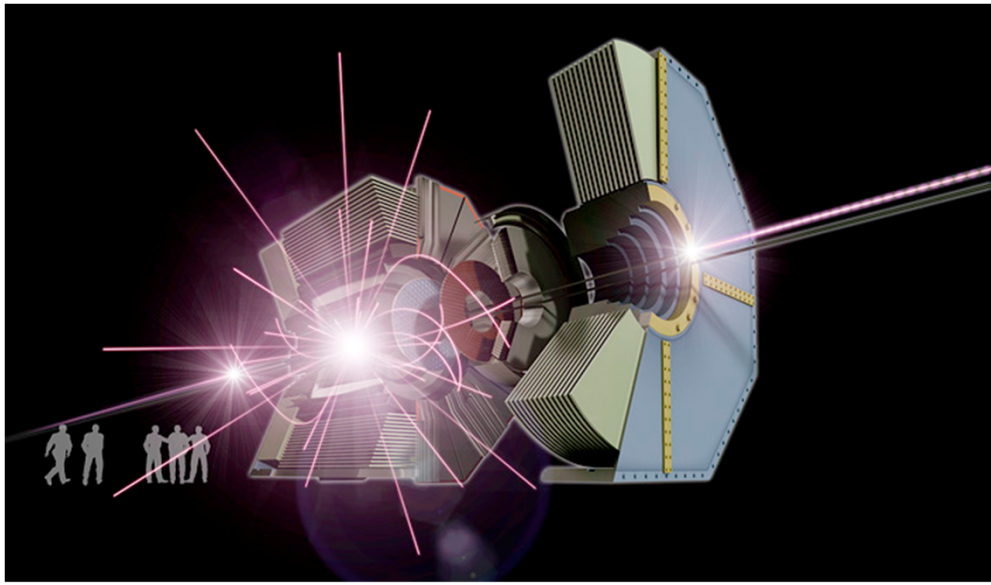
CAMTP University of Maribor

19. Božični simpozij fizikov Univerze v Mariboru
19th Christmas Symposium of Physicists of the University of Maribor

The Dark Side of Belle II



Peter Križan

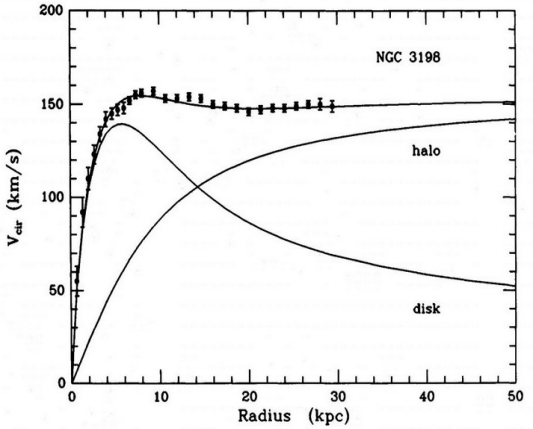
University of Ljubljana and J. Stefan Institute

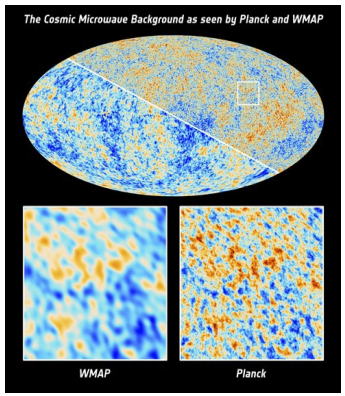
Univerza v Ljubljani

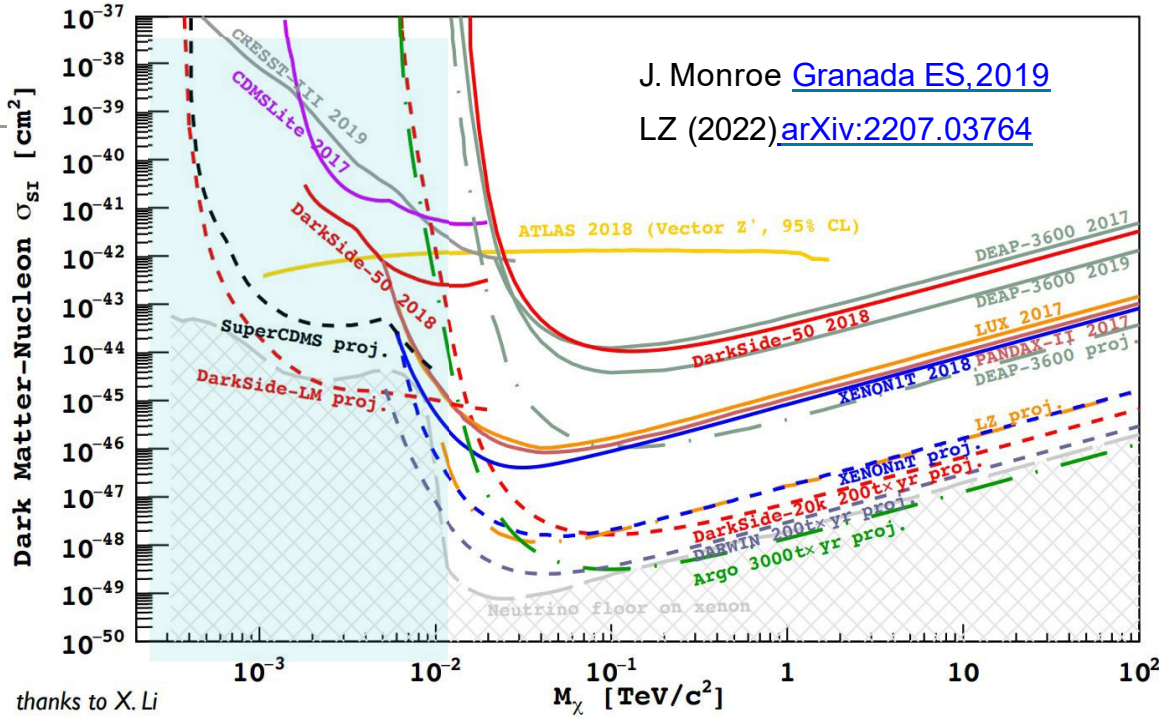
Maribor, December 15, 2022

Dark matter puzzle

Dark matter is one of the most compelling phenomena in support for physics beyond the Standard Model

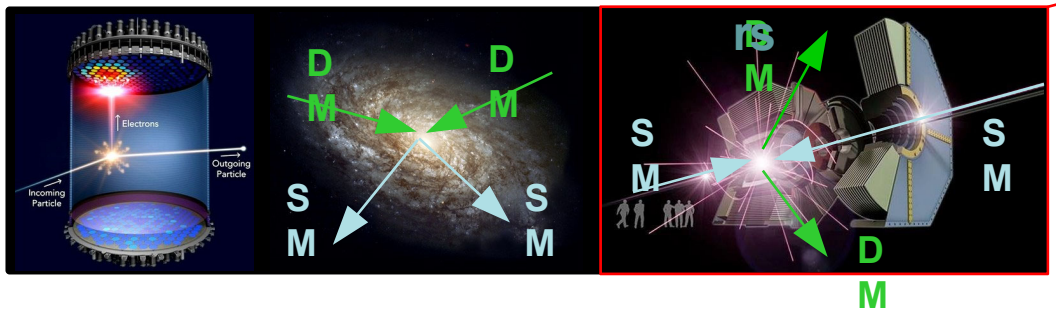






- How to search for it?

Direct **Indirect** **Collide**



Searches at colliders

- DM weakly couples to SM particles and it can be produced in SM particles annihilation at accelerators

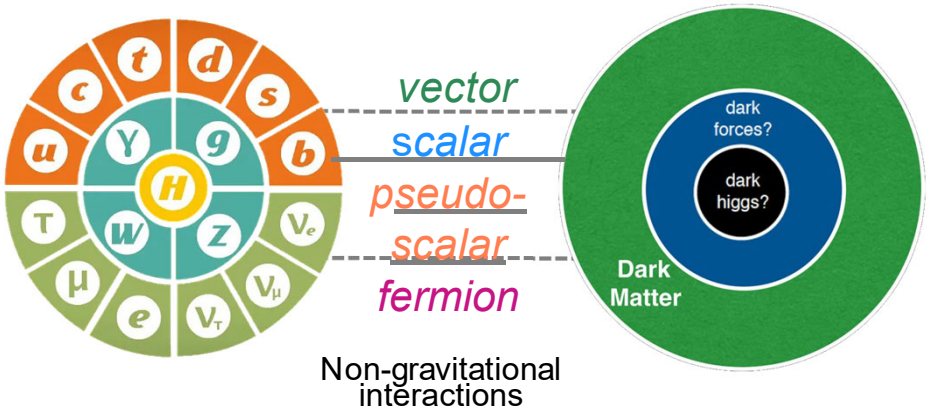
→ several signatures involving light **dark sector mediators** too

This talk: dark sector searches at an e^+e^- collider

Light dark sectors

- Null dark-matter-search results at the electroweak scale by the LHC and direct detection experiments motivates the interest for models with low-mass dark matter candidates

- Theoretical scenarios introducing light dark matter with M ~O(MeV-GeV) need light mediators too
- Dark matter does not interact directly with the Standard Model particles



- Dark matter may interact with Standard Model through several "**portal**" interactions [1, 2]:
  - vector portal (dark photon (*A'*), Z',…)
  - scalar portal (dark scalar (*S*), dark Higgs,…)
  - pseudo-scalar portal (axions, axion-like particles (*ALP*)),
  - neutrino portal (heavy neutrinos (*N*))
- Not just solving the dark matter puzzle. Could explain:
  - some astrophysics anomalies: positron excess in cosmic rays, …, (PAMELA, Fermi, …)
  - some anomalies in *B* meson decays: R_{D^*}, R_{K^*},… (Belle, LHCb, …) → Luka Šantelj (Friday)
  - the $(g-2)_\mu$ anomaly, recently confirmed at Fermilab [3]

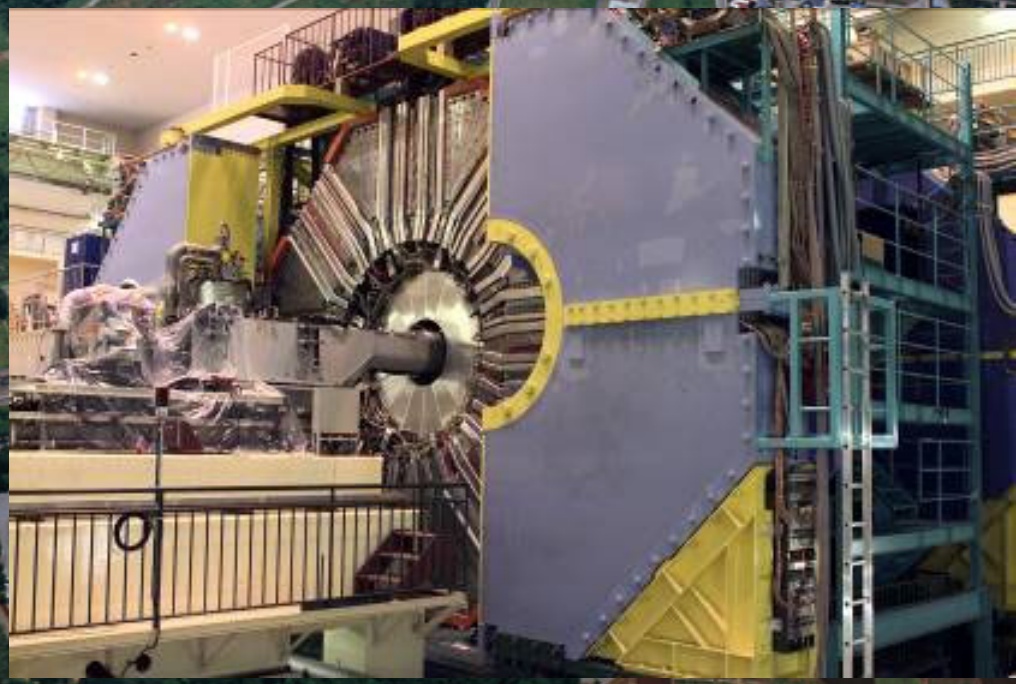
[1] Batell et al., Phys. ReV. D 80, 095024 (2009)
[2] Essig et al., arXiv:1311.0029 (2013)
[3] Abi et al., Phys. Rev. Lett. 126, 141801 (2021)

Outline

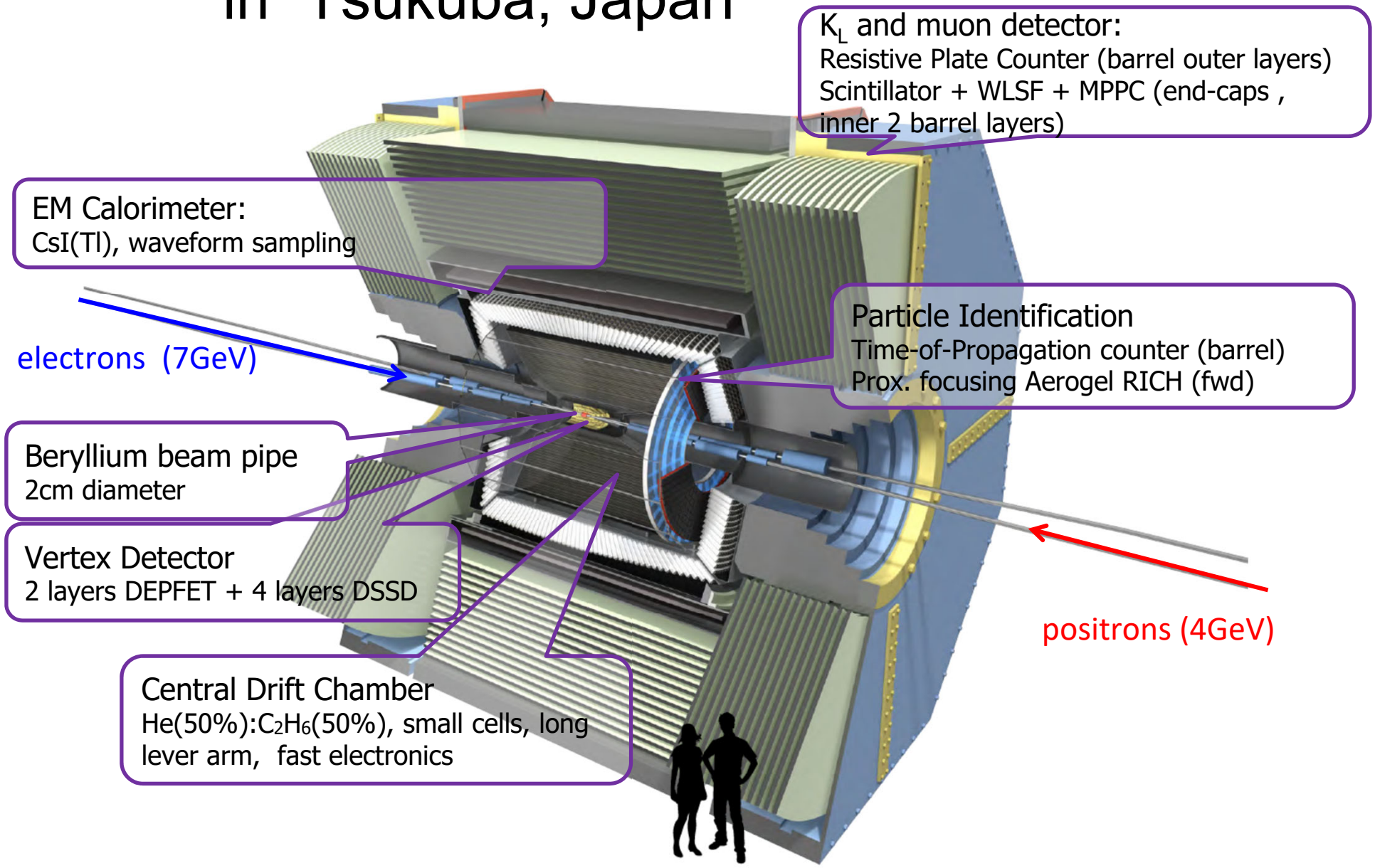
- Belle II and SuperKEKB
- Z′ and leptophilic dark scalars
- Dark photons

Belle II and SuperKEKB

Belle II at SuperKEKB



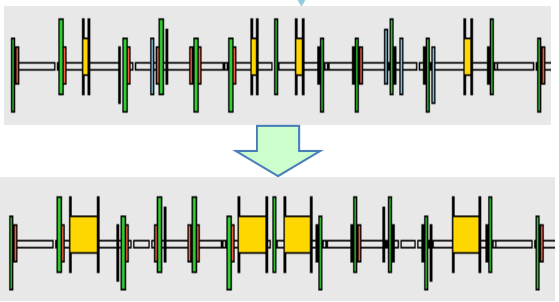
Belle II at the SuperKEKB e^+e^- collider in Tsukuba, Japan



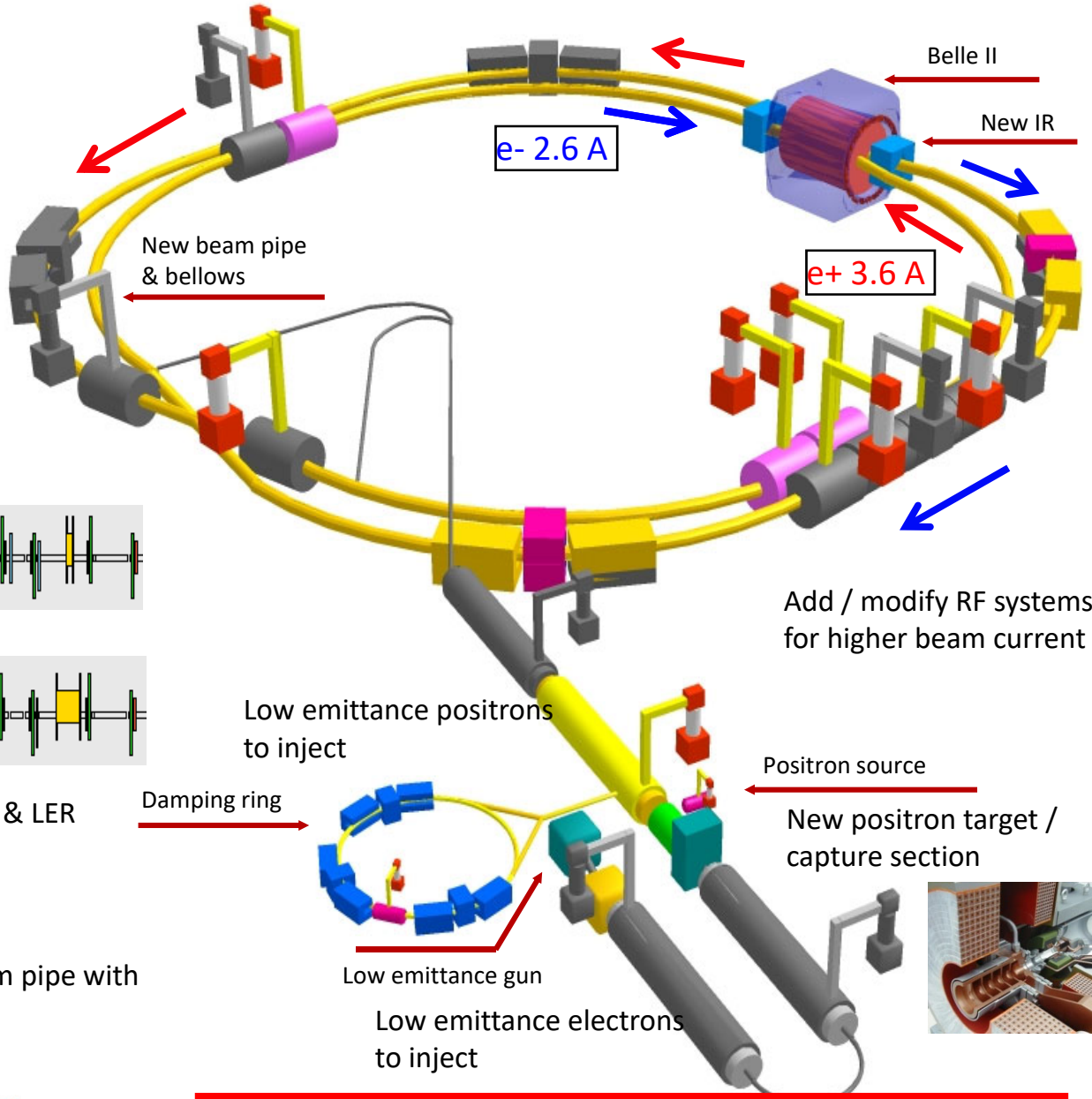
Almost a total upgrade of Belle → Belle II for better performance and higher rate capabilities.

To get x30 higher luminosity KEKB → SuperKEKB

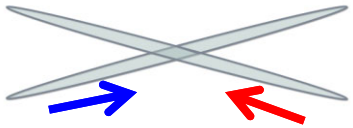
Replace short dipoles with longer ones (LER)



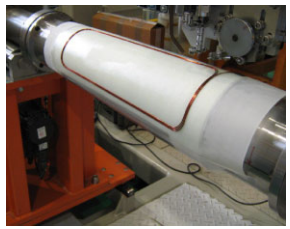
Redesign the lattices of HER & LER to squeeze the emittance



Colliding bunches



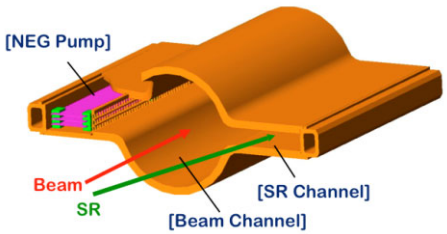
New superconducting /permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

New positron target / capture section

TiN-coated beam pipe with antechambers



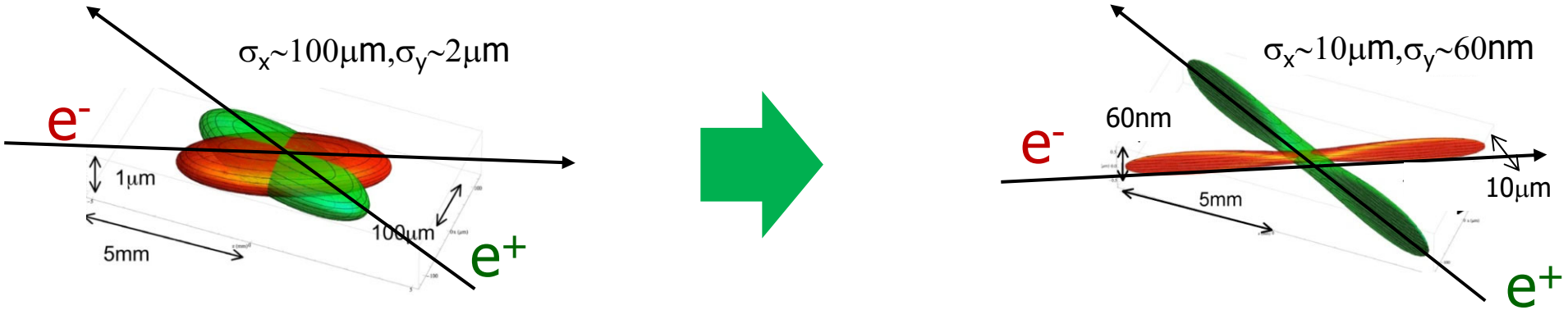
SuperKEKB, the first new collider in particle physics since the LHC

Super KEKB uest for BSM

How big is a nano-beam ?

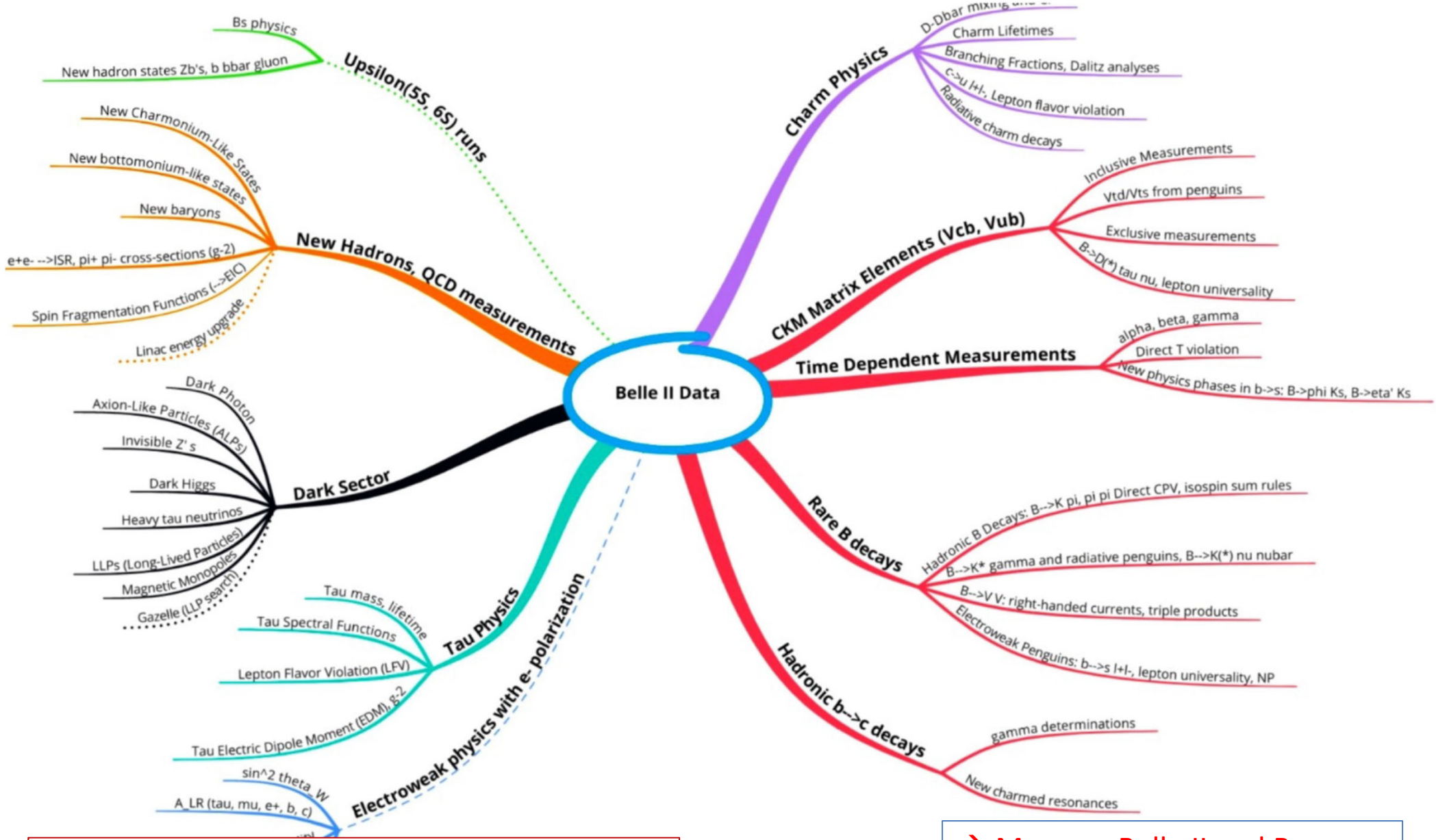
How to go from an excellent accelerator with world record performance – KEKB – to a 30x times better, more intense facility?

In KEKB, colliding electron and positron beams were already much thinner than a human hair...



... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

Physics program

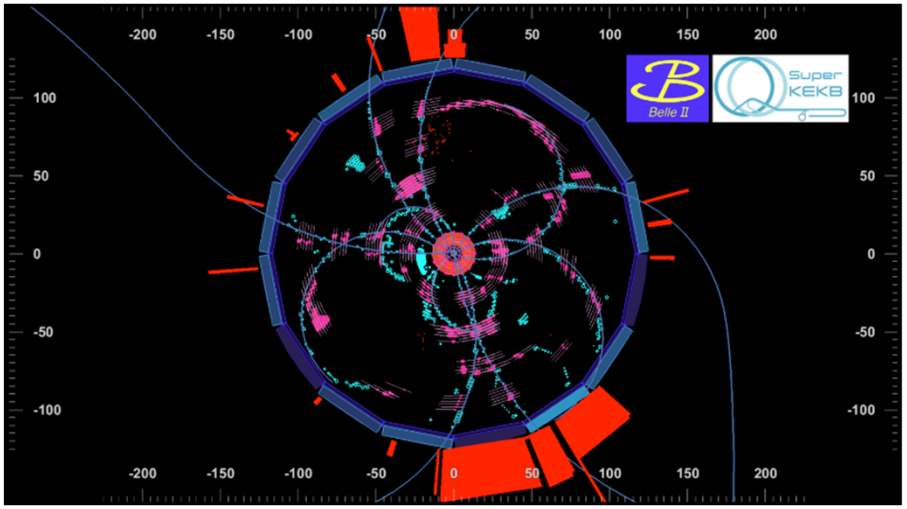


Physics potential summarized in the Belle II 'physics book' PTEP 2019 (2019) 123C01, arXiv:1808.10567

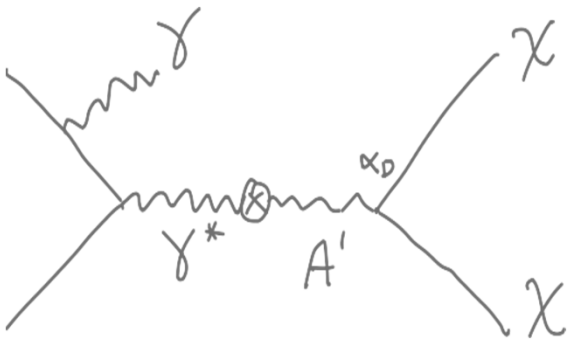
→ More on Belle II and B physics studies → talk by Luka Šantelj on Friday

Advantages of a B factory in the LHC era

Unique capabilities of a B factory:

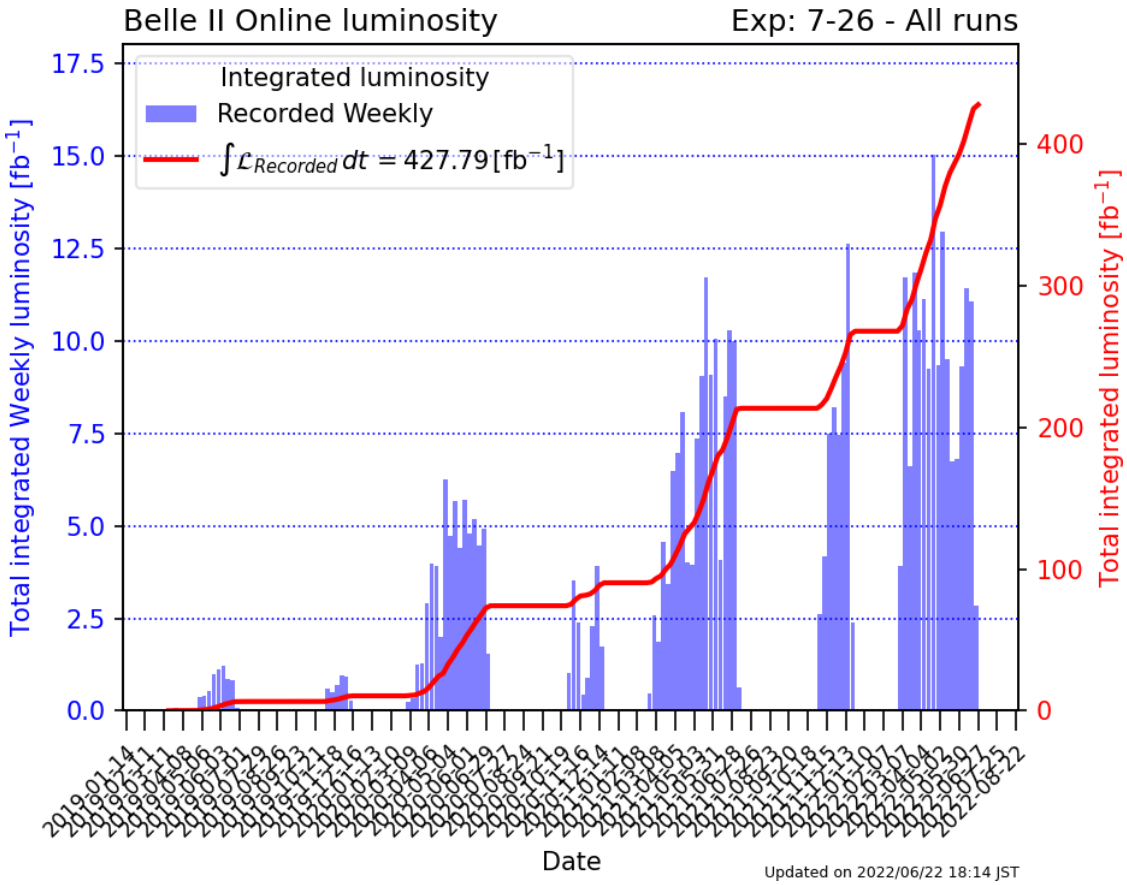


→ Exactly two B mesons produced
→ High flavour tagging efficiency
→ Detection of gammas, π^0s, K_Ls
→ Very clean detector environment
(can study decays with several neutrinos in the final state, tau physics, dark sector)



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

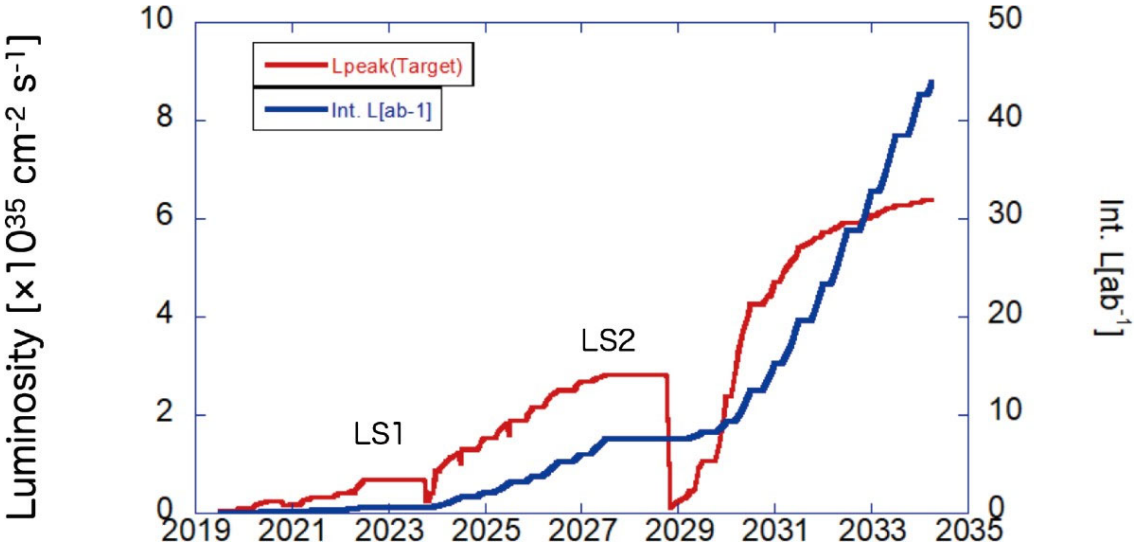
- Belle II has collected 428 fb^{-1} since March 2019.
- Currently in the long shutdown 1 to install the two-layer pixel detector, July 2022 – September 2023.



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.

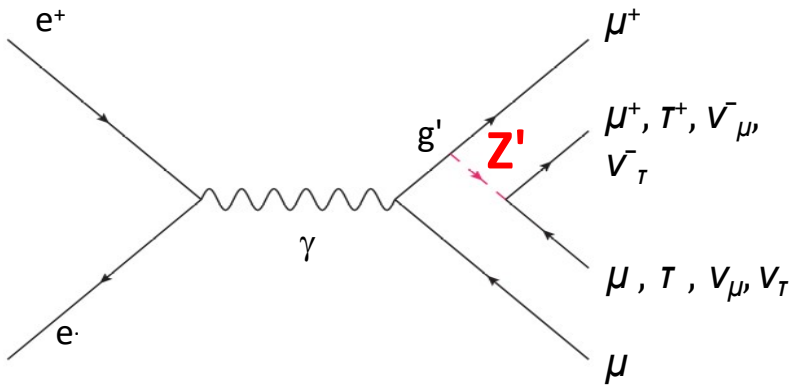


Z′ and leptophilic dark scalars

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

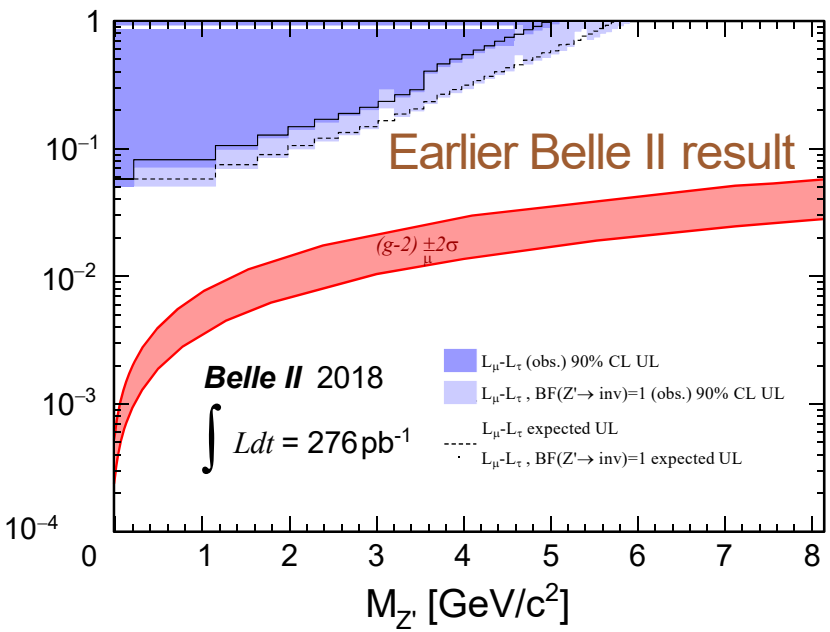
- Existing limits from BaBar, CMS, and Belle on $Z' \rightarrow \mu^+\mu^-$ strongly constrain parameter space relevant for $(g\text{-}2)_\mu$.

Phys. Rev. D 94 (2016) 011102

Phys. Lett. B 792 (2019) 345

Phys. Rev. D 106 (2022), 012003

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



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

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

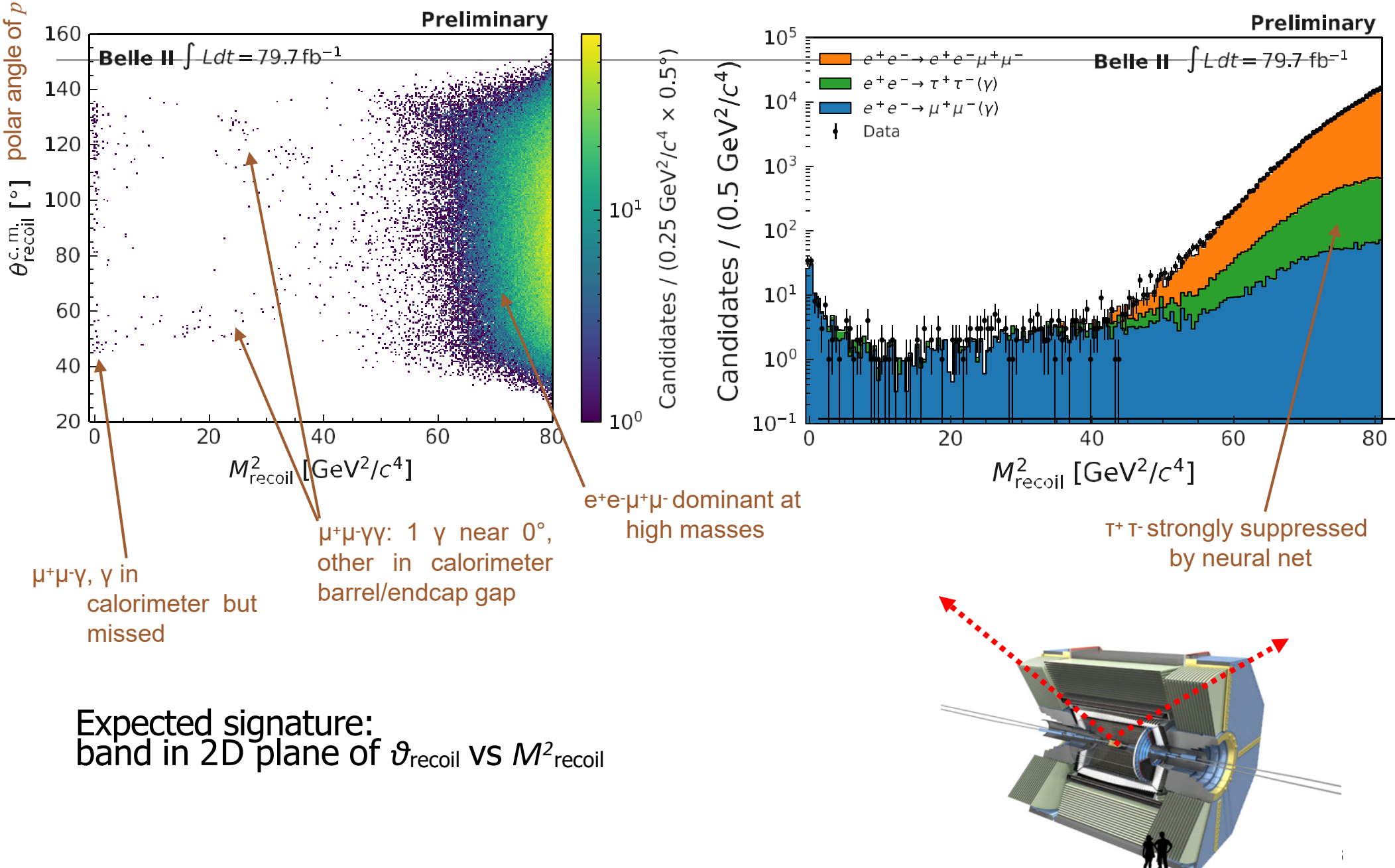
- Signature: pair of muons with missing mass = m_Z.

- 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.

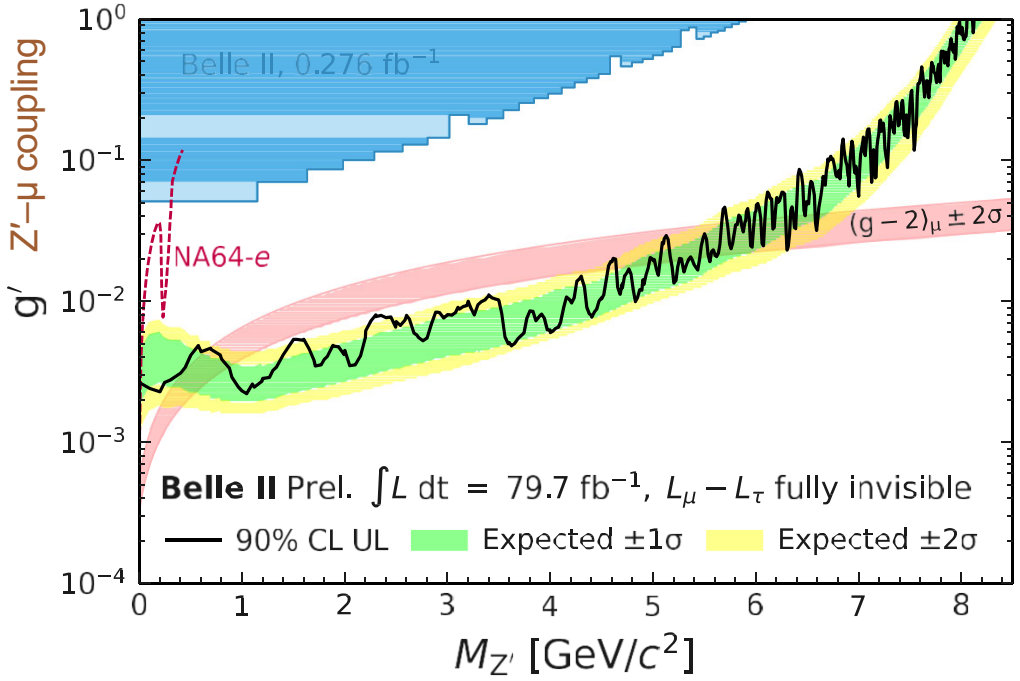
$Z' \rightarrow$ invisible selected events



Expected signature:
band in 2D plane of $\vartheta_{\mathrm{recoil}}$ vs M^2_{recoil}

$Z' \rightarrow$ invisible, results

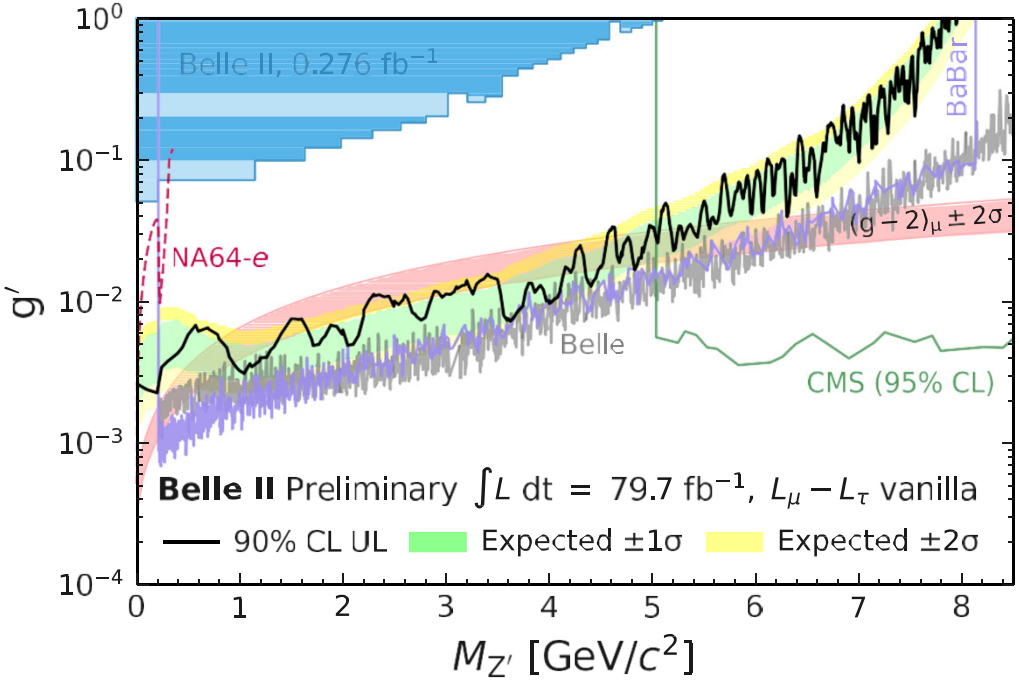
- Fit 2D distribution θ^{cm}_{recoil} vs M^2_{recoil} ; no excess observed



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

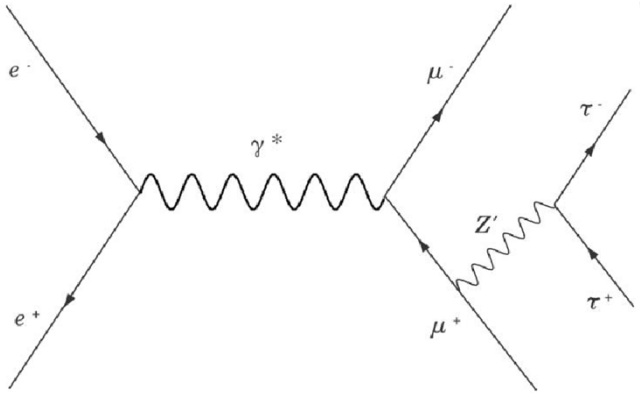
Z′ results, Z′ → standard model only

- 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 $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ events with the Belle II experiment

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



- Leptophilic scalar S with mass-dependent coupling;
  - BaBar has searched for $S \rightarrow e^+e^-$ 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.

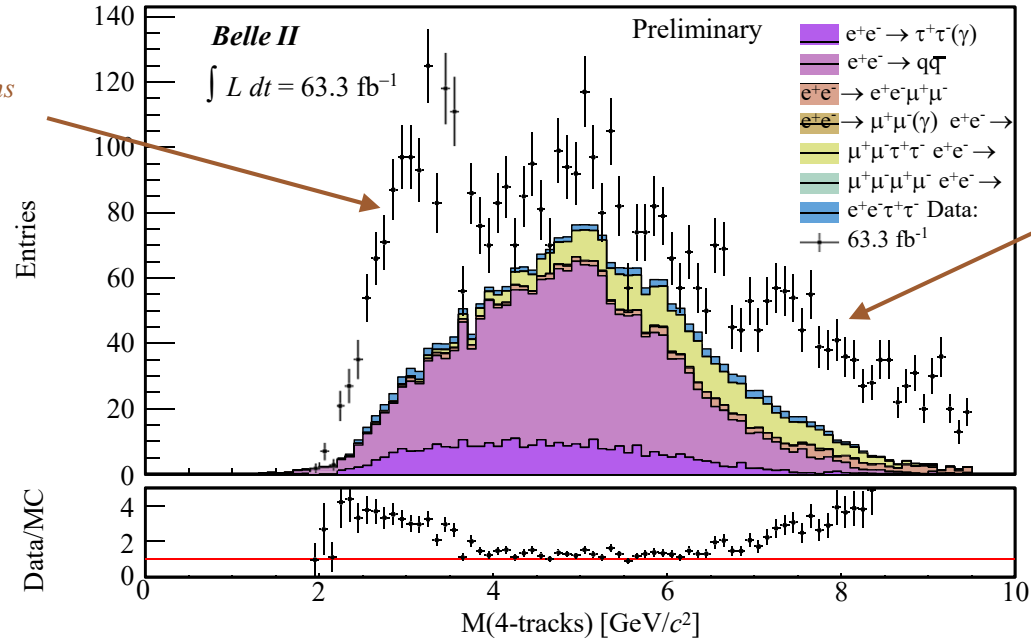
- Tau decays → one charged track and at least one neutrino per tau in the final state → Signature: 4 tracks, including ≥2 muons, missing mass.

Selected events

- Require M(4 tracks) < 9.5 GeV/c² 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

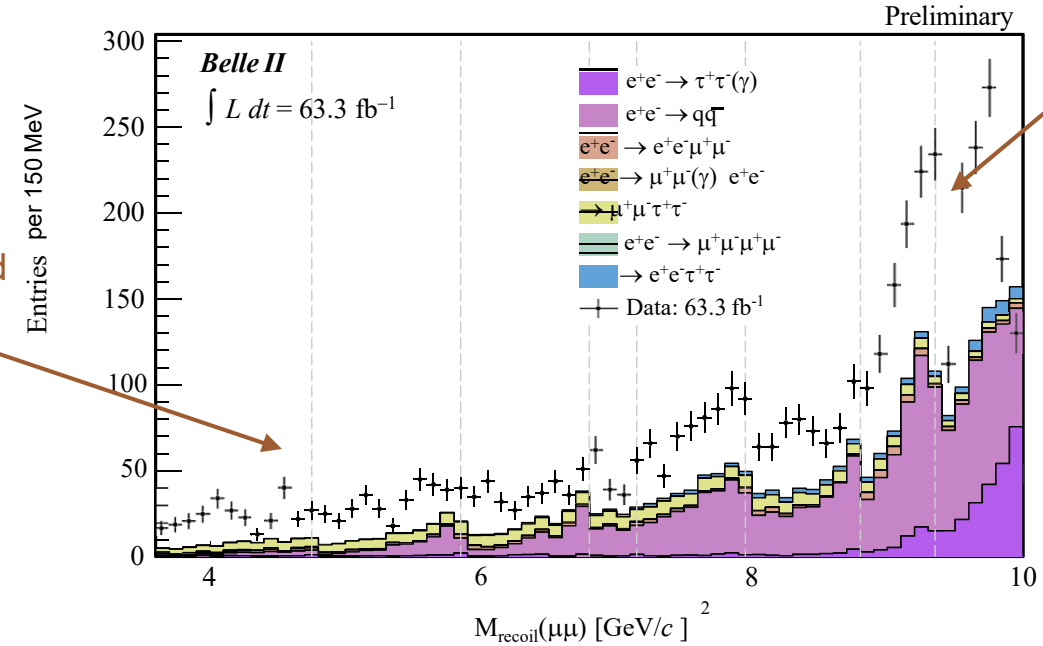


$e^+e^- \to \gamma 4\ell^\pm$ not simulated

- 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.

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

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

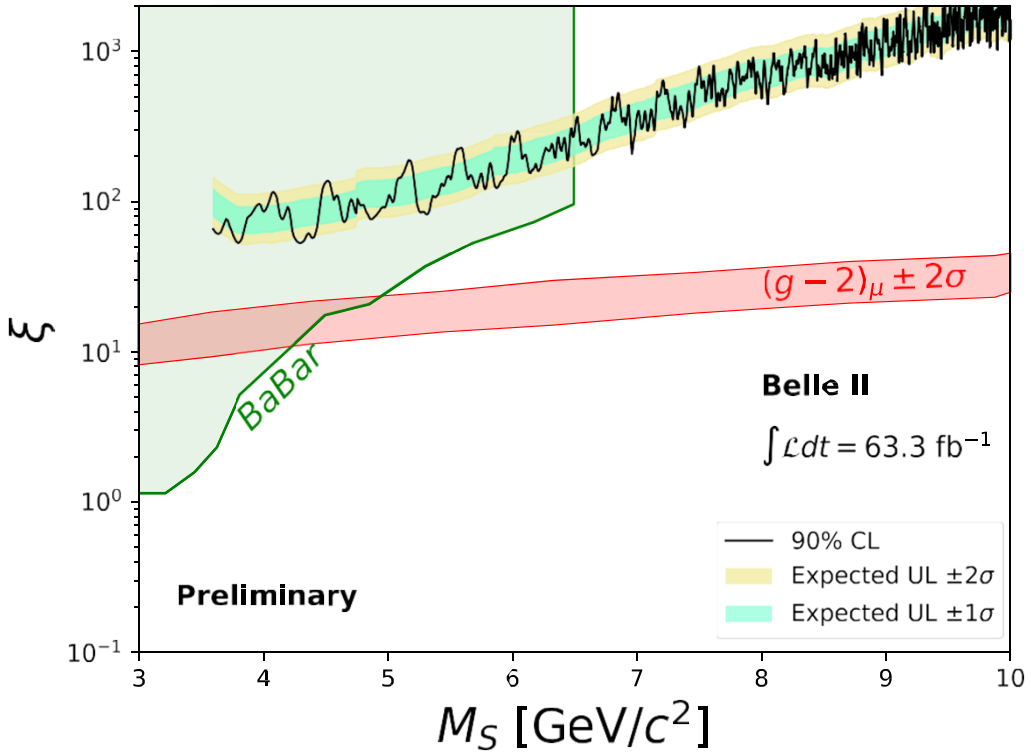


data/MC discrepancies:
No-peaking expected and **understood**

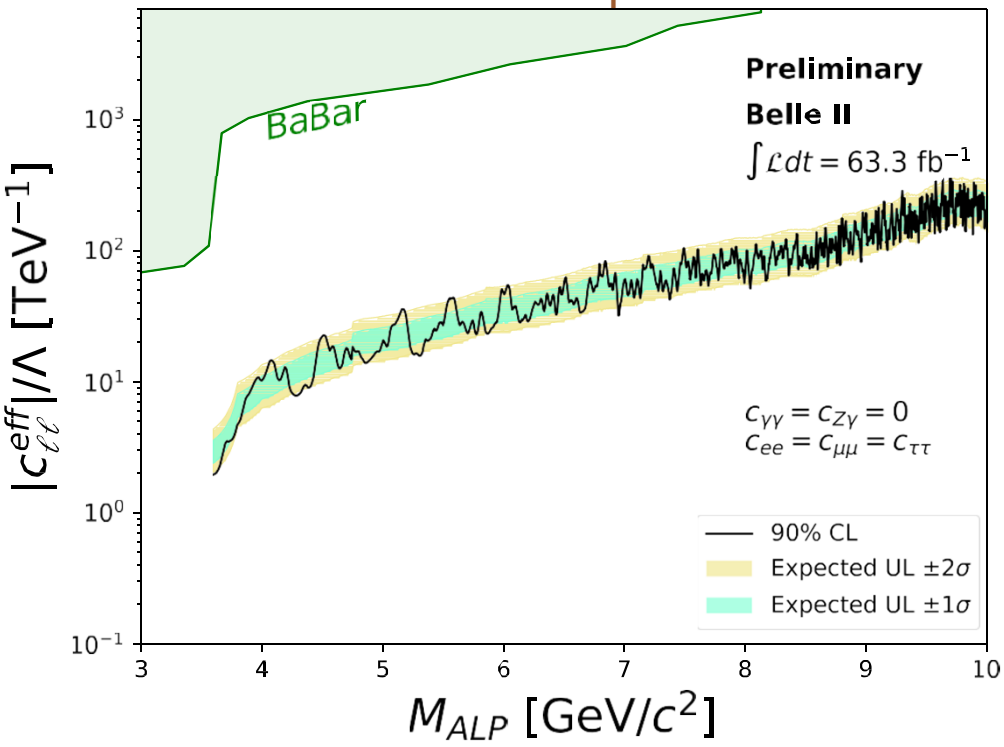
Tau pair resonance results

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

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

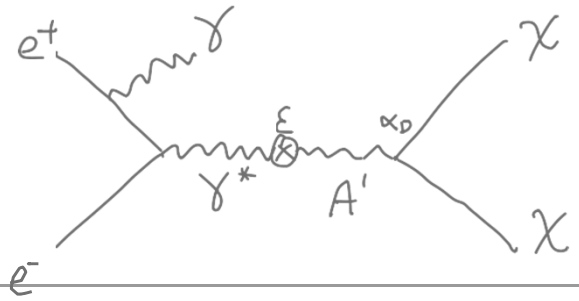


axion-like particle



Dark photons

Dark photons and Belle II



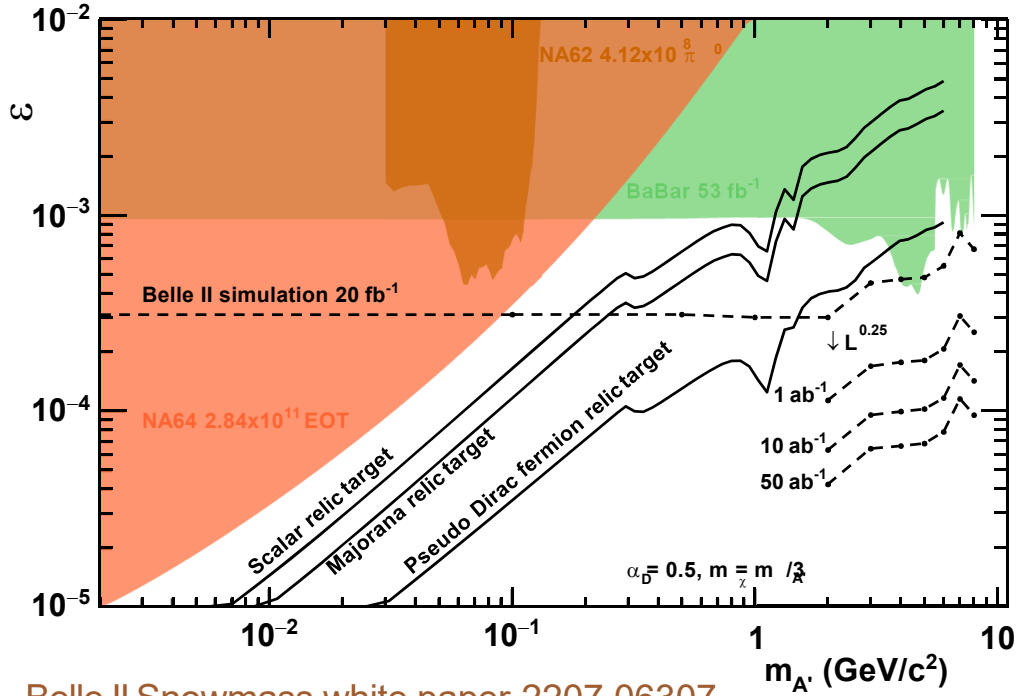
- Simplest case: on-shell production of a dark photon A′ via initial-state radiation. Will decay to dark matter

  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

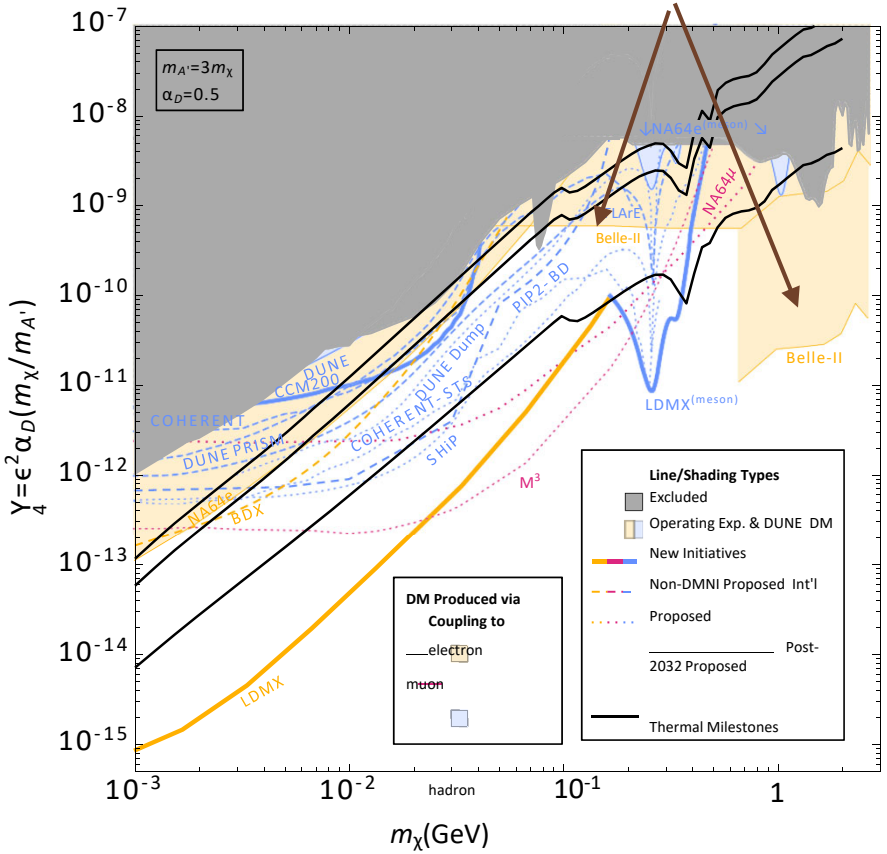
Belle II sensitivity, invisible dark photon decays

- 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

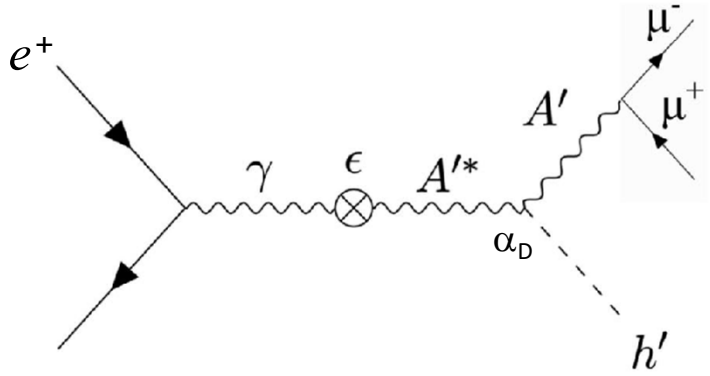
same limits, different parameters



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:

  - $\mu^+\mu^-(\gamma)$;

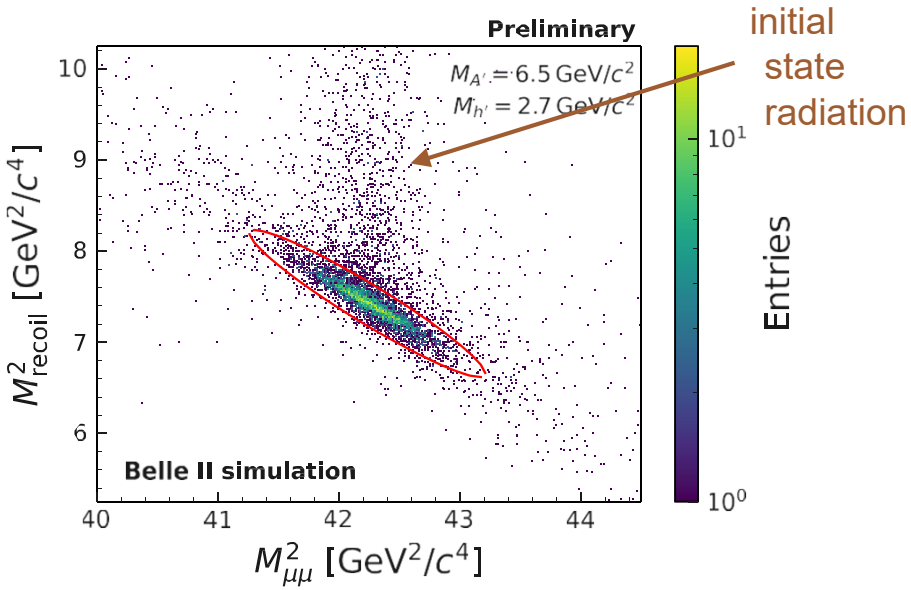
  -$\tau^+\tau^-(\gamma)$ with both $\tau \rightarrow \mu\nu\bar{\nu}$;

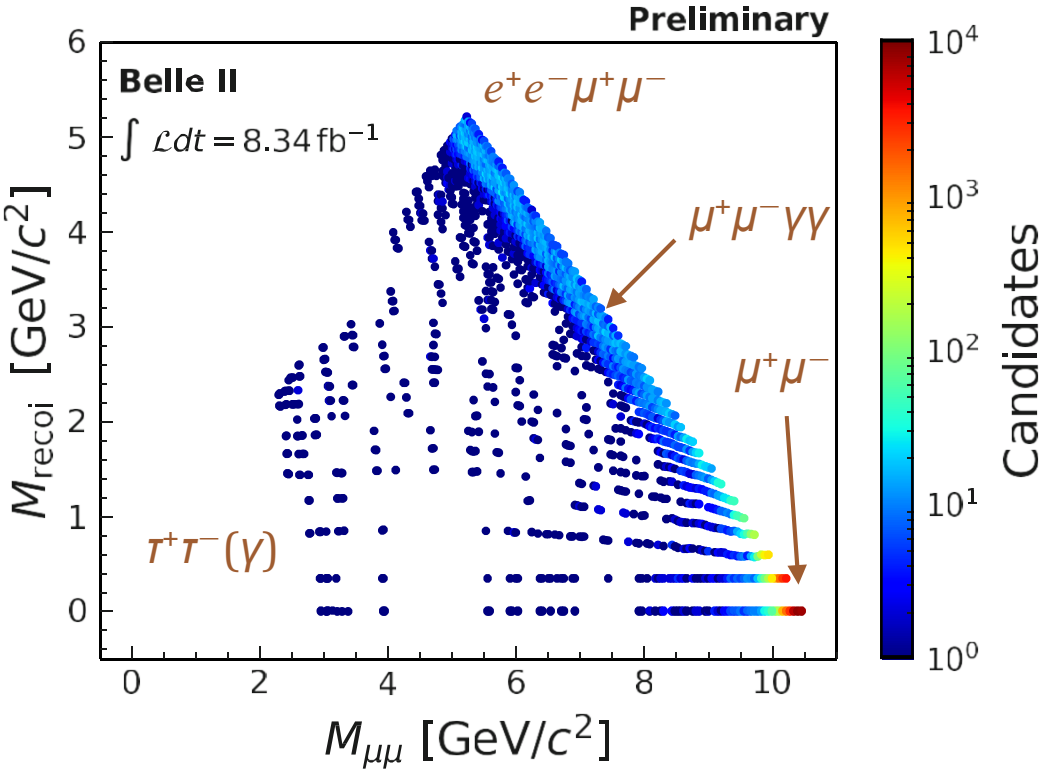
  - $e^+e^-\mu^+\mu^-$.

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

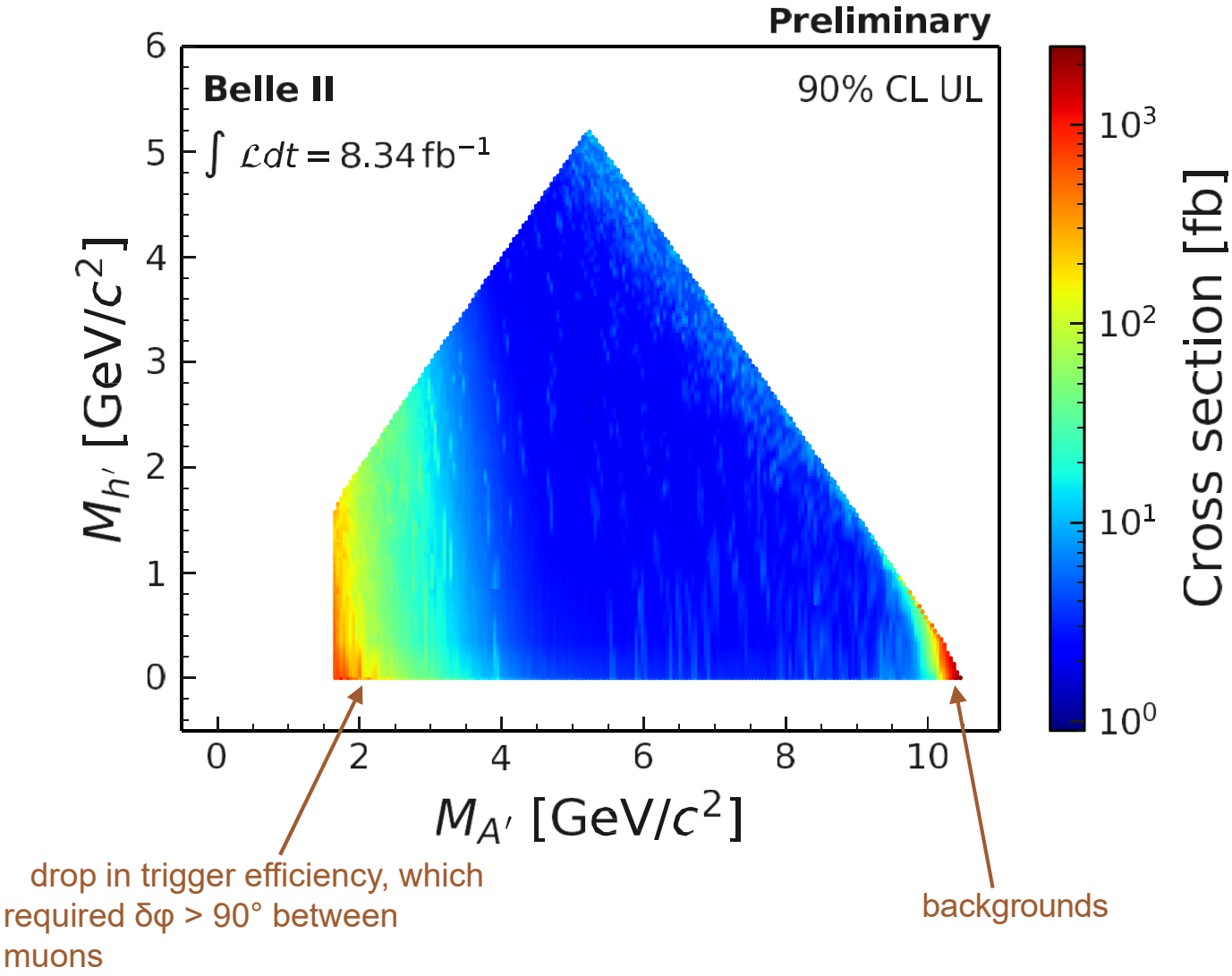
Selected events

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





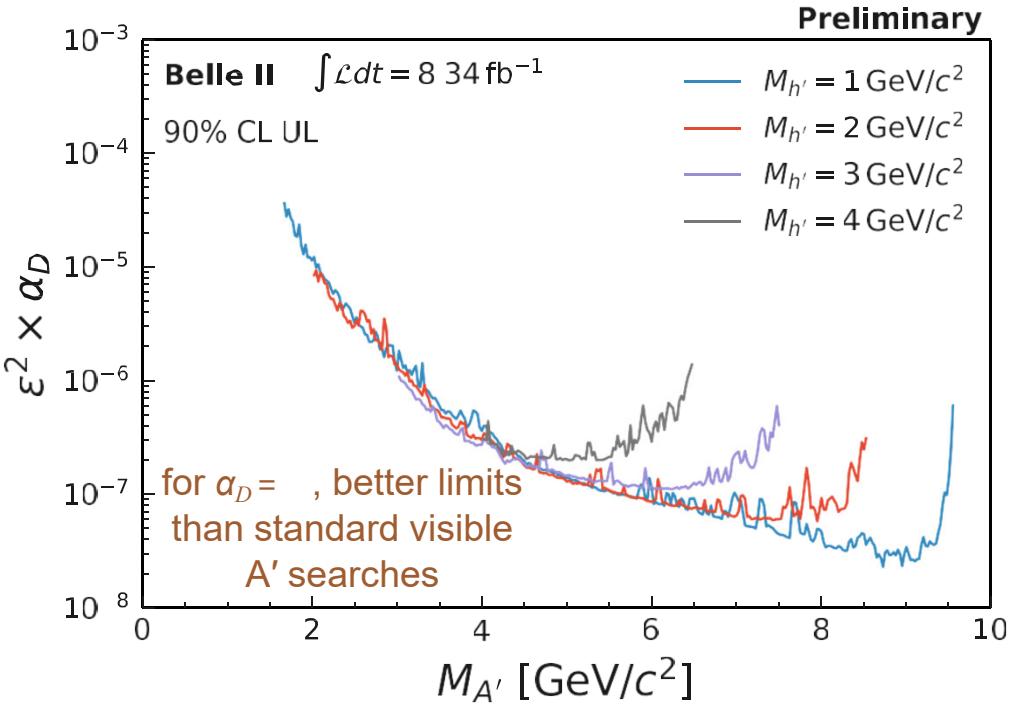
Upper limits on cross sections

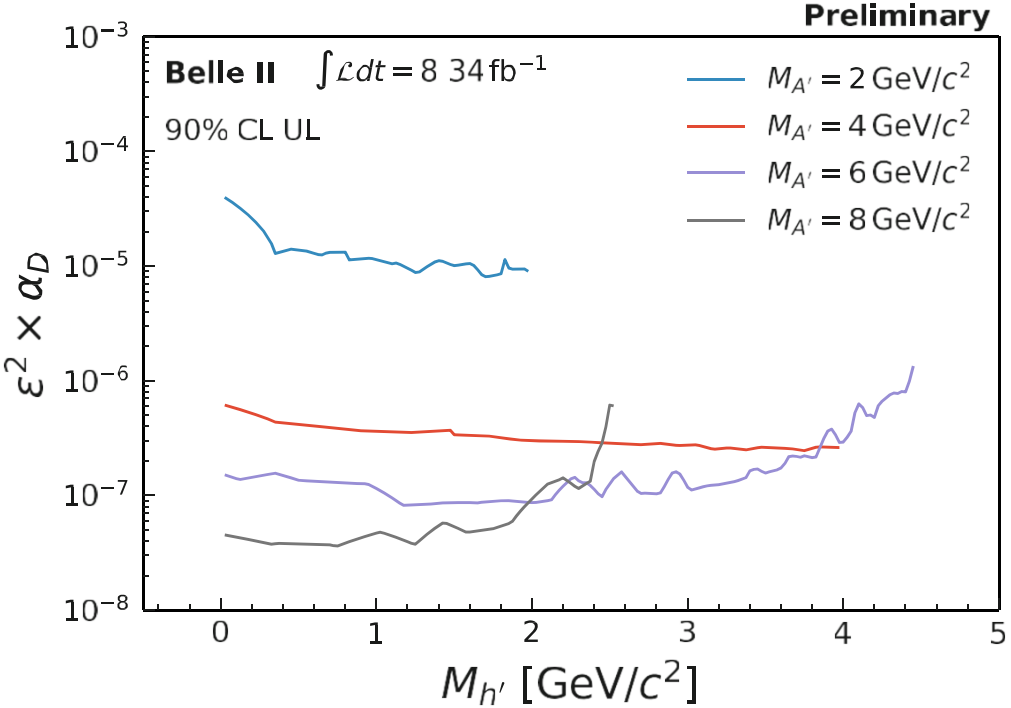


Belle II, “Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment”, 2207.00509, submitted to PRL.

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.