-R. Huang et al., PRD **98**, 095018, (2018) $((F_L^{D^*})_{\rm SM} = 0.441 \pm 0.006)$
- Bhattacharya, S., Nandi, S., Patra, S.K., Eur. Phys. J. C **79**, 268 (2019) $((F_L^{D^*})_{\rm SM} = 0.457 \pm 0.010)$

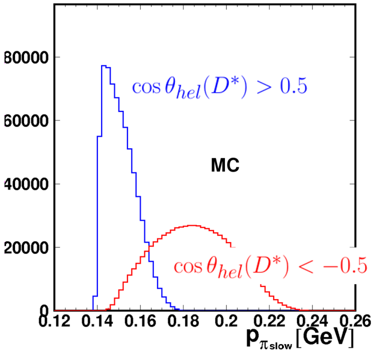
Experimental challenges

Main experimental problem:
strong acceptance effects for $\cos\theta_{\rm hel}(D^*) \geq 0.0$ for large q^2

relative efficiency



distribution of slow $\pi^{\pm}$ from D^*



Effectively only $\cos\theta_{\rm hel}(D^*) < 0$ is useful for $F_L^{D^*}$ measurement

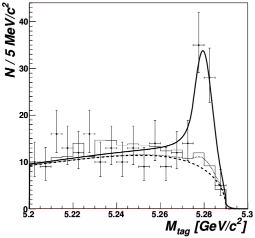
Method of reconstruction

1. Reconstruct **inclusively** $B_{\rm tag}$. First we find B_{sig} candidates: (D^* + (h or ℓ)), from rest of event we reconstruct candidates for B_{tag} and calculate:

   $E_{tag} = \sum_i E_i$ $\quad \mathbf{p}_{tag} = \sum_i \mathbf{p}_i$ variables to identify B_{tag}: $M_{tag} = \sqrt{E^2_{beam} - \mathbf{p}^2_{tag}}$,

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

2. Extract number of signal events by fitting M_{tag} distributions in bins of $\cos\theta_{\rm hel}(D^*)$;

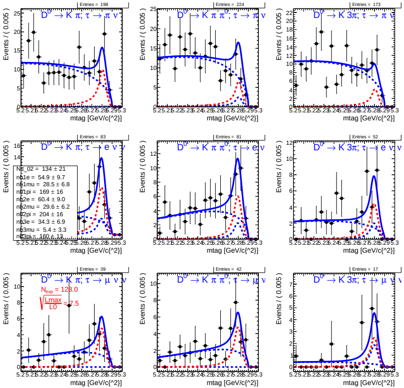


This approach allows for signal extraction using **known** PDF's (CrystalBall and Argus) parametrizations;

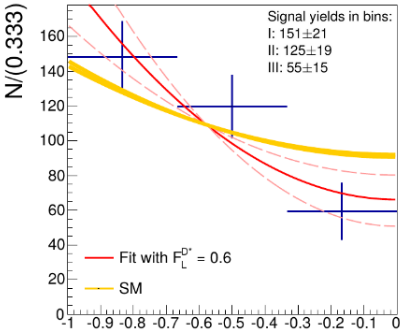
3. Measure $F_L^{D^*}$ from fit to obtained $\cos\theta_{\rm hel}(D^*)$ distribution;

Signal extraction

- the signal yields are extracted from a simultaneous, extended UML-fit to all 9 sub-channels in the M_{tag} distributions
- procedure is performed in 3 bins of $\cos\theta_{\rm hel}(D^*)$ in the range [-1,0];
  I : $-1.0 < \cos\theta_{\rm hel}(D^*) < -0.67$
  II : $-0.67 < \cos\theta_{\rm hel}(D^*) < -0.33$
  III : $-0.33 < \cos\theta_{\rm hel}(D^*) < 0.0$
- example fit projection to $M_{\rm tag}$ distribution in the range $-1.0 < \cos\theta_{\rm hel}(D^*) < -0.67$ on 2nd stream of **Monte Carlo** generic:



Preliminary results for $F_L^{D^*}$ measurement in $B^0 \to D^* \tau \nu$



SM: $F_L^{D^*} = 0.46 \pm 0.03$

$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

- A. Abdesselam *et al.* [Belle], "Measurement of the D^{*-} polarization in the decay $B^0 \to D^{*-}\tau^+\nu_\tau$," arXiv:1903.03102 [hep-ex].
- K. Adamczyk [Belle and Belle-II], "Semitauonic B decays at Belle/Belle II," http://doi.org/10.5281/zenodo.2565845 arXiv:1901.06380 [hep-ex].

- agrees within 1.7 σ of the SM prediction
- dominant systematics from MC statistics (sig, peaking and comb. bkg. PDF shapes) = ± 0.03
- the result obtained assuming the SM dynamics
- last step: uncertainty from signal model in NP scenarios

Prospects @ Belle

- combine charged and neutral B samples to measure D^* polarization

Summary

- $R(D)$, $R(D^*)$, $P_\tau(D^{(*)})$ and $F_L^{D^*}$ in $\overline{B} \to D^{(*)}\tau\nu$ are good probes for NP
- First measurement of τ polarization in $B \to D^*\tau\nu$:

$$P_\tau(D^*) = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$

- First measurement of D^* polarization in $B^0(\overline{B}^0) \to D^*\tau\nu$

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

- measurements sensivity limited by the statistics

Prospects @ Belle II

The Belle II Physics Book, arXiv:1808.10567

- Belle: 0.772 x 10^9 $B\overline{B}$;
- Belle II: $\sim$ 50 x 10^9 $B\overline{B}$ (x 50 Belle statistic) (50 ^{-1}ab)

- expected number of events for $P_\tau(D^*)$ measurement:
  - $\sim$ 4000 in $B^0(\overline{B^0})$ mode (hadronic B_{tag} reconstrucion)
  - $\sim$ 10000 in $B^+(B^-)$ mode (hadronic B_{tag} reconstrucion)
- expected number of events for $F_L^{D^*}$ measurement:
  - $\sim$ 15000 in $B^0(\overline{B^0})$ mode (inclusive B_{tag} reconstrucion)

Room for improvements on Belle/Belle II data

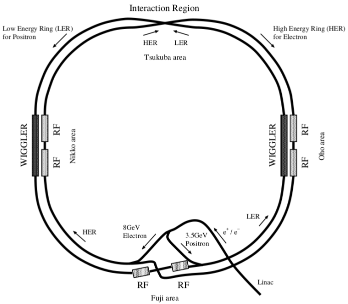
- particle ID done by ML algorithm $\rightarrow$ efficiency/fake rate improvement
- inclusive B_{tag}reconstruction based on BDT
- improved VXD resolution $\rightarrow$ use vertices and IP to create topological discriminator

- higher statistics and better reconstruction efficiencies (i.a. slow π from D^*) should allow for precise measurements of kinematic distributions, e.g. q^2, polarizations, $F_L^{D^*}(q^2)$

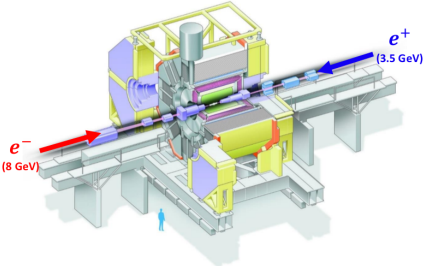
BACKUP

The Belle Experiment

KEKB



Belle detector - multipurpose large-solid-angle magnetic spectrometer



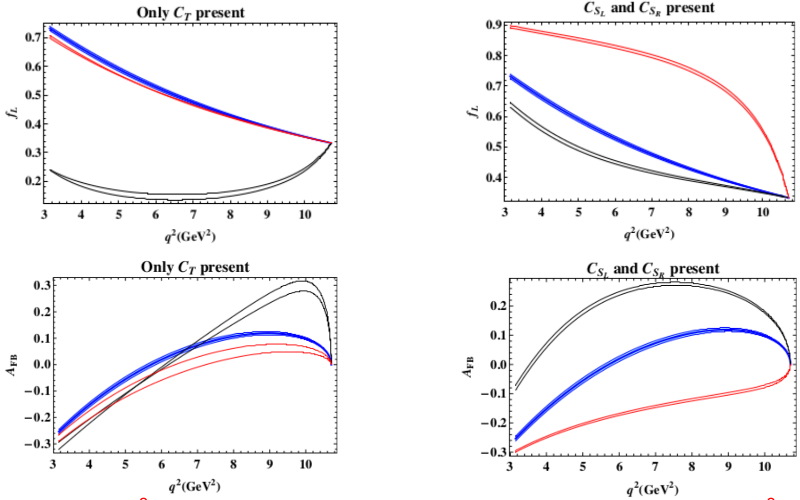
KEKB B-factory - asymmetric e^+e^- collider

$e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (772 x 10^6 $B\overline{B}$)

- clean source of B meson pairs
- reconstruction of one B meson (B_{tag}) provides information on momentum vector and other quantum numbers of another B (B_{sig})
- $E_B = E_{\text{beam}} = \frac{\sqrt{s}}{2}$

Modification of D^* polarization in NP scenarios

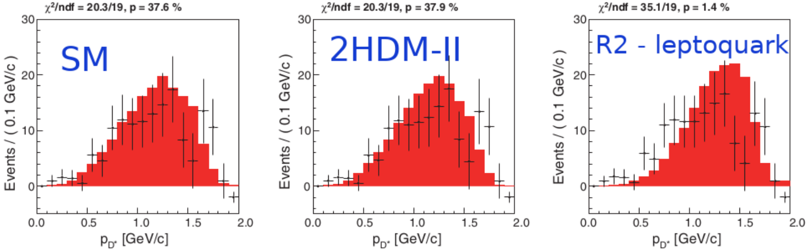
PRD **95 115038, (2017)**



$A_{\mathrm{FB}}(q^2)$ has no additional NP discrimination capability compared to $F_{\mathrm{L}}(q^2)$

Differential observables to examine NP scenarios

PRD **94, 072007 (2016); semileptonic** B_{tag}



- Measured distributions of p_{D*} and p_l consistent with SM but do not provide enough discriminating power due to statistical limitation
- More observables with more data needed to clarify the situation

The angular observables not yet (fully) explored experimentally

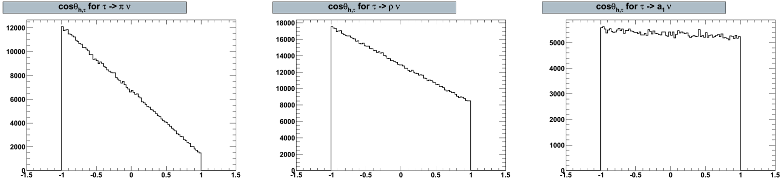
First τ polarization measurement in semitauonic B decys

done by Nagoya group

$\cos\theta_{hel}(\tau)$ can be measured if there is a single ν in τ decay

$\tau \to h\nu_\tau$, $h = \pi, \rho, a_1$

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



$\alpha = 1$ for $\tau \to \pi\nu$

$\alpha = \frac{m_\tau^2 - 2m_V^2}{m_\tau^2 + 2m_V^2}$ for $\tau \to \rho\nu(a_1\nu)$

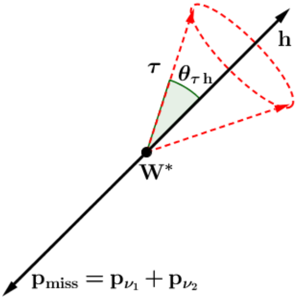
$\alpha = 0.45$ for $\tau \to \rho\nu$

$\cos\theta_{\rm hel}(\tau)$ reconstruction

contribution from Kraków group

τ momentum vector is not fully determined

$\tau \to h\nu_\tau,\ h = \pi, \rho$



$$\begin{array}{l} \qquad\qquad \Lsh D^0\pi \\ B \to D^* W^*(\to \tau\nu) \end{array}$$

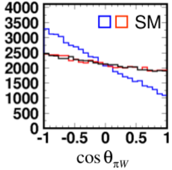
in CM of W^*

- $E_\tau = \frac{M_W^2 + M_\tau^2}{2M_W};\ p_\tau = p_{\nu_1} = \frac{M_W^2 - M_\tau^2}{2M_W};$
- $E_h = \frac{M_W^2 + M_h^2 - M_M^2}{2M_W};$
- $\cos\theta_{\tau h} = \frac{2E_\tau E_h - (M_\tau^2 + M_h^2)}{2E_{\nu_1} p_h}$
- Lorentz transformation from the rest frame of the $\tau^-\overline{\nu}$ to the rest frame of τ: $|\vec{p}_d^{\,\tau}| cos\theta_{\rm hel} = -\gamma|\vec{\beta}|E_d + \gamma|\vec{p}_d^{\,\tau}| cos\theta_{\tau d}$
- $\Rightarrow \cos\theta_{hel}(\tau)$

Validation of BSTD MC generator

contribution from Kraków group

- find disagreement between ISGW2 and BSTD $\rightarrow$ lack of the interference terms important in certain angular distributions
- contribute to validate distributions from BtoSemiTauonicDecays (BSTD) MC generator



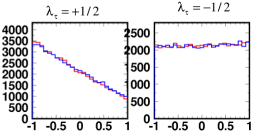
$\square$ $\alpha\Gamma_{+1/2} + \beta\Gamma_{-1/2}$

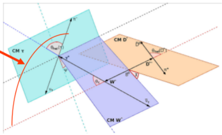
for $P_\tau = -0.5$

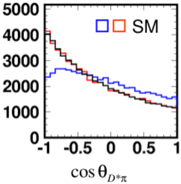
BSTD

ISGW2

Distributions of $\cos\theta_{\pi W}$ in $B \rightarrow D^* \tau(\rightarrow \pi\nu)\nu$







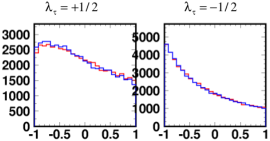
$\square$ $\alpha\Gamma_{+1/2} + \beta\Gamma_{-1/2}$

for $P_\tau = -0.5$

BSTD

ISGW2

Distributions of $\cos\theta_{D^*\pi}$ in $B \rightarrow D^* \tau(\rightarrow \pi\nu)\nu$



$\cos\theta_{D^*\pi} = (\vec{p}_{D^*} \cdot \vec{p}_\pi)/(|\vec{p}_{D^*}||\vec{p}_\pi|)$

in the $\Upsilon(4S)$ rest frame