THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

Status and prospects for light DM and mediator searches at Belle II

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FIPs 2022 Workshop

On behalf of the Belle II collaboration

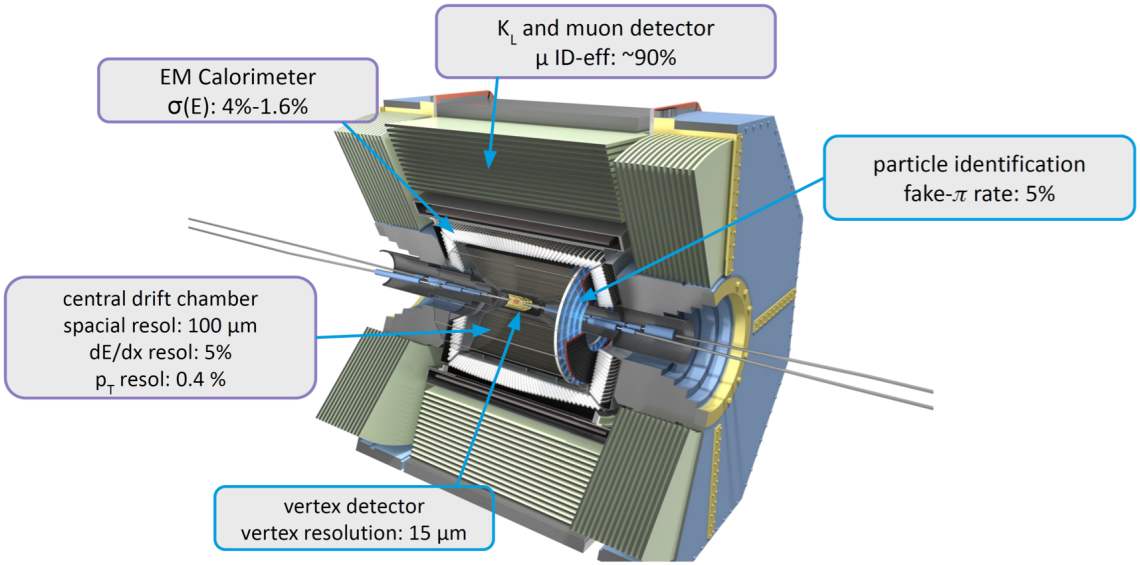
Outline

- Belle II and SuperKEKB
- Z' and leptophilic dark scalars
- Dark photons

Belle II and SuperKEKB

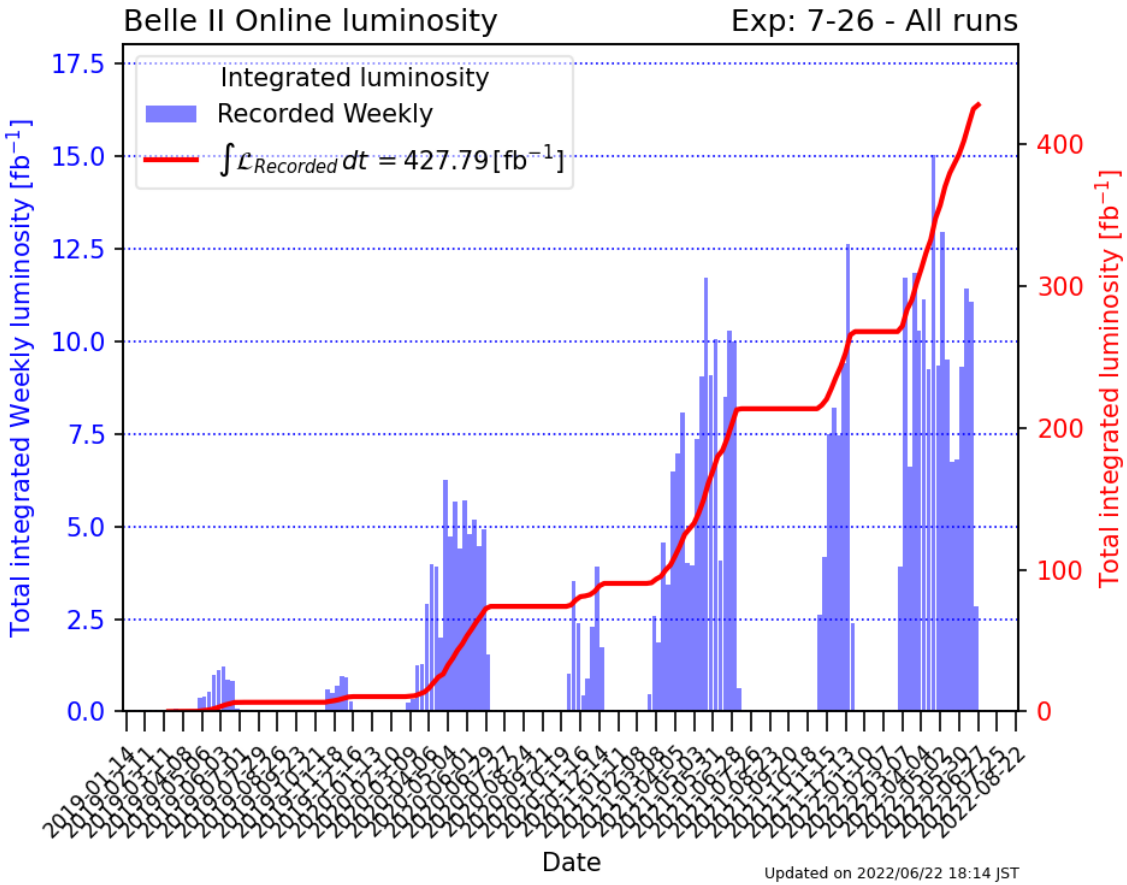
Belle II at the SuperKEKB e^+e^- collider in Tsukuba, Japan

- Almost total upgrade of Belle for better performance and higher rate capabilities.



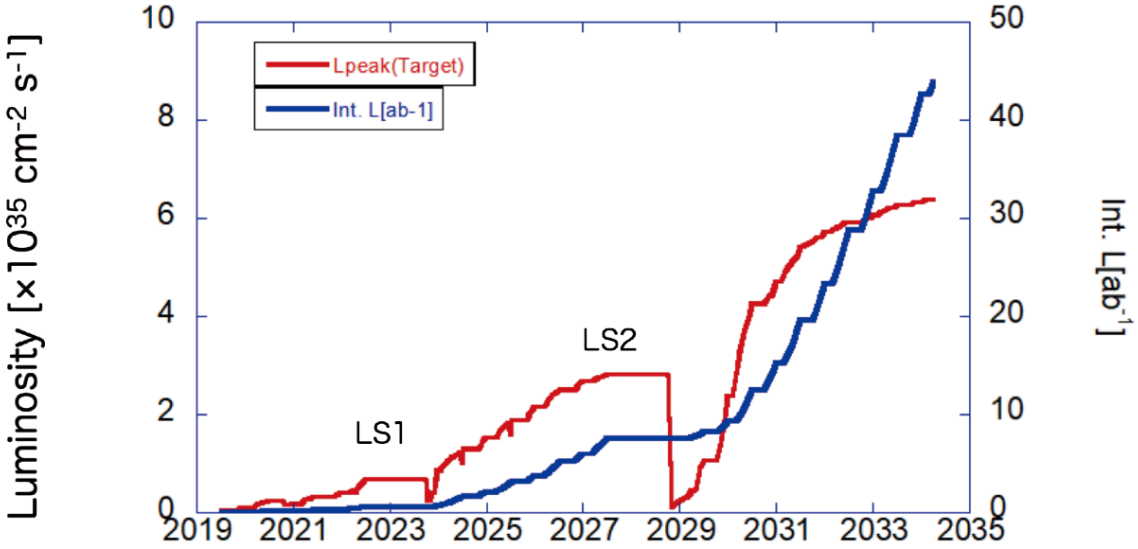
- Key for dark sector:
  - clean e^+e^- environment;
  - loose triggers (single γ, single track); currently, some are very loose. Displaced vertex under development.
  - (in the long run) high luminosity.

- Belle II has collected 428 fb^{-1} since March 2019.
- In long shutdown 1 to install two-layer pixel detector, July 2022 – September 2023.



SuperKEKB

- World's highest instantaneous luminosity collider, 4.7×10^{34} cm^{-2}s^{-1}. Target is 6×10^{35} cm^{-2}s^{-1}:
  - increase current while reducing injection backgrounds;
  - reduce catastrophic beam loss events;
  - control emittance blowup and beam instability;
  - hardware upgrades in LS2 → international task force.

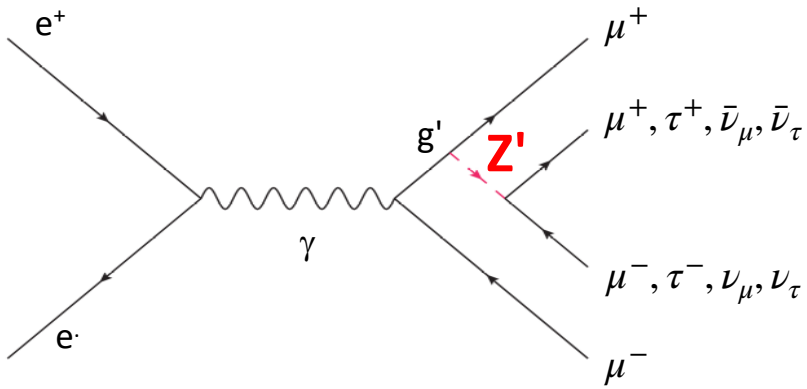


Z′ and leptophilic dark scalars

The $L_\mu - L_\tau$ gauge boson Z′

- Couples only to 2nd and 3rd generations. Evades strong limits from electron production and decay.

- Could explain muon (g-2)$_\mu$, and B decay anomalies R_{D*}, R_K, R_{K*}.



τ⁺ τ⁻ Z′ is also possible, but less sensitive

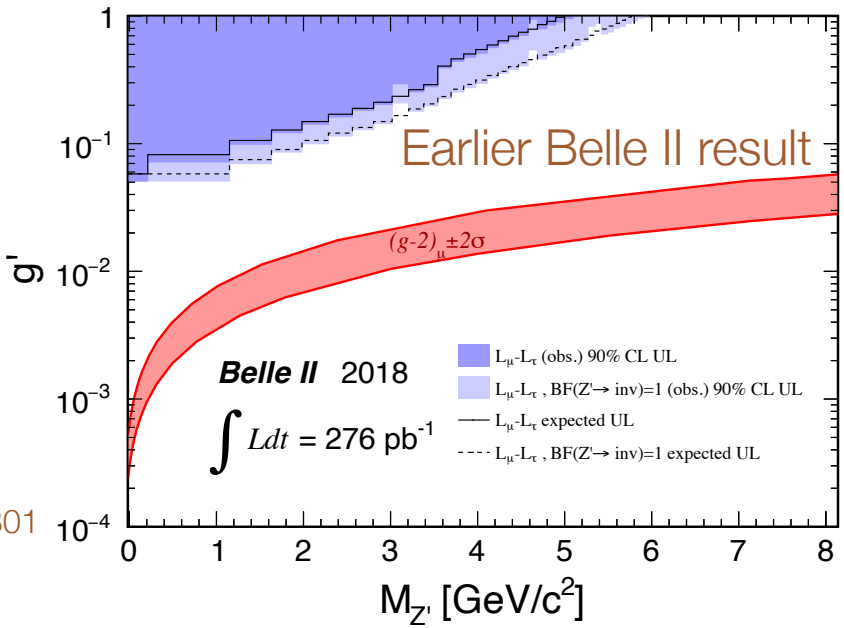
- Existing limits from BaBar, CMS, and Belle on $Z' \to \mu^+\mu^-$ strongly constrain parameter space relevant for $(g\text{-}2)_\mu$.

Phys. Rev. D 94 (2016) 011102

Phys. Lett. B 792 (2019) 345

Phys. Rev. D 106 (2022), 012003

- Only published result on $Z' \to \nu\bar{\nu}$ is early Belle II result
  - most relevant for $m_{Z'} < 2m_\mu$.



Belle II, Phys. Rev. Lett. 124 (2020) 141801

- Also possible that the Z' is the mediator between standard model and dark matter χ, in which case $\mathcal{B}(Z' \to \chi\chi)$ would be dominant even above $2m_\mu$.

Search for an invisible Z′ in the final state with two muons and missing energy at Belle II

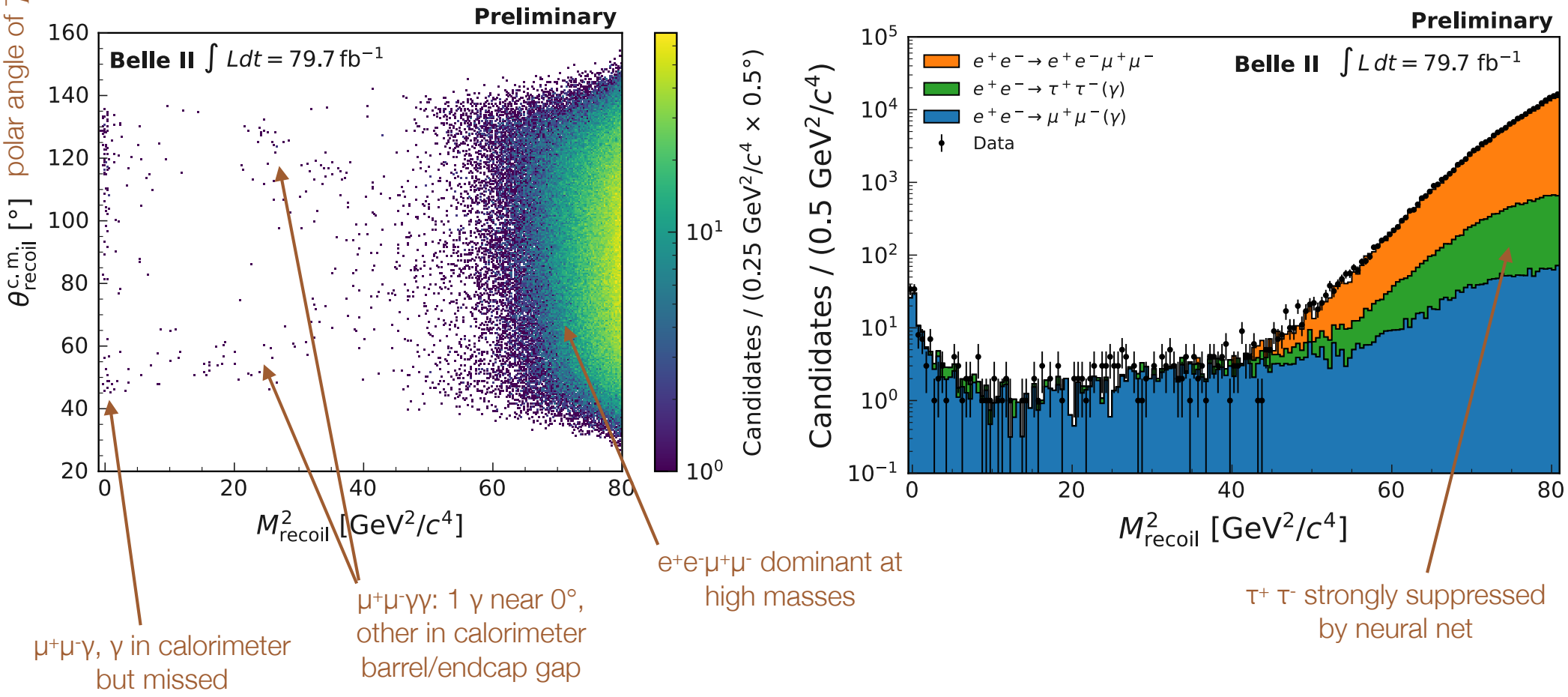
- Signature: pair of muons with missing mass = $m_{Z'}$.

- Backgrounds:
  - $\tau^+\tau^-$, with both $\tau \to \mu\nu\bar{\nu}$;
  - $\mu^+\mu^-\gamma$;
  - $\mu^+\mu^-\gamma\gamma$;
  - $\mu^+\mu^- e^+e^-$;

  out of acceptance or missed

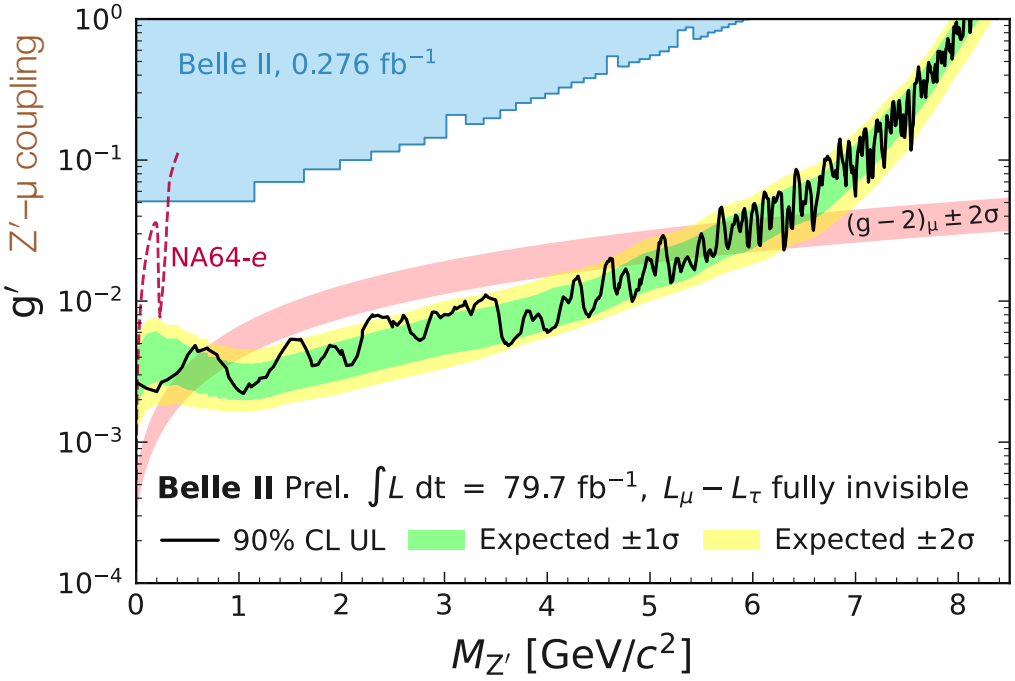
- Key: *Z′* is final state radiation. Train neural net to identify characteristic kinematics.

$Z' \rightarrow$ invisible selected events



$Z' \to$ invisible results, $\mathscr{B}(Z' \to \text{invisible}) = 1$

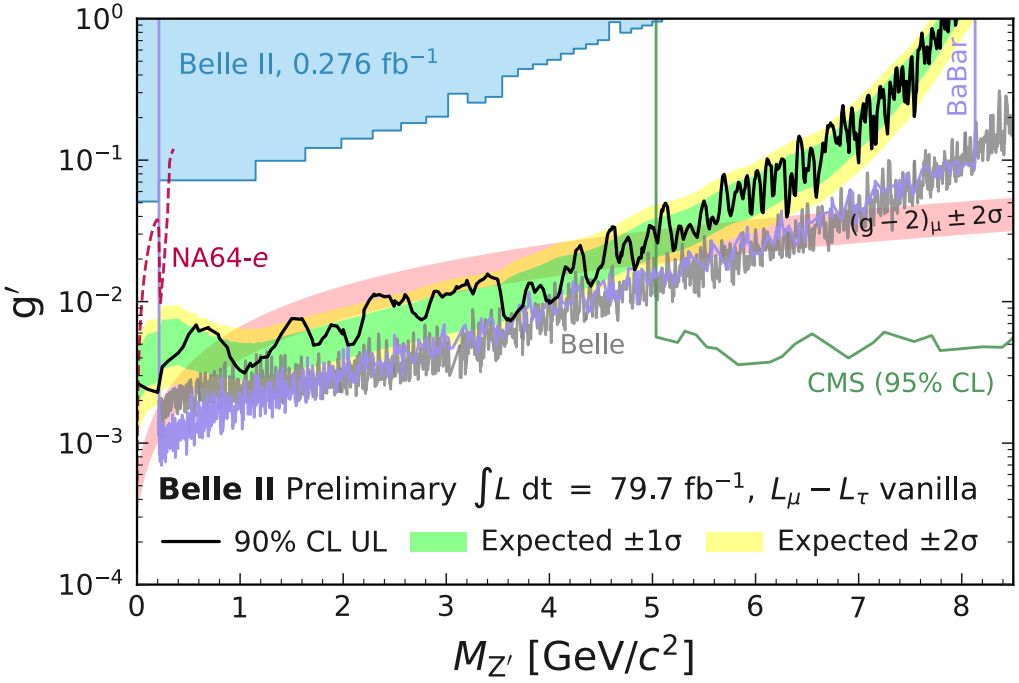
- Fit 2D distribution θ^{cm}_{recoil} vs M^2_{recoil}; no excess observed.



- For $\mathscr{B}(Z' \to \text{invisible}) = 1$, (g-2)$_\mu$ parameter space excluded for 0.8 < M$_{Z'}$ < 5.0 GeV/c^2. First such limits.

Z′ results, Z′ → standard model only

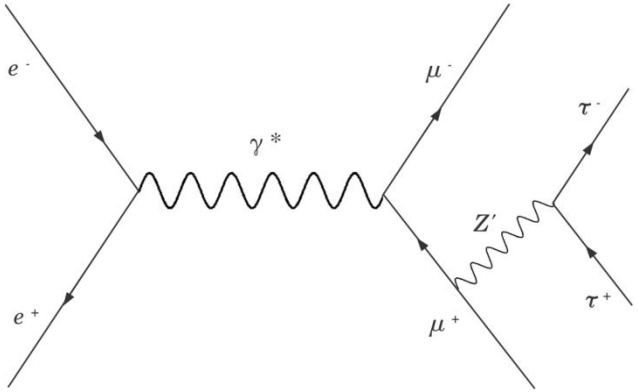
- If Z′ decays only to standard model particles, limits improved below $2m_\mu$, but region could still explain $(g\text{-}2)_\mu$.
  - we have ideas for improvements.



First search for a $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events with the Belle II experiment

- $Z' \to \tau^+\tau^-$ (strong existing μ⁺μ⁻ constraints);

- Leptophilic scalar S with mass-dependent coupling;
  - BaBar has searched for $S \to e^+e^-$ or $\mu^+\mu^-$ in association with a tau pair. Phys. Rev. Lett. 125 (2020) 181801



- Axion-like particle coupling to leptons. Assumed to not couple to γ.

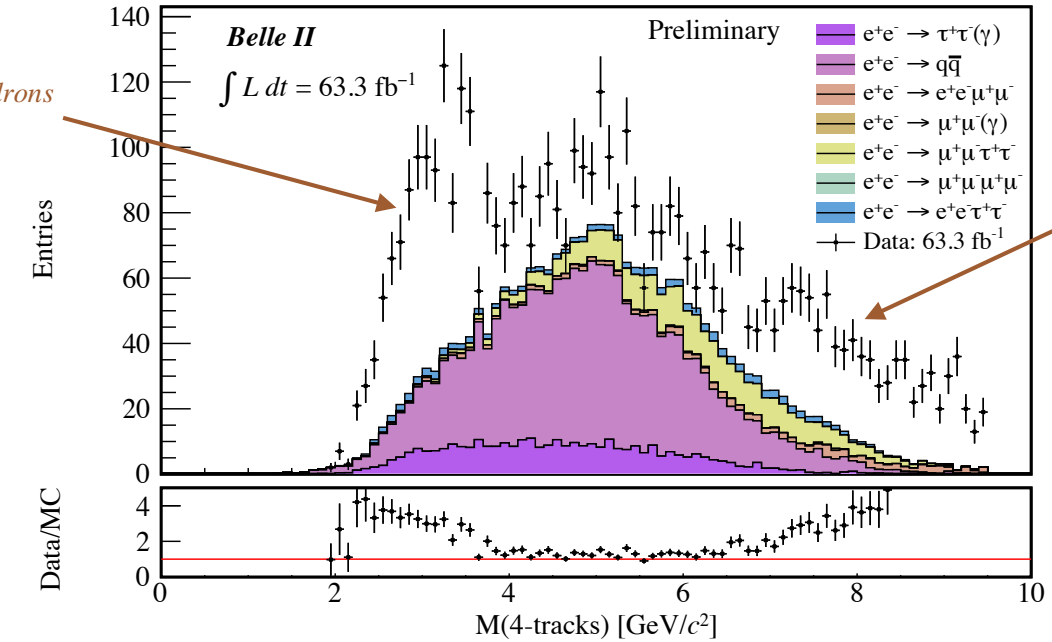
- Signature: 4 tracks, including ≥2 muons, missing mass.

Selected events

- Require M(4 tracks) < 9.5 GeV/c^2 to suppress $e^+e^- \to 4\ell^\pm$

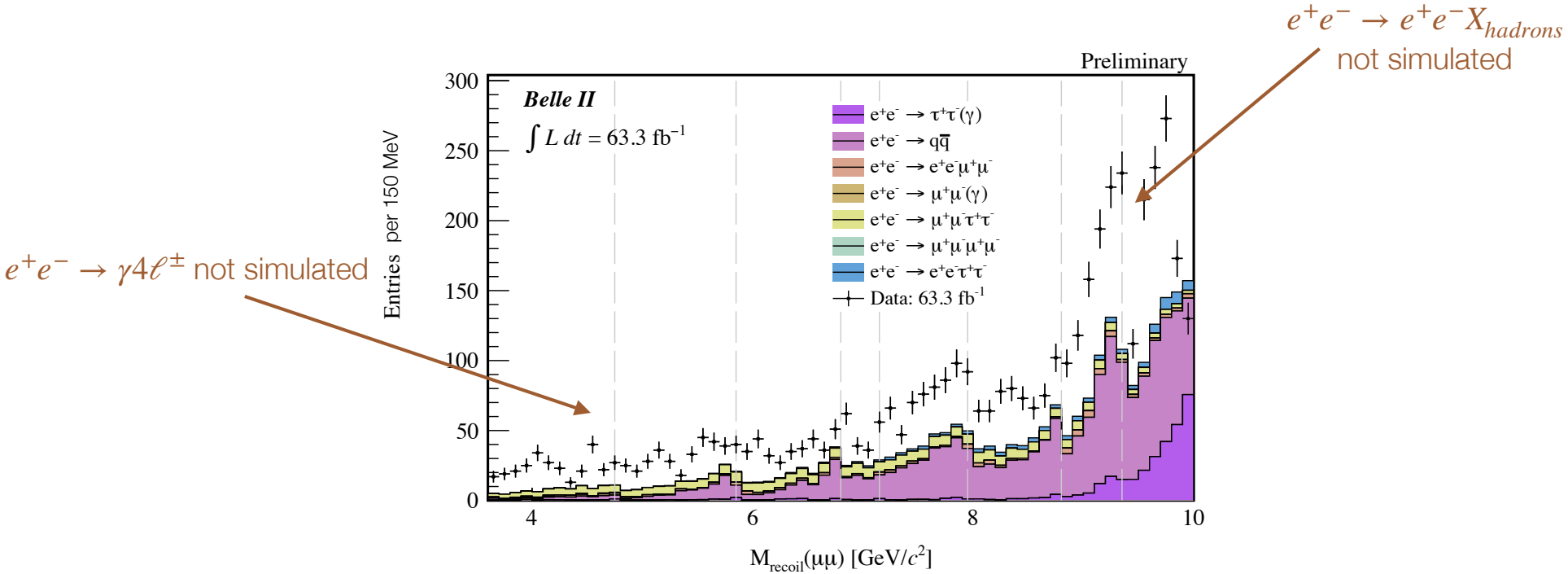
- Train neural net on distinctive kinematic features:
  - final state radiation
  - consistent with tau pair recoiling against muon pair.

$e^+e^- \to e^+e^- X_{hadrons}$ not simulated



$e^+e^- \to \gamma 4\ell^\pm$ not simulated

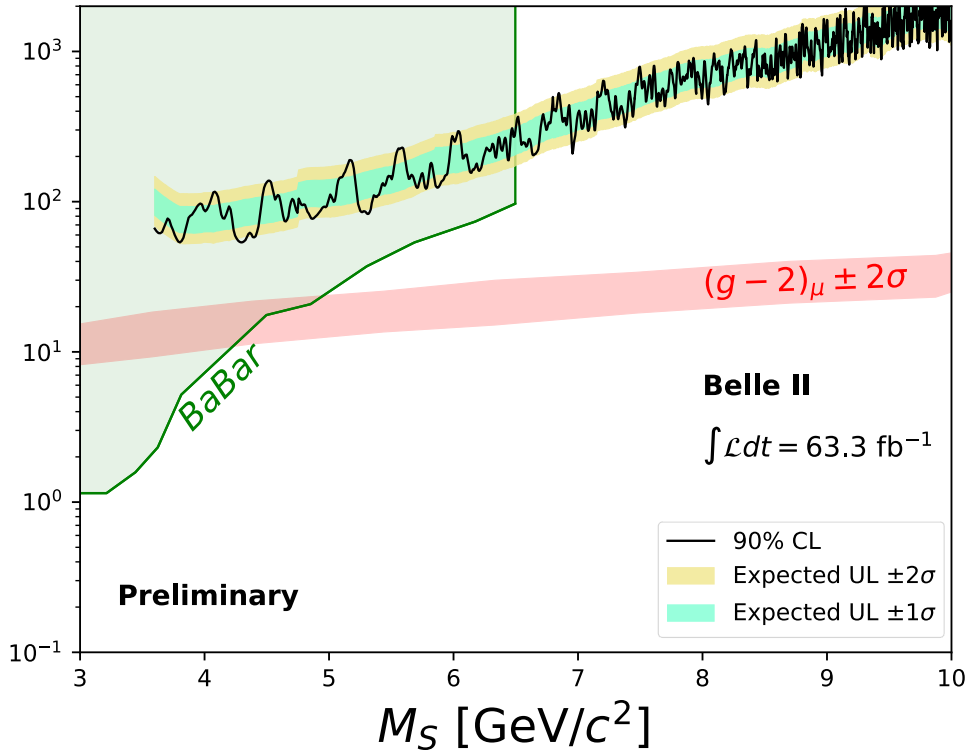
- Look for a peak in the recoil mass spectrum, on a locally-flat background.
  - resolution: 30 MeV @ threshold → 10 MeV @ 6 GeV → 1 MeV @ 10 GeV.



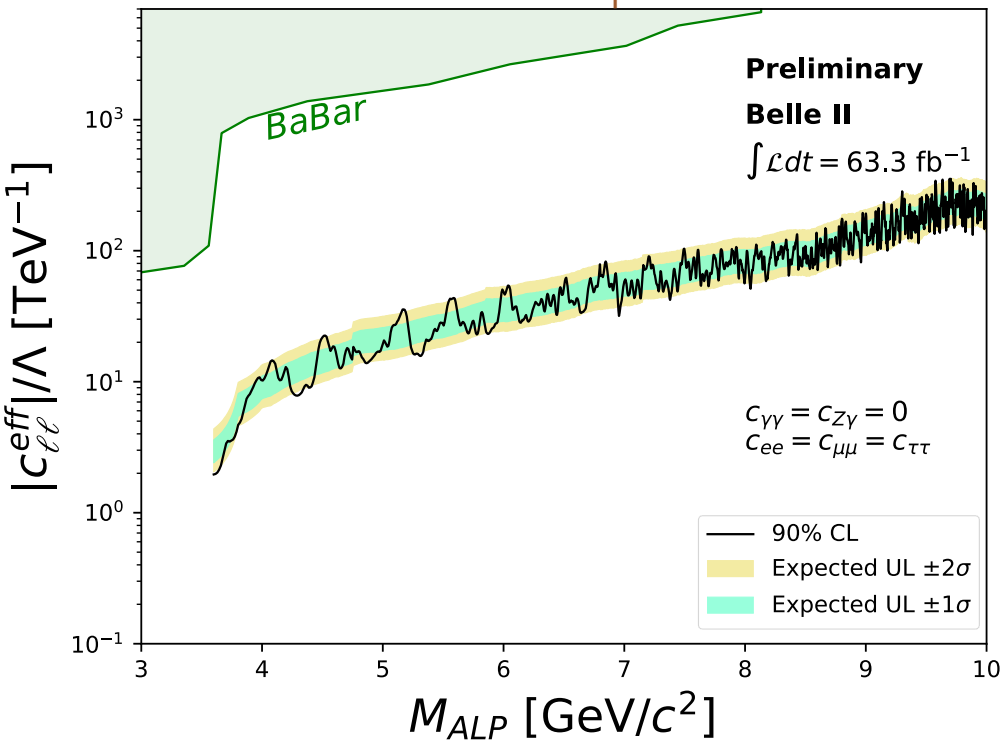
Tau pair resonance results

- First leptophilic scalar limits above 6.5 GeV/c^2.
- World leading limits on axion-like particle decays to leptons.

Leptophilic scalar decaying to $\tau^+\tau^-$



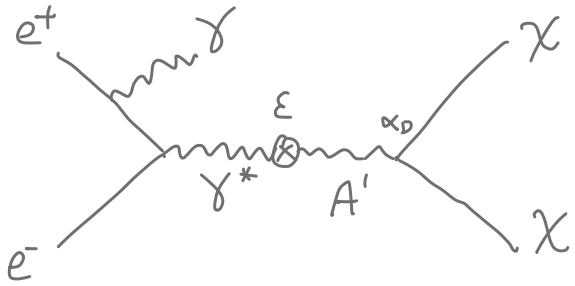
axion-like particle



Dark photons

Dark photons and Belle II

- Simplest case: on-shell production of a dark photon A′ via initial-state radiation. Will decay to dark matter if kinematically allowed. “Single photon” analysis.

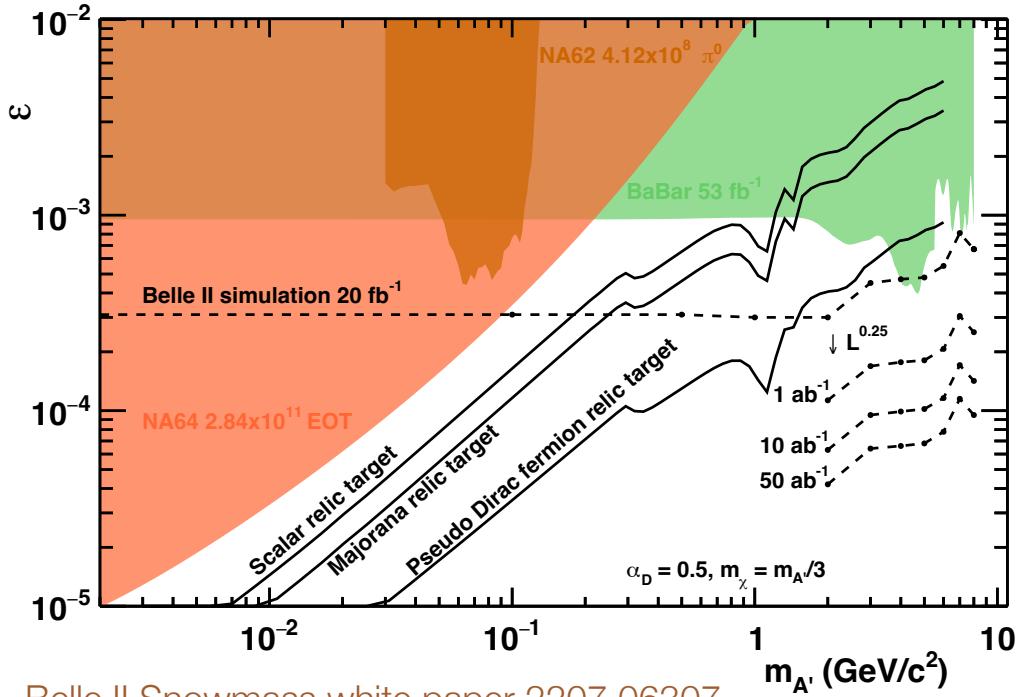


- Plan is to publish on current data set. Challenge is to quantify backgrounds:
  - $e^+e^- \to \gamma\gamma$
  - $e^+e^- \to \gamma\gamma\gamma$
  - $e^+e^- \to \gamma e^+e^-$
  - cosmic rays
  - single beam (non-luminosity)

all but one γ out of acceptance or missed

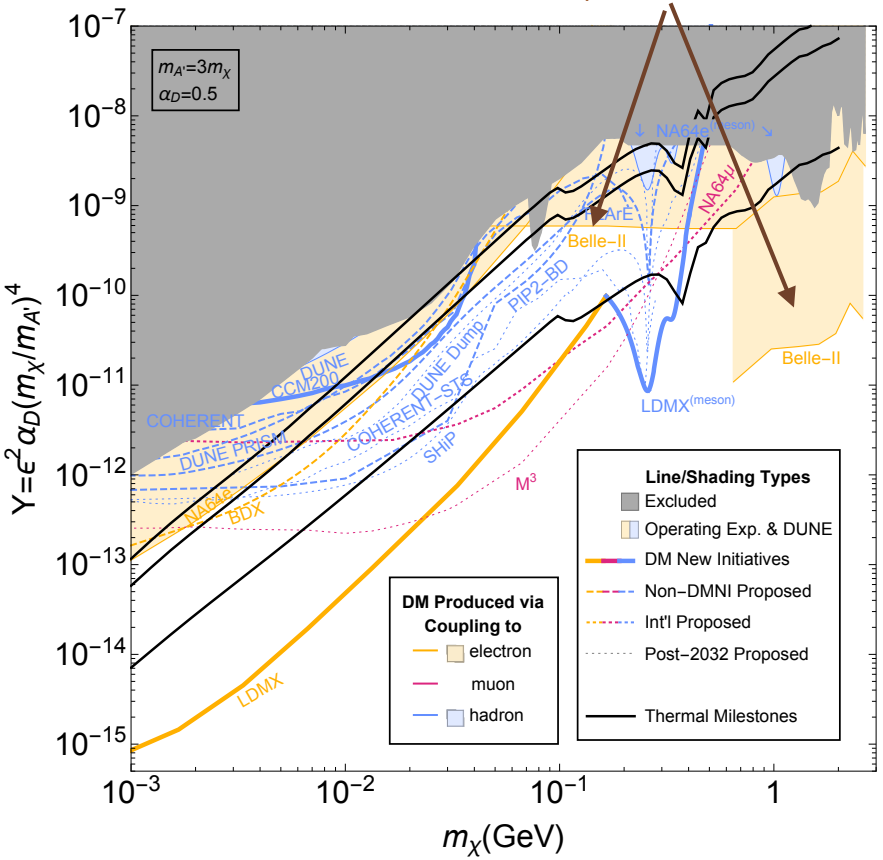
Belle II sensitivity, invisible dark photon decays

- Belle II will have unique sensitivity to regions of parameter space consistent with observed dark matter relic density.



Belle II Snowmass white paper 2207.06307

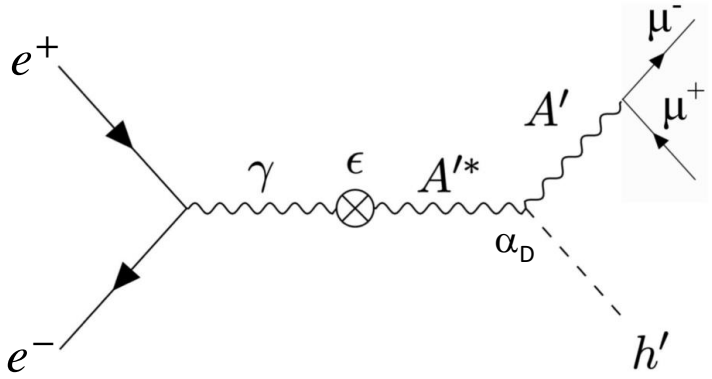
same limits, different parameters



Snowmass RF6 report 2209.04671

Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment

- Dark sector could also contain a dark Higgs h′.



- We consider the case where
  - $m_{A'} < 2m_\chi \Rightarrow$ A′ decays to standard model;
  - $m_{h'} < m_{A'} \Rightarrow$ h′ is long lived / invisible (does not mix with Higgs).

- KLOE studied this configuration at lower mass; BaBar and Belle studied $m_{h'} > m_{A'}$; different signature.

Phys. Lett. B 747, 365 (2015)

Phys. Rev. Lett. 108, 211801 (2012)

Phys. Rev. Lett. 114, 211801 (2015)

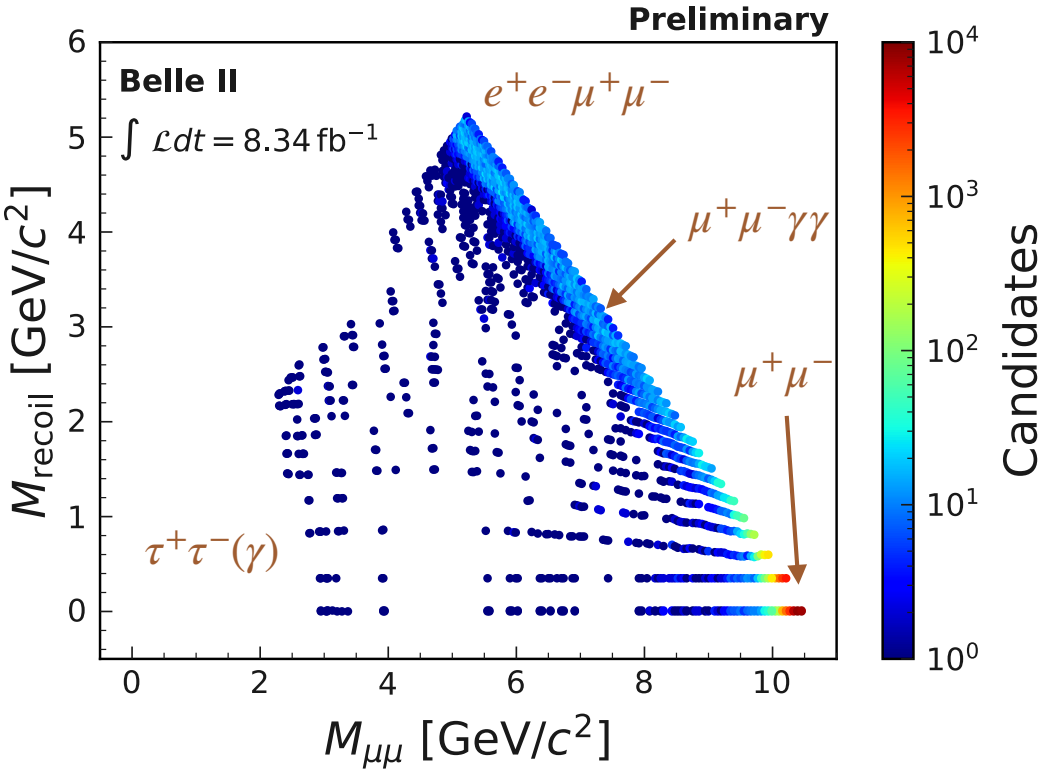
- Signature: muon pair (only) plus missing momentum, but two masses (vs one for invisible Z′):
  - $m_{\mu^+\mu^-} = m_{A'}$;
  - missing mass = $m_{h'}$.

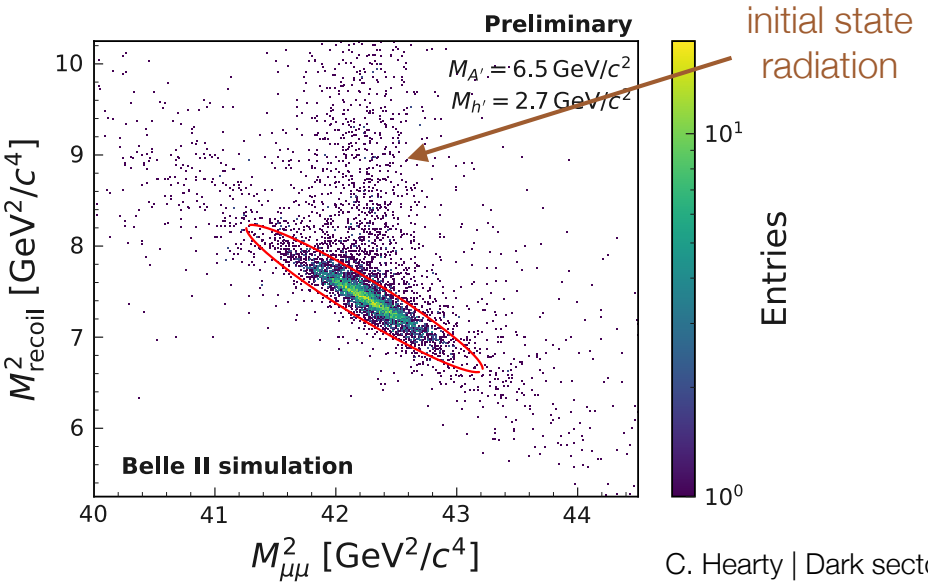
- Backgrounds:
  - $\mu^+\mu^-(\gamma)$;
  - $\tau^+\tau^-(\gamma)$ with both $\tau \to \mu\nu\bar{\nu}$;
  - $e^+e^-\mu^+\mu^-$.

- Require missing momentum to be at wide angles; cut on angular distribution of muons.

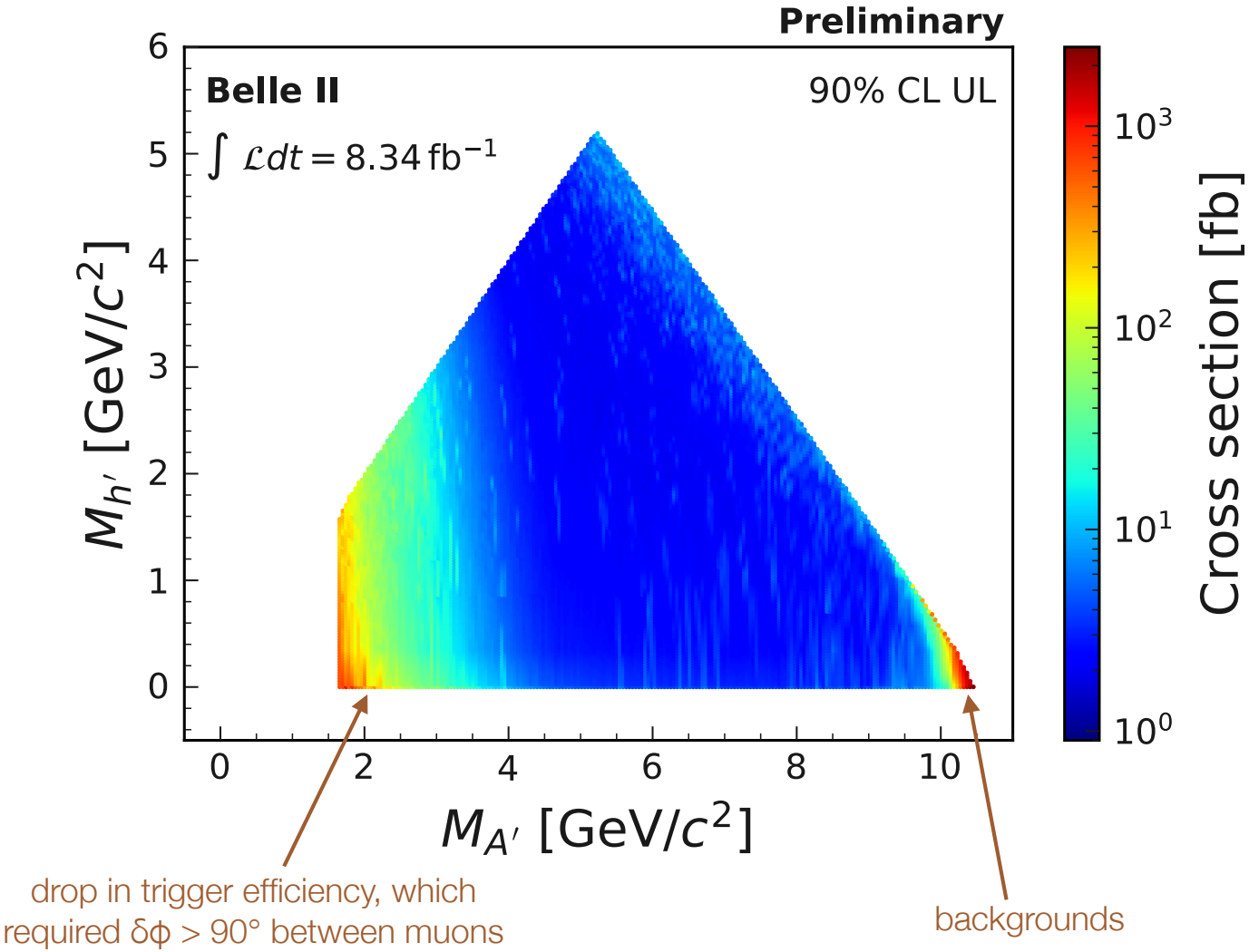
Selected events

- Good agreement with simulation.
- Search for peak in 2D; no excess observed in 9003 ellipses.





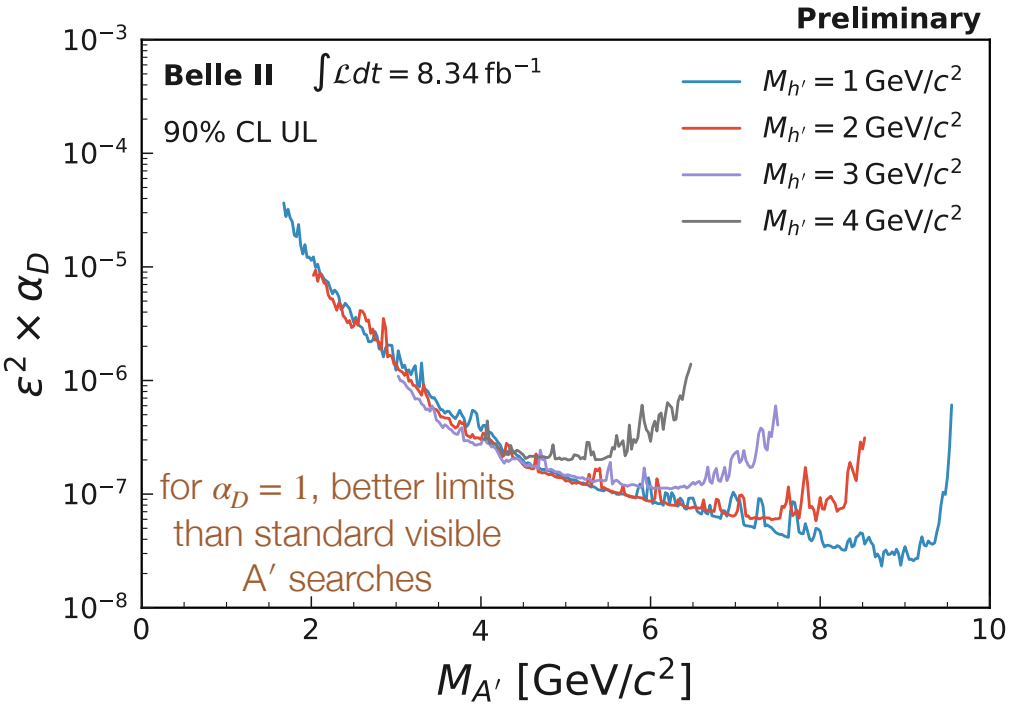
Upper limits on cross sections

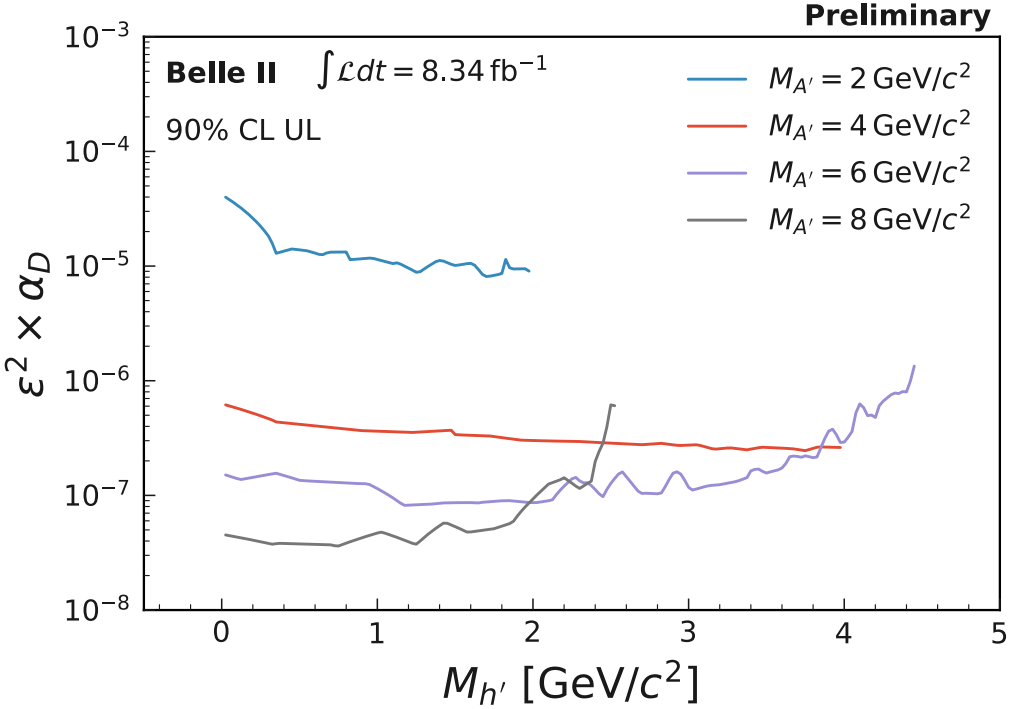


Belle II, “Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment”, 2207.00509, submitted to PRL.

Limits on model parameters

- First limits for this mass range.
- Next update: much more data; good trigger efficiency at low mass.





Summary

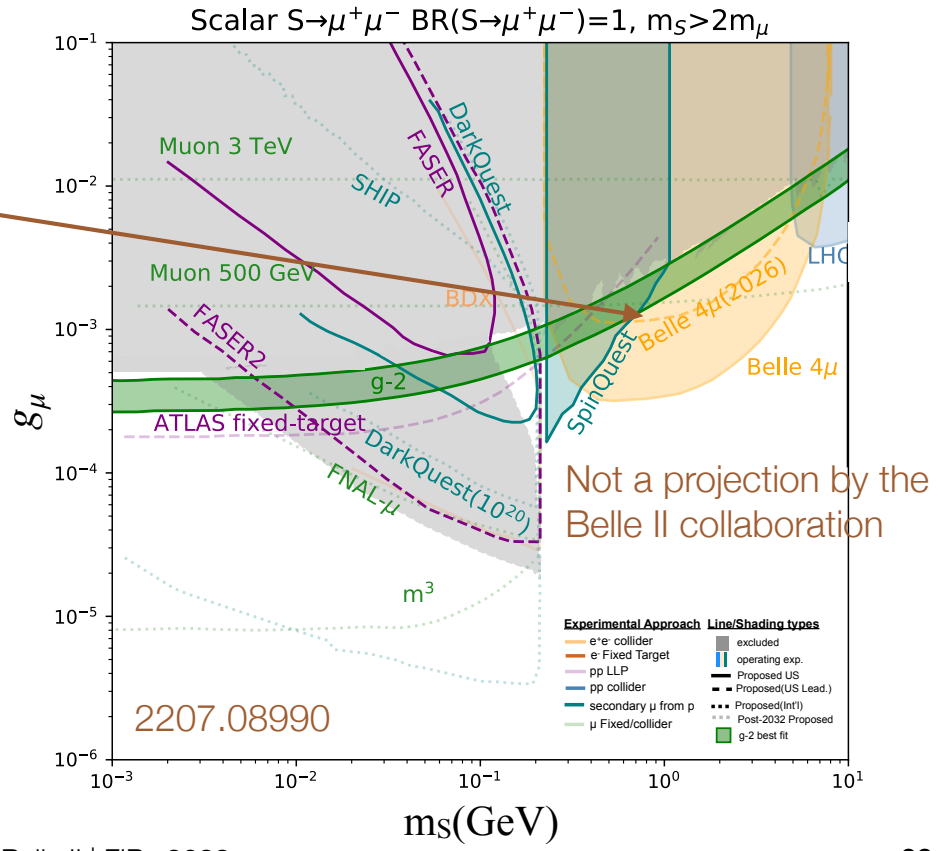
- Belle II has accumulated a near-BaBar sized data set. Several world-leading dark sector results already completed.
  - ALP → γγ: PRL 125 (2020) 161806;
  - Z′ → invisible: PRL 124 (2020) 141801 + update soon;
  - Z′ / S / ALP → tau pair: to be submitted soon;
  - dark Higgsstrahlung: 2207.00509, submitted to PRL.

- Projections show that Belle II has unique sensitivity to dark sector physics. We look forward to further increases to SuperKEKB luminosity following long shutdown 1.

Backup

Outlook for Z′ / scalar → $\mu^+\mu^-$

- For Z′ interpretation, $(g\text{-}2)_\mu$ explanation is already quite constrained by BaBar 4μ result. But leptophilic scalar (or one that couples only to muons) is not excluded.
- Belle II, with a few ab^{-1}, will have significant sensitivity to the scalar models.

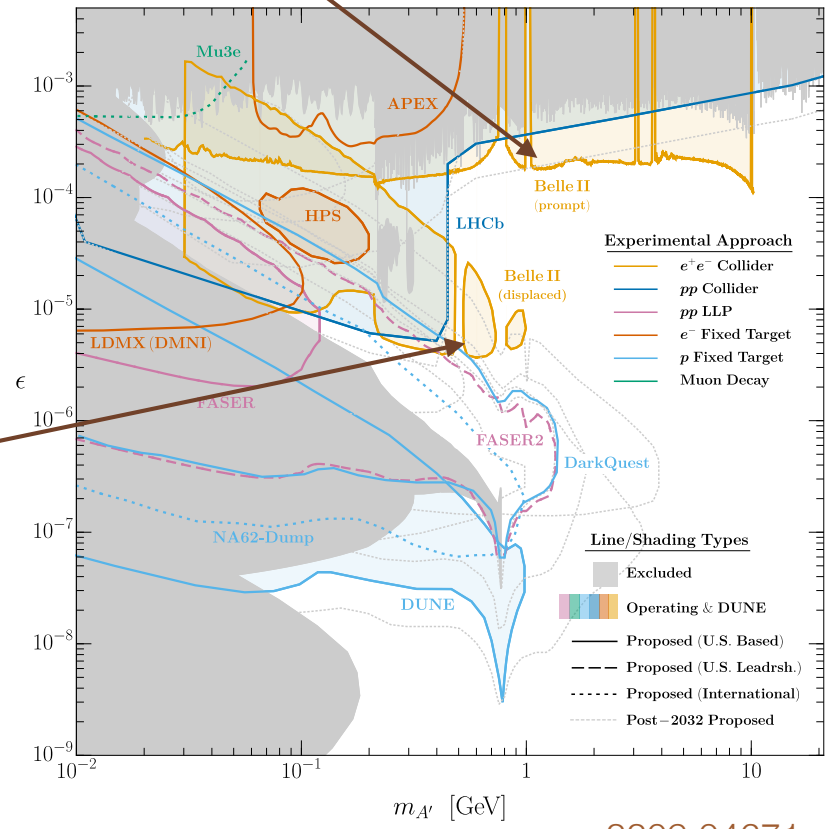


Belle II sensitivity, visible dark photon decays

- Decay to standard model particles if decays to dark matter are forbidden. Belle II will have better mass resolution than BaBar due to larger drift chamber.
- Higher luminosity will give access to smaller couplings ⇒ longer lifetimes / displaced vertices / lower backgrounds.

Belle II displaced from Phys Lett B833 (2022) 137373. Not a projection by the Belle II collaboration

Belle II prompt from 2207.06307

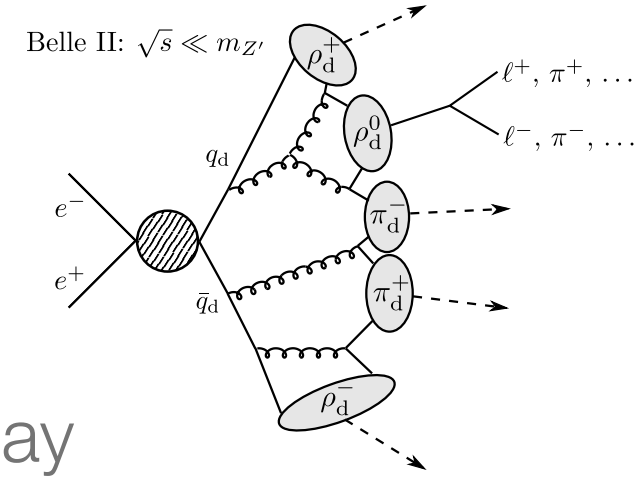


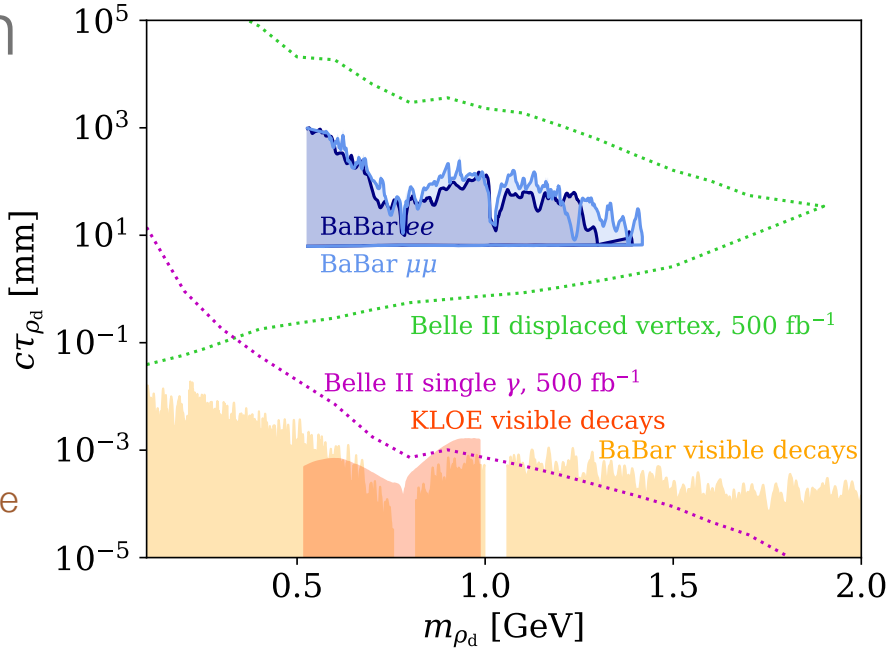
2209.04671

Dark showers

- Dark sector may not be simple; e.g. dark quarks / dark hadrons.

- Dark pions are stable (dark matter); with appropriate masses, dark rhos decay to standard model, typically with displaced vertices.
  - missing energy + displaced vertex is generally interesting.

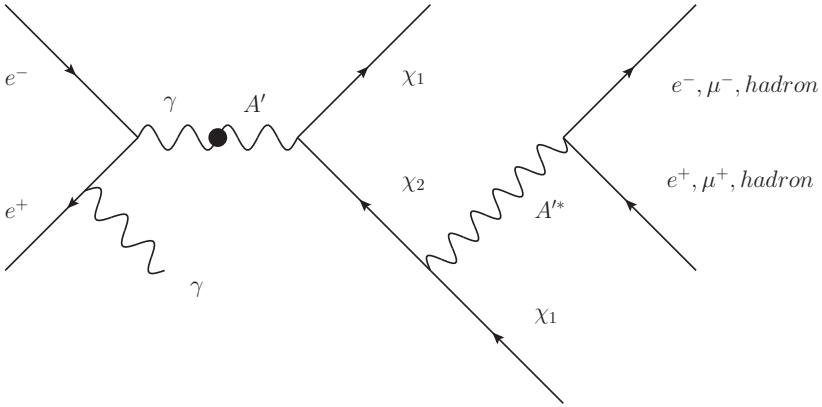




2203.08824
Not a projection by the Belle II collaboration

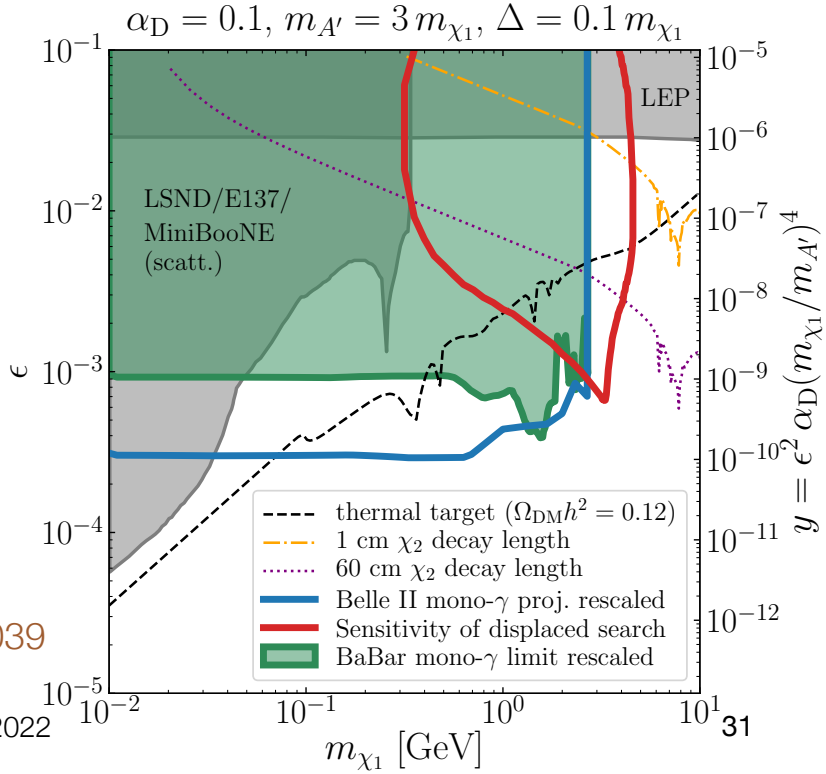
Inelastic dark matter

- Dark photon couples to a pair of dark matter states with small mass splitting.
  -Evades direct detection limits.



- $\chi_2 \to \chi_1 e^+ e^-$ gives a displaced vertex that does not project back to the interaction point.

- Work underway on displaced vertex level 1 trigger.



JHEP 02 (2020), 039