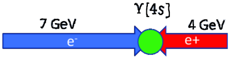
Status and Prospects of Belle II

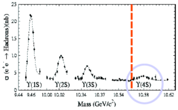
A. Bożek, IFJ PAN Kraków

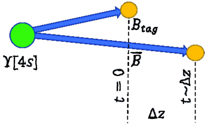
for the Belle II Collaboration

The B-factory idea

- Electron-positron collisions
- $E_{\mathrm{CM}} \approx m_{\Upsilon(4s)}$
- $\Upsilon(4s) \to \bar{B}B$, quantum-entangled
- Asymetric beam energies
  - B decay time distributions via $\Delta z \approx 200\mu$m
  - precision studies of B meson mixing, mixing induced CPV, quantum decoherence, ...
- Target plan 55 billion B meson pairs decays recorded
- Sensitivity in B, charm and τ to $O(10^{-9}) - O(10^{-11})$ branching fractions







Process	σ (nb)
bb	1.1
cc	1.3
Light quark qq	~2.1
τ+τ-	0.9
e+e-	~40

The B-factory idea

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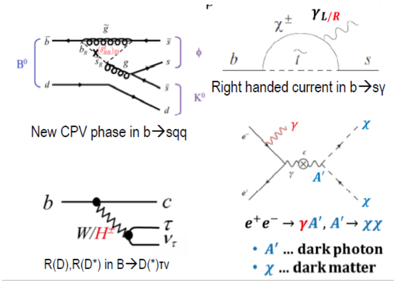
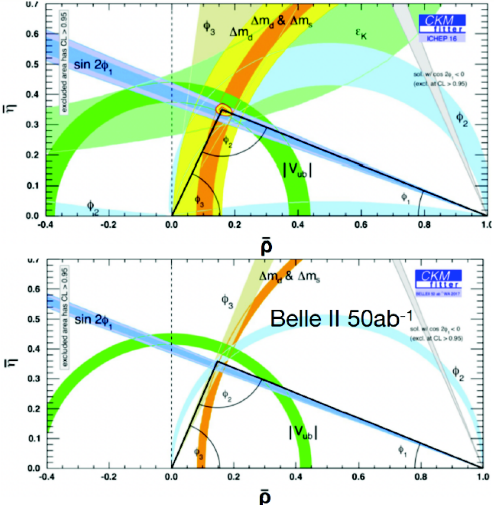


Belle II motivations

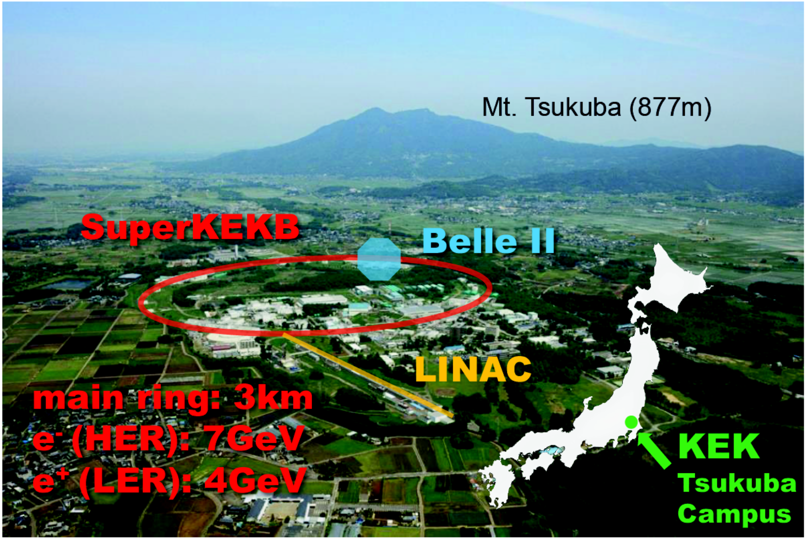
- The original B factory experiments Belle and BaBar confirmed the Kobayashi-Maskawa Mechanism
- A single, irreducible, complex CKM phase can explain all observation in the quark flavor physics
- proven part of Standard Model
- Belle II will look for deviation from the picture to provide evidence of BSM physics
- Several tentions gives room to $O \approx 10\%$ deviation from SM
    - LFVU
    - CPV in D's (LHCb) measurements



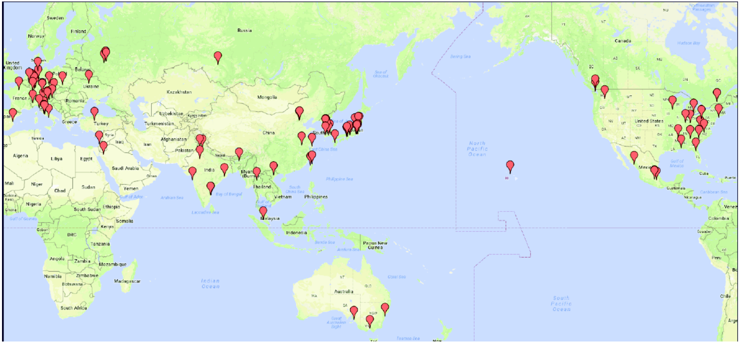
The Belle II physics scope extends far beyond B physics and CPV. Charm, τ, precision EW, Quarkonium physics, dark sector searches etc.

The Belle II Physics Book, ArXiv:1808.10567, 689 pages

SuperKEKB and Belle II



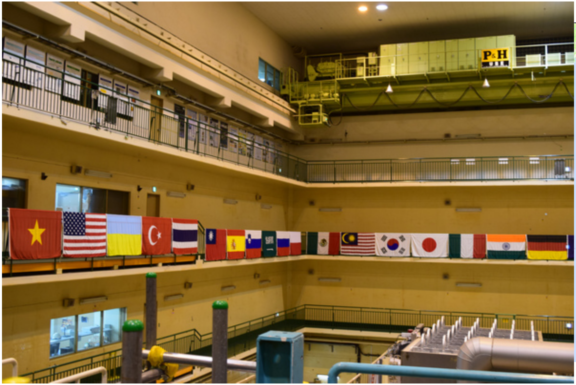
The geography of the international Belle II collaboration

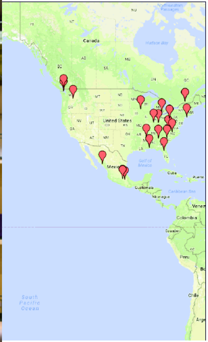


Belle II has grown substantially in recent years

- Over 900 colaborators from 26 countries,
- there are $\approx$ 250 graduate students in the collaboration

The geography of the international Belle II collaboration





Belle II has grown substantially in recent years

- Over 900 colaborators from 26 countries,
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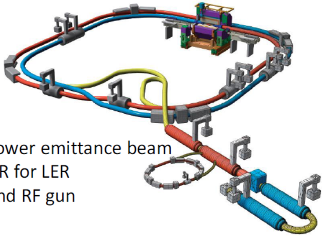
SuperKEKB: the nano beam scheme



Lower emittance beam
DR for LER
and RF gun

Beam current

Beam-beam parameter

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

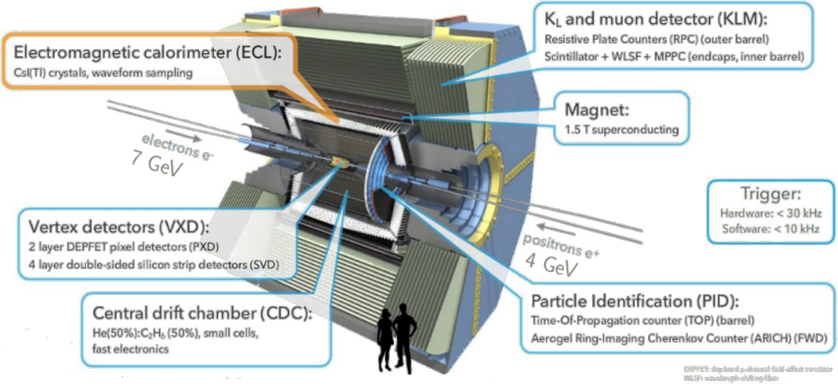
σ: beam size

β function

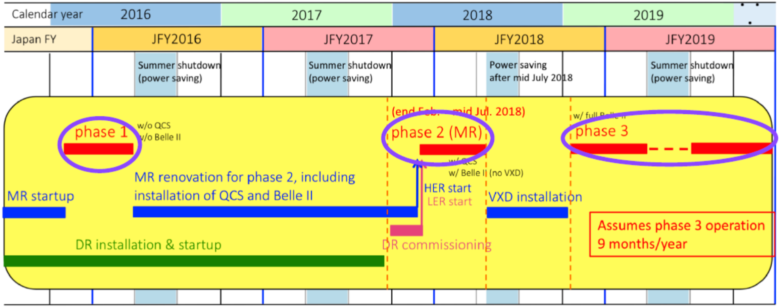
		KEKB		SuperKEKB		units	
		LER	HER	LER	HER		
Beam energy	E_b	3.5	8	4	7.007	GeV	
Beam crossing angle	φ	22		83		mrad	
β function @ IP	β_x^*/β_y	1200/5.9		32/0.27	25/0.30	mm	X 20
Beam current	I_b	1.64	1.19	3.6	2.6	A	X 2
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$	X 40

Belle II detector

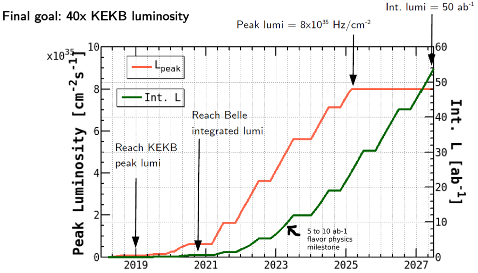
- The Belle II detector has better resolution, PID and capability to cope with higher background



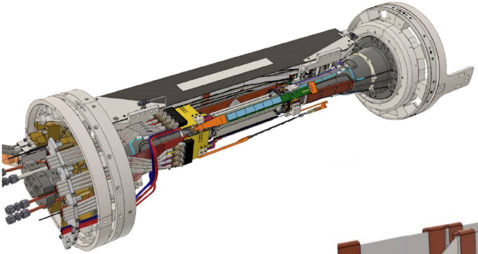
SuperKEKB: commisioning



- Phase 1 : Beam operation without final focus magnets and Belle II
- 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 500pb^{-1}
- Phase 3: 2019 - detector with silicon vertex detector, $\approx$ 9 months of operation



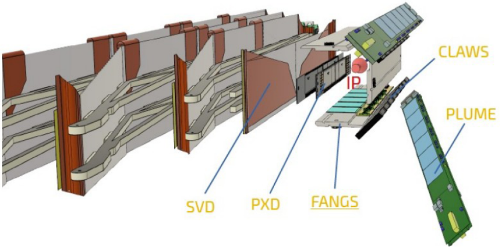
Phase 2 pilot run in 2018



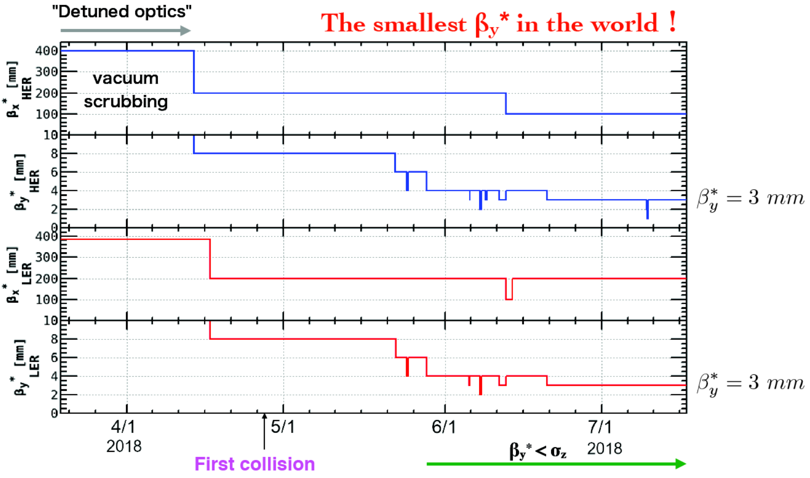
Pilot run with limited vertexing

→ Background monitor detectors replacing most of the silicon tracker

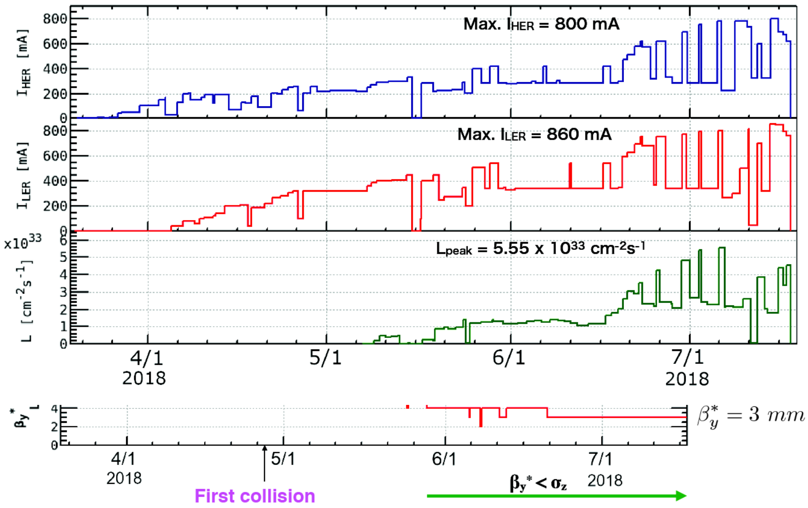
→ One full octant of PXD+SVD (2 + 4 layers)



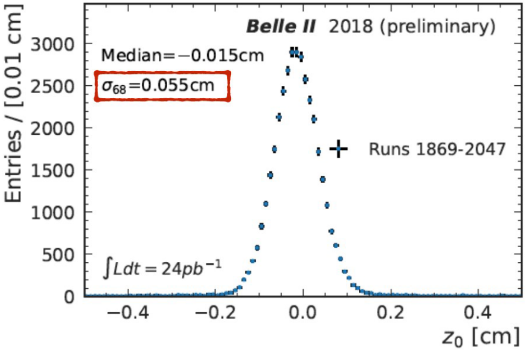
SuperKEKB: phase 2

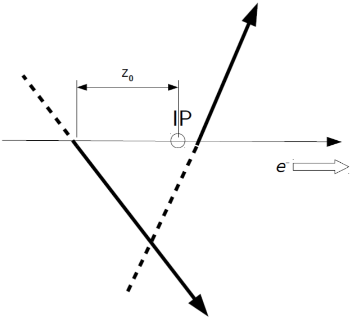


SuperKEKB: phase 2



Phase 2: Interaction region size





Beam spot ~ 10 times smaller than KEKB

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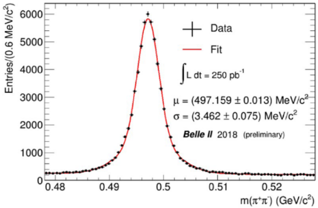
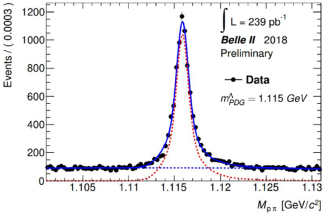
Phase 2: tracking performance

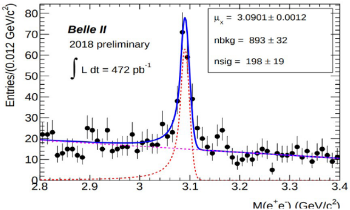
$K_S \to \pi^+\pi^-$



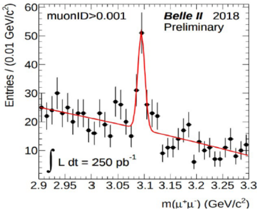
$\Lambda \to p\pi^-$



$J/\psi \to e^+e^-$

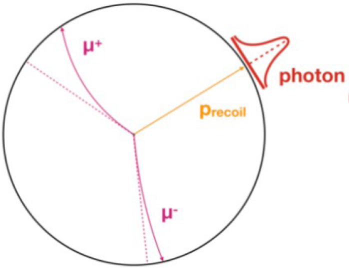


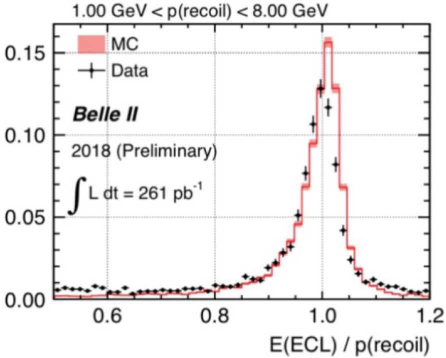
$J/\psi \to \mu^+\mu^-$



Phase 2: Calorymetry

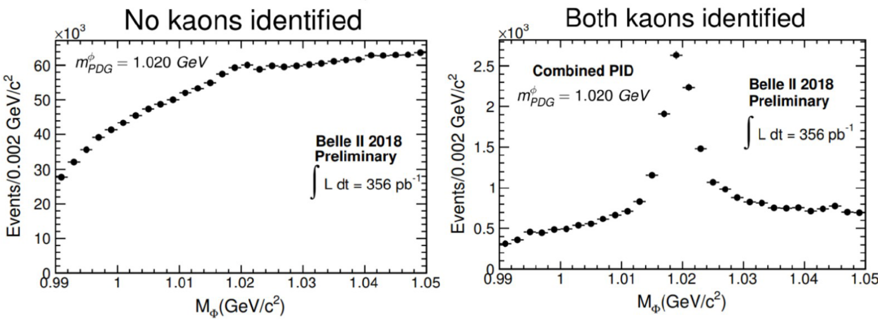
$$e^+e^- \to \mu^+\mu^-\gamma$$





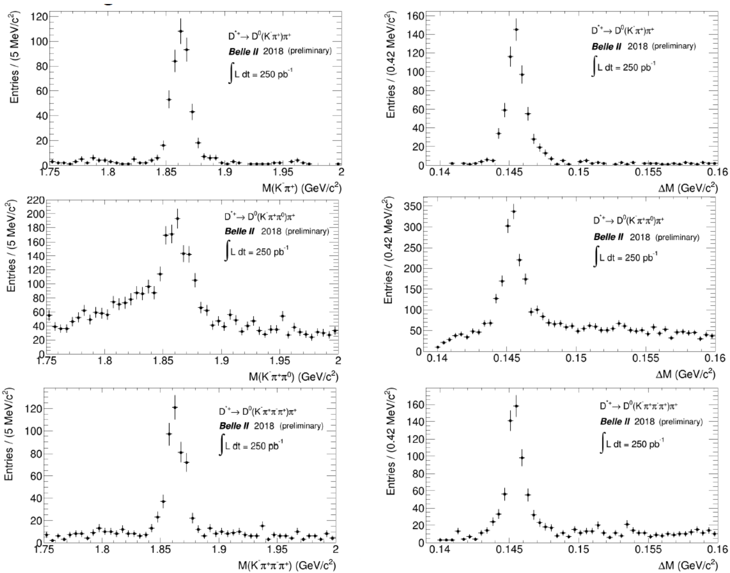
Phase 2: PID perfomance

$$\phi \to K^+ K^-$$

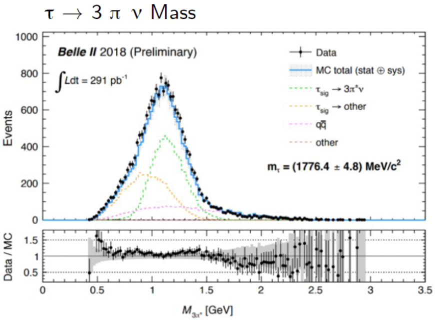


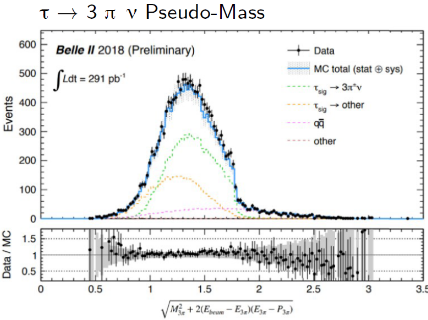
TOP + dE/dx from the drift chamber

Phase 2: Charm rediscovery



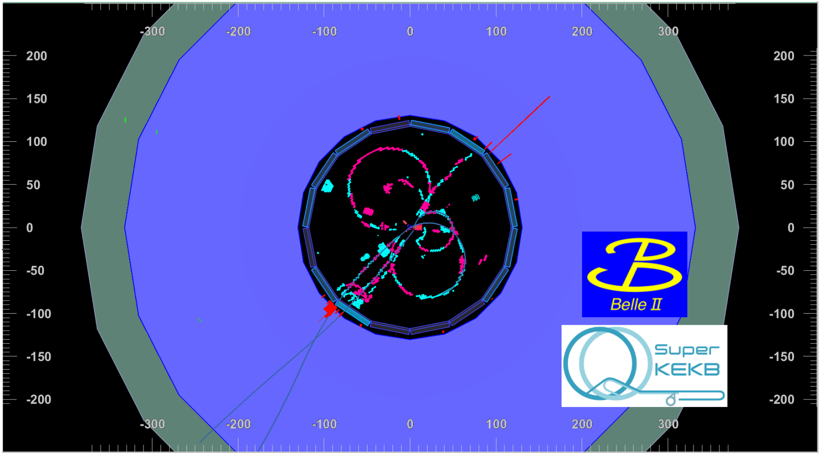
Phase 2: τ rediscovery





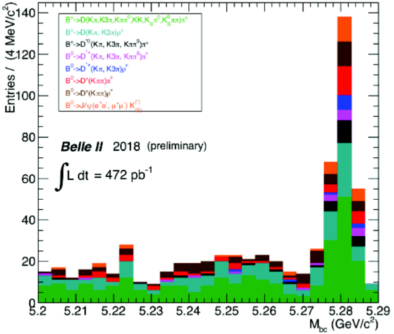
Phase 2: Belle II first B event(s)

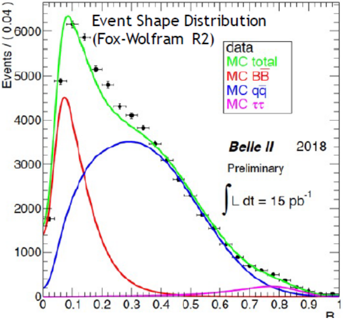
most likely $e^+e^- \to \Upsilon(4s) \to B\bar{B}$



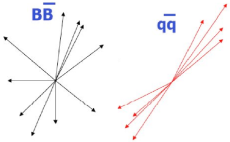
Phase 2: Belle II first *B* event(s)

Hadronic decays reconstructions



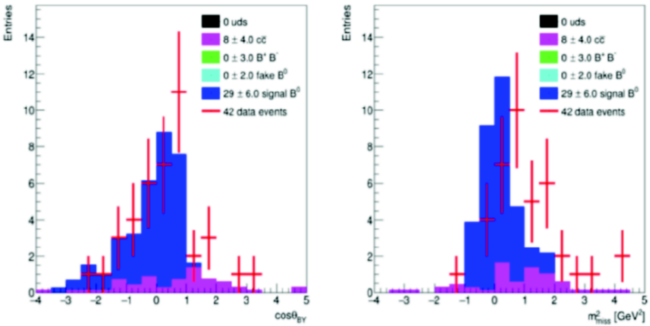


$$M_{bc} = \sqrt{E^2_{beam} - \mathbf{p}^2}$$



Phase 2: Belle II first B event(s)

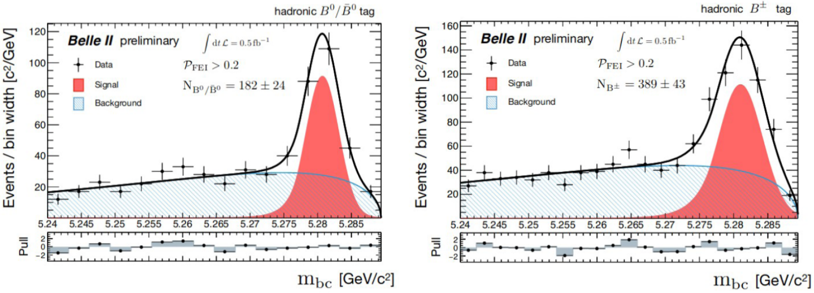
Semileptonic decays reconstruction



$$cos\theta_{B,D^{(*)}\ell} = \frac{2E^{cms}_{beam}E^{cms}_{D^{(*)}\ell} - m_B^2 - M^2_{D^{(*)}\ell}}{2P^{cms}_B \cdot P^{cms}_{D^{(*)}\ell}}$$

Phase 2: Belle II first *B* event(s)

Hadronic tagging performances Full reconstruction



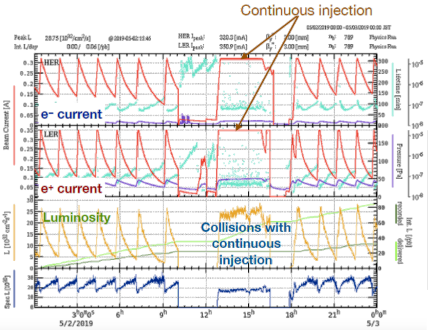
- reconstruct B^0 and $B^{\pm}$ in more then 1000 modes (tag side *B*)
- essenTial for reconstruction of events with missing energy

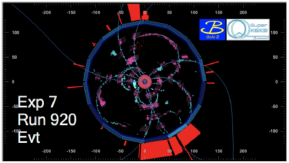
Phase 3 operation

Collision data taking with full coverage Belle II

Started in March 2019

Beam background remediation is the current focus.





- Operation had to stop between April 3rd and 22nd due to a fire accident in one of the test facilities at KEK. Not related to *SuperKEKB* or *Belle II*!

Phase 3 operation

- Belle II aims to collect
  - July 2019 : ~10 fb^{-1}

- **Performance Studies:**

Semileptonic
$B \to \pi l \nu$ and $\rho l \nu$ untagged
(CLEO saw a signal with 2.66 fb^{-1})

Hadronic B Decays
$B \to K \pi$ (10 fb^{-1})
$B \to \phi K$ (10 fb^{-1})
$B \to J/\psi K$ (2-10 fb^{-1})
Time dependent B mixing (10 fb^{-1})
B lifetimes (2-10 fb^{-1})

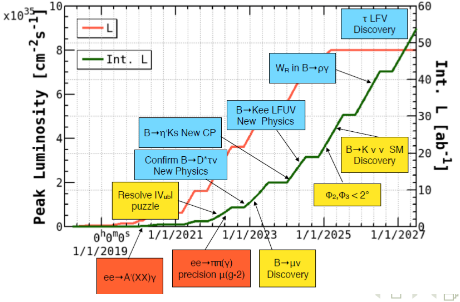
Radiative Electroweak Penguins
$B \to K^* \gamma$ (2 fb^{-1}) rediscovery penguins
$B \to X_s \gamma$ (10 fb^{-1})

Charm
D lifetimes (2 fb^{-1})
$D^0 \to K^+ \pi^-$, $D^0 \to K^+ \pi^- \pi^0$ (10 fb^{-1})

- Publication prospects for dark sector searches.

Summary

- Belle II has successfully concluded the phase 2 physics run
- Phase 3 run started in March 2019
  - full physics run,
  - we are going to collect data meaningful for *B* physics,
  - 10 fb^{-1} by this summer
- The Belle II aim is to explore New Physics in the flavor sector with 50 ab^{-1} data collected at SuperKEKB



backup

Belle II physics

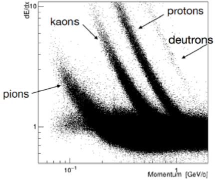
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)	
UT angles & sides				
ϕ_1 [°]	***	0.4	Belle II	
ϕ_2 [°]	**	1.0	Belle II	
ϕ_3 [°]	***	1.0	LHCb/Belle II	CKM
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II	
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II	
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II	
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb	
CP Violation				
$S(B \to \phi K^0)$	***	0.02	Belle II	
$S(B \to \eta' K^0)$	***	0.01	Belle II	CPV
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II	
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II	
(Semi-)leptonic				
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II	(Semi)
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II	LEPTONIC
$R(B \to D\tau\nu)$	***	3%	Belle II	
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb	
Radiative & EW Penguins				
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II	
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II	
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II	
$S(B \to \rho\gamma)$	**	0.07	Belle II	EWP
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II	
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II	
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II	
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb	
Charm				
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II	
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II	CHARM
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II	
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II	
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II	
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II	
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II	TAU
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb	

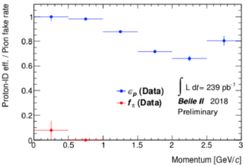
E. Kou, P Urquijo et al. Belle II Physics book, arXiv: 1808.10567 (Accepted to PTEP)

Very Rich Physics Program!

Belle II Particle Identification

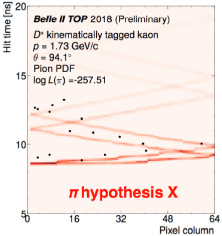
Central Drift Chamber dE/dx

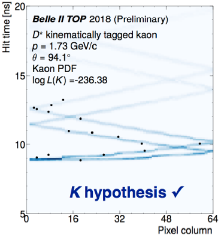


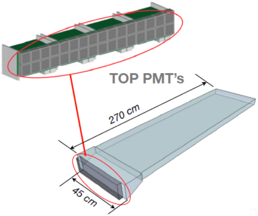


Cherenkov photons observed by TOP detector

$D^{*+} \to D^0 \pi^+$ [$D^0 \to (K^- \pi^\pm)$] x vs t pattern (mapping of Cherenkov ring)

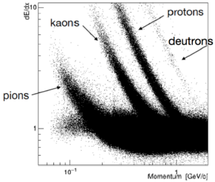


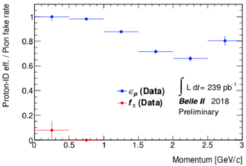




Belle II Vertex Detector (VXD) system

Central Drift Chamber dE/dx





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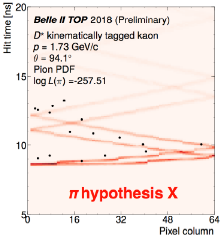
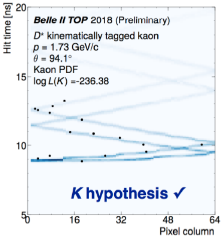
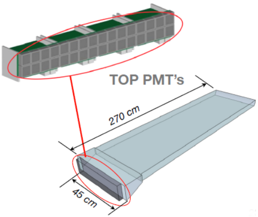
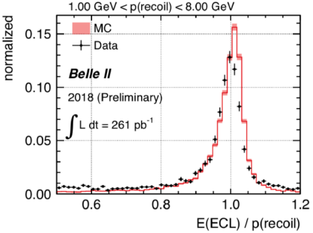




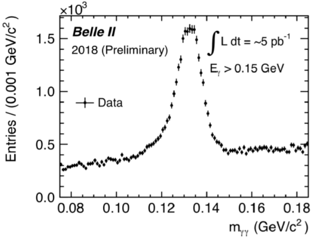


Belle II Photon reconstruction

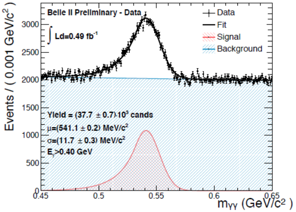
$e^+e^- \to \mu^+\mu^-\gamma$



$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$



- Good reconstruction single photons and pairs.
- Ready for the "dark sector" : single photons

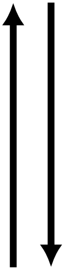
$e^+ e^- \to \gamma X$

$e^+ e^- \to \gamma\ ALP \to \gamma(\gamma\gamma)$

B decays with missing energy

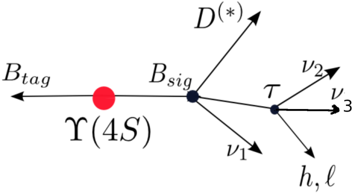
Tagging techniques

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)
  $\epsilon \approx O(0.1\%)$
  (M. Huschle: PRD **92**, 072014, (2015).,
  S. Hirose: PRL **118**, 211801, (2017).)



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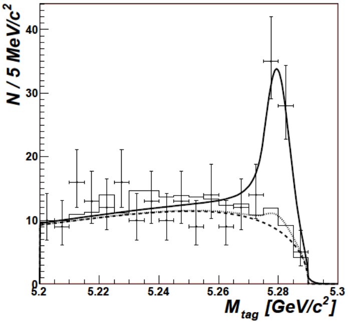
purity

First measurement:



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

B decays with missing energy

Tagging techniques

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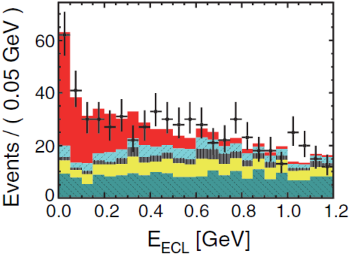
  S. Hirose: PRL **118**, 211801, (2017).)

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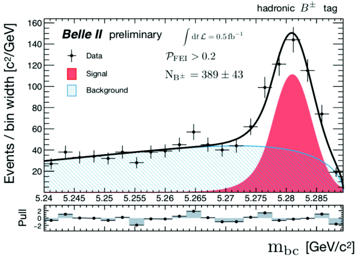
  S. Hirose: PRL **118**, 211801, (2017).)

purity

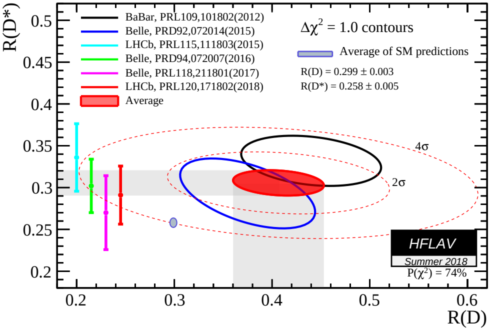
Rest Of the Event (ROI)



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

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

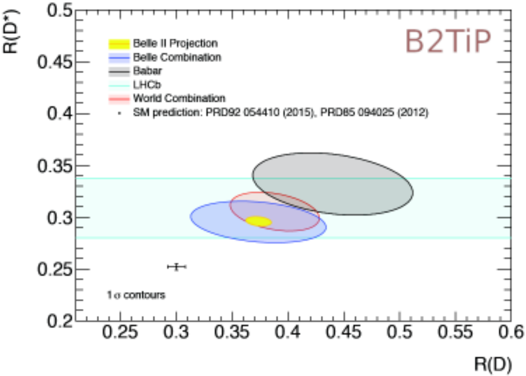
deviation from SM:

$\sim 2.3\sigma$ 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 $R(D^\star)$

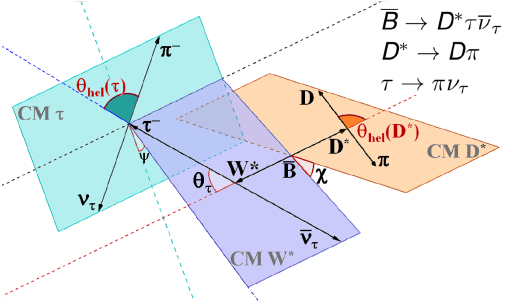
the excess can be confirmed with early data
The ultimate precision (with $50ab^{-1}$) of 3% and 2% will be limited by systematic

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.

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

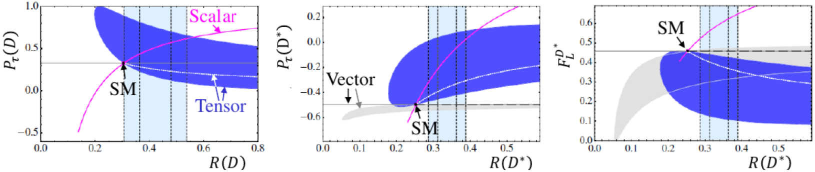
$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

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

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

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

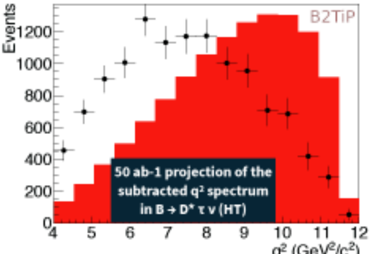
$B \to \bar{D}^{*}\tau^{-}\nu_{\tau}$ differential distribution : q^2



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 $D^\star$

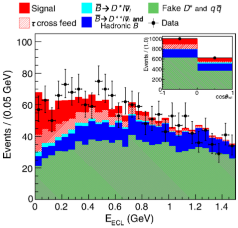


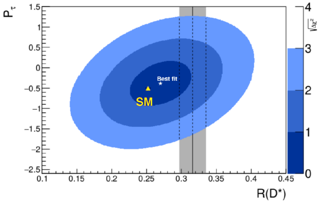
Belle II MC are generated in the SM hypothesis
Block histograms is a 2HDM-type II benchmark

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

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

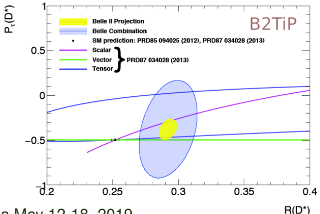
Measured from the two body semileptonic τ ($\to \pi\nu, \to \rho\nu$) decays -experimentally challenging





Belle II perspectives :

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

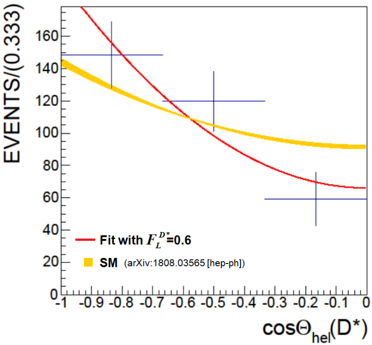


$B \to \bar{D}^{*}\tau^{-}\nu_{\tau}$ differential distribution : $D^{\star}$ polarisation

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

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) $(1.5\ \sigma)$

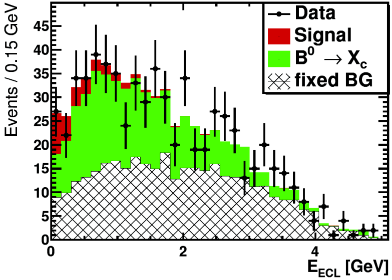
SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) $(1.8\ \sigma)$

$\Rightarrow$ consistent with the SM within 2σ

Expected number of events for $F_L^{D^\star}$ in full data set is ~ 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:

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

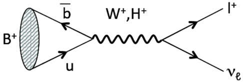
$(1.52 \pm 0.72 \pm 0.13) \times 10^{-4}$

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
$\tau\nu$	10^{-4}	20% uncertainty	15%	6%
$\mu\nu$	10^{-6}	40% uncertainty*	20%	7%
$e\nu$	10^{-11}	Beyond reach	-	-

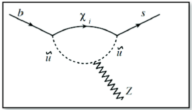
* arxiv:1712.04123 2.4σ excess $[2.9,10.7]\times10^{-7}$ at 90% C.L.

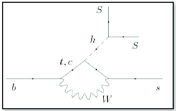
Belle II Full simulation with expected background conditions (hadronic tags only)
S.L. tag expected to have similar sensitivity

Extrapolation of Belle Analysis

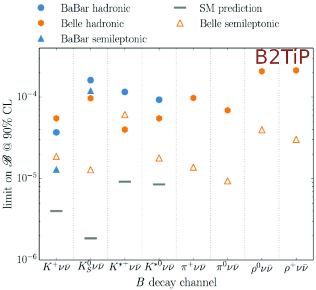
$B \to K\nu\nu$ decays

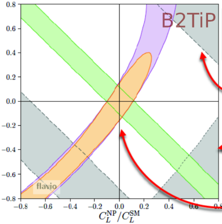
Suppressed in the SM : BRs $10^{-5} - 10^{-6}$ may be enhanced by NP





Current limits





Constraints on new physics contributions to Wilson coefficients C_L, C_R

90% CL excluded by Belle and Babar

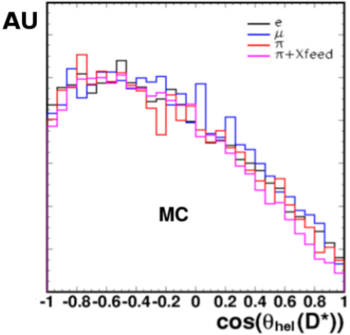
68% CL allowed by Belle II at 50 ab-1

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

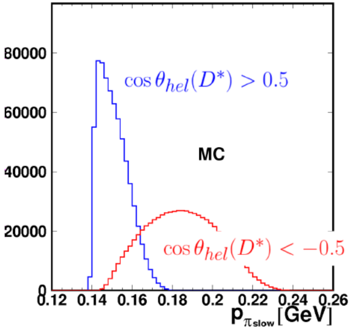
Challenges for $D^{\star}$ *polarisationmeasurement*

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