Low-mass new particle searches at e^+e^- colliders

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INFN – Roma 3

on behalf of the Belle II Collaboration

OUTLINE

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

Why searching today for new low-mass particles?

Dark Matter

- DM candidates at MeV-GeV scale require light mediators ←

Naturalness

- Breaking of high-energy global symmetries often imply light Goldstone bosons: ALP ←

Strong CP problem

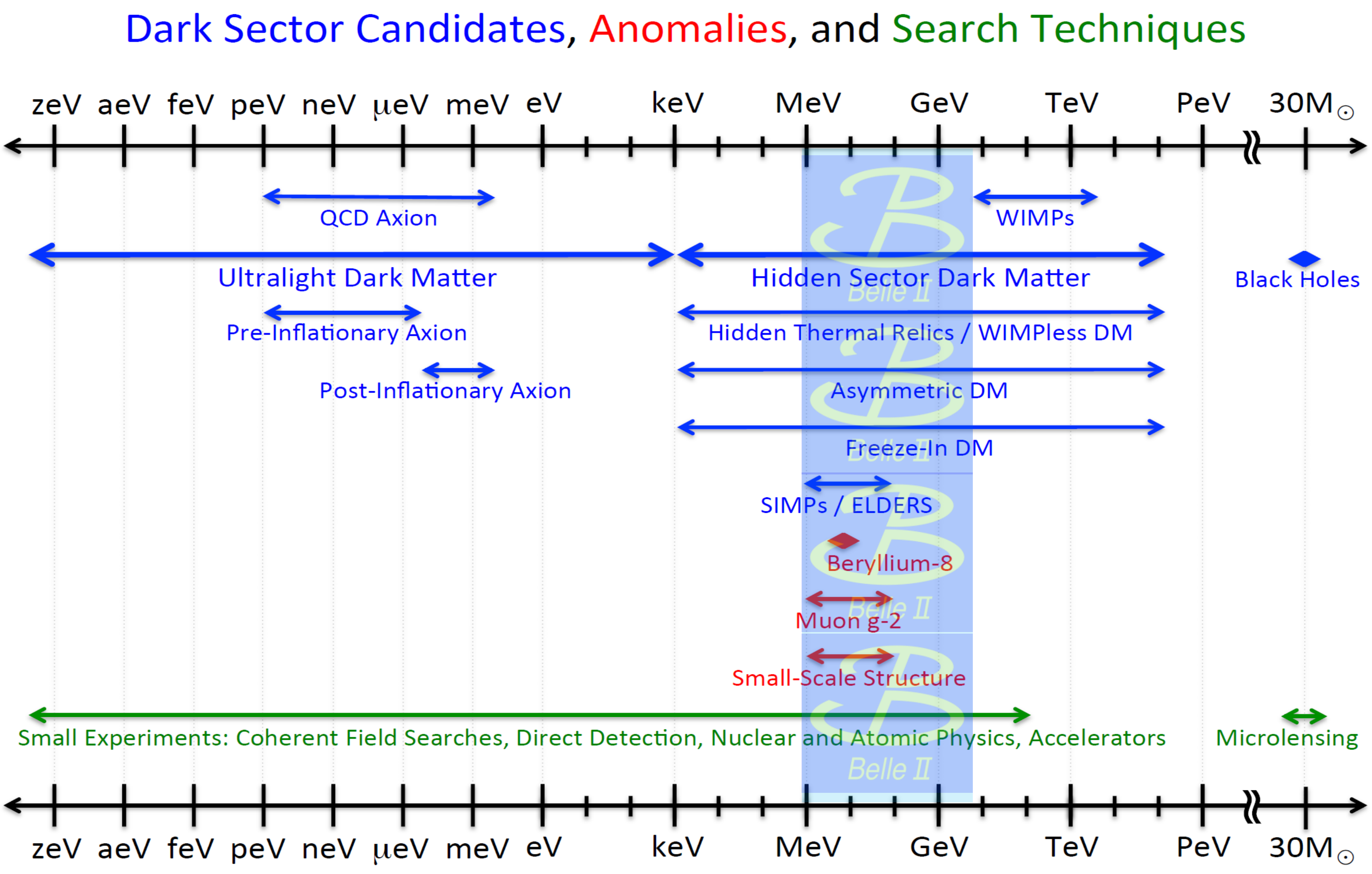
- QCD axion (Goldstone boson)

Neutrino masses and oscillations

- Right handed neutrinos, sterile neutrinos, …

Not exhaustive list

Searching for dark matter



Dark matter/mediators

Vector portal

Dark photon, Z', …

Pseudoscalar portal

Axions, **ALPs**, …

Scalar portal

Dark Higgs, scalars

Neutrino portal

Sterile neutrino

What can we do at e^+e^- colliders that we can't at the LHC?

- 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 long-lifetime signature (LLP)
- Some fully neutral final states accessibility
- Dark sector signatures in B, D, J/ψ, Φ, Υ and τ decays

- Cleanliness and luminosity compensate for cross section → competition

What can we do at e^+e^- colliders that we can't at the LHC?

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- Cleanliness and luminosity compensate for cross section → competition

Today

Focus on flavor factories

Focus mainly on the Belle II experiment

Searching for dark matter at the intensity frontier

KLOE/KLOE-2, BESIII, BaBar, Belle, Belle II: optimal position to probe a dark sector at the GeV scale:

- They operate **exactly** at that scale: $\sqrt{s}$=
  - **DAϕNE ≈ 1 GeV**
  - **BEPC ≈ 3-4 GeV**
  - **(SUPER)KEKB, PEPII ≈ 10-11 GeV**
- Most of the interesting cross sections scale with 1/s
- Unique places to study some rare light meson decays (ϕ, J/ψ, ϒ factories!)

Collected luminosities

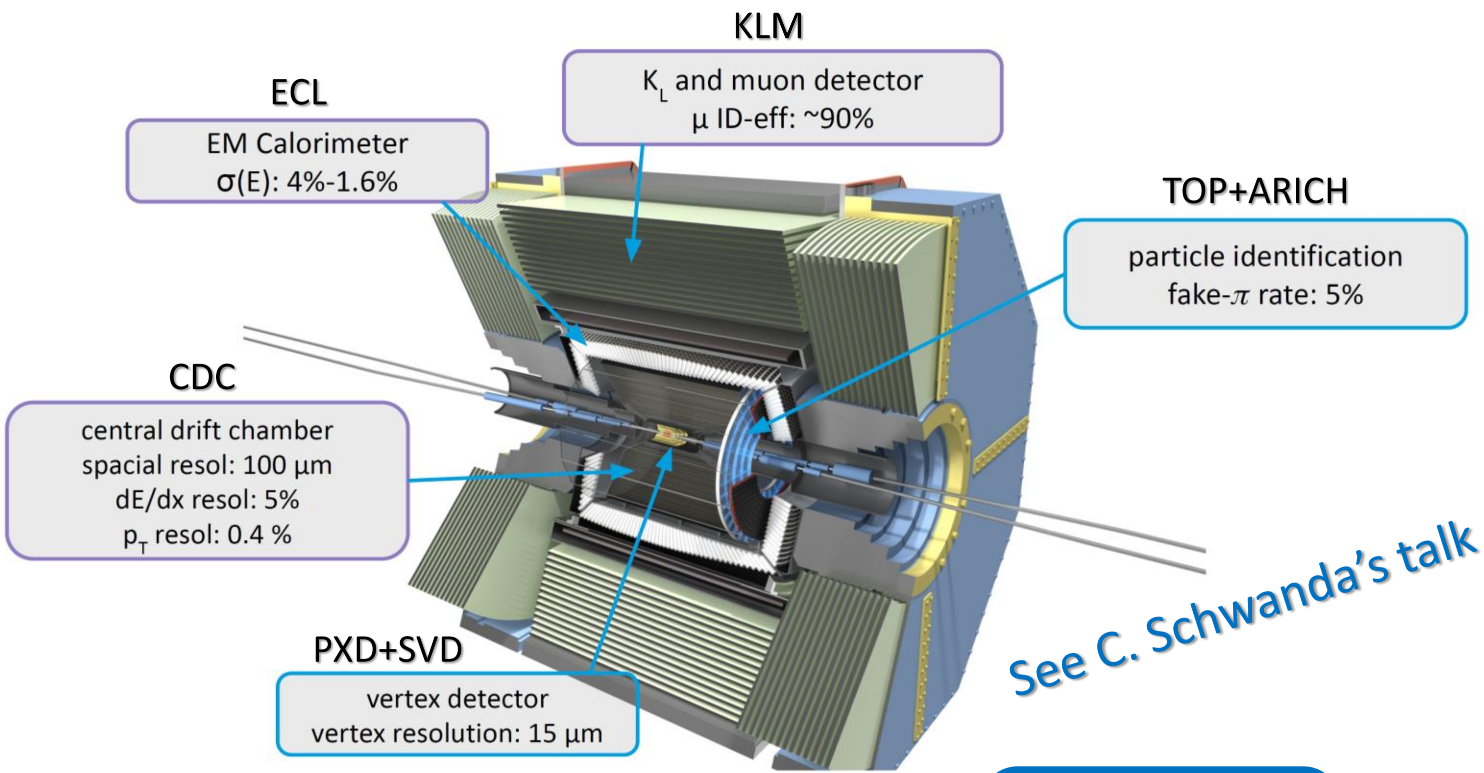
KLOE ≈ 2 fb^{-1}
KLOE-2 ≈ 6 fb^{-1}

BESIII ≈ 45 fb^{-1} at different $\sqrt{s}$, in progress

BaBar ≈ 0.5 ab^{-1}
Belle ≈ 1 ab^{-1}

Belle II ≈ 575 fb^{-1} in progress

Belle II and SuperKEKB



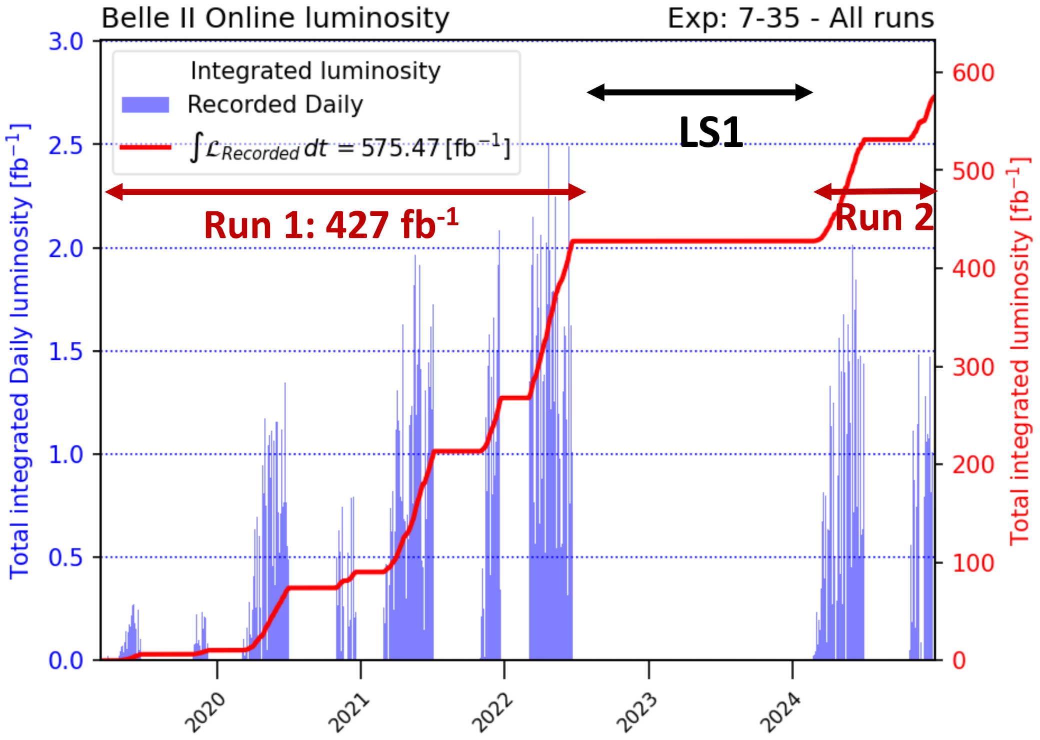
See C. Schwanda's talk

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

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

Final goal : 50 ab^{-1}

Collected luminosity: 2019-2024



Restart data taking in October 2025

Low-mass particle search overview

L_μ-L_τ

Z' → invisible
Z' → $\mu\mu$
Z' → $\tau\tau$

Axion-like particles

ALP→$\gamma\gamma$

Axion-like particles in B decays

B→K ALP, ALP→$\gamma\gamma$

Dark Higgsstrahlung

A'h' h' visibile
A'h' h' invisibile

LLP Dark Higgsstrahlung with IDM

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

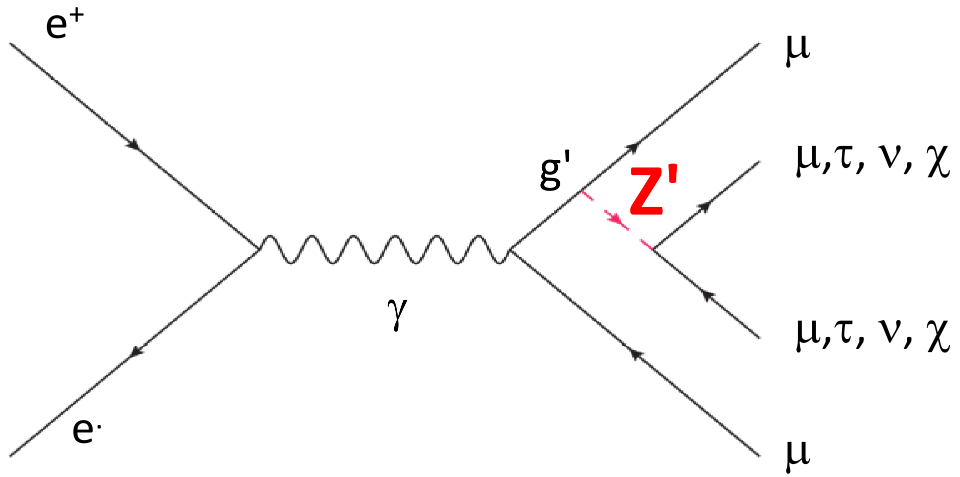
LLP dark scalar in B decays

B→KS S→ee, $\mu\mu$, $\pi\pi$, KK

Z': L_μ - L_τ model

- Gauging L_μ - L_τ , 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



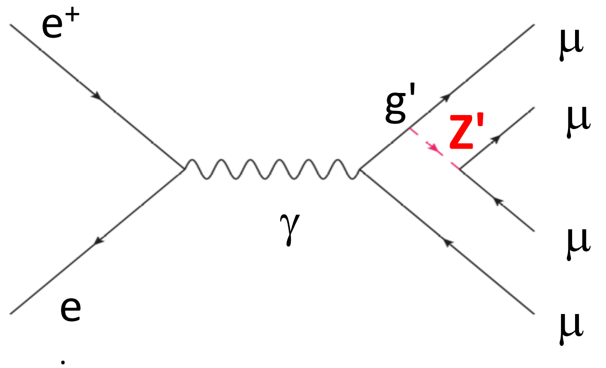
Z' →μμ - muonic dark force: BaBar, Belle

L_μ-L_τ
Z' → μμ

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

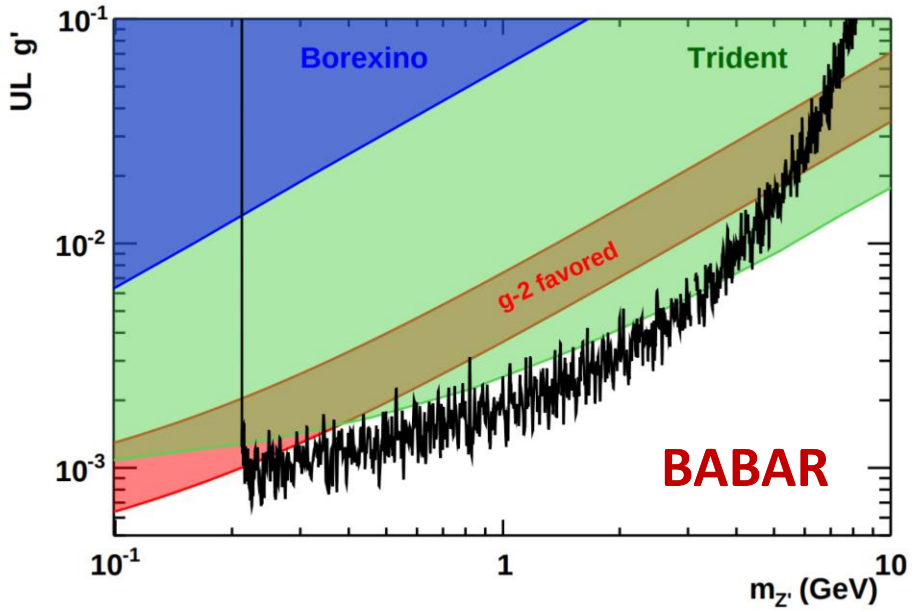
4-track mass ~√s
No extra energy
Signature: narrow M(μμ) peak

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



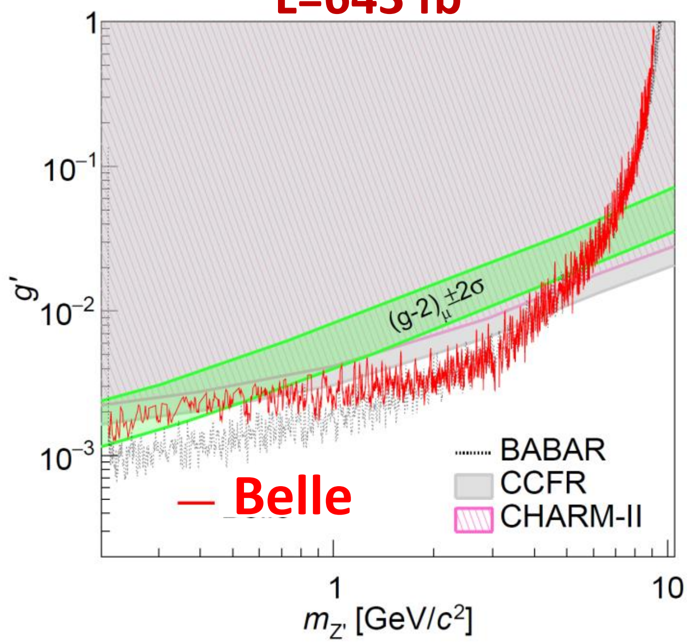
Phys Rev D 94, 011102 (2016)

L=514 fb^{-1}



Phys Rev D 106, 012003 (2022)

L=643 fb^{-1}



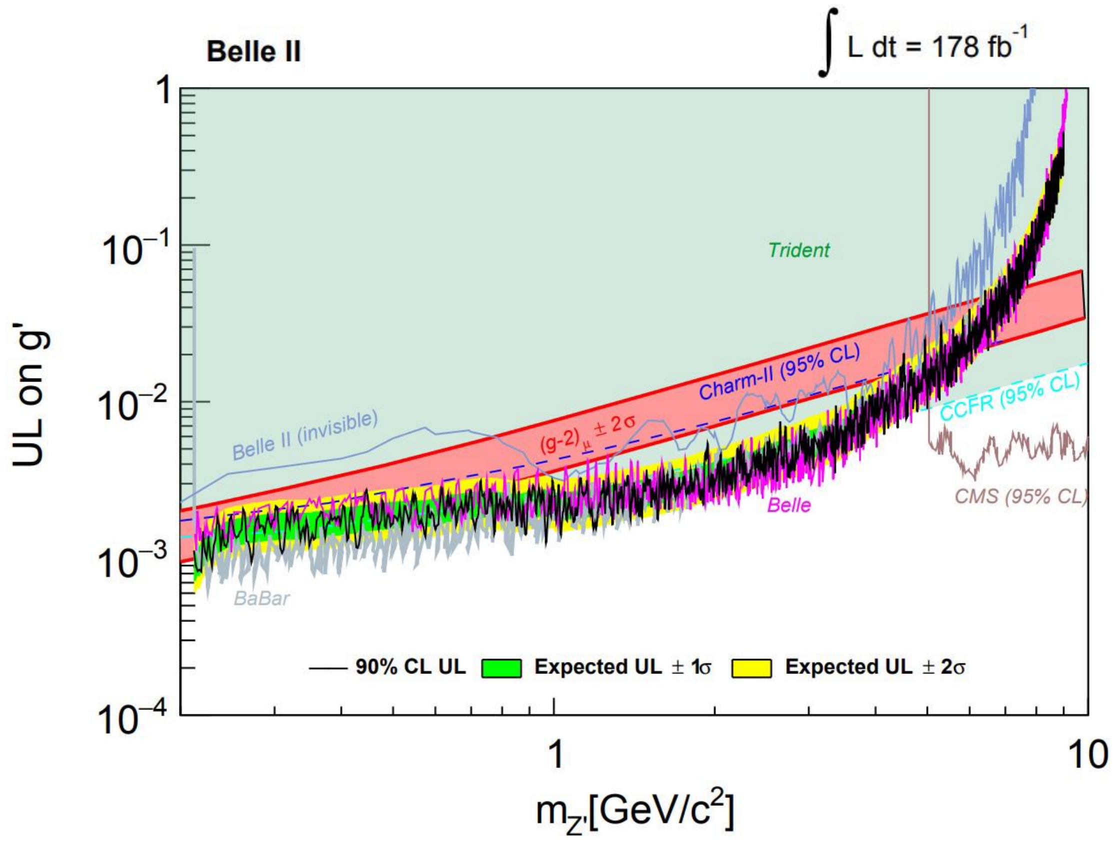
Z’ →μμ - muonic dark force: Belle II

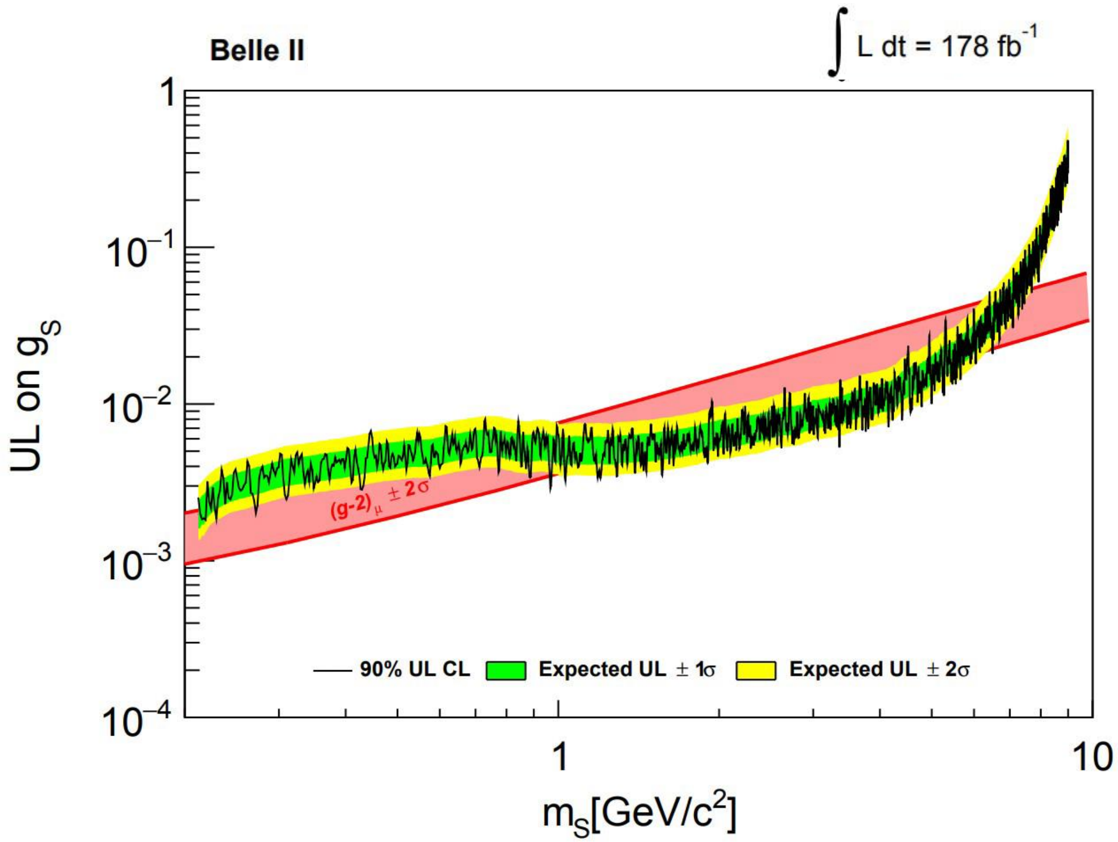
L_μ-L_τ
Z’ → μμ

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

PRD 109, 112015 (2024)

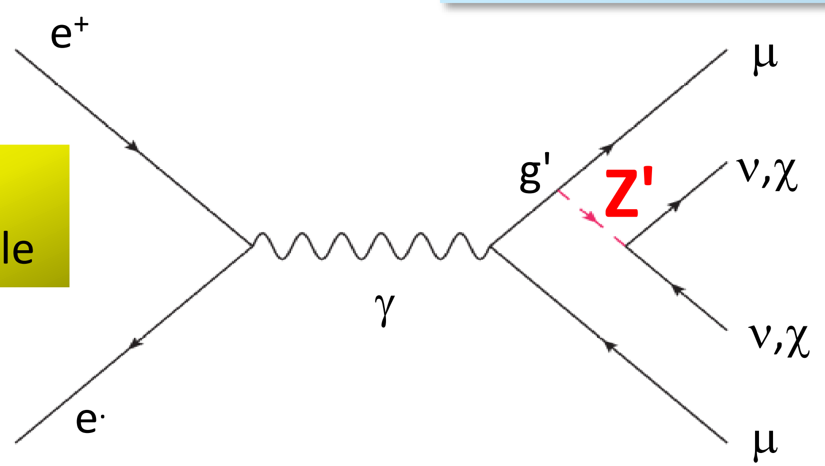
- Limits on Z’ **similar to BaBar and Belle** with much lower lumiosity
- **First limits for the muonphilic scalar** from a dedicated search



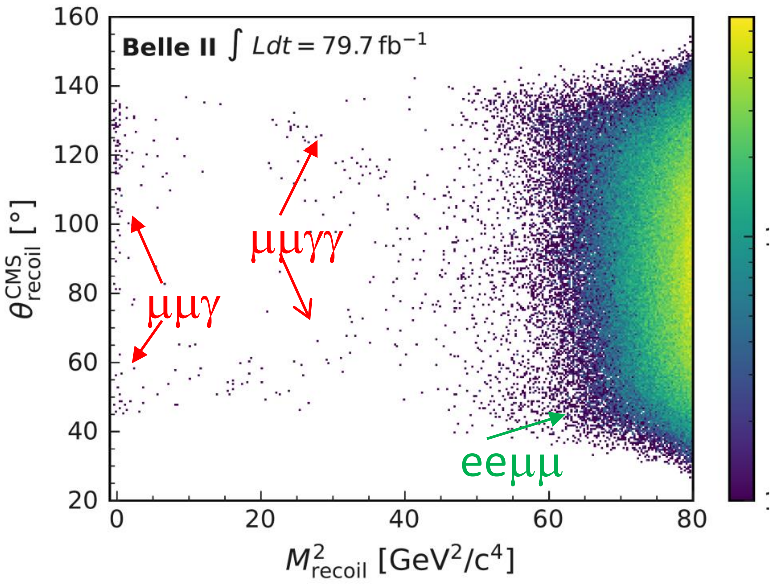


Z' to invisible: Belle II

L_μ-L_τ
Z' → invisible



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

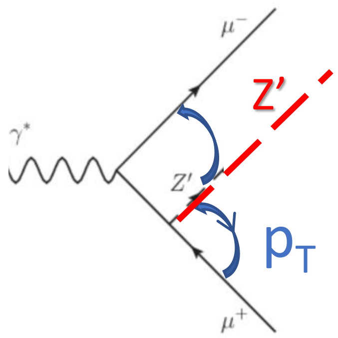


$e^+e^- \to \mu^+\mu^-$ + *missing energy*

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

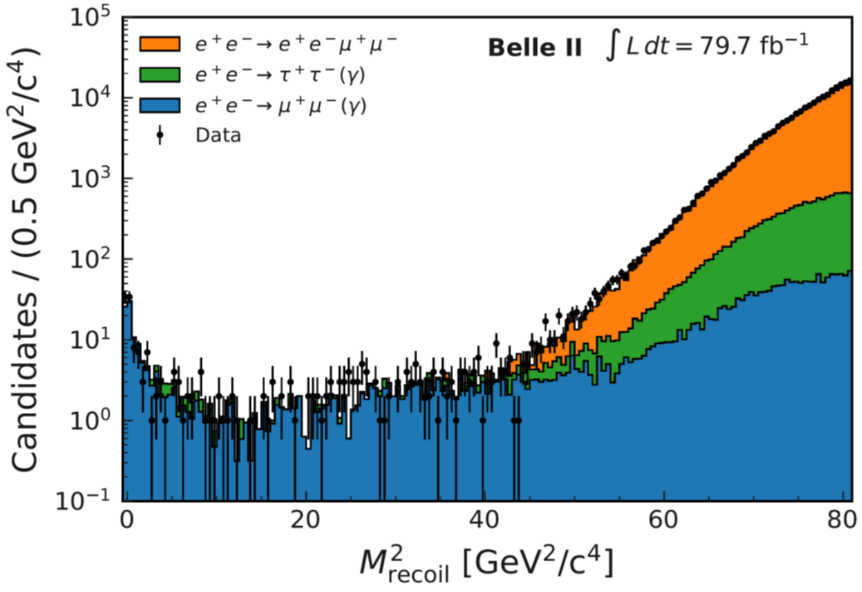
Main backgrounds:

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



FSR vs ISR + τ decay

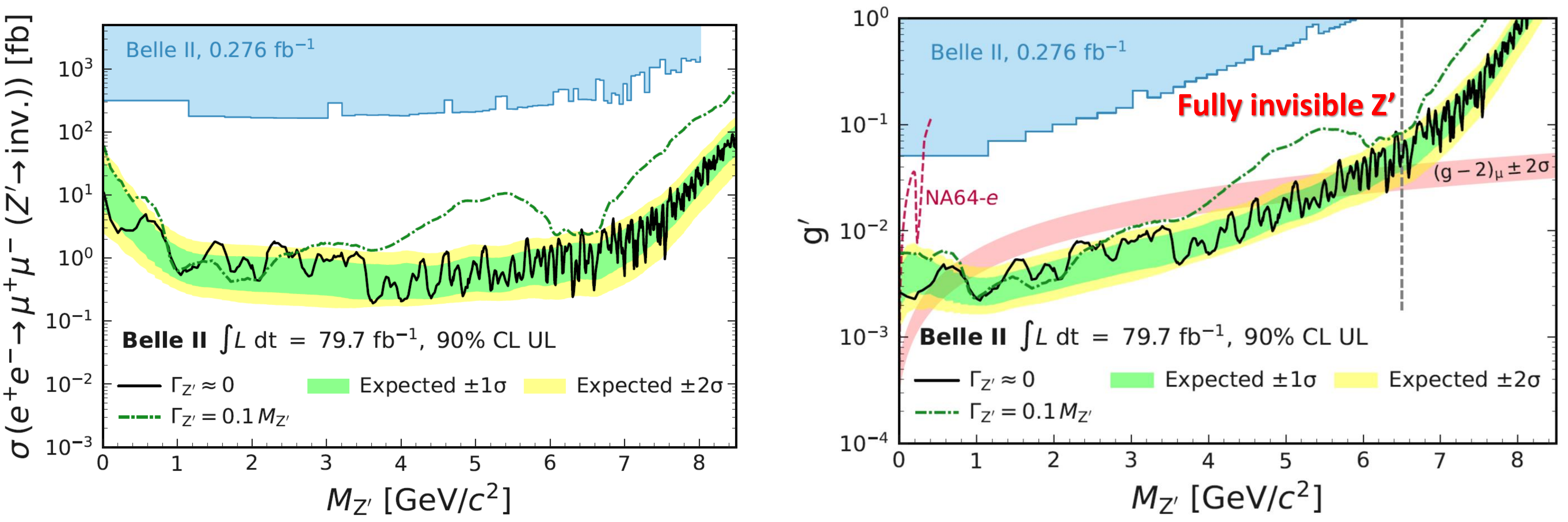
NN trained to optimize Punzi FOM
Eur.Phys.J. C82 (2022) 2, 121



Z' to invisible: Belle II results

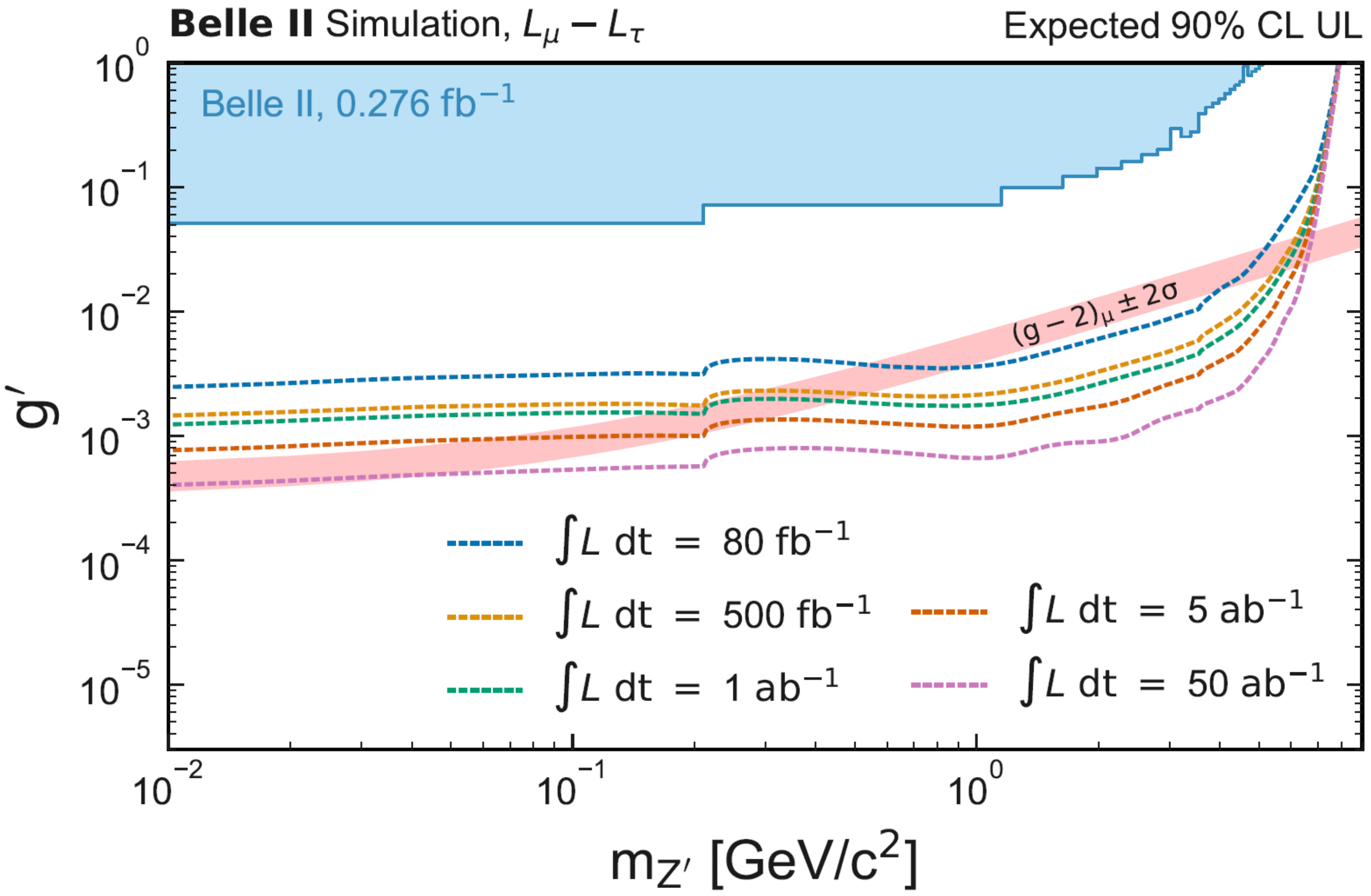
- No excess found
- Set 90%CL exclusion limits on cross section and coupling
  - Vanilla scenario: Z' decays to SM only
  - Fully invisible scenario

PRL 130, 231801 (2023)



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

Z' to invisible: luminosity projections



Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

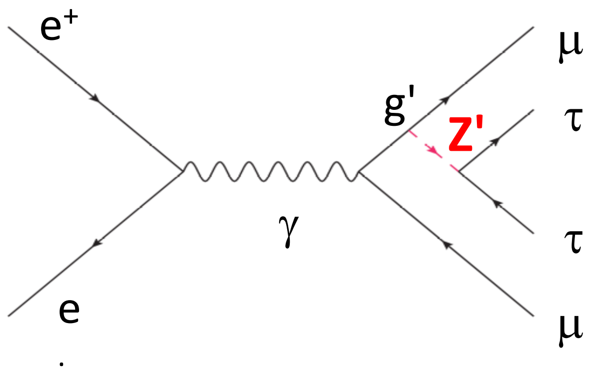
Next update based on Run 1 luminosity almost ready

$Z' \to \tau\tau$: Belle II

$L_\mu - L_\tau$

$Z' \to \tau\tau$

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



Background suppression with NN
- resonance vs $\mu\mu$
- FSR production
- $\tau\tau$ system

Main backgrounds

$e^+e^- \to \tau^+\tau^- (\gamma)$ 1+3 prong

$e^+e^- \to qq$ (q=u,d,s,c)

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

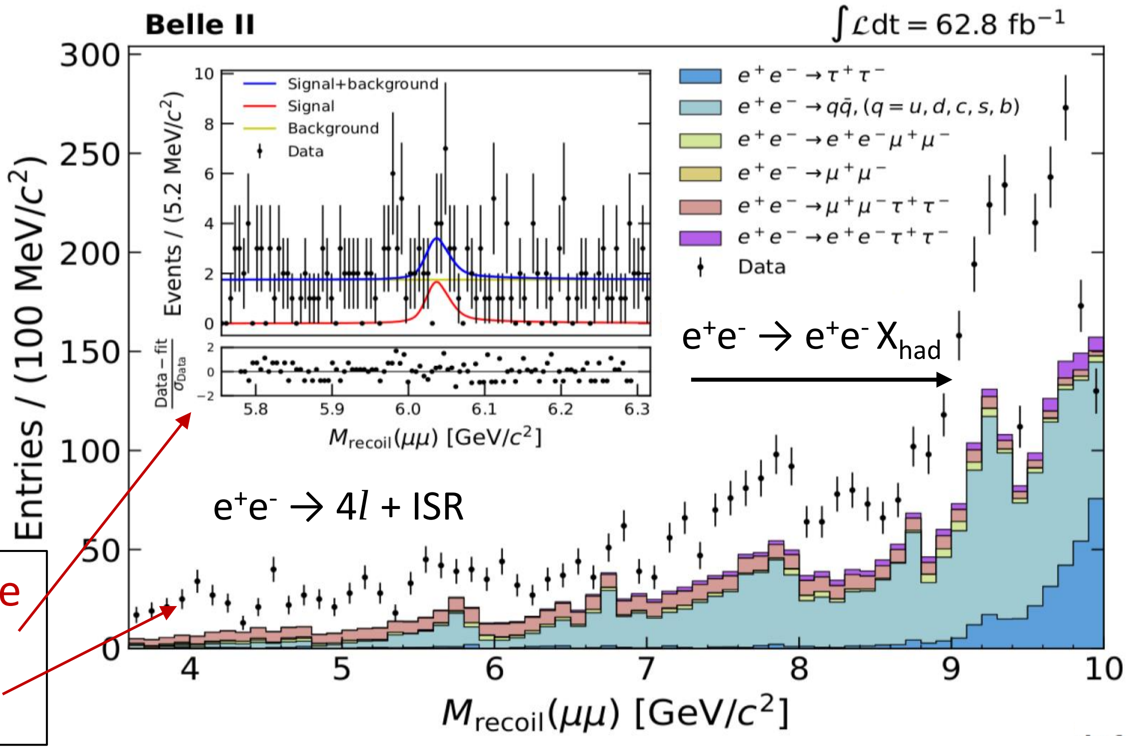
$e^+e^- \to \mu^+\mu^- \tau^+\tau^-$

$e^+e^- \to e^+e^- \tau^+\tau^-$

no ISR in simulation

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

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



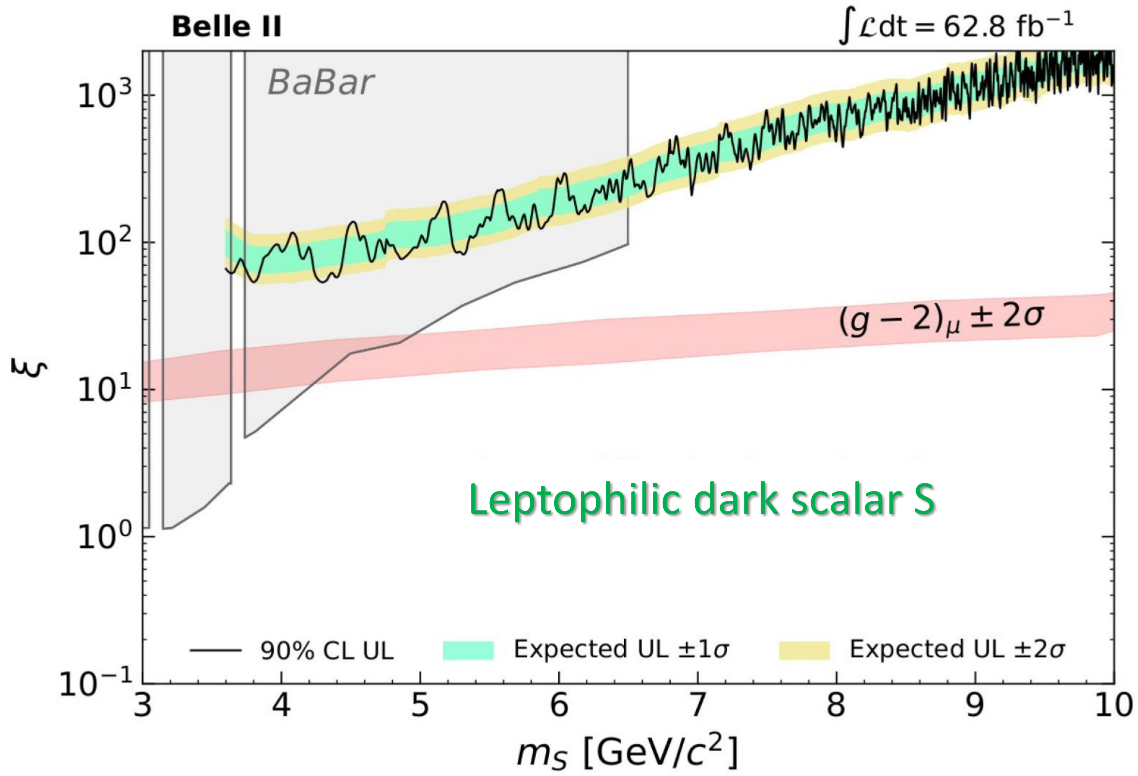
Smooth background on the scale of the signal mass resolution (~10 MeV/c^2)

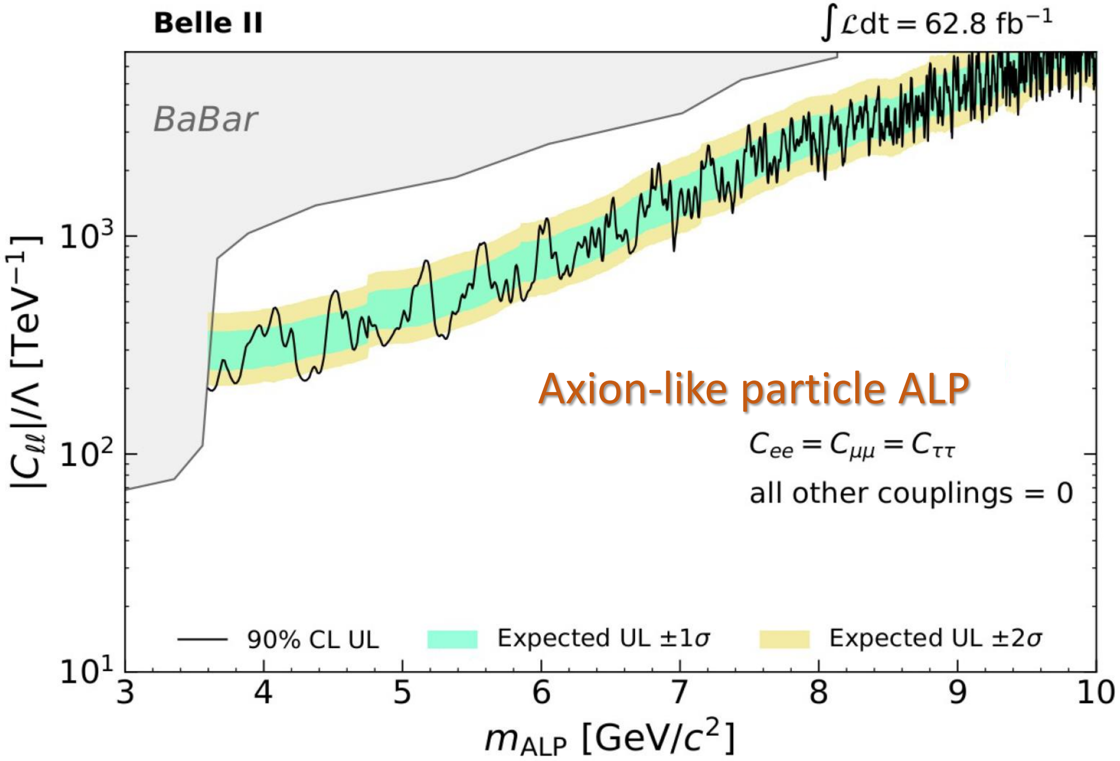
Z' → ττ: Belle II

L_μ-L_τ
Z' → ττ

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

PRL 131, 121802 (2023)

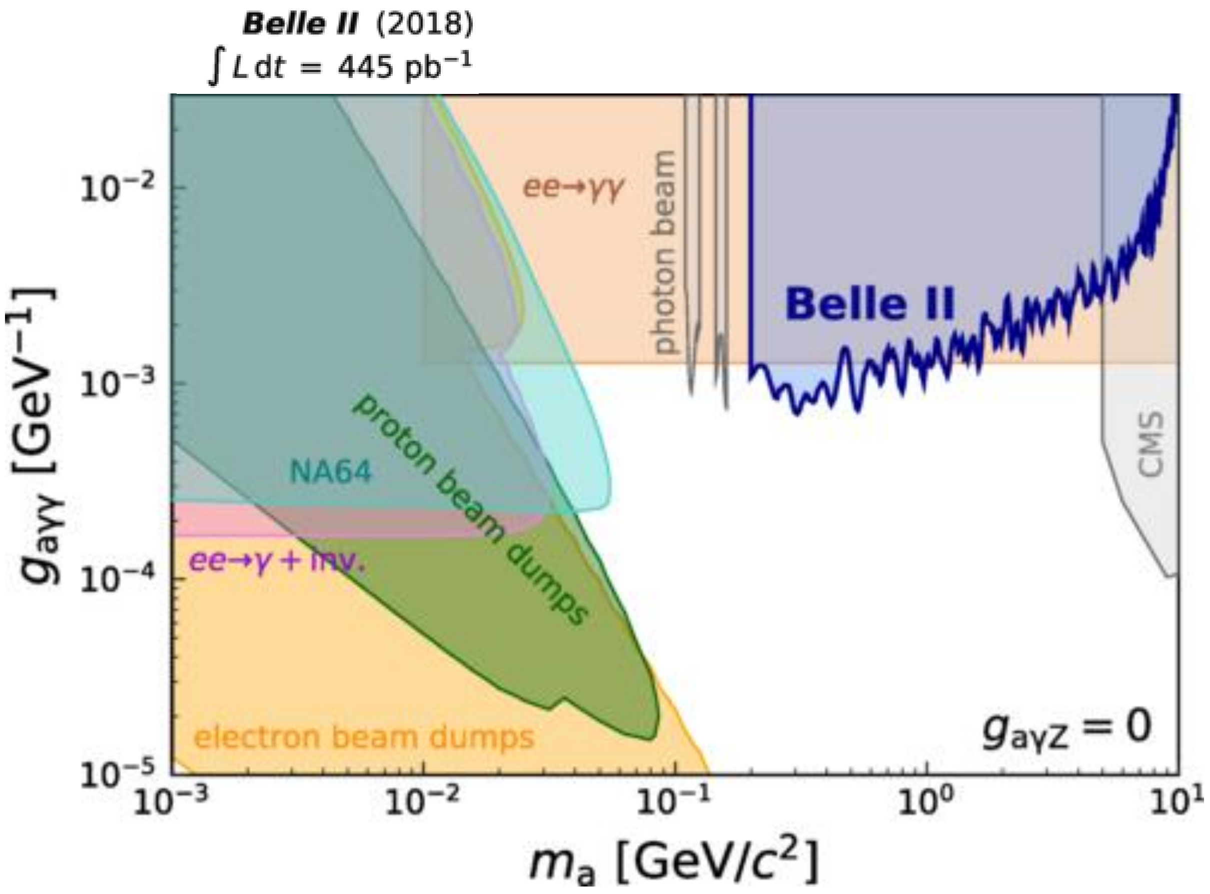


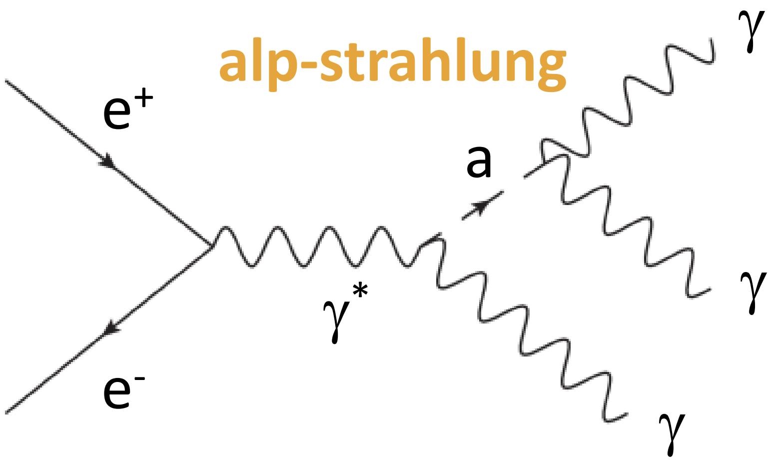


ALP →γγ : Belle II

Axion like particles
ALP→γγ

Pilot run physics results

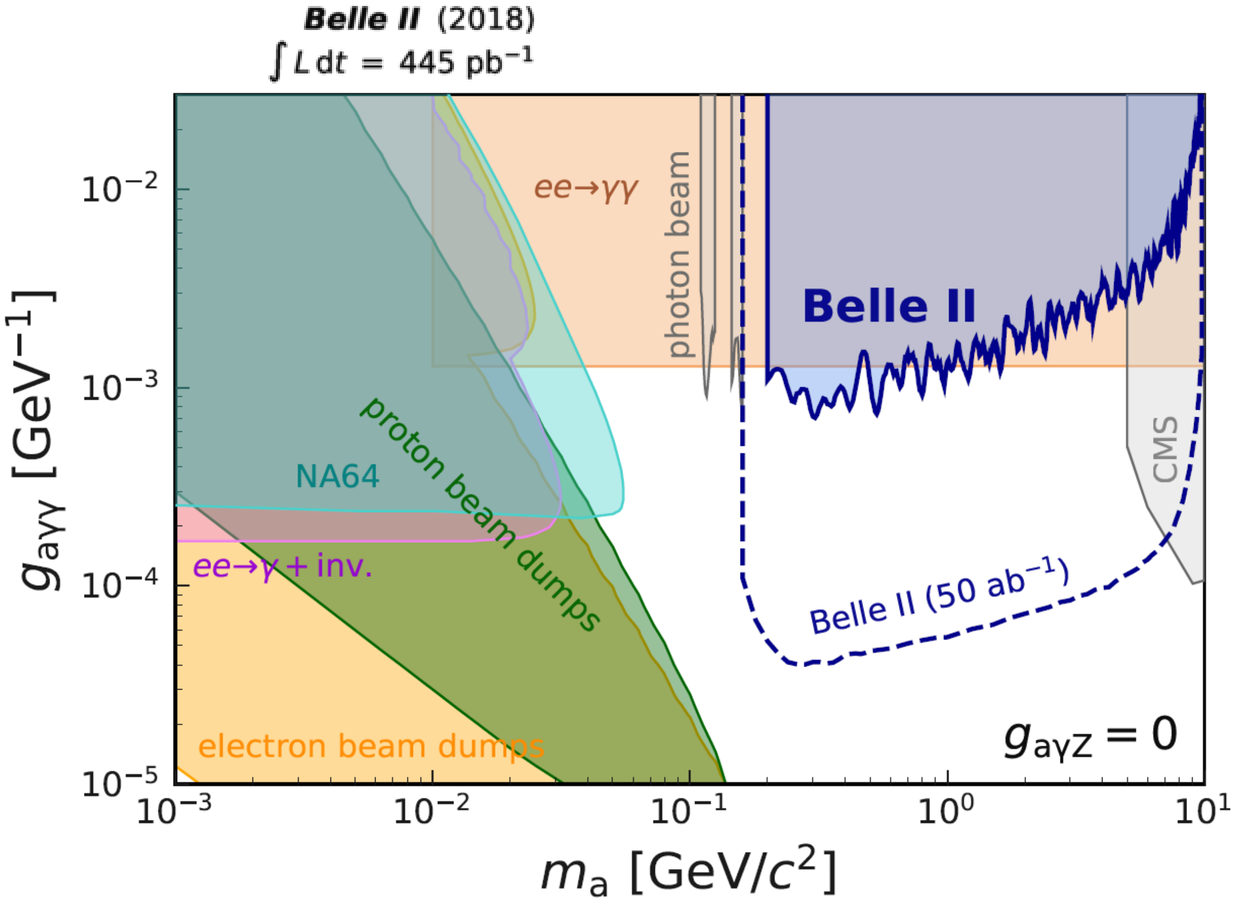


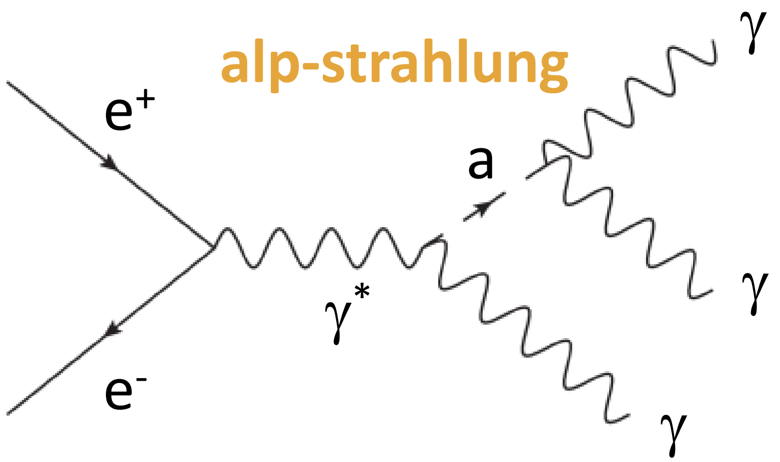


PRL 125, 161806 (2020)

ALP →γγ : luminosity projections

Axion like particles
ALP→γγ





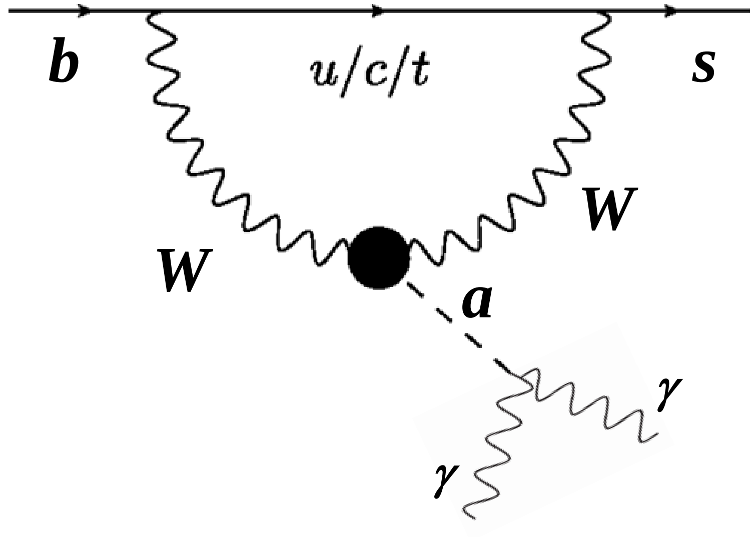
Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

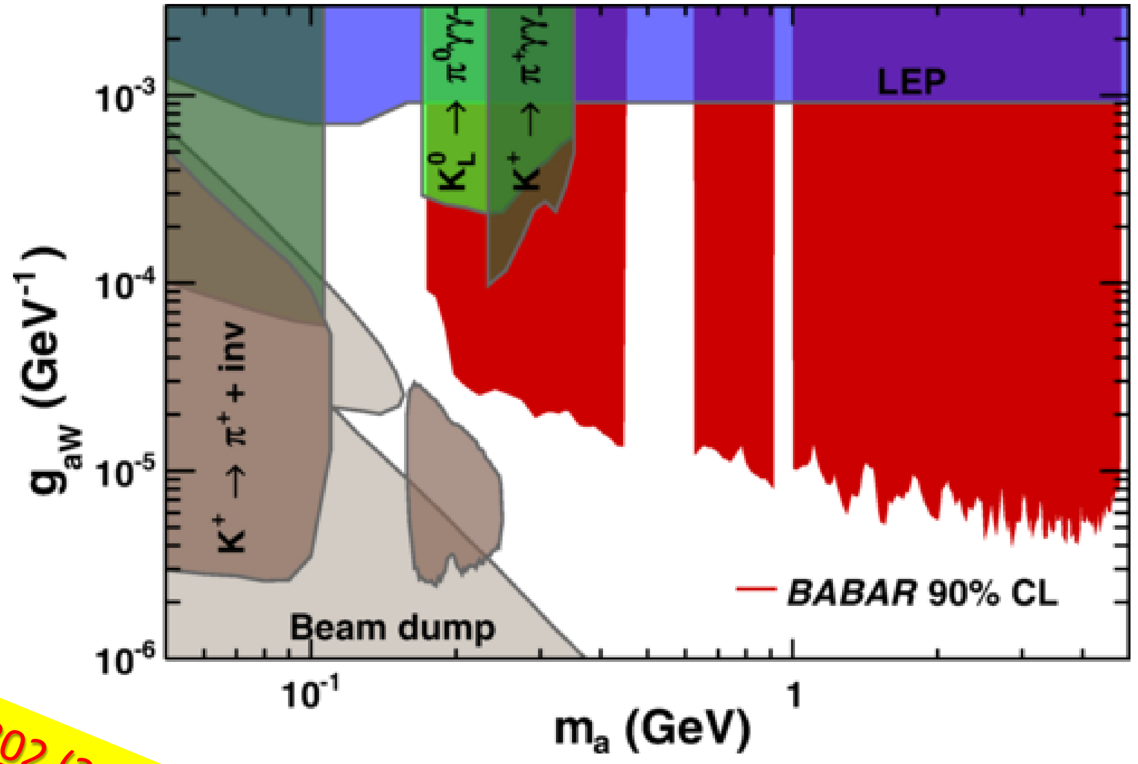
ALP in B→Ka: BaBar

Axion-like particles in B decays
$B \to K$ ALP, ALP→$\gamma\gamma$

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



$B^{\pm} \to K^{\pm}$ a, a → $\gamma\gamma$



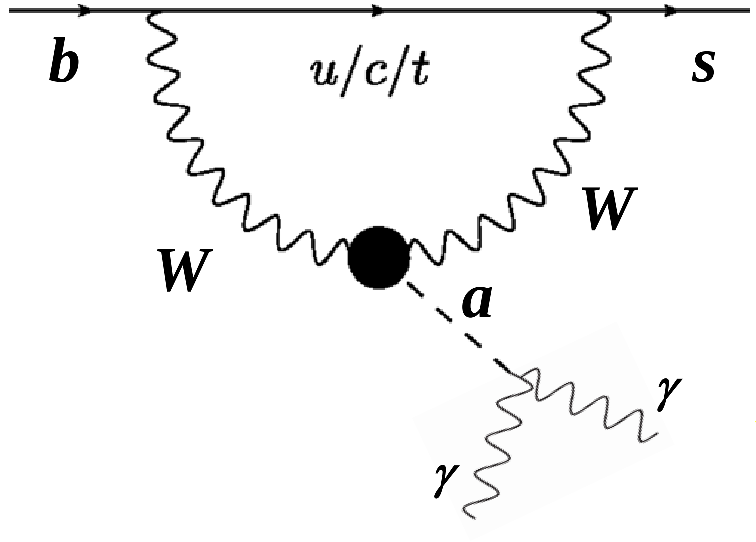
PRL 128, 131802 (2022)

ALP in B→Ka: BaBar … and Belle

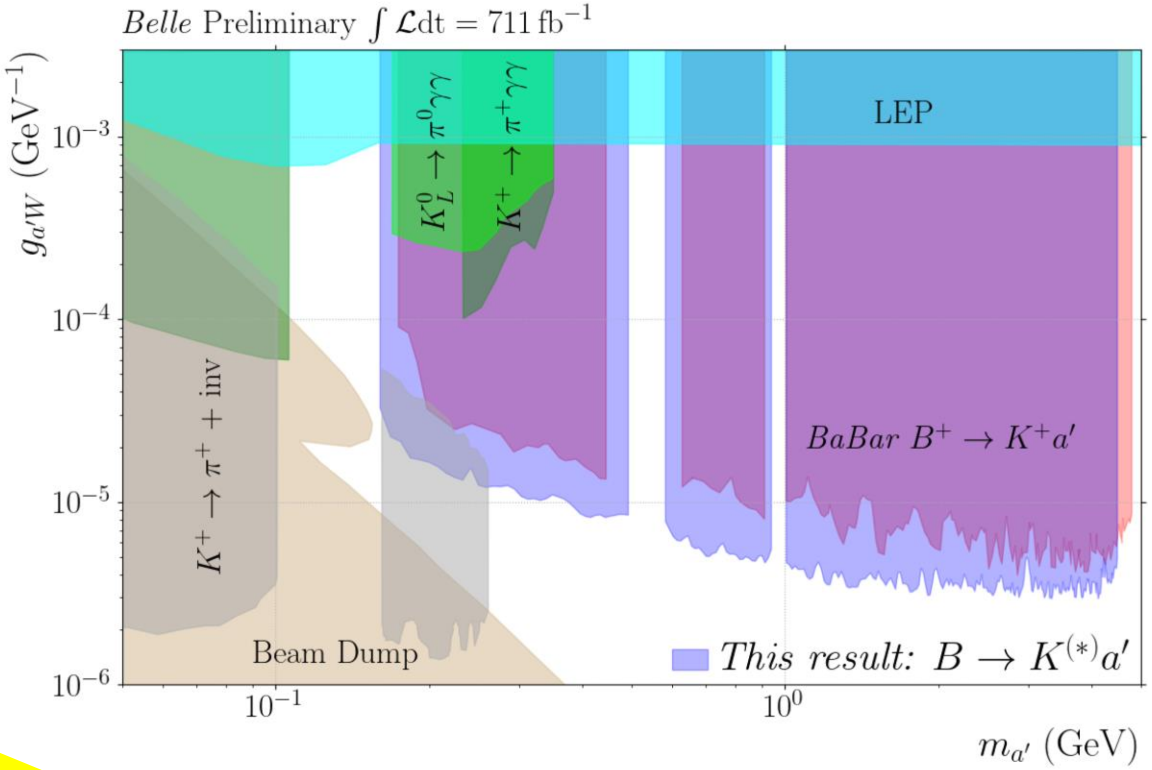
Axion-like particles in B decays
B→K ALP, ALP→γγ

$B^{\pm}\to K^{(*)\pm}$ a, a → γγ
$B^0\to K^{*}/K^0_S$ a, a →γγ

Probe of aWW coupling in b→ s transitions

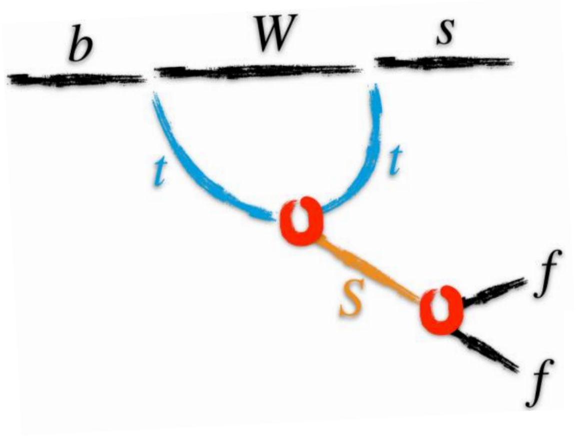


To be submitted to JHEP



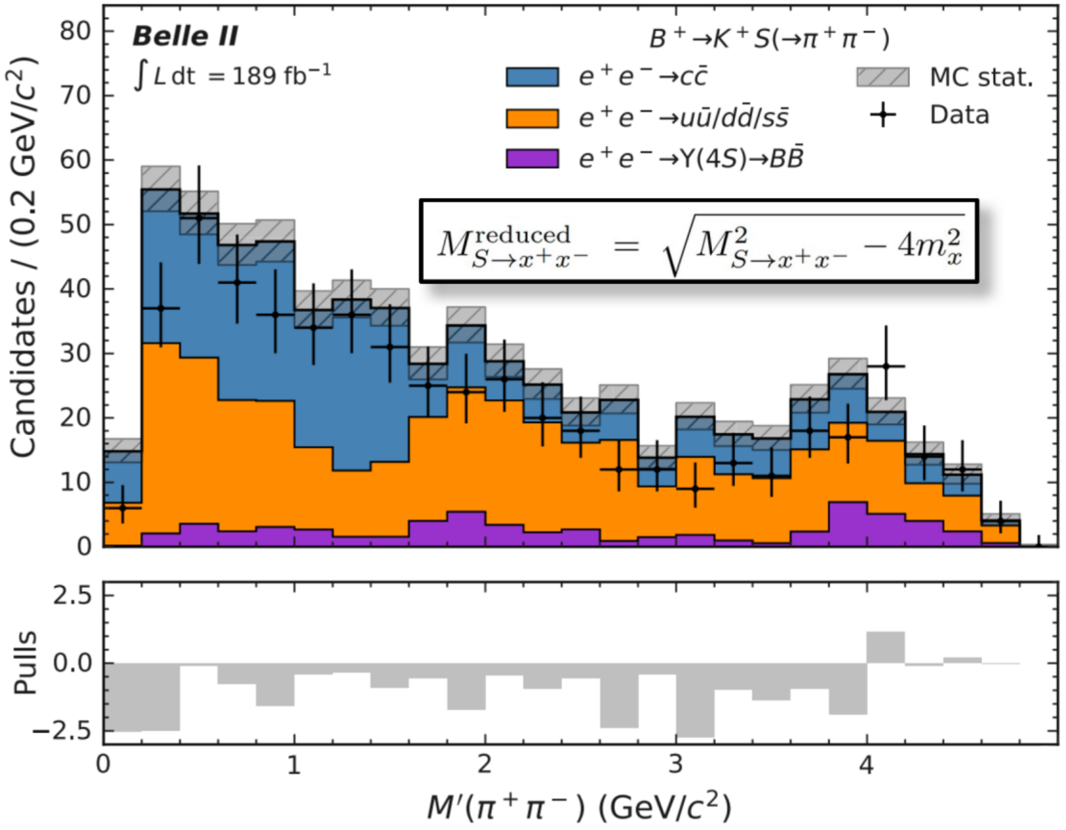
Dark scalar S in b→s transitions: Belle II

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



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

b→s transitions
Mixing with SM Higgs
LLP signature



First dark-sector search in Belle II
- **in B decays**
- **with LLP signature**

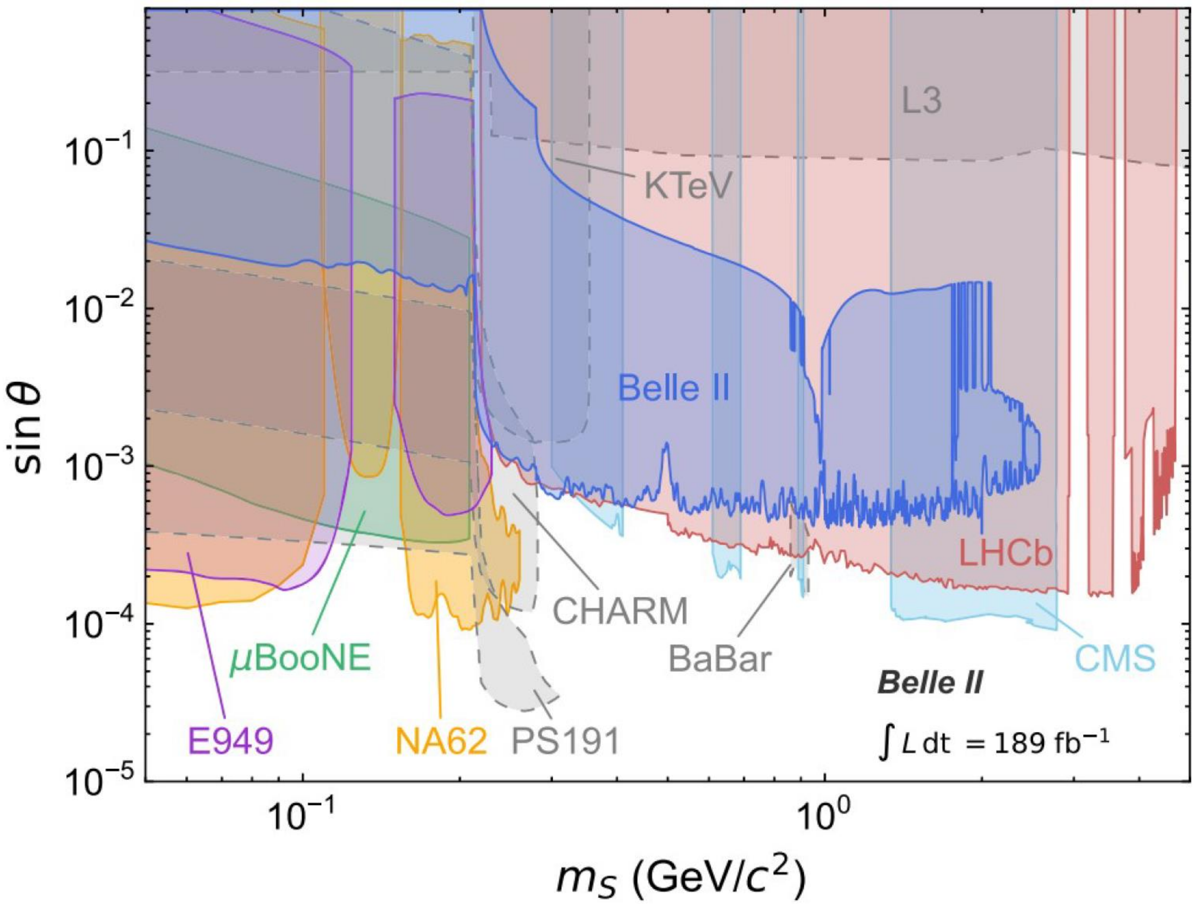
Signal search: fits to the LLP reduced mass for each channel and lifetime

Dark scalar S in b→s transitions: Belle II

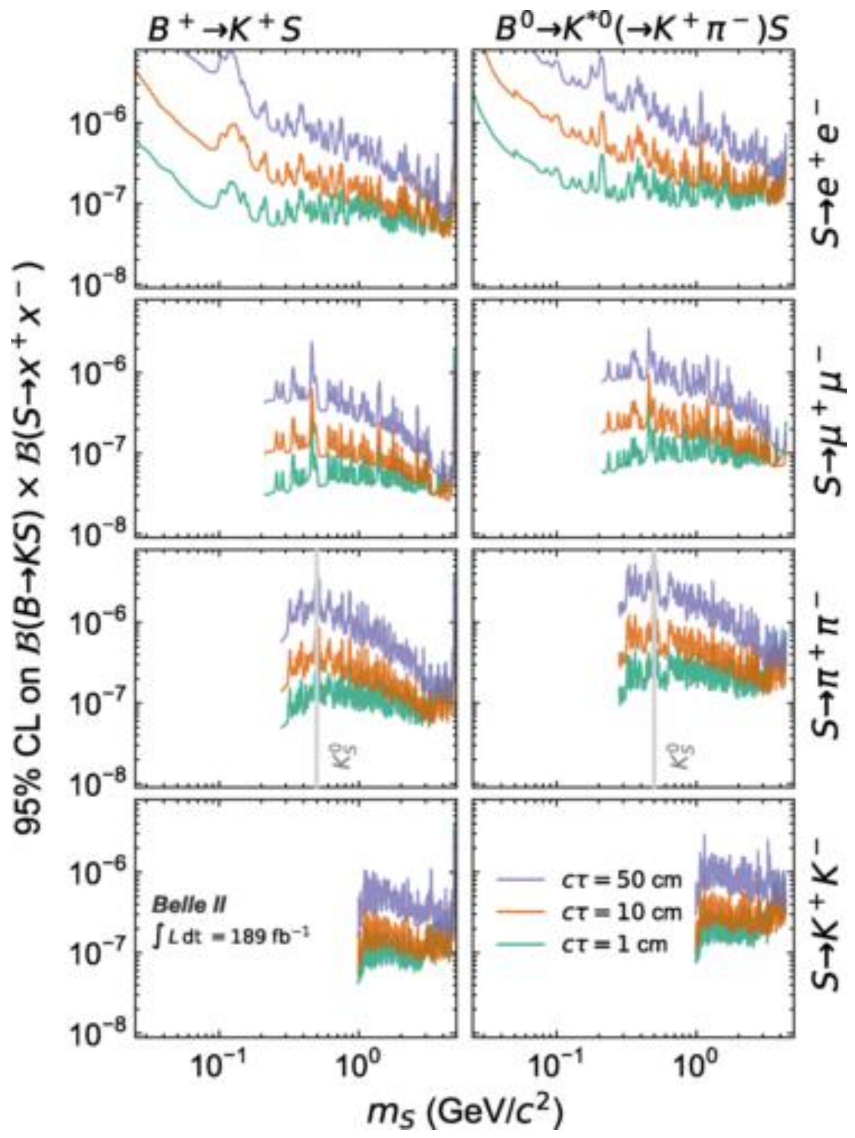
No excess found

- 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

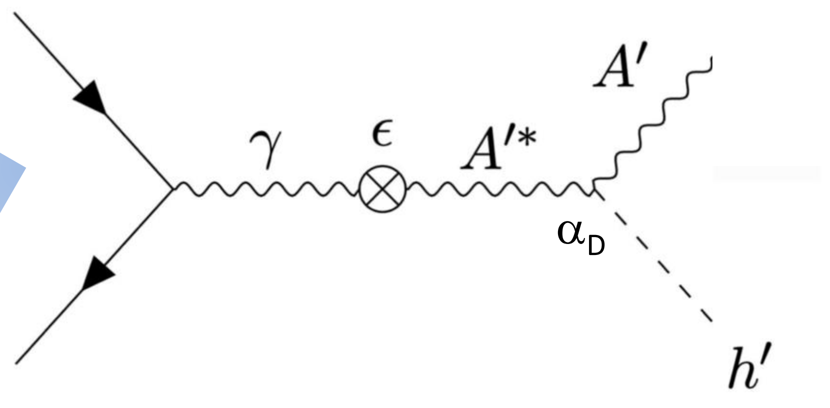


Dark Higgsstrahlung: $e^+e^- \to A'h'$

❑ Dark photon + dark Higgs

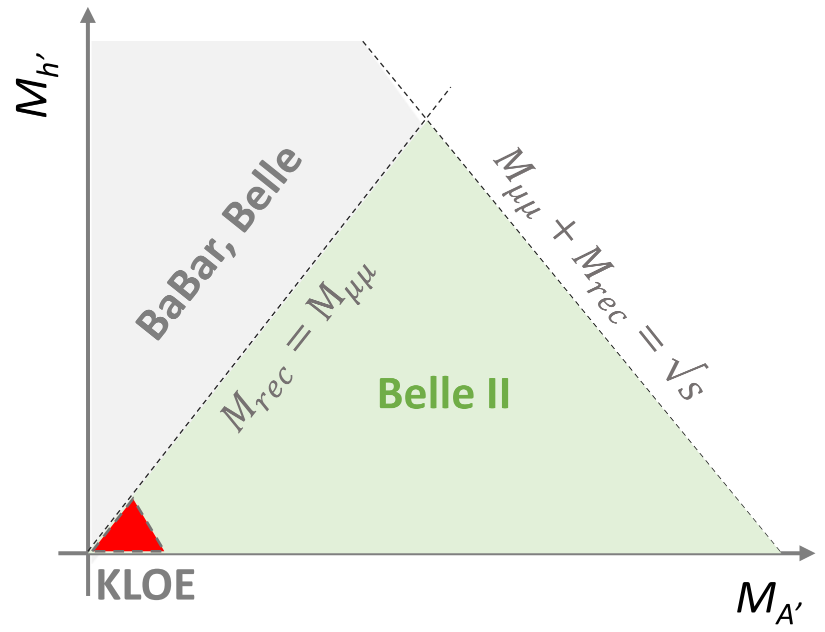
Phys. Rev D79, 115008 (2009)

- 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



❑ Mass hierarchy scenarios

- $M_{h'} > M_{A'}$
  - ➢ $h' \to A'A'$, $e^+e^- \to A'A'A'$
  - ➢ 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



Dark Higgsstrahlung A′h′, h’→ A’A’: Babar, Belle

Dark Higgsstrahlung
A’h’ h’ visibile

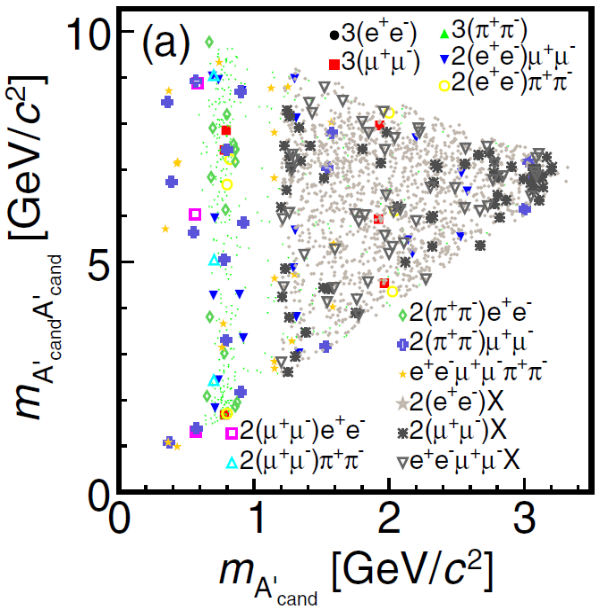
BaBar
PRL 108, 211801 (2012)

Belle
PRL 114, 211801 (2015)

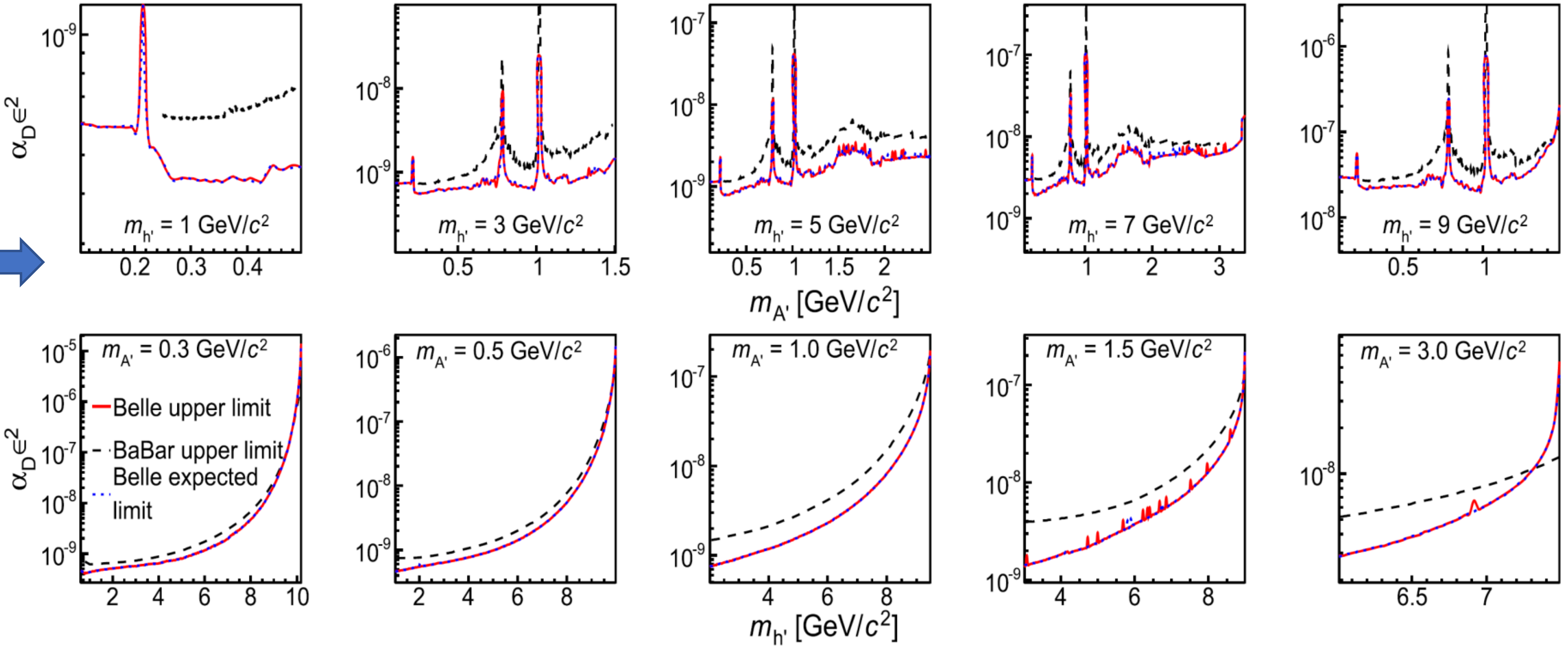
- Three pairs of tracks (ee, μμ, ππ) at the same mass
- No missing energy
- ~ background free (but in the ρ region)

BaBar, Belle

Belle observed events



Belle and BABAR Upper limts 90% CL



Dark HiggsstrahlungA′h′, h′ invisible: KLOE

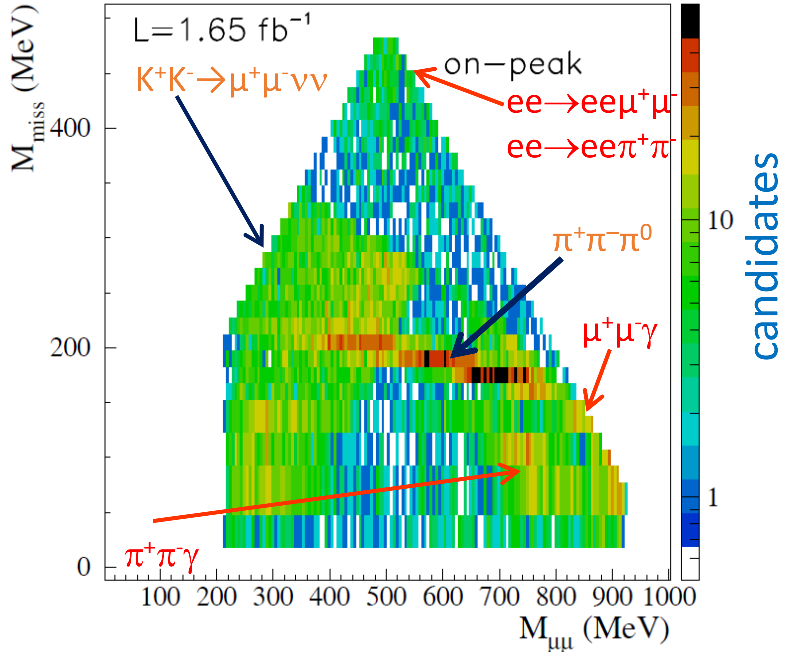
Dark Higgsstrahlung
A′h′ A′→μμ, h′ invisibile

Two muons + missing energy
Background from K^+K^-, $\pi^+\pi^-\pi^0$, $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$, two-photon

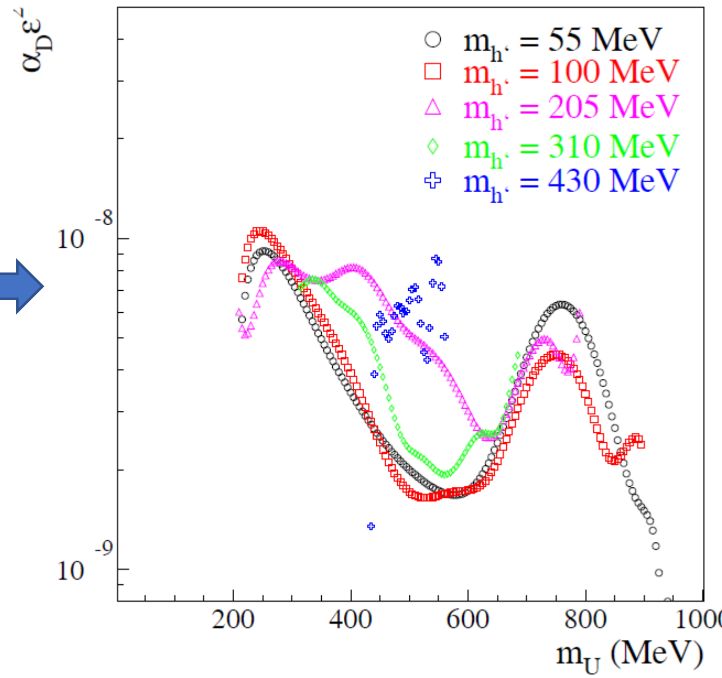
Phys.Lett. B747 (2015) 365

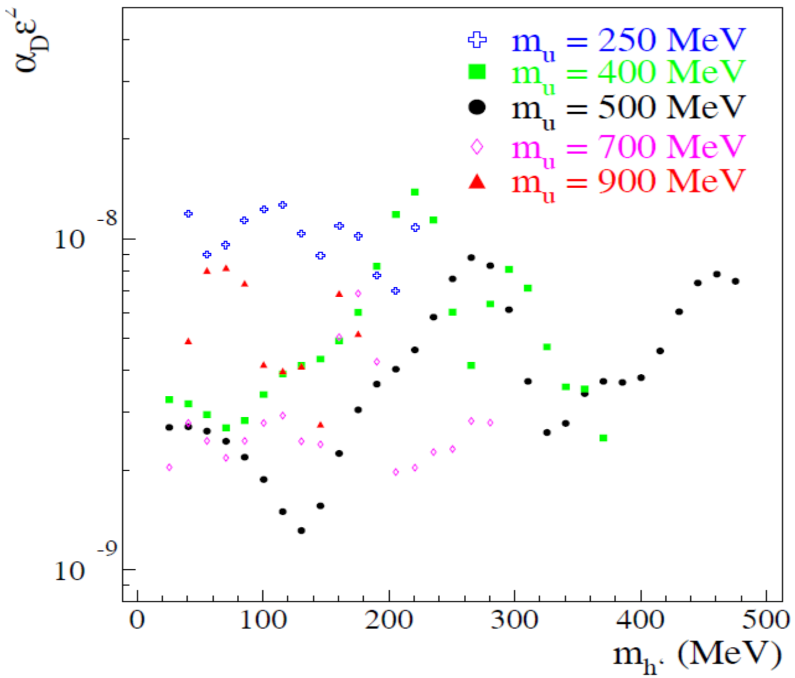
KLOE

Observed events



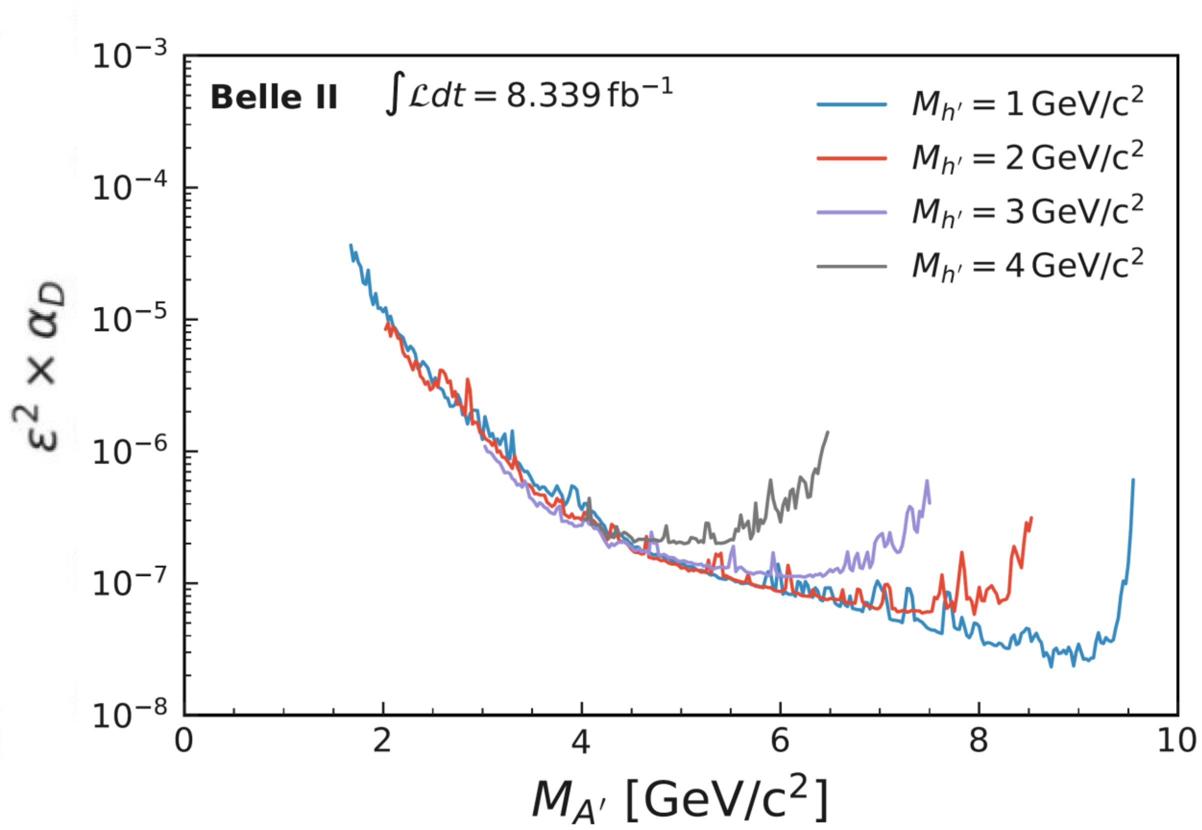
Upper limts 90% CL

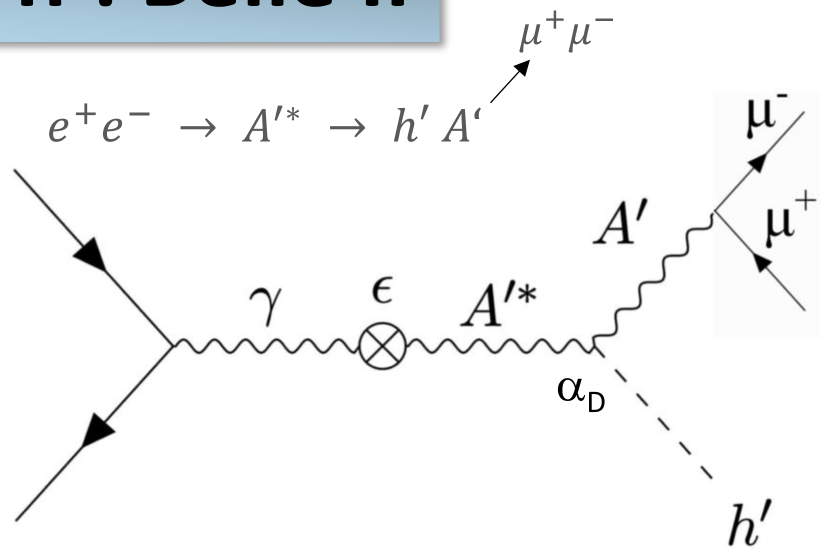




Dark Higgsstrahlung $e^+e^- \to A'h'$: Belle II

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



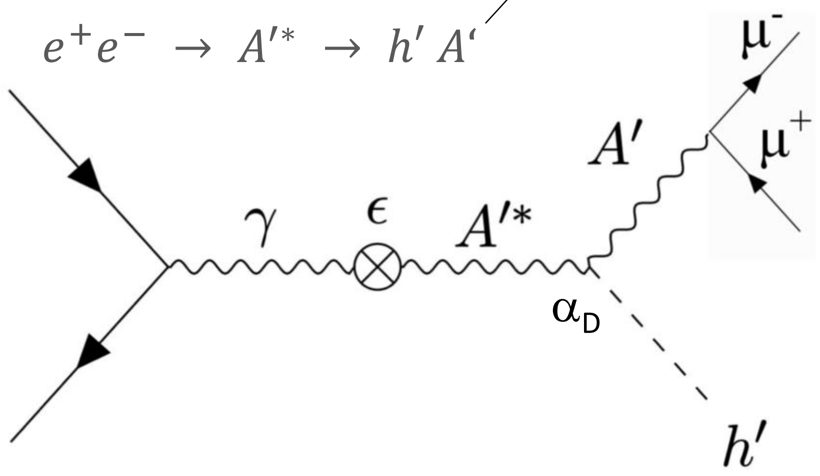


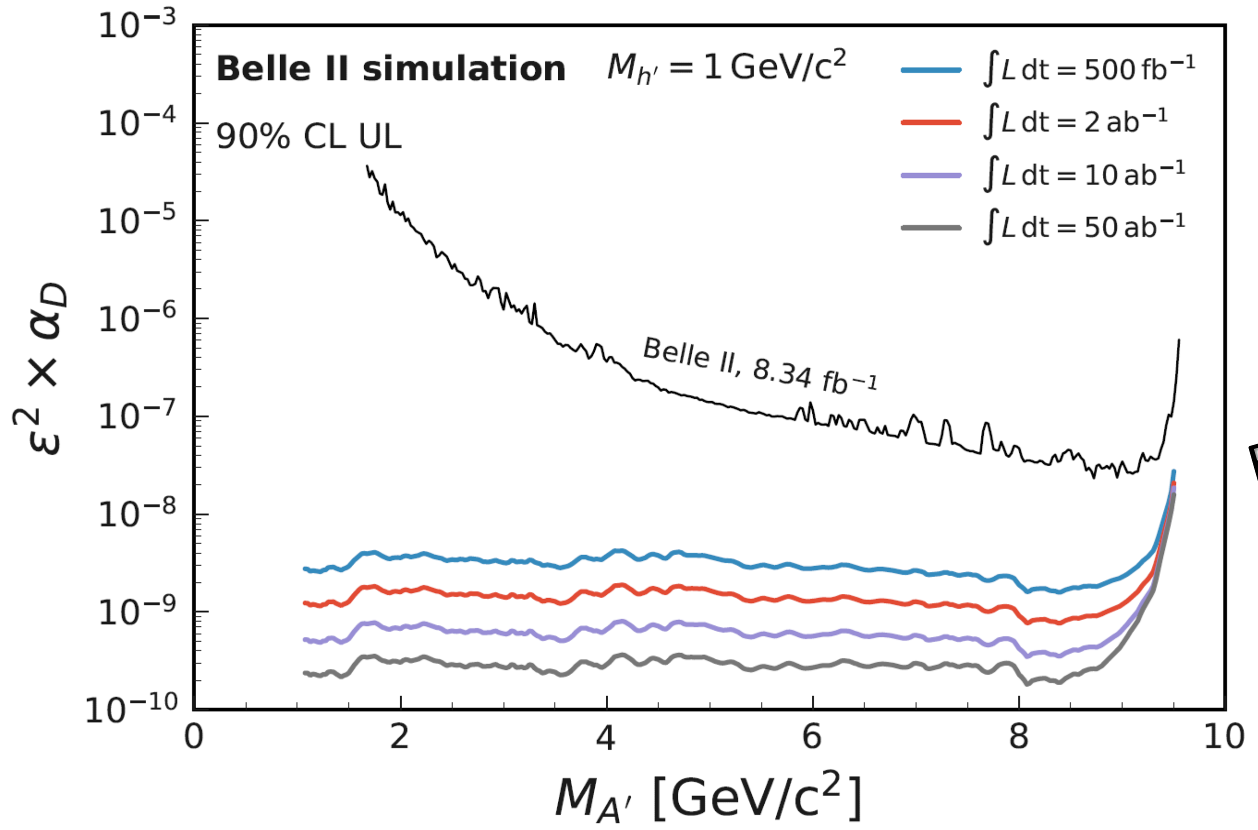
PRL 130, 071804 (2023)

Dark Higgsstrahlung: luminosity projections

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

$e^+e^- \rightarrow A'^* \rightarrow h'\,A'$, $A' \rightarrow \mu^+\mu^-$





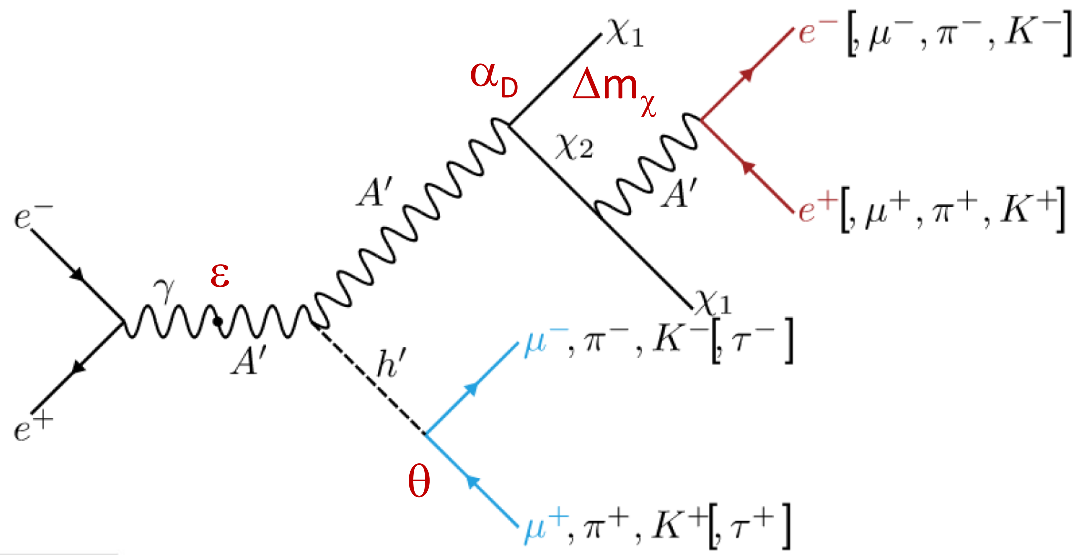
Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

Next update based on Run 1 luminosity in progress

Inelastic dark matter with dark Higgs: Belle II

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' mixes with SM H_0 and is generally long-lived



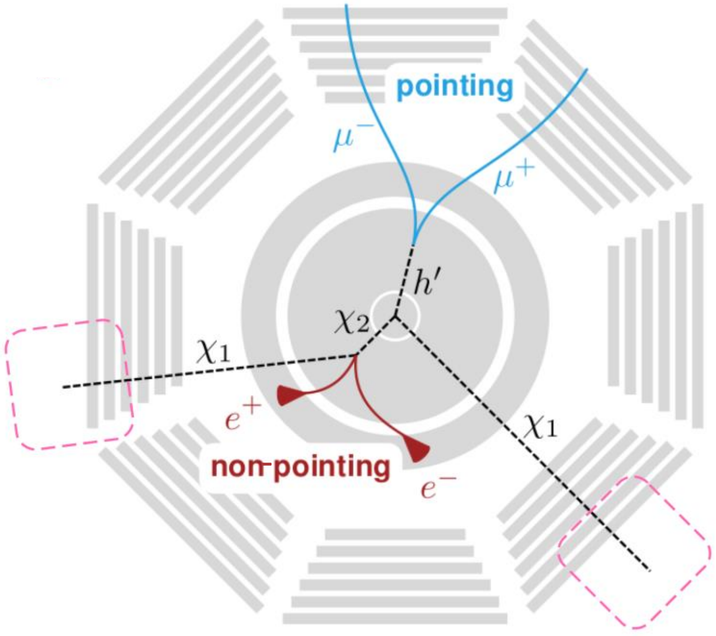
Focus on m(A') > m(χ_1)+m(χ_2)

- 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: Belle II

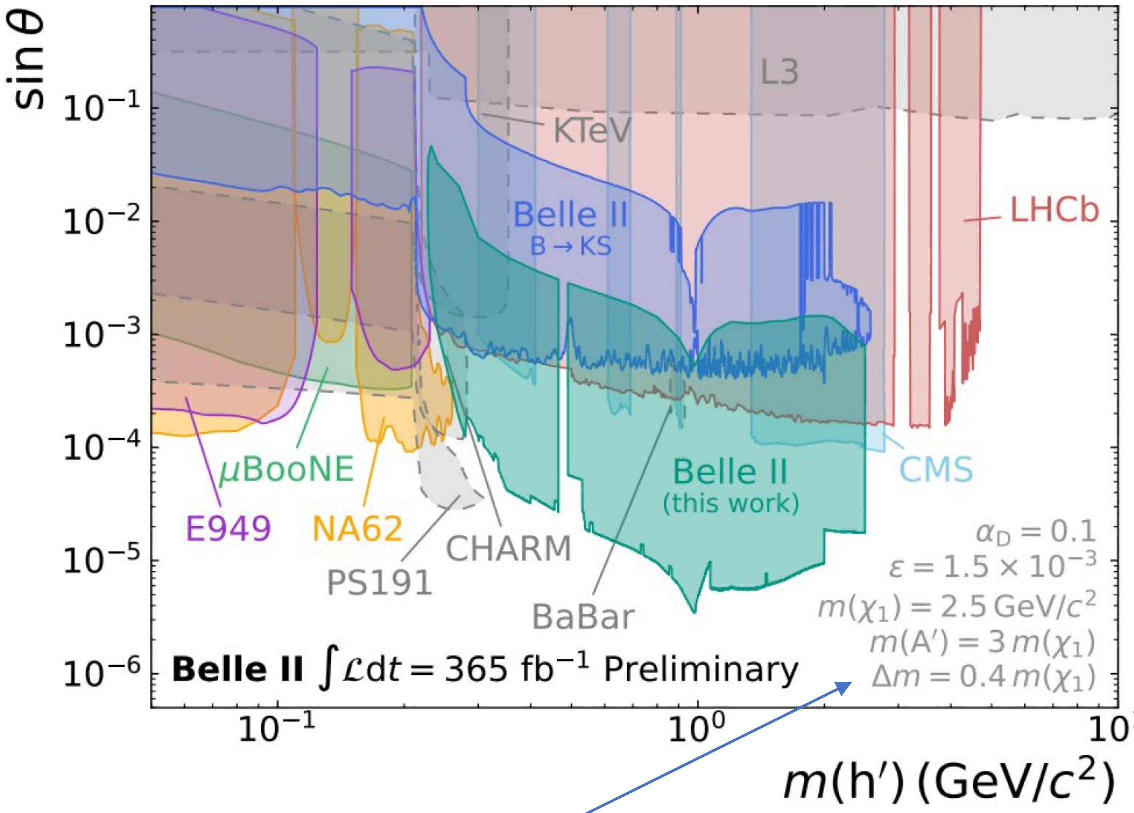
LLP Dark Higgsstrahlung with IDM

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

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** $\rightarrow$ 95% CL upper limits
- Individual final states and their combination
- **Scan m(h')-sinθ 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

To be submitted to PRL

Dark sector searches in Belle II: future directions

- 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)

Short term

- ➢ 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.

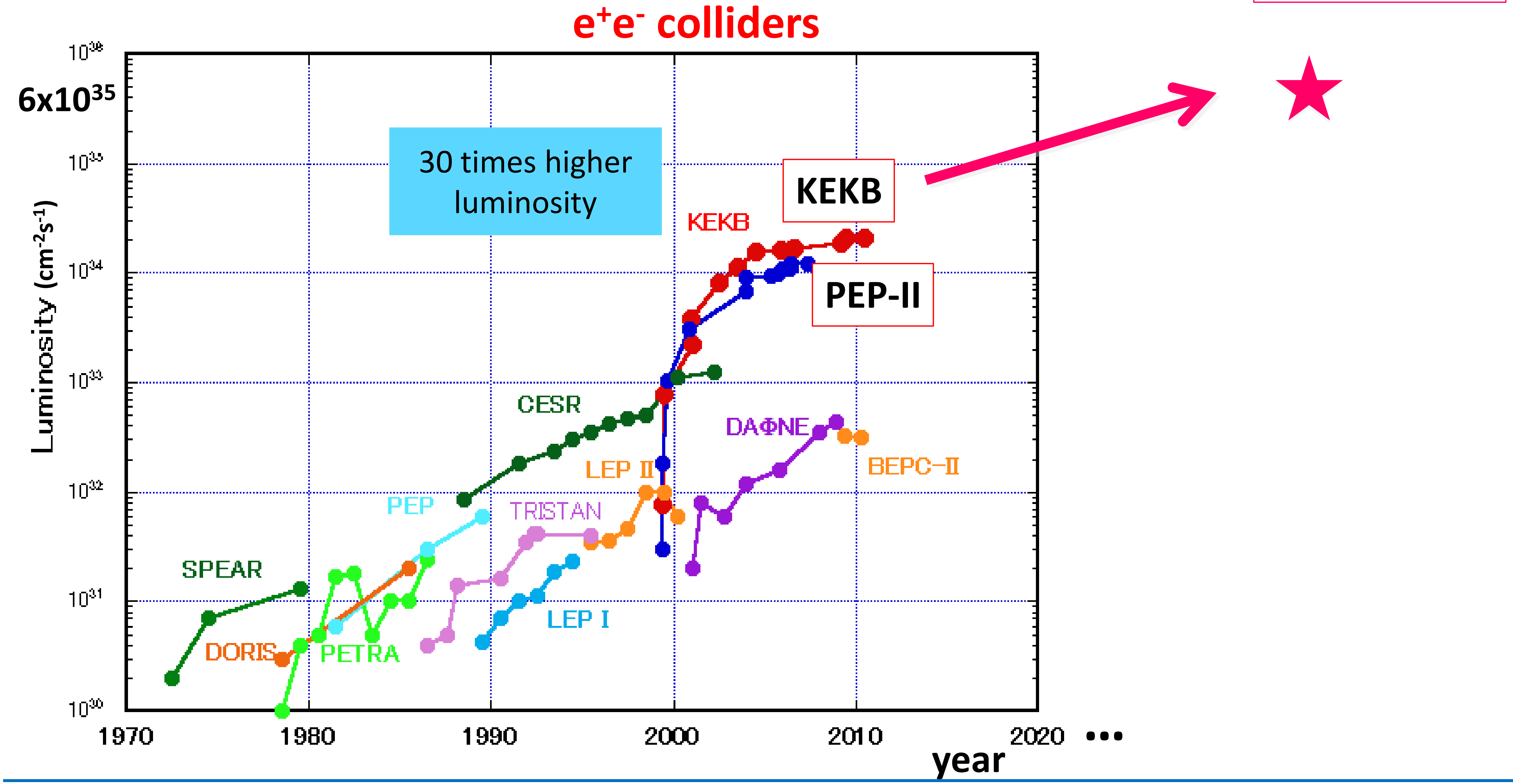
- ❑ Luminosity will increase, background will increase as well
- ❑ Best effort to keep the single-object (track, muon, photon) trigger lines in working conditions
- ❑ Displaced-vertex trigger&tracking needed (efficiency decreases abruptly with lifetime): in preparation

Challenges

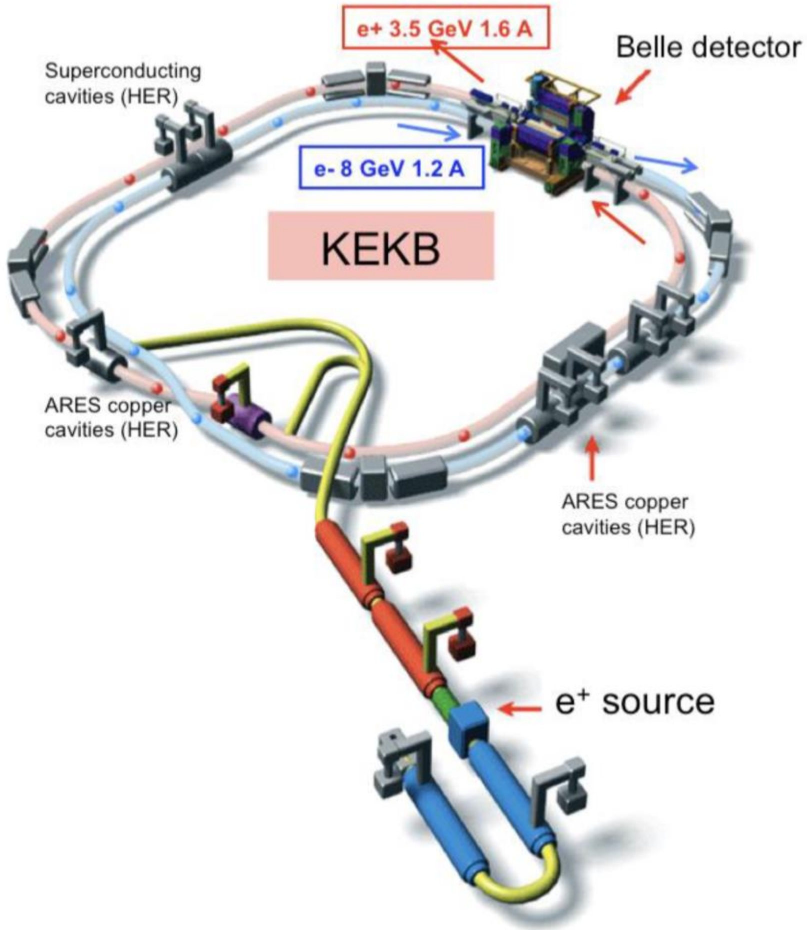
✓ Belle II is expected to lead the world sensitivity in most of the dark sector searches

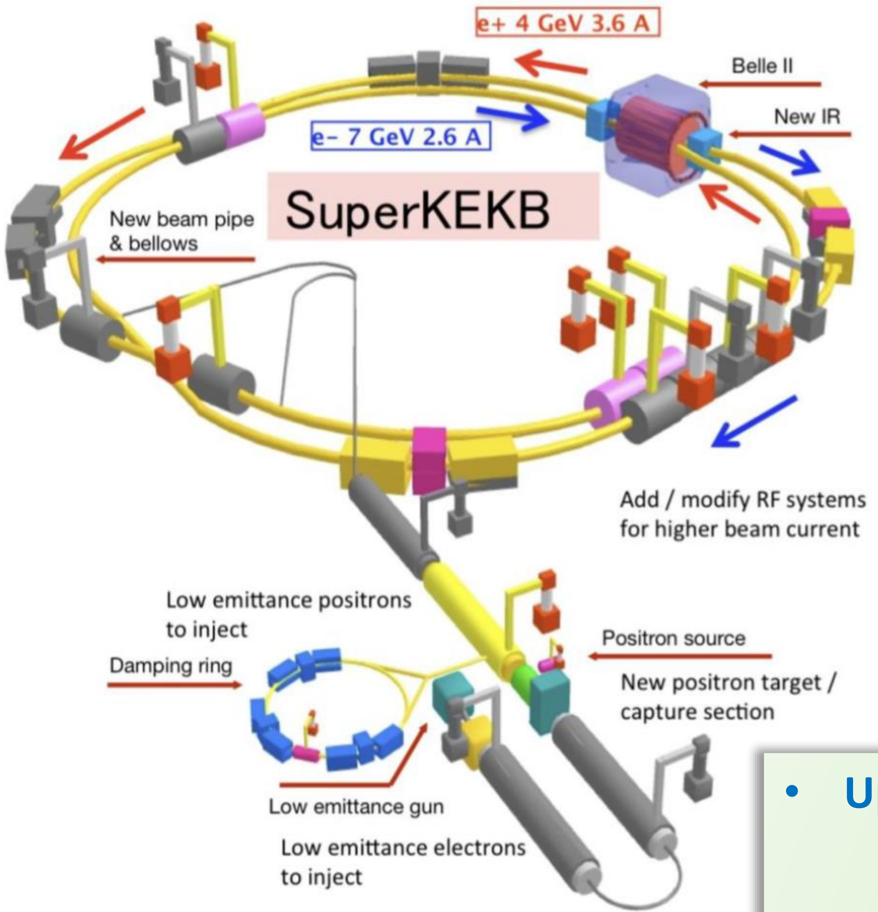
SPARE SLIDES

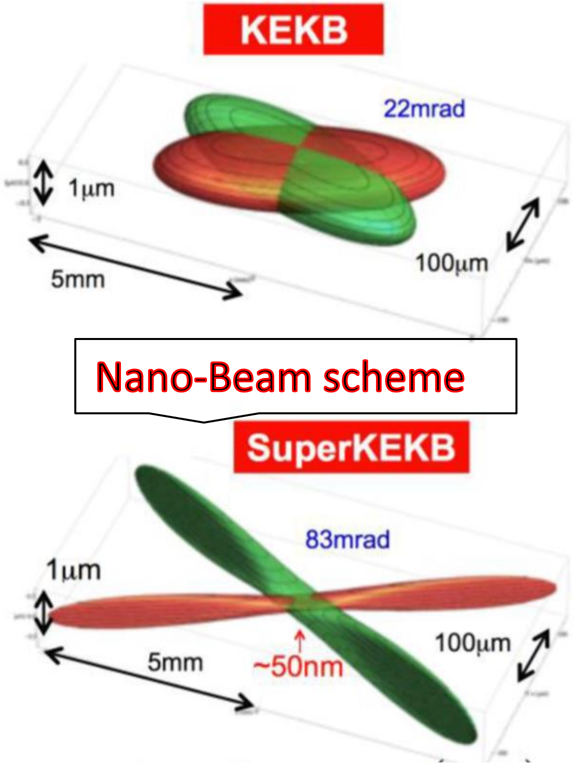
Peak luminosity trend



From KEKB to SuperKEKB







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

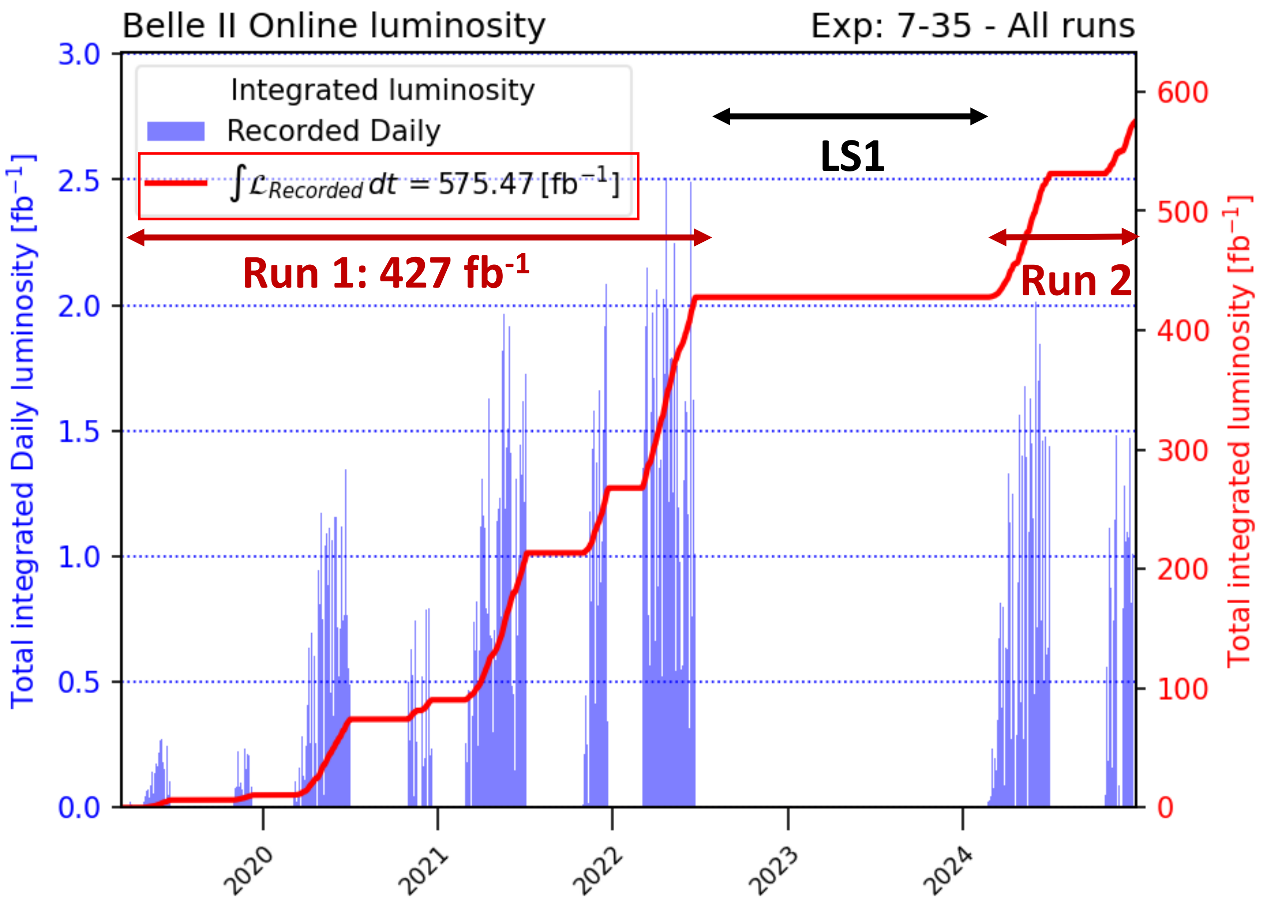
- **Upgraded rings**
  - ➢ New e^+ Damping Ring
  - ➢ Increased currents
- **Nano-beam scheme**
  - ➢ New Final Focus magnets (QCS)
  - ➢ Large crossing angle

x20 → x30

SuperKEKB now

Peak luminosity world record: **5.1 x 10^{34} cm^{-2} s^{-1}**

Collected luminosity up to now: 2019-2024



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}

Restart data taking in October 2025

SuperKEKB now

Run 2

- Back to operations at ~4×10^{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 will extend through 2025
  - Restart data taking in October 2025

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

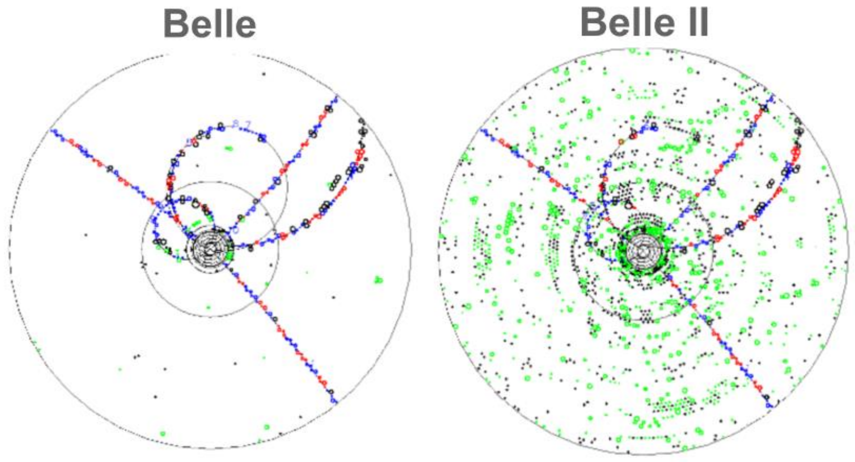
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

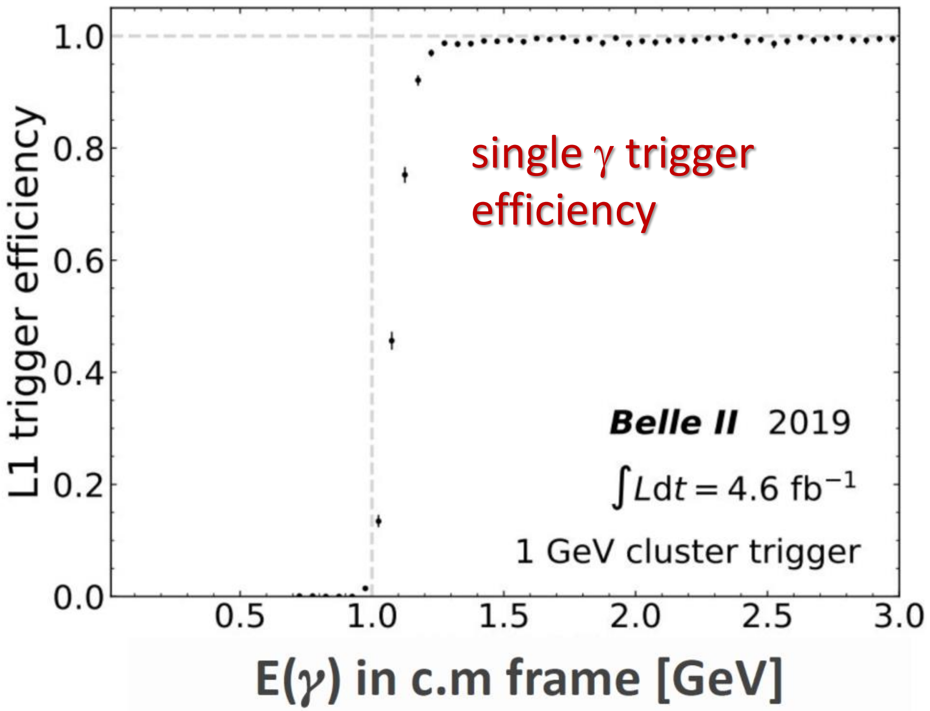
Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

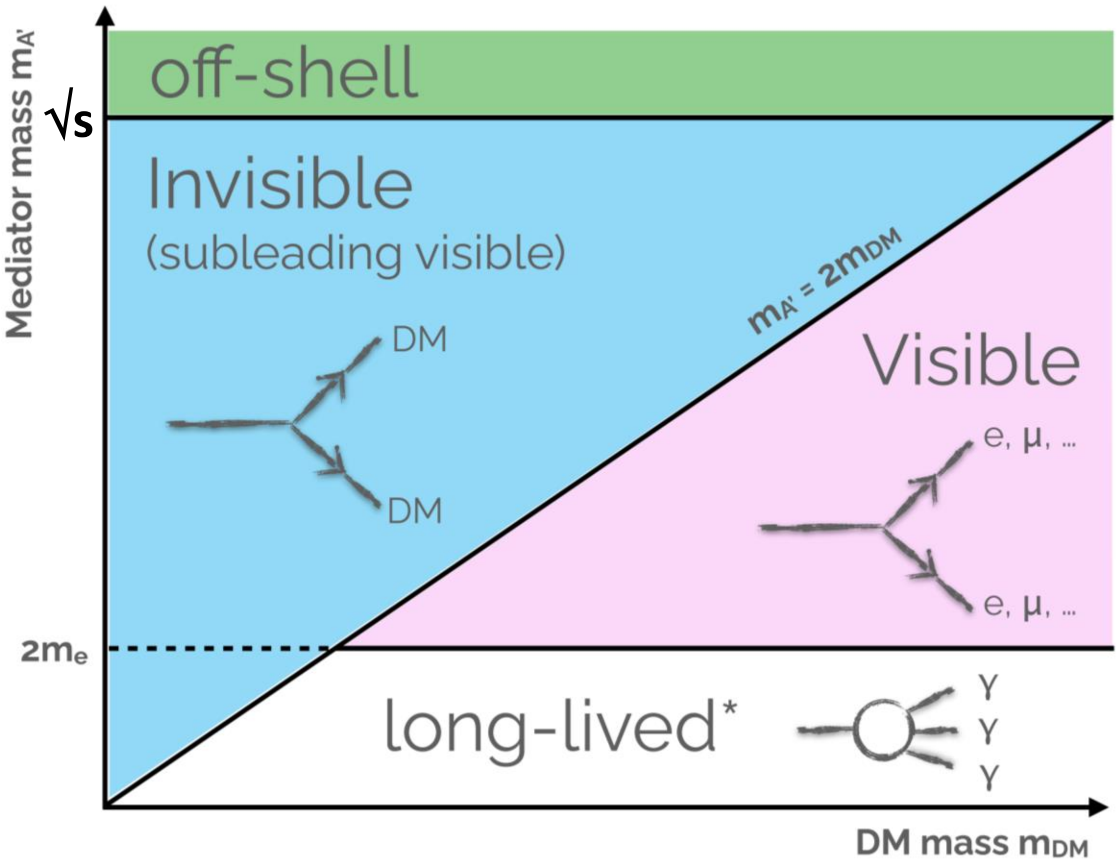
Displaced-vertex trigger
- Under study





Light dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

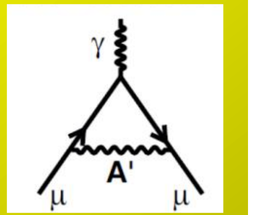


Probability of interaction of LDM detectors is negligible

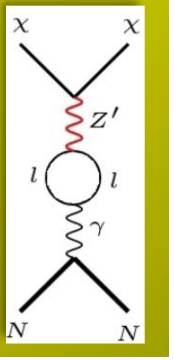
- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g\text{-}2)_\mu$ effect

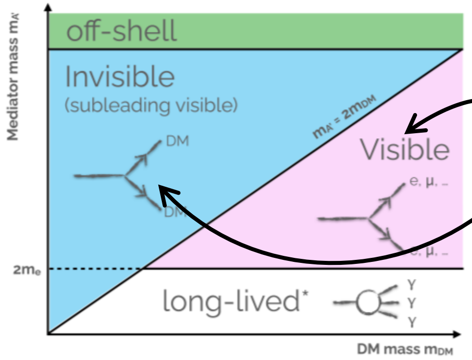


- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits



Search overview: models ↔ signatures ↔ topologies

Models are growing up ~ 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



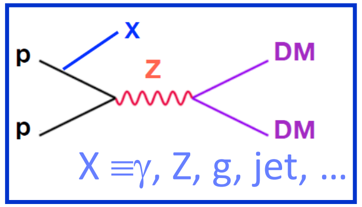
ll (γ) (+missing)

Visible minimal and non minimal dark photons, ALP→ff

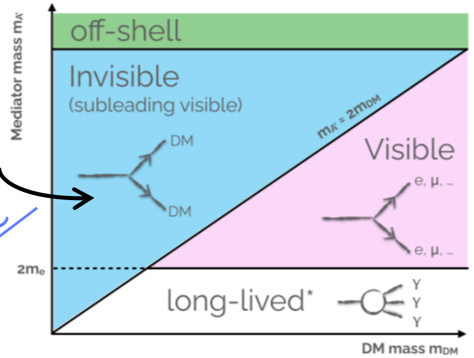
Invisible dark photon, Z'

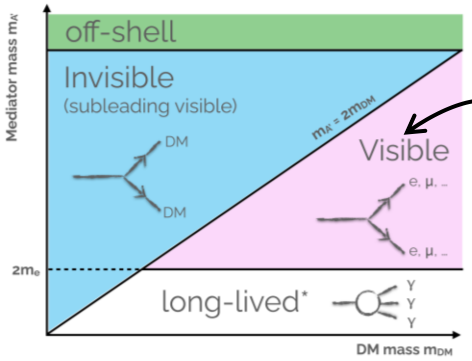
Single γ

Invisible dark photon, ALP →χχ, iDM, LLP



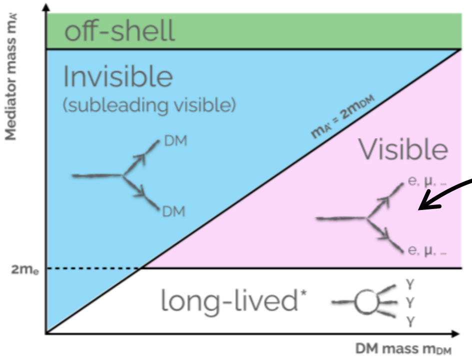
LHC





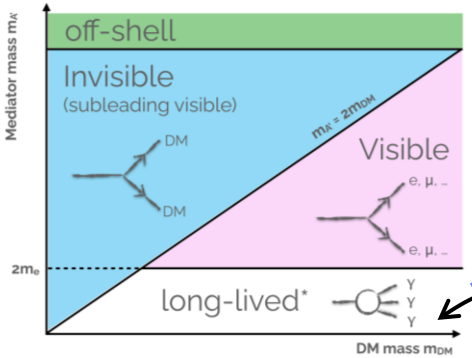
l l l' l'

Visible non minimal dark photons, ALP→ff, scalars, μμττ, ττττ



γγ

Visible ALP → γγ



LLP long-lived particles

Hot topic

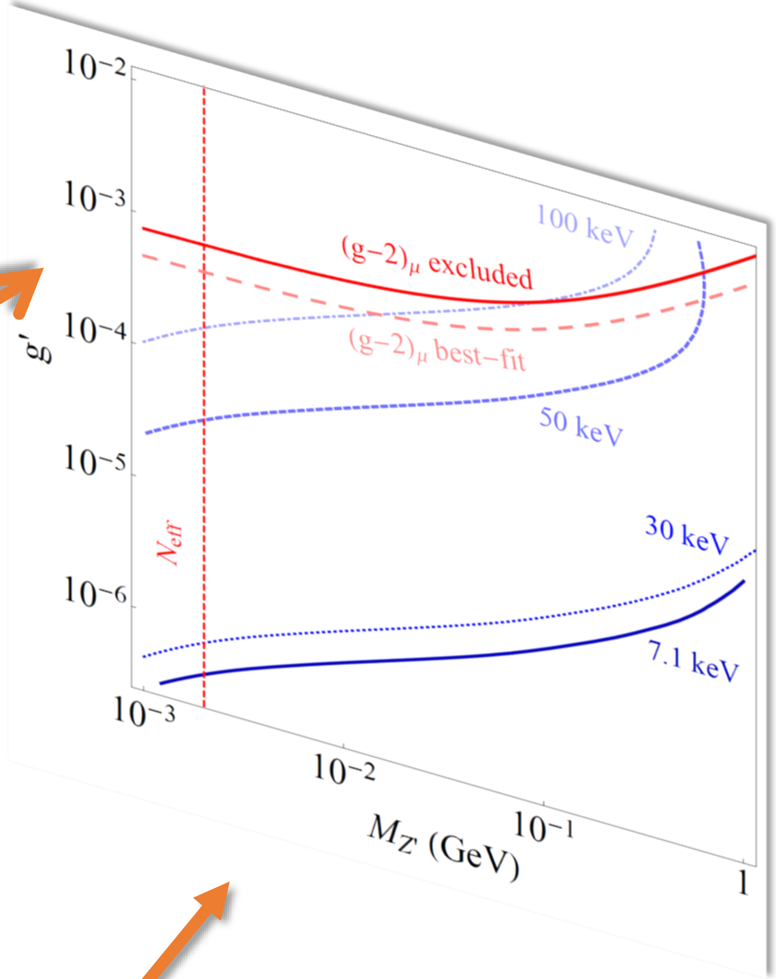
LHC

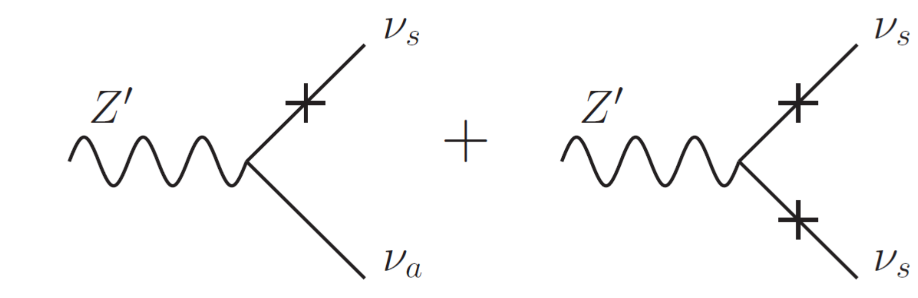
A', ALP→χχ, iDM, scalars

Z': L_μ - L_τ model

- Gauging L_μ - L_τ , 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
  - **$(g-2)_\mu$**
  - **$B \rightarrow K^{(*)}\mu\mu$, R_K, R_{K^*} anomalies**

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





Sterile neutrino abundance

Z': L_μ - L_τ model

- Gauging L_μ - L_τ , 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**
  - **$(g\text{-}2)_\mu$**
  - **$B \rightarrow K^{(*)}\mu\mu$, R_K, R_{K*} anomalies**

Shuve et al. (2014), arXiv 1408.2727
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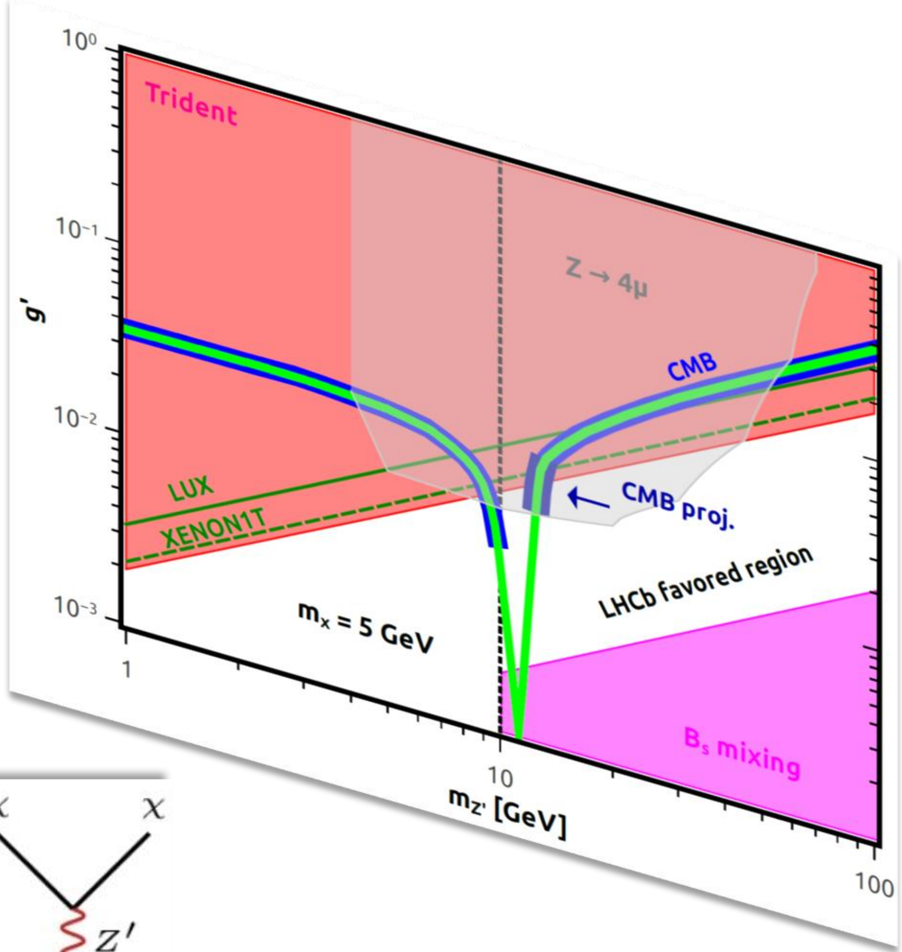
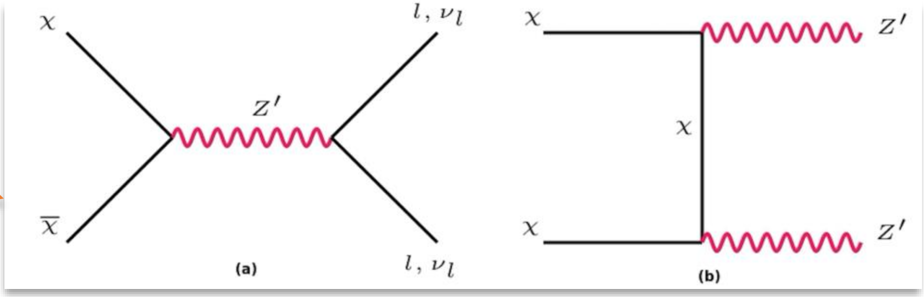
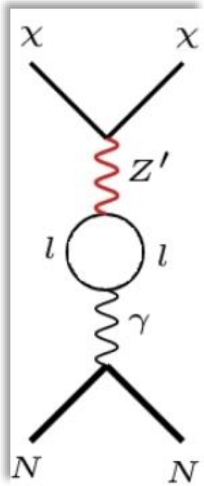


Annihilation



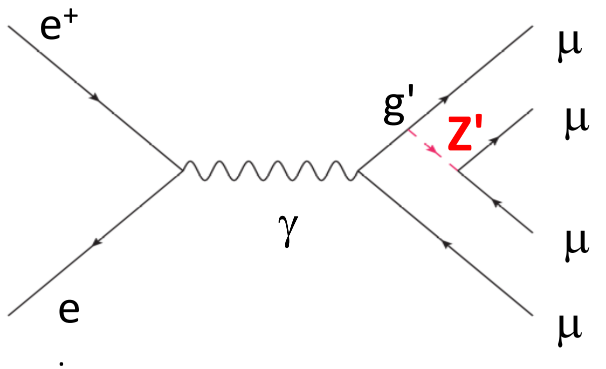


Direct detection

L_μ-L_τ model: Z' → μμ

L_μ-L_τ
Z' → μμ

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



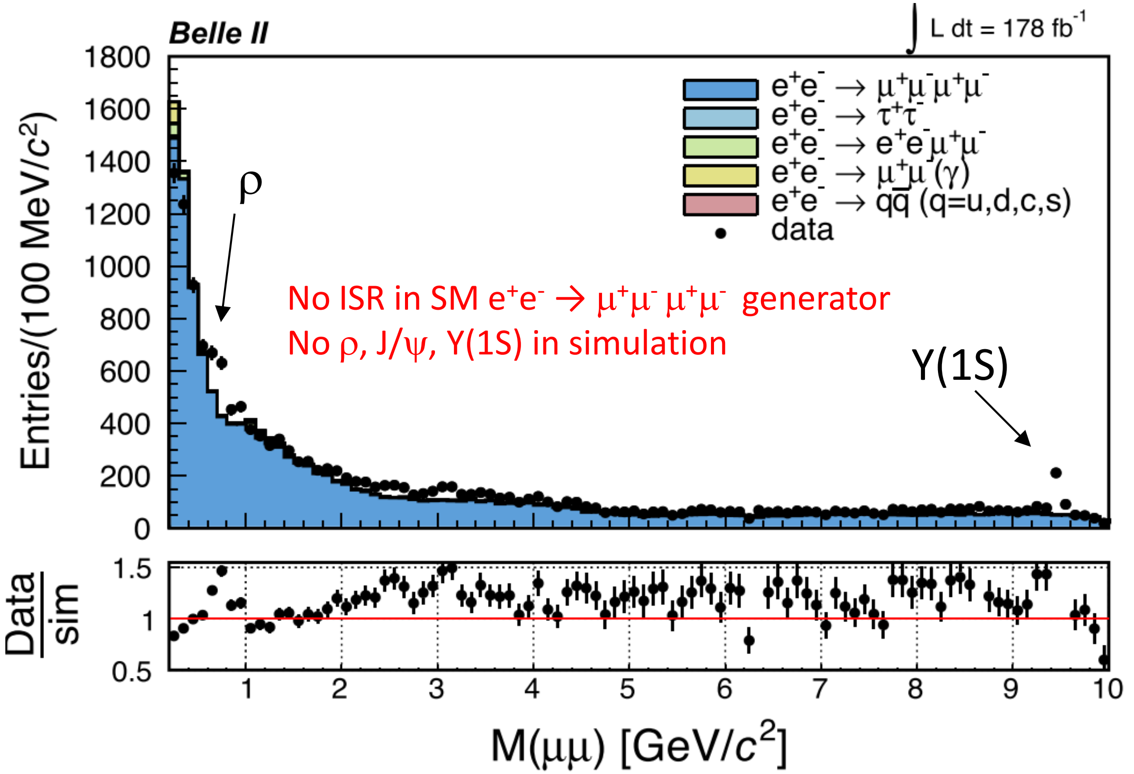
$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

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

Fits to M(μμ)



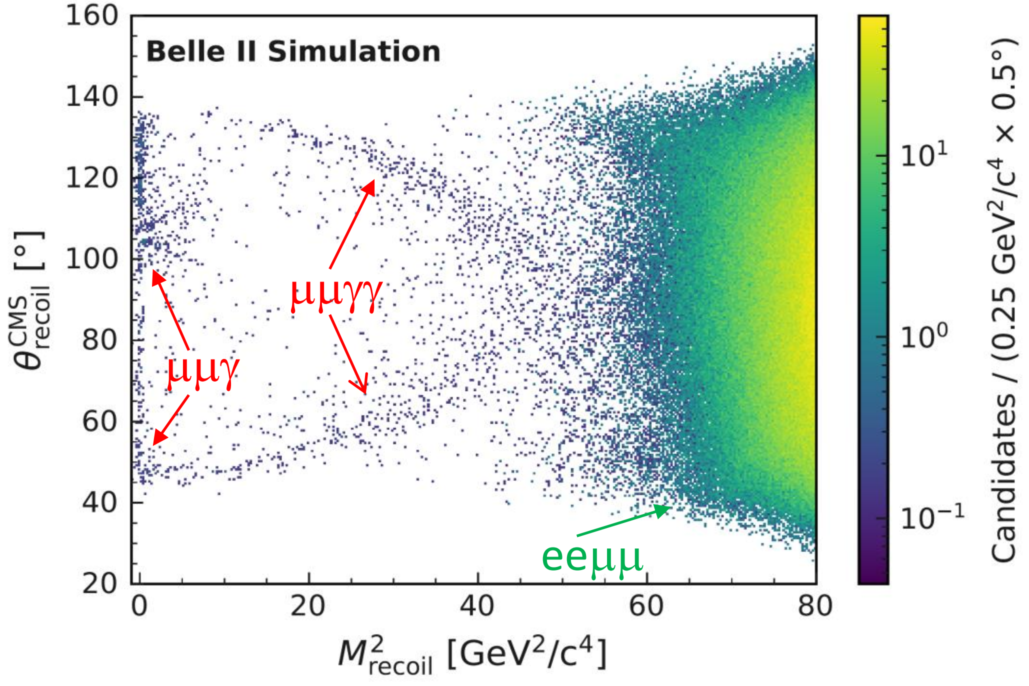
Z’ to invisible: analysis

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

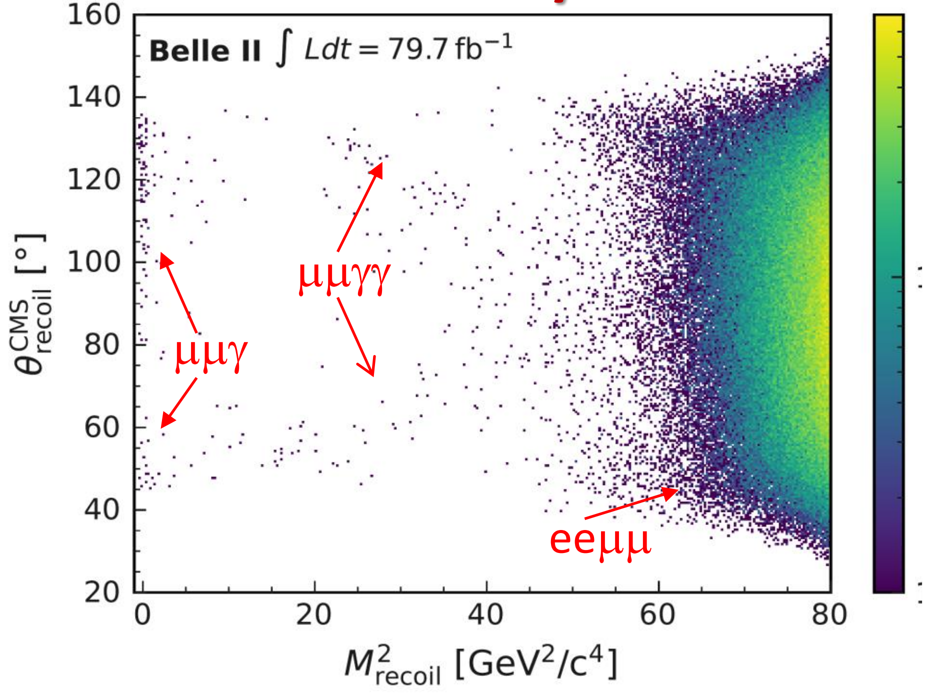
3 control samples

$\mu\mu\gamma$	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}

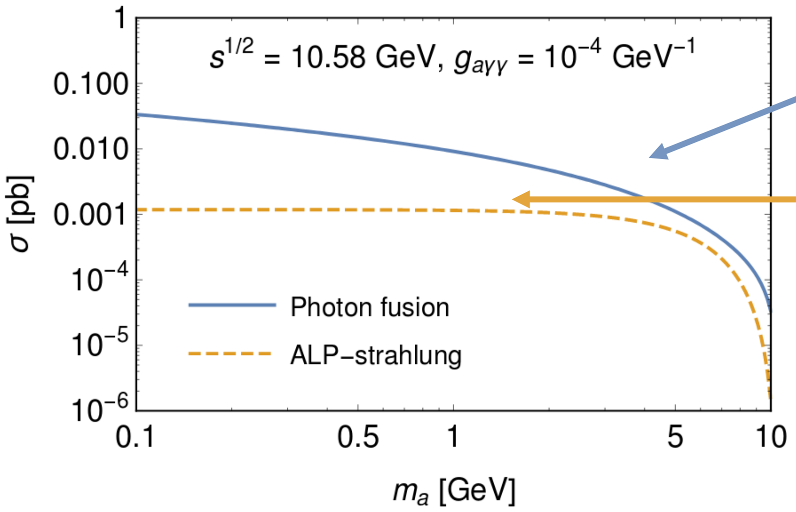


Observed yields



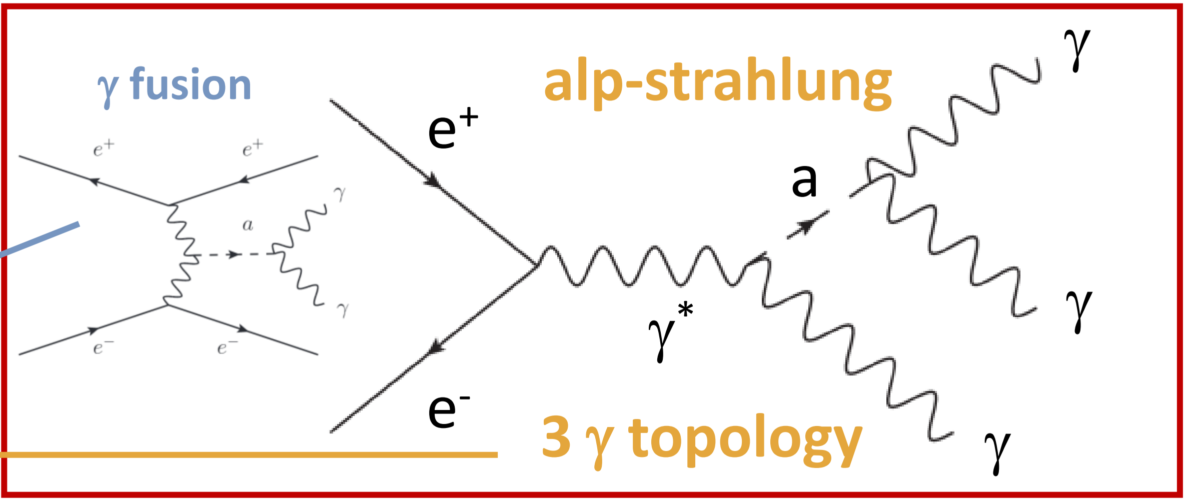
Axion Like Particles (ALPs)

- 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)



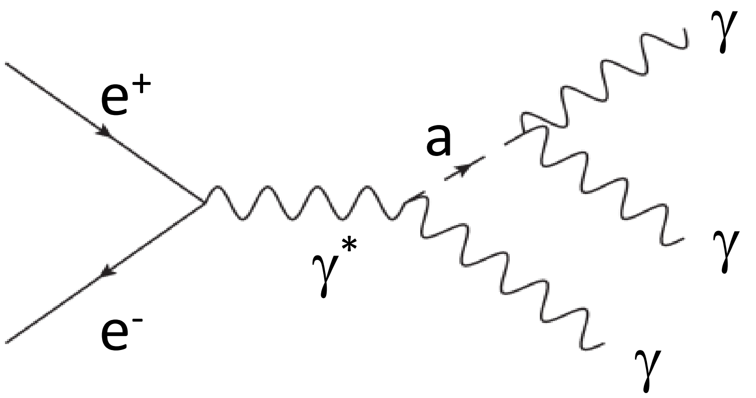
Belle II

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



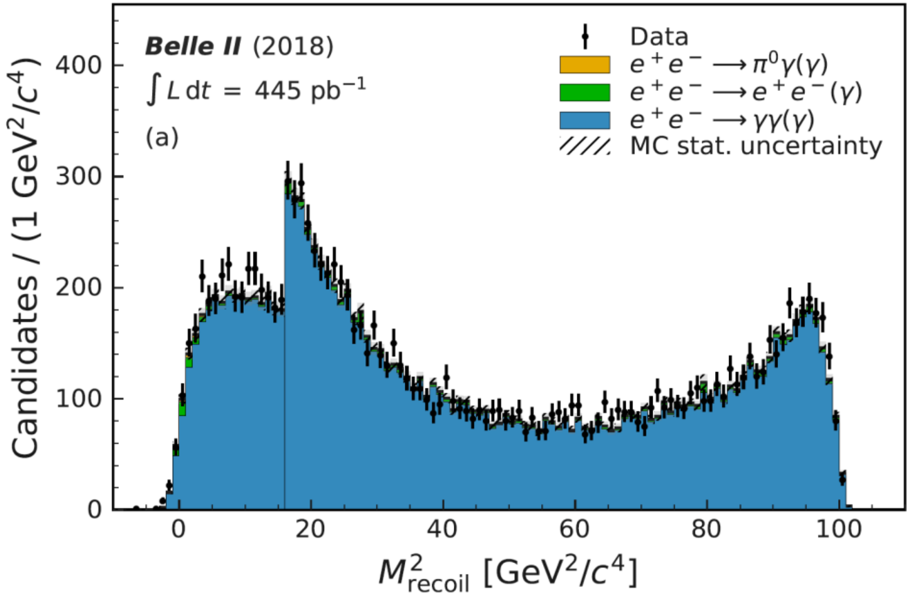
photon fusion sensitivity under study

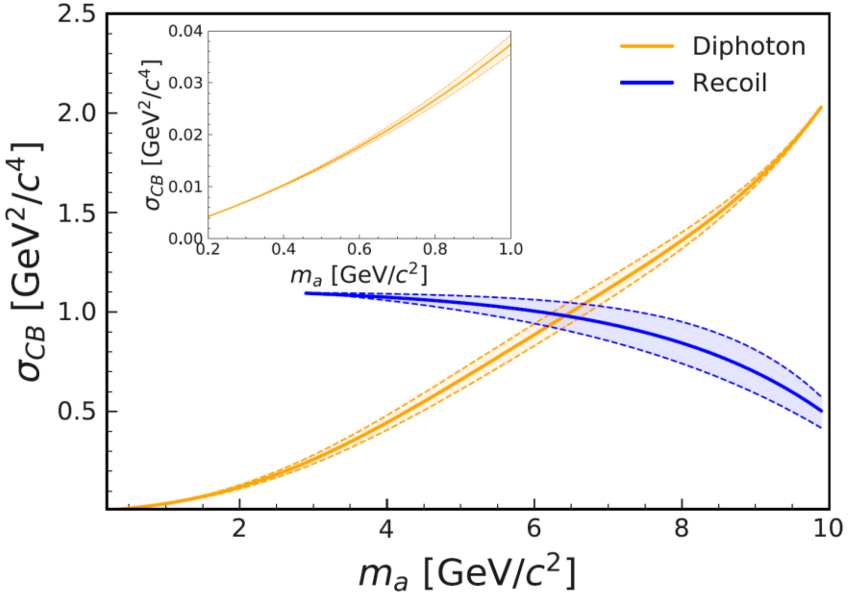
ALP →γγ : observed yields



Pilot run (2018)

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

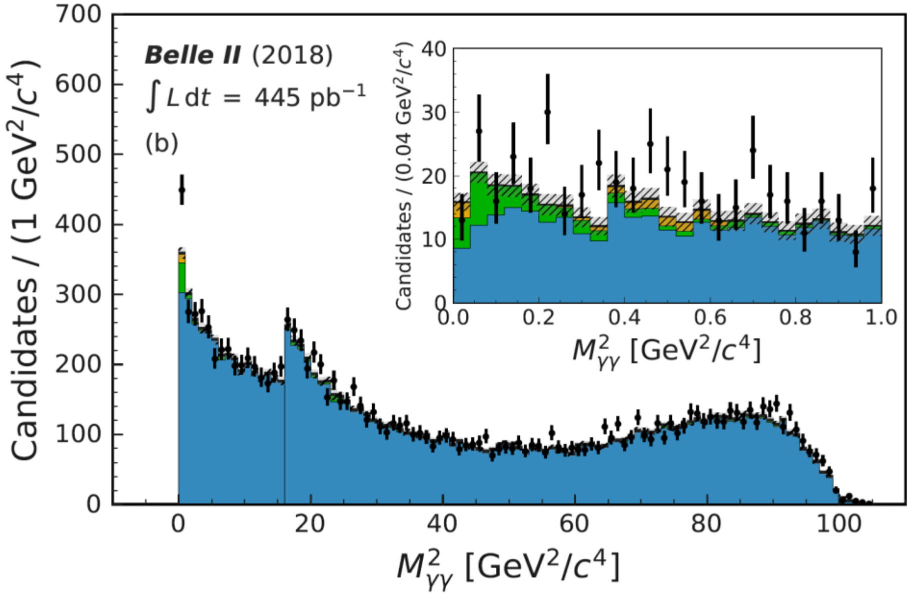




Main backgrounds:

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

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



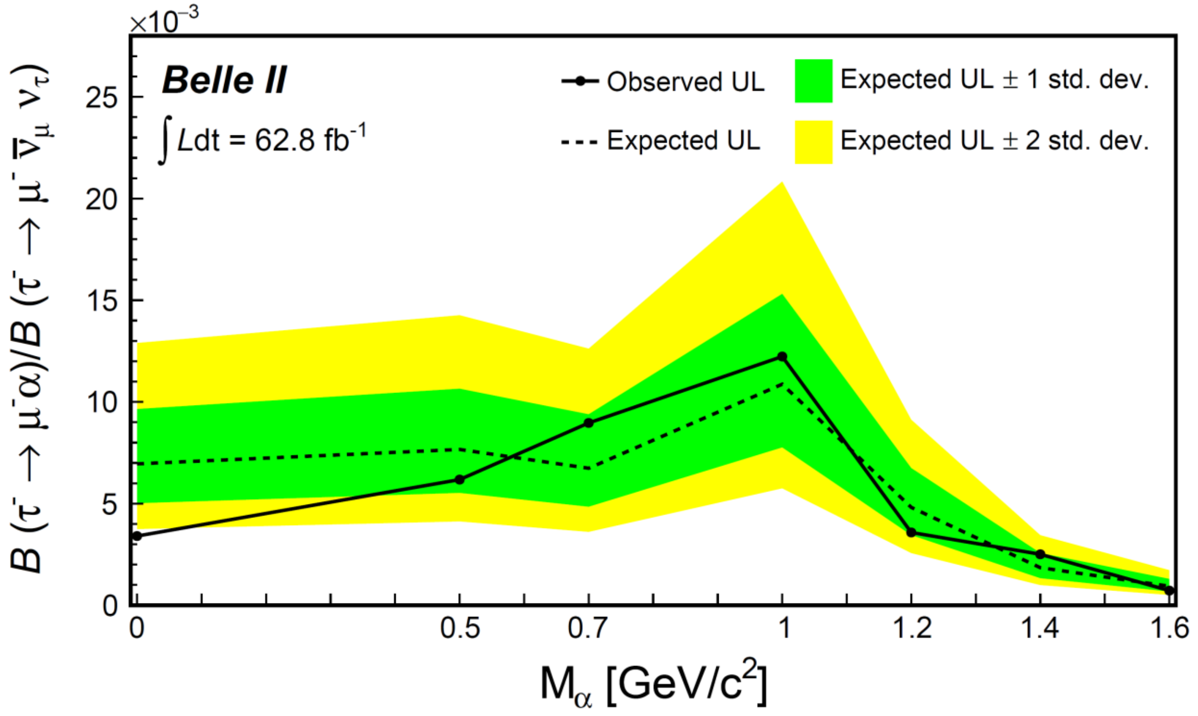
$\tau \to l\alpha$ with invisible α

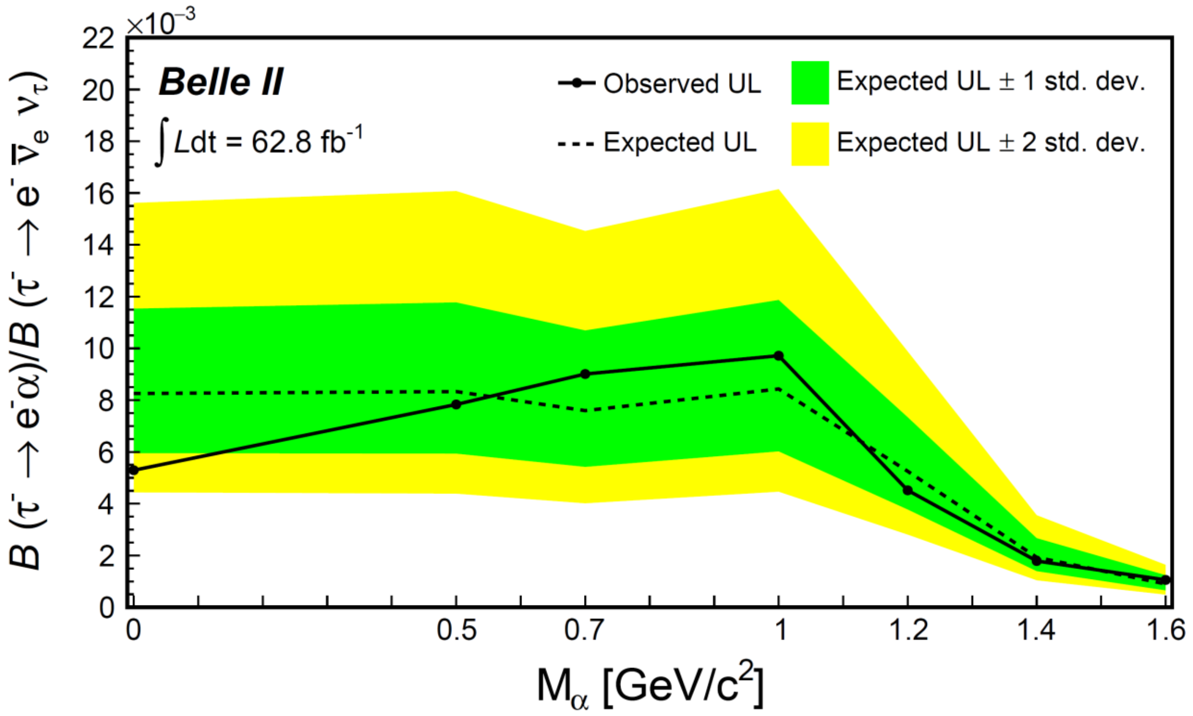
Invisible α in τ decays

$\tau \to l\alpha$ 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

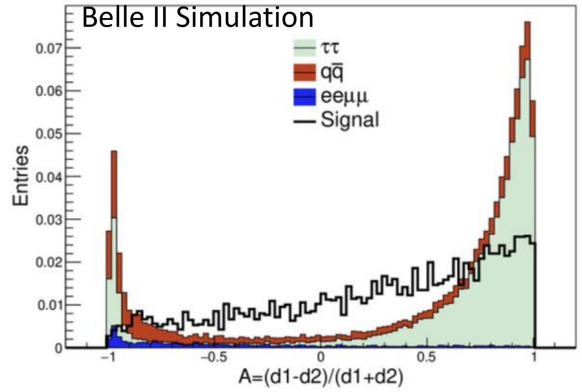
Main backgrounds

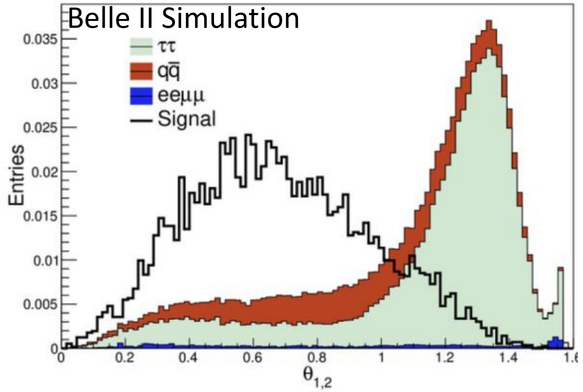
$e^+e^- \to \tau^+\tau^- (\gamma)$ 1+3 prong
$e^+e^- \to qq$ (q=u,d,s,c)

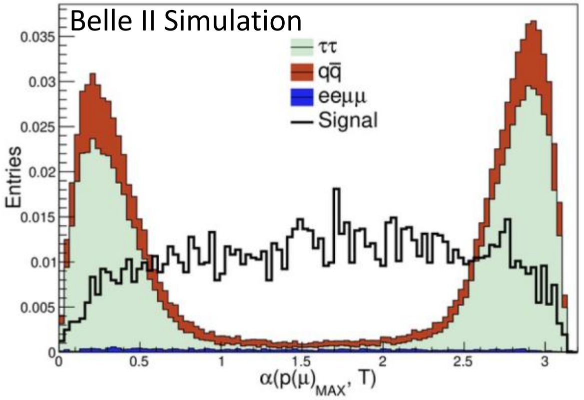
$e^+e^- \to e^+e^- \mu^+\mu^-$
$e^+e^- \to \mu^+\mu^- \tau^+\tau^-$
$e^+e^- \to e^+e^- \tau^+\tau^-$
no ISR in simulation

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

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



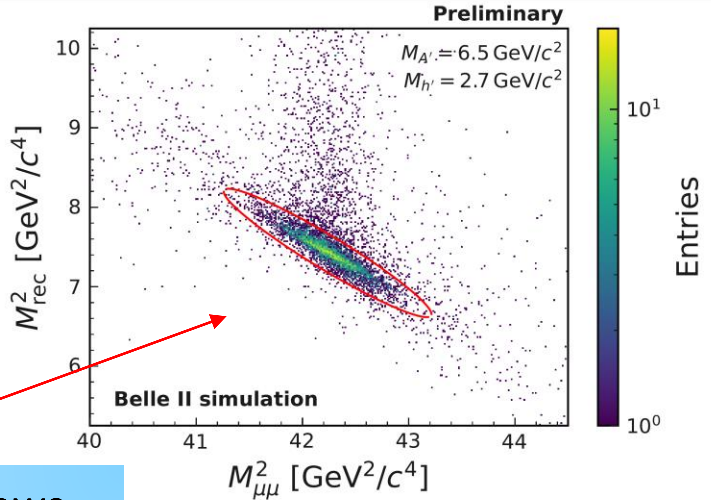




Dark Higgsstrahlung: analysis

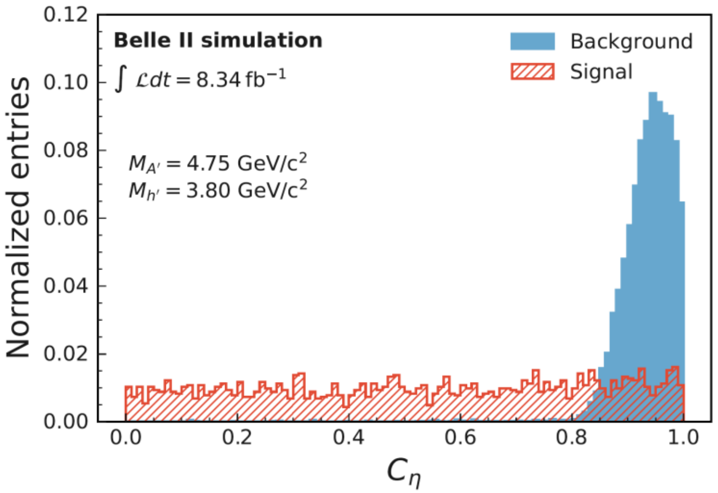
8.34 fb^{-1} (2019)

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

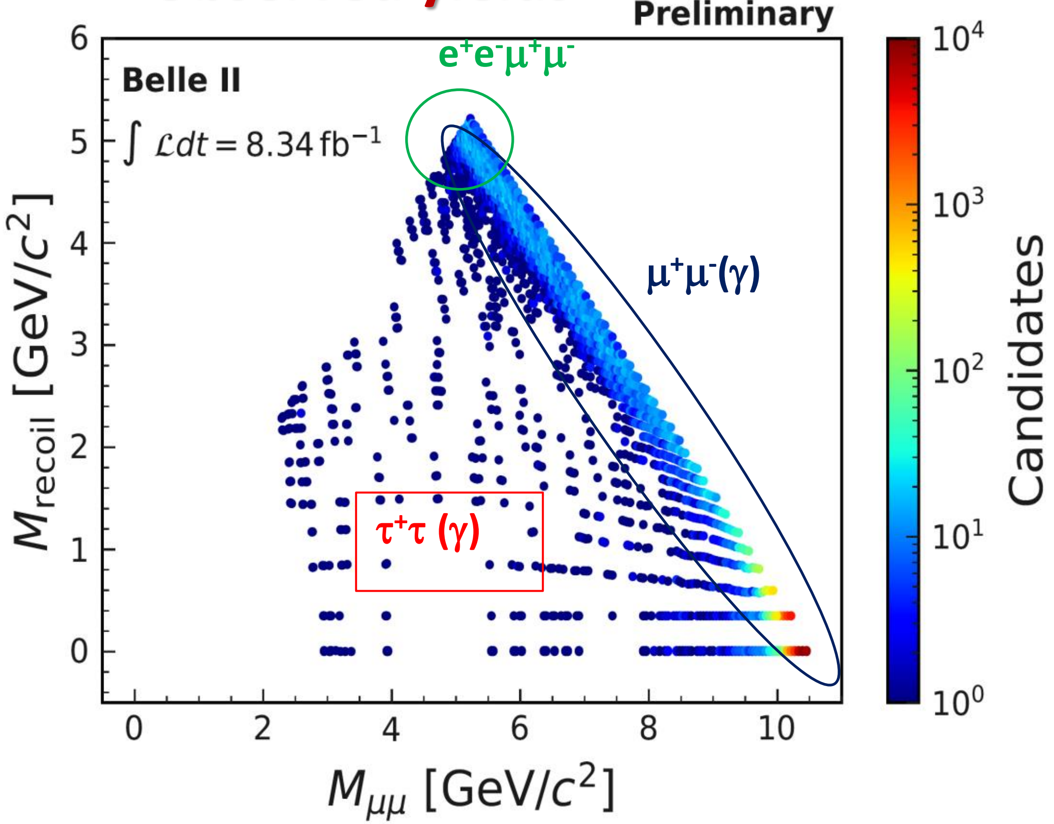
Helicity angle



Backgrounds

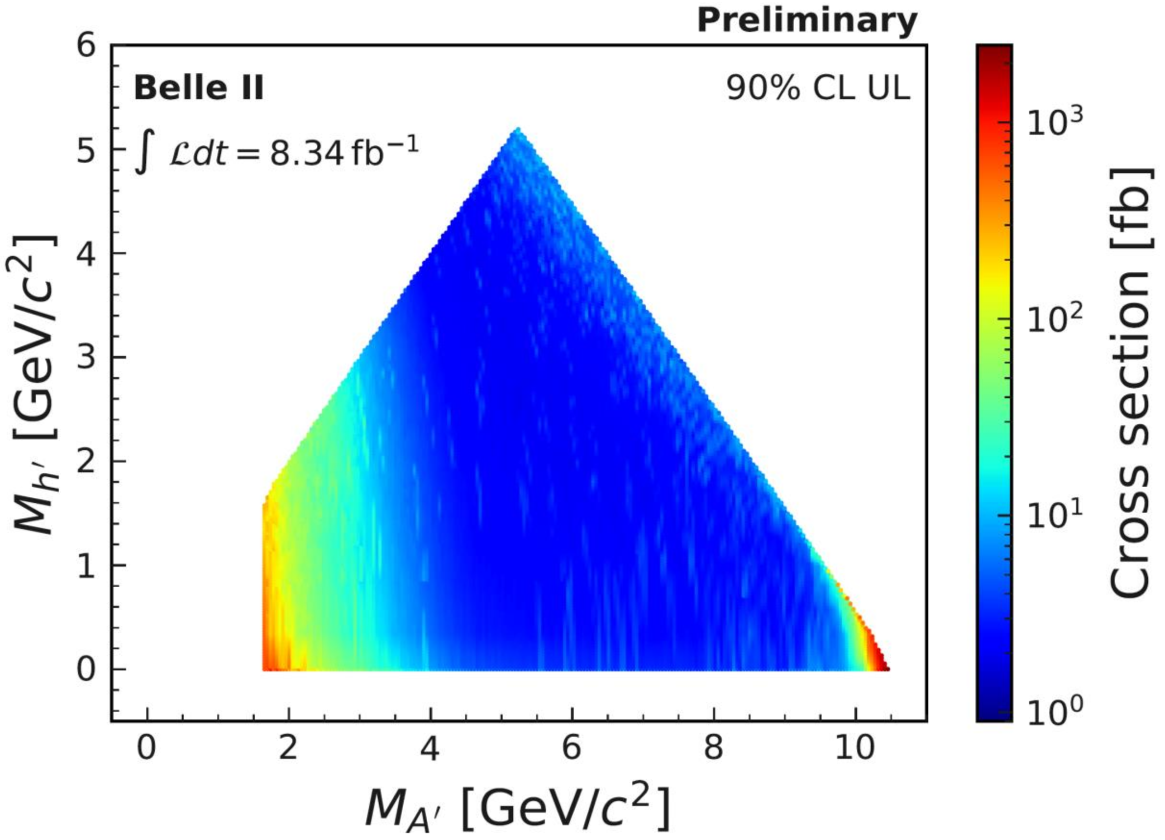
$\mu^+\mu^-(\gamma)$ 79%
$\tau^+\tau^-(\gamma)$ 18%
$e^+e^-\mu^+\mu^-$ 3%

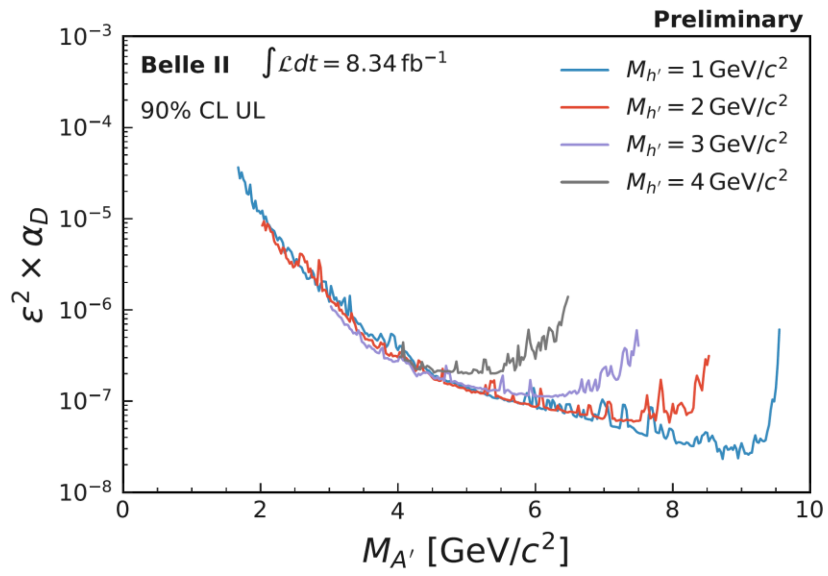
Observed yields

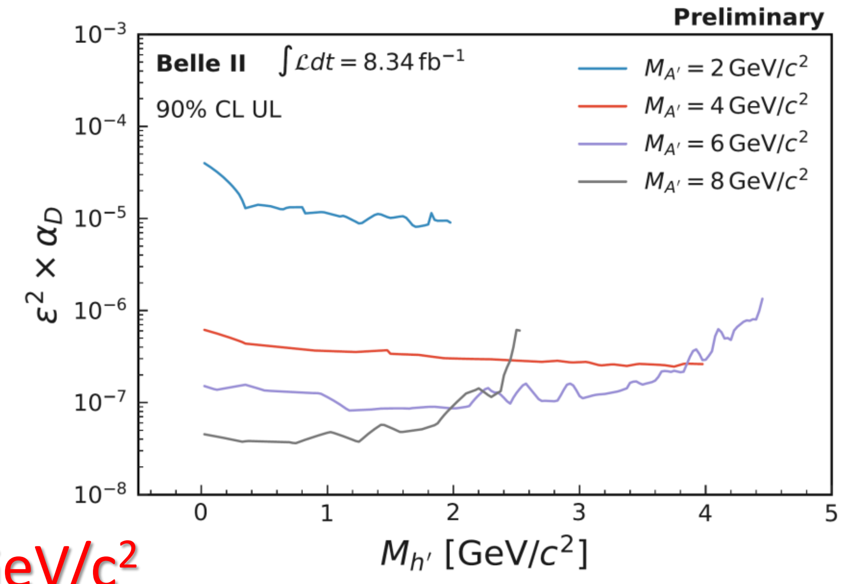


Dark Higgsstrahlung: results

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







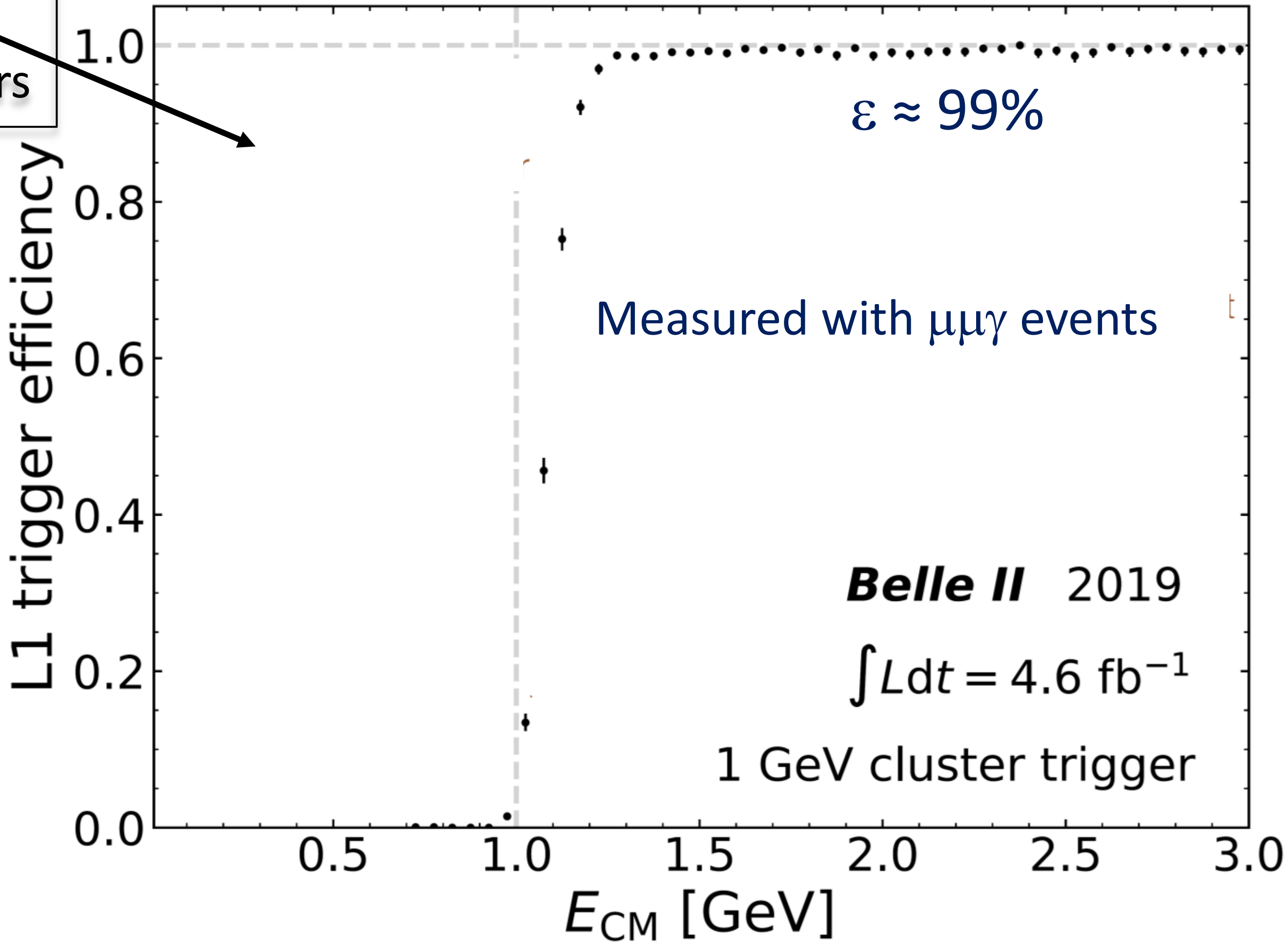
World first for $1.65 < M_{A'} < 10.51$ GeV/c^2

Invisible dark photon: single photon trigger

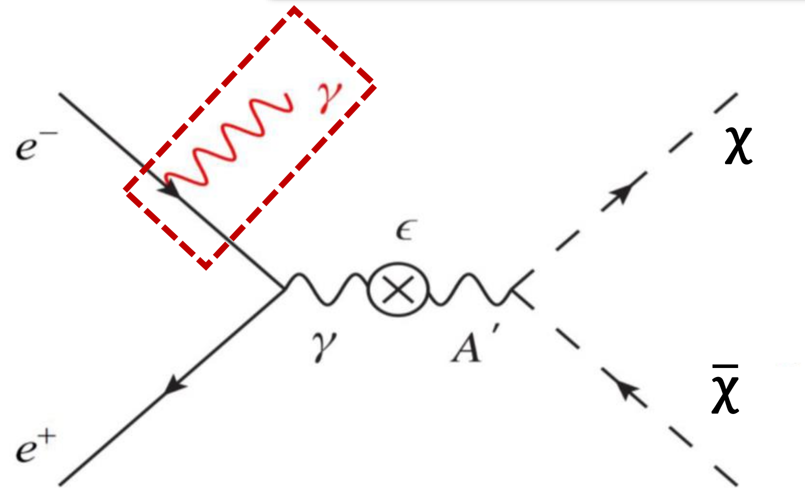
- **E_{CM} > 2 GeV**
- **E_{CM} > 1 GeV** in barrel + no other clusters
- **E_{CM} > 0.5 GeV** in central barrel + no other clusters

Would extend the search range up to $M_{A'} <\approx 10$ GeV (psycological threshold)

Much more aggressive than originally expected.



Invisible dark photon: experimental signature



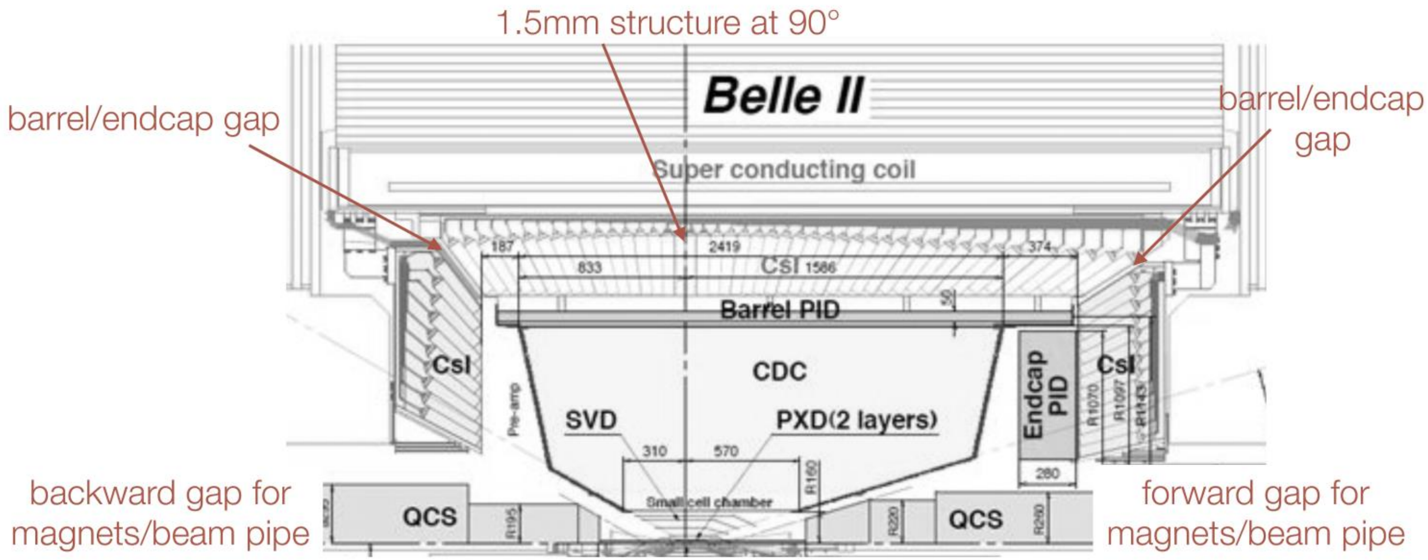
Only **one photon** in the detector

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

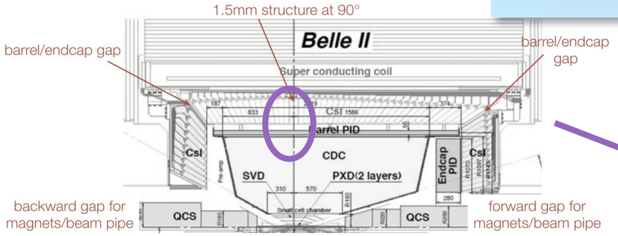


Backgrounds

$e^+e^- \to e^+e^-\gamma(\gamma)$ → 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

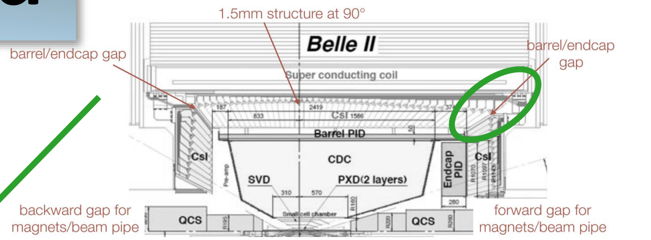


$e^+e^- \rightarrow \gamma\gamma\gamma$

1 γ in 90^0 gap

1 γ out of ECL acceptance

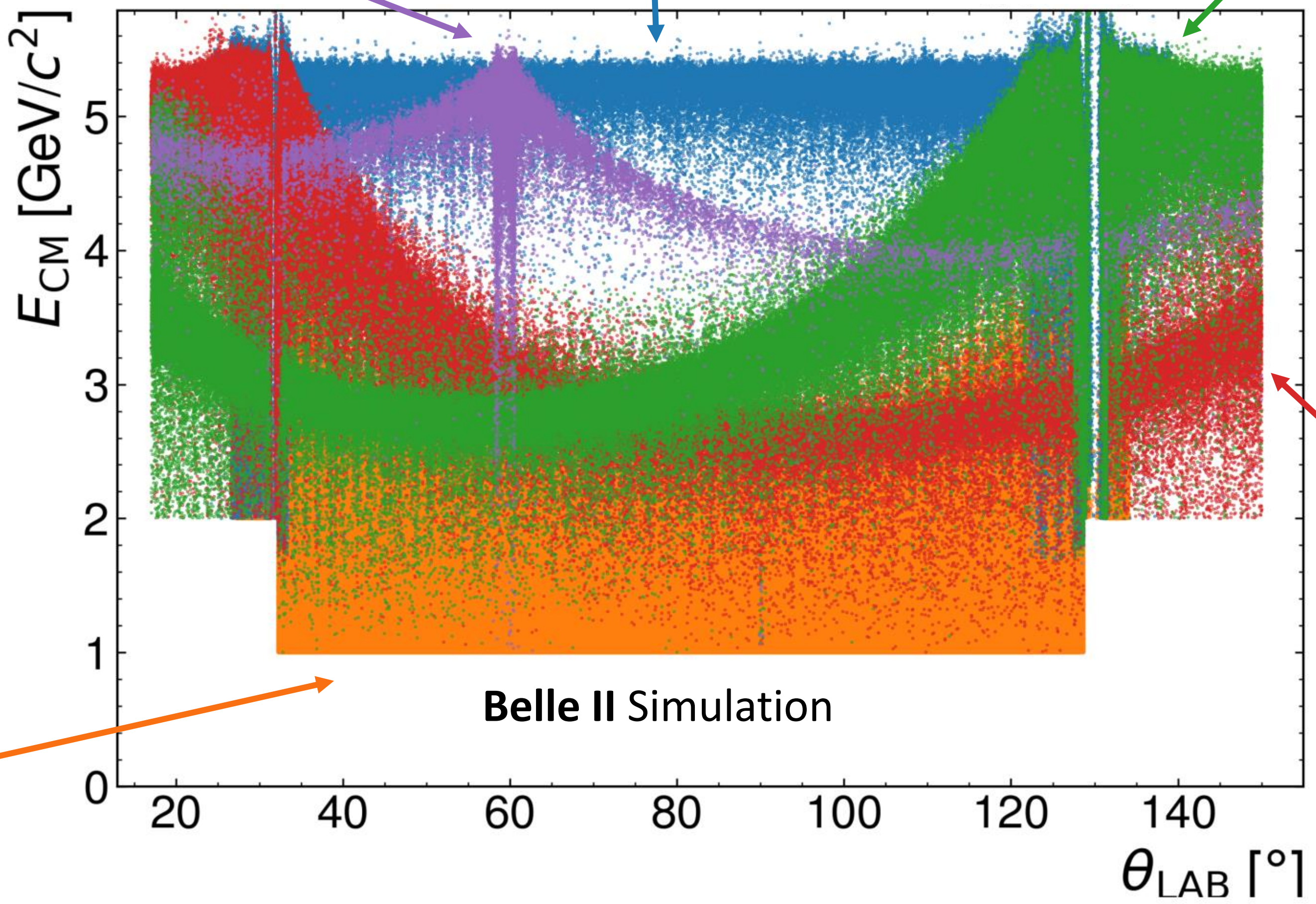
$e^+e^- \rightarrow \gamma\gamma$

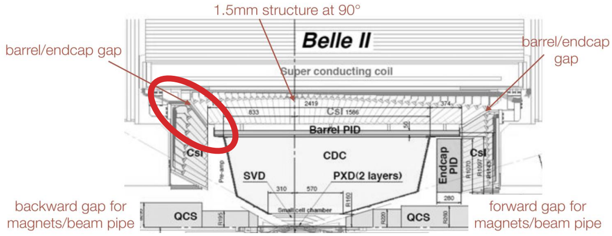


$e^+e^- \rightarrow \gamma\gamma\gamma$

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

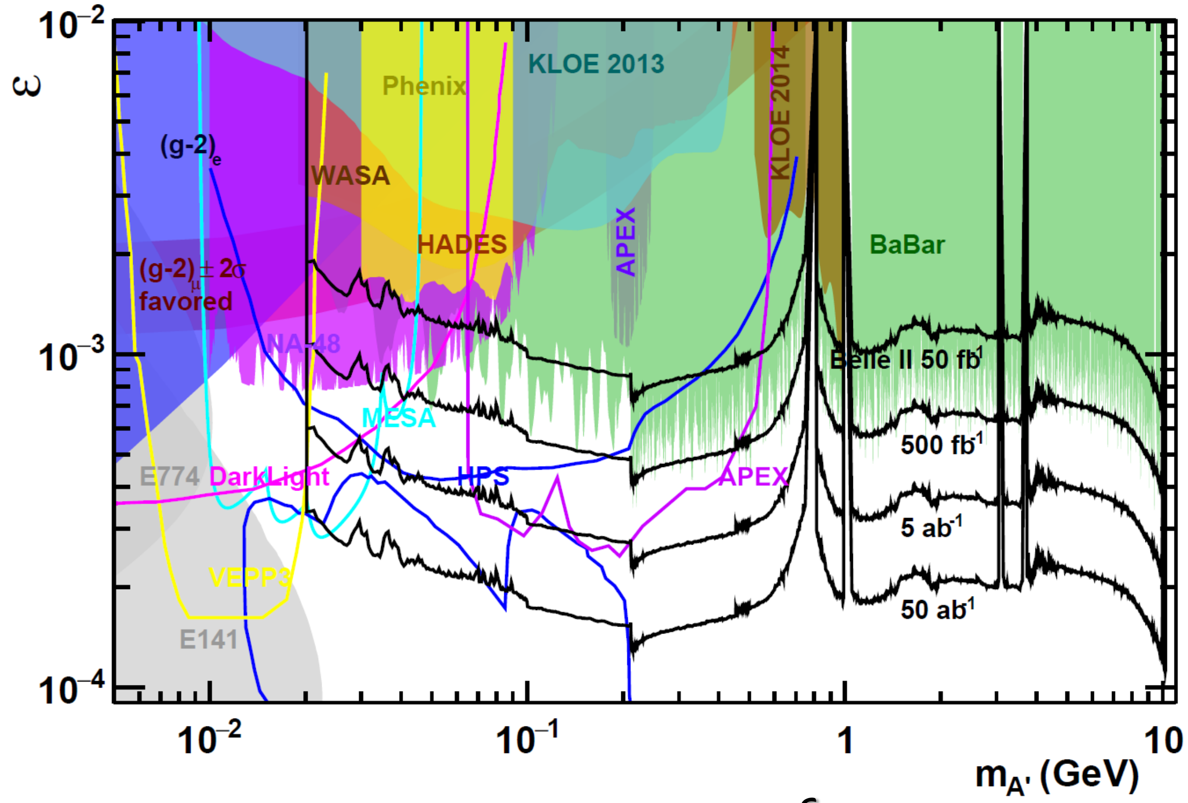
$e^+e^- \rightarrow \gamma\gamma\gamma$

2 γ out of ECL acceptance

Crucial usage of KLM to veto photons in ECL gaps

Dark photon: luminosity projections

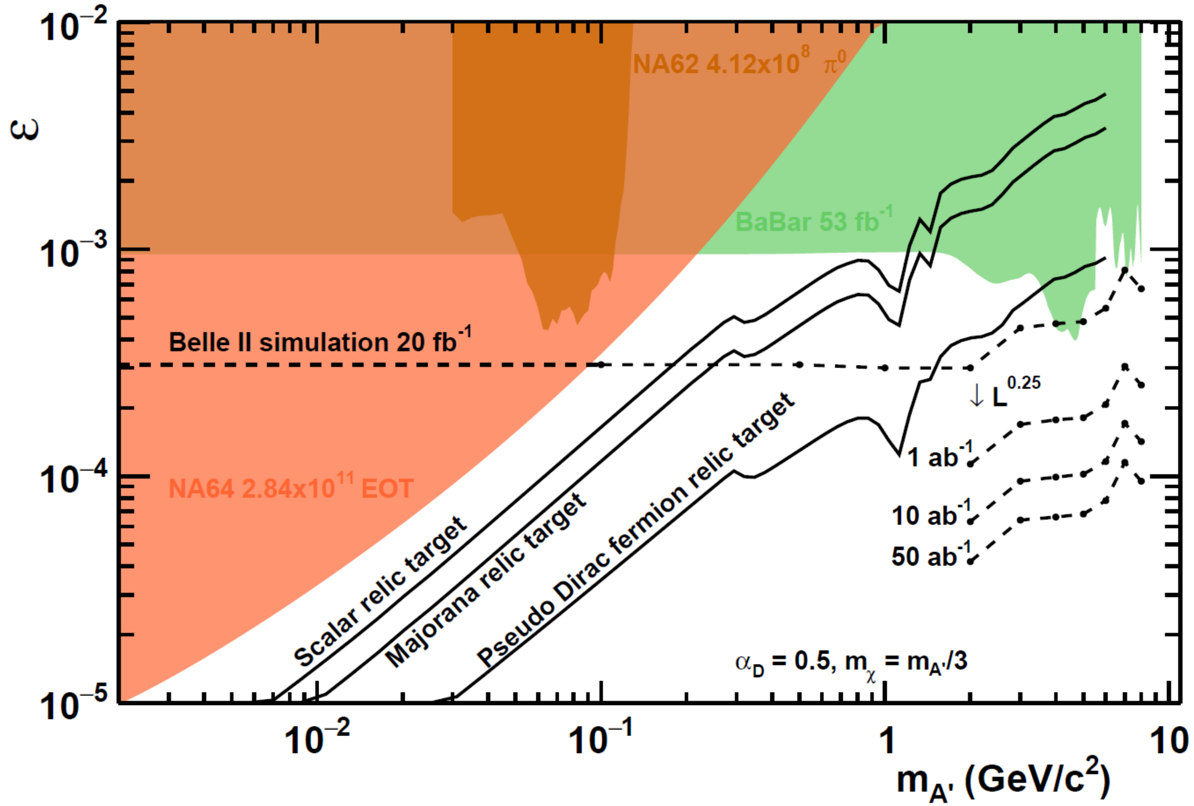
Visible



Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

Invisible



Belle II vs BaBar

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