Physics Overview of the Belle II Experiment

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NAGOYA UNIVERSITY
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe
Belle II
SuperKEKB

Talk Outline

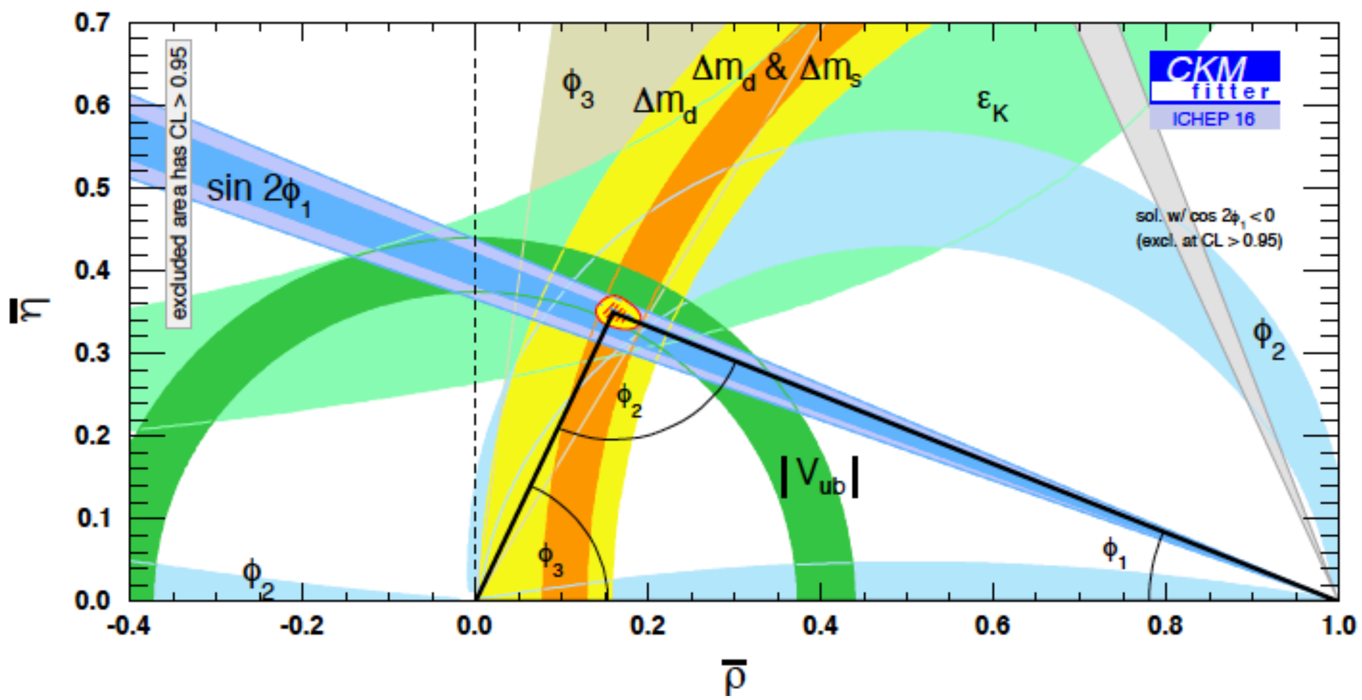
- Introduction
- Belle II physics program
  - CP violation & CKM
  - Lepton universality tests w/ tree and loop processes
  - Lepton flavor violation
  - Dark sector
  - Hadron spectroscopy
- Status and prospect of SuperKEKB/Belle II
- Summary

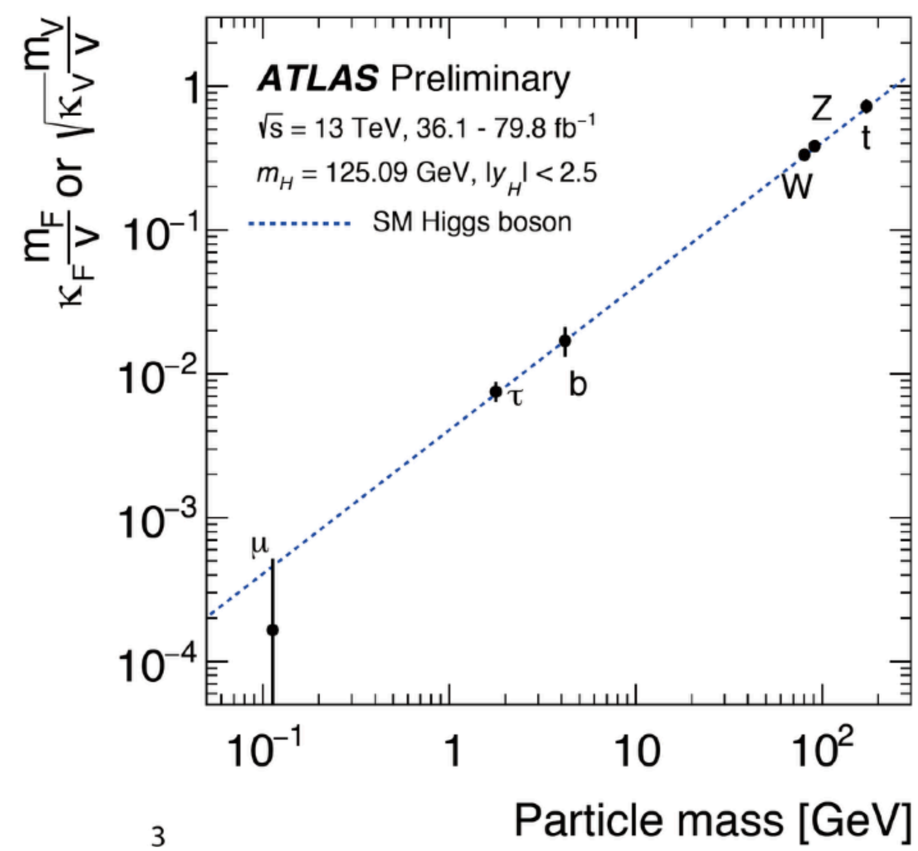
"The Belle II Physics Book"
edited by E. Kou & P. Urquijo
1808.10567 (PTEP 2019)

See talk by Martin Besner
(#113, Future Facilities, June 6)

Perfect SM

- CP violation explained by the mechanism proposed by Kobayashi and Maskawa.
- Higgs has been discovered and its couplings to fermions are being measured.



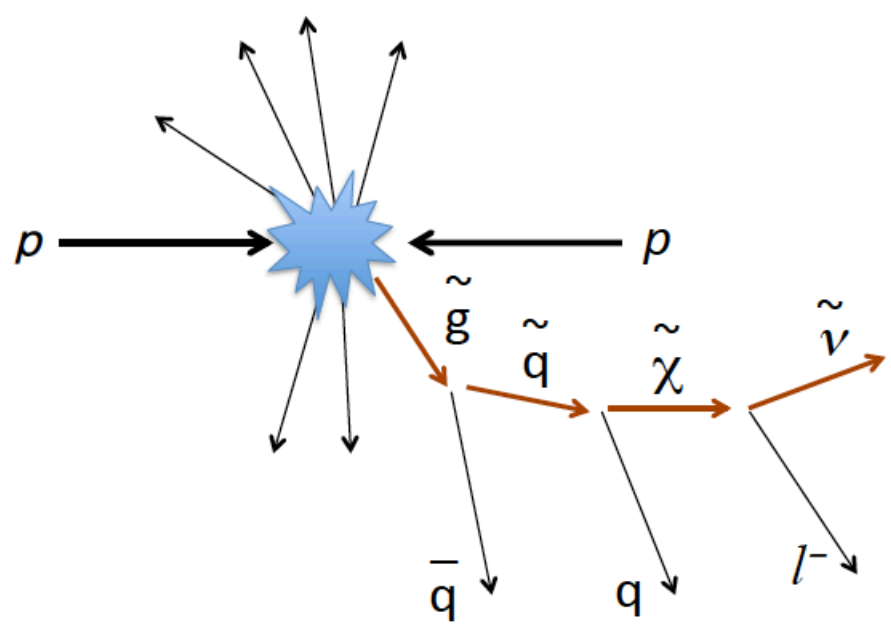


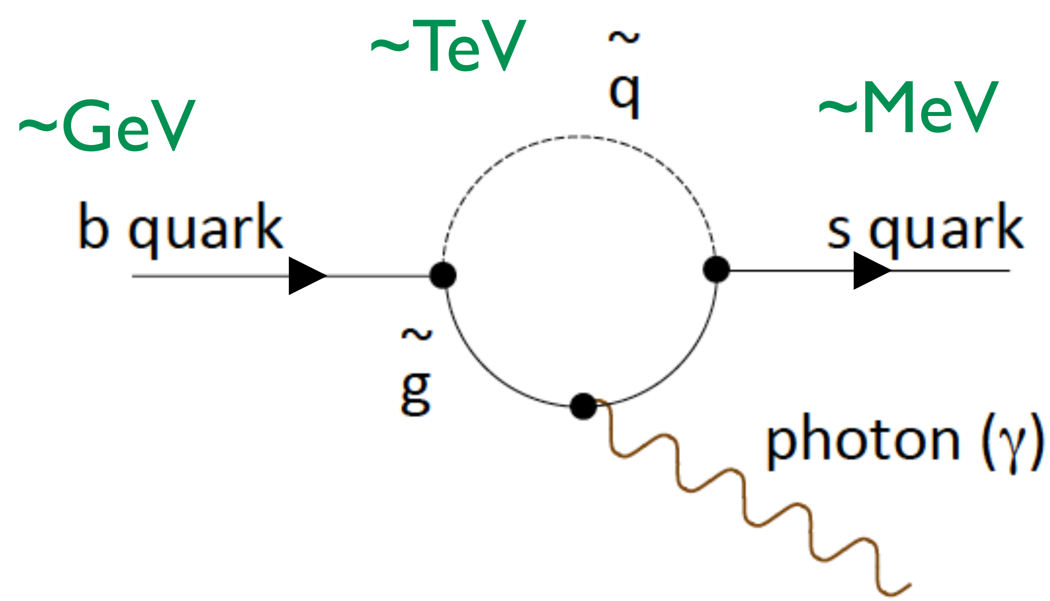
Problems in the SM: naturalness, dark matter, matter-antimatter asymmetry in the Universe, …

→ New Physics beyond the SM

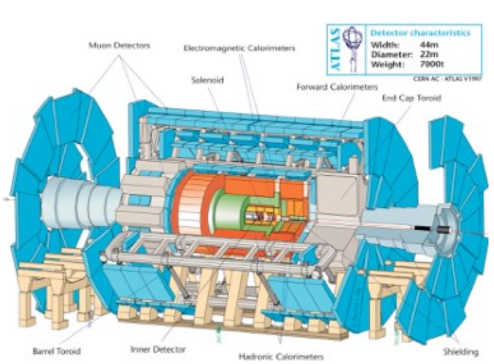
Role of Flavor Physics

- Search for New Physics (NP) through processes sensitive to presence of virtual heavy particles.
- Complementary to direct search at LHC high P_T programs.
- Becoming more and more important, since no NP signal at LHC at this moment.

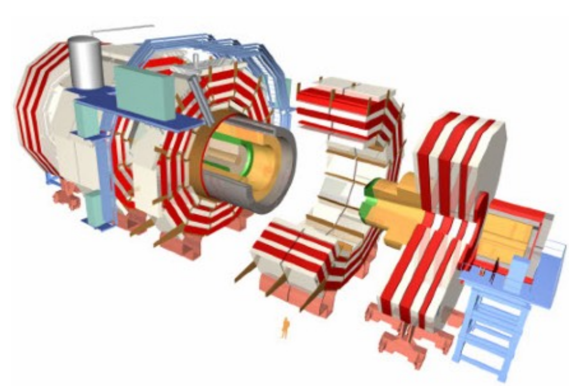




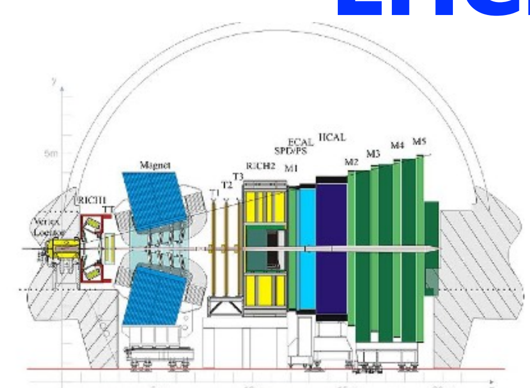
ATLAS



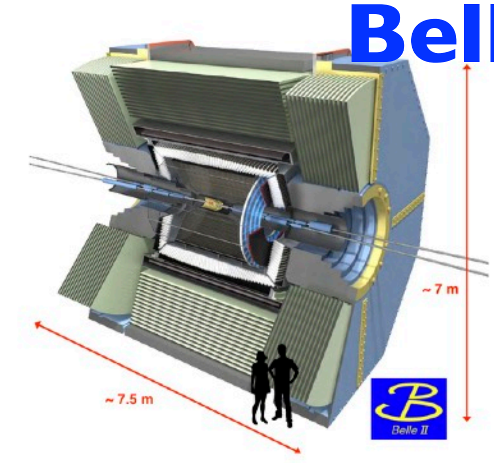
CMS



LHCb



Belle II



SuperKEKB/Belle II

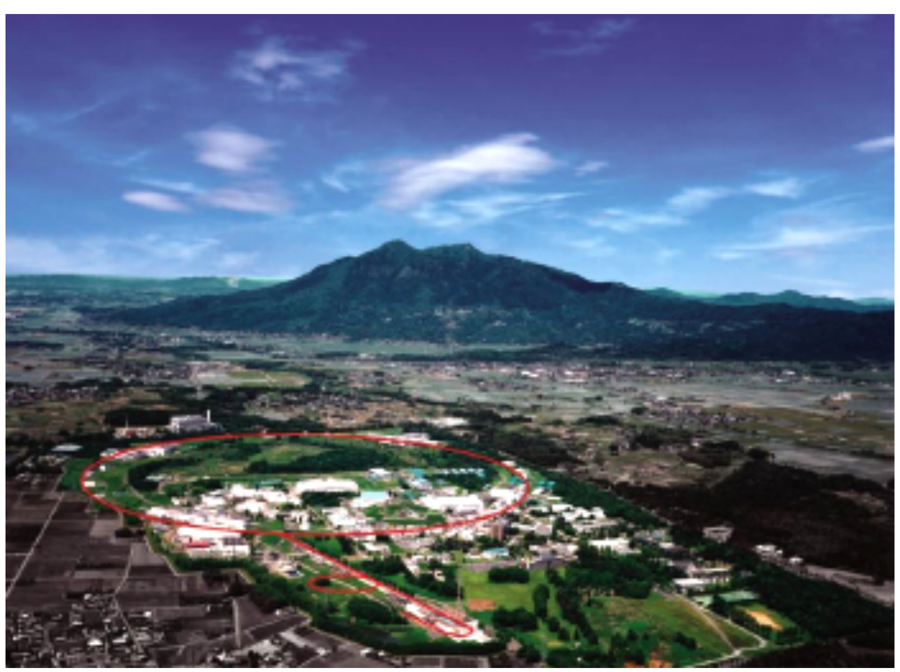
New intensity frontier facility at KEK

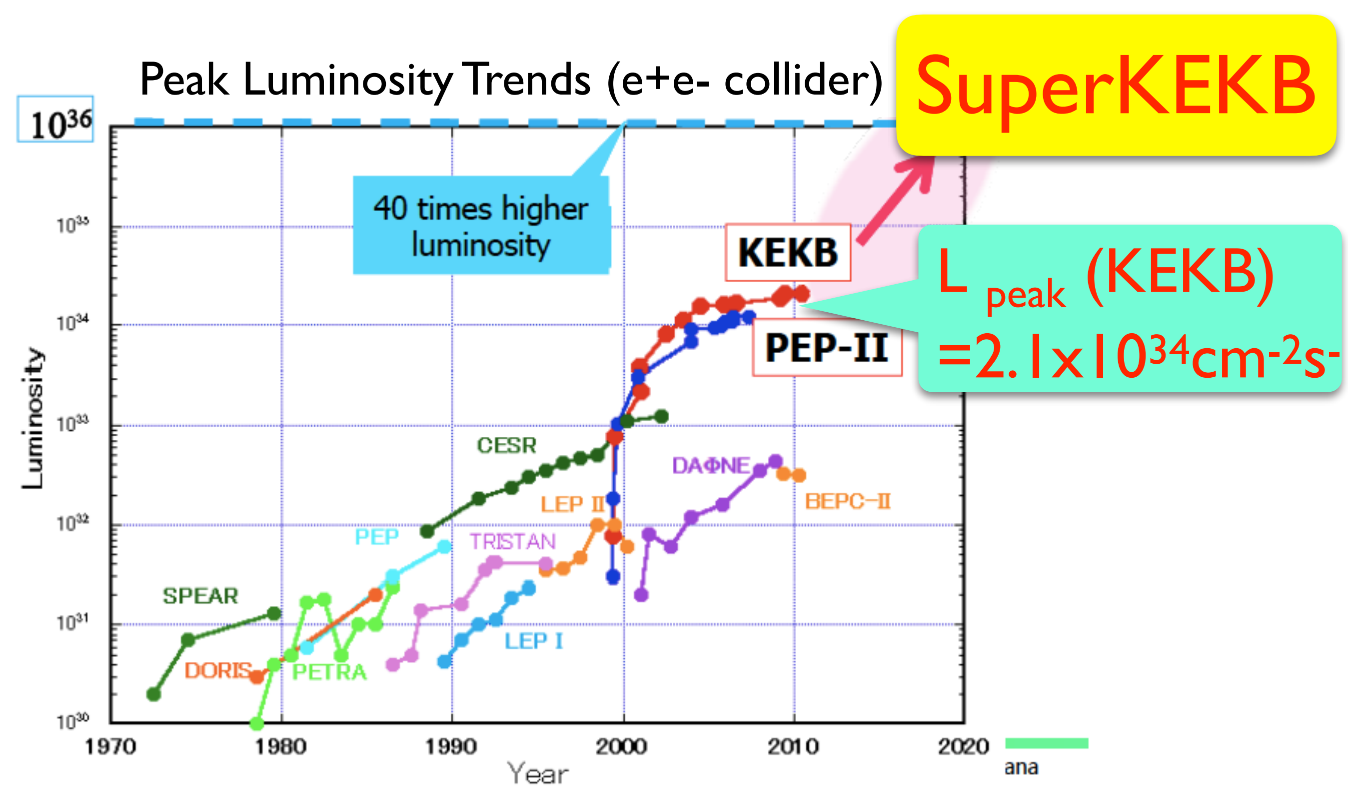
- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\bar{B}$, $\tau^{+}\tau^{-}$ and charms per year !

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

- 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

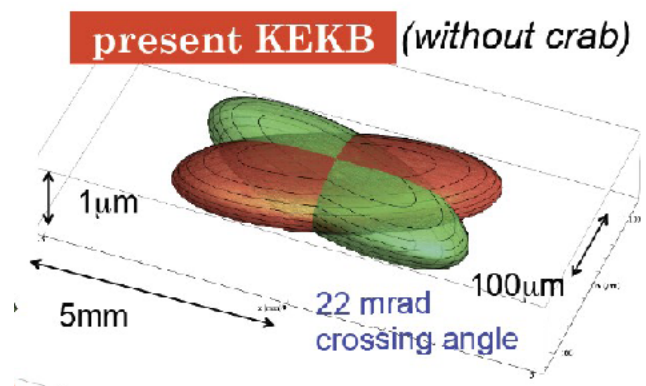
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

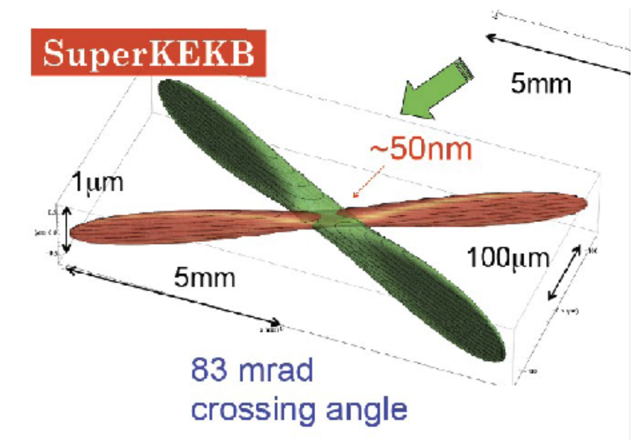
Machine parameters

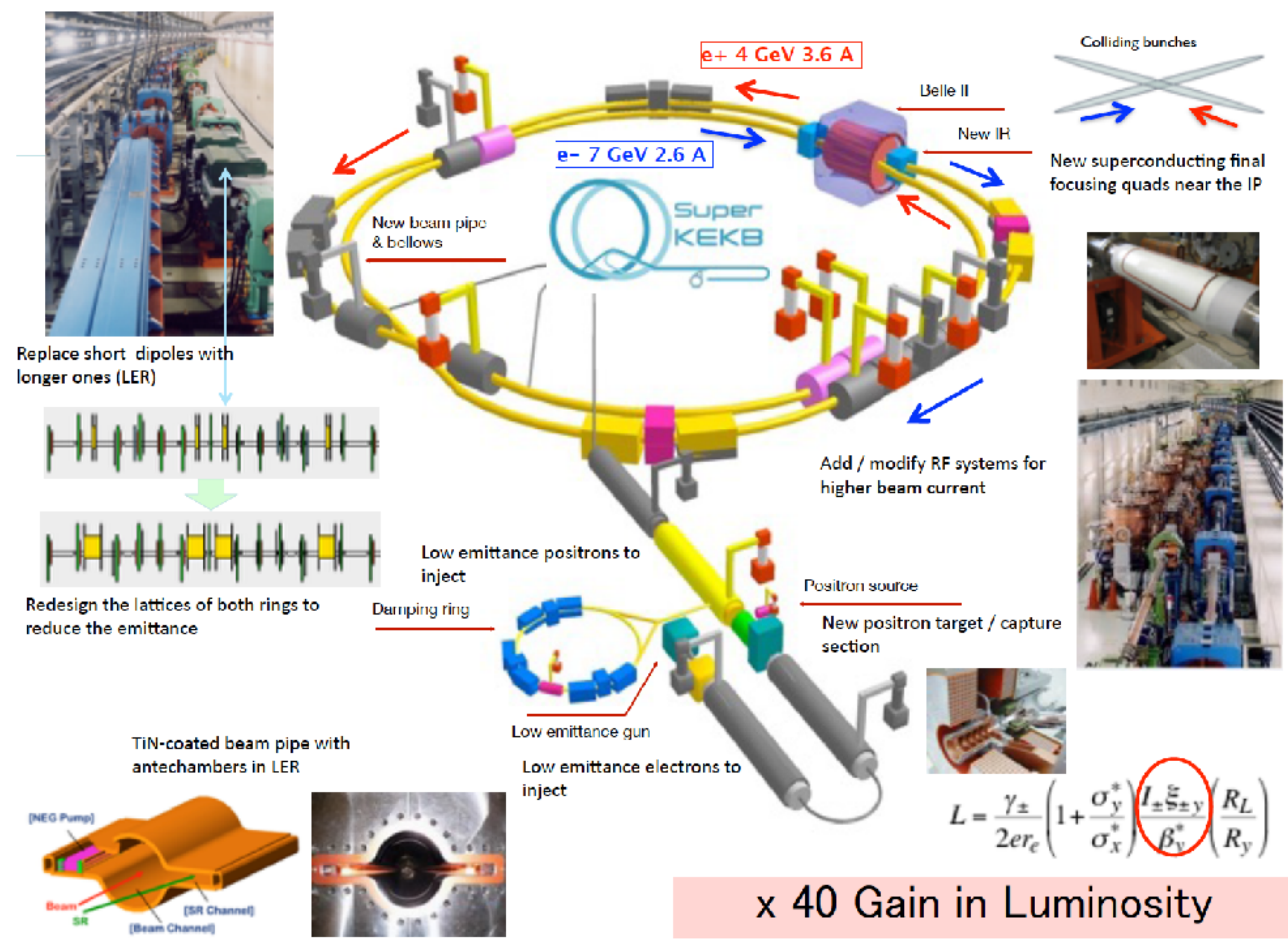
	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L($cm^{-2}s^{-1}$)	80×10^{34}	2.1×10^{34}

x20 (β_y at IP)

x2 (I(A))

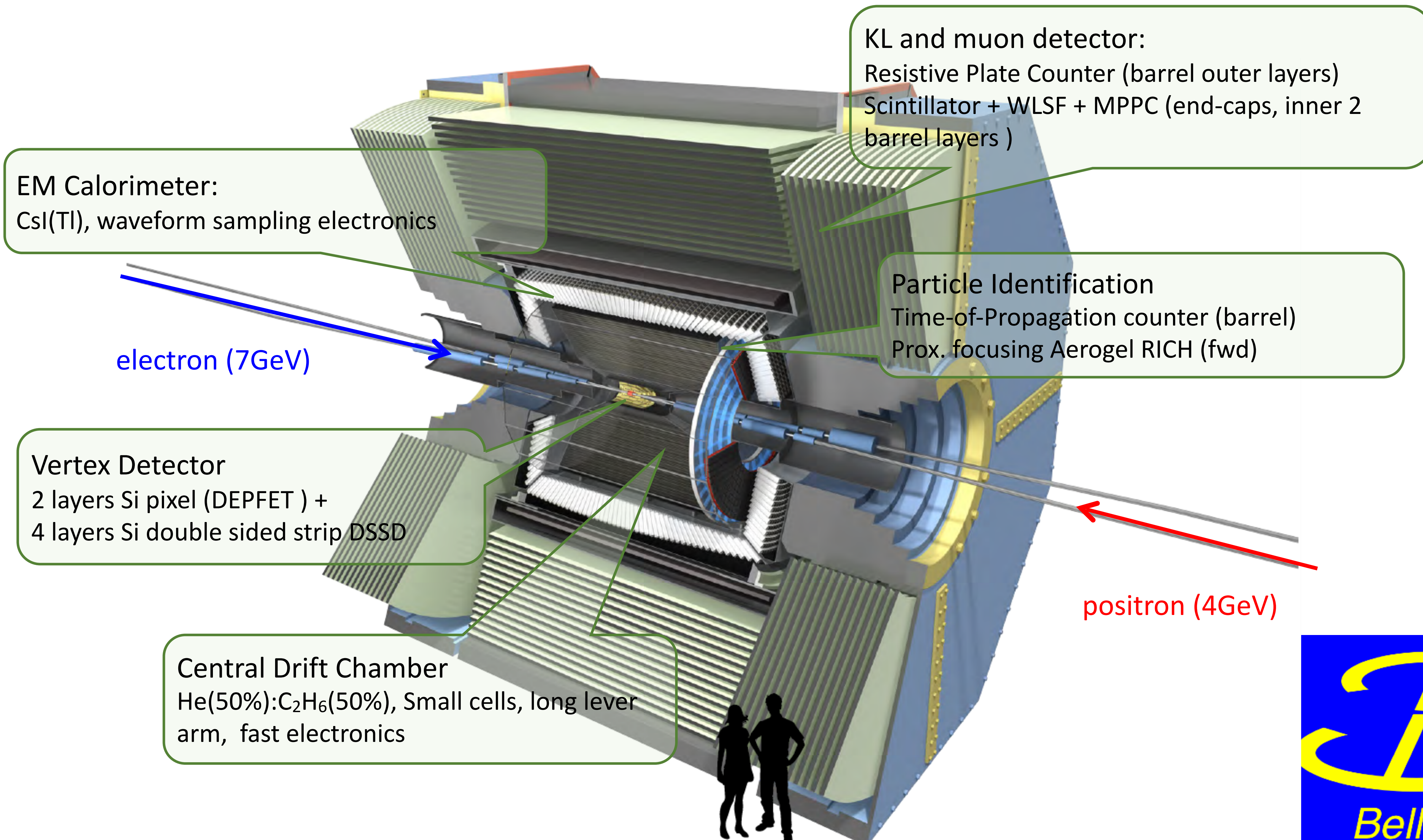




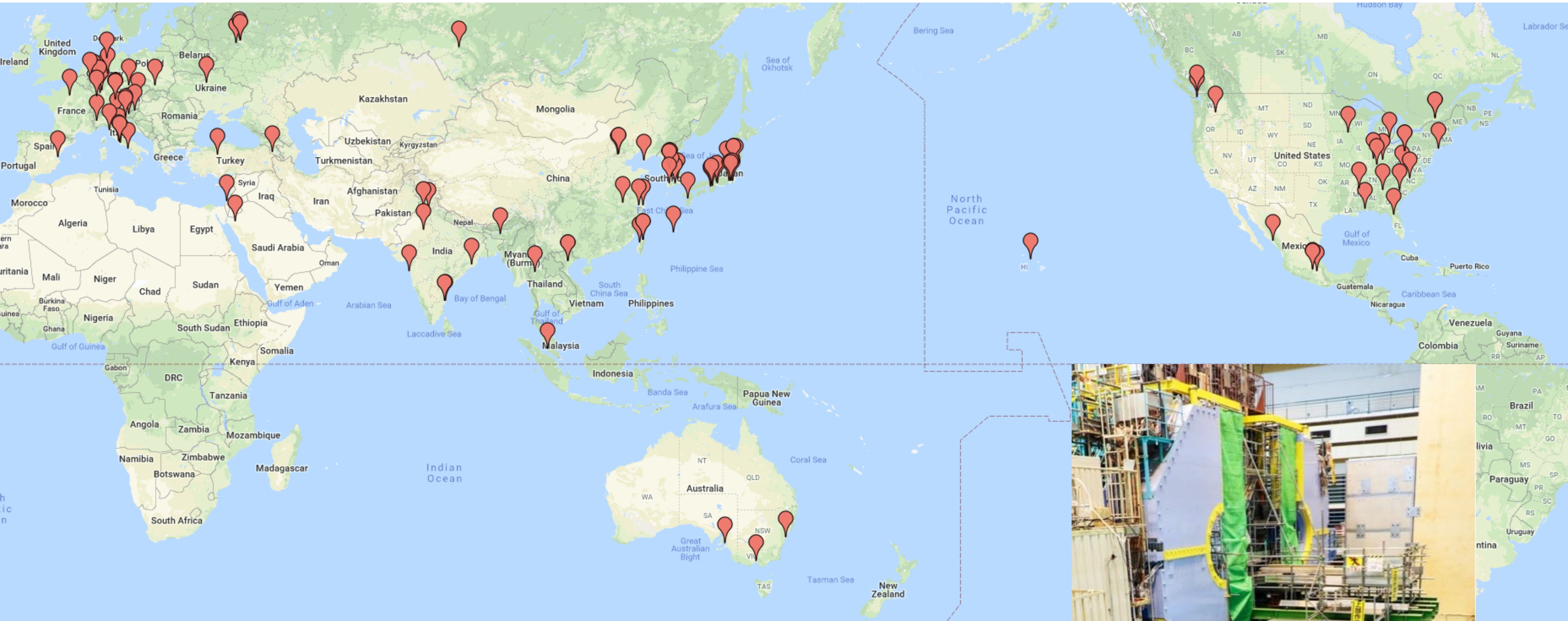


Belle II Detector

- Deal with higher background (x10-20), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity



The Belle II Collaboration



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

Belle II Physics Program

- Precision CKM
- CPV in b→s penguin decays
- Tauonic decays
- FCNC
- Charm decays
- LFV τ decays

+

- Hadron spectroscopy
- Dark sector

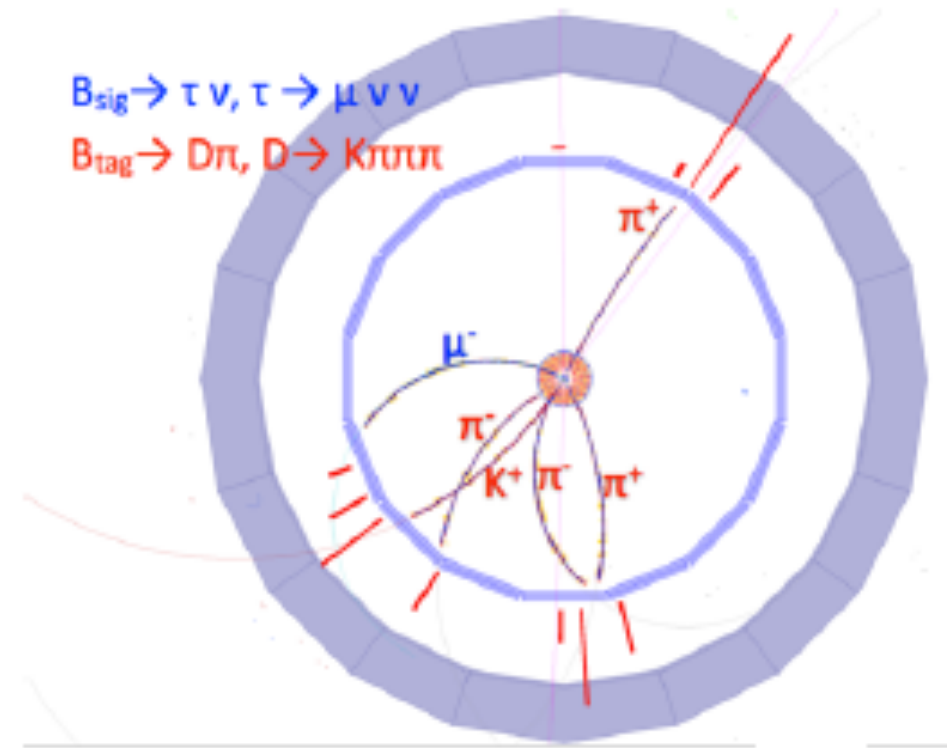
1808.10567

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
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	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
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	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
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	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
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	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
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

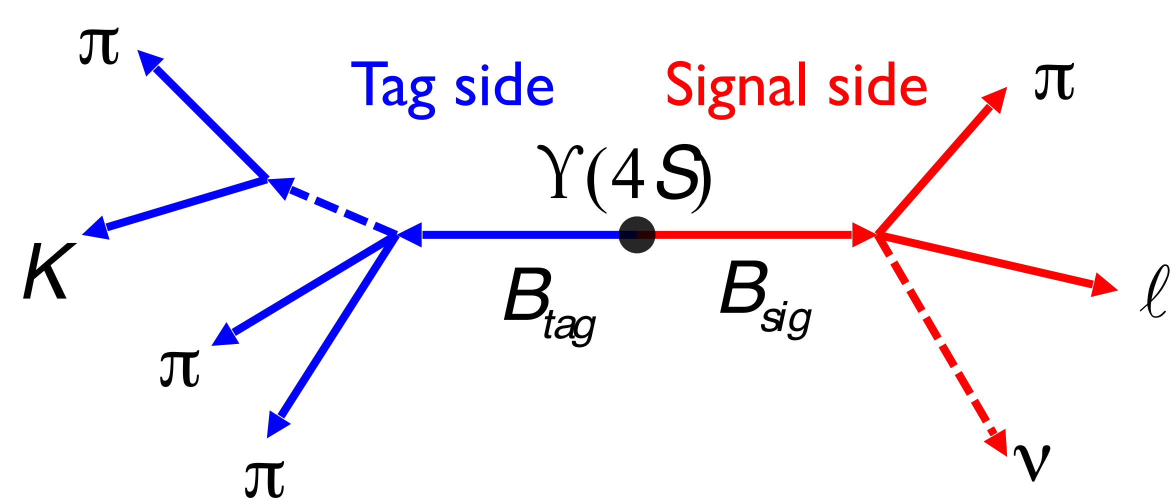
Ultimate measurements down to theory error !

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

- Clean environment
  - Efficient detection of neutrals (γ, π^0, η, …)
- Quantum correlated $B^0\bar{B}^0$ pairs
  - High effective flavor tagging efficiency :
  ~34%(Belle II) ⟷ ~3% (LHCb)
- Large sample of τ leptons
  - Search for LFV τ decays at $O(10^{-9})$



- Full reconstruction tagging possible
  - A powerful tool to measure;
    - b→u semileptonic decays (CKM)
    - decays with large missing energy



$B \to \pi l \nu$
$B \to \tau\nu, D\tau\nu$
$B \to K\nu\nu$

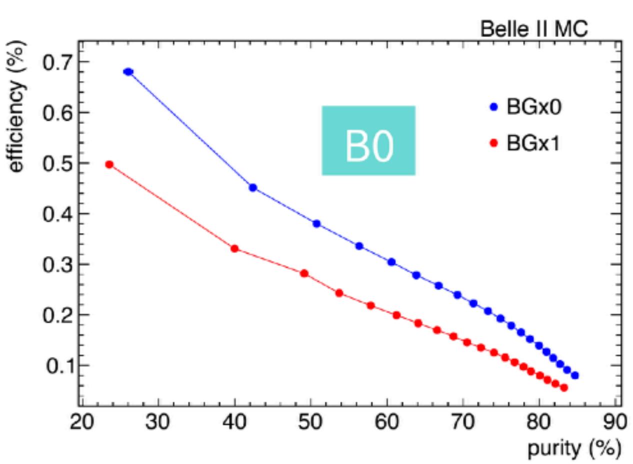
- Systematics different from LHCb
  - Two experiments are required to establish NP

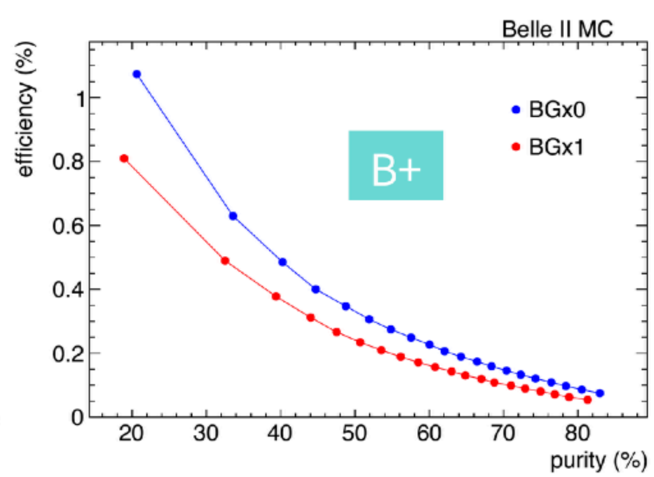
Belle II Full Event Reconstruction

- 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^+: 17→29, B^0: 14→26
- $D^+/D^{*+}/D_s^+$: 18→26, D^0/D^{*0}: 12→17

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





B^+ modes	B^0 modes
$B^+ \to \overline{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \overline{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \overline{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\overline{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \overline{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \overline{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\overline{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\overline{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \overline{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	
$B^+ \to J/\psi K_S^0\pi^+$	

$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \overline{D}^0D^+$	$B^0 \to \overline{D}^0\pi^+\pi^-$
$B^+ \to \overline{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \overline{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \overline{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \overline{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \overline{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$
$B^+ \to \overline{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$
$B^+ \to \overline{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$
$B^+ \to \overline{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

D^+, D^{*+}, D_s^+ modes	D^0, D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	

$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

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

- Below line: not used in Belle NB tag.

More recent update: 1807.08680

CKM fit w/ Belle II + LHCb

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

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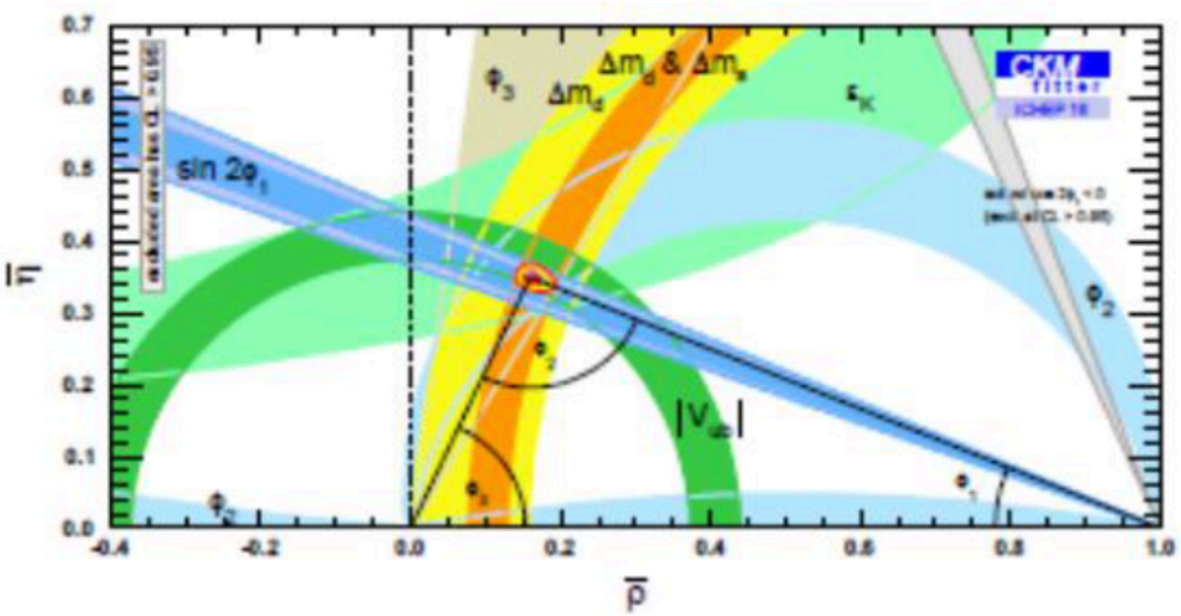
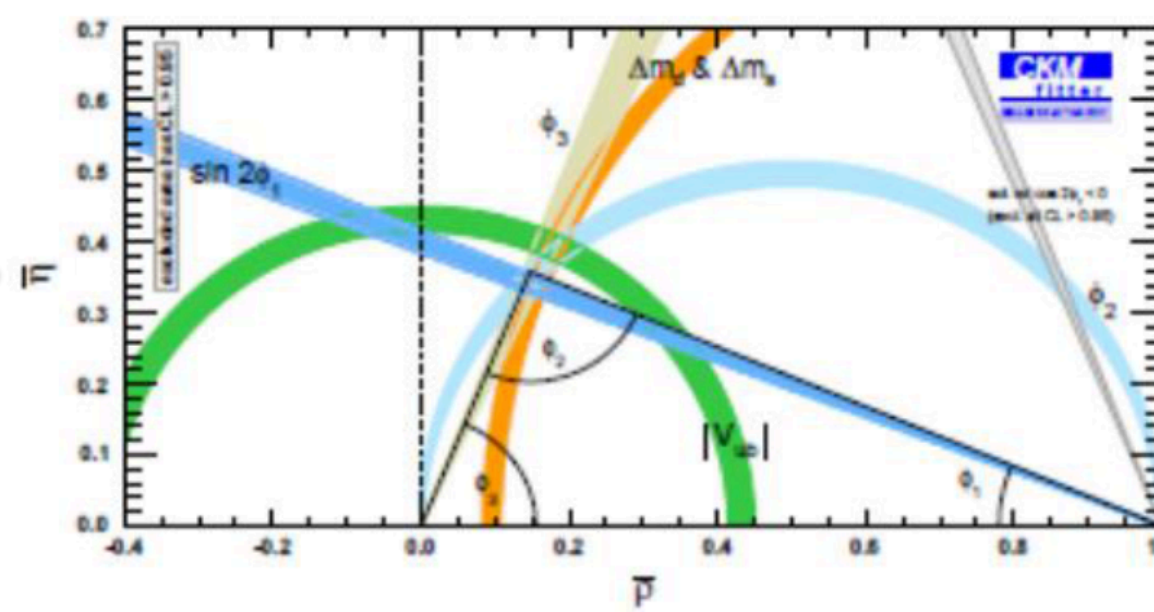
Current world average



Belle II projection @ $50ab^{-1}$



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$\bar{\rho}$	$0.1504^{+0.0121}_{-0.0062}$	$^{+0.0054}_{-0.0044}$	$^{+0.0042}_{-0.0040}$
$\bar{\eta}$	$0.3540^{+0.00069}_{-0.0076}$	$^{+0.0037}_{-0.00040}$	$^{+0.0036}_{-0.00037}$

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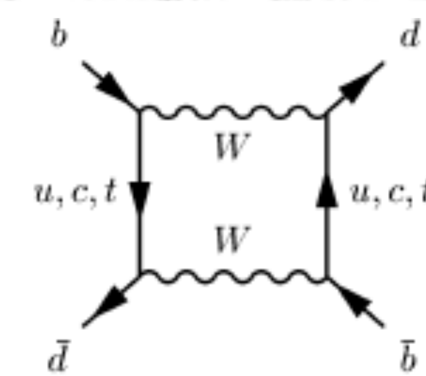
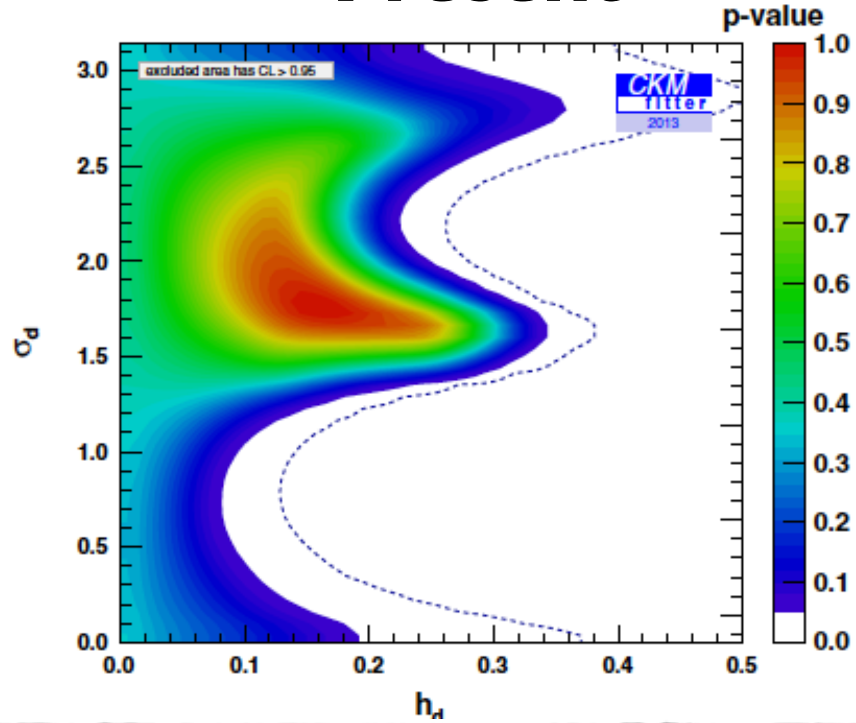
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

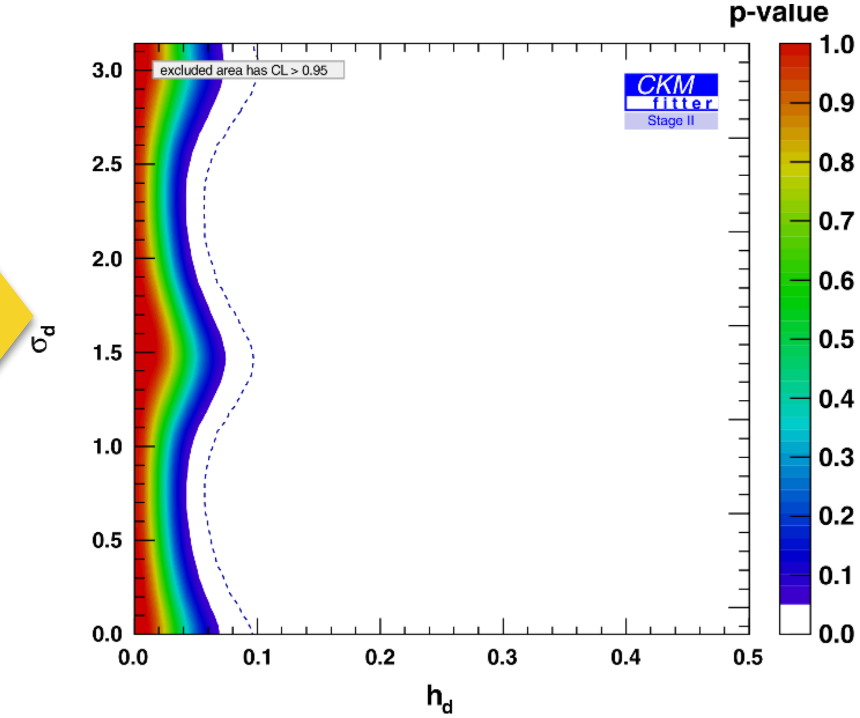
Relative amplitude (h) phase (σ)



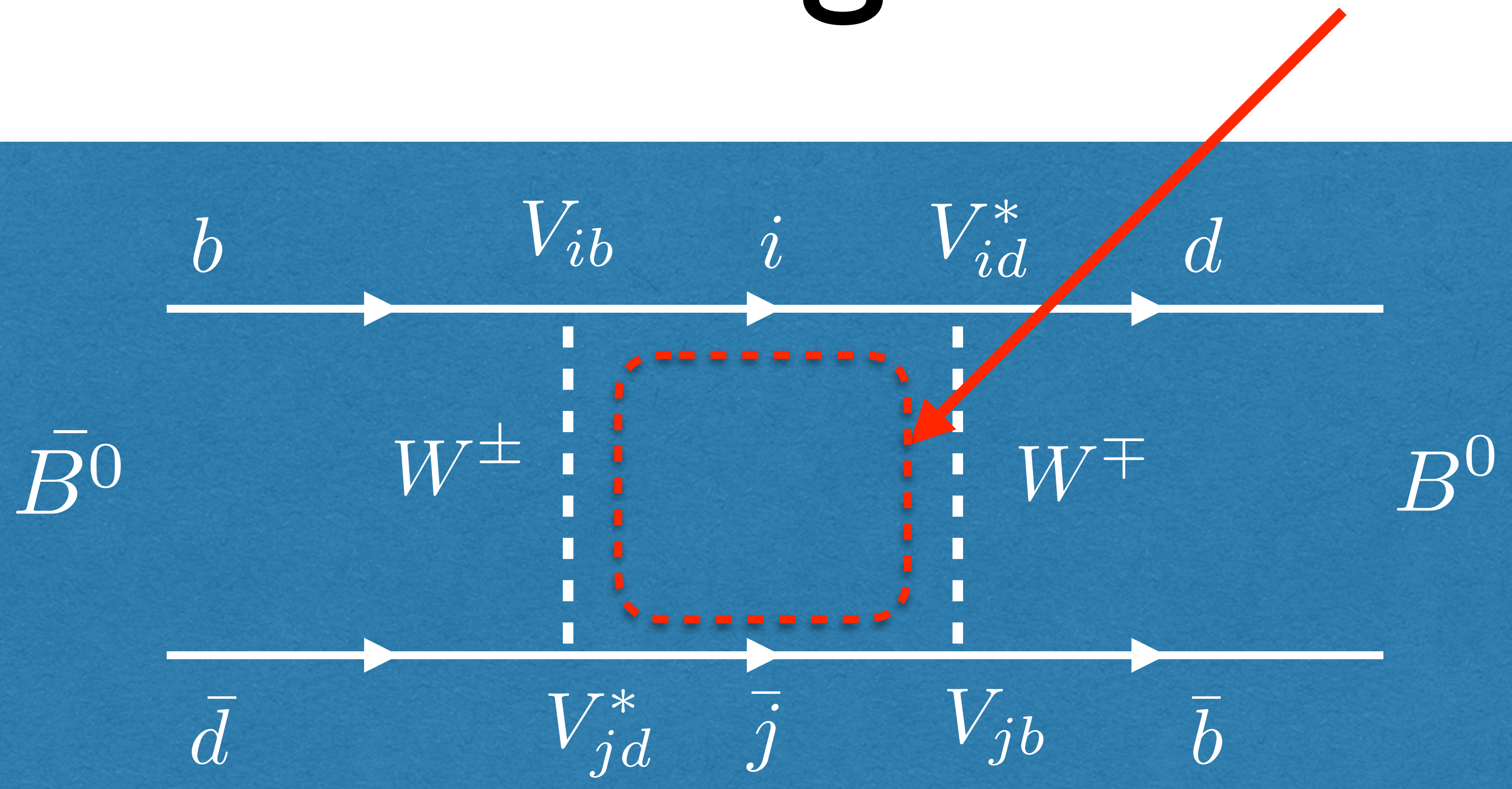
Present



Belle II 50ab^{-1} + LHCb 50fb^{-1}



B-$\bar{\text{B}}$ Mixing and New Physics



$$\frac{C_{ij}^2}{\Lambda^2}(\bar{q}_{i,L}\gamma^\mu q_{j,L})^2,$$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2}\frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg(C_{ij}\lambda^{t*}_{ij}),$$

$$\lambda^t_{ij} = V^*_{ti}V_{tj}$$

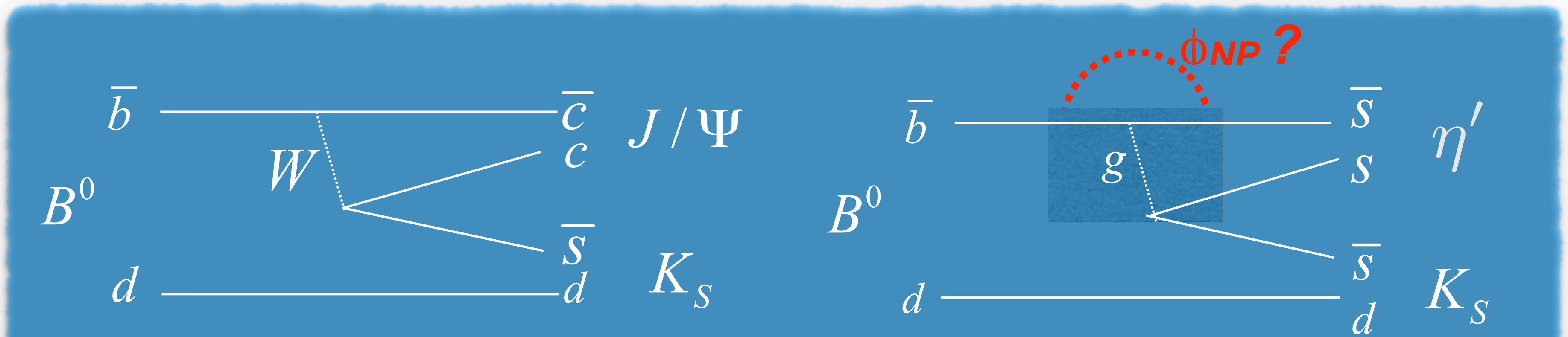
J. Charles et al., PRD89,033016(2014)

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V^*_{tj}\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

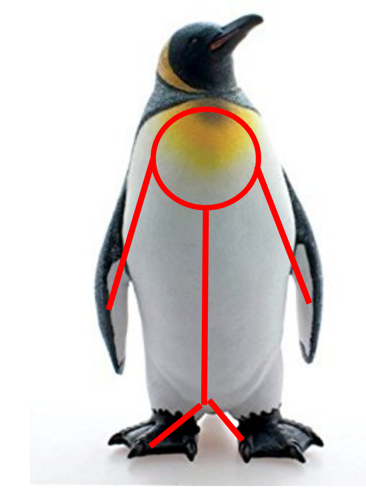
Mass reach (CKM-like): O(1)TeV → O(10) TeV !

CP Violation by New Physics

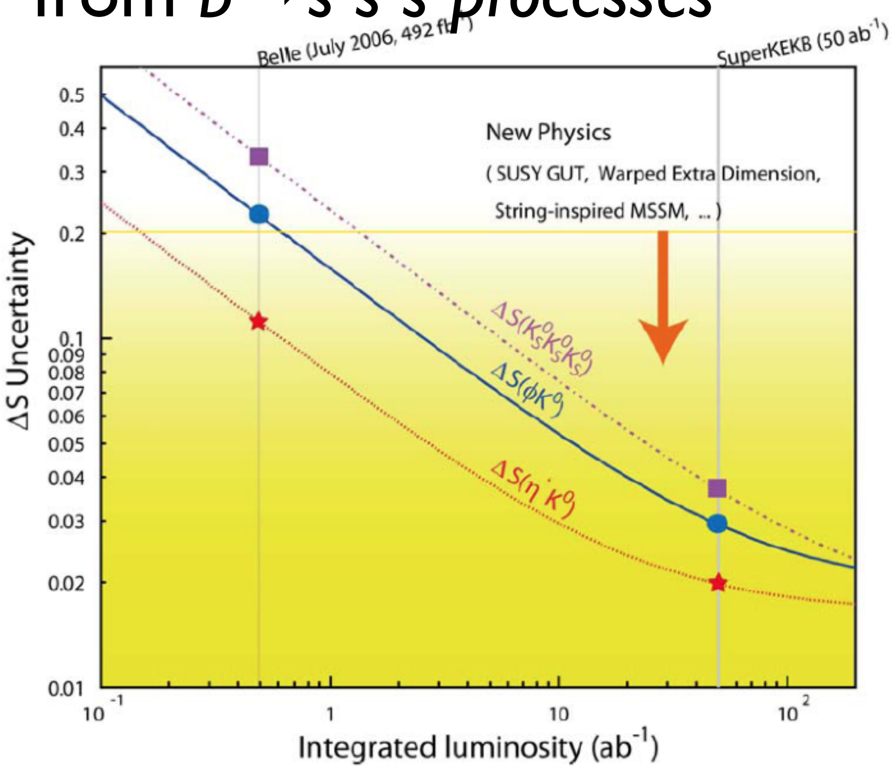
- Belle II provides precise time-dependent CP violation measurement for rare decays (Penguin decays) to test possible NP phase.

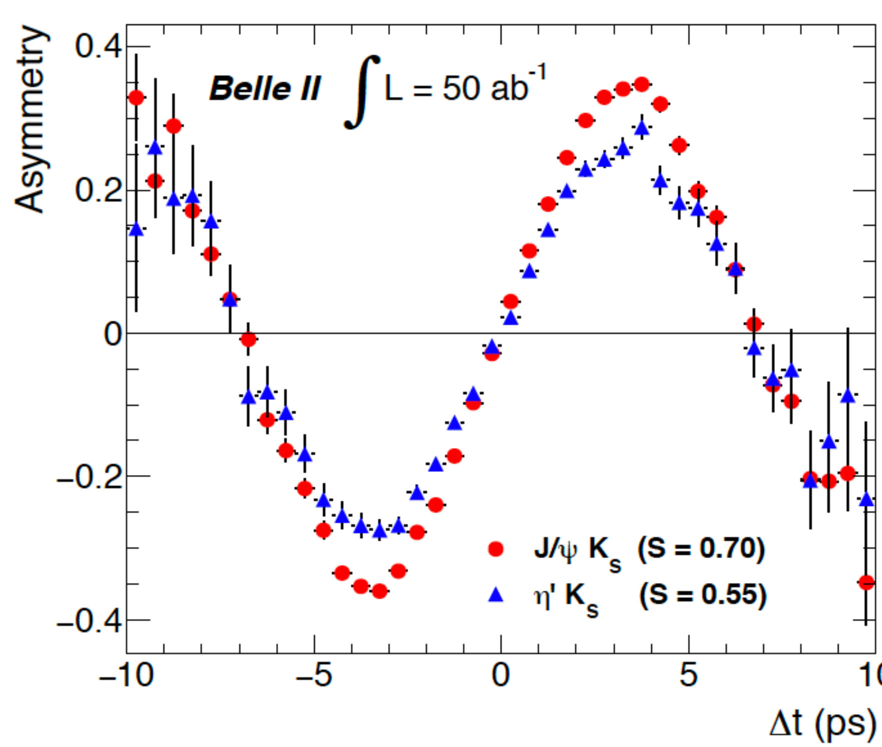


$$\sin 2\phi_1(B \to J/\psi K^0) = \sin 2\phi_1^{\rm eff}(B \to \eta' K^0)$$

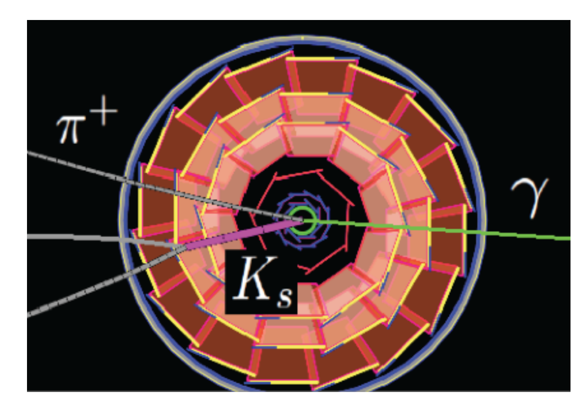


Belle II projection for $\sin 2\varphi_1^{\rm eff}$ from $b \to s\,\bar{s}\,s$ processes





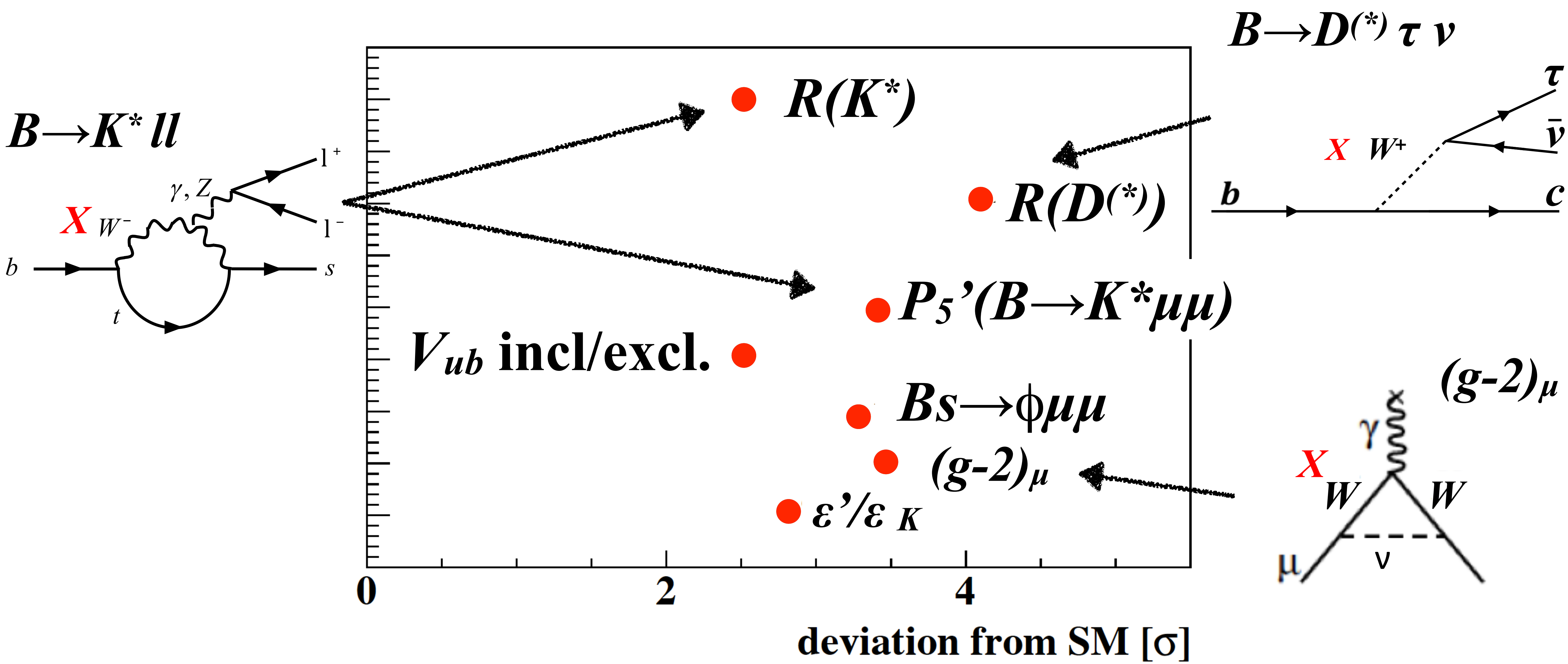
Improved performance w.r.t. Belle
- vertex resolution
- acceptance for Ks → ππ decay vertex



Lepton Non Universality

Observed deviation from SM

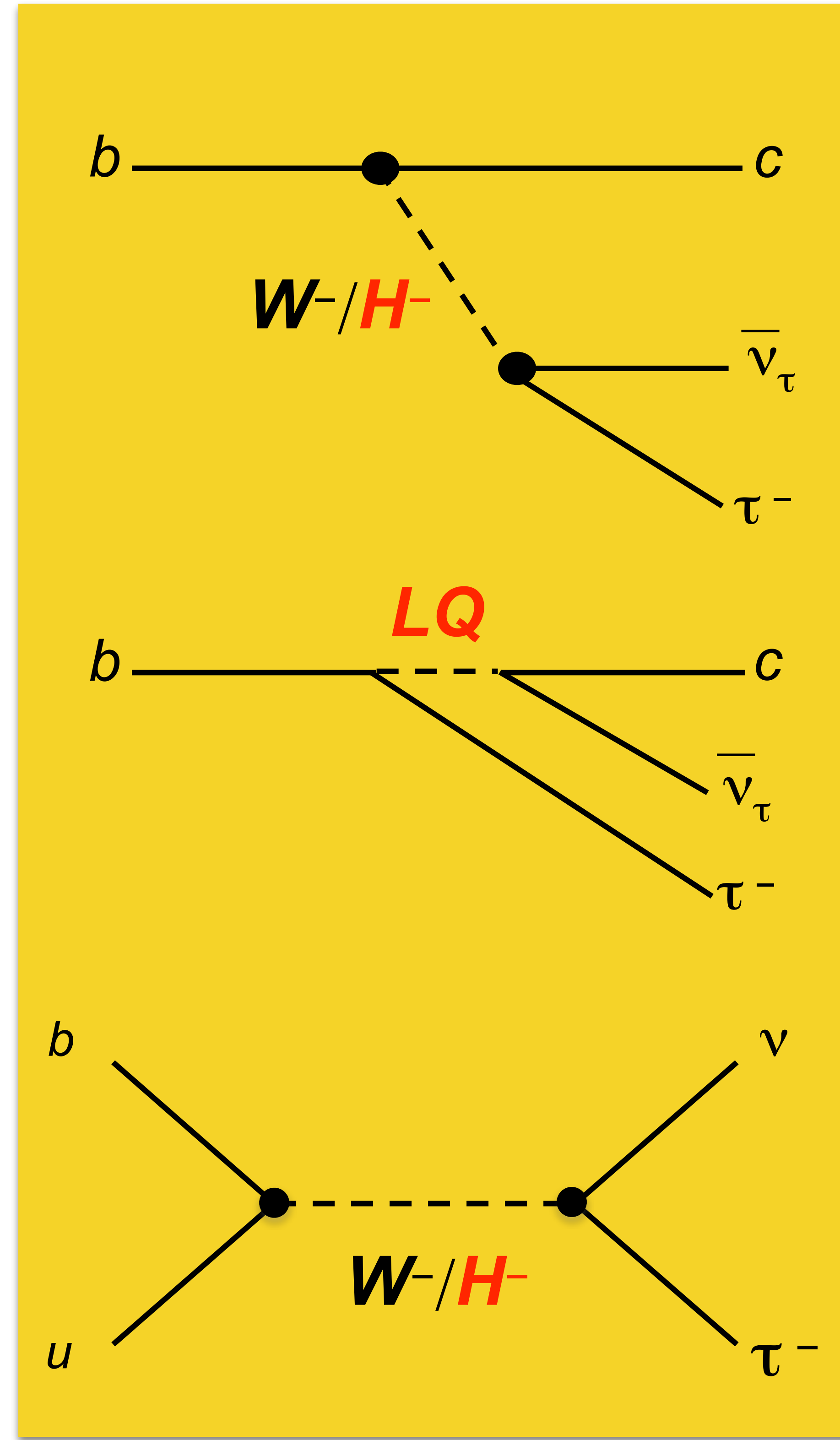
(as of Spring 2018)



It is important to test lepton universality precisely.

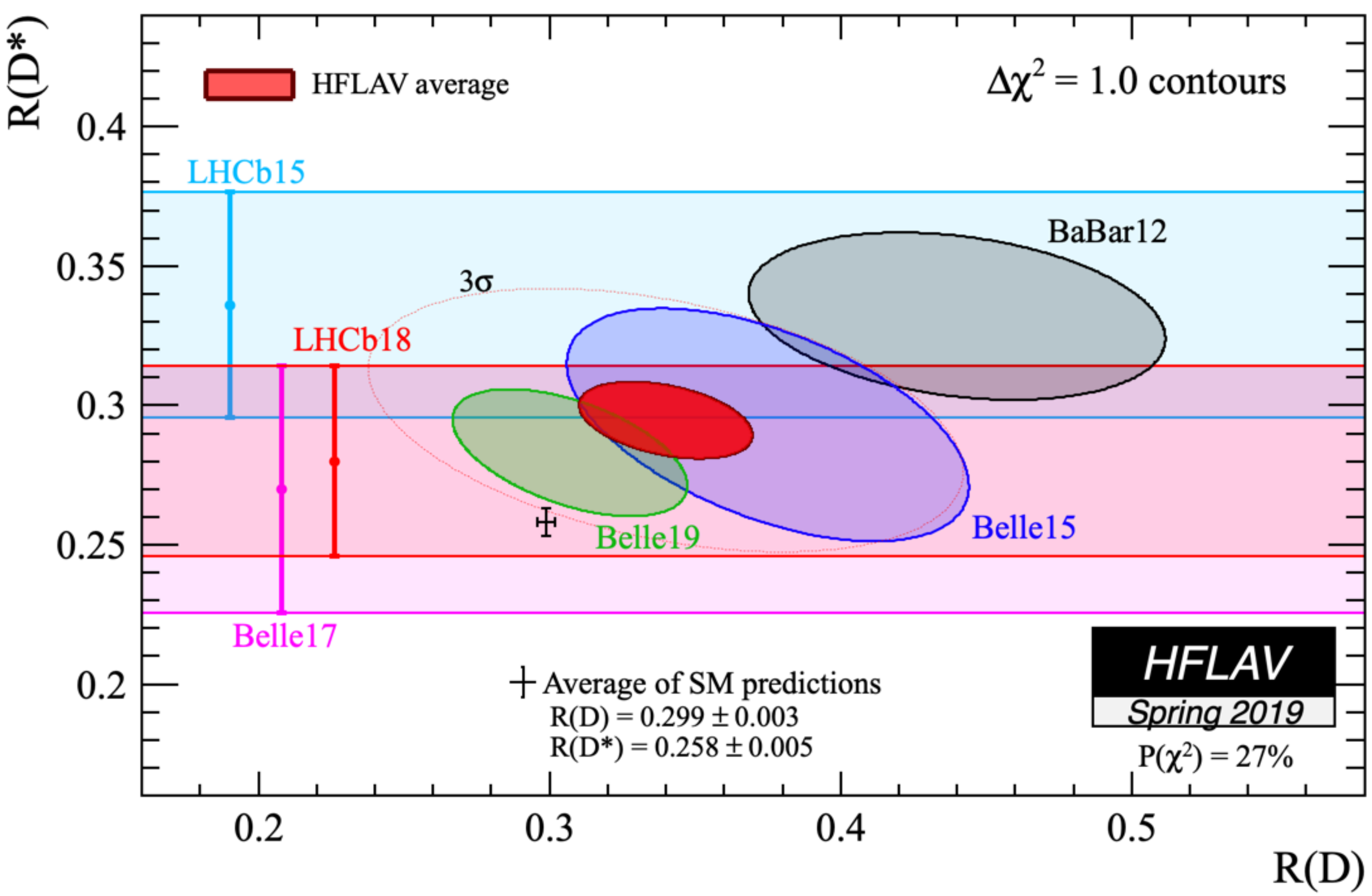
$B \to D^{(*)}\tau\nu$, $B \to \tau\nu$

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



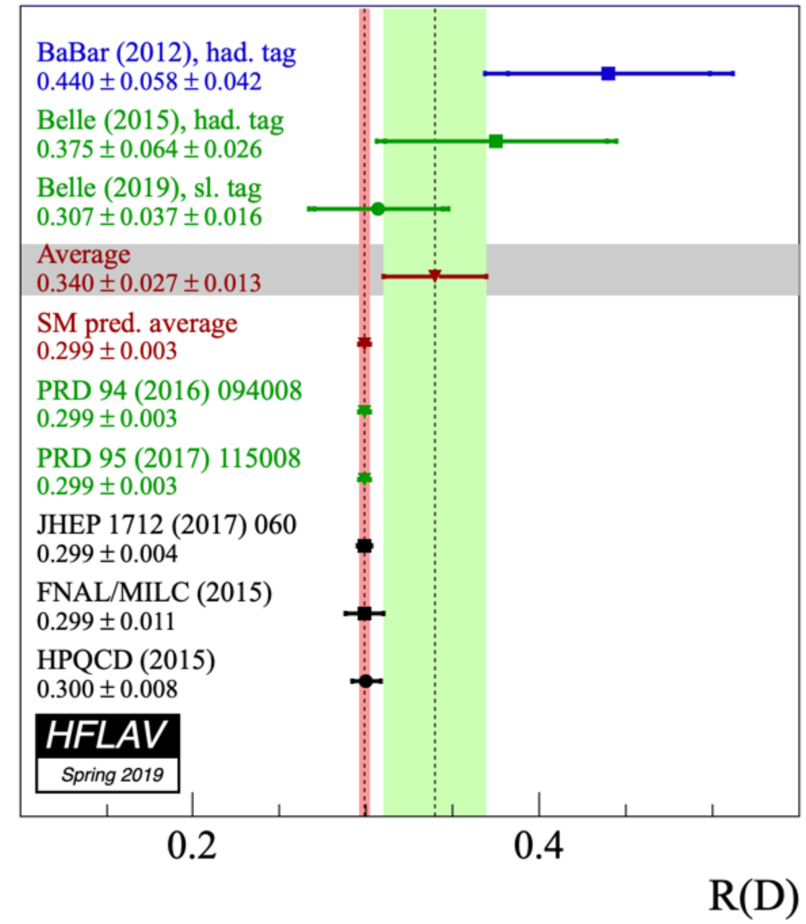
R(D), R(D*)

Spring 2019 update

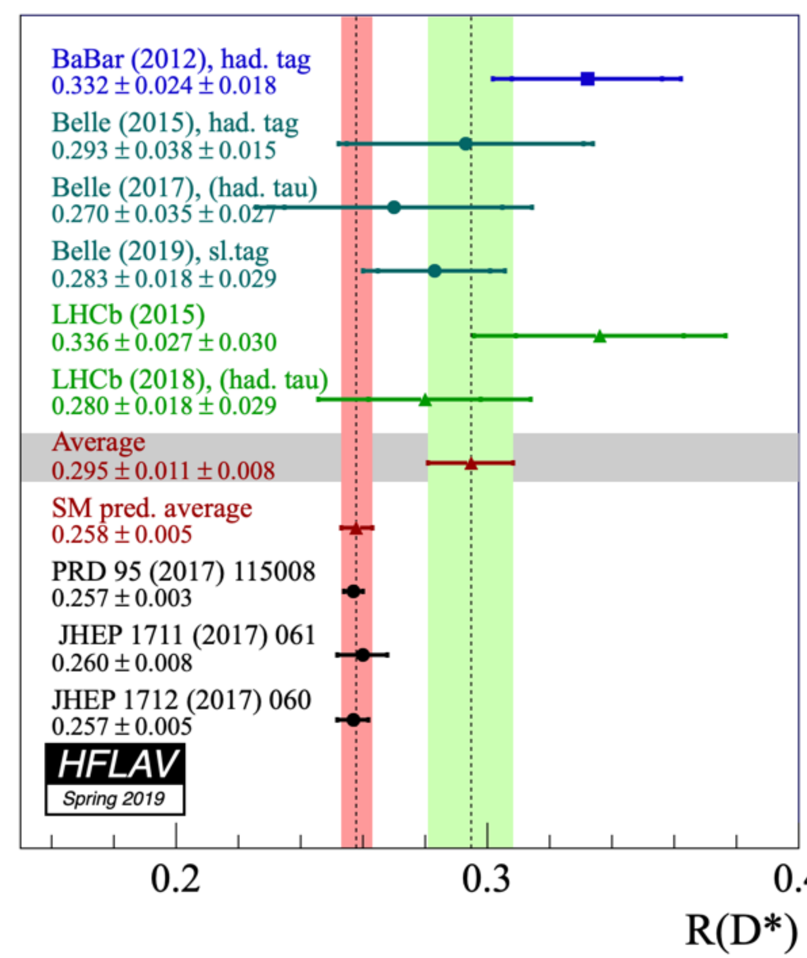


3.1σ deviation from SM

R(D)

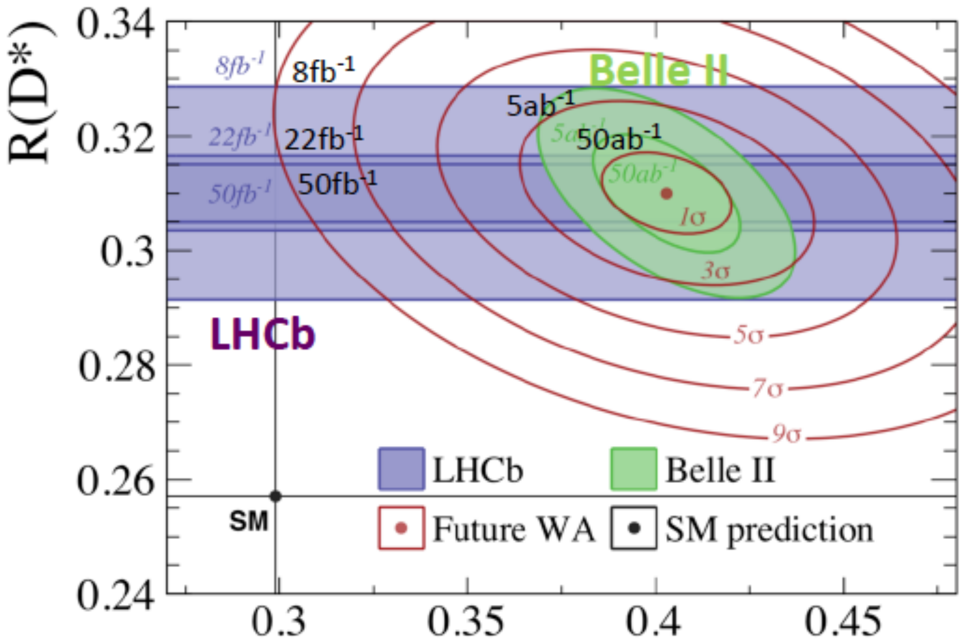


R(D*)

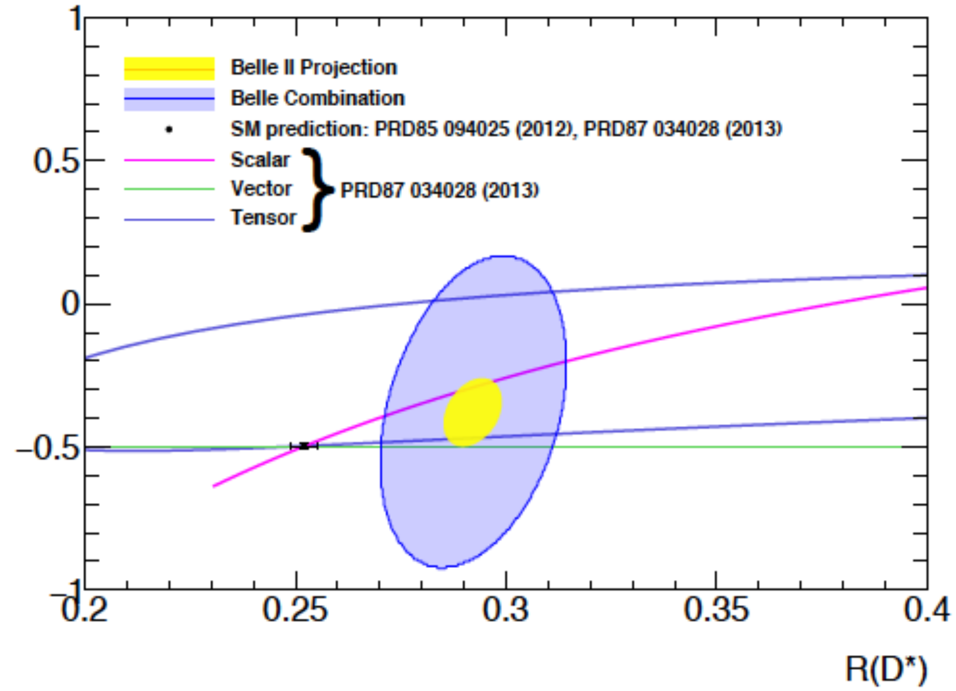


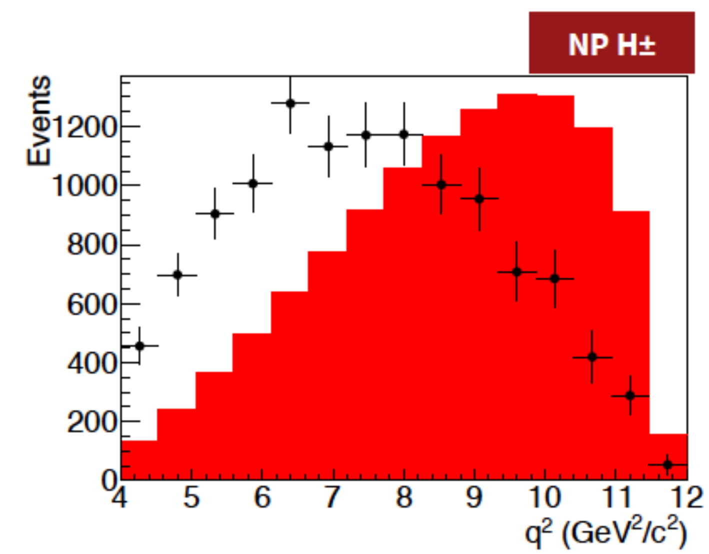
Belle II Projections

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



arXiv:1709.10308





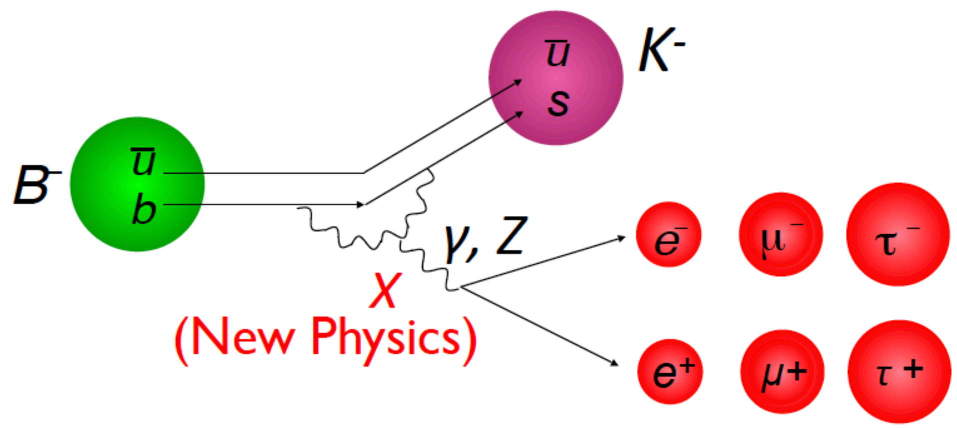
50 ab-1 projection of the subtracted q^2 spectrum in $B \to D^* \tau \nu$ (HT)

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle $0.7\ ab^{-1}$	14	6	16	6	3	7
Belle II $5\ ab^{-1}$	5	3	6	2	2	3
Belle II $50\ ab^{-1}$	2	3	3	1	2	2

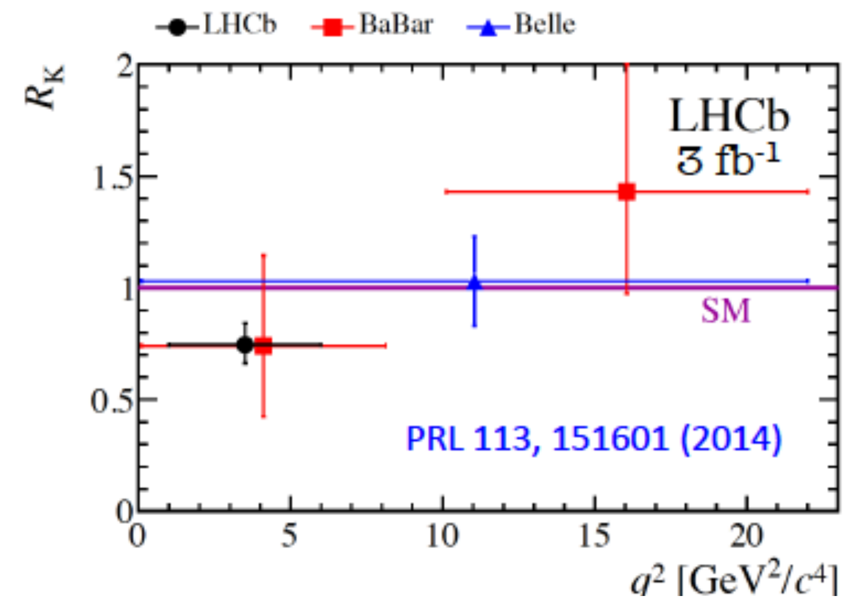
Will soon hit the systematic limit !

- More observables (distributions) !
  - $P(\tau)$, $P(D^*)$
  - $d\Gamma/dq^2$, $d\Gamma/dp_{D(*)}$, $d\Gamma/dp_e$, …
- More modes !
  - $B \to \pi \tau \nu$,
  - $B_S \to D_S \tau \nu$ (at 5S runs) , …

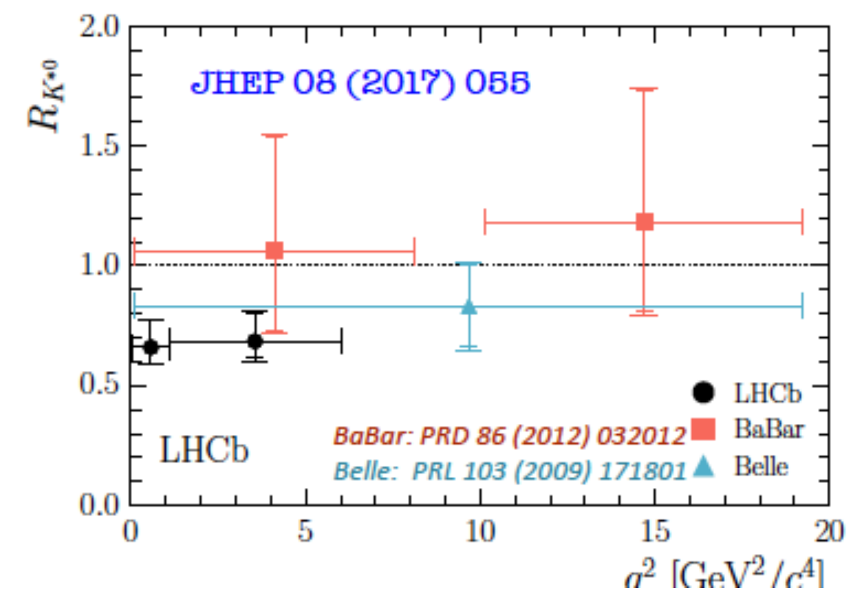
Lepton non-Universality (loop)



Tension in existing data …



R_K



$R_{K^{*0}}$

$$R(K) = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$

$$= 0.745^{+0.09}_{-0.07} \pm 0.036 (1 < q^2 < 6\mathrm{GeV}^2)$$

2.6 σ from SM

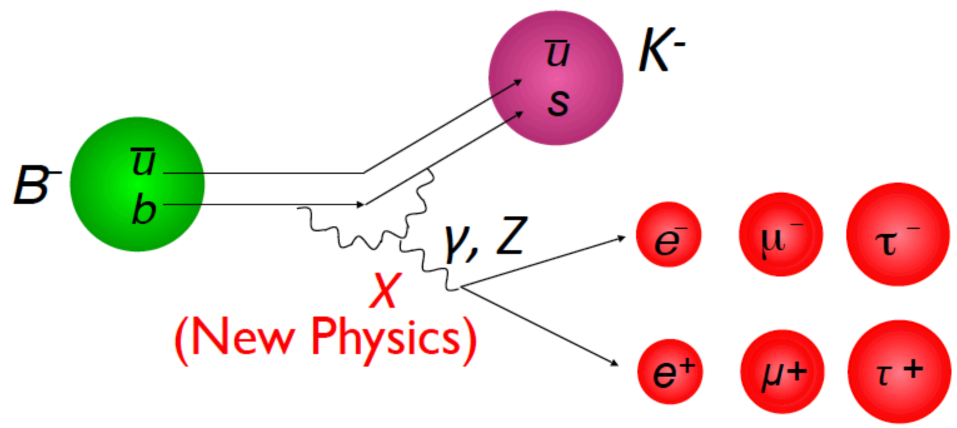
$$R(K^*) = \frac{Br(B \to K^*\mu\mu)}{Br(B \to K^*ee)}$$

$$= 0.66^{+0.11}_{-0.07} \pm 0.03 (0.045 < q^2 < 1.1\mathrm{GeV}^2)$$

$$= 0.69^{+0.11}_{-0.07} \pm 0.05 (1.1 < q^2 < 6\mathrm{GeV}^2)$$

2.1-2.5 σ from SM

Lepton non-Universality (loop)



$$R(K) = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$

$$= R_K = 0.846\ ^{+0.060}_{-0.054}\ (\text{stat})\ ^{+0.014}_{-0.016}\ (\text{syst})$$

update in Mar. 2019
2.5 σ from SM

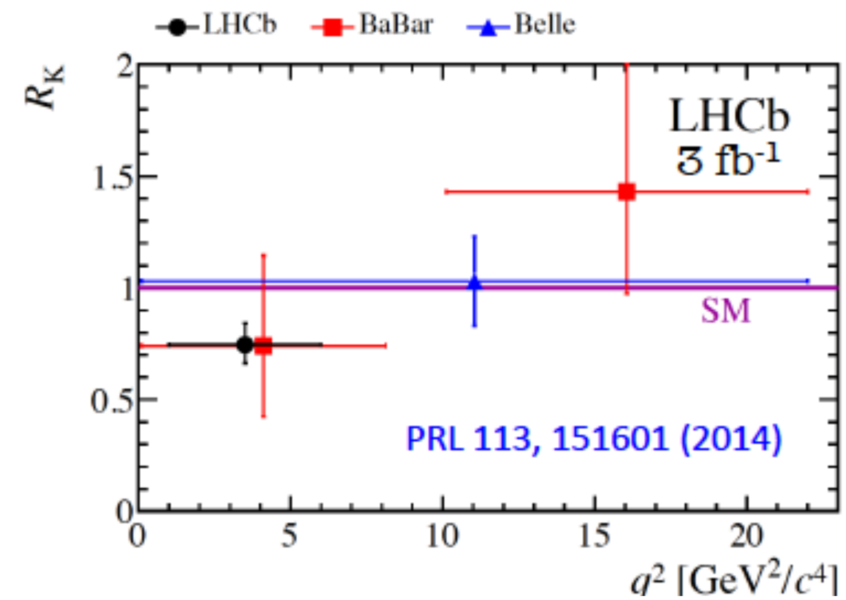
$$R(K^*) = \frac{Br(B \to K^*\mu\mu)}{Br(B \to K^*ee)}$$

$$= 0.66^{+0.11}_{-0.07} \pm 0.03 (0.045 < q^2 < 1.1 \text{GeV}^2)$$

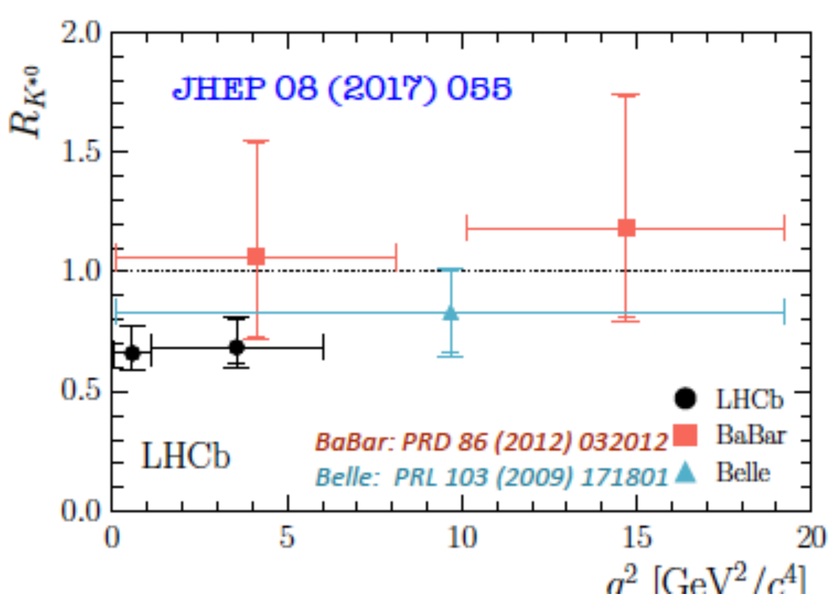
$$= 0.69^{+0.11}_{-0.07} \pm 0.05 (1.1 < q^2 < 6 \text{GeV}^2)$$

2.1-2.5 σ from SM

Tension in existing data …

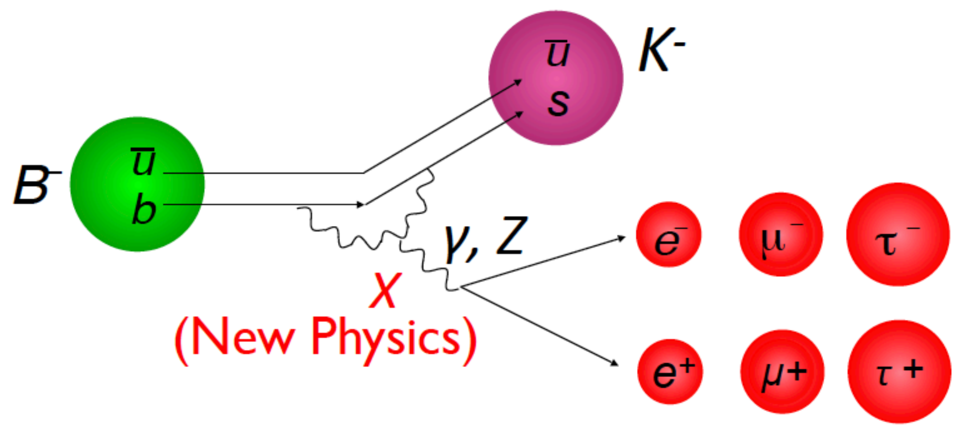


R_K

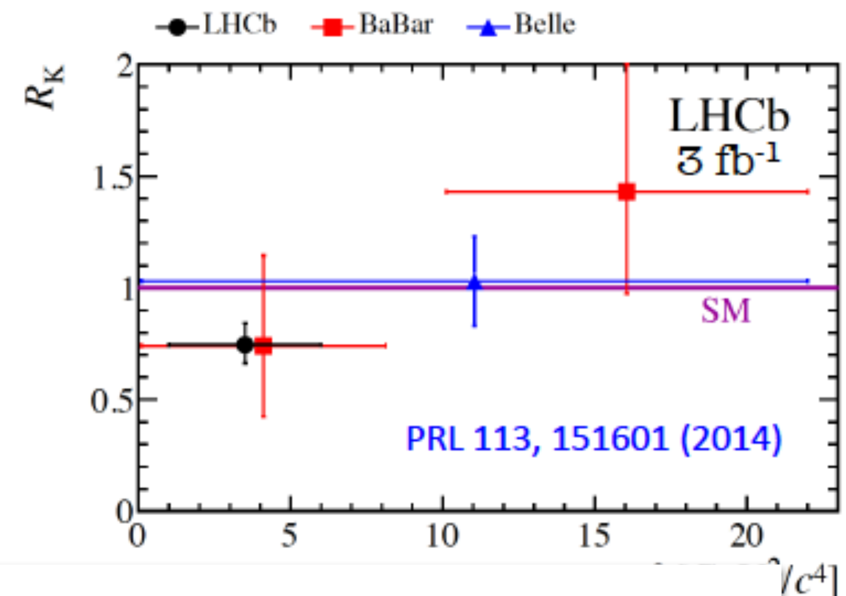


$R_{K^{*0}}$

Lepton non-Universality (loop)



Tension in existing data …



R_K

$$R(K) = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$

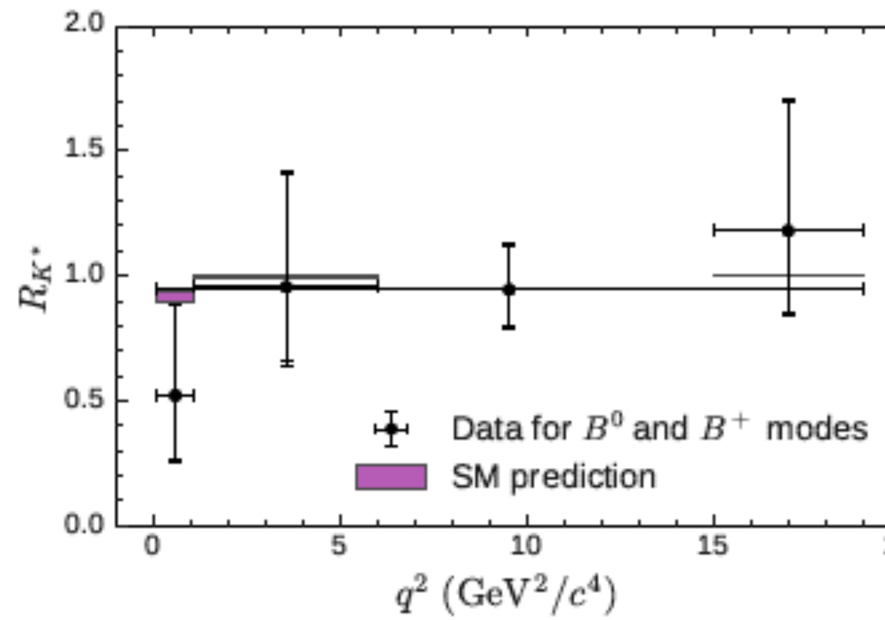
Recent result from Belle
arXiv: 1904.02440v2

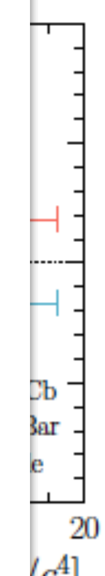
R_{K^*}

$R(K$

TABLE II. Result for R_{K^*}, $R_{K^{*0}}$ and $R_{K^{*+}}$. The first uncertainty is statistical and the second is systematic.

q^2 in GeV$^2/c^4$	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$





$R_{K^{*0}}$

Precision at Belle II : ~3% at 50ab^{-1}.

$b \to s\, l\, l$ inclusive at Belle II

Belle II can provide data from inclusive measurements (less theory ambiguity)

- sum of exclusive, as done by Belle

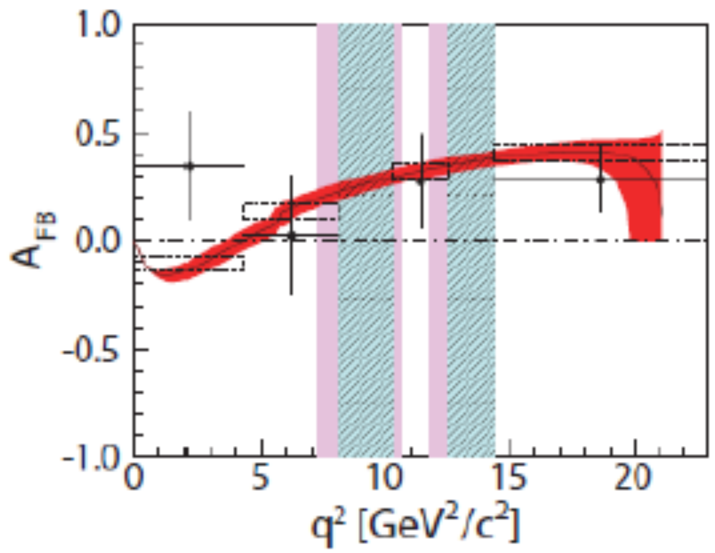
[Belle, arXiv:1402.7134]

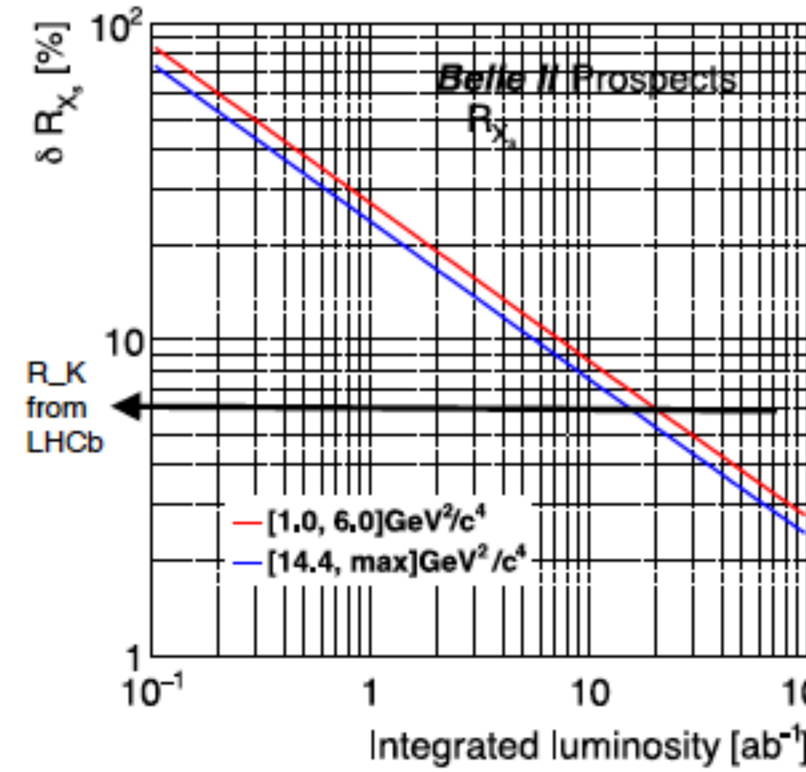
10 modes, $M(X_s) < 2.0$ GeV

50% of total inclusive rate

(goal here was A_{FB}, flavor of B needed)

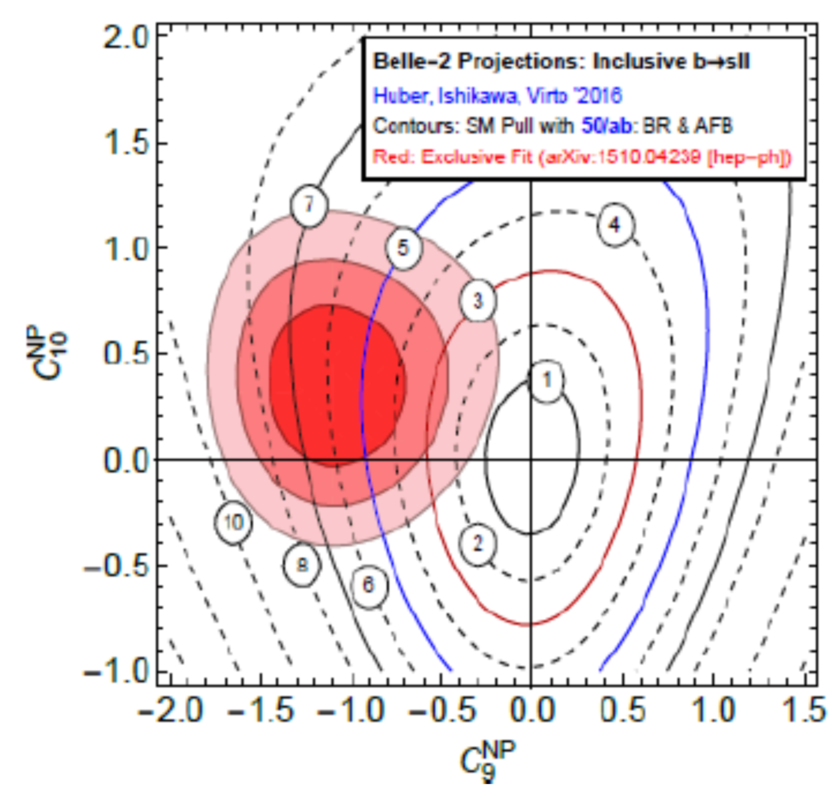
$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$





1808.10567

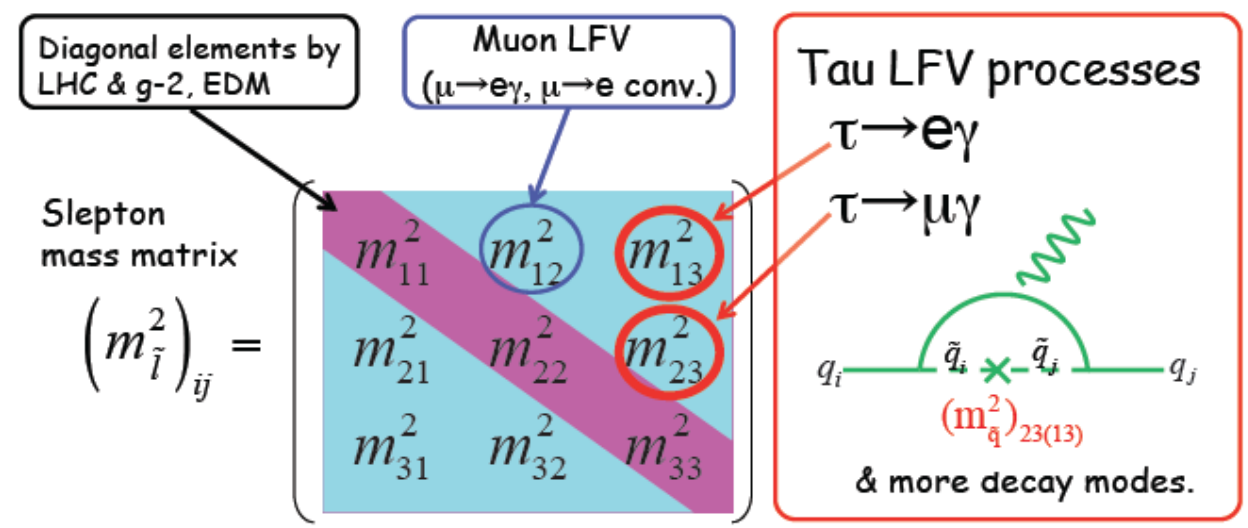
Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7 %	3.1 %
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9 %	2.6 %
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	21%	8.1 %	2.6 %
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[1.0, 3.5]$ GeV^2)	52%	19%	6.1%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[3.5, 6.0]$ GeV^2)	42%	16%	5.2%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ (> 14.4 GeV^2)	38%	15%	4.8%

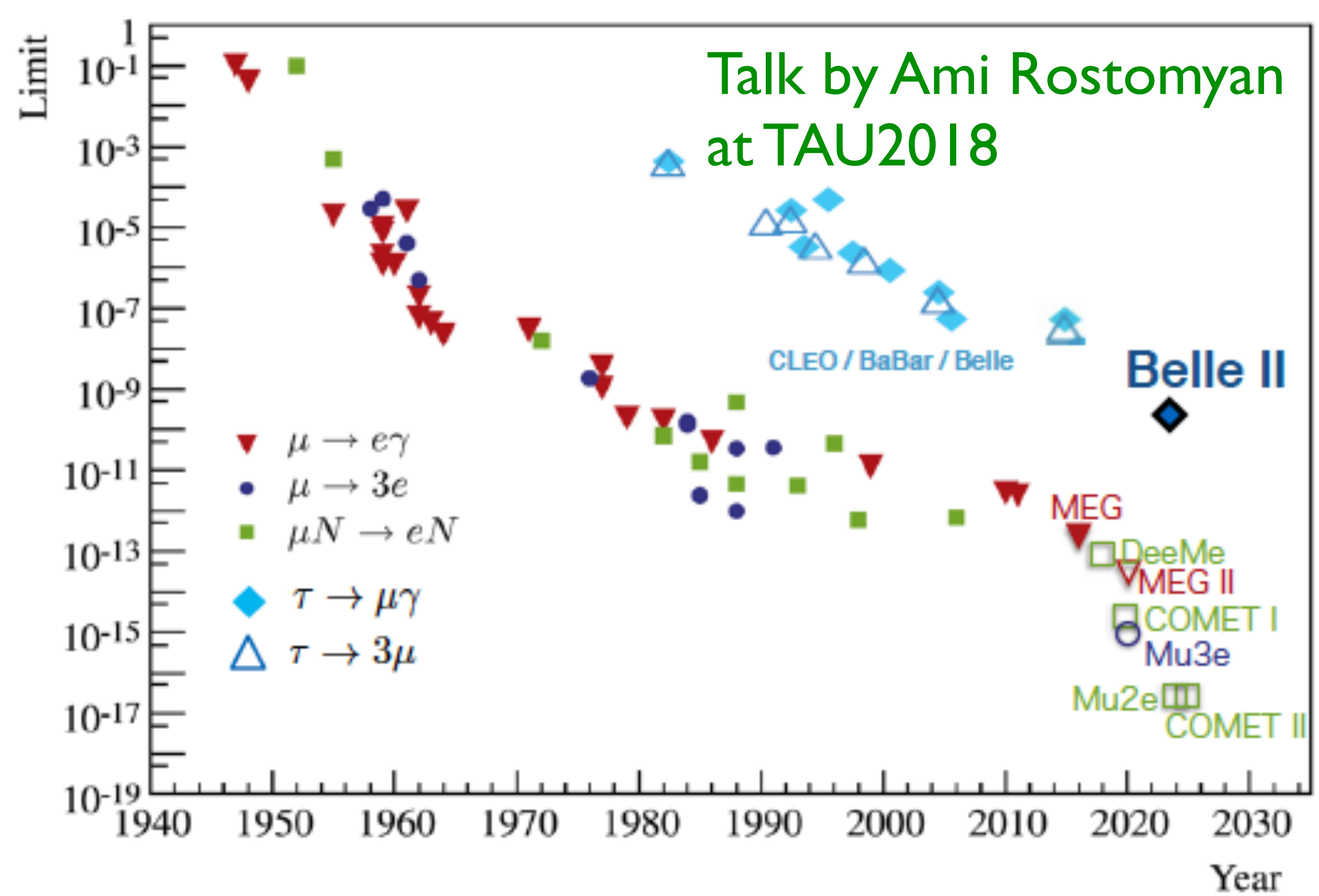


LFV τ Decays

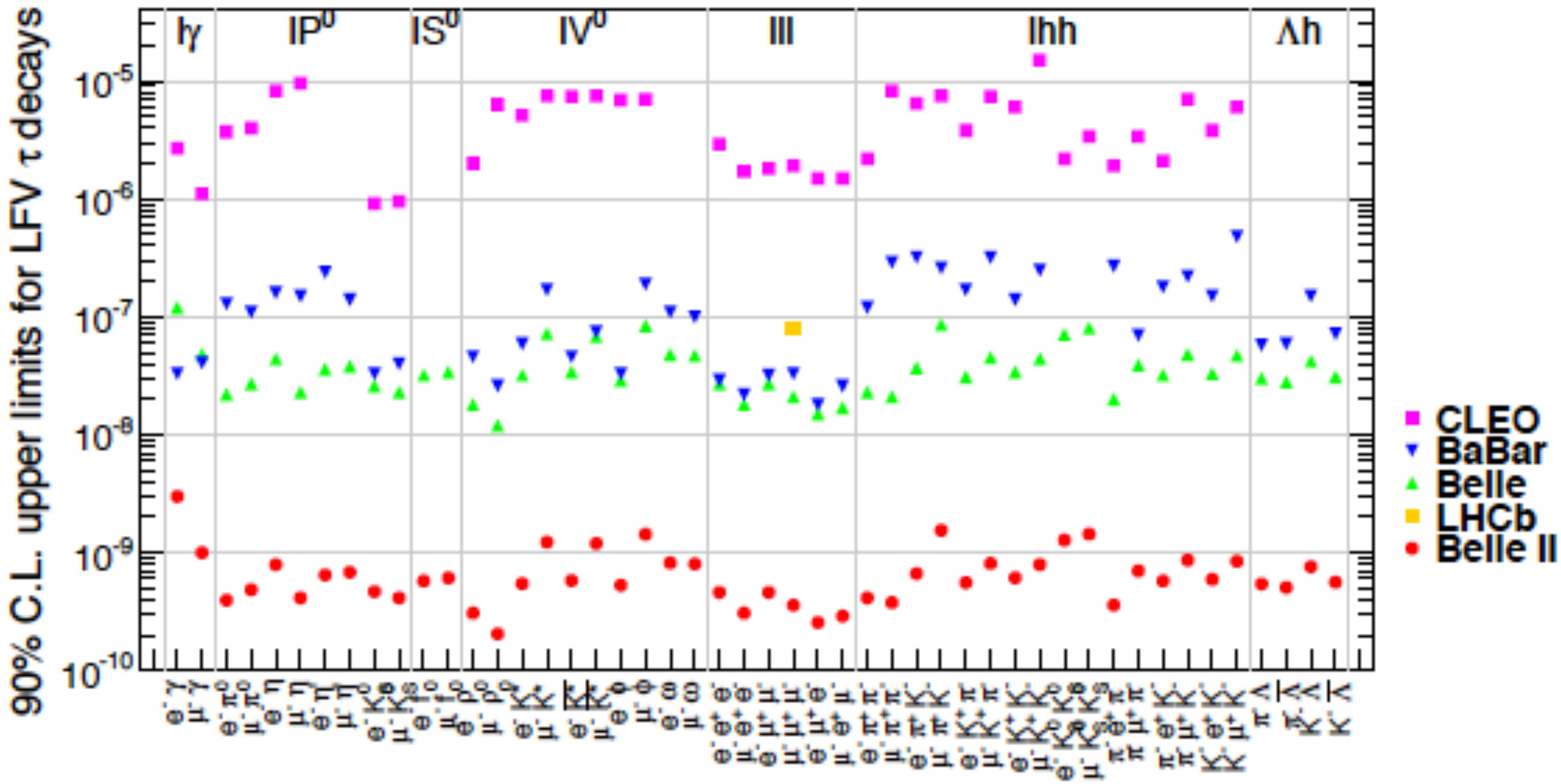
SuperKEKB provides $N(\tau^+\tau^-) \sim N(B\bar{B})$

- Lepton flavor violated in the neutrino sector.
- Some NP models predict LFV to be observed in 'near' future experiments.
- τ is the heaviest charged lepton, sensitive to NP.
- τ LFV complementary to muon programs
  - μ→eγ, eee
  - μ→e conversion





Tau LFV prospect at Belle II

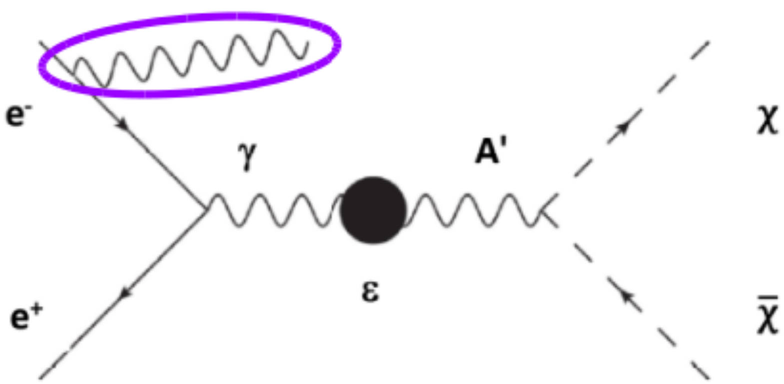


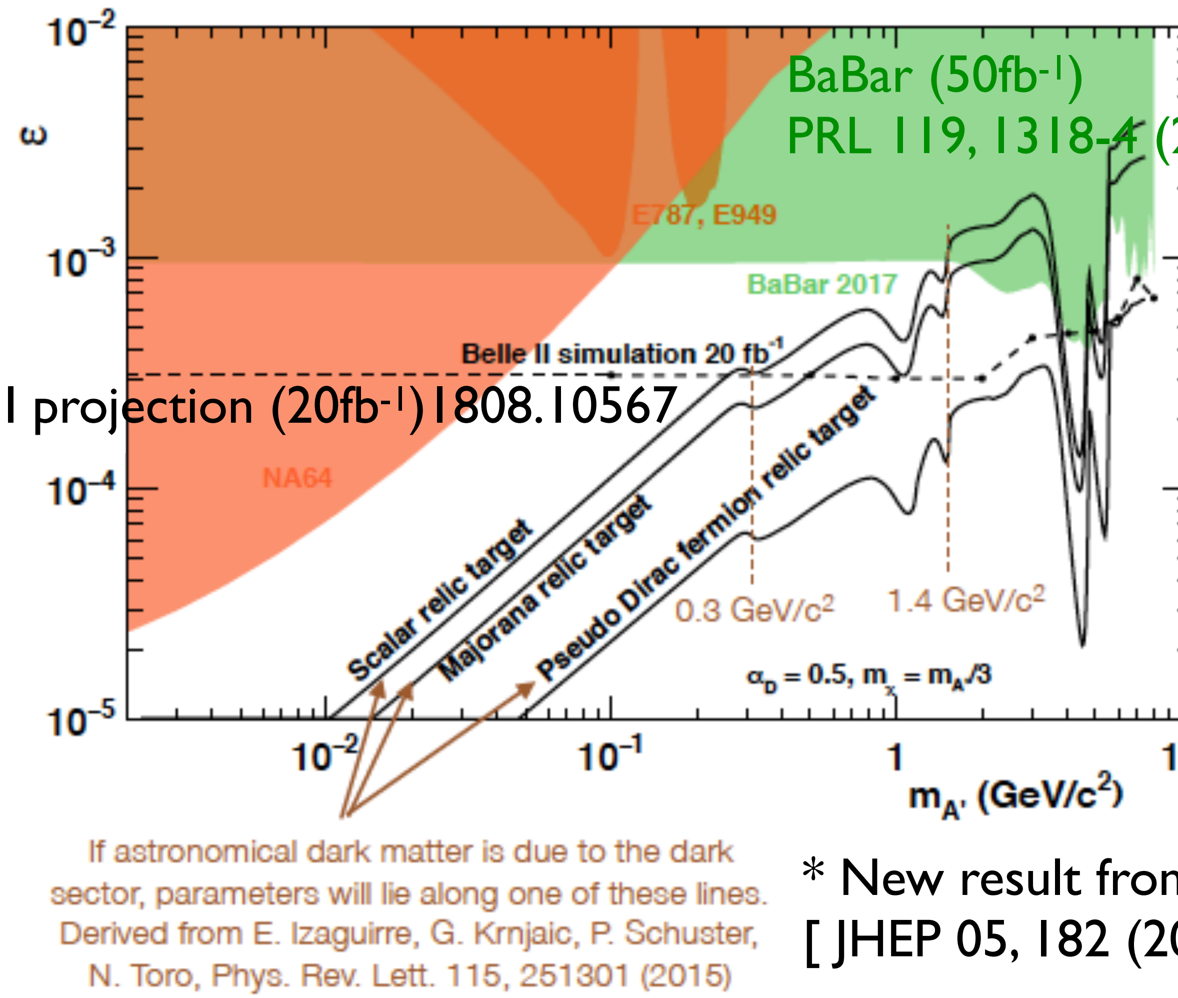
- Belle II will push down the current bounds further by more than an order of magnitude.
- Trying to increase sensitivity by improved analysis technique.

Dark Sector Physics

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

- Dark photon → invisible
  - A single, monochromatic high energy ISR photon. $E^*_\gamma = E^*_{\mathrm{beam}} - \frac{m^2_{A'}}{4E^*_{\mathrm{beam}}}$
  - Background from e+e-→γγ(γ), e+e-γ→γ(γ) due to finite acceptance & imperfect detector
  - Dedicated single photon trigger.



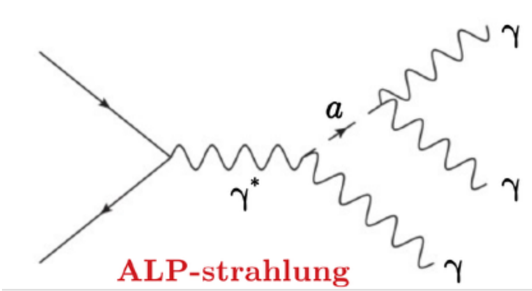


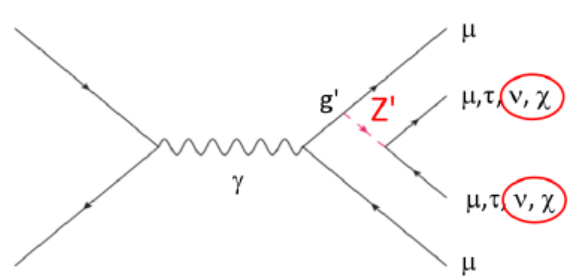
BaBar (50fb⁻¹) PRL 119, 131804 (2017)

Belle II projection (20fb⁻¹) 1808.10567

- Anticipated results also for

Axion Like Particle   Z' → invisible

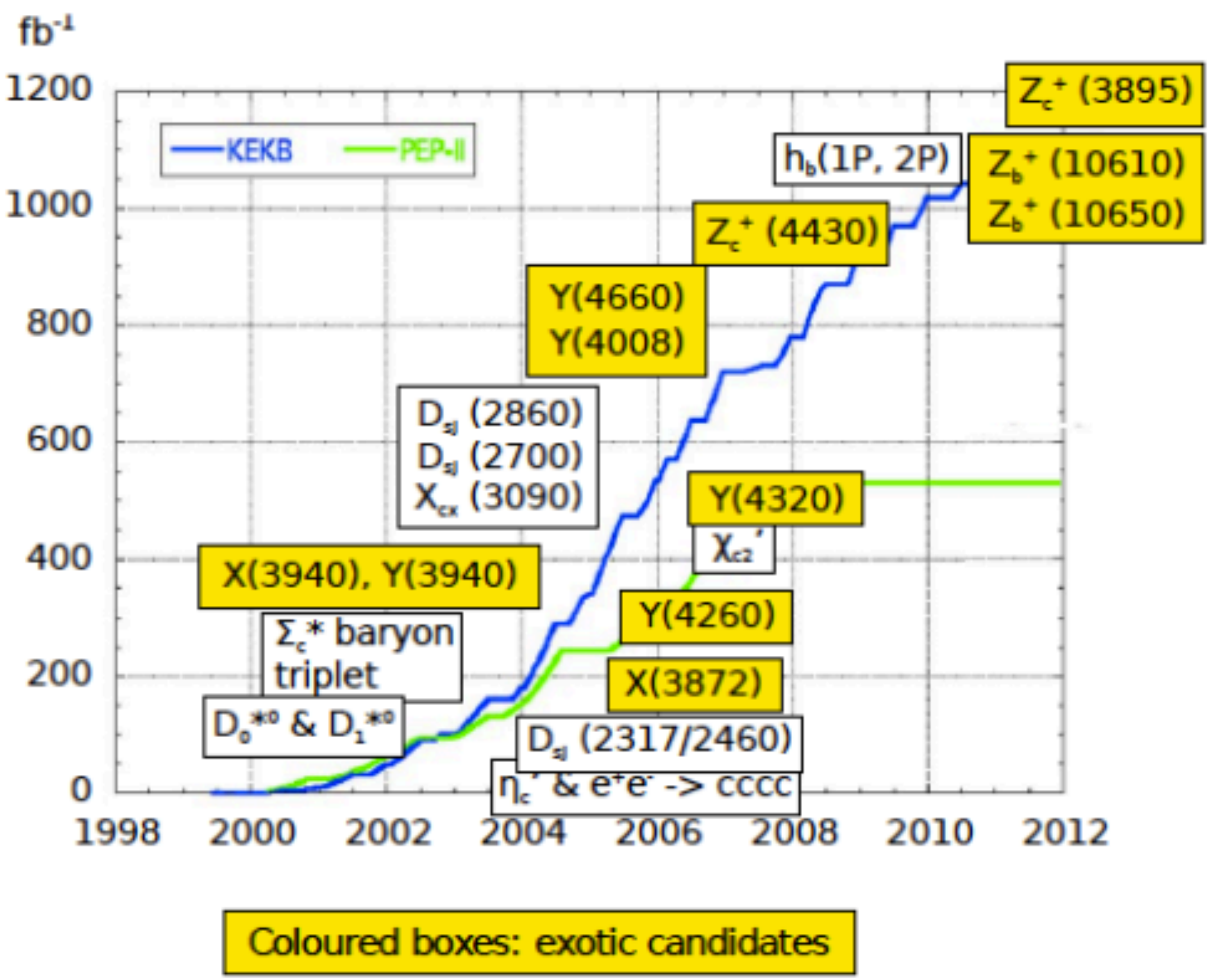




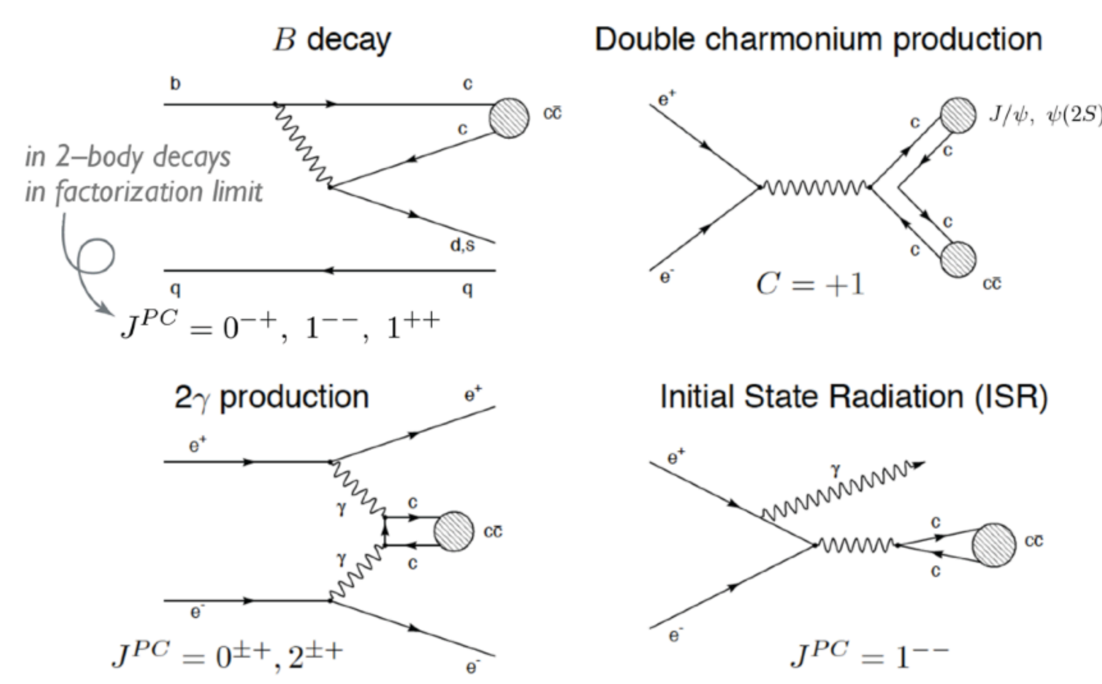
* New result from NA62 [JHEP 05, 182 (2019)]

Hadron Spectroscopy

- In 2003, Belle observed X(3872) in B decays.
- Following discoveries of many exotic states (XYZ) at B factories and hadron colliders have brought new era of hadron spectroscopy.
  - \+ Recent discoveries of P_c at LHCb.



Production channels at B factories

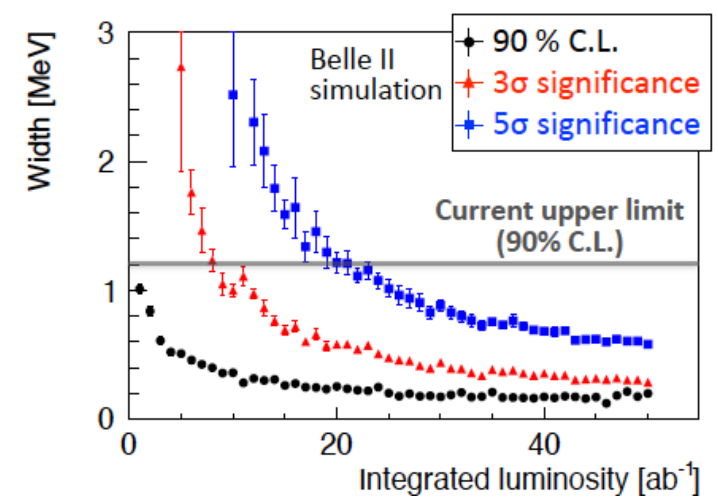


Hadron Spectroscopy

- 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

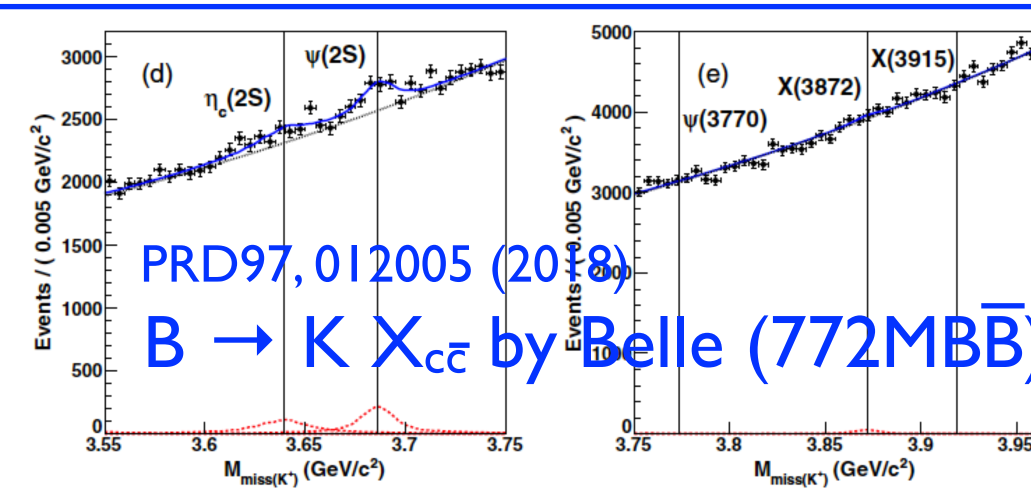
    e.x.: X(3872) width

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



$X \to D^0 D^0 \pi^0$
Belle II MC
(H. Hirata, FPCP2019)

- Variety of approaches
  - B decays
  - ISR → study XYZ at threshold
    - $>1 fb^{-1}/10MeV$ at $E_{cm} \sim 4GeV$
  - Recoil mass → measure absolute branching fraction
  - b sector by running on Υ(5S) …



PRD97, 012005 (2018)

$B \to K X_{c\bar{c}}$ by Belle (772M$B\bar{B}$)

Br[B→KX(3872)] can be measured at Belle II

Also spectroscopies of non exotic quarkonium and baryons.

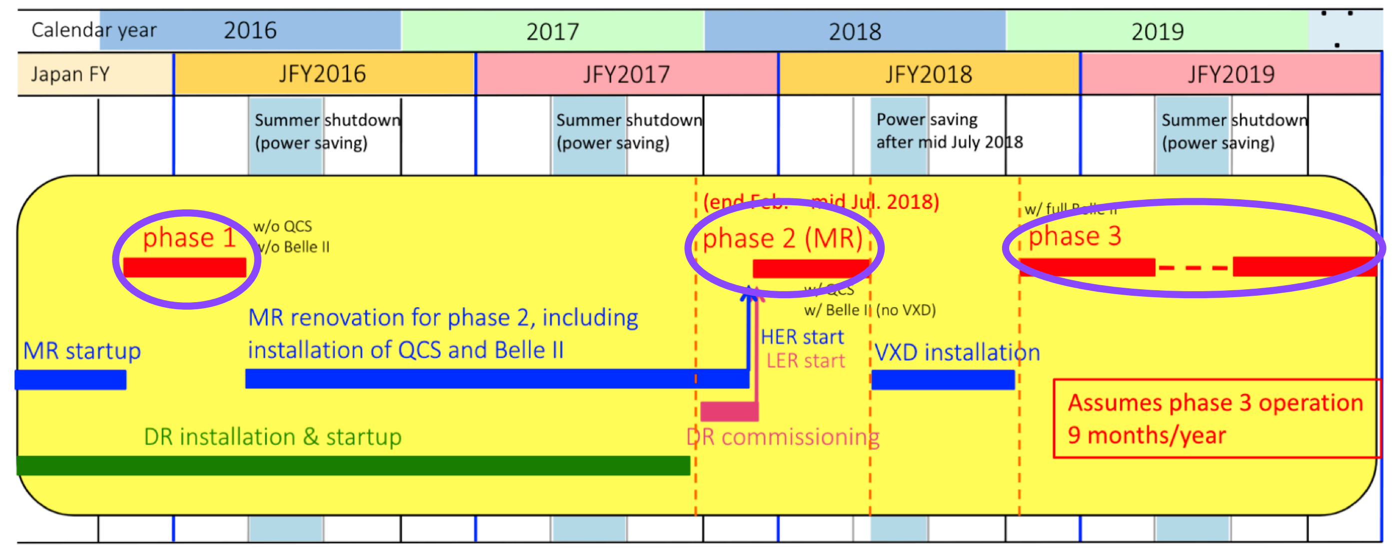
SuperKEKB/Belle II Plan

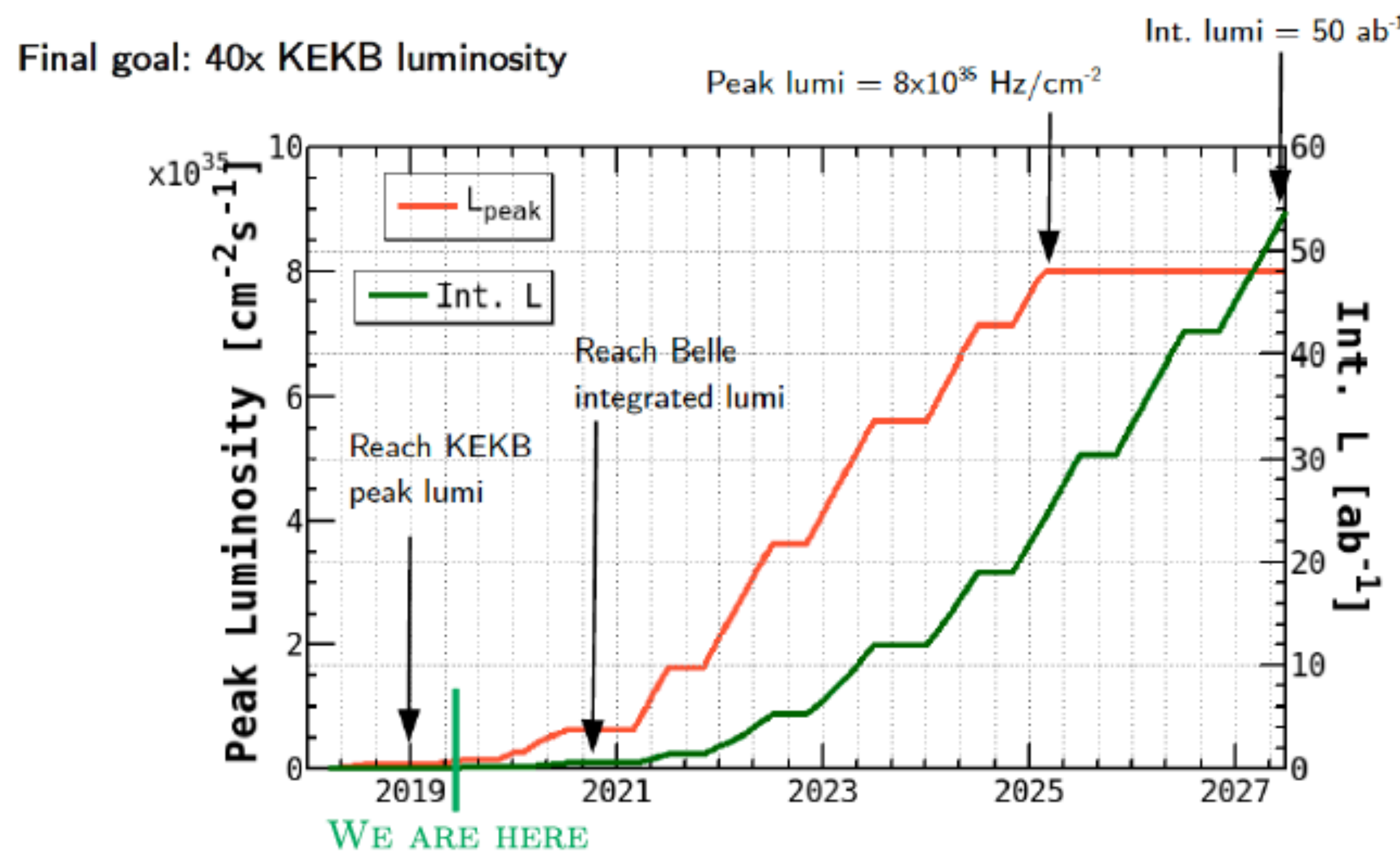
Phase 1 (w/o QCS/Belle II)
- Accelerator basic tuning with single beams

Phase 2 (w/ QCS/Belle II but w/o VXD)
- Verification of nano-beam scheme
- Understand beam background

Phase 3 (w/ full detector)
- $1 ab^{-1}$ after 1 year
- $5 ab^{-1}$ by ~2022
- $50 ab^{-1}$ by ~2027

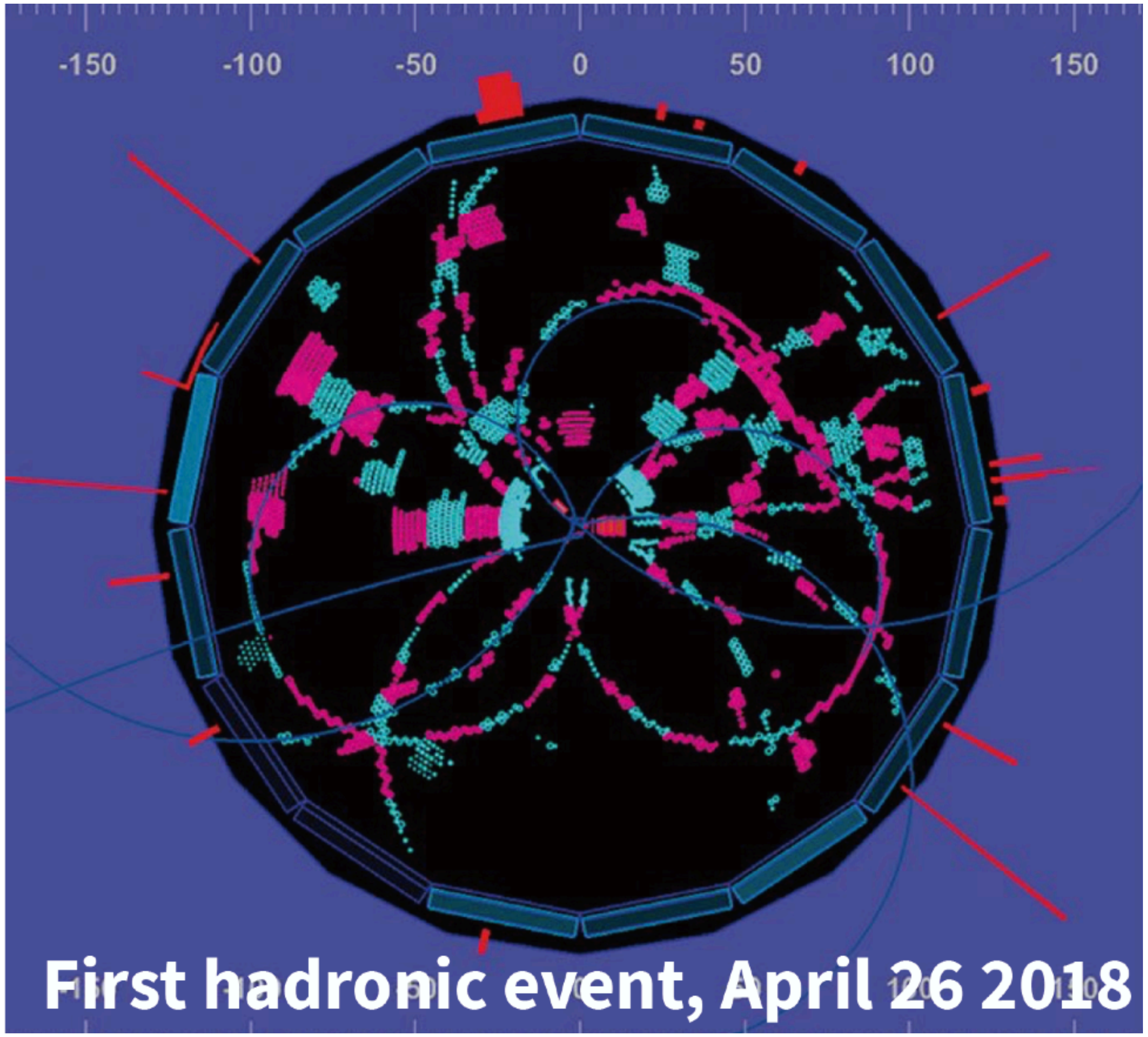
Global Schedule

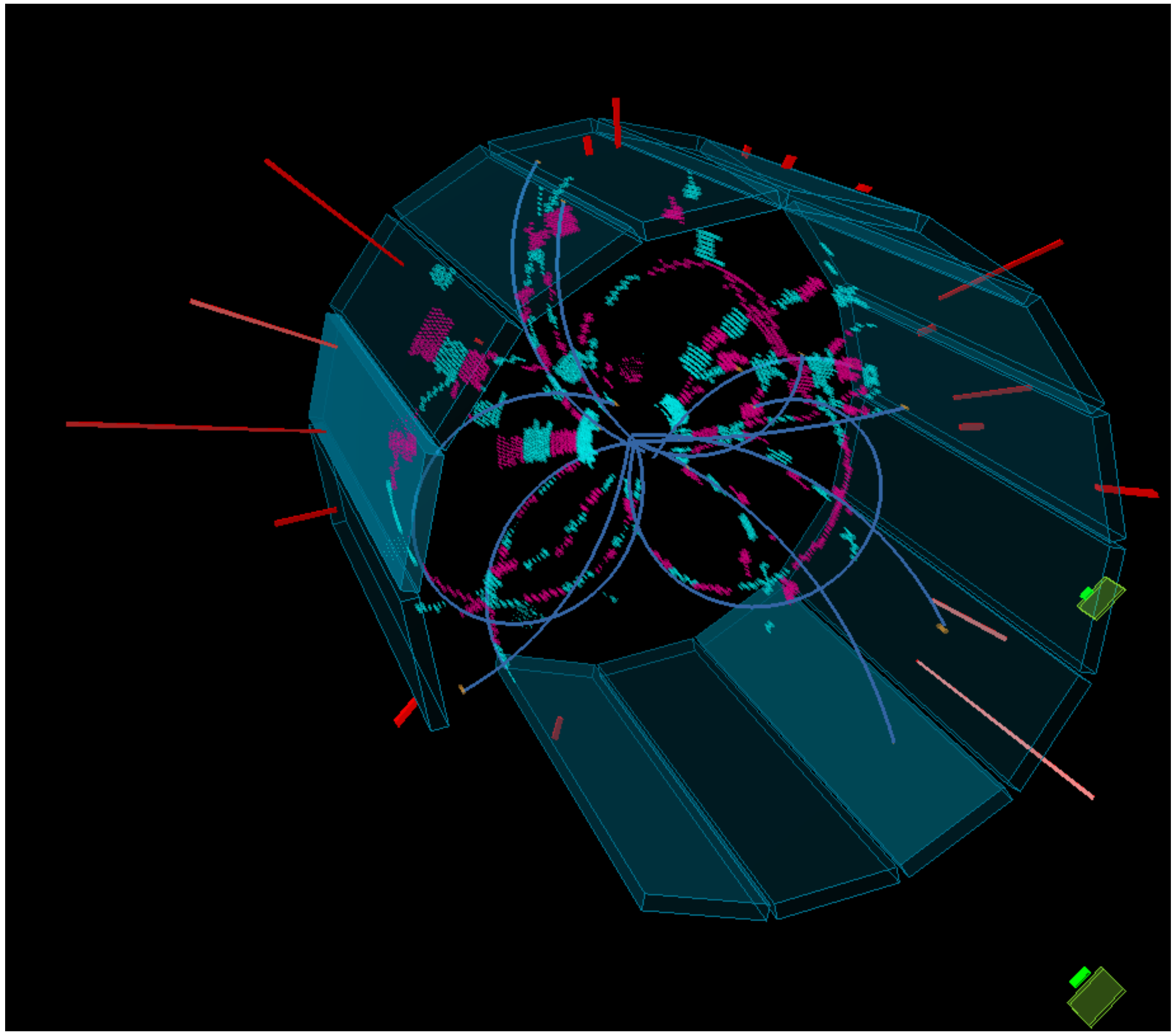




First Collision !

0:38, April 26, 2018





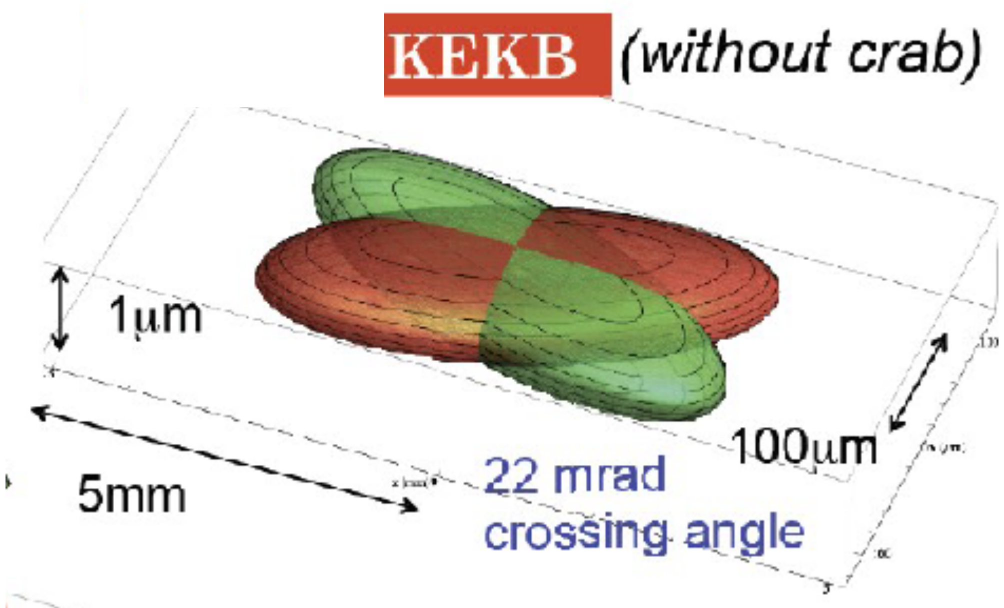
First Collision !

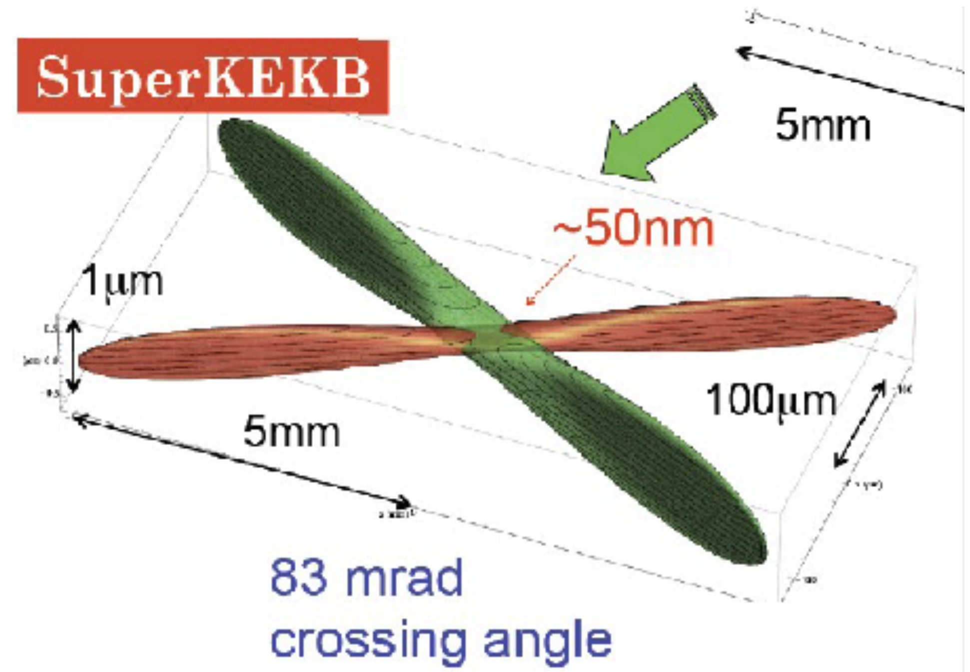
0:38, April 26, 2018

First Collision !

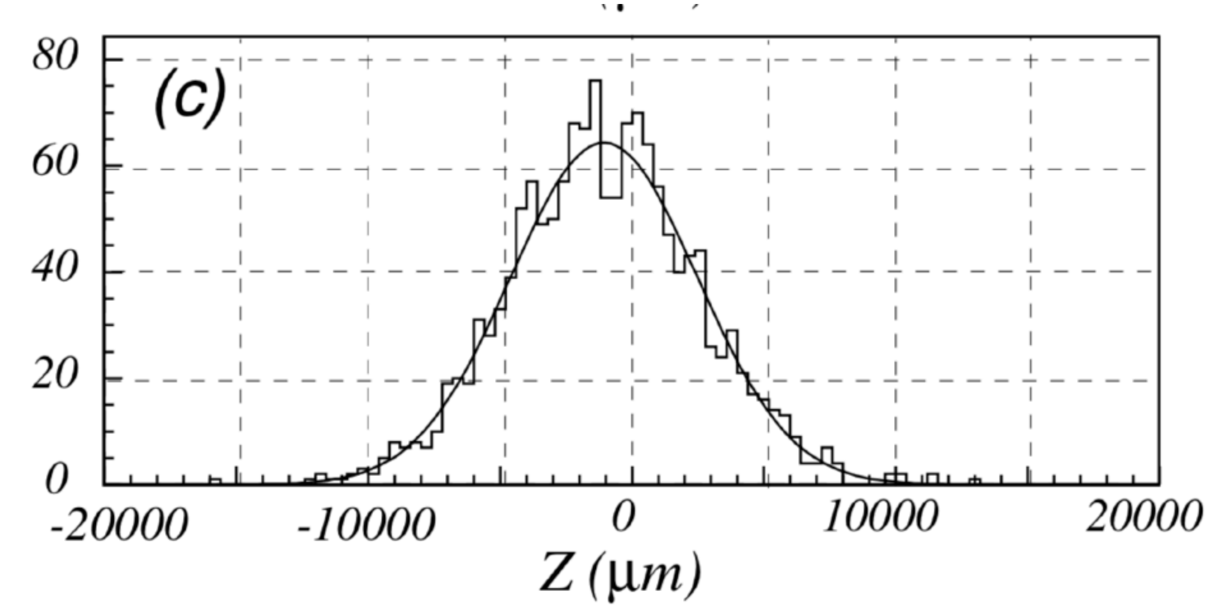
0:38, April 26, 2018

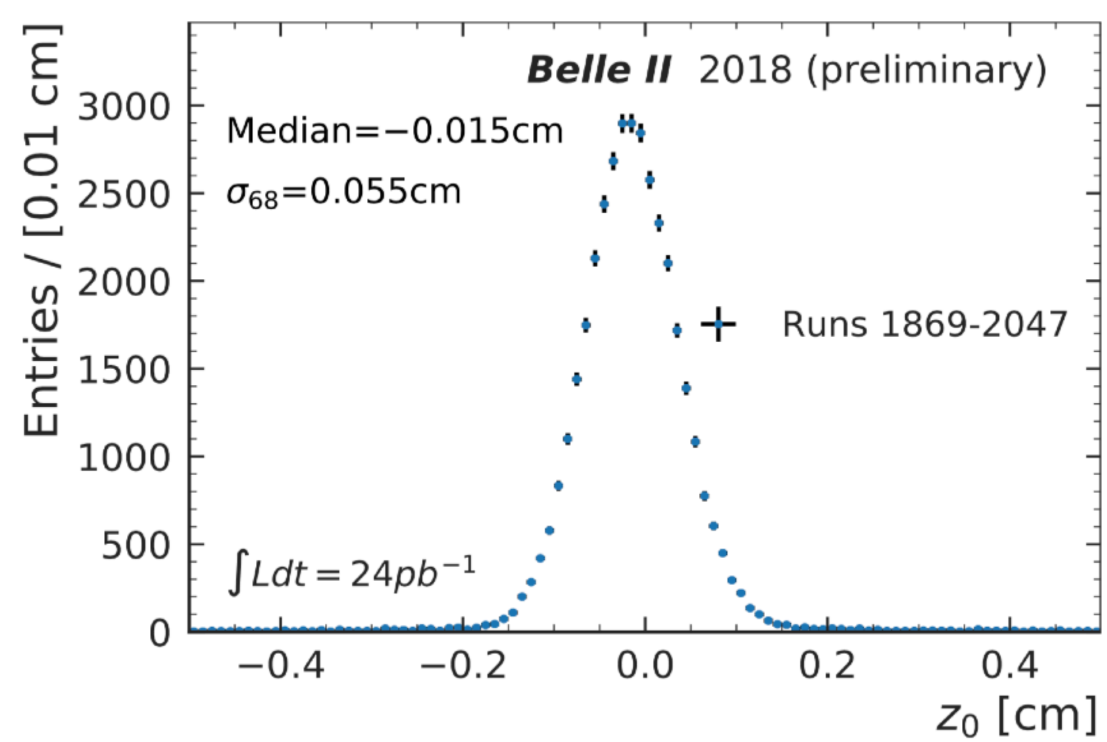
Collision with Nano-Beam





Belle case 1999 data



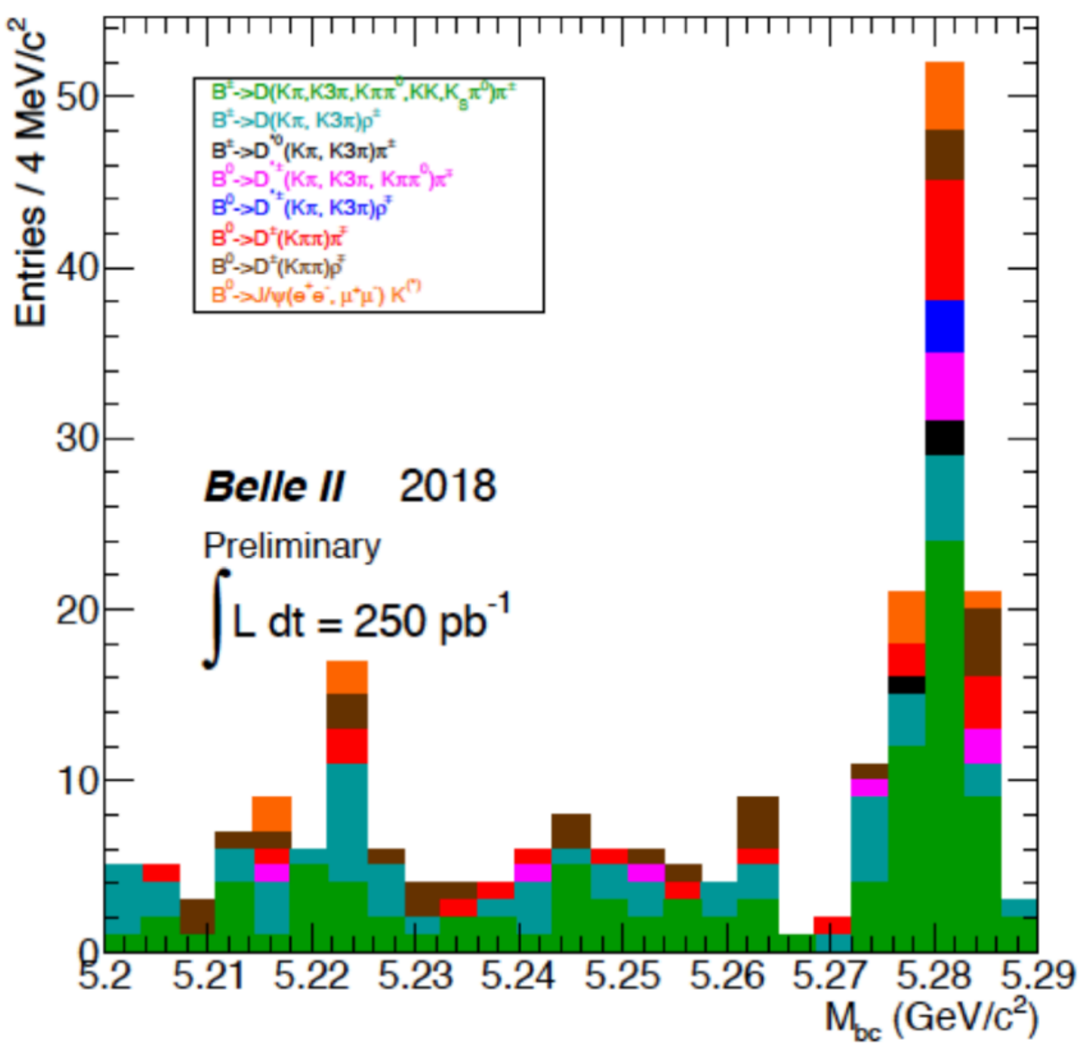


Phase 2 vertex data verify collision spot much shorter than the bunch length.

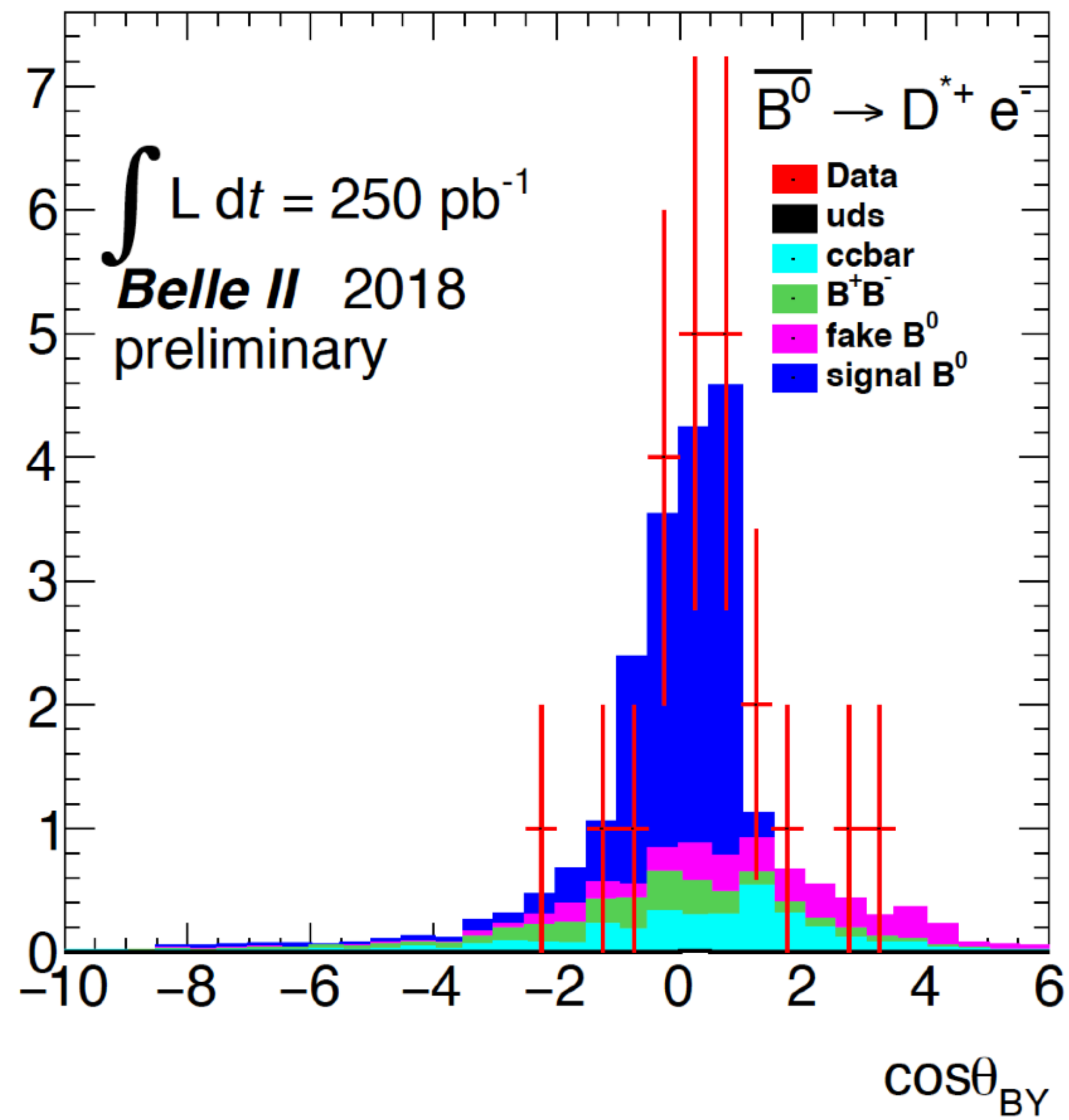
B reconstruction in Phase 2

- B meson signals have been seen in Phase 2 data.

Hadronic B decay modes

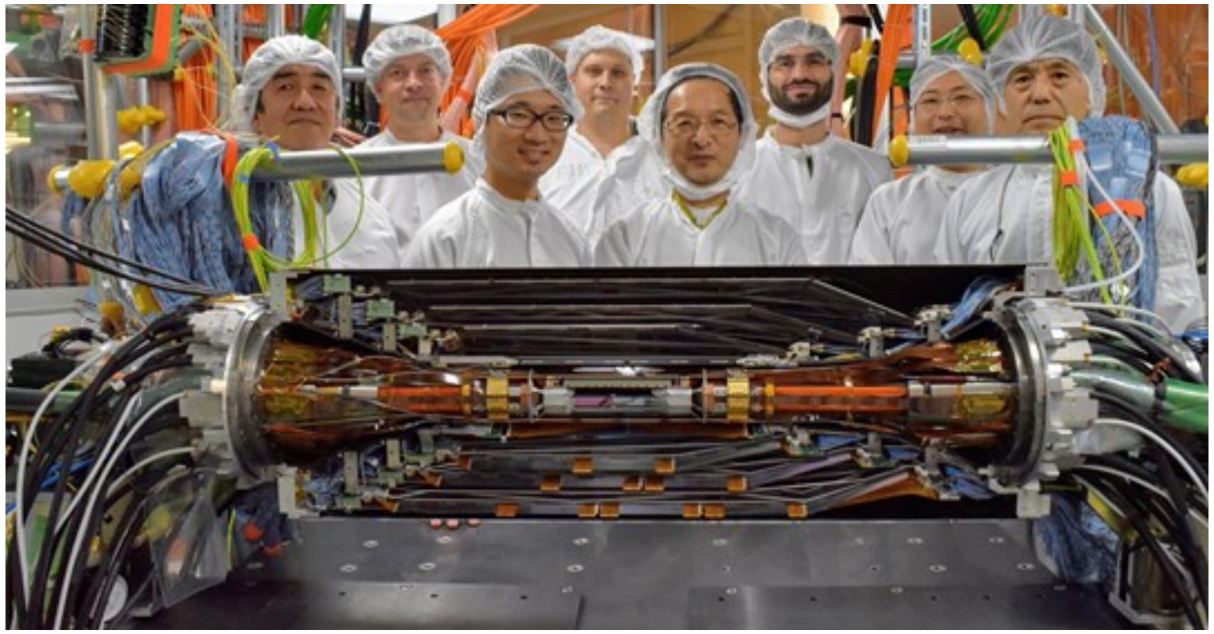


Semileptonic B decay modes

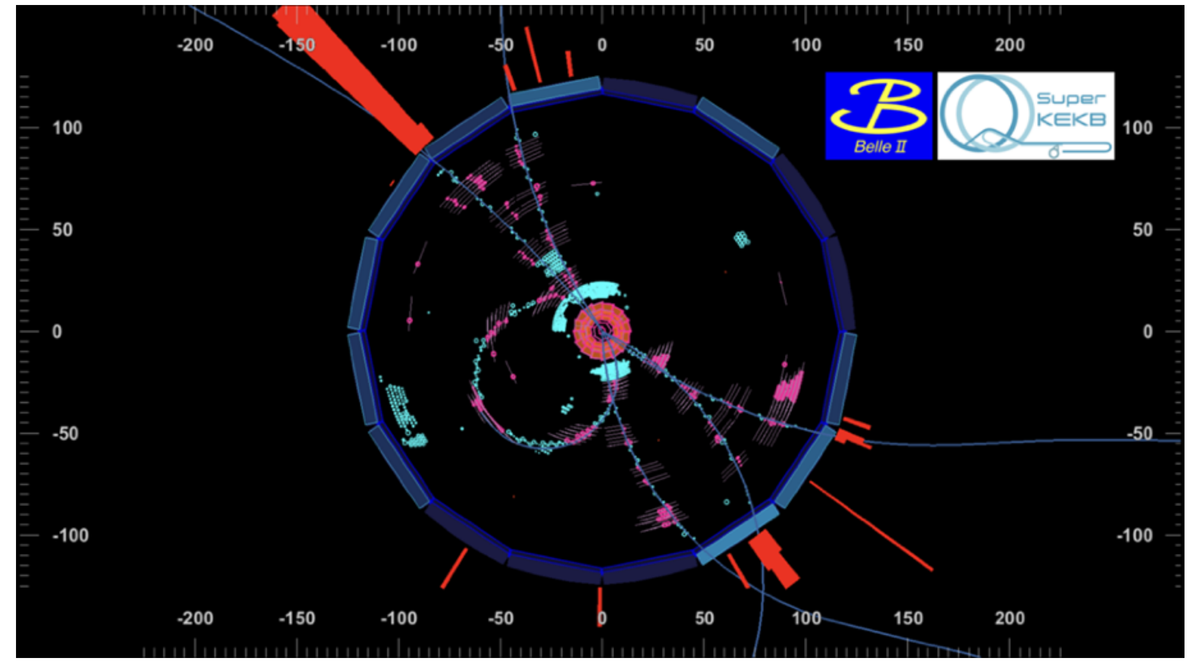


Phase 3 just started !

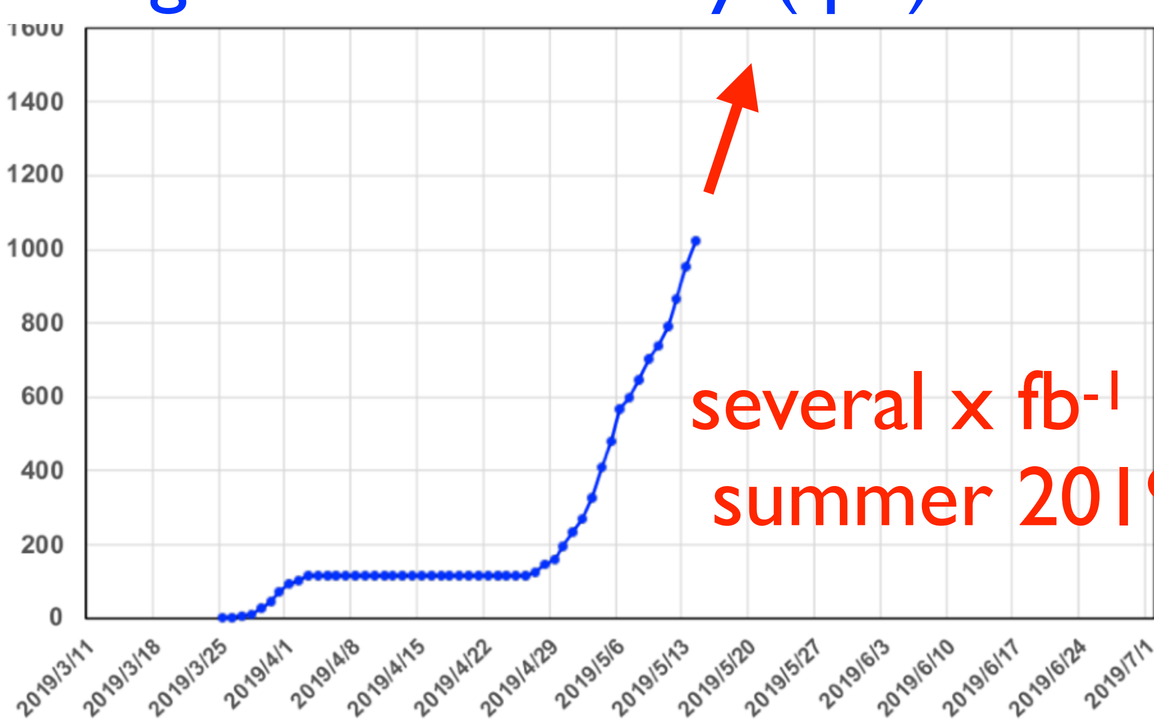
VXD (PXD+SVD) has been installed.



Physics run started on Mar. 25



Integrated luminosity (/pb)



several x fb^{-1} by summer 2019

See talk by Martin Besner (#113, Future Facilities, June 6)

Summary

- The Belle II experiment at SuperKEKB aims to find New Physics beyond the SM with ultimate precision measurement (a few %, typically) of heavy flavor decays ($O(10^{10})$ samples / year).
  - Complementary to LHC high Pt (ATLAS/CMS).
  - Complementary and competing with LHCb.
  - Variety of subjects (including low-energy QCD physics).
- Belle II physics run has just started !
- We expect many exciting results in coming years !

Stay Tuned !

Belle II

Belle II Outreach

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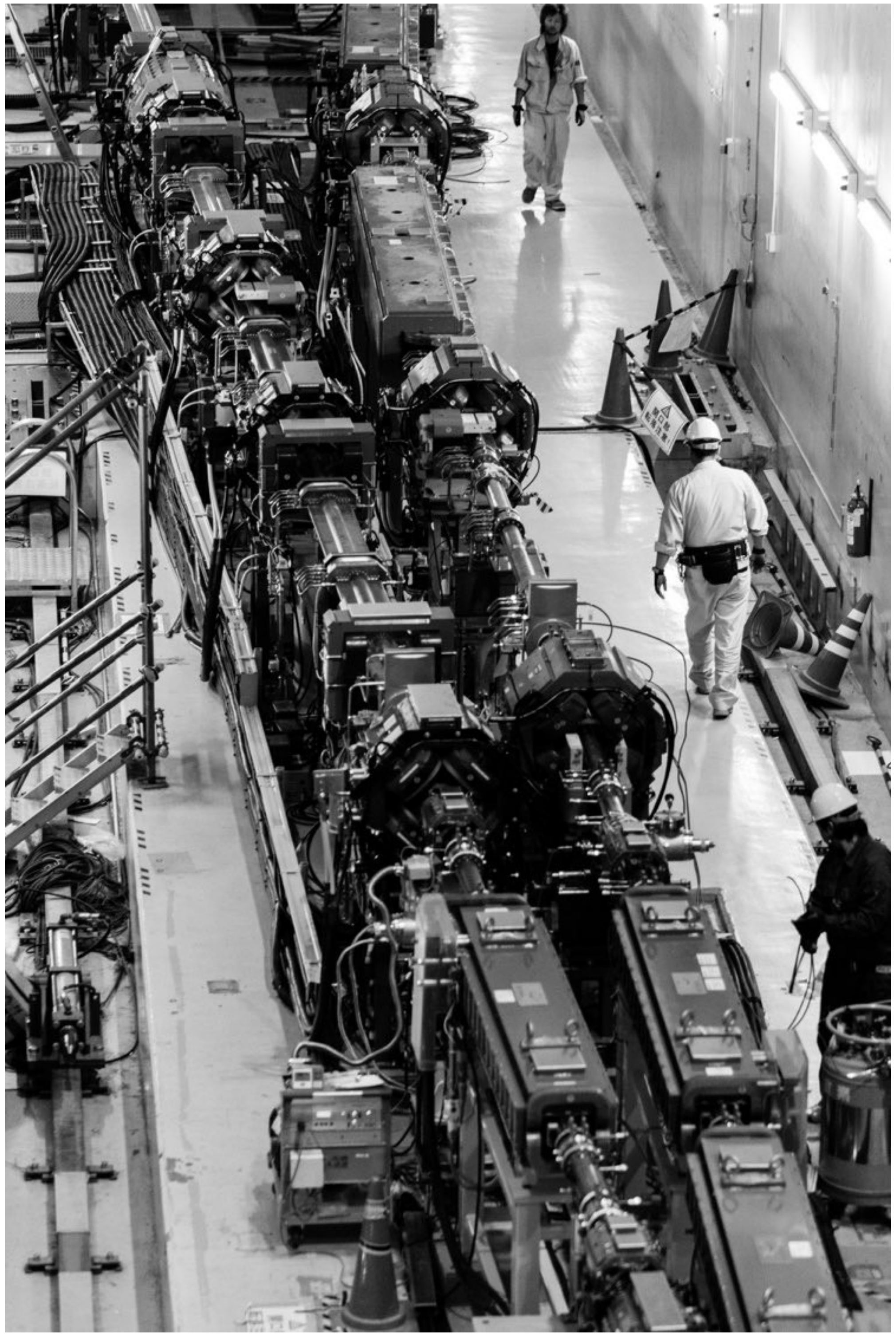
Thank you !

Backup Slides



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.

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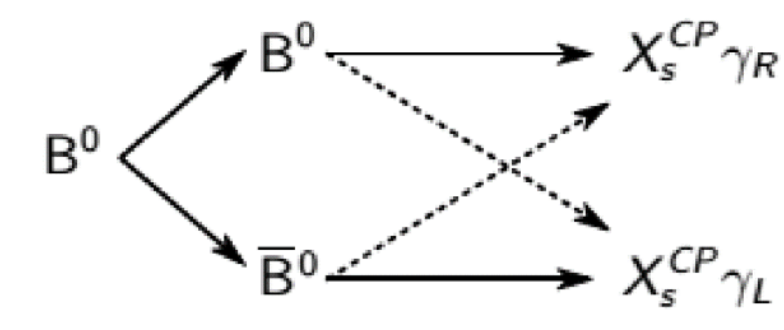
Belle II prospect for $|V_{xb}|$

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

Time-dep. CPV in $b \to s,d + \gamma$

- In SM, photon from b→s,d + γ is almost left-handed.
- Right-handed photon causes interference, and large CPV.



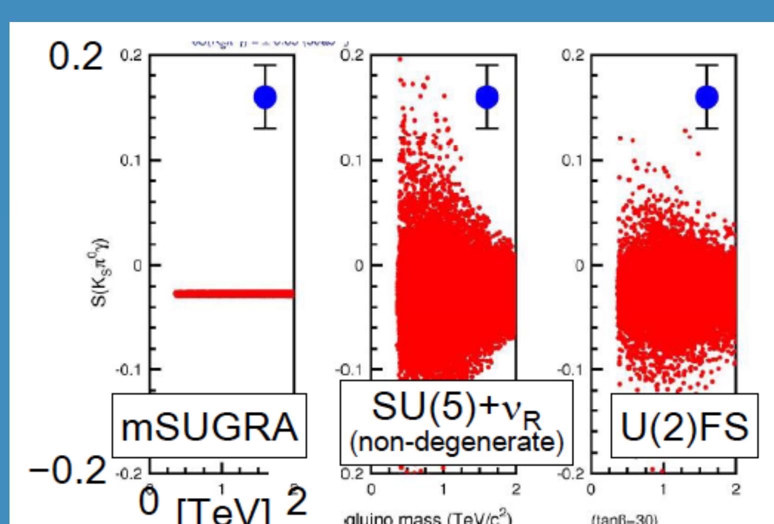
SM prediction

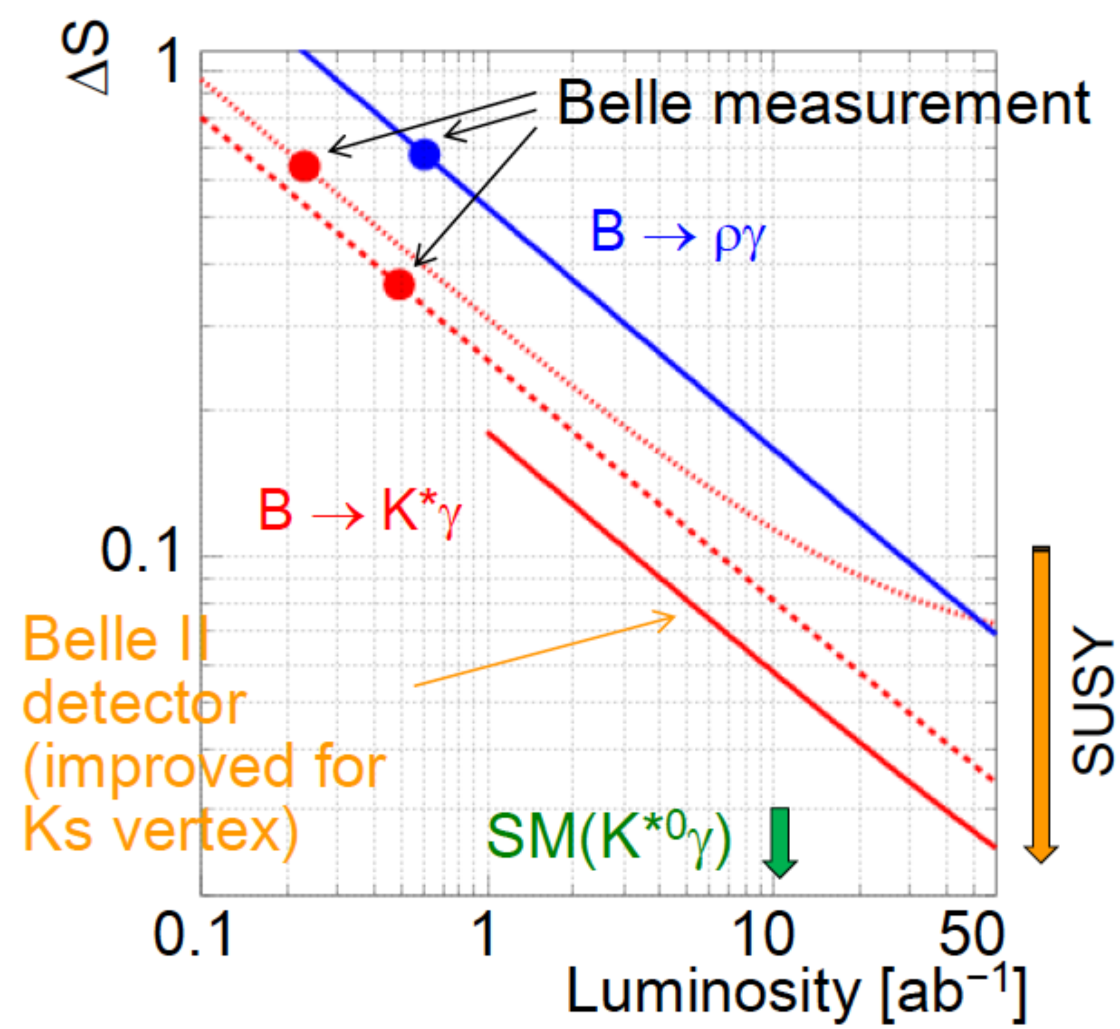
$$S(B \to V\gamma) \simeq -\frac{2m_s}{m_b}\sin 2\phi_1$$

$$|S(B \to K^*\gamma)| \leq 0.02$$

$$|S(B \to \rho\gamma)| \sim 0$$

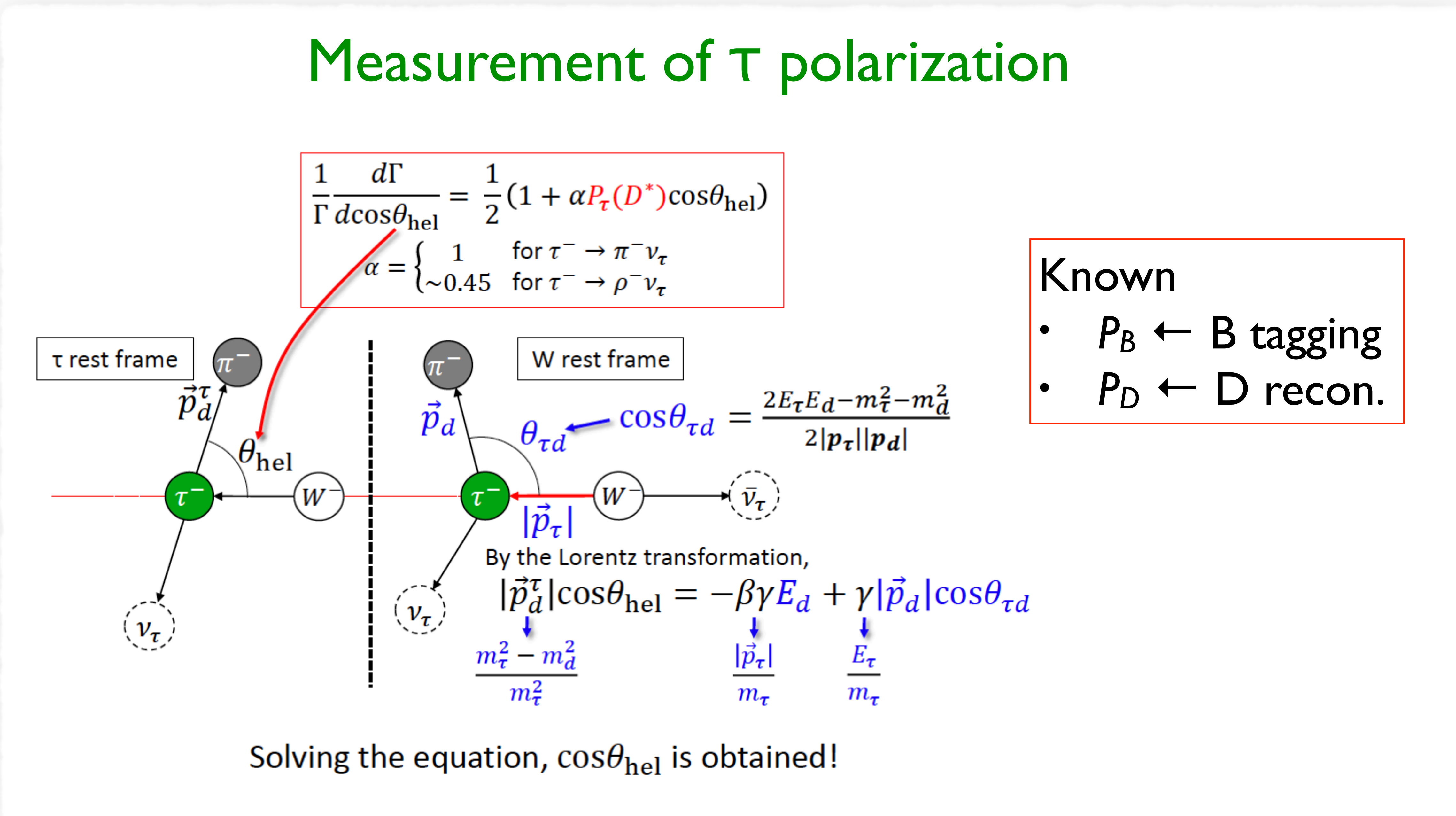
SUSY models





Measurement of τ polarization

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



B → τ ν, l ν at Belle II

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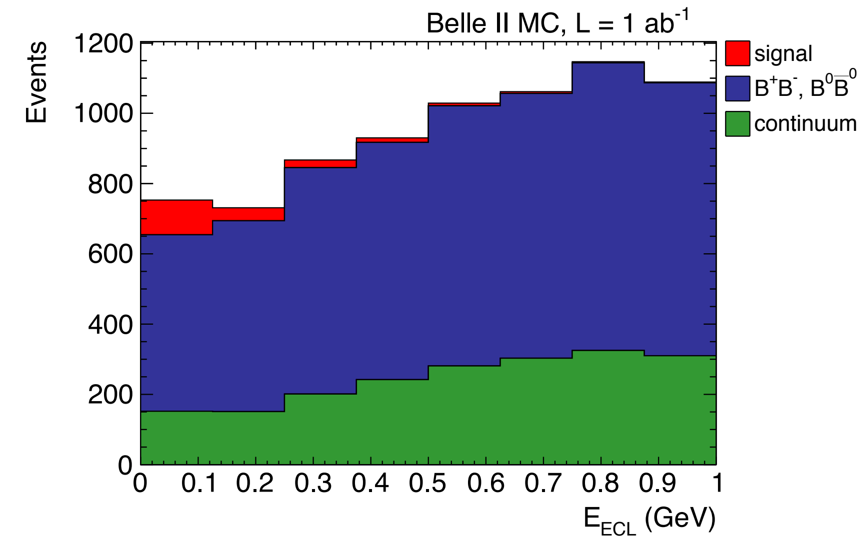
B→τν

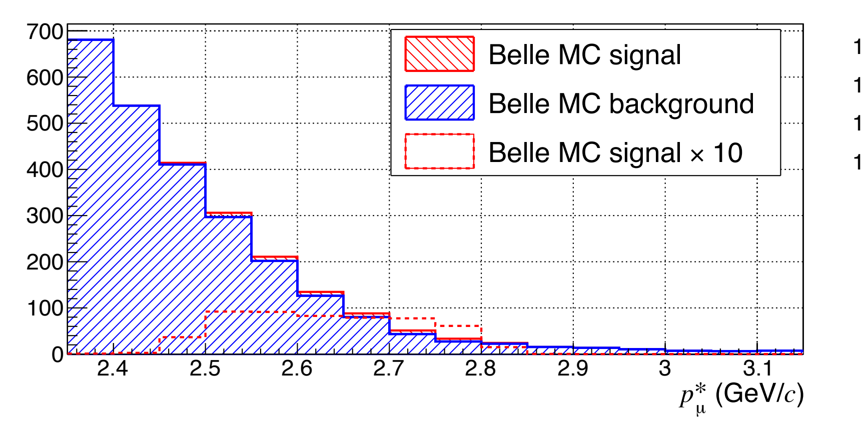
- Exploits high efficiency of the hadronic tag method through the Full Event Interpretation (FEI).
- Selection of photon candidates is important to cope with machine background in Belle II (x20 w.r.t. Belle)
  - Cluster energy, timing, shape (E9/E25)
- Multivariate continuum suppression



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→μν

- Tagged searches are possible, but efficiency is too low
- Extrapolation from Belle to Belle II
  - Branching fraction error : 7%(stat.) at 50ab^{-1}
  - 5σ observation at 6 ab^{-1}



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