Future of Belle II

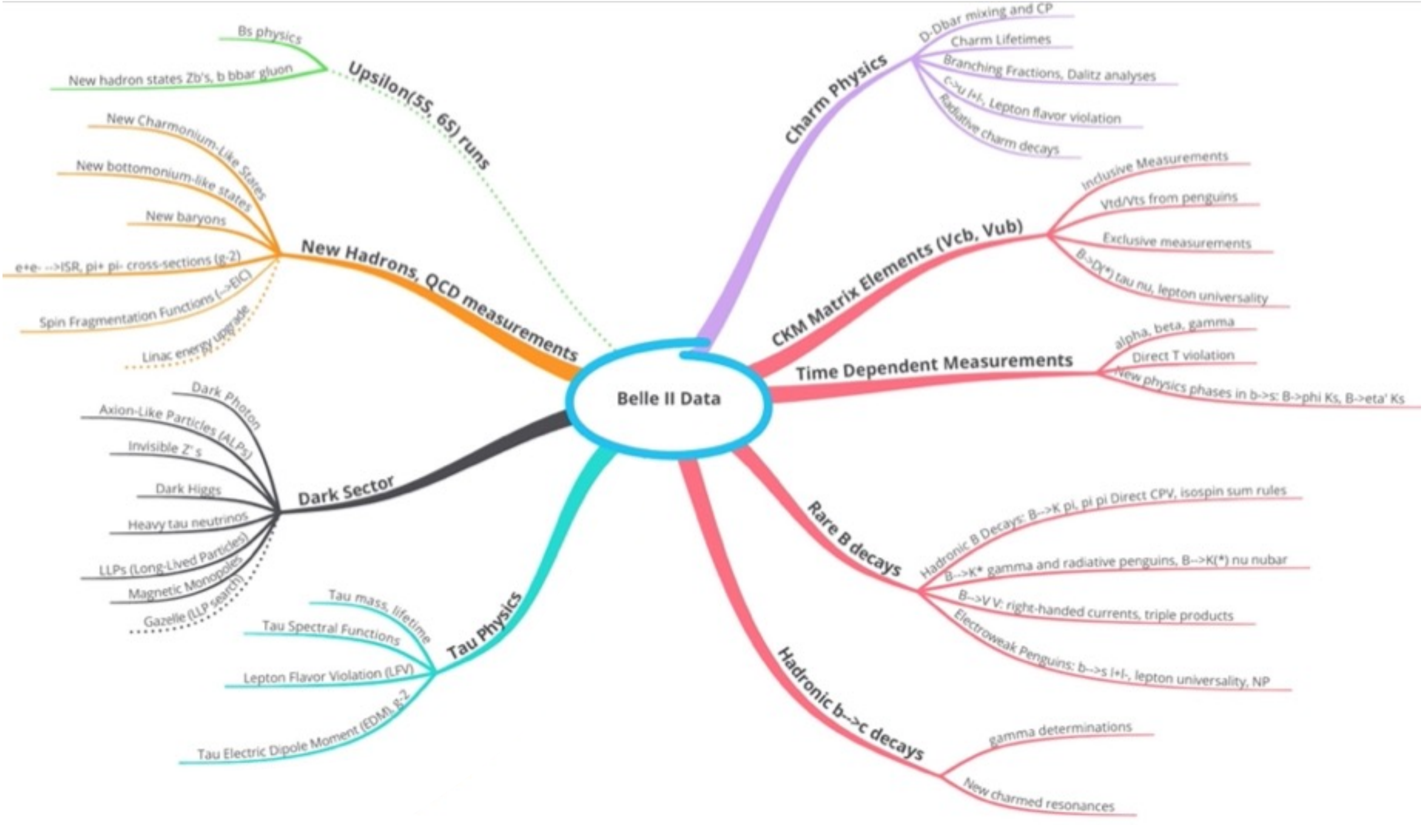
Jerome Baudot,
on behalf of the Belle II collaboration

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
CNRS
Université de Strasbourg

- General concepts for high luminosity super B factory
- On-going activities at SuperKEKB & Belle II (LS1)
- Upgrade plans on the mid-term (LS2)
- Going chiral?

b,c,τ super-factory: SuperKEKB + Belle II

- Belle II physics program at $\sqrt{s} = M_{\Upsilon(4S)}$ & $M_{\Upsilon(1S)\to\Upsilon(6S)}$ from 1 to 50 ab^{-1}
  - ⇒Initial physics book PTEP 12 (2019) 123C01
  - ⇒Updated Snowmass white paper arXiv 2207.06307

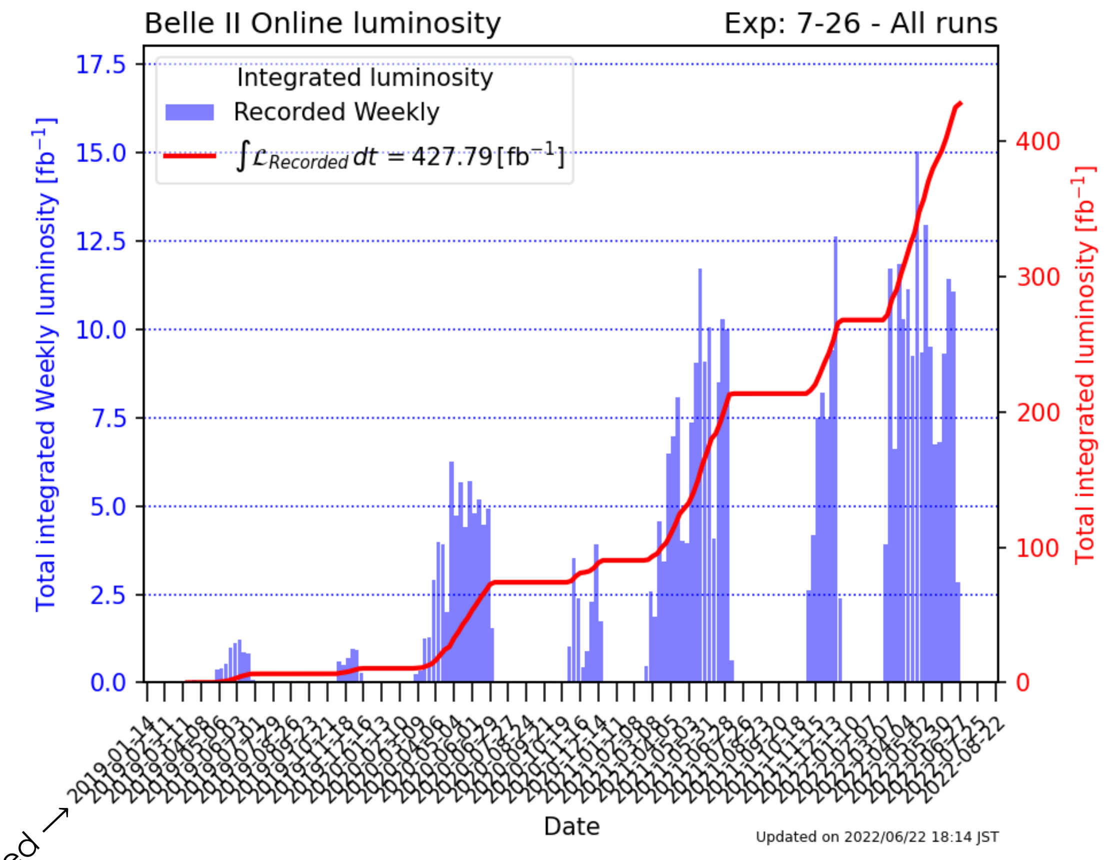


Built up on KEKB + Belle success

- New machine: SuperKEKB
  - $\mathcal{L}_{peak}$ ~ multi 10^{35} $cm^{-2}.s^{-1}$ range
- New detector: Belle II
  - Exploit assets of e+e- collisions
    => hermiticity, Emiss, neutrals
  - Multi-purpose physics
    => precision (vtx, trck), hadron+lepton PID

Belle II physics currently delivering…

- 427.8 fb^{-1} accumulated [including 42/19 fb^{-1} below/above $M_{Y(4S)}$]
- World record peak lumi 4.7x10^{34} cm^{-2}.s^{-1}



Started → in 2019

Already presented @ FPCP:

- *New CPV measurements at e+e- experiments,* J. Skorupa
- *Status and prospects for rare B decays at Belle/Belle II,* G. De Marino
- *New b->u and b->c semi-leptonic results at e+e- experiments,* S. Granderath
- *New non-leptonic hadron decay results at e+e- experiments,* A. Di Canto
- *Recent Belle II results on time-dependent CP violation and charm physics,* J. Bennett
- *Recent Belle II results on the CKM parameters |V_cb| and |V_ub|,* P. Horak
- *Recent Belle II results on radiative and electroweak penguin decays,* J. Cerasoli
- *Recent Belle II results on hadronic B decays,* S. Raiz
- *Recent Belle II results on semitauonic decays and tests of lepton-flavor universality,* P. Lewis
- *Recent tau and dark-sector results at Belle II,* G. Raeuber
- *Recent quarkonium results at Belle II,* Alessandro Boschetti

To come

- *Dark sector at flavour experiments,* Torben Ferber

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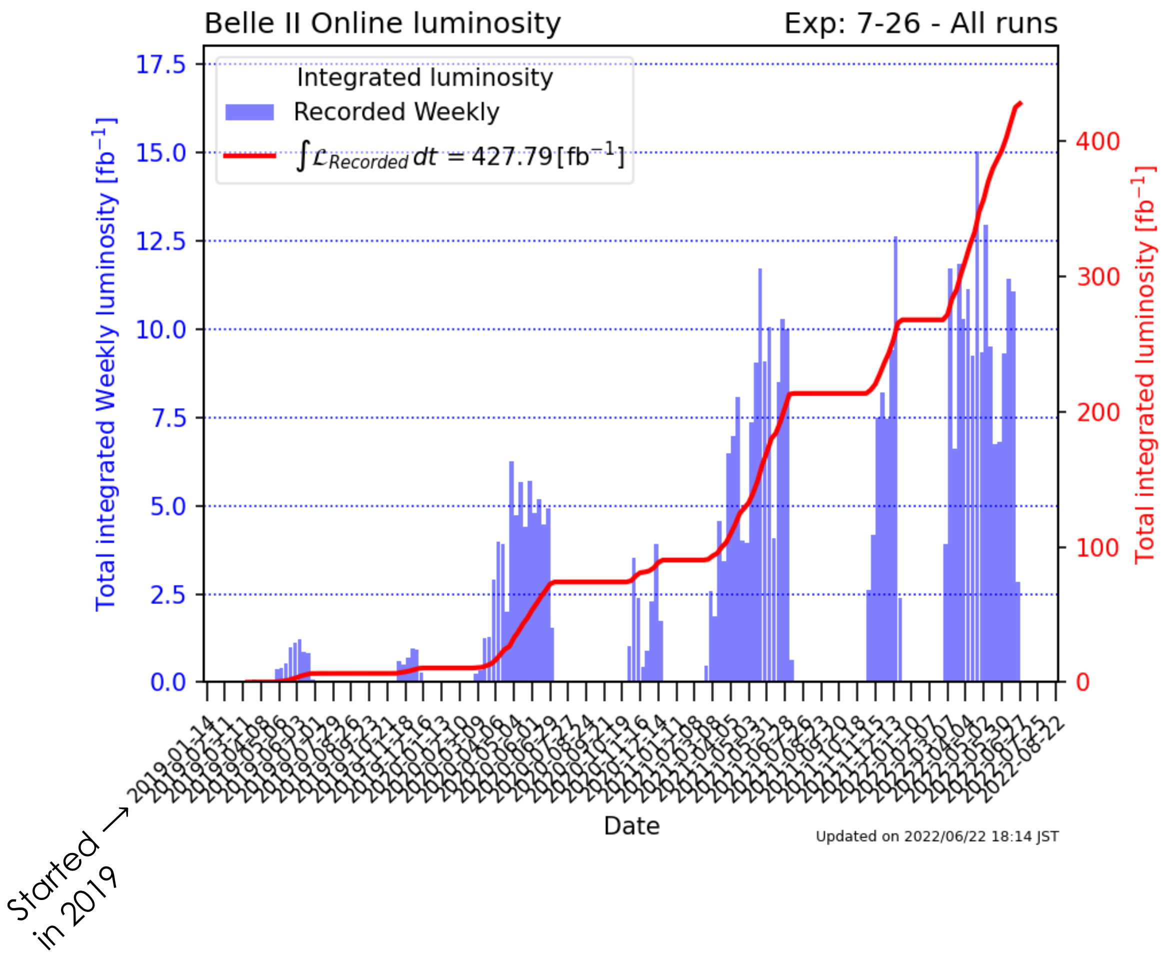

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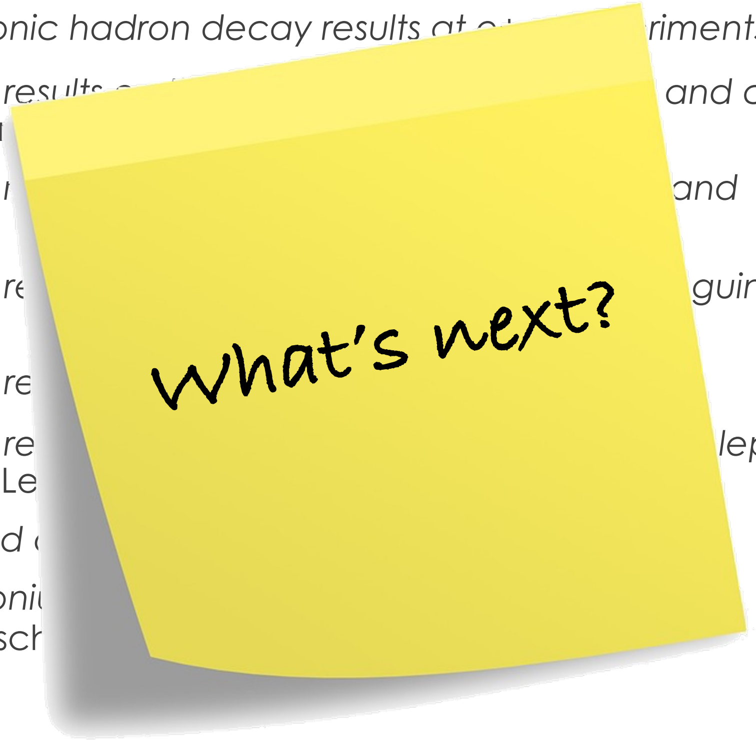
- *Recent tau and …*
- *Recent quarkoni…* Alessandro Bosch…



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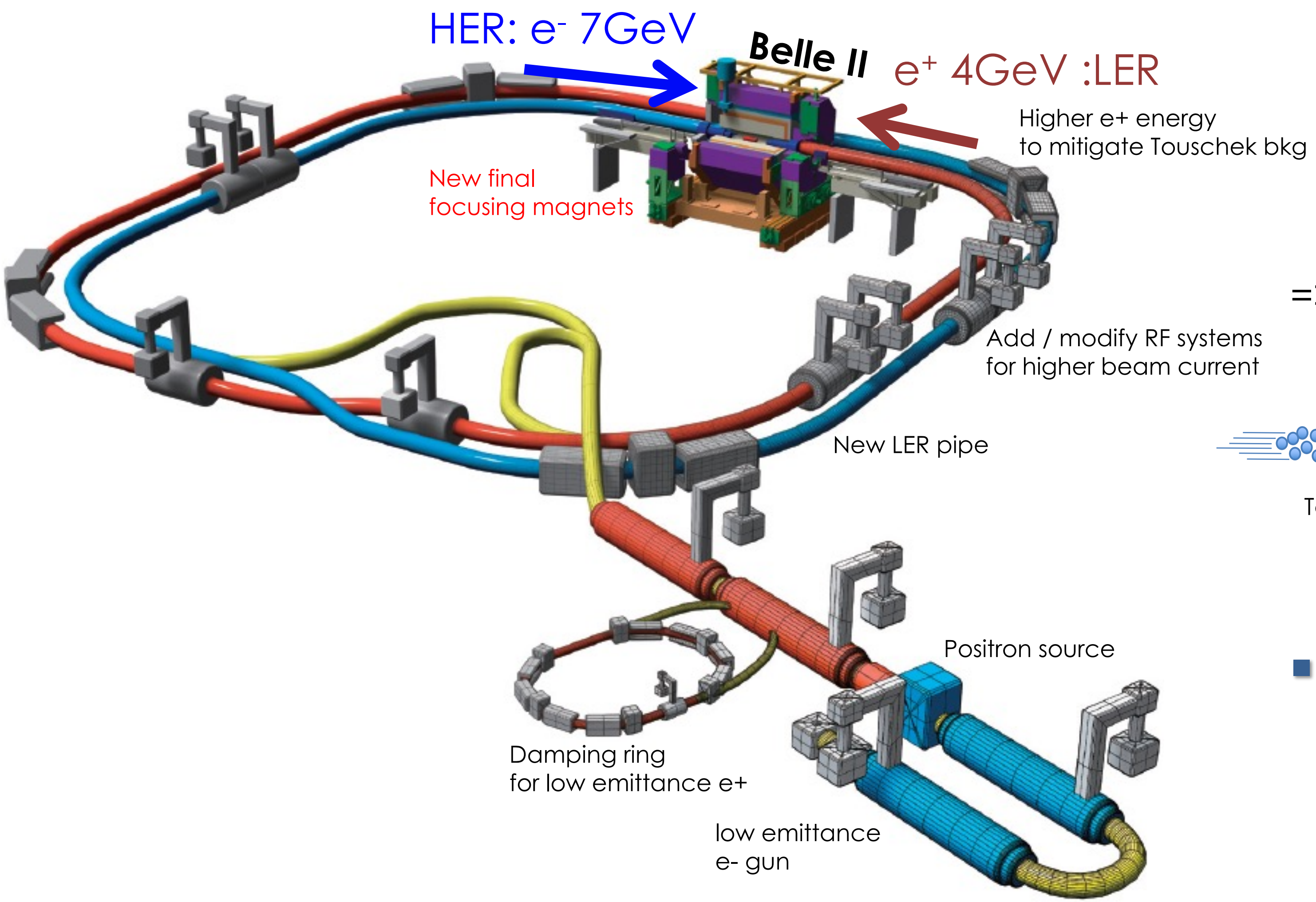
SuperKEKB collider



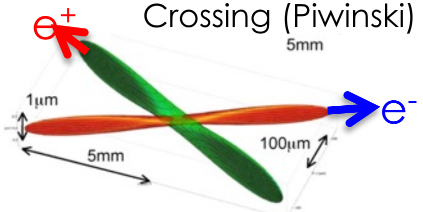
Recipe for high luminosity

Large currents + **Nanobeam scheme**

I_{beam} up to 3.6 A

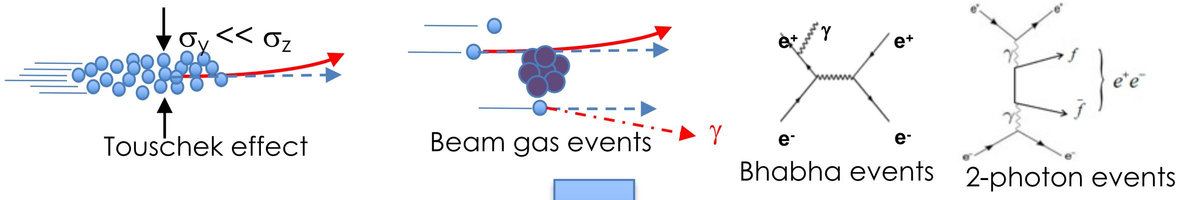
Vertical beam size down to 50 nm

Crossing (Piwinski) angle φ=83 mrad



=> Induces parasitic particles = **beam backgrounds**

– Proportionally to 1/beam size, current, luminosity $\mathcal{L}$



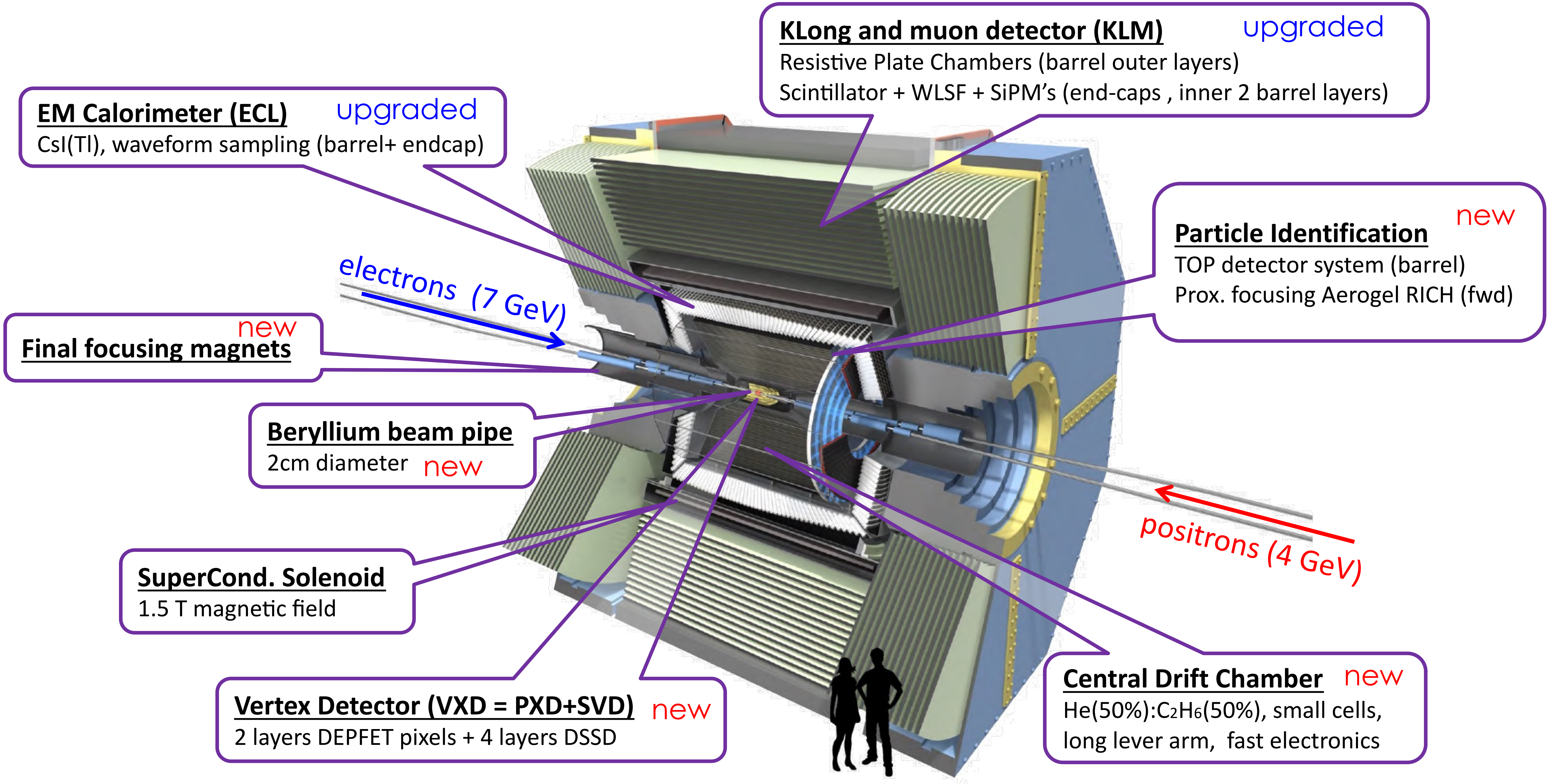
Constraints on detector

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

} → Faster detectors

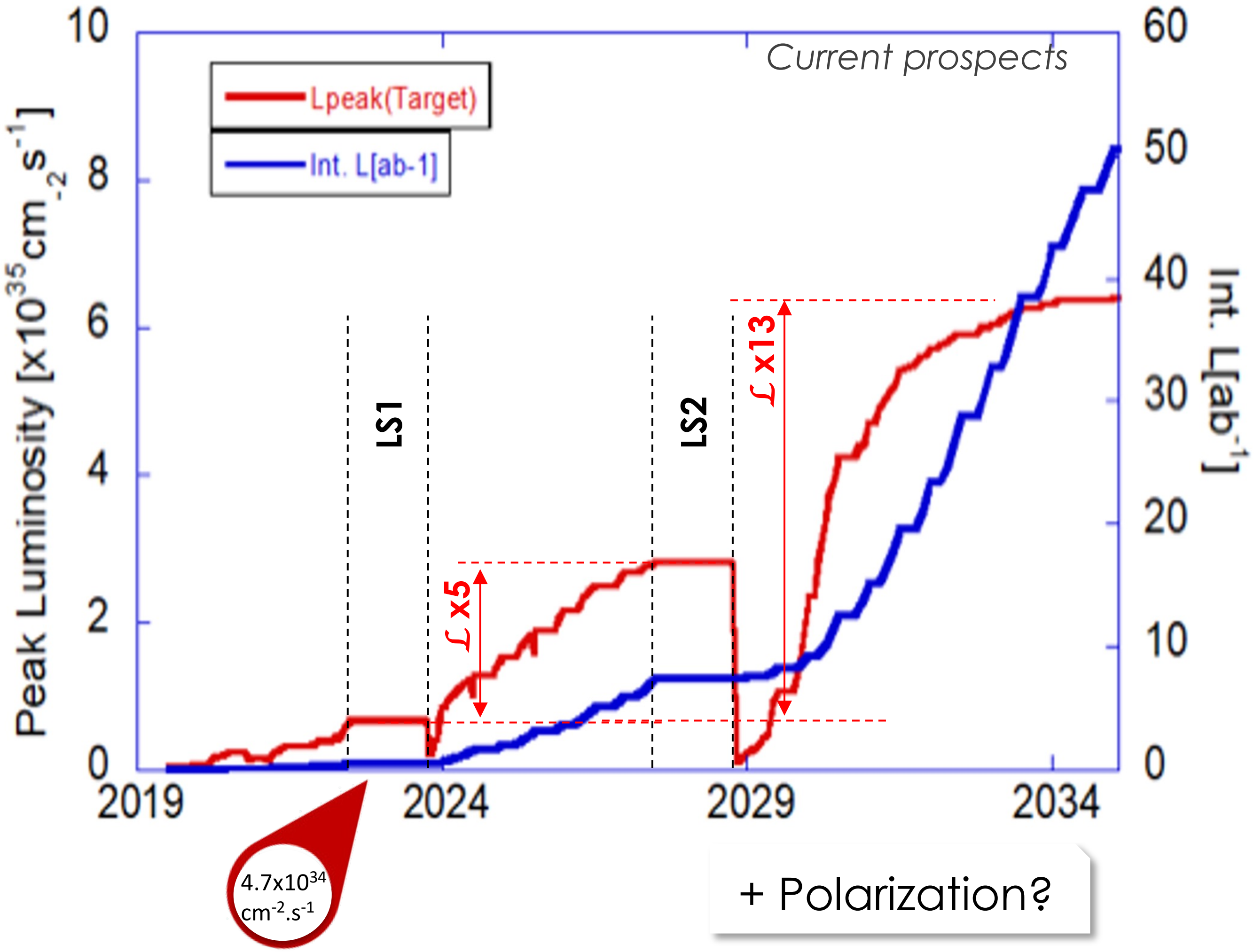
Belle II detector

Upgraded or new / Belle



Physics prospects with luminosity increase

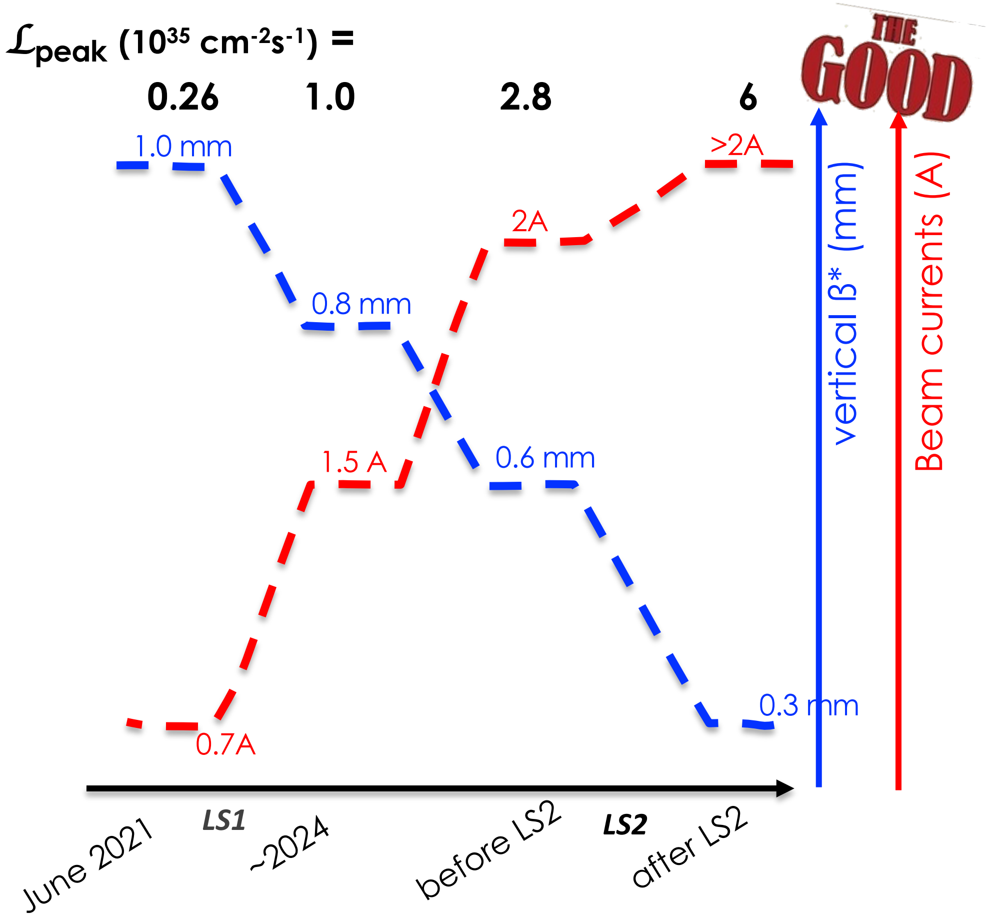
After few years at cutting-edge luminosity, better grasp on how to…



- get the luminosity higher
  - SuperKEKB improvements in LS1
    - Mitigate various background sources
  - SuperKEKB upgrade in LS2
    - Large impact on Interaction Region (IR)
- cope with higher background
- get more physics per ab^{-1}
  - Hierarchical Belle II upgrades
    - Short-term = LS1
    - Mid-term = LS2 ⇒ Snowmass papers arXiv 2203.11349
    - Long-term = beyond LS2
  - Use polarization arxiv:2205.12847

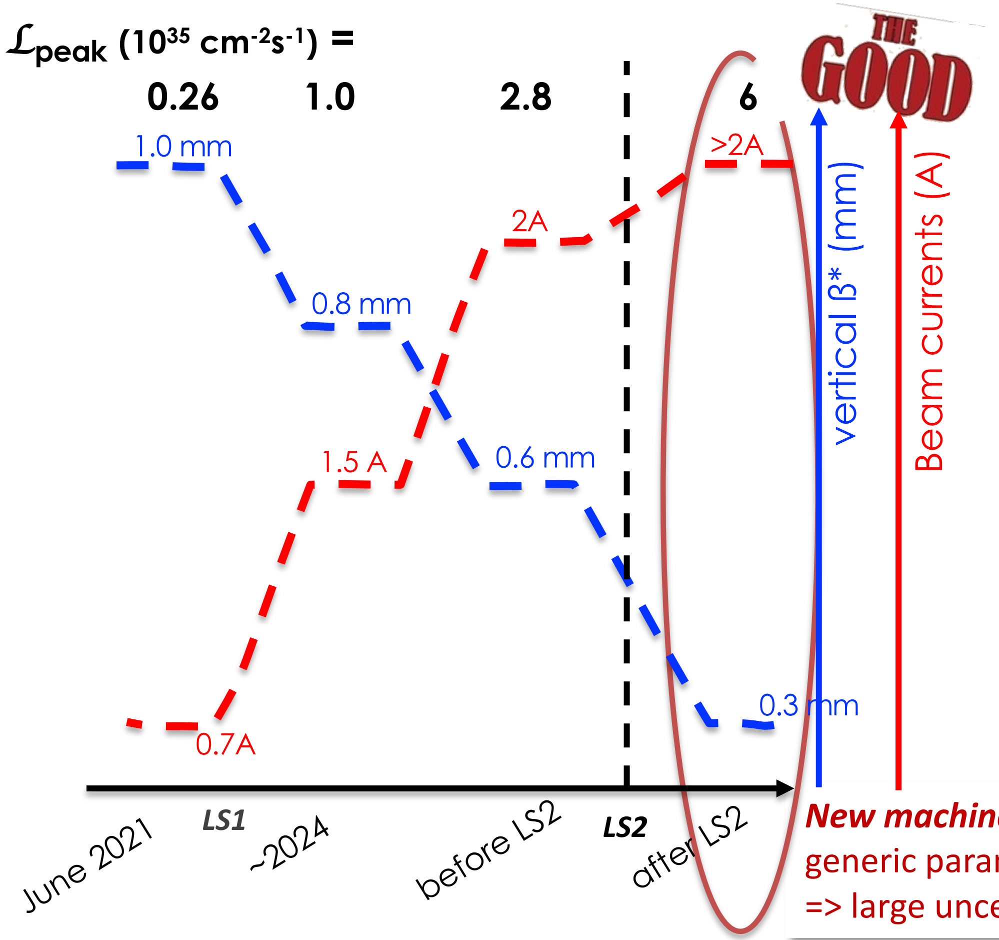
Work in progress

Luminosity vs Beam backgrounds



Luminosity vs Beam backgrounds

- Experience with SuperKEK first operation years
  => confidence on reachable $\mathcal{L}_{peak}$ with present machine lattice

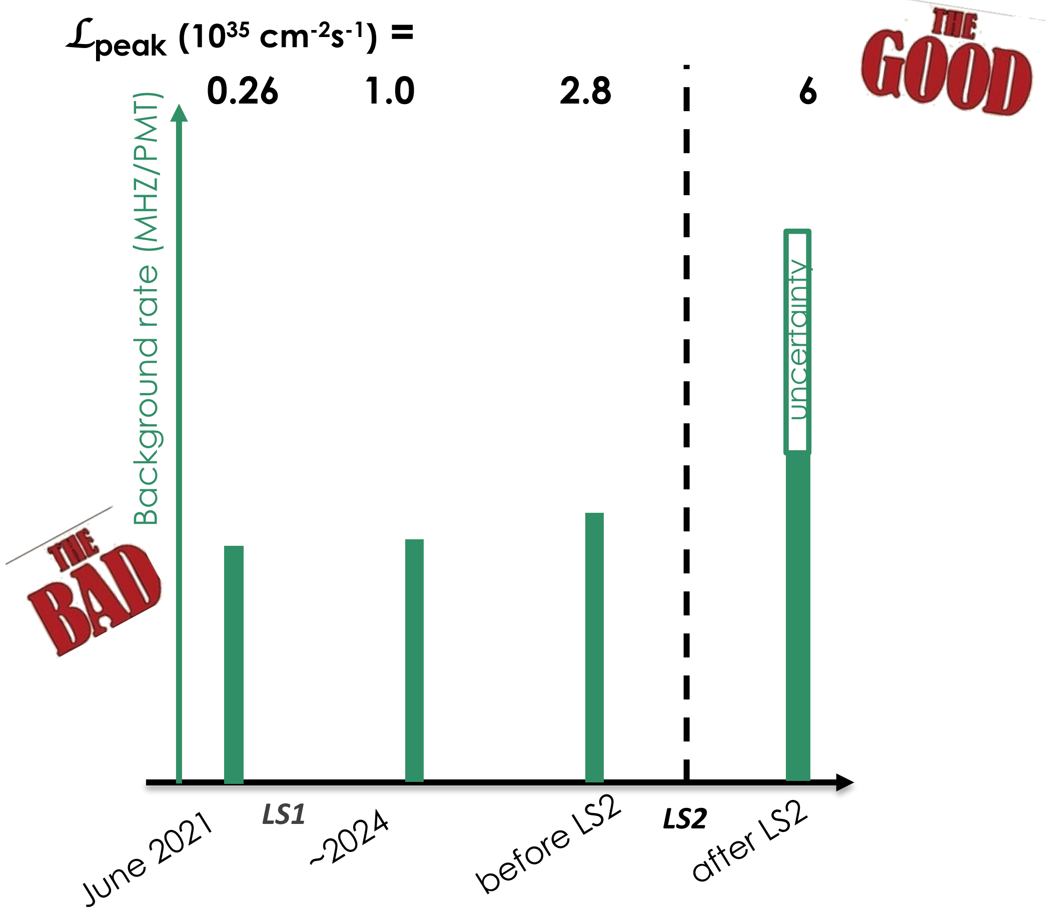


New machine lattice:
generic parameters used here
=> large uncertainties on background

Luminosity vs Beam backgrounds

- Continuous effort to understand background (arXiv 2203.05731) => MC/data ratio now $o(1)$

Predictions example: TOP (each subsystem affected differently)

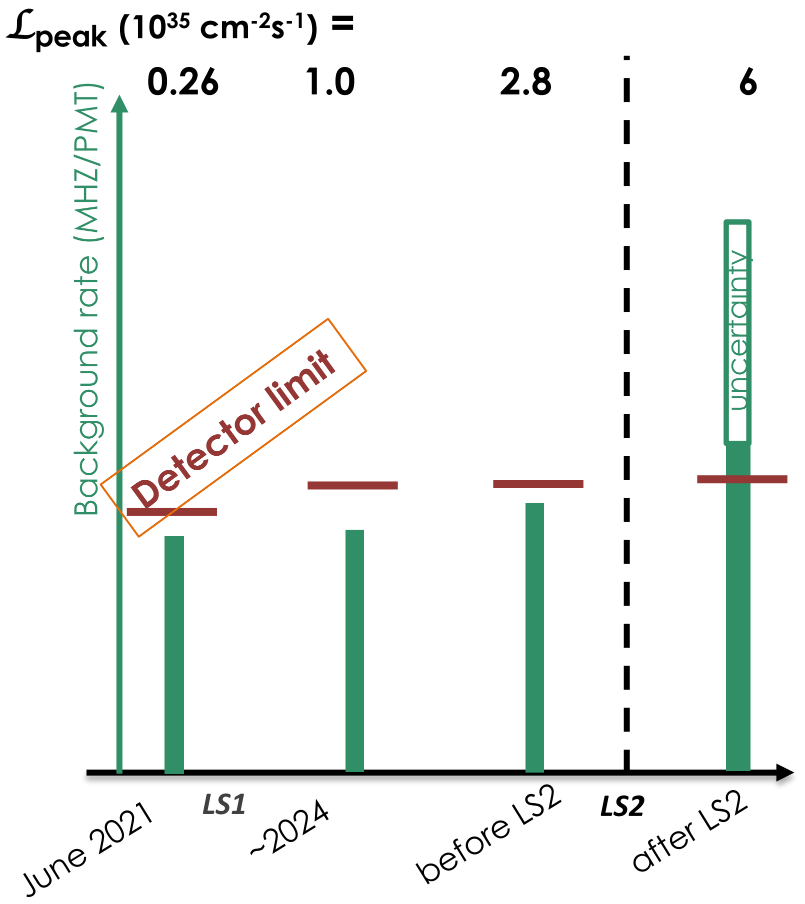


- Operational conditions
  - Complex & adaptable collimator system
  - Injection background from new bunch
  - Sudden beam loss events

  => continuous improvement process

Luminosity vs Beam backgrounds

Predictions example: TOP (each subsystem affected differently)



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

LS1 on-going work: SuperKEKB

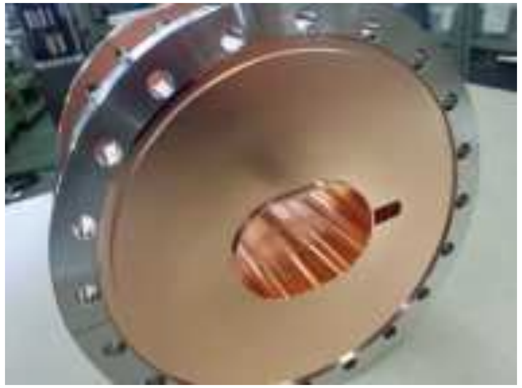
- Countermeasures against sudden beam loss
  - Additional real-time monitoring
  - Faster abort system
- Additional shielding
  - Against neutrons
    - around final focusing magnets (QCS)
    - Around end-caps
- Collimators
  - Non-linear types ⟶ background mitigation
  - Harder head material ⟶ better resilience
- Injection
  - New beam-pipe + faster kicker magnets + new quadrupole magnet

  ⟶ Higher efficiency & mitigated background
- RF cavity replacement

  ⟶ More stable operation and larger beam currents

Shielding on QCS bellow

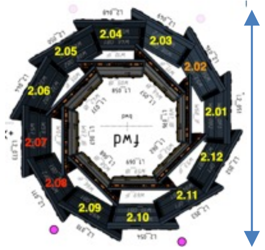
Carbon collimator head



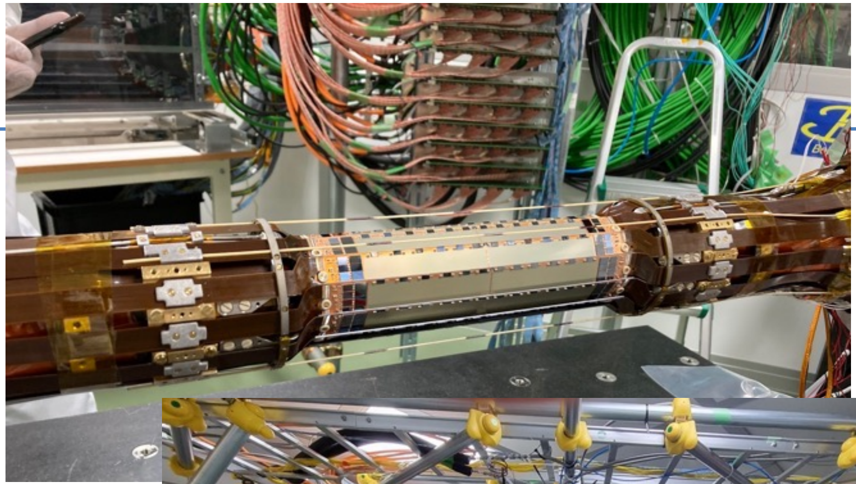
Larger pipe injection

LS1 work: Belle II

- Completion of pixel layers
  - Entirely new 2 complete layers of DEPFET sensors
    - Previously 2nd layer was 17% complete



Diameter 0.04 m



- Time of Propagation robustness
  - Replacement to Atomic Layer Deposited (ALD) Micro-Channel Plate PMT
  - ⟶ Increased lifespan & hit rate limit (3⟶5 MHz/cm^2)

- DAQ
  - New PCIe40 boards used by all subsystems
    - But PXD (specific data path)

Diameter 2.4 m

- CDC
  - Improved gas distribution & monitoring syste
    - Better gain stability

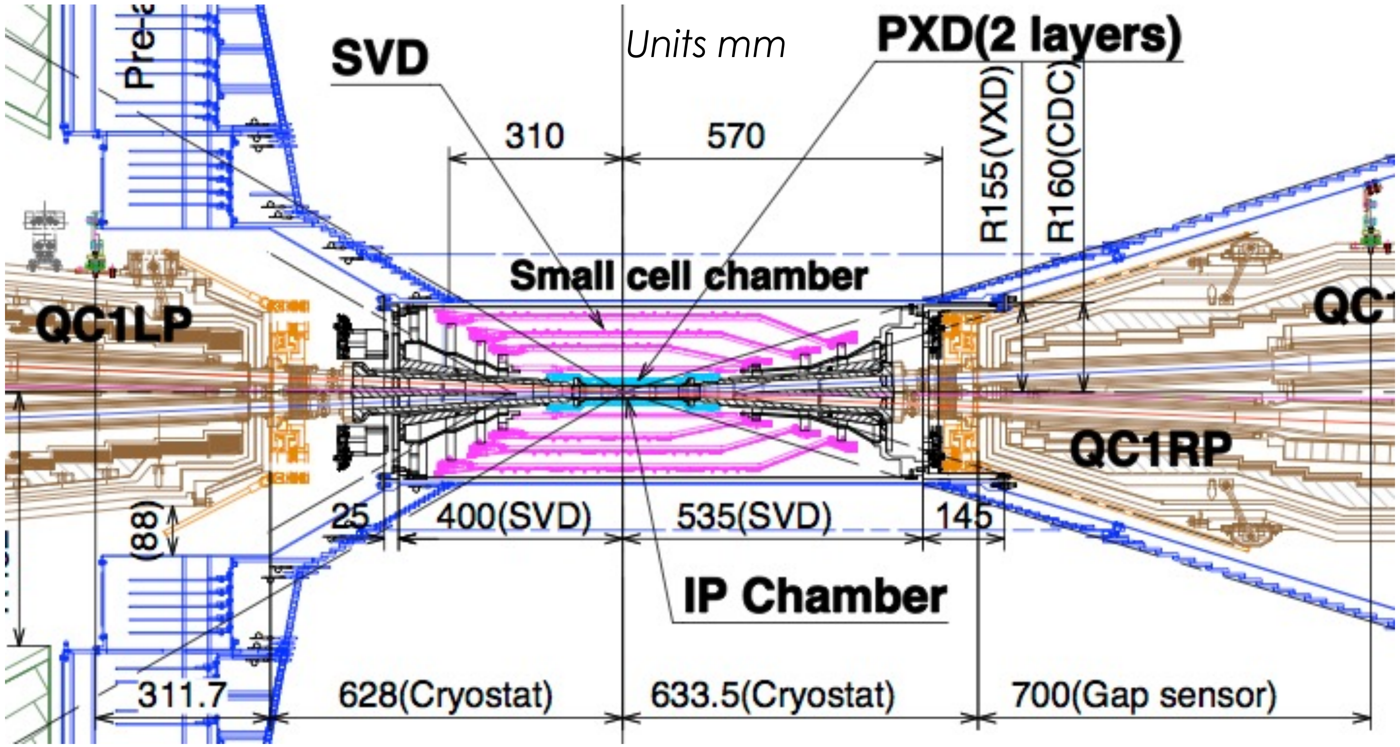
SuperKEKB upgrade for LS2

- **Goals** = allows higher luminosity reaching lower ß* and higher current while limiting beam-beam effects & preserving beam lifetime

<= Guidance from **International Task Force** connecting cross-continental/machine expertise

- Currently **exploring various options** for interaction region
  - 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 will likely change
Schedule for LS2 is indicative

Belle II plans at timeline ≥ LS2

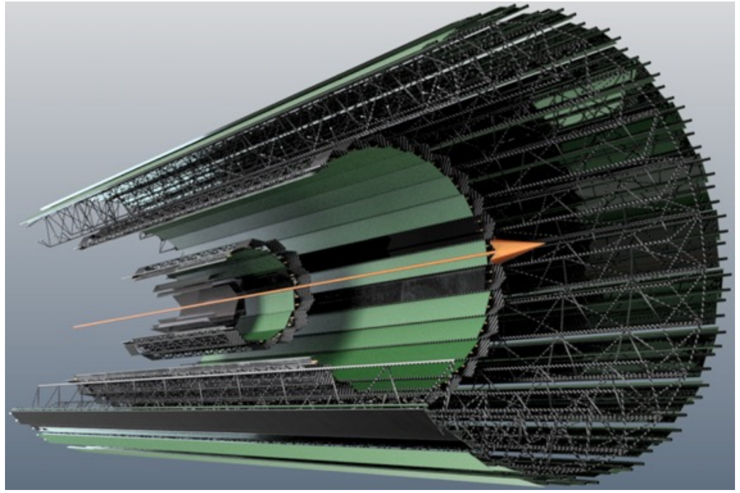
EOI	Upgrade ideas scope and technology	Time scale
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	LS2
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	LS2
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	LS2
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< LS2
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	LS2 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> LS2
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	LS2 and later
Trigger	Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives	< LS2 and later
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> LS2
TPC	TPC option under study for longer term upgrade	> LS2

New Si vertex & tracker

Long term options

New vertex detector preparation (LS2 timeline)

Among most advanced upgrade Belle II project

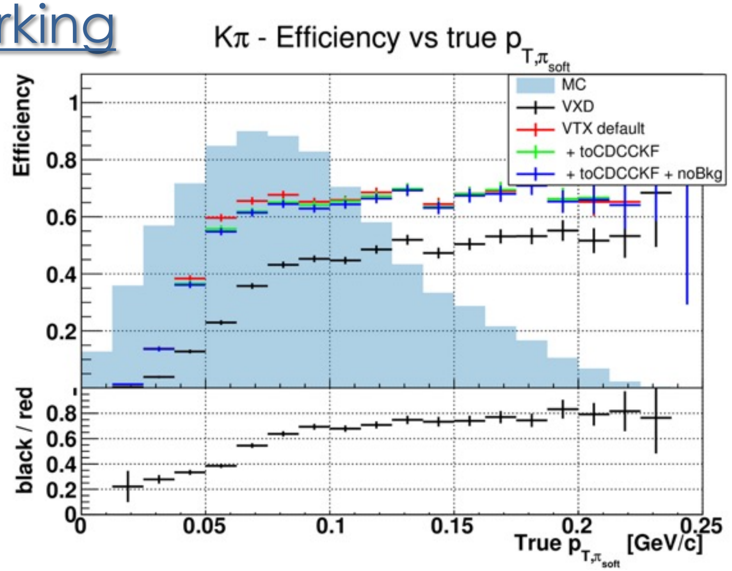


Diam. 28 cm
length 70 cm
=> 1 m^2

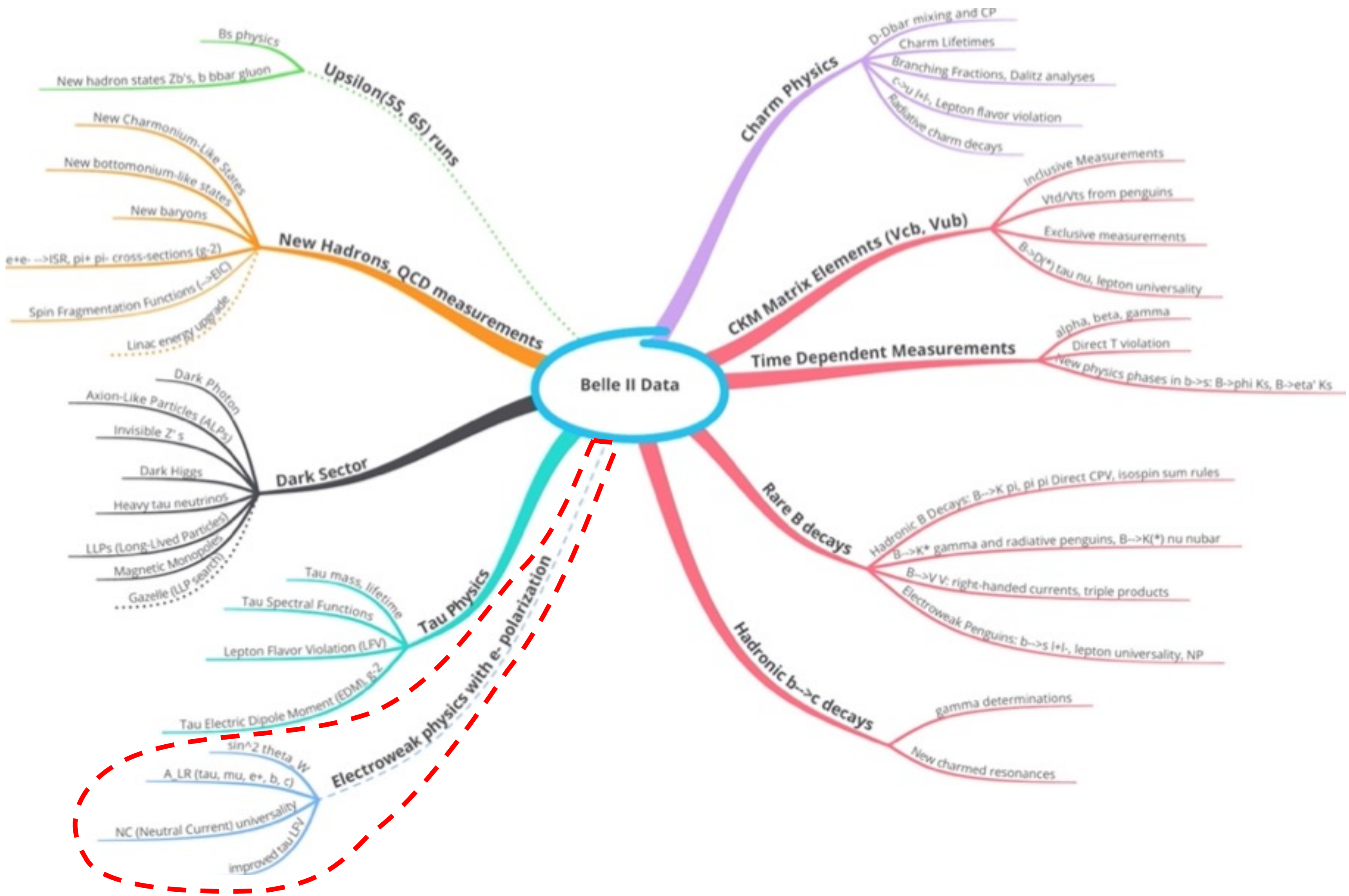
- Concept
  - **5 layers with high space-time granularity & low material budget**
    - Tracking robustness / background rate: occupancy $<\mathcal{O}(10^{-4})$
    - Higher vertexing precision / current VXD
  - Lighter services & "easy" geometry
    - adaptable to potential change of interaction region

- Technical choices
  - **Pixel sensor = MAPS** (main option), SOI (alternative)
    - 30-40 μm pitch with 100 ns integration time
  - All-silicon ladders (PXD-inspired) for inner layers (0.1% X_0)
  - "Standard" supported ladders (ALICE-ITS2 inspired) for outer layers (0.5-0.8 % X_0)

- Physics benchmarking
  - Soft π reconstruction in $B^0 \to D^{*-}\mu^+\upsilon_\mu$
    $\hookrightarrow \overline{D^0}\pi^-$



Going chiral?

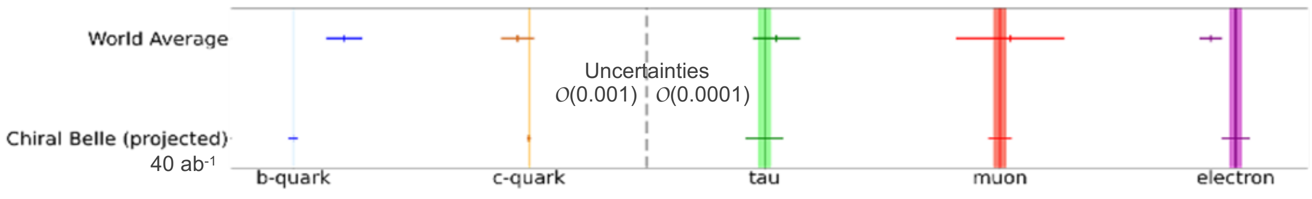


Chiral Belle II: potential physics reach

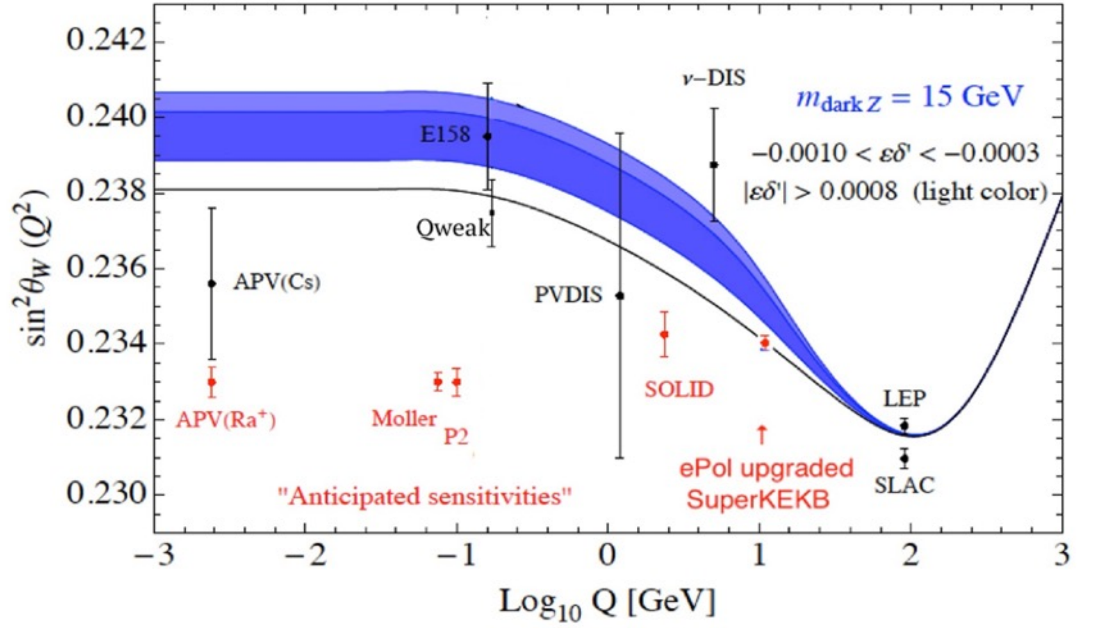
70% polarized electrons

- **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
    - $\tau \to l\gamma$

Uncertainties on g_V^f



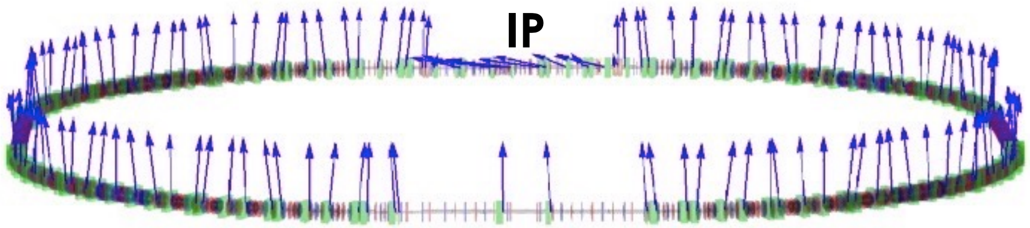
From PRD 92(5)2015

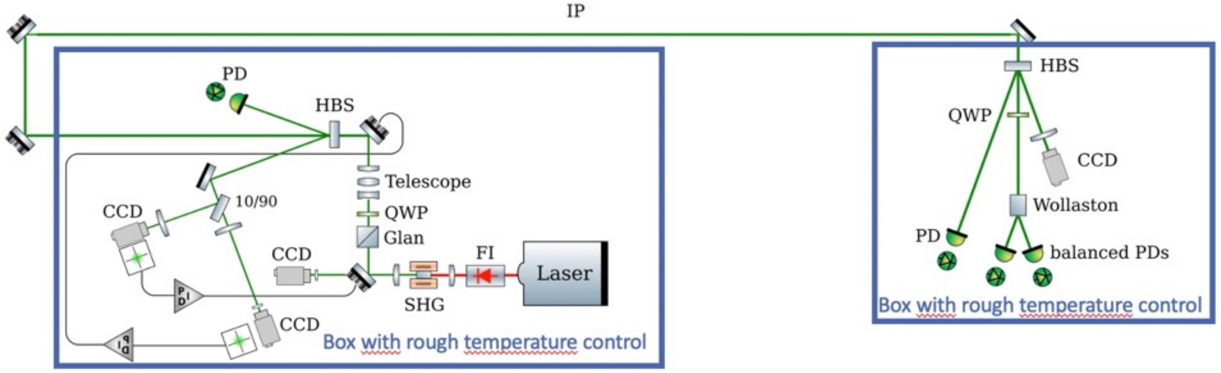


Chiral Belle II: required machine development

Installation during Long Shutdown 2 (~2027)

- Low emittance source
  - Laser on GaAs cathodes under development
  - Need **transverse polarization** for injection in HER
- Spin rotators
  - Get **longitudinal polarization** 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





The future is not for us to predict but to prepare…

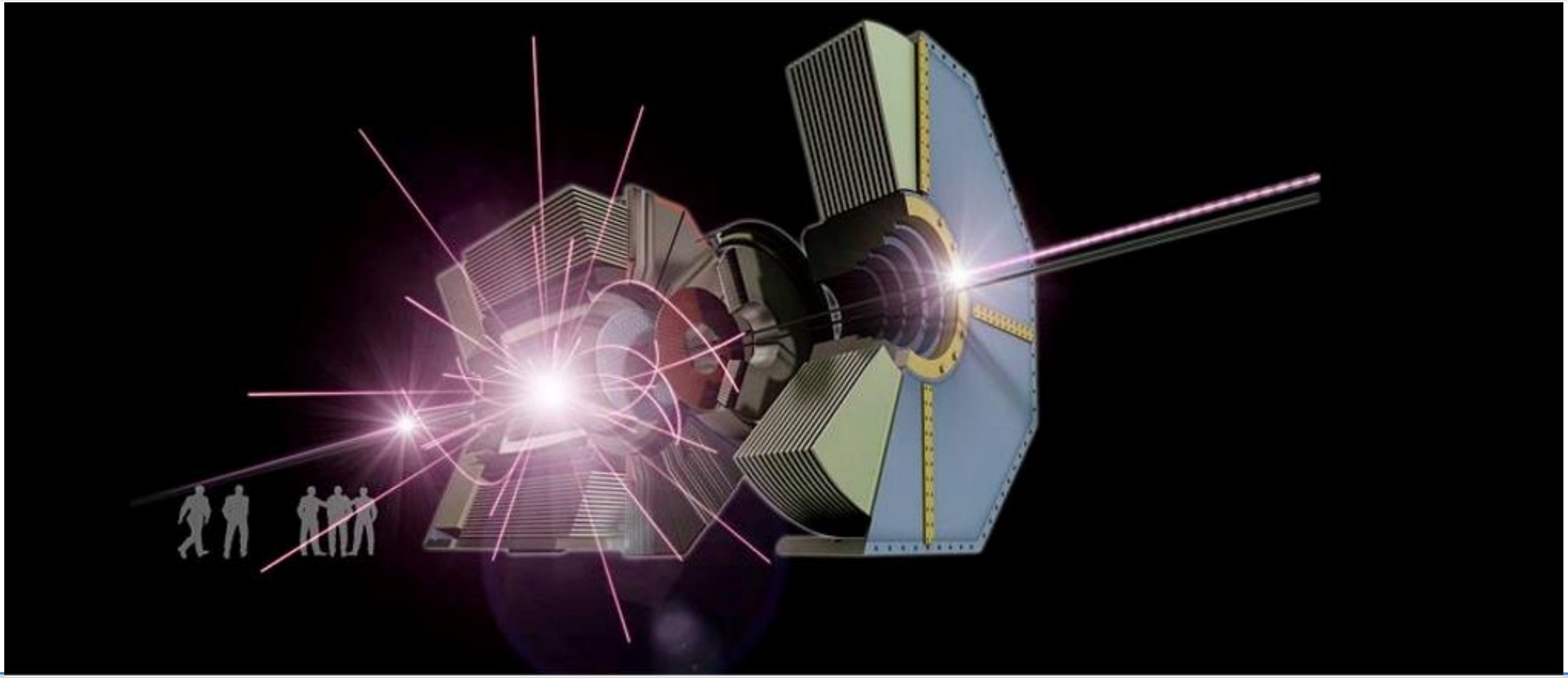
⇒ The Belle II physics book PTEP 12 (2019) 123C01

⇒ Expression of Intent for upgrades (Feb.2021 private)

⇒ Snowmass contributions, physics: arXiv 2207.06307
upgrades: arXiv 2203.11349,
background: arXiv 2203.05731
polarisation: arXiv 2205.12847

⇒ CDR for mid-term upgrade in the writing

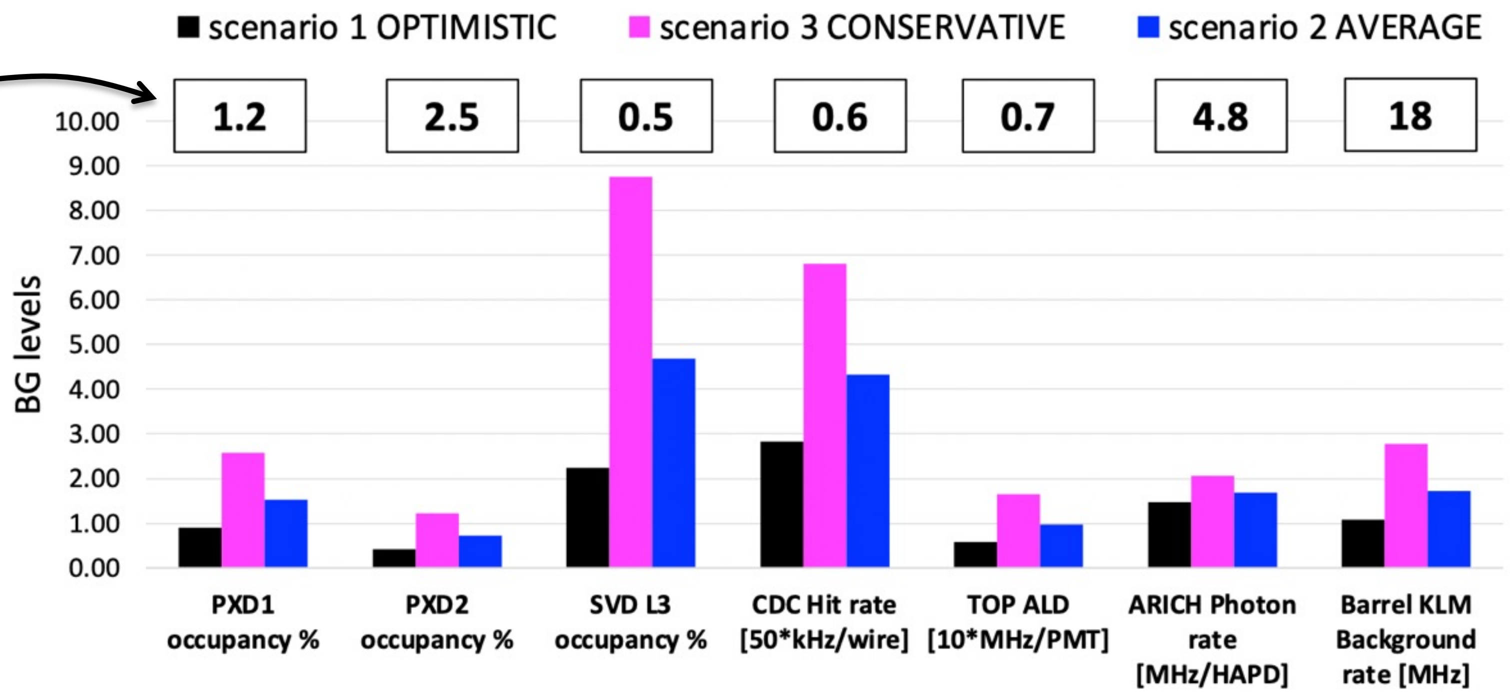
SUPPLEMENTARY SLIDES



Beam background scenarii for luminosity 6x10^{35} cm^{-2}.s^{-1}

Safety factor = $\frac{\text{detector limit}}{\text{Background rate}}$ (conservative scenario)

Detector	BG rate limit		Measured BG
Diamonds	1–2 rad/s		< 130 mrad/s
PXD	3 %		0.1 %
SVD L3, L4, L5, L6	4.7 %, 2.4 %, 1.8 %, 1.2 %		< 0.22 %
CDC	200 kHz/wire		27 kHz/wire
ARICH	10 MHz/HAPD		0.5 MHz/HAPD
Barrel KLM L3	50 MHz		4 MHz
	non-luminosity BG		
	before LS1	after LS1	
TOP ALD	3 MHz/PMT	5 MHz/PMT	1.7 MHz/PMT
	+ luminosity BG		



Work in progress for CDR

Impact on performance & physics

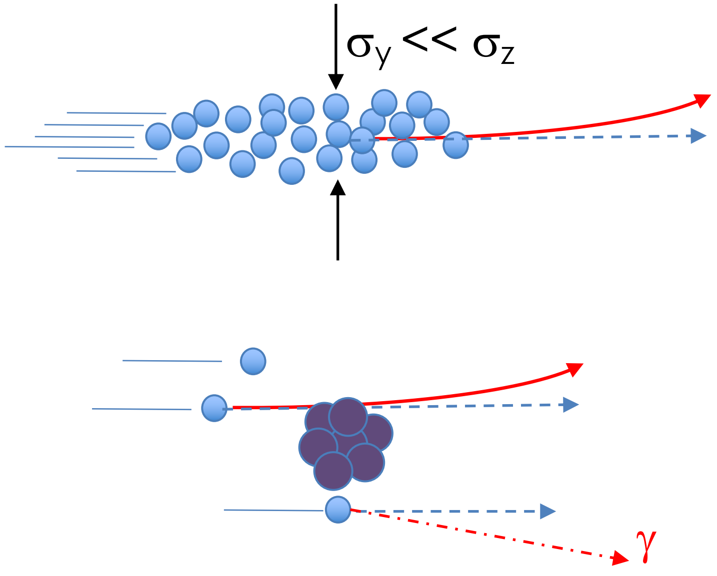
=> Snowmass Belle II : arXiv 2203.11349

Topic	VXD	CDC	PID	ECL	KLM
Low momentum track finding	✓	✓			
Track p, M resolution		✓			
IP/Vertex resolution	✓				
Hadron ID		✓	✓		
$K^0_{\rm L}$ ID				✓	✓
Lepton ID		✓		✓	✓
π^0, γ				✓	
Trigger	✓	✓			

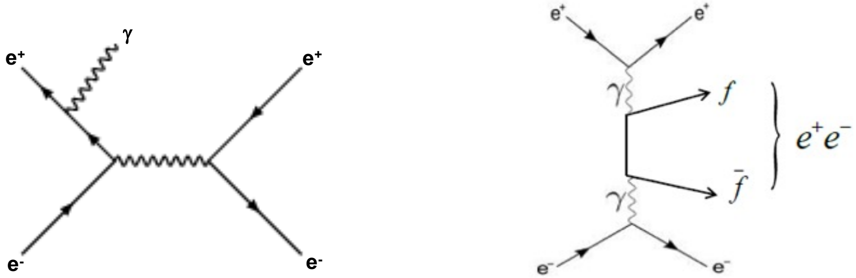
Topic	VXD	CDC (incl. Trigger)	PID	PID(Ω coverage)	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓		✓	✓		✓
R, Polarisation$(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓		✓		
$S_{\rm CP}, C_{\rm CP}(B \to \pi^0\pi^0, K^0_S\pi^0)$	✓	✓			✓	
$S_{\rm CP}, C_{\rm CP}(B \to \rho\gamma)$		✓	✓		✓	
$S_{\rm CP}, C_{\rm CP}(B \to J/\psi K^0_{\rm S}, \eta' K^0_{\rm S})$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches		✓			✓	✓

Beam induced backgrounds

- Single beam effects
  - Touschek ← intra-beam scattering
    - rate $\propto \frac{I_{bunch}^2 \ N_{bunch}}{(\sigma_x \ \sigma_y) \ E_{beam}^3} = \frac{I_{beam}^2}{(\sigma_x \ \sigma_y) \ E_{beam}^3 \ N_{bunch}}$
  - Beam gas ← vacuum residues
    - rate $\propto I_{\text{bunch}} \times N_{\text{bunch}} \times P(I)$
    - Dynamic pressure $P(I) = (p_0 + p_1 I_{beam})$
  - Synchrotron radiation ← magnet bending
    - rate $\propto I_{\text{beam}}$



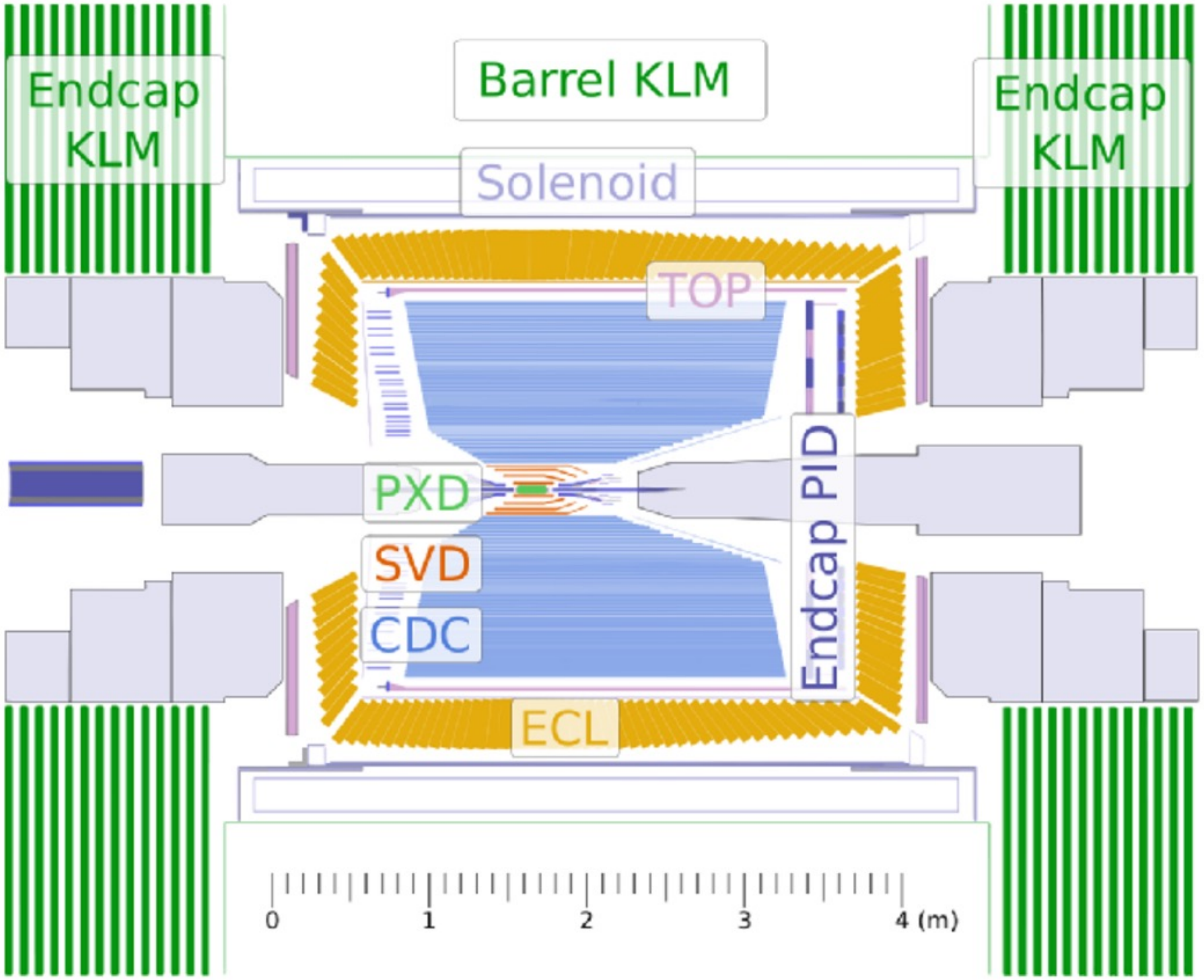
- Beam-beam effects (QED)
  - rate $\propto$ Luminosity

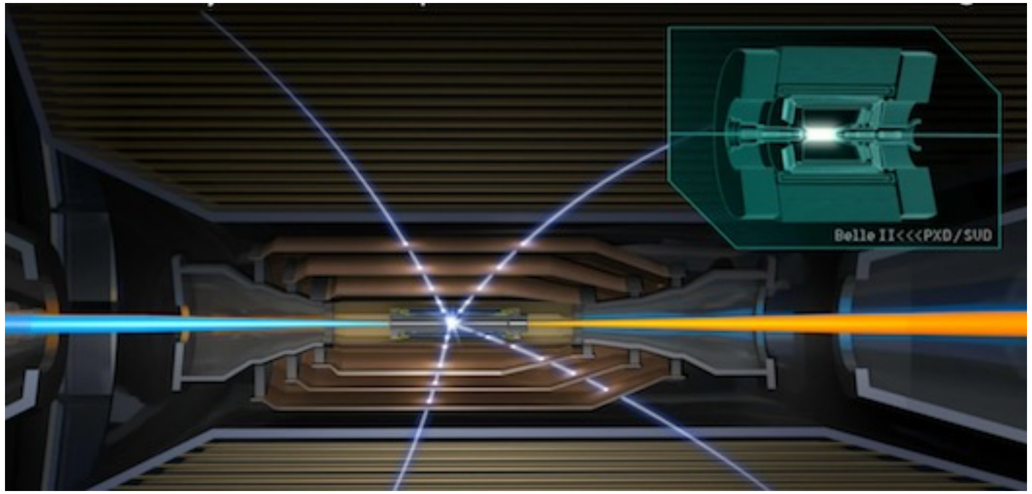


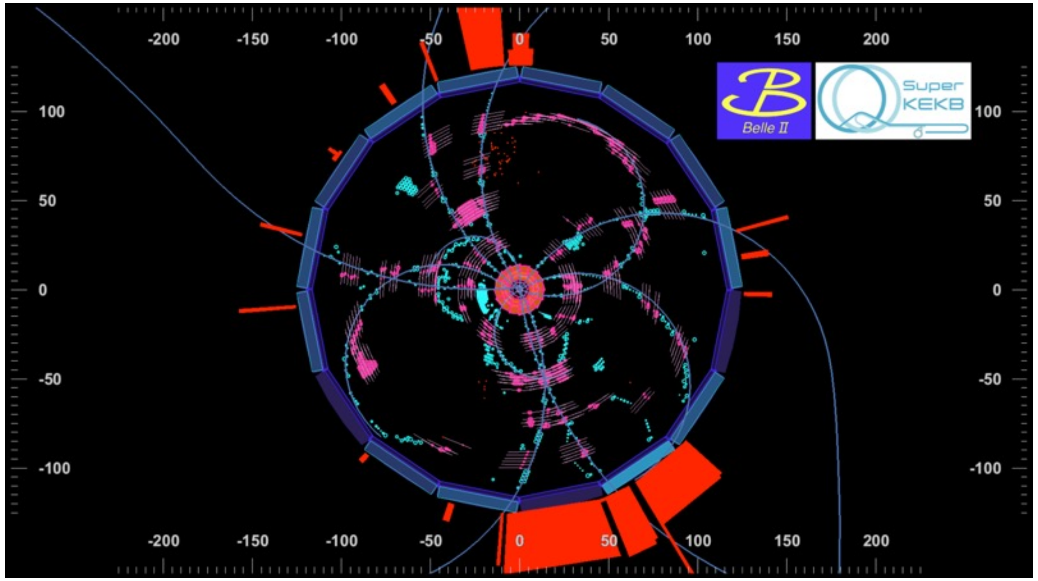
Radiative Bhabha scattering

2-photon interaction

Belle II, another view







Vertex detector: VXD (PXD+SVD)

Rationale

- Be prepared for IR redesign
  (higher Background conditions)
- Improve performance / IP resolution, low p_T tracks
- Be prepared to cover inner CDC (radii 135-240 mm)
- Triggering: possible contribution to L1
- Target **Medium-term**

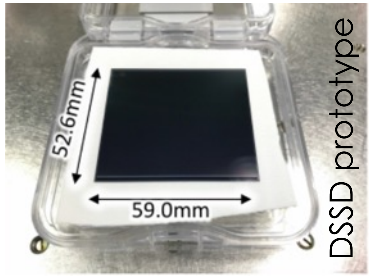
Requirements

5-6 layers over radii	14-135 mm
Spatial resolution	< 15 µm
Total material budget	< (2x0.2% + 4x0.7%) X_0
Hit rate	120 ↘ 1 MHz/cm^2
Total Ionizing Dose (inner)	100 kGy / year
NIEL fluence (inner)	5x10^{13} n_{eq}/cm^2

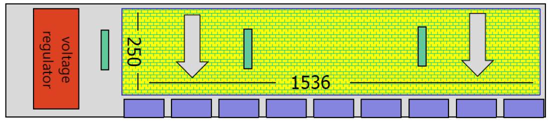
⇒ Higher granularity in time and/or space / current VXD

Prototyping & tests on-going

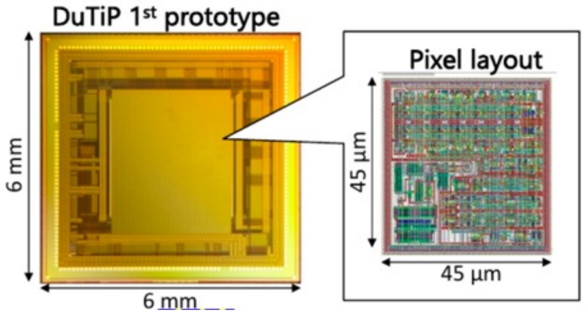
Various proposals



- **Thin and fine-pitch DSSD**
  - Sensor 140 µm thin & z-pitch < 80 µm
  - New ASIC for low noise

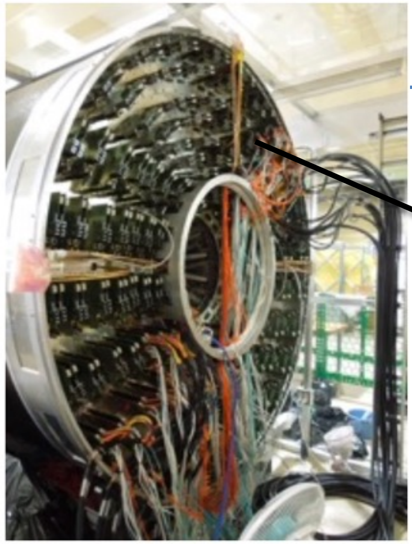


- **Upgraded DEPFET**
  - Higher radiation tolerance through higher gain
  - Faster read-out (few µs) with re-orientation and new ASICs

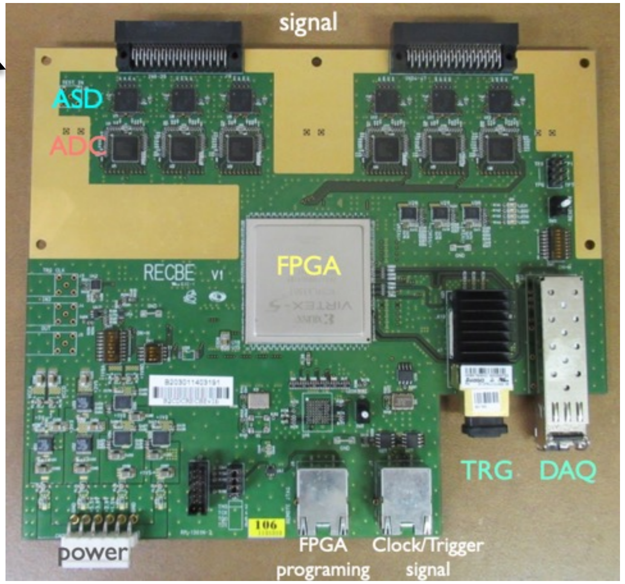


- **SOI pixels**
  - Lapis 200 nm process
  - Dual Time pixel sensor (DuTiP)
  - pitch 45 µm
    2x60 ns integration
- **CMOS-MAPS**
  - Tower 180 nm process
  - Extension of TJ-MONOPIX2 ⟶ OBELIX sensor
  - Pitch <40 µm with 100 ns integration
  - Fully pixelated VXD concept = **VTX**
    with all-Si modules or ALICE-ITS-like ladders

Main tracker: CDC



Current read-out board



Short-/Medium-term

- Robustness against radiation-damage
- Mitigate cross-talk between read-out channels

Replacement of read-out board

- New ASIC
  - all-in-one ASD+ADC, lower cross-talk (100 ↘ 10 mV/7pC)
- Components with higher radiation tolerance
  - Optical transceiver (sensitive to γ and neutrons)
  - FPGA (sensitive to SEU)

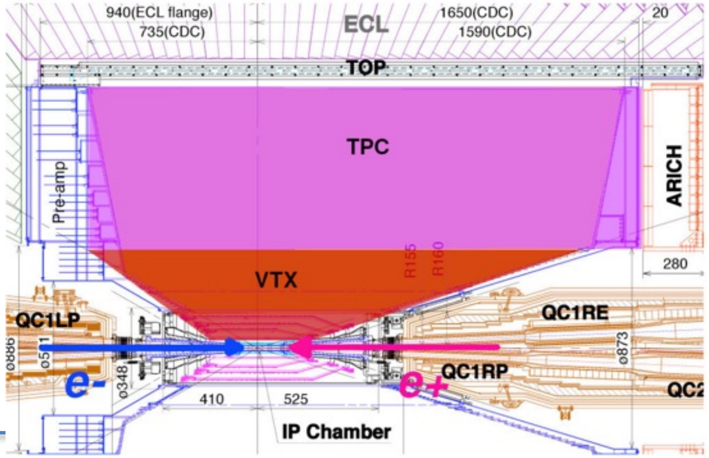
- Tests in 2022
- Mass production 2023

Long-term studies

- Sustaining higher rates & backgrounds

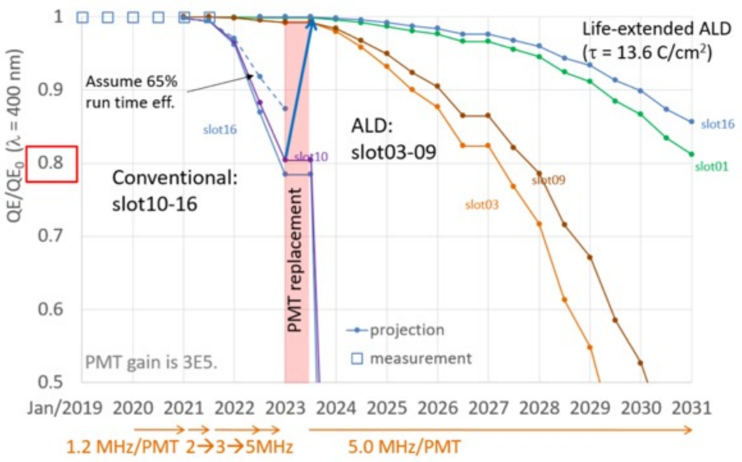
Exploration

- Extended VTX
- TPC tracker
  with pixel read-out
  Gridpix-like 200^2 μm^2



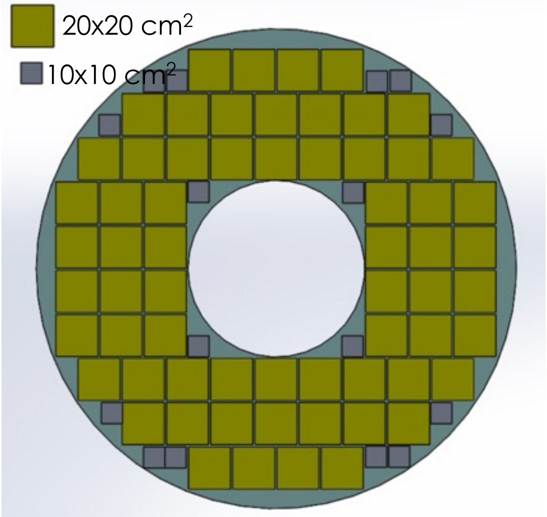
Particle Identification: TOP & ARICH

- Time Of Propagation (TOP)
  - Maintain efficiency against ever higher background
    - Needed already at **short/medium-term**
  - Photon detection devices
    - 2022: move to Atomic Layer Deposited ALD-MCP-PMT
    - 2026: move to life extended ALD-MCP-PMT possibly to SiPM



  - Read-out electronics to accommodate SiPM
    - Better compactness using SiPM dedicated ASICs
    - Allows extra cooling required by SiPM

- Aerogel RICH
  - target **long term**
    - Current Hybrid-APD not adapted beyond 8×10^{35} cm^{-2}.s^{-1}
  - 1st option: SiPM
    - On-going evaluation of various device
      - Single photon detection, Dark count rate, Neutron sensitivity (5×10^{12} n_{eq}/cm^2), Cooling required
  - 2nd option: Large Area Picosecond photodetectors
  - Read-out
    - Upgrade of current ASIC
    - Or new ASIC

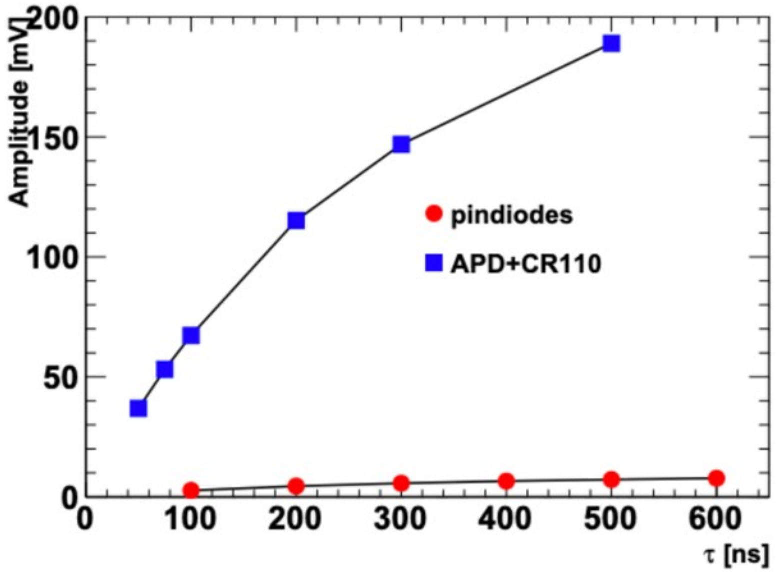


- STOPGAP proposal
  - target **long term**
  - Fill-in gaps between TOP quartz bar
  - CMOS-MAPS with 50 ps timing

Calorimetry: ECL

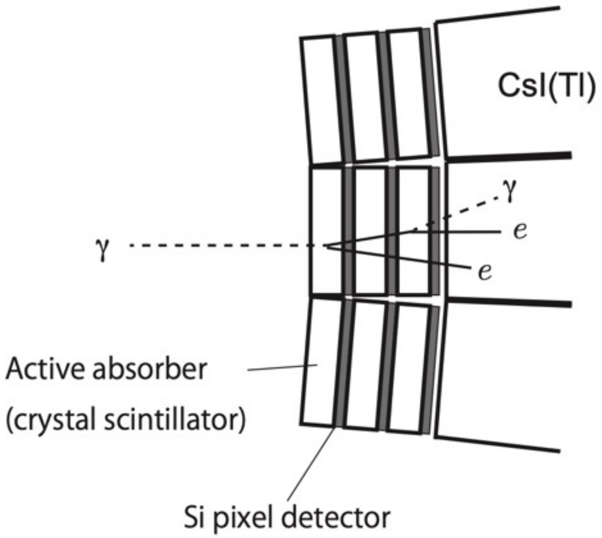
- Rationale
  - Target **long-term**
  - Reduce pile-up from beam-induced background
  - Sensitivity to photon incident angle

- Read-out of current Csi(Tl)
  - From PiN diodes to APD



- Faster cristals
  - Full replacement: Csi(Tl) ⟶ pure Csi
    - From 1 µs to 30 ns light decay tile
  - Photon detection: WLS + APD

- New preshower
  - BGO/LYSO + 1mm^2 Si pixel
    - Angle = 0.08 rad expected @ normal incidence

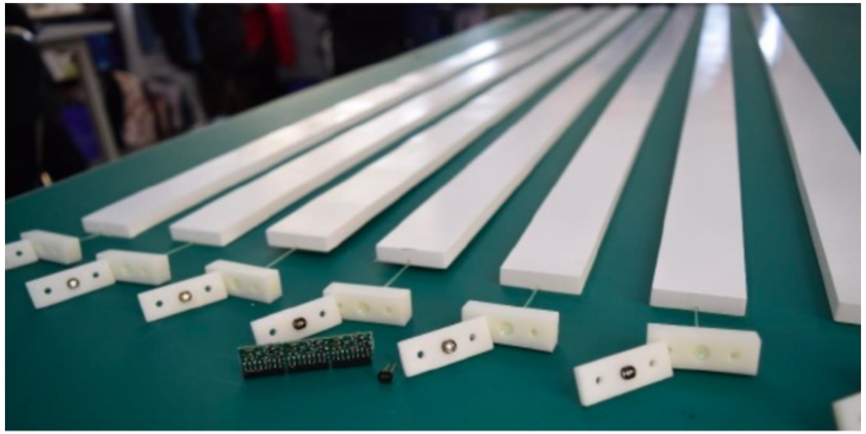


Klong & Muon identification: KLM

- Target **medium to long term**

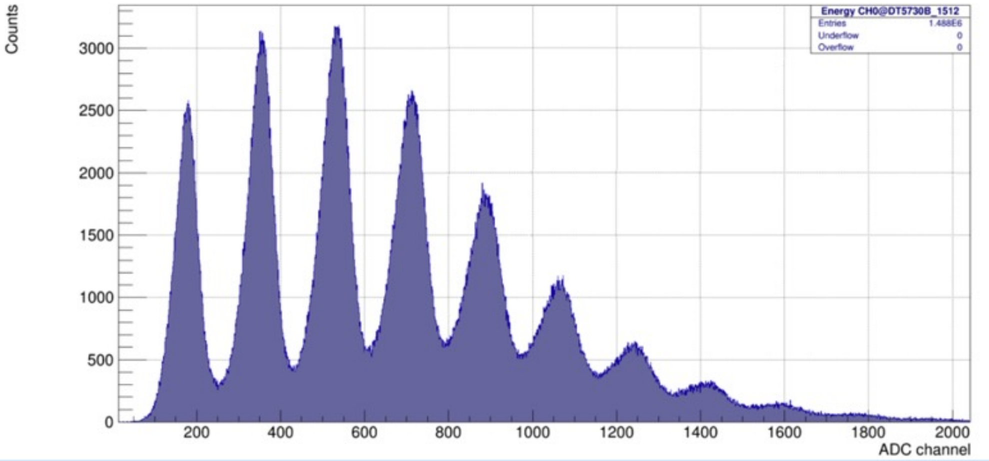
Complete replacement of RPCs with Scintillators

- Rationale: increased rate & robustness of read-out chain
- New system = scint. bars + wave-length shifter fibers + SiPM
  - Already used in first layer & end-cap
- More compact read-out
  - Allowing waveform sampling (time resol.) & improved data push to trigger



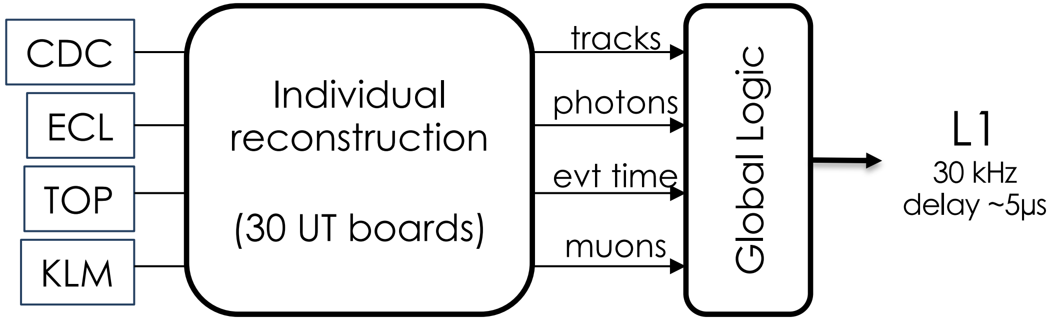
Investigating TOF-like performance

- Rationale: K_L energy & background neutron rejection
- Required time resolution ~30 ps
- R&D on-going with large MPPC + new pre-amp



Trigger

- **Rationale**
  - Keep high-efficiency on hadronic events
  - Improve efficiency on low-multiplicity events (τ, dark sector)
  - **Continuous improvements**



- **Hardware**
  - Deployment of most recent UT4 boards
    - Xilinx Ultrascale with 200k gates, 25 Gbps, DDR4
    - Target 2026
  - New UT5
    - Xilinx Ultrascale+ with 8000k gates, 32 Gbps, UltraRAM
    - Lower #boards needed
    - 2024-32

- **Firmware**

Component	Improvement	Time	#UT
CDC cluster finder	beamBG rejection	2026	10
CDC 2Dtrack finder	increase occupancy limit	2022	4
CDC 3Dtrack finder	enlarge θ angle acceptance	2022	4
CDC 3Dtrack fitter (1)	beamBG rejection	2025	4
CDC 3Dtrack fitter (2)	beamBG rejection	2025	4
Displaced vertex finder	LLP search	2025	1
ECL waveform fitter	resolution	2026	–
ECL cluster finder	beamBG rejection	2026	1
KLM track finder	beamBG rejection	2024	–
VXD trigger	BG rejection	2032	–
GRL event identification	signal efficiency	2025	1
GDL injection veto	DAQ efficiency	2024	–