The Belle II Upgrade Program

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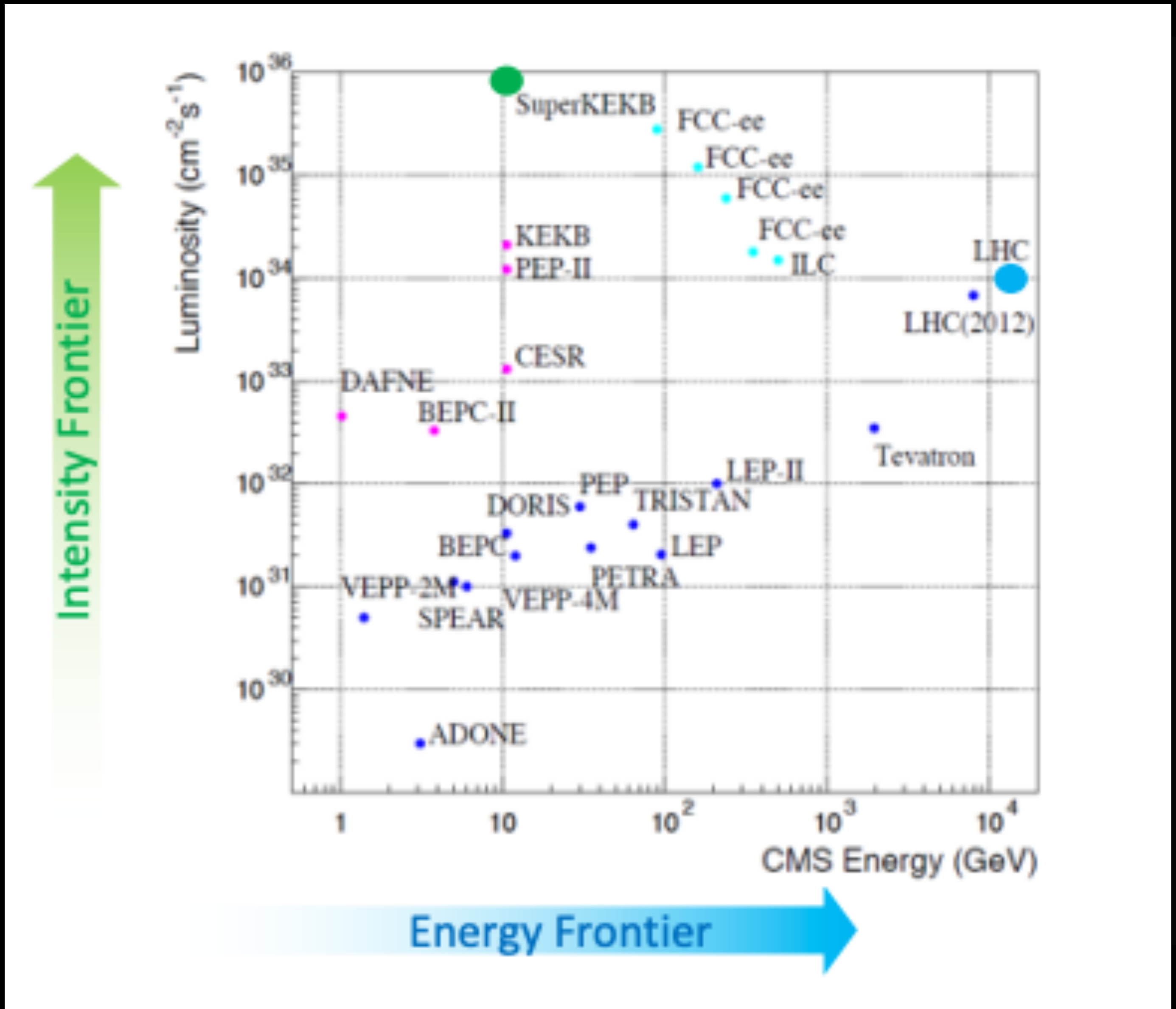
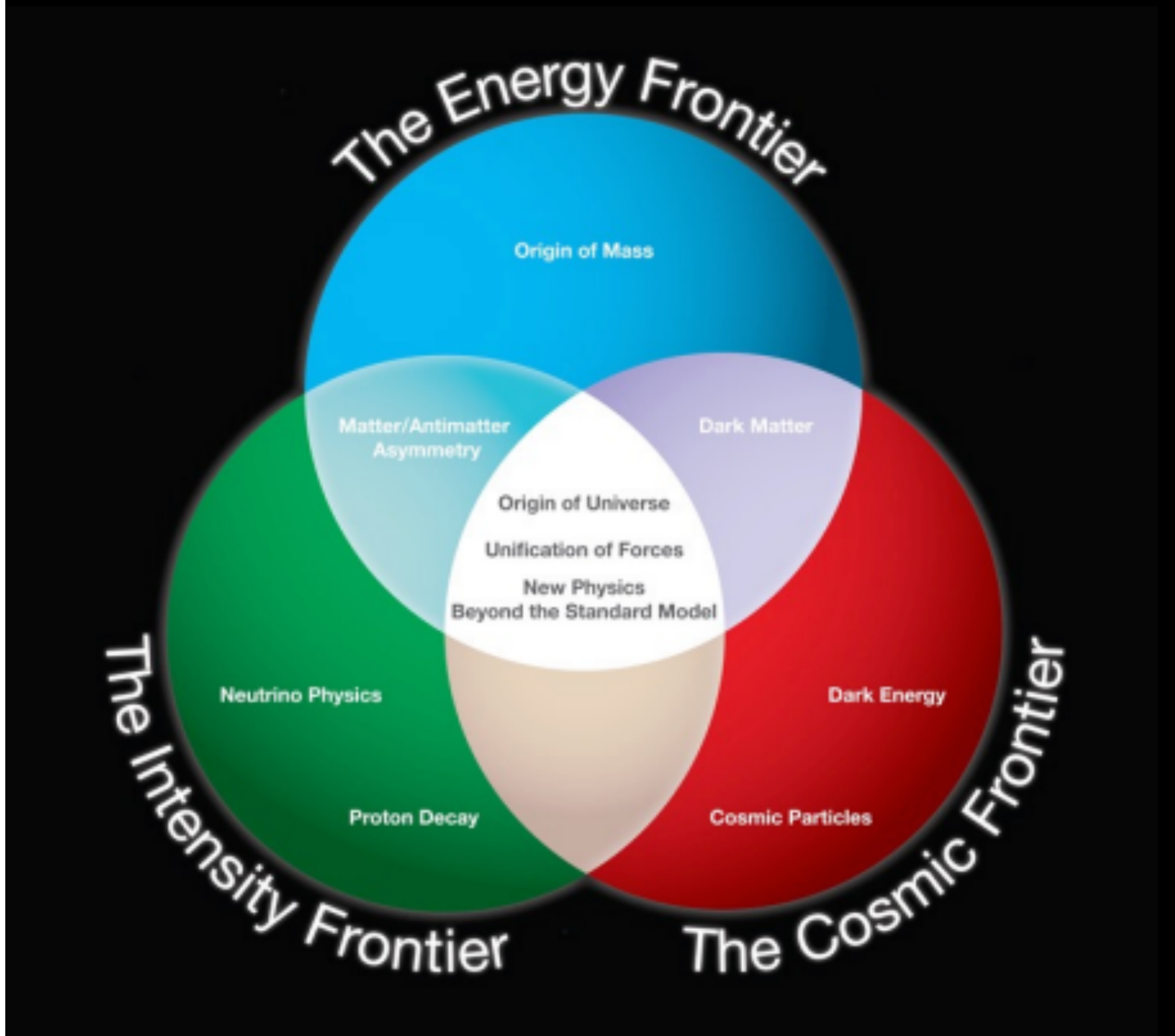
Three Frontiers

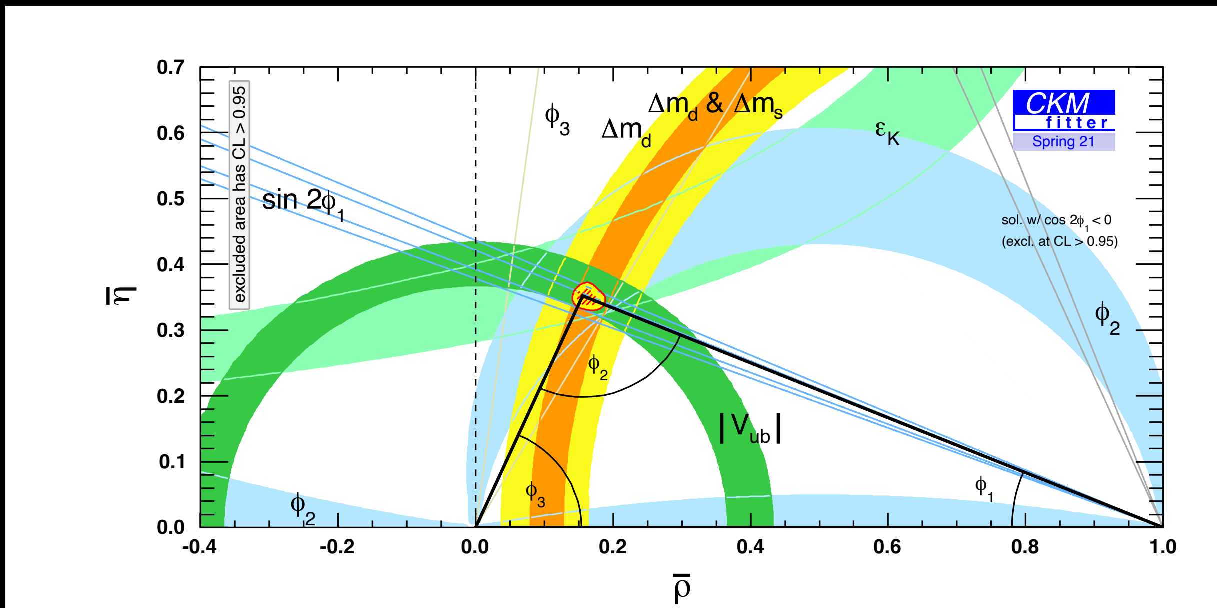




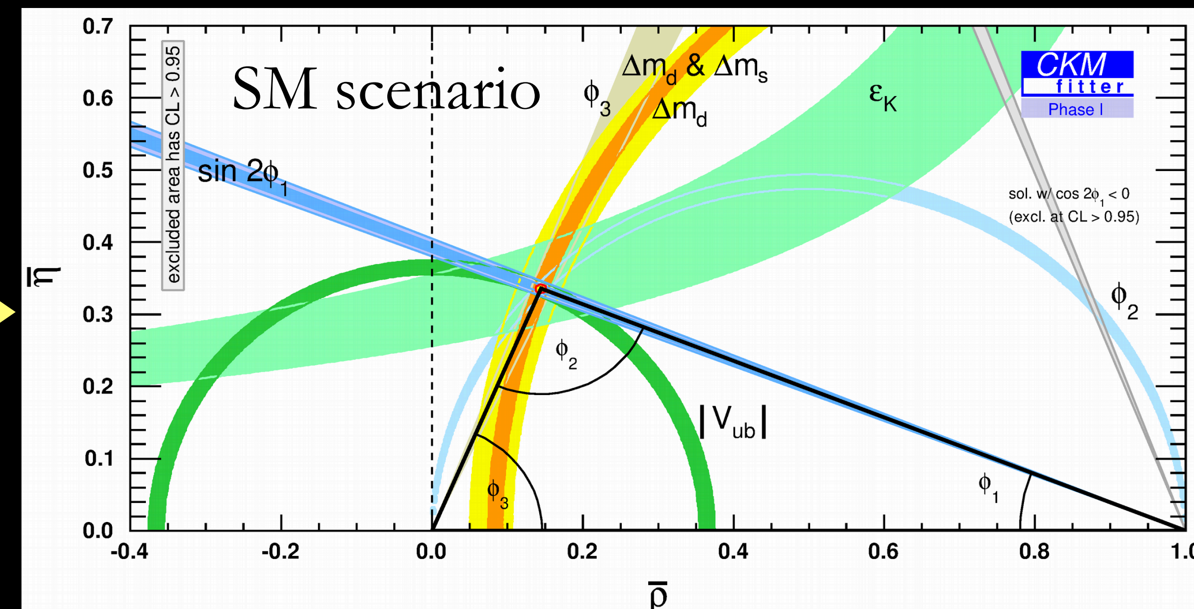
SuperKEKB is an leading machine in intensity frontier. Already reaching 4.7×10^{34} cm^{-2}s^{-1}, with an ultimate target of 6×10^{35} cm^{-2}s^{-1}

Physics Program

Current status



Belle II: 50 ab^{-1} and LHCb: 23 fb^{-1}



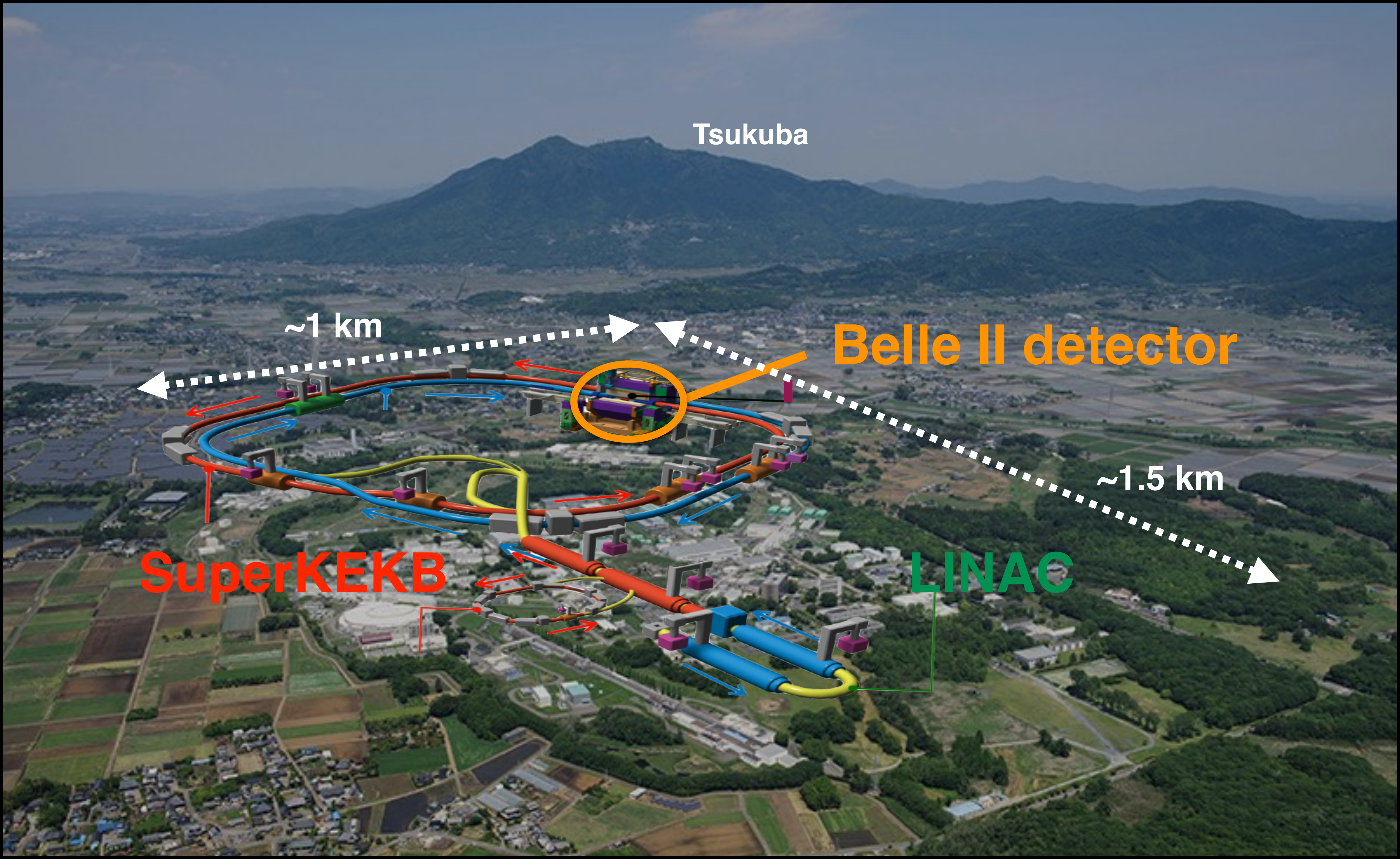
Belle II Physics Book, arXiv:1808.10567

Observable	Belle	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
$\|V_{cb}\|$ incl.	1.8%	1.2%	1.2%
$\|V_{cb}\|$ excl.	$3.0_{ex} \pm 1.4_{th}$%	1.8%	1.4%
$\|V_{ub}\|$ incl.	$6.0_{ex} \pm 2.5_{th}$%	3.4%	3.0%
$\|V_{ub}\|$ excl.	$2.5_{ex} \pm 3.0_{th}$%	2.4%	1.2%
$\sin 2\phi_1$ ($B \to J/\psi K_s$)	**0.667 ± 0.023 ± 0.012**	**0.012**	**0.005**
ϕ_2 [deg]	85 ± 4 (Belle +BaBar)	2	0.6
ϕ_3 [deg] ($B \to D^{(*)}K^{(*)}$)	63 ± 13	4.7	1.5

Triangle can be determined by “1 side and 2 angles” or “2 sides and 1 angle”. It is essential to measure and compare these parameters in both new physics sensitive and not sensitive channels.

In addition to CKM measurements, Belle II Physics program will cover a plenty of important measurements and searches: B semi-leptonic decays, tau physics, dark sector searches, …

SuperKEKB and Belle II Experiment

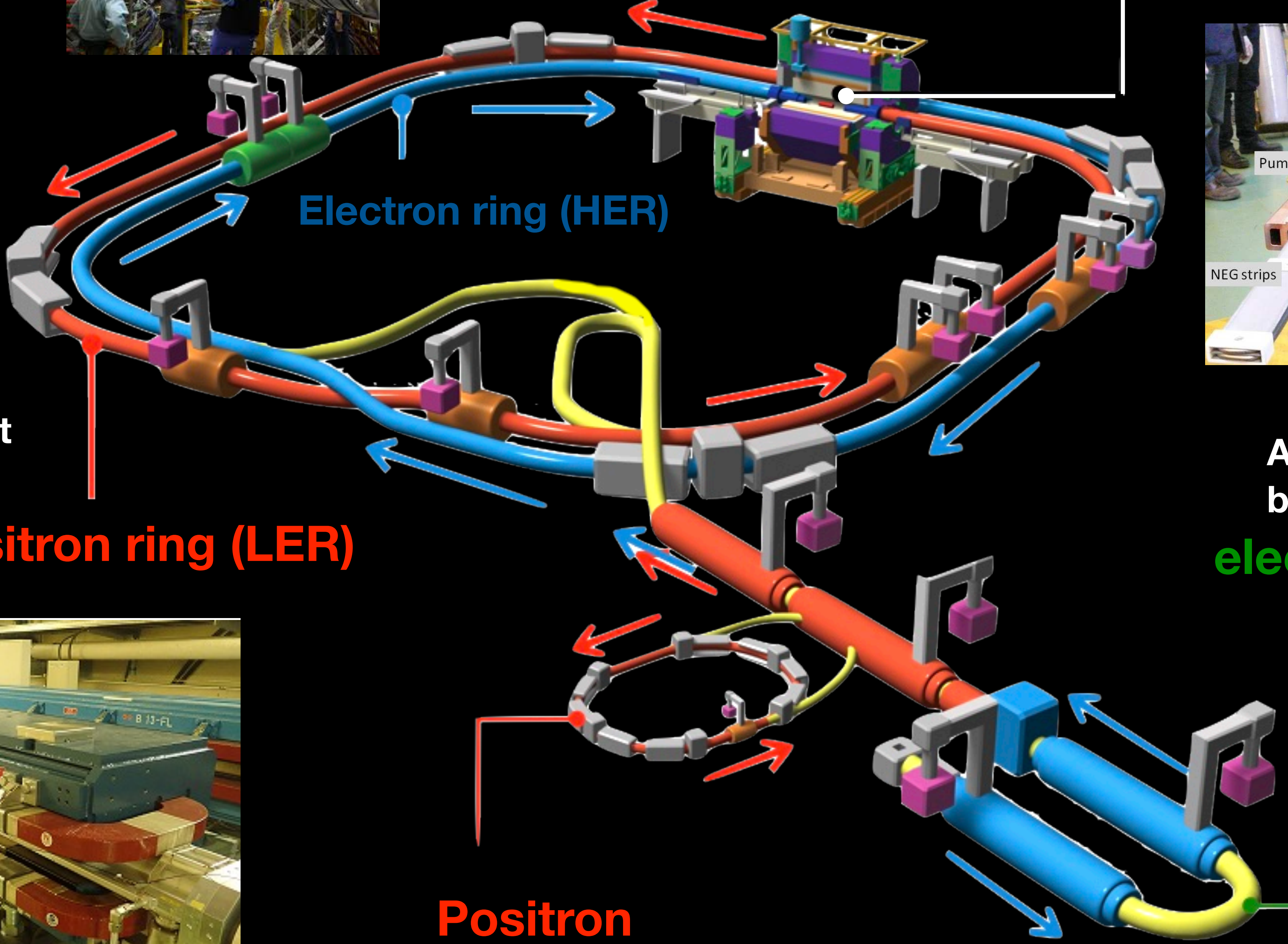


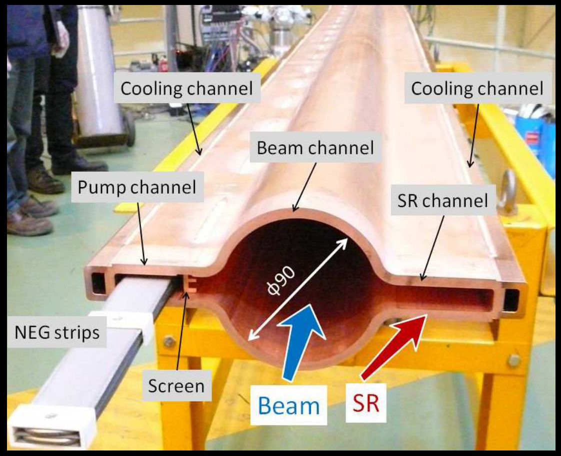
Upgrading to “**Super**”KEKB

QCS magnets

Belle II detector

RF reinforcement





Ante-chamber beam pipe

electron/positron injector

Positron ring (LER)

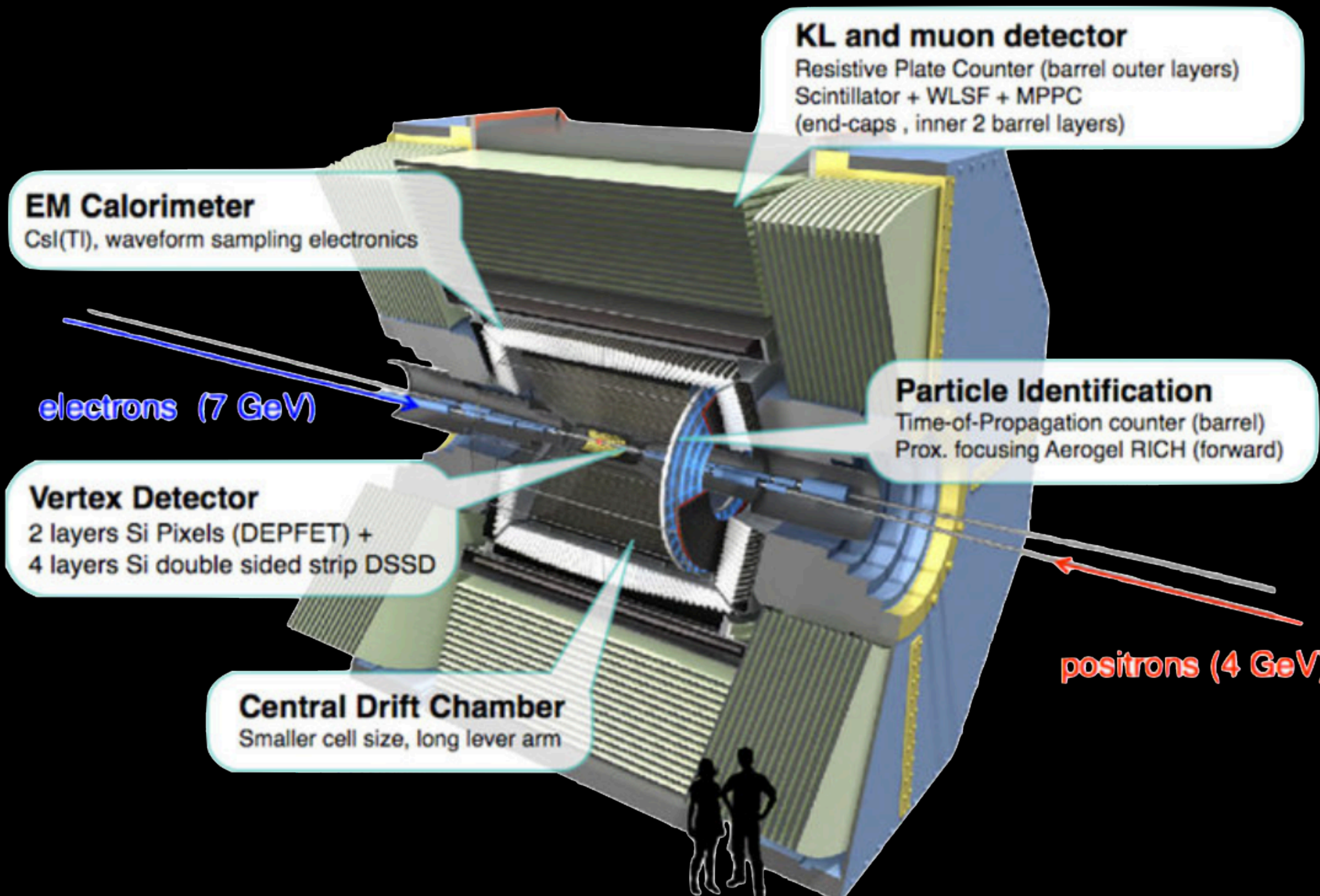
dipole magnets newly installed in LER (~4 m)

Positron dumping ring

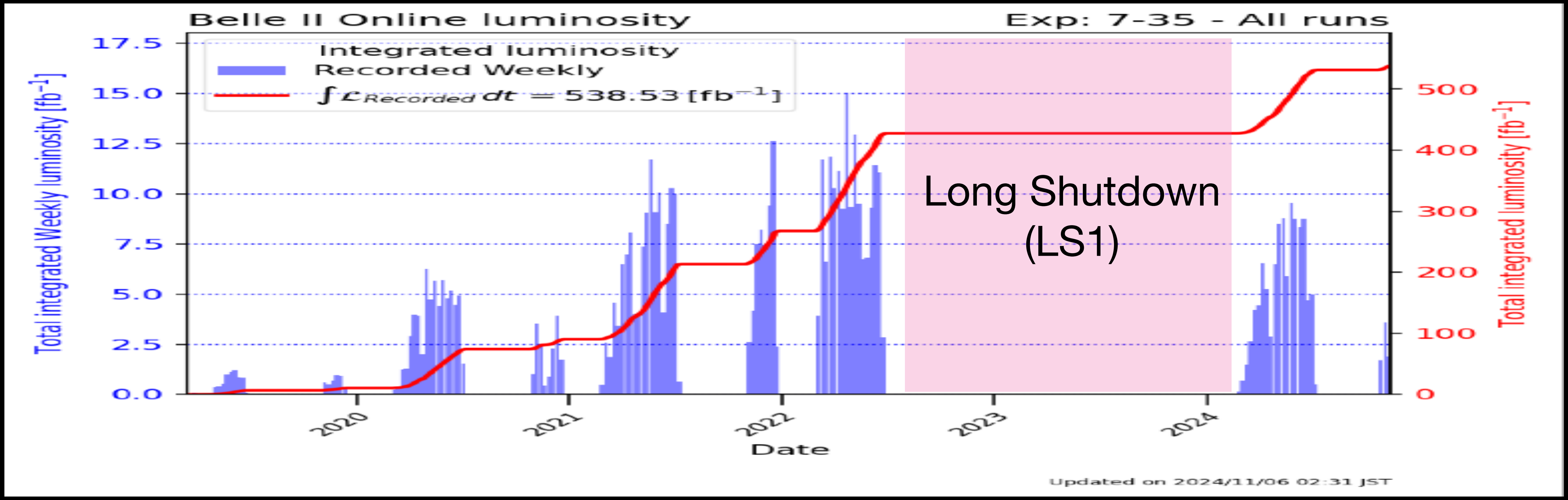
Low-emittance RF gun

Belle II Detector

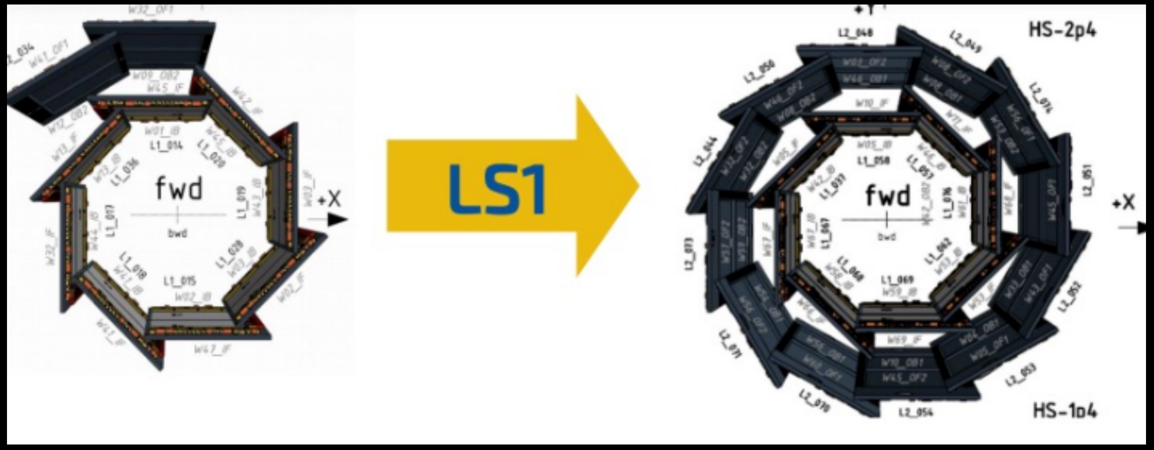
Belle II TDR, arXiv:1011.0352



Machine Operation Status



- **Achievements**
  - World record luminosity: $4.7 \times 10^{34}\ cm^{-2}s^{-1}$
  - Integrated luminosity: $\sim 530\ fb^{-1}$ recorded
  - Early physics analysis
- **Long Shutdown 1 (LS1)**
  - **PXD completion** and machine upgrade



PXD detector

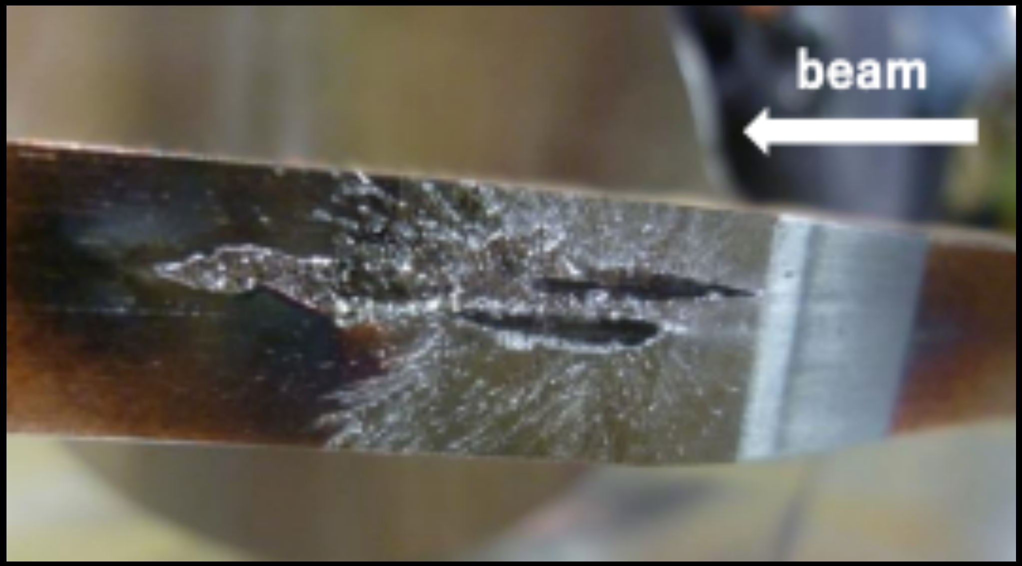
Machine and Detector Upgrade Overview - LS1

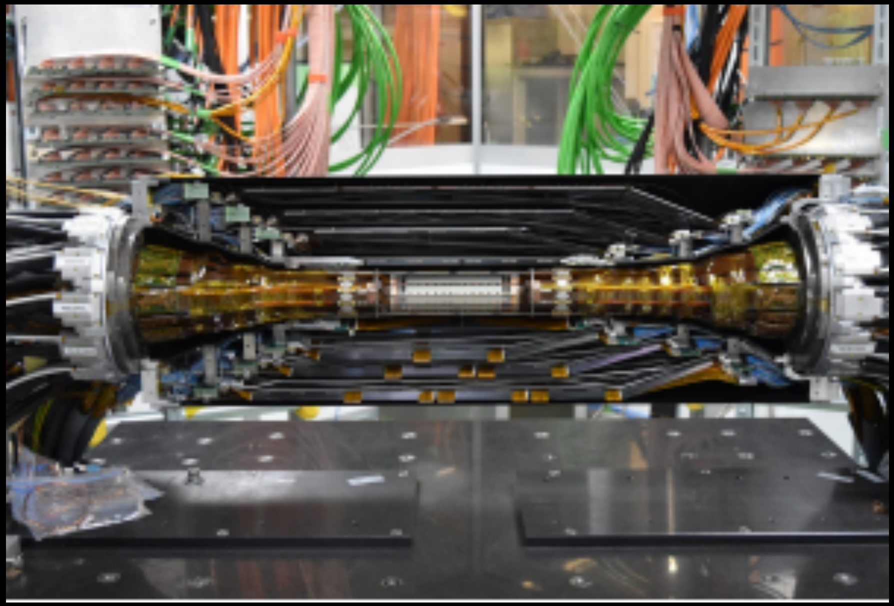
Machine upgrades

- Additional beam loss monitors around the ring
- Neutron background shielding
- Non-linear collimator
- RF cavity replacement, faster kicker magnets, …

Detector upgrades

- Installation of complete PXD
- Replacement of TOP's photomultipliers
- Improved CDC gas distribution and monitoring
- DAQ system upgrade to PCIe40

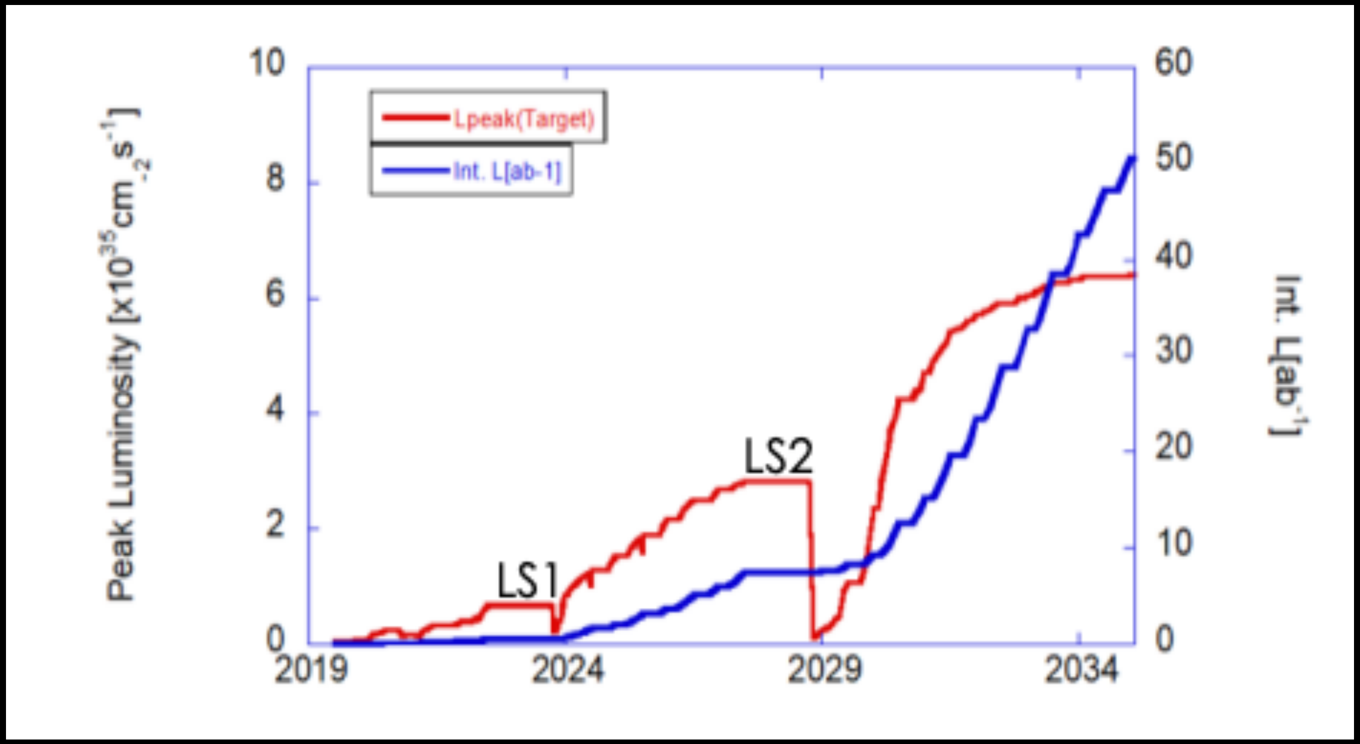




Belle II Upgrade Program

Belle II Upgrade Conceptual Design Report (CDR):
https://arxiv.org/abs/2406.19421

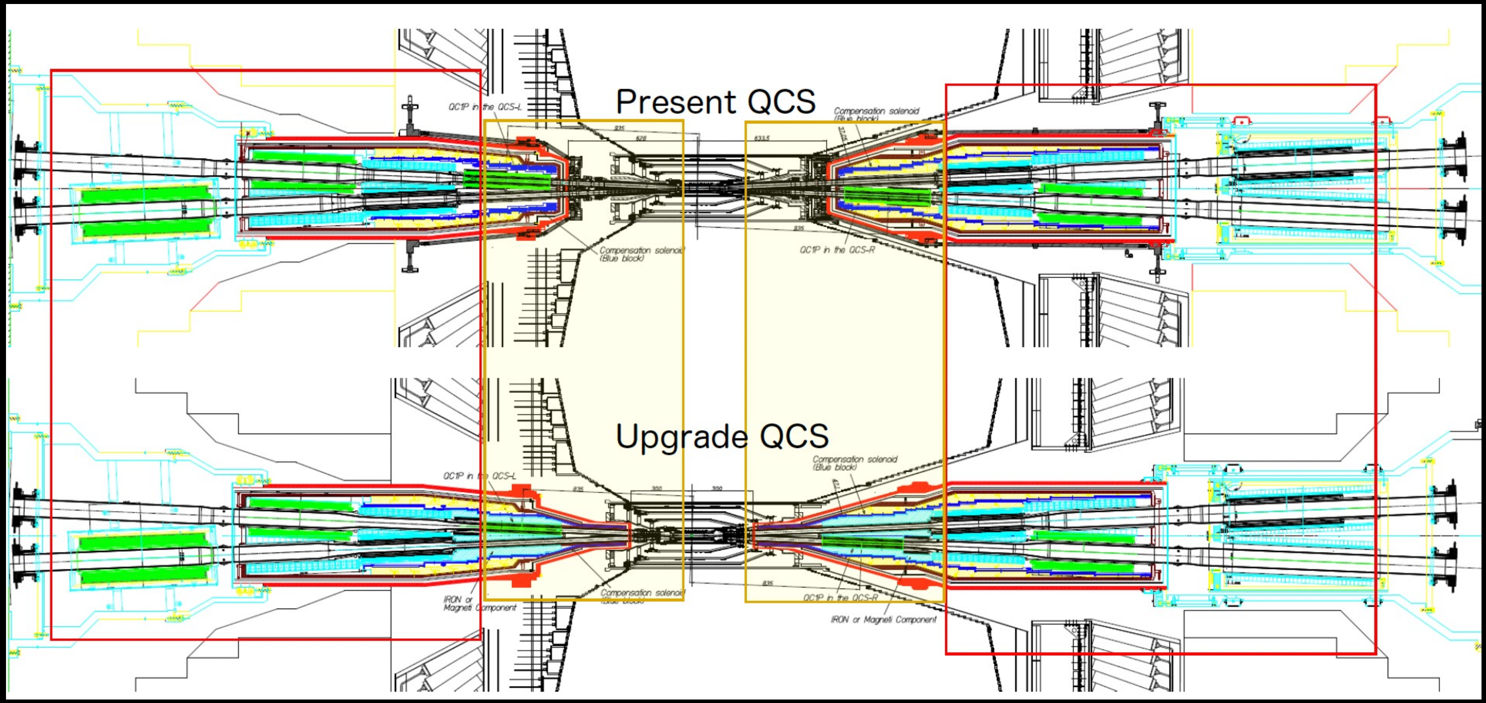
- Enhance Machine Performane and Stability: Address issues like beam blow-up, lifetime, injection power, and beam losses
- Reduce Beam Backgrounds: Mitigate single beam, injection, and luminosity backgrounds



- LS1 Detector consolidation: Upgrade to achieve 2 $\times 10^{35}$ $cm^{-2}s^{-1}$ with more robust components
- LS2 Detector upgrade: Upgrade toward 6 $\times 10^{35}$ $cm^{-2}s^{-1}$ luminosity target including a redesigned IR, a more performant detector, and resilient against machine induced backgrounds

SuperKEKB IR Upgrade

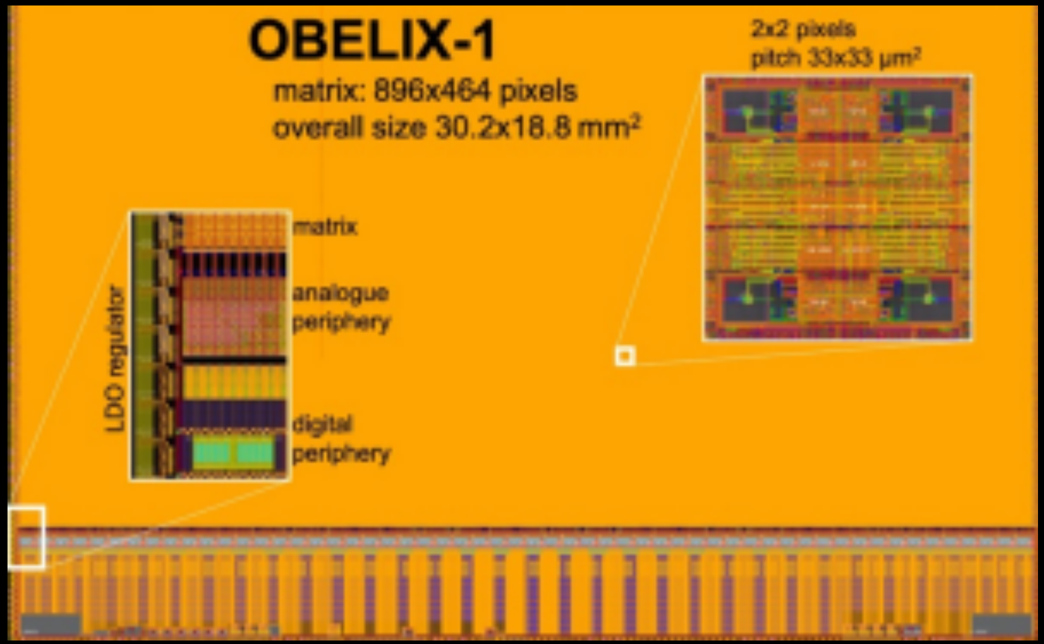
- New Compensation Solenoid: added between the IP and QC1 to improve magnetic field compensation and enhace stablity.



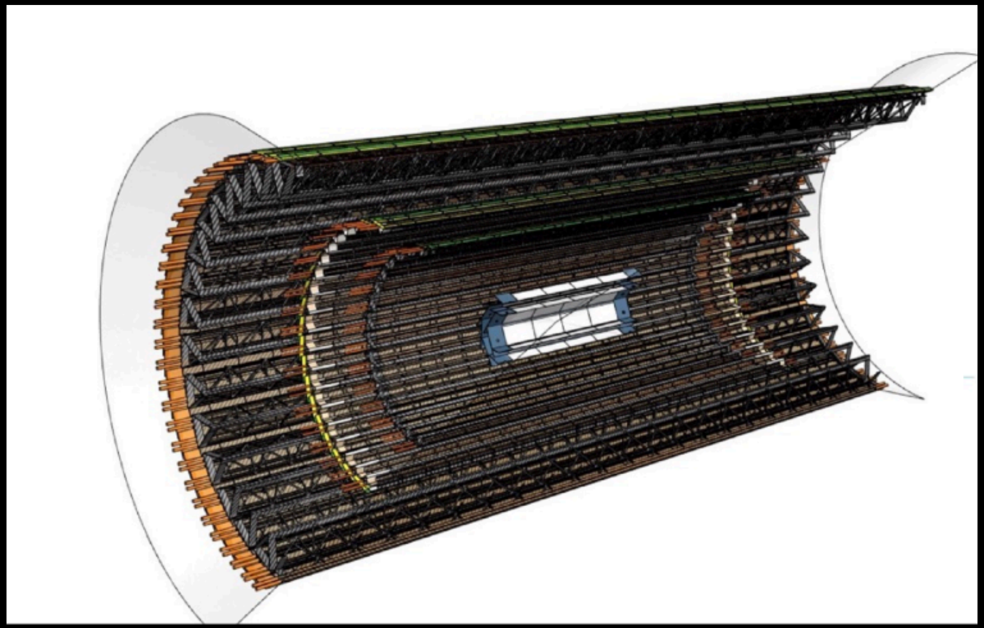
- QC1P Relocation: Moved 100 mm closer to the IP (from 935 mm to 835 mm) to optimize focusing and support high-luminosity operation.
- Redesigned Magnetic Field Profile: Utilizes magnetic yokes and an optimized Bz profile to reduce vertical emittance and improve beam alignment
- New QC1 Magnet with Nb3Sn Wire: Developed with Nb3Sn to allow higher current density and increased field strength, crucial for high luminosity performance.
- Minimized X-Y coupling: Reduced chromatic X-Y coupling between IP and QC1, enhancing beam alignment and overall stability.

Vertex Detector Upgrade: VTX

- SuperKEKB IR modification: Require a full upgrade of the Vertex Detector, transitioning from hybrid (pixels + strips) to an all pixel design.
- CMOS-Based Monolithic Active Pixel Sensor (MAPS) technology
  - Sensor and readout circuit are integrated on the same silicon board.
  - Composed of 5 pixel layers (iVTX 2 and oVTX 3 layers) with thickness < 30 um (~2500 e from MIPs vs 200-250e threshold)
- OBELIX Sensor
  - Design based on TJ-Monopix2 (prototype for HL-LHC ATLAS)
  - Offer high spatial resolution, thin design and cost-effectiveness.

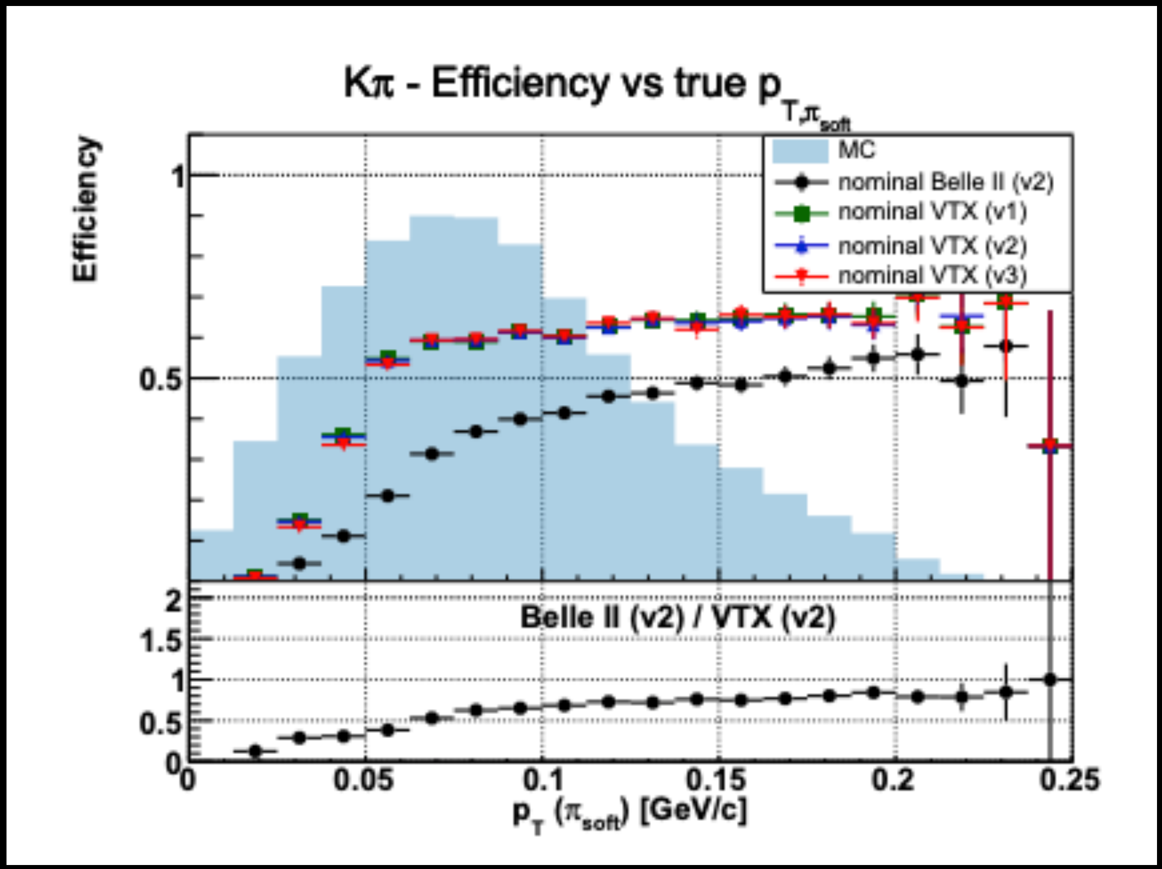


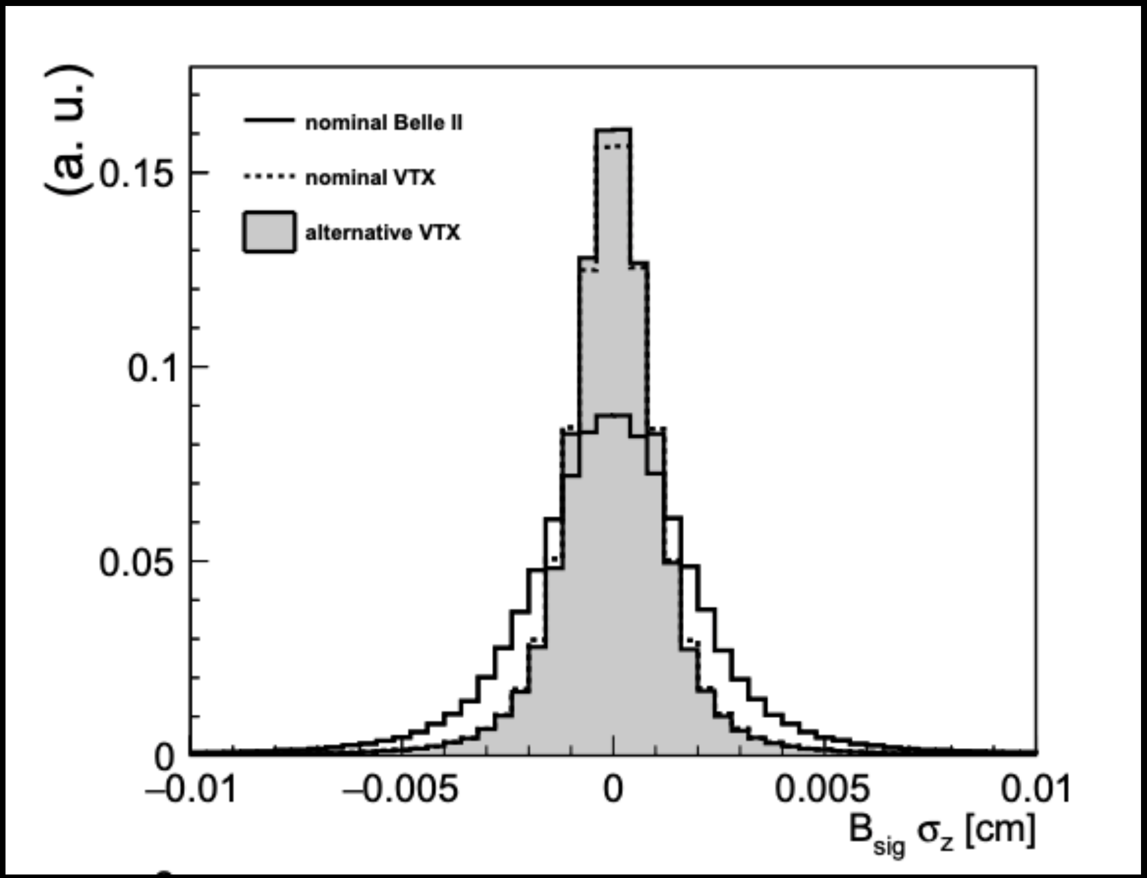
- Pixel Pitch: 30-40 um with single-point resolution < 15 um
- Material Budget: 0.1-0.8% X_0 per layer
- Rad tolerance: total ionizing dose of 100 Mrad and NIEL fluence



Max. radius 14 cm and length 70 cm

Tracking and Vertexing Performance





- Low momentum tracking
  - improved efficiency for soft pions, crucial for R(D*) analysis. $B \to D^* l^+ \nu$ decay ($D^* \to D^0 \pi^-_{soft}$) .
- Vertex Resolution:
  - Up to 35 % improvemnet in vertex resolution along the z-axis for B and K_s^0 decays, crucial for time dependent CP analysis

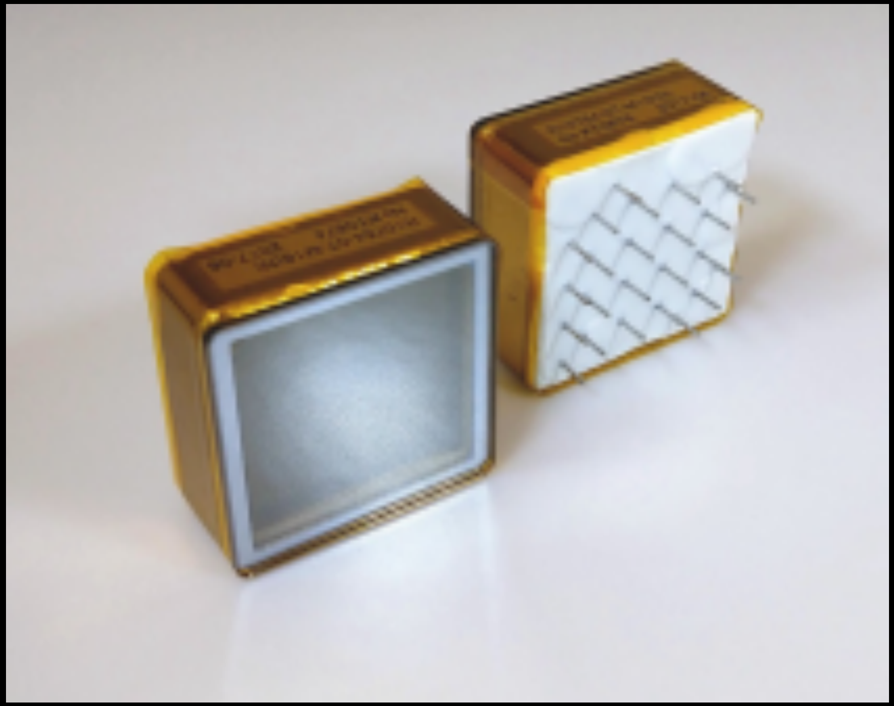
Tracking Upgrade: CDC Front-End Electronics

- Enhances tracking performance under higher beam backgrounds, reduced cross-talk, and improves radiation tolerance. Designed to withstand doses up to ~1 kGy and neutron fluence of 1.0×10^{14} n/cm^2.

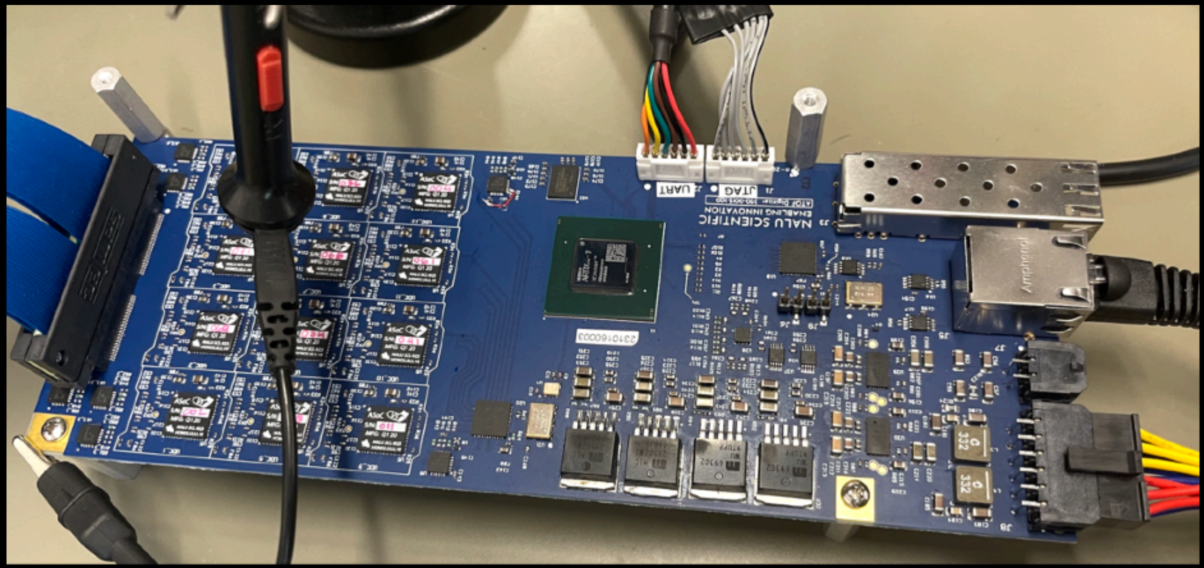
- New front-end design:
  - CMOS65nm 8-channel ASIC: Each board contains 6 ASICs with TDC and Flash ADC
  - FPGA: Enables on-board data processing and improved data transfer for trigger system.
  - Data trasmission: high-speed QSFP modules for reliable and faster data transmission.
  - Low power consumption

TIme of Propagation Detector

- MCP-PMTs: Currently experiencing degradation due to higher-than-expected background levels. They will be replaced with lifetime-extended ALD-PMTs (Atomic Layer Deposition), which can handle a higher accumulated charge, increasing durability through the duration of Belle II.



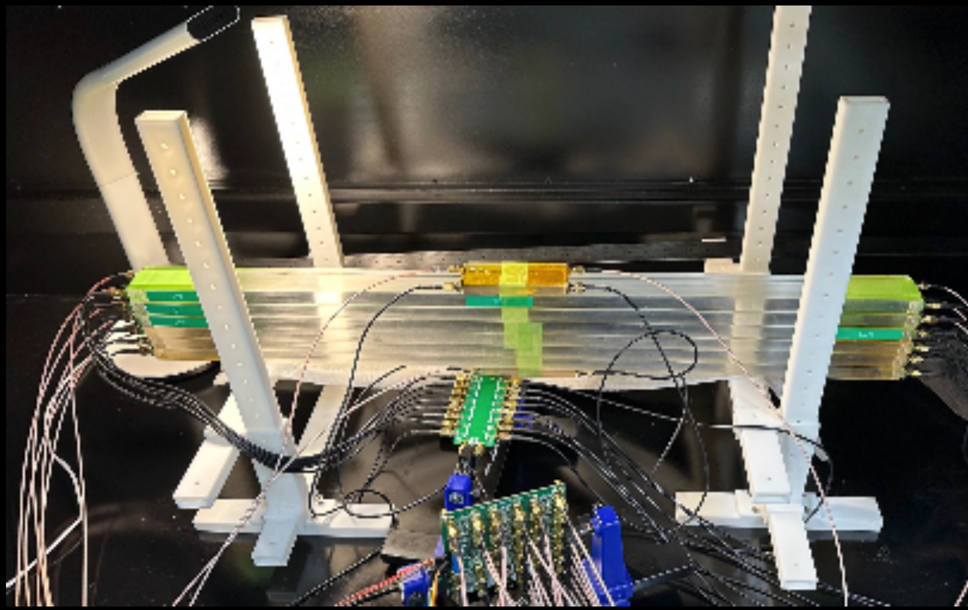
- ASoC (Analog to Digital Conversion System on Chip) under development by Nalu LLC. Features 2.5 GSa/s and 4-channels, with reduced power consumption.



https://science.osti.gov/-/media/np/pdf/sbir-sttr/SBIR-STTR-2020/day-2/Mostafanezhad_2020_DOE_NP_Exchange_Meeting-Nalu_SBIR_ASoC.pdf

KL and Muon Detector Upgrade

- Option 1): Replace remaining RPCs in the barrel with scintillators equipped with SiPM to improve time resolution and enhance higher KL efficiency. This requires substantial work, including re-designing electronics for feature extraction.



- Option 2): Switch from streamer mode to avalanche mode. This reduces the charge, increases rate capability, and minimizes sensitivity to background neutron flux.
  - Gas Mixture Modification: identify a suitable gas mixture, introducing an electronegative gas (e.g., SF6) may help suppress streamer formation
  - Preamplifier: Install low-noise preamplifiers near the detector to boost the avalanche-mode signals before transmission.

Trigger Upgrade

- Upgrading the trigger hardware to UT5 will enable the implementation of more advanced algorithms such as ML. Additionally, optical transmission speed will be significantly improved.

UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Versal
Sub FPGA (Xilinx)	– –	Artex7	Artex7, Zynq
# Logic gate	500k	2000k	8000k
Optical transmission rate	8 Gbps	25 Gbps	58 Gbps
# UT boards	30	30	10
Cost per a board (k$)	15	30	50
Time schedule	2014-	2019-2026	2024-2032

- In the CDC TRG, the integration of ML-based tracking algorithm is expected to improve vertex resolution from 10 cm to 5 cm and reduce the trigger rate, primarily from background sources, by 50%. In the ECL TRG upgrade is anticipated to reduce pile-up effects.

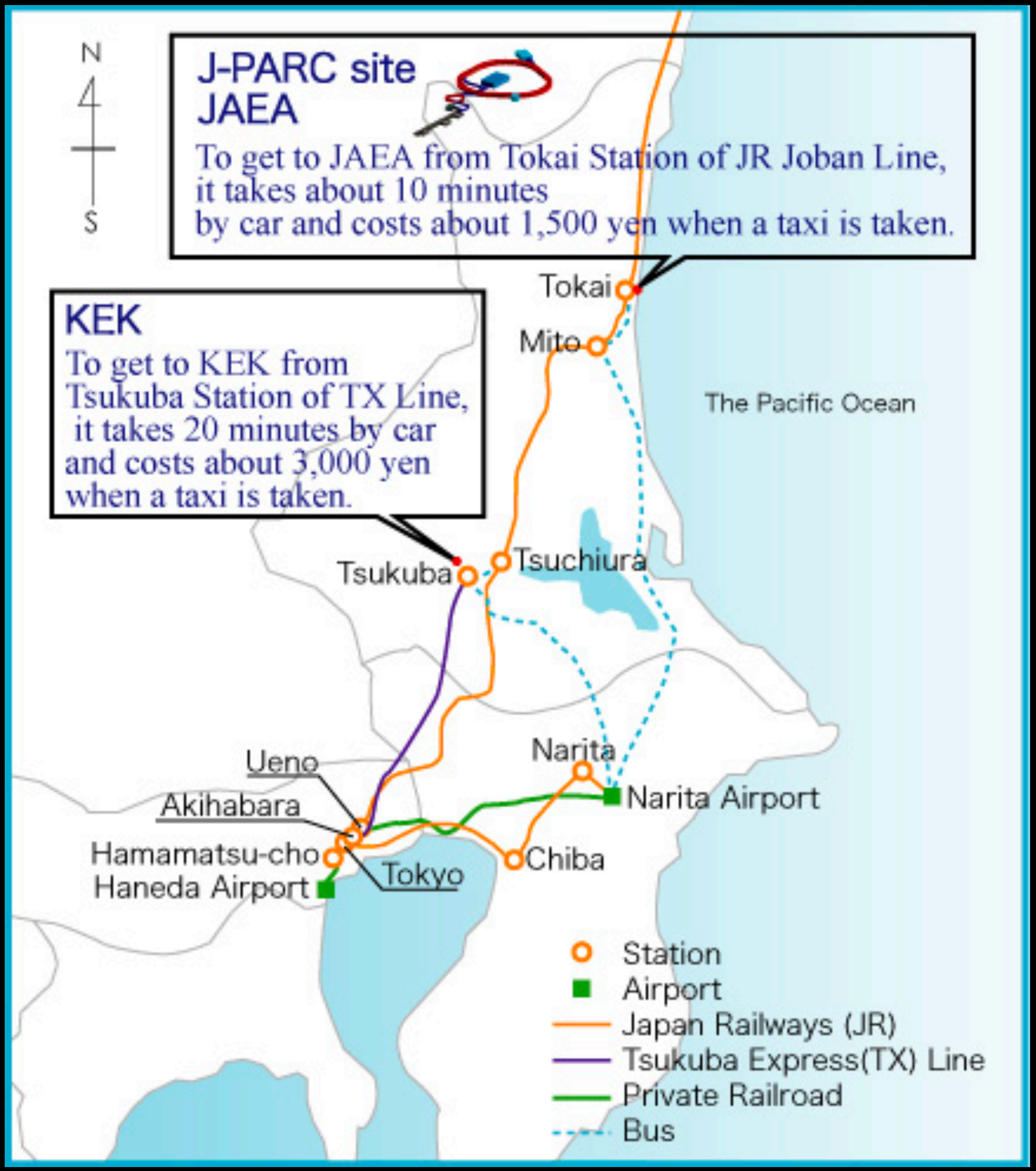
Summary

Thank you!

Backup

KEK (**K**oh **E**nerugii butsurigaku **K**enkyuusho)

high energy physics lab



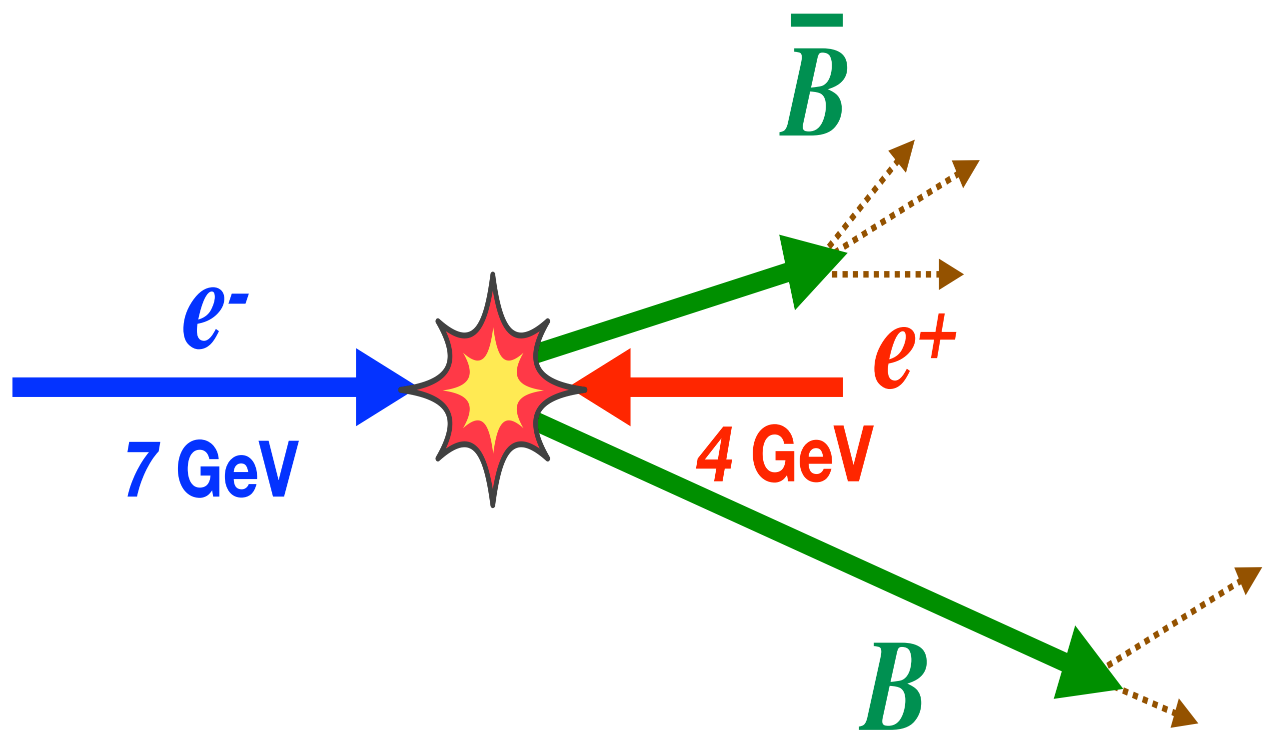
Two sites:

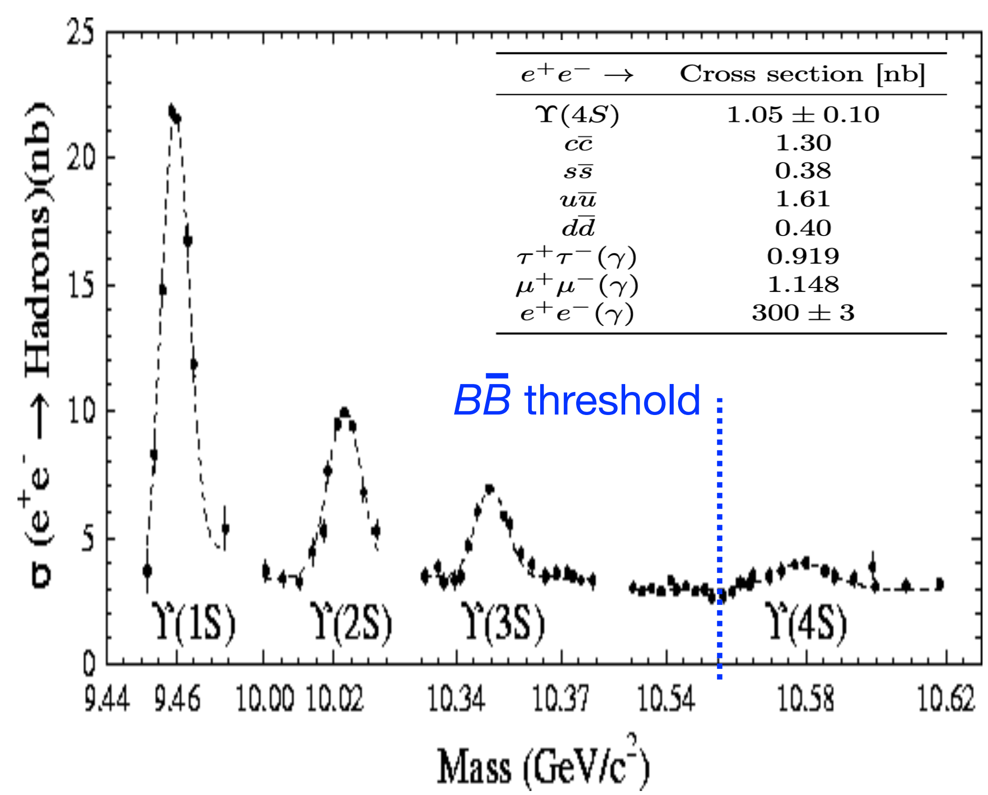
- Tsukuba,
- Tokai (J-PARC)

IPNS (Institute of Particle and Nuclear Studies)

- **SuperKEKB/Belle II,**
- **T2K/HK,**
- LHC-ATLAS, ILC,
- **COMET, muon g-2/EDM,**
- POLARBEAR, LiteBIRD
- TUCAN

Introduction — B-factories





In B-Factories, e^+ and e^- collide at 10.58 GeV to make *Y(4S)* resonance decaying into B^+B^- and $B^0\bar{B}^0$ in 96% of the time. Belle (~1 ab^{-1}) and BaBar (~0.5 ab^{-1}) played a crucial role in establishing large ***CP violation*** in the B-meson system in the SM and constrained on the ***CKM matrix.***

Nano beam scheme

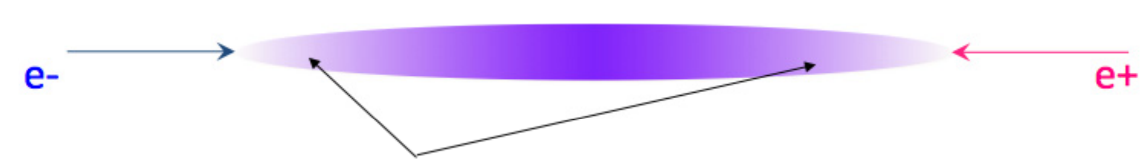
Squeezing vertical β function (β_y^*) at Interaction Point (IP)

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

- **Small vertical beam size (σ_y~60 nm): β_y^* ~0.3mm (x 1/20)**
- **Larger beam current (x 2)**

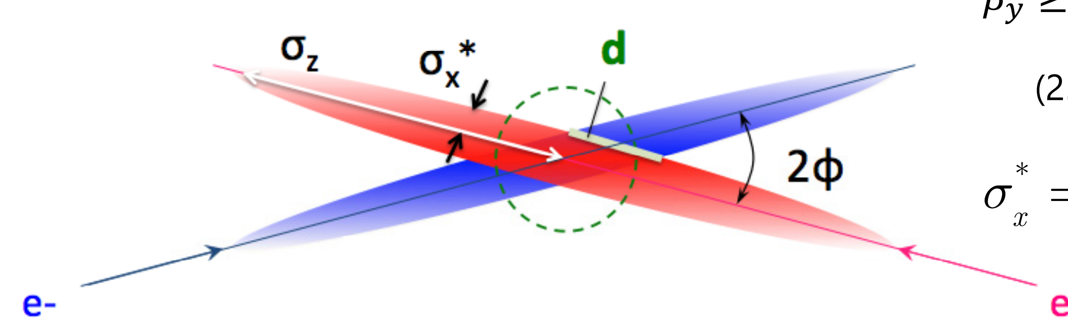
- In the nano-beam scheme with large crossing angle, effective bunch length (*d*) can be much shorter (β_y^* ~σ_z)
- Small β_x^* and small emittance (ε_x) are also the key → **positron DR**
- Positron beam energy from 3.5 to 4.0 GeV to increase beam lifetime (still ~O(10) min maximum)

head-on collision



Beam size blow-up due to collisions in large β_y

large angle collision



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

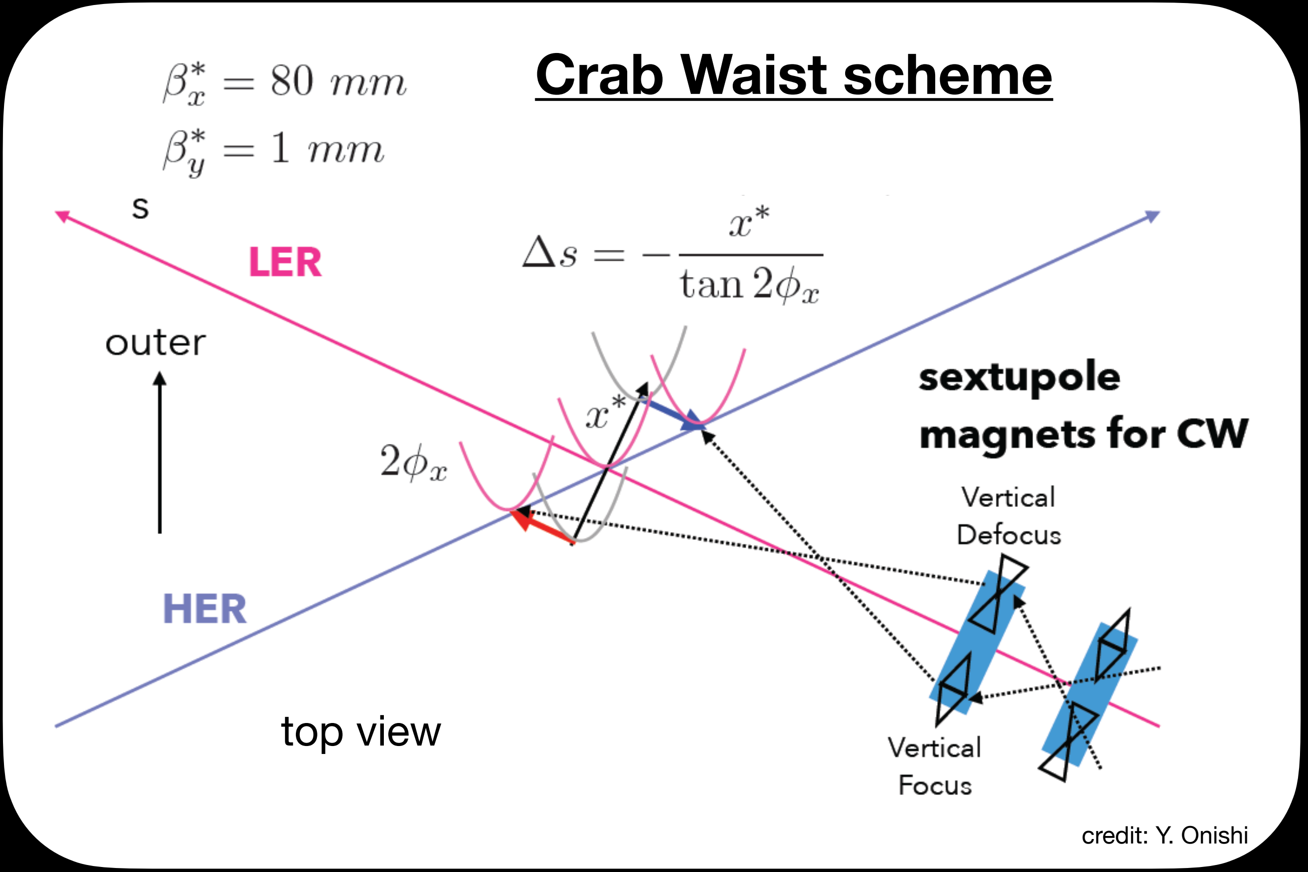
(250 ~ 300μm)

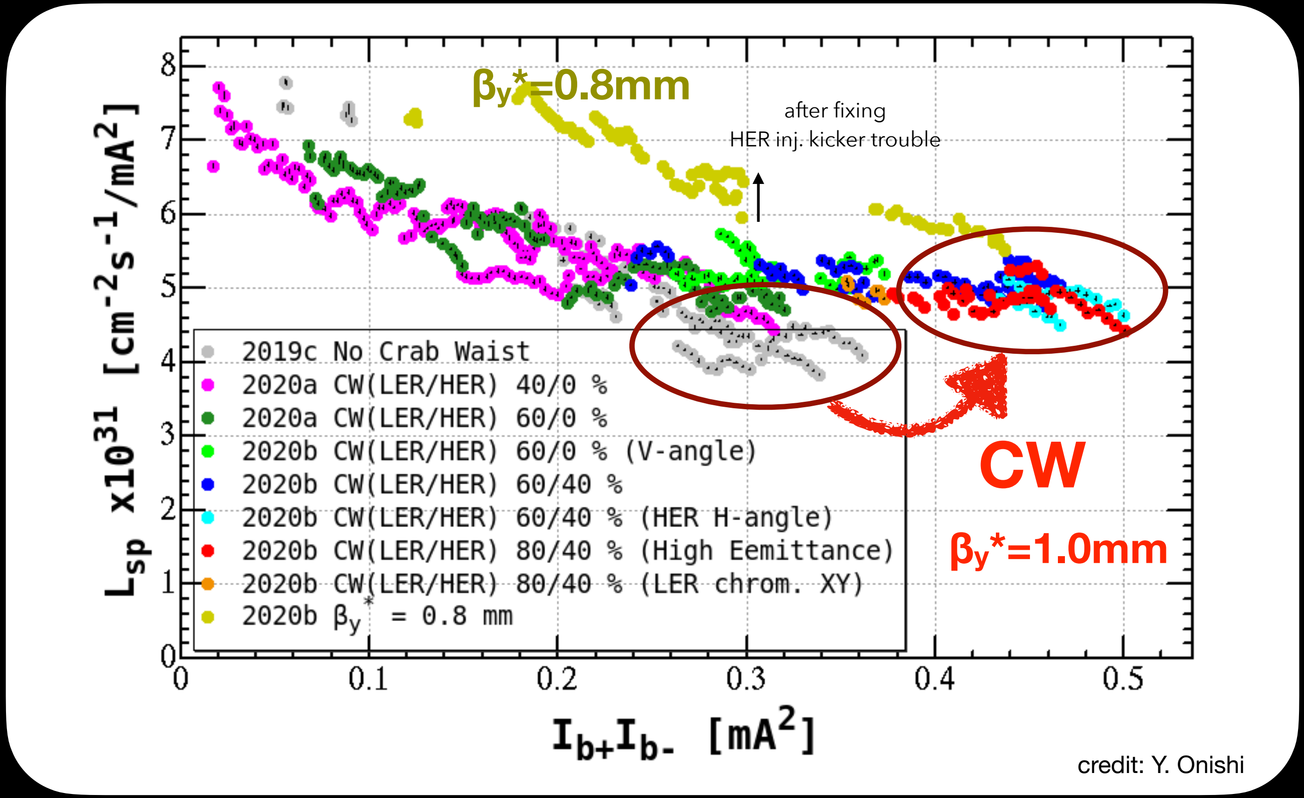
$$\sigma_x^* = \sqrt{\beta_x^* \varepsilon_x}$$

Due to hourglass effect, the luminosity does not increase when $\beta_y^* < \sigma_z$.

Specific luminosity

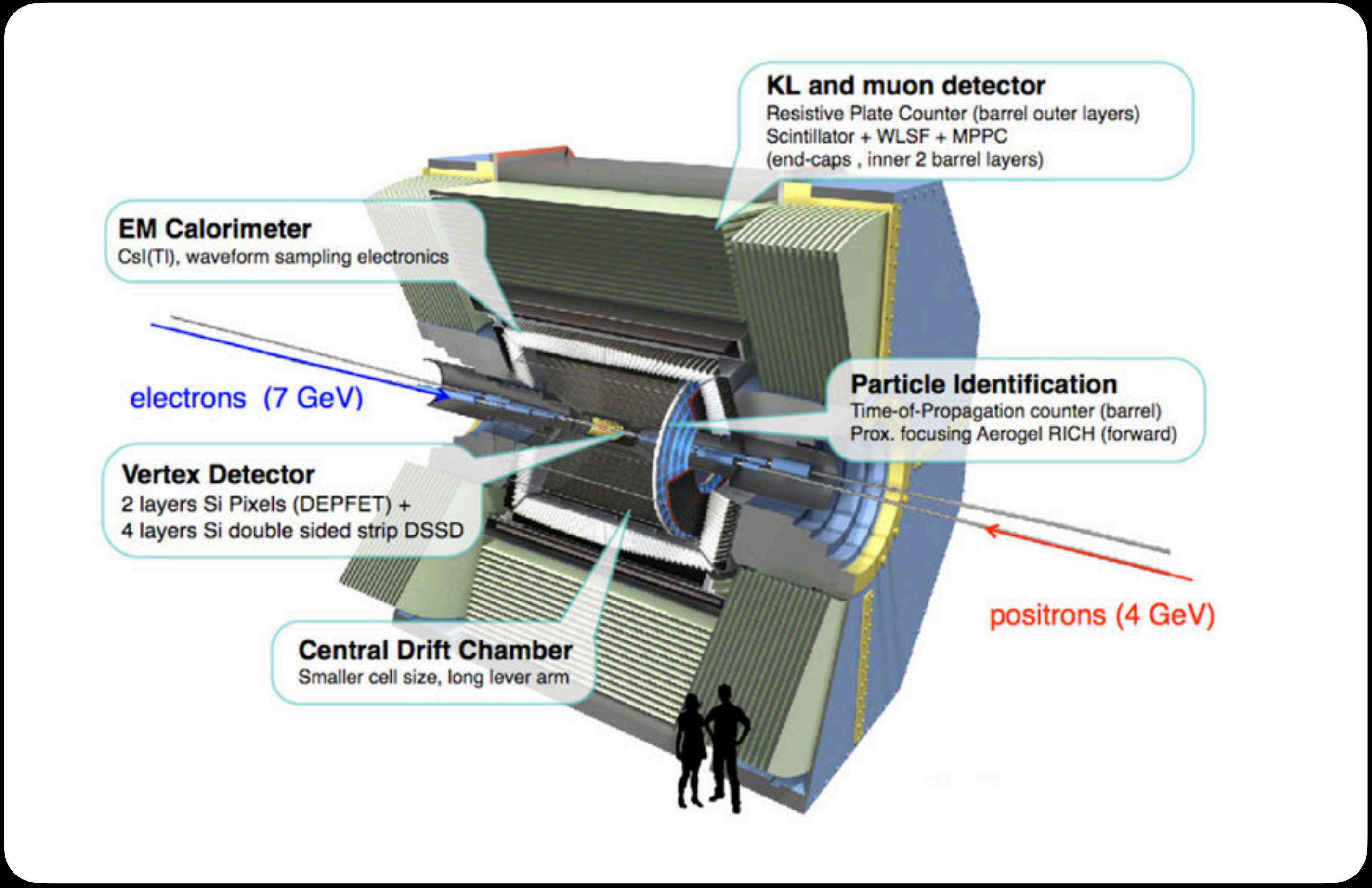
- Beam waist (minimum of vertical beam size) is aligned with the other beam axis by rotatable sextupole magnets
  → **Crab waist (CW)**
- CW mitigates ***beam size blow-up due to beam-beam effect***
  → background mitigation and higher (specific) luminosity at IP
- Luminosity performance is evaluated to be independent of total beam current (specific luminosity, $\boldsymbol{L_{SP}}$).
  → **Significant improvement with CW and/or beam size squeezing**





Belle II detector

Detector looking similar to Belle, but it is practically a brand new!



Belle II TDR, arXiv:1011.0352

Improved vertex reconstruction

- Smaller beam pipe (ϕ7.5 → 5)
- A 2-layer silicon pixel detector (PXD)
- 4-layer silicon strip detector (SVD) extended to a larger radius
- Larger volume and smaller drift cell in tracking chamber (CDC)

Improved PID and energy measurement

- Improved K/π separation (TOP and ARICH)
- Wave-form sampling robust against pile-up (ECL)
- Endcap RPC was replaced by scintillator in Muon/K_L detector (KLM)

Other improvements

- New triggers (e.g. dark sector searches)
- Analysis tools with decent machine learning techniques
- Grid computing

Machine parameters (at design)

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	**3.5**	**8**	**4**	**7.007**	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	5.3	nm
Emittance ratio	κ	0.88	0.66	0.27	0.24	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		3.2/0.27	2.5/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.0886	0.081	
Bunch Length	sz	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	sx^*	150	150	10	11	um
Vertical Beam Size	sy^*	0.94		0.048	0.062	um
Luminosity	**L**	**2.1×10^{34}**		**8×10^{35}**		**$cm^{-2}s^{-1}$**

Note: beam energy changed because positron beam (Touschek) lifetime is too short while accepting smaller boost ($\beta\gamma$ = **0.42 → 0.28**) of decayed particles.