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Belle II: Physics Prospects and Current Status

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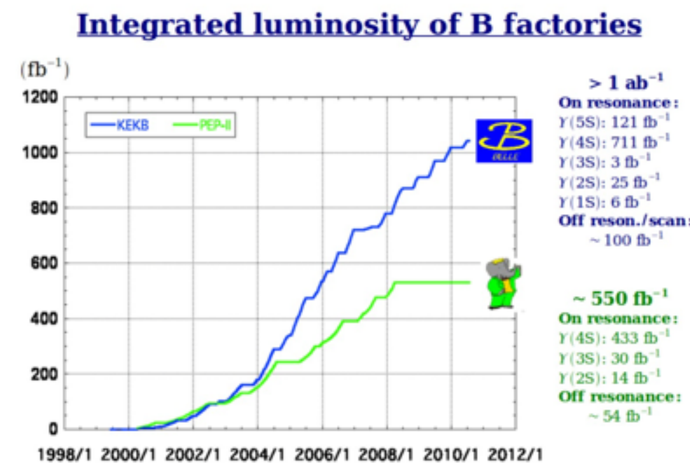
(On behalf of the Belle II Collaboration)

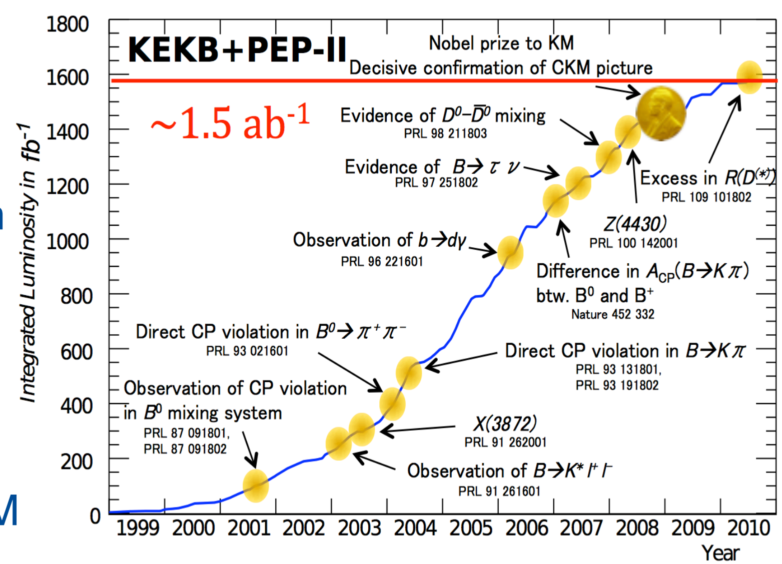
3rd International Conference on Particle Physics and Astrophysics

Moscow, October 2 - 5, 2017

The legacy of the *B*-factories

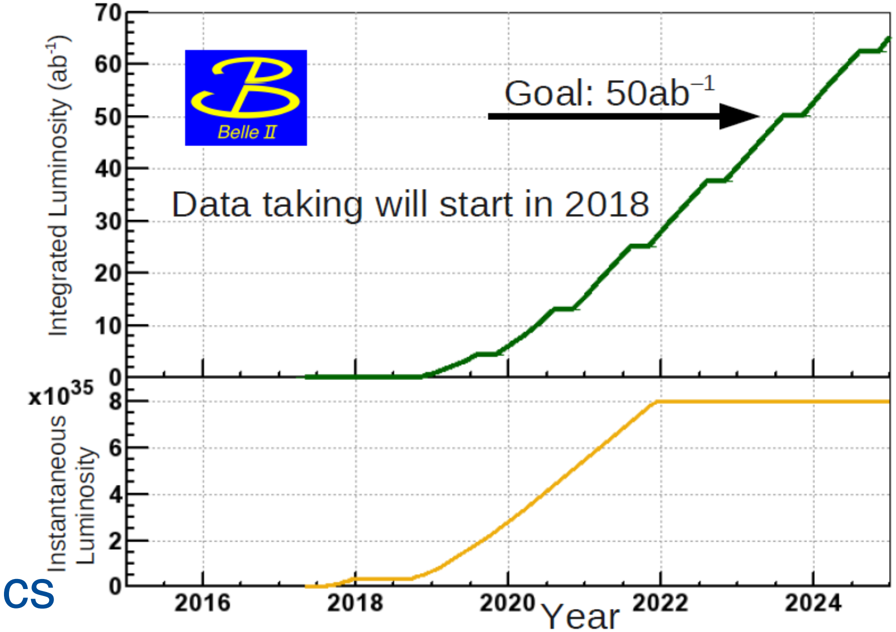
- The 1st generation of *B*-factories, BaBar and Belle collected about 1.5 ab^{-1} of data during 1999 – 2010.
- Made significant contribution to the understanding of the flavor dynamics in the Standard Model.
  - Discovery of CP violation and confirmation of the CKM description of flavor physics.
  - Precision measurement of the CKM matrix elements and the angles of the unitarity triangle.
  - Search for rare decays such as $B \to \tau\nu, D\tau\nu$
  - Constraints on various new physics models from the measurement of $b \to s\gamma$ branching ratio.
  - Observation of several new hadronic states, such as X, Y, Z states.
  - Strong evidence of *D* meson mixing.
  - Constraints on CP-odd light Higgs in the NMSSM and other charged Higgs model.





Belle II at SuperKEKB

- KEKB $e^+ e^-$ collider is being upgraded to SuperKEKB collider.
  - 40 times more luminosity than KEKB; Collect 50 ab^{-1} by 2024.
  - Belle detector is getting upgraded to Belle II detector to deal with the higher background due to the higher luminosity.

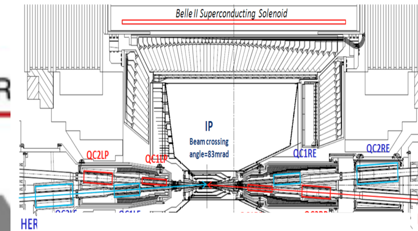


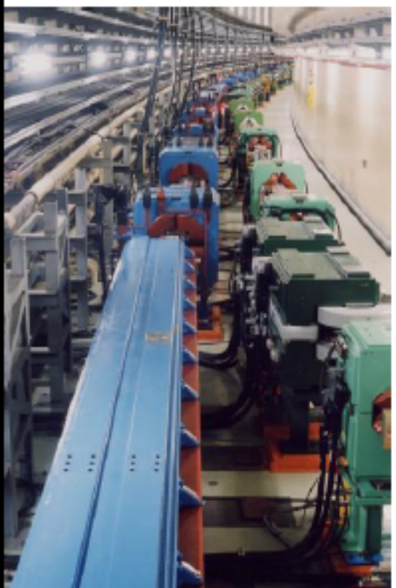
- Belle II provides a unique opportunity to constrain and search for new physics at the intensity frontier in a complementary way to LHC.
  - Most of the final state particles are exclusively reconstructed. Much cleaner environment.
  - Search for NP through precision measurement of rare and suppressed processes
    - Still room for corrections from NP at *O*(10%).
  - Resolve the tensions between results from *B* –factories. Explore these possible hints for NP with higher precision.
- Only a few selected topics will be presented in this talk.

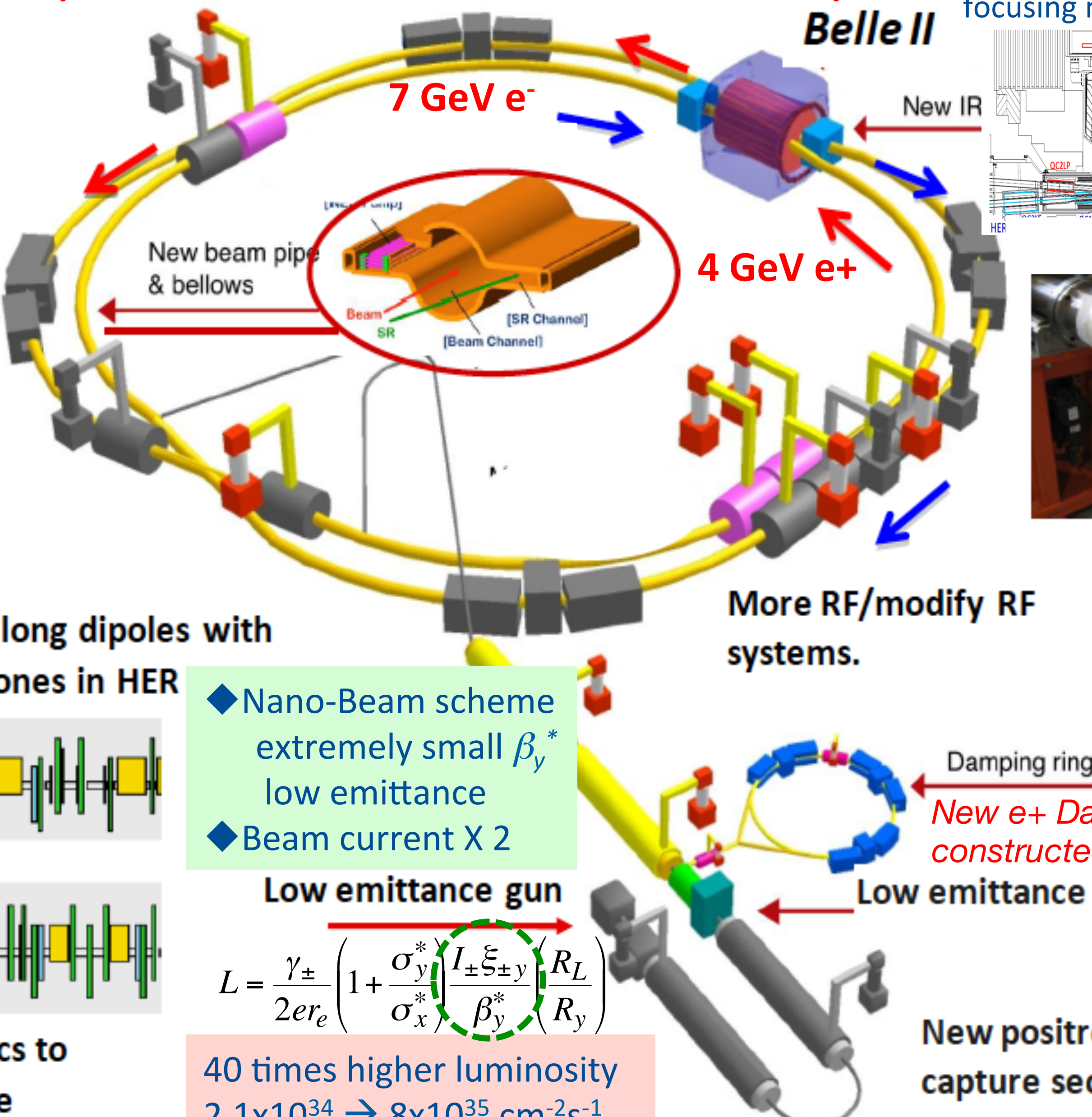
KEKB upgrade → SuperKEKB(nano-beam)

Feb 2016: First turns at SuperKEKB; 2017: All accelerator hardware now in place.

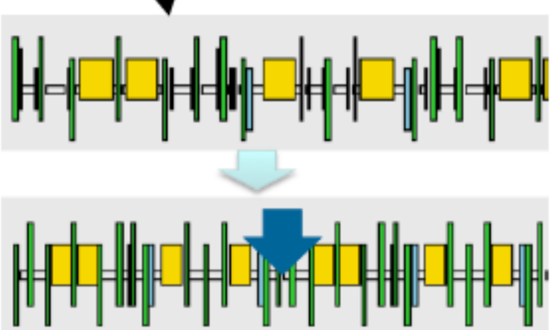
New superconducting final focusing magnets near the IP







Replace long dipoles with shorter ones in HER



Redesign the HER arcs to reduce the emittance

- Nano-Beam scheme extremely small β_y^* low emittance
- Beam current X 2

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

40 times higher luminosity $2.1\times10^{34} \rightarrow 8\times10^{35}$ $cm^{-2}s^{-1}$

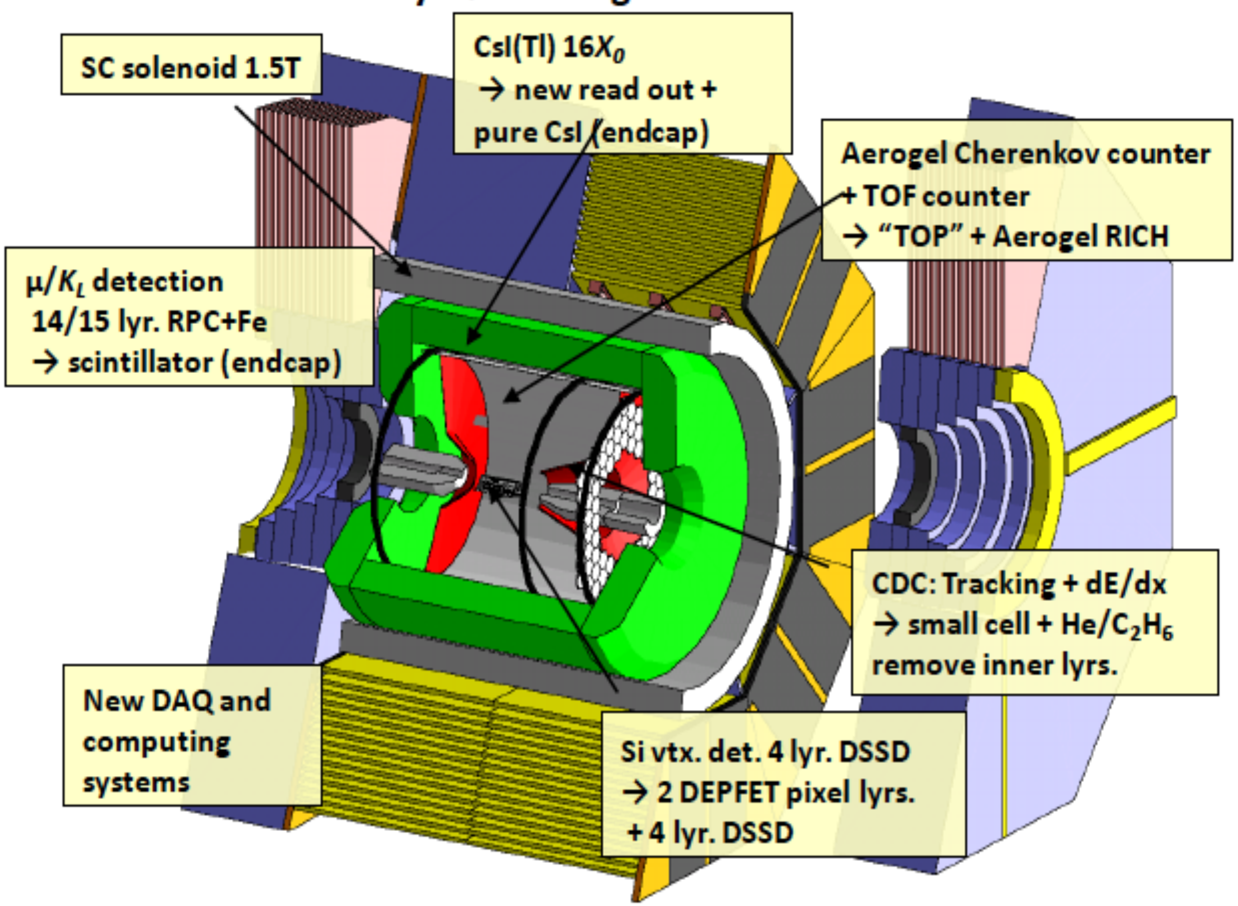
Detector upgrade

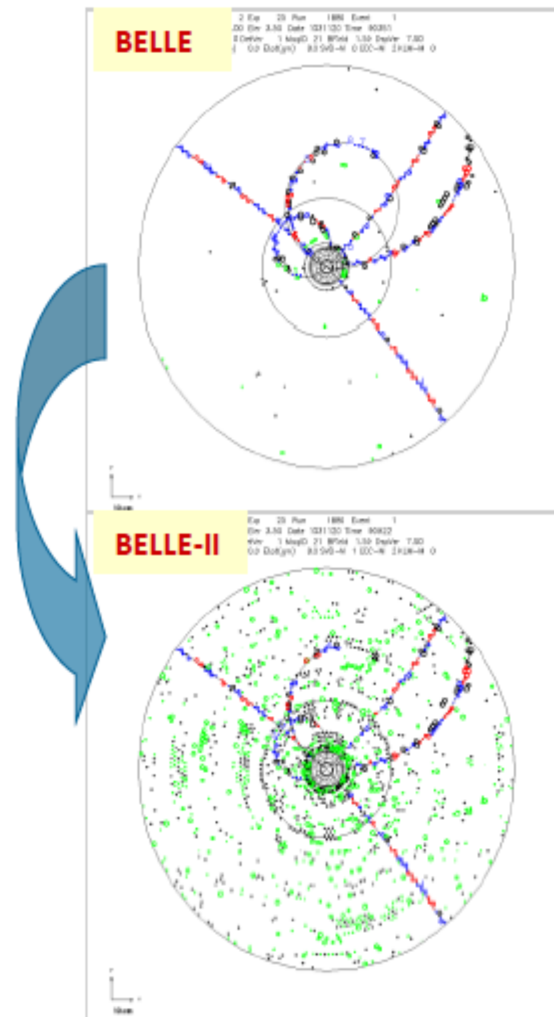
Critical issues at $L = 8 \times 10^{35}/cm^2/sec$

- **Higher event rate**
  - higher rate trigger, DAQ and computing

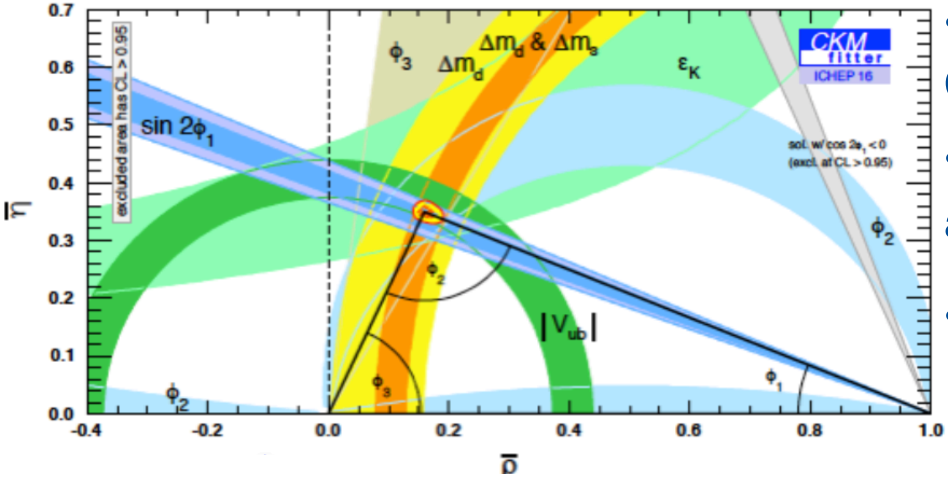
  \+

  - **Improve performance**
    - try better PID options
    - low p μ identification for $b \to s\mu\mu$ efficiency
    - hermeticity → missing E "reconstruction"
- **Higher background**
  - radiation damage and occupancies
  - fake hits and pile-up noise in the ECL





Belle II Physics Prospects – CKM



- Is the unitary triangle really a triangle

Currently, $(\alpha+\beta+\gamma)=(175\pm 9)^{\circ}$

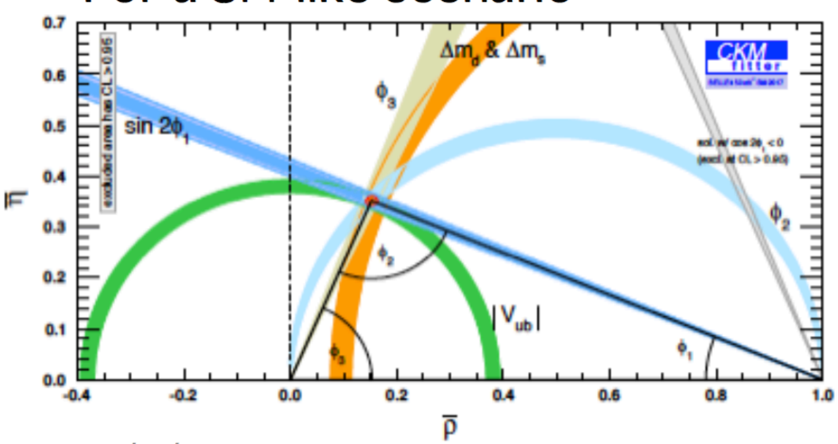
- Angle $\phi_1(\beta)$ is measured with 1^{o} accuracy; angles $\phi_2(\alpha)$ and $\phi_3(\gamma)\sim 5-15^{0}$ accuracy

- Accuracies for $V_{cb}\sim 3\%; V_{ub}\sim 10\%;$ $V_{td}\sim 7\%; V_{ts}\sim 6\%; V_{td}/V_{ts}\sim 3\%$

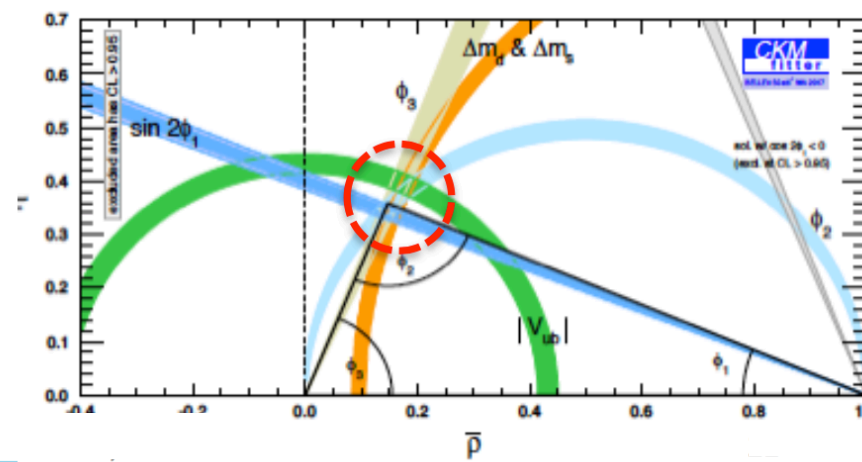
$\varphi_1(\beta)$ [deg.]	0.4
$\varphi_2(\alpha)$ [deg.]	1.0
$\varphi_3(\gamma)$ [deg.]	1.0 (w/LHCb)

$\|V_{cb}\|$ incl.	1%
$\|V_{cb}\|$ excl.	1.5%
$\|V_{ub}\|$ incl.	3%
$\|V_{ub}\|$ excl.	2% (w/LHCb)

For a SM-like scenario



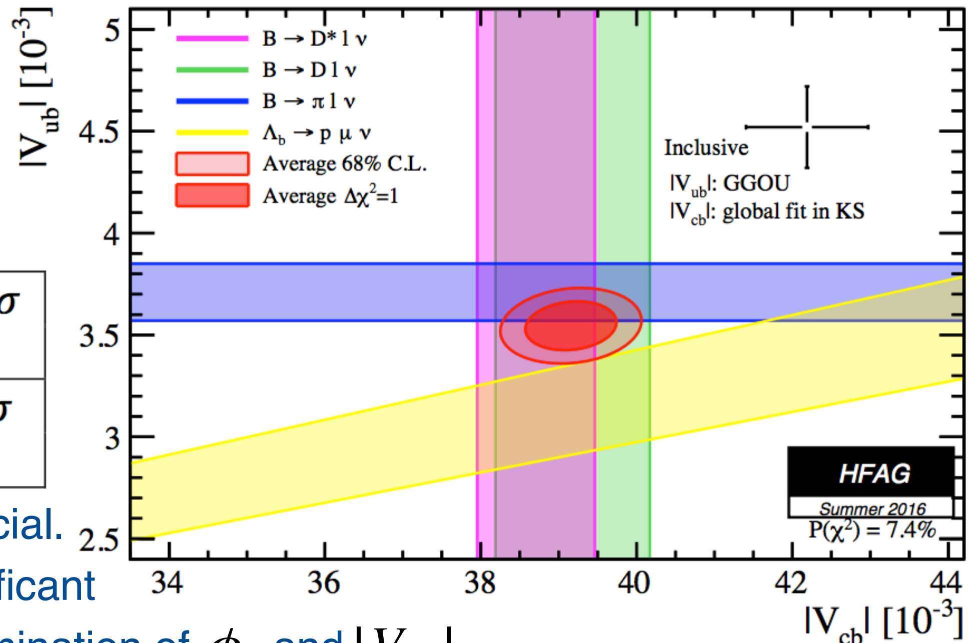
If the current WAs hold



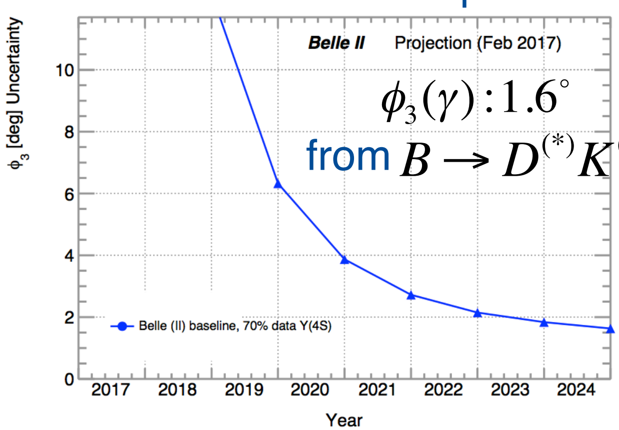
Belle II Physics Prospects – CKM

- Tension in the Inclusive and Exclusive measurements of V_{cb} and V_{ub}
  - ✓ Inclusive: $B \to X_c l\nu, B \to X_u l\nu$, Hadronic tag, SL tag, Untagged.
  - ✓ Exclusive: $B \to D^{(*)} l\nu, B \to \pi l\nu$

$\|V_{ub}\|$	$(4.49 \pm 0.23)\times 10^{-3}$	**(Inc.)**	2.8σ
	$(3.72 \pm 0.16)\times 10^{-3}$	**(Exc.)**	
$\|V_{cb}\|$	$(42.2 \pm 0.8)\times 10^{-3}$	**(Inc.)**	2.9σ
	$(39.2 \pm 0.7)\times 10^{-3}$	**(Exc.)**	



- Improvement in theoretical calculation is crucial.
- With a larger dataset, Belle II will make significant contribution to the improvement in the determination of ϕ_3 and $|V_{ub}|$



$\phi_3(\gamma): 1.6^\circ$

from $B \to D^{(*)} K^{(*)}$

Belle II ϕ_3 sensitivity projection

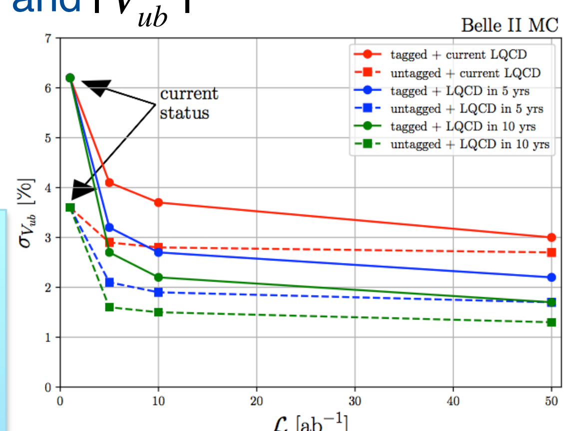
$|V_{ub}|$ Currently:

$\delta_{\exp} \sim 3.4\%,\ \delta_{th} \sim 4.5\%$

Expected precision from

$B \to \pi l \nu$ (Untagged)

$$\delta^{50ab^{-1}}_{|V_{ub}|} = 1.3\%$$



Forecast of $|V_{ub}|$ sensitivity in $B \to \pi l \nu$

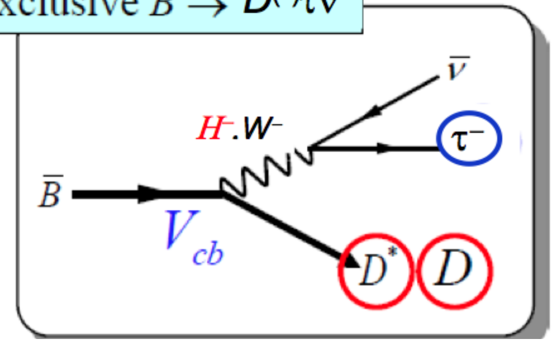
Belle II Physics Prospects – $B \to D^{(*)}\tau\nu$

- $b \to cl\nu$ transitions are sensitive to NP models with charged Higgs, i.e. 2-Higgs Doublet Model -type II (2HDM-II)

  $H^{\pm} - l$ coupling is proportional to the lepton mass.

✓ Theoretical Uncertainty: 2-5%
✓ Branching fraction: 1-2%, $|V_{cb}|$ mediated, no helicity suppression.
✓ Charged Higgs couples at the tree level.
✓ Can enhance the rate by an order of magnitude.

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



At the B-factories, measure the ratio: $R(D^{(*)}) = \dfrac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$

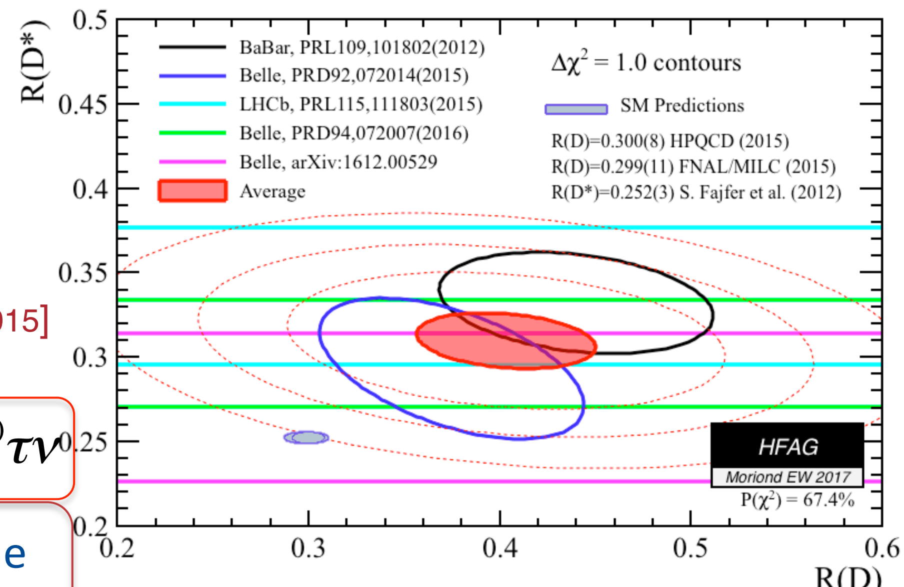
➢ Various uncertainties cancel in the ratio. Very clean theoretical predictions:

$$R(D) = 0.300 \pm 0.008, \quad 0.299 \pm 0.011$$

[HPQCD 2015, FNAL/MILC 2015]

$$R(D^*) = 0.252 \pm 0.003$$

[S. Fajfer et. al. 2012]

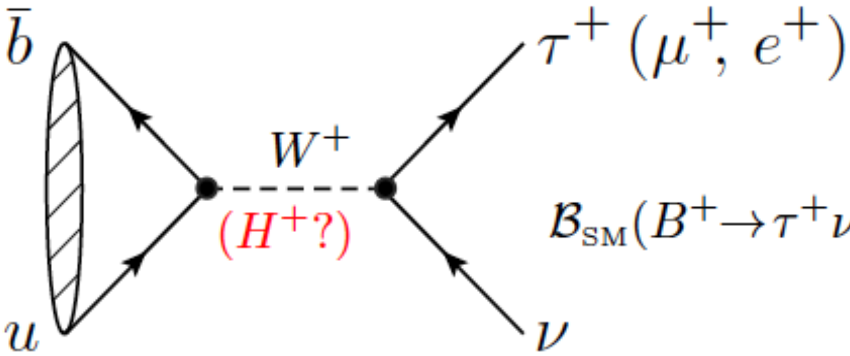


4σ deviation from the SM observed in $B \to D^{(*)}\tau\nu$

Interest in D* and tau polarizations. Recent Belle result: $P(\tau) = -0.38 \pm 0.51^{+0.21}_{-0.16}$ PRL 118, 211801 (2017)

~2-3% precision with 50 ab^{-1} : 14σ deviation.

Belle II Physics Prospects – $B \to \tau\nu$



Sensitive to existence of a charged Higgs

Measurable via other modes*

Phase space

Lattice QCD*

$$\mathcal{B}_{\rm SM}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$= 0.75^{+0.10}_{-0.05} \times 10^{-4}$$

Helicity suppression
Makes $\tau\nu \gg \mu\nu \gg e\nu$ but with precisely determined ratios

In the type II 2-Higgs doublet model (2HDM) (W.S. Hou, PRD 48, 2342 (1993)),

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}_{\rm SM} \times r_H, \quad r_H = \left(1 - \tan^2\beta \frac{m_B^2}{m_{H^\pm}^2}\right)^2$$

If $\tan^2\beta \frac{m_B^2}{m_{H^\pm}^2}$ $< 2, \; r_H < 1,$ $\gg 2, \; r_H \gg 1.$

$\tan\beta$ is the ratio of the VEVs of the two doublets.

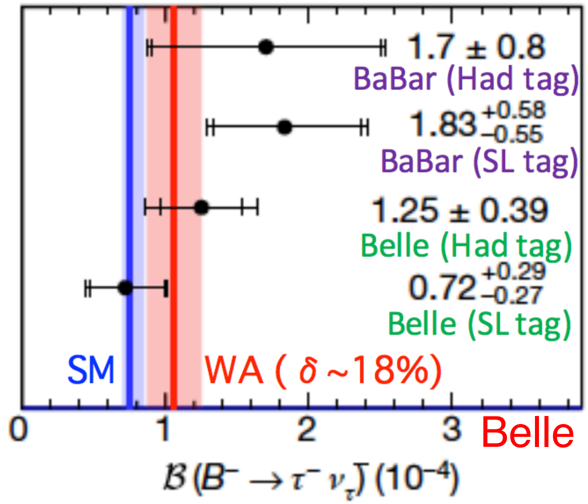
A charged Higgs breaks lepton universality.

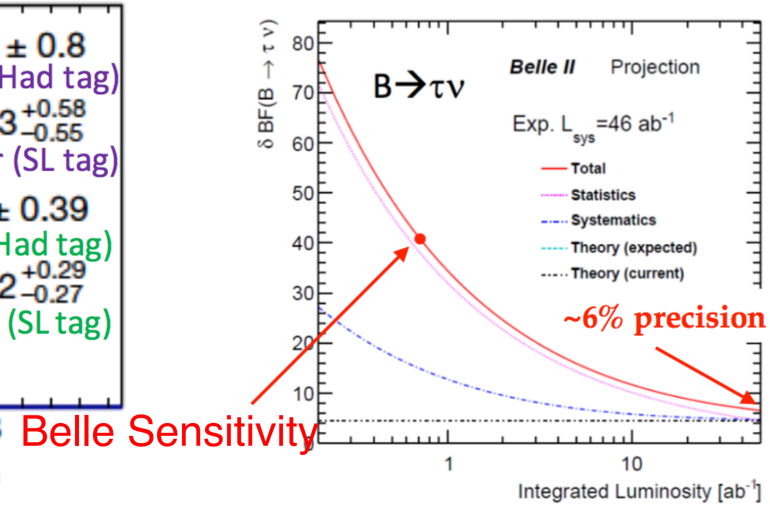
Belle II Physics Prospects – $B \to \tau\nu$

- Current world average (hadronic and SL tag)

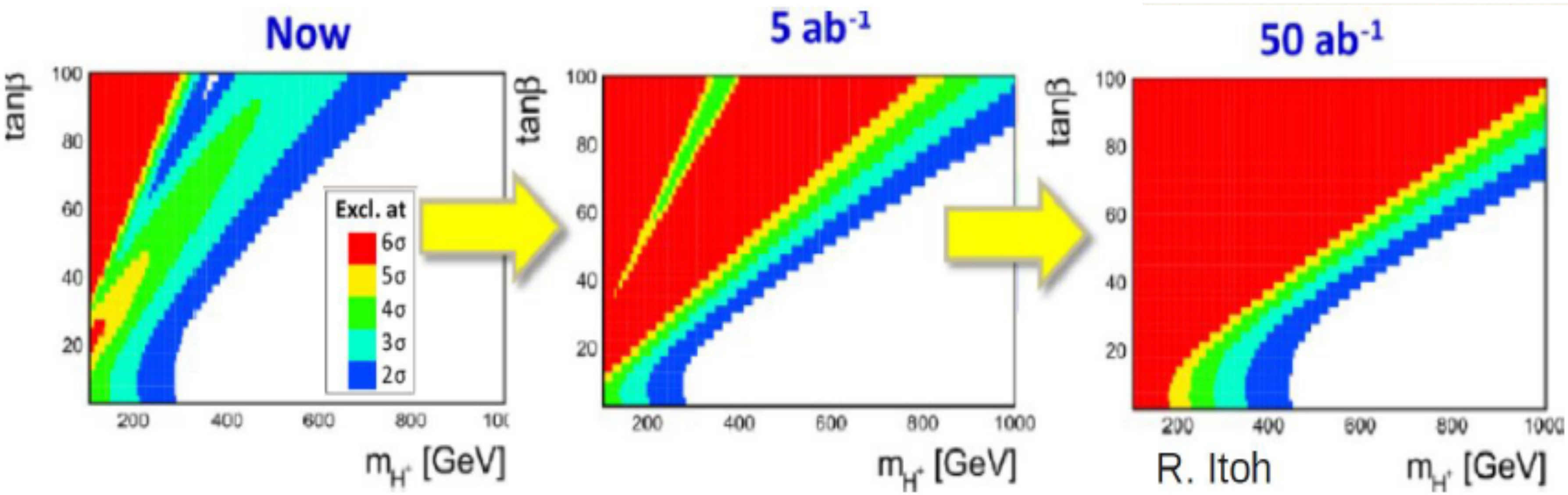
$$BR = (1.09 \pm 0.24) \times 10^{-4}$$

- No deviation from SM.
- With 50 ab^{-1}, the experimental sensitivity will reach ~6%.





Belle II projections for charged Higgs sensitivity



Belle II Physics Prospects – Charm Physics

- Strong evidence of $D^0 - \bar{D}^0$ mixing at the *B*-factories. Similar to neutral kaon mixing.
  - *D^0* meson mass eigenstates are expressed as:

$$\left|D^0_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle \quad \text{with } p^2 + q^2 = 1$$

If *p = q,* the two mass eigenstates are CP-even and CP-odd; otherwise CP is violated.

- Charm mixing is characterized by the parameters: $x = \Delta m / \Gamma$ and $y = \Delta\Gamma / 2\Gamma$

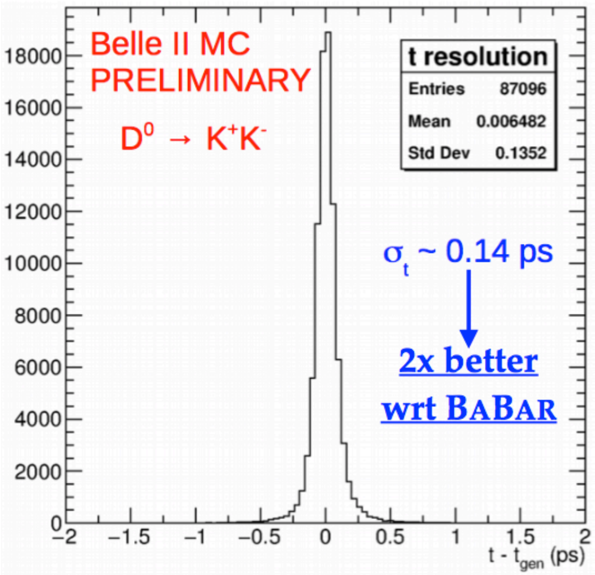
Δm and $\Delta\Gamma$ are the mass and decay width differences of mass eigenstates, respectively and Γ is the average D^0 decay width and ϕ, the phase of (*q/p*).

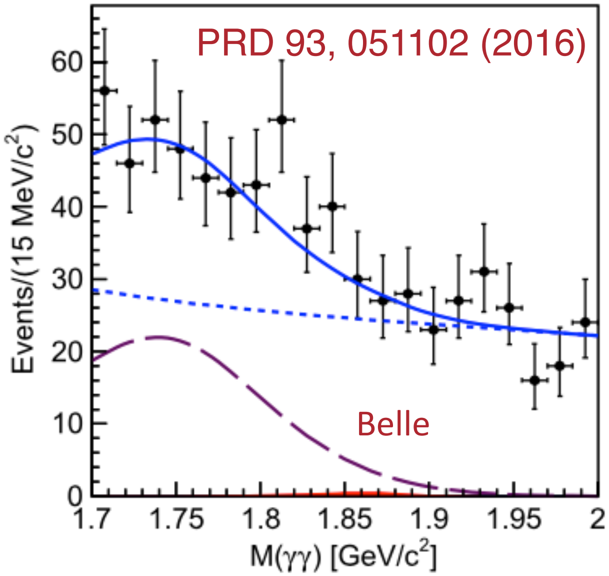
Charm mixing in $D^0 \to K_s \pi^+ \pi^-$

	Belle Uncertainty ($\sim$0.9 ab^{-1})	Belle II Uncertainty ($\sim$50 ab^{-1})
x	~ 0.21%	~0.08%
y	~0.17%	~0.05%
|q/p|	~0.18	~0.06
ϕ	~0.21	~0.07

Belle II Physics Prospects – Charm Decays

- Large data sample from Belle II will improve the measurements of mixing parameter in the charm sector.
    - Will enable direct and indirect measurements of CPV.
        - Substantial improvement in the proper time resolution with respect to the *B*-factories.
        - New tagging method based on the rest of the event are being developed.

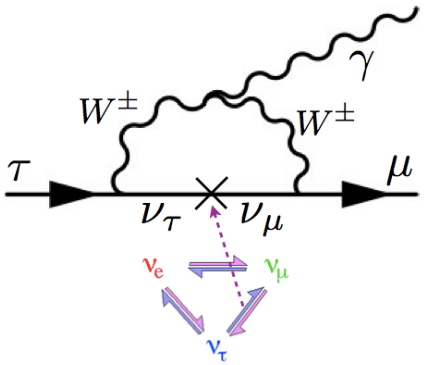




- Search for rare decays in the charm sector such as $D^0 \to \gamma\gamma$
    - FCNC mode: Expected BF ~ 10^{-8}
    - Belle: BF < 8.5 X 10^{-7} @90% CL.
    - Belle II Sensitivity with 50 ab^{-1} data: BF ~ 10^{-7} – 10^{-8}

Lepton Flavor Violation in τ Decays

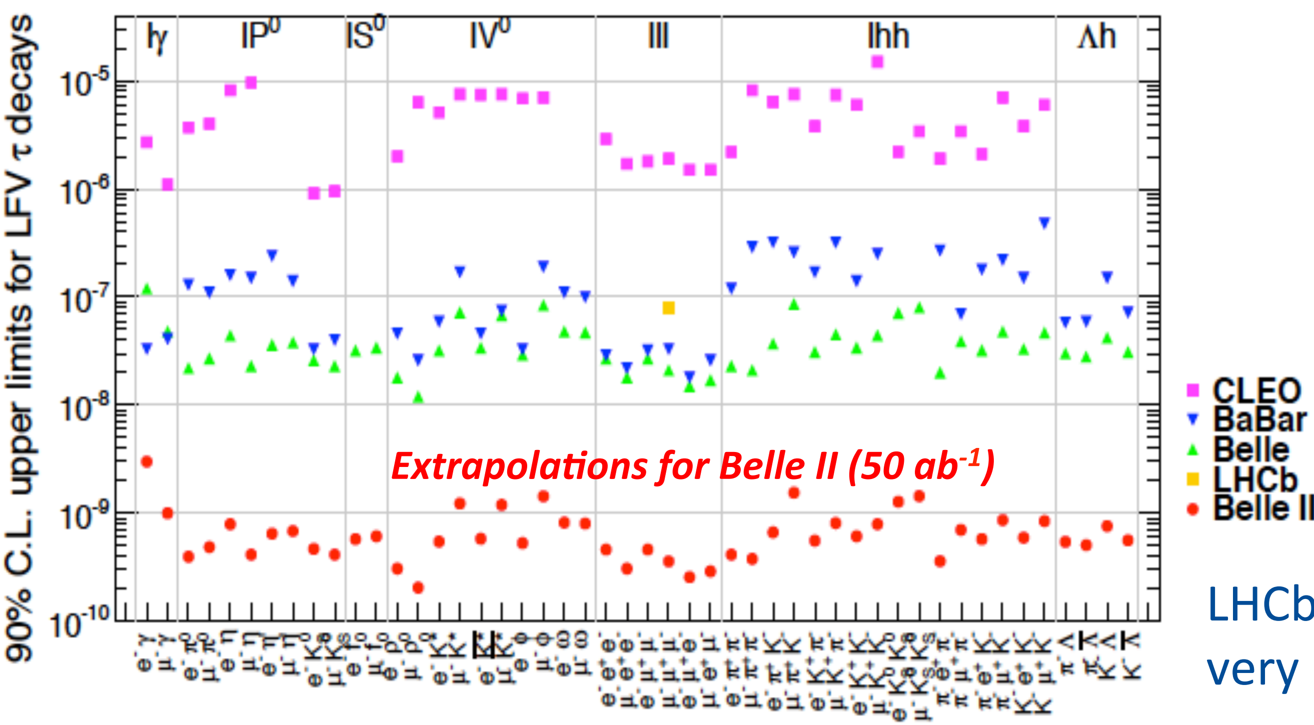
- LFV violation in the charged leptons is highly suppressed in the SM even after the inclusion of neutrino masses:
  - Neutrino masses are expected to be much smaller compared to the electroweak scale, $M_W \approx 80.4$ GeV.
  - Searches of LFV in the SM is beyond experimental reach:

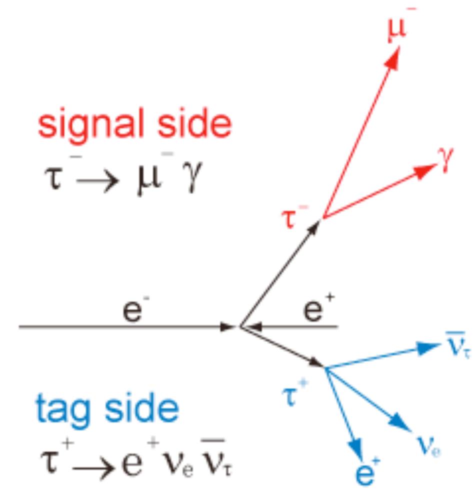


$$B(\tau \to l\gamma) \propto \left(\frac{M_{\nu_\tau}^2 - M_{\nu_l}^2}{M_W^2} \right)^2 \approx 10^{-50} \sim 10^{-54}$$

- Observation of LFV in the charged lepton is a clear signal for NP beyond SM:
  - Many extensions of the SM such as supersymmetry, little Higgs models, extra dimensions predict enhanced LFV.
  - LFV in τ decays can be as high as $O(10^{-8})$
    - Within the reach of Belle II

Lepton Flavor Violation in τ Decays



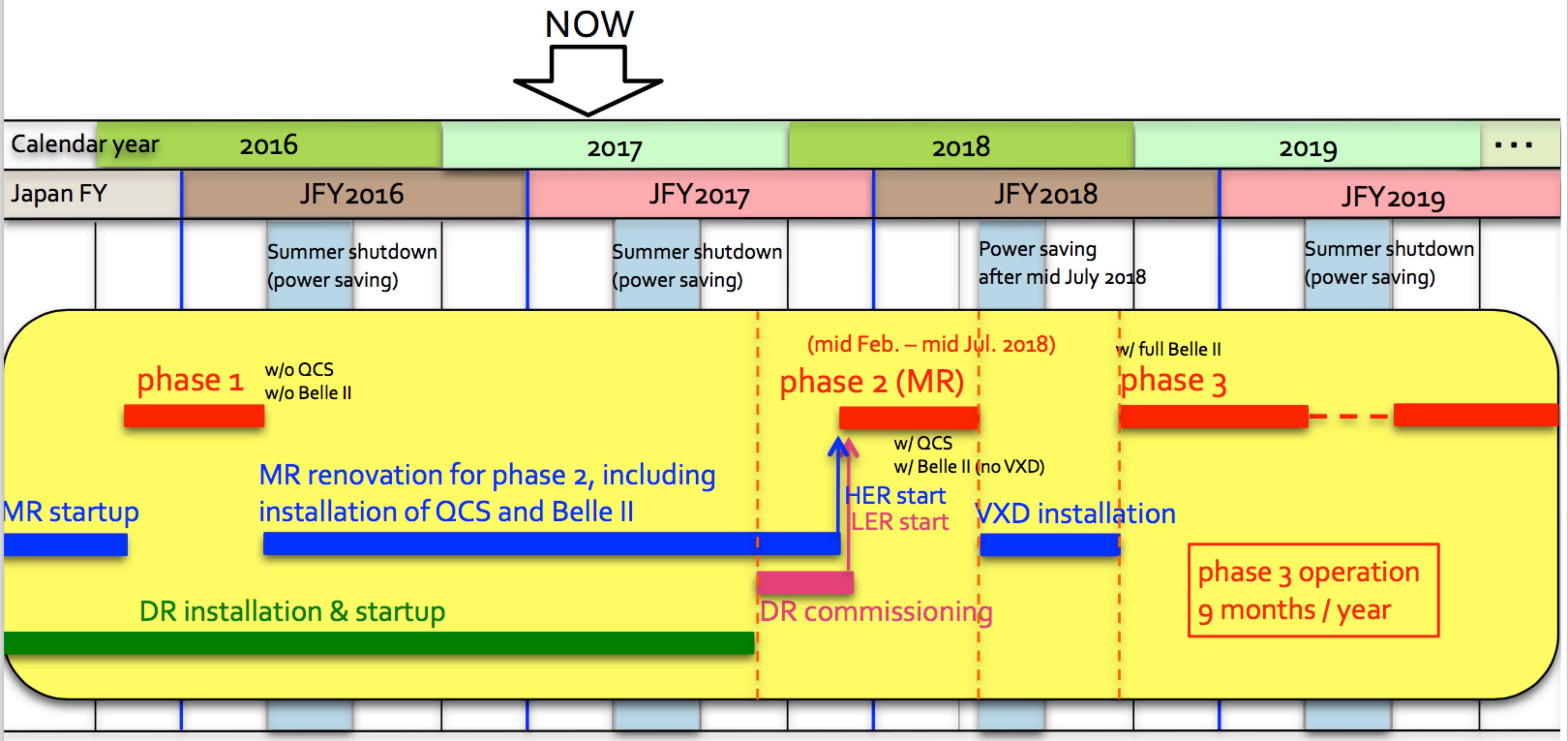


LHCb, CMS and ATLAS have very limited capabilities.

- Belle II: Sensitivity for LFV decay rates is over 100 times higher than Belle for the cleanest channels ($\tau \to l\gamma$) and over 10 times higher for other modes, such as $\tau \to l\gamma$ (due to irreducible background contributions)
- Belle II will collect about 10^{11} τ leptons compared to 10^9 presently available.

SuperKEKB/Belle II Schedule

- Phase I (2016): beams, no collisions, cosmics
- Phase II (2018): collisions, complete Belle II detector except SVD.
- Phase III (end of 2018 – 2024): Full Belle II detector on, Physics run.



Summary

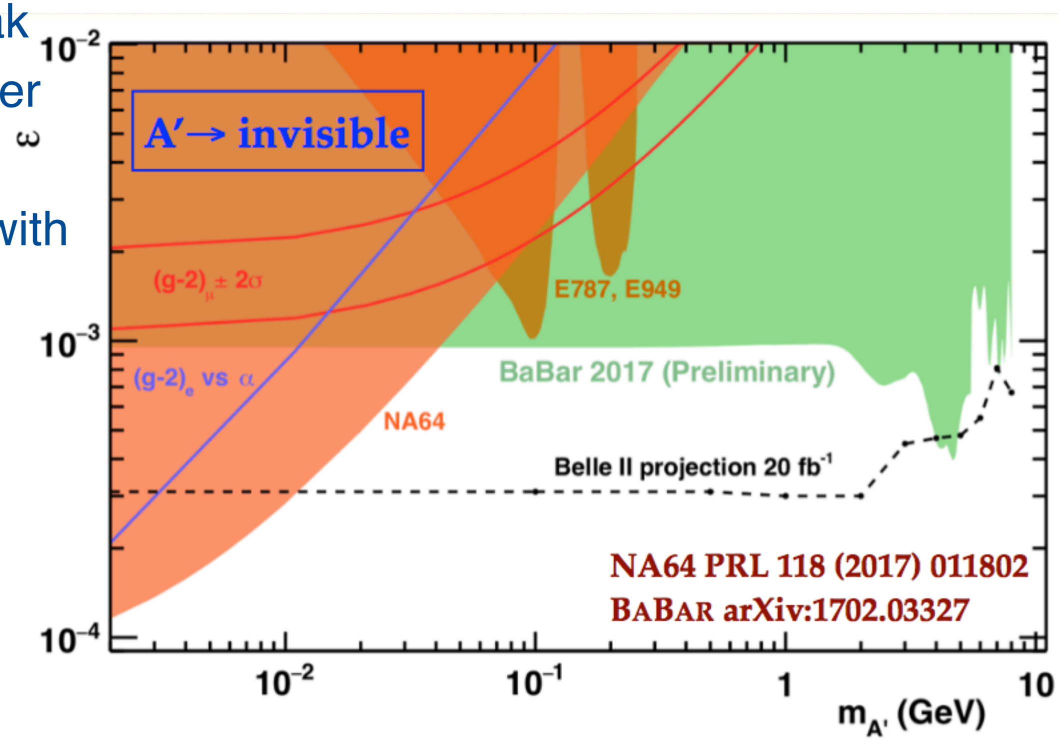
- *B*-factories have already provided unprecedented information on the flavor dynamics in the SM.
  - CPV in *B*-meson decays, evidence for D meson mixing.
  - Provided unexpected new results: new states such as the X, Y, Z states.
  - Hints of NP through measurement of lepton non-universality, in the decay of $B \to D^{(*)}\tau\nu$

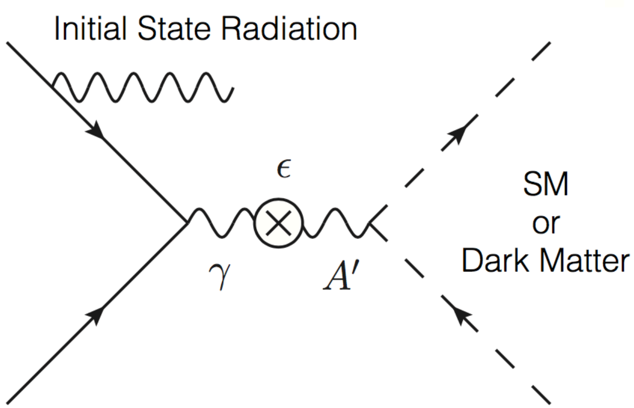
- Belle II experiment under construction currently.
  - Start of full Physics run: 2018, reach 50 ab^{-1} by 2023 – 2024.
  - Belle II detector rolled to the beam collision point in April 2017. Detector integration is continuing.
  - Accelerator commissioning is ongoing, beam was turned on in Feb 2016.
  - Belle II with 50 ab^{-1} data will provide greater sensitivity and complimentary approach to LHCb in many areas of flavor physics.
    - Unparalleled sensitivity to Unitarity triangles, CPV in the charm physics, spectroscopy, NP searches at the loop level ⋯

Backup Slides

Dark sector searches

- Theoretical models attempting to explain the muon *(g-2)* anomaly introduces a low-mass spin-1 particle, A$^{/}$
  - Gauge coupling of electroweak scale to dark matter, much smaller coupling to SM hypercharge.
  - Can mix with the SM photon with a mixing strength $\varepsilon << 1$
  - Values as high as $\varepsilon \sim 10^{-3}$ and masses in the GeV range possible.





- Challenging signature:
  - Special single photon trigger required.
  - The early dataset from Belle II will provide an unique opportunity for searches in the dark sector

Physics Prospects: Belle II Vs LHCb

Observables	Expected th. 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	Belle II/LHCb
$\lvert V_{cb}\rvert$ 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
CPV			
$S(B \to \phi K^0)$	***	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

	Observables	Belle or LHCb*	Belle II		LHCb	
		(2014)	5 ab^{-1}	50 ab^{-1}	2018	50 fb^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$	2.9%	0.9%		
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$	3.5%	2.3%		
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	30%	25%		
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	$-32 \pm 21 \pm 9$	11	6		
	$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-3}]$	3.4*			0.5	0.1
	A_Γ $[10^{-2}]$	0.22	0.1	0.03	0.02	0.005
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	0.29	0.09		
	$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$	0.08	0.03		
Charm Mixing	$x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	0.14	0.11		
	$y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	0.08	0.05		
	$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	0.10	0.07		
	$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	6	4		
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7		
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12		
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3		

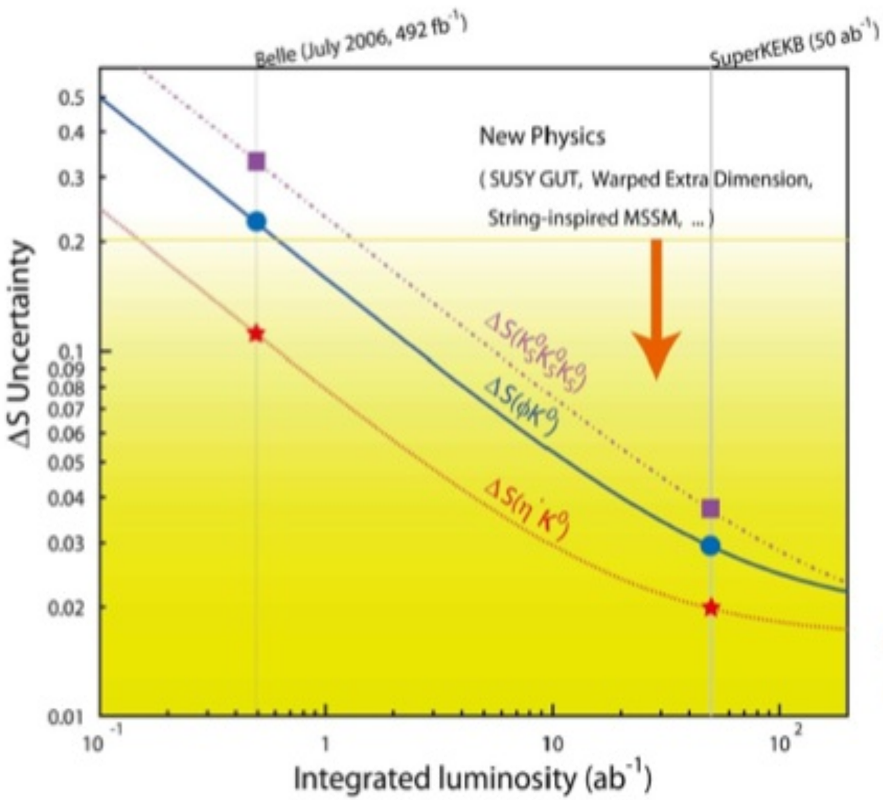
Example: $b \to s \bar{s} s$ decays

Value of $\sin 2\phi_1$ differs slightly between $B^0 \to \phi K_S$ and $B \to J/\psi K_S$ decays

$$\Delta S = \sin 2\phi_1^{\phi K_s} - \sin 2\phi_1^{J/\psi K^0} = 0.22 \pm 0.17$$

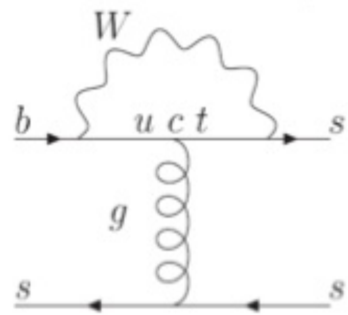
In the SM it should be: $\Delta S = 0$ (*Theory: ±0.02*)

➡ **If not**: New Physics might contribute

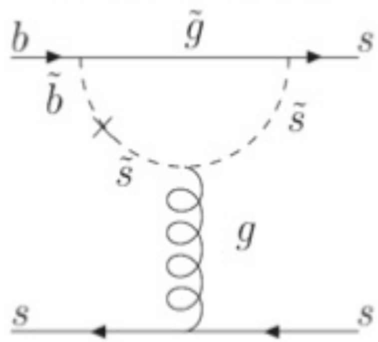


A.G. Akeroyd et al.
(arXiv: 1002.5012)

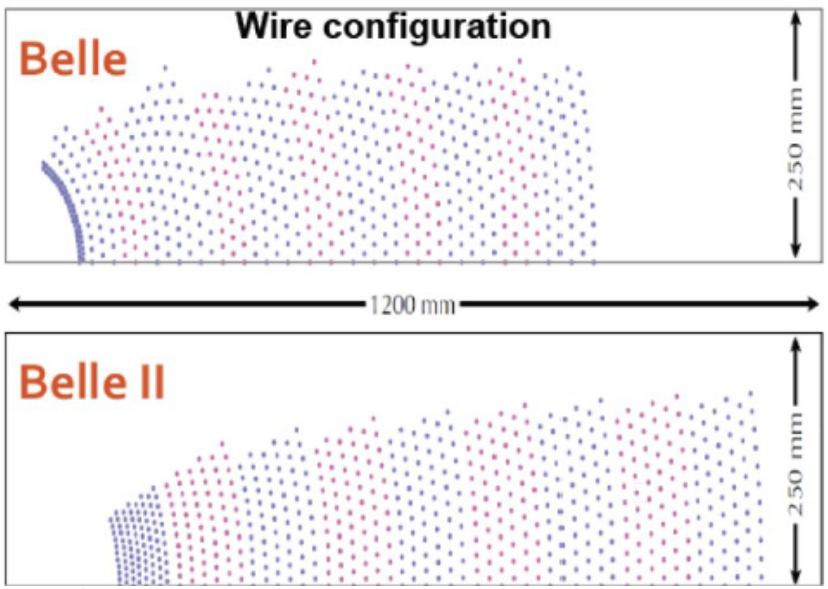
SM $B^0 \to \phi K_S$



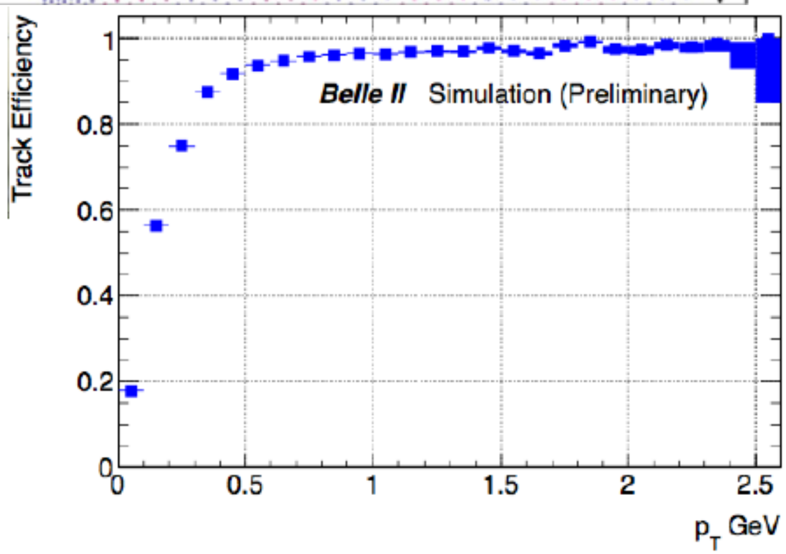
New Physics particles
can contribute

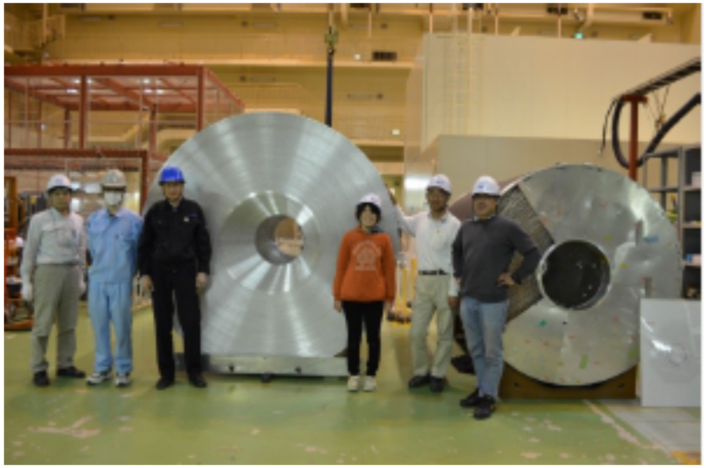


Central Drift Chamber (CDC)

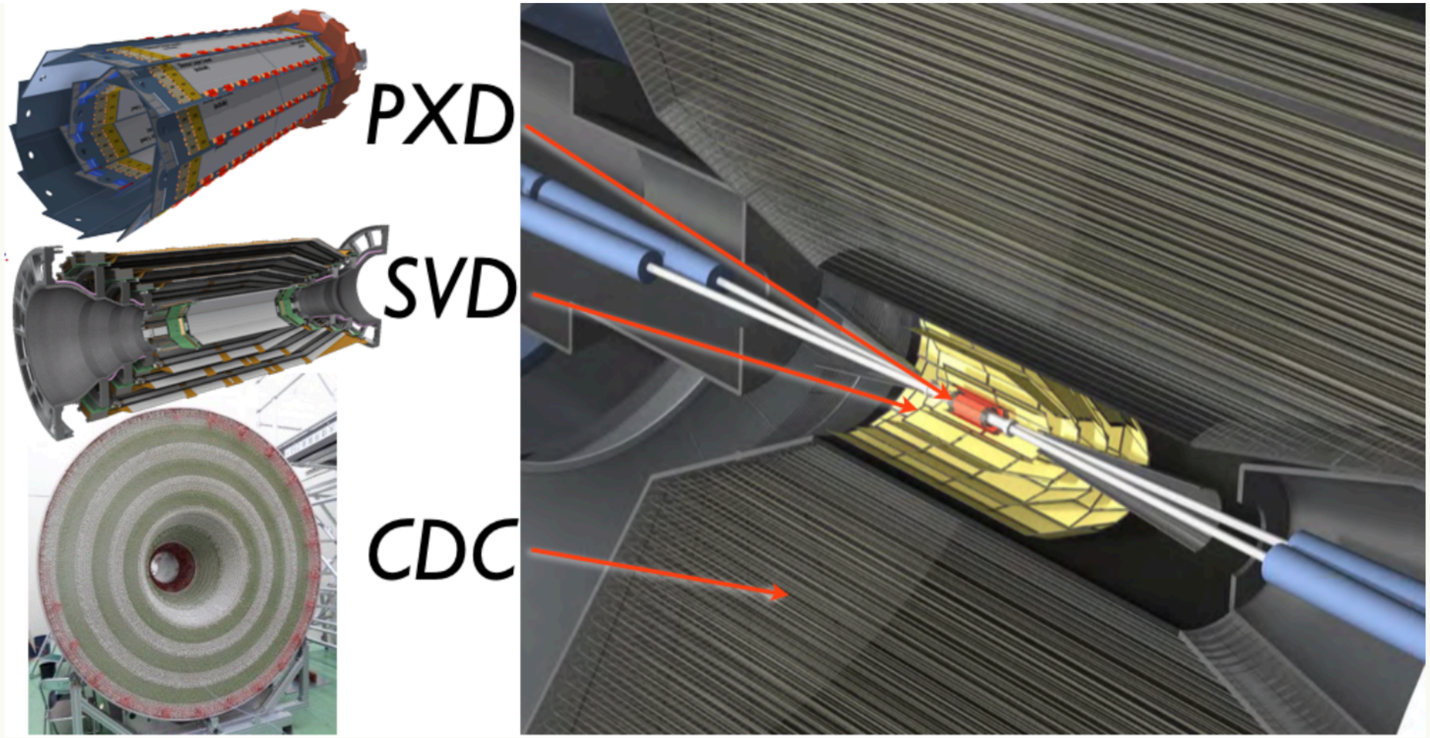


	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	$He:C_2H_6$	$He:C_2H_6$
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)





Belle II Tracking Detectors



Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20$ μm (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\leq z \leq$ 159 cm	14 k	$\sigma_{r\phi} = 100$ μm, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\%p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\%p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

SuperKEKB nanobeams

At SuperKEKB, we increase the luminosity based on "Nano-Beam" scheme (originally proposed for SuperB by P. Raimondi)

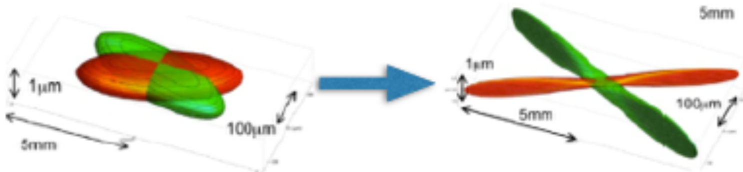
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Luminosity Gain

- Vertical β function at IP: 5.9 → 0.27/0.30 mm (x20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (x2)

→ L = 2×10^{34} → 8×10^{35} $cm^{-2}s^{-1}$ (x40)

To get 40x luminosity of Belle



Reduce beam size to a few 100 atomic layers!

Parameter		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathcal{L}$	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

Belle II Collaboration

As of Mar. 2017

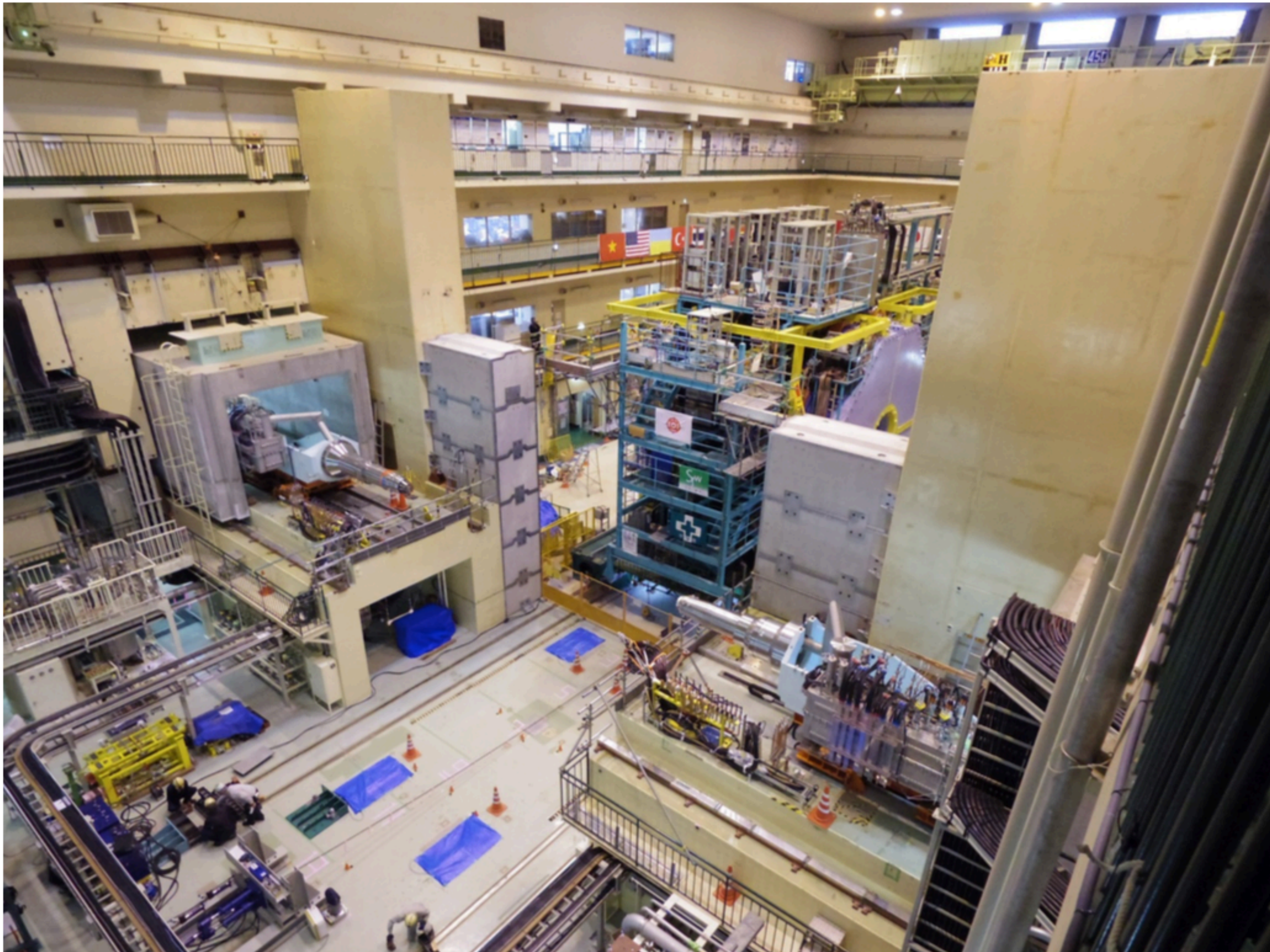
23countries/regions
101 institutions
~750 researchers

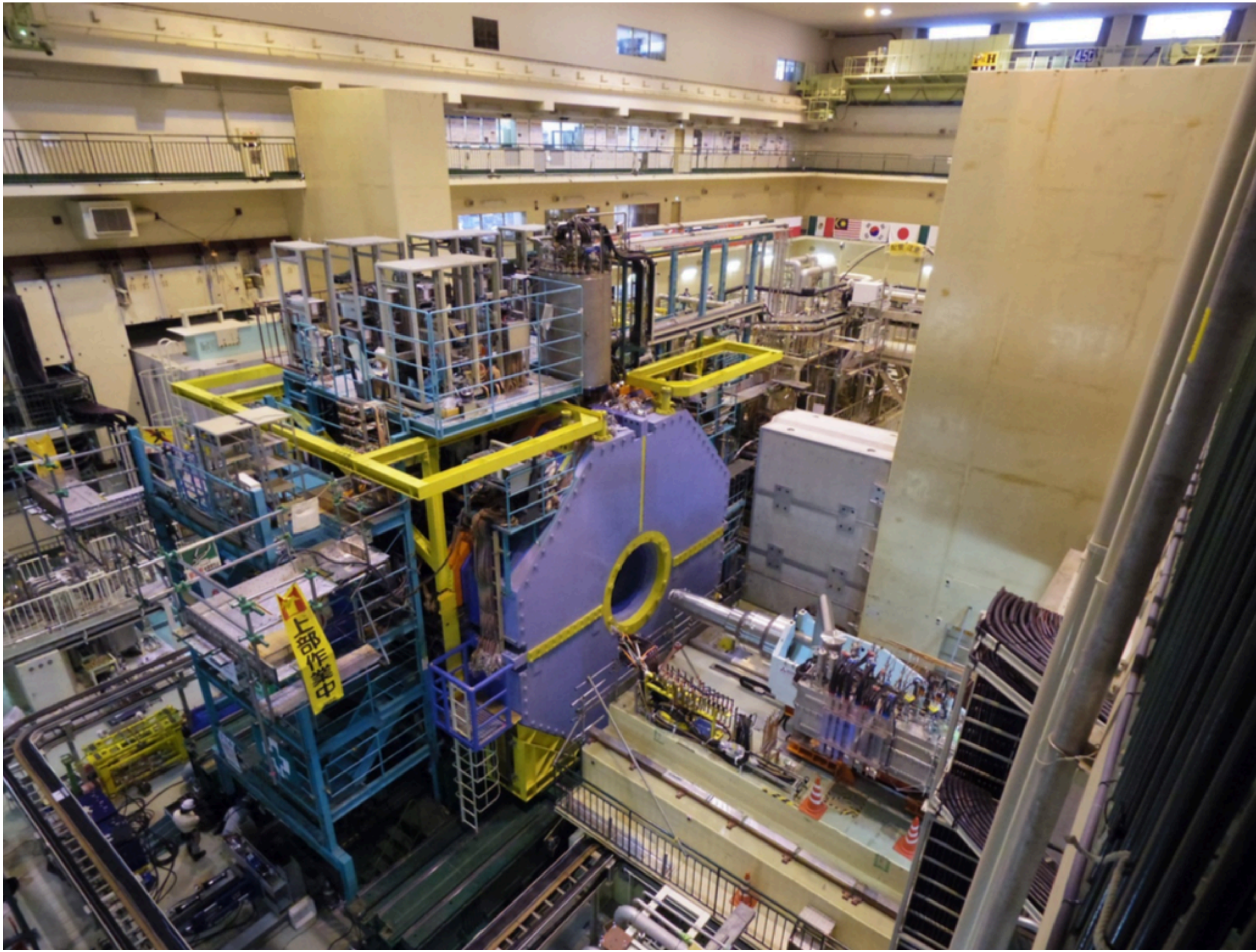
+France since June 2017

Europe	285
Austria	14
Czechia	7
Germany	110
Italy	73
Poland	11
Russia	46
Slovenia	17
Spain	4
Ukraine	3

Asia			345
Saudi Arabia	3	Korea	44
Australia	36	Malaysia	5
China	29	Vietnam	2
India	40	Taiwan	22
Japan	161	Thailand	2
		Turkey	1

America	119
Canada	23
Mexico	11
USA	85

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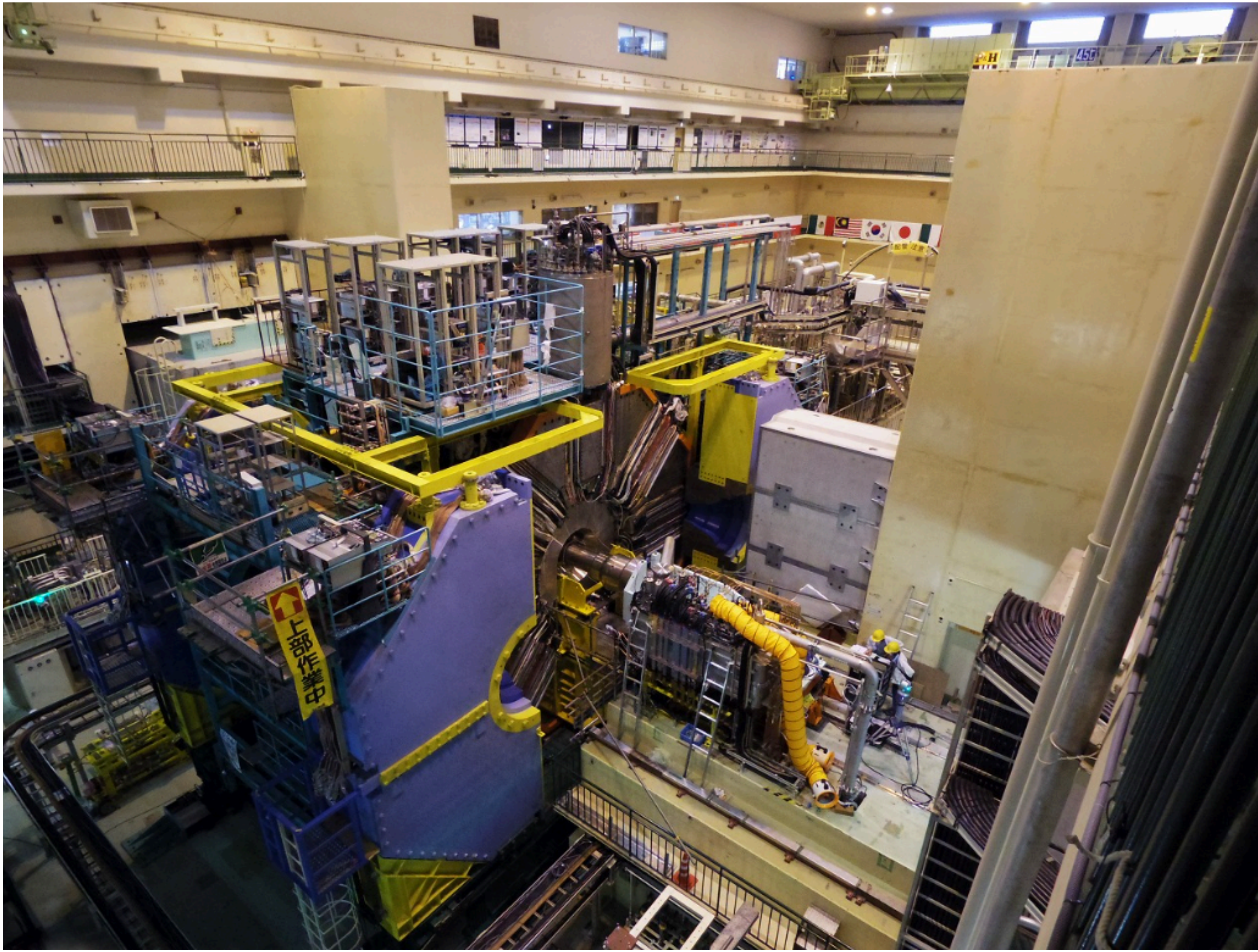
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