Dark sector and tau results from Belle II

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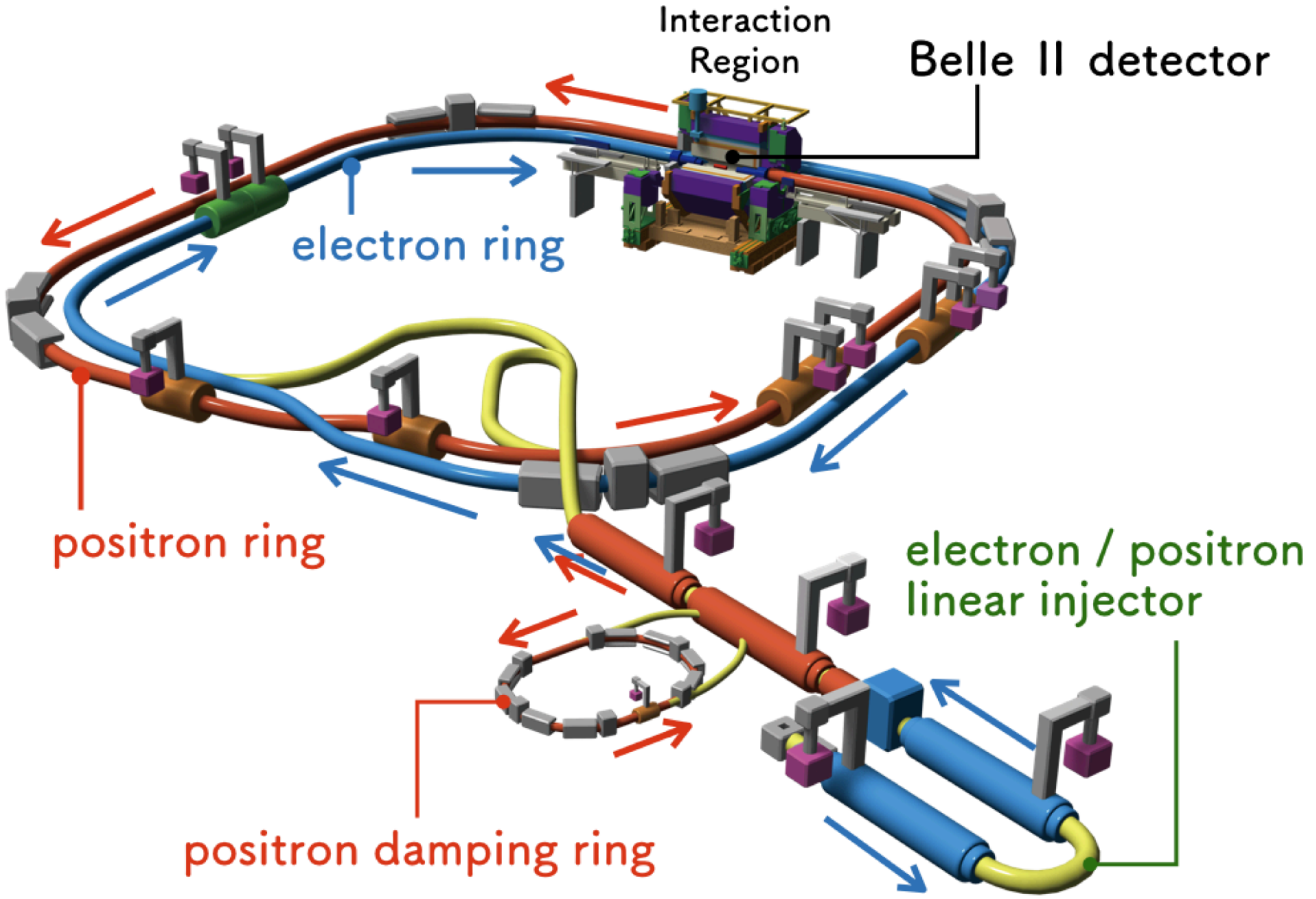
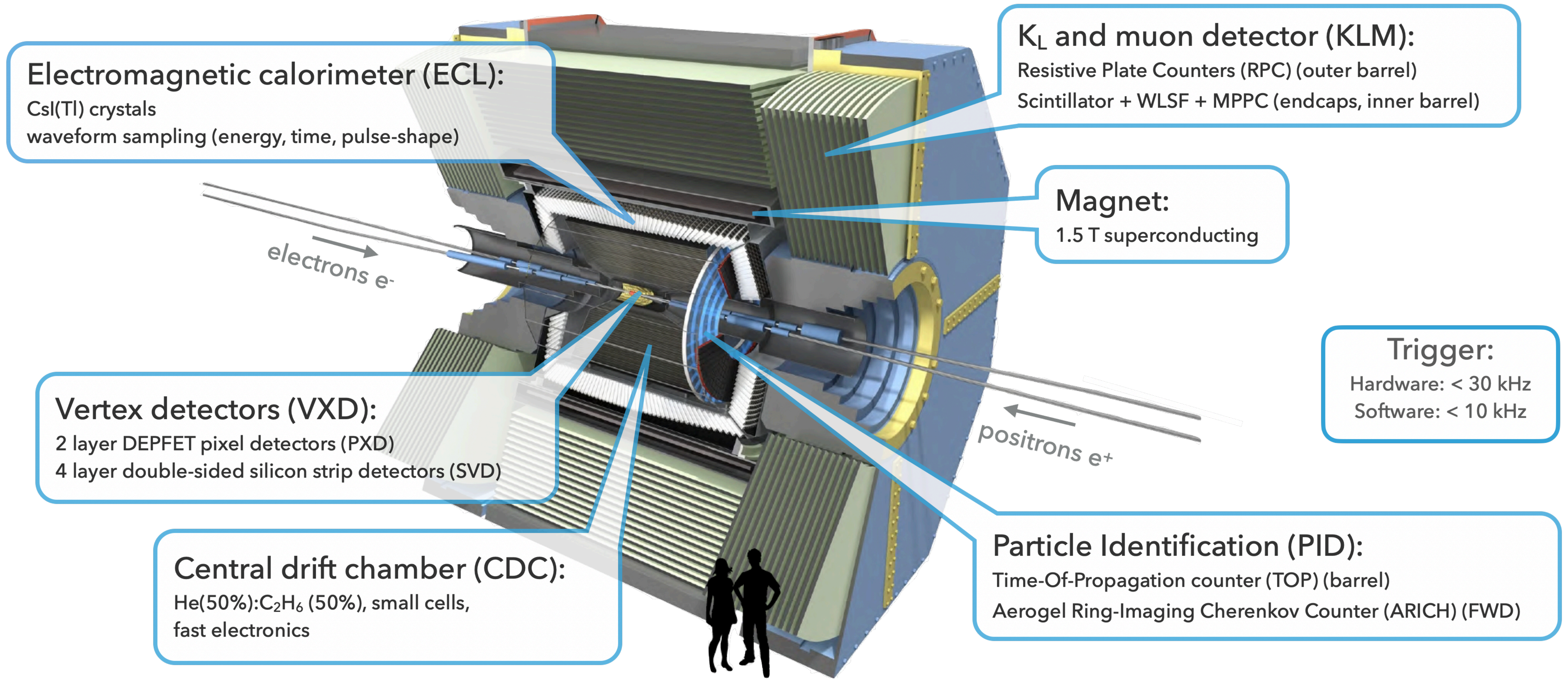
on behalf of the Belle II Collaboration

February 25th, 2022

Dark Sector / Tau Physics at Belle II

- The Belle II experiment aims to make precise measurements of CP violation in the weak sector, as well as find **New Physics Beyond the Standard Model** of Particle Physics.
- Current aim is to collect $50\ ab^{-1}$.
- Suitable for low multiplicity events: See Bertrand's talk
    - Clean environment
    - High sensitivity to mass range up to $10\ GeV/c^2$
    - Effective triggers for low multiplicity events
- Many physics analyses: Z', Axion-Like particles, dark photon

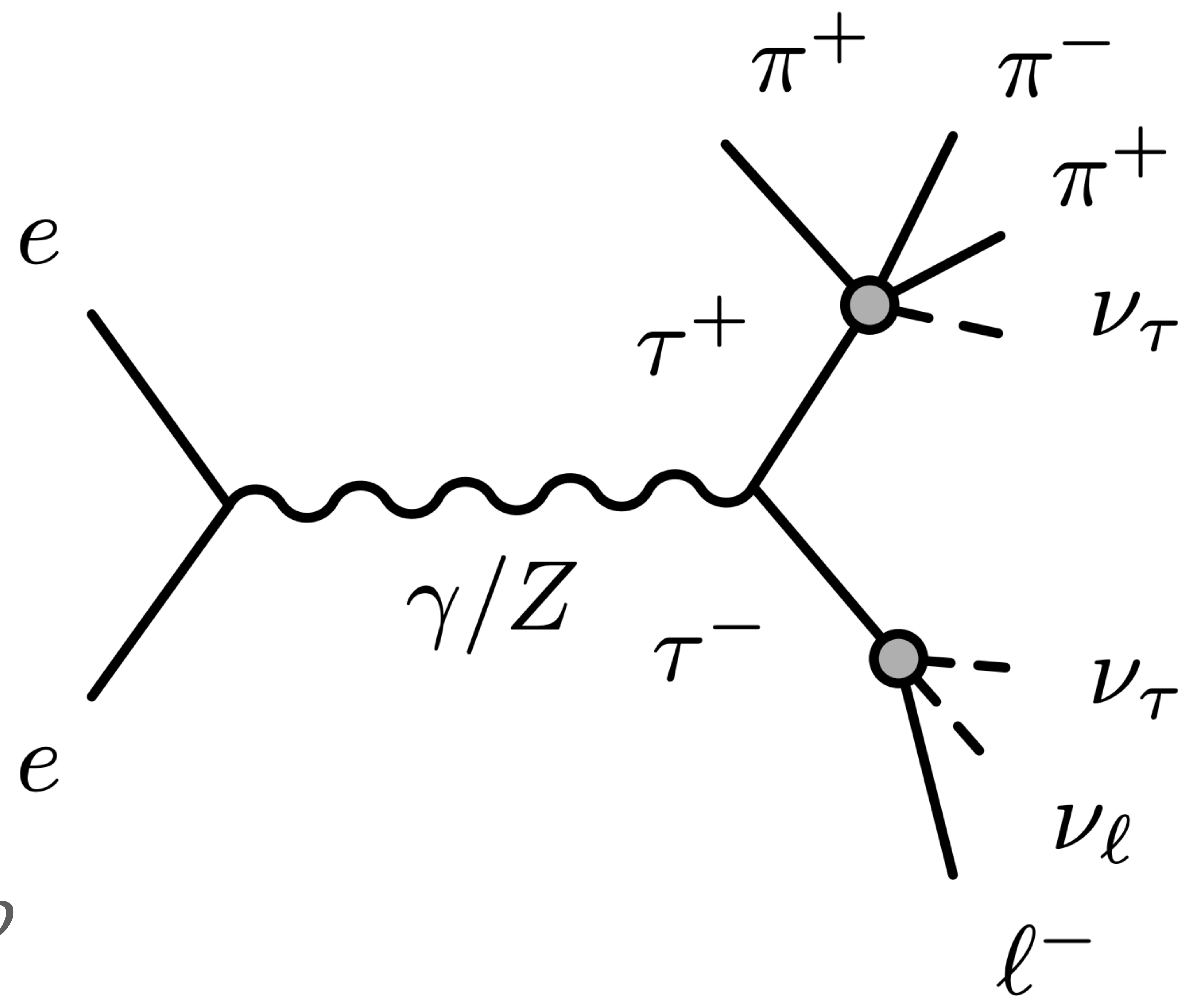




Tau Mass Measurement

What?

- Determine the tau mass with high precision
- Looking at consistency between the lifetime, mass, and leptonic branching fractions: $B_{\tau l}^{SM} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$



How?

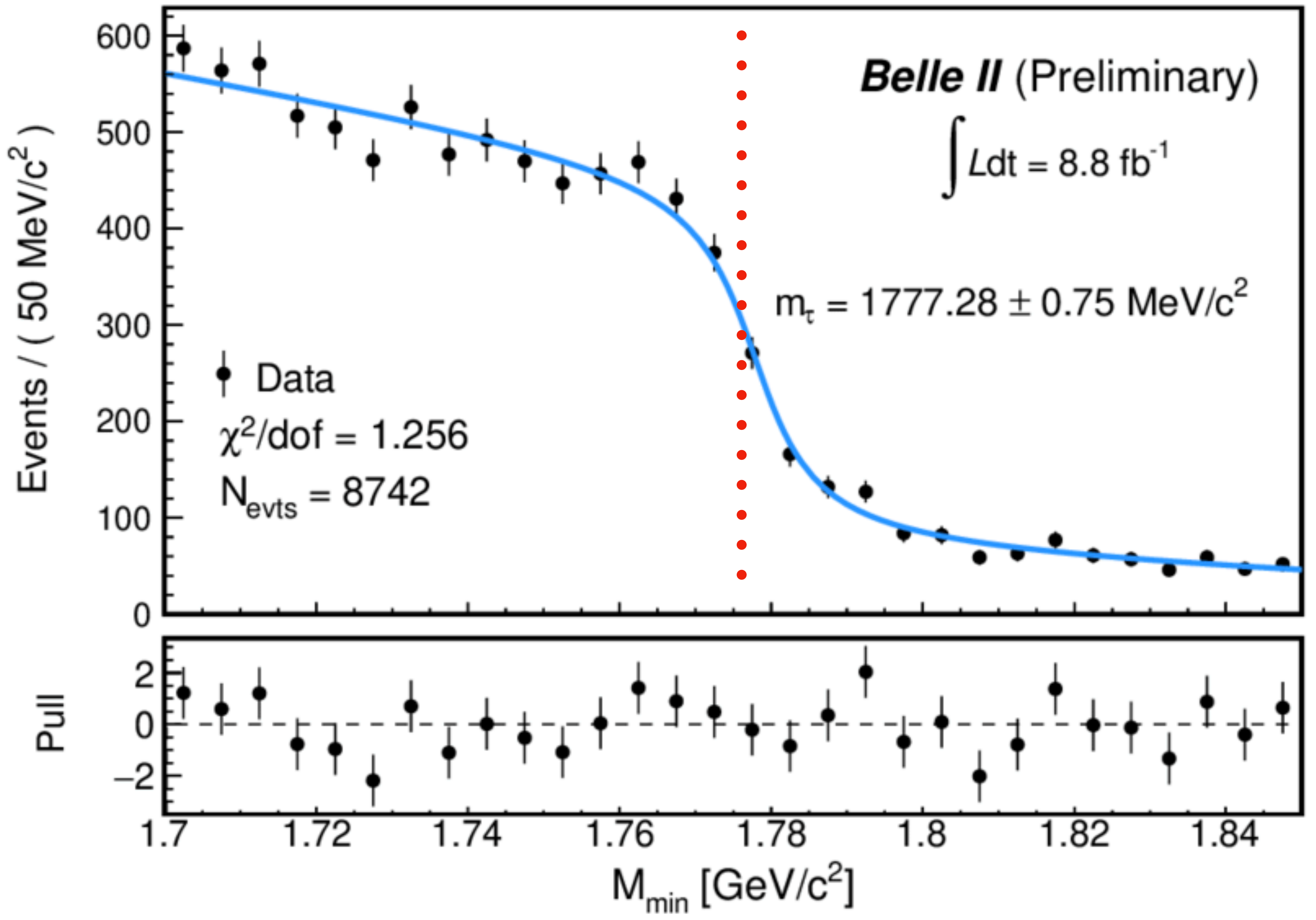
- High cross section of $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92\, nb$
- Belle II looks into $e^+e^- \rightarrow \tau^+\tau^-$:
  - 3 prong decay $\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$
  - 1 prong decay $\tau^- \rightarrow l^-\nu_\tau\nu_l$, $h^-\nu_\tau$, also $\pi^-\pi^0\nu_\tau$

Tau Mass Measurement

Method

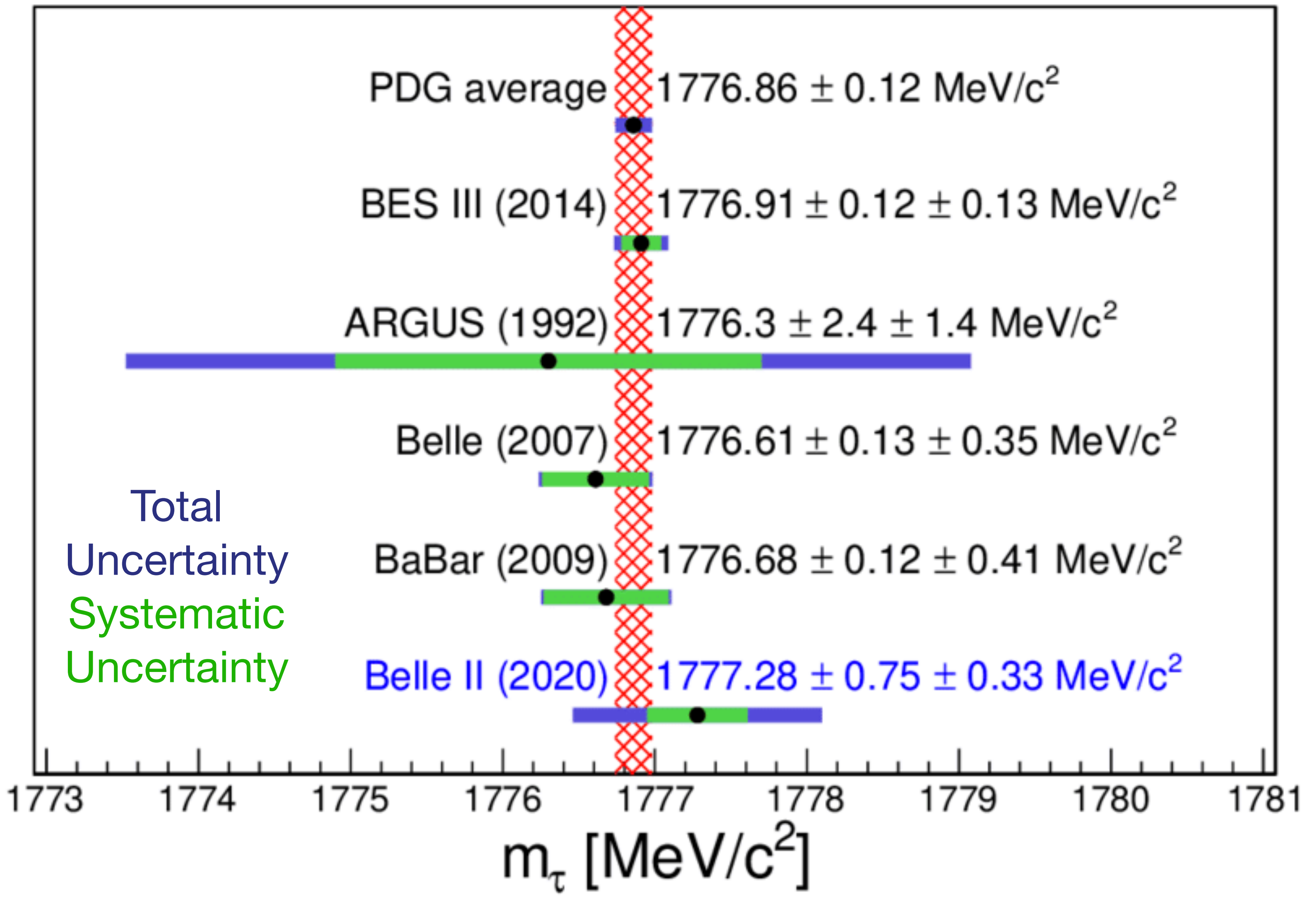
- Apply mass extraction
- $M_{min} = \sqrt{m_{3\pi}^2 + 2\left(E_{beam}^{COM} - E_{3\pi}\right)\left(E_{3\pi} - |p_{3\pi}|\right)} \leq m_\tau$

  (H. Albrecht et al. (ARGUS Collaboration, Phys. Lett. B 292, 221 (1992).)



Results

- Using dataset of $8.8\, fb^{-1}$
- $m_\tau = 1777.28 \pm 0.75$ (stat.) ± 0.33 (syst.) MeV/c^2
- Systematic uncertainty dominated by track momentum scale from magnetic field
- Better systematic precision is expected in the future
- Other tau studies ongoing: τ lifetime, LFV τ: $\tau \rightarrow l + \alpha$ etc

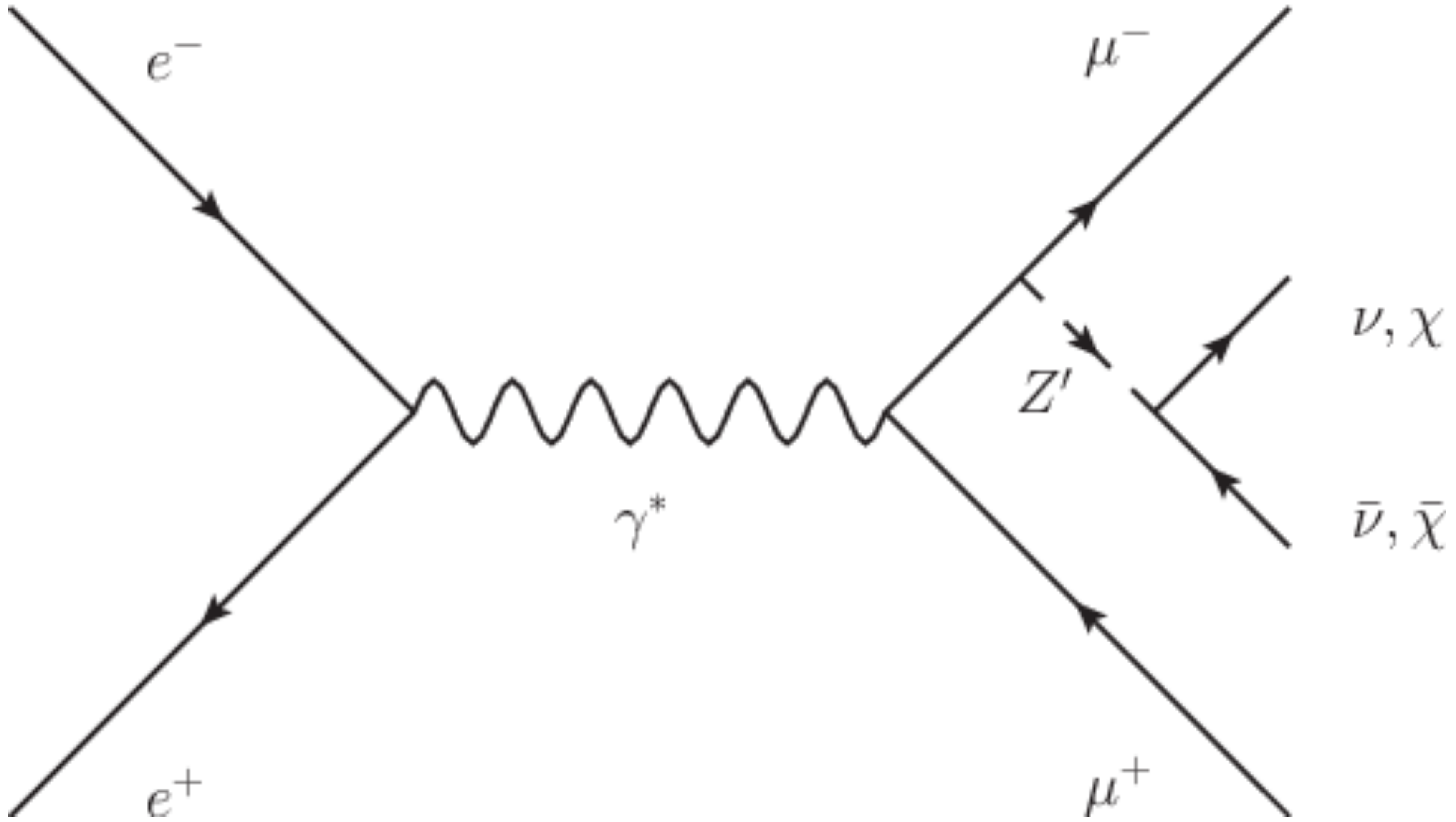


F. Abudinen et al. (Belle II), (2020), arXiv:2008.04665 [hep-ex].

Invisibly decaying Z'

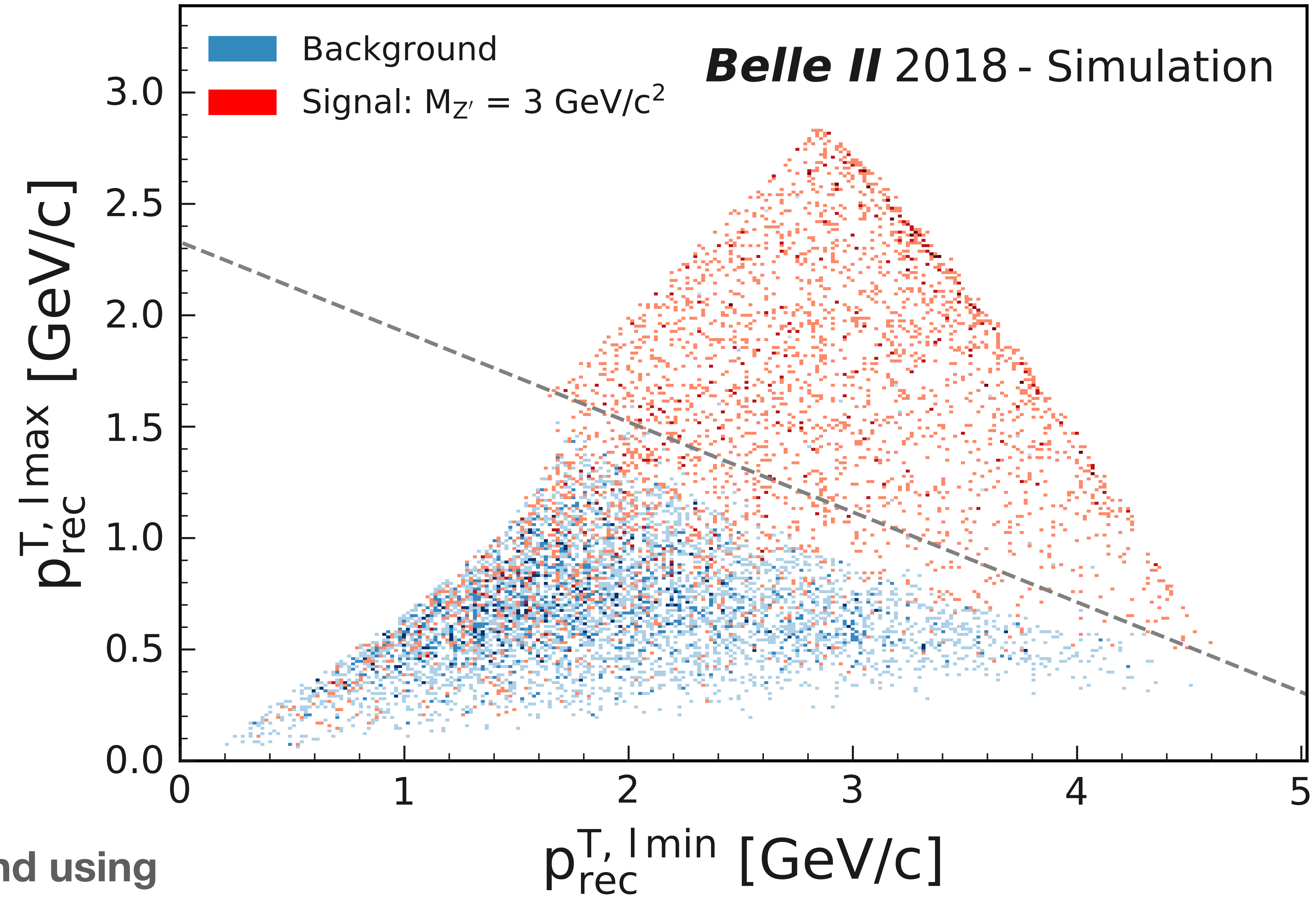
What?

- Hypothetical gauge boson Z' coupling to 2nd, 3rd generation leptons $(L_\mu - L_\tau)$
- May explain dark matter, $(g-2)_\mu$ anomaly, $b \to s\mu^+\mu^-$ anomaly



How?

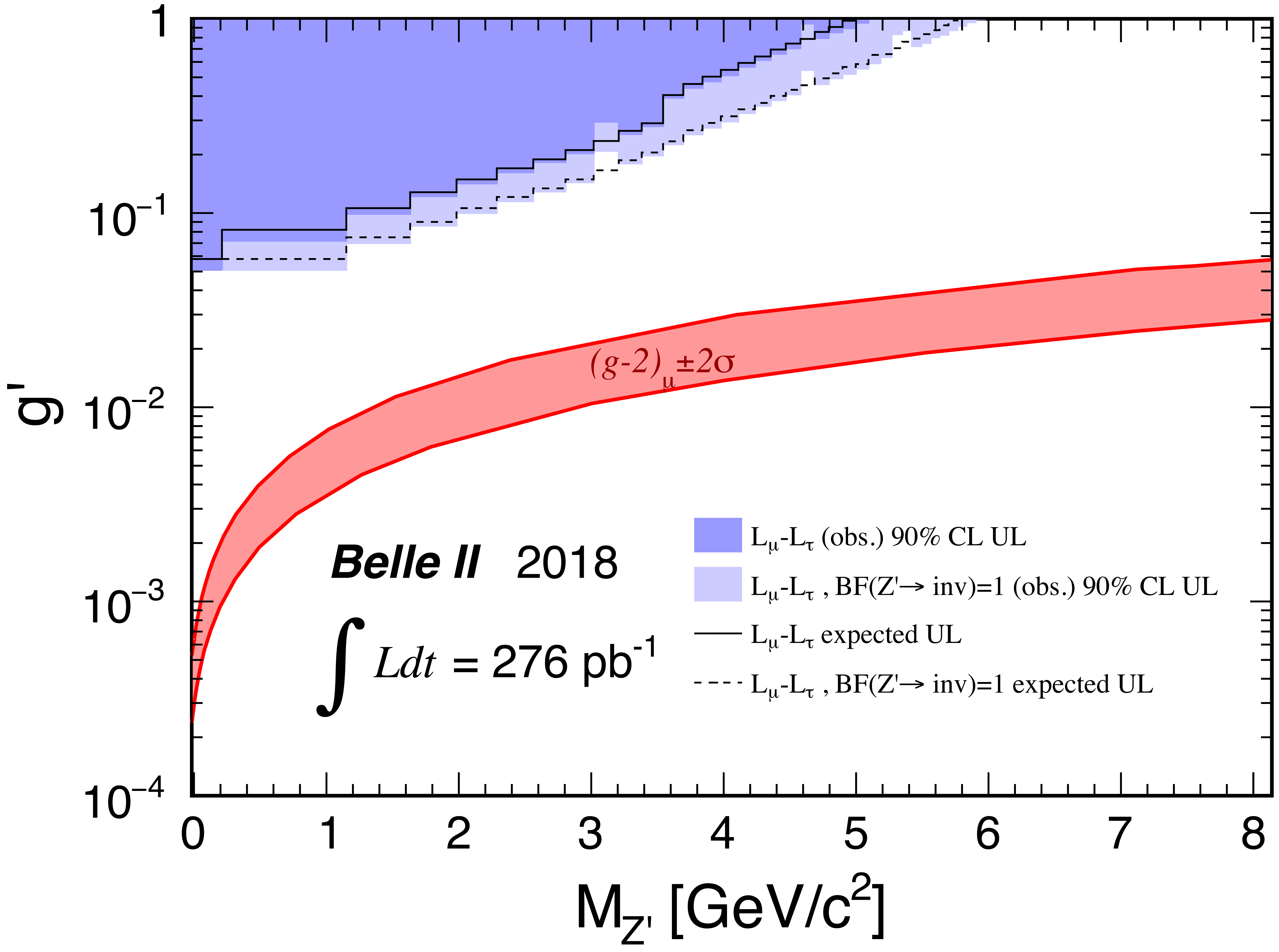
- Belle II looks into $e^+e^- \to \mu^+\mu^- Z';\ Z' \to$ invisible
- Final state: Two muons + missing energy
- Bump hunt in recoil mass of $\mu^+\mu^-$
- Backgrounds: $e^+e^- \to \tau^+\tau^-(\gamma); \tau^\pm \to \mu^\pm\nu\nu$, $e^+e^- \to \mu^+\mu^-(\gamma),\ \ e^+e^- \to e^+e^-\mu^+\mu^-$



Rejecting background using differences in kinematics

I. Adachi, and et al., Physical Review Letters 124 (2020), 10.1103/phys- revlett.124.141801.

Invisibly decaying Z'



Results

- No significant excess was found
- Update this year where we will reach the $(g-2)_\mu$ band

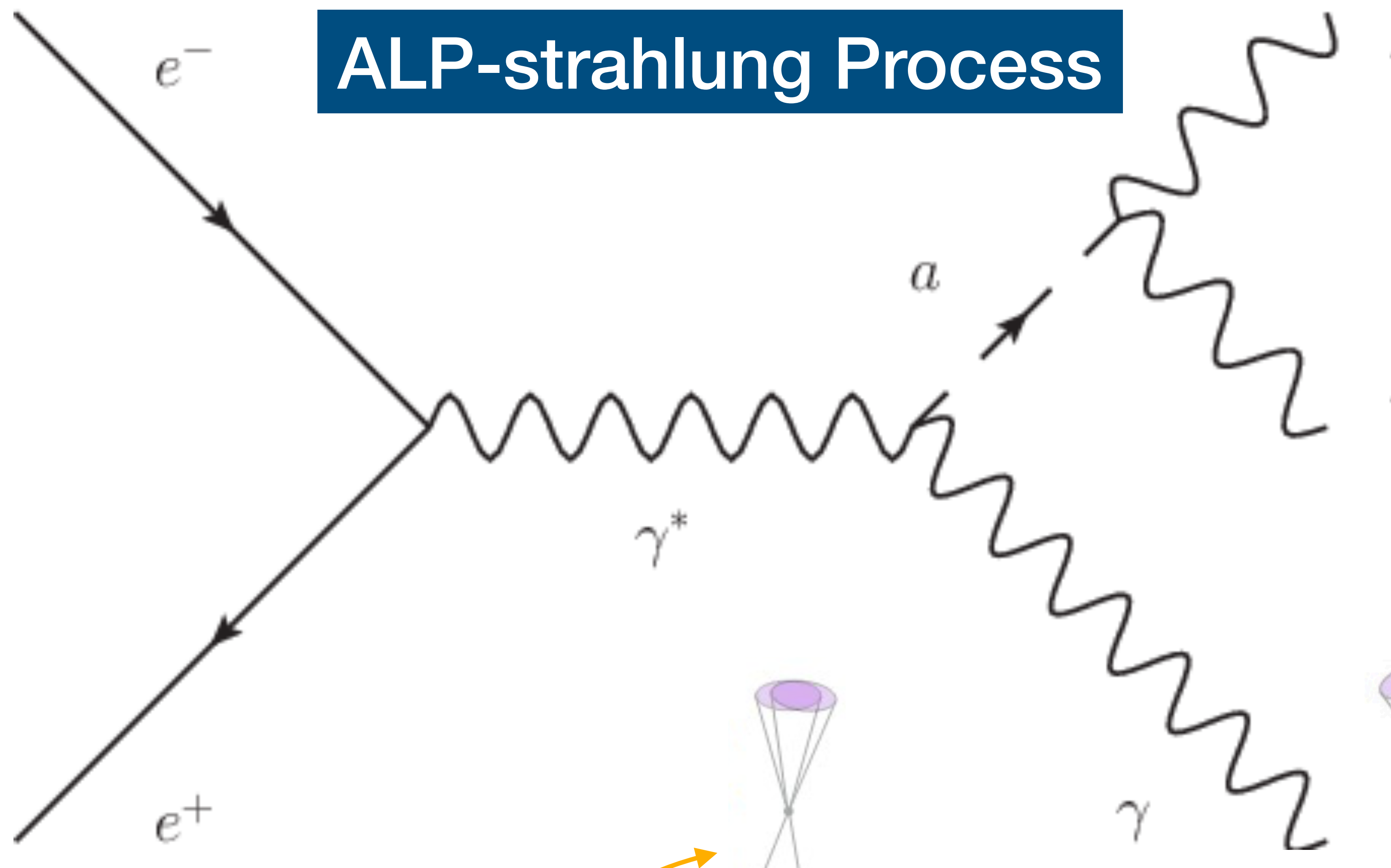
90% CL upper limits on coupling constant g'. Dark blue shows the exclusion regions for g' at 90% CL, while light blue are is when the branching fraction $Z' \to$ invisible is predicted to be 1.

I. Adachi, and et al., Physical Review Letters 124 (2020), 10.1103/physrevlett.124.141801.

Axion-Like Particle (ALP)

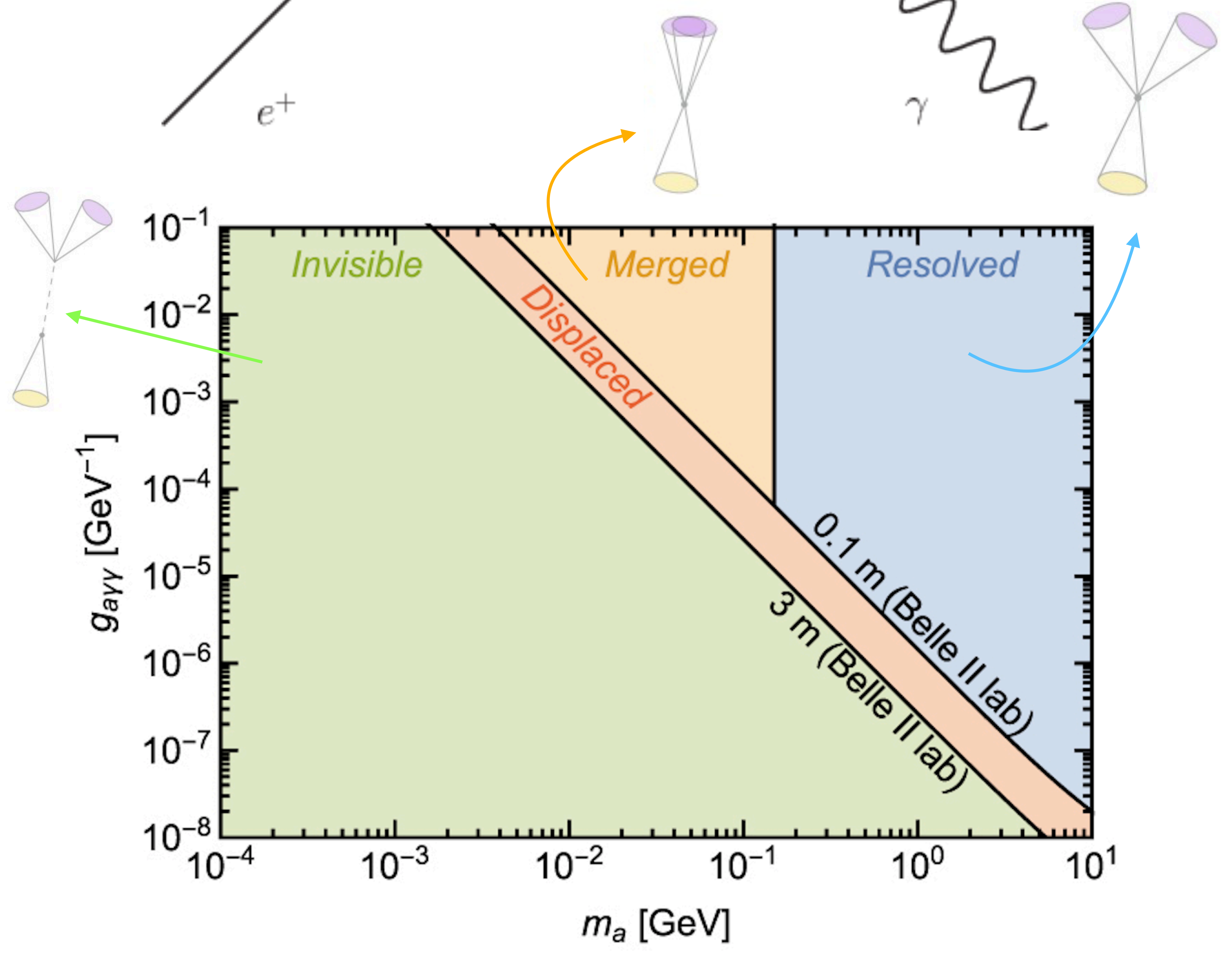
What?

- Pseudoscalars coupling mainly to bosons
- No mass coupling constraint unlike QCD Axion
- May be a mediator connecting SM to dark matter candidates



How?

- Belle II looks into $e^+e^- \rightarrow \gamma a;\, a \rightarrow \gamma\gamma$
- Final state: Three isolated photons with the total mass consistent with the center of mass energy
- Background: $e^+e^- \rightarrow \gamma\gamma\gamma$ (high σ)

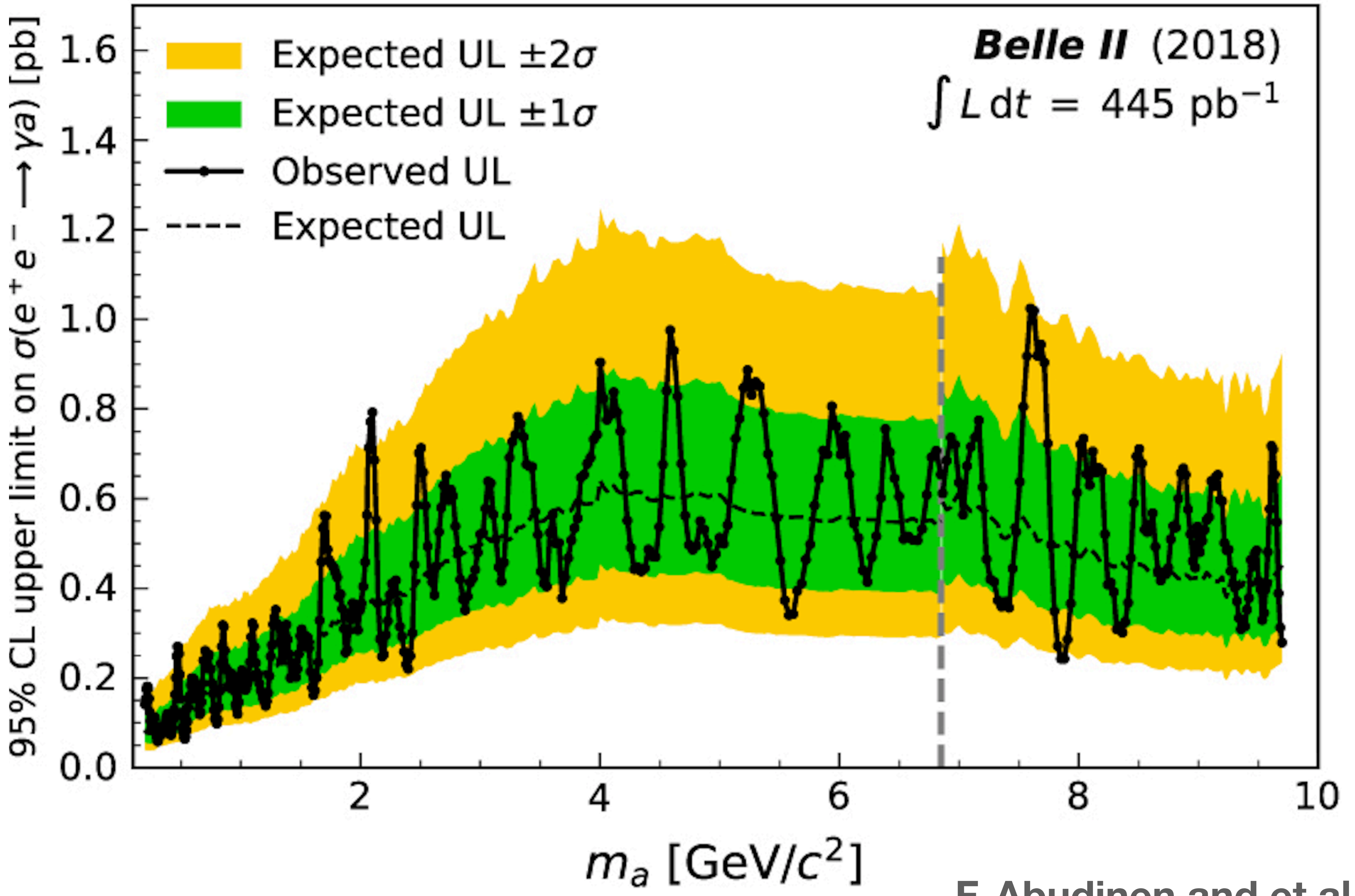


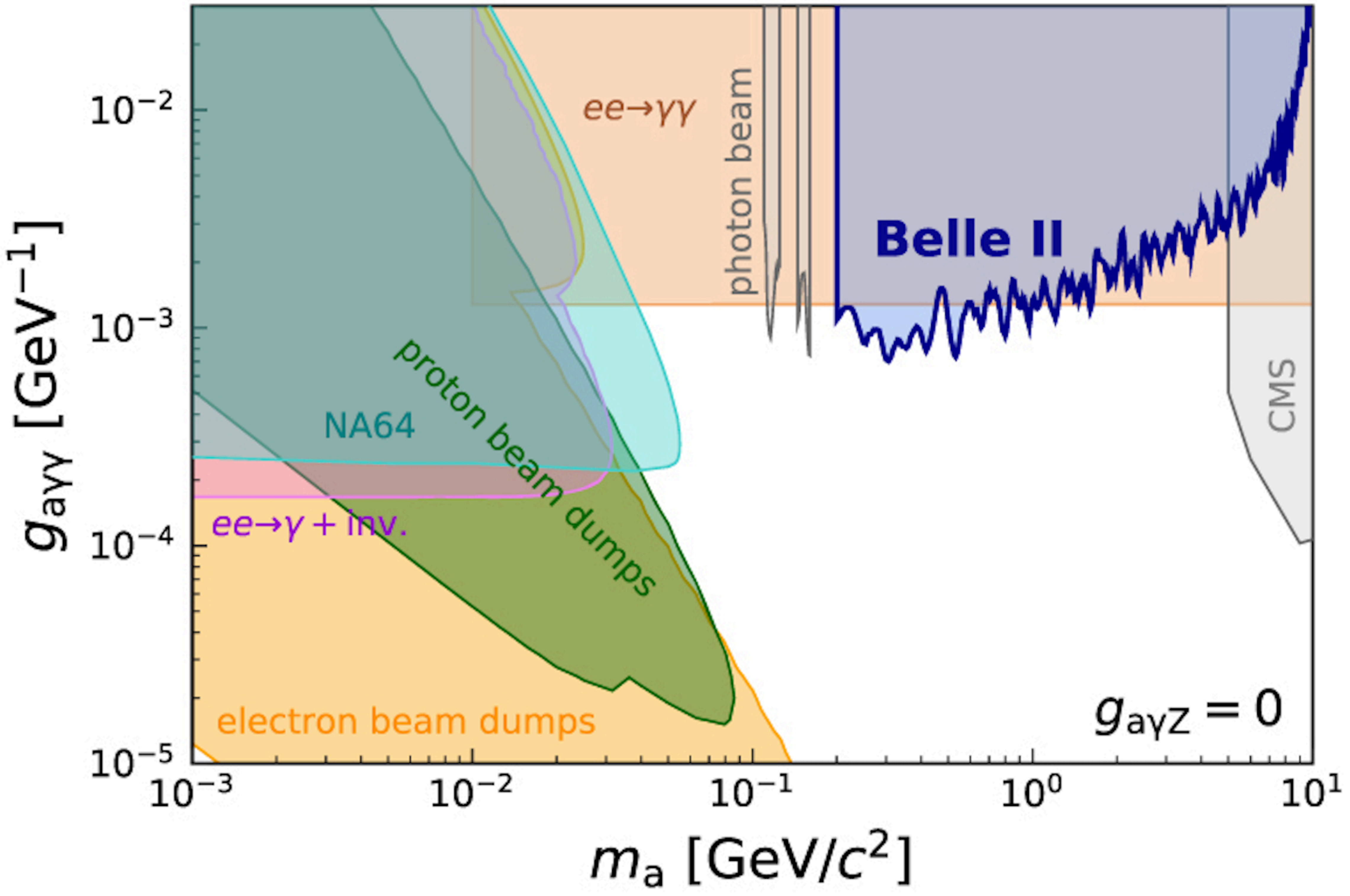
M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, Journal of High Energy Physics 2017 (2017), 10.1007/jhep12(2017)094.

Axion-Like Particle (ALP)

Results

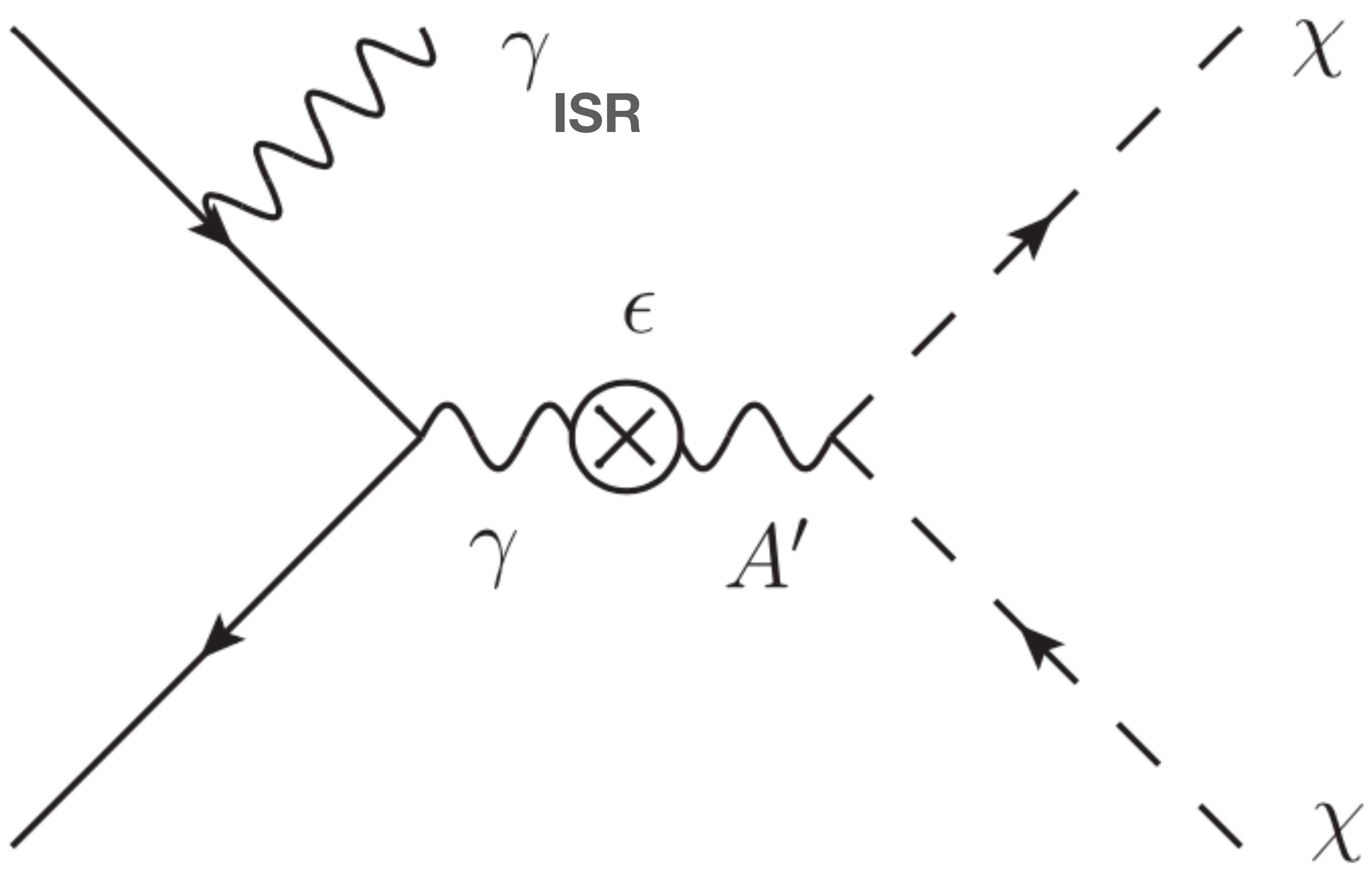
- Mass range of $0.2 < m_a < 9.7\ GeV/c^2$
- Using $455\ pb^{-1}$ of data, no significant excess was found
- This is only a small amount of the final target data set





F. Abudinen and et al., Physical Review Letters 125 (2020), 10.1103/physrevlett.125.161806.

Invisibly Decaying Dark Photon

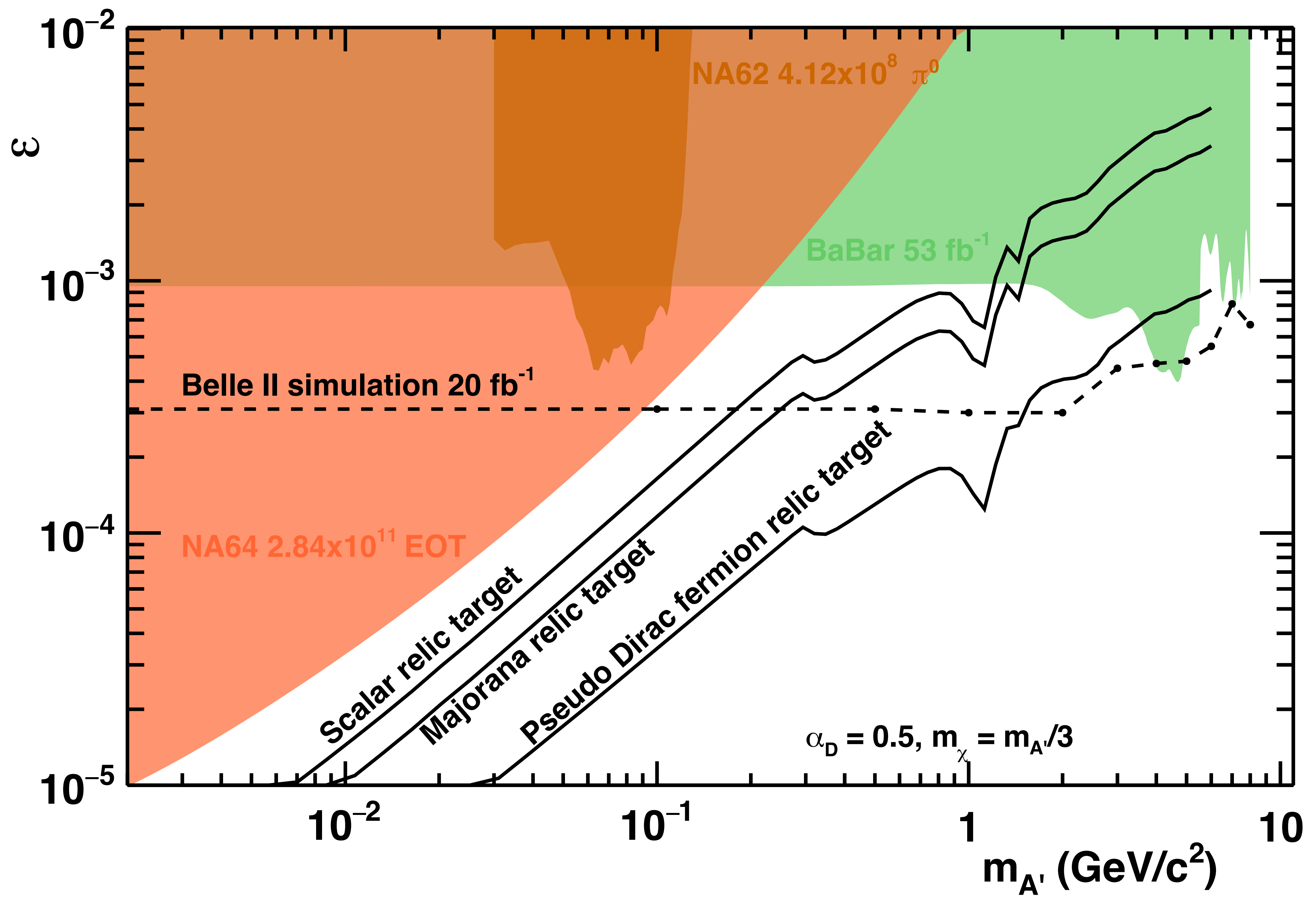


What?

- Dark sector mediator which couples to SM photon

How?

- Belle II looks for $e^+e^- \to \gamma_{ISR}\ A';\ \ A' \to \chi\chi$
- Final state: single γ + missing energy
- $m_{A'}^2 = 4E^*_{beam}(E^*_{beam} - E^*_{\gamma_{ISR}})$; Easy to find A' mass
- Newly designed trigger allows sensitivity down to 0.5 GeV single photon



Based on M. Graham, C. Hearty, M. Williams, Annu. Rev. Nucl. Part. Sci. 2021. 71:37

Invisibly Decaying Dark Photon

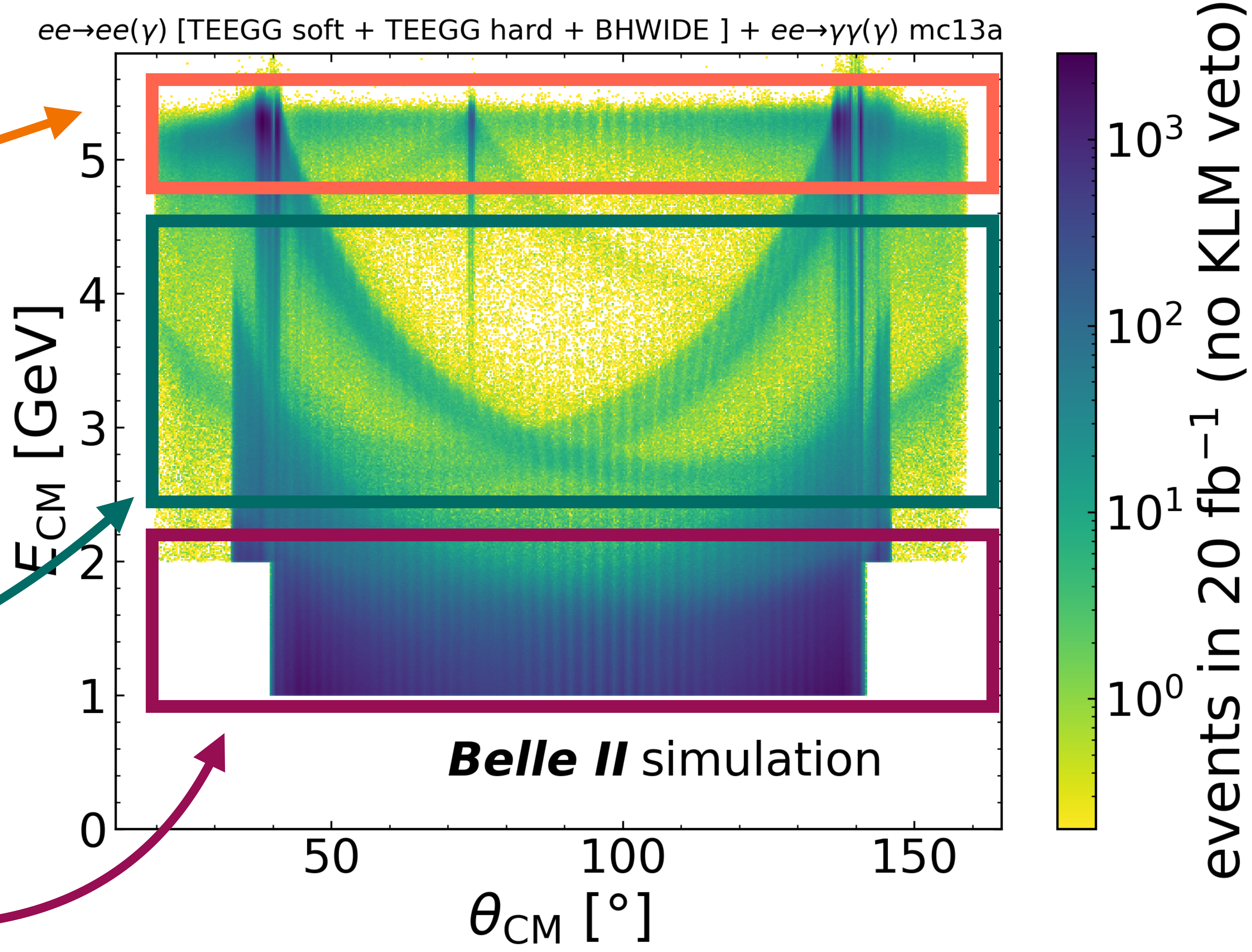
Method (Background Studies)

- When the dark photon is light, single photon has E^* ~ 5 GeV, dominant background: $e^+e^- \to \gamma\gamma$, missing 1 γ

$e^+e^- \to \gamma\gamma\gamma$ background where 2 γs are not reconstructed

$e^+e^- \to e^+e^-\gamma$ background where e^+e^- are outside the tracking chamber acceptance

Predicted Background γ's Energy against Location

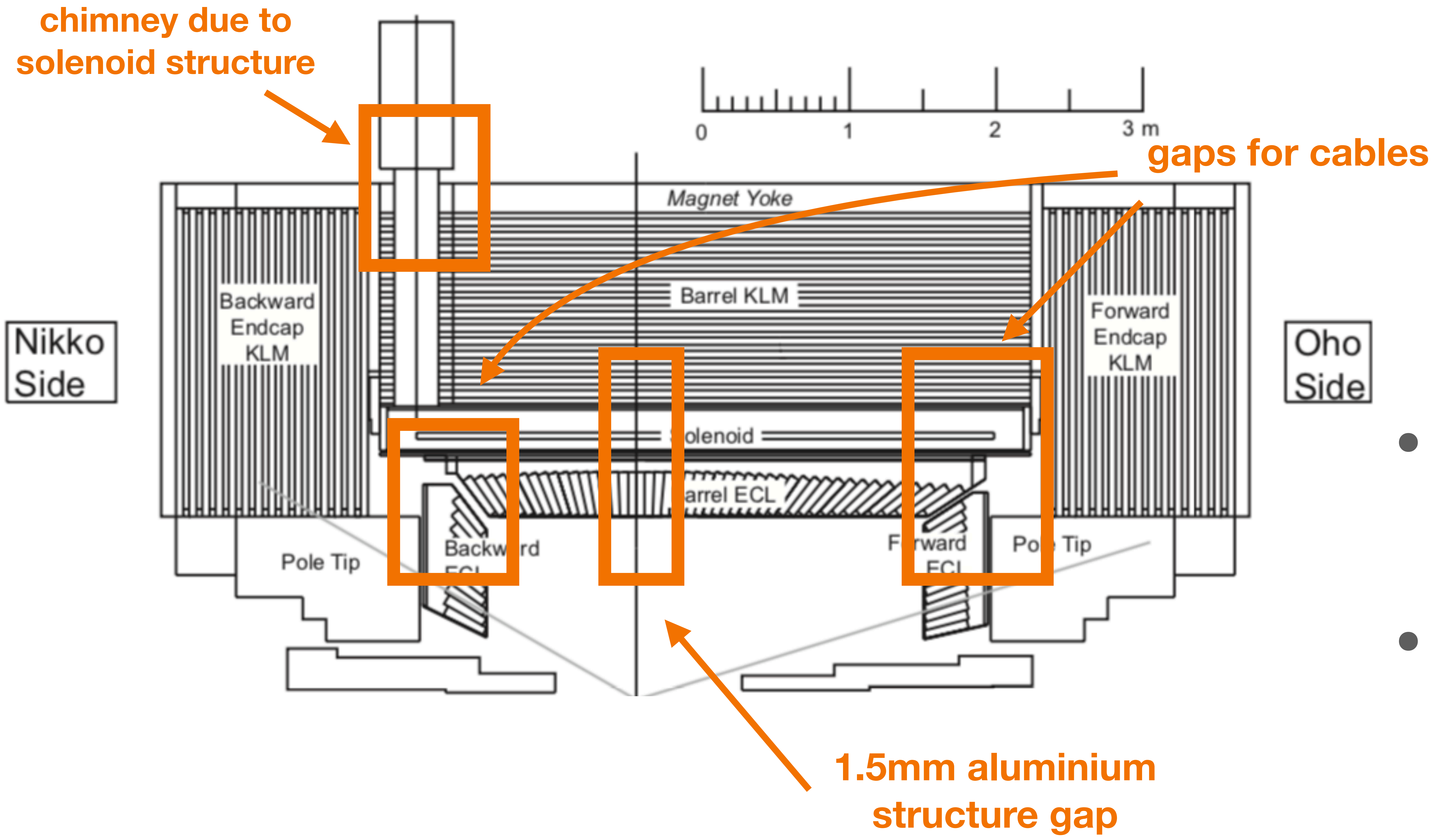


Belle II Simulation Preliminary

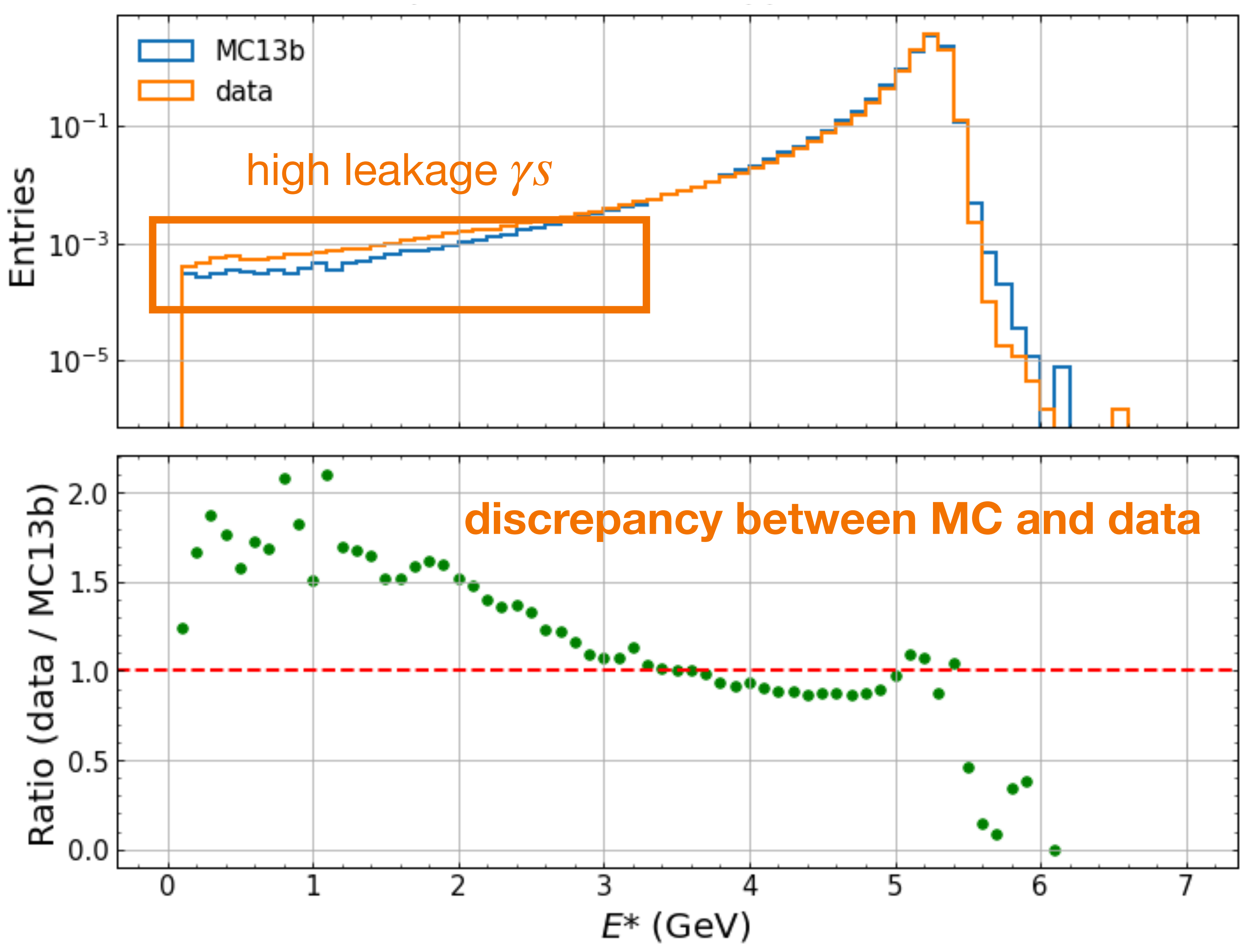
Invisibly Decaying Dark Photon

Method (Background Studies)

Problematic Regions in Detector (gaps)



E* of Probe Photon of $e^+e^- \to \gamma\gamma$ Sample



- How likely are we to miss a γ in our detector?
- Main detectors: Electromagnetic Calorimeter (ECL) and K-Long Muon (KLM) Detector

Conclusion

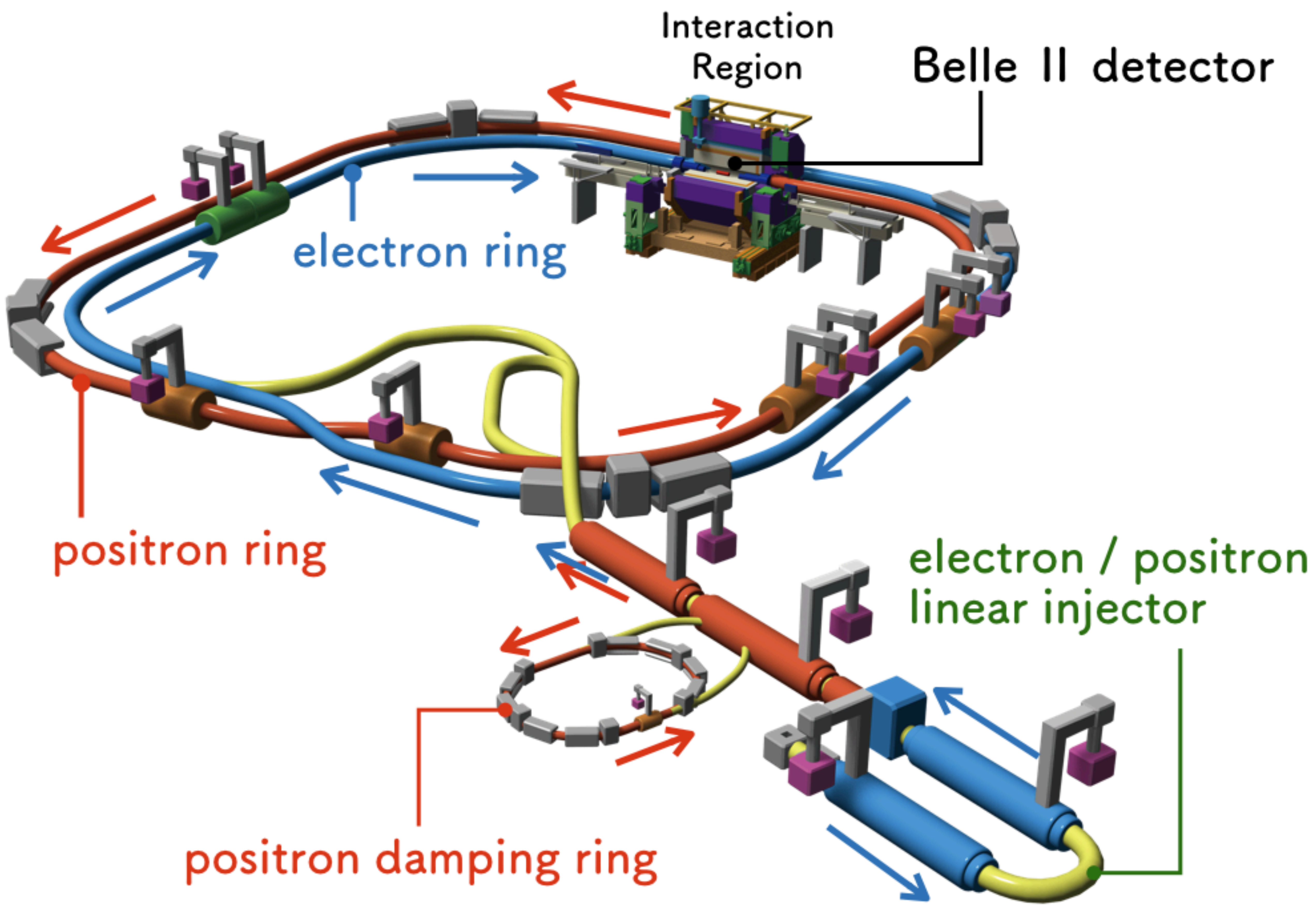
- Many ongoing physics analyses for tau and dark sectors at Belle II

- We are competitive in light dark sector searches

- Increased luminosity and upgraded detector will allow further improvements in searches and new results

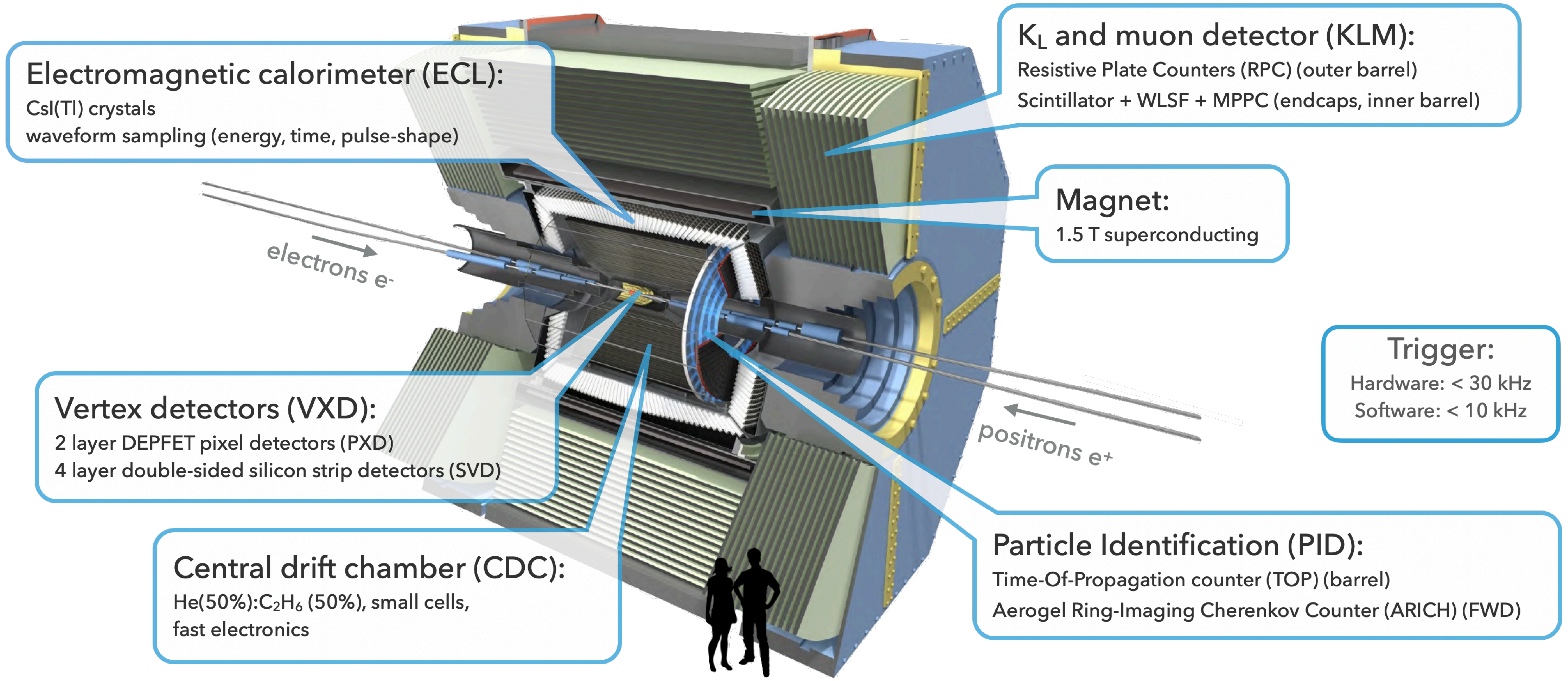
Backup Slides

SuperKEKB



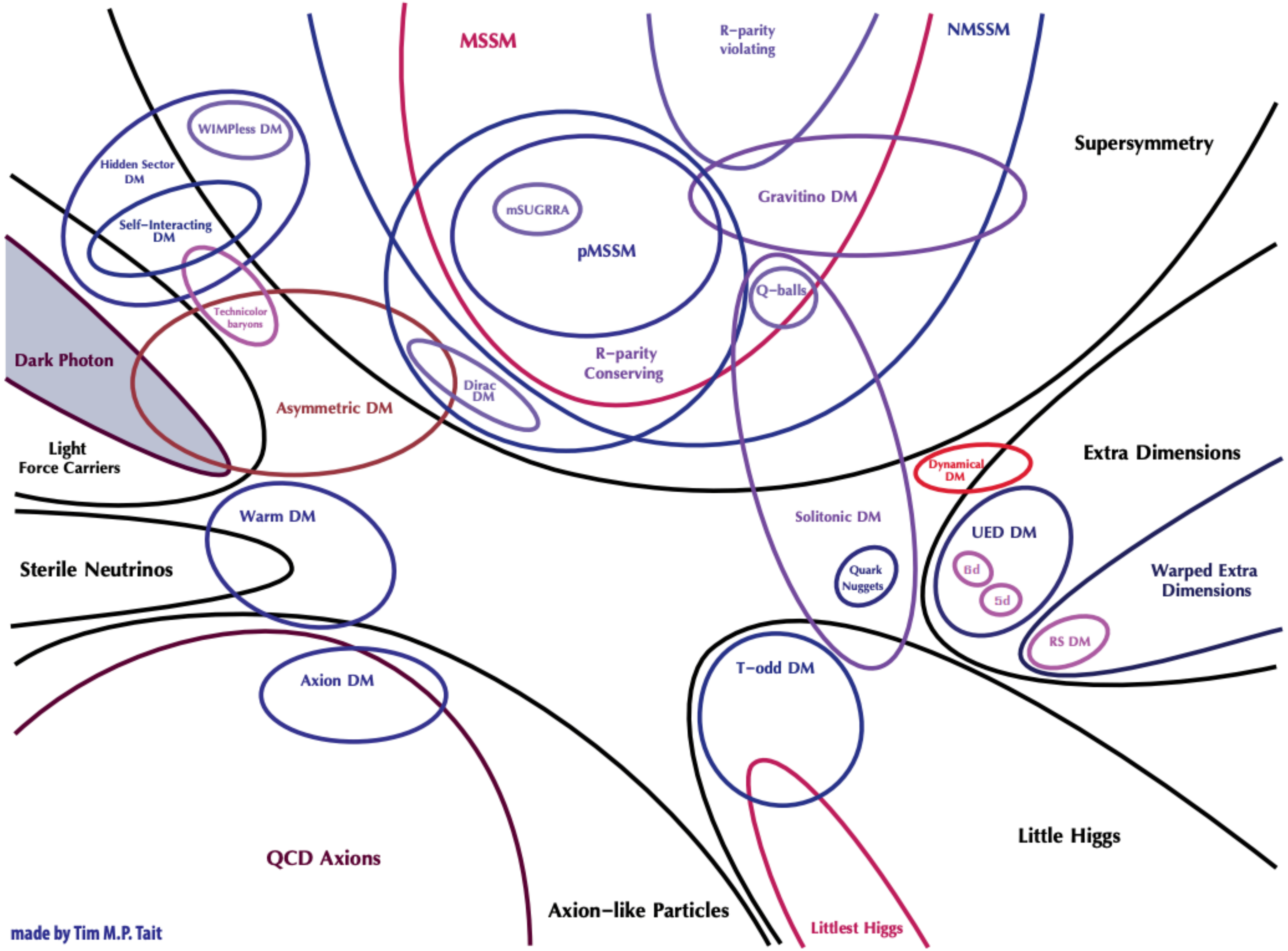
- SuperKEKB is an asymmetric particle accelerator with a circumference of 3 km located in Japan.
- Operates at resonance energy of $\Upsilon(4S)$ at 10.58 GeV.
- New world record for instantaneous luminosity of $2.4 \times 10^{34} cm^{-2} s^{-1}$ was achieved in June 2020.

Belle II



- The BelleII experiment aims to make precise measurements of CP violation in the weak sector, as well as find New Physics Beyond the Standard Model of Particle Physics.
- Current aim is to collect $50ab^{-1}$.
- International collaboration with nearly 1000 physicist and engineers from 115 institutions in 26 countries.

Dark Sector Theory

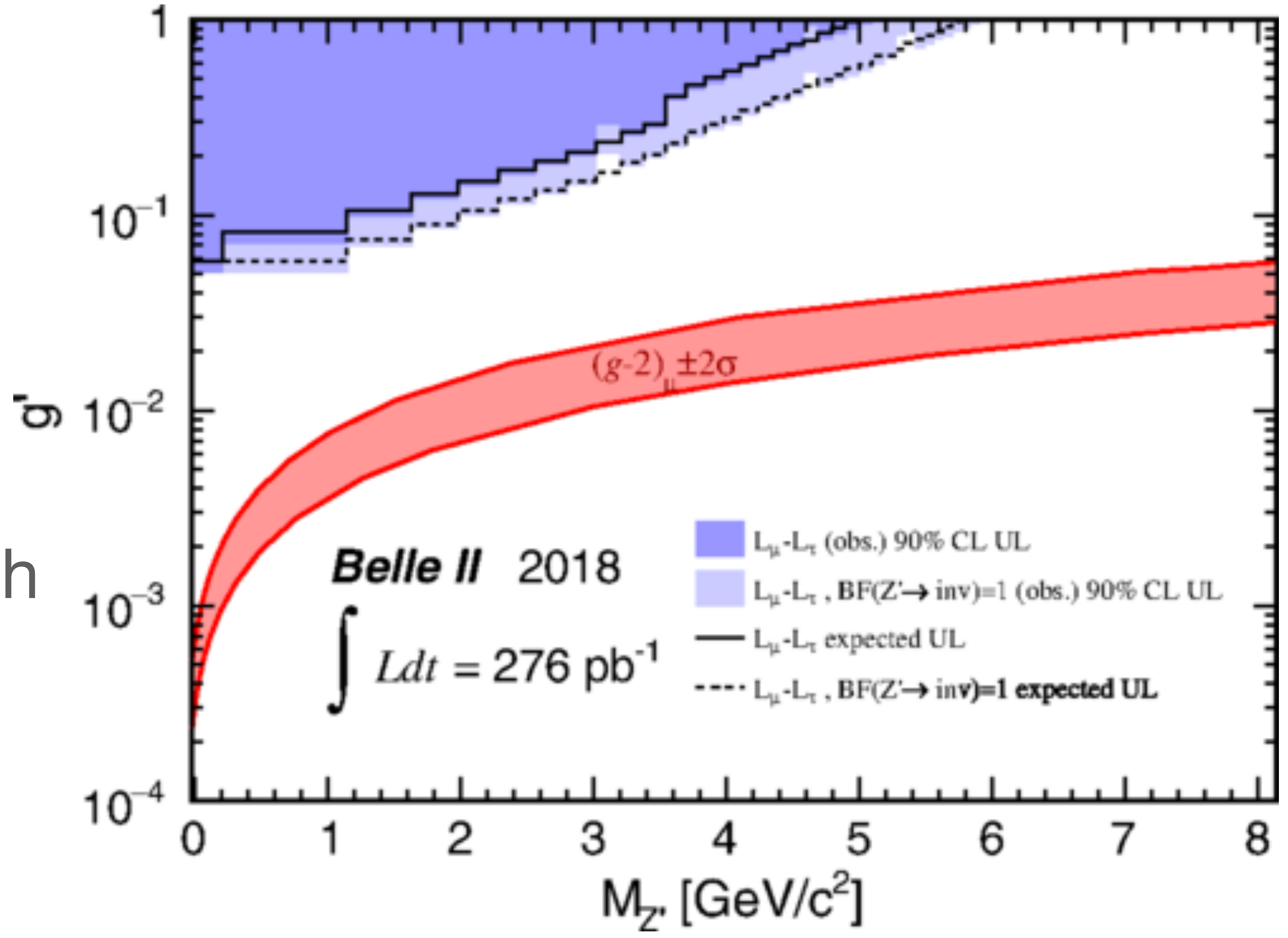


Feng J.L. et al., Planning the future of U.S. Particle Physics (Snowmass 2013): Chapter 4: Cosmic Frontier, 2014, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013, [arXiv:hepex/1401.6085]

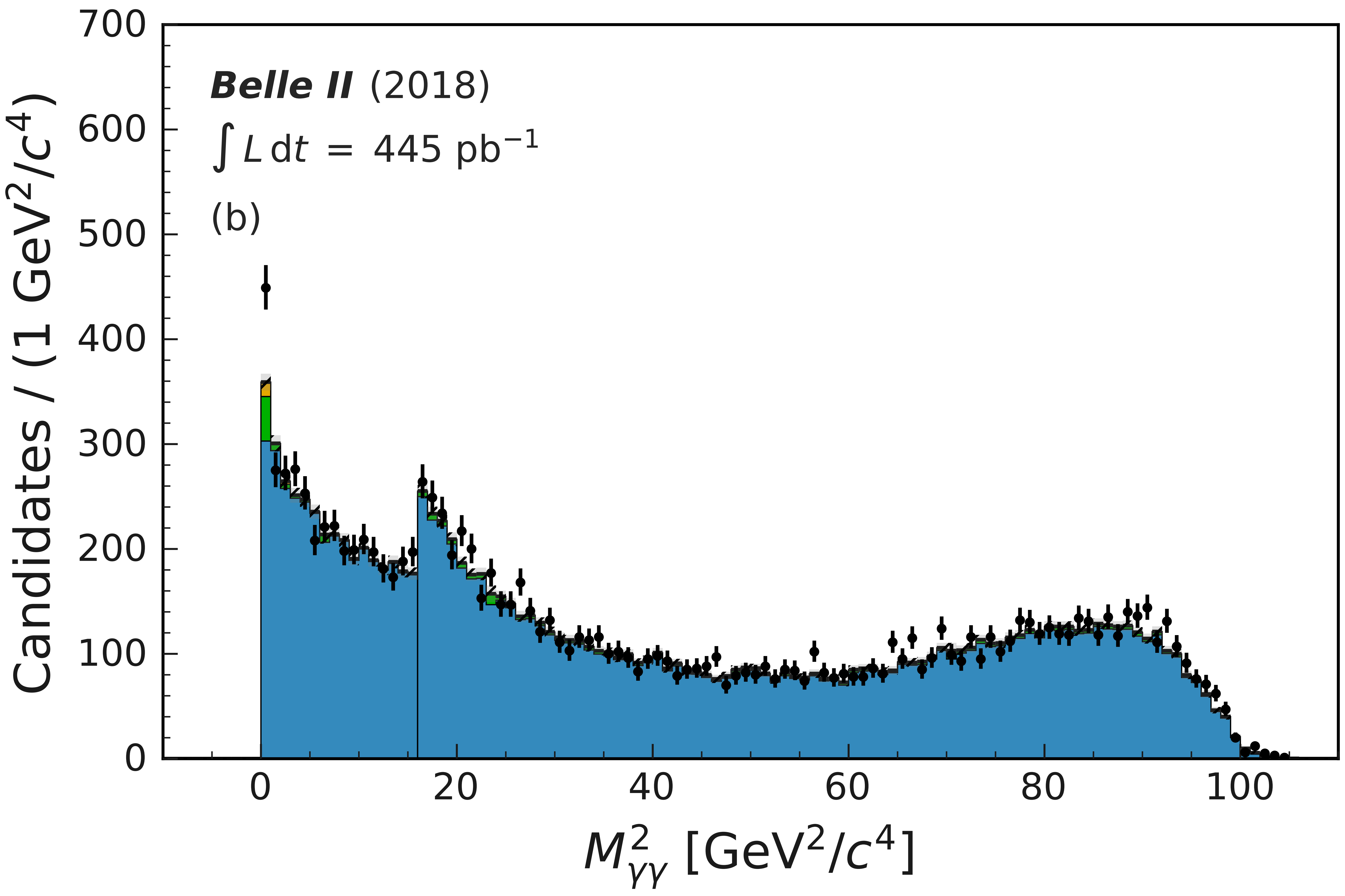
Invisibly decaying Z'

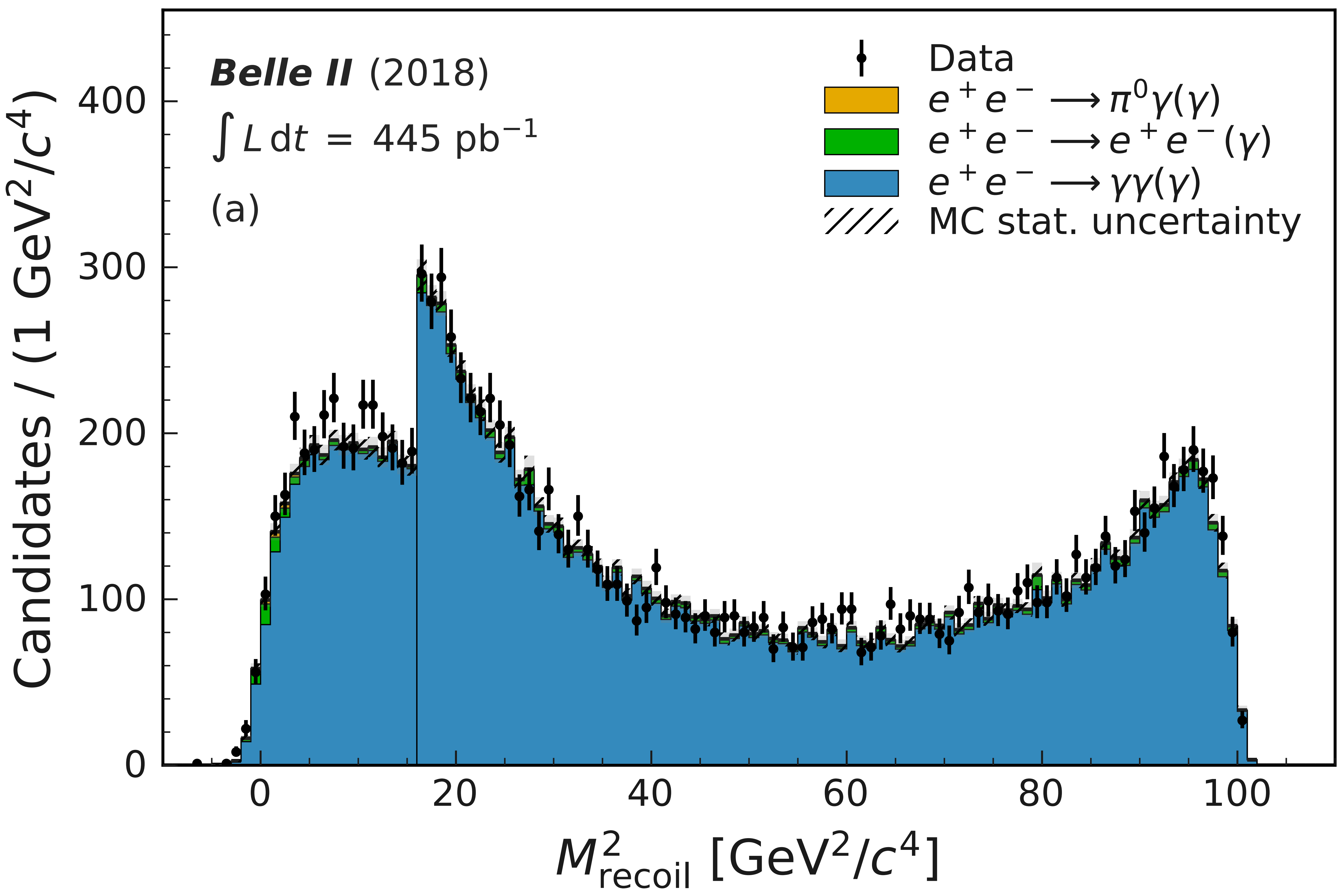
Method

- Selection criteria:
  - Only two tracks per event from IP
  - p_T of muons $> \ 1\ GeV$
  - Recoil momentum points to calorimeter with no photons within a $15°$ cone around it
  - Extra energy in calorimeter $< \ 0.4\ GeV$



Axion-Like Particle (ALP)





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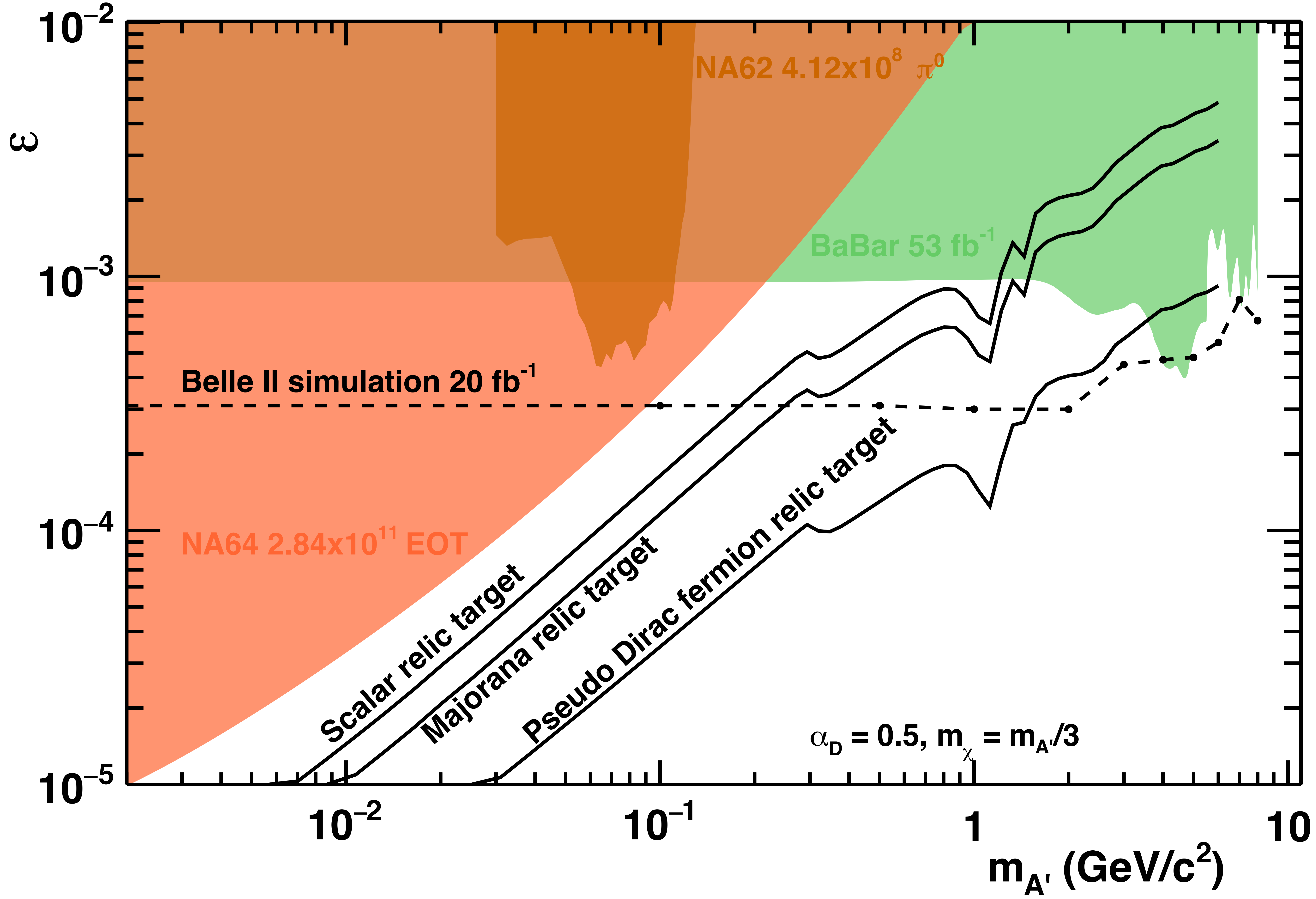
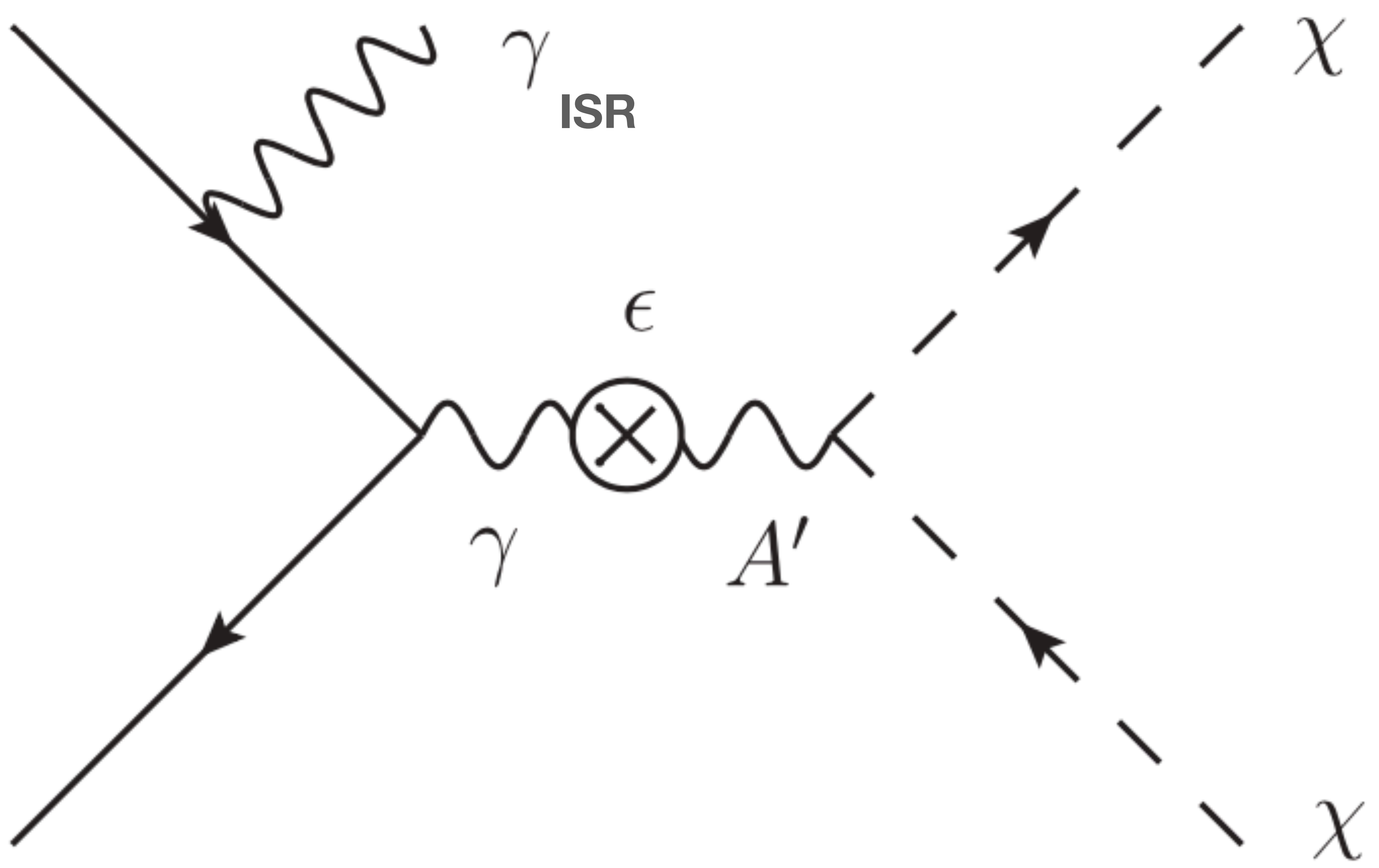
Invisibly Decaying Dark Photon



Based on M. Graham, C. Hearty, M. Williams, Annu. Rev. Nucl. Part. Sci. 2021, 71:37

Dark Photon Theory

- Dark photon has a small coupling to the EM current from kinetic mixing between the SM hyper charge and A’ field strength tensors
- Mixing induced coupling is suppressed by ϵ, providing a portal which dark photons interact with SM particles
- 3 unknown parameters: strength of kinetic mixing, dark photon mass, and decay branching fraction of the dark photon into invisible dark sector final states



Invisibly Decaying Dark Photon

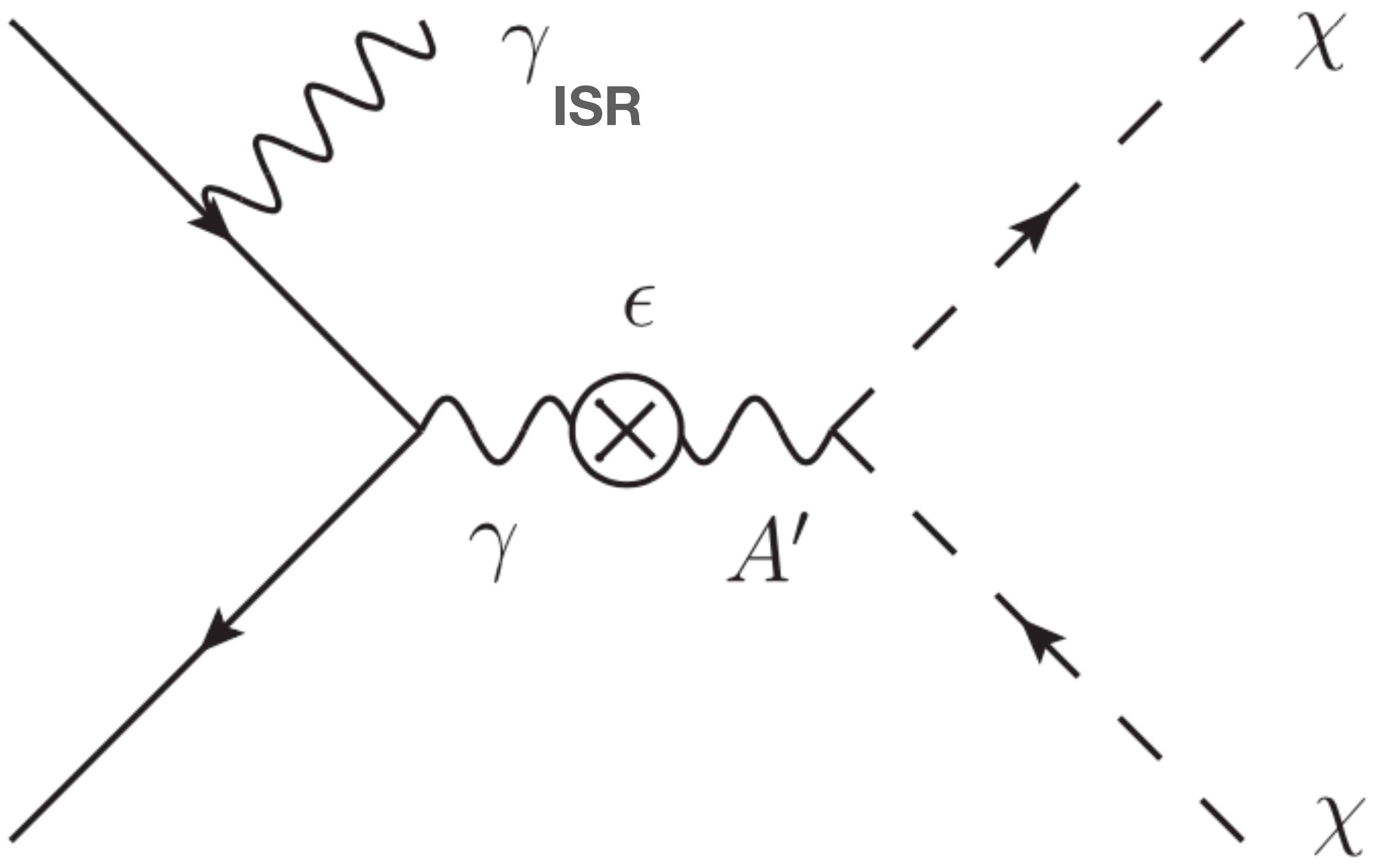
Searches in Other Experiments

- Direct competitor: BaBar

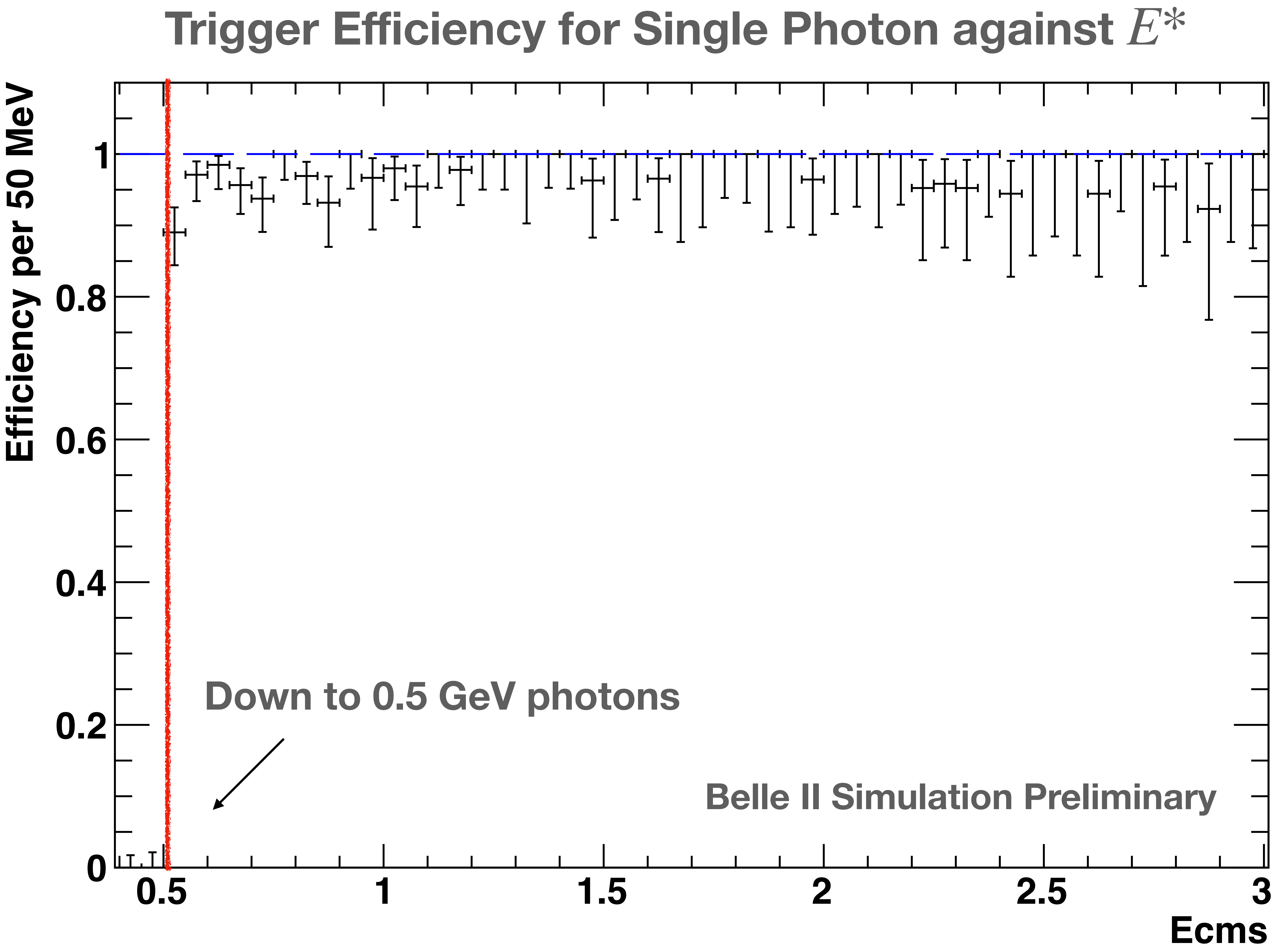
Phys. Rev. Lett.119 (2017) 13, 131804

- Complementary search: NA64

https://arxiv.org/abs/1906.00176



Invisibly Decaying Dark Photon



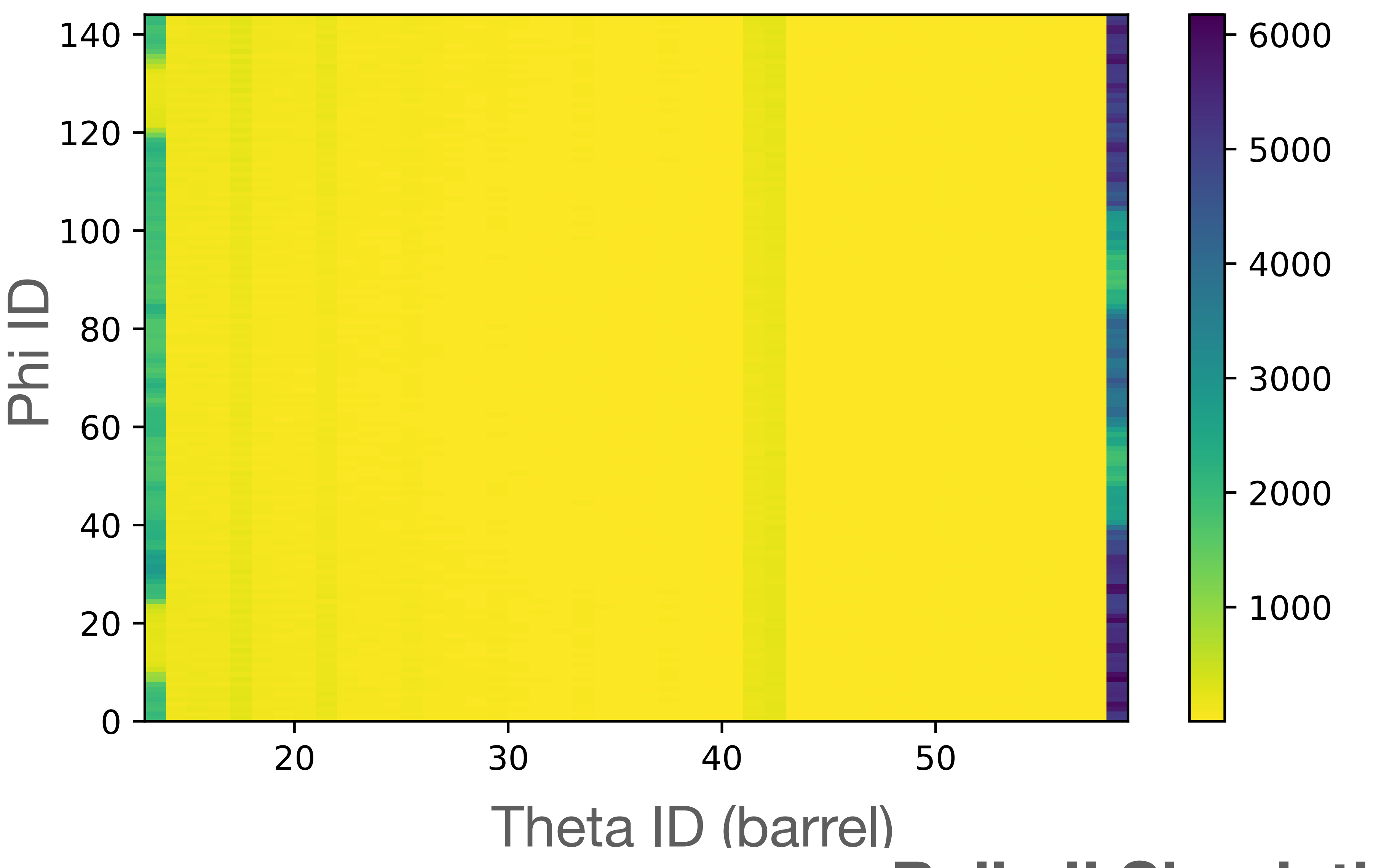
Invisibly Decaying Dark Photon

Studying Efficiency of Sub-detectors with $e^+e^- \to \gamma\gamma$ background

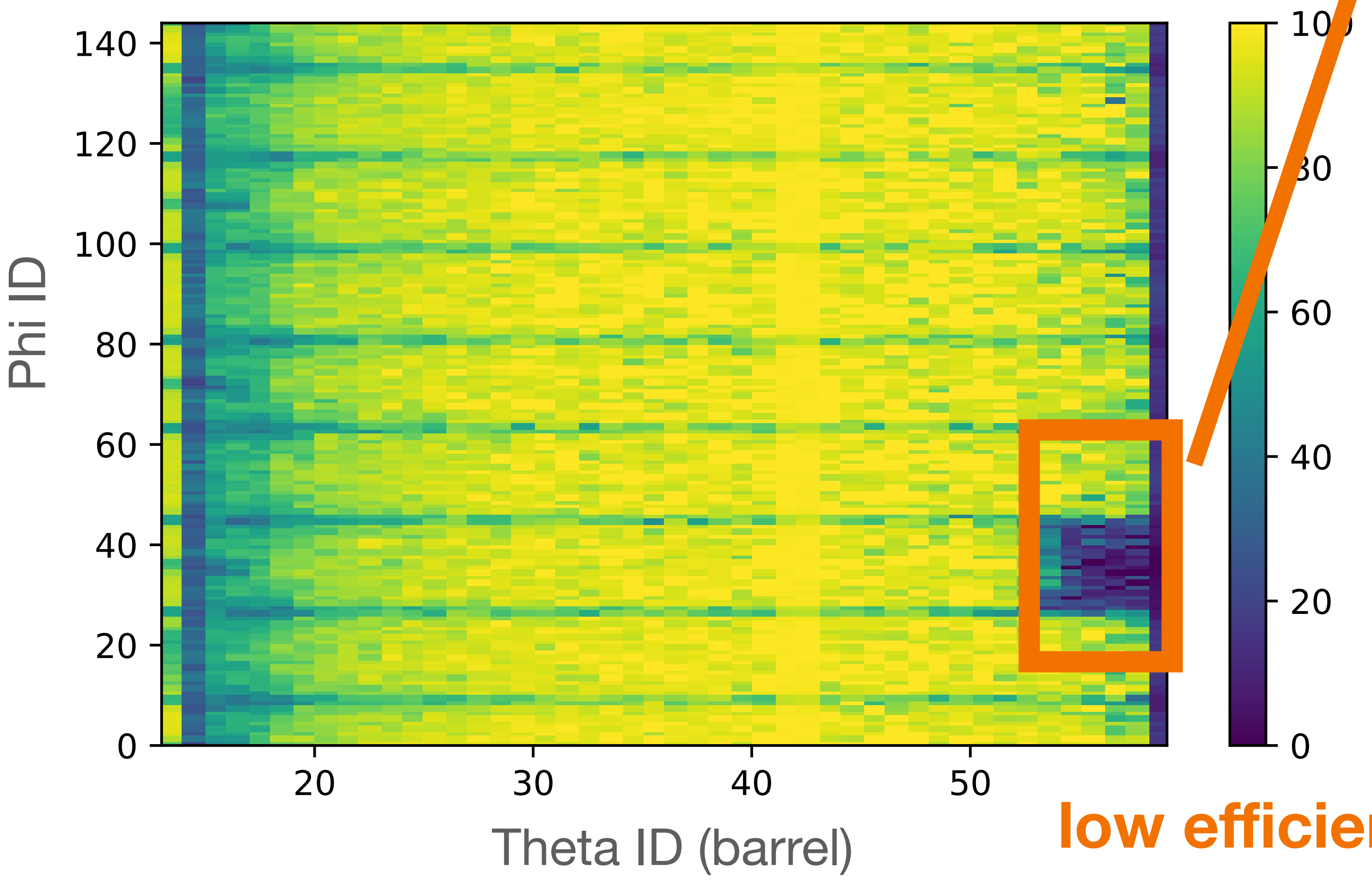
- Most of background come from gaps in the detectors, with a "high leakage γ" (roughly 4% of all γs)
- Study efficiency of detectors as a function of leakage energy; $E_{leak} = E_{beam} - E_{calorimeter}$ using $e^+e^- \to \gamma\gamma$ control sample

~ 4% of all photons are highly leaking

Photons in ECL with Leakage Energy > 2.8 GeV per crystal

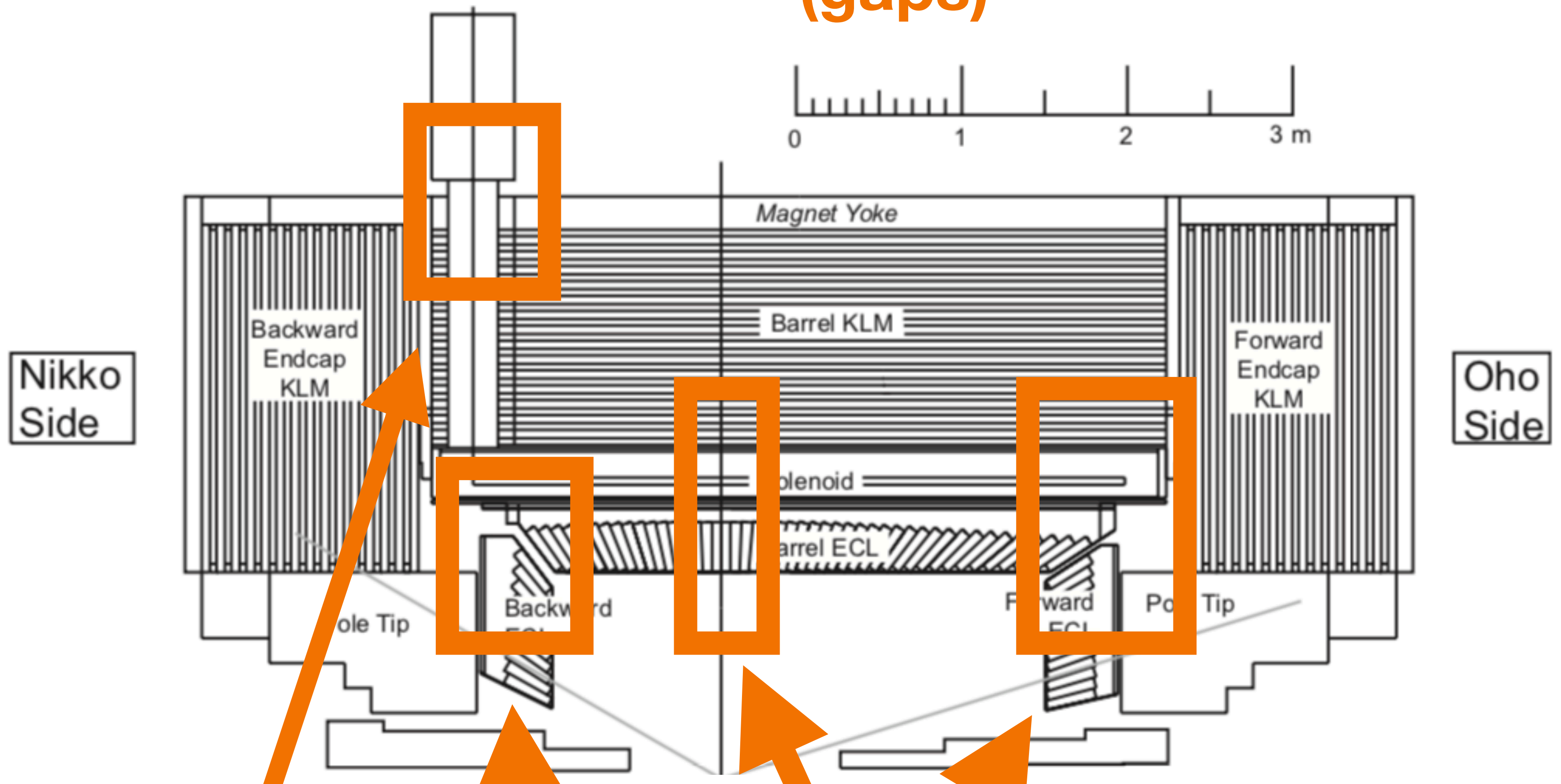


Fraction of the photons also detected in the KLM



Belle II Simulation Preliminary

Problematic Regions in Detector (gaps)



gaps for cables

1.5mm aluminium structure gap

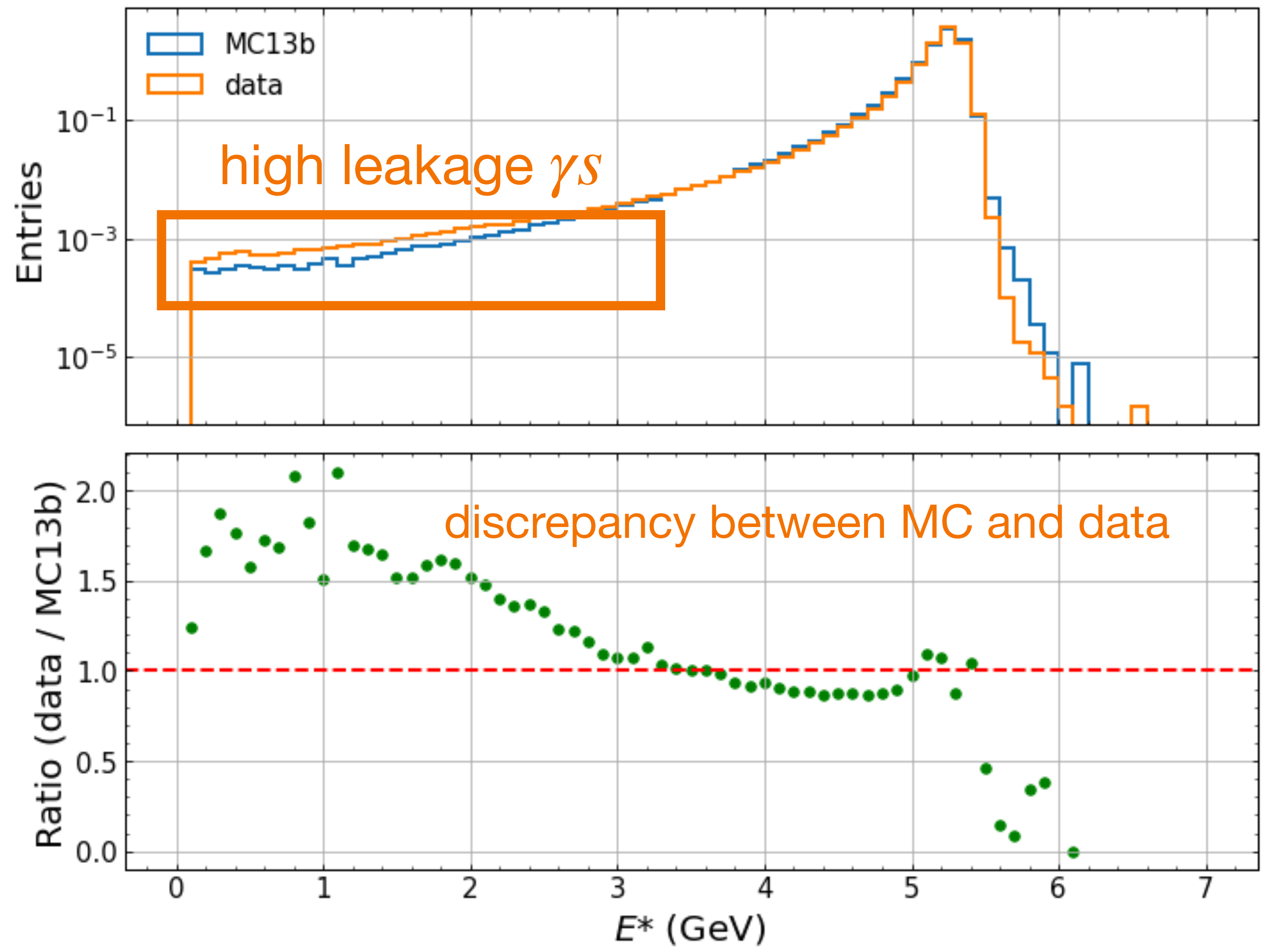
low efficiency due to solenoid structure

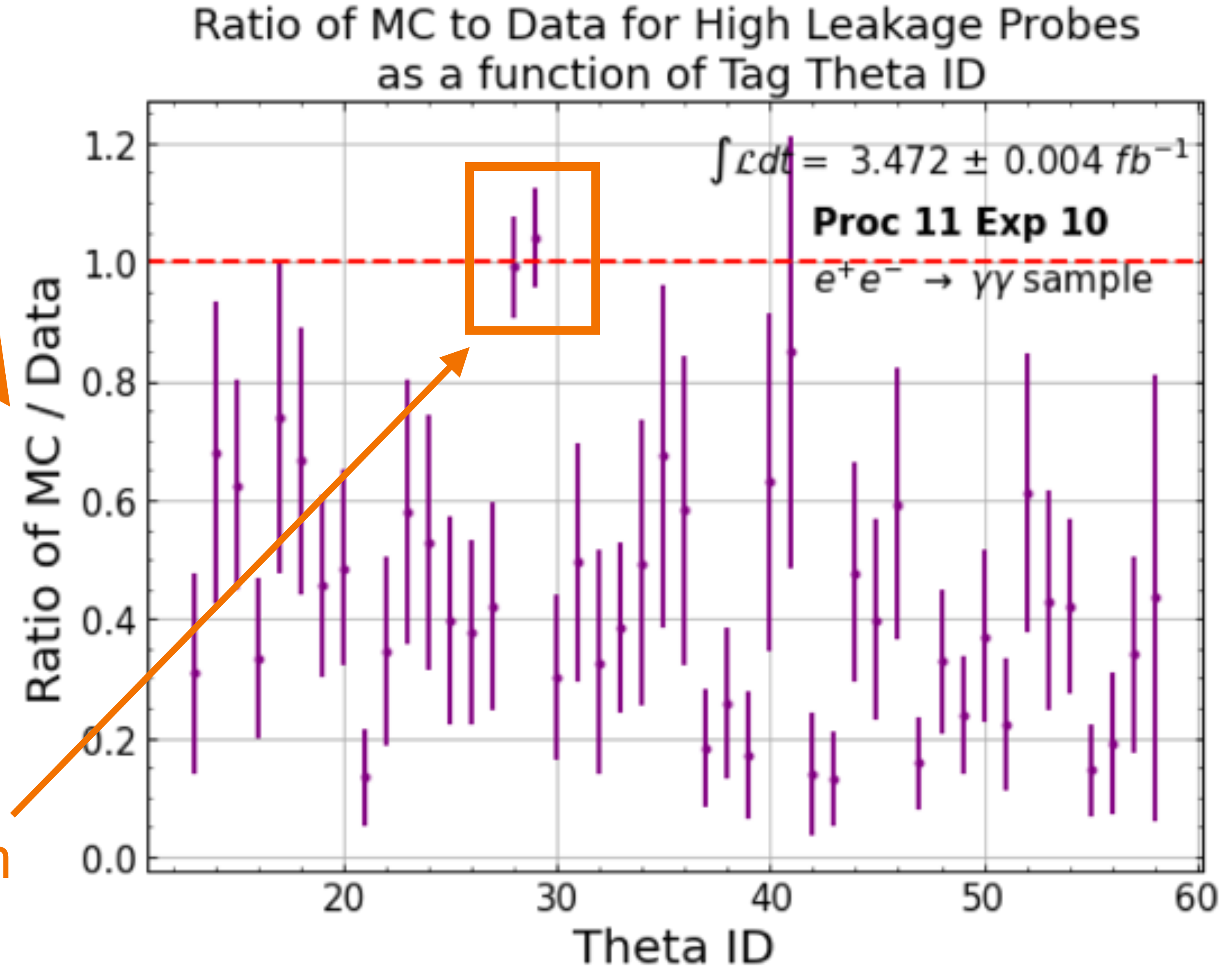
Invisibly Decaying Dark Photon

Monte Carlo (MC) and Data discrepancy with $e^+e^- \rightarrow \gamma\gamma$ background

- Next stage is to understand the background uncertainty on data (pre-blind process)
- Currently we see many more high leakage photons in data than in MC
- Gaps between crystals may be larger in data than MC
- Currently trying to quantify background in data by scaling MC

E* of Probe Photon of $e^+e^- \rightarrow \gamma\gamma$ Sample





good agreement in 1.5 mm gap

Belle II Simulation Preliminary