Status of the Belle II Detector

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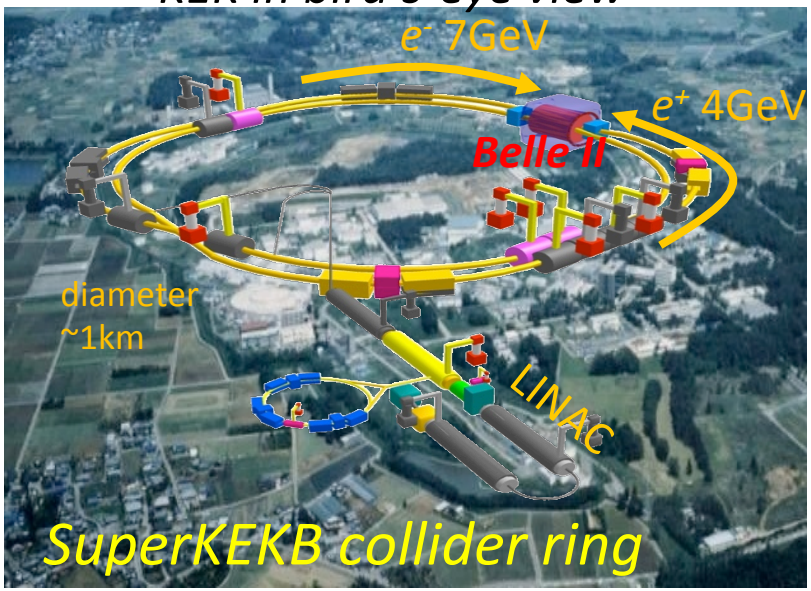
on behalf of the Belle II collaboration

HINT2016 (Dec. 5, 2016)

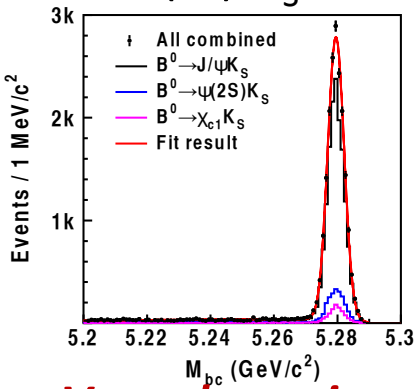
Belle II Experiment

- **SuperKEKB: An e^+-e^- collider with the world highest luminosity, 8.0×10^{35} $cm^{-2}s^{-1}$. (KEKB: 0.2×10^{35} $cm^{-2}s^{-1}$)**
  - ***B factory → Flavor factory***: A large number of B mesons, D mesons, and τ leptons are produced.
  - Target integrated luminosity: 50 ab^{-1} (KEKB: 1 ab^{-1})
- **Belle II experiment: Search for new physics beyond the standard model**
  - Experimentally clean measurement
    - Full event reconstruction
    - Missing particle measurement, inclusive measurement
  - Start of physics data taking: 2018

KEK in bird's-eye view



$B^0\to(c\bar{c})K^0_S$ reconstructed mass



Belle data
PRL 108 171802

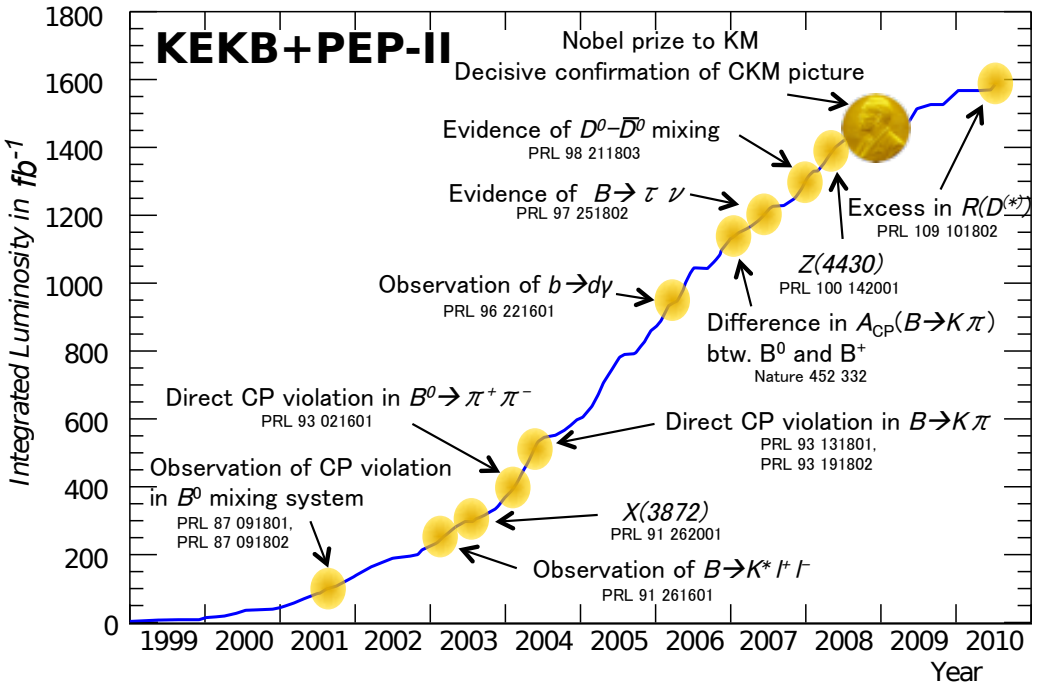
events in signal region

Beam constraint mass:
$M_{bc}=\mathrm{sqrt}(E_{beam}^2-P_B^2)$

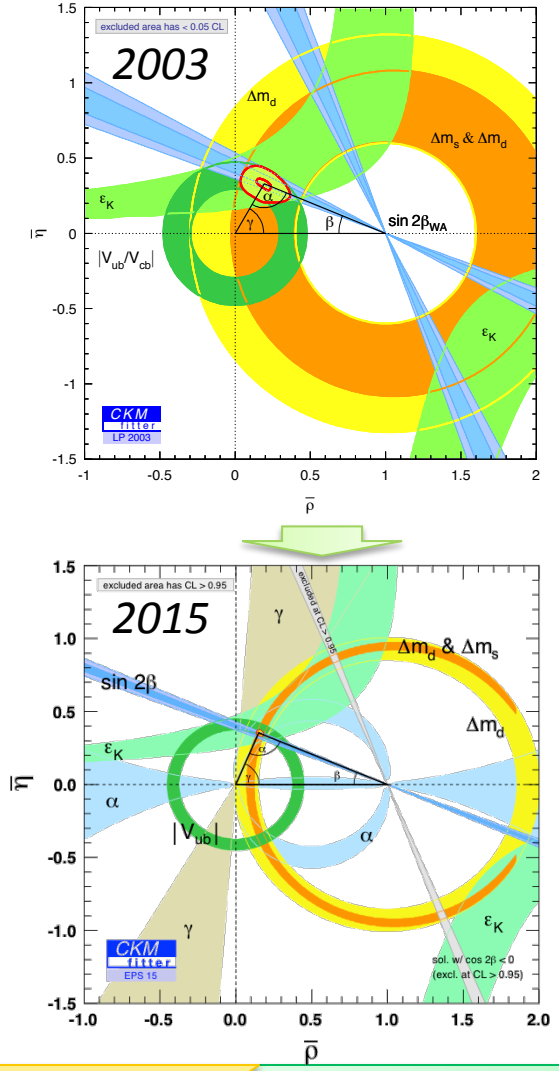
Very clean signal !

Achievements on Old B-Factories

Integrated luminosity of KEKB + PEP-II



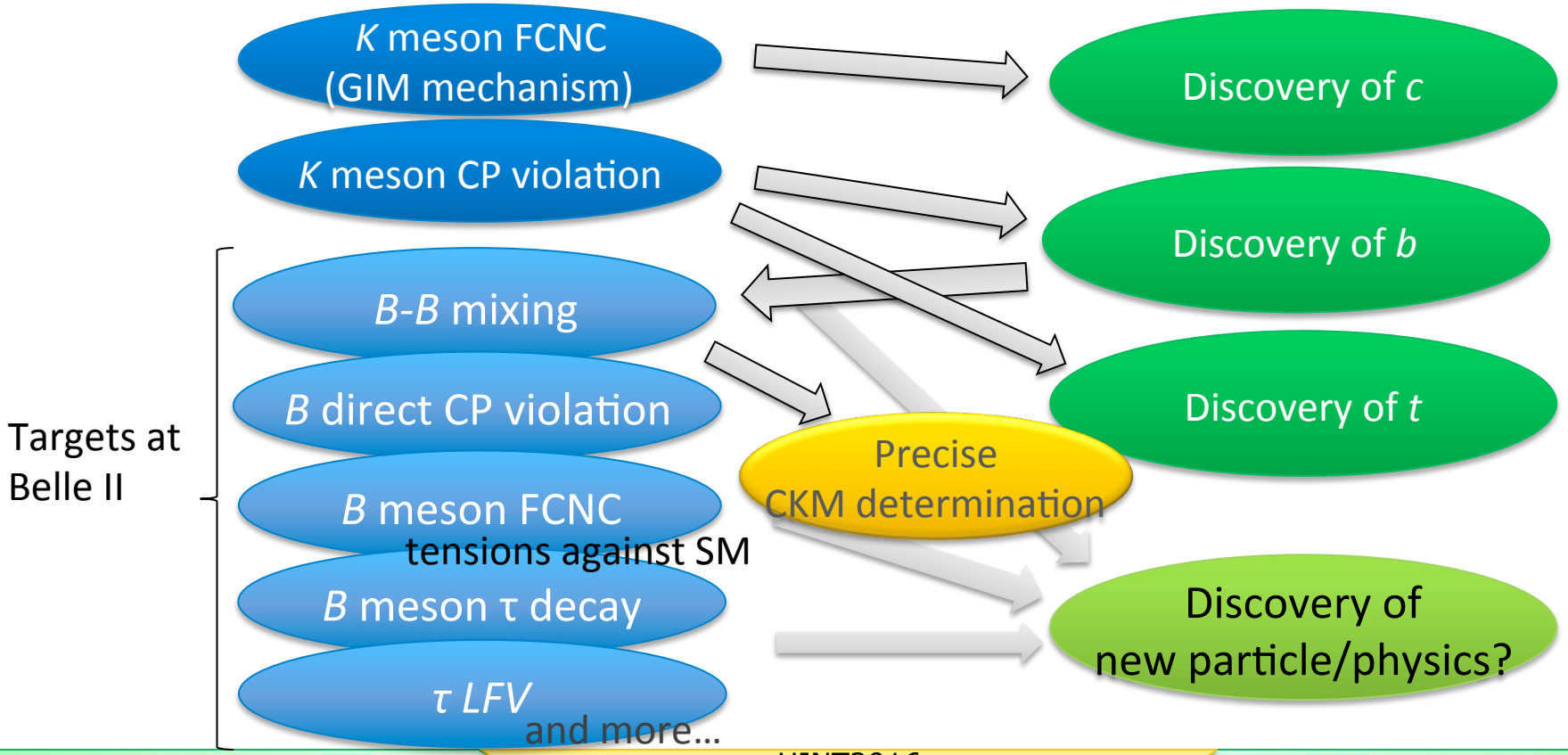
Wolfenstein ρ-η parameters (2003 - 2015)



- **A number of successful achievements for particle physics in Belle+Barbar**
- **Especially, conclusive evidence of KM theory and precise determination of CKM matrix elements**

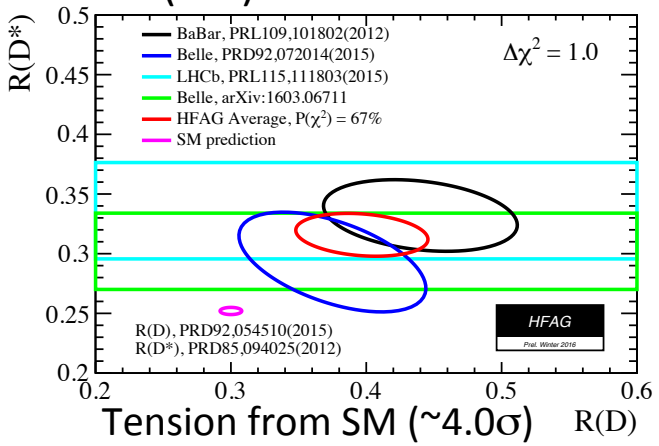
Direct and Indirect Measurement in Flavor Physics

- **Observation of new phenomena + precise measurement (indirect measurement) and Discovery of new particle/physics (direct measurement) cooperatively develop the flavor physics.**



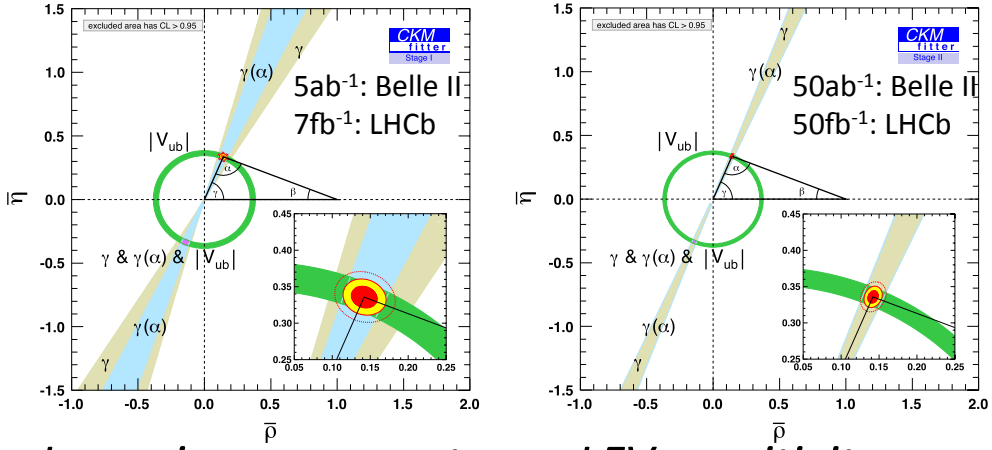
New Physics Search at Belle II

$R(D^{(*)})$ determination



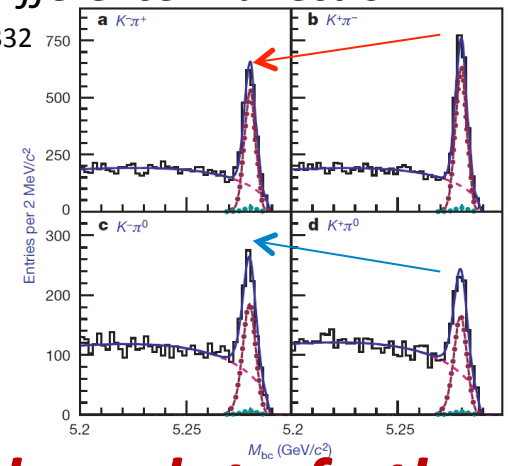
Precise unitary triangle test

PRD 89,033016 (2014)

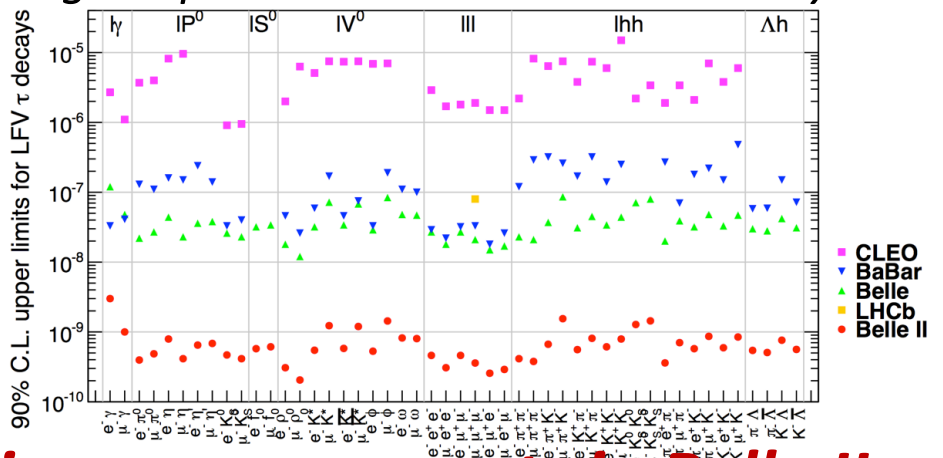


Difference in direct CPV in $B \to K\pi$

Nature 452 332



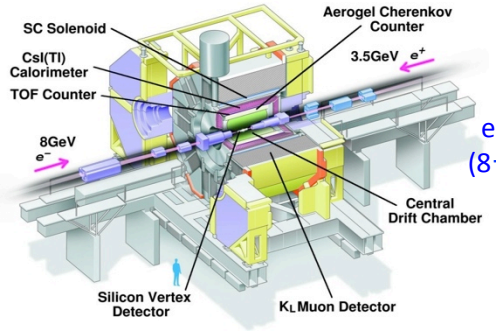
Large improvement on τ LFV sensitivity

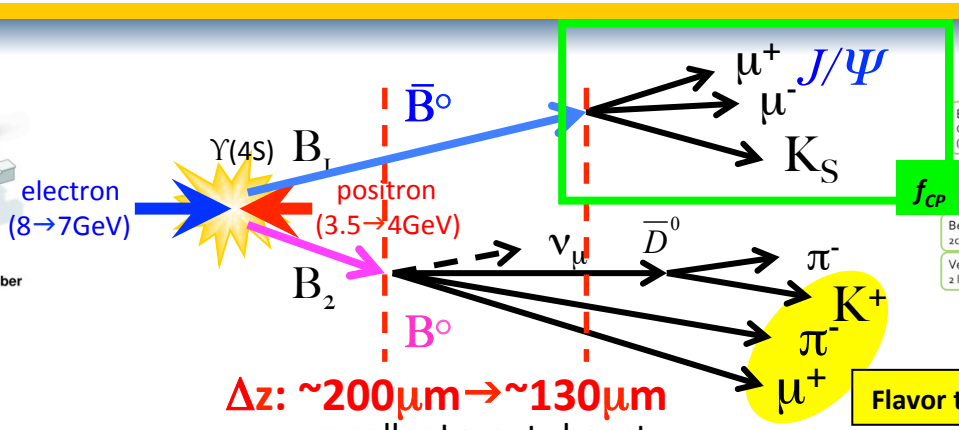


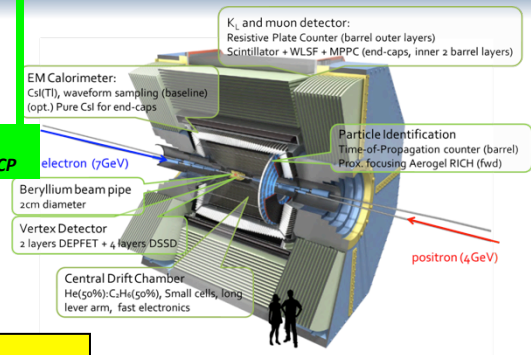
Also a lot of other interesting measurements in Belle II

(Rare B decay and τ LFV at Belle II: Wed. morning session)

Challenges toward Belle II Experiment







$$A_{CP}^{J/\phi K_S}(\Delta t) = \sin(2\beta)\sin(\Delta m_d \Delta t)$$

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

BELLE

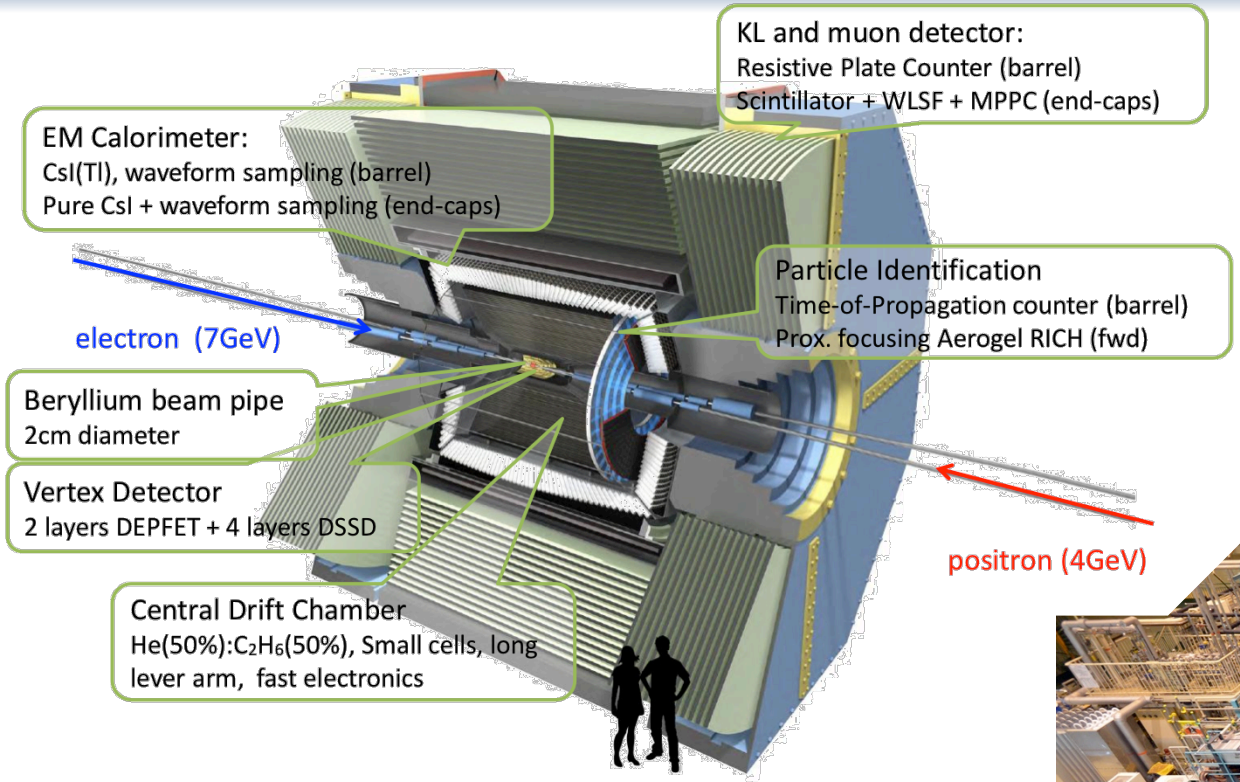
E_{HER} = 8GeV
E_{LER} = 3.5GeV
$\beta\gamma$ = 0.425
$\beta\gamma c\tau$ = 200μm
θ_X = 22mrad

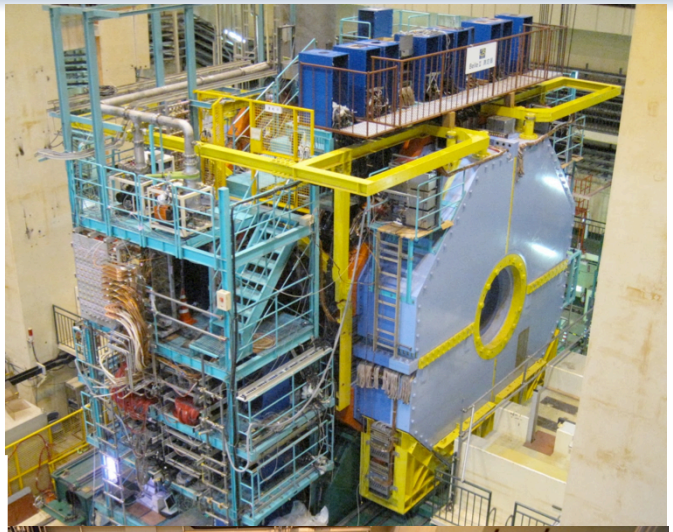
E_{HER} = 7GeV
E_{LER} = 4GeV
$\beta\gamma$ = 0.28
$\beta\gamma c\tau$ = 130μm
θ_X = 83mrad

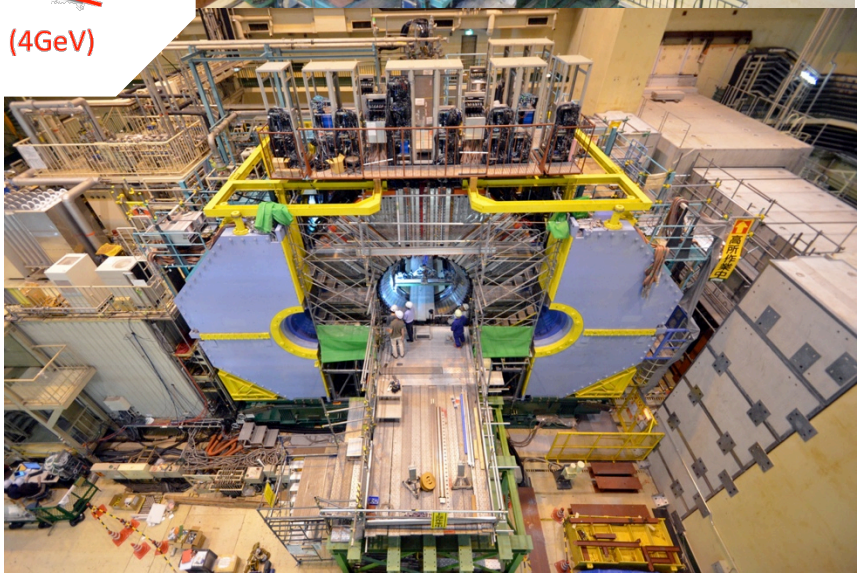
Belle II

- **High beam background**
  - Fine segmentation and fast readout → occupancy reduction
  - Replacement of detectors
- **Improve detection efficiency for neutral particles**
  - Larger VXD outer radius → Improvement on K_S detection efficiency
  - New scintillators in KLM → Improvement on K_L detection efficiency
- **Smaller Lorentz boost (for lower beam emittance and longer beam life)**
  - Smaller VXD inner radius → Improvement on vertex position resolution

Belle II Detector Overview

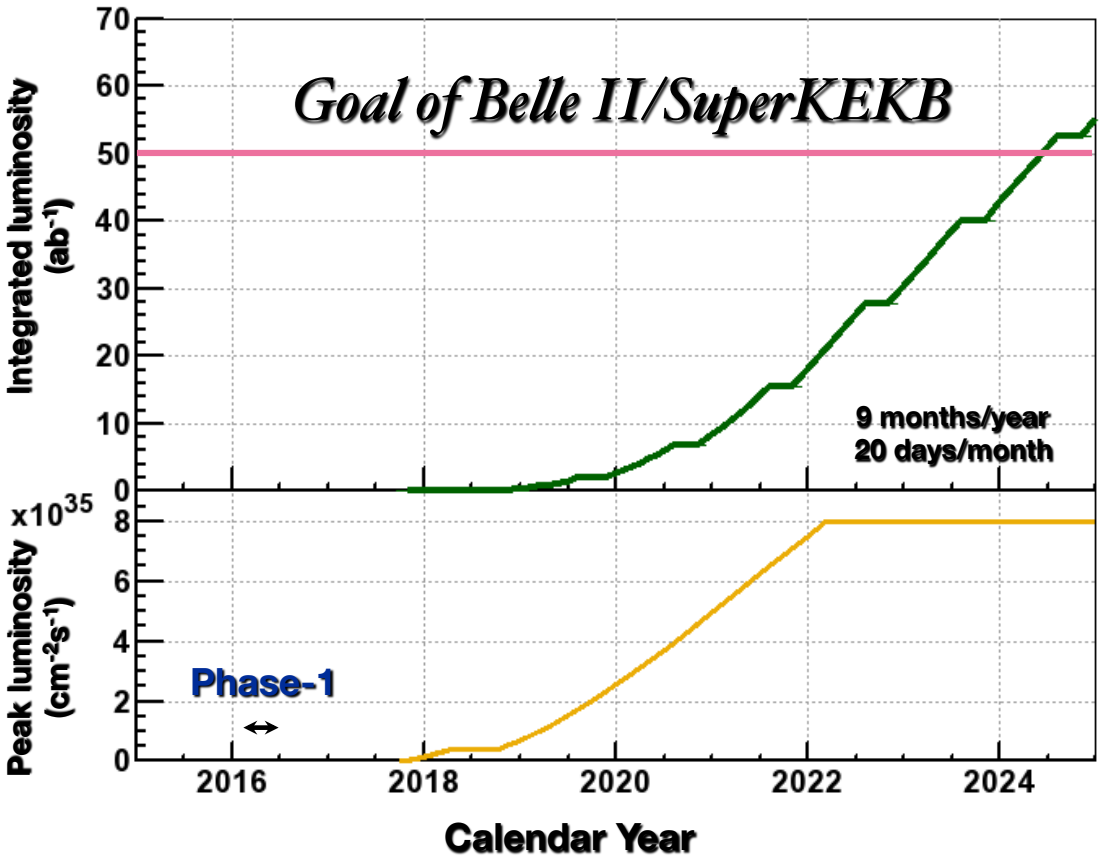






- **Belle II Acceptance: θ: 17°-150° × ϕ: 0-2π**
- **Magnetic field in CDC volume: 1.5 T**
- **Particle identification**
  - Charged hadron ID: TOP, ARICH + (dE/dx) CDC, SVD
  - Electron ID: ECL
  - Muon ID: KLM

SuperKEKB luminosity prospection



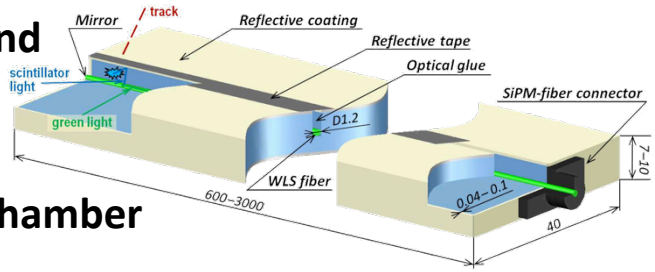
- **phase-1 (done)**
  - Beam commissioning
- **phase-2 (Jan. 2018)**
  - Beam BG measurement
  - Belle II detector with partial vertex sensors
- **phase-3 (Dec. 2018)**
  - Physics running
  - Full Belle II detector

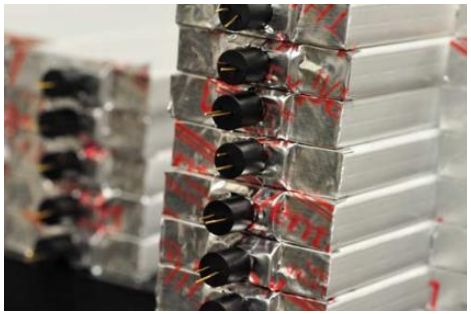
Expected numbers of produced particles at 50 ab^{-1}

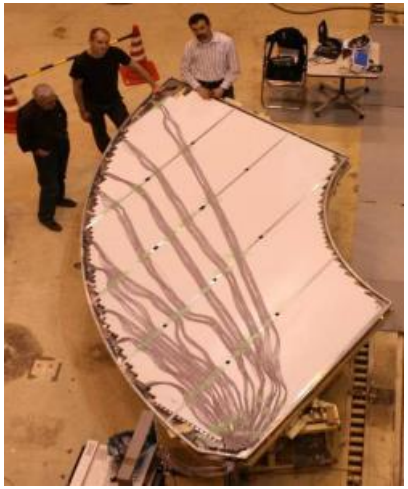
Process	$\sigma[nb]$	No. events [$\times 10^9$]
$B\bar{B}$	1.1	55
$q\bar{q}$ (q=u,d,s)	2.52	185.45
$\tau^+\tau^-$	0.92	45.95

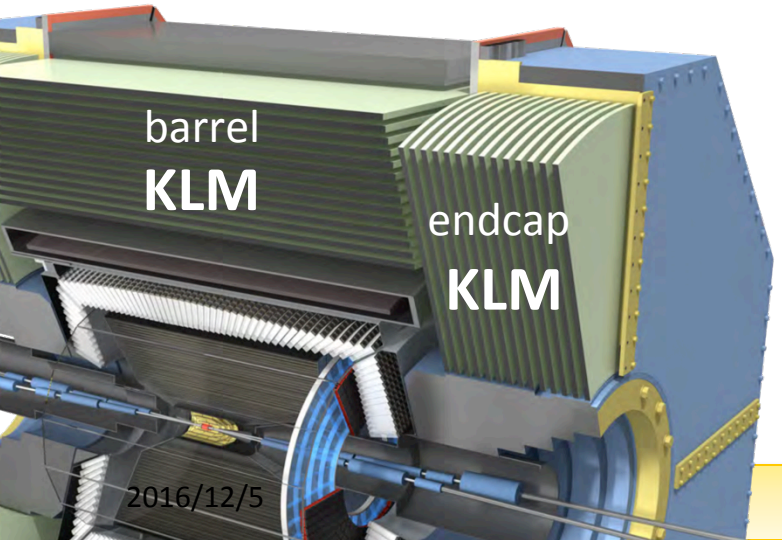
K_L/Muon Detector (KLM) Upgrade

- **Alternating layers of iron plates and detector components.**
  - Iron plates for K_L hadron shower and magnetic field return yoke
- **In Belle, all were Resistive Plate Chamber (RPC).**
- **Upgrade for beam BG tolerance:**
  - All detectors in endcap and inner 2 layers in barrel were replaced into plastic scintillators.
- **Readout electronics is partially installed, and remains are under production.**
  - will be ready by the summer 2017.

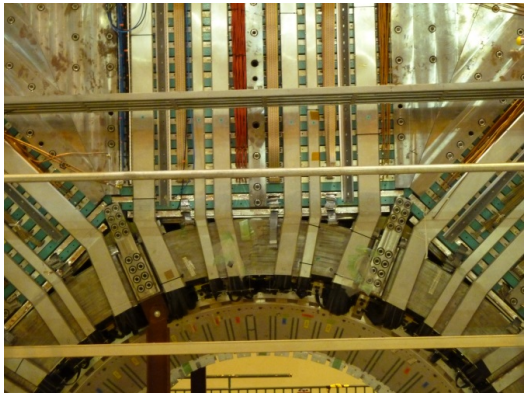








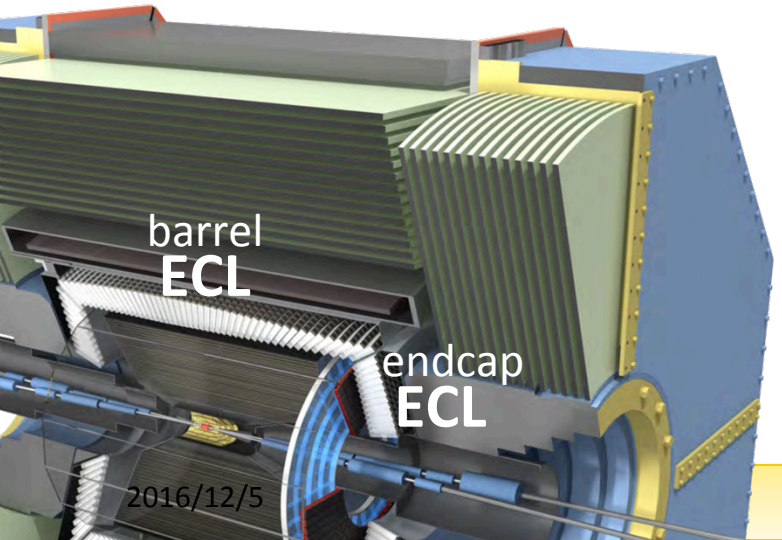
Barrel (inner 2lyrs) installation completed in Nov. 2013



Endcap installation completed in Oct. 2014

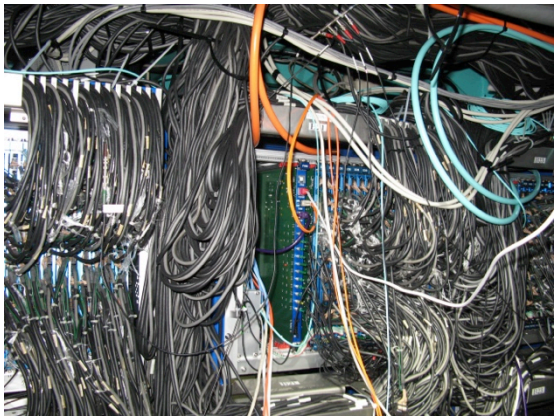
Electromagnetic Calorimeter (ECL) Upgrade

- **In Belle: CsI(Tl) crystals with PIN-photodiode**
- **Upgrade for beam BG tolerance:**
  - CsI(Tl) in endcap are replaced with pure CsI.
    - Time constant: 1μs → 30ns
  - Waveform sampling analysis in new readout electronics
- **Barrel ECL: under cosmic ray commissioning**
  - Typical timing resolution < 4.5ns
- **Endcap ECL: to be installed**
  - BWD: Jan. 2017
  - FWD: Oct. 2017 with ARICH

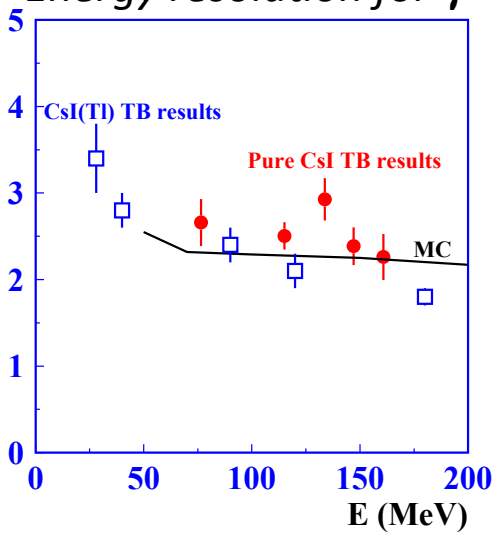


size	6cm x 6cm x 30cm
rad. length	16.1 X_0
number	8736 (~43 tons)

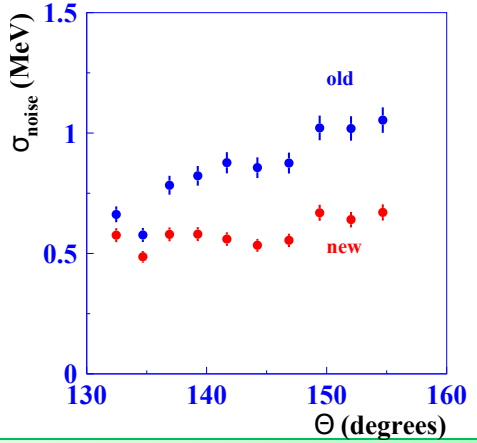
Installed new ECL readout



Energy resolution for γ

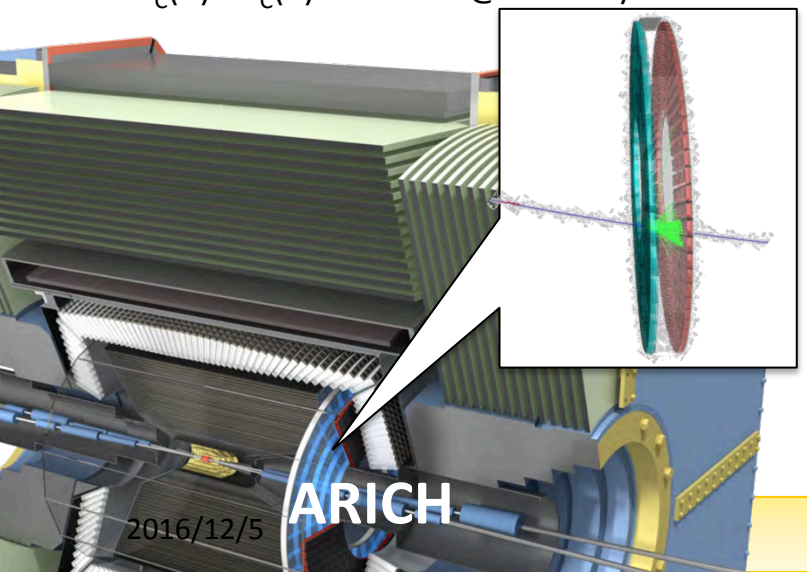


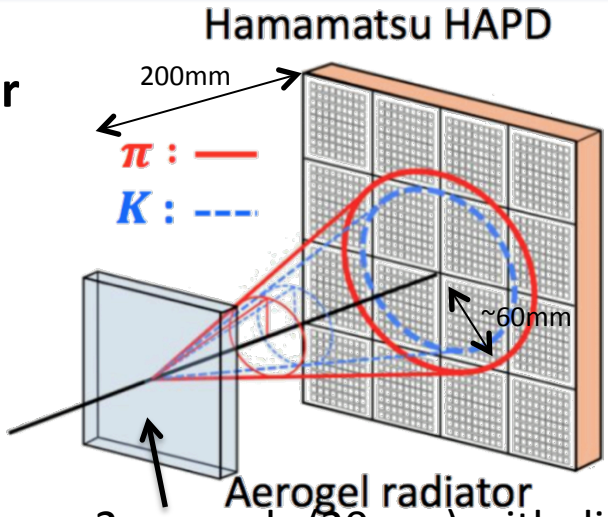
Pileup noise suppression due to new electronics



Endcap PID detector (ARICH)

- **Aerogel Ring Imaging Cherenkov (ARICH) detector**
  - readout with 420 HAPDs
- **Cherenkov lights from 2 aerogels with different refraction indices are focused on HAPD surface.**
  - π threshold: 0.4 GeV/c
  - K threshold: 1.5 GeV/c
  - $\theta_C(\pi)$: 307 mrad @ 3.5GeV/c
  - $\theta_C(\pi)$- $\theta_C(K)$: 30 mrad @ 3.5GeV/c





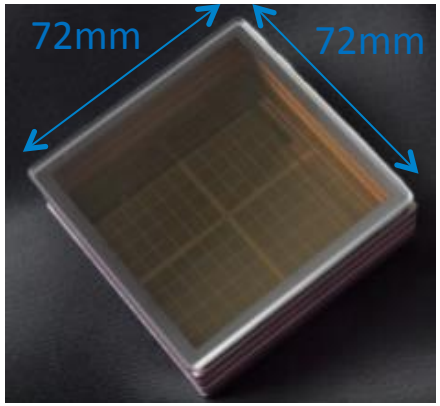
2 aerogels (20mm) with different refractive indices

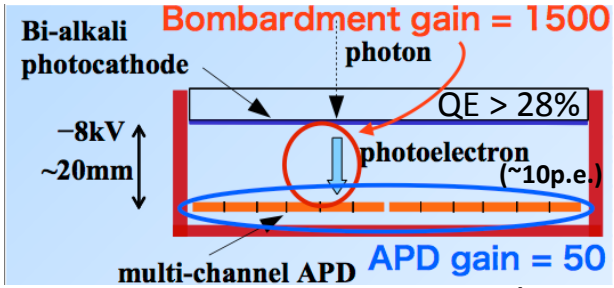
Aerogel properties

	Aerogel1	Aerogel2
Refractive index	~1.045	~1.055
Transmission length [mm]	40~60	30~50

HAPD (HPK)

Hybrid Avalanche Photo Detector



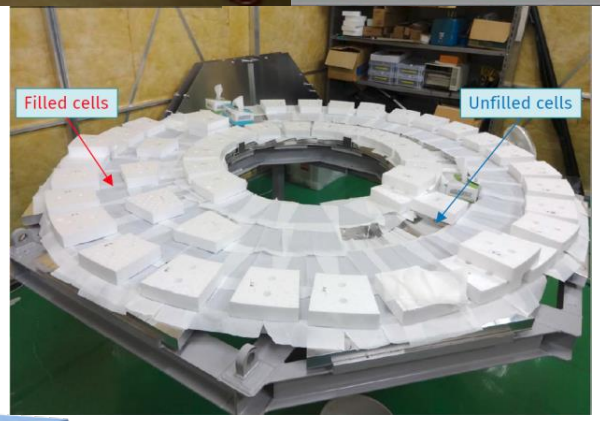


HAPD total gain: ~7x10^4

5mm pitch pixelated 12x12 ch. APD

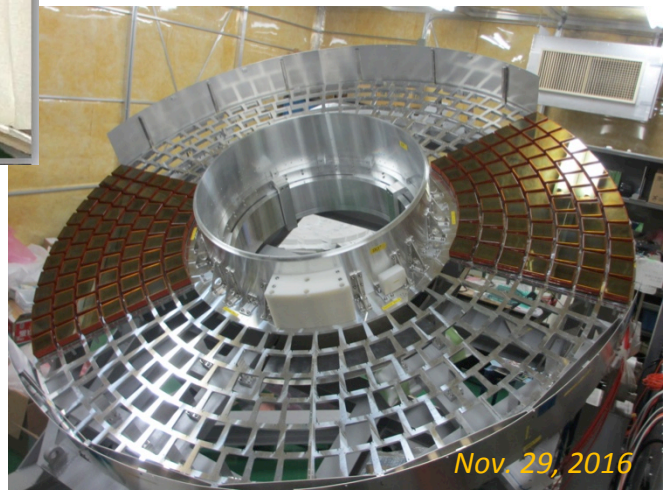
Endcap PID detector (ARICH) Assembly

- **Assembly of ARICH is on-going and will be completed in Mar. 2017.**
- **Clear ring image of cosmic ray has been confirmed.**
- **ARICH and FWD-endcap ECL will be combined and installed to Belle II on Oct. 2017.**

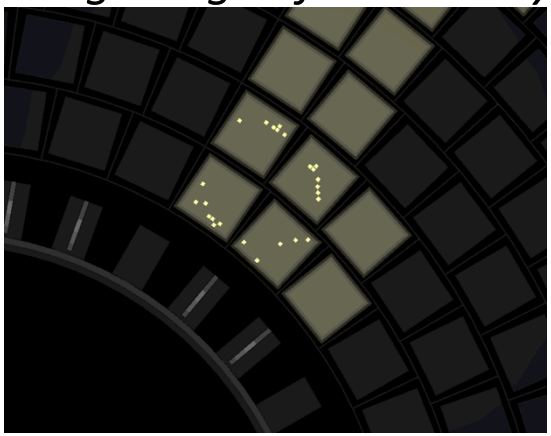


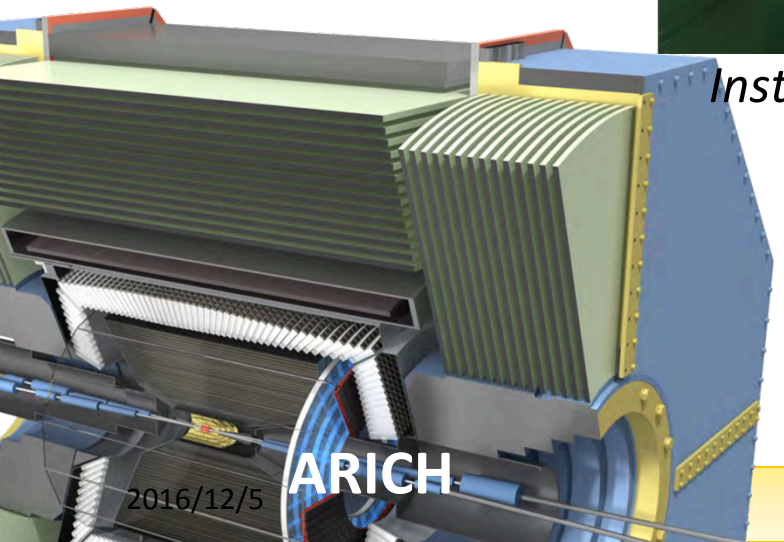
Installed aerogel tiles

Installed HAPD (2 sectors)



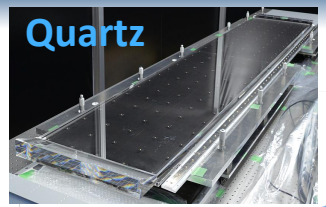
Ring image of cosmic ray



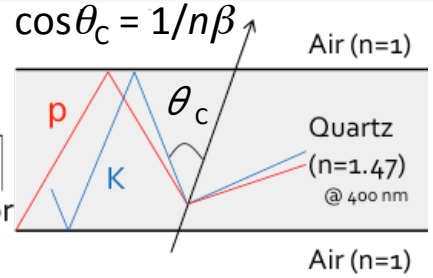


Barrel PID detector (TOP)

- **Time of Propagation (TOP) detector**
  - Path lengths of Cherenkov lights for K/π are different due to different emission angles.
  - To identify K/π, measure TOP of ~20 photons with a time resolution < 50 ps (as well as TOF).
- **Cherenkov photons detected with Micro Channel Plate PMT (MCP-PMT).**
  - 16 detectors, 512 MCP-PMTs



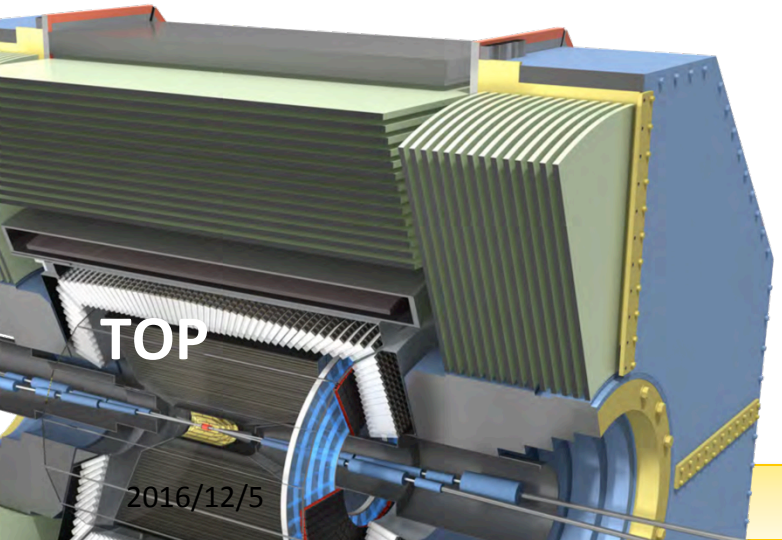
$\mathrm{TOP} \propto \cos\theta_c = 1/n\beta$

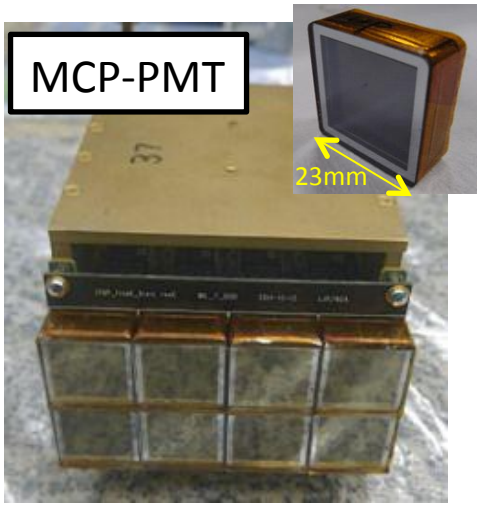


Requirements for quartz

Surface reflection	> 99.90%
Bulk transmittance	> 98.5%/m
Flatness	< 6.3um
Roughness	< 5 Å (RMS)
Parallelism	< 4 arcsec

(for largest surfaces)





MCP-PMT Specification

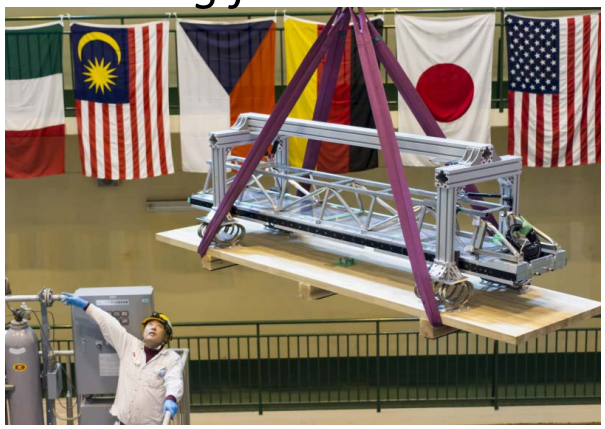
- Small dead region
- Gain > 5×10^5 in 1.5T
- Transit time spread < 40ps
- QE~28% at λ=380nm

Barrel PID detector (TOP) Installation

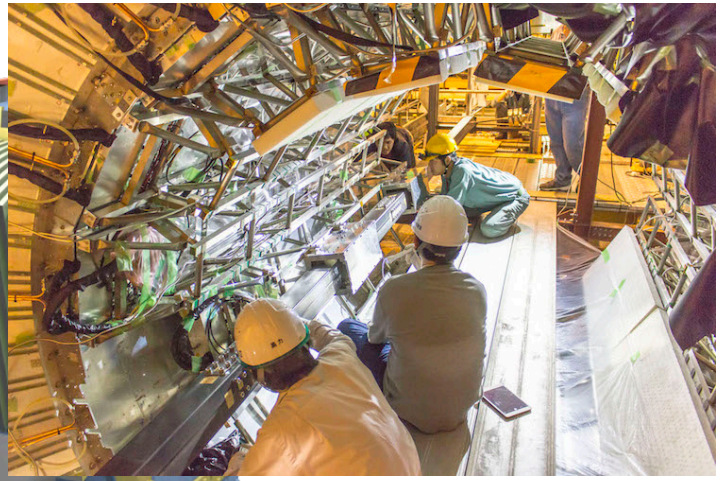
- **TOP detector was installed**
  - Shims inserted to prevent PMT rotation due to magnetic field.
- **Detector readiness was confirmed with laser and cosmic ray data taking.**

Detector assembly

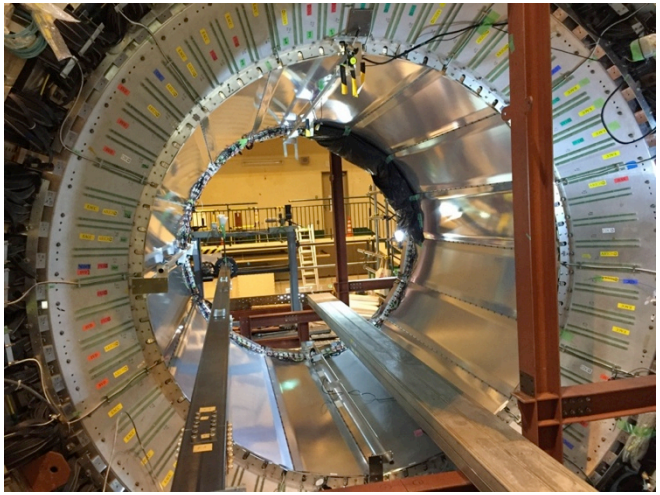
Moving for installation

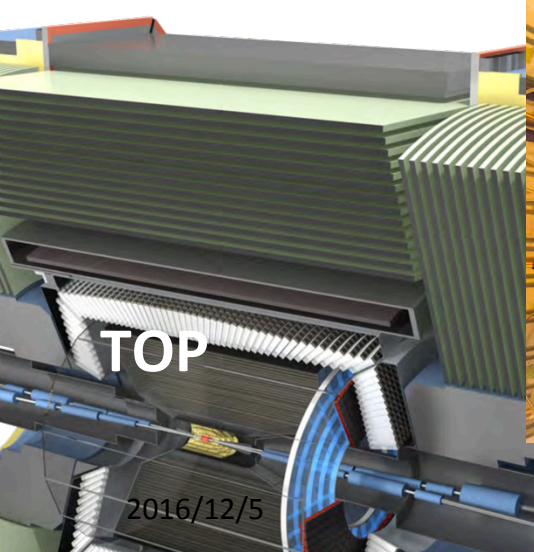


Detector installation in Belle II



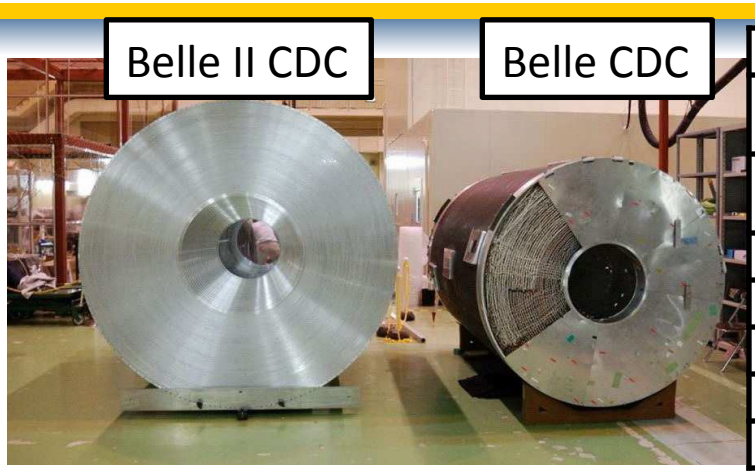
All detectors were installed



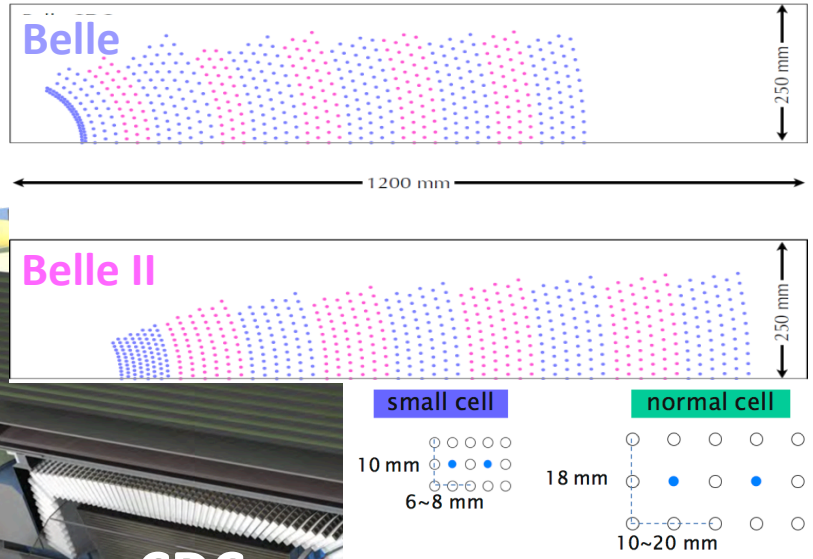


Central Drift Chamber (CDC) Upgrade

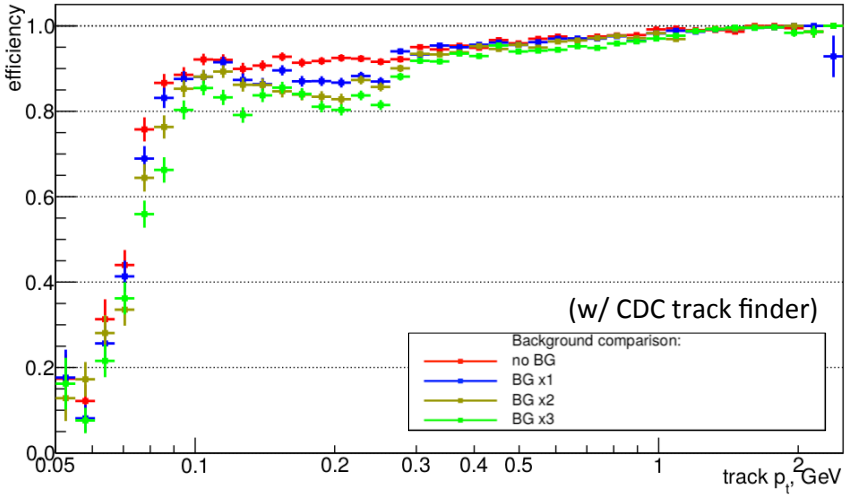
- **Larger outer radius: Improved momentum resolution**
  - Belle:863mm → Belle II 1111mm
- **Small cell**
  - lower occupancy
  - capacity for higher hit rate



	Belle II
inner most sense wire	r=168mm
outer most sense wire	r=1111.4mm
Number of layers	56
Total sense wires	14336
Gas	He:C_2H_6
sense wire	W(Φ30μm)
field wire	Al(Φ120μm)



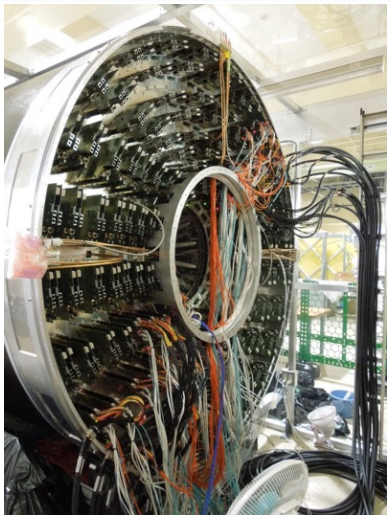
Simulated CDC track reconstruction efficiency



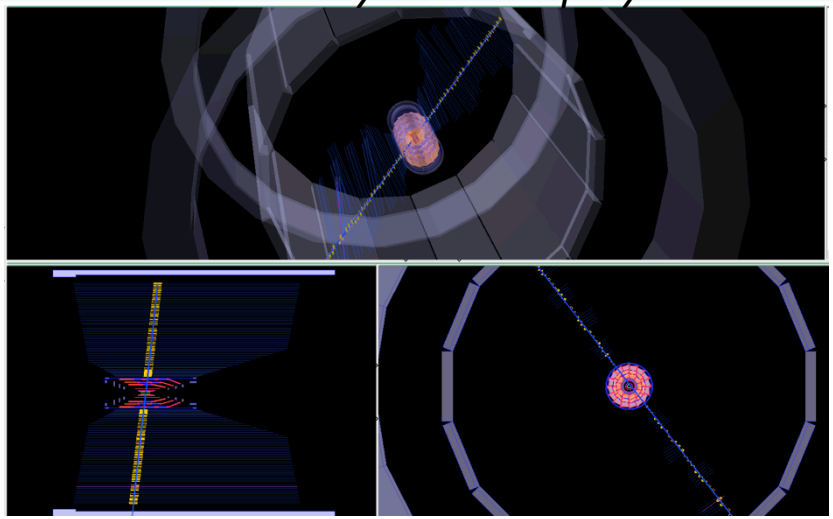
Stable tracking performance even for factor 3 of predicted BG from beam at designed luminosity.

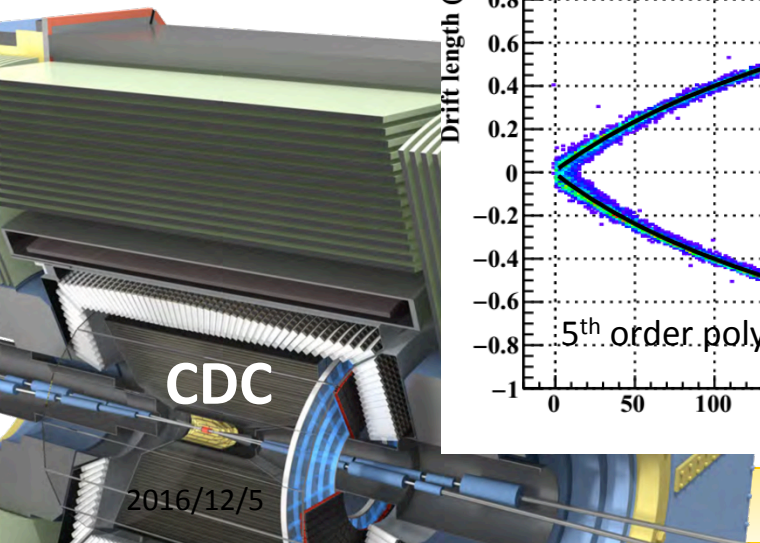
Central Drift Chamber (CDC) Test

- **Cosmic ray test was performed before CDC installation**
  - Drift curves were measured
  - Excellent hit-position resolution was confirmed.



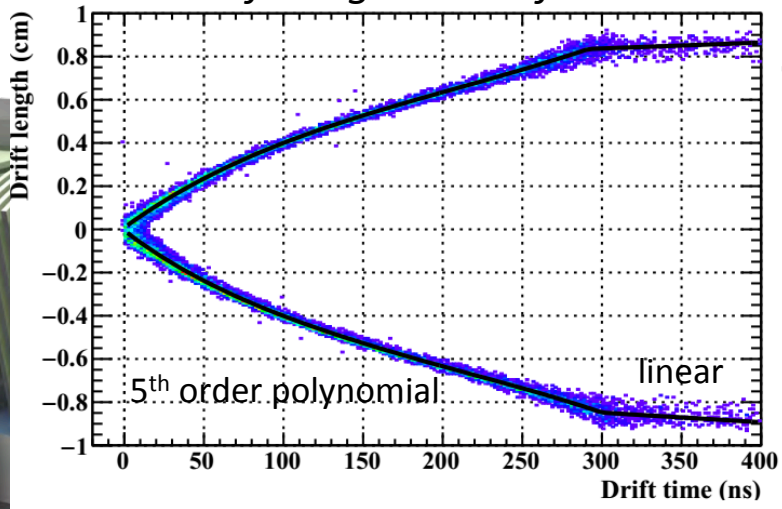
cosmic ray event display





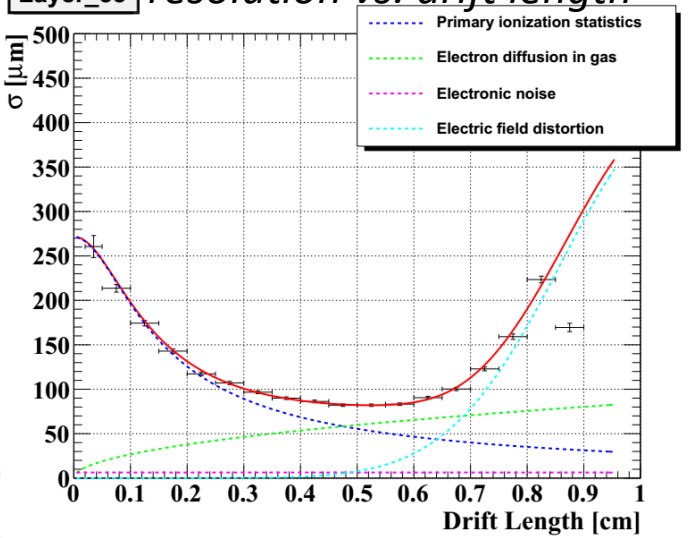
Lay_55

drift length vs. drift time



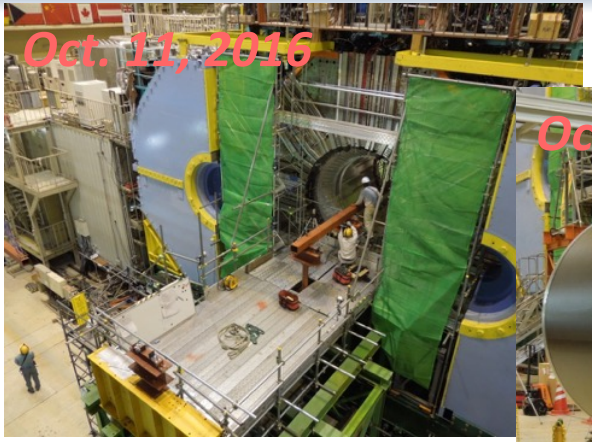
Layer_55

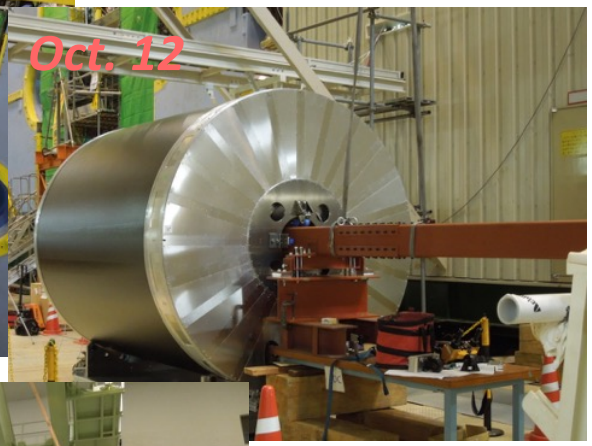
resolution vs. drift length

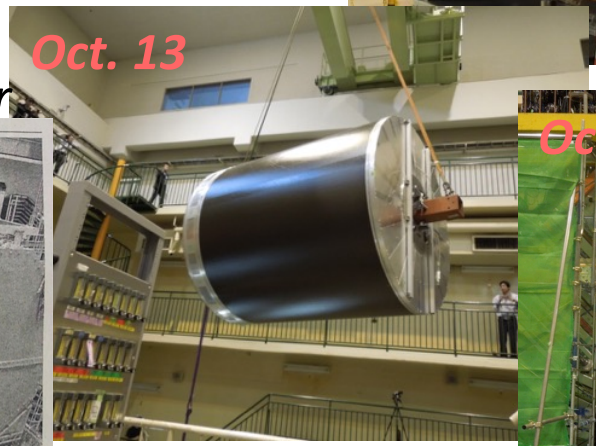


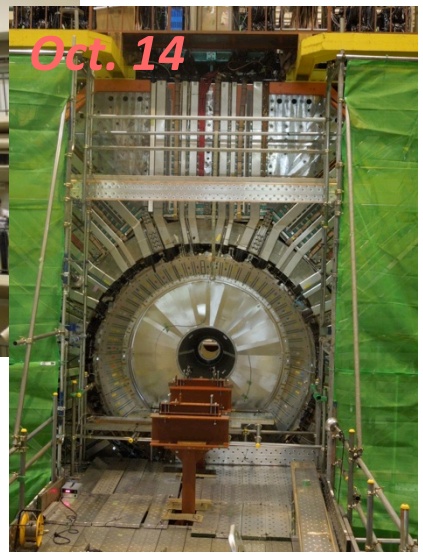
Central Drift Chamber (CDC) Installation

- **CDC detector was installed in Belle II in this Oct.**
- **Preparation for cosmic ray commissioning is now on-going.**









Article in a local news paper

新粒子発見に期待

つくばの高エネ研 検出器取り付け

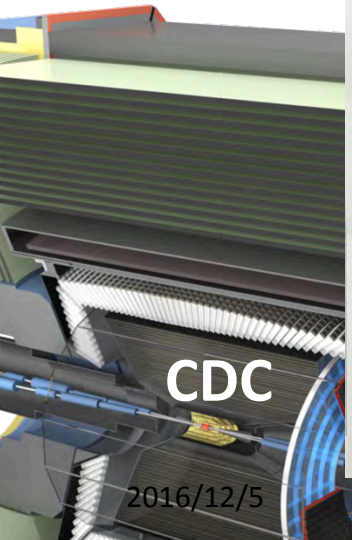
高エネルギー加速器研究機構（つくば市）の大型加速器施設で、新粒子発見などのカギとなる測定装置「Belle Ⅱ」に、重要な粒子検出器を取り付ける作業が13日、報道陣に公開された。

「Belle Ⅱ」の内部には、様々な検出器がバウムクーヘンのような層構造で設置されている。今回設置された「中央飛跡検出器（CDC）」は、直径約2・2㍍、長さ約2・4㍍の筒形で、内部に張り巡らせた多数の金属線により、加速器で生じた粒子の飛ぶ向きと勢いがわかる。

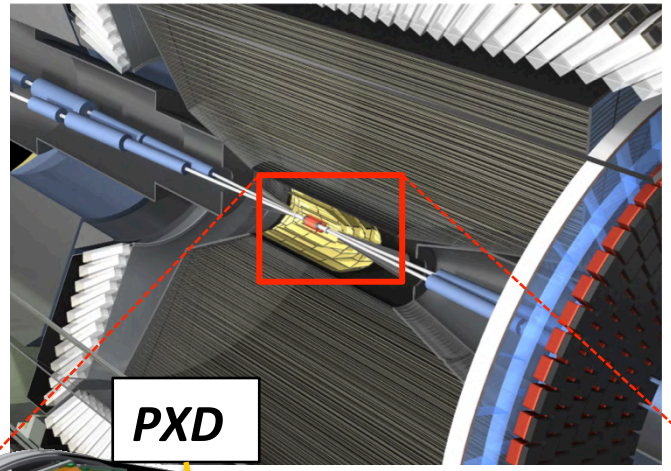
約3億円をかけて開発され、1秒当たりのデータ収集頻度は約3万回と、以前の検出器に比べ60倍に向上する。

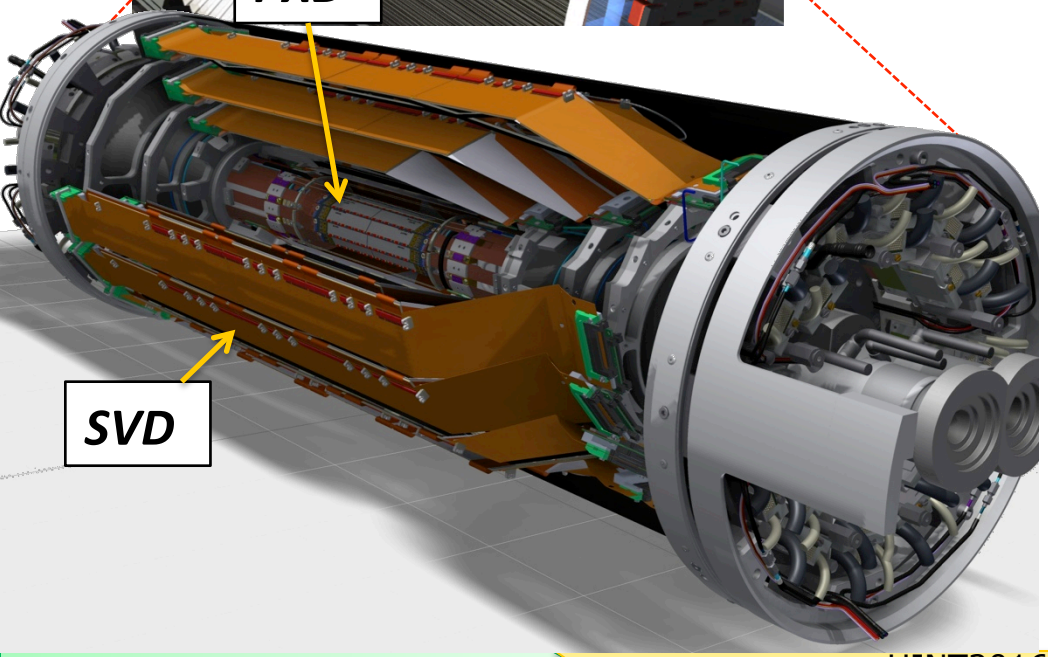
この日はクレーンでCDCをつり上げ、測定装置が設置された地下施設内を慎重に移動。装置中央のトンネル内部にピタリと挿入した。今後調整を行い、来年秋の稼働を目指す。

測定装置の中心部にあるトンネル内に挿入されるCDC（13日、高エネルギー加速器研究機構で）

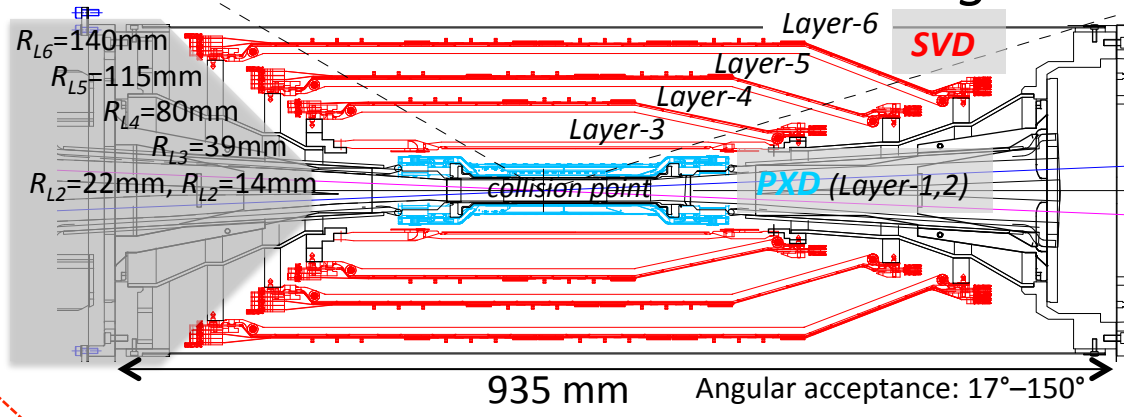


Belle II Vertex Detectors





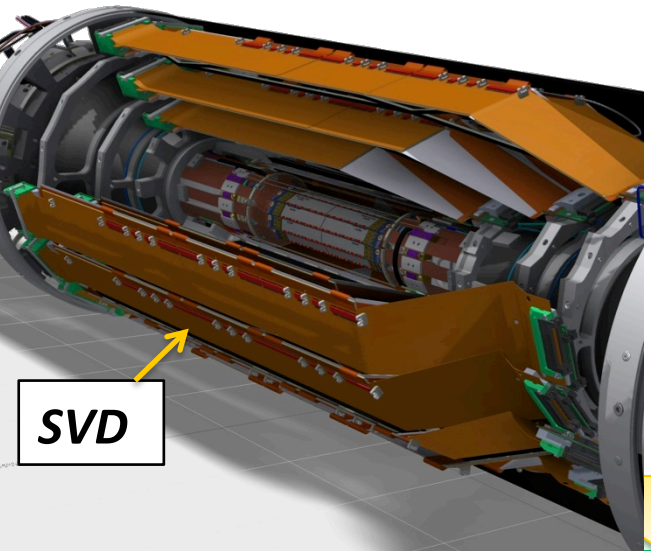
PXD+SVD cross section drawing



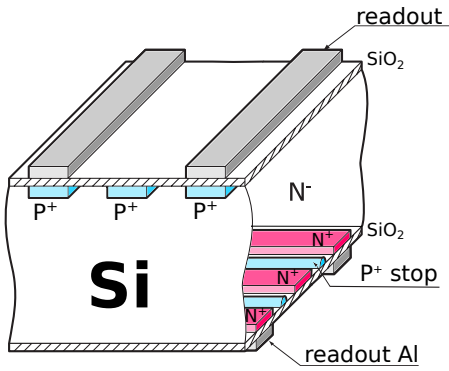
- **Belle II vertex determination is performed by 2 Si detectors.**
- **PiXel Detector (PXD): L1, L2**
  - Innermost 2 layers
  - Based on DEPFET pixels
- **Silicon Vertex Detector (SVD): L3-6**
  - Outer 4 layers
  - Double-sided Si strip detectors (DSSDs)

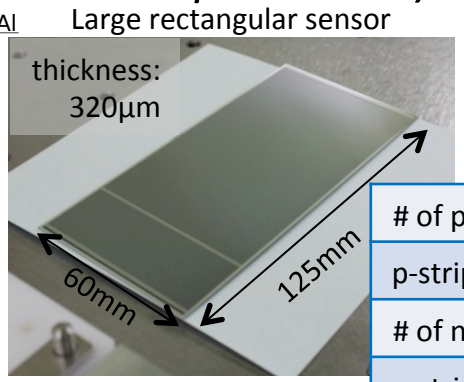
Silicon Vertex Detector (SVD)

- **SVD ladder consists of DSSDs.**
- **Material budget: 0.7% X_0 per layer**
- **Front-end ASIC: APV25**
  - originally developed for CMS Si tracker
  - Shaping time: 50ns
  - Radiation hardness: > 1MGy
- **Chip-on-sensor concept**
  - minimize the analog path length (capacitive noise)



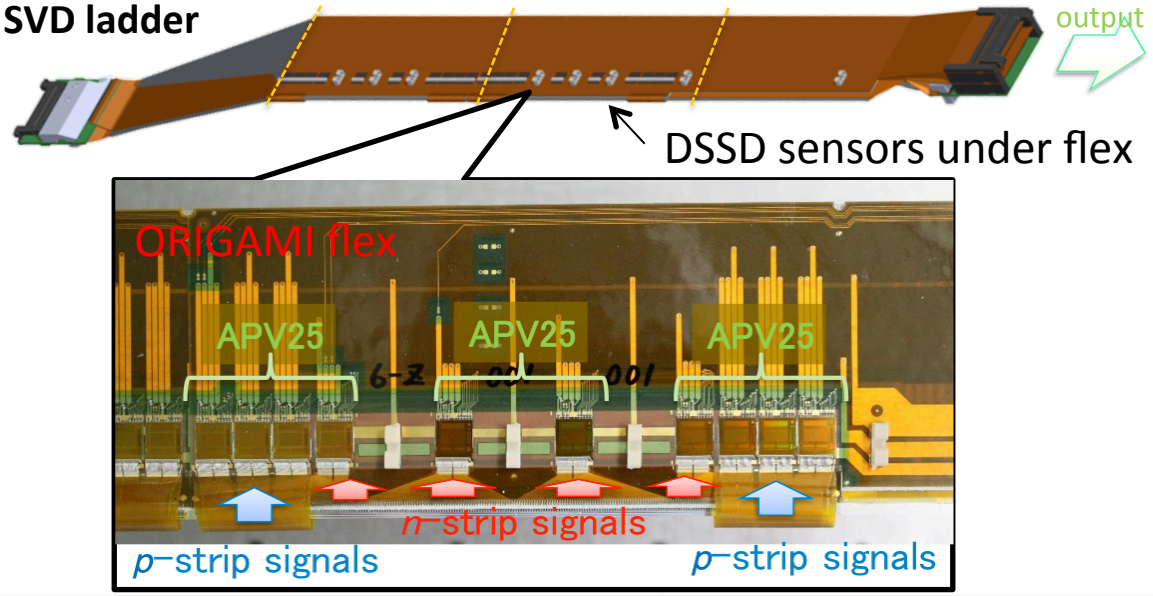
DSSD (Double-sided Si strip detector)





# of p-strips	768
p-strip pitch	50-75μm
# of n-strips	512-768
n-strip pitch	160-240μm

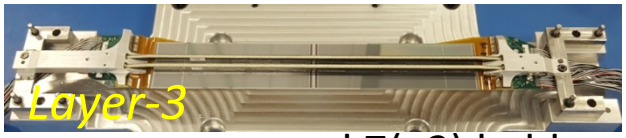
Novel chip-on-sensor concept



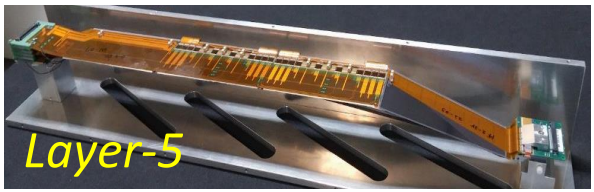
Silicon Vertex Detector (SVD)

- **SVD ladders under mass-production**
  - All Layer-3 ladders already completed.
- **SVD will be ready in Dec. 2017.**
- **Performance of SVD ladder is well tested in beam tests.**
  - Position resolution consistent with expectation
  - Excellent hit efficiency: > 99%

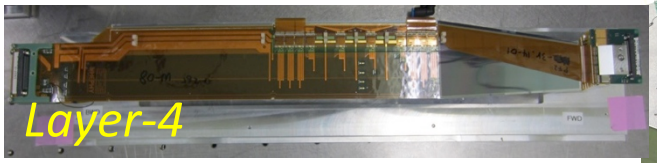
Assembled ladders in mass-production



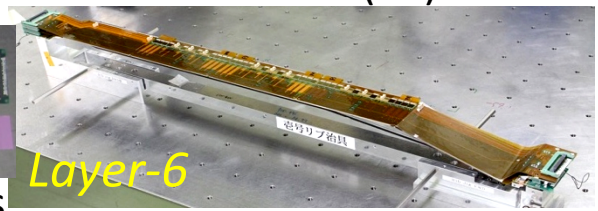
need 7(+2) ladders



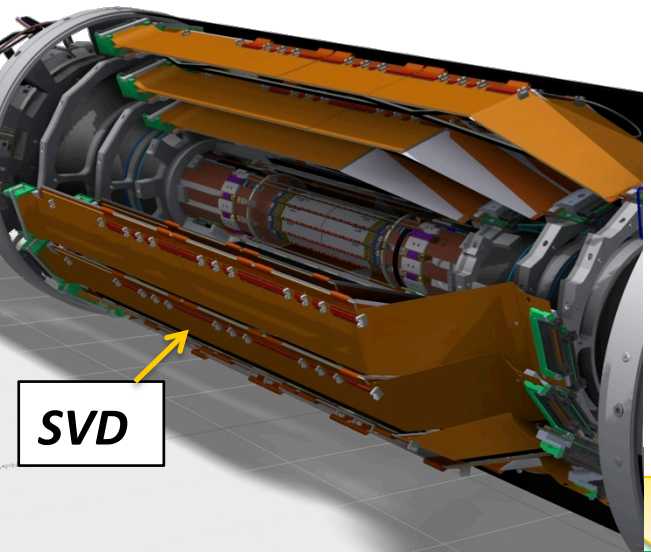
need 12(+3) ladders



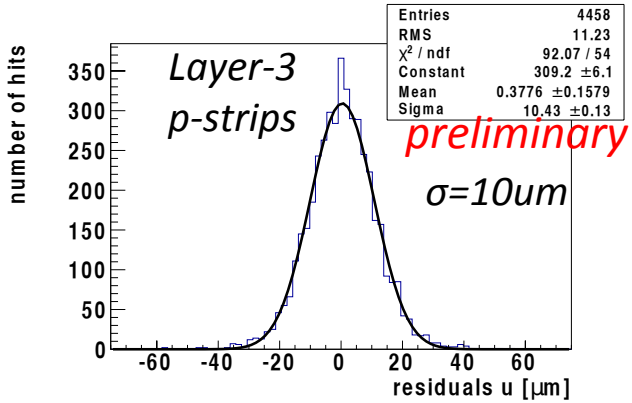
need 10(+2) ladders



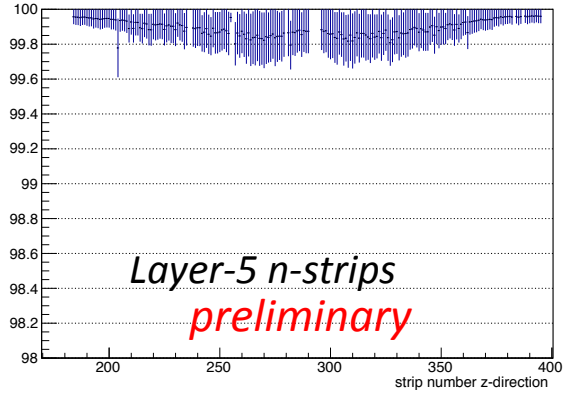
need 16(+4) ladders



Residual distribution



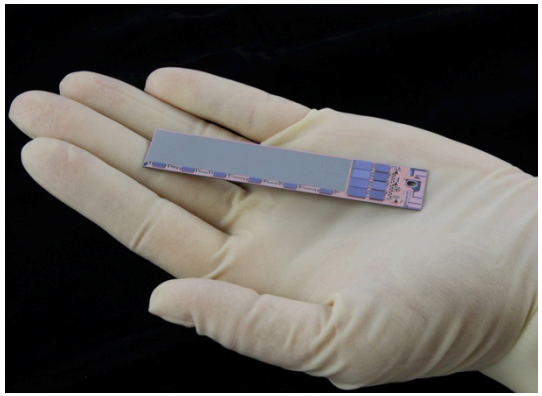
DSSD hit efficiency



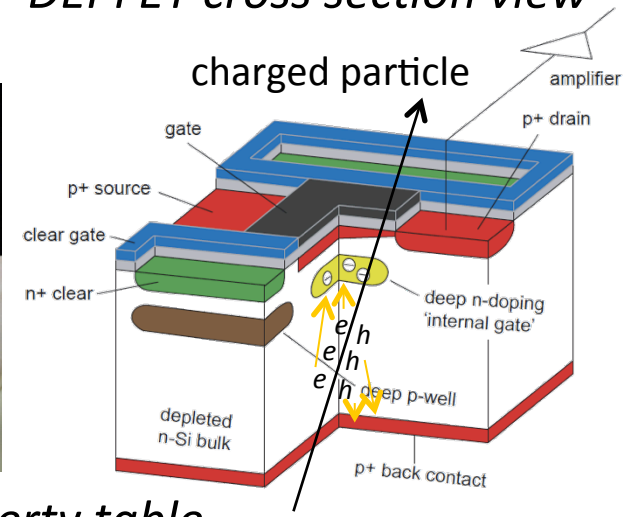
Pixel Detector (PXD)

- **Depleted P-channel FET (DEPFET) pixel sensor**
  - FET transistor on a fully depleted Si bulk
  - Additional n-implant causing a potential minimum below the transistor channel (= internal gate)
    - amplification: ~500 pA/*e*
- **Material budget: 0.2% X_0 per layer**
  - small multiple scattering

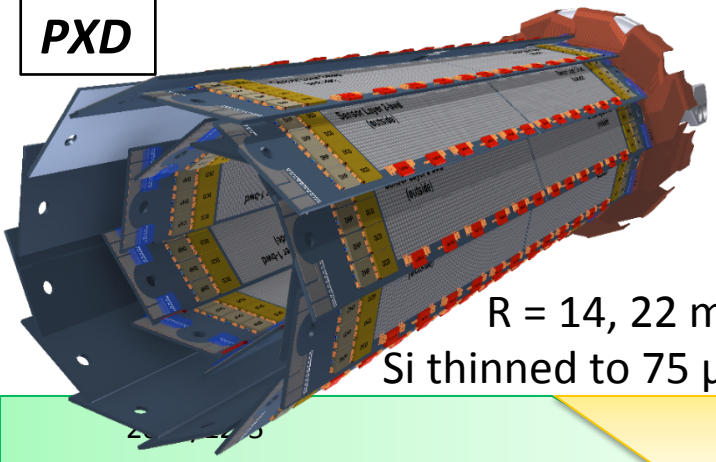
DEPFET PXD



DEPFET cross section view



PXD



R = 14, 22 mm
Si thinned to 75 µm

PXD property table

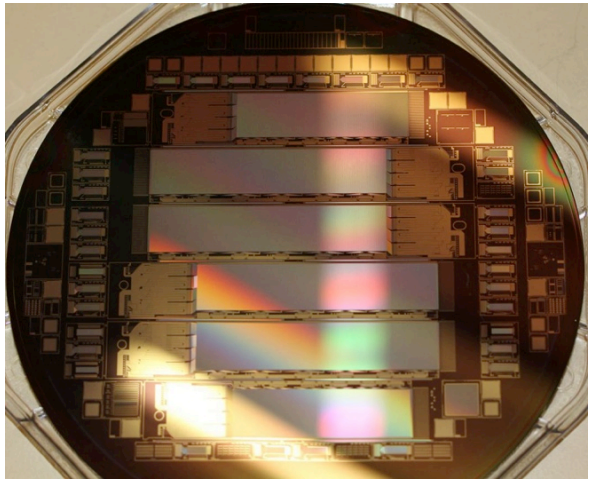
DEPFET PXD	L1	L2
# ladders	8	12
# pixles/module	768x250	768x250
total no. of pixels	3.1 x 10^6	4.6 x 10^6
Pixel size [um^2]	55x50, 60x50	70x50, 85x50
ladder size [mm^2]	15x136	15x170

Frame time: 20um, Duty cycle: 1

Pixel Detector (PXD)

- **96 sensors out of 172 produced (@ Oct. 2016)**
  - 40 sensors needed
  - 74/96 (87.5%): working sensors (>97.5% pixels)
  - 64/96 (66.7%): prime grade sensors (>99% pixels)
  - Entire production finished by Dec. 2016
- **Production yield better than expected (>50%)**
- **PXD delivered to KEK by Dec. 2017**

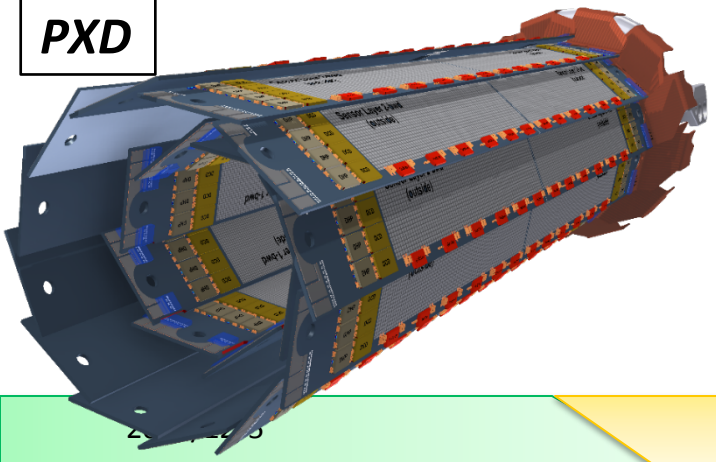
DEPFET sensor wafer



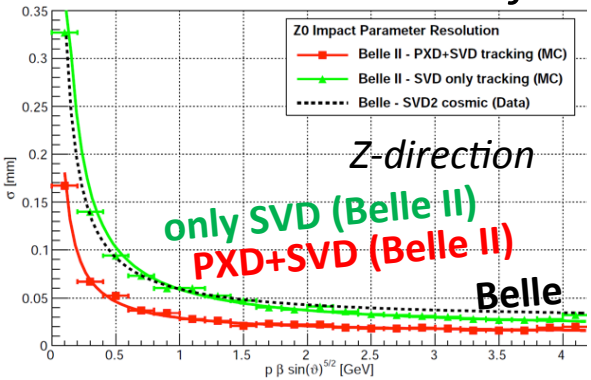
produced at MPG-HLL (Munich)

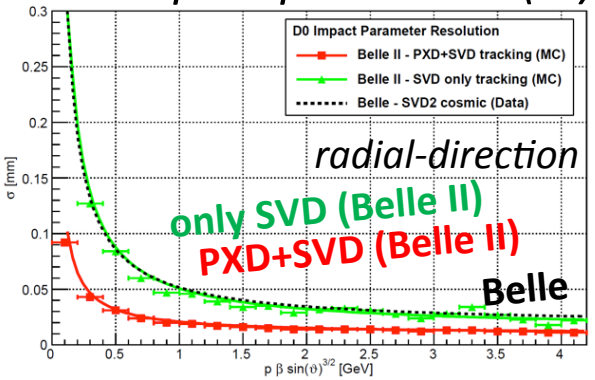
- **Excellent vertex resolution with PXD+SVD confirmed**
  - σ_{IP} ~ 20um at p_T = 2GeV/c

PXD



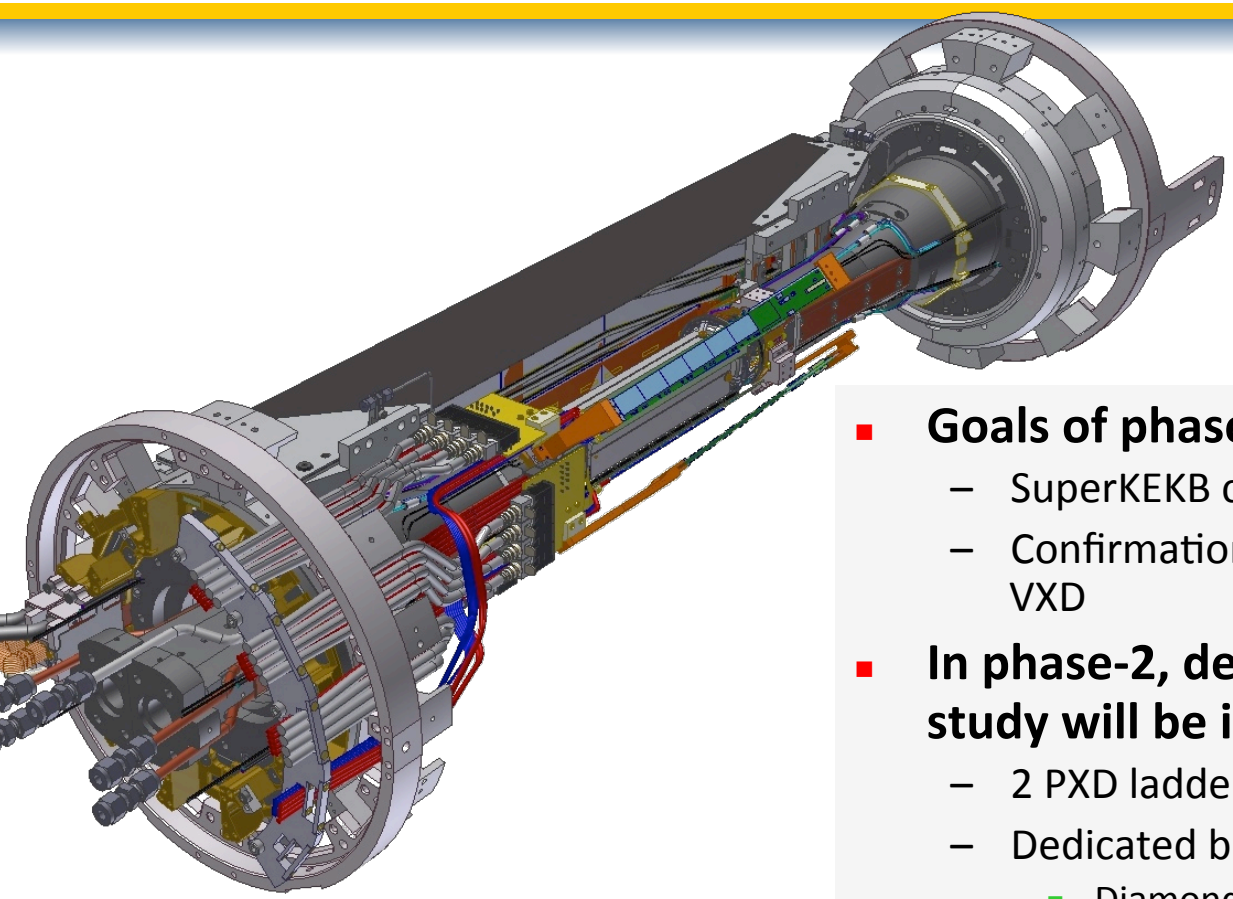
Simulated resolution for track impact parameter (IP)





Improved resolutions from Belle.

Phase-2 VXD beam background study



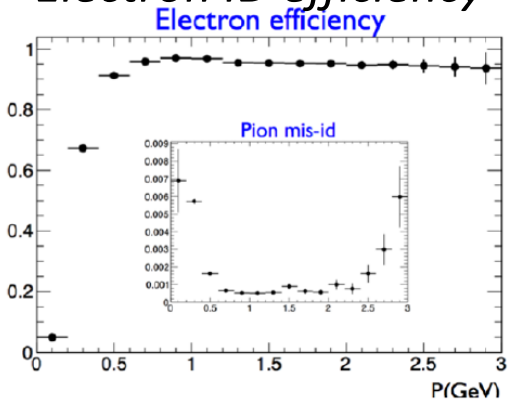
- **Goals of phase-2:**
  - SuperKEKB commissioning
  - Confirmation of radiation safe environment for VXD
- **In phase-2, detectors for beam background study will be installed in the VXD region.**
  - 2 PXD ladders + 4 SVD ladders
  - Dedicated beam BG monitors:
    - Diamond detectors
    - FANGS (Hybrid Si pixel detector with FE-I4)
    - CLAWS (Scintillator+MPPC array)
    - PLUME (Double-sided pixelated CMOS: MIMOSA-26 sensors)

Belle II Particle Reconstruction

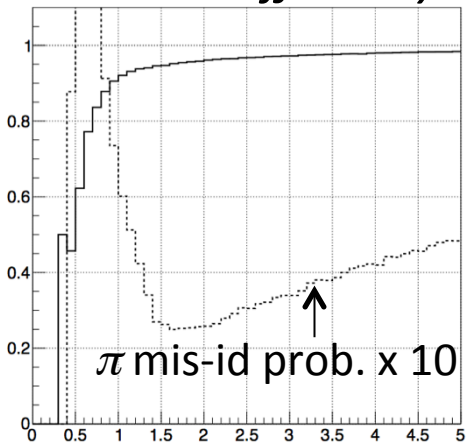
Particle ID relies on likelihood based selection with information from different sub-detectors.

- **Electron ID**
  - provided by ECL energy deposition
  - Eff. >90% at moderate momentum
- **Muon ID**
  - Penetration depth and transverse scattering of the track in KLM
  - Eff. ~90-98% above 1GeV/*c*
- **Hadron ID**
  - using combined information of TOP, ARICH, and dE/dx(CDC, SVD)
  - Eff.>90% for momentum > 0.5 GeV/*c*

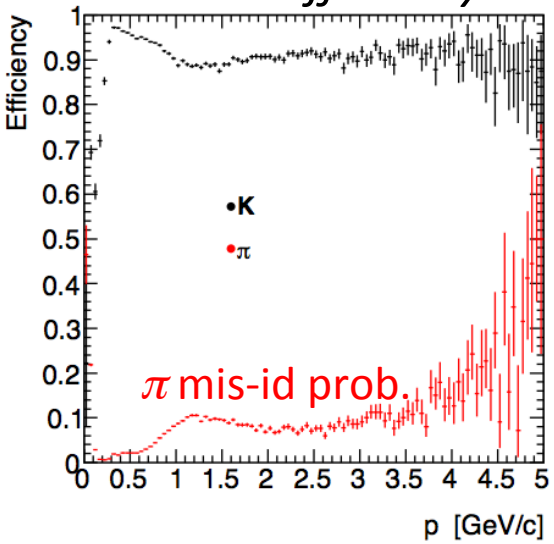
Electron ID efficiency



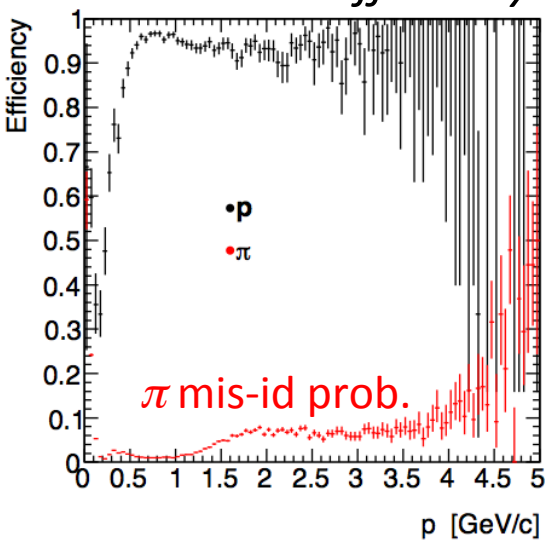
Muon ID efficiency



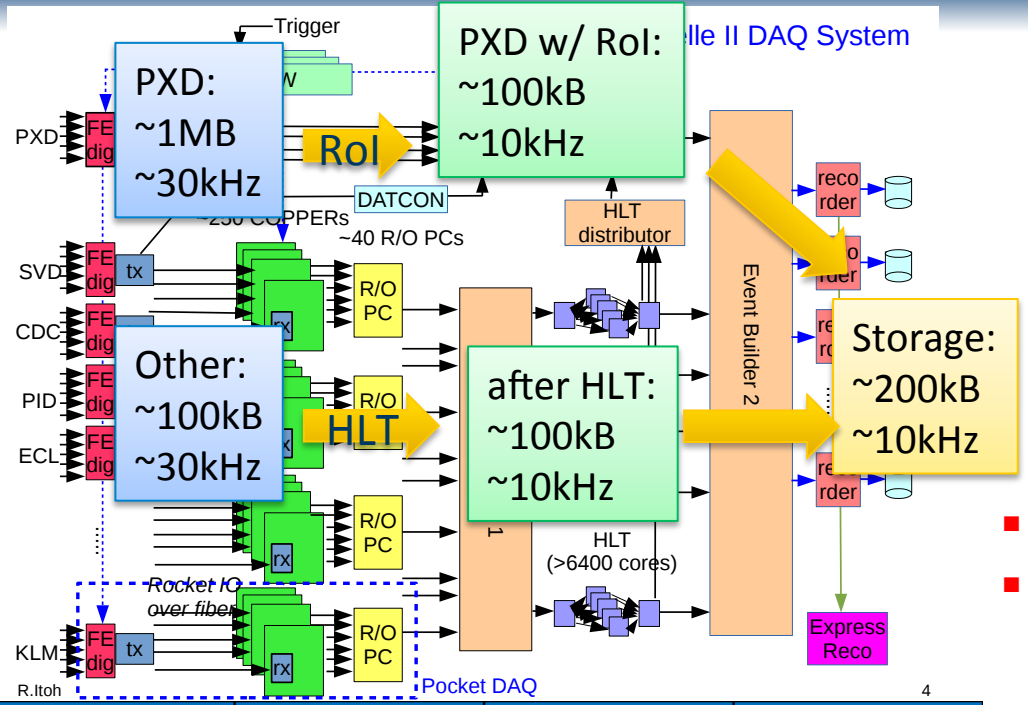
Kaon ID efficiency



Proton ID efficiency



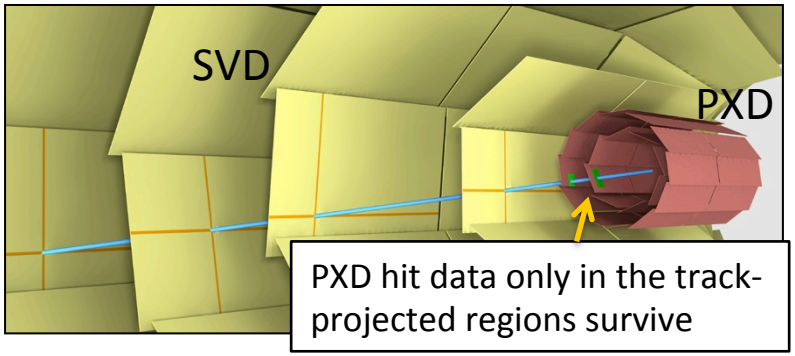
DAQ for Belle II Detectors



Experiment	Event size [kB]	Rate @ Storage [event/sec]	Rate @ Storage [MB/sec]
Belle II	~200	~10,000	~2,000
ALICE (Pb-Pb)	50,000	100	4,000
ALICE (p-p)	2,000	100	200
ATLAS	~700	600	400
CMS	~1,000	500	several 100s
LHCb	55	4,500	250

(LHC experiments: as seen in 2011/2012 runs)

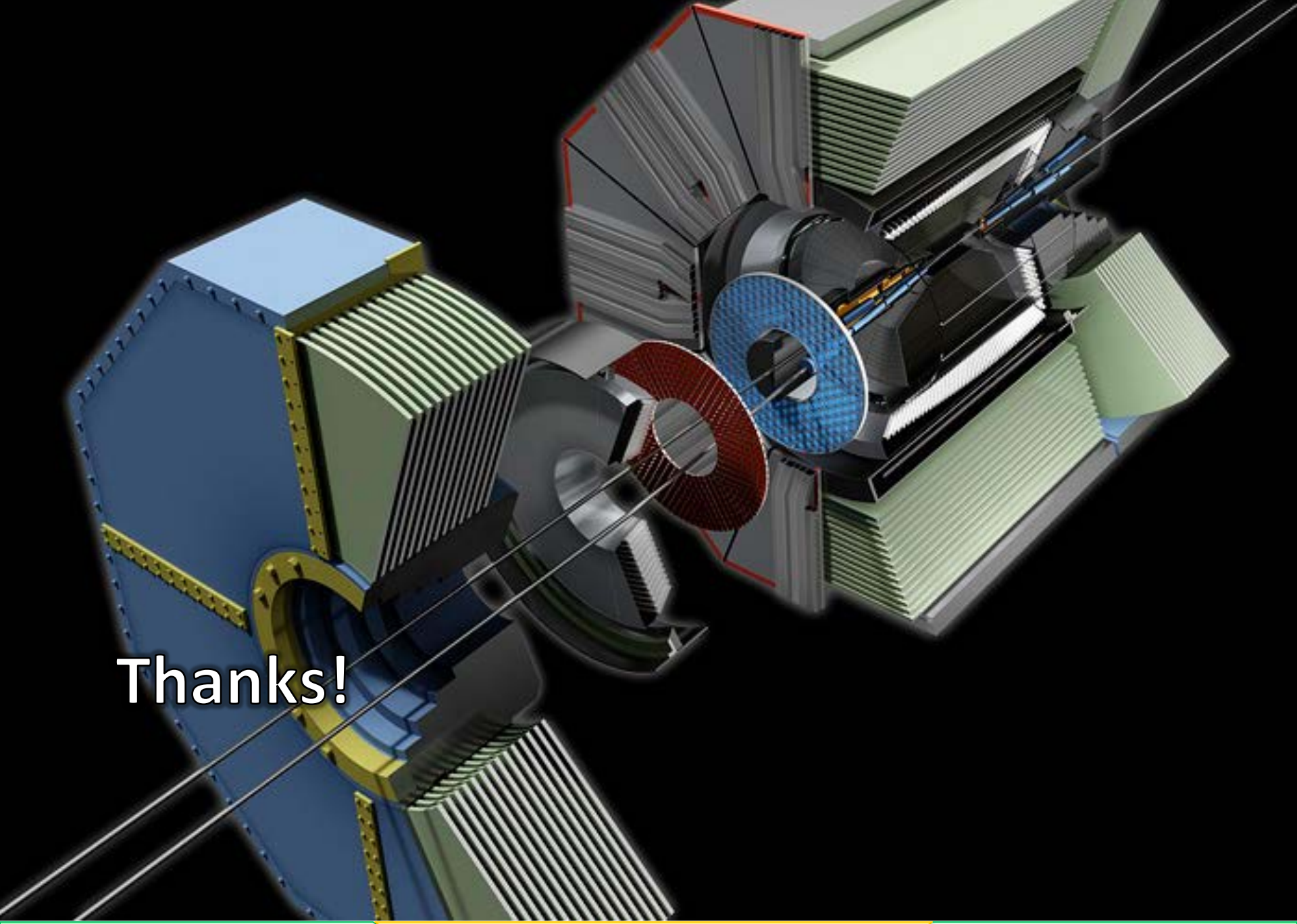
Region of Interest (RoI) data reduction scheme on PXD



- **Level-1 trigger: 30kHz in max.**
- **Event size:**
  (PXD) ~1MB/ev,
  (Other detectors) ~100kB/ev in total
- **High Level Trigger (HLT) event rate reduction: by a factor of ~3**
  - ~30kHz → ~10kHz
- **RoI PXD data reduction: factor of ~10**
  - ~1MB → ~100kB
- **Online data rate @ storage: ~2GB/s**

Summary

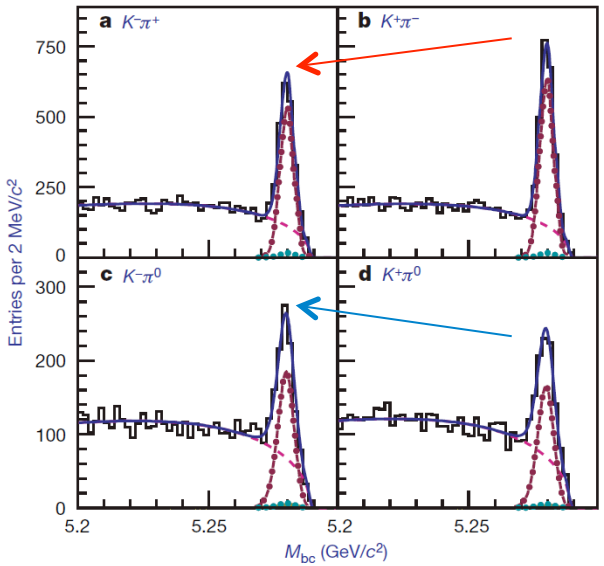
- **The Belle II experiment takes shape!**
- **Detector construction is on-going.**
  - KLM, barrel-ECL, TOP, and CDC have been installed already.
  - endcap-ECL and ARICH will be installed by autumn 2017.
- **Phase-2 will start Jan. 2018.**
  - SuperKEKB commissioning
  - Survey beam BG in the VXD region
    - without full VXD
- **Phase-3 will start Dec. 2018.**
  - full Belle II detector


Thanks!

Belle II Collaboration

- 23 countries/regions
- 101 institutions
- 696 collaborators (Oct. 2016)

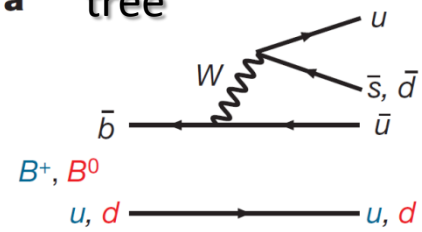
Difference in direct CPV B→Kπ



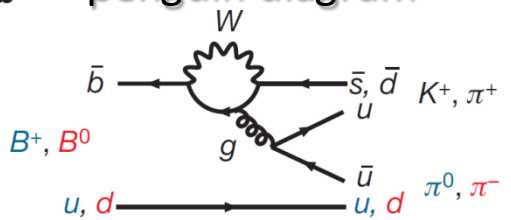
Mode	BR[10^{-6}]	A_{CP}
$B^+ \to \pi^+ K^0$	23.1 ± 1.0	0.009 ± 0.025
$B^+ \to \pi^0 K^+$	12.8 ± 0.6	0.047 ± 0.026
$B_d^0 \to \pi^- K^+$	19.7 ± 0.6	-0.093 ± 0.015
$B_d^0 \to \pi^0 K^0$	10.0 ± 0.6	-0.12 ± 0.11

Diagrams **a** and **b** doesn't change by u<->d swapping.

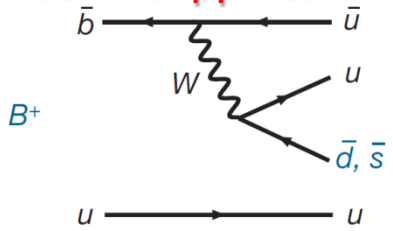
a tree



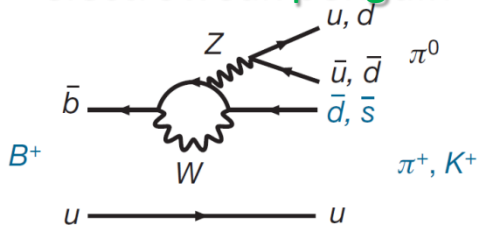
b penguin diagram



c color-suppression



d electroweak penguin



Isospin sum rule:

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\Gamma(K^0\pi^+)}{\Gamma(K^+\pi^-)}$$

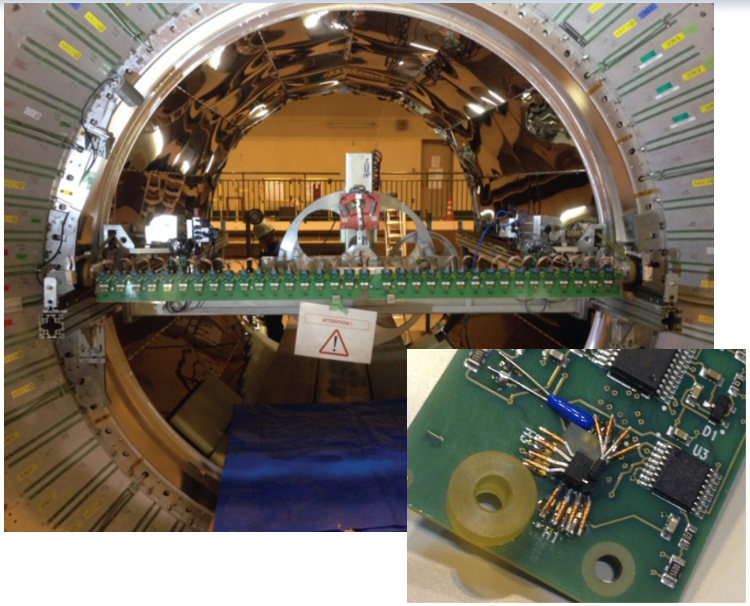
$$- A_{CP}(K^+\pi^0)\frac{2\Gamma(K^+\pi^0)}{\Gamma(K^+\pi^-)} - A_{CP}(K^0\pi^0)\frac{2\Gamma(K^0\pi^0)}{\Gamma(K^+\pi^-)}$$

$$= 0\ (?)$$

This formula will be checked precisely in Belle II.

New physics can be coupled here.

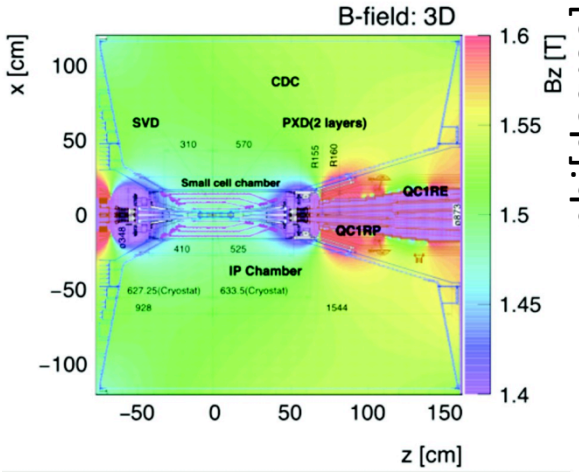
Magnetic Field Survey



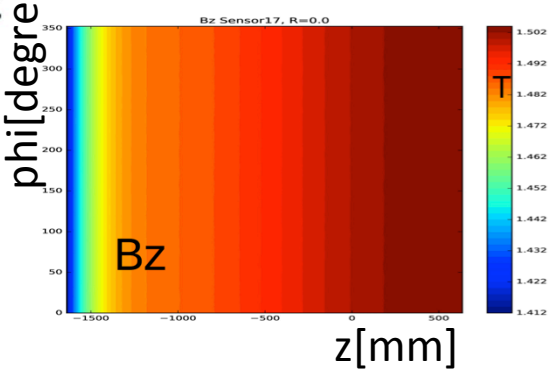
Hall probe

- **Full 3D mapper**
- **34 hall probes on carbon fiber arms**

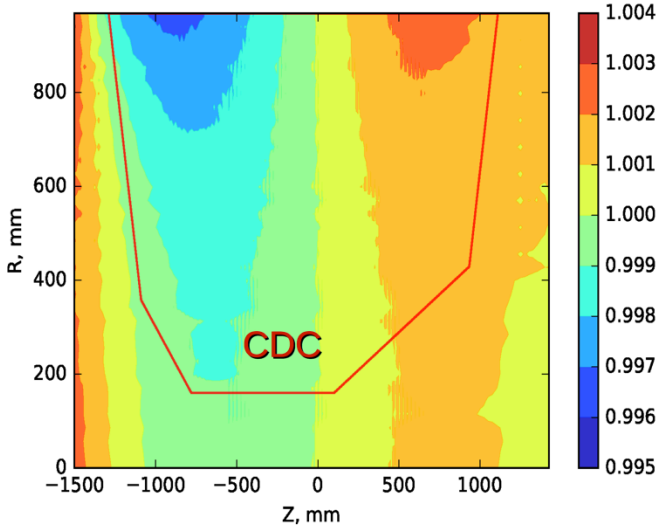
Simulation



Measurement



Ratio btw. measurement and simulation



- Overall reasonable agreement between data and simulation
- Data can be used for further tune of the simulation to reach 0.1% goal