The Upgrade of the Belle II experiment at SuperKEKB

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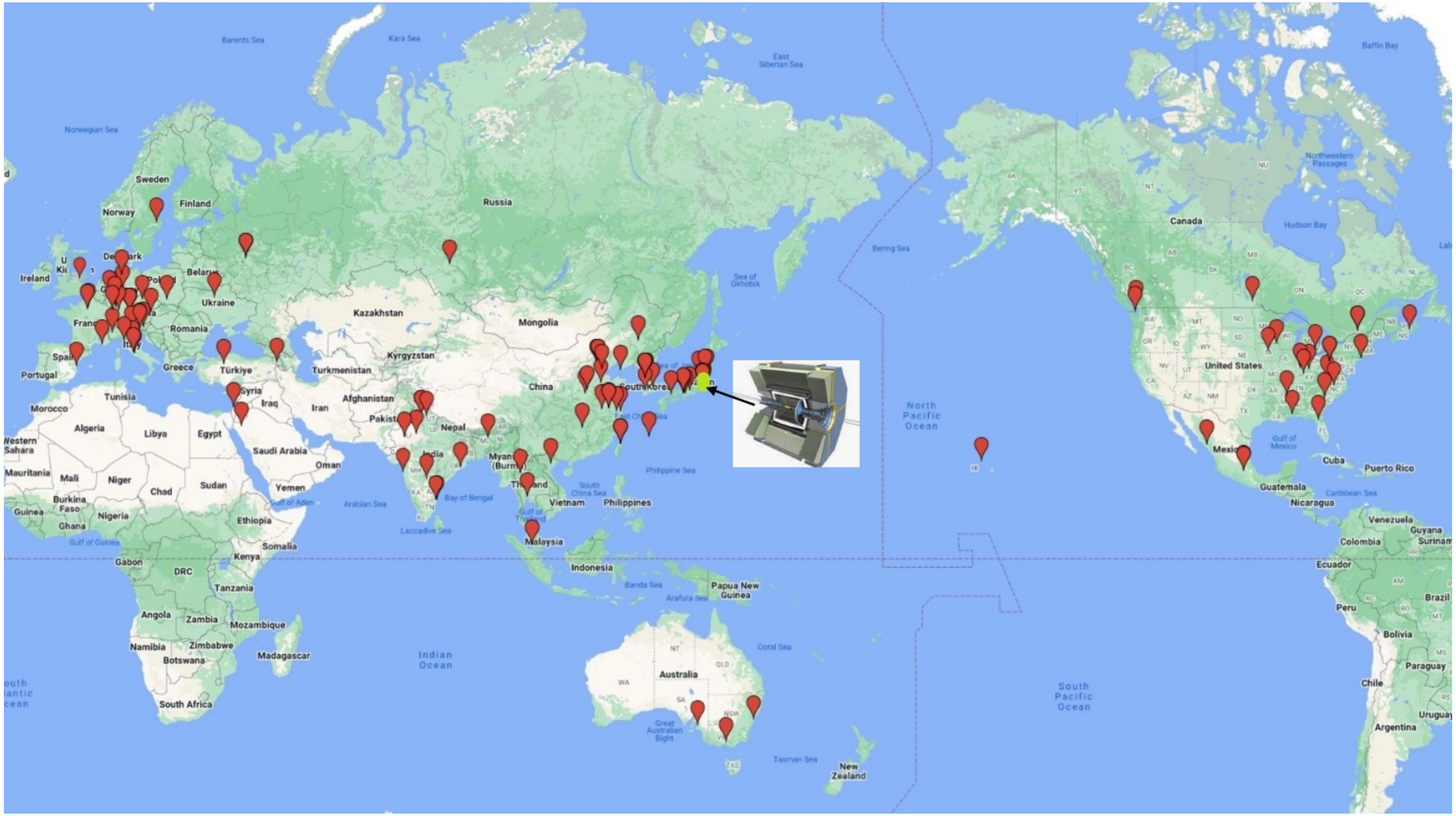
A.D.MCCCVIII

Belle II

The Belle II Collaboration

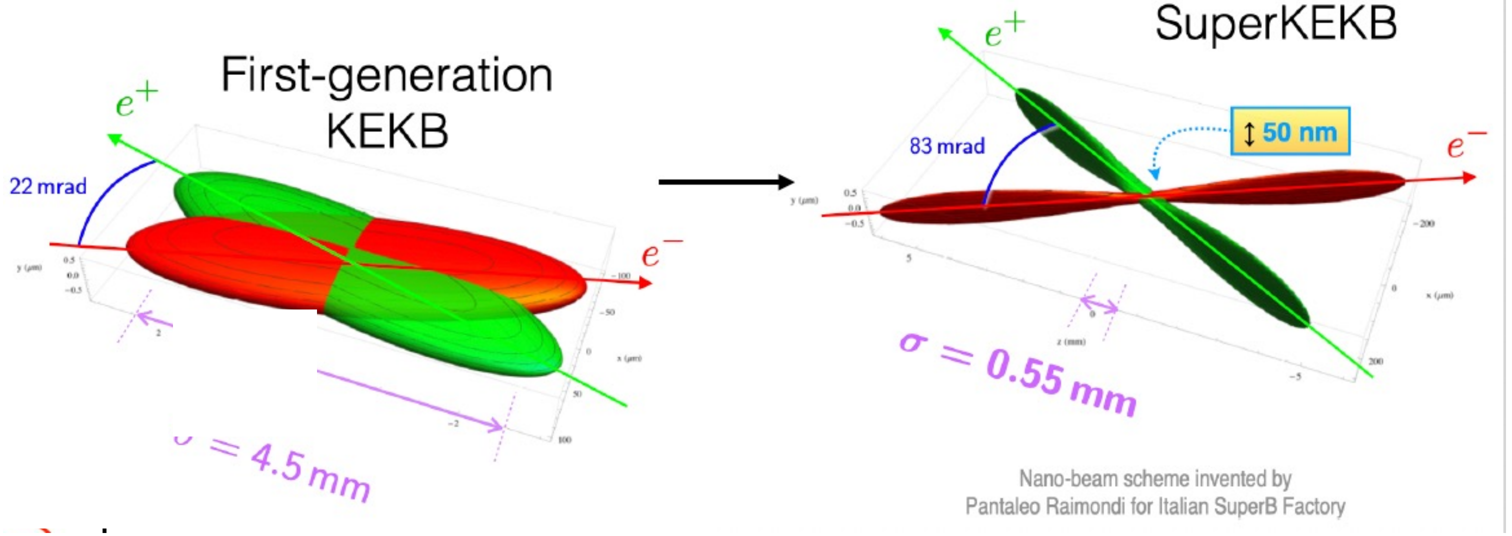


~1200 physicist and engineers from 122 institutions in 28 countries/regions

The SuperKEKB

The Intensity Frontier: search for rare new phenomena using medium energy high-luminosity machine

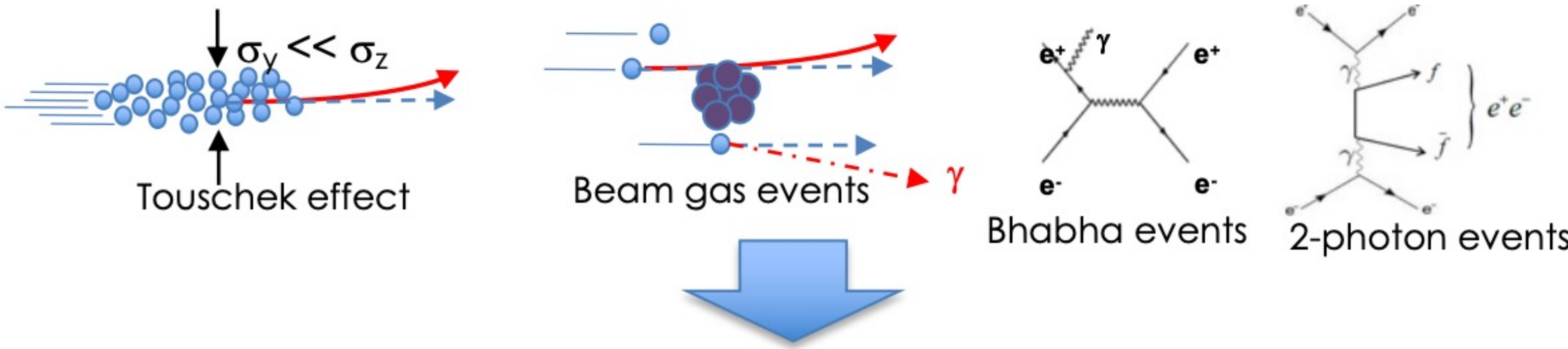
1. High luminosity accelerator SuperKEKB
2. High-resolution and large-coverage detector Belle II
3. Ultimate goal: 50 ab^{-1} by operating at $6x10^{35}$ $cm^{-2}s^{-1}$



Induces parasitic particles → **beam backgrounds**

- Significant upgrade of the KEKB accelerator to achieve 30x instantaneous luminosity and multi-ab^{-1} sample
- In the nominal configuration:
  - x1.5 by increasing beam currents
  - x20 by nano-beam scheme

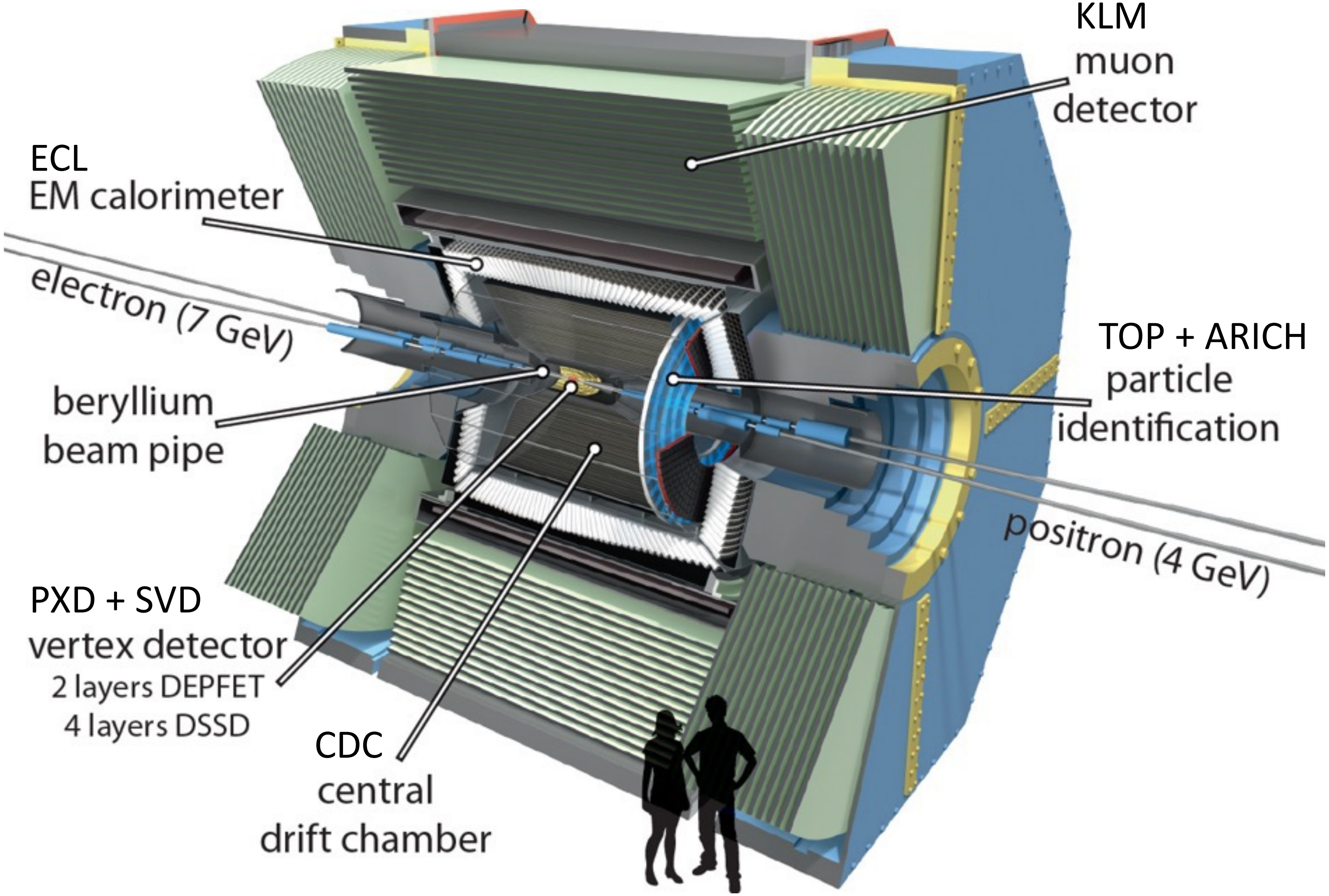
$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,\mathrm{eff}} \sqrt{\varepsilon_y \beta^*_y}}$$



Constraints on detector
- Low boost (ß ↘.28) → Better vertexing
- High trigger rate
- High background rate

} → Faster detectors

The Belle II Detector



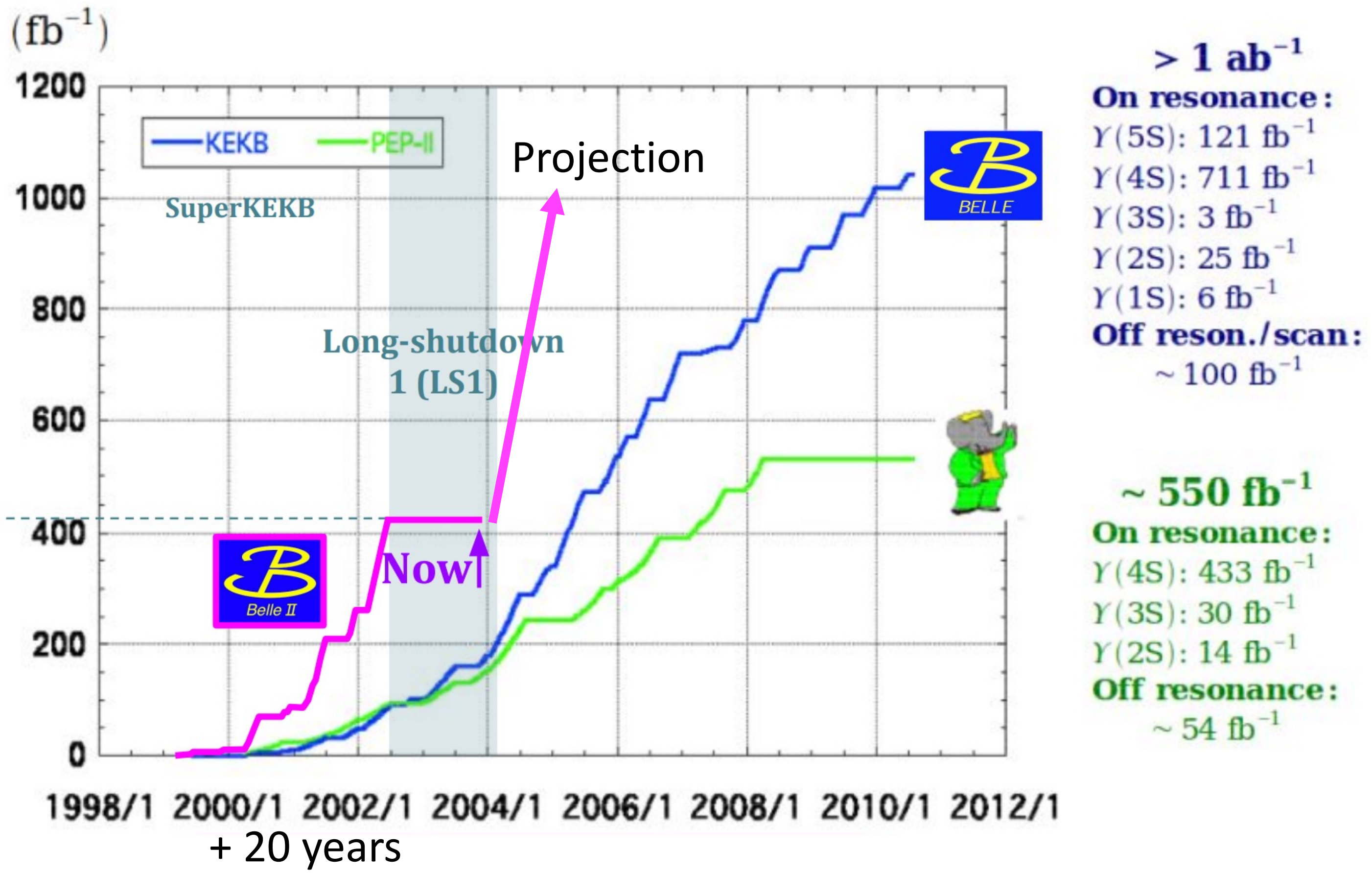
Luminosity status

World record luminosity $4.7 \times 10^{34}\ cm^{-2}s^{-1}$

LS1 completed

- installation of the complete 2-layer pixel detector and other detector works
- improvements on accelerator side to reach higher luminosities and mitigate machine background

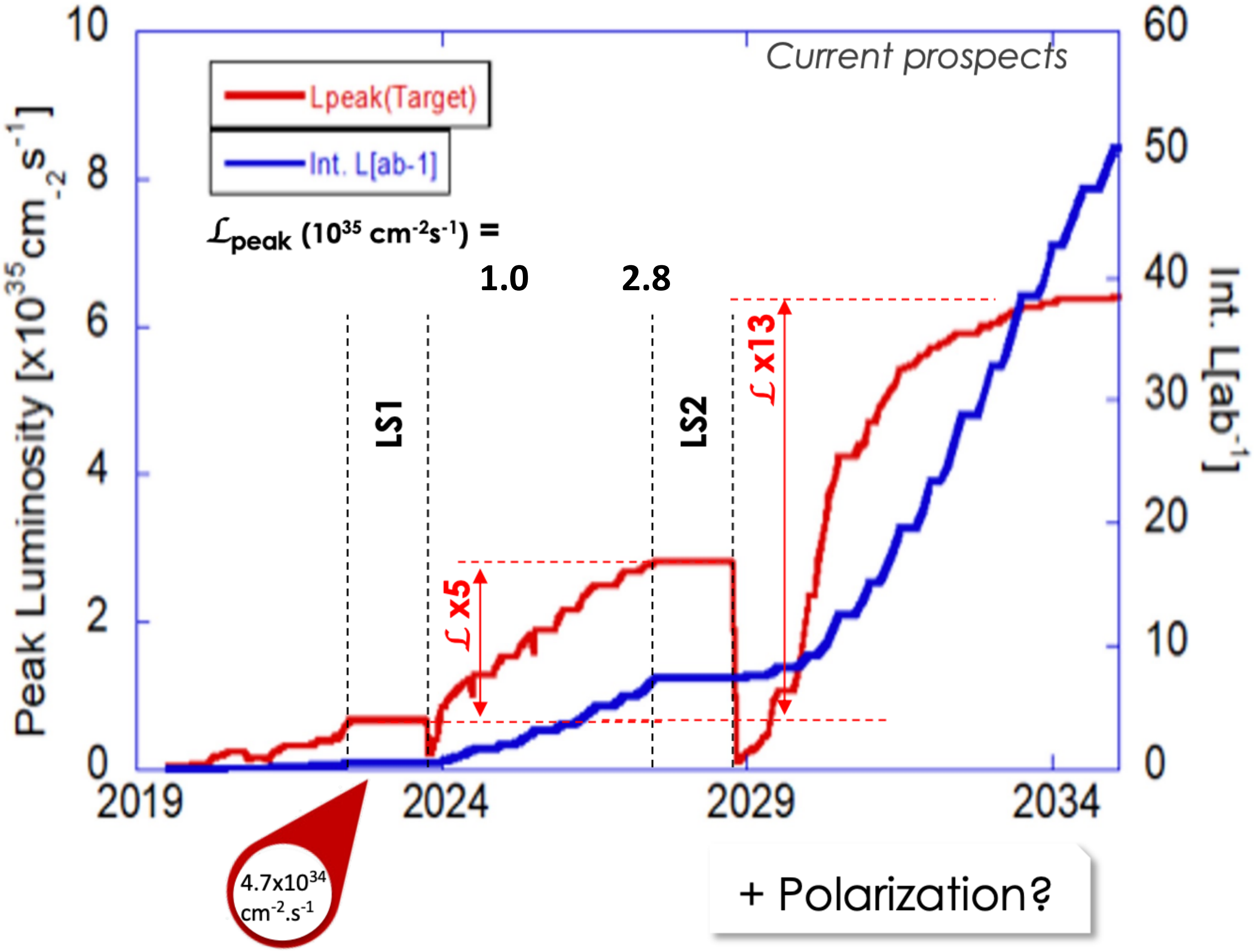
Integrated luminosity ~430 fb^{-1}



Projected luminosity

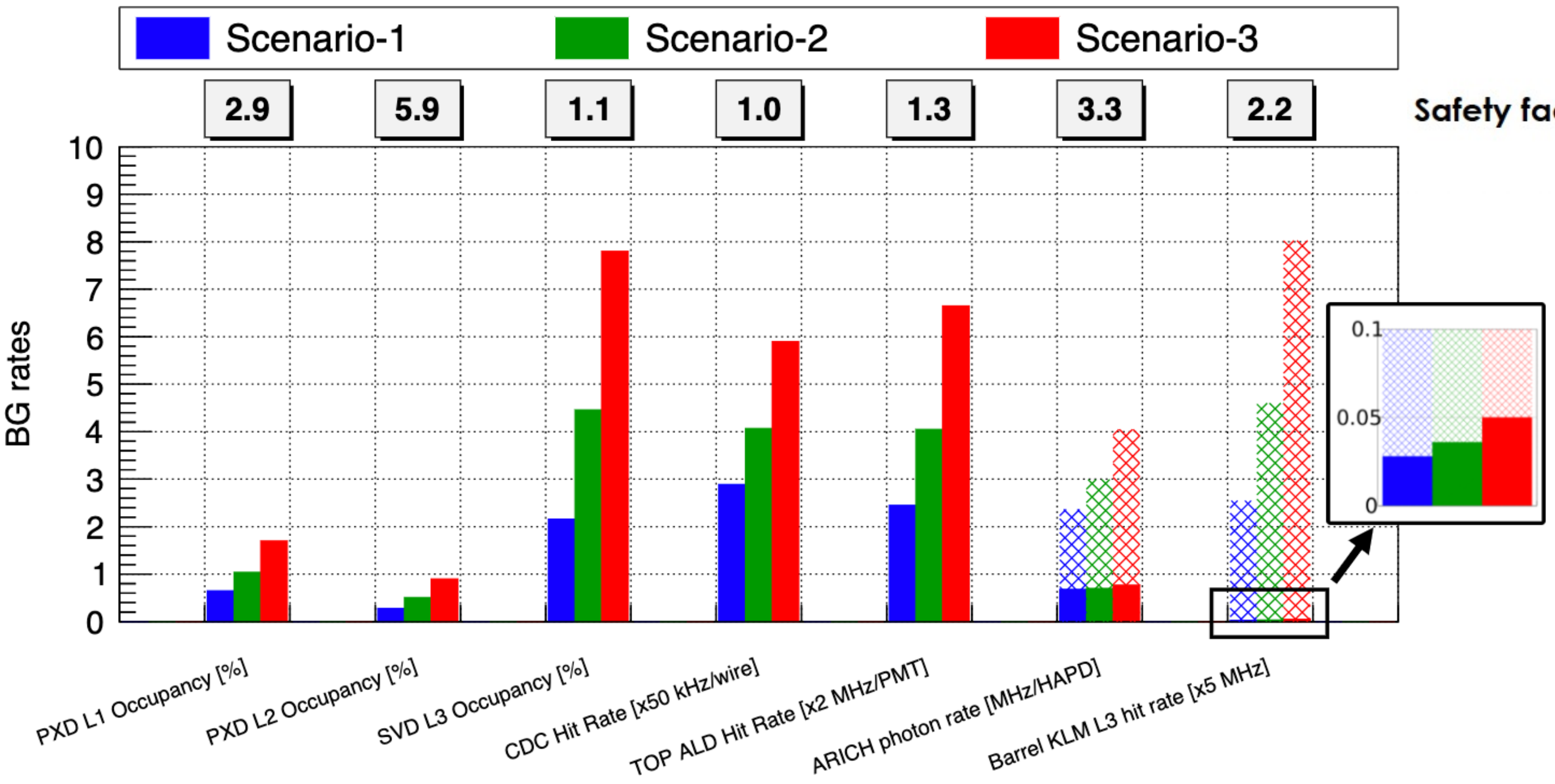
- 120-fold increase in integrated luminosity ($0.4 \rightarrow 50\ ab^{-1}$)
- 13-fold increase in instantaneous luminosity ($0.5 \rightarrow 6\times10^{35}\ cm^{-2}s^{-1}$)

- Get the luminosity higher
  - SuperKEKB improvements in LS1
    - Mitigate various background sources
  - SuperKEKB upgrade in LS2
    - Large impact on Interaction Region (IR) to reach 2.8 $6\times10^{35}\ cm^{-2}s^{-1}$ before LS2
- Cope with higher background
- Get more physics per ab^{-1}
- Big challenge both for **Accelerator and Detector**



Projected luminosity for SuperKEKB

Luminosity vs Beam Background



Safety factor = $\frac{\text{detector limit}}{\text{Background rate}}$

(Intermediate scenario)

Operational conditions:

- Complex collimator system
- Injection background from new bunch
- Sudden beam loss events

Continuos improvement process

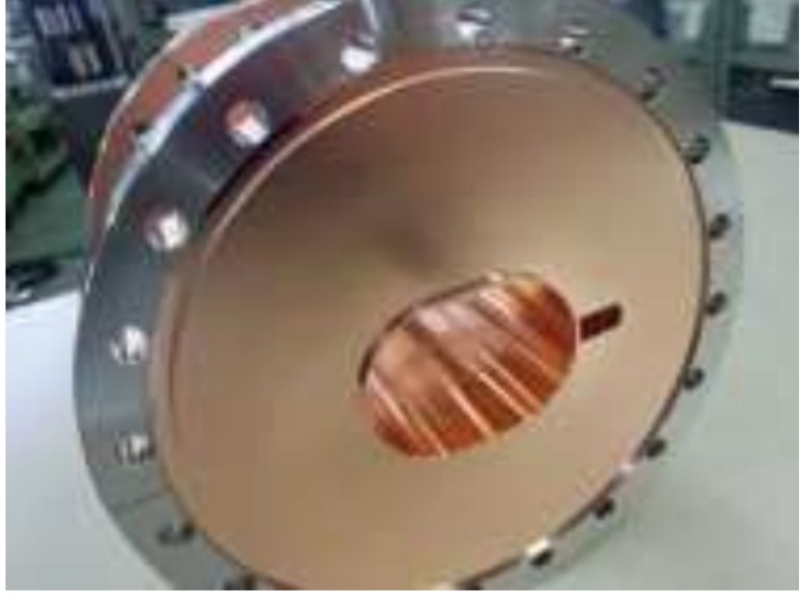
Present knowledge:

- From LS1 to LS2: $1\text{x}10^{35} < \text{Lpeak} < 2.8\text{x}10^{35}$ $\text{cm}^{-2}\text{s}^{-1}$
  - Beam background high but tolerable without performance loss
- Beyond LS2: up to $6\text{x}10^{35}$ $\text{cm}^{-2}\text{s}^{-1}$
  - Systems getting close or reaching current limits:
  - Main tracker (CDC), central PID (TOP), Silicon tracker (SVD)

Long Shutdown1（LS1）

Started in July 2022 –
motivated by the installation of the completed PXD

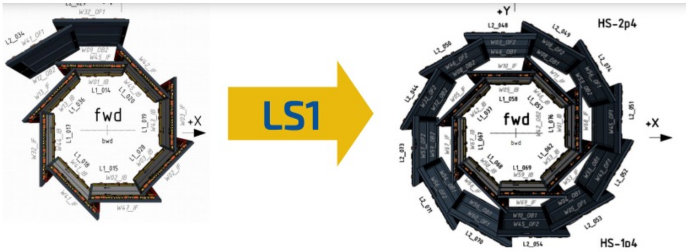
- Machine consolidation
  - Counteracts against sudden beam loss
    - Real time monitoring
    - Faster abort system
  - Collimator head should survive severe beam loss
    - Harder head material, better resistance
    - NLC for background mitigation
  - Improved neutron shielding
    - Around final focus magnets (QCS)
    - Around endcaps
  - RF cavity replacement
    - More stable operation
    - Higher currents
  - Injection → higher efficiency and mitigated background
    - Faster kicker magnet
    - New quadrupole focusing magnet
    - New large aperture beam pipe
  - Operations restarted in January 2024

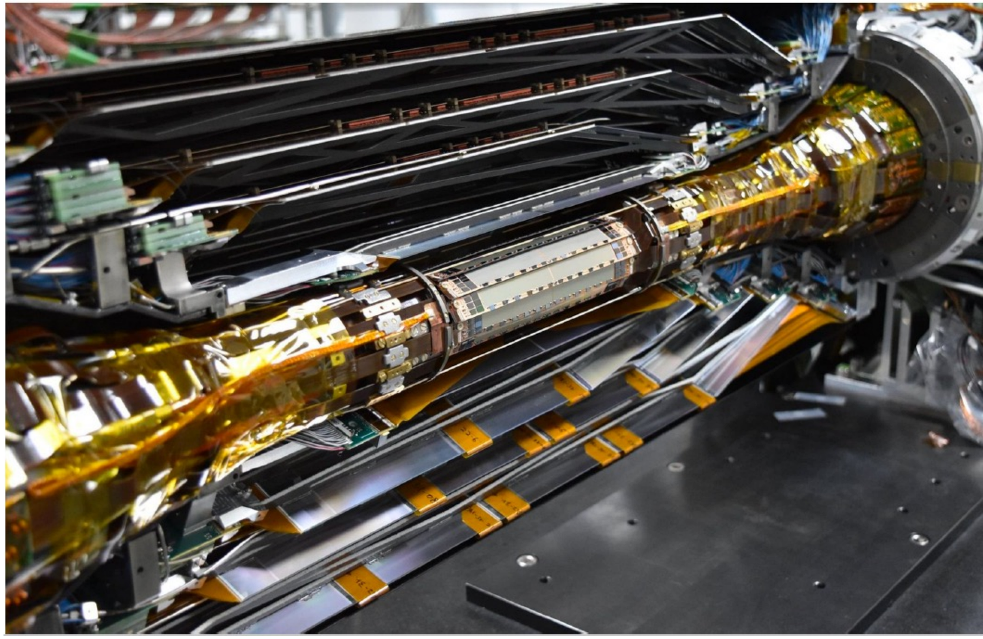


Larger pipe injection

Carbon collimator head

Long Shutdown1 (LS1)

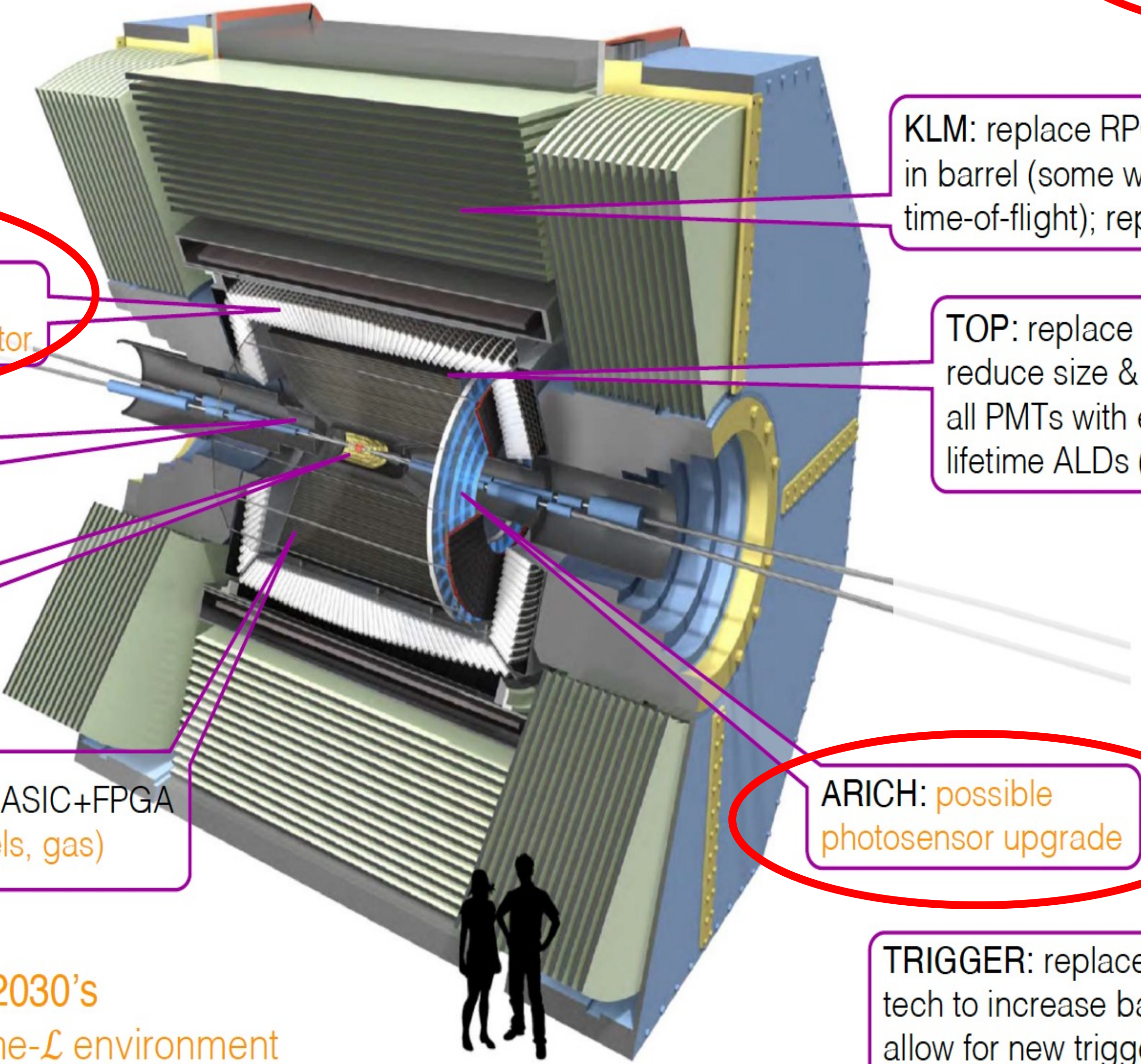




- Detector upgrade
  - Installation of complete pixel detector
    - 2 new complete layers of DEPFET sensors (second layer was 17% complete)
  - Replacement of ~50% of TOP to Life Extended Atomic Layer Deposition (ALD) MCP-PMTs
    - Increased lifespan & hit rate limit (3 ⟶5 MHz/cm^2)
  - Improved CDC gas distribution and monitoring system
    - Better gain stability
  - DAQ system upgrade to PCIe40 for all subsystem
    - But PXD (specific data path)

Belle II Upgrade schedule from LS2

Longer term Upgrades.
Behind LS2



More distant future: ~mid-2030's
✓ Detector R&D for extreme-$\mathcal{L}$ environment

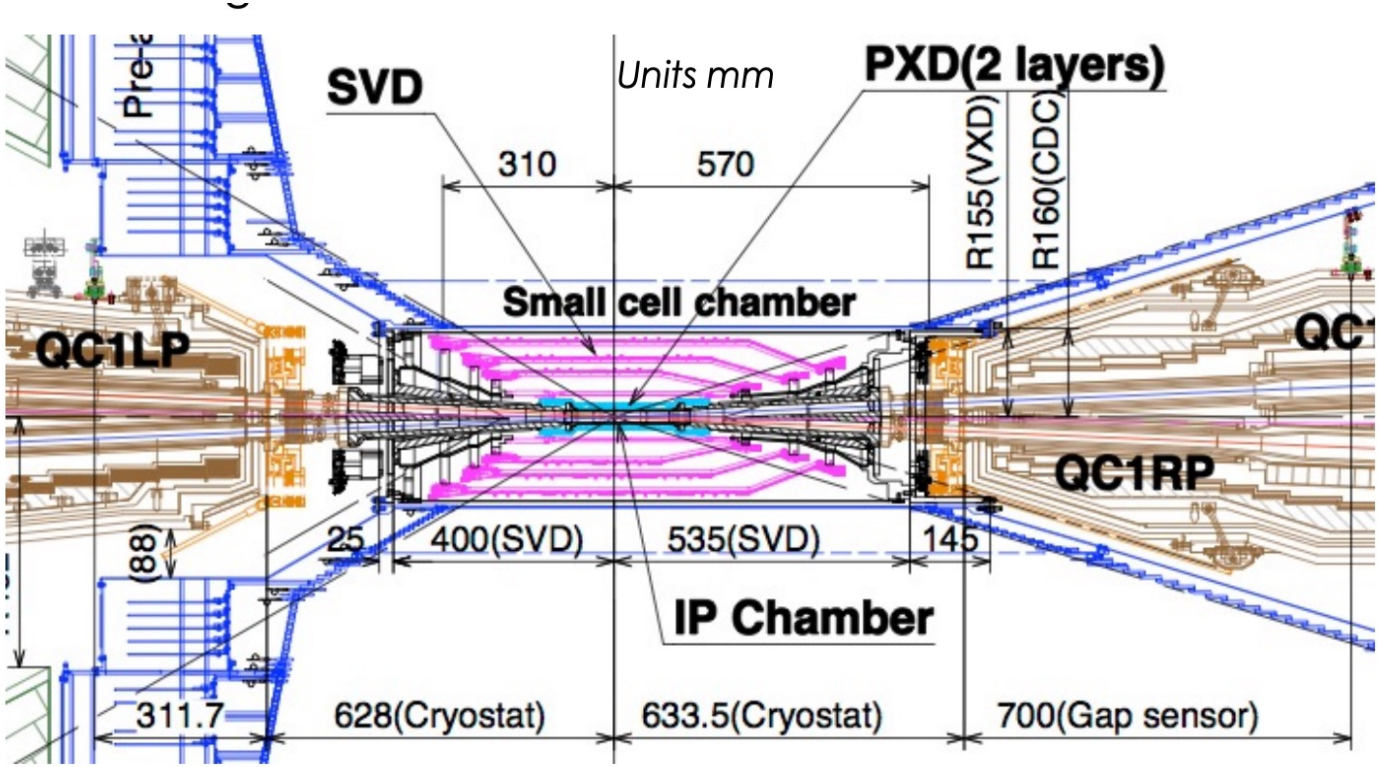
Machine Upgrade hypothesis for LS2

GOAL: higher luminosity while limiting beam beam effects & preserving beam lifetime

A major redesign of the Interaction Region (IR) may be required to reach 6×10^{35} $cm^{-2}s^{-1}$

IR has various options:

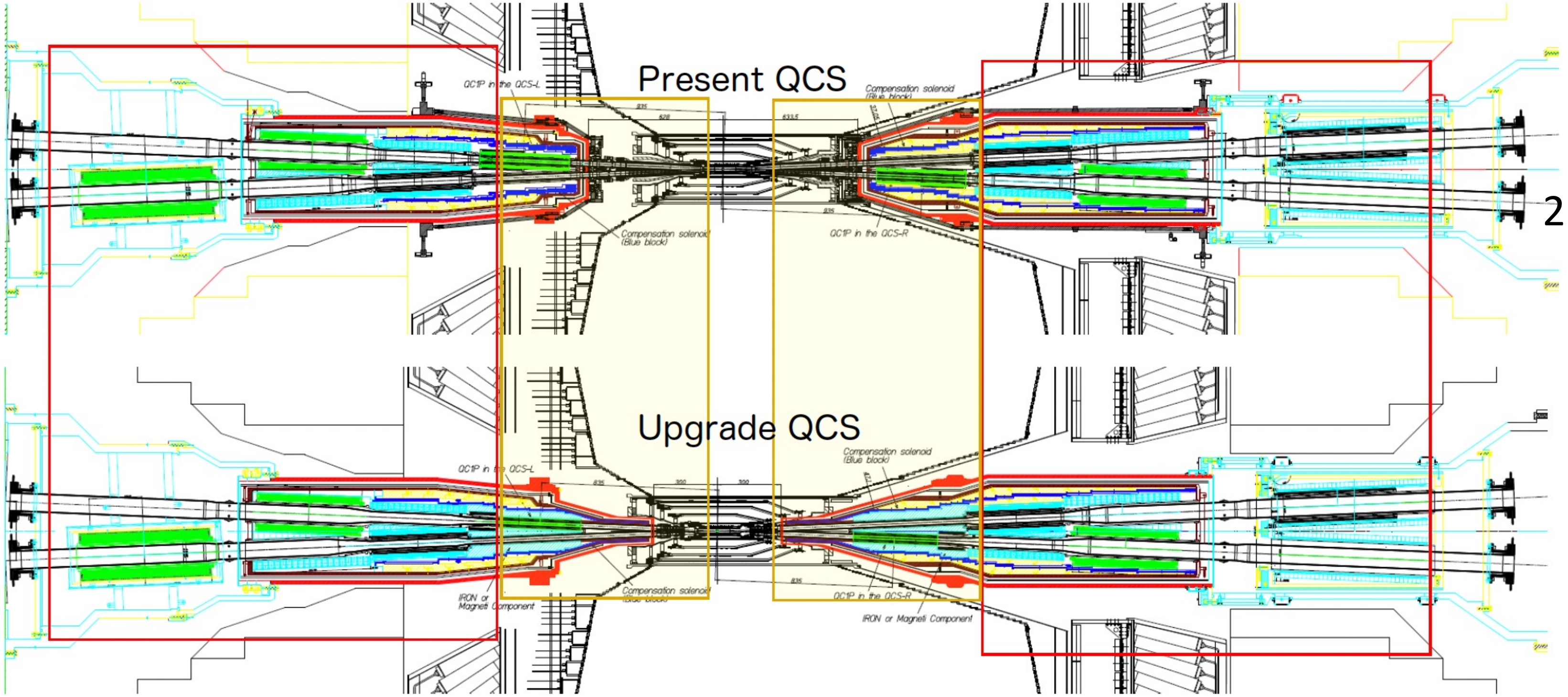
- Position of final focusing magnets (QC) closer to IP
- New QC magnets
- Additional solenoid for lower emittance while compensating Belle II field
- Need feed-back from 2024 beam operation
- **Belle II envelope in interaction region still under study → schedule for LS2 is indicative**



Interaction Region Upgrade

Motivations:

- Limit beam-beam effects, preserve beam lifetime



Different scenario are under investigation

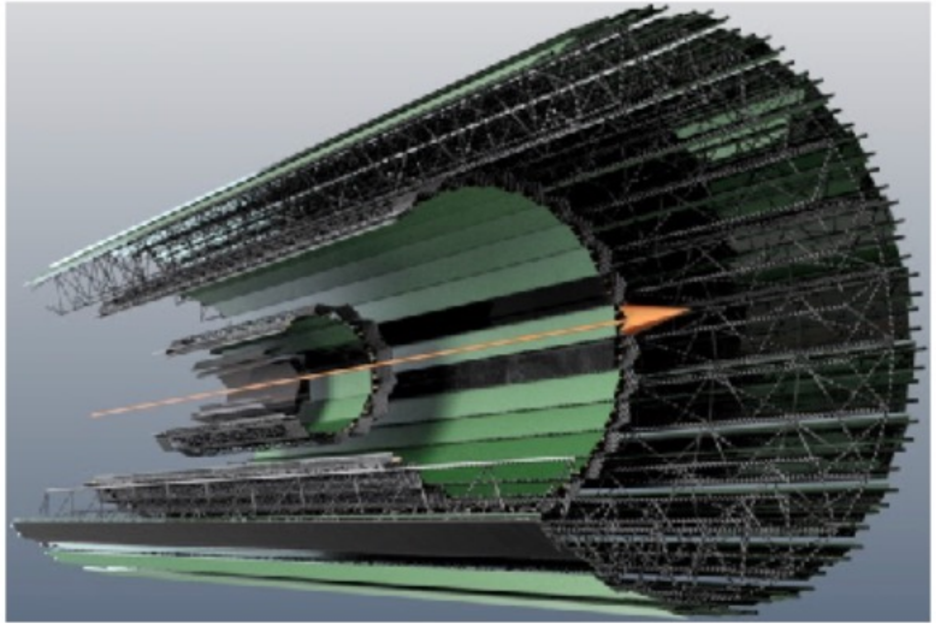
1) Moderate scale modification: new QC1 with larger physical aperture closer to the IP - keeping the boundary as is
   - R&D on Nb_3Sn quadrupole magnet

2) Larger scale modification (in addition to 1) - requires detector modification
   - Optical evaluation of the anti solenoid field profile
   - R&D on Nb_3Sn thin solenoid
   - New cryogenic system for anti solenoid coils

VXD Upgrade requirements → new VTX

Motivations:

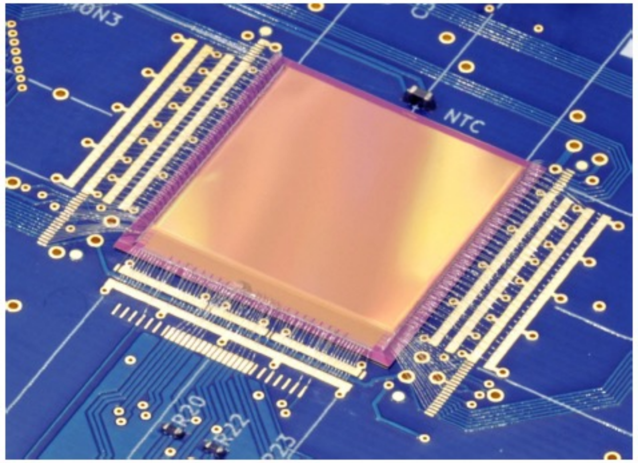
- Cope with larger background rates
- Improve momentum and impact parameter resolution at low p_T
- Simplify vertex system (pixels + strips → pixels)
- Operation without data reduction
- Be safe in case of accident



Max radius 14 cm & length 70 cm → 1 m^2

Concept:

- 5 layers with high space-time granularity & low material budget
  - Robustness against high radiation environment (innermost layer) - occupancy < $\mathcal{O}(10^{-4})$
  - Higher vertexing precision
- Lighter services and simpler design
  - adaptable to potential change of interaction region

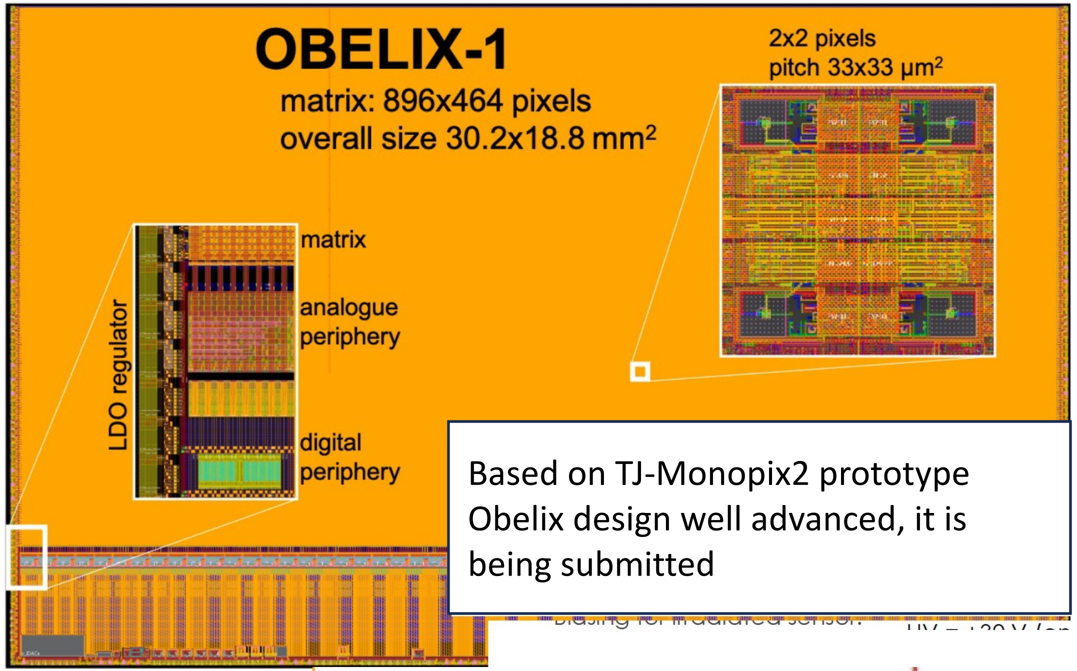


VTX Upgrade Specifications

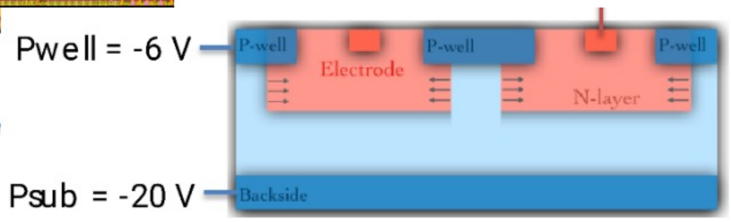
- Depleted monolithic active CMOS pixels
- Sensitive layer thickness < 30 µm (~2500e from MIPs vs. 200-250e threshold)
- Sensor thickness < 50 µm
- iVTX: innermost 2 layers, self-supported, cooling under study
- oVTX: outer 3 layers, CF structure, single-phase coolant
- Prototype (TJMonopix2, developed for ATLAS) has largely met these specifications, including irradiation tests
- New OBELIX DMAPS sensor, targeting Belle II specific application, now in final design phase

OBELIX-1 specifications & layout

Pitch	33 µm
Signal ToT	7 bits
Integration time	50 To 100 ns
Time stamping	~5 ns for hit rate < 10 MHz/cm²
Hit rate max for 100% eff.	120 MHz/cm²
Trigger handling	30 KHz with 10 µs delay
Trigger output	~10 ns resolution with low granularity
Power (with hit rate)	120 to 200 mW/cm² (1 to 120 MHz/cm2)
Bandwidth	1 output 320 MHz

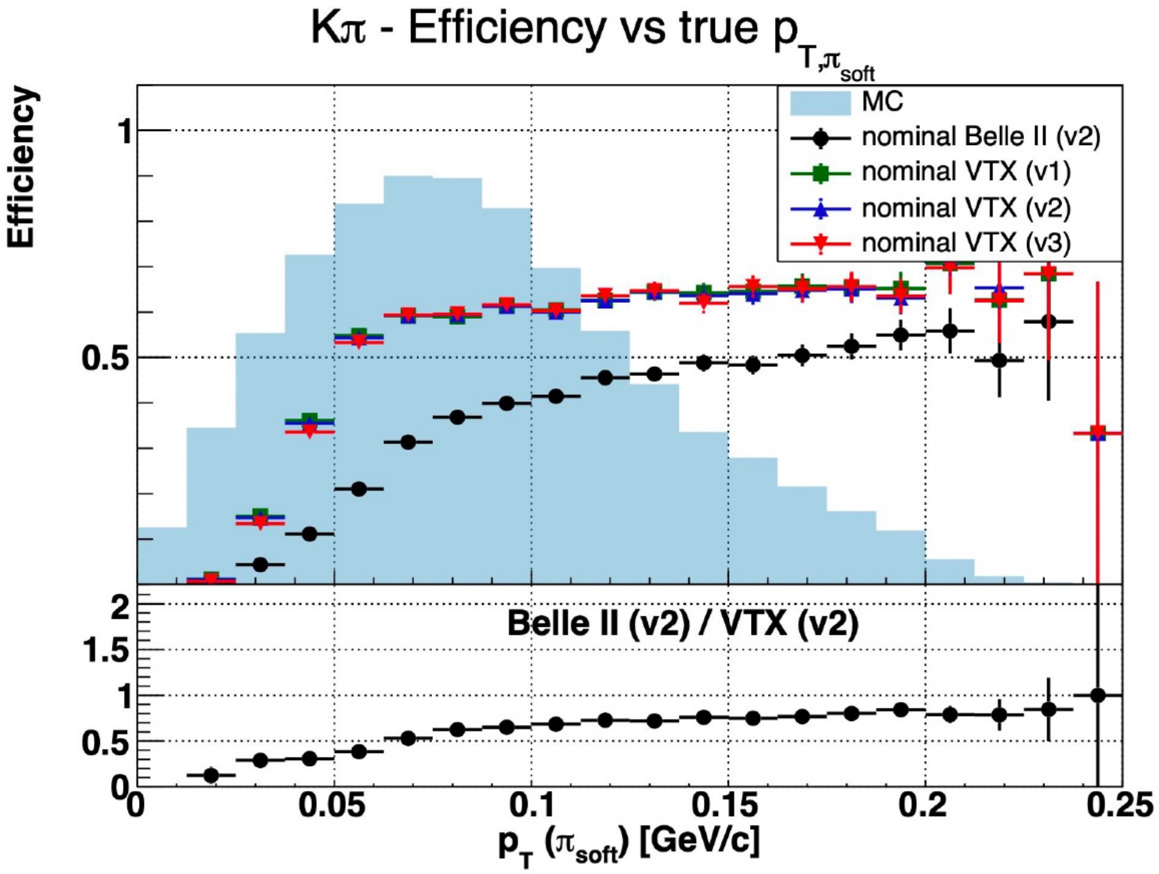


Based on TJ-Monopix2 prototype Obelix design well advanced, it is being submitted



VTX Upgrade Physics Impact

- $B^0 \rightarrow D^*l\nu$: "bread-and-butter" physics for Belle II (R(D*), angular analysis, |Vcb|, B-tagging, …)
- Slow pion from D* decay: low-p → low-efficiency
- ~70% improvement in efficiency
- ~35% better B-decay vertex resolution



VTX (v1) optimistic bg scenario
VTX (v2) intermediate bg scenario
VTX (v3) conservative bg scenario

CDC Upgrade – new FE electronics

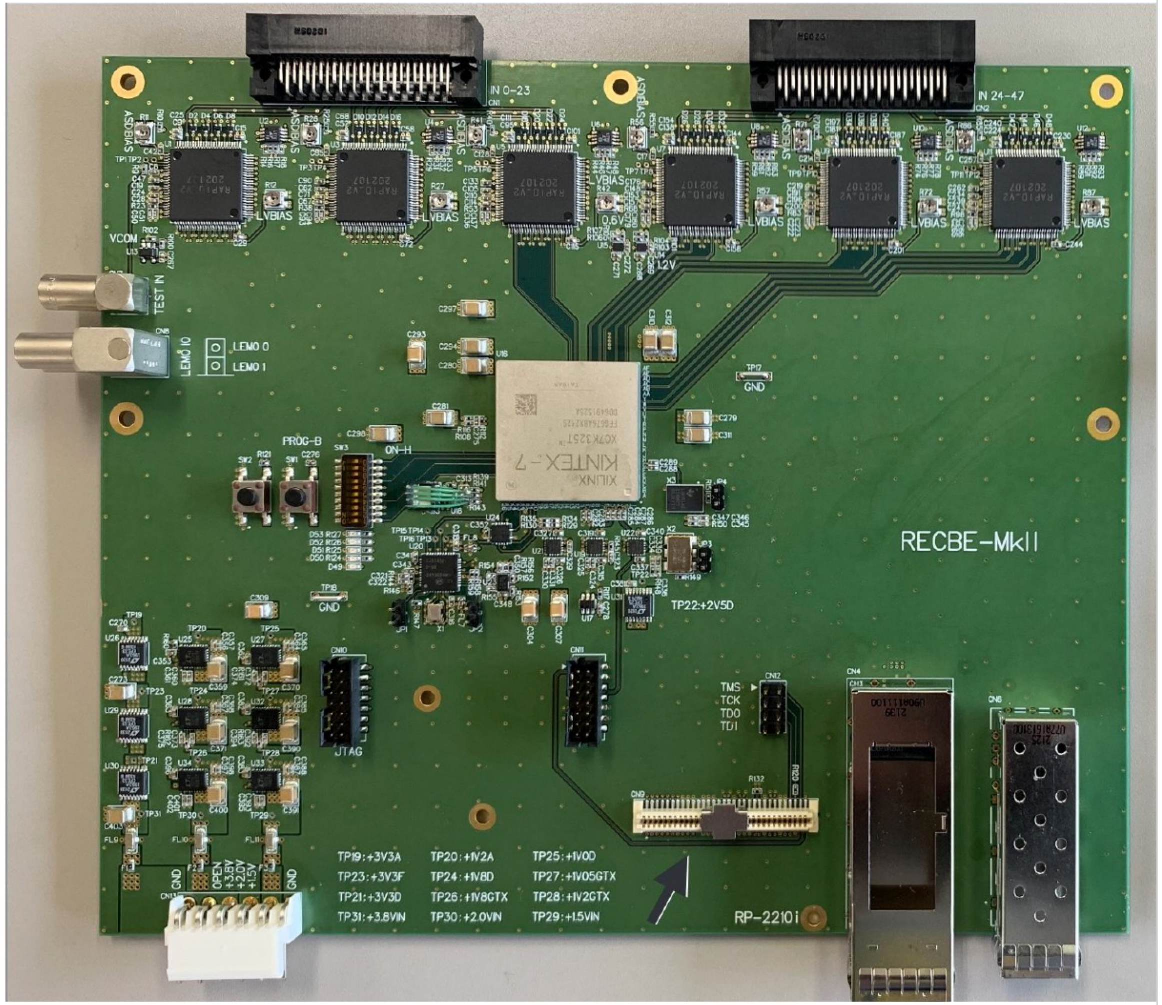
Motivations:

- Towards better tracking performance
- Reduce cross-talk, power consumption, and increase output bandwidth
- Improve radiation tolerance

Concept:

- New: ASICs, FPGA, optical module
  - ASIC chips to measure signal timing and digitize waveform
  - FPGA for online data processing and for the trigger and data acquisition systems
  - Rad-hard fiber transceivers, QSFP for data transfer to the trigger and DAQ

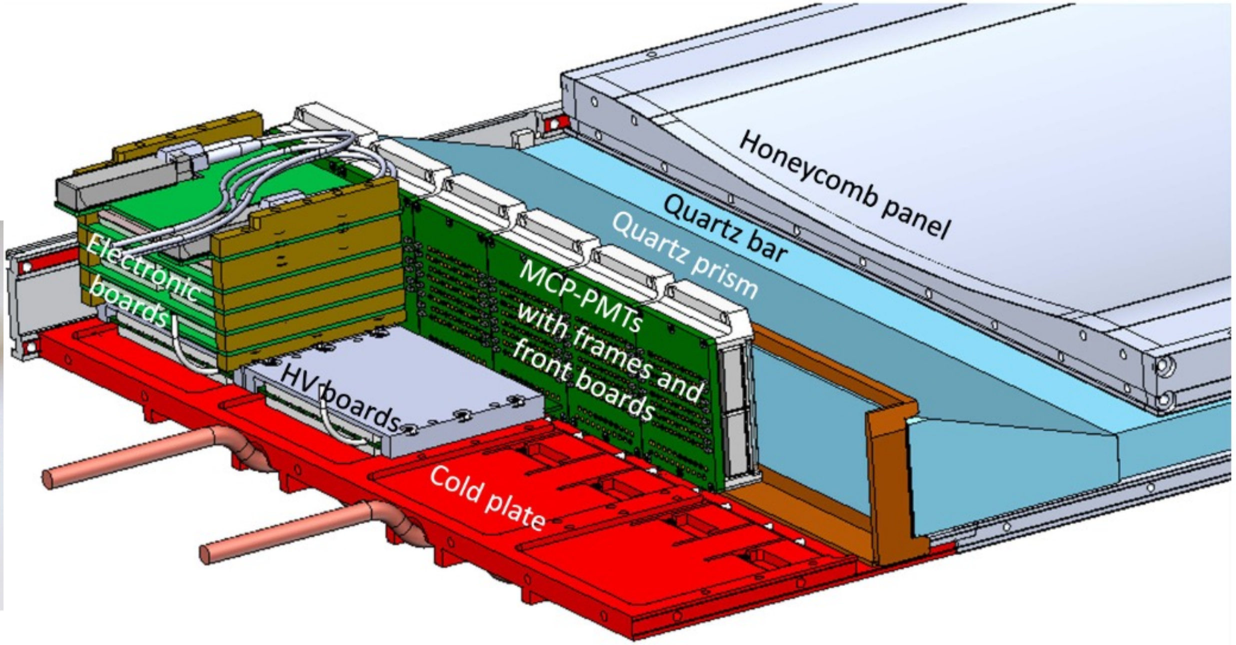
Prototype front-end board upgrade



PID Upgrade: Time of Propagation counter

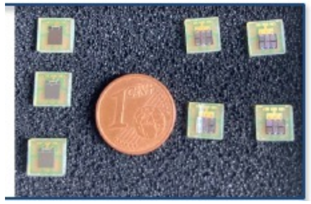
Motivations:

- MCP-PMTs degrading under higher-than-expected backgrounds
- Performance improvements
- Better particle-ID performance
- Feature extraction inside ASIC
- Reduced power consumption

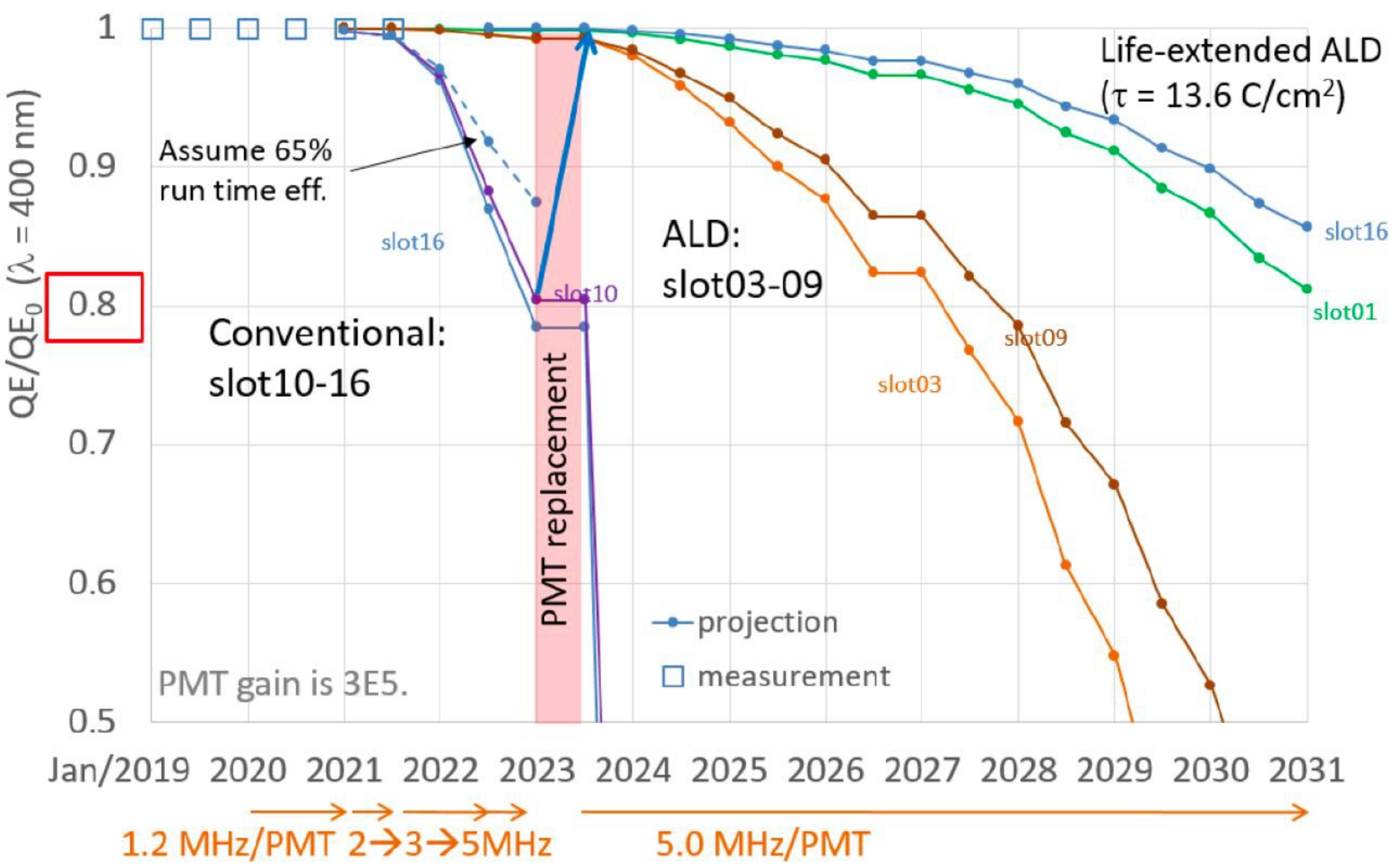


Concept:

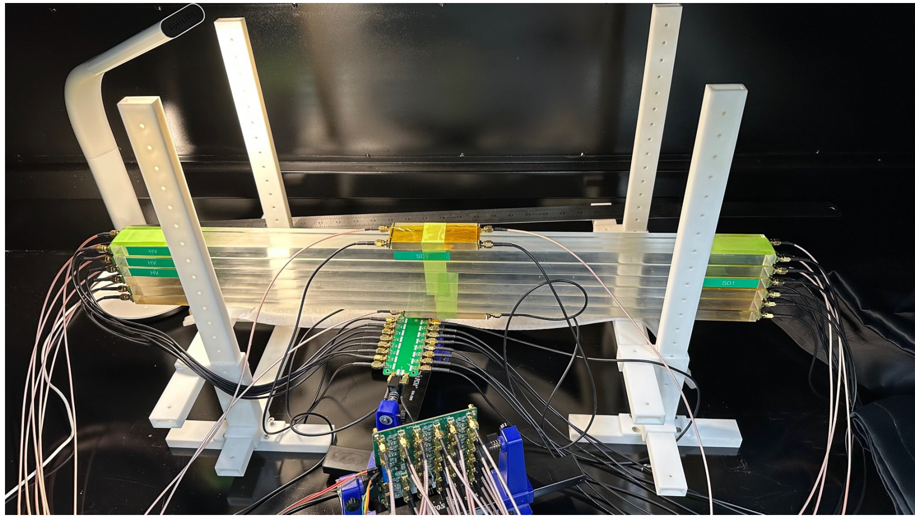
- Technology implementation for LS2
  - Complete 50% MCP-PMT's upgrade with Lifetime-extended ALD-PMTs with better radiation tolerance
  - Future option: redesign front-end boards (ASoC) with Gbps to FPGA Lower power budget and more compact design (to accommodate potential SiPM's)
- Beyond LS2: R&D for SiPM photosensors



PID Upgrade: QE degradation



KLM Upgrade: K_L^0 and muon detector

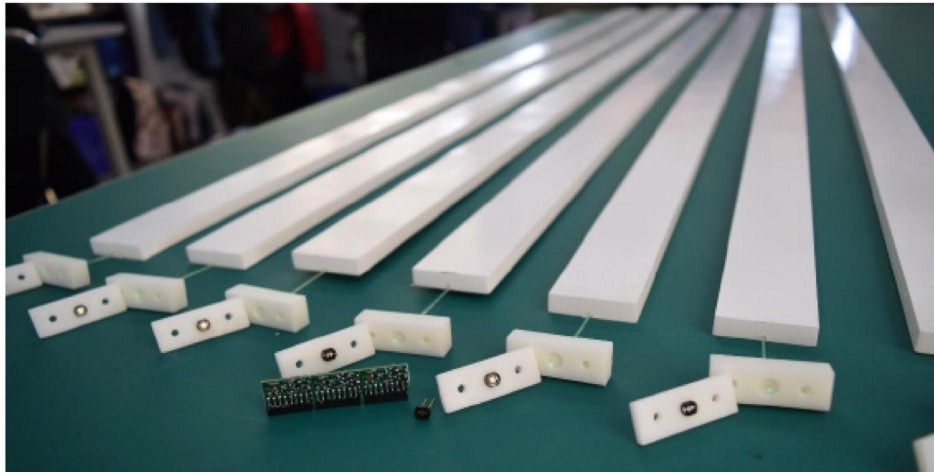


New capability: K_L^0 energy measurement

- Replace remaining RPC's in barrel with scintillators + SiPM's (very complex operation)
- Fast timing (~100 ps) gives K_L^0 E via TOF (13% momentum resolution @1.5 GeV)
- Not settled: physics impact still under study

Readout upgrades

- Re-design electronics layout with feature-extraction ASIC inside panel, only digital I/O (optical)
- Replace many km of twisted-pair ribbon cables with a few fibers

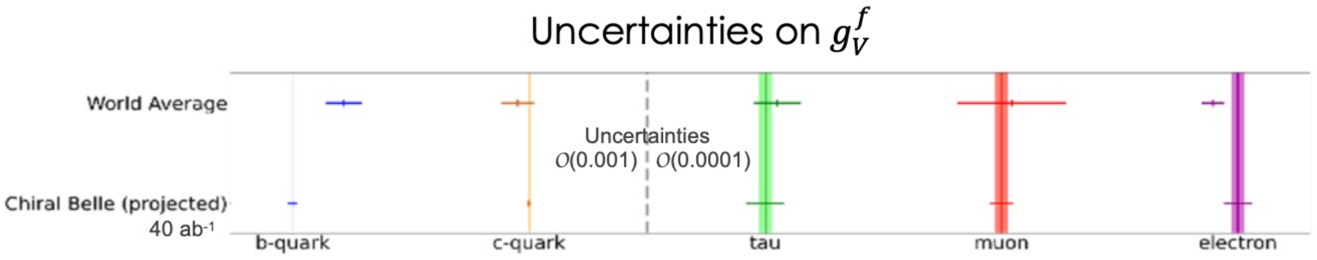


RPC in avalanche mode

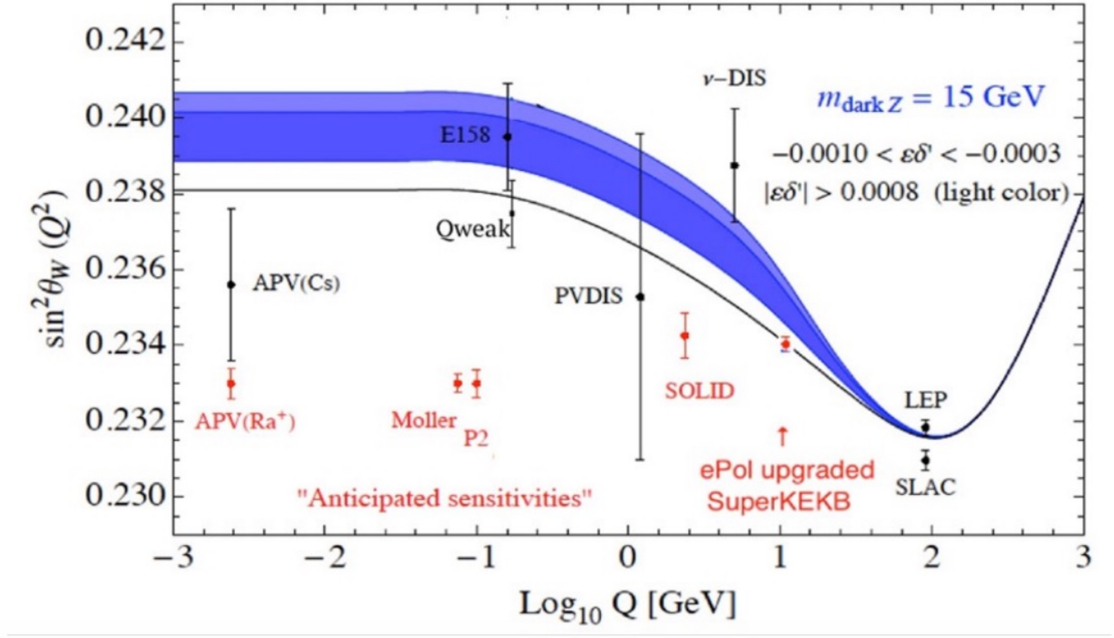
- From streamer to avalanche → less charge → larger rate capability
- Gas composition with electronegative element SF_6 to be studied →
- Overall efficiency only slightly lower
- Amplification of the signal → new FE boards
- Method applied for ATLAS RPC – new SiGe preamp (ϵ = 95% with $\langle Q \rangle \simeq$ 2 pC)

Chiral Belle II – potential physics reach

- Electroweak vector neutral current
  - Tensions in $A_{FB}^{0,b}$ (LEP) / A_{LR}(SLC)
  - Left-right asymmetries with 5 fermions: b, c, e, μ, τ
- Dark sector
  - Sensitivity to light Z_{dark} through $\sin^2\theta_W$
- Tau physics
  - Unique place for g-2
    - Sensitivity ~O(10^{-5}) with 50 ab^{-1}
  - Additional background suppression in LFV channels
    - Using helicity distributions
    - $\tau \rightarrow \ell\gamma$

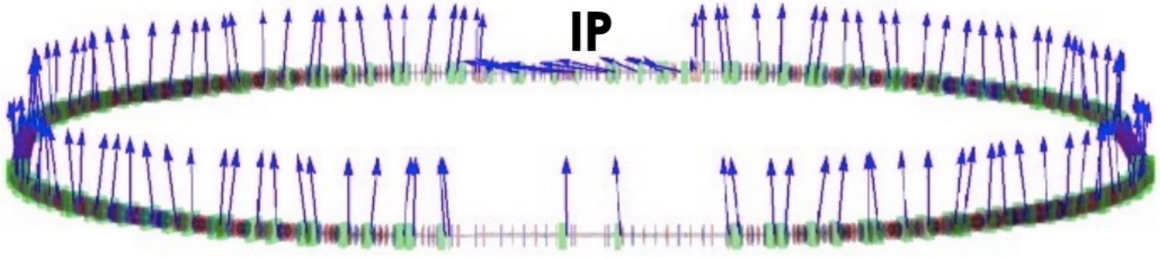


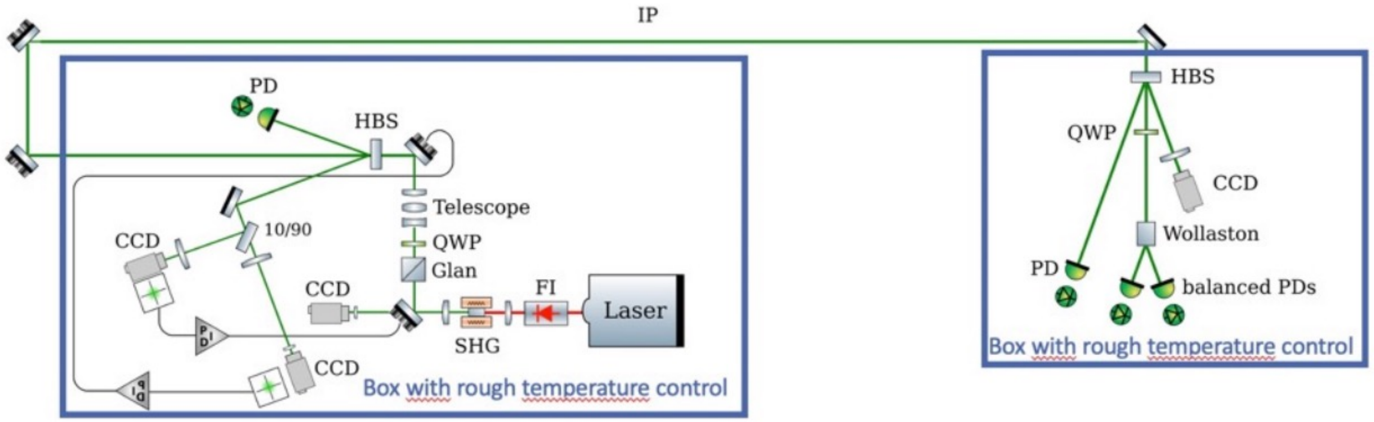
From PRD 92 055005 (2015)



Chiral Belle II – impact on IR

- Low emittance polarised source
  - Laser on GaAs cathodes under development
  - Need transverse polarization for injection in HER
- Spin rotators
  - Get longitudinal polarization electrons before IP
  - Option1: additional spin-rotator magnets => repositioning of some magnets
  - Option 2: replace two magnets with new combined-magnets dipole + rotator
- Compton polarimeter
  - Follows HERA experience
  - Monitor polarization at 0.5% absolute precision





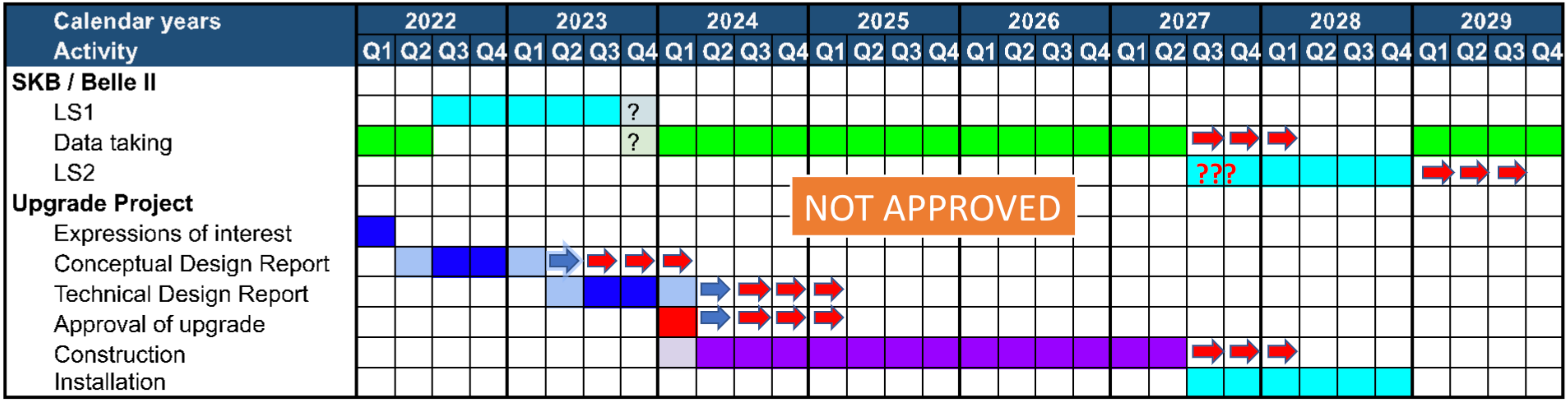
Summary

- Restarted data taking for Run2 February 2024 after upgrades in LS1
  - PXD2
  - IR work to improve beam stability, background control and higher luminosity
- Rich upgrade program in the LS2 – CDR (Conceptual Design Report) under publication

- New Run2
  - First collision at LER/HER $\boldsymbol{\beta}^*$ = 8 mm on Feb. 20th at 22:13 (JST)
  - Physics run at $\boldsymbol{\beta}^*$ = 1 mm – reached March 7th (goal is $\boldsymbol{\beta}^*$ = 0.6 mm)
  - Collected abuout 50 fb^{-1}; goal is to reach 1.5 fb^{-1} lumi /day
- Looking forward to new physics results before the LS2 which will prepare the machine and the Belle II detector for its absolute best performance → exciting times ahead!

Backup slides

Notional schedule

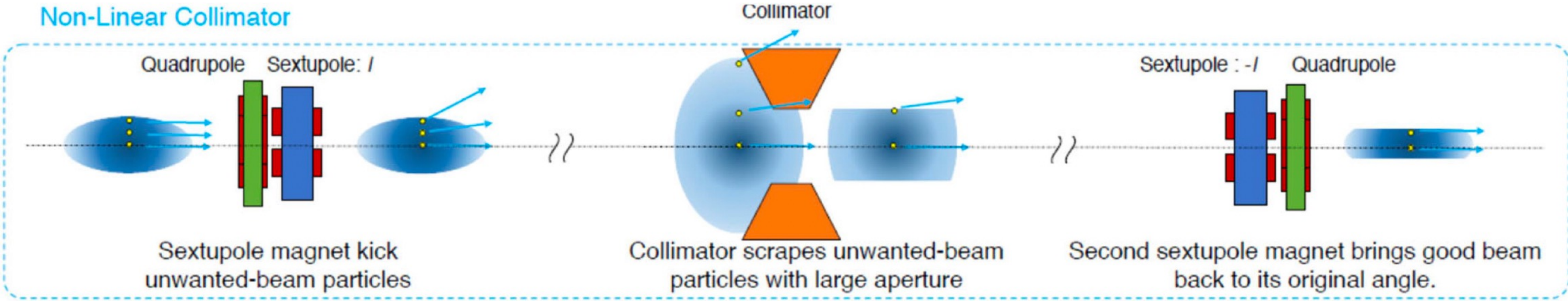


Belle II Upgrade schedule

Table 1.2: Known short and medium-term Belle II subdetector upgrade plans, sorted by time scale. MDI is the Machine-Detector-Interface, while RMBA is Radiation Monitoring and Beam Abort system. Moving from inner to outer radius, the current Belle II sub-detectors are: Silicon Pixel Detector (PXD), Silicon Strip Detector (SVD), forming the VerteX Detector (VXD), Central Drift Chamber (CDC), Time of Propagation Counter (TOP), Aerogel Rich Counter (ARICH), Electromagnetic Calorimeter (ECL), K-Long Muon System (KLM), Trigger and Data aquistion (TRG/DAQ), including the High Level Trigger (HLT).

Subdetector	Function	upgrade activity	time scale
MDI	RMBA	Faster and more performant electronics	medium-term
VXD	Vertex Detector	all-pixels DMAPS CMOS sensors (VTX)	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
TOP	PID, barrel	Replace not-life-extended ALD MCP-PMTs +SiPM option	medium-term
		Front end electronics upgrade	medium-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		upgrade of electronics readout and proportional mode RPC readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		hardware and firmware improvements	continuous
DAQ		add 1300-1900 cores to HLT	short/medium-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e ID	Add pre-shower detector in front of ECL	long-term
		Complement ECL PiN diodes with APDs or SiPM	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term

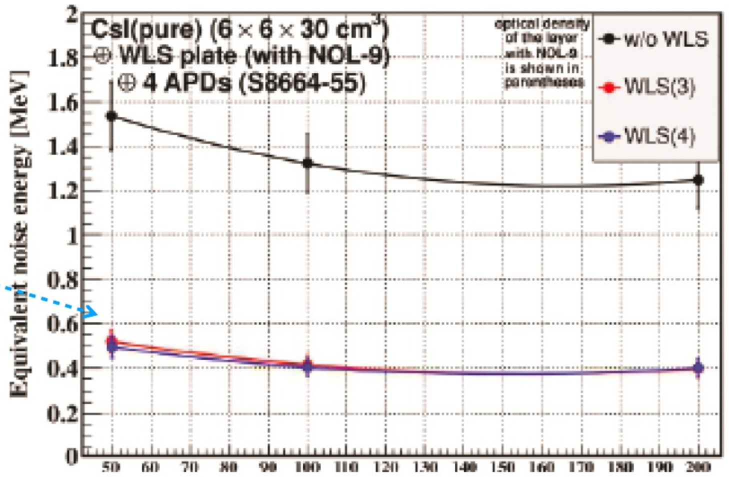
Non Linear Collimators (NLC)

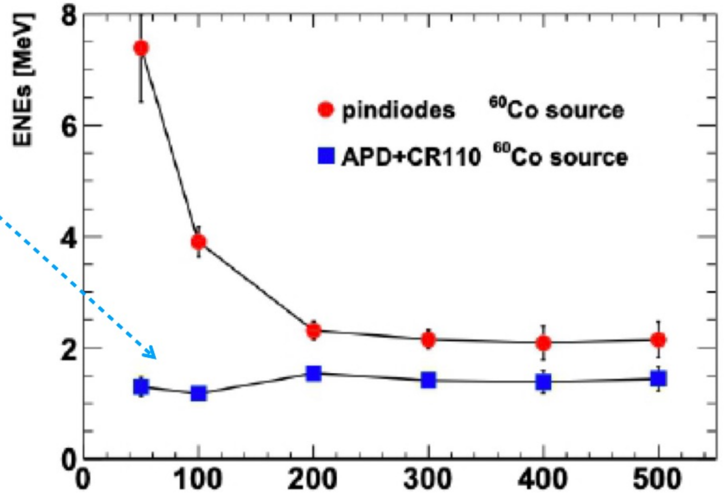


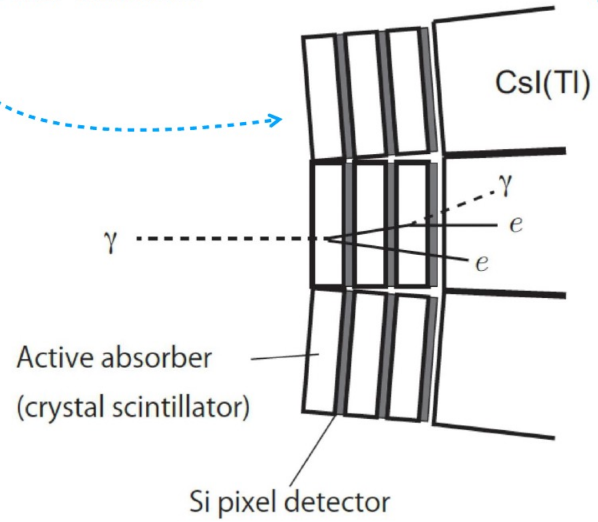
ECL Upgrade

✓ **beyond LS2 …**

- replace CsI(Tl) with pure CsI (or LYSO or $LaBr_3$) for shorter pulses & less pile-up
- add wavelength-shifting plate for better energy resolution
- replace PIN-diode sensors with APDs (or SiPMs) for better energy resolution
- front-end readout re-design
- add pre-shower detector



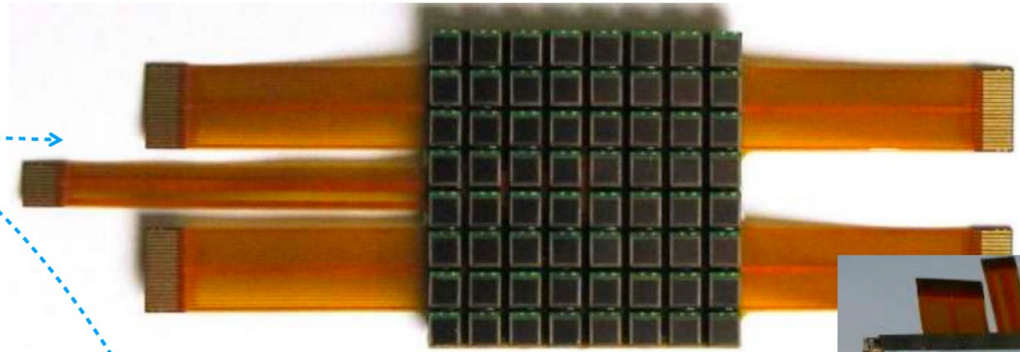


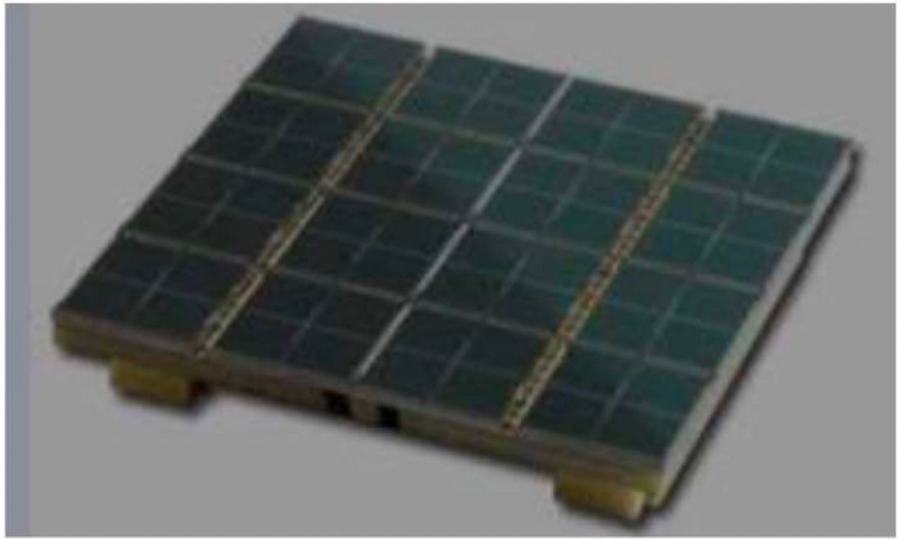


ARICH Upgrade

✓ **beyond LS2 …**

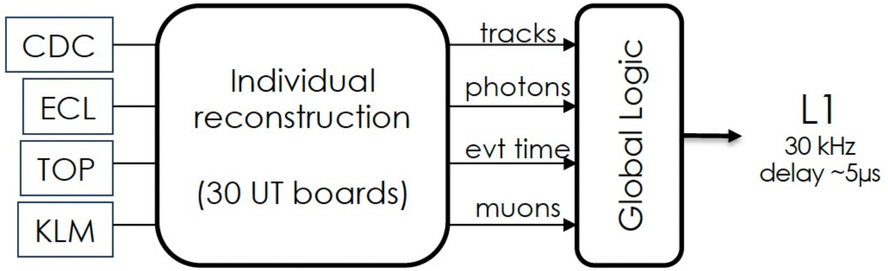
- R&D for SiPM photosensors or MCP-PMTs / LAPPD
- R&D for compatible readout (custom or FASTiC from LHCb)
- R&D for aerogel upgrade





- STOPGAP proposal
  - target **long term**
  - Fill-in gaps between TOP quartz bar
  - CMOS-MAPS with 50 ps timing

Trigger Belle II Upgrade



UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Varsal
Sub FPGA (Xilinx)	−−	Artex7	Artex7, Zynq
# Logic gate	500k	2000k	8000k
Optical transmission rate	8 Gbps	25 Gbps	58 Gbps
RAM	−−	DDR4	DDR4, UltraRAM
# UT boards	30	30	10
Cost per a board (k$)	15	30	50
Time schedule	2014-	2019-2026	2024-2032

- More powerful hardware UT4 and UT5 trigger boards
- Avoid merger boards, more bandwidth
  - Using all CDC TDC and ADC information → Vertex resolution improved x2 and 50% trigger rate reduction
- Keep high-efficiency on hadronic events and improve on low-multiplicity

Component	Feature	Improvement	Time	#UT
CDC cluster finder	transmit TDC and ADC from all wires with the new CDC front end	beamBG rejection	2026	10
CDC 2Dtrack finder	use full wire hit patterns inside clustered hit	increase occupancy limit	2022	4
CDC 3Dtrack finder	add stereo wires to track finding	enlarge θ angle acceptance	2022	4
CDC 3Dtrack fitter (1)	increase the number of wires for neural net training	beamBG rejection	2025	4
CDC 3Dtrack fitter (2)	improve fitting algorithm with quantum annealing method	beamBG rejection	2025	4
Displaced vertex finder	find track outside IP originated from long loved particle	LLP search	2025	1
ECL waveform fitter	improve crystal waveform fitter to get energy and timing	resolution	2026	–
ECL cluster finder	improve clustering algorithm with higher BG condition	beamBG rejection	2026	1
KLM track finder	improve track finder with 2D information of hitting layers	beamBG rejection	2024	–
VXD trigger	add VXD to TRG system with new detector and front end	BG rejection	2032	–
GRL event identification	implement neural net based event identification algorithm	signal efficiency	2025	1
GDL injection veto	improve algorithm to veto beam injection BG	DAQ efficiency	2024	–

Screenshot