

Dark sector searches at Belle II

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INFN – Roma 3

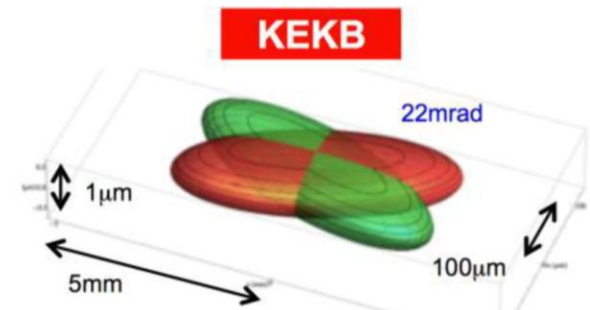
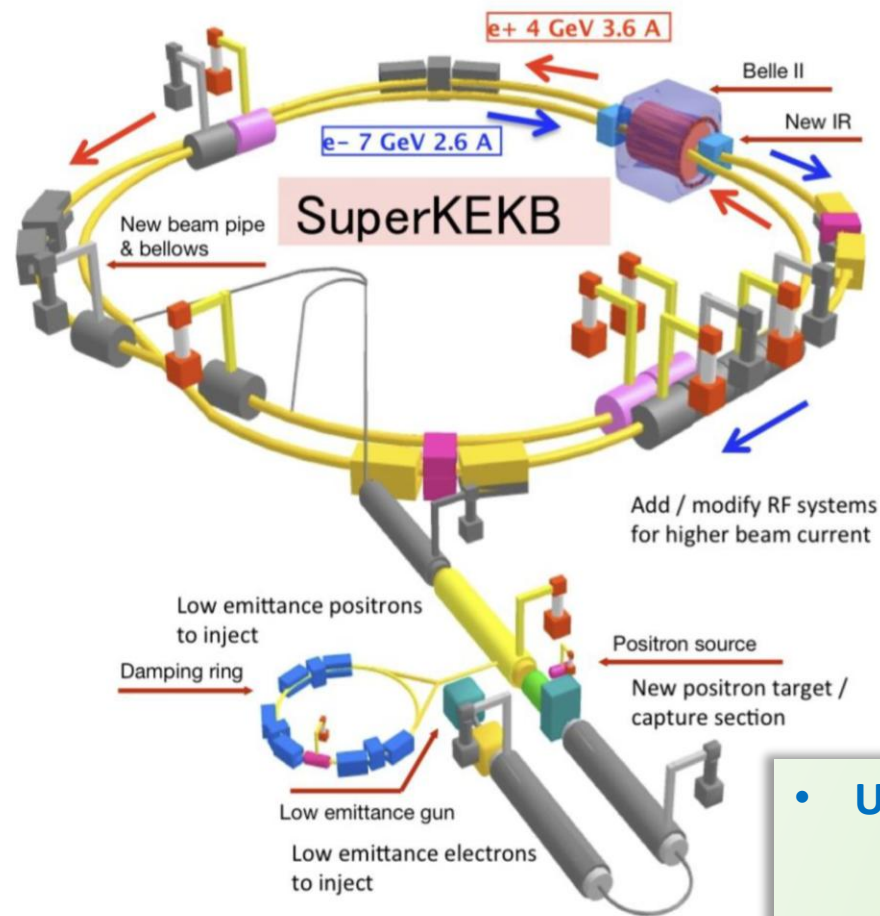
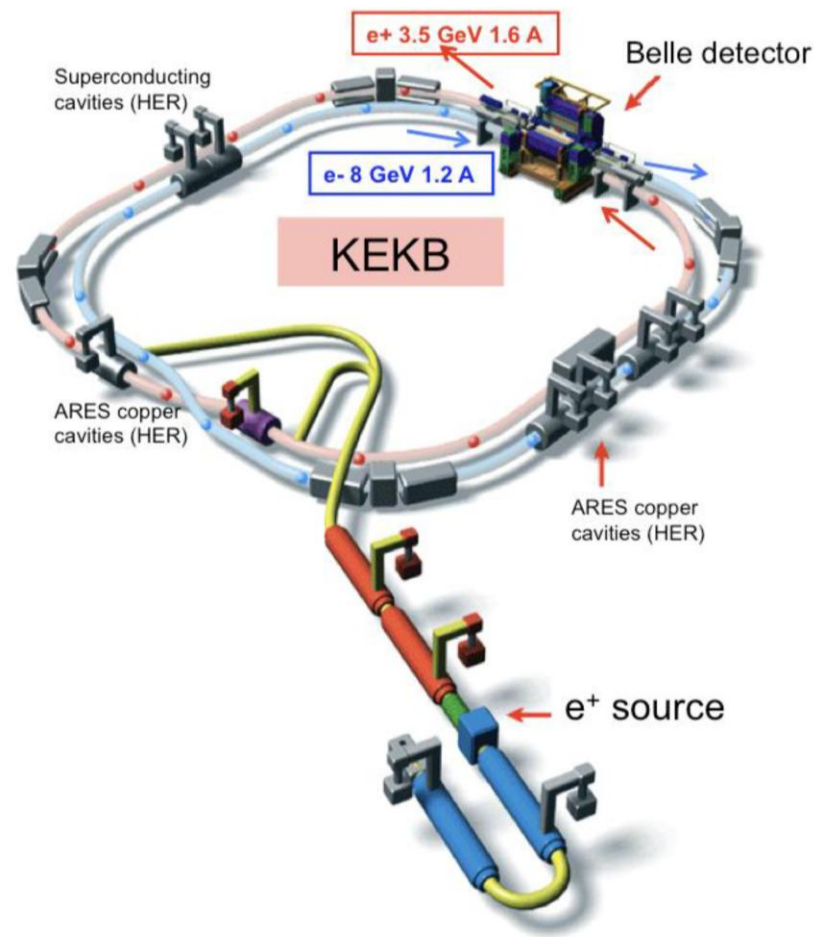
on behalf of the Belle II Collaboration

OUTLINE

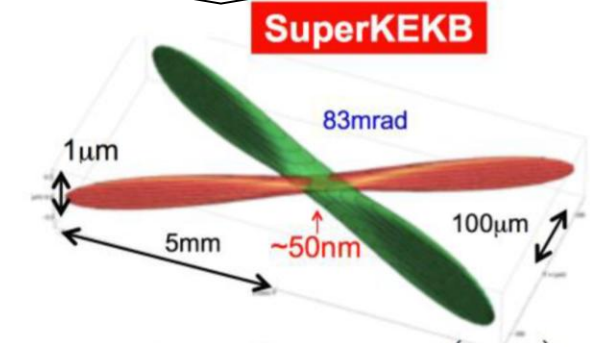
- ✓ Belle II and SuperKEKB
- ✓ Vector portals
 - $Z' \rightarrow$ invisible, $\mu\mu, \tau\tau$
- ✓ Scalar portals
 - $S \rightarrow \mu\mu, \tau\tau$
 - $B \rightarrow K S$ **LLP**
- ✓ Dark Higgsstrahlung $A'h'$
 - $A' \rightarrow \mu\mu + h'$ invisible
 - $IDM + h' \rightarrow \mu\mu, \pi\pi, KK$ **LLP**
- ✓ Pseudoscalar portals
 - $ALP \rightarrow \tau\tau$
 - $B \rightarrow K ALP, ALP \rightarrow \gamma\gamma$
- ✓ Perspectives & Summary



From KEKB to SuperKEKB



Nano-Beam scheme



- moderately increased beam currents
- Squeeze beams @IP by $\sim 1/20$

- Upgraded rings
 - New e⁺ Damping Ring
 - Increased currents
 - Nano-beam scheme
 - New Final Focus magnets (QCS)
 - Large crossing angle
- x20
- x30

SuperKEKB now

Peak luminosity world record: $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Run 1 (2019-2022)

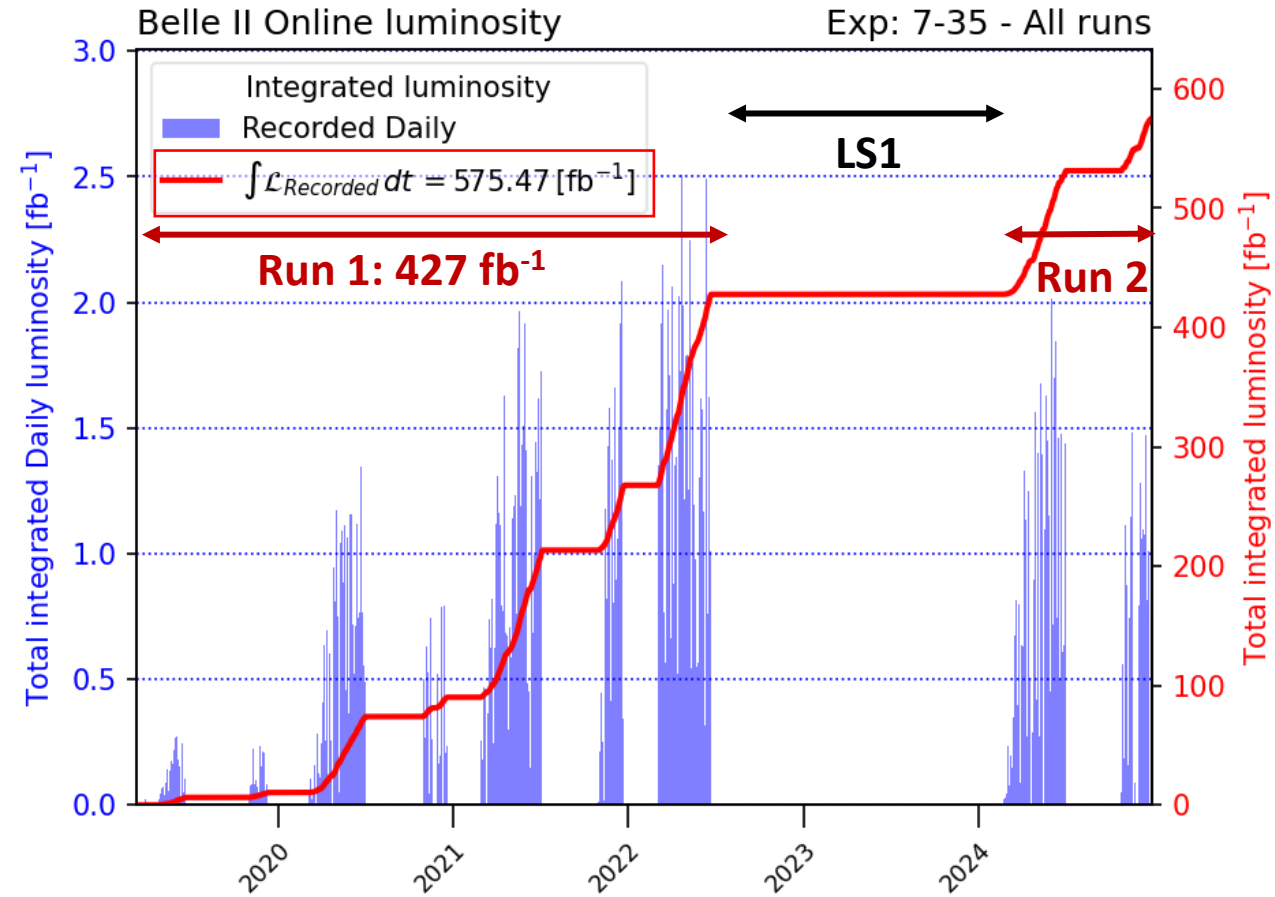
- Collected 427 fb^{-1} $\frac{1}{2}$ Belle data size
~1 Babar data size

Run 2 started in spring 2024

- Upgraded detector (PXD2, TOP PMT)
- World record luminosity $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Largely dedicated to machine studies

Final goal : 50 ab^{-1}

Collected luminosity up to now: 2019-2024



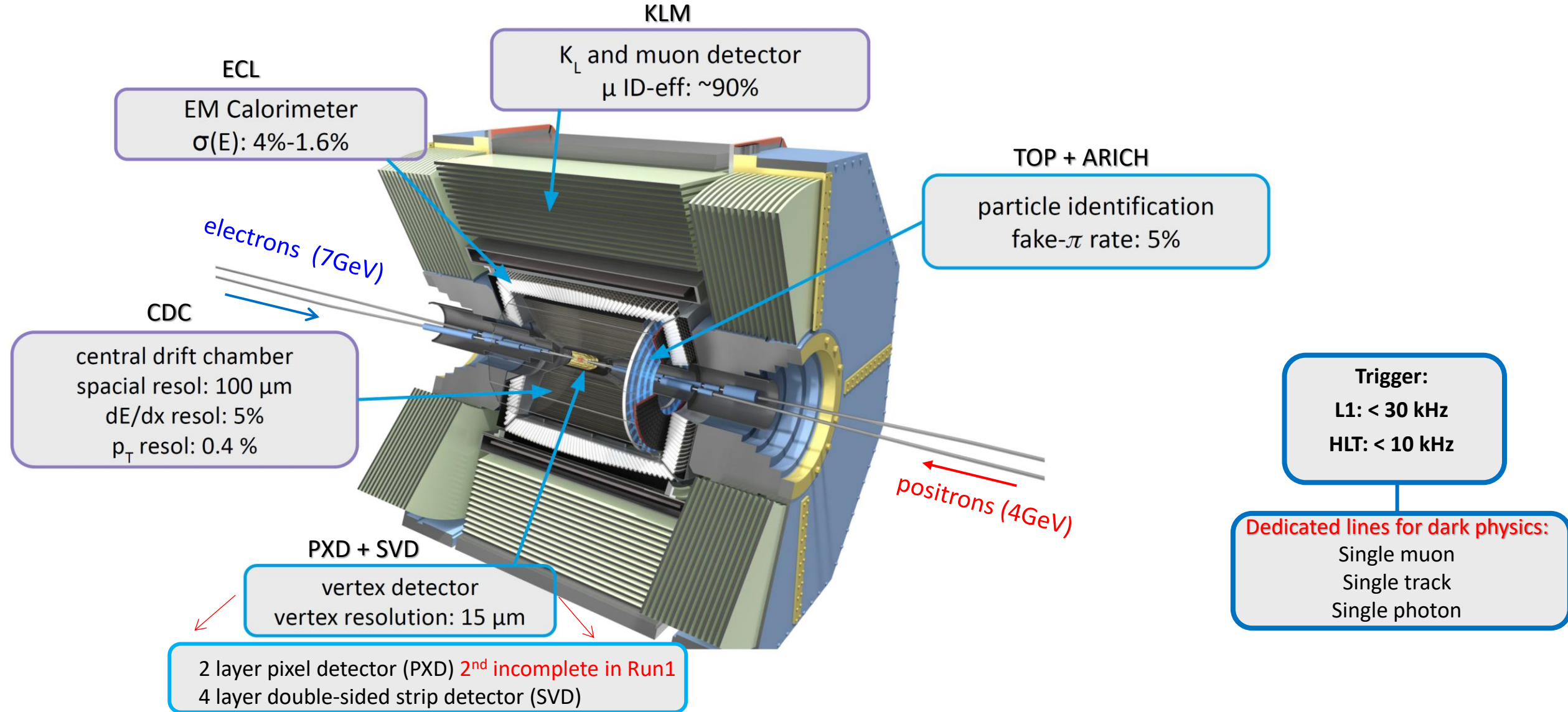
Restart data taking in October 2025

SuperKEKB now

Run 2

- Back to operations at $\sim 4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- **Sudden beam losses (SBL)** happened frequently
 - Significant beam charge loss (> a few %) that occurs suddenly without any precursory phenomena
 - **Very large dose** in the detector
- Two such losses led to **damage of 2% of the new PXD** installed during LS1
 - **Turned off PXD** as a precautionary measure until beam loss mitigated
- So far Run 2 largely dedicated to machine studies
 - $\sim 130 \text{ fb}^{-1}$ collected
- **Now confident to have reached comprehension of how SBL start**
 - Remediation begun during past summer shutdown and will extend through 2025
 - Restart data taking in October 2025

Belle II detector



Belle II trigger

Dark sector physics

- Low multiplicity signatures
- Huge backgrounds from beam, Bhabha, two-photon fusion

Level 1 hardware-based combines info from CDC, ECL, KLM

- Tracks, clusters, muons
- Two-track trigger
- Three-track trigger
- $E_{ECL} > 1$ GeV trigger

Single muon

- CDC + KLM

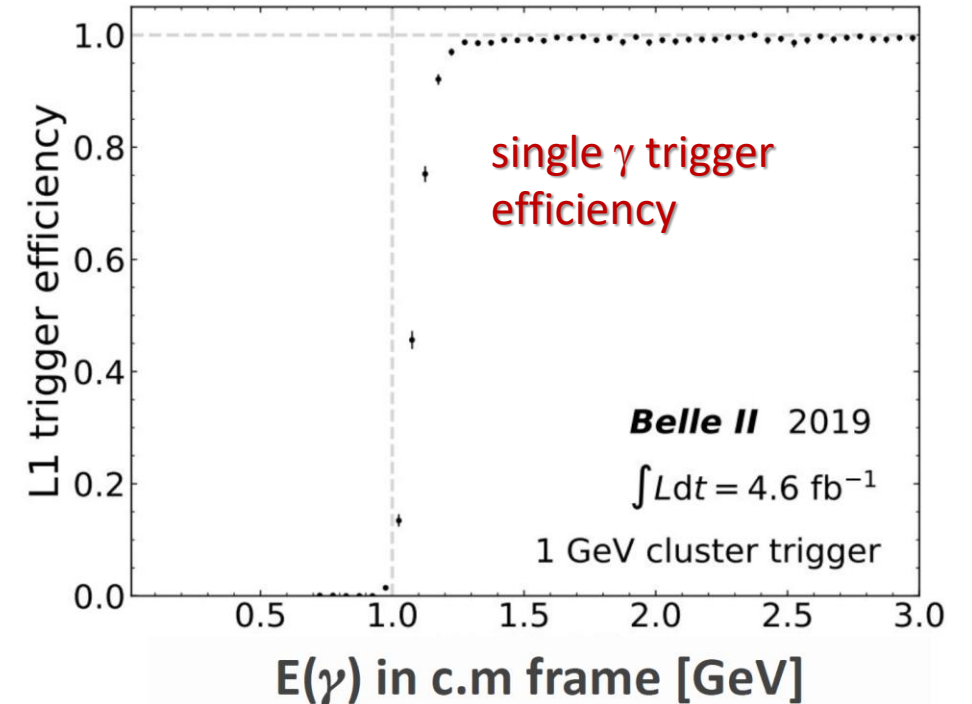
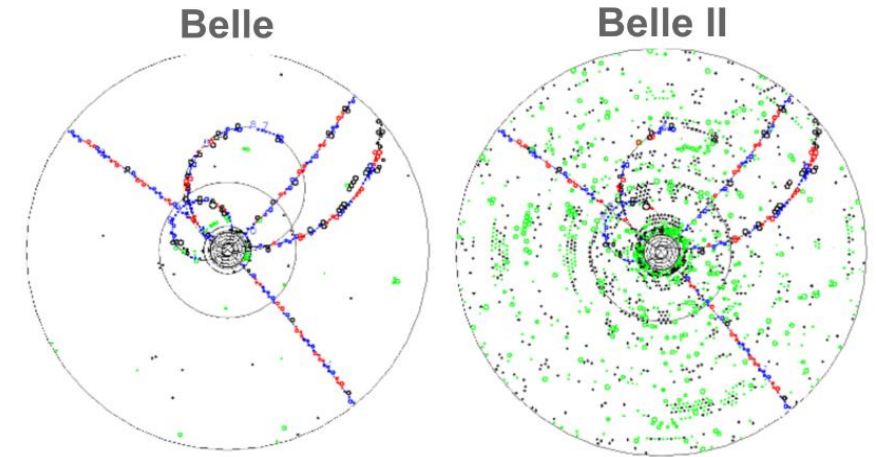
Single track

- Neural based

Single photon

- $E_\gamma > 0.5, 1, 2$ GeV

Displaced-vertex trigger
• Under study



What can we do at B-factories that we can't at the LHC?

- Closeness to the light region
- Clean, low background, «energy conserving» environment, closed kinematics
- 3d momentum conservation, as opposed to p_T
- Full Event Interpretation



- Low multiplicity signatures
 - Missing energy channels
 - Invisible particles, often in closed kinematics regime
 - Also an extreme case of LLP
 - Some fully neutral final states accessibility
 - Dark sector signatures in B and τ decays
- Cleanliness and luminosity sometimes compensate for cross section → competition

Belle II dark sector search overview: results

$$L_\mu - L_\tau$$

$Z' \rightarrow$ invisible

$Z' \rightarrow \mu\mu$

$Z' \rightarrow \tau\tau$

Axion like particles

$a \rightarrow \tau\tau$

Axion like particles

$B \rightarrow K a, a \rightarrow \gamma\gamma$

Dark Higgsstrahlung

$A'h'$ $A' \rightarrow \mu\mu, h'$ invisible

LLP Dark Higgsstrahlung with IDM

$A'h'$ $A' \rightarrow \chi_1\chi_2, h' \rightarrow \mu\mu, \pi\pi, kk$

LLP dark scalar in B decays

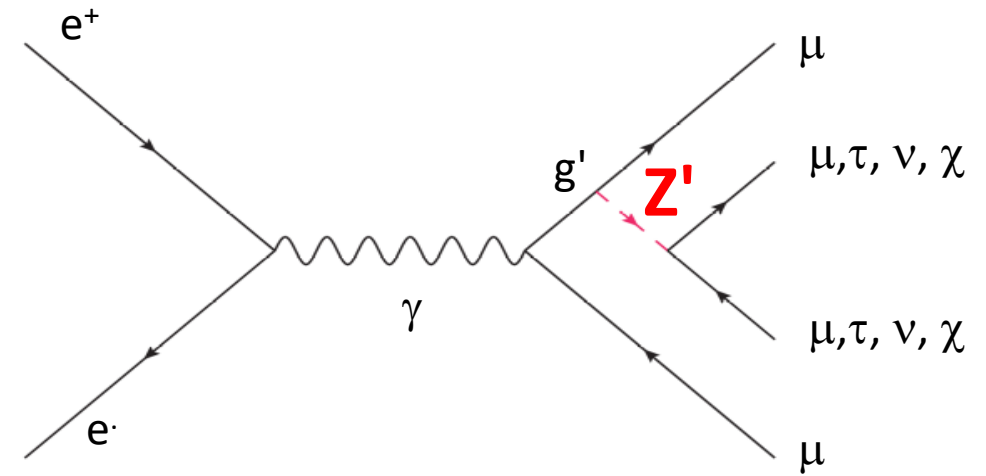
$B \rightarrow KS$ $S \rightarrow ee, \mu\mu, \pi\pi, KK$

Z' : $L_\mu - L_\tau$ model

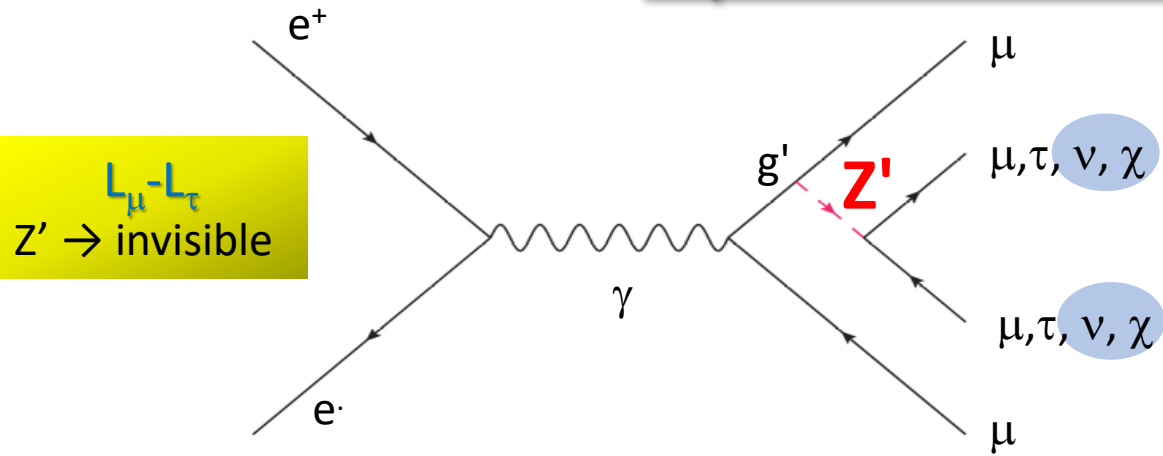
- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2^o and 3^o lepton family
- Anomaly free (by construction)
- It may solve
 - **dark matter puzzle** ➤ Sterile ν 's
➤ Light Dirac fermions
 - $(g-2)_\mu$
 - $B \rightarrow K^{(*)} \mu\mu$, R_K , R_{K^*} anomalies

Shuve et al. [Phys. Rev. D 89, 113004 \(2014\)](#)

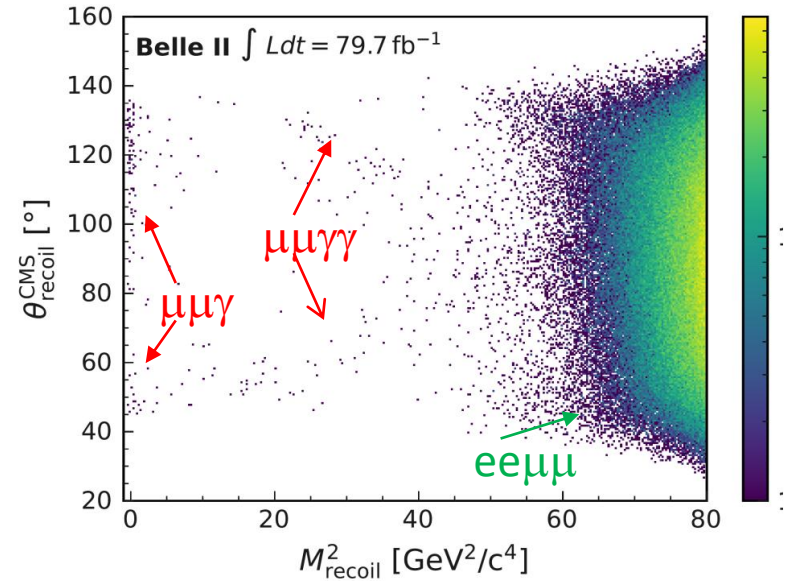
Altmannshofer et al. [JHEP 1612 \(2016\) 106](#)



$L_\mu-L_\tau$ model: Z' to invisible



bands in θ_{recoil} vs M_{recoil}^2 due to γ lost in ECL gaps



$e^+e^- \rightarrow \mu^+\mu^- + \text{missing energy}$

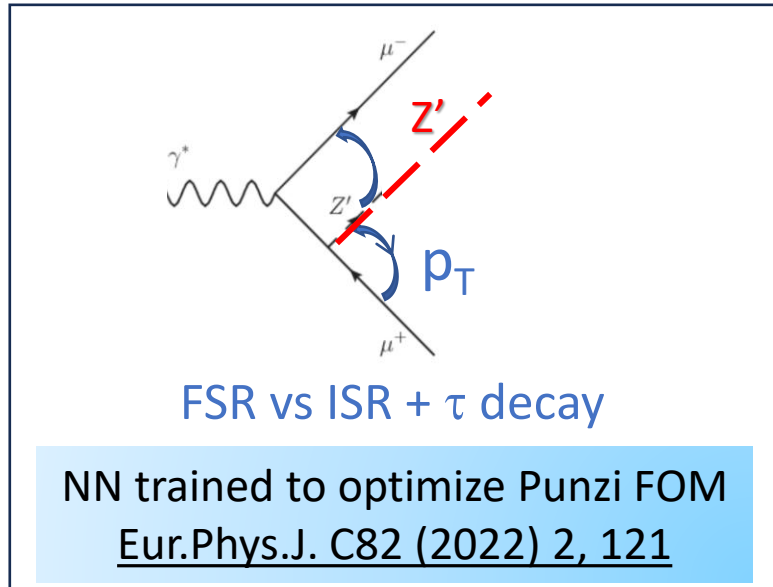
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Main backgrounds:

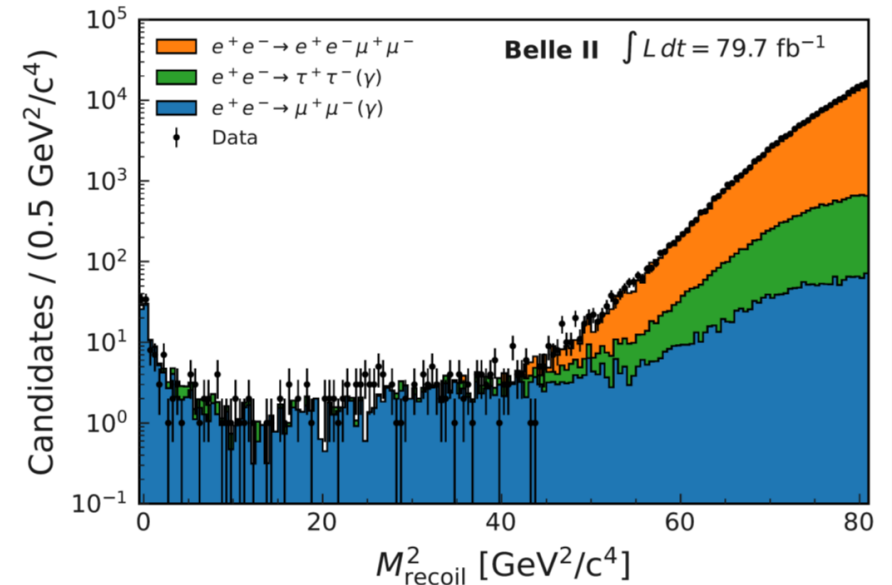
$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

$e^+e^- \rightarrow \tau^+\tau^- (\gamma), \tau^\pm \rightarrow \mu^\pm \nu$

$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$



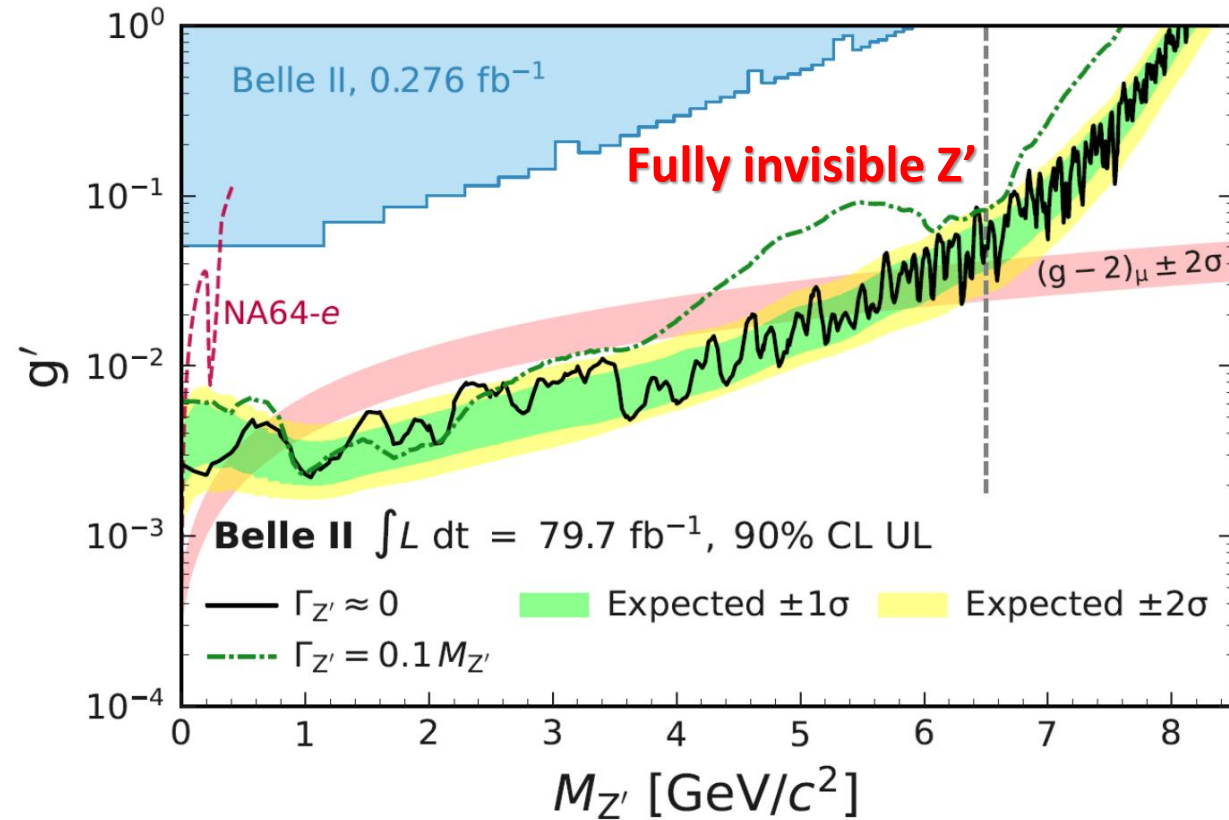
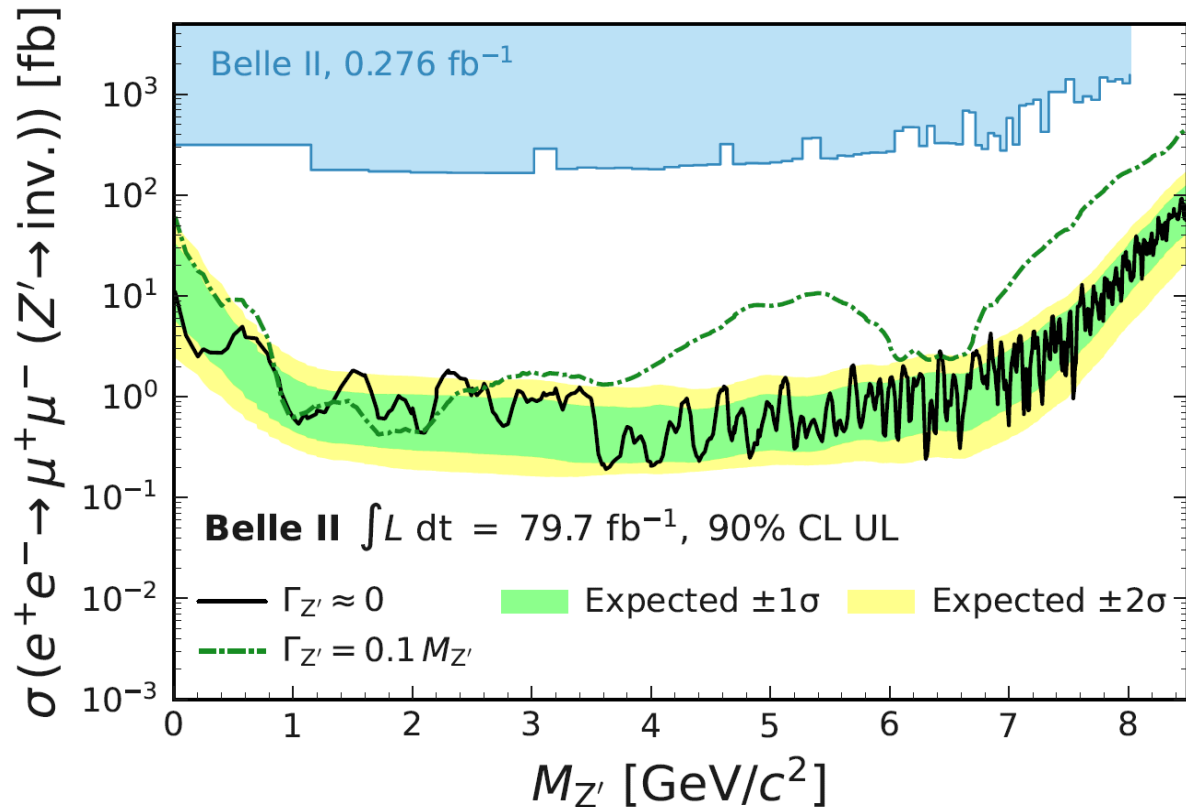
NN trained to optimize Punzi FOM
Eur.Phys.J. C82 (2022) 2, 121



Z' to invisible: results

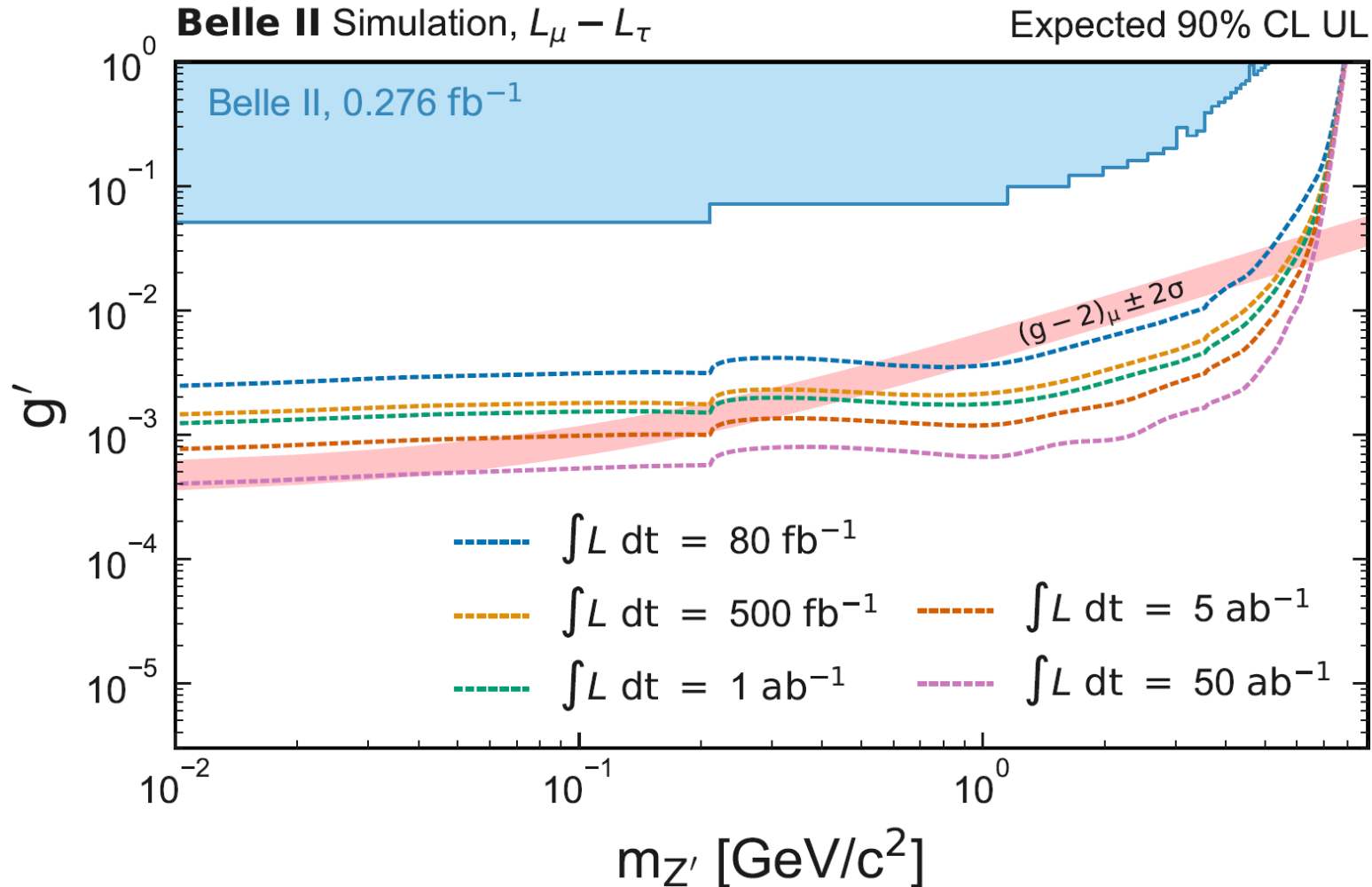
PRL 130, 231801 (2023)

- No excess found
- Set 90%CL exclusion limits on cross section and coupling
 - Vanilla scenario: Z' decays to SM only
 - Fully invisible scenario



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

Z' to invisible: luminosity projections



Belle II physics reach @ Snowmass
[arXiv: 2207.06307v1](https://arxiv.org/abs/2207.06307v1)

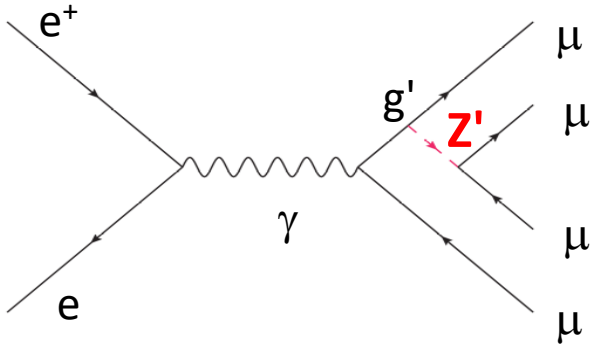
Next update based on Run 1
luminosity almost ready

$L_\mu-L_\tau$ model: $Z' \rightarrow \mu\mu$

$L_\mu-L_\tau$
 $Z' \rightarrow \mu\mu$

Reinterpreted also as

- Muonphilic dark scalar $S \rightarrow (g-2)_\mu$



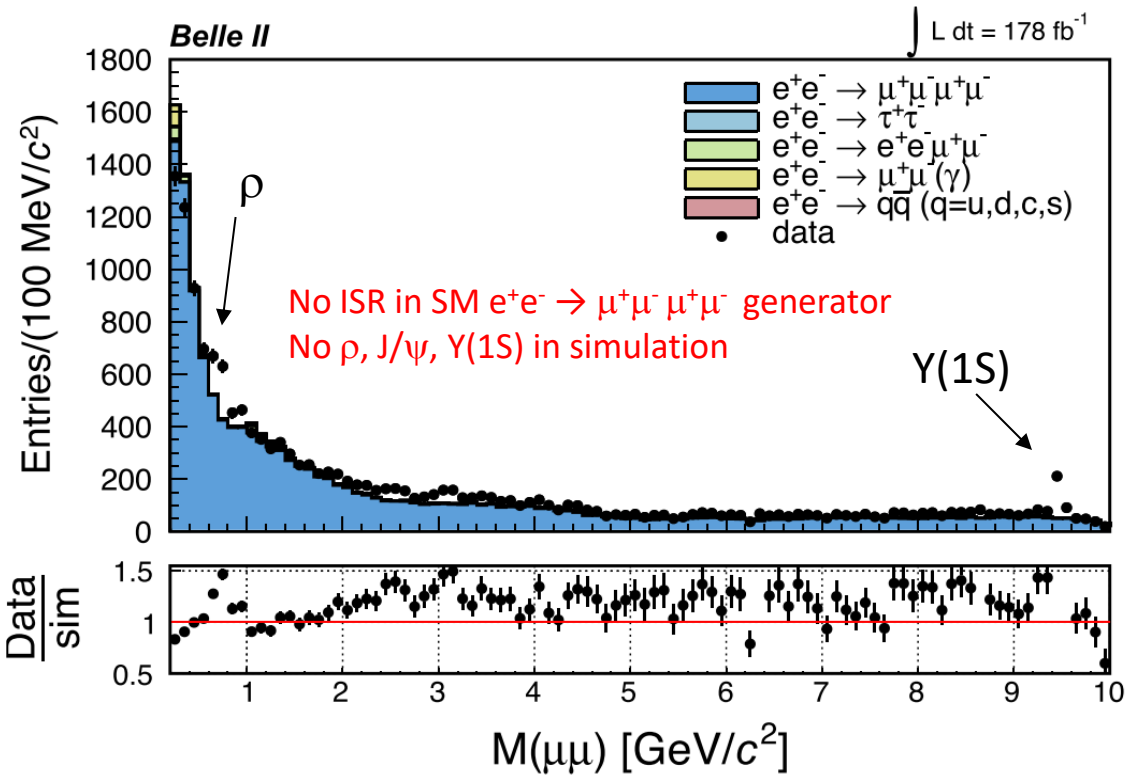
$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

4-track mass $\sim \sqrt{s}$
 No extra energy
 Signature: narrow $M(\mu\mu)$ peak

Main background: SM $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

- Aggressive background suppression through NN based on kinematic features
- Characteristic background momentum scale
 - Signal as FSR
 - $\mu\mu$ helicity angle

Fits to $M(\mu\mu)$



$L_\mu-L_\tau$ model: $Z' \rightarrow \mu\mu$

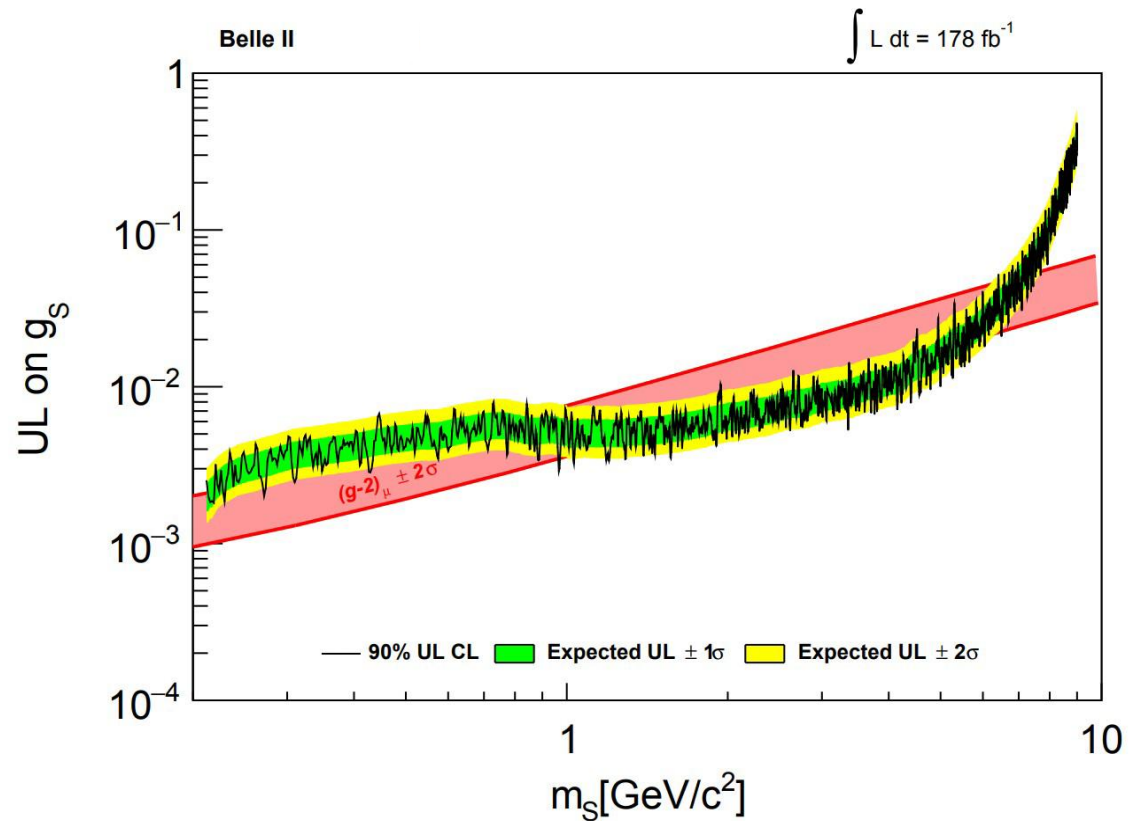
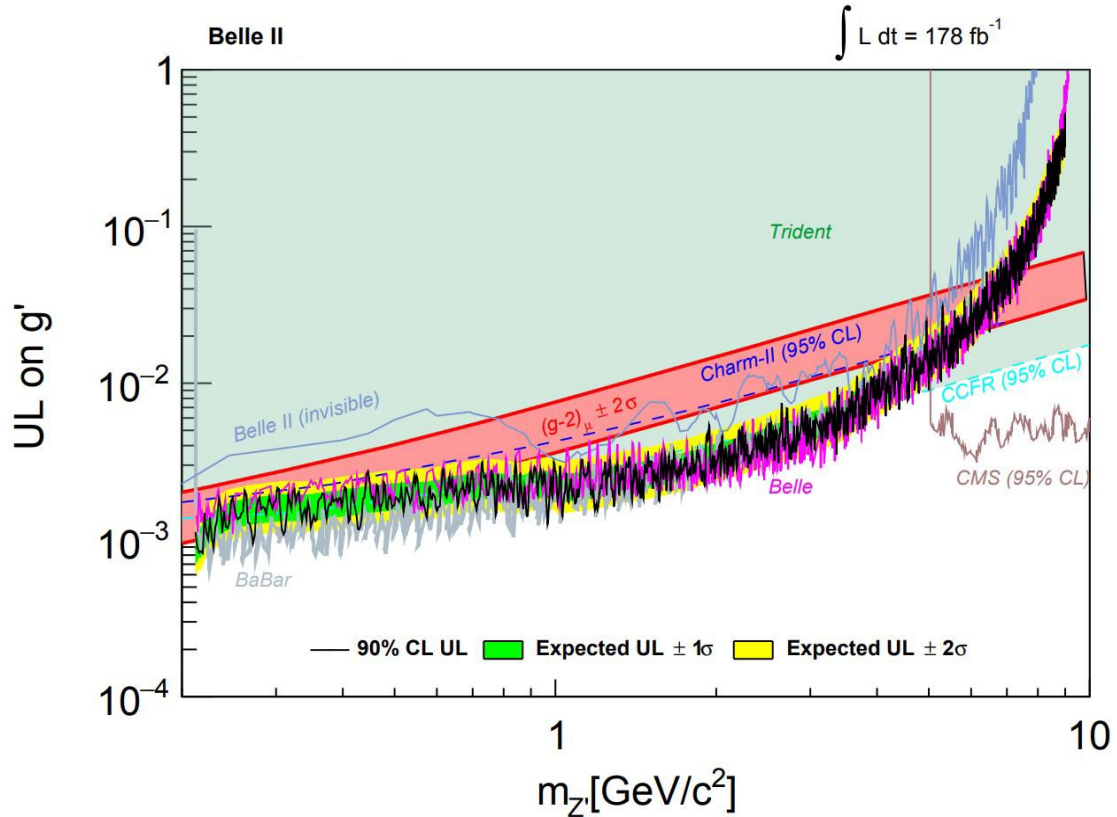
$L_\mu-L_\tau$
 $Z' \rightarrow \mu\mu$

Reinterpreted also as

- Muonphilic dark scalar $S \rightarrow (g-2)_\mu$

PRD 109, 112015 (2024)

- No excess
- Limits on Z' similar to BaBar and Belle with much lower luminosity
- **First limits for the muonphilic scalar** from a dedicated search



$L_\mu - L_\tau$ model: $Z' \rightarrow \tau\tau$

$L_\mu - L_\tau$
 $Z' \rightarrow \tau\tau$

- Reinterpreted also as
- Leptophilic dark scalar $S \rightarrow (g-2)_\mu$
 - ALP with τ coupling

Background suppression with NN

- resonance vs $\mu\mu$
- FSR production
- $\tau\tau$ system

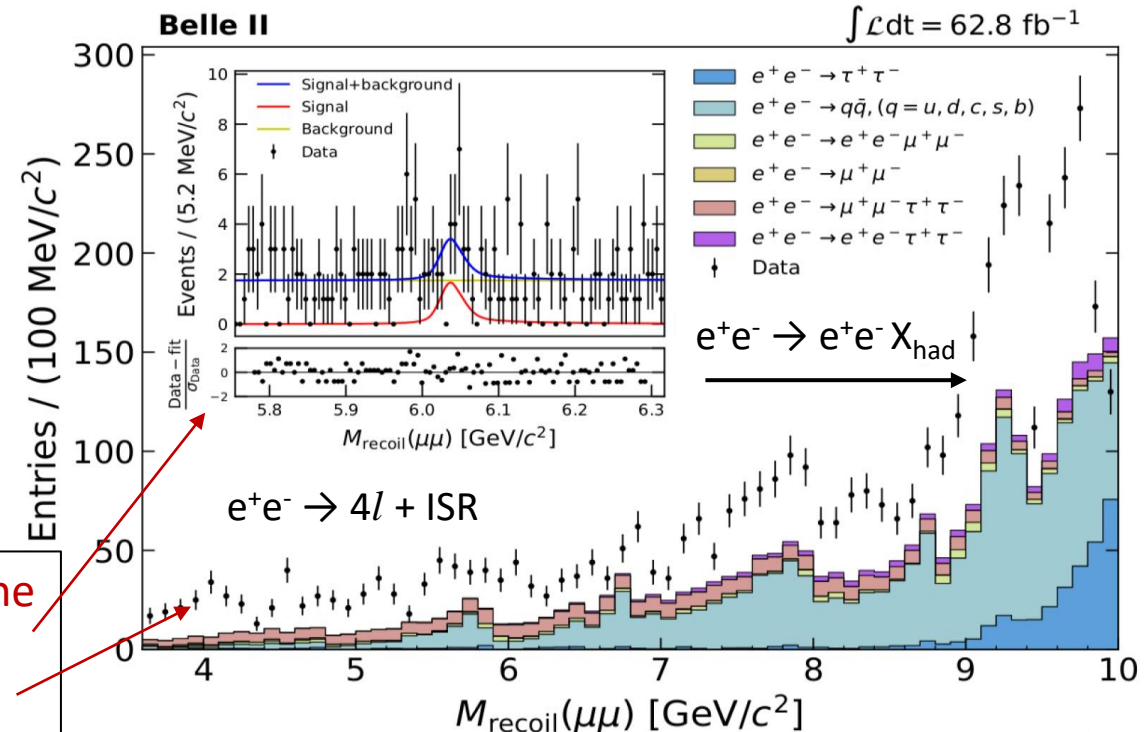
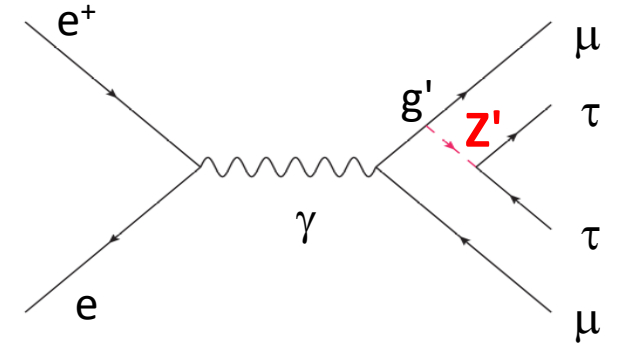
Main backgrounds

$e^+e^- \rightarrow \tau^+\tau^- (\gamma)$ 1+3 prong
 $e^+e^- \rightarrow qq$ ($q=u,d,s,c$)

$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$
 $e^+e^- \rightarrow \mu^+\mu^- \tau^+\tau^-$
 $e^+e^- \rightarrow e^+e^- \tau^+\tau^-$
 $e^+e^- \rightarrow \mu^+\mu^- \pi^+\pi^-$ not simulated

no ISR in simulation

$e^+e^- \rightarrow e^+e^- X_{\text{had}}$ not simulated



Smooth background on the scale of the signal mass resolution ($\sim 10 \text{ MeV}/c^2$)

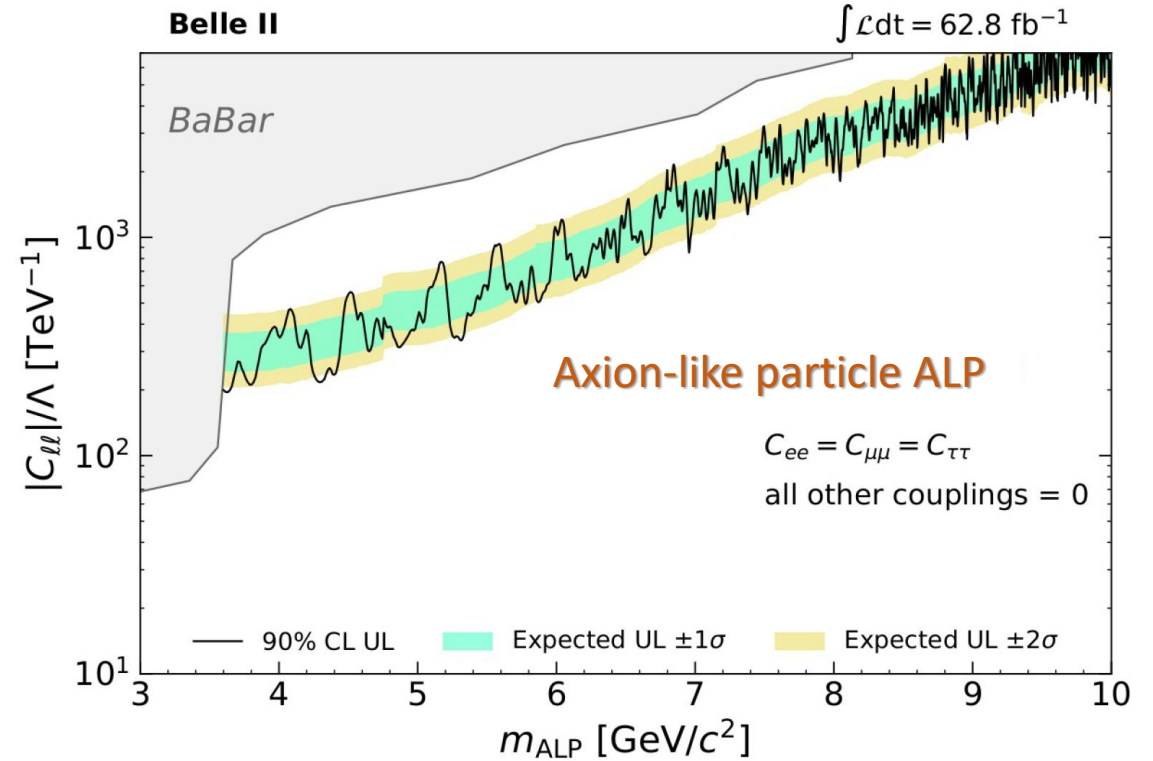
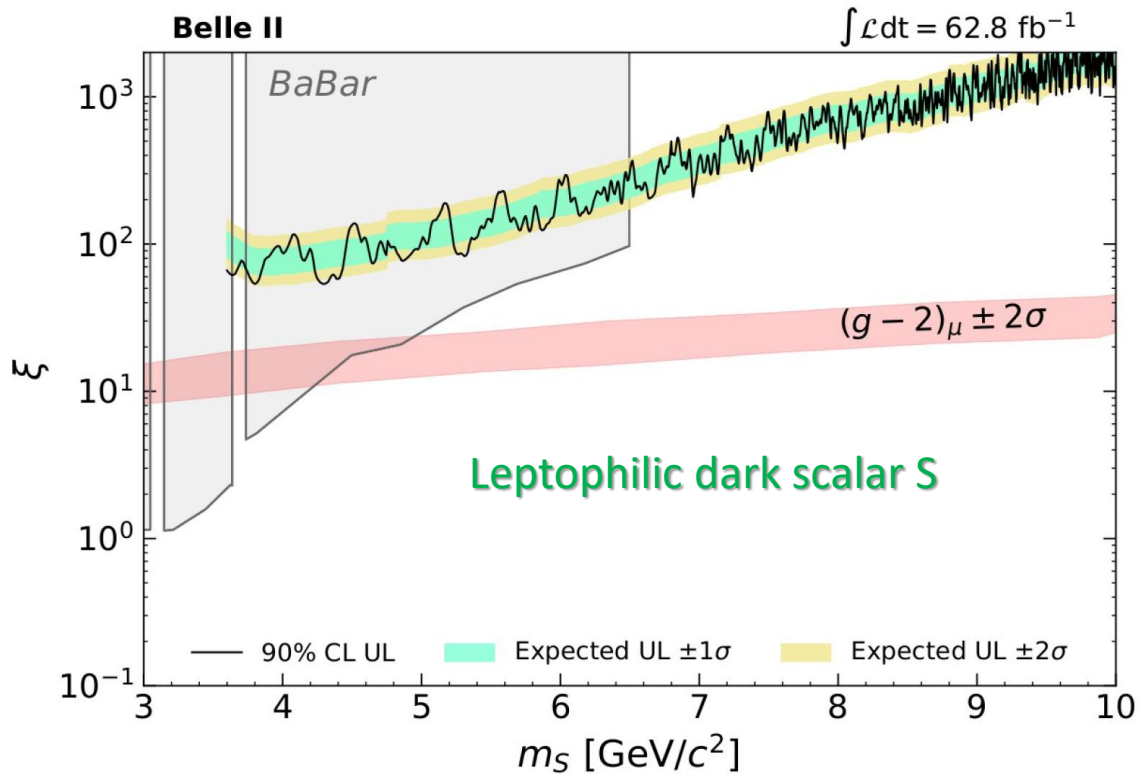
$L_\mu-L_\tau$ model: $Z' \rightarrow \tau\tau$

$L_\mu-L_\tau$
 $Z' \rightarrow \tau\tau$

Reinterpreted also as

- Leptophilic dark scalar $S \rightarrow (g-2)_\mu$
- ALP with τ coupling

PRL 131, 121802 (2023)

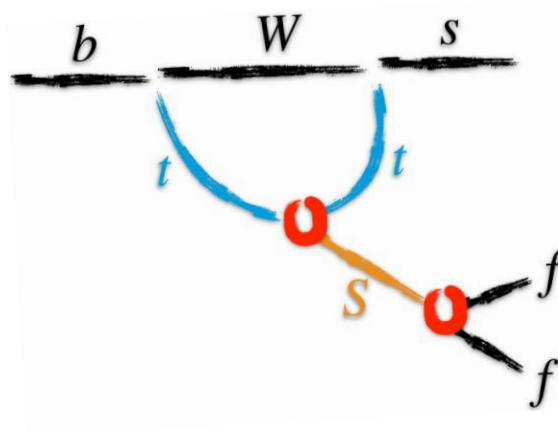


Dark scalar S in $b \rightarrow s$ transitions

LLP dark scalar in B decays

$B \rightarrow kS$ $S \rightarrow ee, \mu\mu, \pi\pi, KK$

$b \rightarrow s$ transitions
Mixing with SM Higgs
LLP signature



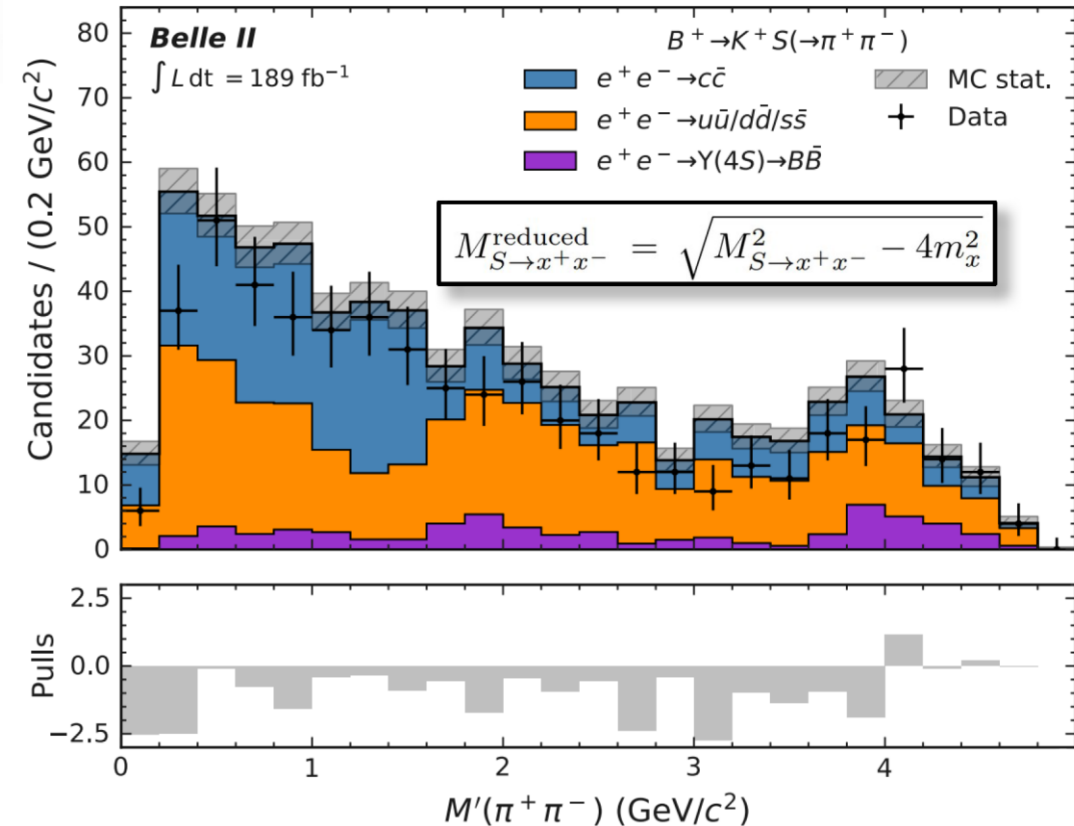
$B^+ \rightarrow K^+ S, B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] S$

$S \rightarrow e^+ e^- / \mu^+ \mu^- / \pi^+ \pi^- / K^+ K^-$

First dark-sector search in Belle II

- in B decays
- with LLP signature

Signal search: fits to the LLP reduced mass for each channel and lifetime

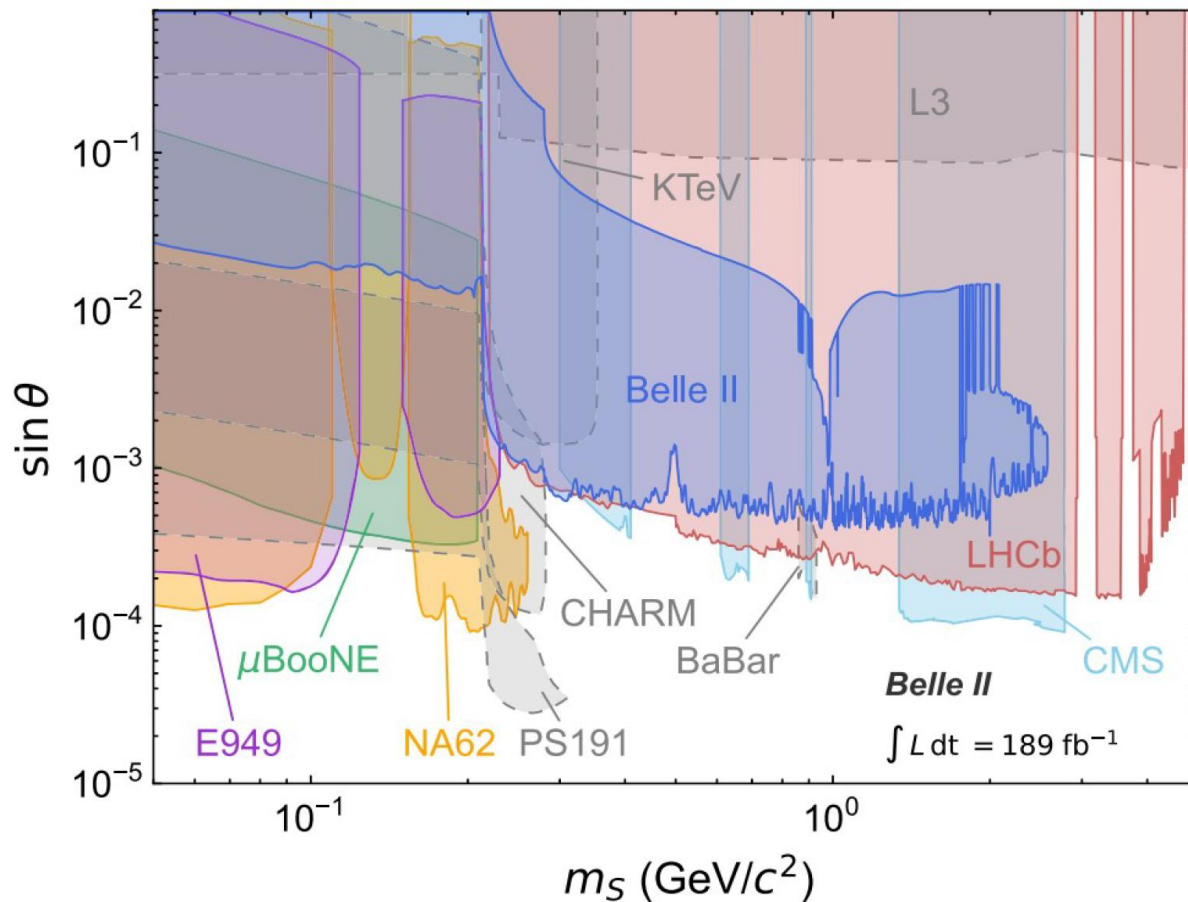


Dark scalar S in $b \rightarrow s$ transitions

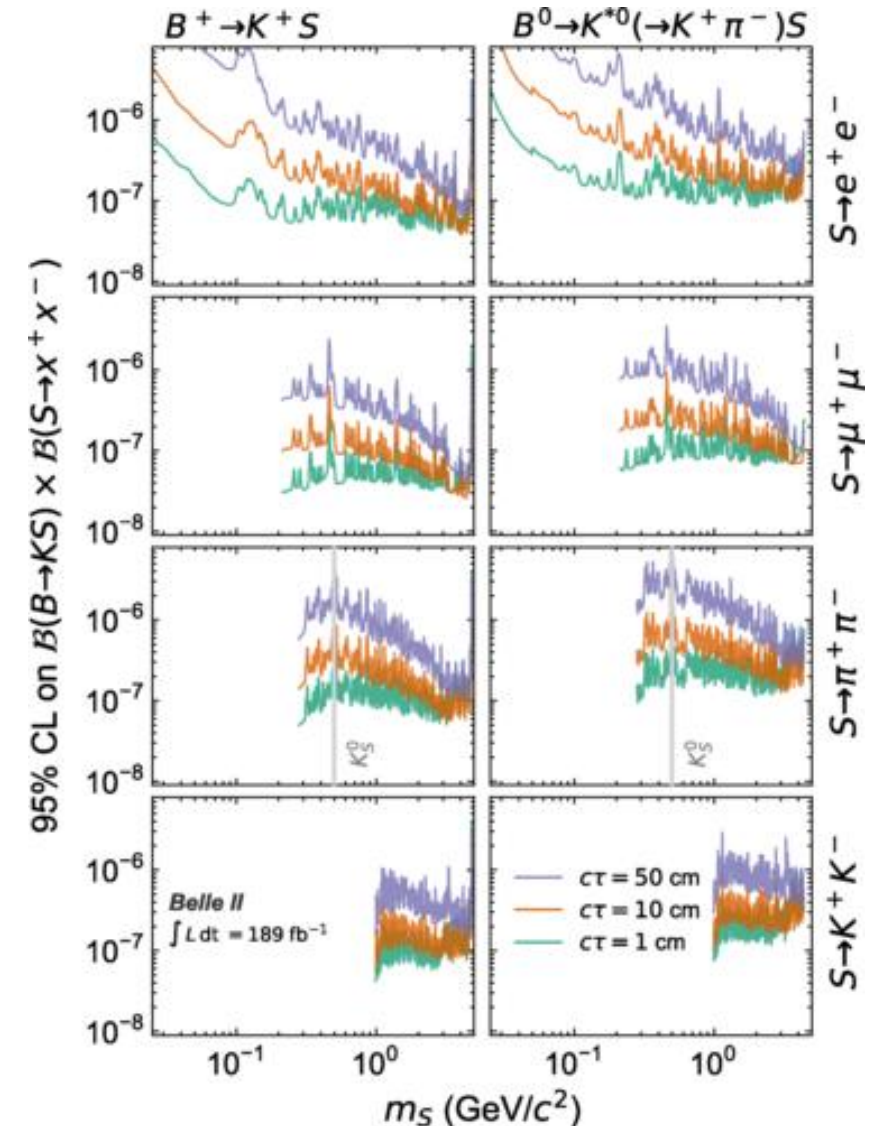
No excess found

- First model-independent limits on $B(B \rightarrow KS) \times B(S \rightarrow x+x')$
- First limits on decays to hadrons

PRD 108, L111104 (2023)



Limits for each channel and lifetime



ALP in $B \rightarrow Ka$ (Belle)

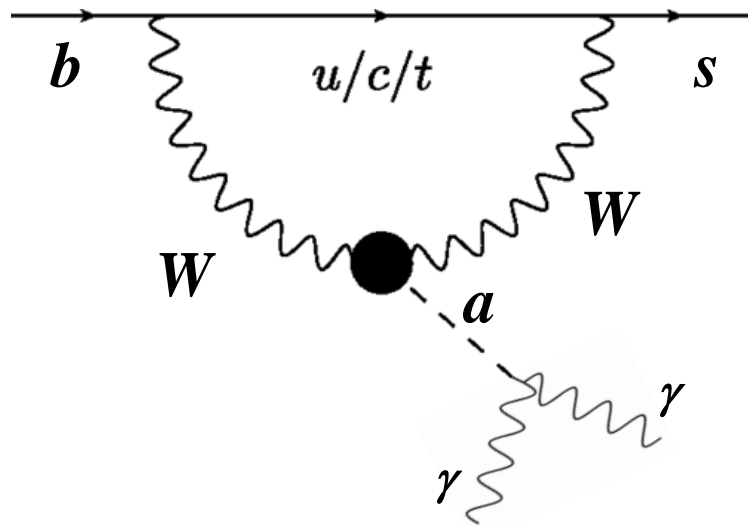
Axion-like particles in B decays

$B \rightarrow K$ ALP, $ALP \rightarrow \gamma\gamma$

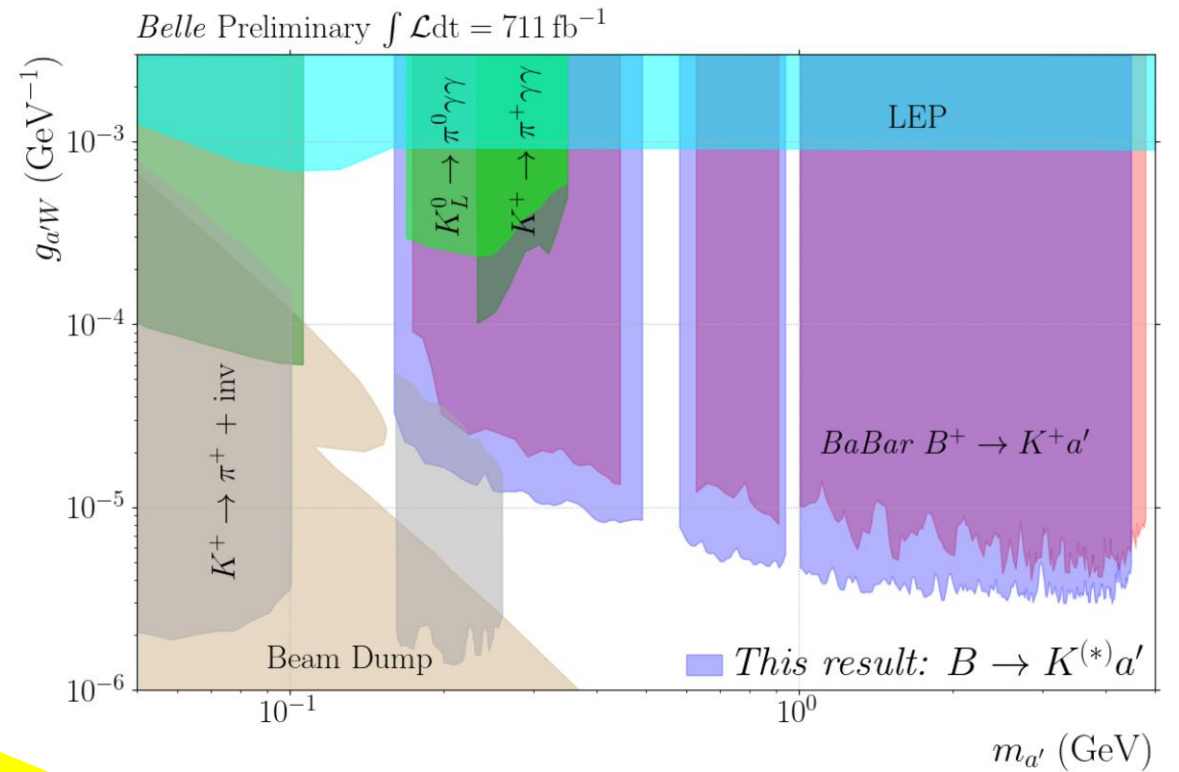
$B^\pm \rightarrow K^{(*)\pm} a, a \rightarrow \gamma\gamma$

$B^0 \rightarrow K^*/K^0_s a, a \rightarrow \gamma\gamma$

Probe of aWW coupling in $b \rightarrow s$ transitions

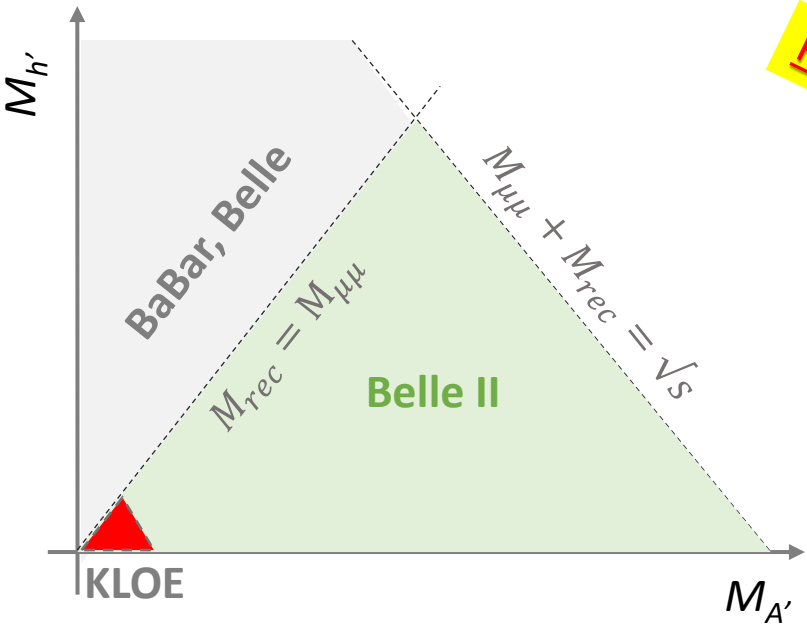
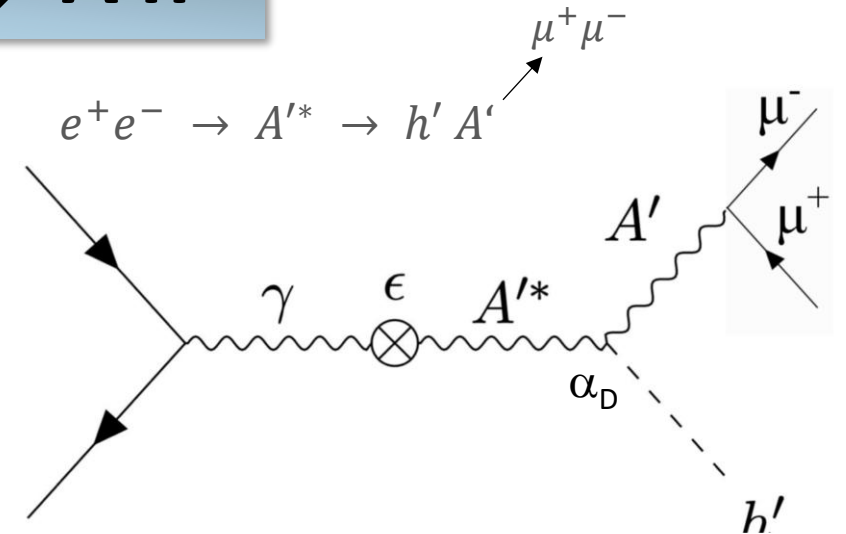


To be submitted to JHEP

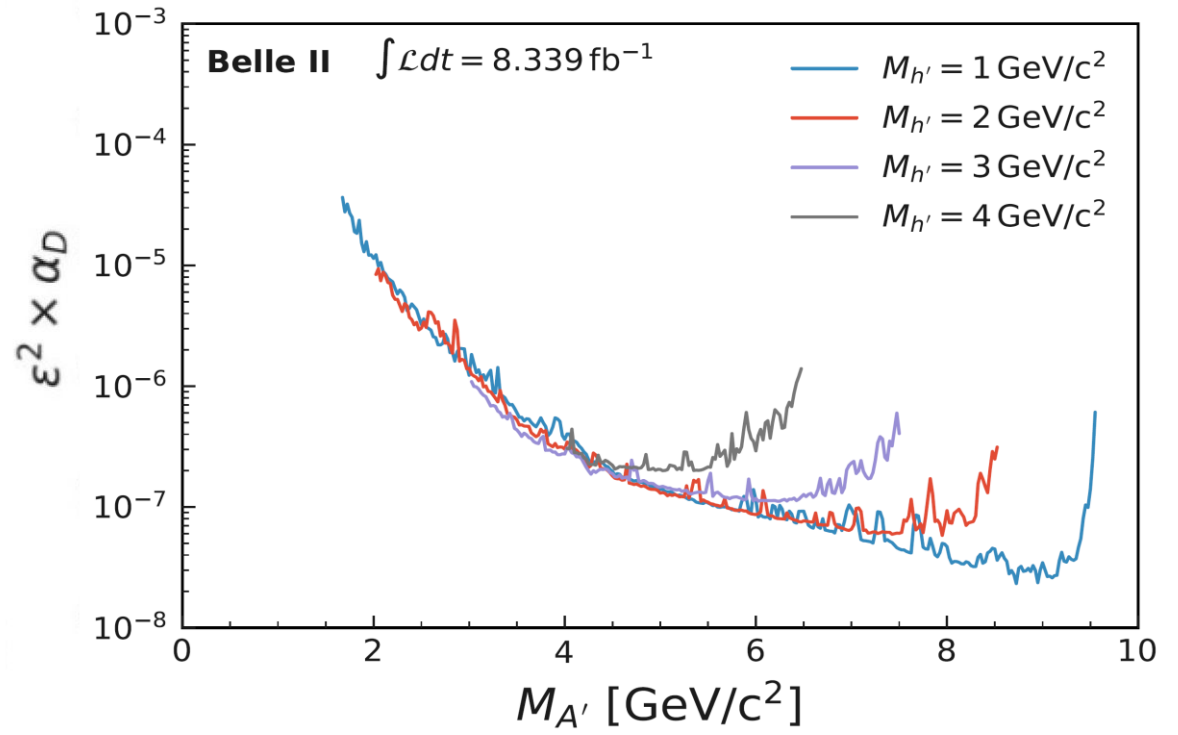


Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

Dark Higgsstrahlung
 $A'h'$ $A' \rightarrow \mu\mu$, h' invisibile



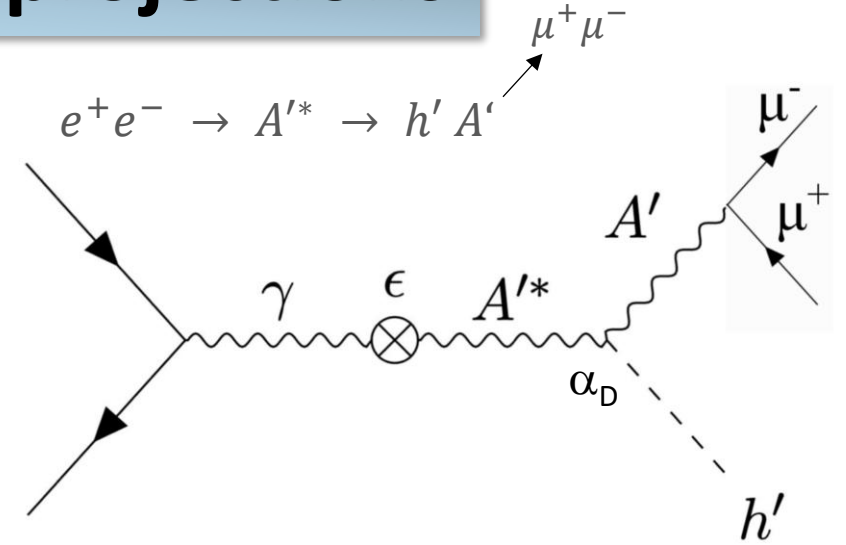
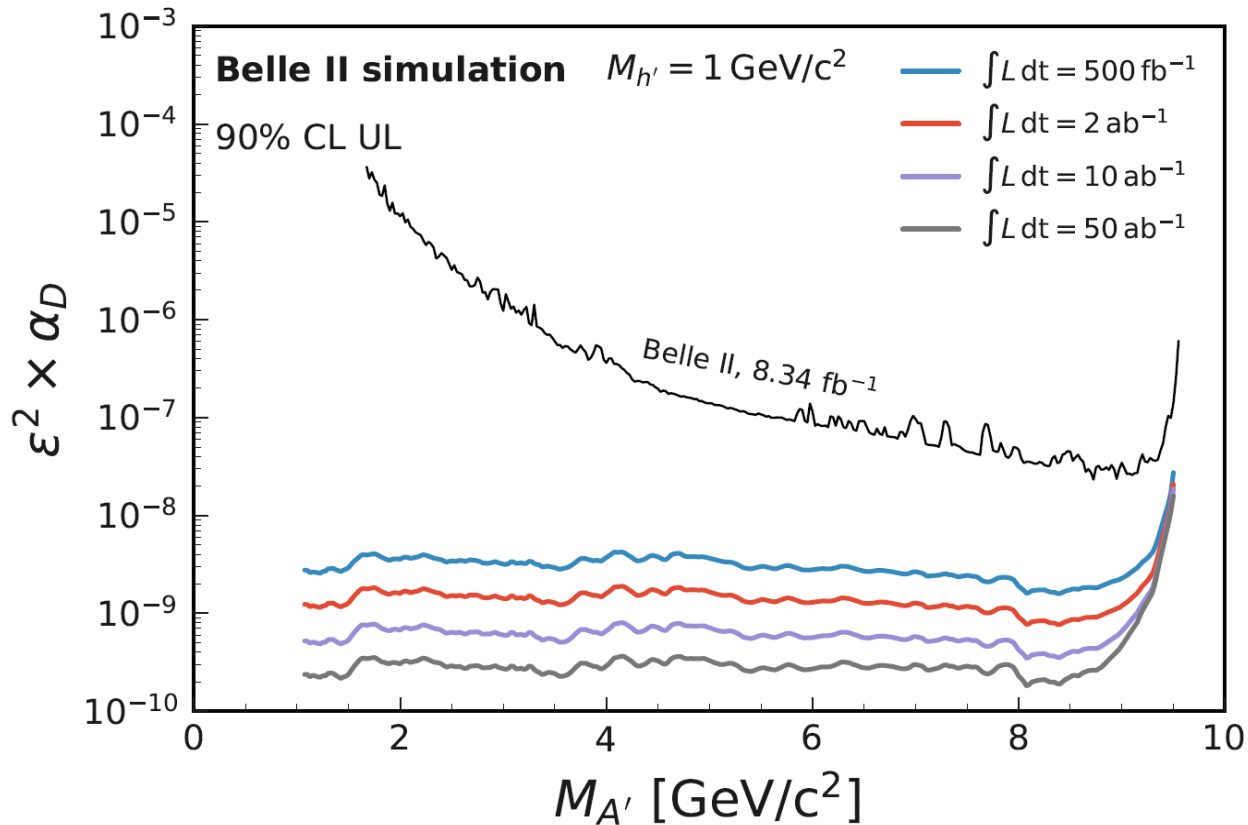
PRL 130, 071804 (2023)



Dark Higgsstrahlung: luminosity projections

Dark Higgsstrahlung

$A'h'$ $A' \rightarrow \mu\mu$, h' invisible



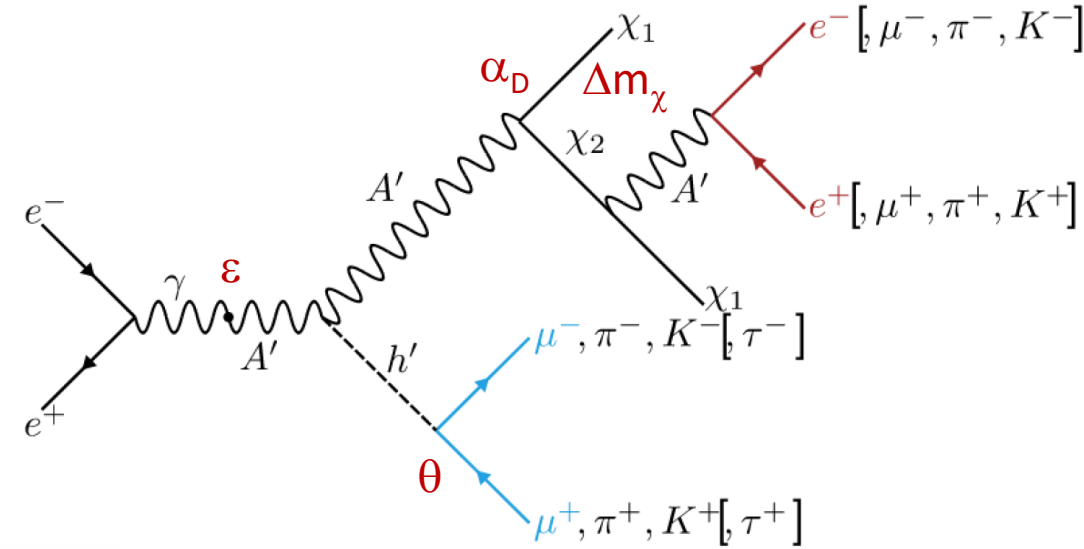
Belle II physics reach @ Snowmass
[arXiv: 2207.06307v1](https://arxiv.org/abs/2207.06307v1)

Next update based on Run 1
 luminosity in progress

Inelastic dark matter with dark Higgs

NEW

- Two dark matter states χ_1 and χ_2 with a small mass splitting
- **Eludes constraints from direct searches**
- χ_1 is stable \rightarrow dark matter candidate
- χ_2 is generally long-lived
- h' is generally long-lived and mixes with SM H_0



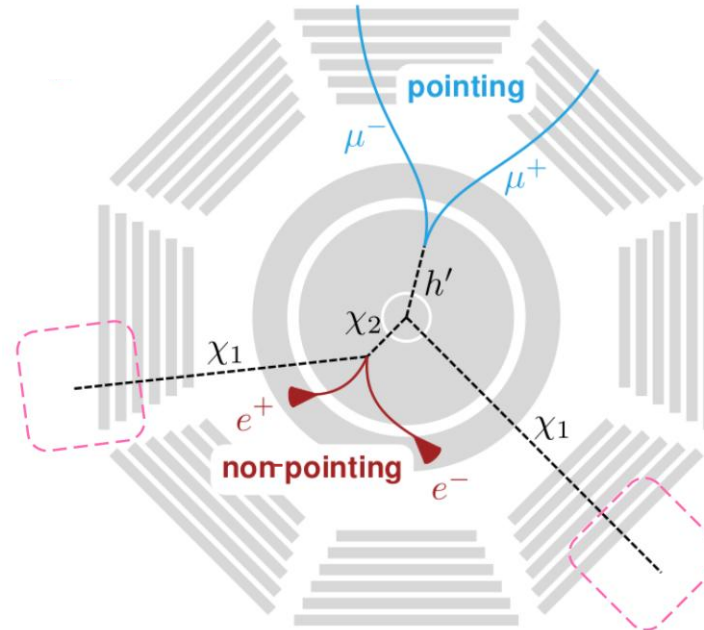
Focus on $m(A') > m(\chi_1) + m(\chi_2)$

- $A' \rightarrow \chi_1 \chi_2$

Up to two displaced vertices

$\chi_2 \rightarrow \chi_1 A'$ non-pointing + missing energy

$h' \rightarrow x^+ x^-$ pointing

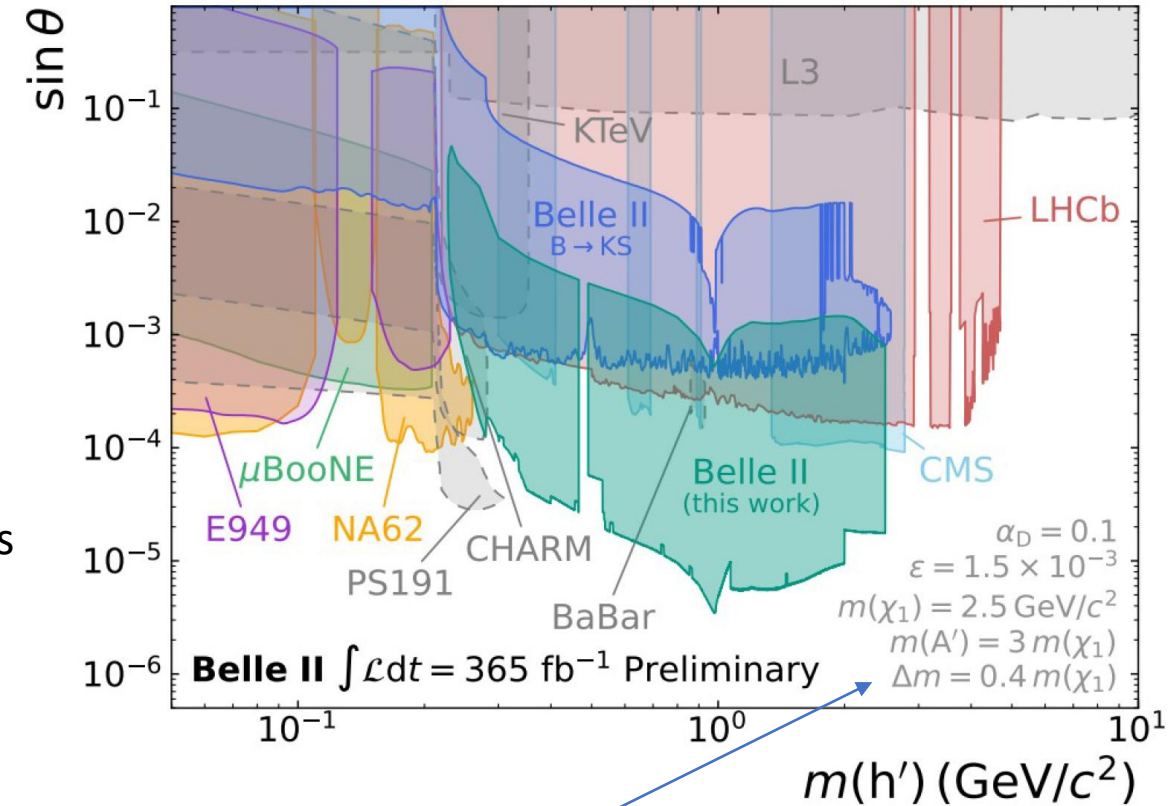


$\chi_2 \rightarrow \chi_1 e^+ e^-$ only, due to ECL-only trigger

Inelastic dark matter with dark Higgs

Challenging for tracking and trigger (displaced tracks)
Almost zero background analysis

- **Cut & count strategy** to extract signal yields
- **Background estimated in data** from sidebands
- **No excess found** → 95% CL upper limits
- Individual final states and their combination
- **Scan $m(h')$ - $\sin\theta$ space** for different values of the other parameters



Process cross section does not depend on θ (efficiency does)
Many more (~ 30) plots for different parameter configurations

Dark sector searches in Belle II: future directions

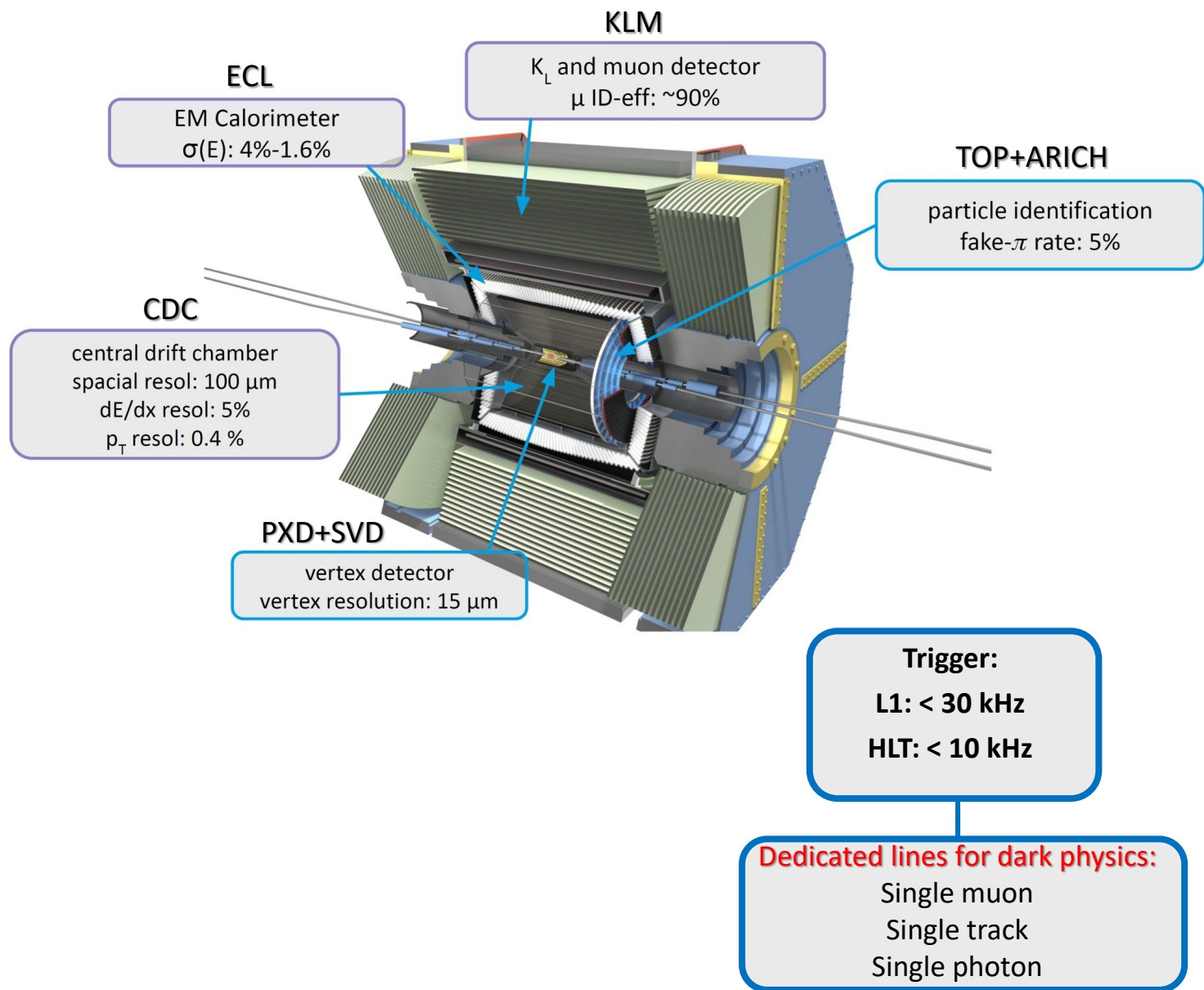
Short term

- Align all the searches at least to the full Run 1 luminosity 427 fb^{-1}
- In most cases with improved analysis techniques: second/third generation searches
- We have already reasonable luminosity projections for some of the analyses (Snowmass)
- Enter the dark photon business: both visible and (especially) invisible
- LLP searches will have a considerable weight in the next years (especially with a **new displaced-vtx trigger&tracking**) Low SM background, open the possibility to explore small couplings
- Some searches are motivated more than others by the $g-2$ anomaly. Their future may depend by external inputs.
- ❑ Luminosity will increase, background will increase as well
- ❑ Best effort to keep the single-object (track, muon, photon) trigger lines in working conditions
- ❑ Displaced-vertex trigger&tracking needed (efficiency decreases abruptly with lifetime): in preparation
- ✓ Belle II is expected to lead the world sensitivity in most of the dark sector searches

Challenges

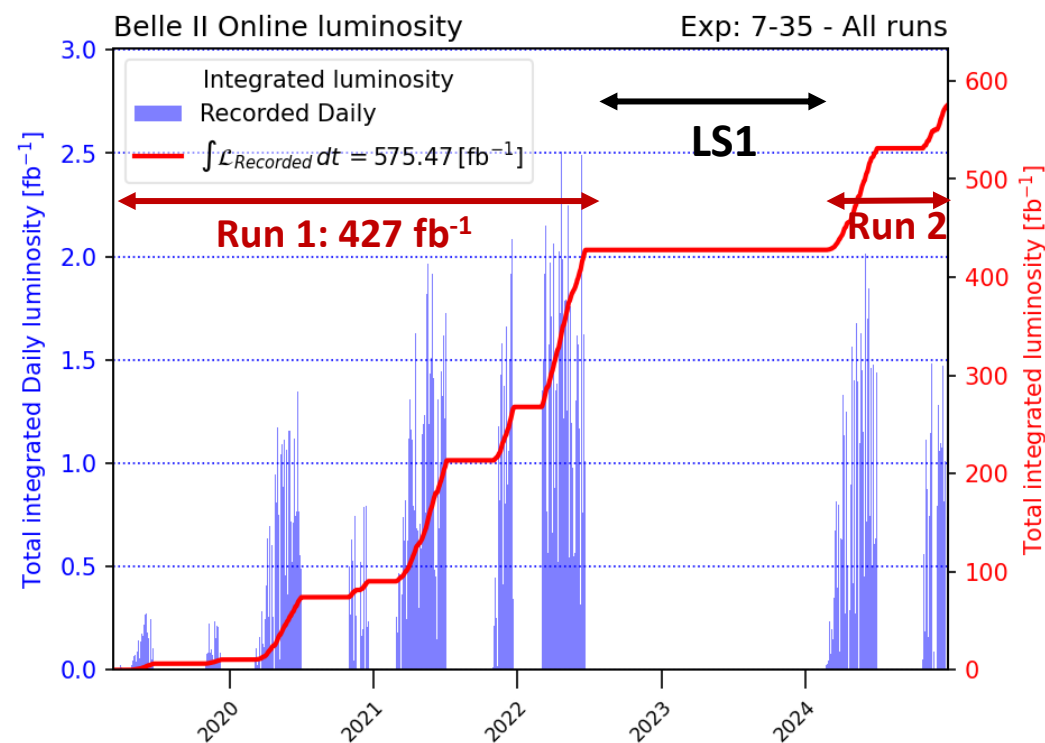
SPARE SLIDES

Belle II and SuperKEKB



Final goal : 50 ab⁻¹

Collected luminosity: 2019-2024



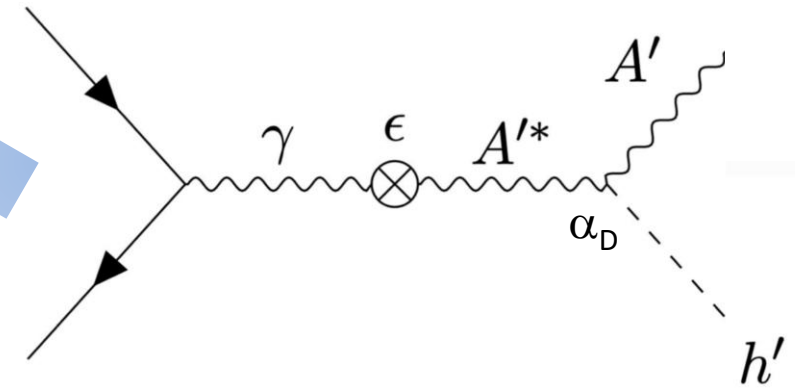
Restart data taking in October 2025

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

Dark photon + dark Higgs

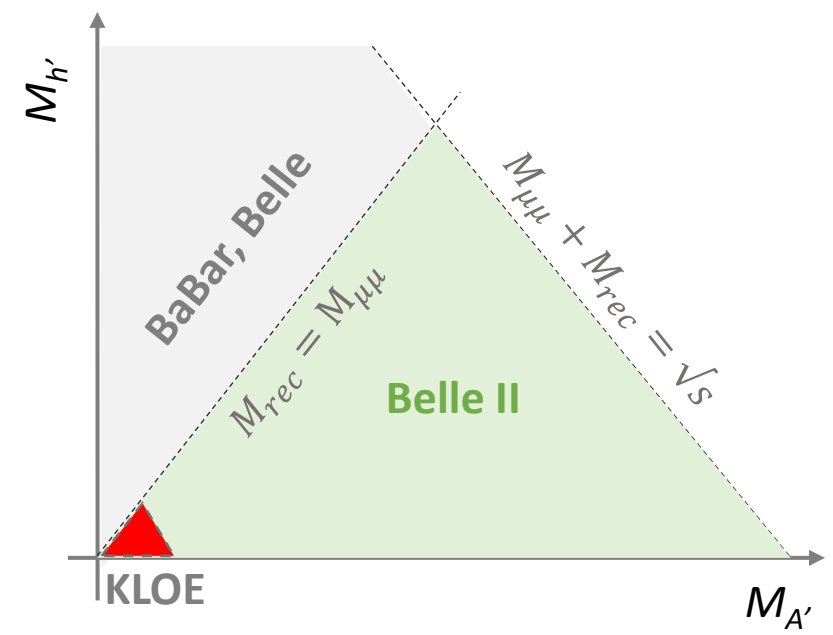
- dark Higgs h'
 - gives mass to A' through SSB
 - no mixing of h' with SM Higgs
 - coupling α_D in the dark sector, $\epsilon^2 \alpha_D$ overall

Phys. Rev D79, 115008 (2009)

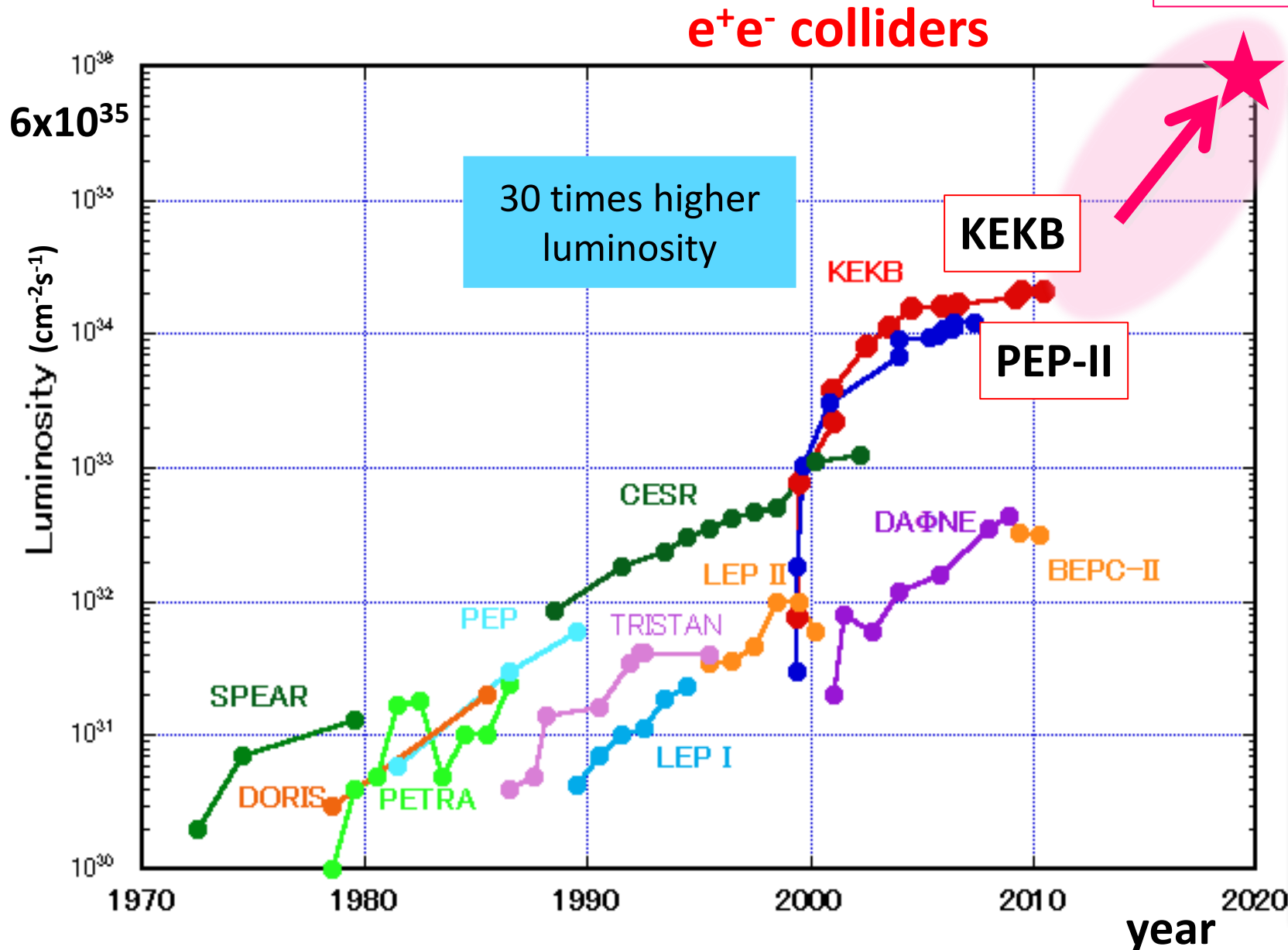


Mass hierarchy scenarios

- $M_{h'} > M_{A'}$
 - $h' \rightarrow A'A'$, $e^+e^- \rightarrow A'A'A'$
 - probed by Babar and Belle
- $M_{h'} < M_{A'}$
 - Invisible h' (long-lived), missing energy
 - 2d peak in $M_{\mu\mu}$ and M_{recoil}
 - Probed by **KLOE**, **Belle II**



Peak luminosity trend



Final goal: $L = 50 \text{ ab}^{-1}$

Very rich physics program

Flavour physics

- CKM matrix
- CPV in B decays

BSM physics

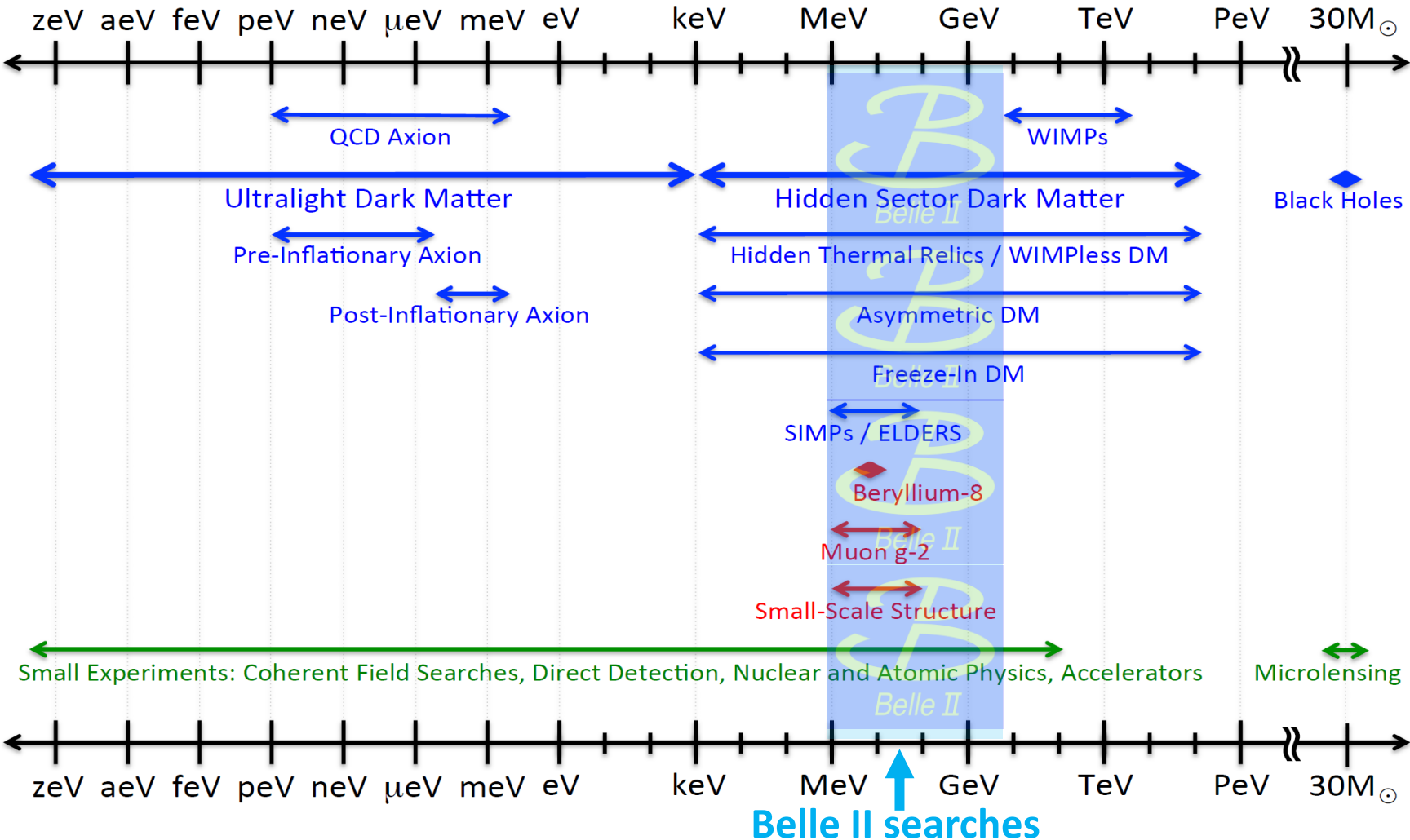
- Rare decays
- NP in loops in $b \rightarrow s\gamma$, $b \rightarrow sll$
- $B \rightarrow D^{(*)}\tau\nu$
- LFV in τ decays

New particles (quarkonium)

Dark sector

Searching for dark matter

Dark Sector Candidates, Anomalies, and Search Techniques



Dark matter/mediators

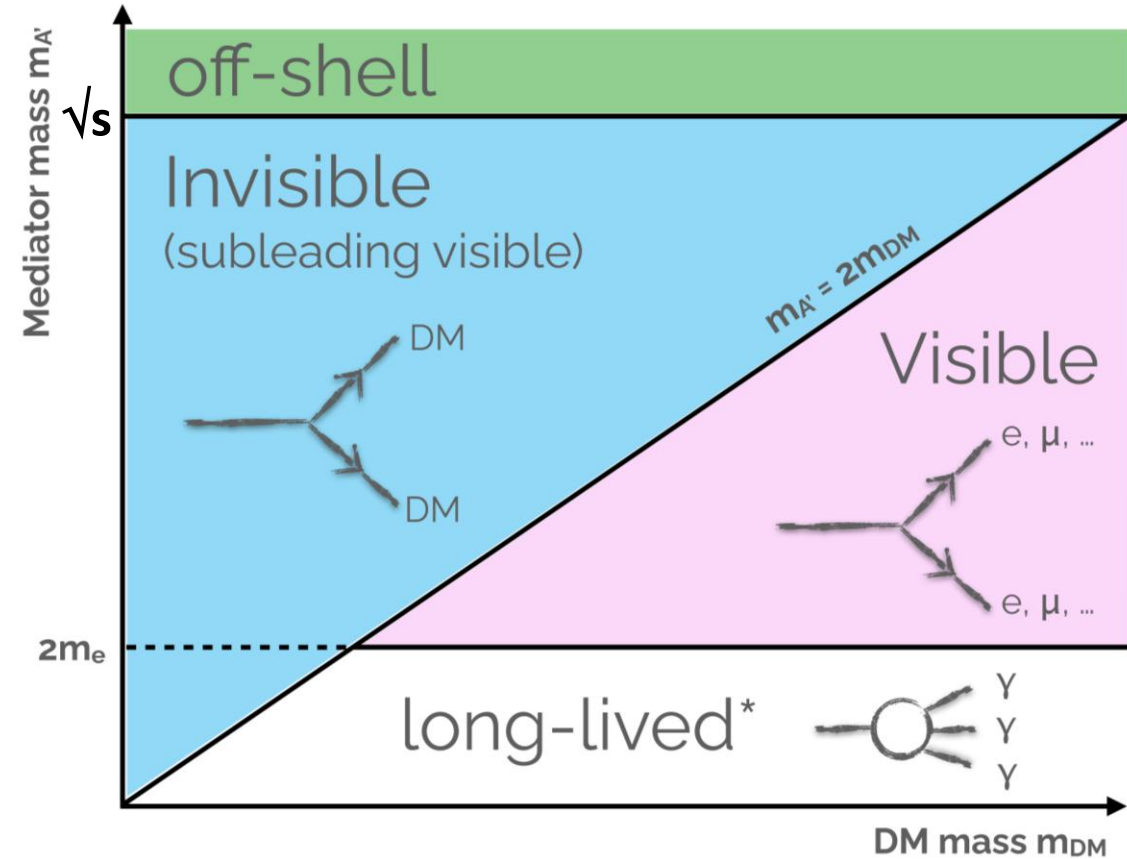
- Vector portal** ←
 - Dark photon, Z' , ...
- Pseudoscalar portal** ←
 - Axions, **ALPs**, ...
- Scalar portal** ←
 - Dark Higgs, scalars
- Neutrino portal** ←
 - Sterile neutrino

Light dark matter hunt

Different signatures depending on the DM \leftrightarrow mediator mass relation

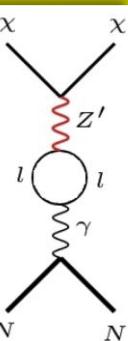
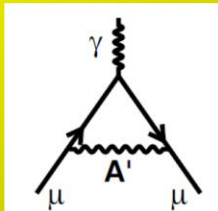
Probability of interaction of LDM detectors is negligible

- Search for mediators
- Search for missing energy signature
- Search for both



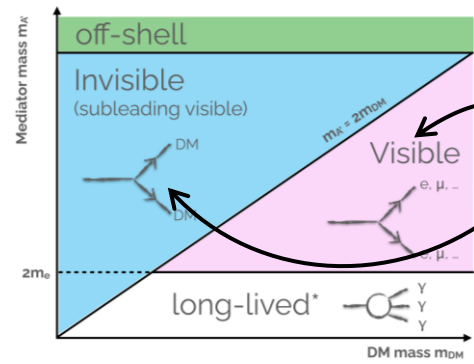
Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, ...)
- Explanation of the $(g-2)_\mu$ effect
- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, ...)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits



Search overview: models \leftrightarrow signatures \leftrightarrow topologies

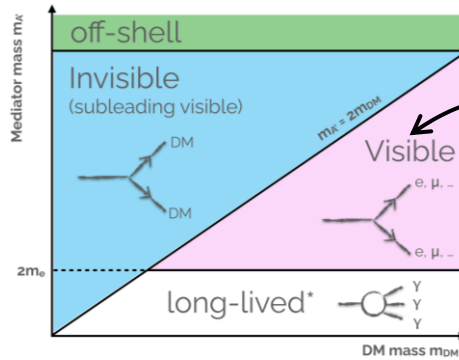
Models are growing up \sim exponentially (a warm thank's to theoreticians to provide us so many ideas). They should be used both to exclude (or confirm!) and as wonderful excuses to search for signatures & topologies as model independently as possible



// (γ) (+missing)

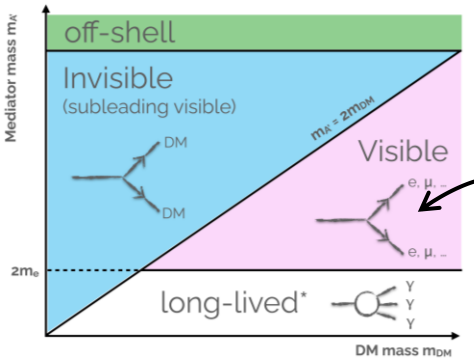
Visible minimal and non minimal dark photons, ALP \rightarrow ff

Invisible dark photon, Z'



/// LLP

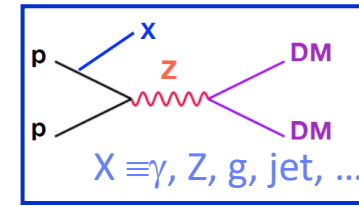
Visible non minimal dark photons, ALP \rightarrow ff, scalars, $\mu\mu\tau\tau$, $\tau\tau\tau$



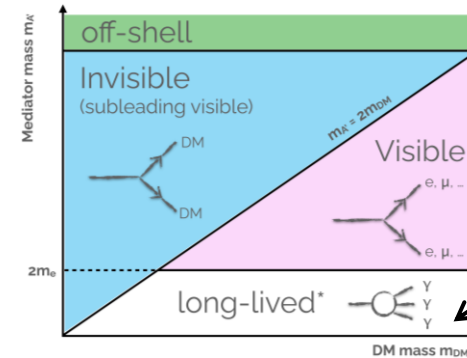
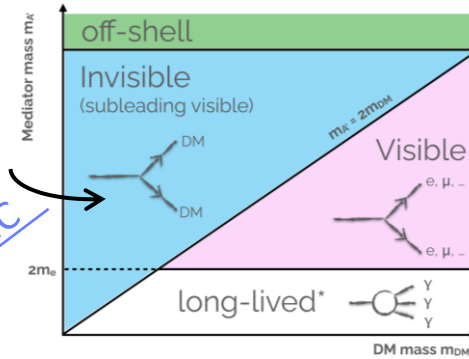
$\gamma\gamma$

Visible ALP $\rightarrow \gamma\gamma$

Single γ
Invisible dark photon, ALP $\rightarrow \chi\chi$, iDM, LLP



LHC



LLP long-lived particles

Hot topic

LHC

A', ALP $\rightarrow \chi\chi$, iDM, scalars

From KEKB to SuperKEKB



Beam-beam parameter

$$\xi_{y\pm} = \frac{r_e}{2\pi} \frac{N_{\mp} \beta_y^*}{\gamma_{\pm} \sigma_y^* (\sigma_x^* + \sigma_y^*)} R_{\xi_{y\pm}} \propto \frac{N_{\mp}}{\sigma_x^*} \sqrt{\frac{\beta_y^*}{\epsilon_y}}$$

Beam current

$$L = \frac{\gamma_{e\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left(\frac{I_{e\pm} \xi_y^{e\pm}}{\beta_y^*} \right) \left(\frac{R_L}{R_{\xi_y}} \right)$$

Lorentz factor

Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

Lumi. reduction factor (crossing angle) & Tune shift reduction factor (hour glass effect)
0.8 ~ 1 (short bunch)

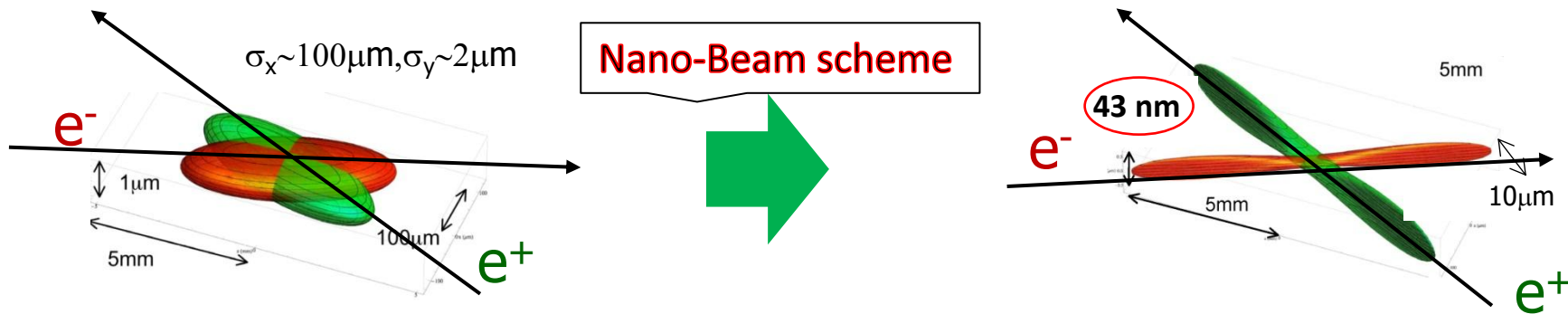
Vertical beta function@IP

- (1) Smaller β_y^*
- (2) Increase beam currents
- (3) Increase ξ_y

$\beta_y^* = 0.30/0.30$ mm
 $I_{+/-} = 2.8/2.0$ A

x30

- New e⁺ Damping Ring
- New Superconducting Final Focus (QCS)



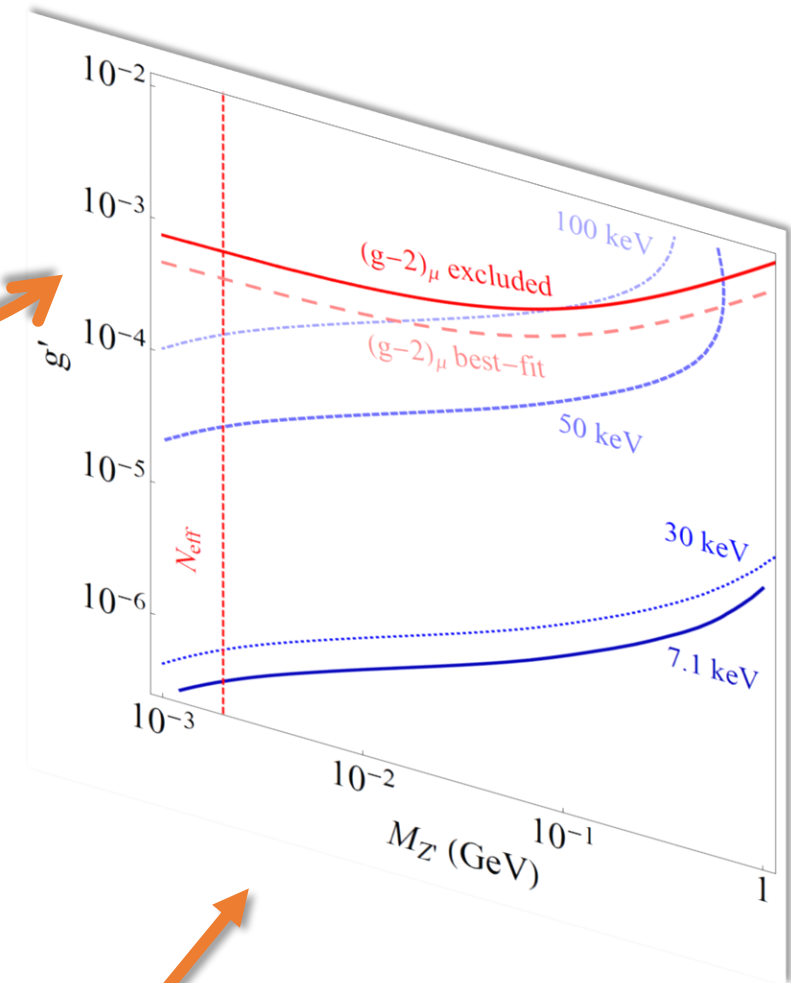
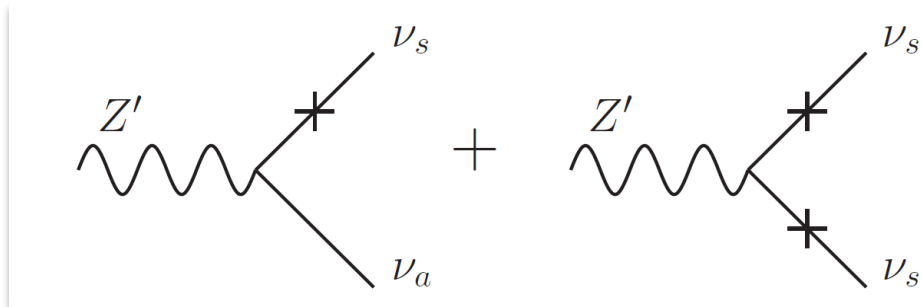
... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers

Z': $L_\mu - L_\tau$ model

- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2^o and 3^o lepton family
- Anomaly free (by construction)
- It may solve
 - dark matter puzzle
 - $(g-2)_\mu$
 - $B \rightarrow K^{(*)} \mu \mu$, R_K , R_{K^*} anomalies

Sterile ν 's
Light Dirac fermions

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026



Sterile neutrino abundance

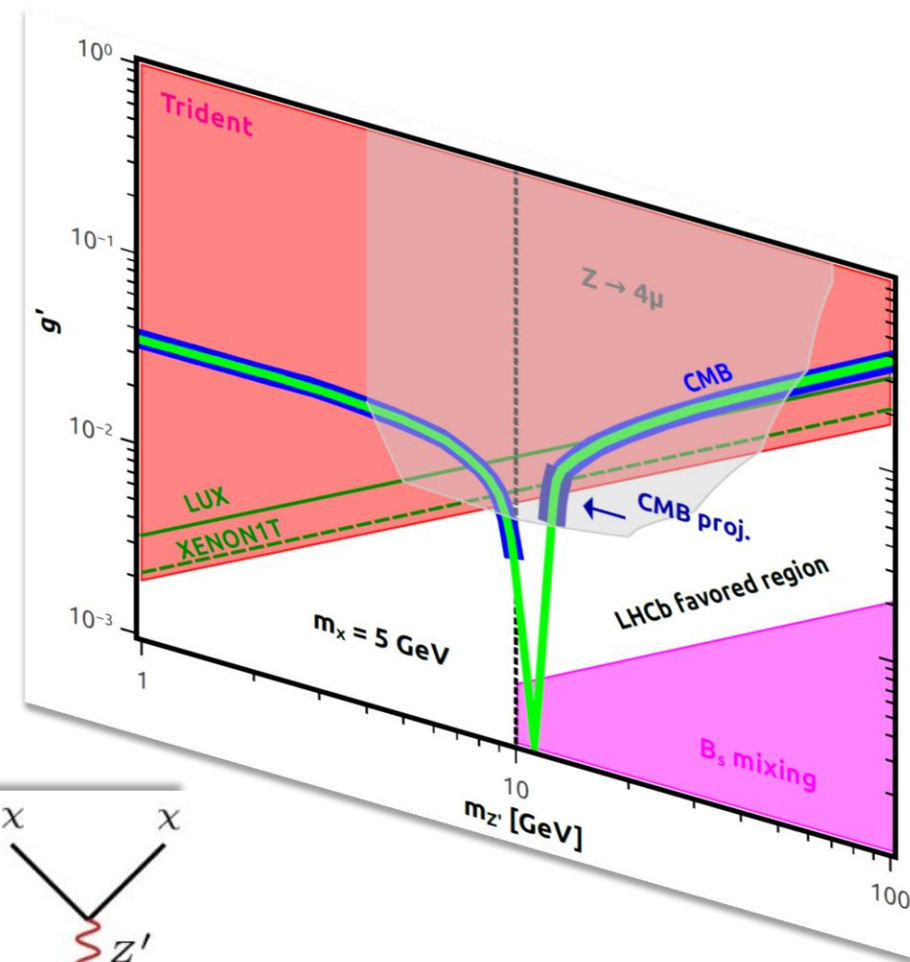
Z' : $L_\mu - L_\tau$ model

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- A new gauge boson which couples only to the 2^o and 3^o lepton family
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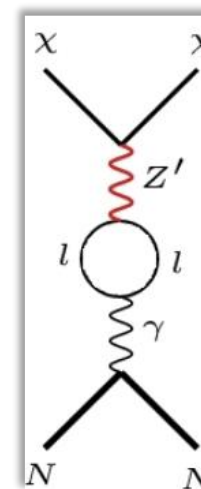
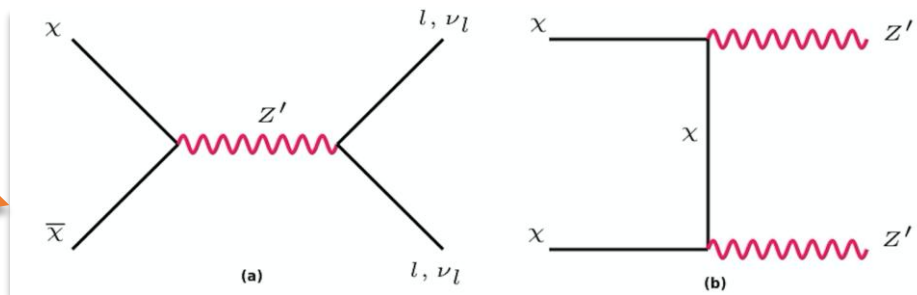
- dark matter puzzle
 - Sterile ν 's
 - Light Dirac fermions
- $(g-2)_\mu$
- $B \rightarrow K^{(*)} \mu\mu$, R_K , R_{K^*} anomalies

Shuve et al. (2014), arXiv 1408.2727

Altmannshofer et al. (2016) arXiv 1609.04026



Annihilation



Direct detection

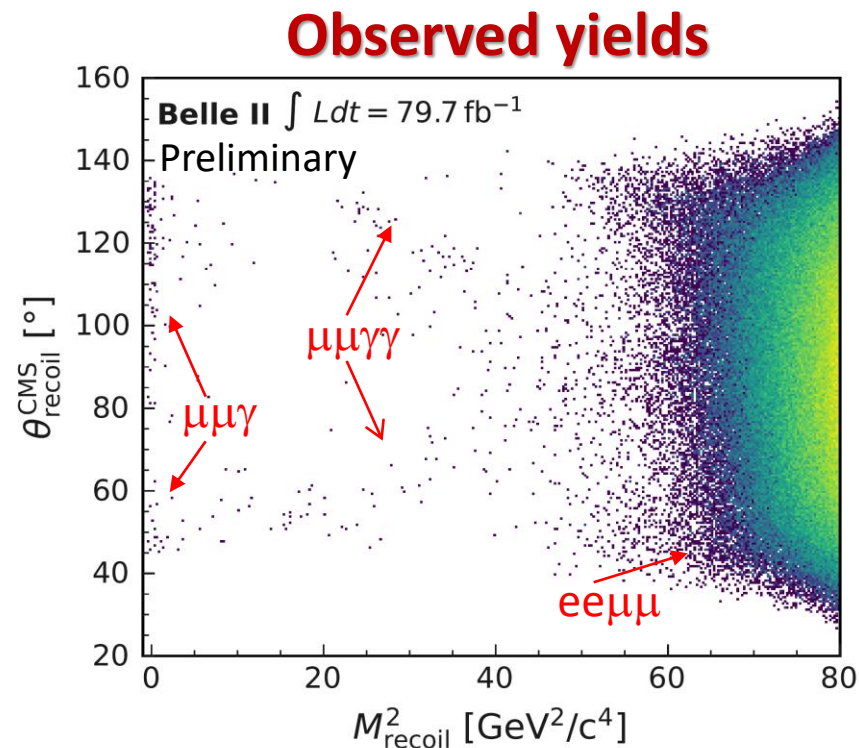
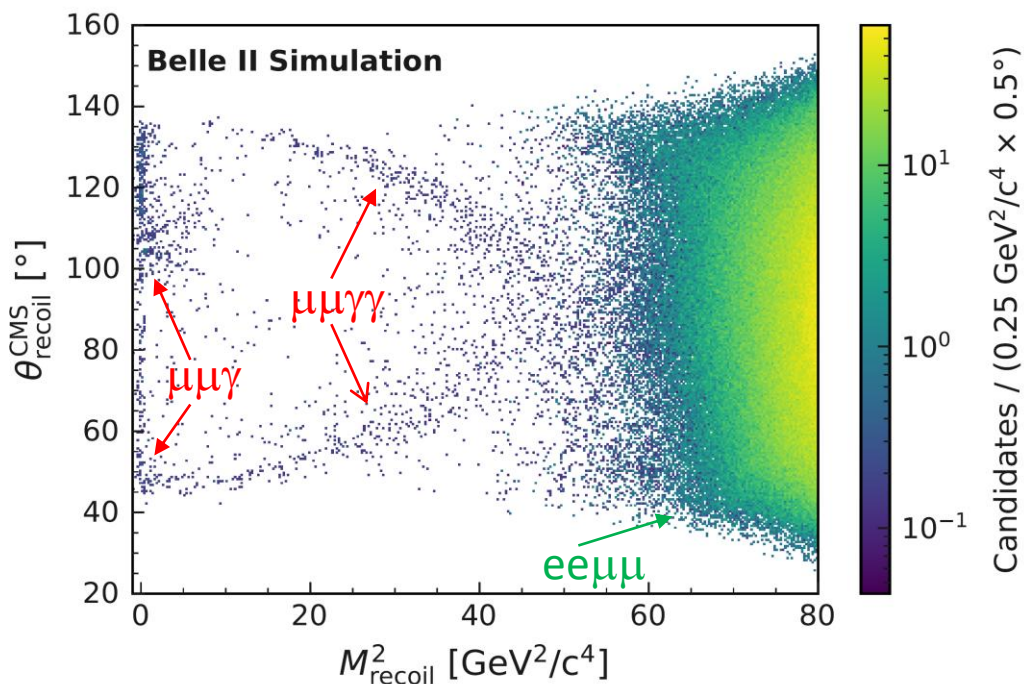
Z' to invisible: analysis

- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to $\sim 7 \text{ GeV}/c^2$
- $e^+e^-\mu^+\mu^-$ 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_{recoil}^2

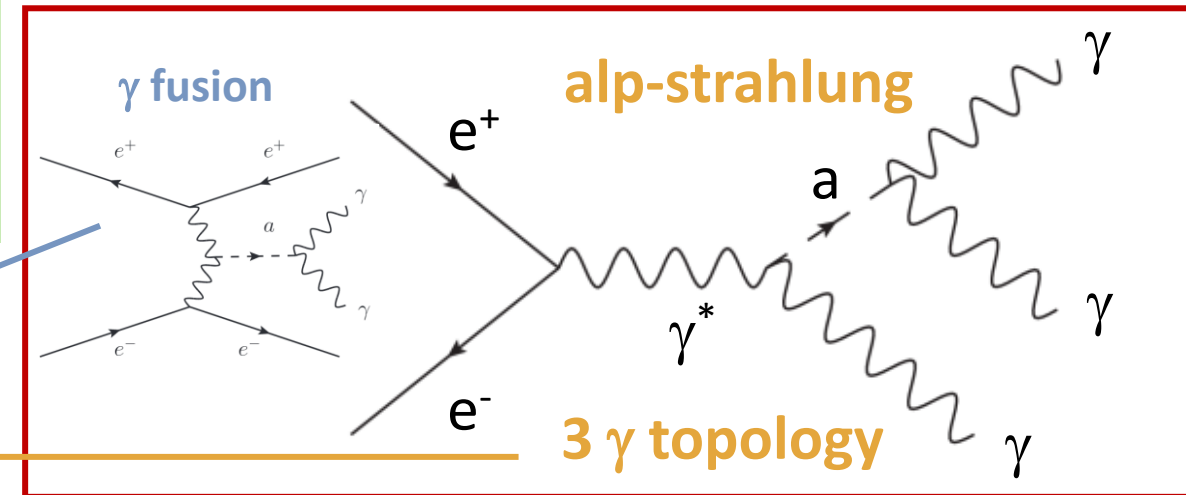
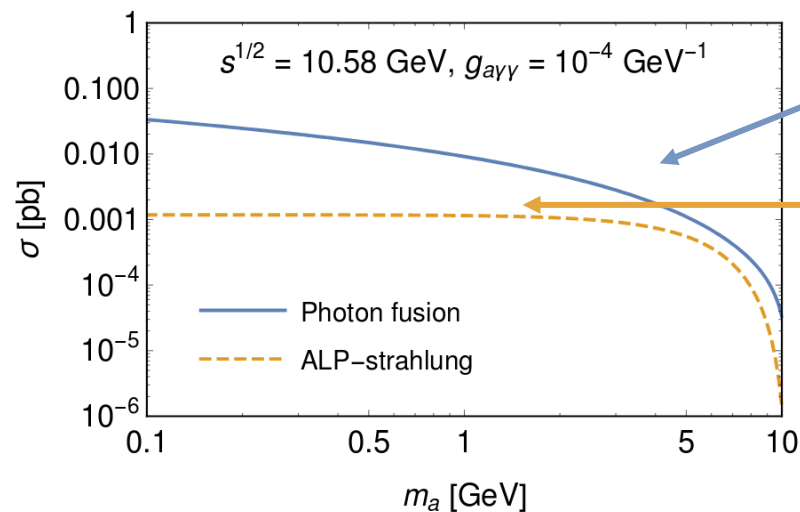


Axion Like Particles (ALPs)

- Appear in SM extensions after some global (i.e. family) symmetry breaking
- Pseudo-Goldstone bosons → Naturally light
- Cold dark matter candidates if m_a is sub MeV
- Couple naturally to photons
- Can couple LFV to fermions
- No mass ↔ coupling relationship (as for QCD)

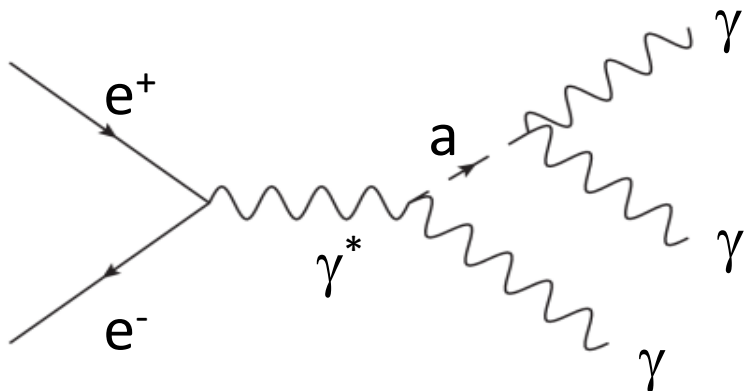
Belle II

- Focus on coupling to photons: $g_{a\gamma\gamma}$
- **Alp-strahlung** + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 m_a^3$



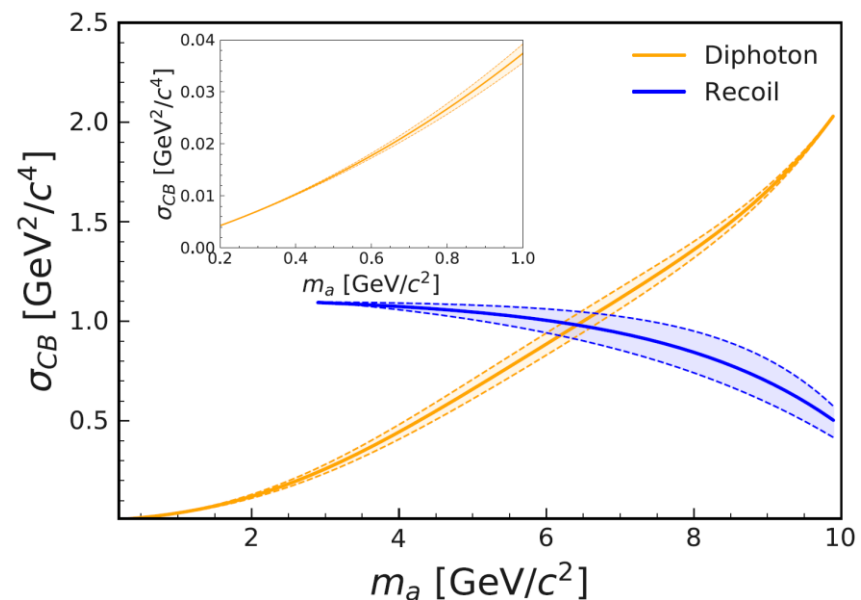
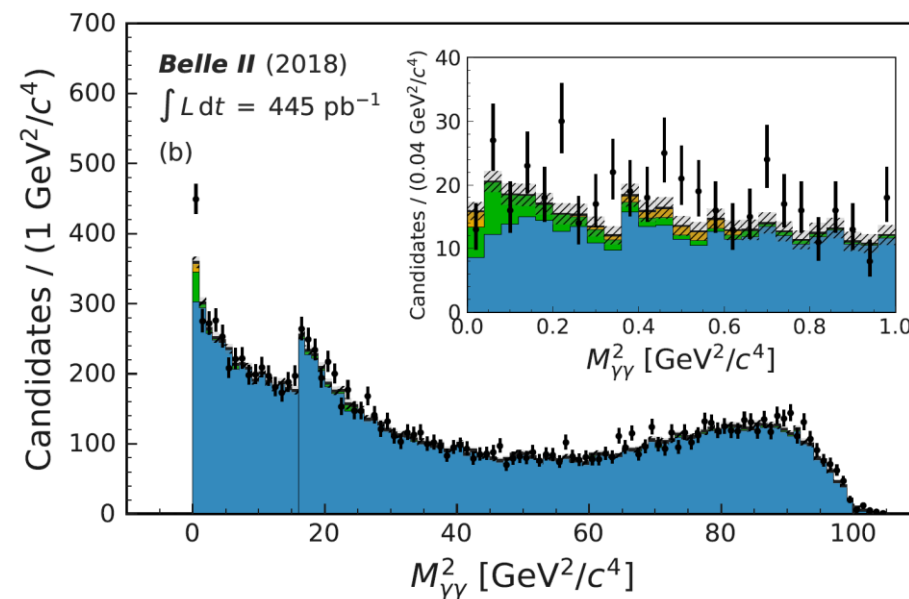
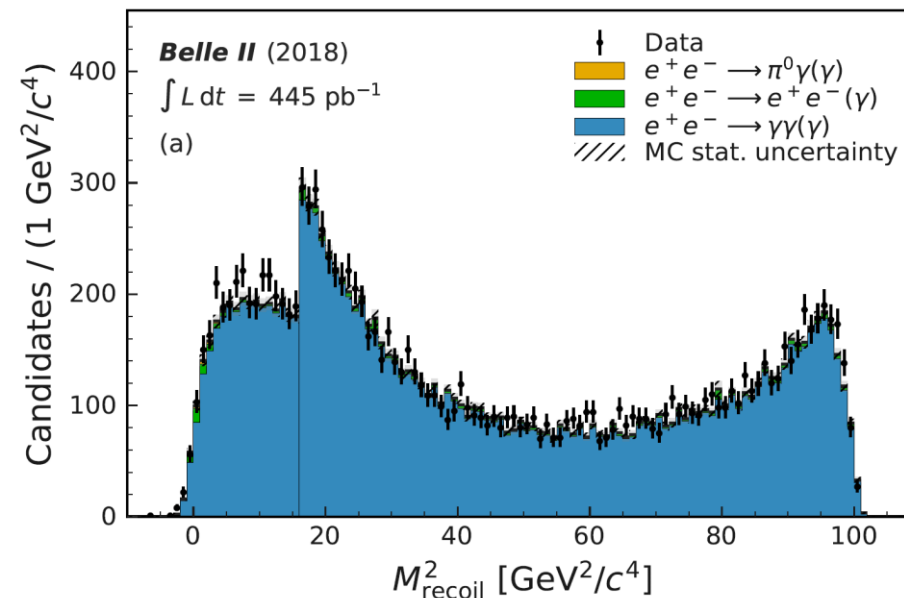
photon fusion sensitivity under study

ALP $\rightarrow \gamma\gamma$: observed yields



Pilot run (2018)

Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)



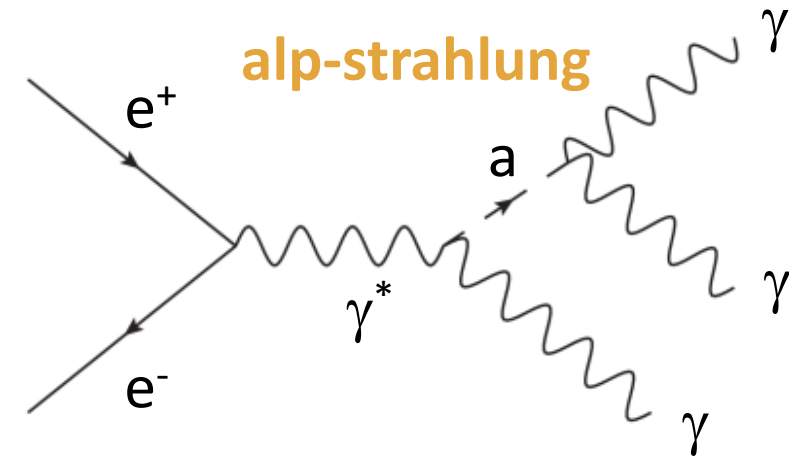
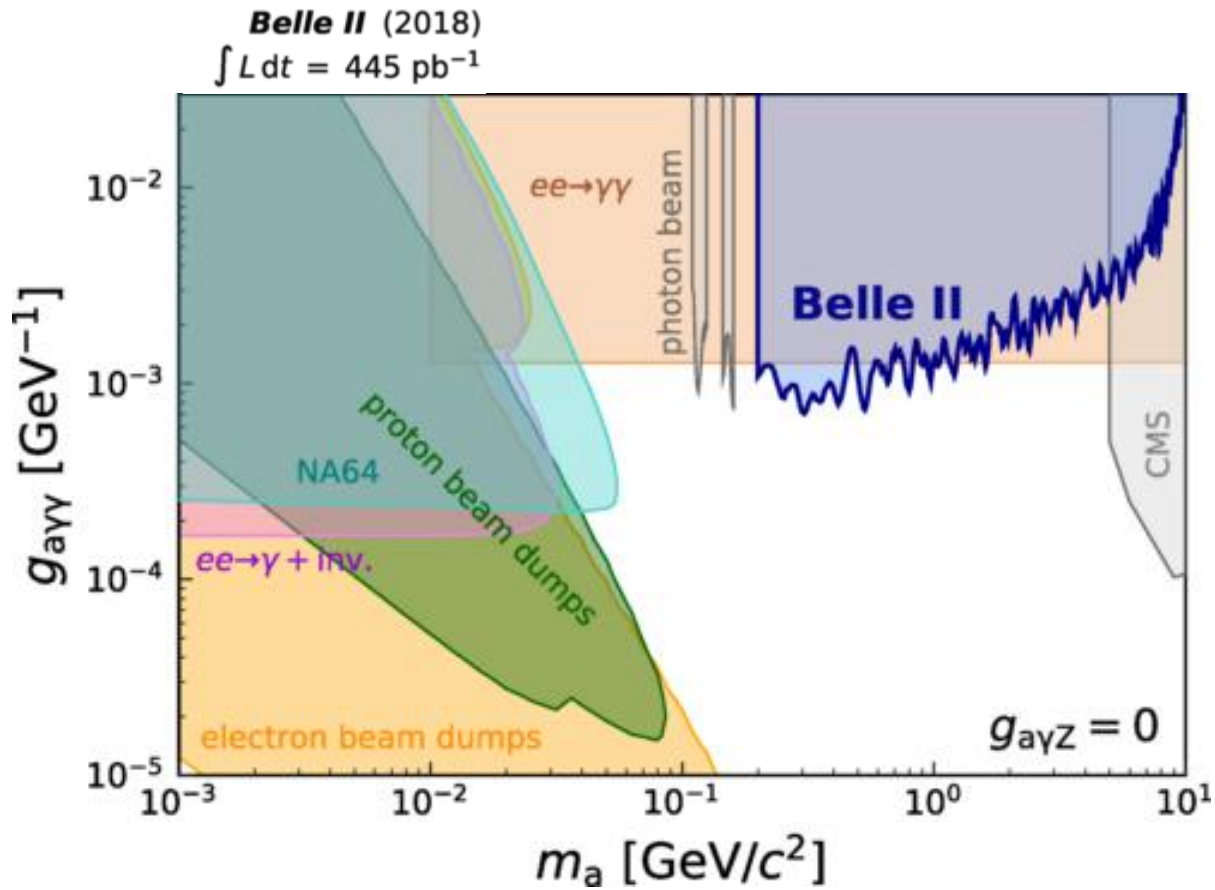
Main backgrounds:
 $e^+e^- \rightarrow \gamma\gamma\gamma$
 $e^+e^- \rightarrow e^+e^-\gamma$

ALP $\rightarrow \gamma\gamma$: results

Axion like particles

ALP $\rightarrow \gamma\gamma$

Pilot run physics results

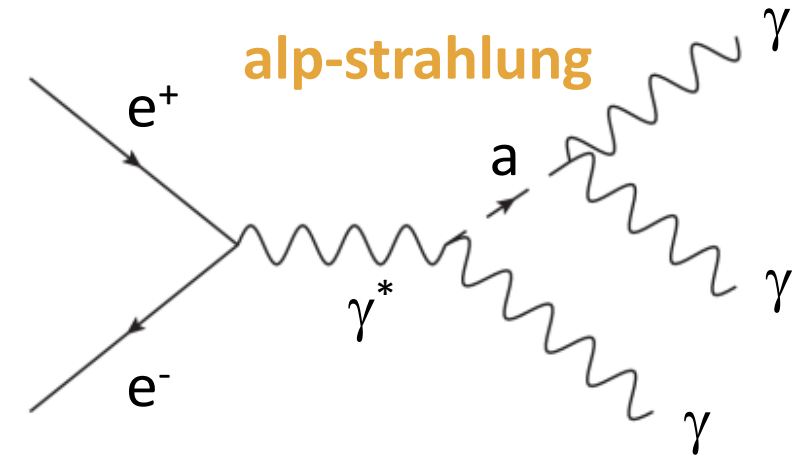
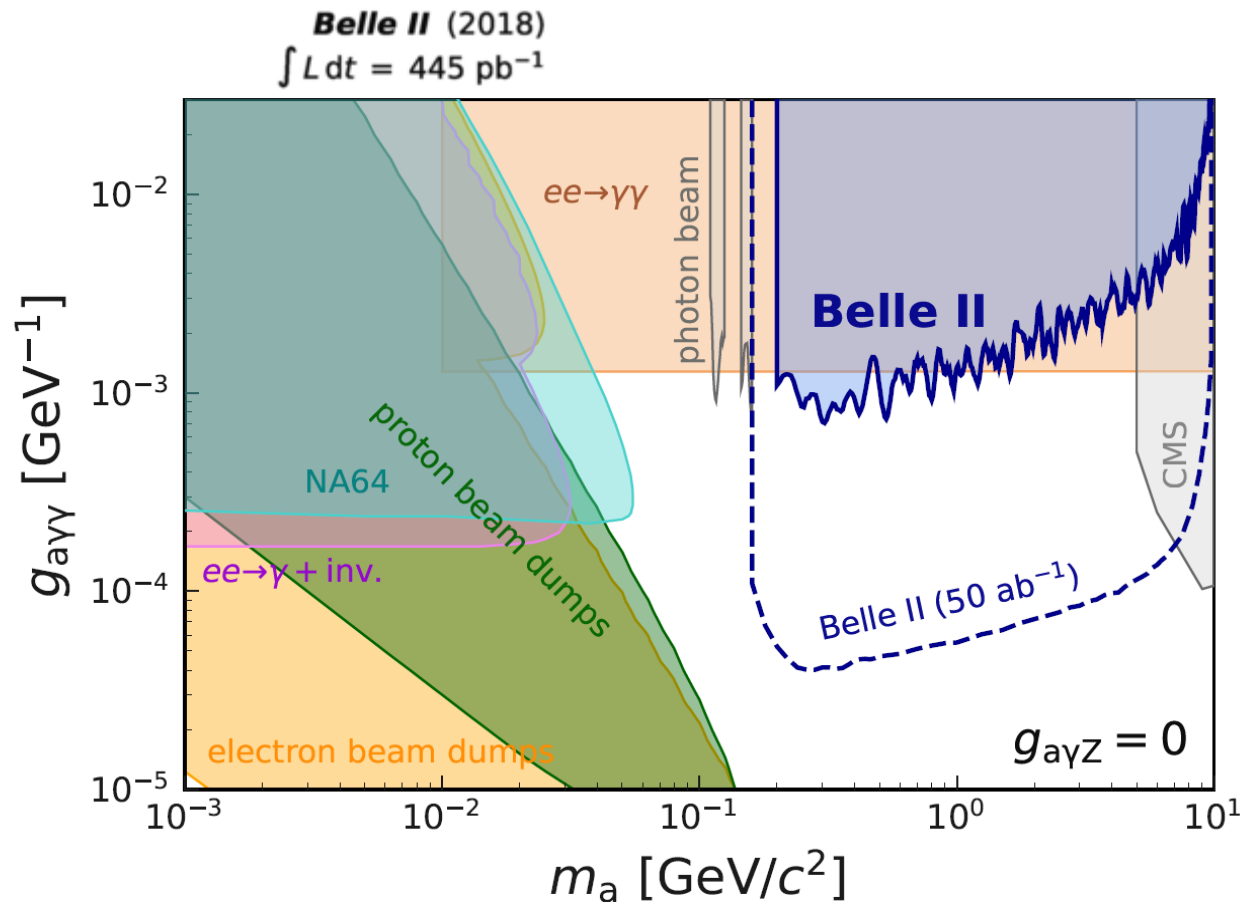


PRL 125, 161806 (2020)

ALP $\rightarrow \gamma\gamma$: luminosity projections

Axion like particles

ALP $\rightarrow \gamma\gamma$



Belle II physics reach @ Snowmass

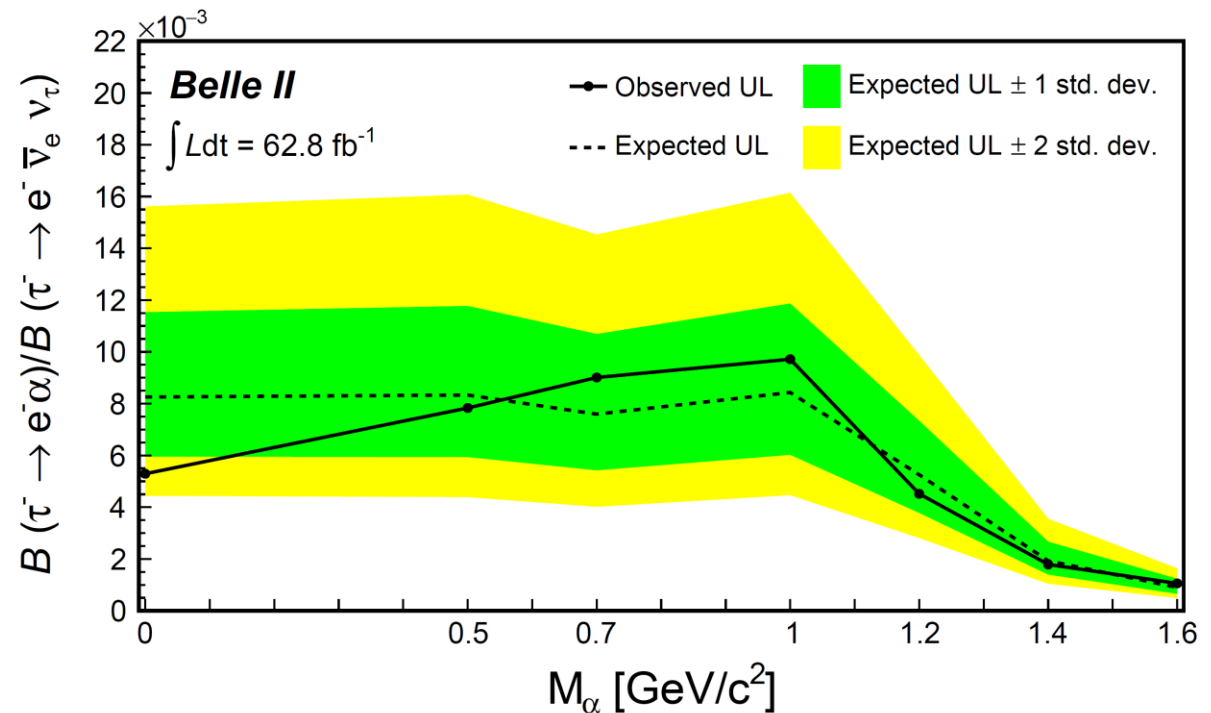
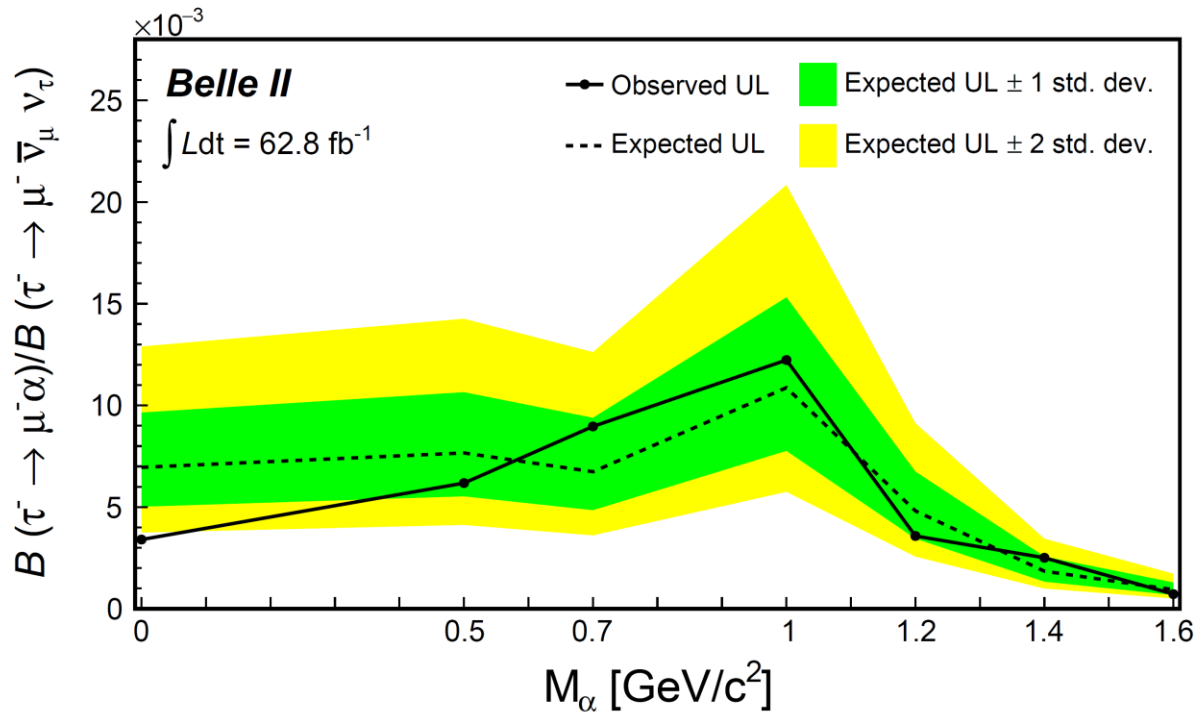
[arXiv: 2207.06307v1](https://arxiv.org/abs/2207.06307v1)

$\tau \rightarrow l\alpha$ with invisible α

Invisible α in τ decays
 $\tau \rightarrow l\alpha$ $l=e,\mu$

LFV, possible ALP candidate

PRL 130, 181803 (2023)



63.3 fb⁻¹ (2019-2020)

Z', S, ALP → ττ: analysis

3-track OR single muon trigger
 1-prong τ decays (+ neutrals)
 4-tracks
 2 μ + 2x e/μ/π
 M(4-track) < 9.5 GeV/c²
 Scan M_{recoil} (μμ)

Background suppression
NN MLP (Multi Layer Perceptron)
 8 MLP ranges in M_{recoil} (μμ)

- resonance vs μμ
- FSR production
- ττ system

Main backgrounds

e⁺e⁻ → τ⁺τ⁻ (γ) 1+3 prong
 e⁺e⁻ → qq (q=u,d,s,c)

e⁺e⁻ → e⁺e⁻ μ⁺μ⁻

e⁺e⁻ → μ⁺μ⁻ τ⁺τ⁻

e⁺e⁻ → e⁺e⁻ τ⁺τ⁻

e⁺e⁻ → μ⁺μ⁻ π⁺π⁻

no ISR in simulation

not simulated

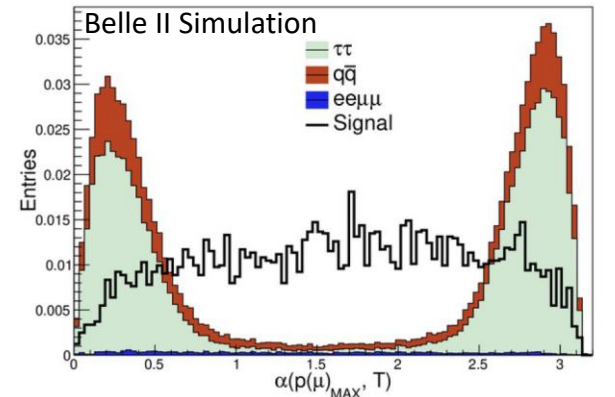
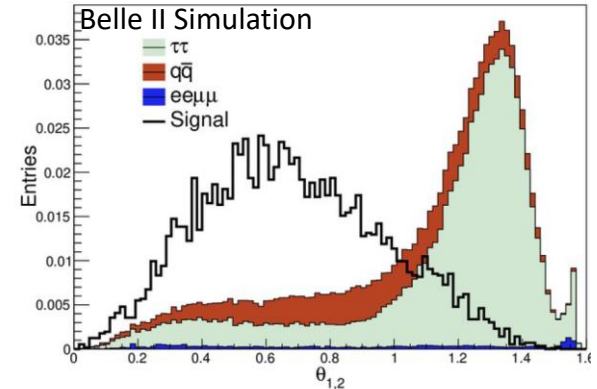
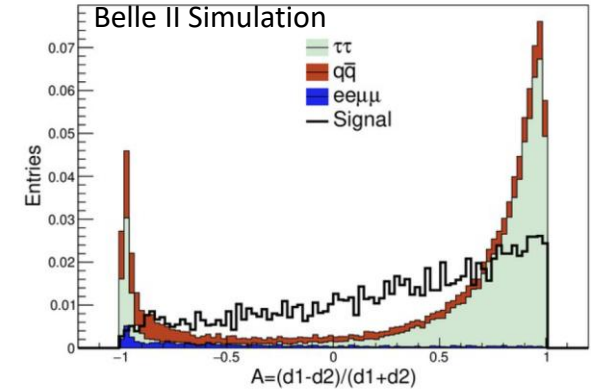
e⁺e⁻ → e⁺e⁻ X_{hadronic}

not simulated

Optimize selections for Z' → ττ
 99% background reduction

Control sample

2 π + 2x e/μ/π

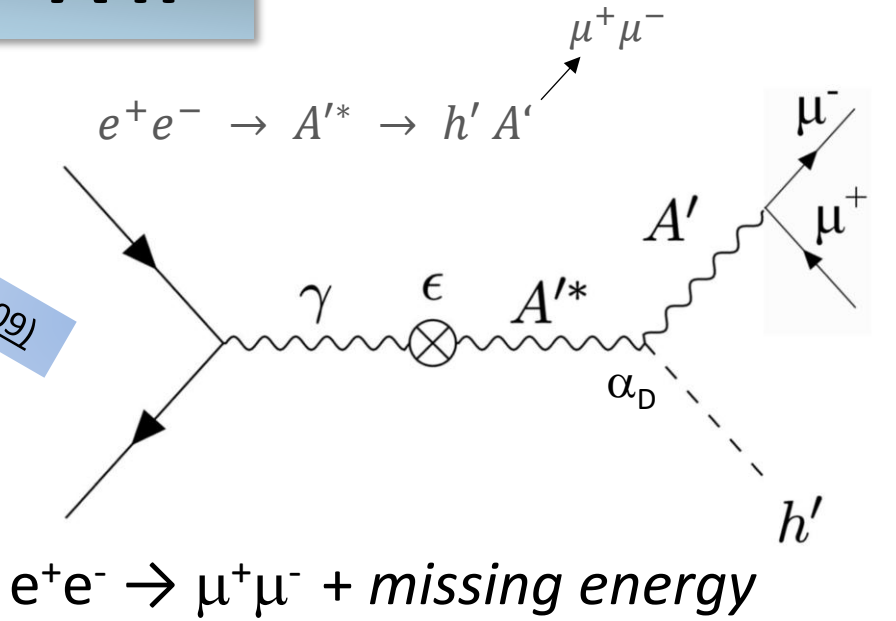


Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

Dark photon + dark Higgs

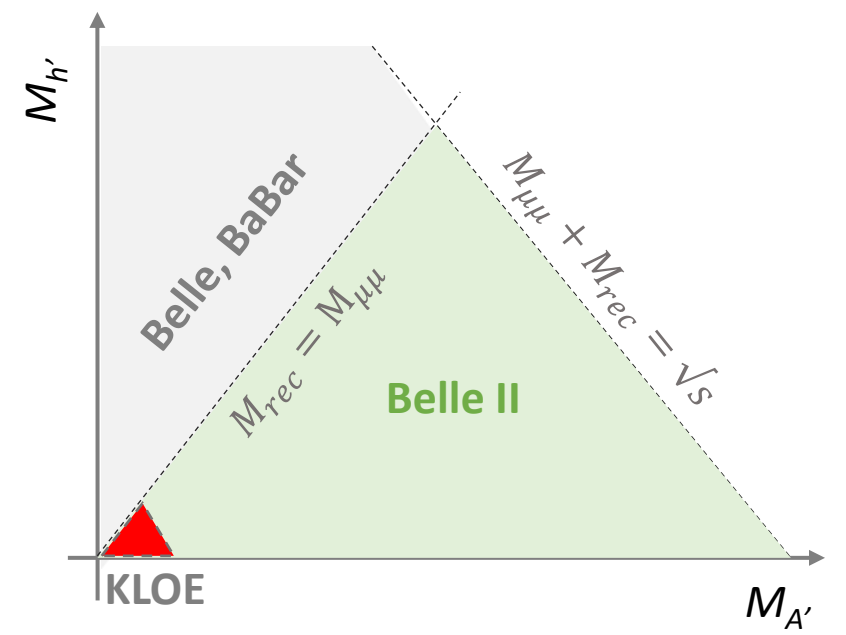
- dark Higgs h'
 - gives mass to A' through SSB
 - no mixing of h' with SM Higgs
 - coupling α_D in the dark sector, $\epsilon^2 \alpha_D$ overall

Phys. Rev D79, 115008 (2009)



Mass hierarchy scenarios

- $M_{h'} > M_{A'}$
 - $h' \rightarrow A'A', e^+e^- \rightarrow A'A'A'$
 - probed by Babar and Belle
- $M_{h'} < M_{A'}$ **this search**
 - Invisible h' (long-lived), missing energy
 - 2d peak in $M_{\mu\mu}$ and M_{recoil}
 - Probed by **KLOE**
 - Largely unconstrained



Dark Higgsstrahlung: analysis

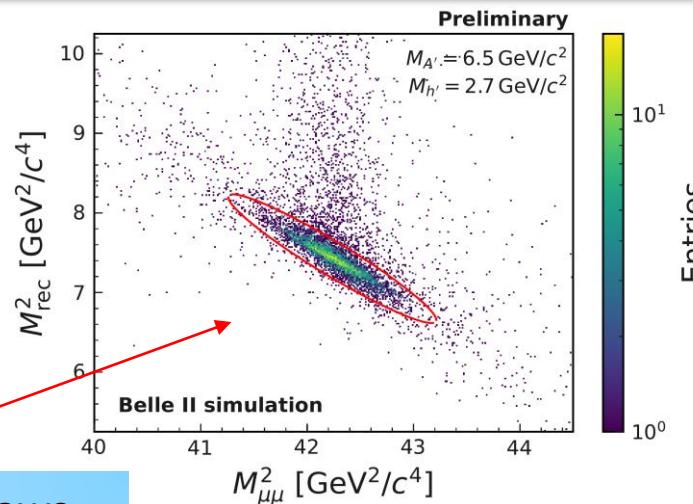
Morioud

8.34 fb⁻¹ (2019)

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

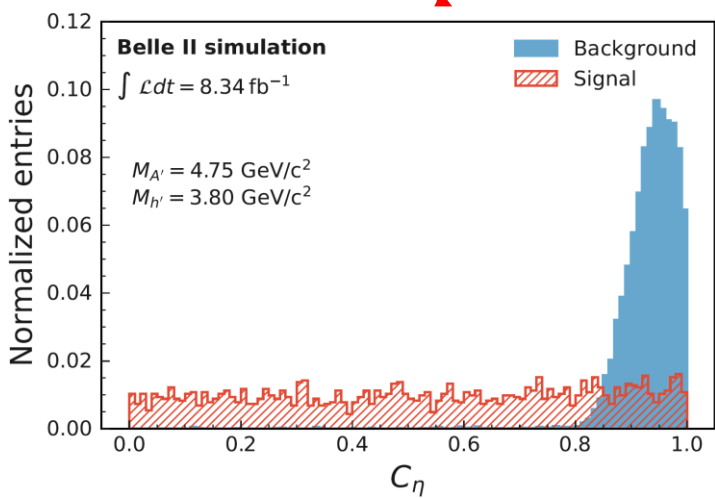
~9000 overlapping elliptical mass windows

Helicity angle

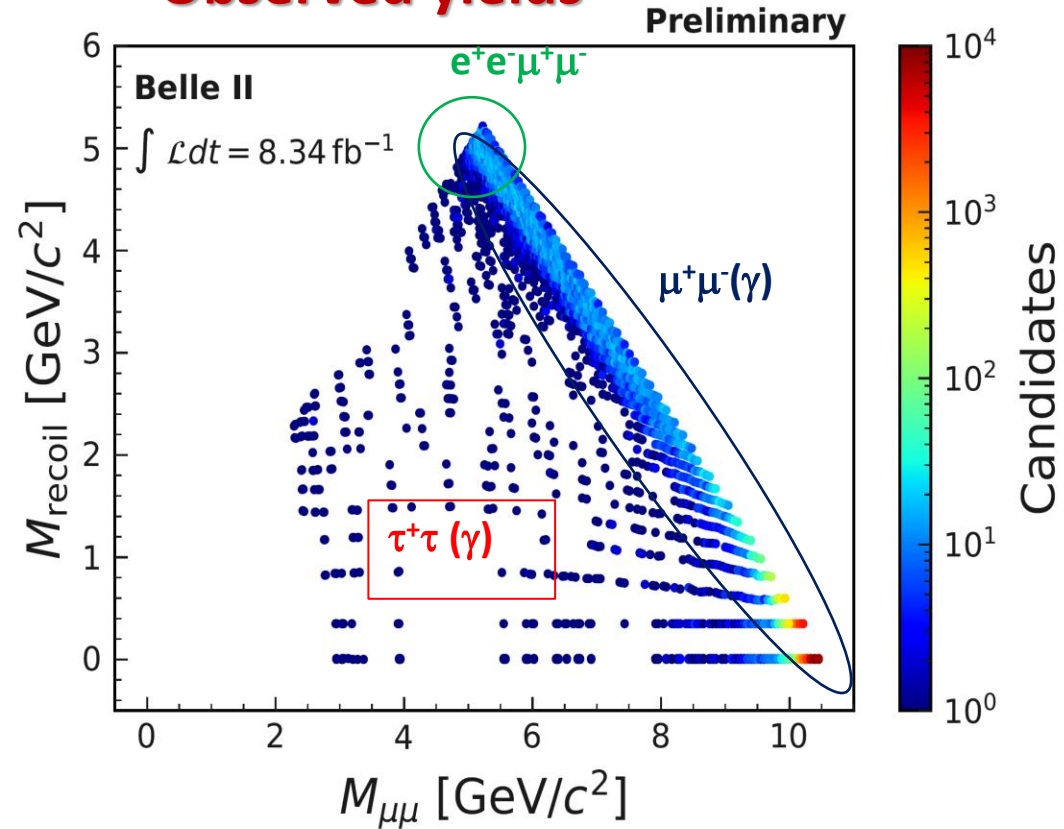


Backgrounds

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



Observed yields

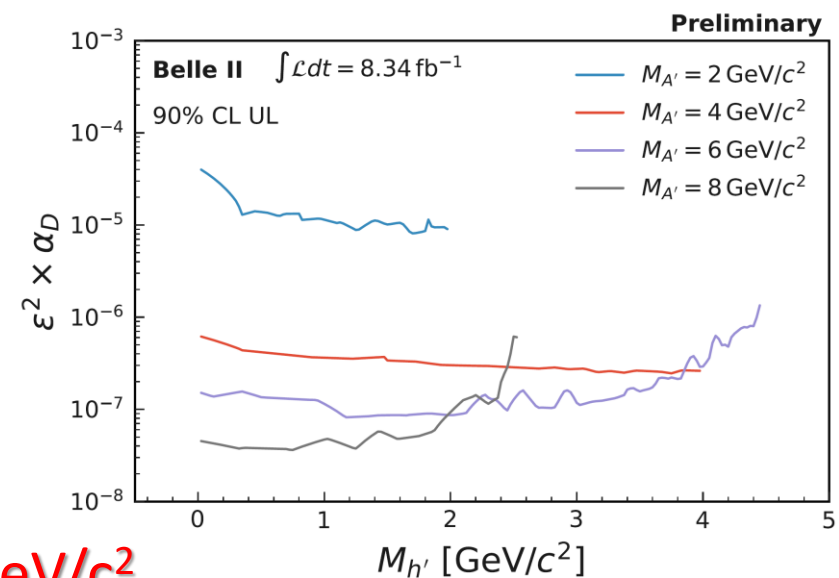
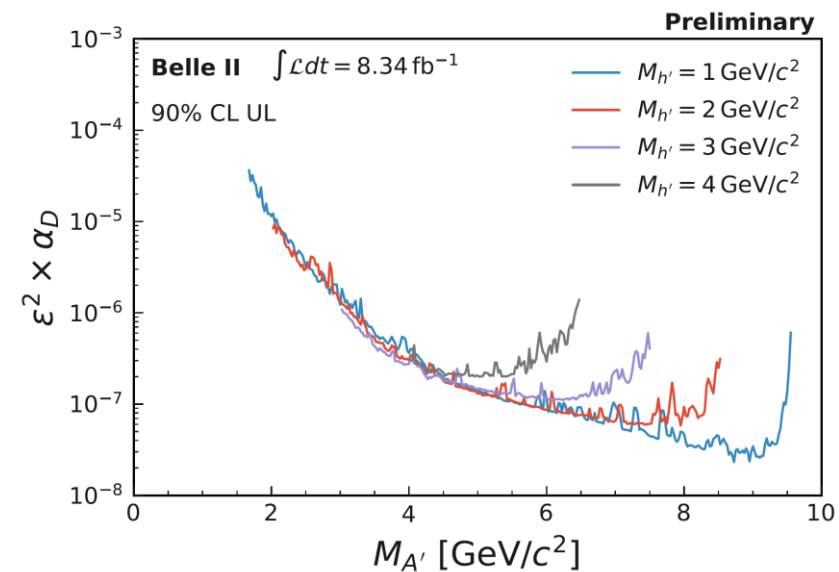
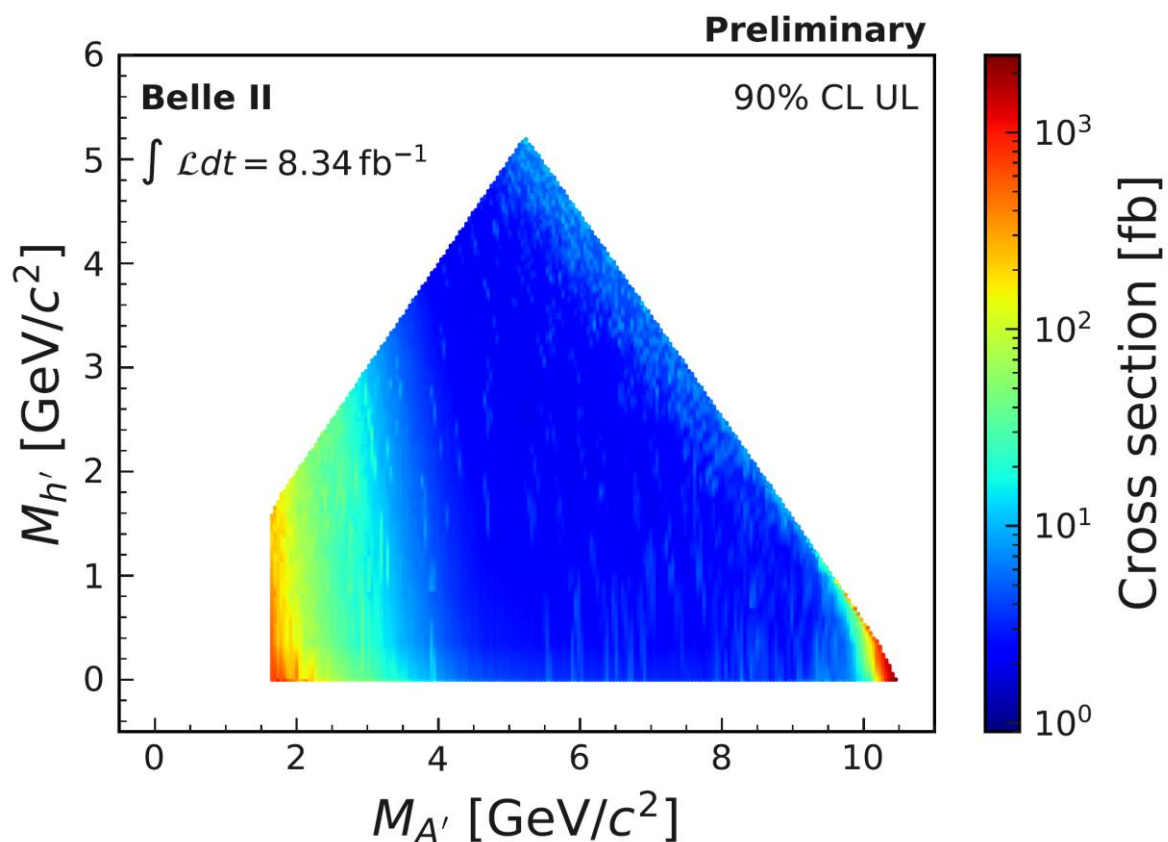


Dark Higgsstrahlung: results

No excess found

Upper limits on σ and $\varepsilon^2 \alpha_D$

most sensitive for $4 < M_{A'} < 9.7 \text{ GeV}/c^2$



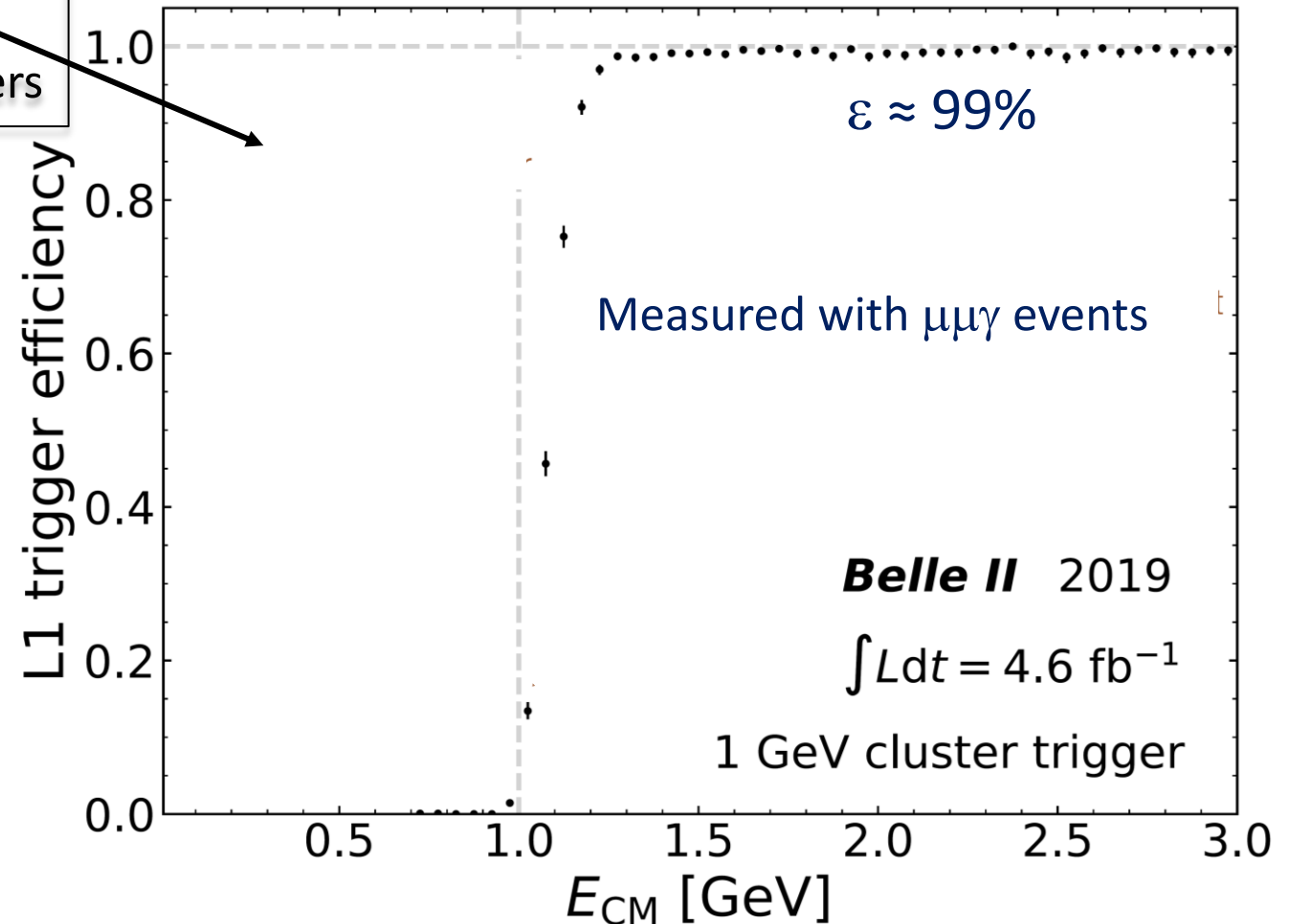
World first for $1.65 < M_{A'} < 10.51 \text{ GeV}/c^2$

Invisible dark photon: single photon trigger

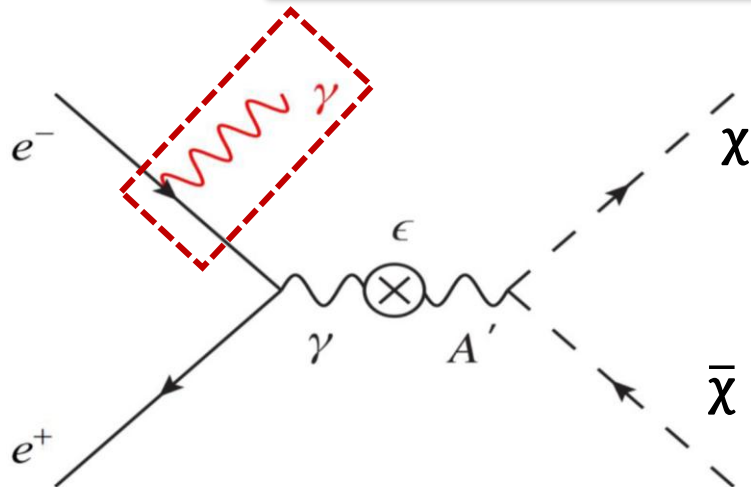
- $E_{\text{CM}} > 2 \text{ GeV}$
- $E_{\text{CM}} > 1 \text{ GeV}$ in barrel + no other clusters
- $E_{\text{CM}} > 0.5 \text{ GeV}$ in central barrel + no other clusters

Would extend the search range up to $M_{A'} \lesssim 10 \text{ GeV}$ (psychological threshold)

Much more aggressive than originally expected.



Invisible dark photon: experimental signature



Only **one photon** in the detector

Needs a **single photon trigger**
(not available in Belle, $\approx 10\%$ of data in BaBar)

Needs an excellent knowledge of the **detector acceptance**

$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

Bump in recoil mass or photon energy

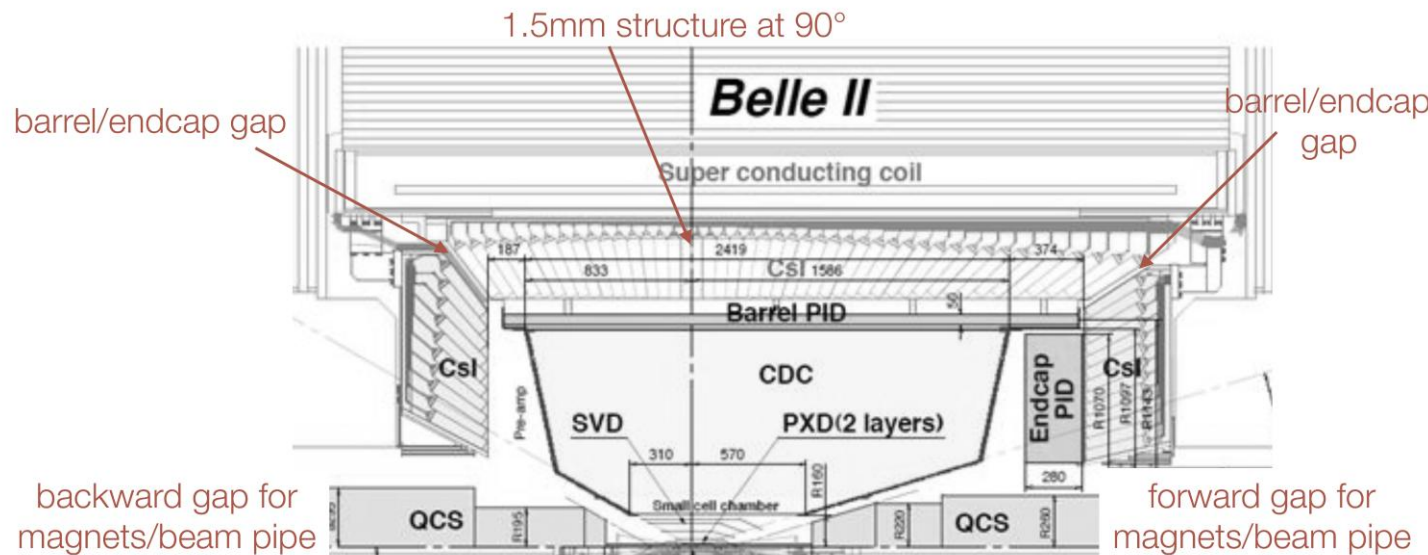
Backgrounds

$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ → high $M_{A'}$ region

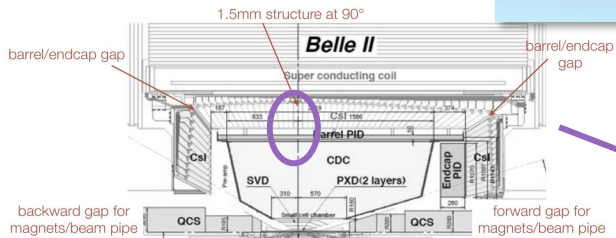
$e^+e^- \rightarrow \gamma\gamma(\gamma)$ → low $M_{A'}$ region

Cosmics

$e^+e^- \rightarrow \gamma\nu\nu$

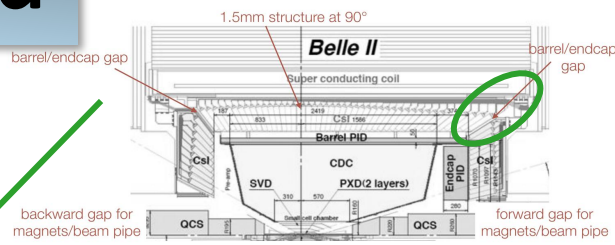


Invisible dark photon: background

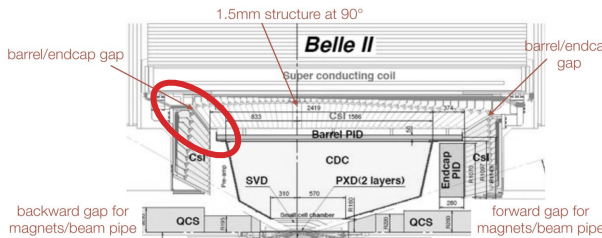
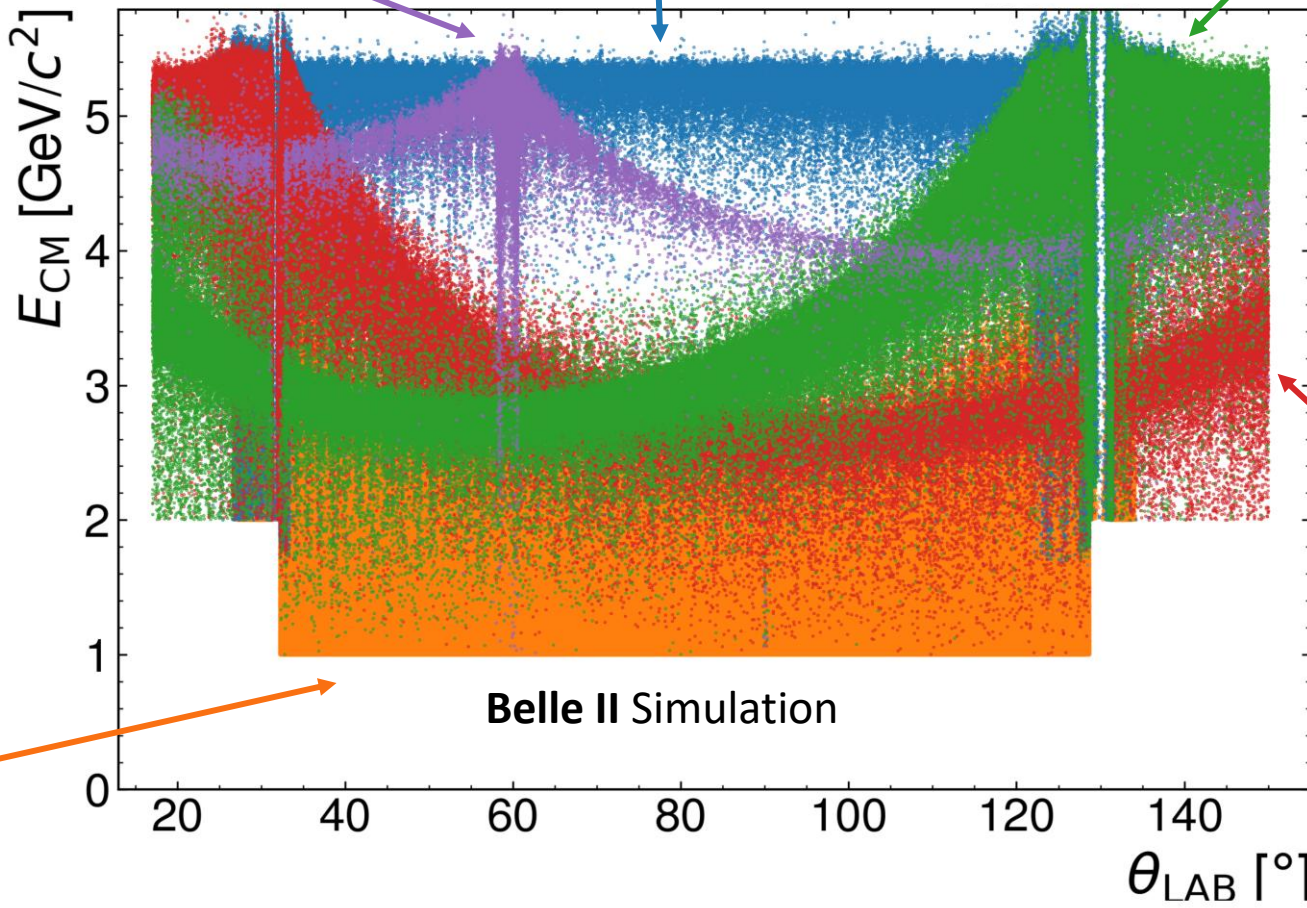


$e^+e^- \rightarrow \gamma\gamma\gamma$
1 γ in 90° gap
1 γ out of ECL acceptance

$e^+e^- \rightarrow \gamma\gamma$



$e^+e^- \rightarrow \gamma\gamma\gamma$
1 γ in FWD gap
1 γ out of ECL acceptance



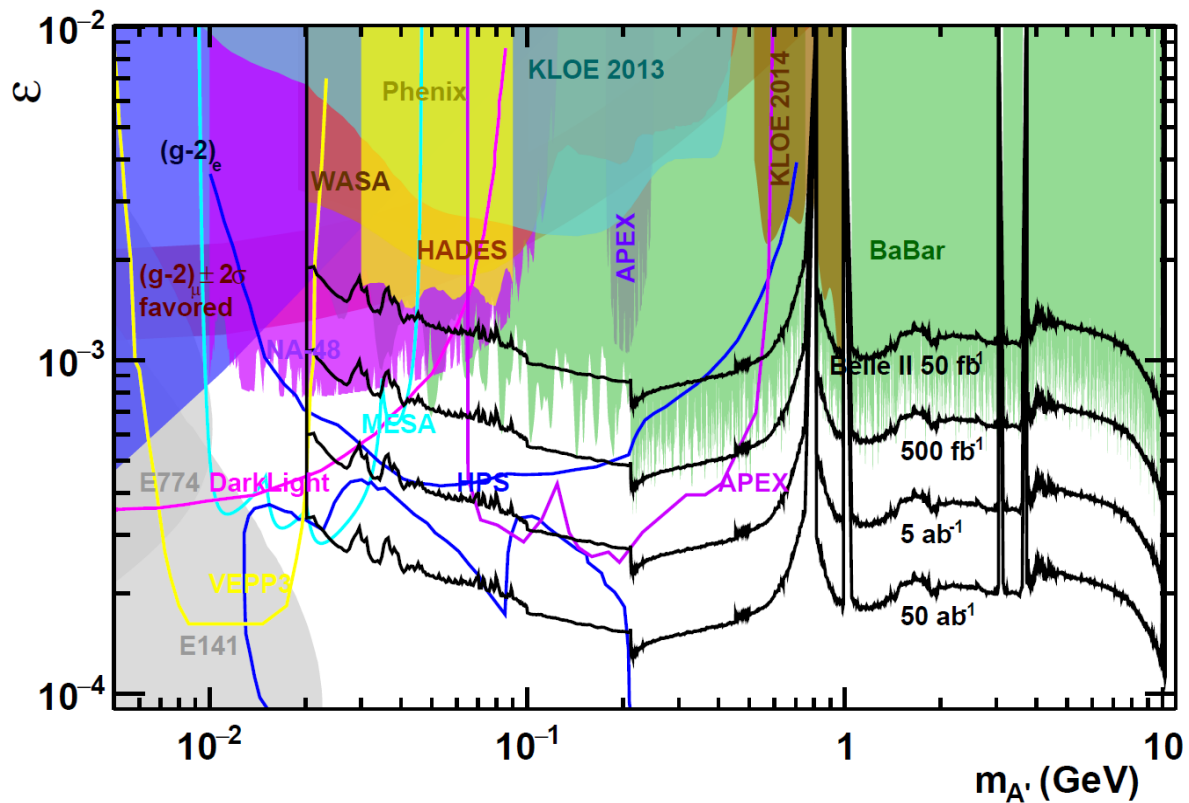
$e^+e^- \rightarrow \gamma\gamma\gamma$
1 γ in BWD gap
1 γ out of ECL acceptance

$e^+e^- \rightarrow \gamma\gamma\gamma$
2 γ out of ECL acceptance

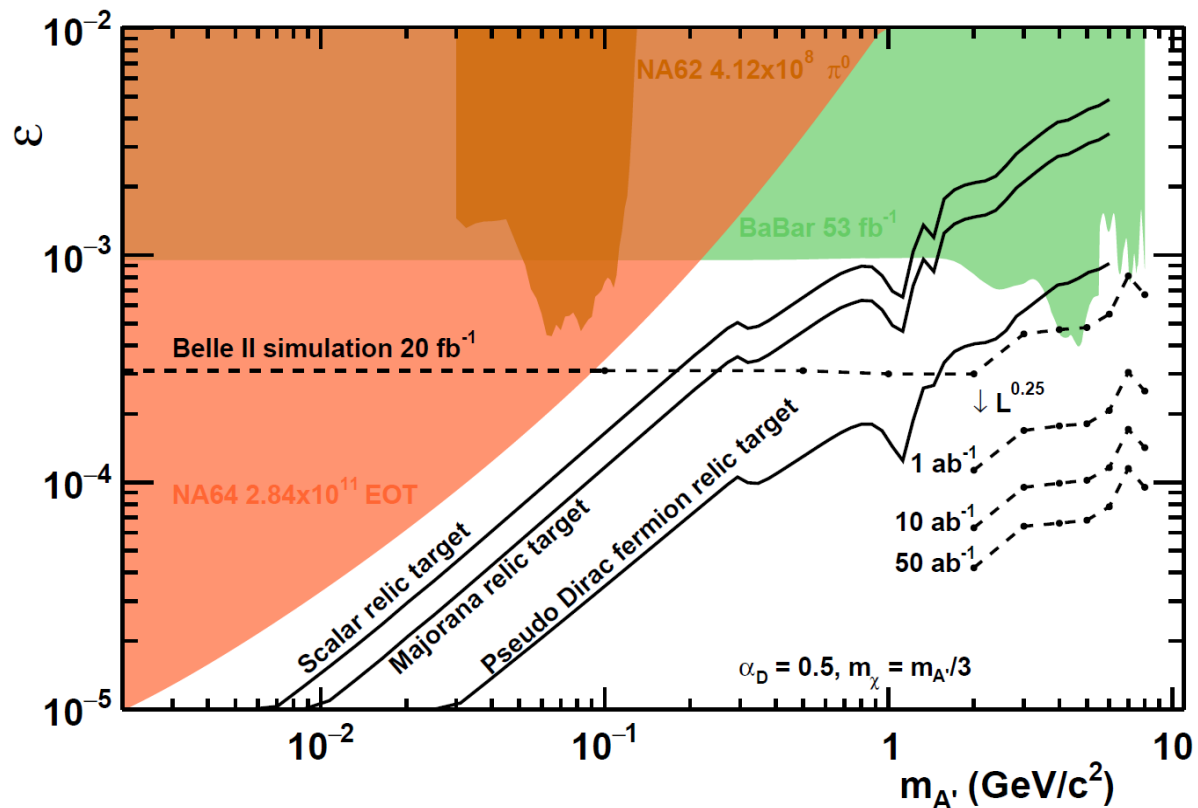
Crucial usage of KLM to veto photons in ECL gaps

Dark photon: luminosity projections

Visible



Invisible



Belle II physics reach @ Snowmass
[arXiv: 2207.06307v1](https://arxiv.org/abs/2207.06307v1)

Belle II vs BaBar

- ✓ Calorimeter with no projective cracks in ϕ
- ✓ Larger acceptance
- ✓ KLM veto