



# The prospect of Belle II

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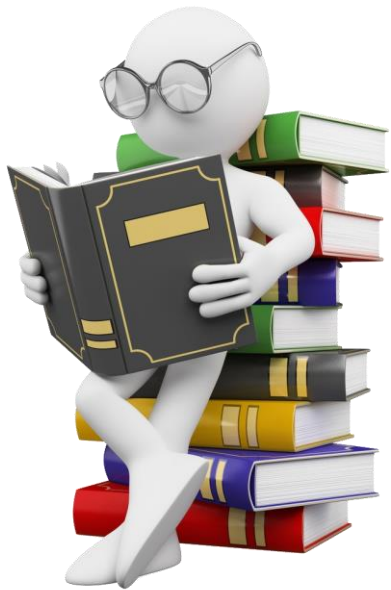
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## Outline

- **The status of Belle II accelerator/detector**
- **Belle II luminosity projection**
- **B signals in Phase 2 data**
- **Advantage in Belle II physics analysis**
- **Prospect in various physics topics including: CKM, Test Lepton Universality; LFV  $\tau$  Decays; Hadron Spectroscopy; ....**

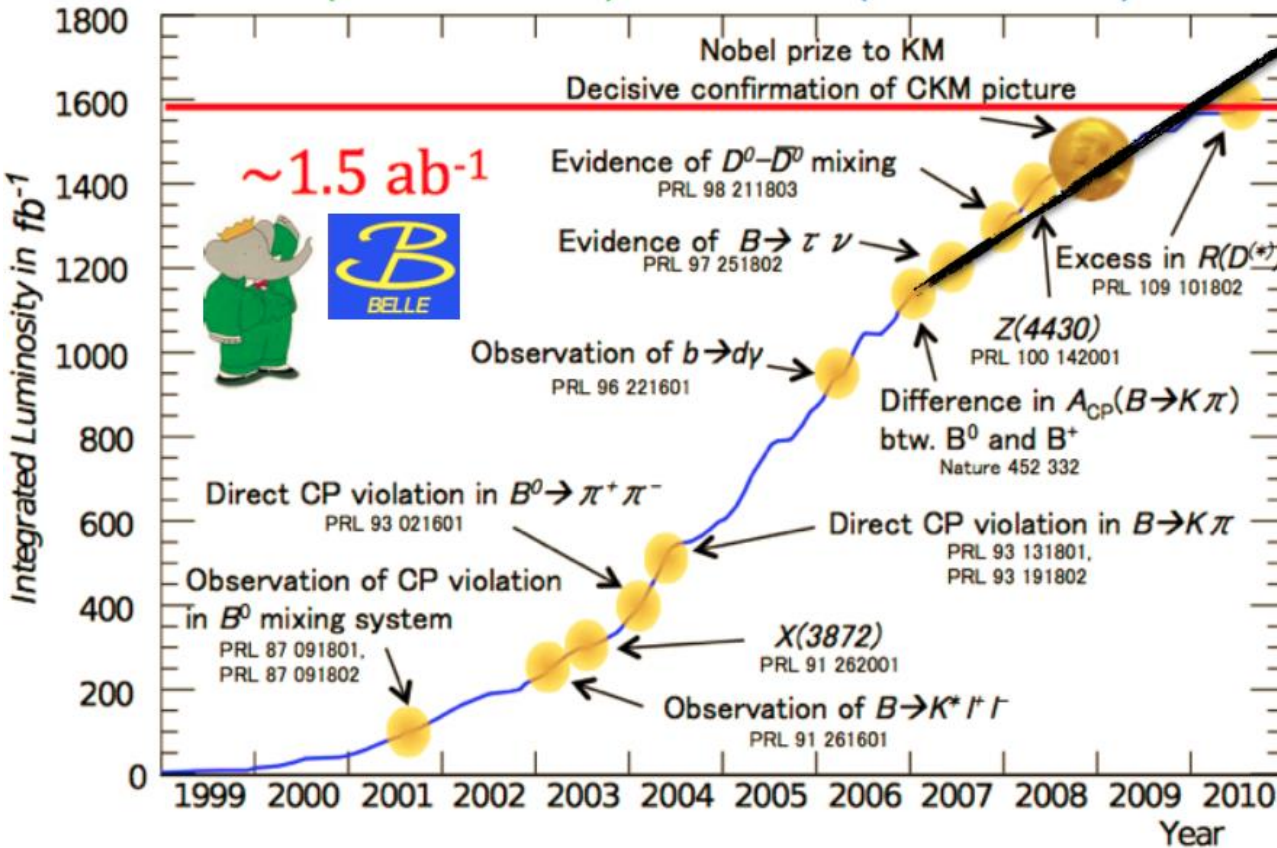


Due to rich physics, here I just selected a few topics as examples. For more details, please refer to Belle II physics book: [arXiv:1808.10567](https://arxiv.org/abs/1808.10567)

# B-factories in the last decade



BaBar (PEPII@SLAC) and Belle (KEKB@KEK)



- ➔ Belle and BABAR have a produced a large number of important results, since the beginning of their data taking
- ➔ Competition between the two experiments has helped in pulling out the best from the two datasets

The Physics of B factories  
EPJC 74, 3026 (2018)

Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

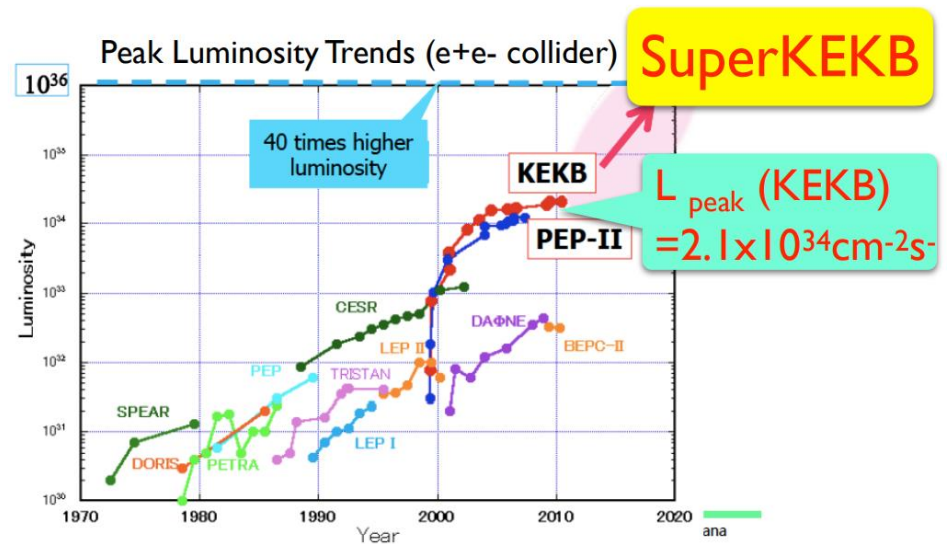
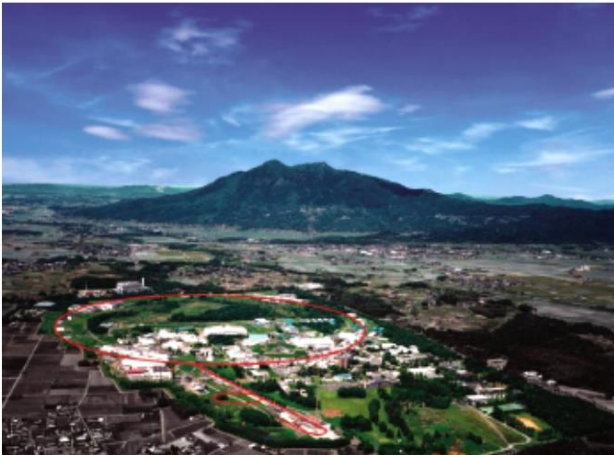
# SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity ;  $L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$   
 $\Rightarrow \sim 10^{10} \text{ } \bar{B}B, \tau^+\tau^-$  and charms per year !

$$L_{\text{int}} > 50 \text{ ab}^{-1}$$

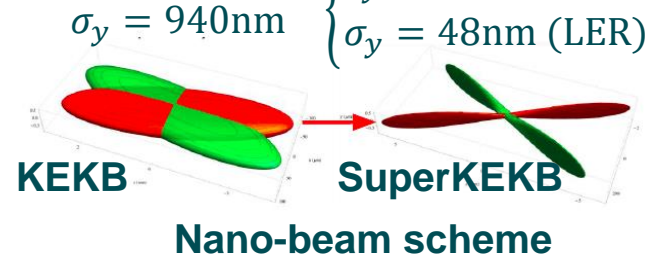
- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more



*The first particle collider after the LHC !*

# SuperKEKB Accelerator

$$\left\{ \begin{array}{l} \sigma_y = 62\text{nm (HER)} \\ \sigma_y = 48\text{nm (LER)} \end{array} \right.$$



Change of the collision energy to increase beam lifetime

7.0GeV  
2.6A  $e^-$



4.0GeV  
3.6A  $e^+$



New final focusing magnets

Key upgrades:

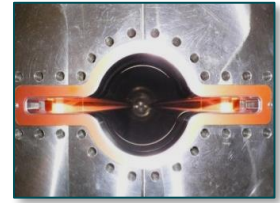
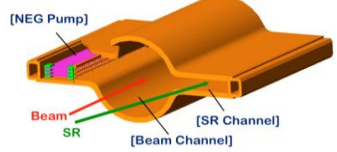
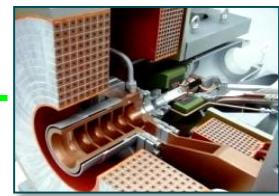
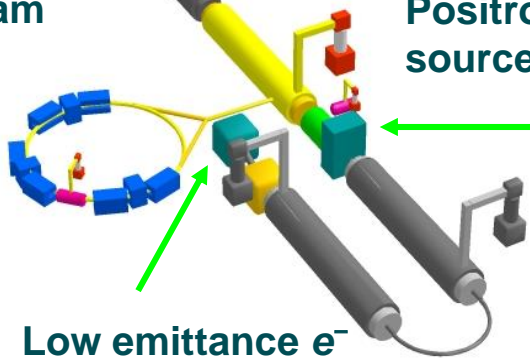
Longer magnets (LER) than KEKB by 4m

More RF cavities to increase the beam currents

Damping ring for a low emittance  $e^+$  beam

Positron source

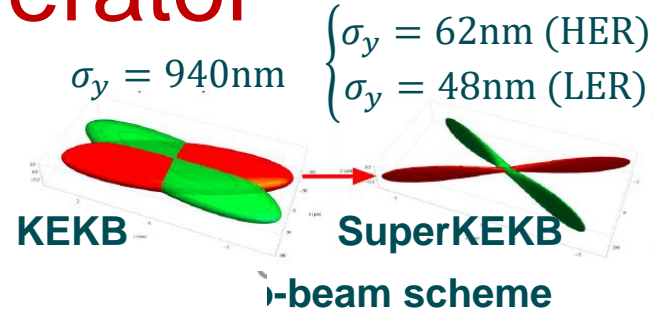
New beam pipe design to reduce the SR



# SuperKEKB Accelerator



Change of the collision energy to increase beam lifetime



Key upgrades:

$$\text{Luminosity} = \frac{\gamma_{\pm}}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \zeta_{\pm y} R_L}{\beta_y^* R_y}$$



New final focusing magnets

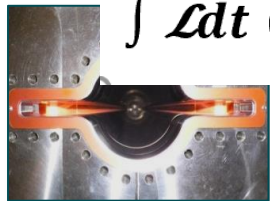
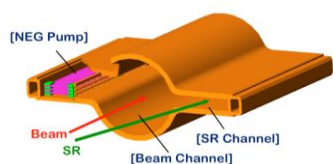
Longer magnets (LER) than KEKB by 4m

Dam  
emitt

	KEKB (HER/LER)	SuperKEKB (HER/LER)	
$B_y^*$ (mm)	5.9/5.9	0.30/0.27	x20
$I_{\text{beam}}$ (A)	1.19/1.64	2.6/3.6	x2
$\mathcal{L}$ ( $\text{cm}^{-2}\text{s}^{-1}$ )	$2.11 \times 10^{34}$	$80 \times 10^{34}$	x40
$\int \mathcal{L} dt$ ( $\text{ab}^{-1}$ )	1	50	x50

More RF cavities to  
increase the beam  
currents

New beam pipe design  
to reduce the SR



Low emittance  $e^-$



# Belle II Detector

EM Calorimeter (ECL):  
CsI(Tl), waveform sampling

KL and muon detector (KLM):  
Resistive Plate Counter (barrel)  
Scintillator + WLSF + MPPC (end-caps)

electron  
(7GeV)

Beryllium beam pipe  
2cm diameter

Vertex Detector (VXD)  
2 layers DEPFET (PXD)  
4 layers DSSD (SVD)

Particle Identification  
Time-of-Propagation counter (barrel, TOP)  
Prox. focusing Aerogel RICH (fwd, ARICH)

positron  
(4GeV)

Central Drift Chamber (CDC)  
He(50%):C<sub>2</sub>H<sub>6</sub>(50%), Small cells,  
long lever arm, fast electronics

General purpose 4 $\pi$  Detector  
Improved PID, Vertex detector  
High background tolerance



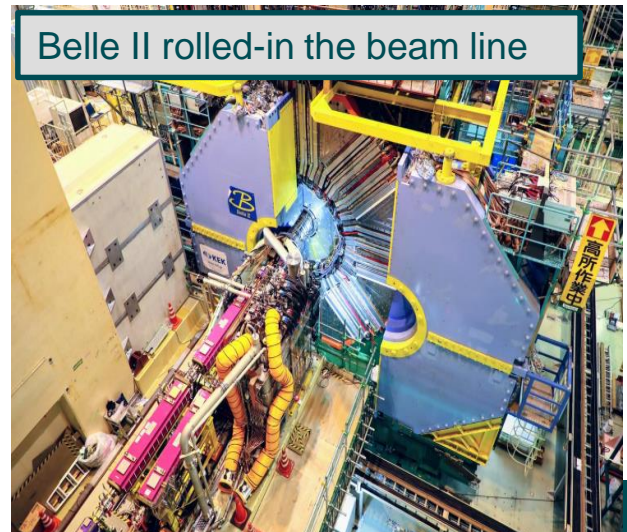
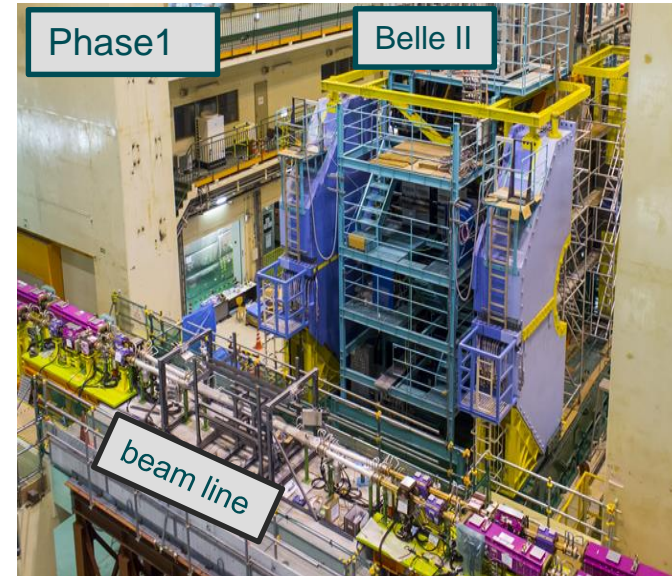
# From the Belle to Belle II

## What has been changed?

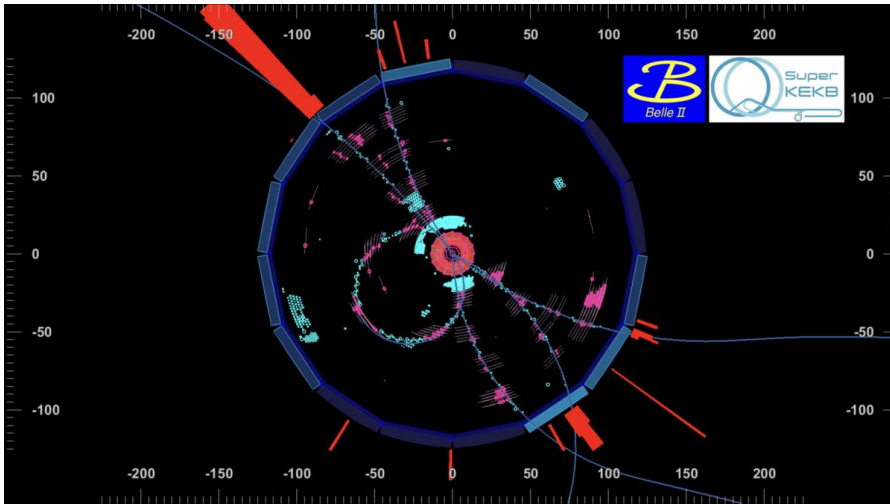
- **PXD**, **vertex resolution** in z direction (beam direction) will be factor 2 better than before:  
50  $\mu\text{m}$  (Belle)  $\rightarrow$  25  $\mu\text{m}$  (Belle II)
- **TOP**: no TOF (time-of-flight) detector anymore, but TOP (time-of-propagation) will do the timing of the Cerenkov light. Time resolution  $\sim$  50 ps. TOP detector surface is polished to nanometer precision for total reflection of Cerenkov light
- **KLM**: inner 2 layers of barrel + all layers in the endcap replaced by scintillators, because of large background
- **ECL** readout electronics exchanged, fast **FADC** sampling for identify pile-up of pulses
- Huge gain in **luminosity** in Belle II compared to Belle: factor **x40**. How?
  - factor 2 by beam current: 1.64/1.19 A (Belle)  $\rightarrow$  3.6/2.6 A for  $e^+(e^-)$  beam in Belle II
  - factor 20 by "**nano-beam**" principle (collision point in vertical direction will be only 59 nm)

# Belle II and SuperKEKB Upgrade History

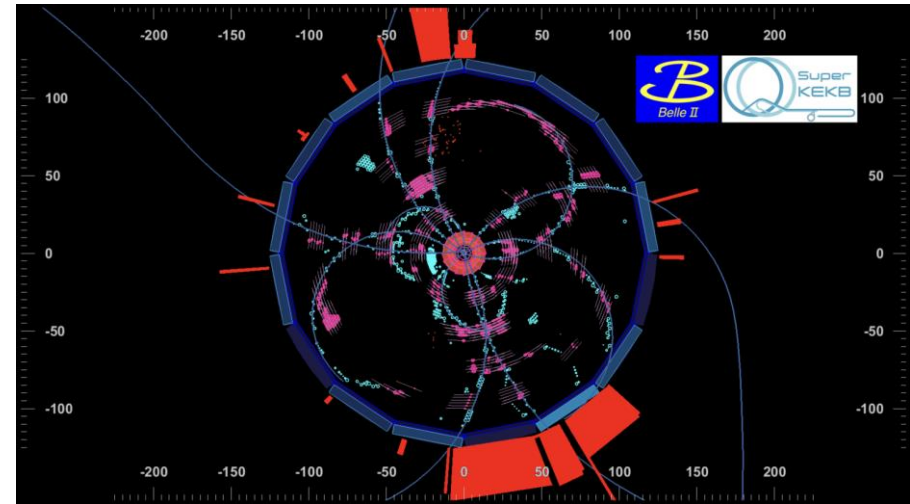
- 2010, Belle and KEKB operation completed
  - Started upgrade to Belle II and SuperKEKB
- **2016 Phase 1 Commissioning**
  - SuperKEKB single beams
  - no collisions, without Belle II
- 2017 Belle II Detector rolled-in to the beam line
- **2018 March-July Phase 2 Commissioning**
  - First e+e- collisions at SuperKEKB
    - Confirm the nano-beam scheme
  - **Data taking with Belle II Detector (w/o VXD, but background detectors (BEASTII))**
    - Confirm the background condition for final VXD
- **2019 March- Phase 3 Operation**
  - **Physics run with the full Belle Detectors with the VXD (PXD+SVD) installed**
  - Aim at the design luminosity  $8 \times 10^{35} / \text{cm}^2/\text{s}$
  - Search for the new physics



# Kick-off of the Belle II Phase 3 Physics Run



The first hadronic event in the Belle II Phase3 physics run



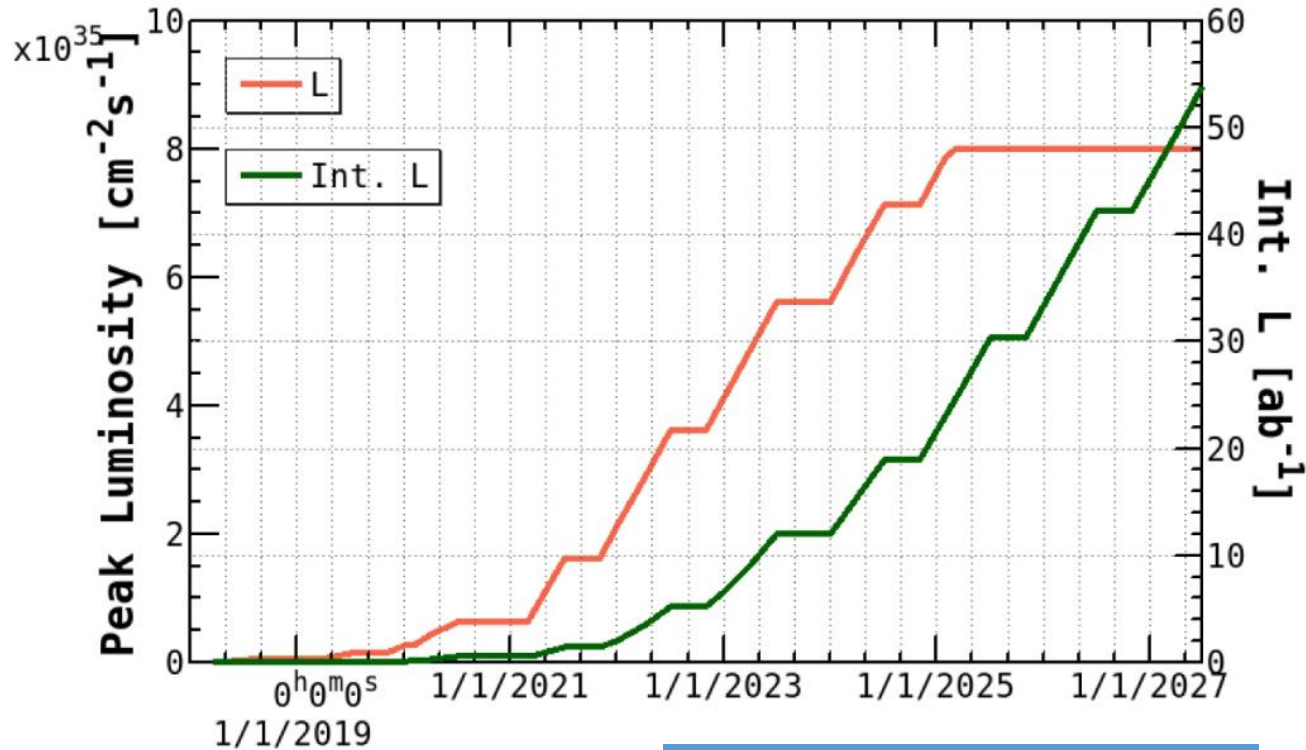
The first “B - anti-B like” event in the Belle II Phase3 physics run

On **March 25 19:44 (JST), 2019**, electron-positron collisions have restarted at the SuperKEKB collider, and the Belle II experiment has now kicked off its physics data taking.

Belle II will perform a broad range of extremely high precision and fundamental measurements in flavor physics, particularly of properties of the bottom quark, charm quark, and tau lepton. In recent years, there has been a great deal of excitement worldwide about a number of intriguing hints of new physics in the decays of B mesons, particles which contain bottom quarks.

# SuperKEKB Luminosity Projection

Plan of instantaneous and integrated luminosity at SuperKEKB.



## Phase 3 (w/ full detector)

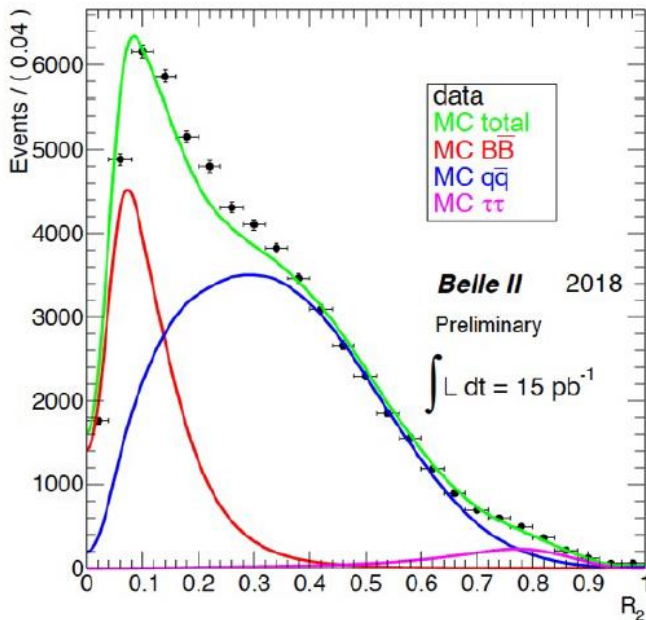
- $1\text{ab}^{-1}$  after 1 year
- $5\text{ab}^{-1}$  by  $\sim 2022$
- $50\text{ab}^{-1}$  by  $\sim 2027$

Process	$\sigma$ (nb)
bb	1.1
cc	1.3
Light quark qq	$\sim 2.1$
$\tau^+\tau^-$	0.9
$e^+e^-$	$\sim 40$

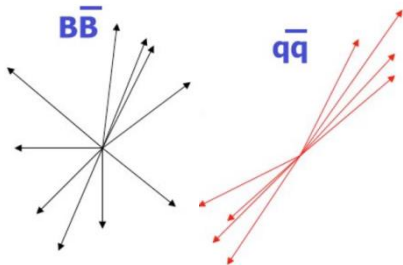
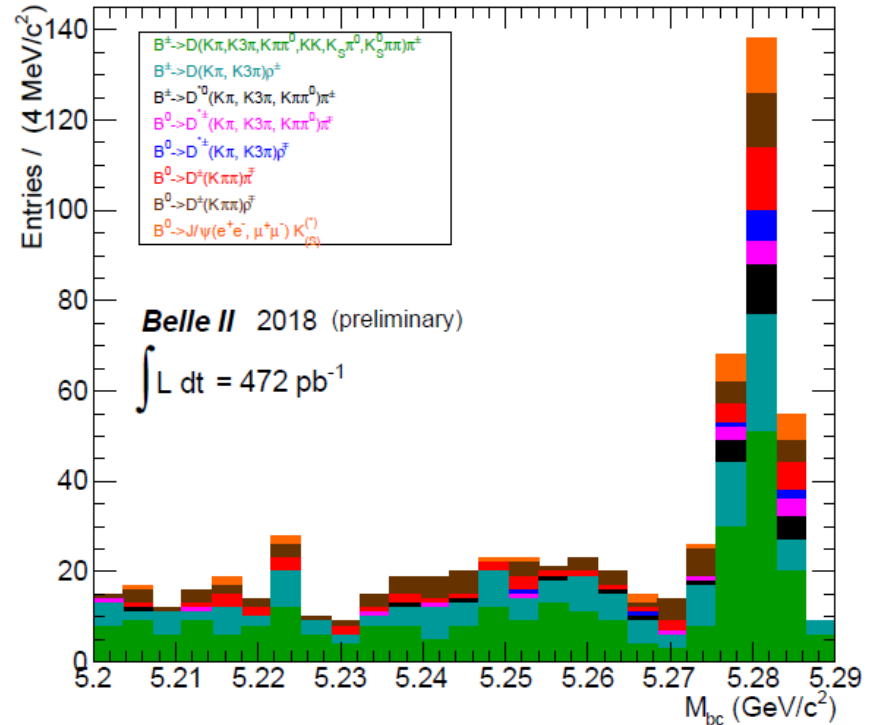
# Rediscovery of B mesons

Event Shape Distribution  
(Fox-Wolfram R2)

$$M_{bc} = \sqrt{(E_{cm} / 2)^2 - p_{recon}^2}$$



Spherical  $R_2$  Jet-like



- Clearly observed the excess of BB events in early phase 2 Data
  - “Rediscovered” reconstructed B mesons.
- Full reconstruction analysis chain is working well.

# Physics at Belle II

Ultimate precision, 50 ab<sup>-1</sup>

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2027)
<b>UT angles &amp; sides</b>			
$\phi_1$ [°]	***	0.4	Belle II
$\phi_2$ [°]	**	1.0	Belle II
$\phi_3$ [°]	***	1.0	LHCb/Belle II
$ V_{cb} $ incl.	***	1%	Belle II
$ V_{cb} $ excl.	***	1.5%	Belle II
$ V_{ub} $ incl.	**	3%	Belle II
$ V_{ub} $ excl.	**	2%	Belle II/LHCb
<b>CP Violation</b>			
$S(B \rightarrow \phi K^0)$	***	0.02	Belle II
$S(B \rightarrow \eta' K^0)$	***	0.01	Belle II
$A(B \rightarrow K^0 \pi^0)$ [10 <sup>-2</sup> ]	***	4	Belle II
$A(B \rightarrow K^+ \pi^-)$ [10 <sup>-2</sup> ]	***	0.20	LHCb/Belle II
<b>(Semi-)leptonic</b>			
$\mathcal{B}(B \rightarrow \tau \nu)$ [10 <sup>-6</sup> ]	**	3%	Belle II
$\mathcal{B}(B \rightarrow \mu \nu)$ [10 <sup>-6</sup> ]	**	7%	Belle II
$R(B \rightarrow D \tau \nu)$	***	3%	Belle II
$R(B \rightarrow D^* \tau \nu)$	***	2%	Belle II/LHCb

**CKM**

**QUARKONIUM**

**DARK SECTOR**

**CPV**

*Very Rich Physics Program!*

**(Semi) LEPTONIC LFUV**

<b>Radiative &amp; EW Penguins</b>			
$\mathcal{B}(B \rightarrow X_s \gamma)$	**	4%	Belle II
$A_{CP}(B \rightarrow X_{s,d} \gamma)$ [10 <sup>-2</sup> ]	***	0.005	Belle II
$S(B \rightarrow K_S^0 \pi^0 \gamma)$	***	0.03	Belle II
$S(B \rightarrow \rho \gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \rightarrow \gamma \gamma)$ [10 <sup>-6</sup> ]	**	0.3	Belle II
$\mathcal{B}(B \rightarrow K^* \nu \bar{\nu})$ [10 <sup>-6</sup> ]	***	15%	Belle II
$\mathcal{B}(B \rightarrow K \nu \bar{\nu})$ [10 <sup>-6</sup> ]	***	20%	Belle II
$R(B \rightarrow K^* \ell \ell)$	***	0.03	Belle II/LHCb
<b>Charm</b>			
$\mathcal{B}(D_s \rightarrow \mu \nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \rightarrow \tau \nu)$	***	2%	Belle II
$A_{CP}(D^0 \rightarrow K_S^0 \pi^0)$ [10 <sup>-2</sup> ]	**	0.03	Belle II
$ q/p (D^0 \rightarrow K_S^0 \pi^+ \pi^-)$	***	0.03	Belle II
$\phi(D^0 \rightarrow K_S^0 \pi^+ \pi^-)$ [°]	***	4	Belle II
<b>Tau</b>			
$\tau \rightarrow \mu \gamma$ [10 <sup>-10</sup> ]	***	< 50	Belle II
$\tau \rightarrow e \gamma$ [10 <sup>-10</sup> ]	***	< 100	Belle II
$\tau \rightarrow \mu \mu \mu$ [10 <sup>-10</sup> ]	***	< 3	Belle II/LHCb

**EWP**

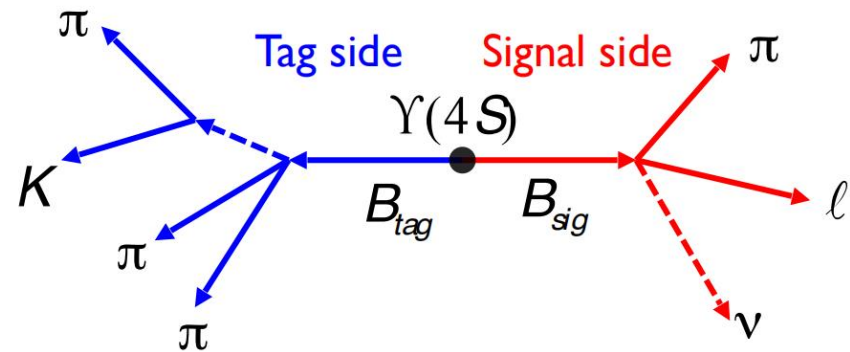
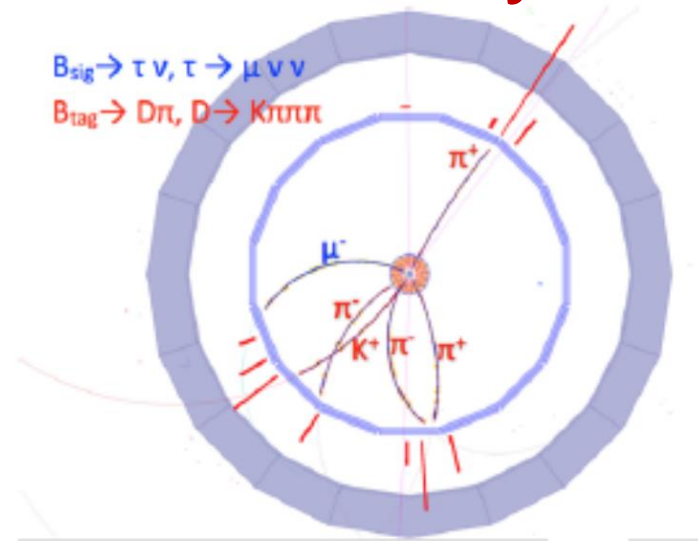
**CHARM**

**TAU**

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

# Advantage of $e^+e^-$ Flavor Factory

- Clean environment
  - Efficient detection of neutrals ( $\gamma, \pi^0, \eta, \dots$ )
- Quantum correlated  $B^0\bar{B}^0$  pairs
  - High effective flavor tagging efficiency :  
 $\sim 34\%$ (Belle II)  $\longleftrightarrow$   $\sim 3\%$  (LHCb)
- Large sample of  $\tau$  leptons
  - Search for LFV  $\tau$  decays at  $O(10^{-9})$
- Full reconstruction tagging possible
  - A powerful tool to measure;
    - $b \rightarrow u$  semileptonic decays (CKM)
    - **decays with large missing energy**
- Systematics different from LHCb
  - Two experiments are required to establish NP



- $B \rightarrow \pi \ell \nu$
- $B \rightarrow \tau \nu, D \tau \nu$
- $B \rightarrow K \nu \nu$

# Dark Sector Physics at Belle II

Search for the direct production of low-mass new particles will be highlights in early running period of Belle II

- Dark photon  $\rightarrow$  invisible

- A single, monochromatic high energy ISR photon.  $E_\gamma^* = E_{\text{beam}}^* - \frac{m_{A'}^2}{4E_{\text{beam}}^*}$

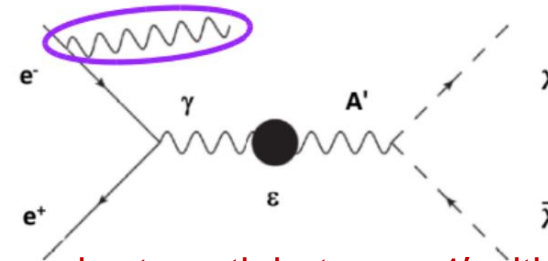
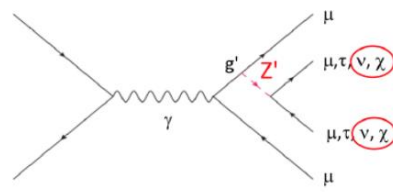
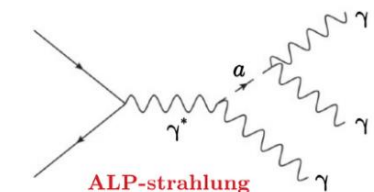
- Background from  $e^+e^- \rightarrow \gamma\gamma(\gamma)$ ,  $e^+e^- \gamma \rightarrow \gamma(\gamma)$  due to finite acceptance & imperfect detector

- Dedicated single photon trigger.

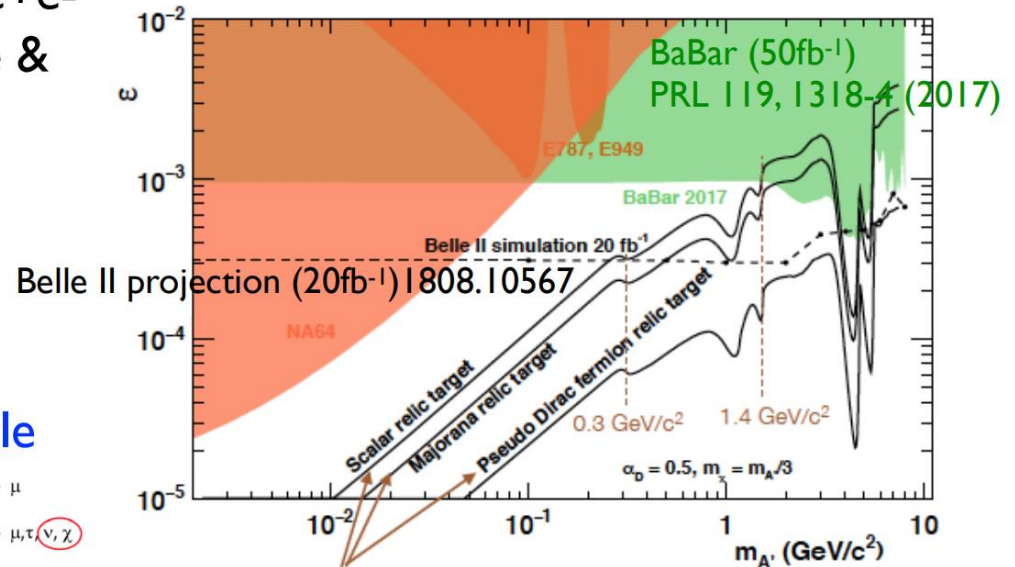
- Anticipated results also for

Axion Like Particle

$Z' \rightarrow$  invisible



$\epsilon$ : mix strength between  $A'$  with ordinary photon



If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines. Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

\* New result from NA62 [JHEP 05, 182 (2019)]

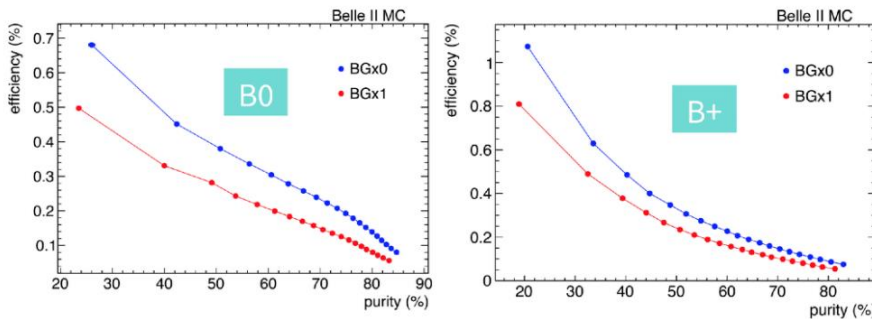
# Belle II Full Event Interpretation

- Belle II has developed a new “Full Event Interpretation” tool based on fast BDT.

Number of decay modes used in tagging (Belle → Belle II)

- B<sup>+</sup>: 17 → 29, B<sup>0</sup>: 14 → 26
- D<sup>+</sup>/D<sup>\*+</sup>/D<sub>s</sub><sup>+</sup>: 18 → 26, D<sup>0</sup>/D<sup>\*0</sup>: 12 → 17

Tag algorithm date	MVA	Efficiency	Purity
Belle v1 (2004)	Cut-based (Vcb)	-	-
Belle v3 (2007)	Cut-based	0.1	0.25
<b>Belle NB (2011)</b>	<b>Neurobayes</b>	<b>0.2</b>	<b>0.25</b>
Belle II FEI (2017)	Fast BoostedDecisionTree	0.5	0.25



- + NEW FEI method based on semileptonic tag Fast BDT tag in B → D(\*) l ν + B → D(\*) π l ν.

More recent update: 1807.08680

B <sup>+</sup> modes	B <sup>0</sup> modes	D <sup>+</sup> , D <sup>*+</sup> , D <sub>s</sub> <sup>+</sup> modes	D <sup>0</sup> , D <sup>*0</sup> modes
B <sup>+</sup> → $\bar{D}^0\pi^+$	B <sup>0</sup> → D <sup>-</sup> π <sup>+</sup>	D <sup>+</sup> → K <sup>-</sup> π <sup>+</sup> π <sup>+</sup>	D <sup>0</sup> → K <sup>-</sup> π <sup>+</sup>
B <sup>+</sup> → $\bar{D}^0\pi^+\pi^0$	B <sup>0</sup> → D <sup>-</sup> π <sup>0</sup> π <sup>0</sup>	D <sup>+</sup> → K <sup>-</sup> π <sup>+</sup> π <sup>0</sup>	D <sup>0</sup> → K <sup>-</sup> π <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^0\pi^+\pi^0\pi^0$	B <sup>0</sup> → D <sup>-</sup> π <sup>+</sup> π <sup>0</sup>	D <sup>+</sup> → K <sup>-</sup> K <sup>+</sup> π <sup>+</sup>	D <sup>0</sup> → K <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>-</sup>
B <sup>+</sup> → $\bar{D}^0\pi^+\pi^-\pi^0$	B <sup>0</sup> → D <sub>s</sub> <sup>+</sup> D <sup>-</sup>	D <sup>+</sup> → K <sup>-</sup> K <sup>+</sup> π <sup>0</sup> π <sup>0</sup>	D <sup>0</sup> → π <sup>-</sup> π <sup>+</sup>
B <sup>+</sup> → D <sub>s</sub> <sup>+</sup> $\bar{D}^0$	B <sup>0</sup> → D <sup>+</sup> π <sup>+</sup>	D <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>+</sup>	D <sup>0</sup> → π <sup>-</sup> π <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^{*0}\pi^+$	B <sup>0</sup> → D <sup>+</sup> π <sup>0</sup> π <sup>0</sup>	D <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup>	D <sup>0</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^{*0}\pi^+\pi^0$	B <sup>0</sup> → D <sup>+</sup> π <sup>+</sup> π <sup>-</sup>	D <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>+</sup> π <sup>-</sup>	D <sup>0</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>-</sup>
B <sup>+</sup> → $\bar{D}^{*0}\pi^+\pi^-\pi^0$	B <sup>0</sup> → D <sup>+</sup> π <sup>0</sup> π <sup>0</sup> π <sup>-</sup>	D <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>+</sup> π <sup>0</sup> π <sup>-</sup>	D <sup>0</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>-</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^{*0}\pi^+\pi^-\pi^0\pi^0$	B <sup>0</sup> → D <sub>s</sub> <sup>+</sup> D <sup>-</sup>	D <sup>+</sup> → D <sup>0</sup> π <sup>+</sup>	D <sup>0</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>-</sup> π <sup>0</sup>
B <sup>+</sup> → D <sub>s</sub> <sup>+</sup> $\bar{D}^0$	B <sup>0</sup> → D <sub>s</sub> <sup>+</sup> D <sup>-</sup>	D <sup>+</sup> → D <sup>+</sup> π <sup>0</sup>	D <sup>0</sup> → K <sup>-</sup> K <sup>+</sup>
B <sup>+</sup> → D <sub>s</sub> <sup>+</sup> $\bar{D}^{*0}$	B <sup>0</sup> → D <sub>s</sub> <sup>+</sup> D <sup>-</sup>	D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> K <sub>s</sub> <sup>0</sup>	D <sup>0</sup> → K <sup>-</sup> K <sup>+</sup> K <sub>s</sub> <sup>0</sup>
B <sup>+</sup> → $\bar{D}^0K^+$	B <sup>0</sup> → J/ψ K <sub>s</sub> <sup>0</sup>	D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> π <sup>+</sup> π <sup>-</sup>	D <sup>0</sup> → D <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → J/ψ K <sup>+</sup>	B <sup>0</sup> → J/ψ K <sup>+</sup> π <sup>+</sup>	D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> K <sup>-</sup> π <sup>-</sup>	D <sup>*0</sup> → D <sup>0</sup> γ
B <sup>+</sup> → J/ψ K <sup>+</sup> π <sup>+</sup> π <sup>-</sup>	B <sup>0</sup> → J/ψ K <sub>s</sub> <sup>0</sup> π <sup>+</sup>	D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> K <sup>-</sup> π <sup>0</sup> π <sup>0</sup>	
B <sup>+</sup> → J/ψ K <sup>+</sup> π <sup>0</sup>		D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> K <sub>s</sub> <sup>0</sup> π <sup>+</sup> π <sup>-</sup>	
B <sup>+</sup> → J/ψ K <sub>s</sub> <sup>0</sup> π <sup>+</sup>		D <sub>s</sub> <sup>+</sup> → K <sup>-</sup> K <sub>s</sub> <sup>0</sup> π <sup>+</sup> π <sup>+</sup>	
B <sup>+</sup> → D <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>0</sup>	B <sup>0</sup> → D <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>0</sup>	D <sub>s</sub> <sup>+</sup> → K <sup>+</sup> K <sup>-</sup> π <sup>+</sup> π <sup>-</sup>	D <sup>0</sup> → K <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^0\pi^+\pi^-\pi^0$	B <sup>0</sup> → D <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>-</sup>	D <sub>s</sub> <sup>+</sup> → π <sup>+</sup> π <sup>0</sup>	D <sup>0</sup> → K <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>-</sup>
B <sup>+</sup> → $\bar{D}^0D^+$	B <sup>0</sup> → $\bar{D}^0\pi^+\pi^0$	D <sub>s</sub> <sup>+</sup> → π <sup>+</sup> π <sup>+</sup> π <sup>-</sup> π <sup>0</sup>	D <sup>0</sup> → π <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>-</sup>
B <sup>+</sup> → $\bar{D}^0D^+K^0$	B <sup>0</sup> → D <sup>-</sup> D <sup>0</sup> K <sup>+</sup>	D <sup>+</sup> → K <sup>+</sup> K <sub>s</sub> <sup>0</sup> K <sub>s</sub> <sup>0</sup>	D <sup>0</sup> → π <sup>-</sup> π <sup>0</sup> π <sup>0</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^{*0}D^+K^0$	B <sup>0</sup> → D <sup>-</sup> D <sup>0</sup> K <sup>+</sup>	D <sup>+</sup> → D <sup>+</sup> γ	D <sup>0</sup> → K <sup>-</sup> K <sup>+</sup> π <sup>0</sup>
B <sup>+</sup> → $\bar{D}^{*0}D^{*+}K^0$	B <sup>0</sup> → D <sup>-</sup> D <sup>0</sup> K <sup>+</sup>	D <sub>s</sub> <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>+</sup>	
B <sup>+</sup> → $\bar{D}^{*0}D^{*+}K^0$	B <sup>0</sup> → D <sup>-</sup> D <sup>0</sup> K <sup>+</sup>	D <sub>s</sub> <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>+</sup>	
B <sup>+</sup> → $\bar{D}^0D^0K^+$	B <sup>0</sup> → D <sup>-</sup> D <sup>+</sup> K <sub>s</sub> <sup>0</sup>	D <sub>s</sub> <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>0</sup>	
B <sup>+</sup> → $\bar{D}^{*0}D^0K^+$	B <sup>0</sup> → D <sup>-</sup> D <sup>+</sup> K <sub>s</sub> <sup>0</sup>	D <sub>s</sub> <sup>+</sup> → K <sub>s</sub> <sup>0</sup> π <sup>0</sup> π <sup>0</sup> π <sup>+</sup>	
B <sup>+</sup> → $\bar{D}^0D^{*0}K^+$	B <sup>0</sup> → D <sup>-</sup> D <sup>+</sup> K <sub>s</sub> <sup>0</sup>	D <sub>s</sub> <sup>+</sup> → D <sub>s</sub> <sup>+</sup> π <sup>+</sup>	
B <sup>+</sup> → $\bar{D}^{*0}D^{*0}K^+$	B <sup>0</sup> → D <sup>-</sup> D <sup>+</sup> K <sub>s</sub> <sup>0</sup>		
B <sup>+</sup> → $\bar{D}^{*0}\pi^+\pi^0\pi^0$	B <sup>0</sup> → D <sup>-</sup> π <sup>+</sup> π <sup>0</sup> π <sup>0</sup>		

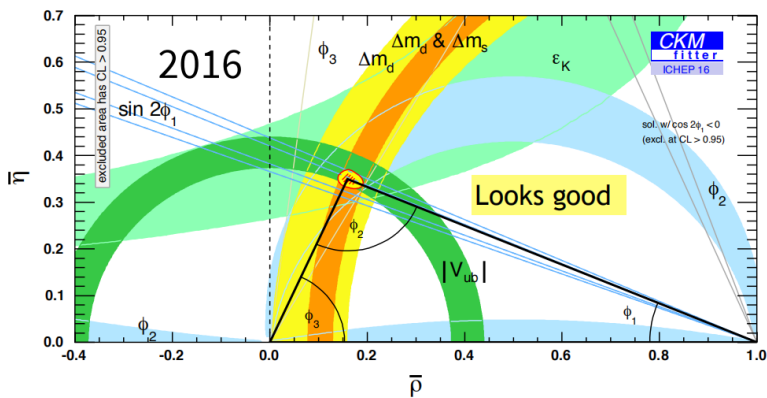
Below line: not used in Belle NB tag.

# CKM fit with Belle II + LHCb

Input	Current WA	SM value Belle II	SM value Belle II+LHCb
$A$	$0.8227^{+0.0066}_{-0.0136}$	$+0.0025$ $-0.0027$	$+0.0024$ $-0.0028$
$\lambda$	$0.22543^{+0.00042}_{-0.00031}$	$0.00036$ $-0.00030$	$0.00035$ $-0.00030$
$\bar{\rho}$	$0.1504^{+0.0121}_{-0.0062}$	$+0.0054$ $-0.0044$	$+0.0042$ $-0.0040$
$\bar{\eta}$	$0.3540^{+0.00069}_{-0.0076}$	$+0.0037$ $-0.00040$	$+0.0036$ $-0.00037$

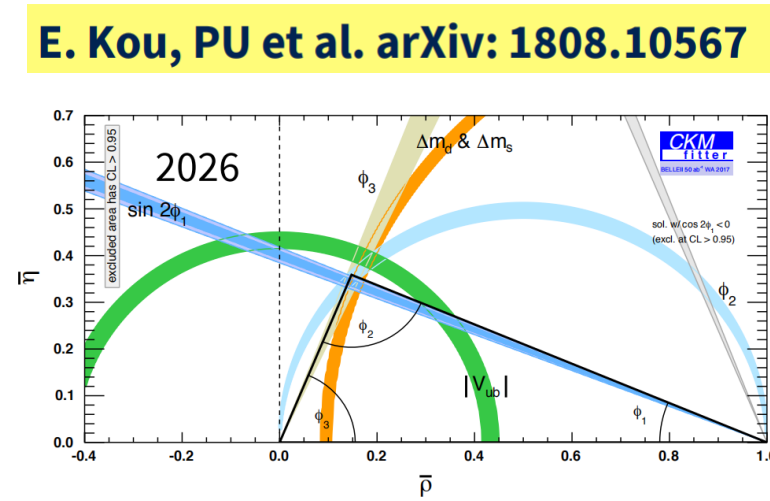
1808.10567

- Precision improvements require improved uncertainties and resolved tensions, e.g.  $|V_{ub}|$  inc.-excl.



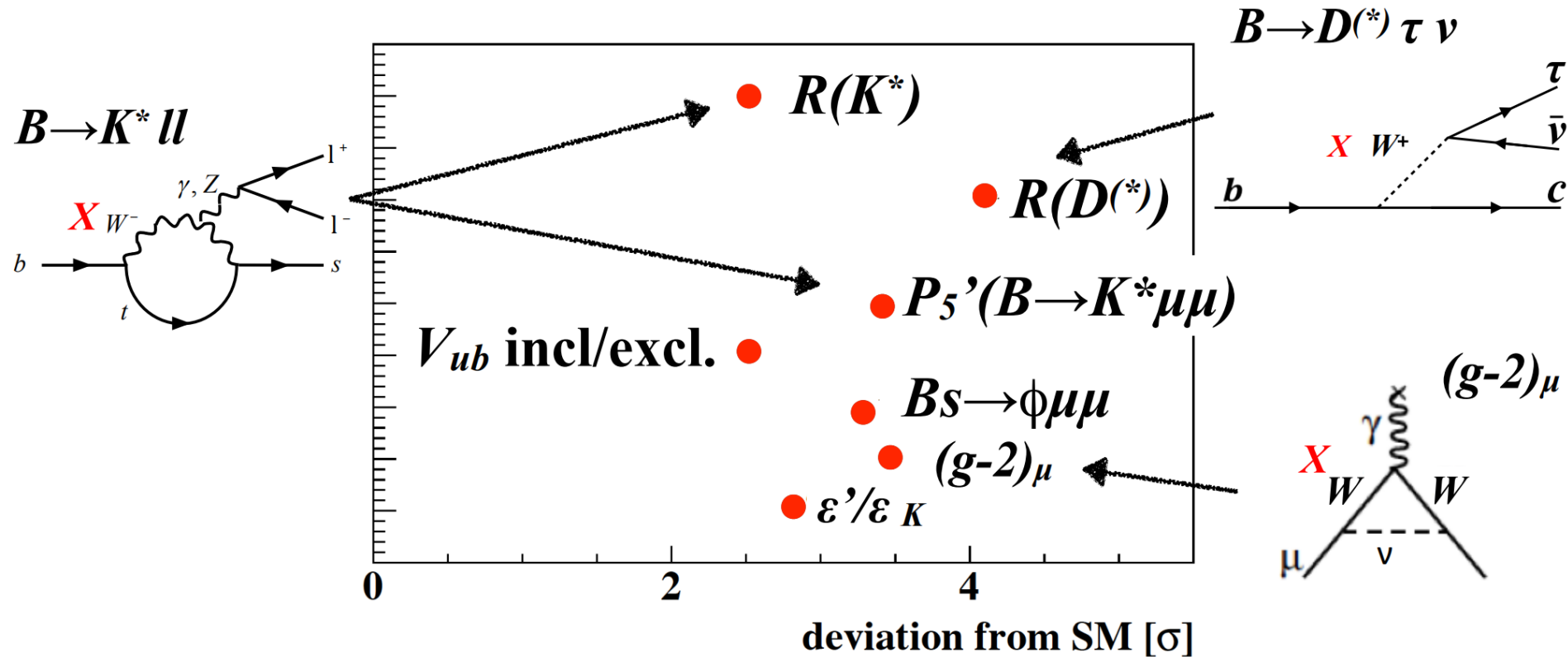
$\Phi_3 \sim 1-1.5^\circ$  at LHCb & Belle II

$|V_{ub}| \sim 1.2\%$  Belle II



# Test Lepton Universality

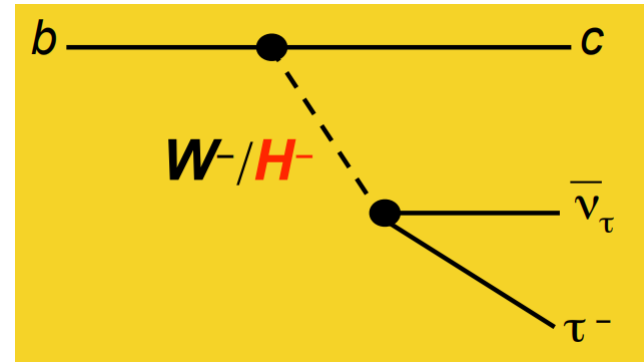
Observed deviation from SM  
(as of Spring 2018)



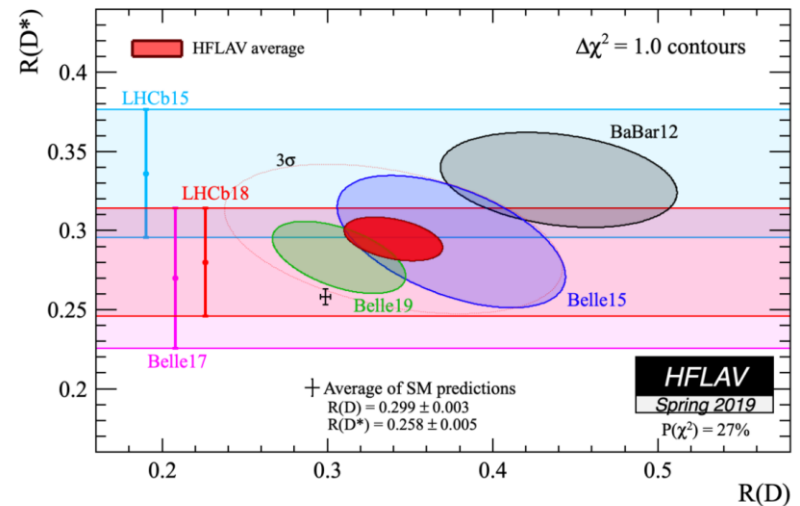
It is important to test lepton universality precisely.

# $B \rightarrow D(*) \tau \nu$

- New Physics may appear at tree level.
- 3rd generation quark (b) and lepton ( $\tau$ ) involved.
  - large masses  $\rightarrow$  sensitivity to NP
  - Charged Higgs, Leptoquark, ...
- $B \rightarrow D(*) \tau \nu$  and  $B \rightarrow \tau \nu$  are complementary
- Quantities of interest
  - Lepton Flavor Universality :
    - $R(D), R(D^*)$
  - Polarization:  $P_\tau, P_{D^*}$
  - $q^2$  distribution etc.



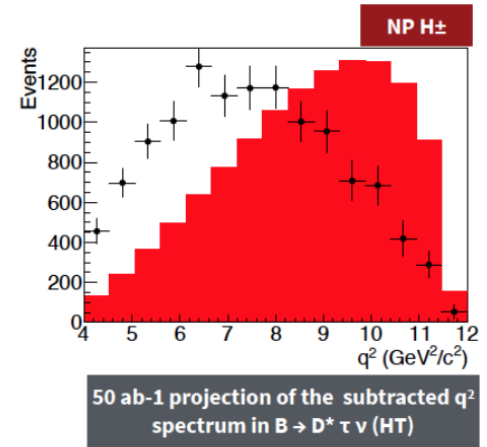
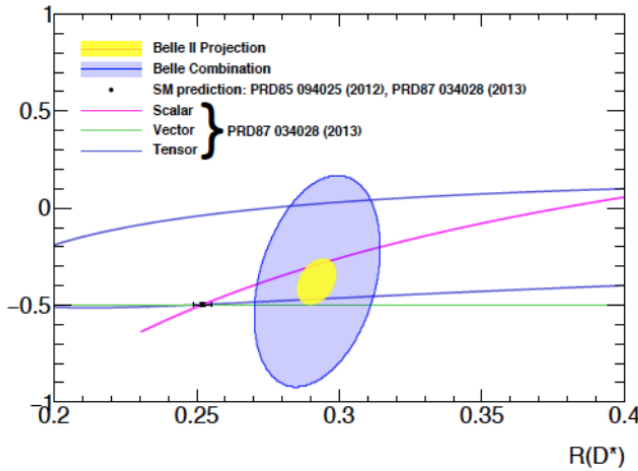
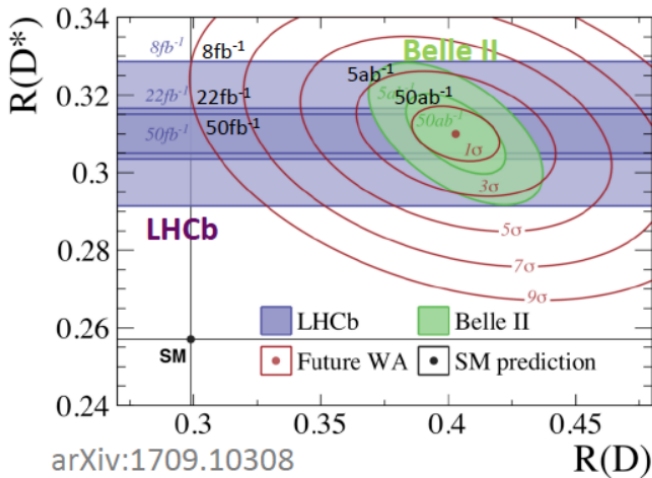
Spring 2019 update



3.1  $\sigma$  deviation from SM

# Belle II sensitivity

- Lepton universality violation may be established even with  $5\text{ab}^{-1}$  (2020).
- High statistics data will provide more detailed information, such as  $\tau$  polarization,  $q^2$  distribution, to discriminate type of NP.



	$\Delta R(D)$ [%]			$\Delta R(D^*)$ [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab <sup>-1</sup>	14	6	16	6	3	7
Belle II 5 ab <sup>-1</sup>	5	3	6	2	2	3
Belle II 50 ab <sup>-1</sup>	2	3	3	1	2	2

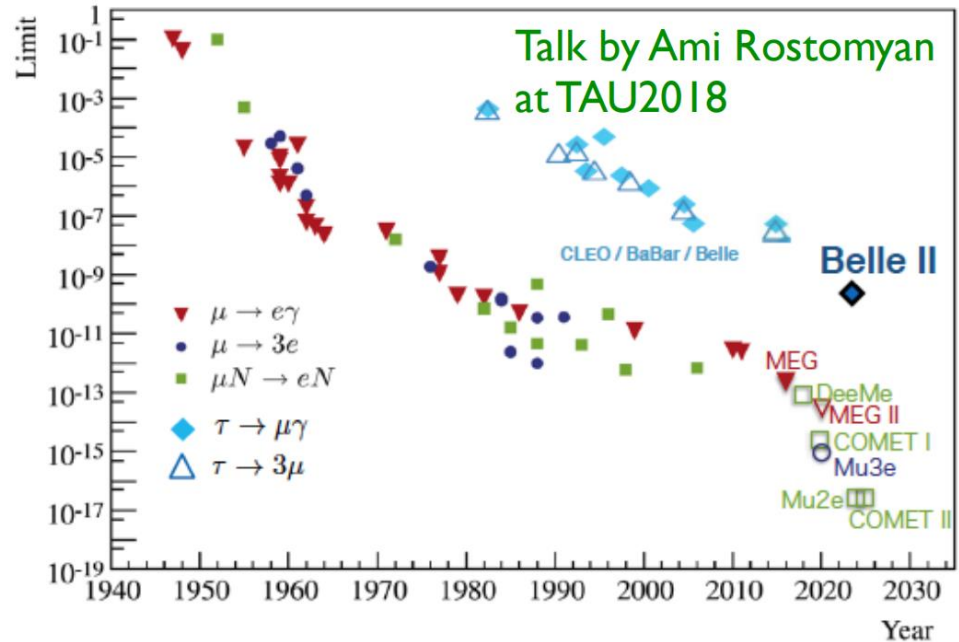
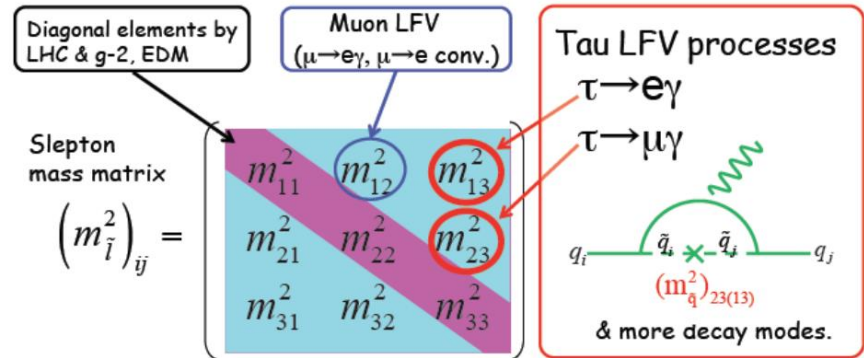
Will soon hit the systematic limit !

- More observables (distributions) !
  - $P(\tau), P(D^*)$
  - $d\Gamma/dq^2, d\Gamma/dp_{D^*}, d\Gamma/dp_e, \dots$
- More modes !
  - $B \rightarrow \pi \tau \nu,$
  - $B_s \rightarrow D_s \tau \nu$  (at 5S runs) , ...

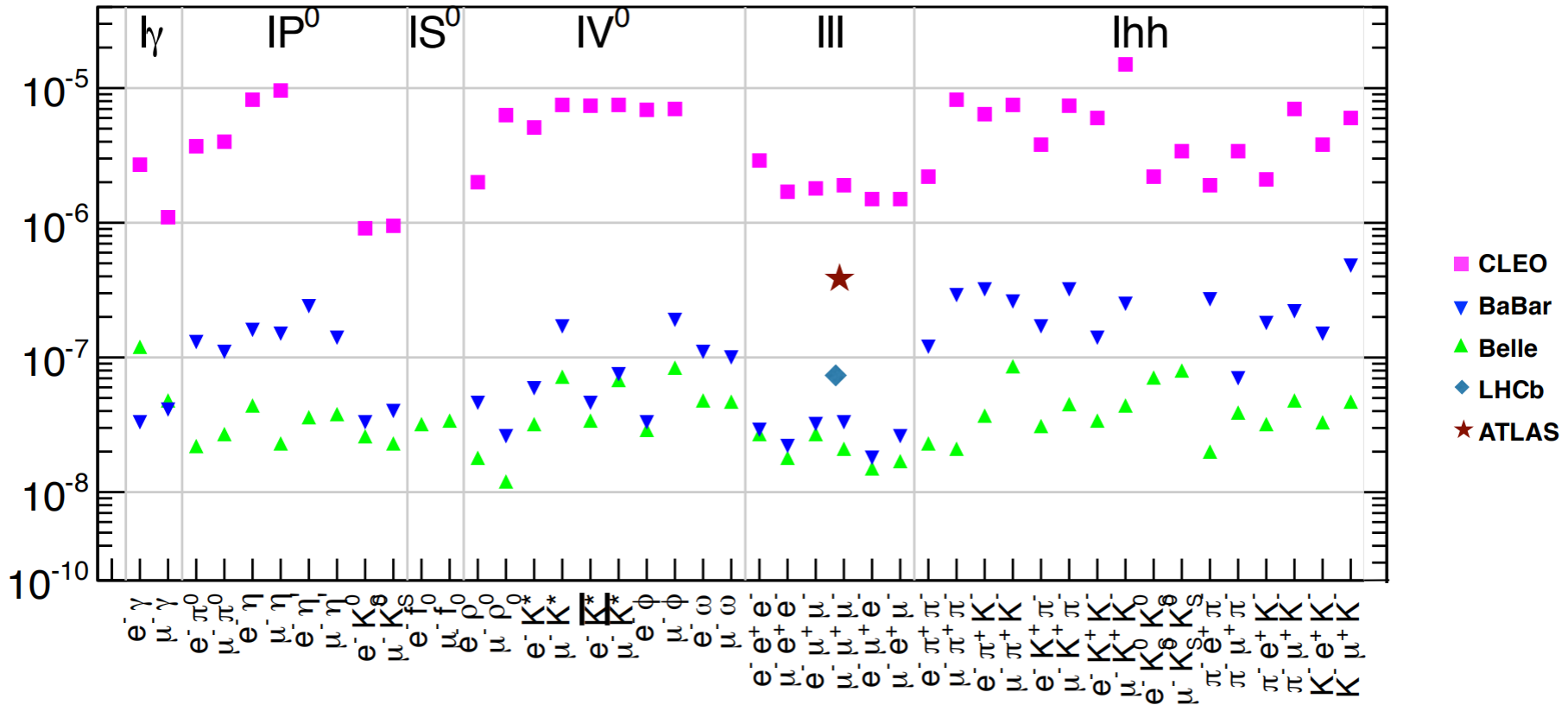
# LFV $\tau$ Decays

SuperKEKB provides  $N(\tau^+\tau^-) \sim N(B\bar{B})$

- Lepton flavor violated in the neutrino sector.
- Some NP models predict LFV to be observed in 'near' future experiments.
- $\tau$  is the heaviest charged lepton, sensitive to NP.
- $\tau$  LFV complementary to muon programs
  - $\mu \rightarrow e\gamma, eee$
  - $\mu \rightarrow e$  conversion

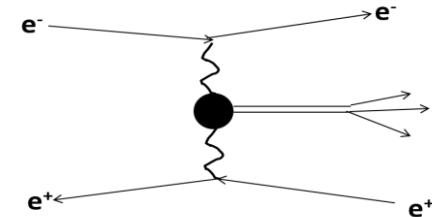
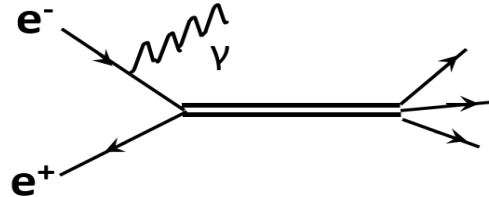
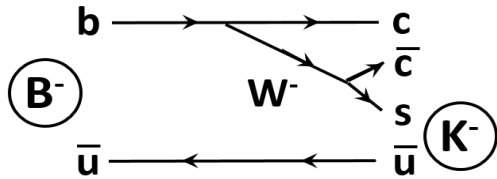


# Prospect on LFV $\tau$ Decays at Belle II



- Belle II will push down the current bounds further by more than an order of magnitude.
- Trying to increase sensitivity by improved analysis technique.

# B-factory = hadron factory!



## B meson decay

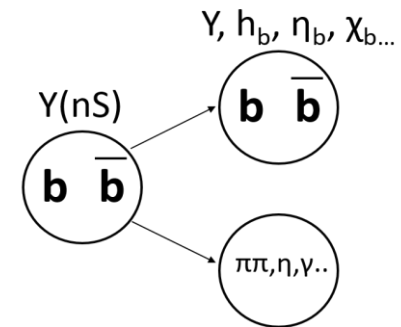
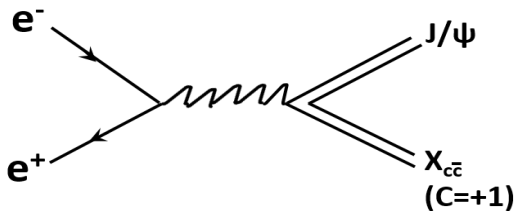
- $1^+, 0^{-/+} \dots$
- $X(3872), Z(4430) \dots$
- Open charm hadrons

## Initial state radiation

- $J^{PC}=1^{--}$
- $Y(4260)$

## Two photon collision

- $J^{PC}=0^{++}, 2^{++} \dots$
- Extract two photon width



## Double charmonium

- C-even charmonium

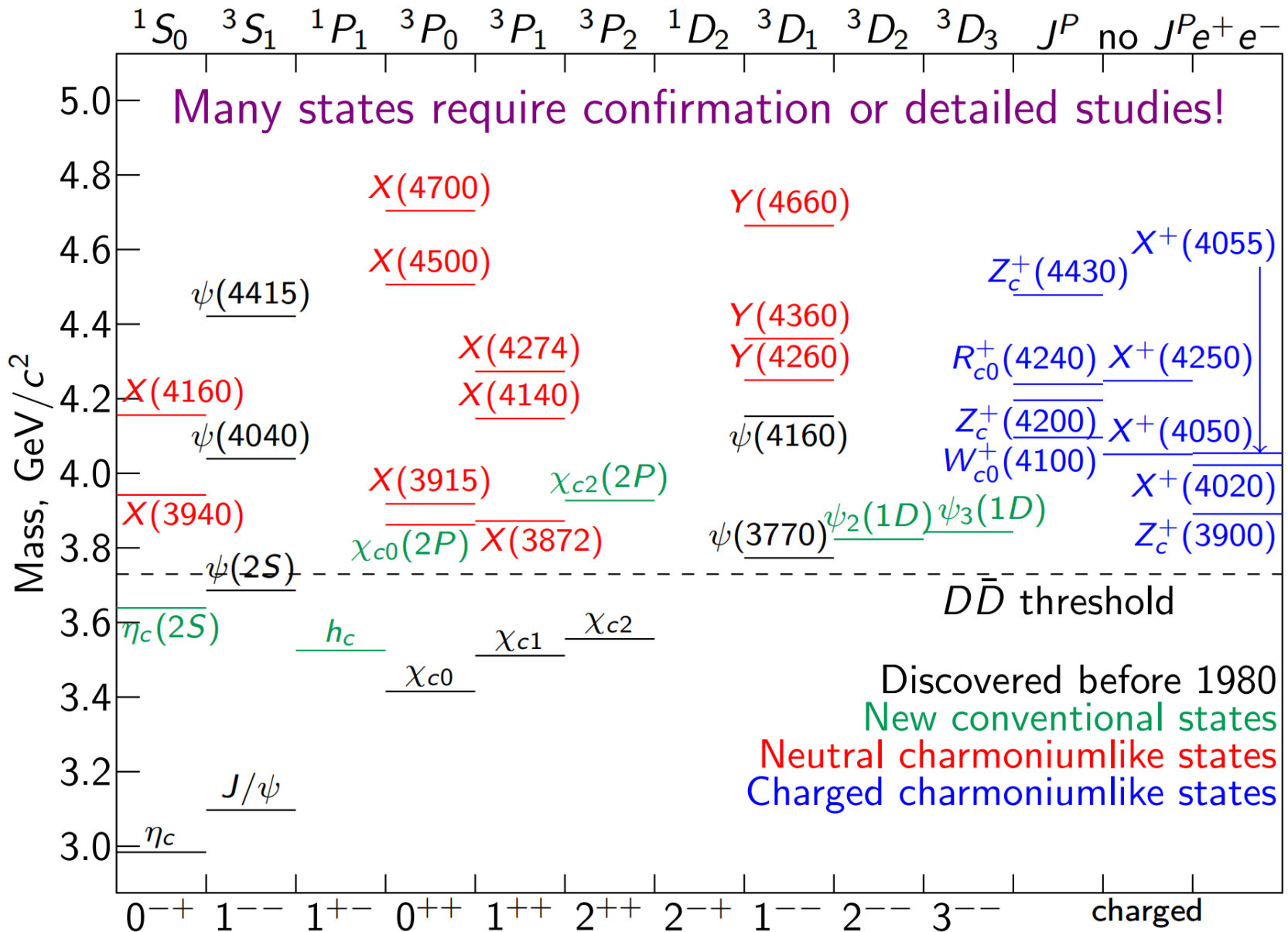
## $e^+e^- \rightarrow c\bar{c}$

Charm, mesons/baryons

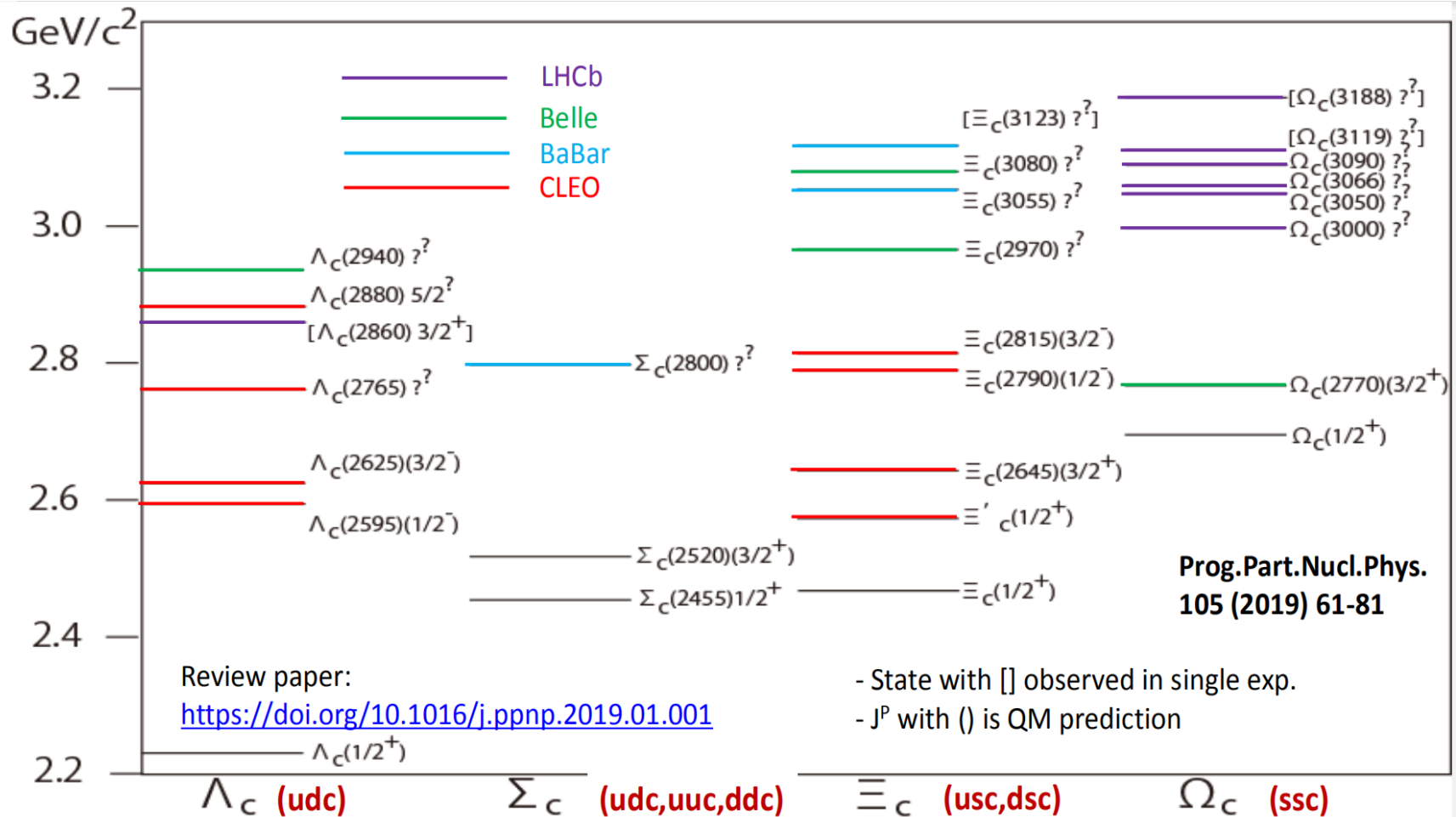
## Bottomonium transition

$Z_b$  states

# Hadron Spectroscopy

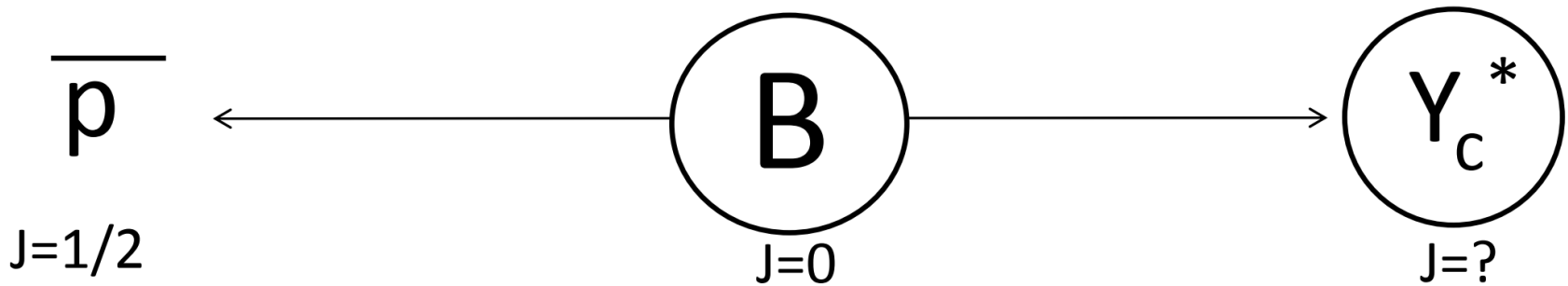


# Observed charmed baryons

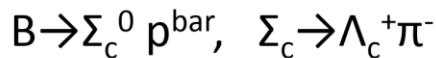


# J<sup>P</sup> determination at Belle II

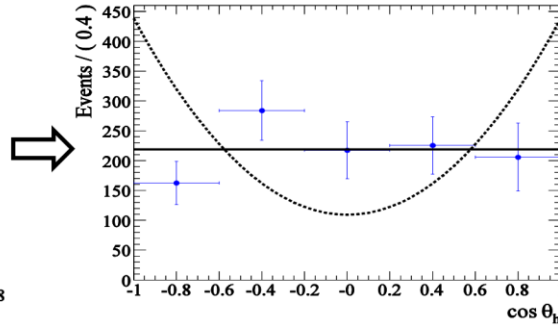
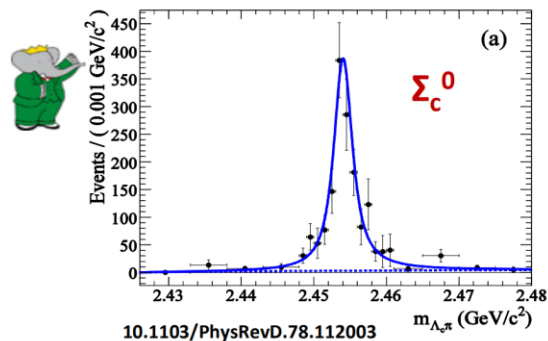
- B-meson two body decay constrains the helicity to be 1/2 as B meson has spin zero and proton has spin 1/2. This largely reduce uncertainty
- Statistics at current B-factory is not good enough for higher excited states.



## Example

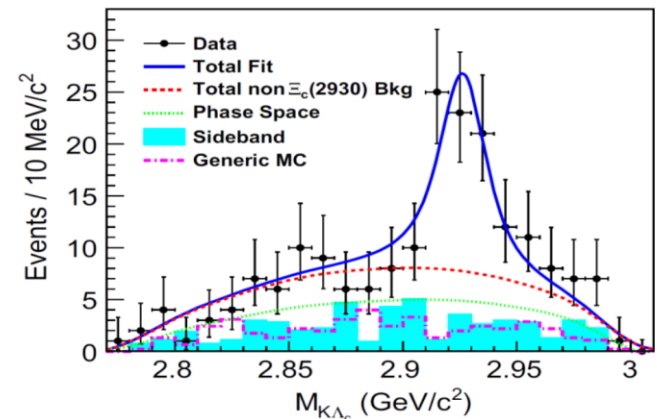
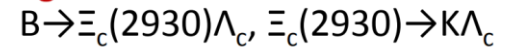


$\Lambda_c^+ \pi^-$  angular distribution



$S=1/2$ , exclude 3/2 by  $\sim 4\sigma$

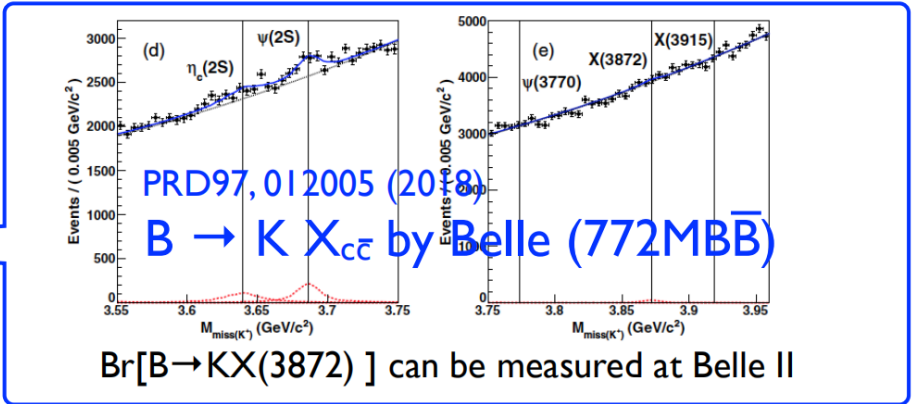
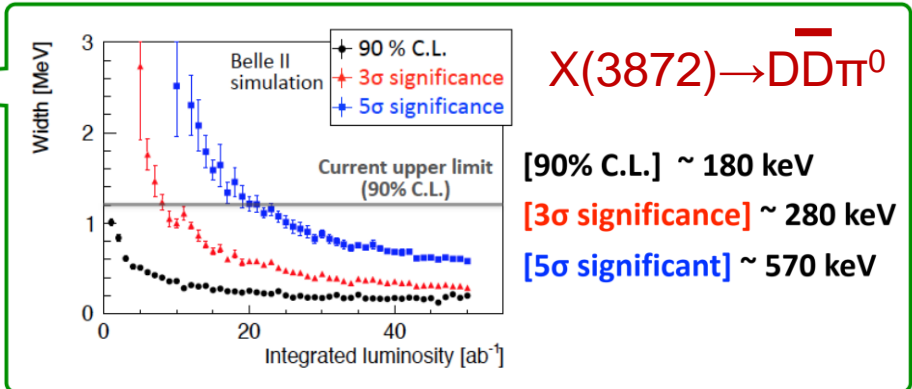
Higher excited states observed!



# Hadron Spectroscopy at Belle II

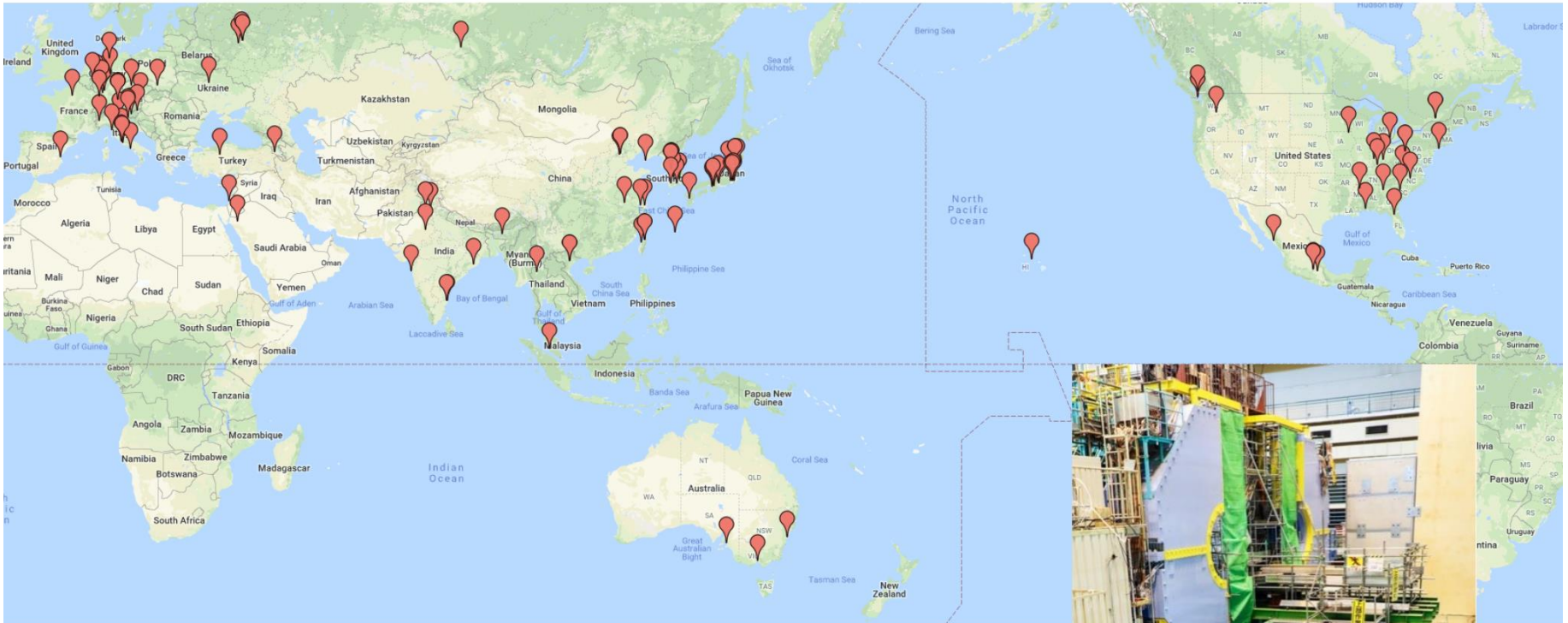
- High statistics data at Belle II enables us to do
  - Search for new states near thresholds
  - Amplitude analyses to determine  $J^{PC}$
  - Precise determination of resonance parameters
    - e.x.: X(3872) width
- Variety of approaches
  - B decays
    - ISR  $\rightarrow$  study XYZ at threshold
      - $> 1 \text{ fb}^{-1} / 10 \text{ MeV}$  at  $E_{\text{cm}} \sim 4 \text{ GeV}$
    - Recoil mass  $\rightarrow$  measure absolute branching fraction
    - b sector by running on  $\Upsilon(5S)$  ...

State	Production and Decay	N
X(3872)	$B \rightarrow K X(3872)$ , $X(3872) \rightarrow J/\psi \pi^+ \pi^-$	$\simeq 14400$
Y(4260)	ISR, $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$	$\simeq 29600$
Z(4430)	$B \rightarrow K^\mp Z(4430)$ , $Z(4430) \rightarrow J/\psi \pi^\pm$	$\simeq 10200$



*Also spectroscopies of non exotic quarkonium and baryons.*

# The Belle II Collaboration



- Belle II has now grown to  $\sim 1000$  researchers from 112 institutions in 26 countries.
- Large international collaboration hosted by KEK, Japan

# Summary



- Belle II has successfully concluded the phase 2 physics run
- Phase 3 run started in March 2019: there is much better vertexing, particle ID than in Belle; and full reconstruction on tag side is notably improved over Belle/BaBar.
- Belle II aims to explore NP in the flavor sector with  $50\text{ab}^{-1}$  with ultimate precision measurement (a few % typically) of heavy flavor decays.
- Variety of subjects (including low-energy QCD, dark photon, exotic states, mesons/baryons, ...)
- **We expect many exciting results in the coming years !**

Belle II physics book (arXiv:1808.10567):

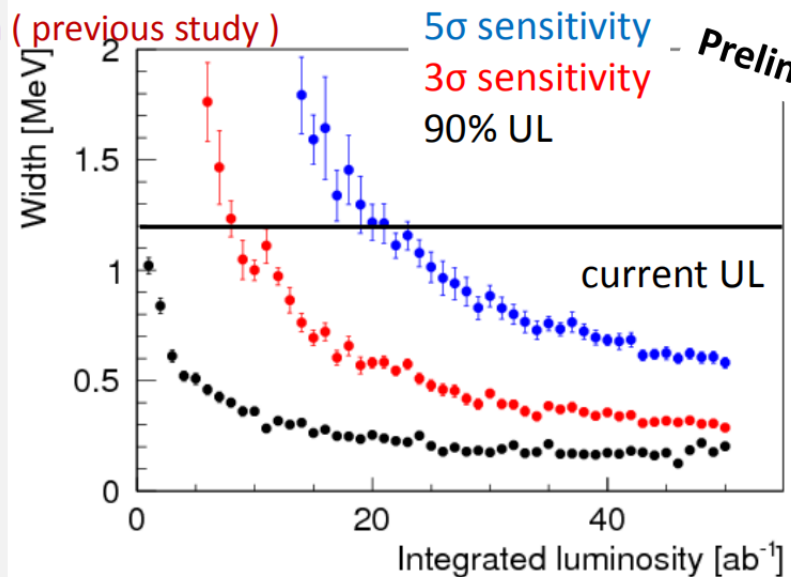
<https://confluence.desy.de/display/BI/B2TiP+ReportStatus>

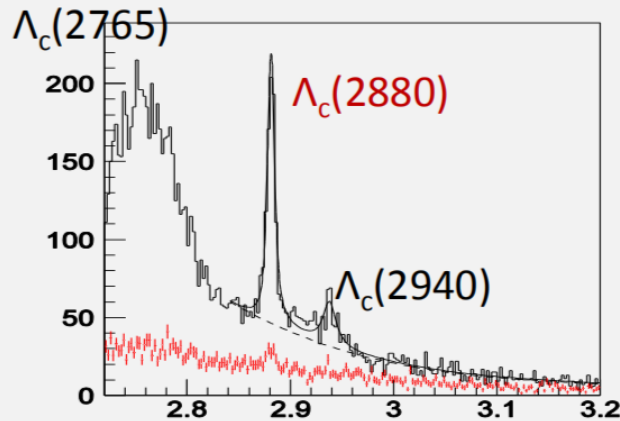
# Total width with $X(3872) \rightarrow D\bar{D}\pi^0$ decay mode

- In general, the mass resolution is better for smaller mass difference.
- The mass difference is smallest in  $D\bar{D}\pi^0$  mode.
- The mass resolution is **680 keV: ~3 times better than  $J/\psi\pi^+\pi^-$  mode.**
  - No width measurement at Belle (1) due to poor statistics
- No bias seen up to  $O(100 \text{ keV})$  in the simulation.
- The expected 90% UL is 180 keV.

Decay	Mass difference (MeV/c <sup>2</sup> )
$J/\psi\pi^+\pi^-$	~500
$DD\pi^0$	7

Total width (previous study)



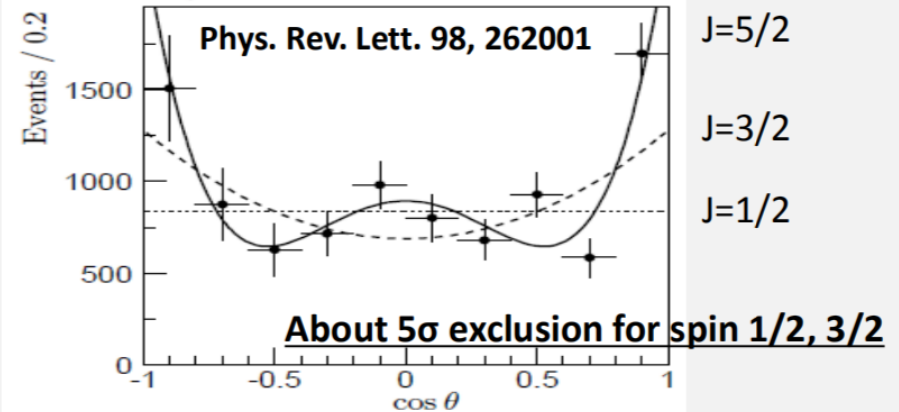


$M(\Sigma_c \pi)$

The decay angular distribution for spin 5/2.

$$W_{5/2} = \frac{3}{8} [\rho_{55} 2(5 \cos^4 \theta - 2 \cos^2 \theta + 1) + \rho_{33} (-15 \cos^4 \theta + 14 \cos^2 \theta + 1) + \rho_{11} 5(1 - \cos^2 \theta)^2]$$

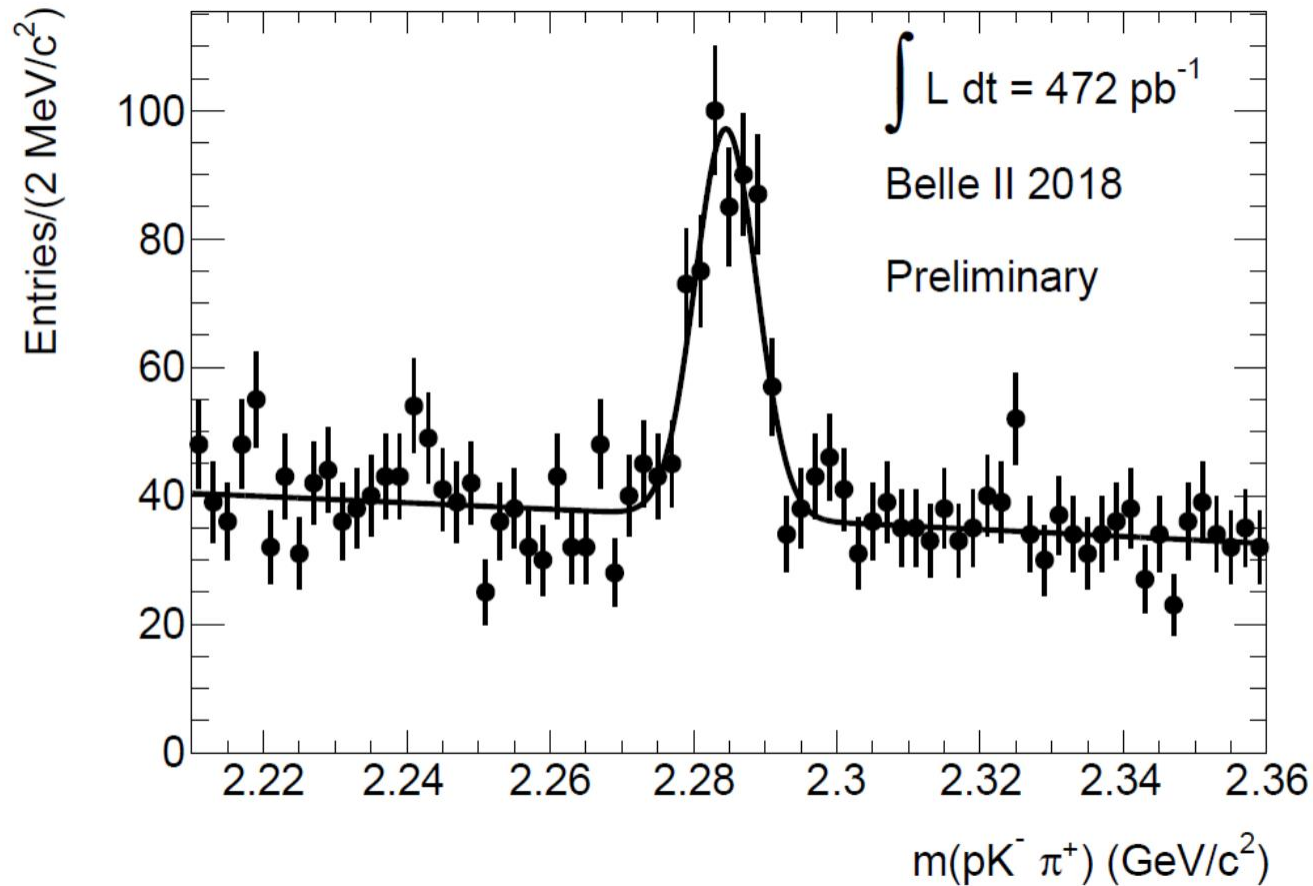
$\Lambda_c^+(2880) \Sigma_c \pi$  decay angular distribution



- Decay angular distribution depends on helicity fraction ( $\rho_{ij}$ ).  
Difficult to predict  $\rho_{ij}$  in continuum production.
- If a charm baryon is not polarized ( $\rho_{ij}$  have same value), angular distribution becomes flat.  
→ It is difficult to distinguish spin 1/2 and no polarization.

- J<sup>P</sup> determination is essential.

# $\Lambda_c^+$ in Belle II phase2 data!



# Prospect for CKM

- For  $|V_{xb}|$ , Belle II is able to perform both inclusive and exclusive measurements with B tagging, including
  - detailed studies of exclusive decays to understand the difference, which is presently seen.
- Interplay with theoretical studies is important.

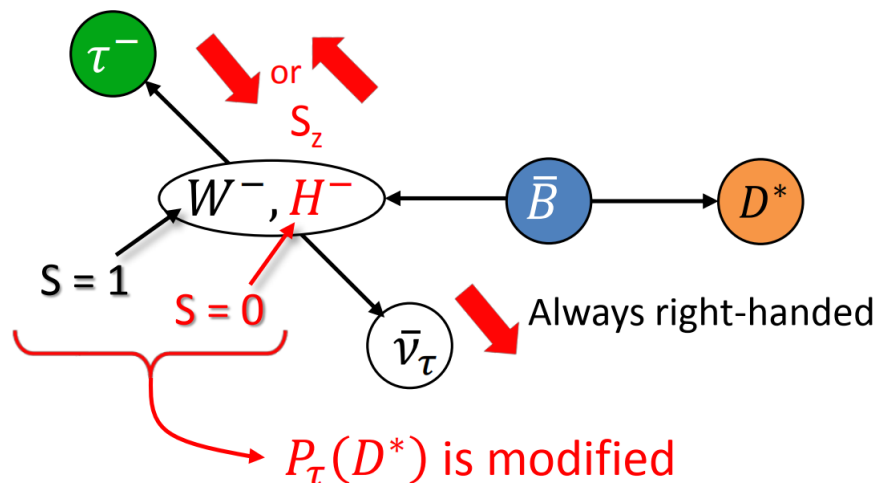
1808.10567

## Belle II prospect for $|V_{xb}|$

% uncertainties	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory <b>Lattice projections</b>	Total
$ V_{ub} $ exclusive (had. tagged)					
711 fb <sup>-1</sup>	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab <sup>-1</sup>	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab <sup>-1</sup>	0.4	(0.3, 1.0)	1.2	0.9	1.7
$ V_{ub} $ exclusive (untagged)					
605 fb <sup>-1</sup>	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab <sup>-1</sup>	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab <sup>-1</sup>	0.3	(0.3, 0.8)	0.9	0.9	1.3
$ V_{ub} $ inclusive					
605 fb <sup>-1</sup> (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab <sup>-1</sup>	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab <sup>-1</sup>	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

# Polarizations in $B \rightarrow D^* \tau \nu$

- $R(D^{(*)})$  deviations from SM (by  $\sim 3.8\sigma$  as of 2018) motivates further study
- Detailed kinematic information of the final-state particles, e.g. angular observables, can provide a good clue for NP signature (*if there is any!*)



$$\mathcal{P}_\tau^{\text{SM}} = -0.497 \pm 0.014$$

by M. Tanaka & R. Watanabe,  
PRD 87, 034028 (2013)

- In 2017, Belle has reported world-first measurement of  $P_\tau$  in  $B \rightarrow D^* \tau \nu$

$$\mathcal{P}_\tau(D^*) = -0.38 \pm 0.51_{-0.16}^{+0.21}$$

# Measurement of $\tau$ polarization

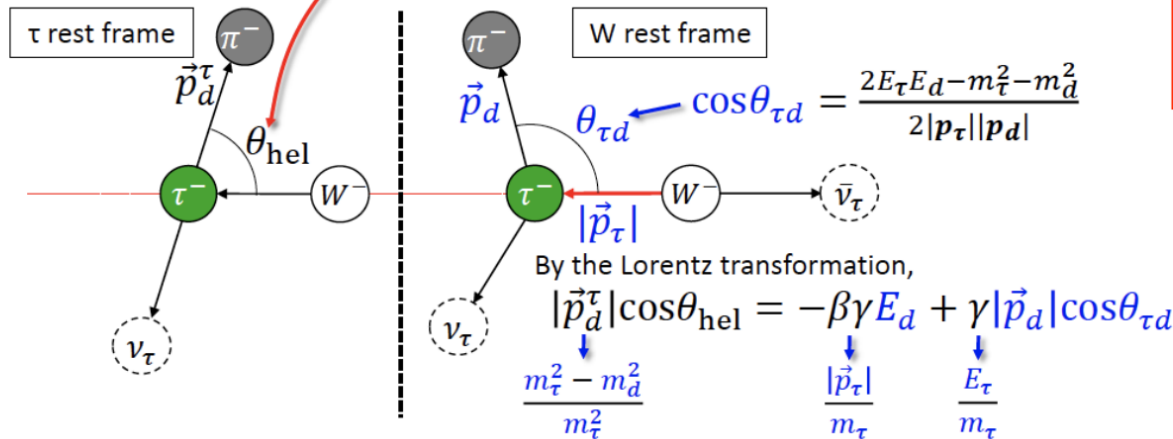
- Belle II will be able to measure distributions; such as  $\tau$  polarization,  $q^2$  distribution, to discriminate type of NP.

## Measurement of $\tau$ polarization

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

$$\alpha = \begin{cases} 1 & \text{for } \tau^- \rightarrow \pi^- \nu_{\tau} \\ \sim 0.45 & \text{for } \tau^- \rightarrow \rho^- \nu_{\tau} \end{cases}$$

- Known
- $P_B \leftarrow$  B tagging
  - $P_D \leftarrow$  D recon.



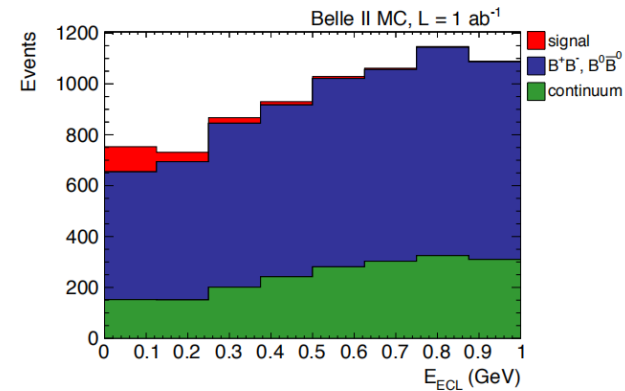
Solving the equation,  $\cos\theta_{\text{hel}}$  is obtained!

# B $\rightarrow$ $\tau \nu, l \nu$ at Belle II

1808.10567

## B $\rightarrow$ $\tau \nu$

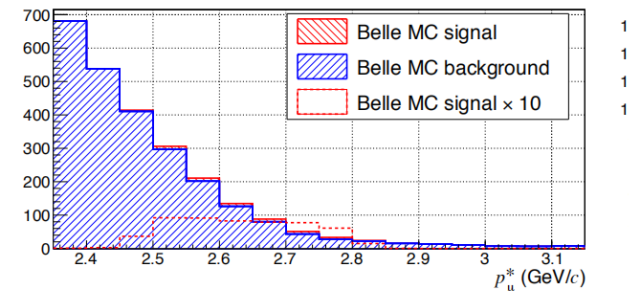
- Exploits high efficiency of the hadronic tag method through the Full Event Interpretation (FEI).
- Selection of photon candidates is important to cope with machine background in Belle II (x20 w.r.t. Belle)
  - Cluster energy, timing, shape (E9/E25)
- Multivariate continuum suppression



$E_{ECL}$		< 1 GeV	< 0.25 GeV
without background	Background yield [events]	12835	2062
	Signal yield [events]	332	238
	Signal efficiency (%)	3.8	2.7
with background	Background yield [events]	7420	1348
	Signal yield [events]	188	136
	Signal efficiency (%)	2.2	1.6

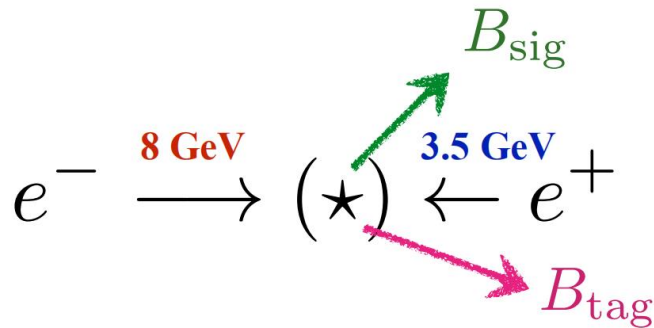
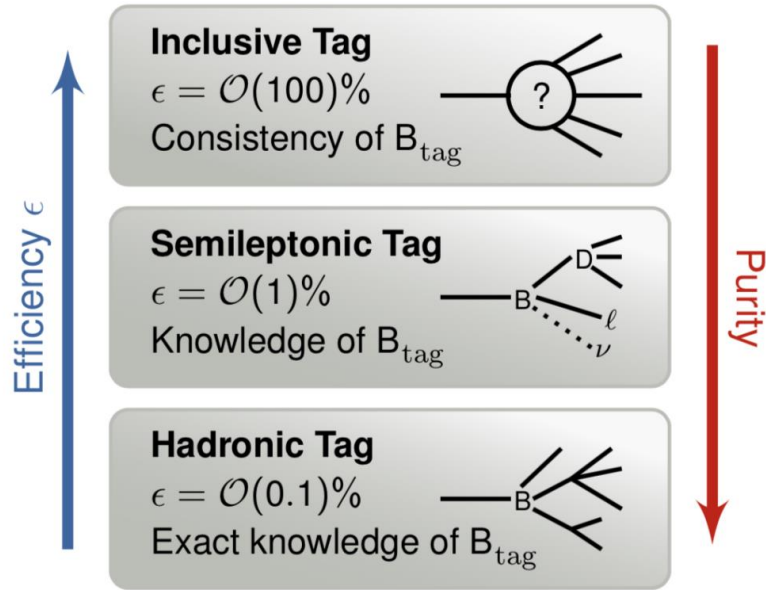
## B $\rightarrow$ $\mu \nu$

- Tagged searches are possible, but efficiency is too low
- Extrapolation from Belle to Belle II
  - Branching fraction error : 7%(stat.) at 50ab<sup>-1</sup>
  - 5 $\sigma$  observation at 6 ab<sup>-1</sup>



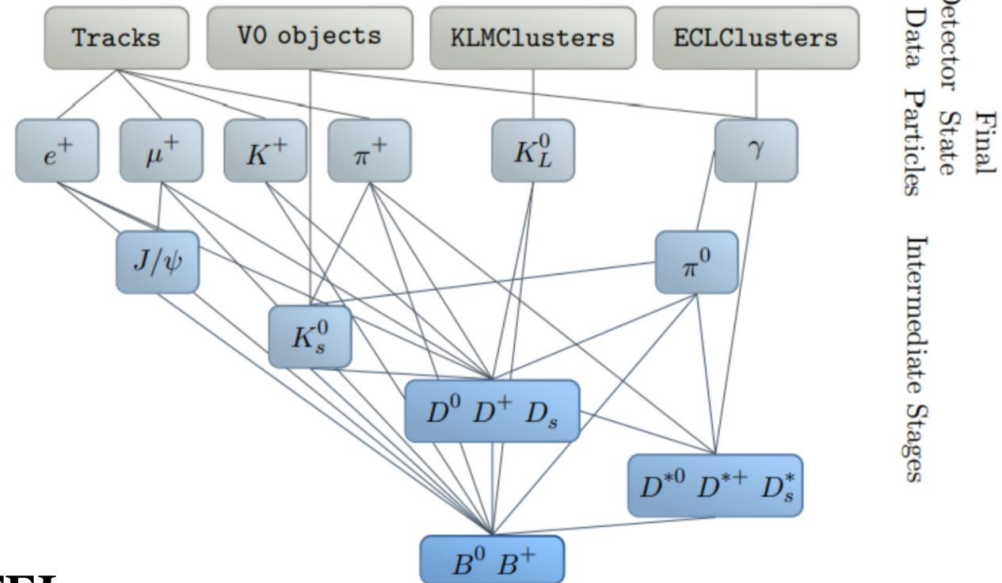
Experiment	Upper limit @ 90% C.L.	Comment
Belle [225]	$2.7 \times 10^{-6}$	Fully reconstructed hadronic tag, 711 fb <sup>-1</sup>
Belle [226]	$1.1 \times 10^{-6}$	Untagged analysis, 711 fb <sup>-1</sup>
BaBar [222]	$1.0 \times 10^{-6}$	Untagged analysis, 468 $\times 10^6$ $B\bar{B}$ pairs

# B-tagging and FEI



## Exclusive Tagging: The Full Event Interpretation (FEI)

Keck, T., et al. Comput Softw Big Sci (2019)



### FEI

- the most evolved version of B-tagging S/W
- developed for Belle II; used in several Belle studies
  - $\mathcal{O}(200)$  decay chains with BDT trained for each
  - $\mathcal{O}(10k)$  decay chains in 6 stages
  - $\times 3$  high MC efficiency than existing Belle algorithm