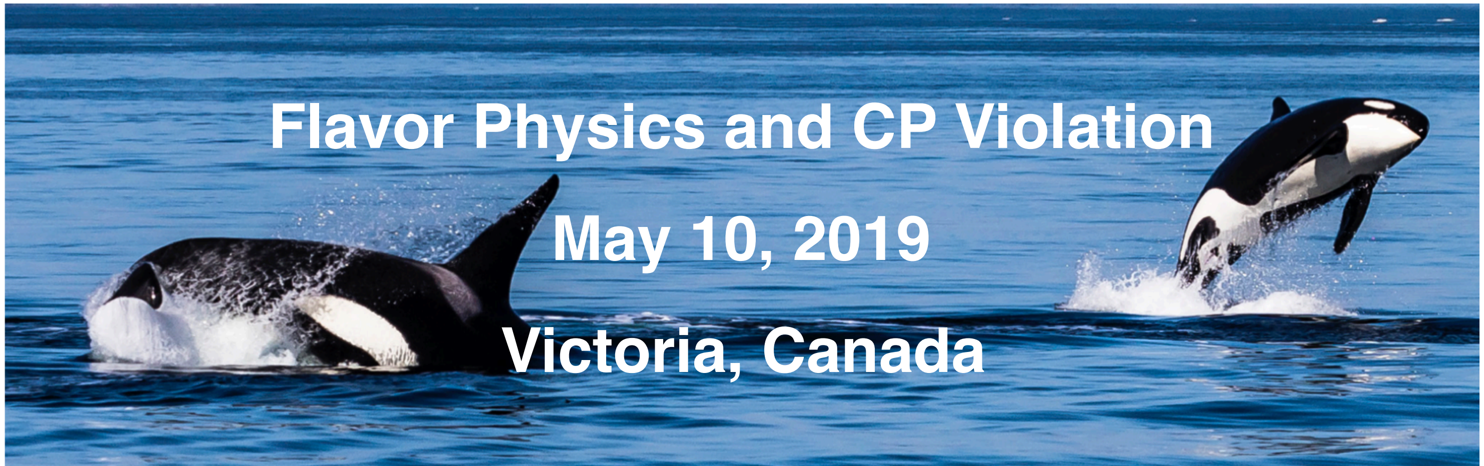
Belle II and *SuperKEKB* Status and Progress

Hülya Atmacan

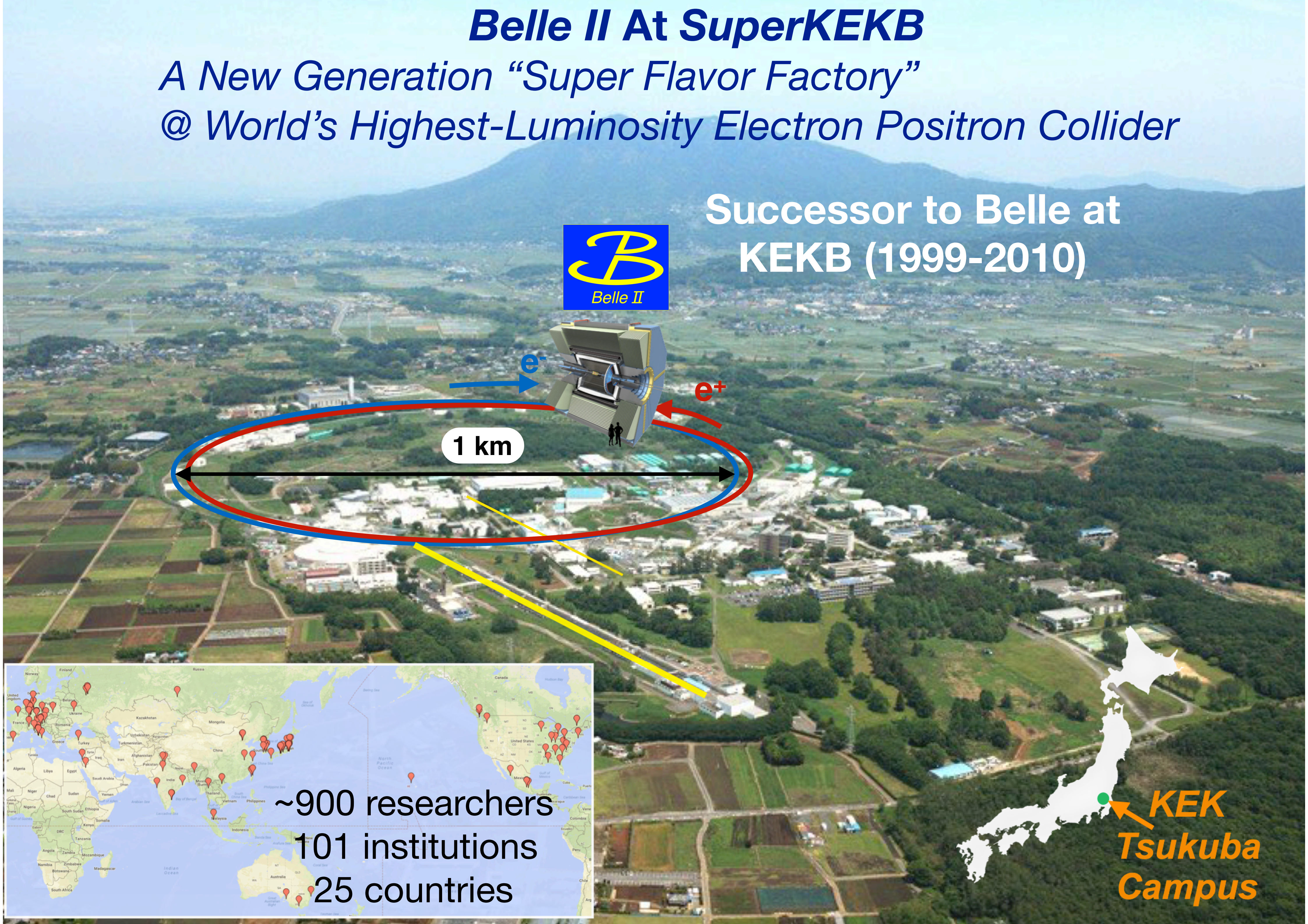
University of Cincinnati

On Behalf of the Belle II Collaboration



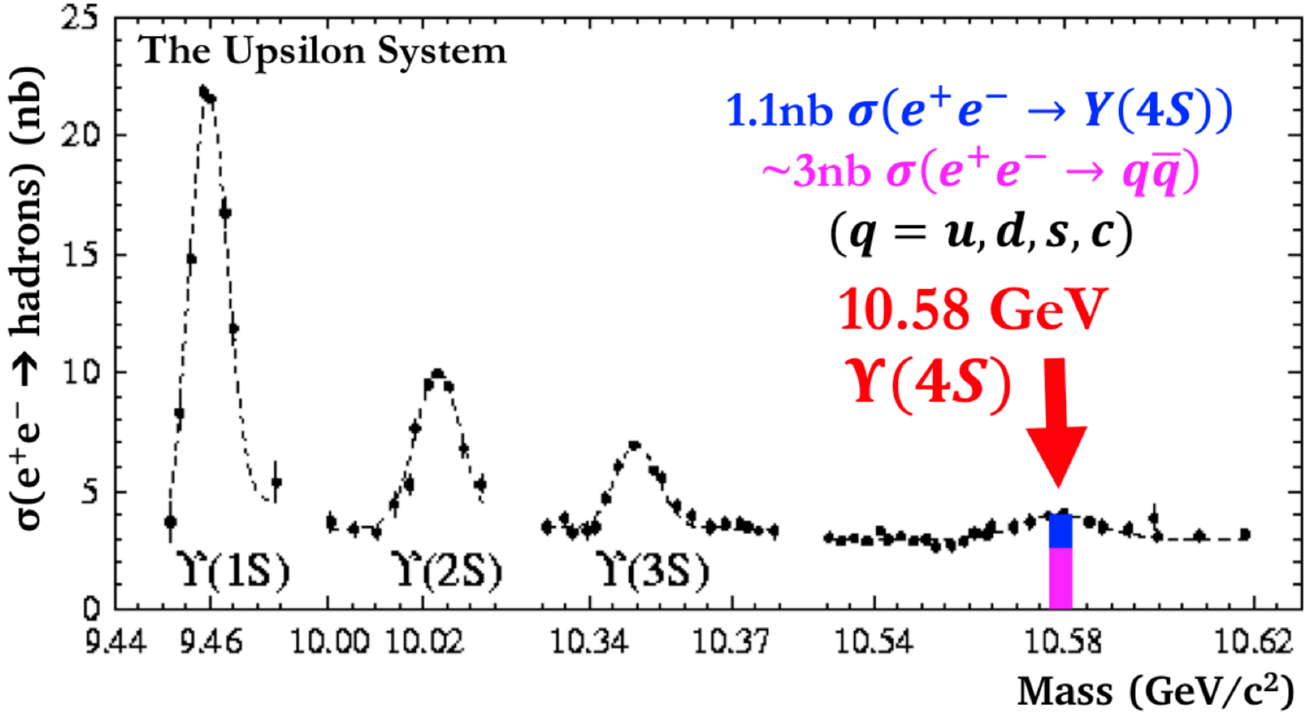
Outline

- Introduction
- *KEKB* to *SuperKEKB*
- *Belle* to *Belle II*
- *Belle II* and *SuperKEKB* upgrade history (with results of early data and current status)
- Summary
- Some *Belle II* physics prospects will be covered by Emi Kou.


Belle II At SuperKEKB
A New Generation "Super Flavor Factory"
@ World's Highest-Luminosity Electron Positron Collider
Successor to Belle at KEKB (1999-2010)
Belle II
e-
e+
1 km
~900 researchers
101 institutions
25 countries
KEK
Tsukuba
Campus

Belle II At *SuperKEKB*

- *Belle II* plans to collect 50 ab^{-1} of $e^+ e^-$ collisions at (or close to) the Υ(4S) resonance:
  - **a (Super) B-factory** (~1.1x10^9 $B\overline{B}$ pairs/ab^{-1})
  - **a (Super) charm factory** (~1.3x10^9 $c\bar{c}$ pairs/ab^{-1})
  - **a (Super) τ factory** (~0.9 x10^9 $\tau^+ \tau^-$ pairs/ab^{-1}).

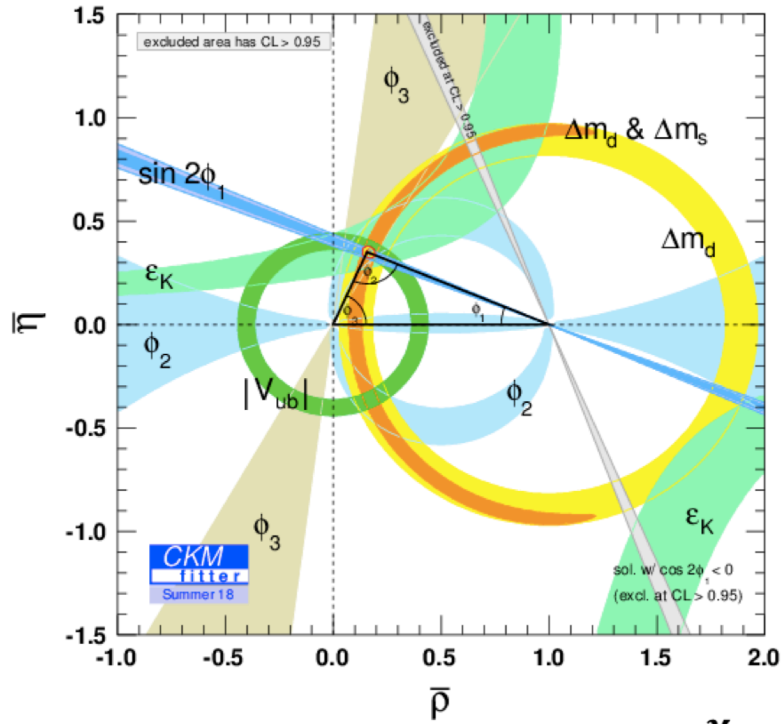


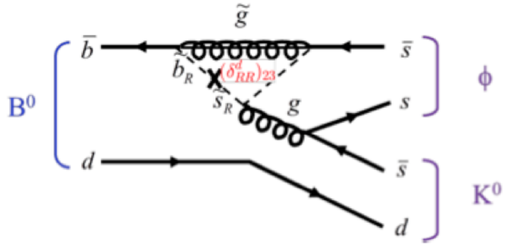
$$\mathscr{B}(\Upsilon(4S) \to B\bar{B}) > 96\,\%$$

Belle II At SuperKEKB

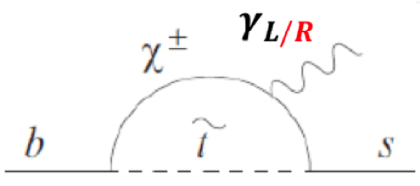
- CKM precision metrology.
- Search for New Physics (NP)
  - New CPV phases,
  - Multiple Higgs,
  - New FCNC, RH current etc.
  - Sources of LFV beyond SM
  - Dark photon/sector

  ……
- Need significantly more data!
- Ultimate goal of Belle II:
  50 ab^{-1} data sample

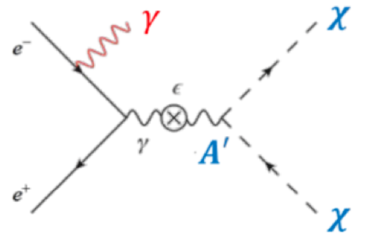




New CPV phase in b→sqq

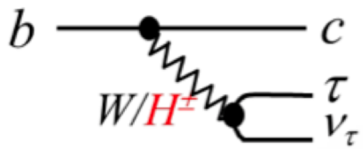


Right handed current in b→sγ



$e^+e^- \to \gamma A', A' \to \chi\chi$

- A' ... **dark photon**
- χ ... **dark matter**



R(D),R(D*) in B→D(*)τν

Belle II Physics

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2027)
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

CKM

CPV

(Semi) LEPTONIC LFUV

EWP

CHARM

TAU

Ultimate precision, 50 ab^{-1}

QUARKONIUM

DARK SECTOR

Very Rich Physics Program!

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

Belle II Talks in FPCP 2019

B Physics

"First look at time dependent CP violation using early Belle II data" **Stefano Lacaprara**

"Measurement of the CKM angle gamma with Belle II" **Niharika Rout**

"B lifetime and B0bar B0 mixing results from early Belle II data" **Jakub Kandra**

"Semileptonic and leptonic B decay results from early Belle II data" **Markus Prim**

"Early physics prospects for radiative and electroweak penguin decays at Belle II" **Justin Tan**

Quarkonium Physics

"Sensitivity to the X(3872) total width at the Belle II experiment" **Hikari Hirata**

"Exotic quarkonium physics prospects at Belle II" **Jake Bennett**

Tau Physics

"Prospects for tau lepton physics at Belle II" **David Rodriguez Perez**

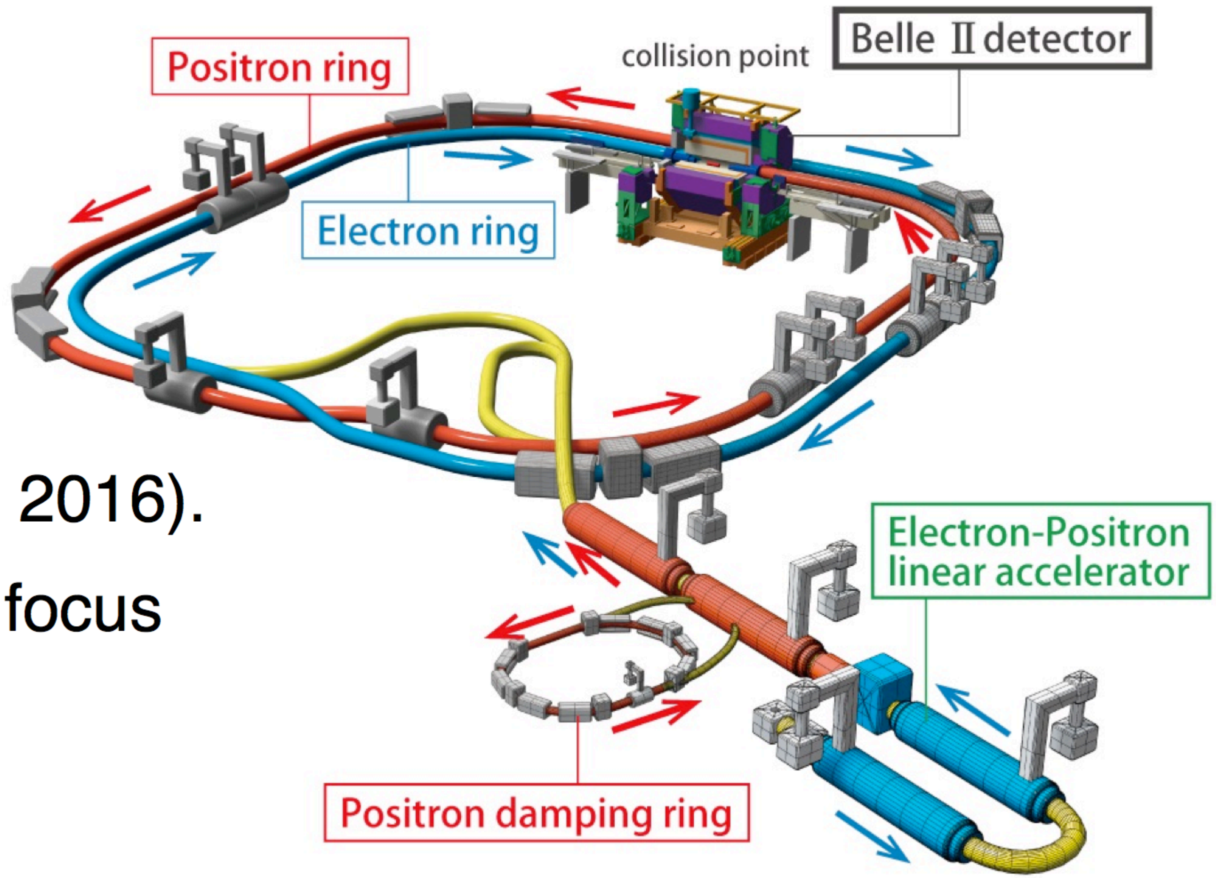
Dark Sector

"Dark sector physics with Belle II" **Chris Hearty**

"What we will, what we might, learn from Belle II and the LHCb upgrade" Emi Kou

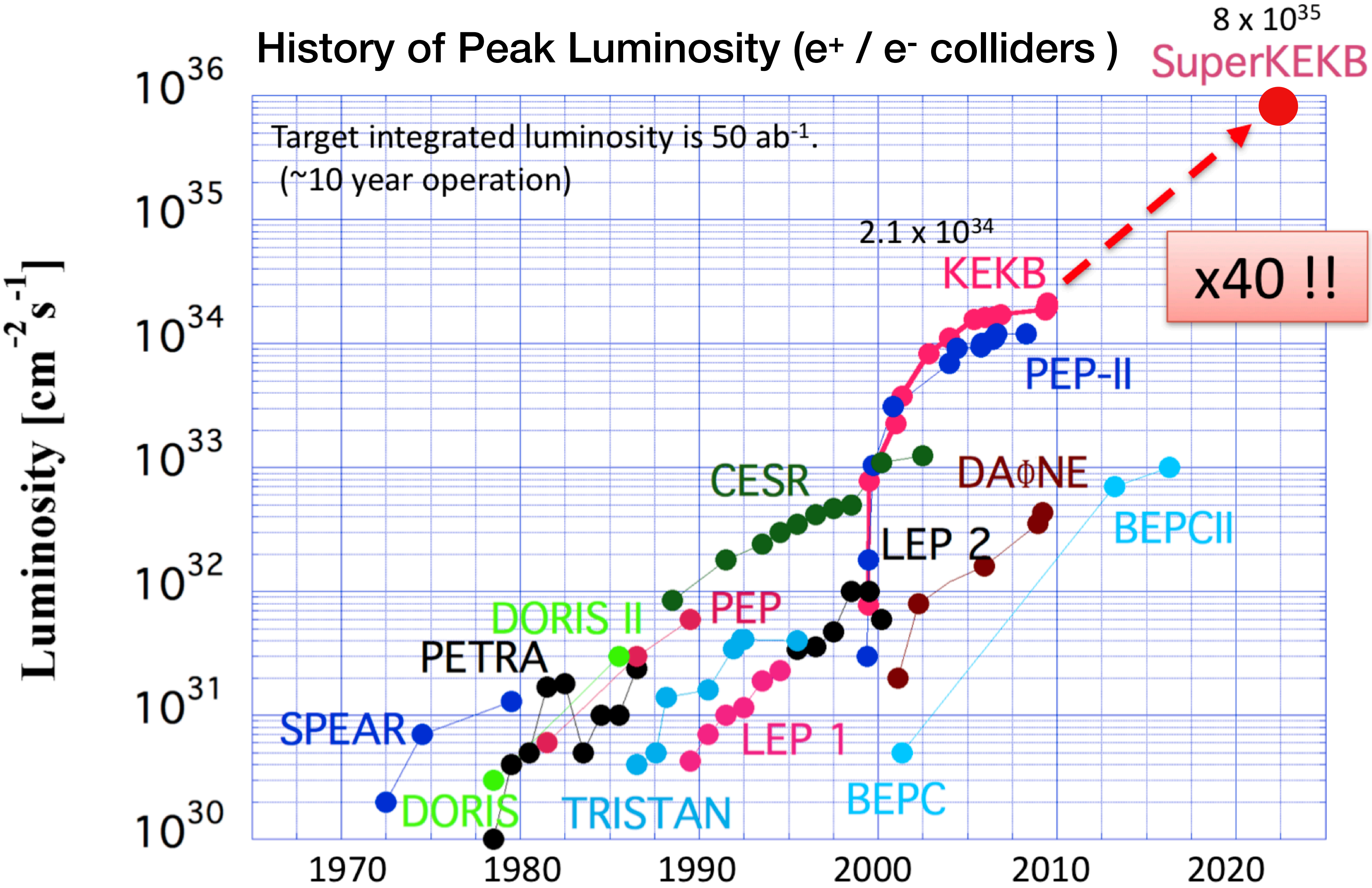
KEKB to *SuperKEKB*

- New e^+ damping ring (commissioned 2018).
- New 3 km e^+ ring vacuum chamber (commissioned in 2016).
- New superconducting final focus (commissioned in 2018)

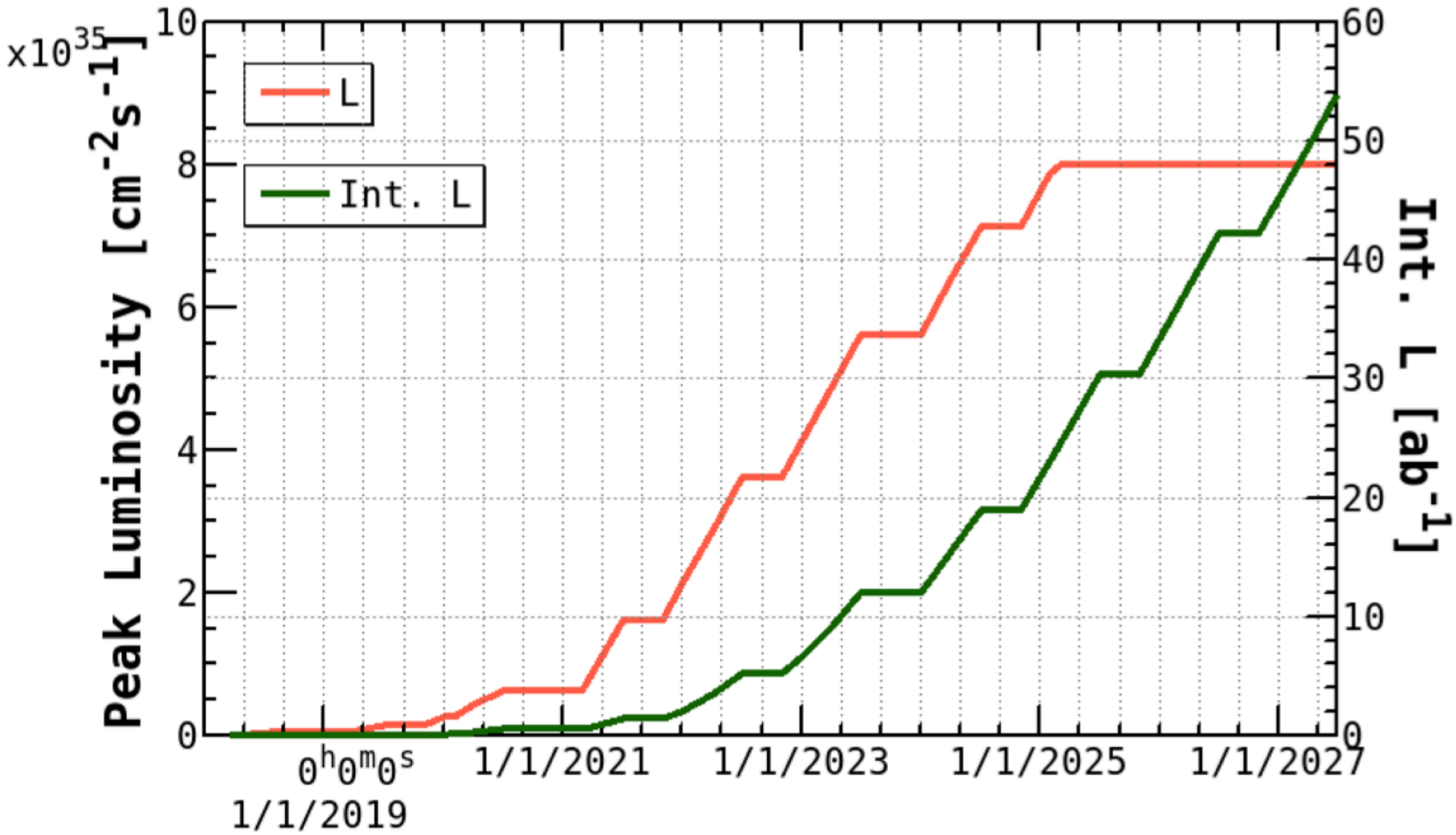


***gray - reused, color - new**

SuperKEKB Luminosity Target



SuperKEKB Luminosity Projection



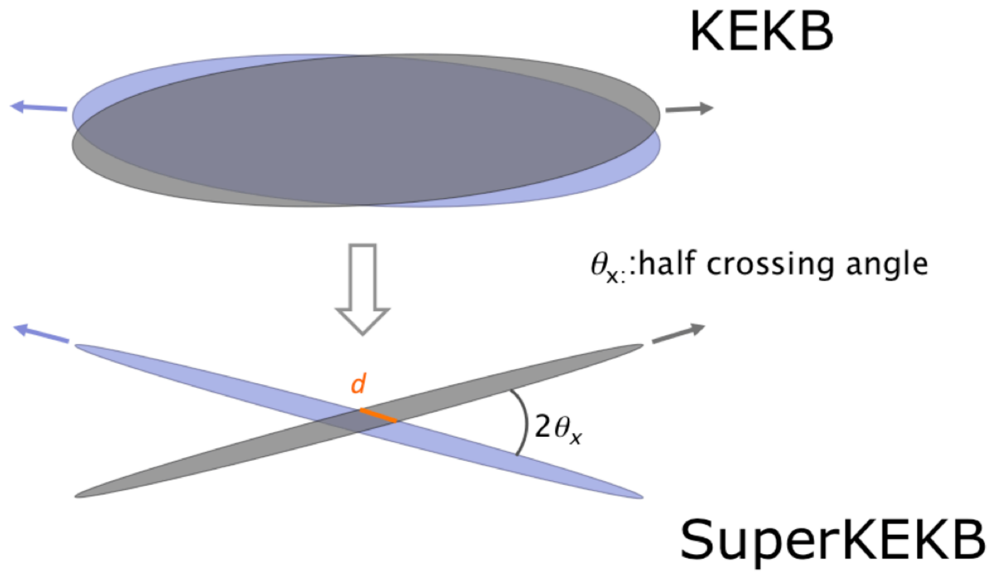
Accumulate 50 ab^{-1} , x50 of *BELLE / KEKB*

Strategies to Increase Luminosity

"nano beam" scheme is employed
[proposed by P. Raimondi]

	SuperKEKB e+ / e−	KEKB e+ / e−
E (GeV)	4.0/7.0	3.5/8.0
CM boost (βγ)	0.28	0.425
β_y at IP (mm)	0.27/0.3	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
L($cm^{-2}s^{-1}$)	80×10^{34}	2.1×10^{34}

Reduce beam size to a few 100 atomic layers



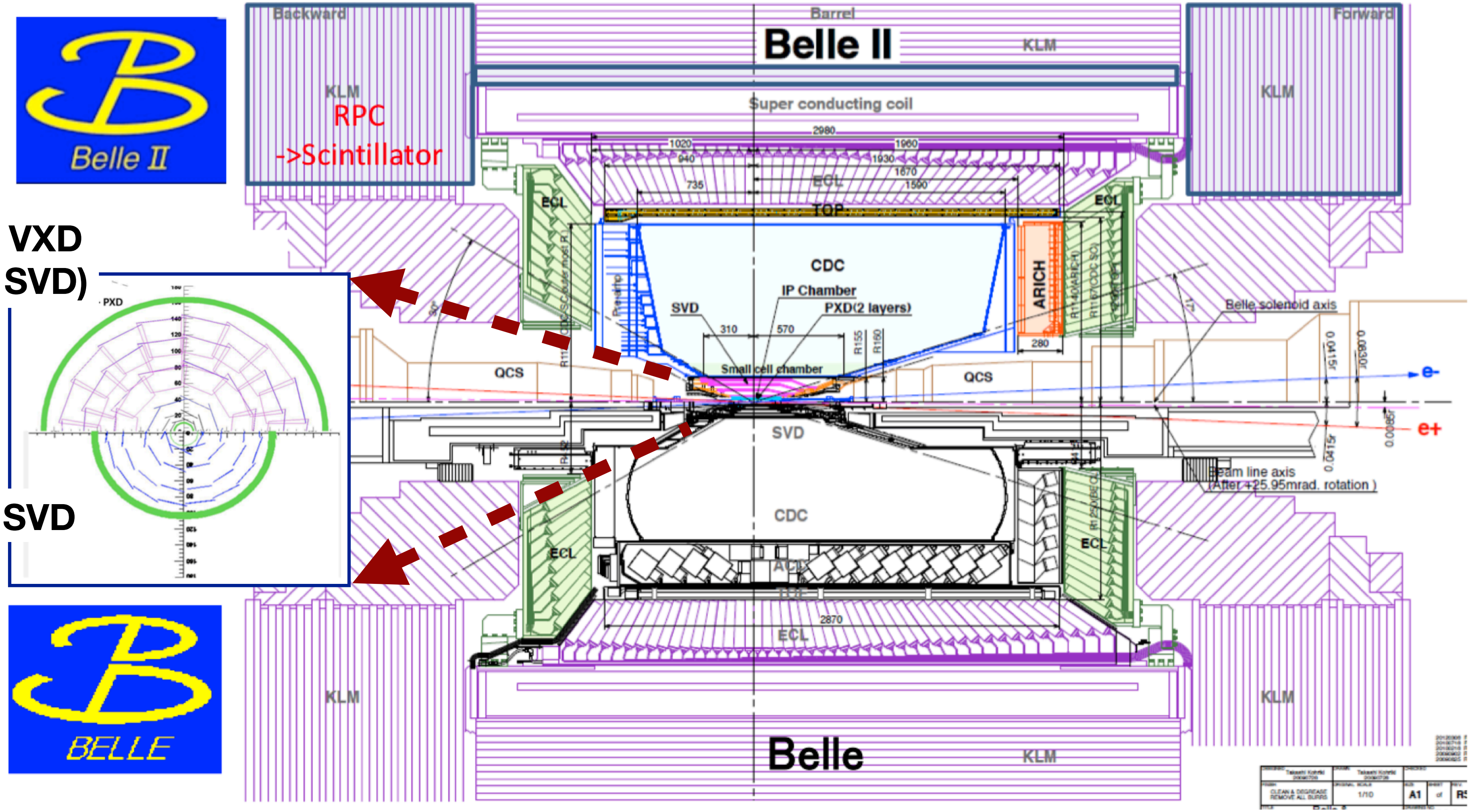
Beam at IP will be squeezed by 1/20.

Beam currents will be doubled.

40 times higher!

Belle to *Belle II* (Detector Layout)

Belle II VXD (PXD + SVD)



Belle SVD

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

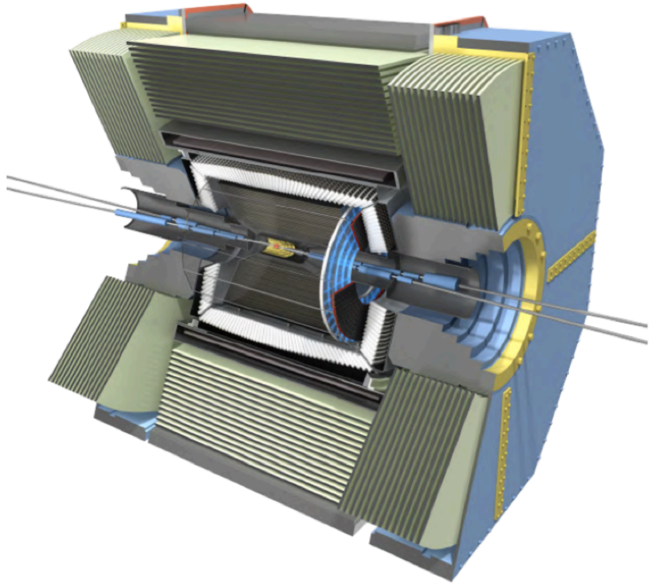
(Endcap and inner two layer of Barrel for neutron BG)

Max 30 kHz L1 trigger.

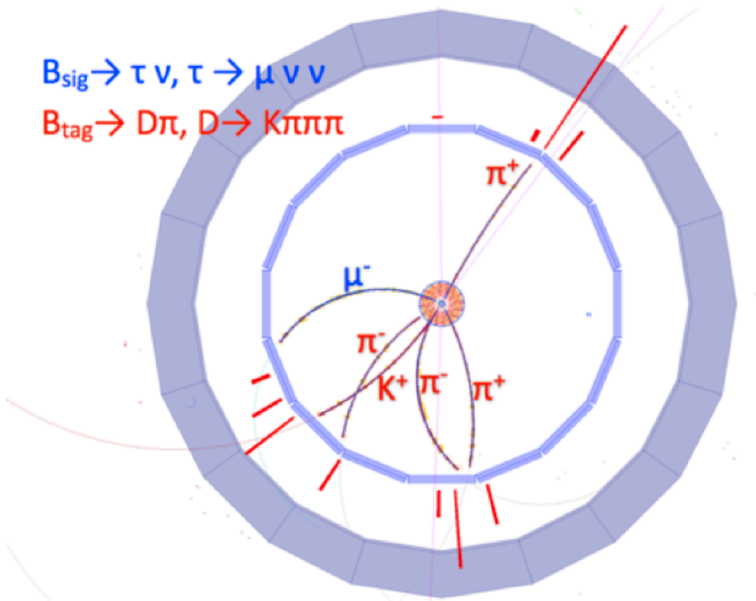
Offline computing:
Distributed over the world via the GRID

Strengths of *SuperKEKB* and *Belle II*

- Very clean sample of quantum correlated $B^0\overline{B^0}$ pairs.
- High effective flavor-tagging efficiency (~37%).
- Belle 2 can also measure K_S and K_L .
- Efficient reconstruction of neutrals (π^0, K_s, K_L, η, η', ρ^+ etc.)
- Dalitz plot analyses, missing mass analyses straightforward.
- Systematics quite different than those of LHCb
  - If NP is seen by one experiment, it should be confirmed by the other.

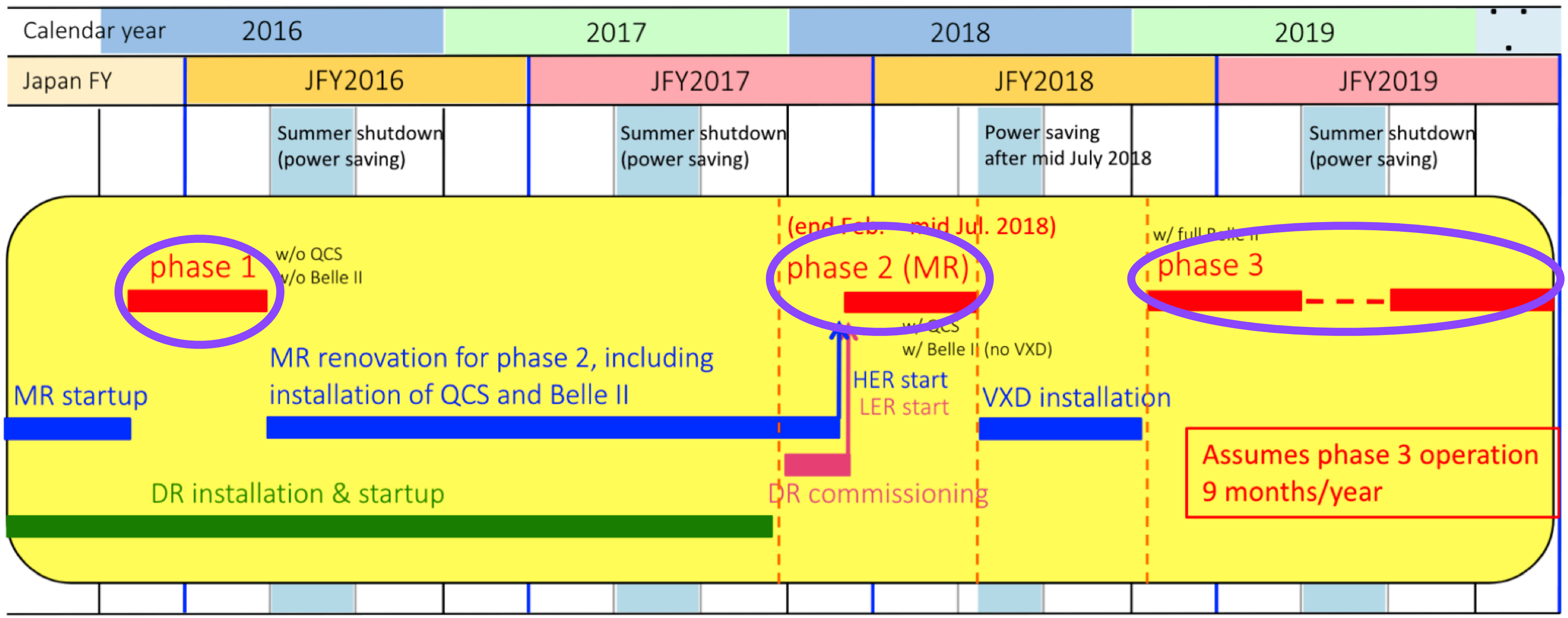


Belle II covering ≳ 90% of 4π



Belle II MC

Global Schedule



Phase 1: SuperKEKB commissioning without final focusing and without Belle II detector. (January - June 2016)

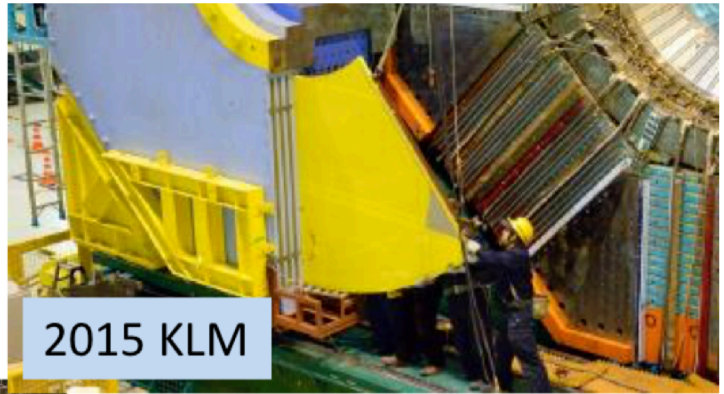
Phase 2: Collision data taking with final focusing. Belle II with no final vertex detector. (April - July 2018. Recorded ~500 pb^{-1})

Phase 3: Collision data taking with full Belle II detector. **STARTED MARCH 2019**!

Belle II and *SuperKEKB* Upgrade History

- 2010, Belle and KEKB operation completed
  - Started upgrade to Belle II and SuperKEKB

Sub-detector installation


2015 KLM

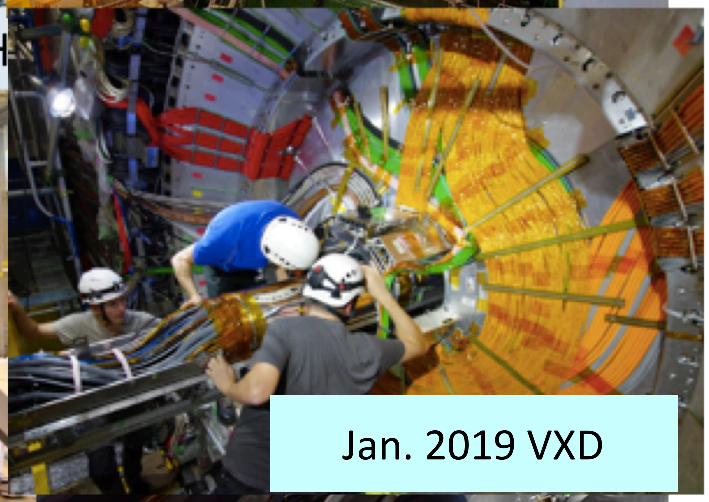

May 2016: TOP


Oct. 2016: CDC


Jan. 2017 BWD ECL

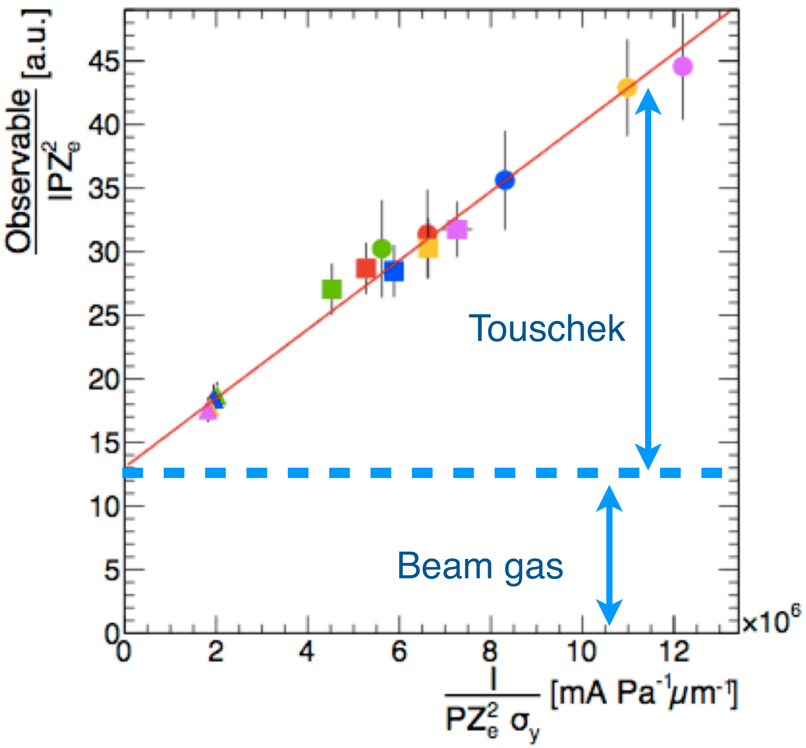

Apr 2017
Belle roll-in

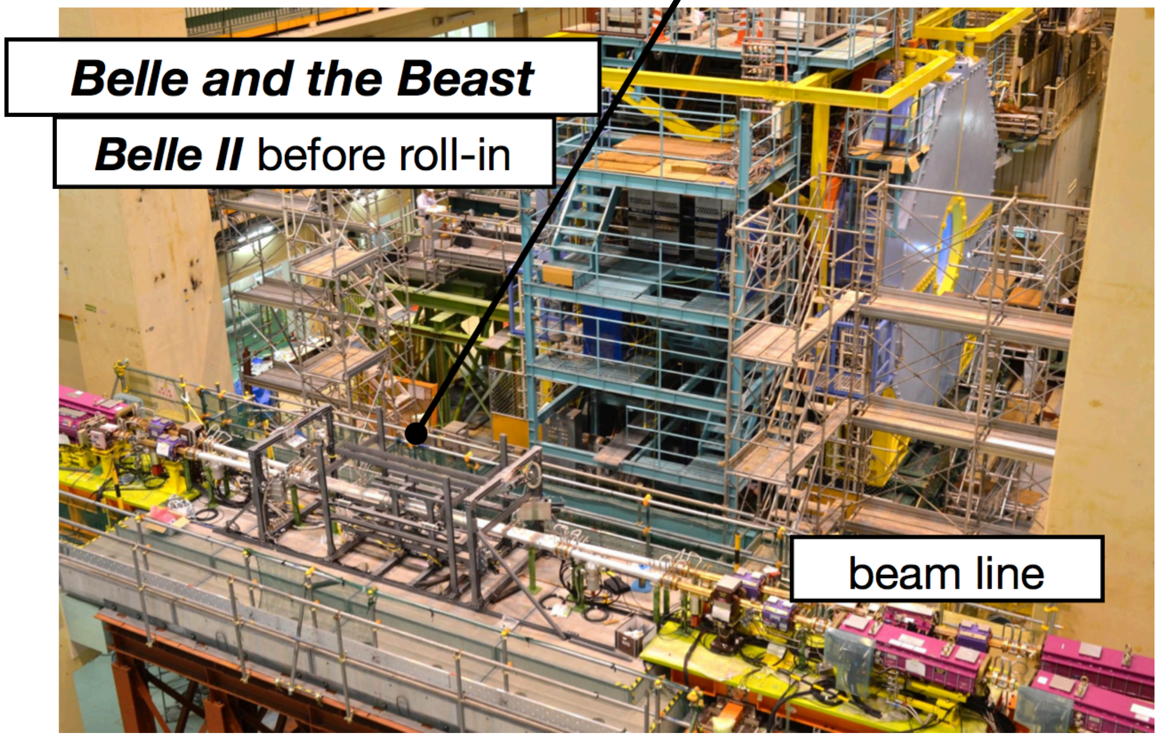

Aug.2017:ARICH


Jan. 2019 VXD

Belle II and *SuperKEKB* Upgrade History

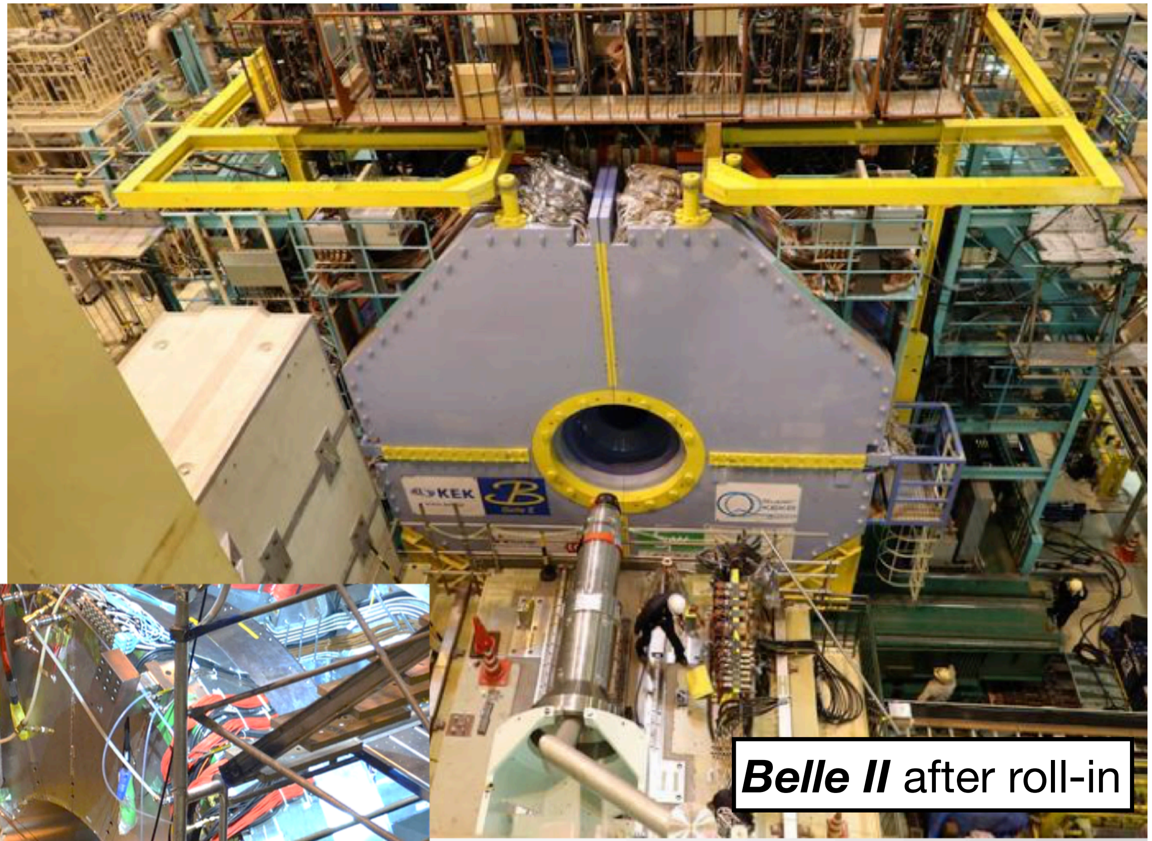
- **2016, January - June Commissioning:**
  "Phase I" :
- Only for single beam background studies.
- no final focusing, no collisions, and without Belle II.
- **B**eam **E**xorcism for **A ST**able Experiment II Detector:
  - Background commissioning detector (diodes, TPCs, crystals).
- Tune accelerator optics, vacuum scrubbing, beam studies, validation of Belle II beam background simulations.





Belle II and *SuperKEKB* Upgrade History

- **2017, Belle II Detector rolled-in to the beam line**



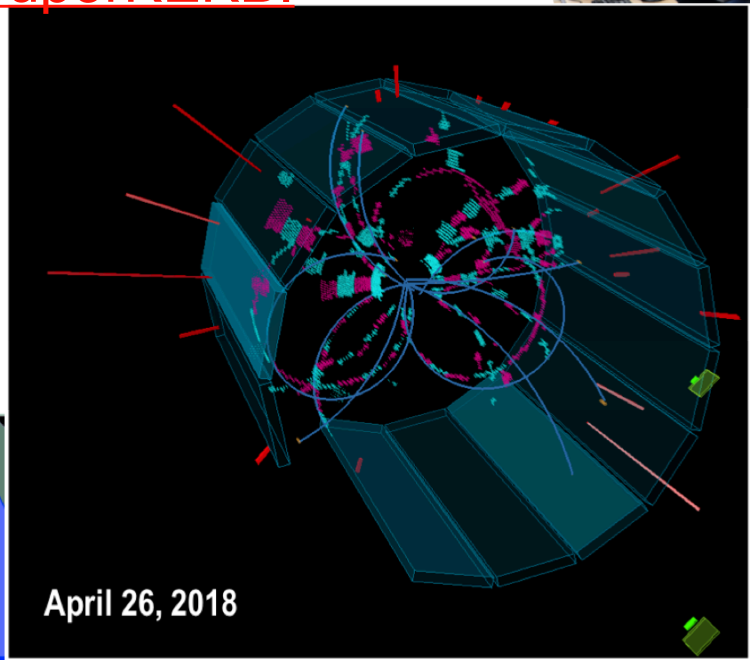
Belle II after roll-in

January 2018: The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector

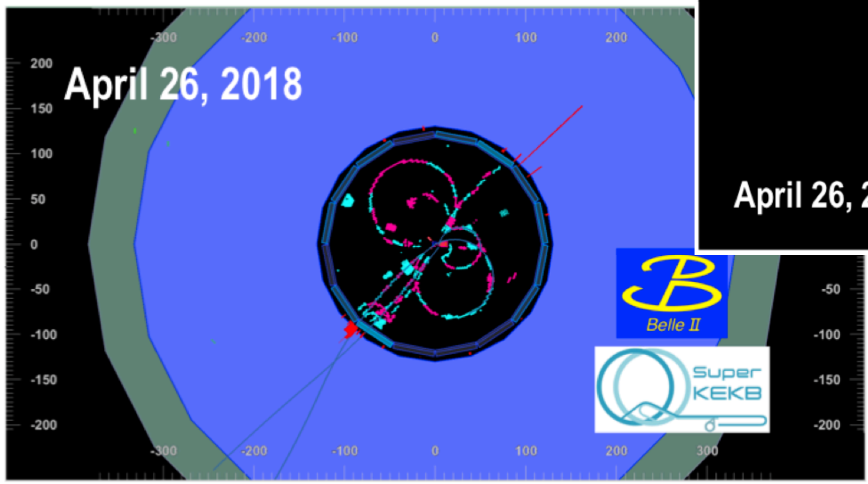
Belle II and *SuperKEKB* Upgrade History

- **2018, April - July Commissioning.**
  - **"<u>Phase 2</u>" :** Collision data taking with final focusing. Belle II with no final VXD.

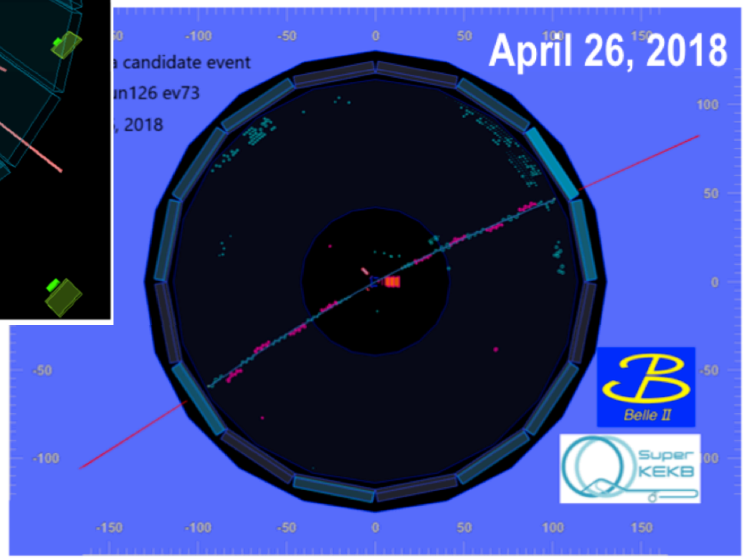
<u>First $e^+ e^-$ collisions at SuperKEKB.</u>



$B\bar{B}$ like event



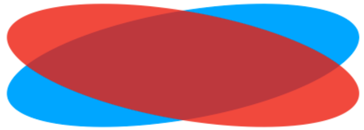
Hadronic event



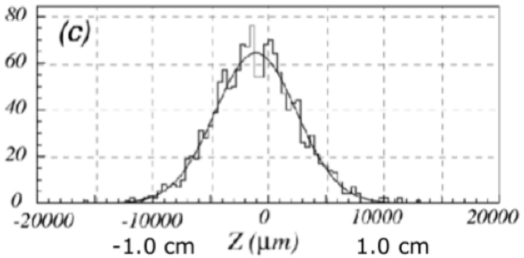
Bhabha event

Phase 2: Beam Profile

Ordinary collision KEKB

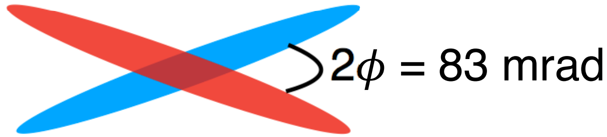


Z vertex distribution



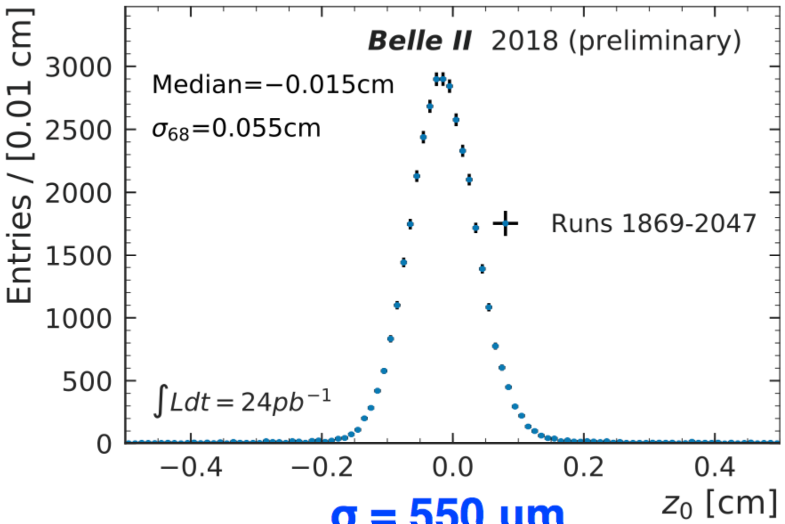
σ = 4.5 mm

Nano-Beam (SuperKEKB)

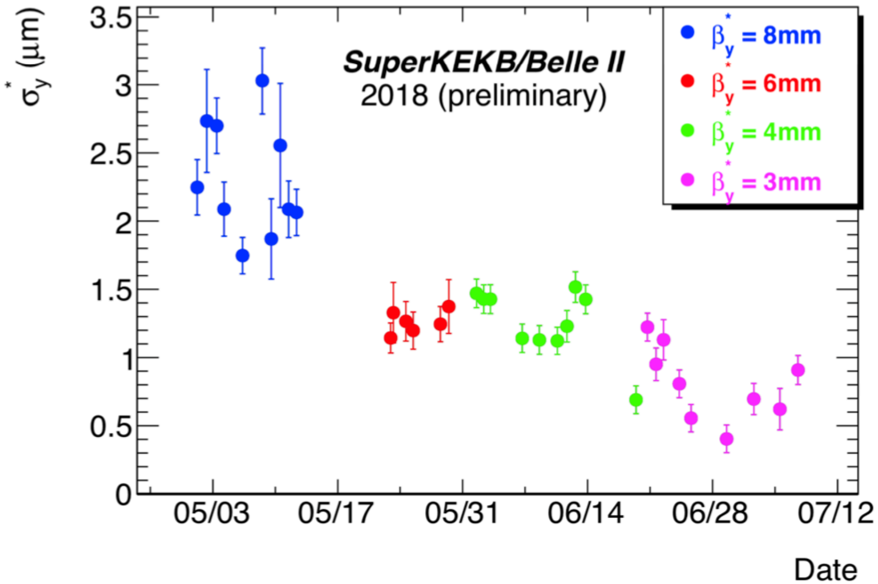


Z vertex distribution

Belle II case 2018 data



σ = 550 μm



The nano beam scheme is working!

Succeeded to reduce $\beta_y^* = 3$ mm and $\sigma_y = 400$ nm

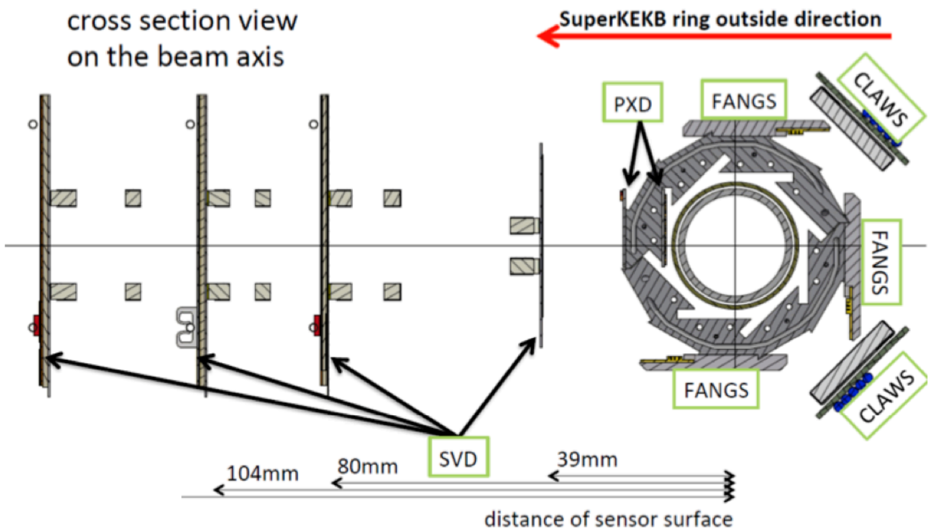
(Final target $\beta_y^* = 0.3$ mm)

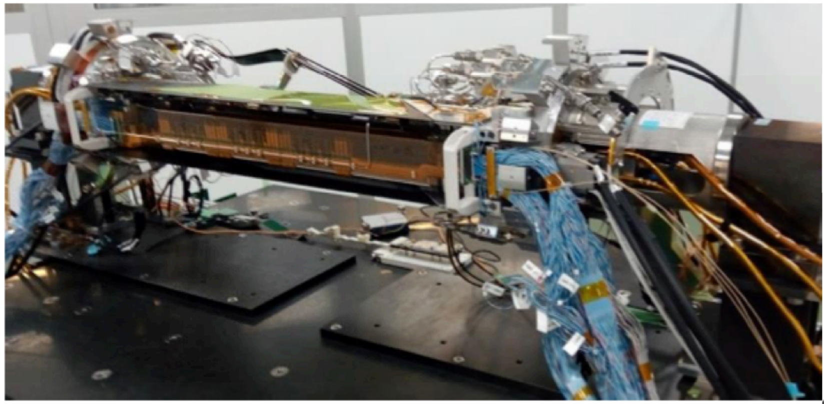
$L_{peak} = 5.55 \times 10^{33}\ cm^{-2}s^{-1}$

Belle II recorded ~ 500 pb^{-1}

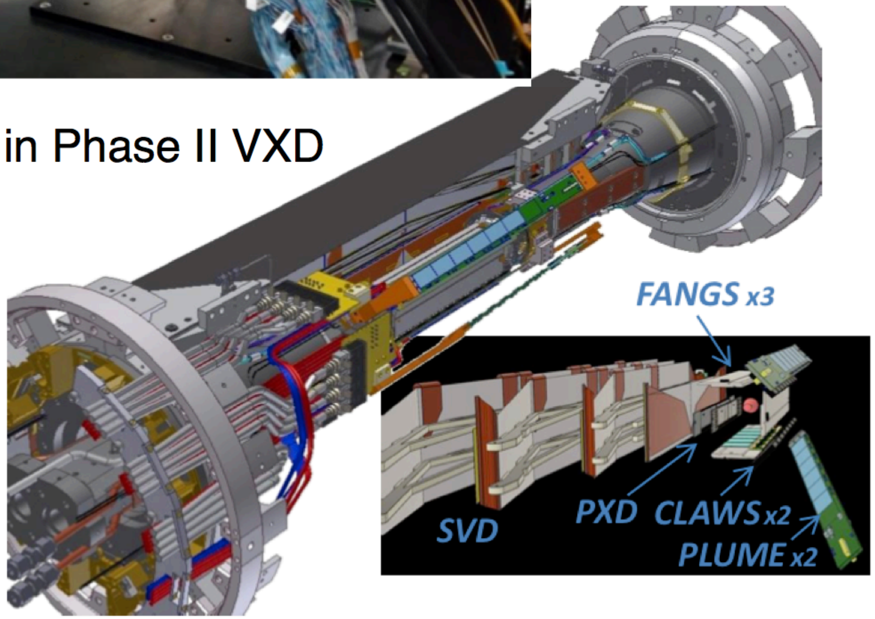
Phase 2: Partial VXD (1)

- Belle II with partial VXD: 1 sector of PXD and SVD with background sensors.

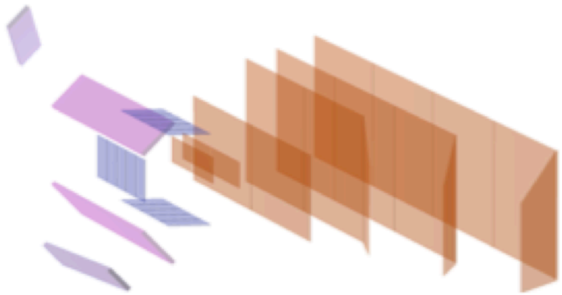




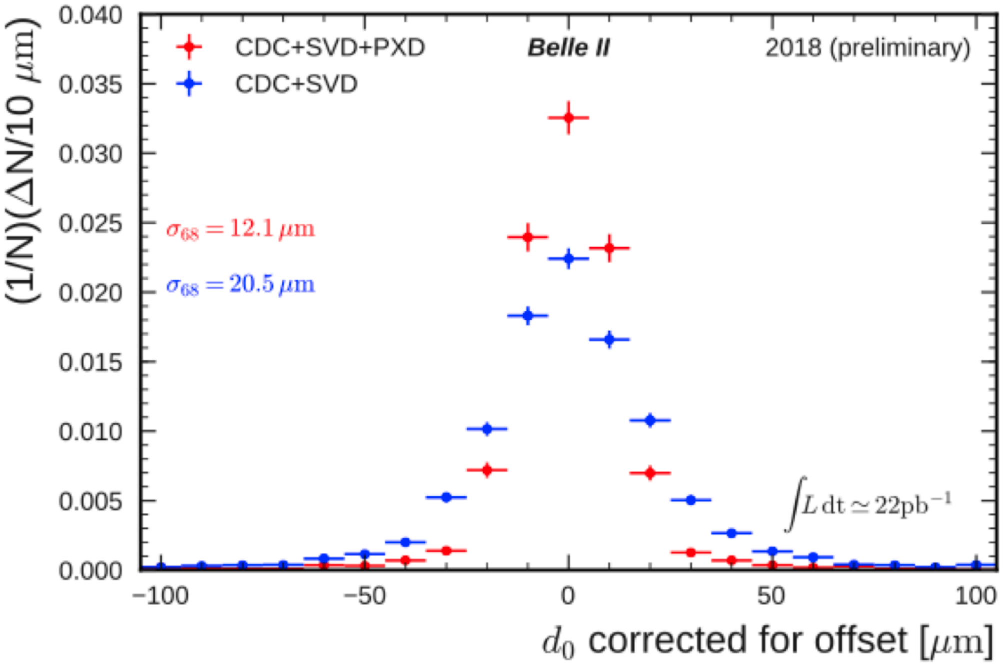
BG Sensors in Phase II VXD

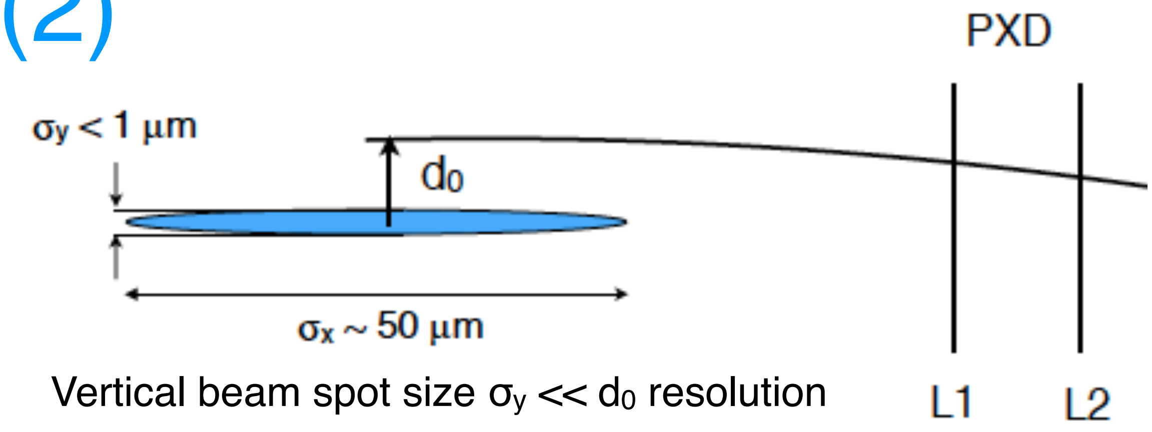


Layout of Phase 2 VXD



Phase 2: Partial VXD (2)



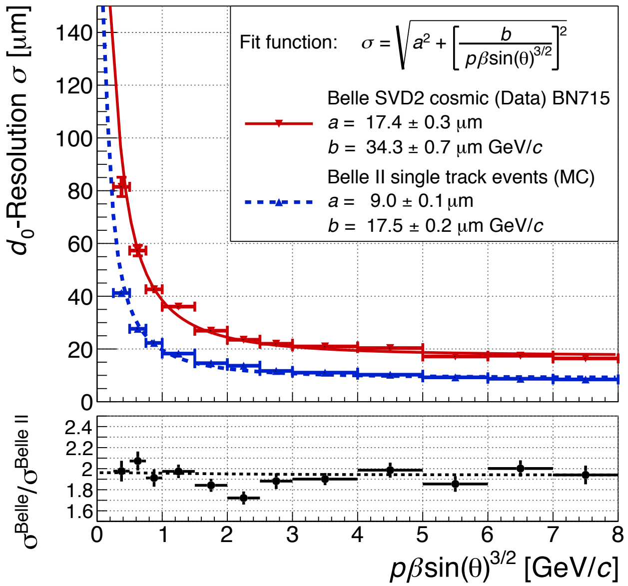


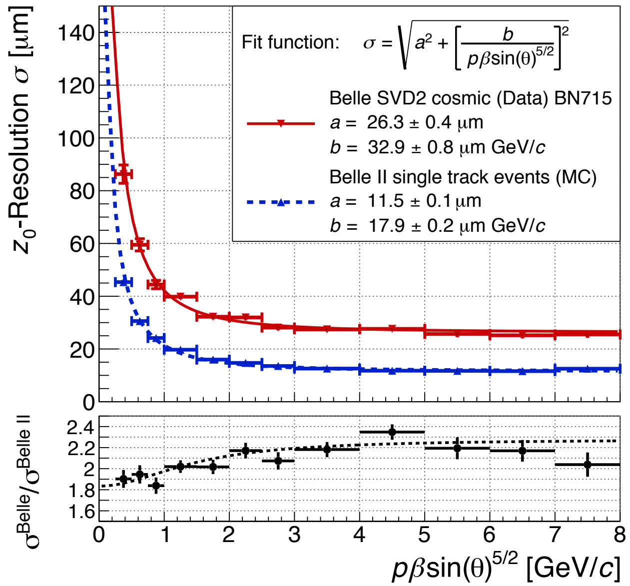
Vertical beam spot size $\sigma_y \ll d_0$ resolution

⇒width of distribution is measure of resolution

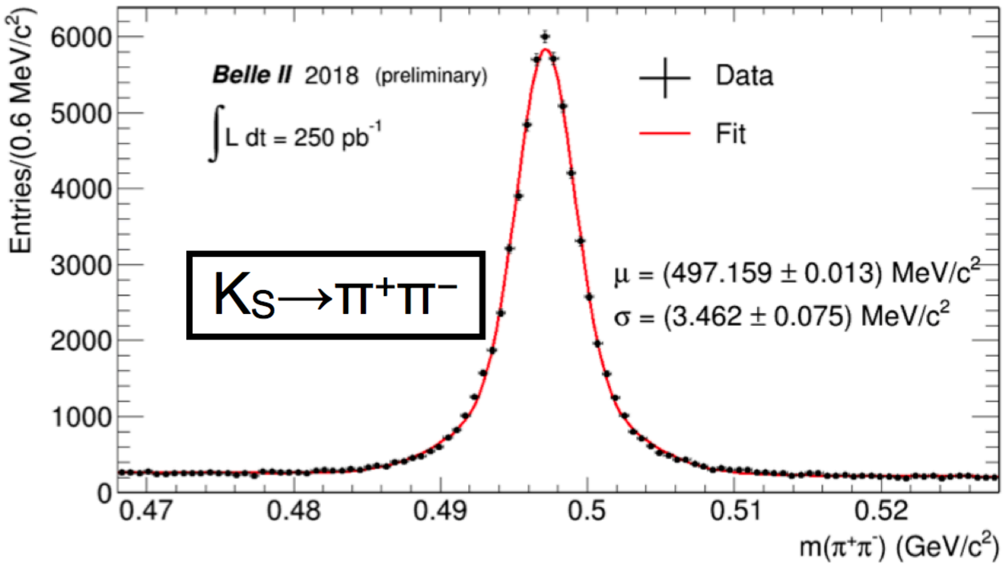
Transverse impact parameter, d_0, resolution is **12 μm (CDC+SVD+PXD)** (expected is 10 μm).

Belle II MC vs Belle

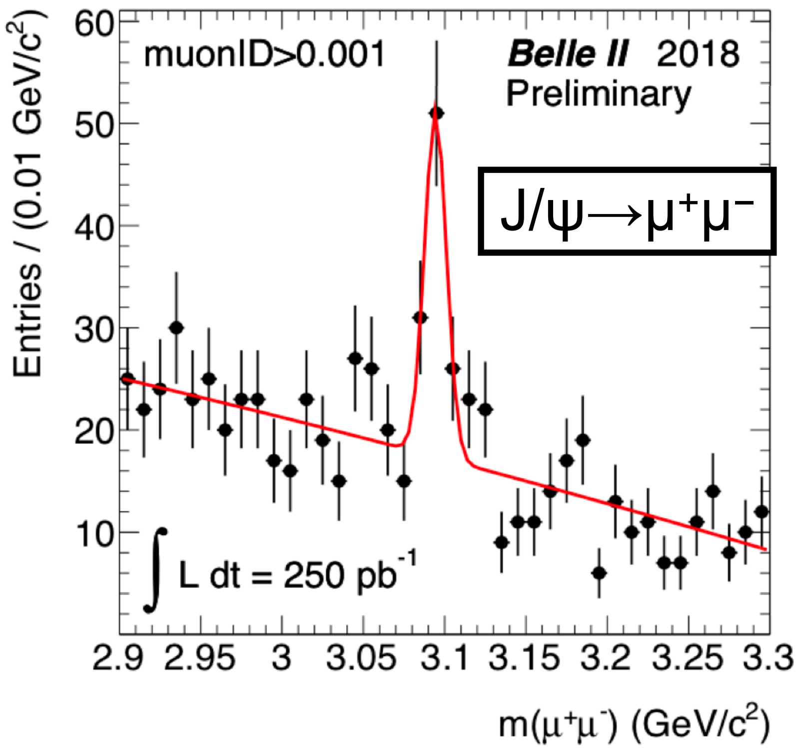


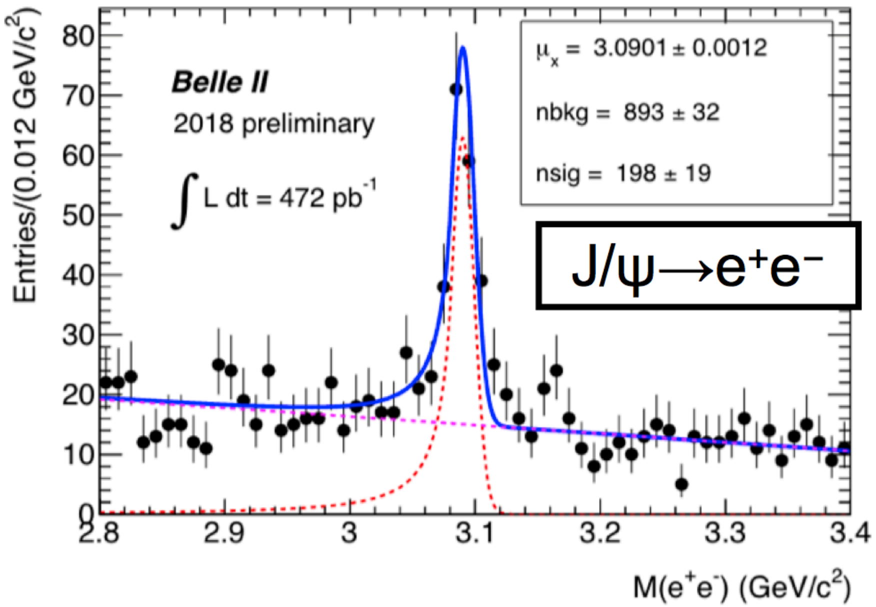


Phase 2: Track Reconstruction



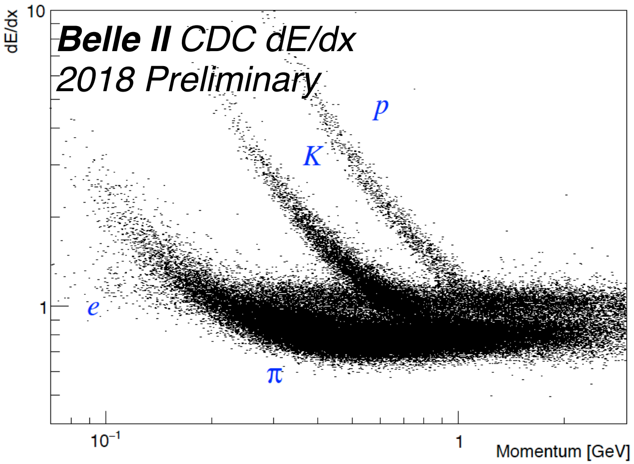
- Tracks have been reconstructed with CDC and partially installed VXD.
- Detector alignment and B field are well understood.

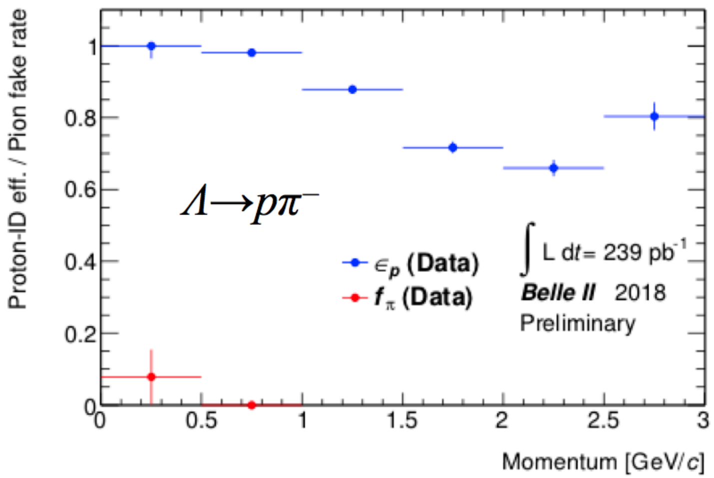




Phase 2: Particle Identification

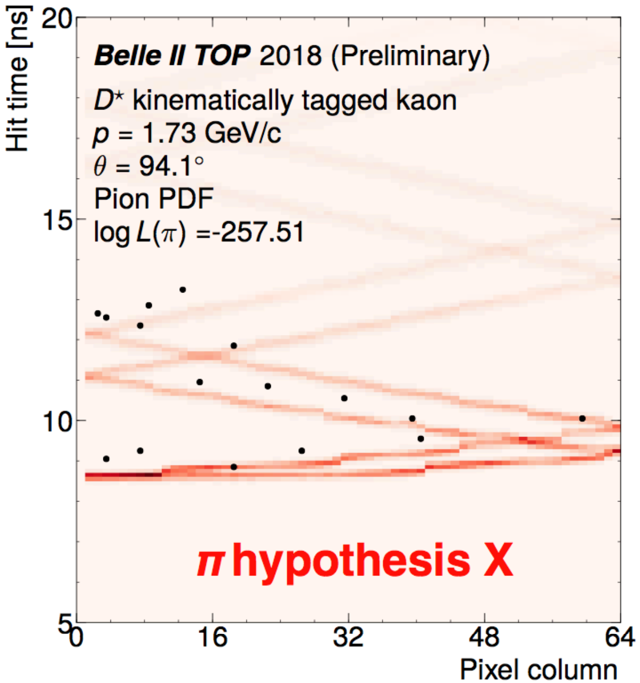
Central Drift Chamber dE/dx

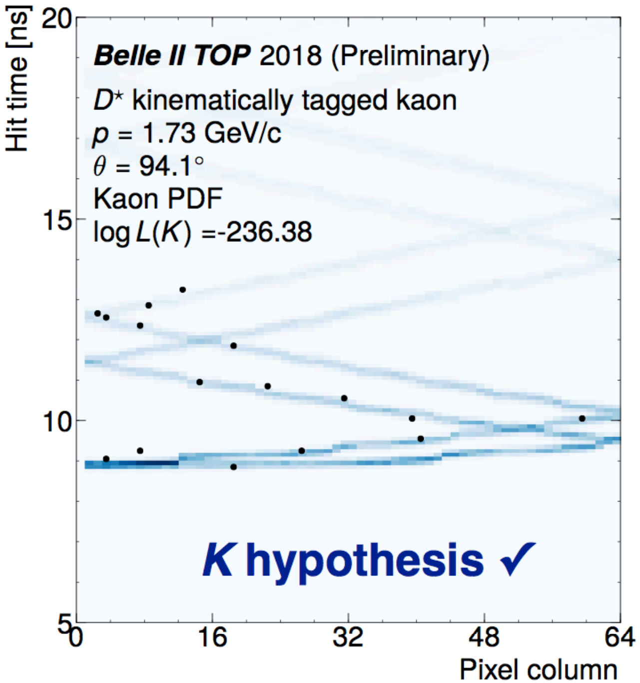


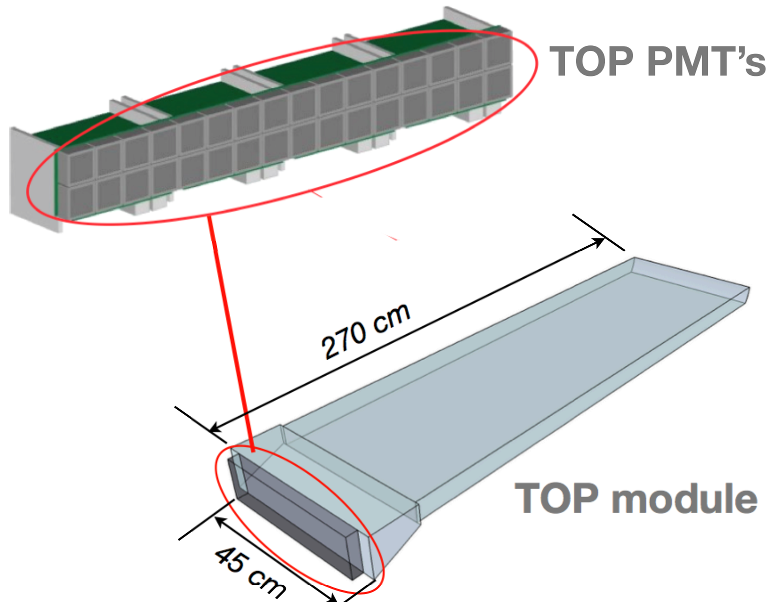


Cherenkov photons observed by TOP detector

$D^{*+} \to D^0\pi^+$ [$D^0 \to (K^-\pi^+)$] x vs t pattern (mapping of Cherenkov ring)







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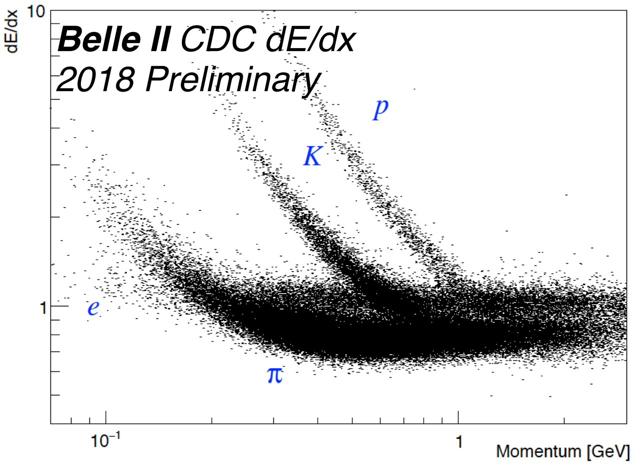
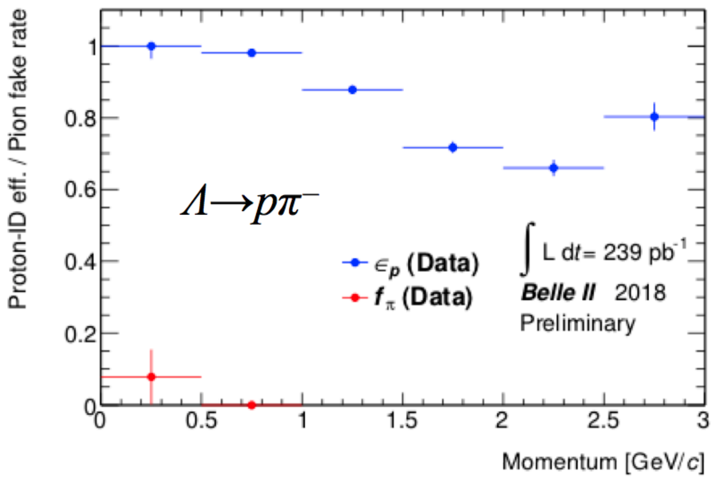
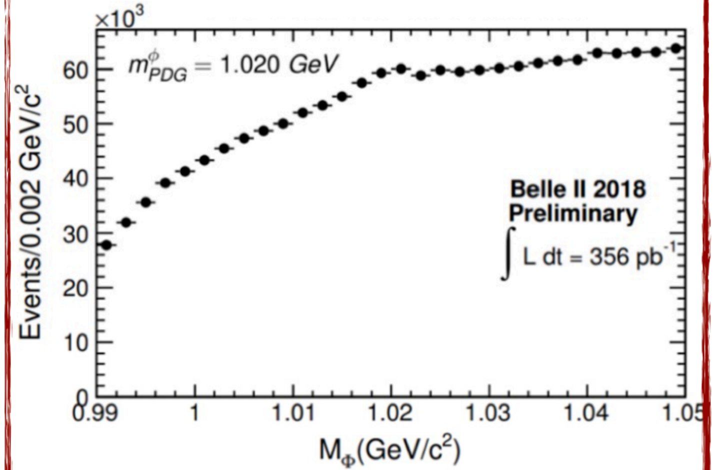
Central Drift Chamber dE/dx





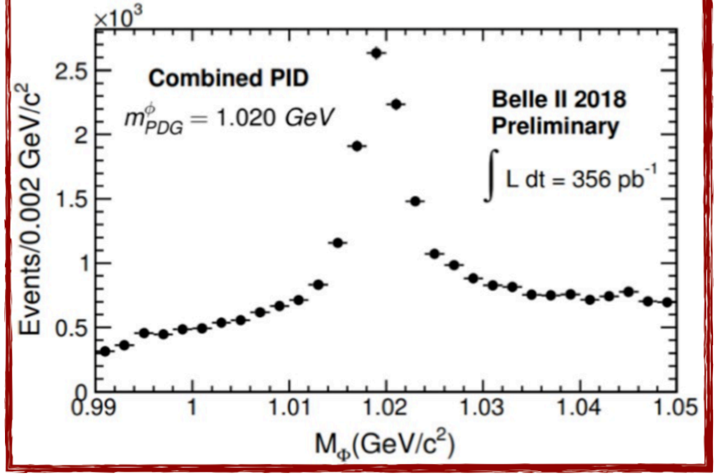
Rediscovery of ϕ

No PID requirement



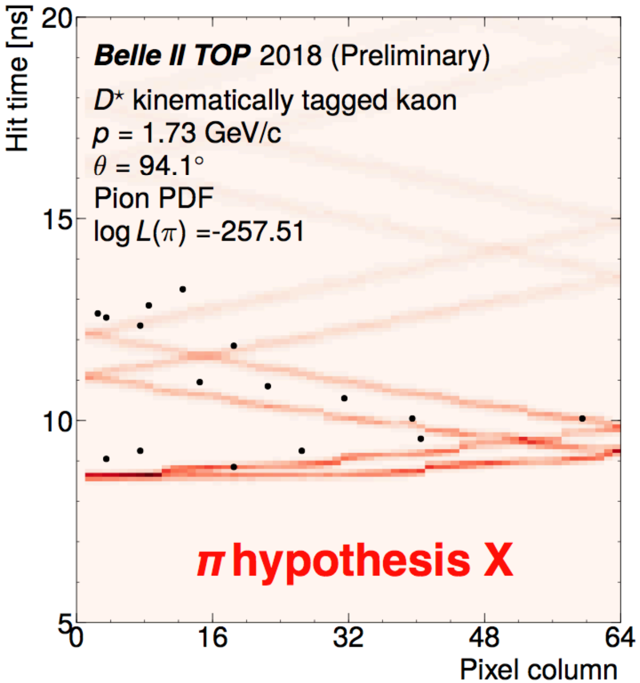
TOP + dE/dx from CDC

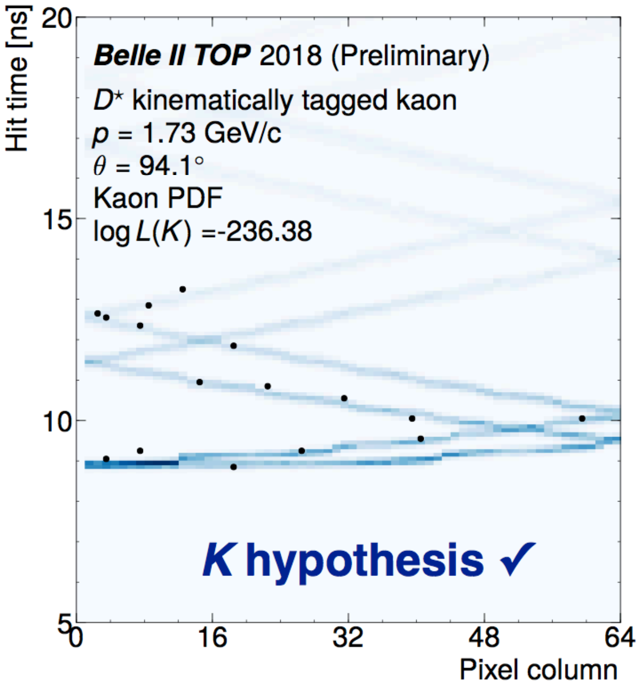
Both kaons are identified



Cherenkov photons observed by TOP detector

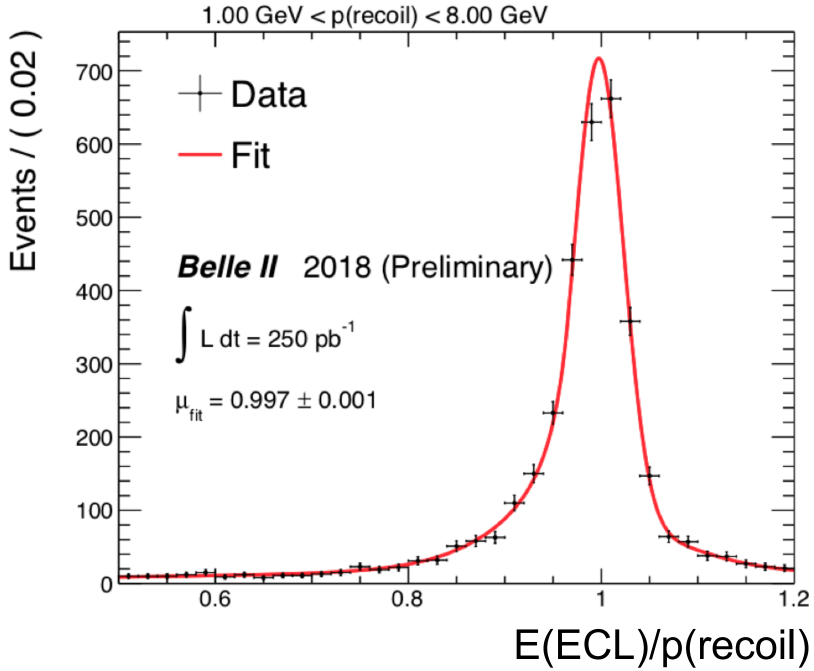
$D^{*+} \to D^0 \pi^+$ [$D^0 \to (K^- \pi^\pm)$] x vs t pattern (mapping of Cherenkov ring)



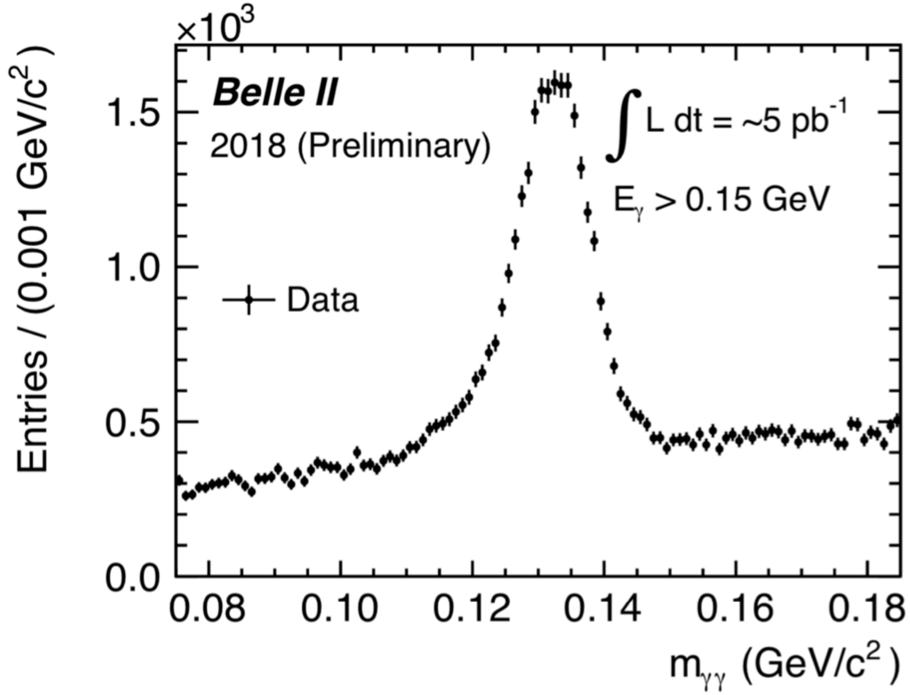


Phase 2 : Photon Reconstruction

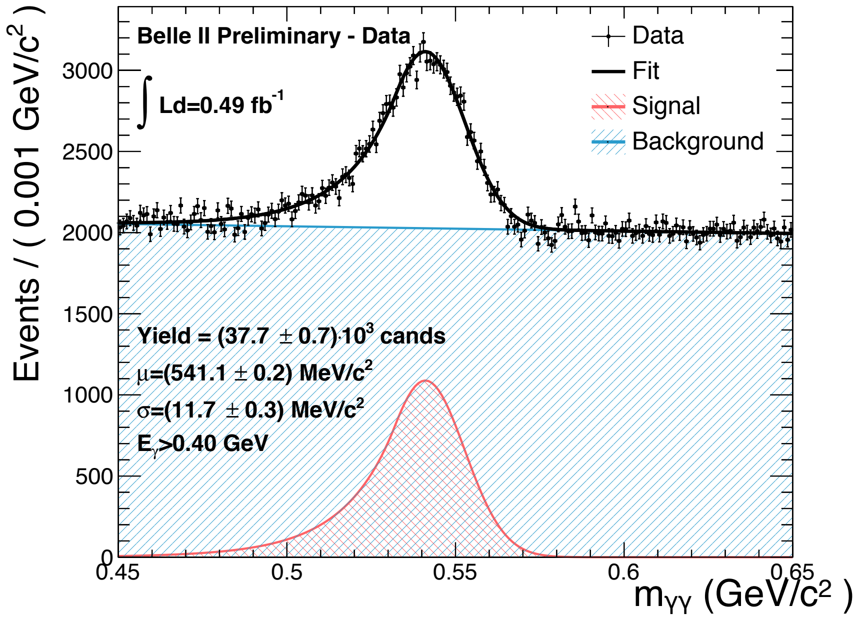
$e^+e^- \rightarrow \mu^+\mu^-\gamma$



$\pi^0 \rightarrow \gamma\gamma$



$\eta \rightarrow \gamma\gamma$



- Good reconstruction single photons and pairs.
- Ready for the “dark sector” : single photons

$$e^+ e^- \rightarrow \gamma X$$

$$e^+ e^- \rightarrow \gamma ALP \rightarrow \gamma(\gamma\gamma)$$

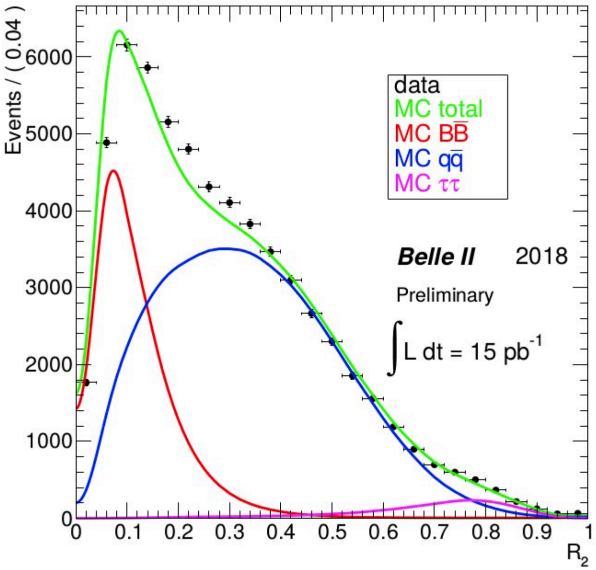
See Christopher Hearty’s talk

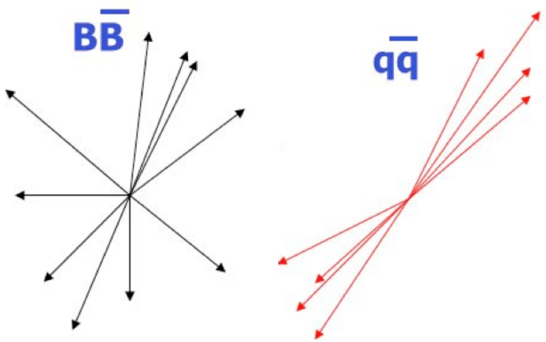
Phase 2: Hadronic *D* and *B* Reconstruction

Event Topology (fits to R_2) tells us we are seeing B's

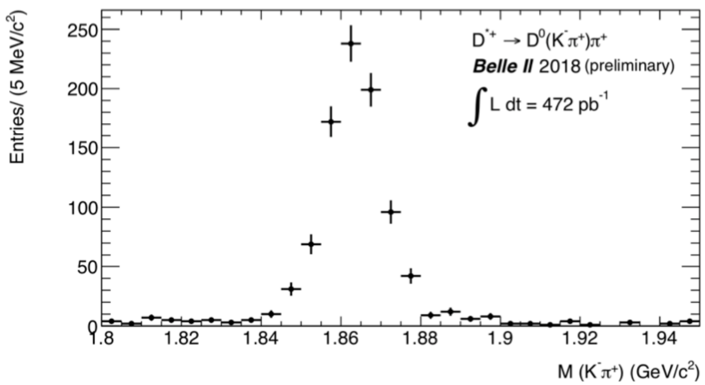
$R_2 = H_2/H_0$

$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E^2_{\mathrm{vis}}} P_l(\cos\theta_{ij}) ,$$

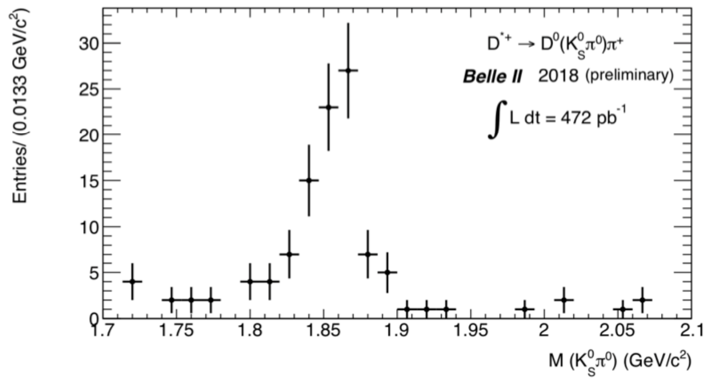




$D^0 \rightarrow K^- \pi^+$



$D^0 \rightarrow K_S \pi^0$



Difficult to see at LHCb!

Phase 2: Hadronic *D* and *B* Reconstruction

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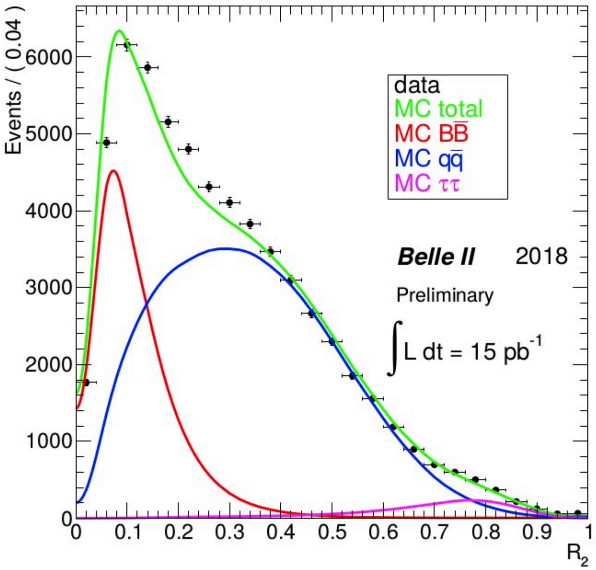
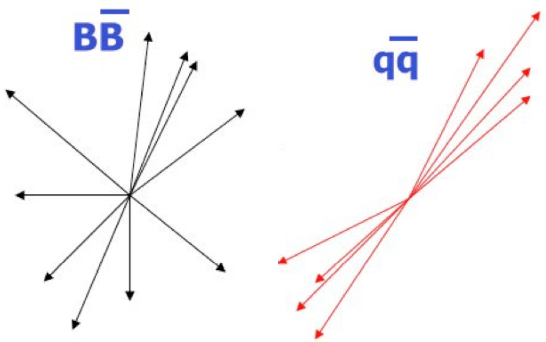
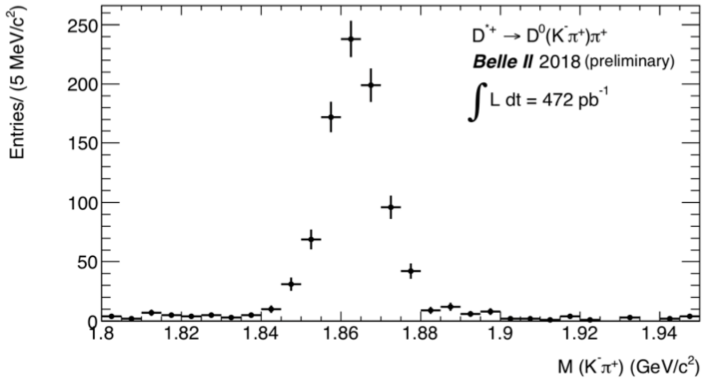
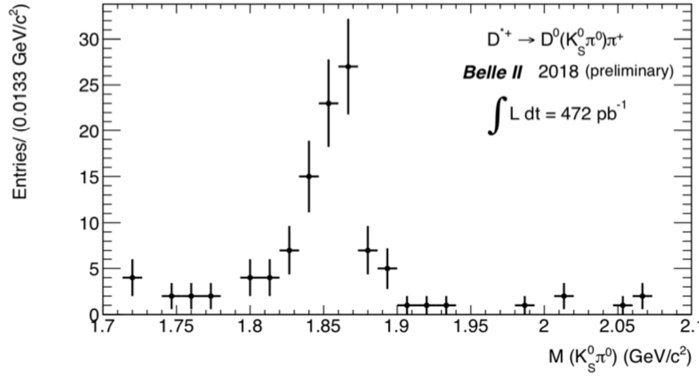




$D^0 \rightarrow K^- \pi^+$

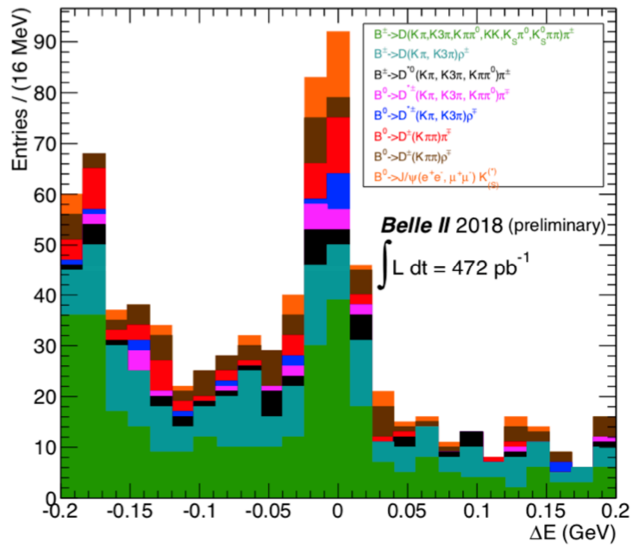


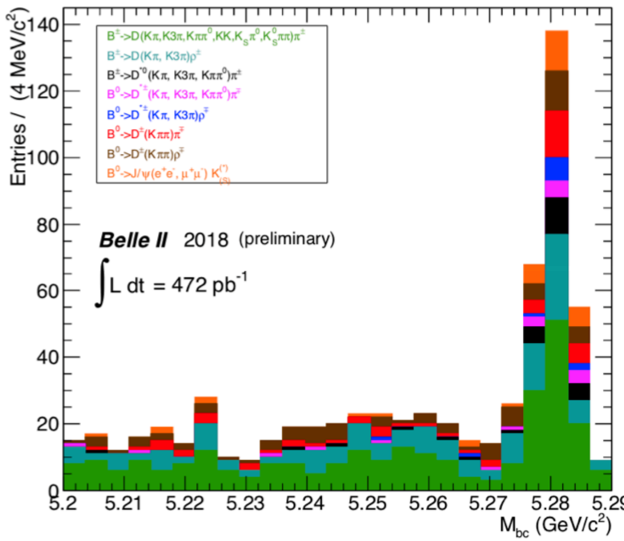
$D^0 \rightarrow K_S \pi^0$



Difficult to see at LHCb!

$B \rightarrow D^{(*)} h$, $B \rightarrow J/\psi K^{(*)}$



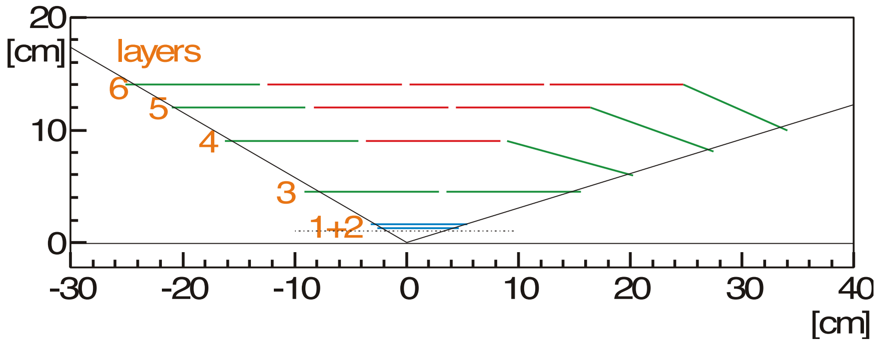


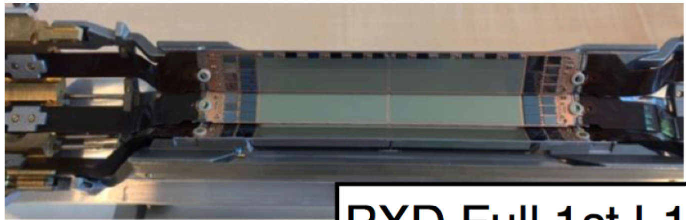
$$\Delta E = E_{cm}/2 - E_{recon}$$

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

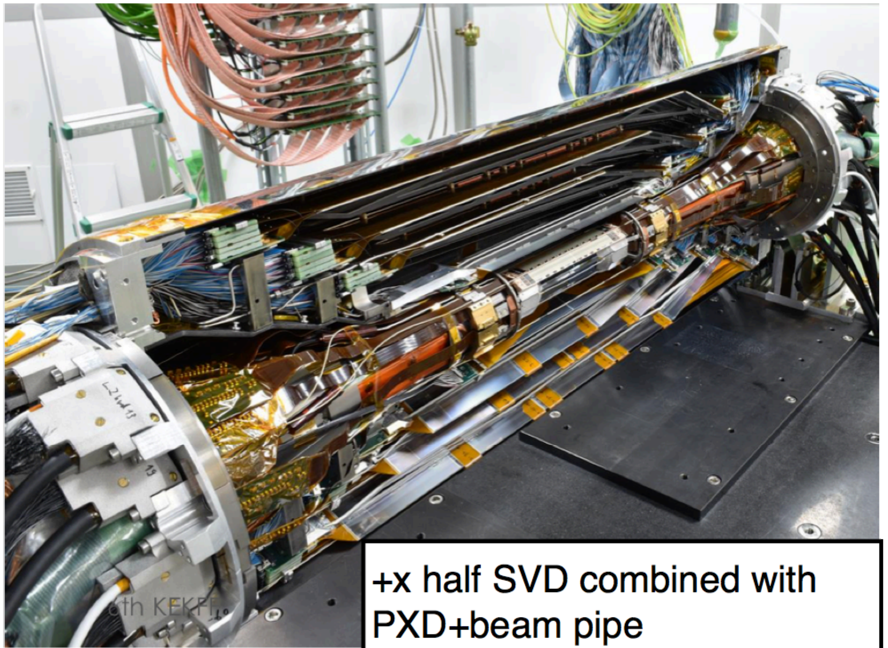
Belle II and *SuperKEKB* Upgrade History

- **2018, New Vertex Detector**



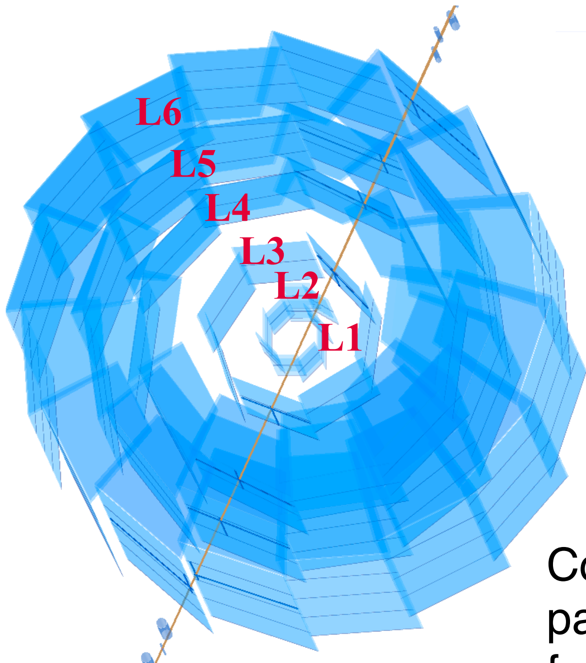


PXD Full 1st L1 and 1/6 of L2. Rest will be added in 2020



+x half SVD combined with PXD+beam pipe

VXD Installation

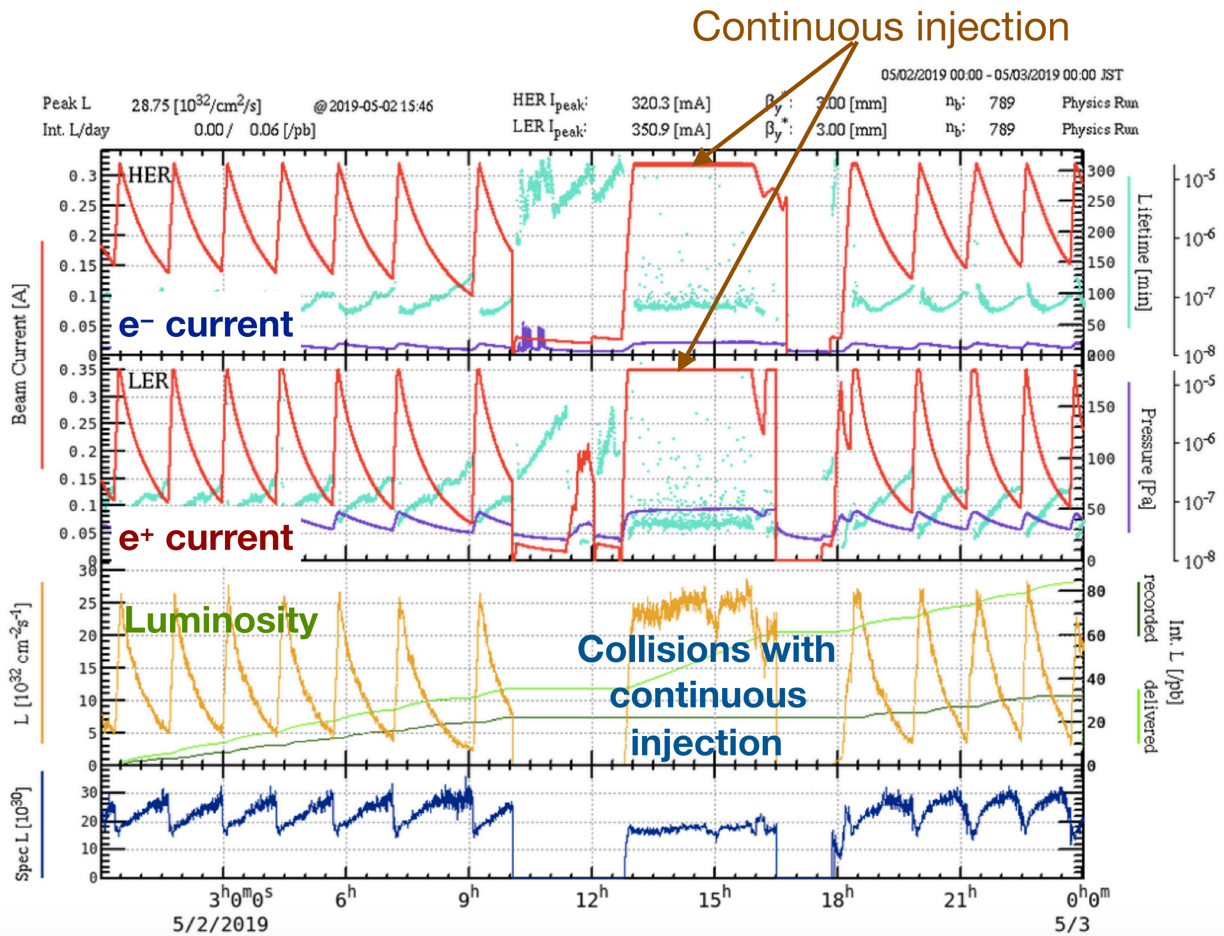


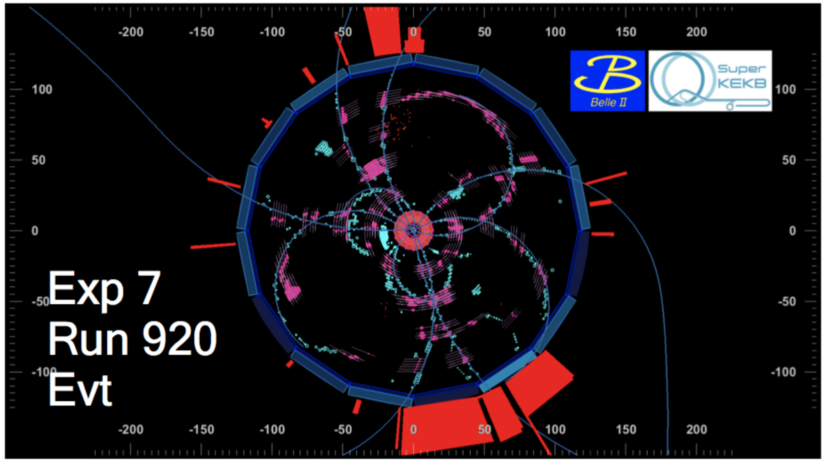
Cosmic track is passing through the full vertex detector.

"Phase 3"

- **Phase 3:** Collision data taking with full Belle II
- STARTED in MARCH 2019!

Beam background remediation is the current focus.





- Operation had to stop between April 3rd and 22nd due to a fire accident in one of the test facilities at KEK. Not related to *SuperKEKB* or *Belle II*!

Early Phase 3

- Belle II aims to collect
  - July 2019 : ~10 fb^{-1}

- **Performance Studies:**

Semileptonic
$B \to \pi l \nu$ and $\rho l \nu$ untagged
(CLEO saw a signal with 2.66 fb^{-1})

Hadronic B Decays
$B \to K \pi$ (10 fb^{-1})
$B \to \phi K$ (10 fb^{-1})
$B \to J/\psi K$ (2-10 fb^{-1})
Time dependent B mixing (10 fb^{-1})
B lifetimes (2-10 fb^{-1})

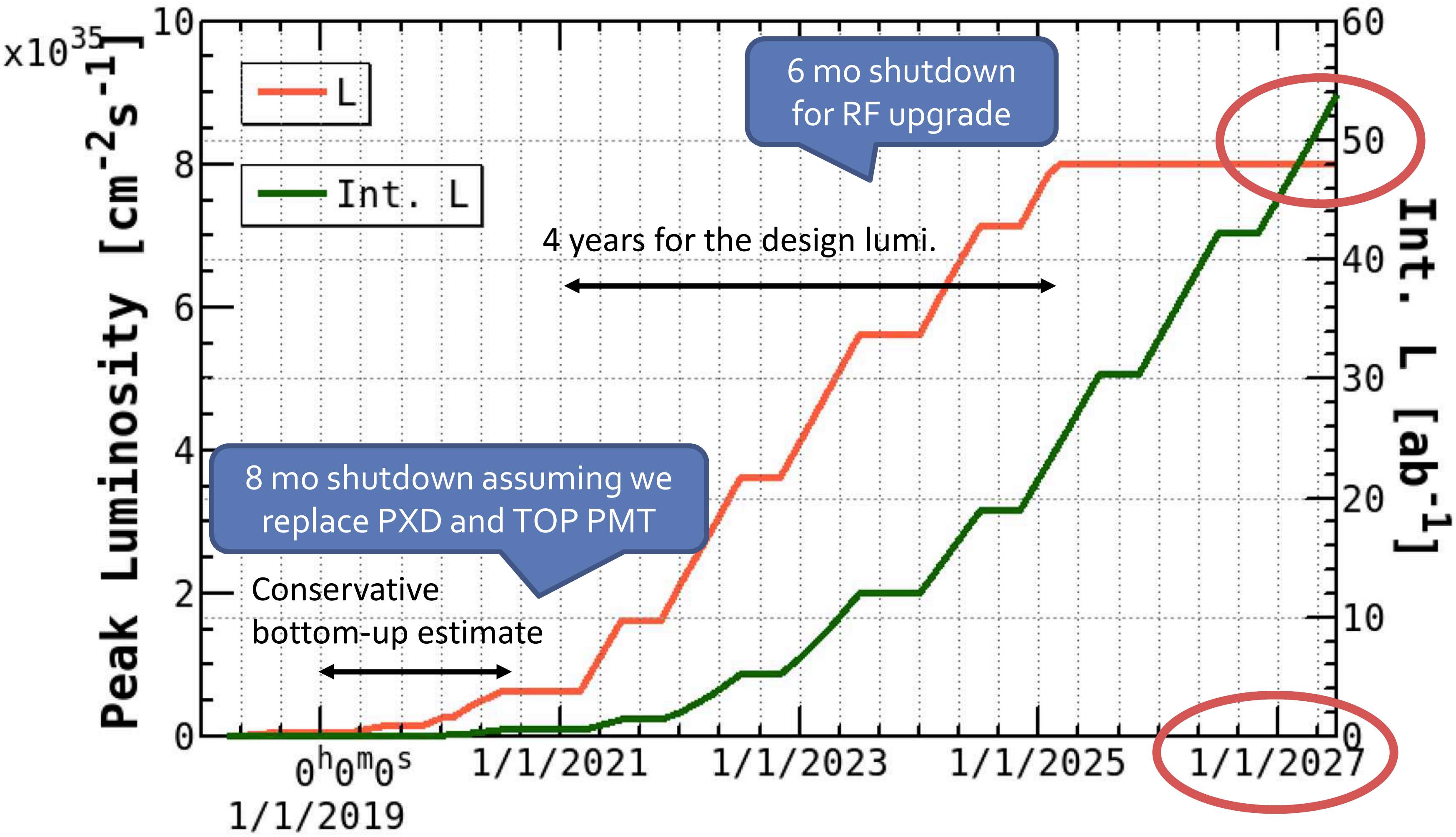
Radiative Electroweak Penguins
$B \to K^* \gamma$ (2 fb^{-1}) rediscovery penguins
$B \to X_s \gamma$ (10 fb^{-1})

Charm
D lifetimes (2 fb^{-1})
$D^0 \to K^+ \pi^-$, $D^0 \to K^+ \pi^- \pi^0$ (10 fb^{-1})

- Publication prospects for dark sector searches.

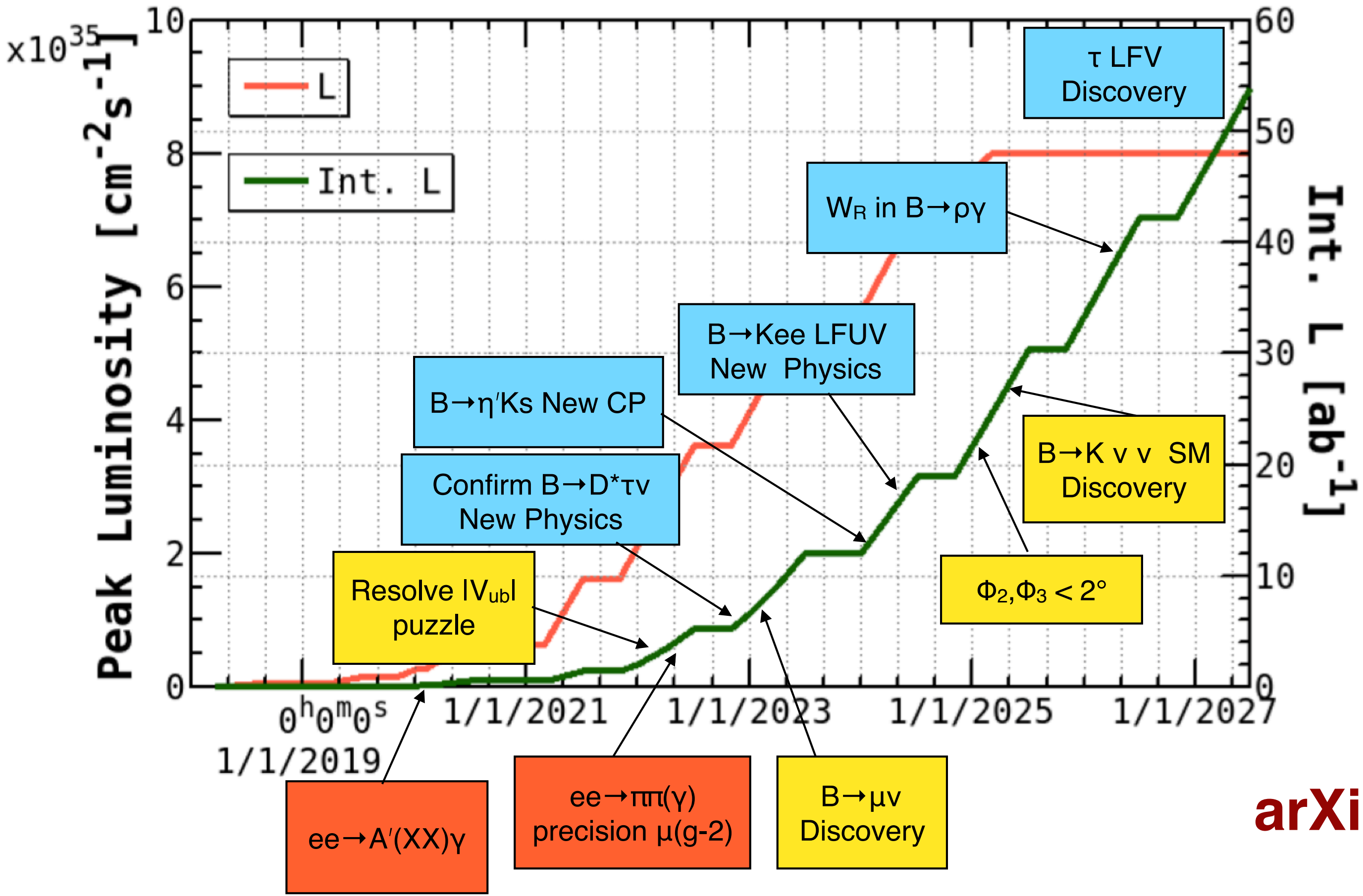
Early Phase 3

- Belle II aims to collect
  - July 2019 : ~10 fb^{-1}
- December 2019 : ~100 fb^{-1}
- 2020 : > 500 fb^{-1} (BaBar)
- 2021 : > 1 ab^{-1} (Belle)



Summary

- Initial data taking, “Phase 2”, has been completed in July 2018.
- Belle II is now constructed and installed.
- The full physics data taking, “Phase 3”, started in March 2019!
- Belle II aims to explore New Physics in flavor sector with 50 ab^{-1} data collected at SuperKEKB.

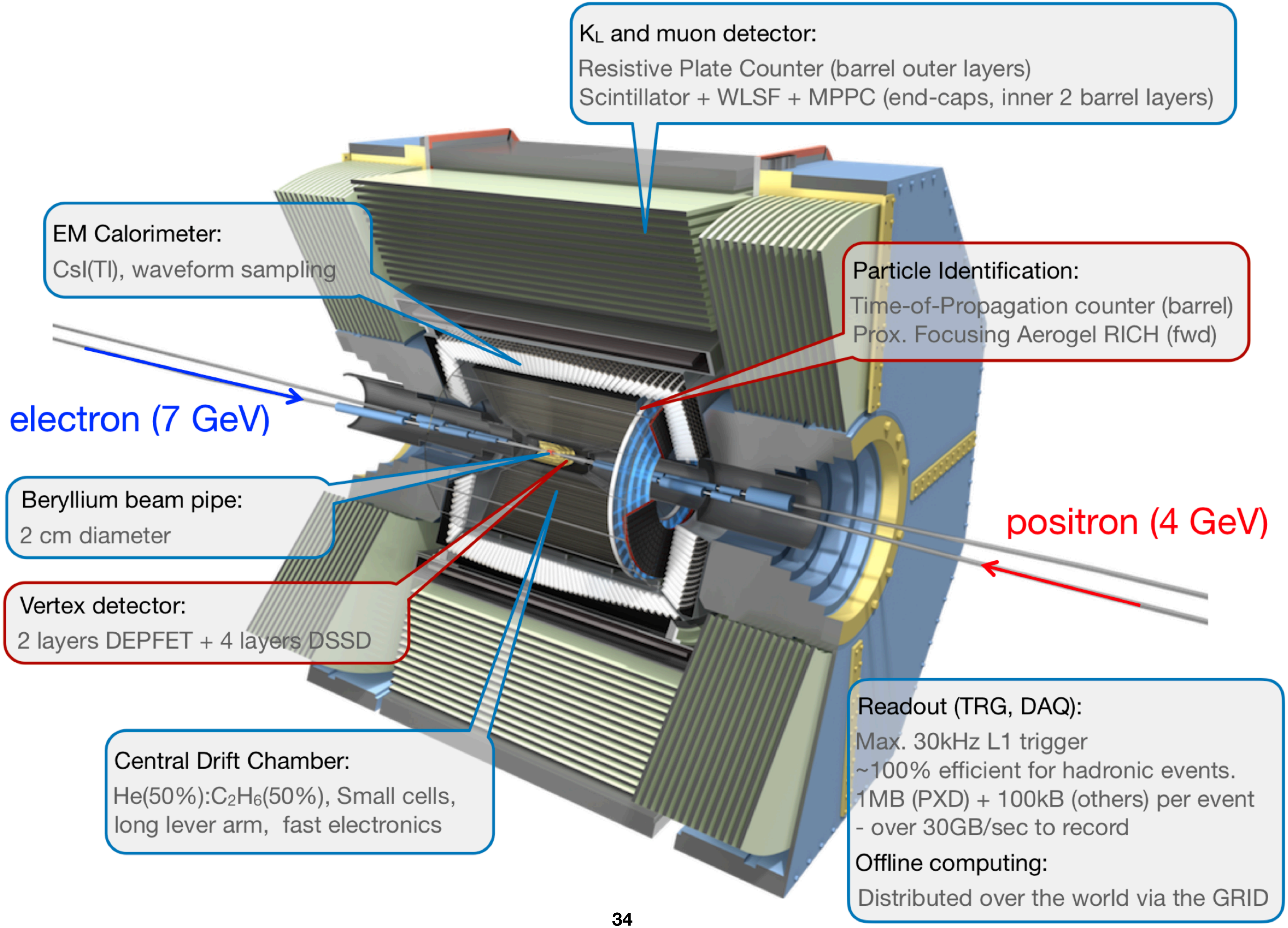


arXiv: 1808.10567

THANK YOU!

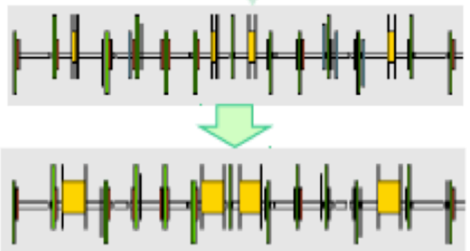
スーパーケックビー
SuperKEKB
加速器
いよいよ衝突実験
ビーム衝突点用超伝導電磁石
QCS
Belle II 測定器
Belle II Detector
線形加速器(電子陽電子入射器)
Linear Accelerator
超伝導高周波加速空洞
Superconducting Cavities
常伝導高周波加速空洞
Normal Conducting (ARES) Cavities
ビーム輸送路
Beam Transport Line
ダンピングリング
Damping ring
大学共同利用機関法人
高エネルギー加速器研究機構
KEK
High Energy Accelerator Research Organization

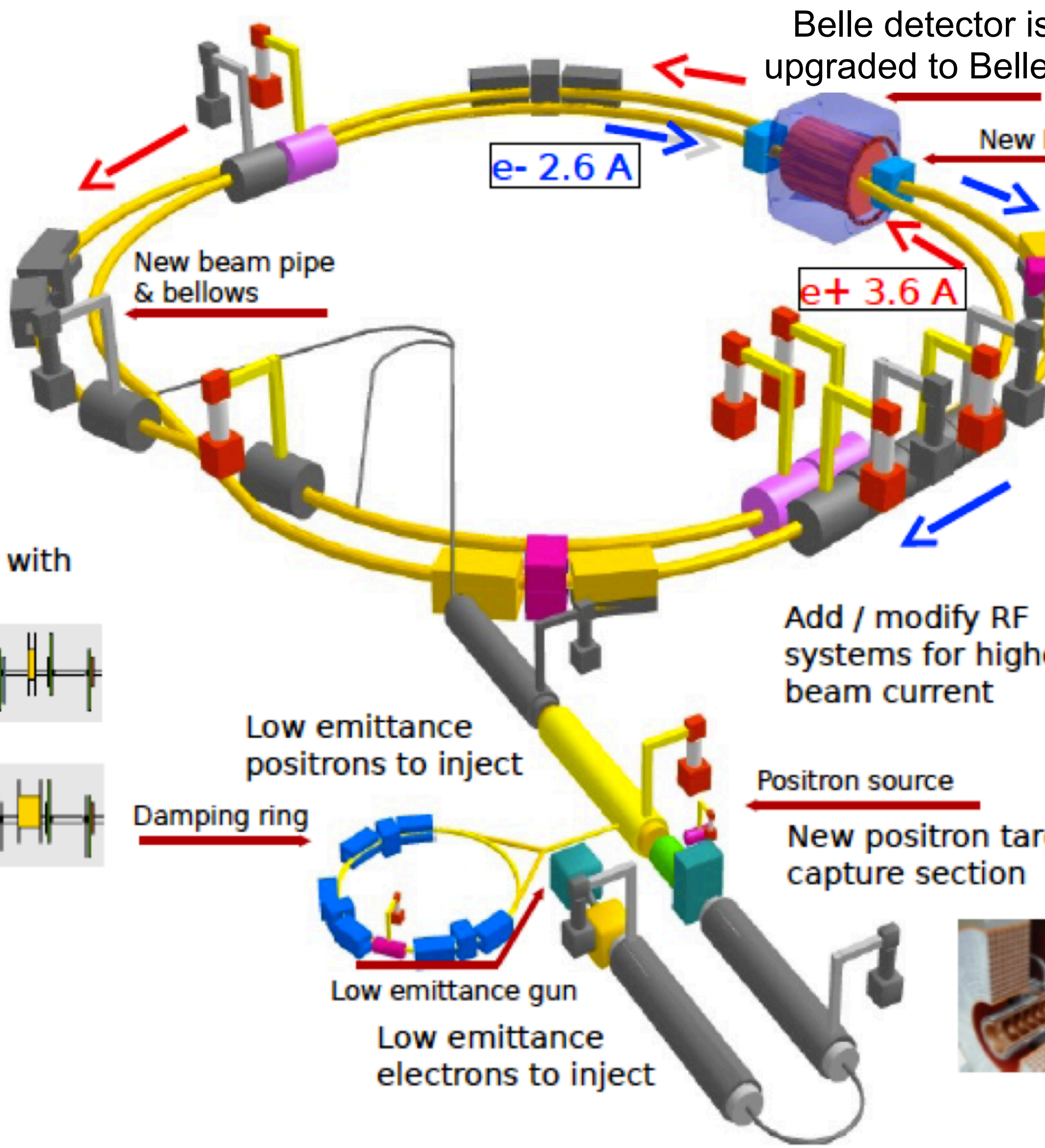
Belle II Detector



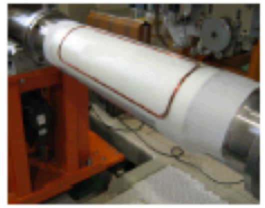
KEKB to *SuperKEKB*

Replace short dipoles with longer ones (LER)

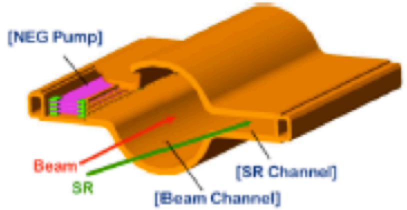




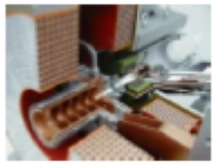
New superconducting /permanent final focusing quads near the IP



TiN-coated beam pipe with antechambers



Redesign the lattices of HER & LER to squeeze the emittance



***gray - reused, color - new**

Strategies to Increase Luminosity

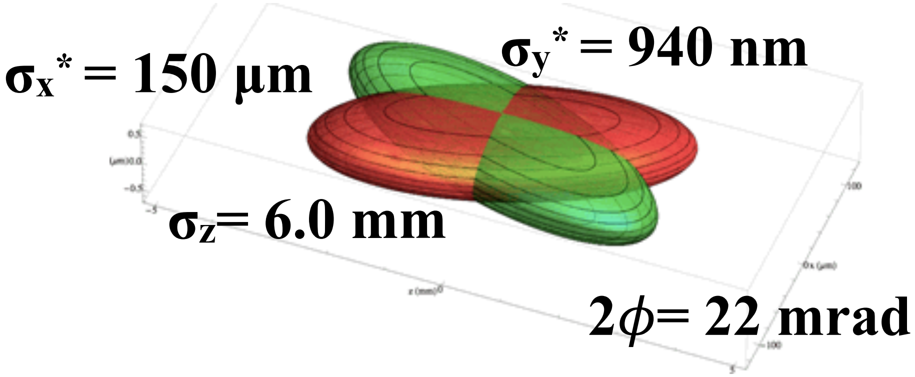
Beam current

Beam-beam parameter

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

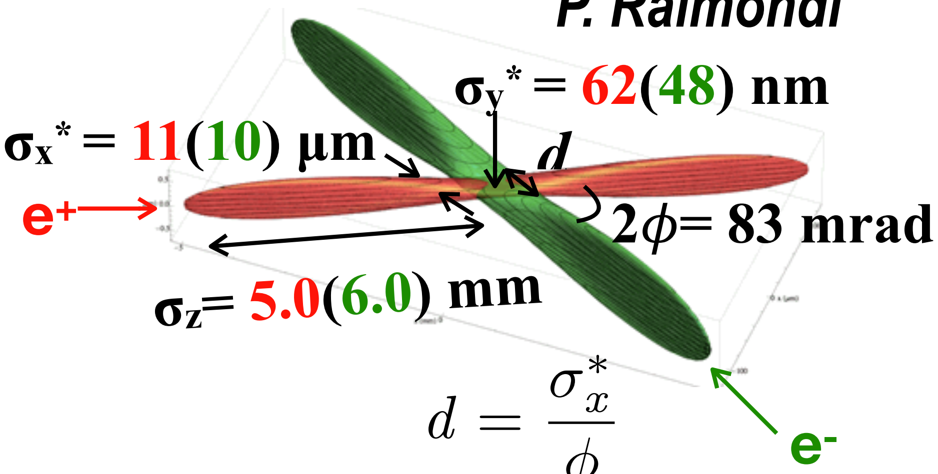
Vertical beta function @ IP

KEK



SuperKEKB (Nano Beam Scheme)

P. Raimondi



$$d = \frac{\sigma_x^*}{\phi}$$

	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 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

Factor 20 Factor 2 **Factor 40**