Belle II Experiment Highlights and Future Prospects

2023 CAP Congress

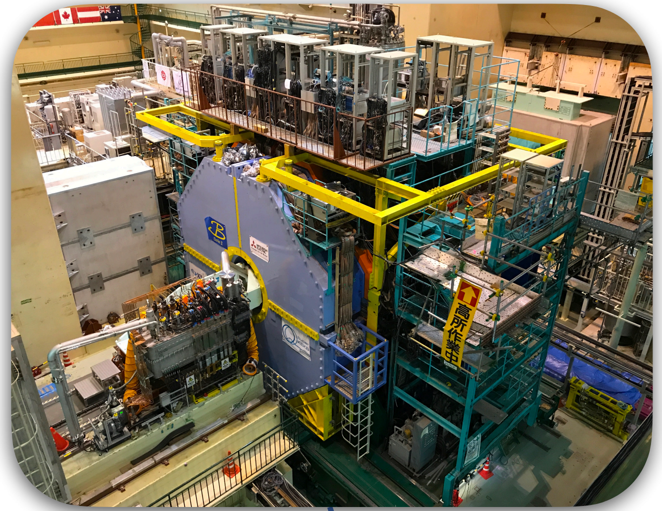
June 21 2023

Savino Longo on behalf of the Canadian Belle II group

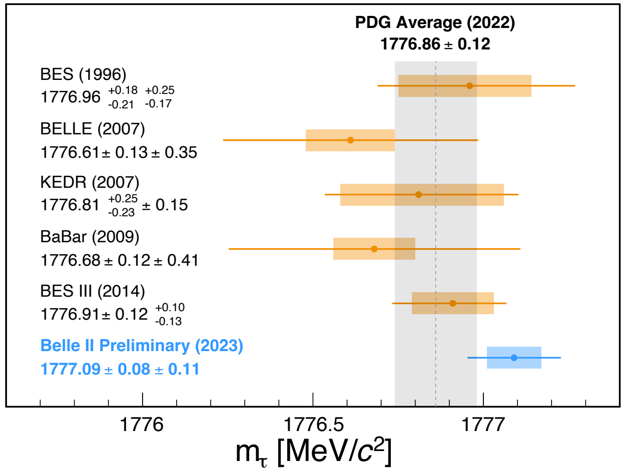
University of Manitoba

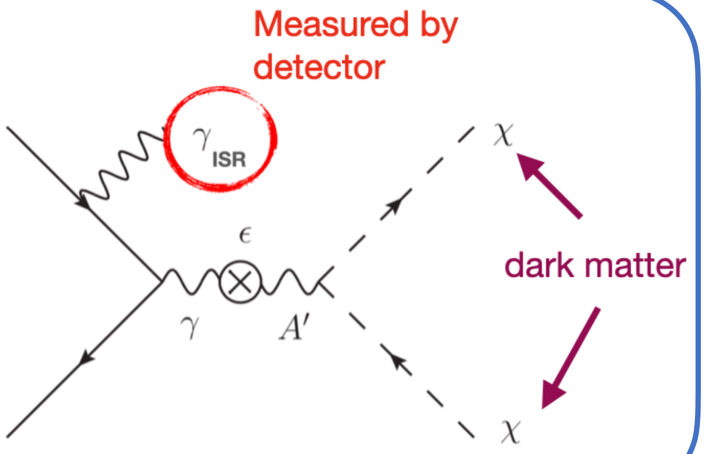
Savino.Longo@umanitoba.ca

Outline



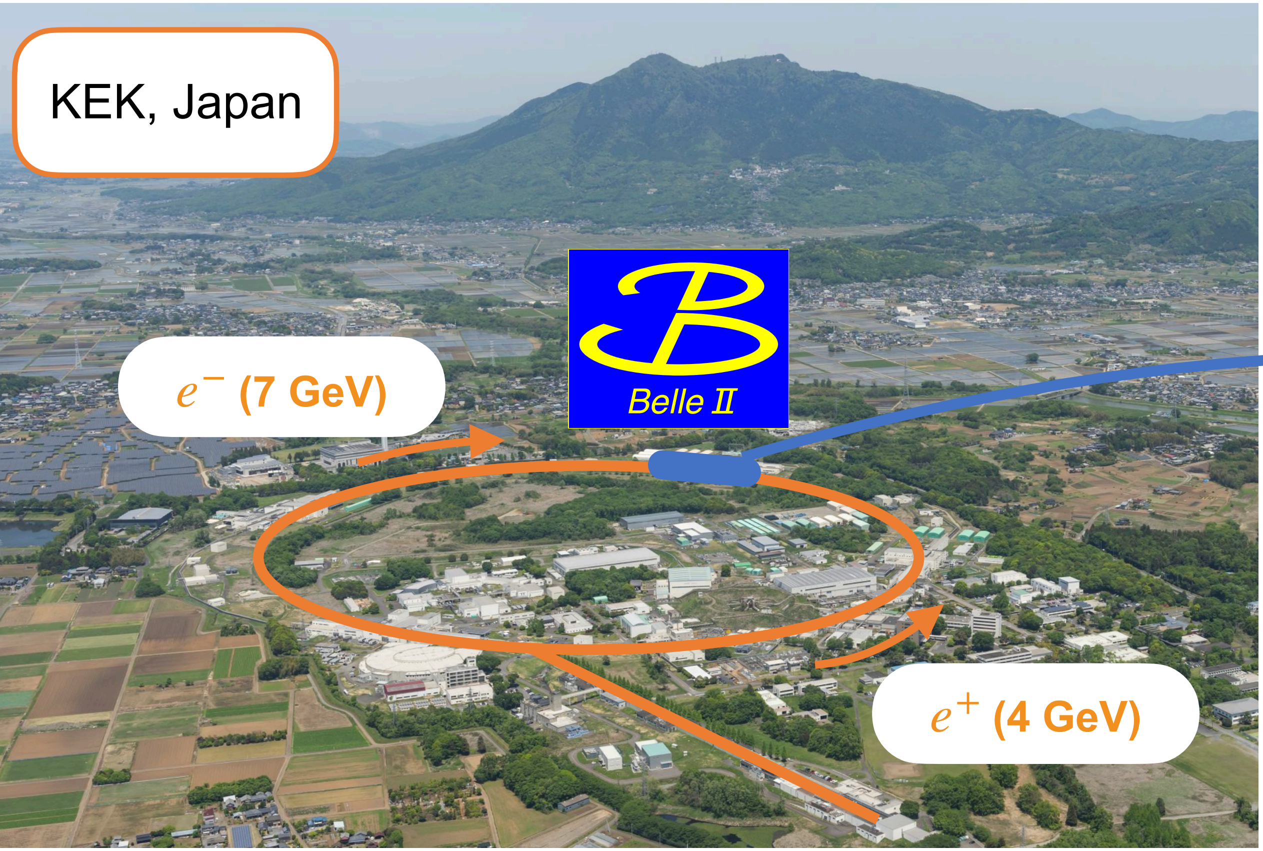
- Belle II Experiment Status
- Recent Belle II Physics Highlights
- Ongoing Work and Future Prospects

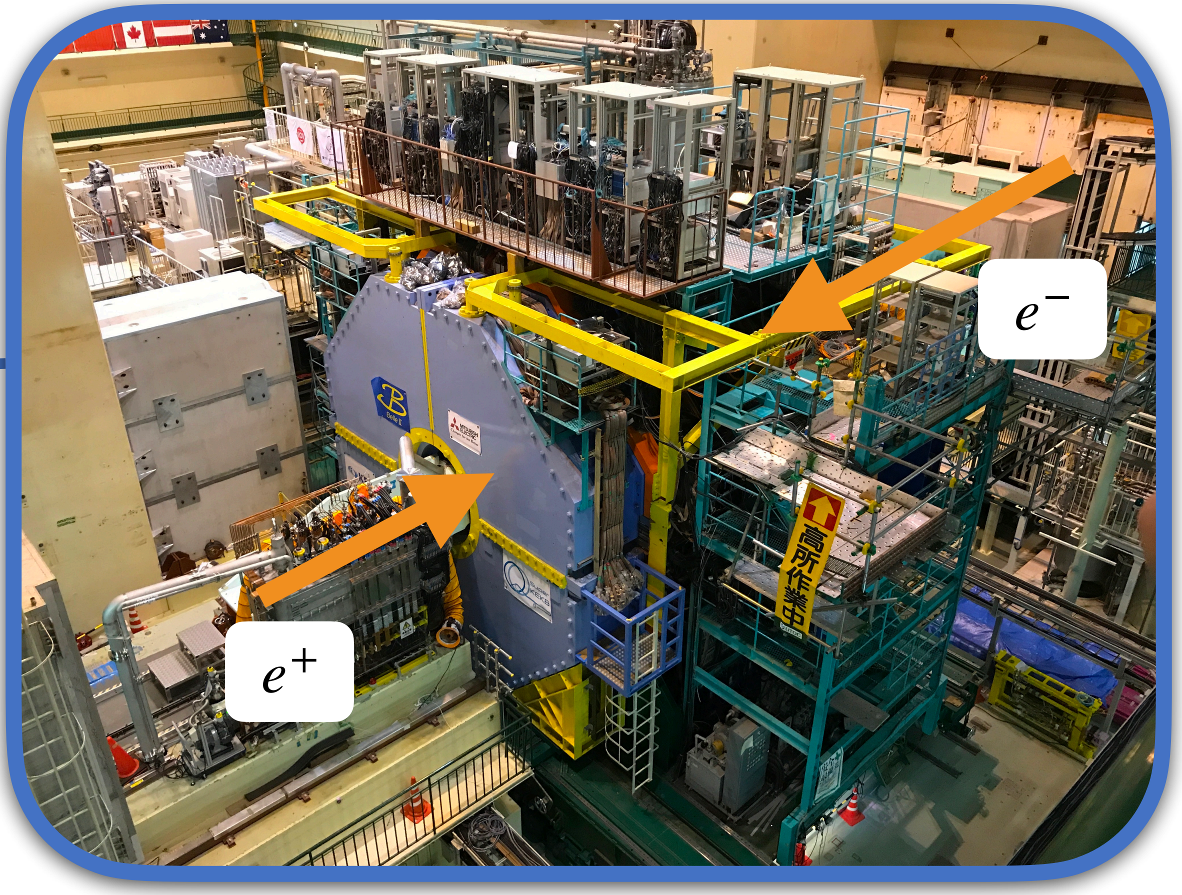




Belle II Experiment at SuperKEKB

- Next generation B-meson Factory searching for new physics at the intensity frontier.
- Asymmetric-energy e^+e^- collisions at or near $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV).
- Targets integrated luminosity of 50 ab^{-1} over experiment lifetime. (Belle ~ 0.7 ab^{-1}, BaBar ~ 0.4 ab^{-1})





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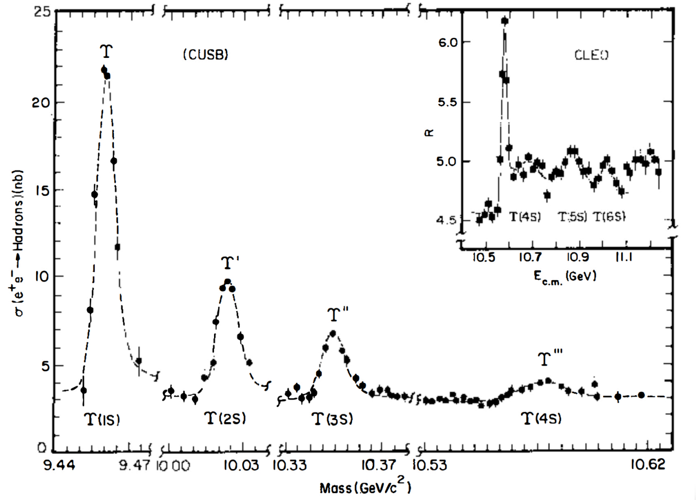
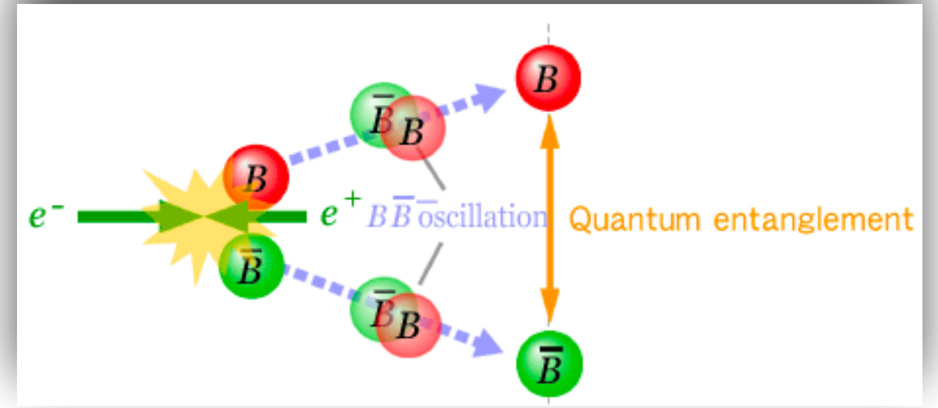
Belle II Physics Program

- Collision energy tuned to $\Upsilon(4S)$ (10.58 GeV).
  - >96% of $\Upsilon(4S)$ decay to entangled B meson pair.
  - Enables precise characterization of CKM matrix and Charge Parity violation.



- Extensive charm, tau and dark sector physics programs also pursued.



		Production σ (nb)
$e^+e^- \rightarrow$	$b\bar{b}$	1.1
	$c\bar{c}$	1.3
	light $q\bar{q}$	2.1
	$\tau^+\tau^-$	0.9
	Dark Sector	?

- Precise determination of missing energy/momentum enabled by:
  - ✓ Minimal collision pile-up
  - ✓ Well-known initial conditions
  - ✓ Hermetic detector with high detection efficiency for charged and neutral particles.

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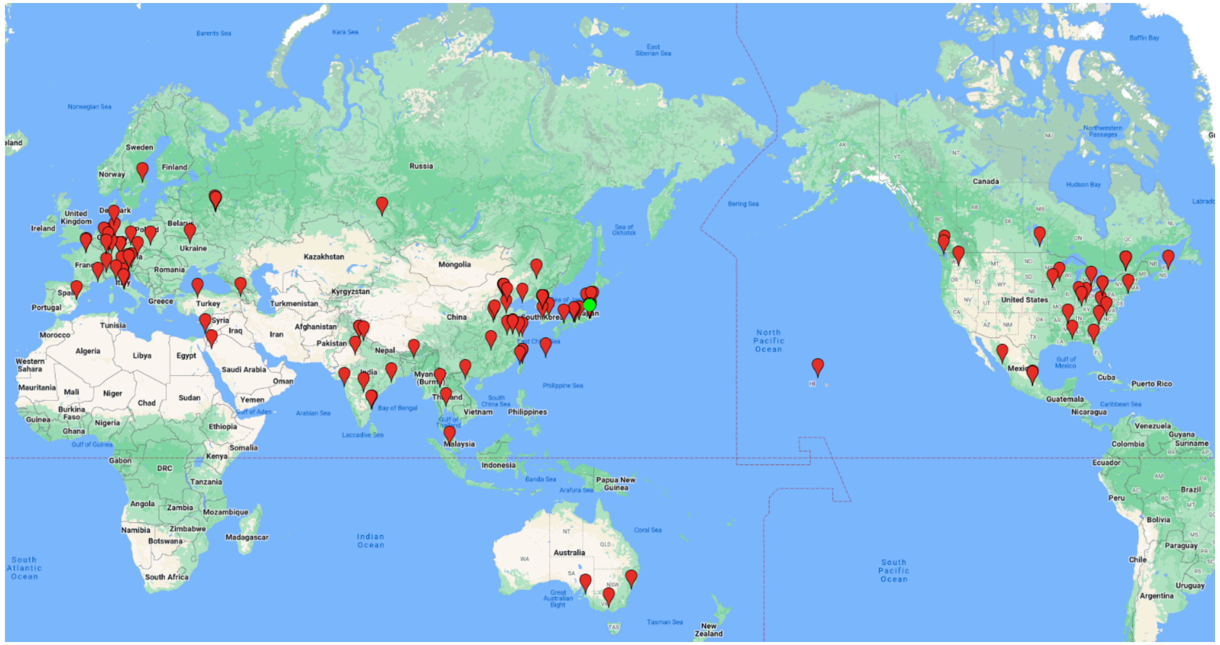
https://www2.kek.jp/en/press/2007/BellePress9e.html

Belle II Collaboration and Canadian Participation

- International collaboration of ~1,100 physicists from over 120 institutes, and 26 countries and regions.
- Seven Canadian institutes.

➡15 grant eligible, 1 computing physicist, 3 postdocs, 11 graduate students, and 5 undergraduates.



U. British Columbia:
C. Hearty, J. McKenna, M. De Nuccio, M. Wakai, D. Crook

U. Victoria:
M. Roney, R. Sobie, R. Kowalewski, T. Junginger, M. Ebert, T. Grammatico, A. Beaubien, N. Tessema, S. Gholipourverki, S. Taylor

McGill:
A. Warburton, R. van Tonder, A. Fodor, T. Shillington, K. Chu, G. Leverick

U. Manitoba:
S. Longo, J. Mammei, W. Deconinck, M. Gericke, I. Na, S. Saha, A. Tseragotin, A. Shakib

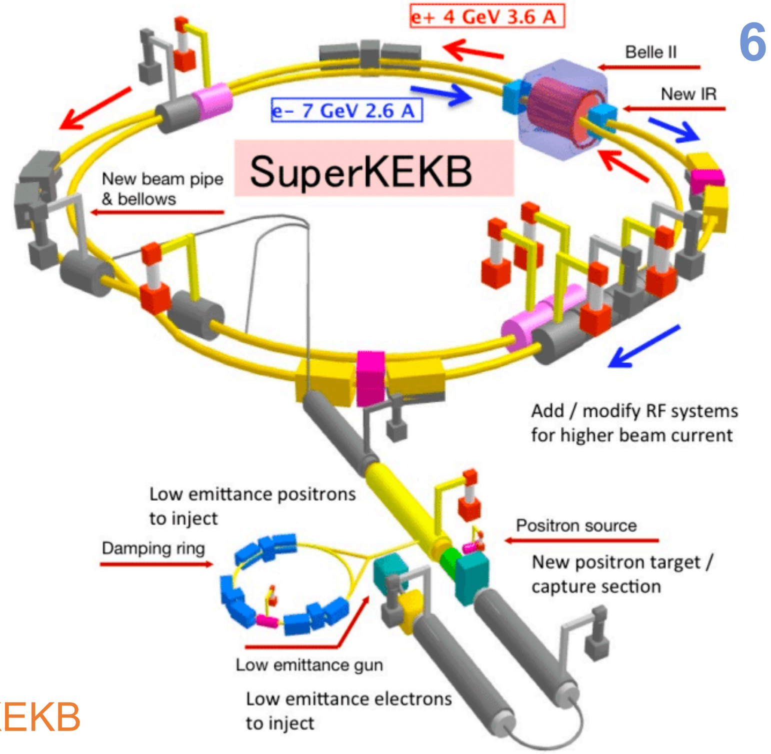
U. Alberta:
S. Robertson

St. Francis Xavier:
H. Ahmed, E. Hunt, M. Penner

TRIUMF:
R. Baartman, T. Planche

SuperKEKB Collider

- Targets final luminosity of $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$ (~40x KEKB collider)
- Achieved through novel nano-beams and higher beam currents.

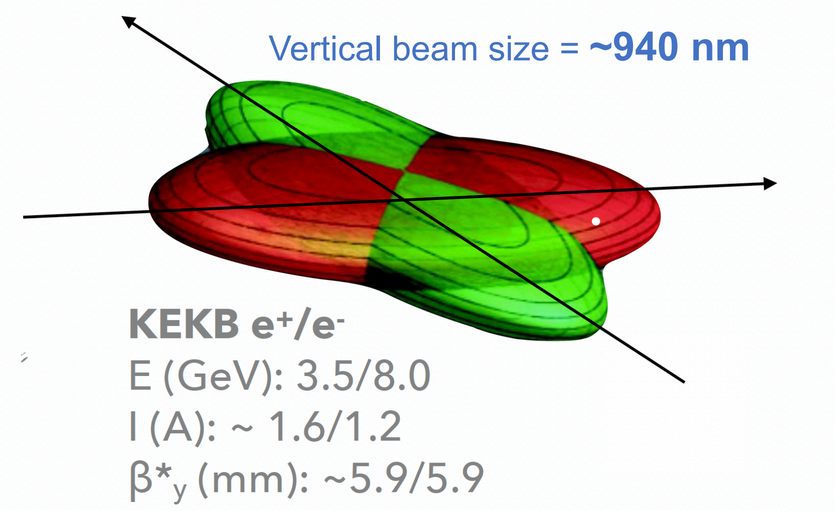


Beam current doubled from KEKB

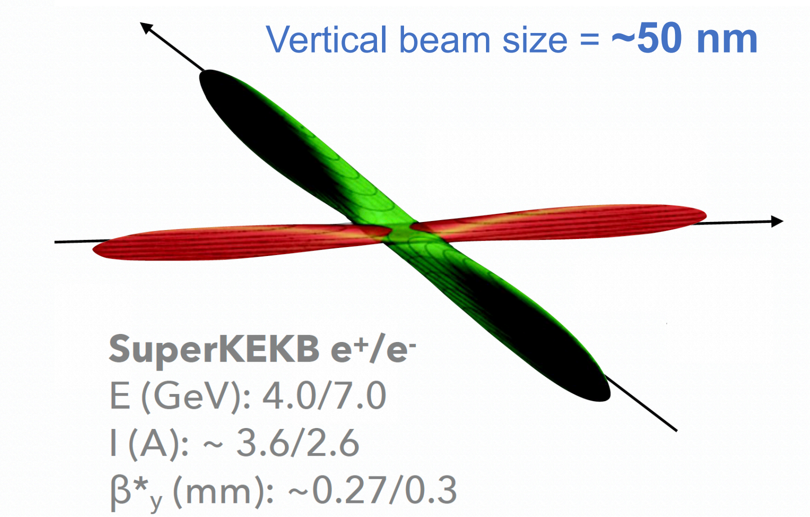
$$L = \frac{\gamma_{\pm}}{2er_e}\left(\frac{I_{\pm}\xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Vertical beam size at interaction point x20 smaller from KEKB

Previous generation



SuperKEKB nano-beams



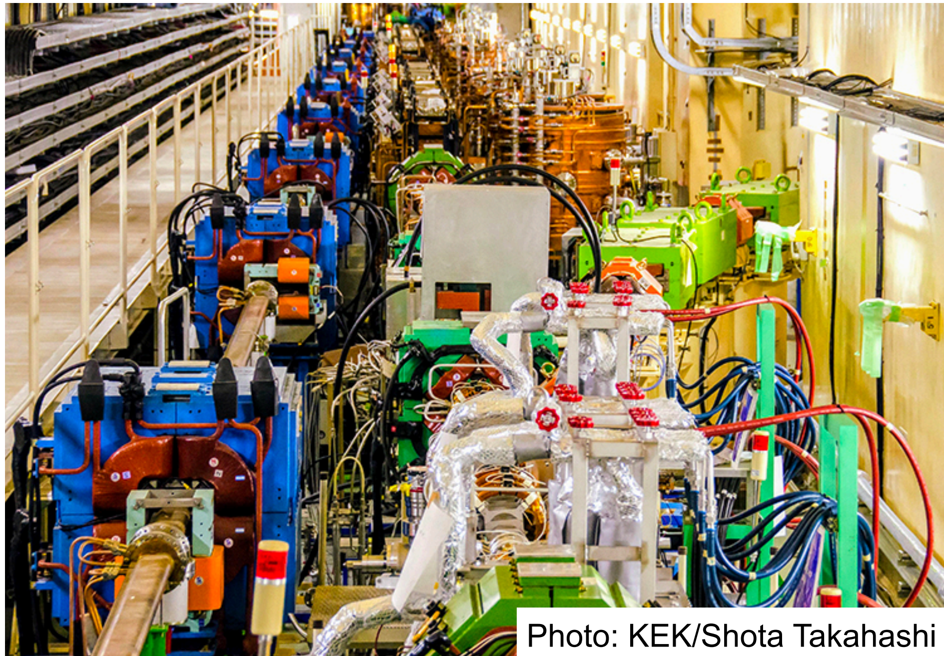


Photo: KEK/Shota Takahashi

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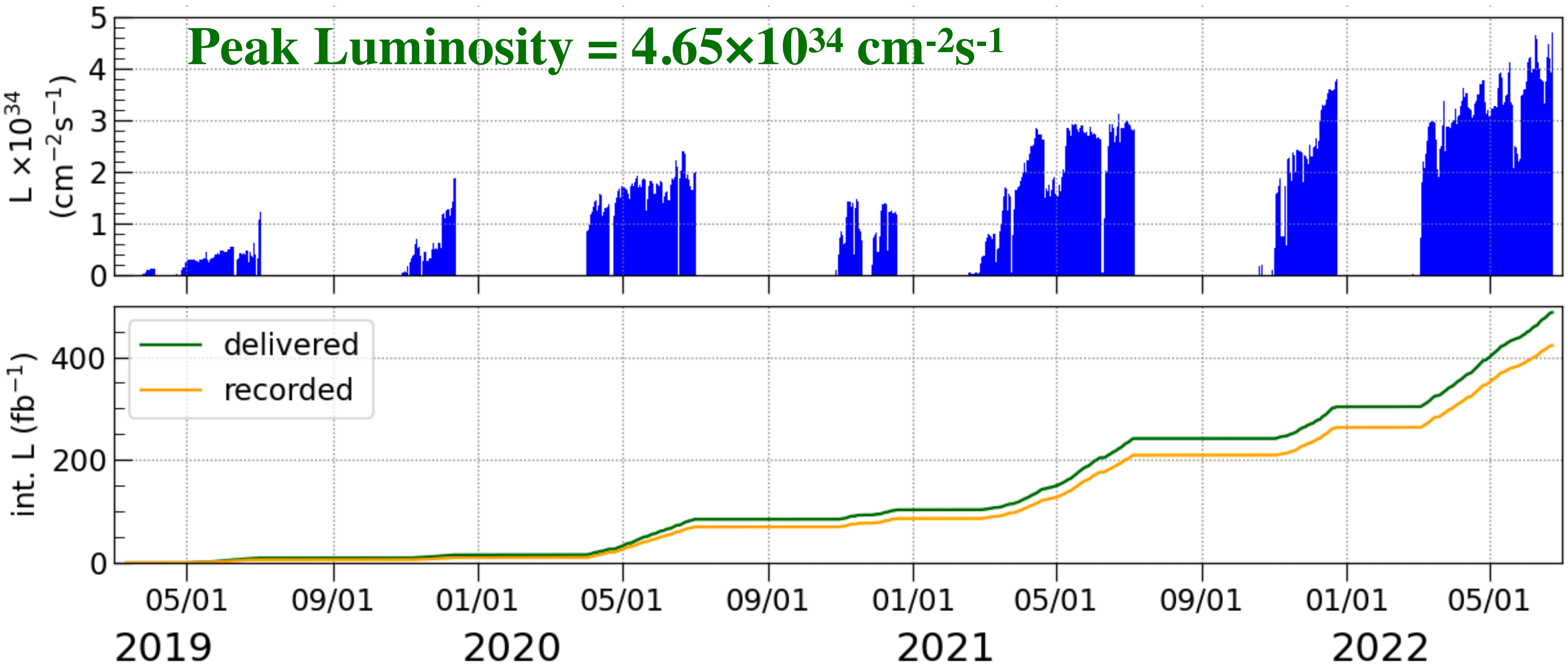
SuperKEKB Operation

- SuperKEKB has doubled the world-record for instantaneous luminosity since starting physics operation in 2019.
- Peak luminosity of $4.65 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ achieved in most recent operating period.



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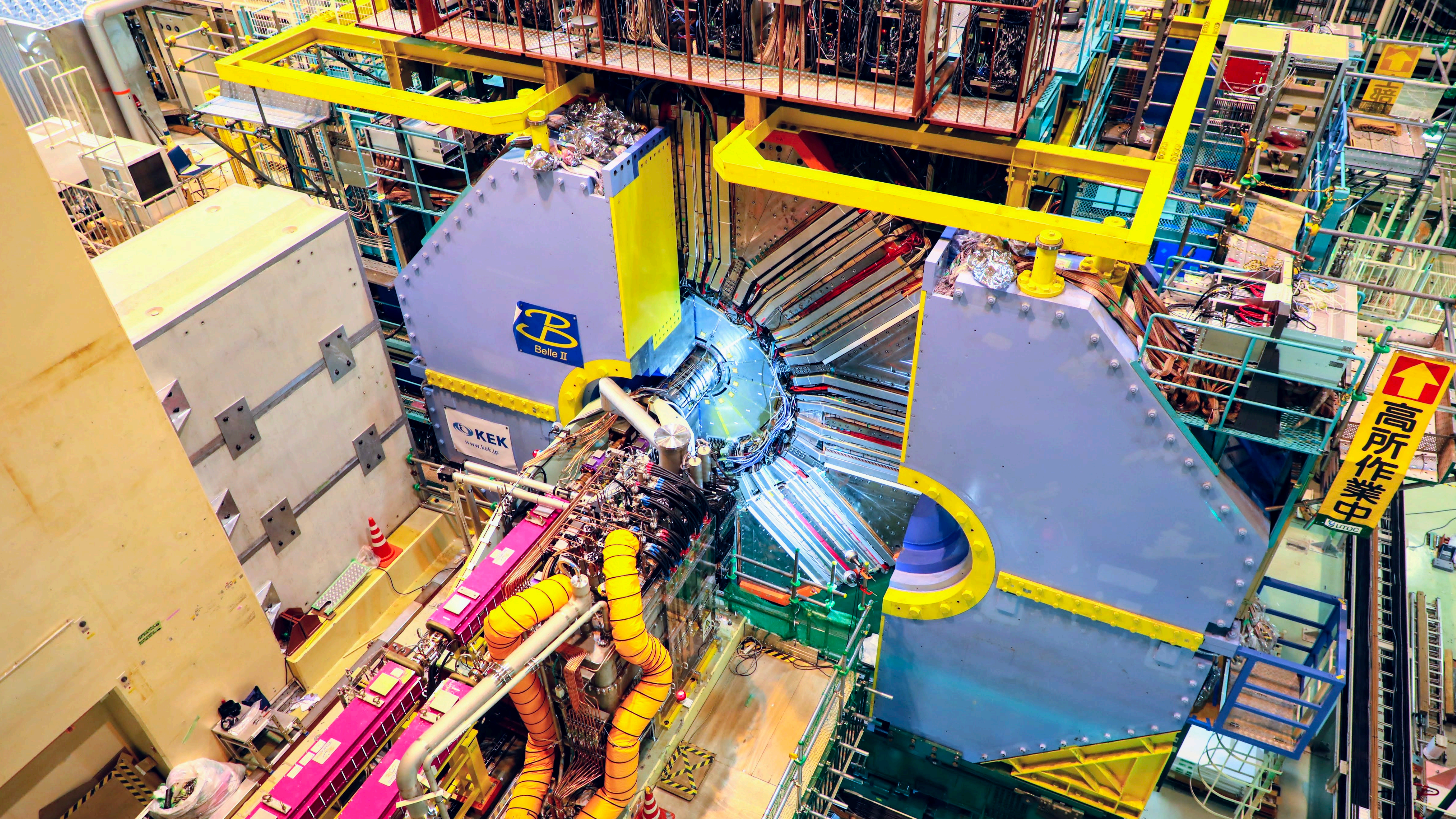
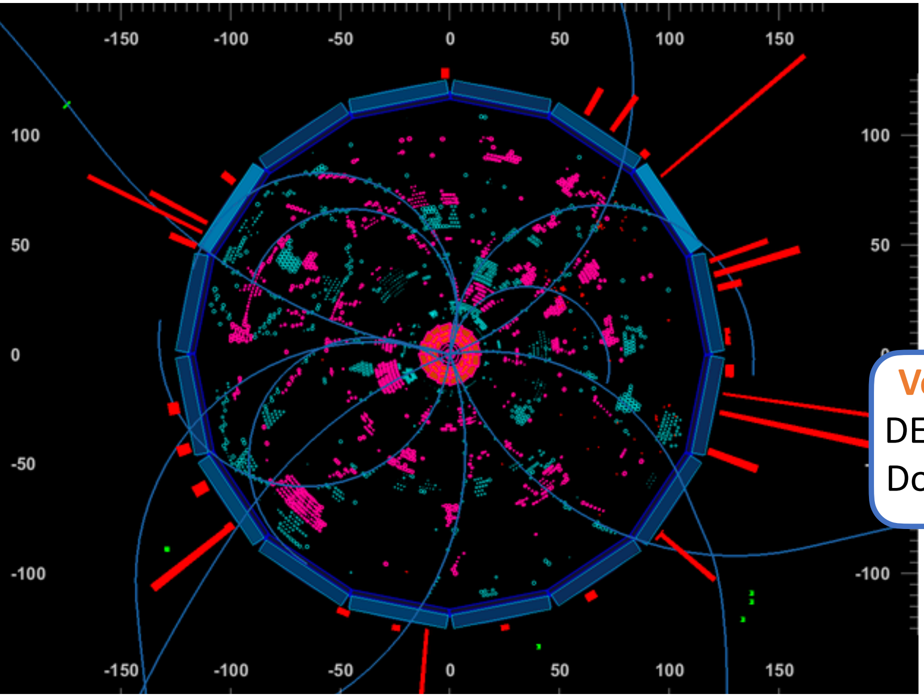

Belle II
KEK
www.kek.jp
高所作業中

Belle II Detector

Operates as magnetic spectrometer with high detection efficiency for charged and neutral particles.

- Canada provides ~11% of Belle II computing resources.
- CFI-IF awarded for new Tier-1 data storage centre.



Electromagnetic Calorimeter
CsI(Tl) with waveform sampling
5D Calorimetry: Position, energy, time, and pulse shape for particle ID.

K_L^0 and Muon detector
Inner Barrel/Endcaps: Scintillating Strips
Outer Barrel: Resistive Plate Counter

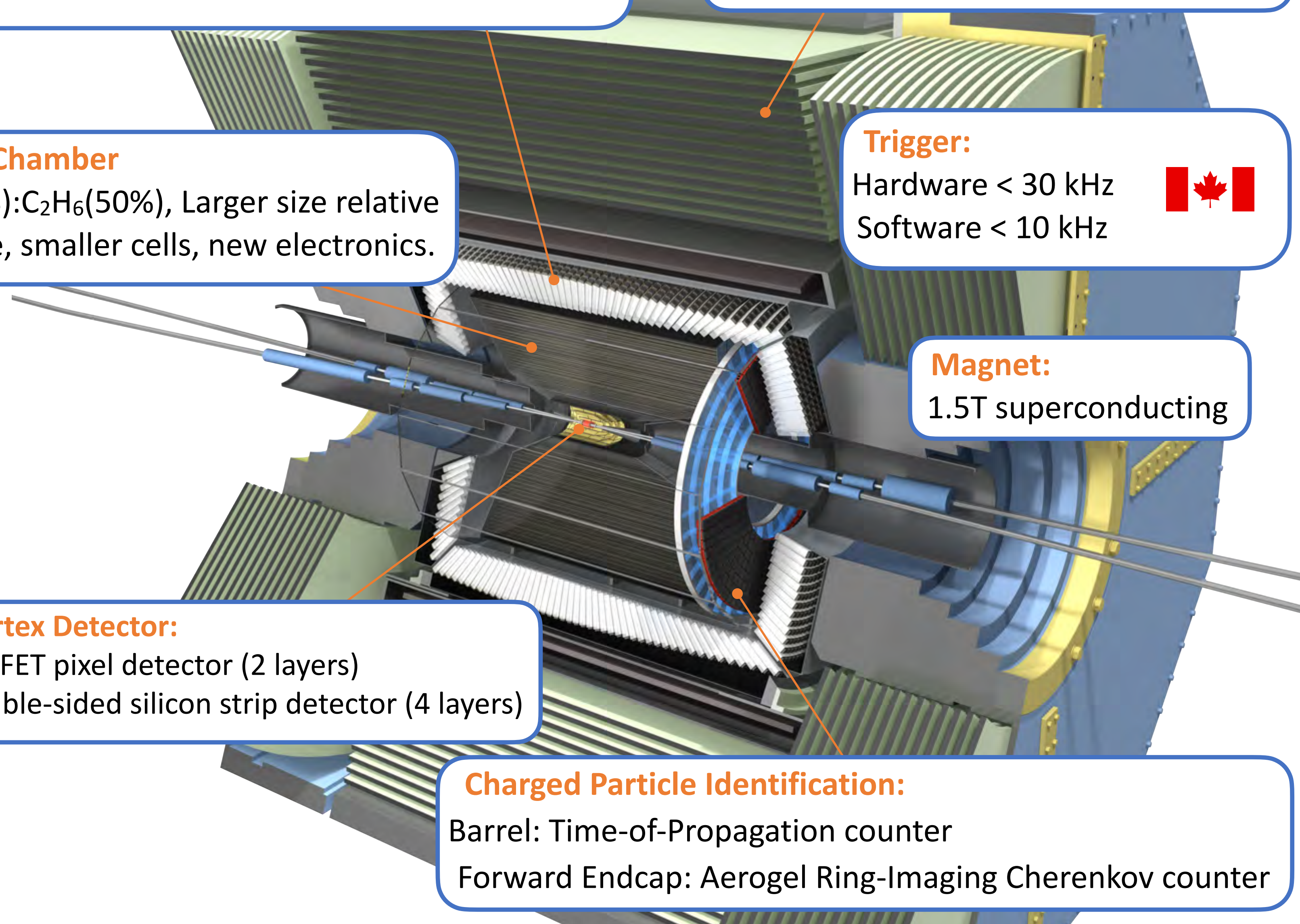
Drift Chamber
He(50%):C_2H_6(50%), Larger size relative to Belle, smaller cells, new electronics.

Trigger:
Hardware < 30 kHz
Software < 10 kHz

Magnet:
1.5T superconducting

Vertex Detector:
DEPFET pixel detector (2 layers)
Double-sided silicon strip detector (4 layers)

Charged Particle Identification:
Barrel: Time-of-Propagation counter
Forward Endcap: Aerogel Ring-Imaging Cherenkov counter



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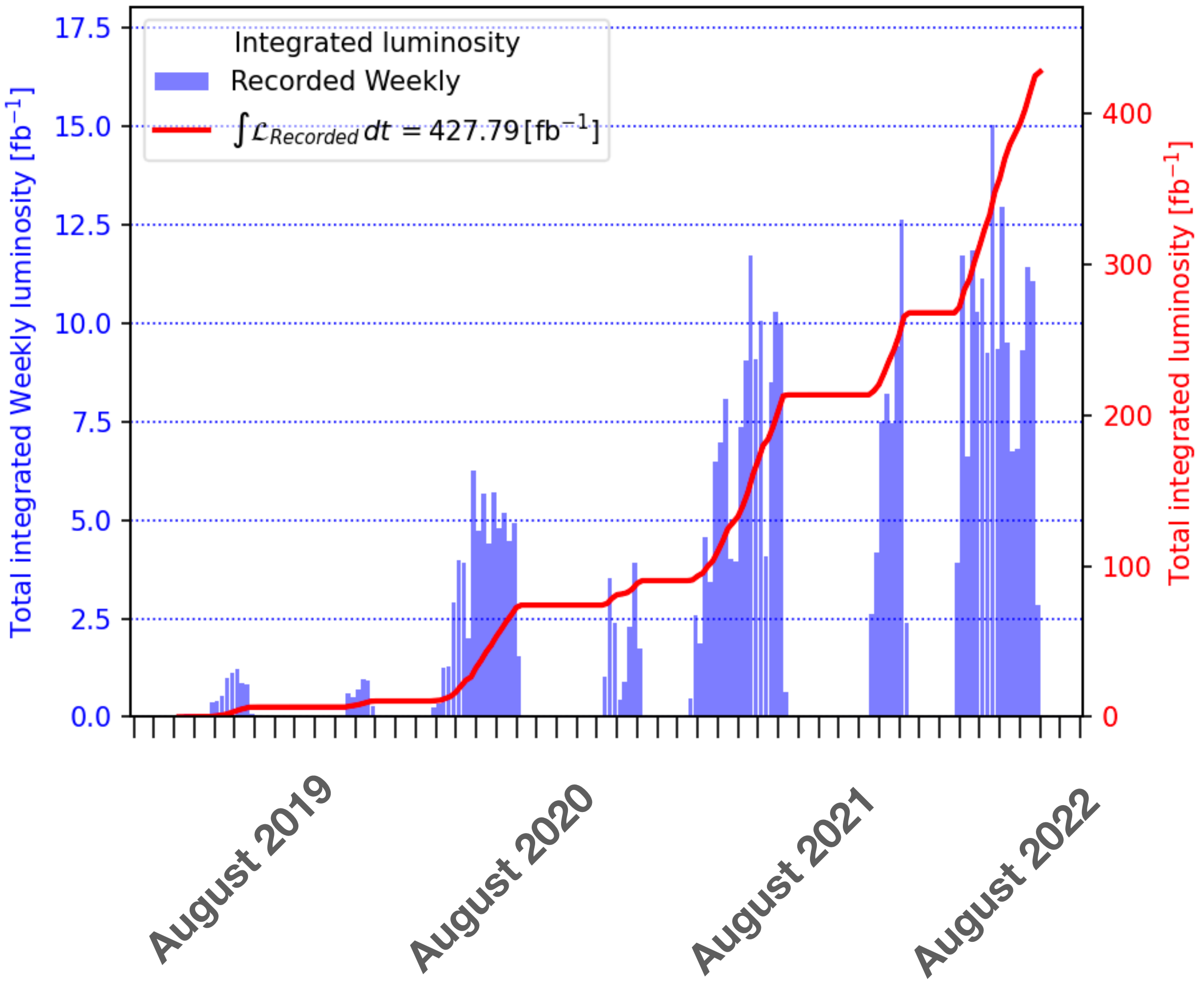
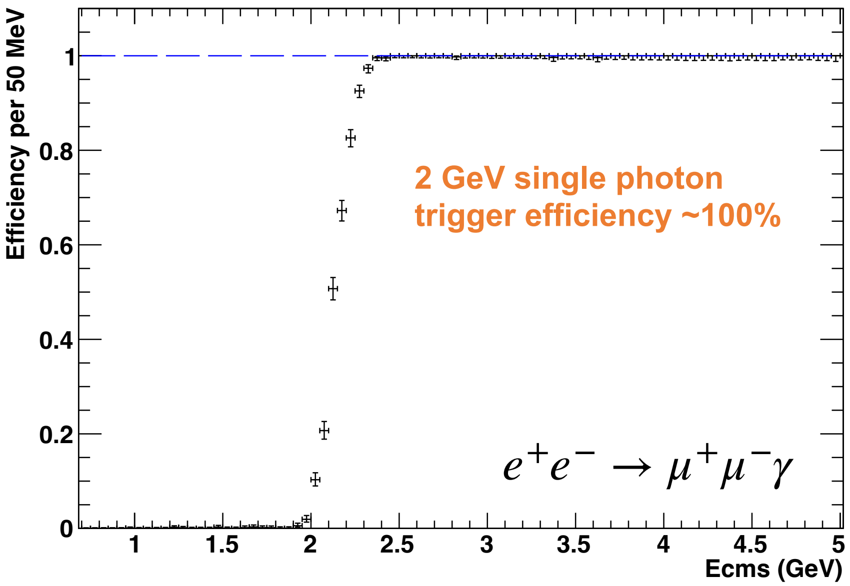
Belle II Dataset

- Total dataset to-date is 427/fb.
  - Equivalent to BaBar dataset was achieved in 1/4 the time and during pandemic.
- Specialized "Dark Sector Triggers" (eg. single photon, single track), enabled for entire dataset.
  - Belle did not have single photon trigger, and BaBar had only for ~10% of dataset.





Single Photon Level 1 Trigger Lines:

- At least one photon with E_{CMS} > 2 GeV
- One E_{CMS} > 1 GeV photon in barrel + no other energetic photons
- One E_{CMS} > 0.5 GeV photon in central barrel + no other energetic photons

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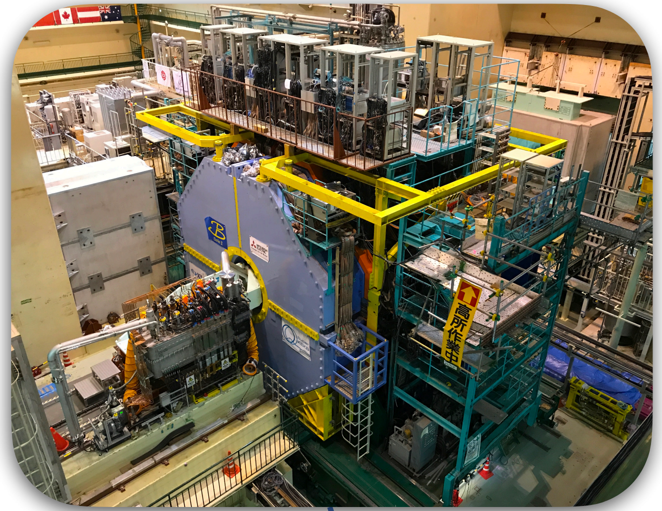

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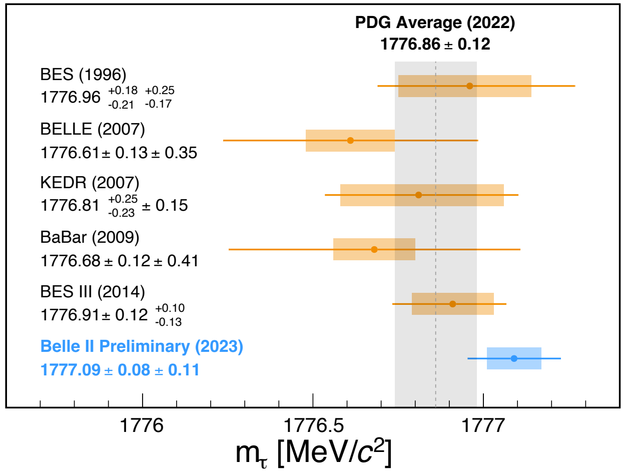
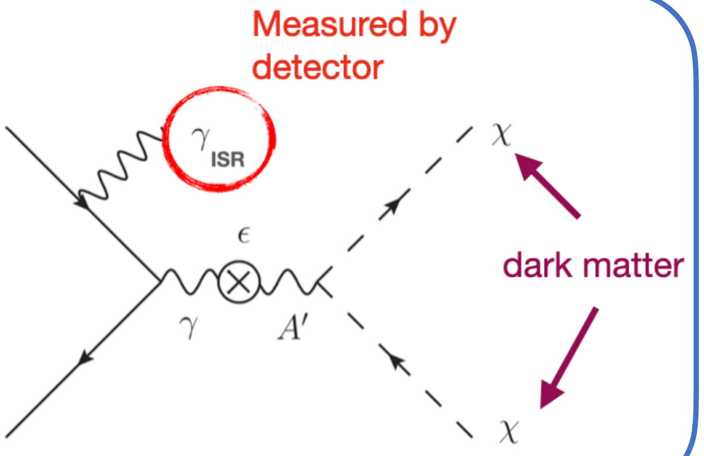
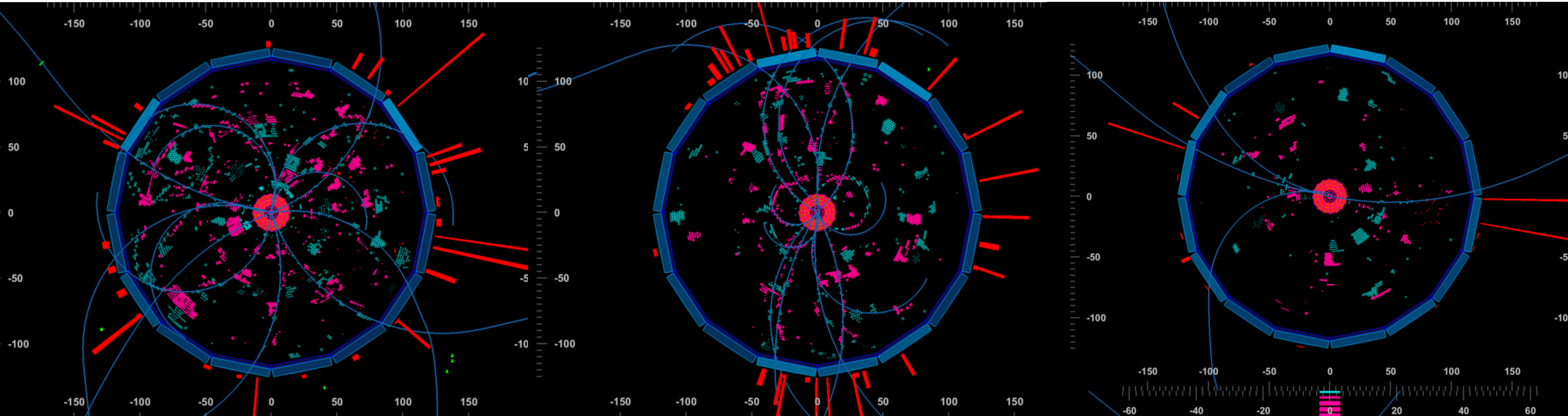
- Ongoing Work and Future Prospects





Recent Belle II Physics Highlights

- Total of 22 papers published/accepted/submitted. (Belle II Journal Publications)
- 10 papers published/accepted in last year.
- This talk will highlight a subset of results from the past year.



Testing Light-lepton Universality

- Standard Model predicts same electroweak coupling for all leptons "Lepton Flavour Universality" (LFU).
- Precision $e - \mu$ universality test completed with 189/fb using inclusive semileptonic decays with hadronic tag.

$$e^+e^- \to \Upsilon(4S) \to B_{tag}\,\bar{B}_{sig}$$

B_{tag} fully reconstructed.

$\bar{B}_{sig} \to X\ell\nu \qquad \ell = e, \mu$

$X =$ anything

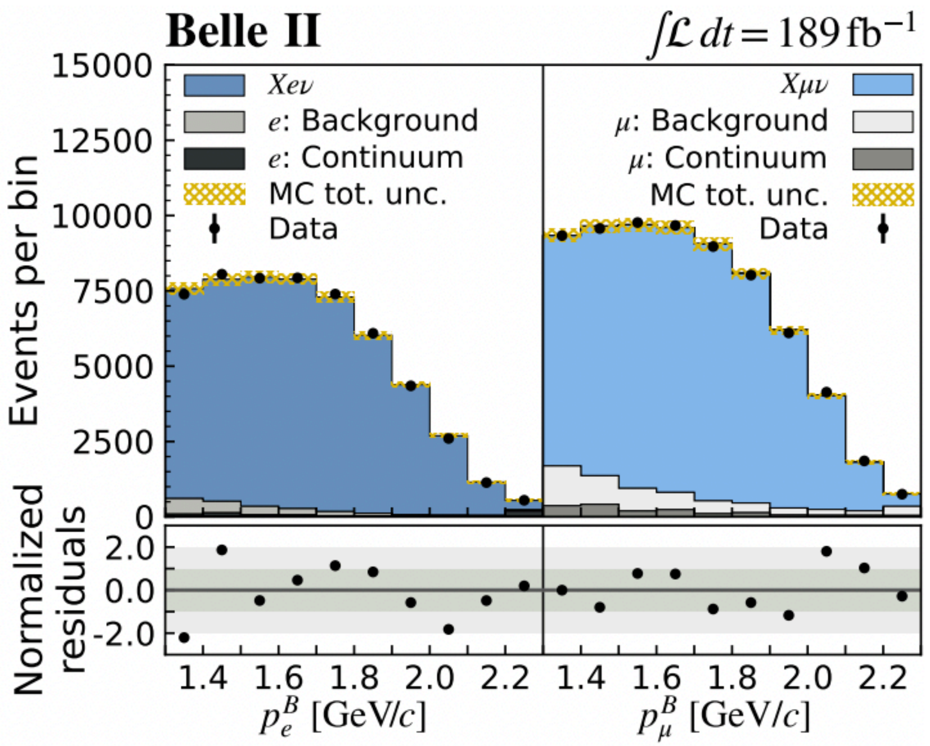
- Background constrained with off-resonance data. Yield measured with simultaneous fit to p_e^B and p_μ^B spectra.
- Work ongoing to extend to tau flavour.

$$R(X_{e/\mu}) = \mathcal{B}(B \to X\,e\,\nu)/\mathcal{B}(B \to X\,\mu\,\nu)$$
$$= 1.007 \pm 0.009\ (\text{stat}) \pm 0.019\ (\text{syst})$$

Consistent with Standard Model prediction

Most precise test of $e - \mu$ universality in semileptonic B decays

arXiv:2301.08266 Accepted to Phys. Rev. Lett.



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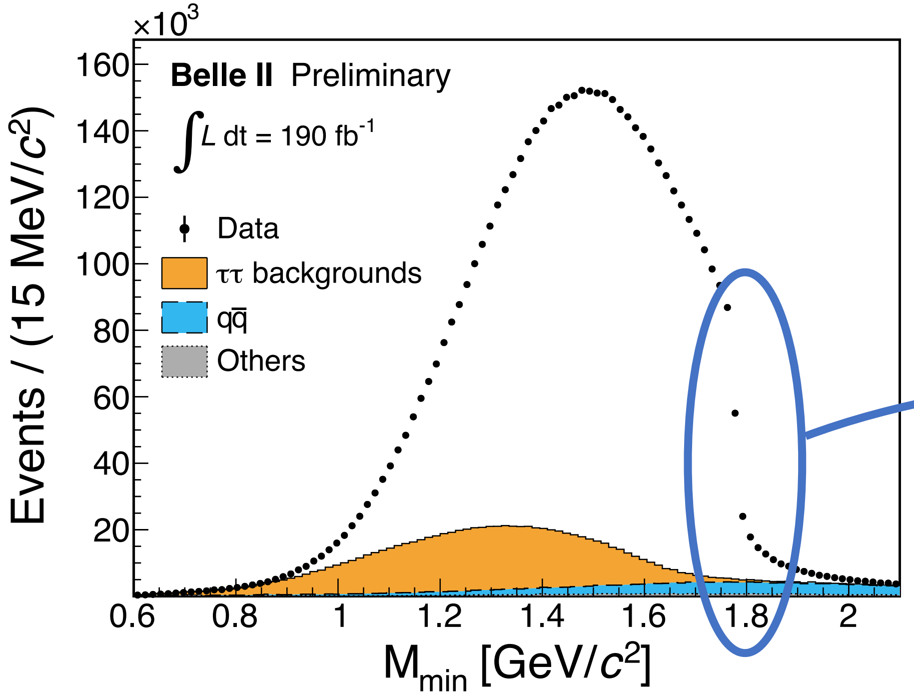
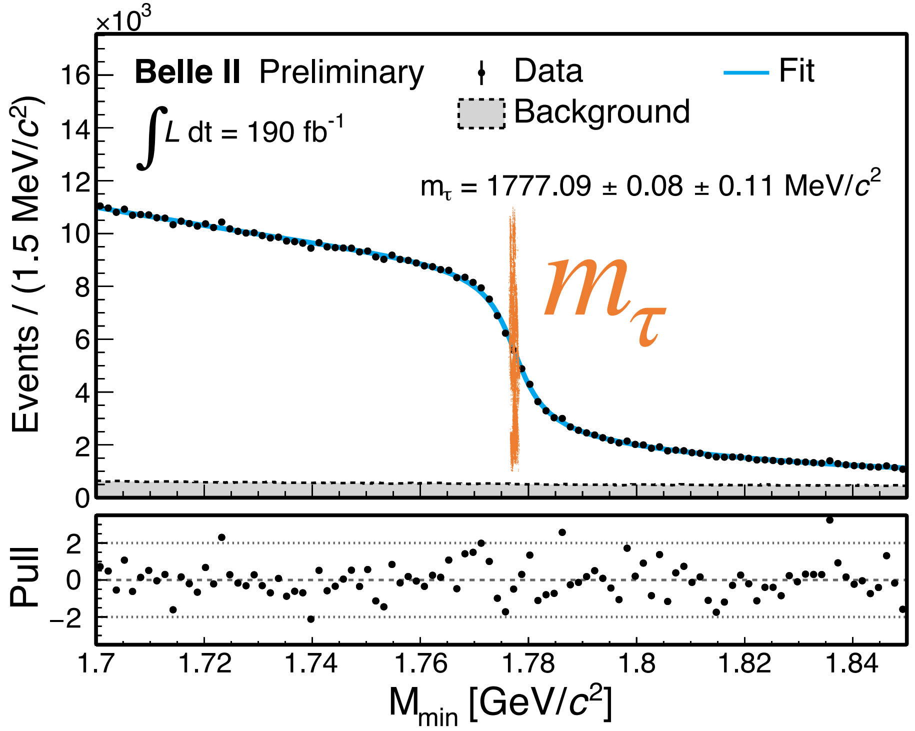
Precise Measurement of the τ Mass

- τ mass is fundamental parameter of the Standard Model. Uncertainty enters in precision tests of Lepton Flavour Universality, predictions of τ branching fractions, and α_s measurements at τ-mass scale.
- Analysis selects $e^+e^- \to \tau^+\tau^-$ events containing decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.
- Assume neutrino co-linear with $\overrightarrow{p}_{3\pi}$ to obtain: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$
- τ mass extracted from threshold of this distribution measured using fit to empirical function.





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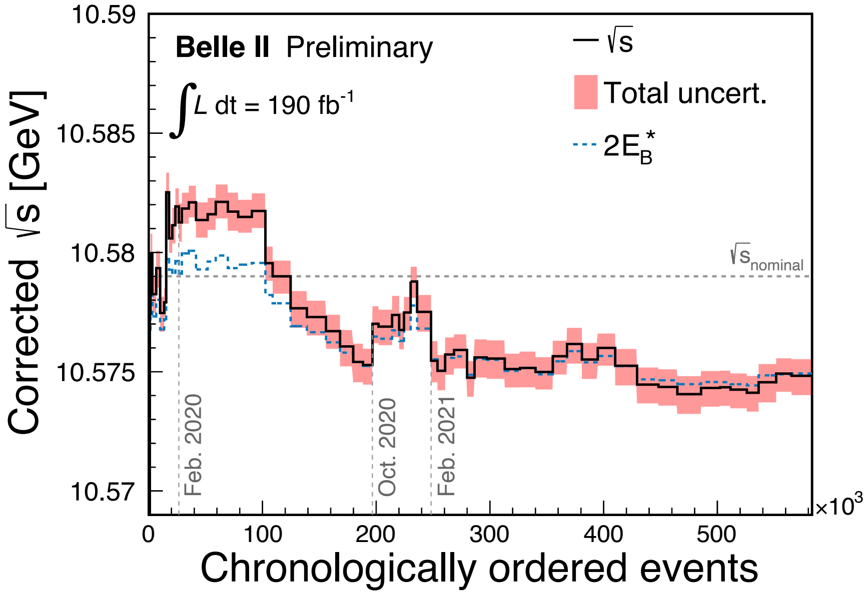
Precise Measurement of the τ Mass

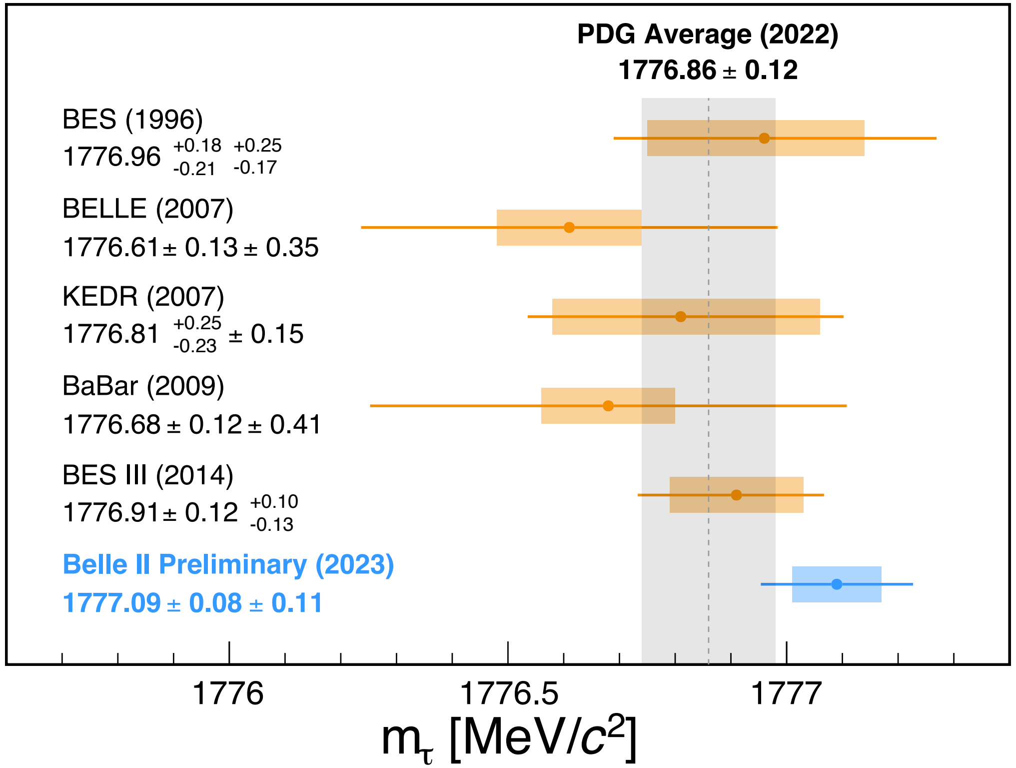
- Precise knowledge of beam energy and track momentum scale required for measurement.
- Result is most precise measurement to-date of the τ mass.

$$\sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

Submitted to Phys. Rev. D arXiv:2305.19116



Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	$\leq$ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11



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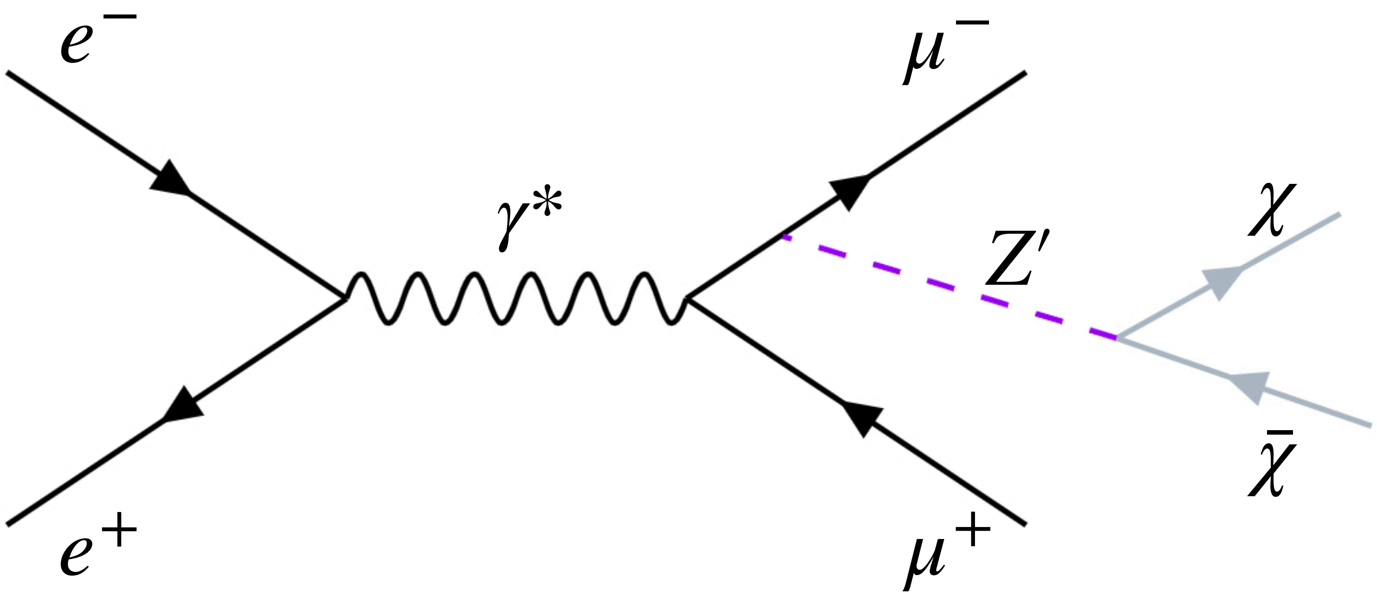
Invisible Z' Search

- Search for massive Z' vector boson with coupling to only muon and tau ($L_\mu - L_\tau$ extension of SM).
  - Predicts dark matter candidate and could explain current muon $g-2$ tension.`

    B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
    W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, J. High Energy Phys. 12 (2016) 106.
    W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. Lett. 113, 091801 (2014).
- Search completed at Belle II via $e^+e^- \to \mu^+\mu^- Z', Z' \to$ Invisible



Recoil mass computed with detected muons peaks at Z' mass.

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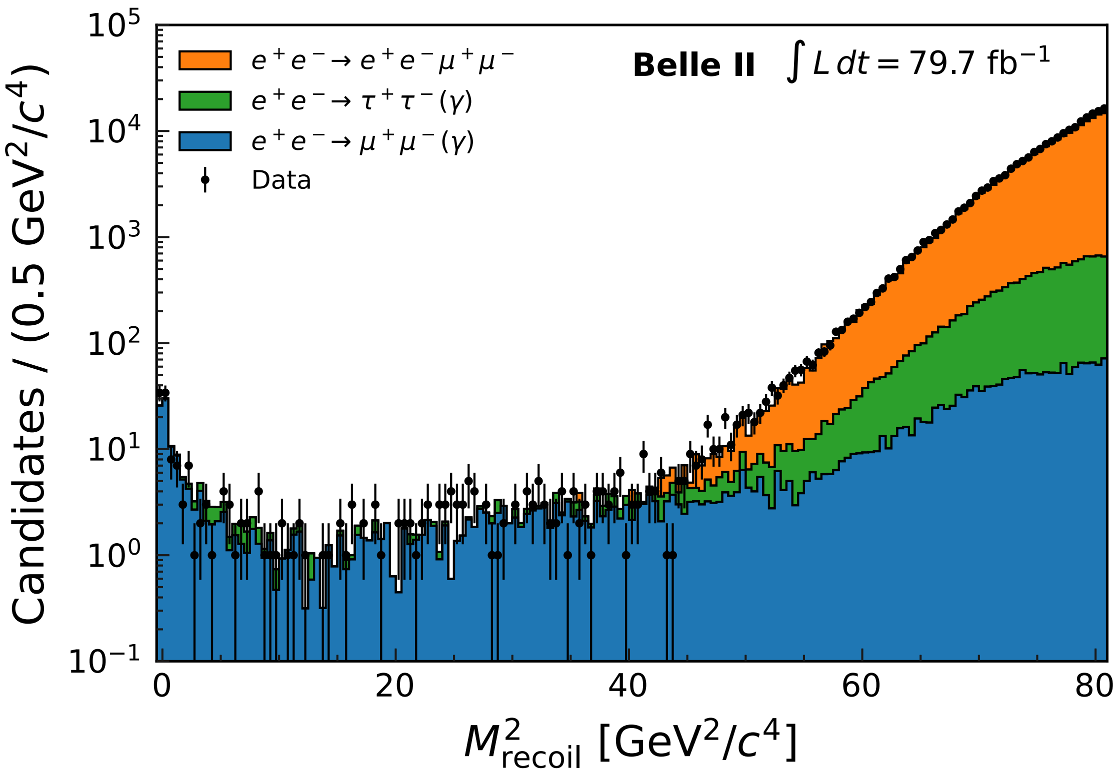
Invisible Z' Search

- Backgrounds arise from:

  $e^+e^- \to \mu^+\mu^-(\gamma)$ where photon is not reconstructed

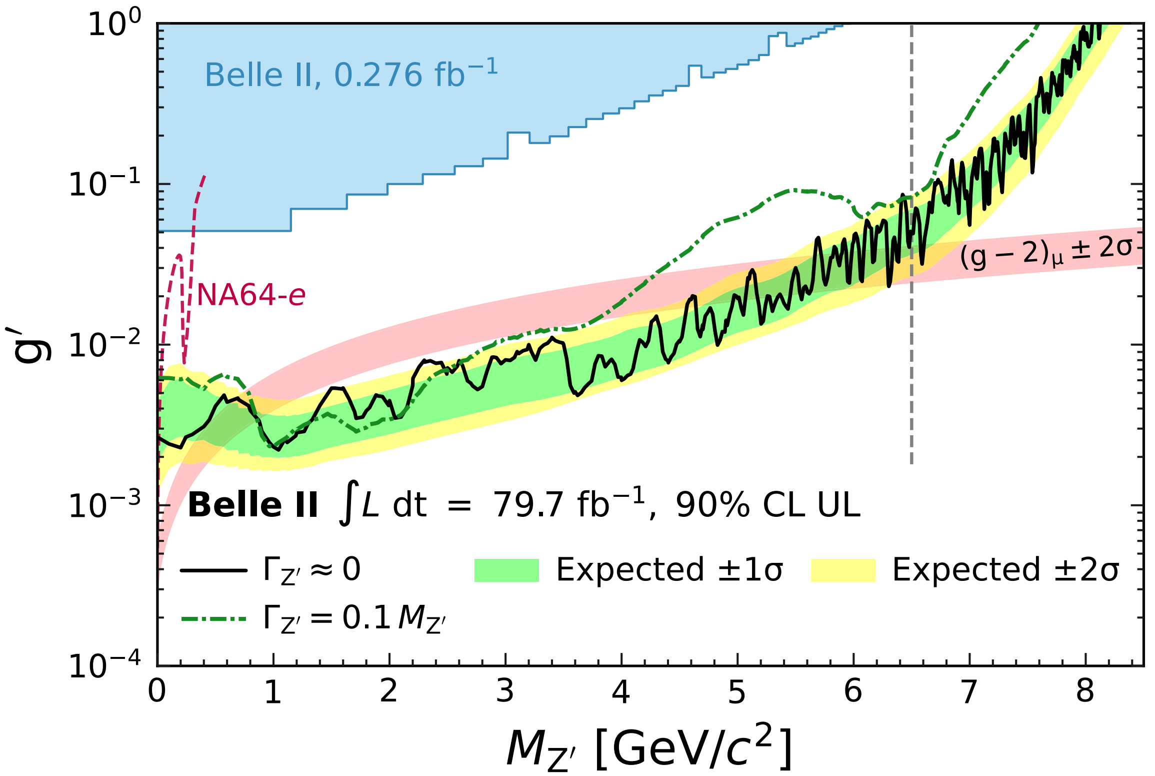
  $e^+e^- \to \tau^+\tau^-(\gamma)$ neutrinos escape detector

  $e^+e^- \to e^+e^-\mu^+\mu^-$ with e^+e^- not in acceptance



- No significant excess observed in 79.7/fb.
- Part of Z' parameter space, which could explain muon $g-2$ tension is excluded.

Belle II Collaboration Phys. Rev. Lett. 130, 231801 (2023)



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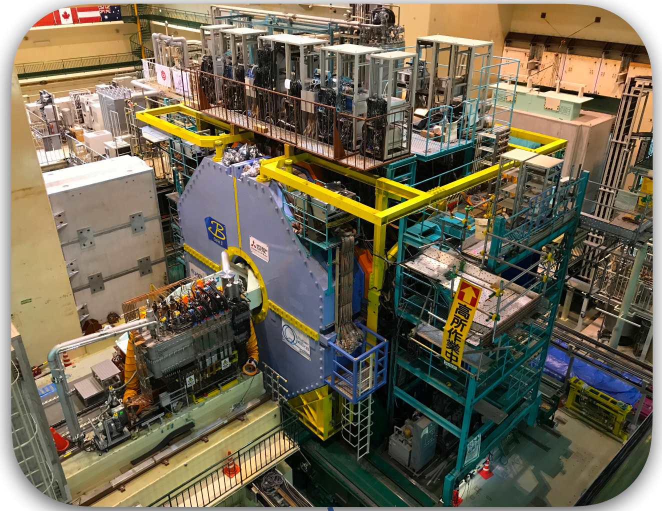
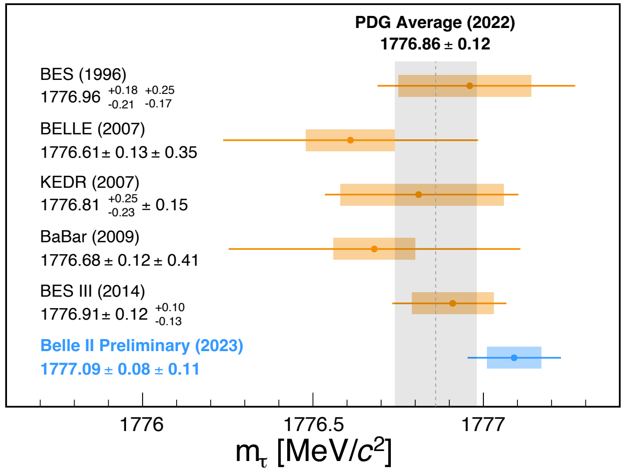
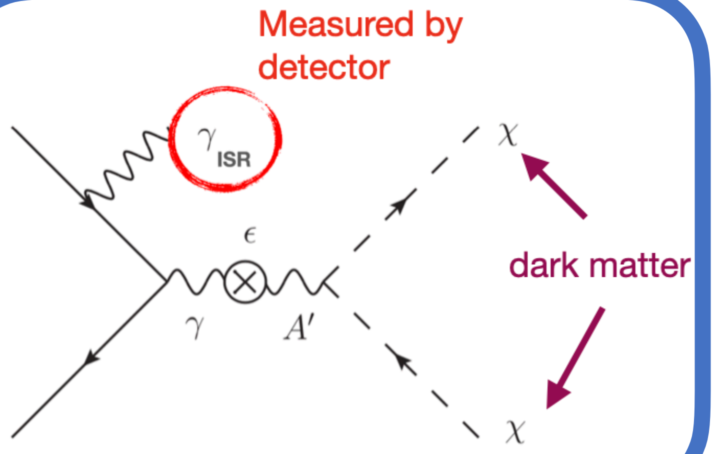


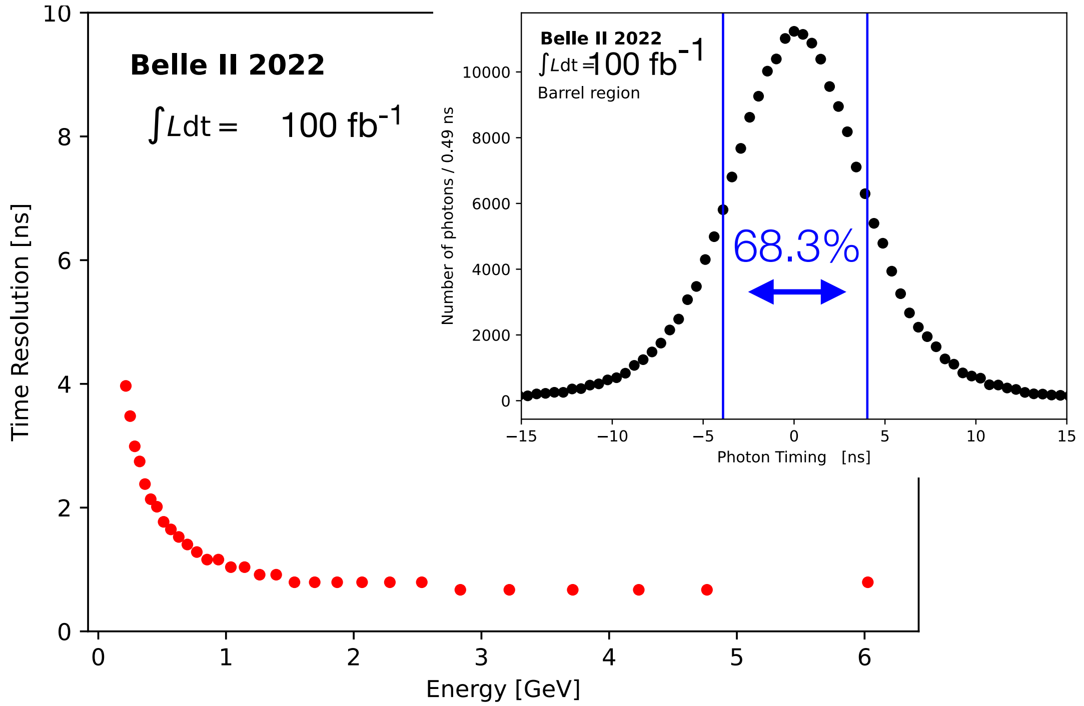




Photon Timing and Pulse Shape Discrimination Calibrations

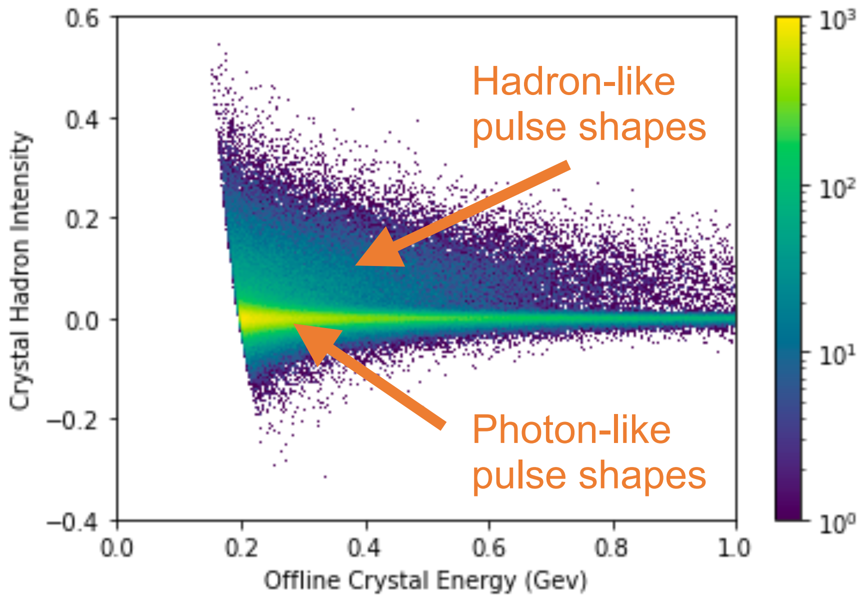
- Calorimeter timing is critical to reject beam-background photons.
- Automated tool under development to calibrate photon timing resolution with $e^+e^- \to \mu^+\mu^-\gamma$ events.

Raynette van Tonder



- First evaluations of pulse shape discrimination performance over time.

Arina Tseragotin
Ali Rajabi Shakib



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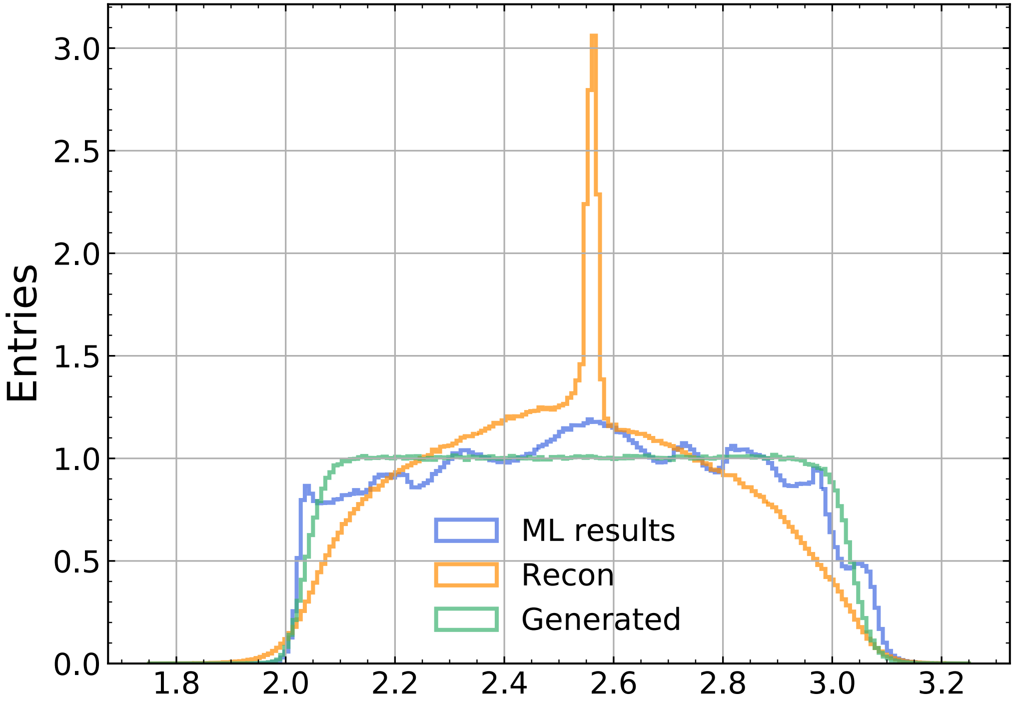
Machine Learning to Improve Position Reconstruction in the Calorimeter

Miho Wakai

- Known bias in calorimeter reconstruction tends to put photon position towards the center of the crystal.
- Limits high-momentum π^0 mass resolution.
- Feedforward neural network trained to improve position reconstruction of a photon in the calorimeter.

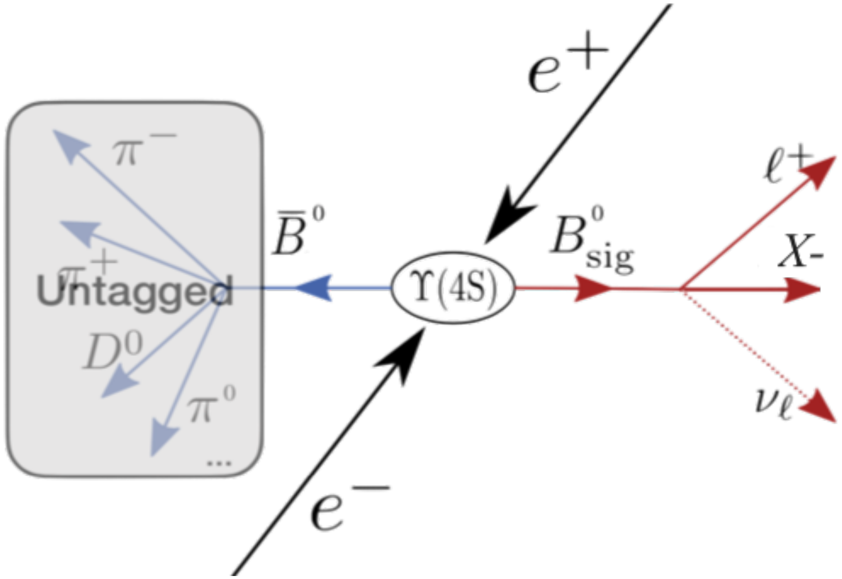


Photon θ along crystal face (~6 cm)

- Network uses energies of 5×5 grid of crystals in photon cluster to predict photon position.
- Network reduces bias and improves high-momentum π^0 mass resolution by 7%.
- Paper in preparation.

Inclusive analysis of $B \to X_u \ell \nu$

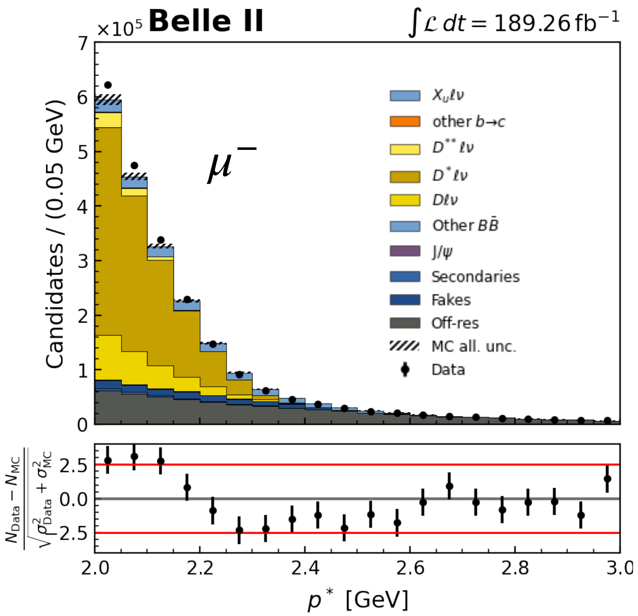
Andrea Fodor

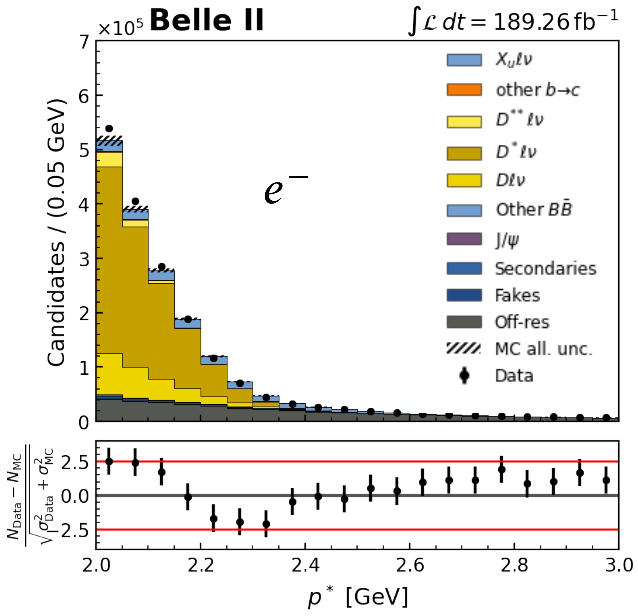


- Semileptonic B-meson decays play a critical role in the determination of the CKM quark- mixing matrix elements $|V_{ub}|$ and $|V_{cb}|$.
- Measurement of branching fraction of $B \to X_u \ell \nu$ decays via:

Inclusive and untagged analysis: *Only the outgoing lepton is selected and the companion B meson is not reconstructed.*

- Use **endpoint region of the lepton momentum ($p^*_\ell > 2.0$ GeV)** in the CM frame to avoid the dominant background from the decay $B \to X_c \ell \nu$





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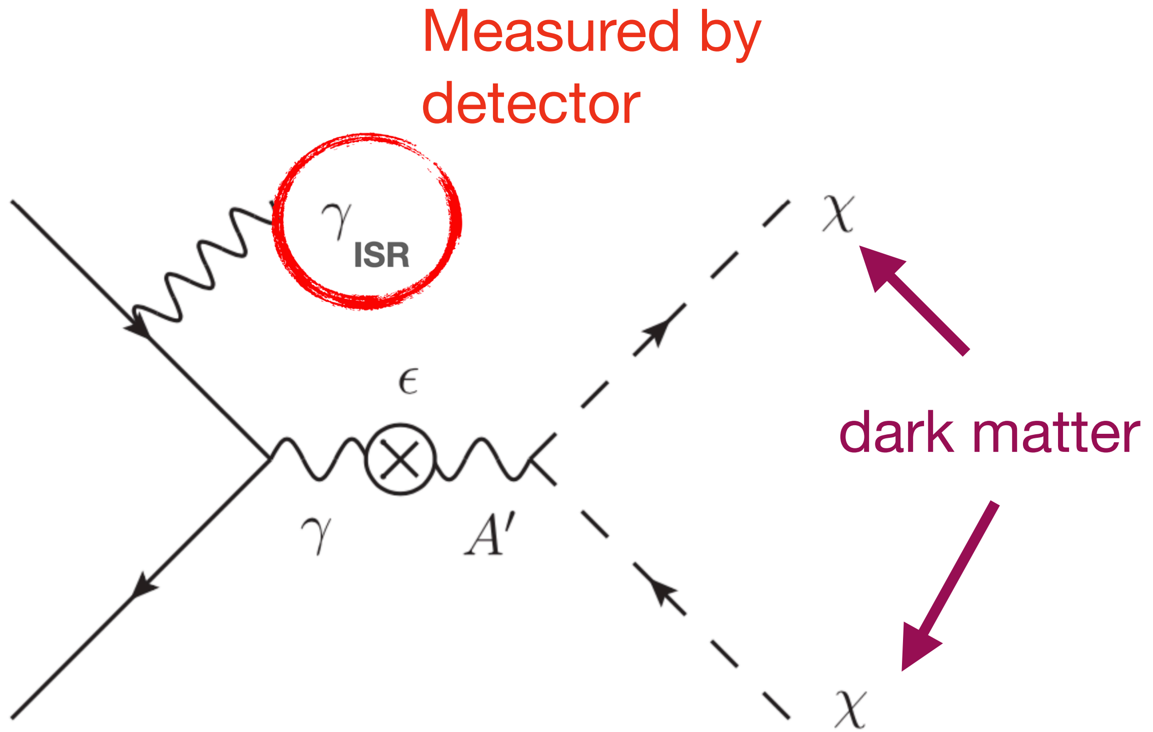
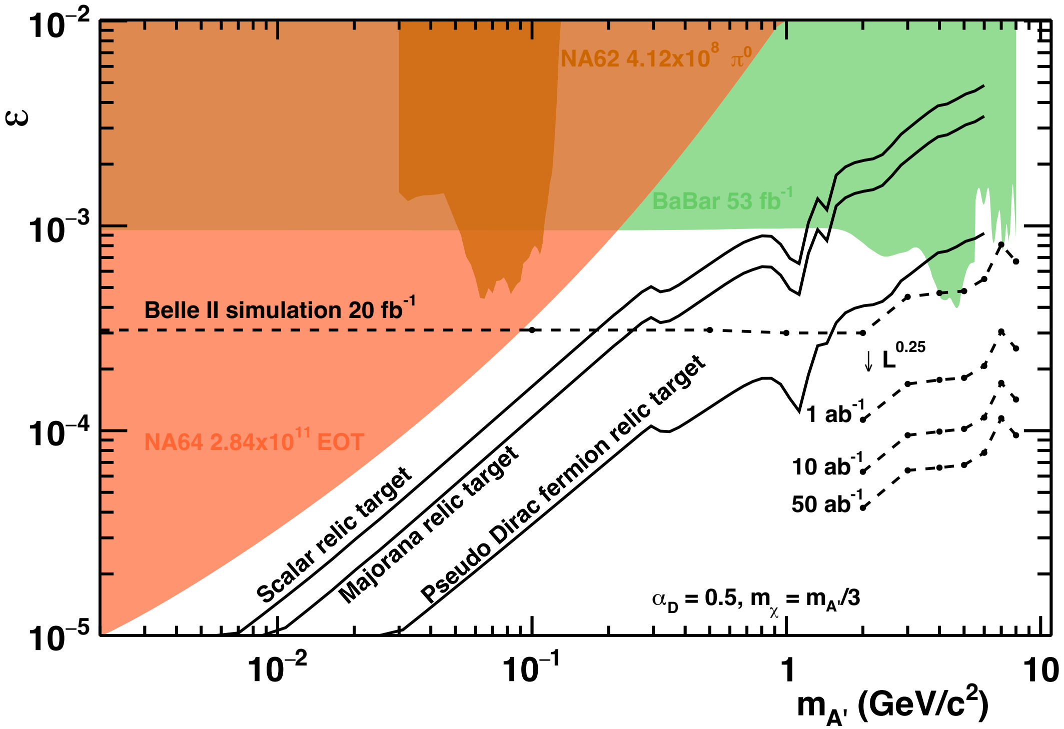
Dark Photon Search (Invisible Decays)

Daniel Crook
Michael De Nuccio

- Dark photon is a spin-1 gauge boson that would mediate the dark EM force.
- Interacts through kinetic mixing with Standard Model photon.
- If dark photon is allowed kinematically to decay to dark matter, detector signature is a single high energy photon.
- Belle II will explore parameter space consistent with observed relic DM abundance.





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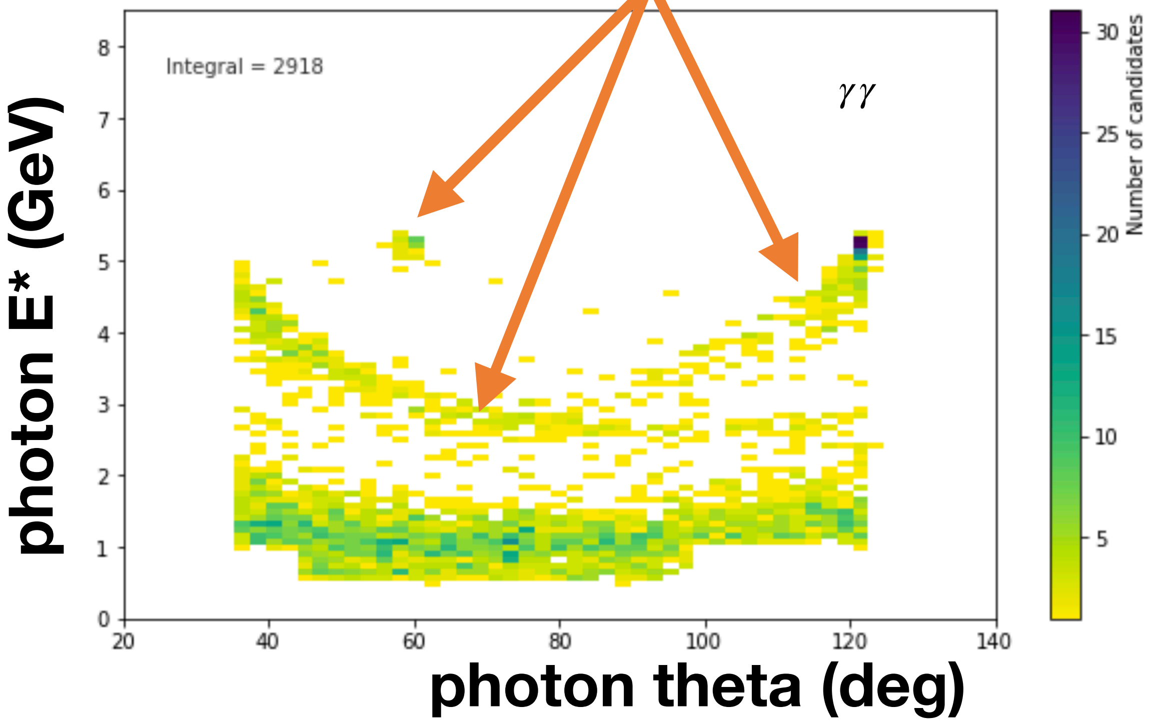
Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond arXiv:2207.06307

Dark Photon Search (Invisible Decays)

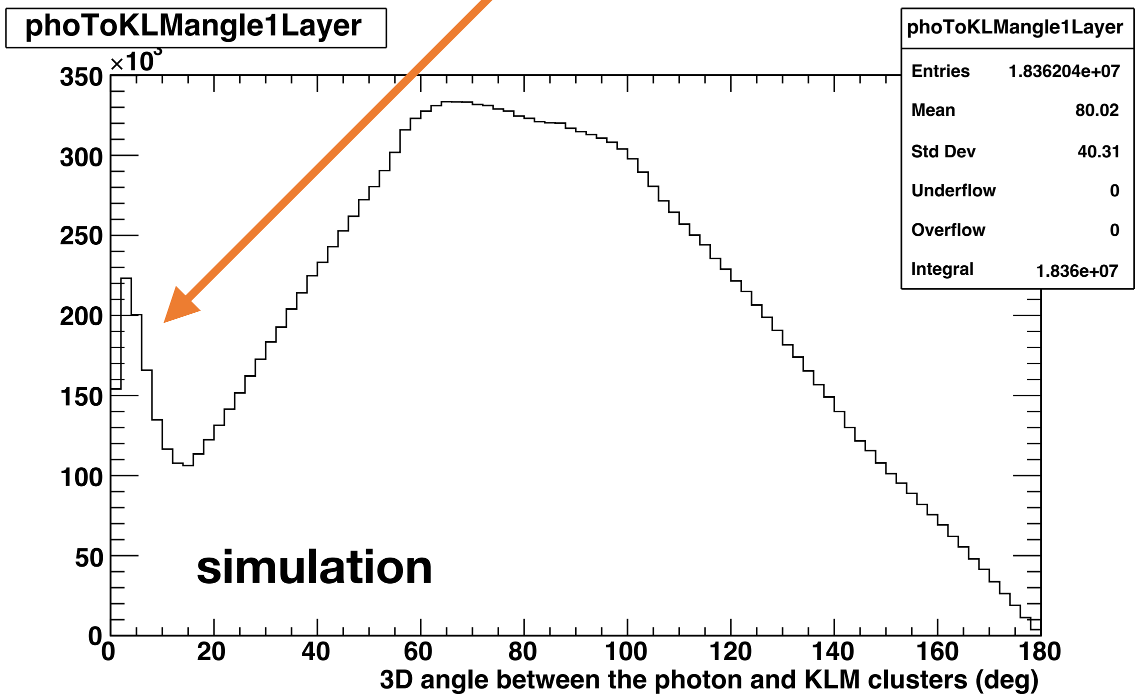
Daniel Crook
Michael De Nuccio

- Main analysis backgrounds:
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$, with all but one out of acceptance or missed
  - $e^+e^- \rightarrow e^+e^-\gamma_{ISR}$ with e^+e^- out of acceptance or missed
  - Cosmics
  - Beam background

Missed other photon due to detector gaps



Photons detected in KLM



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Dark Photon Search (Visible Decays)

Thomas Grammatico

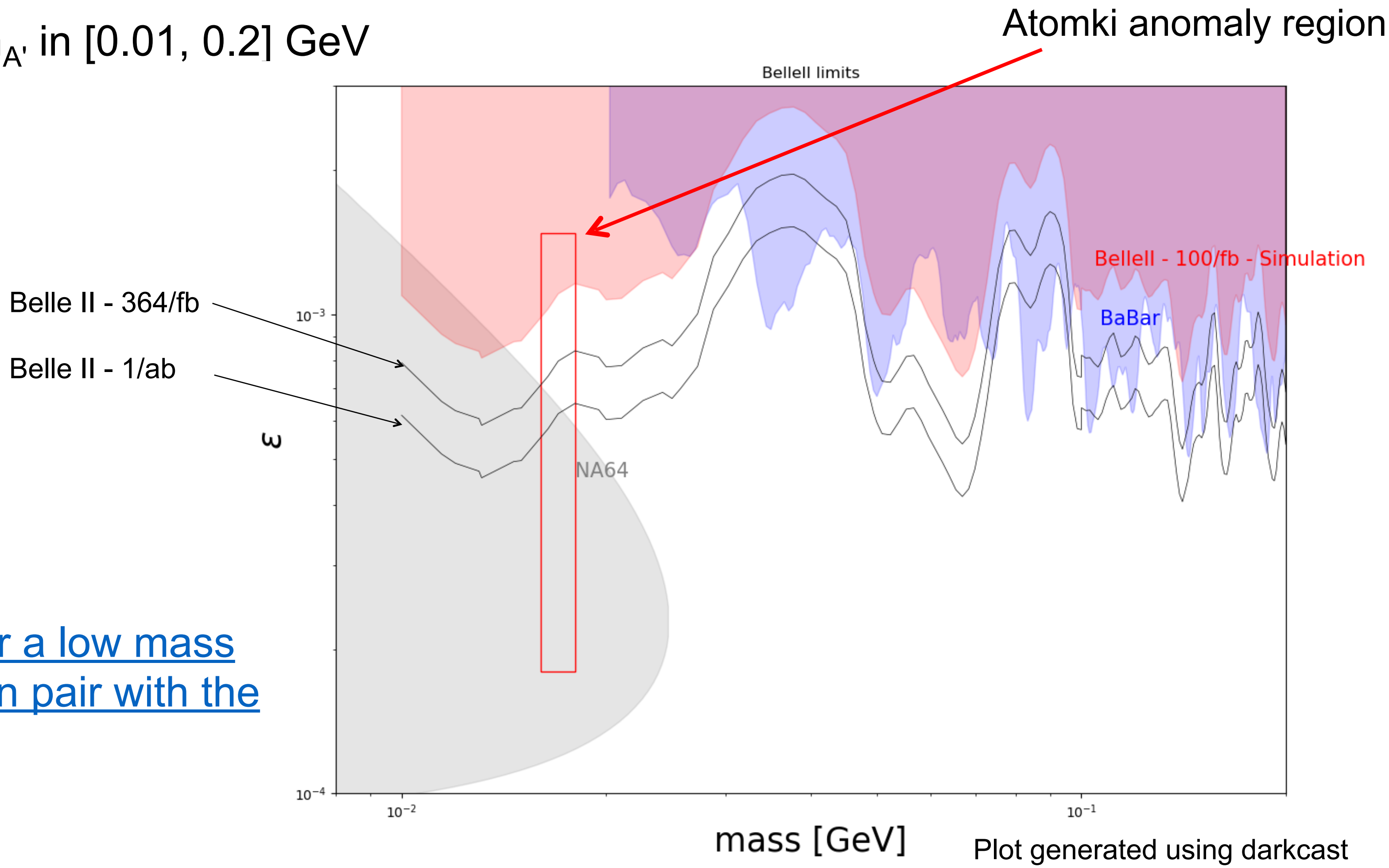
- Atomki collaboration observed an **anomaly** in decay of **beryllium** excited states to **electron pair** [Phys. Rev. Lett. 116, 042501 (2016)]
  - ~ 17 MeV **protophobic** dark photon? Unknown experimental/nuclear physics effect?

- Study $e^+e^- \rightarrow \gamma\,[A' \rightarrow e^+ e^-]$ decays ; $m_{A'}$ in [0.01, 0.2] GeV

- Main backgrounds are radiative Bhabha and $e^+e^- \rightarrow \gamma[\gamma \rightarrow e^+e^-]$ photon conversion events

- Pre-preliminary study with Belle II simulated samples shows promising results

See talk: **Thomas Grammatico** Search for a low mass dark photon decaying to an electron-positron pair with the Belle II detector



Plot generated using darkcast

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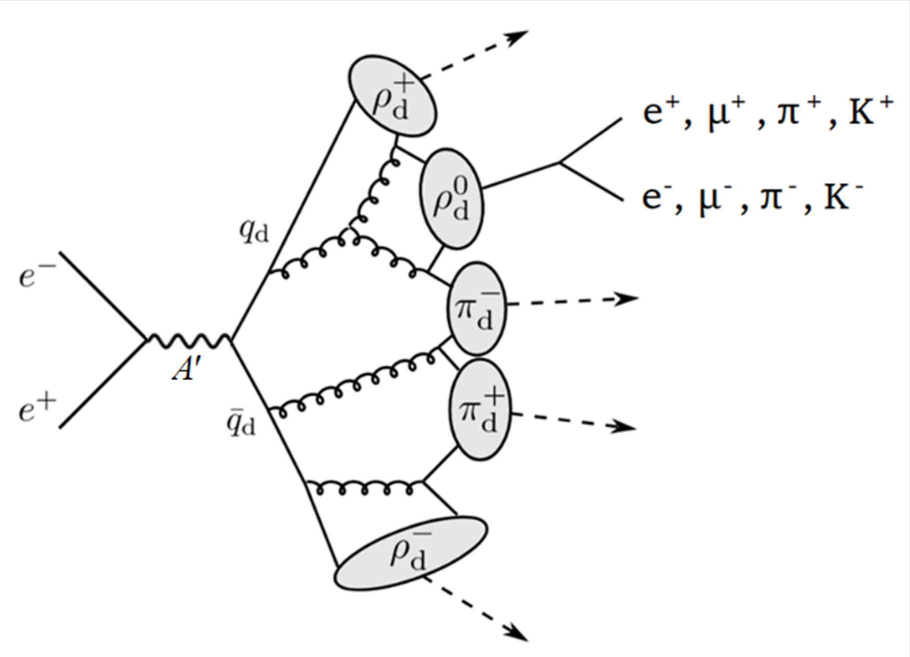
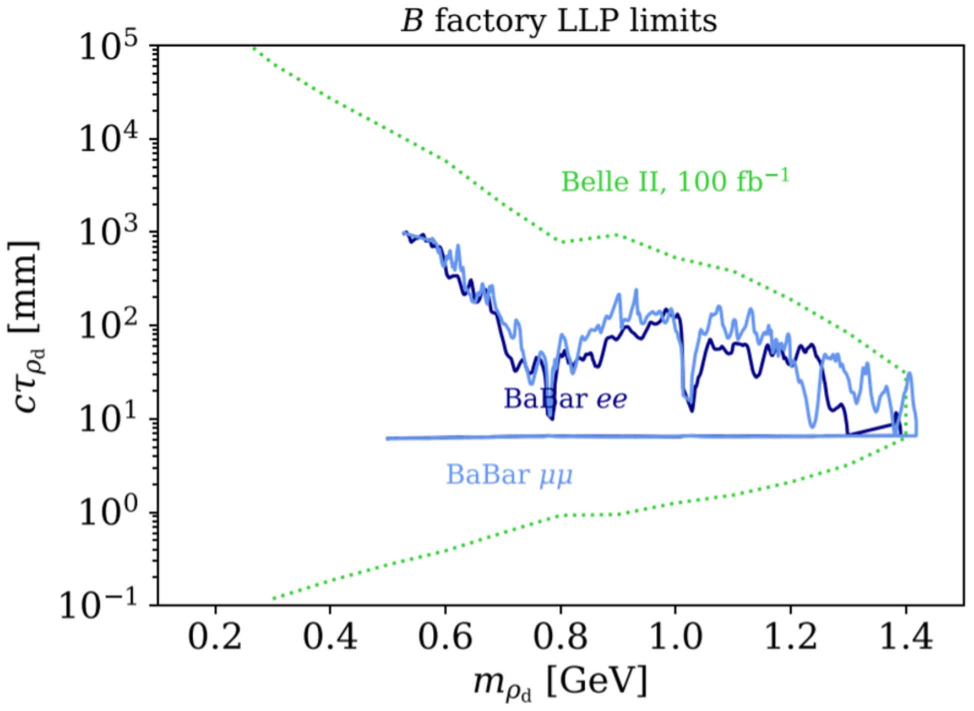
Dark Shower Search at Belle II

Miho Wakai

- Strongly interacting dark sector coupled to SM through a dark photon mediator.
- Dark quarks form bound states: dark pseudoscalars $\pi_d^0, \pi_d^\pm$ and vector mesons $\rho_d^0, \rho_d^\pm$.
- Dark pions are stable and are the dark matter candidates.
- ρ_d^0 couples to the SM through kinetic mixing.
- Detector signature is displaced vertex with two charged tracks.





E. Bernreuther et al. Forecasting dark showers at Belle II, 2022

Chiral Belle Upgrade: Polarized SuperKEKB Beams

- Canada-led upgrade initiative to introduce polarized beams at SuperKEKB (aim for 70% polarized).
- Would open wide-range of new and unique physics opportunities.

✓ Mu pair ALR

✓ Tau pair ALR

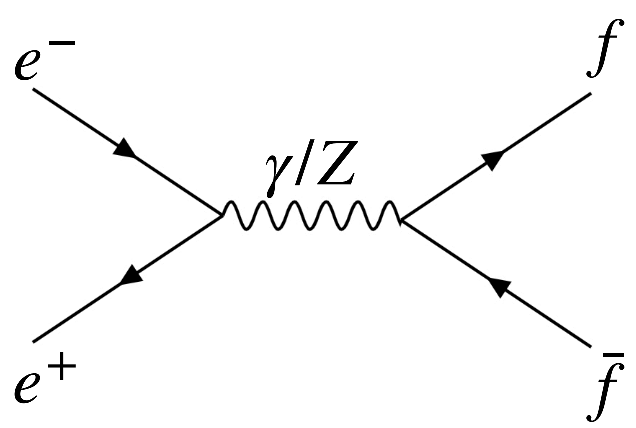
✓ Charm and bottom pair ALR

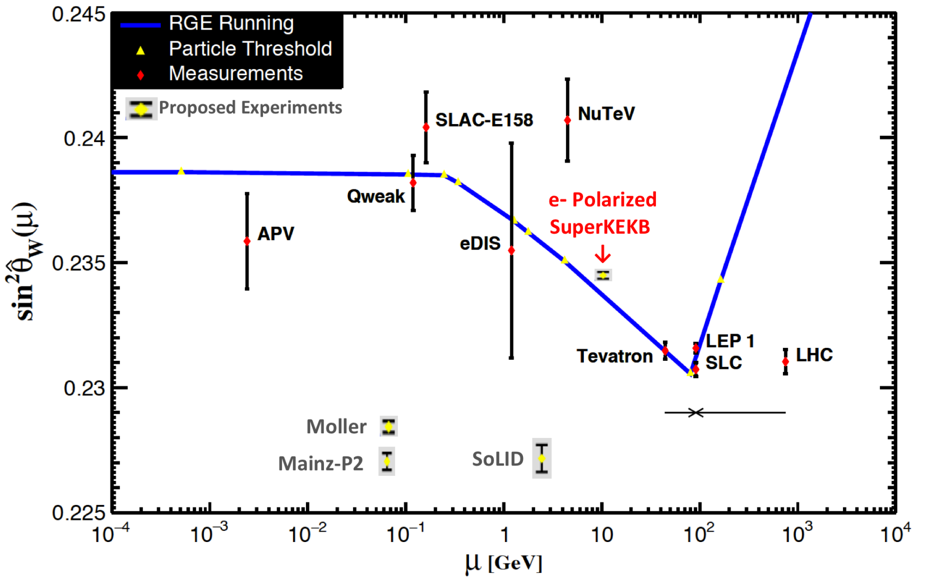
✓ $\sin^2 \theta_W$

✓ Tau $g-2$, Tau EDM, Tau LFV

ALR = Left-Right Asymmetry

$$A^f_{LR}(\mathrm{SM}) = \frac{\sigma^f_{\mathbf{L}} - \sigma^f_{\mathbf{R}}}{\sigma^f_{\mathbf{L}} + \sigma^f_{\mathbf{R}}} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g^e_A g^f_V$$





- Technical Design Report in preparation. See talk:

20 Jun 2023, 16:45
Michael Roney [The Chiral Belle Project: Polarized Beams at SuperKEKB/Belle II]

arXiv:2205.12847: Snowmass 2021 White Paper Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation

Belle II Talks @ CAP 2023

19 June 2023, 14:00

Thomas Grammatico (Search for a low mass dark photon decaying to an electron-positron pair with the Belle II detector

19 June 2023, 17:00

Alexandre Beaubien Simulating noise waveforms in the Belle II electromagnetic calorimeter (ECL) using generative adversarial neural networks (GANs)

21 June 2023, 11:00

Garrett Leverick Discriminating Hadronic Split Offs Using the KLM at Belle-II

21 June 2023, 11:15

Caleb Miller Demonstration of Tau Polarimetry for SuperKEKB Polarization Upgrade

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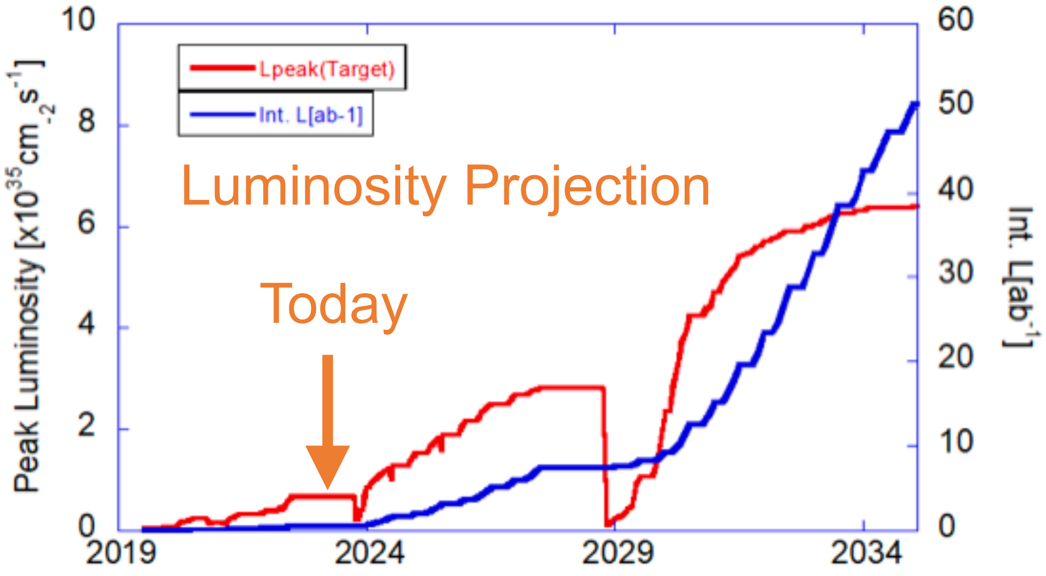
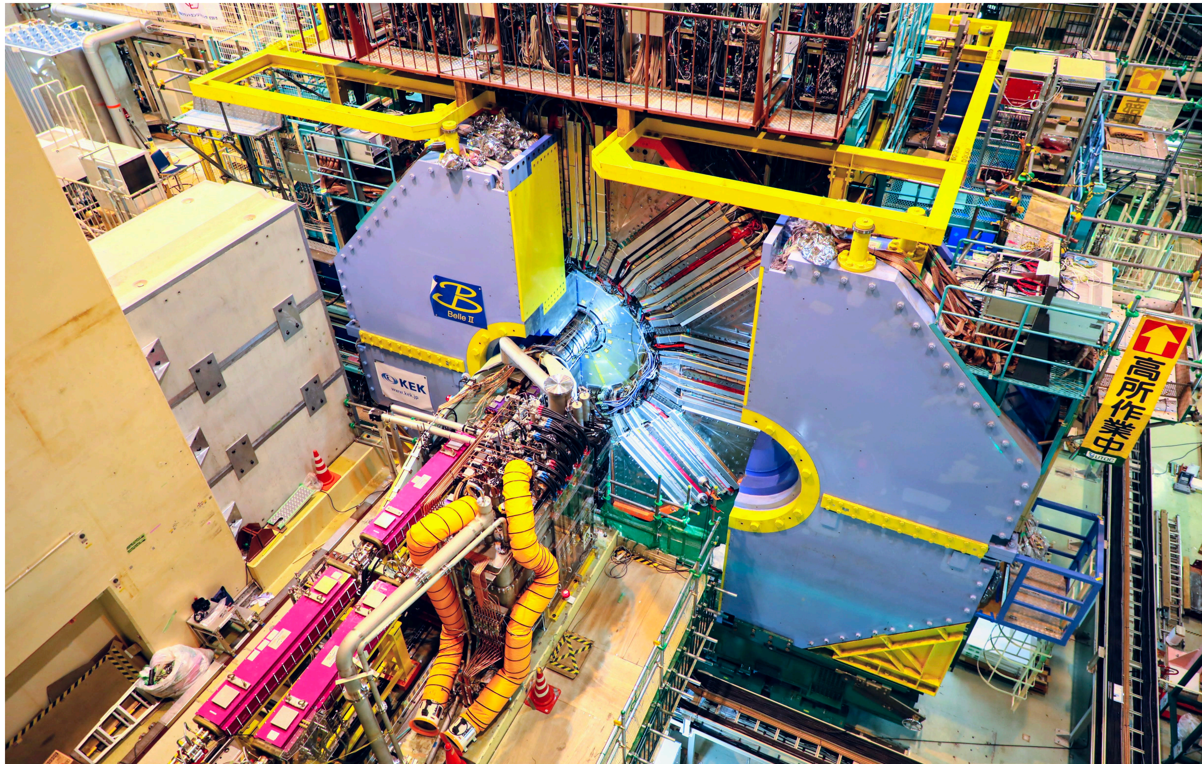
Conclusion

- Belle II is a world-unique facility with many exciting physics opportunities.
- Multiple world-leading results published since arrival of first data.
- Luminosity and physics output expected to continue to ramp up.
    - Anticipate 120 times more data to arrive over experiment lifetime.



Many opportunities for new personnel interested in joining!



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