The Belle II Experiment: Status and Physics Prospects

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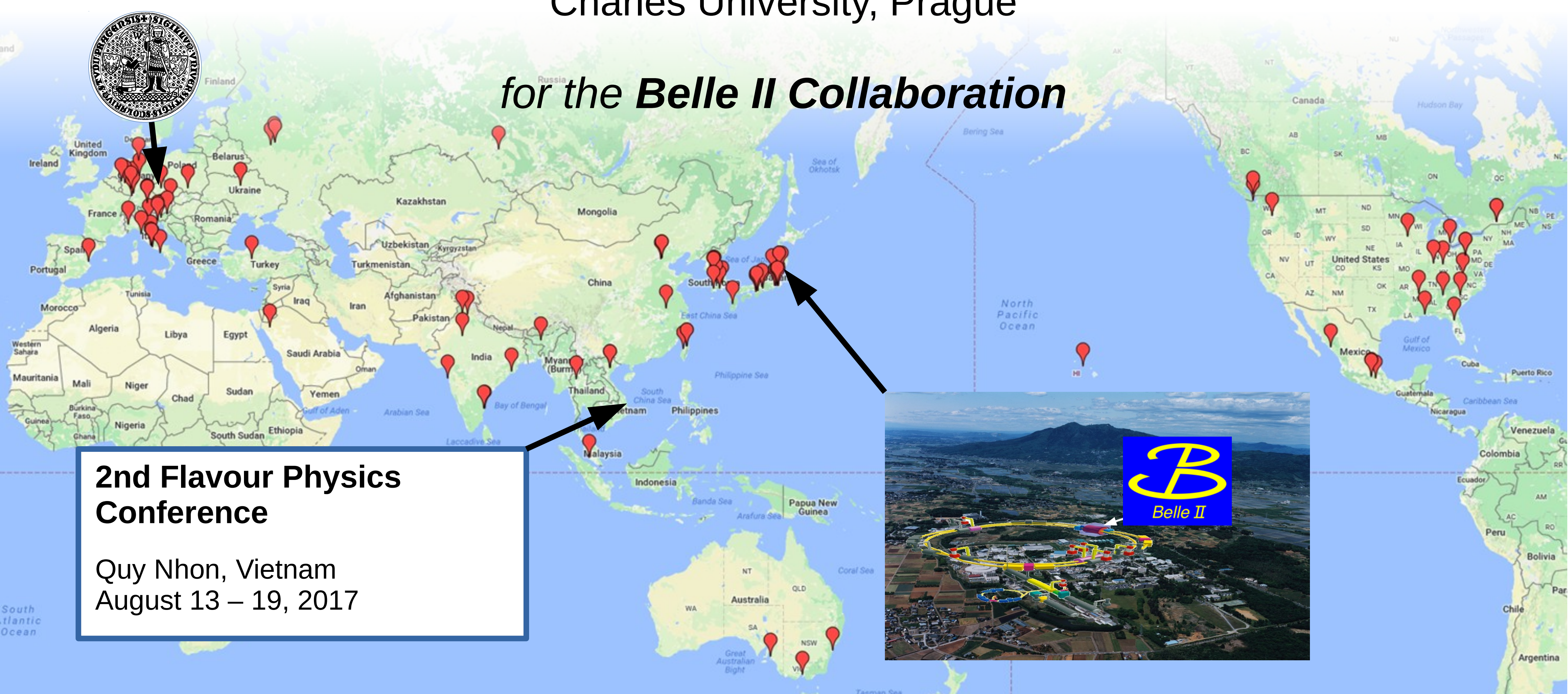
*for the **Belle II Collaboration***



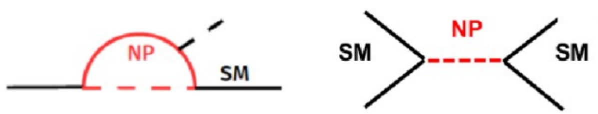
2nd Flavour Physics Conference

Quy Nhon, Vietnam
August 13 – 19, 2017

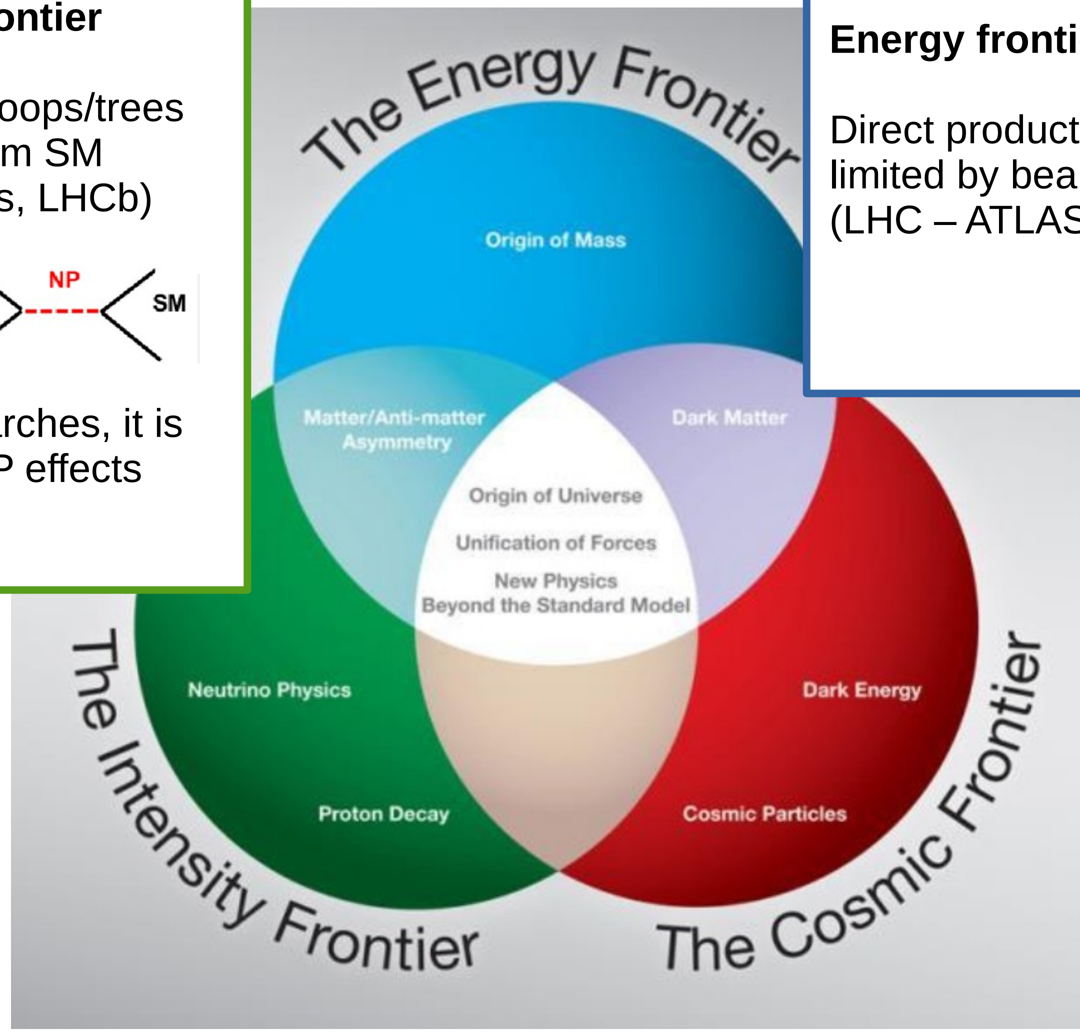
The hunt for New Physics

Intensity / precision frontier

New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)

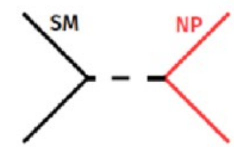


If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays

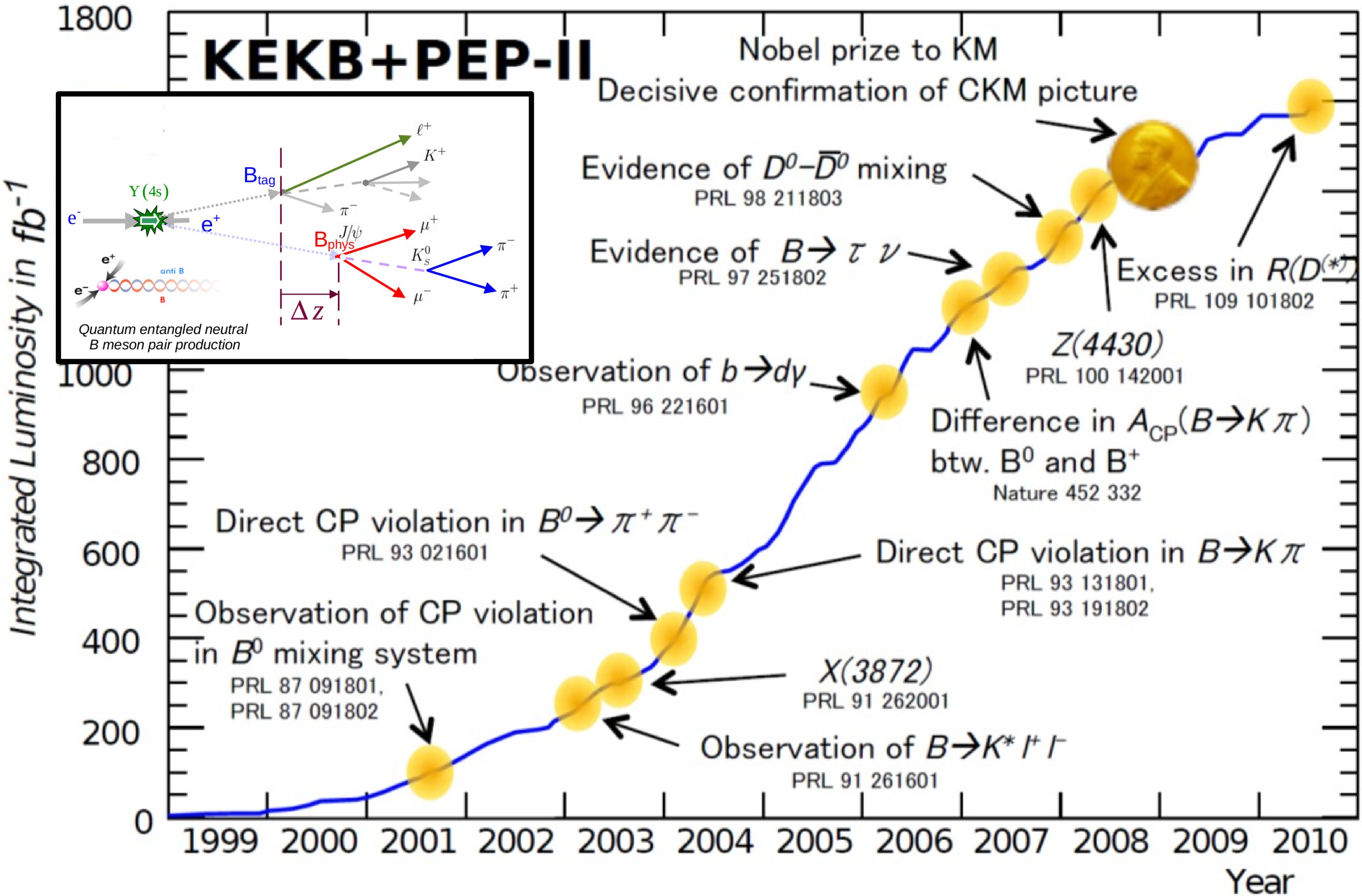


Energy frontier

Direct production of new particles - limited by beam energy
(LHC – ATLAS, CMS)

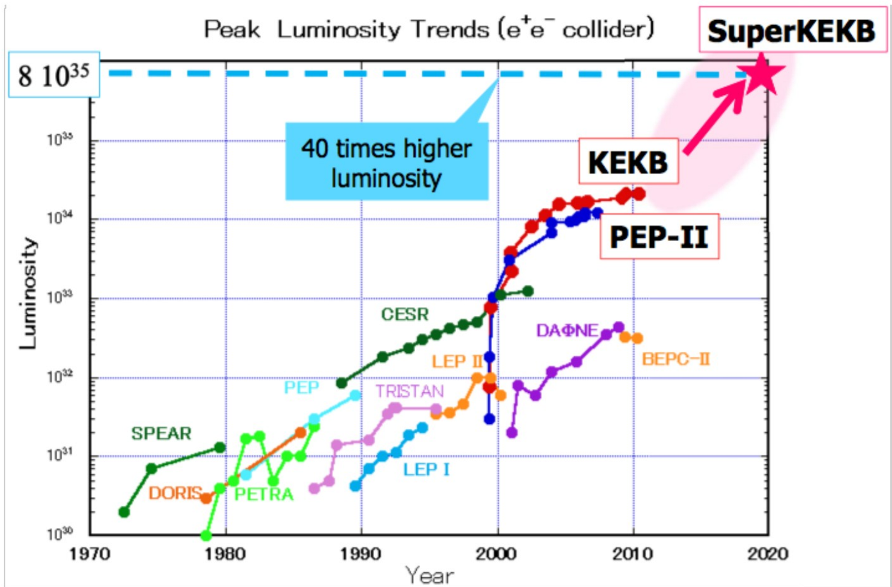


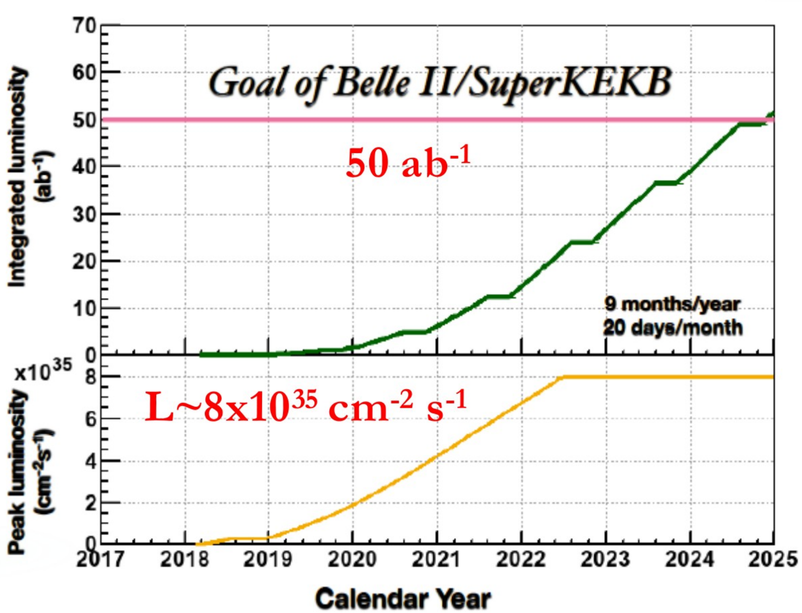
Rich legacy of B-Factories



The next generation Super-B-Factory

$\mathscr{L}_{peak}=2\cdot10^{34} \rightarrow 8\cdot10^{35}/cm^2s$



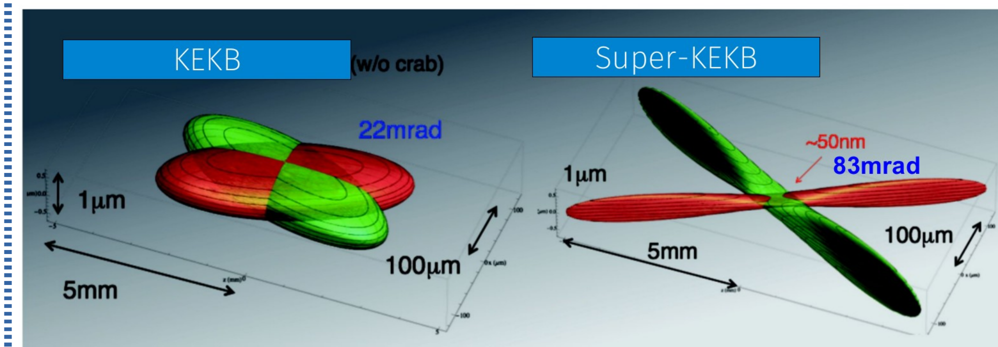


40 x KEKB luminosity: **Nano-beam**

beam current

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

vertical beta function at IP

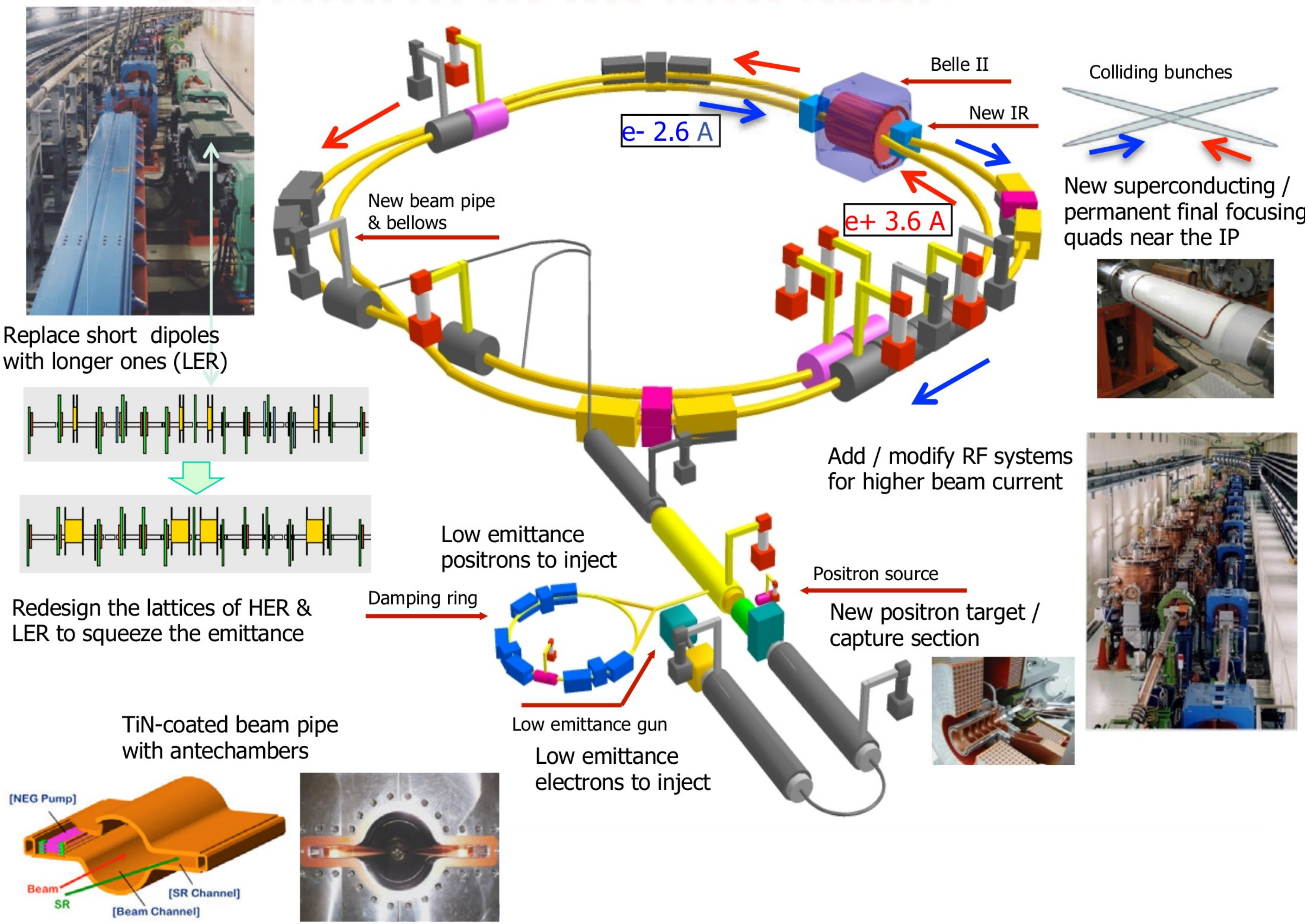


	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

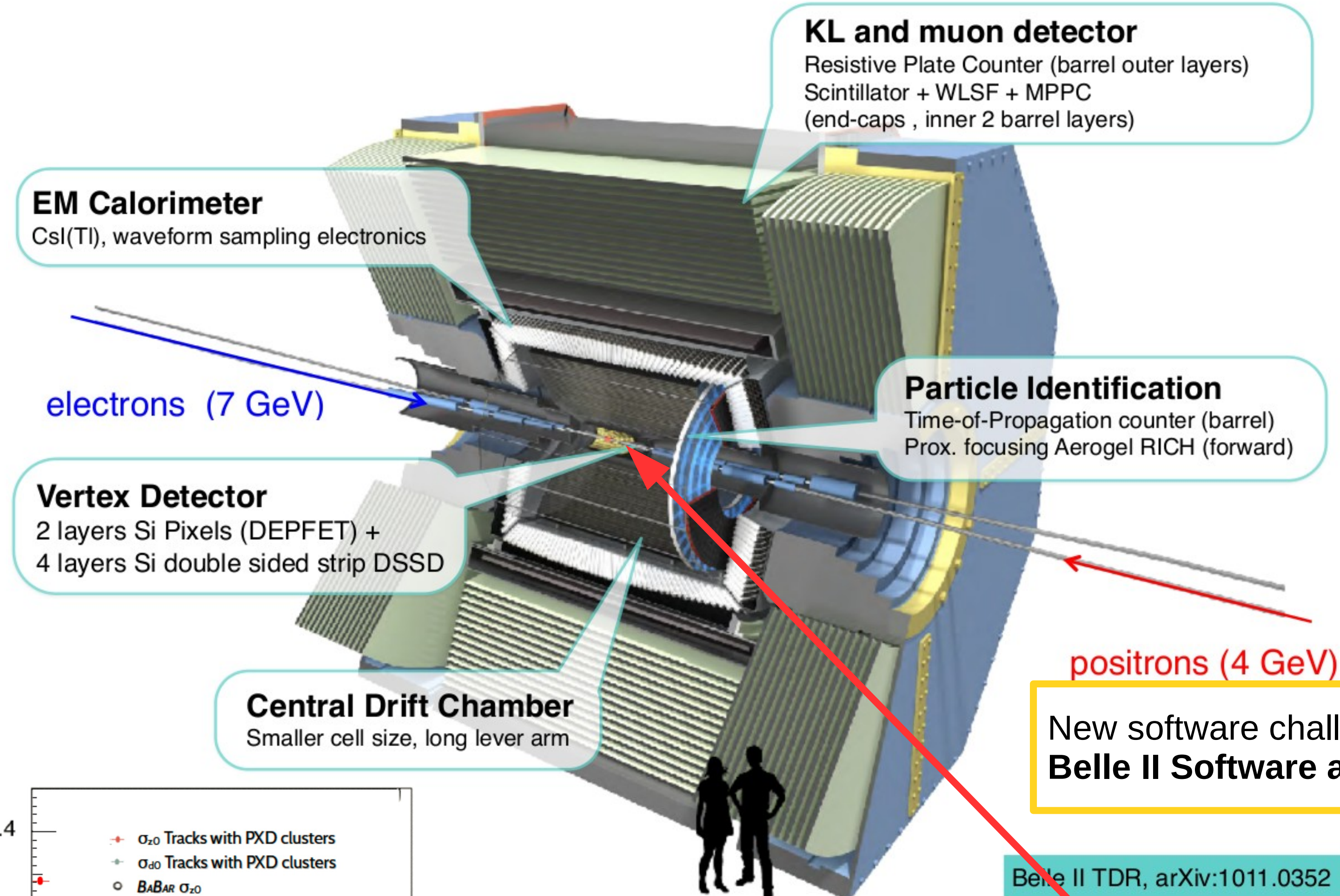
factor 20

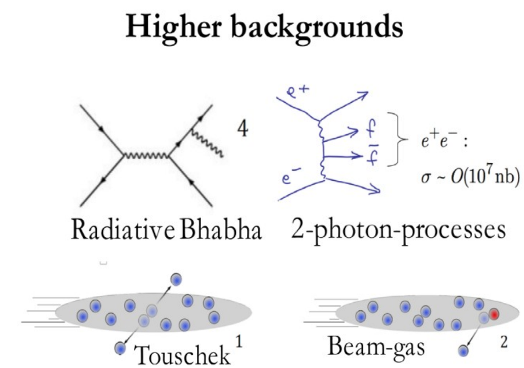
factor 2-3

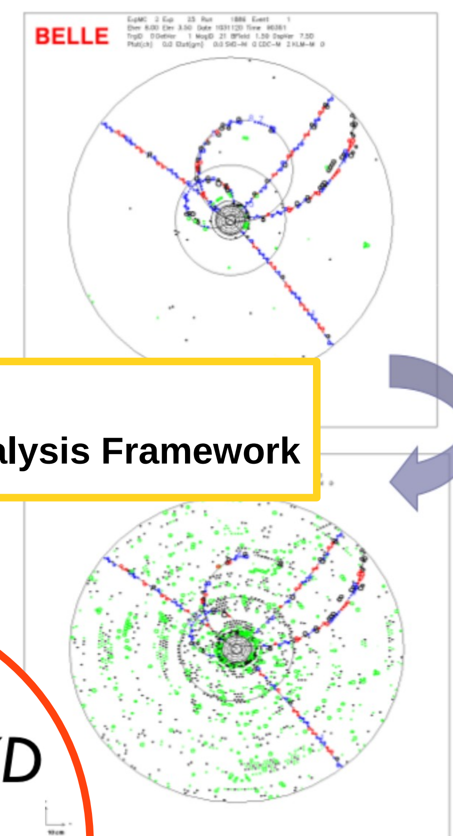
KEKB → SuperKEKB



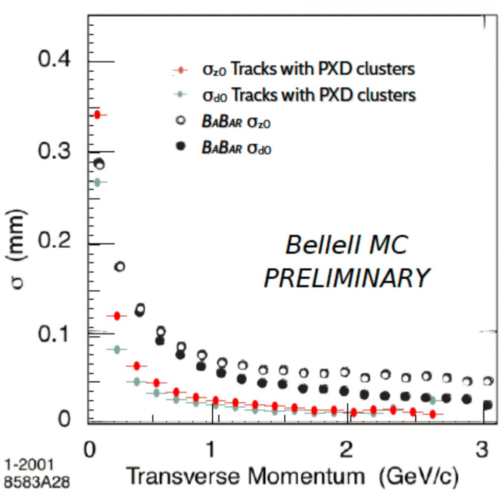
Belle → Belle II

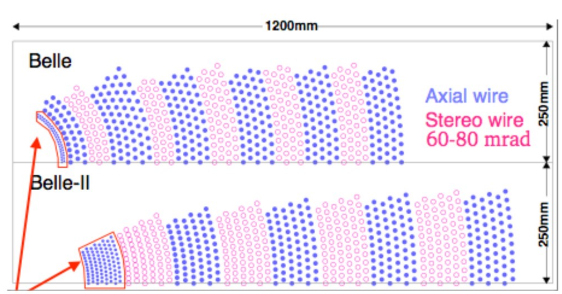


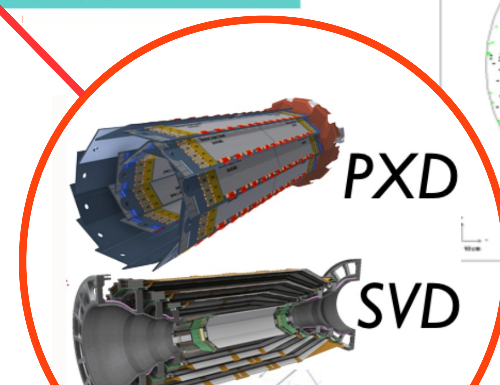




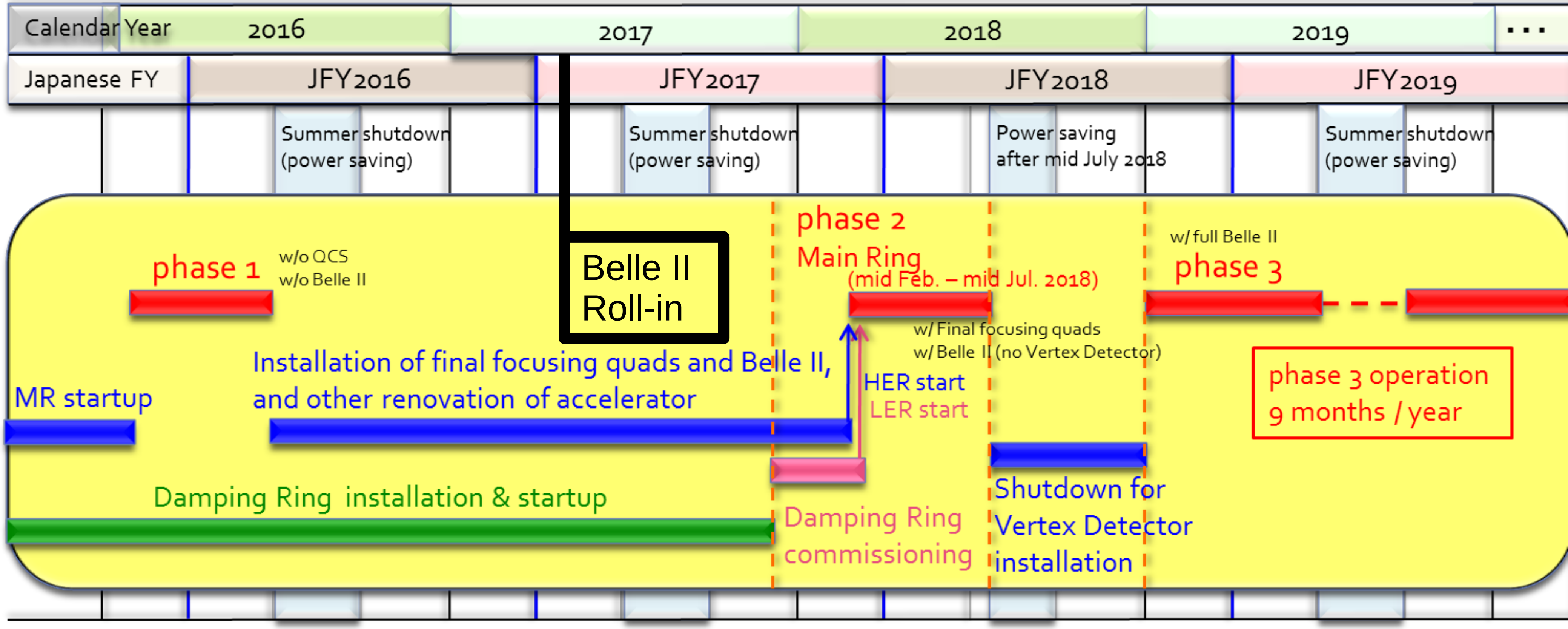
New software challenges:
Belle II Software and Analysis Framework







Status & Schedule

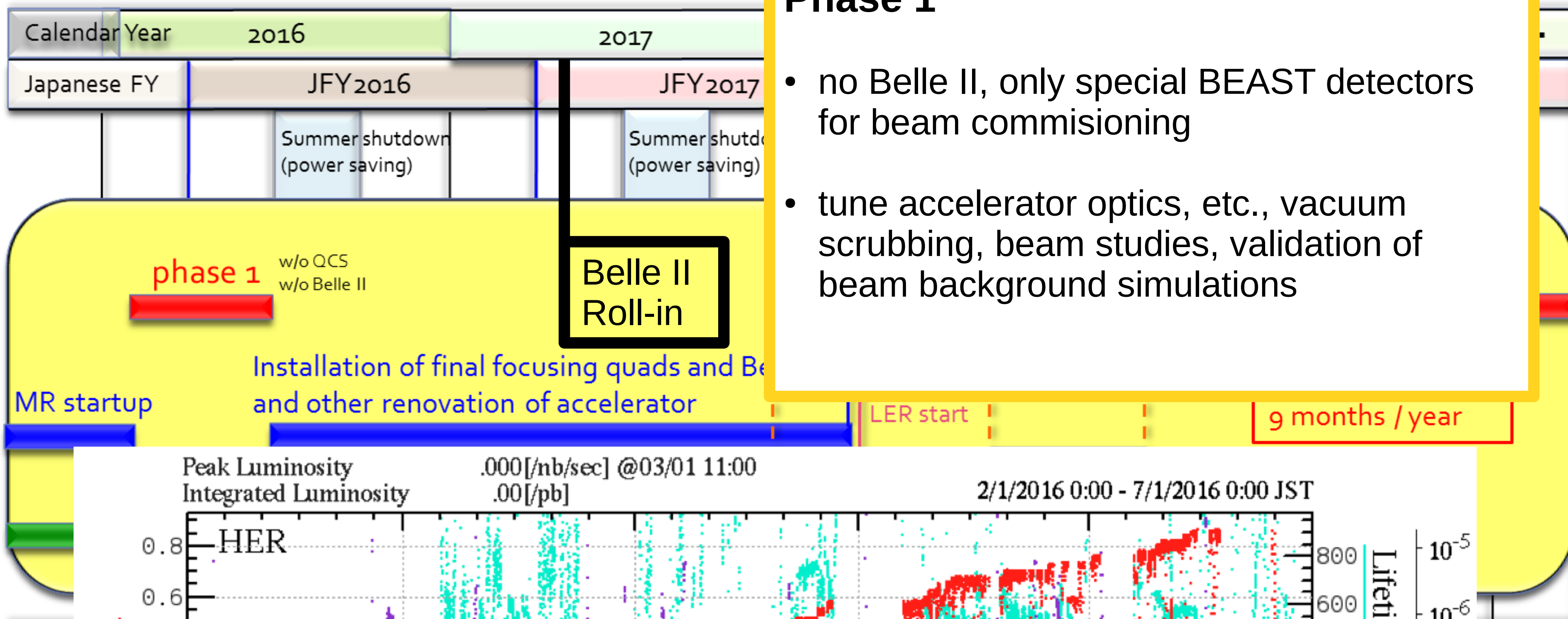


Phase 1 (2016): beams, no collisions, cosmics

Phase 2 (2018): collisions, complete Belle II detector except for Vertex Detector

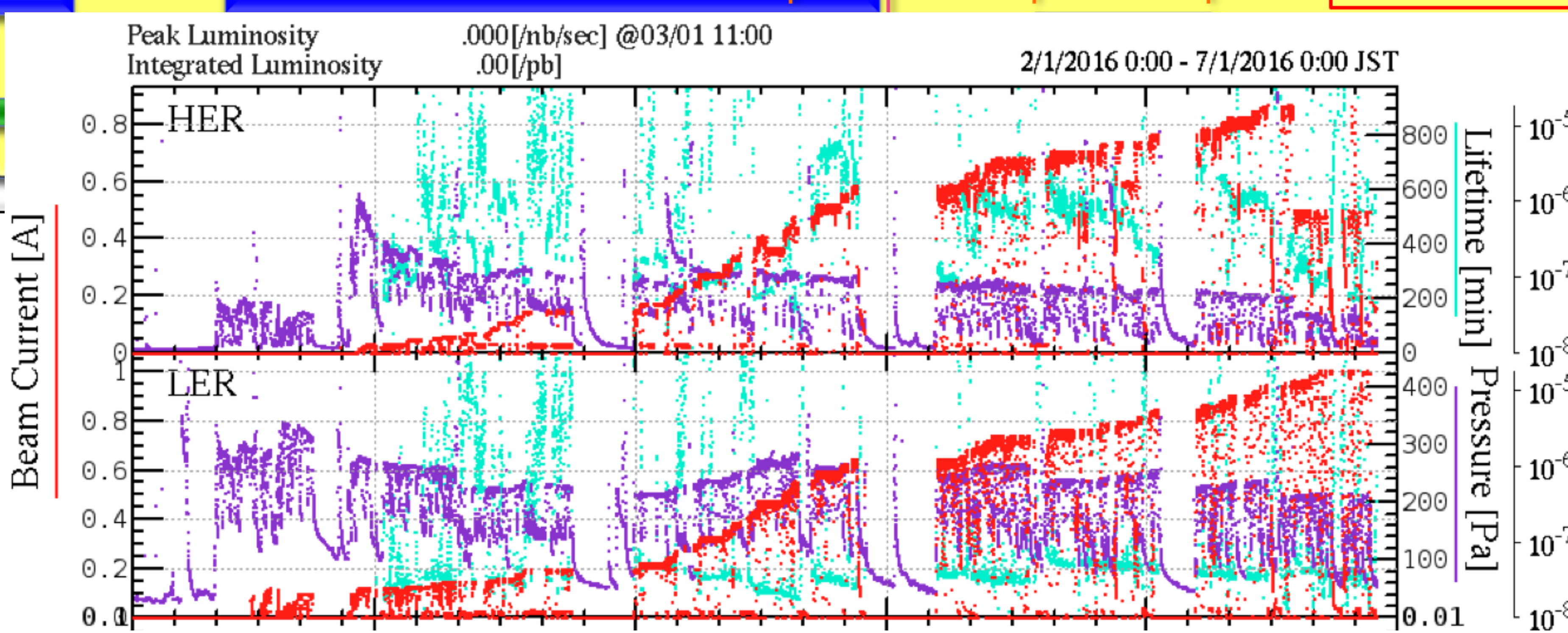
Phase 3 (end 2018 – 2024): full Belle II detector

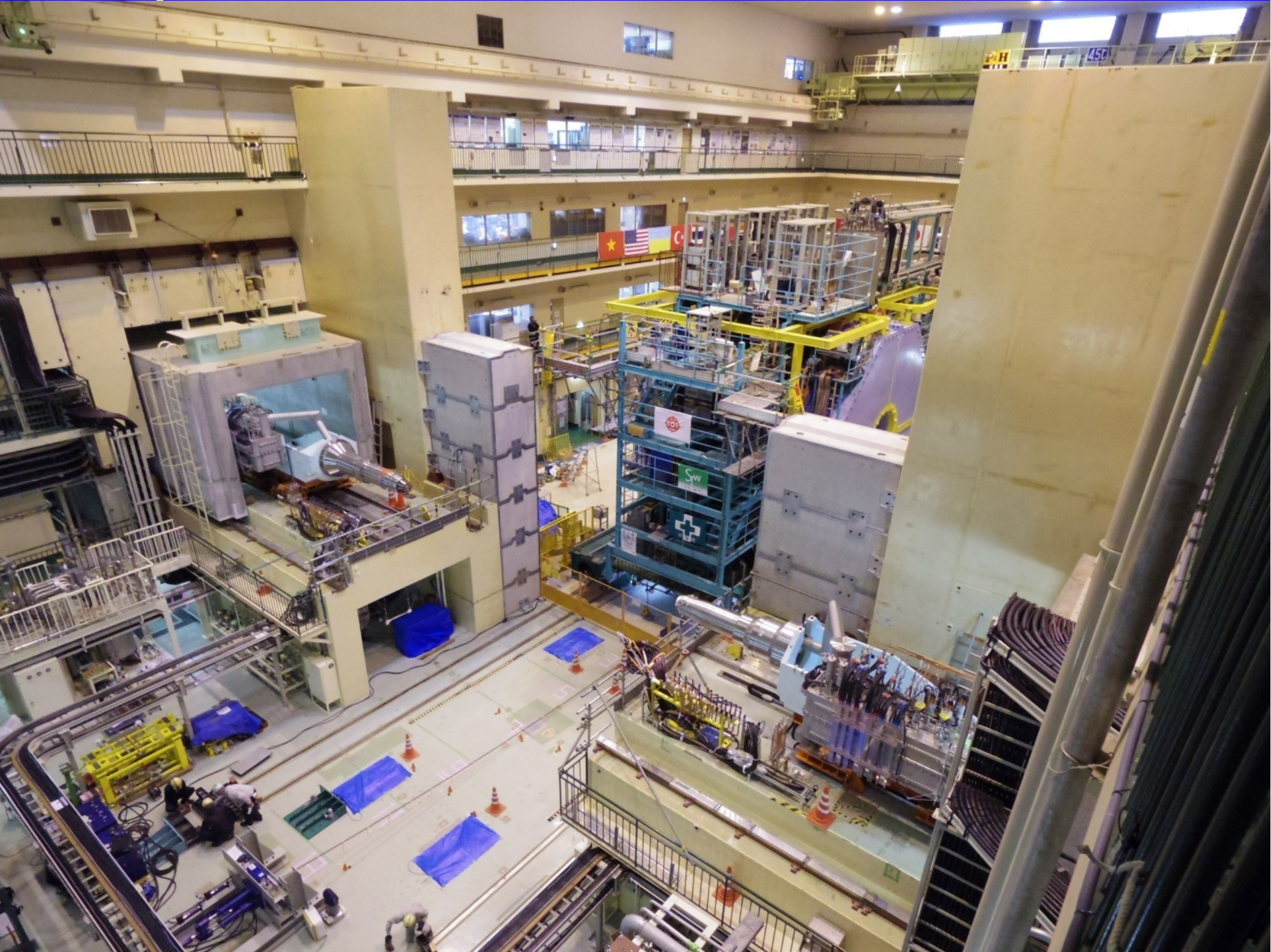
Phase 1: Done!



Phase 1

- no Belle II, only special BEAST detectors for beam commisioning
- tune accelerator optics, etc., vacuum scrubbing, beam studies, validation of beam background simulations

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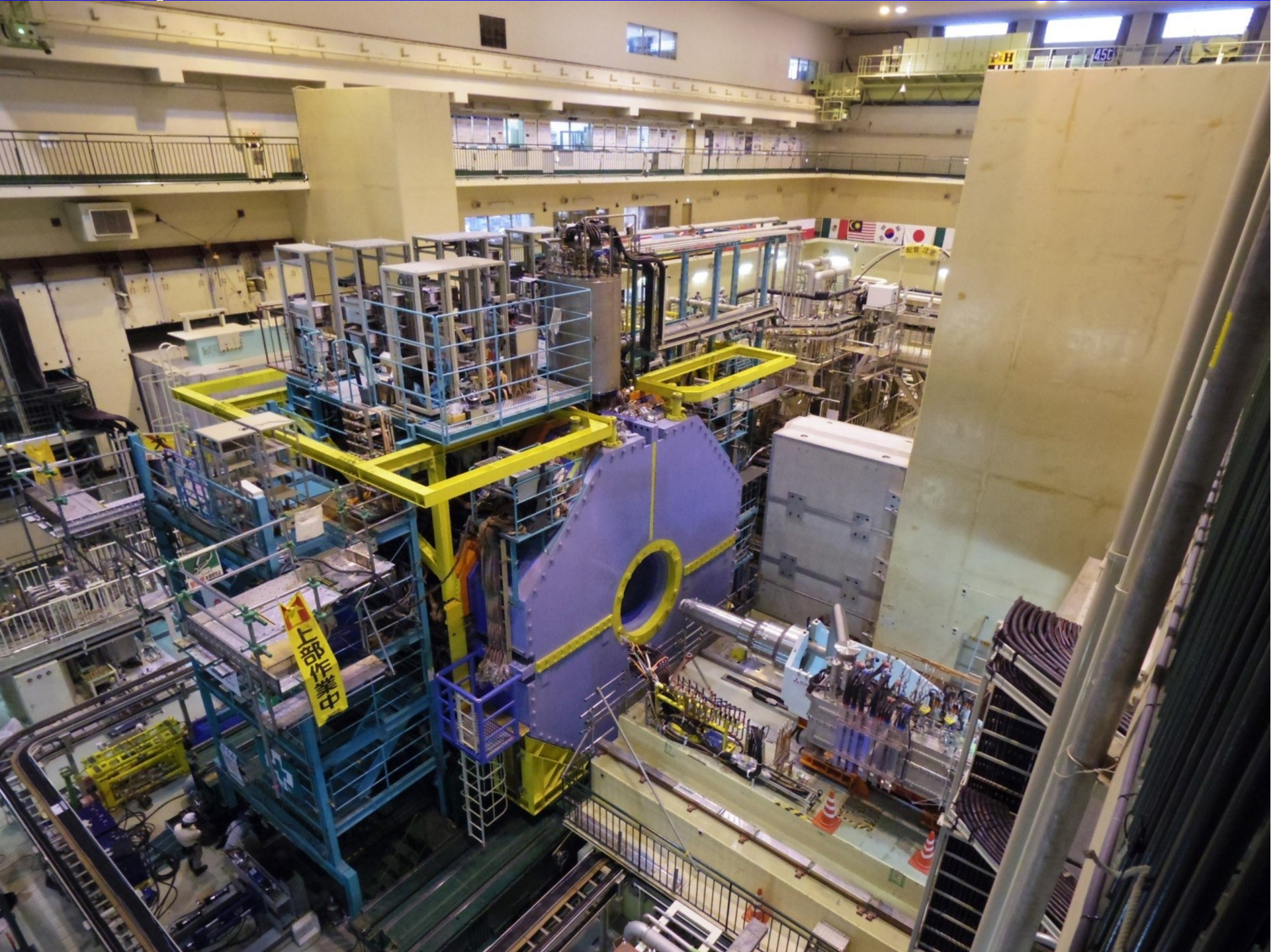
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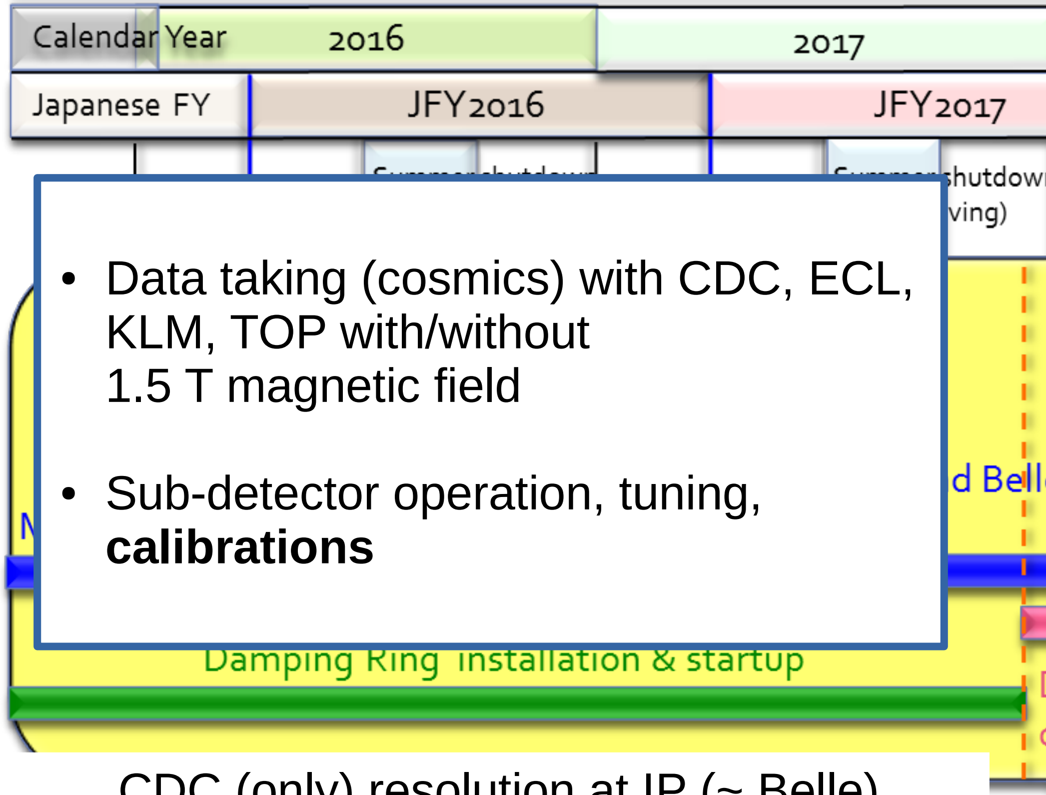
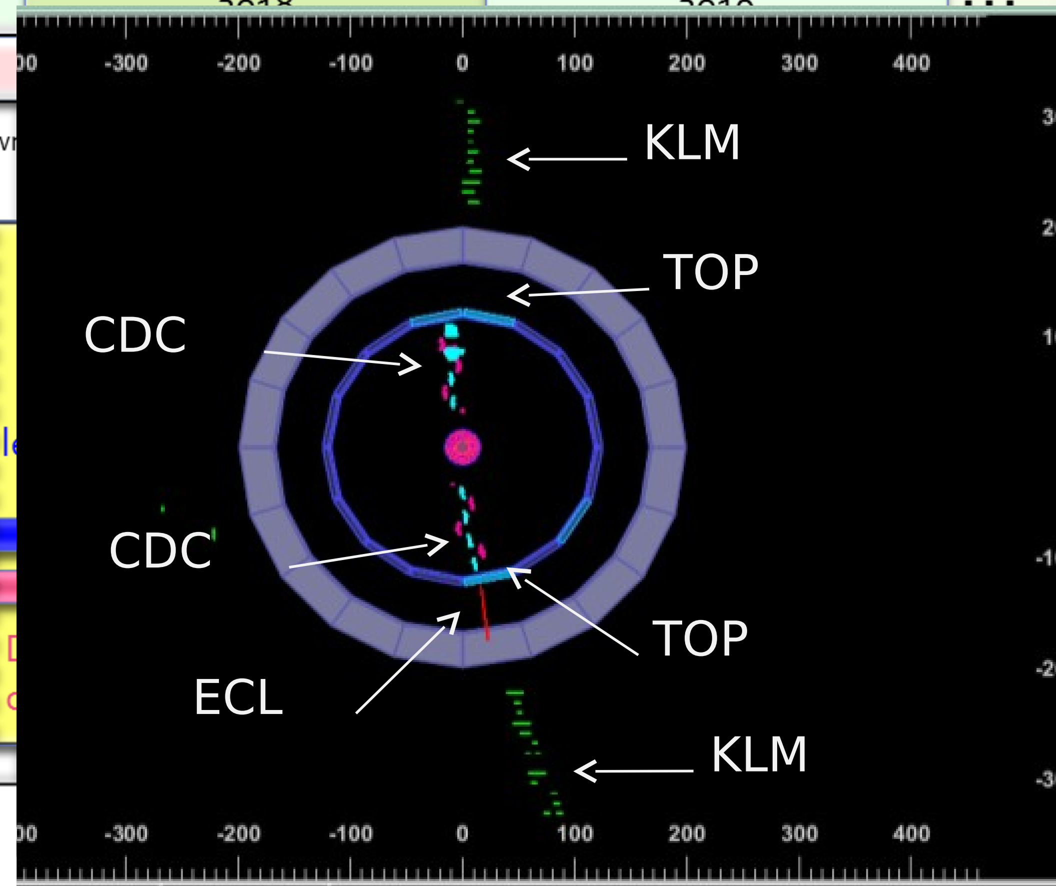
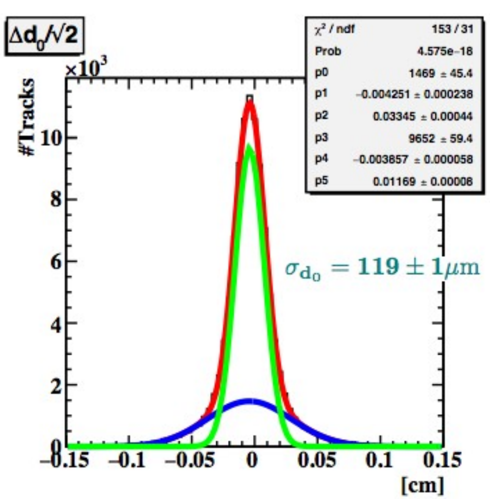
Global Cosmic Run: In progress

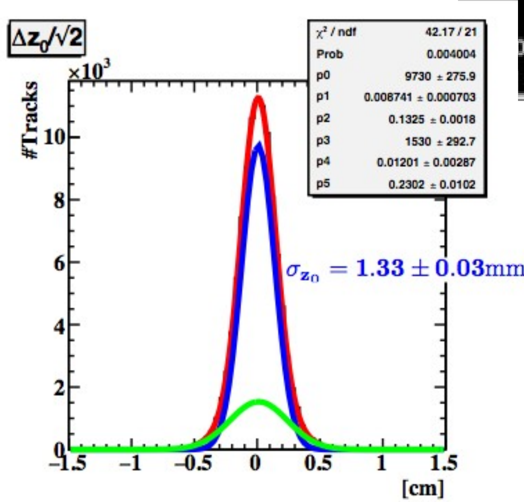


- Data taking (cosmics) with CDC, ECL, KLM, TOP with/without 1.5 T magnetic field
- Sub-detector operation, tuning, **calibrations**



CDC (only) resolution at IP (~ Belle)





Belle II Calibration Framework

- Automatization calibration workflow, algorithm dependencies, monitoring...
- Novel approaches to calibration: simultaneous alignment + calibration of vertex, drift chamber, muon system … global fit using **Millepede II**

doi:10.1016/j.nima.2006.05.157

Belle II Physics Prospects

Only selection of examples
(Sorry if I did not include your favourite)

Physics overview

See next talk by Nibedita

With 50 ab-1 of e^+e^- collisions at (or close to) Y(4S) we have/can:

- (Super) B-Factory (~ 1.1 x 10^9 $B\bar{B}$ pairs per ab^{-1})
- (Super) Charm-Factory (~ 1.3 x 10^9 $c\bar{c}$ pairs per ab^{-1})
- (Super) Tau-Factory (~ 0.9 x 10^9 tau pairs per ab^{-1})

- Use Initial State Radiation (ISR) to effectively scan $e^+e^- \rightarrow$ light hadrons cross-section in range [0.5 – 10] GeV

- Exploit the clean e^+e^- environment to probe existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ...

- **CPV in B decays** ($B \rightarrow J/\psi K^0, K^0\pi^0\gamma, K\pi$)
- **(Semi)leptonic B decays** ($B \rightarrow D^{(*)}l\nu, \pi l\nu, \tau\nu, \mu\nu$)
- **Rare B decays** ($B \rightarrow K^{(*)}\nu\nu, K^{(*)}ll, X_s\gamma, X_sll, \gamma\gamma$)
- **Charm physics** ($D \rightarrow l\nu$, mixing, CPV)
- **LFV** tau decays ($\tau \rightarrow 3l, l\gamma$)
- **Dark Sector, Spectroscopy** (also early physics)

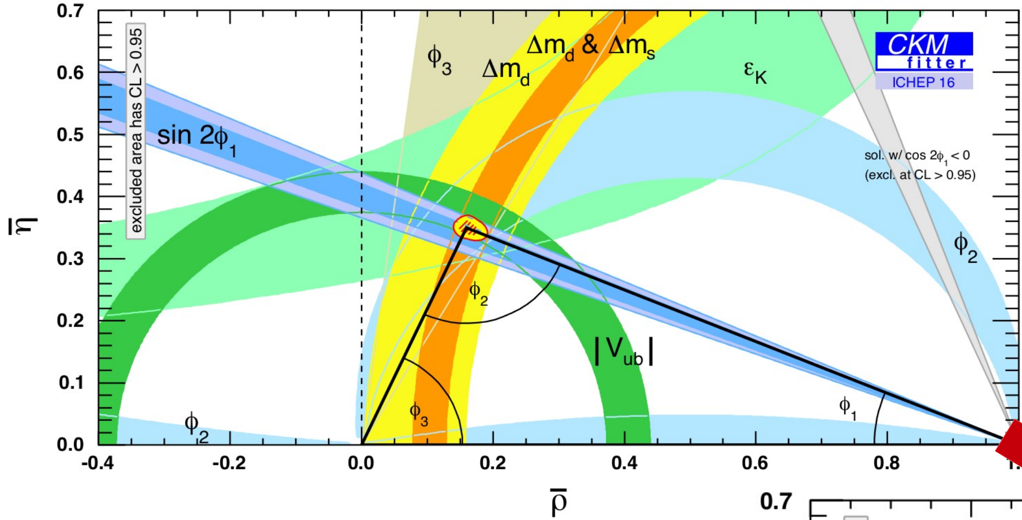
Well defined initial state – Belle II can handle:

- neutral final states $\pi^0\pi^0$, $K_S\pi^0(\gamma)$, $K_SK_SK_S$
- final states with missing energy $\tau\nu$, $D^{(*)}\tau\nu$
- inclusive modes, e.g. $B \rightarrow X_s\gamma$, $B \rightarrow X_s l^+l^-$

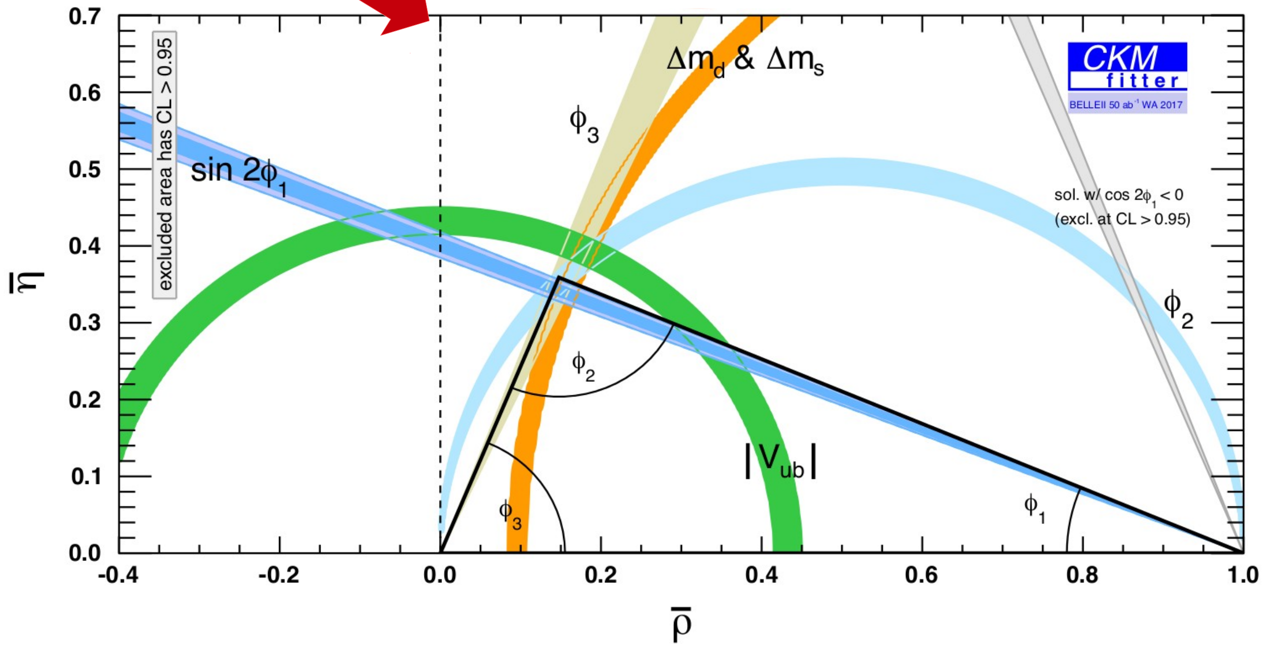
*Belle II **complementary** to LHCb on indirect searches, but also **competitive** in some studies*

Unitarity Triangle in the precision era

Enhanced precision of UT parameters (sides, angles)

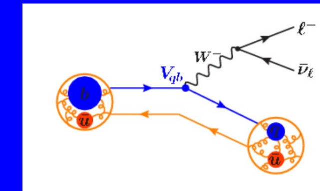


UT angles with ~ 1% uncertainity for 50 ab^{-1}



Inconsistency between angles or/and sites → New Physics

Semileptonic B decays



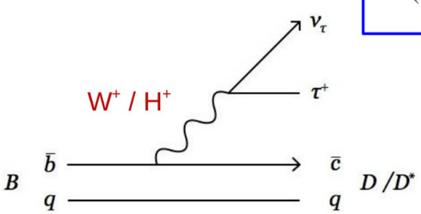
$B \to D^{(*)} \tau \nu$

Hot topic: Ratios R(D(*))

- **Lepton universality** test
- Very clean theory prediction
- World average 4 sigma away from SM

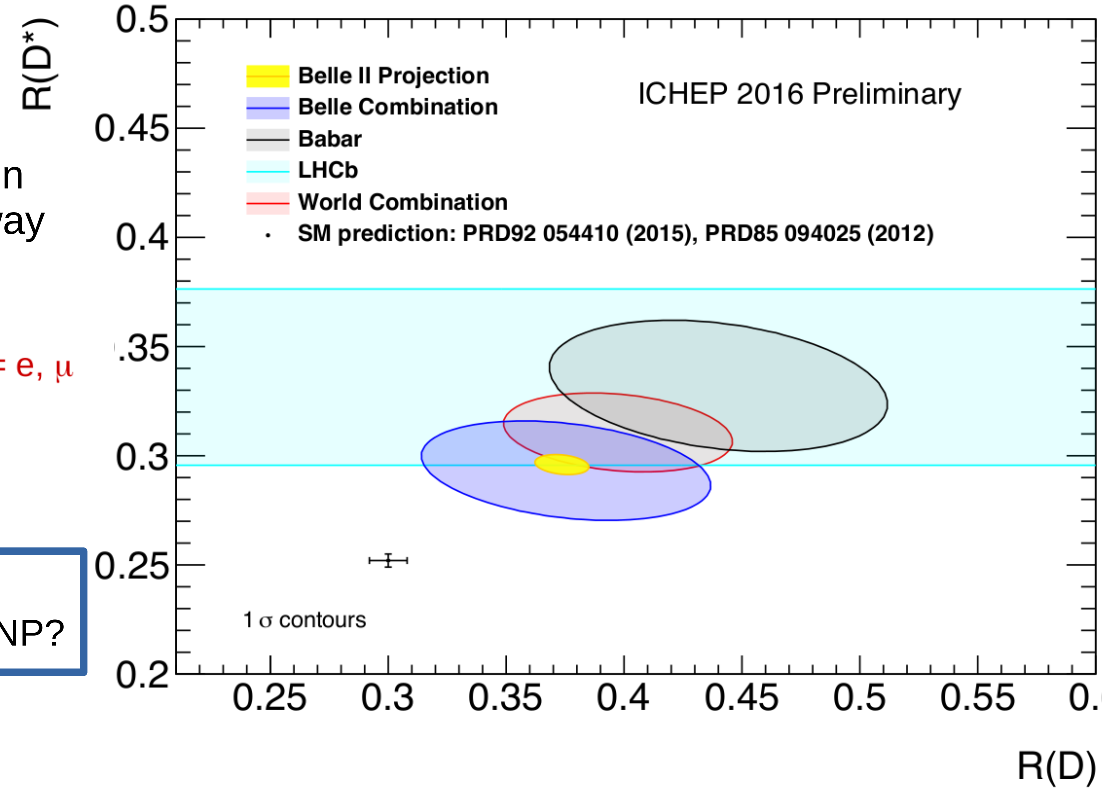
$$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}$$

l = e, μ



sensitive to charged scalars (ex. charged Higgs)
→ *BF modification*

Belle II can reach
3% sensitivity for R(D(*)) → NP?

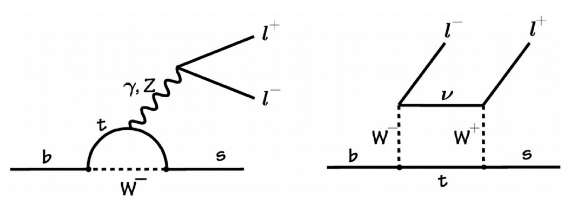


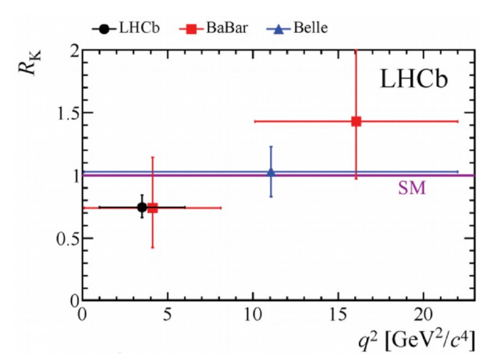
Electroweak Penguins

Lepton Flavor Universality violation in $B^+ \to K^+ l^+ l^-$?

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+\to K^+e^+e^-]}{dq^2}\, dq^2} \approx 1$$

Confirmation from Belle II will be crucial
(good efficiency for electrons and muons
in wide q^2 range)





2.6σ tension from latest LHCb measurement

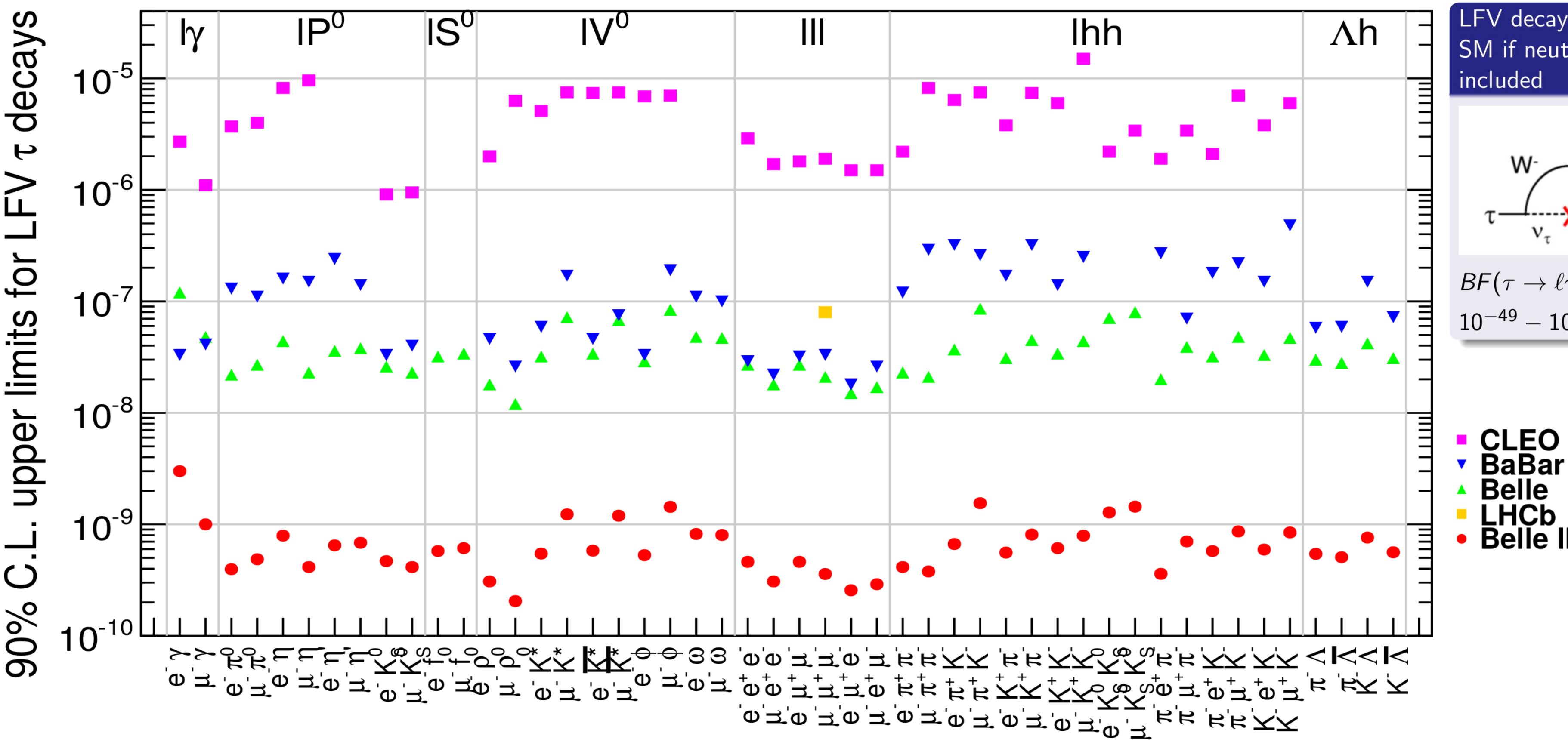
Tau Physics

Lepton Flavour Violation in τ decays

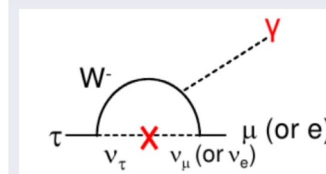
- In the SM, lepton flavour violating decays, like $\tau \rightarrow \mu\,\gamma$, are forbidden/highly supressed, while NP could enhance their BF's significantly
- Belle II can access final states with neutrals $(\gamma, \pi^0, \eta^{(\prime)}, \ldots)$
- Control of beam backgrounds crucial

Sizable enhancement of BF by new physics models for LFV tau decays

model	reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}



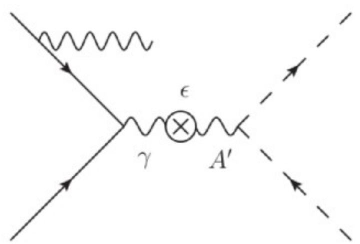
LFV decay only allowed in SM if neutrino mixing included



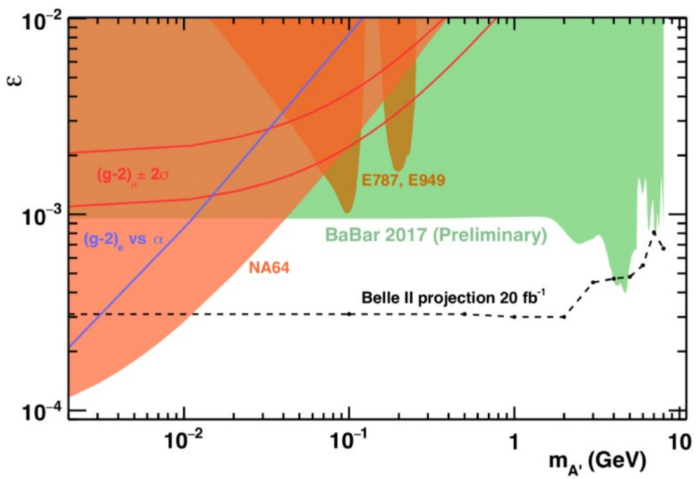
$BF(\tau \to \ell\gamma) \approx \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \approx 10^{-49} - 10^{-54}$

e+e- → light hadrons, dark things, spectroscopy, exotic states...

Dark Photon Search

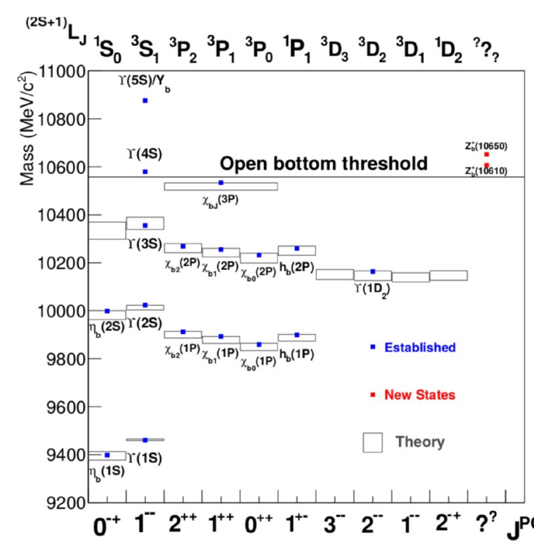


Special single photon trigger required



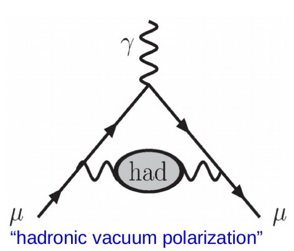
Early Physics (2018)

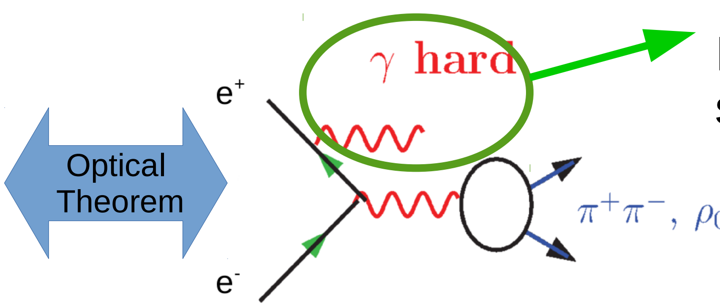
Bottomonium States



e^+e^- → light hadrons

- Long standing discrepancy between theory and experiment in the $(g-2)_\mu$ (3.5 sigma)
- Most of the uncertainity in the theory comes from the hadronic controbution:





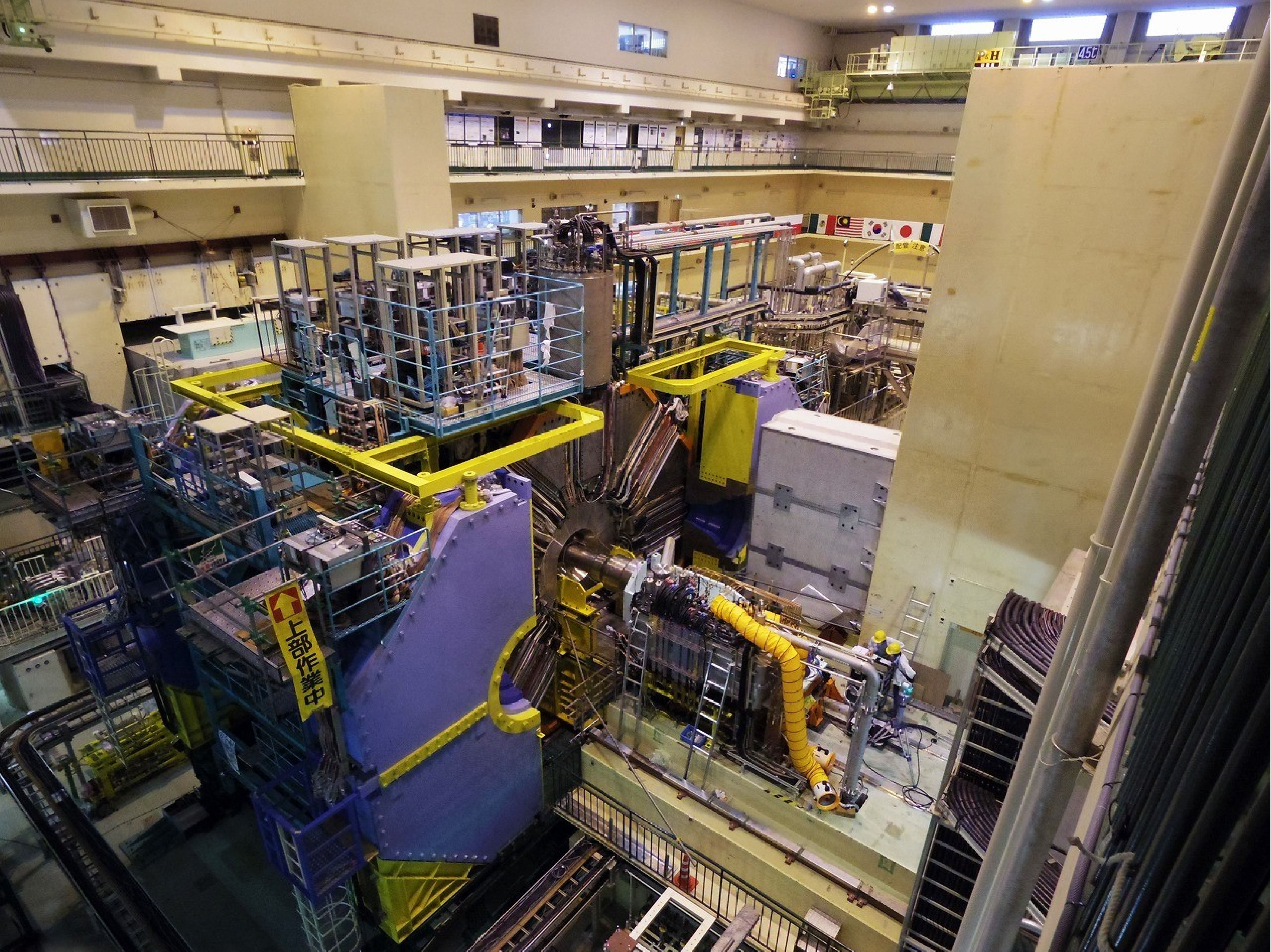
ISR: Energy scan

Belle II

Summary

- New Super-B-factory generation under successful commisioning
- Belle II will join LHCb in the hunt for New Physics just in time – competitive but also complementary
- Several tensions in SM known, Belle II can give definitive resolution
- If NP found at LHC, Belle II could reveal its flavour structure and/or weak phases. If not, precision measurements at Belle II even more important
- First physics without vertex early 2018, 2018/2019: full detector

Thank you for your attention!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Belle II & 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* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 2018	LHCb 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		

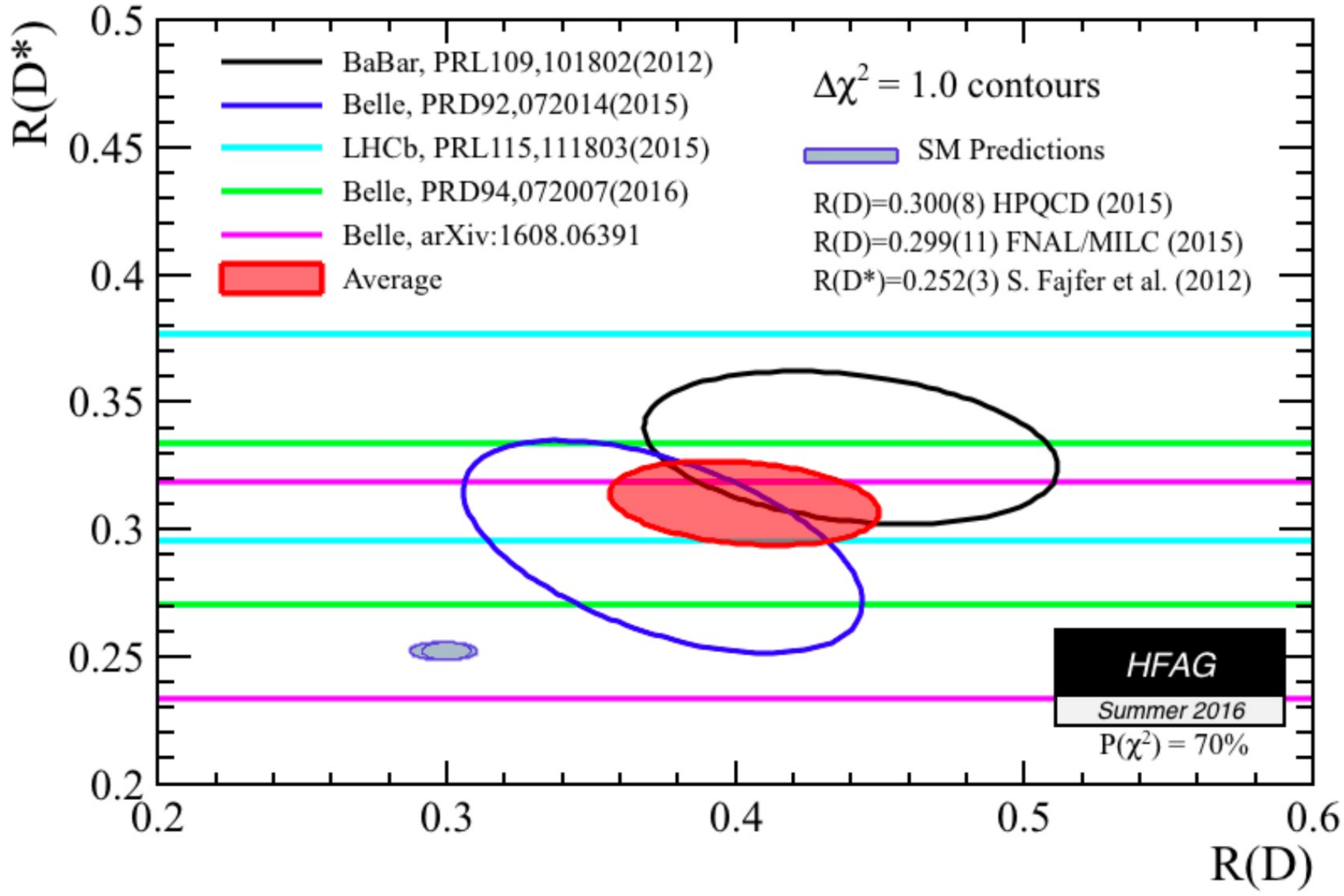
Phase 2 Physics

WG	Mode	Description	Benchmark study or Unique measurement?
Semileptonic	B→X l ν	Benchmark analysis in Υ(4S)	Benchmark
Semileptonic	B(s)→X l ν in Υ(6S), Di-leptons	B and B_s counting in Υ(6S)	Unique
EWP	B→K*γ	Benchmark analysis in Υ(4S)	Benchmark
BtoCharm	B → Dπ. D*π, D → hh, K_S X	Benchmark analysis in Υ(4S)	Benchmark
Bottomonium	Υ(6S) → ππ + Υ(nS)/hb	Zb substructure	Unique
Bottomonium	Υ(6S) cross section, R_b	Cross section measurement and Rb decomposition at Υ(6S)	Unique
Bottomonium	π π Υ(pS)	ECM 10.75 GeV decay → π π Υ(pS)	Unique
Low-multiplicity	ee → γ A', A'→ missing	Dark matter via dark photon	Unique
Low-multiplicity	ee → γ A'→ γ γ	Axion like dark sector for large A' masses (tri-photon final state)	Unique

Expected data sample @ full luminosity

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$ Υ(4S)	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

assuming 100% running at each energy


R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, arXiv:1608.06391
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
HFAG
Summer 2016
P(χ²) = 70%

Expected SuperKEKB Backgrounds

Phase I (no collisions)

***Touschek* scattering:**
- intra-bunch scattering process
- dominant with highly compressed beams
- 20 times higher

Beam-gas scattering:
- Bremsstrahlung (negligible) & Coulomb interactions (up to 100 times higher) with residual gas atoms & molecules

Synchrotron radiation:
- emission of photons by charged particles (e^+e^-) when deflected in *B*-field

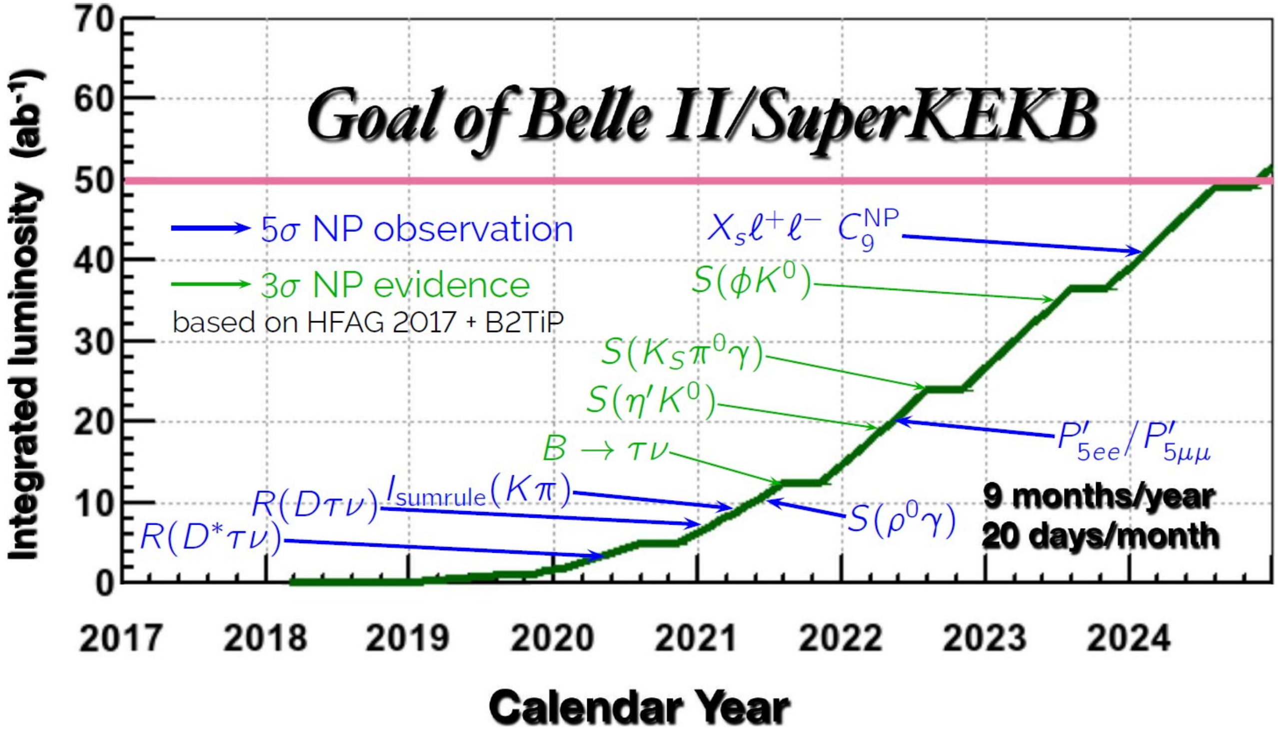
Phase 2 (collisions)

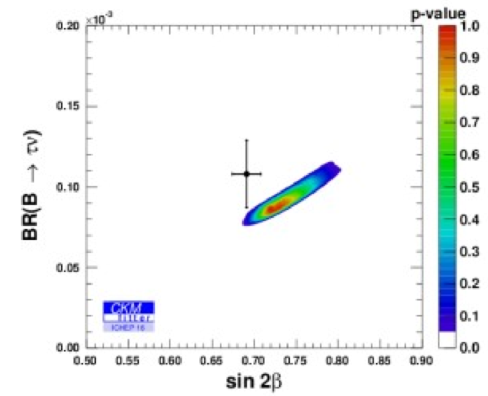
***Radiative Bhabha* process:**

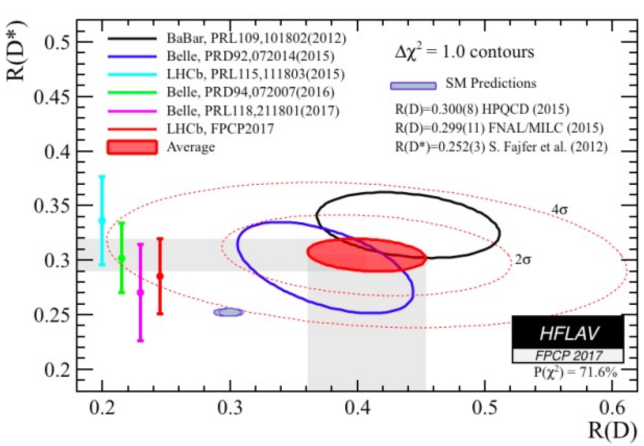
photon emission prior or after *Bhabha* scattering
interaction with iron in the magnets leads to neutron background

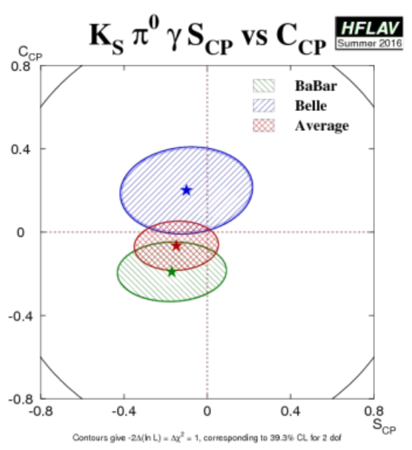
***Two photon* process:**
- very low momentum e^+e^- pairs via $e^+e^- \rightarrow e^+e^-e^+e^-$
- increased hit occupancy in inner detectors

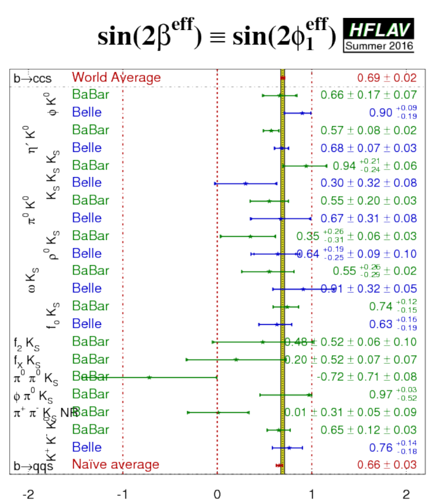
Injection Background:
- covered later in the talk

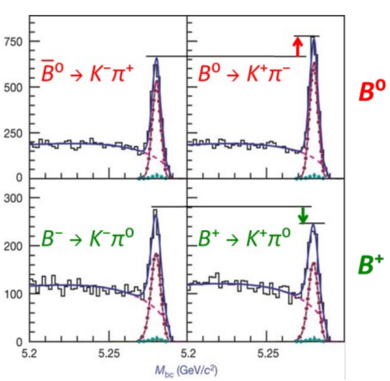

Goal of Belle II/SuperKEKB
Integrated luminosity (ab⁻¹)
Calendar Year
5σ NP observation
3σ NP evidence
based on HFAG 2017 + B2TiP
$X_s \ell^+ \ell^-$ C_9^{NP}
$S(\phi K^0)$
$S(K_S \pi^0 \gamma)$
$S(\eta' K^0)$
$B \to \tau\nu$
$P'_{5ee} / P'_{5\mu\mu}$
$S(\rho^0\gamma)$
$I_{sumrule}(K\pi)$
$R(D\tau\nu)$
$R(D^*\tau\nu)$
9 months/year
20 days/month
2017
2018
2019
2020
2021
2022
2023
2024


BR(B → τν)
sin 2β
p-value


R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
HFLAV
FPCP 2017
P(χ²) = 71.6%


$K_S \pi^0 \gamma$ S_{CP} vs C_{CP}
HFLAV
Summer 2016
BaBar
Belle
Average
C_{CP}
S_{CP}


$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$
HFLAV
Summer 2016
World Average 0.69 ± 0.02
Naïve average 0.66 ± 0.03


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