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' →invisible, μμ,ττ
- ✓ Scalar portals
  - ➢ S → μμ, ττ
  - ➢ B →K S **LLP**
- ✓ Dark Higgsstrahlung A'h'
  - ➢ IDM + h' → μμ, ππ, KK **LLP**
- ✓ Pseudoscalar portals
  - ➢ ALP →ττ
  - ➢ B →K ALP, ALP →γγ
  - ➢ B →K X, X → invisible **LLP**
- ✓ Perspectives & Summary

SuperKEKB now

SuperKEKB vs KEKB

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

$\mathcal{L}$ → **6x10^{35} cm^{-2}s^{-1}**

x20 × x30

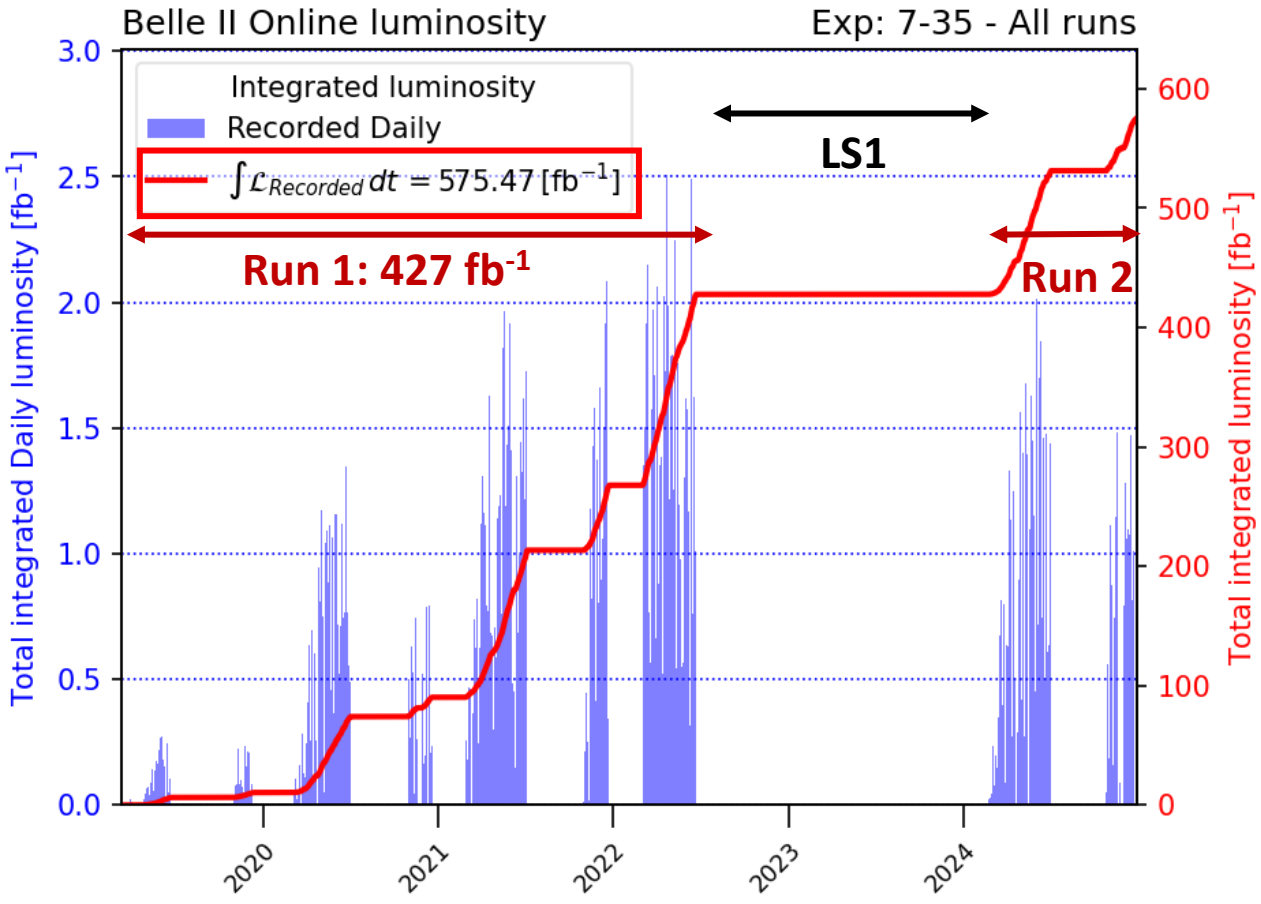
Belle $\int \mathcal{L} dt$ = 711 fb^{-1}

Run 1 (2019-2022)
- Collected 427 fb^{-1} ½ Belle data size ~1 Babar data size

Run 2 started in spring 2024
- Upgraded detector (PXD2, TOP PMT)
- World record luminosity 5.1x10^{34}cm^{-2}s^{-1}
- Largely dedicated to machine studies

Final goal : 50 ab^{-1}

Collected luminosity up to now: 2019-2024



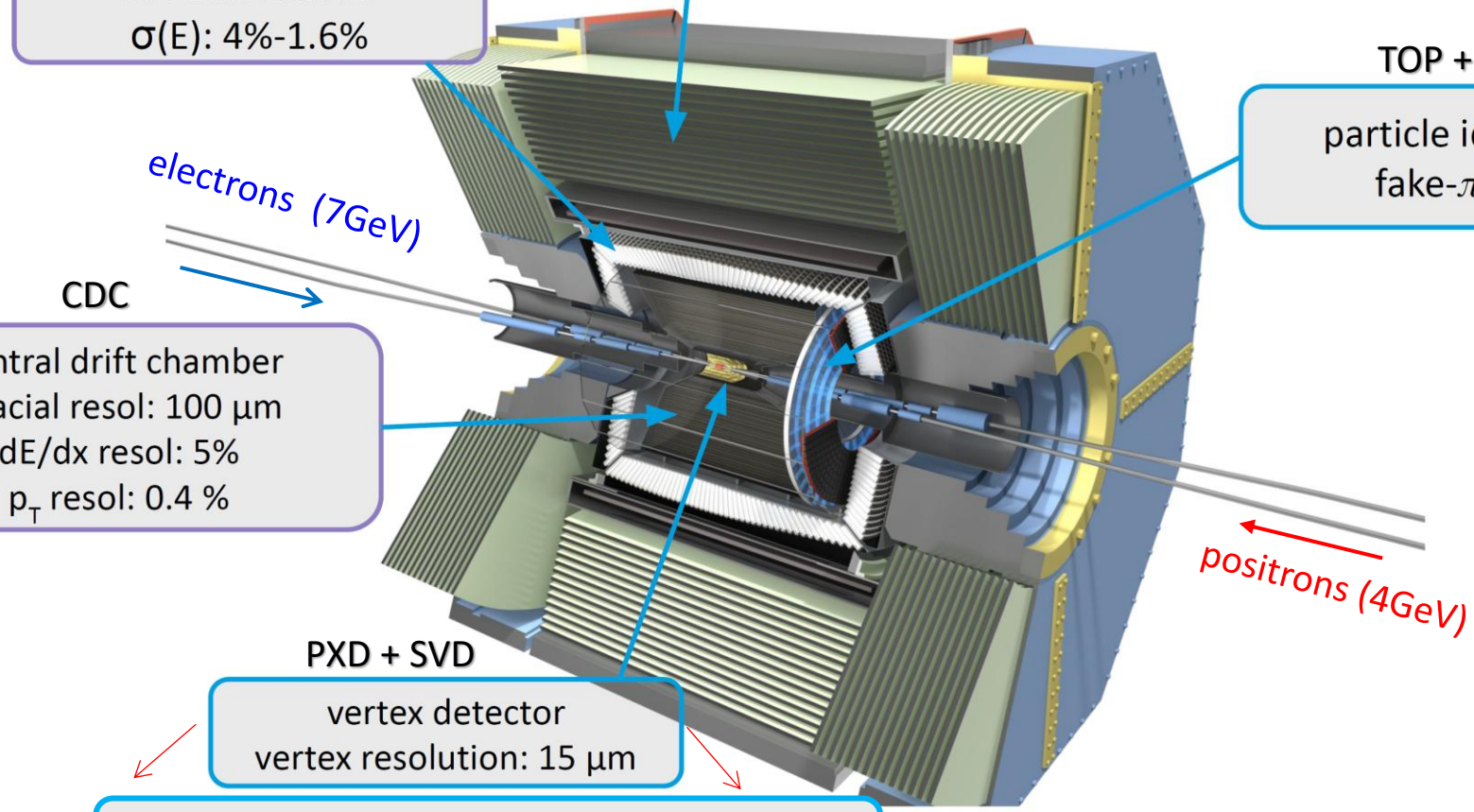
Restart data taking in November 2025

SuperKEKB now

Run 2

- Back to operations at ~$4x10^{34}$ $cm^{-2}s^{-1}$
- **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
  - ~130 fb^{-1} collected
- **Now confident to have reached comprehension of how SBL start**
  - Remediation begun during past summer shutdown and extend through 2025
  - Restart data taking in Fall 2025

Belle II detector



KLM

K_L and muon detector
μ ID-eff: ~90%

ECL

EM Calorimeter
σ(E): 4%-1.6%

TOP + ARICH

particle identification
fake-π rate: 5%

electrons (7GeV)

CDC

central drift chamber
spacial resol: 100 μm
dE/dx resol: 5%
p_T resol: 0.4 %

positrons (4GeV)

PXD + SVD

vertex detector
vertex resolution: 15 μm

2 layer pixel detector (PXD) 2nd incomplete in Run1
4 layer double-sided strip detector (SVD)

Trigger:
L1: < 30 kHz
HLT: < 10 kHz

Dedicated lines for dark physics:
Single muon
Single track
Single photon

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

$\sigma(e^+e^- \rightarrow BB) \approx 1.1$ nb
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) \approx 0.9$ nb

- Cleanliness and luminosity compensate for cross section → competition

Belle II dark sector search overview: results

Shown today

L_μ-L_τ
Z' → invisible
Z' → μμ
Z' → ττ

Axion like particles
a→ττ

Axion like particles
B→K a, a→γγ

(LLP) Axion like particles et al
B→h X, X→ invisible

LLP dark scalar in B decays
B→KS S→ee, μμ, ππ, KK

LLP Dark Higgsstrahlung with IDM
A'h' A'→$\chi_1\chi_2$, h'→μμ, ππ, KK

Not shown today

Axion like particles
ALP→γγ

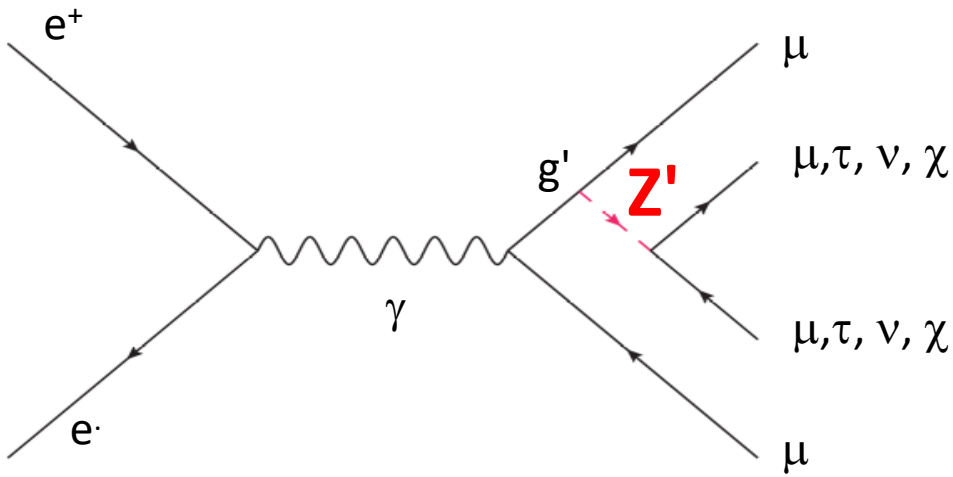
Invisible α in τ decays
$\tau \to l\alpha$

Dark Higgsstrahlung
A'h' A'→μμ, h' invisibile

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

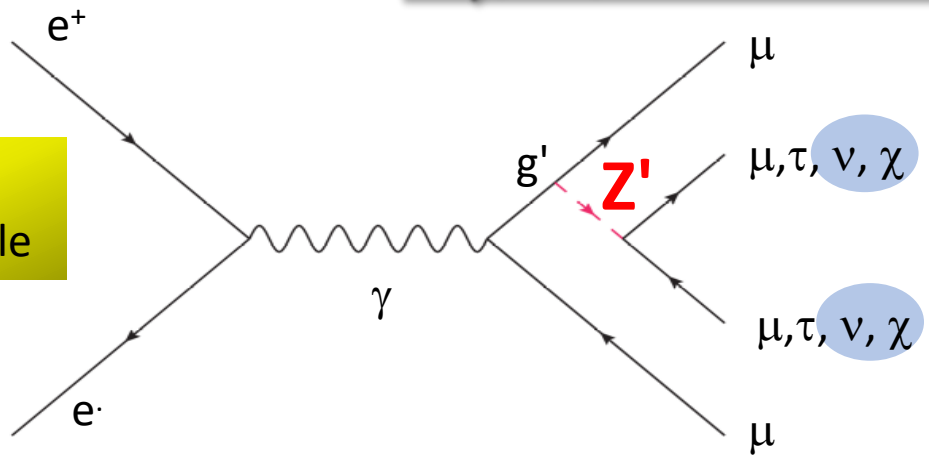
- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / Light Dirac fermions
  - $(g-2)_\mu$
  - $B \to K^{(*)}\mu\mu$, R_K, R_{K^*}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

Shuve et al. Phys. Rev. D 89, 113004 (2014)
Altmannshofer et al. JHEP 1612 (2016) 106

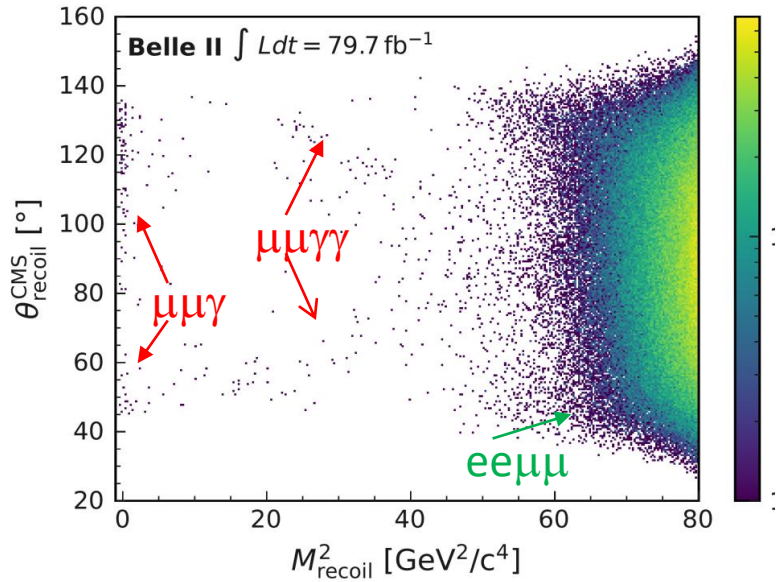


L_μ-L_τ model: Z' to invisible

L_μ-L_τ
Z' → invisible



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

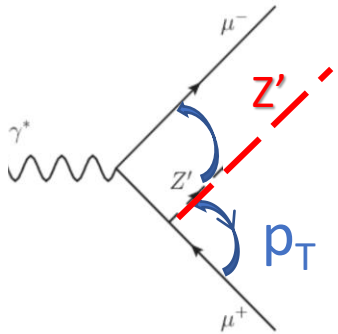


$e^+e^- \to \mu^+\mu^-$ + *missing energy*

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

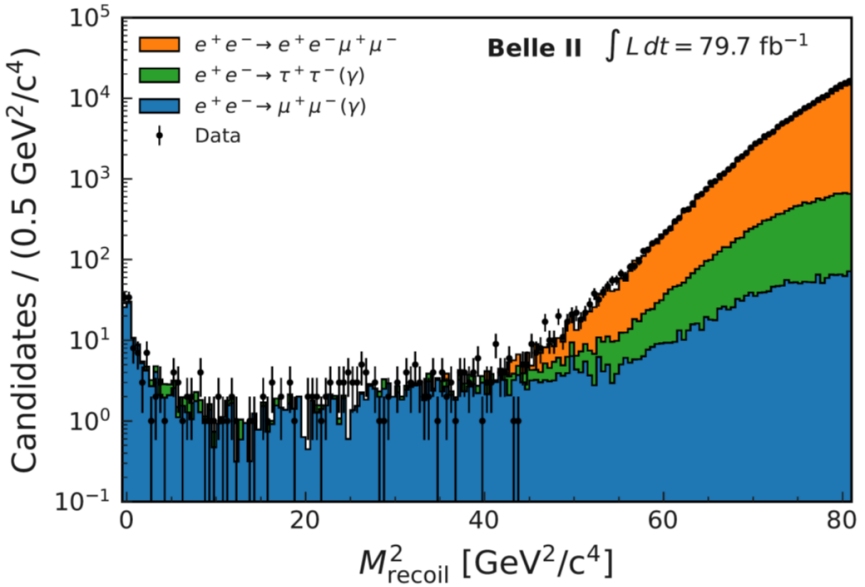
Main backgrounds:

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



FSR vs ISR + τ decay

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

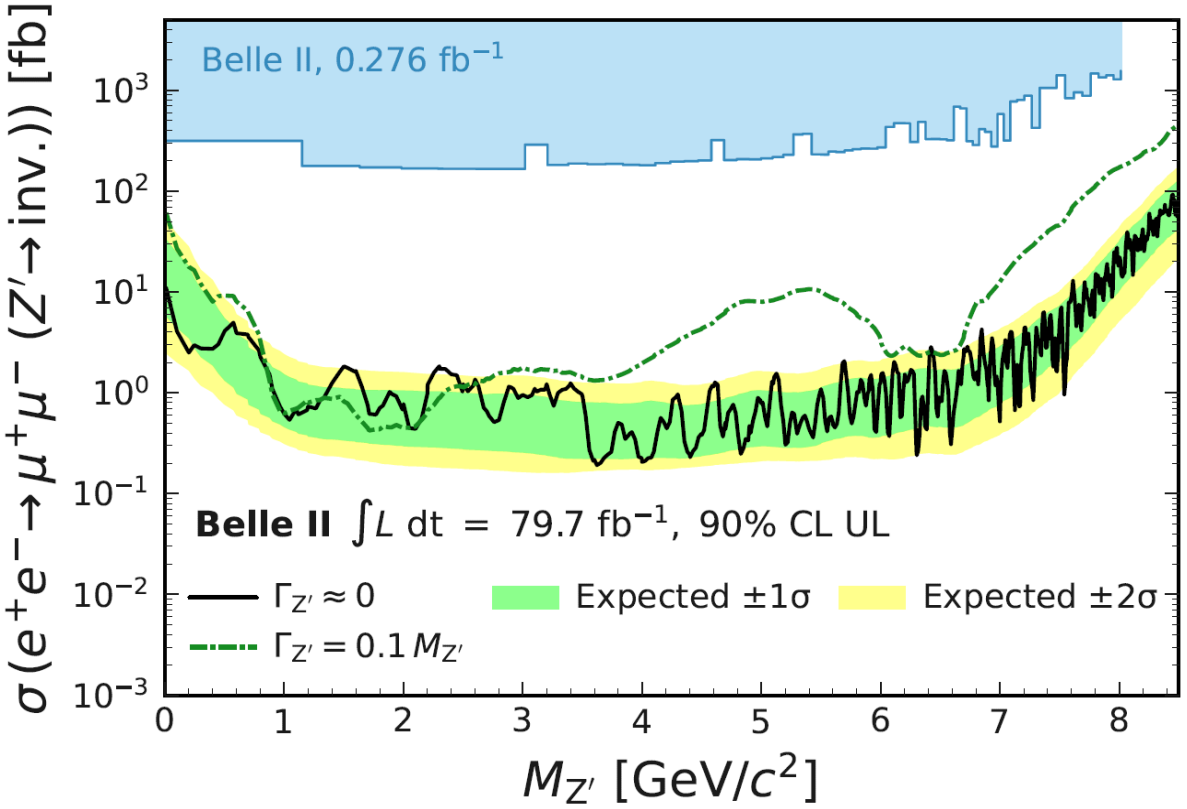


Z’ to invisible: results

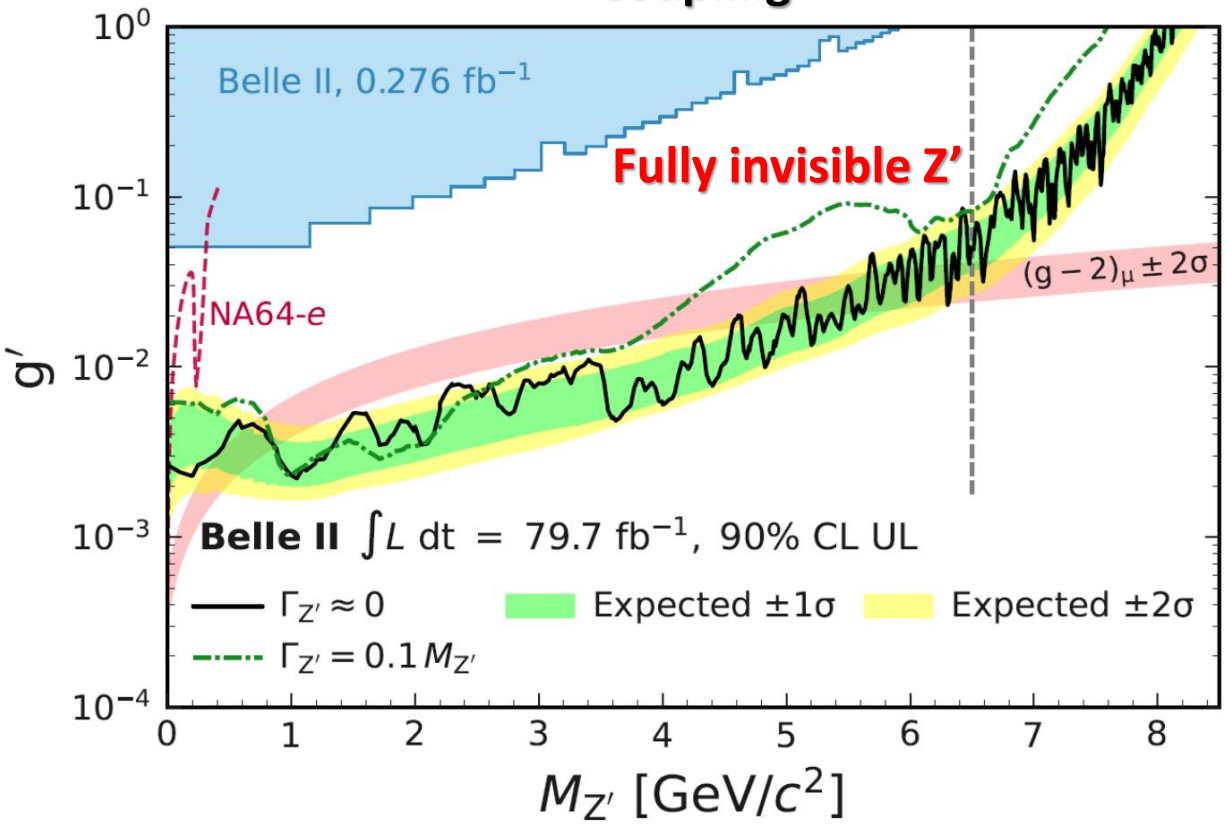
- No excess found
- Set 90%CL exclusion limits on cross section and coupling
  - Vanilla scenario: Z’ decays to SM only
  - Fully invisible scenario

PRL 130, 231801 (2023)

Cross section



Coupling



Z’ to invisible: results

- No excess found
- Set 90%CL exclusion limits on cross section and coupling
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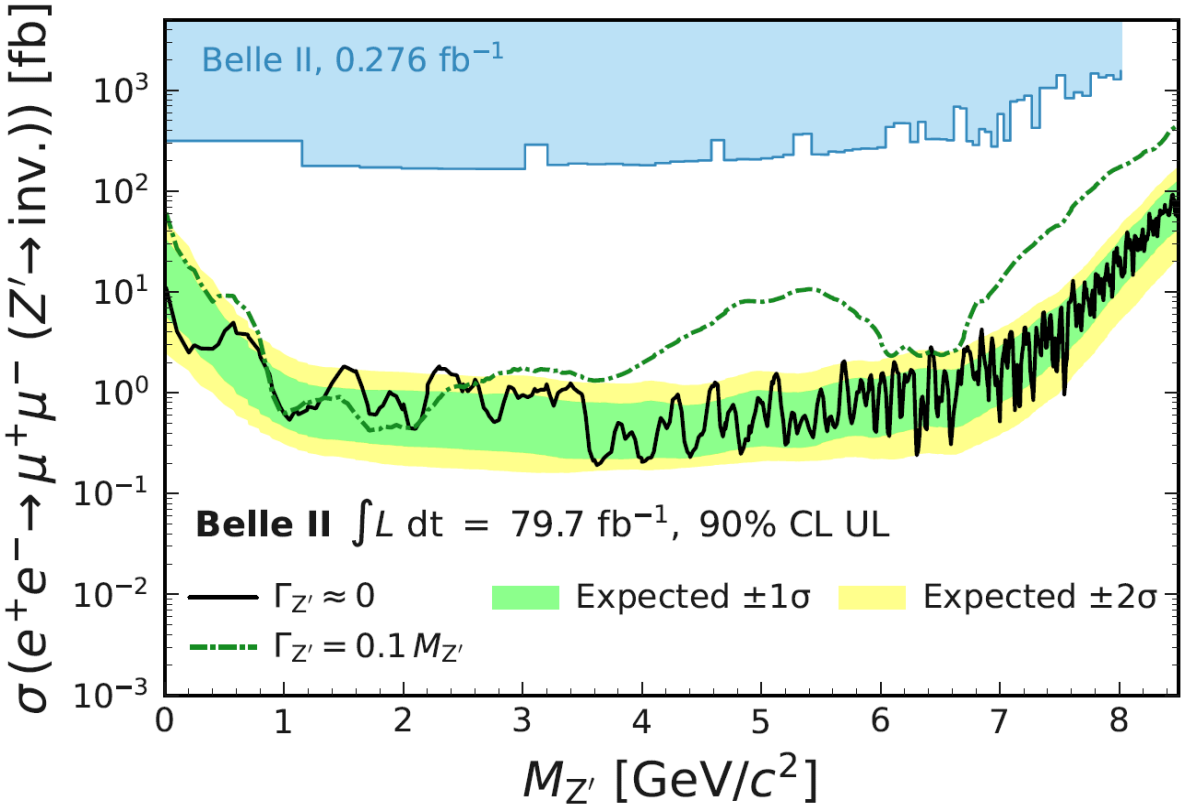
  - Fully invisible scenario

Next update based on Run 1 luminosity almost ready

PRL 130, 231801 (2023)

Cross section



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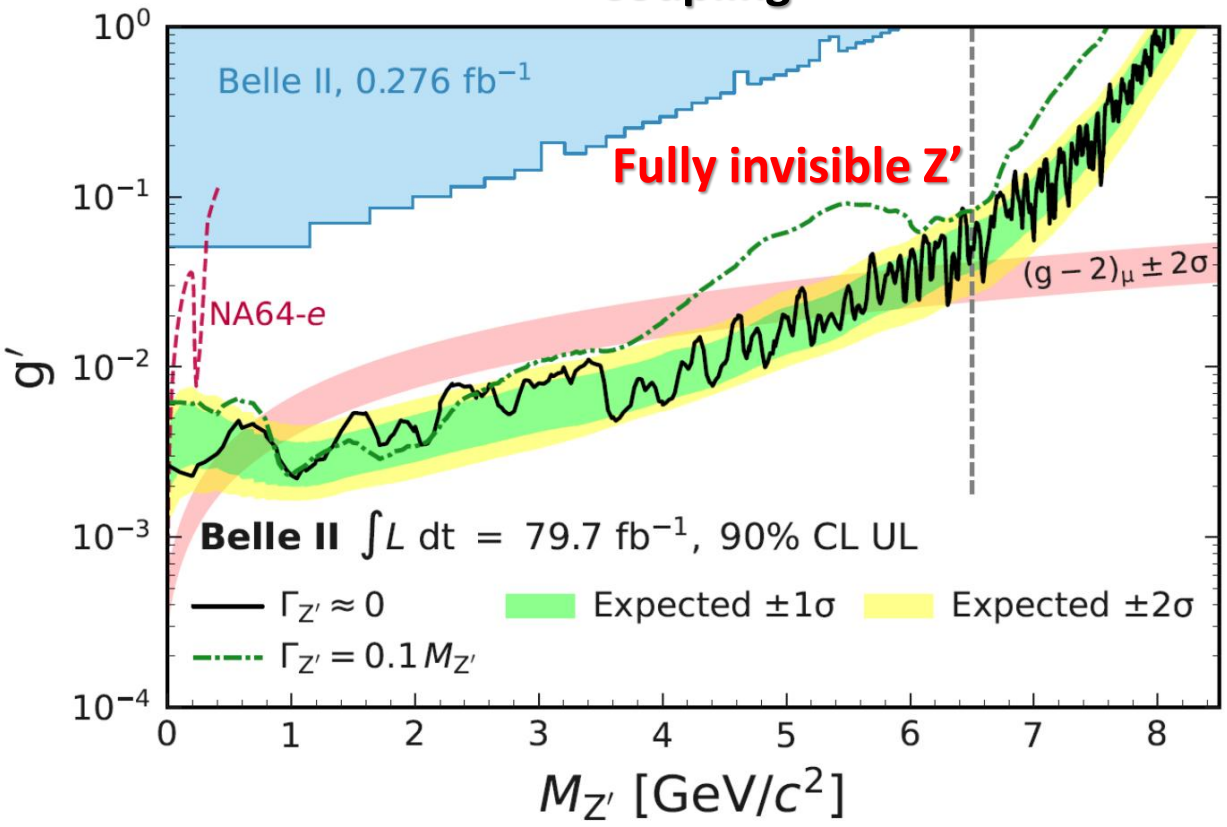
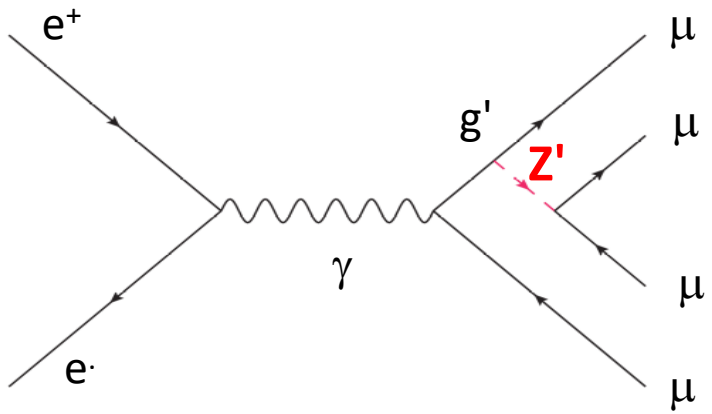


L_μ-L_τ model: Z' → μμ

L_μ-L_τ
Z' → μμ

Reinterpreted also as
- Muonphilic dark scalar S → $(g-2)_\mu$



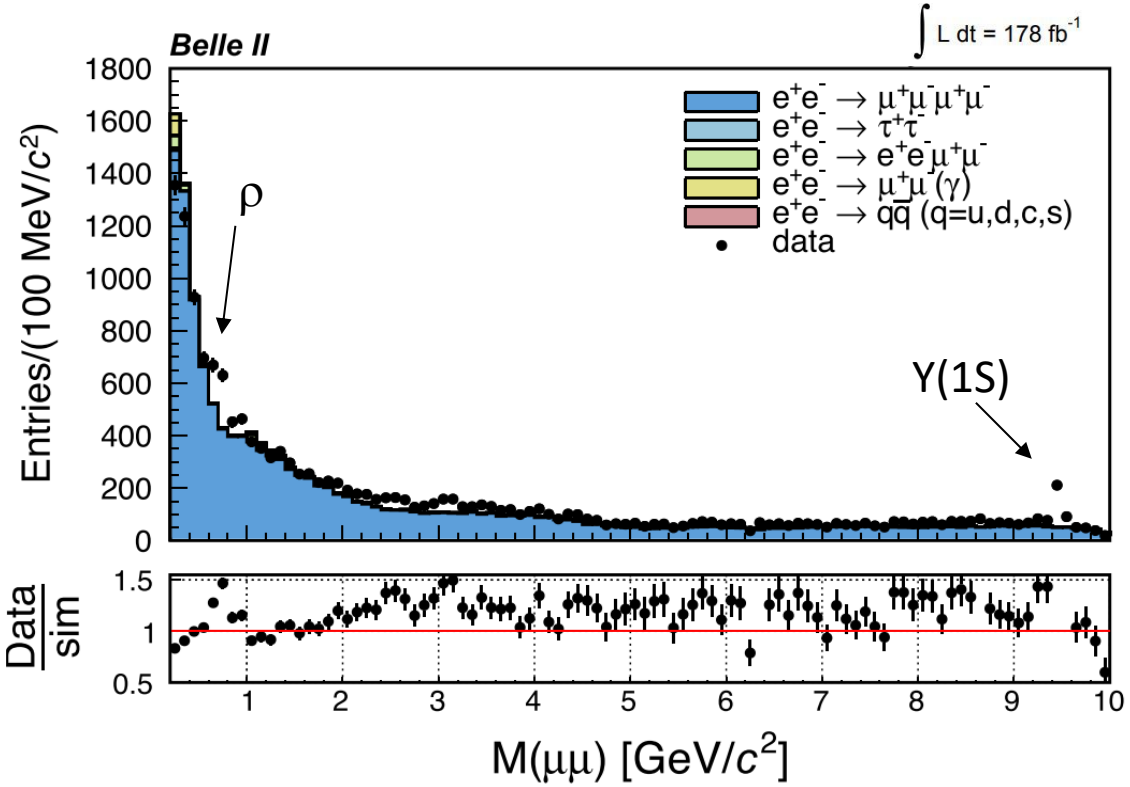
$e^+e^- \to \mu^+\mu^- \mu^+\mu^-$

4-track mass ~√s
No extra energy
Signature: narrow M(μμ) peak

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

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

Fits to M(μμ)



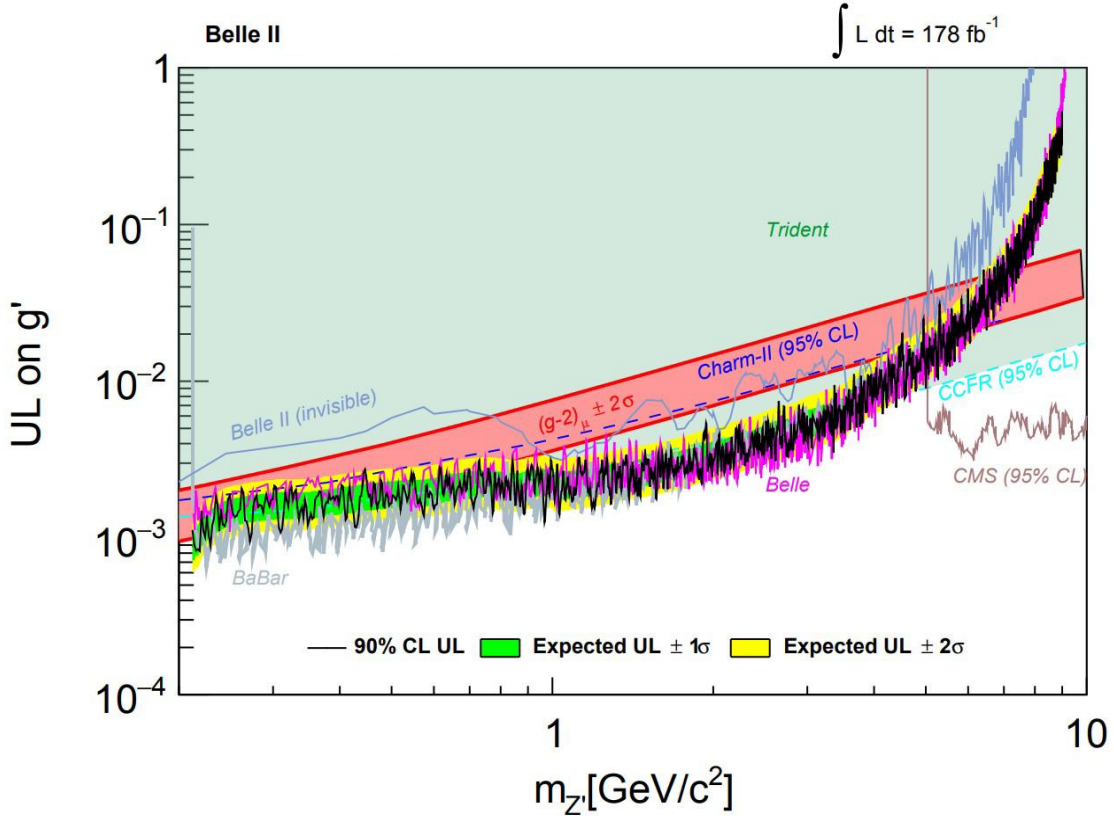
L_μ-L_τ model: Z' → μμ

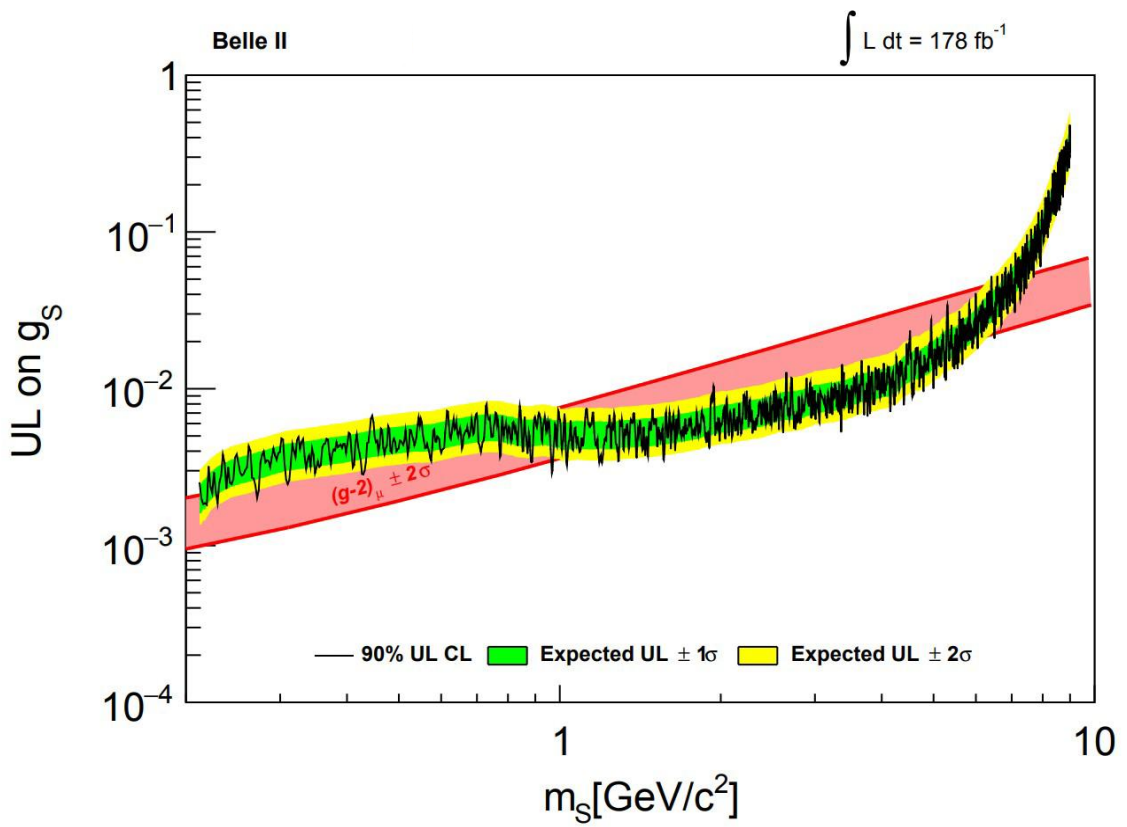
L_μ-L_τ
Z' → μμ

Reinterpreted also as
- Muonphilic dark scalar S → $(g\text{-}2)_\mu$

PRD 109, 112015 (2024)

- No excess
- Limits on Z' **similar to BaBar (514 fb^{-1}) and Belle (643 fb^{-1})** with much lower luminosity
- **First limits for the muonphilic scalar** from a dedicated search

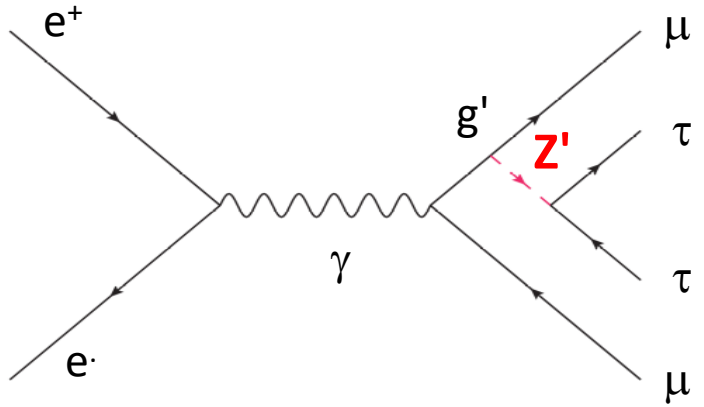




L_μ-L_τ model: Z' → ττ

L_μ-L_τ
Z' → ττ

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



Background suppression with NN
- resonance vs μμ
- FSR production
- ττ system

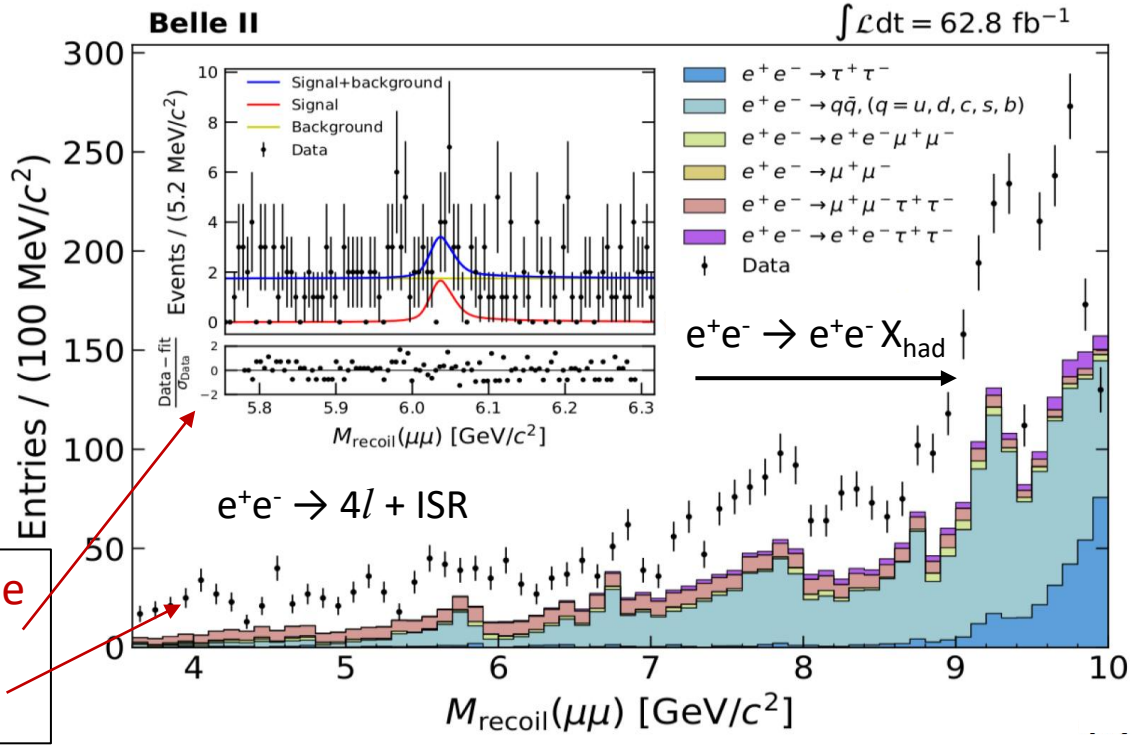
Main backgrounds

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

$e^+e^- \to e^+e^-\mu^+\mu^-$
$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$
$e^+e^- \to e^+e^-\tau^+\tau^-$
} no ISR in simulation

$e^+e^- \to \mu^+\mu^-\pi^+\pi^-$ not simulated

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



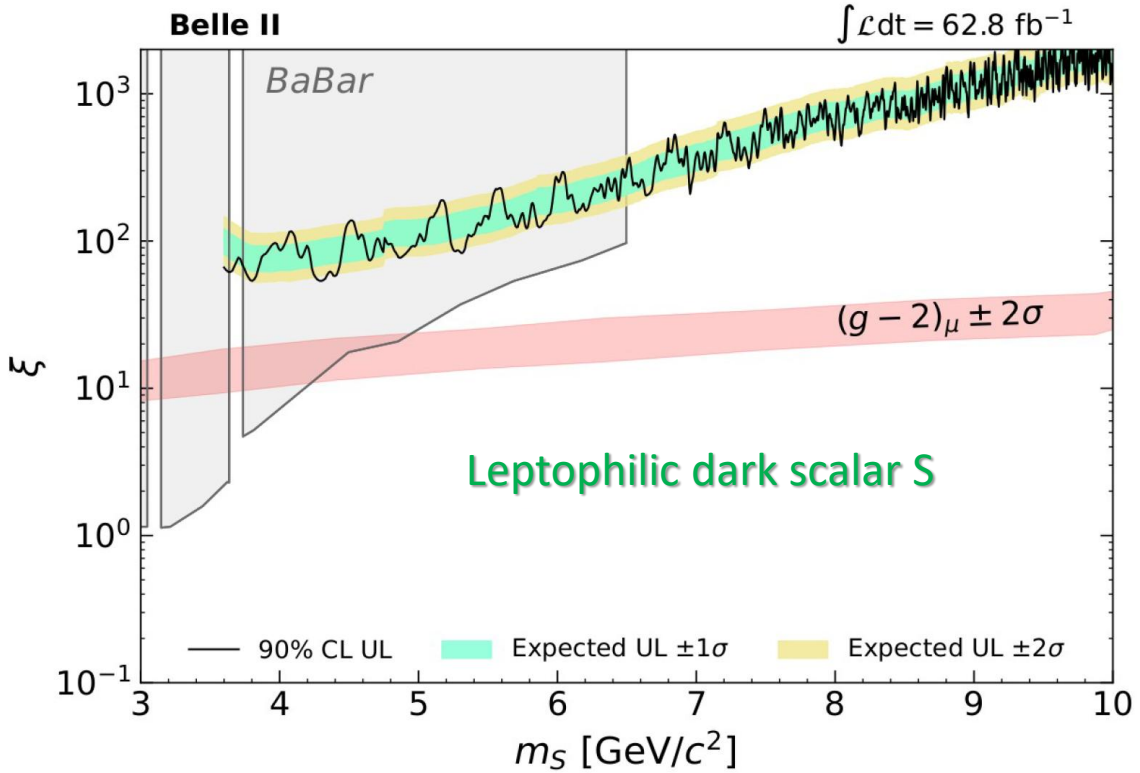
Smooth background on the scale of the signal mass resolution (~10 MeV/c^2)

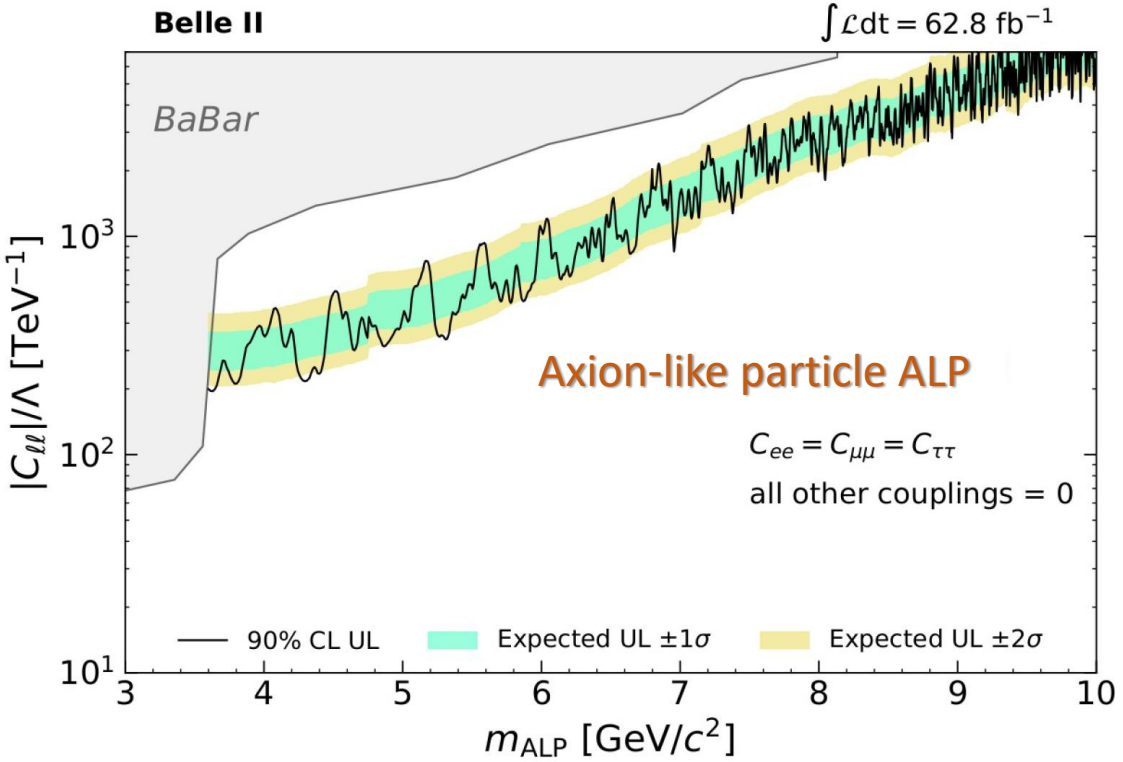
L_μ-L_τ model and more: X → ττ

L_μ-L_τ
$Z' \to \tau\tau$

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

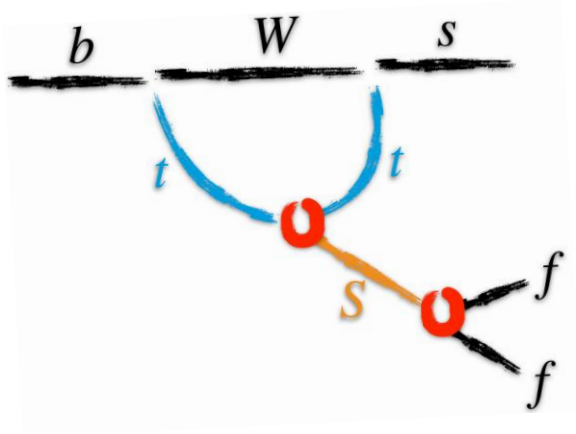
PRL 131, 121802 (2023)





Dark scalar S in b→s transitions

LLP dark scalar in B decays
B→kS S→ee, μμ, ππ, KK

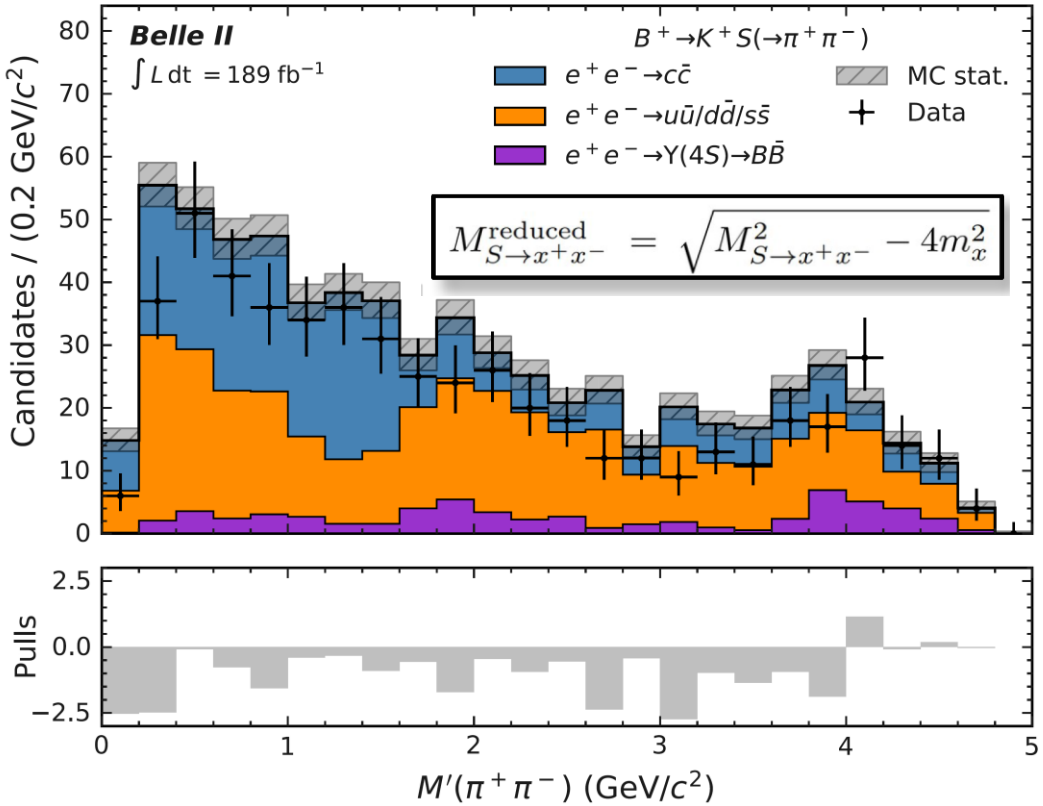


b→s transitions
Mixing with SM Higgs
LLP signature

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

$B^+ \to K^+ S$, $B^0 \to K^{*0}[\to K^+\pi^-]S$
$S \to e^+e^-$/ $\mu^+\mu^-$ / $\pi^+\pi^-$ / K^+K^-

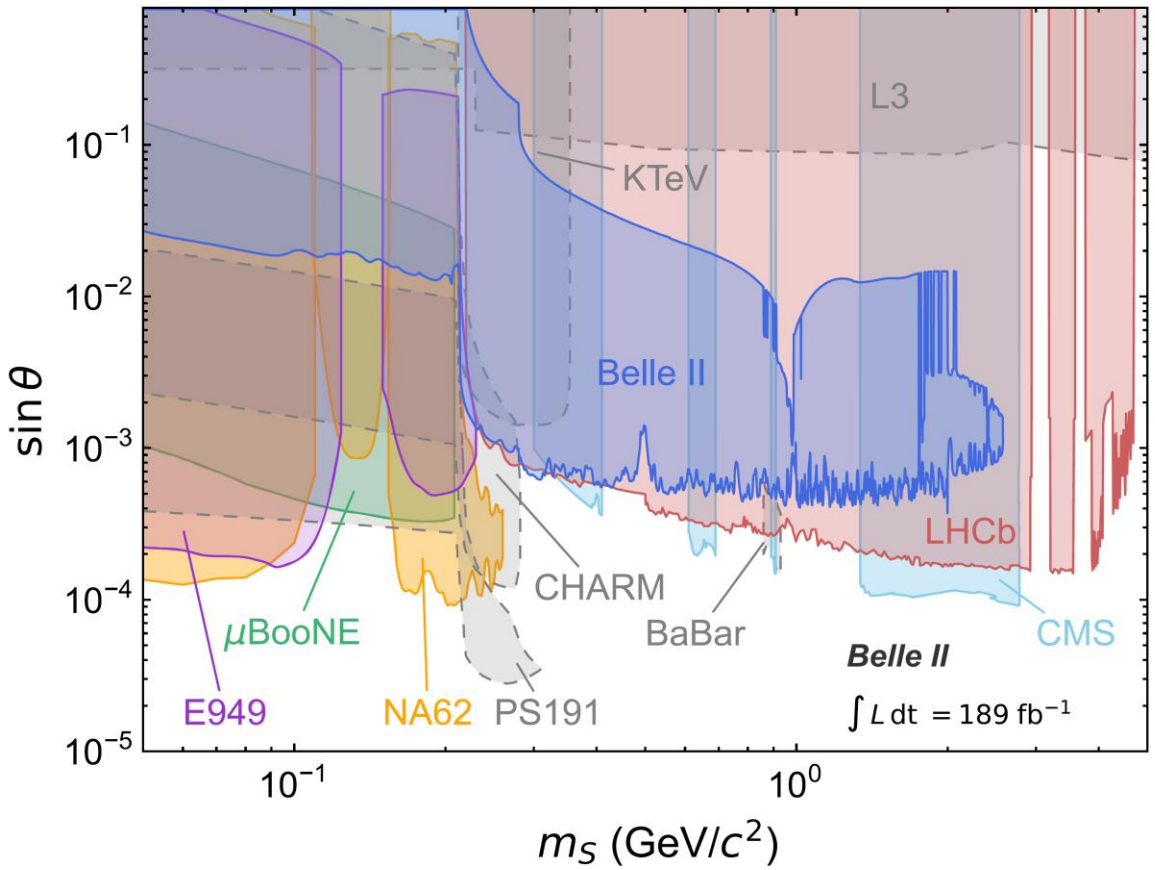


Dark scalar S in b→s transitions

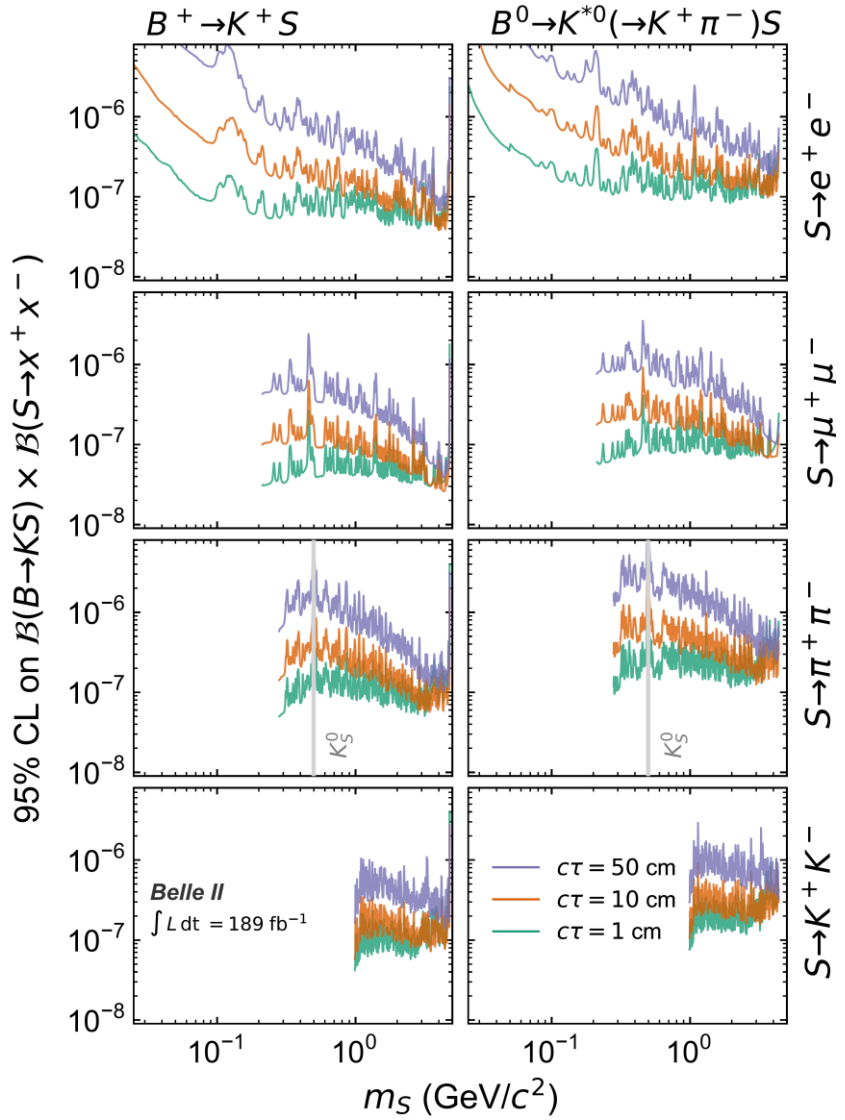
No excess found

- First model-independent limits on B(B→KS)xB(S →x+x-)
- First limits on decays to hadrons

PRD 108, L111104 (2023)



Limits for each channel and lifetime



ALP in B→Ka (Belle)

NEW

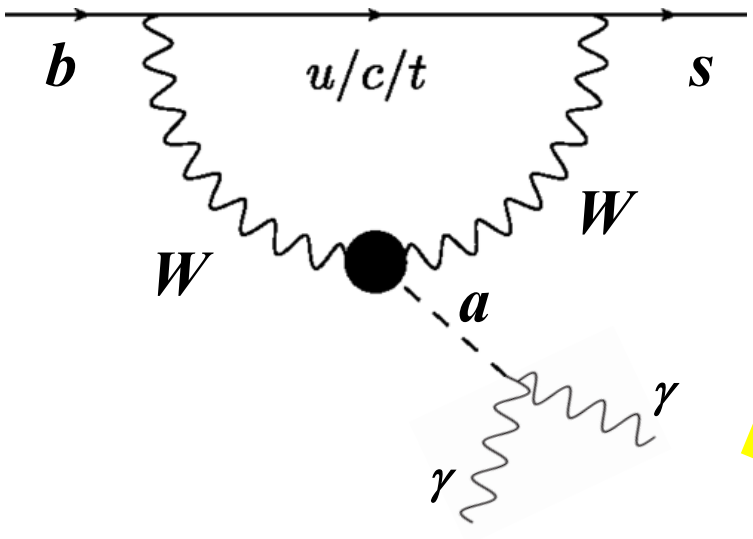
Axion-like particles in B decays
B→K ALP, ALP→γγ

Multiple B/kaon modes studied wrt BaBar

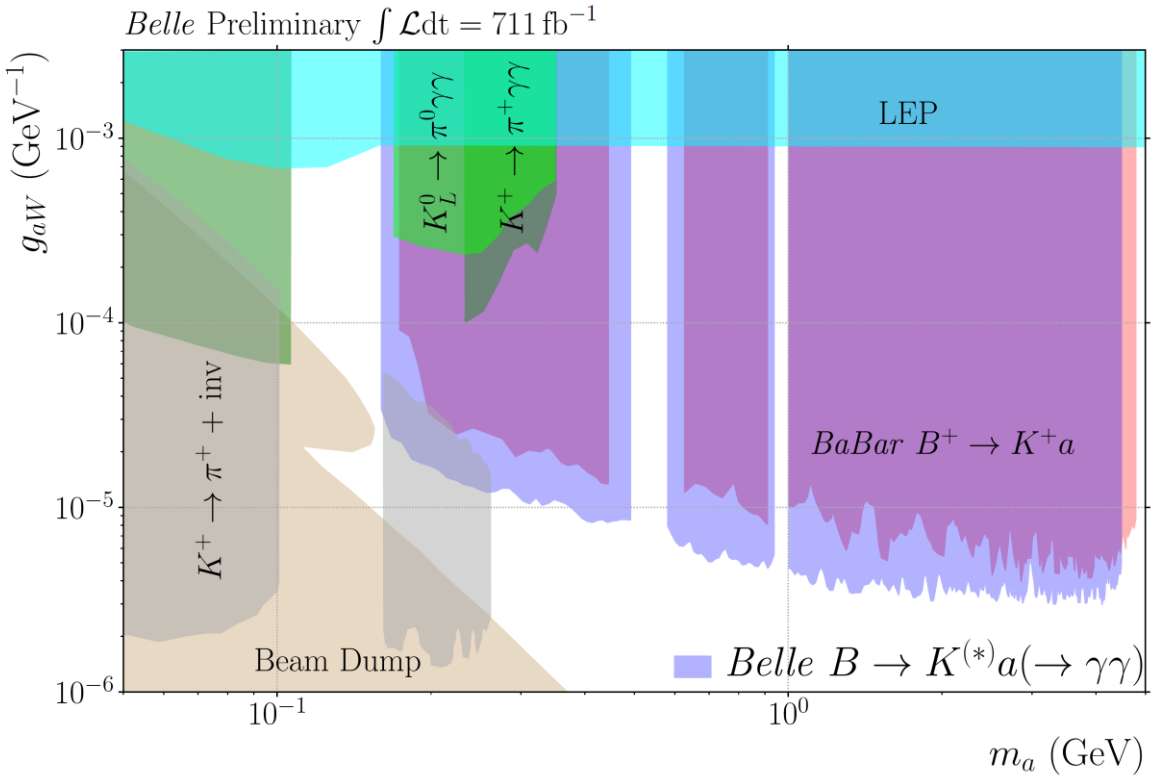
$B^{\pm} \rightarrow K^{(*)\pm} a,\ a \rightarrow \gamma\gamma$

$B^{0} \rightarrow K^{*}/K^{0}_{S}\ a,\ a \rightarrow \gamma\gamma$

Probe of aWW coupling in b→ s transitions



Submitted to JHEP
arXiv:2507.01249



π^0, η, η′ regions vetoed

$B \to h\,X\,(\to \text{invisible})$ at Belle

NEW

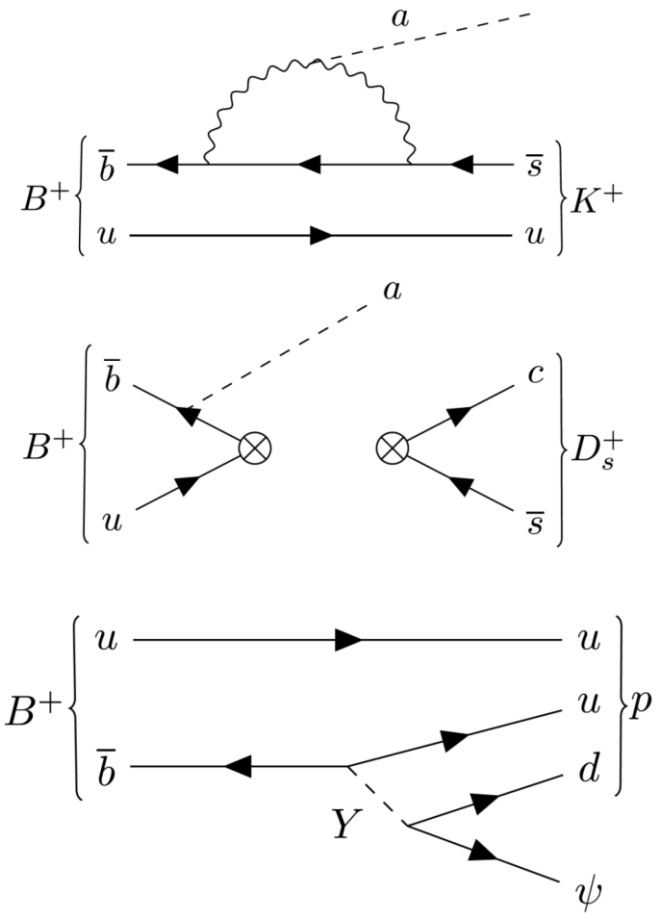
Feebly-interacting invisible particles in B decays
$B^+ \to h^+ X,\ B^0 \to \overline{D}^0 X$

$B^+ \to h^+ X \quad h^+ = \pi^+, K^+, p, D_S^+$
$B^0 \to \overline{D}^0 X$

$X \to$ ALP, dark scalar, mesogenesis, …

X invisible → LLP or decays to dark sector particles

Extra motivation: Belle II observed excess in $B^+ \to K^+ \nu\nu$ (particularly for $B^+ \to K^+ a$)



Analysis optimized for two-body decay

Both B mesons are reconstructed, B_{tag} and B_{sig}

- B_{sig} is just one track K, π, p, or $D_S \to KK\pi$, or $\overline{D}^0$ to 3 different channels
- B_{tag} is reconstructed using our Full Event Interpretation algorithm

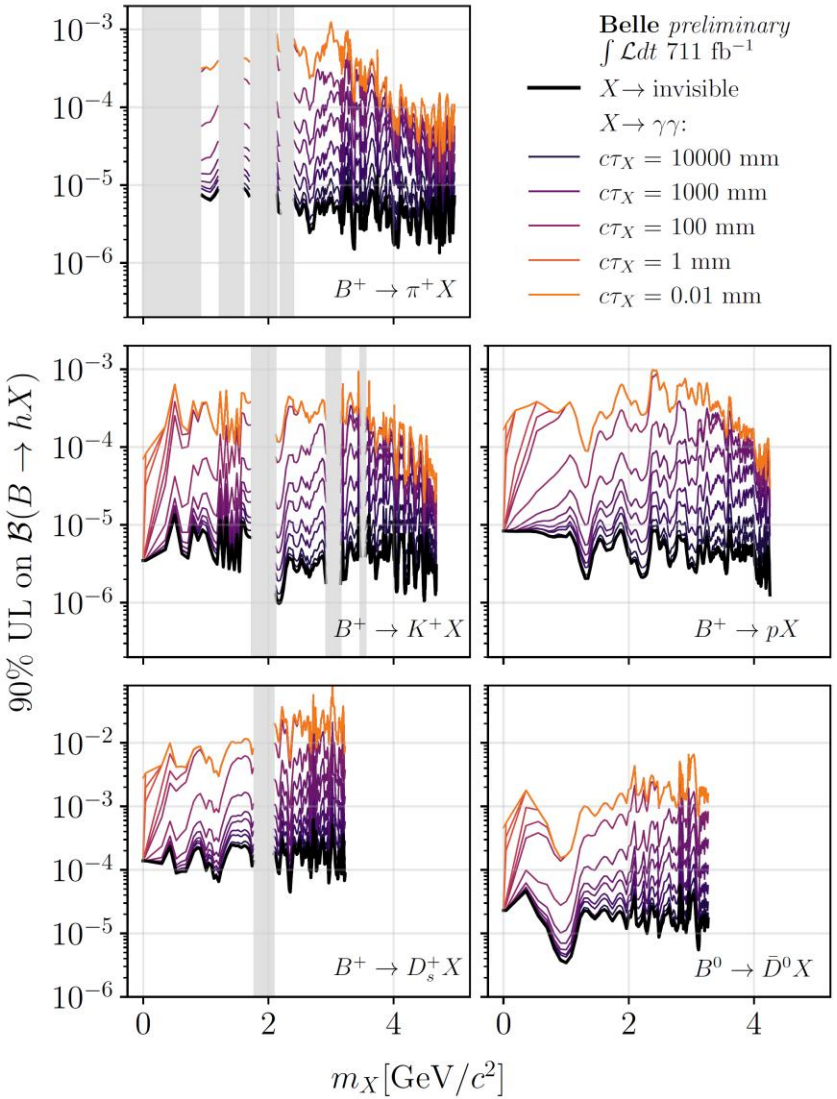
Signal extracted from momentum p_h in the B_{sig} rest frame

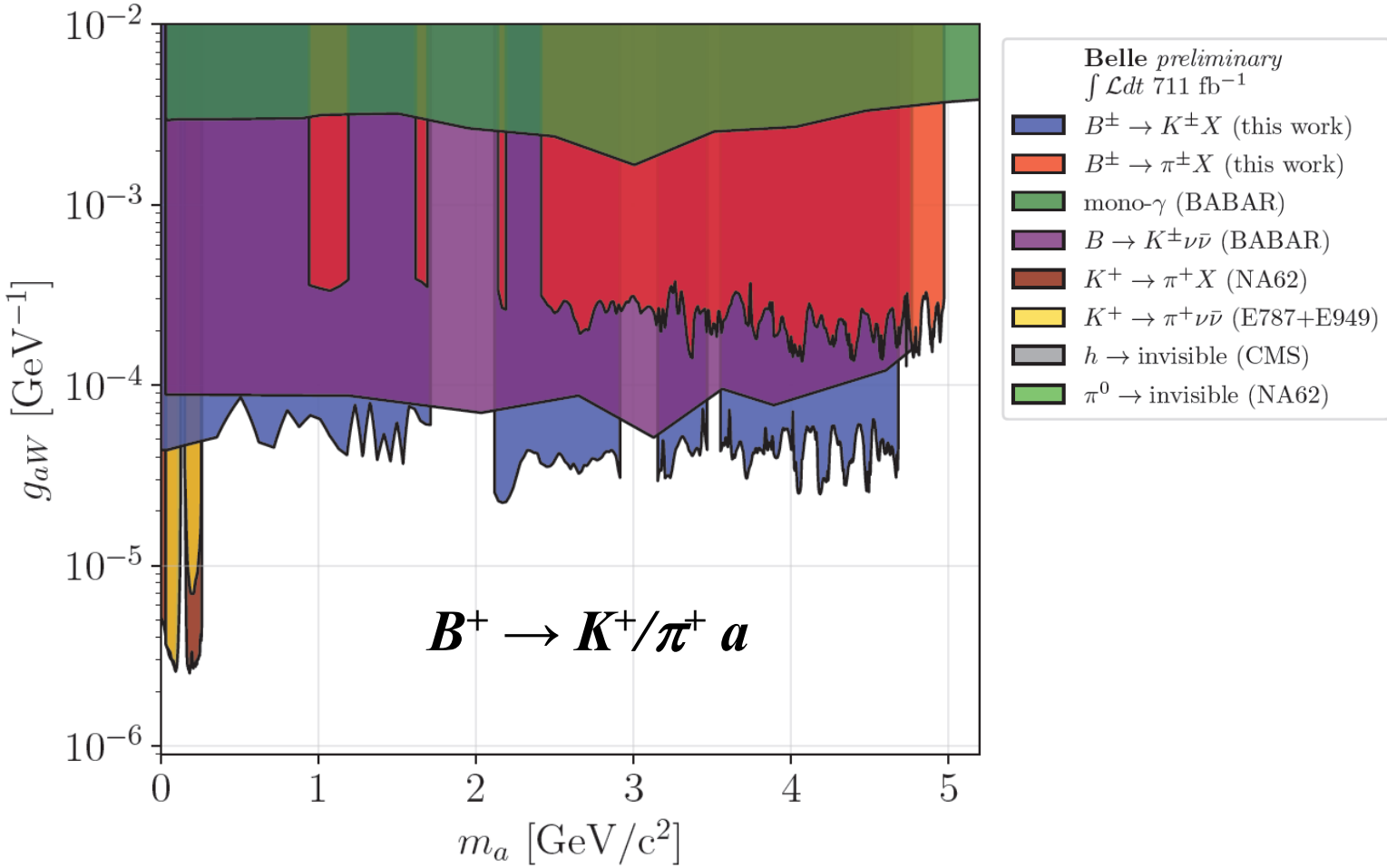
Main backgrounds: ee→qq, ee →BB and SM peaking backgrounds

$B \to h\,X$ ($\to$invisible) at Belle

To be submitted to PRL

Limits on $\mathcal{B}(B \to h\,X)$ for each channel



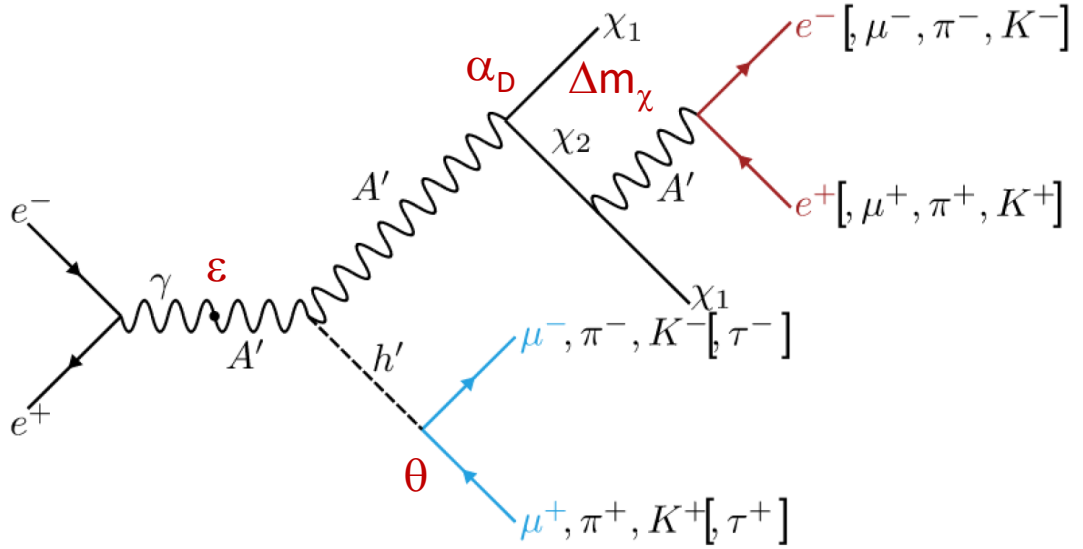


Narrow SM peaking backgrounds are vetoed

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 → dark matter candidate
- χ_2 is generally long-lived
- h' is generally long-lived and mixes with SM H_0



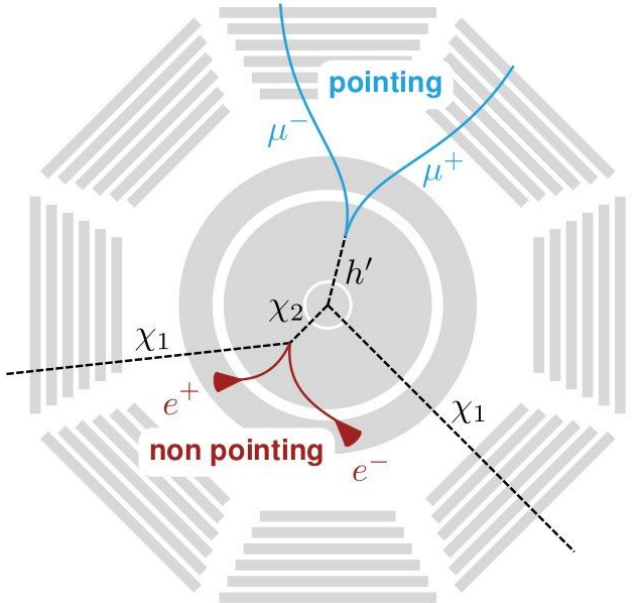
Focus on m(A') > m(χ_1)+m(χ_2)

- A'→ χ_1 χ_2

Up to two displaced vertices

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

h' → x^+x^- pointing



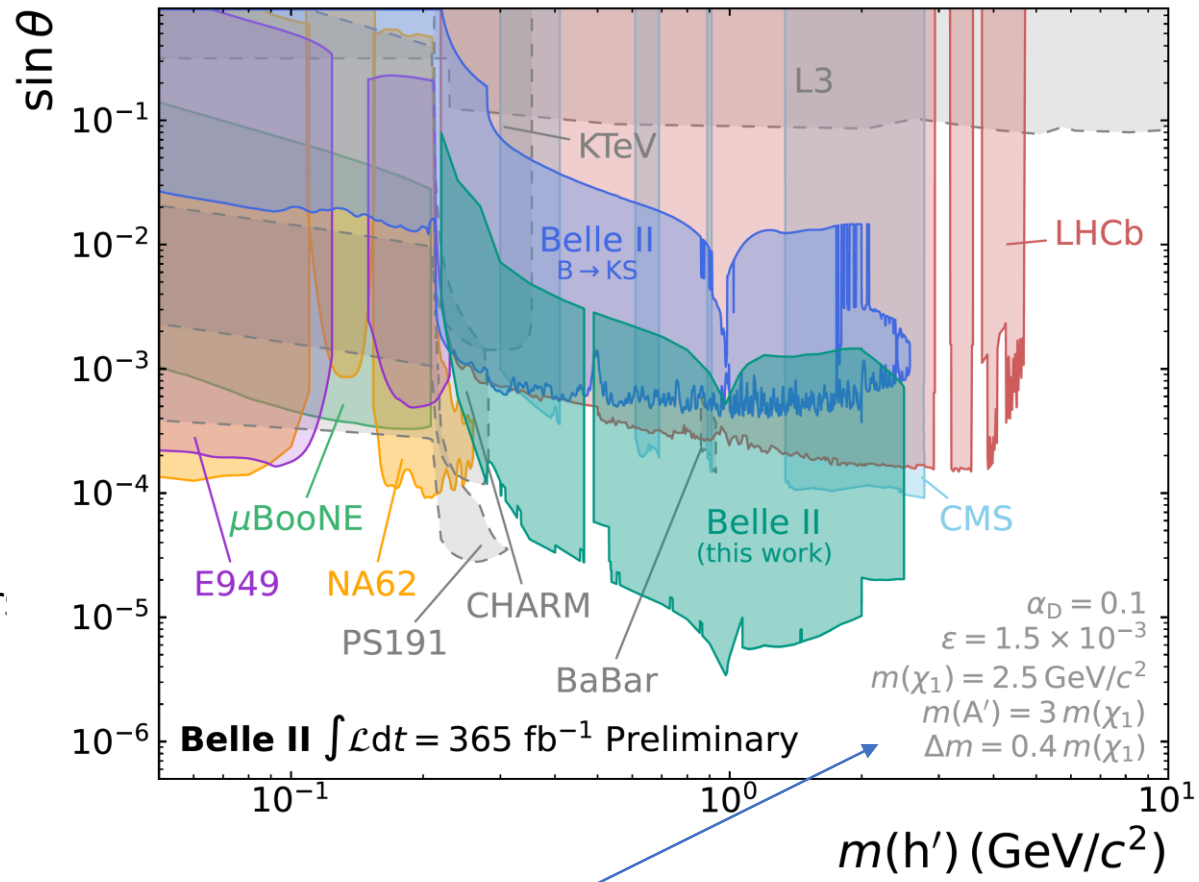
$\chi_2 \to \chi_1 e^+e^-$ only, due to ECL-only trigger

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')-sinθ space** for different values of the other parameter



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

Accepted by PRL
arxiv 2505.09705

Dark sector searches in Belle II: summary and perspectives

✓ Belle II is leading and expected to lead the world sensitivity in many light dark sector searches

Short term

- Align all the searches at least to the full Run 1 luminosity
- Enter the dark photon business: both visible and (especially) invisible

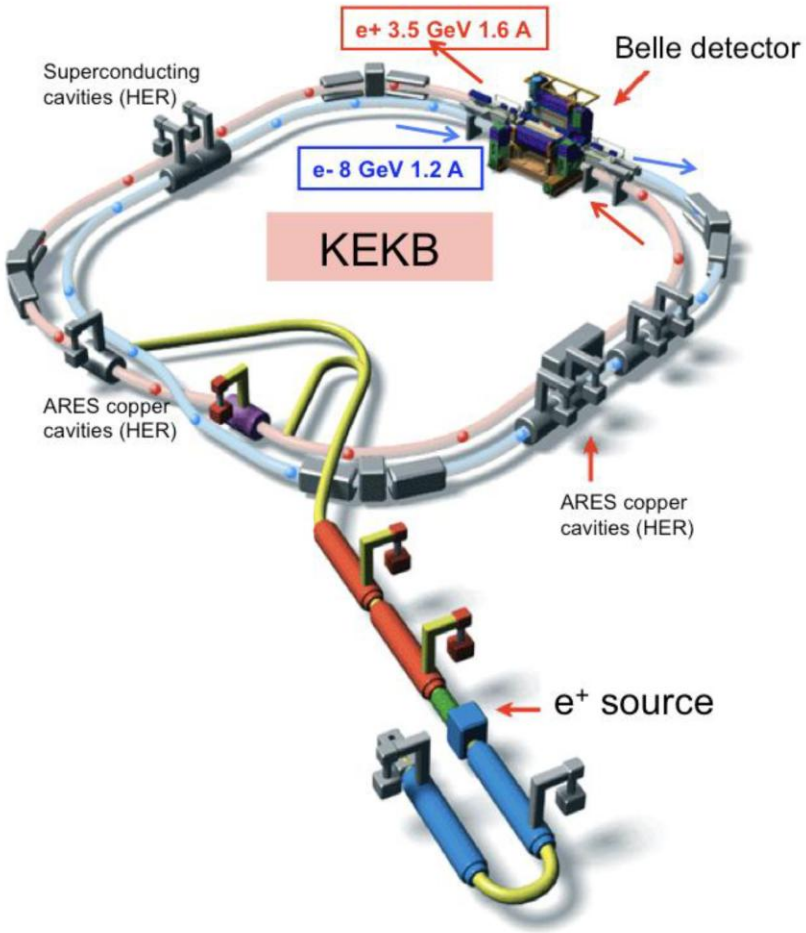
➢ LLP searches will have a considerable weight in the next years (especially with a **new displaced-vtx trigger&tracking**) Low SM background, open the possibility to explore small couplings

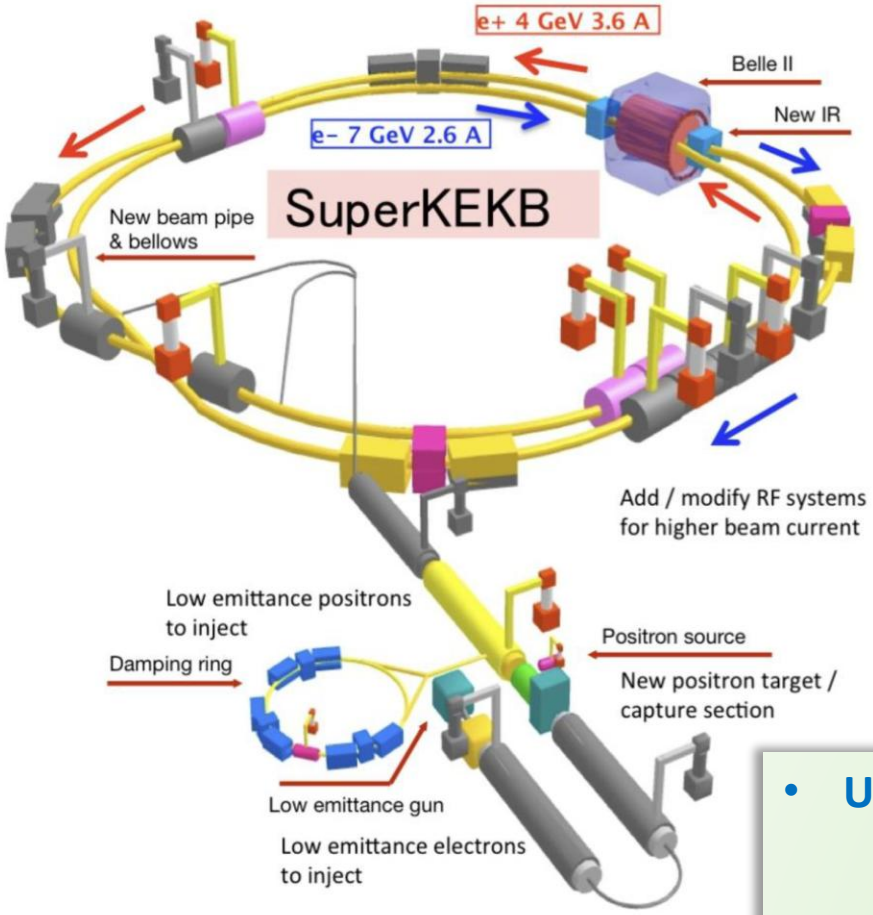
Challenges

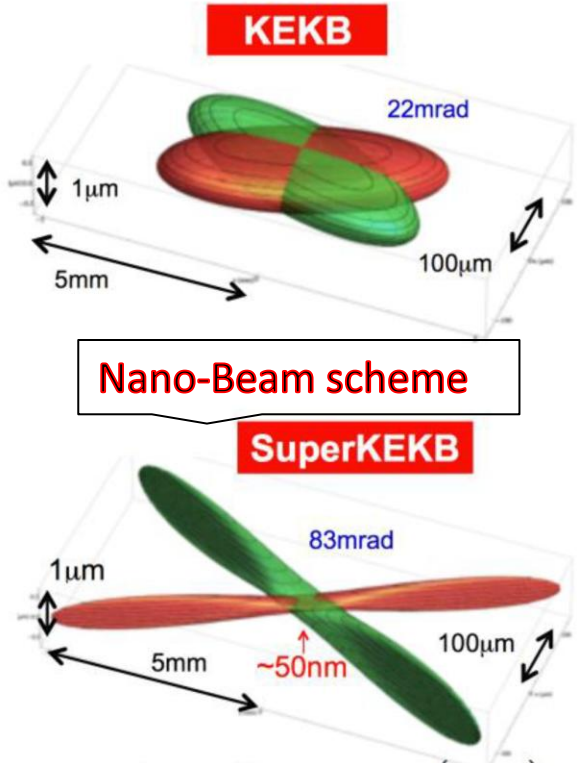
❑ Luminosity will increase, background will increase as well
❑ Best effort to keep the single-object (track, muon, photon) trigger lines in working conditions
❑ Displaced-vertex trigger&tracking needed (efficiency decreases abruptly with lifetime): in preparation

SPARE SLIDES

From KEKB to SuperKEKB







- moderately increased beam currents
- Squeeze beams @IP by ~1/20

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

x20 x30

From KEKB to SuperKEKB

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

Beam-beam parameter

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

Lorentz factor

Beam current

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

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

Classical electron radius

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

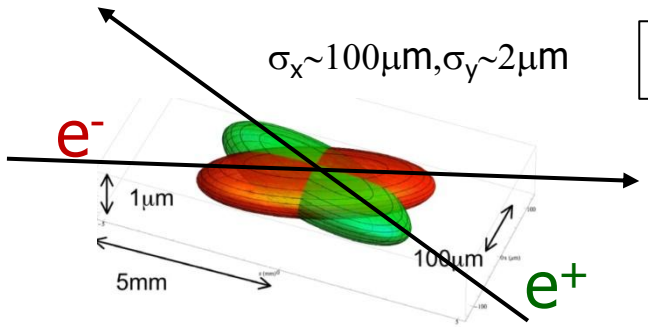
Vertical beta function@IP

x30

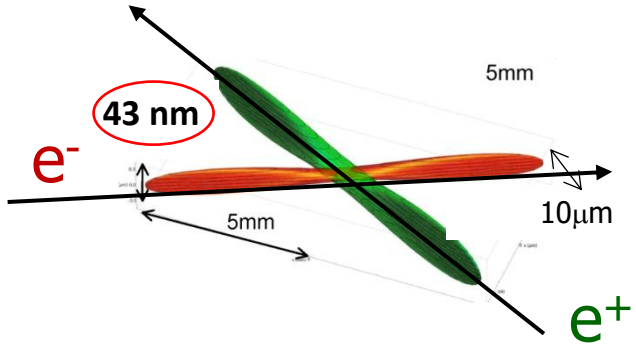
(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

β^*_y=0.30/0.30 mm

$I_{+/-}$=2.8/2.0 A

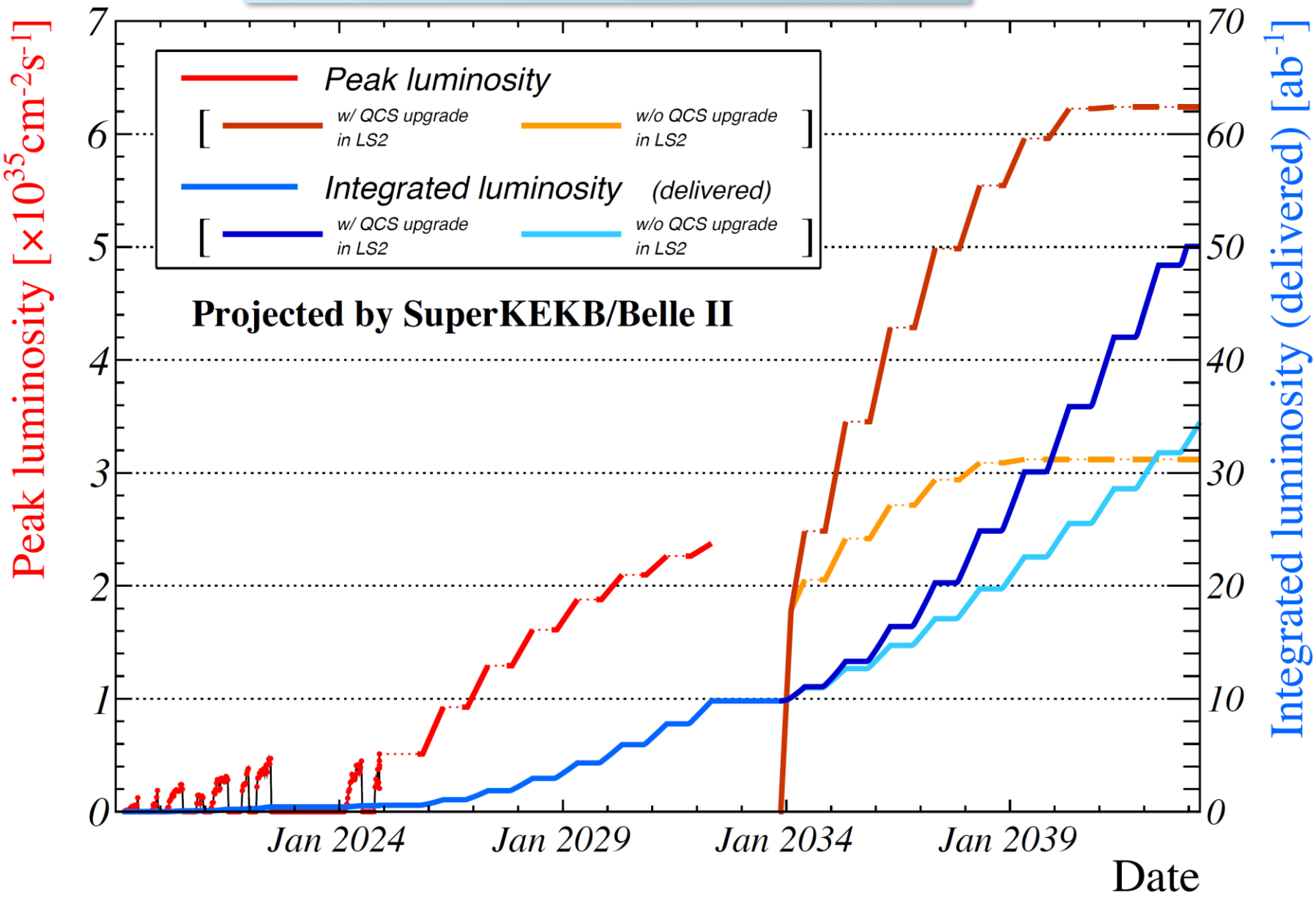


Nano-Beam scheme



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

Luminosity projections



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

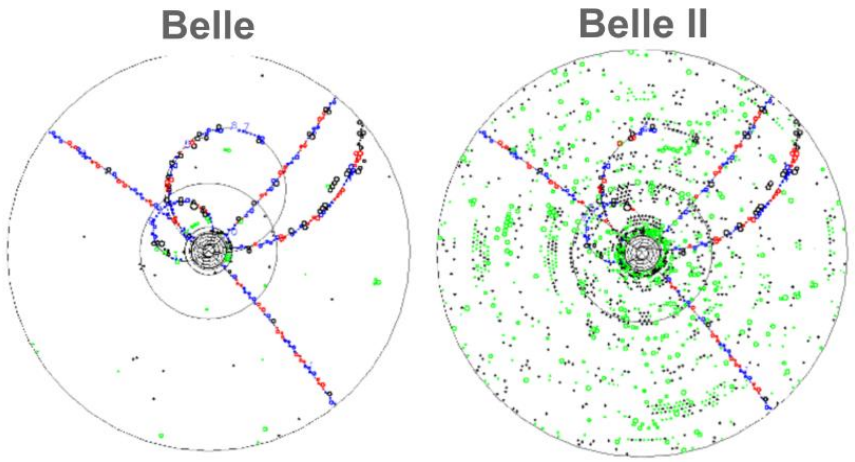
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

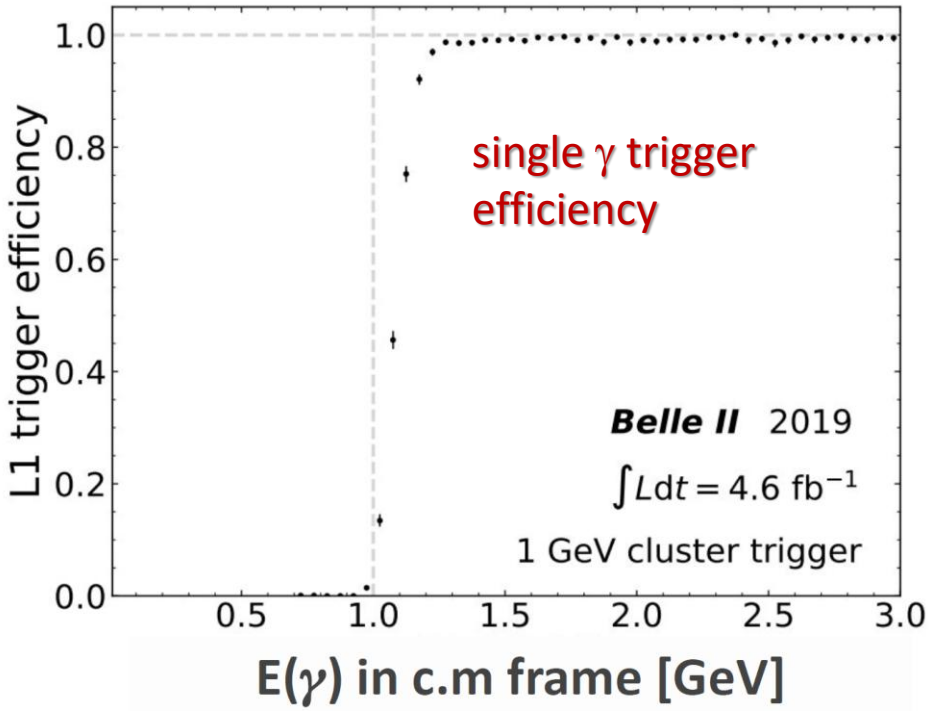
Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

Displaced-vertex trigger
- Under study





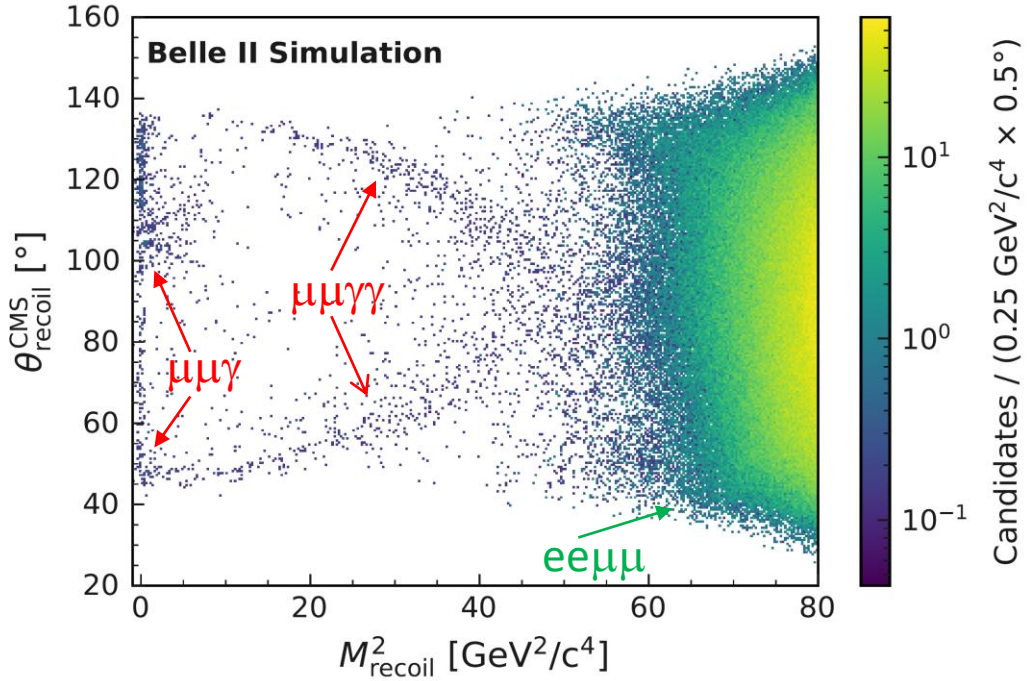
Z’ to invisible: analysis

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

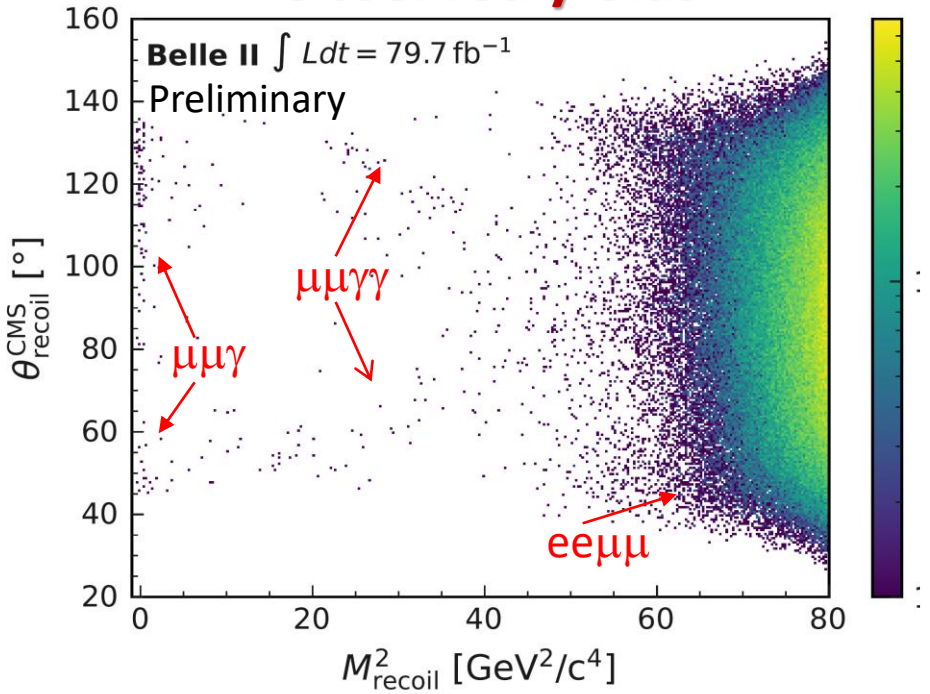
3 control samples

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

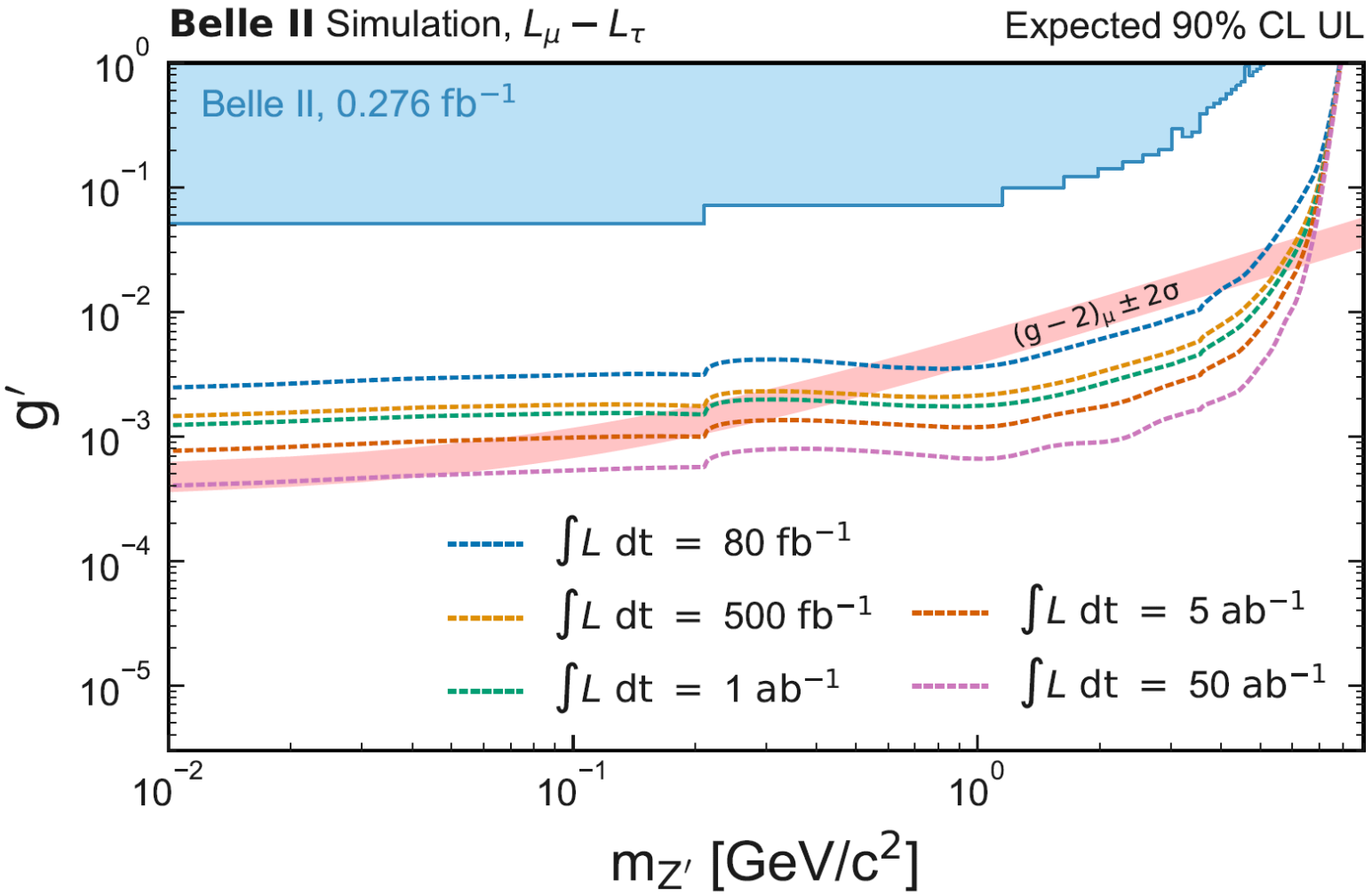
Look for bumps in θ_{recoil} vs M^2_{recoil}



Observed yields



Z’ to invisible: luminosity projections



Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

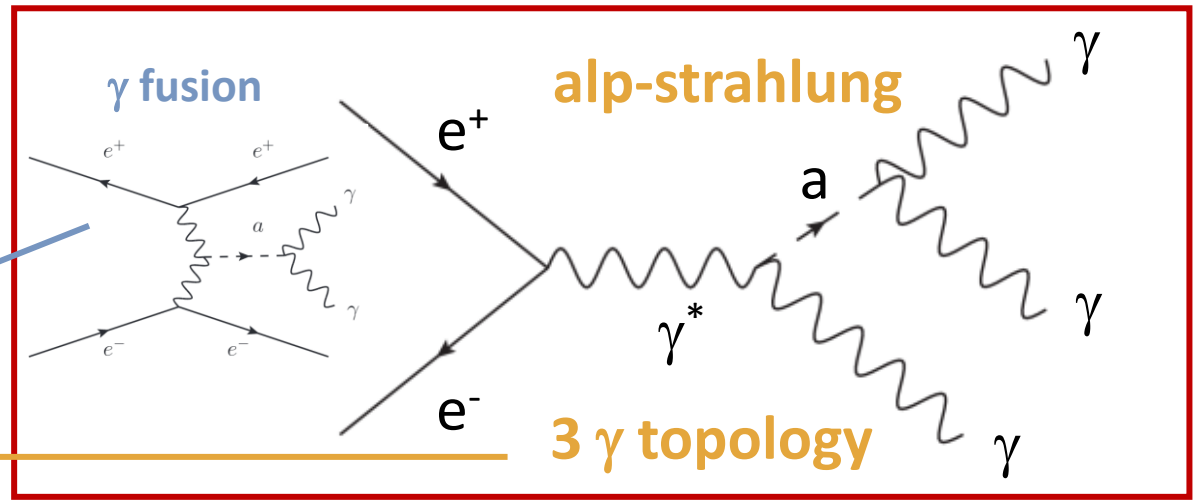
Next update based on Run 1 luminosity almost ready

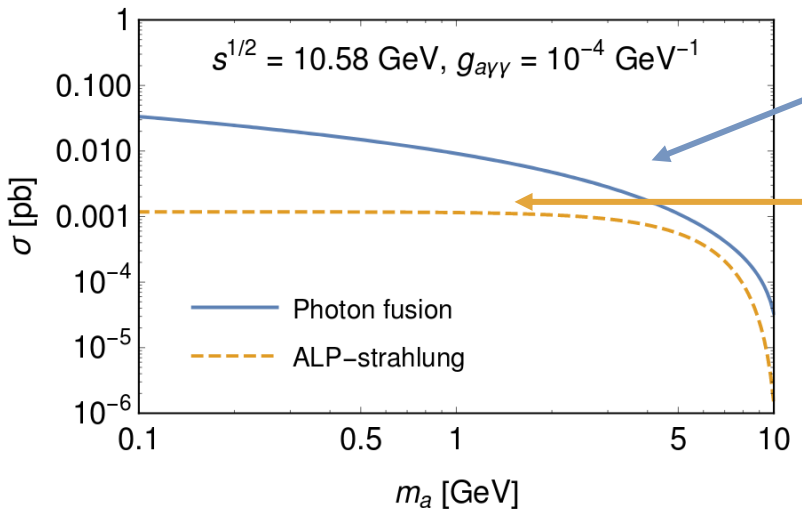
Axion Like Particles (ALPs)

- 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

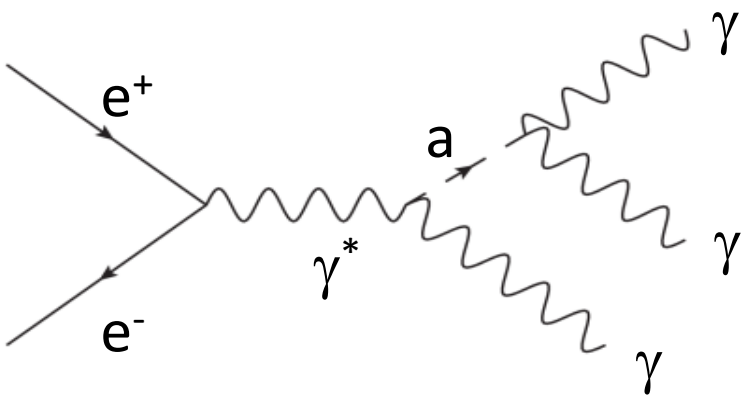
- Focus on coupling to photons: $g_{a\gamma\gamma}$
- **Alp-strahlung** + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$



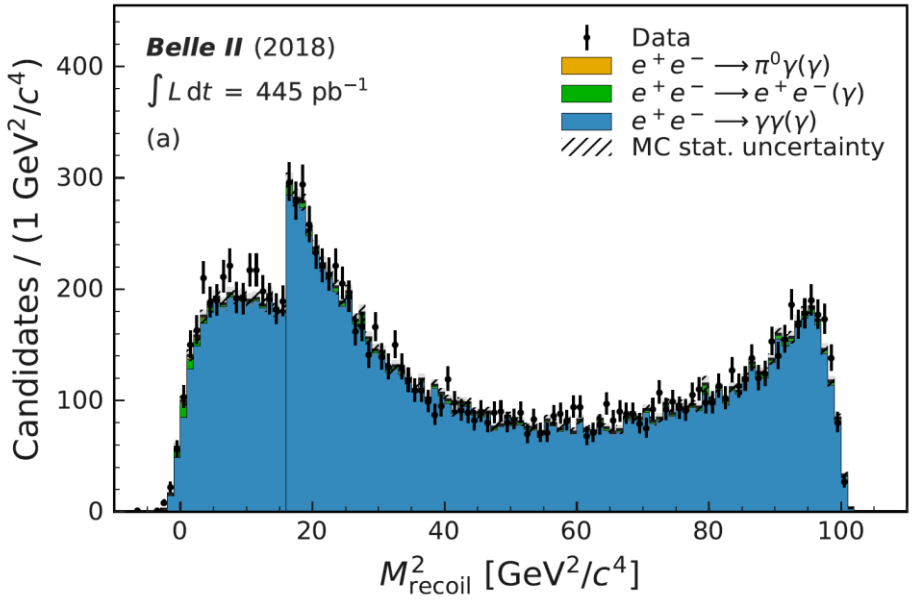


photon fusion sensitivity under study

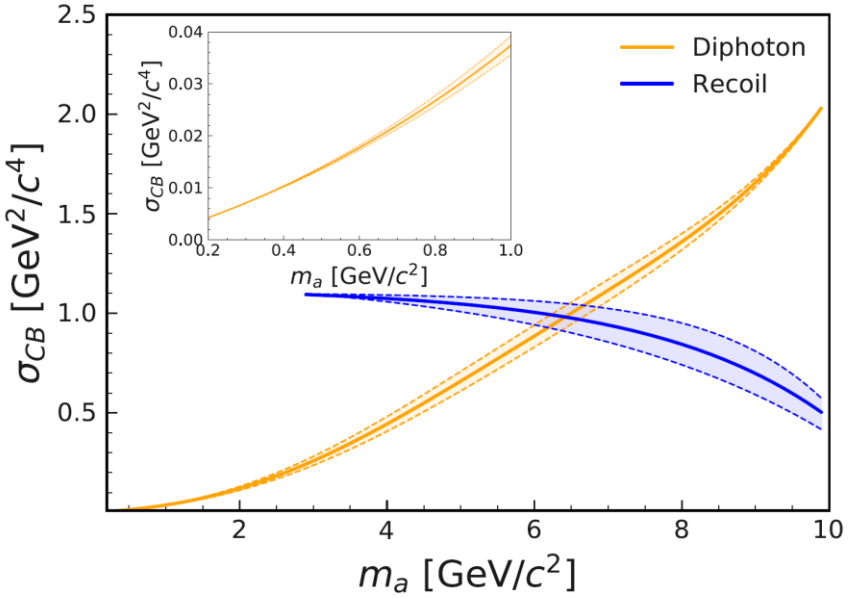
ALP →γγ : observed yields



Pilot run (2018)



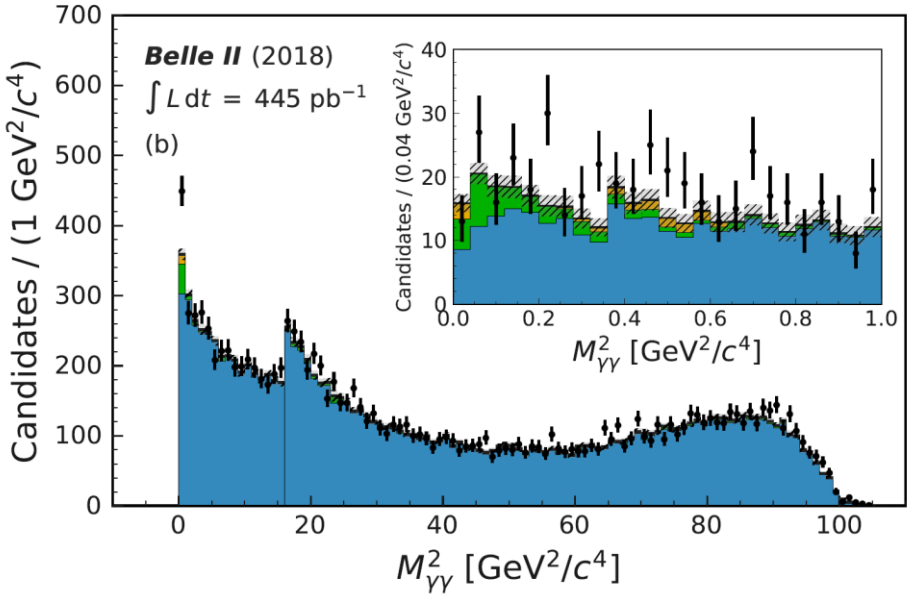
Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)



Main backgrounds:

$e^+e^- \to \gamma\gamma\gamma$

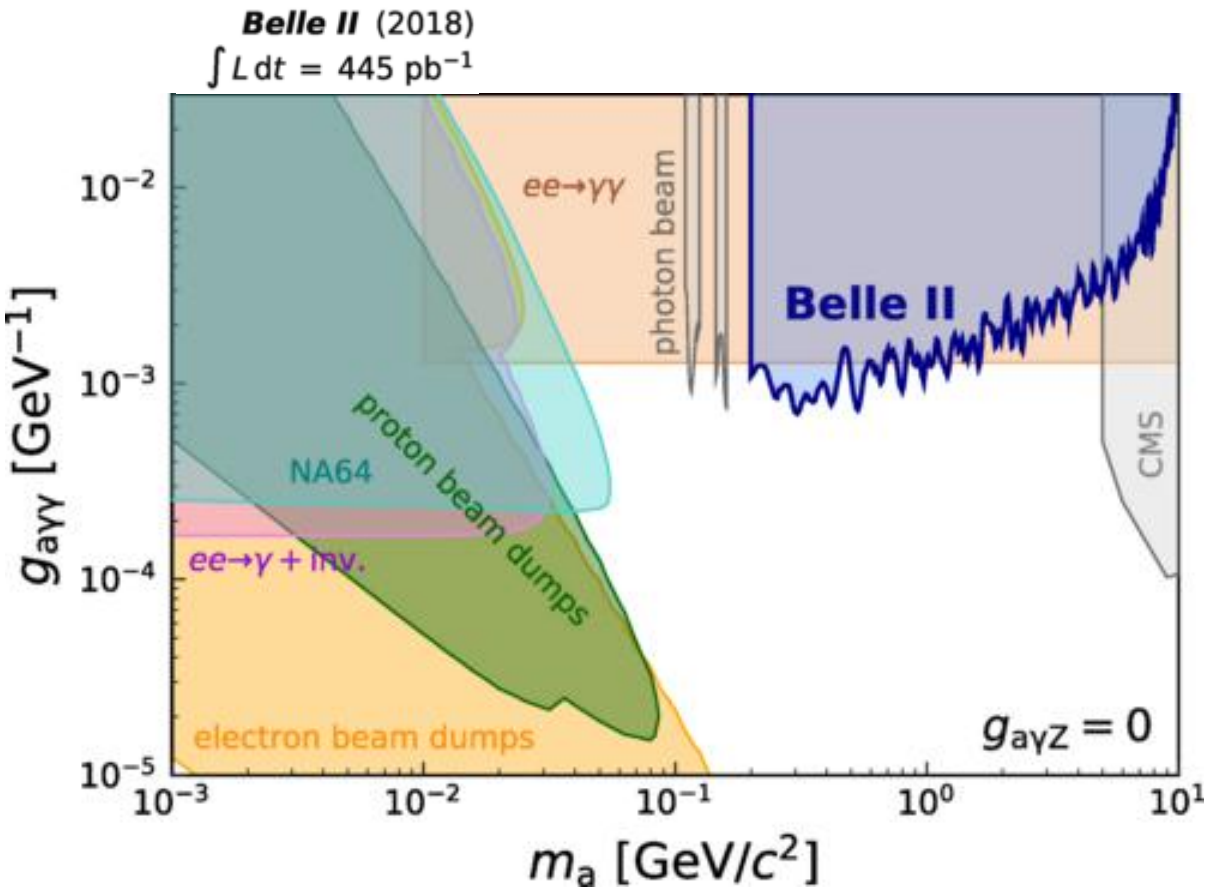
$e^+e^- \to e^+e^-\gamma$

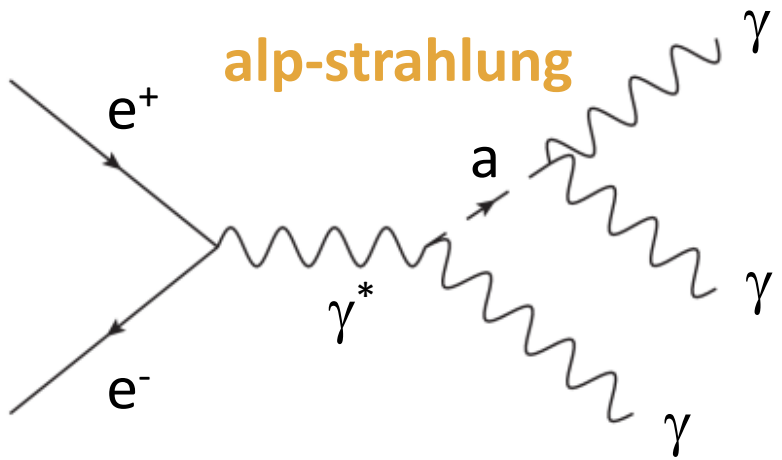


ALP →γγ : results

Axion like particles
ALP→γγ

Pilot run physics results

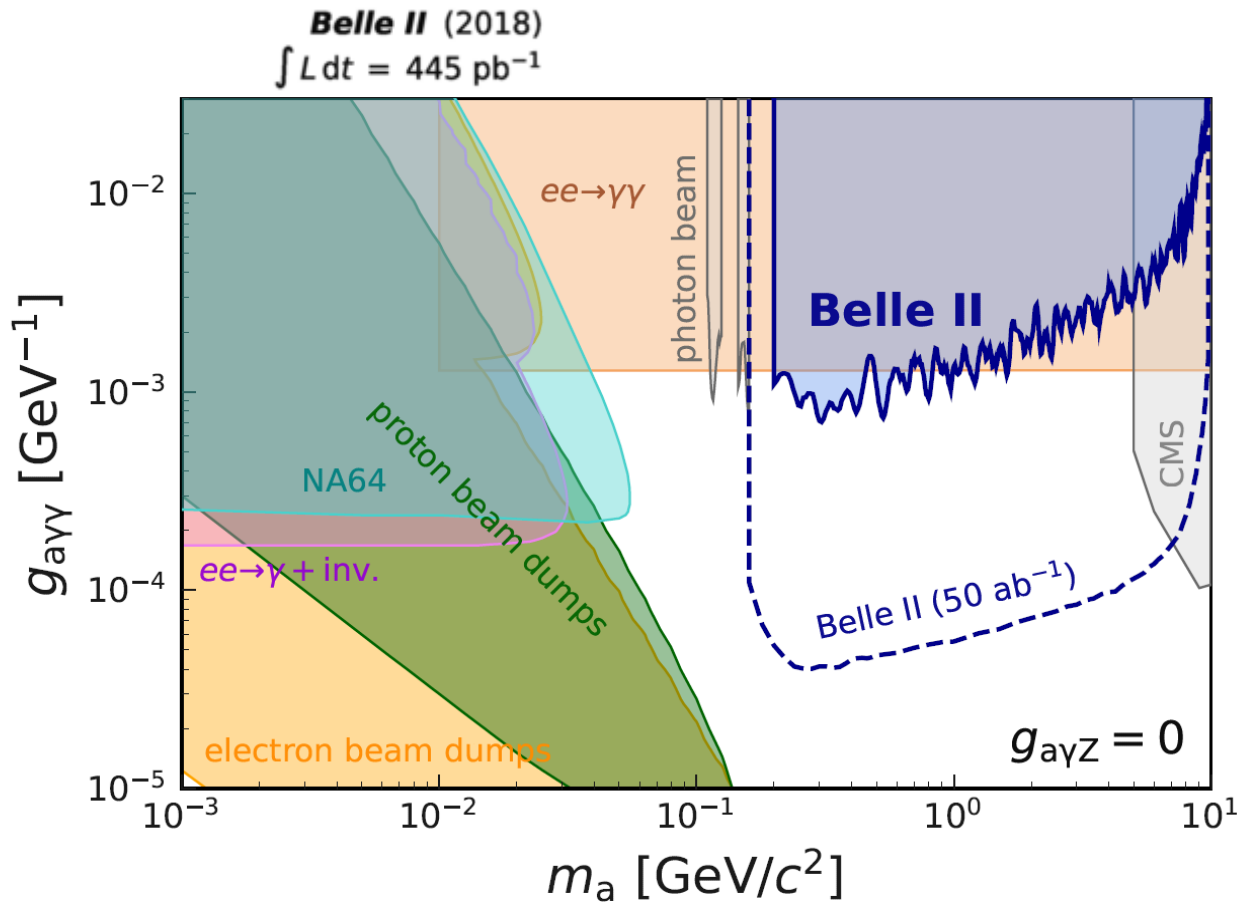


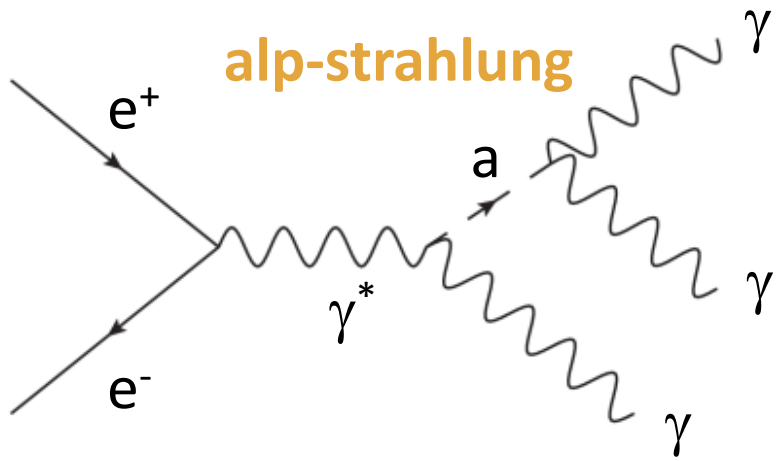


PRL 125, 161806 (2020)

ALP →γγ : luminosity projections

Axion like particles
ALP→γγ





Belle II physics reach @ Snowmass

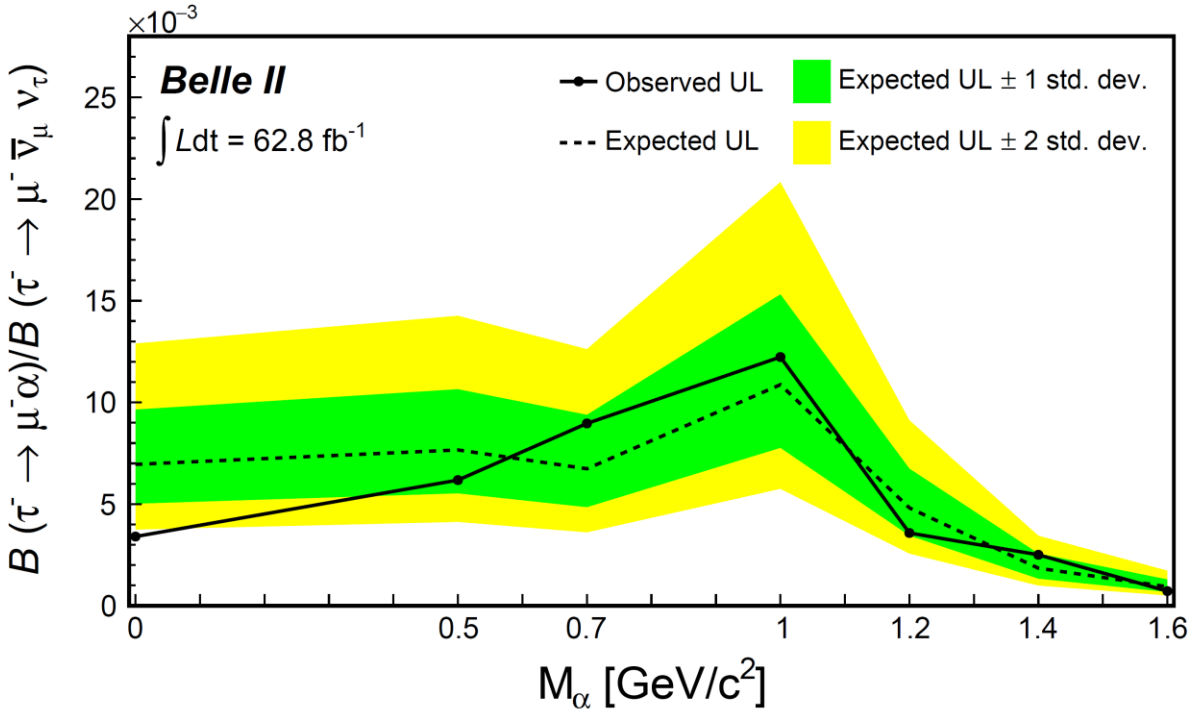
arXiv: 2207.06307v1

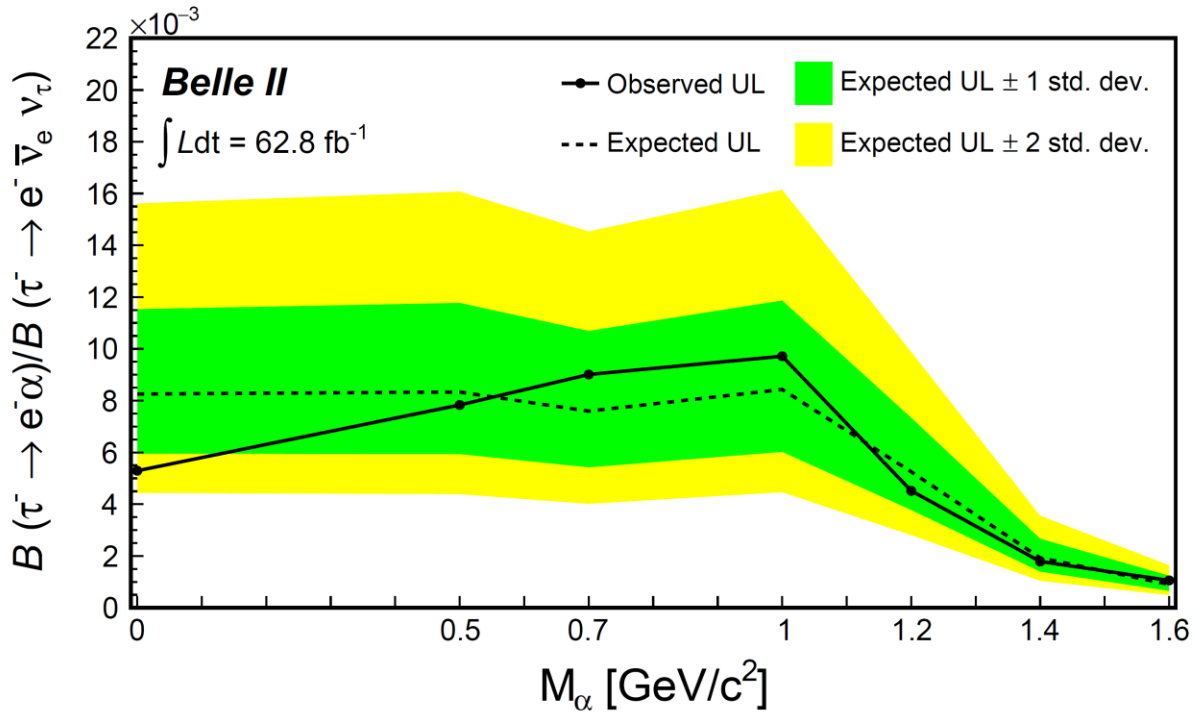
$\tau \to l\alpha$ with invisible α

Invisible α in τ decays
$\tau \to l\alpha$ l=e,μ

LFV, possible ALP candidate

PRL 130, 181803 (2023)





Z', S, ALP → ττ: analysis

63.3 fb^{-1} (2019-2020)

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/c^2
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

Optimize selections for Z' → ττ
99% background reduction

Control sample
2 π + 2x e/μ/π

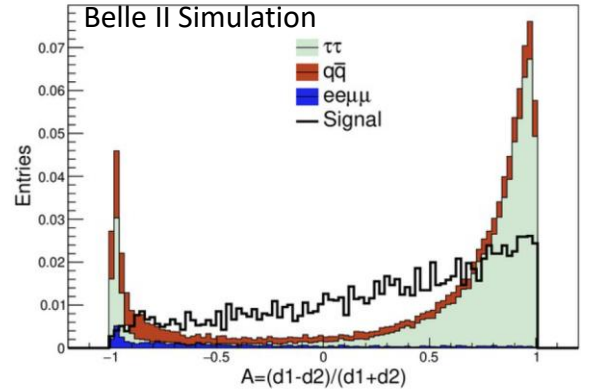
Main backgrounds

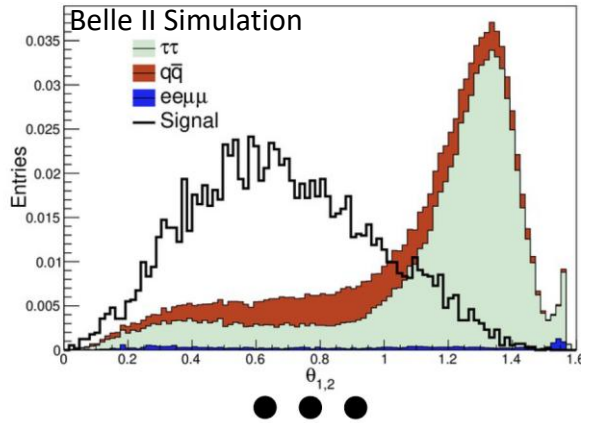
$e^+e^- \to \tau^+\tau^-$ (γ) 1+3 prong
$e^+e^- \to qq$ (q=u,d,s,c)

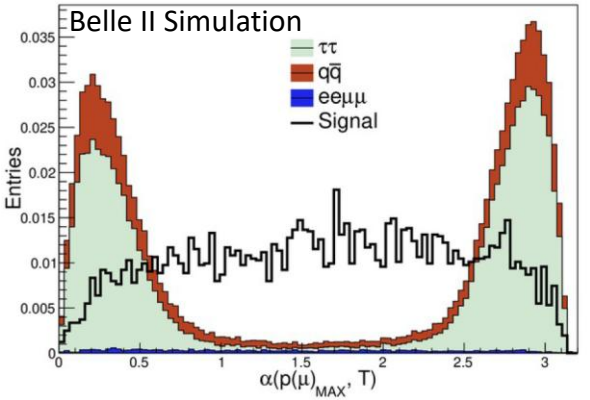
$e^+e^- \to e^+e^- \mu^+\mu^-$
$e^+e^- \to \mu^+\mu^- \tau^+\tau^-$
$e^+e^- \to e^+e^- \tau^+\tau^-$
} no ISR in simulation

$e^+e^- \to \mu^+\mu^-\pi^+\pi^-$ not simulated

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



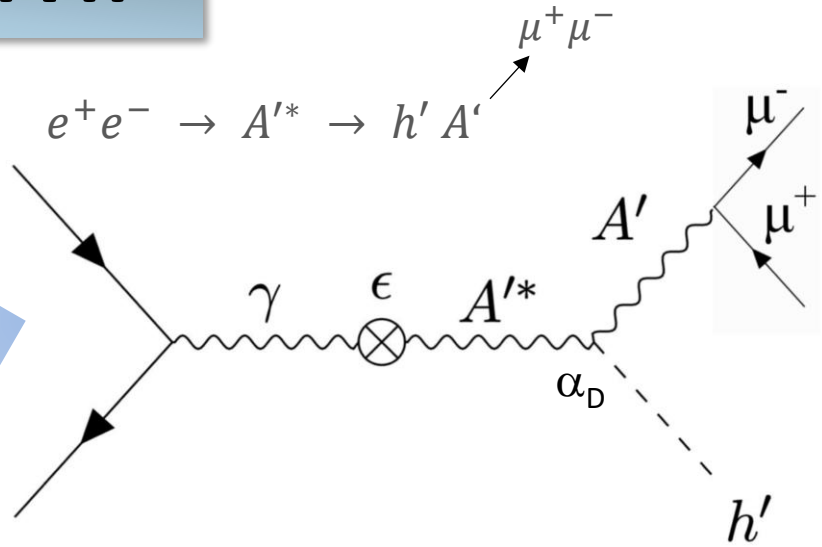




Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

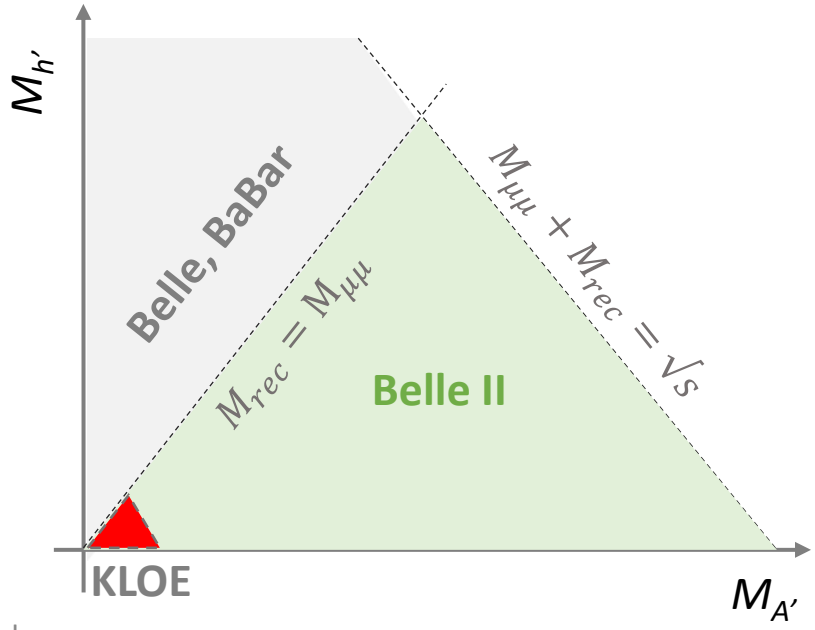
- **Dark photon + dark Higgs**
  - dark Higgs h'
    - gives mass to A' through SSB
    - no mixing of h' with SM Higgs
    - coupling α_D in the dark sector, $\varepsilon^2 \alpha_D$ overall

Phys. Rev D79, 115008 (2009)



$e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*

- **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

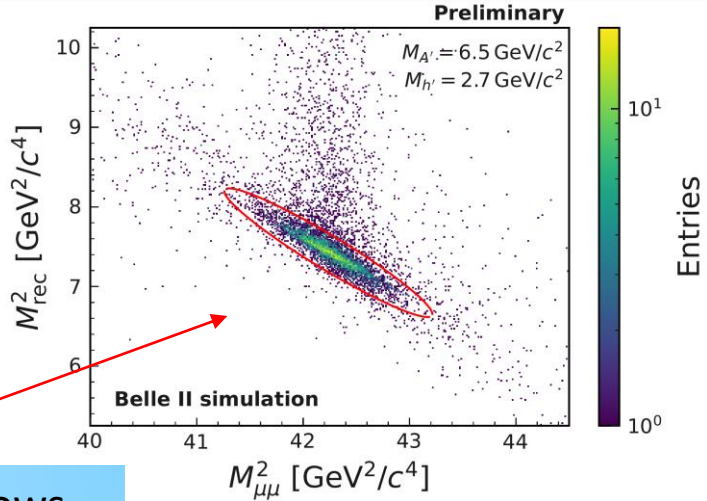


Dark Higgsstrahlung: analysis

Moriond

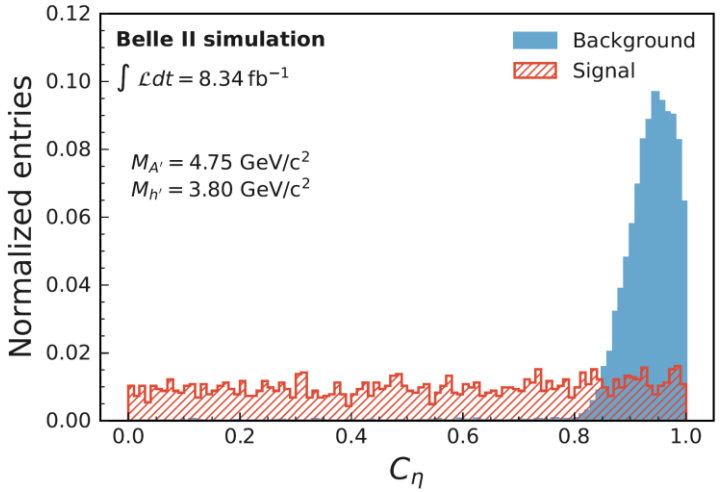
8.34 fb^{-1} (2019)

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

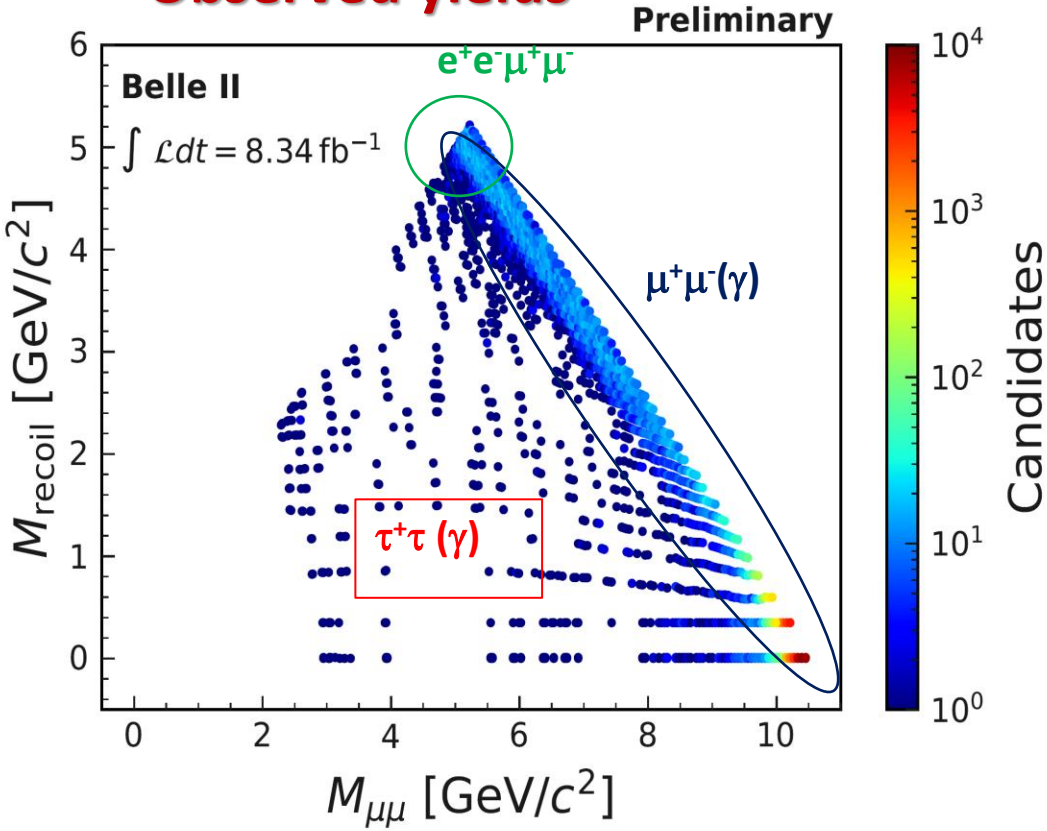
Helicity angle



Backgrounds

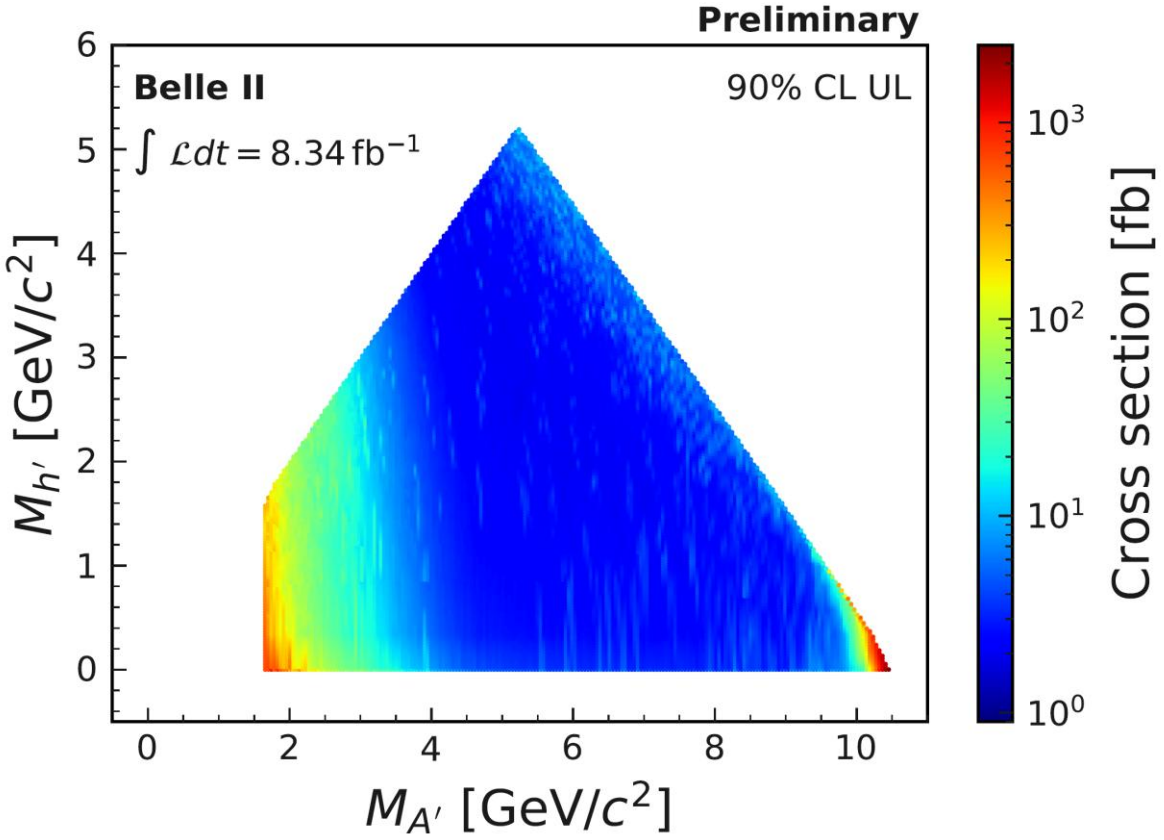
$\mu^+\mu^-(\gamma)$ 79%
$\tau^+\tau\ (\gamma)$ 18%
$e^+e^-\mu^+\mu^-$ 3%

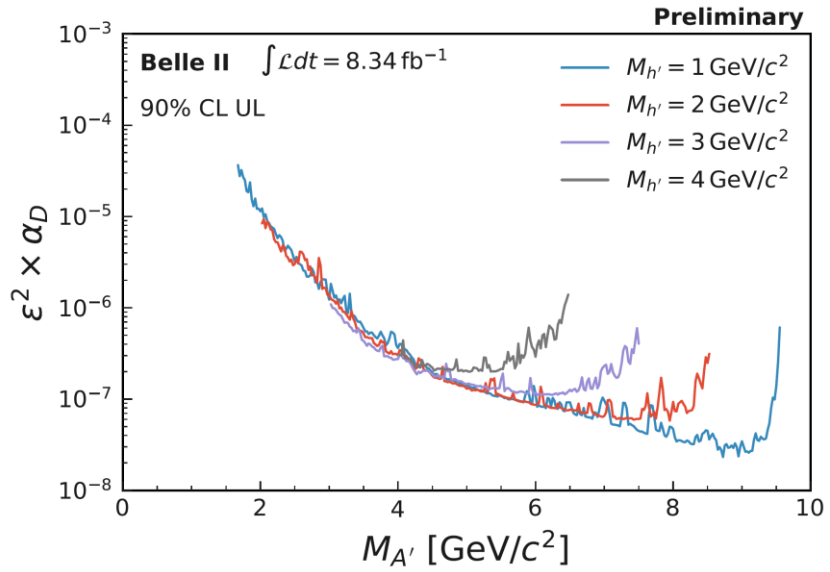
Observed yields

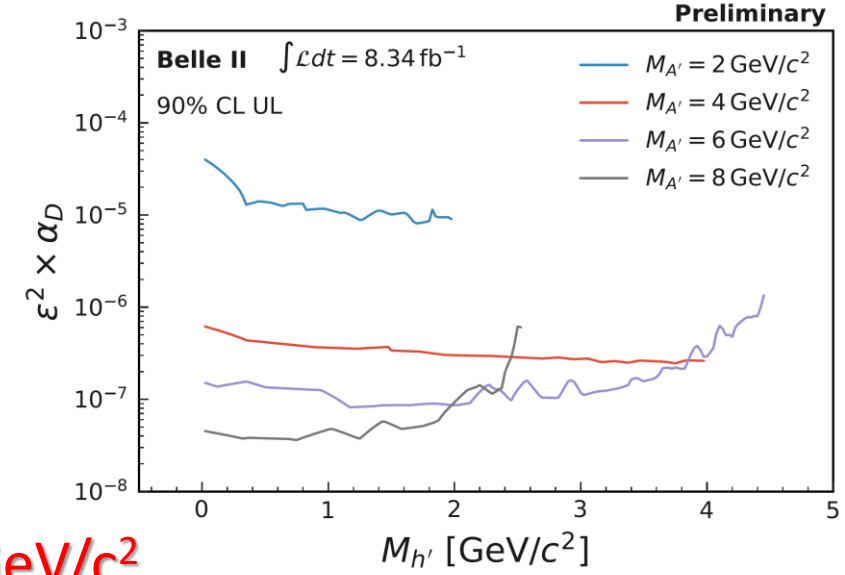


Dark Higgsstrahlung: results

No excess found
Upper limits on σ and $\varepsilon^2 \alpha_D$
most sensitive for $4 < M_{A'} < 9.7$ GeV/c^2



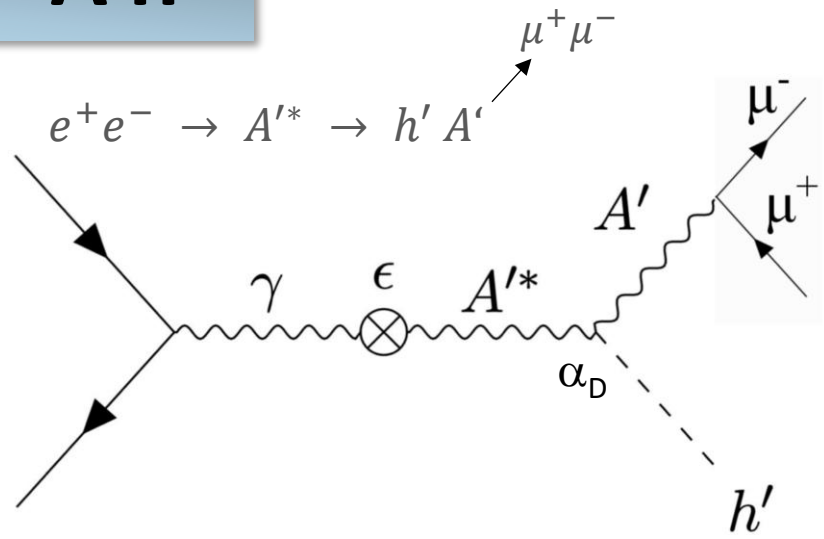


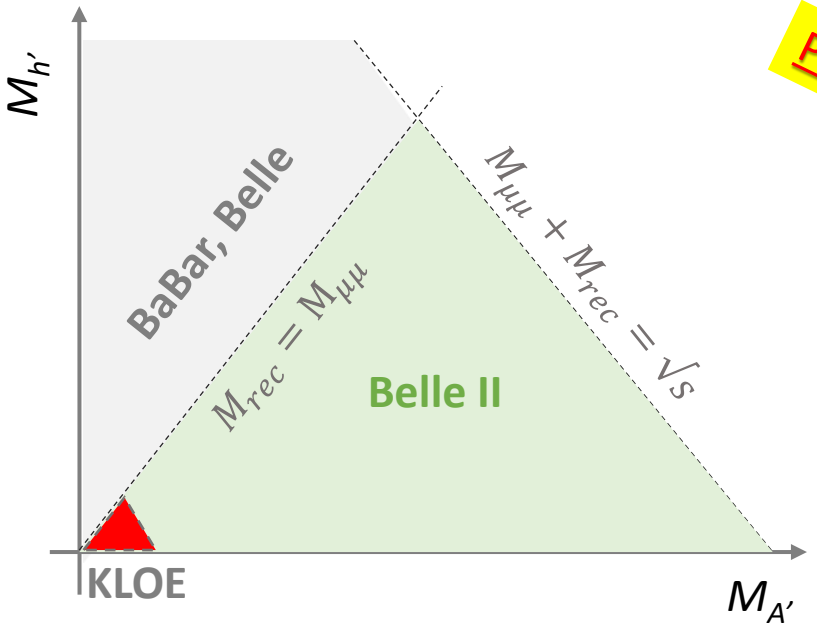


World first for $1.65 < M_{A'} < 10.51$ GeV/c^2

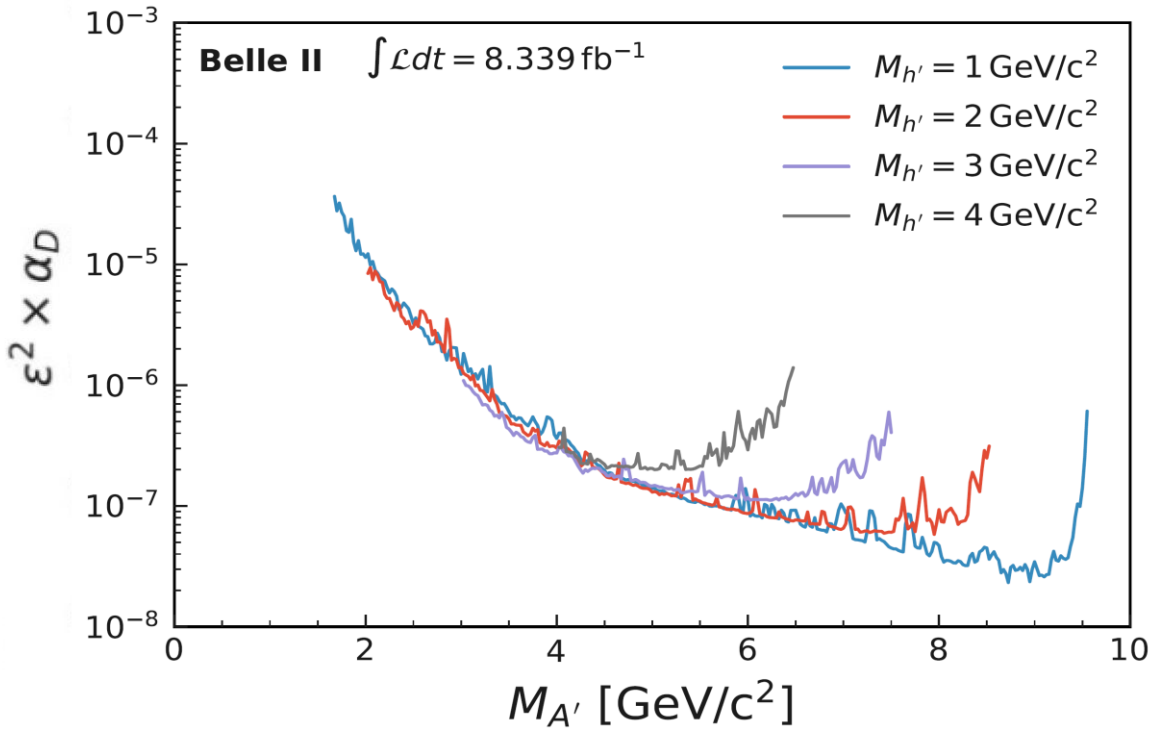
Dark Higgsstrahlung: $e^+e^-\rightarrow A'h'$

Dark Higgsstrahlung
A'h' A'→μμ, h' invisibile



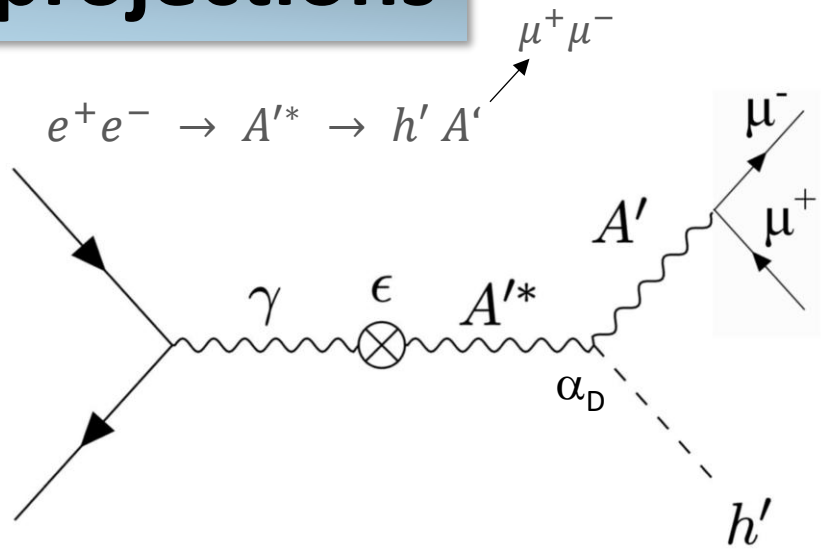


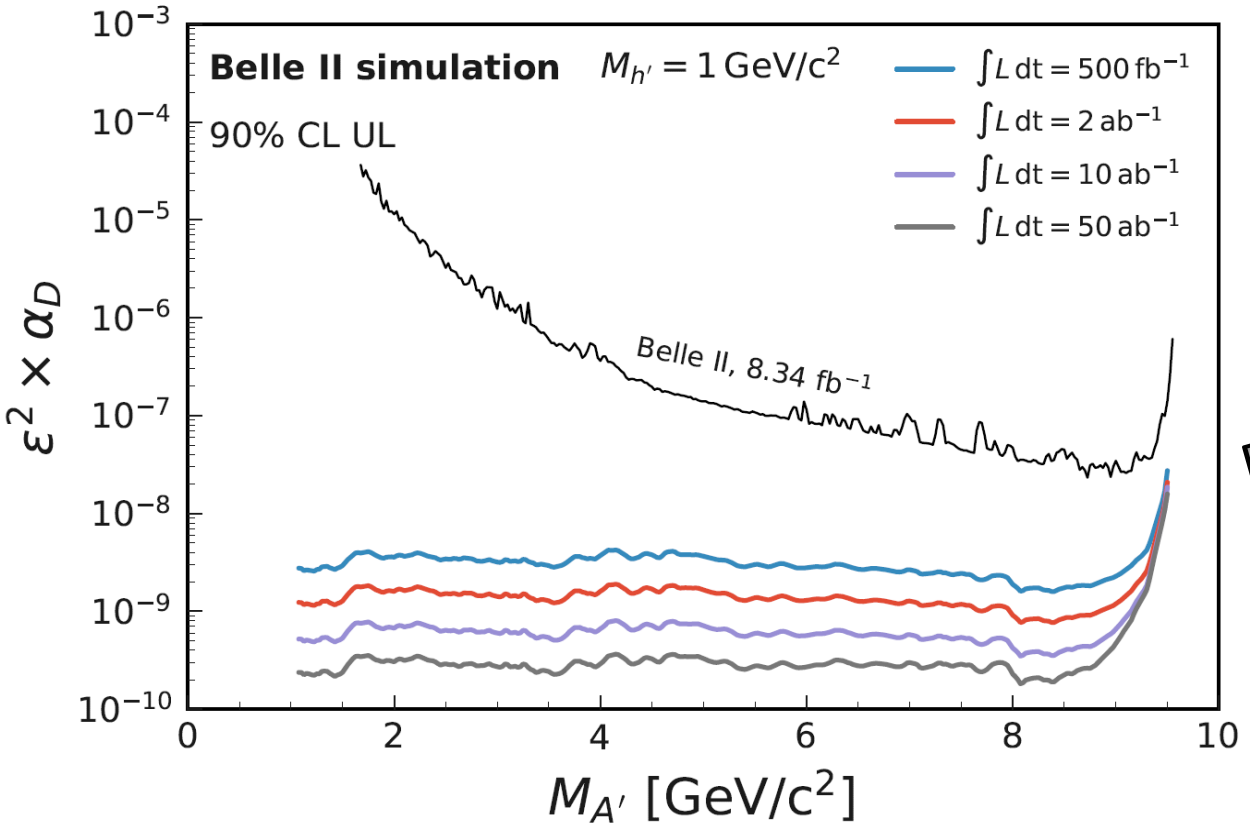
PRL 130, 071804 (2023)



Dark Higgsstrahlung: luminosity projections

Dark Higgsstrahlung
A'h' A'→μμ, h' invisibile





Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

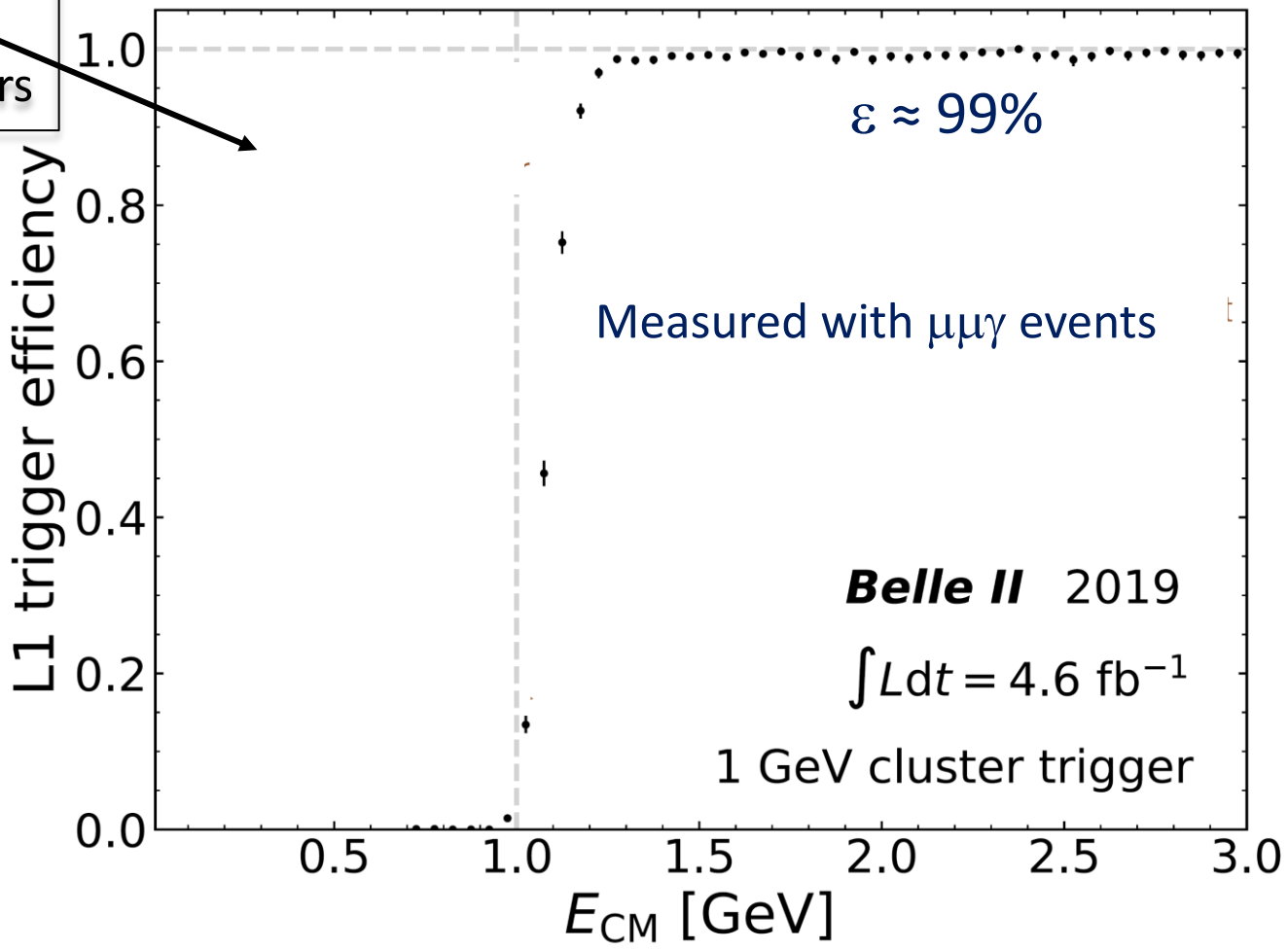
Next update based on Run 1 luminosity in progress

Invisible dark photon: single photon trigger

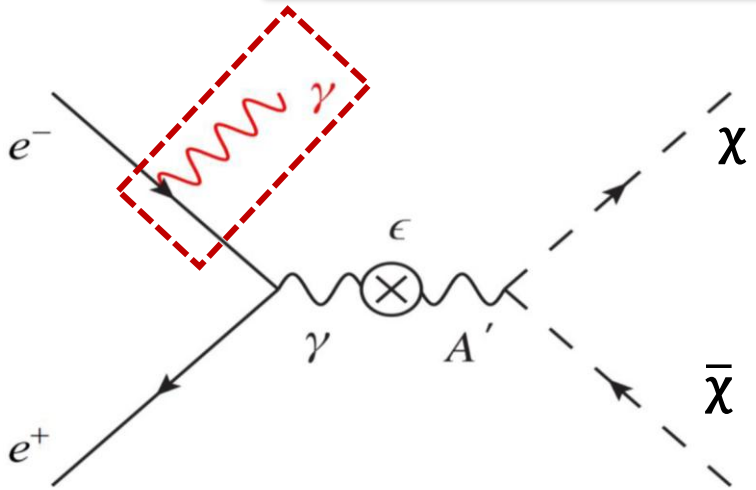
- E_{CM} > 2 GeV
- E_{CM} > 1 GeV in barrel + no other clusters
- E_{CM} > 0.5 GeV in central barrel + no other clusters

Would extend the search range up to $M_{A'}$<≈10 GeV (psycological 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, ≈ 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

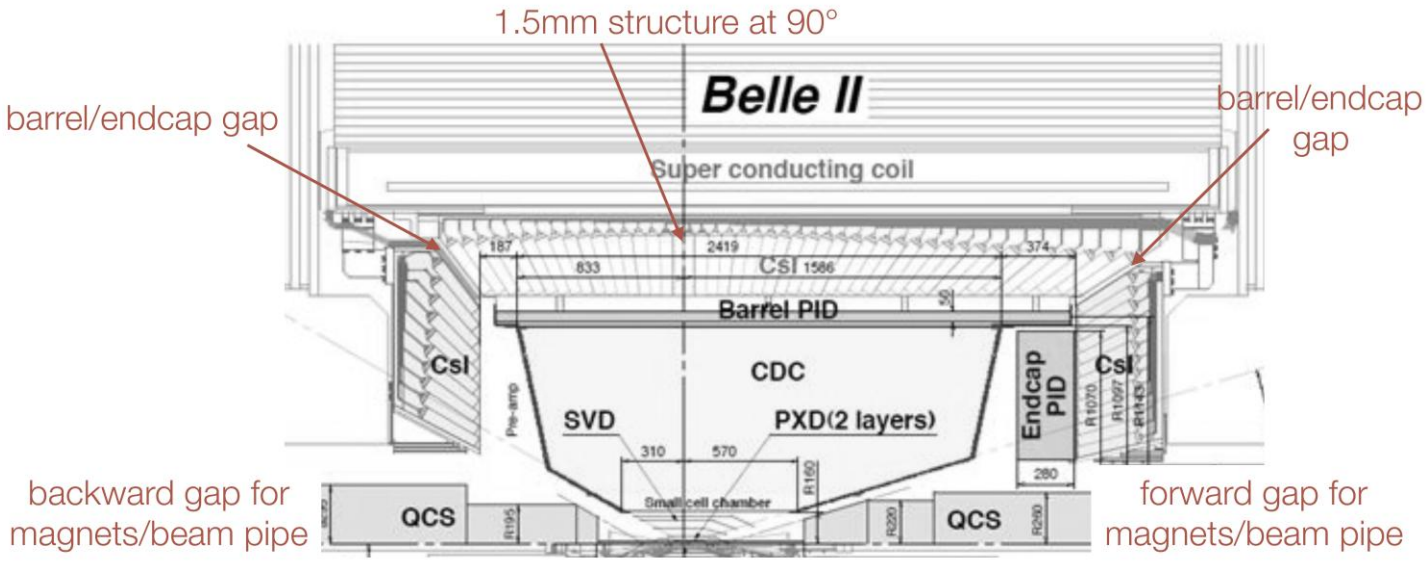
Backgrounds

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

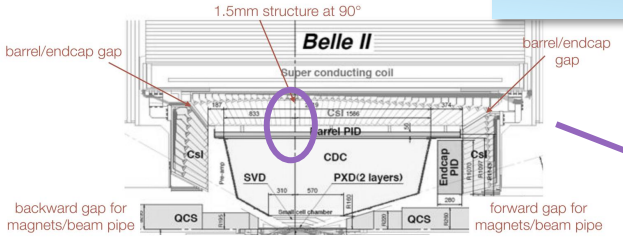
$e^+e^- \to \gamma\gamma(\gamma)$ → low $M_{A'}$ region

Cosmics

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



Invisible dark photon: background

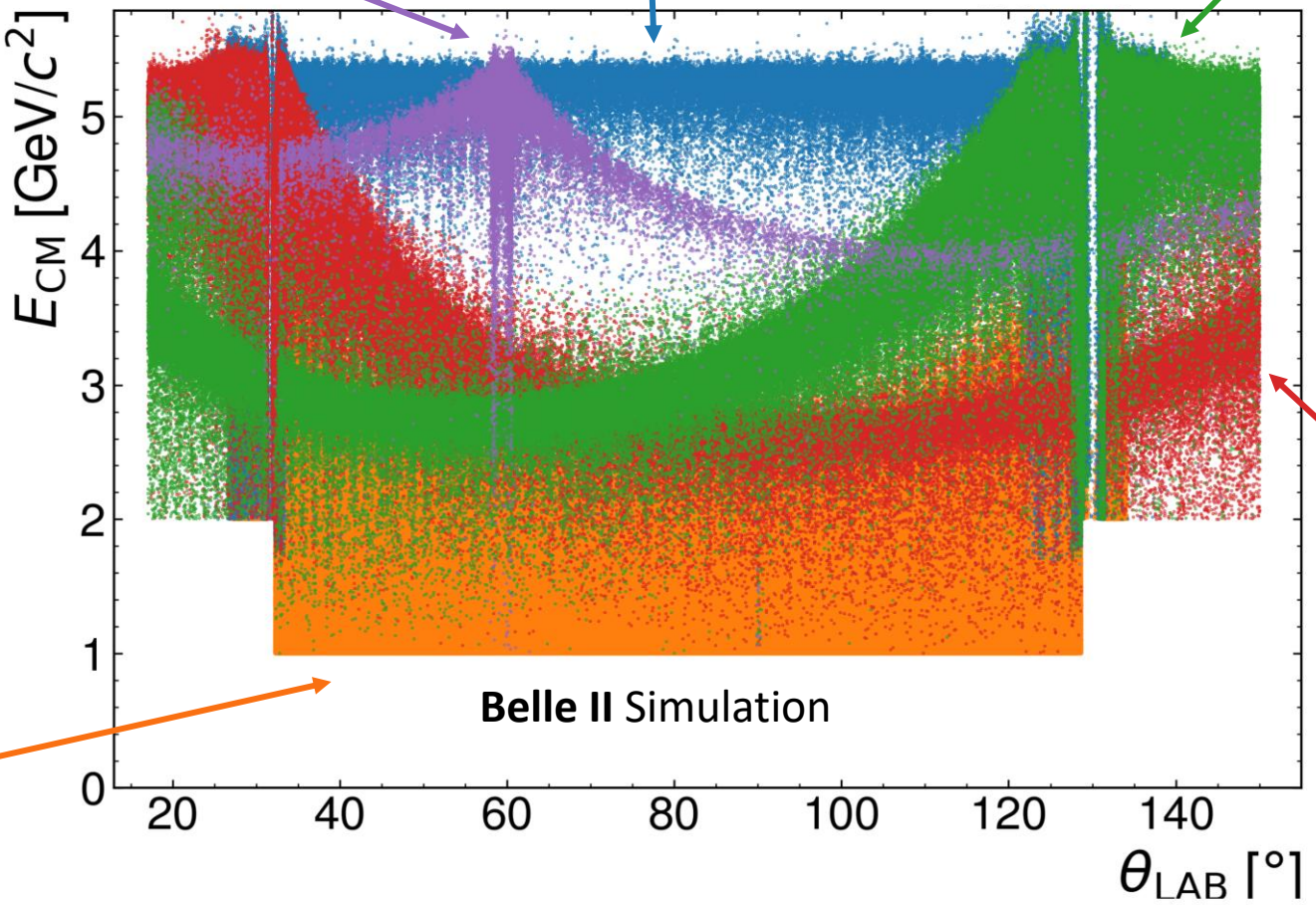


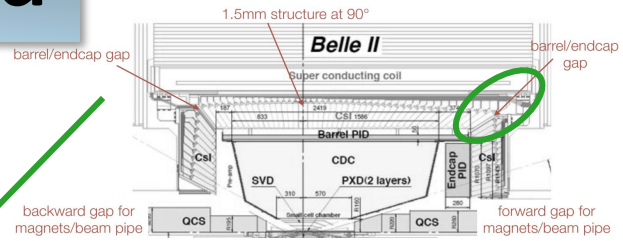
$e^+e^- \to \gamma\gamma\gamma$

1 γ in 90^0 gap

1 γ out of ECL acceptance

$e^+e^- \to \gamma\gamma$





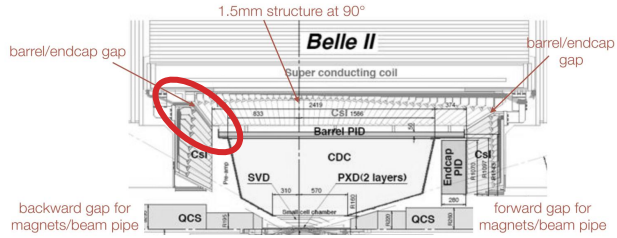
$e^+e^- \to \gamma\gamma\gamma$

1 γ in FWD gap

1 γ out of ECL acceptance

$e^+e^- \to \gamma\gamma\gamma$

2 γ out of ECL acceptance



$e^+e^- \to \gamma\gamma\gamma$

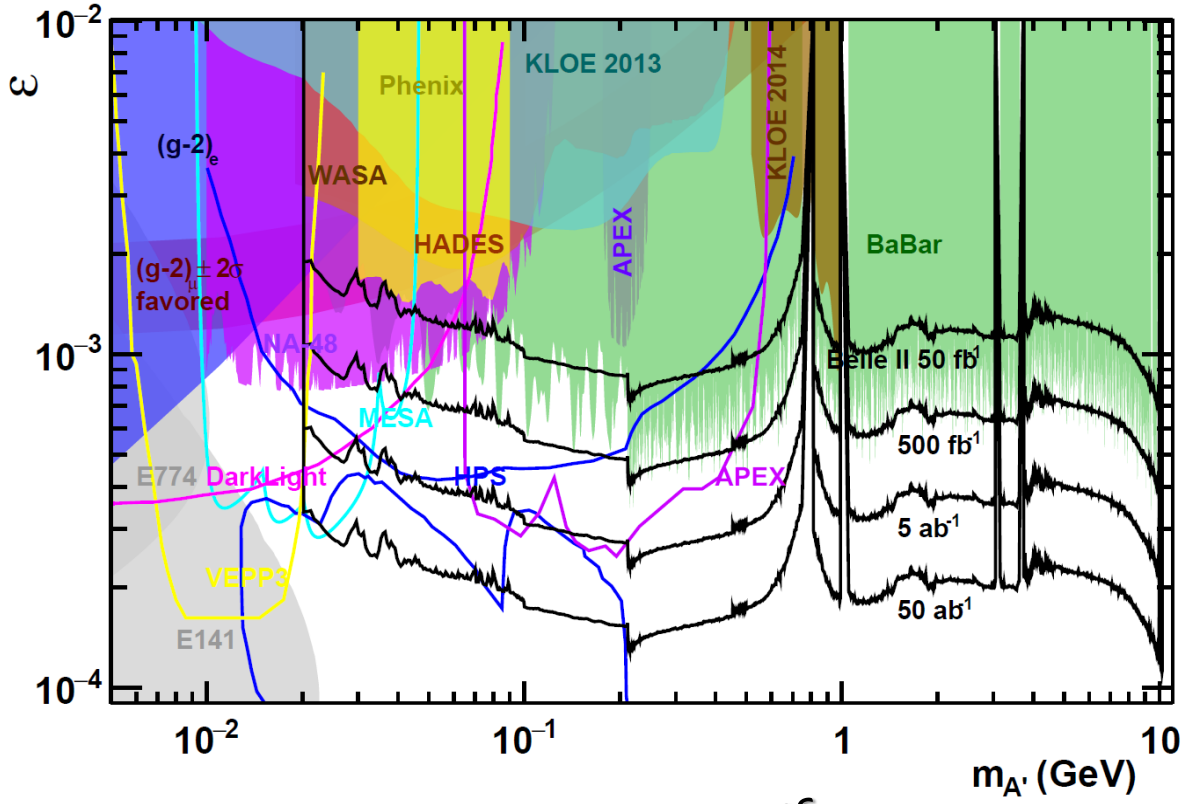
1 γ in BWD gap

1 γ out of ECL acceptance

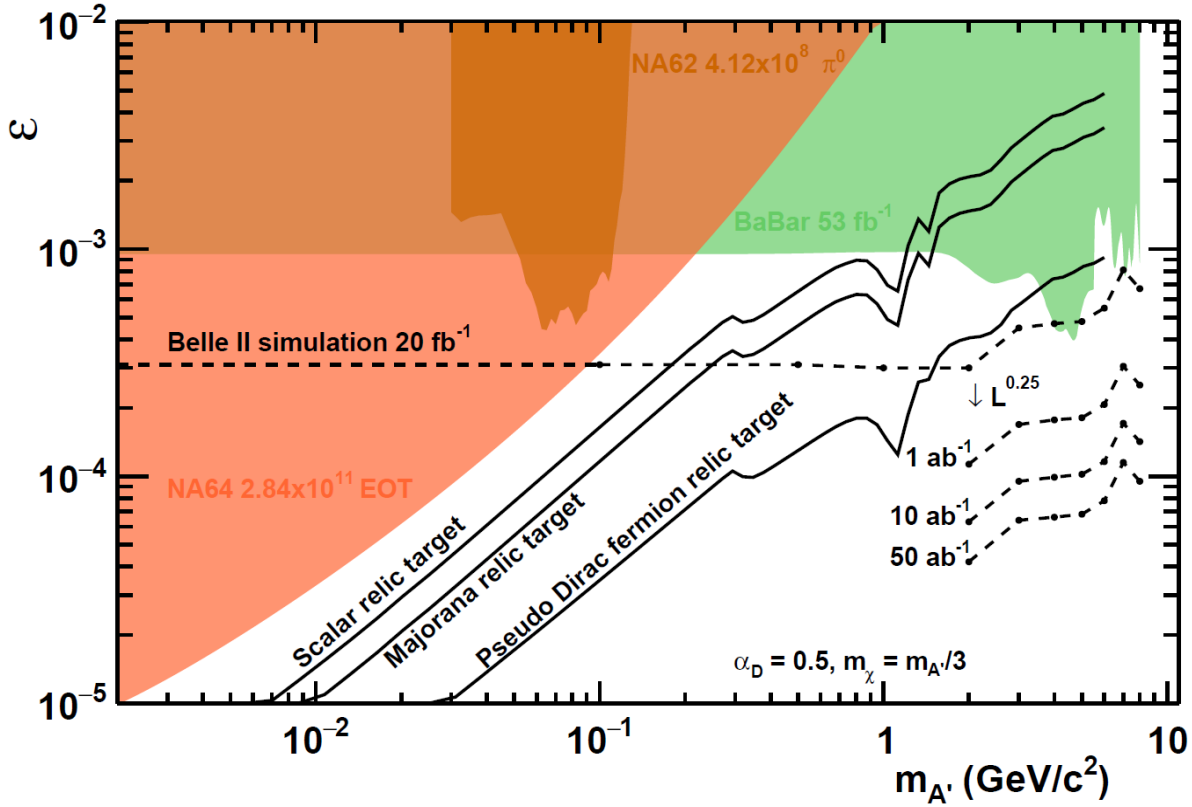
Crucial usage of KLM to veto photons in ECL gaps

Dark photon: luminosity projections

Visible



Invisible



Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

Belle II vs BaBar

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