Recent Dark-Sector Results at Belle II

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on behalf of the Belle II Collaboration

The Dark Side of the Universe (DSU 2022)
University of New South Wales, Sydney, Australia
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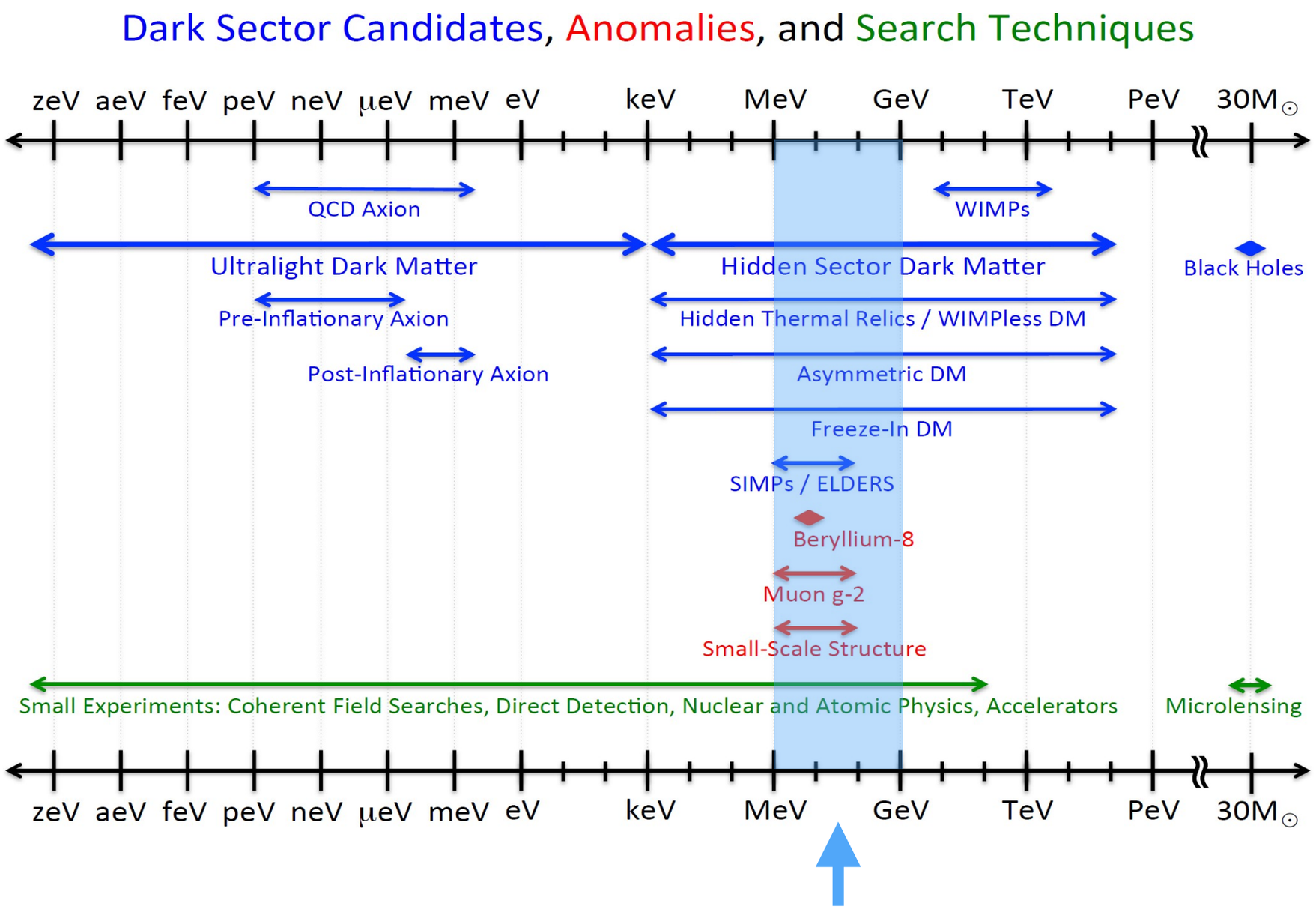
Outline

- Search for Dark Sector @ Belle II and SuperKEKB
- Recent Belle II Results
  - $Z' \rightarrow$ invisible ($L_\mu - L_\tau$ model)
  - $\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$
  - Dark Higgsstrahlung
- Summary

Search for Dark Matter

arxiv:1707.04591



Dark matter/mediators

Vector portal

Dark photon, Z', …

Pseudoscalar portal

Axions, **ALPs**, …

Scalar portal

Dark Higgs, **scalars**

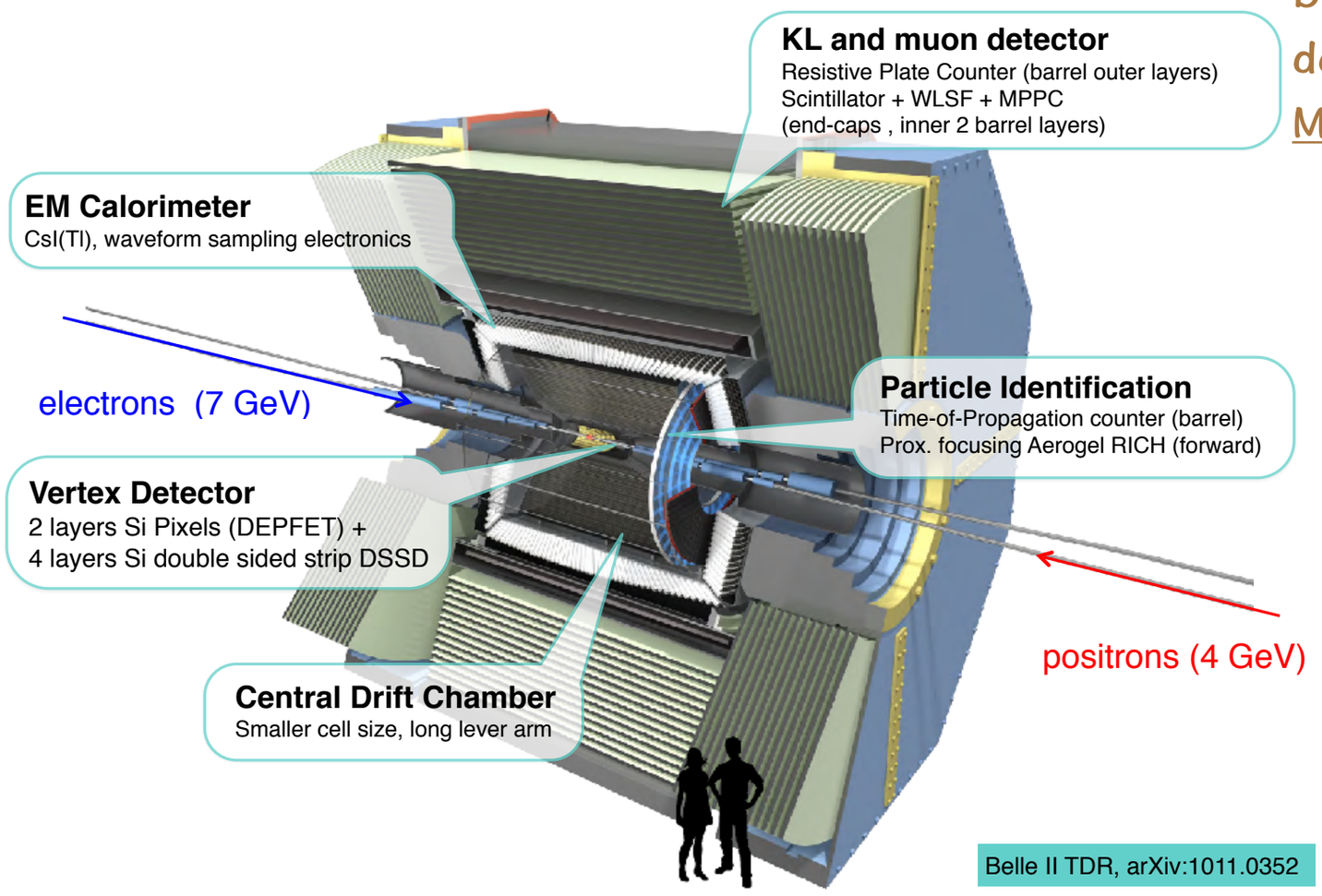
Neutrino portal

Sterile neutrino

Belle II direct searches

Search for Dark Sector @ Belle II

Details about the Belle II detector can be found in Marco Milesi's talk



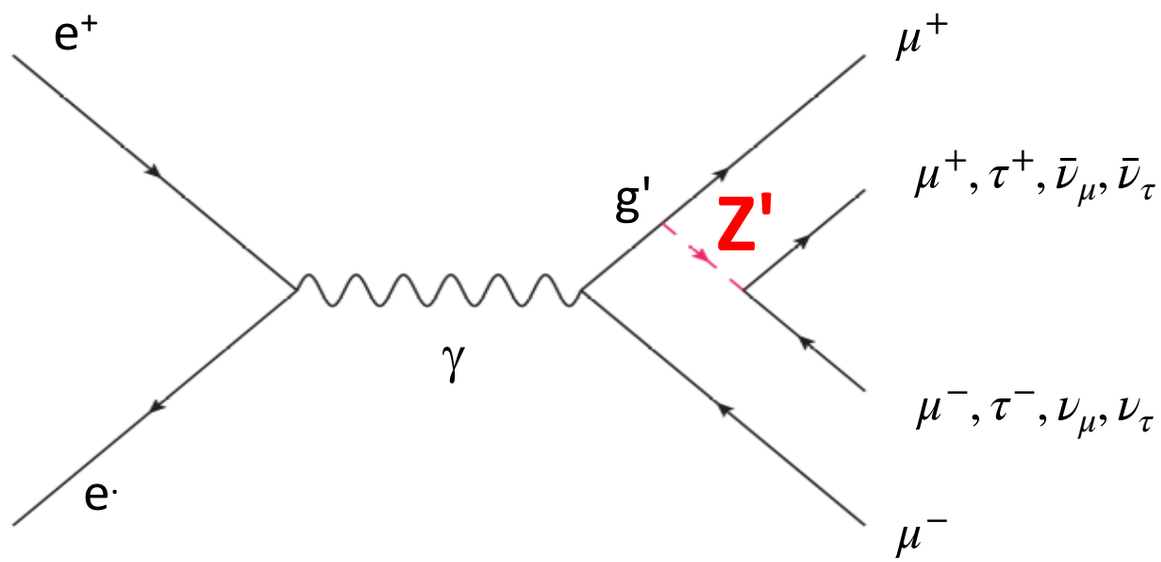
Belle II TDR, arXiv:1011.0352

- Key for dark sector:
  - Clean e^+e^- environment; known initial state
  - Dedicated hardware-based trigger for low multiplicity physics;
    - Combined information from CDC, ECL, KLM
  - High luminosity (in long run)

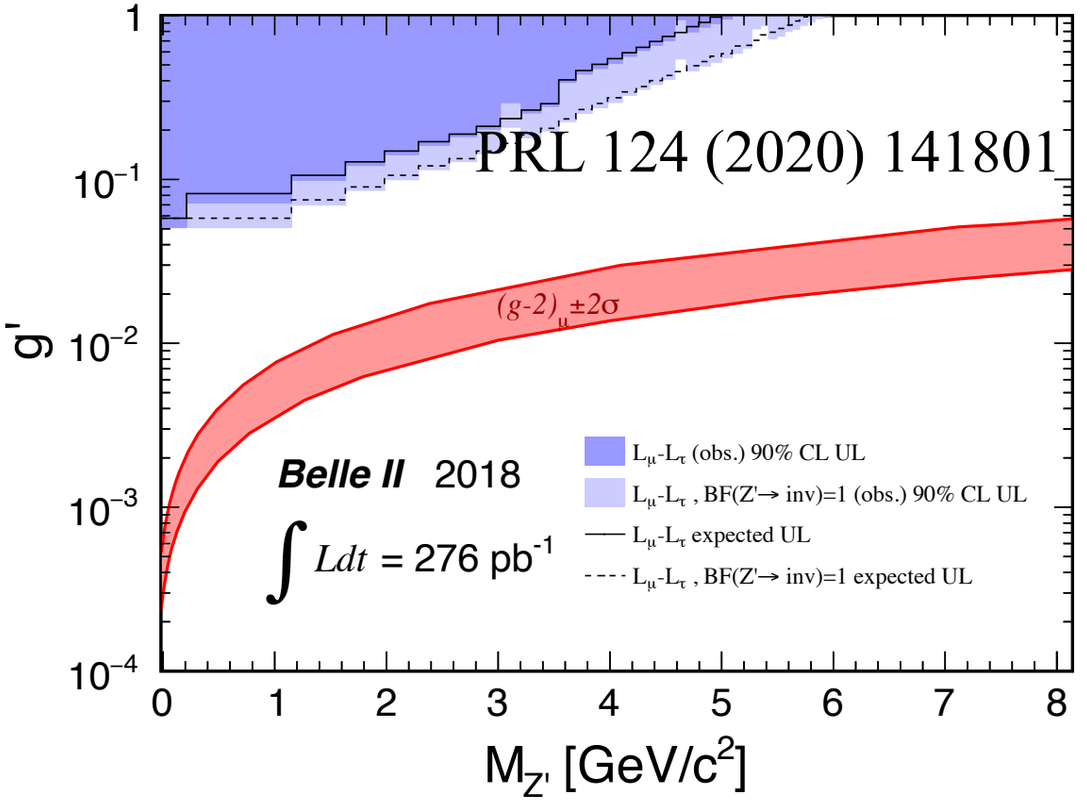
$L_\mu - L_\tau$ gauge boson Z'

- New Z' boson couples only to the 2nd or 3rd generation leptons
  - Could explain
    - $(g-2)_\mu$
    - B decay anomalies $R_{D^{(*)}}$, $R_{K^{(*)}}$).

  He et al. PRD 43 R22(R) (1991)
  Shuve et al. PRD 89 113004 (2014)
  Altmannshofer et al. JHEP12(2016)106



- Previous constraints for $Z' \to \mu^+\mu^-$
  by BaBar(2016), Belle(2022), CMS(2019)
- $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible
  - Assumed decay to neutrinos or dark matter (χ)
    - If $m_{Z'} < 2m_\mu$, Z' decays to neutrinos
    - $\mathcal{B}(Z' \to \chi\chi)$ would be dominant even above $2m_\mu$
  - Most recent result by Belle II
    PRL 124 (2020) 141801

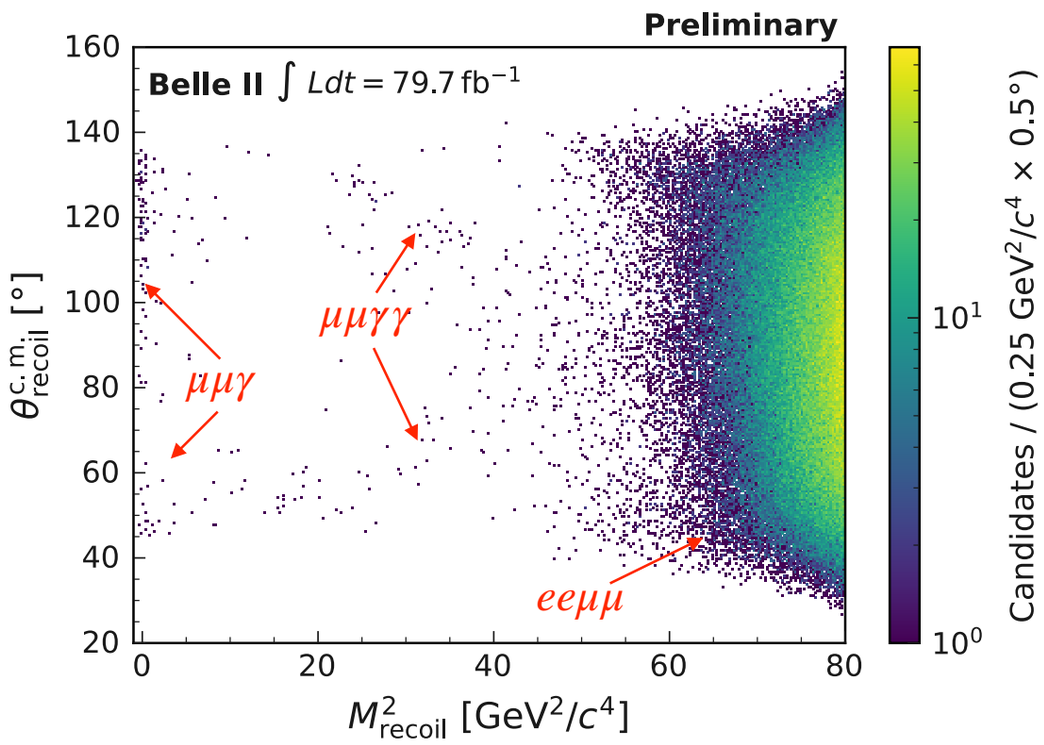


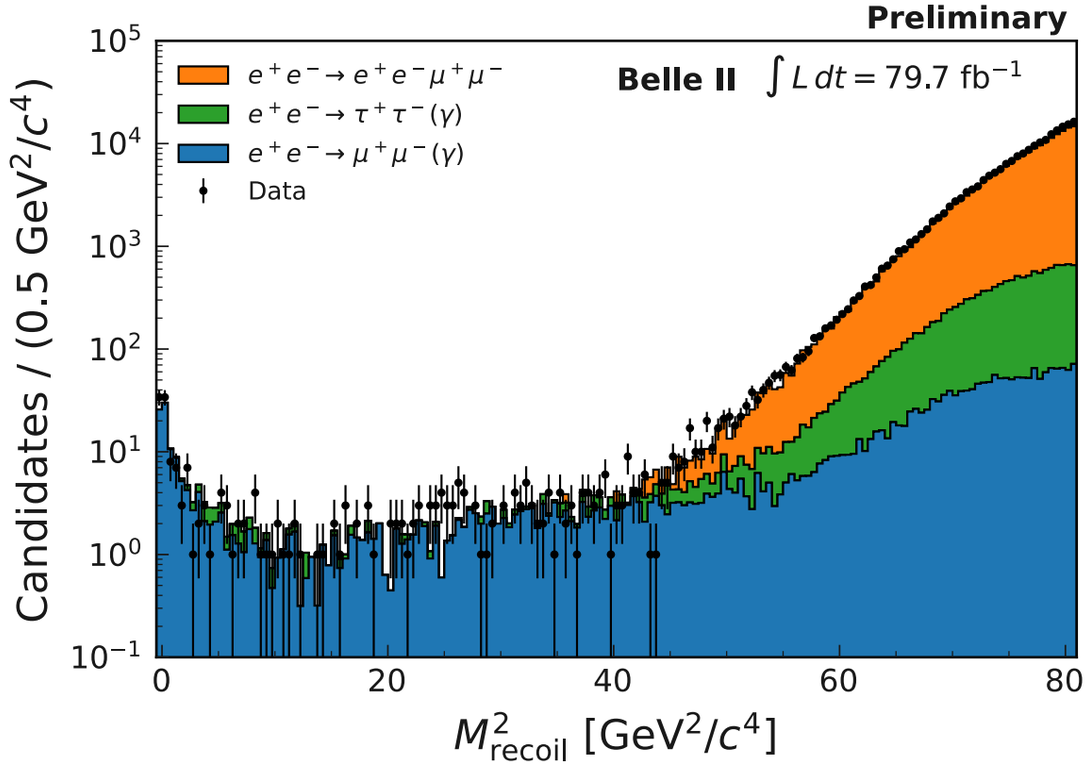
$Z' \rightarrow$ invisible

Preliminary

- Analysis with 2019-2020 Belle II data (79.7 fb^{-1})
- Signal:
  $\mu^+\mu^-$ + missing Energy
  - $M^2_{\text{recoil}}(\mu\mu) = s + M(\mu\mu)^2 - 2\sqrt{s}(E^{CMS}_{\mu^+} + E^{CMS}_{\mu^-})$
- Backgrounds:
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
  - $e^+e^- \rightarrow \mu^+\mu^-e^+e^-$
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$, both $\tau \rightarrow \mu\nu\bar{\nu}$

  → Outside of acceptance
- Z' is final state radiation. Train neural net to identify characteristic kinematics
- Look for peaks in M^2_{recoil} vs $\theta^{\text{CMS}}_{\text{recoil}}$ (polar angle of recoil momentum)



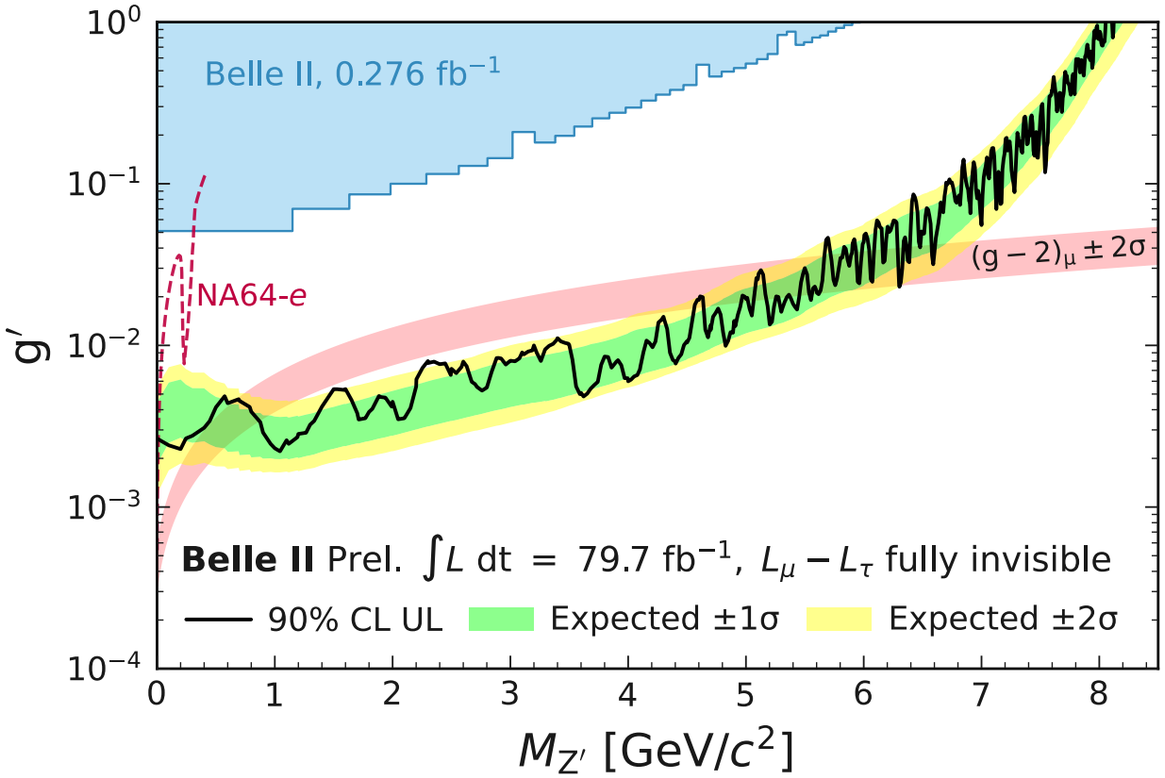


$Z' \rightarrow$ invisible

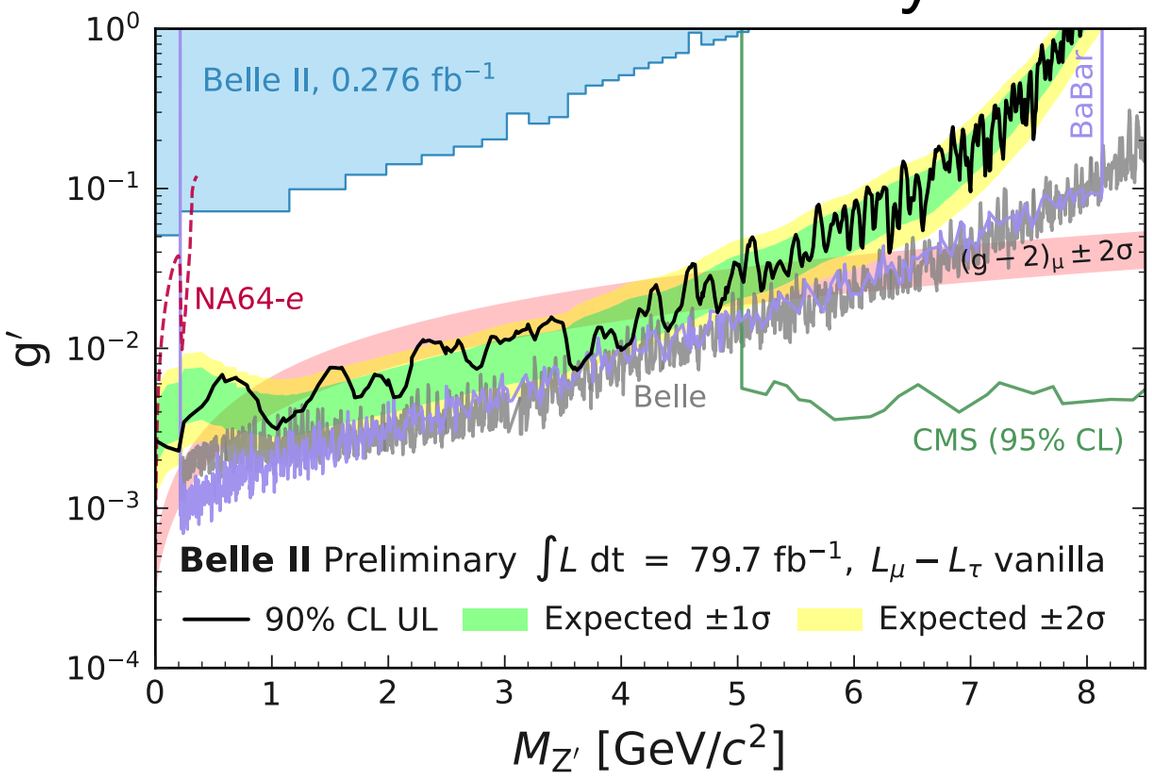
- Fit performed in different mass windows with flat backgrounds. No significant signal excess found.
- Set 90% CL exclusion limits on cross section and coupling (g')
  1. For $\mathcal{B}(Z' \rightarrow \text{invisible}) = 1$
  2. If Z' only decays to SM particles

Preliminary

$Z' \rightarrow$ invisible



$Z' \rightarrow$ SM only



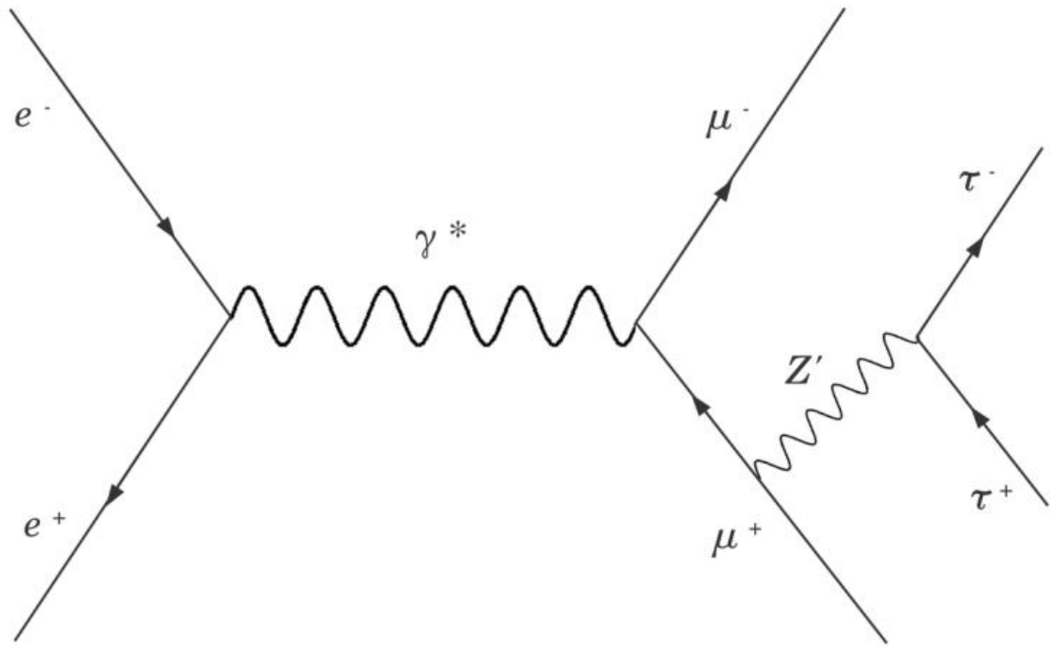
Excluded $(g-2)_\mu$ parameter space between 0.8 to 5.0 GeV/c^2

Limits improved below $2m_\mu$ still consistent with $(g-2)_\mu$

$\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$

- Extend Z' search to permit $\tau^+\tau^-$ pair in final state.
- Probe three different models in one go
  - Z' (vector portal)
    JHEP 12 (2016) 106
  - Leptophilic scalar ***S*** (scalar portal)
    PRD 95 (2017) 075003

$$\mathscr{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} S \ell$$



  - Search for $S \to e^+e^-$ or $\mu^+\mu^-$ in association with a τ pair has been done by BaBar(2020).
- Axion-like particle (***ALP***) (pseudoscalar portal) arXiv:2110.10698
  - Coupling to leptons but no coupling to γ

$$\Gamma(\mathrm{ALP} \to \ell^+\ell^-) = \frac{m_{\mathrm{ALP}} m_\ell^2}{8\pi\Lambda^2} |c_{\ell\ell}^{eff}|^2 \sqrt{1 - \frac{4m_\ell^2}{m_{\mathrm{ALP}}^2}}$$

$Z'/S/$**ALP** $\rightarrow \tau^+\tau^-$

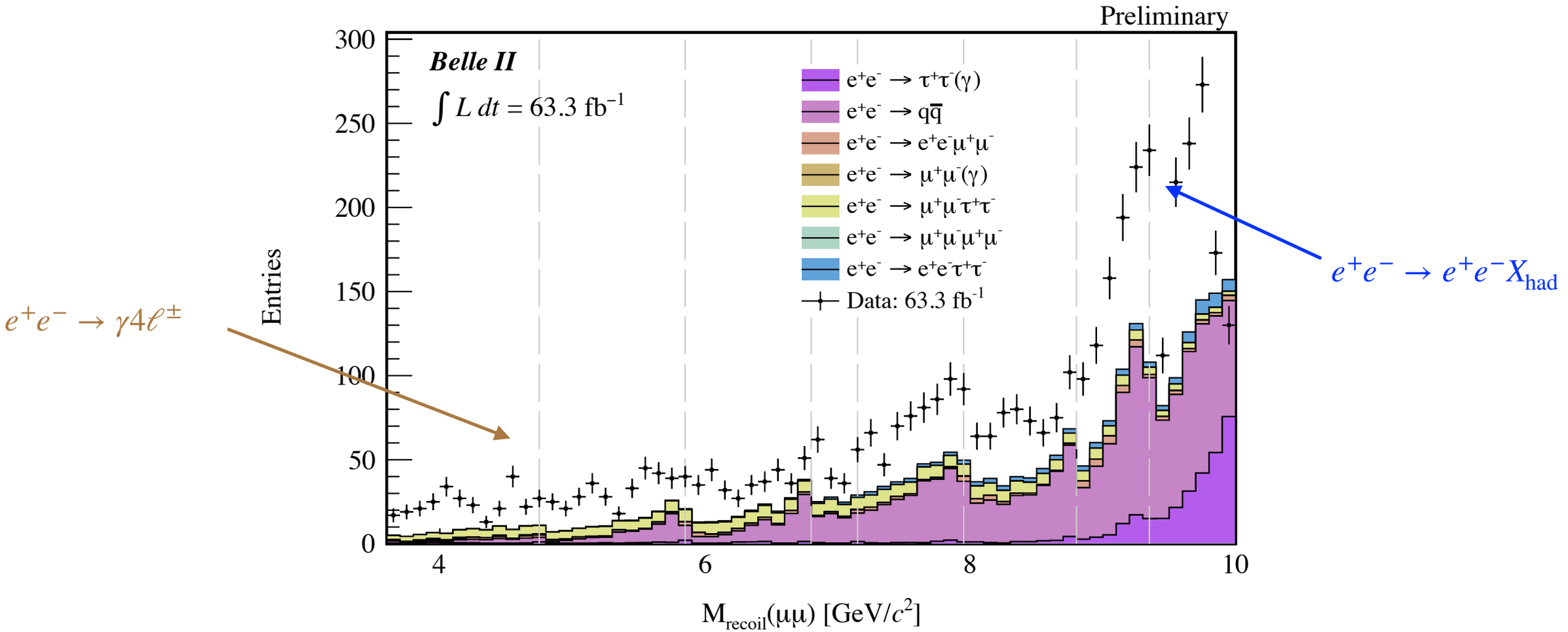
Preliminary

- Analysis with $63.3\ \mathrm{fb}^{-1}$
- Signature:
  - 1-prong τ decays
    - 4-tracks: $\mu^+\mu^- + 2(e, \mu, \pi)$
  - $M(\tau\tau) = M_{\mathrm{recoil}}(\mu\mu)$
  - $M(\text{4 tracks}) < 9.5\ \text{GeV}/c^2$
- Backgrounds:
  - $e^+e^- \rightarrow \tau\tau(\gamma)$
  - $e^+e^- \rightarrow q\bar{q}$
  - $e^+e^- \rightarrow 4\ell$
  - **Un-modelled**
    - $e^+e^- \rightarrow e^+e^- X_{\mathrm{had}}$
    - $e^+e^- \rightarrow \mu^+\mu^-\pi^+\pi^-$
    - $e^+e^- \rightarrow \gamma 4\ell$ (Initial state radiation)
- 8 neural networks trained for different ranges in $M_{\mathrm{recoil}}(\mu\mu)$

$Z'/S/\mathbf{ALP} \to \tau^+\tau^-$

- Scan over $M_{\text{recoil}}(\mu\mu)$ above floating background
- No peaking structures in $M_{\text{recoil}}(\mu\mu)$

Preliminary

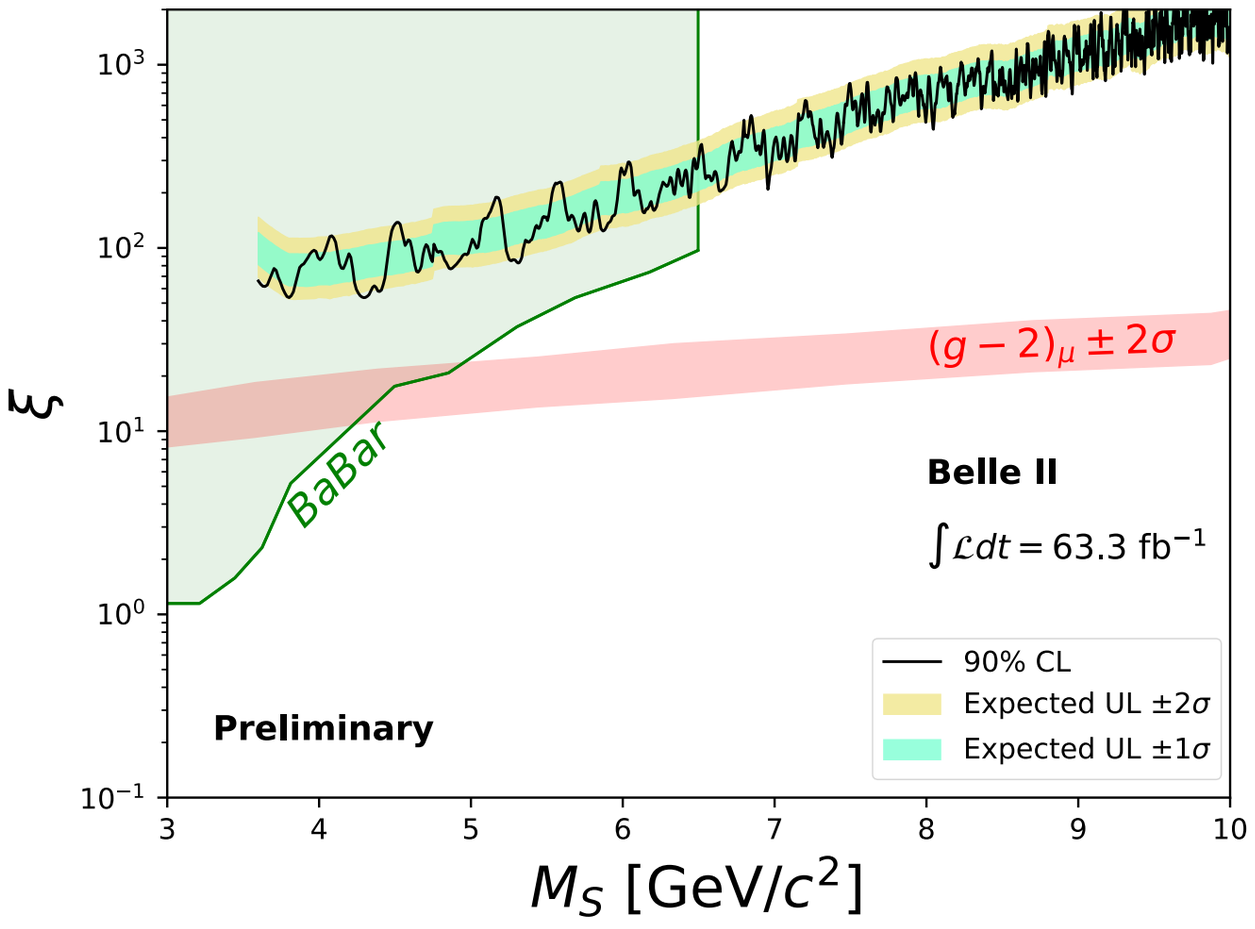


$Z'/S/\mathbf{ALP} \to \tau^+\tau^-$

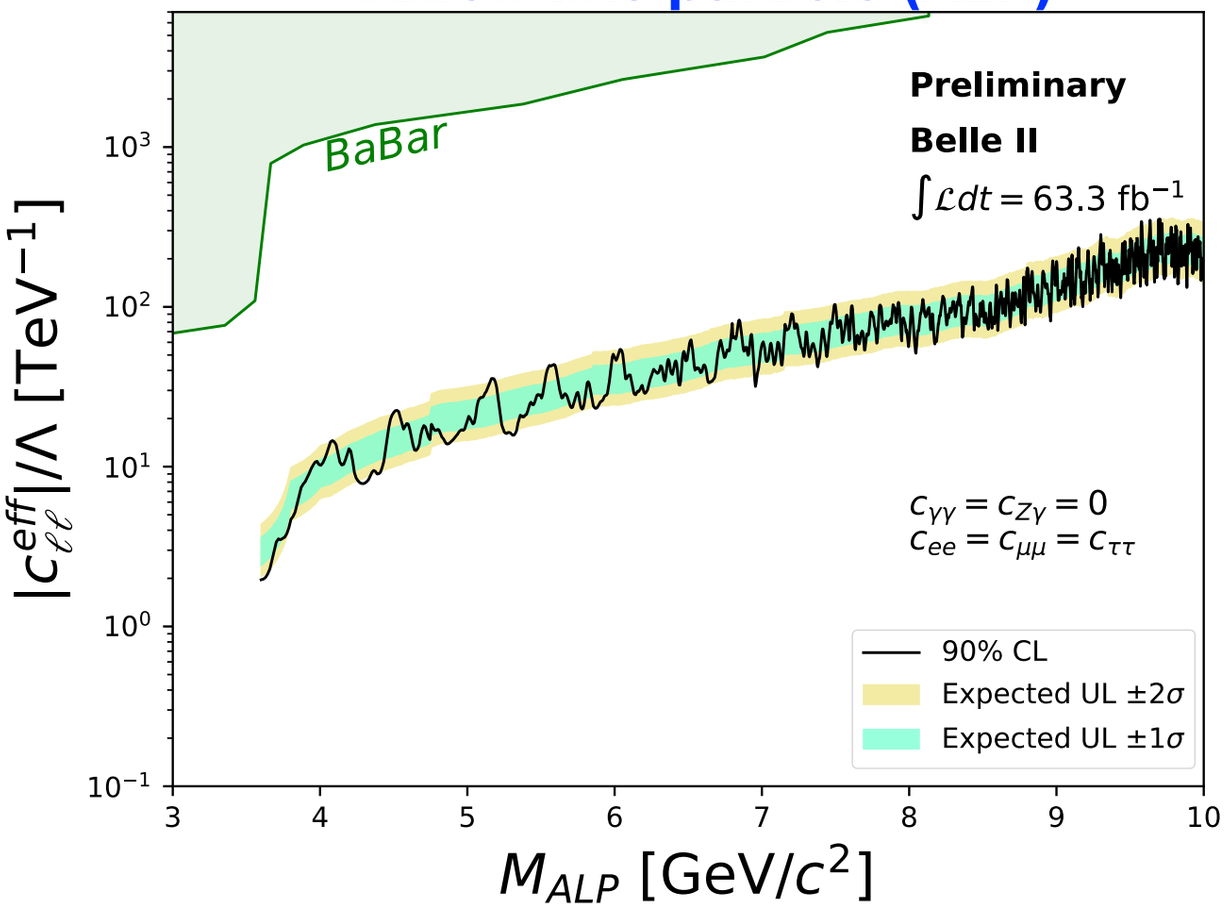
Belle II

Preliminary

Leptophilic scalar (S)



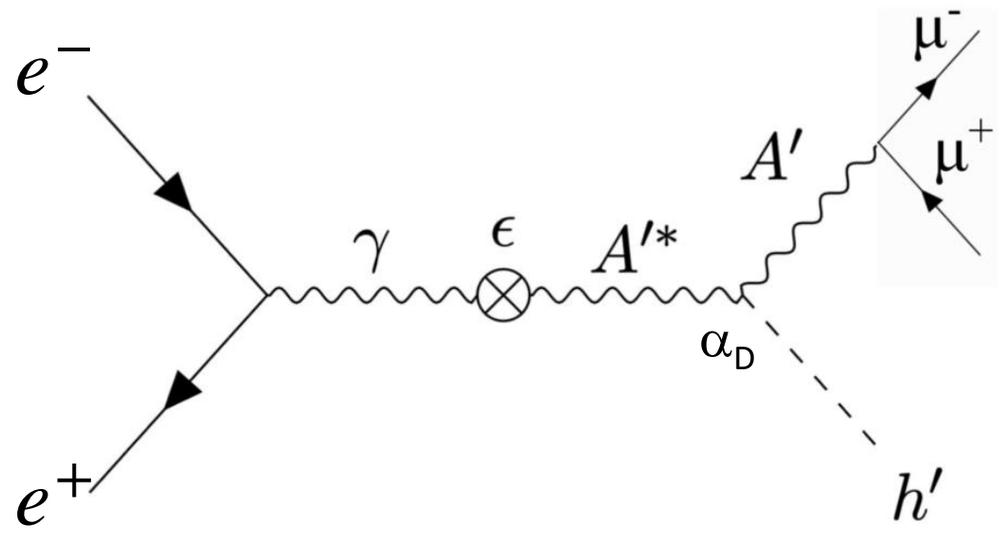
Axion-like particle (ALP)

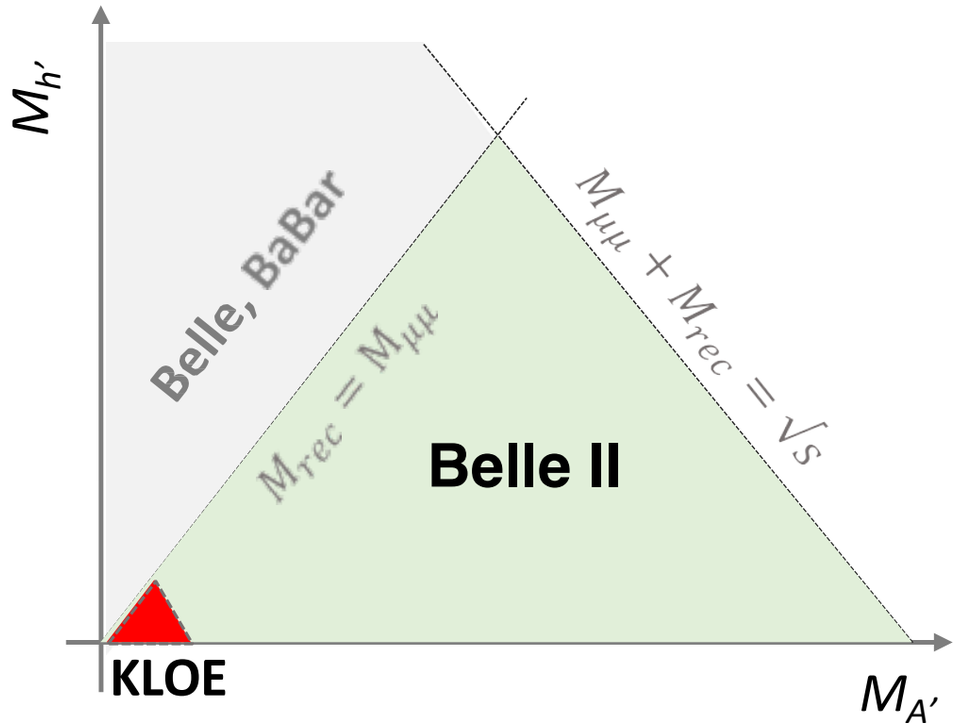


- First constraints on coupling strength for $M_S > 6.5$ GeV/c^2.
- First direct constraints from $\mathrm{ALP} \to \tau\tau$ on effective coupling

Dark Higgsstrahlung

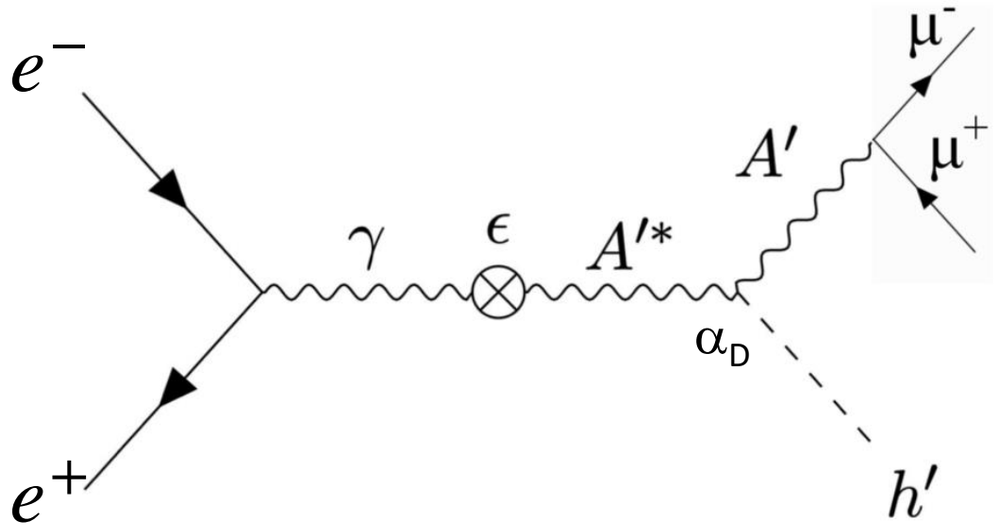
- Dark sector could contain a dark Higgs h'
  - Dark photon A'
    couples with kinetic mixing ϵ to SM
  - Dark Higgs h'
    No mixing with SM Higgs
    coupling to A' is α_D
  - Effective coupling = $\epsilon^2\alpha_D$
- Consider two scenarios here:
  - $M_{h'} > M_{A'}$
    h' decays, $h' \to A'A'$
    $e^+e^- \to A'h'(\to A'A')$
    probed by BaBar(2012) and Belle(2015)
  - $M_{h'} < M_{A'}$
    h' is long lived (undetectable/invisible)
    Studied by KLOE(2015) (at lower energy)
    Largely unconstrained





$e^+e^- \to A'h'$

- Analysis with $8.34\ \mathrm{fb}^{-1}$
- $e^+e^- \to A'(\to \mu^+\mu^-)h'(\to$ invisible)
- Signal:
  - $\mu^+\mu^-$ + missing Energy
  - Two masses (vs one for invisible Z'):
    - $M_{\mu^+\mu^-} = M_{A'}$
    - missing mass $M_{\mathrm{recoil}} = M_{h'}$
    - 2D peak in $M_{\mu\mu}$ vs M_{recoil}

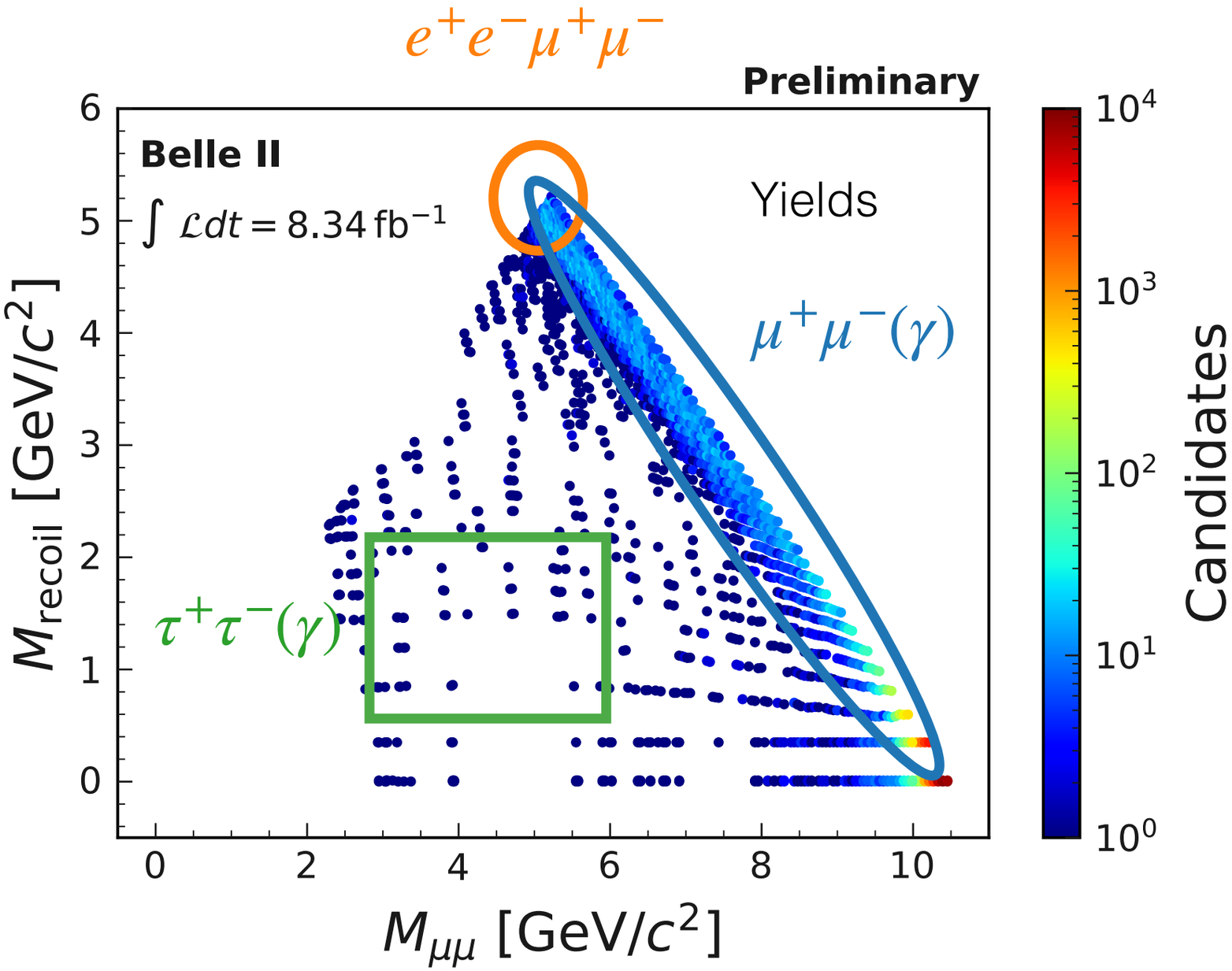


- Backgrounds: (Same as $Z' \to$ invisible)
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \mu^+\mu^-e^+e^-$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$

Accepted by PRL

$e^+e^- \to A'h'$

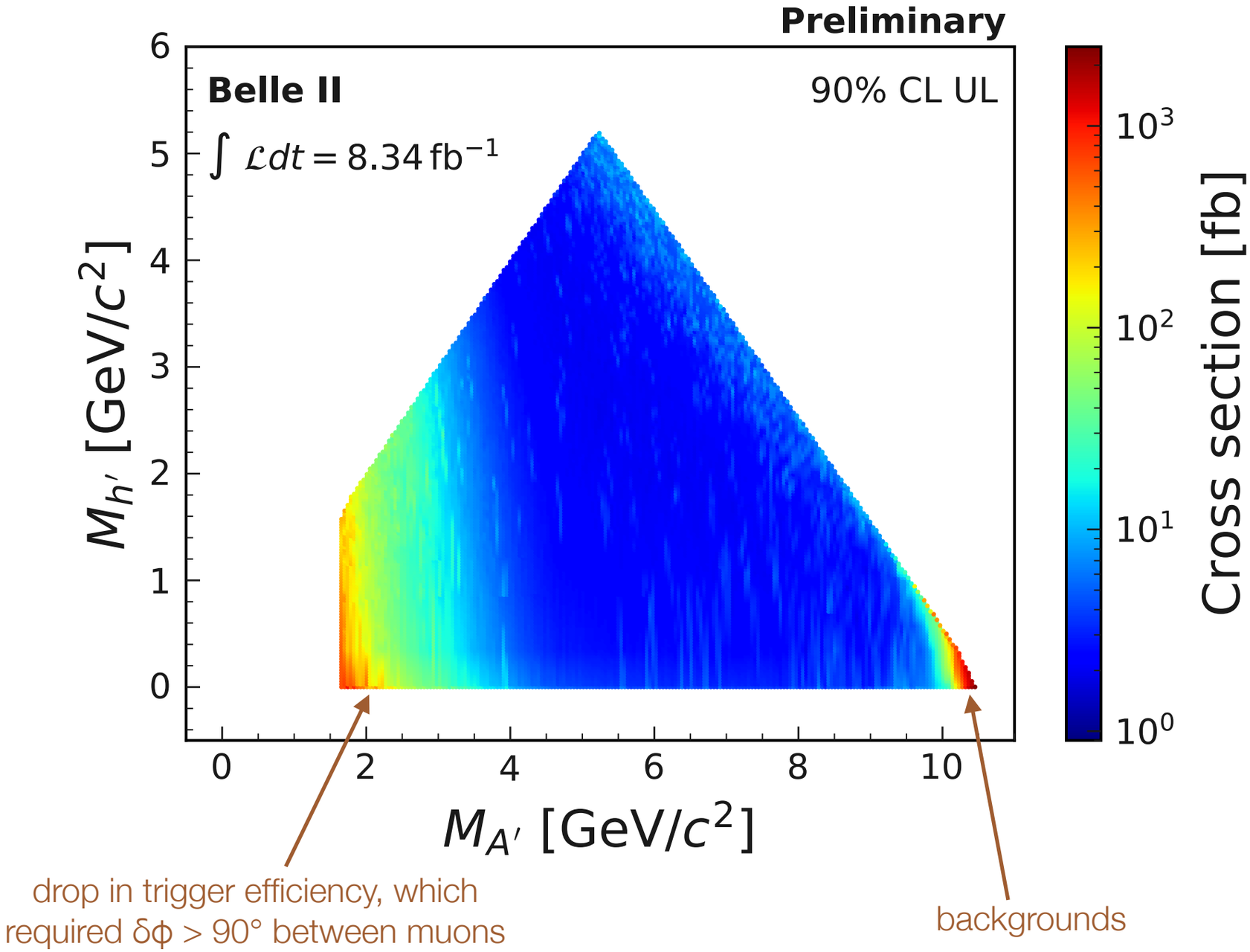
- Searching signal above the expected background in different mass windows.
- No excess observed in ~9000 overlapping mass windows



Accepted by PRL

$e^+e^- \to A'h'$

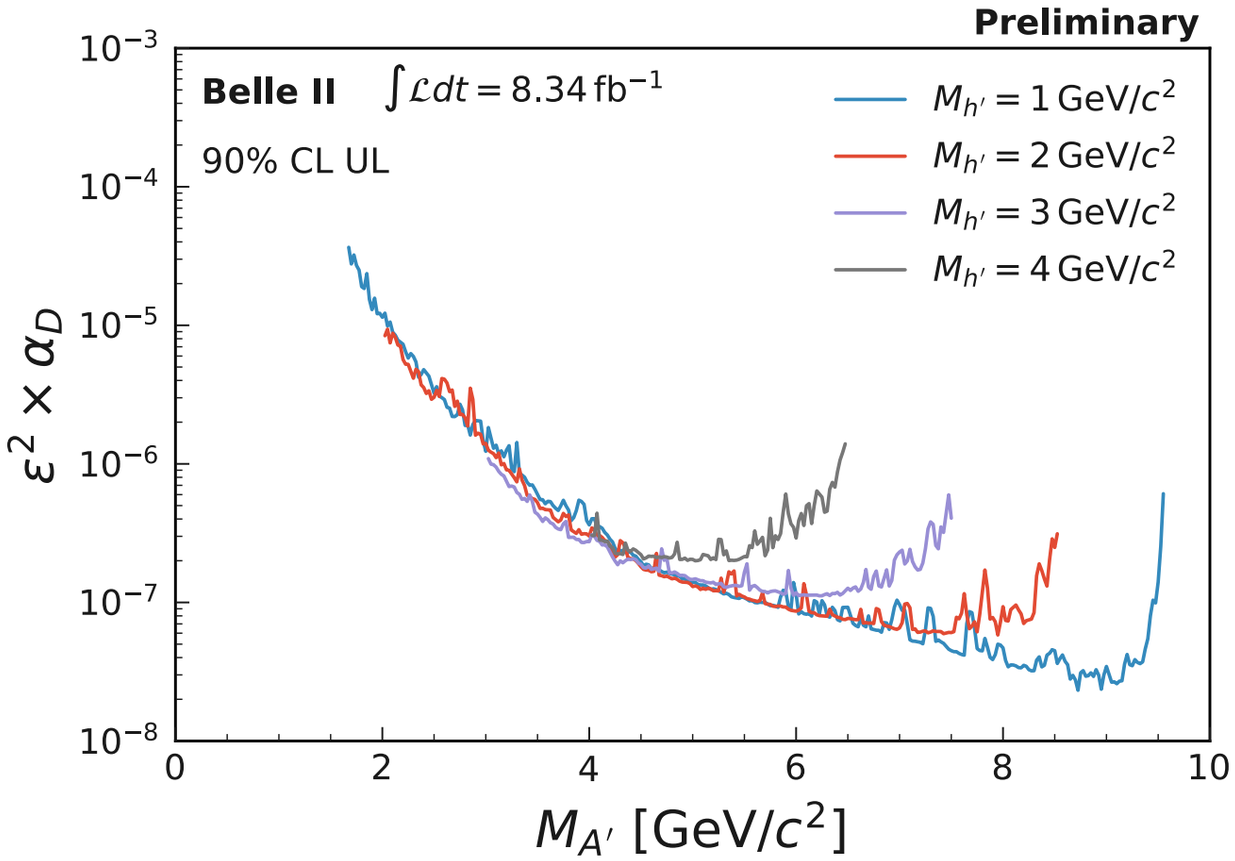
- Upper limits on cross sections

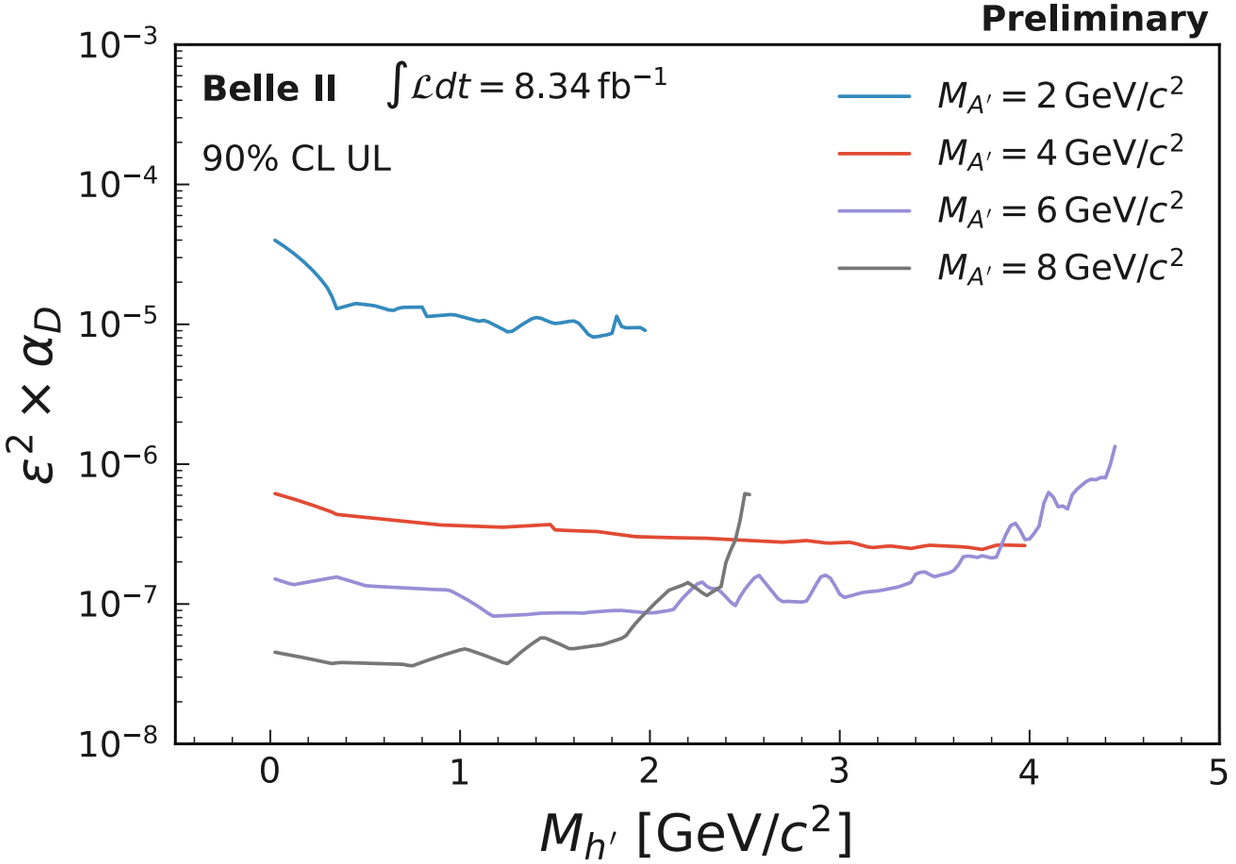


Accepted by PRL

$e^+e^- \to A'h'$

- Limits on effective coupling ($\epsilon^2\alpha_D$)





- First limits for $1.65 < M_{A'} < 10.51\ \mathrm{GeV}/c^2$
- Next update: much more data; good trigger efficiency at low mass.

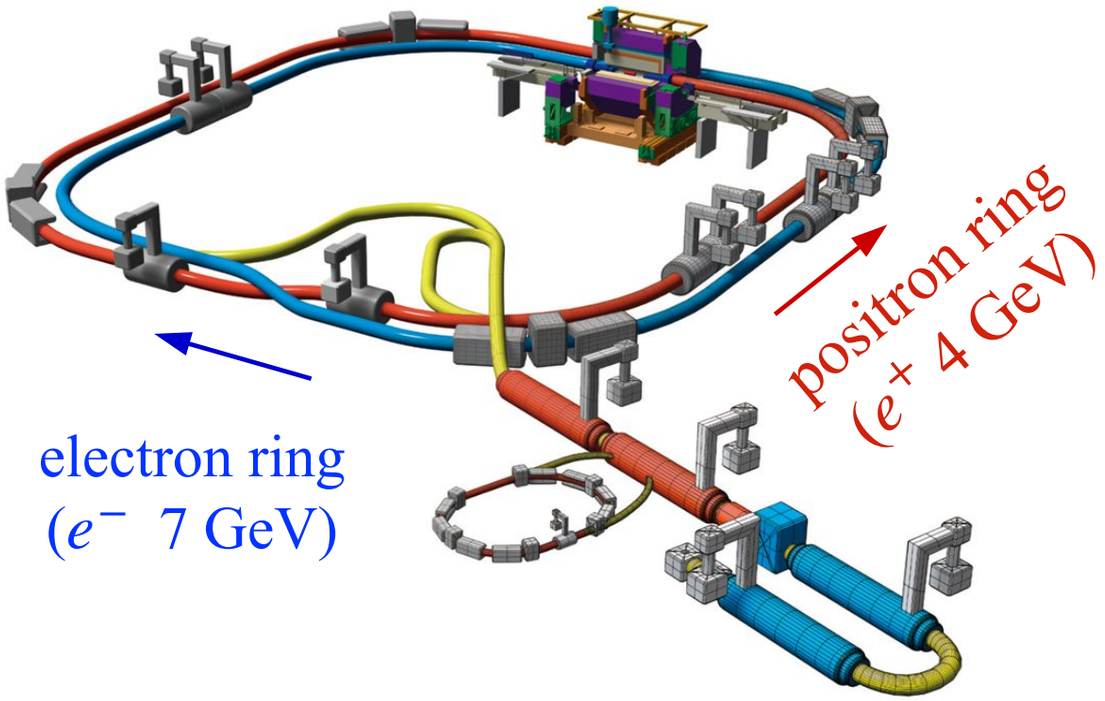
Accepted by PRL

Summary

- Belle II at SuperKEKB has great potential thanks to low-background collisions, hermeticity, dedicated triggers.
- World-leading sensitivity in dark sector searches @ Belle II for:
  - $Z' \rightarrow$ invisible ; PRL 124 (2020) 141801, arxiv:2212.03066 (to PRL)
  - $Z'/S/$ALP $\rightarrow \tau^+\tau^-$; to be submitted for publication soon
  - Dark Higgsstrahlung ; arxiv:2207.00509, accepted by PRL.
- In next few years, Belle II will collect 100x the dataset collected up to now
  - It will lead the exploration of dark sectors in the MeV - GeV mass range

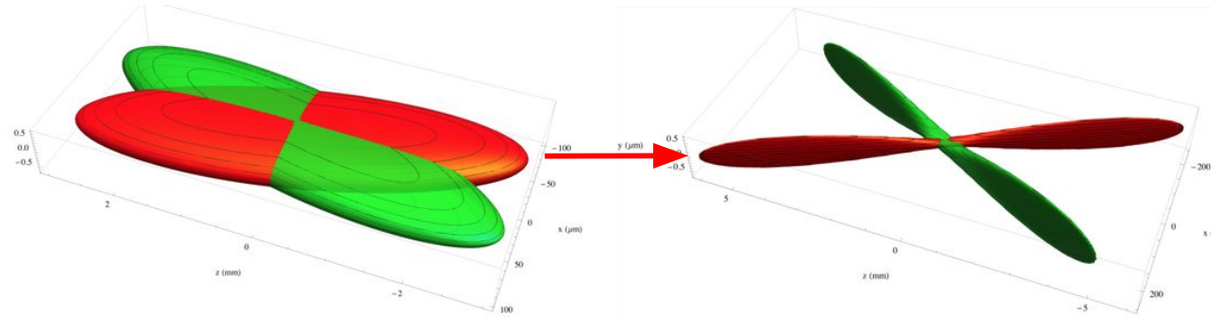
Backup

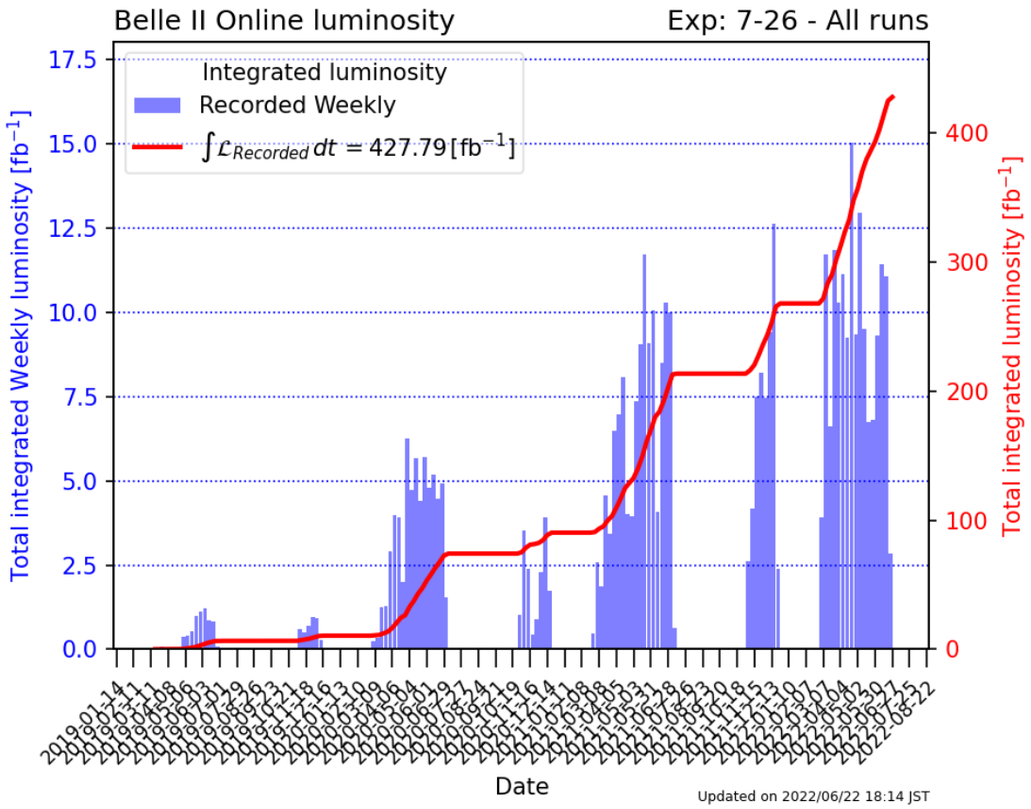
SuperKEKB



- Upgrade of KEKB
- 30 × KEKB best instantaneous luminosity achieved by
  - **150%** of beam current
  - **1/20** of beam size (nanobeam scheme)

KEKB SuperKEKB





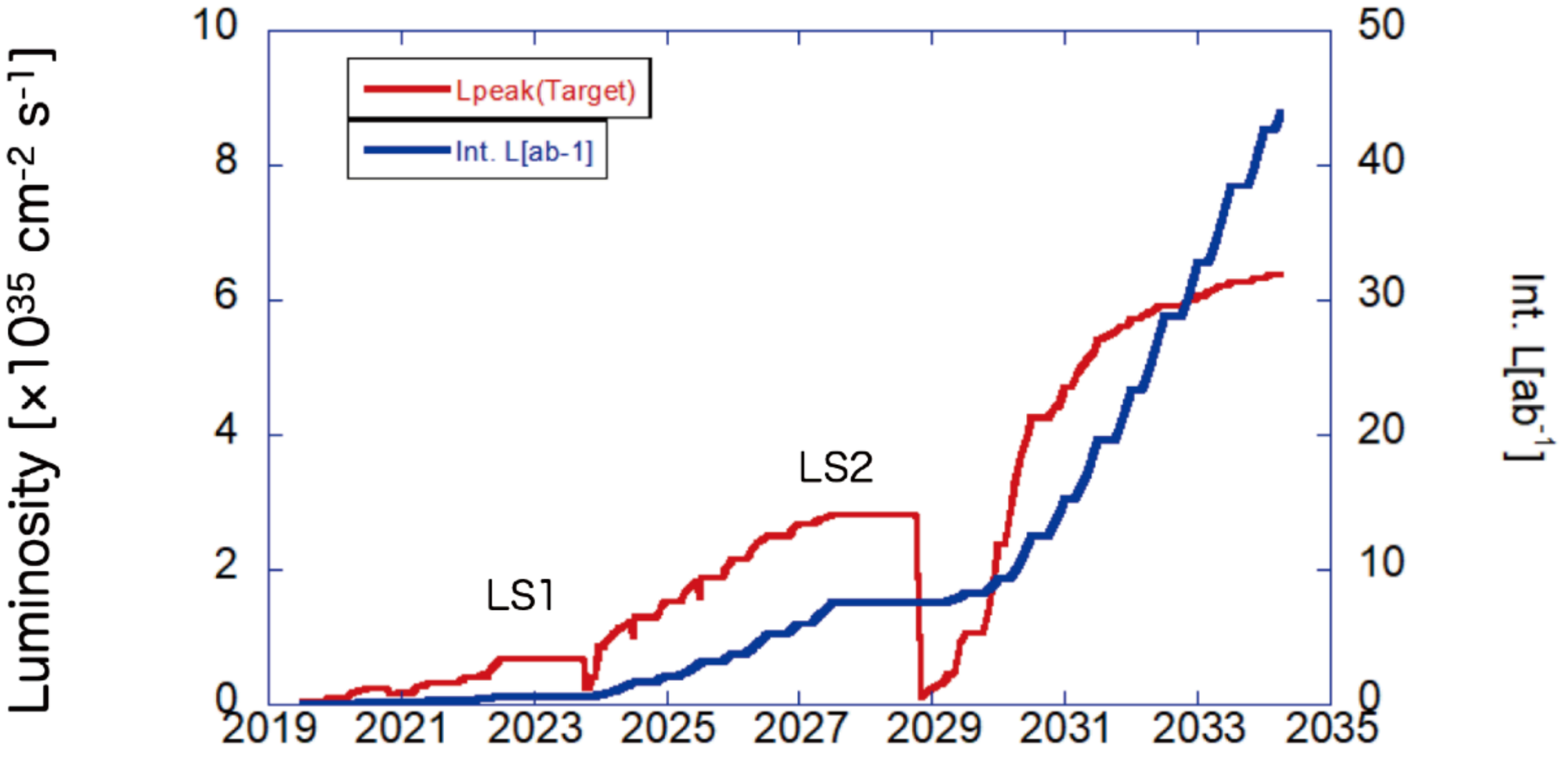
- Well-defined initial state kinematics
  - No additional interactions
  - Low physics backgrounds
- Absolute branching fractions measurement
- Collected 428 fb^{-1} since March 2019.
- In long shutdown 1 to install two-layer pixel detector, July 2022 – September 2023.

SuperKEKB Long-term plan

- World's highest instantaneous luminosity collider,

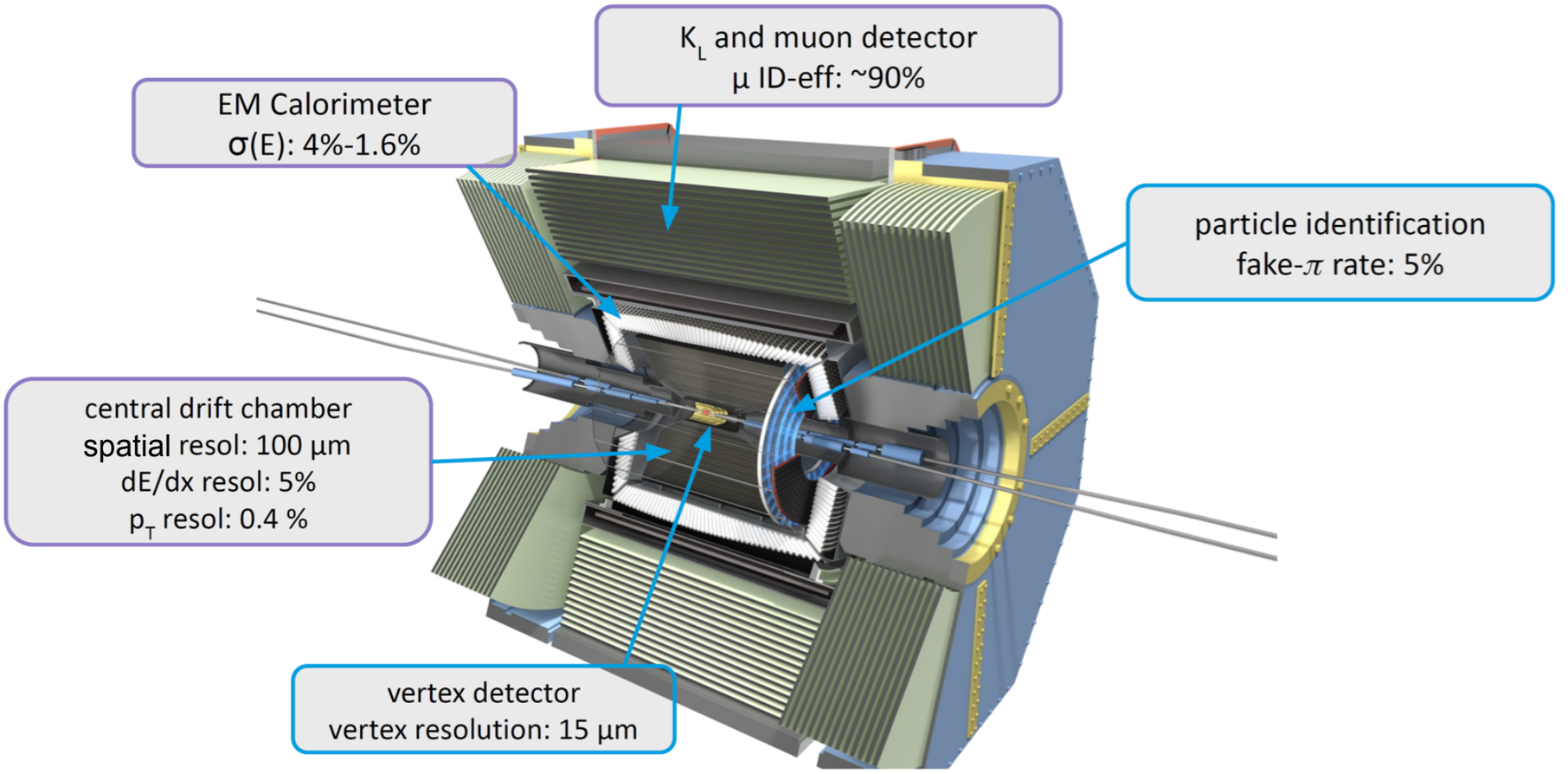
  $4.7 \times 10^{34}\ cm^{-2}s^{-1}$. Target is $6 \times 10^{35}\ cm^{-2}s^{-1}$:

  - increase current while reducing injection backgrounds;
  - hardware upgrades in LS2 → international task force.



Goal : 50 ab^{-1}

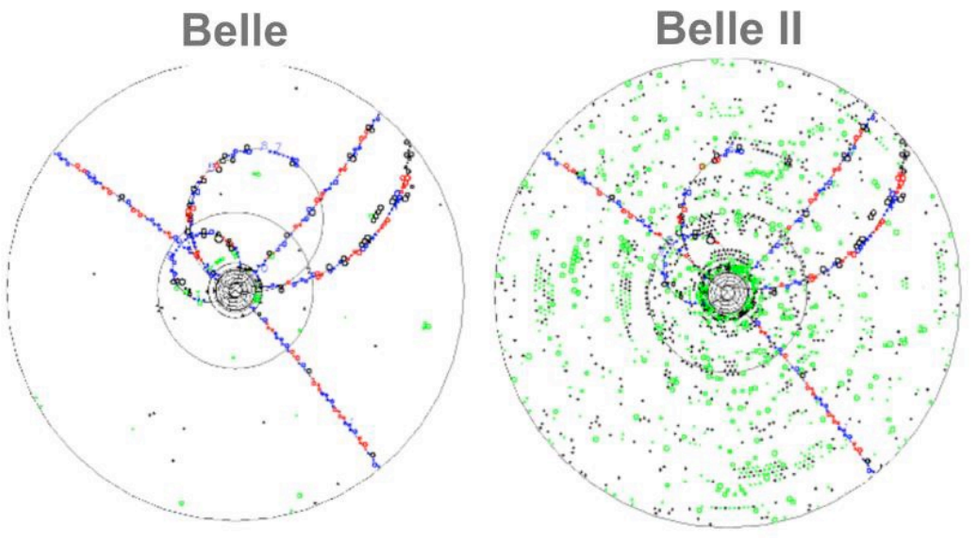
Belle II @ SuperKEKB



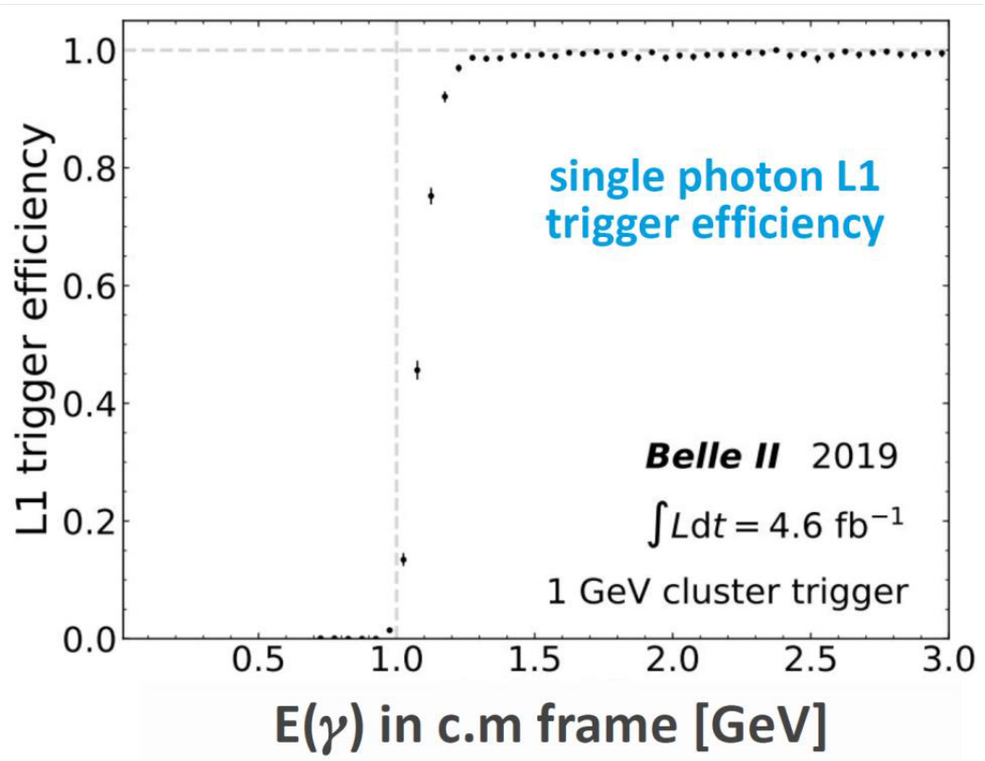
- ✦ High reconstruction efficiency with very low trigger bias.
- ✦ Improved particle identification
- ✦ Uniform performance in reconstruction of final states involving photons from $\pi^0, \rho^{\pm}, \eta, K_S^0$ …
- ✦ Good vertex resolution
- ✦ Analyses with missing particles as initial state perfectly known

Trigger @ Belle II

- Level 1 hardware-based combines info from CDC, ECL, KLM
  - Tracks, clusters, muons
  - Two-track trigger
  - Three-track trigger
  - $E_{ECL} > 1.0$ GeV trigger



- Low multiplicity trigger
  - Single muon (CDC + KLM)
  - Single track (Neural based)
  - Single photon ($E_\gamma > 0.5,\ 1.0,\ 2.0$ GeV)



$L_\mu - L_\tau$ gauge boson Z'

- Partial widths for $Z' \to \ell^+\ell^-$ and for $Z' \to \nu_\ell \bar{\nu}_\ell$:

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{g' M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{24\pi}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}$$

$$\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{g' M_{Z'}}{12\pi}$$

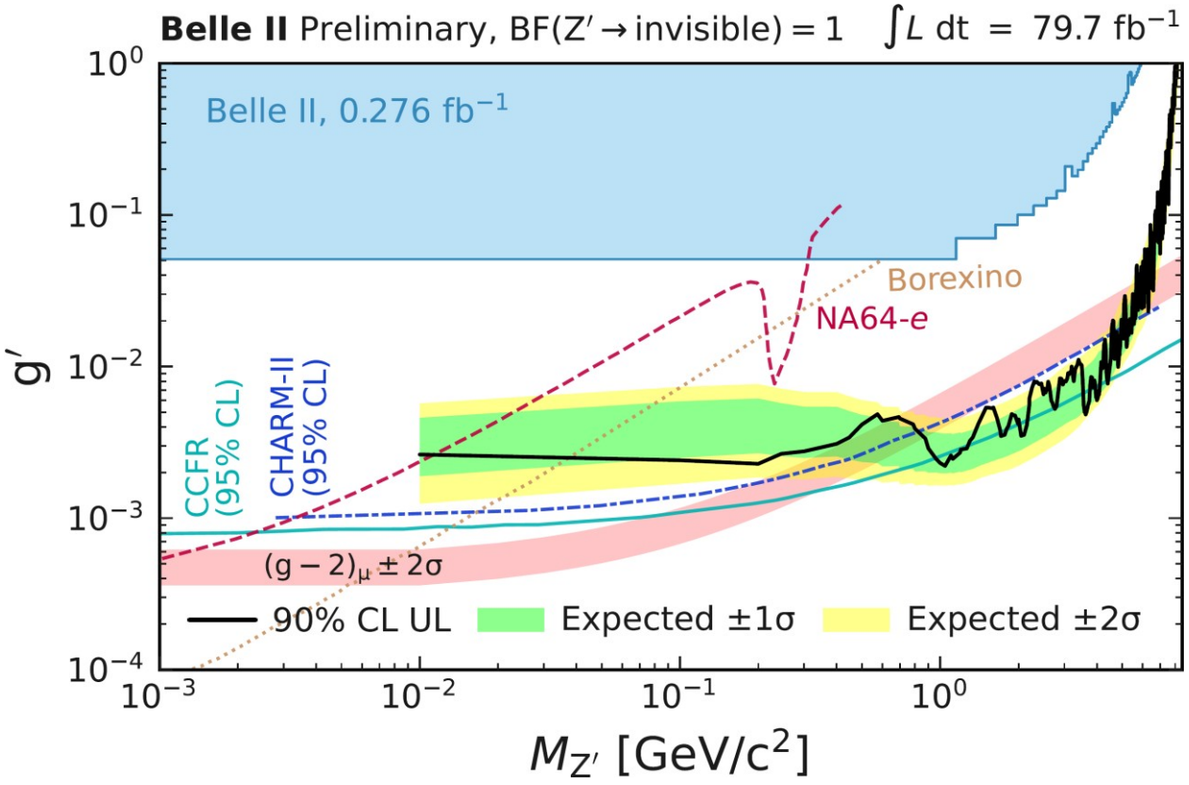
- Decay branching fraction of Z' boson decay to invisible:

$$\mathscr{B}(Z' \to \text{invisible}) = \frac{2\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell)}{2\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) + \Gamma(Z' \to \mu^+\mu-) + \Gamma(Z' \to \tau + \tau-)}$$

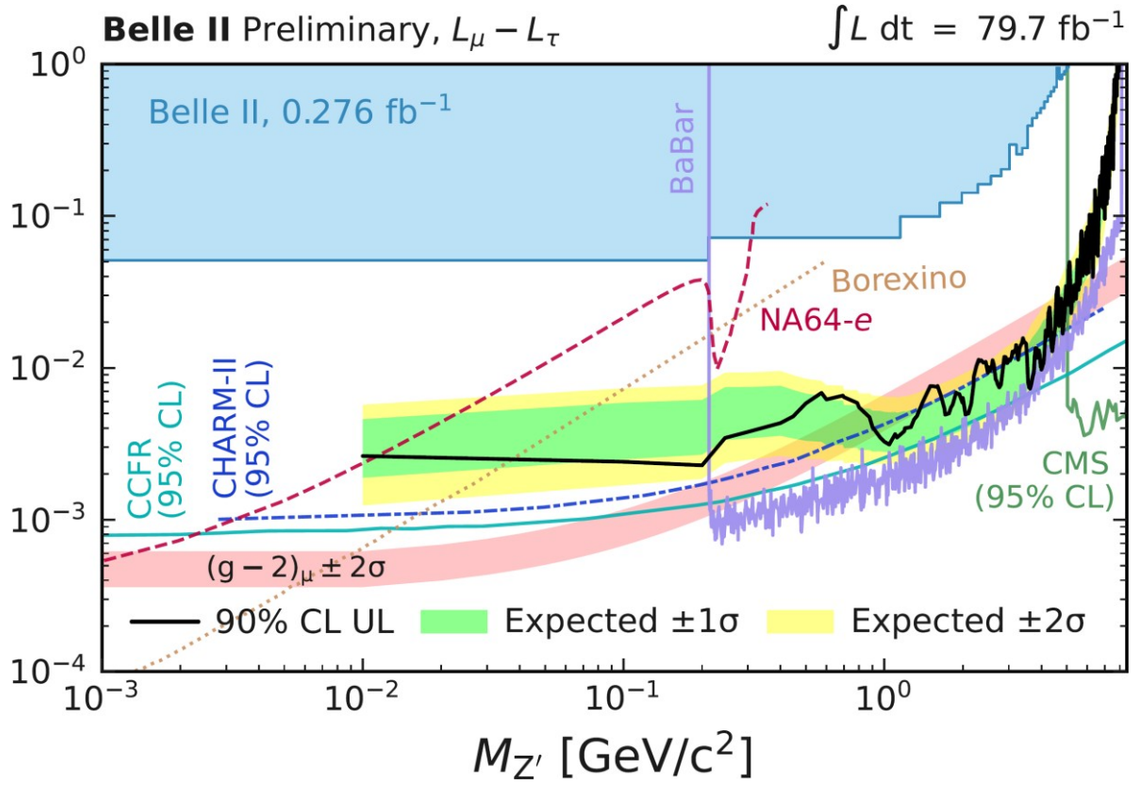
$Z' \rightarrow$ invisible

- 90% CL exclusion limits on cross section and coupling in low $M_{Z'}$

$Z' \rightarrow$ invisible



$Z' \rightarrow$ SM only

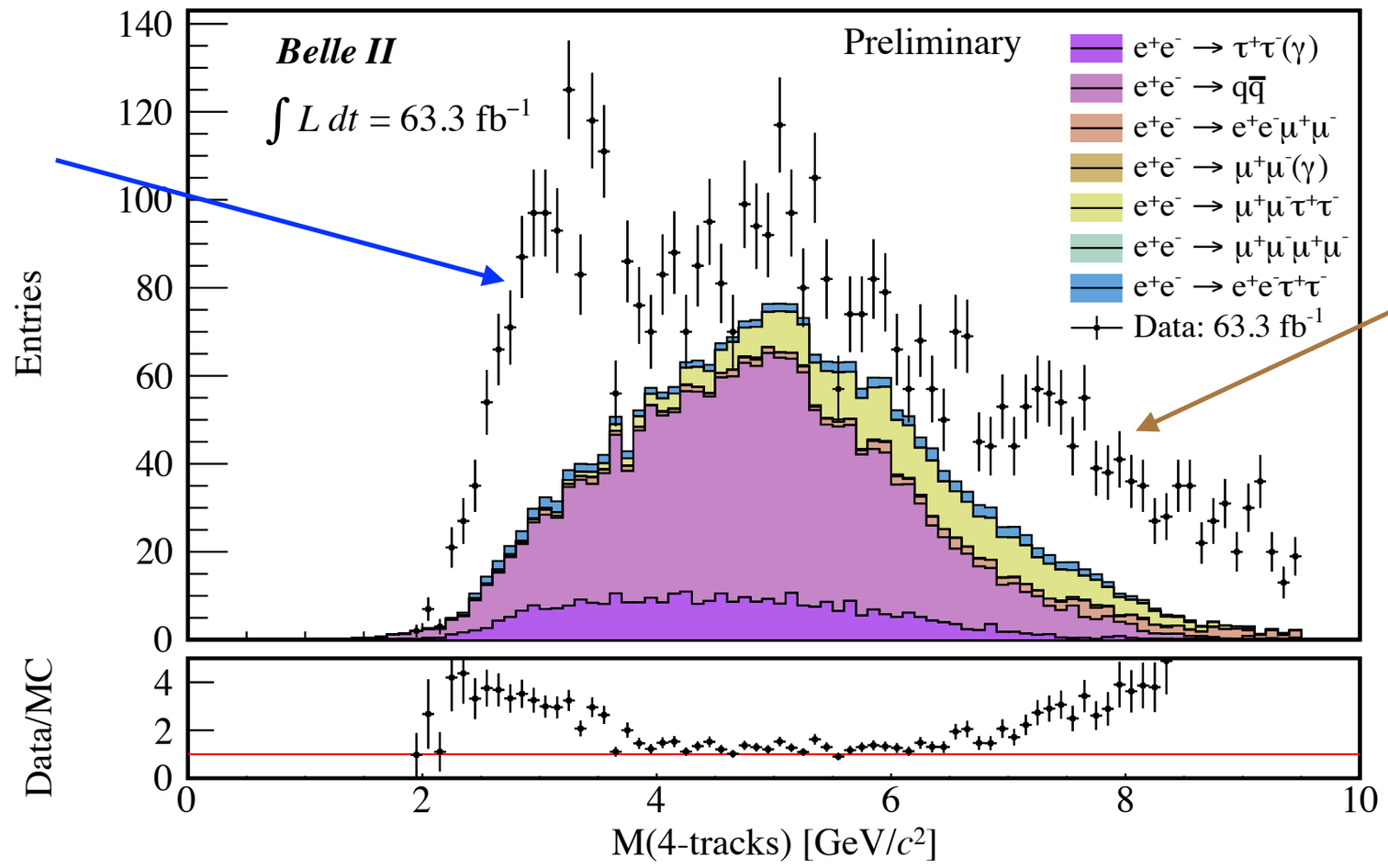


$Z'/S/\mathbf{ALP} \to \tau^+\tau^-$

- Data/MC discrepancies expected.
  - Due to un-modelled backgrounds

Preliminary

$e^+e^- \to e^+e^- X_{\text{had}}$



$e^+e^- \to \gamma 4\ell^{\pm}$

$Z'/S/\mathbf{ALP} \to \tau^+\tau^-$

- No excess, set upper limit with 90% CL on Z' cross section