Belle II
Results and Prospects

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on behalf of the Belle II collaboration

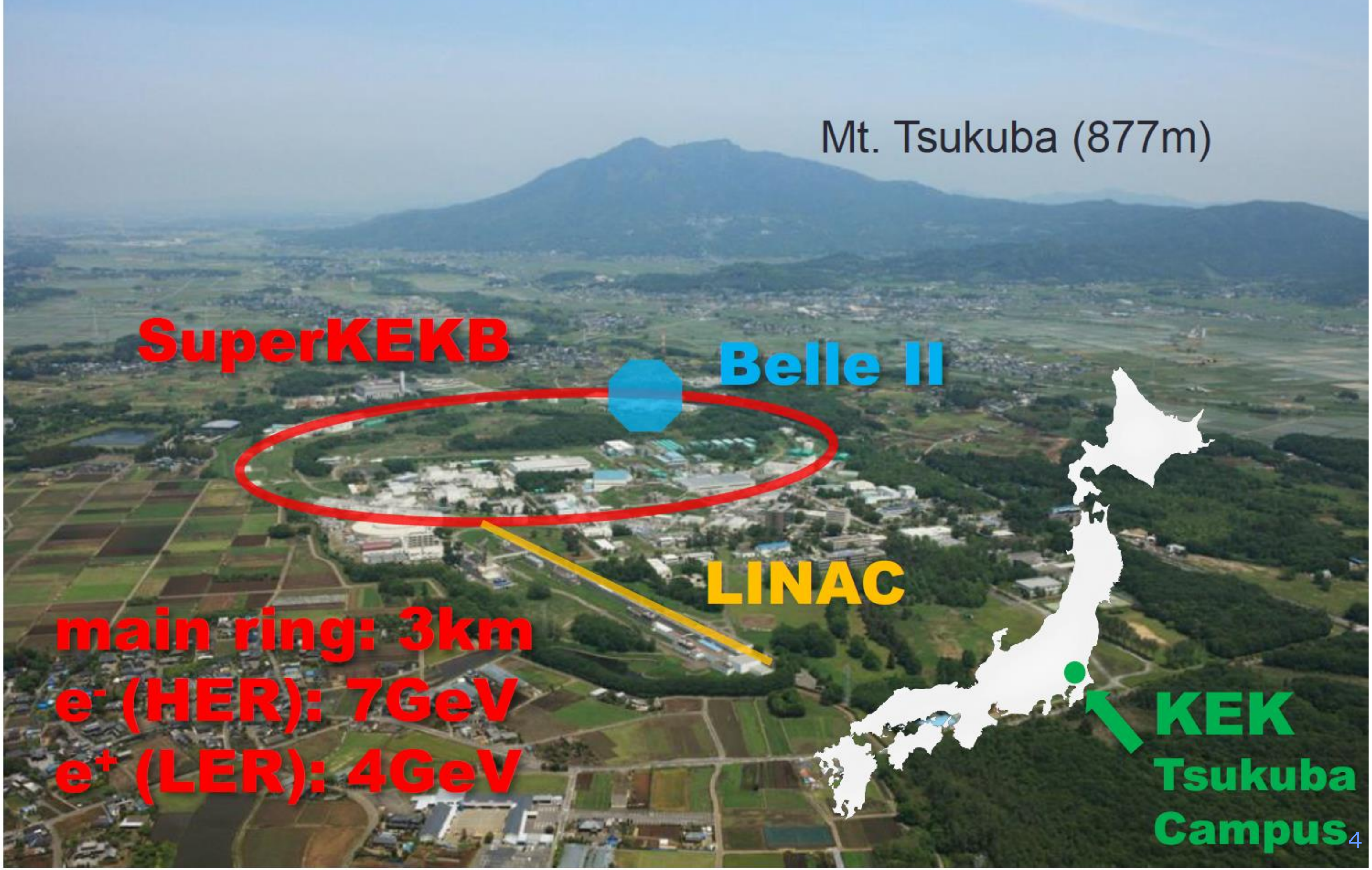
Opportunities at Future High Energy Colliders IFT
Madrid, June 2019

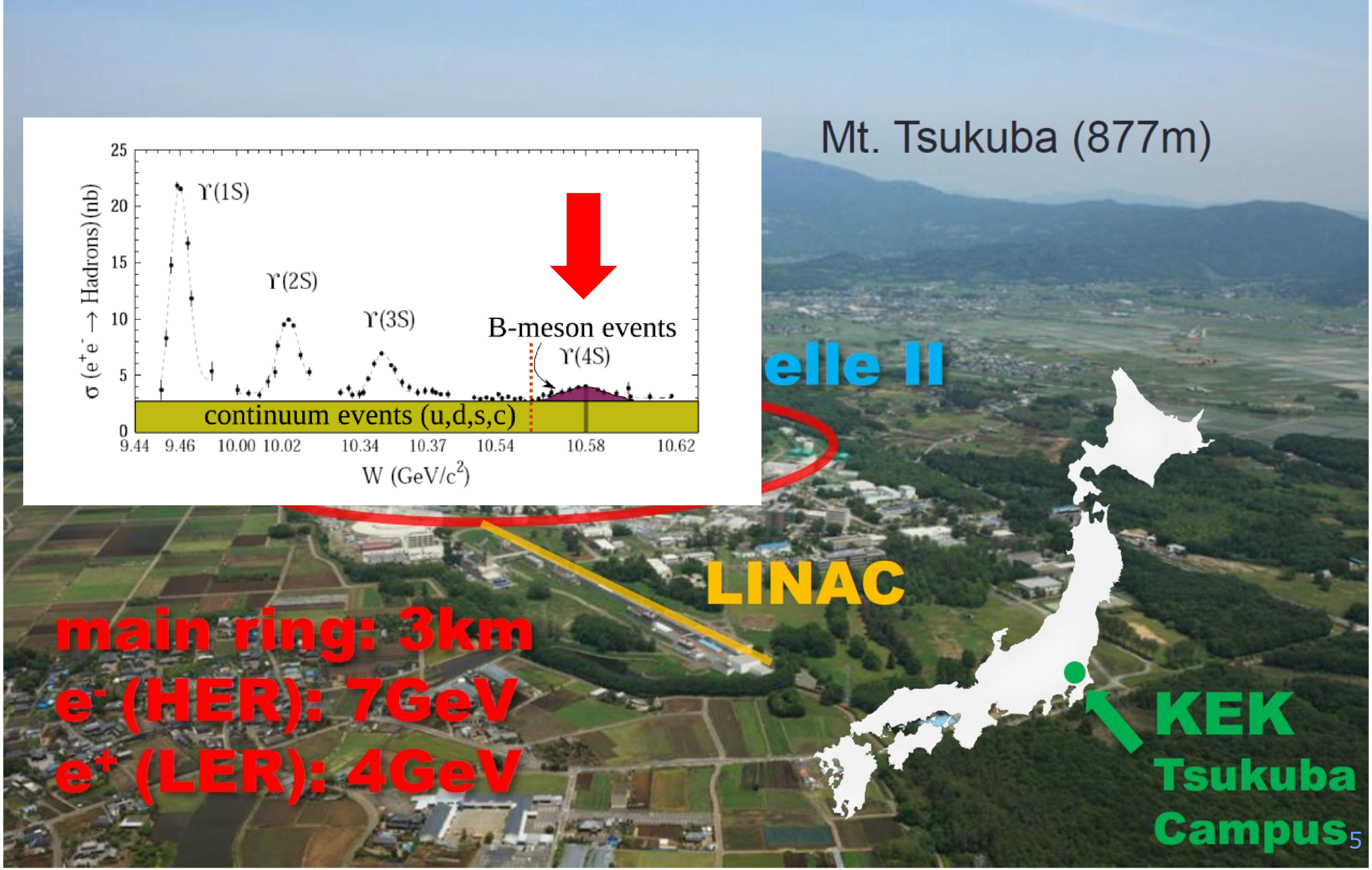
Outline

- Introduction
- What we can see in Belle II
- SuperKEKB and Belle II
- On-going Physics Run (Phase III)
- Conclusion

Belle II Experiment

- B Factory experiment at world's **highest luminosity e^-e^+** collider, SuperKEKB in Japan.
- Precise measurements in clean environment
  - Search for rare/forbidden decay
  - Compare with SM prediction precisely
- Rich physics programs
  - Measure B, D and τ decays


Mt. Tsukuba (877m)
SuperKEKB
Belle II
LINAC
main ring: 3km
e^- (HER): 7GeV
e^+ (LER): 4GeV
KEK
Tsukuba
Campus



Mt. Tsukuba (877m)
elle II
LINAC
main ring: 3km
e⁻ (HER): 7GeV
e⁺ (LER): 4GeV
KEK
Tsukuba
Campus
B-meson events
ϒ(1S)
ϒ(2S)
ϒ(3S)
ϒ(4S)
continuum events (u,d,s,c)
σ (e⁺e⁻ → Hadrons) (nb)
W (GeV/c²)
0
5
10
15
20
25
9.44
9.46
10.00
10.02
10.34
10.37
10.54
10.58
10.62

Belle II Collaboration

~1000 members, 26 countries

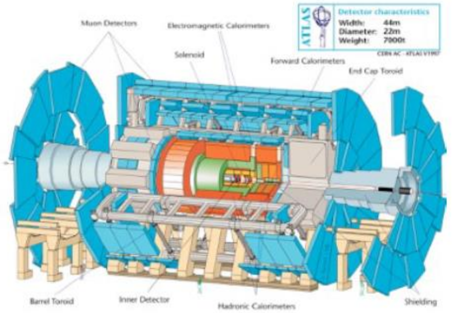
Ways to find new physics

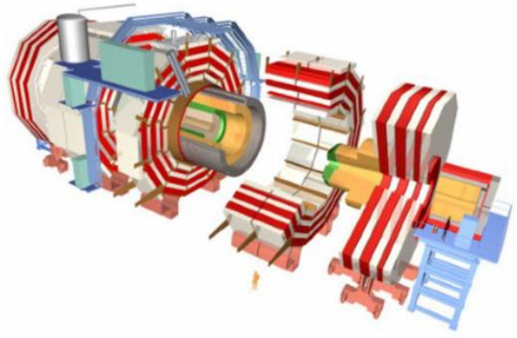
Energy frontier

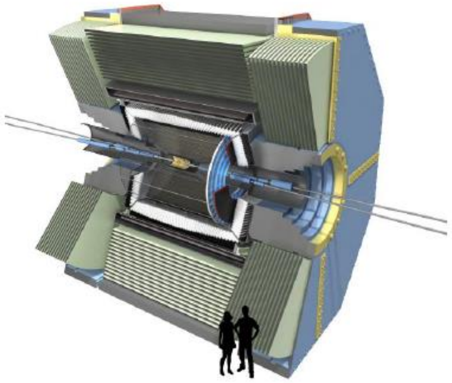
- Directly produce heavy particles coming from new physics
- ATLAS, CMS

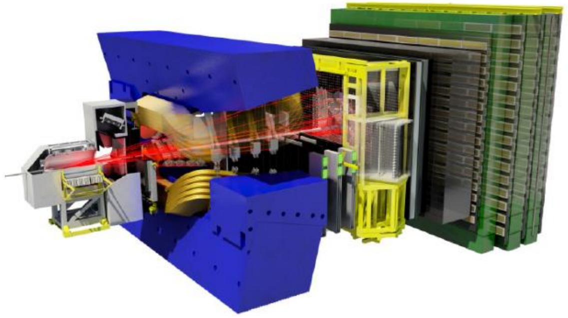
Luminosity frontier

- Precisely measure many processes which can be affected by new physics in loop.
- Belle II, LHCb



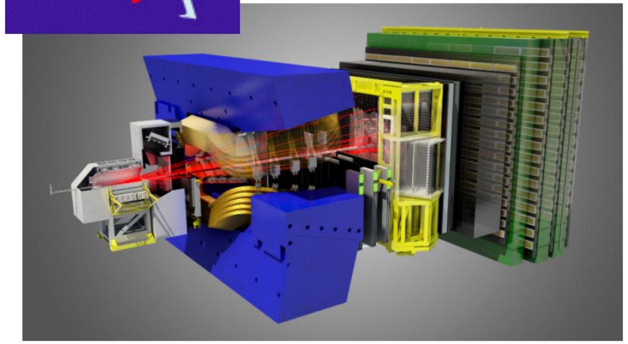






Belle II and LHCb

- LHCb
  - pp collisions
  - Powerful: B mesons can be produced quickly



- Belle II
  - ee collisions
  - Clean: Less background.

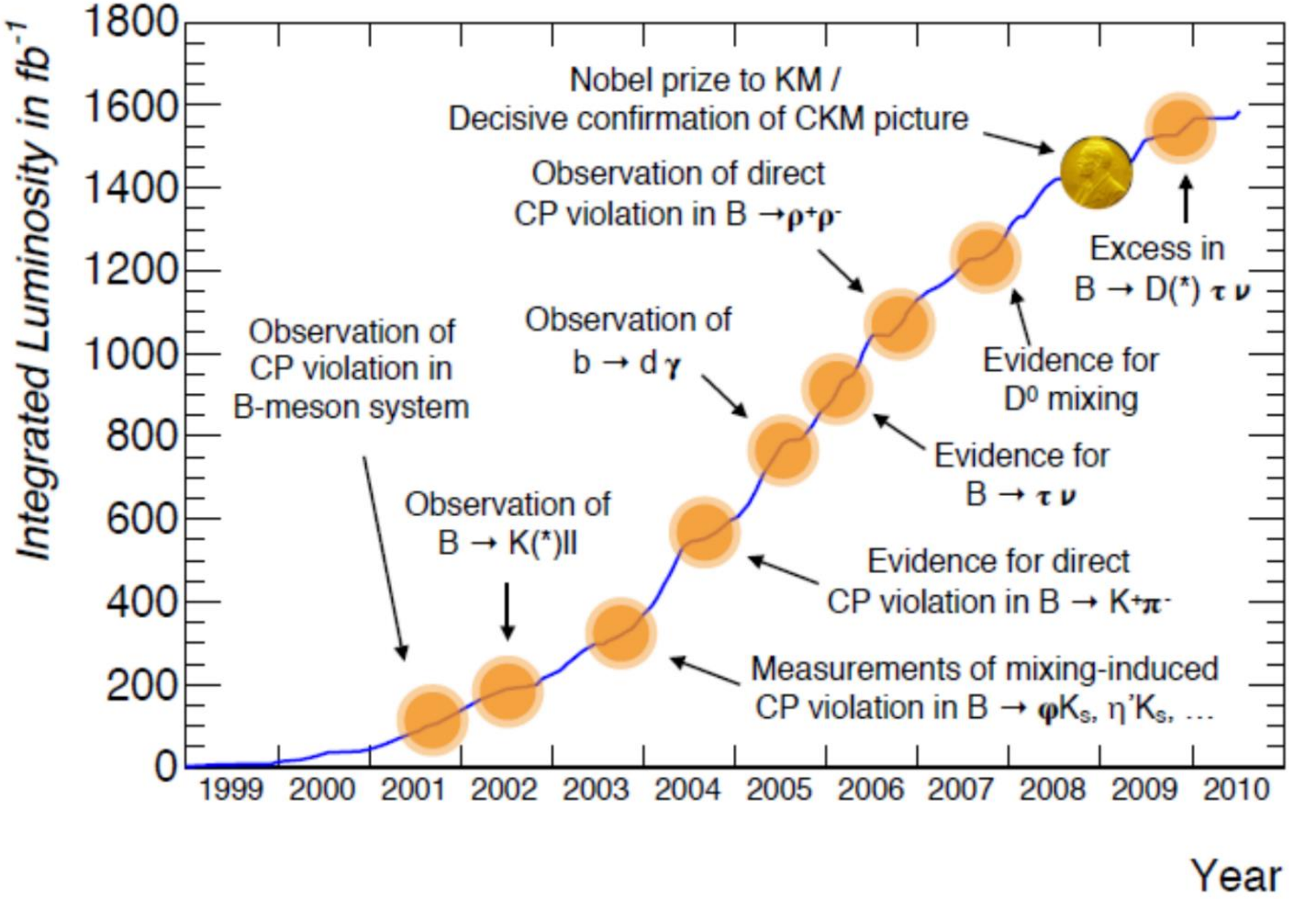
What we can see in Belle II

- Reveal new physics at high mass scales, even beyond the direct reach of the LHC

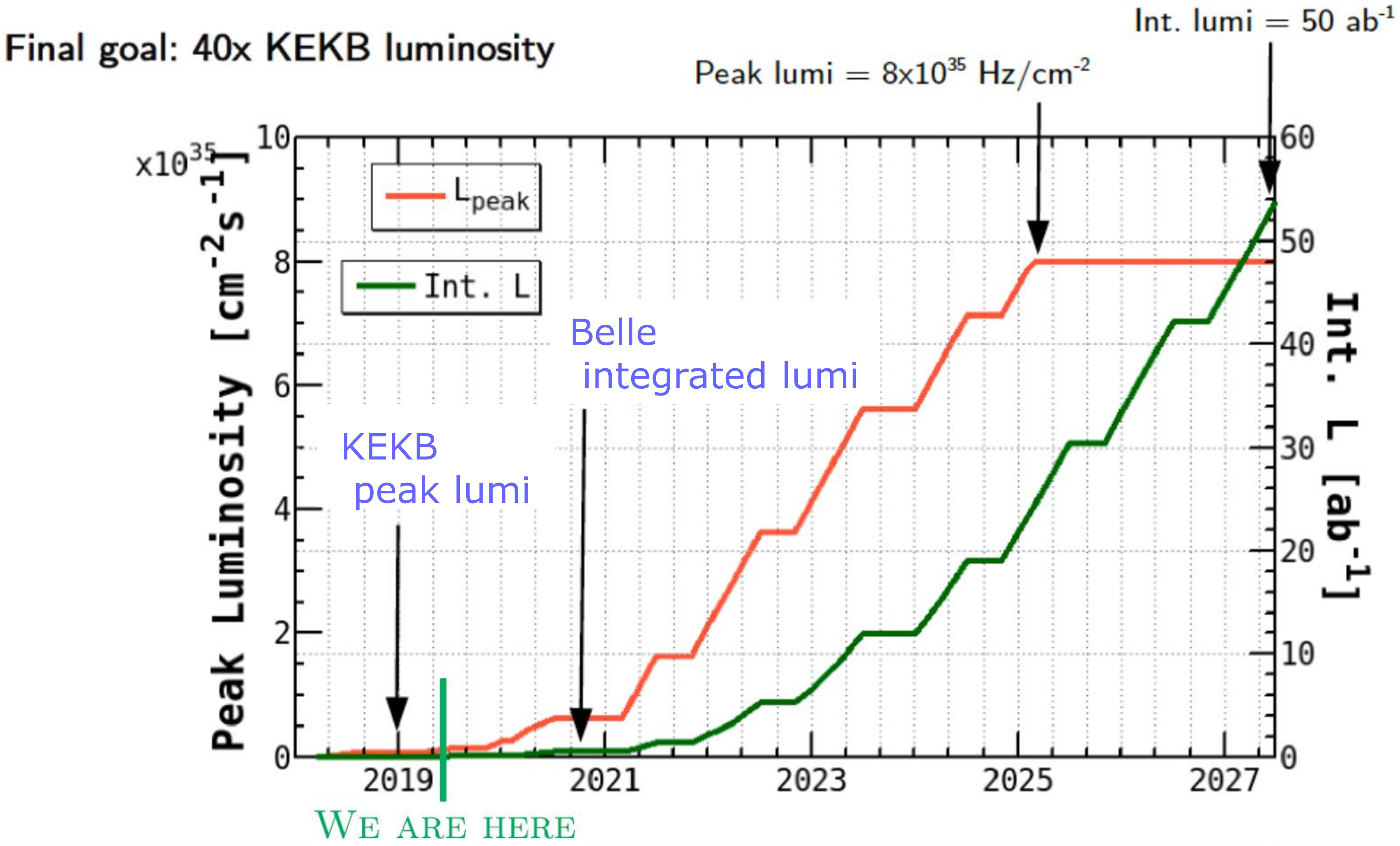
- Belle II will access a large number of new observables to test for new physics in flavor transitions in the quark and lepton sectors.
  - CP violating phases in the quark sector?
  - multiple Higgs bosons?
  - lepton flavor violation beyond the SM?
  - …

Previous B factory experiments

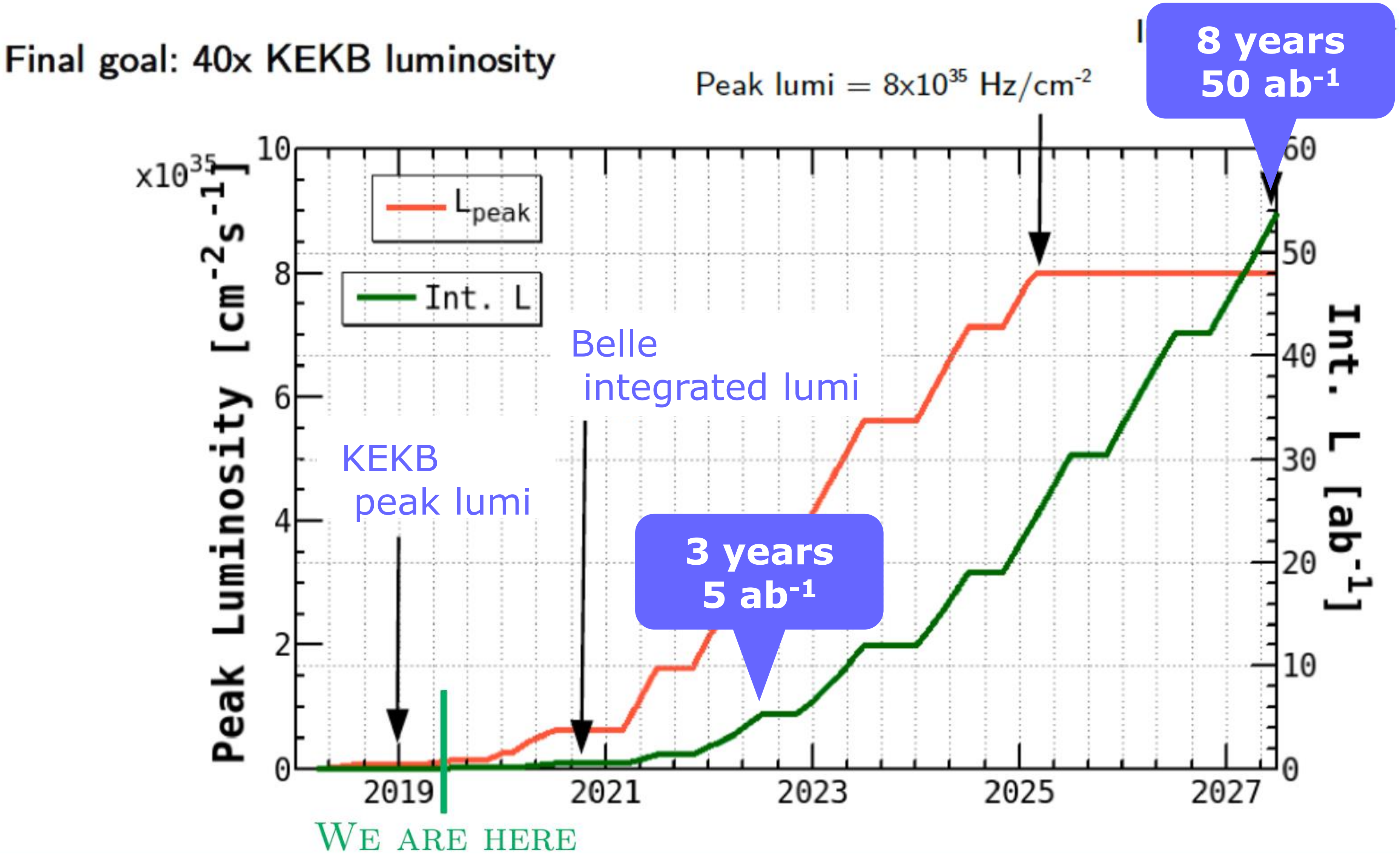
- The B factories Belle and BaBar (1999 to 2010) recorded over 1.5 ab^{-1} of data.
- Both experiments provided the experimental confirmation that led to the 2008 Nobel prize.



Data Accumulation



Data Accumulation

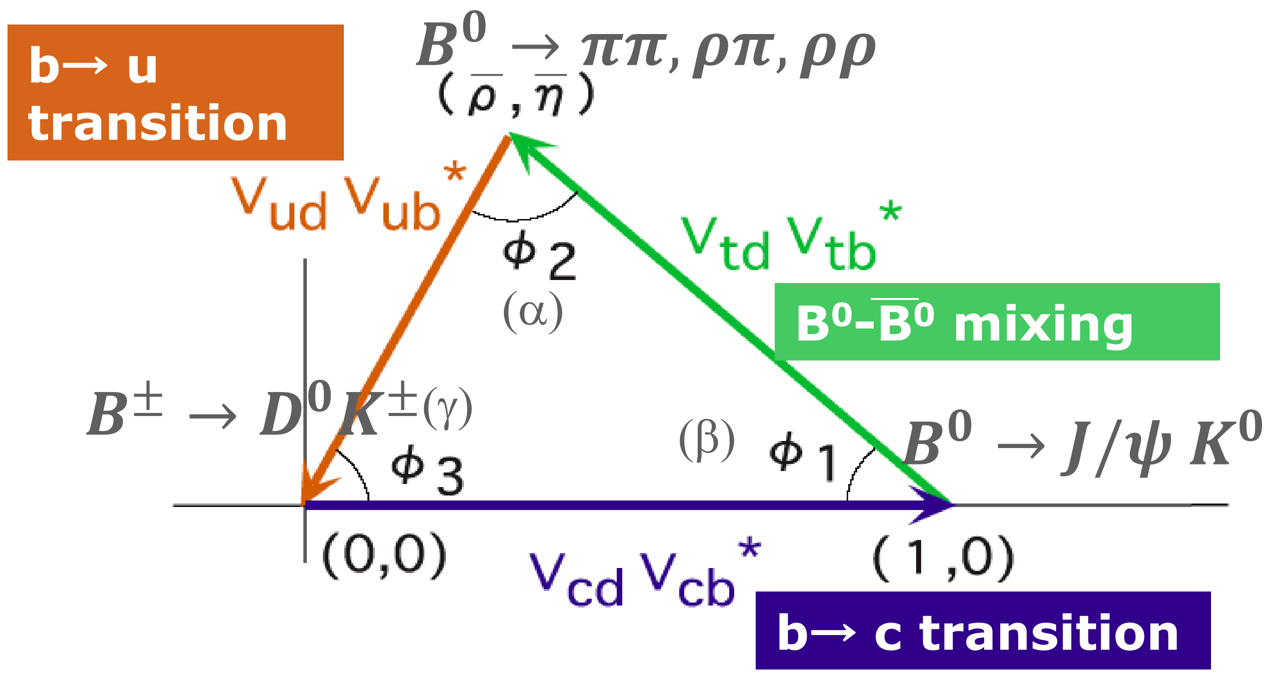


CKM unitarity triangle

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

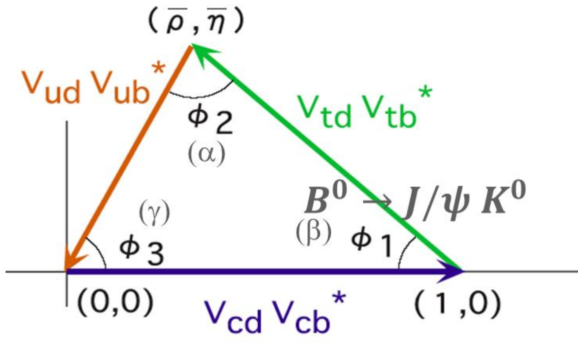
by Wolfenstein parametrization

Belle II measures all the angles and sides.



$$V_{td} V_{tb}^* + V_{cd} V_{cb}^* + V_{ud} V_{ub}^* = 0$$

Time dependent CP



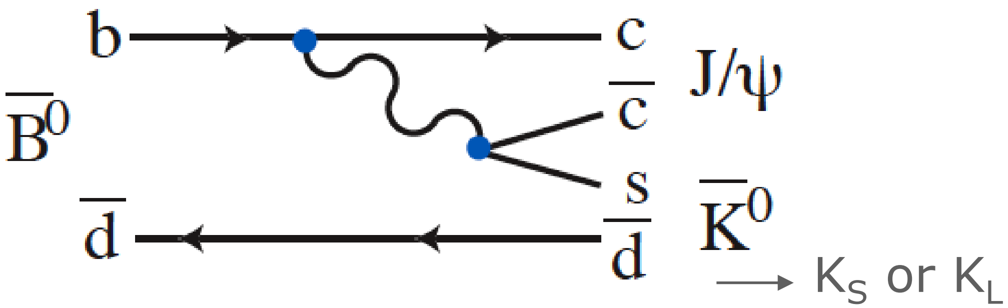
$$A_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

$$= S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

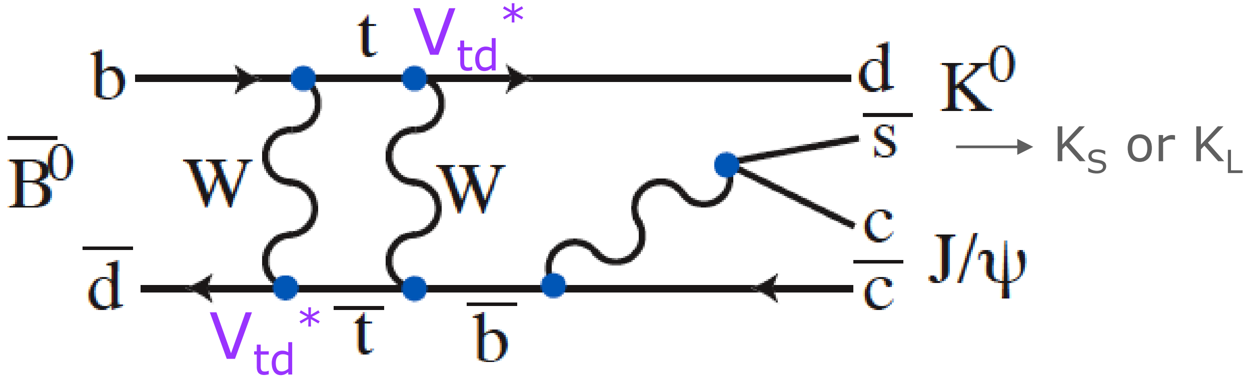
S : mixing induced CPV
A : direct CPV

$$= -\xi_{CP} sin2\phi_1 sin(\delta m \cdot \Delta t)$$

(1) Decay



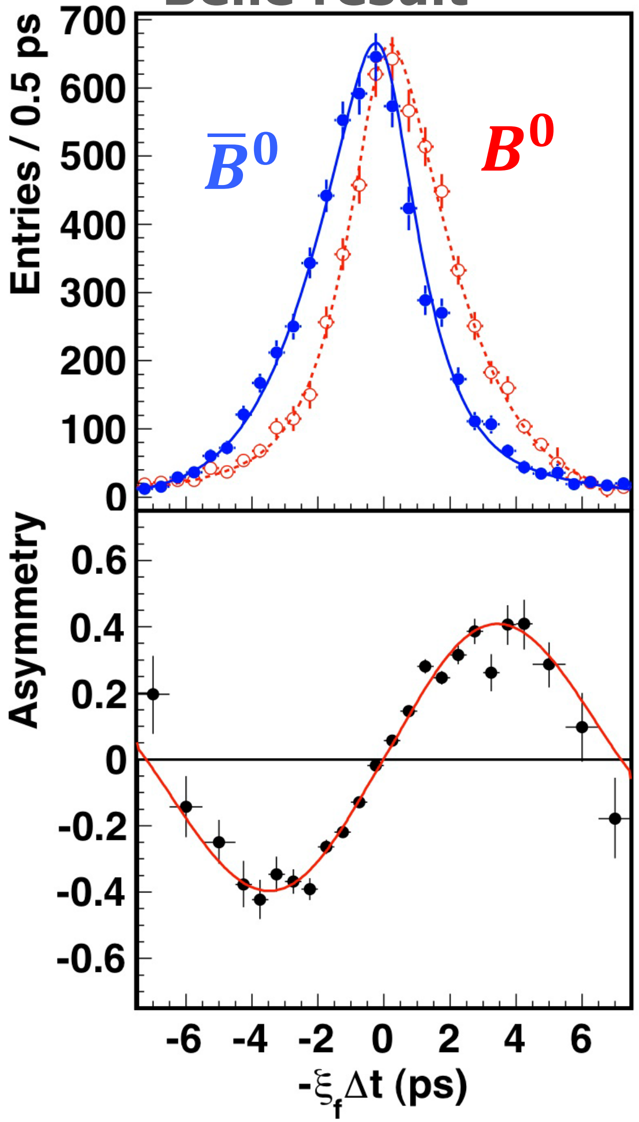
(2) Decay with mixing

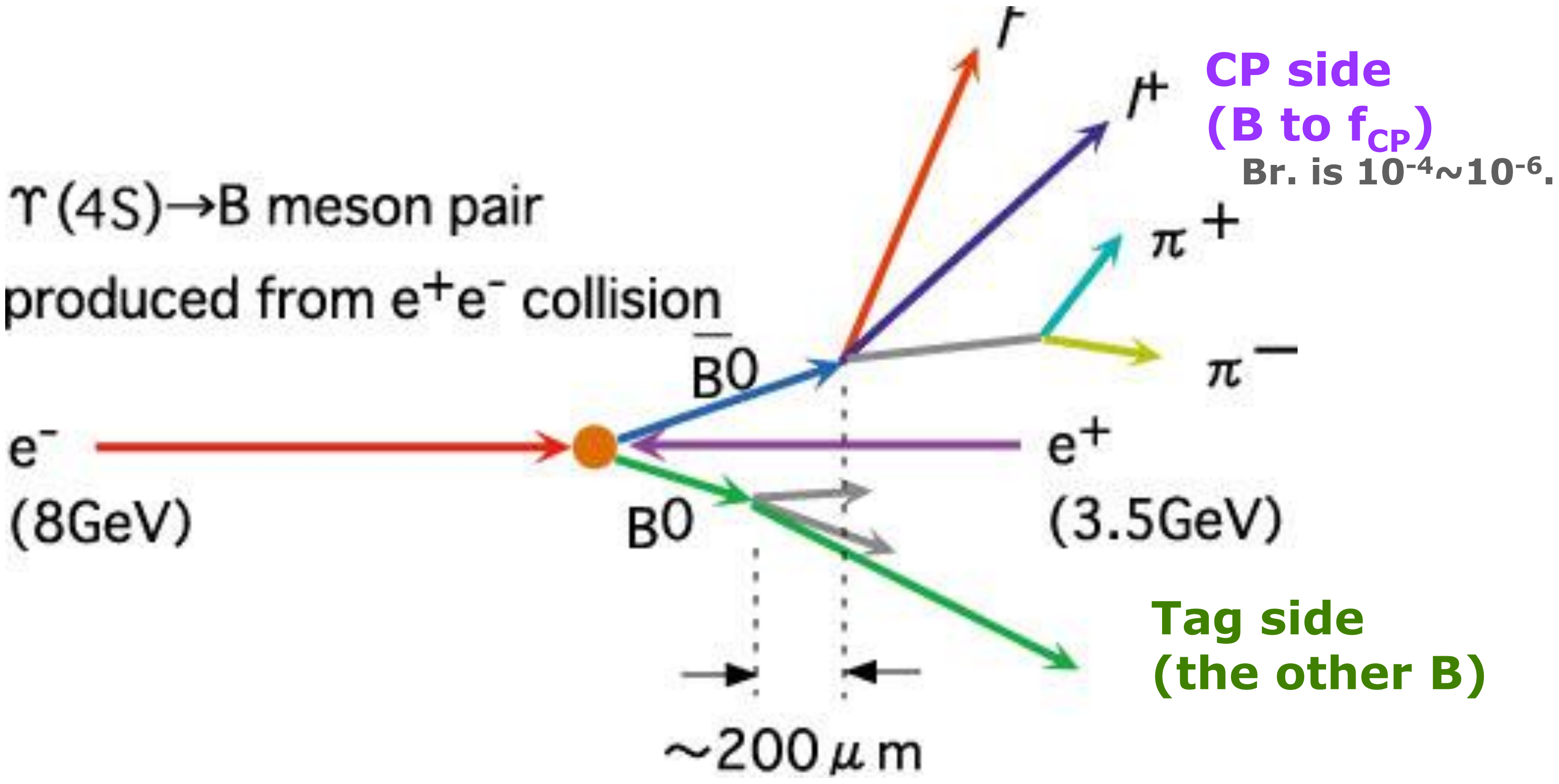


We have to measure time dependence (i.e. $\Delta t \neq 0$) to see the mixing contribution.

Time dependent CP

Belle result

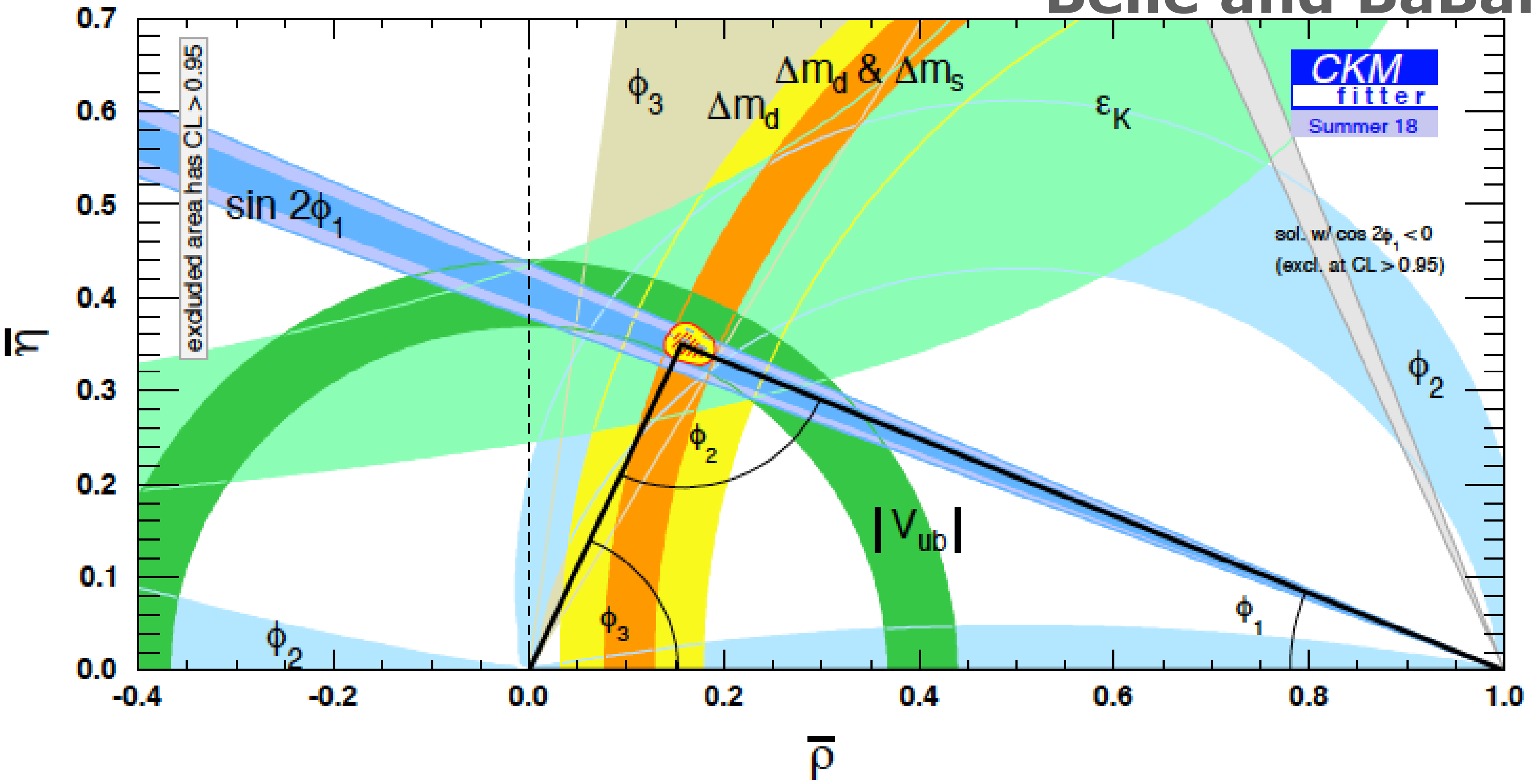




Δz measurement

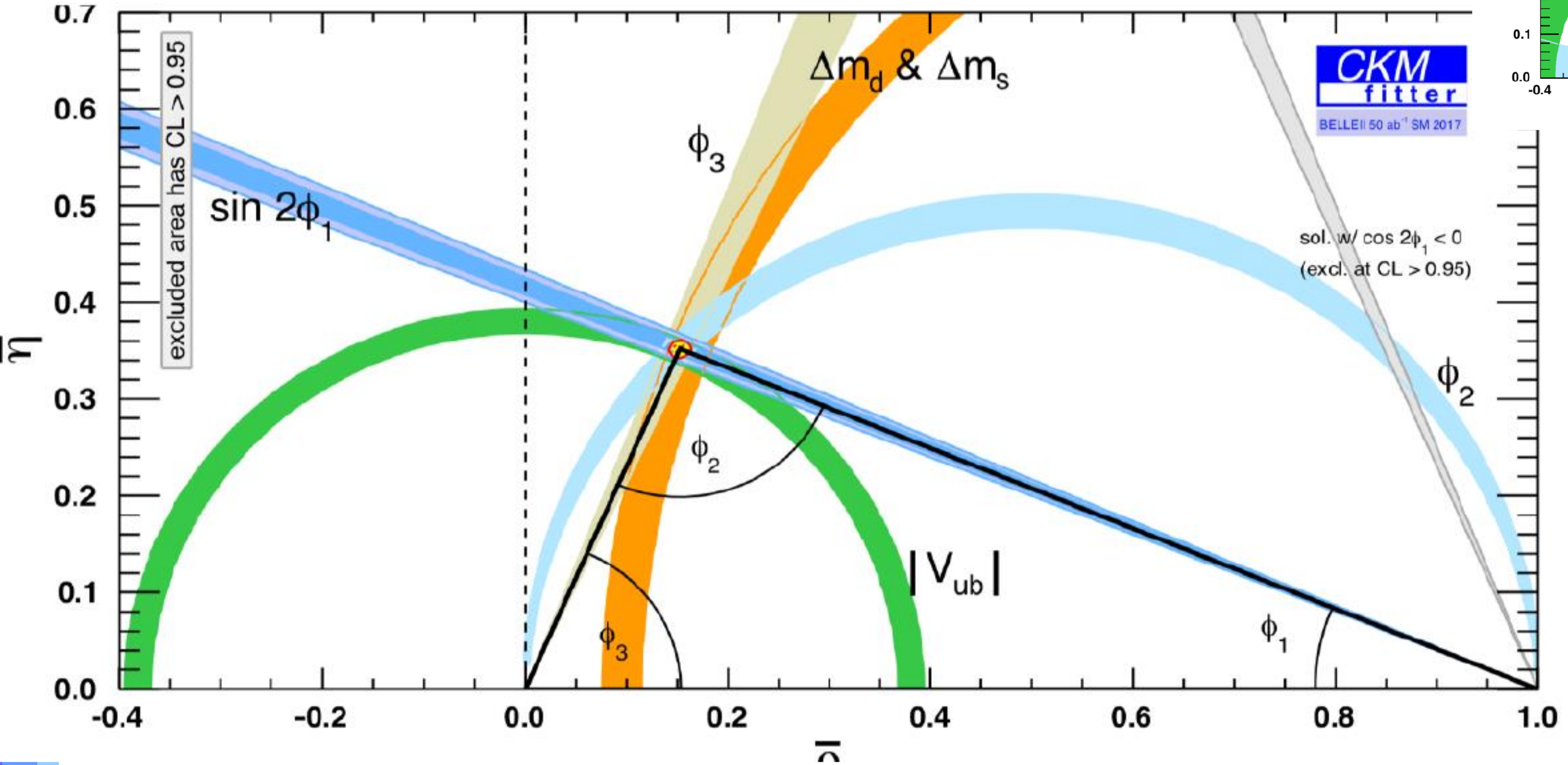
Current CKM Matrix

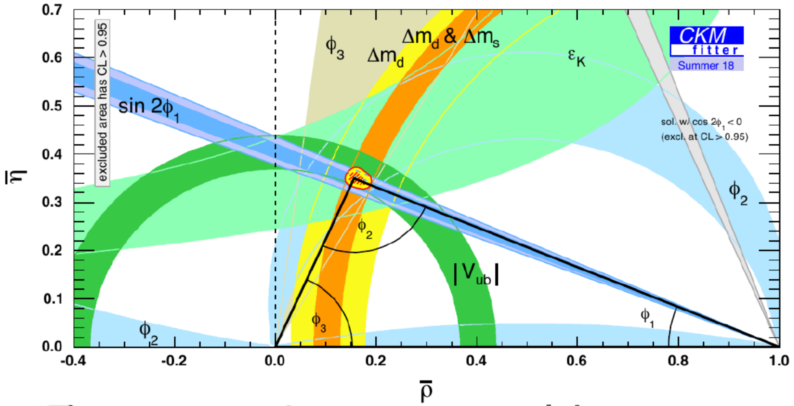
Belle and BaBar



We can find the area the triangle apex which is compatible with all the measurements. Kobayashi-Maskawa theory is OK at this precision.

Prospects of CKM matrix

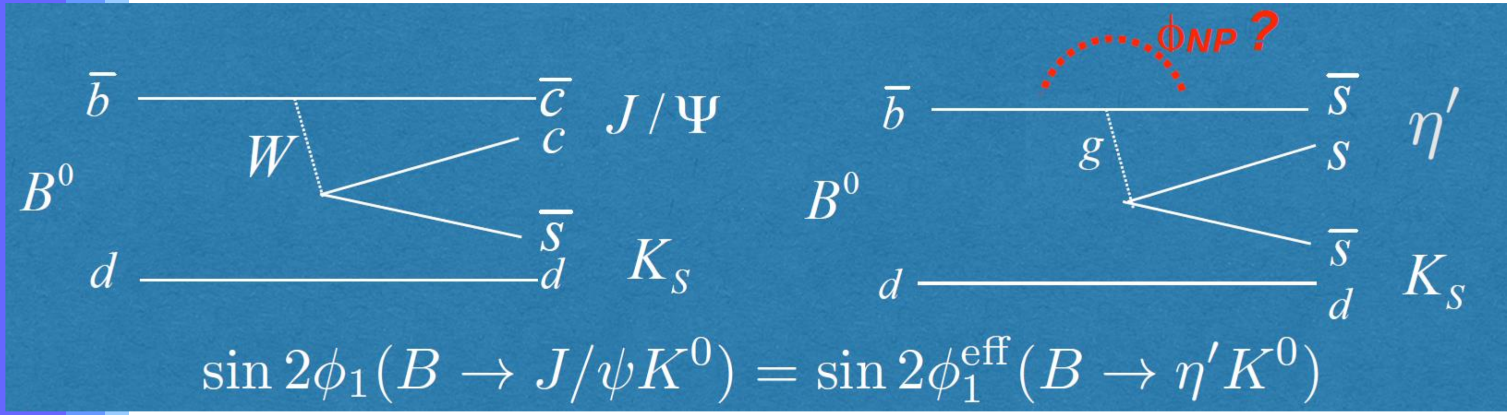




Current world average

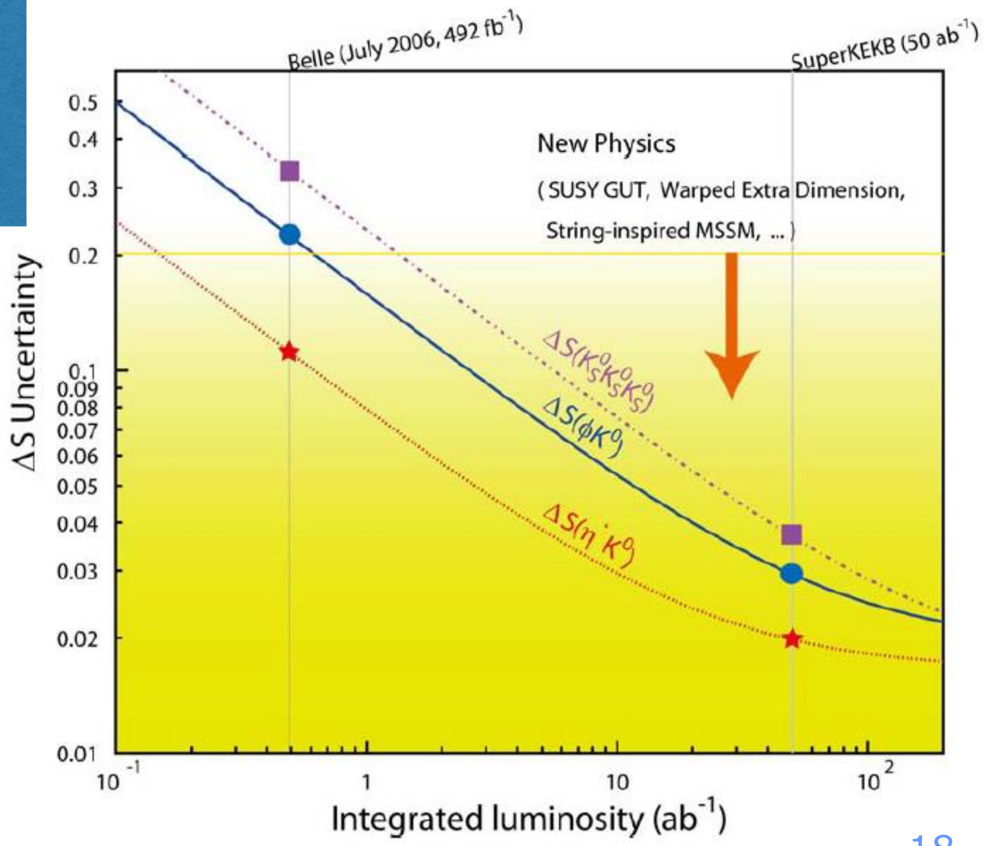
Belle II projection @ 50 ab^{-1}

CP Asymmetry beyond KM



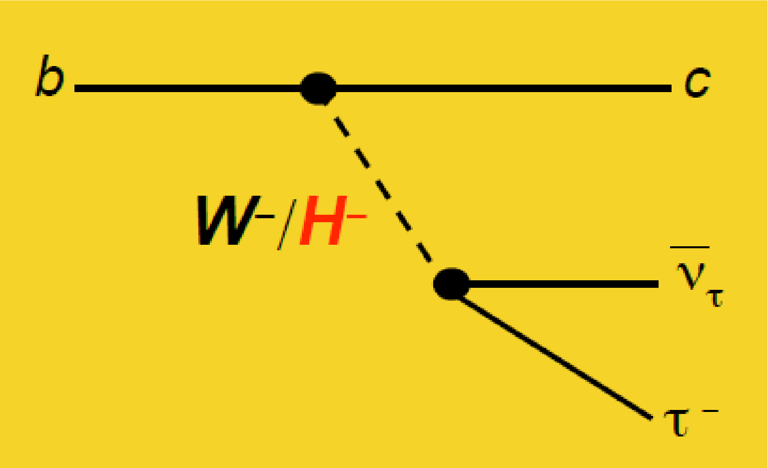
- CP asymmetry in $b \to s\bar{s}s$
  - $\mathrm{B} \to \phi K_s,\ \eta' K_s,\ K_s K_s K_s$
    Uncertainty from theory is a few %.
- New physics may affect in Penguin loop.
- Belle II will measure more precise to new physics region.

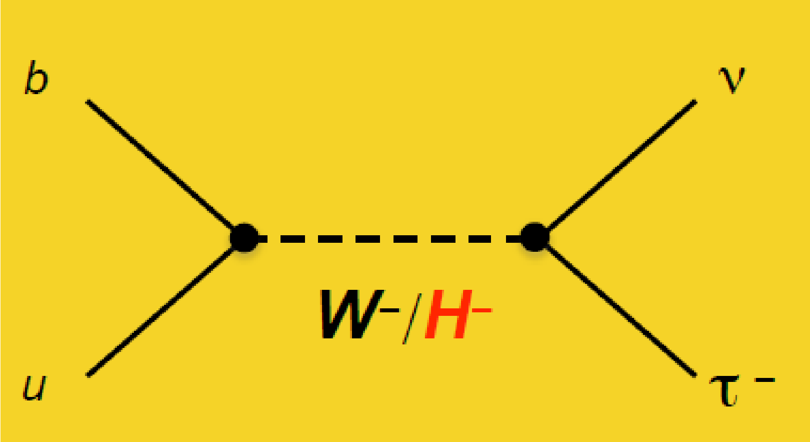
Total error of $\sin 2\phi_1 - \sin 2\phi_1^{\mathrm{eff}}$



Charged Higgs

- Many new physics predicts charged Higgs.
- $B \to \tau\nu$, $B \to D\tau\nu$ is good tool to probe new physics.
  - Charged Higgs affects the branching fraction of these decays in tree level.
  - Because of large masses the difference b/w NP and SM is large.
    $B \to \tau\nu$: $(1 - M_B^2 \tan\beta^2 / M_H^2)^2$

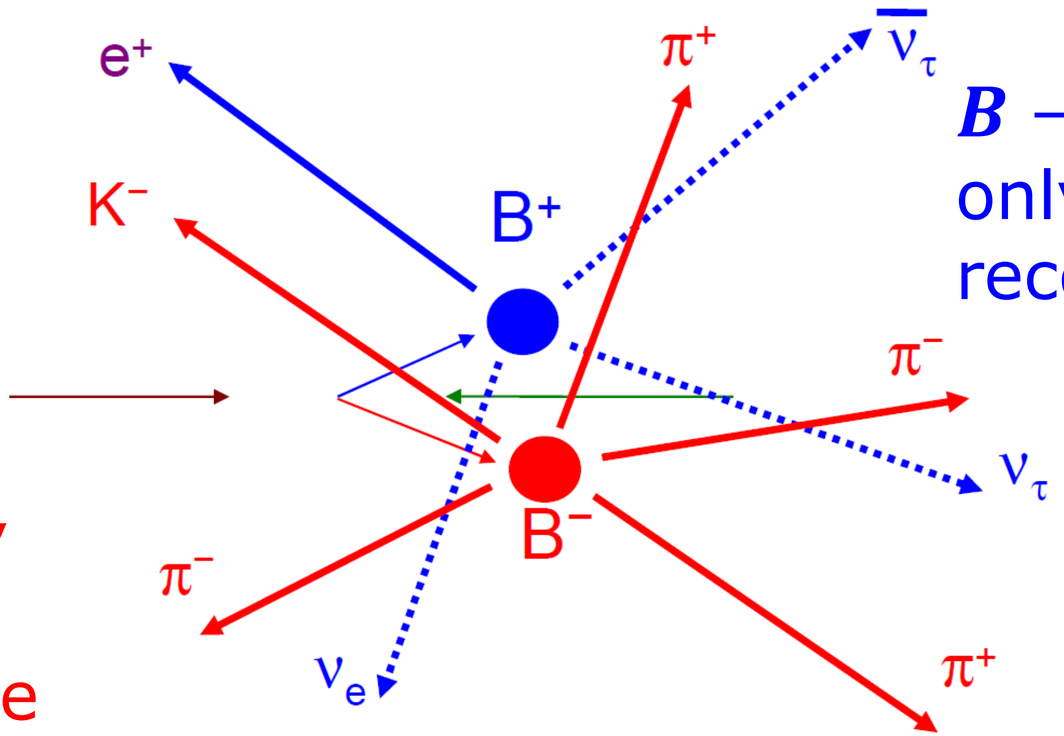




Full Reconstruction

- Full reconstruction in tag side is essential to measure the decay with large missing energy.
  - One of the advantages of e^+e^- collider experiment

$$B^+ \to \tau^+ \nu_\tau$$
$$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$$



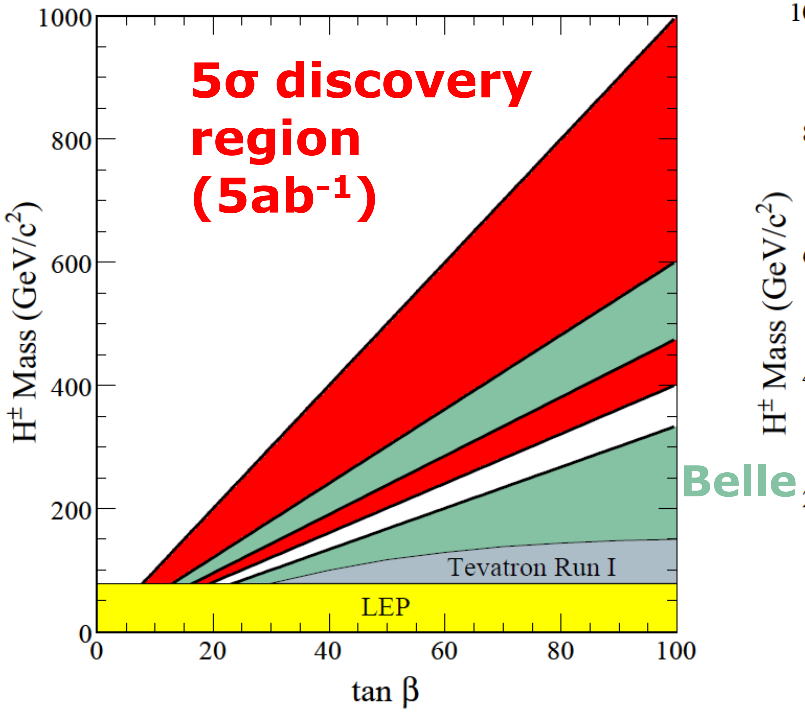
$B \to \tau\nu$ signal side: only e is reconstructed

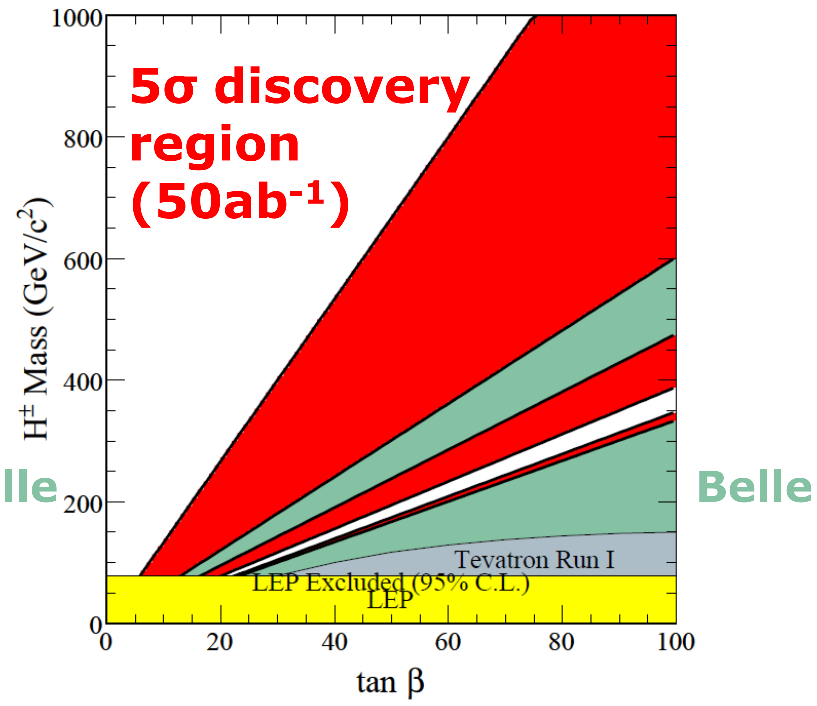
Tag side: B^- is fully reconstructed by using hadronic mode

Charged Higgs |Prospects

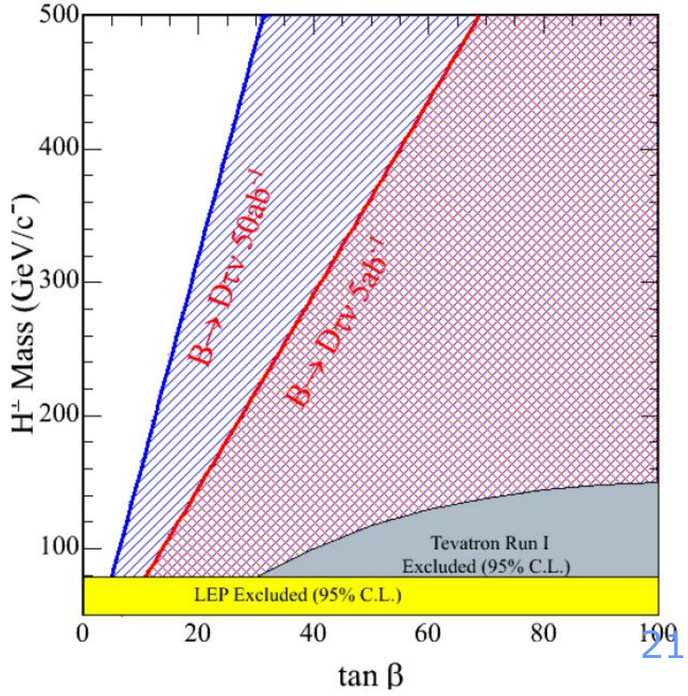
- Statistics limits the accuracies.
  - The study of the MSSM Higgs through this decay modes is only possible with the statistical power of SuperKEKB.

$B \to \tau\nu$





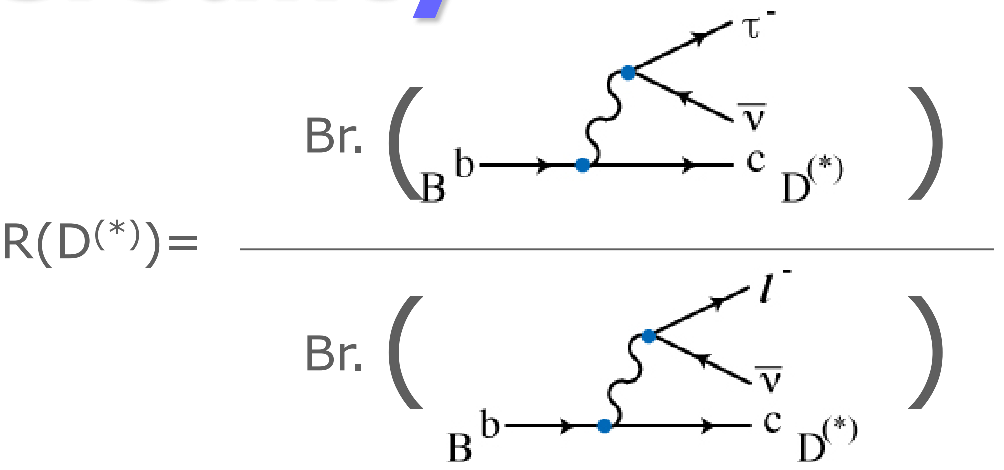
$B \to D\tau\nu$

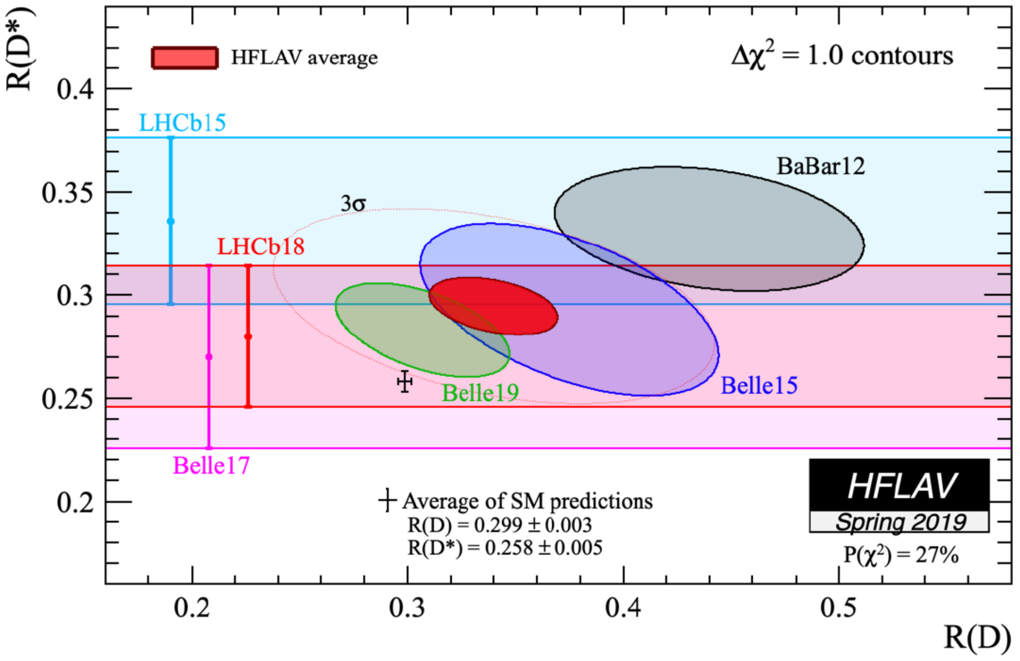


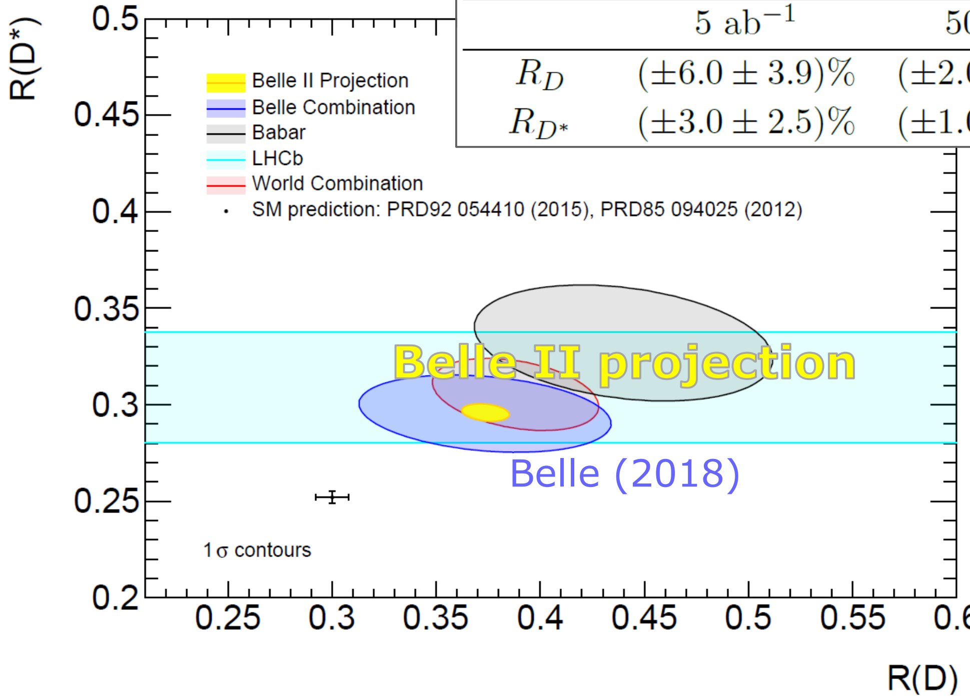
Lepton Universality

- The discrepancy b/w SM and measurement is 3.1 σ
- SM prediction is very solid.

- We can confirm the excess with ~5 ab^{-1} data.

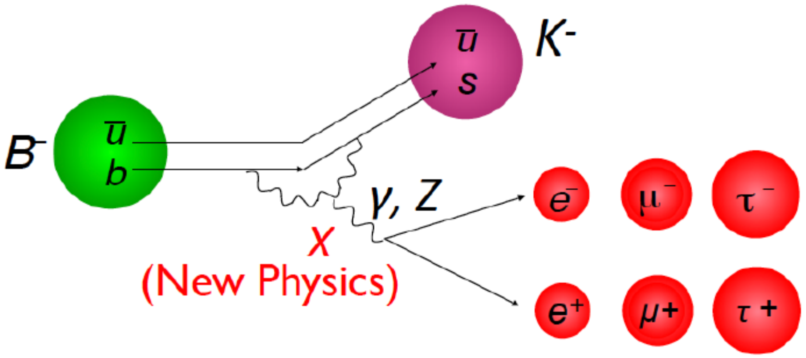






	$5\ ab^{-1}$	$50\ ab^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$

Lepton Universality in loop



stat syst

$$R(K) = 0.846 \begin{smallmatrix} +0.060 \\ -0.054 \end{smallmatrix} \begin{smallmatrix} +0.016 \\ -0.014 \end{smallmatrix}$$

2.5σ from SM

LHCb-PAPER-2019-009 22 March 2019

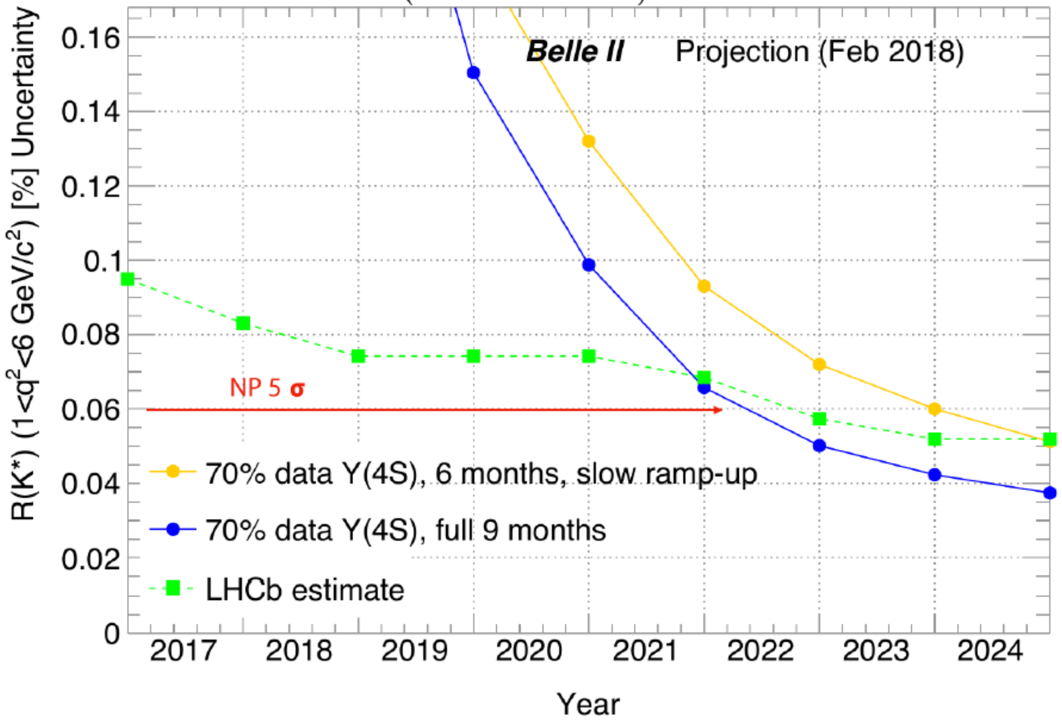
$$R(K^*)$$

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

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

2.1-2.5σ from SM

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

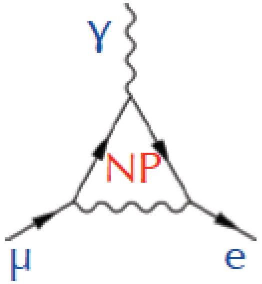


Note: LHCb value is extrapolated from run-1 result

Flavor Violation in Charged Lepton Sector

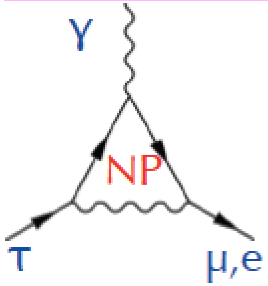
- SM does not have any mechanism to change flavor in lepton sector.
- Direct evidence of NP
  - Sensitive to wide-range of models.
  - Model-independent, important to synergy with other measurements to specify possible models.

MEG II

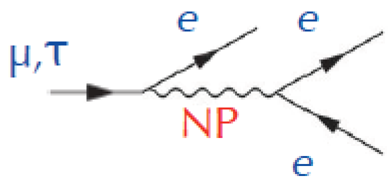


$\mu \to e\gamma$

Belle II, LHCb

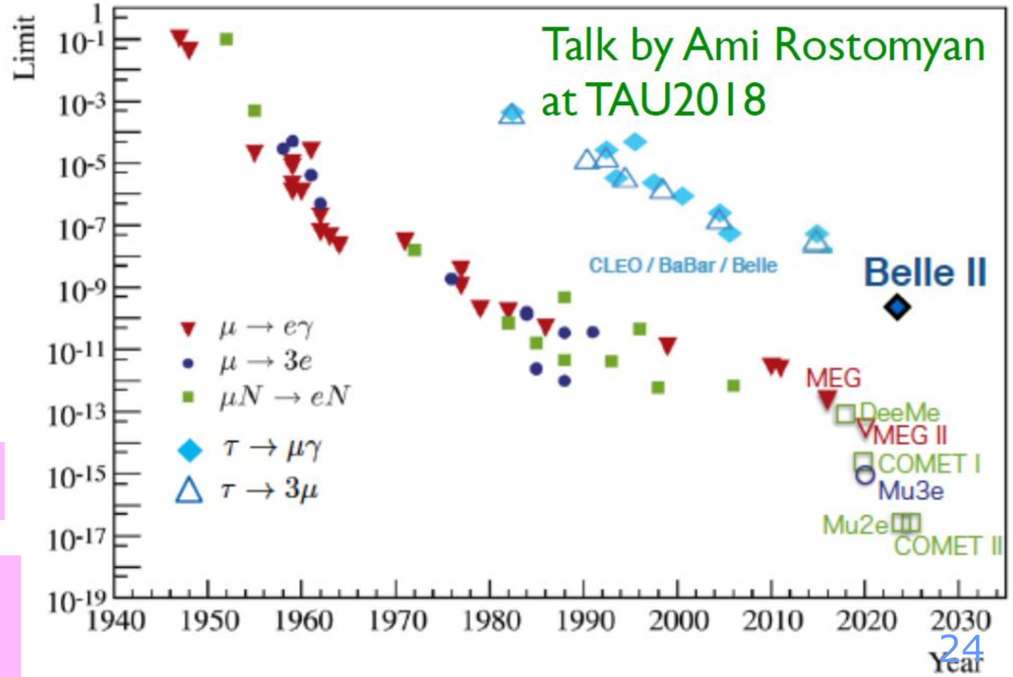


$\tau \to \mu\gamma$
$\tau \to e\gamma$



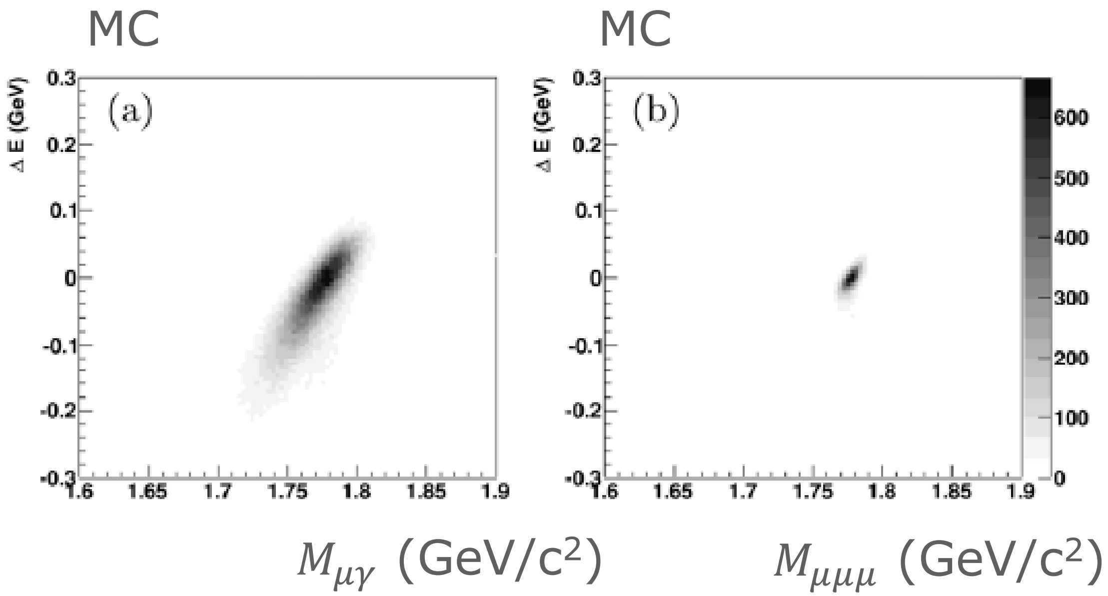
$\mu \to eee$ **Mu3e**

$\tau \to eee$ **Belle II LHCb**



τLFV Golden Channels

- τ→μγ
  - Many NP predicts the largest branching fraction in τLFV modes.
- τ→3μ
  - Sensitive to Higgs mediated model, Double-charged Higgs
  - Clean channel. Sensitivity goes up proportional to statistics.



As example

$$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \to \mu^- \gamma)}$$

Little Higgs w/ T-parity	MSSM (dipole)	MSSM (Higgs)
0.4 … 2.3	$\sim 1 \times 10^{-3}$	0.06 … 0.1

JHEP0705(2007)013

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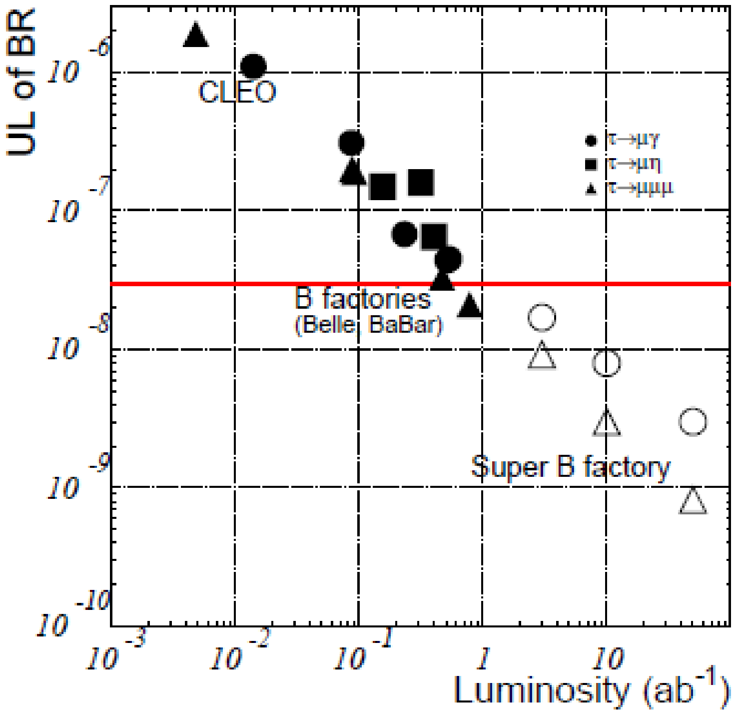


With several ab^{-1} data we will update the search!

As example

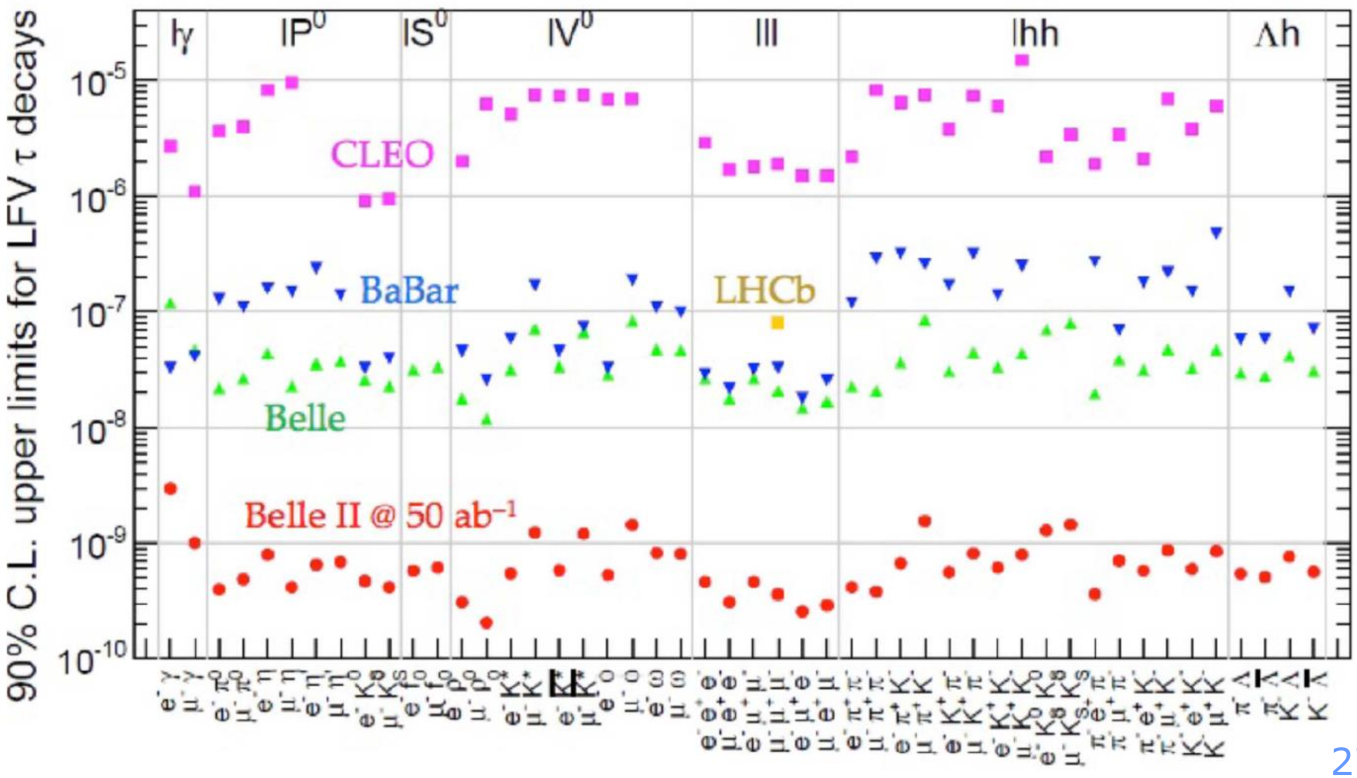
$$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \to \mu^- \gamma)}$$

Little Higgs w/ T-parity	MSSM (dipole)	MSSM (Higgs)
0.4 … 2.3	$\sim 1 \times 10^{-3}$	0.06 … 0.1

Tau LFV in Belle II

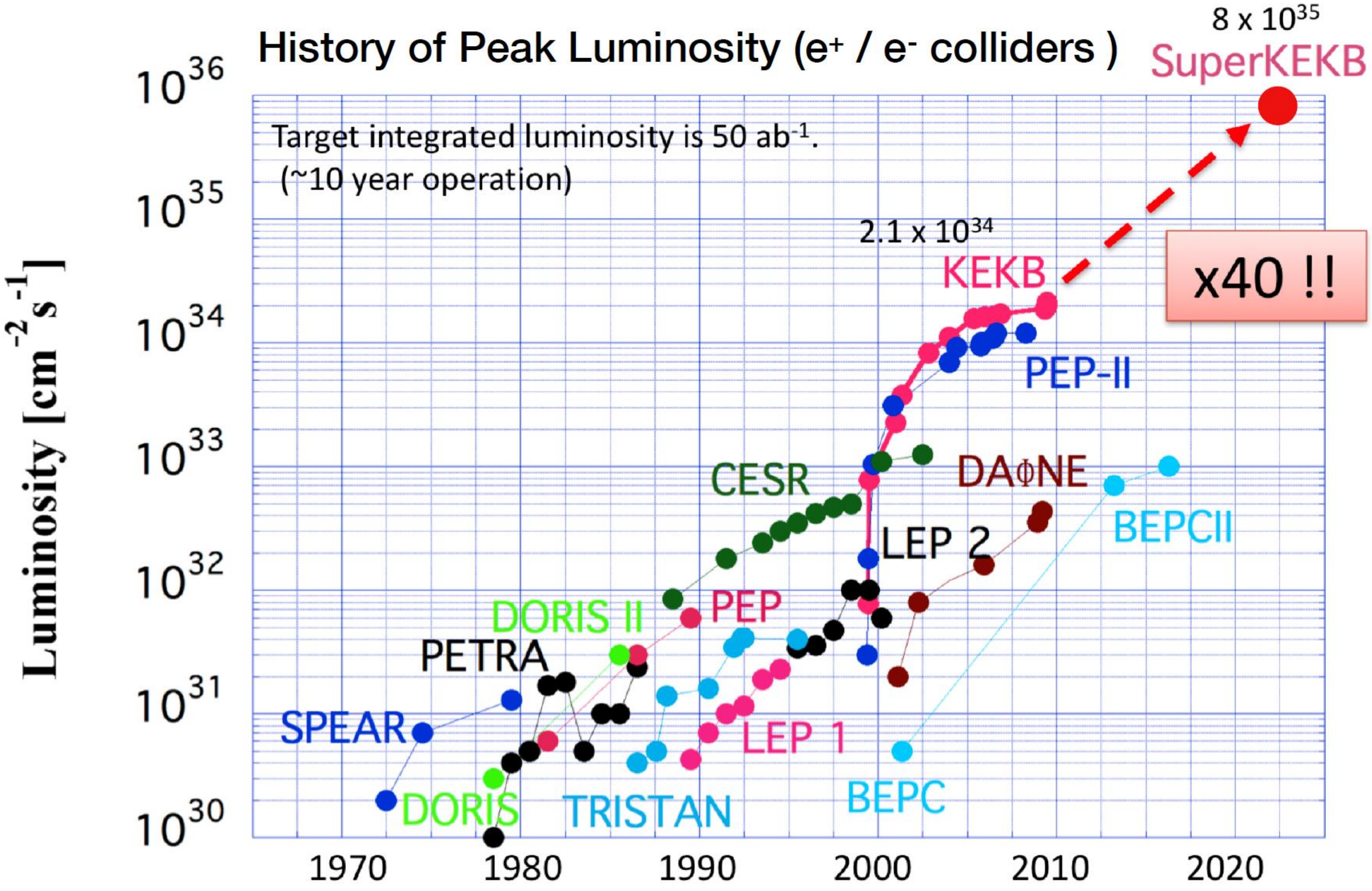
- Belle II is not only B factory but also tau factory.
  - Measuring tau flavor violating decay is one of important topics in Belle II.
- Clean environment of Belle II is good to see such a low-multiplicity events.

We'll cover many tau LFV decays down to 10^{-9} level.



SuperKEKB and Belle II

SuperKEKB target



Luminosity

Lorentz factor

Beam current

Beam-beam factor

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

Beam aspect ratio
(flat beam ~ 1-2%)

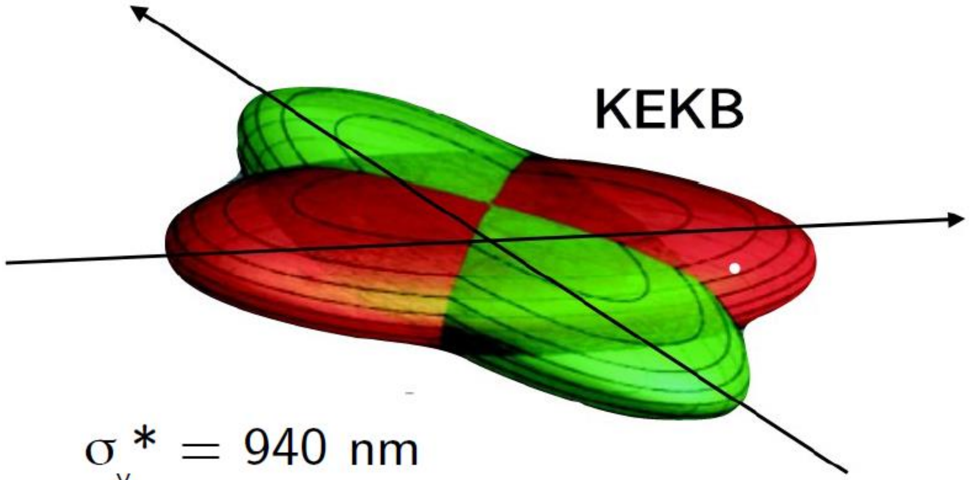
Vertical beta
function at IP

Geometrical corrections
(Hourglass effect...)

Brute force: Increase the current (x2)
Precision: denser beams, smaller β* (x20) → **Nano-beam scheme**

Nano-beam scheme

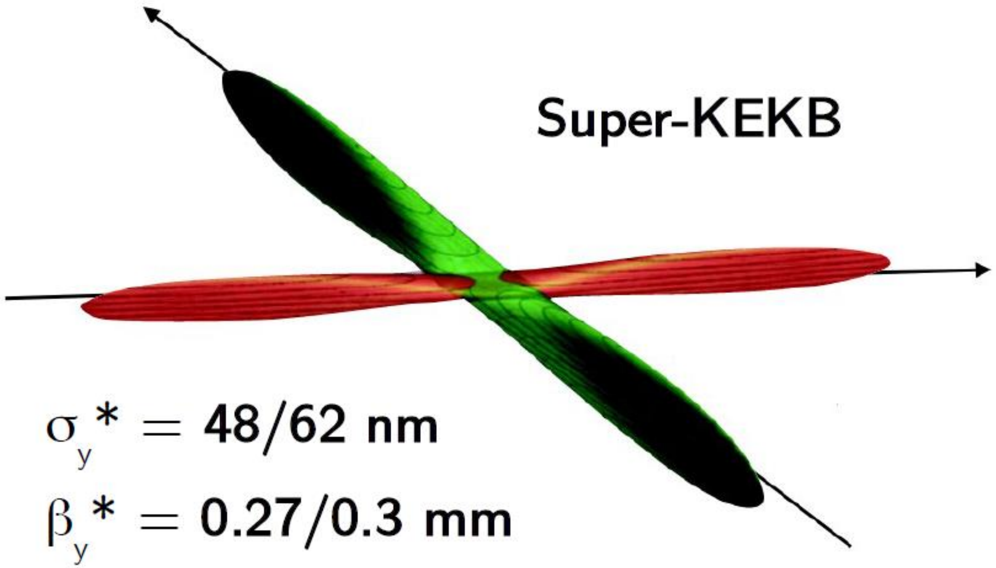
- Collide longer and thinner bunches with large crossing angle.



$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm

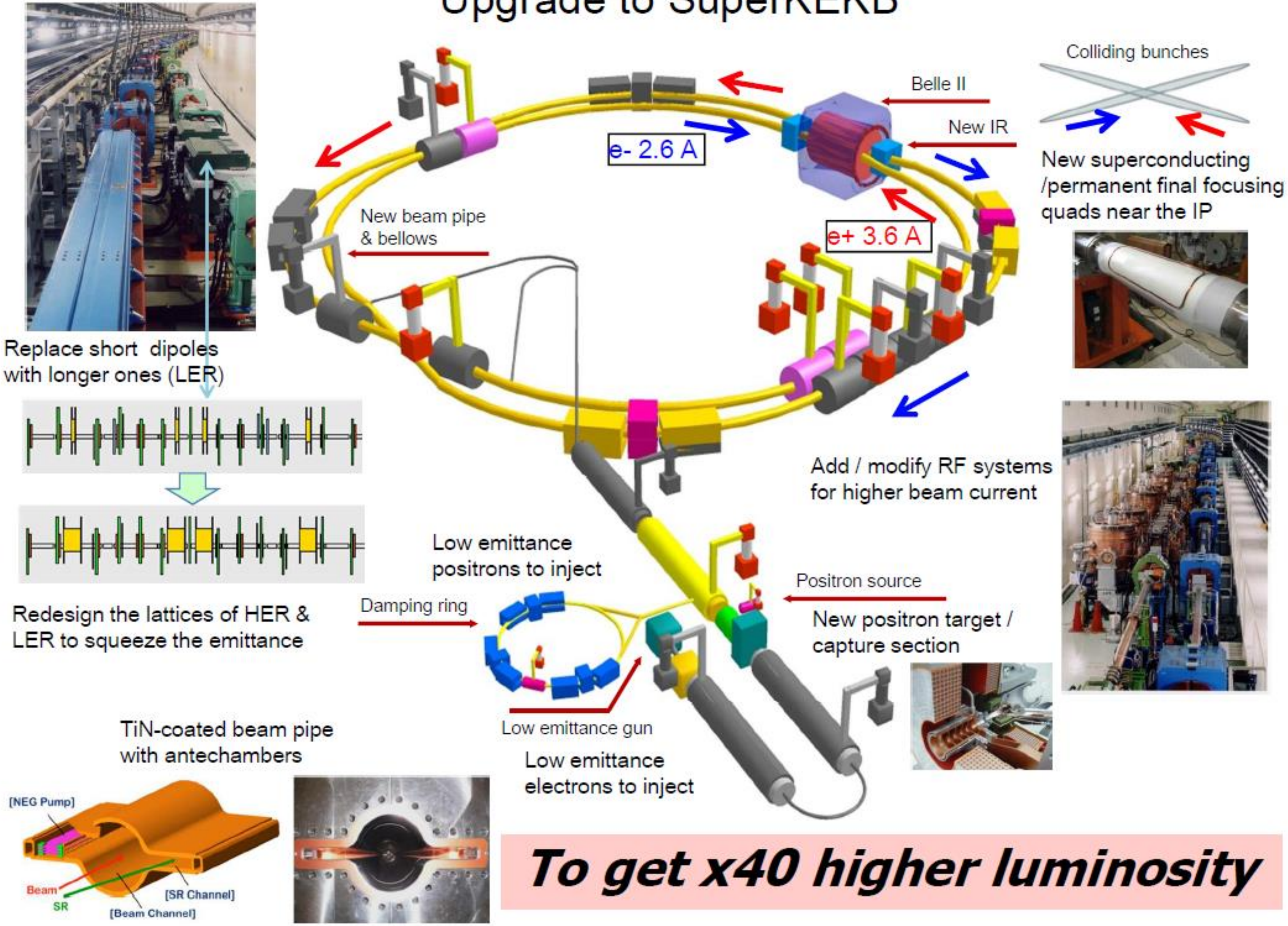


$\sigma_y^* = 48/62$ nm

$\beta_y^* = 0.27/0.3$ mm

$\sigma_x^* = 10.1/10.7$ μm

Upgrade to SuperKEKB



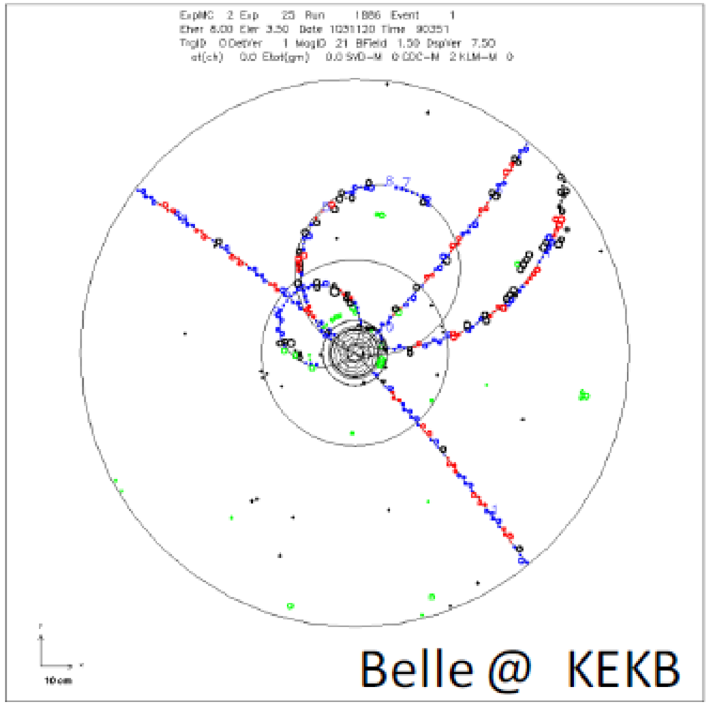
SuperKEKB Specs

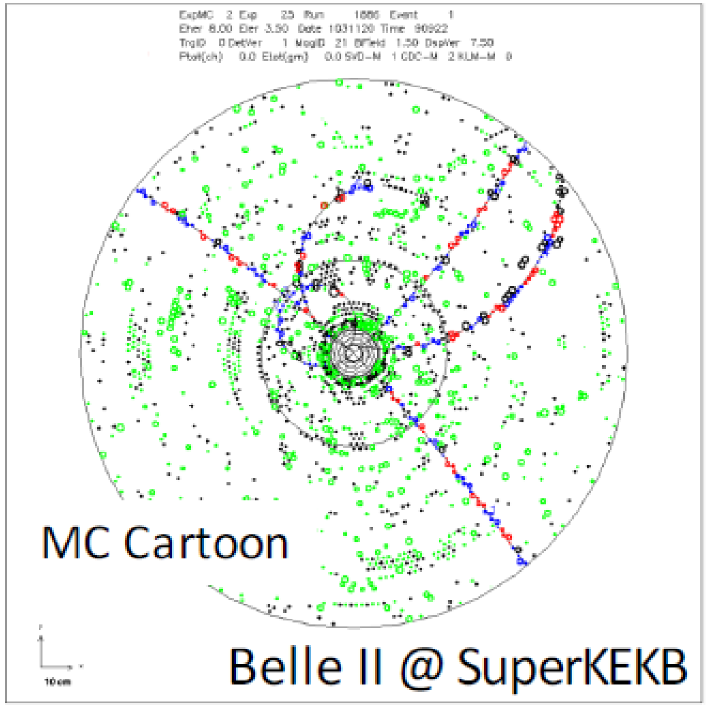
		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Beam crossing angle	φ	22		83		mrad
β function @ IP	β_x^*/β_y	1200/5.9		32/0.27	25/0.30	mm
Beam current	I_b	1.64	1.19	3.6	2.6	A
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

Belle to Belle II

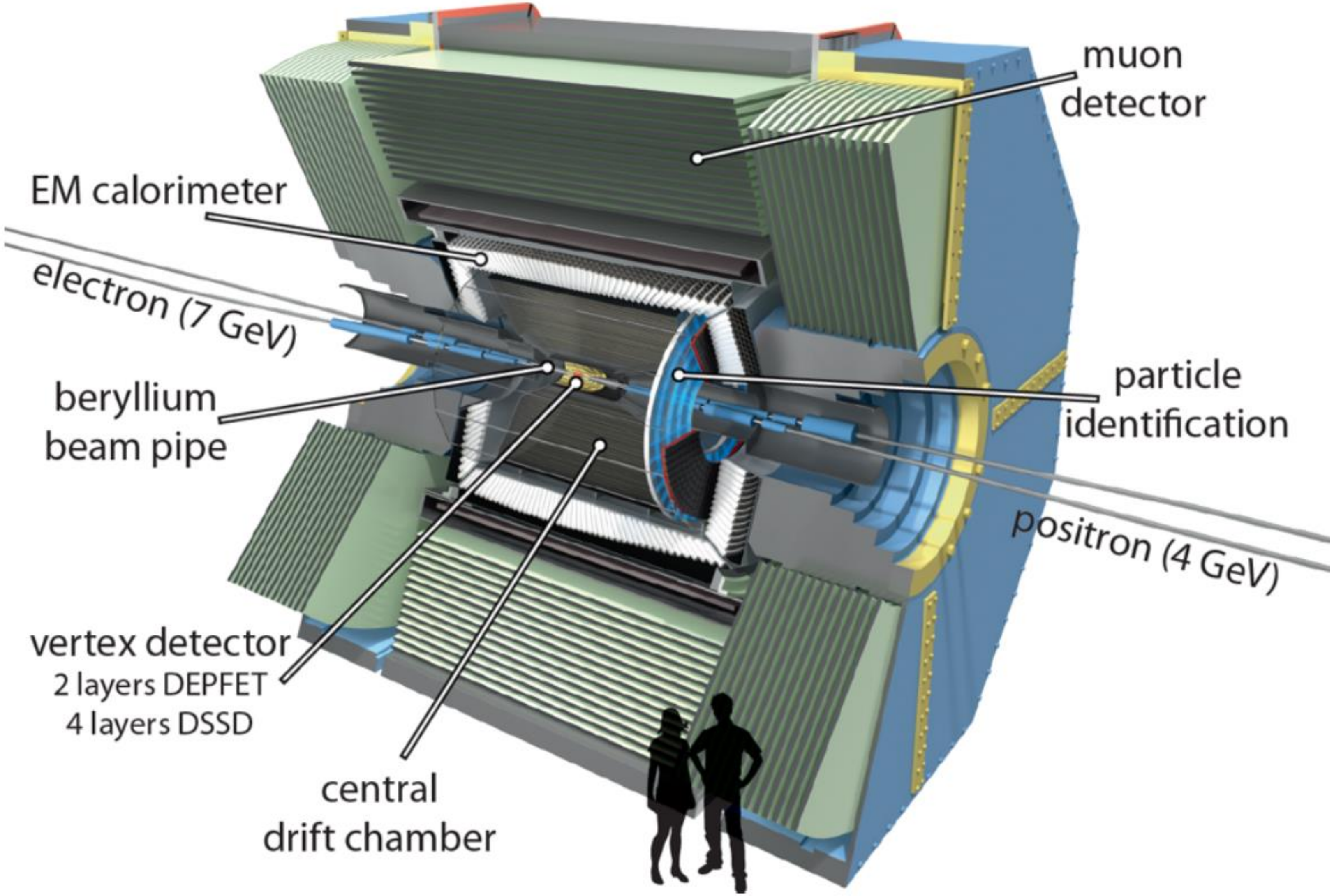
Higher luminosity causes
- Higher event rate
- Higher background

Detector should be upgraded to have same or better performance in the SuperKEKB environment.

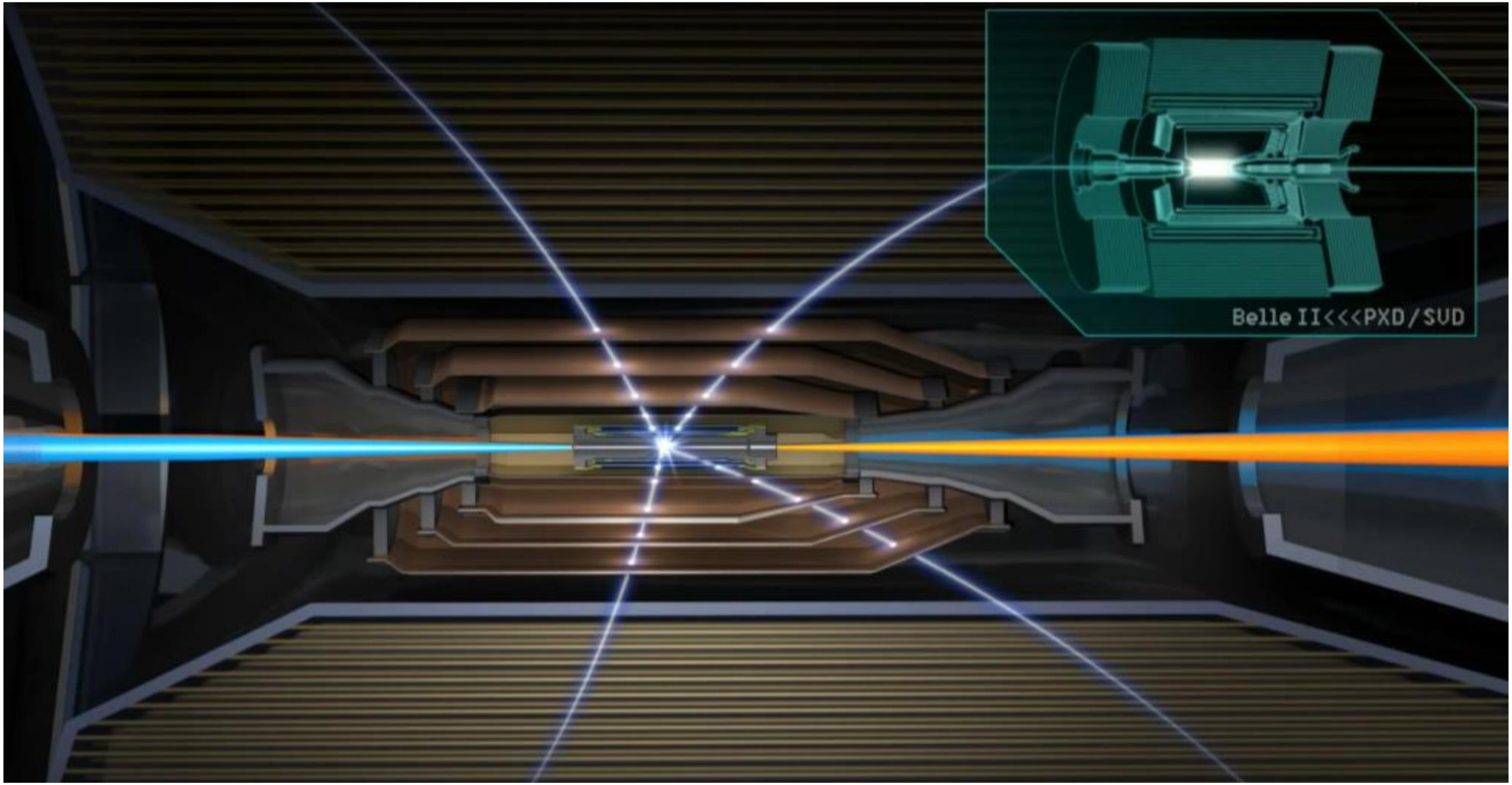




Belle II Detector

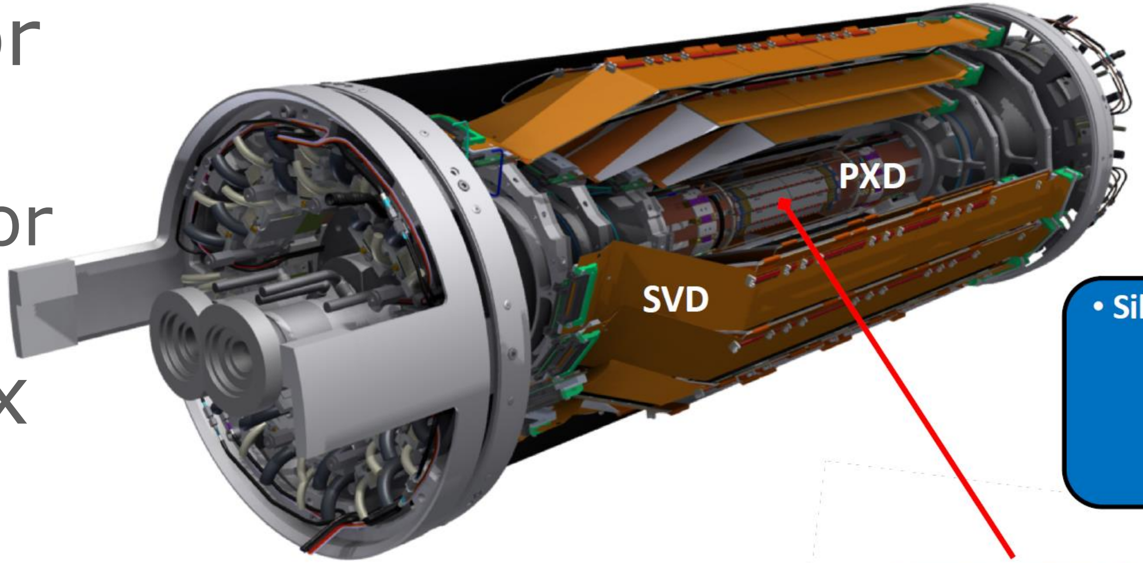


Vertex Detector

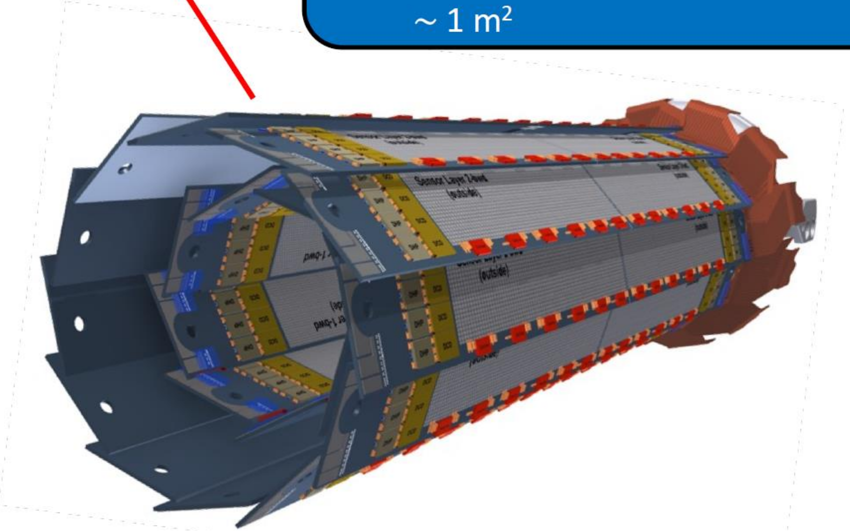


Pixel Detector & Silicon Vertex detector

- Pixel Detector (PXD)
  - New detector in Belle II.
- Silicon Vertex detector (SVD)
  - Larger outer radius to cover

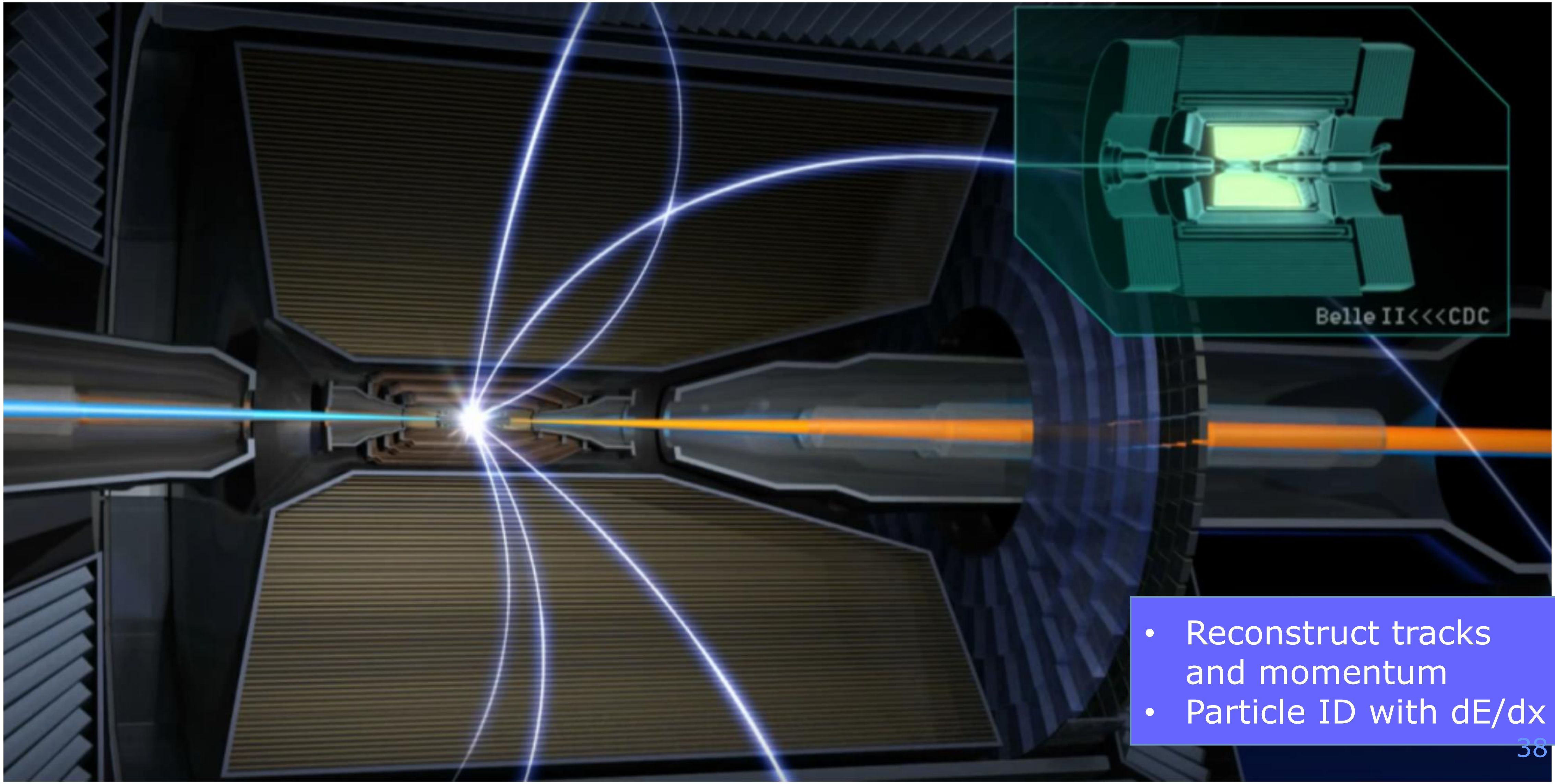


- **Silicon Vertex Detector (SVD)**
  4 layers of DSSD
  r = 3.8 cm, 8.0 cm, 11.5 cm, 14 cm
  L = 60 cm
  ~ 1 m^2



- **Pixel Detector (PXD)**
  2 layers of DEPFET pixels
  r = 1.4 cm, 2.2 cm
  L = 12 cm
  ~ 0.027 m^2

Central Drift Chamber

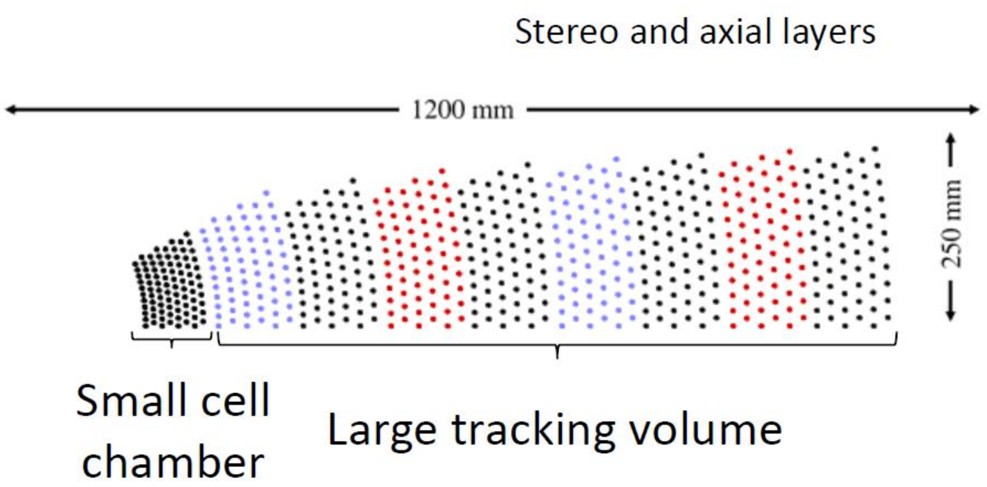


- Reconstruct tracks and momentum
- Particle ID with dE/dx

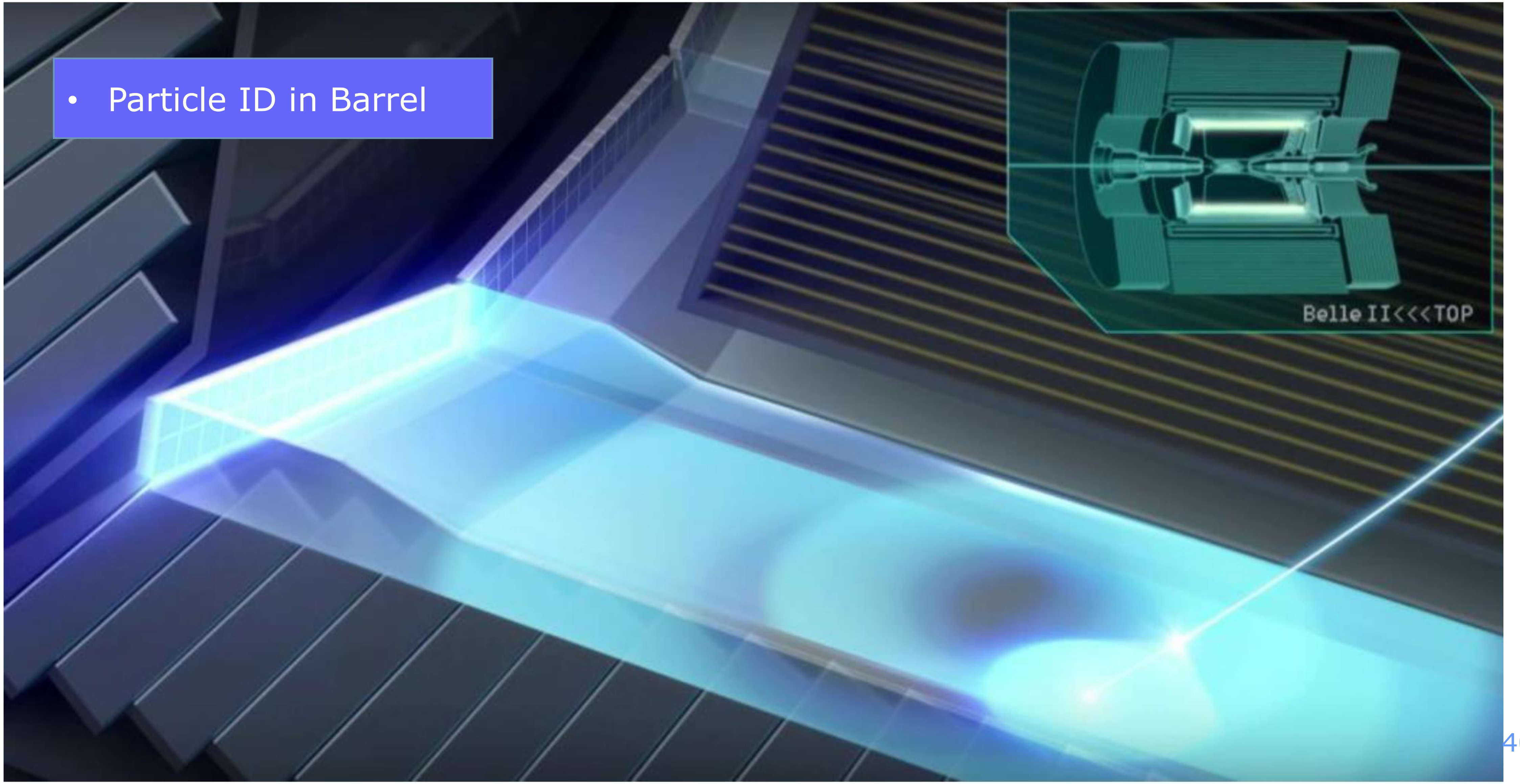
CDC in Belle II

- Smaller cell
  - reduce hit rate on one cell against increase background.
- Larger outer radius
  - Better momentum resolution
- Upgrade DAQ to reduce dead time

	Belle II CDC
Number of layers	56
Total sense wires	14336
Gas	He:C_2H_6 (1:1)
Sense wire	Au-W (ø30 µm)
Field wire	Al (ø126 µm)

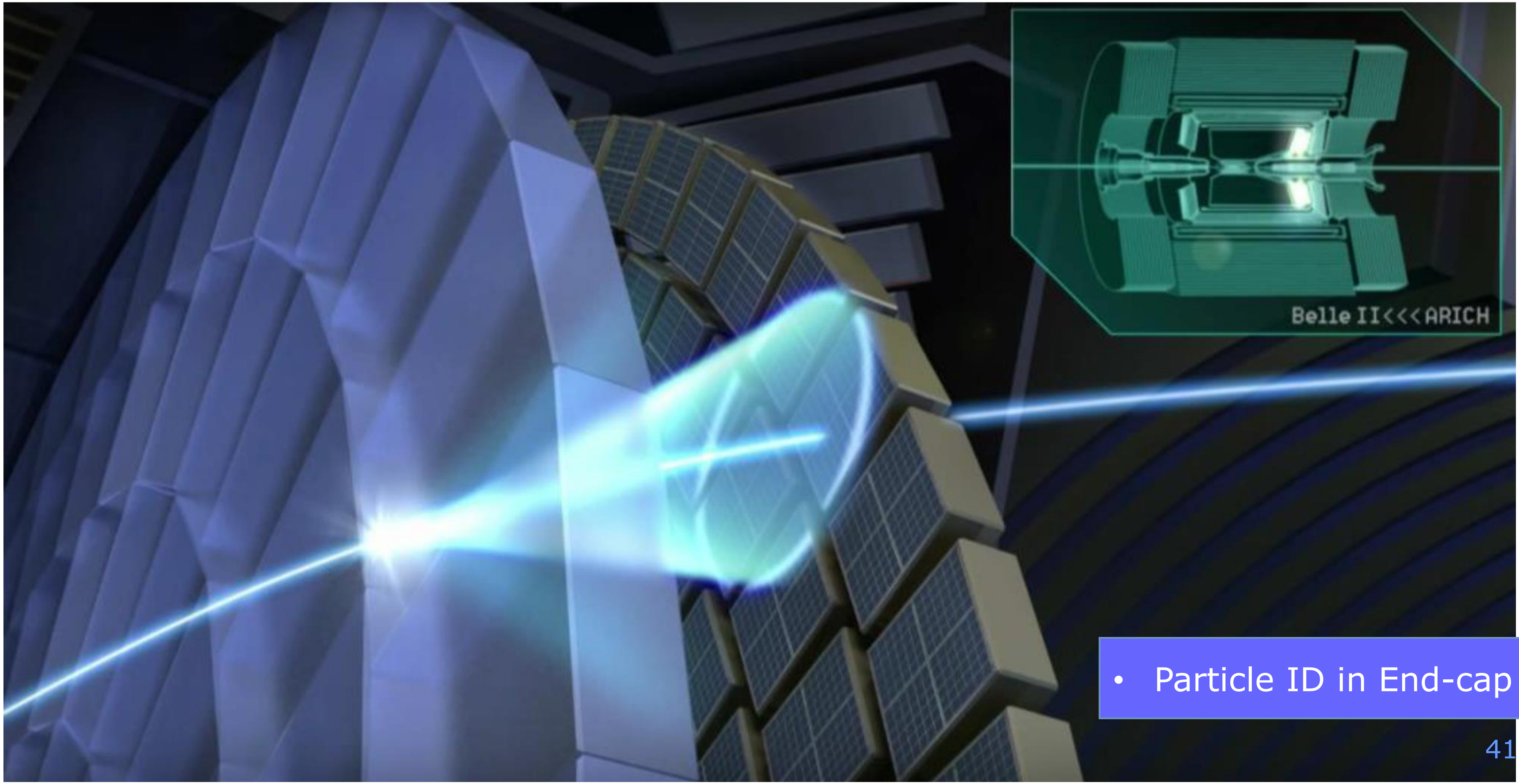


Time Of Propagation (TOP) counter



- Particle ID in Barrel

Aerogel Ring Imaging Cherenkov (ARICH) counter

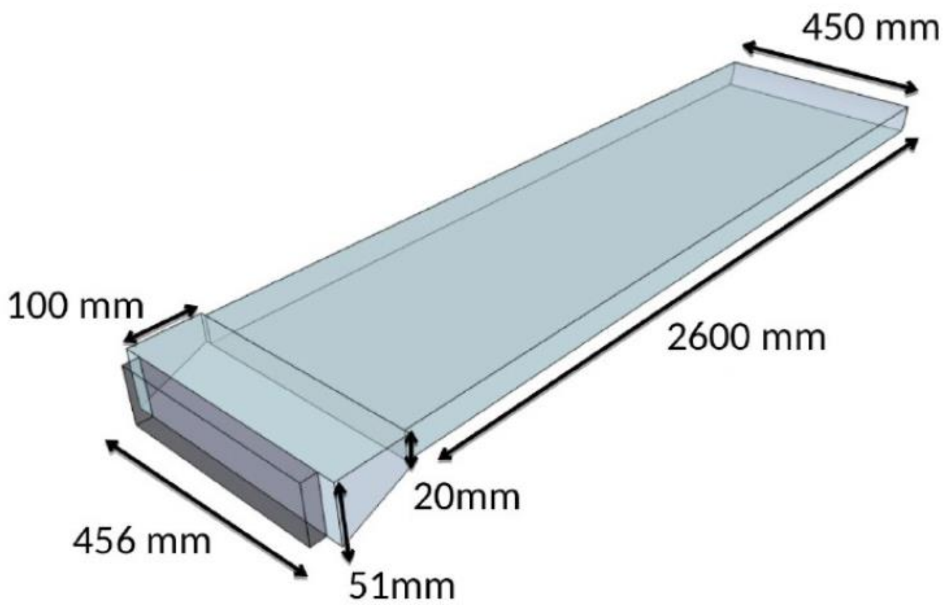


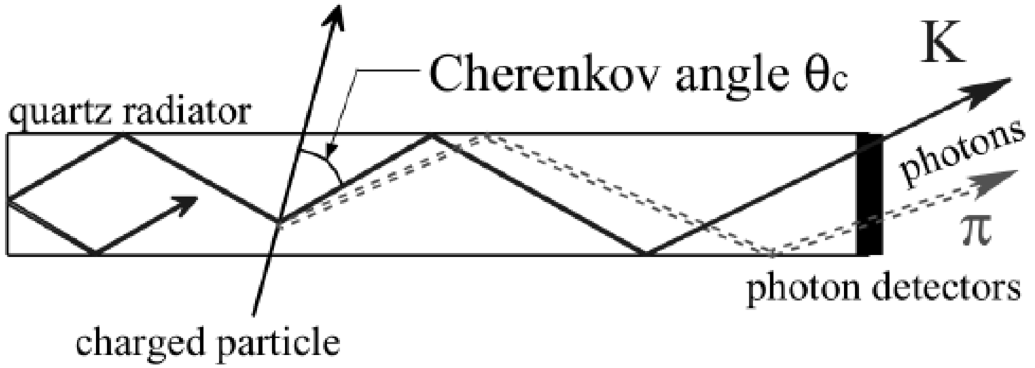
- Particle ID in End-cap

Time Of Propagation (TOP) counter

K/π ID by measuring difference of path length.

- 16 modules arranged around the interaction point
- Backward side: expansion prism, PMTs and readout
- Forward side: spherical mirror

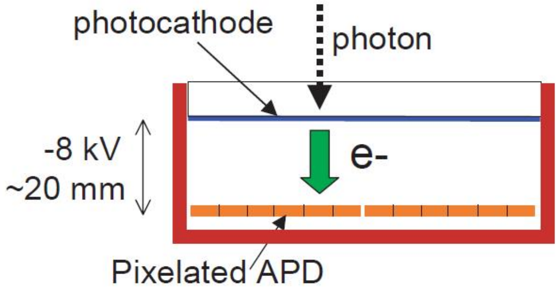


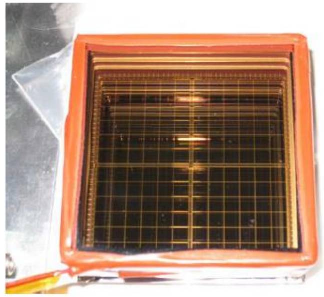


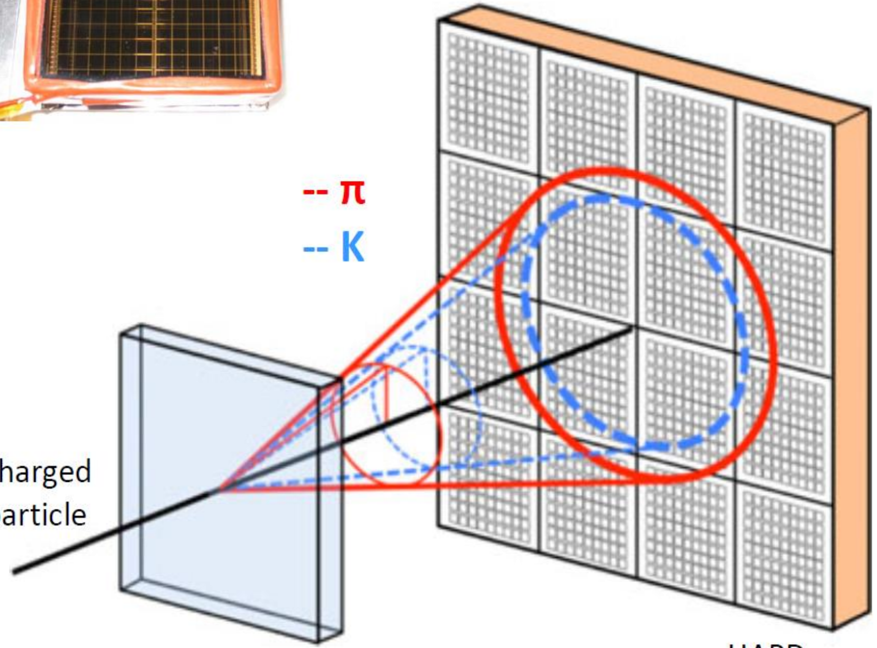
Aerogel Ring Imaging Cherenkov (ARICH) counter

K/π ID with Cherenkov imaging

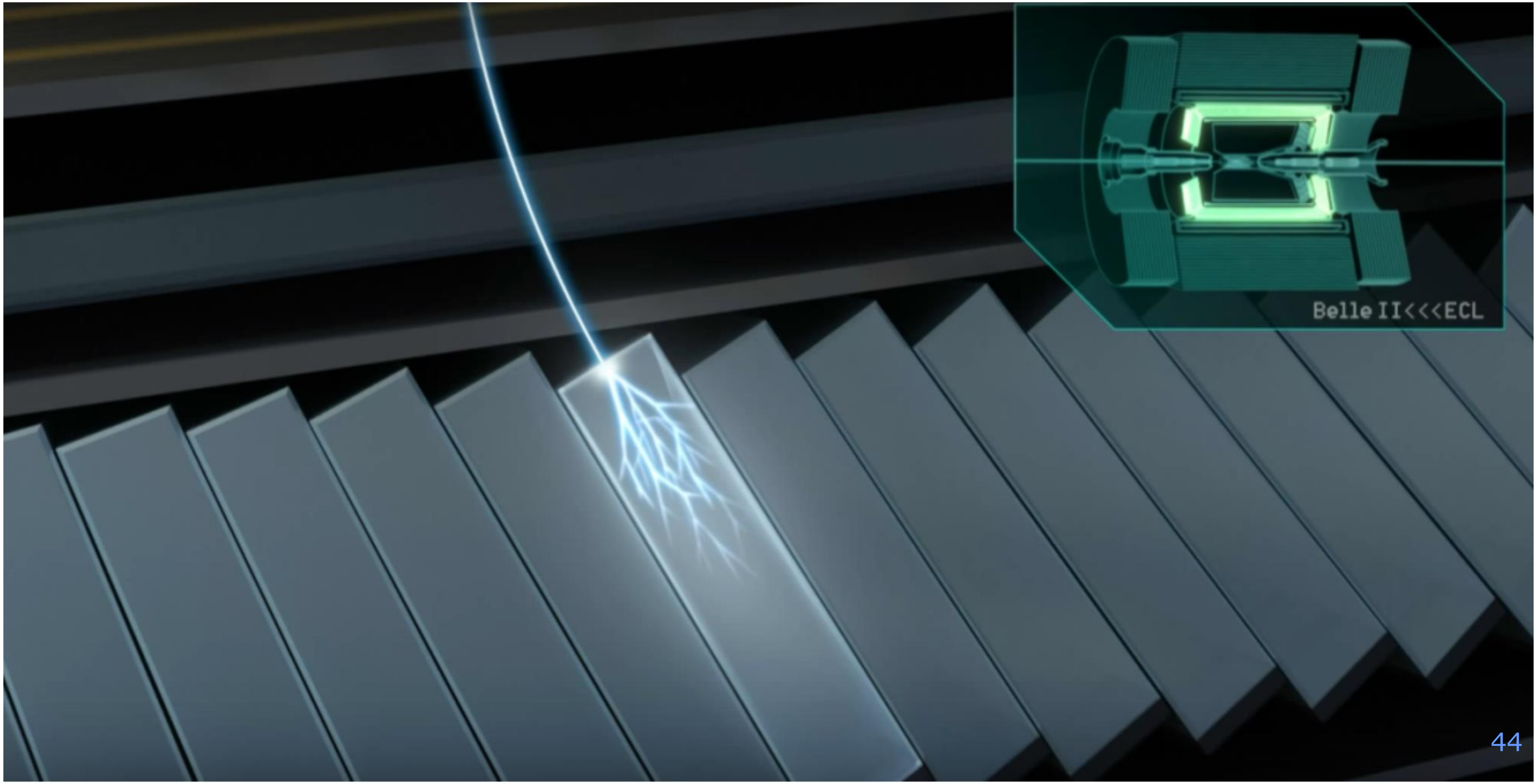
- Silica Aerogel radiator
  - n = 1.045-1.055
- Hybrid Avalanche Photo Detectors
  - 420 units, 144 channels each, 5 mm pixelated
  - Gain = $7 \cdot 10^5$
  - QE > 28%



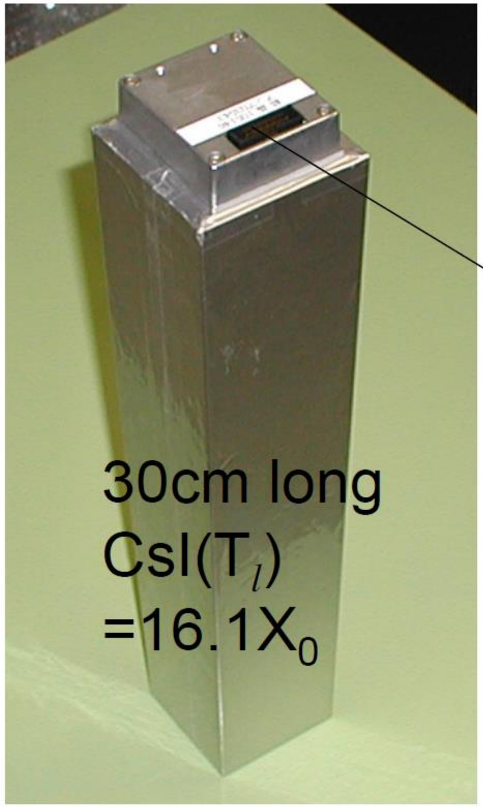


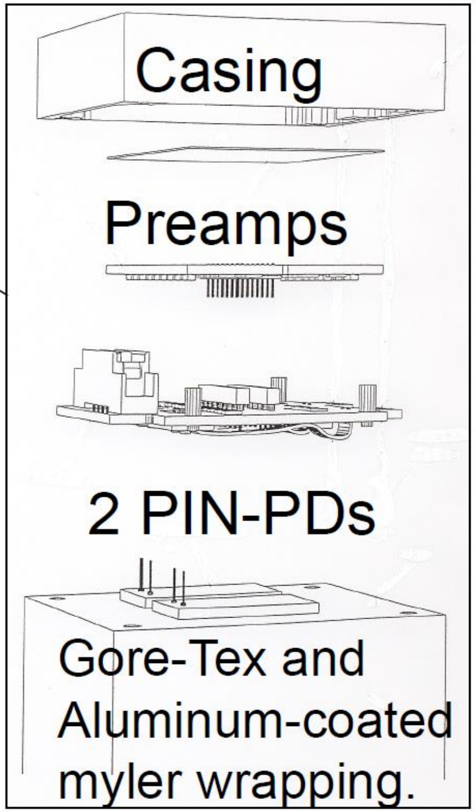


Electromagnetic Calorimeter



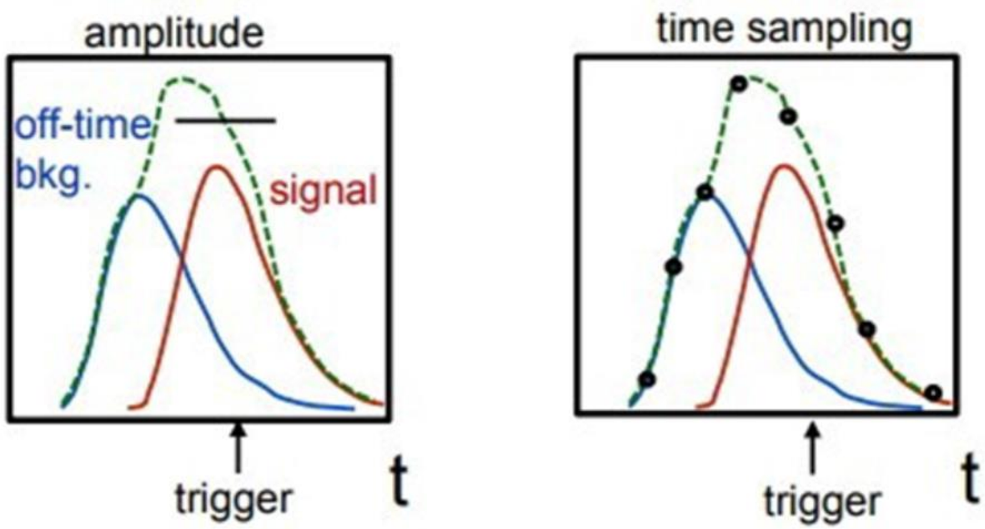
Electromagnetic Calorimeter



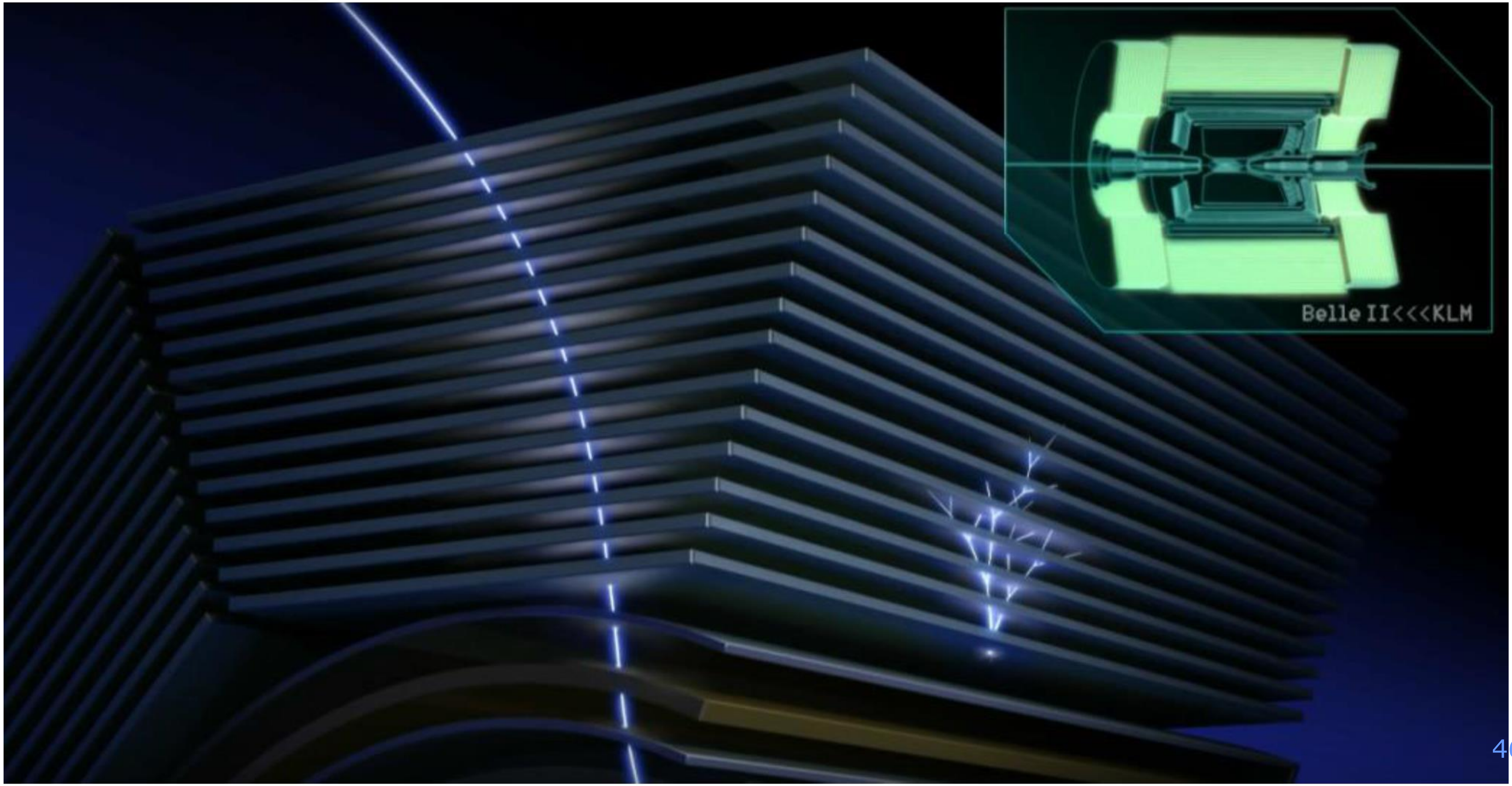


- CsI(Tl) crystals
  - 16.1 X_0 (30 cm)
  - Reuse

- New electronics 2 MHz waveform sampling for the barrel part



K_L and Muon Separation



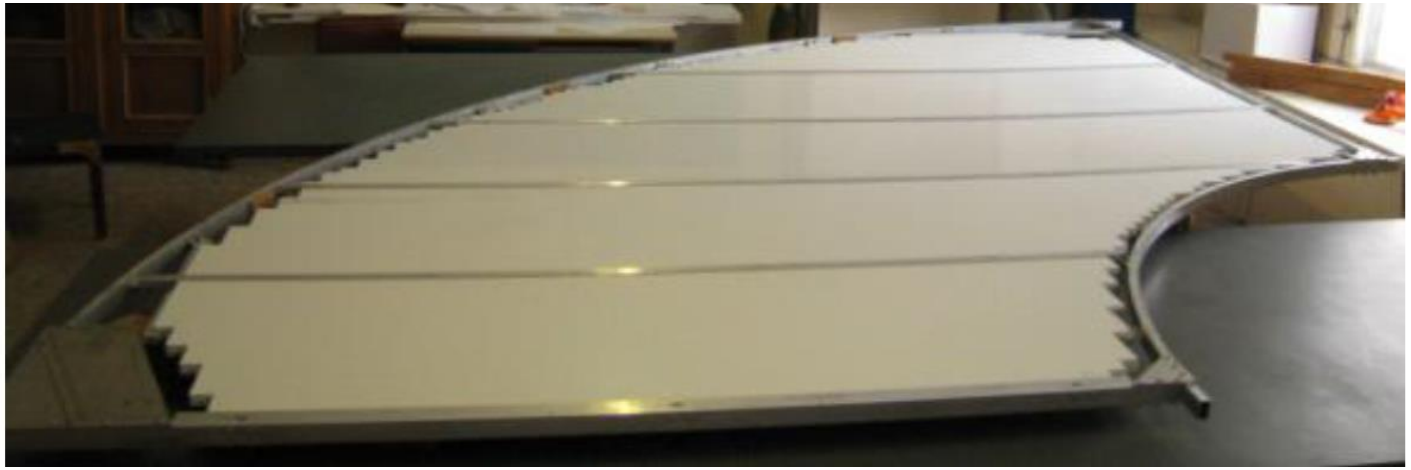
K_L and Muon Separation

Barrel: Belle RPCs reused

- Two inner layers replaced by scintillator strips (BKG)
- Scintillator strips with WLS fibers
- Hamamatsu SiPM S10362

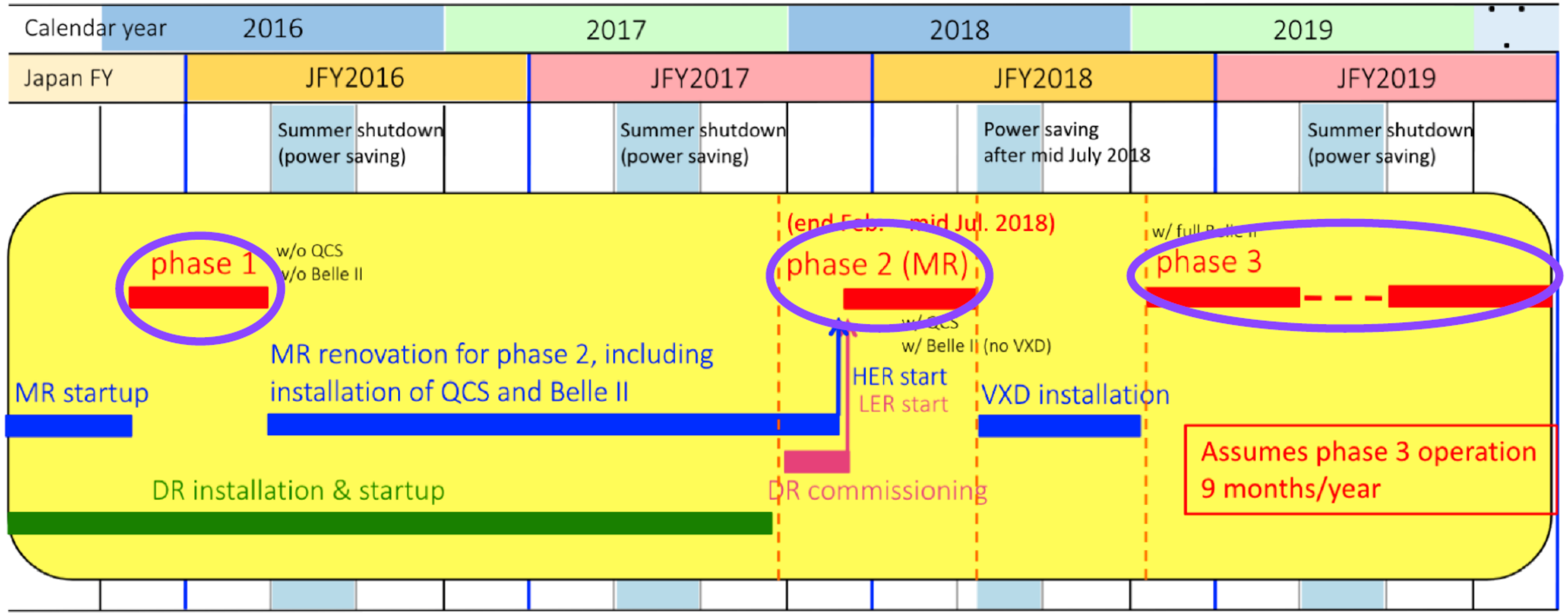
Endcap:

- RPCs replaced with polystyrene scintillators
- 99% geometrical acceptance. $\sigma \sim 1$ns



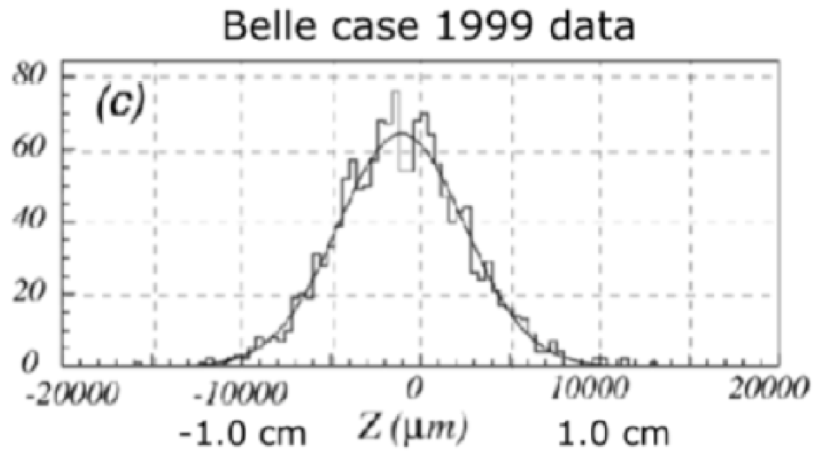
Belle II status

- **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} at $\Upsilon(4S)$)
- **Phase 3:** Collision data taking with full Belle II detector. **STARTED MARCH 2019**.



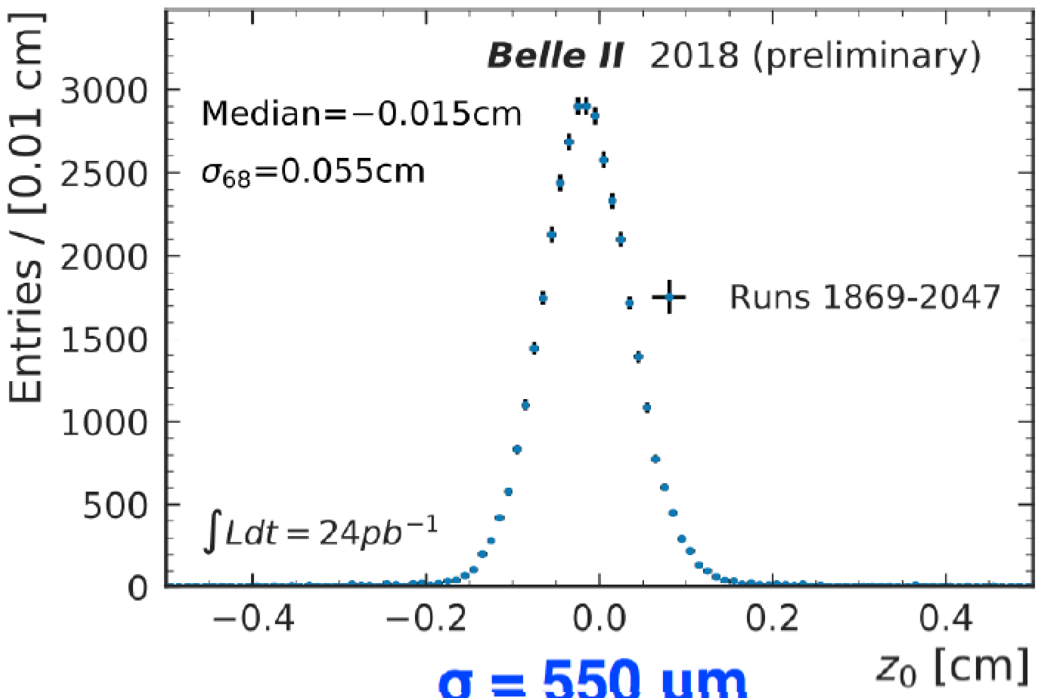
Nano-beam

- Nano-beam scheme works successfully.



σ = 4.5 mm

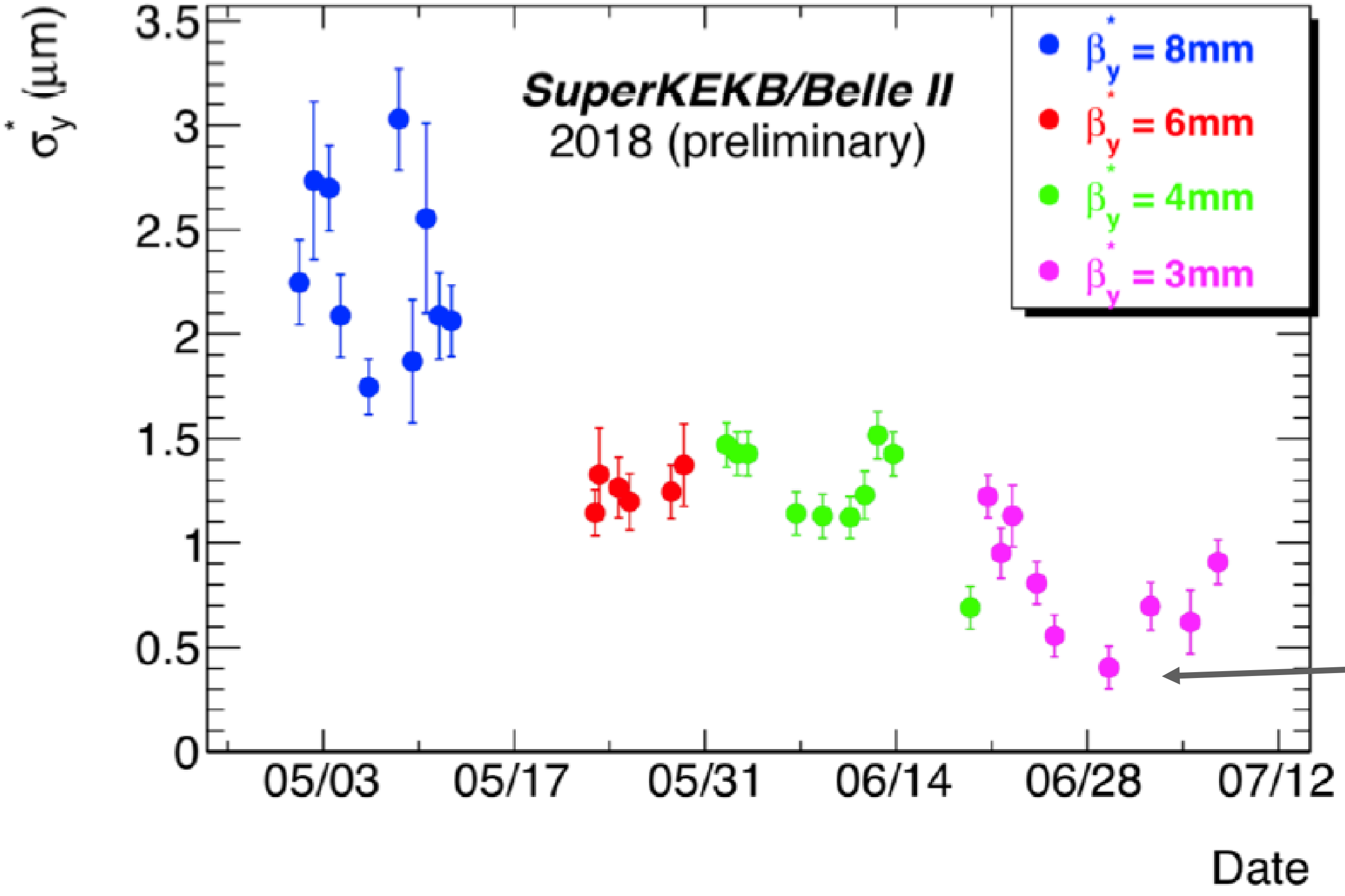
Belle II case 2018 data



σ = 550 μm

Nano-beam

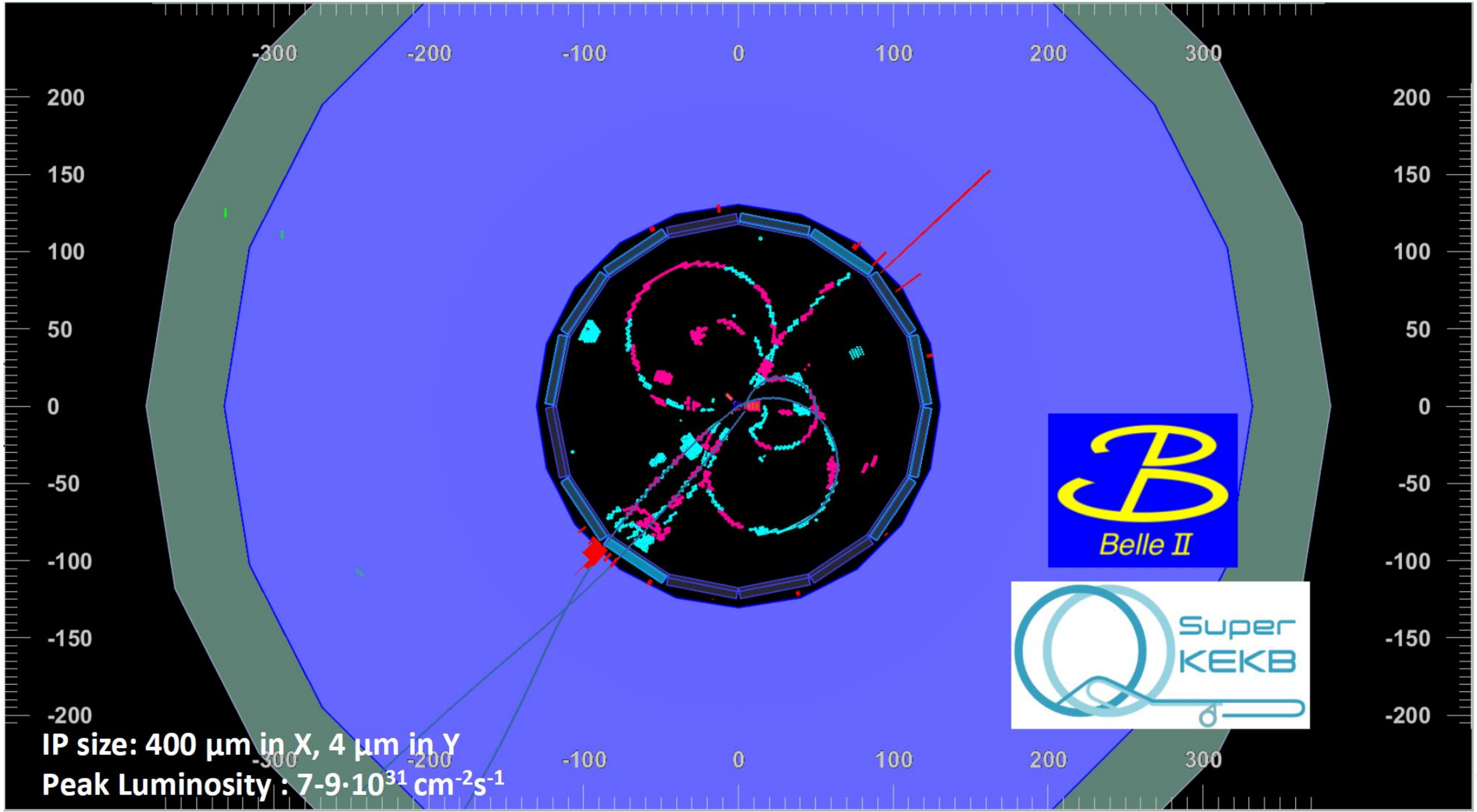
- Nano-beam scheme works successfully.



Final target 0.3 mm

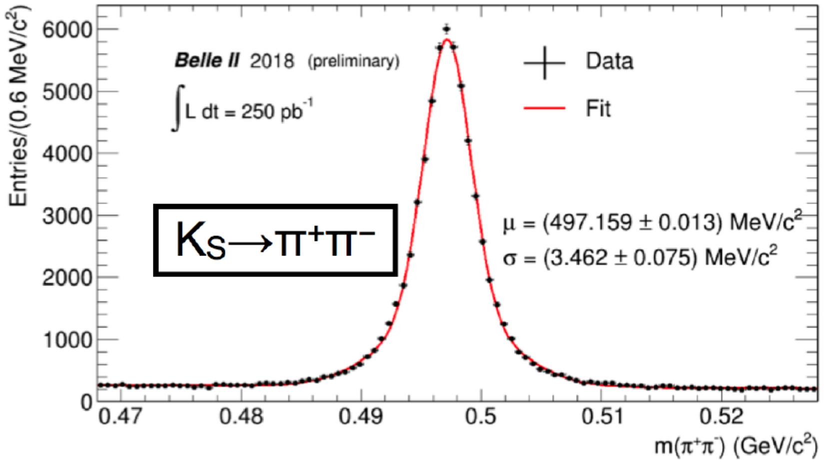
World record
σ = 400nm

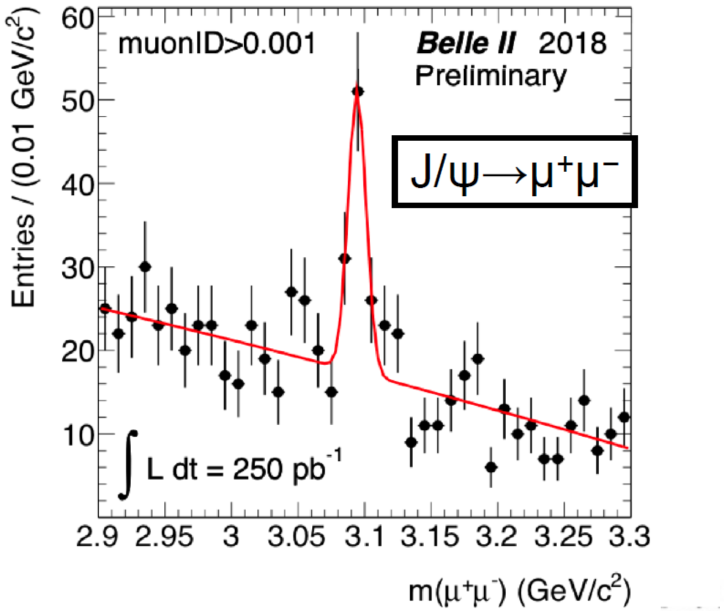
Belle II first event (April 2018)

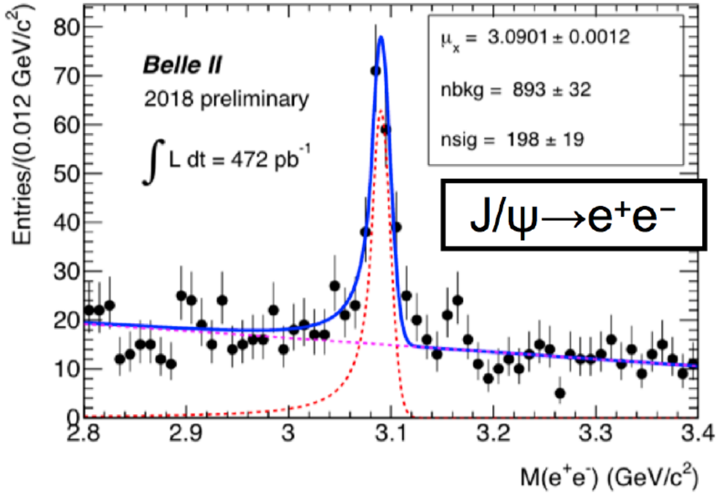


Track Reconstruction

- Charged particle are successfully reconstructed by Belle II trackers, CDC and partial VXD.



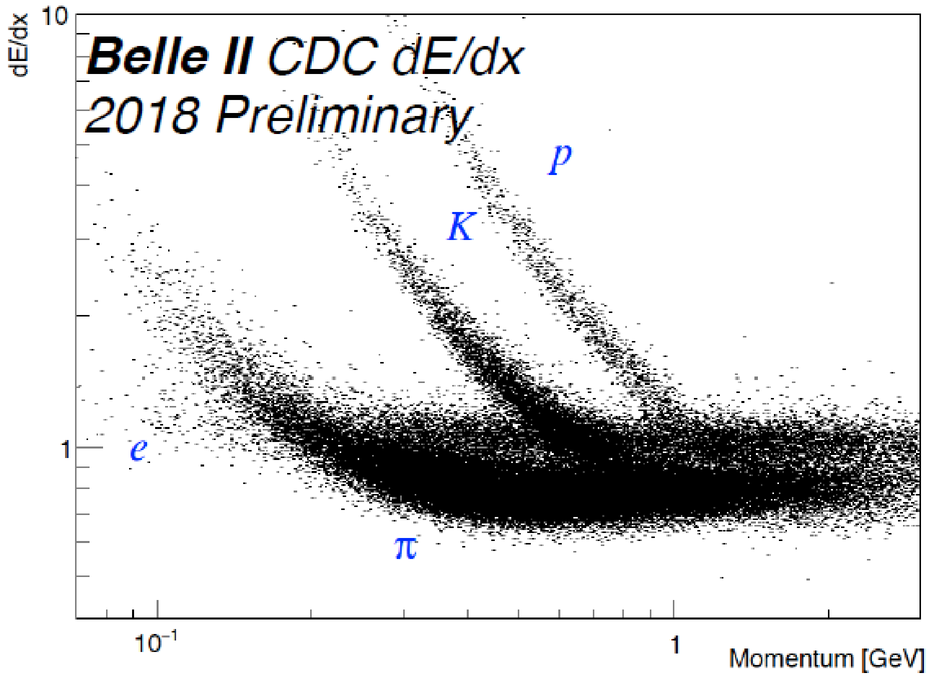


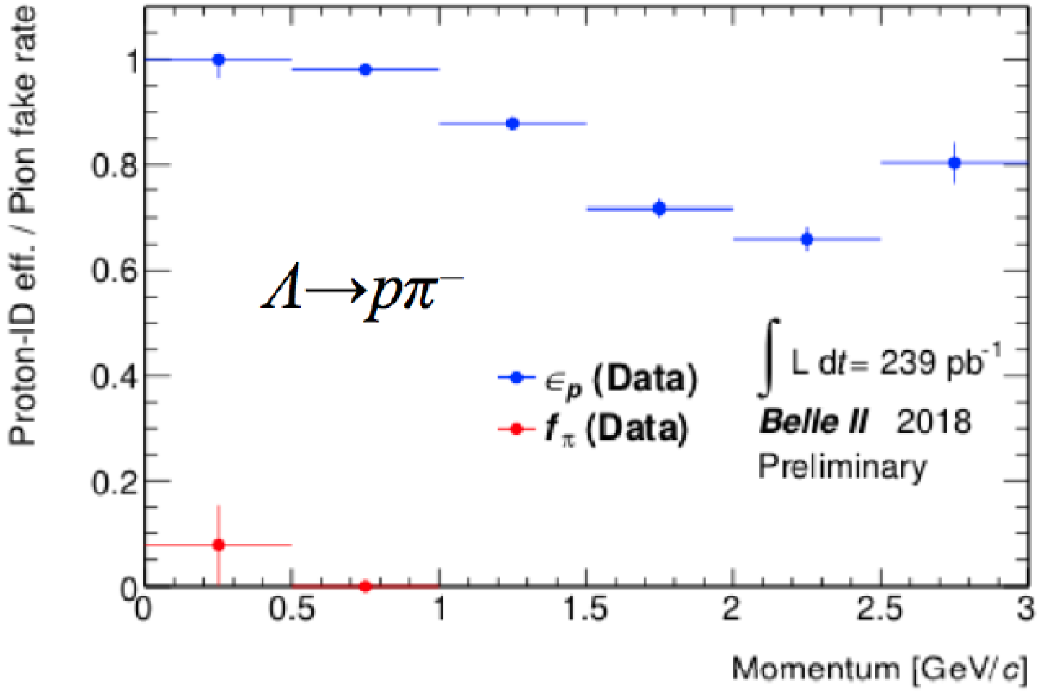


Particle Identification

- Particles are identified by **CDC**, TOP, and ARICH

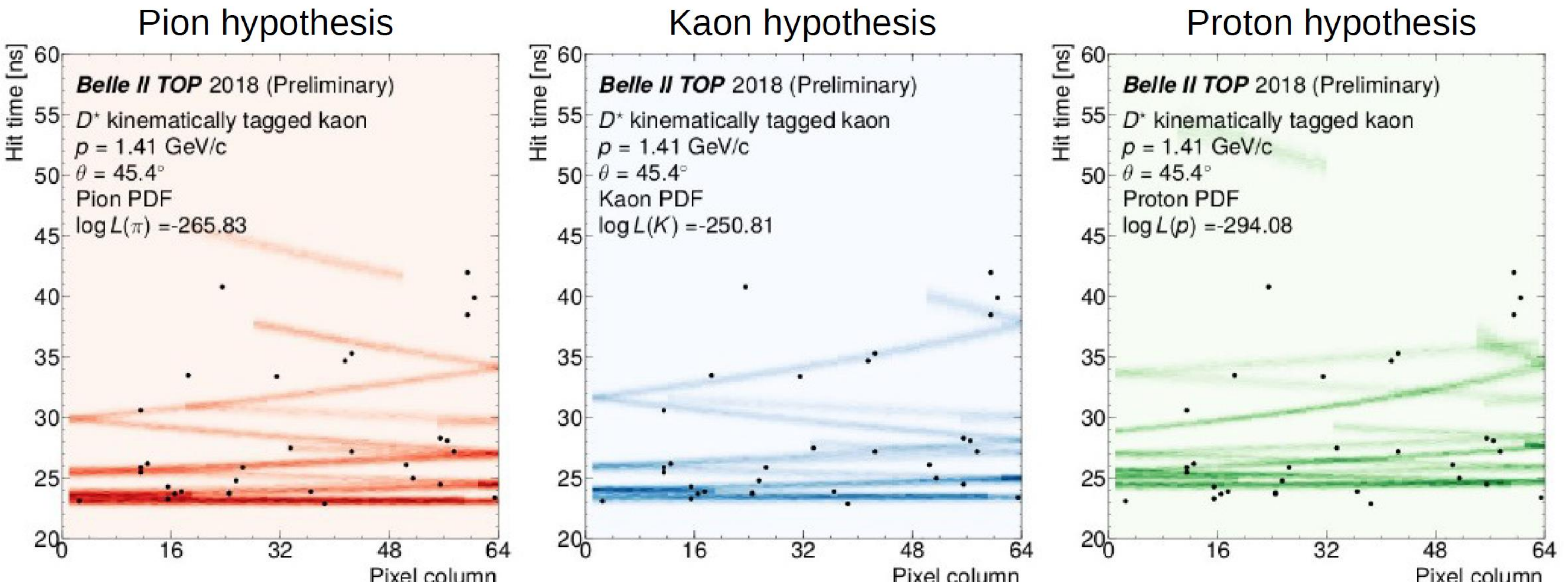
Central Drift Chamber dE/dx





Particle Identification

- Particles are identified by CDC, **TOP**, and ARICH

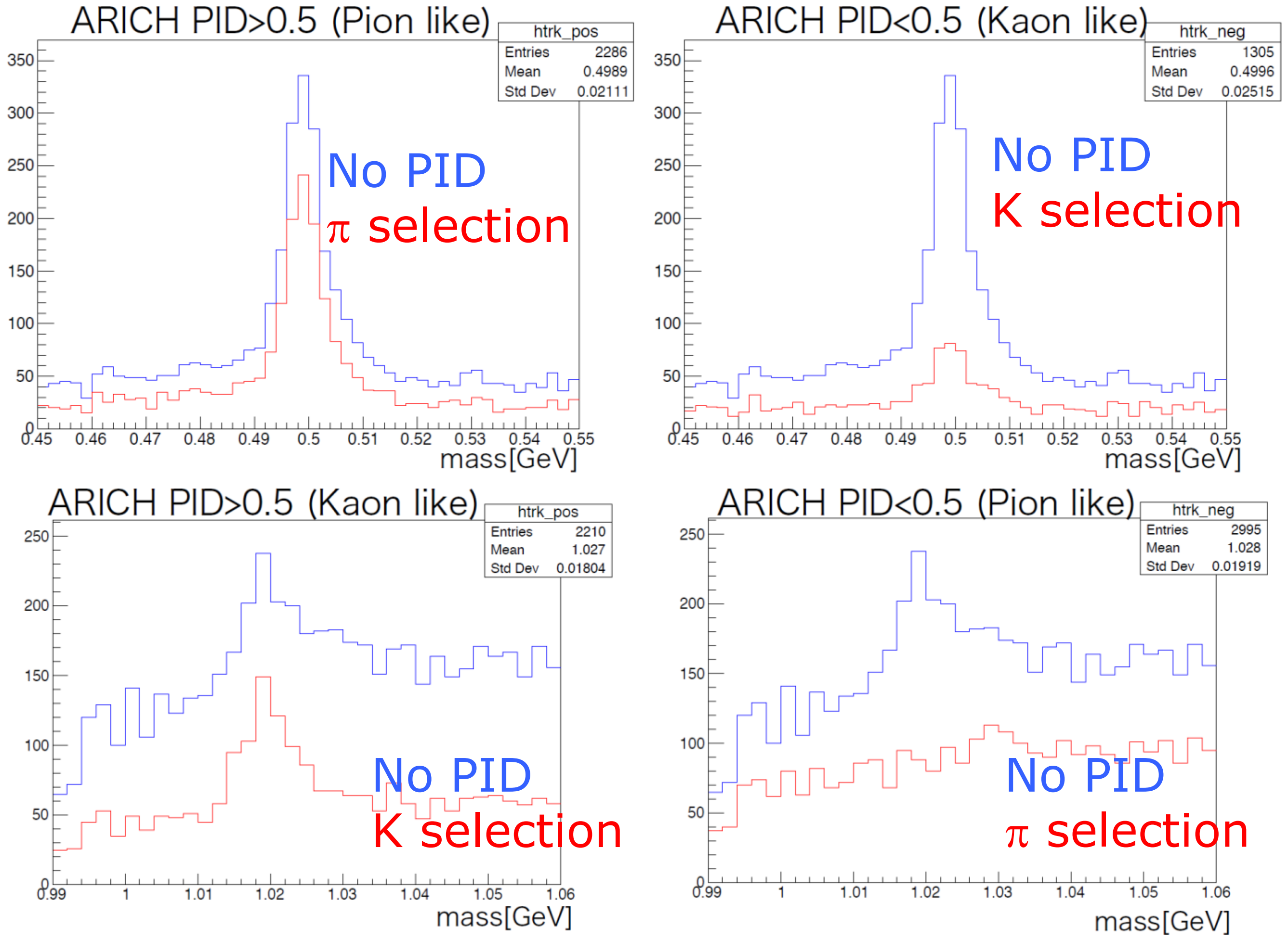


Particle Identification

- Particles are identified by CDC, TOP, and **ARICH**

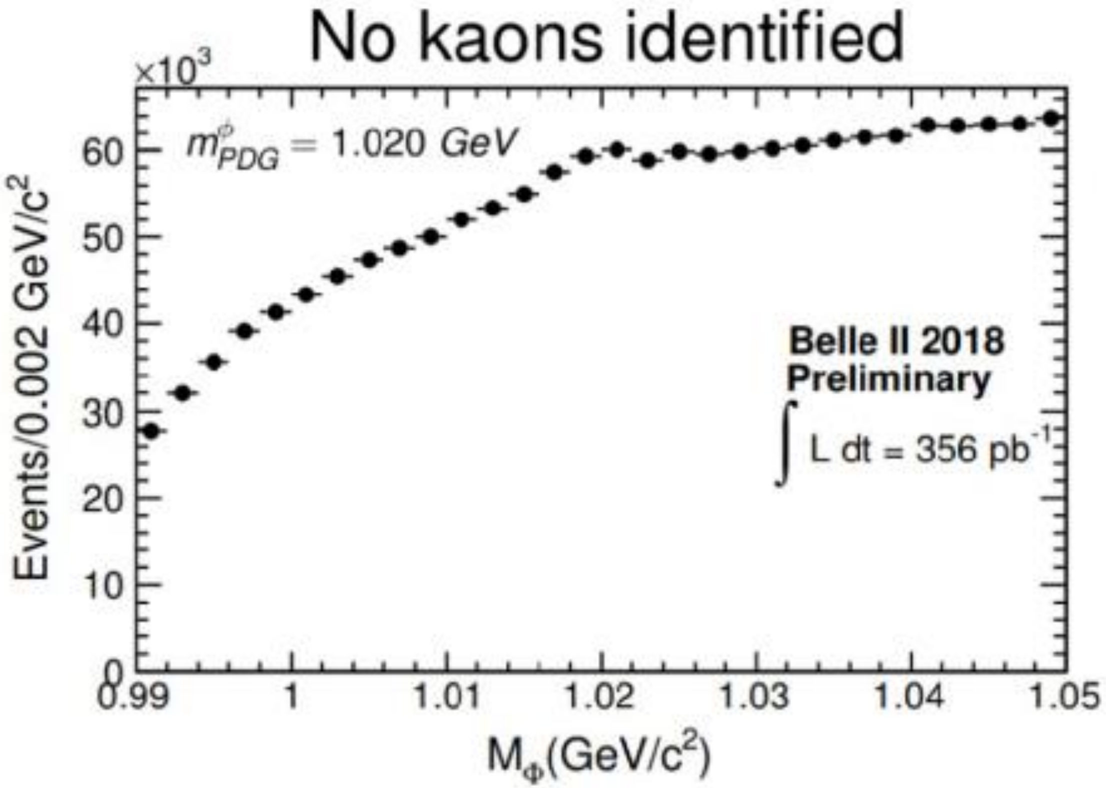
$K_s \to \pi^+\pi^-$

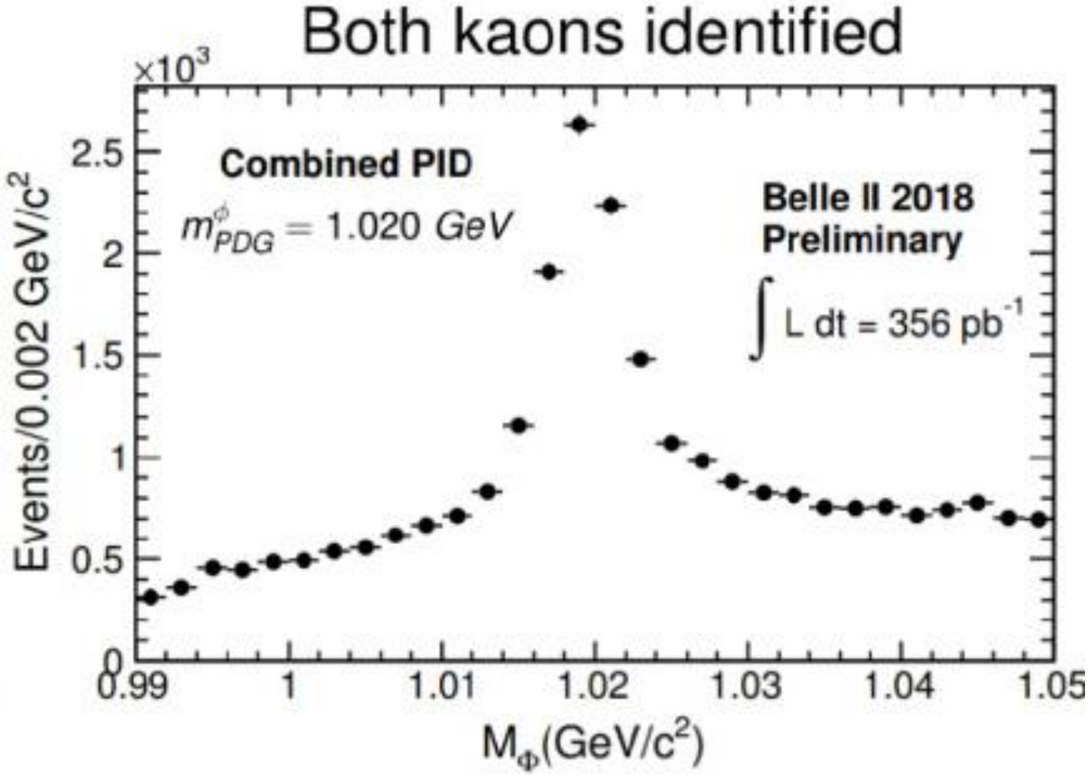
$\phi \to K^+K^-$



Particle Identification

- Particles are identified by CDC, TOP, and ARICH

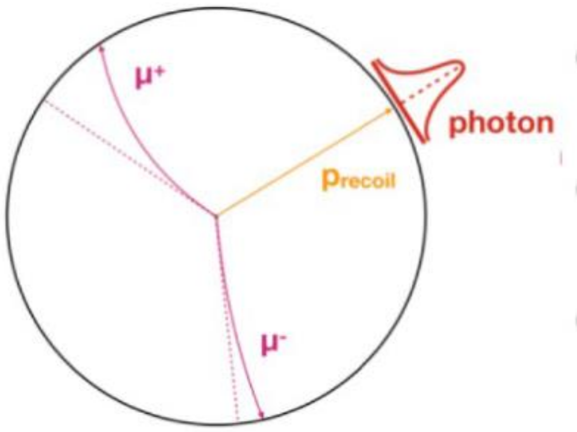




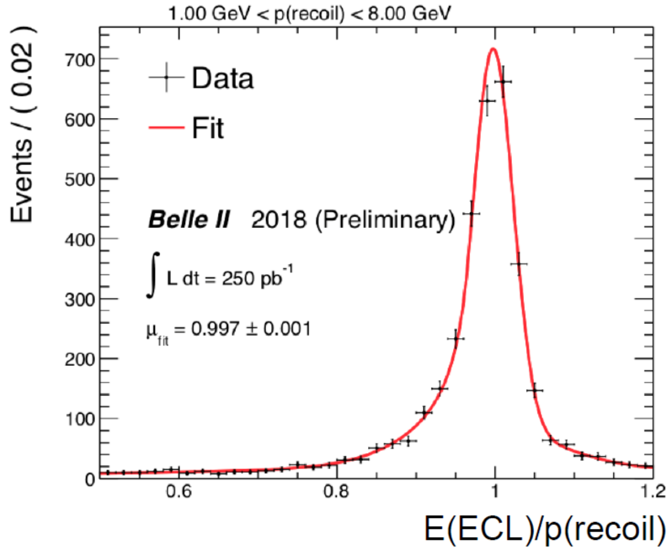
$\phi \to K^+K^-$ resonstruction

Photon Reconstruction

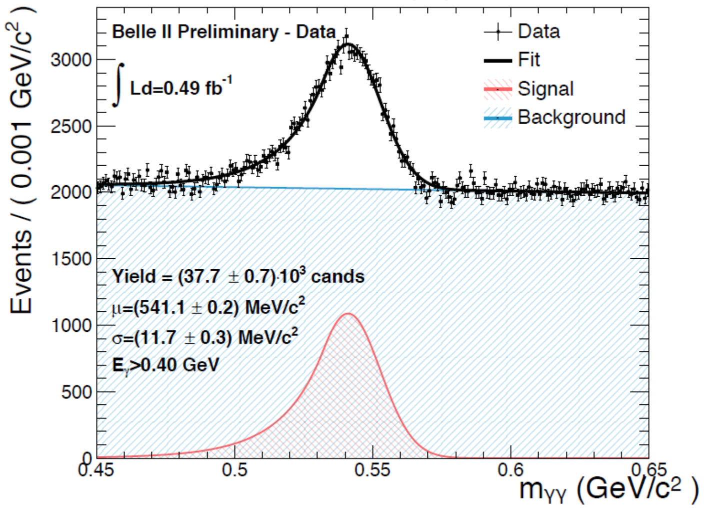
- Photon is reconstructed with several modes.



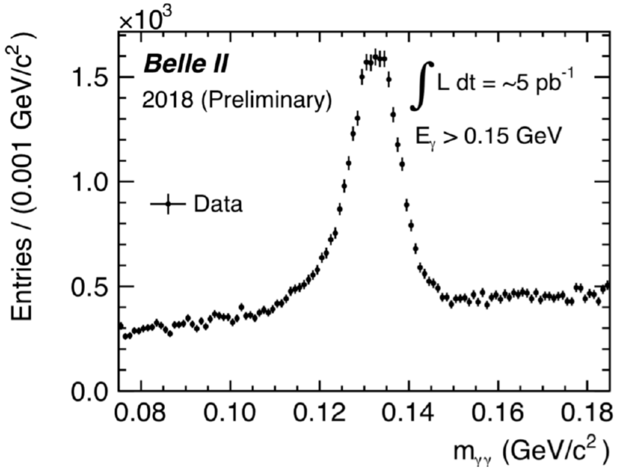
$e^+e^- \to \mu^+\mu^-\gamma$



$\eta \to \gamma\gamma$



$\pi^0 \to \gamma\gamma$

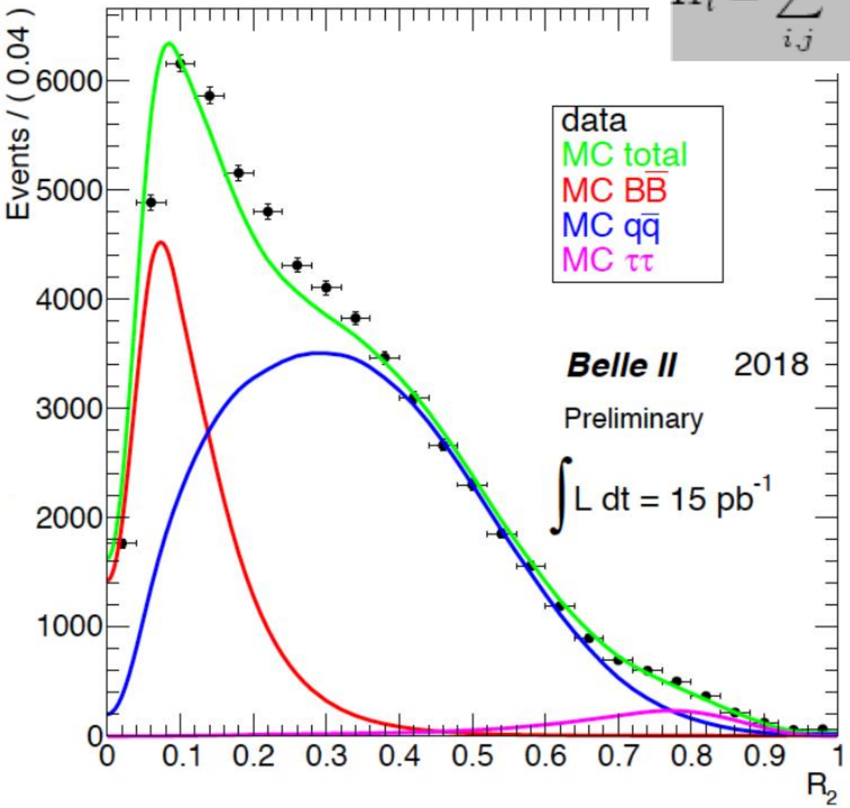


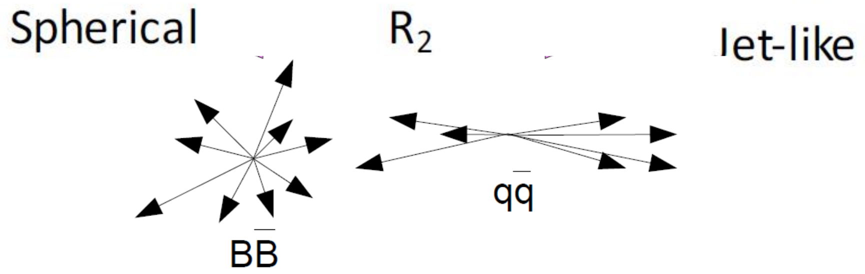
Event Shape

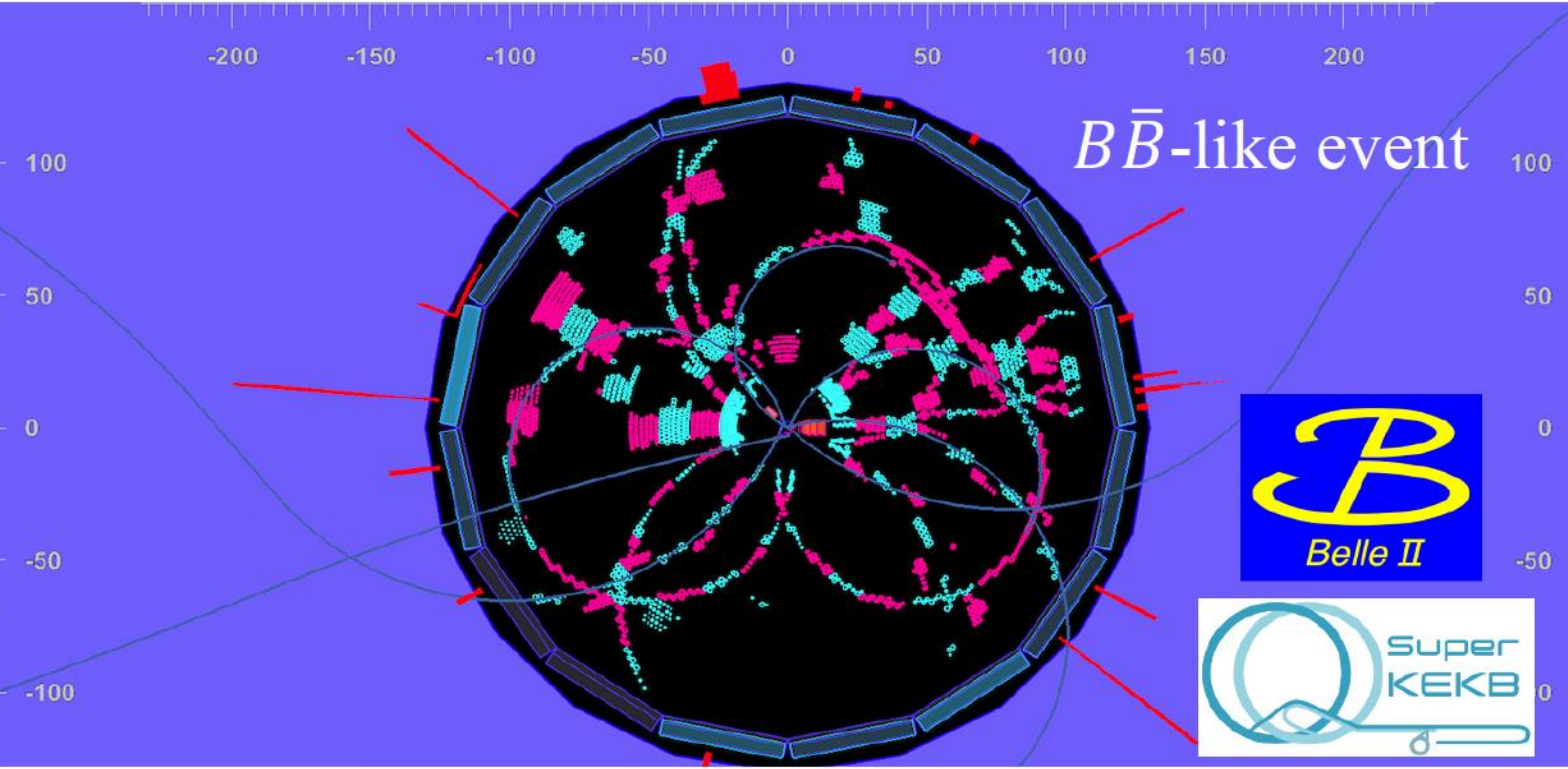
$R_2 = H_2/H_0$

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

- BB events are spherical shape.
- Obtained data contains rich BB samples.
  - Collider energy is well-tuned at the BB resonance 4S.



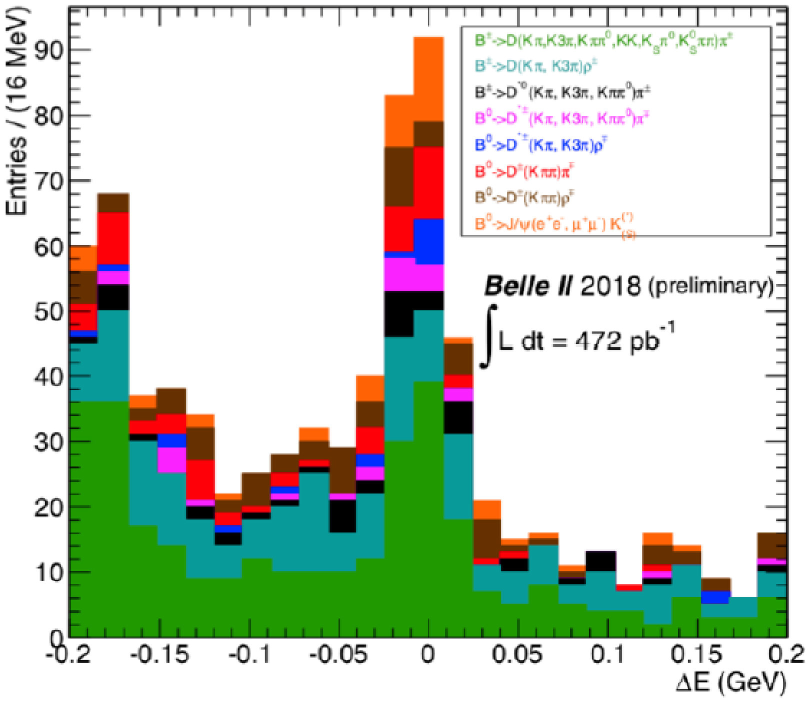



$B\bar{B}$-like event
-200
-150
-100
-50
0
50
100
150
200
100
50
0
-50
-100
Belle II
Super
KEKB

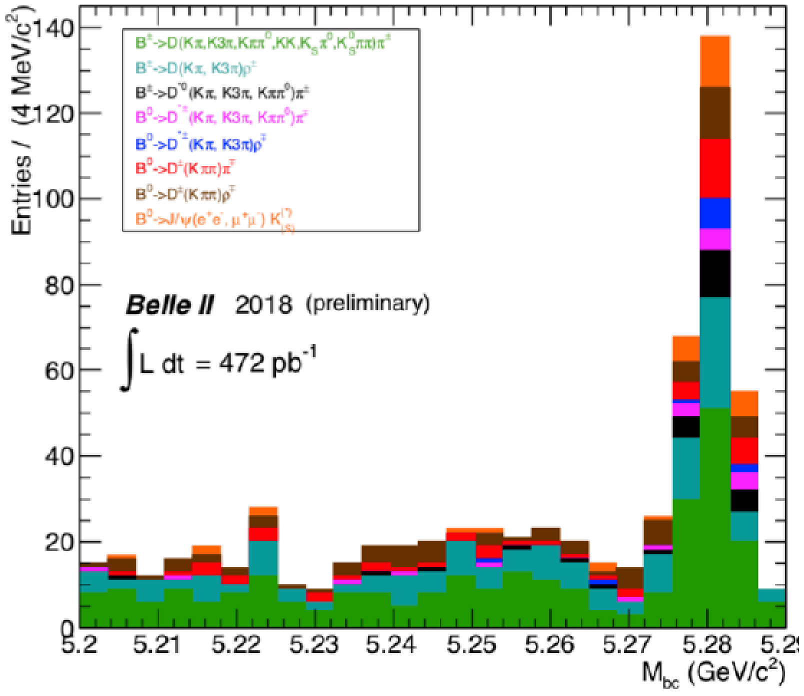
B Reconstruction

We successfully reconstructed B events.

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

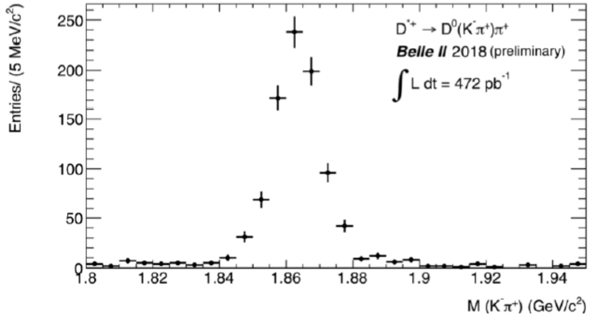


$$\Delta E = E_{cm}/2 - E_{recon}$$

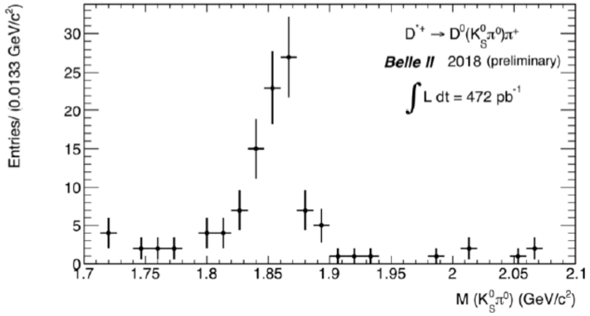


$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p_{recon}^2}$$

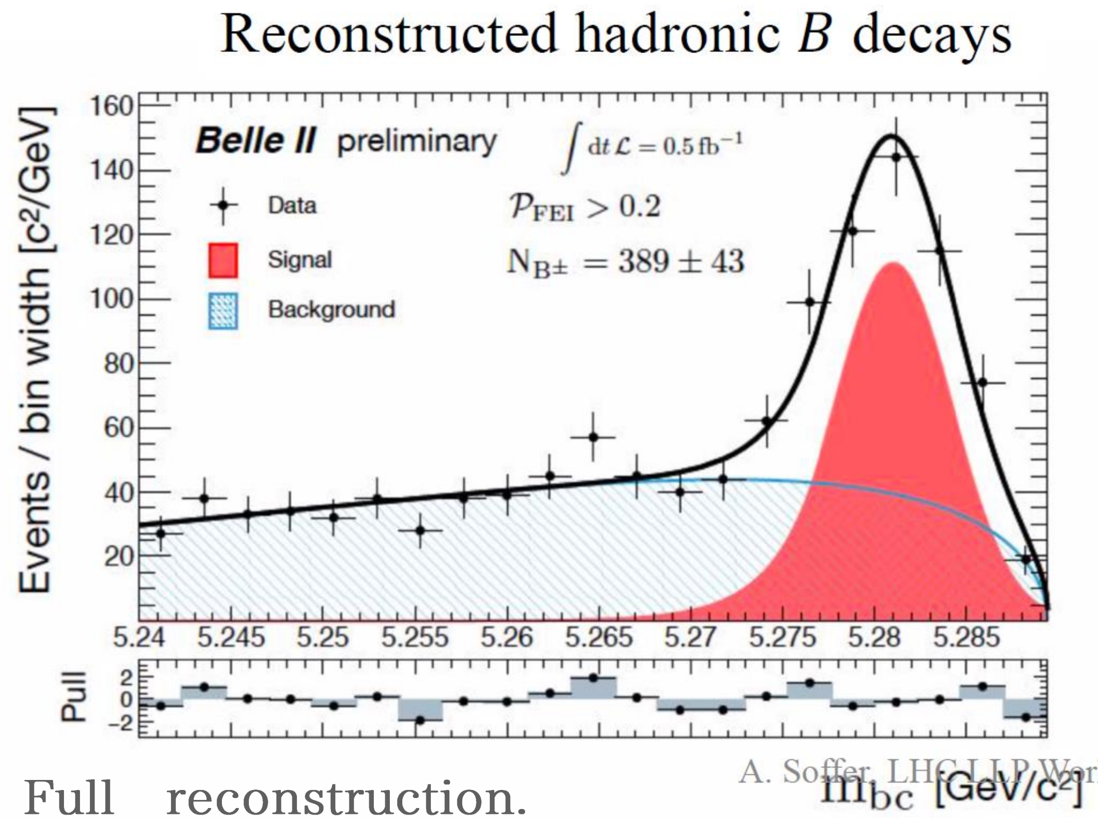
$D^0 \to K^- \pi^+$

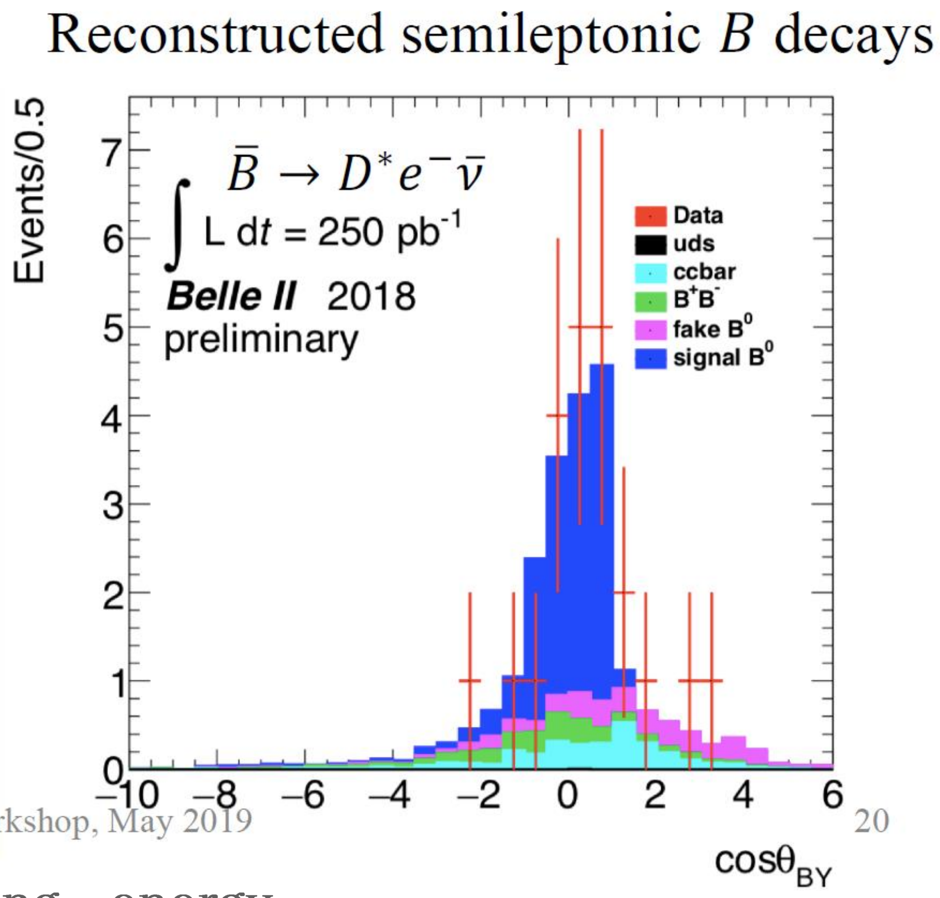


$D^0 \to K_S \pi^0$



B Reconstruction

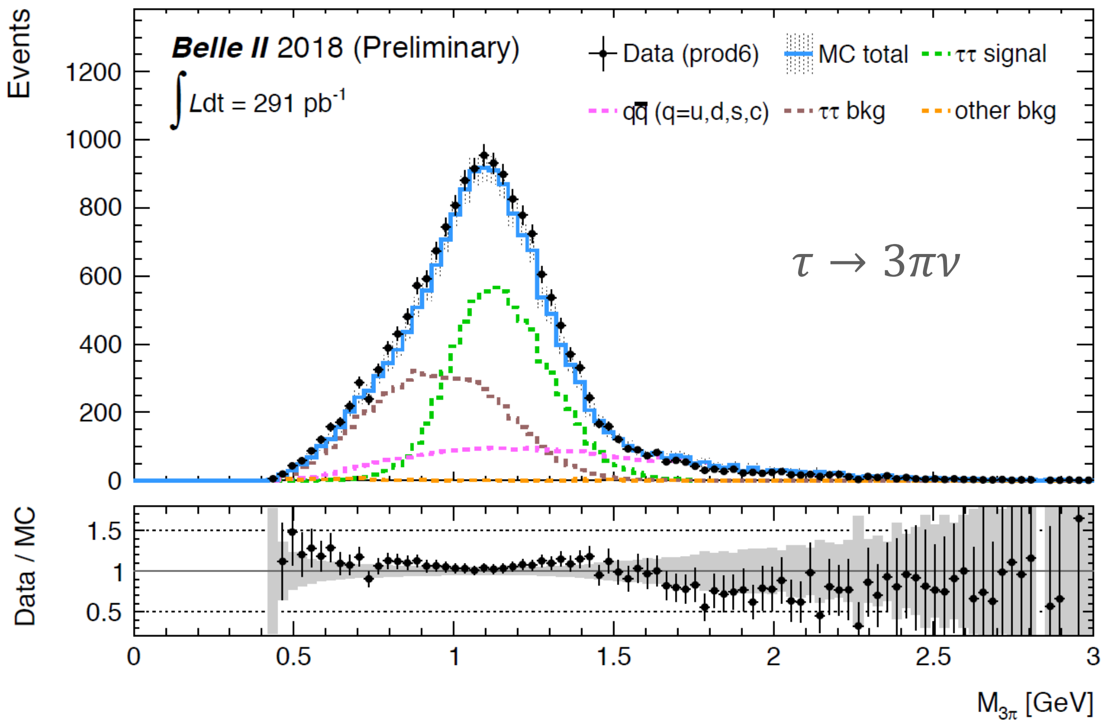




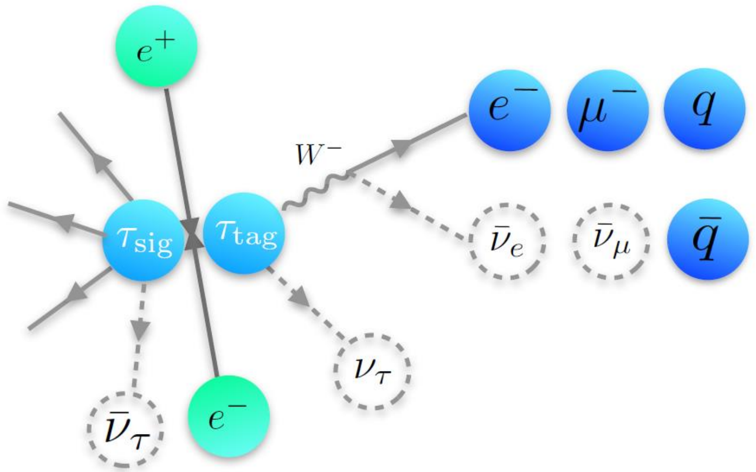
Full reconstruction.
Essential reconstruct events with missing energy

Tau

- Tau mass measurement with 3x1 prong
- Obtained data is understood well.
- Need more statics for cLFV search. MC study is on-going for coming data.

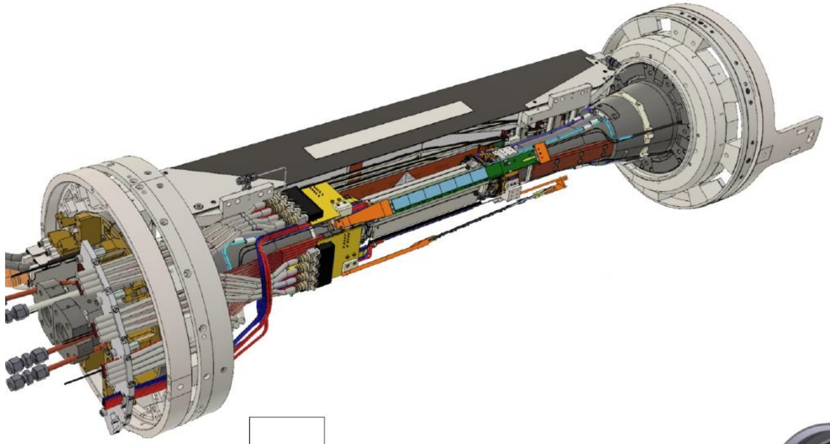


3x1 prong decays

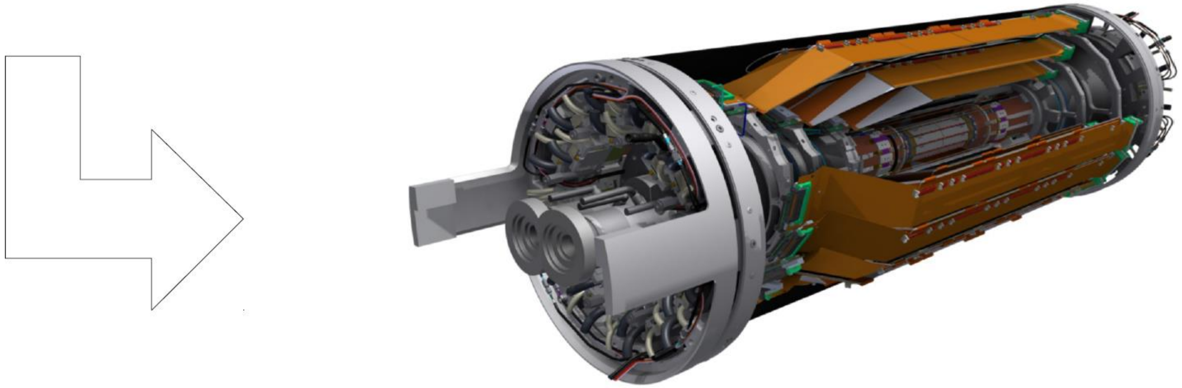


Phase III

- Physics run with ALL detectors.
- Accelerator tuning is also on-going.



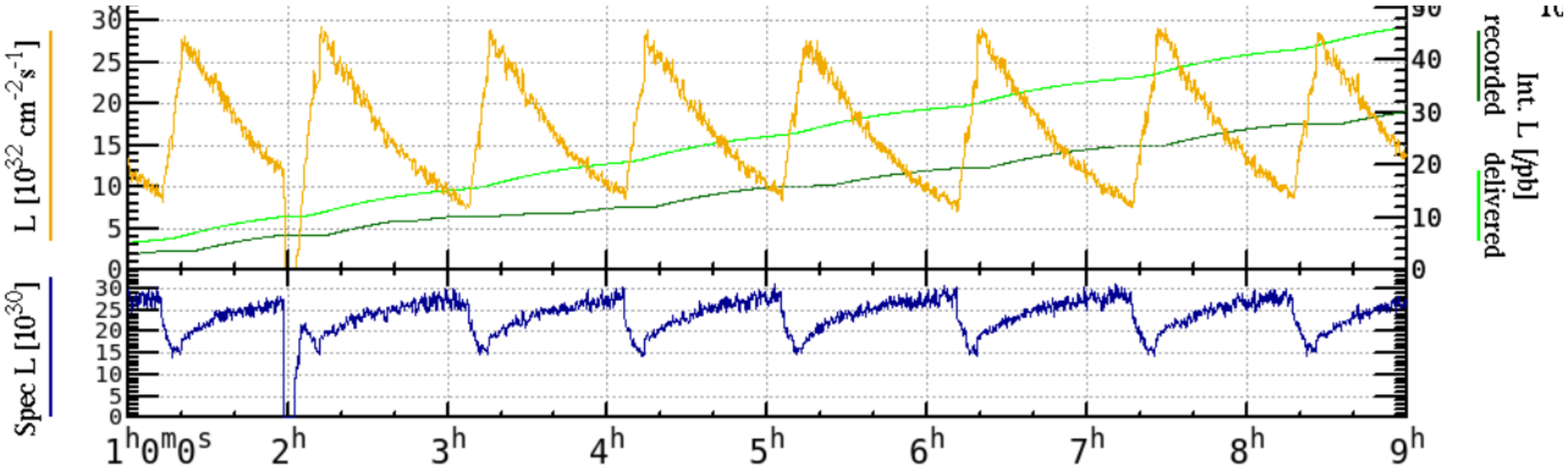
Phase 3 = (almost) final setup for physics
→ 4 full layers of silicon strips
→ 1 + 1/6 full layers of pixel
→ full installation approx in 2020



Continuous injection

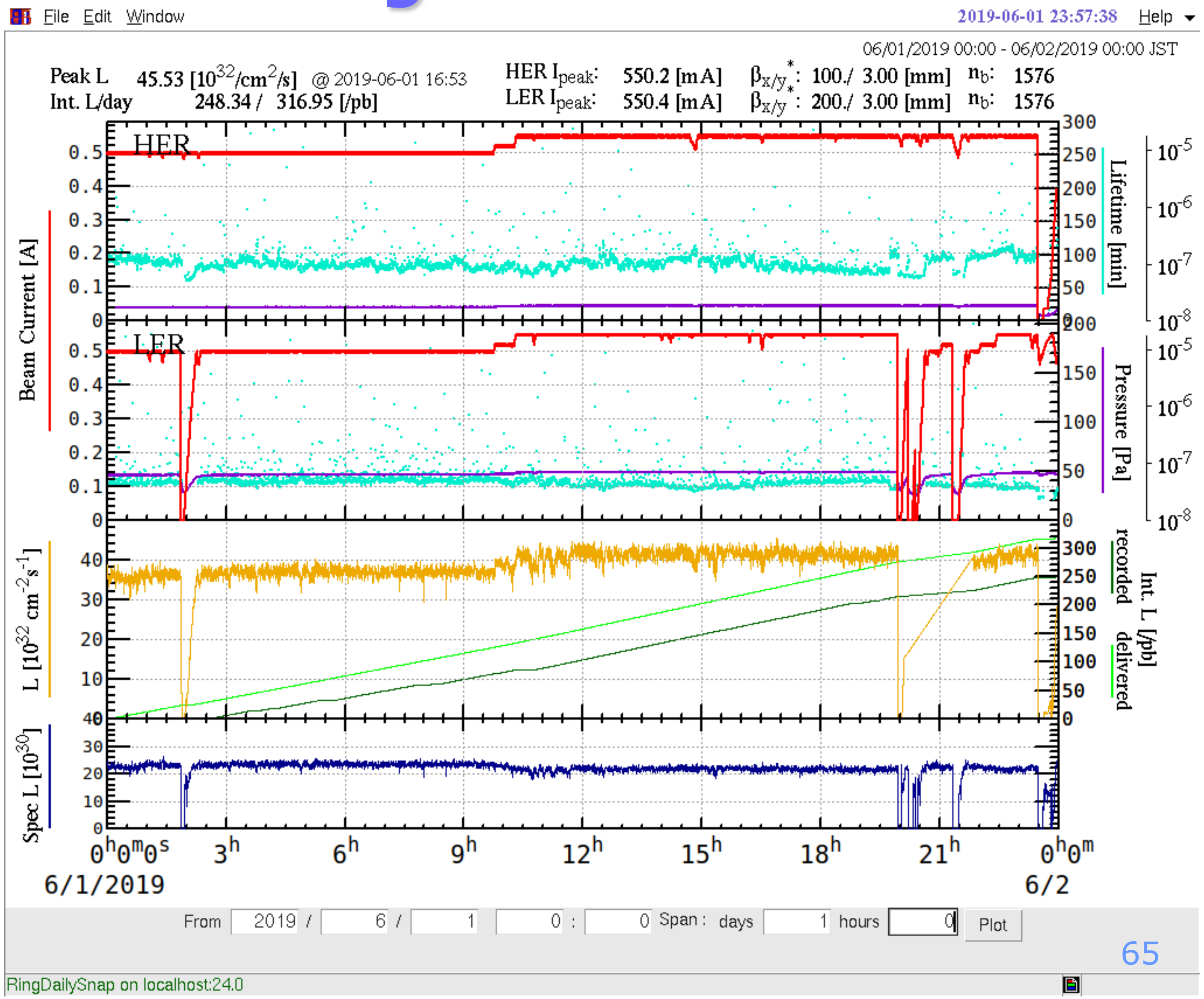
- Beam lifetime is several minutes at designed luminosity.
  - Continuous injection is necessary.

Normal injection (May 6th)



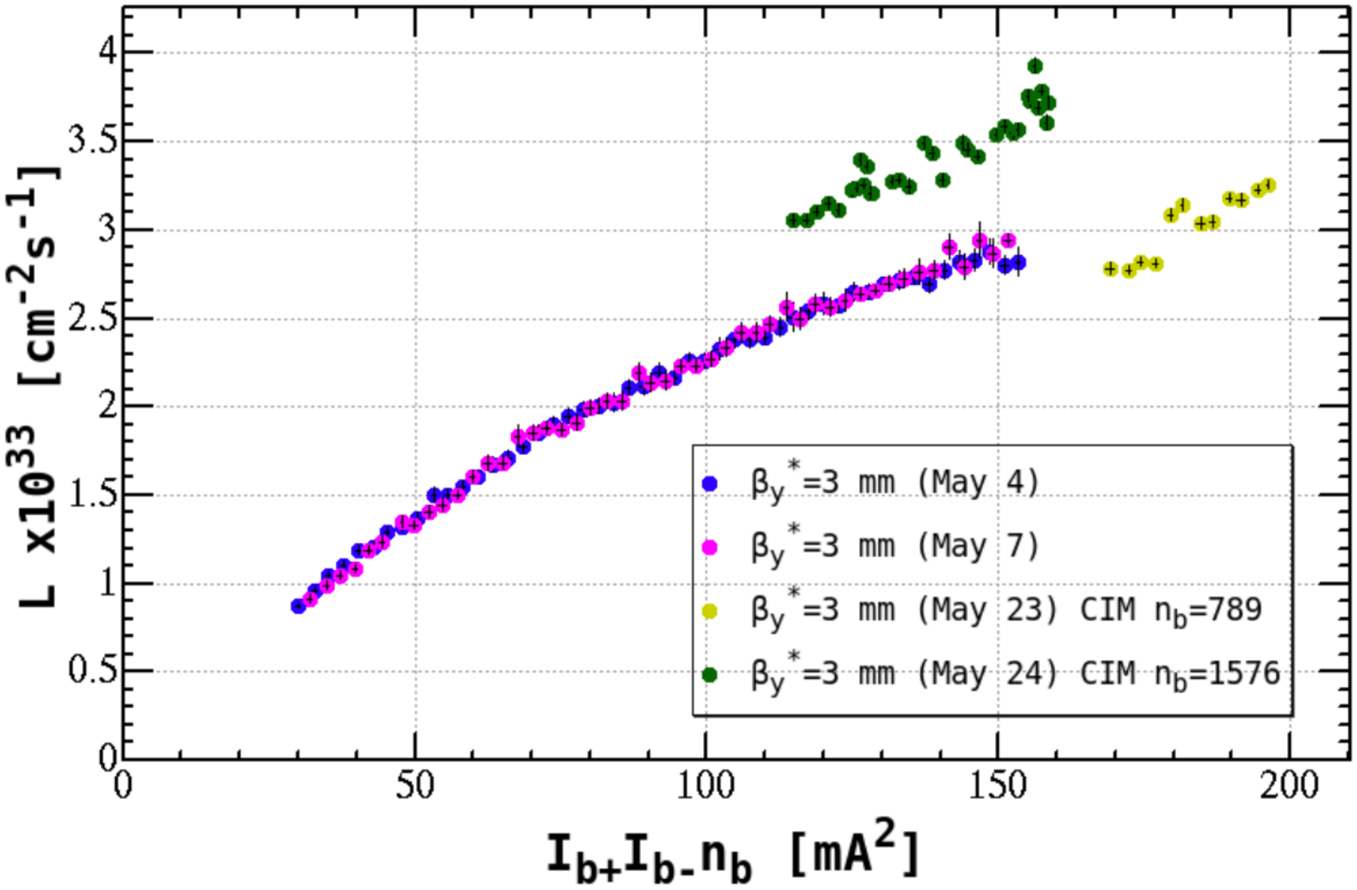
Continuous injection

- Beam lifetime is several minutes at designed luminosity.
  - Continuous injection is necessary.

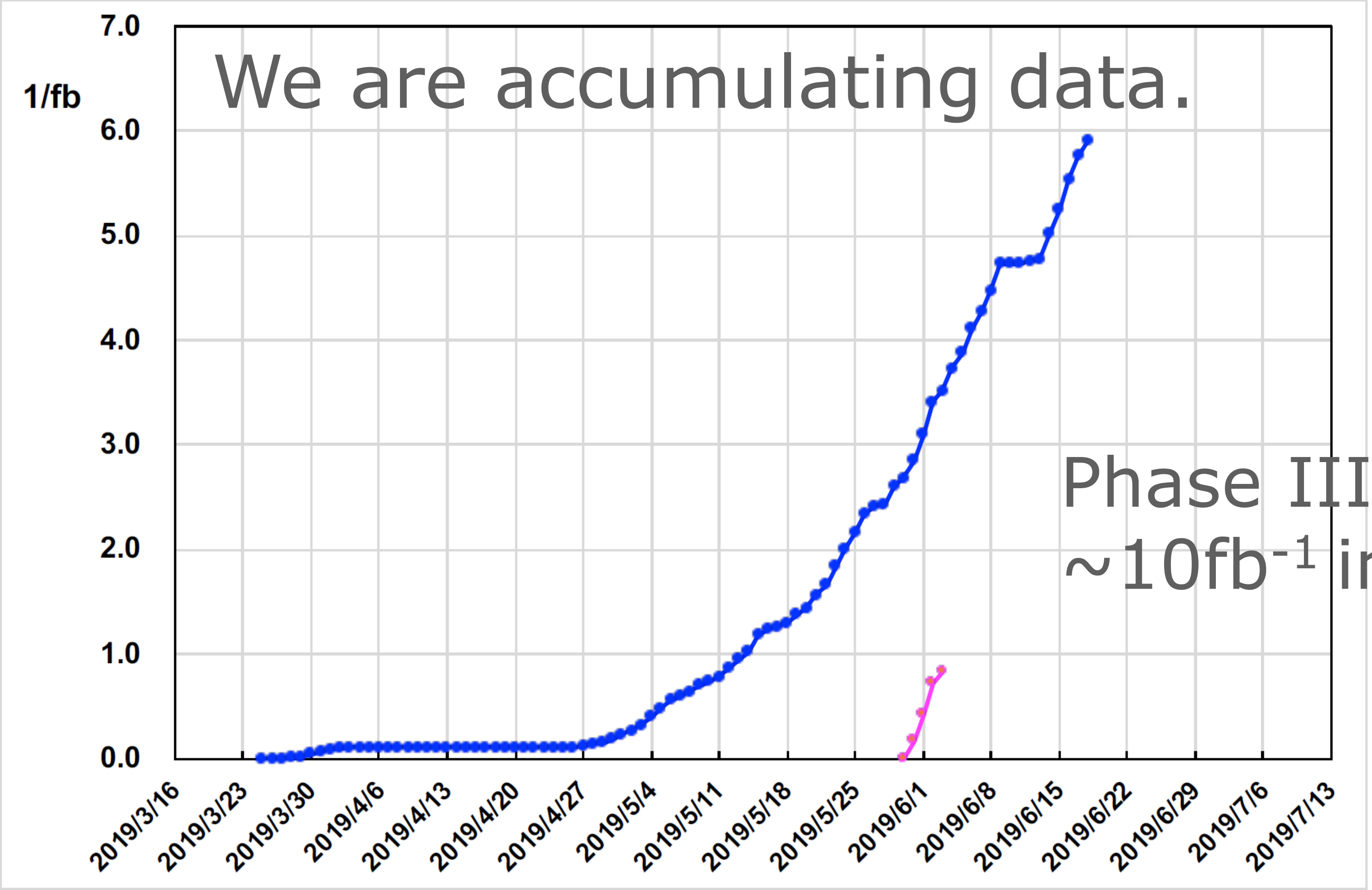


Going further

- We are increasing beam current and number of bunch.
- Further beam squeezing will be performed from this autumn.
  - Final target 0.3 mm



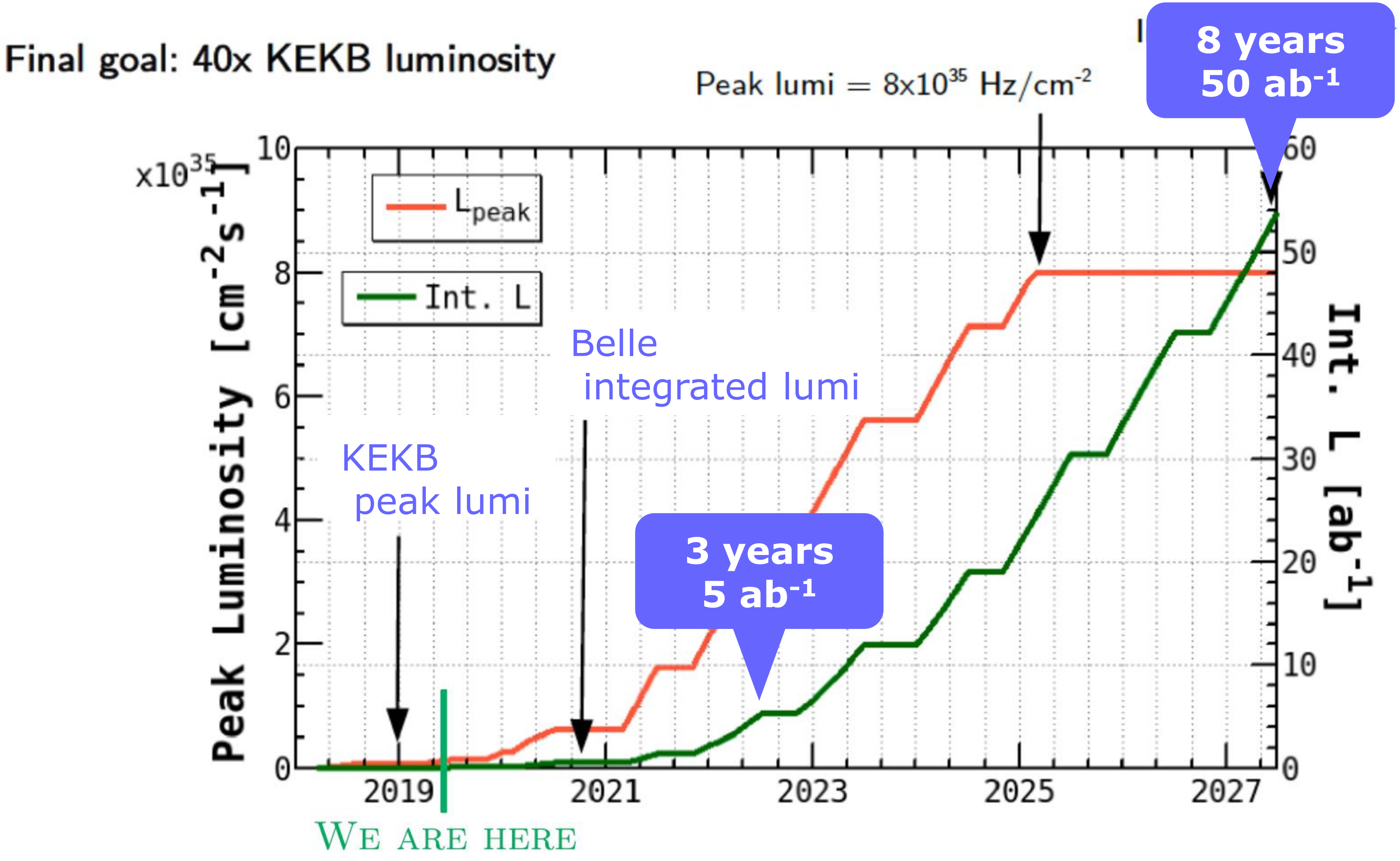
Integrated Luminosity



We are accumulating data.

Phase III Goal:
~10fb^{-1} in June.

Data Accumulation



Summary

- Belle II experiment at SuperKEKB aims at reveal new physics to perform precise measurements of heavy flavor decays.

- We succeed in operating the Belle II detectors and SuperKEKB.
  - Belle II detector performance was confirmed with several decay channels.
  - Further work in SuperKEKB is underway to reach the target luminosity step-by-step.

- Physics run with the full detector is running.
- Soon we'll have many exciting physics result!

Back up

Belle II Physics

Observables	Expected the. accuracy		Expected exp. uncertainty	Facility (2027)
UT angles & sides				
ϕ_1 [°]	***	**CKM**	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				
$S(B \to \phi K^0)$	***	**CPV**	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		**(Semi)**		
$\mathcal{B}(B \to \tau \nu)$ $[10^{-6}]$	**	**LEPTONIC**	3%	Belle II
$\mathcal{B}(B \to \mu \nu)$ $[10^{-6}]$	**	**LFUV**	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				
$\mathcal{B}(B \to X_s \gamma)$	**	**EWP**	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
$\mathcal{B}(B \to K^* \nu \bar{\nu})$ $[10^{-6}]$	***		15%	Belle II
$\mathcal{B}(B \to K \nu \bar{\nu})$ $[10^{-6}]$	***		20%	Belle II
$R(B \to K^* \ell \ell)$	***		0.03	Belle II/LHCb
Charm				
$\mathcal{B}(D_s \to \mu \nu)$	***	**CHARM**	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				
$\tau \to \mu \gamma$ $[10^{-10}]$	***	**TAU**	< 50	Belle II
$\tau \to e \gamma$ $[10^{-10}]$	***		< 100	Belle II
$\tau \to \mu \mu \mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

Ultimate precision, 50 ab^{-1}

QUARKONIUM

DARK SECTOR

Very Rich Physics Program!

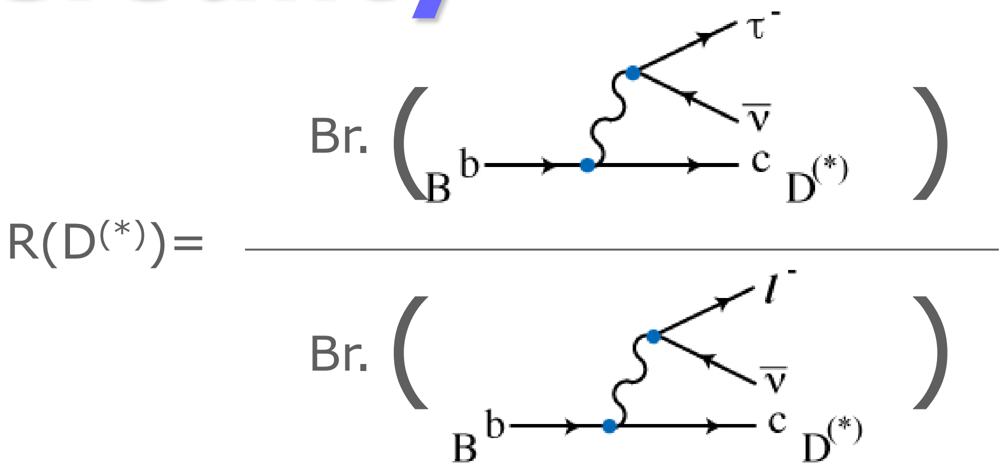
E. Kou, P. Urquijo et al.
Belle II Physics book,
arXiv: 1808.10567
(Accepted to PTEP)

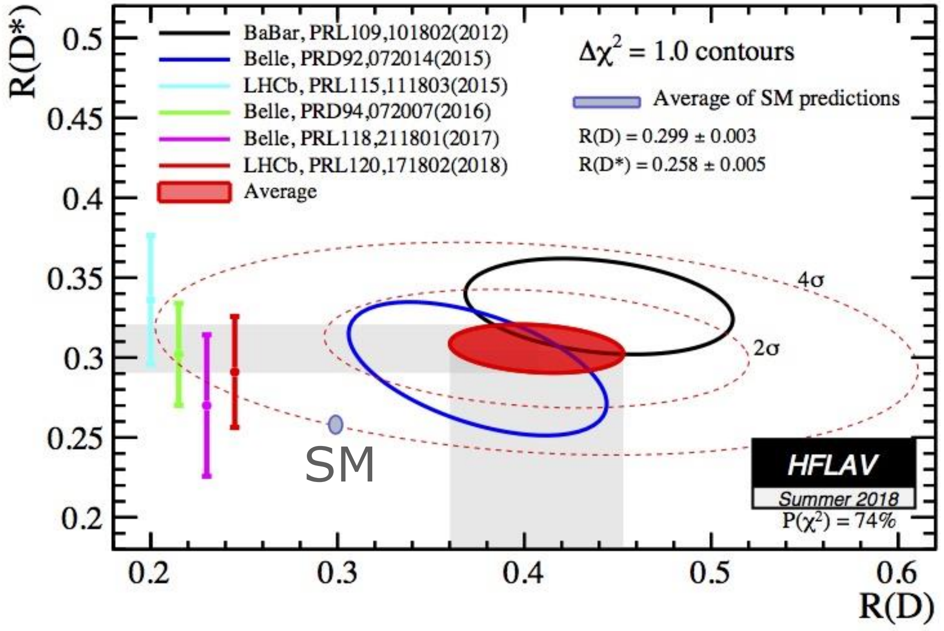
6

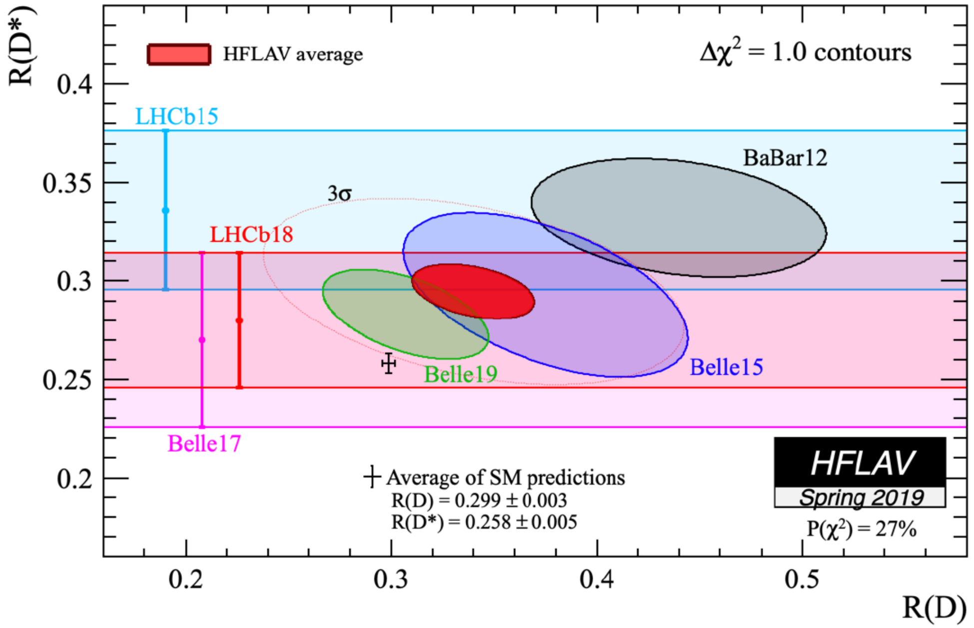
Lepton universality

- The discrepancy b/w SM and measurement was ~4σ

->**3.1σ** :Updated in 2019







Prospects

- What we can see near future (several fb^{-1} level),

Semileptonic B decays

- $B \to \pi l \nu$ and $\rho l \nu$

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})
- $B \to X_s \gamma$ (10 fb^{-1})

Non-B physics

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

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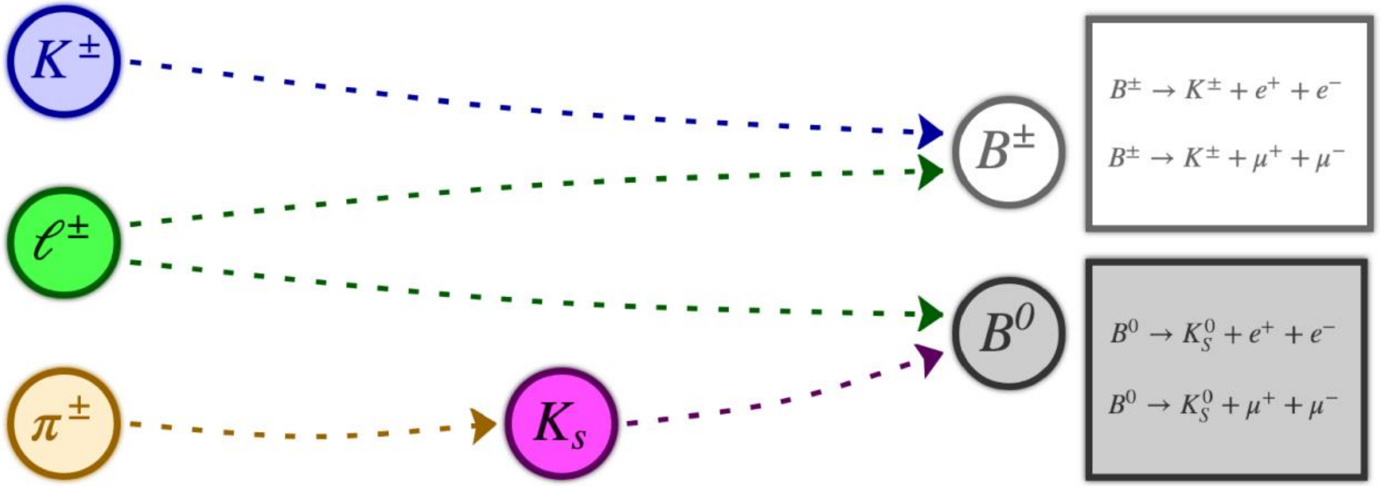
The reconstruction process

- particle id > 0.1 (pid $= \mathcal{L}_p / \sum_i \mathcal{L}_i$)
- Good track fit ($\chi^2 > 0.001$)
- Near the IP ($d_0 < 0.5$ and $|z_0| < 2$)

- vertex fit
- cuts in position according to p
- 0.468 GeV $< M < 0.528$ GeV

- 5.22 GeV < m_{bc} < 5.29 GeV
  $m_{bc} = \sqrt{E_{\text{beam}} - p^2_{B,\text{reco}}}$
- -0.1 GeV < ΔE < 0.05 GeV e ch.
  -0.05 GeV < ΔE < 0.05 GeV μ ch.
  $\Delta E = E_{B,\text{reco}} - E_{\text{beam}}$



Axion-like particle (ALP)

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