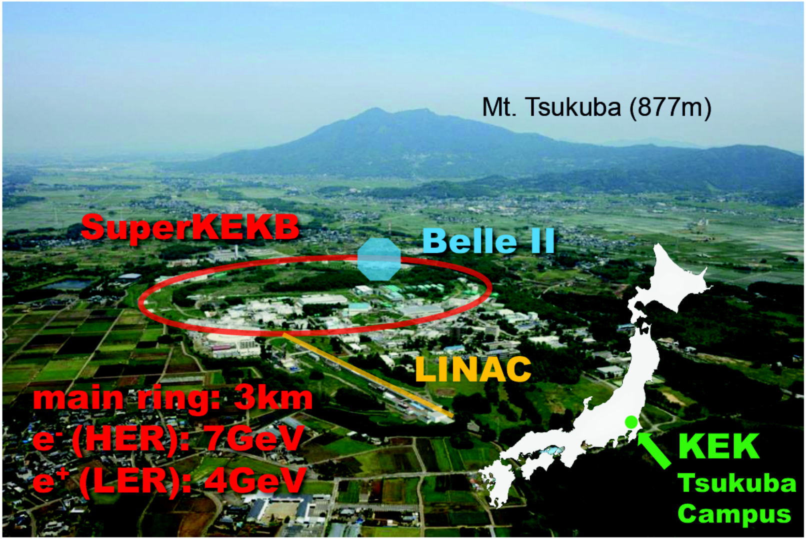
B decays with missing energy, Belle II perspective

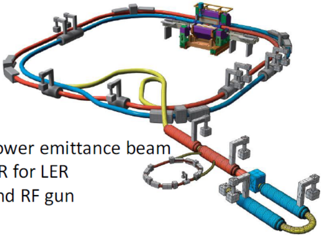
A. Bożek, IFJ PAN Kraków

for the Belle II Collaboration

SuperKEKB and Belle II



SuperKEKB: the nano beam scheme



Beam current

Beam-beam parameter

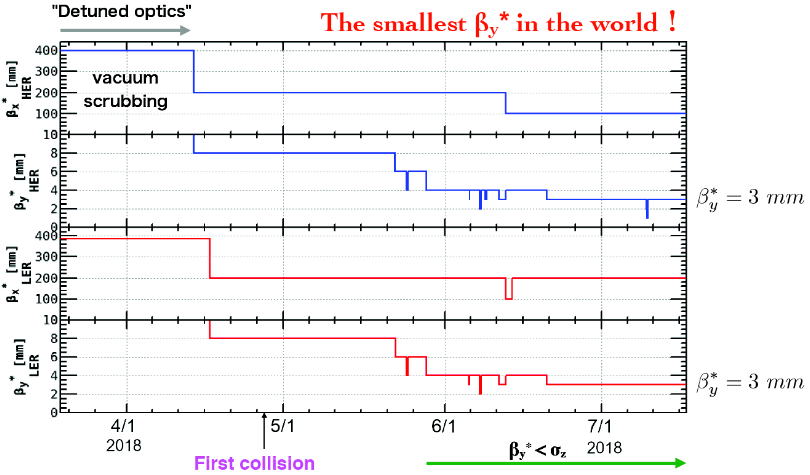
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

σ: beam size

β function

		KEKB		SuperKEKB		units	
		LER	HER	LER	HER		
Beam energy	E_b	3.5	8	4	7.007	GeV	
Beam crossing angle	φ	22		83		mrad	
β function @ IP	β_x^*/β_y	1200/5.9		32/0.27	25/0.30	mm	X 20
Beam current	I_b	1.64	1.19	3.6	2.6	A	X 2
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$	X 40

SuperKEKB: the nano beam scheme



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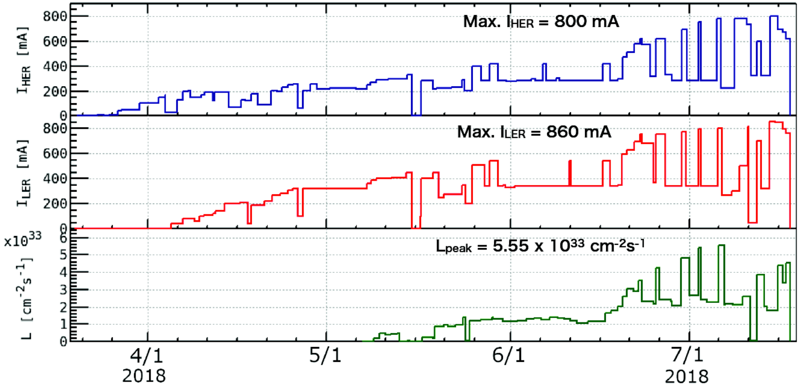

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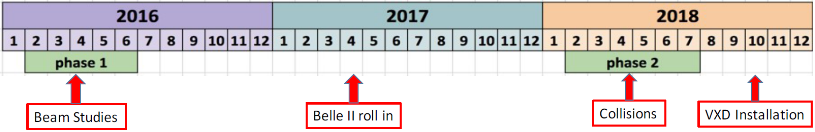
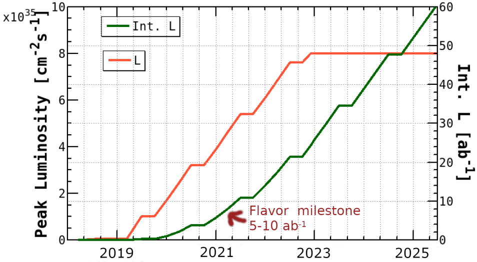
SuperKEKB: commisioning

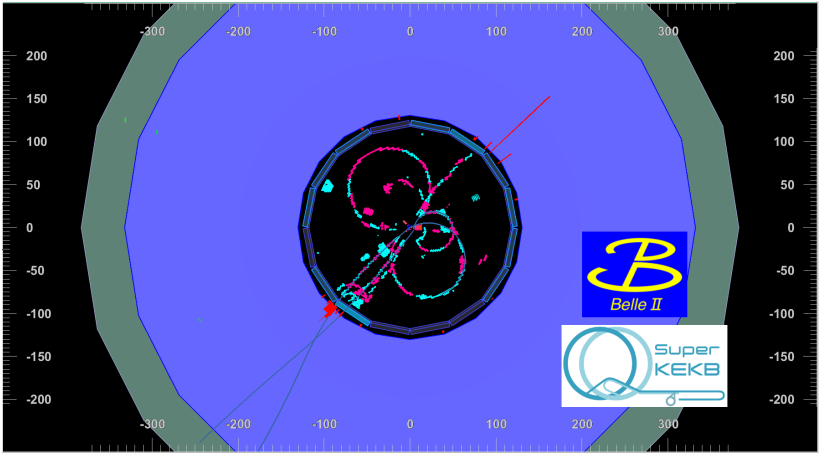


- Phase 1 : Beam operation without final focus magnets and Belle II
  - Commissioning of beam transportation and vacuum scrubbing
  - Only single beam studies
- Phase 2(ended on July 2018) :
  - No final vertex detector but one ladder/layer with background sensors
  - Achieved Luminosity of $5.5 \times 10^{33} cm^{-2} s^{-1}$
  - recorded integrated luminosity of $500 pb^{-1}$
- Phase 3: 2019 - detector with silicon vertex detector, $\approx$ 8 months of operation

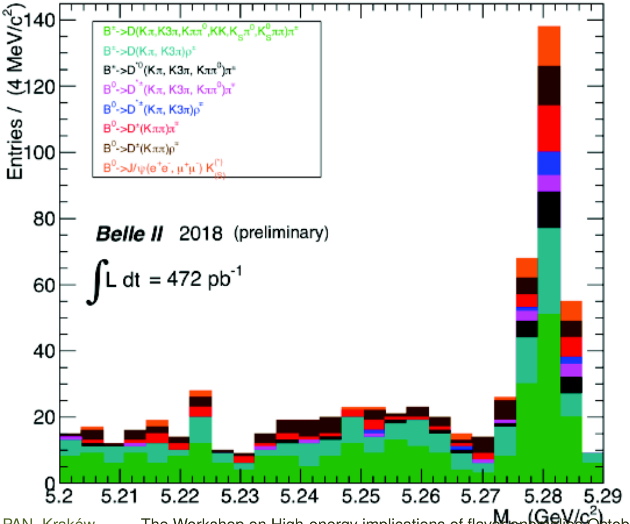


Belle II first event(s)

most likely $e^+e^- \to \Upsilon(4s) \to B\bar{B}$



Belle II first event(s)



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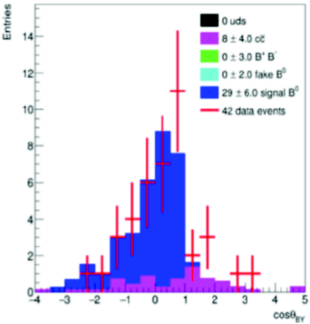
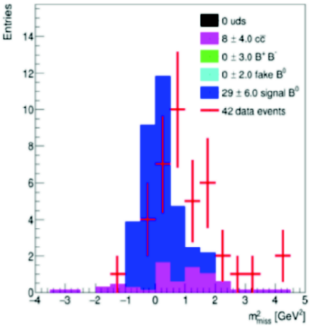
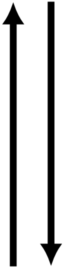




B decays with missing energy

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)
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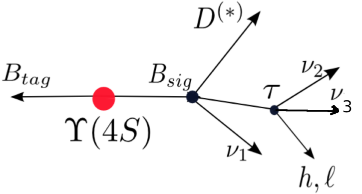
  S. Hirose: PRL **118**, 211801, (2017).)



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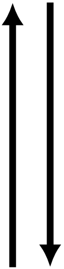

purity

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  $B \to$ *hadrons* (inclusive modes)
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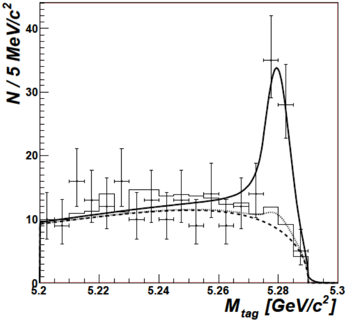
First measurement:



A. Matyja: PRL **99**, 191807, (2007).

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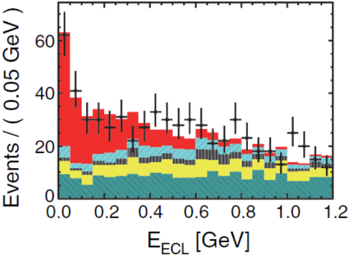
purity

Semileptonic tagging:



E_{ECL} remaining energy in the calorimeter

Y. Sato: PRD **94**, 072007, (2016).

B decays with missing energy

Tagging techniques

efficiency

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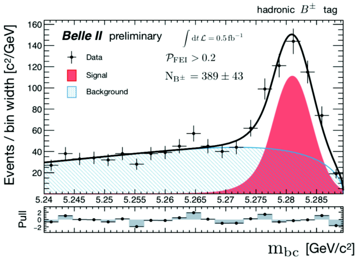
purity

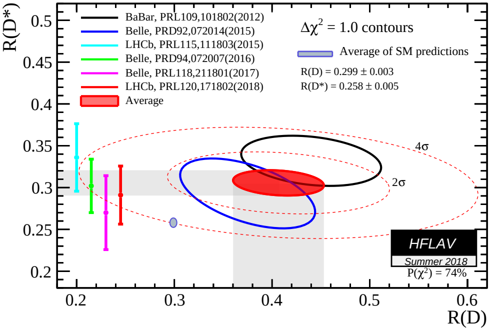
Rest Of the Event (ROI)



$B \to \bar{D}^{(\star)}\tau^+\nu_\tau$ current 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

$$R_D = 0.407 \pm 0.039_{stat} \pm 0.024_{syst}$$

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

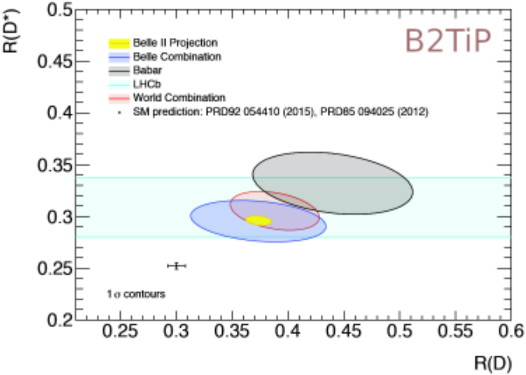
deviation from SM:

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

$\sim 3.0\sigma$ for $R(D^*)$

$\sim 3.7\sigma$ tension between SM and combined $R(D^{(*)})$ experimental results

$B \to \bar{D}^{(\star)}\tau^+\nu_\tau$ Belle II projection



Belle II will improve the statistical uncertainty on $R(D)$ and $R(D^\star)$ with $\sim 5ab^{-1}$ accumulate data we can achieve

- $\sim 6\%$ uncertainty on $R(D)$
- $\sim 3\%$ uncertainty on $R(D^\star)$

the excess can be confirmed with early data
The ultimate precision (with $50ab^{-1}$) of 3% and 2% will be limited by systematic

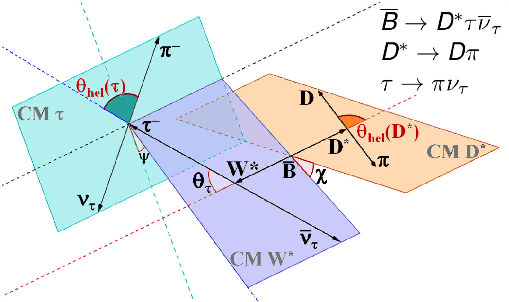
The major contribution to systematic is the uncertainty on $D^{\star\star}$ component.

In Belle II:

- we will study in details $B \to \bar{D}^{(\star\star)}X$ decays,
- especially $B \to \bar{D}^{(\star\star)}\ell^+\nu_\tau$ decays,
- a simultaneous determination of $R(D)$, $R(D^\star)$ and may be $R(D^{\star\star})$ components is possible.

B2TiP *Belle II Theory Interface Platform report*

Kinematic variables describing $B \to \bar{D}^{(*)}\tau^-\nu_\tau$



$q^2 \equiv M_W^2$ - 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

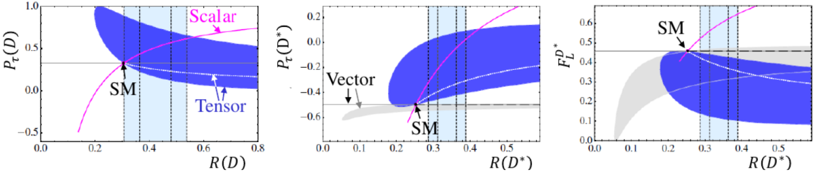
$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

$\alpha = 1.0$ for $\tau \to \pi\nu$; $\alpha = 0.45$ 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, $\cos\theta_{\rm hel}(\tau)$ and $\cos\theta_{\rm hel}(D^*)$ can be reconstructed at B-factories with hadronic decays of $B_{\rm tag}$

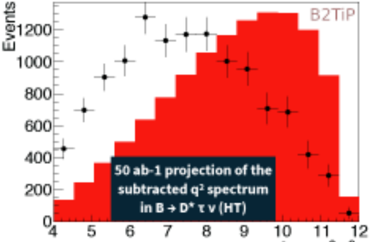
$B \to \bar{D}^{*} \tau^{-} \nu_{\tau}$ differential distribution : q^2



M.Tanaka,R.Watanabe - arXiv:1212.1878v1

Differential distribution can be measured to constrain NP contributions

Detailed measurement of q^2 and other kinematic distributions including polarization of the τ and $D^\star$

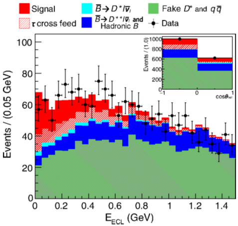


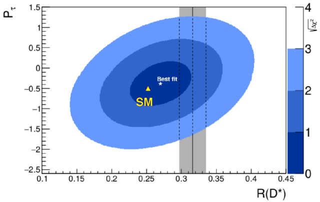
Belle II MC are generated in the SM hypothesis
Block histograms is a 2HDM-type II benchmark

$B \to \bar{D}^{*}\tau^{-}\nu_{\tau}$ differential distribution : τ polarisation

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

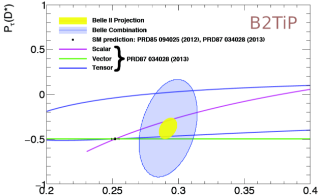
Measured from the two body semileptonic τ ($\to \pi\nu, \to \rho\nu$) decays -experimentally challenging





Belle II perspectives :

	5 ab^{-1}	50 ab^{-1}
$P_\tau(D^\star)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

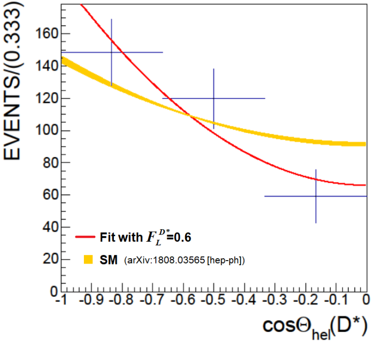


$B \to \bar{D}^*\tau^-\nu_\tau$ differential distribution : $D^\star$ polarisation

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

All τ decays are usable.

Belle result presented on CKM2018:



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

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

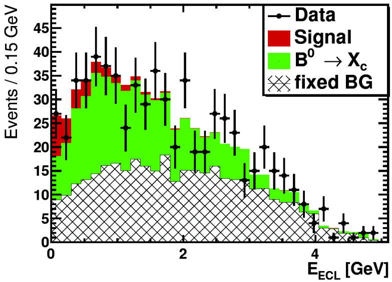
SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) (1.8 σ)

$\Rightarrow$ consistent with the SM within 2σ

Expected number of events for $F_L^{D^*}$ in full data set is $\sim$ 15000.

Testing lepton flavor universality in $b \to u$ semileptonic decays

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



Feasibility already demonstrated with Belle. No statistically significant signal was observed $\mathcal{B}(B \to \pi \tau^+ \nu_\tau) < 2.5 \times 10^{-4}$

Phys. Rev. Lett. 118, 211801 (2017)

Central value:

$\mathcal{B}(B \to \pi \tau^+ \nu_\tau) =$

$(1.52 \pm 0.72 \pm 0.13) \times 10^{-4}$

Belle II extrapolation of uncertainty

$R_\pi^{5ab^{-1}} \pm 0.23$ or $R_\pi^{50ab^{-1}} \pm 0.09$

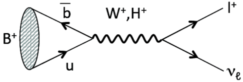
Testing lepton flavor universality with leptonic B decays

Very clean theoretically, hard experimentally SM is helicity suppressed
Sensitive to NP contribution (charged Higgs)

$$R^{\tau\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau e} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau\pi} = \frac{\Gamma(B \to \tau\nu)}{\Gamma(B \to \pi l\nu)}$$



$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

Mode	SM BR	Current meas.	Belle II 5 ab-1	Belle II 50 ab-1
τν	10^{-4}	20% uncertainty	15%	6%
μν	10^{-6}	40% uncertainty*	20%	7%
eν	10^{-11}	Beyond reach	-	-

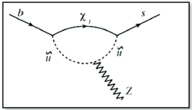
* arxiv:1712.04123 2.4σ excess $[2.9,10.7]\times10^{-7}$ at 90% C.L.

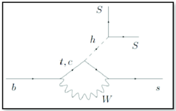
Belle II Full simulation with expected background conditions (hadronic tags only)
S.L. tag expected to have similar sensitivity

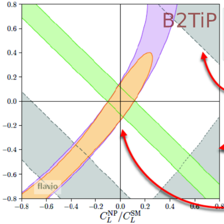
Extrapolation of Belle Analysis

$B \to K\nu\nu$ decays

Suppressed in the SM : BRs $10^{-5} - 10^{-6}$ may be enhanced by NP





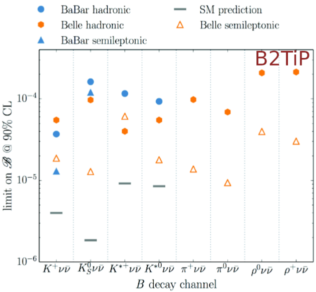


Constraints on new physics contributions to Wilson coefficients C_L, C_R

90% CL excluded by Belle and Babar

68% CL allowed by Belle II at 50 ab^{-1}

Current limits



Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	25%	9.3%

Summary

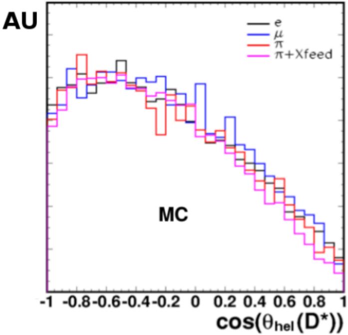
- Belle II started to run on collision this year,
- from next year we are going to collect data meaningful for B physics,
- B decays with missing energy are one of the focus of Belle II,
- in 2020 we should surpass current luminosity accumulated by B-factories

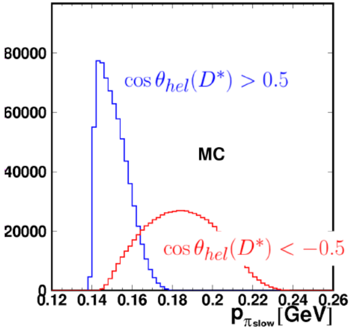
Challenges for $D^{\star}$ *polarisationmeasurement*

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

Measurement of τ polarization in B decays

- **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