Dark Sector Searches at Belle II

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On behalf of the Belle II Collaboration.
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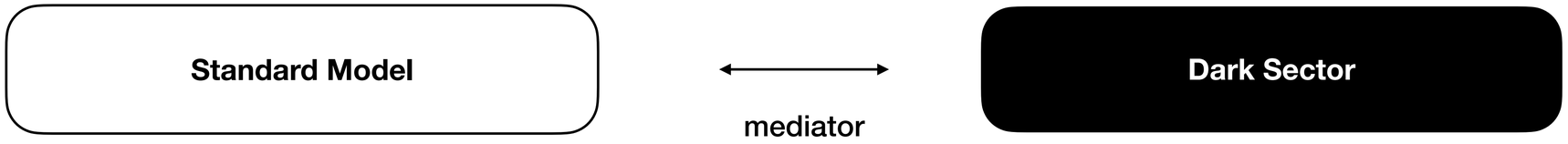
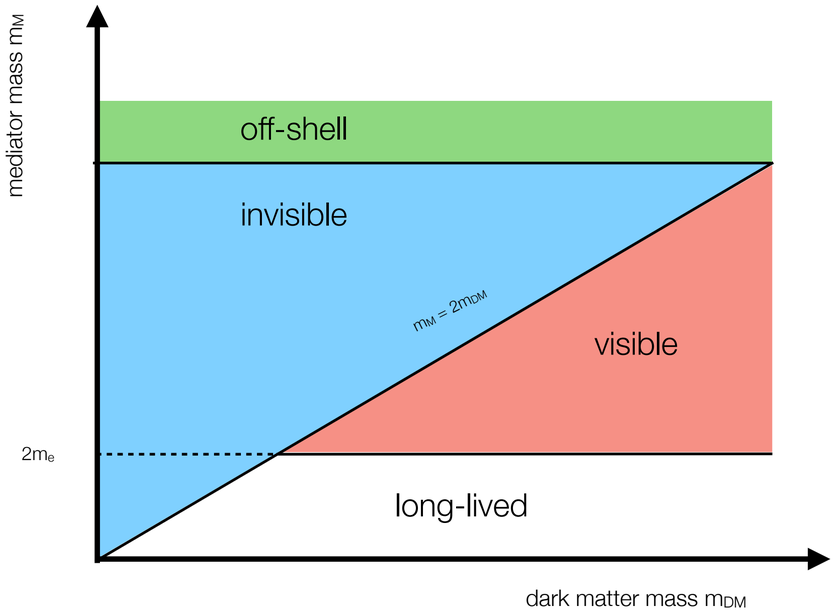
Dark Sector Searches



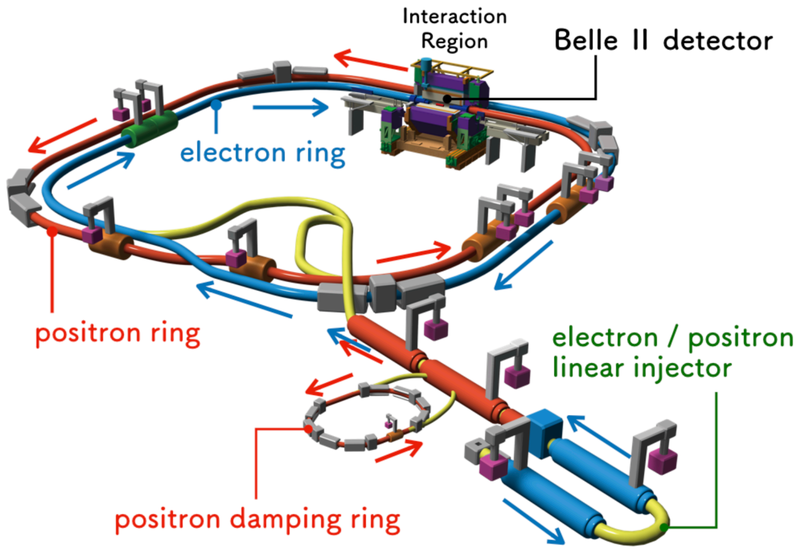
- Possible portals between Standard Model and Dark Sector.
  - Vector portal (dark photon(A'), Z').
  - Pseudo-scalar: ALPs
  - Scalar portal: Dark Higgs
  - Neutrino: Sterile Neutrinos

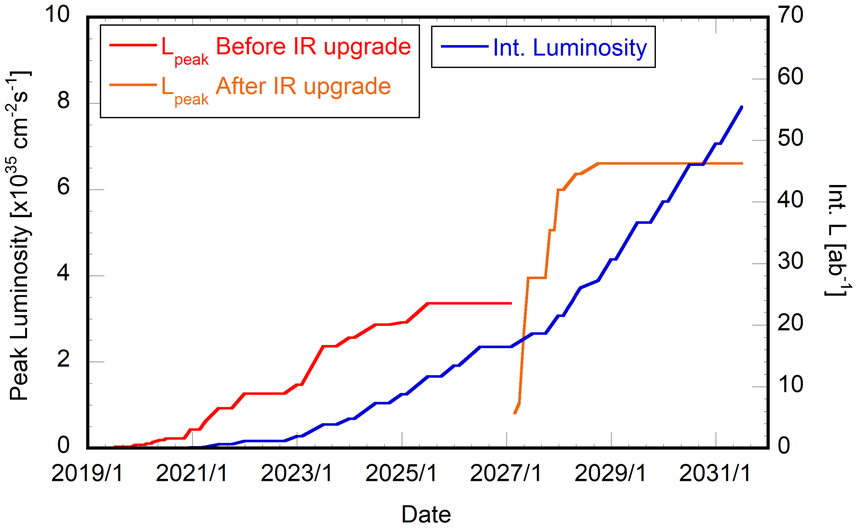


- Typical signatures : low multiplicity, missing energy, isolated mono photon, displaced tracks etc.

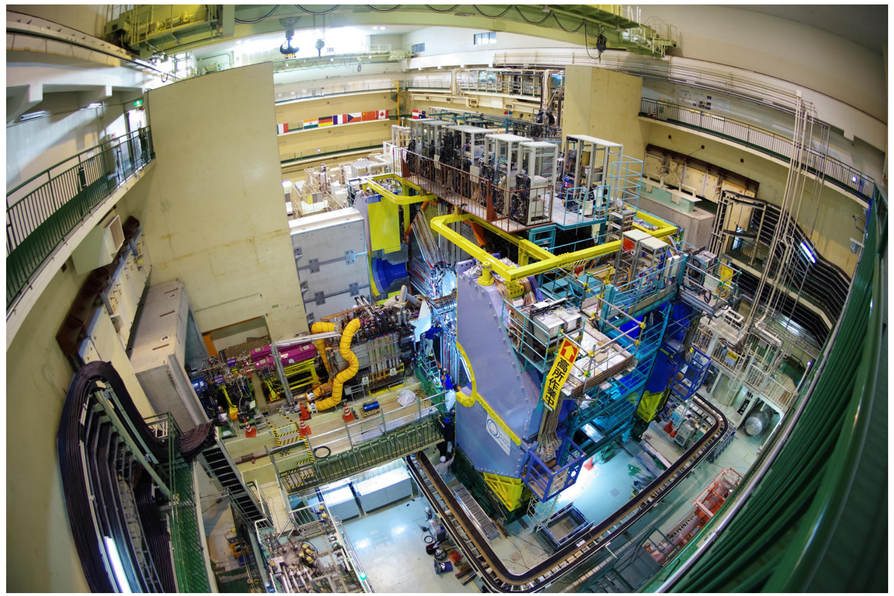
SuperKEKB

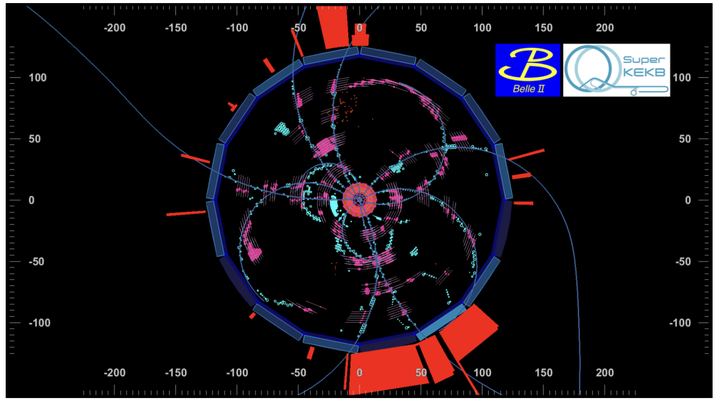
- Super *B*-factory, located in Tsukuba - KEK laboratory - Japan.
- An asymmetric e^+e^- collider, operated around 10.58 GeV (=$m_{\Upsilon(4S)}$).
- Higher beam currents and smaller beam spot compared to KEKB.
- Nanobeam scheme: expected instantaneous luminosity of 6×10^{35} cm^{-2}s^{-1}
- Achieved a new luminosity world record, 3.1×10^{34} cm^{-2}s^{-1}
- Collected 213 fb^{-1} up to now.
- Aim to collect 50 ab^{-1} of data.

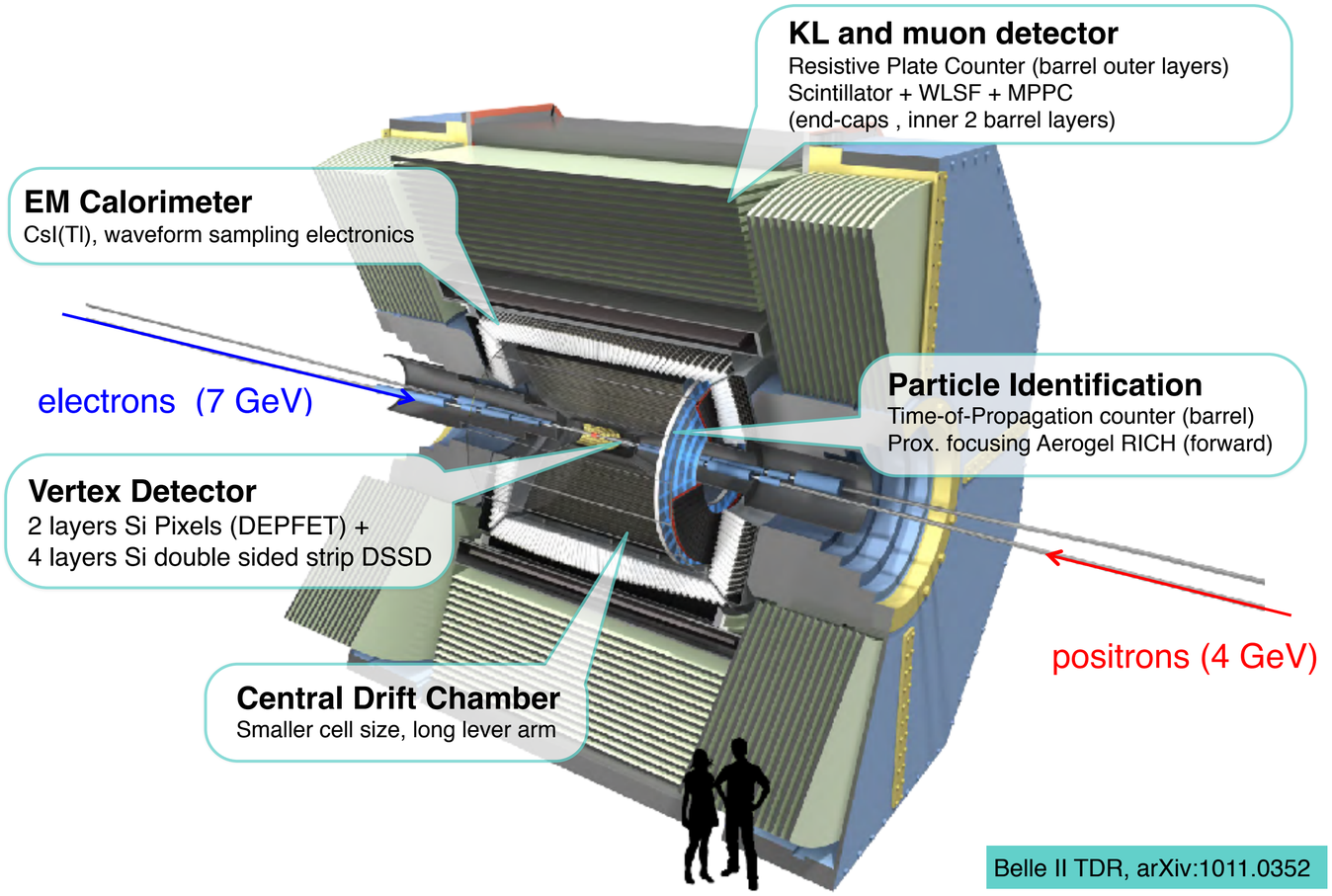




Belle II detector







Belle II TDR, arXiv:1011.0352

- Hermetic detector, excellent PID and dedicated trigger system.

Belle II Trigger System

- A trigger system suitable for dark sector and low multiplicity searches.

- Belle II trigger system consists of two levels
  1. low level trigger implemented in hardware (L1)
  2. software-based high level trigger (HLT)

- Dedicated dark sector/low-multiplicity trigger lines

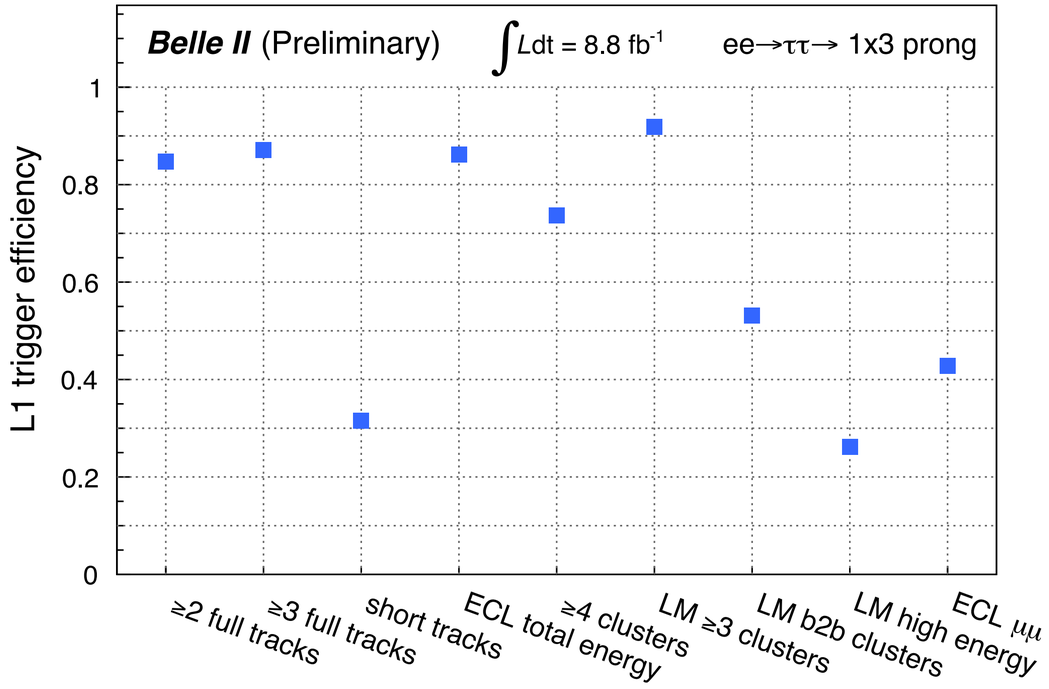
  - Single photon trigger (not available at Belle).

  - ECL clusters with various energy levels and angular separation.

  - 3D tracks are reconstructed with a neural network approach.

  - Single track trigger.

  - Combination of full/short/neuro tracks.



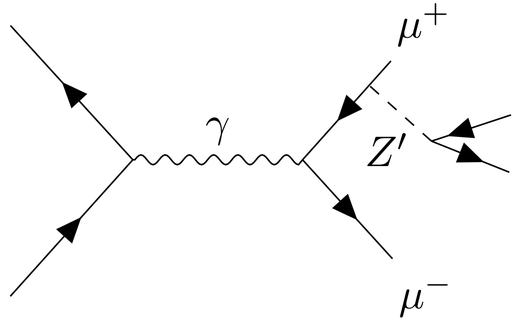
LM=> (Low Multiplicity)

Full tracks : higher momentum tracks.
Short tracks: low momentum tracks.

Invisible Z'

Published search PRL 124, 141801 (2020)

- An extra $U(1)'$ gauge boson.
- Which couples to $L_\mu - L_\tau$(1) current via a new coupling g'.
- Could explain $(g-2)_\mu$, $b \to s\mu\mu$ (2) anomalies.

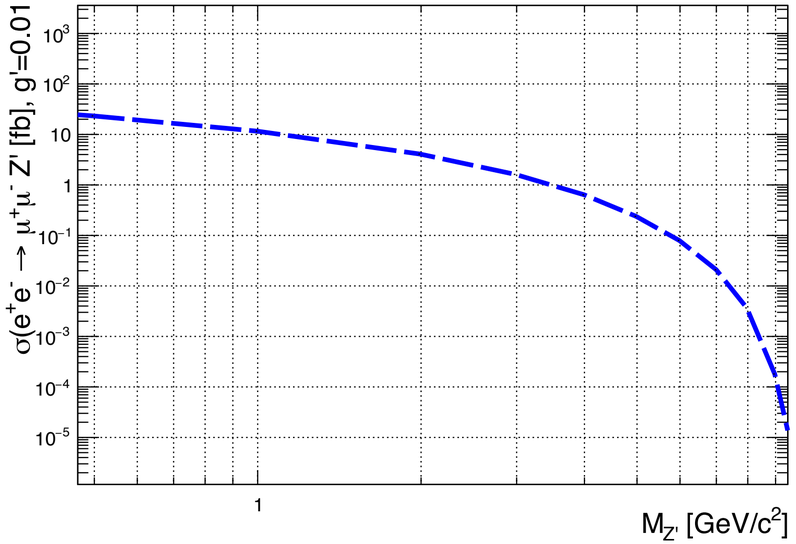


$$
\begin{aligned}
M_{Z'} < 2M_\mu \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/3.
\end{aligned}
$$

if $M_{Z'} > 2M_\chi$

$$BF(Z' \to \chi\bar{\chi}) \approx 1$$

$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$



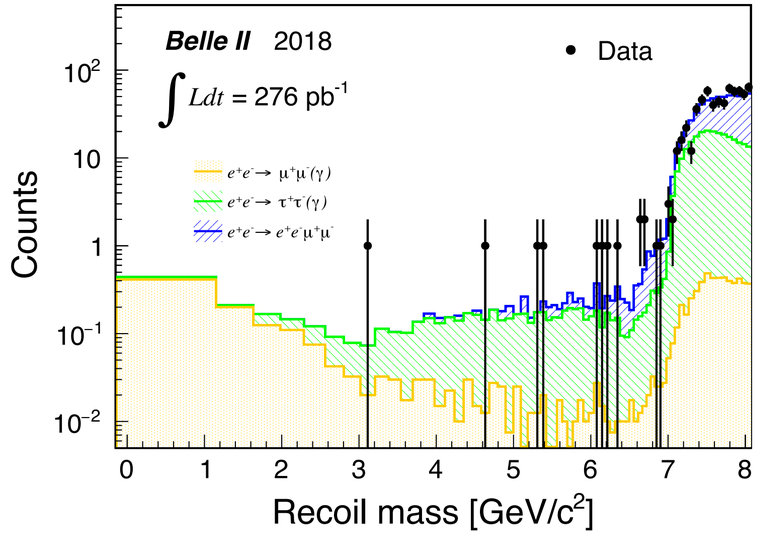
1 PRD 89, 113004 (2014)
($L_\mu - L_\tau$ model)

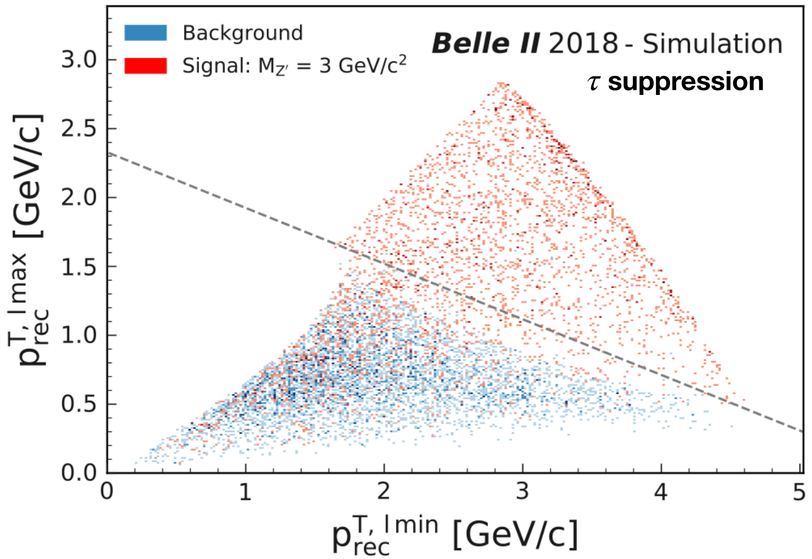
2 JHEP 1612 (2016) 106
(Flavour Decay Anomalies)

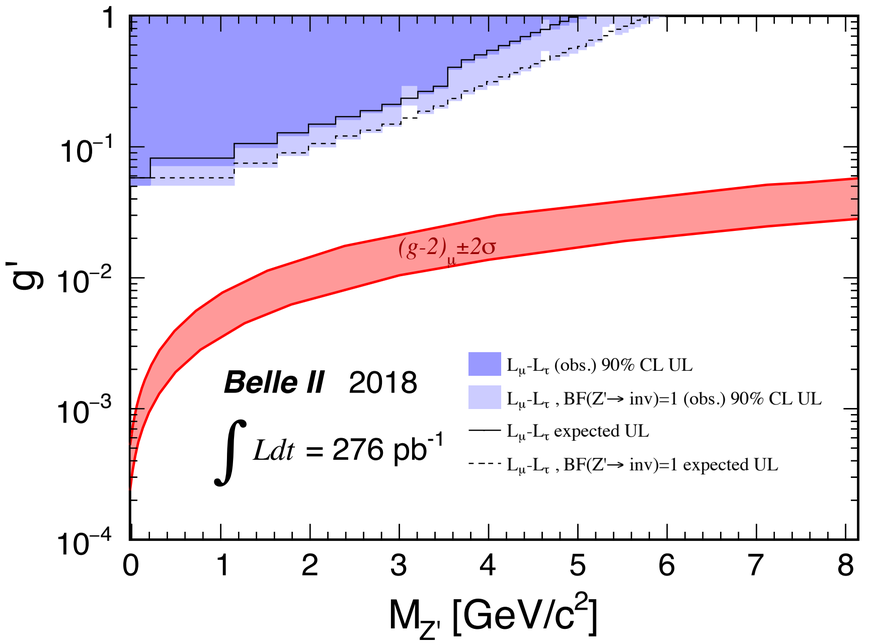
Invisible Z'

- Blind analysis.
- Use early data (276 pb^{-1}), Belle II not completed (no tracking).
- Main Strategy : look for a peak in recoil mass distribution against $\mu\mu$ pair.
- Main experimental challenges: missing energy signature, main backgrounds are $\mu\mu(\gamma), \tau\tau(\gamma)(\tau \to \mu\nu\nu), \mu\mu ee$. $\tau\tau(\gamma)$ events has the biggest contribution, suppressed by dedicated tau-suppression procedure.
- Major systematics coming from tau-suppression technique (~22%) and Data MC disagreement (~12.5%).
- Compute UL on production cross-section and coupling constant (g').

PRL 124, 141801 (2020)

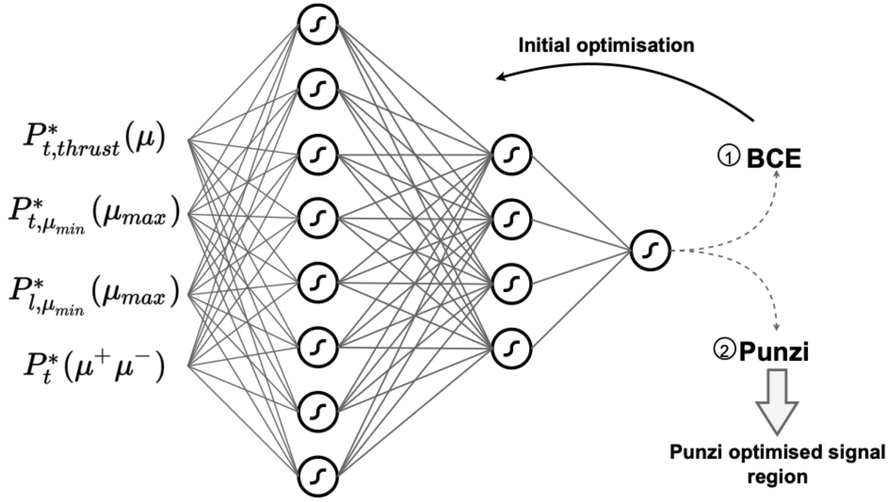


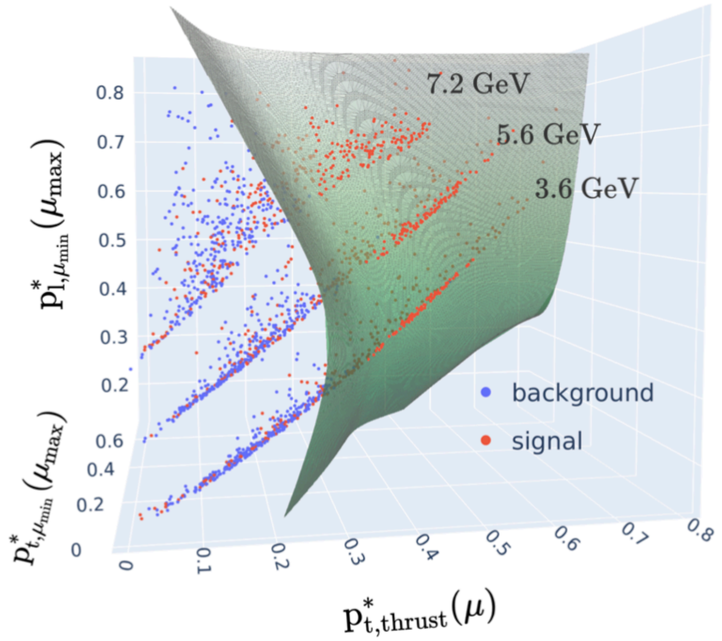


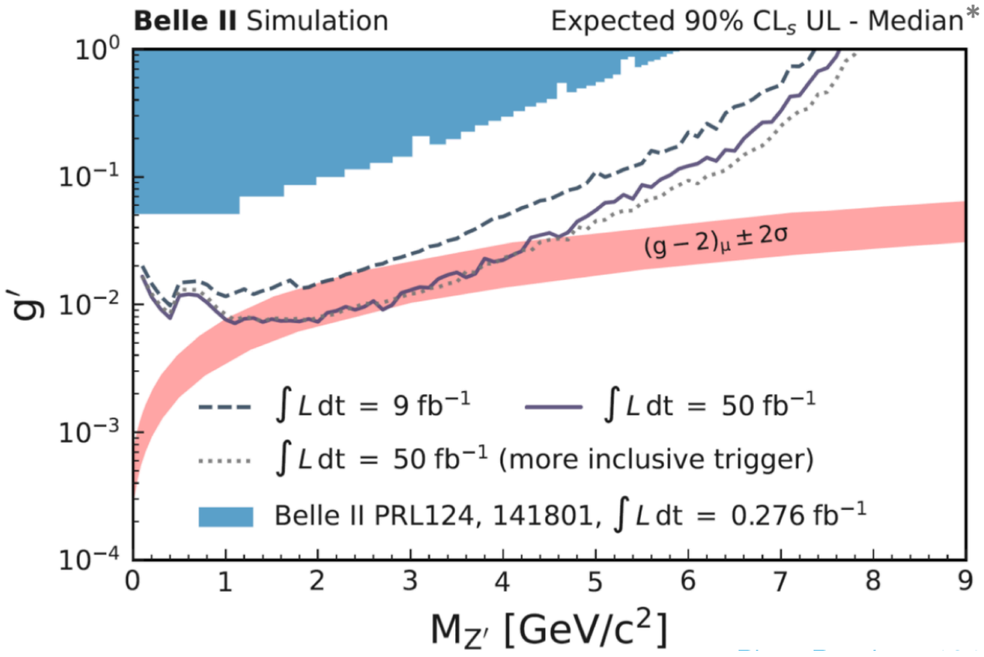


Future and beyond about Invisible Z'

- Updating to a ~80 fb^{-1} sample (factor ~300x in luminosity).
- Better understanding of detector, improved Particle ID, new trigger lines.
- Advanced MVA tools (Punzi net (it is a step of neural network training that optimize the selection by maximizing the Punzi figure of merit, and that allows one to simultaneously optimize for all the mass points))





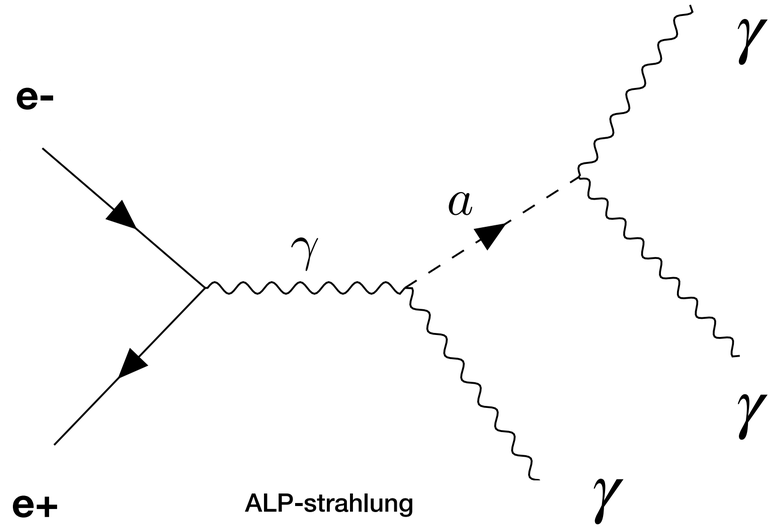


- Limit on the sensitivity is for special case having consideration of $BF[Z' \rightarrow \text{invisible}\ ] = 1$
- More information in the Backup.

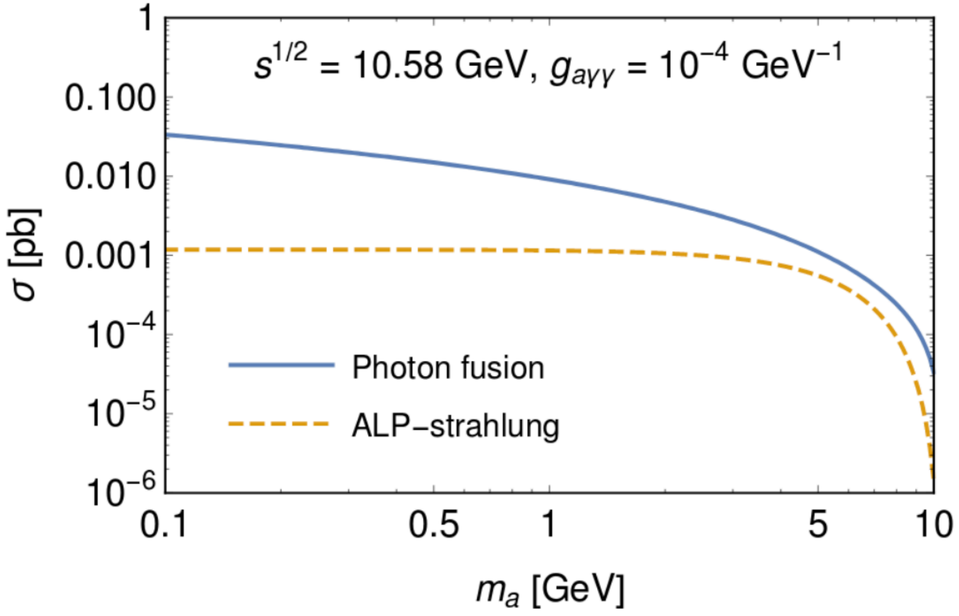
Axion-like particles (ALPs)

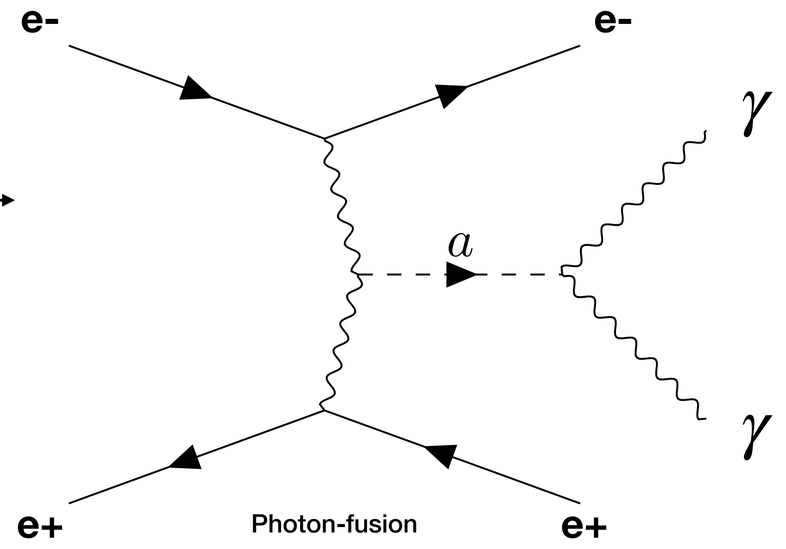
Published search Phys. Rev. Lett. 125, 161806 (2020)

- Axion Like Particles are pseudo-scalars coupling mainly to bosons.
- Explore photon coupling ($g_{a\gamma\gamma}$) in ALP-strahlung process (Photon fusion sensitivity under study) at Belle II.
- 3 photons energies summing up to beam energy and no tracks in the event.



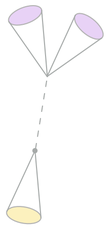
JHEP 1712 (2017) 094



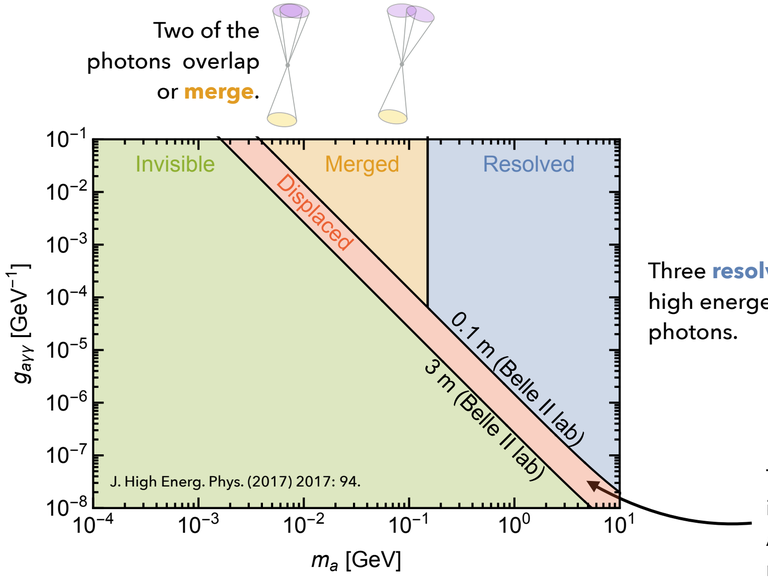


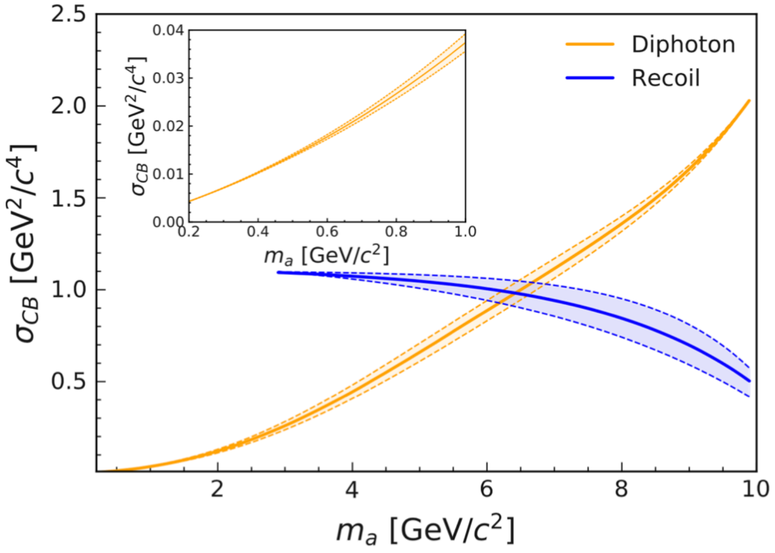
Axion-like particles (ALPs)

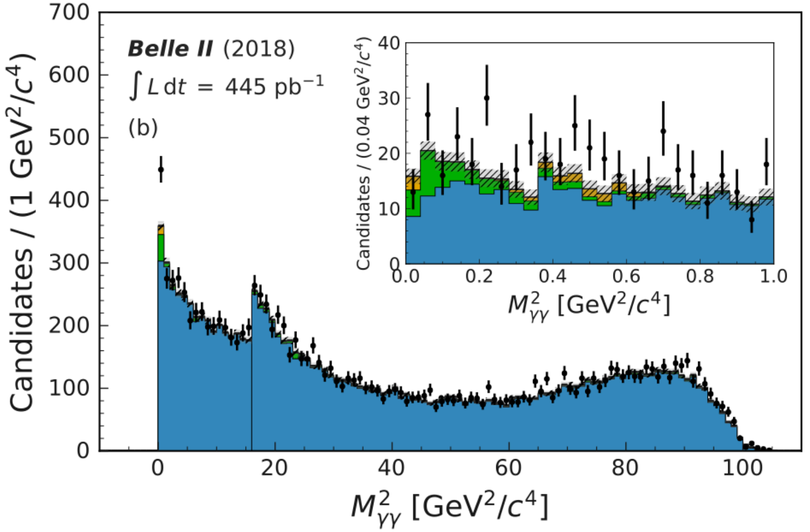
- Blind analysis.
- Use early data (445 pb^{-1}).
- Main strategy : Look for a peak in di-photon (at low ALP mass) and recoil mass (at high ALP mass).
- Main experimental challenges : missing energy signature, main background components are $\gamma\gamma(\gamma), ee\gamma, P\gamma, P = \pi^0/\eta/\eta', P \to \gamma\gamma$
- The dominant source of systematic uncertainty coming from Background shape.

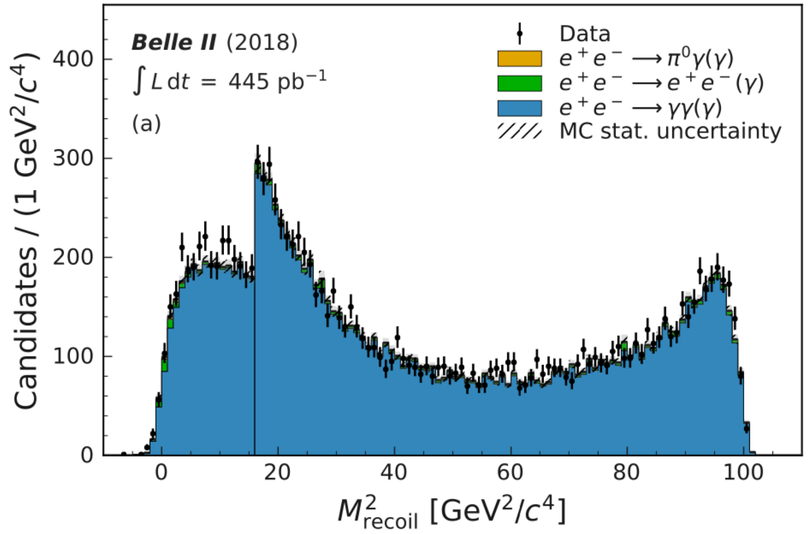


ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



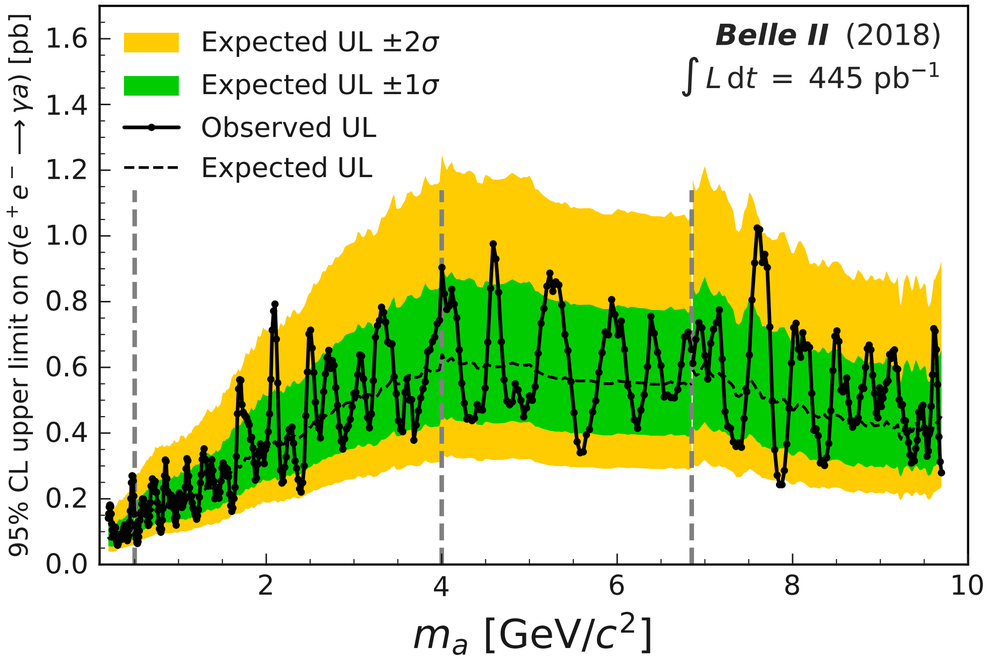


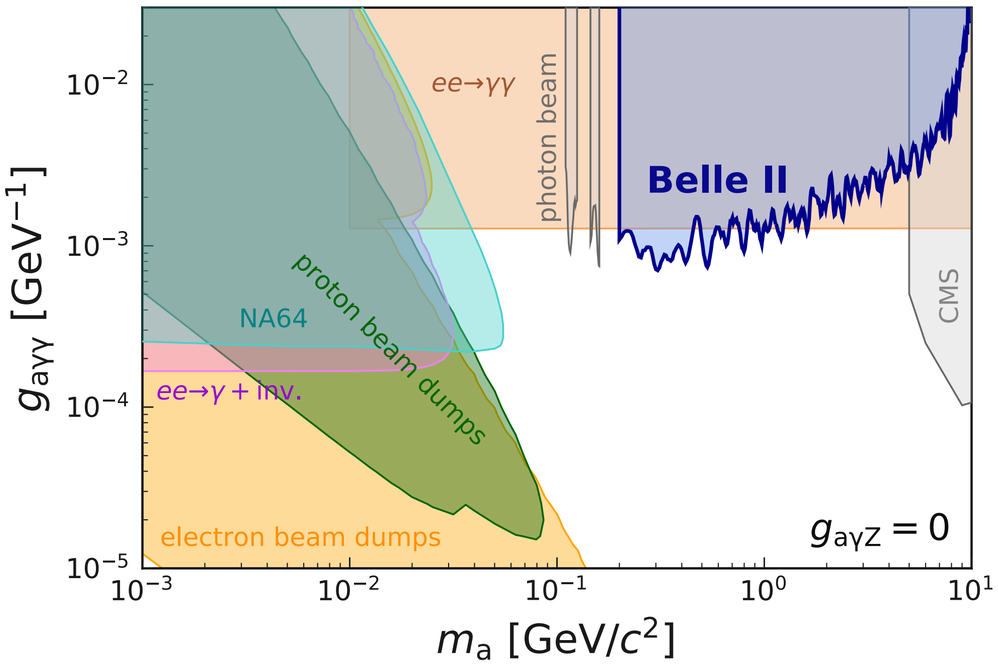




Axion-like particles (ALPs)

Phys. Rev. Lett. 125, 161806 (2020)



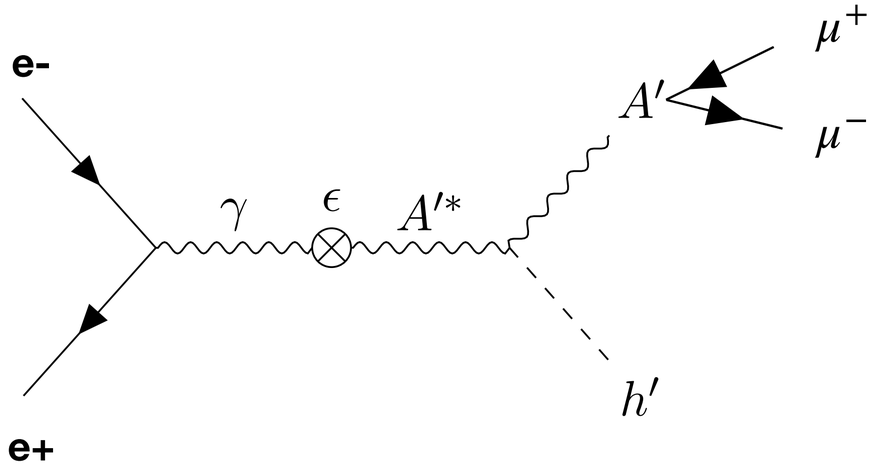


- Search performed in mass range from 0.2 to 9.7 GeV.
- No excess was found (highest local significance of 2.8σ), upper limit to the cross section and coupling constant.
- To be repeated with more data.

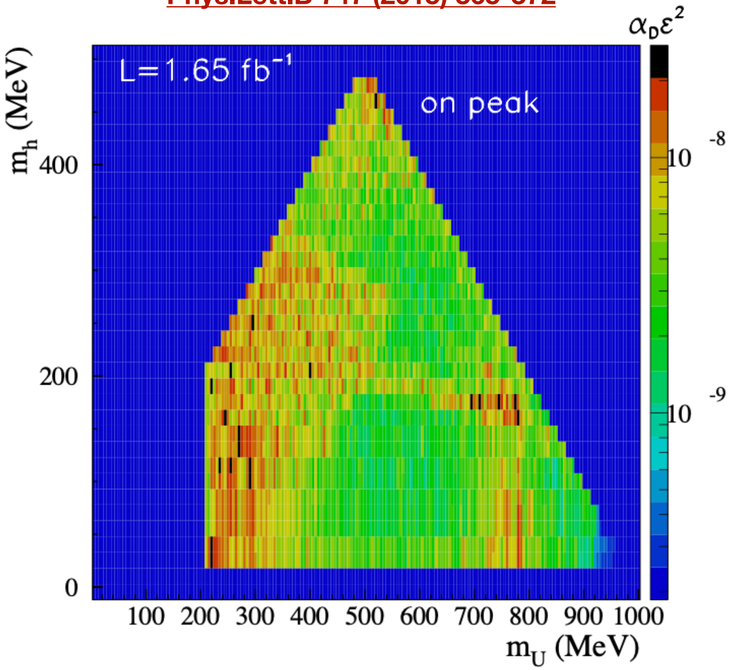
Dark Higgsstrahlung

Ongoing search

- In analogy to SM a spontaneous symmetry breaking mechanism to give mass to the dark photon A' through a dark Higgs h'.
- Focus on $m_{h'} < m_{A'}$. h' has large lifetime to escape the detection and A' decays to muons.
- Previously done by KLOE, which explored smaller phase space.
- For $m_{h'} > 2m_{A'}$, h' decays to A' pair, six charged particle in final state, investigated by Babar and Belle.

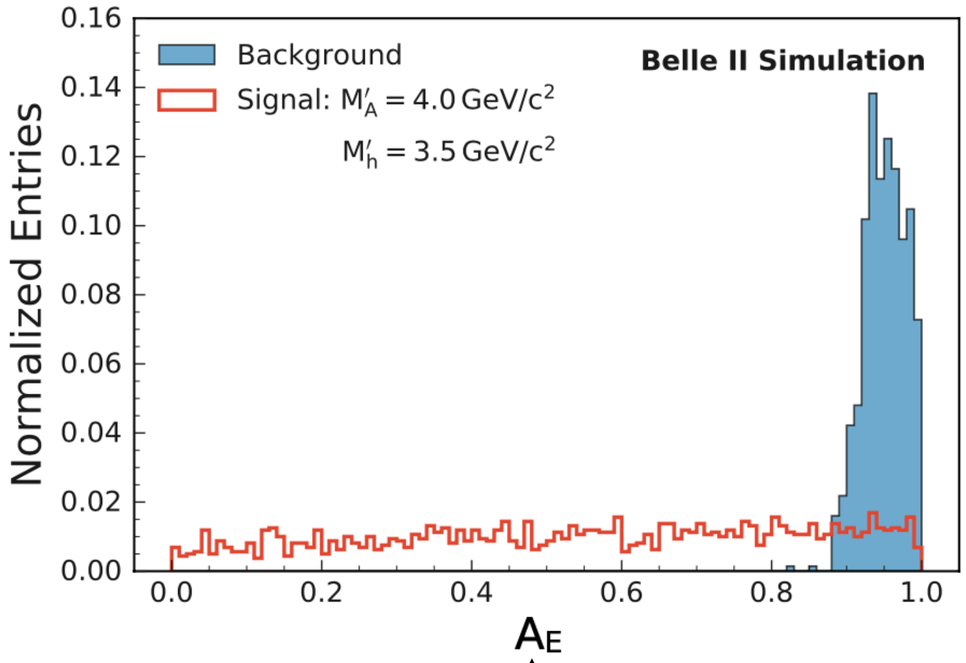


Phys.Lett.B 747 (2015) 365-372



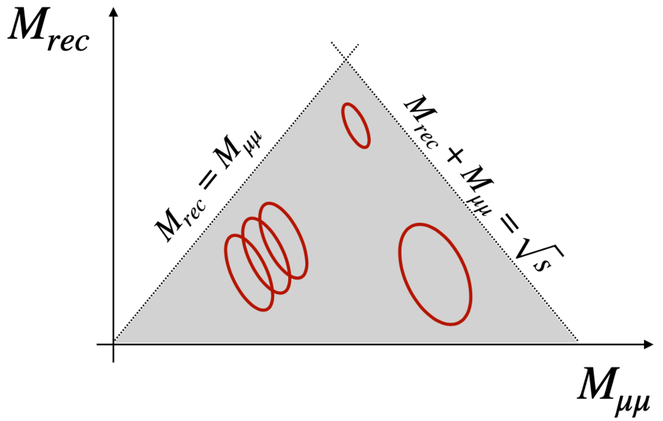
Dark Higgsstrahlung

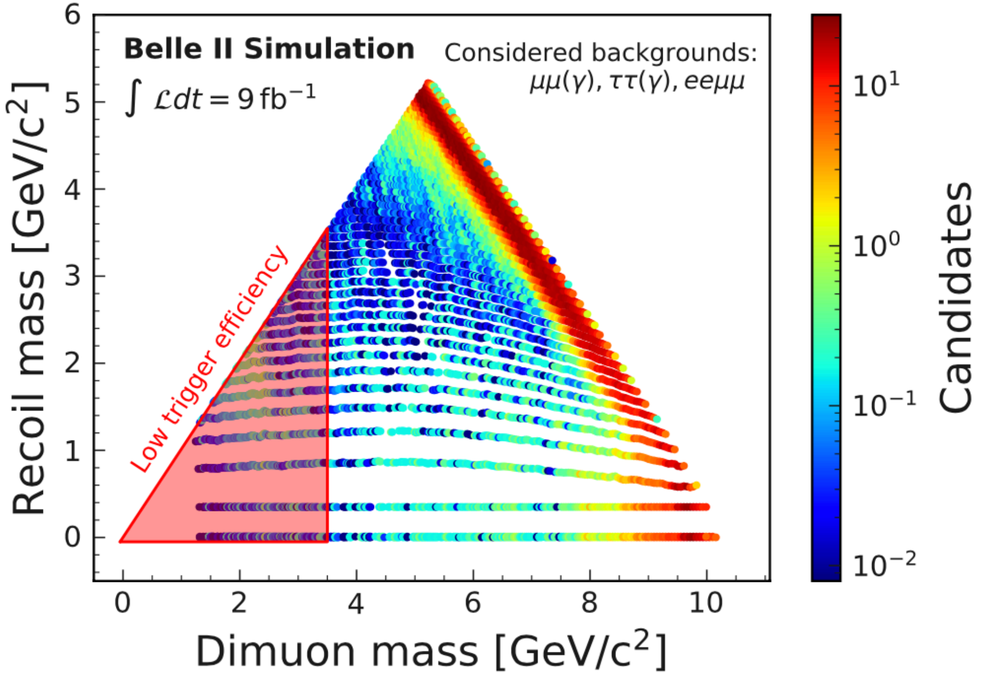
- Blind analysis.
- Dataset : 8.3 fb^{-1}.
- Look for two oppositely charged muons plus missing energy.
- Find a peak in the 2D distribution of recoil vs dimuon mass.
- Main experimental challenges: missing energy, main contributing backgrounds are $\mu\mu(\gamma)$, $\tau\tau(\gamma)$, $ee\mu\mu$. Background suppression based on kinematic features (helicity angle, energy asymmetry between muons).
- Major systematics come from discrepancies in background shape and signal efficiency.

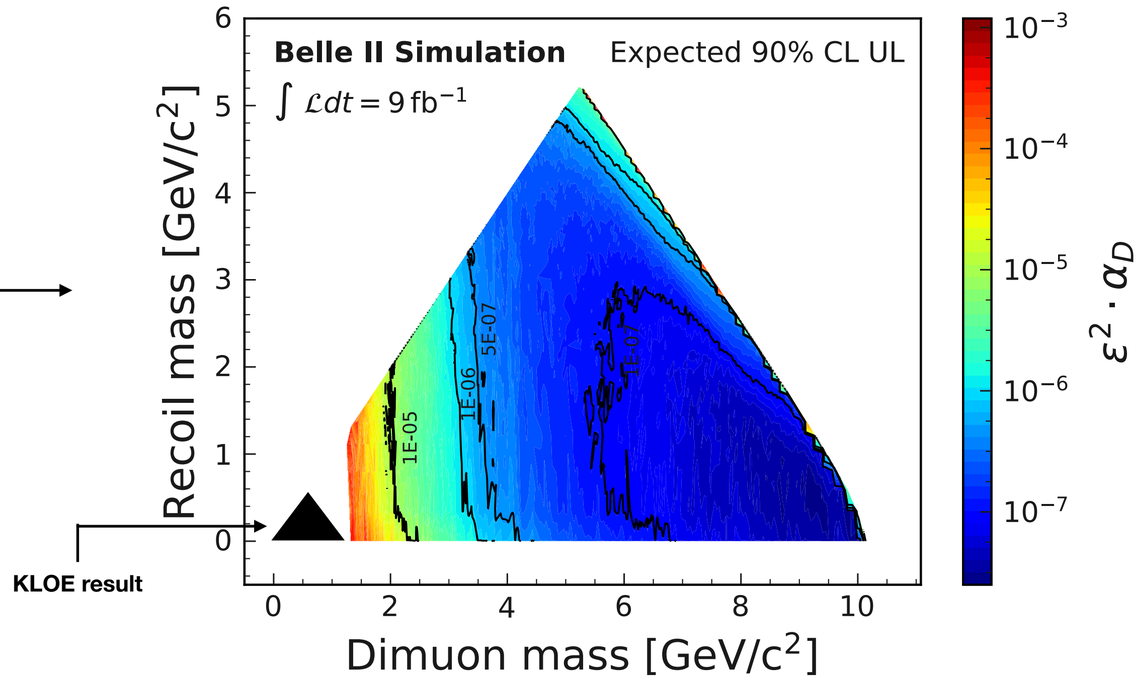


Dark Higgsstrahlung

- Scan+count in elliptical mass windows, continuous grid of 9k (overlapping) ellipses.
- Set UL on the kinematic mixing parameter times dark coupling constant ($\epsilon^2 \cdot \alpha_D$).
- Recently unblinded, paper to be published soon.







Summary

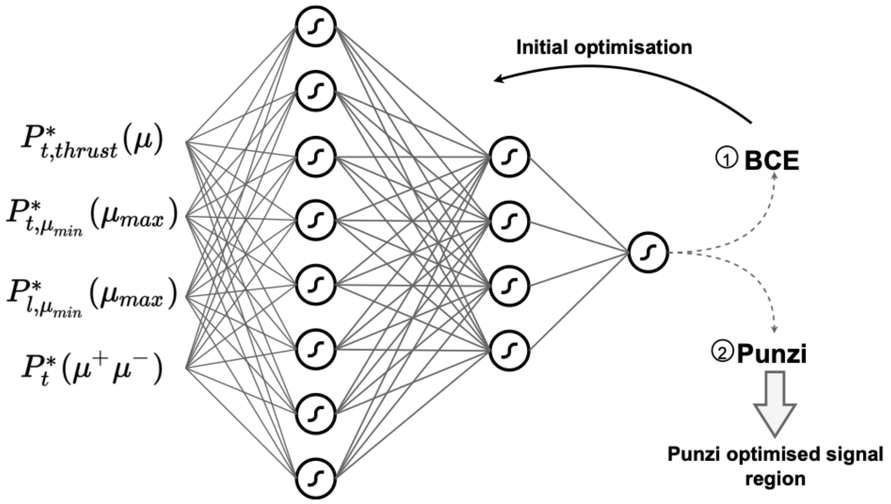
- Broad and active program of Dark Sector physics at Belle II.
- Published results:
  - Invisible Z' PRL124,141801(2020)
  - ALPs search Phys. Rev. Lett. 125, 161806 (2020).
- Ongoing searches:
  - Dark Higgs (going to be published soon)
  - Invisible Z' (update)
  - Visible Z' ($Z' \to \mu\mu, Z' \to \tau\tau$)
  - Inelastic Dark Matter
  - Dark Photon.
  - Long-lived Dark Higgs ($B \to Kh'$)
  - Magnetic Monopoles.
  - … Many more!
- Belle II will be leading the field of light dark matter searches in the coming years.

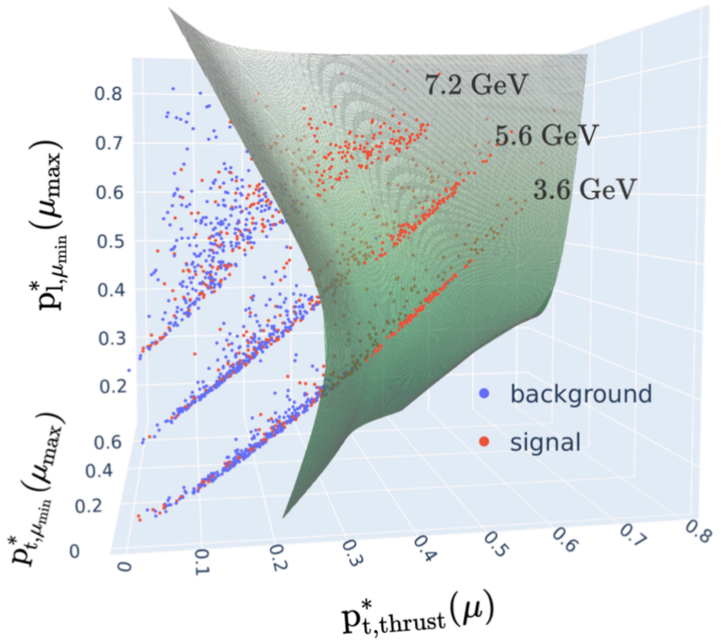
Thank you!

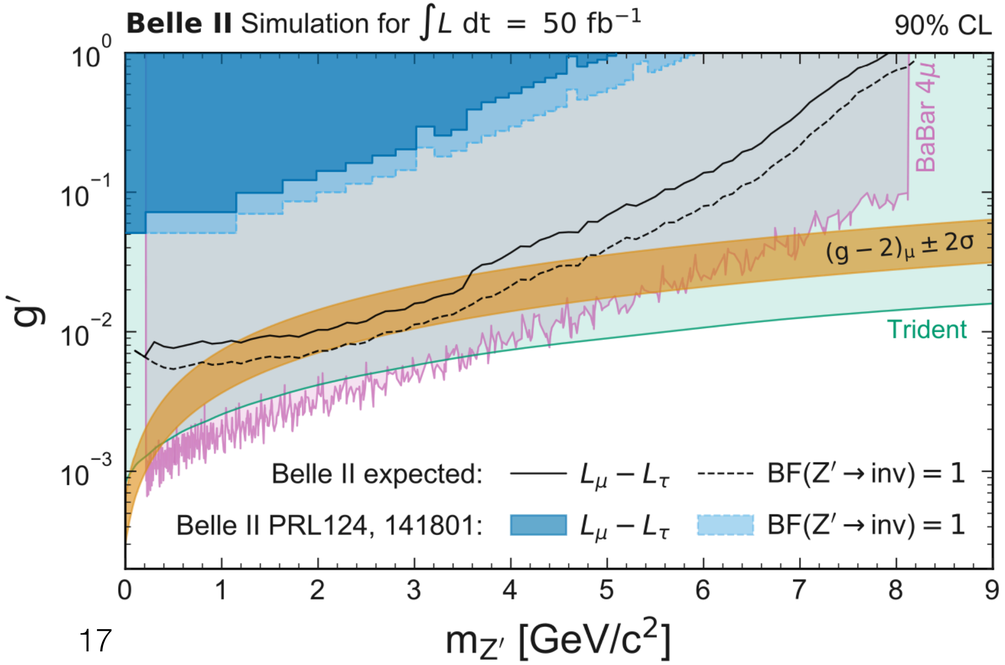
Back up slides

Future and beyond about Invisible Z'

- Plan to repeat the study with ~80 fb^{-1} of data and publish soon.
- We could gain ~285 times from luminosity.
- Better understanding of detector, improved Particle ID, new trigger lines.
- Advanced MVA tools (Punzi net)





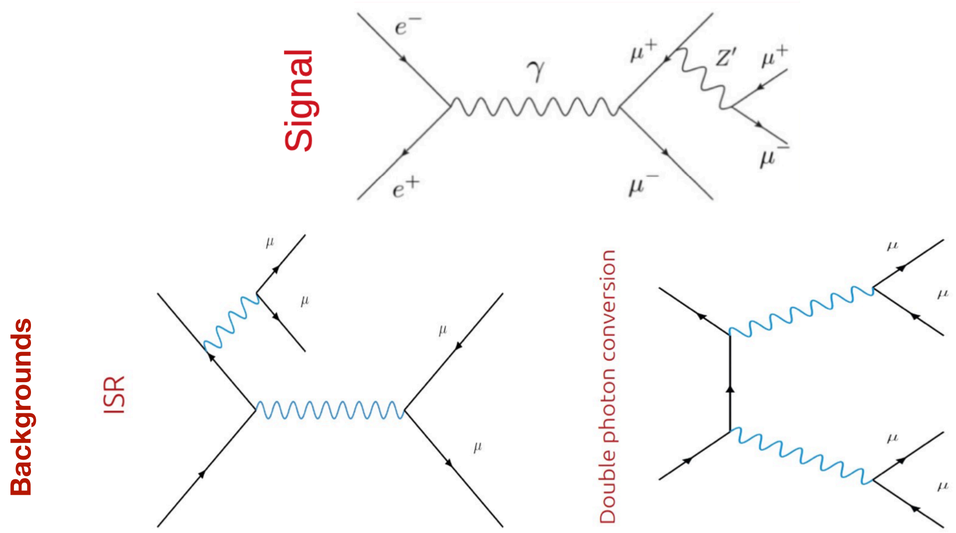


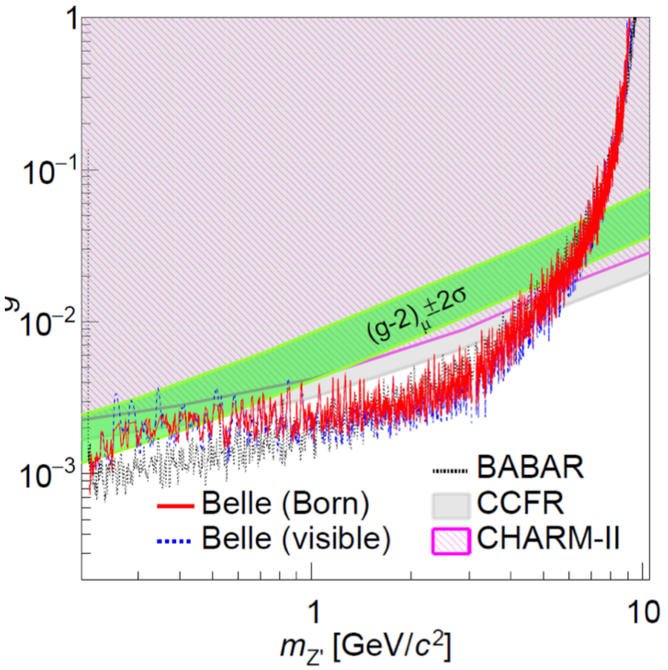
Babar limit does not constrain to the fully invisible Z'

Visible $Z'(\rightarrow \mu\mu)$

- Also studies ongoing on, $e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \mu^+\mu^-)$, called the muonic dark force.
- First Search by Babar using 514 fb^{-1} of data, no significant signal observed.
- Planning to use aggressive background suppression strategy using Neural networks.
- Main challenging backgrounds are $\mu\mu\mu\mu$, $\mu\mu(\gamma)$.

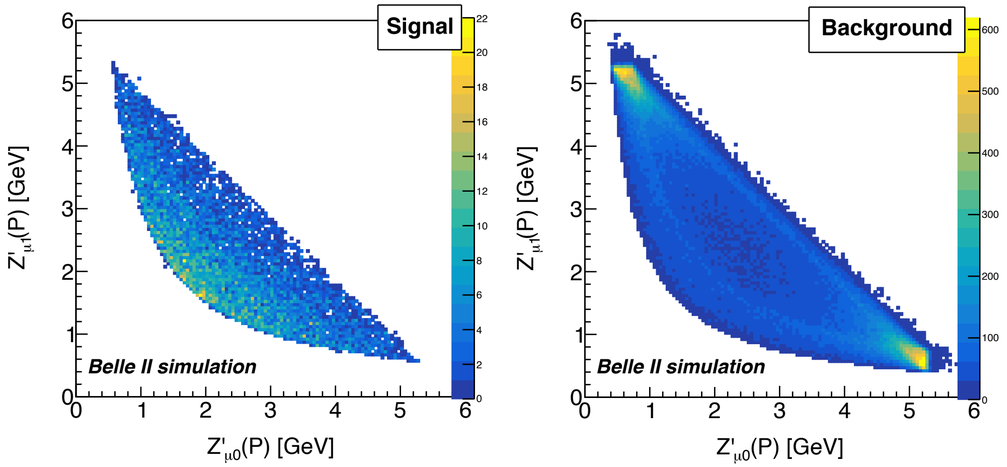
Ongoing searches





Visible $Z'(\rightarrow \mu\mu)$

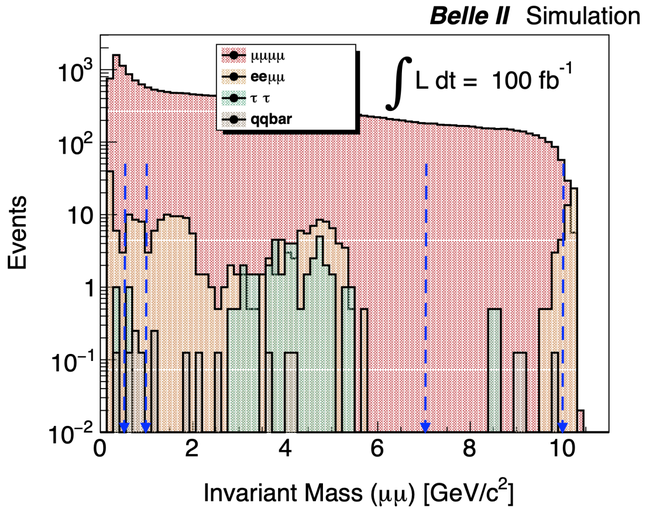
- Artificial Neural network (MultiLayer Perceptron) used for 4 different mass regions with 15 discriminating variables.

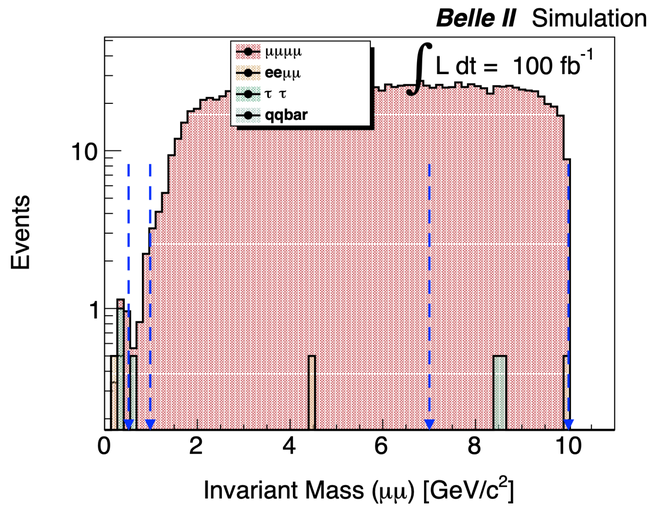


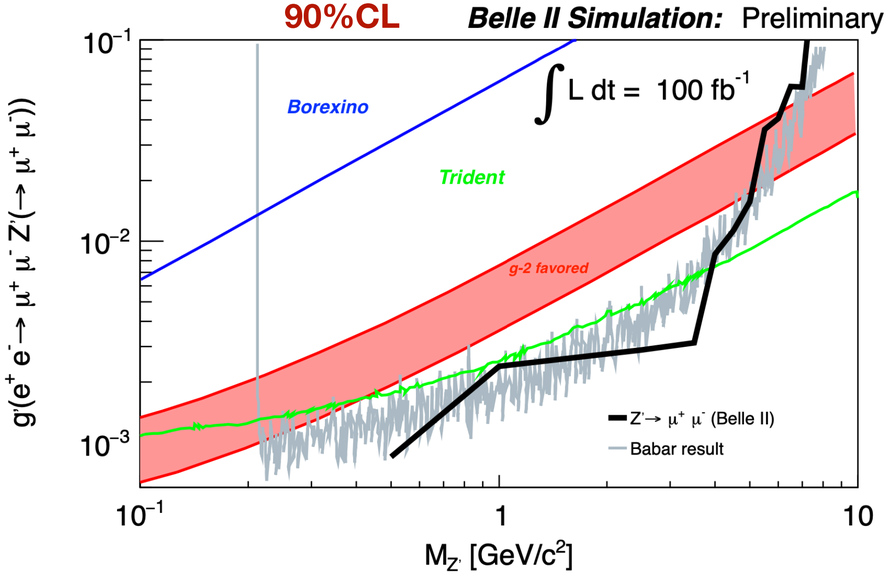
- Promising results at 100 fb^{-1} (very preliminary)
- Work in progress.

$Z' \rightarrow \mu\mu$ (Background suppression)

Ongoing searches





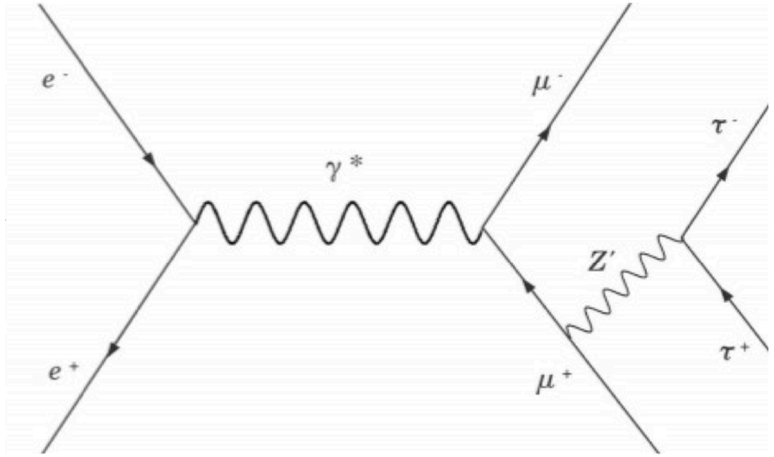


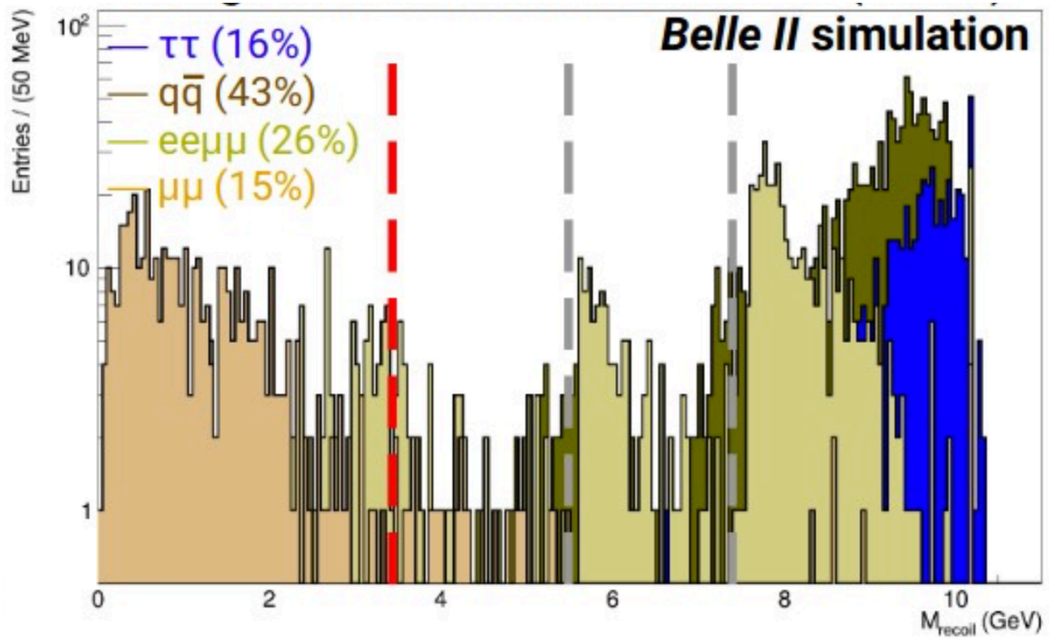
Visible $Z'(\rightarrow \tau\tau)$

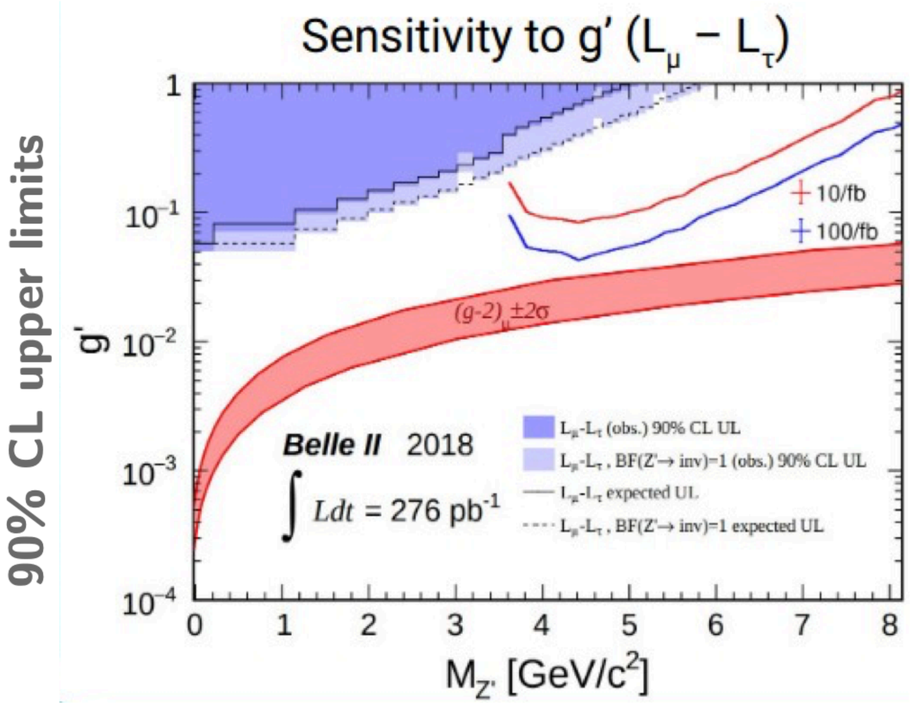
First time search

Ongoing searches

- Also studies ongoing on $e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \tau^+\tau^-)$.
- Almost model independent analysis.
- Challenging due to neutrinos.
- Profit from clean environment and MVA techniques.
- Searching for bump in the recoil mass spectrum of the muon pair.

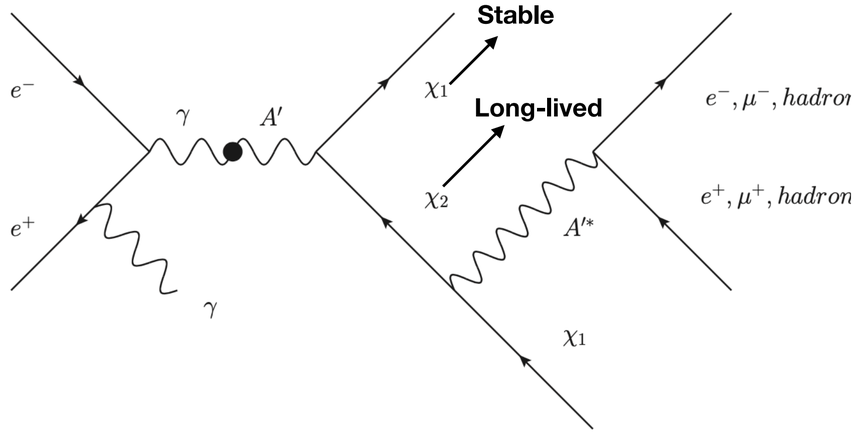






Inelastic Dark matter (iDM)

- Model introduces a dark photon A' and two dark matter states χ_1 and χ_2 with a small mass splitting.
- Initial state radiation photon for triggering the events.
- Search peak in recoil mass of the ISR photon.
- Backgrounds : $e^+e^- \to \gamma\gamma(\gamma)$, $e^+e^- \to K^0_S K^0_L(\gamma)$
- Signal yield estimated by counting events in ISR photon window (final analysis will use template fit)
- New displaced vertex trigger under consideration



Ongoing searches

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