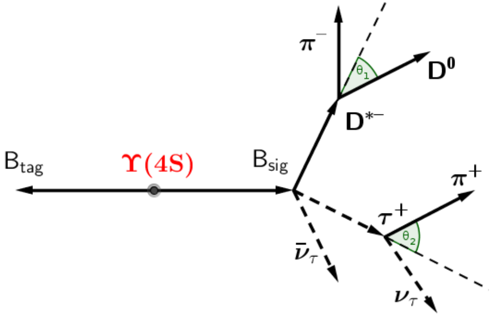
B to semitauonic decays at Belle/Belle II



Outline:

- Physics motivation & experimental situation
- Polarization measurements in $B \to D^* \tau \nu$ by Belle
- Prospects for Belle/Belle II

Karol Adamczyk
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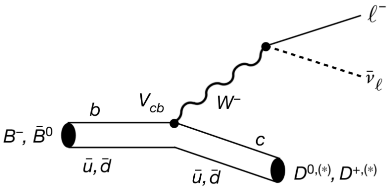
for the Belle Collaboration

Physics motivation



Observables

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

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

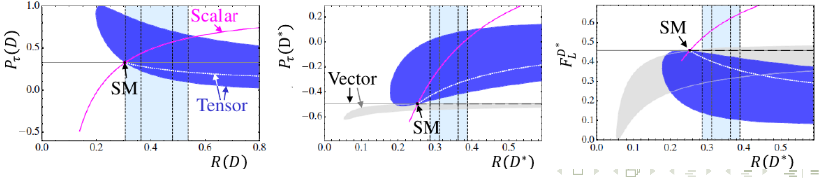
$F_L^{D^*}$: fraction of longitudinal polarization of D^*

SM: $F_L^{D^*} = [0.44 - 0.46] \pm < 10\%$

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

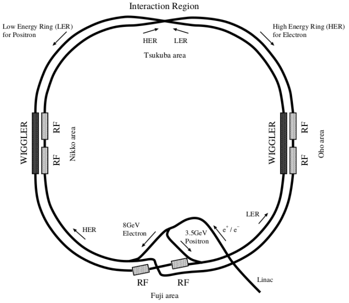
SM: $P_\tau(D^*) \approx -0.5$

New Physics scenarios

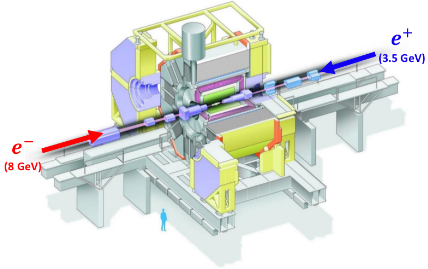


The Belle Experiment

KEKB



Belle detector - multipurpose large-solid-angle magnetic spectrometer



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

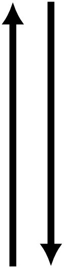
$$e^+e^- \to \Upsilon(4S) \to B\overline{B} \qquad (772 \times 10^6\ B\overline{B})$$

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

Experimental techniques

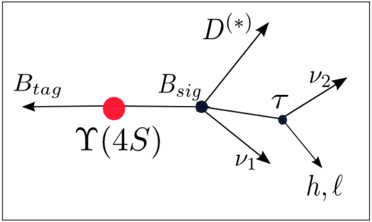
Tagging techniques

efficiency



purity

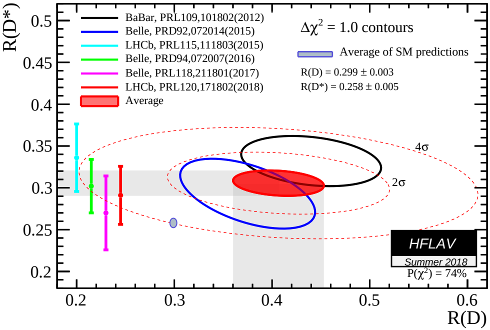
- Inclusive
  $B \to$ *hadrons* (inclusive modes)
  $\epsilon \approx O(1\%)$
  (A. Matyja: PRL **99**, 191807, (2007).,
  A. Bozek: PRD **82**, 072005, (2010).)
- Semileptonic
  $B \to D^{(*)}\ell\nu_\ell$
  $\epsilon \approx O(0.3\%)$
  (Y. Sato: PRD **94**, 072007, (2016).)
- Hadronic
  $B \to$ *hadrons*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



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



SM predictions

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

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

HFLAV

$$R_D = 0.407 \pm 0.039_{stat} \pm 0.024_{syst}$$
$$R_{D^*} = 0.306 \pm 0.013_{stat} \pm 0.007_{syst}$$

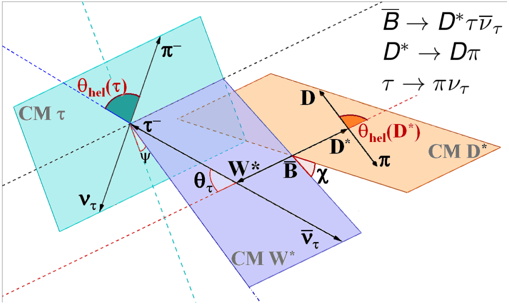
deviation from SM:

$\sim 2.3\sigma$ for $R(D)$

$\sim 3.4\sigma$ for $R(D^*)$

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

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



$q^2 \equiv M_W^2$ - 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

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

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

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

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

Measurement of τ polarization in B decays

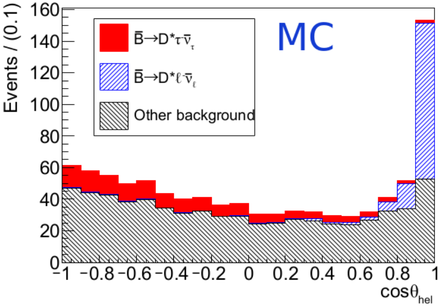
Phys. Rev. Lett. **118**, 211801 (2017); Phys. Rev. D **97**, 012004 (2018)

- **both $\bar{B}^0$ and B^- decays are used; only 2 body τ decays: $\tau \to \pi\nu, \rho\nu$**
- 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 $\tau \to \pi\nu$)

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

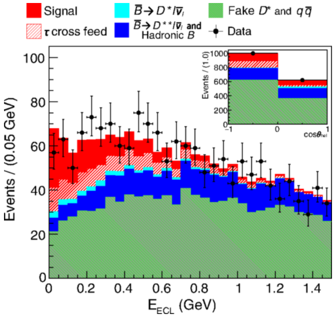
Experimental challenges

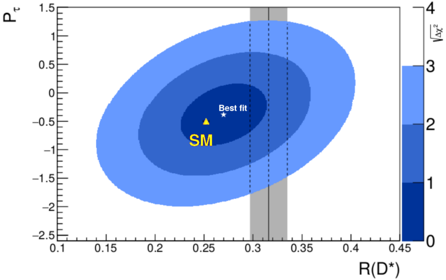
- Distribution of $\cos\theta_{hel}(\tau)$ is modified by:
  - cross-feeds from other τ decays (contribute mainly in the region of $\cos\theta_{hel}(\tau) < 0$)
  - peaking background (concentrated around $\cos\theta_{hel}(\tau) \approx 1$)
- corrections for detector effects: acceptance, asymmetric $\cos\theta_{\rm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



Result on $P_\tau(D^*)$

Phys. Rev. Lett. **118**, 211801 (2017); Phys. Rev. D **97**, 012004 (2018)





$$P_\tau(D^*) = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$
$$R(D^*) = 0.270 \pm 0.035(stat.)^{+0.028}_{-0.025}(syst.)$$

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

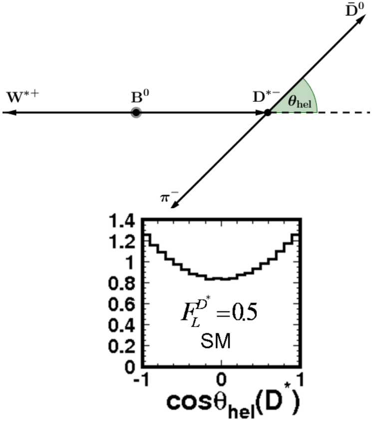
- first measurement of $P_\tau(D^*)$; the result excludes $P_\tau(D^*) > +0.5$ at 90% C.L.
- combined $R(D^*)$ and $P_\tau(D^*)$ result is consistent with the SM within 0.6σ

D^* polarization studies

$R(D^{(*)})$ systematically above the SM expectations, surprisingly large effect 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
- + not affected by cross-feeds between different τ decays

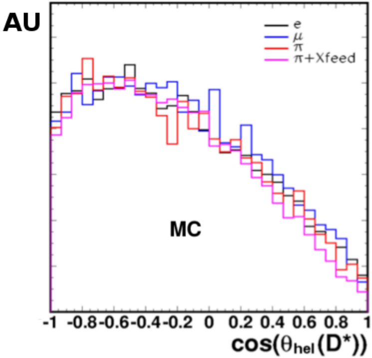
Theoretical papers (D^* polarization studies):

- M. A. Ivanov, J. G. Koerner, C. T. Tran, Phys. Rev. **D 94**, 094028 (2016)
- A.K. Alok, D. Kumar, S. Kumbahar, and S U. Sankar, Phys. Rev. **D 95**, 115038 (2017)
- Z.-R. Huang et al., arXiv:1808.03565 [hep-ph].

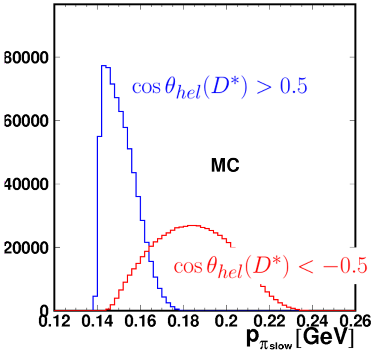
Challenges for D^* polarization measurement

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

efficiency



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



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

D^* polarization - analysis method

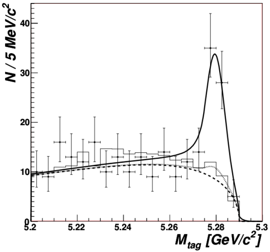
- Extract signal yield in bins of $\cos\theta_{hel}(\tau)$ in the range of $-1 < \cos\theta_{hel}(\tau) < 0$
- Extract F_L from fit to $\cos\theta_{\mathrm{hel}}(D^*)$ distribution

- Employ **inclusive** B_{tag} reconstruction method
- Select clean decay chains:
  $B^0 \to D^{*-}(\to \overline{D}^0\pi^-)\tau^+\nu$;
  $D^0 \to K\pi, K\pi\pi^0, K\pi\pi\pi$;
  $\tau \to e\nu\nu; \mu\nu\nu; \pi\nu$

Method of **inclusive** reconstruction of $B_{\rm tag}$

1. Create candidates for B_{sig} daughters: D^* + (d_τ = h or ℓ))
2. Reconstruct B_{tag} inclusively form all remaining particles
   $E_{tag} = \sum_i E_i \quad \mathbf{p}_{tag} = \sum_i \mathbf{p}_i$
   consistency of $B_{\rm tag}$ candidates checked using $M_{tag} = \sqrt{E^2_{beam} - \mathbf{p}^2_{tag}}$,
   $\Delta E_{tag} = E_{beam} - E_{tag}$
3. Suppres bkg using observables sensitive to multiple neutrion final states (e.g. visible energy, missing mass, . . .)
4. Extract number of signal events by fitting M_{tag} distribution

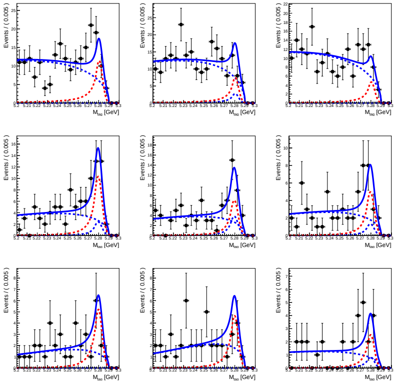
PRL **99**, 191807



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

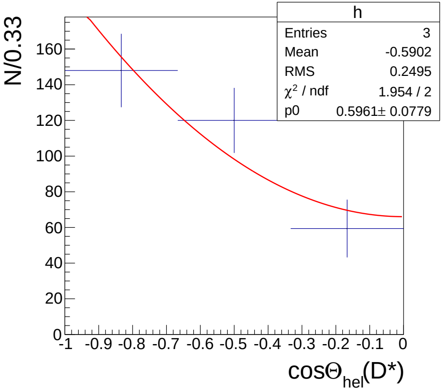
Signal extraction

- 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 $\cos\theta_{\text{hel}}(D^*)$ in the range [-1,0];
  I : $-1.0 < \cos\theta_{\text{hel}}(D^*) < -0.67$
  II : $-0.67 < \cos\theta_{\text{hel}}(D^*) < -0.33$
  III : $-0.33 < \cos\theta_{\text{hel}}(D^*) < 0.0$
- example fit projection to M_{tag} distribution in the range $-1.0 < \cos\theta_{\text{hel}}(D^*) < -0.67$



Result on $F_L^{D^*}$ for $B^0 \to D^* \tau \nu$

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



Number of events in:
I bin: 151 ± 21
II bin: 125 ± 19
III bin: 55 ± 15
- signal yields corrected for accaptance variations

Dominant systematics:
- MC statistics (AR shape and peaking backgroud) $= \pm 0.03$

$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al) (1.5 σ)

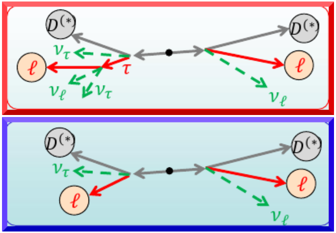
SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) (1.8 σ)

$\Rightarrow$ consistent with the SM within 2σ

Prospects @ Belle

- $F_L^{D^*}$ also for $B^{\pm}$
- simultaneous measurement of $R(D)$ and $R(D^*)$ with semileptonic tag
  - in the previous analysis only: $B^0\overline{B^0} \to (D^{*-}\ell^+)(D^{*+}\ell^-)$
  - add B decays modes: $B^0\overline{B^0} \to (D^-\ell^+)(D^+\ell^-))$
    $B^+B^- \to (\overline{D}^{(*)0}\ell^+)(D^{(*)0}\ell^-))$

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



analysis made in BASF2 (Belle II software framework) using FEI (Full Event Interpretation - a new exclusive tagging algorithm for multivariate analysis with BDT classifier)

more details about FEI

in Moritz Gelb talk on "B to l nu gamma at Belle“

Prospects @ Belle II

The Belle II Physics Book, arXiv:1808.10567

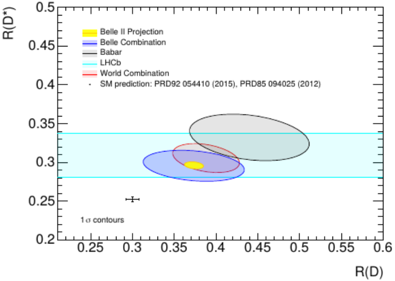
- Belle: 0.772 x 10^9 $B\overline{B}$;
- Belle II: $\sim$ 50 x 10^9 $B\overline{B}$ (x 50 Belle statistic) (50 ^{-1}ab)
- expected number of events for $P_\tau(D^*)$ measurement:
  - $\sim$ 4000 in $B^0(\overline{B^0})$ mode (hadronic $B_{\rm tag}$ reconstrucion)
  - $\sim$ 10000 in $B^+(B^-)$ mode (hadronic $B_{\rm tag}$ reconstrucion)
- expected number of events for $F_L^{D^*}$ measurement:
  - $\sim$ 15000 in $B^0(\overline{B^0})$ mode (inclusive $B_{\rm tag}$ reconstrucion)
- expected precision (the statistical and systematic errors respectively)

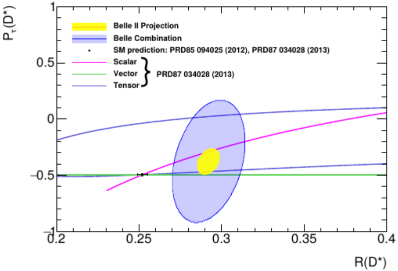
	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

Prospects @ Belle II

The Belle II Physics Book, arXiv:1808.10567

- expected constraints on R_D vs. R_{D^*}; R_{D^*} vs. $P_\tau^{D^*}$ compared to existing experimental constraints from Belle





- higher statistics and better reconstrucion efficiencies should allow for precise measurements of kinematic distributions, e.g. q^2 and polarizations

Summary

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

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

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

$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

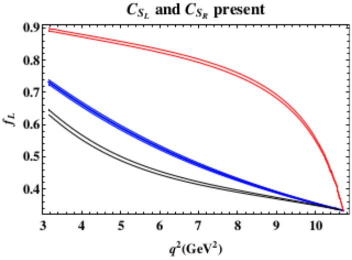
- measurements sensivity limited by the statistics
- measurments of characteristics of semitauonic B decays will be important topic @ Belle II

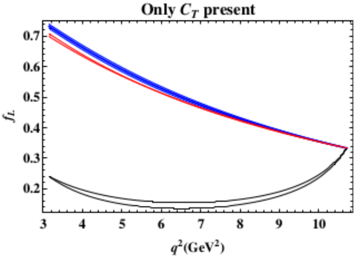
BACKUP

D^* polarization - NP scenarios

- SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al)
  SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al)
- $F_L^{D^*}$ can be significantly modified in the presence of NP contributions; in particular $F_L^{D^*}$ is enhanced (decreased) by the scalar(tensor) operators

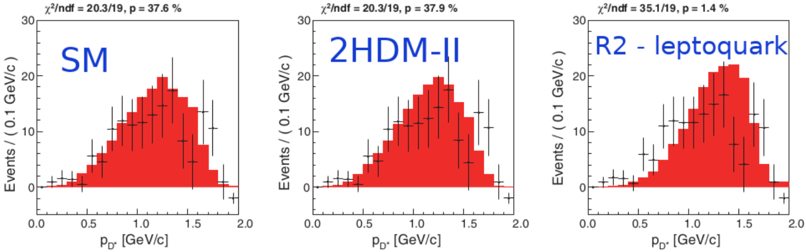
Phys. Rev. D 95, 115038





Momentum spectra to examine NP scenarios

Phys. Rev. D 94, 072007 (2016); semileptonic B_{tag}



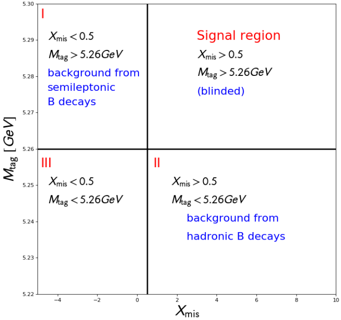
- Measured distributions of p_{D*} and p_l consistent with SM but statistically limited
- More observables with more data needed to clarify the situation

Background callibration

Sources of peaking background:

$D^* \ell\nu$, $D^{**} \ell\nu$

Phase space divided in four regions:



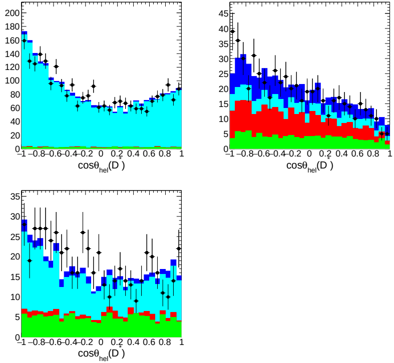
$$X_{mis} = \frac{E_{mis} - |\vec{p}_{D^*} + \vec{p}_h|}{\sqrt{E_{beam}^2 - M_B^2}} \text{ (similar to } M_M^2)$$

$$E_{mis} = E_{beam} - E_{D^*} - E_h$$

Simultanous fit to the following variables:
M_{tag}, X_{mis}, ΔE, M_W^2, π energy, D^* energy, R_2, $m_{D^{*\pm}} - m_{D^0}$

$\rightarrow$ find scale factors for bkg components

control distributions for $\cos\theta_{hel}(D^*)$ in I, II and III region for $B \rightarrow D^*(D \rightarrow K\pi)\tau(\rightarrow e\nu\nu)\nu$:

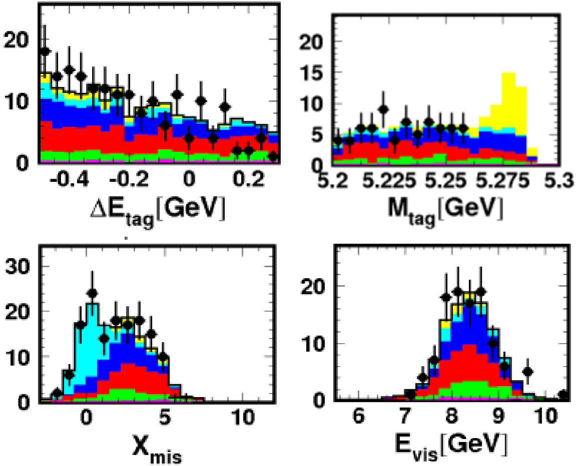


BKG COMPONENTS:

- $D^{**}\ell\nu$
- $D^*\ell\nu$
- hadronic combinatorial B decays
- charm + uds

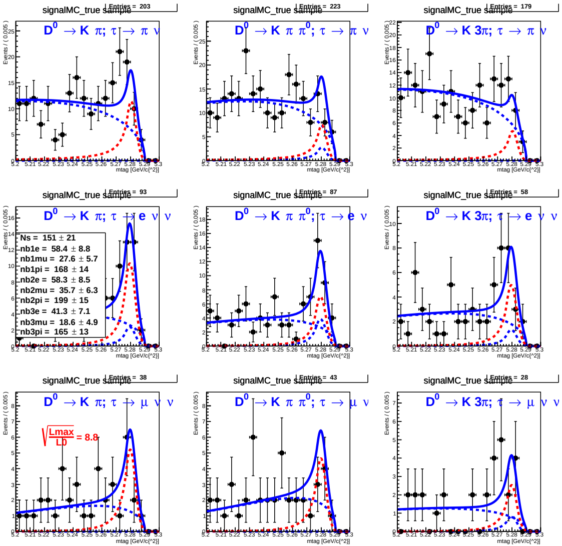
Check backgroud model with final selection criteria

Example distributions for final selection criteria
(e.g. $D^*\mu$ sample in $-0.67 < \cos\theta_{\rm hel}(D^*) < -0.33$)



- $D^{**}\ell\nu$
- $D^*\ell\nu$
- hadronic combinatorial B decays
- charm + uds

Signal box opening - extraction of signal yield



DATA: number of events in I bin: 151 ± 21