The Belle II experiment: status and physics program

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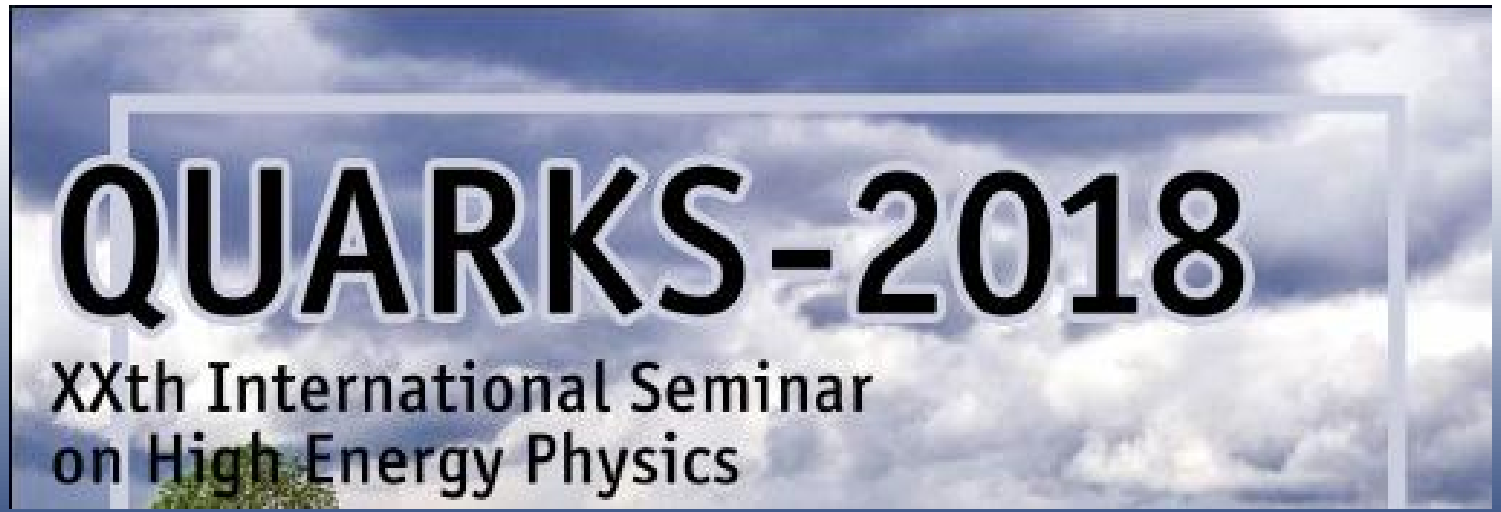
On behalf of Belle II collaboration

May 31, 2018

Budker Institute of Nuclear Physics

and

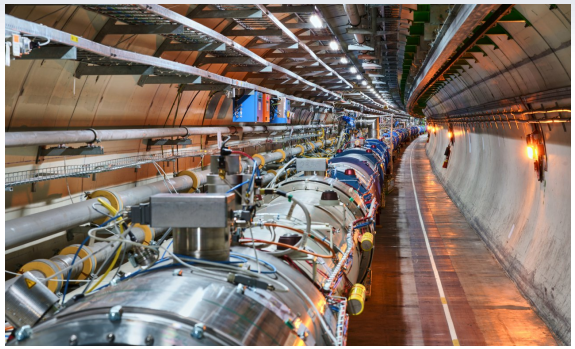
Novosibirsk State University



Introduction

Flavor factory in LHC era

Two complementary approaches for HEP



1. Energy frontier (LHC):
   Direct search for new particles in pp collisions up to $E_{\mathrm{cm}} = 14$ TeV.

2. Intensity frontier (SuperKEKB):
   Search for new physics from CP asymmetries, inclusive decay processes, rare decays.

Advantages of SuperKEKB and Belle II

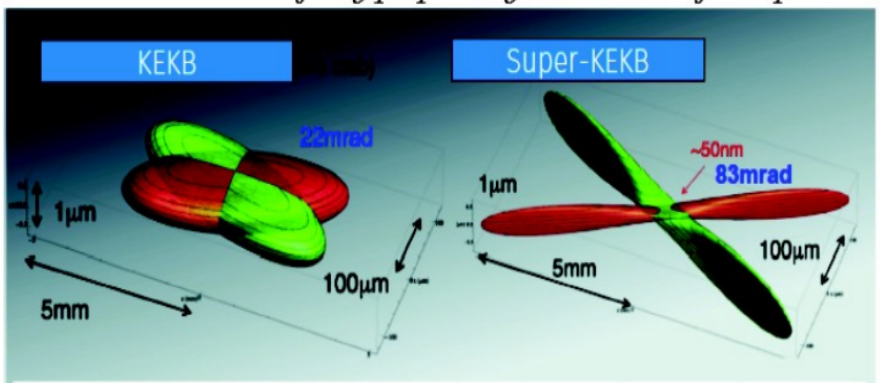
1. Low background environment: excellent γ (π^0, η, η' etc.) and K_L reconstruction
2. High B, D and τ reconstruction efficiencies and low trigger bias. Large sample of τ leptons
3. Straightforward Dalitz plot and missing mass analyses, flavor tagging method
4. Cross-check of new physics with LHCb

Belle II: status

2. Belle II status
   - SuperKEKB
   - Belle II detector
   - First collisions

SuperKEKB design concept

Nano-beam scheme firstly proposed by P. Raimondi for SuperB



	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

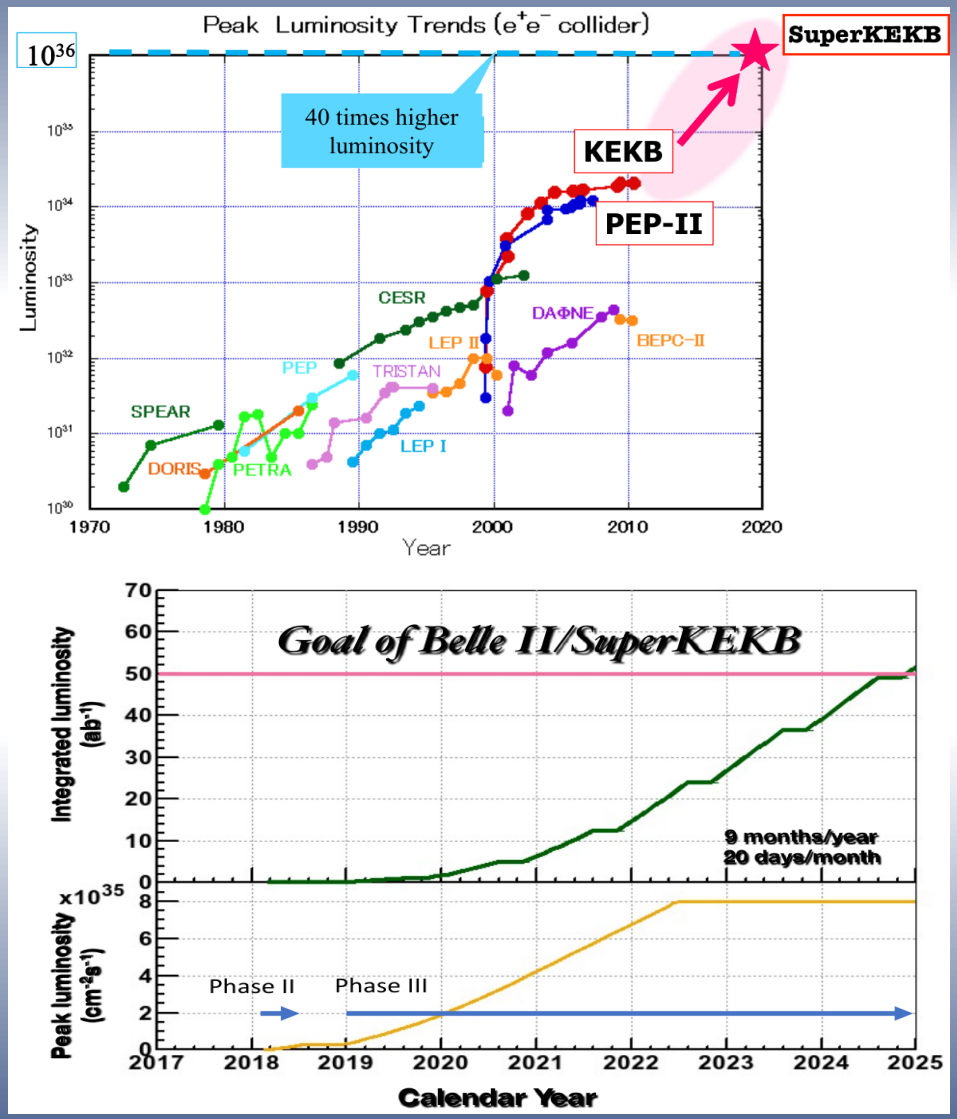
reduced boost

factor~ 40-50

Lorentz factor beam current

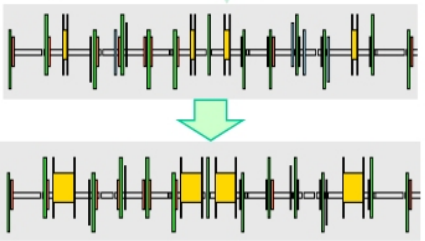
$$\text{Luminosity } L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma^*_y}{\sigma^*_x}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

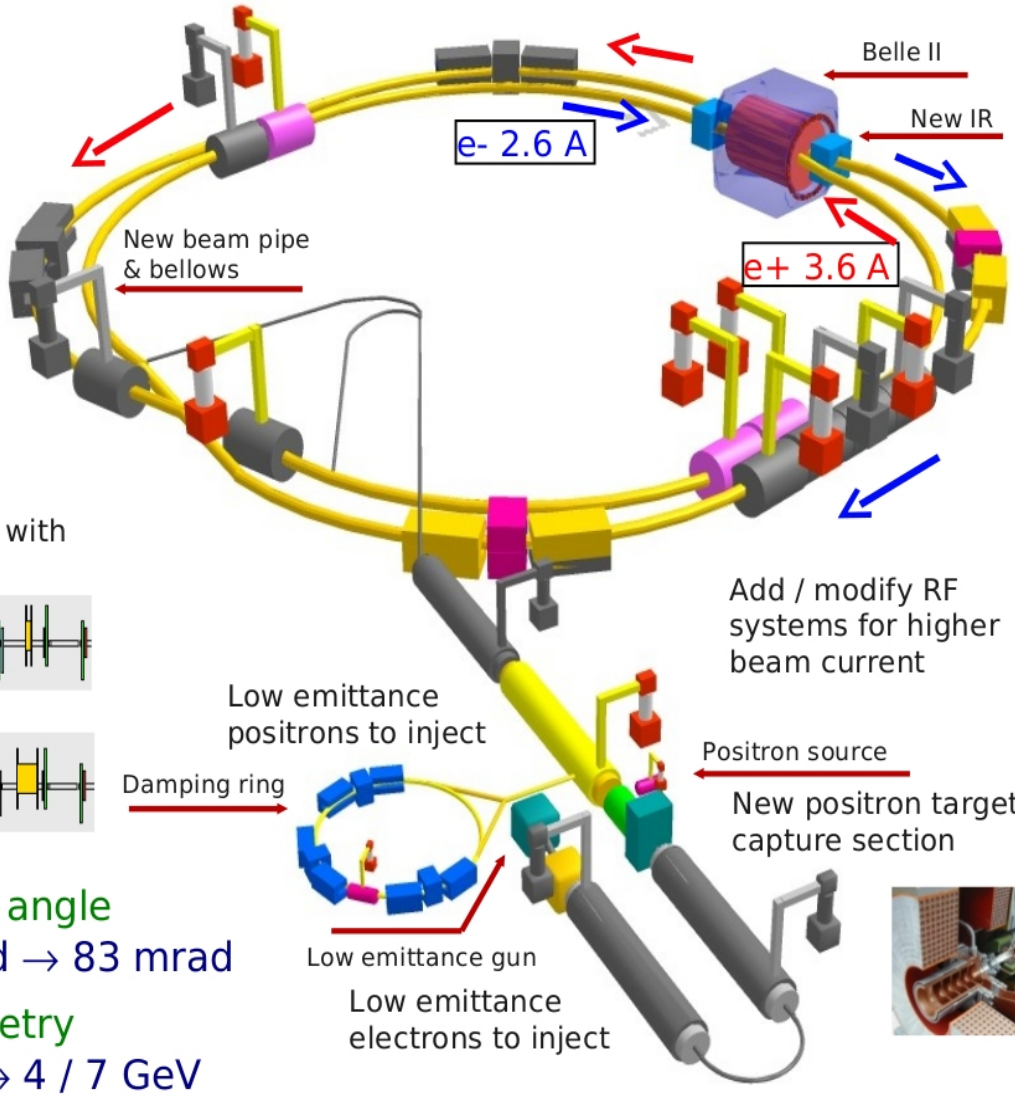
Beam size ratio at IP vertical beta function at IP Geometrical reduction factors



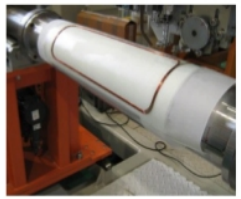
SuperKEKB

Replace short dipoles with longer ones (LER)

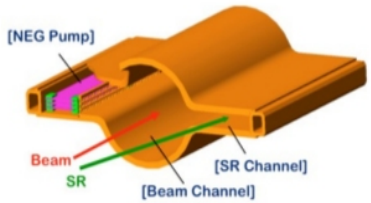




New superconducting /permanent final focusing quads near the IP



TiN-coated beam pipe with antechambers



Add / modify RF systems for higher beam current

Redesign the lattices of HER & LER to squeeze the emittance

New positron target / capture section

Larger crossing angle

$2\phi = 22 \text{ mrad} \rightarrow 83 \text{ mrad}$

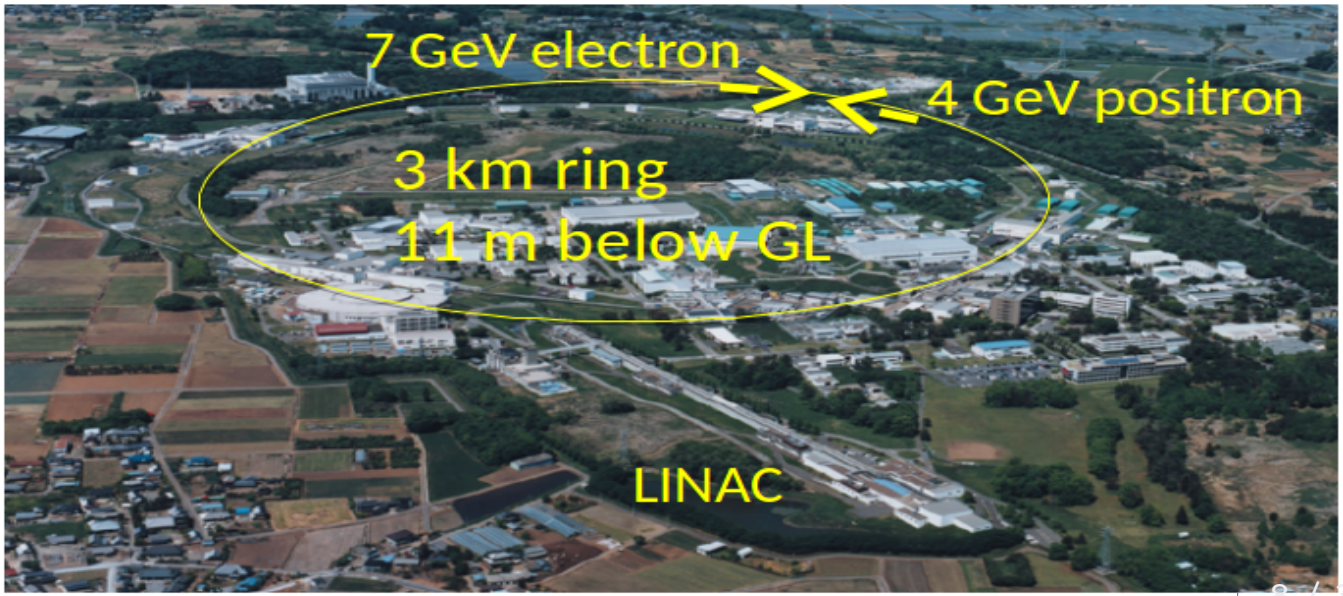
Smaller asymmetry

3.5 / 8 GeV $\rightarrow$ 4 / 7 GeV

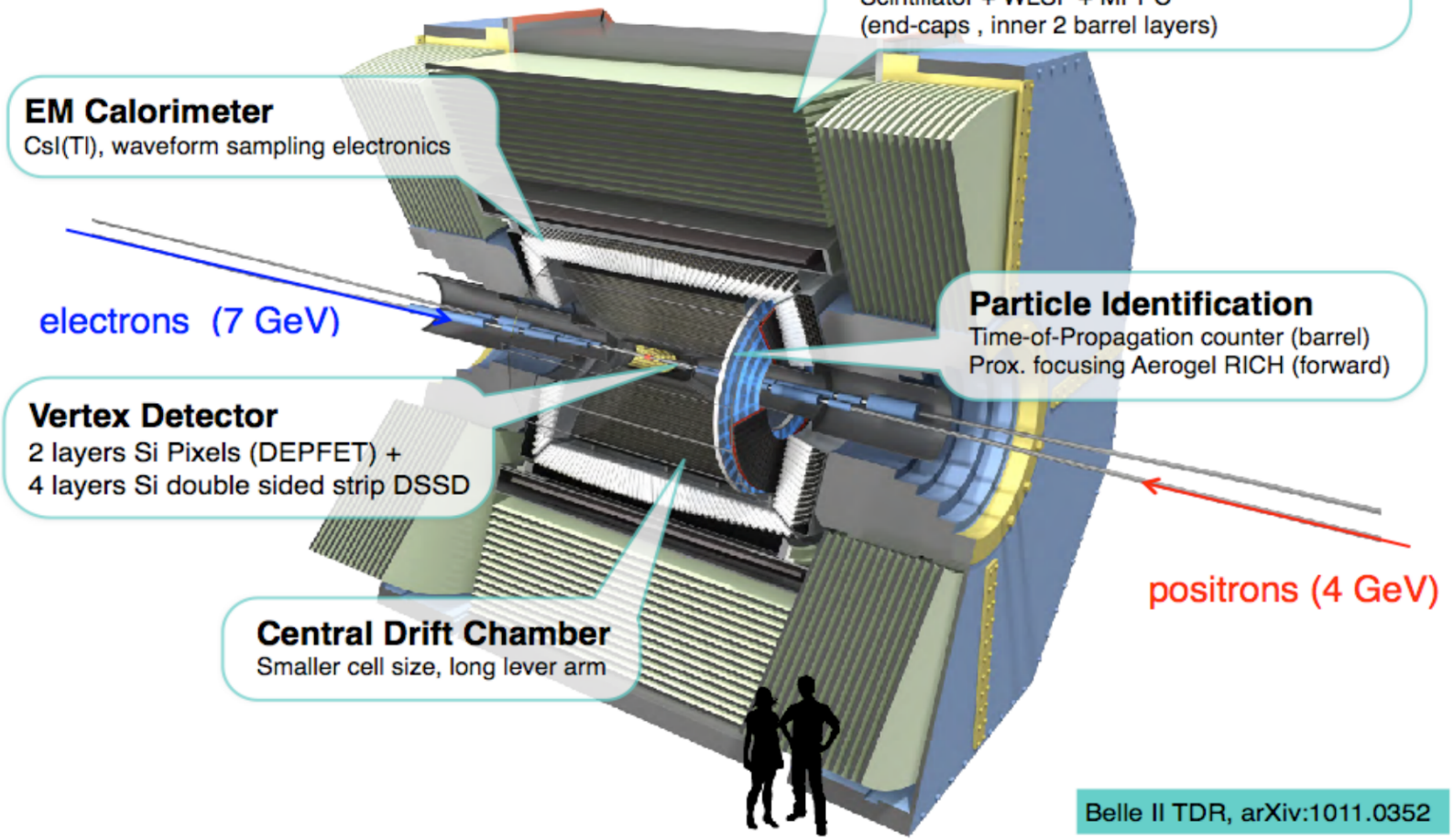
SuperKEKB

SuperKEKB Main Ring

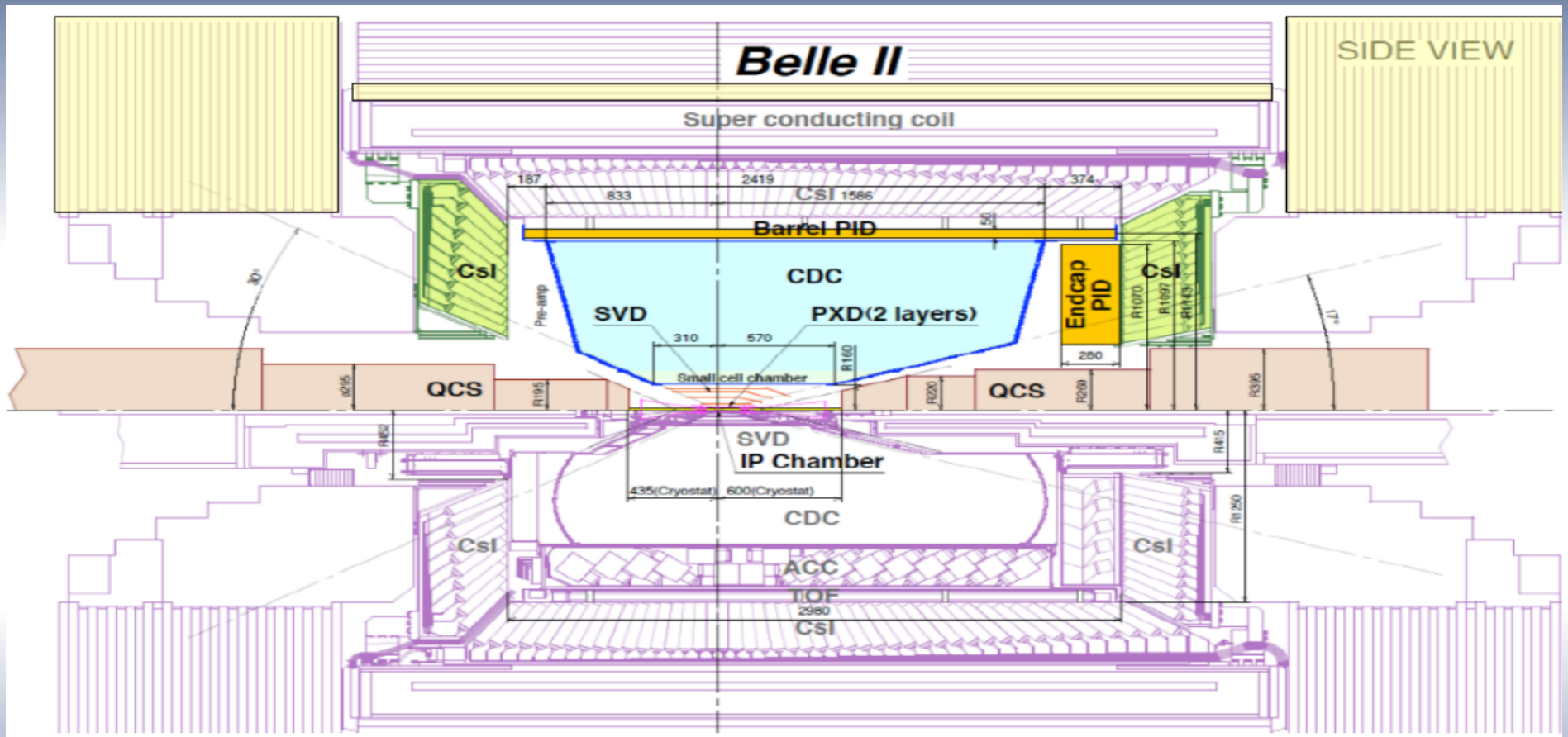
The tunnel was originally built for
TRISTAN (1986-1995)
And then reused for
► KEKB (1998-2010,ended before the big earthquake)
And again for
► SuperKEKB (under construction)



Belle II detector



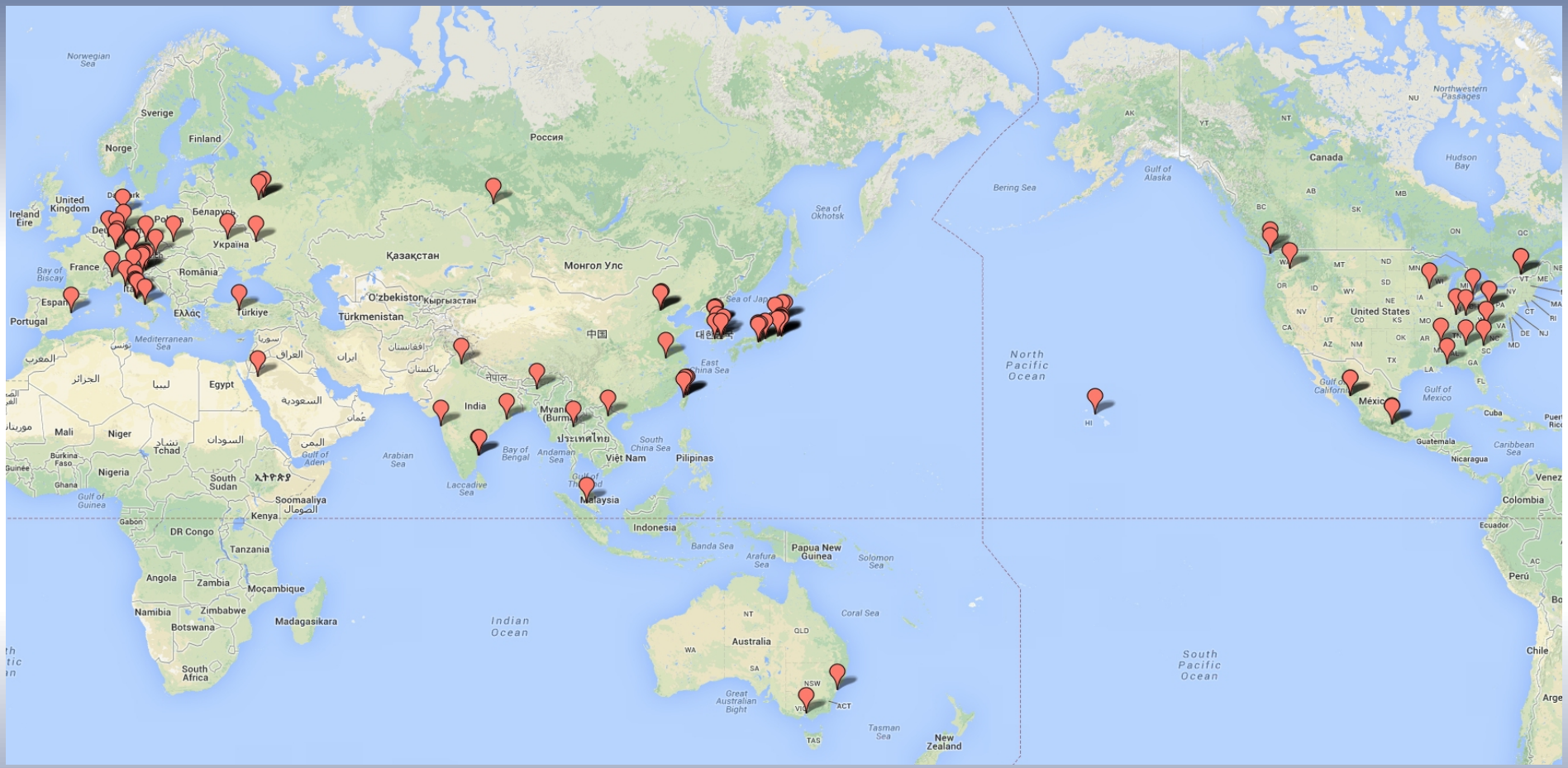
Belle II detector



SVD 4 layers (DSSD)	→	2 DEPFET + 4 DSSD
CDC:		small cell, long lever arm
ACC+TOF	→	TOP+ARICH
ECL:		waveform sampling
KLM: RPC	→	Scintillator+SiPM

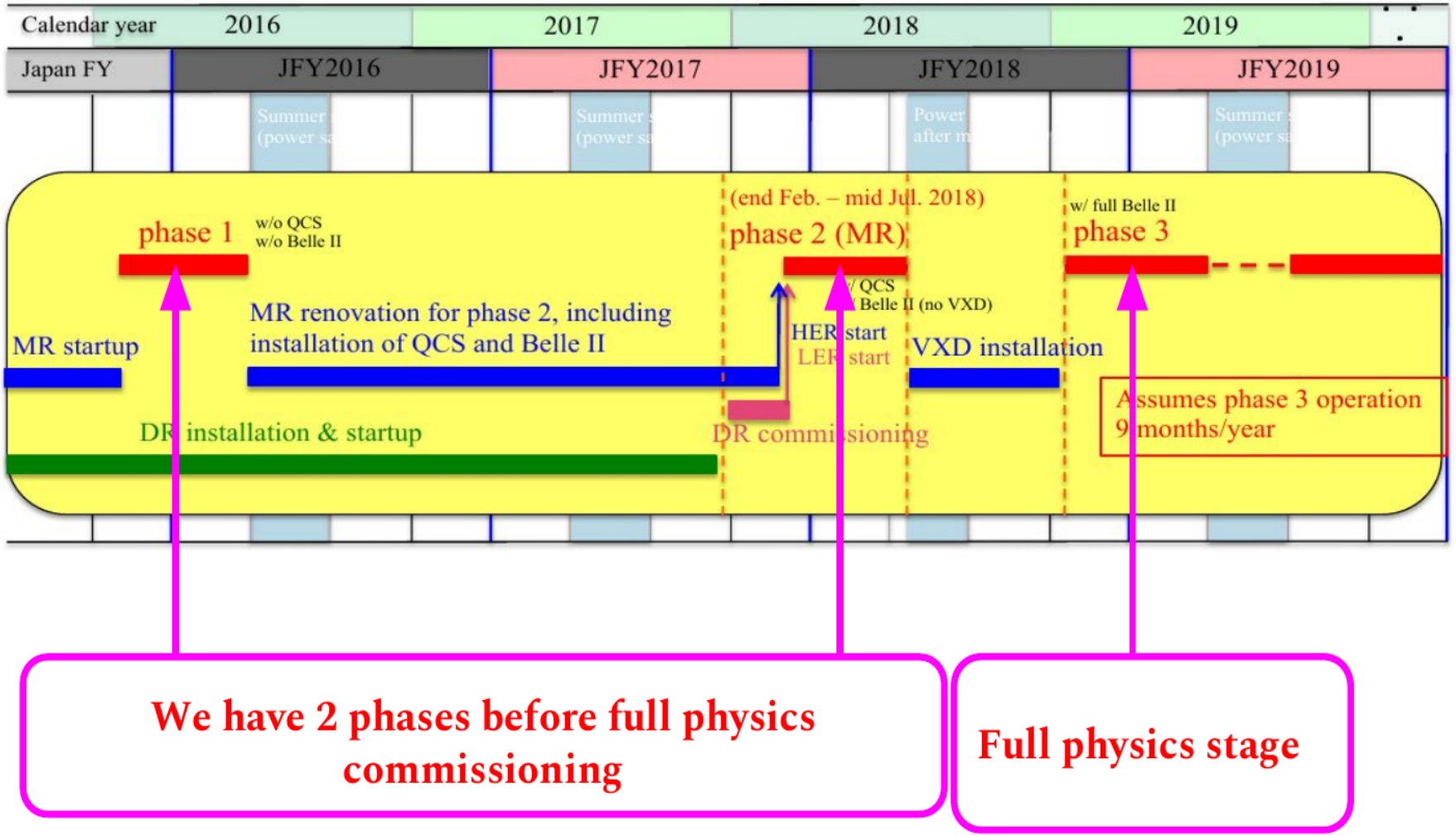
TDR
arXiv:1011.0352

Belle II collaboration

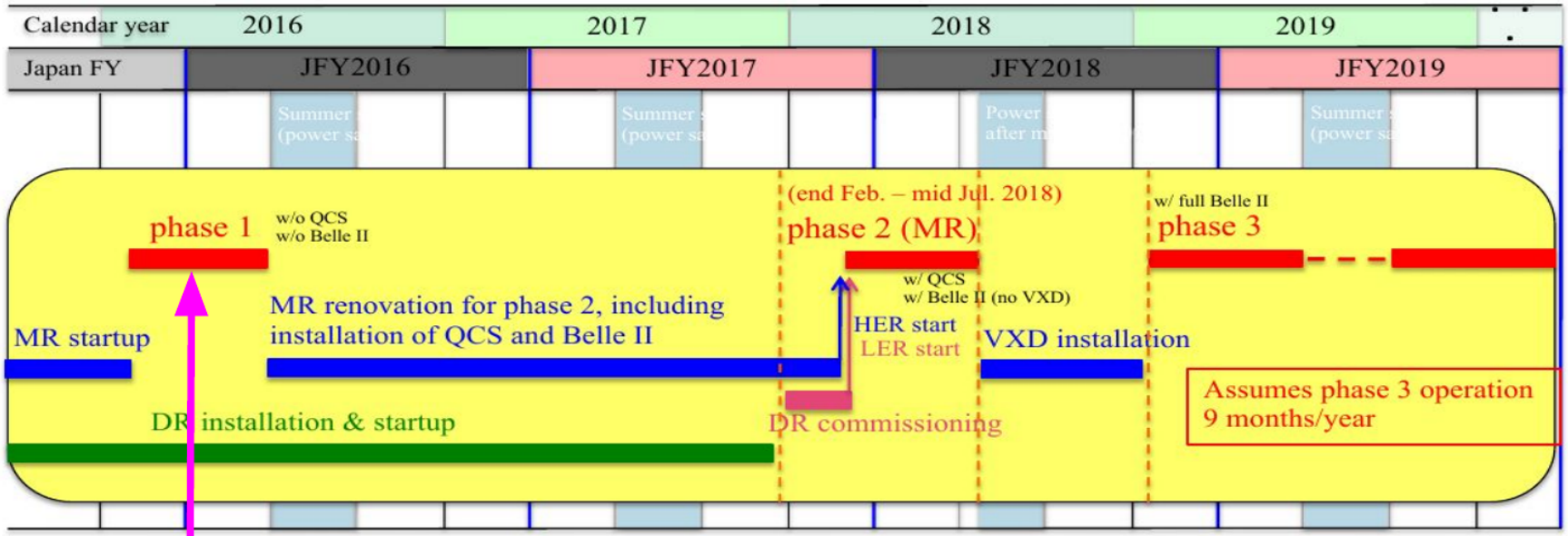


- More than 800 physicists from 106 institutions
- 24 countries / regions

Belle II schedule



Belle II schedule

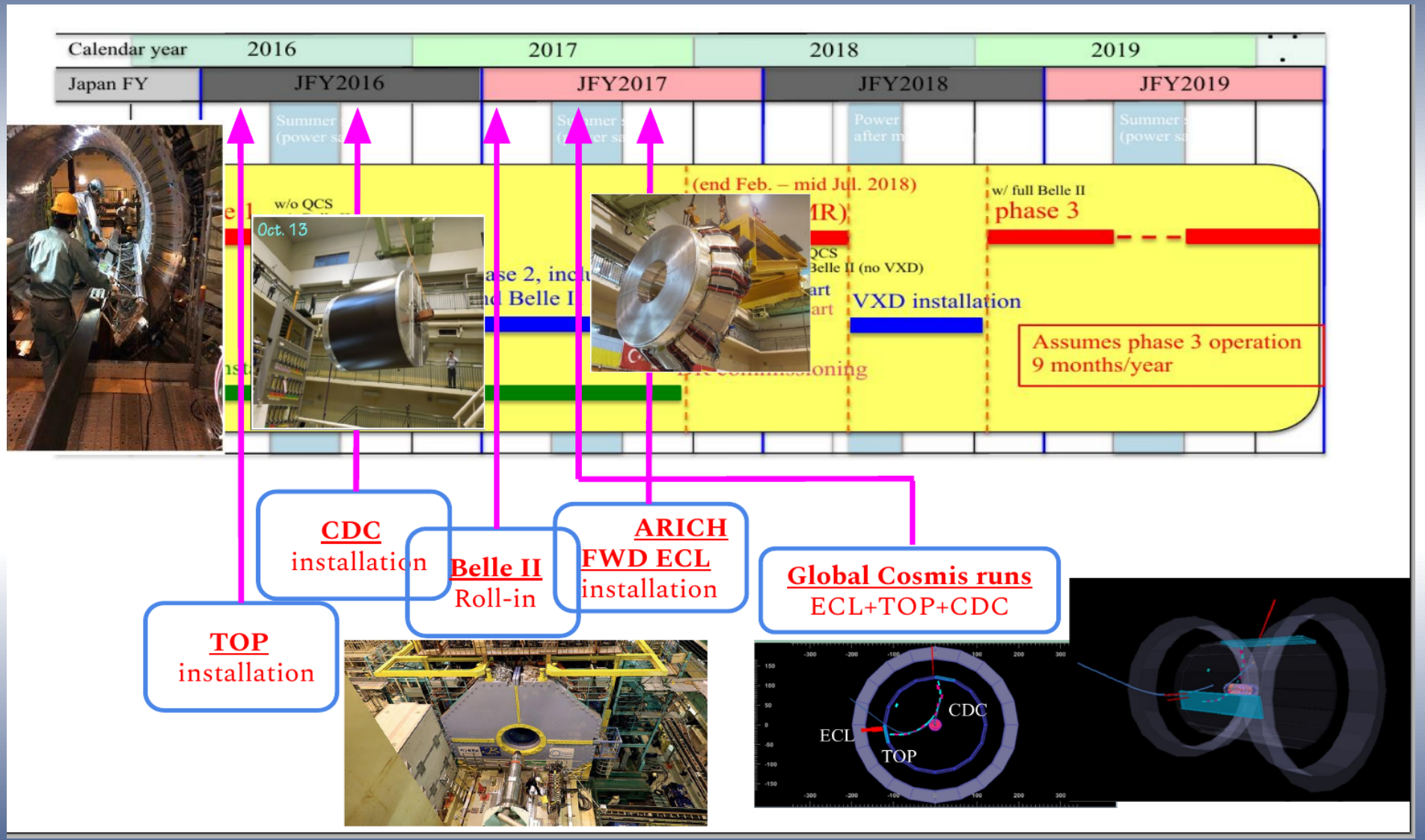


Phase I: BEAST II
No collisions
No QCS, No Belle II
Vacuum scrubbing
Beam bkg study

Beam **E**xorcism for **A** **S**table Experimen**T** **II**
(**BEAST II**):
Measure and characterise
beam background
for a safe roll-in of Belle II

Background sources:
- Touschek scattering
- Beam gas scattering
- Synchrotron radiation
- Radiative Bhabha
- 2 γ process

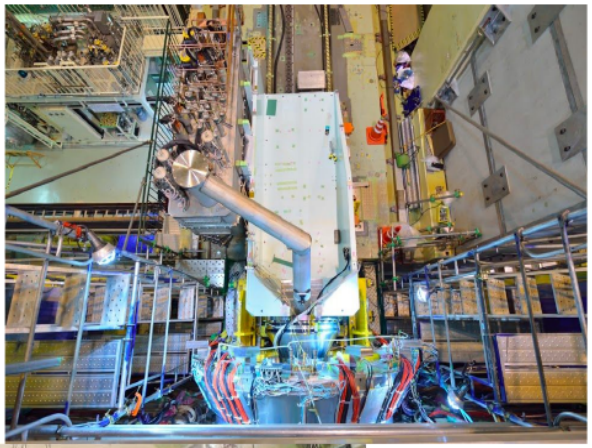
Belle II schedule



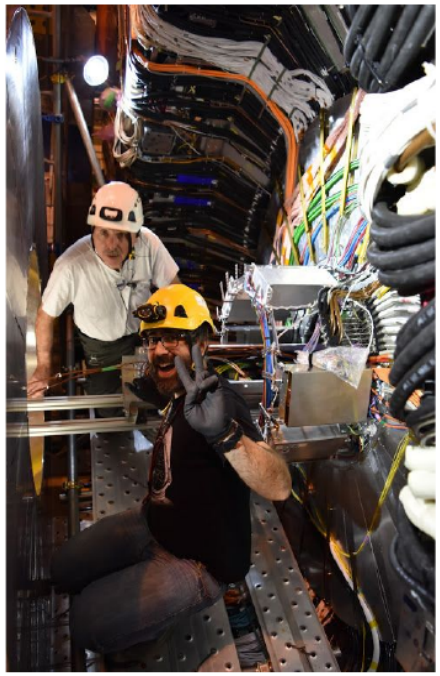
Belle II schedule

Belle II Roll-in

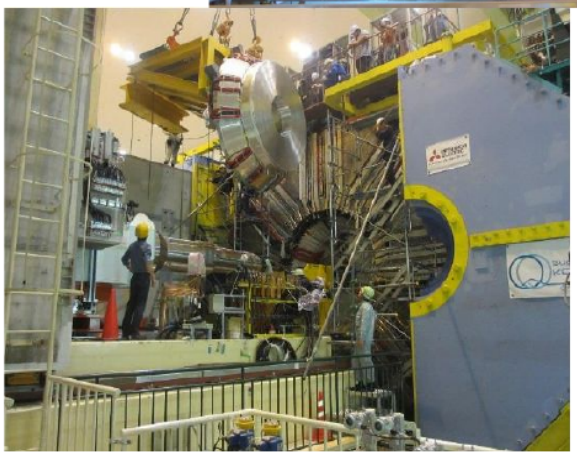
QCS solenoid installation



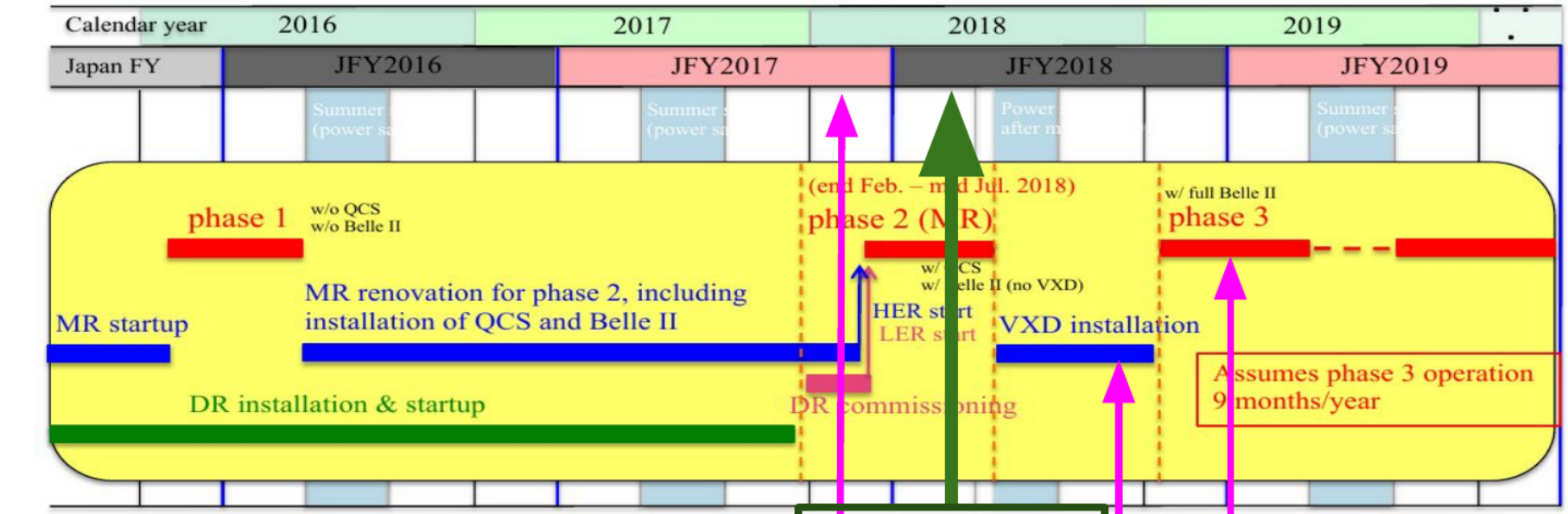
BEAST II Phase 2 VXD installation



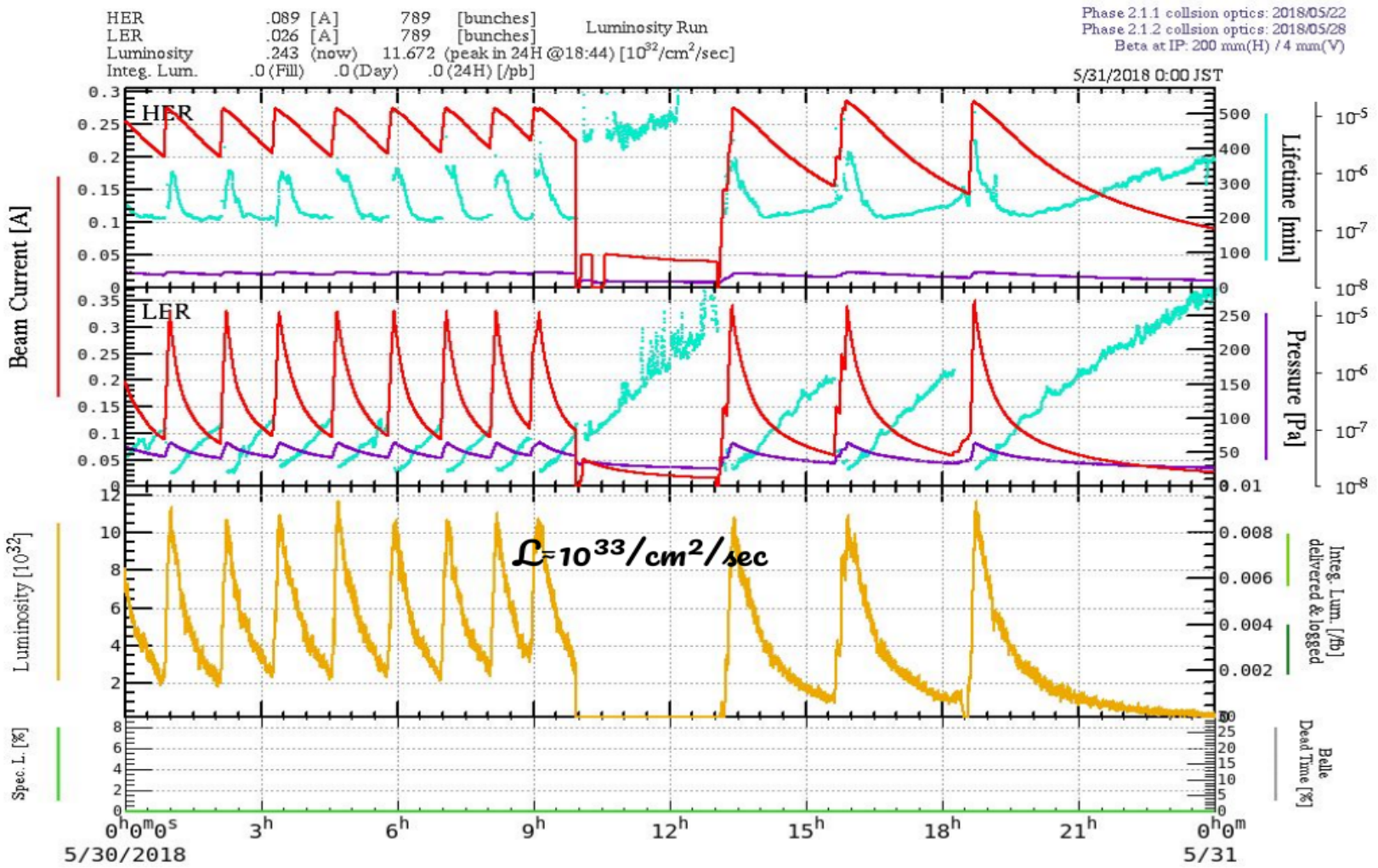
ARICH+FWD ECL installation



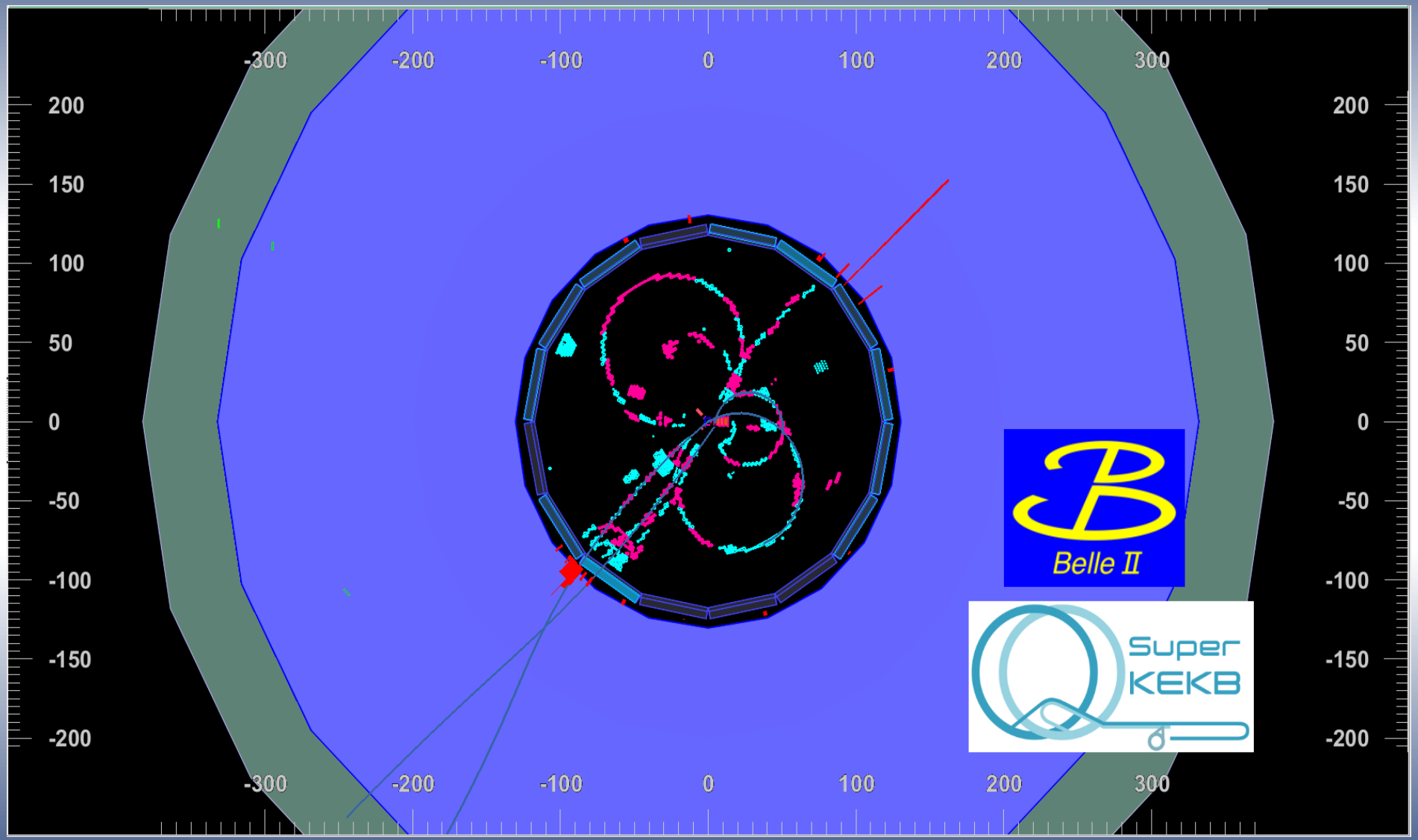
Belle II schedule



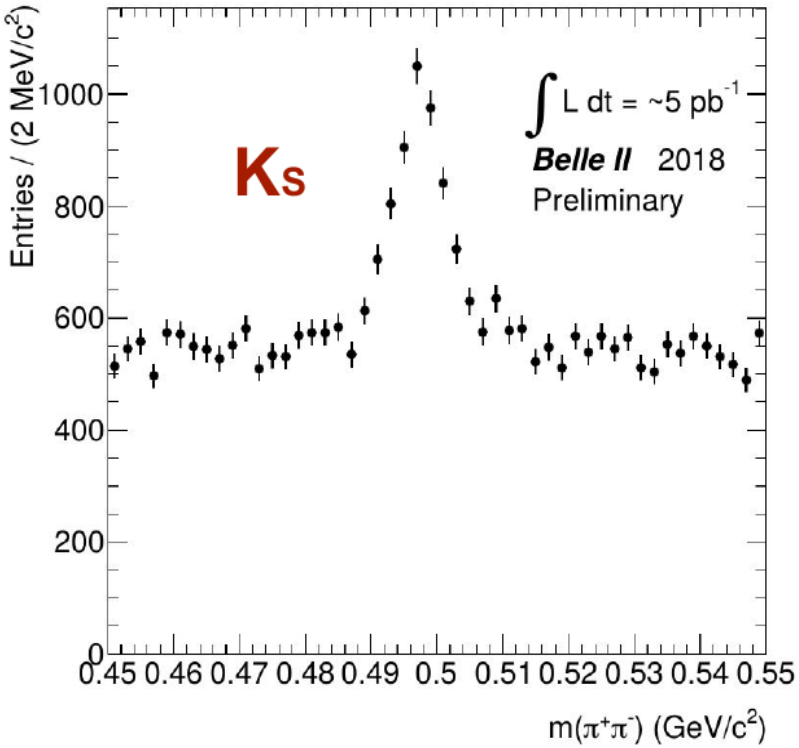
First collisions: SuperKEKB operation

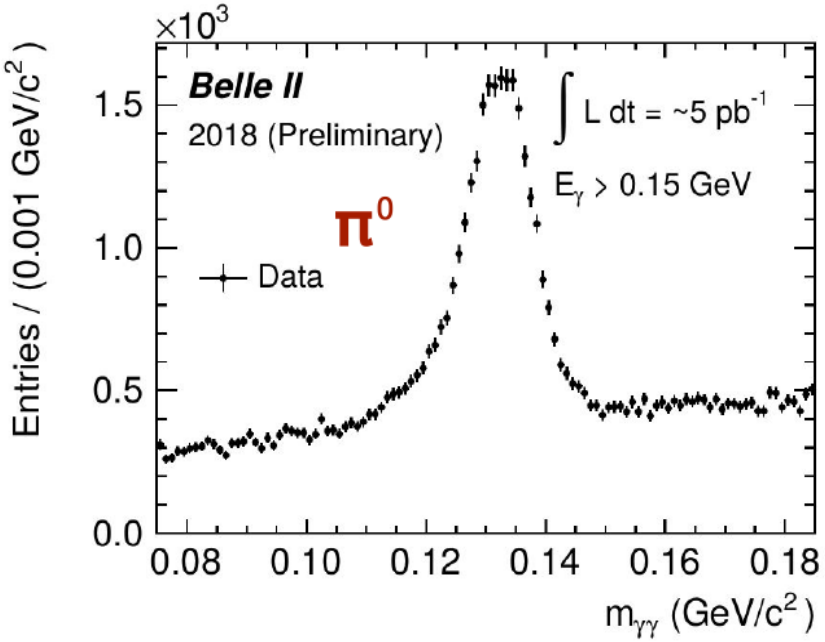


First collisions: Event display



First collisions: First bumps

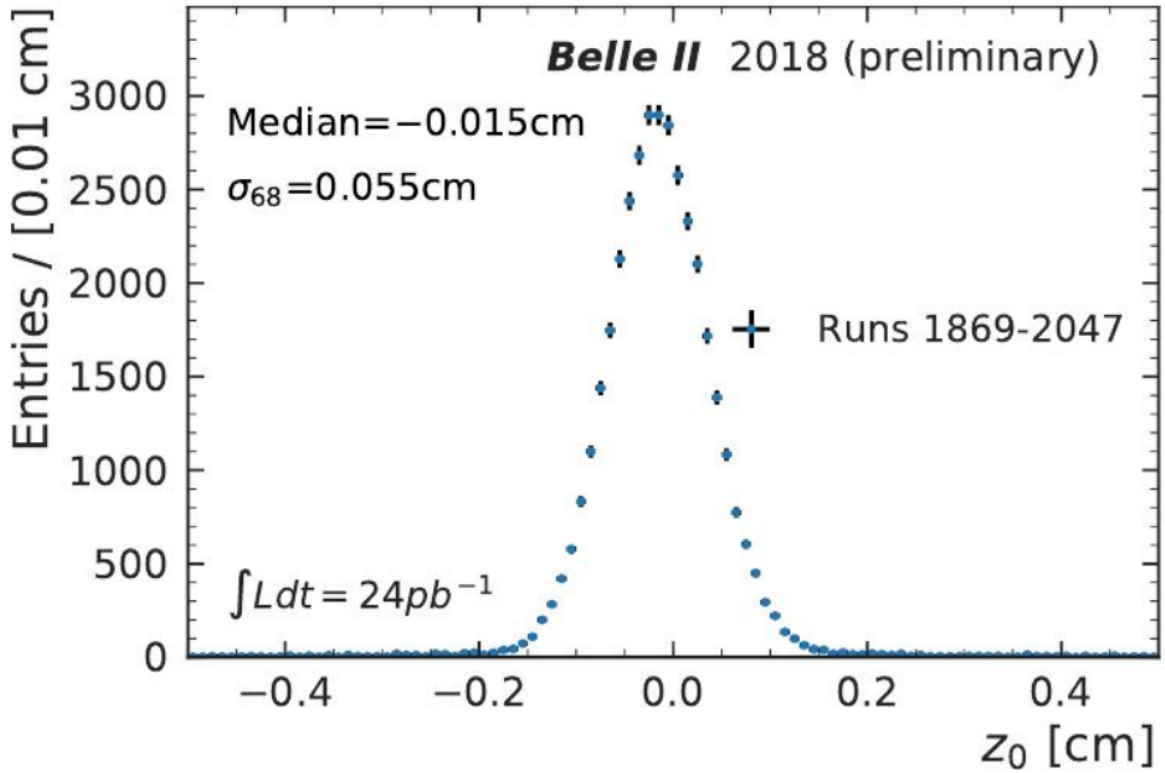




Study of PID selection and resolution is ongoing

First collisions: Interaction vertex

Longitudinal component of the interaction vertex



Belle II: physics

3 Belle II physics

- Overview
- $B^+ \to \tau^+ \nu_\tau$
- $\bar{B}^0 \to D^{(*)+} \tau^- \bar{\nu}_\tau$
- $\bar{B}^0 \to \pi^+ \tau^- \bar{\nu}_\tau$
- $B \to K^{(*)} l^+ l^-$, $l = e, \mu$
- $\Upsilon(6S)$ physics
- Dark sector

Physics overview

Belle II Theory Interface Platform Workshop Series (2015-2018)
To be submitted to PTEP

WG1
Semileptonic & Leptonic B decays
- Semileptonic b → c, b→ u transitions
- Charged leptonic decays $B^+ \to e/\mu/\tau\ \nu$
- Radiative leptonic decays $B^+ \to l\nu\gamma$

WG2
Radiative & Electroweak penguins
- Inclusive and exclusive radiative b → s, b→ d decays
- Electroweak penguins b→s l^+l^-, B→(K)$\nu\nu$
- Rare and forbidden Bs→$\gamma\gamma$, B→$\tau\tau$

WG3
$\alpha=\phi_2, \beta=\phi_1$
- α/ϕ_2:B→$\varrho\pi$,$\varrho\varrho$
- β/ϕ_1:B→ϕKs
- TCPV in radiative decays

WG4
$\gamma=\phi_3$
- Charm CP eigenstates
- Double Cabibbo suppressed
- Three-body decays B→D(Ks$\pi\pi$)K

WG5
Charmless Hadronic B decays
- Direct CPV
- 2,3-body hadronic modes
- QCD factorisation

WG6
Charm physics
- Direct CPV
- Leptonic and Semileptonic decays
- Radiative and rare decays

WG7
Quarkonium(like)
- Bottomonia (exotics)
- Charmonia (exotics)
- Energy scan studies

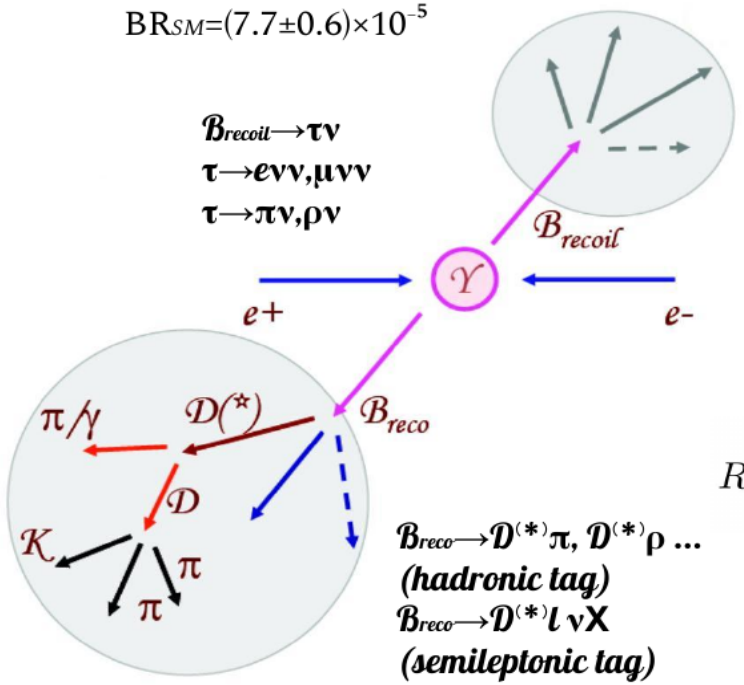
WG8
Tau, low multiplicity & EW
- Tau physics:, LFV, CPV, lepton universality
- Low multiplicity
- Dark photon searches

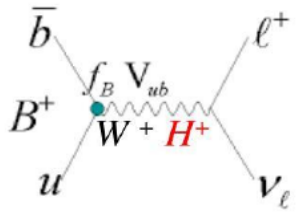
WG9
New physics
- Dark sector
- 2-Higgs doublet model
- Extended gauge sector

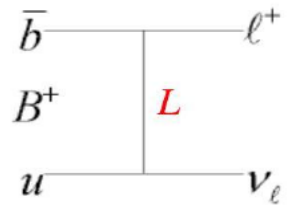
$B^+ \to \tau^+ \nu_\tau$

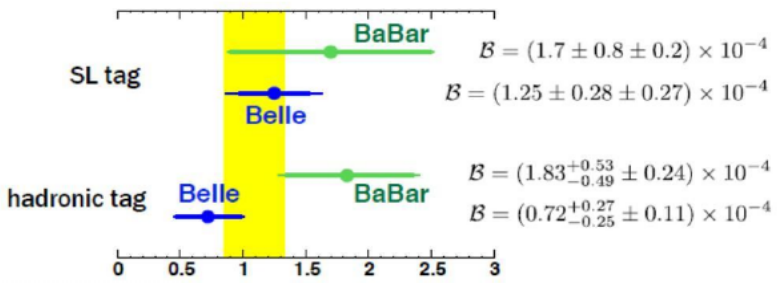
$$BR_{SM}(B^+ \to \tau^+ \upsilon) = \frac{G_F^2}{8\pi} f_B^2 |V_{ub}|^2 M_B \tau_B m_\tau^2 \left(1 - \frac{m_\tau^2}{M_B^2}\right)^2$$

$BR_{SM} = (7.7 \pm 0.6) \times 10^{-5}$



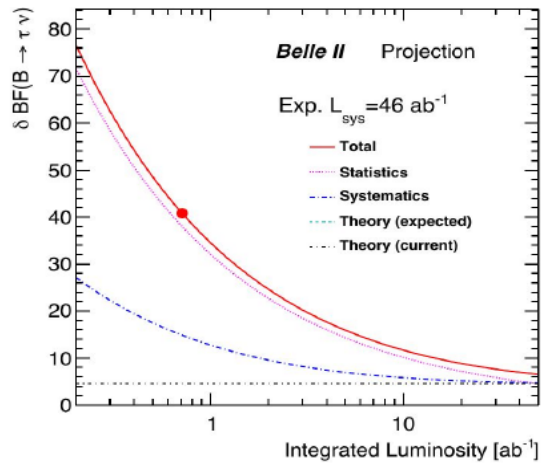






$$R_{\rm pl} = \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)}$$

10% sensitivity
@ Belle II



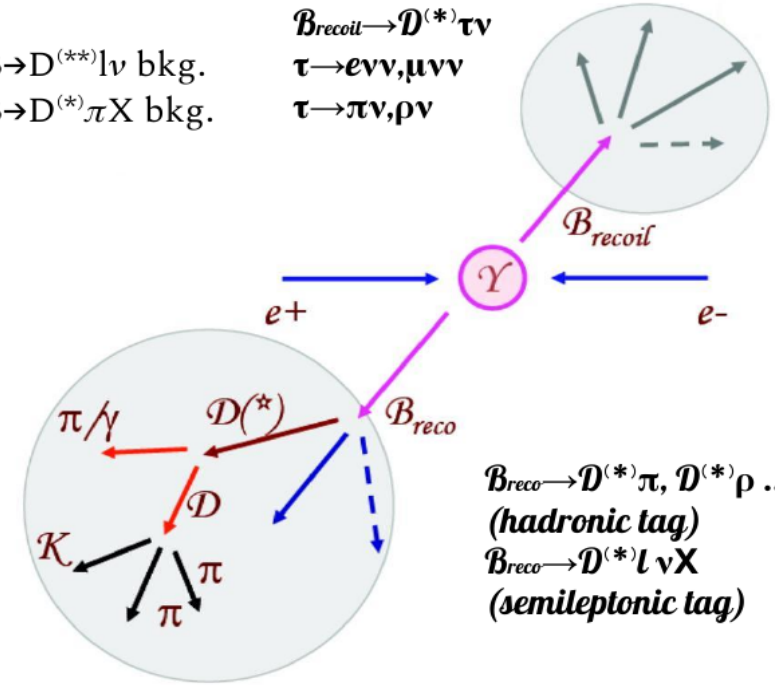
	(Hadronic tag)	(Semileptonic tag)	(Inclusive hadronic tag)
Purity	High	←	Low
Efficiency	Low	→	High

$\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$

Experimental approach is similar to that used in B→τν

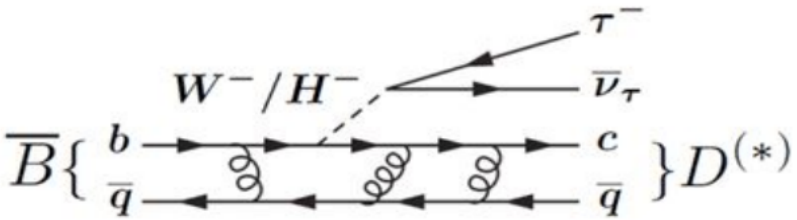
B→D$^{(**)}$lν bkg.
B→D$^{(*)}$πX bkg.

$\mathcal{B}_{recoil}\to D^{(*)}\tau\nu$
$\tau\to e\nu\nu,\mu\nu\nu$
$\tau\to\pi\nu,\rho\nu$



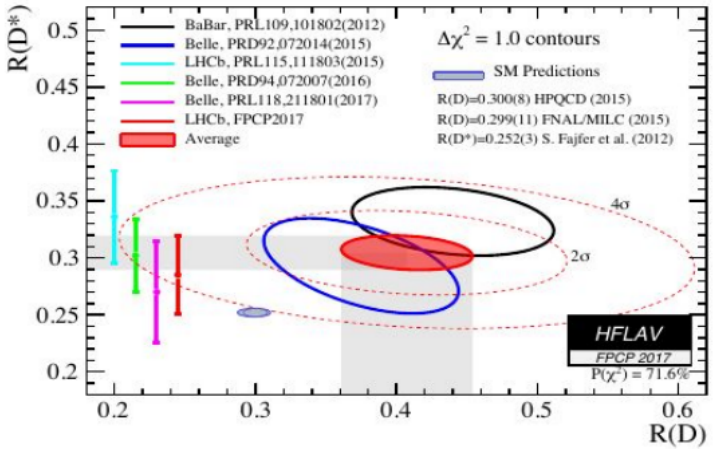
$\mathcal{B}_{reco}\to D^{(*)}\pi$, $D^{(*)}\rho$ ...
(hadronic tag)
$\mathcal{B}_{reco}\to D^{(*)}l\,\nu X$
(semileptonic tag)

	(Hadronic tag)	(Semileptonic tag)	(Inclusive hadronic tag)
Purity	High	←	Low
Efficiency	Low	→	High



$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B \to D^{(*)}\ell\nu_\ell)} \quad \ell = e, \mu$$

Theoretical uncertainties in form factors and |Vcb| cancel out

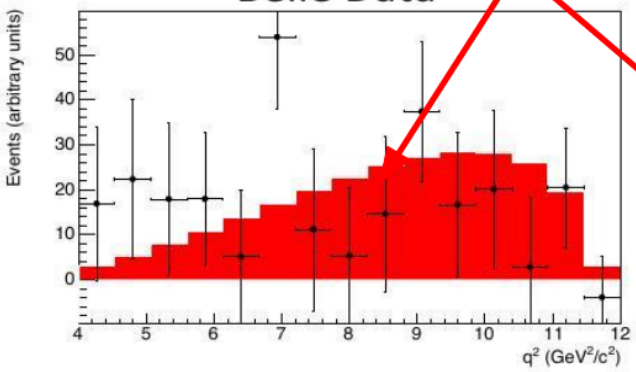


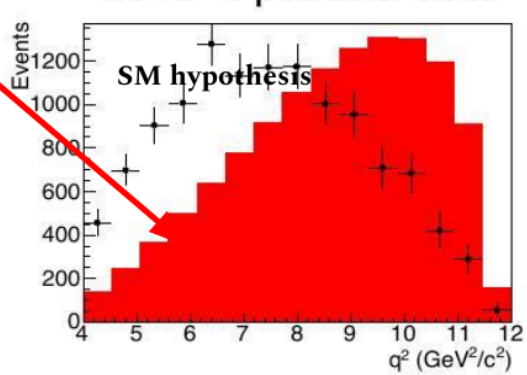
3.9σ discrepancy, p-value = 8.3 x 10^{-5}

$\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$

2HDM type II
tan β/mH=0.5 (GeV/c²)$^{-1}$

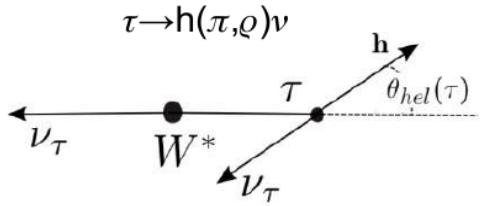
50 ab^{-1}projection





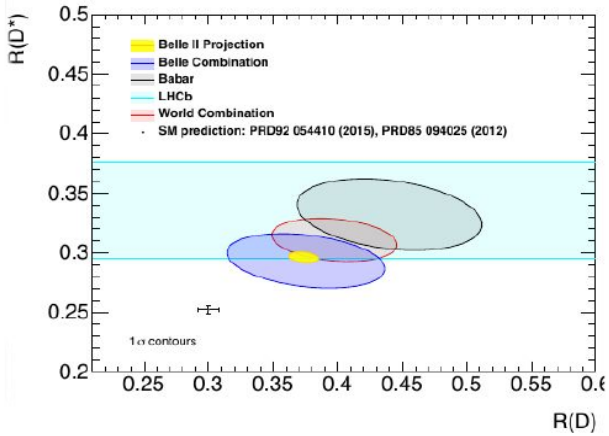
$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

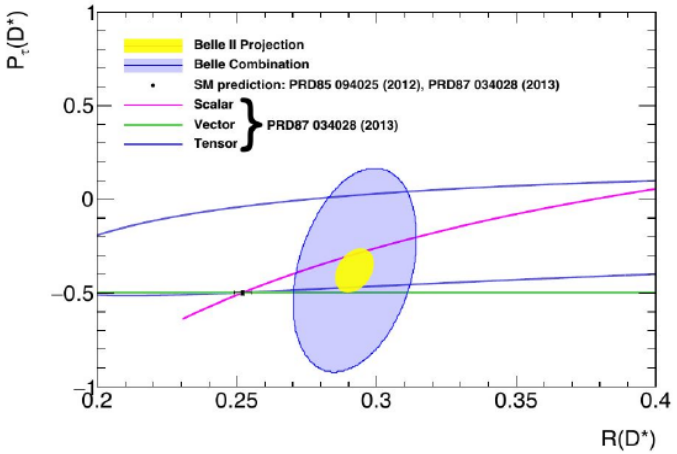
$\Gamma^{+(-)}$ – decay rate with τ helicity +½ (-½)



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

- NP mass scale probe @ Belle II could be about 5 - 10 TeV.





$\bar{B}^0 \to \pi^+ \tau^- \bar{\nu}_\tau$

How about b→u ?

$$R_\pi \equiv \frac{\mathcal{B}(B \to \pi \tau \bar{\nu}_\tau)}{\mathcal{B}(B \to \pi \ell \bar{\nu}_\ell)}$$

Current data have already disfavoured NP contributions larger than that of the SM

Belle II extrapolation

$$R_\pi^{5\,\mathrm{ab}^{-1}} = 0.64 \pm 0.23\,,$$

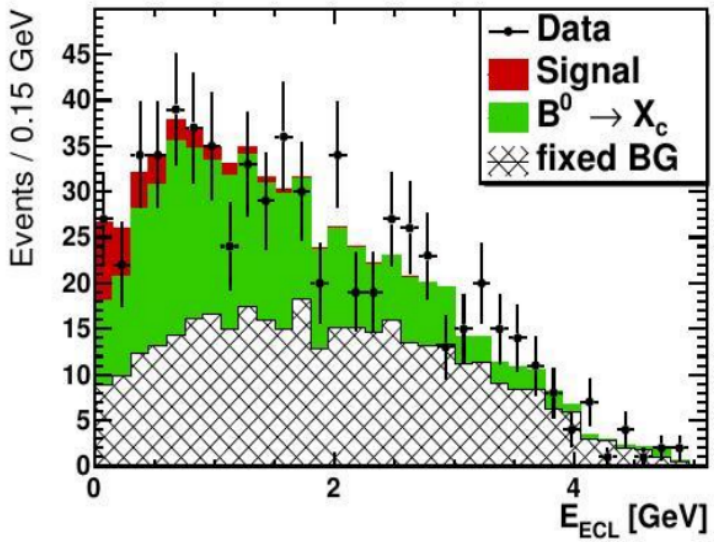
$$R_\pi^{50\,\mathrm{ab}^{-1}} = 0.64 \pm 0.09\,.$$

Belle, PRD, 93, 032007 (2016)

$\mathcal{B}(B \to \pi\tau\nu) < 2.5 \times 10^{-4}$ @ 90% CL

$\mathcal{B}(B \to \pi\tau\nu) = (1.52 \pm 0.72 \pm 0.13) \times 10^{-4}$

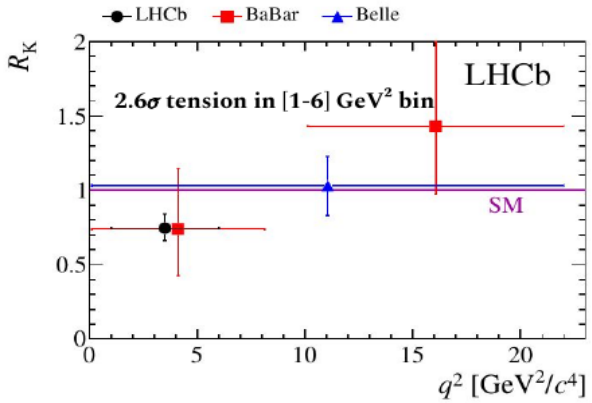
$R_\pi(\mathrm{SM}) = 0.641 \pm 0.016$ $R_\pi(\mathrm{exp}) = 1.05 \pm 0.51$

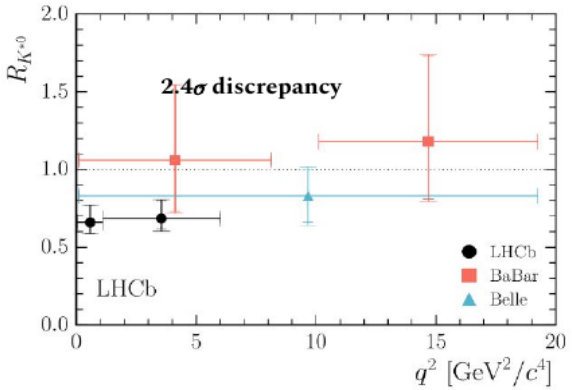


$B \to K^{(*)} l^+ l^-,\ l = e, \mu$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

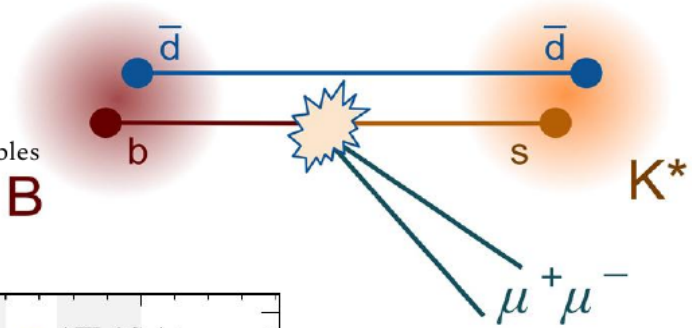
- Theoretical uncertainties cancel in the ratio
- The SM prediction is 1 with high precision
- R_K and R_{K^*} give complementary info

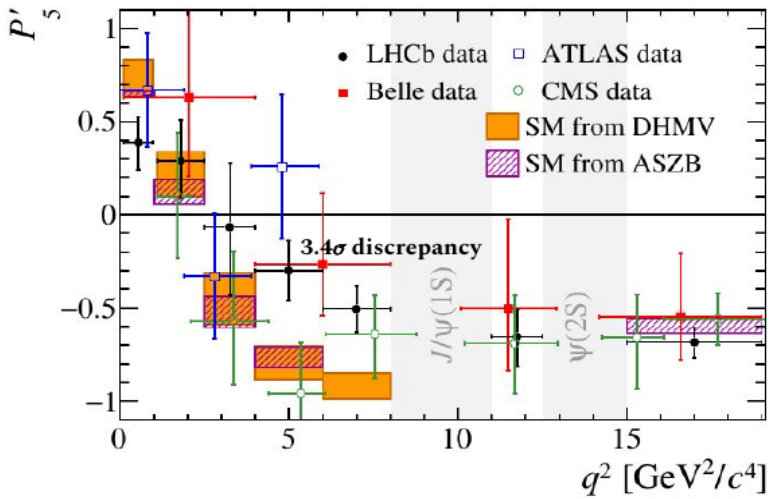




$$P_5' \ (B \to K^* \mu^+ \mu^-)$$

One of the optimised angular observables

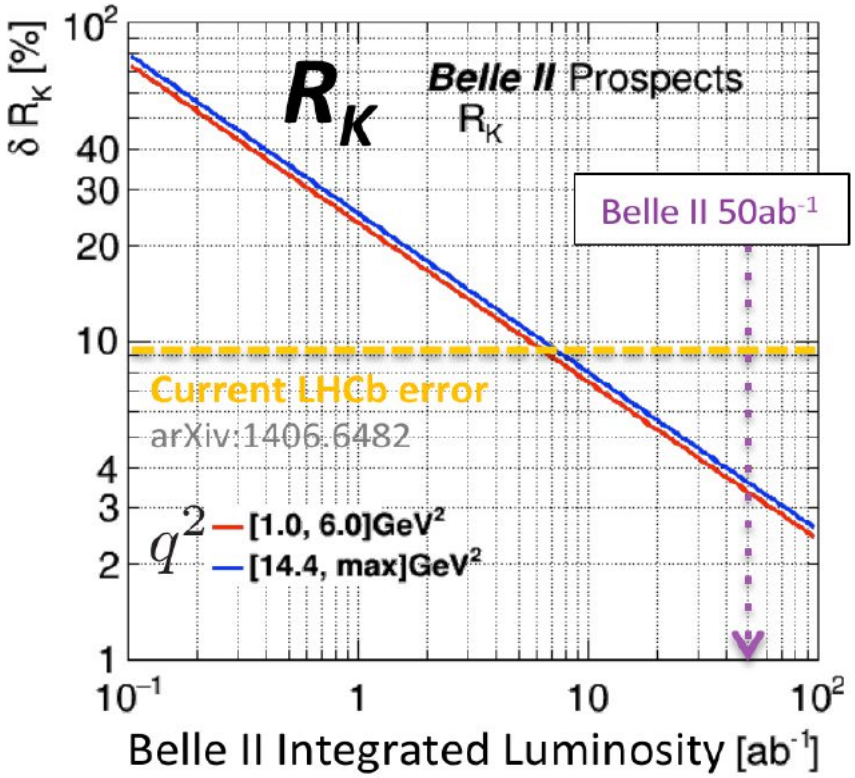


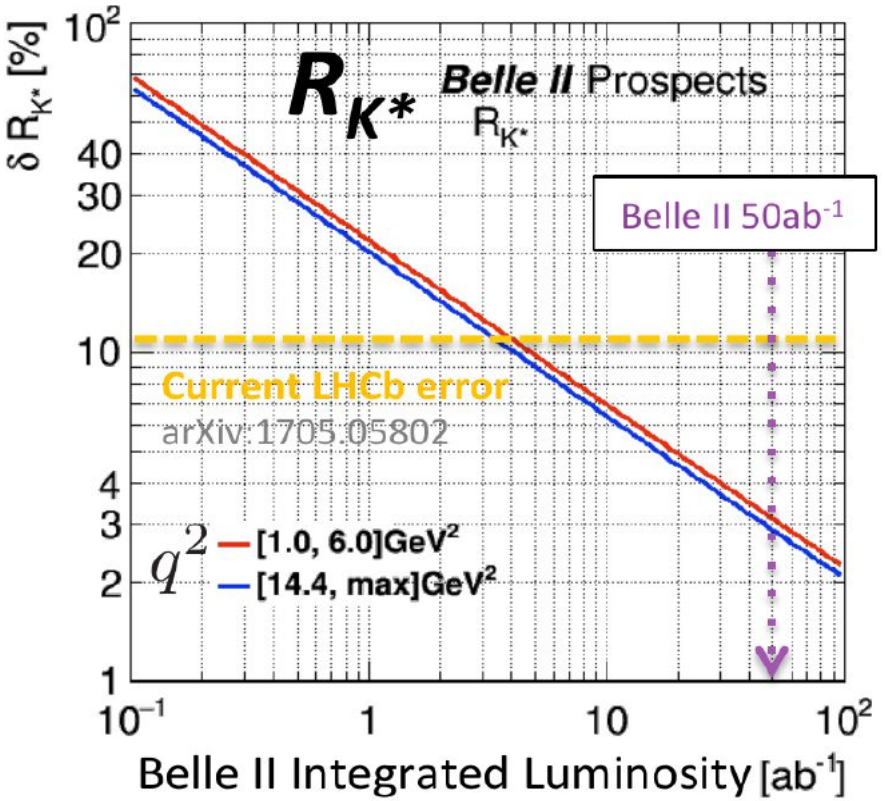


Ongoing discussion about the interpretation and theory predictions

$B \to K^{(*)} l^+ l^-,\ l = e, \mu$

- Belle II experiment is an unique place where it is possible to perform the cross-checks with LHCb for R_K, R_{K^*} and P'_5
- Belle II has great sensitivity to the $B \to K^* e^+ e^-$
- Belle II measurement will be statistically limited (3% uncertainty with full Belle II statistics)





$\Upsilon(6S)$ physics

- Operating point @ Y(6S)=Y(11020) is the Belle II first physics opportunity
- Belle collected 5.6 fb^{-1} but not all "on-peak"
- Search for Y(6S) closed-flavour decays is interesting for bottomonium(like) studies
- Rich decay scheme to search for isovector Z_b and W_{bJ} states as well as isoscalar X_b states
- New conventional states $h_b(3P)$ and Y(2D) can be also found

1 $\Upsilon(6S) \to Z_b^+ \pi^- \to h_b(1P, 2P)\, \pi^+ \pi^-$

2 $\Upsilon(6S) \to Z_b^+ \pi^- \to \Upsilon(1S, 2S, 3S)\, \pi^+ \pi^-$

3 $\Upsilon(6S) \to Z_b^+ \pi^- \to \eta_b\, \rho$

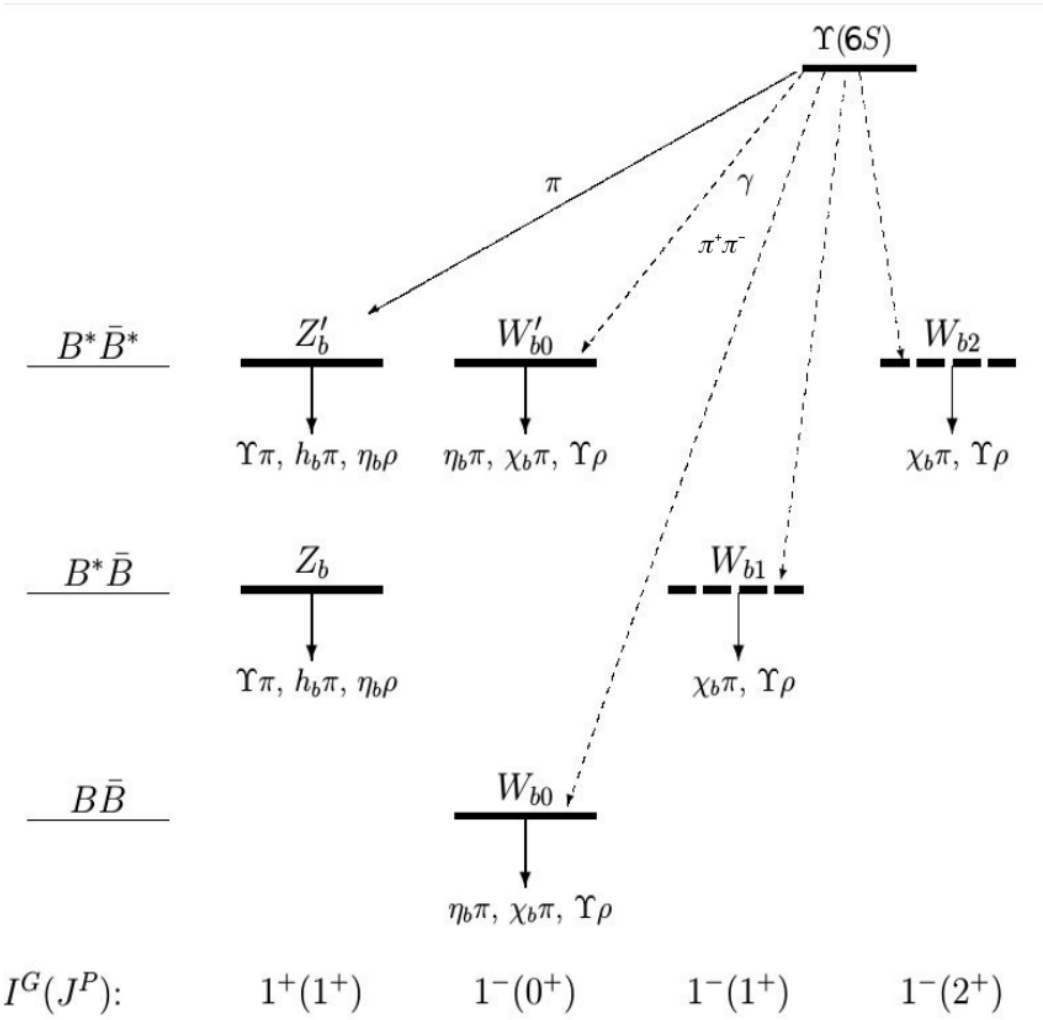
4 $\Upsilon(6S) \to W_b^0\, \gamma,\ W_b \to \eta_b\, \pi, \chi_b \pi, \Upsilon \rho$

5 $\Upsilon(6S) \to W_b^0\, \pi^+ \pi^-,\ W_b \to \eta_b\, \pi, \chi_b \pi, \Upsilon \rho$

6 $\Upsilon(6S) \to \gamma\, X_b\ (\to \omega\, \Upsilon(1S))$

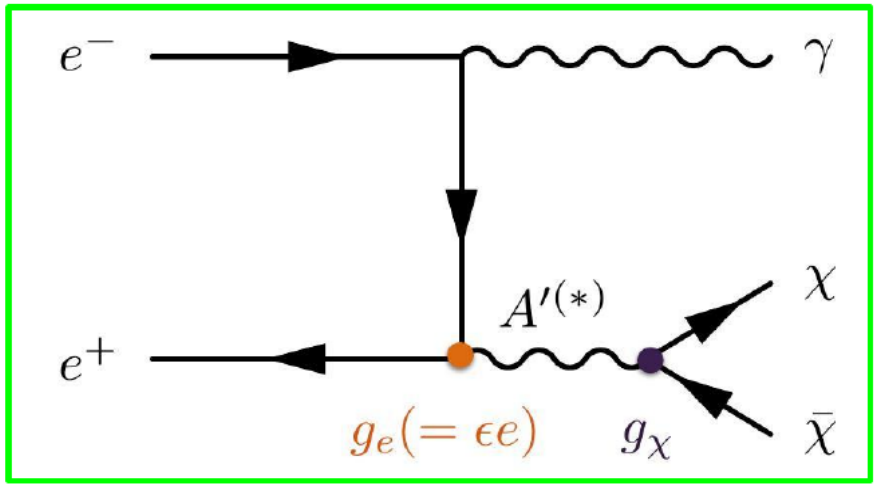
7 $\Upsilon(6S) \to \pi\, \pi\, X_b\ (\to \omega\, \Upsilon(1S))$

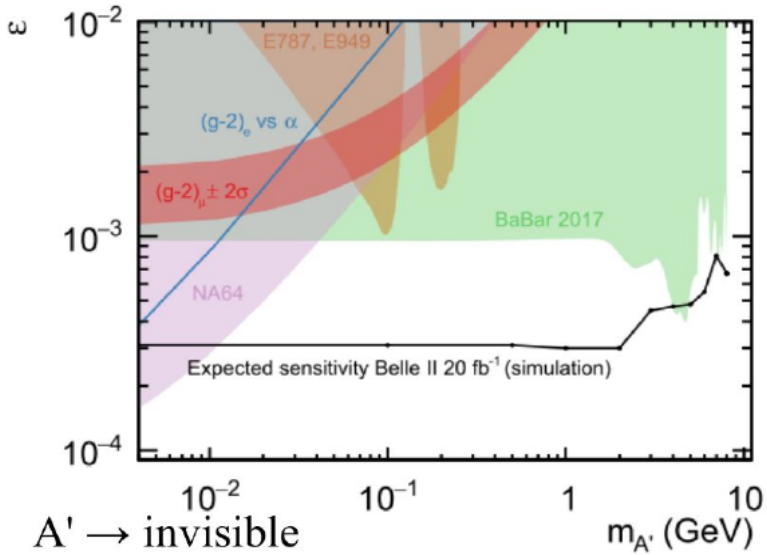
8 QCD hybrids in BB*



Dark sector

- Belle II is the good place for dark force mediator invisible (also visible) searches
- Possibility to provide results with limited statistics (Belle II first physics opportunity)
- Search for Dark Photon decaying into light DM requires efficient single photon trigger.
- Single photon trigger was not available at Belle but it will be available at Belle II





SM Background

- $e^+e^- \to \gamma\not{\chi}$
  resonant, peaked at $m^2_{\chi\bar{\chi}} = 0$
- $e^+e^- \to \gamma\not{e}^+\not{e}^-$
  non-resonant, exponential shape
- $e^+e^- \to \gamma\not{\chi}\not{\chi}$
  non-resonant, exponential shape

Summary

1. SuperKEKB is completing the commisioning phase and first collisions achieved one month ago!
   - Belle II roll-in in April 2017
   - First collisions in April 2018
2. Phase 2 data taking has been started
   - First luminosity $\sim 10^{33}/\mathrm{cm}^2/\mathrm{sec}$
   - Background study, detector checkout, first physics studies
3. Physics commissioning with full Belle II in early 2019
4. Belle II physics potential is enormous!
   - Belle II hopes to shed light on the New Physics hints currently observed (and maybe more)

Appendices

LHCb - Belle II $R(K^*)$ comparison