The Belle II Upgrade Program

Keisuke Yoshihara

University of Hawaii at Manoa

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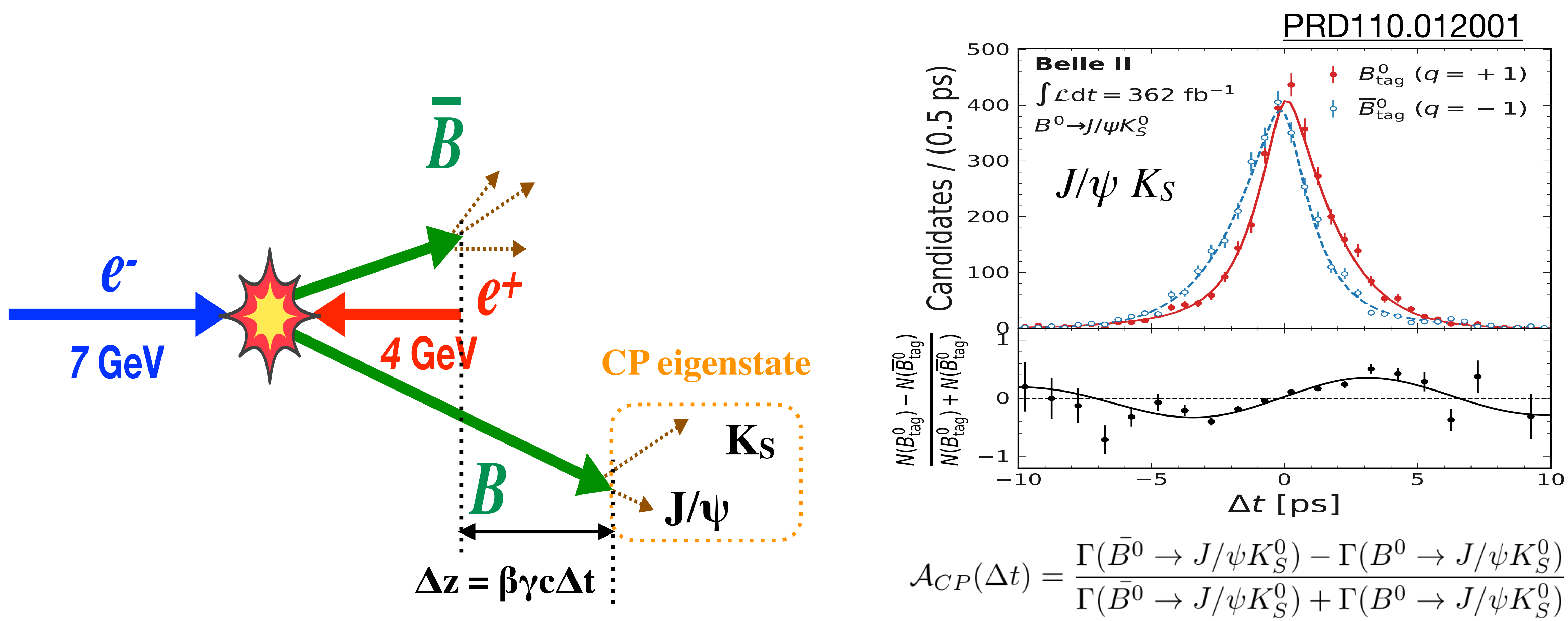
Belle II Upgrade Conceptual Design Report (CDR):

https://arxiv.org/abs/2406.19421

SuperKEKB/Belle II: Next generation B-factory

e^+e^- beams collide at the energy of *Y(4S)* res. (10.58 GeV) and pairs of neutral B-mesons are produced in a quantum entangled state.



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K_S^0) - \Gamma(B^0 \to J/\psi K_S^0)}{\Gamma(\bar{B}^0 \to J/\psi K_S^0) + \Gamma(B^0 \to J/\psi K_S^0)}$$

CP violation in B-meson decay was discovered by predecessors —KEKB/Belle ($1ab^{-1}$) and PEP-II/BaBar (550 fb^{-1}).

Belle II Physics Program

[**Belle II Physics Book (PTEP)**](https://doi.org/10.1093/ptep/ptaa008)

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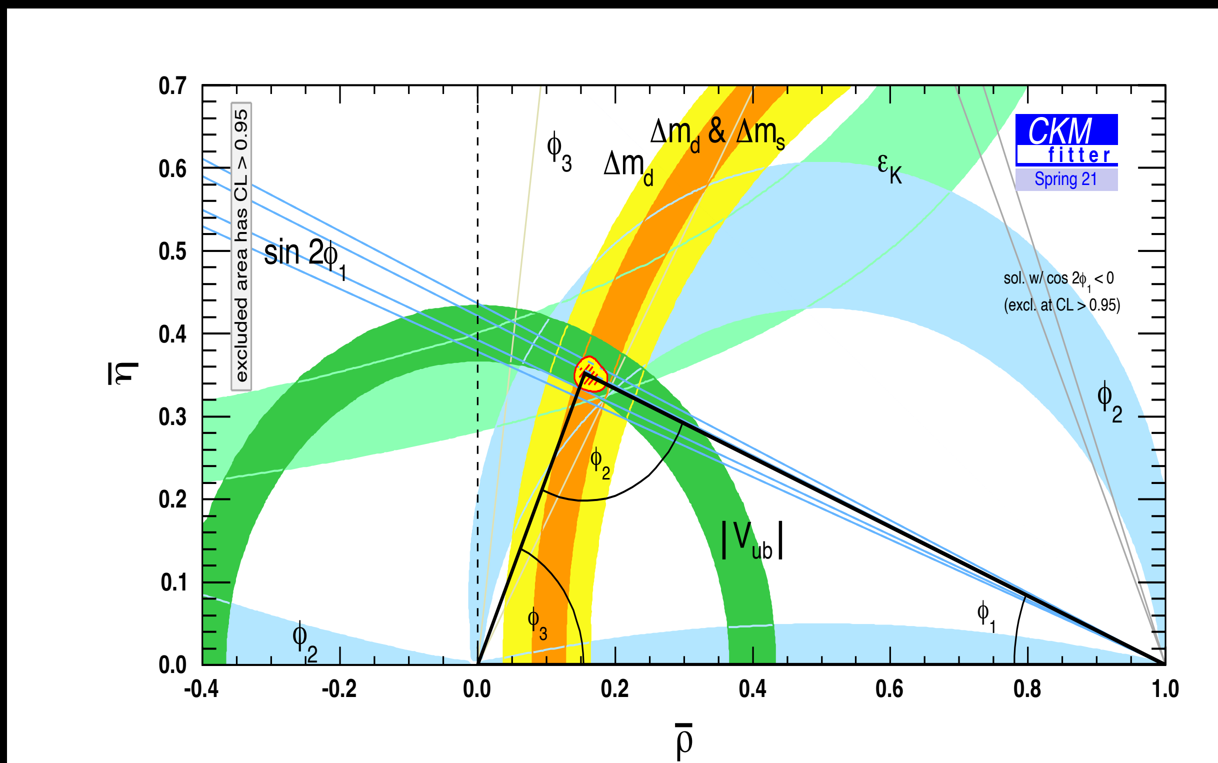
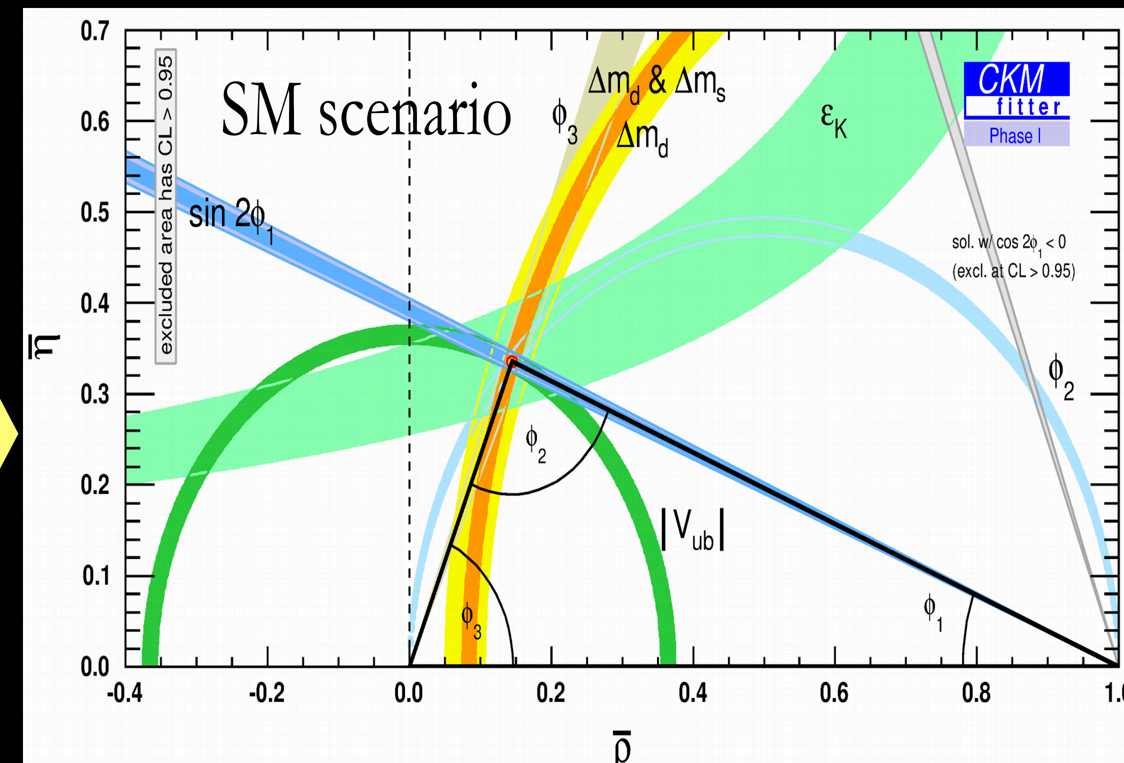
As of 2021



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



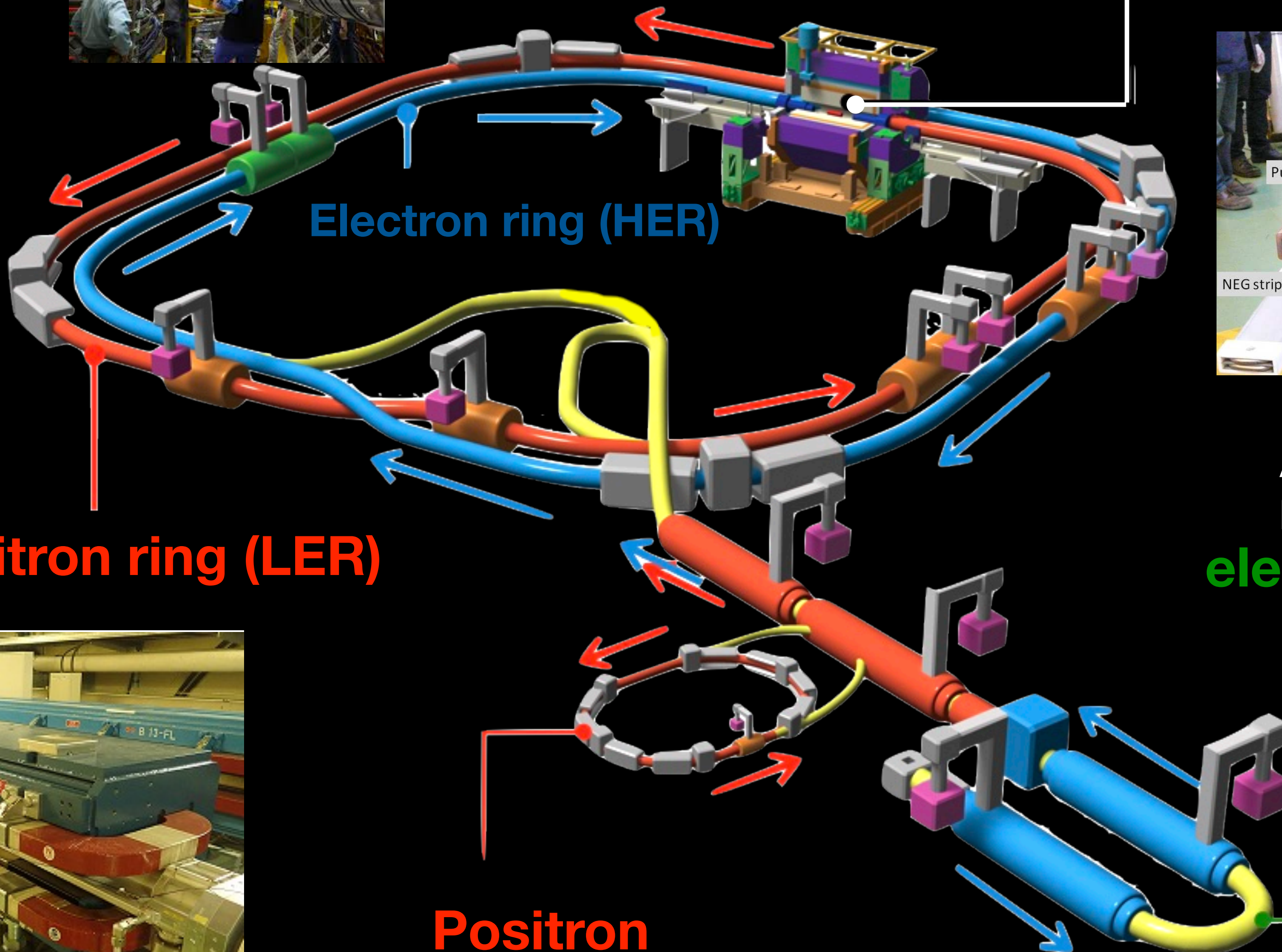
Belle II's unique capabilities:

- Missing energy decays:
  - Evidence of $B \to K\nu\overline{\nu}$ (PRD109.112006),
  - Measurements of $B \to D^{(*)}\, \tau\, \overline{\nu}_\tau$ (PRD110.072020)
- Dark Sector (neutrals, missing energy): $e^+e^- \to \gamma a,\ a \to \gamma\gamma$ (PRL125.161806)
- τ leptons

SuperKEKB (construction completed in 2018)

QCS magnets

RF reinforcement



Belle II detector

Interaction Point

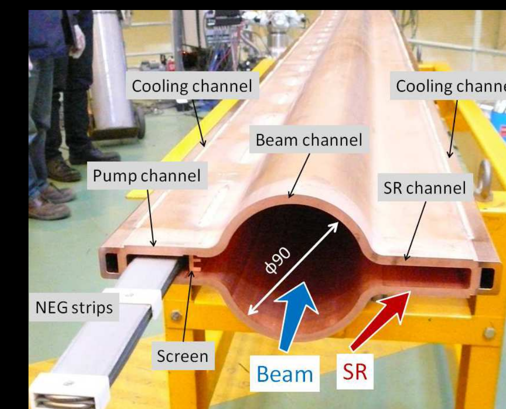
Electron ring (HER)

Positron ring (LER)

Positron dumping ring

electron/positron injector

Low-emittance RF gun



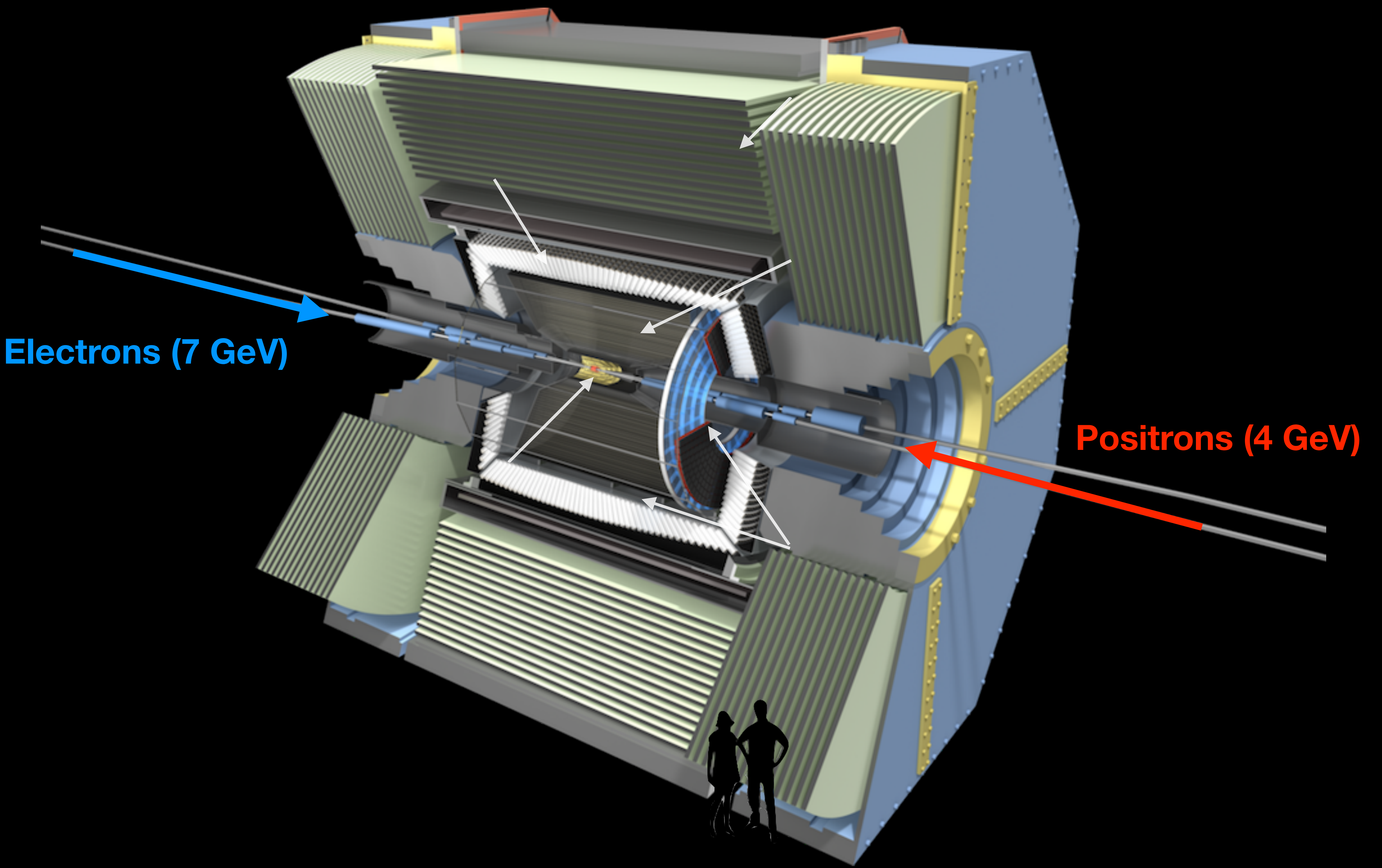
Ante-chamber beam pipe

dipole magnets newly installed in LER (~4 m)

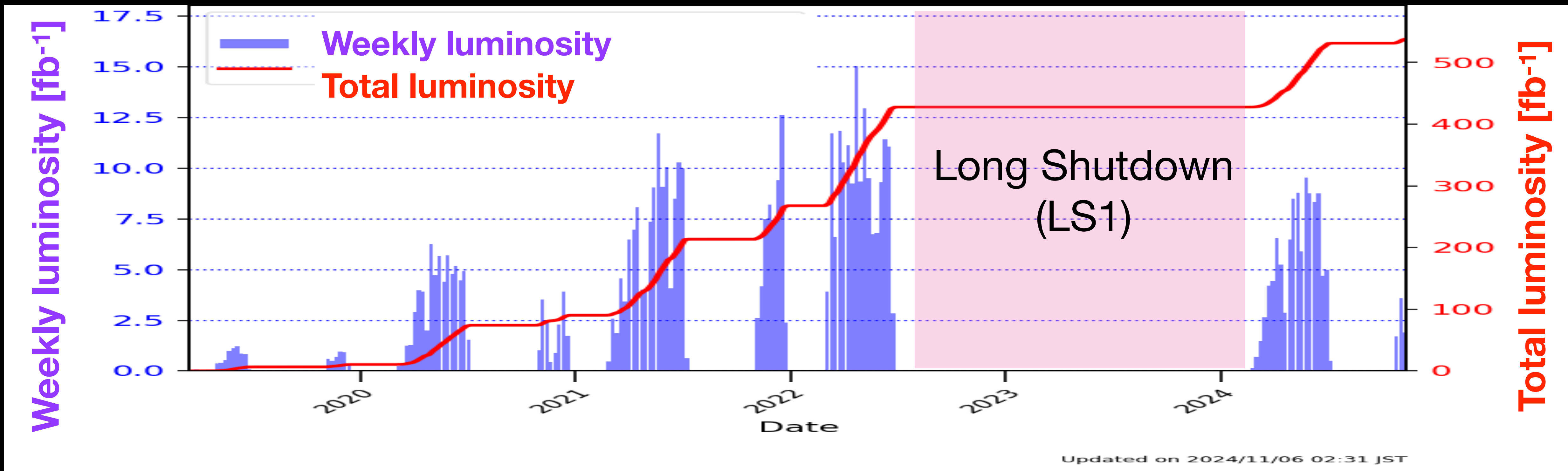
First e^+e^- nano beam accelerator (β_y^*= 0.3 mm)

Belle II Detector

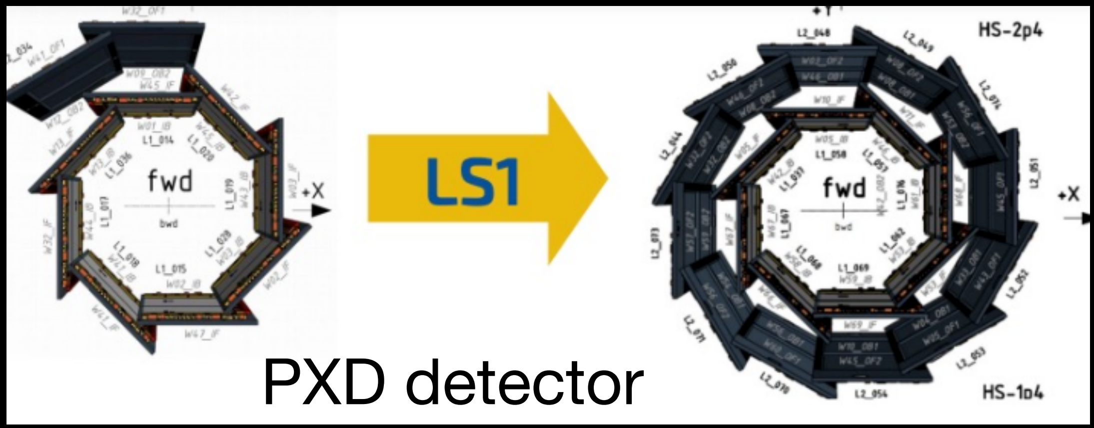
Belle II TDR, arXiv:1011.0352



Status of SuperKEKB



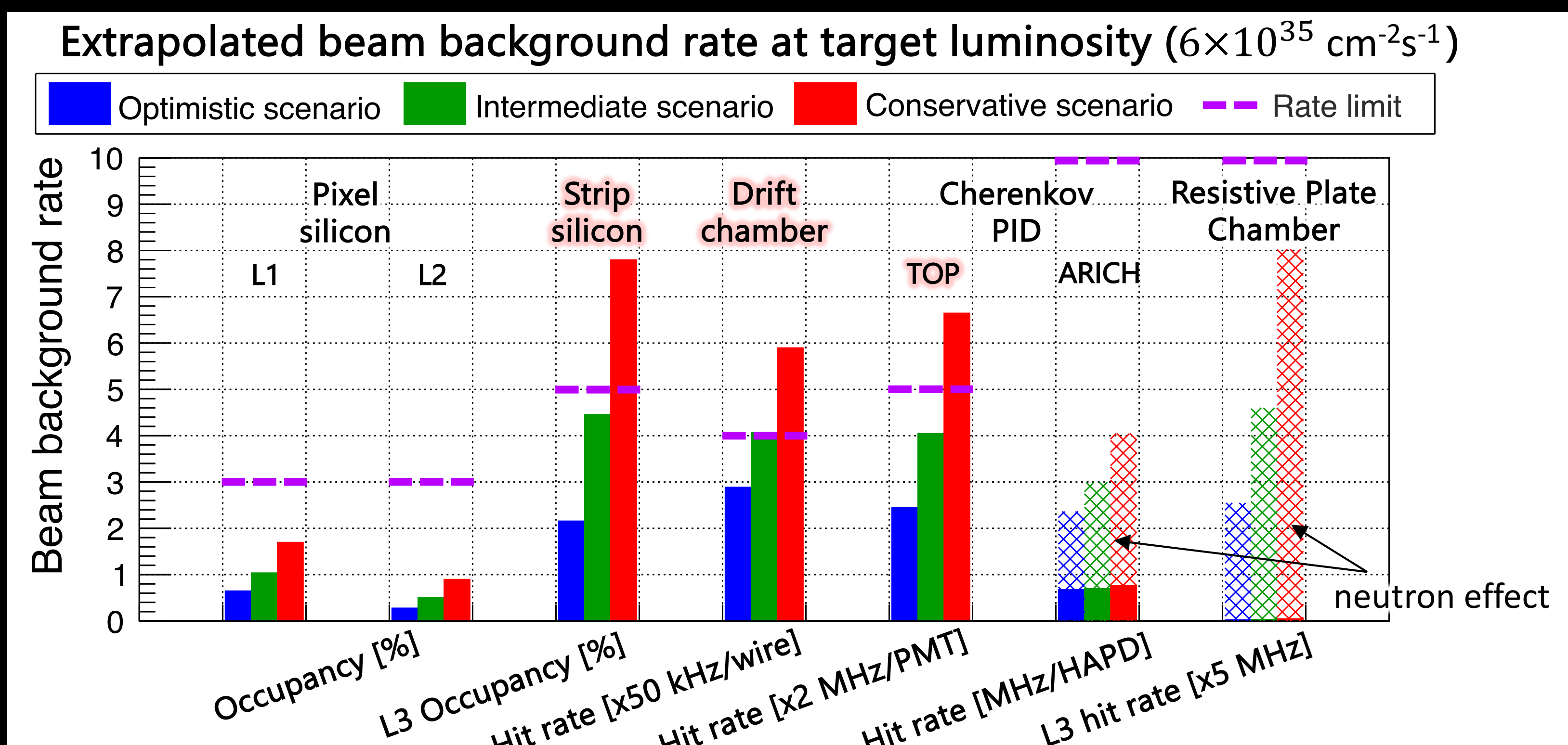
- **Achievements**
  - World record luminosity:
    4.7×10^{34} $cm^{-2}s^{-1}$ (June 2022)
  - Integrated luminosity:
    ~540 fb^{-1} recorded (max 2.5 fb^{-1}/day)
  - Physics publications: 45 papers as of Sep 2024

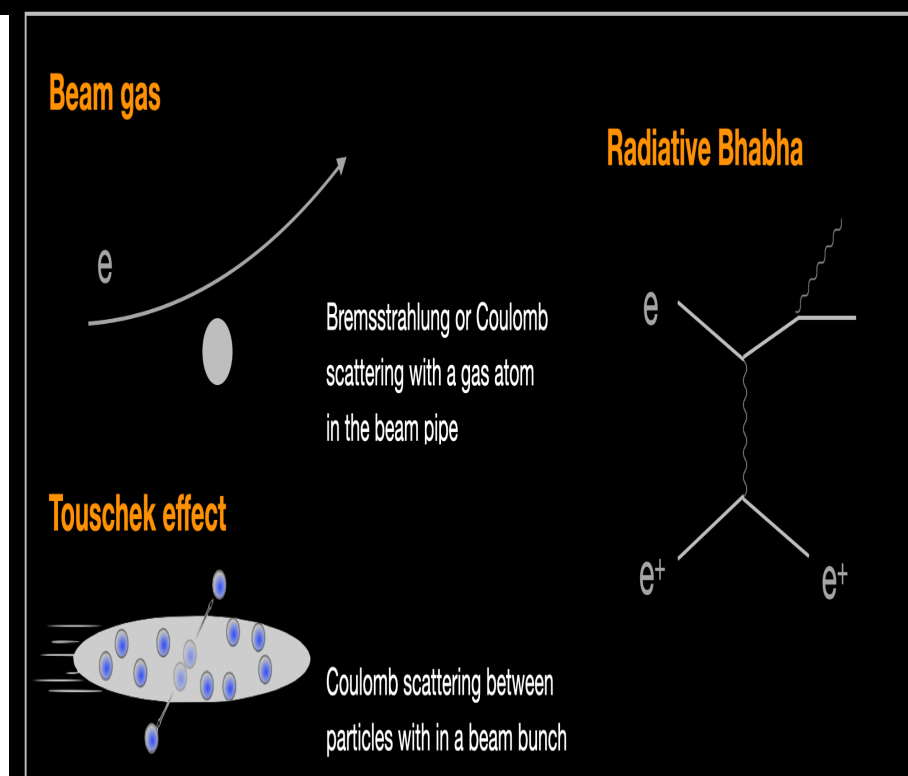


- **Long Shutdown 1 (LS1)**
  - **PXD completion**, Non-linear collimator, additional beam monitors

Higher Luminosity Increases Backgrounds

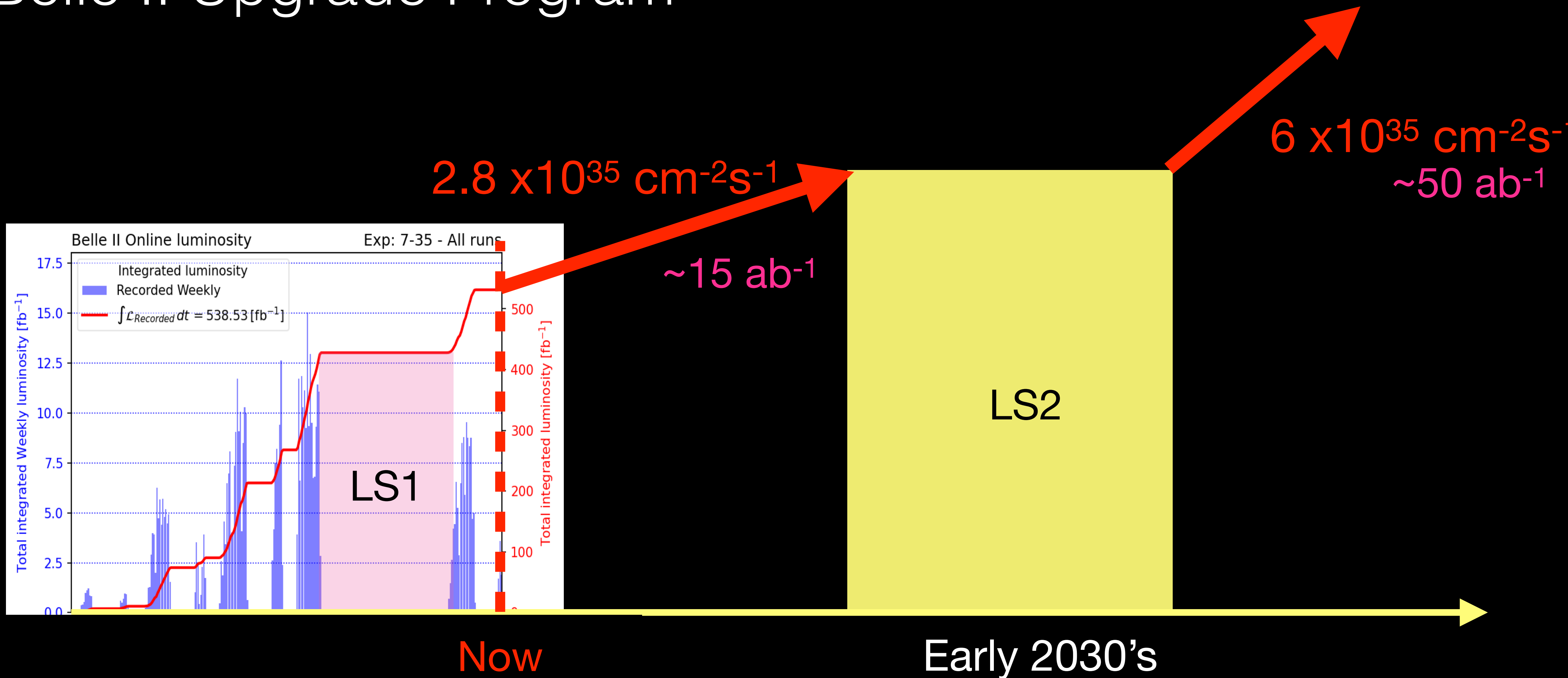
Beam-induced background rates impact detector performance and longevity.





Many sub-detector systems lack the margin to handle higher backgrounds at the target luminosity.

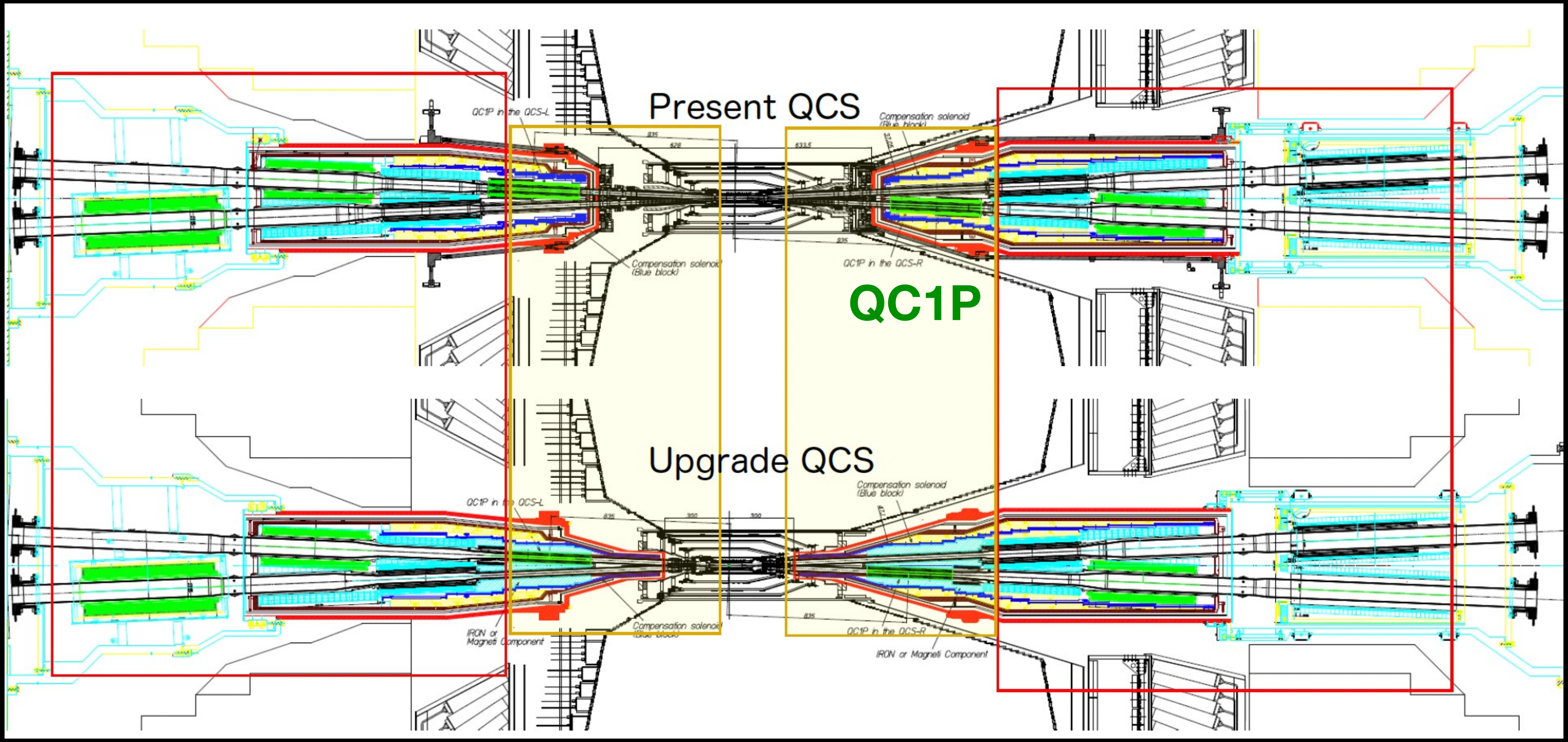
Belle II Upgrade Program



- Difficult to reach $\beta_y^* = 0.3$ mm without IR modification
- LS2 upgrade: a redesigned IR, an enhanced detector, and increased robustness against beam-backgrounds
- Establish nano beam scheme for future HEP (Synergy with FCC-ee)

Required

SuperKEKB IR Upgrade towards $\beta_y^* = 0.3$ mm

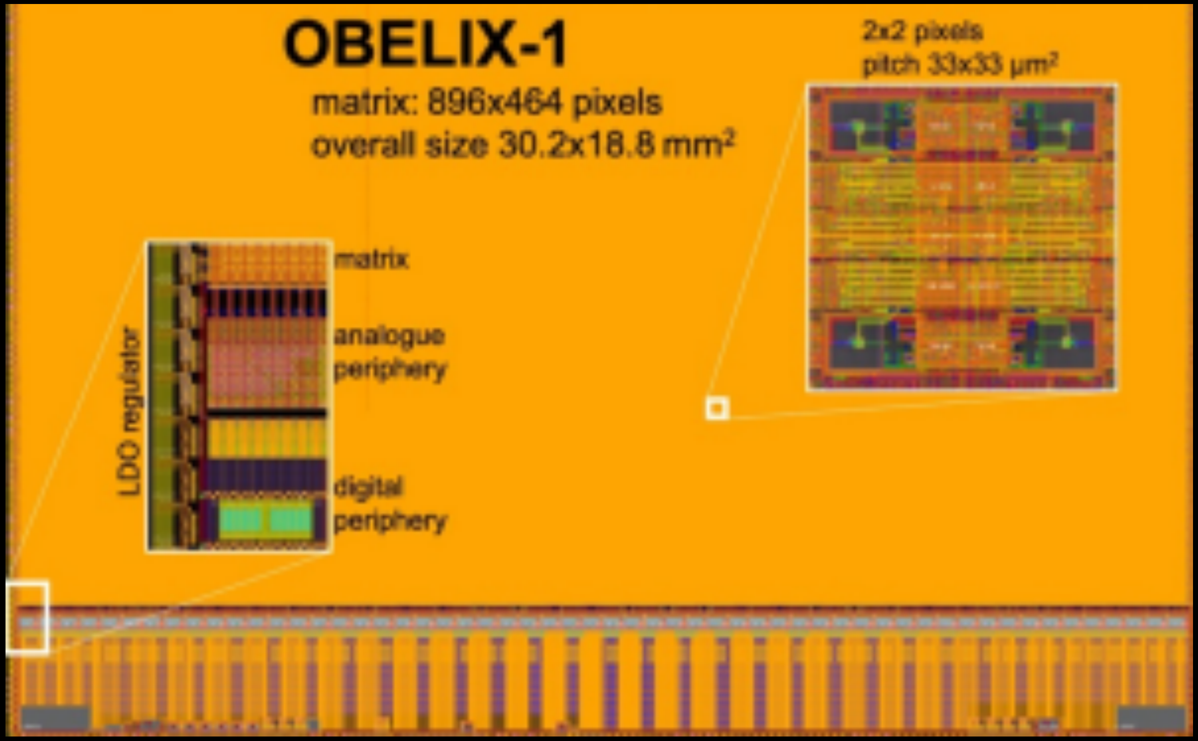


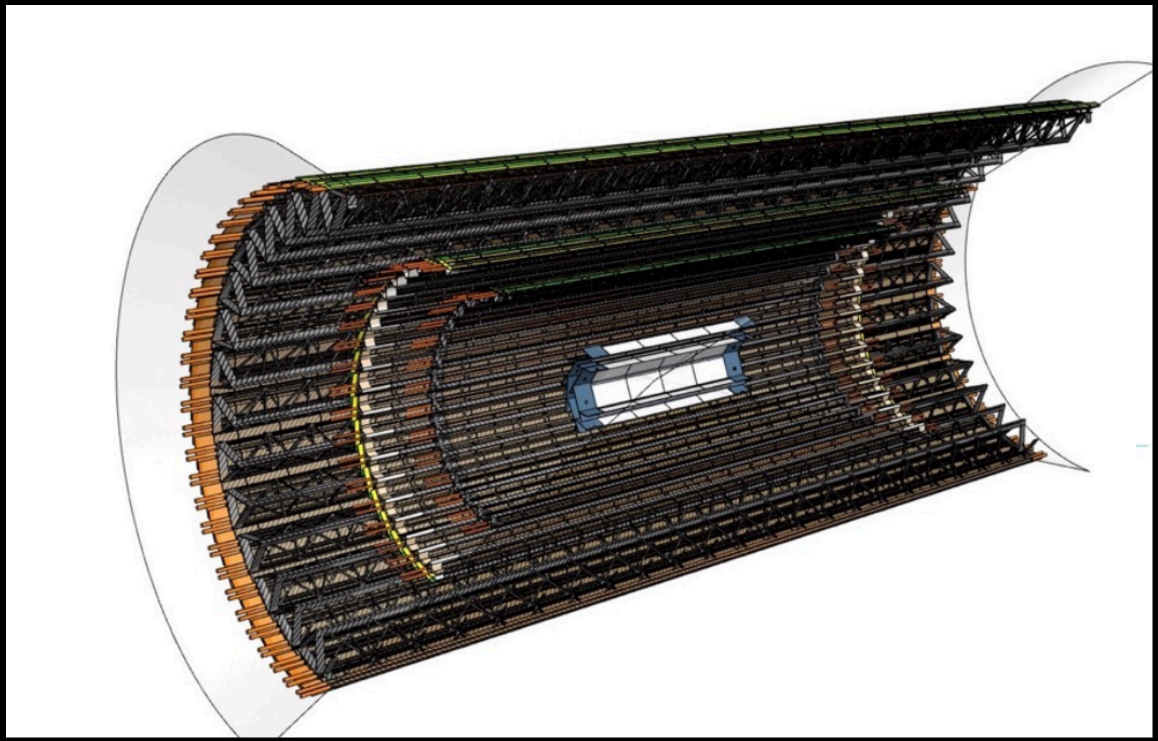
- A new QC1 Magnet
  - Move QC1P 100 mm closer to the IP
  - Utilize Nb_3Sn to support higher current
- Install a new compensation solenoid near the IP
- Minimize chromatic X-Y coupling between the IP and QC1

Vertex Detector Upgrade: VTX

Required

- A full VXD upgrade is required with IR modification
- DEPFET Pixel → CMOS Pixel
- Monolithic Active Pixel Sensor (MAPS) technology (sensor + readout)
- OBELIX (Optimised BELle II monolithic pIXel) Sensor, based on TJ-Monopix2 prototype (developed for HL-LHC ATLAS)



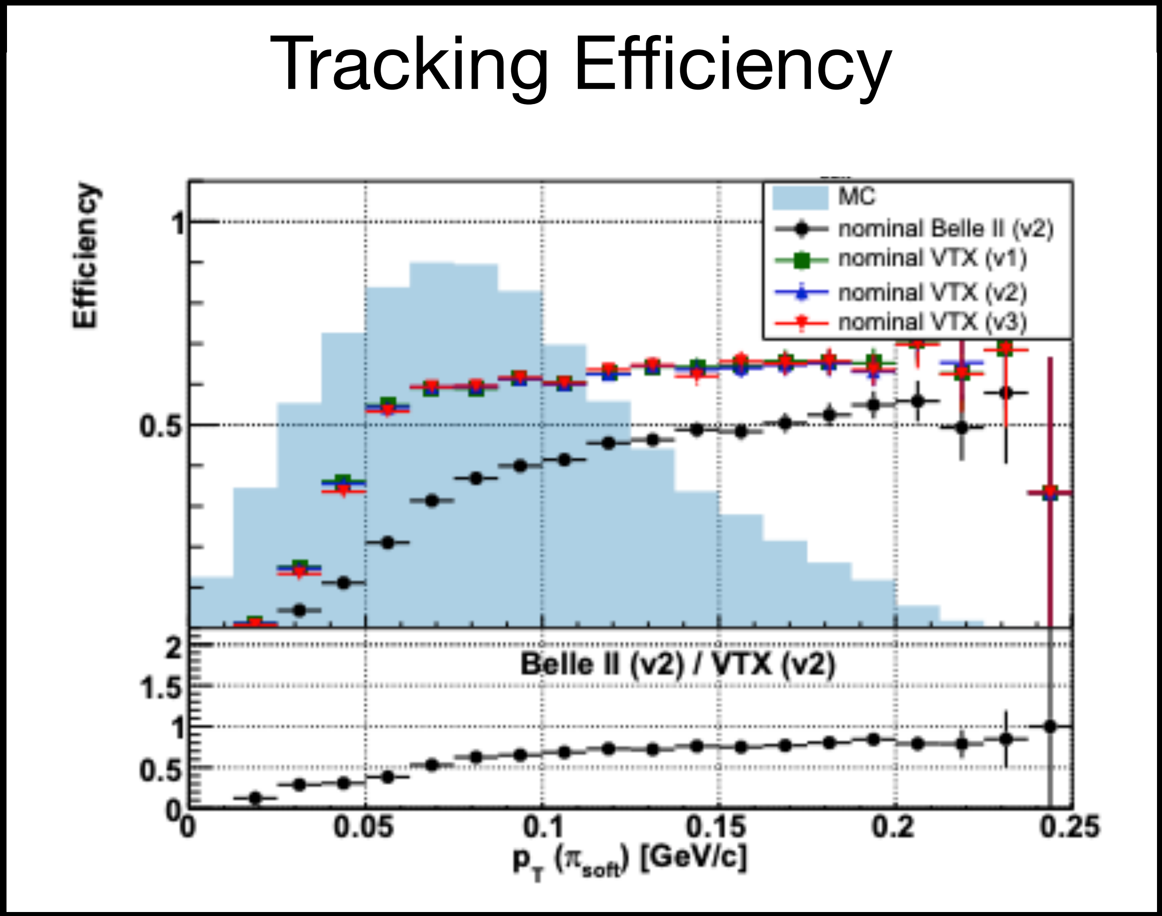


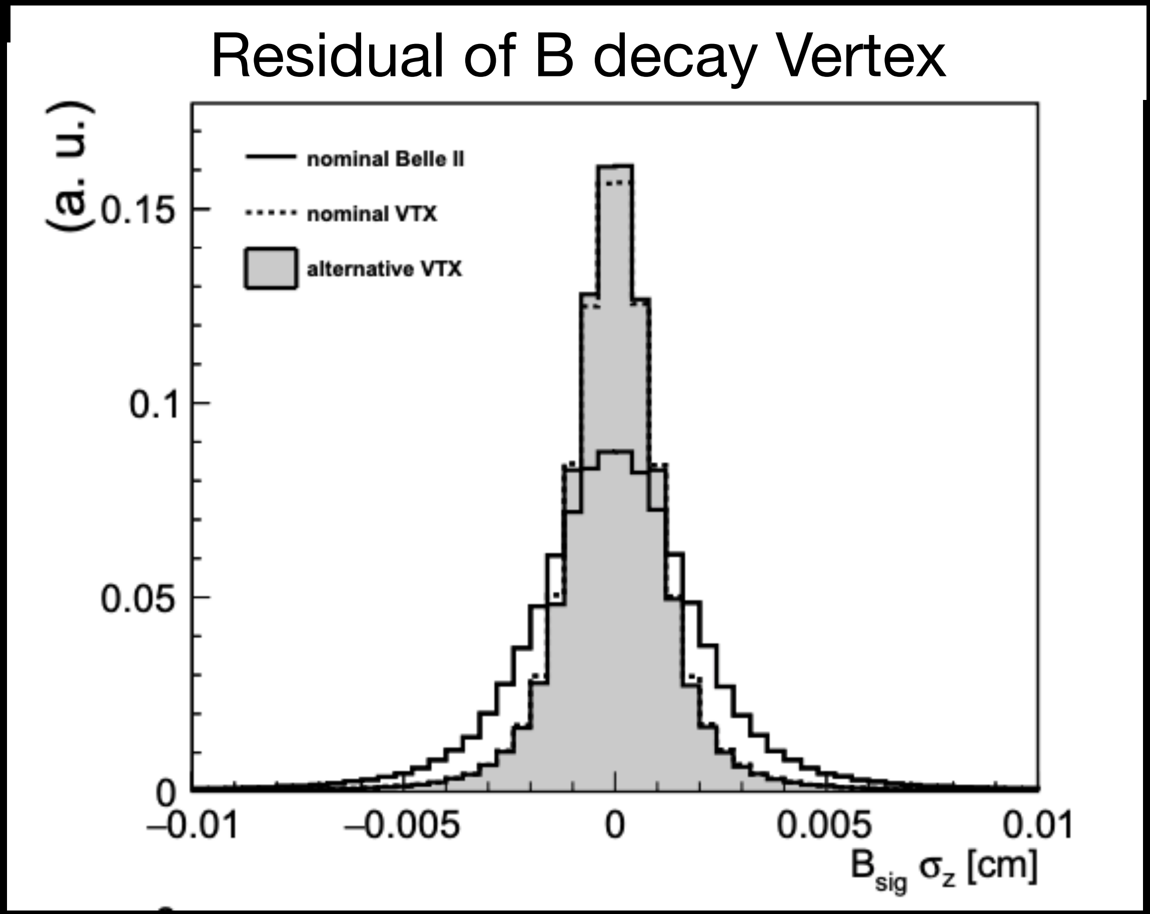
- Pixel Pitch: 30-40 um with single-point resolution < 15 um
- Material Budget: 0.1-0.8% X_0 per layer
- Rad tolerance: total ionizing dose of 100 Mrad and NIEL fluence

- Max. radius 14 cm and length 70 cm

Tracking and Vertexing Performance

https://arxiv.org/abs/2406.19421





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

Drift Chamber (CDC): Front-End Electronics

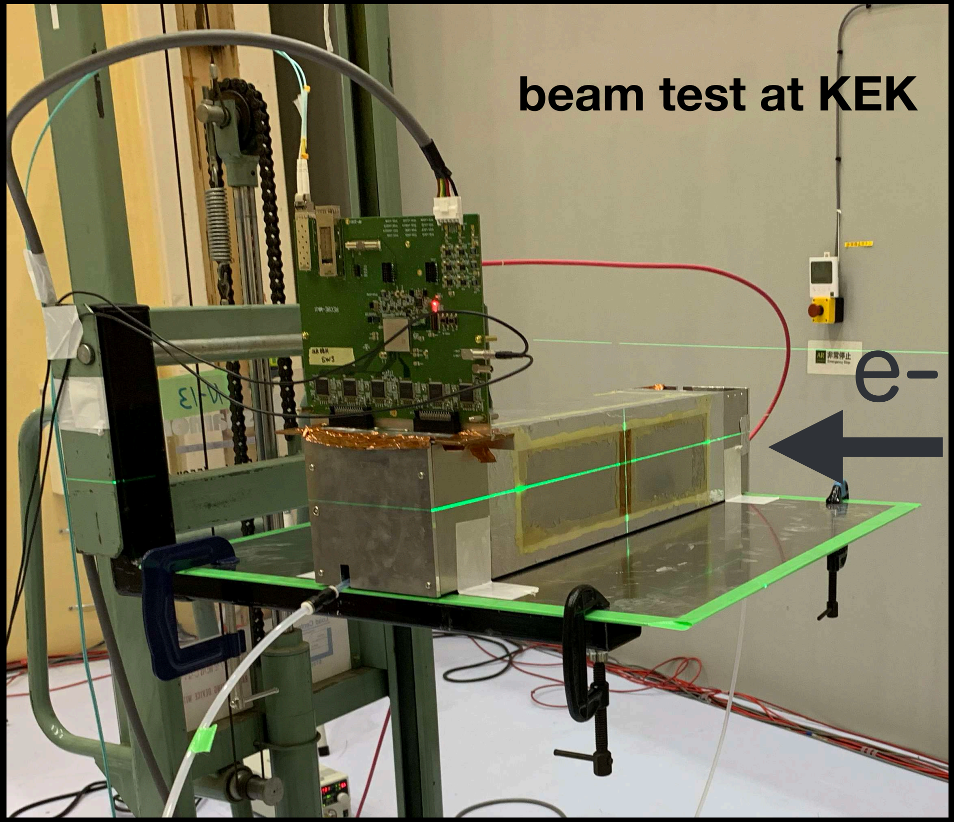
Required

Readout Electronics Upgrade

- CMOS 65nm 8-chan ASIC (ASD + FADC)
- FPGA (Xilinx Kintex-7)
- QSFP module (~100 Gbps)
- Low power consumption

Performance Characterization

- Beam tests at KEK to evaluate time-resolution and basic performance.
- Irradiation tests for ASIC, QSFP, and FPGA, with gamma rays and neutrons

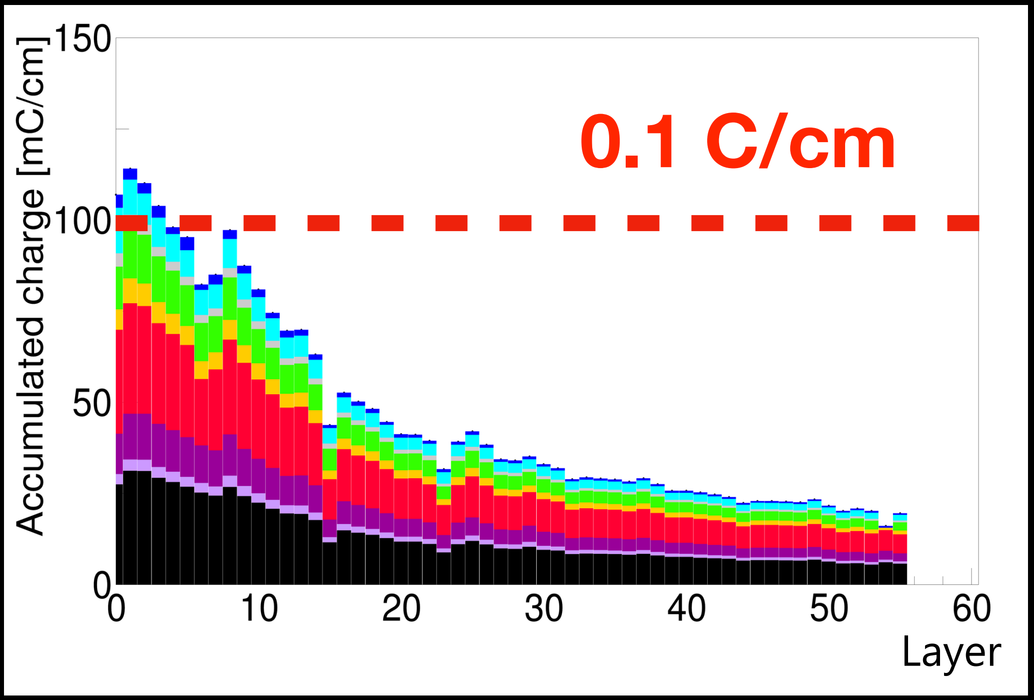


Drift Chamber (CDC): Chamber Replacement

R&D Phase

Aging Effect

- Projected ~6% gain drop at an accum. charge of 1 C/cm per wire foreseen.
  - Currently, the inner layers have accumulated ~0.1 C/cm

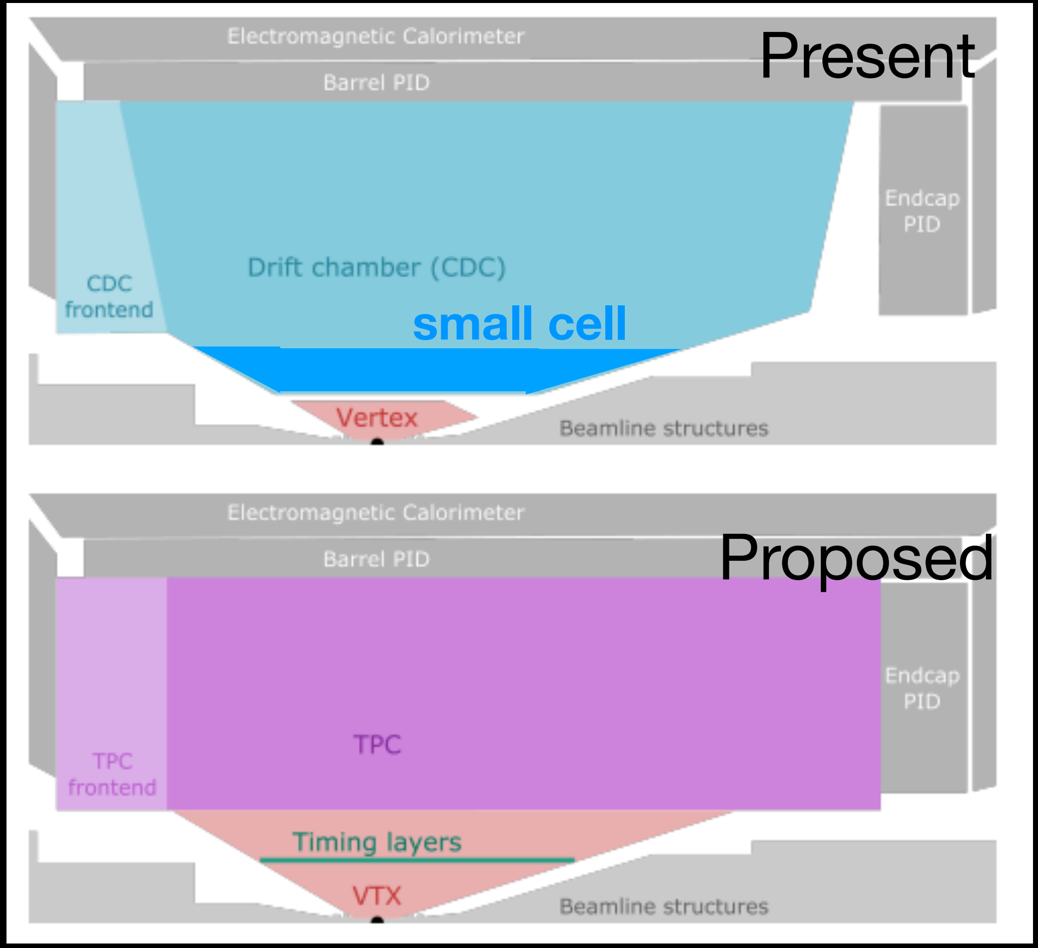


Upgrade Options

- Replacing the small cell or the entire CDC with new chambers or silicon detectors

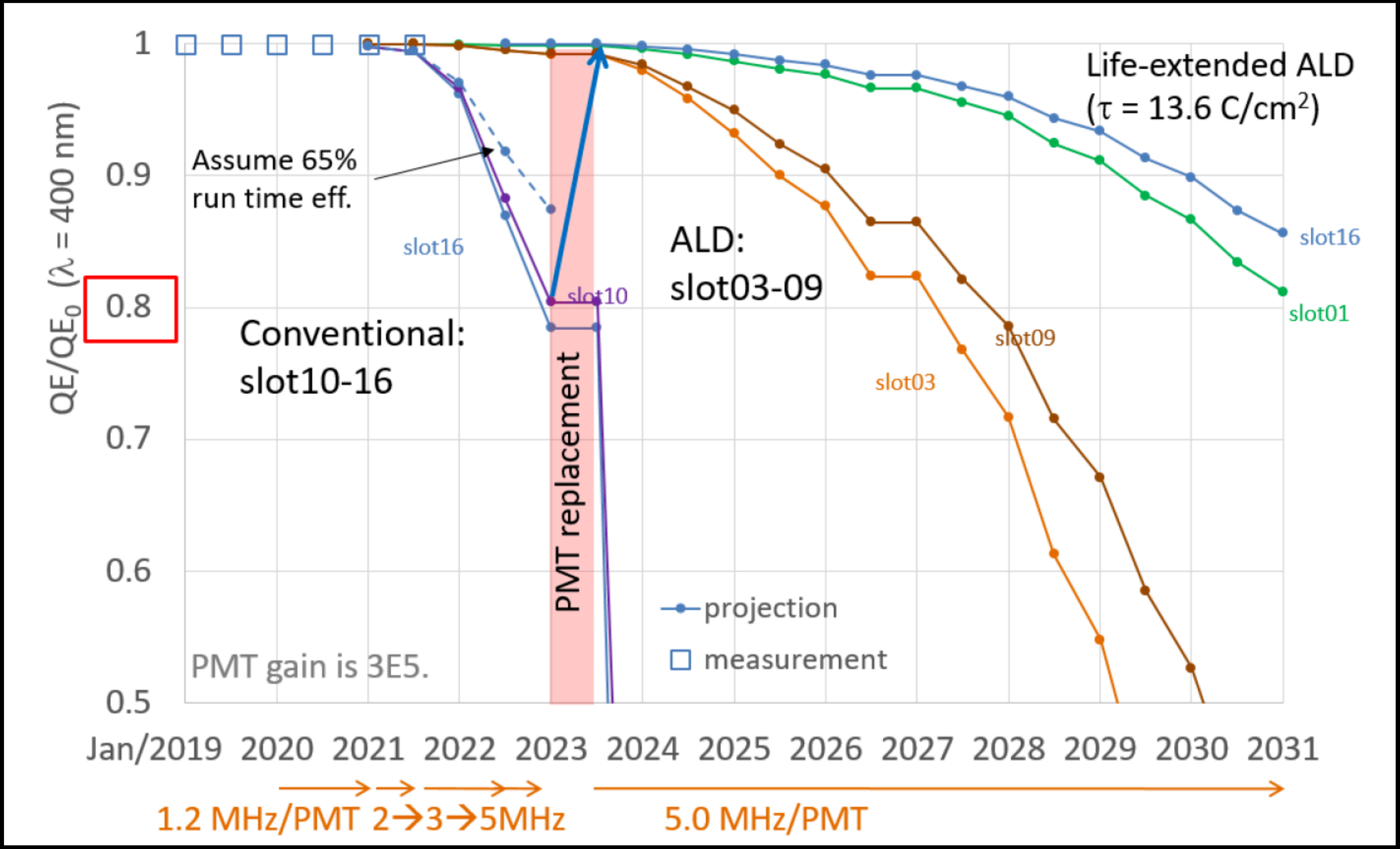
US Belle II

- Hybrid approach: Combination of silicon layers and a TPC with an LGAD timing layer



https://arxiv.org/pdf/2203.07287

Time of Propagation Detector (TOP)



We continuously monitor beam-background levels and the degradation of Quantum Efficiency (QE)

TOP Upgrade Plan

Required


R10754-07-M16 Hamamatsu

MCP-PMT Replacement

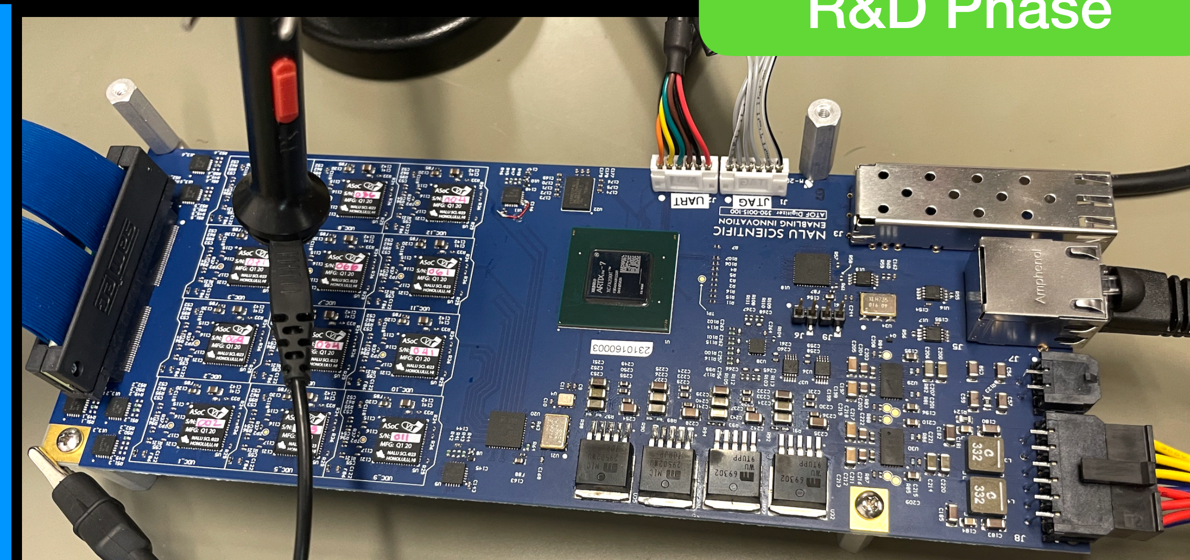
- Conventional PMTs will be replaced with lifetime-extended ALD-PMTs (Atomic Layer Deposition) for a higher accumulated charge.
- Further improvement may be pursued.

US Belle II

Readout Electronics Upgrade

- 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.

R&D Phase


ASoC Eval Board from Nalu

K_L and Muon Detector (KLM)

R&D Phase

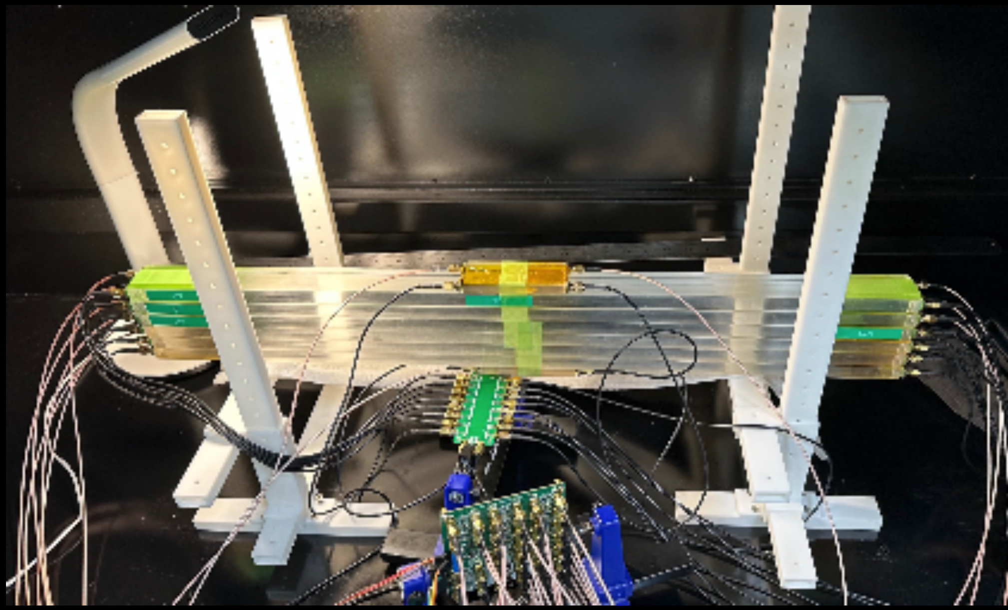
US Belle II

RPC streamer mode to avalanche mode

- Reduced charge will increase rate capability, and minimize sensitivity to background neutron flux.
- Identify a suitable gas mixture, (e.g., SF6)
- Install low-noise preamp near the detector.

Replace RPCs with Scint. in the barrel

- Better time resolution and higher K_L efficiency.
- Substantial work, including re-designing electronics for feature extraction.



Trigger Hardware Upgrade to UT5

Required

UT3

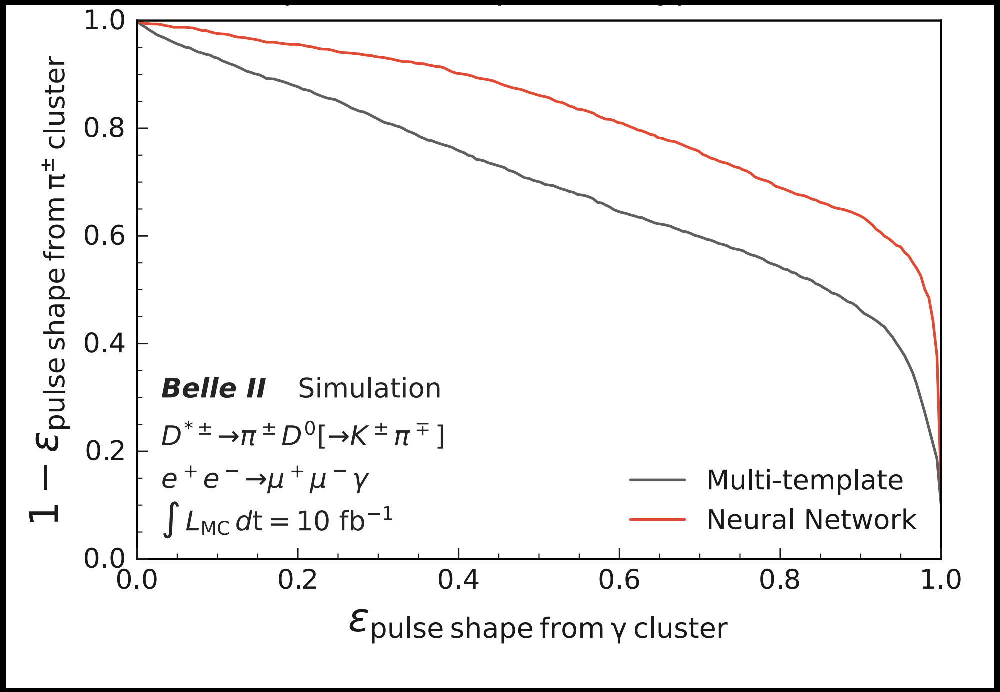
UT4

UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Versal
Sub FPGA (Xilinx)	– –	Artix7	Artix7 , 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

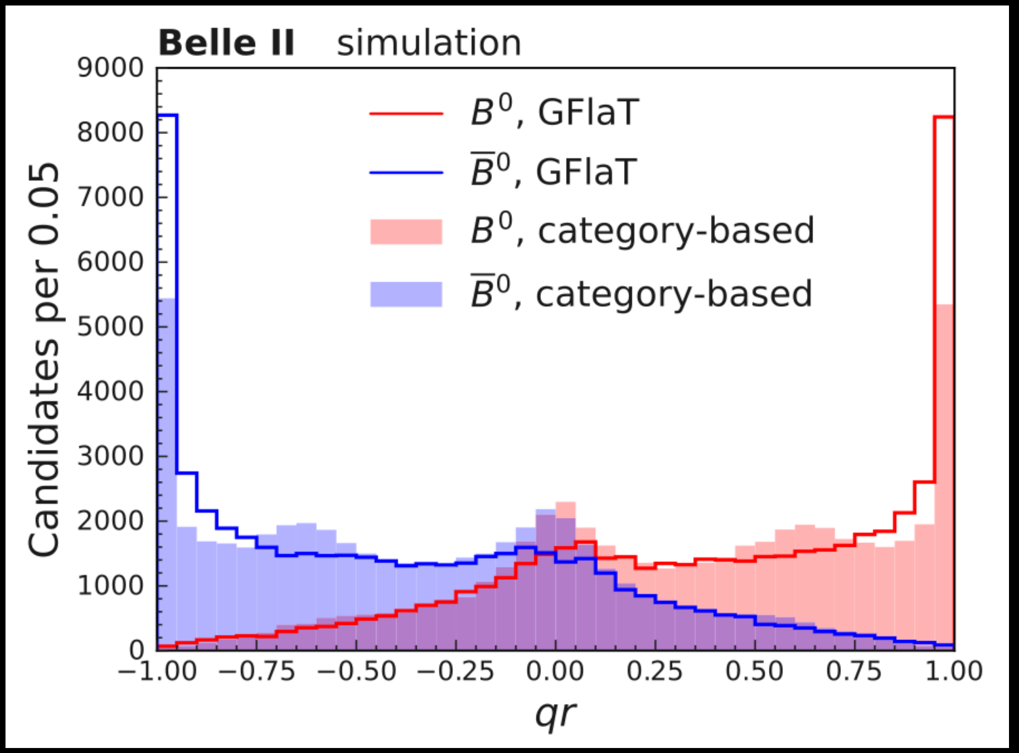
- Upgrading to UT5 will enable advanced ML-based algorithms
- Optical transmission speed will be significantly improved.
- ML-based tracking algorithms in CDC TRG improves vertex resolution from 10 to 5 cm and reduce the TRG rate by 50%.
- ECL TRG: substantial reduction in pile-up effects.

ML/AI in the Belle II Upgrade

- FPGA implementation with HLS
  - NN-based single track trigger — Done
  - DNN track trigger — Ongoing
  - Real-time waveform discrimination on the front-end board (ECL) — Idea



- Improved Reconstruction
  - GNN-based tracking — Ongoing
  - GNN for B-meson rec. (link) — Ongoing



- Beam abnormality detection
  - ML/AI for beam diagnositcs monitors (e.g., BOR) — Idea

Summary

- To fully exploit physics opportunities at Belle II and to cope with higher beam background, the detector upgrade is crucial.

- Key Upgrades:
  - Interaction Region (IR): Need modification for high luminosity
  - Vertex Detector (VTX): MAPS technology to improve vertex resolution.
  - CDC and TOP: Improved capability for higher beam backgrounds

- Join us:
  - KLM Postdoc opening: https://inspirehep.net/jobs/2829210
  - Other Belle II Postdoc positions available (See hepinspire)

Thank you!

Backup

Nano beam scheme

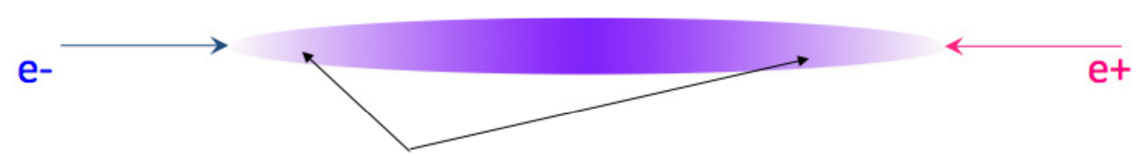
Squeezing vertical β function (β_y^*) at Interaction Point (IP)

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

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

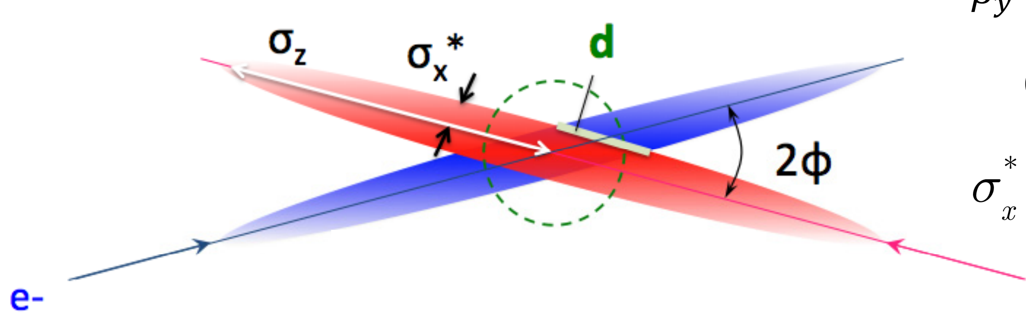
- In the nano-beam scheme with large crossing angle, effective bunch length (*d*) can be much shorter (β_y^* ~σ_z)
- Small β_x^* and small emittance (ε_x) are also the key → **positron DR**
- Positron beam energy from 3.5 to 4.0 GeV to increase beam lifetime (still ~O(10) min maximum)

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 $\beta_y^* < \sigma_z$.

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.

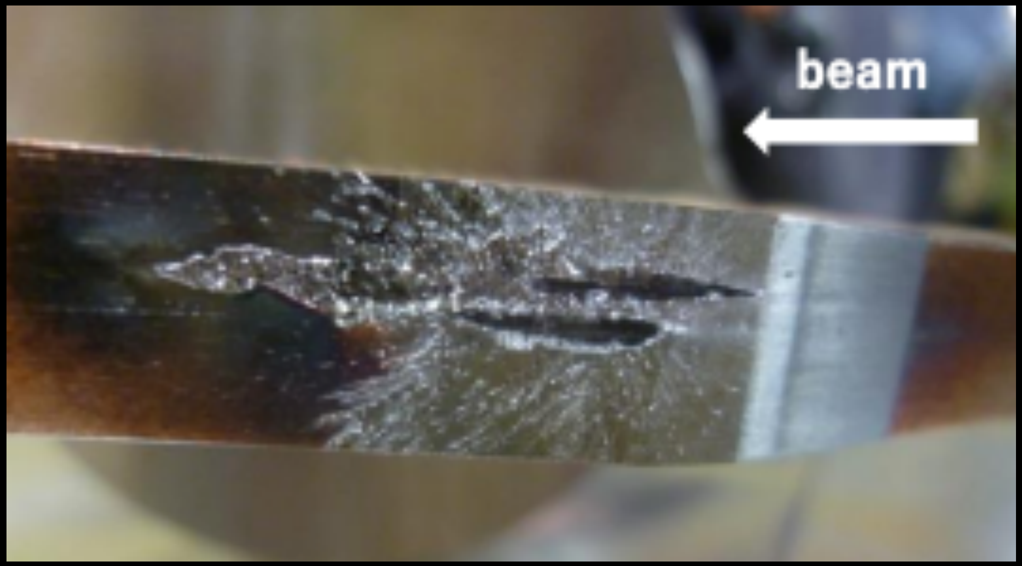
Machine and Detector Upgrade Overview - LS1

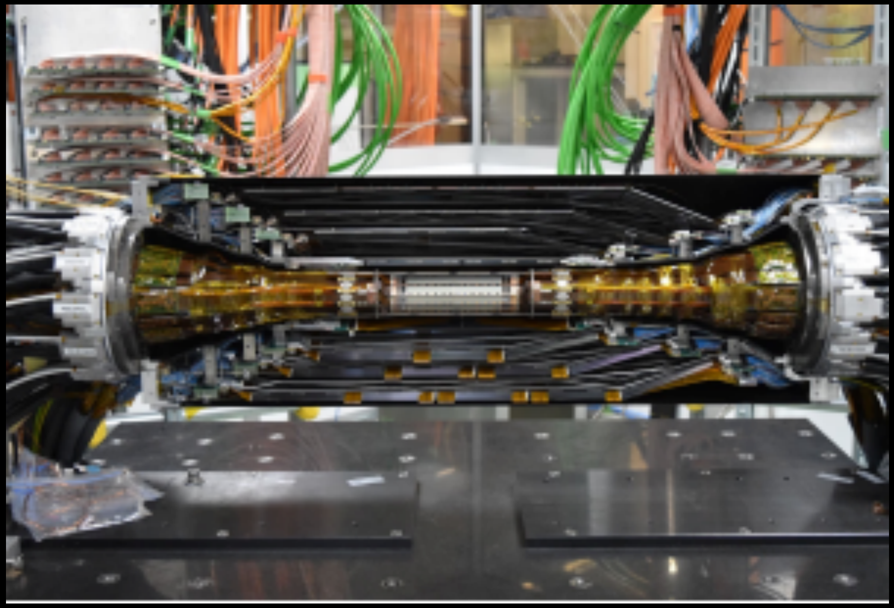
Machine upgrades

- 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



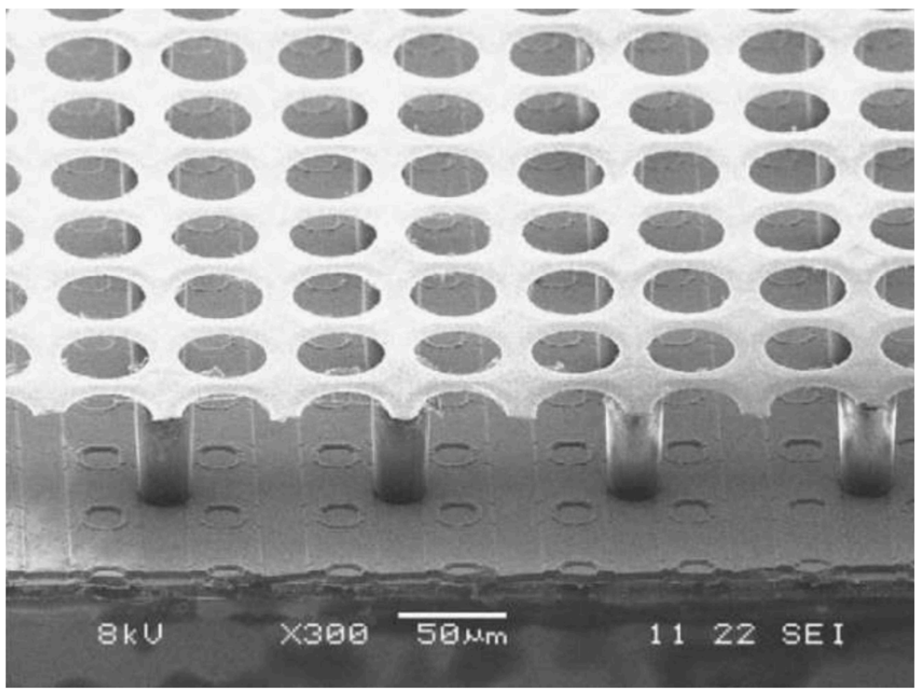


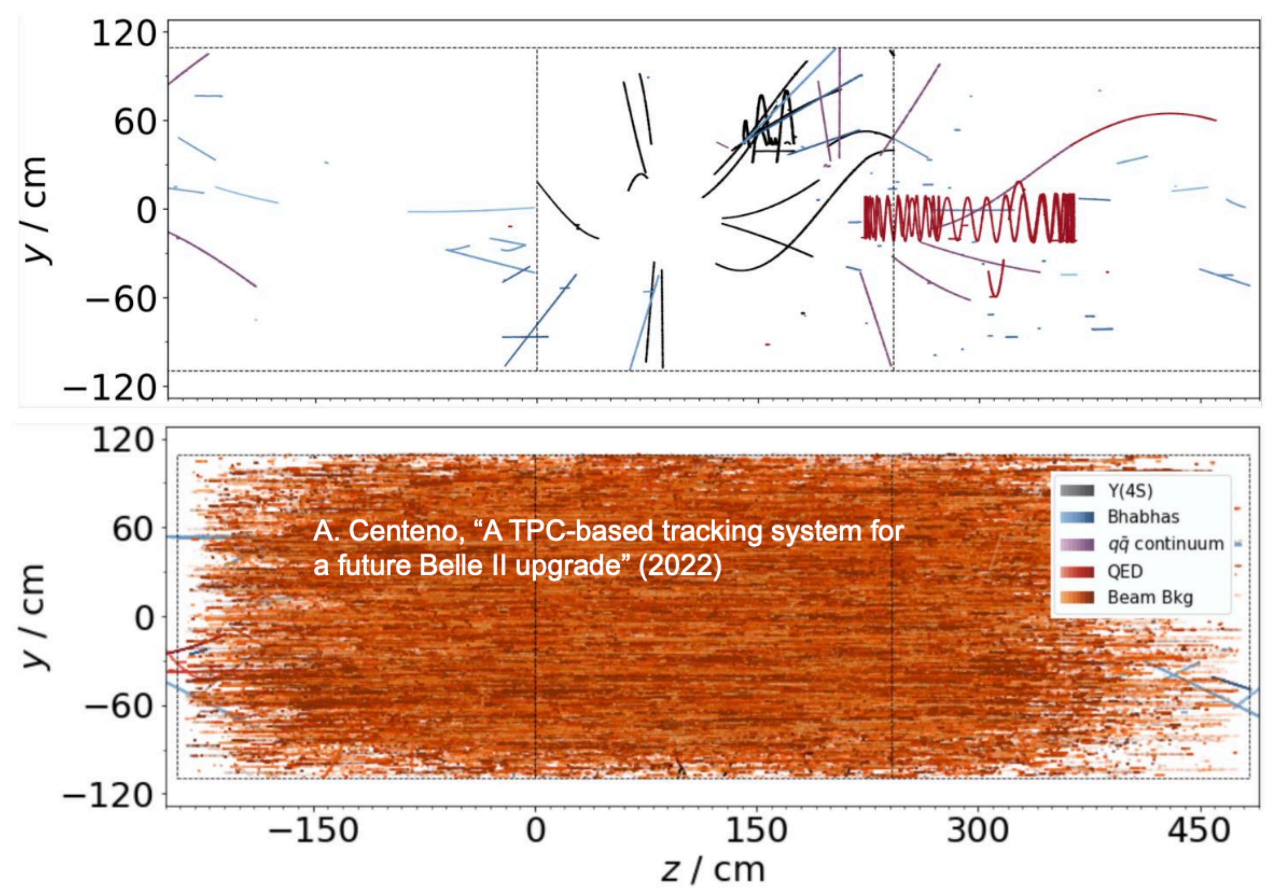
TPC

see Lewis 11/19, Yoshihara 11/21

Belle-II TPC upgrade: promising if finely segmented

Low-threshold, low-gain pixel readout could control IBF and meet design specs





Consideration of a GridPix-like object for
"1:1 mapping of electrons:pixels → optimal resolution,"
– P. Lewis, Snowmass 2022

VTX specification

Upgrade motivation:

- Cope with larger background activity
- Improve momentum and impact parameter resolution in low p_T region
- Simplify tracking chain with all layers involved
- Contribution to Level 1 trigger
- Operation without data reduction

Key sensor specifications:
- Pixel pitch 30-40 μm
- Integration time $\lesssim$100 ns
- Power dissipation $\lesssim 200\ \mathrm{mW/cm^2}$

Improve physics reach per ab^{-1}

Radius range	14 – 135 mm
Tracking & Vertexing performance	
Single point resolution	< 15 μm
Material budget	0.2% X_0 / 0.7% X_0 inner- / outer- layer
Robustness against high radiation environment (innermost layer)	
Hit rate	~ 120 MHz/cm²
Total ionizing dose	~ 10 Mrad/year
NIEL fluence	~ 5e13 n_{eq}/cm²/year

cmarinas@ific.uv.es

SuperKEKB synergy with FCC-ee

The Central Role of SuperKEKB-Belle II in HEP

The ARC would like to emphasize that the SuperKEKB accelerator is a frontier machine and is a world leader in Accelerator Technology with ambitious goals for high peak and integrated luminosity. This accelerator is led by a highly dedicated group of experts who have encountered and overcome technical obstacles, and who will find new issues as they approach the ultimate accelerator design goals. The achievements accomplished by this team and the KEK laboratory are already being incorporated into future collider designs and the worldwide accelerator community is carefully watching the impressive progress of this very exciting enterprise.

ARC March 2024

From the P5 report and from international accelerator laboratories:
Need to make e+e- nanobeams work well at SuperKEKB for the future of HEP.

FUTURE CIRCULAR COLLIDER **mid-term review recommendations for FCC-ee acc. design**

from FCC SAC, FCC CRP, CERN SPC, and CERN FC

- **identify residual risks to achieving the design luminosity, with lessons to be learnt from other facilities like SuperKEKB, and specify required further critical-path R&D**

cmarinas@ific.uv.es 5

Belle II Publications