DARK SECTOR PHYSICS AT BELLE II

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ON BEHALF OF THE BELLE II COLLABORATION

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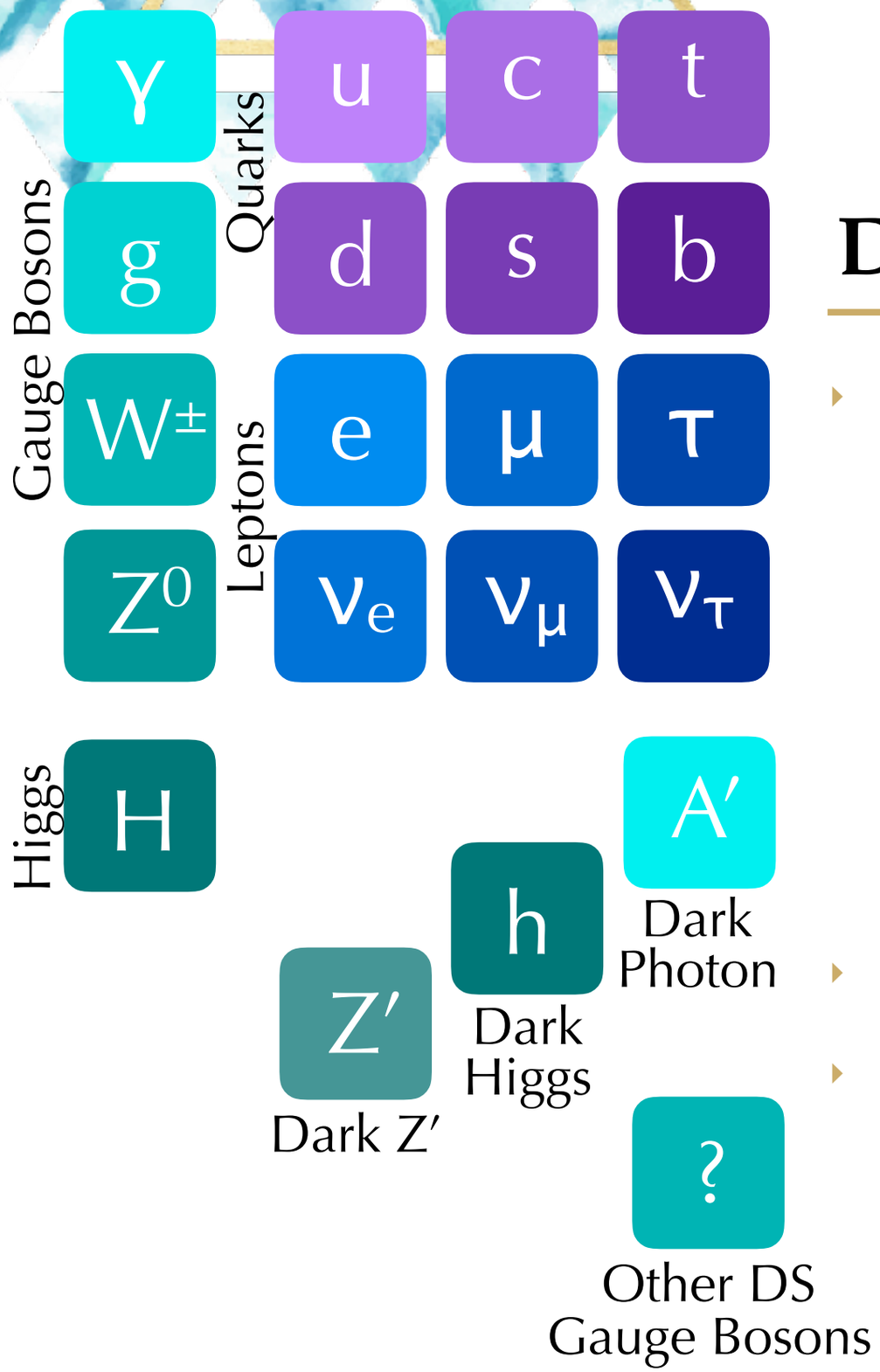
THE UNIVERSITY OF MELBOURNE

Dark Sector Portals at Belle II



- If DM is **not WIMP (or fermionic)**, a portal must exist between the dark sector and the visible sector.
  - Vector Portal: A′, Z′ ← **Detailed Today**
  - Psuedoscalar Portal: ALPs
  - Scalar Portal: h
  - Neutrino Portal: Sterile Neutrinos
- Status of Belle II — **First Physics data-taking**
- Why are we powerful for dark sector? — **performance studies** using first dataset

Processes & Mass Regimes Probed by Belle II

- **Dark Photon Searches:** R. Essig et al. (2009) https://arxiv.org/abs/0903.3941
  B. Battle et al. (2009) https://arxiv.org/abs/0903.0363
  - $e^+e^- \to \gamma A'$; $A' \to$ invisible (monophoton search)
  - $e^+e^- \to \gamma A'$; $A' \to e^+e^-$, $\mu^+\mu^-$
- **Dark Z′ Searches:** B. Shove, I. Yavin (2014) https://arxiv.org/abs/1403.2727
  W. Altmannshofer et al. (2016) https://arxiv.org/abs/1609.04026
  - $e^+e^- \to \mu^+\mu^- Z'$; $Z' \to \mu^+\mu^-$, invisible
  - $e^+e^- \to \mu^+e^- Z'$; $Z' \to$ invisible (LFV Model)
- **ALP searches:** M. Dolan et al. (2017) https://arxiv.org/abs/1709.00009
  - $e^+e^- \to \gamma$+ALP; ALP$\to\gamma\gamma$ (tri-photon search)
- **Dark Higgs**:
  - $e^+e^- \to \tau^+\tau^- h$; $h \to$ dilepton
- **"Axiflavons"**: E. Izaguirre et al (2017) https://arxiv.org/pdf/1611.09355.pdf
  D. Aloni et al (2018) https://arxiv.org/pdf/1811.03474.pdf
  - $B^+ \to K^+ a$ OR $B^0 \to D^0 a$; $a \to \gamma\gamma$, gg, invisible (ALPs in EWP decays)
- **Others**: Long-lived particles, Magnetic Monopoles, etc…

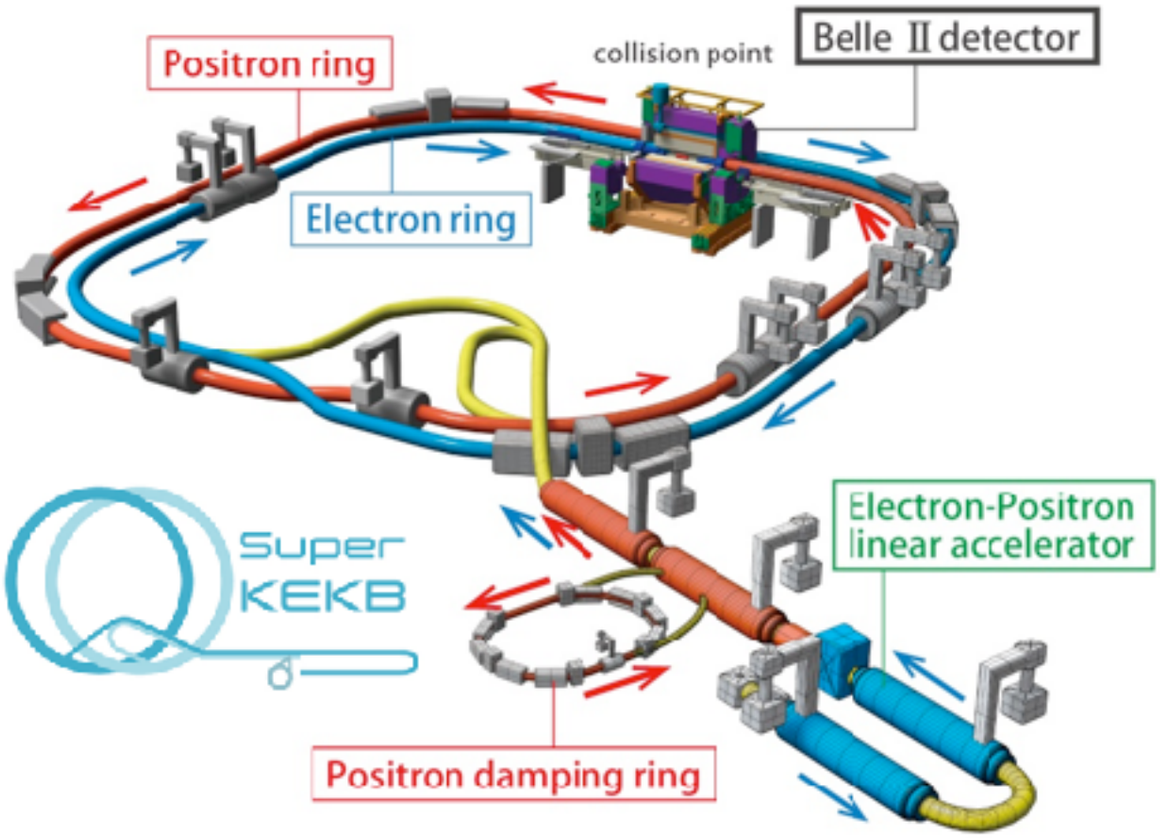
Belle II is probing DS mediators at the MeV-GeV scale

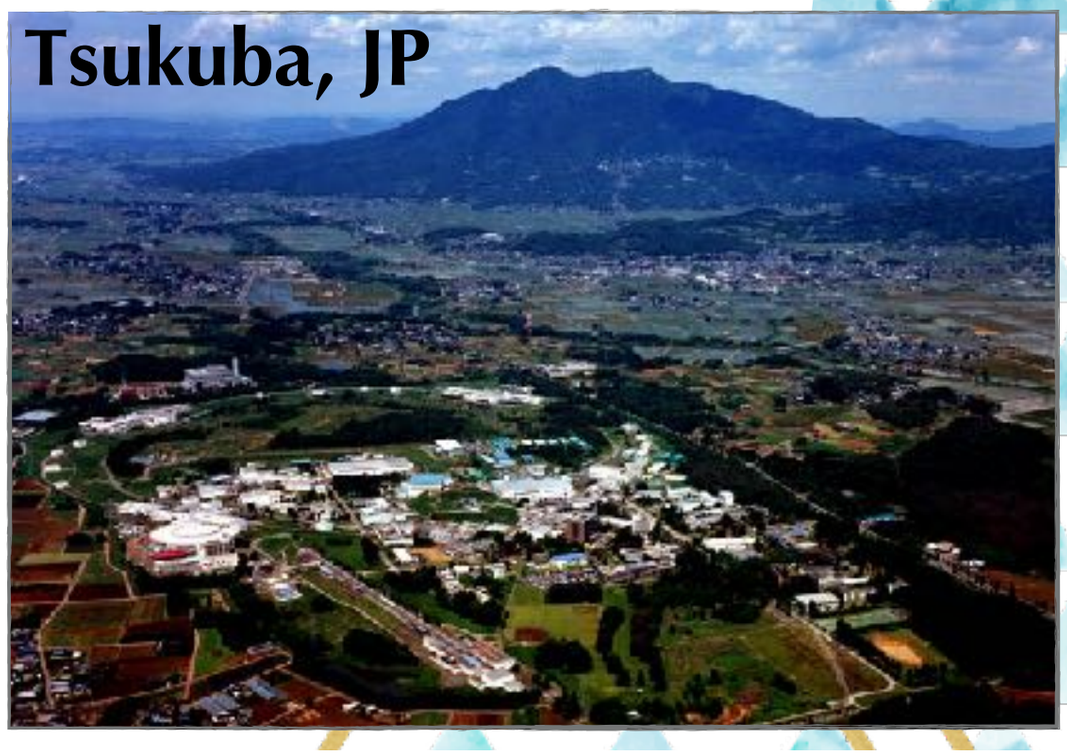
Mass resolution:
Direct O(10) MeV / c^2
Recoil O(100) MeV / c^2

E. Kou, P. Urquijo, et al. ***The Belle II Physics Book*** (2018) https://arxiv.org/abs/1808.10567

SuperKEKB and Belle II

- Asymmetric e^+e^- collisions at $\Upsilon(4S)$ resonance (10.58 GeV)
- Nominally a *B-Factory*
- 900+ members, 100+ institutions, 26 countries



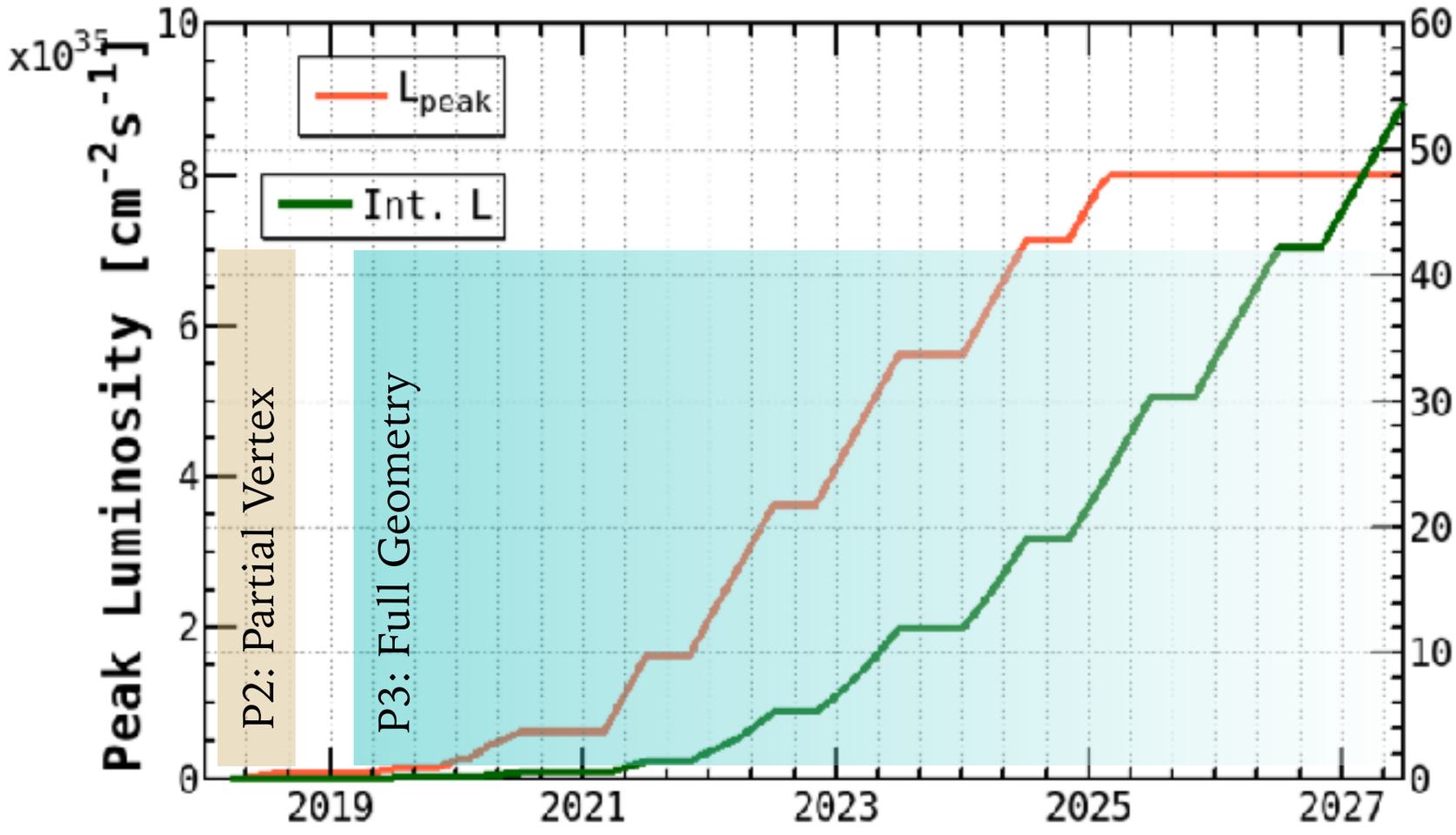


SuperKEKB — The Luminosity Frontier

- Phase 2: 2018
  - First physics data (500 pb^{-1})
  - Partial vertex detector
- Phase 3: 2019 onwards
  - Physics run from March 2019 (~6.5 fb^{-1})
  - Will run 7-9 months/year
- Goal: 2027
  - Will reach **50 ab^{-1}**

SuperKEKB will have the world's highest luminosity

Discussion today surrounding analyses with 2018/2019 data, as well as performance studies



SuperKEKB Phase 3 (Belle II Physics Run) Starts

2019/03/11 Pressrelease ACC IPNS

On March 11th, 2019, Phase 3 operation of the SuperKEKB project began successfully, marking a major milestone in the development of Japan's leading particle collider. This phase will be the physics run of the project, in which the Belle II experiment will start taking data with a fully instrumented detector.

The KEKB accelerator, operated from 1999 to 2010, currently holds the world record luminosity for an electron-positron collider. Super

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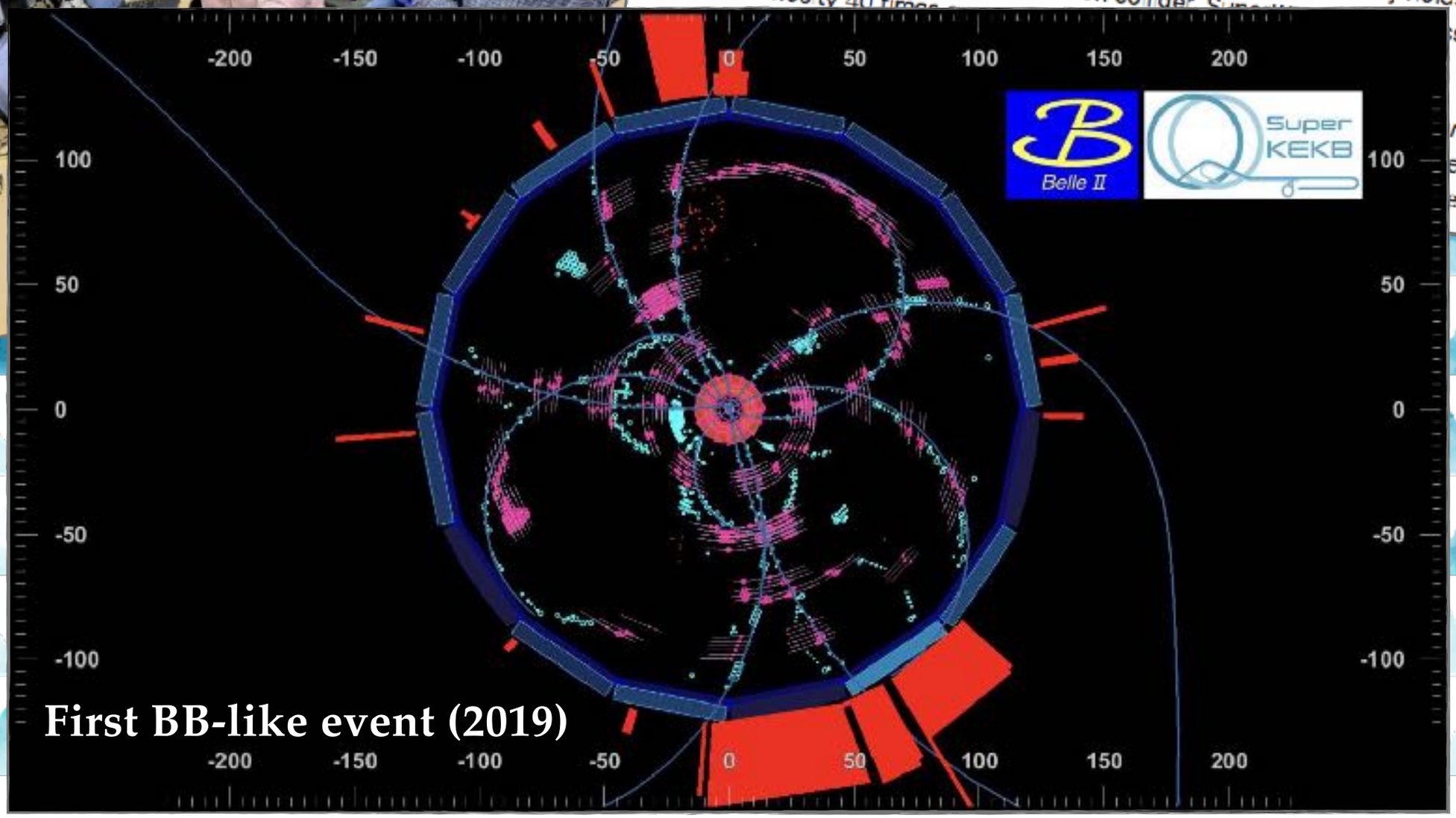
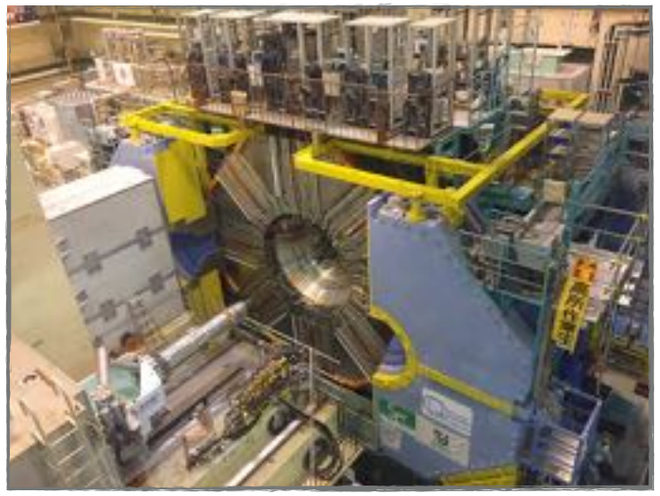
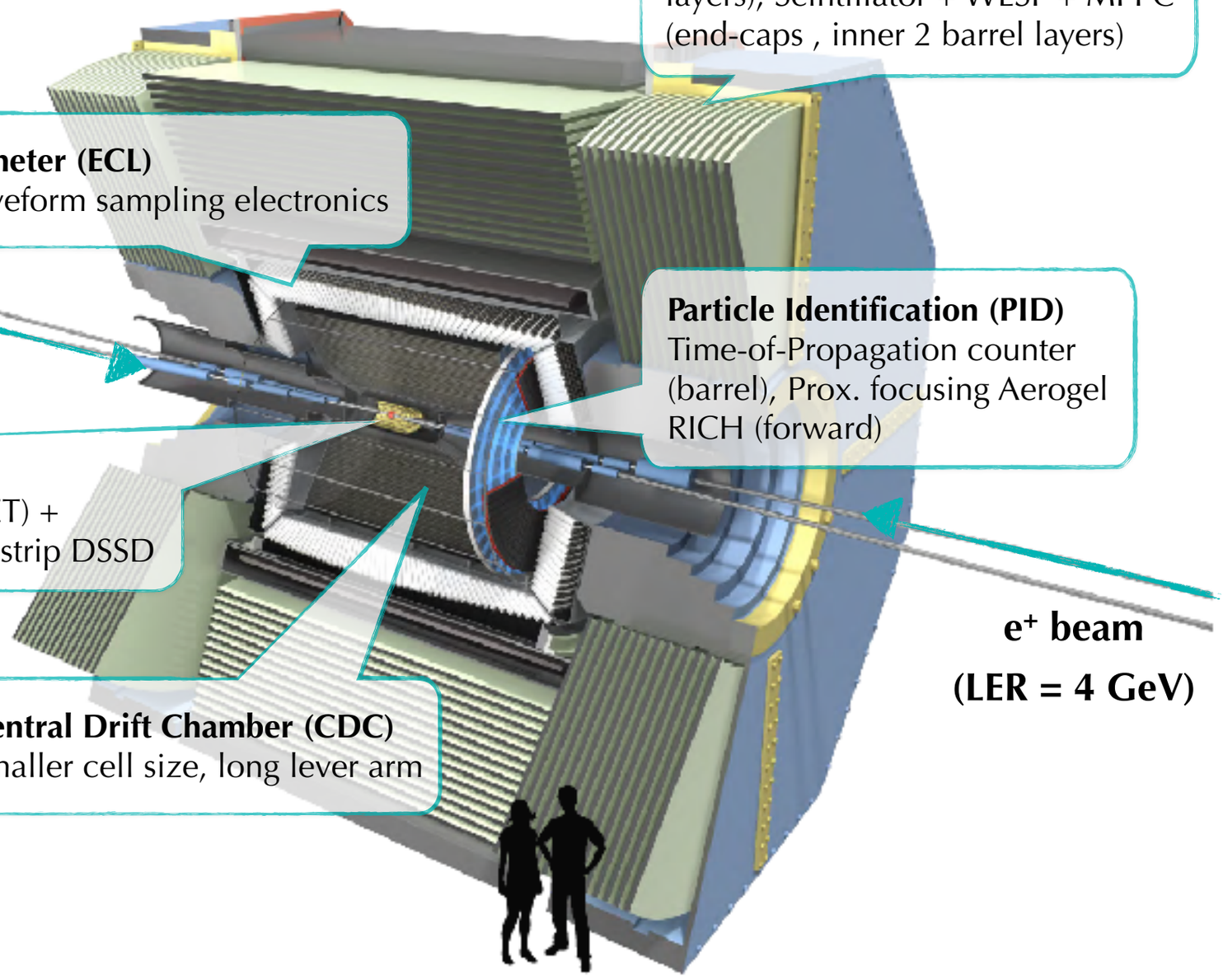
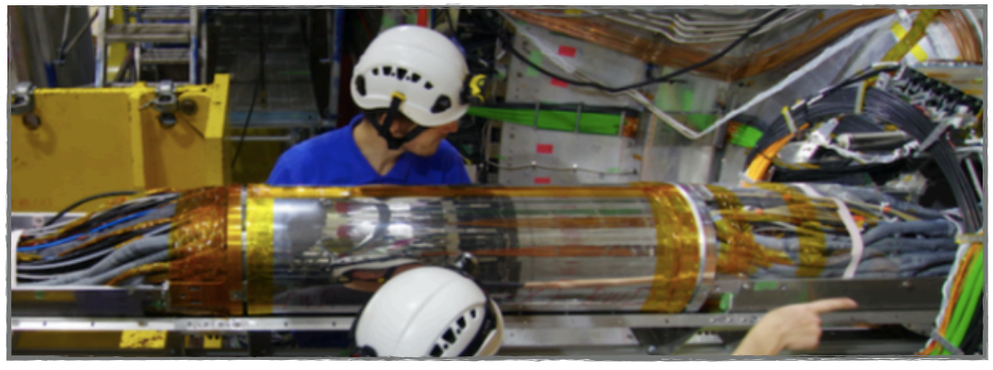


First BB-like event (2019)

The Belle II Detector



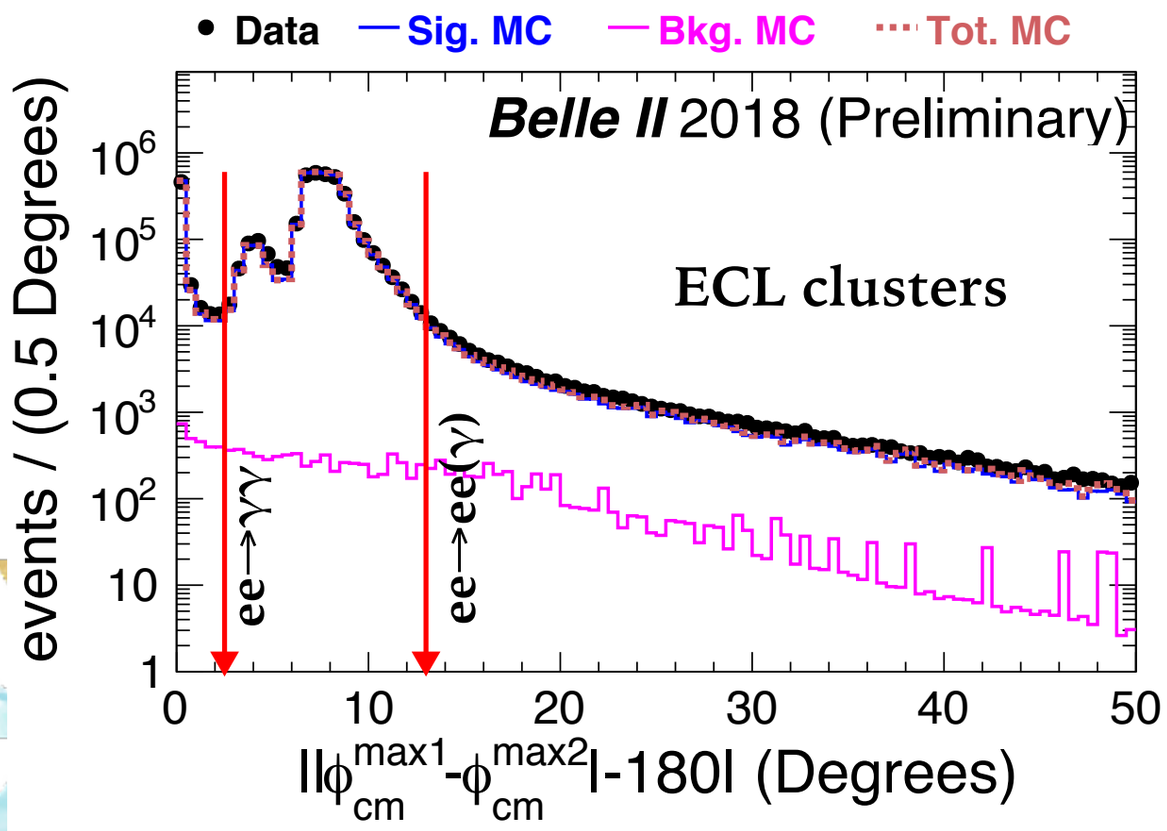


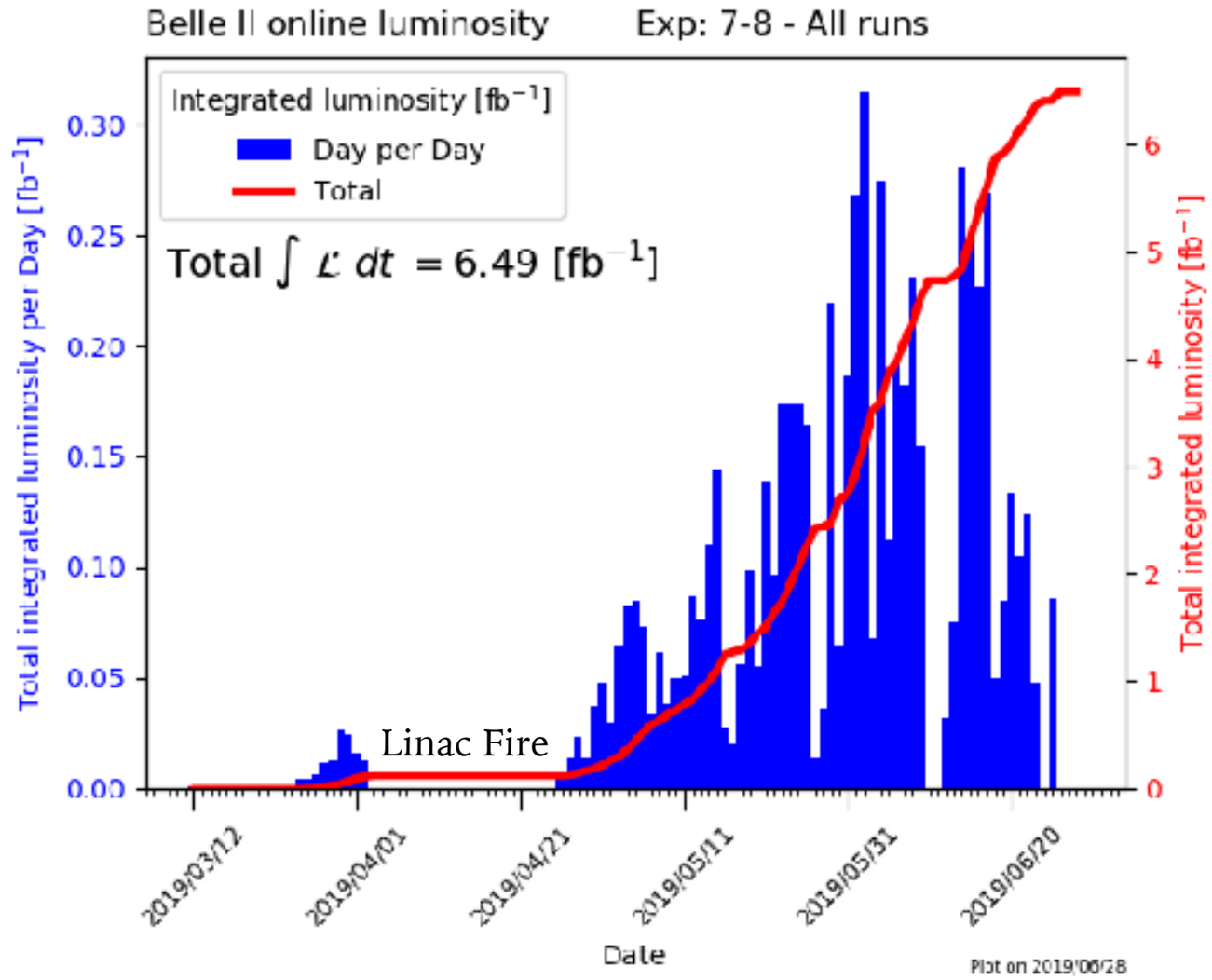


The Dataset — First Phase 3 Physics Run

- 2 months of data collection
- $L_{peak} \sim 5.5 \times 10^{33} / cm^2 / s$ ($\beta_y^* = 3mm$)
- By late July, SuperKEKB hit $L_{peak} \sim 1.2 \times 10^{34} / cm^2 / s$ ($\beta_y^* = 2mm$)

Comparable to PEP-II best recorded, but **background 3x too large to turn on Belle II**





First Belle II Physics publication to be submitted

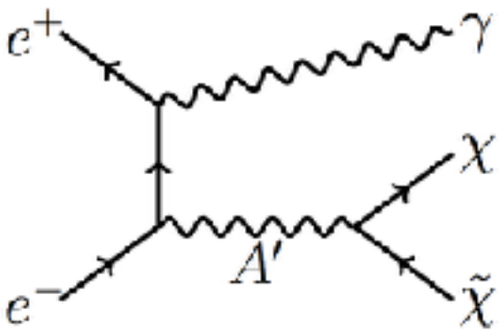
Dark Photon (A′) Searches

- Vector portal, A′, coupling to SM photon via kinetic mixing with a mixing strength parameter ε

$$\mathcal{L} \supset \varepsilon A_\mu J^\mu_{SM}$$

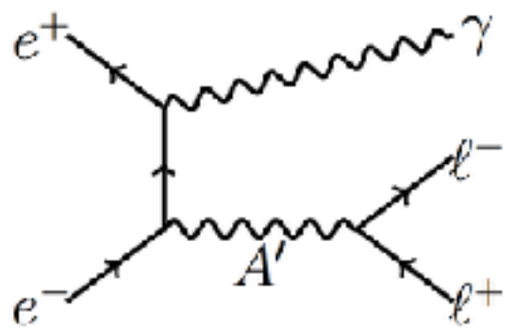
R. Essig et al. (2009) https://arxiv.org/abs/0903.3941
B. Battle et al. (2009) https://arxiv.org/abs/0903.0363

- Search for $e^+e^- \rightarrow A'\gamma$; $A' \rightarrow$ dilepton pair or invisible



Fit the recoil mass squared peak:

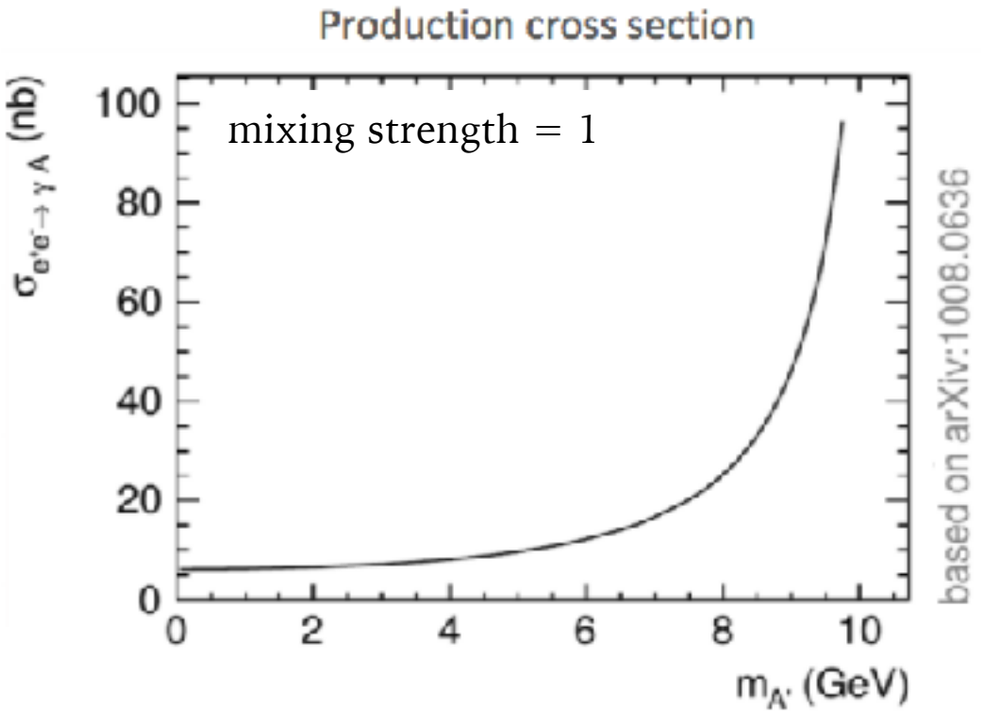
$$\vec{P}_{A'} = \vec{P}_{beam} - \vec{P}_\gamma$$

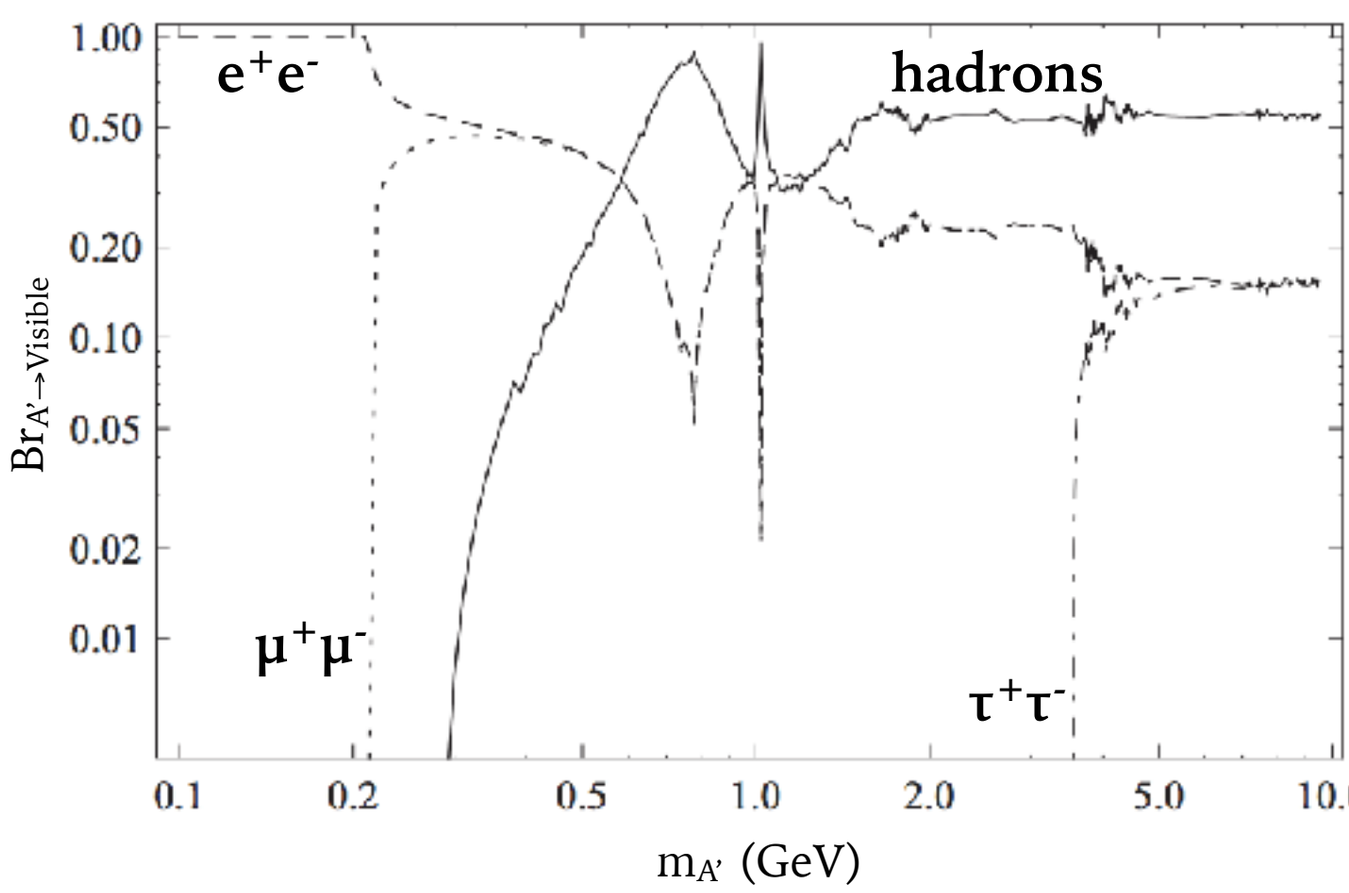


Fit the invariant mass peak from daughters:

$$\vec{P}_{A'} = \vec{P}_{\ell^+} + \vec{P}_{\ell^-}$$

Necessity for a dedicated DS Trigger system at Belle II…





Dedicated Dark Sector Trigger

- Hardware (L1) trigger
  - 3D tracking implemented in drift chamber trigger
  - 3D calorimeter Bhabha veto logic available in calorimeter trigger to identify Bhabha events with high purity
  - Matching of drift chamber tracks to calorimeter clusters
- Software high level trigger (HLT)
  - Reconstructs events online using offline reconstruction algorithms
  - 6000 cpu cores at target luminosity
- O(10 nb) acceptance (corresponding to trigger rate of 10 kHz at peak luminosity) — suppressed QED events, without throwing out DS modes

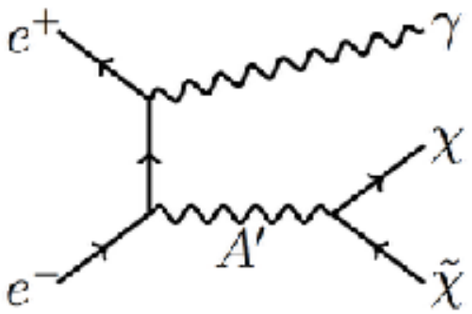
First data taking was done with very loose triggers

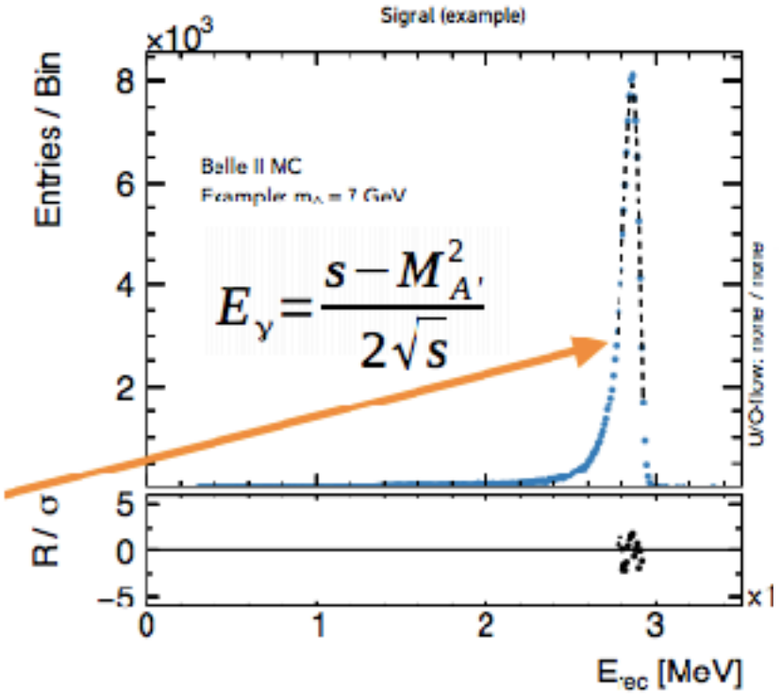
Process	σ (nb)
$e^+e^-(\gamma)$	300 ± 3
$\mu^+\mu^-(\gamma)$	1.148
$\tau^+\tau^-(\gamma)$	0.919
$\gamma\gamma(\gamma)$	4.99 ± 0.05
$e^+e^-e^+e^-$	39.7 ± 0.1
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1
	≈ 366

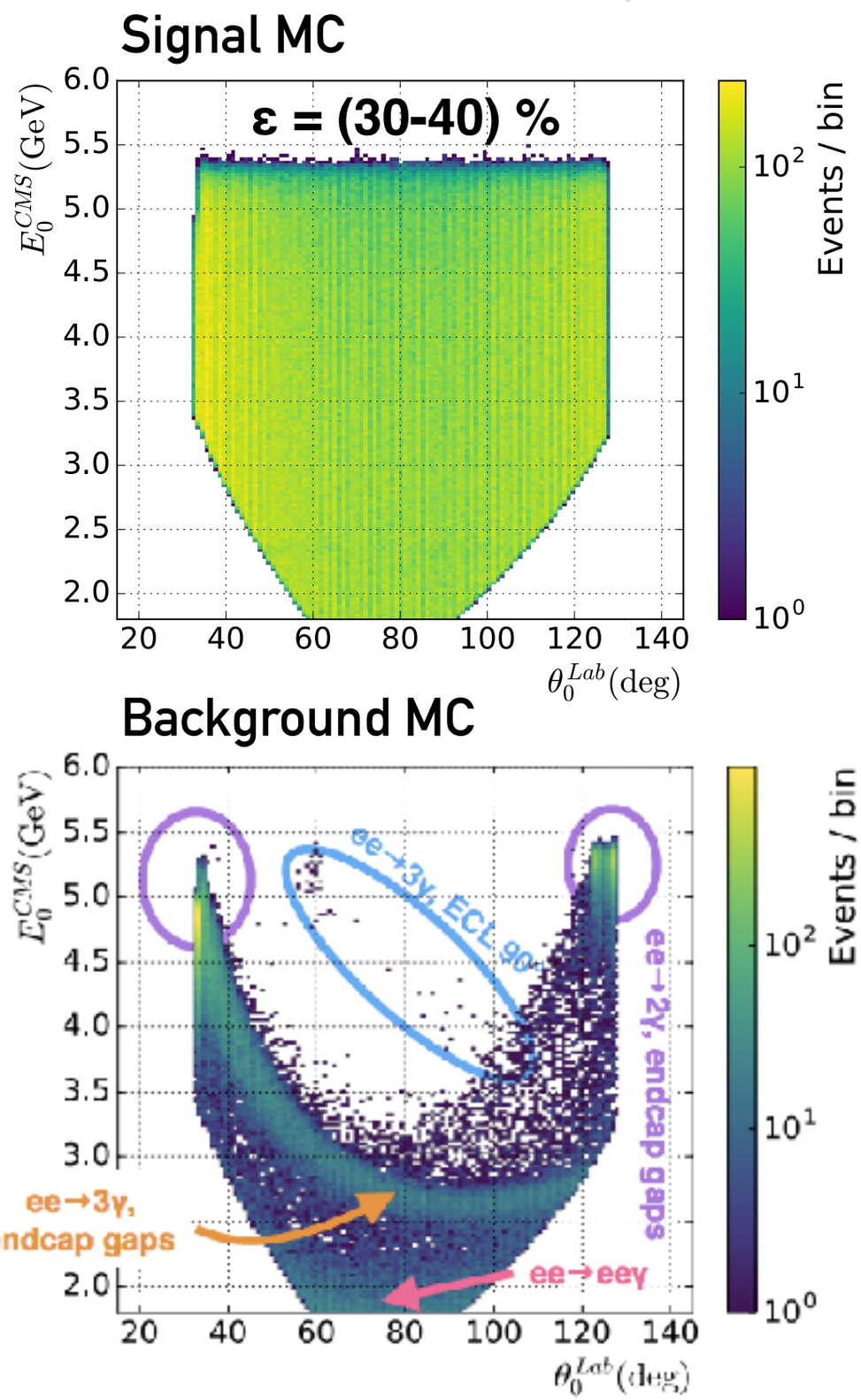
Similarities between dark sector signatures and radiative bhabha-like events means that many dark sector signatures were thrown out by the trigger in previous experiments.

Dedicated Dark Sector Trigger

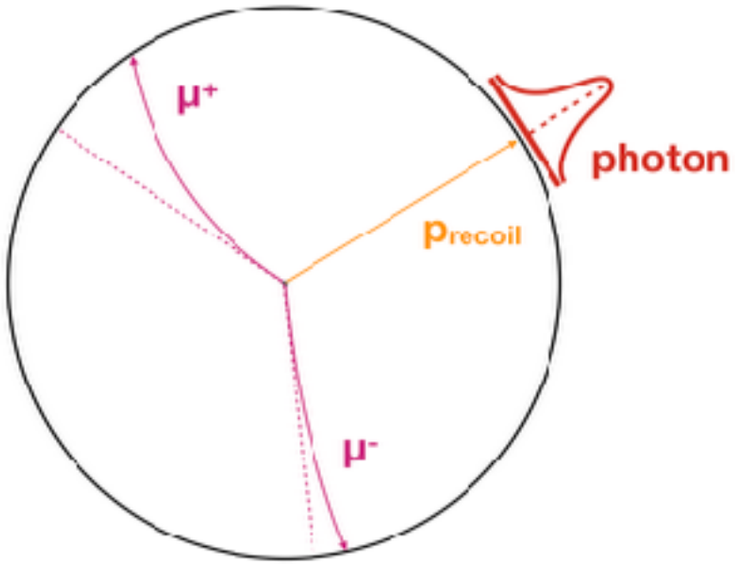
- Considering our *monophoton* signature, we recognize the need for a dedicated dark sector trigger
- Backgrounds: all final state particles except γ outside detector geometry
- Specifically, we can trigger on events with a single high-energy photon in the barrel region of the ECL



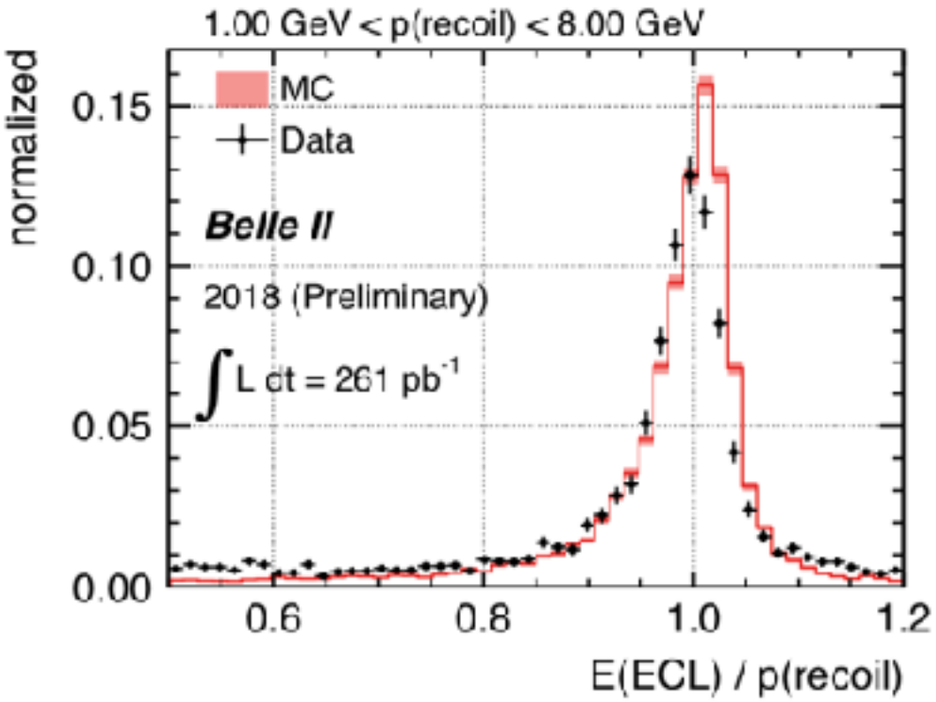




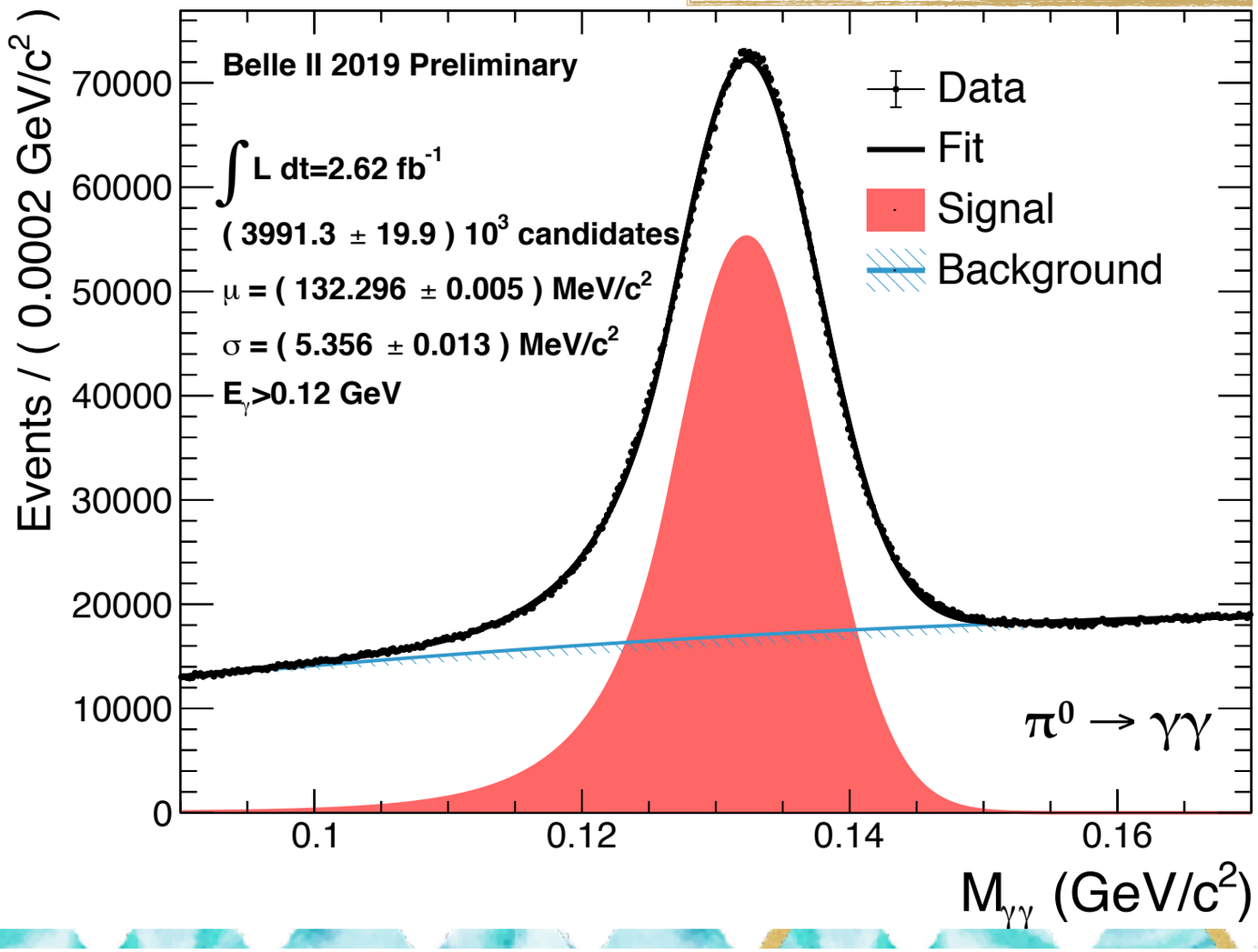
Photon Reconstruction and Resolution



- Proper photon reconstruction is crucial in DS searches.
- Photon energy resolution directly impacts the sensitivity to many DS modes.

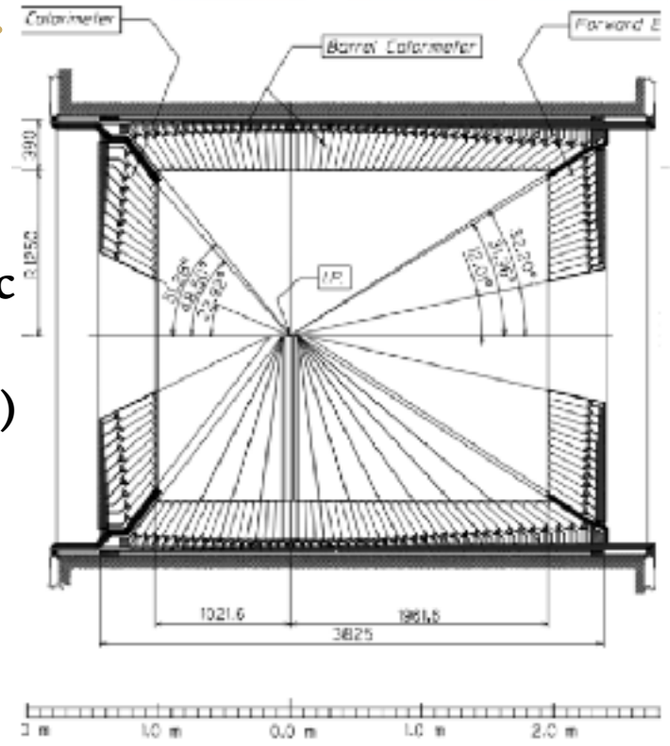


Resolution ~5 MeV/c^2

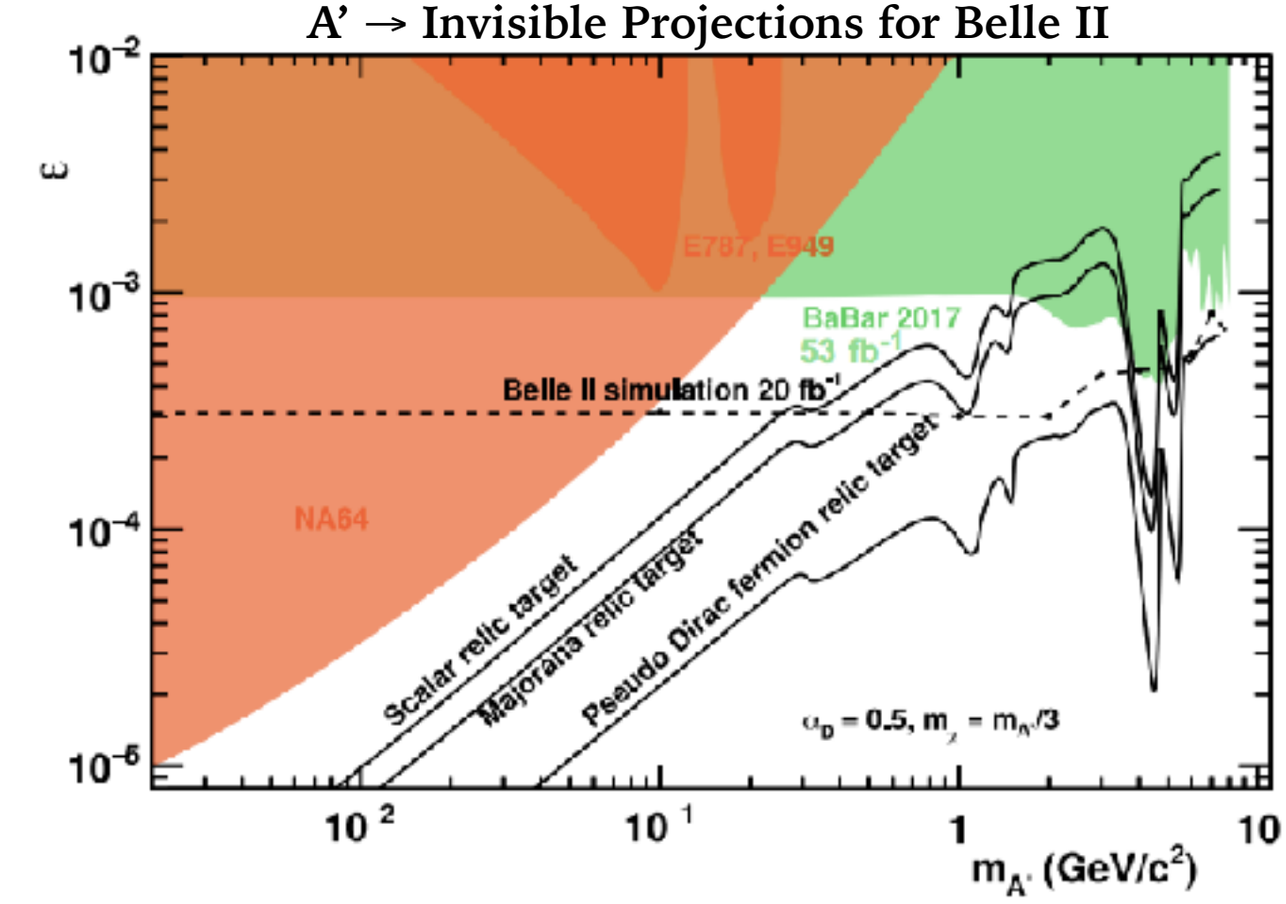


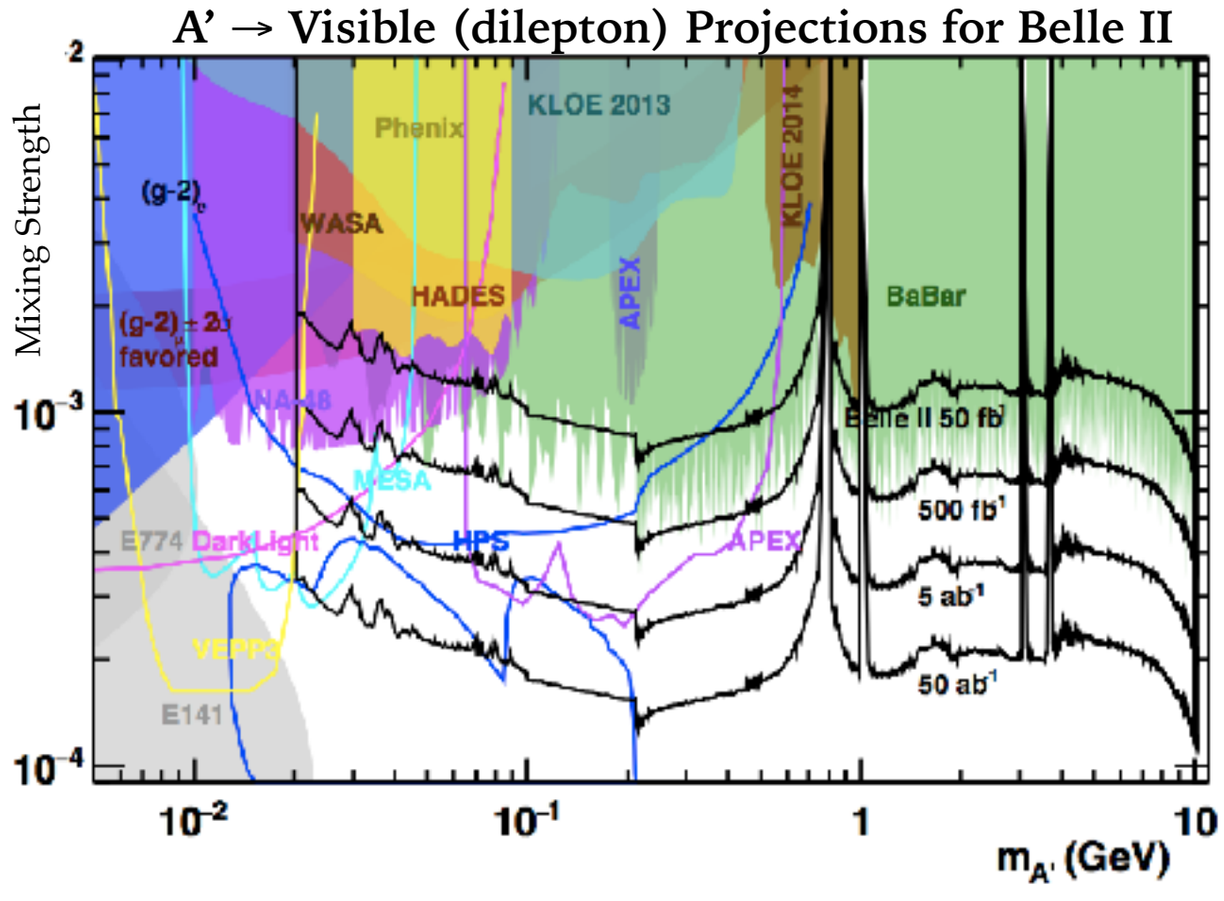
Dark A′ Projections for Belle II

- Belle II is competitive in these searches:
  - offset *pointing angle of Calorimeter crystals* (avoid introduction of gaps between crystals)
  - Smaller boost and larger Calorimeter — larger acceptance
- This results in an increase in efficiency for photon detection, as well as lepton ID in the Calorimeter



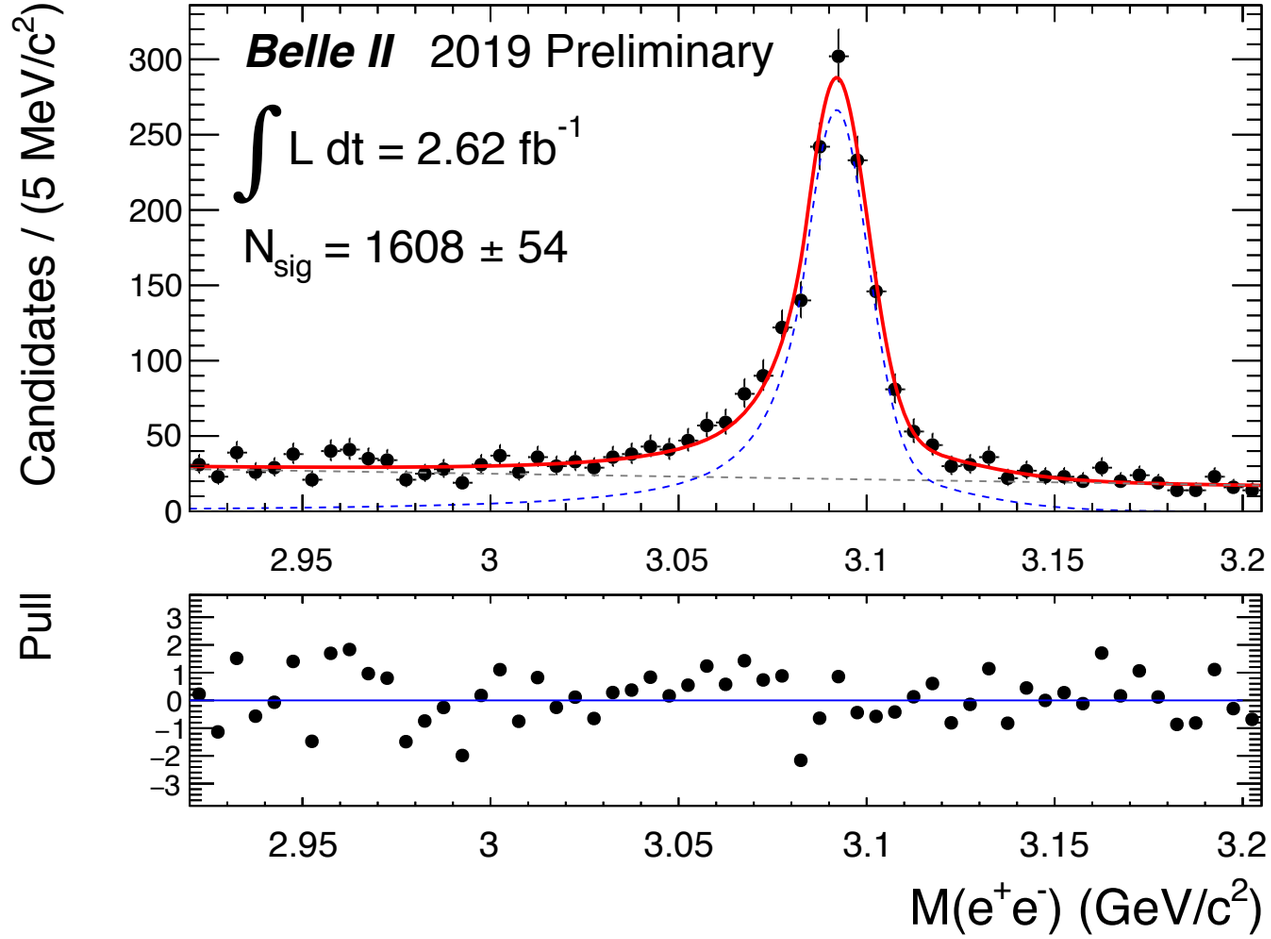
Electromagnetic Calorimeter Geometry (ECL)

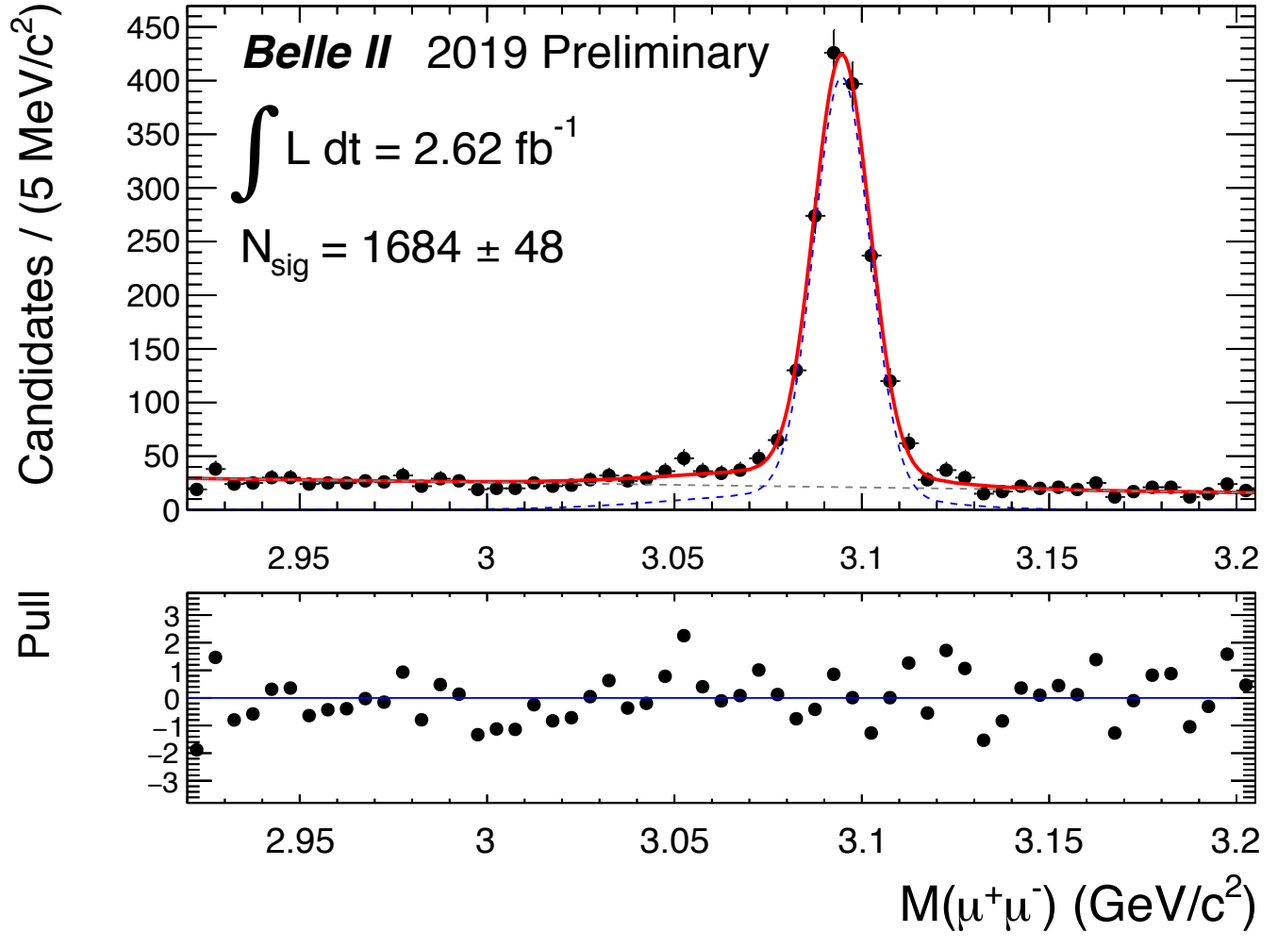




Lepton Reconstruction in Phase 3

- Signals for $B \to J/\psi X$ in ~1/2 of Phase 3 data.
- Radiative tail present in dielectron sample — analysis included Bremsstrahlung recovery.
- Successful reconstruction indicates Belle II has equally strong capabilities for electrons and muons.
- Fine resolution for dilepton events — critical for searches like $A' \to$ dilepton, as well as other DS searches.





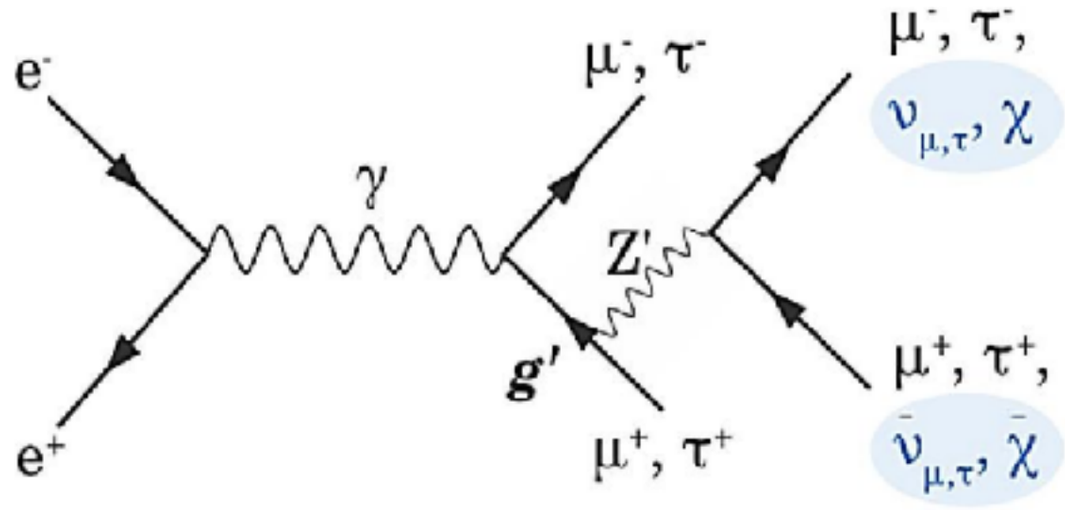
DARK Z′→INVISIBLE (L_μ-L_τ Model)

- Vector portal, Z′, coupling to μ and τ

$$\mathcal{L} \supset q_\chi g' \bar{\chi} \gamma_\alpha \chi Z'^\alpha$$

DM charge under $U(1)_{\mu\text{-}\tau}$ (set to 1)

- Search for $e^+e^- \rightarrow \mu^+\mu^-$+inv, where Z′ decays to sterile neutrinos or DM



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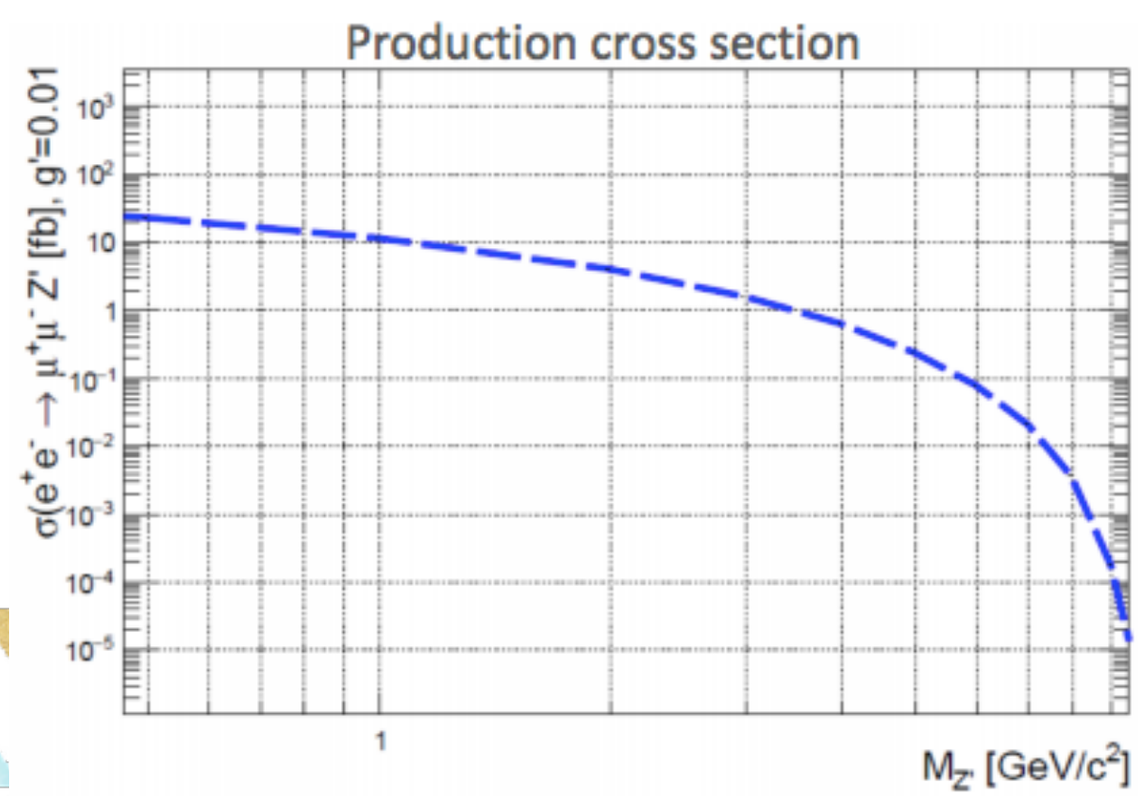
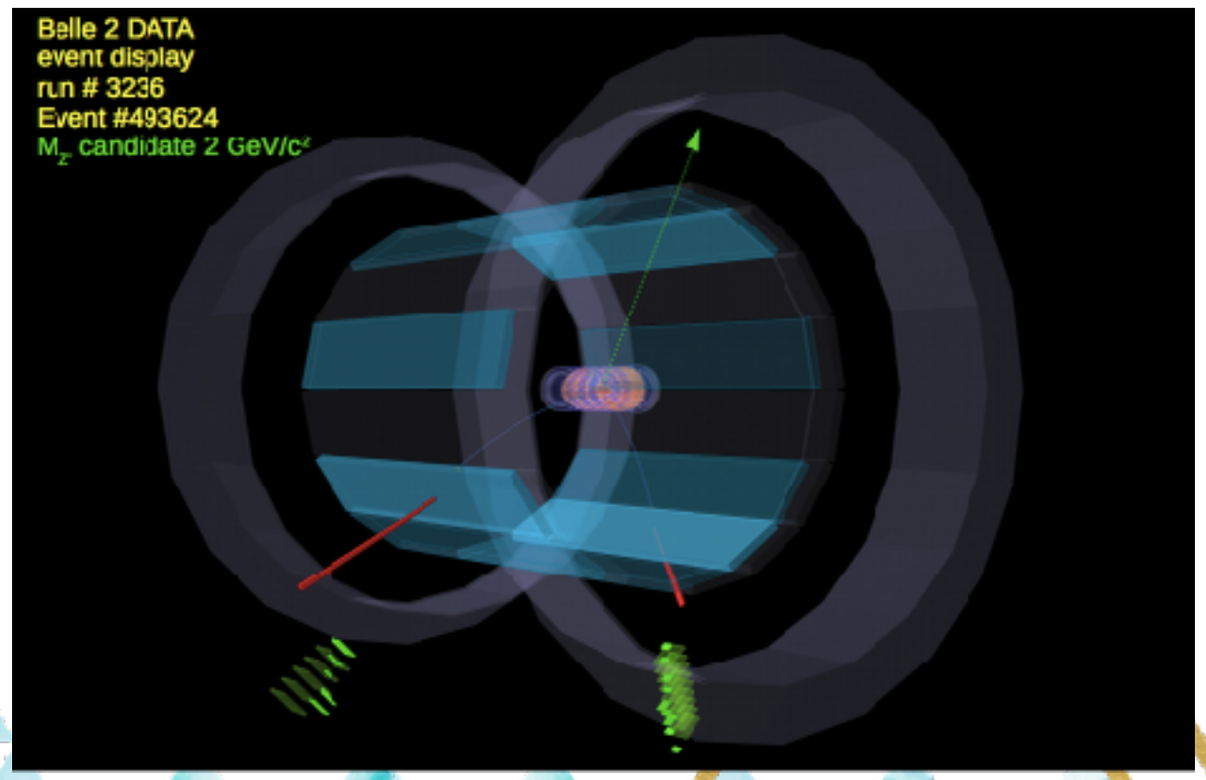


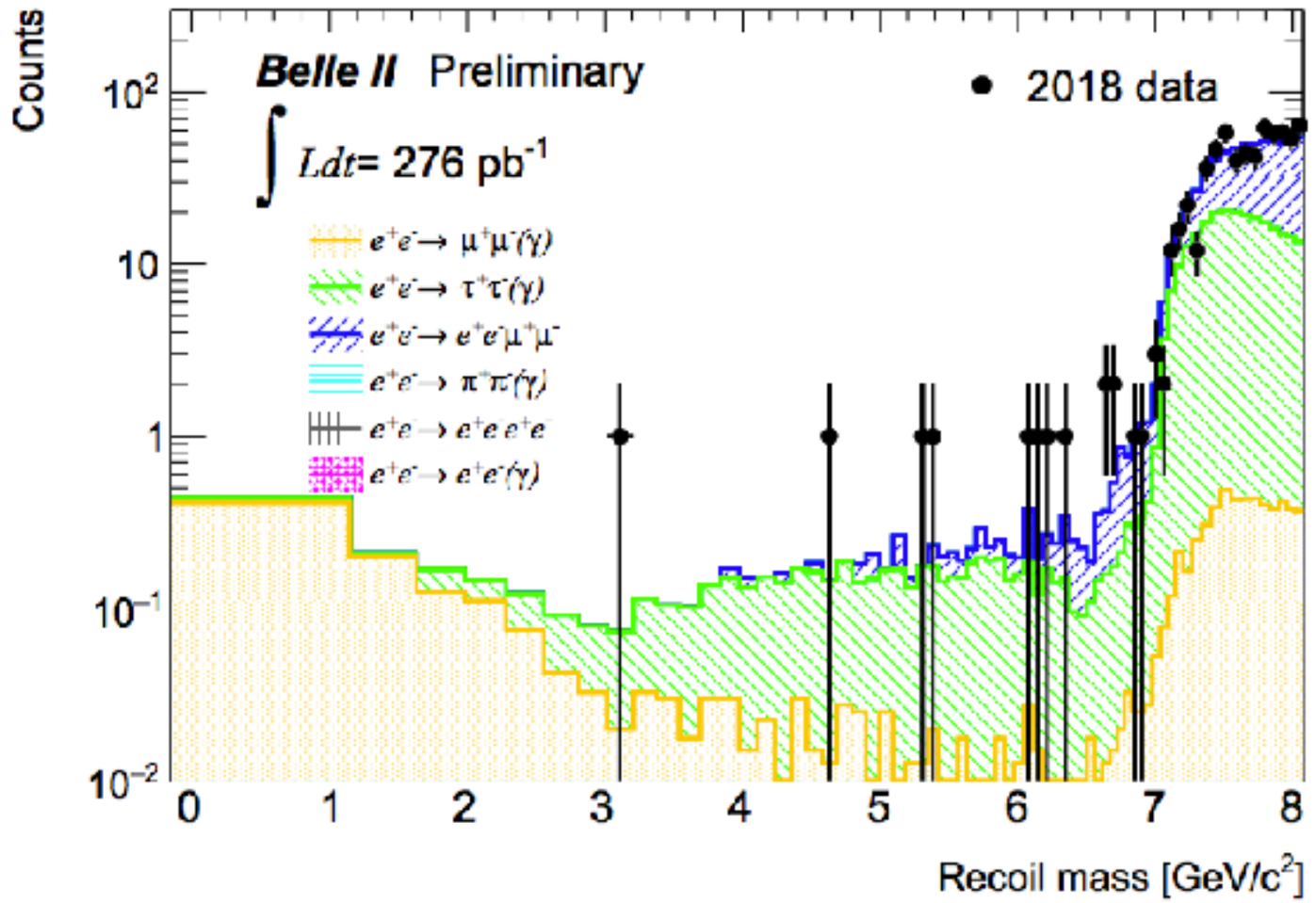


DARK Z′→INVISIBLE (L_μ-L_τ Model)

- Signal Signature:
  - fit to the recoil mass:

    $$\vec{P}_{Z'} = \vec{P}_{beam} - \vec{P}_{\mu^+\mu^-}$$

  - nothing in *rest of event*
- Background Sources:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$ [$\tau \to \mu\nu\nu$]
  - $e^+e^- \to \mu^+\mu^- e^+e^-$
- tau suppression implemented



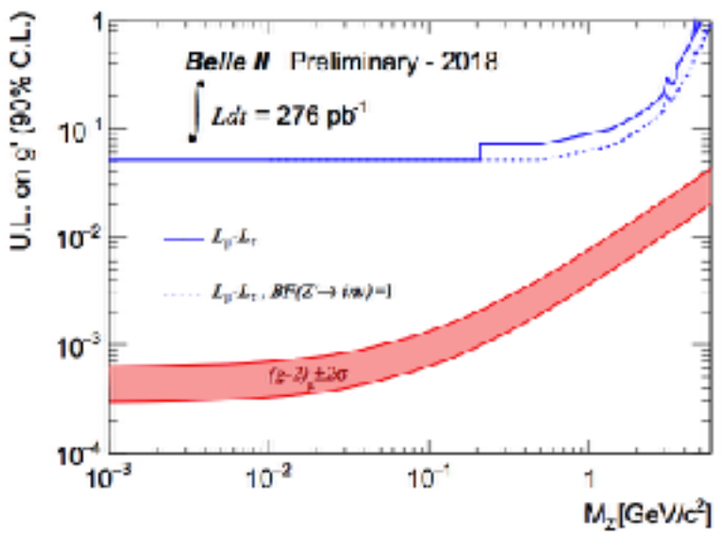
Sources of Systematic Uncertainty
Tracking — 4%
Trigger — 4%
Lepton ID — 4%
Luminosity — 1.5%
Analysis Selection (Background) — 22%
Muon Yields (Signal) — 12.5%
Muon Yields (Background) — 2%

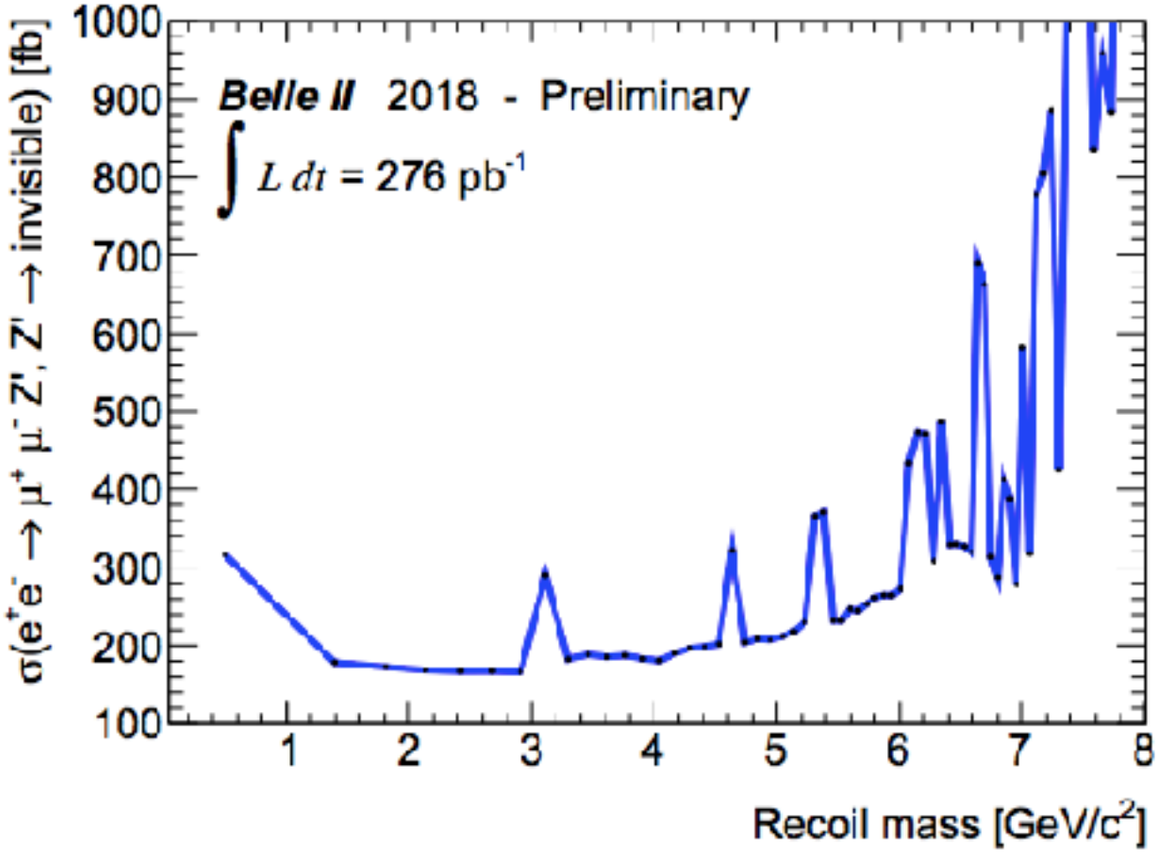
Systematic uncertainties resulting from poor Data/MC agreement and limited statistics

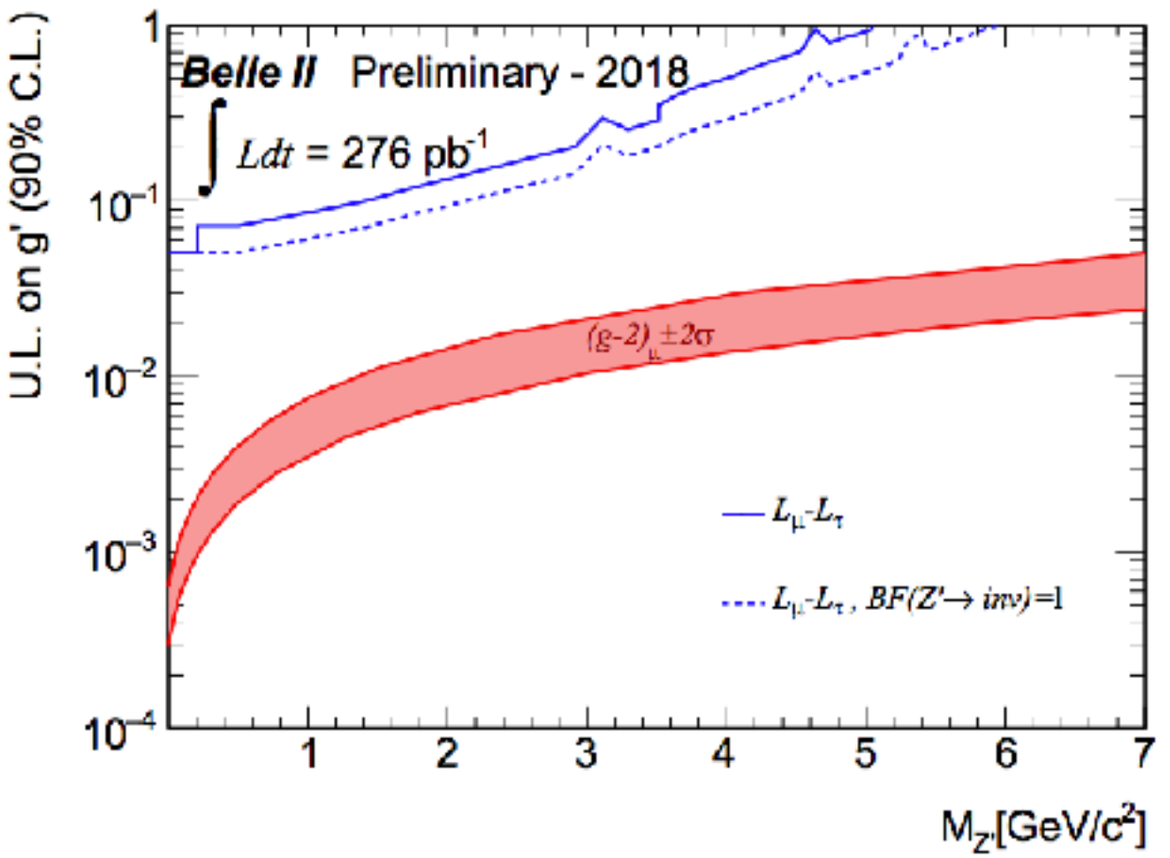
DARK Z′→INVISIBLE (L_μ-L_τ Model)

- First results for Z′ to invisible **(publishing very soon)**
- Only using 276 pb^{-1} due to trigger conditions for two-track events
- No sensitivity in parameter space $M_{Z'} > 8.0\ GeV/c^2$ — tapering of production cross-section in this regime
- Consistent with SM, constraints on g′ presented

Able to probe MeV scale DM candidates

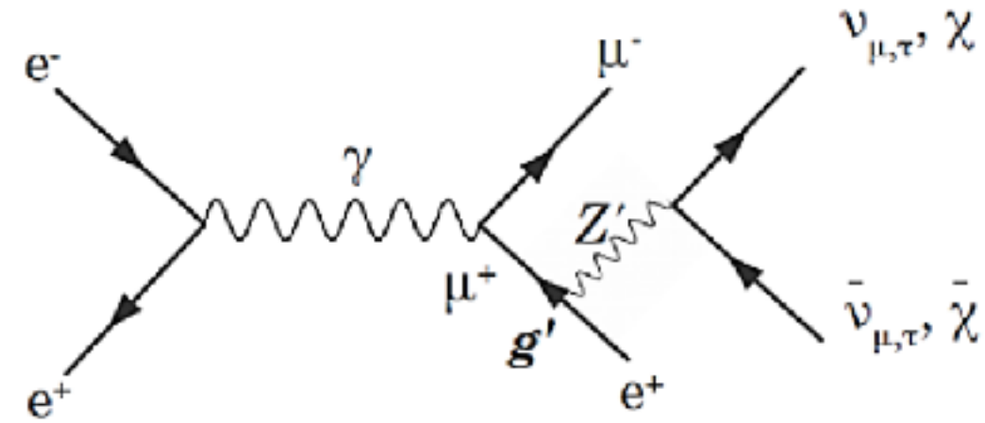




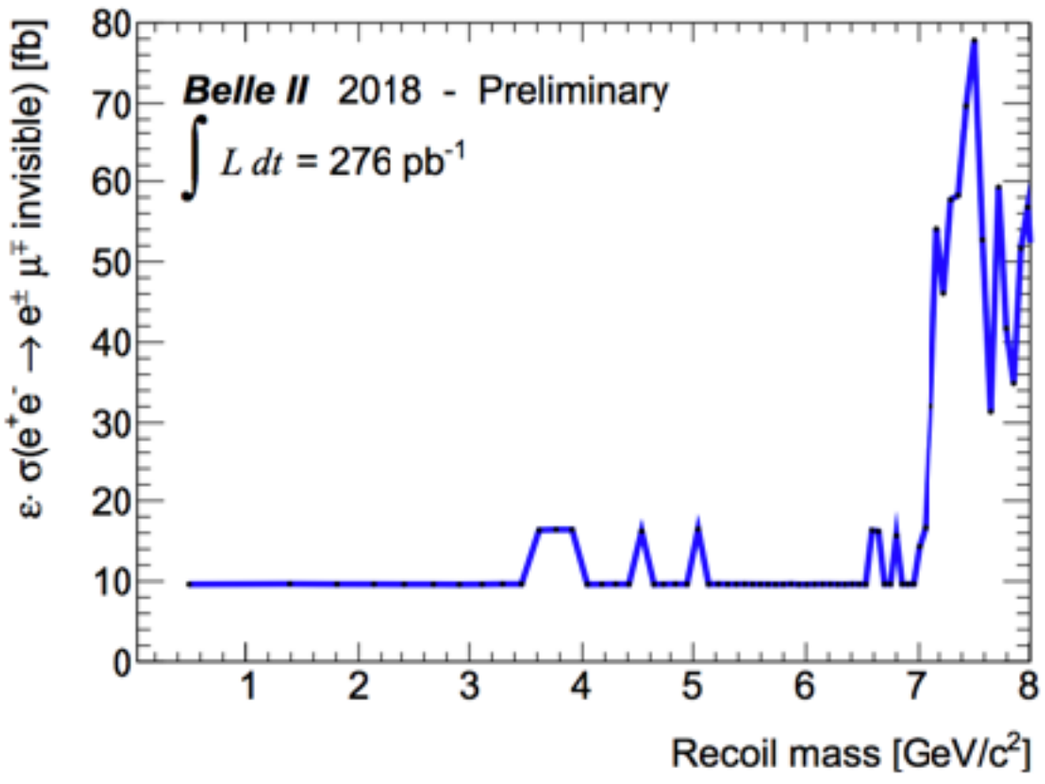


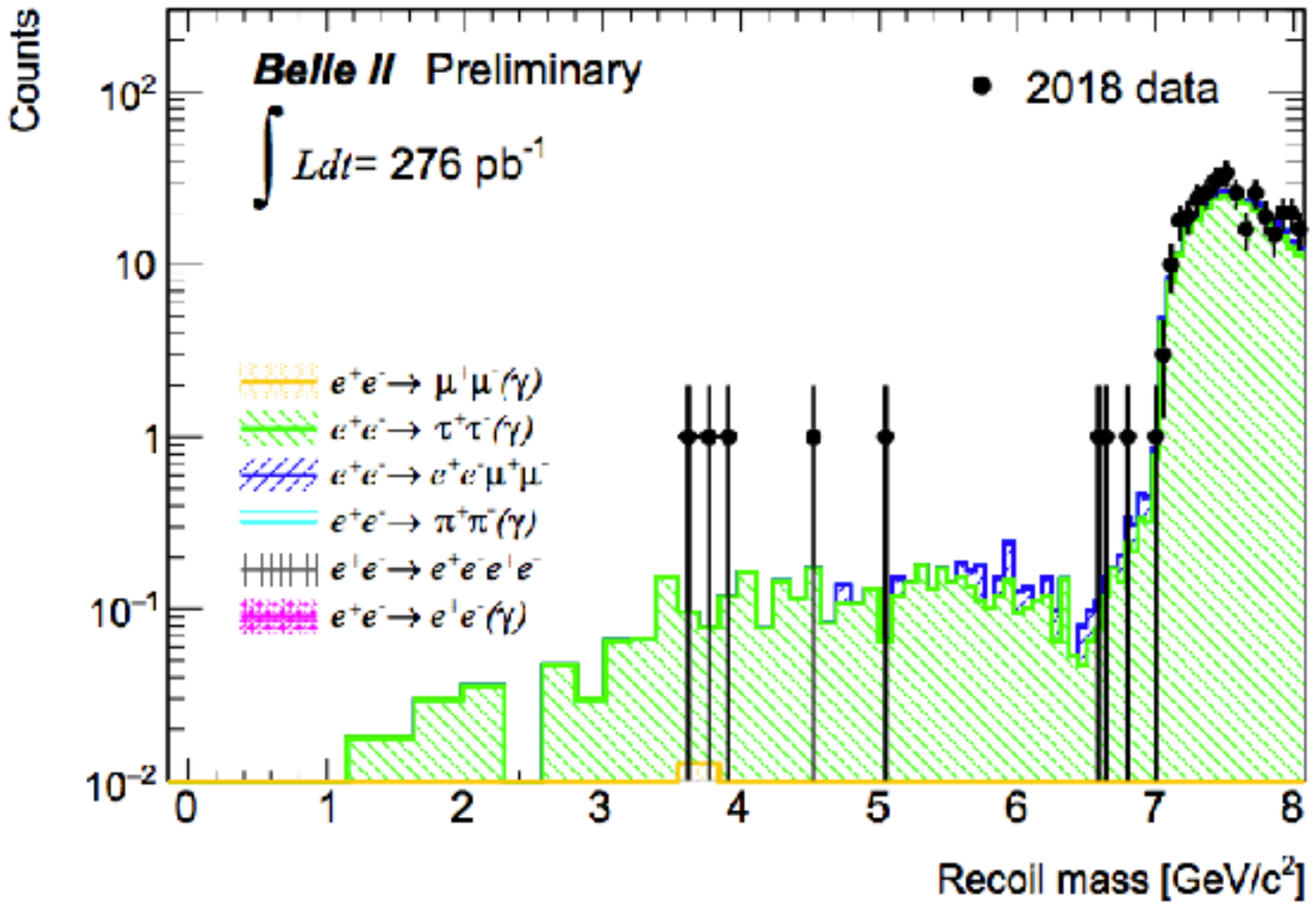
DARK Z′→INVISIBLE (LFV MODEL)

- Search for $e^+e^- \rightarrow e^+\mu^-$+inv, where Z′ decays to sterile neutrinos or DM
- Same analysis selection criteria as the non-LFV case
- Much cleaner — background from converted taus, $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ [$\tau \rightarrow \mu\nu\nu$]
- Efficiencies are model dependent, but no LFV model currently exists



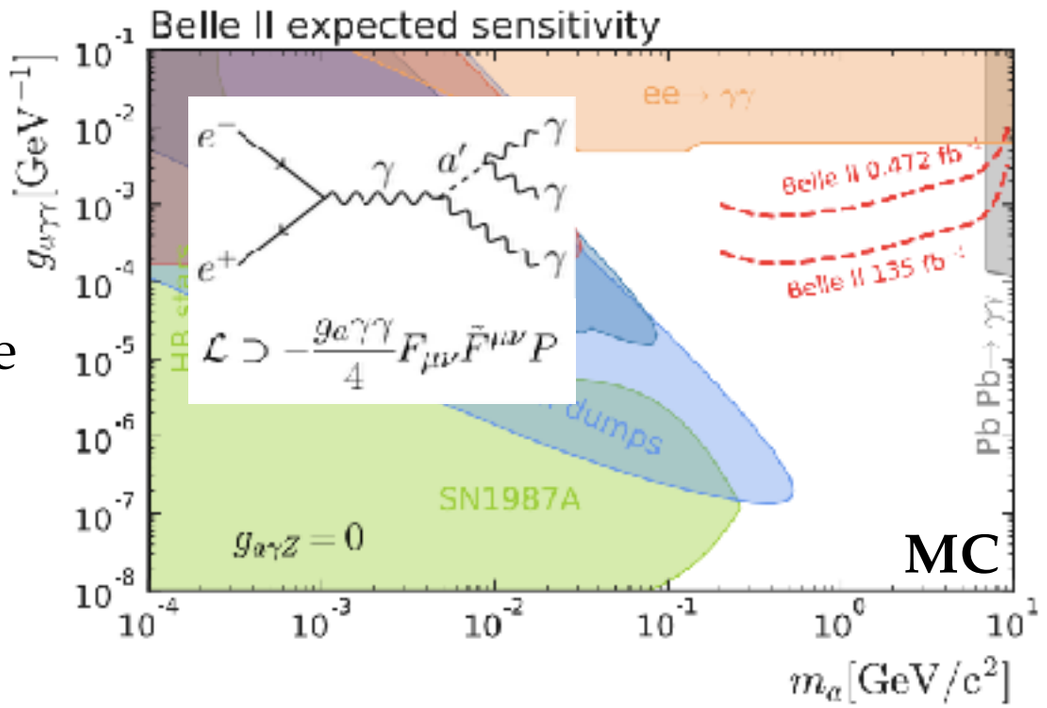
I. Galon et al. (2016) https://arxiv.org/abs/1610.08060
I. Galon, J. Zupan (2017) https://arxiv.org/abs/1701.08767

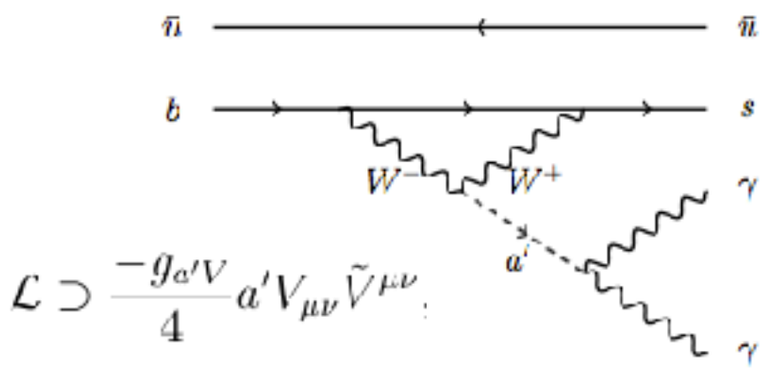




Other Dark Sector Searches

- **ALP searches**:
  - $e^+e^- \to \gamma + \text{ALP}$; $\text{ALP} \to \gamma\gamma$ (*tri-photon* search)
  - Performed in 0.472 fb^{-1} of data (2018)
  - Calorimeter performance is primary hurdle
  - Analysis currently under internal review





- **"Axiflavons"**:
  - $B^+ \to K^+ a'$ OR $B^0 \to D^0 a'$; $a' \to \gamma\gamma$, gg, invisible (ALPs in EWP decays)

Search could proceed via a *recoil mass-squared* fit:

$$\vec{P}_{a'} = \vec{P}_{e^+e^-} - \vec{P}_{B_{tag}} - \vec{P}_{K/D}$$

- **Others**: Dark Higgs, Long-lived particles, Magnetic Monopoles, etc…

Conclusion

- Belle II data taking has begun and the **first physics analyses** are underway — active DS program
- Looking forward to many **publications** in the near future
  - Standard Candle Luminosity Measurements
  - $Z' \rightarrow$invisible analysis (276 pb^{-1} of 2018 data)
  - $A' \rightarrow$invisible analysis (*monophoton* search)
  - Many more under internal review…
- **Performance Studies** are promising
  - Lepton ID
  - Trigger System
  - Tracking Quality
- Exciting DS prospects with our **increasing data sample**

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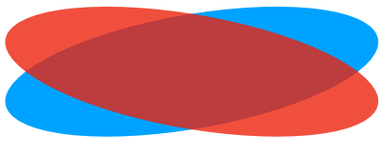
SuperKEKB — The Luminosity Frontier

- 40 times the peak luminosity (design luminosity of $L_{peak} \sim 8 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$) of KEKB
  - 2 times as much current
  - 20 times smaller vertical beam size

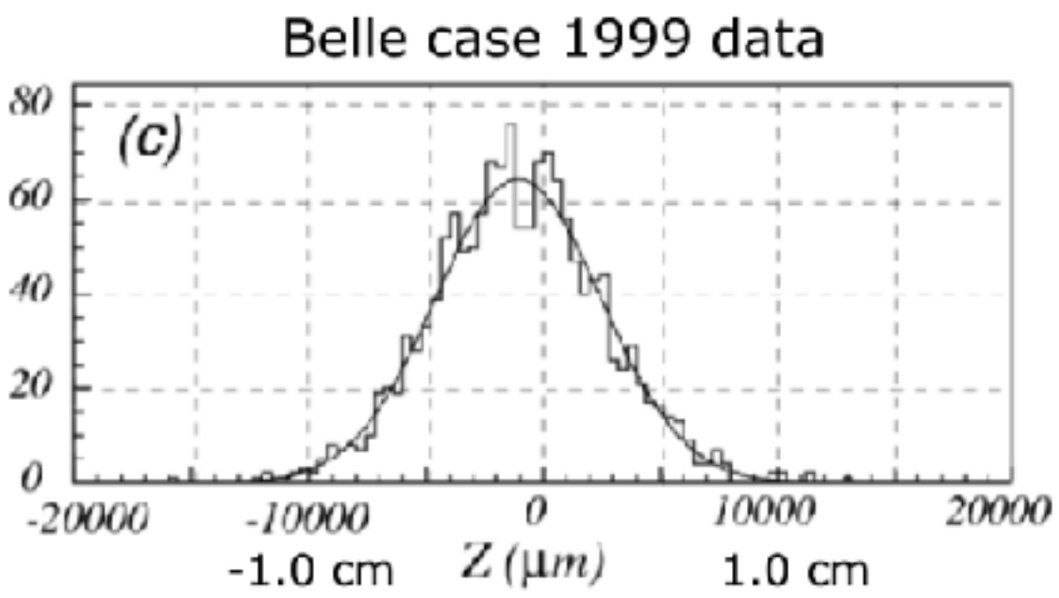
Beam Current

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

Vertical Beta Function

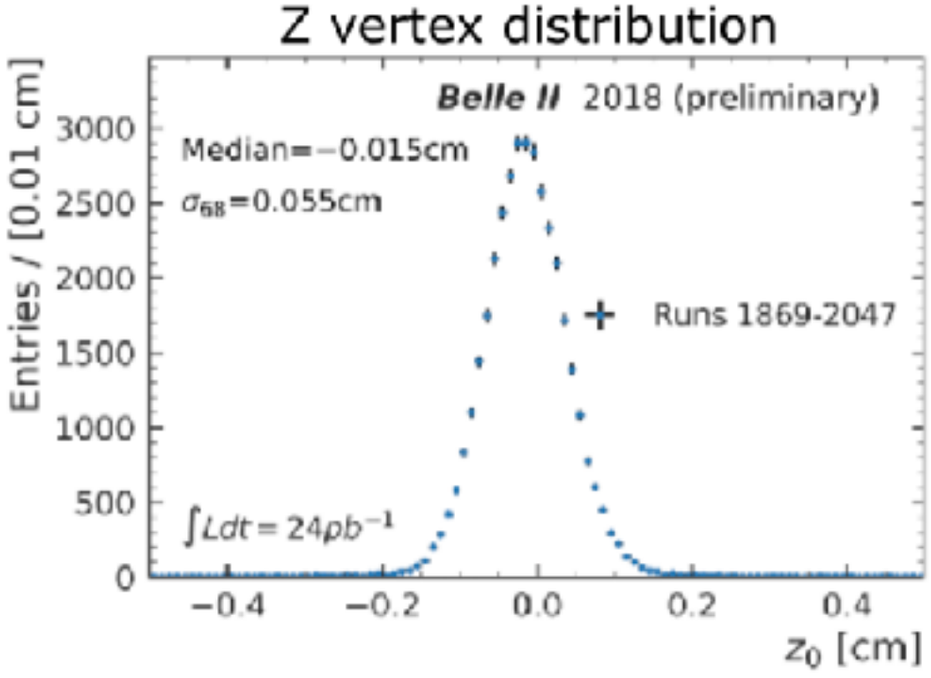


Ordinary collision (KEKB)



σ = 4.5 mm

Nano-Beam (SuperKEKB Phase2)



σ = 550 μm

SuperKEKB will have the world's highest luminosity

HADRON ID

- Separation of e and μ from charged hadrons (particularly pions) is critical for many of our dark sector signatures