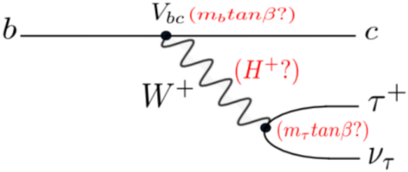
D^* and τ polarization measurements in $\bar{B} \to D^* \tau \nu$



Outline:

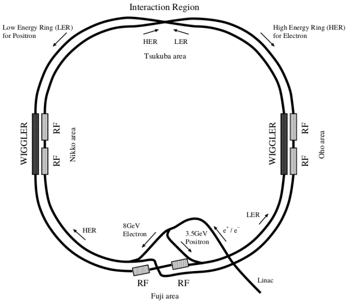
- Experimental situation & motivation
- τ polarization measurement in $B \to D^* \tau \nu$ by Belle
- prospects for D^* polarization measurements
- Summary

Karol Adamczyk
H. Niewodniczański Institute of Nuclear Physics

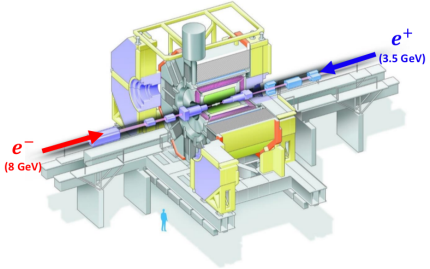
for the Belle Collaboration

The Belle Experiment

KEKB



Belle detector - multipurpose large-solid-angle magnetic spectrometer



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

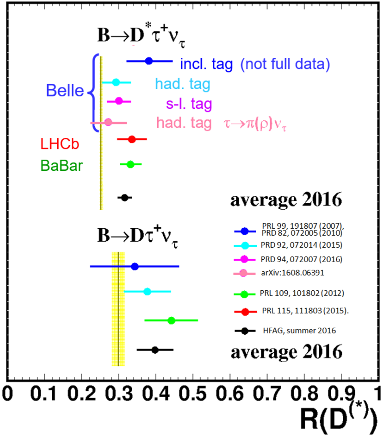
$e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (772 x 10^6 $B\overline{B}$)

- 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})
- $E_B = E_{\text{beam}} = \frac{\sqrt{s}}{2}$

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



Tagging techniques:

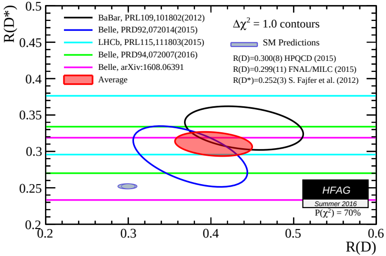
Inclusive	$B \to hadrons$ (inclusive modes) $\epsilon \approx O(1\%)$
Semileptonic	$B \to D^{(*)}\ell\nu_\ell$ $\epsilon \approx O(0.2\%)$
Hadronic	$B \to hadrons$ (exclusive modes) $\epsilon \approx O(0.1\%)$

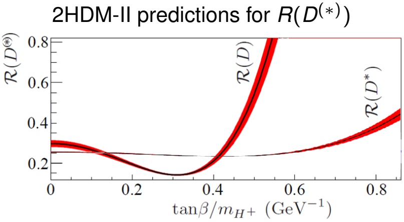
Recent, statistically independent results from Belle:

- $R(D^*)$ measurement with semileptonic tagging; Phys. Rev. D 94, 072007
- $R(D^*)$ and τ polarization measurements with non-leptonic τ decays; https://arxiv.org/abs/1608.06391 (preliminary); final result will be released soon

Belle $R(D^{(*)})$ averages about 2σ away from the SM;

Experimental situation





based on PRL 109, 101802 (2012)

$\sim 4\sigma$ tension between SM and combined $R(D^{(*)})$ by BaBar, Belle and LHCb

Tantalizing but inconclusive hints of a deviation from the Standard Model in $b \to c\tau\nu$ transitions:

- $R(D^{(*)})$ systematically above the SM expectations, surprisingly large effect for $R(D^*)$
- More observables with more data needed to clarify the situation;

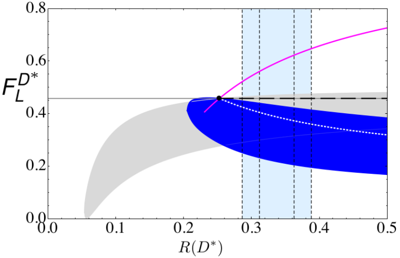
Angular observables not yet (fully) explored experimentally.

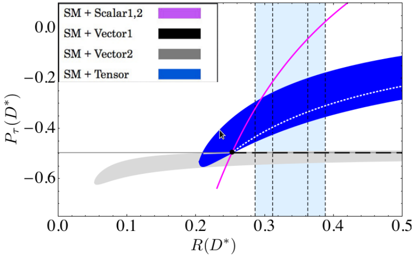
Motivation

D^* and τ polarizations in semitauonic B decays are 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)





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

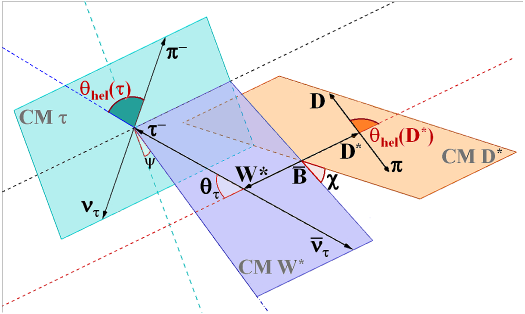
$$P_\tau = \frac{\Gamma(\lambda_\tau = +1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = +1/2) + \Gamma(\lambda_\tau = -1/2)}$$

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

SM: $F_L^{D^*} = 0.46 - 0.53$

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

Kinematic variables describing $B \to D^* \tau \nu$



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

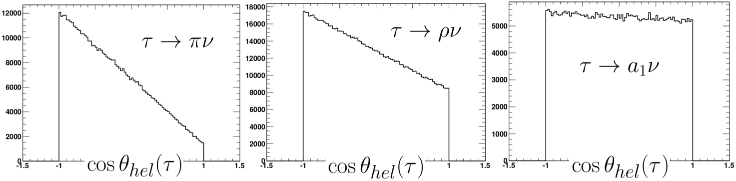
$q^2 \equiv M_W^2$ - effective mass squared of the $\tau\nu$ system
θ_τ - angle between τ&B in W^* rest frame
$\theta_{\rm hel}(D^*)$ - angle between D&B in D^* rest frame
$\theta_{\rm hel}(\tau)$ - angle between π& direction opposite to W^* in τ rest frame
χ - angle between the $\tau\nu$ and D^* decay planes
(M_M^2 - missing mass squared (effective mass of neutrinos))

> M_W^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 $B_{\rm tag}$

τ polarization measurement

$\cos\theta_{hel}(\tau)$ can be measured if there is a single ν in τ decay
$\tau \to h\nu_\tau$, $h = \pi, \rho, a_1$

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

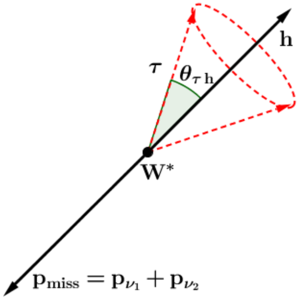


$\alpha = 1$ for $\tau \to \pi\nu$

$\alpha = \frac{m_\tau^2 - 2m_V^2}{m_\tau^2 + 2m_V^2}$, $\alpha = 0.45$ for $\tau \to \rho\nu$

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

τ momentum vector is not fully determined;



in CM of W^*

- $E_\tau = \frac{M_W^2 + M_\tau^2}{2M_W}$; $p_\tau = p_{\nu_1} = \frac{M_W^2 - M_\tau^2}{2M_W}$;
- $E_h = \frac{M_W^2 + M_h^2 - M_M^2}{2M_W}$;
- $\cos\theta_{\tau h} = \frac{2E_\tau E_h - (M_\tau^2 + M_h^2)}{2p_{\nu_1} p_h}$
- boost to τ rest frame can be done $\Rightarrow$ $\cos\theta_{hel}(\tau)$

Experimental challenges

- for $\tau \to \pi(\rho)\nu$ modes combinatorial background from poorly known hadronic B decays
- 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 $\cos\theta_{hel}(\tau) \approx 1$)

Measurement of τ polarization

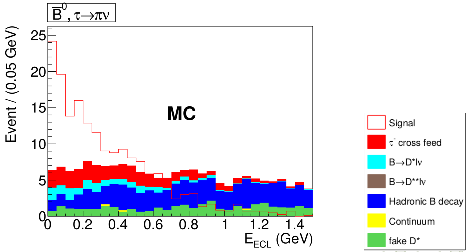
- both $\bar{B}^0$ and B^- decays are used; $\tau \to \pi\nu, \rho\nu$
- sample divided into two bins of $cos\theta_{\rm hel}$: $-1 < cos\theta_{\rm hel} < 0$; $0 < cos\theta_{\rm hel} < 0.8$ (for $\tau \to \pi\nu$)

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

- corrections for detector effects: acceptance, asymmetric $\cos\theta_{\rm hel}$ bins, crosstalks between different τ decays

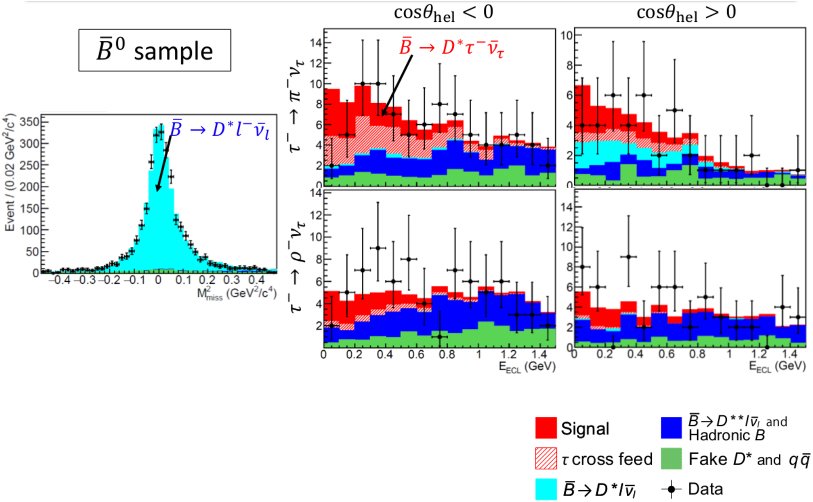
$P_\tau(D^*)$measured simultanously with $R(D^*)$

- normalization mode extracted in $M^2_{\rm miss} = (p_{\rm beam} - p_{\rm B_{tag}} - p_{D^*} - p_l)^2$;
- signal extracted in $E_{\rm ECL}$ (remaining energy in the electromagnetic calorimeter)



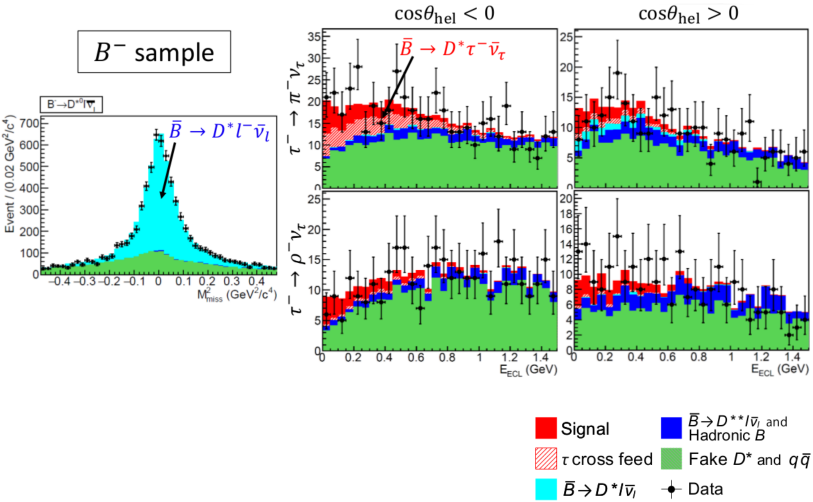
Signal extraction

2D ML fit to E_{ECL} and M^2_{miss} distributions



Signal extraction

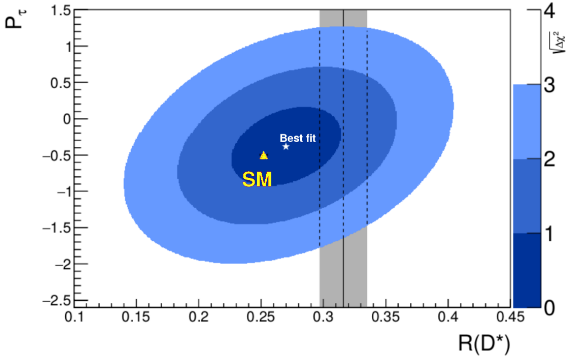
2D ML fit to E_{ECL} and M^2_{miss} distributions



Results

https://arxiv.org/abs/1608.06391 (preliminary)

$$P_\tau(D^*) = -0.44 \pm 0.47(stat.)^{+0.20}_{-0.17}(syst.)$$
$$R(D^*) = 0.276 \pm 0.034(stat.)^{+0.029}_{-0.026}(syst.)$$

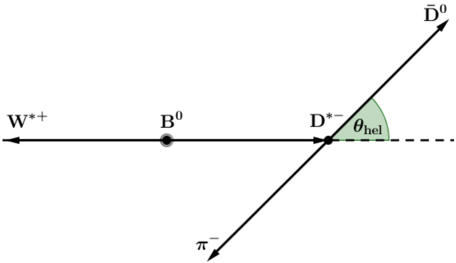


- first measurement of $P_\tau(D^*)$
- combined $R(D^*)$ and $P_\tau(D^*)$ result is consistent with the SM within 0.6σ

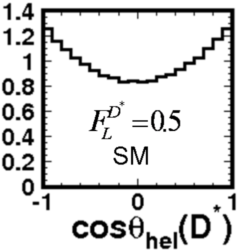
D^* polarization studies

Easier to measure than τ polarization

- \+ all τ decays are useful
- \+ not affected by cross-feeds between different τ decays



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



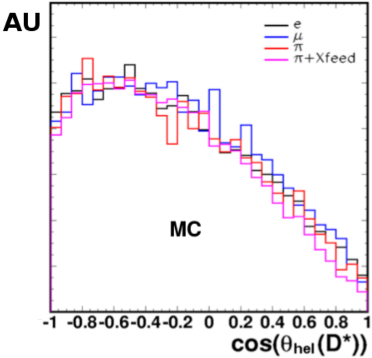
Recent theoretical papers with D^* polarization studies:

- https://arxiv.org/abs/1607.02932
- https://arxiv.org/abs/1606.03164
- https://arxiv.org/abs/1602.03030
- https://arxiv.org/abs/1509.07259

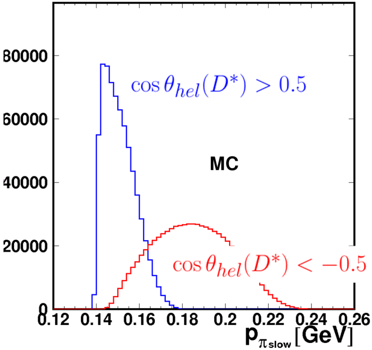
Challenges for D^* polarization measurement

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

efficiency



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



At Belle using only $B^0 \to D^{*-}\tau^+\nu_\tau$ expected stat. uncertainty: $F_L^{D^*} = X \pm \sim 0.1(stat)$
$\Rightarrow$ competitive test of NP

Summary

- about 4σ tension between SM and combined $R(D^{(*)})$ by BaBar, Belle and LHCb
- Polarizations in $\bar{B} \to D^* \tau \nu$ are interesting observables sensitive for NP that can be measured at B factories
- First constraint on τ polarization and new, independent measurement of $R(D^*)$

preliminary results:

$$P_\tau(D^*) = -0.44 \pm 0.47(stat.)^{+0.20}_{-0.17}(syst.)$$
$$R(D^*) = 0.276 \pm 0.034(stat.)^{+0.029}_{-0.026}(syst.)$$

- ongoing analysis at Belle: D^* polarization measurement
- polarization measurments in semitauonic B decays will be important topic at Belle II

BACKUP

Modification of D^* polarization in NP scenarios

https://arxiv.org/abs/1607.02932

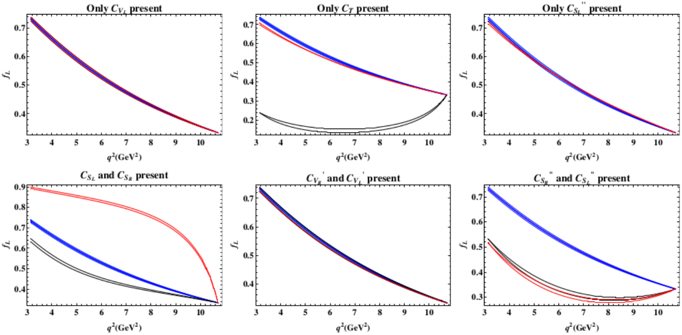
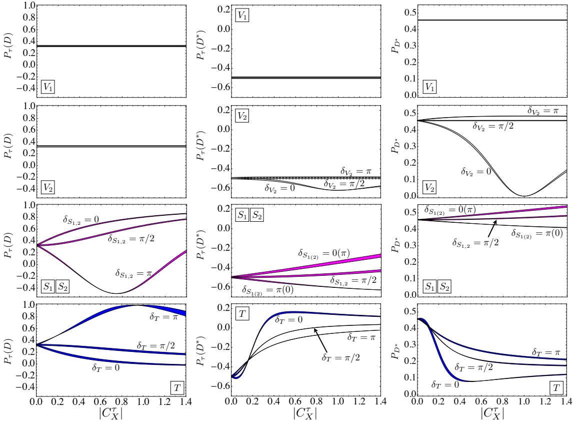


FIG. 1: Plots of D^* longitudinal polarization fraction $f_L(q^2)$ as a function of the dilepton invariant mass q^2 in the decay $\bar{B} \to D^* \tau \bar{\nu}$. The blue band in all the plots corresponds to the SM prediction. The band is due to theoretical uncertainties, mainly due to form factors, added in quadrature. The plot in the left panel of top row represents $f_L(q^2)$ prediction in the presence of NP couplings $C_{V_L} = (0.18 \pm 0.04)$ (black band) and $C_{V_L} = (-2.88 \pm 0.04)$ (red band). The black and red bands in the middle panel of the top row are for $f_L(q^2)$ with NP couplings $C_T = (0.52 \pm 0.02)$ and $C_T = (-0.07 \pm 0.02)$, respectively. The red band in the right panel of top row corresponds to $C''_{S_L} = (-0.46 \pm 0.09)$. In the left panel of bottom row, the black and red bands correspond to NP coefficients $(C_{S_L}, C_{S_R}) = (-1.02, 1.25)$ and $(3.08, -2.84)$, respectively. In the bottom middle panel, $f_L(q^2)$ prediction for $(C'_{V_L}, C'_{V_R}) = (0.18, -0.01)$ and $(-2.88, 0.01)$ are shown by black and red bands, respectively. $f_L(q^2)$ for NP couplings $(C''_{S_R}, C''_{S_L}) = (0.96, 2, 41)$ (black band) and $(-6.34, -2.39)$ (red band) are shown in right panel of bottom row. (Color online)

Examples of interesting distributions and observables

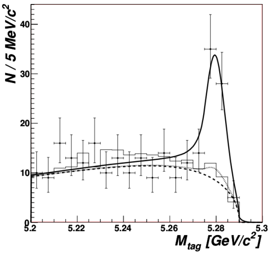


Predictions on the branching ratios as functions of the absolute value of Wilson coefficient $\left|C_X^\tau\right|$ for $X = V_{1,2}, S_{1,2}, T$. The predictions of new physics effects for the operators $\mathcal{O}_X^{e,\mu}$ are given by the lines for $\delta_X = \pi/2$ in these graphs. The light blue horizontal bands represent the experimental values. (arXiv:1212.1878v3)

Method

1. Reconstruct **inclusivly** $B_{\rm tag}$;
   First we find B_{sig} candidates: (D^* + (h or ℓ)), from rest of event we reconstruct candidates for B_{tag} and calulate: $E_{tag} = \sum_i E_i$ $\quad \mathbf{p}_{tag} = \sum_i \mathbf{p}_i$
   variables to identify B_{tag}: $M_{tag} = \sqrt{E_{beam}^2 - \mathbf{p}_{tag}^2}$, $\Delta E_{tag} = E_{beam} - E_{tag}$
2. Extract number of signal events by fitting M_{tag} distributions in bins of $\cos\theta_{\rm hel}(D^*)$;

   PRL **99**, 191807

   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;