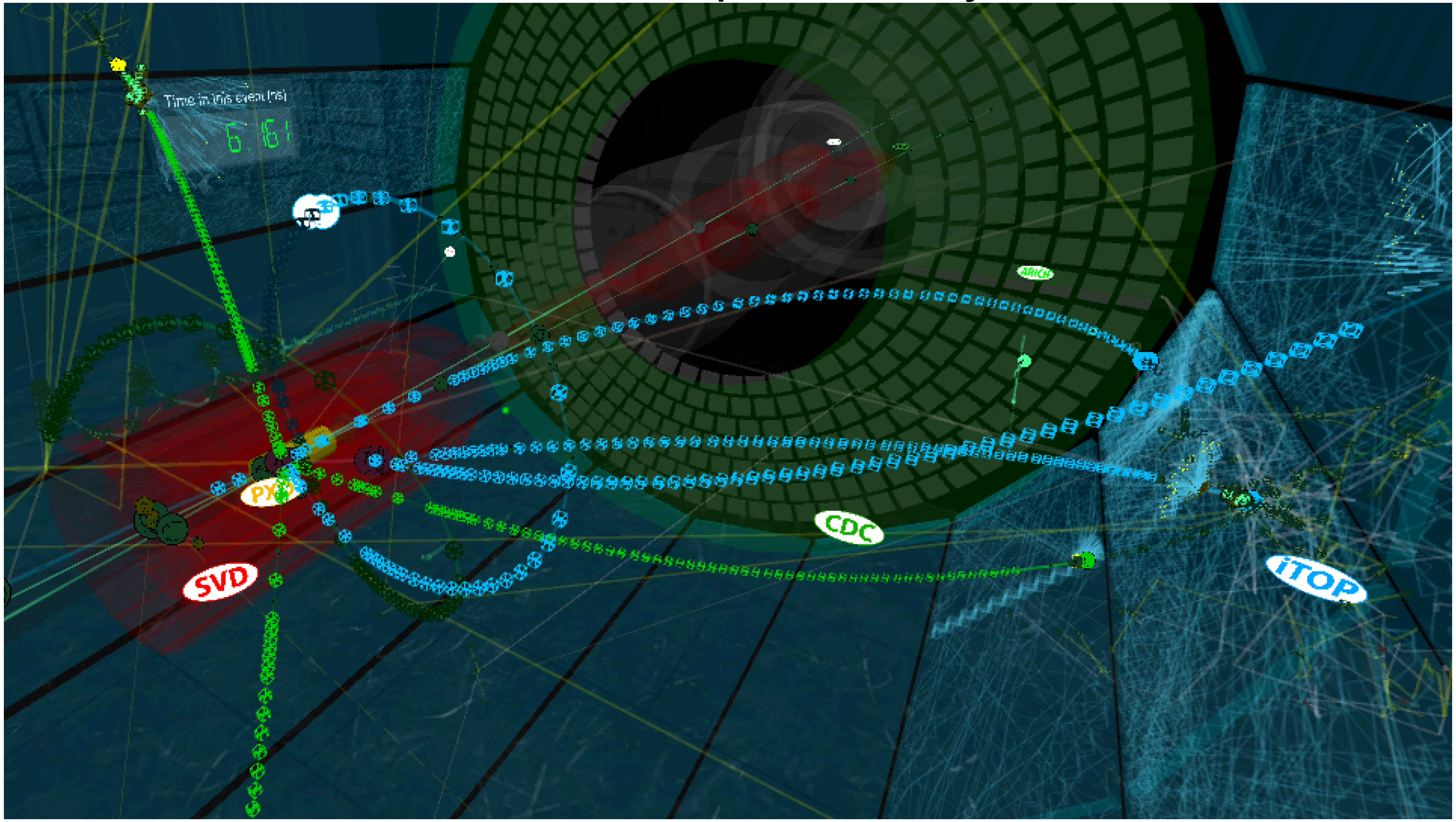
Particle Identification in the Belle II Detector

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

IAS HEP2021 Workshop   January 14, 2021



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

Belle II is looking for evidence of New Physics

SuperKEKB + Belle II is the *Intensity Frontier facility* for beauty mesons, charm mesons and τ leptons.

Unique new physics capabilities and unique detector capabilities ("single B meson beam," neutrals, neutrinos), clean environment with good systematics, which are **critical for New Physics searches**: *charged Higgs, new weak couplings and phases, lepton flavor violation, …*

Photo credit: Ron Lipton *(Fermilab)*

2014 US P5 report: This provides unique sensitivity to physics at energy scales far higher than can be accessed directly at colliders.

from Tom Browder's 2017 Belle II Summer School presentation

Belle II Physics "Mind Map" for Snowmass 2021

From *The Belle II Physics Book*, PTEP **2019**, 123C01 (2019)

Snowmass LOIs: confluence.desy.de/display/BI/Snowmass+2021

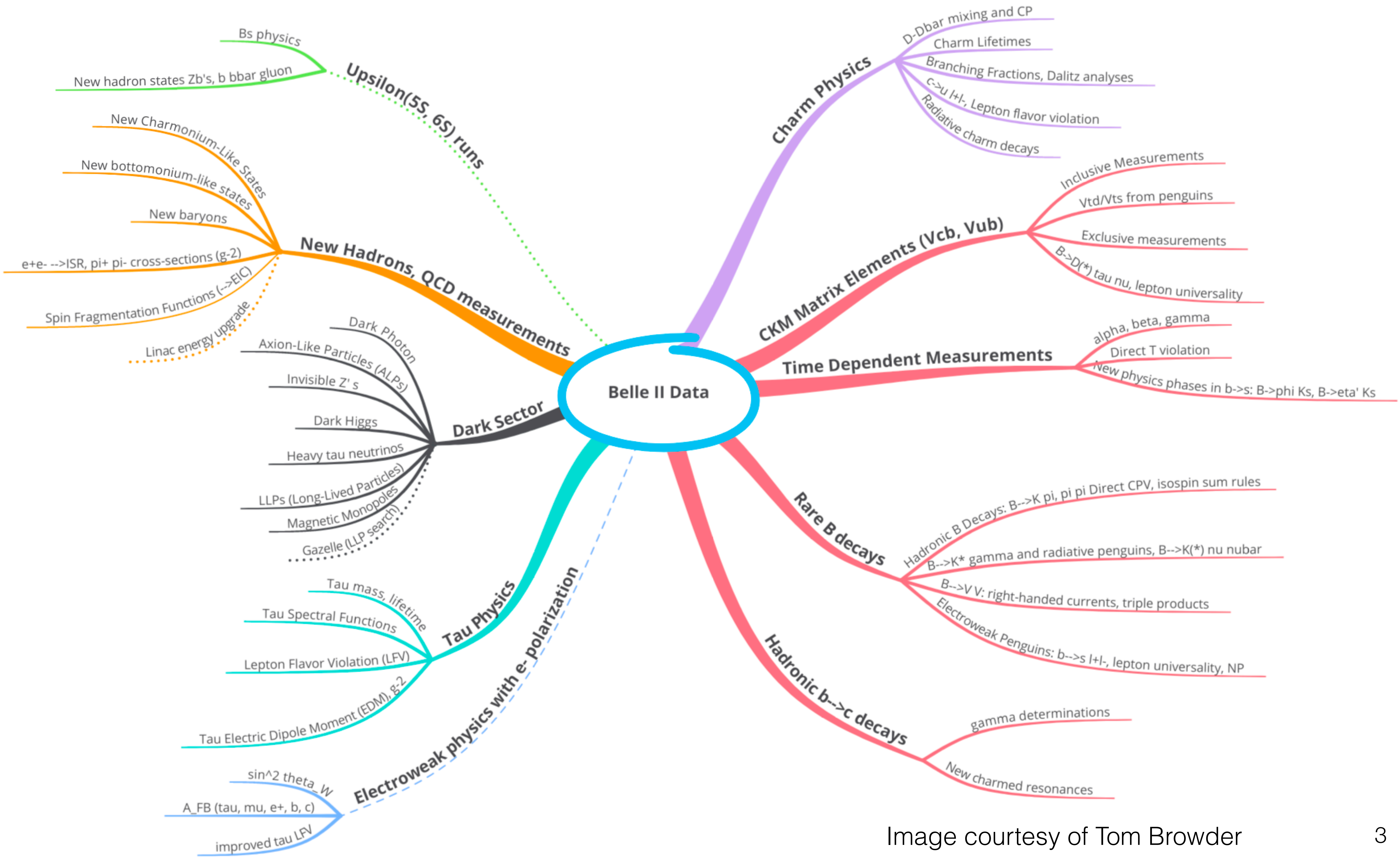
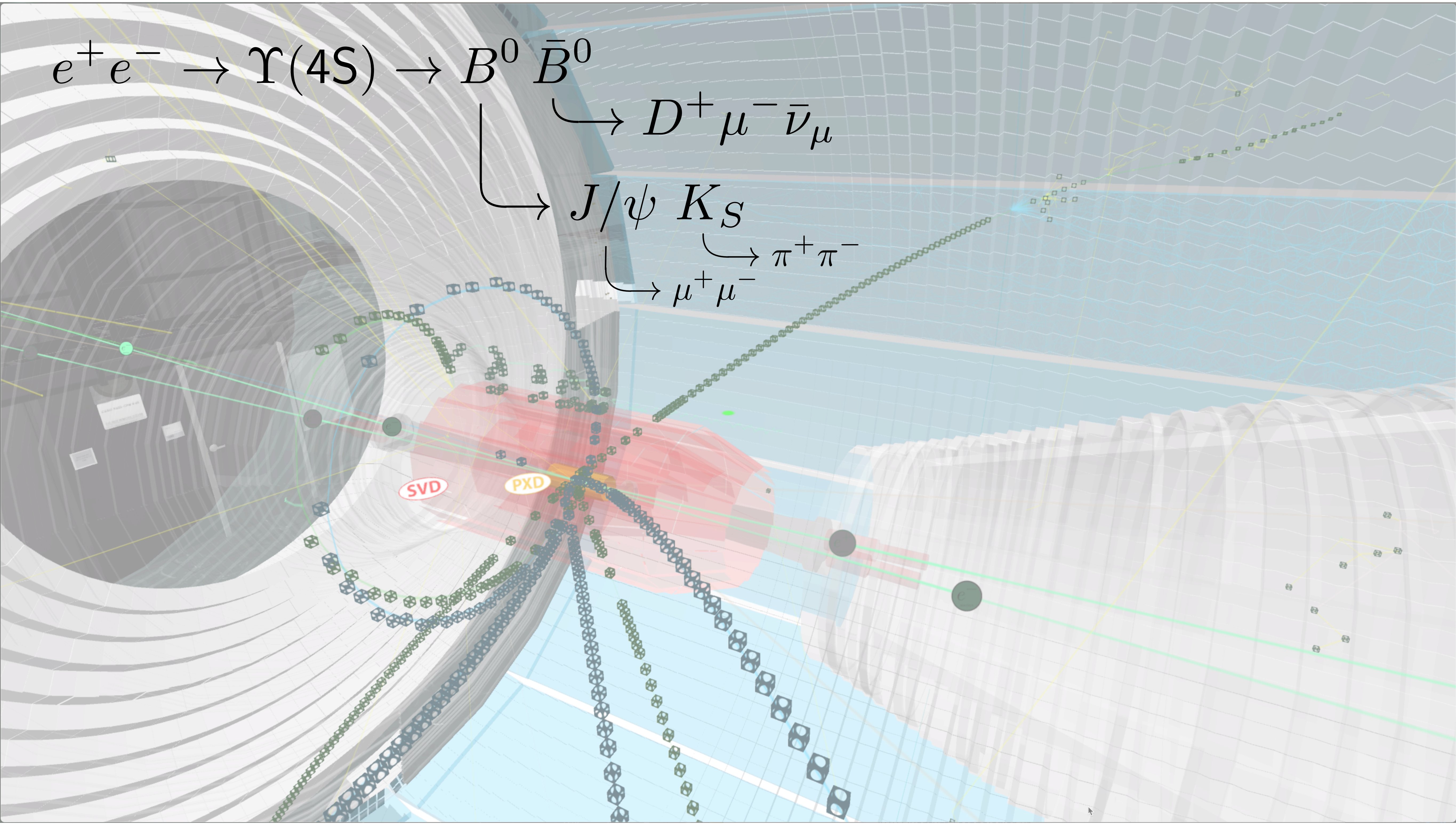
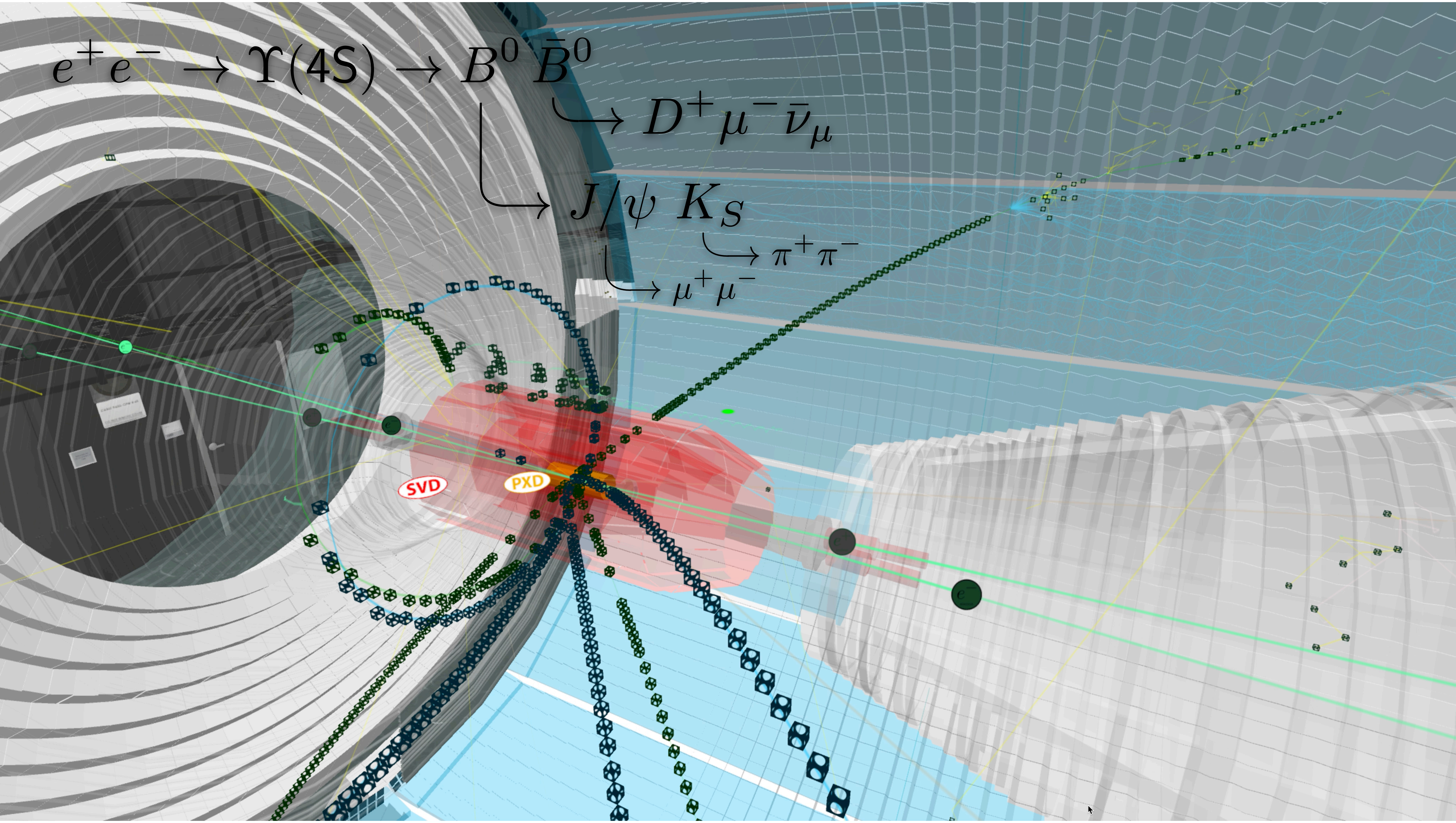


Image courtesy of Tom Browder

A canonical $B\overline{B}$ Event: the "Golden Mode"



A canonical $B\bar{B}$ Event: the "Golden Mode"

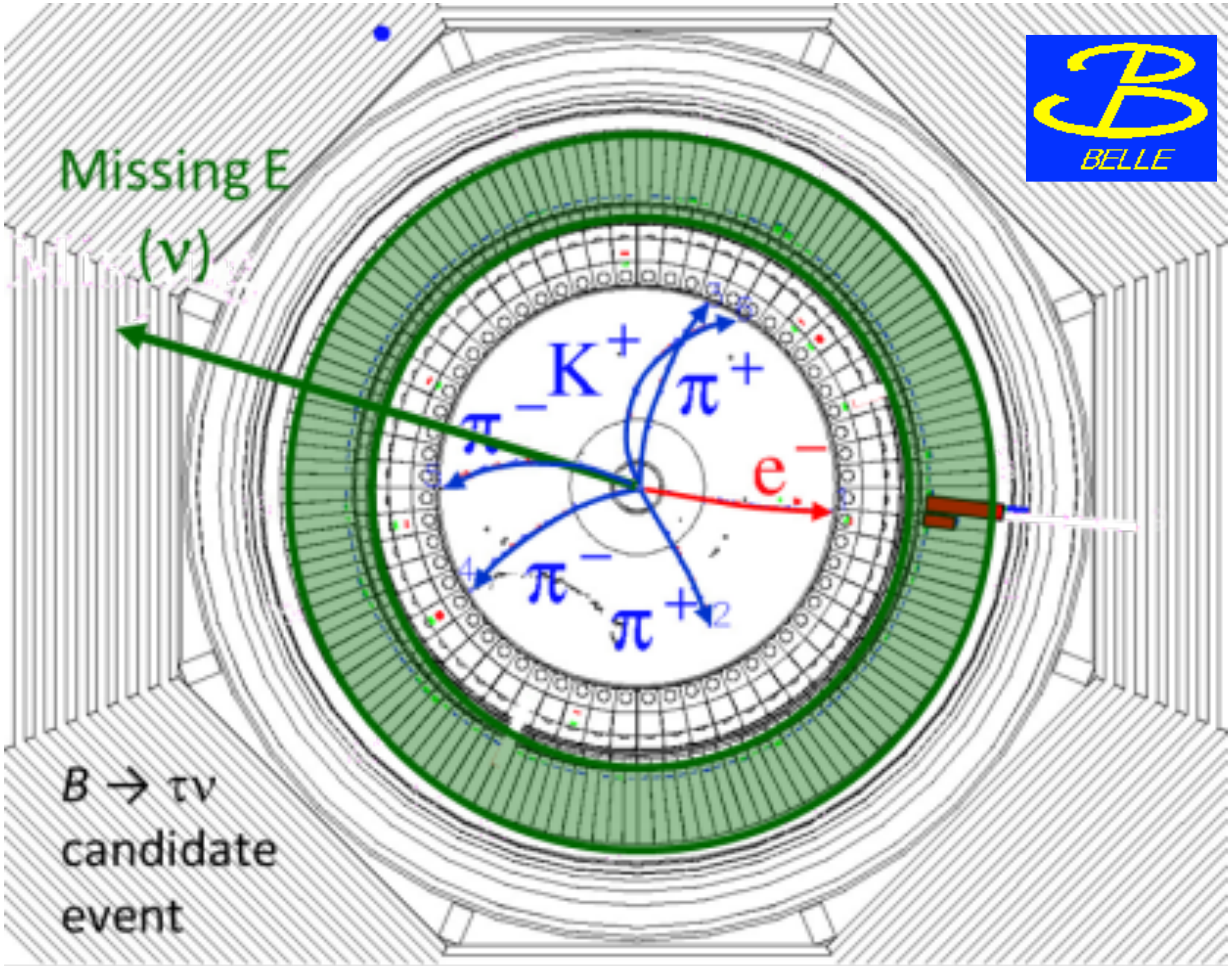


from "Belle II in Virtual Reality"

Example of a $B^+ \to \tau^+ \nu$ decay *in Belle data*

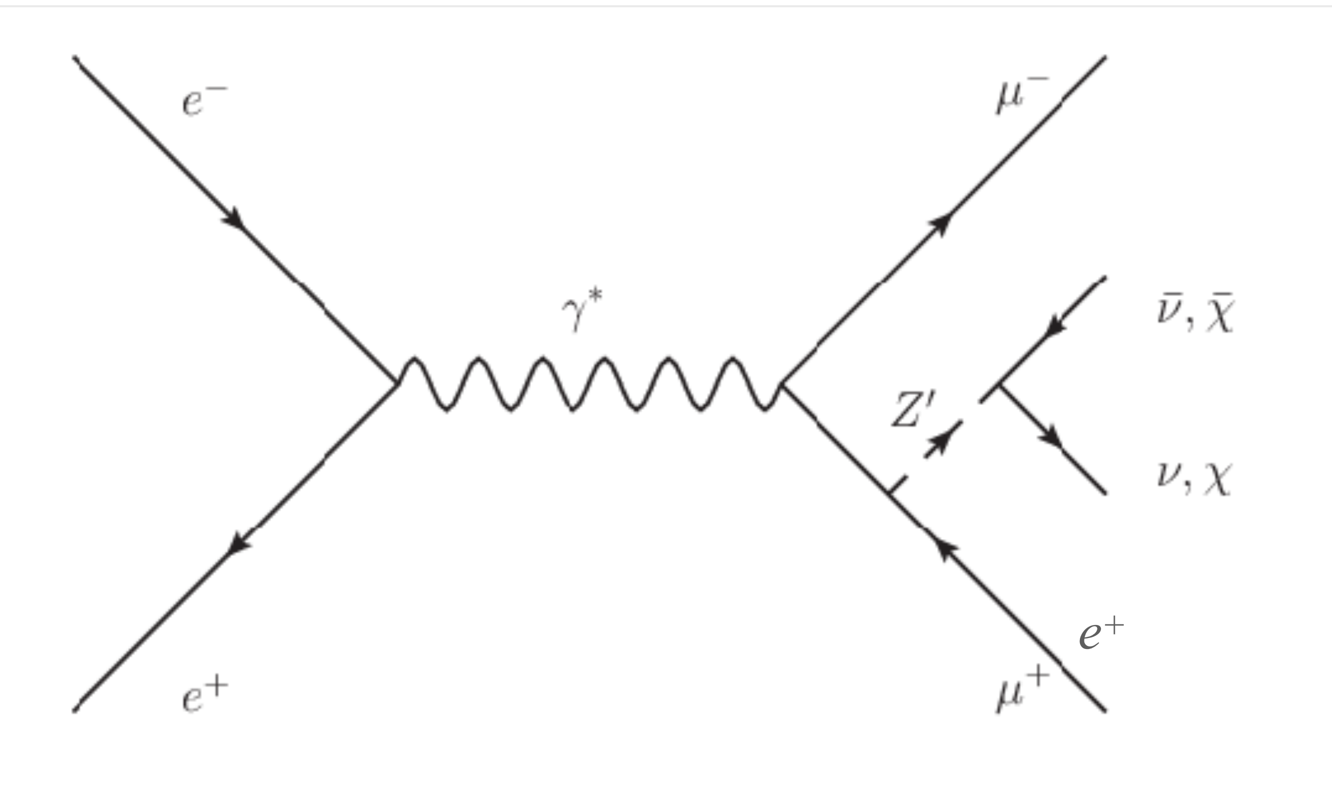
$$B^+ \to D^0 \pi^+$$
$$\hookrightarrow K^+ \pi^- \pi^+ \pi^-$$

$$B^- \to \tau^- \bar{\nu}$$
$$\hookrightarrow e^- \nu \bar{\nu}$$



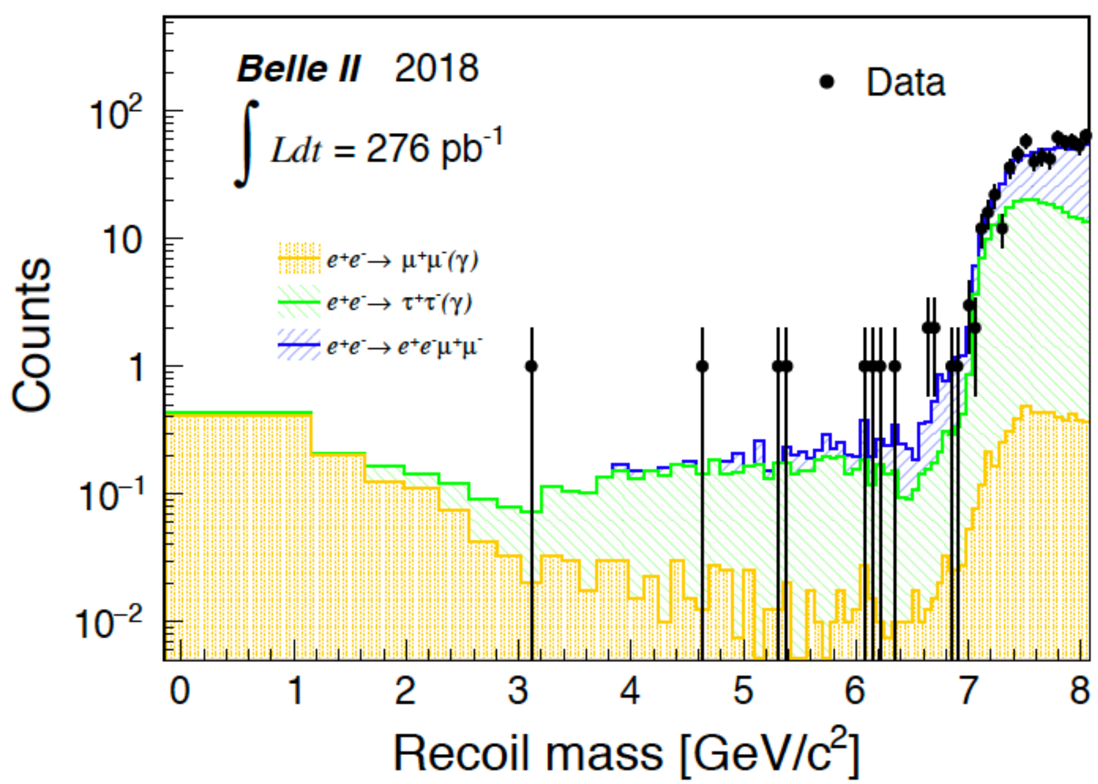
Clean e^+e^- environment and kinematic constraints *(known initial 4-momentum, hadronic tag decay)* make this possible

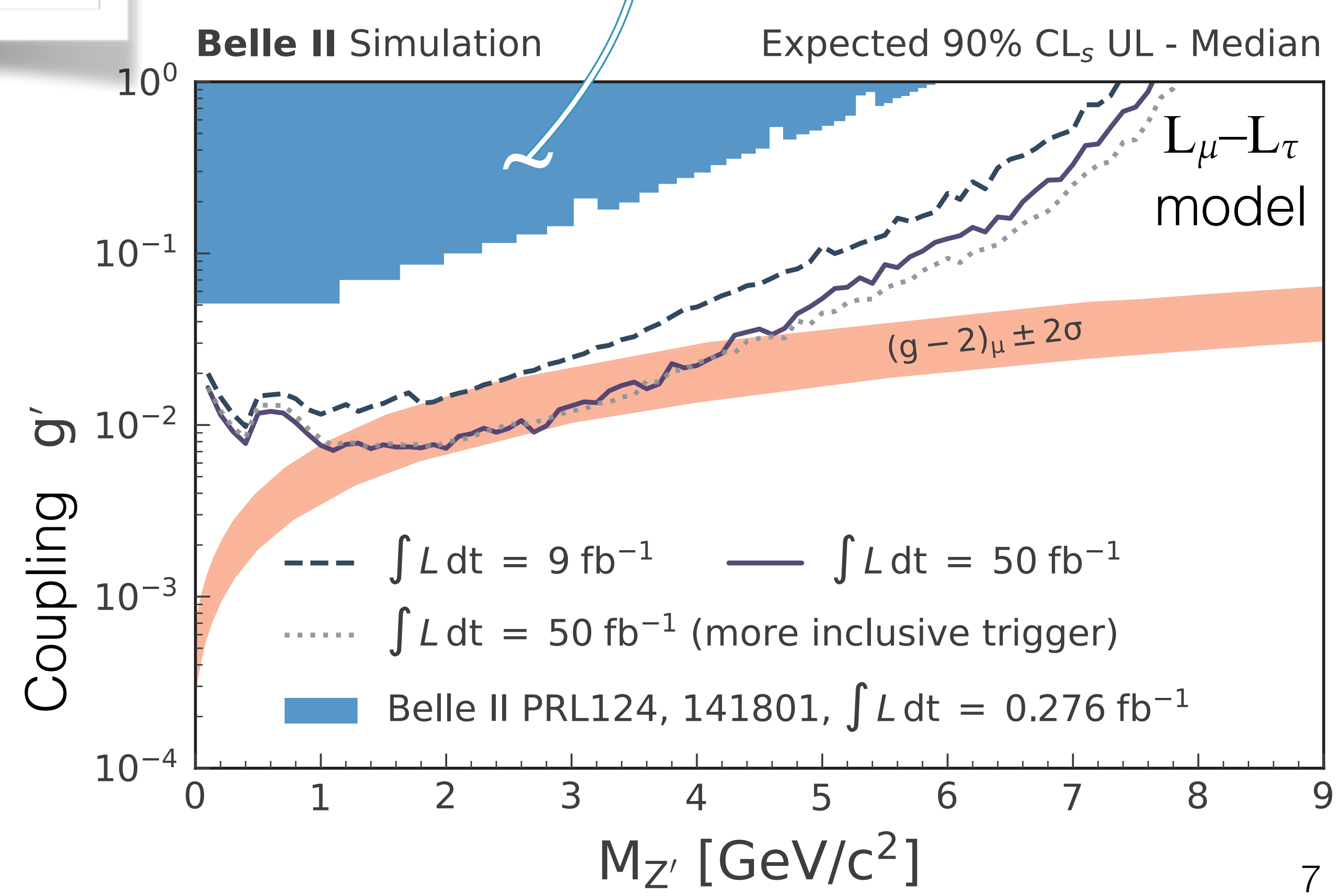
Dark-matter search: $Z' \to$ invisible



Signature: invisible recoil against a $\mu\mu$ or μe pair

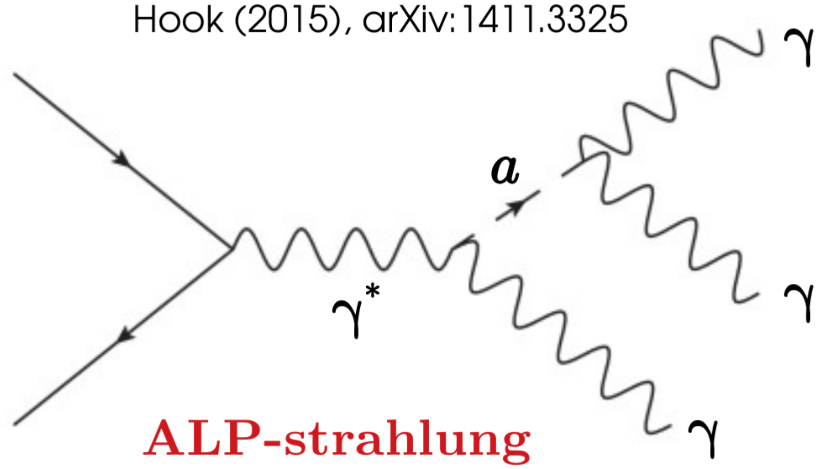
- Poorly constrained at low Z' mass
- Might explain muon g–2 anomaly
- PRL **124**, 141801 (2020)





Axion-like pseudoscalars coupling to bosons

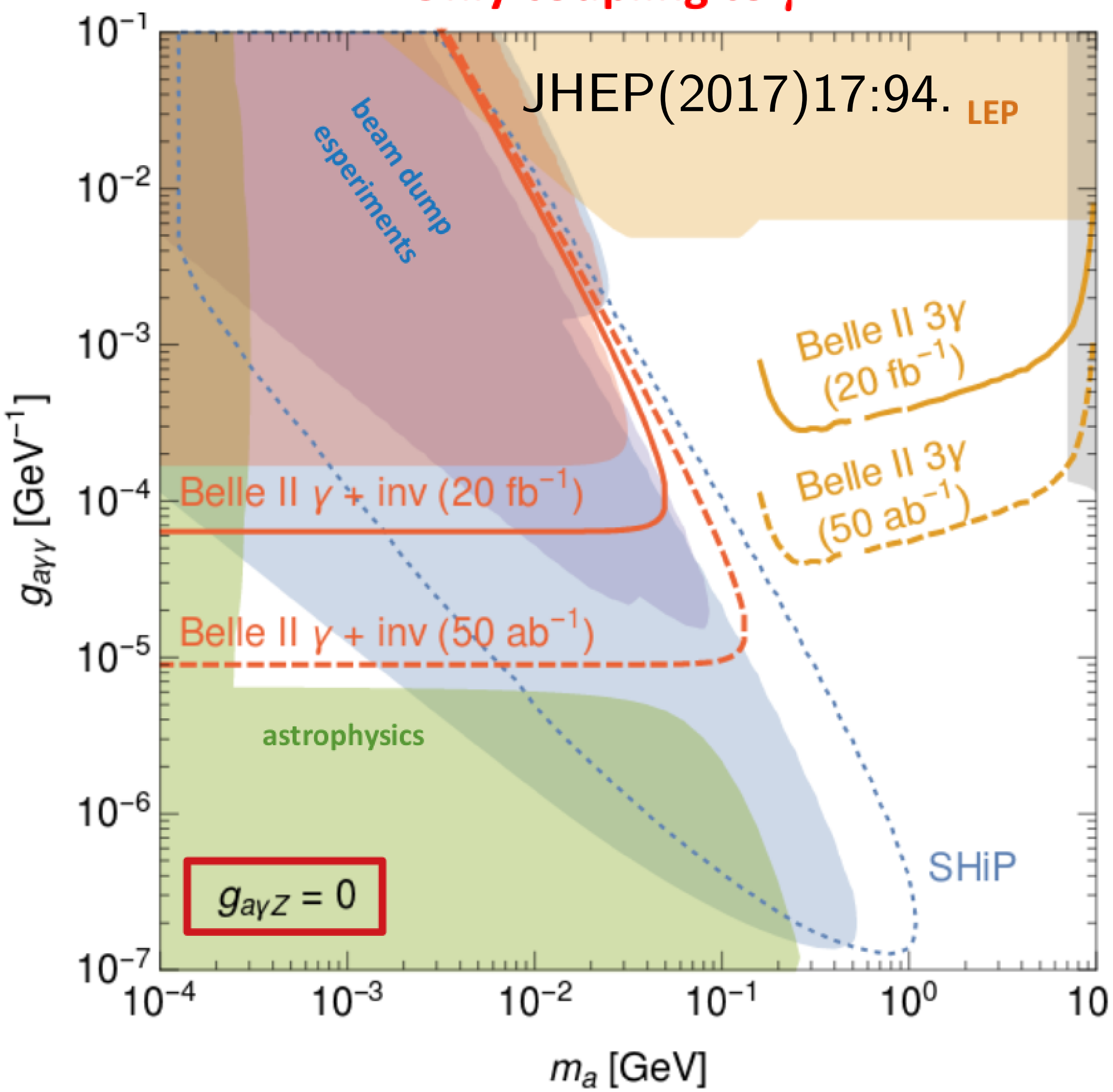
Hook (2015), arXiv:1411.3325



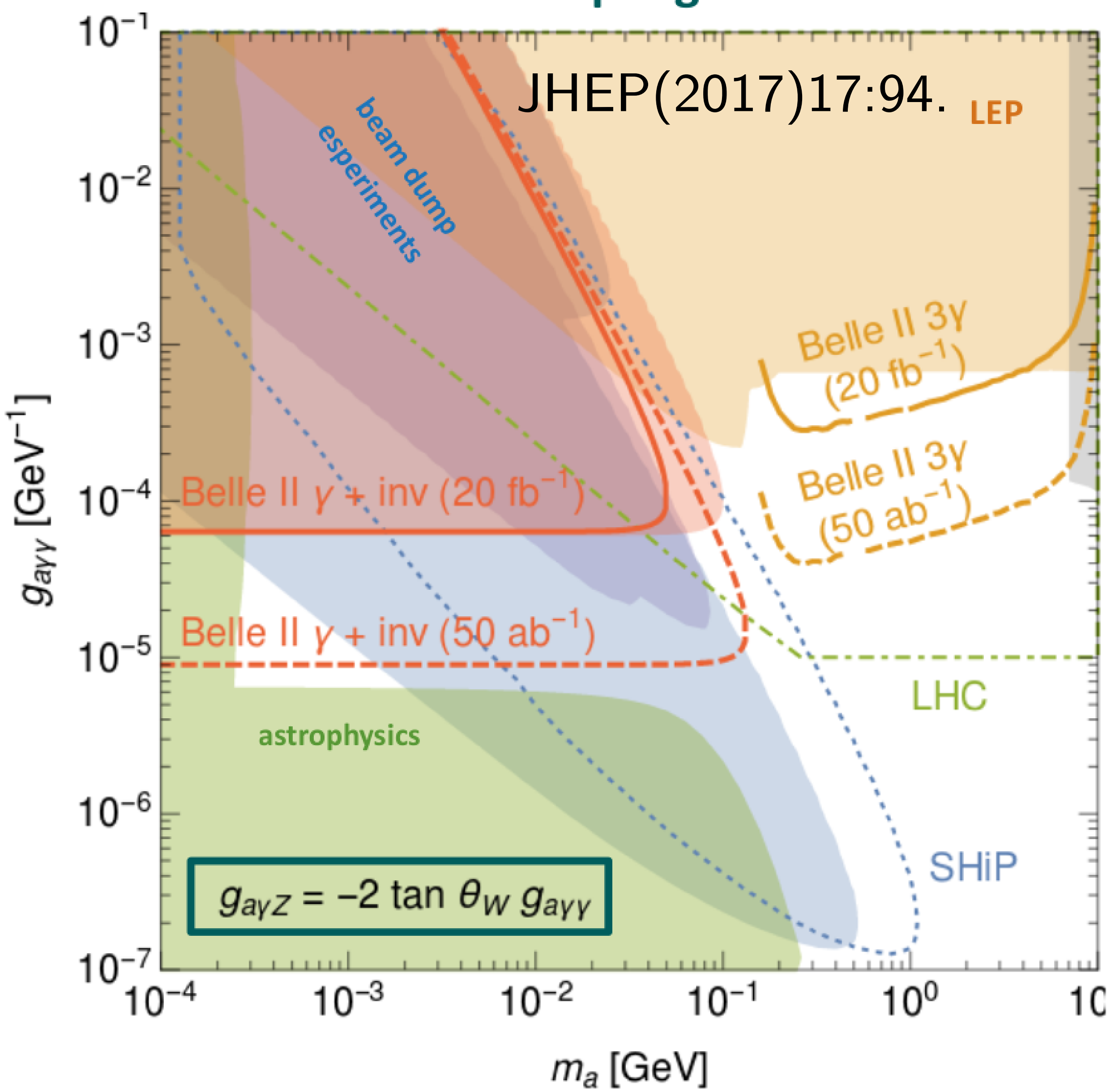
3-photon final state in ALP-strahlung

1-photon if $a \to \chi\chi$

Only coupling to γ

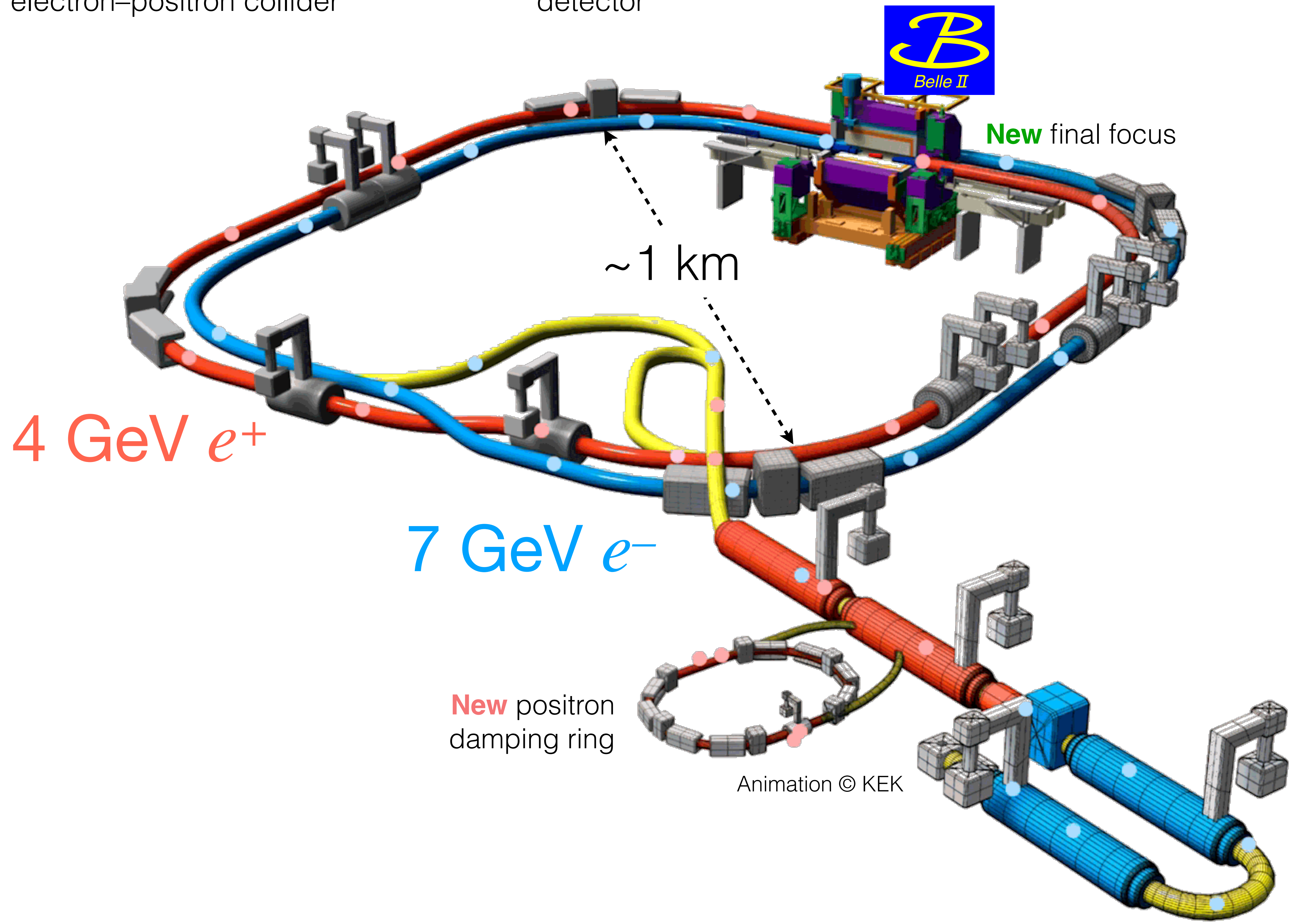


With coupling to Z



SuperKEKB and Belle II: 2nd generation B Factory

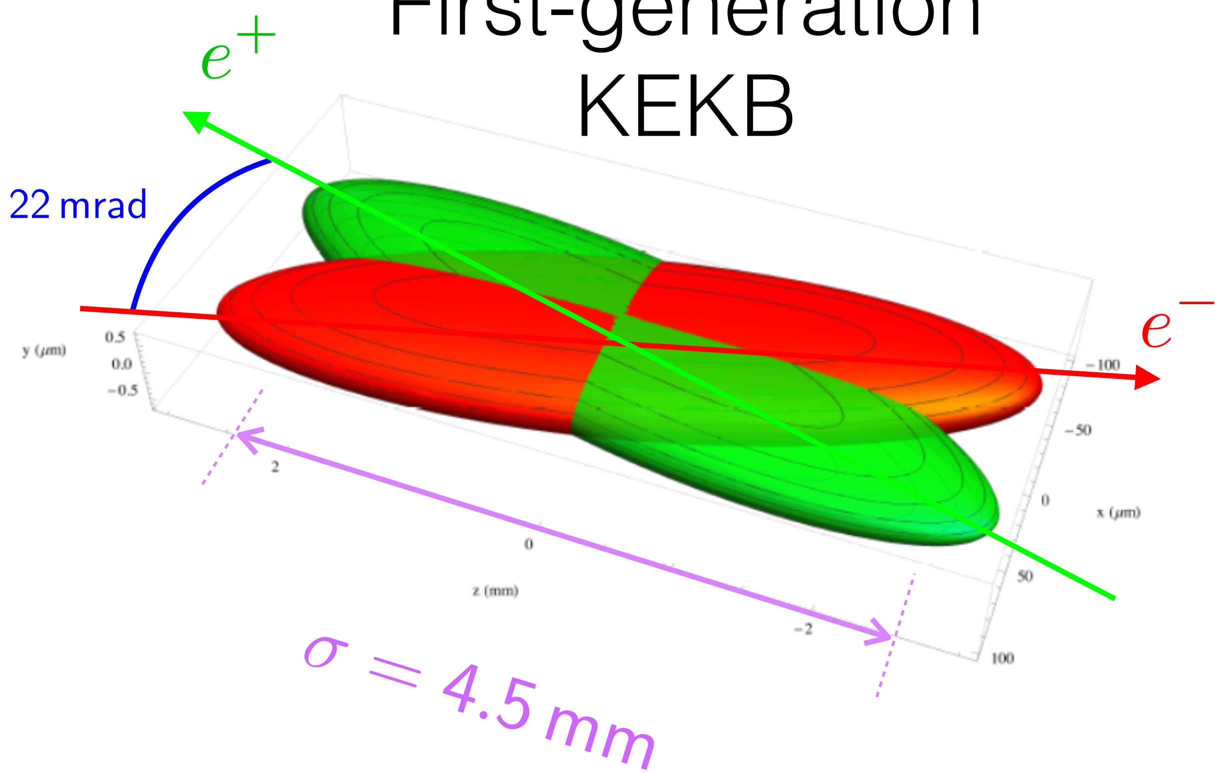
electron–positron collider detector



$$c\bar{c},\ s\bar{s},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

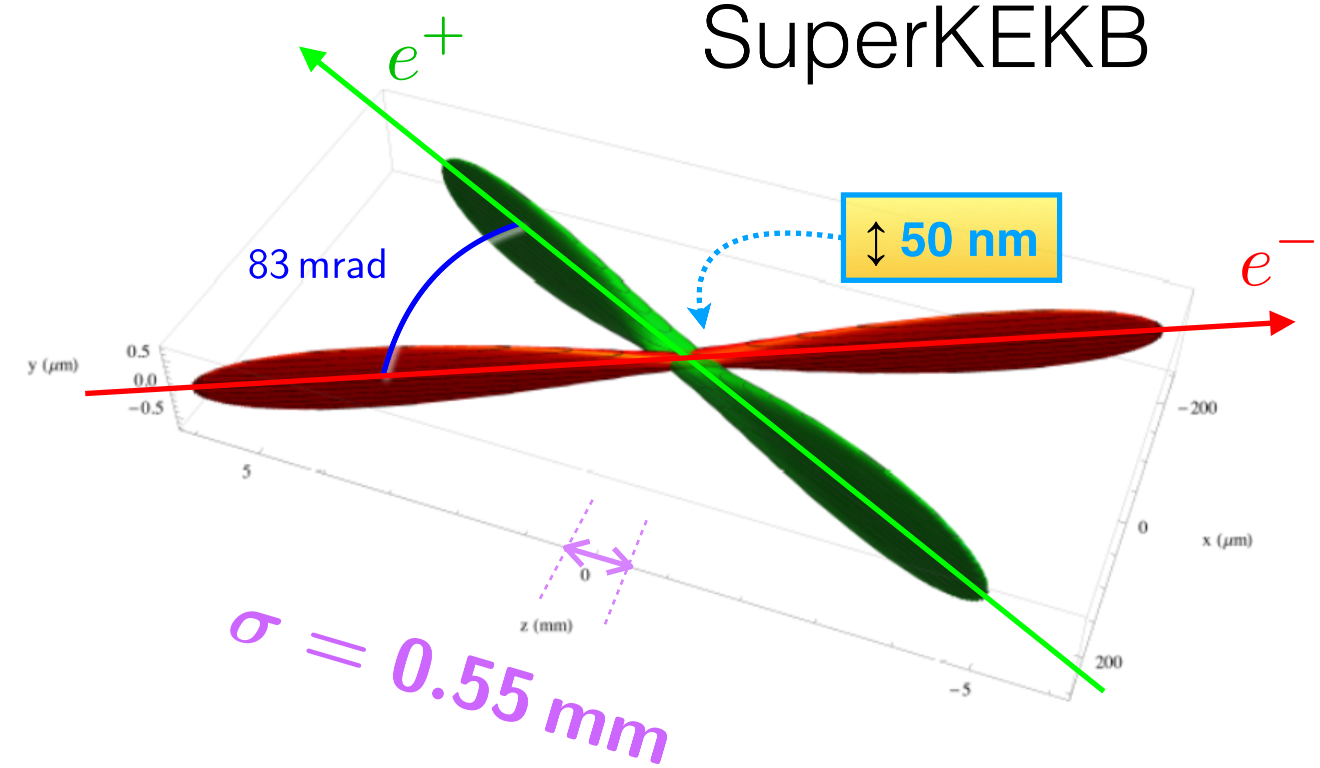
High luminosity achieved by squeezing beams @ IP

First-generation
KEKB



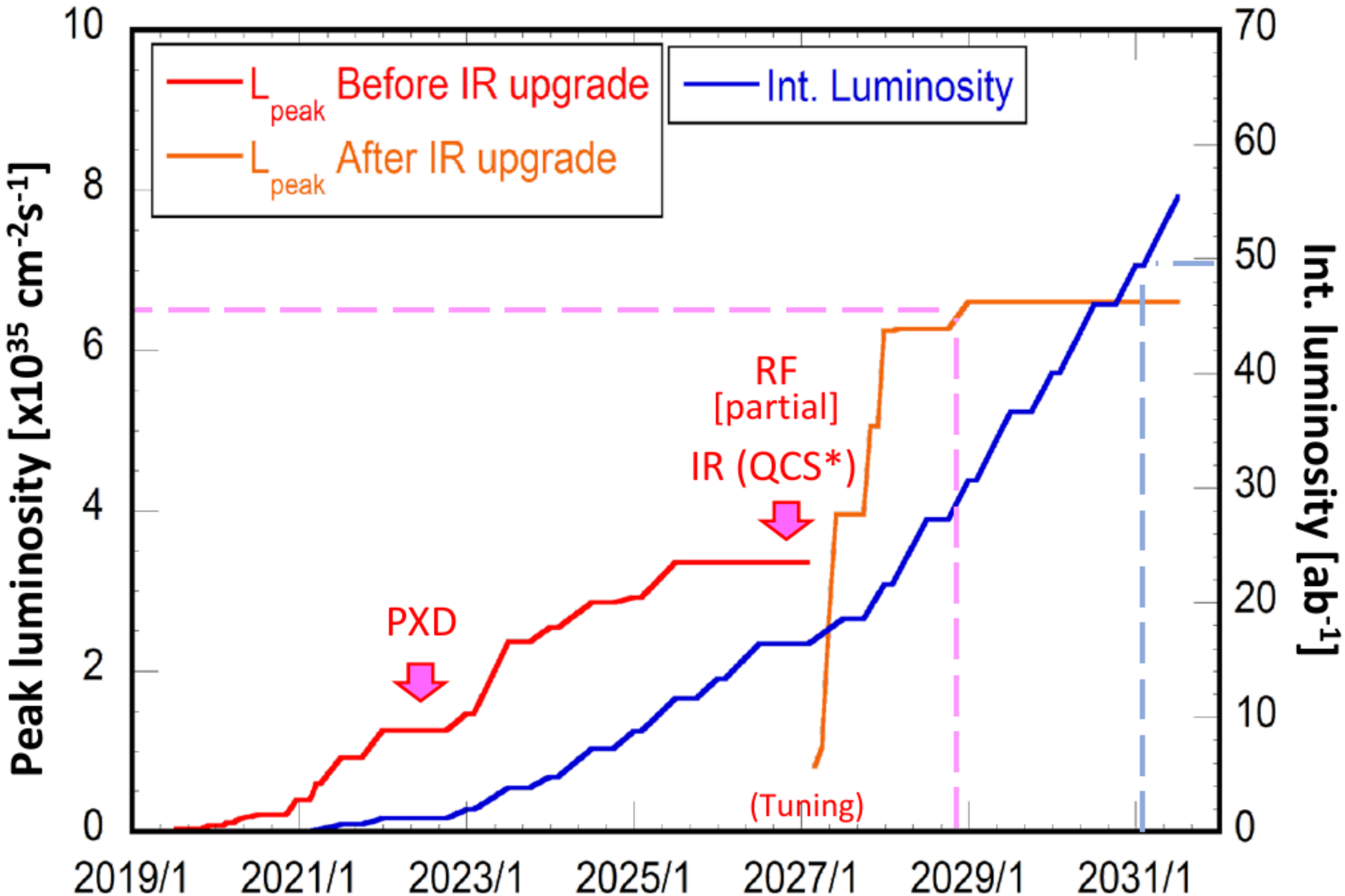
- ✓ Beam currents ≈doubled
- ✓ Much smaller β_y^*

SuperKEKB



Nano-beam scheme invented by
Pantaleo Raimondi for Italian SuperB Factory

SuperKEKB peak & integrated luminosity vs time



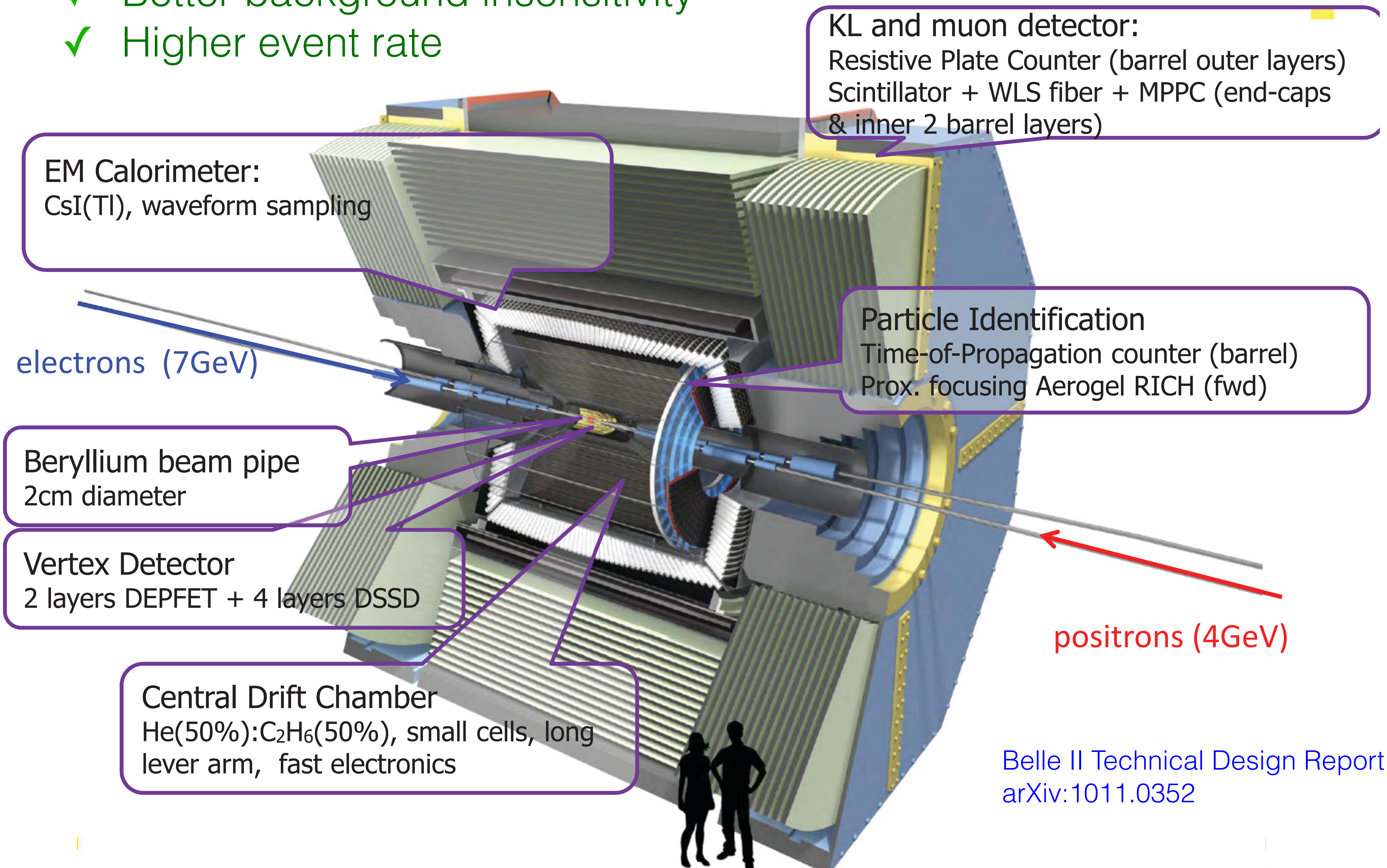
Four steps:

- ✓ *Intermediate luminosity:* (1→3) x 10^{35}/cm^2/sec, 5 ab^{-1}
- ✓ *High Luminosity:* 6 x 10^{35}/cm^2/sec, 50 ab^{-1} with a detector upgrade
- ✓ Beam-polarization upgrade, advanced R&D
- ✓ *Ultra high luminosity:* 4 x 10^{36}/cm^2/sec, 250 ab^{-1}, R&D project

Belle II is a significant upgrade of Belle

- ✓ Improved vertexing and tracking
- ✓ Improved hadron identification
- ✓ Better background insensitivity
- ✓ Higher event rate

I'll focus on these



Belle II Technical Design Report
arXiv:1011.0352

Advanced & innovative technologies in Belle II

developed in collaboration with industry

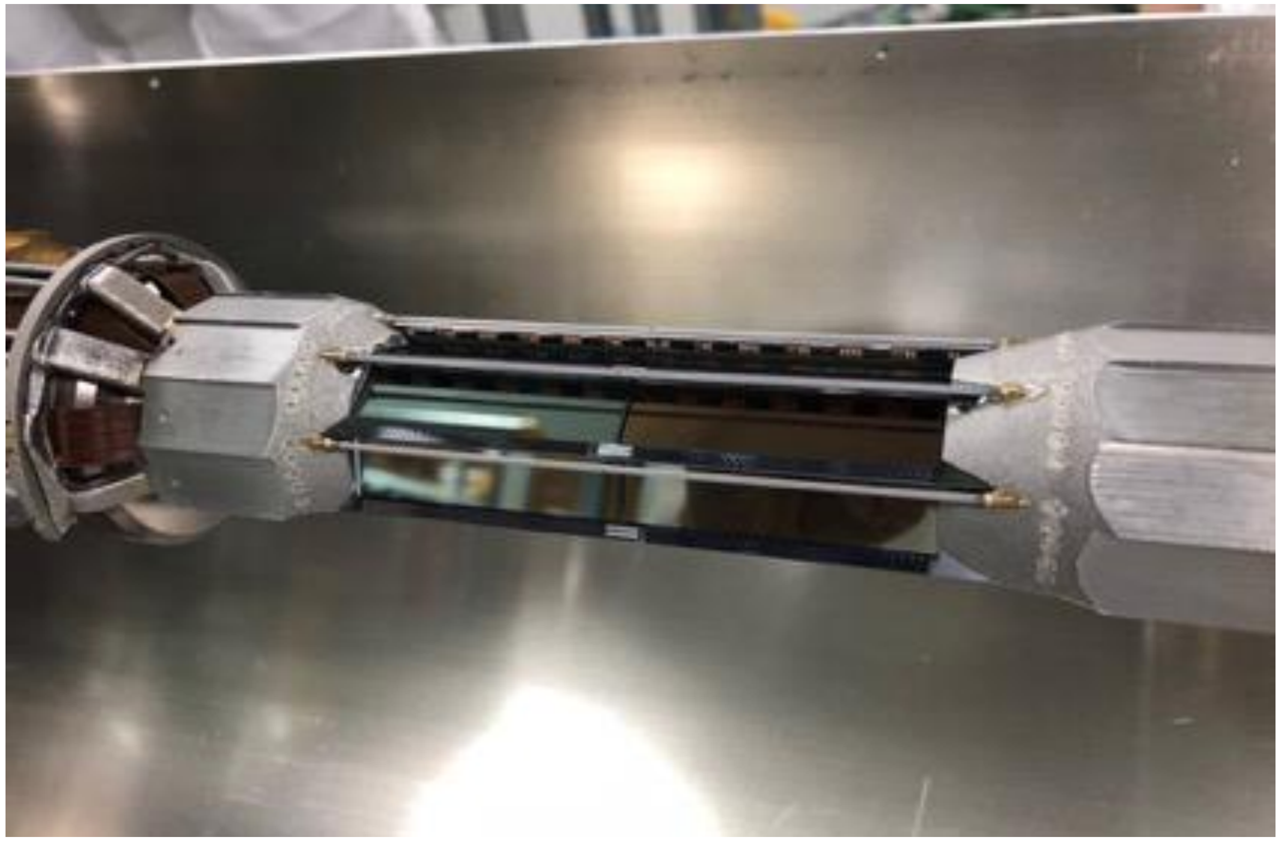
- ✓ Pixelated photosensors
  - MCP-PMTs in imaging time-of-propagation detector (iTOP)
  - HAPDs in aerogel ring-imaging Cherenkov detector (ARICH)
  - MPPCs *(aka SiPMs)* in K_L–muon detector (KLM)
- ✓ DEPFET pixel sensors in vertex detector
- ✓ Front-end custom ASICS for waveform sampling with precise timing
  - APV2.5 *(adapted from CMS)* in silicon-strip vertex detector (SVD)
  - 3 custom ASICs in pixel vertex detector (PXD)
  - TARGETX ASIC in KLM
  - IRSX ASIC in iTOP
  - KEK-custom ASICs in ARICH & drift chamber (CDC)
- ✓ High-performance data-acquisition system for 30 kHz trigger rate
  - high-throughput network switches to aggregate event data
  - large computer farm for high-level software trigger
- ✓ TPCs and diamond sensors for background monitoring/characterization

Vertex Detector

Component	r (mm)
Beam pipe	10
Pixels – layer 1	14
Pixels – layer 2	22
Strips – layer 3	39
Strips – layer 4	80
Strips – layer 5	104
Strips – layer 6	135

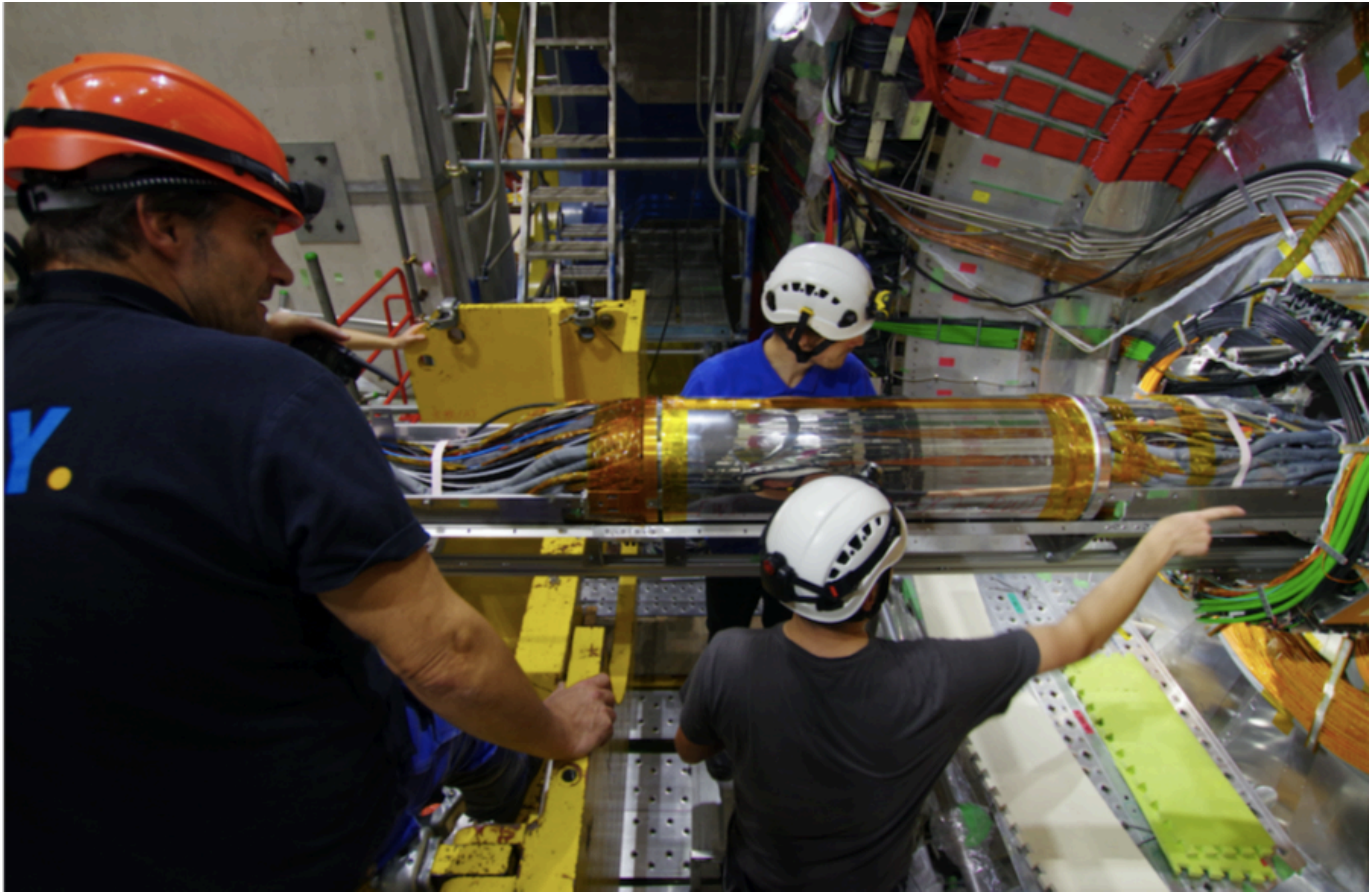
beryllium beam pipe at interaction point

assembled silicon-strip vertex detector (SVD)



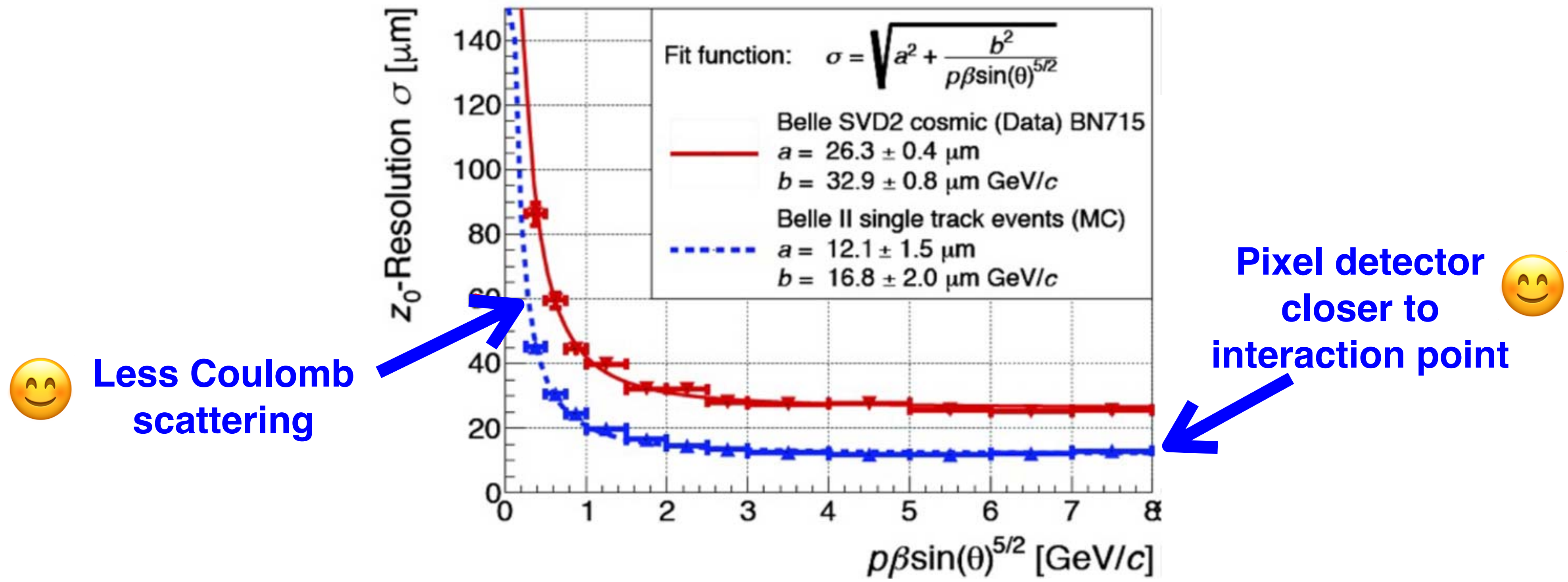
partially assembled pixel detector (PXD)

Vertex Detector installation: Nov 21, 2018

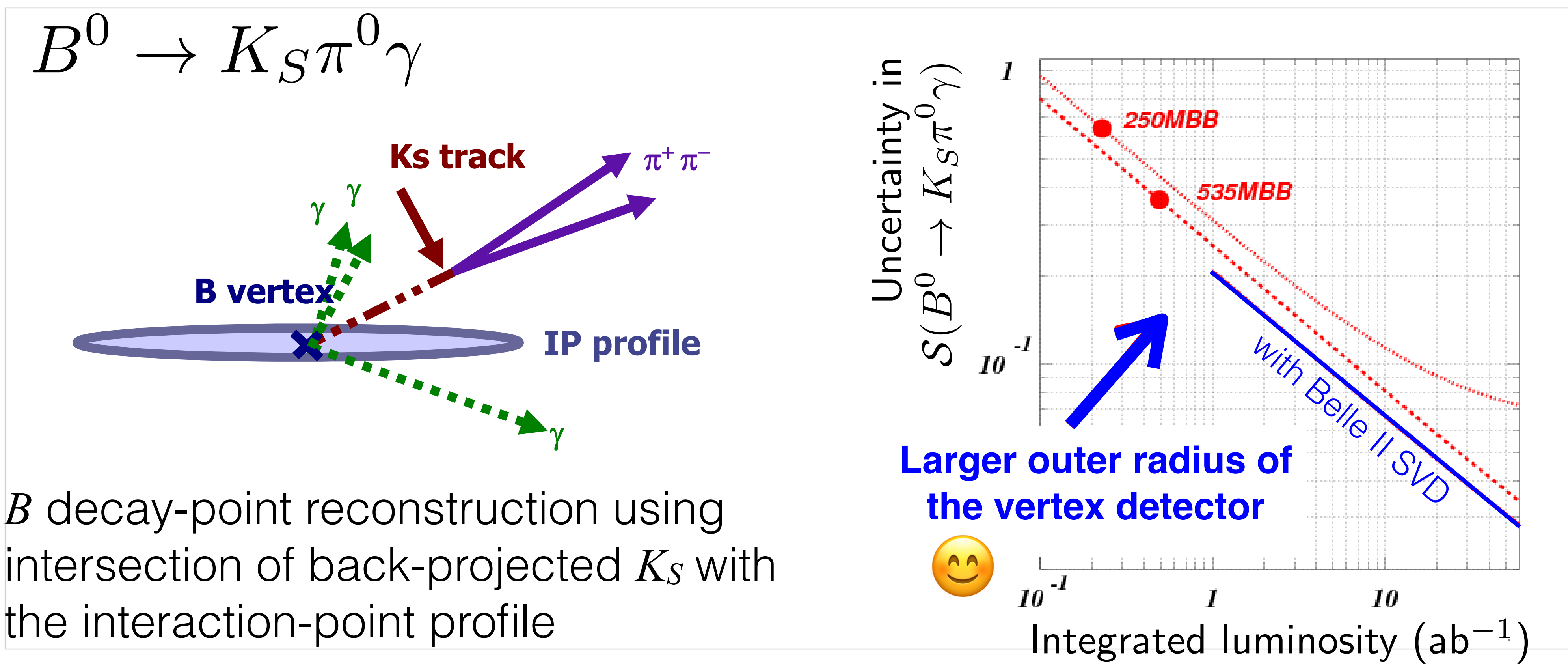


Pixel Detector (PXD): Layer 1 and partial Layer 2
Silicon-strip Vertex Detector (SVD): all 4 layers

Vertexing performance improves significantly vs Belle



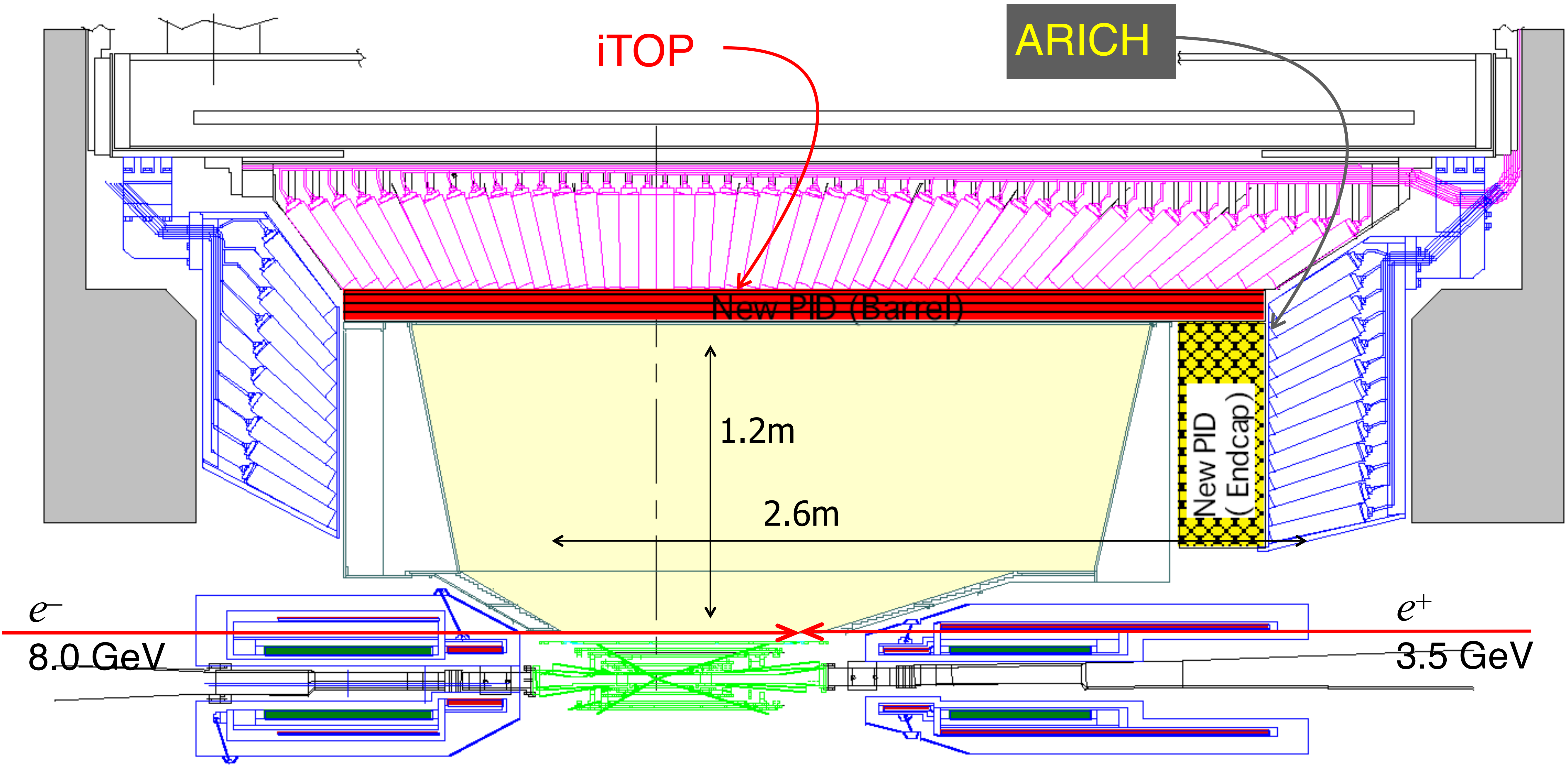
Improved vertexing is vital for a key time-dependent CP-violation measurement



B decay-point reconstruction using intersection of back-projected K_S with the interaction-point profile

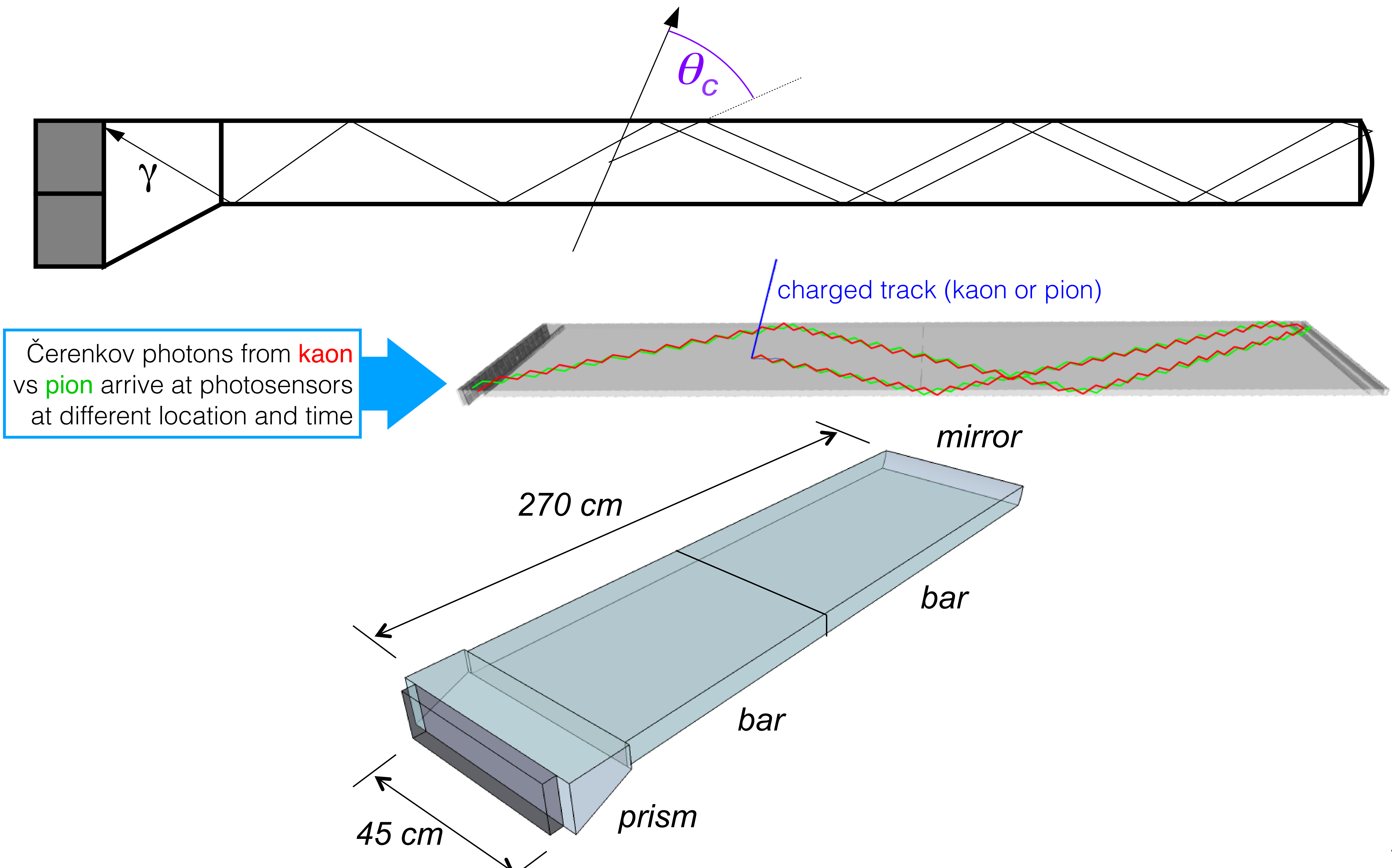
Hadron ID detectors: iTOP and ARICH

- ✓ Distinguish π from K with high efficiency and low fake rate
- ✓ Fit within existing electromagnetic calorimeter
- ✓ Accommodate larger-radius drift chamber
- ✓ Operate in 1.5T solenoidal magnetic field

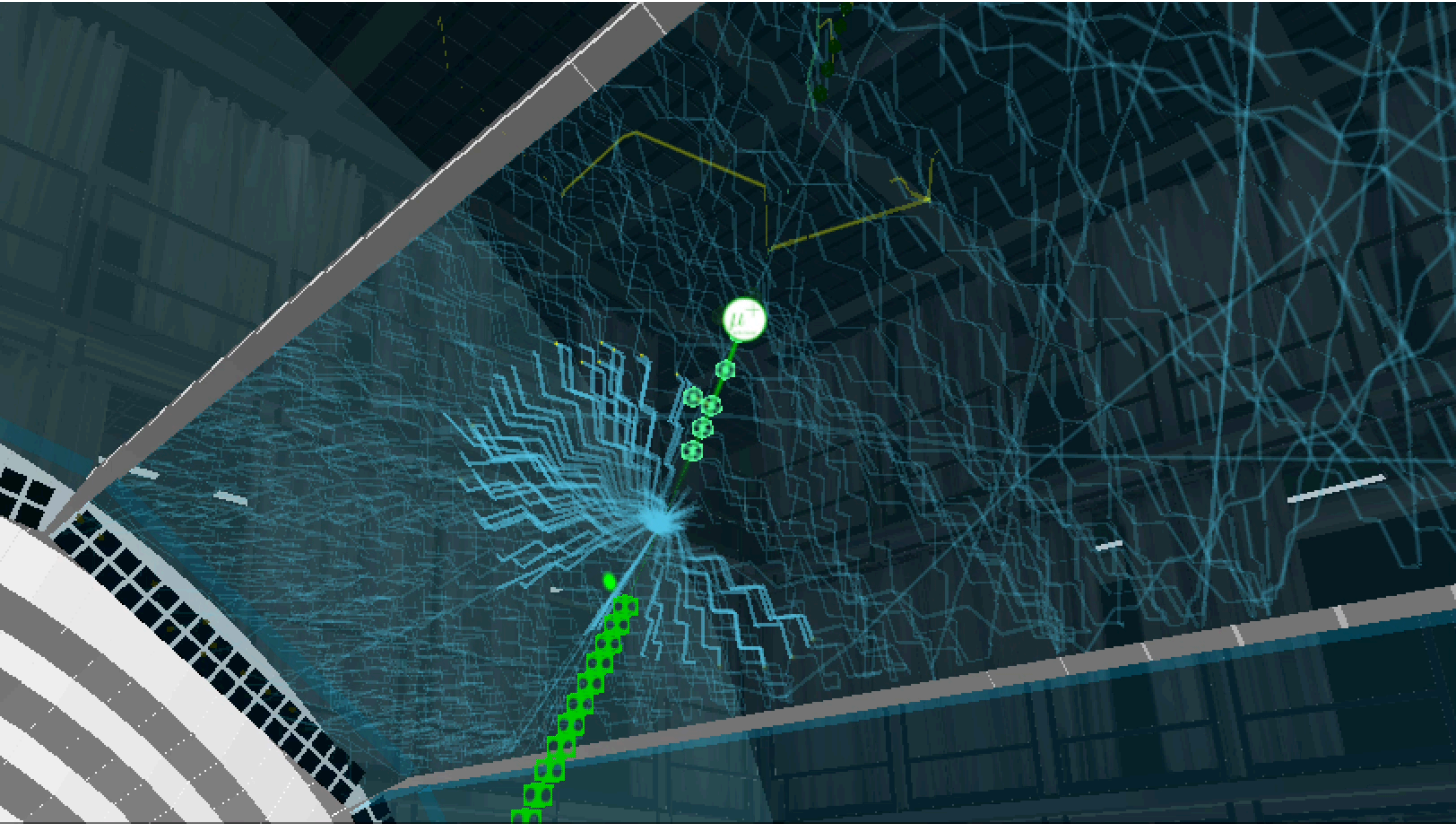


Hadron ID: measure the Čerenkov cone

Barrel PID uses imaging time-of-propagation counter (16 quartz staves)

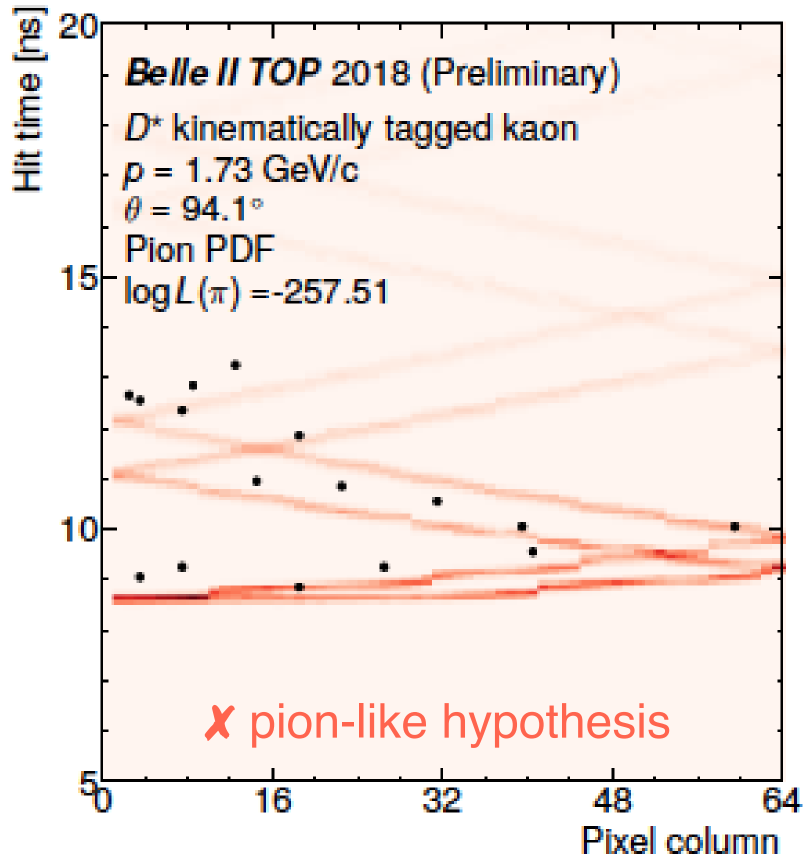


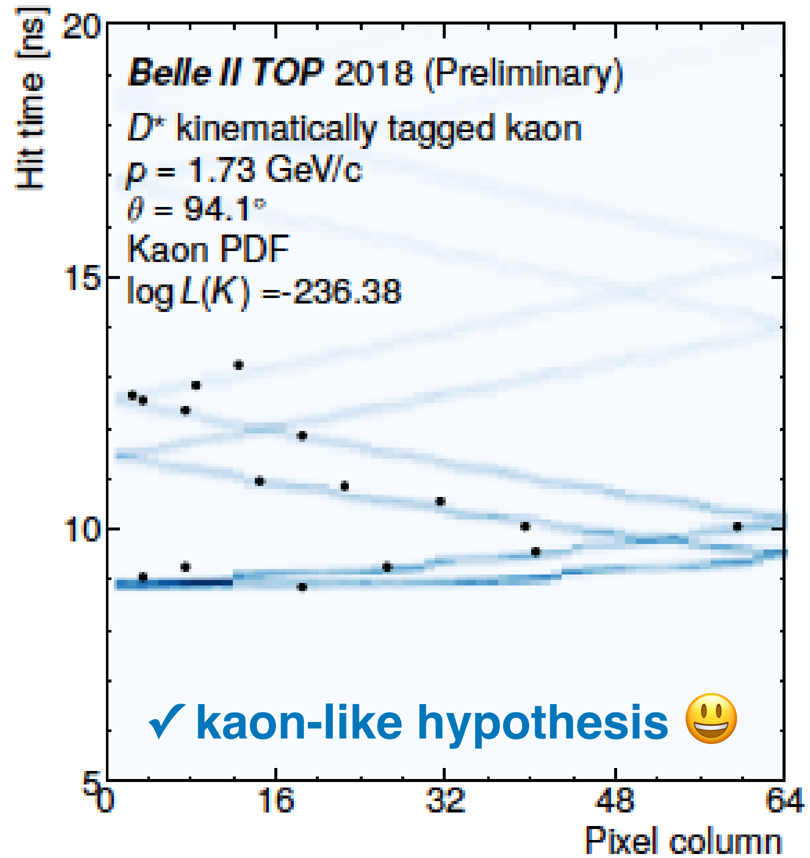
Čerenkov light in the iTOP (barrel hadron ID)

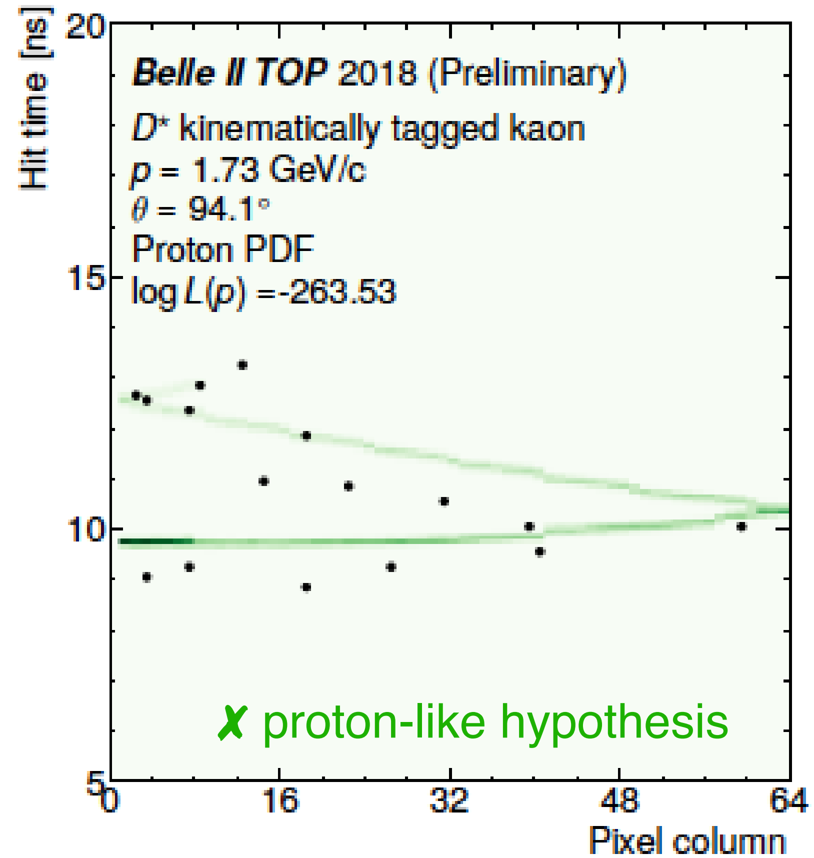


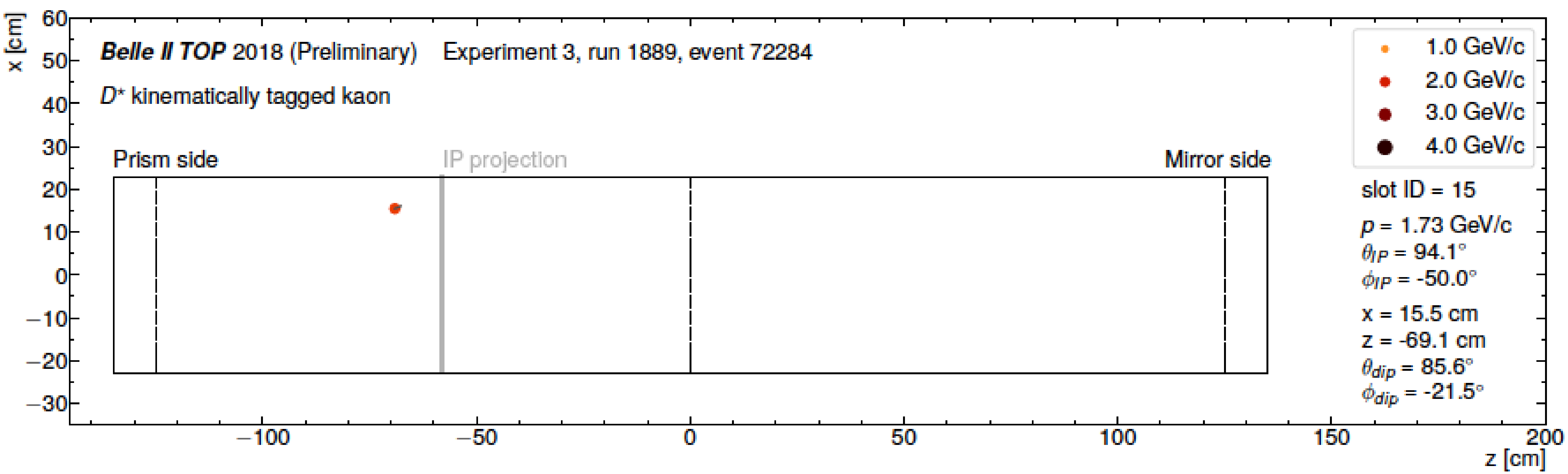
from “Belle II in Virtual Reality”

Measure the Čerenkov cone in barrel PID (iTOP)



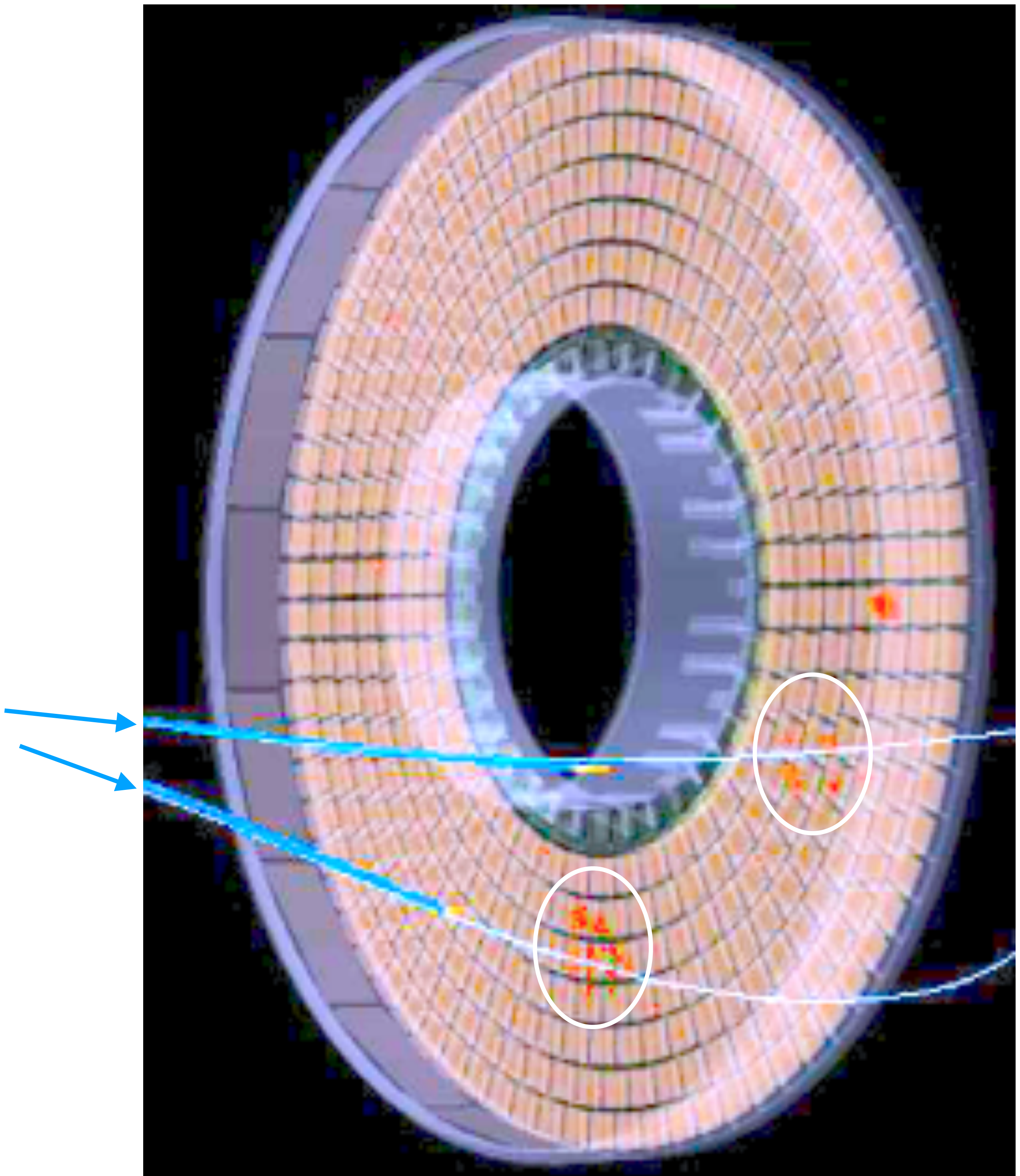


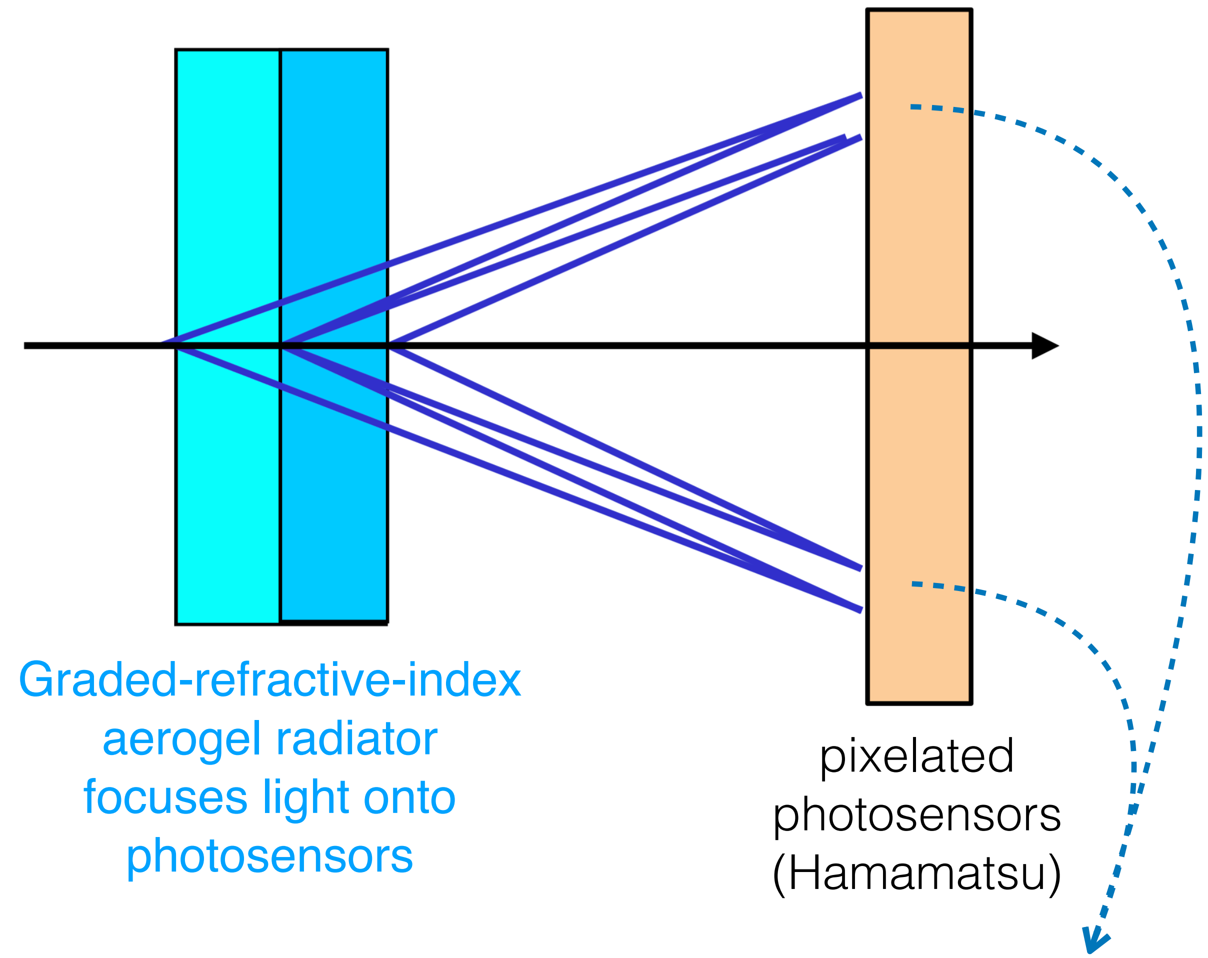


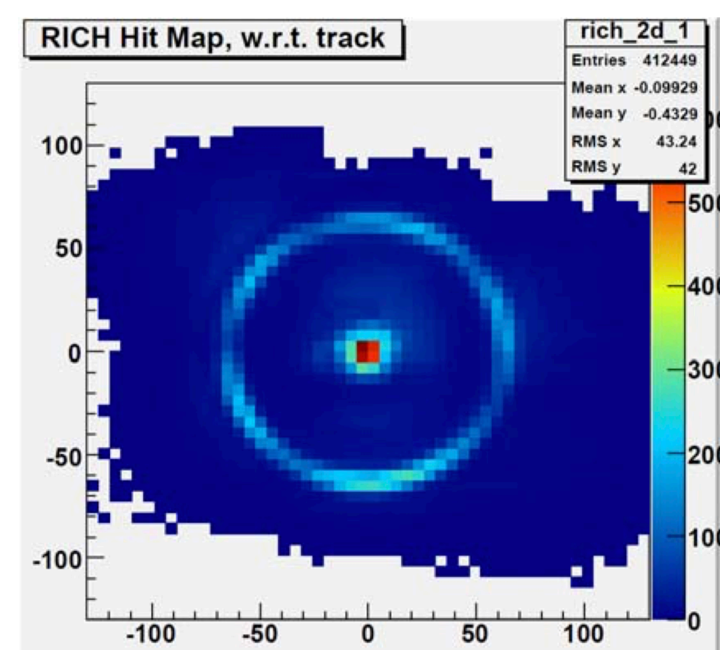


Measure the Čerenkov cone in endcap PID (ARICH)

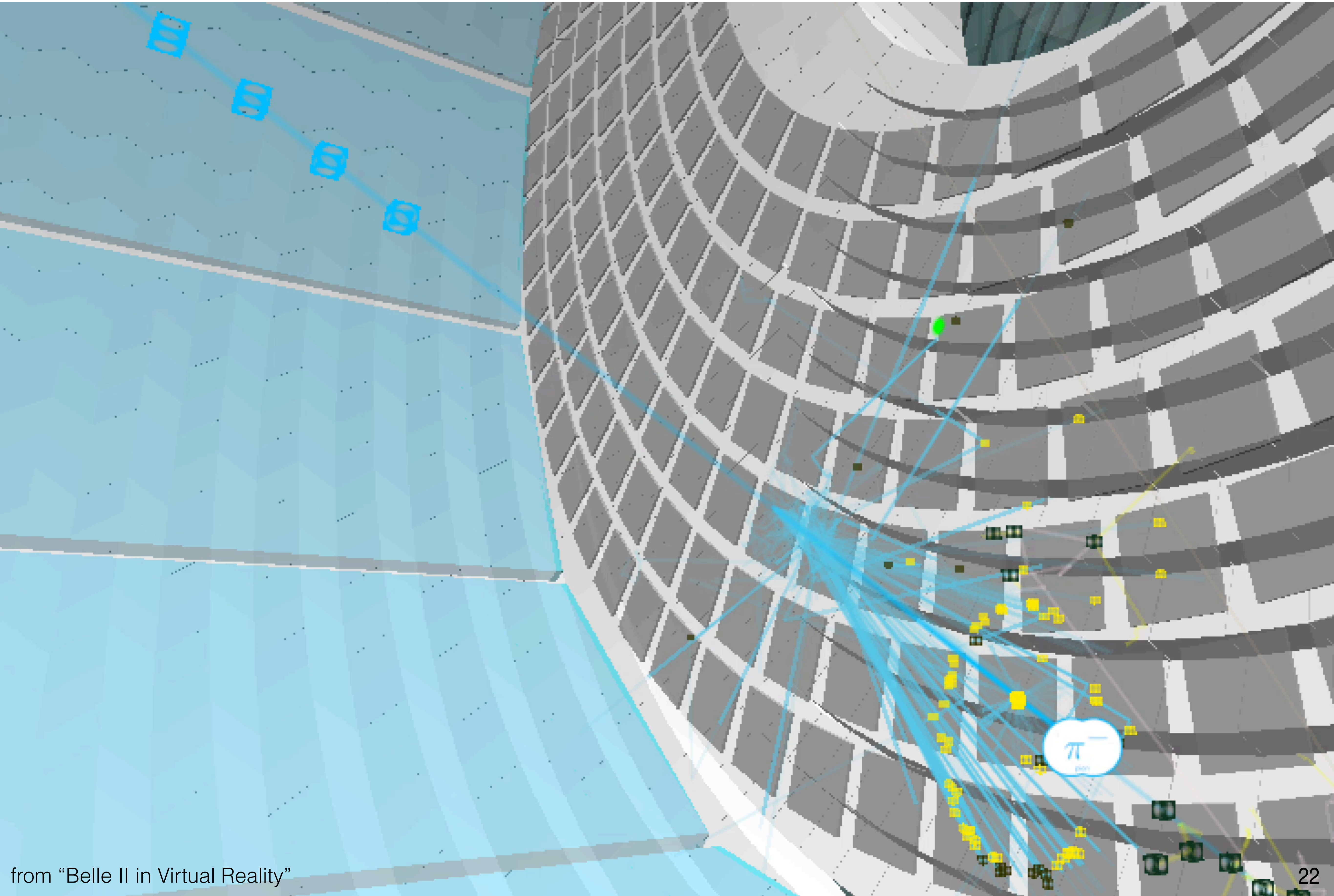
Forward-endcap PID uses aerogel RICH with two-layer radiator (“focusing”)







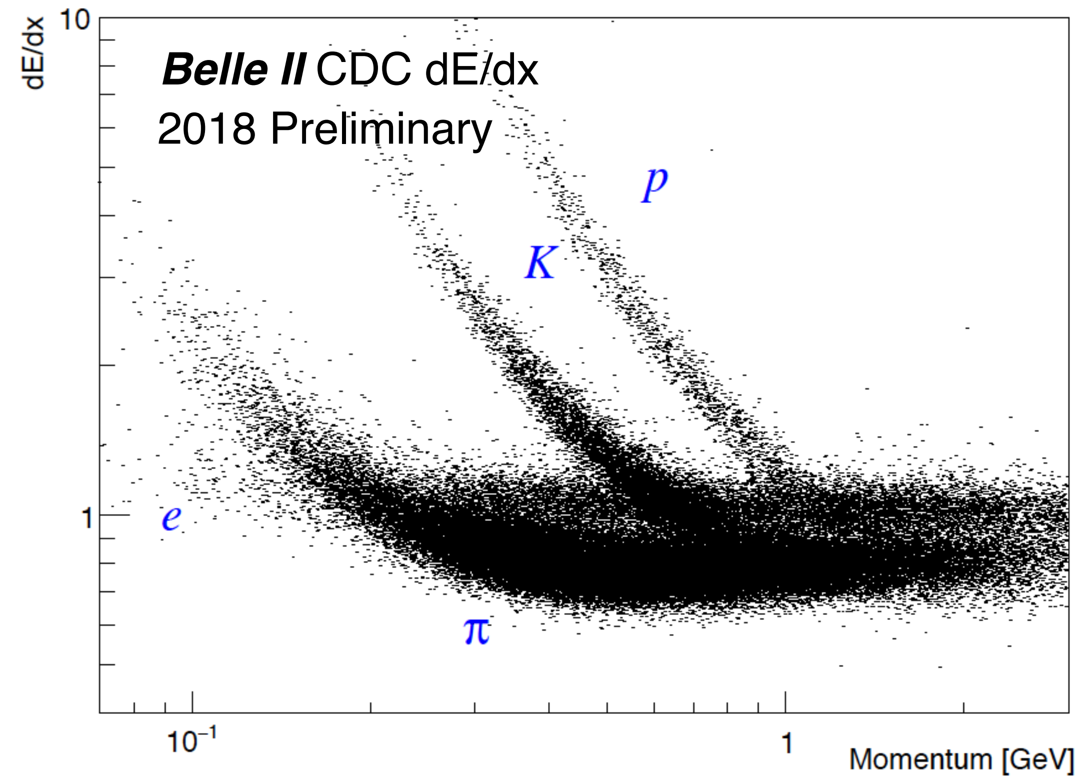
Čerenkov light in the ARICH (forward hadron ID)



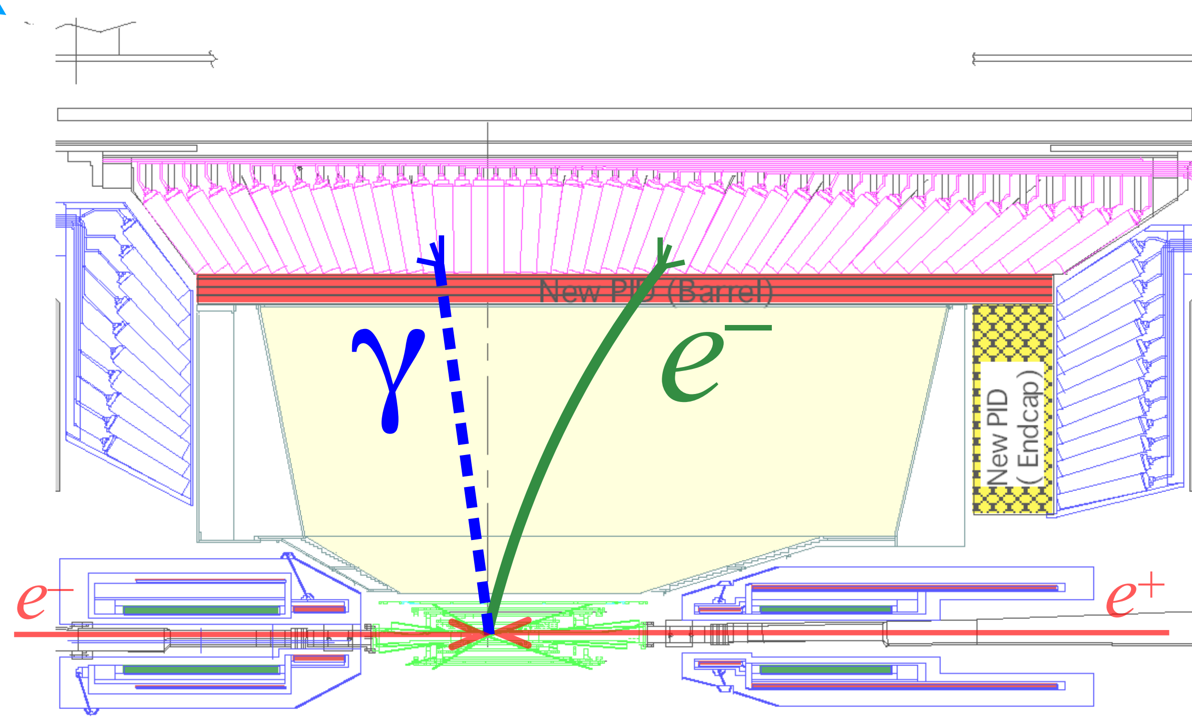
from “Belle II in Virtual Reality”

Other particle ID detectors: CDC+SVD, ECL, KLM

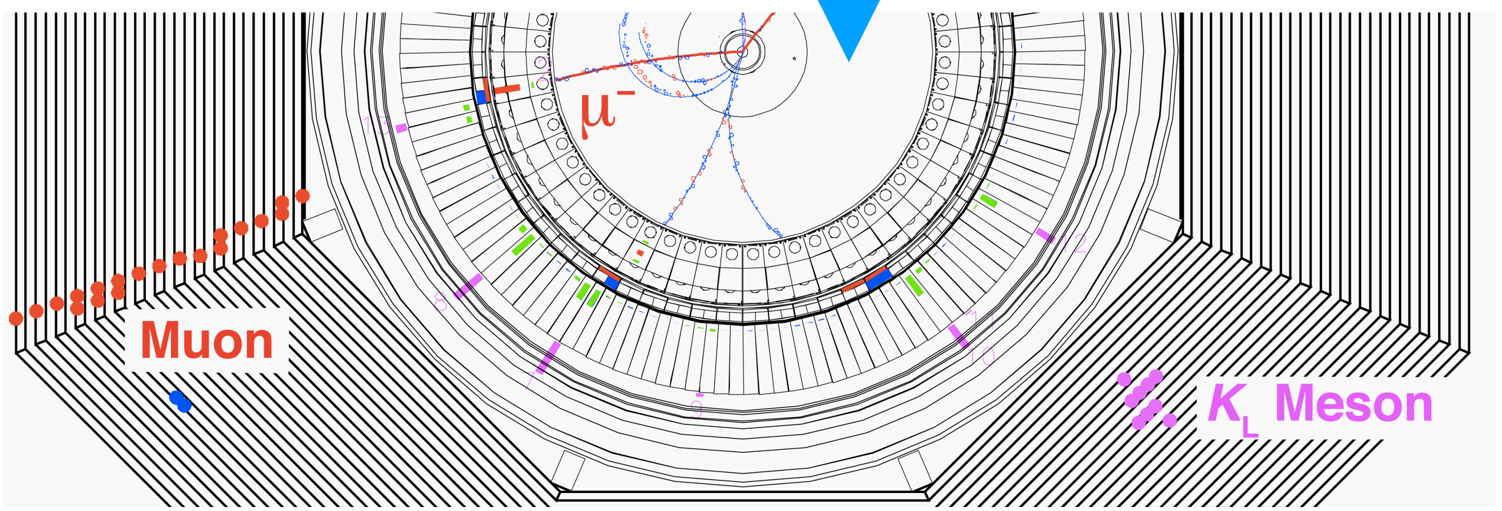
- ✓ CDC+SVD: use dE/dx for known momentum to distinguish among charged-particle hypotheses



- ✓ ECL: electromagnetic showers identify electrons/positrons (with CDC track) and photons (no aligned CDC track)



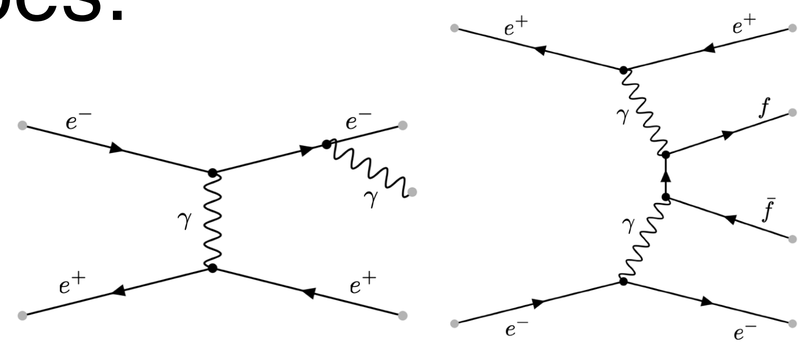
- ✓ KLM: hadronic shower identifies K_L meson (no CDC track); hits aligned with CDC track identifies muon



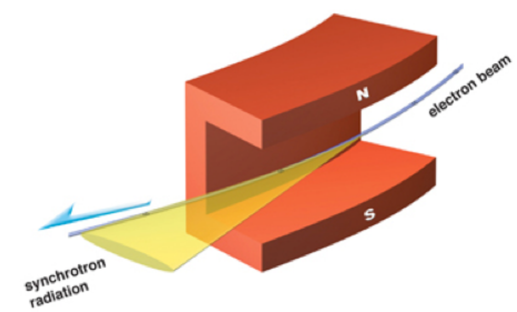
Management of accelerator-induced backgrounds is critical for detector operation and physics extraction

Background types:

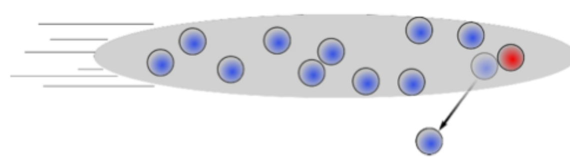
- Beam-beam



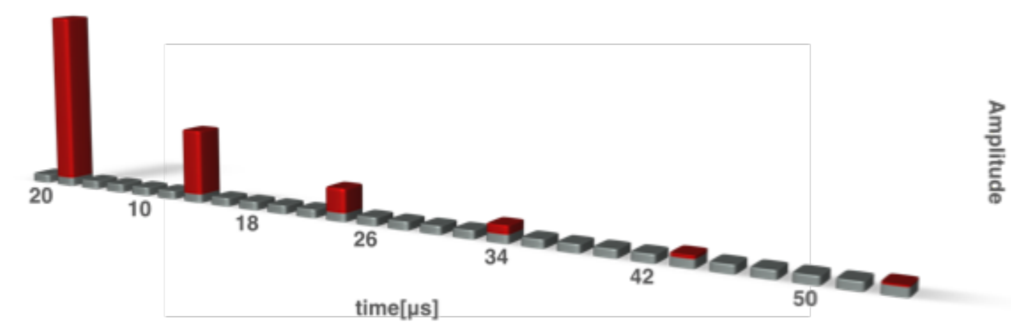
- Synchrotron



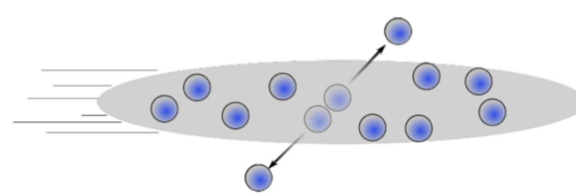
- Beam-gas



- Injection transients



- Touschek



Potential negative impacts:

- Reduced beam lifetime
- Shortened lifetime of Belle II detector components
- Instantaneous damage to these components
- Increased hit occupancy in detectors
- Reconstruction and analysis challenges

Summary

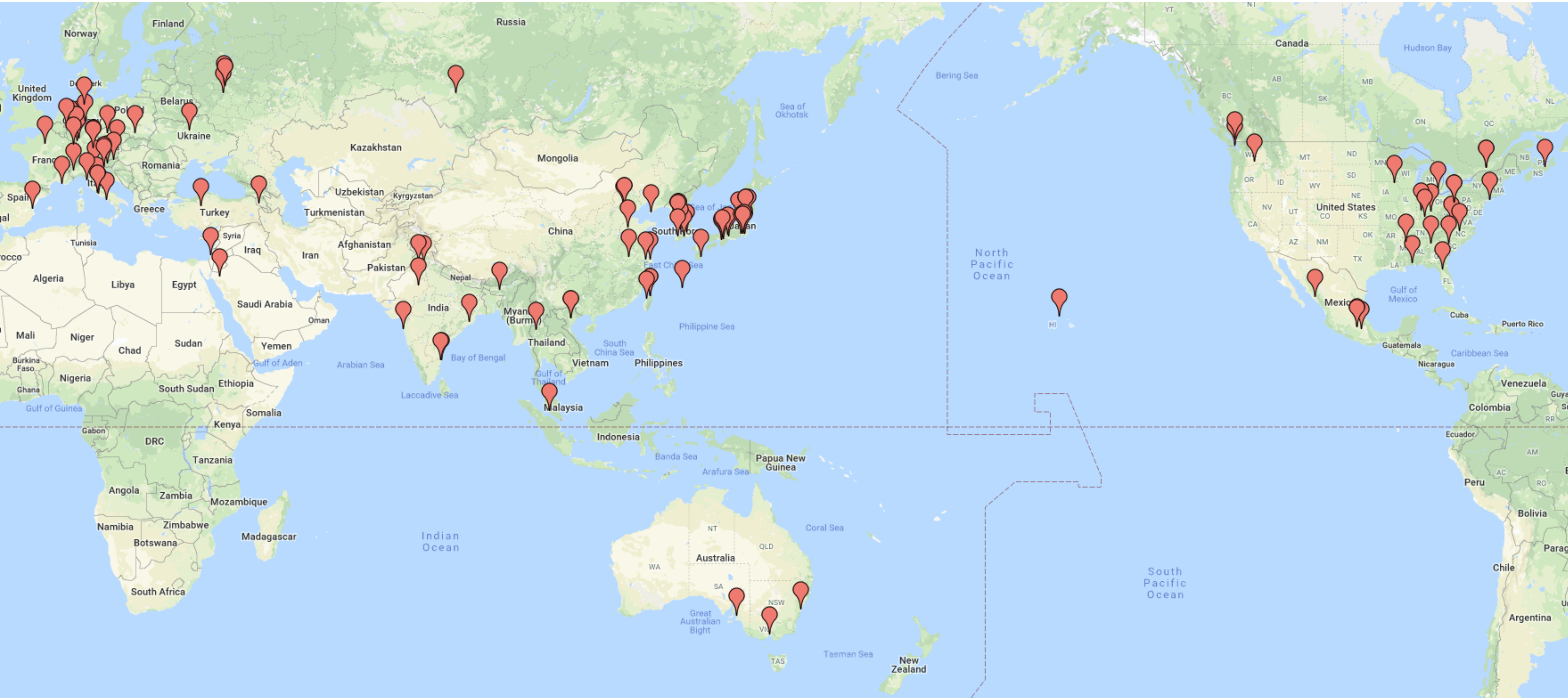
- Belle II will explore New Physics and make precision measurements of SM physics with 50x more data than Belle.
- Belle II Physics Book – PTEP **2019**, 123C01 (2019) – provides a wealth of detail on the machine, detector, analysis tools and physics.
- Belle II design was optimized for the physics reach, subject to the constraints of the accelerator final-focus design and the re-use of electromagnetic calorimeter and solenoid+yoke.
- Backgrounds must be characterized, modeled accurately and mitigated for successful operation.

Animations from the Belle II virtual reality app: see www.phys.vt.edu/~piilonen/VR/

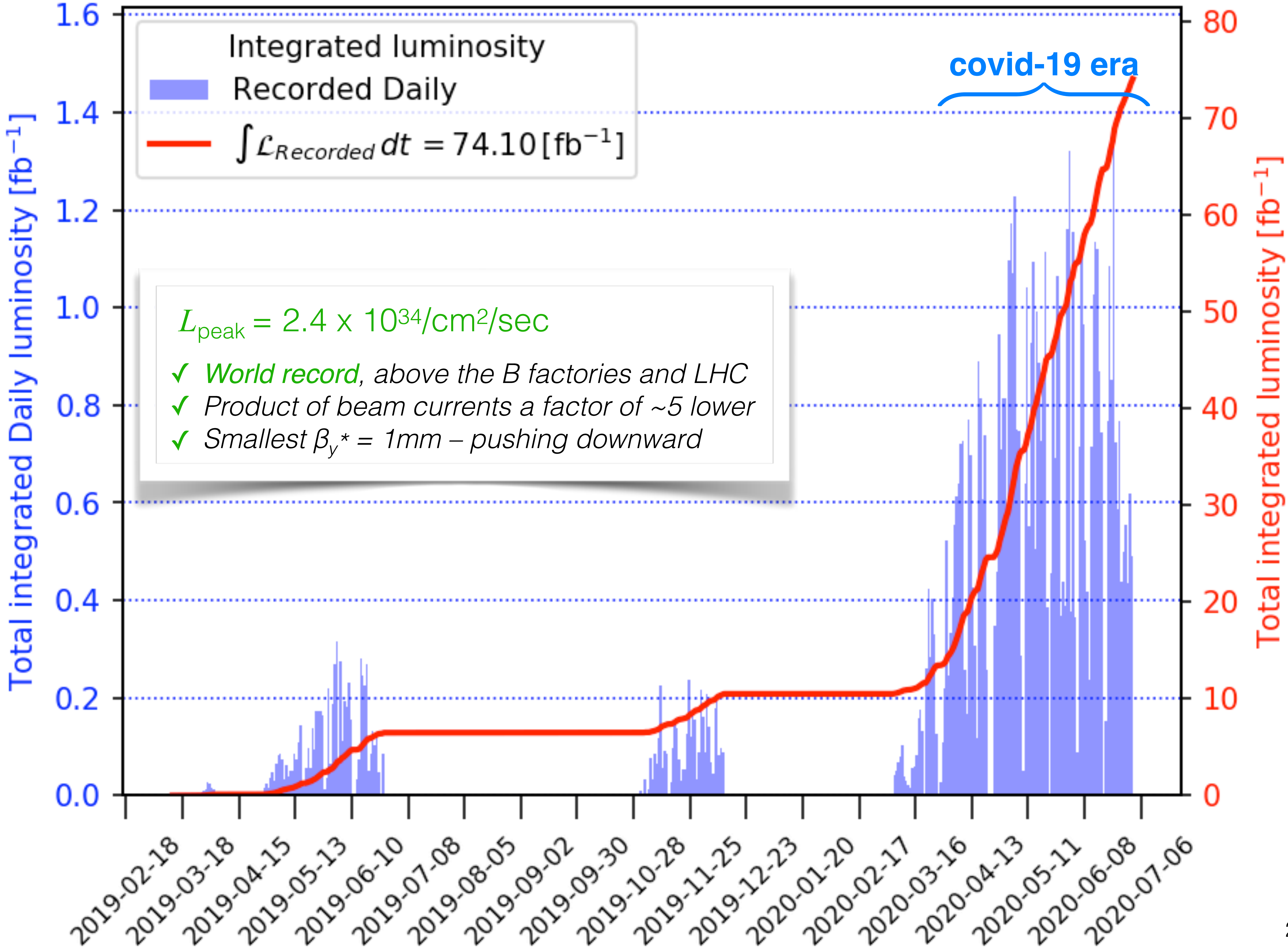
Backup

Belle II collaboration

- 1050 active collaborators … 15% are women and 32% are graduate students
- 120 institutions
- 26 countries/regions



Belle II Integrated Luminosity



L_{peak} = 2.4 x $10^{34}/cm^2/sec$

- ✓ *World record, above the B factories and LHC*
- ✓ *Product of beam currents a factor of ~5 lower*
- ✓ *Smallest β_y* = 1mm – pushing downward*

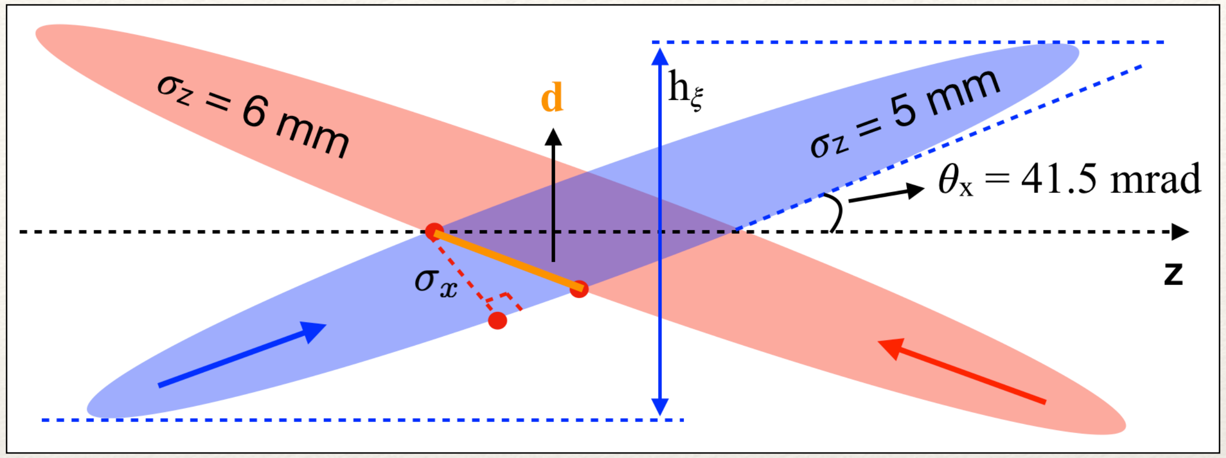
KEKB - SuperKEKB parameters

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

$$\phi_{Piw} = \frac{\sigma_z}{\sigma_x^*} tan\theta_x$$

Hourglass effect condition:

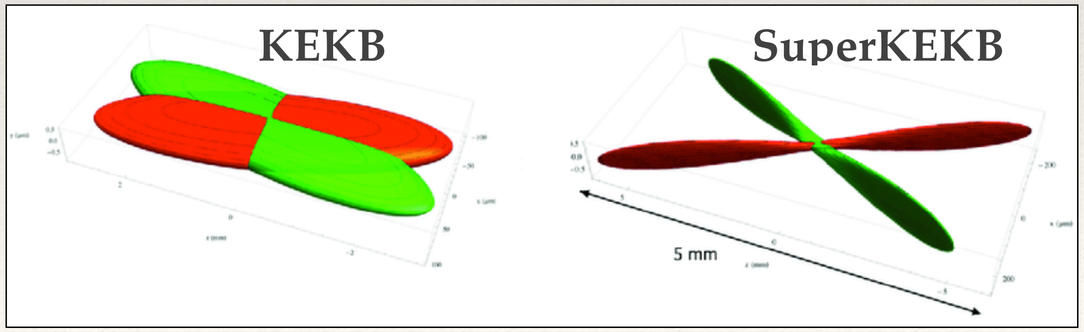
$$\beta_y^* \geq d = \frac{\sigma_x^*}{sin(2\theta_x)}$$



	KEKB		SuperKEKB	
	LER	HER	LER	HER
E [GeV]	3.5	8.0	4.0	7.0
θ_x [mrad]	0 (11)		41.5	
ε_x [nm]	18	24	3.2	4.6
ε_y [pm]	150	150	8.64	12.9
β_x^* [mm]	1200	1200	32	25
β_y^* [mm]	5.9	5.9	0.27	0.30
σ_x^* [μm]	147	170	10.1	10.7
σ_y^* [nm]	940	940	48	62
n_b	1584		2500	
I [A]	1.64	1.19	3.6	2.6
L [cm^{-2} s^{-1}]	2.1 x 10^{34}		8.0 x 10^{35}	

$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp \beta_y^*}{\sigma_y^*(\sigma_x^* + \sigma_y^*)}R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$



Belle II physics program is broad and deep

Emphasis on new-physics reach in each section

Belle II Theory Interface Platform (B2TIP) Workshop series, 2015-2018:

WG1
Semileptonic & Leptonic B decays

WG2
Radiative & Electroweak Penguins

WG3
α/φ_2 β/φ_1

WG4
γ/φ_3

WG5
Charmless Hadronic B Decay

WG6
Charm

WG7
Quarkonium(-like)

WG8
Tau, low multiplicity

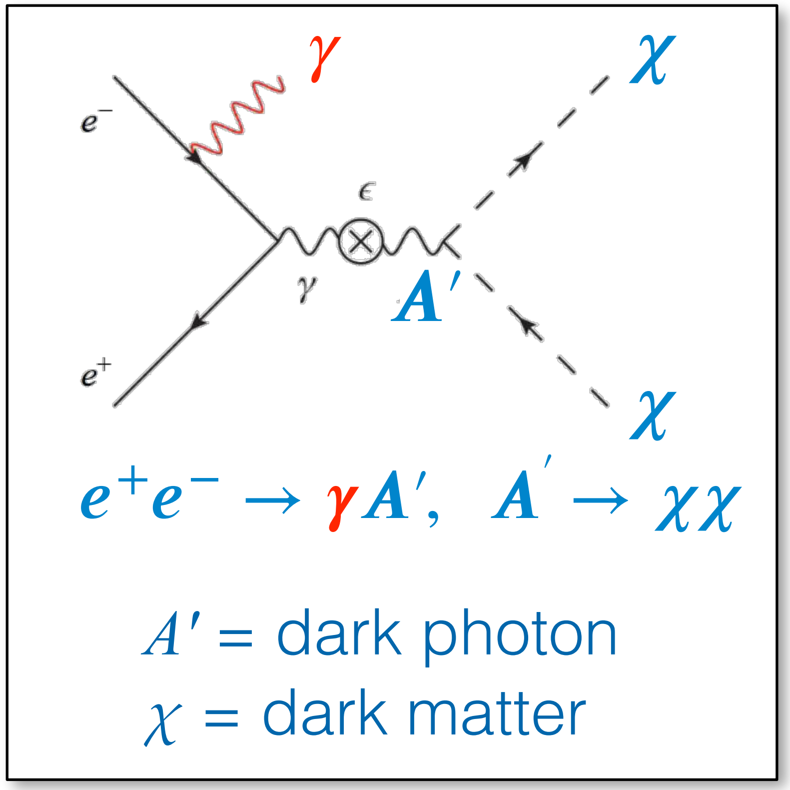
WG9
New Physics

The Belle II Physics Book
Emi Kou and Phill Urquijo, editors

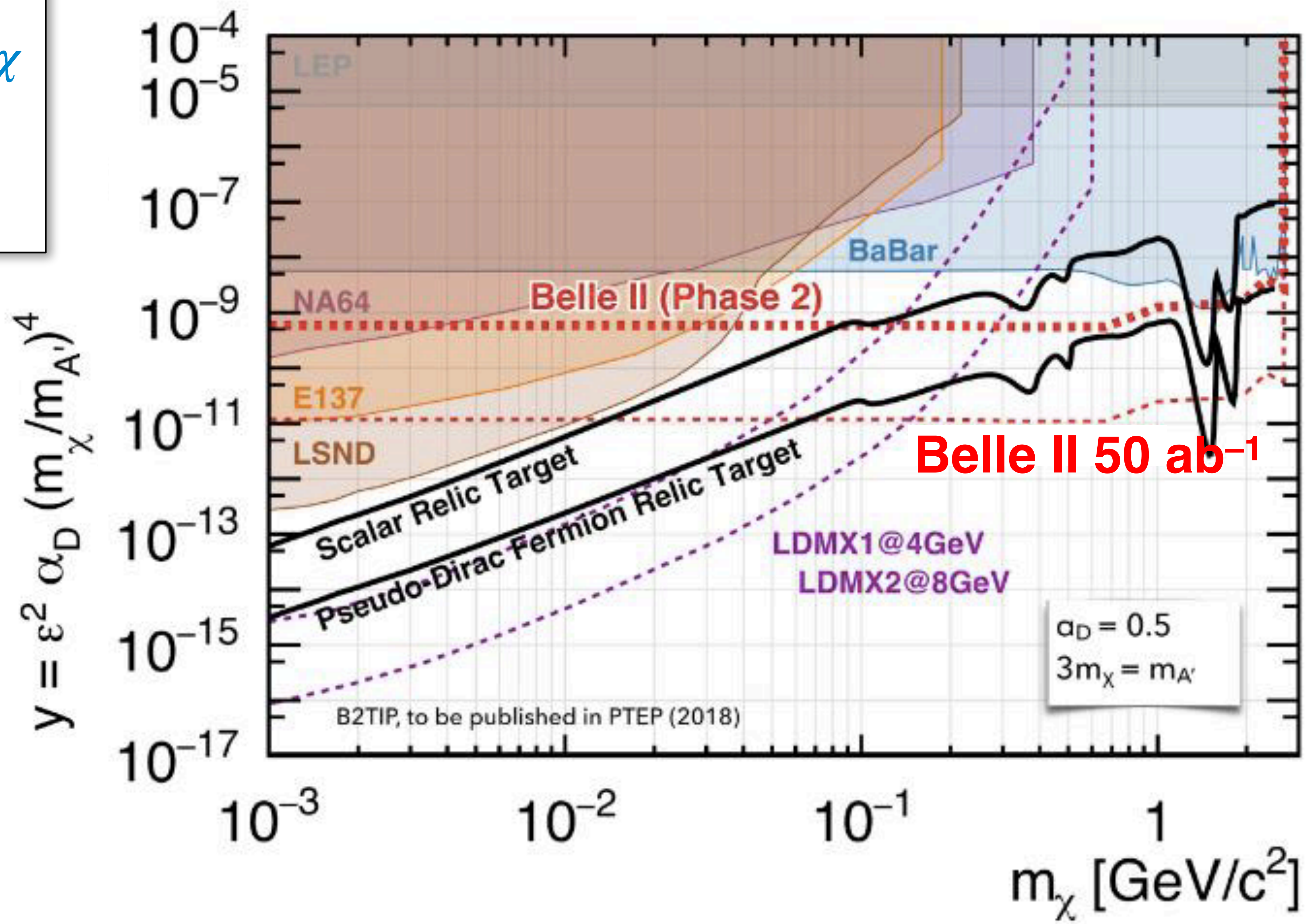
PTEP **2019**, 123C01 (2019)
arXiv: 1808.10567

… a fruitful collaboration among theorists and experimentalists

Dark-photon search requires single-photon trigger

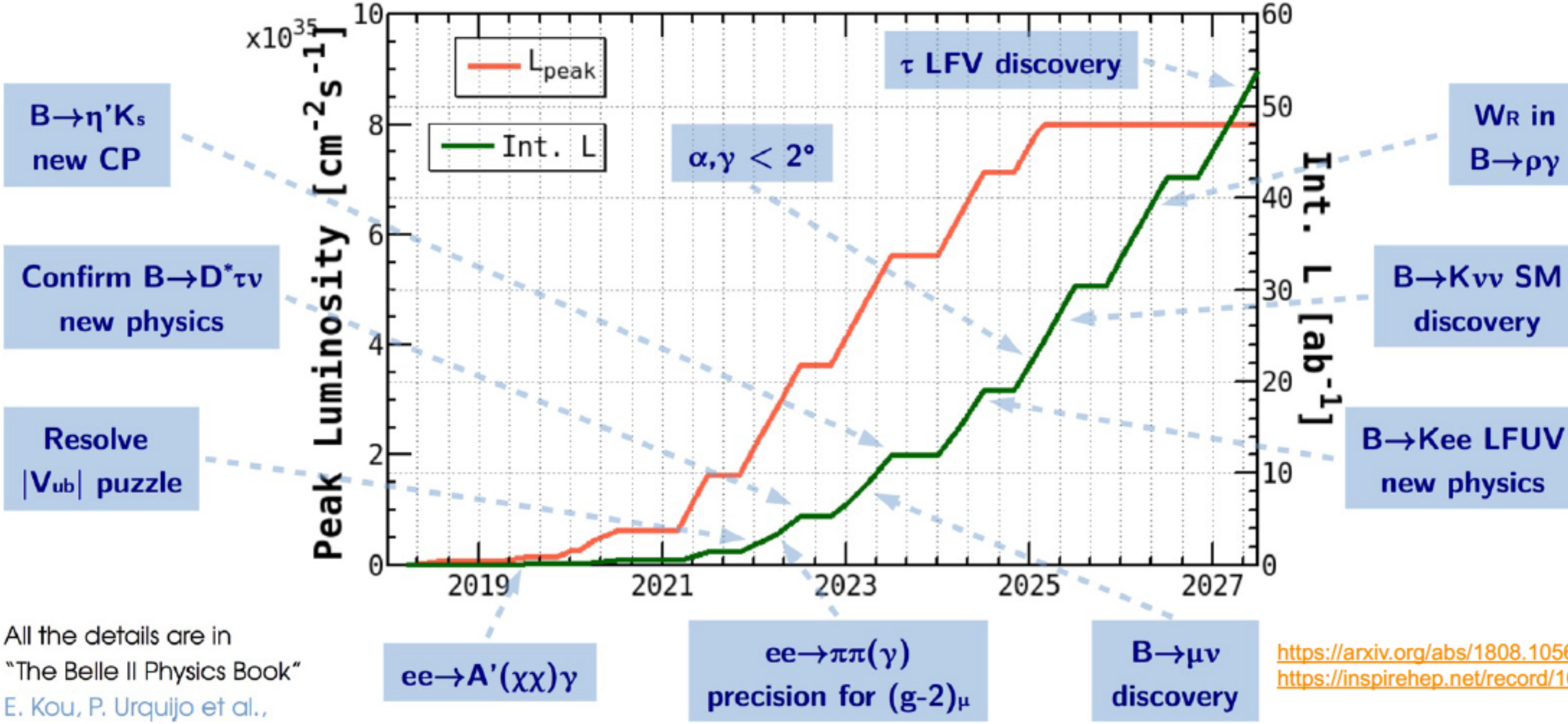


since the event contains exactly one photon … and nothing else



New-physics prospects for Belle II

based on the Belle II Physics Book



All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

Visualization by Giacomo De Pietro

Belle II conference papers at ICHEP 2020:

- ✓ Measurement of the branching ratios of $B^0 \to D^{(*)-} \ell^+ \nu$ (untagged) 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-008, arXiv:2008.07198

- ✓ Calibration of the Belle II hadronic Full Event Interpretation (FEI) 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-005, arXiv:2008.06096
- ✓ Measurement of the hadronic mass moments of $B \to X_c \ell^+ \nu$ decays 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-011, arXiv:2009.04493
- ✓ Measurement of the branching ratios of $B^0 \to D^{*-} \ell^+ \nu$ (using hadronic FEI) 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-009, arXiv:2008.10299
- ✓ Rediscovery of $B^0 \to \pi^- \ell^+ \nu$ (using the hadronic FEI) 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-007, arXiv:2008.08819

- ✓ Calibration of the Belle II B Flavor Tagger 8.7 fb^{-1}
  BELLE2-CONF-PH-2020-004, arXiv:2008.02707
- ✓ Rediscovery of $B \to \phi K^{(*)}$ decays, and measurement of the longitudinal polarization fraction of $B \to \phi K^*$ 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-006, arXiv:2008.03873
- ✓ Branching ratios and direct CP asymmetries of $B \to$ charmless decays 34.6 fb^{-1}
  BELLE2-CONF-PH-2020-012, arXiv:2009.09452

- ✓ Measurement of the τ lepton mass 8.8 fb^{-1}
  BELLE2-CONF-PH-2020-010, arXiv:2008.04665

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More Belle II results at ICHEP 2020:

- ✓ Inclusive $B^0 \to X_u\, e\, \nu$ from the lepton momentum endpoint 34.6 fb^{-1}
  BELLE2-NOTE-PL-2020-026
- ✓ Preparatory studies for $B^+ \to \tau^+ \nu$ 34.6 fb^{-1}
  BELLE2-NOTE-PL-2020-023
- ✓ $e^+e^- \to J/\psi\, \gamma$ ISR 37.8 fb^{-1}
  BELLE2-NOTE-PL-2020-017
- ✓ $D^0 \to K_S\, \pi^+ \pi^-$ 9.6 fb^{-1}
  BELLE2-NOTE-PL-2020-010
- ✓ "Wrong sign" D^0 decays 37.8 fb^{-1}
  BELLE2-NOTE-PL-2020-021
- ✓ $D^0 \to K_S\, K_S$ 37.8 fb^{-1}
  BELLE2-NOTE-PL-2020-020
- ✓ $D^0 \to K_S\, \pi^0$ 34.6 fb^{-1}
  BELLE2-NOTE-PL-2020-022
- ✓ Measurement of the D^0 lifetime 9.6 fb^{-1}
  BELLE2-NOTE-PL-2020-008
- ✓ $D_s^+ \to \phi\, \pi^+,\, K^{*+} K^-,\, K_S\, K^+$ 8.8 fb^{-1}
  BELLE2-NOTE-PL-2020-016
- ✓ Rediscovery of the Λ_c 8.8 fb^{-1}
  BELLE2-NOTE-PL-2020-008
- ✓ Time-dependent analysis of $B^0 \to J/\psi\, K_S$ 34.6 fb^{-1}
  BELLE2-NOTE-PL-2020-011
- ✓ Trigger performance for the single-photon analysis ($e^+e^- \to A'\gamma$) 34.6 fb^{-1}
  BELLE2-NOTE-PL-2020-009

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Belle II Notes (Public)