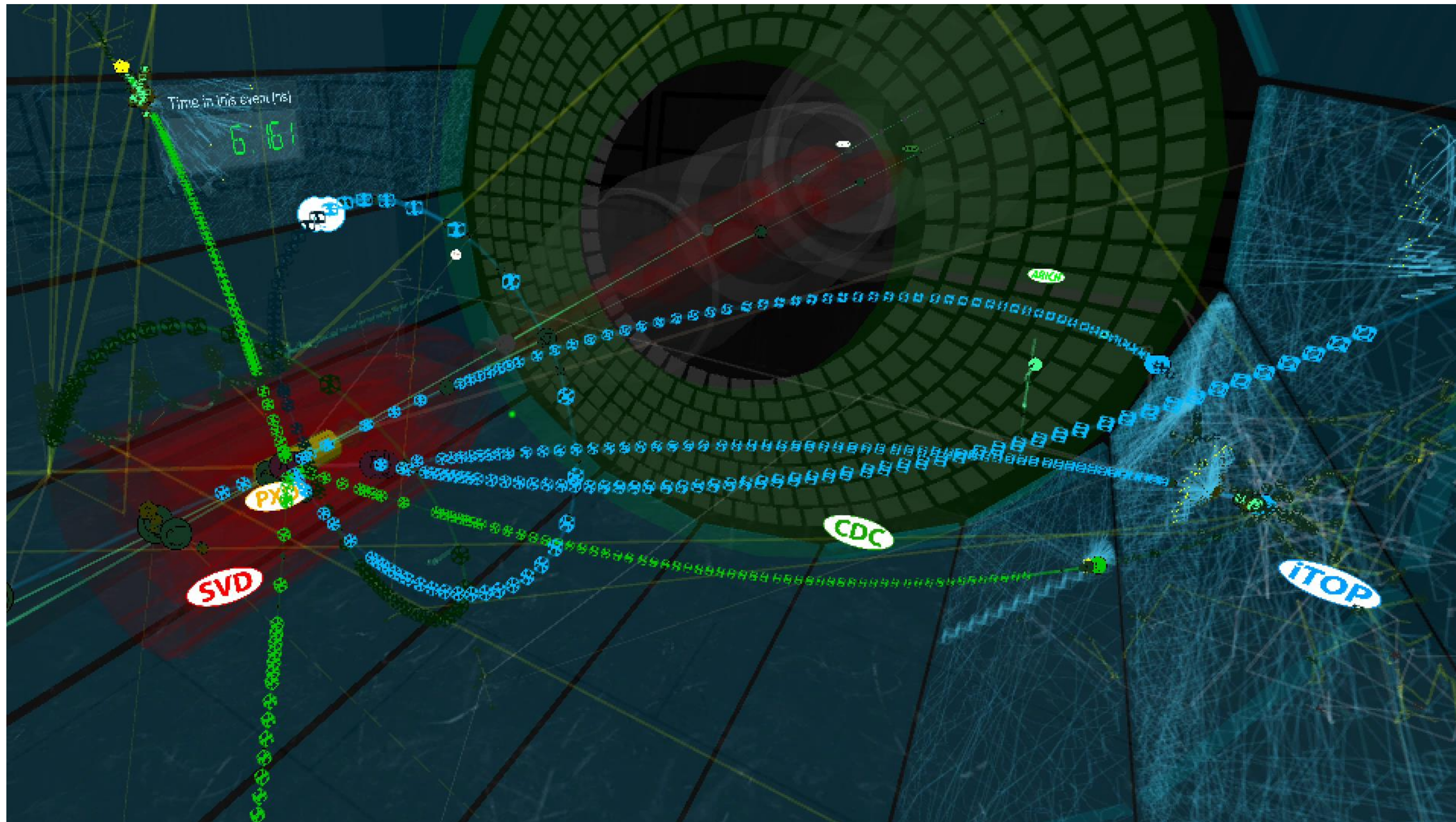


# The Belle II Upgrade Program

Leo Piilonen, Virginia Tech  
on behalf of the Belle II Collaboration

31st Lepton-Photon Symposium      Melbourne Australia      July 2023



This work supported by

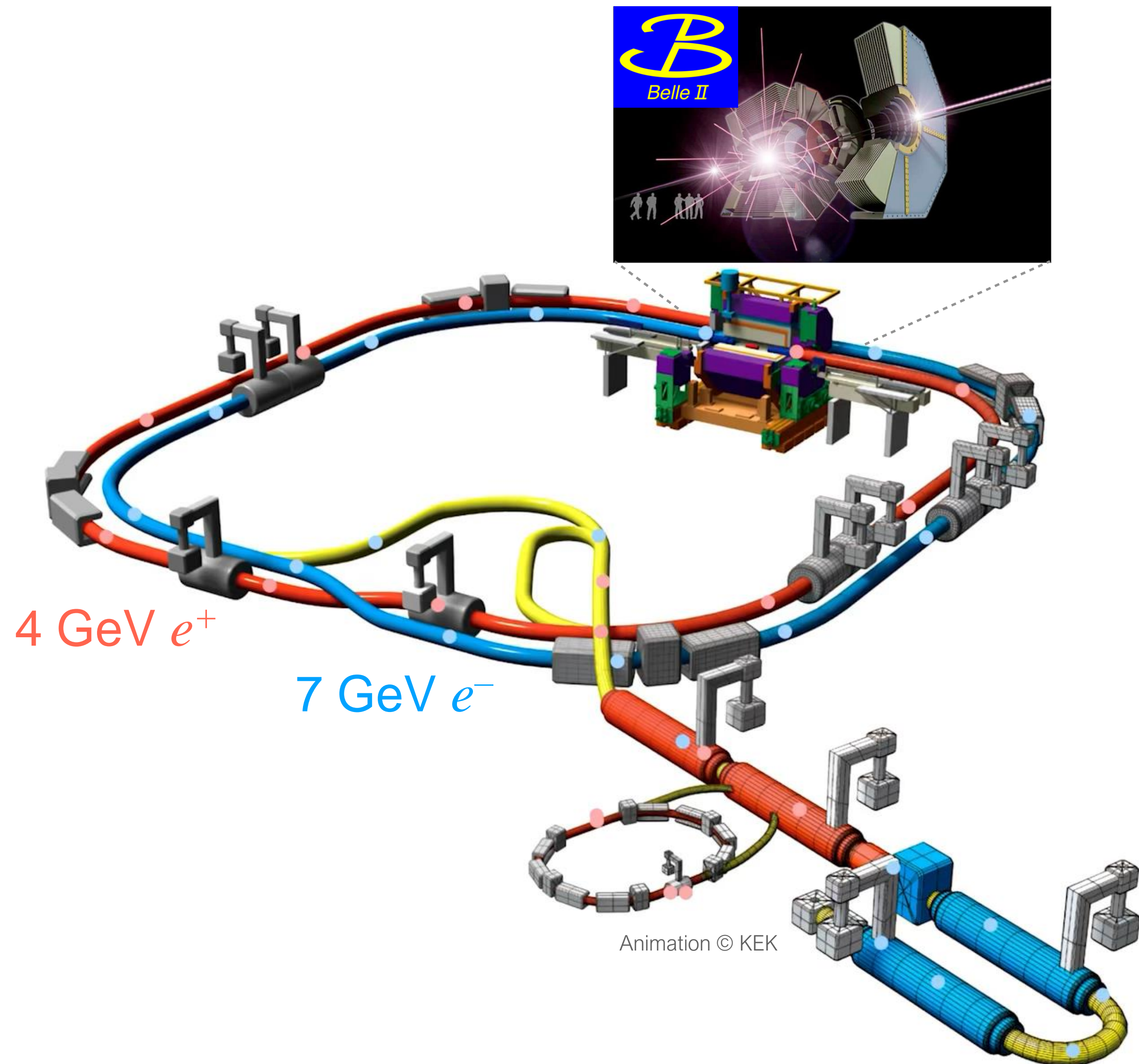


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# SuperKEKB and Belle II: 2<sup>nd</sup> generation *B* Factory



- ✓ 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  $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - path to reach  $2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$  identified
  - long march to reach target of  $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$



# 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 $2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

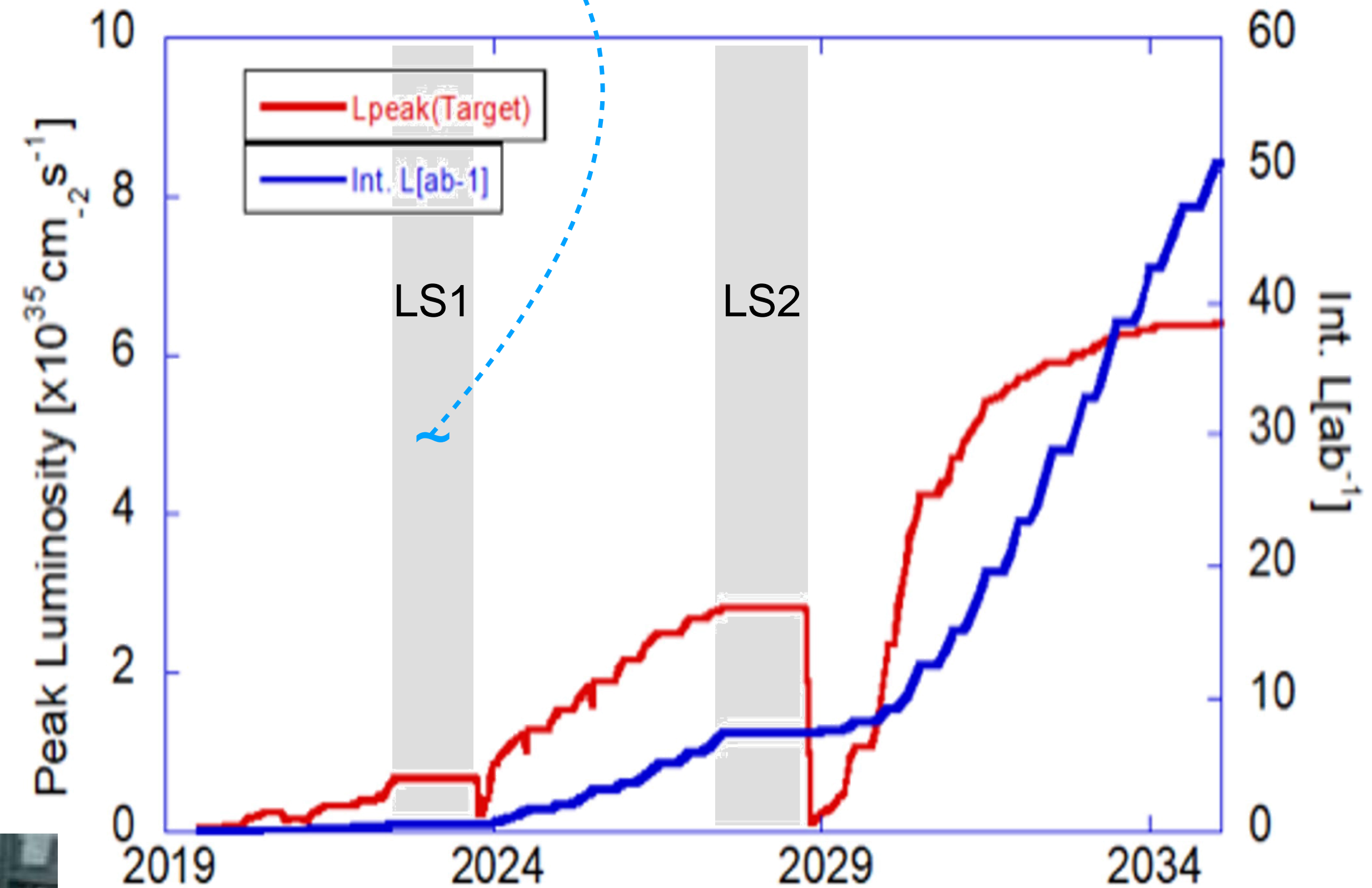
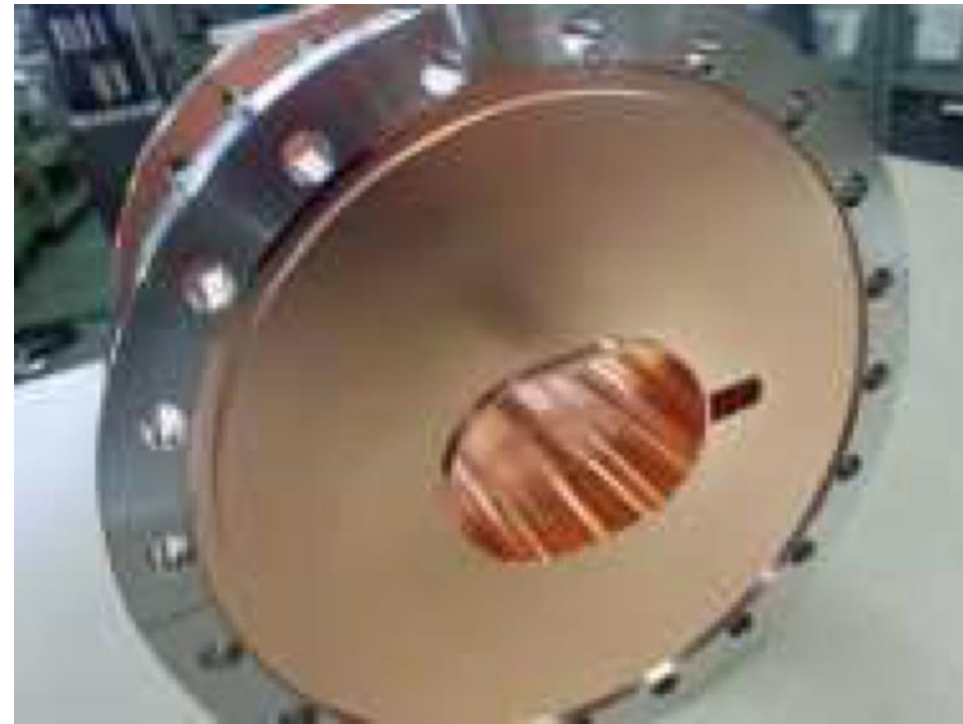
- ✓ Consolidate and address accelerator limitations:
  - international task force at work to assist
  - many countermeasures deployed
  - more countermeasures in development
- ✓ Consolidate and address detector limitations:
  - complete the installation of full pixel detector
  - complete the installation of more robust time-of-propagation photomultiplier tubes

## Improvements toward $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- ✓ 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

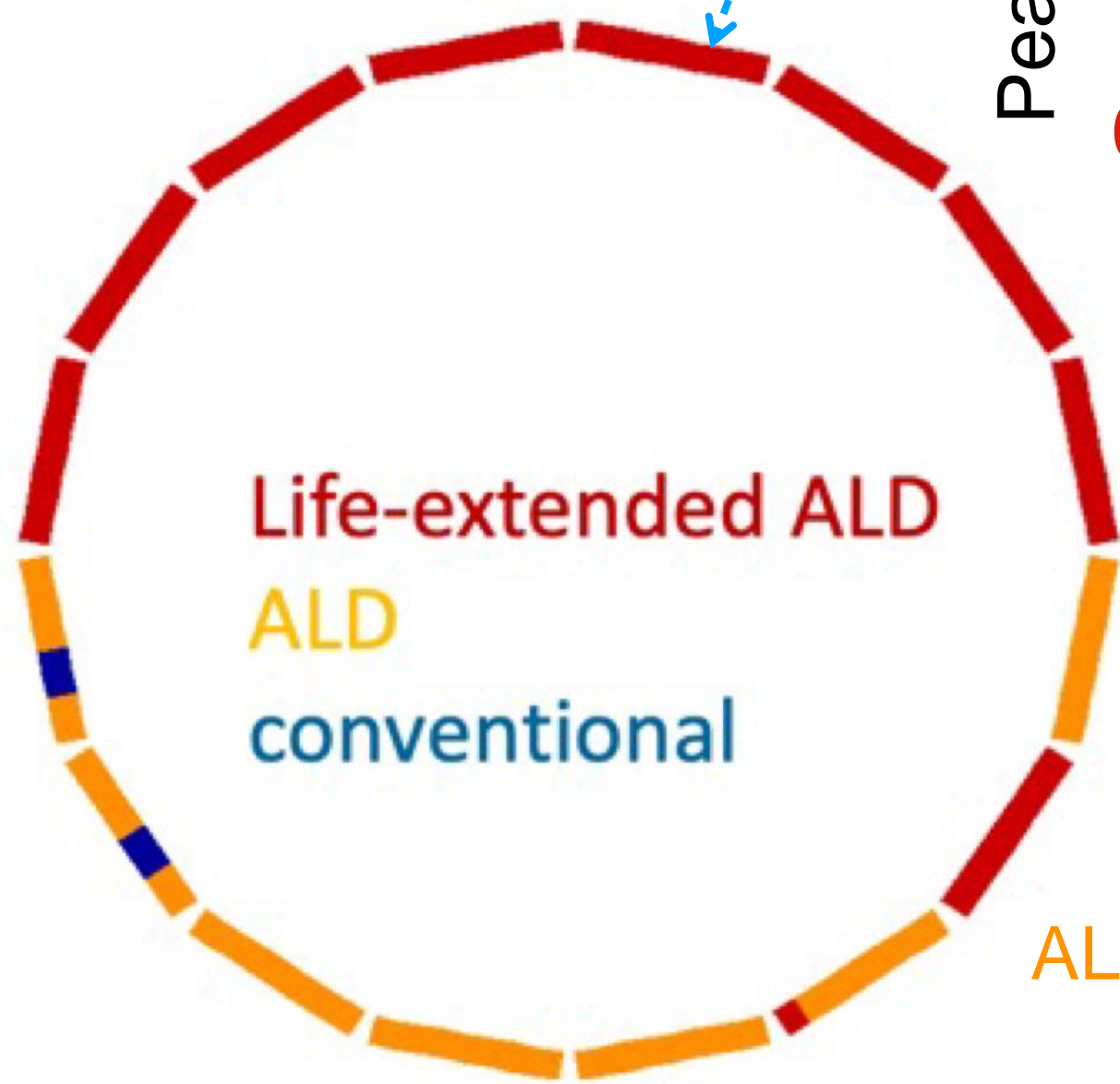
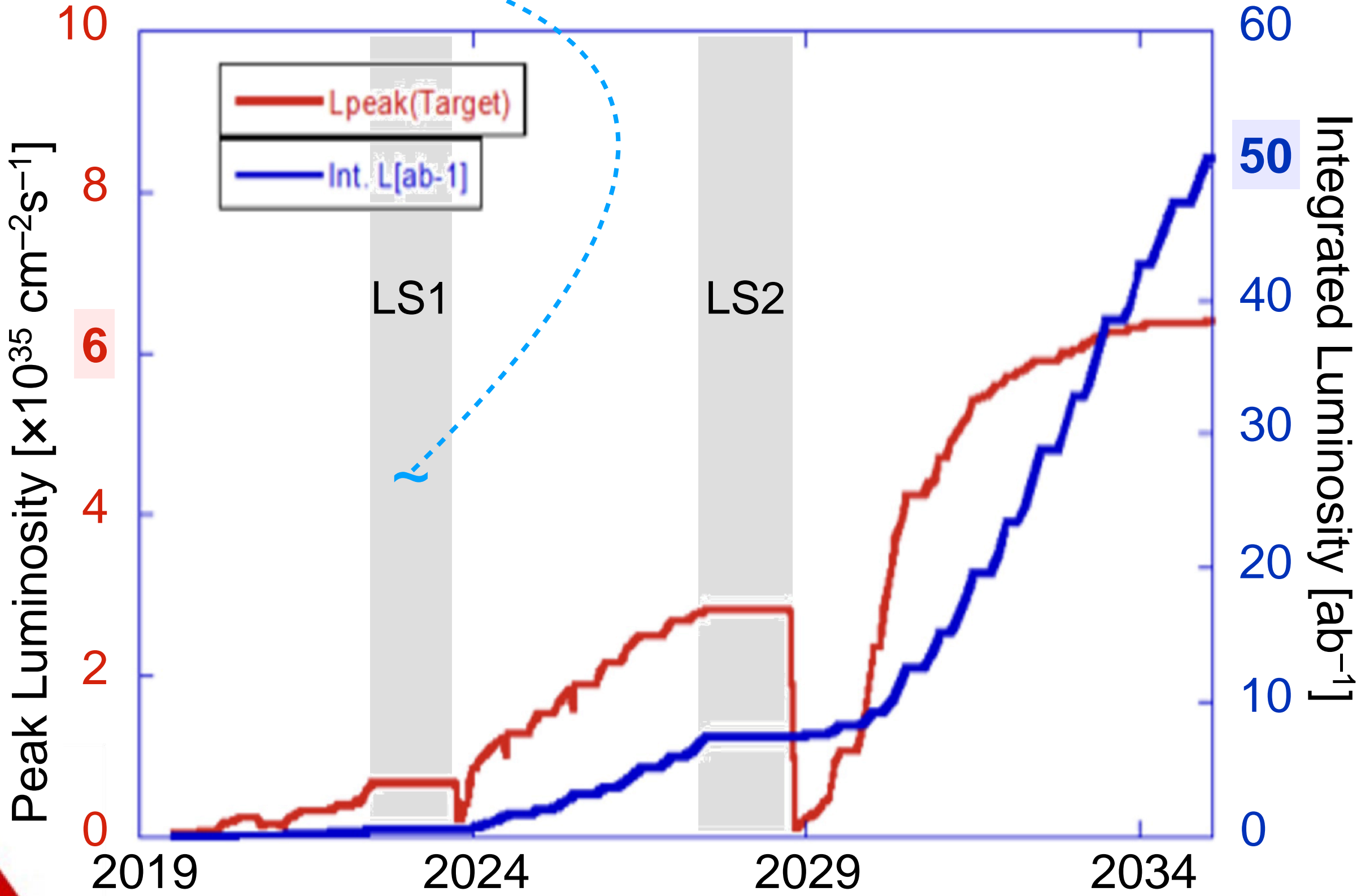
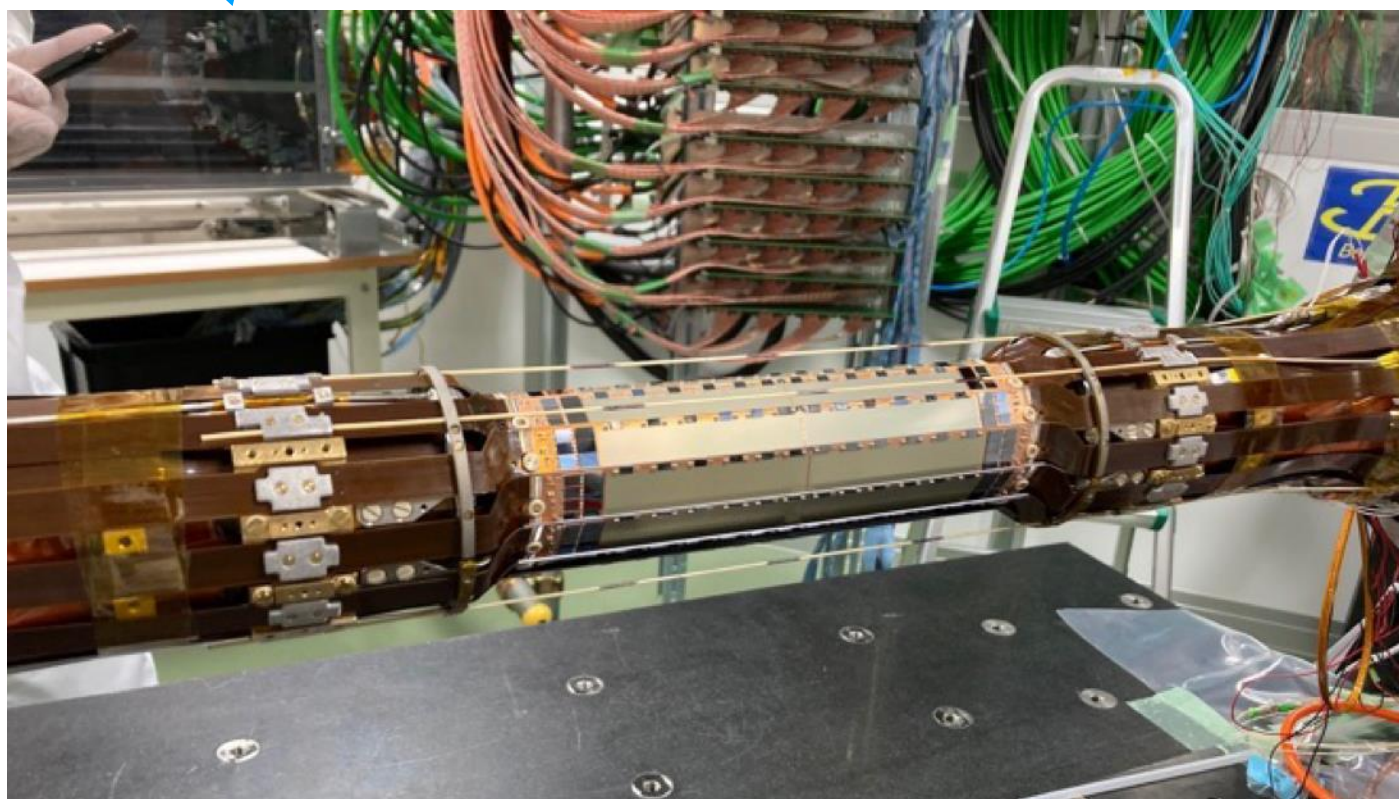
- countermeasures against sudden beam loss
- additional shielding around final-focus magnets and endcaps against beamline neutrons
- more resilient collimators (harder material)
- non-linear collimator to reduce beam halo
- RF cavity replacement for stability, higher currents
- at injector: faster kicker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

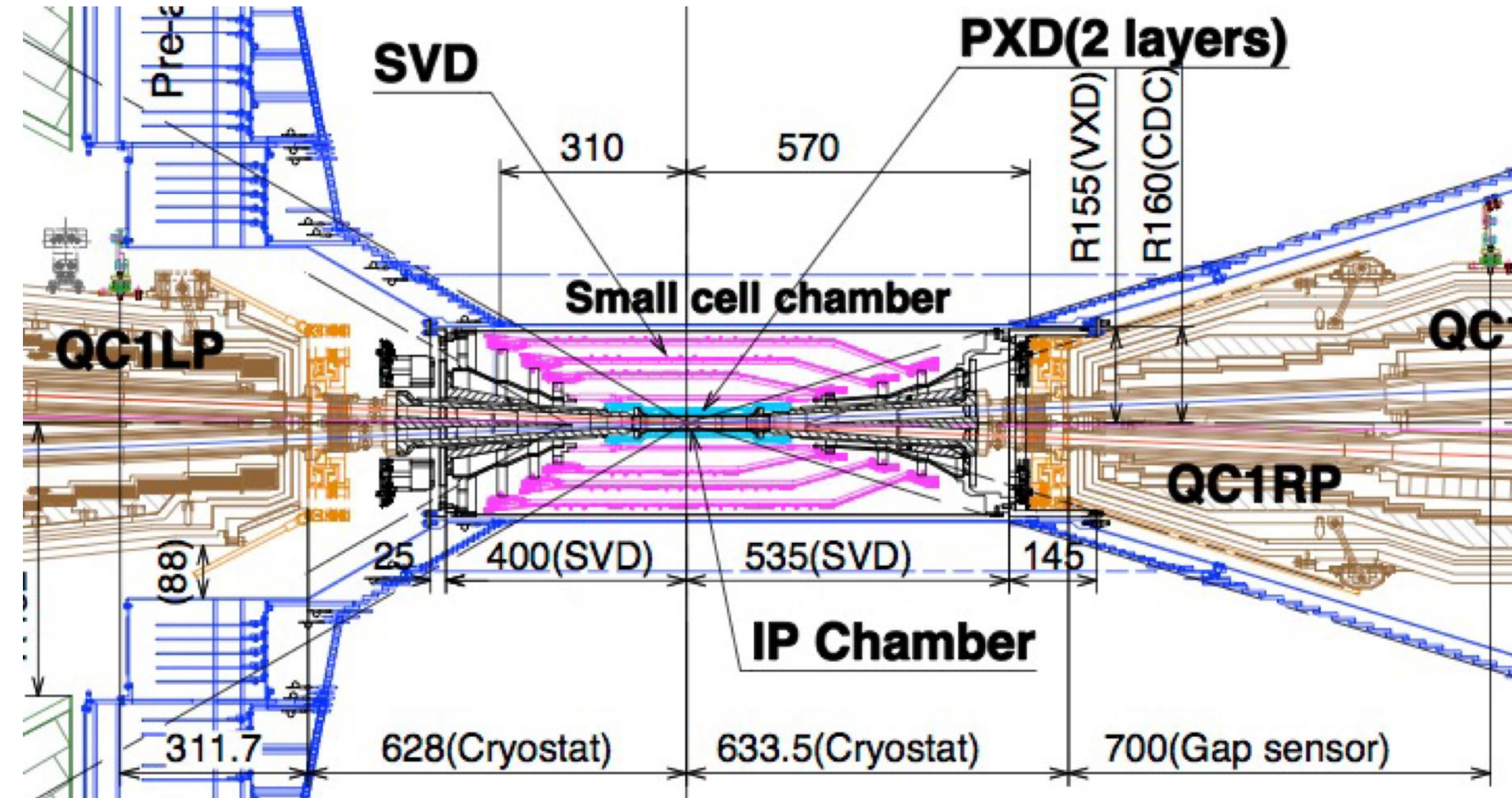


# Accelerator upgrades during Long Shutdown 2: ~2028-2029

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

## ✓ **goal:** higher $\mathcal{L}$ with lower $\beta^*$ 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  $250 \text{ ab}^{-1}$



# Detector upgrades during LS2 or beyond

See Snowmass white papers:

[arXiv:2203.11349](https://arxiv.org/abs/2203.11349) for detector upgrade

[arXiv:2207.06307](https://arxiv.org/abs/2207.06307) for physics reach

[arXiv:2203.05731](https://arxiv.org/abs/2203.05731) for backgrounds

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

**IR:** accommodate QCS replacement and repositioning

**VXD:** all pixels

- DMAPS
- SOI-DuTiP

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

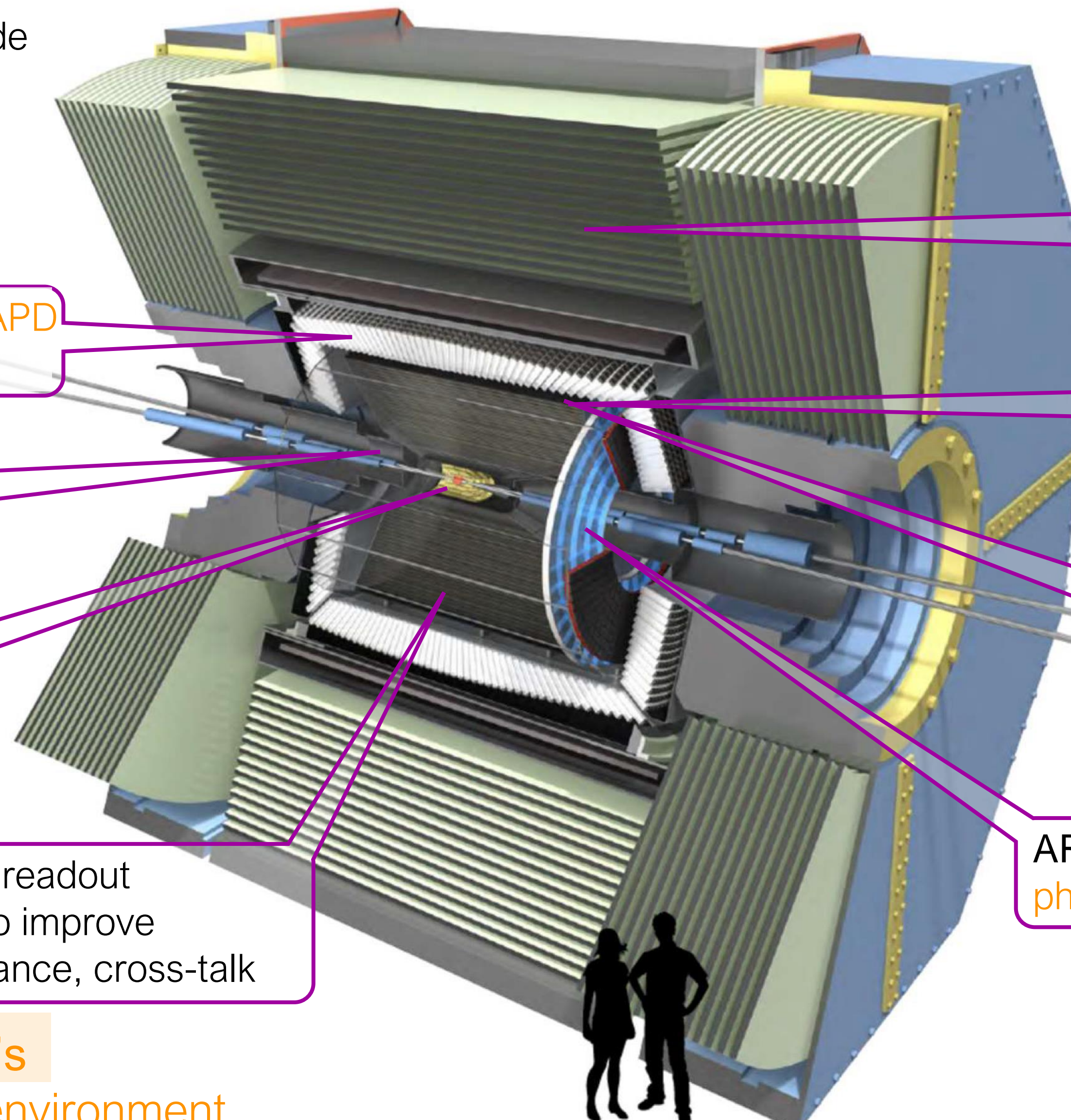
**KLM:** replace RPCs with scintillators in barrel (some with fast timing for  $K_L$  time-of-flight); replace readout

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

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

**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

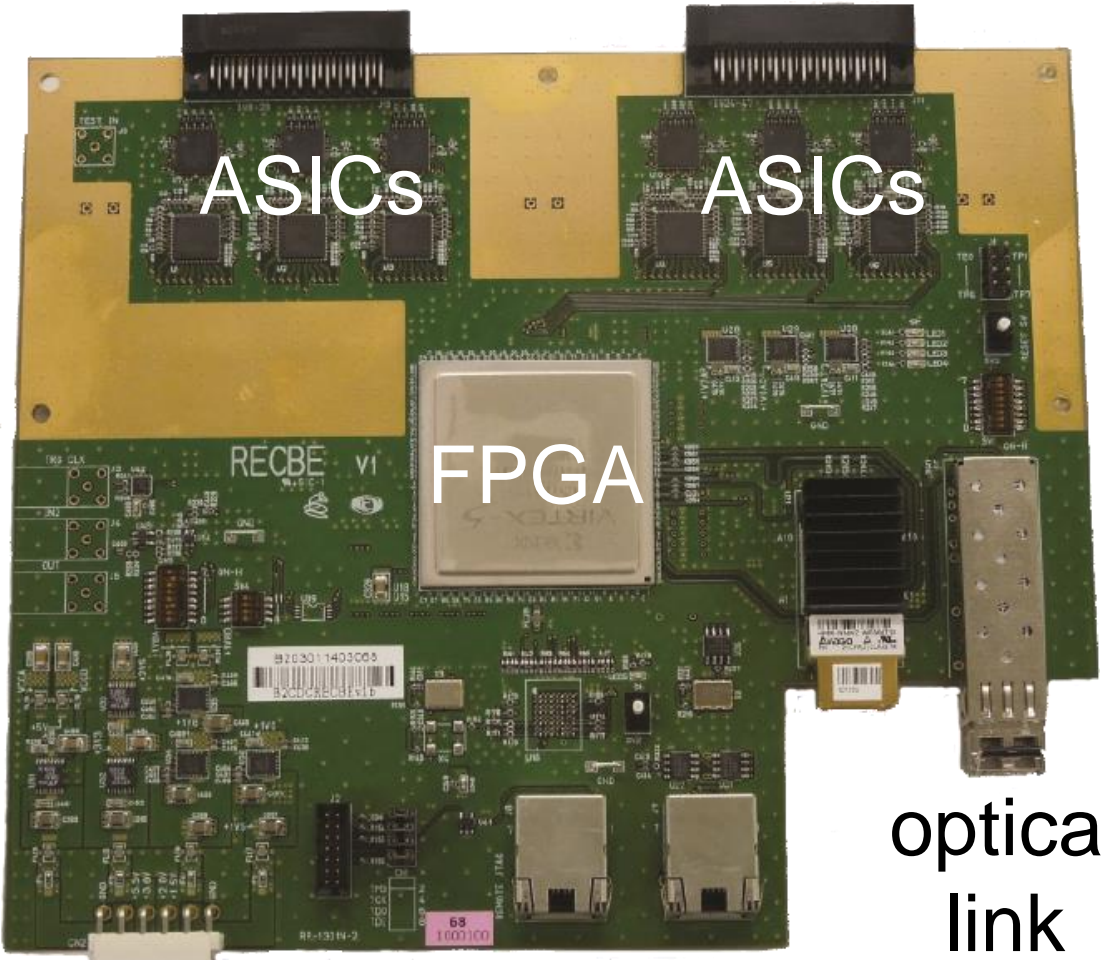
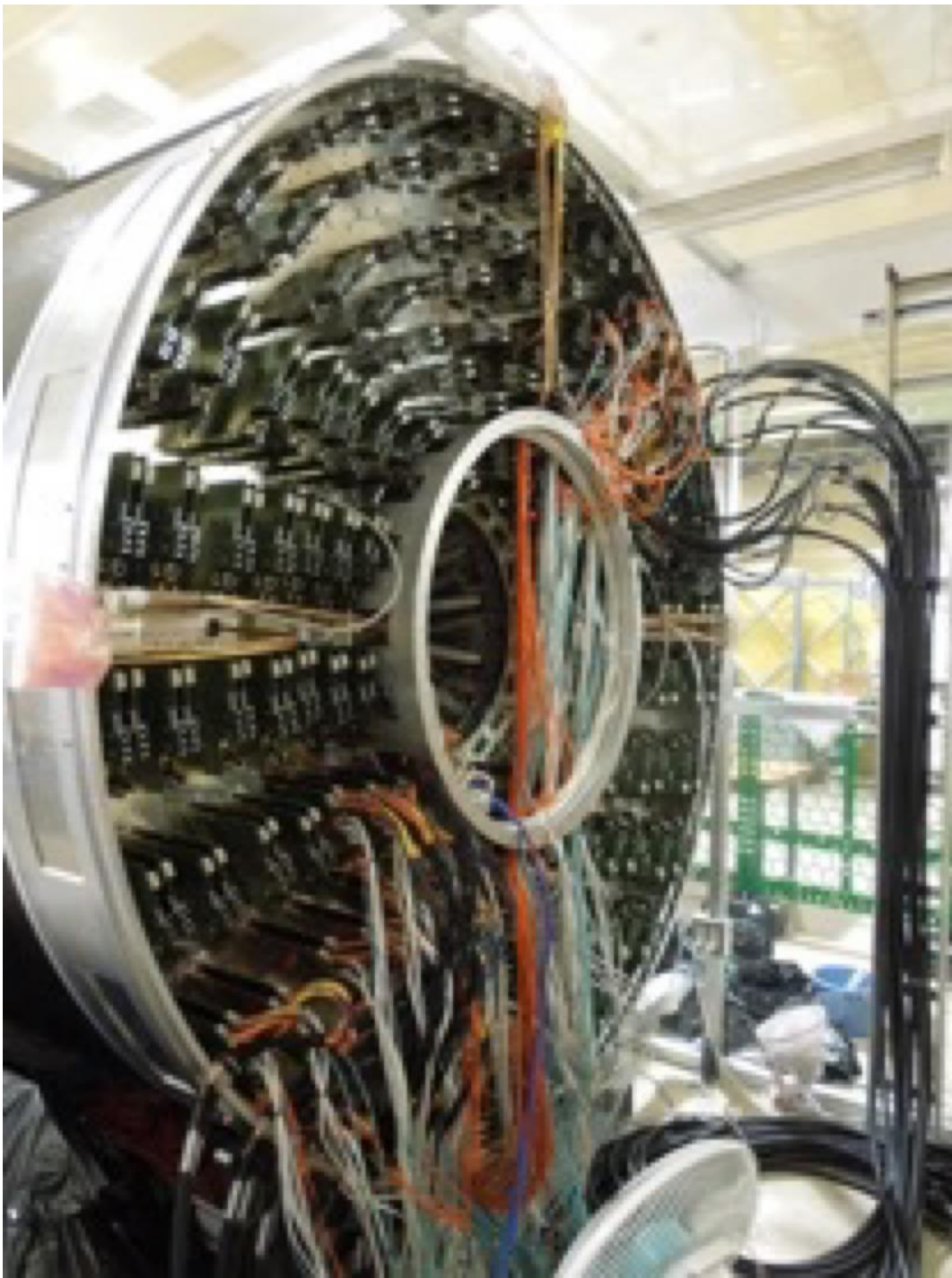
the present board	upgrade
separated chips, ASD and FADC	functions of ASD and FADC are in one chip. ~60% reduction is expected in ASD+FADC
~100mV pulse height induced in neighbor ch with 7pC input	~10mV pulse height induced in neighbor ch with 7pC input + double thresholds
Virtex-5	Kintex-7
SFP for DAQ (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

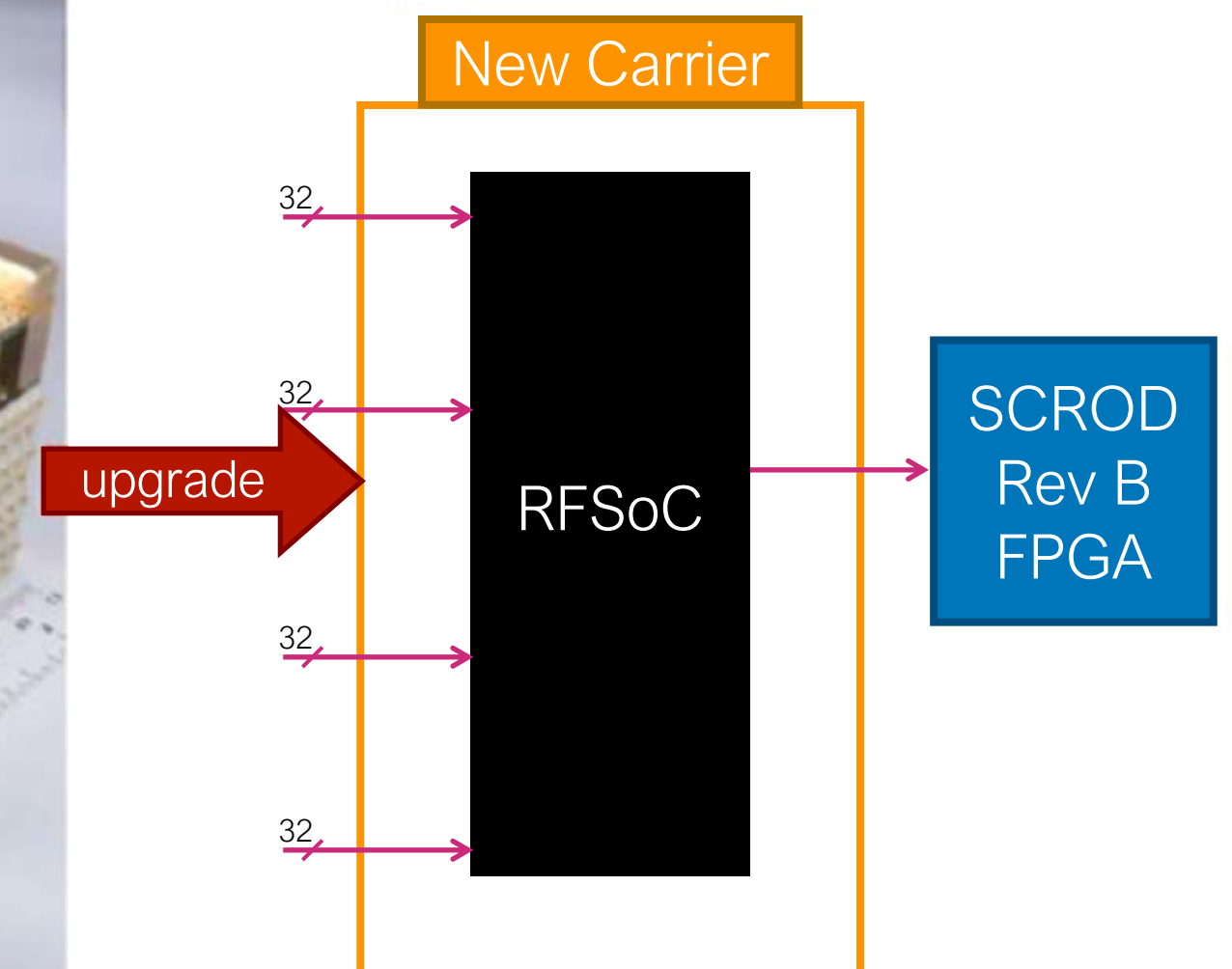
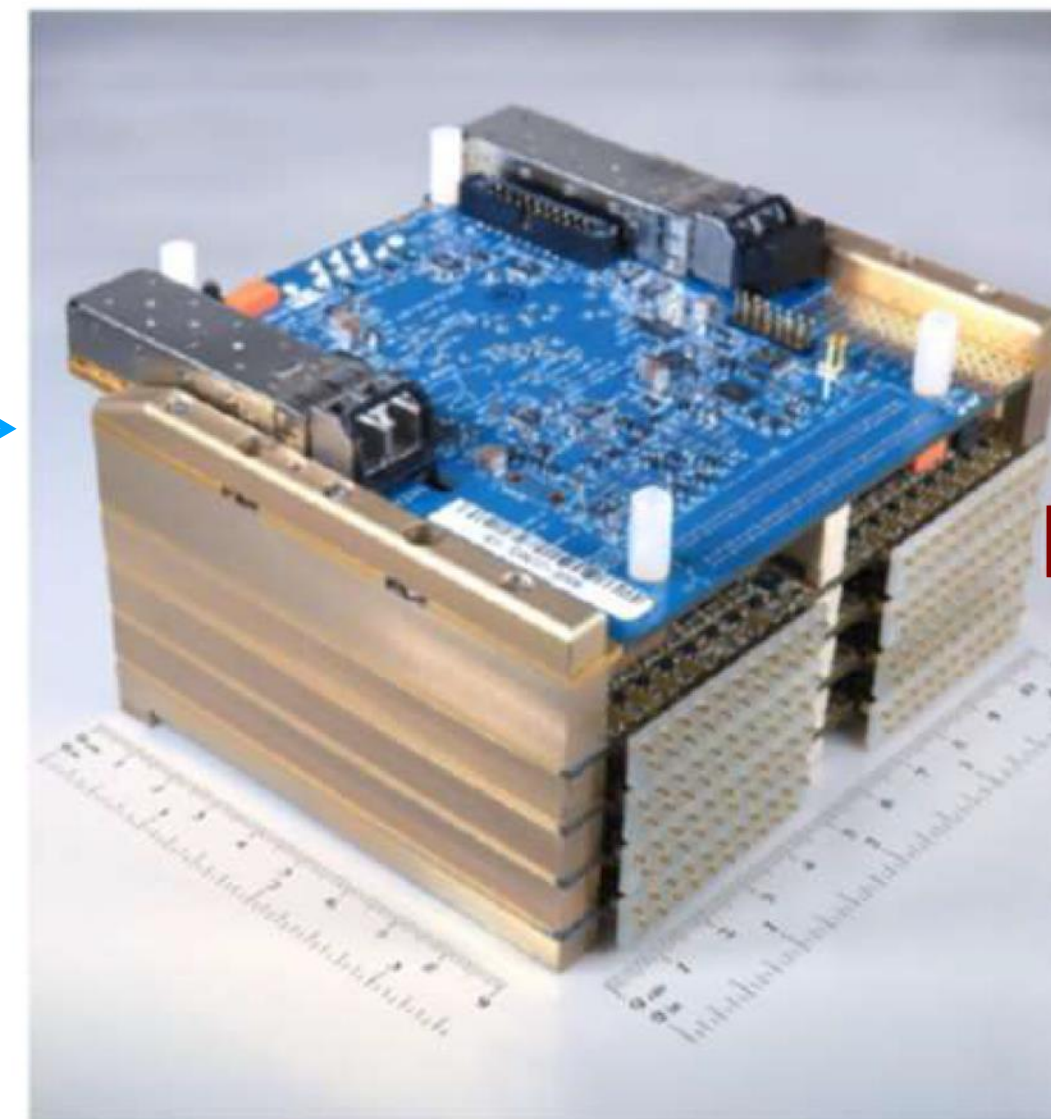
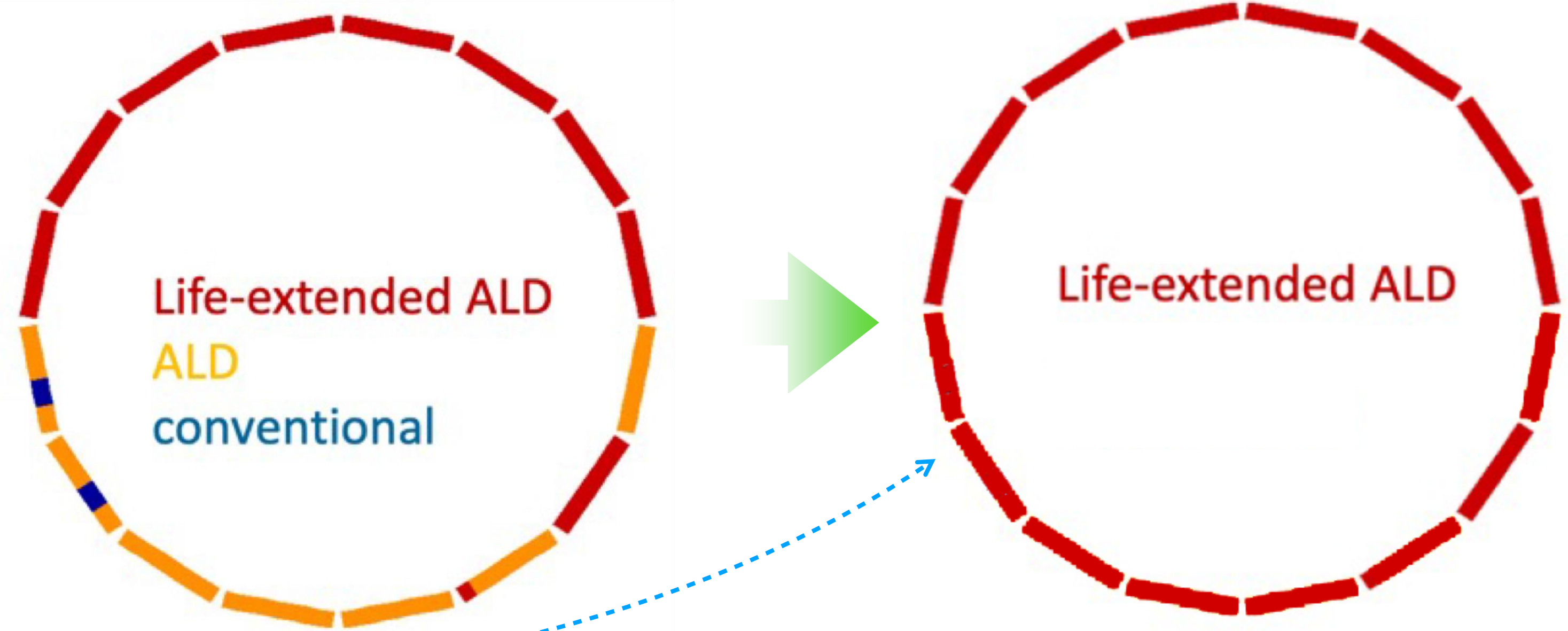
- ⦿ better particle-ID performance
- ⦿ feature extraction inside ASIC
- ⦿ reduced power consumption

## ✓ 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

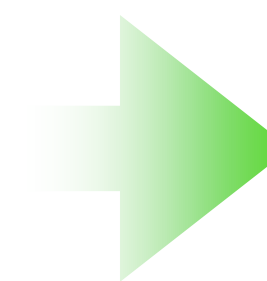
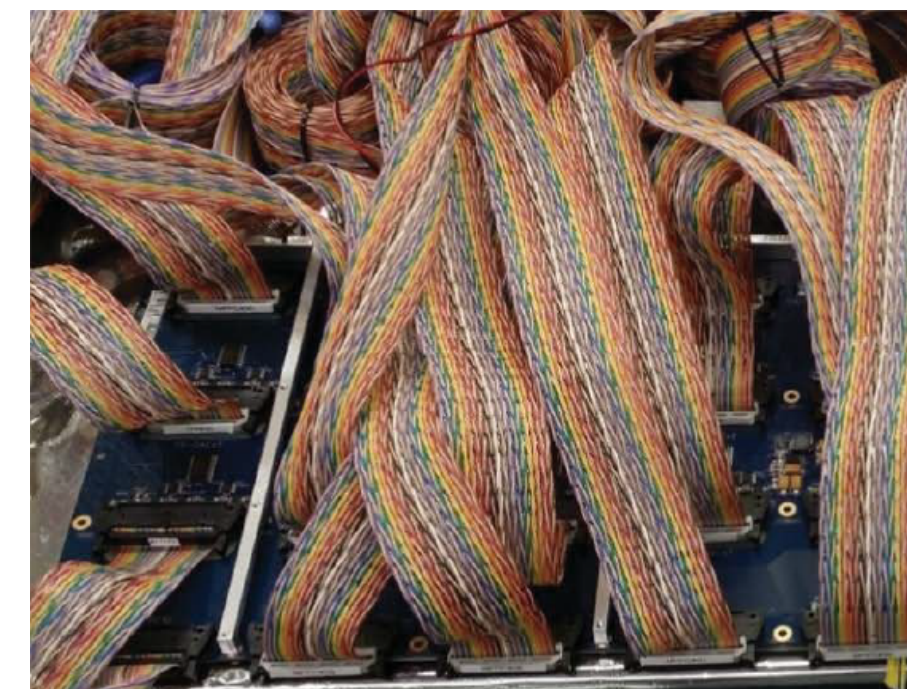
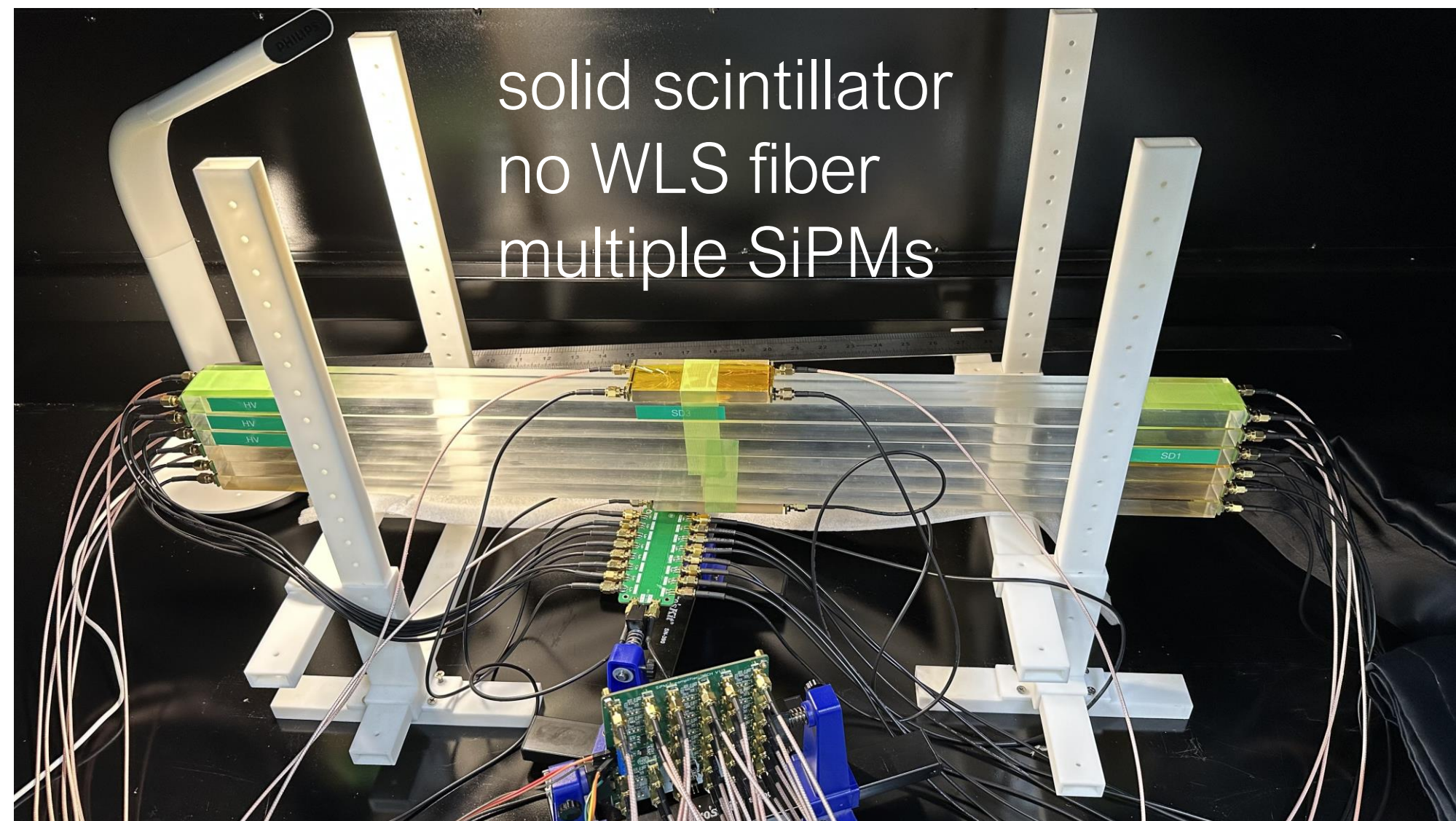
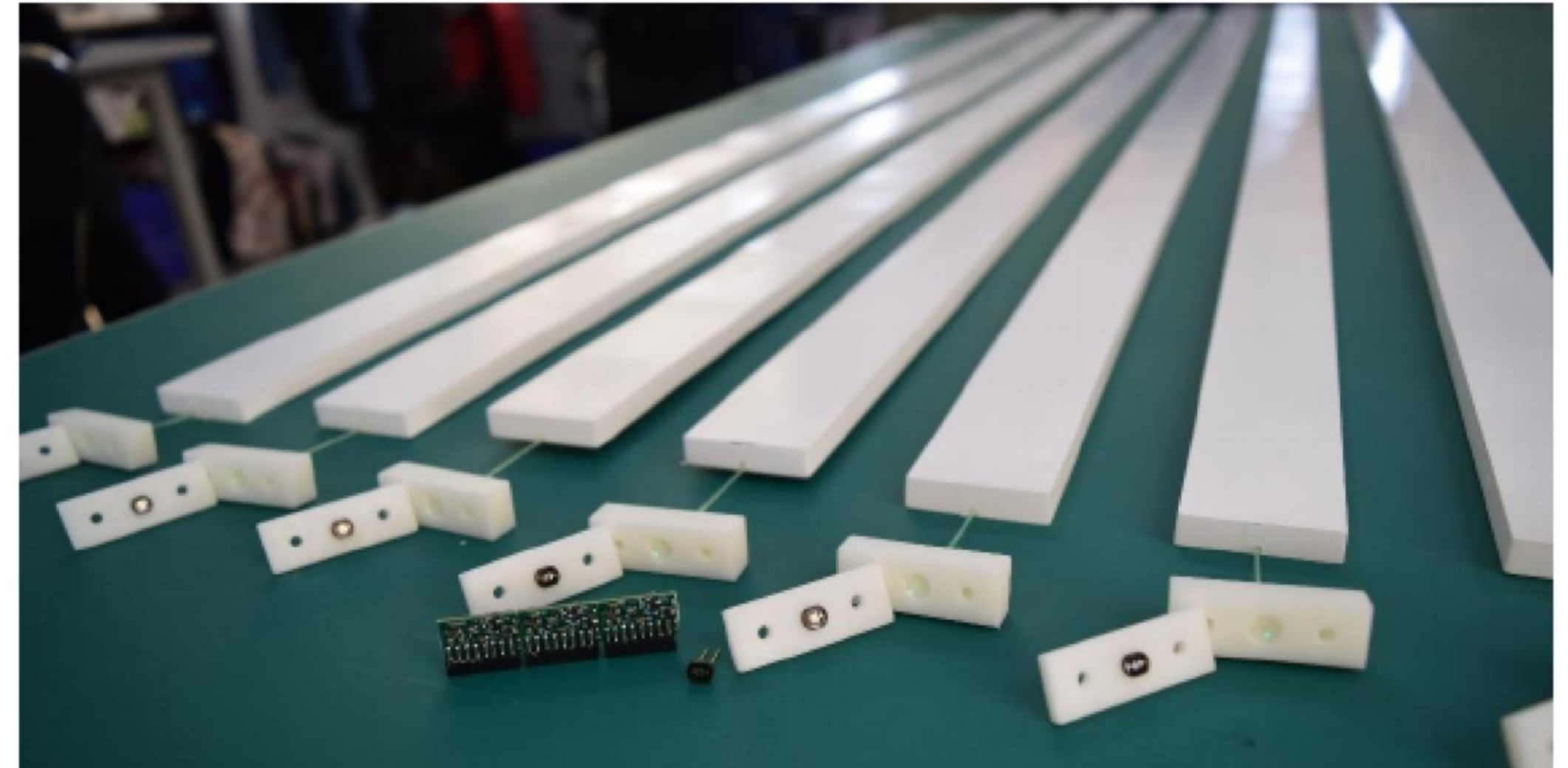




# K-long & Muon Detector upgrades

## ✓ 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



2x CAT-7  
Fiber optic  
48V Power



# Future vertex detector design options

## ✓ requirements

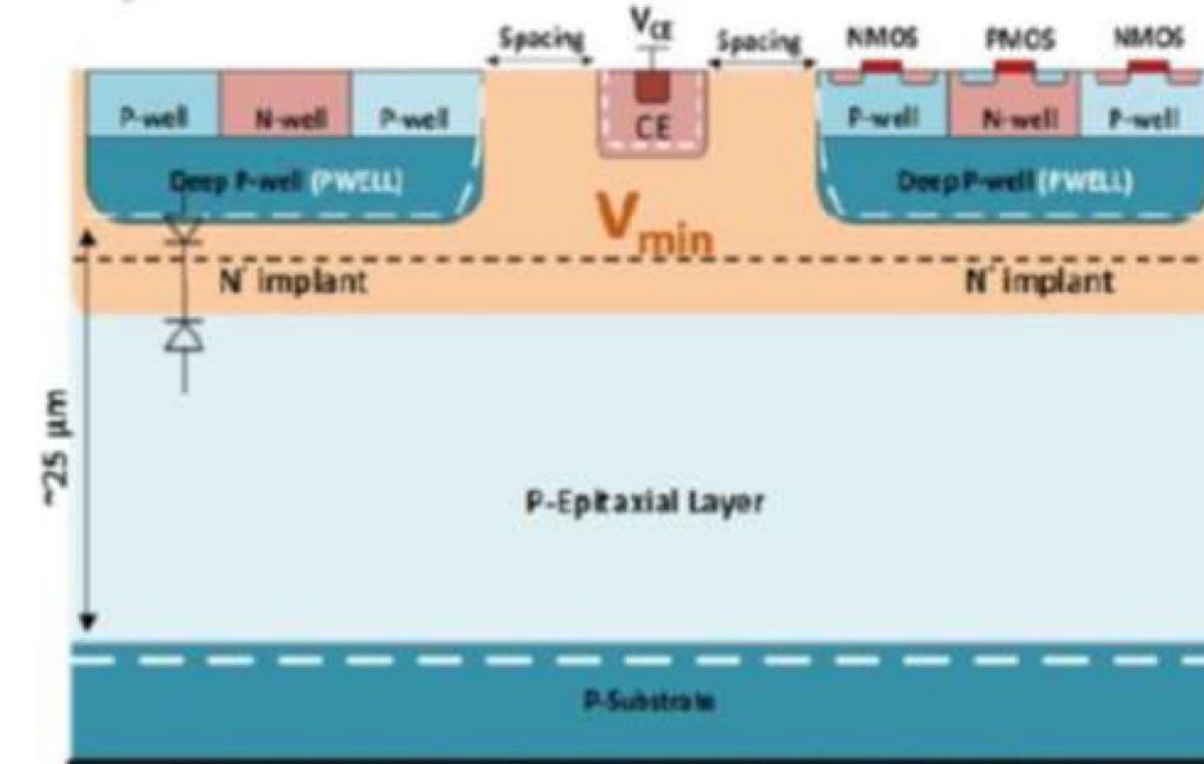
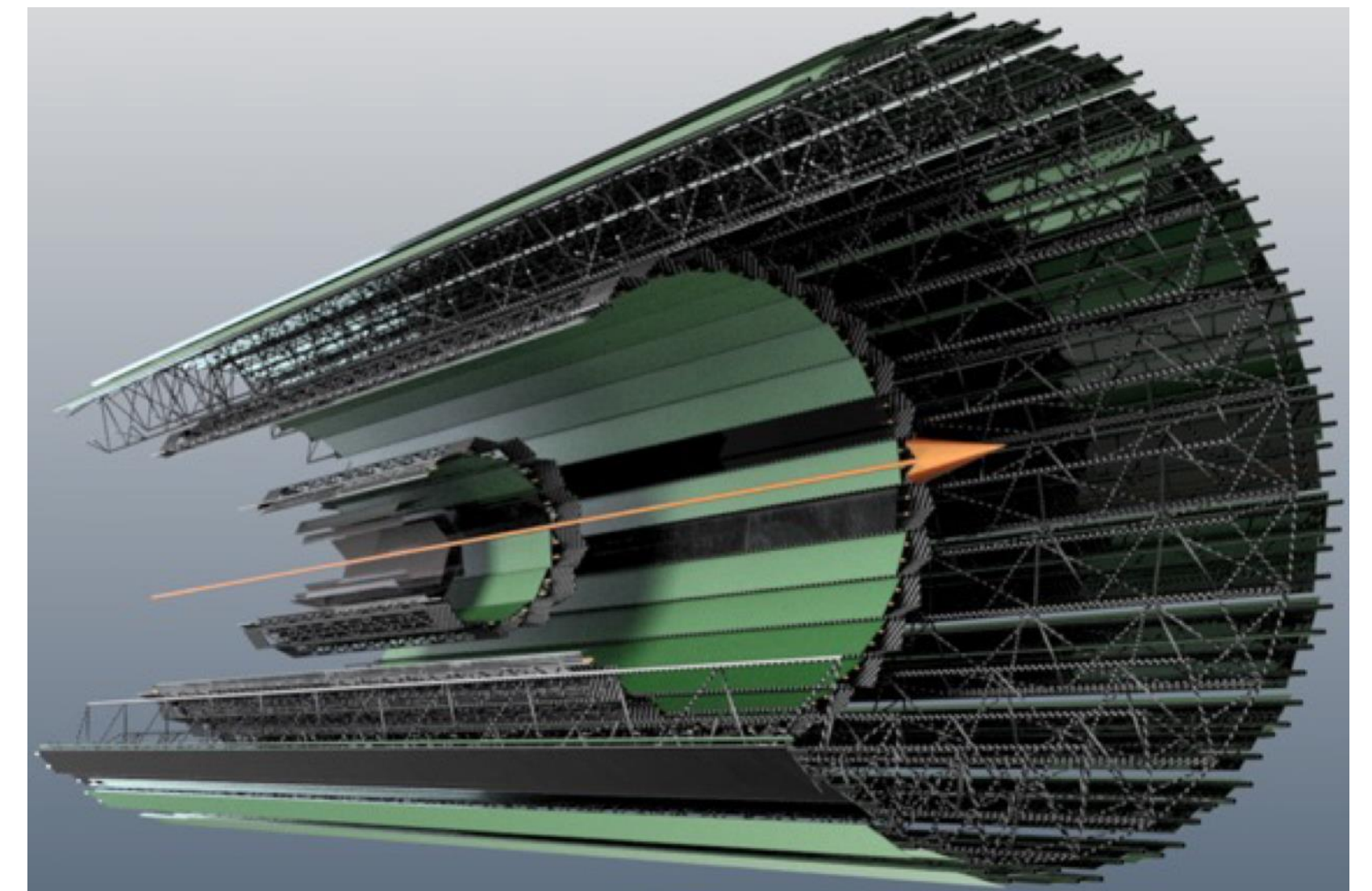
- vertexing/tracking equal to current VXD
- robustness against high-radiation environment

## ✓ performance improvements

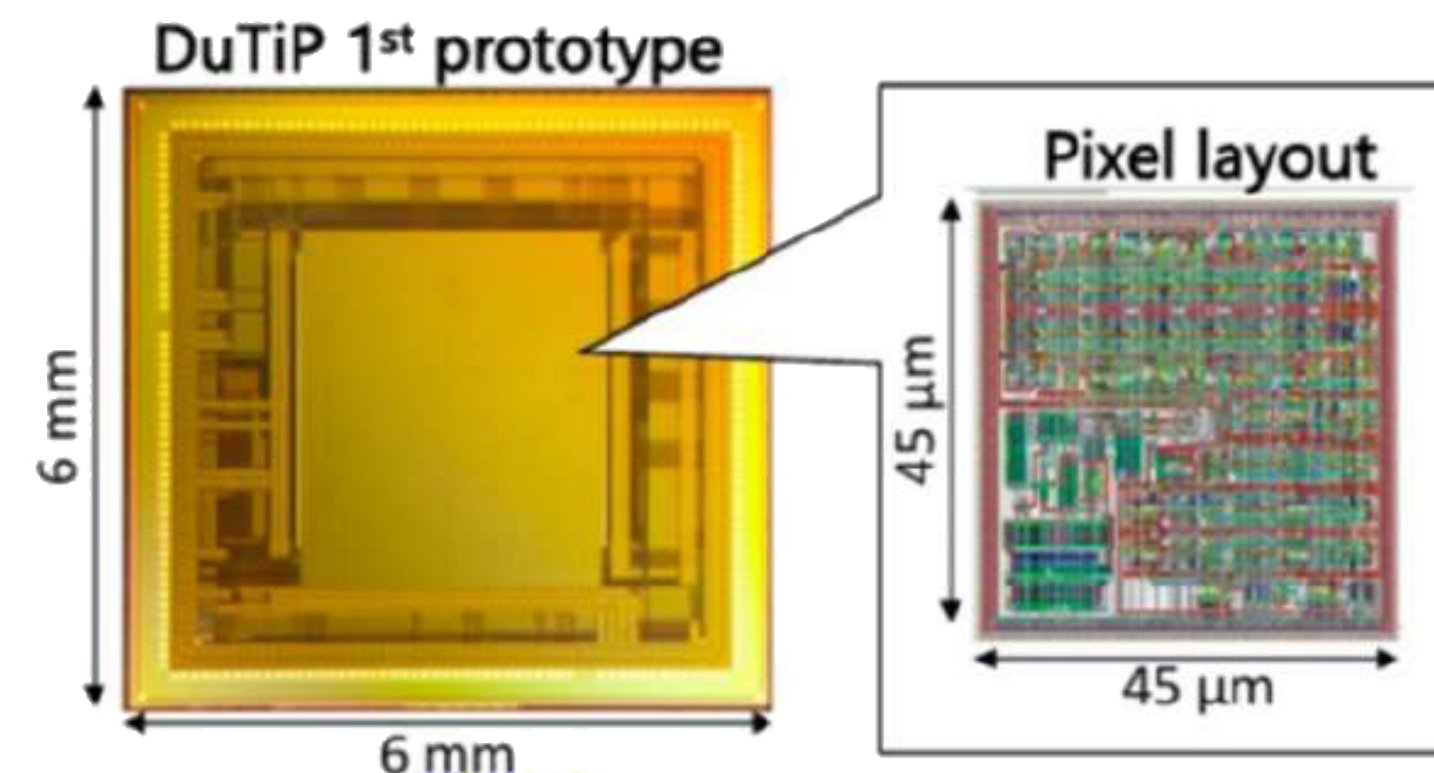
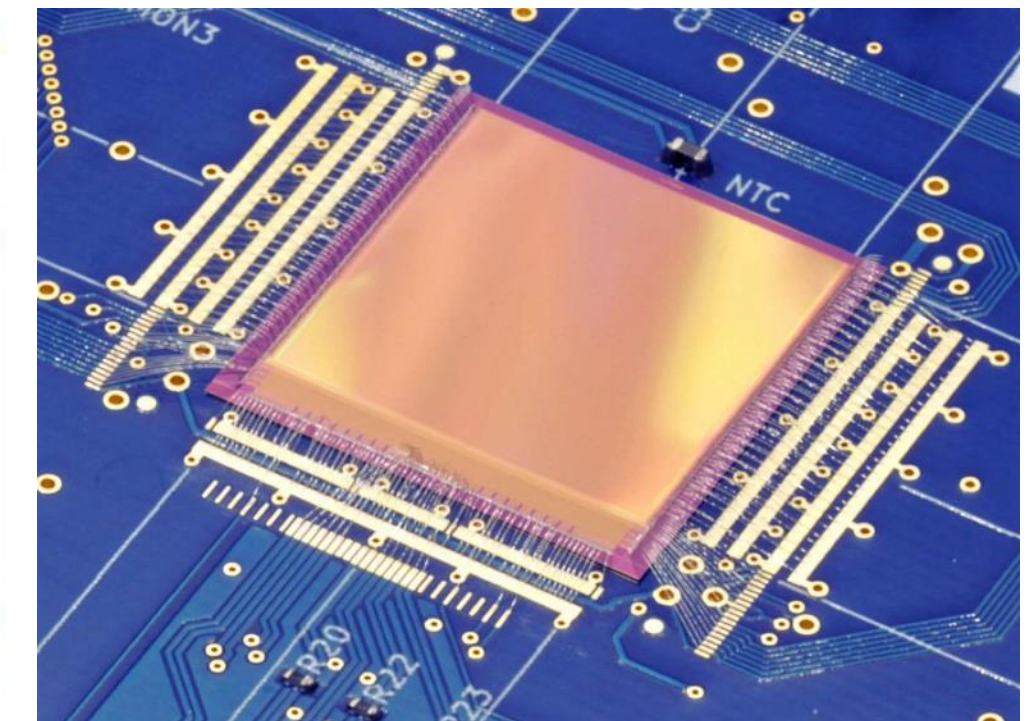
- better vertex resolution
- better tracking performance for soft tracks
- possible contribution to the Level 1 trigger

## ✓ technology options

- CMOS-MAPS pixels [default]
  - Tower 180 nm process
  - Extension of TJ-MONOPIX2 → OBELIX sensor
  - $<40\text{ }\mu\text{m}$  pitch, 100 ns integration
- SOI pixels [alternate]
  - Lapis 200 nm process
  - Dual Time Pixel (DuTiP) sensor
  - $45\text{ }\mu\text{m}$  pitch,  $2\times 60\text{ ns}$  integration



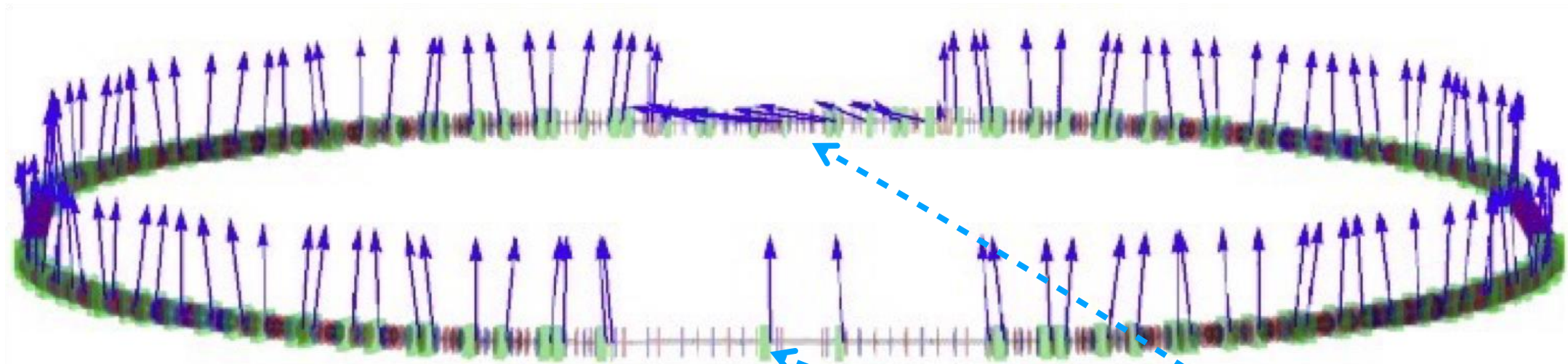
W. Snoeys et al. <https://doi.org/10.1016/j.nima.2017.07.046>





# Beam polarization & “Chiral Belle” beyond LS2 [or sooner?]

See Snowmass white paper [arXiv:2205.12847](https://arxiv.org/abs/2205.12847)



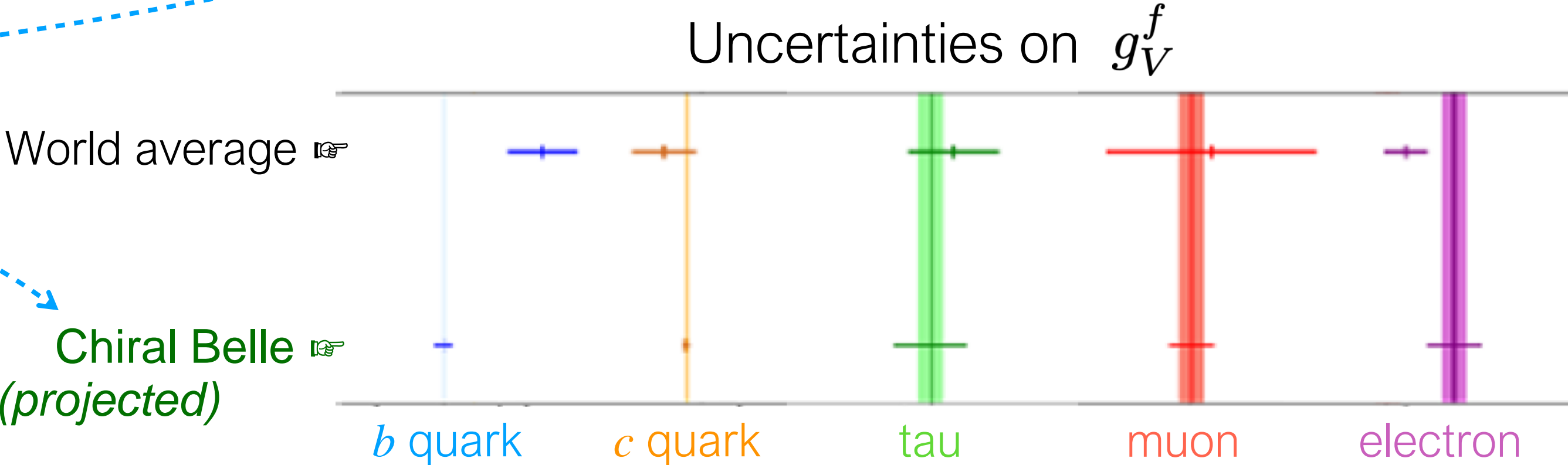
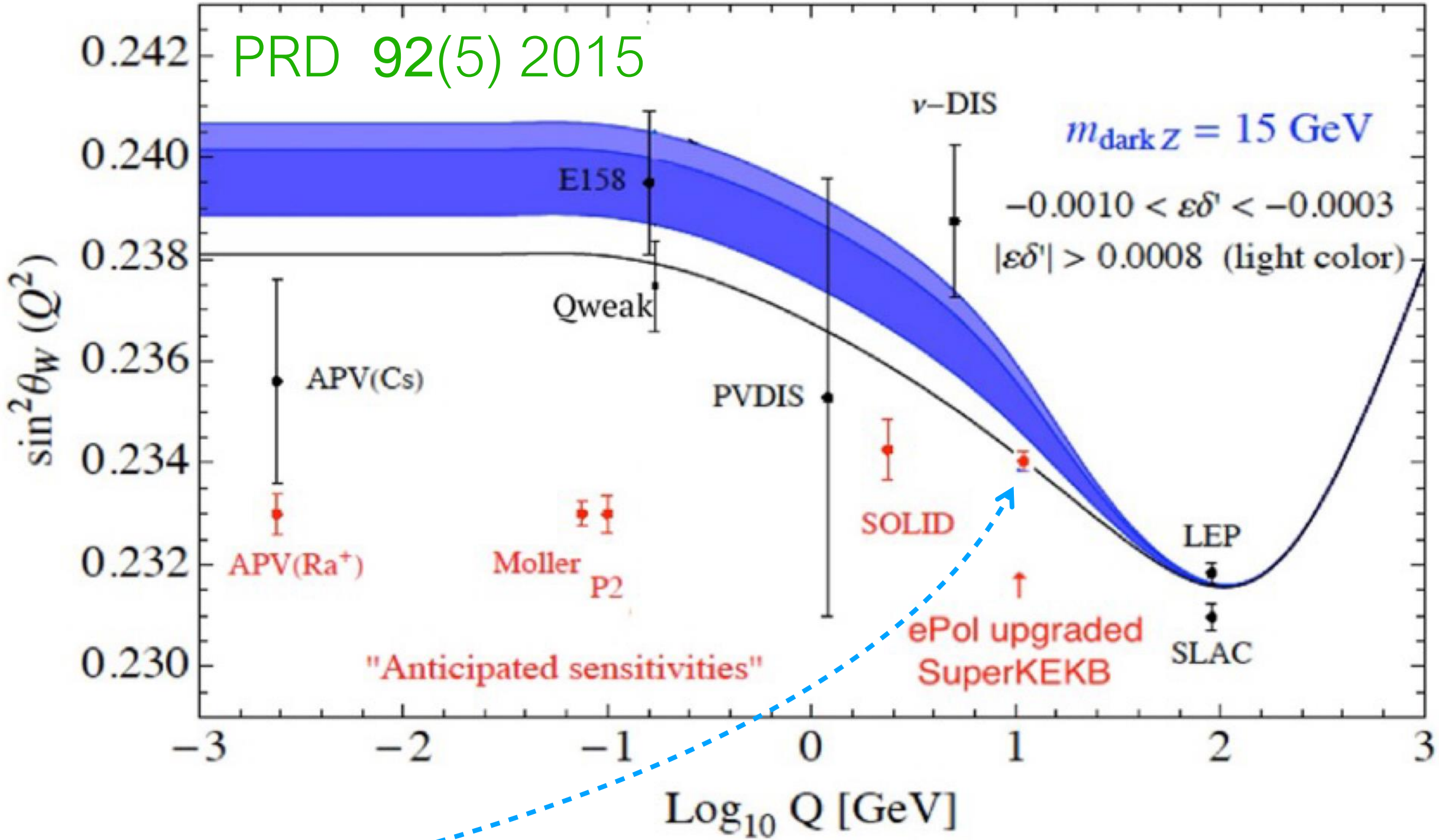
*$e^-$  spin vector in SuperKEKB*

✓ **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  $Z_{\text{dark}}$  via  $\sin^2\theta_W$
- left-right asymmetries with 5 fermions
- tau  $g-2$ : sensitivity of  $\mathcal{O}(10^{-5})$  w/50  $\text{ab}^{-1}$
- background suppression in  $\tau \rightarrow \ell \gamma$  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  $250 \text{ ab}^{-1}$ 
  - ⦿ start planning for even higher peak luminosity
  - ⦿ evolved detector that can operate at extreme luminosity

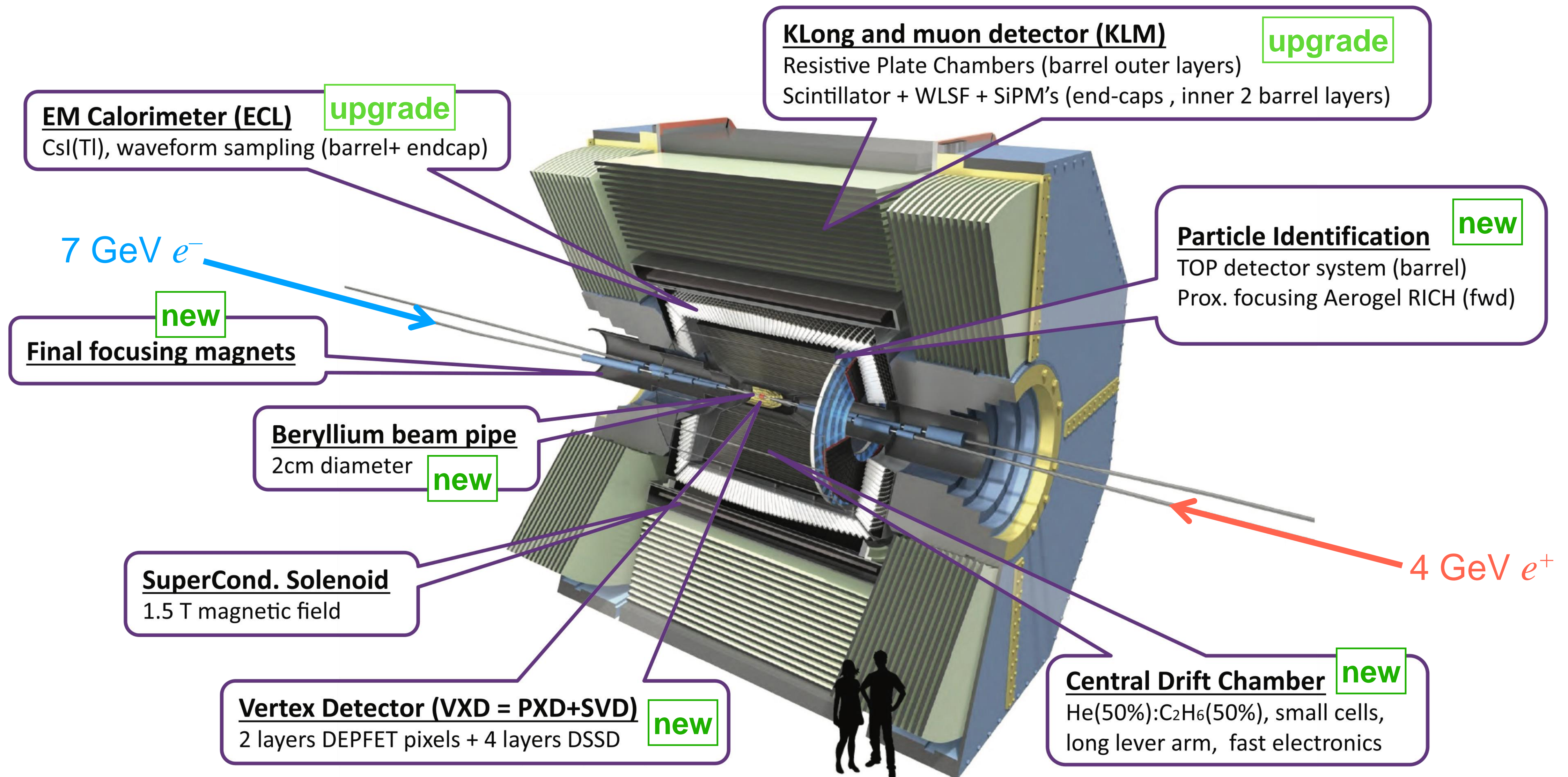


# Backup



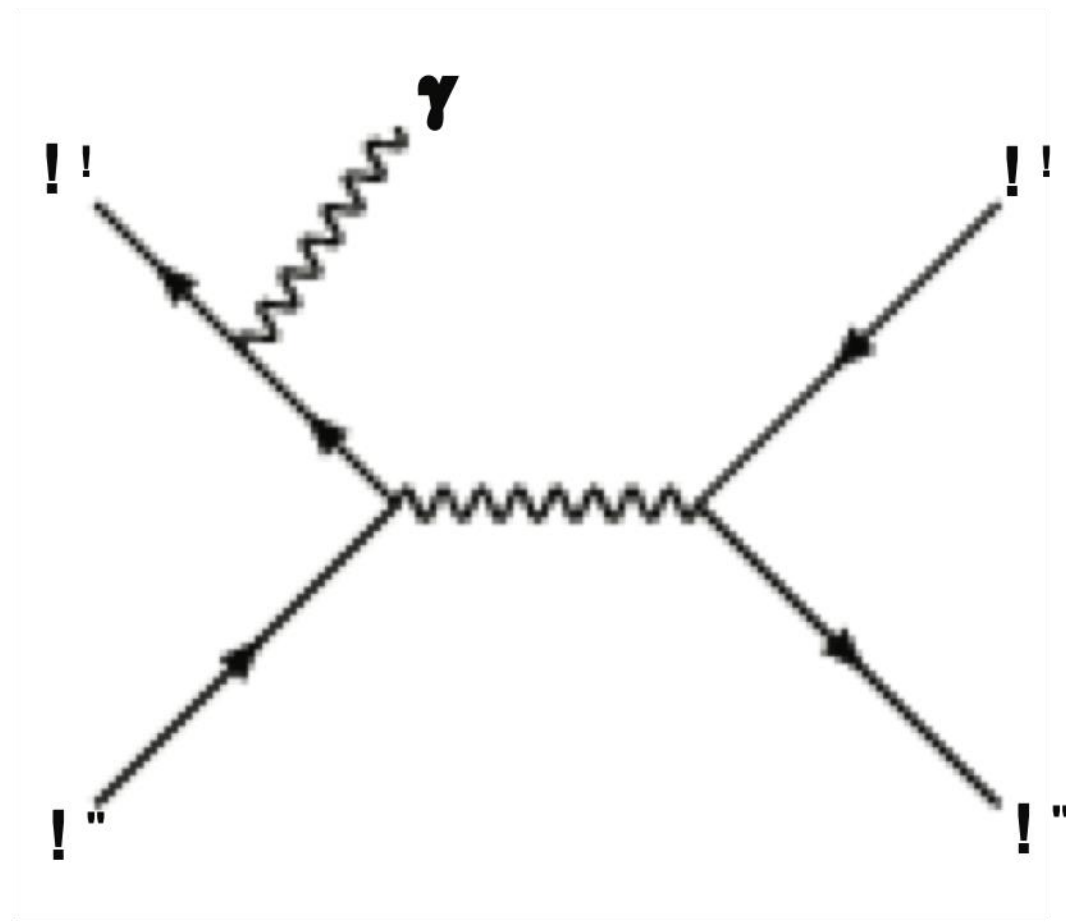
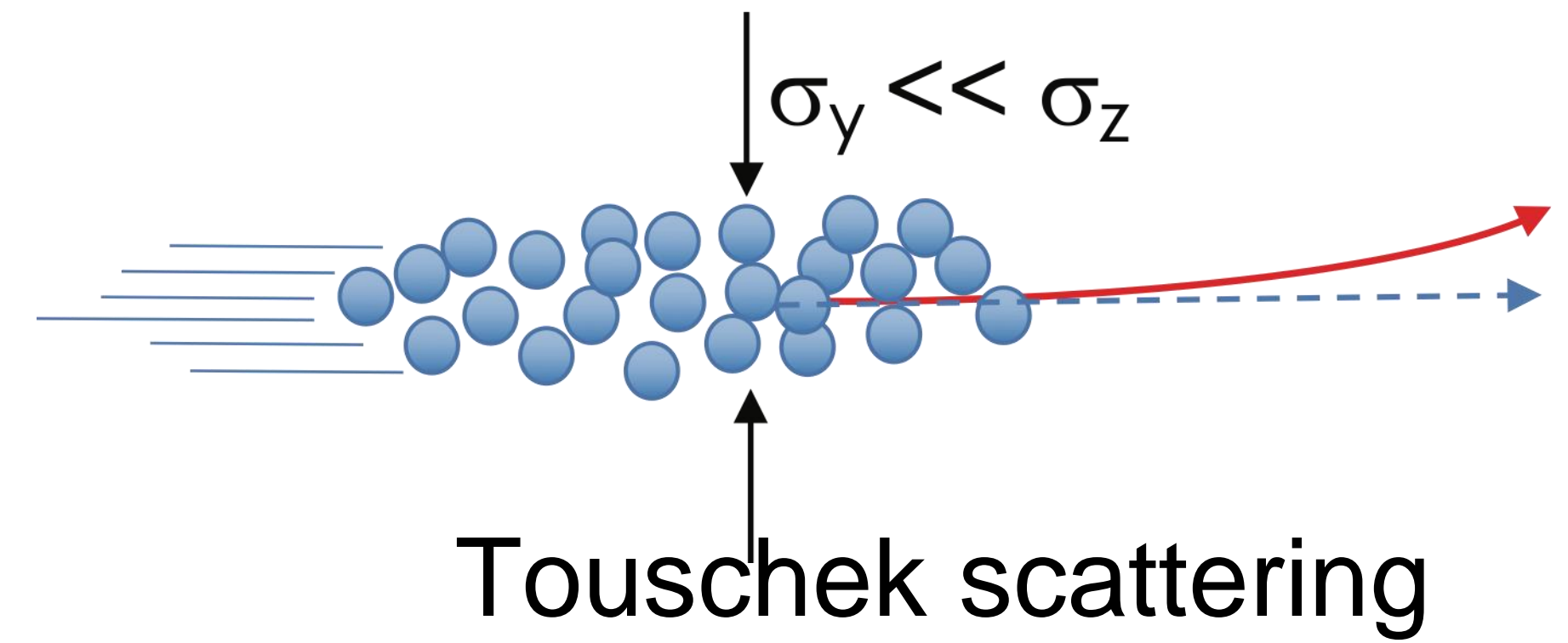
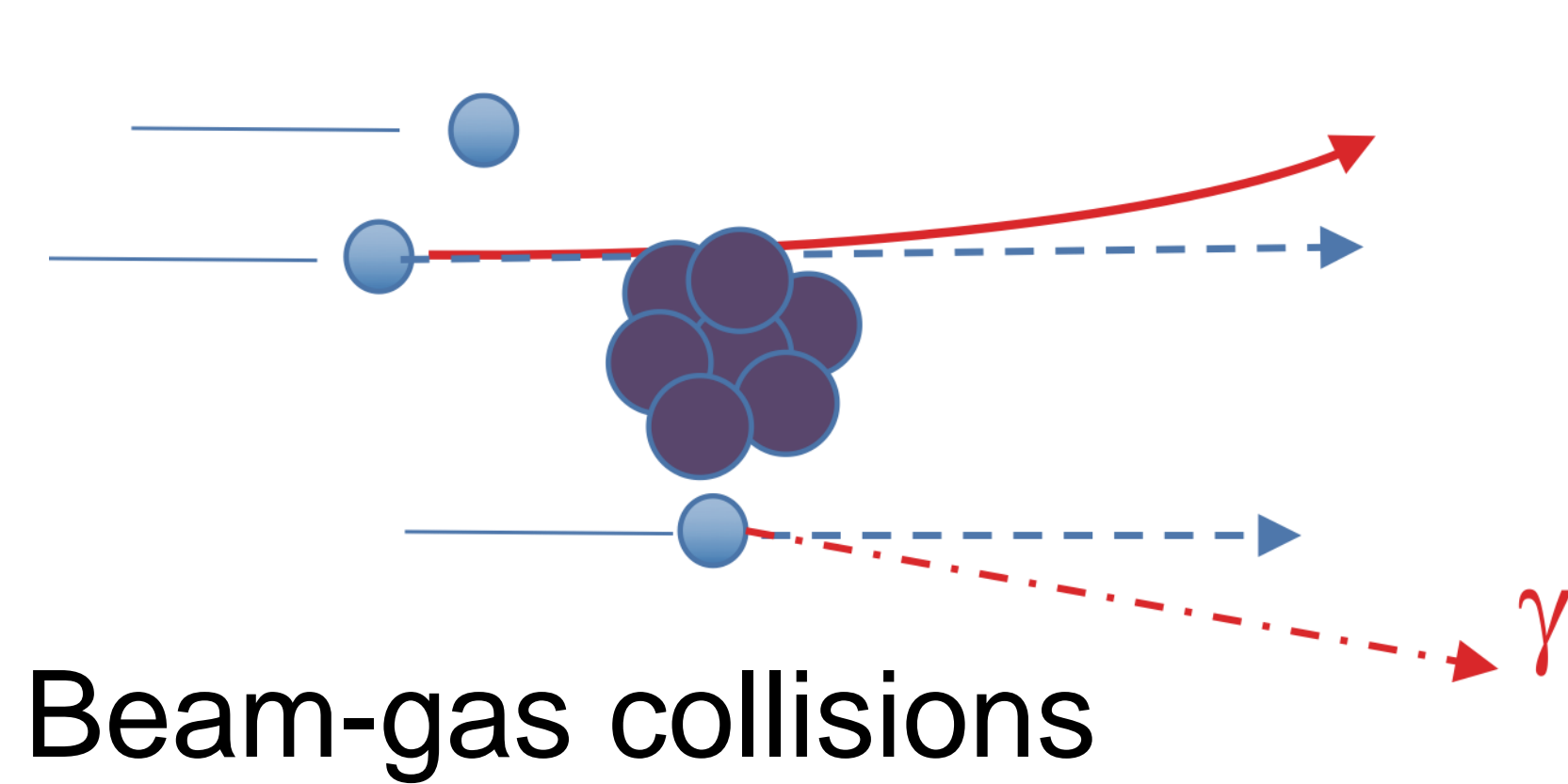


# Belle II vs first-generation Belle detector

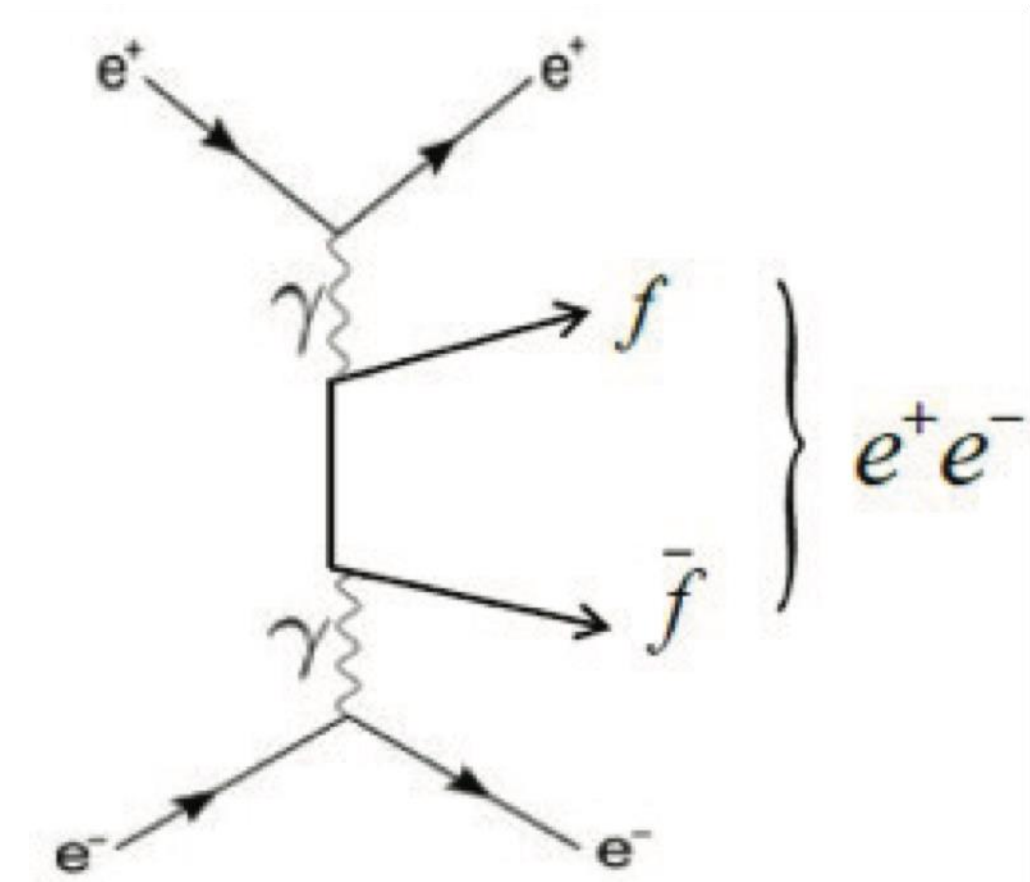




# Backgrounds must be managed for optimal physics extraction



Radiative Bhabha scattering

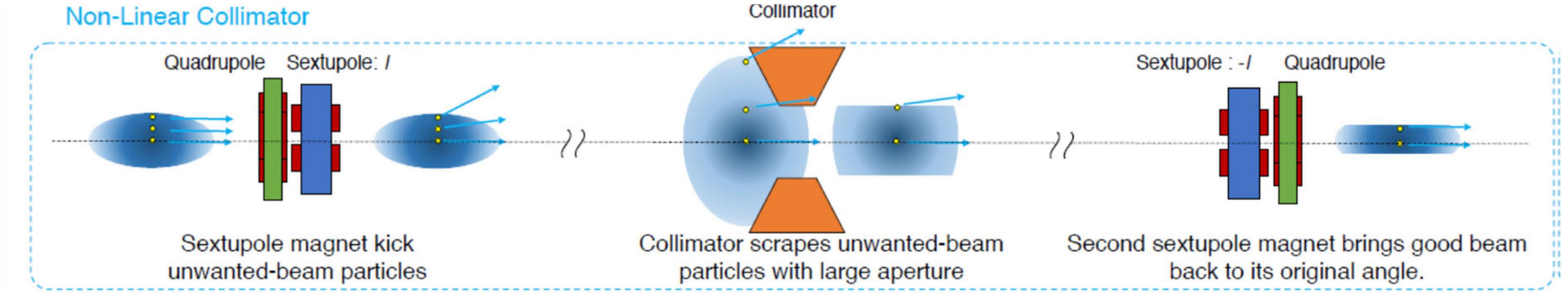


Two-photon processes

... + neutrons from stray beam particles striking beam-line structures



# Non-linear collimator + sextupoles remove stray beam particles





# Detector upgrades and time scale

see Snowmass white paper ([arXiv 2203.11349](https://arxiv.org/abs/2203.11349))

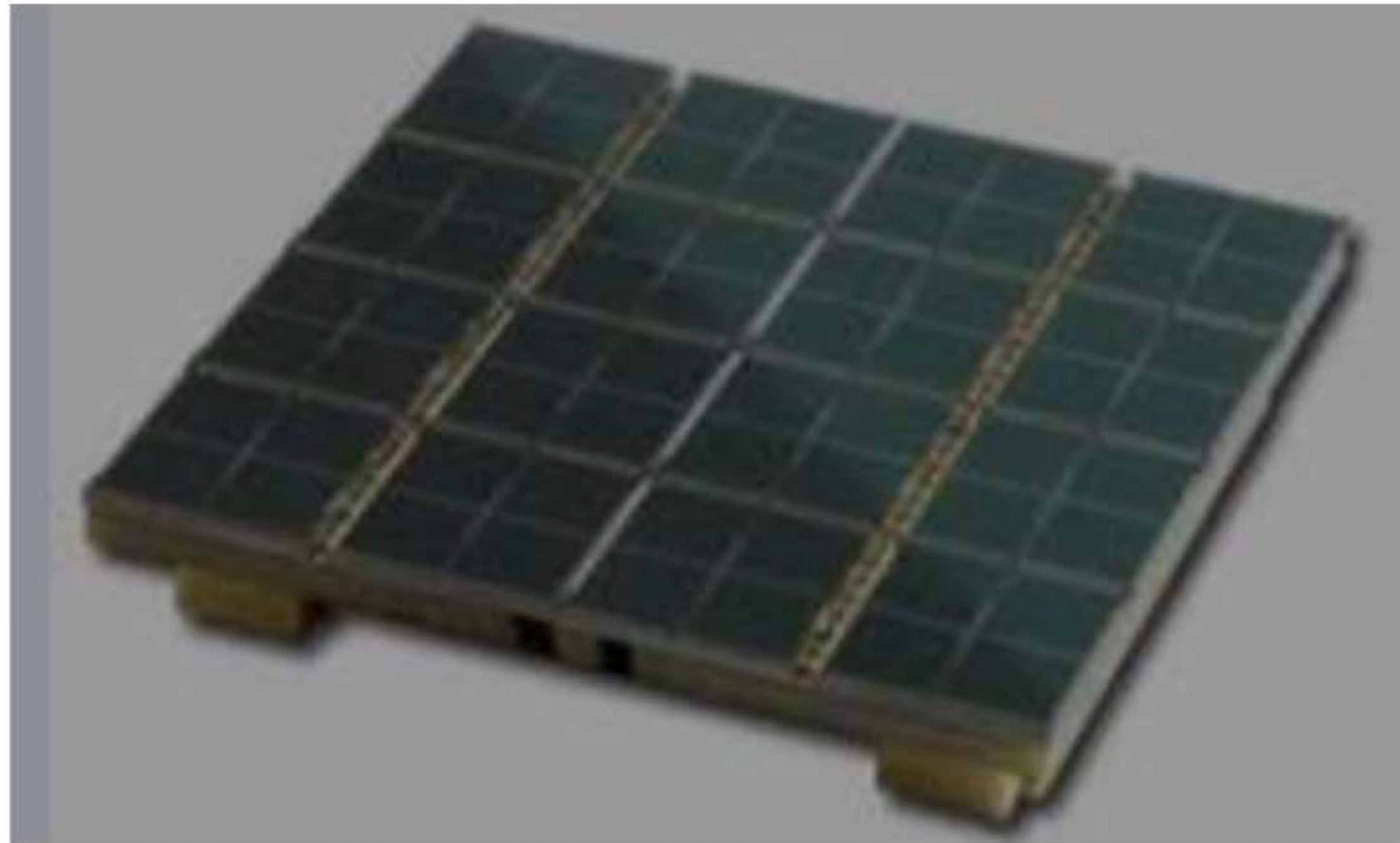
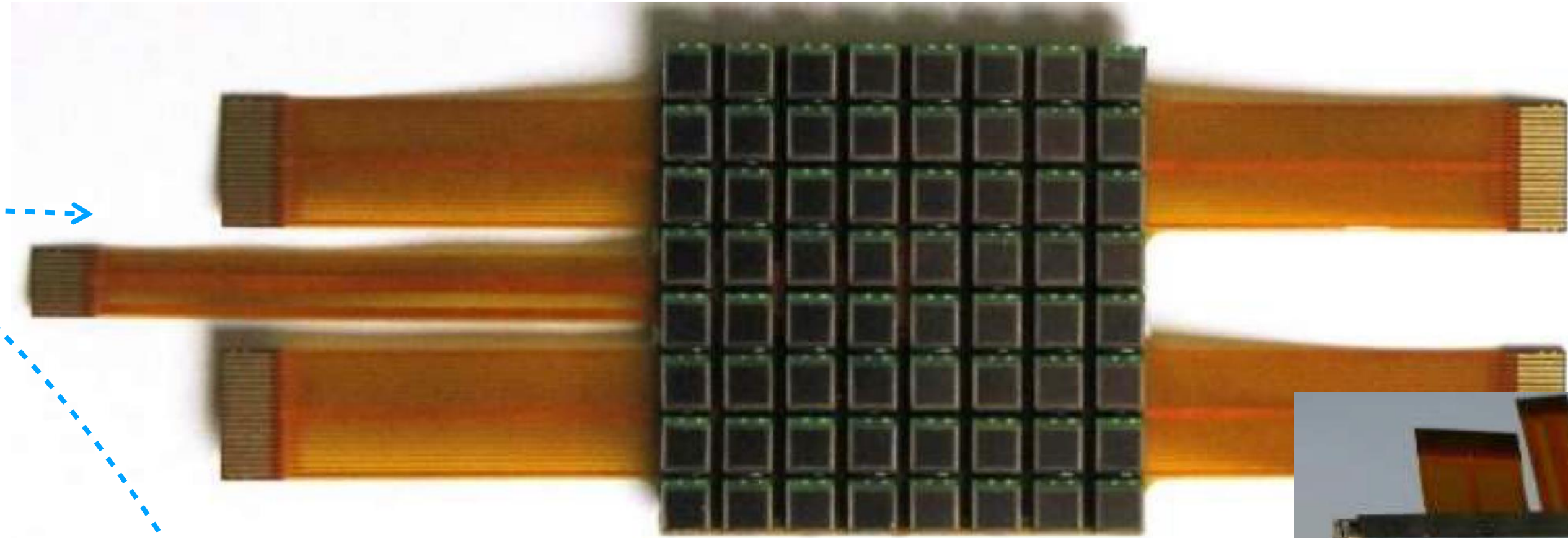
	Subdetector	Function	upgrade idea	time scale
Silicon Pixel Detector	PXD	Vertex Detector	2 layer installation new DEPFET	short-term medium-term
Silicon Strip Detector	SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
	PXD+SVD	Vertex Detector	all-pixels: SOI sensors all-pixels: DMAPS CMOS sensors	medium-term medium-term
Central Drift Chamber	CDC	Tracking	upgrade front end electronics replace inner part with silicon replace with TPC w/ MPGD readout	short/medium-term medium/long term long-term
Time of Propagation Counter	TOP	PID, barrel	Replace conventional MCP-PMTs Replace not-life-extended ALD MCP-PMTs STOPGAP TOF and timing detector	short-term medium-term 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	$\gamma, e$ ID	add pre-shower detector in front of ECL Replace ECL PiN diodes with APDs Replace CsI(Tl) with pure CsI crystals	long-term long-term long-term
K-long and Muon Detector	KLM	$K_L, \mu$ ID	replace 13 barrel layers of legacy RPCs with scintillators on-detector upgraded scintillator readout timing upgrade for K-long momentum measurement	medium/long-term medium/long-term medium/long-term
Level 1 Hardware Trigger	Trigger		firmware improvements	continuous
Data Acquisition System + Software High-Level Trigger	DAQ		PCIe40 readout upgrade add 1300-1900 cores to HLT	ongoing 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<sub>3</sub>) 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

