The Belle II Upgrade Program

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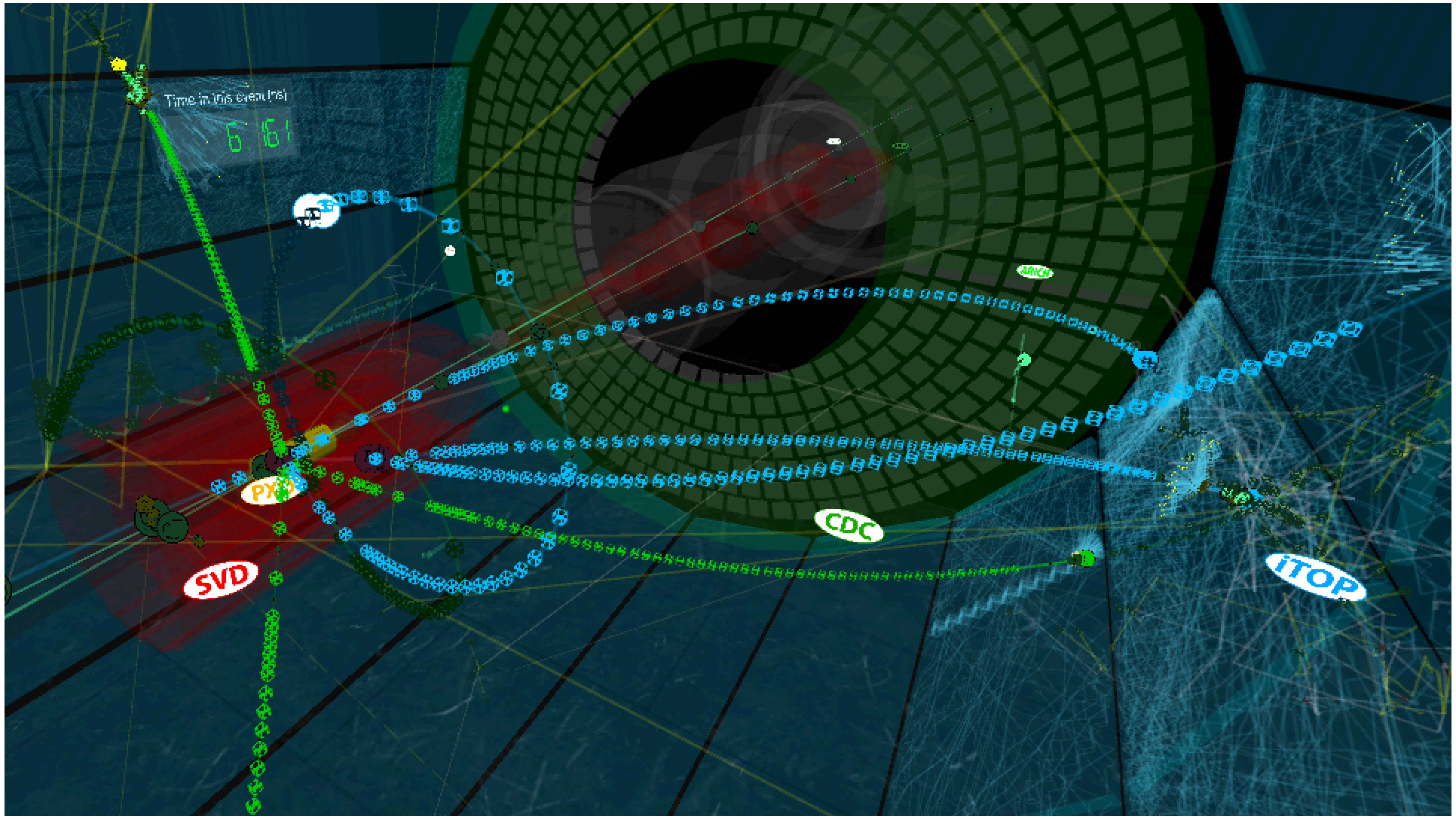
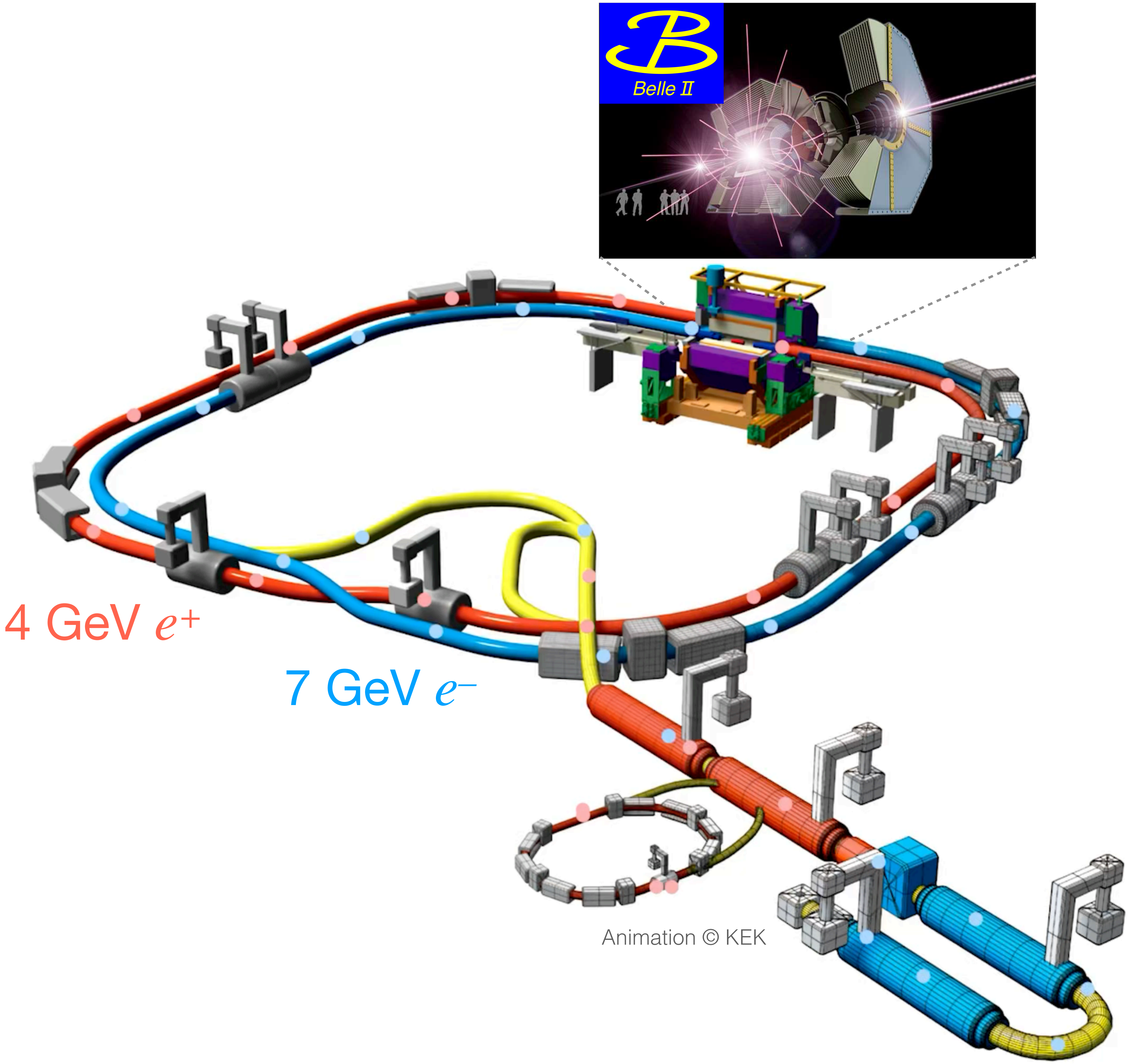
on behalf of the Belle II Collaboration

31st Lepton-Photon Symposium Melbourne Australia July 2023



This work supported by U.S. DEPARTMENT OF ENERGY | Office of Science

SuperKEKB and Belle II: 2nd generation B Factory



- ✓ Phase 1 (2016):
  - no detector, no beam collisions
  - test ring operation with single beams
  - bake (3 km)·2 of accelerator vacuum chambers
- ✓ Phase 2 (2018):
  - first collisions with complete accelerator
  - incomplete detector: vertex detector replaced by background-characterization detector
- ✓ Phase 3 (2019 ⋯):
  - luminosity run with *mostly* complete detector
  - partial pixel detector (layer 1 + partial layer 2) + full 4-layer strip detector for B vertexing
  - first physics paper in January 2020
  - challenging operations throughout pandemic
- ✓ Novel and complex accelerator:
  - record peak luminosity of 4.7×10^{34} cm^{-2} s^{-1}
  - path to reach 2×10^{35} cm^{-2} s^{-1} identified
  - long march to reach target of 6×10^{35} cm^{-2} s^{-1}

Path to the future

Steep path to higher luminosity

✓ Accelerator performance and stability:
- beam blow-up due to beam-beam effects
- lower beam lifetime than expected
- transverse mode coupling instabilities
- low machine stability
- sudden beam loss
- injector limitations
- aging infrastructure

✓ Accelerator-induced backgrounds in detector:
- Single-beam: beam-gas, Touschek
- Collisions: radiative Bhabha scattering, two-photon processes
- continuous-injection backgrounds
- prudent management needed to avoid compromising the physics program

Mitigation measures toward 2×10^{35} cm^{-2} s^{-1}

✓ Consolidate and address accelerator limitations:
- international task force at work to assist
- many countermeasures deployed
- more countermeasures in development

✓ Consolidate and address detector limitations:
- complete the installation of full pixel detector
- complete the installation of more robust time-of-propagation photomultiplier tubes

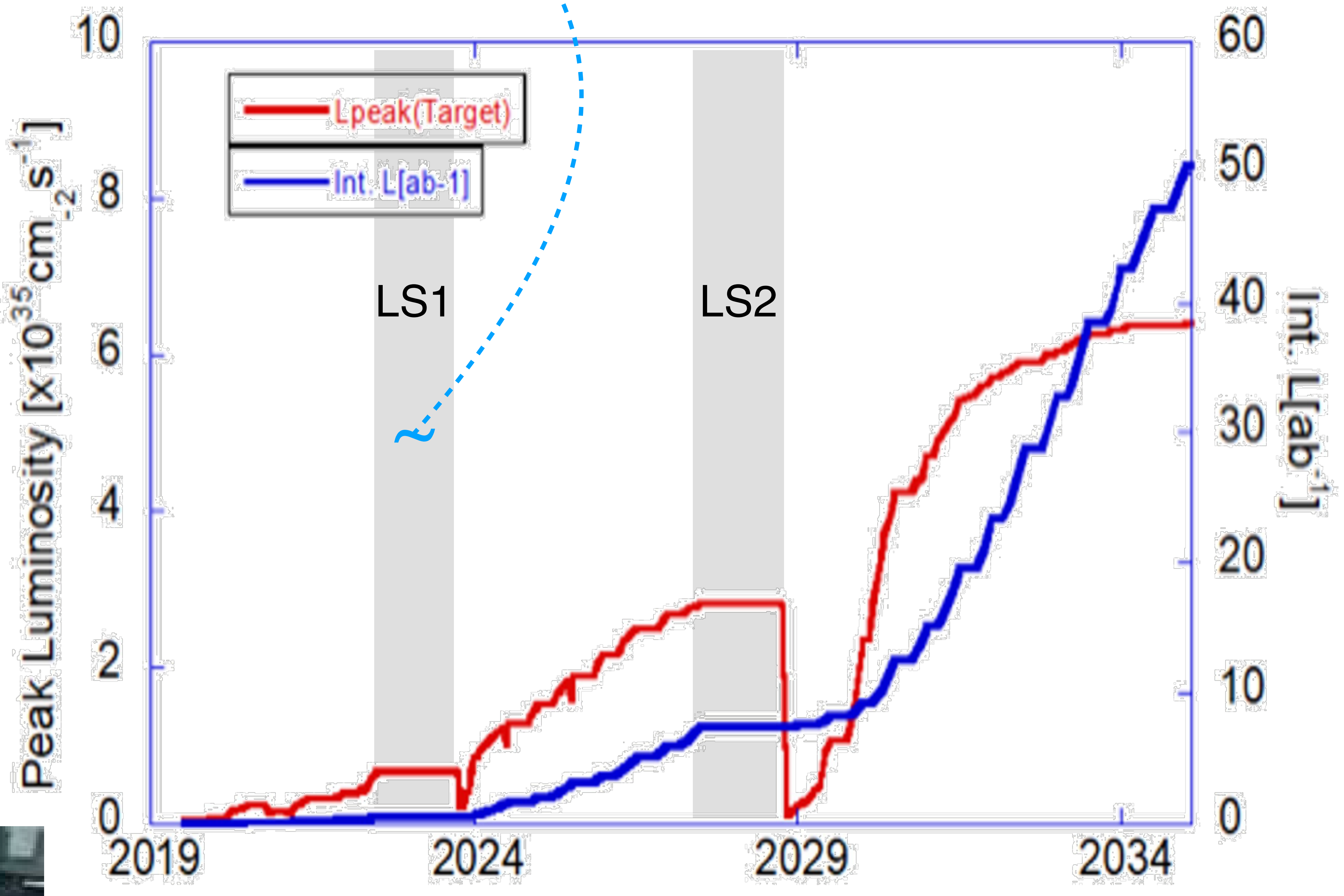
Improvements toward 6×10^{35} cm^{-2} s^{-1}

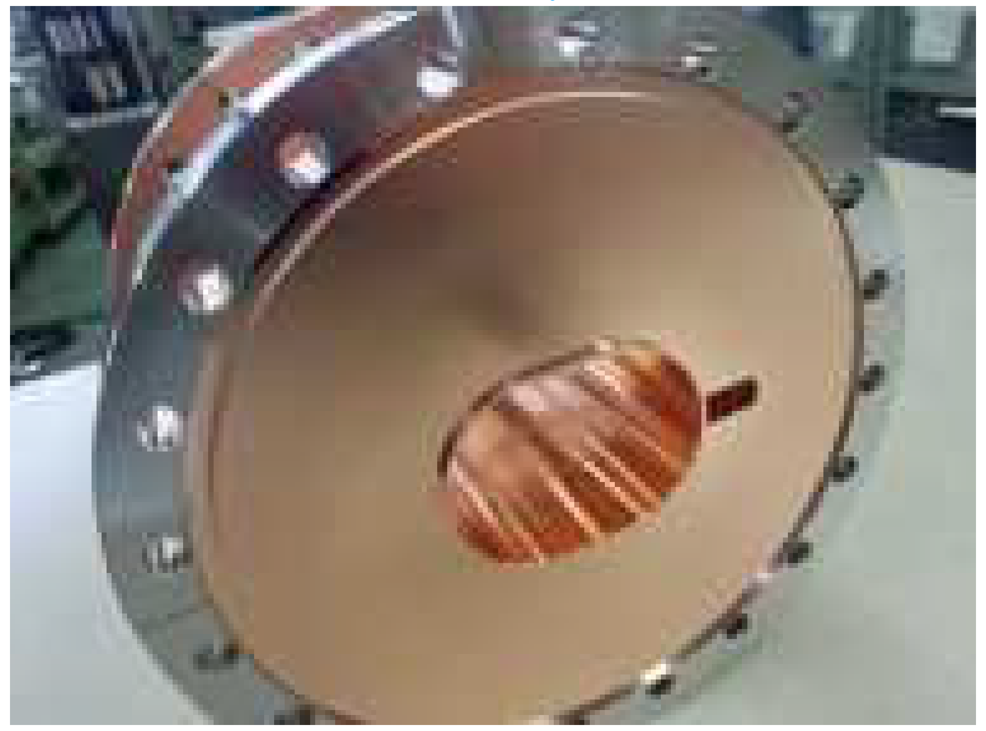
✓ **Accelerator:**
- major redesign of interaction region, perhaps
- possibility of polarized beams

✓ **Detector:**
- improve robustness against backgrounds at higher peak luminosity
- improved physics performance

Accelerator upgrades during Long Shutdown 1: 2022-2023

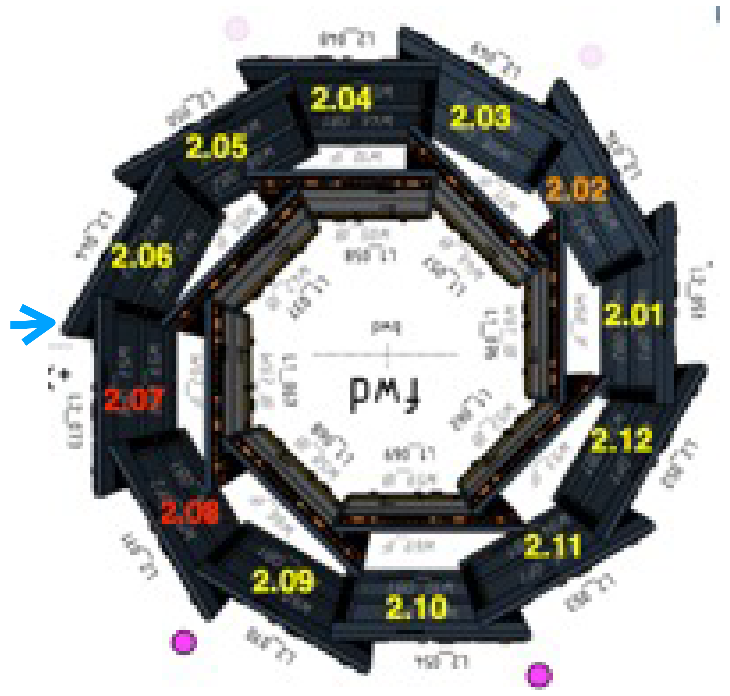
- countermeasures against sudden beam loss
- additional shielding around final-focus magnets and endcaps against beamline neutrons
- more resilient collimators (harder material)
- non-linear collimator to reduce beam halo
- RF cavity replacement for stability, higher currents
- at injector: faster kicker magnet, new focusing magnet, new large-aperture beam pipe

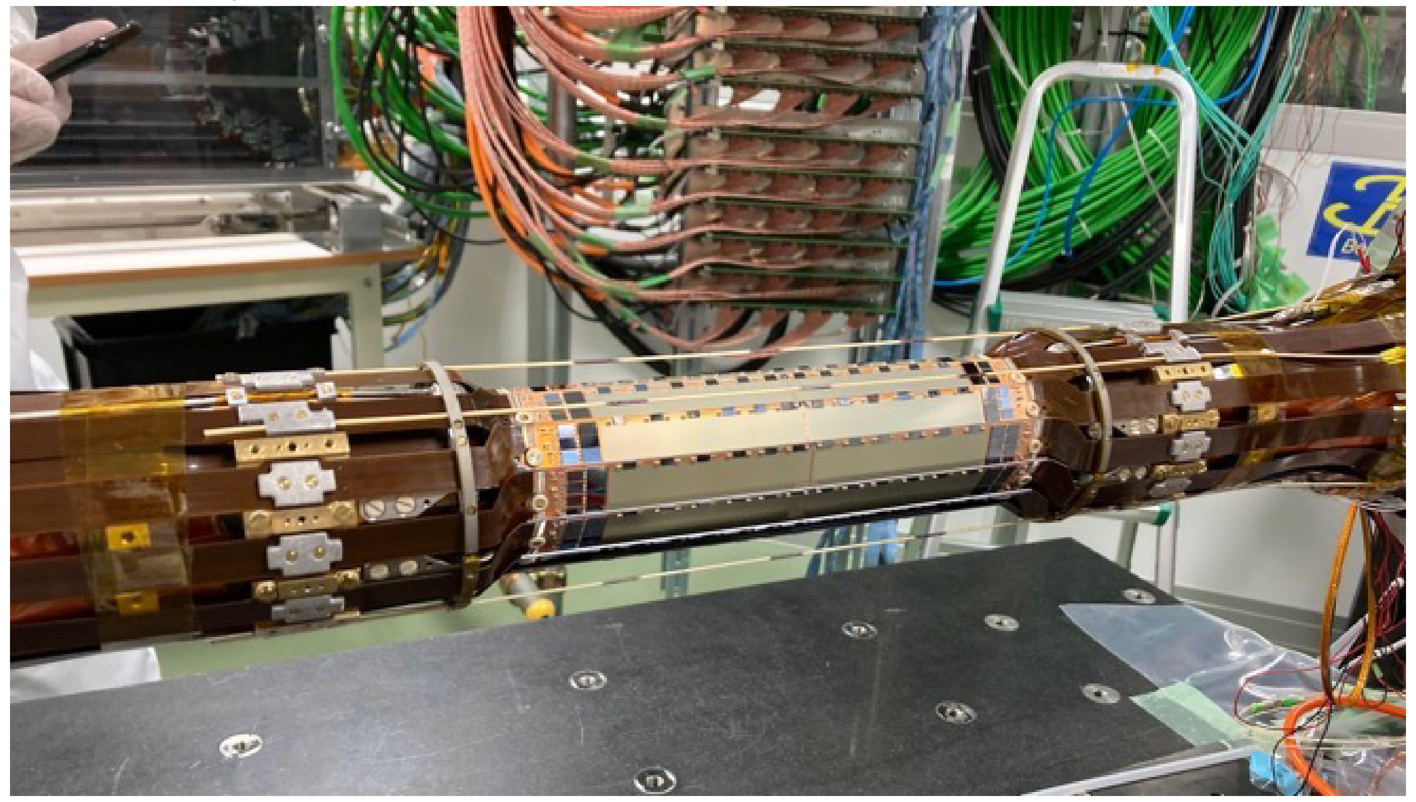


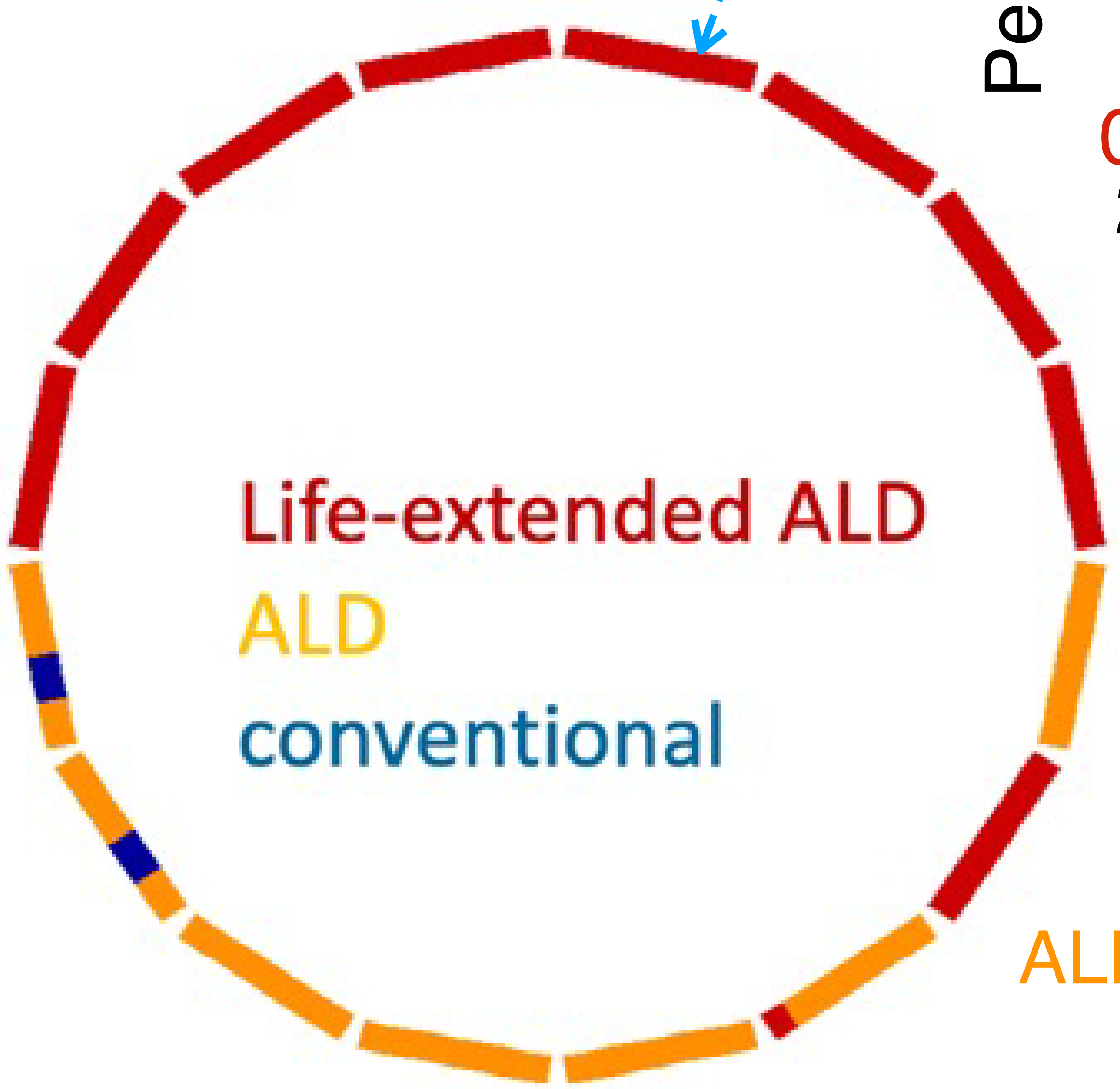


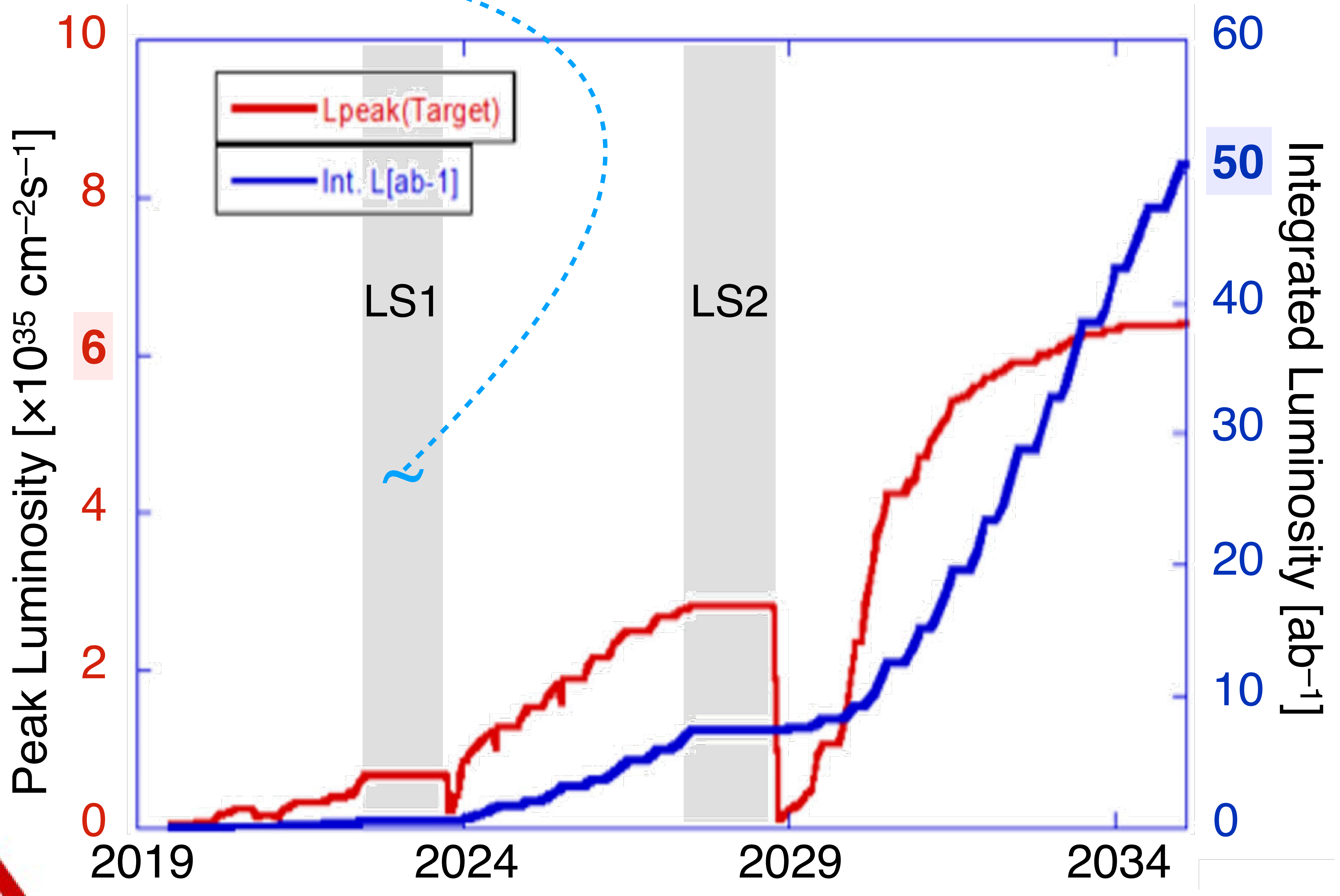
Detector upgrades during LS1

- installation of complete pixel detector
- replacement of time-of-propagation counter's photomultipliers: increased lifespan, robustness
- data-acquisition system upgrade to PCIe40
- improved gas distribution, gain stability and monitoring for drift chamber









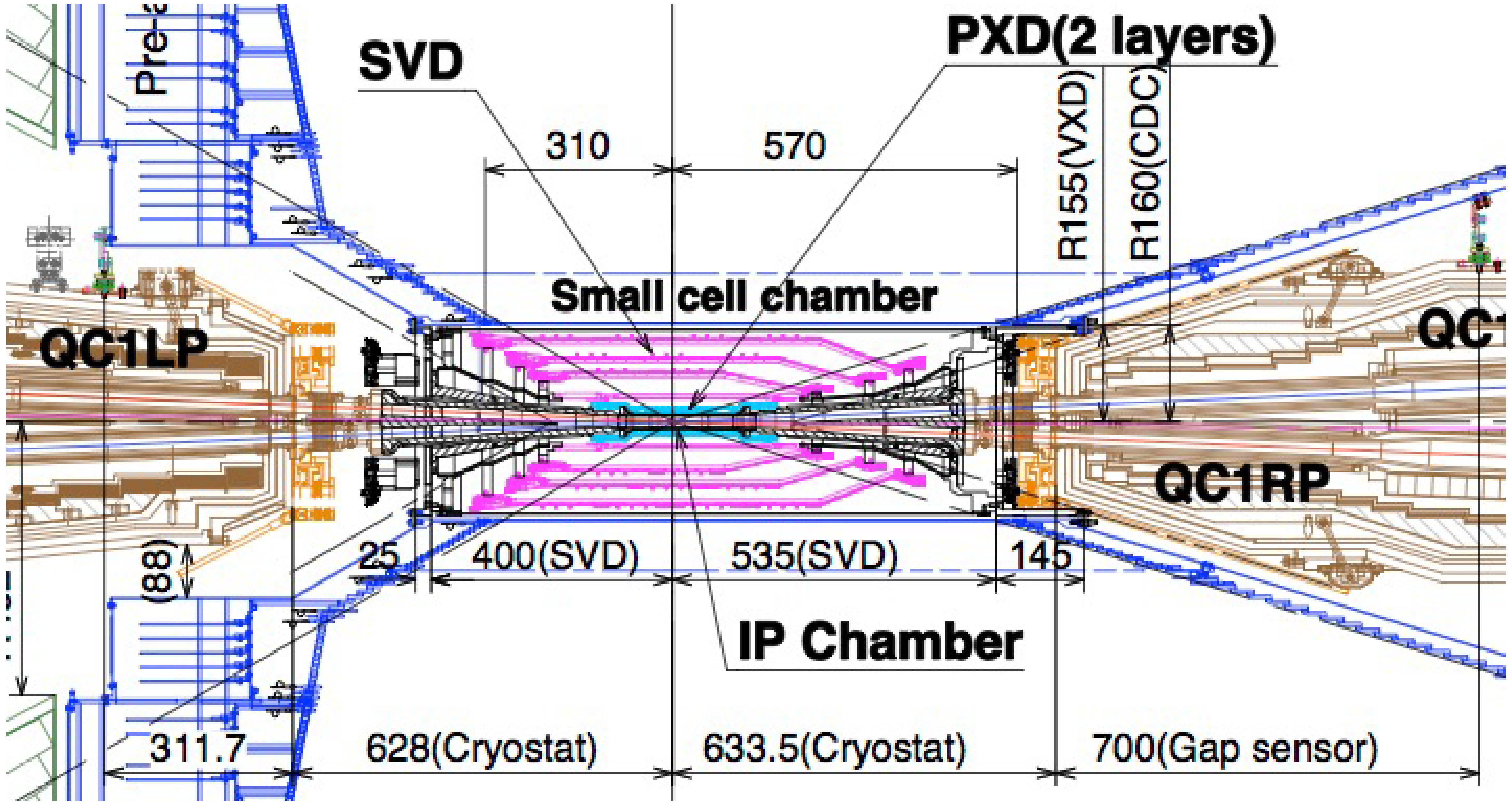
ALD = Atomic Layer Deposition
micro-channel plate photomultiplier tube

Accelerator upgrades during Long Shutdown 2: ~2028-2029

in cooperation with the International Task Force to leverage cross-continental expertise

✓ **goal:** higher $\mathcal{L}$ with lower β^* and higher currents

- limit beam-beam effects, preserve beam lifetime
- reposition final-focus (QC) magnets closer to IP
- new design for final-focus magnets
- additional compensating solenoid inside QC magnets near final focus to reduce emittance
- designs will be informed by 2024+ experience

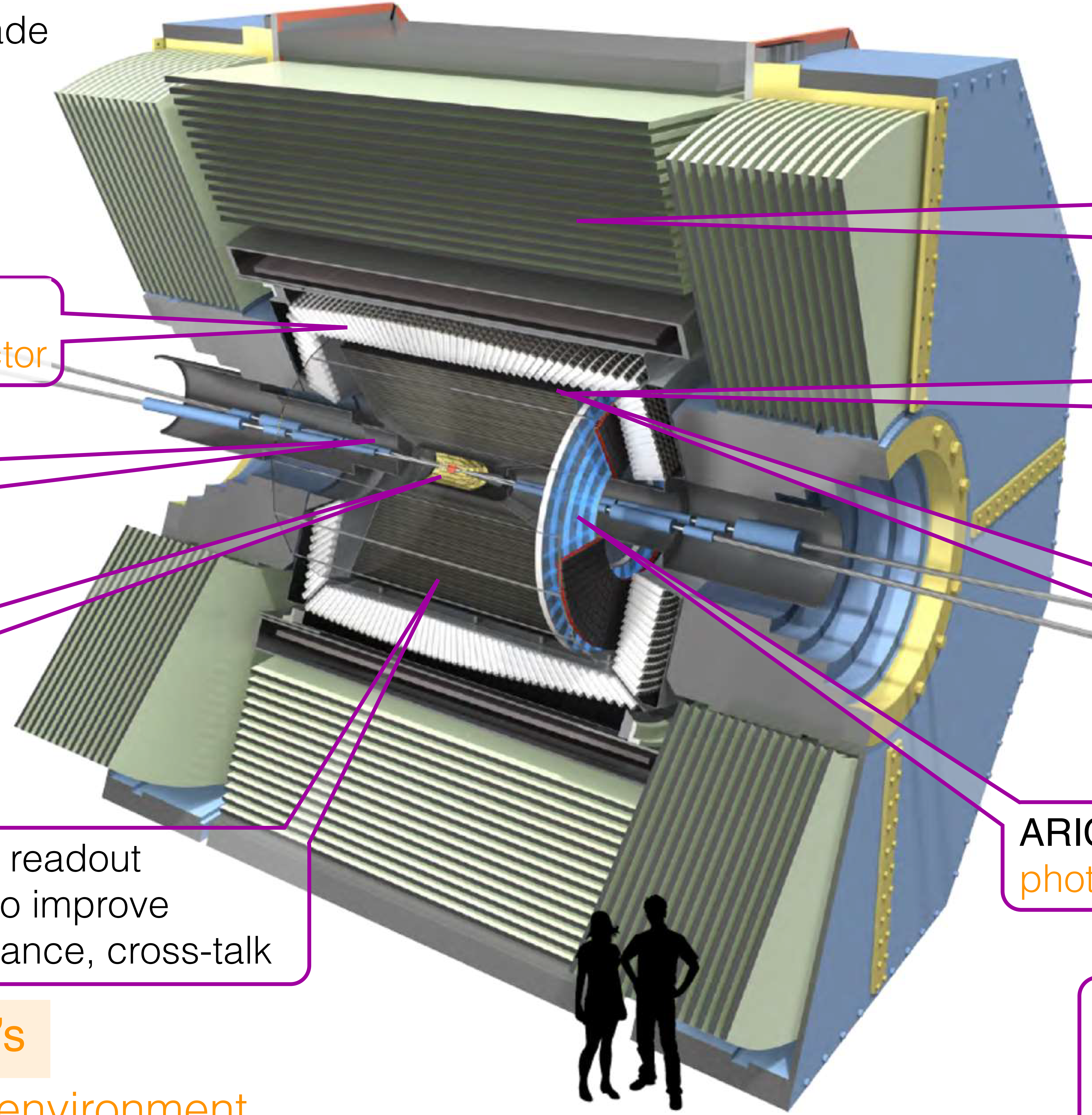


More distant future: ~mid-2030's

✓ Accelerator R&D for significant $\mathcal{L}$ increase, with possibility of polarized beams [maybe sooner?]
✓ … toward integrated luminosity of 250 ab^{-1}

Detector upgrades during LS2 or beyond

See Snowmass white papers:
arXiv:2203.11349 for detector upgrade
arXiv:2207.06307 for physics reach
arXiv:2203.05731 for backgrounds



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace all PMTs with extended-lifetime ALDs (or SiPMs?)

IR: accommodate QCS replacement and repositioning

VXD: all pixels
- DMAPS
- SOI-DUTIP

STOPGAP: close gaps between TOP quartz bars, provide timing layers for track trigger

CDC: replace readout ASIC+FPGA to improve radiation tolerance, cross-talk

ARICH: possible photosensor upgrade

TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030’s

✓ Detector R&D for extreme-$\mathcal{L}$ environment

Central Drift Chamber front-end readout upgrades

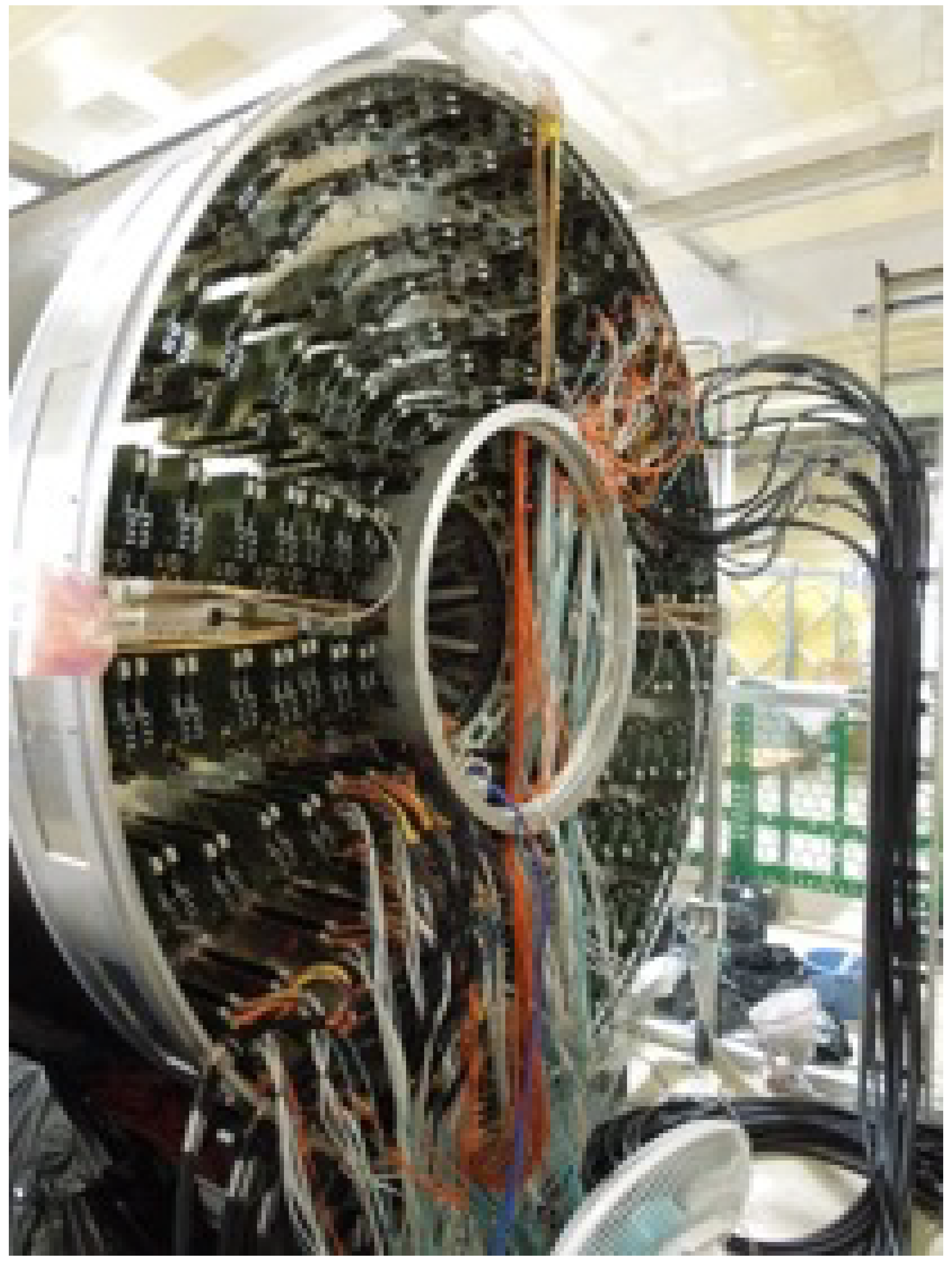
the present board	upgrade
separated chips, ASD and FADC	functions of ASD and FADC are in one chip. ~60% reduction is expected in ASD+FADC
~100mV pulse height induced in neighbor ch with 7pC input	~10mV pulse height induced in neighbor ch with 7pC input + double thresholds
Virtex-5	Kintex-7
SFP for DAQ (1kGY) Avago HFBR-7934WZ for TRG (300-400Gy)	QSFP
SFP for DAQ Avago HFBR-7934WZ for TRG (3.125Mb/s)	one QSFP in stead of two different optical transceivers

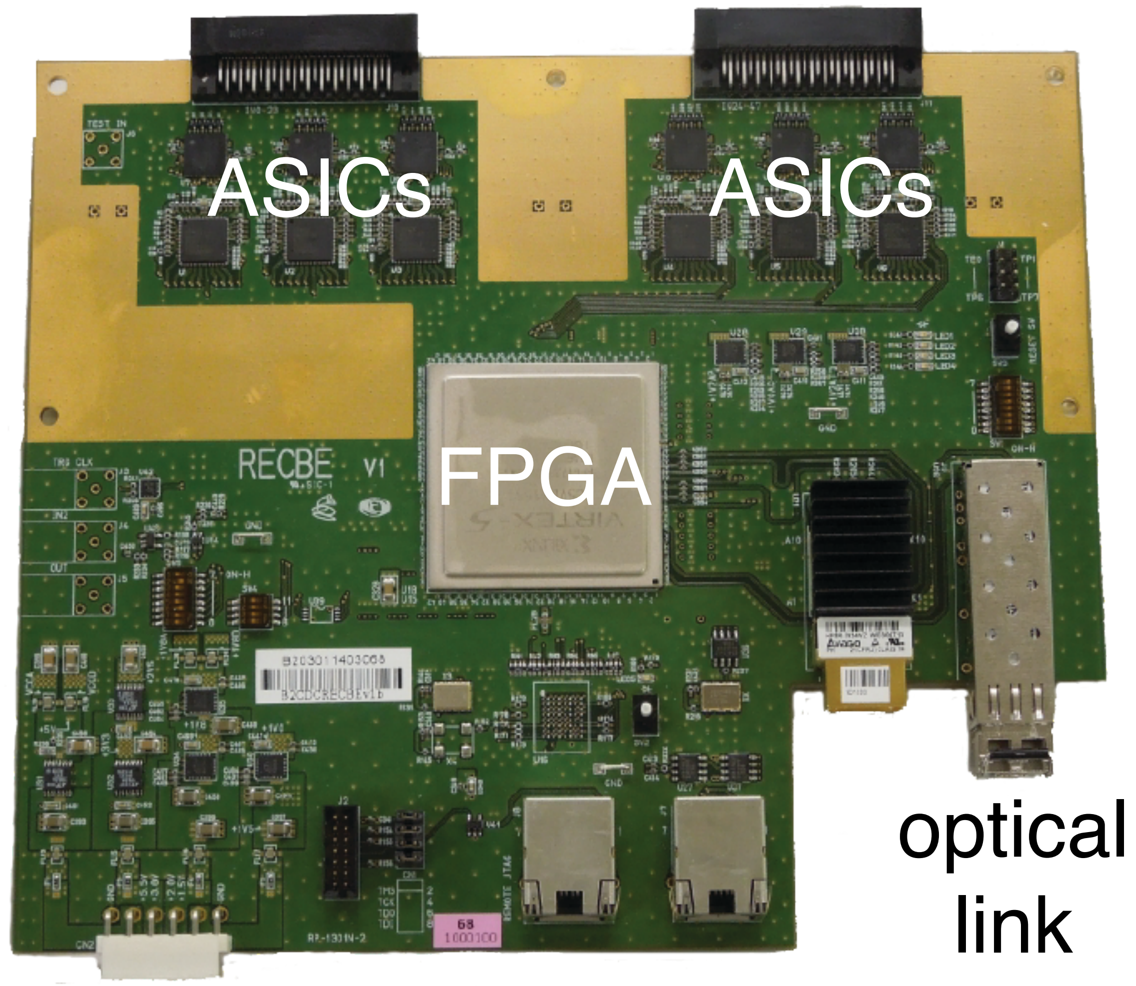
✓ improvements during LS2

- better tracking performance
- reduced power consumption
- reduced cross-talk
- increased output bandwidth

✓ technology implementation

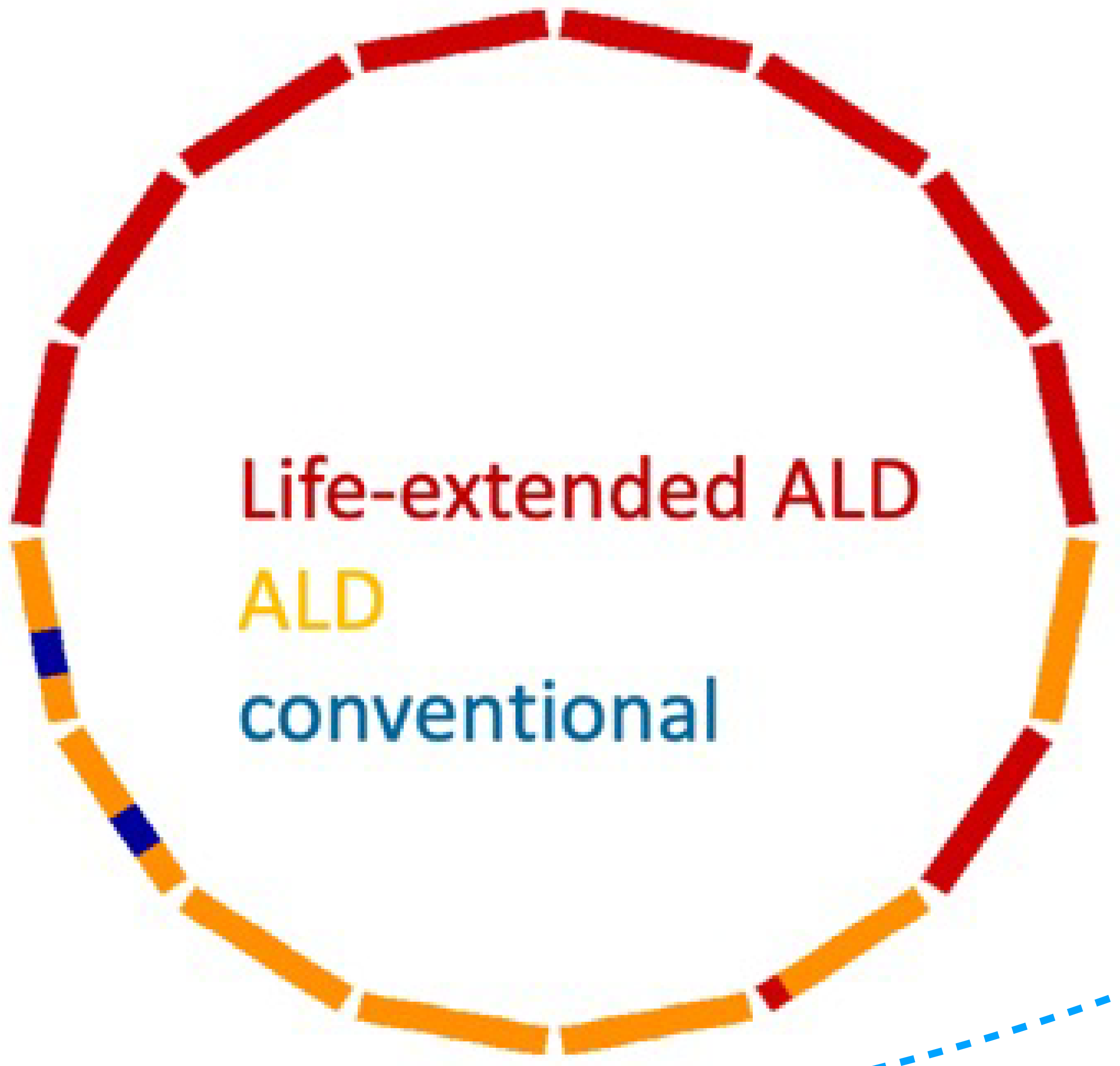
- new ASIC
- new FPGA
- new optical module

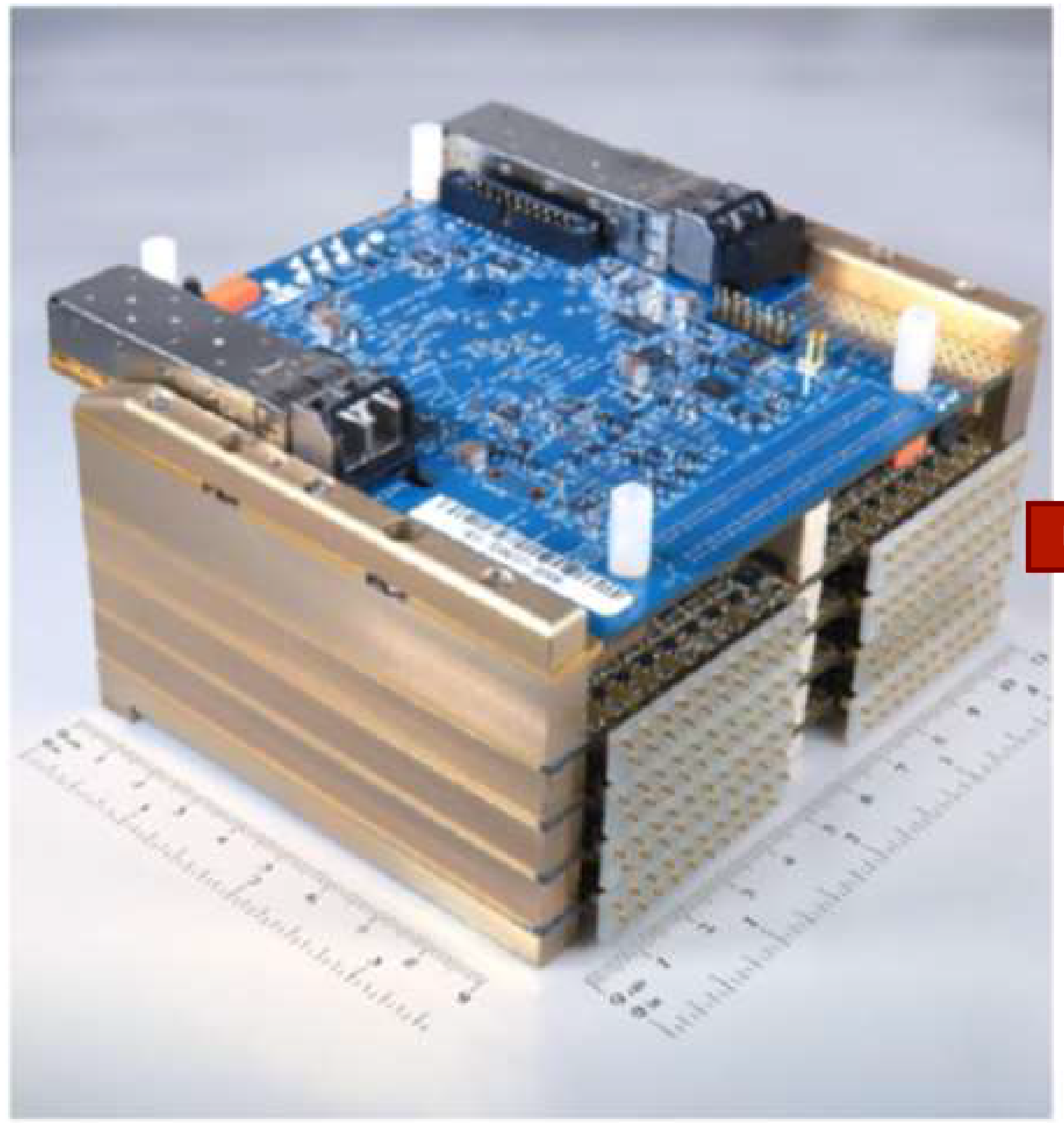


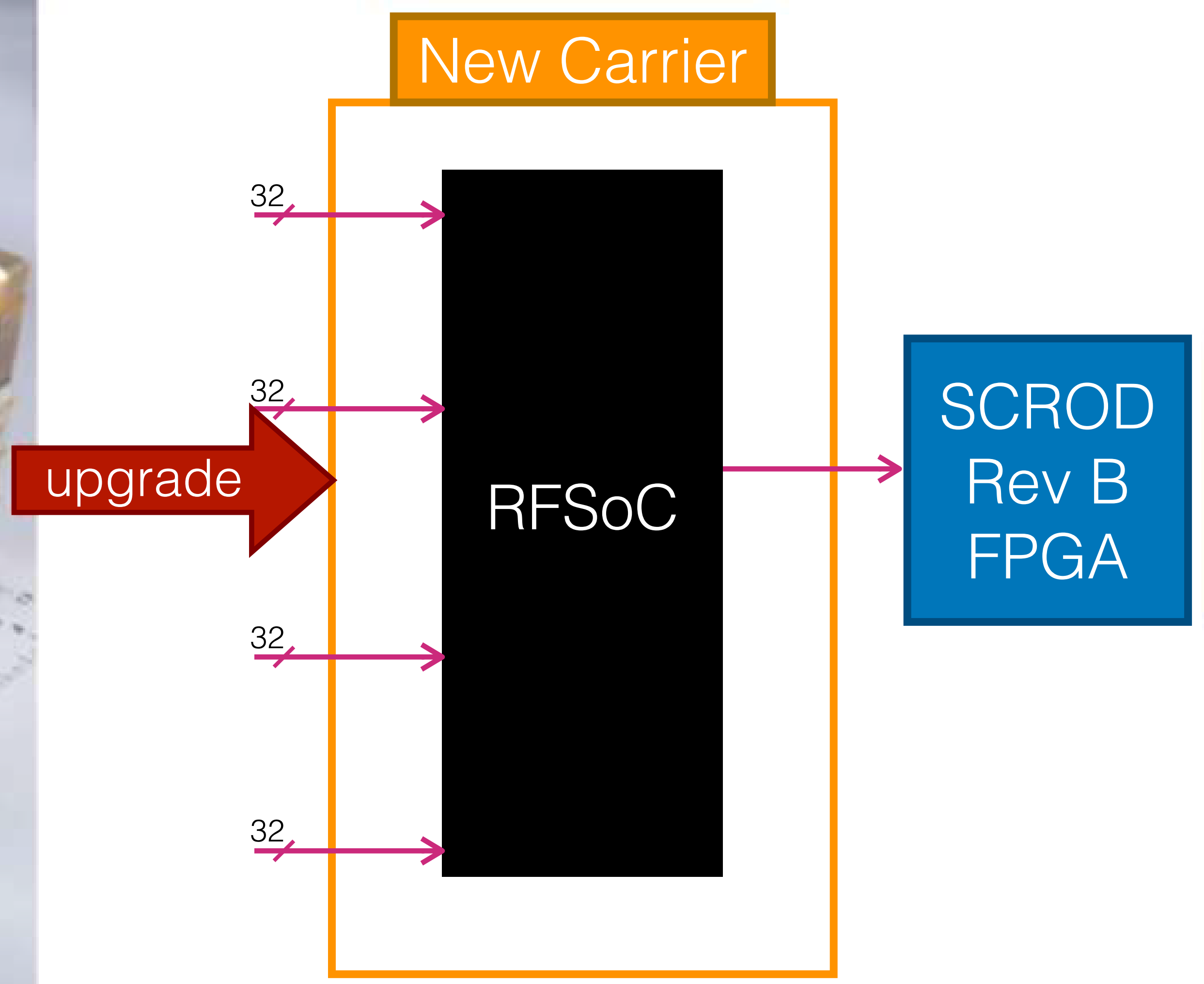


Time of Propagation Counter upgrades

- ✓ **requirements**
  - extended photosensor lifetime
  - better radiation tolerance
- ✓ **performance improvements**
  - better particle-ID performance
  - feature extraction inside ASIC
  - reduced power consumption
- ✓ **technology implementation in LS2**
  - all PMTs are lifetime-extended ALDs
  - RFSoC (for 5G phones) [default]
  - … or custom TDC ASIC
  - redesigned front-end board stack
- ✓ **beyond LS2 …**
  - R&D for SiPM photosensors



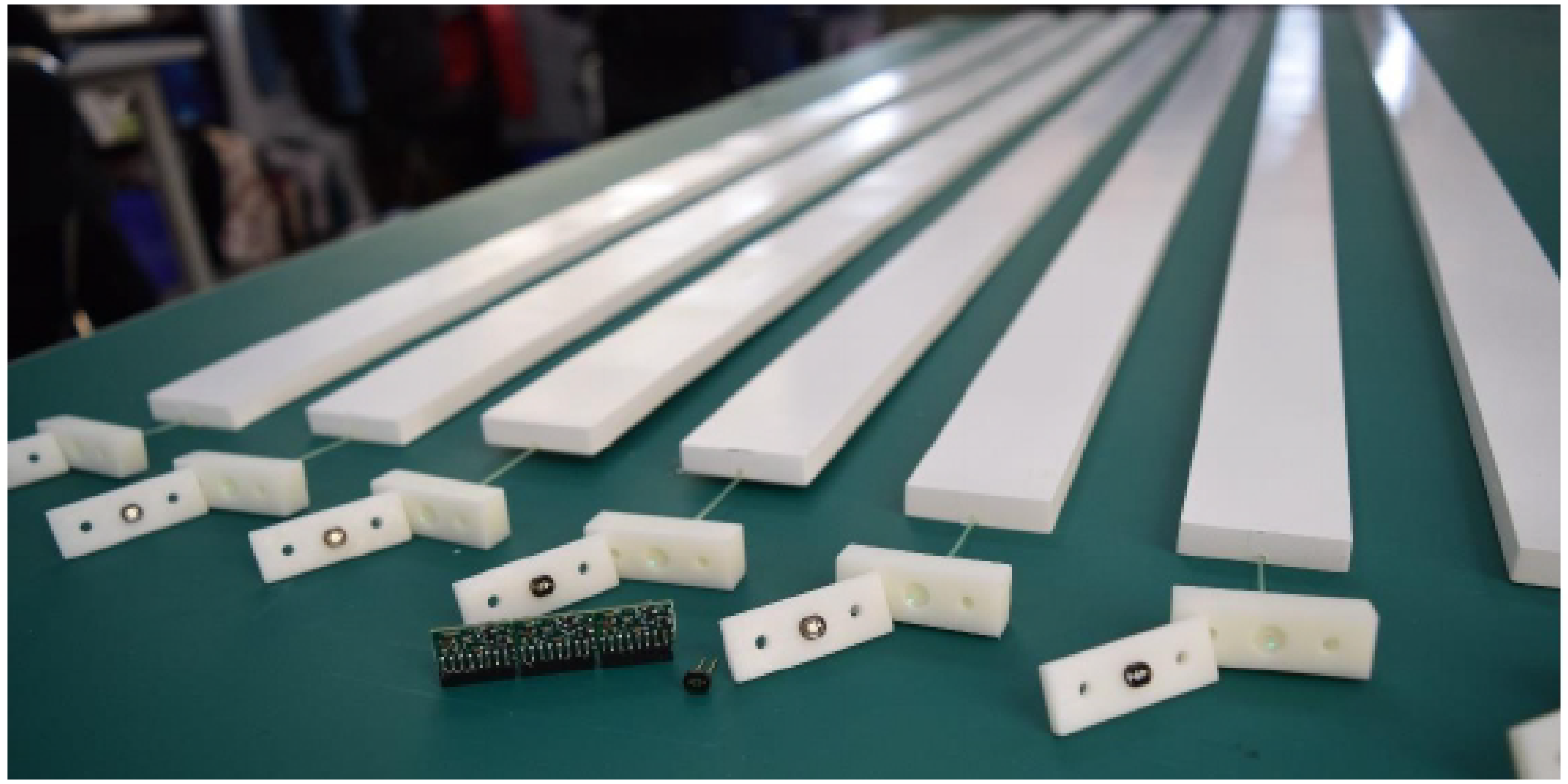


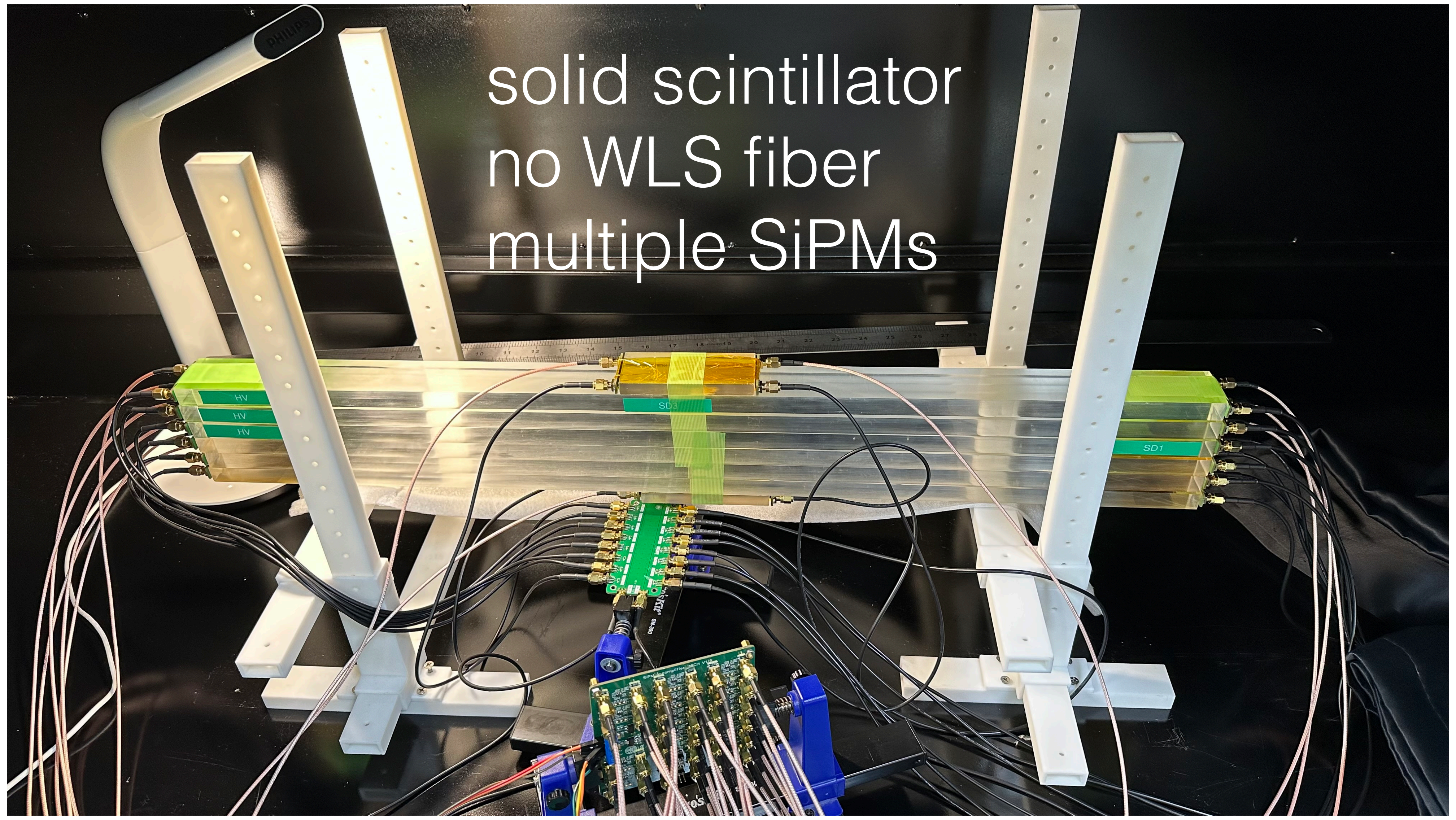


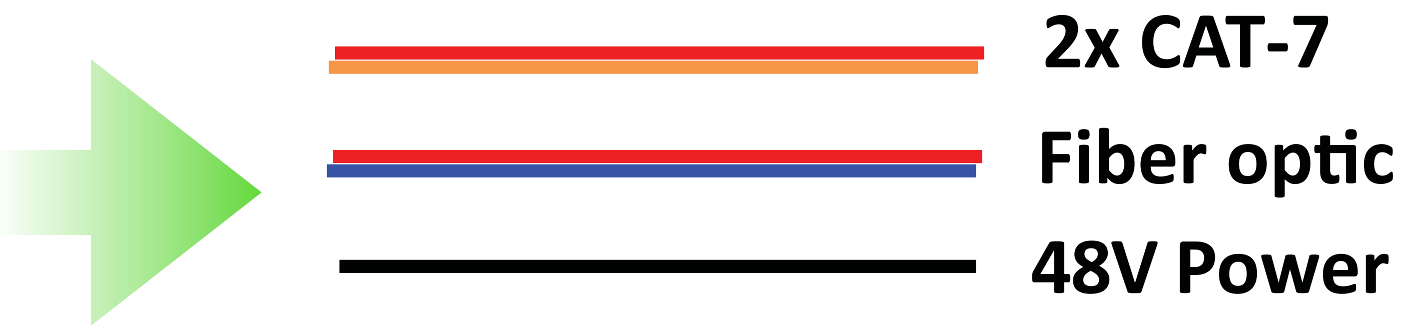
K-long & Muon Detector upgrades

✓ **during or beyond LS2 …**

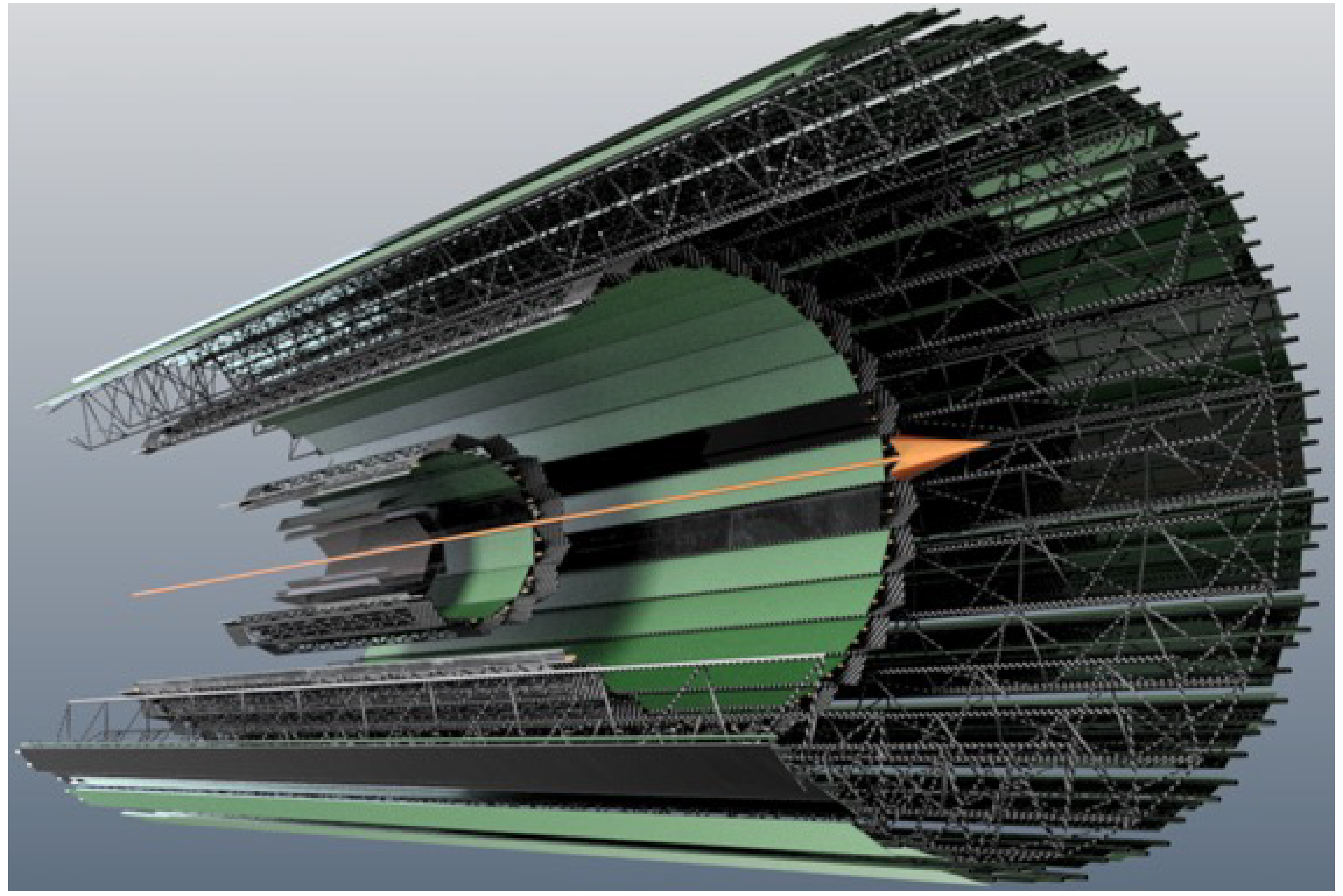
- replace remaining RPCs in barrel with scintillator strips
- re-design electronics layout with feature-extraction ASIC inside panel, only digital I/O [optical/ethernet]
- high-resolution timing for K-long momentum via time of flight



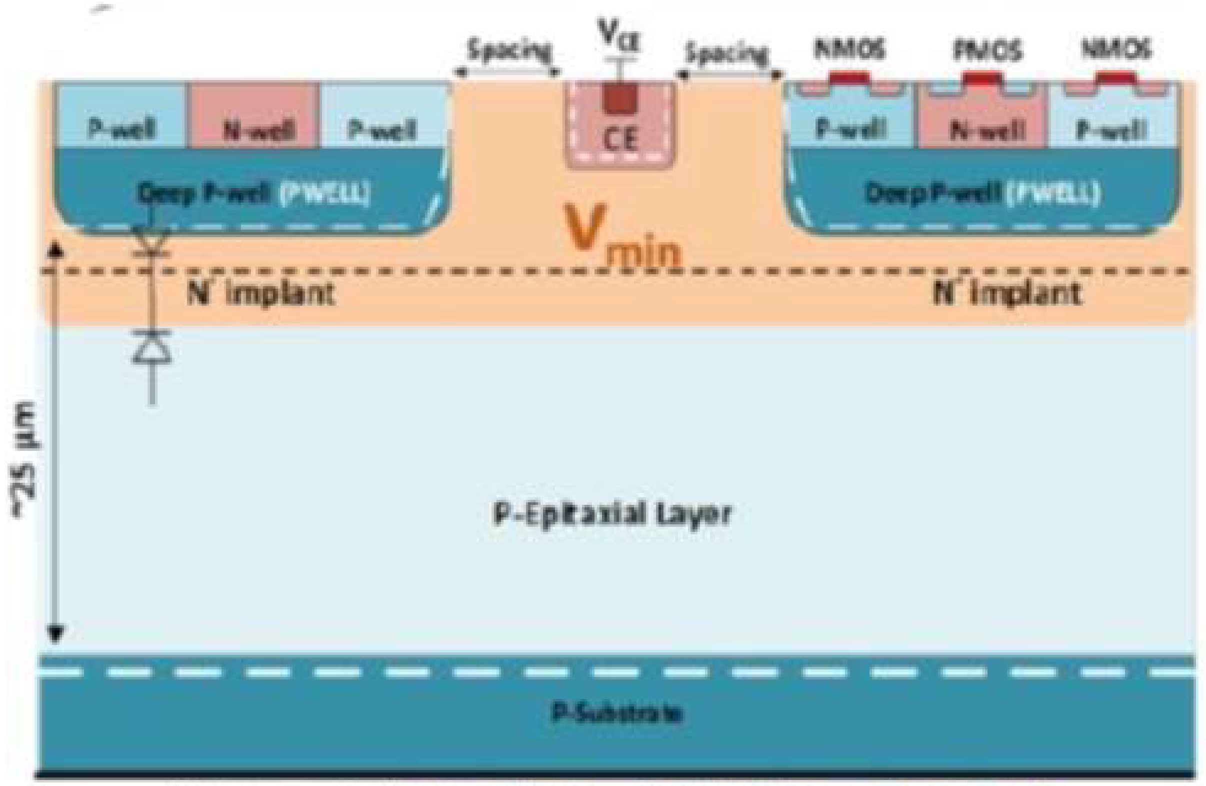




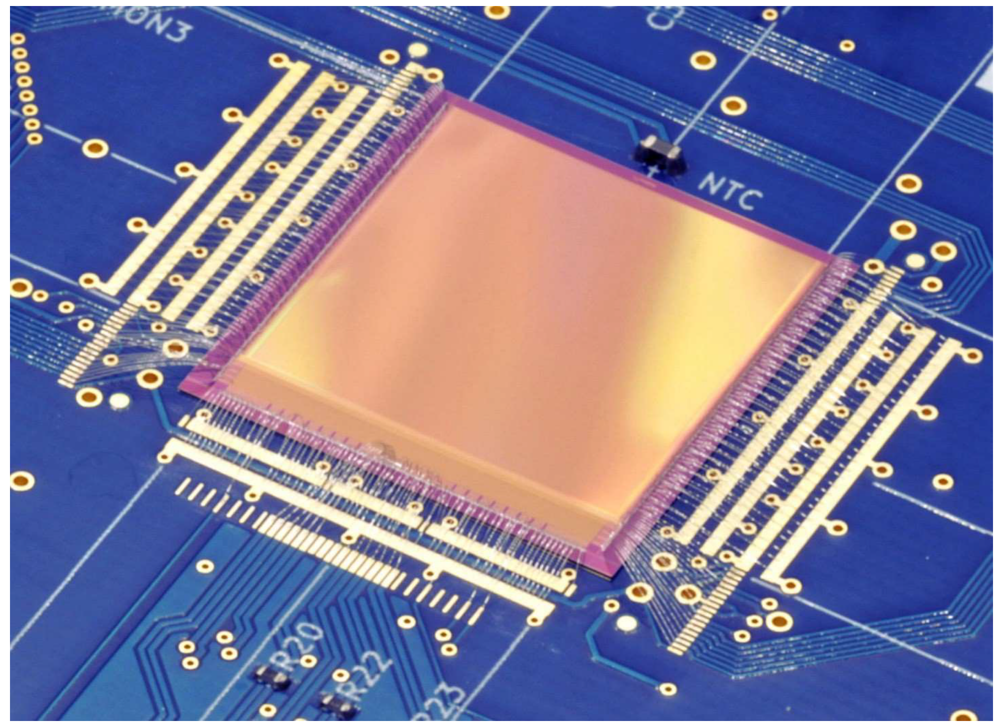
Future vertex detector design options

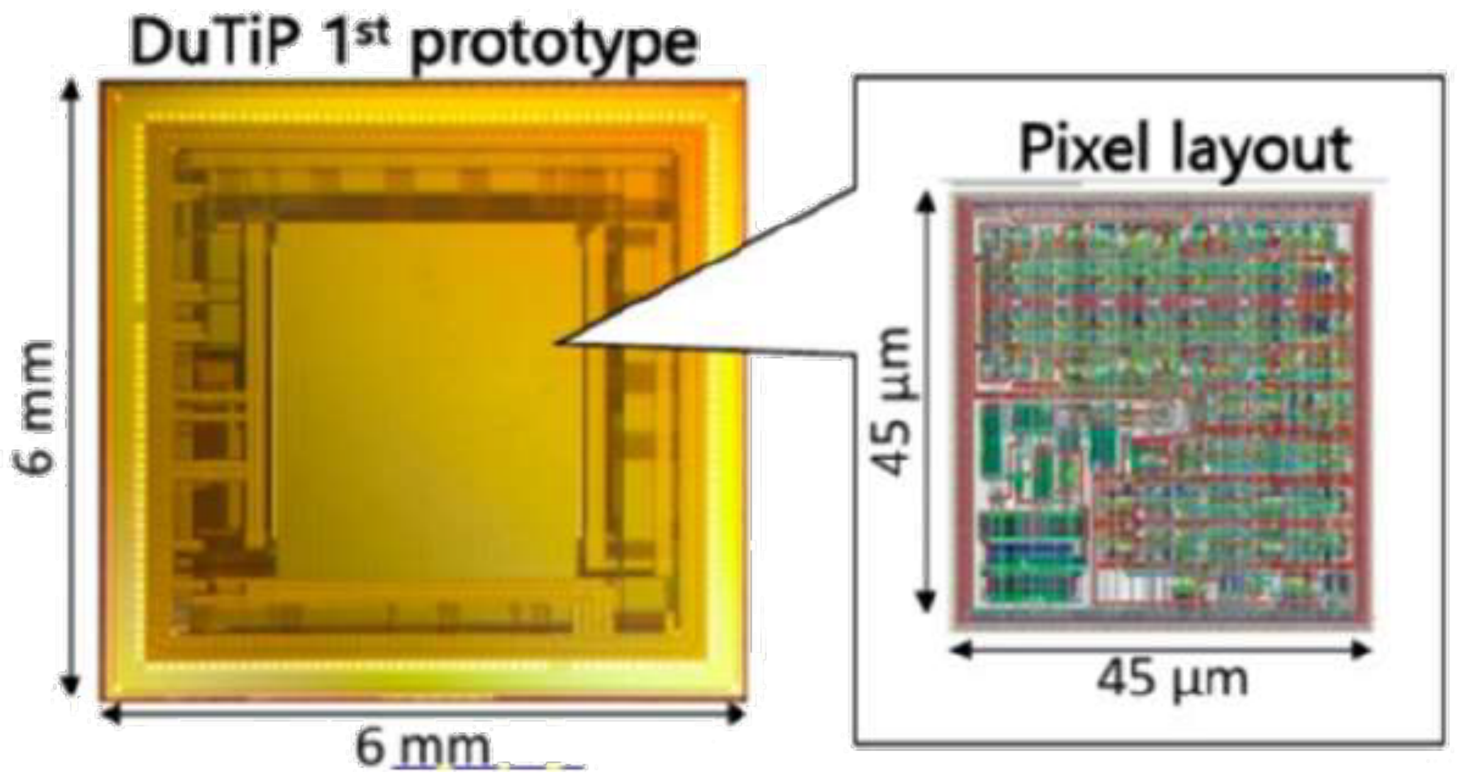


- ✓ **requirements**
  - vertexing/tracking equal to current VXD
  - robustness against high-radiation environment
- ✓ **performance improvements**
  - better vertex resolution
  - better tracking performance for soft tracks
  - possible contribution to the Level 1 trigger
- ✓ **technology options**
  - CMOS-MAPS pixels [default]
    - Tower 180 nm process
    - Extension of TJ-MONOPIX2 → OBELIX sensor
    - <40 μm pitch, 100 ns integration
  - SOI pixels [alternate]
    - Lapis 200 nm process
    - Dual Time Pixel (DuTiP) sensor
    - 45 μm pitch, 2×60 ns integration



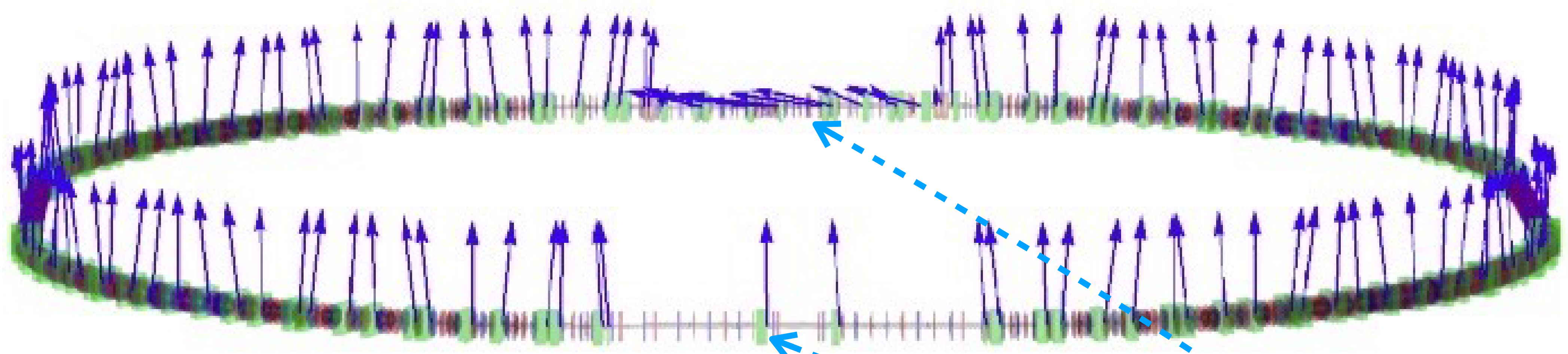
W. Snoeys et al. https://doi.org/10.1016/j.nima.2017.07.046





Beam polarization & "Chiral Belle" beyond LS2 [or sooner?]

See Snowmass white paper arXiv:2205.12847



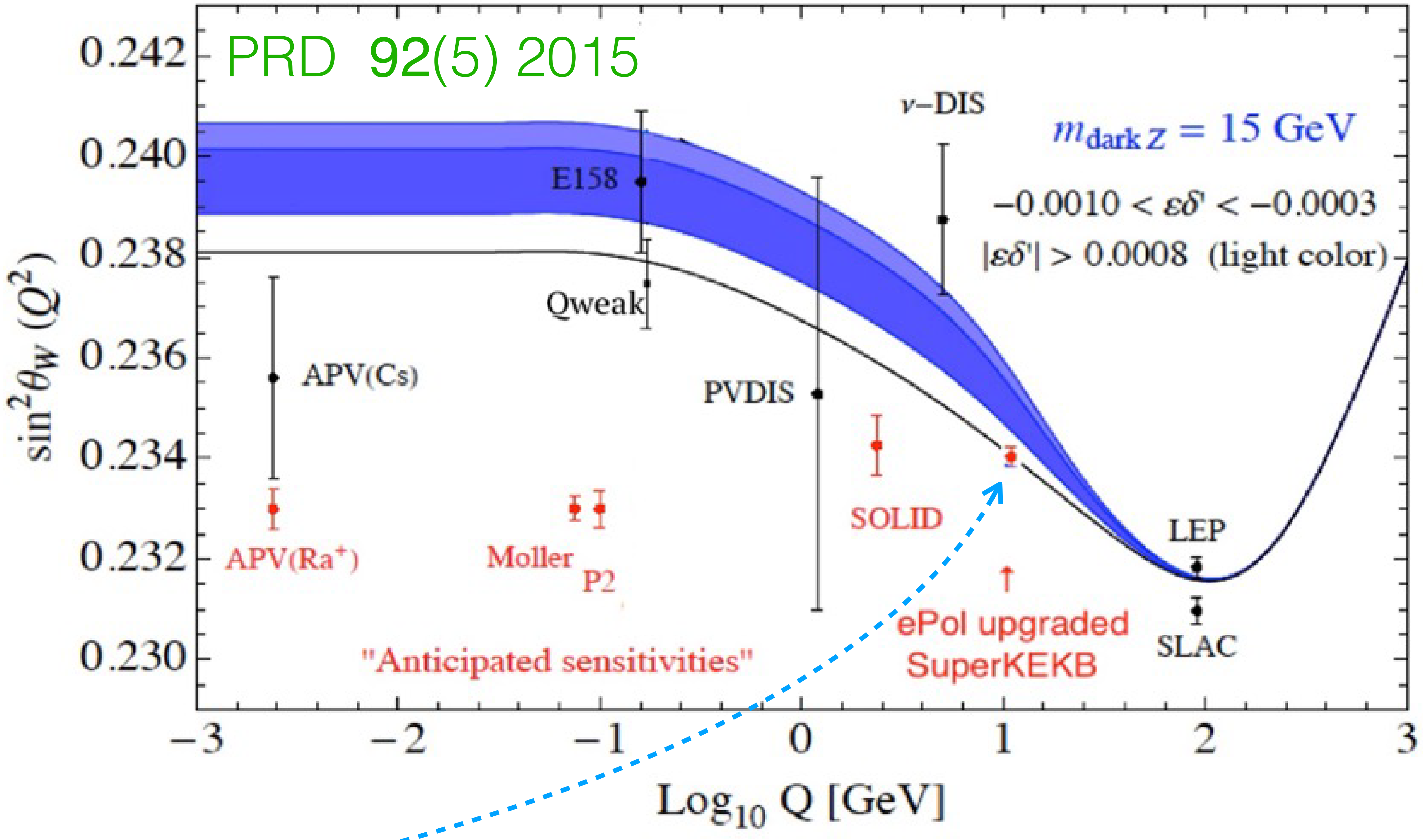
e^- spin vector in SuperKEKB

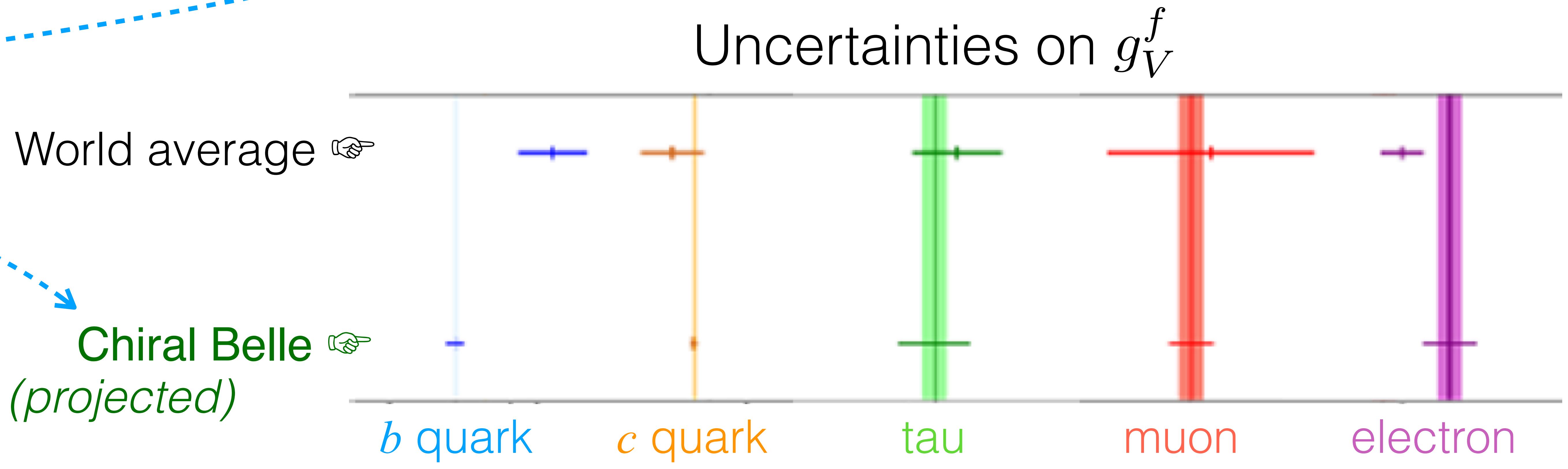
✓ Polarized electrons (70%)

- Transverse polarization at injection
- Rotate to longitudinal at interaction point
- Compton polarimeter for 0.5% precision

✓ with polarized electrons …

- sensitivity to EW neutral vector current
- sensitivity to light Z_{dark} via $\sin^2\theta_W$
- left-right asymmetries with 5 fermions
- tau g–2: sensitivity of $\mathcal{O}(10^{-5})$ w/50 ab^{-1}
- background suppression in $\tau \to \ell\,\gamma$ using helicity distributions





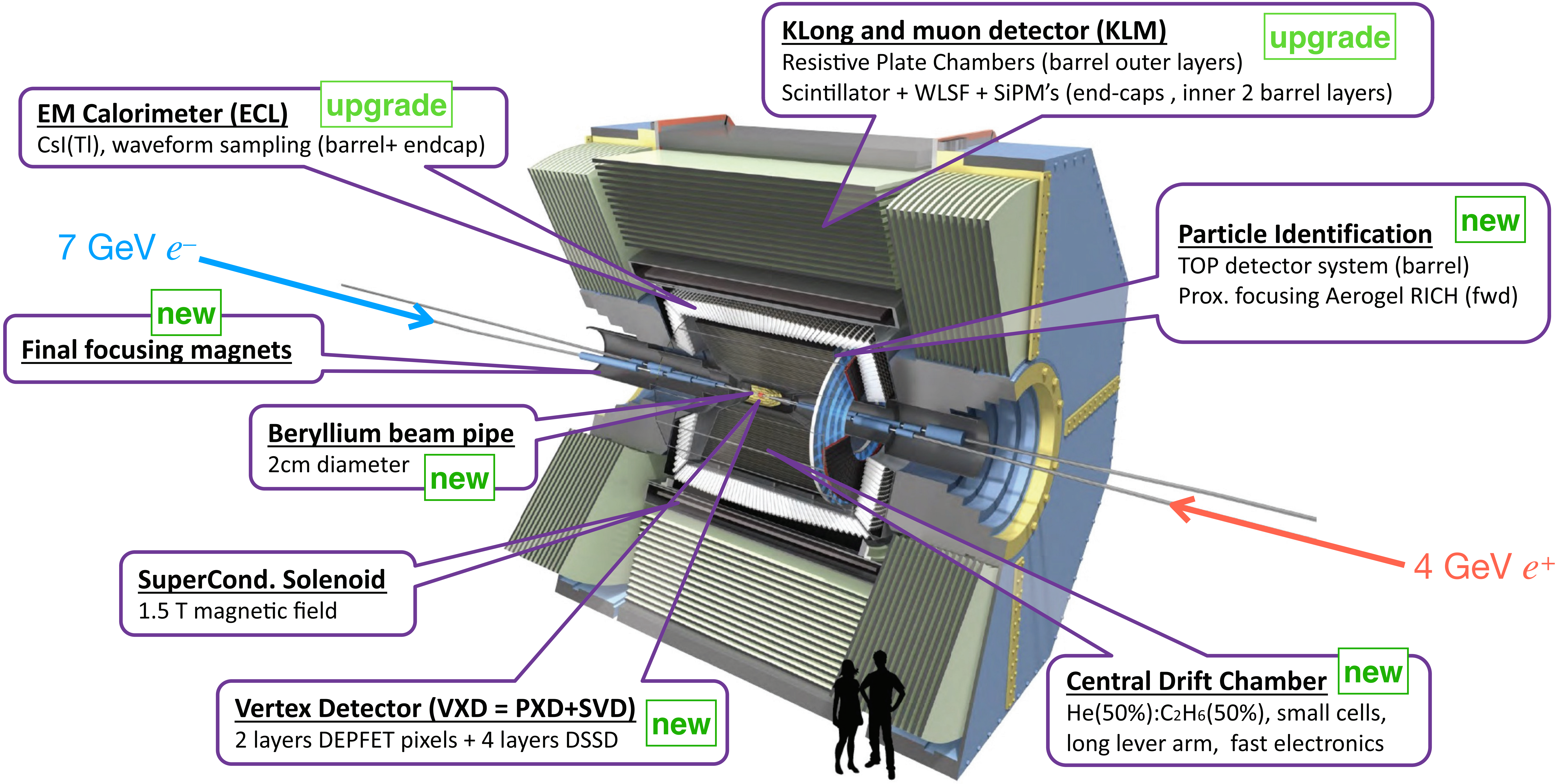
Summary and outlook

courtesy F. Forti

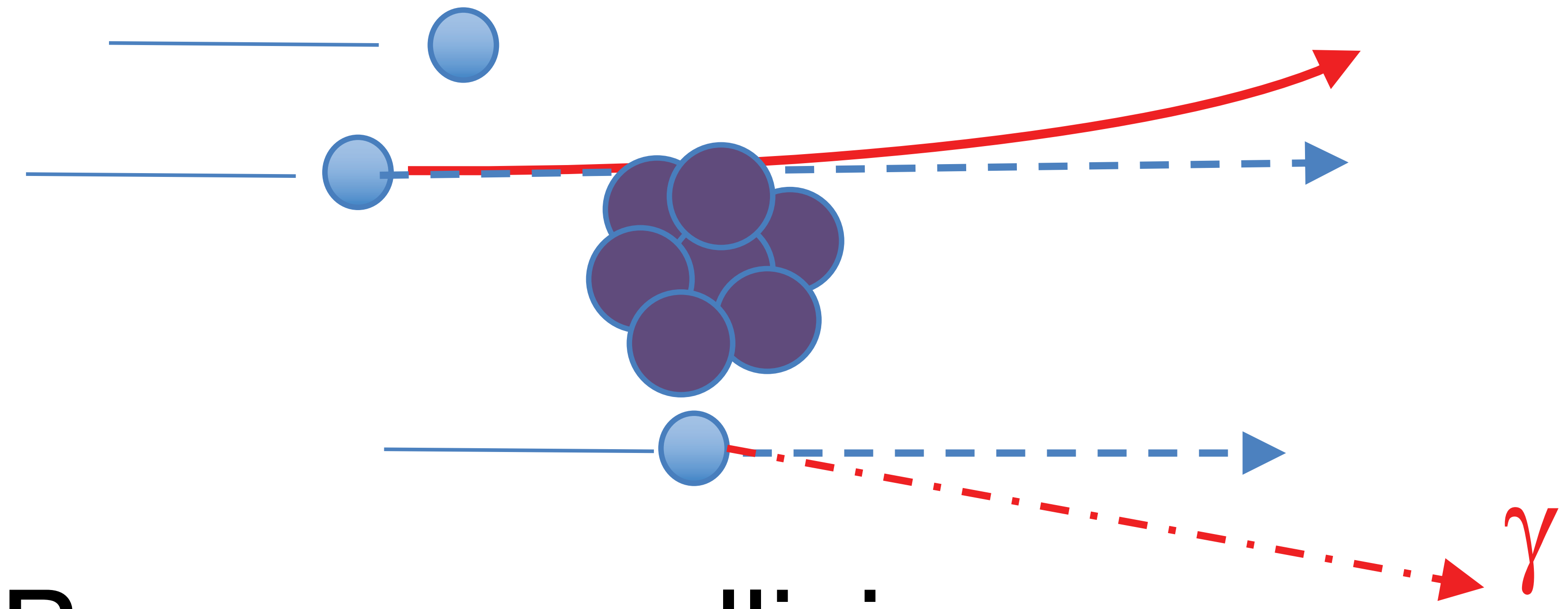
- ✓ Belle II and SuperKEKB have started a successful physics run
- ✓ Accelerator improvements are being studied and implemented to reach target luminosity
- ✓ Detector upgrade ideas are being explored and R&D is in progress for
  - more robustness against backgrounds and radiation damage
  - better physics performance
  - readiness for accelerator's redesign of interaction region
- ✓ The Belle II upgrade organization is in place
  - Upgrade Working Group and Upgrade Advisory Committee are directing the effort and establishing priorities
  - Conceptual Design Report is in preparation
- ✓ Longer term upgrade perspectives past LS2 … toward 250 ab^{-1}
  - start planning for even higher peak luminosity
  - evolved detector that can operate at extreme luminosity

Backup

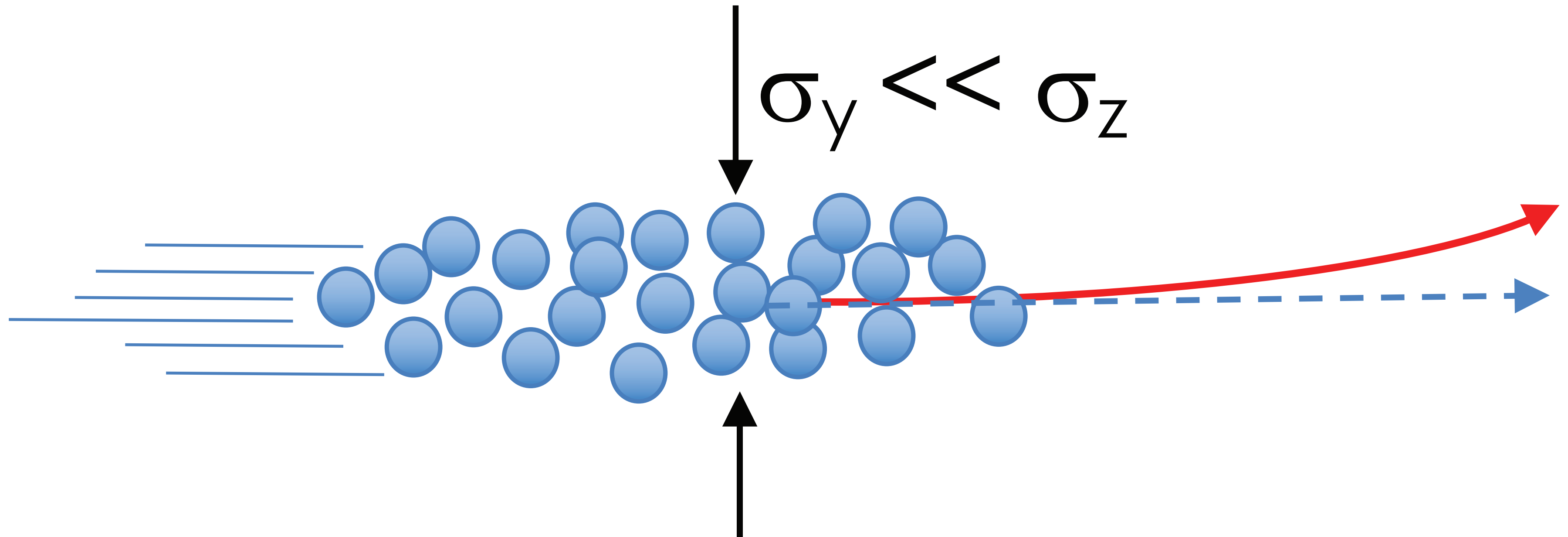
Belle II *vs* first-generation Belle detector



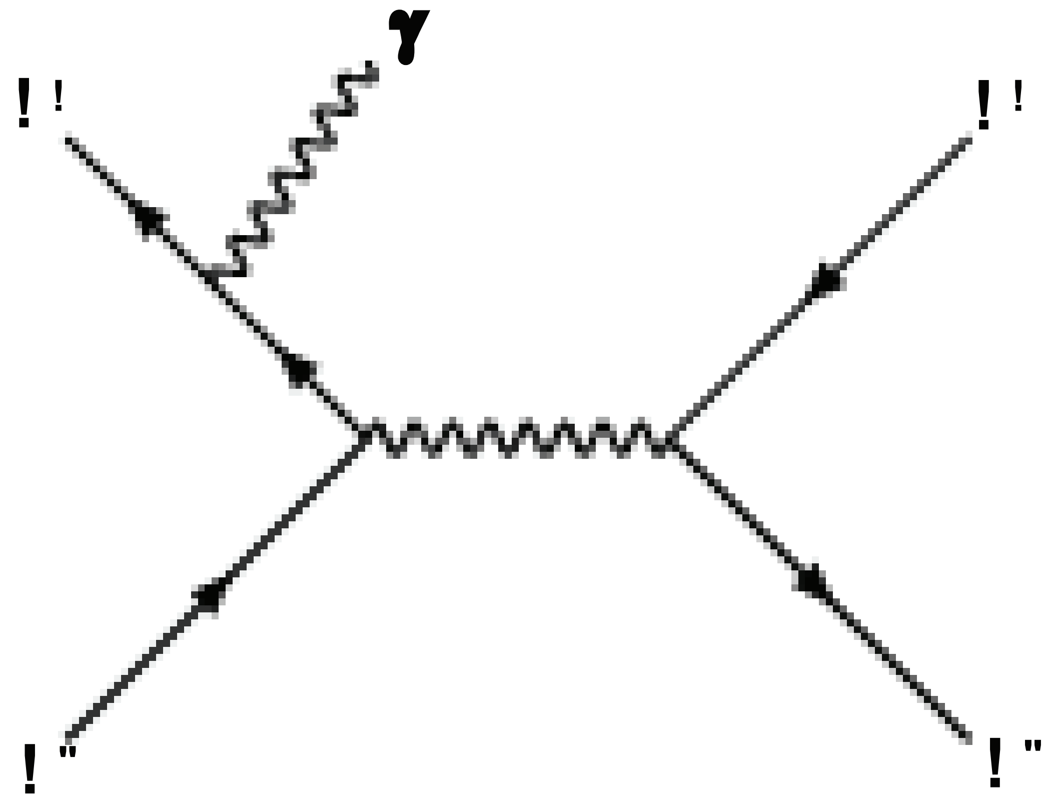
Backgrounds must be managed for optimal physics extraction



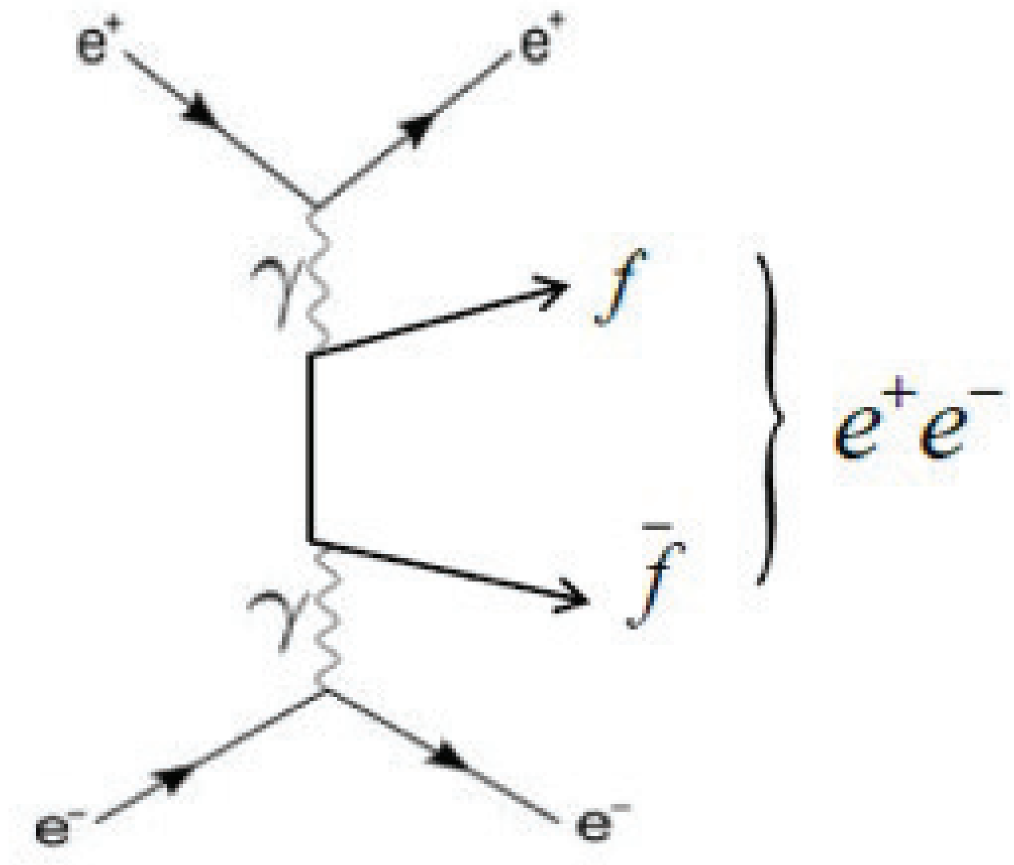
Beam-gas collisions



Touschek scattering



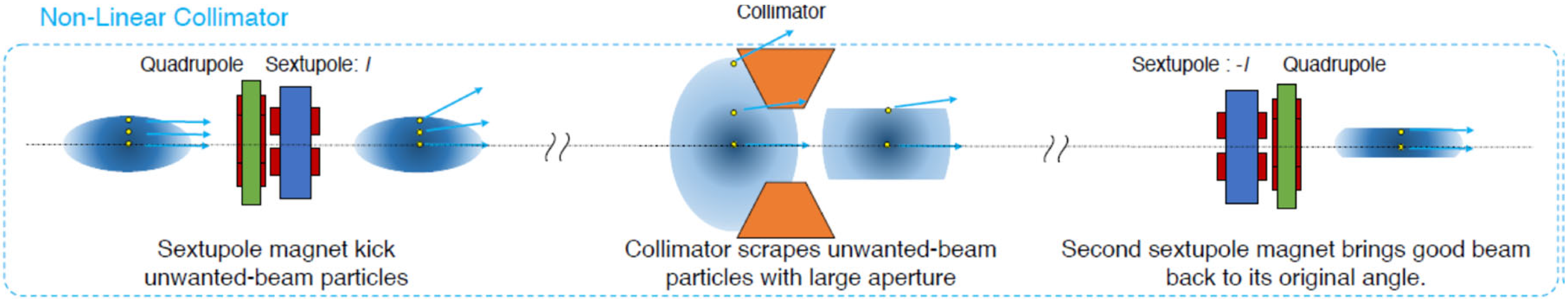
Radiative Bhabha scattering



Two-photon processes

… + neutrons from stray beam particles striking beam-pipe structures

Non-linear collimator + sextupoles remove stray beam particles



Detector upgrades and time scale

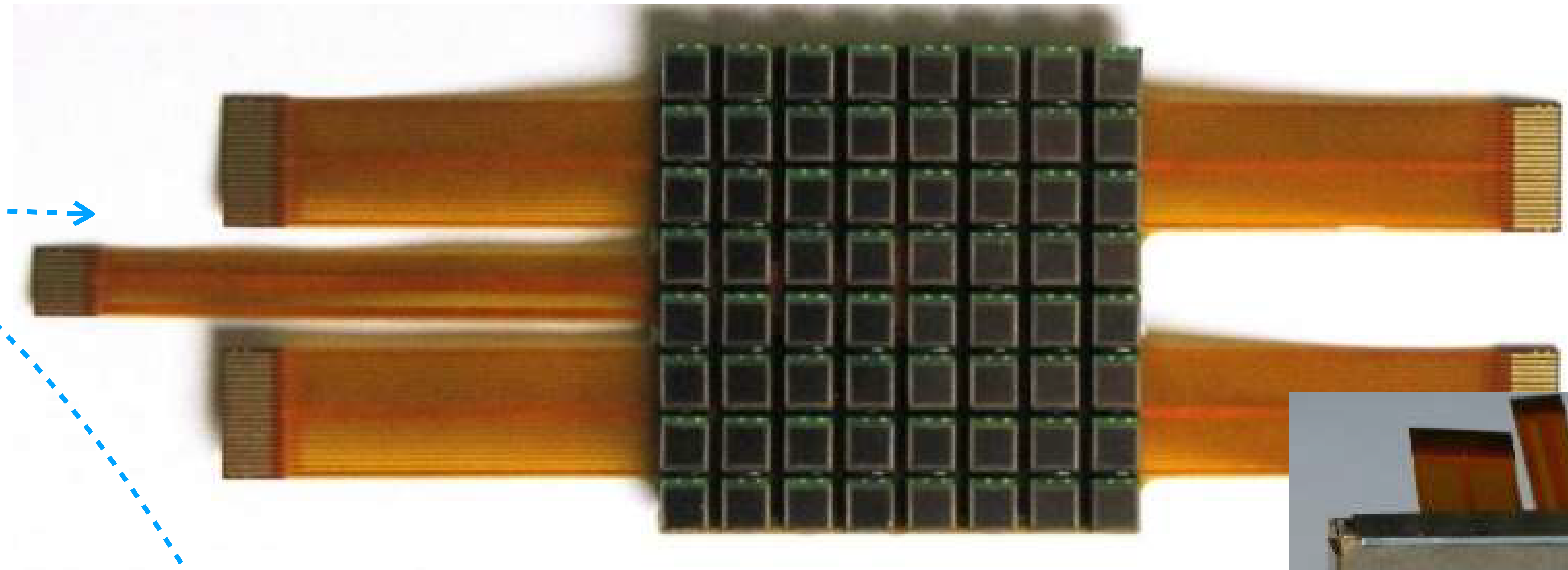
see Snowmass white paper (arXiv 2203.11349)

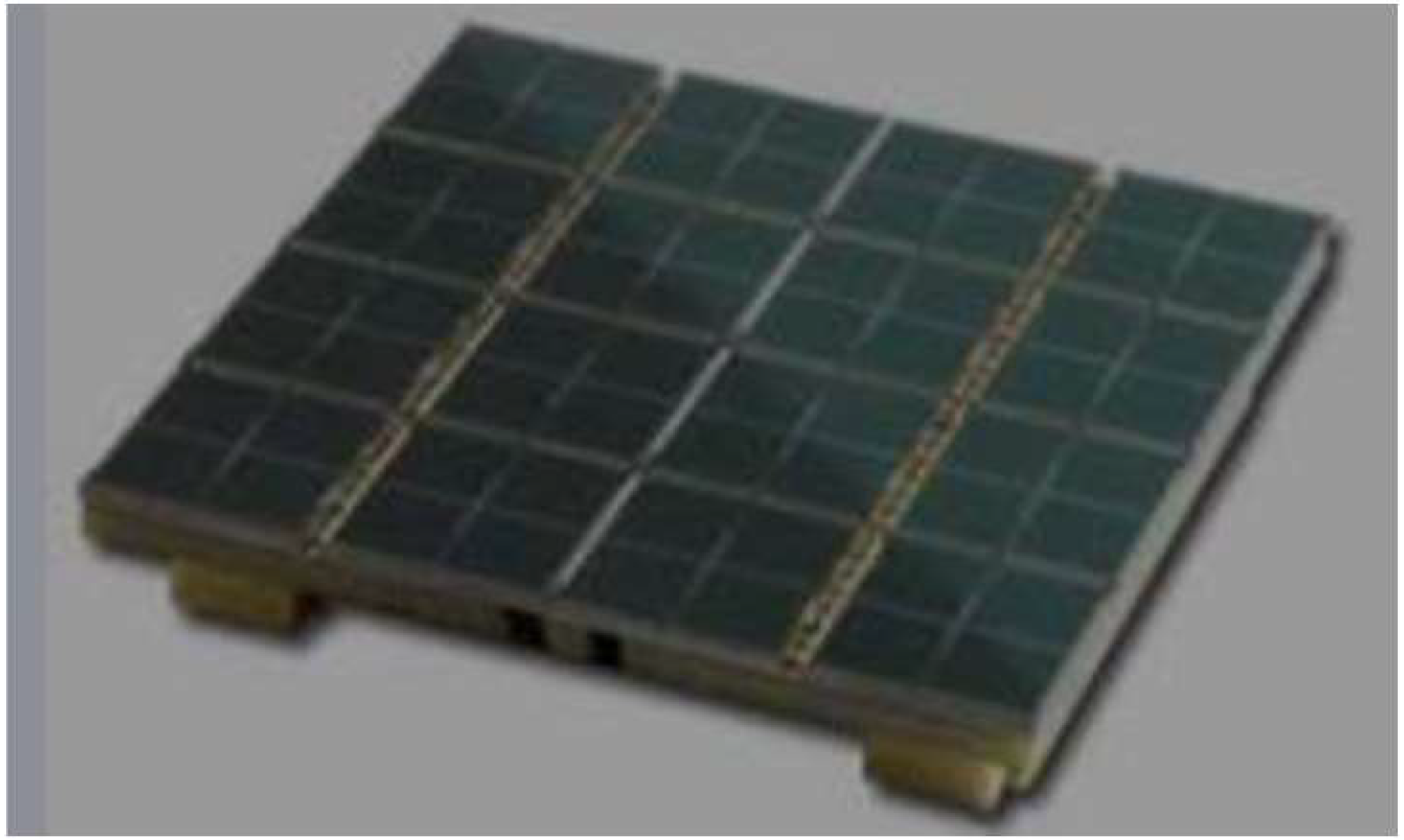
	Subdetector	Function	upgrade idea	time scale
Silicon Pixel Detector	PXD	Vertex Detector	2 layer installation	short-term
			new DEPFET	medium-term
Silicon Strip Detector	SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
	PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
			all-pixels: DMAPS CMOS sensors	medium-term
Central Drift Chamber	CDC	Tracking	upgrade front end electronics	short/medium-term
			replace inner part with silicon	medium/long term
			replace with TPC w/ MPGD readout	long-term
Time of Propagation Counter	TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
			Replace not-life-extended ALD MCP-PMTs	medium-term
			STOPGAP TOF and timing detector	long-term
Aerogel Ring-Imaging Cerenkov Counter	ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
			replace HAPD with Large Area Picosecond Photodetectors	long-term
Electromagnetic Calorimeter	ECL	γ, e ID	add pre-shower detector in front of ECL	long-term
			Replace ECL PiN diodes with APDs	long-term
			Replace CsI(Tl) with pure CsI crystals	long-term
K-long and Muon Detector	KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
			on-detector upgraded scintillator readout	medium/long-term
			timing upgrade for K-long momentum measurement	medium/long-term
Level 1 Hardware Trigger	Trigger		firmware improvements	continuous
Data Acquisition System + Software High-Level Trigger	DAQ		PCIe40 readout upgrade	ongoing
			add 1300-1900 cores to HLT	short/medium-term

Aerogel Ring-Imaging Cerenkov Counter upgrades

✓ **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





Electromagnetic Calorimeter upgrades

✓ **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