Recent dark sector results at Belle II

For the Belle II collaboration, Shintaro Ito (KEK)

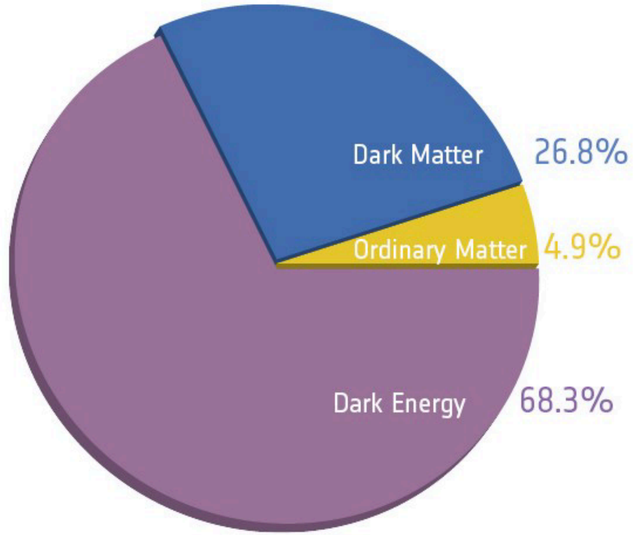
2022 August 17th @ Phi to Psi 2022

Outline

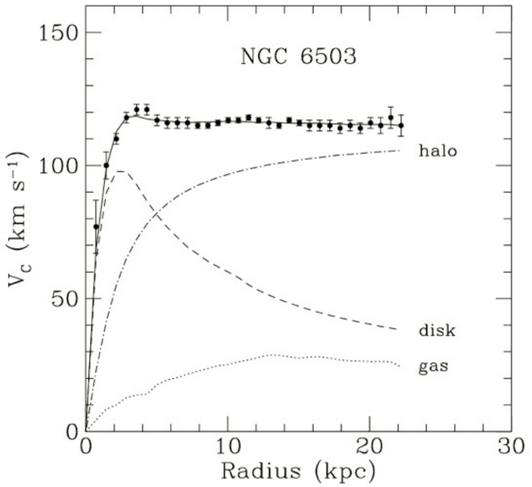
- Dark matter.
- SuperKEKB and Belle II.
- Dark sector at Belle II.
- New results of dark sector searches.
  - Dark Higgsstrahlung
  - $Z' \to \text{invisible}$
  - $Z', S, \text{ALP} \to \tau\tau$
- Summary and future prospects.

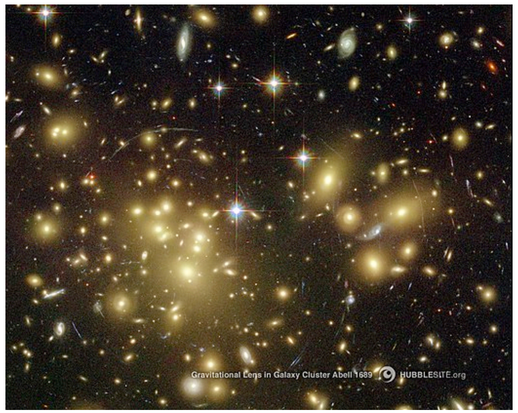
Dark Matter

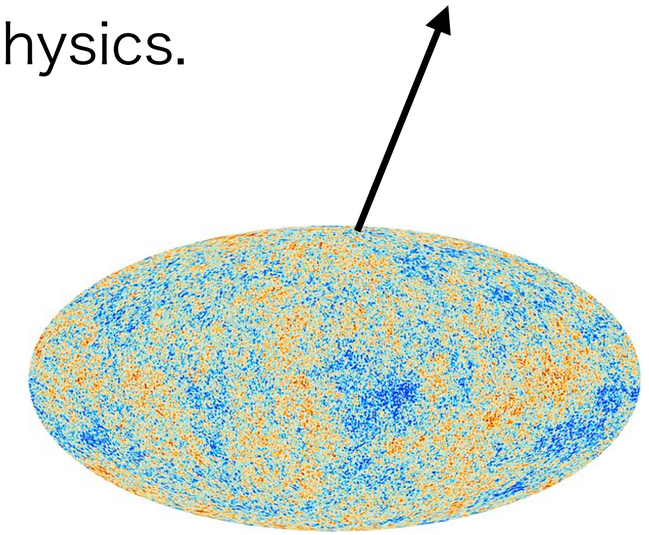
- There are some evidences for existence of dark matter,
  - Galaxy rotation curve.
  - Gravitational lens.
  - Measurement of cosmic microwave background.
    ➡ Density of dark matter in universe: **26.8%**



- However, dark matter is not included in the SM.
  - Many searches have been performed, but not observed yet.
  - Dark matter is one of the most important problem in physics.



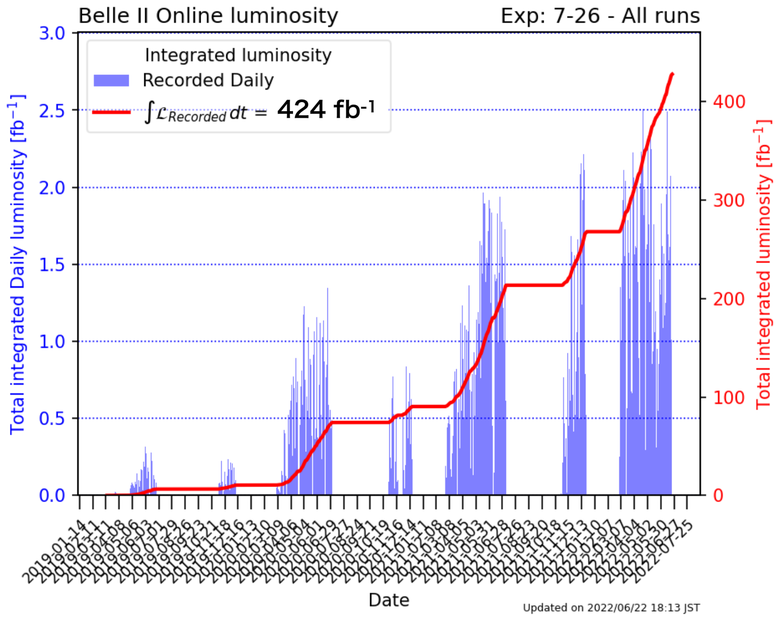


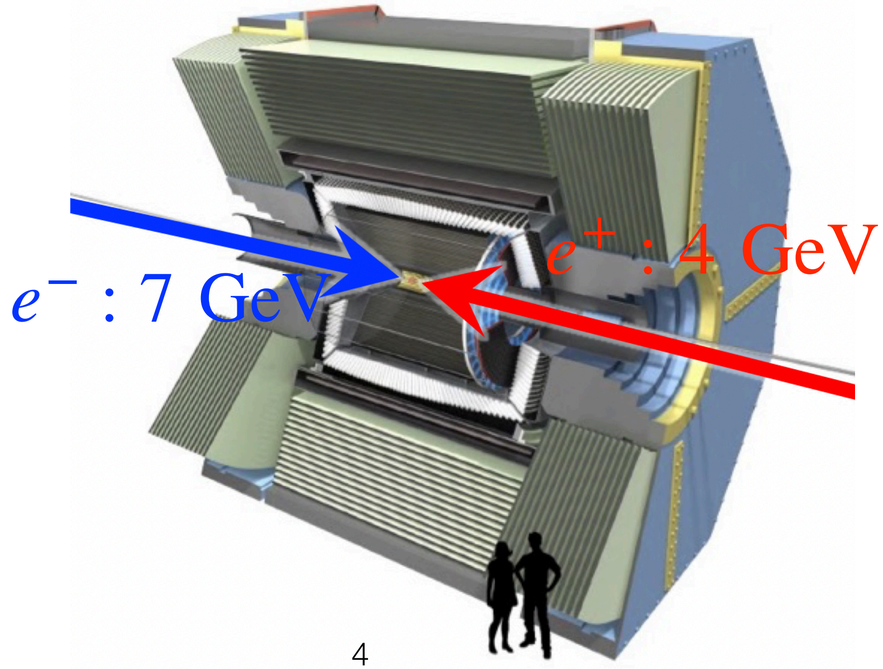


SuperKEKB and Belle II

- Belle II at SuperKEKB: e^+e^- collider experiment.
  - Mainly $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ with $\sqrt{s} = 10.58$ GeV (others: $\Upsilon(nS)$ with $\sqrt{s} \simeq 10$ GeV/c^2).
  - Flavor physics, dark matter searches, and so on.
- Until the run in June 2022, $\mathscr{L}_{\rm peak} = 4.7 \times 10^{34}$ cm^{-2} s^{-1} (world record) and $\mathscr{L}_{\rm int} = 424$ fb^{-1}.

  ➡ Goal of Belle II: $\mathscr{L}_{\rm int} = 50$ ab^{-1}





From inside	
PXD	Vertex
SVD	Vertex, track
CDC	Track, momentum
TOP, ARICH	K/π ID
ECL	Photon, electron
KLM	K_L、μ ID

Dark Sector Searches in Belle II

- $\sqrt{s} = 10.58\ \mathrm{GeV}$ so mass up to $\sim 10\ \mathrm{GeV}/c^2$ would be search region.

  - Scalar portal: dark Higgs
  - Vector portal: dark photon, Z'
  - Pseudo scalar portal: axion, ALPs
  - Fermion portal: sterile neutrinos (and more?)

  ➡ These may also explain anomaly of muon g-2.

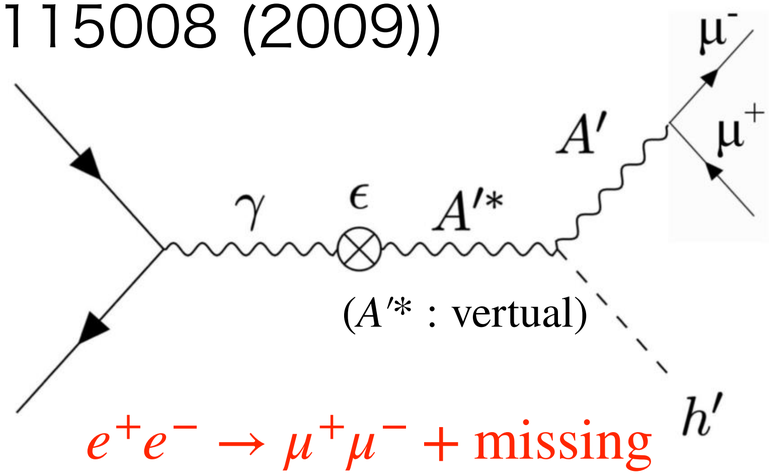
- Typical processes
  - $e^+e^- \to \mathrm{SM\ particles} + X\ (\mathrm{visible\ or\ invisible})$ e.g. $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ visible or invisible.
  - B (or others e.g. τ) $\to \mathrm{SM\ particles} + X\ (\mathrm{visible\ or\ invisible})$ e.g. $B \to Ka$

- Some of these processes have not been sought in the Belle or BaBar experiments, and could be searched in Belle II by improvement of trigger condition.

Dark Higgsstrahlung: $e^+e^- \to A'h'$

- Dark Higgsstrahlung process $e^+e^- \to A'h'$ (Phys. Rev. D 79, 115008 (2009))
  - Dark photon A'
    - couples to the SM with kinematic mixing ϵ
  - Dark Higgs h'
    - $M_{A'}$ can arise from spontaneous symmetry breaking
    - no mixing with the SM Higgs.
    - couples with the constant α_D

      ➡ The cross section for dark Higgsstrahlung $\sigma \propto \epsilon^2 \alpha_D$.



$e^+e^- \to \mu^+\mu^- + \text{missing}$

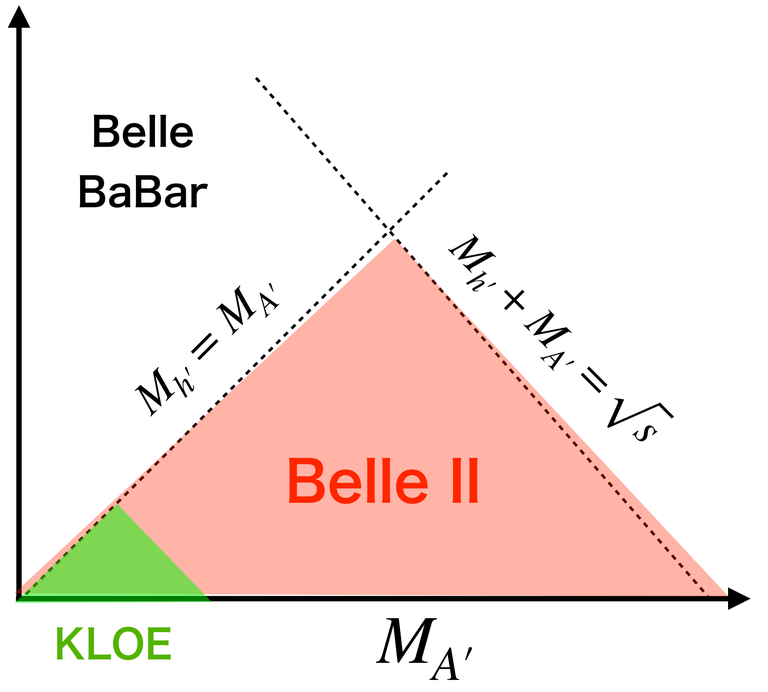
- $M_{h'} > M_{A'}$: dark Higgs is visible: $h' \to$ two dark photons

  ➡ Constrained by Belle and BaBar ($\epsilon^2 \alpha_D < 10^{-9} \sim 10^{-8}$).

- $M_{h'} < M_{A'}$: dark Higgs is **invisible**

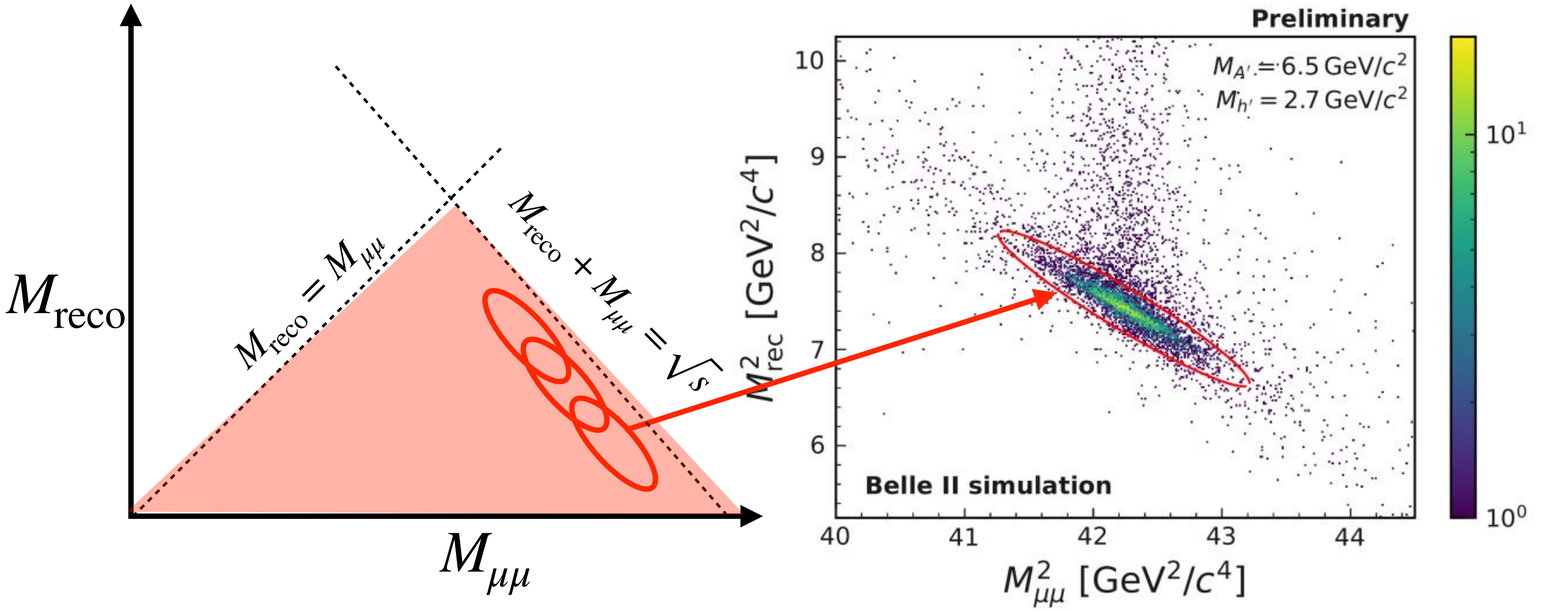
  ➡ Only searched for by KLOE.

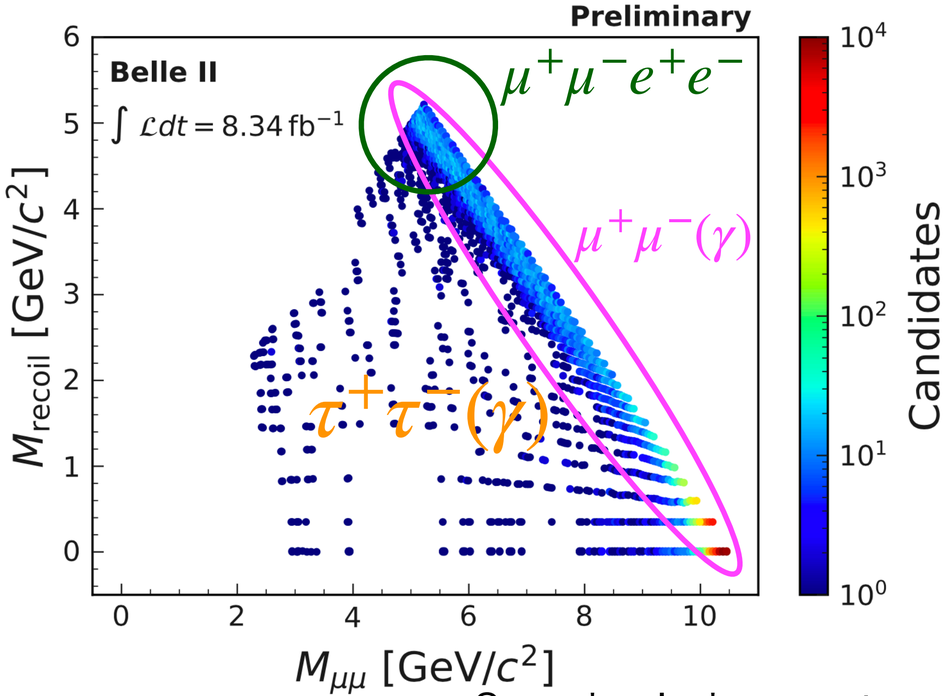
  ➡ **Large room to be searched for**.



Dark Higgsstrahlung: $e^+e^- \to A'h'$ Analysis

- Data set: 8.34 fb^{-1} (2019)
- Scan M_{reco} vs $M_{\mu\mu}$ plot ⇒ about 9,000 overlapping elliptical mass windows.
  - Dark photon: $A' \to \mu^+\mu^-$, $M_{\mu\mu} > 1.65\ \mathrm{GeV}/c^2$ due to dimuon trigger efficiency.
  - Dark Higgs: invisible, recoil mass M_{recoil} against dimuon system.
- Dominant backgrounds: $e^+e^- \to \mu^+\mu^-(\gamma)$ (79%), $e^+e^- \to \tau^+\tau^-(\gamma)$ (18%), $e^+e^- \to \mu^+\mu^-e^+e^-$ (3%)



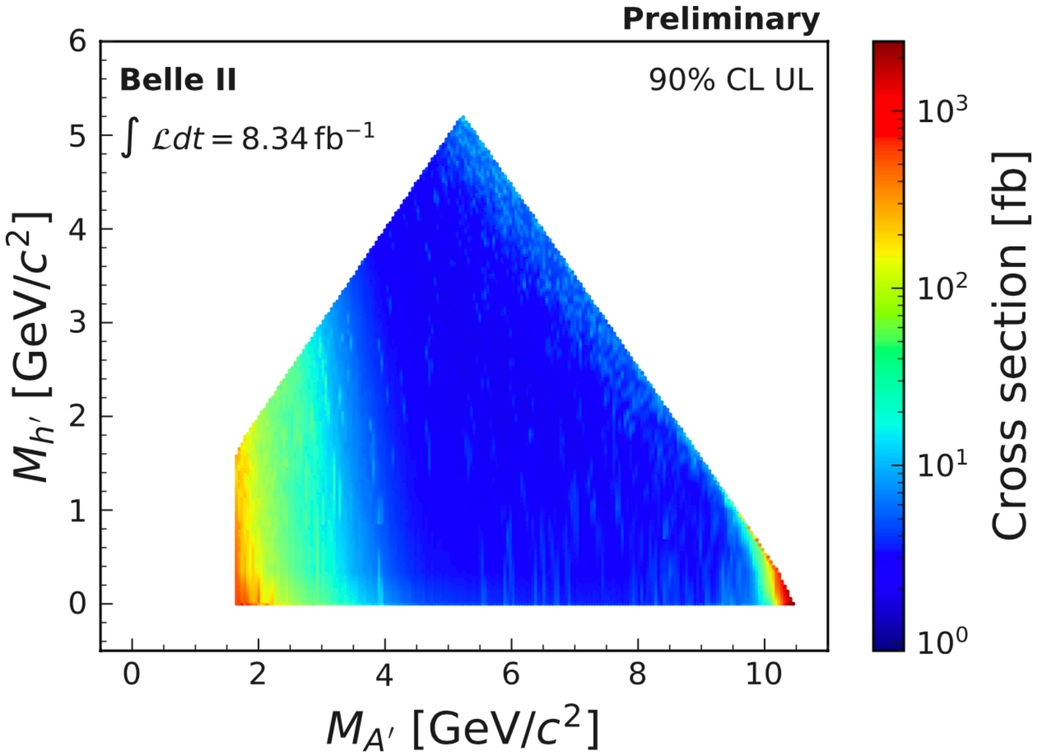


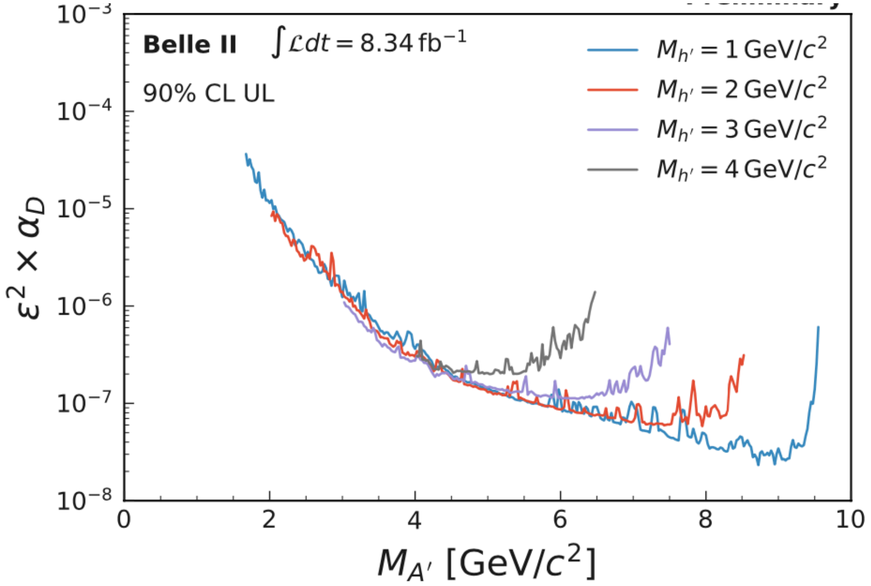
Search window centers.

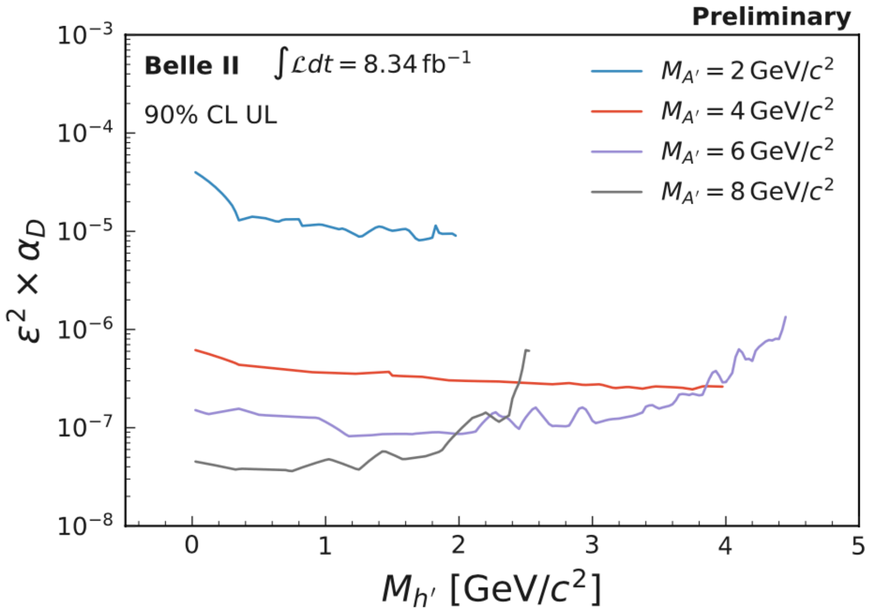
Dark Higgsstrahlung: $e^+e^- \to A'h'$ Results

- No excess beyond background found.
- 90% ULs were set on σ and $\epsilon^2\alpha_D$.
- World first results for $1.65 < M_{A'} < 10.51$ GeV/c^2

➡arXiv:2207.00509





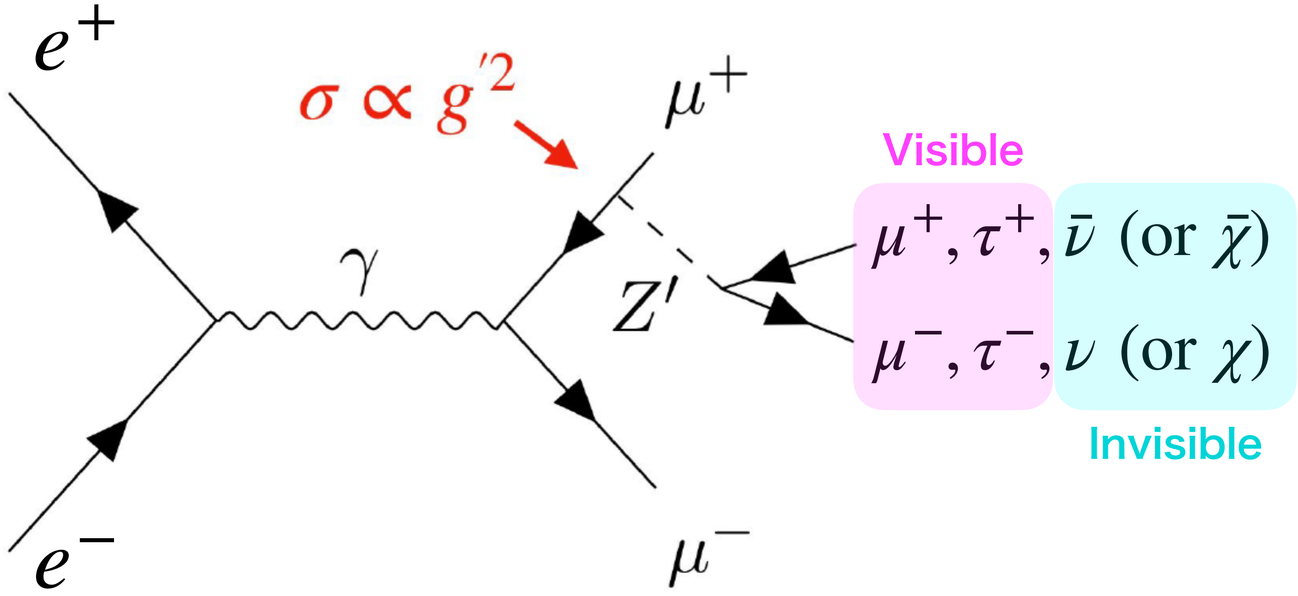


Z' in $L_\mu - L_\tau$ Model

- The $L_\mu - L_\tau$ extension of the SM (PRD 89 113004 (2014), JHEP 12 (2016) 106) gauges the difference of the leptonic muon and tau number.
  ➡New vector boson Z', couples to only 2nd and 3rd lepton family.

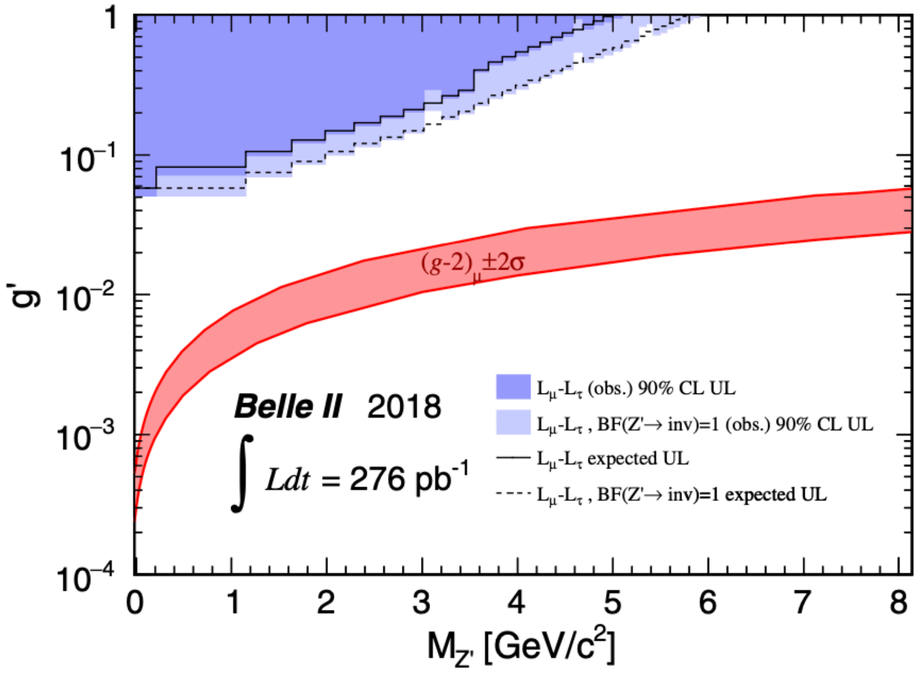
- This may solve
  - Dark matter phenomenology
  - Muon g-2 discrepancy between data and theory
  - Anomalies reported in LHCb (R_K, R_{K^*}).

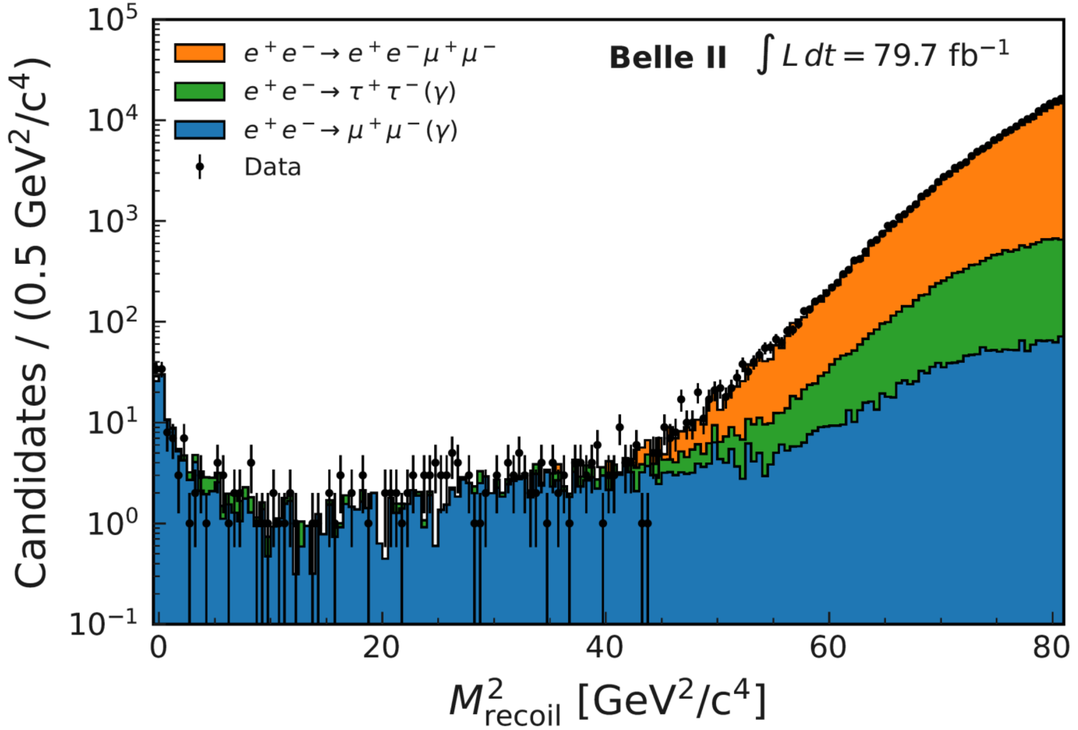
- New results
  - $Z' \to \text{invisible}\ (e^+e^- \to \mu^+\mu^- + \text{missing})$
  - $Z' \to \tau\tau\ (e^+e^- \to \mu^+\mu^- Z')$



Invisible Z' Analysis

- Initial analysis (276 pb^{-1}) was published in PRL 124, 141801 (2020).
  ➡ Updated using 2019-2020 data, 79.7 fb^{-1}.
  ➡ Event selection cuts were optimized with introducing NN.
- Search for bumps in recoil mass M_{recoil} against dimuon.
- Dominant backgrounds are $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$, and $e^+e^- \to \mu^+\mu^-e^+e^-$.



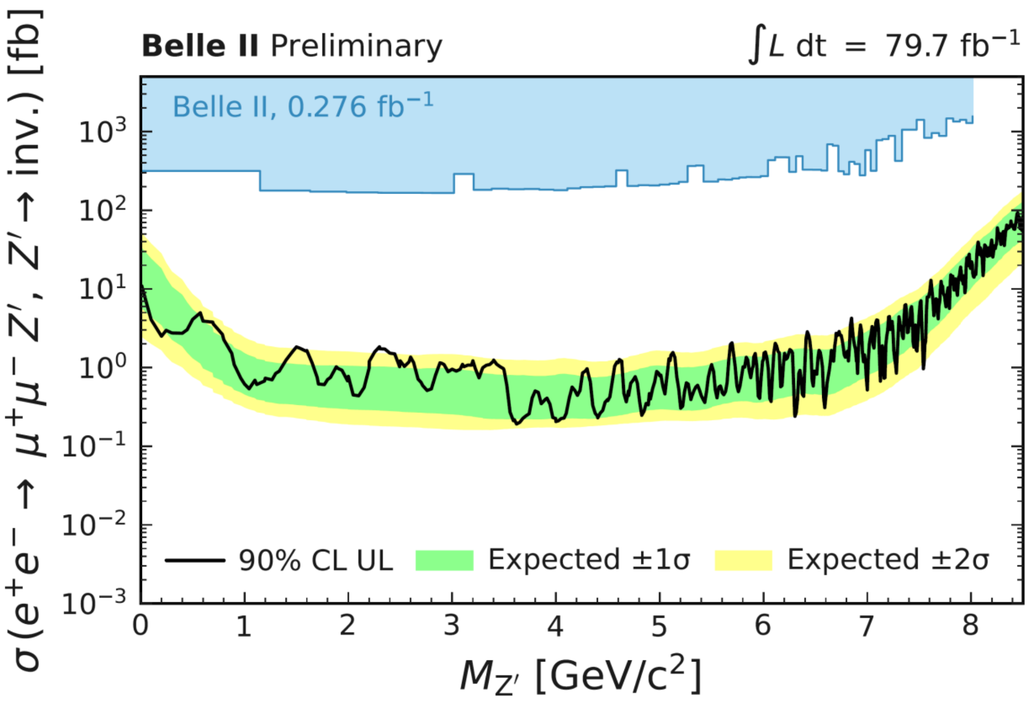


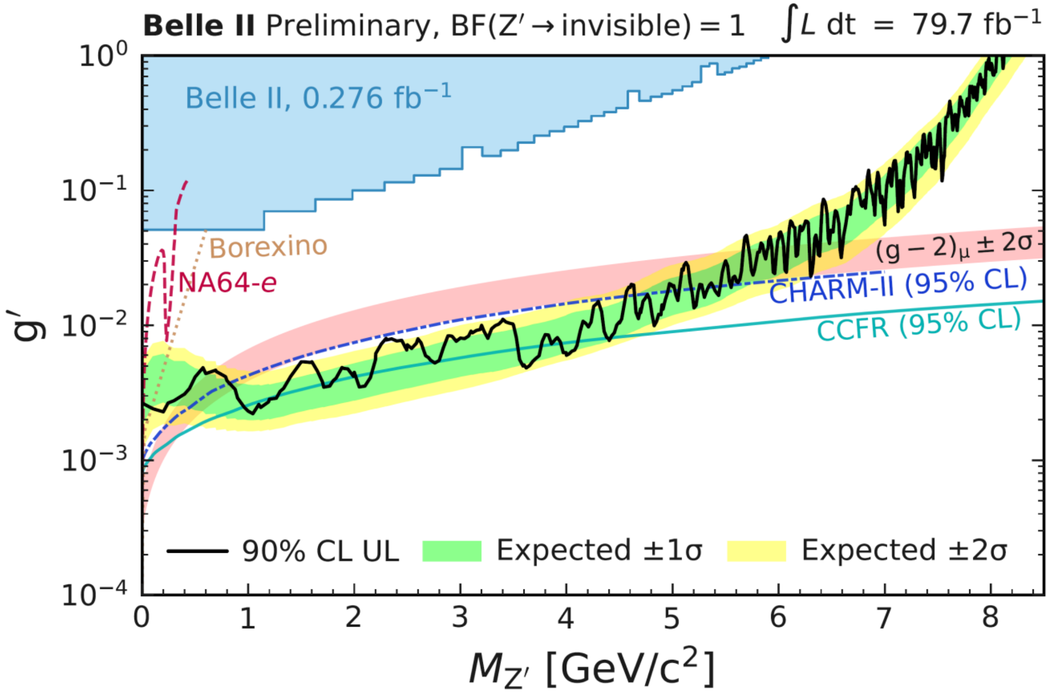
Results of Invisible Z' Search

- No excess above background was found.
- 90% CL ULs were set on the cross section σ and coupling g'.

➡ If mass of dark matter is $< m_{Z'}/2$, $BF(Z' \to \text{invisible}) \approx 100\,\%$.

➡ **Fully invisible Z' as origin of $(g-2)_\mu$ was excluded for $0.8 < M_{Z'} < 5.0\ \text{GeV}/c^2$.**



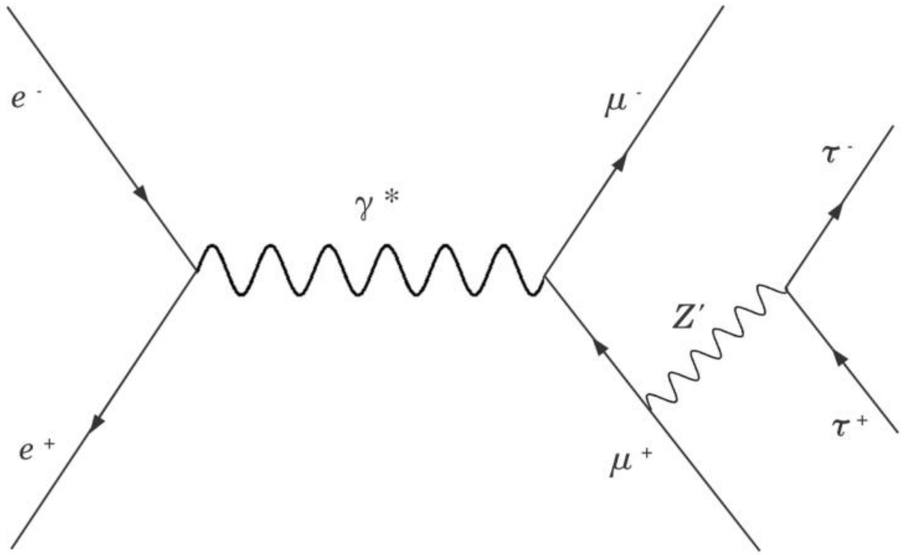


Z', S, ALP $\rightarrow \tau\tau$

- New results for $e^+e^- \rightarrow \mu^+\mu^- Z', S, \text{ALP}$ and $Z', S, \text{ALP} \rightarrow \tau\tau$
  - Z' : $L_\mu - L_\tau$ model.
  - S: dark leptophilic scalar model, PRL 125, 181801 (2020).
  - ALP: JHEP12 (2017) 044 (different model with $a \rightarrow \gamma\gamma$)

  ➡ **First search of these decays into $\tau\tau$.**

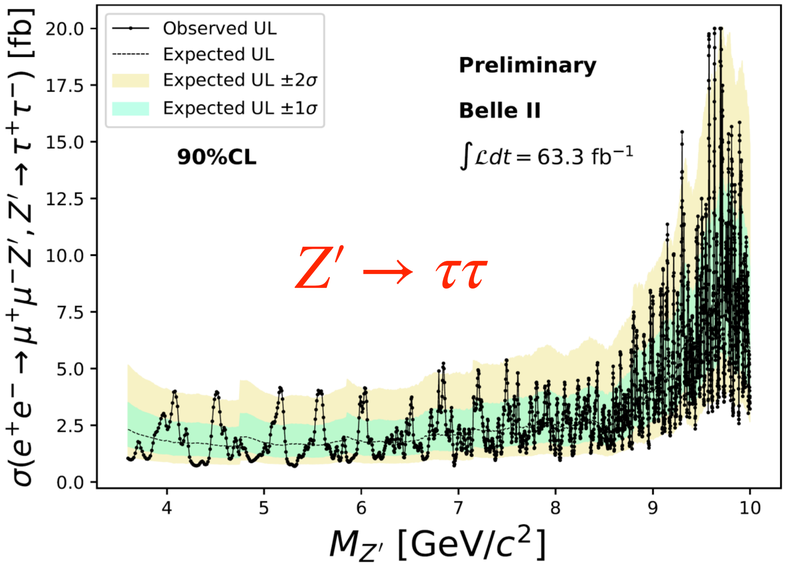
- Analysis using 2019-2020 data set, 63.3 fb^{-1}.
  - Scan recoil mass $M_{\text{recoil}}(\mu\mu)$
  - Background suppression with NN.

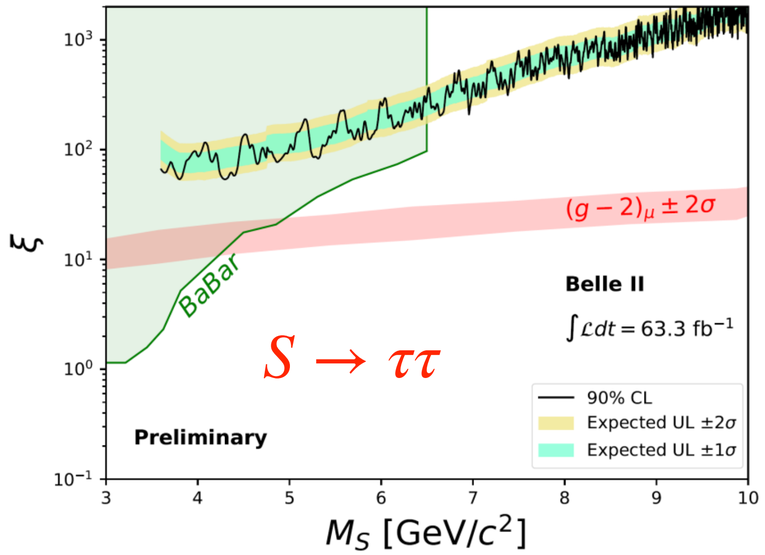


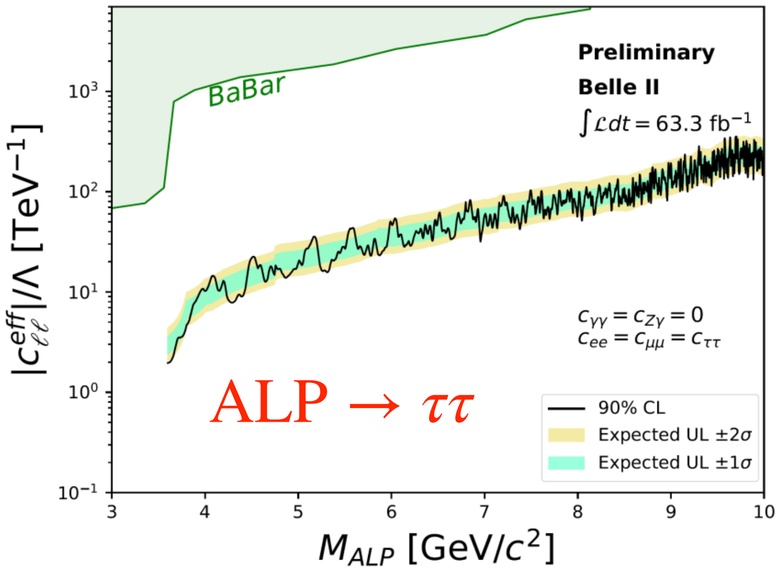
※ Initial analysis $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$ was performed and published in PRL 125, 161806 (2020)

Results of Z', S, ALP $\to \tau\tau$ Search

- No excess found.
- Set 90% CL ULs on the cross section and couplings for several models.
  - First constraint on S for $M_S > 6.5\ \mathrm{GeV}/c^2$.
  - First direct search for $\mathrm{ALP} \to \tau\tau$.







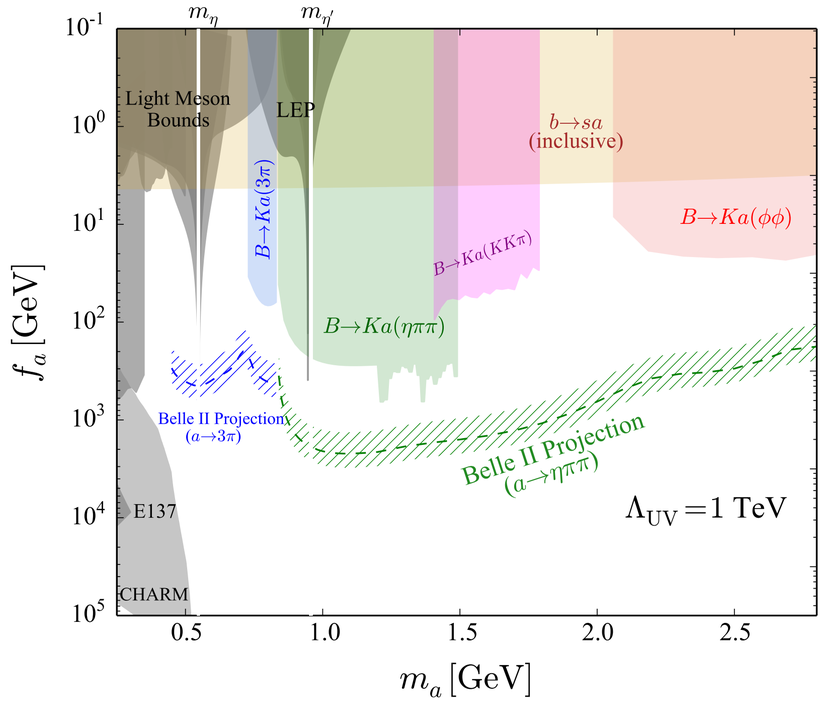
Summary & Future Prospects

- Dark sector scenarios are very important.
- Belle II is good playgrounds for dark sector searches.

  ➡ At present, 424 fb^{-1} has been collected.
- **New results: world leading results has been obtained.**
  - Dark Higgsstrahlung: arXiv: 2207.00509.
  - $Z' \to$ invisible
  - Z', S, ALP $\to \tau\tau$

  ⇒Papers are under preparation.
- Many other dark sector searches are ongoing, e.g.
  - $B \to Ka$: heavy QCD axion ($a \to$ hadrons), ALPs ($a \to \gamma\gamma$)
  - $B \to KS$: dark scalar ($S \to \ell^+\ell^-$)
  - $e^+e^- \to \gamma A'$, $A' \to$ invisible

  ➡ More world leading results are expected.

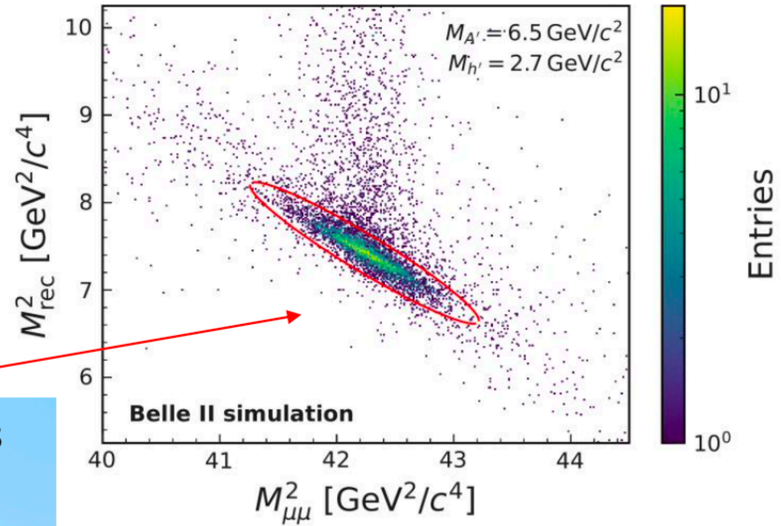


PRD 104, 055036 (2021)

Backup

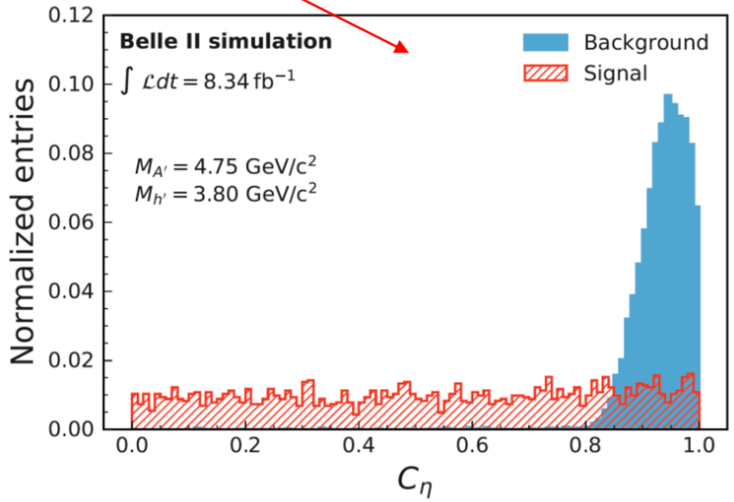
Dark Higgsstrahlung

Two-track trigger
Two muons, $p_T^{\mu\mu} > 0.1$ GeV/c
Recoil points to barrel ECL
No extraenergy
Scan M_{recoil} vs $M_{\mu\mu}$



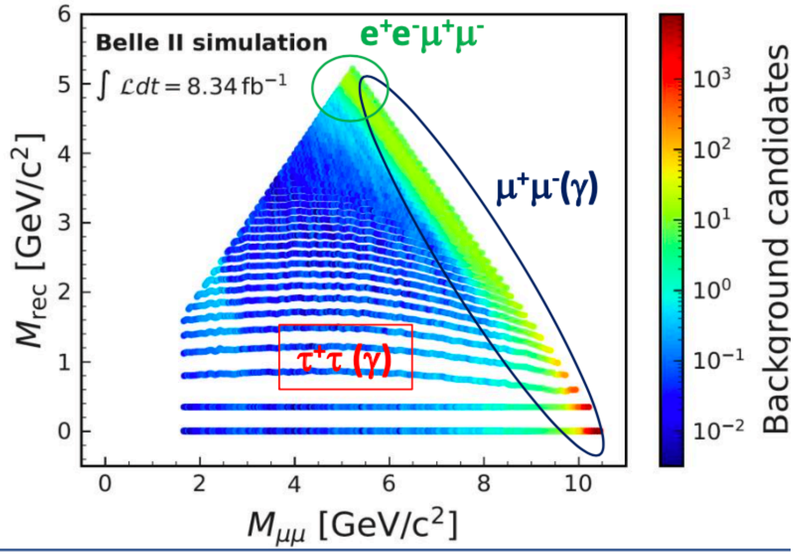
~9000 overlapping elliptical mass windows

Helicity angle

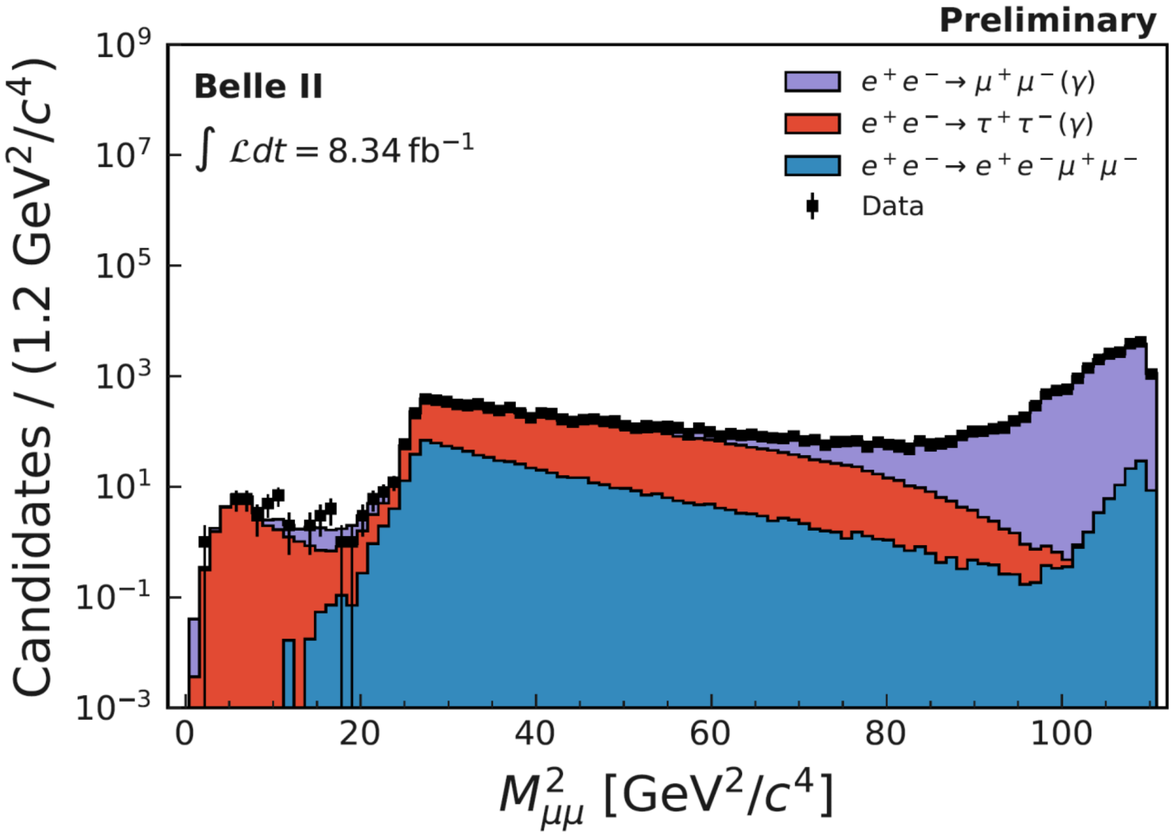


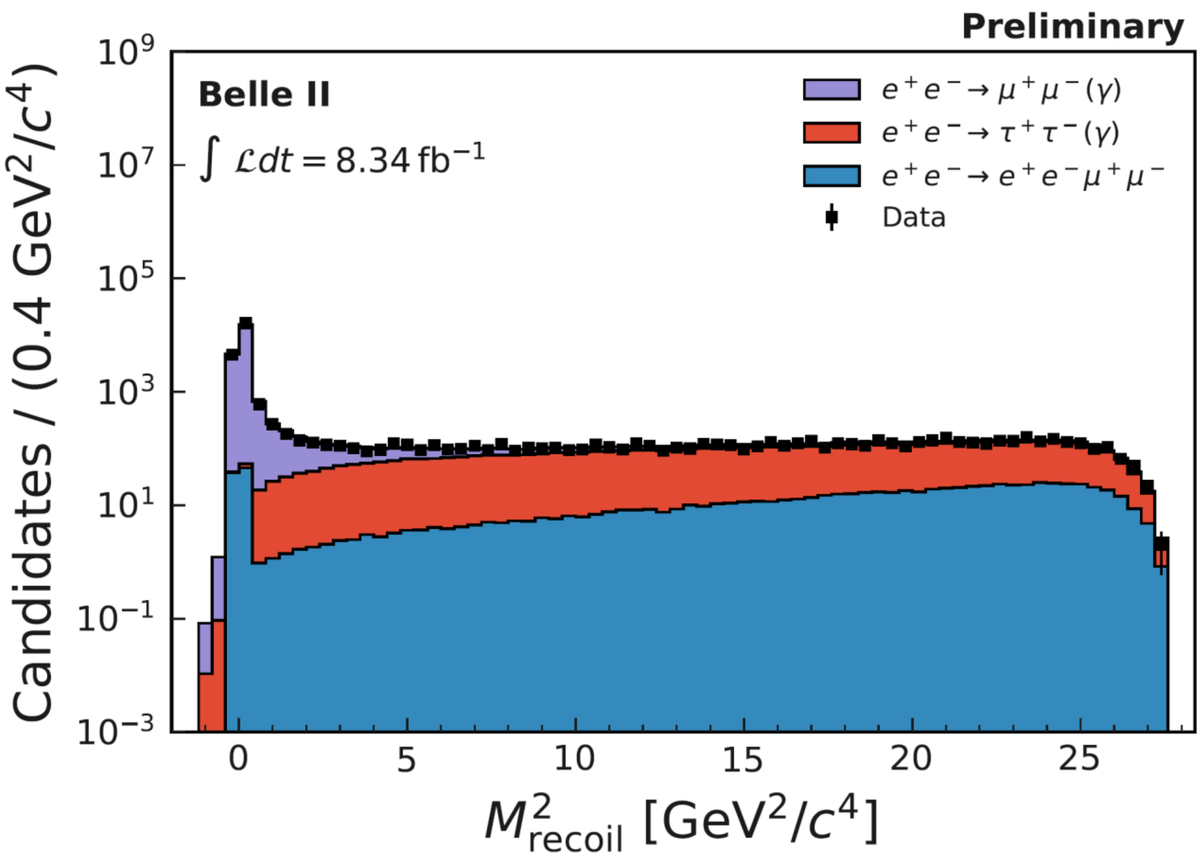
Backgrounds

$\mu^+\mu^-(\gamma)$ 79%
$\tau^+\tau$ (γ) 18%
$e^+e^-\mu^+\mu^-$ 3%



Dark Higgsstrahlung





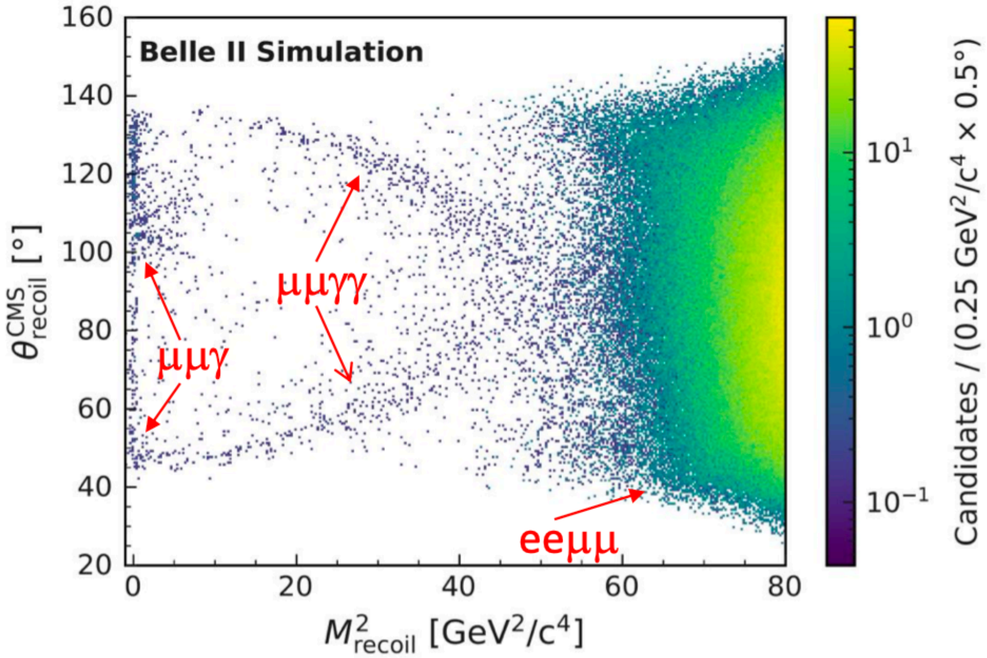
$Z' \rightarrow$ Invisible

- $\tau^+\tau^-$ (γ) almost 100% suppressed
- $\mu^+\mu^-$ (γ) dominates up to ~7 GeV/c^2
- $e^+e^-\mu^+\mu^-$ dominates for high masses

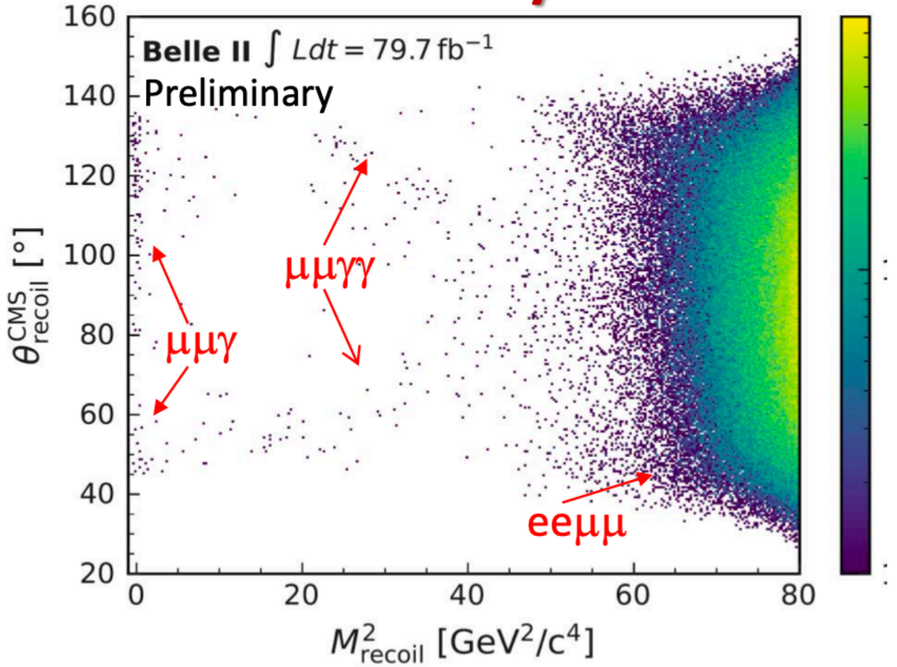
3 control samples

$\mu\mu\gamma$	selection+NN studies	low mass
$e\mu$	selection+NN studies	medium+high mass
$ee(\gamma)$	γ veto studies	

Look for bumps in θ_{recoil} vs M^2_{recoil}



Observed yields



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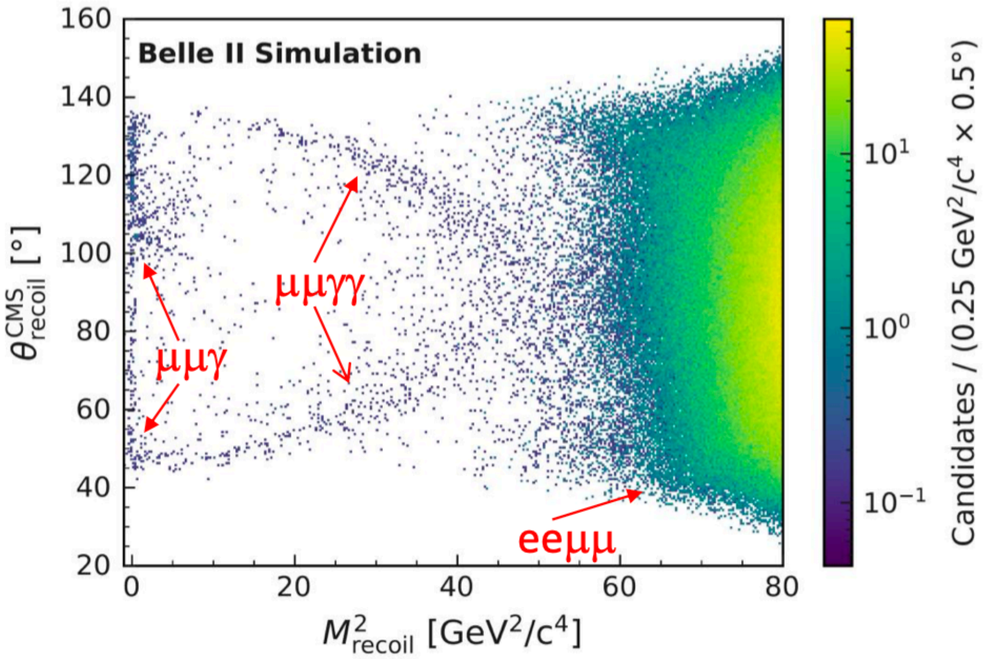


Look for bumps in θ_{recoil} vs M^2_{recoil}

3 control samples

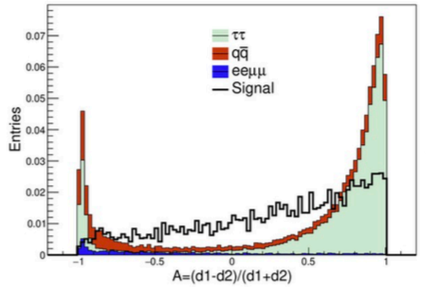
μμγ	selection+NN studies	low mass
eμ	selection+NN studies	medium+high mass
ee(γ)	γ veto studies	

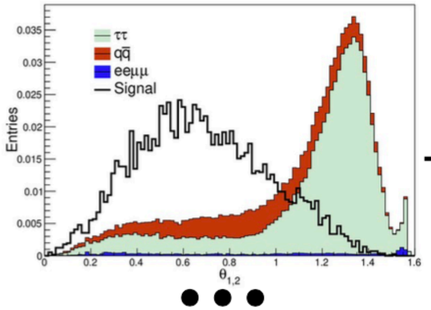
Systematics

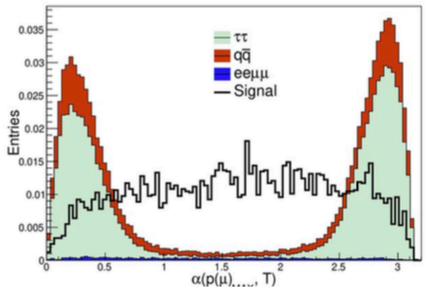
Source	Low mass	Medium mass	High mass
selections	2.7%	6.5%	8.3%
Mass resolution	10%	10%	10%
Background shapes	3.2%	8.6%	25%
Photon veto	34%	5%	5%
luminosity	1%	1%	1%

$Z' \to \tau\tau$

- Background suppression: MLP (Multi-Layer Perceptron (NN)) based
  - ➔ 14 variables for the MVA training: sensitive to the presence of $\tau\tau$ resonance produced as FSR from one of the 2 μ







training

MVA
(8 MLPs)

training

99% bkg. rejection
signal ε: 33% → 13%
Initially negligible $\mu\mu\tau\tau$ and $ee\tau\tau$ are no longer such