Belle II

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

IAS HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

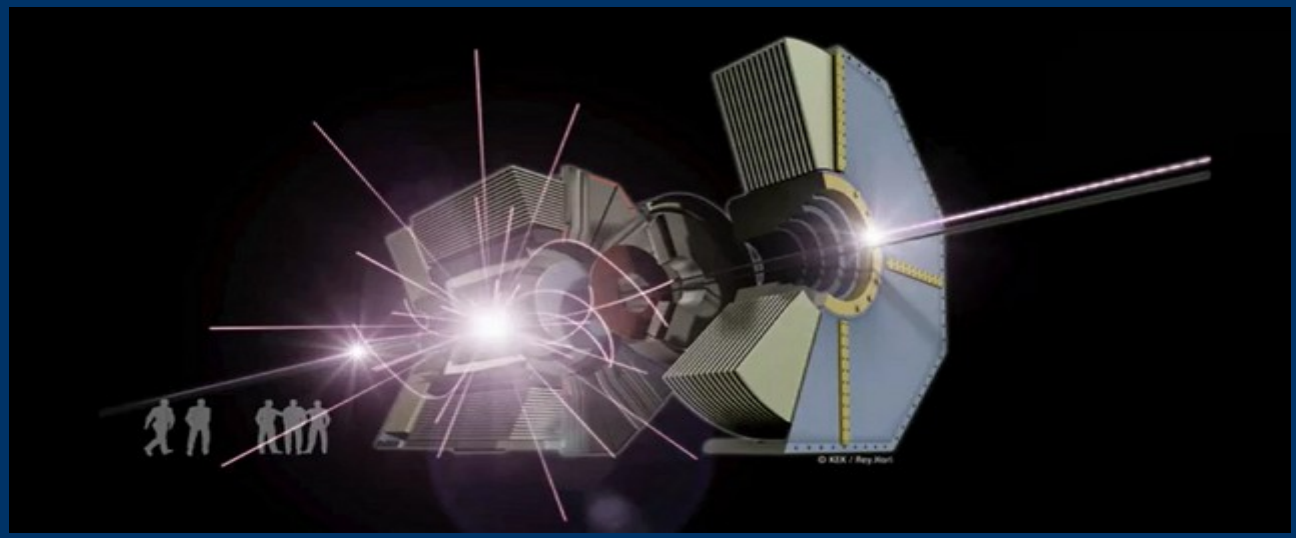
8 – 26 Jan 2018

High Energy Physics

The Belle II experiment:

status and physics prospects

Jing-Ge Shiu/NTU
On behalf of the Belle II collaboration



The Belle II experiment

Outline

- SuperKEKB and Belle II
- Physics prospects
- Status and schedule

The Belle II experiment

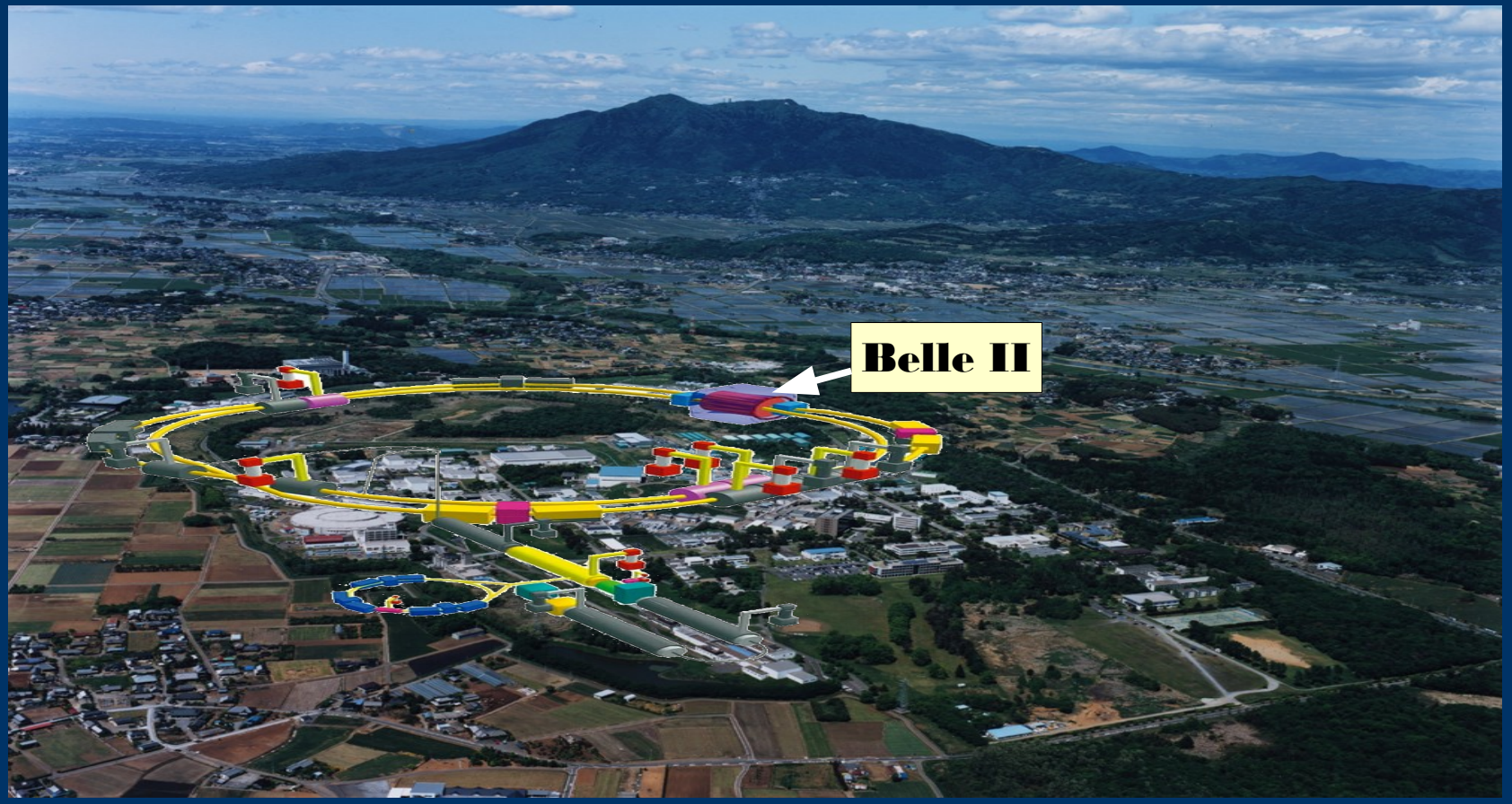
Outline

- SuperKEKB and Belle II
  - Introduction
  - SuperKEKB
  - Belle II
- Physics prospects
- Status and schedule

SuperKEKB @

KEK 大学共同利用機関法人 高エネルギー加速器研究機構

Tsukuba, ~ 1.5 hours away from Tokyo



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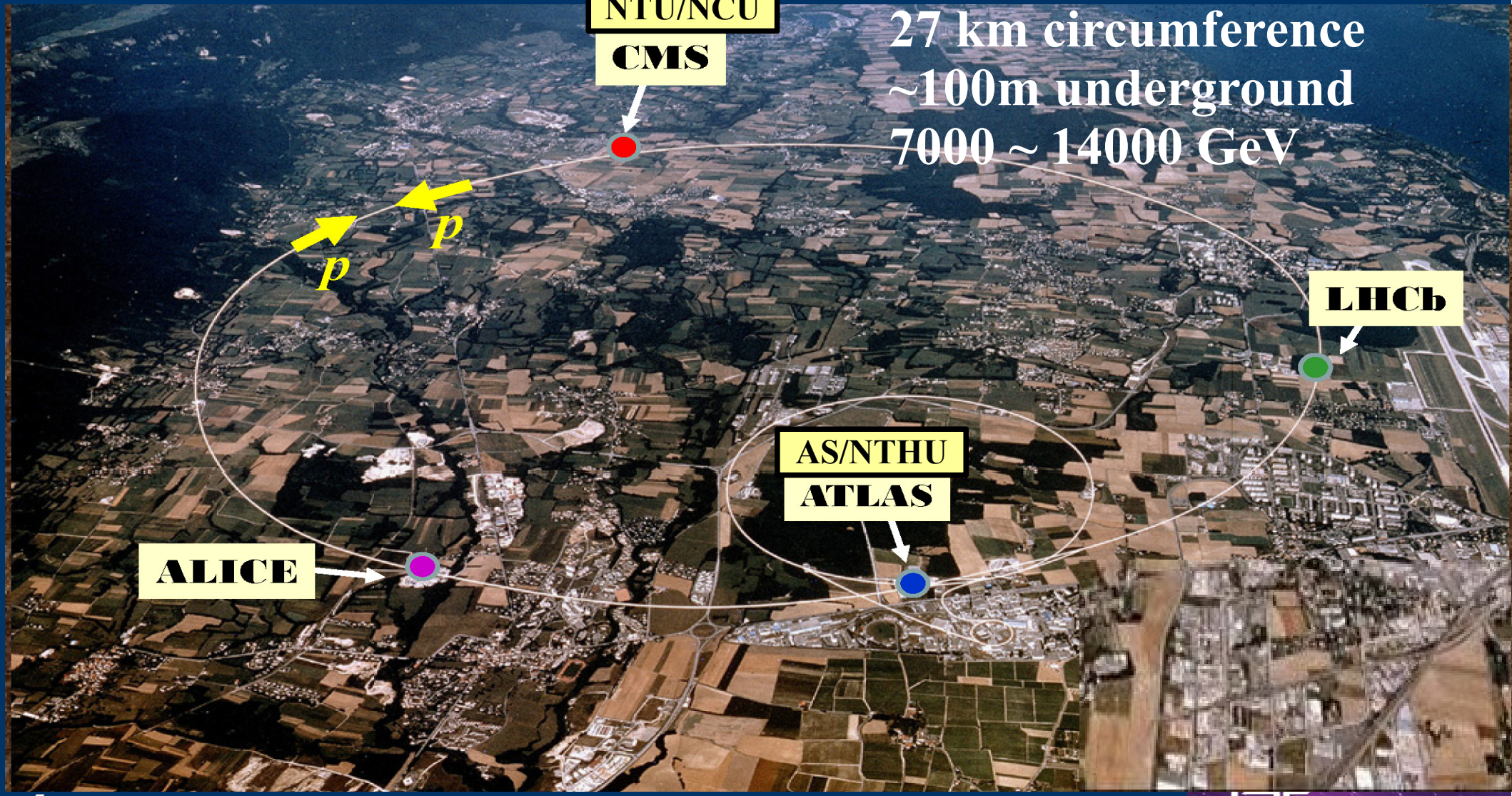
LHC

27 km circumference
~100m underground
7000 ~ 14000 GeV



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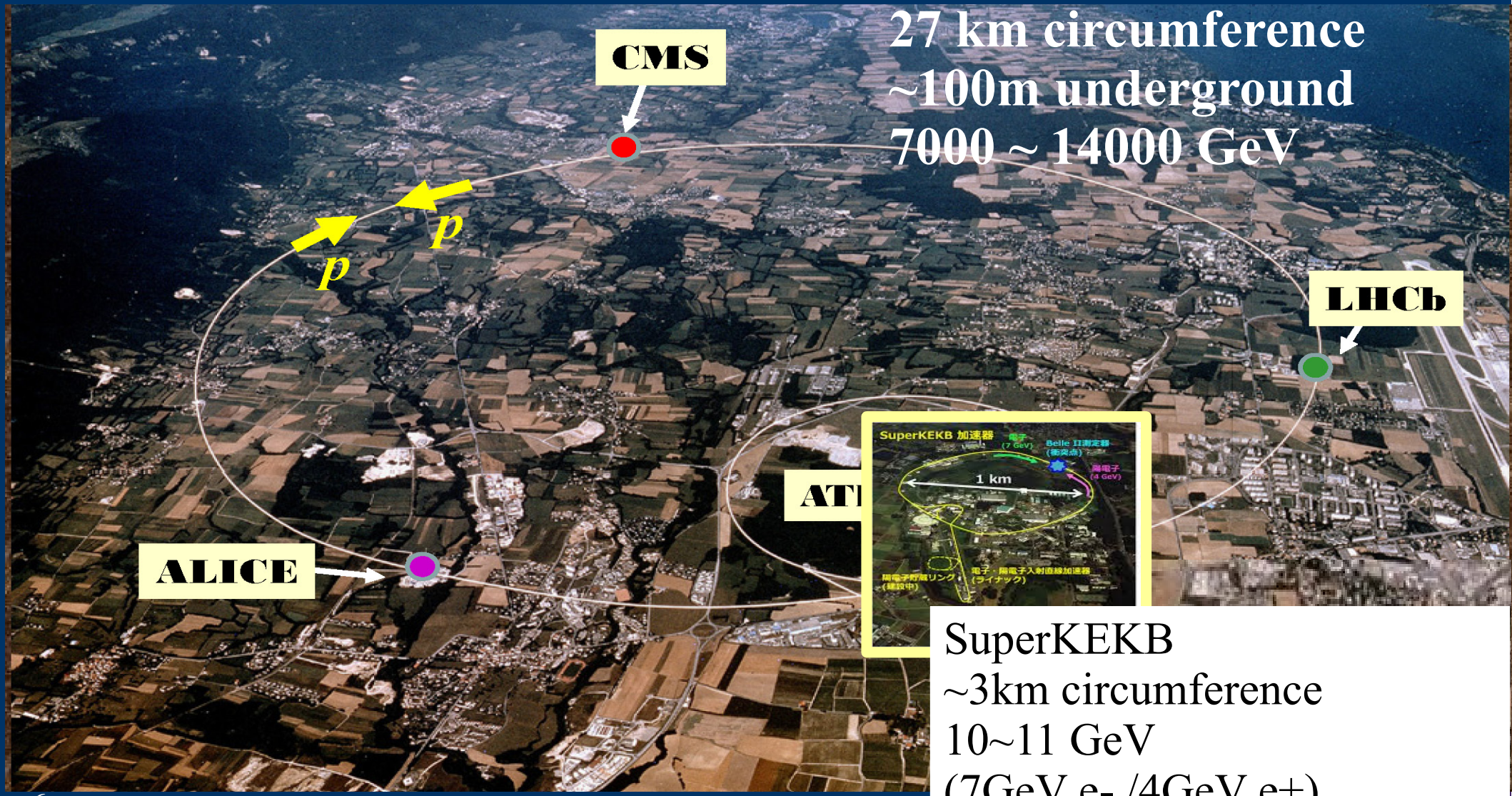
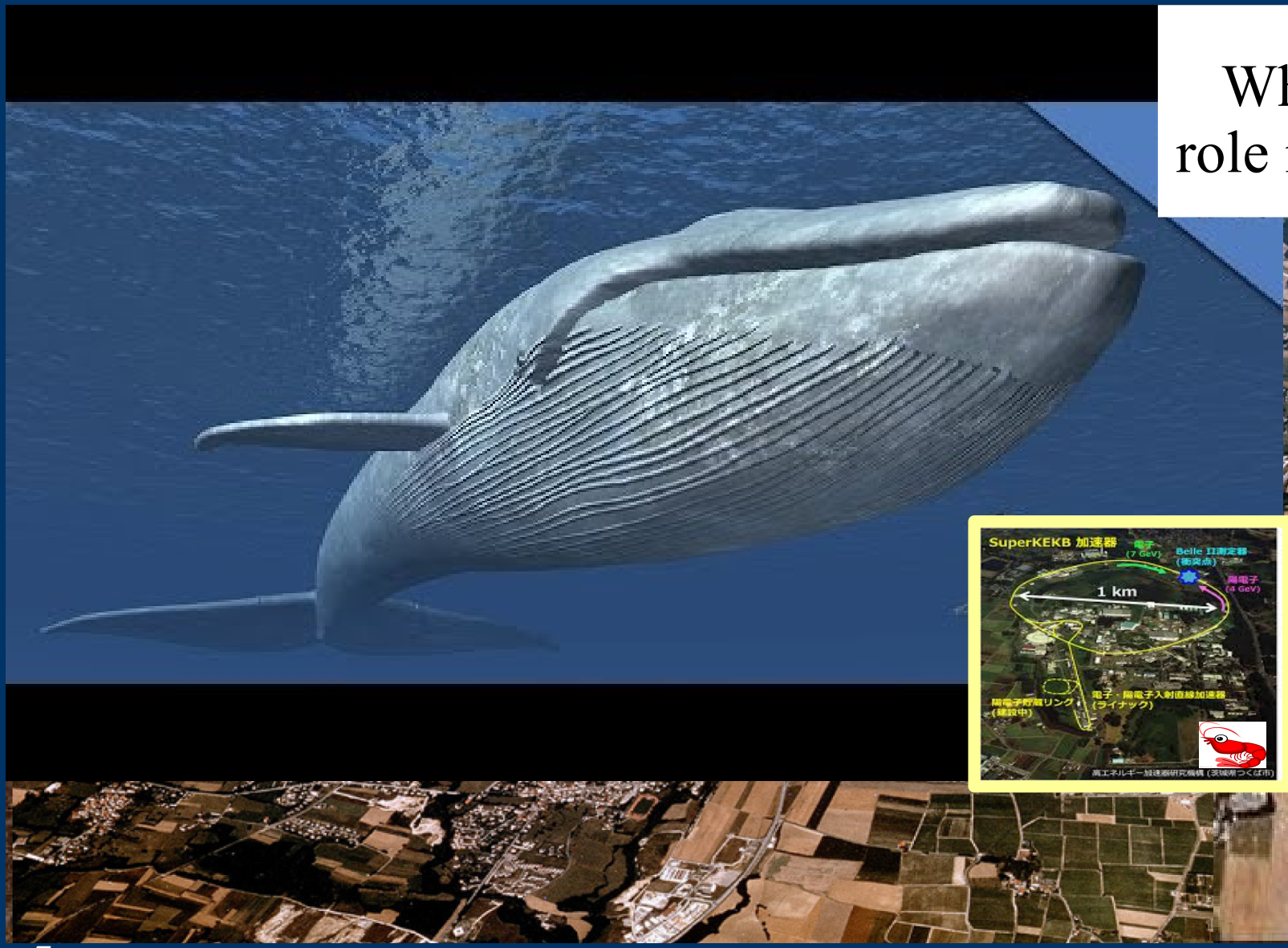


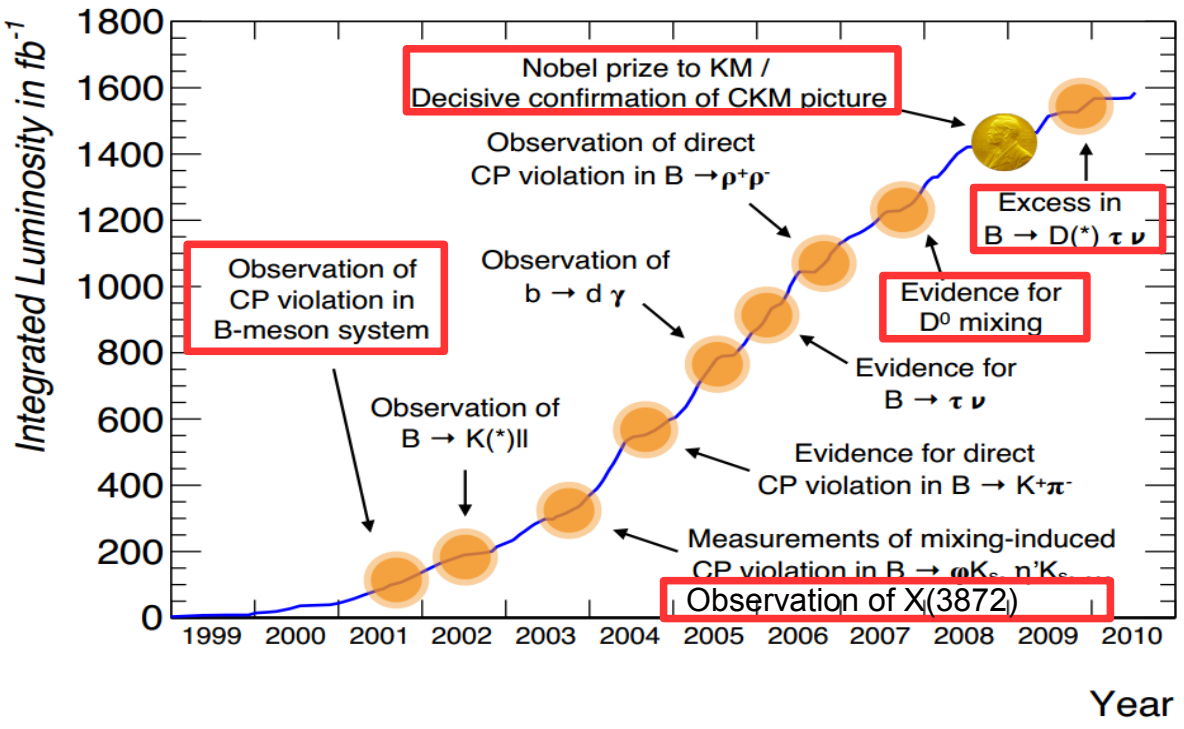
SuperKEKB
~3km circumference
10~11 GeV
(7GeV e- /4GeV e+)

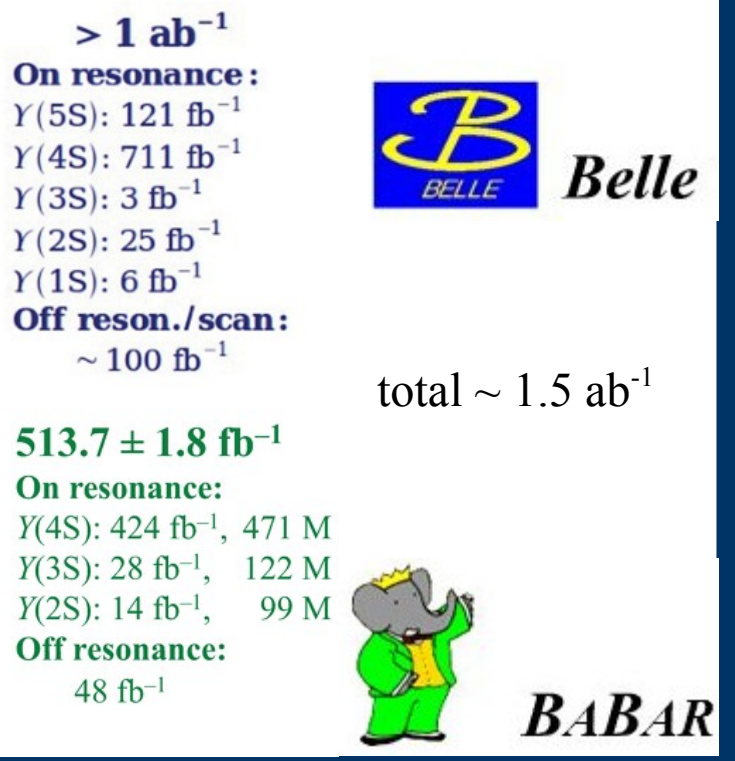
What is Belle II's role in this LHC era?



Why Belle II

Last generation B factories achieved great success in B (charm, τ) physics studies and explored possible new physics





However, there are still remaining puzzles and open questions

- large matter/antimatter asymmetry in the universe (the truth is out there!)
- anything beyond the SM (where is the NP)?
- those "dark" things …..

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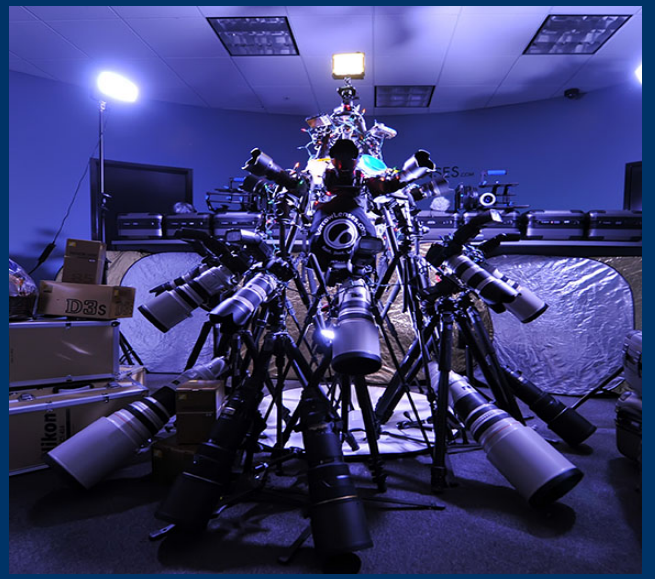
Two approaches for HEP:

Energy frontier (direct search)

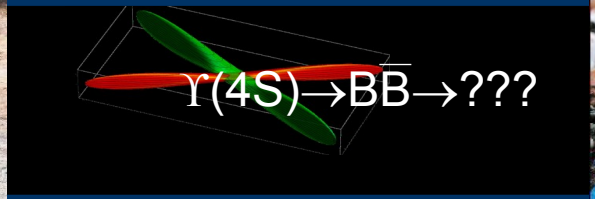
→ powerful in energy scale to search for new particles and physics. (LHC)



complementary with each other

Precision/intensity frontier

→ focus on a certain energy range for precision measurements to search for anomalies from the SM and new physics from rare decays (SuperKEKB + Belle II)



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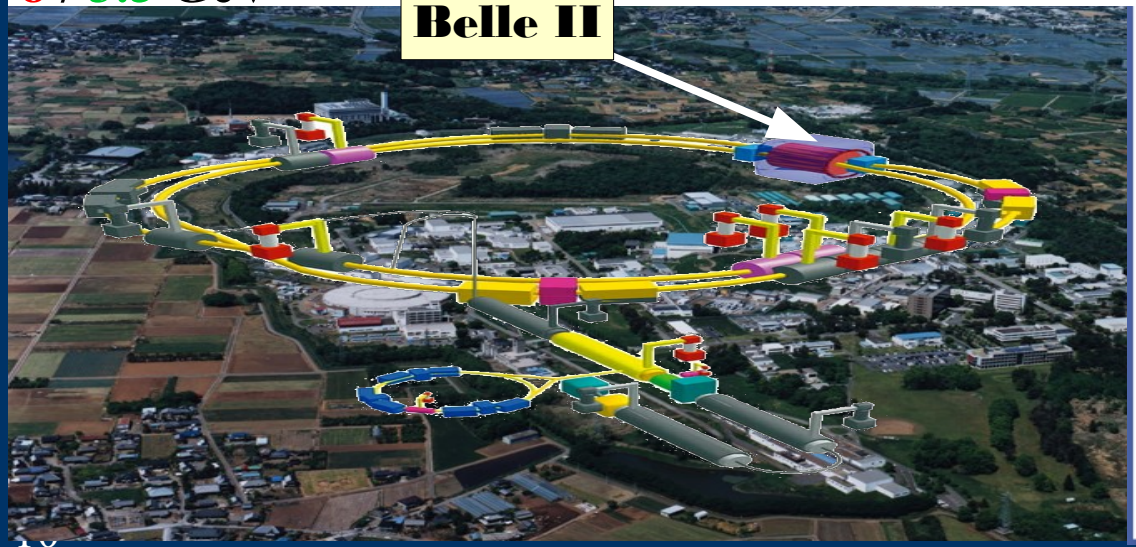
SuperKEKB: going beyond the KEKB

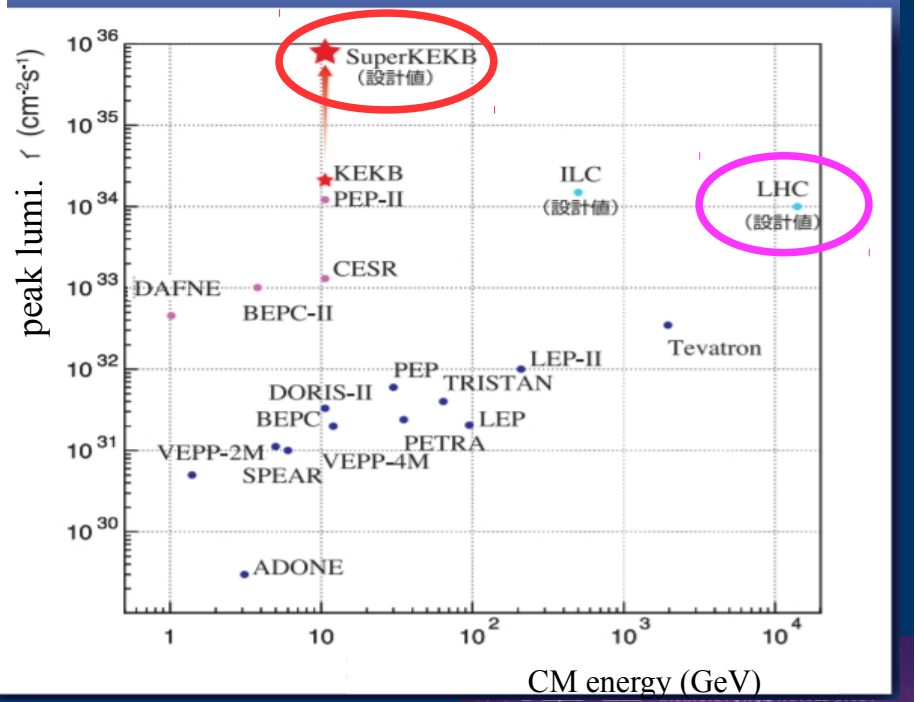
founded in 2008, groundbreaking in 2011

peak luminosity 8×10^{35} $cm^{-2}s^{-1}$ (40 x KEKB)

Belle II: $50 ab^{-1}$ data (50 x Belle)

→ high precision measurements; rare decays





Luminosity of KEKB and SuperKEKB

	KEKB achieved		SuperKEKB nano-beam	
	LER	HER	LER	HER
E_{beam} (GeV)	**3.5**	**8**	**4**	**7**
I_{beam} (A)	**1.6**	**1.2**	**3.6**	**2.6**
β_y (mm)	**5.9**	**5.9**	**0.27**	**0.30**
luminosity ($cm^{-2}s^{-1}$)	**2.1×10^{34}**		**8.0×10^{35}**	

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

→ $\beta\gamma \sim 2/3$

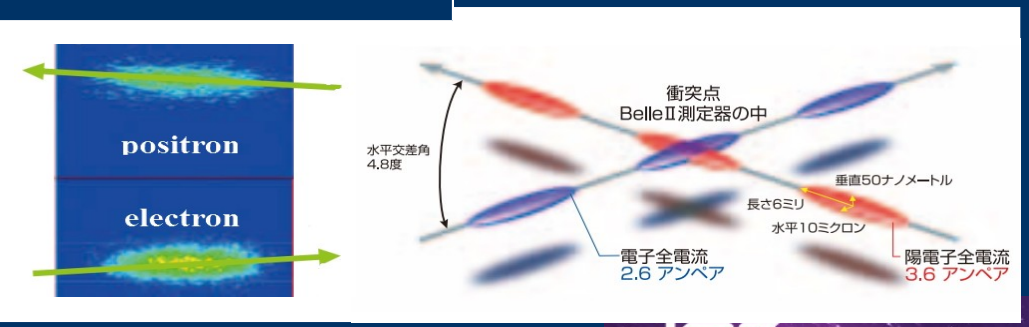
→ factor 2

→ factor 20

→ factor 40

nano beams with high beam currents
low emittance 4.6 nm /3.2 nm

→ high intensity frontier



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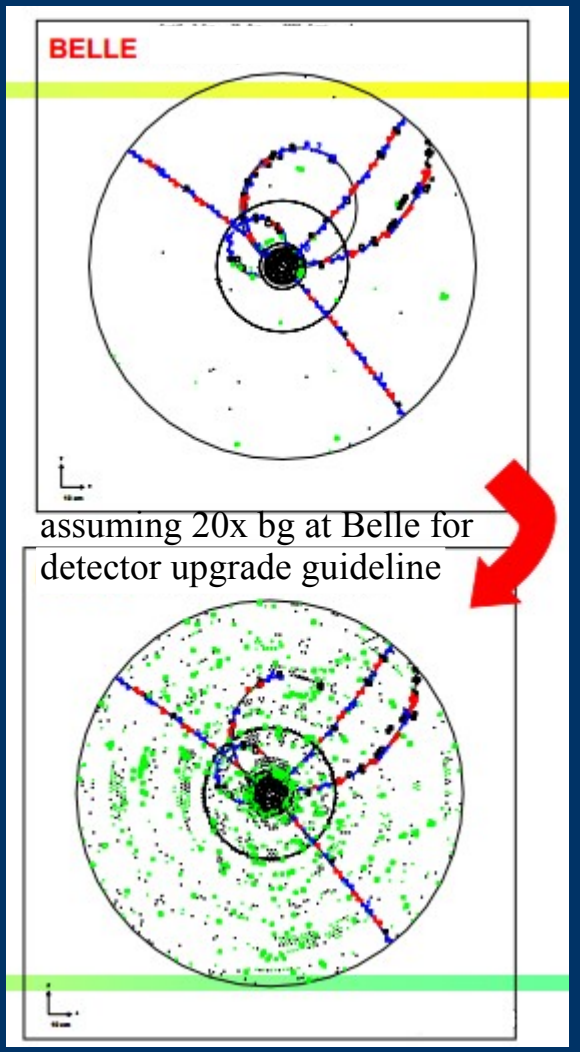
Requirements for the Belle II detector

(critical issues at $L = 8 \times 10^{35}/cm^2/s$)

- Higher event rate
  - ➔ higher trigger rate, DAQ, computing
- Higher background
  - ➔ radiation damage → **BEAST2**
  - ➔ occupancy
  - ➔ fake hits and pile-up noise
- βγ reduced by a factor of 1.5
- Upgrade
  - ➔ better vertexing/tracking
    - ➢ pixel + silicon strip **(VXD)**
    - ➢ new CDC larger volumn smaller cell
  - ➔ better particle identification
  - ➔ faster readout electronics and computing
  - ➔ faster and flexible trigger system
    - ➢ z-vertex trigger to reduce beam background



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Belle II

TDR : arXiv:1011.0352v1 [physics.ins-det]
based on Belle but with upgrades/renovations

ECL
photon, electron
CsI(Tl)
waveform sampling

KLM
Klong, muon
RPC+scintillator (barrel)
scintillator (end-caps)

1.5T solenoid

e^- (7 GeV)

TOP/RICH
particle identification
TOP(barrel): DIRC
RICH(fwd): aerojel

VXD
vertexing
PXD: 2 layers DEPFET
SVD: 4 layers DSSD

e^+ (4 GeV)

CDC
charged particle tracking
track z-vertex trigger
smaller cell size, long level arm
He(50%)+C_2H_6(50%)

L1 trigger rate ~ 20 kHz
GRID computing

except VXD, all others are ready in 2017.

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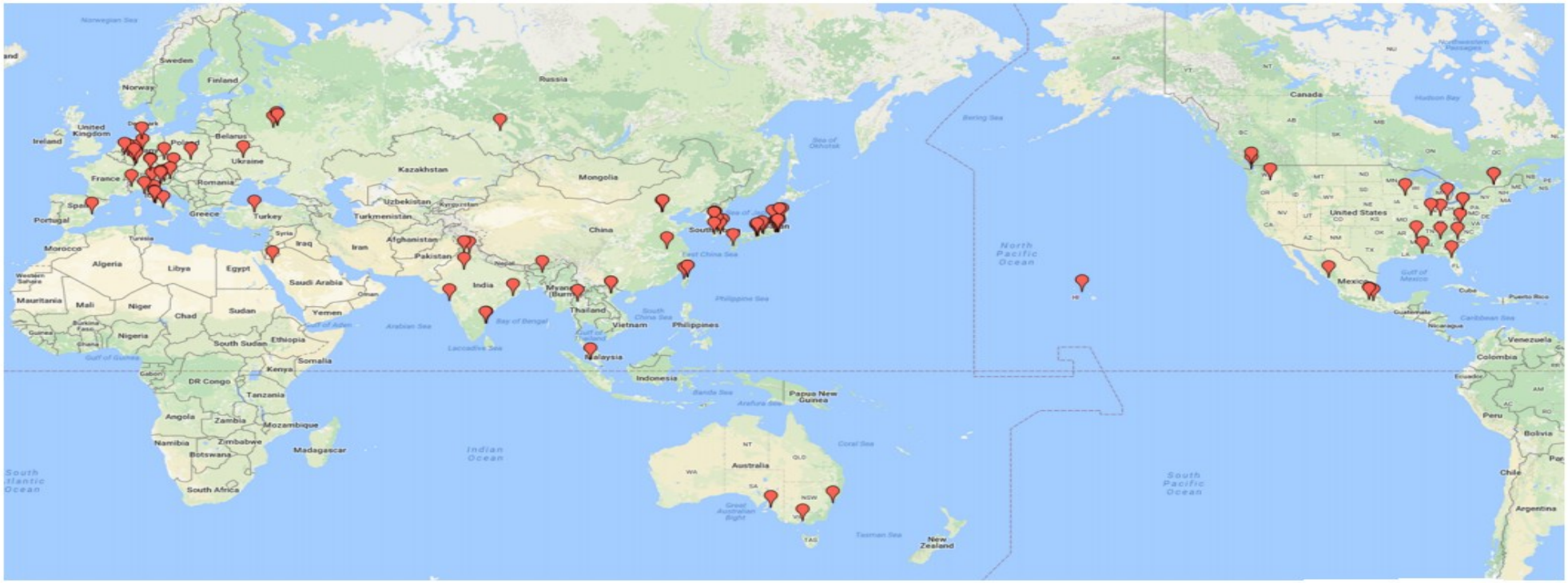
Belle II Collaboration



>700 members
106 institutions

The Belle II experiment

Outline

- SuperKEKB and Belle II
- Physics prospects
- Status and schedule

Belle II physics prospect

P. Urquijo,Nucl. Part. Phys. Proc. 263-264 (2015) 15-23
P. Krizan, Phys. Sci. T158 (2013) 014024
"Belle II-Theory Interface Platform"
https://confluence.desy.de/display/BI/B2TiP+WebHome
(report of Belle II physics book will be submitted to PTEP)
Dolan, M.J., Ferber, T., Hearty, C. et al. J. High Energ. Phys. (2017) 2017: 94.

- B physics
  - ➔ precision measurements of CKM elements
  - ➔ rare B decays
  - ➔ other B decay physics, ...
- Charm physics (Mixing, CPV in charm, rare charm decays,...)
- τ physics (LFV, CPV, ...)
- others
  - ➔ bottomonium spectrum
  - ➔ exotics state (tetraquark, …)
  - ➔ other new physics searching (Higgs BSM, dark sector, ALP, leptoquark, …)

★ advantage with decays with neutral particles in the final states.

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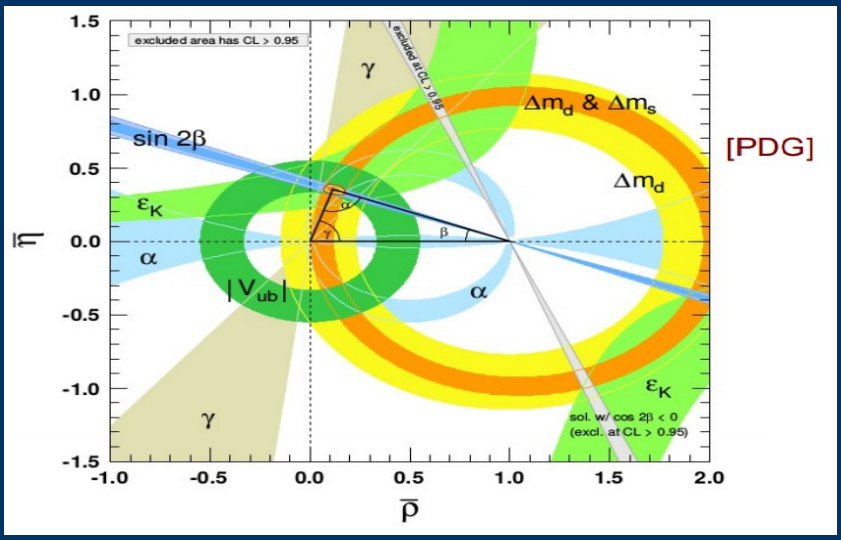
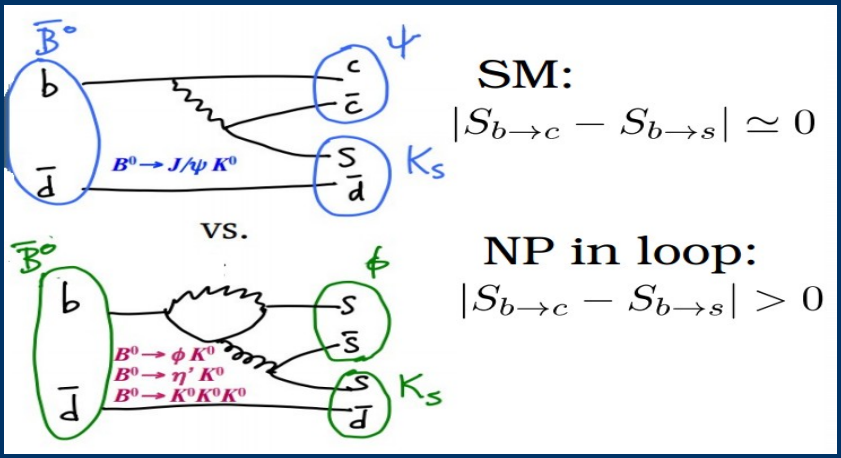
Belle II physics prospect – CKM

- is the unitary triangle really a triangle?
  current $\alpha+\beta+\gamma = (175\pm9)^\circ$ (PDG)
  → Belle II expects to improve the precision
  $\beta \sim 0.3^\circ$, $\alpha \sim 1.0^\circ$, $\gamma \sim 1.5^\circ$
  (precision 5~10% → 1~3%)



- precision measurements of $\sin(2\beta)=\sin(2\phi_1)$
  remains an important topic to check the consistency of the unitary triangle and to search for new source of CPV
  e.g. $\Delta S = \sin(2\beta_{\varphi k^0_S}) - \sin(2\beta_{J/\psi k^0_S})$
  → with 50ab^{-1} data, Belle II can check possible NP contributions even just a small deviation $\Delta S \sim 0.02$



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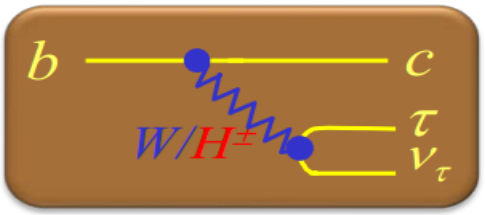
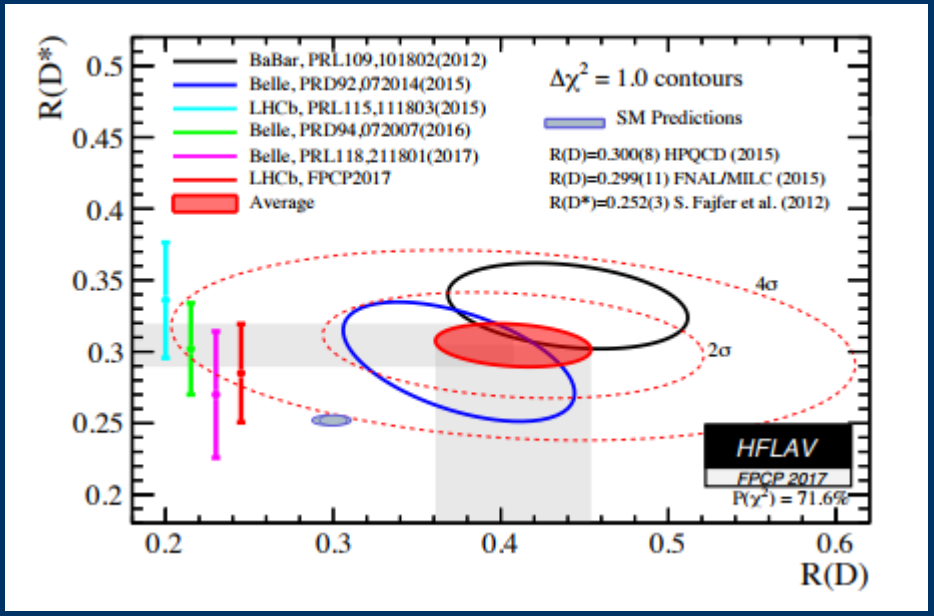
Belle II physics prospect B →D(*) τν

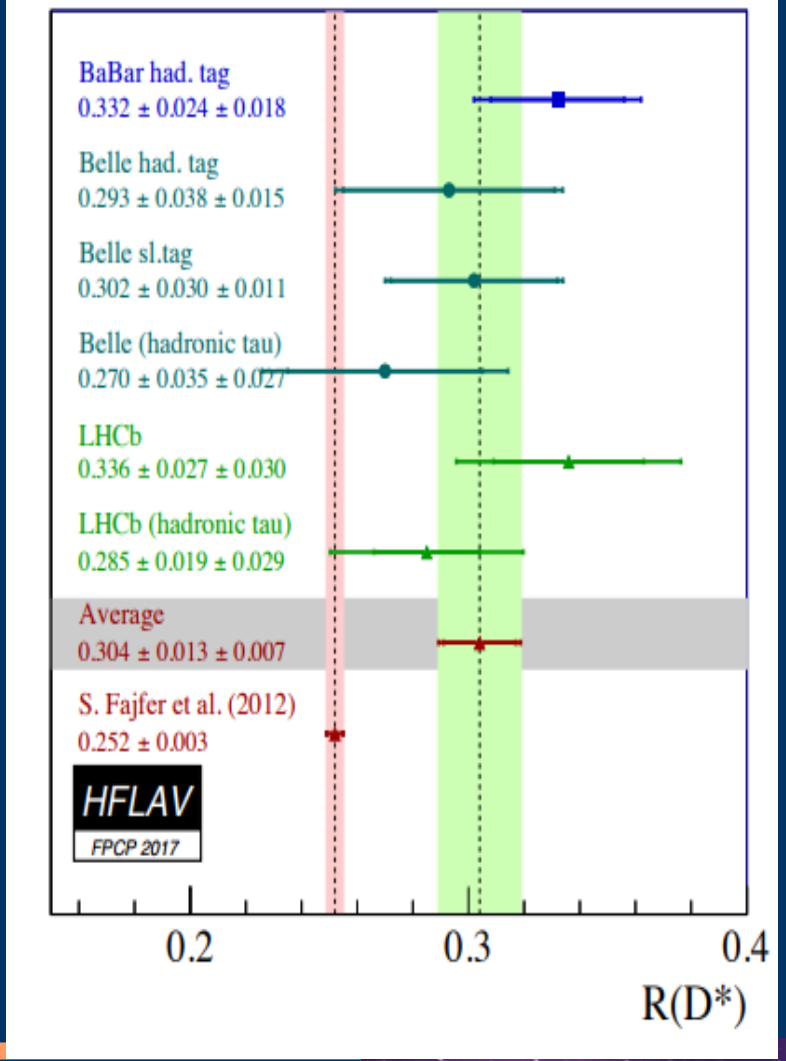


$$R(D^{(*)}) = \frac{\Gamma(B^0 \to D^{(*)} \tau \nu)}{\Gamma(B^0 \to D^{(*)} l \nu)_{l=\mu,e}}$$

larger BF in the SM (~1%)
discrimination of W and H by differential distribution



Belle PRD 97, 012004 (2018) also on τ polarization



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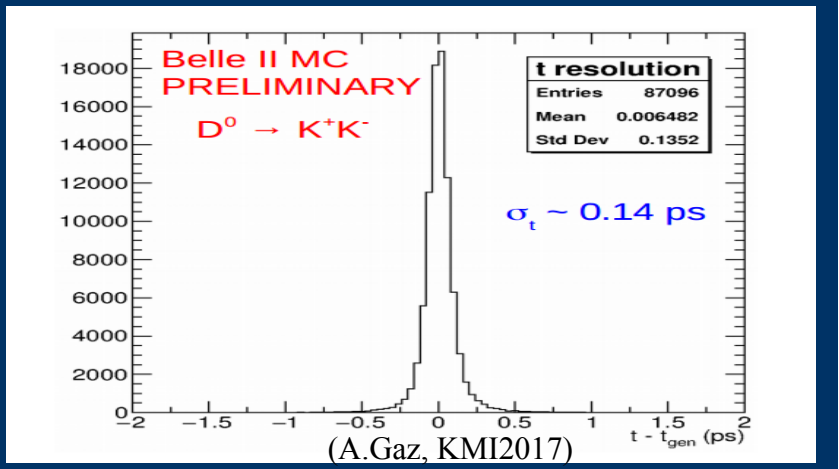
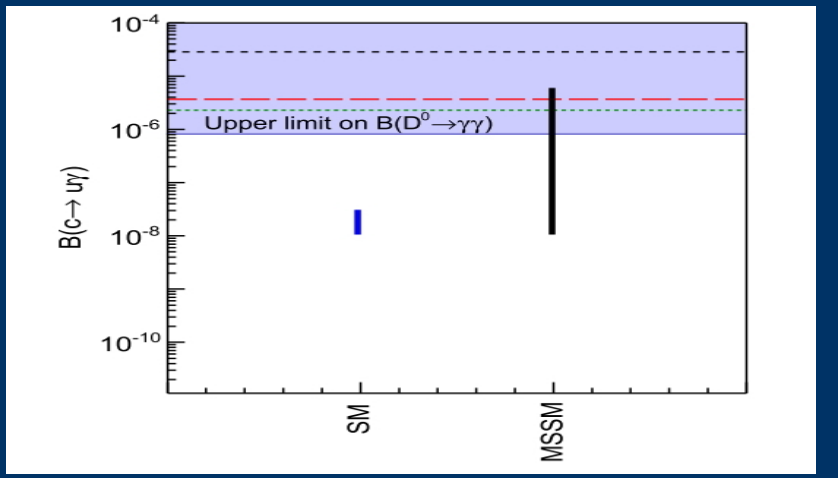
Belle II physics prospect – charm physics

- B factories discovered the D^0 -$\overline{D}^0$ mixing.
  - ➔ Belle II will improve the measurements of the mixing parameters and look for CPV.
  - ➔ with improved vertexing, proper time resolution for D^0 decays ~ 0.14 ps (0.27 ps @ Babar)



(A.Gaz, KMI2017)

- Rare charm decays, e.g.
  - ➔ $D^0 \rightarrow \gamma\gamma$
  - ➔ predicted BF a few x 10^{-8}
  - ➔ Belle result 8.5×10^{-7} @ 90%CL (PRD 93, 051102(R), 2016; 832 fb^{-1} data)
  - ➔ expected to reach 10^{-7}~10^{-8} (with full Belle II data)



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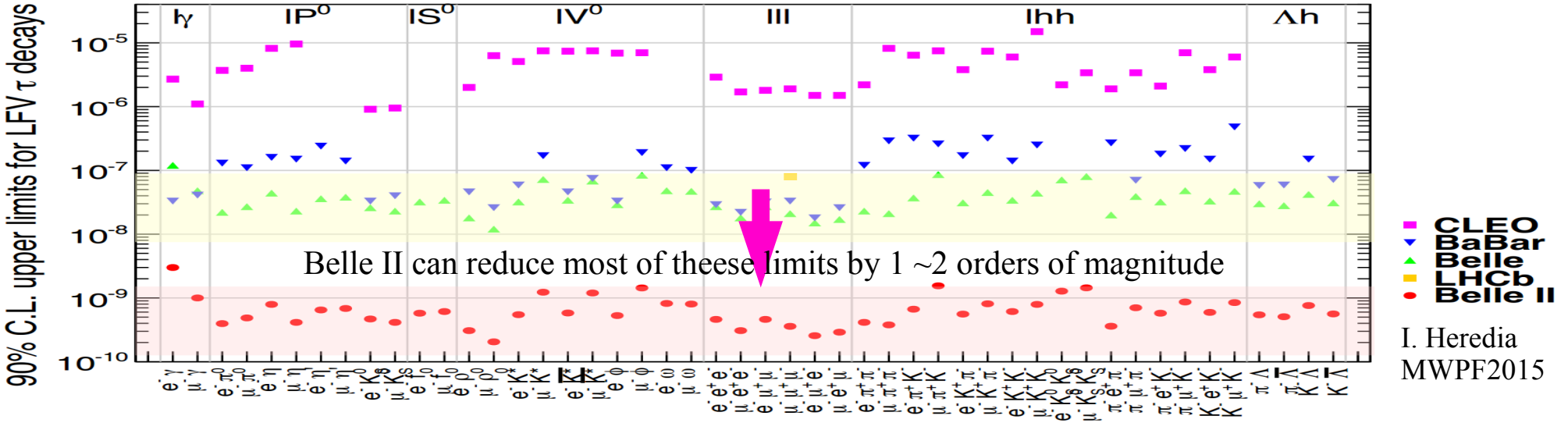
Belle II physics prospect – tau LFV

LFV is suppressed in SM → a few models predict enhancements within Belle II's reach.



$\tau \to \mu\gamma$

main background from $ee \to \mu\mu\gamma_{ISR}$

reduce sensitivity by a factor ~7

$\tau \to \mu\mu\mu$

very clean mode

reduce sensitivity by a factor of 50

	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \mu\mu\mu)$	
mSUGRA+seesaw	10^{-7}	10^{-9}	PRD 66(2002) 115013
SUSY+SO(10)	10^{-8}	10^{-10}	PRD 68(2003) 033012
SM+seesaw	10^{-9}	10^{-10}	PRD 66(2002) 034008
Non-Universal Z'	10^{-9}	10^{-8}	PLB 547(2002) 252
SUSY+Higgs	10^{-10}	10^{-7}	PLB 566(2003) 217
possible reach by Belle II (50 ab^{-1})	$<10^{-9}$	$< 10^{-10}$	→ good to test NP

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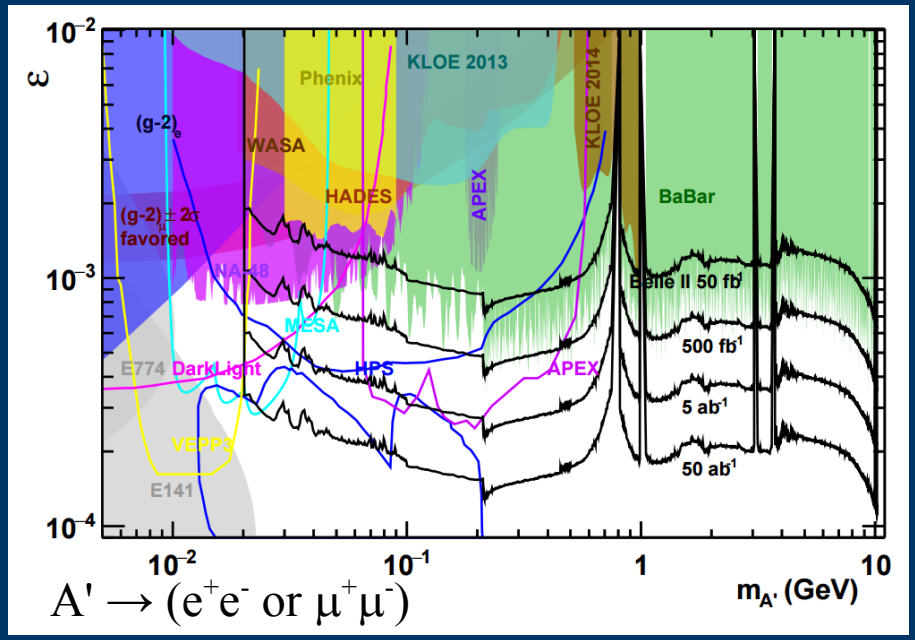
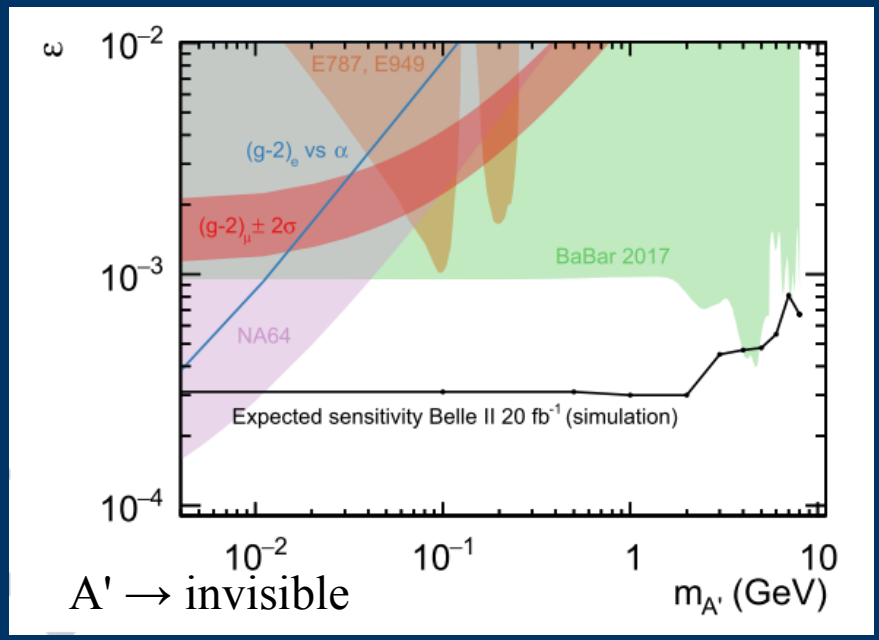
potential early physics topics (in 2018~2019)

possible to collect 300fb^{-1} data, possible for some physic studies

single photon events, special trigger configuration is considered in the trigger menu.

$e^+e^- \rightarrow \gamma A', \quad A' \rightarrow$ invisible or (e^+e^- or $\mu^+\mu^-$) (dark photon)





$\varepsilon^+\varepsilon^- \rightarrow \gamma \alpha', \quad a' \rightarrow$ invisible (ALP)

$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow$ invisible (light Higgs)

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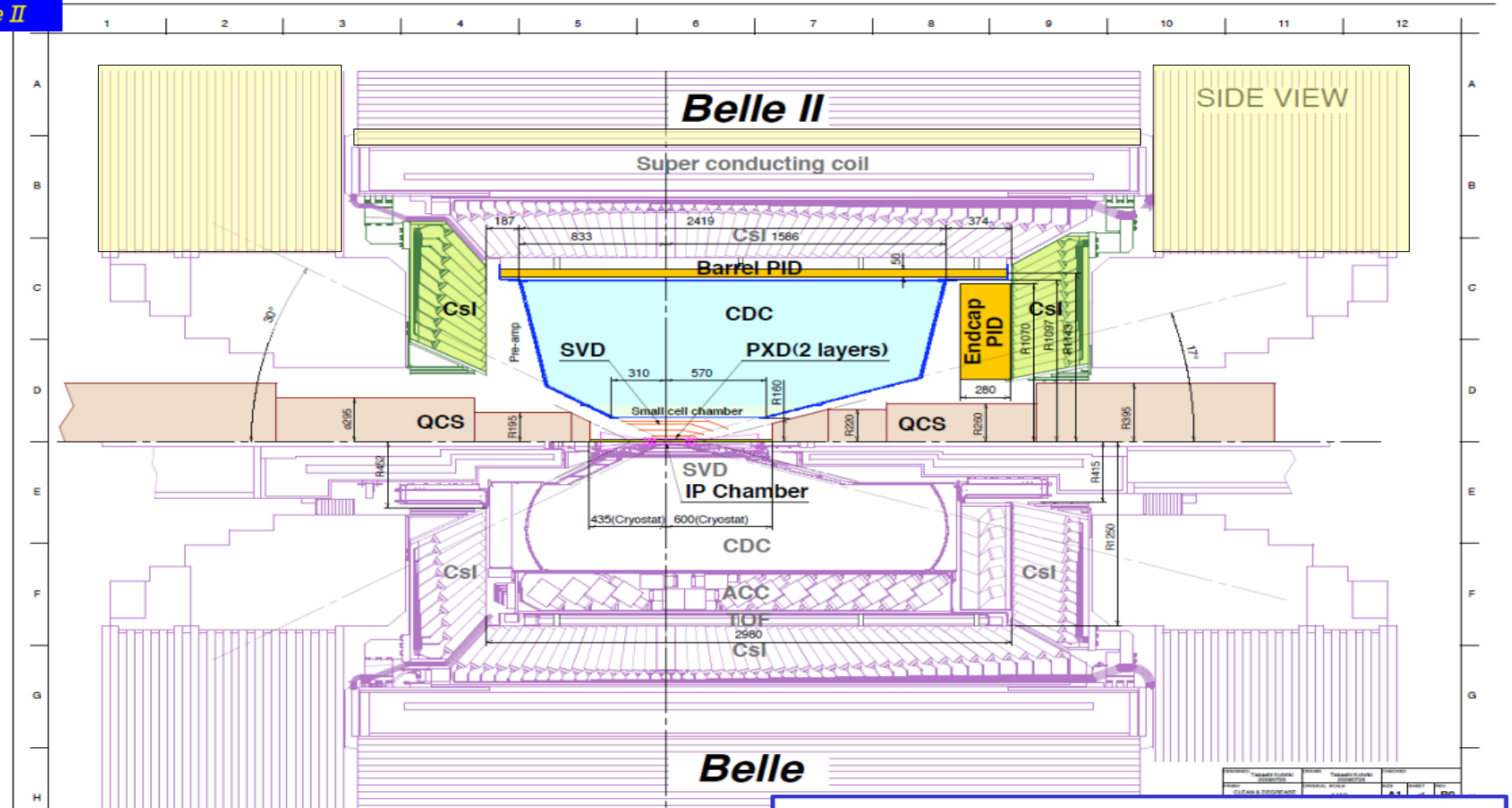
The Belle II experiment

Outline

- SuperKEKB and Belle II
- Physics prospects
- Status and schedule
  - detector status
  - schedule
    - 2016 phase 1
    - 2017 GCR
    - 2018 phase 2
    - .....

Belle II (top) compared with Belle (bottom)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm

ACC+TOF → TOP+A-RICH
ECL: waveform sampling
KLM: RPC → Scintillator +SiPM (end-caps)

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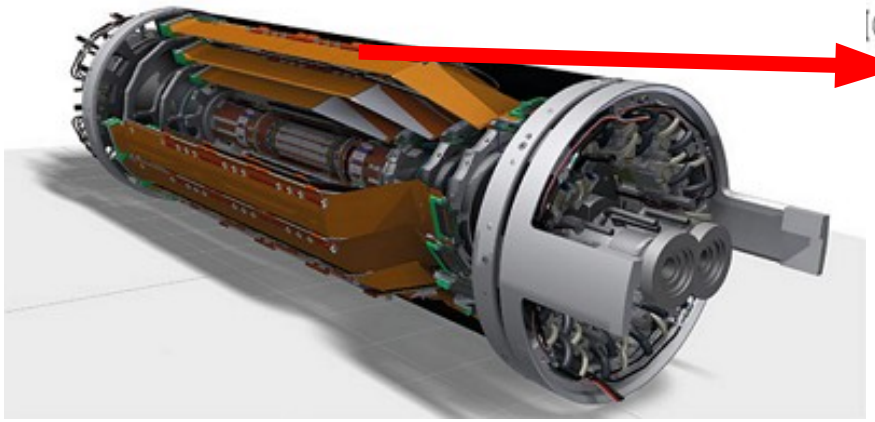
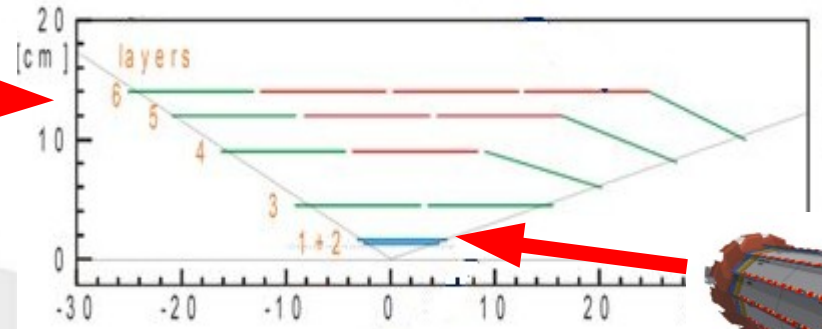
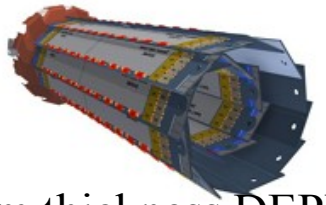
VXD = SVD + PXD





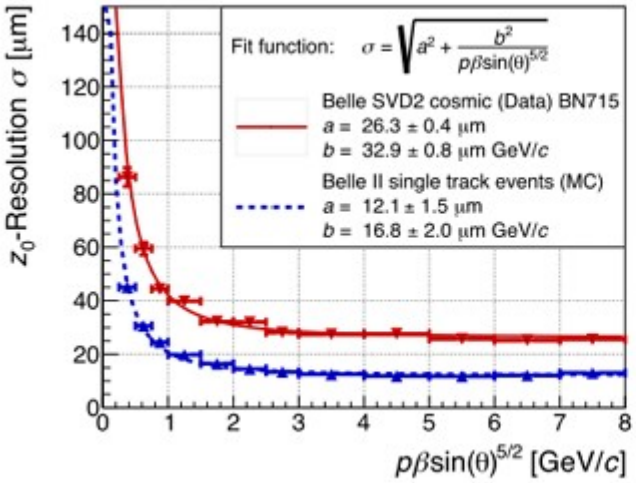


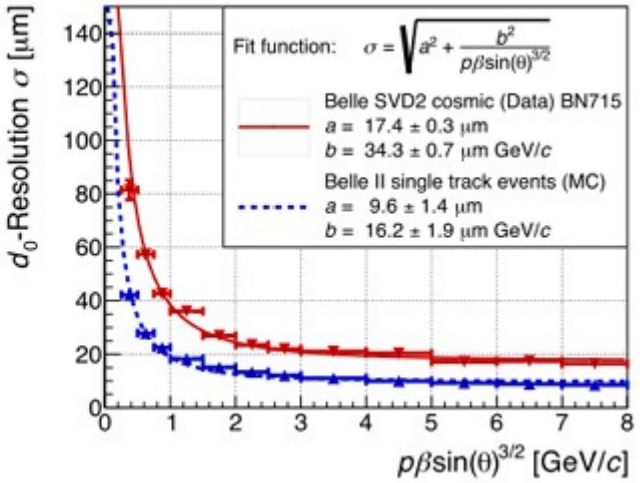
76 µm thickness DEPFET

4 layers DSSD (SVD)
2 layers DEPFET (PXD)

final focus quadrupole
„intergrated“ into VXD

vertex resolution improved
by a factor of 2
(compared to Belle)





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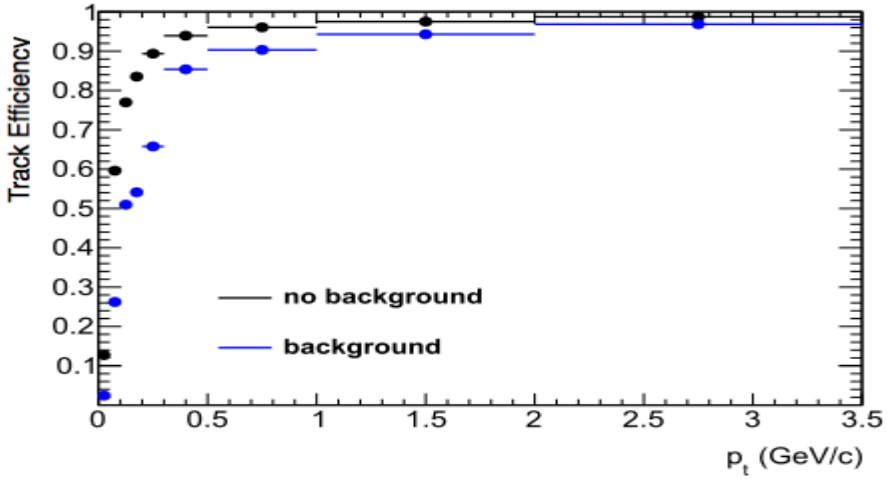
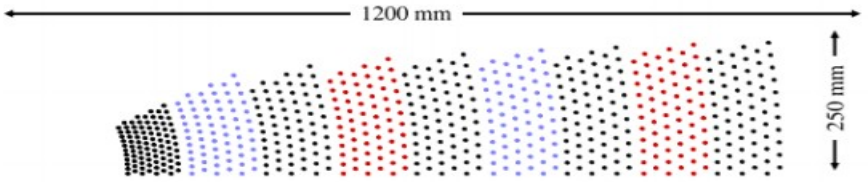
CDC
(central drift chamber)

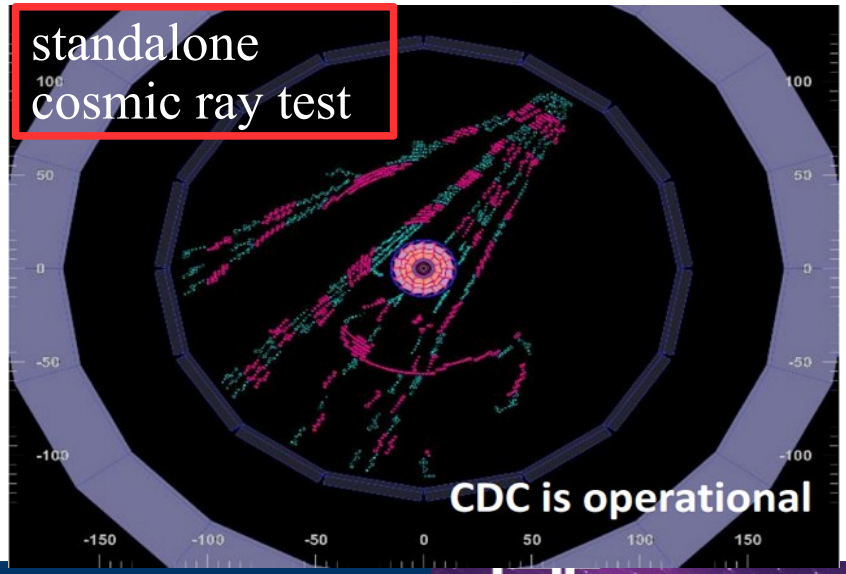
- charged track reco. and momentum determination
- particle identification via dE/dx
- charged track trigger



$$\frac{\sigma_{p_t}}{p_t} \sim 0.3\%/\beta \oplus 0.1\% \cdot p_t[GeV/c]$$

$$\sigma\left(\frac{dE}{dx}\right)\Big|_{\text{MIP}} \sim 5\%$$





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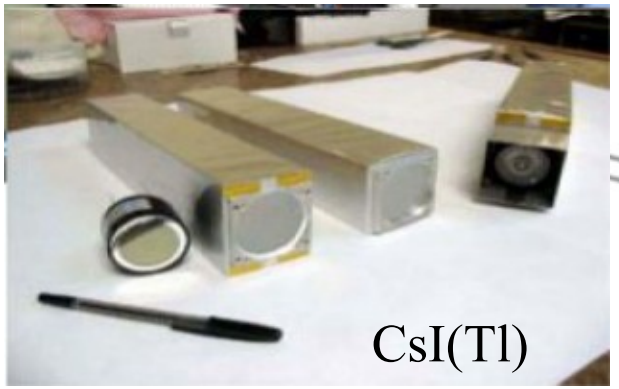
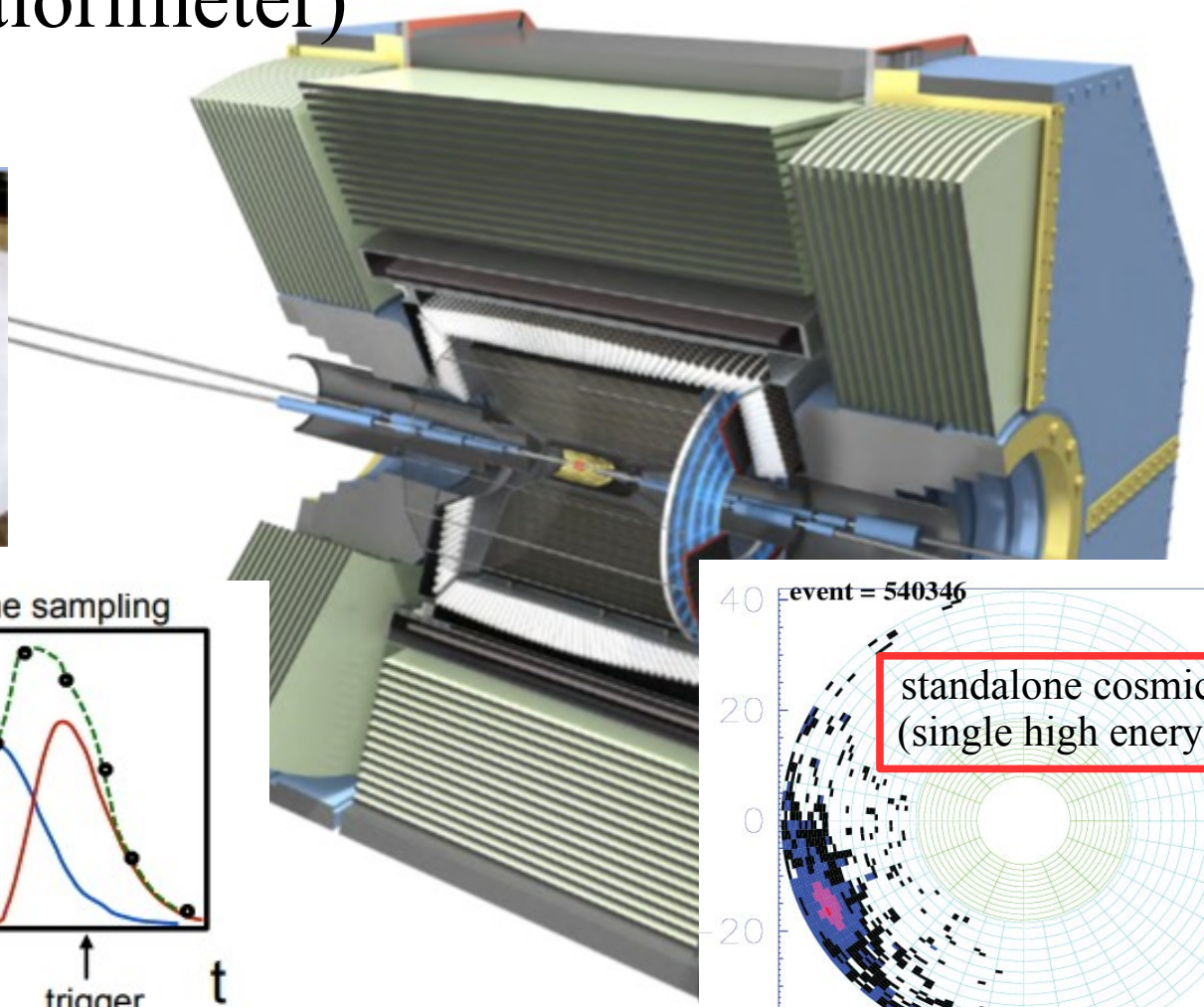
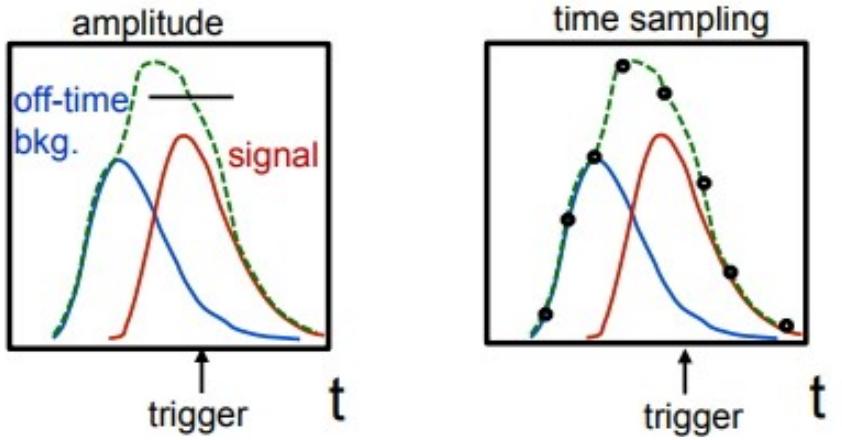
ECL (EM calorimeter)





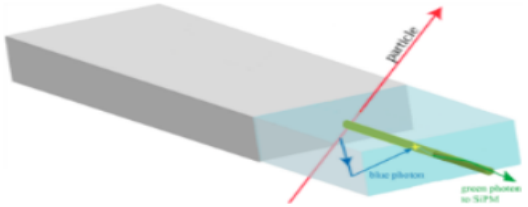


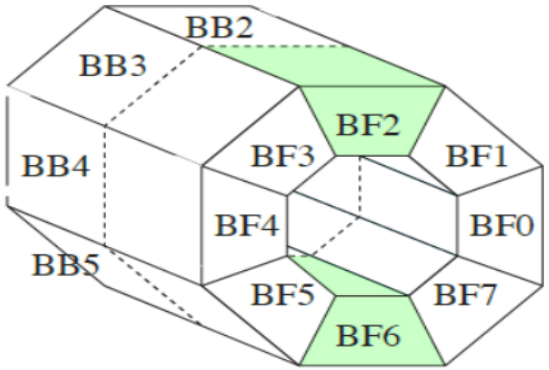
waveform sampling to reject off timing hits

standalone cosmic ray test
(single high enery shower)

KLM (K_ℓ and μ detector)

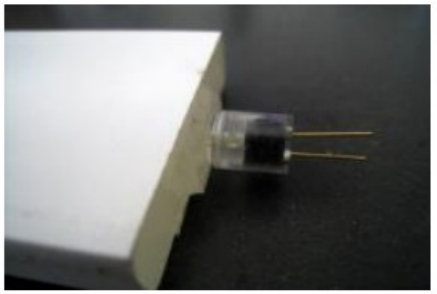
Interleaved with the iron plates of the flux return yoke





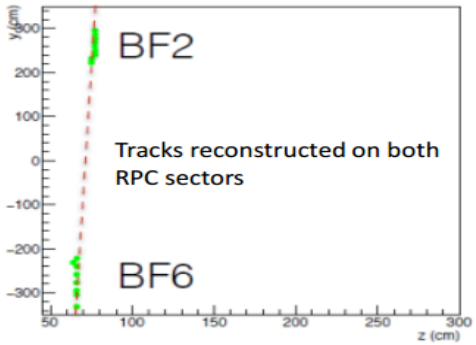
- Barrel:

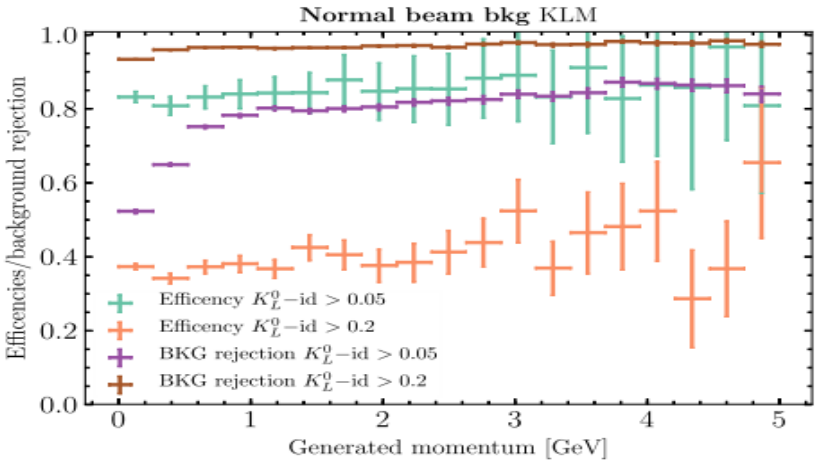
Belle RPCs reused
Two inner layers replaced by scintillator strips
Scintillator strips with WLS fibers
Hamamatsu SiPM S10362

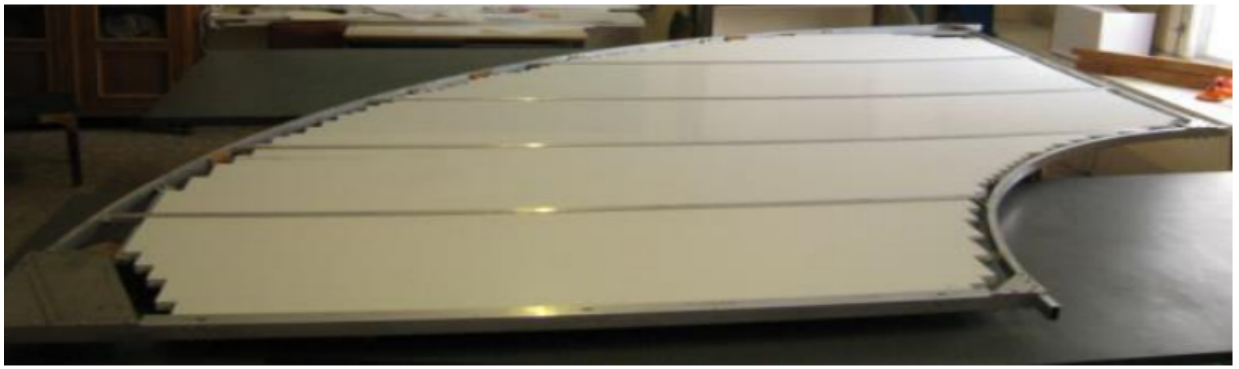


- Endcap:

RPCs replaced with polystyrene scintillators
99% geometrical acceptance. σ ~ 1ns







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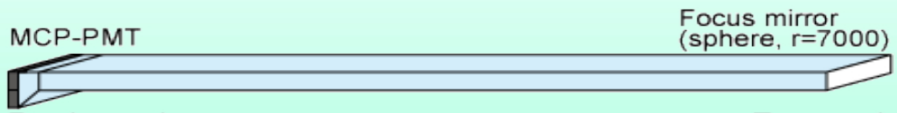
Particle Identification devices

Barrel PID: TOP (Time Of Propagation)



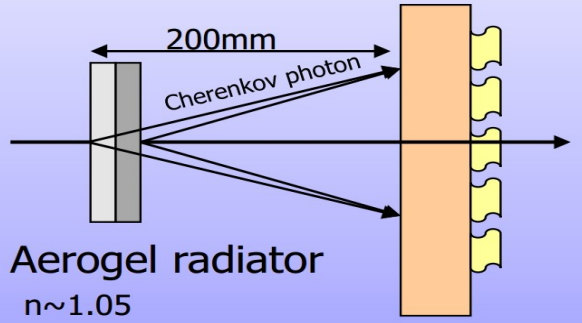
Quartz radiator

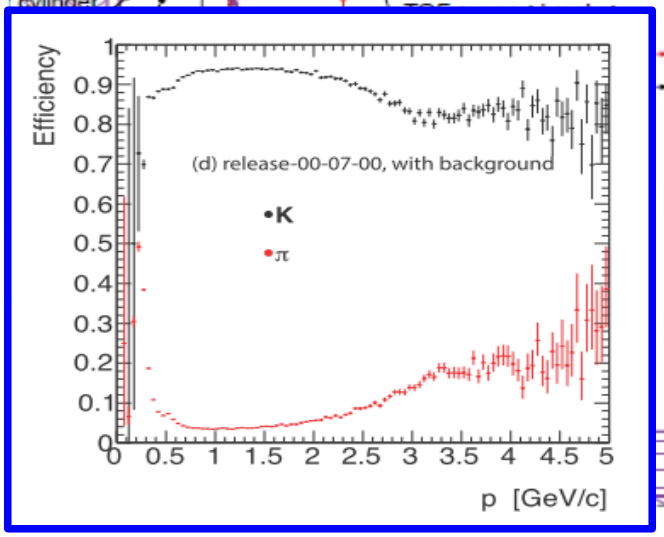
Focusing mirror

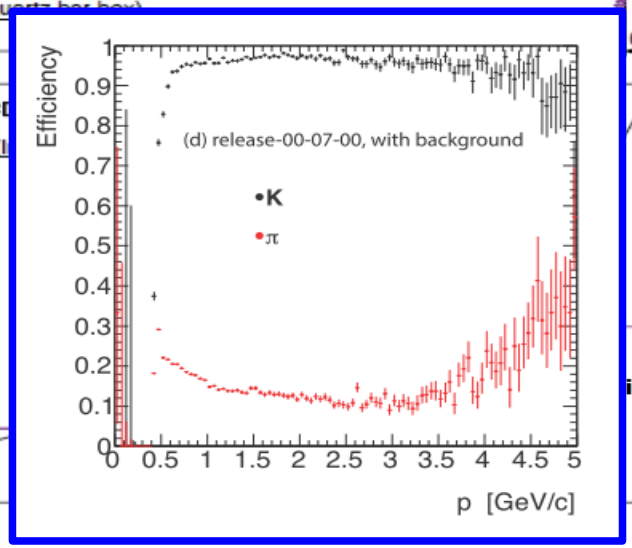
Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

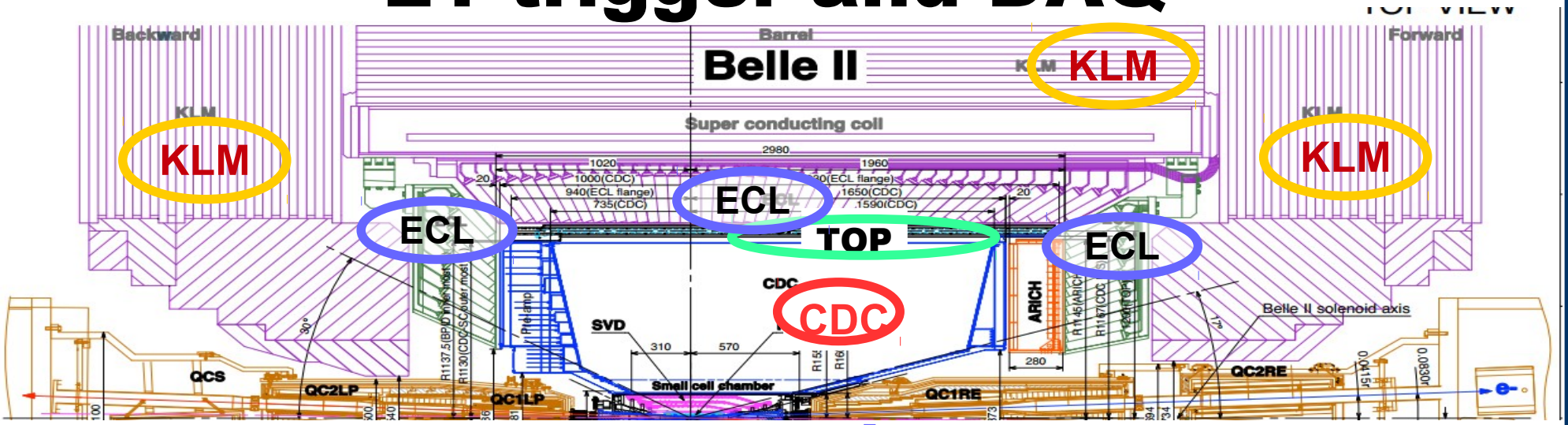
EndCap PID: aerogel RICH







L1 trigger and DAQ



Belle II Level 1 trigger
(CDC + ECL + TOP + KLM)
beam bunch crossing 254 MHz (max.)
nominal beam background rate ~10 MHz
nominal L1 trigger rate ~20 KHz
L1 max. latency 5 μs
L1 z-vertex trigger
L1 Global Reconstruction Logic

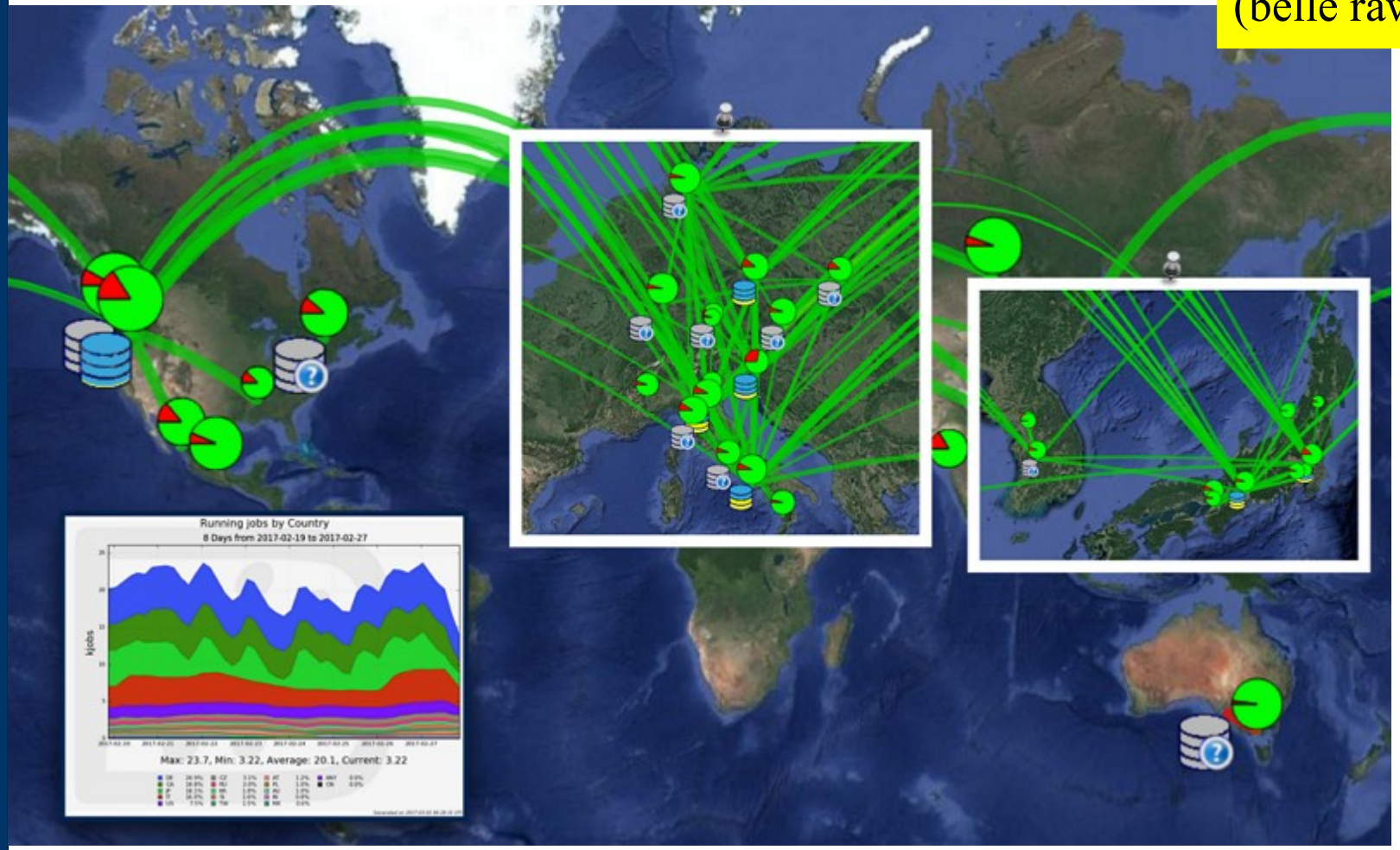
Belle II software platform
BASF2 (ROOT/C++/Python)

DAQ, HLT, and analysis

* HLT output rate 6 KHz (1.8 GB/s)

GRID for Belle II (facilitated by DIRAC)

raw data 20 PB/yr
total 100 PB
(belle raw data total 1 PB)



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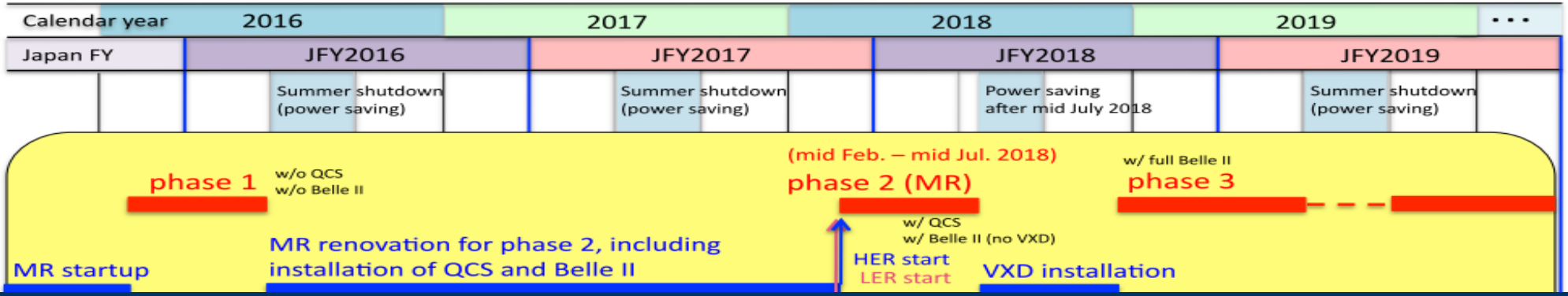
Schedule in the recent years



2011
ground breaking

Before full physics commissioning:
there are 3 phases for SuperKEKB

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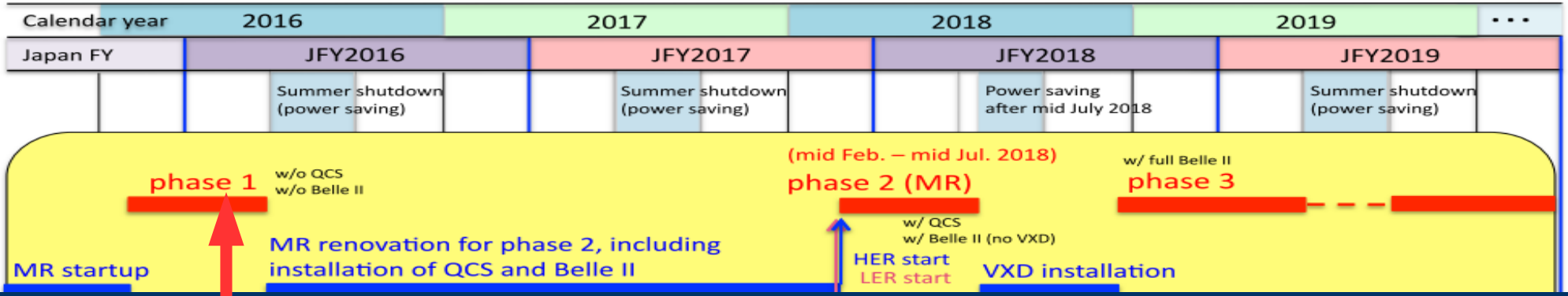
Schedule in the recent years



2011
ground breaking

accelerator back to be online
SuperKEKB/Belle II no longer being "next generation"

Phase 1: beam practice
BEAST2 phase 1
no collision
no Belle II
vacuum scrubbing
background study

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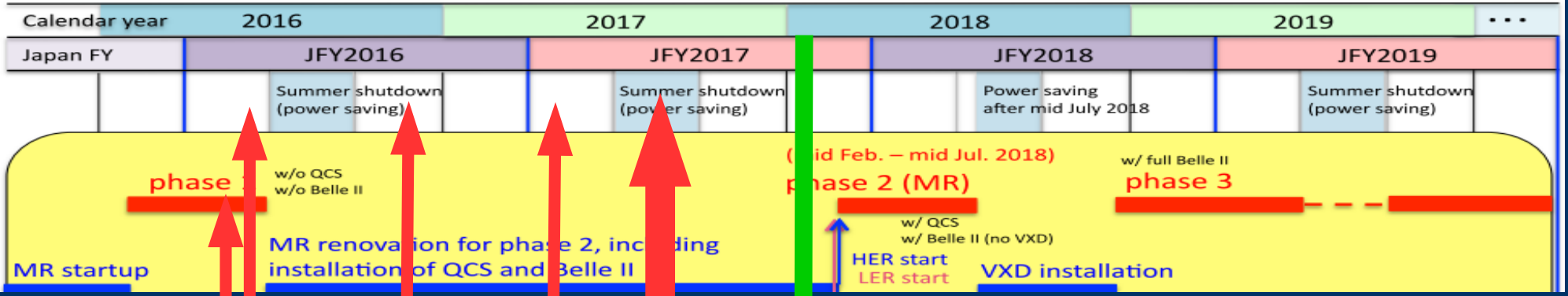
Schedule in the recent years



2011
ground breaking

TOP

CDC

Belle II roll-in

QCS (for final focusing)

now

GCR (global cosmic ray runs)

Phase 1: beam practice
BEAST2 phase 1
no collision
no Belle II
vacuum scrubbing
background study

Belle II outer detectors (ECL+KLM+TOP+CDC+RICH)
Belle II is reloaded

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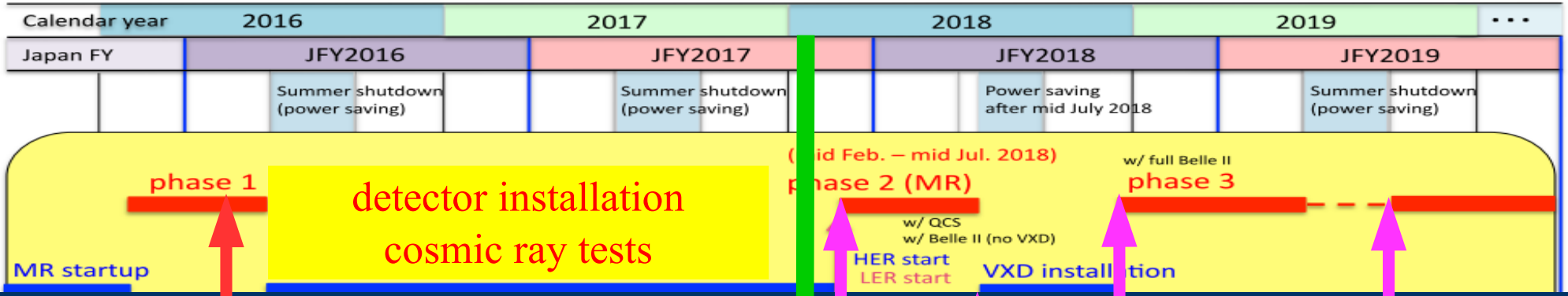
Schedule in the recent years



2011
ground breaking

Phase 1: beam practice
BEAST2 phase 1
no collision
no Belle II
vacuum scrubbing
background study

now

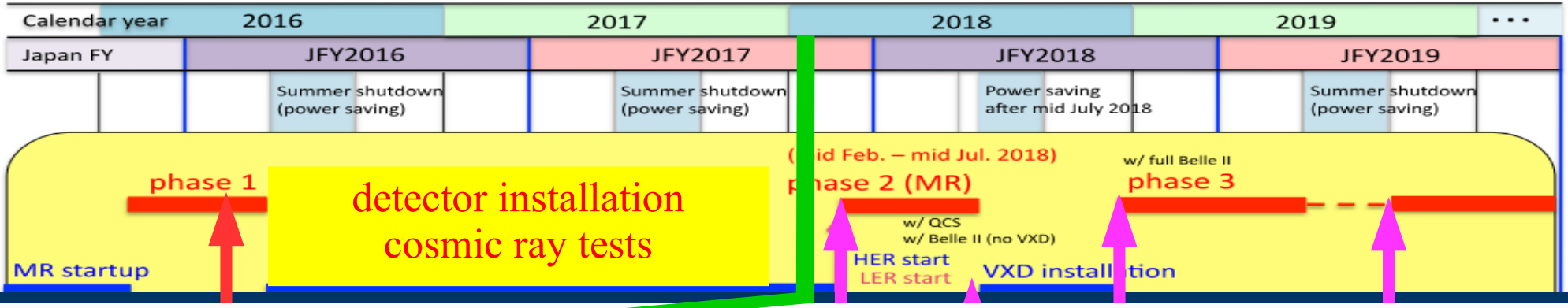
Phase 2: beam collision
BEAST2 phase 2
no VXD

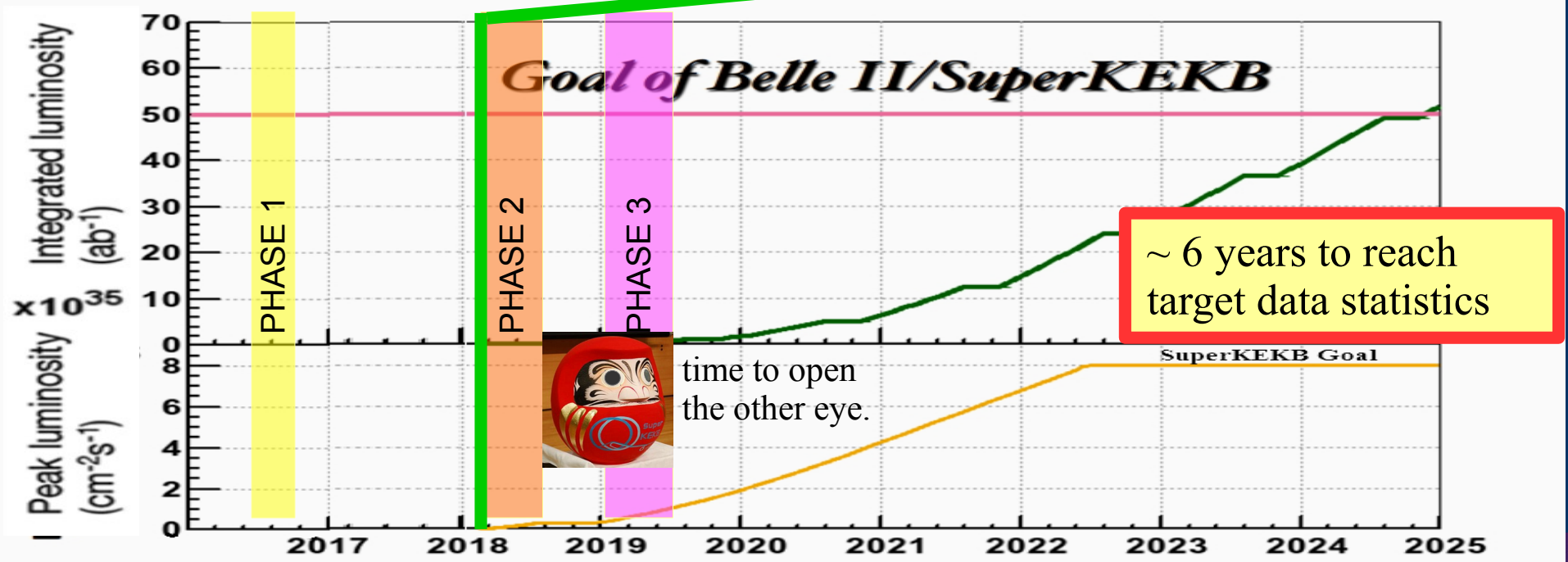
VXD
(SVD+PXD)

Phase 3: increasing lumi.
full Belle II
physics run 1

keep running,
and running,
and running,
.....

Schedule in the recent years





Belle II

Phase 1

2016 Feb. ~ Jun.
SuperKEKB
beam commissioning
(no collision)

Done!! 卒業

beam bg/machine study

Phase 2

2018 Feb~July
collision tuning
partial Belle II
(no vertexing)

$L \geq 10^{34}/cm^2/s$

possible early measurements

Phase 3 ...

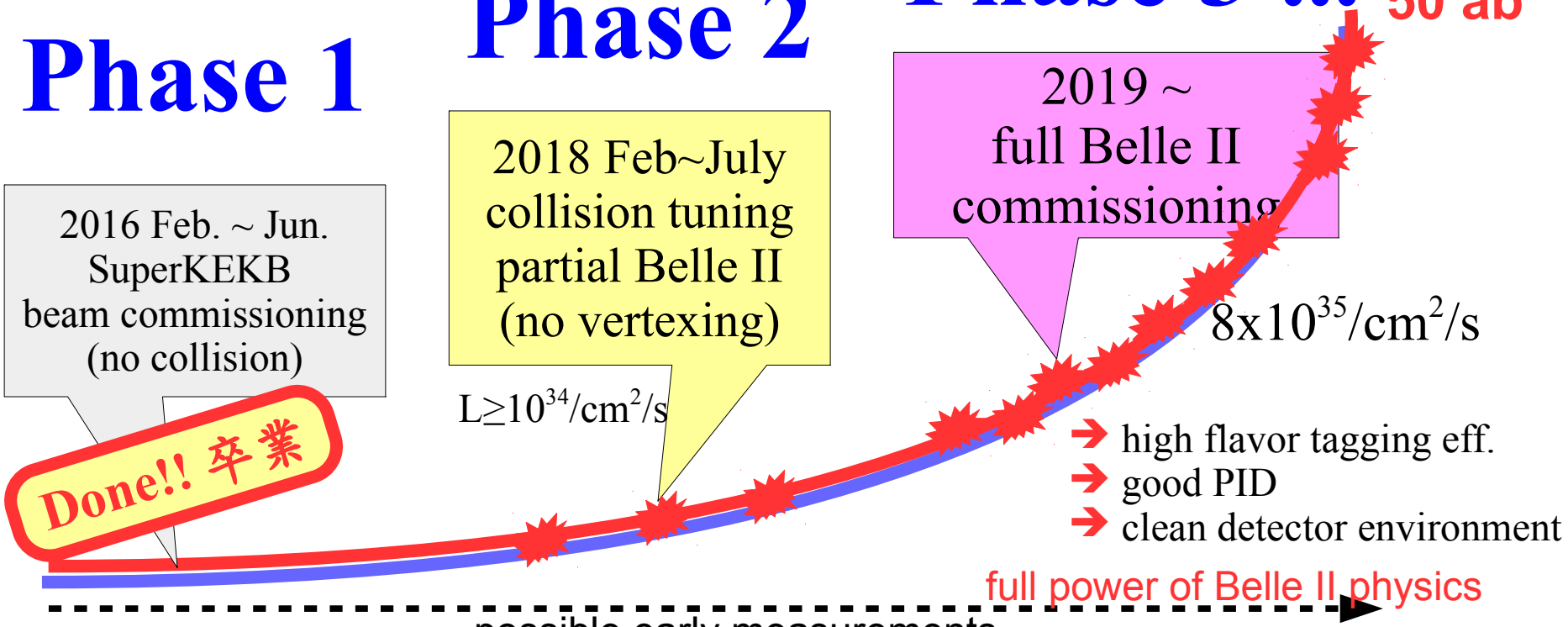
2019 ~
full Belle II
commissioning

$8 \times 10^{35}/cm^2/s$

50 ab^{-1}

- high flavor tagging eff.
- good PID
- clean detector environment

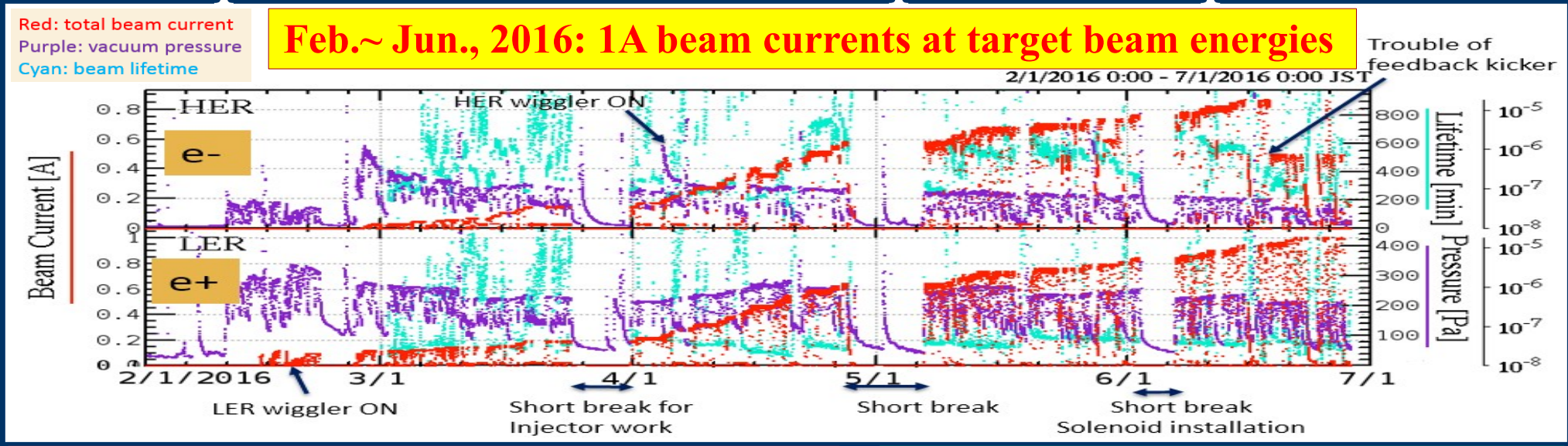
full power of Belle II physics

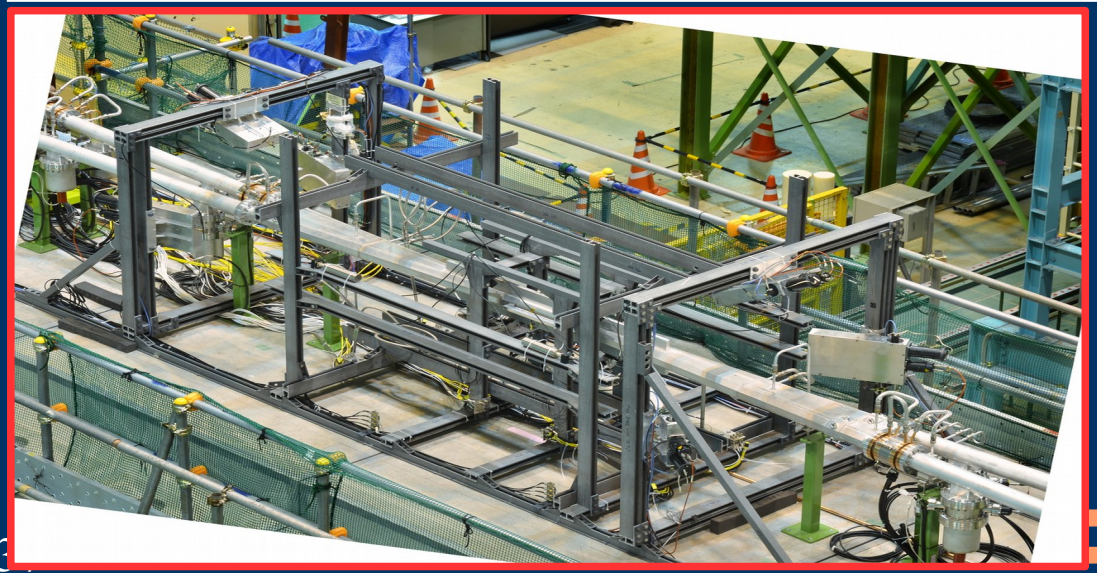


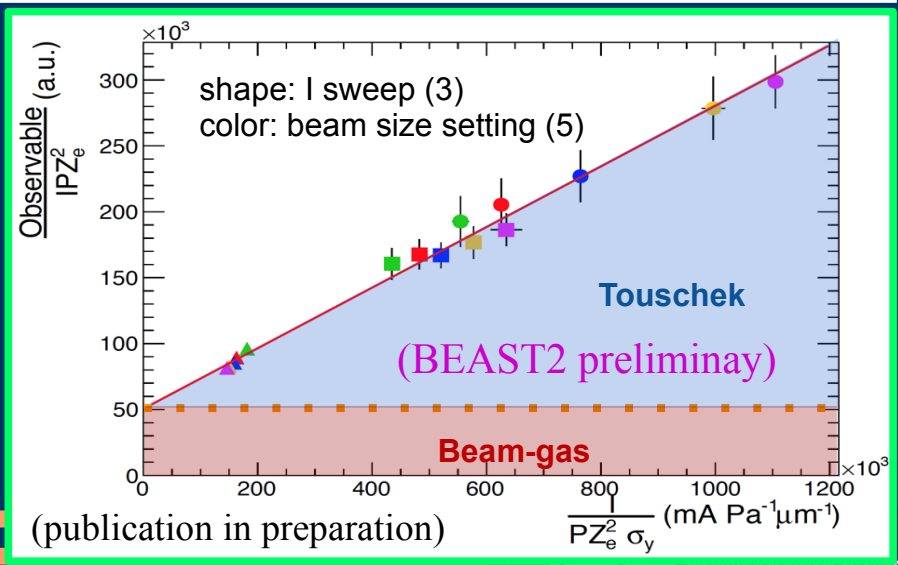
SuperKEKB/BEAST2 phase 1 opeation

Red: total beam current
Purple: vacuum pressure
Cyan: beam lifetime

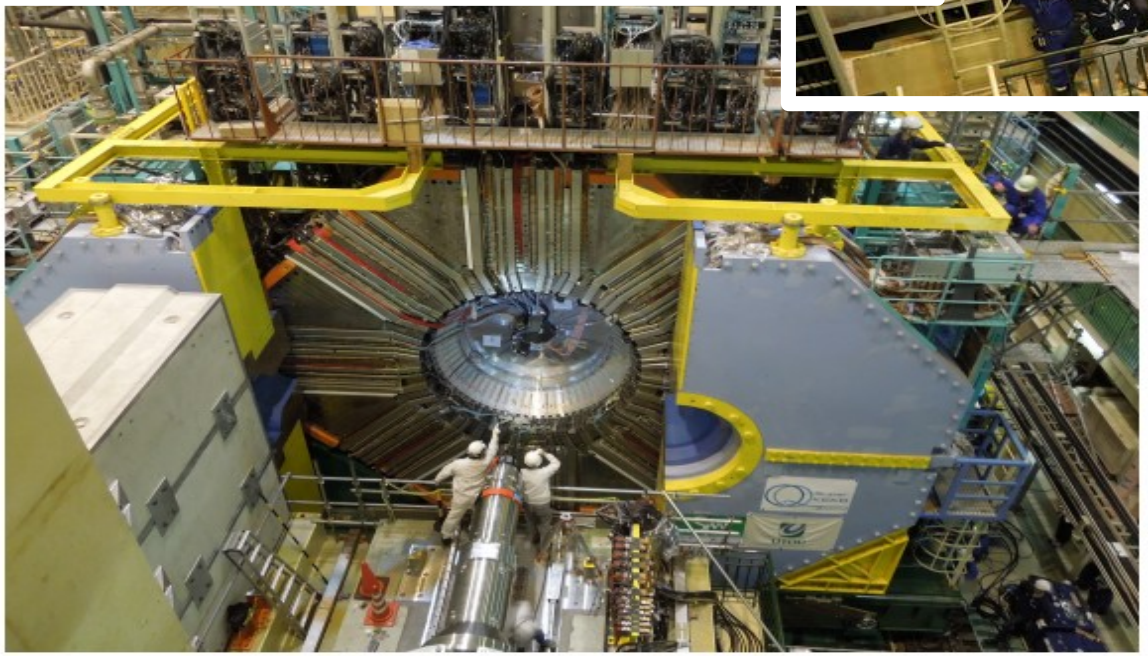
Feb.~ Jun., 2016: 1A beam currents at target beam energies





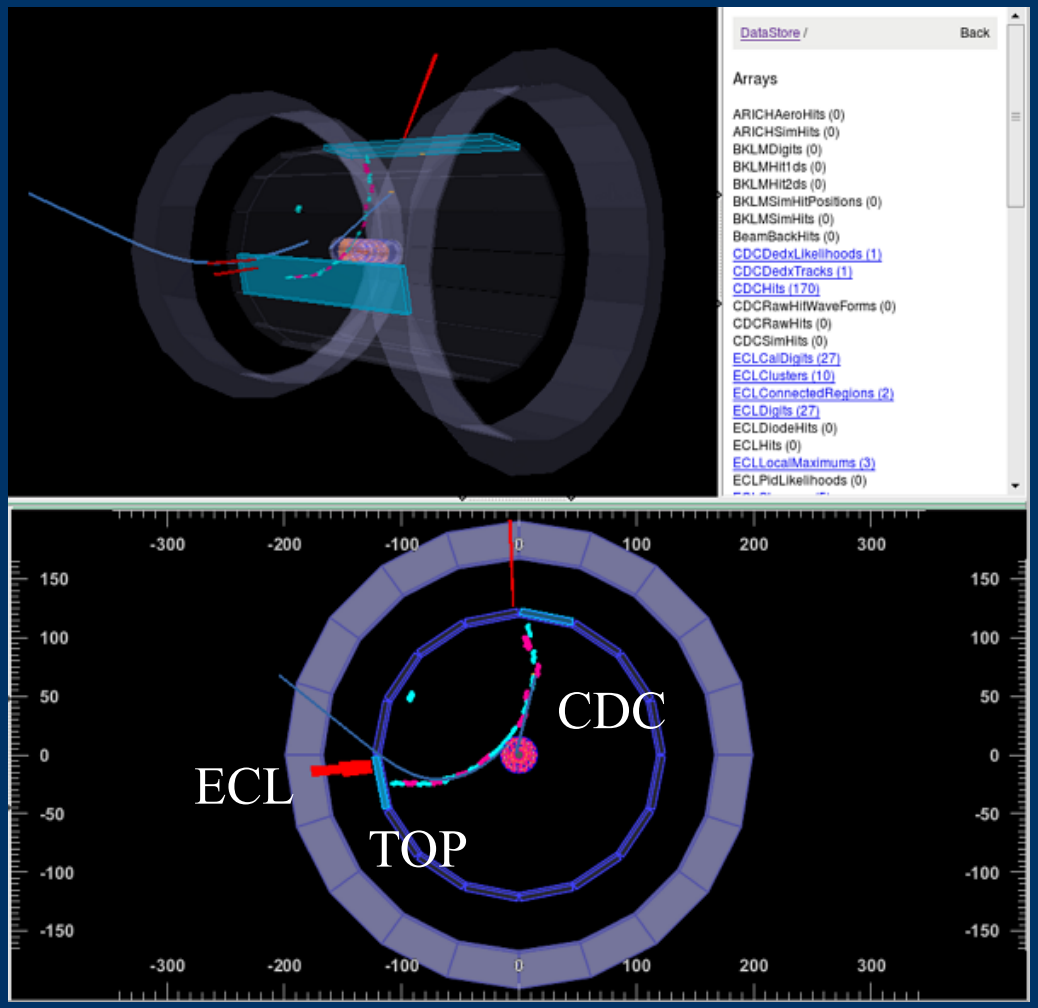


Belle II roll-in (April 11, 2017)



Belle II
in position now
(~~VXD~~)

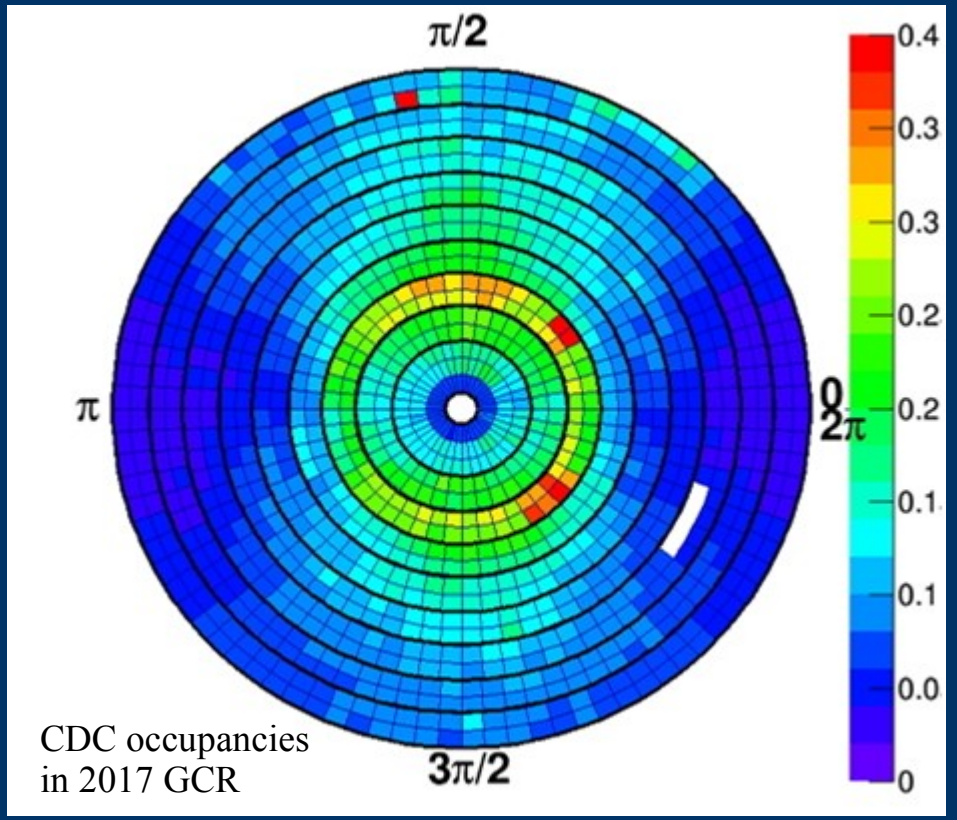
Belle II 2017 summer GCR



ECL/TOP/CDC are read-out simultaneously

magnetic ON
(B-field mapper inside CDC)

simplified trigger by ECL+CDC (10-100 Hz)
detector/DAQ performance studies



CDC occupancies
in 2017 GCR

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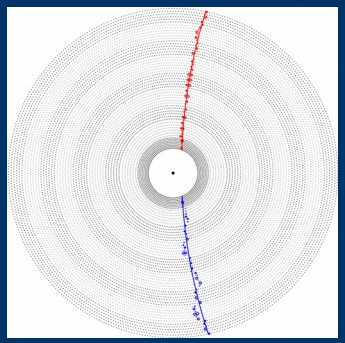
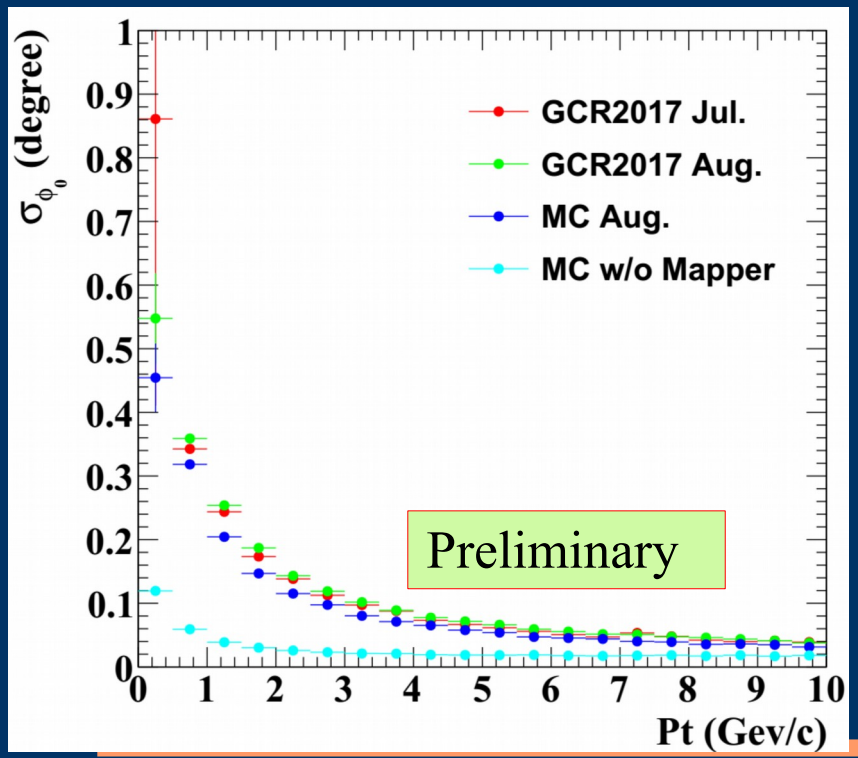
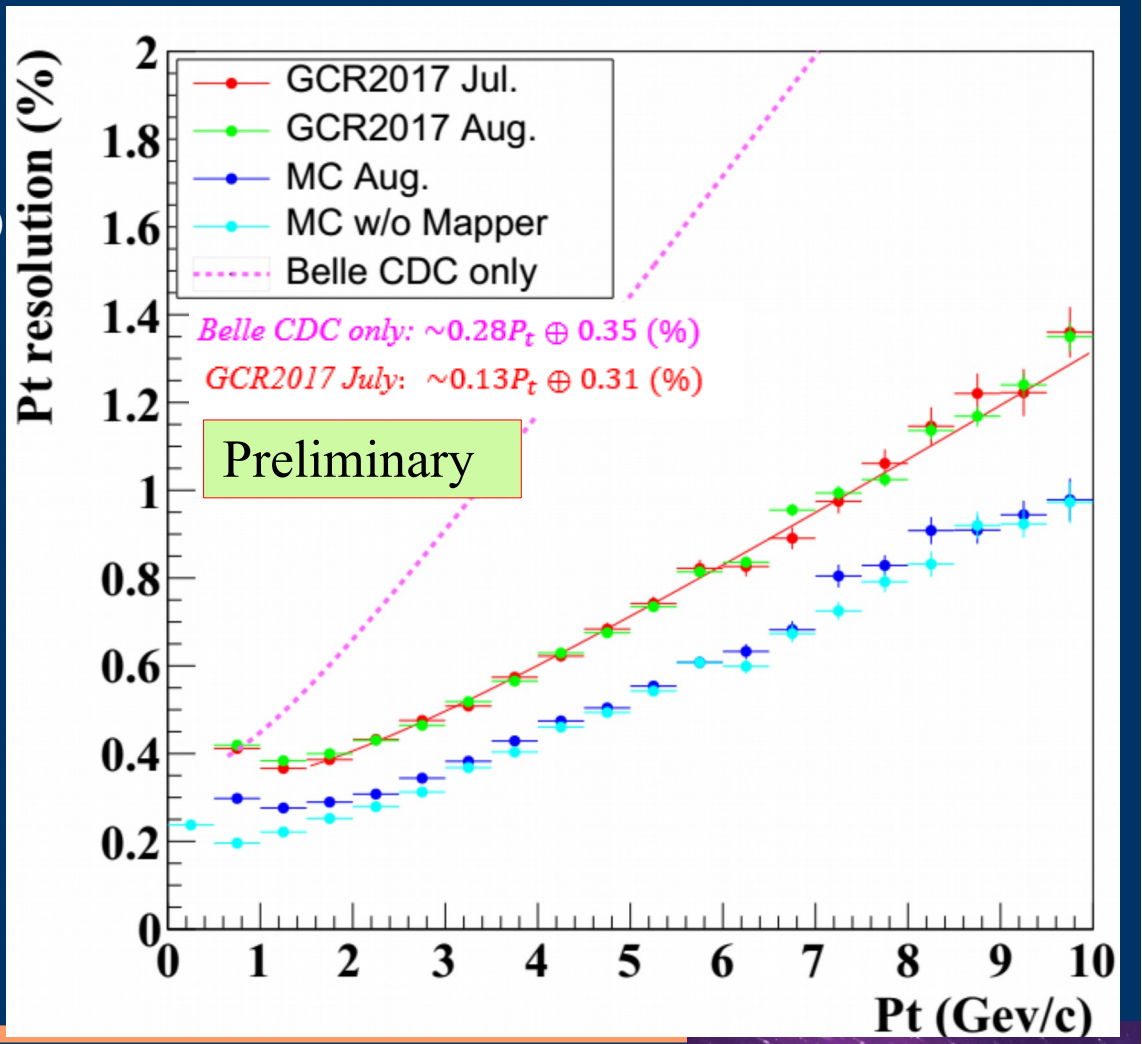
Belle II 2017 summer GCR



Event selections:

- $|d_0| < 3$cm (~IP tracks)
- $-5\text{cm} < z_0 < 15$ (~IP track)
- $|\tan\lambda| < 0.45$
  (reduce the effect of mapper)





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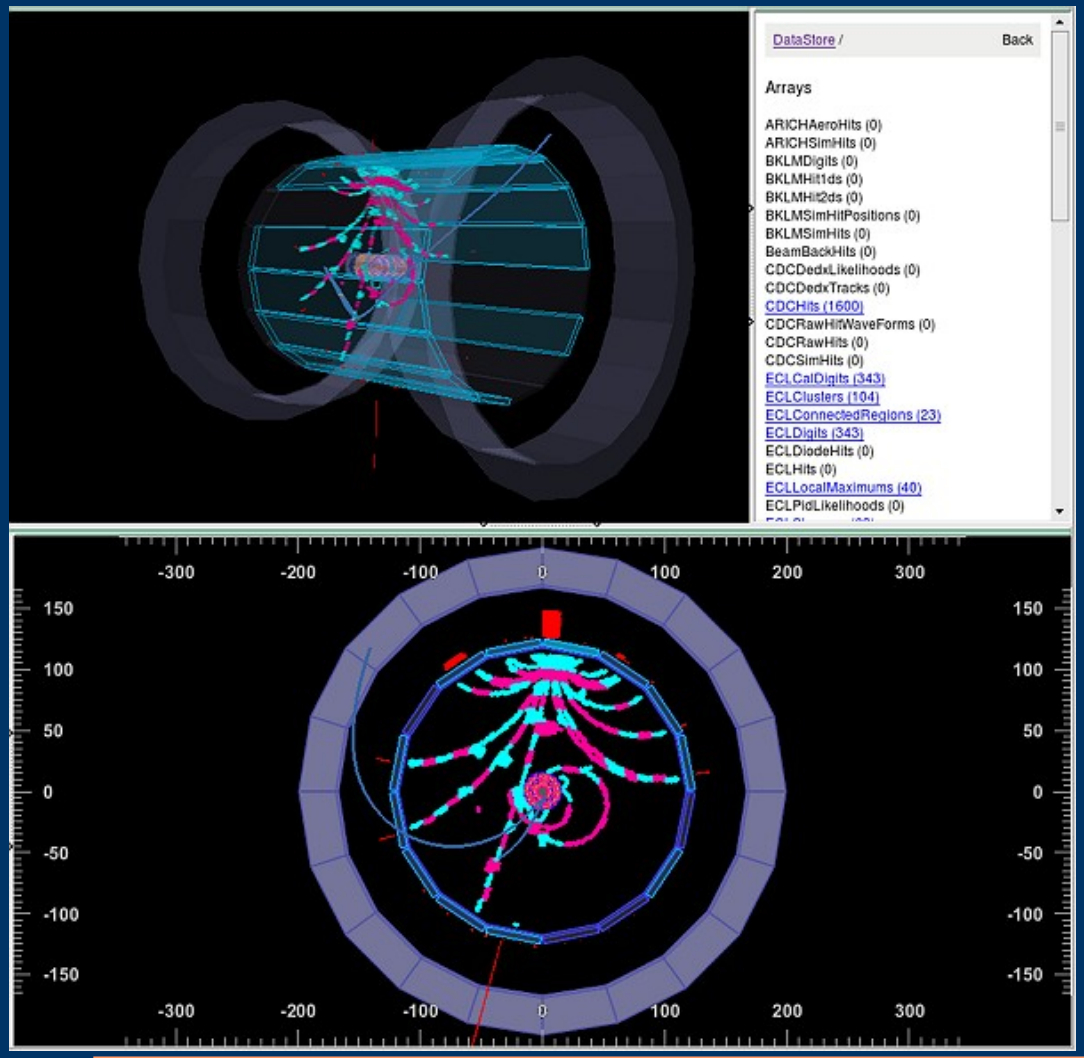
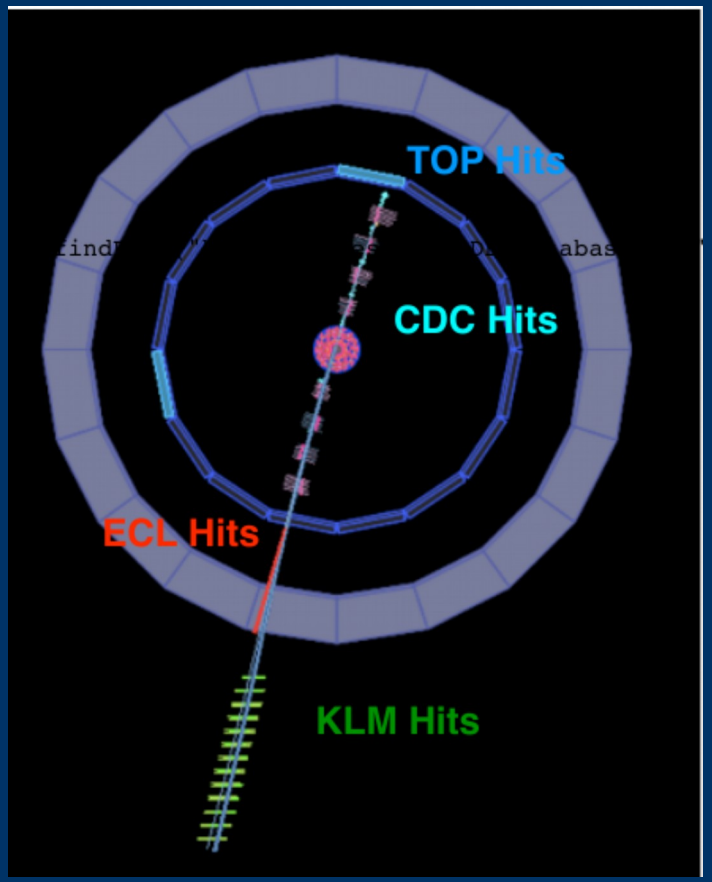
Belle II 2017 summer GCR



After 2017 GCR, KLM readout in (magnetic field off)



KLM/ECL/TOP/CDC (RICH) ready for commissioning

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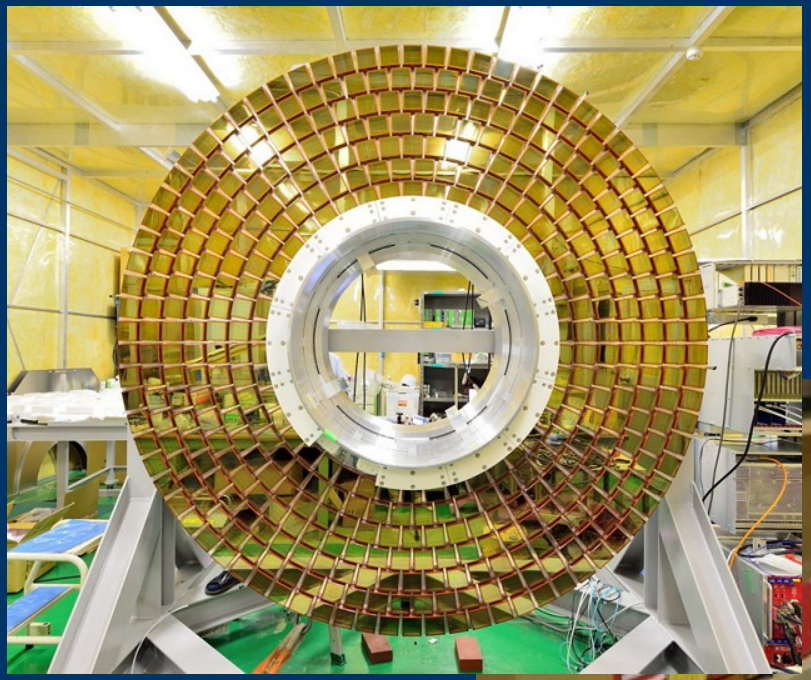
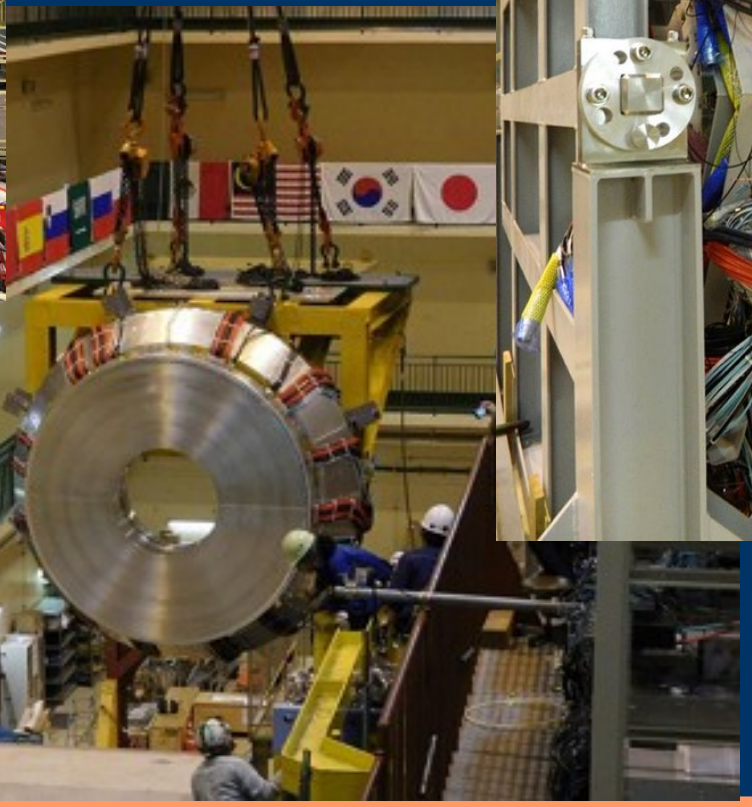


2017 Oct.

RICH is implemented in Belle II



All outer detectors are in position

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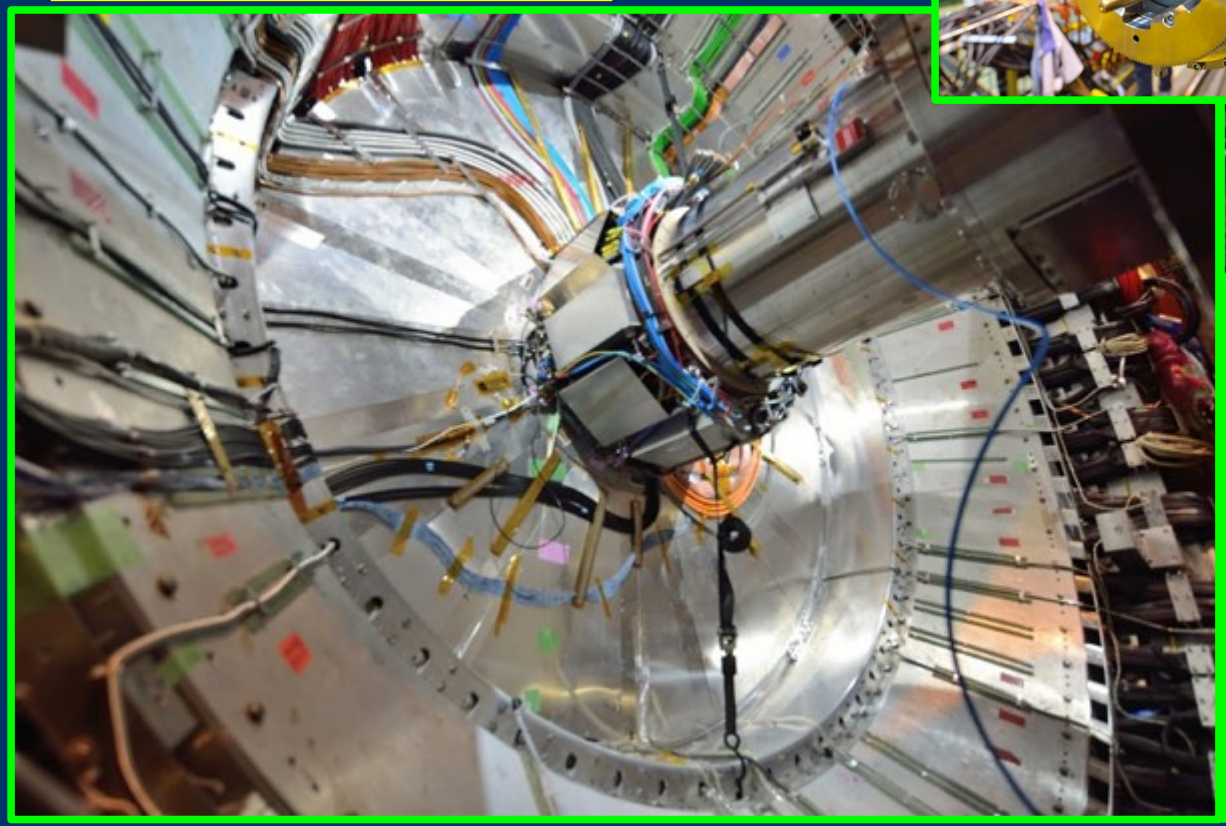
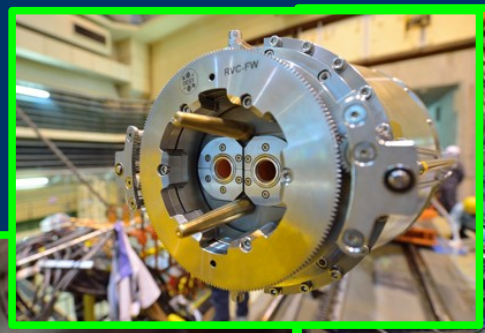
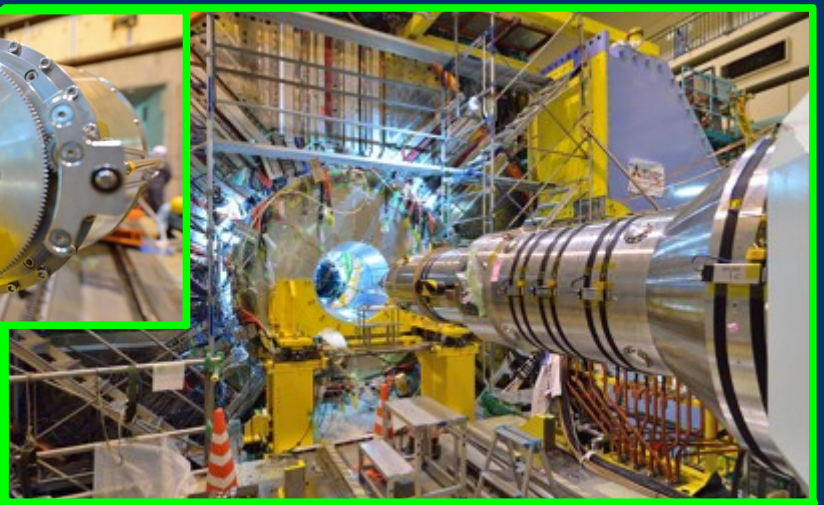
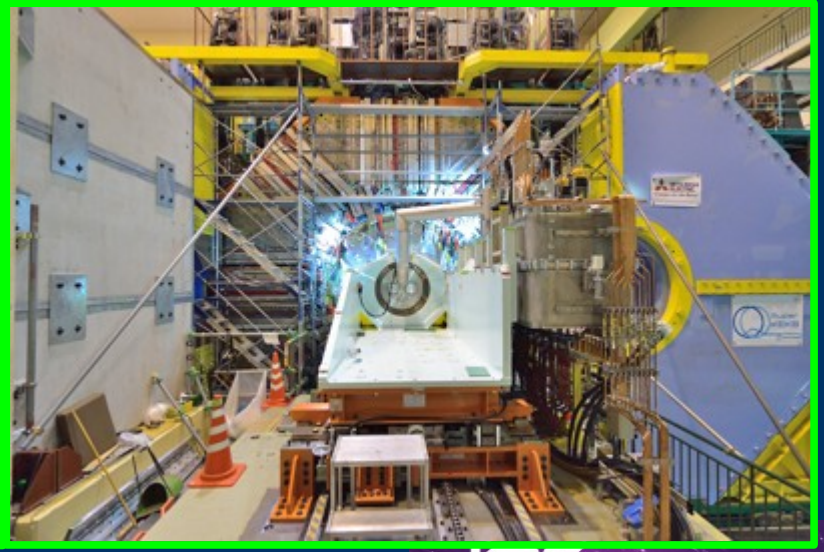
2018,0114 QCSL and QCSR integrated into the Belle II IR

SuperKEKB
one step forward
to collision









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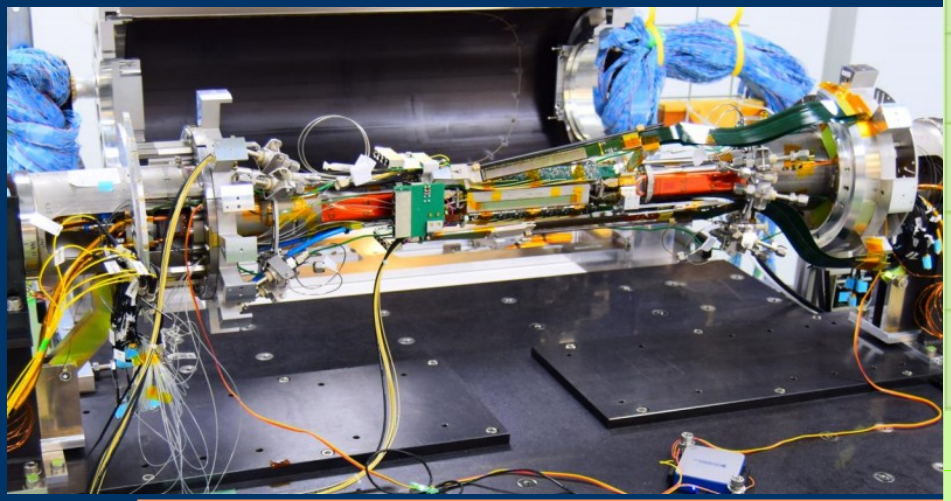
Phase 2 opeation
(Feb./Mar. - July 2018)

Beast2 detectors
Belle II VXD prototype
Belle II outer detectors

reach $L \geq 10^{34}/cm^2/s$
beam collissions (expecting 20 fb^{-1})

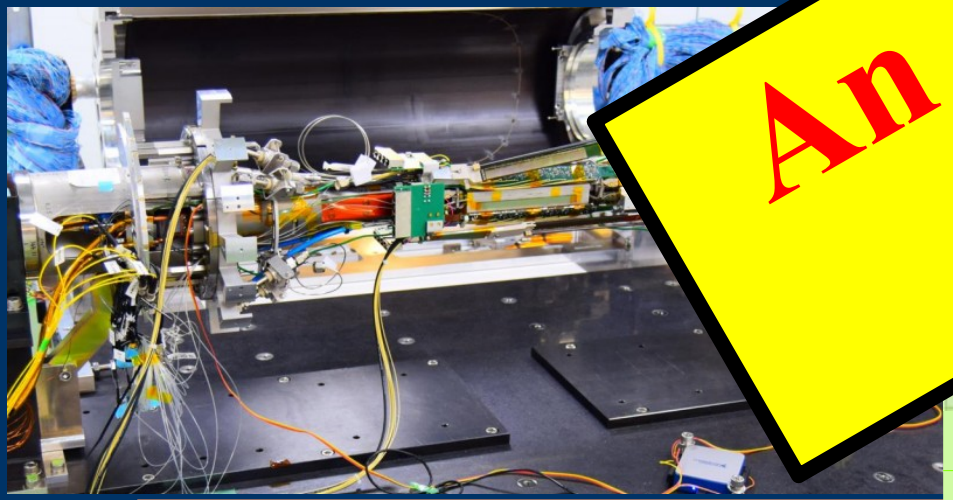


sensor	number	location	unique measurement
Belle II PXD	2 ladders	VXD	**in-situ occupancy, full Belle II tracking, vertexing**
Belle II SVD	4 ladders	VXD	
diamond sensors	8 diamonds	VXD	ionizing dose in VXD → **BEAM abort**
FANGS "LHC style" silicon pixel sensors	3 arms 15 chips	VXD	MIPs & x-rays > 10 keV @ 40 MHz → **Synchrotron x-ray spectrum**
CLAWS Scintillators w/ SiPMTs	2 ladders	VXD	X-rays or track counting w/ 1-ns timing → **injection background**
PLUME "ILC style" silicon pixels sensor	2 ladders	VXD	Two-sided silicon pixels → **tracklets w/ pointing**
Micro-TPC nuclear recoil detectors	8	VXD dock	**fast neutrons:** rate, directional & spectral information
He-3 tube neutron detectors	4	VXD dock	**thermal neutrons:** rate
Scintillators	40+40	around QCS	X-ray and total loss distribution versus position, → **collimator adjustment**
PIN diodes		around QCS	amount of beam background around QCS → **collimator adjustment**
FPGA	2	beam pipe	
LYSO-ECL	4+4	ECL	

Phase 2 opeation
(Feb./Mar. - July 2018)

Beast2 detectors
Belle II VXD prototype
Belle II outer detectors

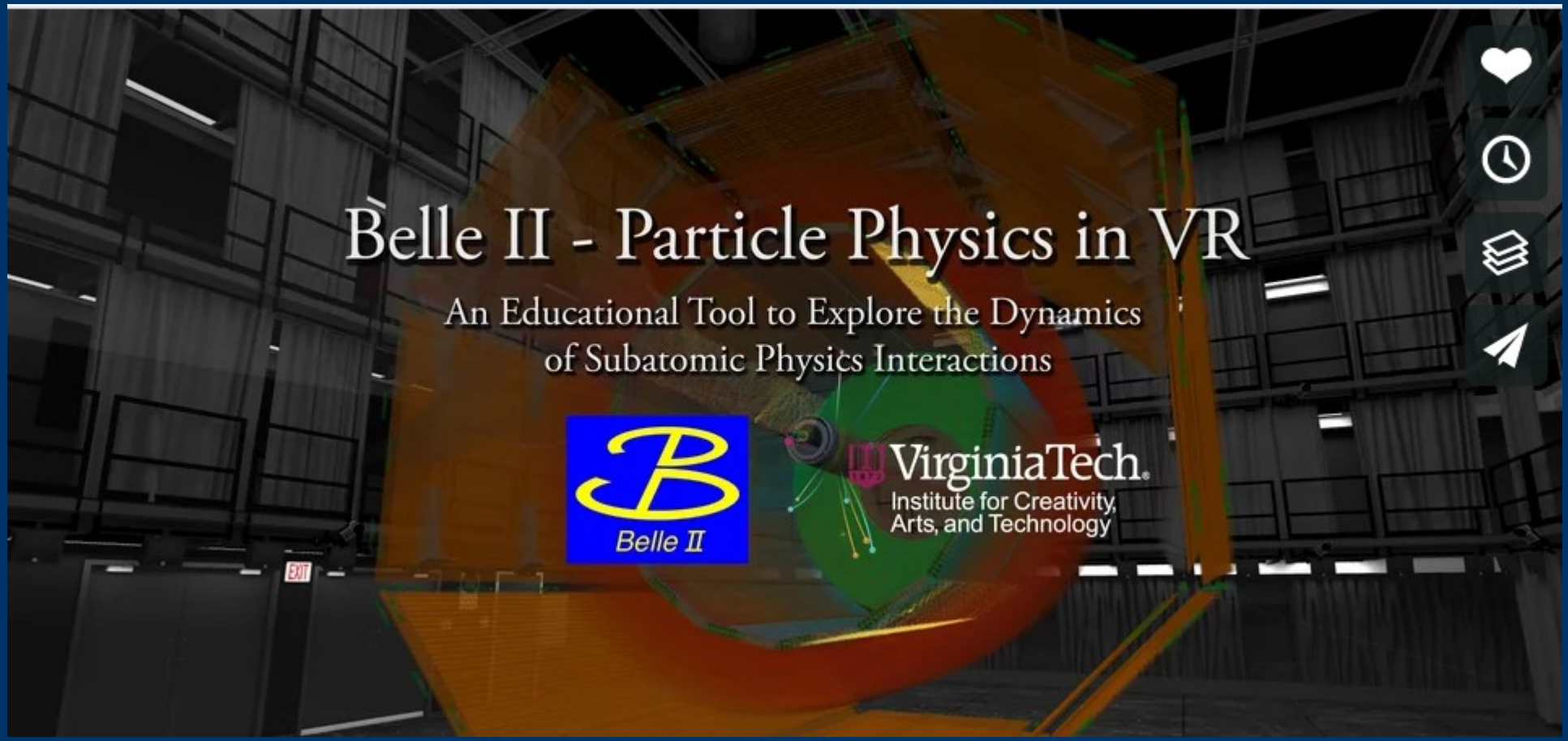
reach $L \geq 10^{34}/\text{cm}^2/\text{s}$
beam collissions (expecting 20 fb^{-1})



sensor	number	location	unique measurement
Belle II PXD	2 ladders	VXD	in-sit… …ancy, full Belle II …vertexing
Belle II SVD	4 ladders	VXD	
diamond sensors	8 diamonds		…n VXD …t
FANGS "LHC style" silicon pixel sensors	3…		…0 MHz → …m
CLAW… Scint…			…g w/ 1-ns …n background
			…ed silicon pixels → **tracklets w/ pointing**
		…dock	**fast neutrons:** rate, directional & spectral information
		VXD dock	**thermal neutrons:** rate
	40+40	around QCS	X-ray and total loss distribution versus position, → **collimator adjustment**
PIN diodes		around QCS	amount of beam background around QCS → **collimator adjustment**
FPGA	2	beam pipe	
LYSO-ECL	4+4	ECL	

An exciting year for Belle II

Belle II VR by Virginia Tech group (led by Prof. Leo Piilonen)
https://vimeo.com/214899668



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Summary

- The SuperKEKB + Belle II will be ready for commissioning soon
  - 40x higher instantaneous lumi.
  - 50 ab^{-1} data statistics.
  - Belle → Belle II
- SuperKEKB first beam circulations in 2016
  - Belle II roll-in in April 2017
  - prepare 1st collision in the coming months (2018)
- Physics commissioning with full Belle II in early 2019.
  - precision measurements of CKM
  - B, charm and τ physics
  - exotics states, dark sector, ALP, light Higgs, ….
- A new era to explore new physics in intensity frontier; friendly competition and complementarity with other experiments.

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BACKUP

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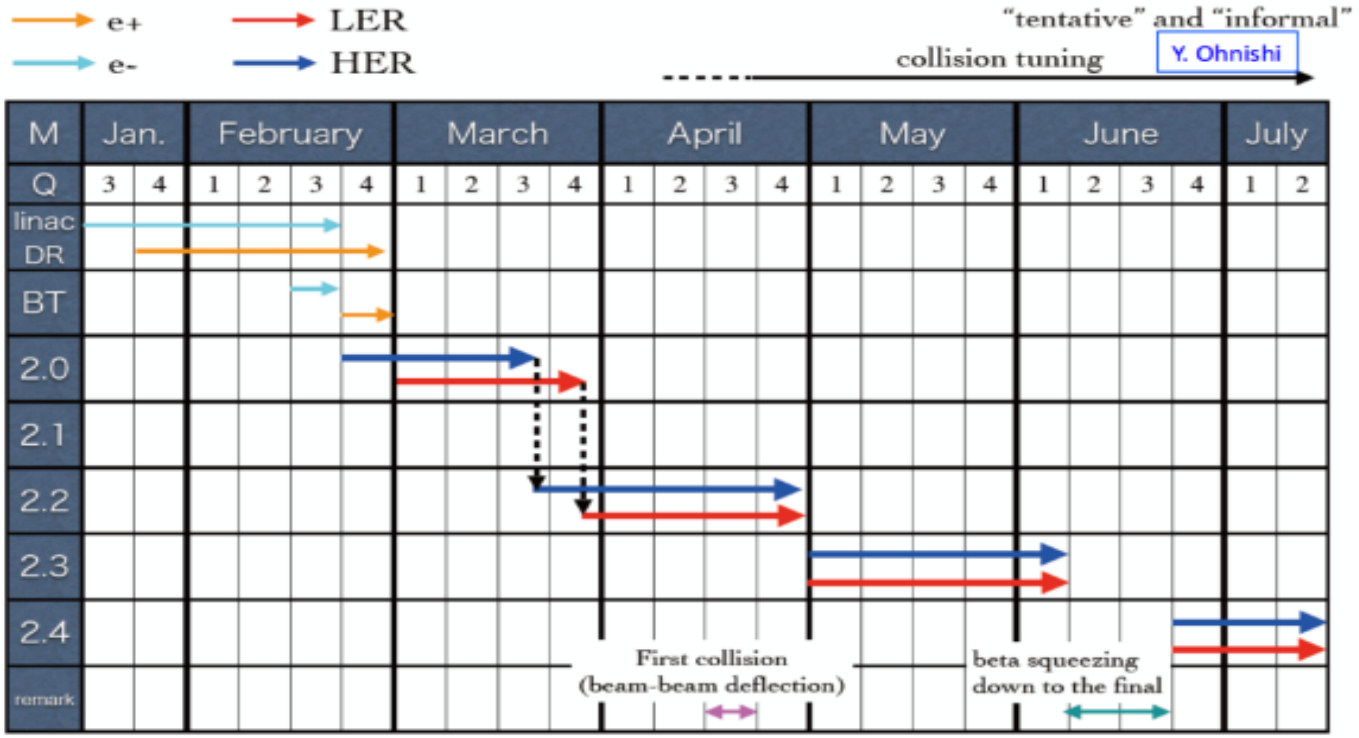
~20 fb^{-1}, could be more. Our job to prepare for publications with 2018 data.



Y. Ohnishi, June B2GM

	Phase 2.2 (8x8)	Phase 2.3 (4x8)	Phase 2.4 (4x4)
L [cm^{-2}s^{-1}]	**1 x 10^{34} (tentative target)**	2 x 10^{34}	4 x 10^{34}

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Required injector beam parameters

Stage	KEKB (final)		Phase-I		Phase-II		SuperKEKB (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1 A	1 A	–	–	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	primary e- 10 → 4	4
Norm. Emittance ($\gamma\beta\varepsilon$) (μrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.125%	0.125%	0.5%	0.5%	0.16%	0.1%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 / 50 Hz		25 / 50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Eventually		4+1 rings (LER, HER, DR, PF, PF-AR)	

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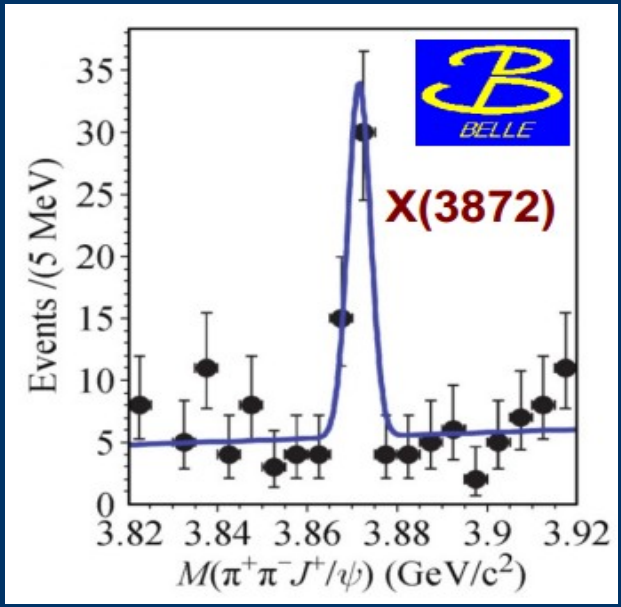
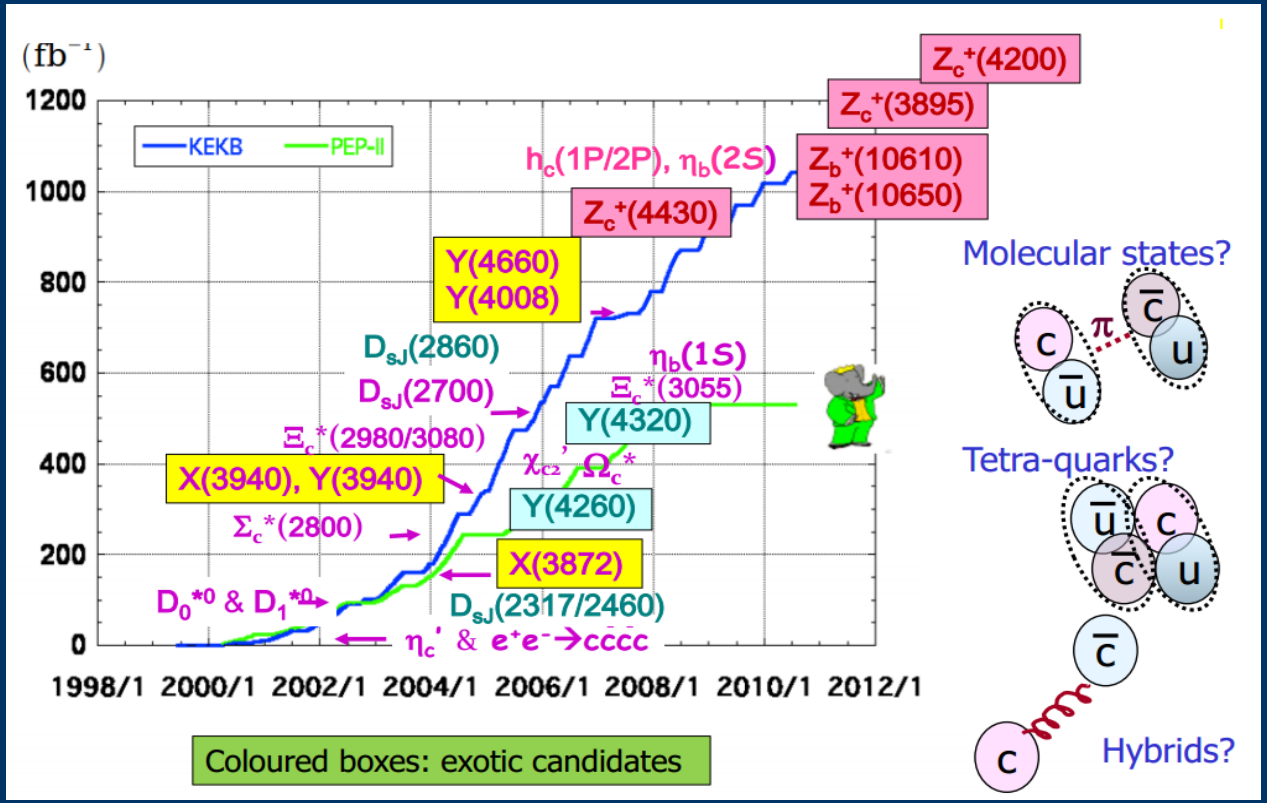
Belle II physics prospect – hadron spectroscopy

Many new states are observed, which do not fit in the traditional quark model.
More are expected in Belle II, opening a door for exotic state studies.

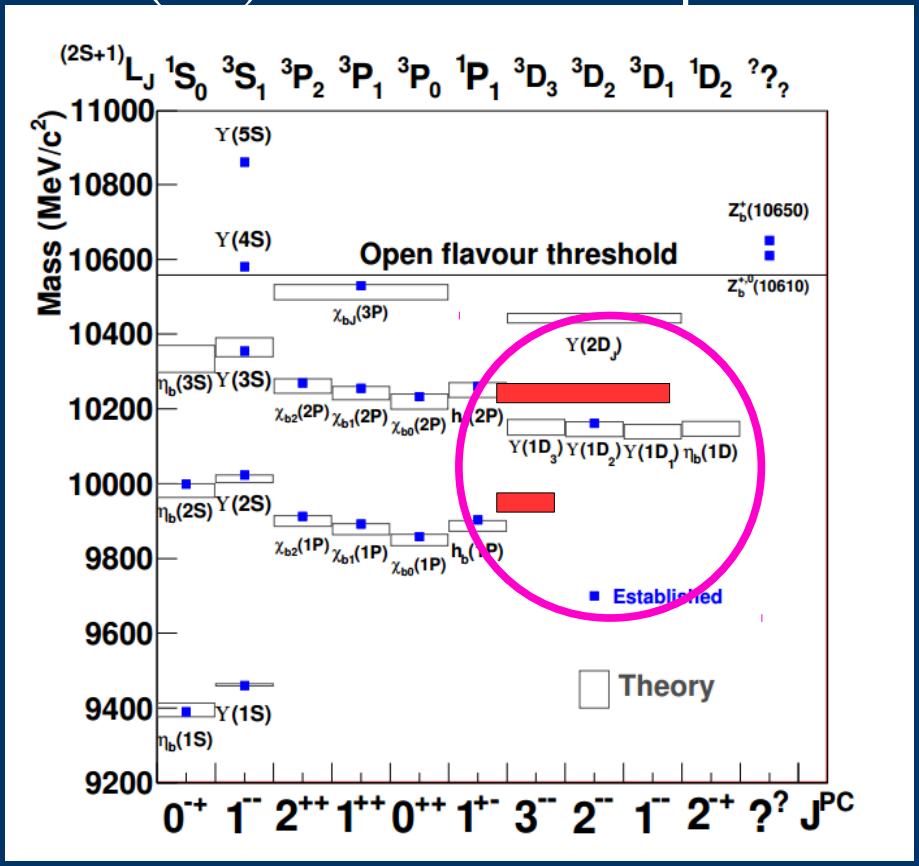


First exotic state observed.
[PRL 91, 262001 (2003)]



Belle II physics prospect --- early measurements

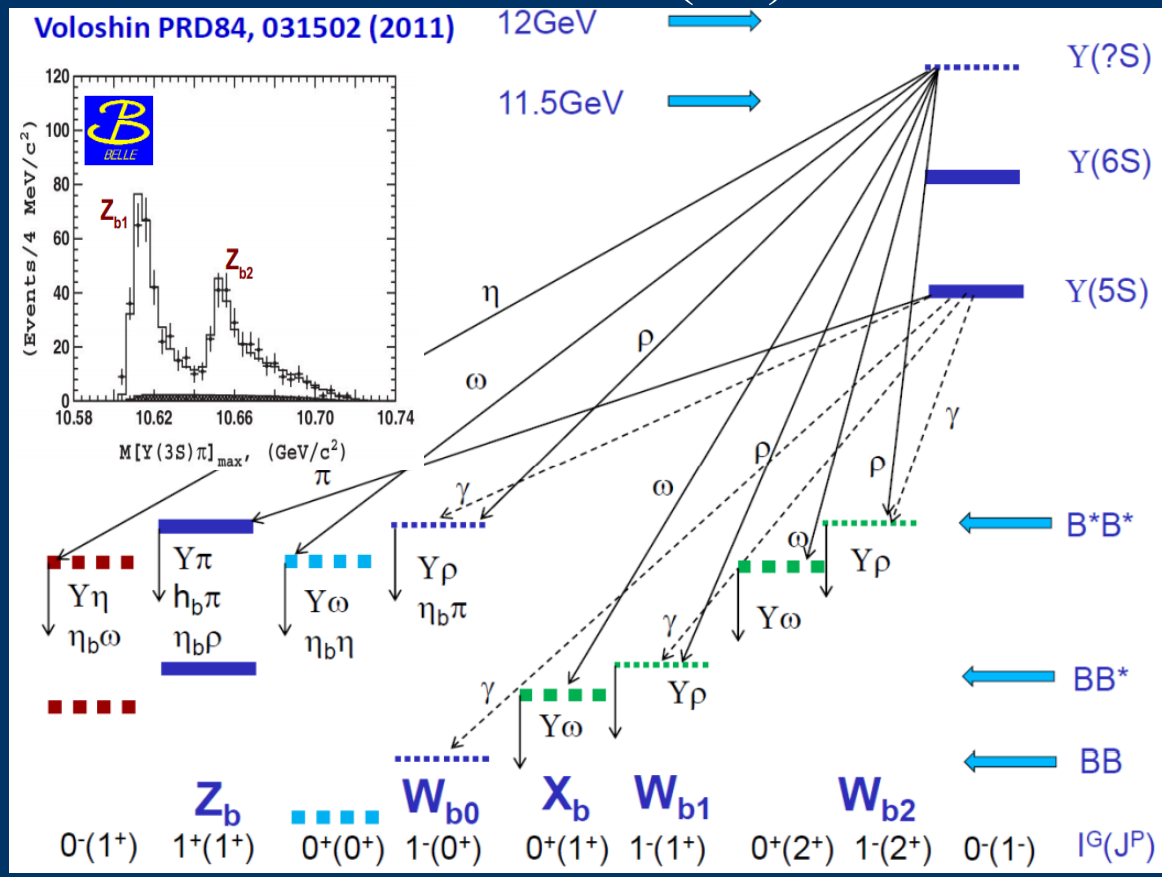
$\Upsilon(3S)$ bottomonium spectrum



$\Upsilon(1D_2)$ has been measured by CLEO/BaBar.

$\Upsilon(1D_1)\Upsilon(1D_3)\Upsilon(2D)$ are not seen yet.

Above $\Upsilon(4S)$



4-quark state Zb(10610/10650) found by Belle in anomalous $\Upsilon(5S) \rightarrow \pi\pi\Upsilon(nS)$ transitions,
Similar anomaly in $\Upsilon(6S)$ decay not confirmed

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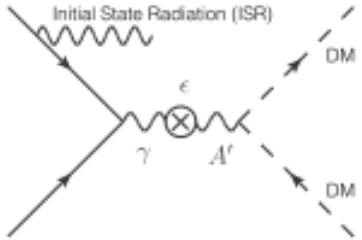
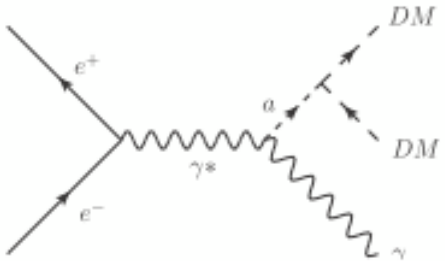
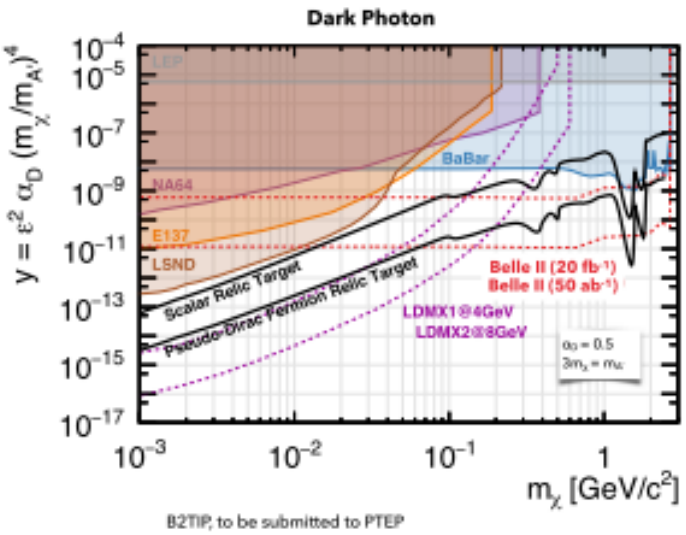
Single photons ee→ γ A' (and a'): Sensitivity

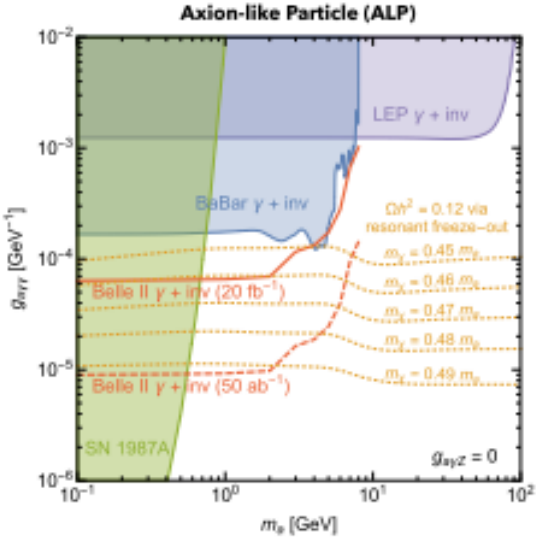
T. Ferber





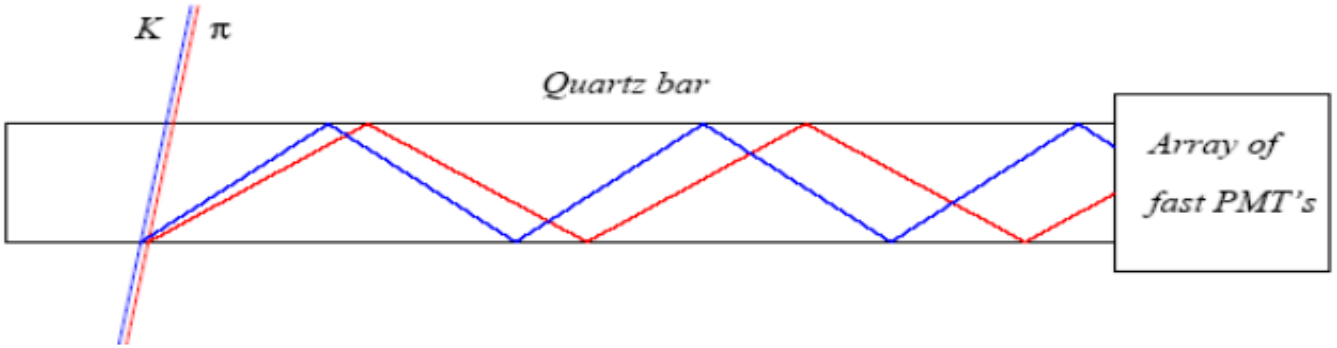


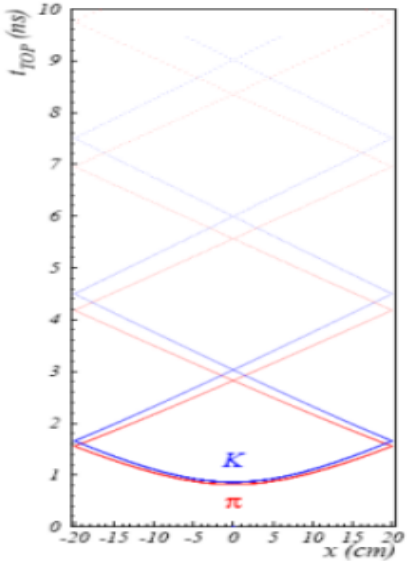
B2TIP, to be submitted to PTEP



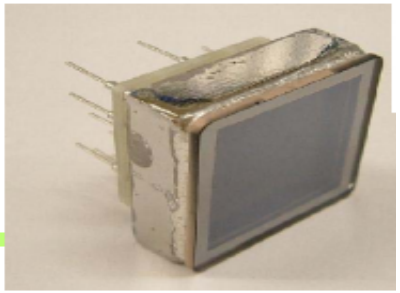
Dolan, M.J., Ferber, T., Hearty, C. et al.
J. High Energ. Phys. (2017) 2017: 94.
https://doi.org/10.1007/JHEP12(2017)094

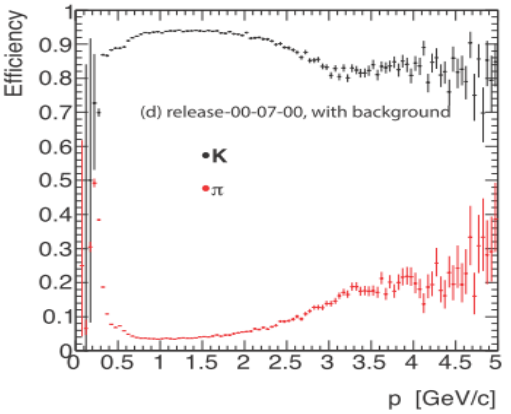
Barrel PID: TOP (Time Of Propagation)





- Cherenkov ring imaging with precise time measurement.
- Uses internal reflection of Cherenkov ring images from quartz
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5





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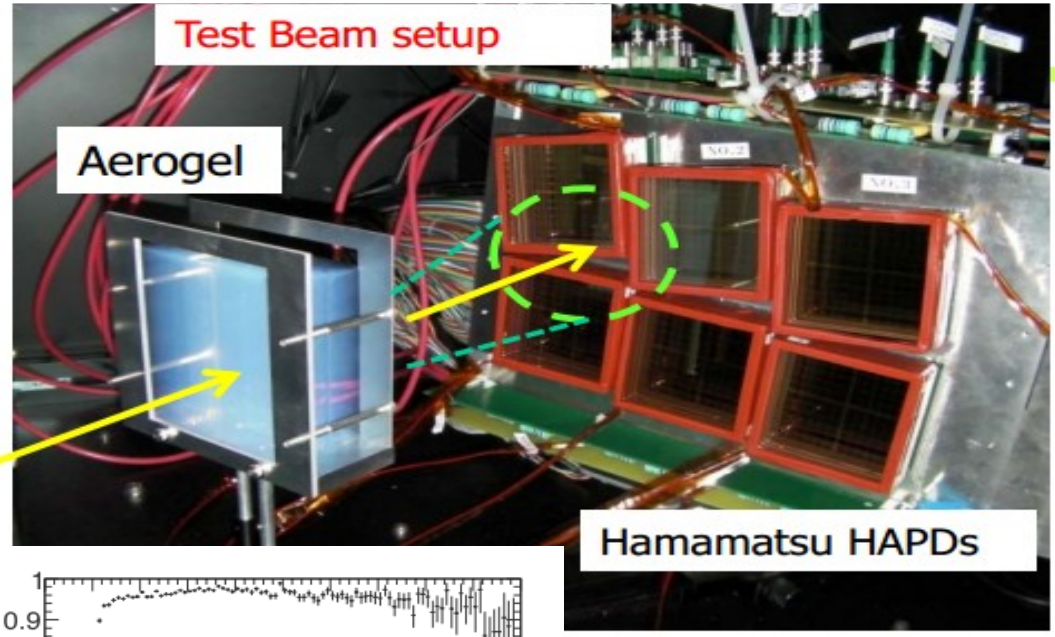
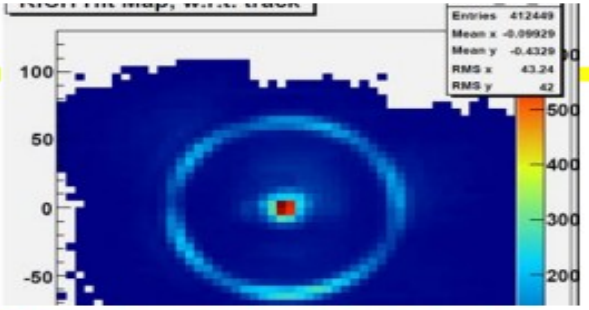
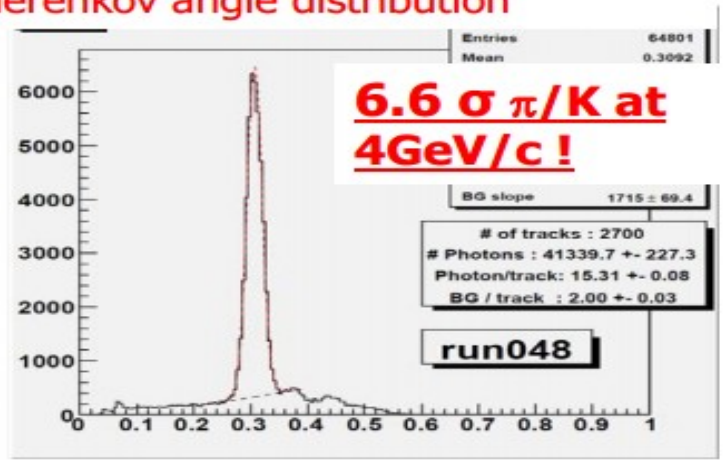
EndCap PID: ARICH (K/π separation)

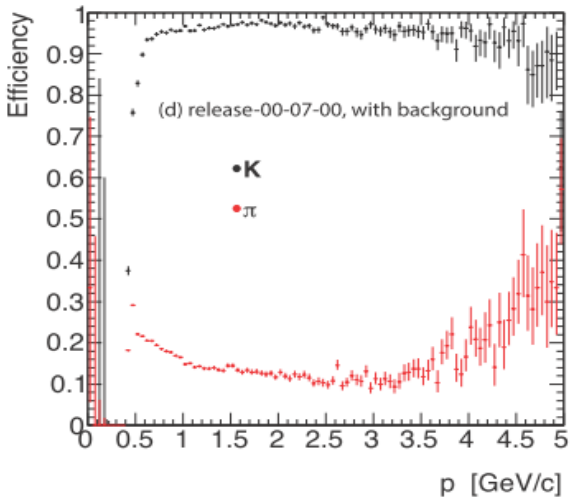


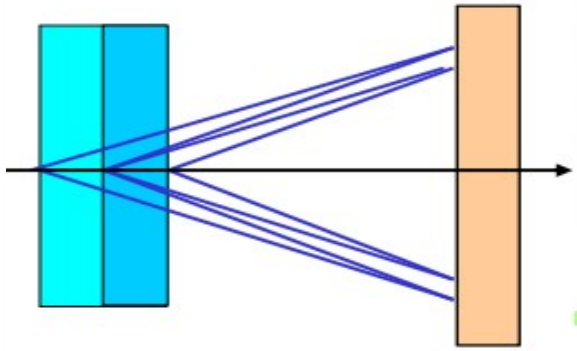


Clear Cherenkov image observed

Cherenkov angle distribution







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