Dark sector in Belle II

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INFN – Roma 3

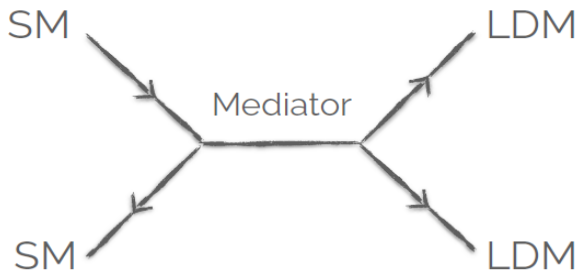
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK

- ✓ Belle II and a light dark sector
- ✓ Search of
  - ➢ ALP→γγ
  - ➢ Z' to invisible
  - ➢ Z', S, ALP →ττ
  - ➢ Dark Higgsstrahlung A'h'
  - ➢ A' visible + invisible
  - ➢ LLP signatures
- ✓ Perspectives & Summary

Dark matter hunt with a light sector

See R.Franceschini's talk



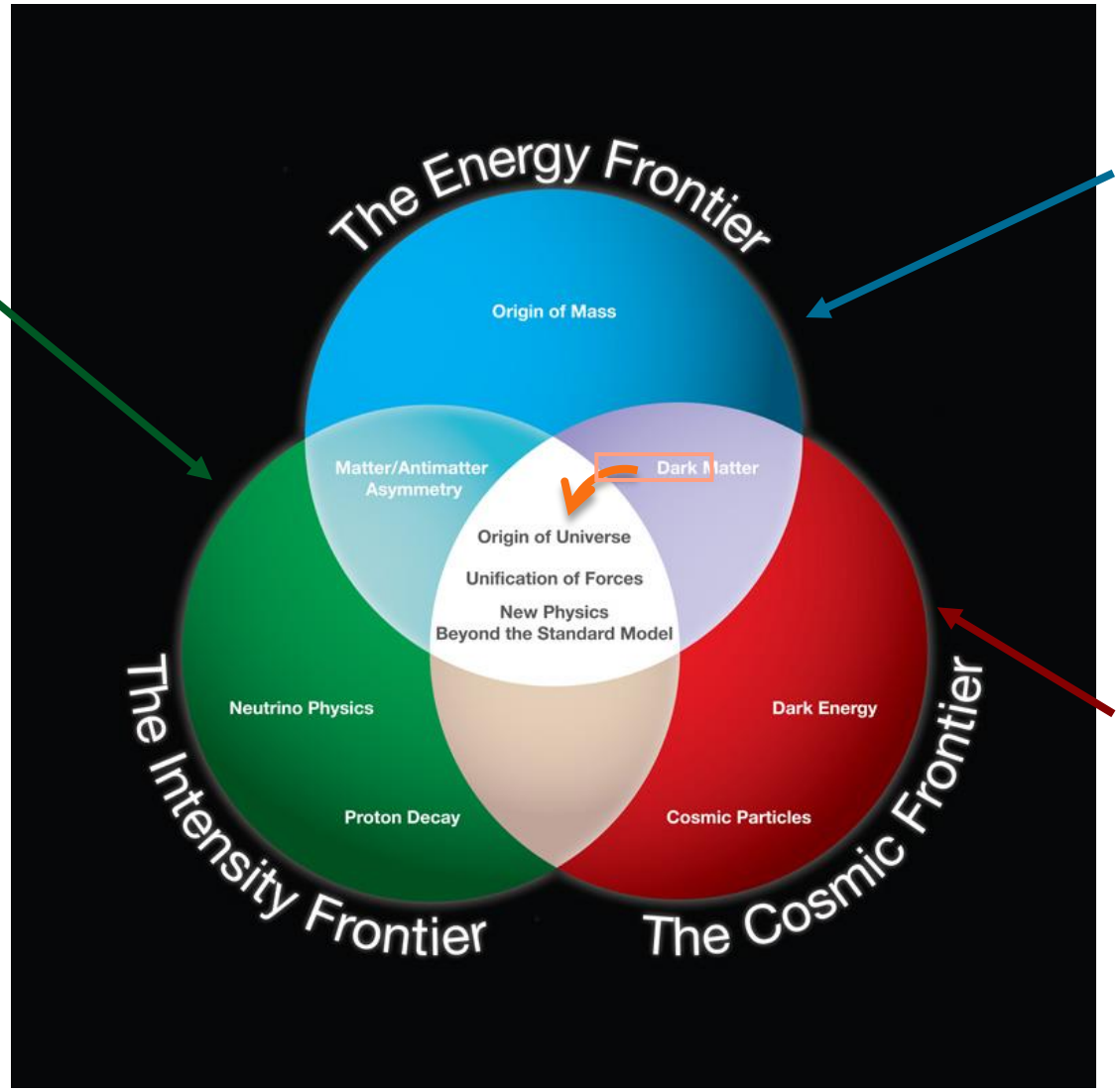
Light Dark Matter Mediators
→ portals

Vector portal
Dark photon, **Z'**, …

Pseudoscalar portal
QCD Axions, **ALPs**, …

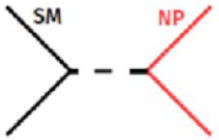
Scalar portal
Dark Higgs, **scalars**

Neutrino portal
Sterile neutrino



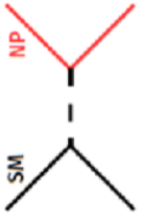
Energy frontier

Direct production of new particles - limited by beam energy
(LHC – ATLAS, CMS)



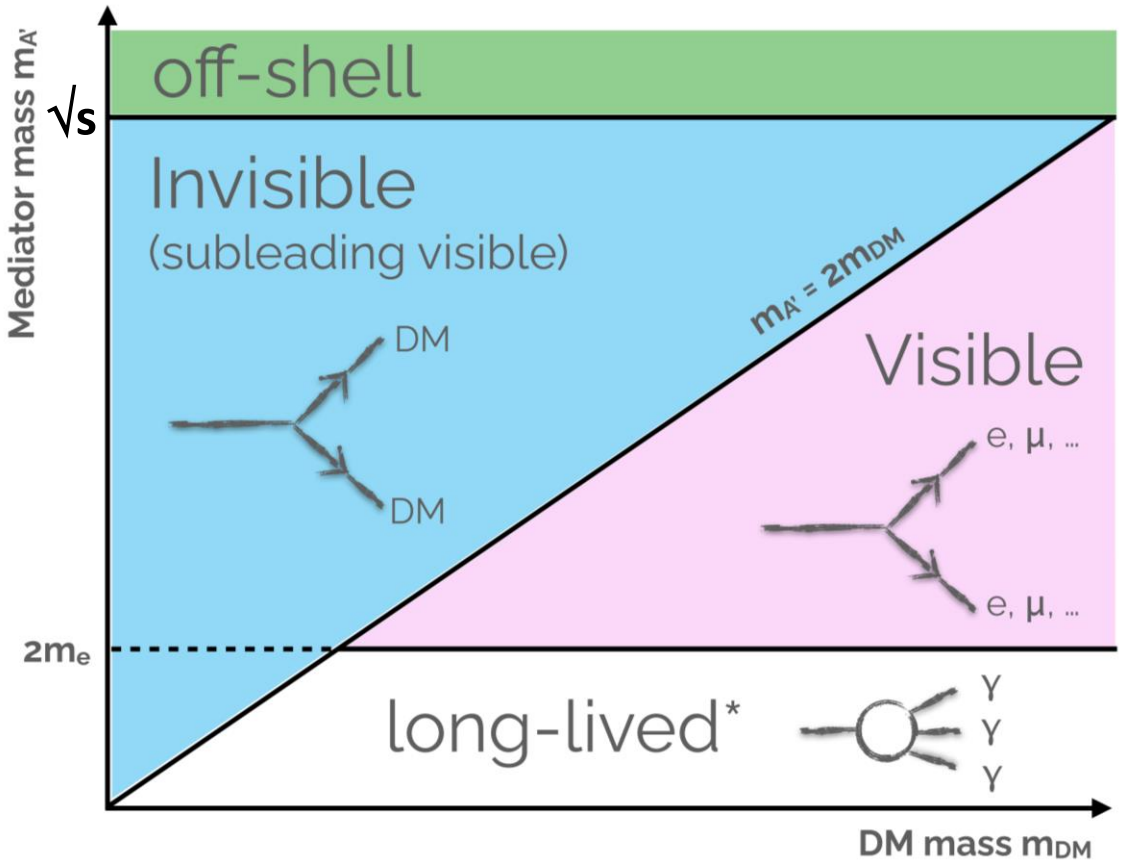
Cosmic frontier

Direct effect search in (mostly) underground experiments



Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation



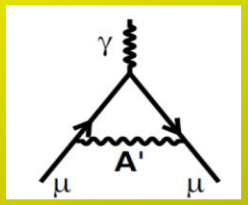
e^+e^- colliders

Probability of DM ↔ detector interaction negligible

- Mostly low multiplicity signatures
- Missing energy channels
- Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessibility

Additional benefits

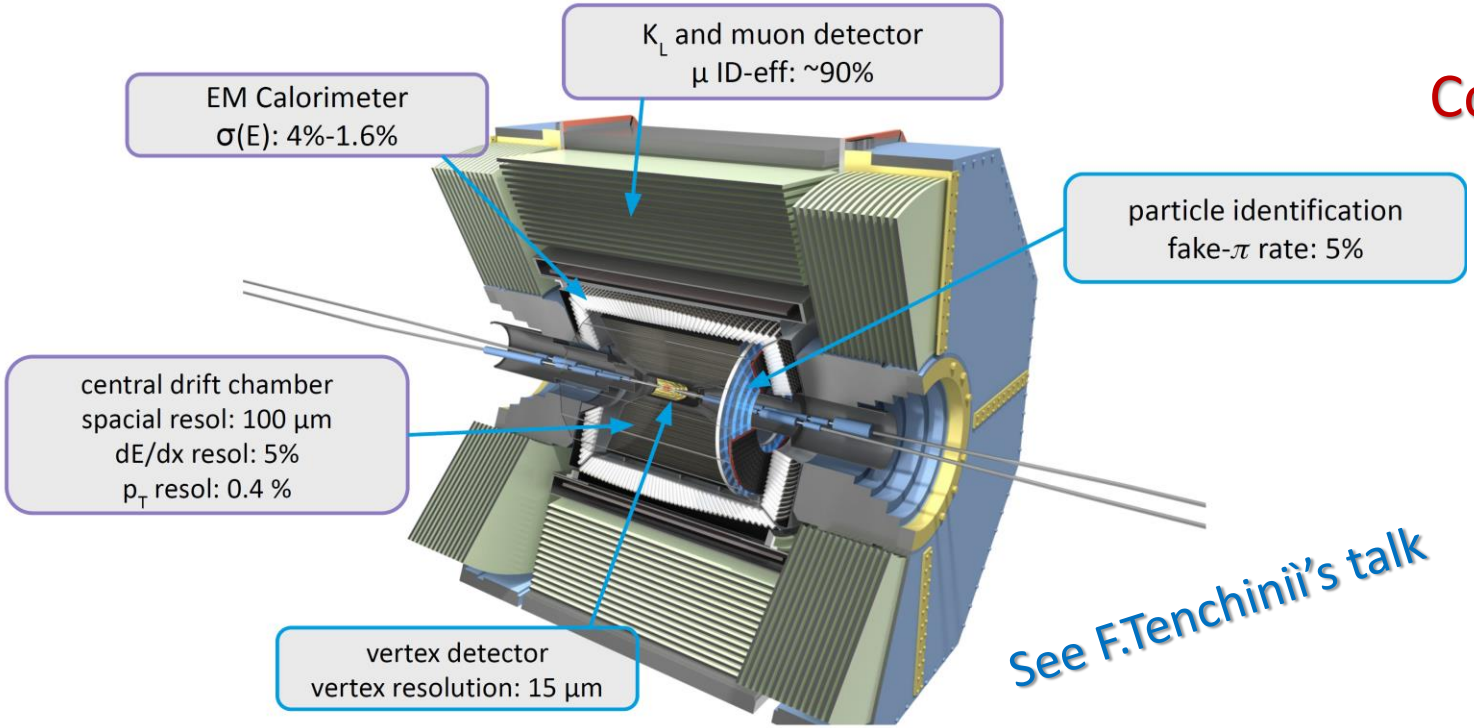
- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g-2)_\mu$ effect →



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

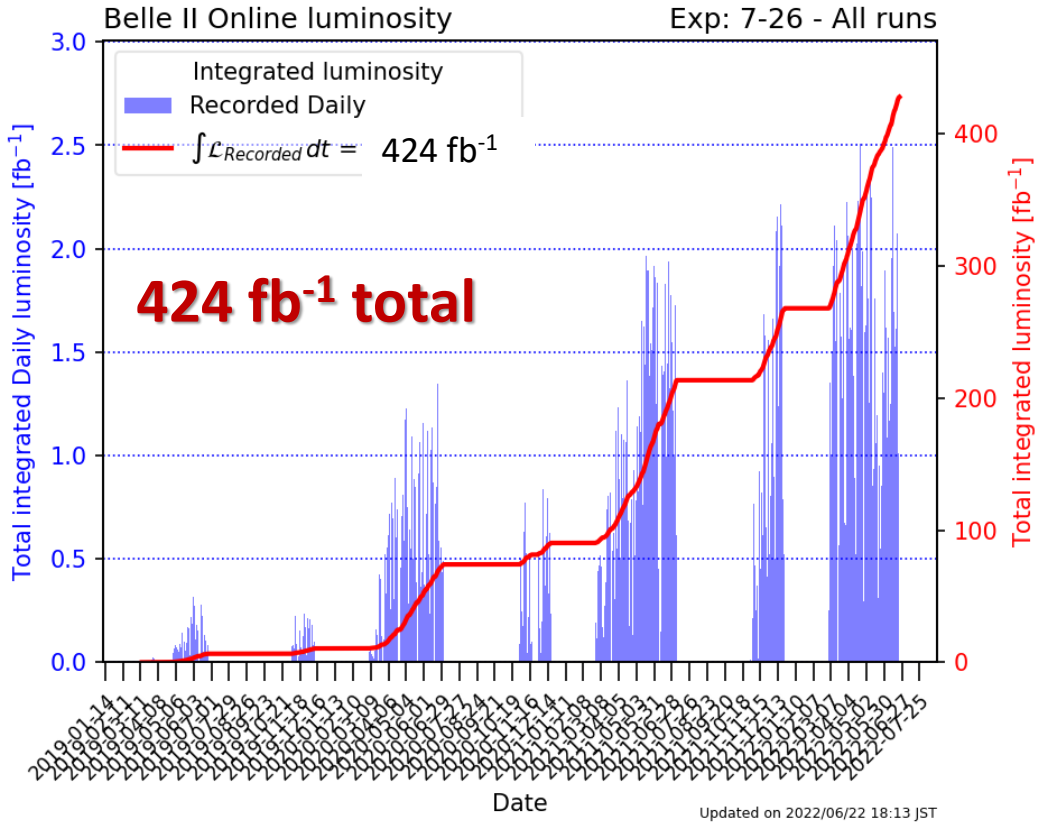
Belle II detector

Final goal : 50 ab^{-1}



See F.Tenchinii's talk

Collected luminosity up to now: 2019-2022



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

Single muon
- Drift ch. + μ detector

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

Resume physics run in fall 2023

Key factors for dark sector physics: trigger, high backgrounds, precise knowledge of acceptance/vetoes, PID

Dark-sector searches: results and projections

- ✓ Belle II and a light dark sector
- ✓ Search of
  - ➢ ALP→$\gamma\gamma$
  - ➢ Z' to invisible
  - ➢ Z', S, ALP →$\tau\tau$
  - ➢ Dark Higgsstrahlung A'h'
  - ➢ A' visible + invisible
  - ➢ LLP signatures
- ✓ Perspectives & Summary

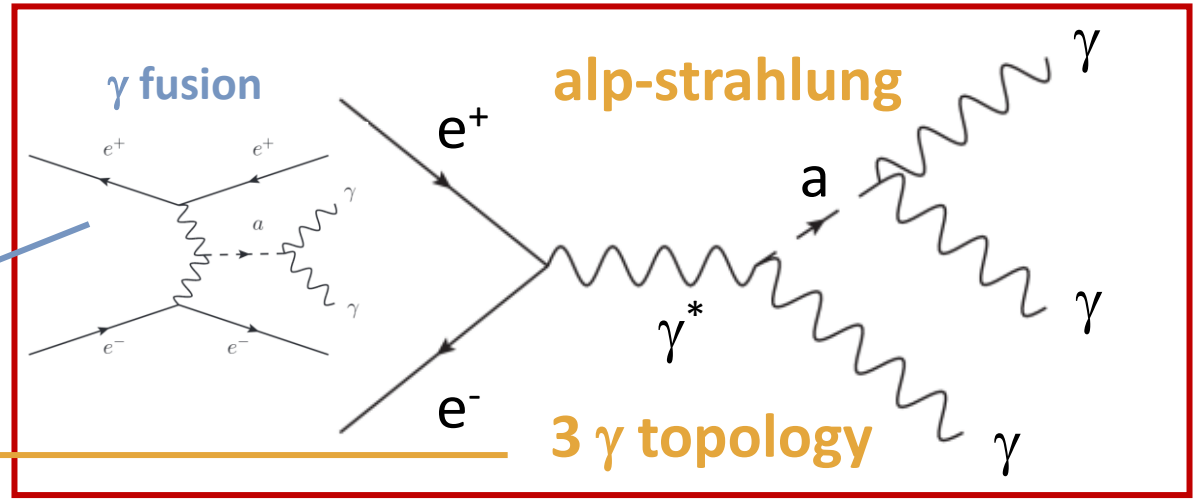
Axion Like Particles (ALPs)

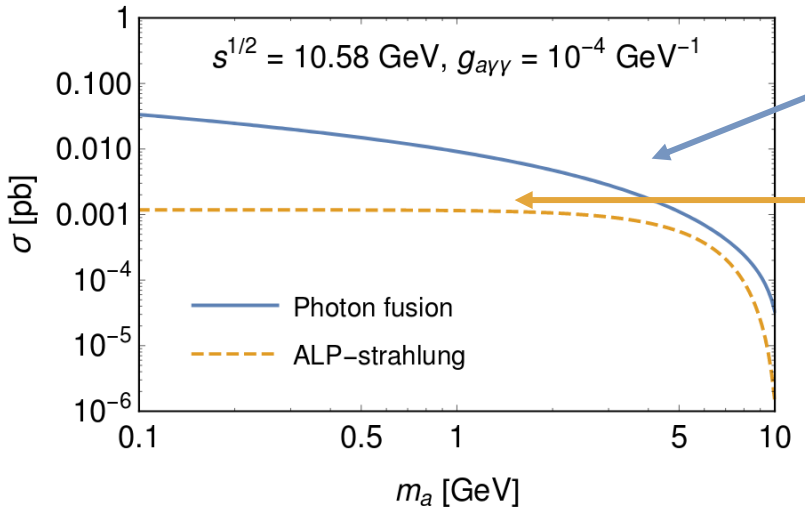
2020

- 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
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$

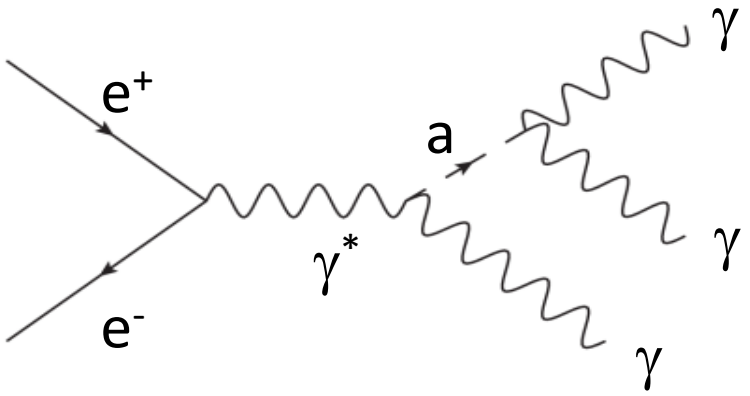




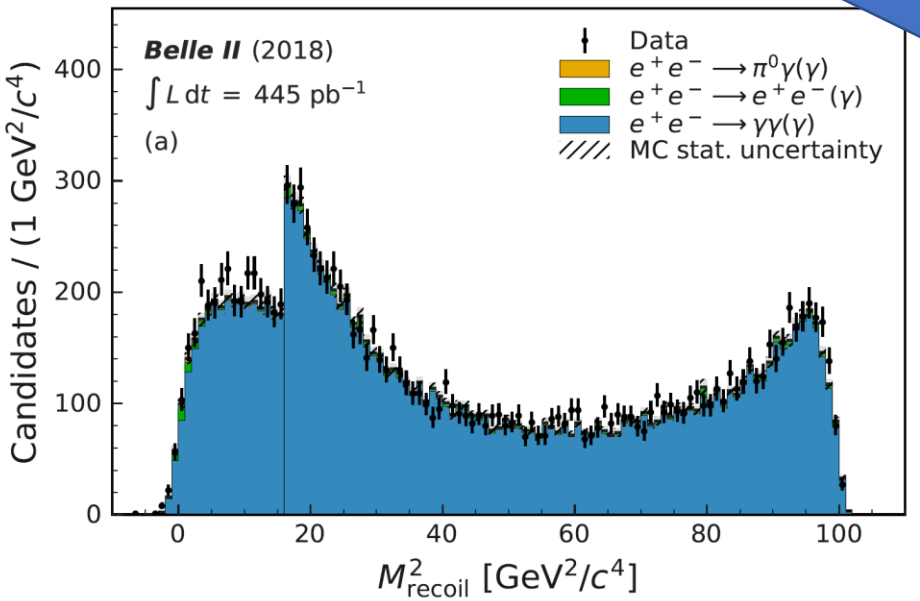
photon fusion sensitivity under study

ALP →γγ : observed yields

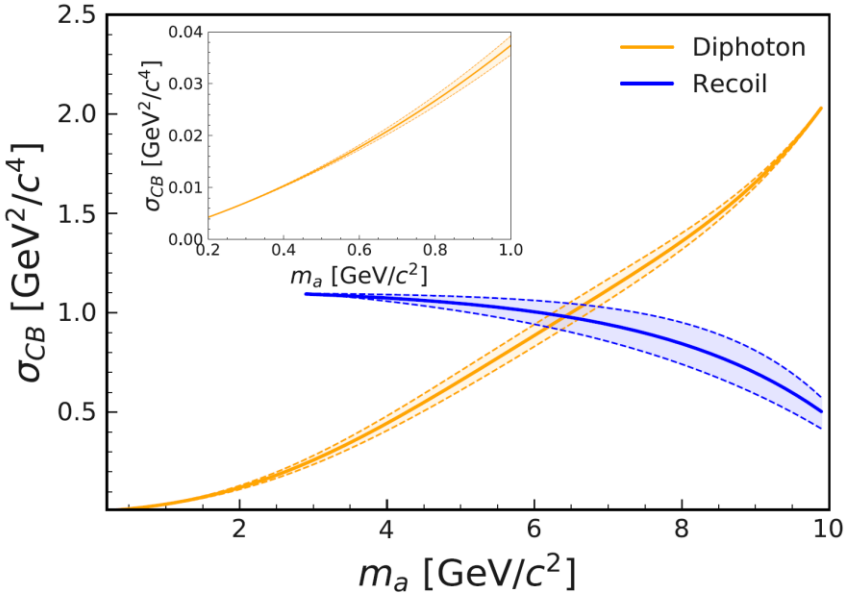
2020



Pilot run (2018)



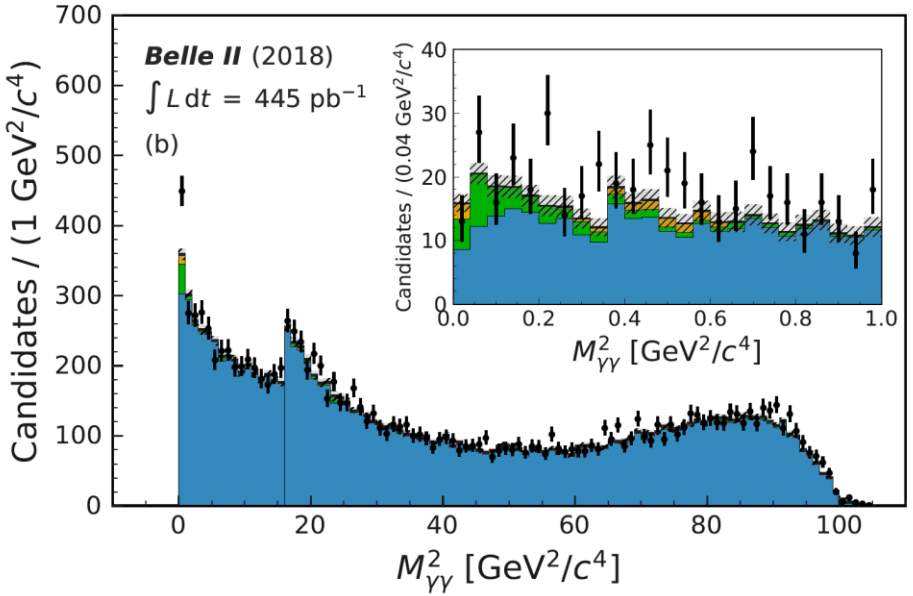
Search for peaks either in the recoil invariant mass (high m_a)
or in diphoton mass (low m_a)



Main backgrounds:

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

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



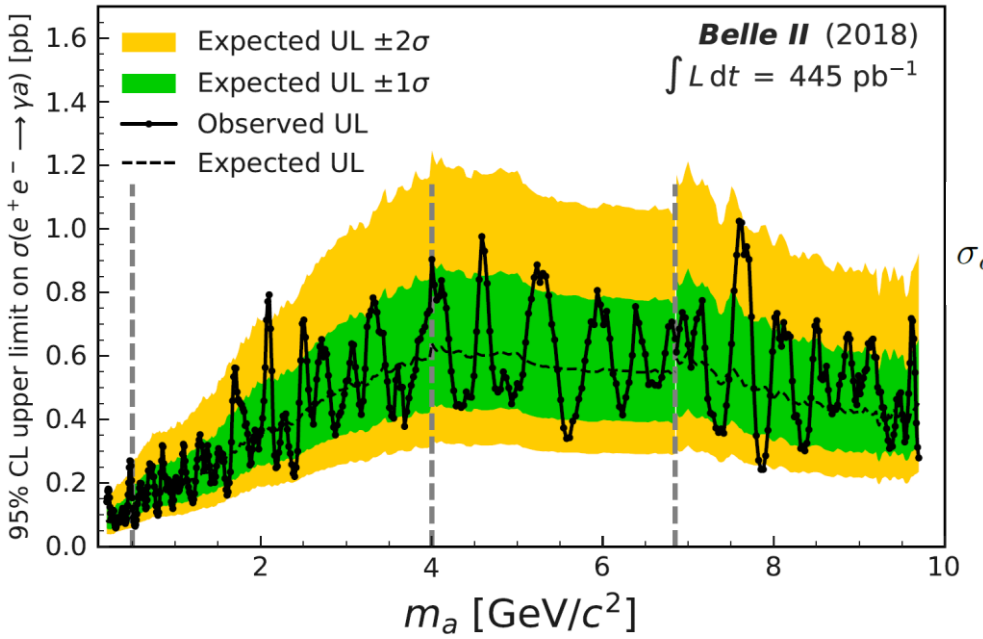
ALP →γγ : results

2020

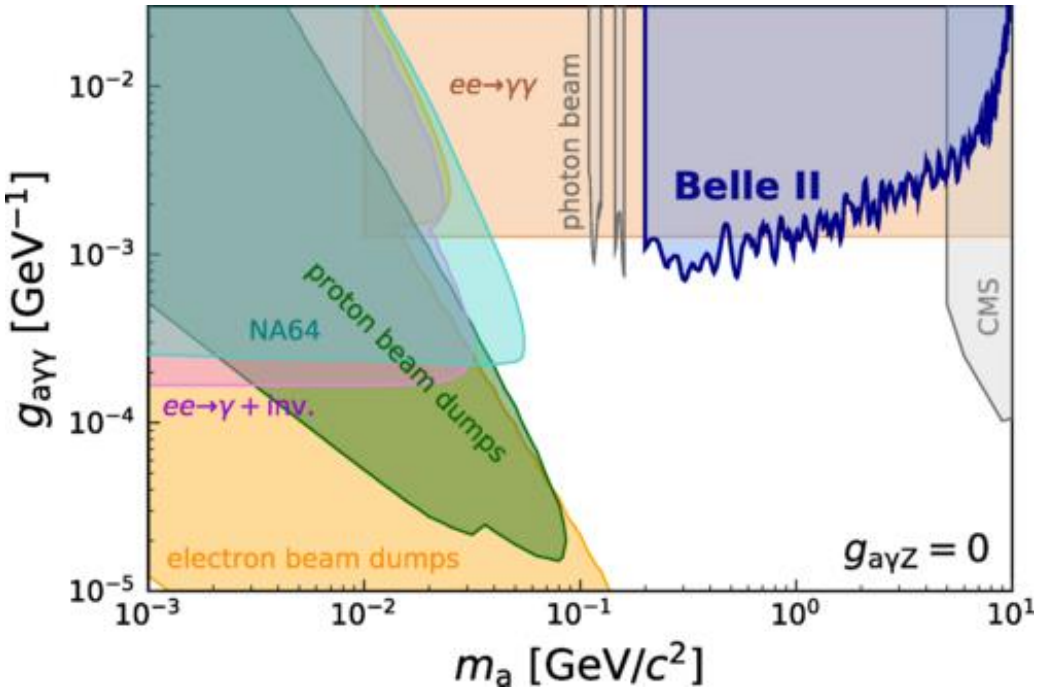
- ~500 fits in sliding ranges with steps of half resolution
- No peaking backgrounds expected
- $0.2 < m_a < 9.7$ GeV/c^2

Second Belle II physics paper

PRL 125 (2020) 161806



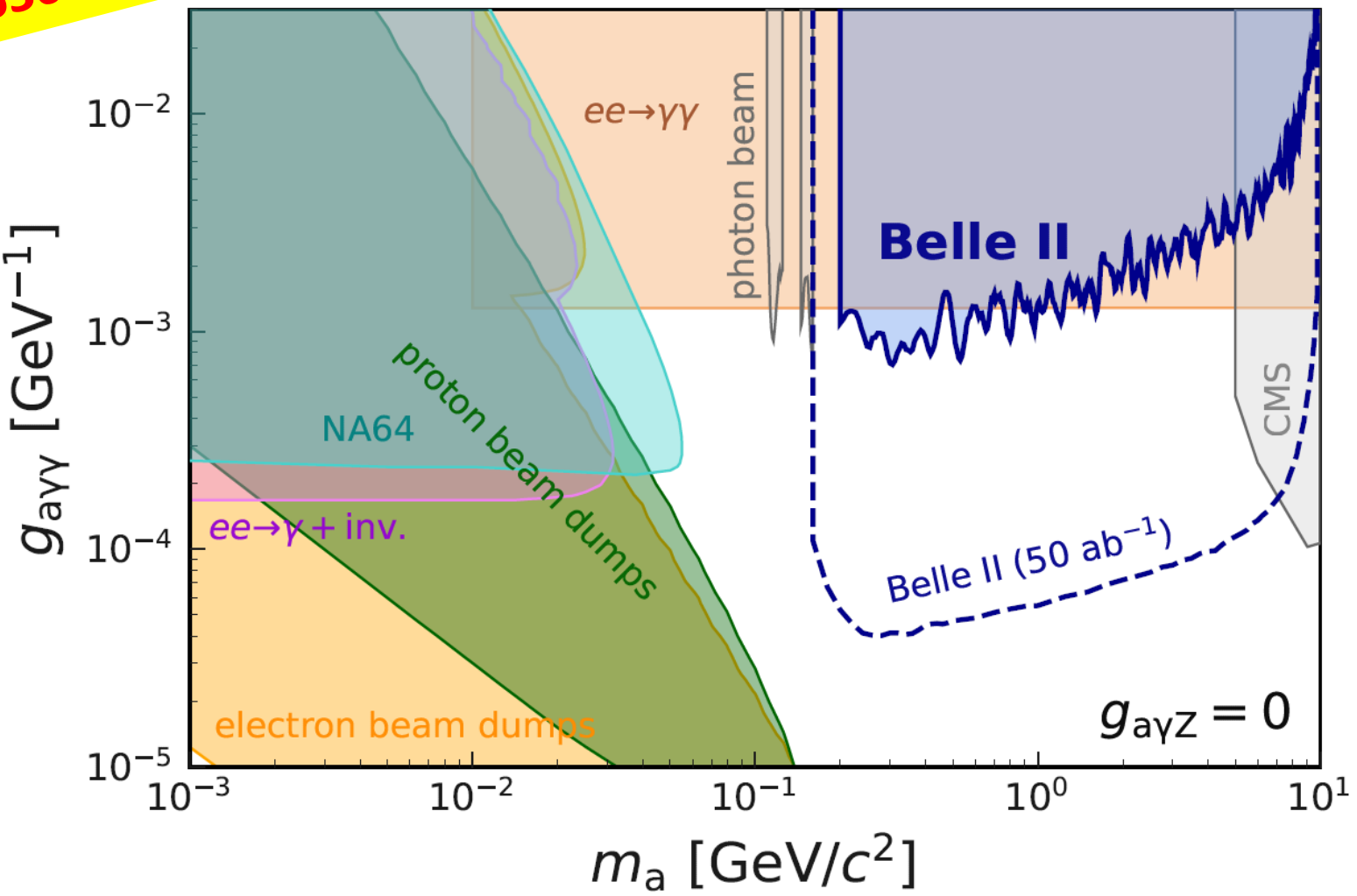
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24}\left(1-\frac{m_a^2}{s}\right)^3$$



ALP →γγ : luminosity projections

Belle II physics reach @ Snowmass

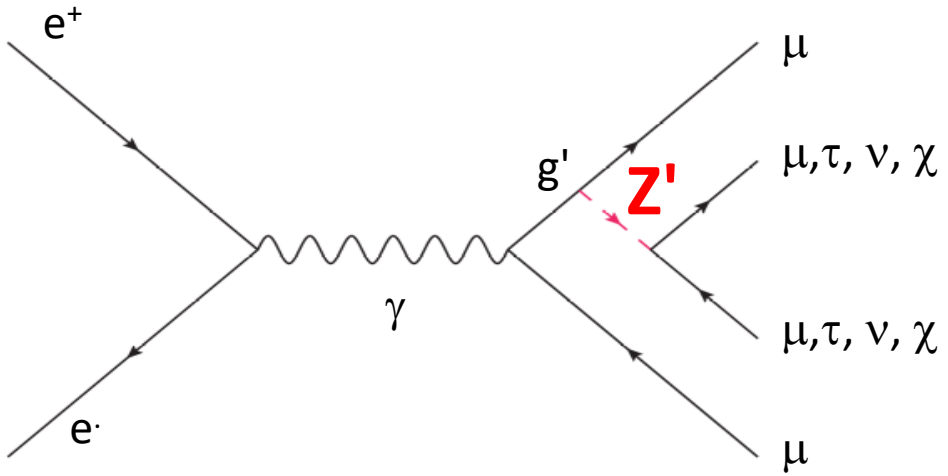
arXiv: 2207.06307v1



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



Z'→μμ → **BABAR**, **Belle**, **CMS** $Z^0 \to Z'\mu\mu$

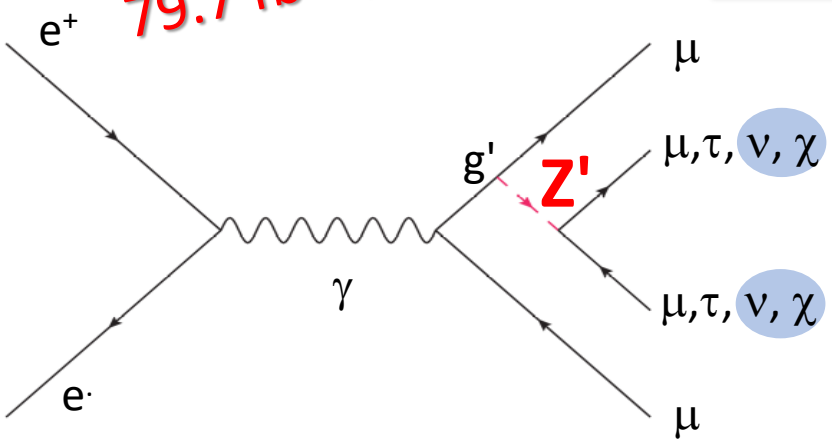
Z'→invisible → **Belle II 2020**, **Belle II** (new), **NA64-*e***

Z'→ττ → **Belle II** (new)

Z' to invisible: analysis

ICHEP

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



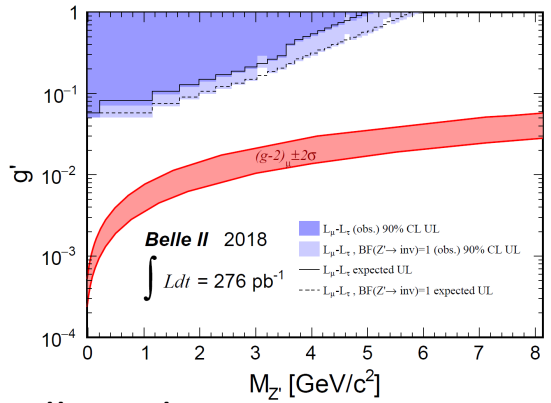
$e^+e^- \to \mu^+\mu^-$ + *missing energy*

Main backgrounds:

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

Old result

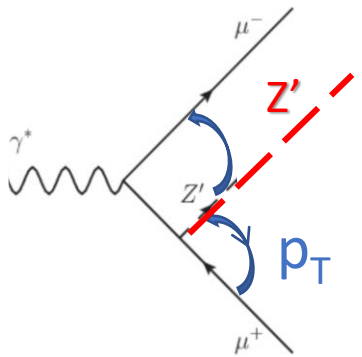
PRL 124 (2020), 141801



First Belle II physics paper

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

Two-track trigger
Two muons, $p_T^\mu > 0.4$ GeV/c
Recoil → barrel ECL $M_{recoil}<2$ GeV/c^2
No extra-energy, γ veto



FSR vs ISR + τ decay

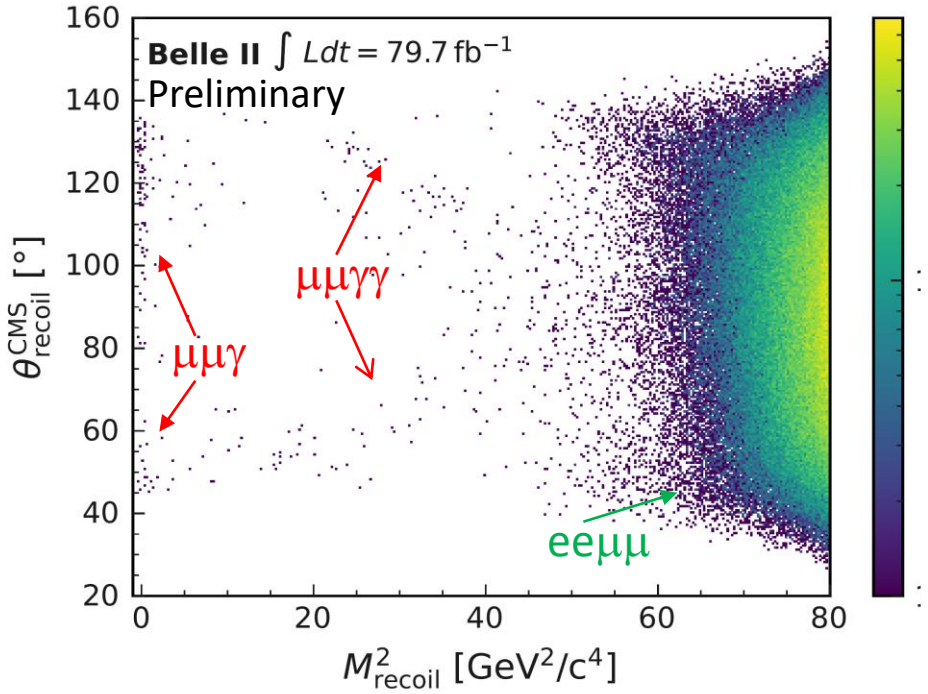
NN trained to optimize Punzi FOM
Eur.Phys.J.C 82 (2022) 2, 121

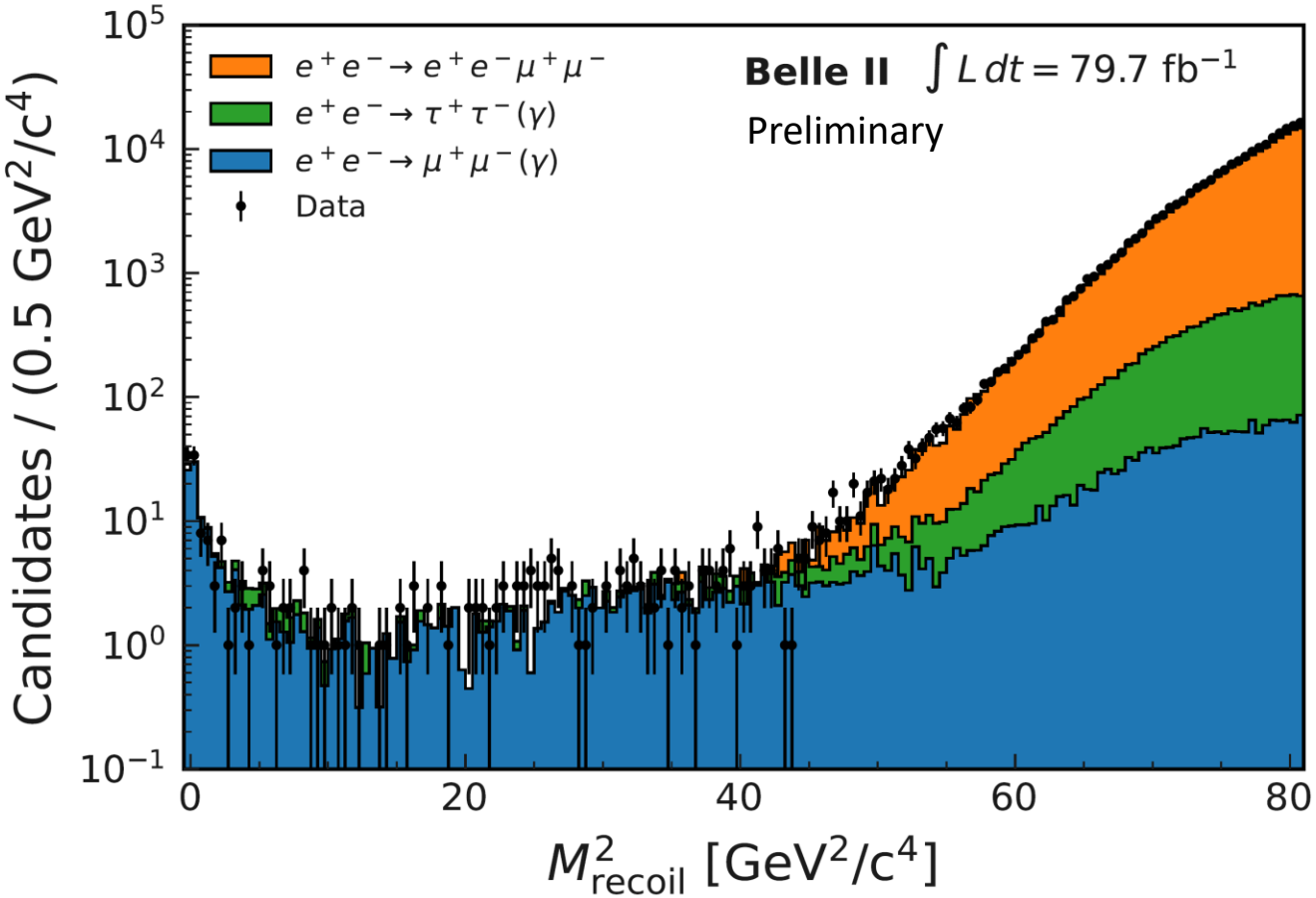
Z' to invisible: observed yields

ICHEP

- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to ~7 GeV/c^2 ⟶ bands in θ_{recoil} vs M^2_{recoil} due to γ lost in ECL gaps
- $e^+e^-\mu^+\mu^-$ dominates for high masses

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

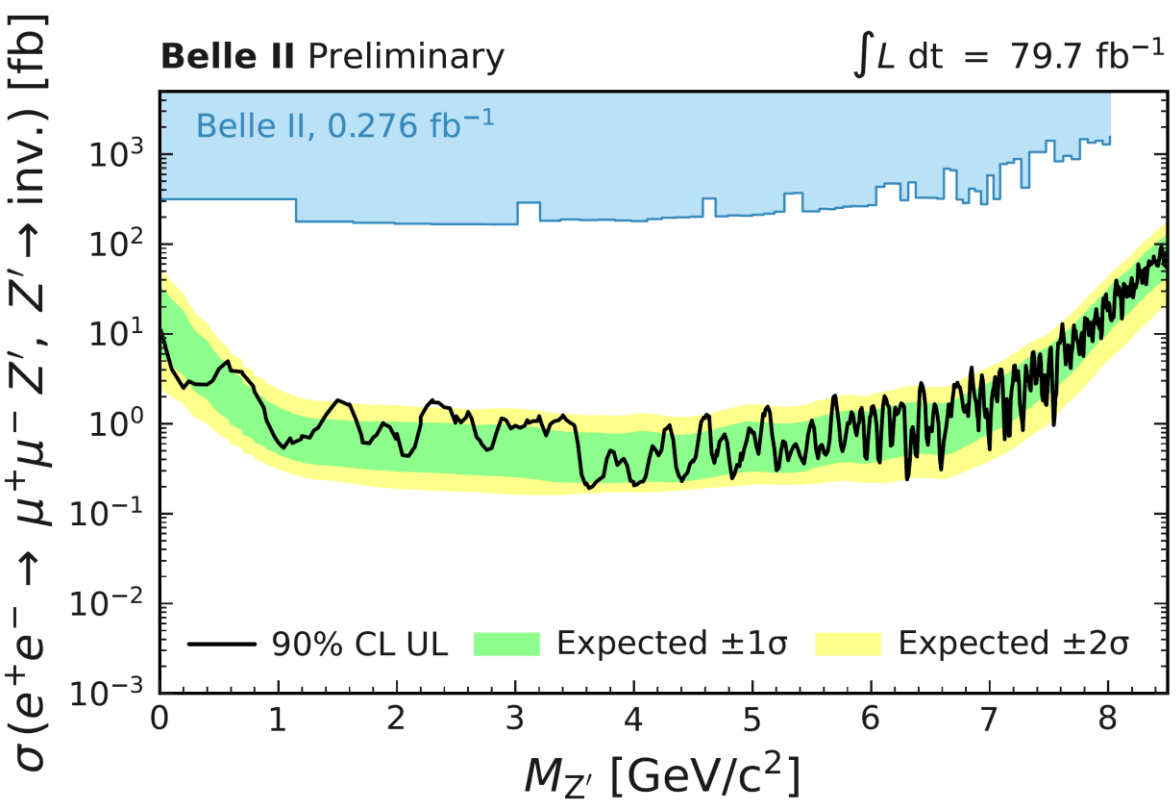


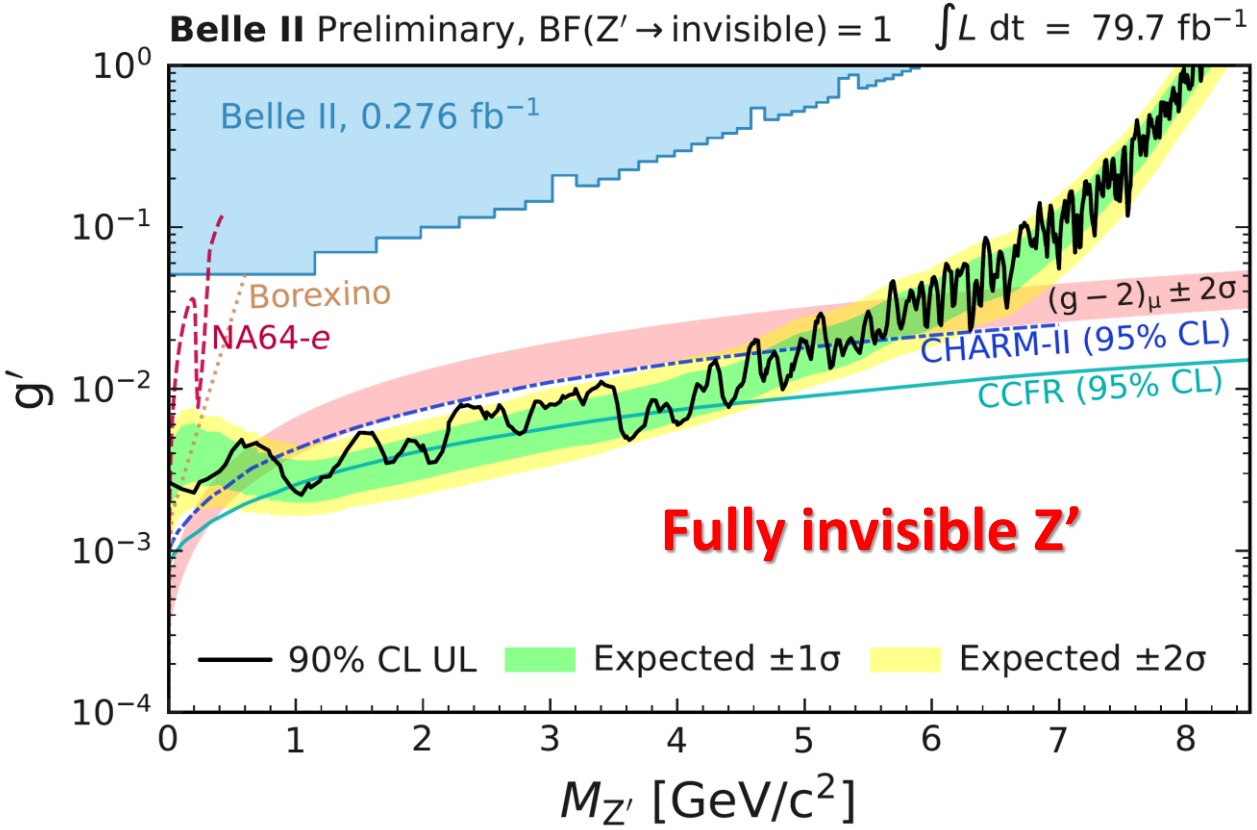


Z' to invisible: results

ICHEP

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



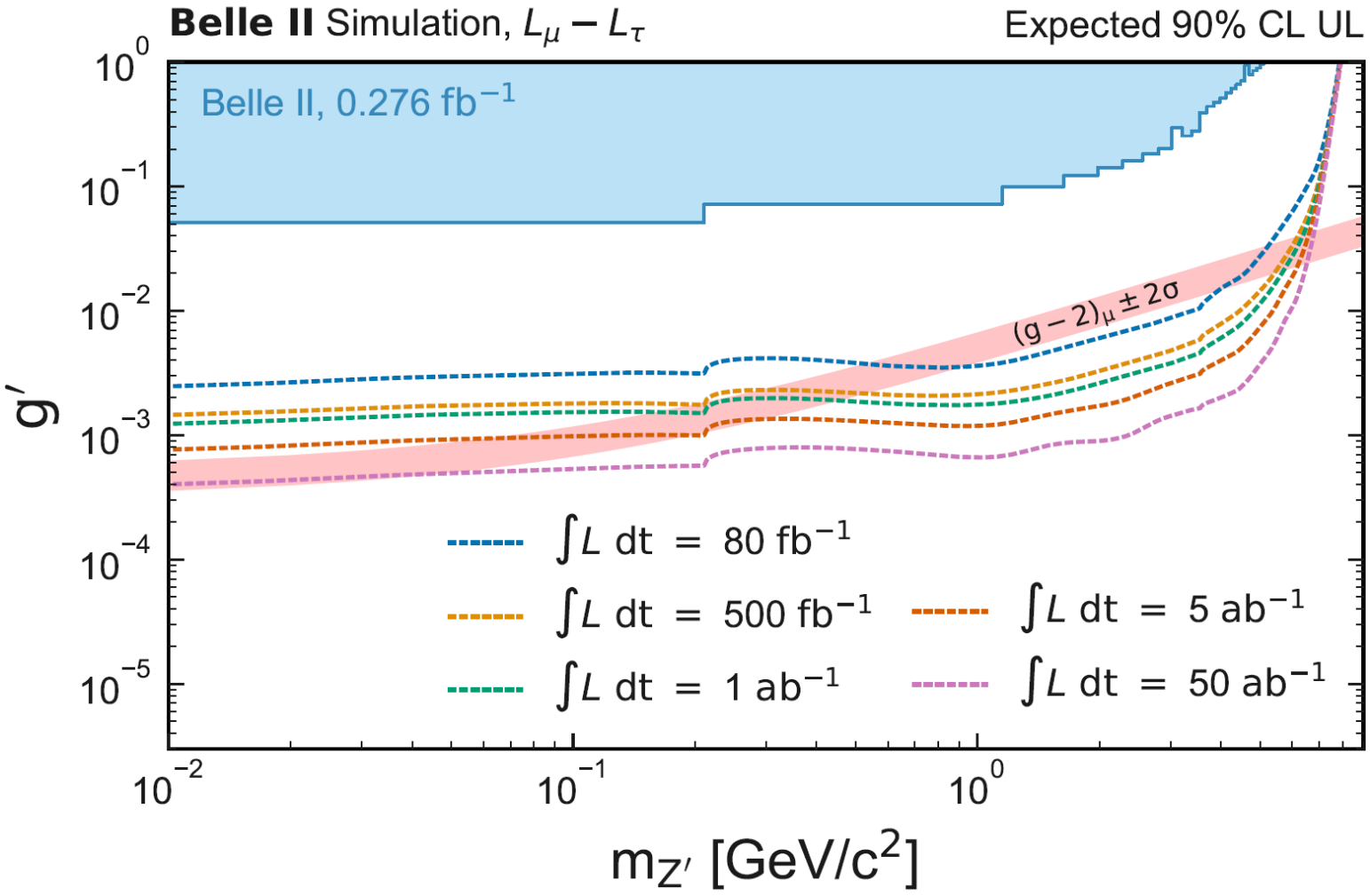


fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Z’ to invisible: luminosity projections

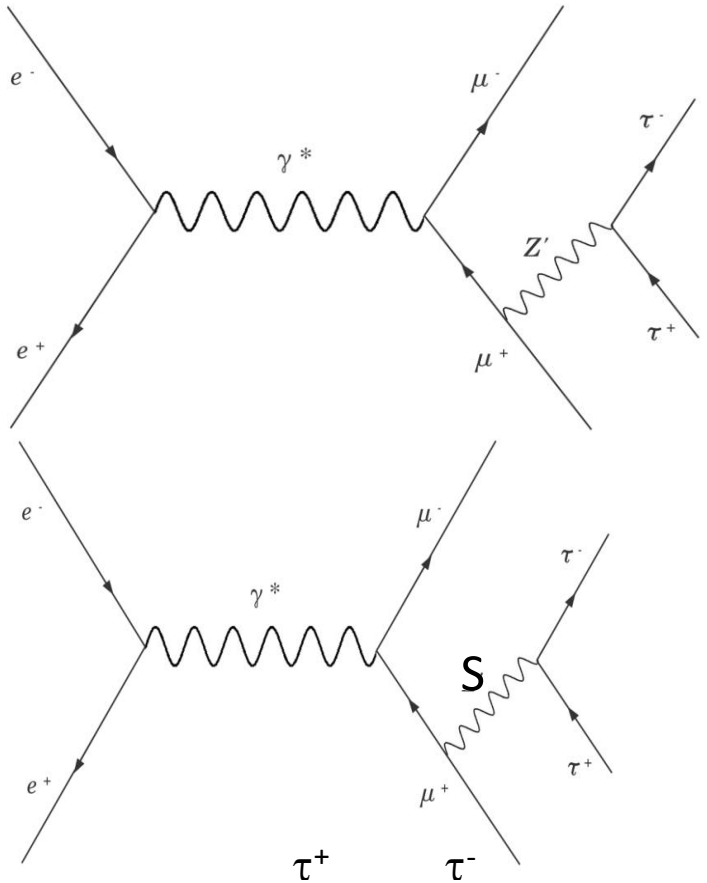
Belle II physics reach @ Snowmass

arXiv: 2207.06307v1



Z', S, ALP → ττ

ICHEP



Z' L_μ - L_τ model

First time search in ττ

Leptophilic scalar S model

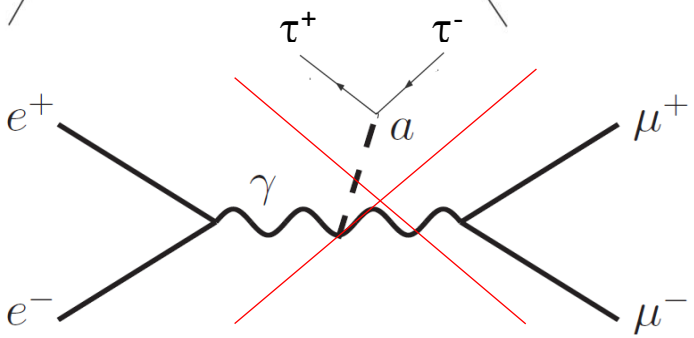
Yukawa couplings

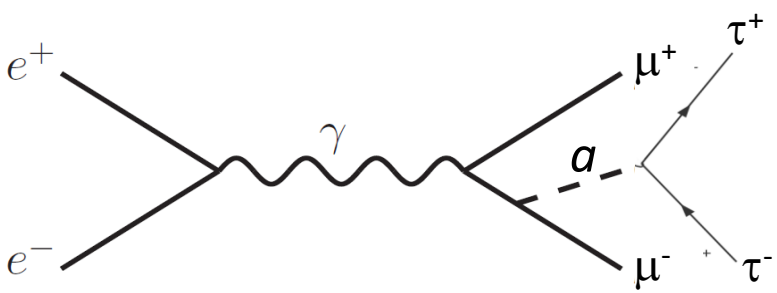
Contraints by BaBar in S→μμ

First time search in ττ

$\mu\mu\tau\tau$ final states

$M_{Z',S,a} = M_{recoil}(\mu\mu)$





ALP → ττ

$C_{ee}=C_{\mu\mu}=C_{\tau\tau}$ $C_{\gamma\gamma}= C_{Z\gamma}=0$

Yukawa-like effective couplings

ALP-τ coupling unconstrained

Z', S, ALP → ττ: analysis

ICHEP

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

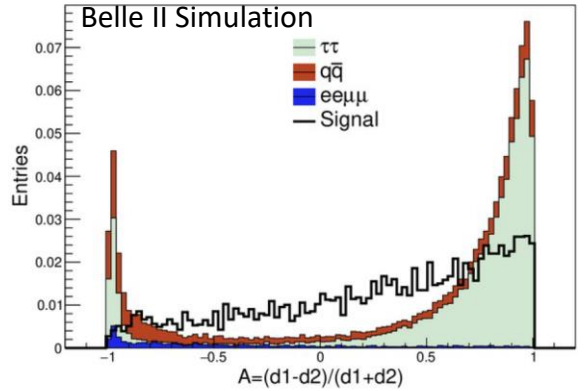
Main backgrounds

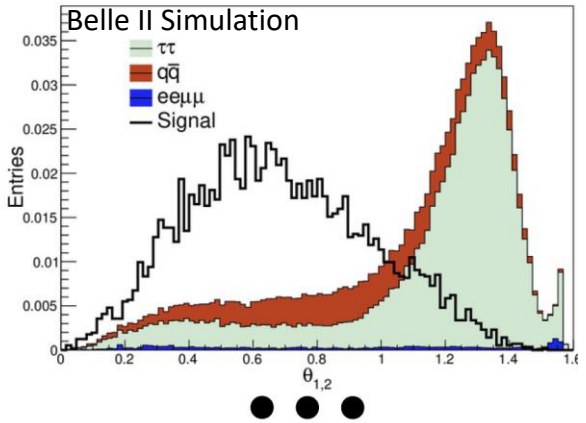
$e^+e^- \to \tau^+\tau^-$ (γ) 1+3 prong
$e^+e^- \to qq$ (q=u,d,s,c)

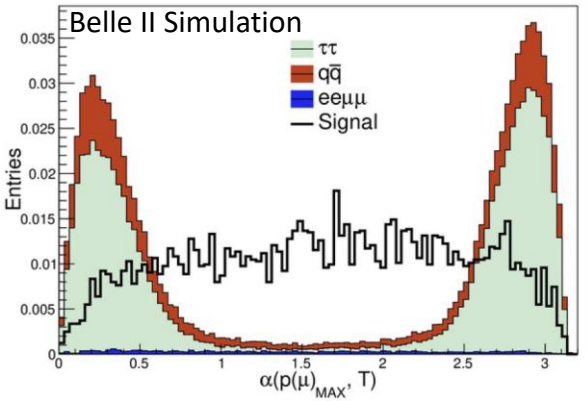
$e^+e^- \to e^+e^- \mu^+\mu^-$
$e^+e^- \to \mu^+\mu^- \tau^+\tau^-$
$e^+e^- \to e^+e^- \tau^+\tau^-$
} no ISR in simulation

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

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

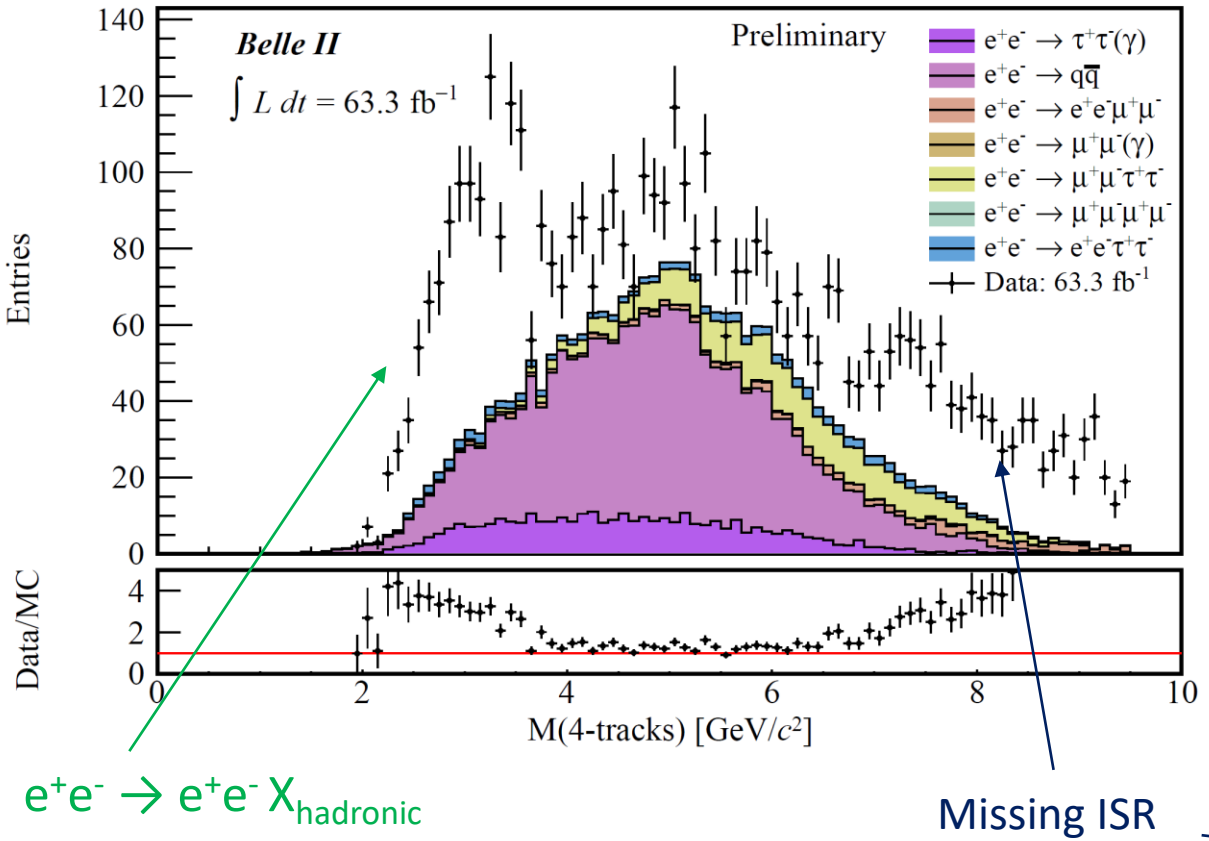






Z', S, ALP → ττ: observed yields

ICHEP

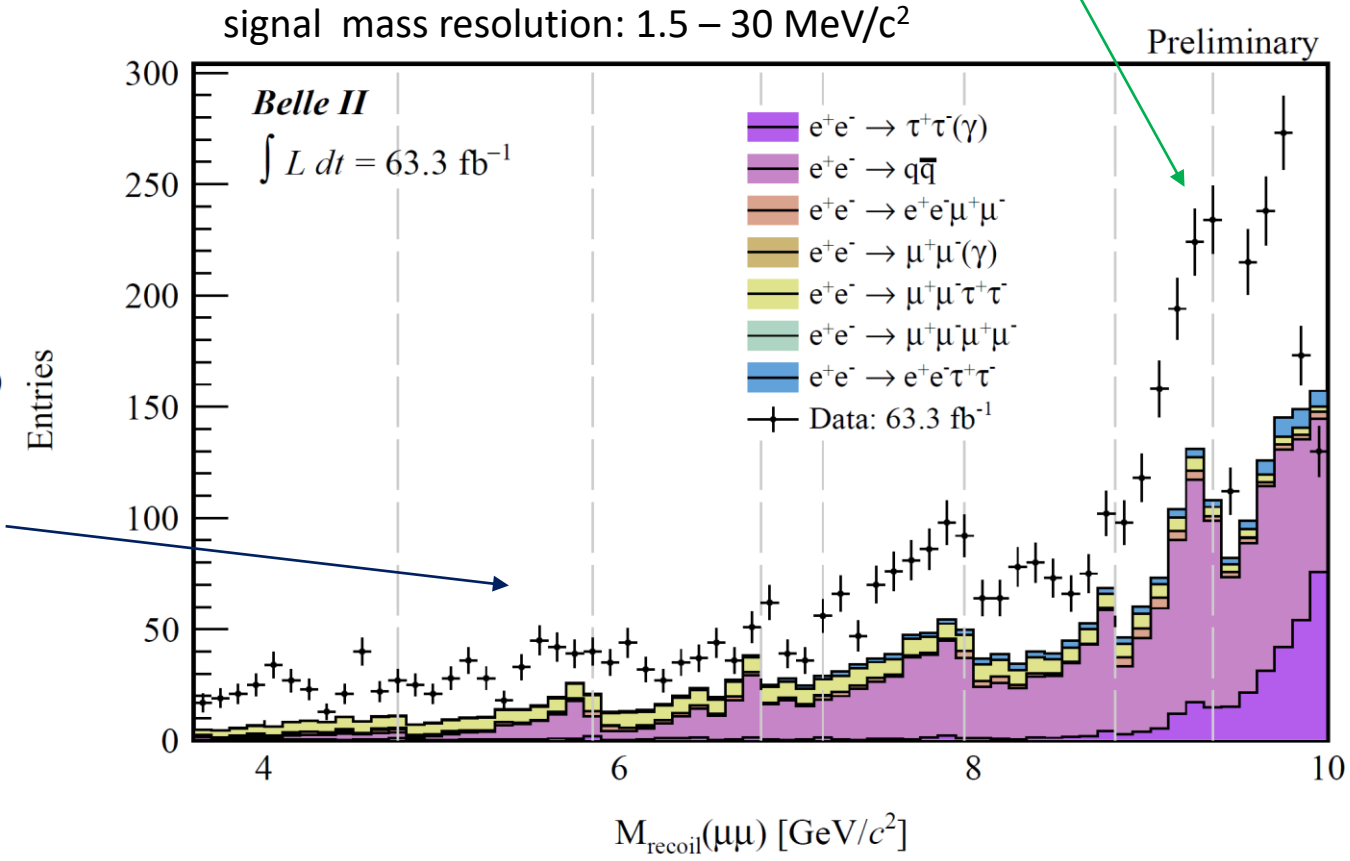


$e^+e^- \to e^+e^- X_{hadronic}$

Missing ISR

$e^+e^- \to e^+e^- X_{hadronic}$

signal mass resolution: 1.5 – 30 MeV/c^2



Discrepancies expected and understood

Non-peaking in M_{recoil} (μμ)

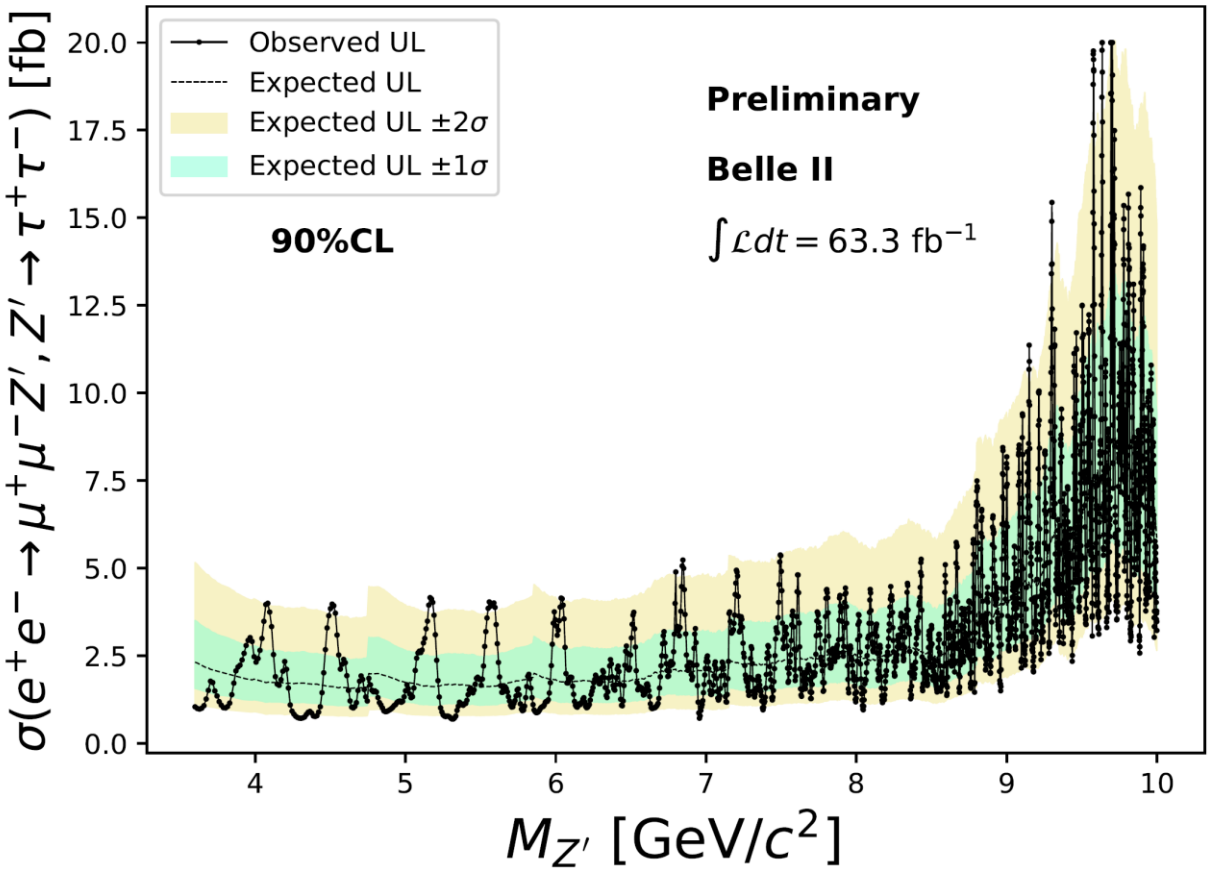
- signal mass resolution: 1.5 – 30 MeV/c^2

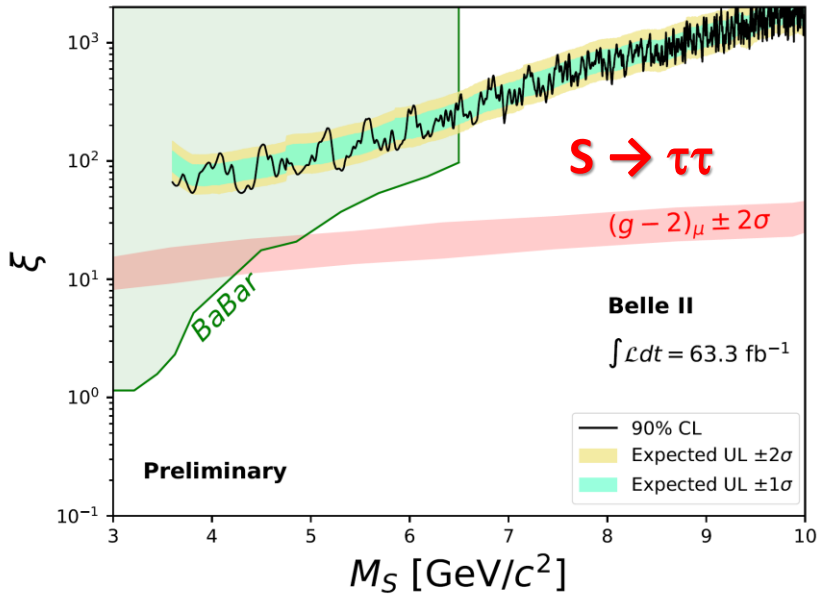
Background floated in the fit

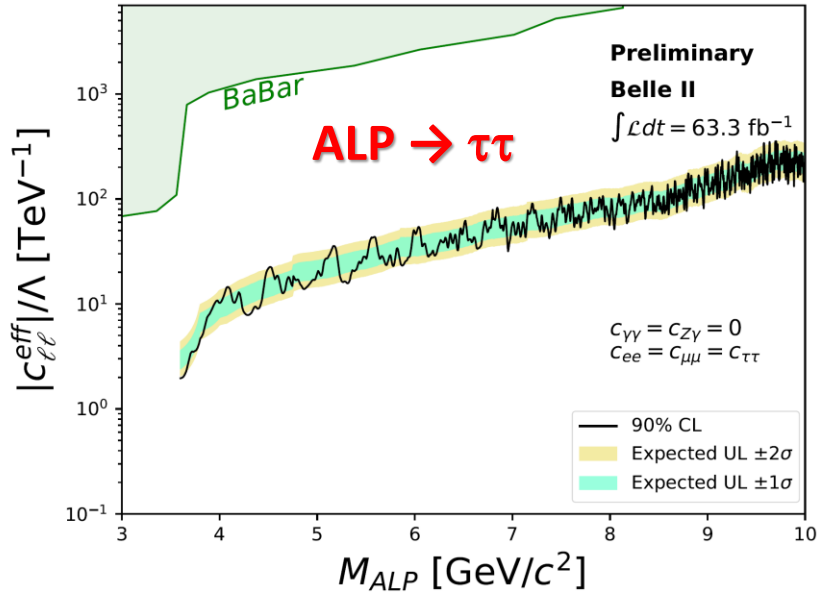
Z', S, ALP → ττ: results

ICHEP

- No excess found
- Set 90%CL exclusion limits on cross section and couplings
  - First constraints on S for $M_S > 6.5$ GeV/c^2
  - First direct constraints for ALP → ττ





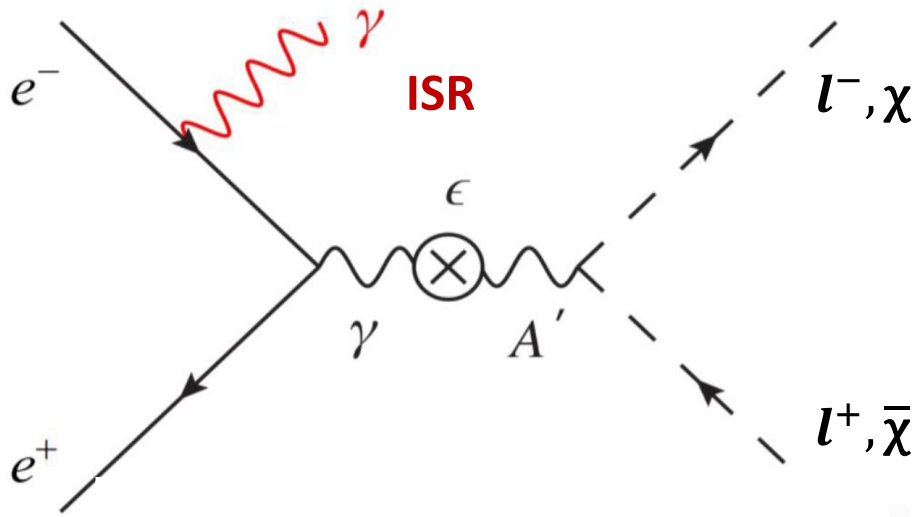


Dark photon: introduction

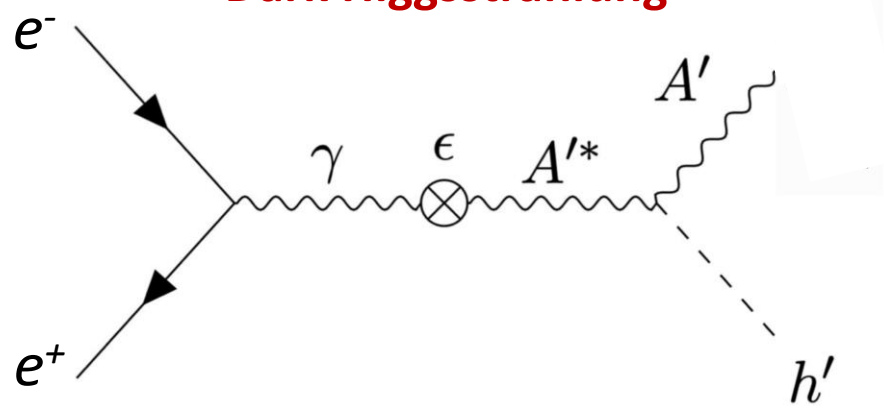
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P.Fayet, Nucl. Phys. B **187**, 184 (1981)

- Paradigm of the vector portal extension of the SM
- QED inspired: U(1)' → new spin 1 gauge boson A'
- Couples to SM hypercharge Y through kinetic mixing ε
- Couples to dark matter with strength α_D
- Mass through Higgs or Stuckelberg mechanism

Production at e^+e^- colliders



Dark Higgsstrahlung



two basic scenarios depending on A′ vs χ DM mass relationship

$m_{A'} < 2m_\chi \Rightarrow$ A' decays visibly to SM particles (*l*, *h*)

$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

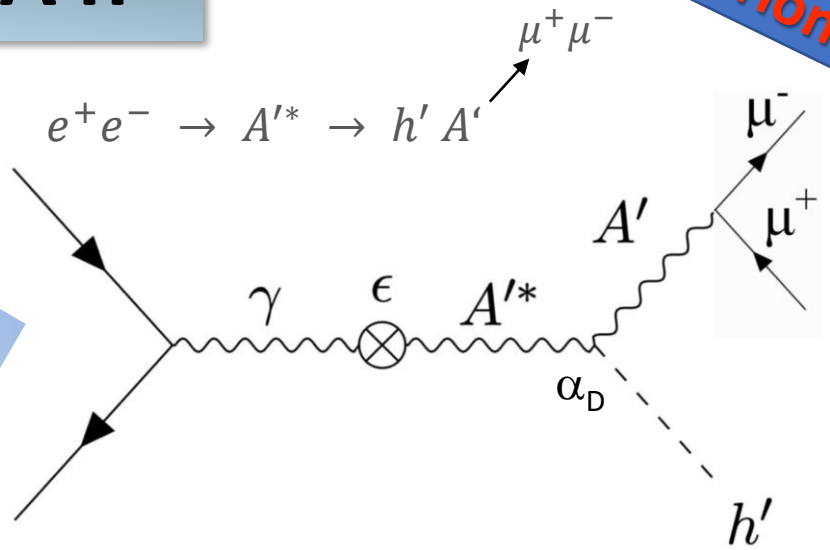
Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

Moriond

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

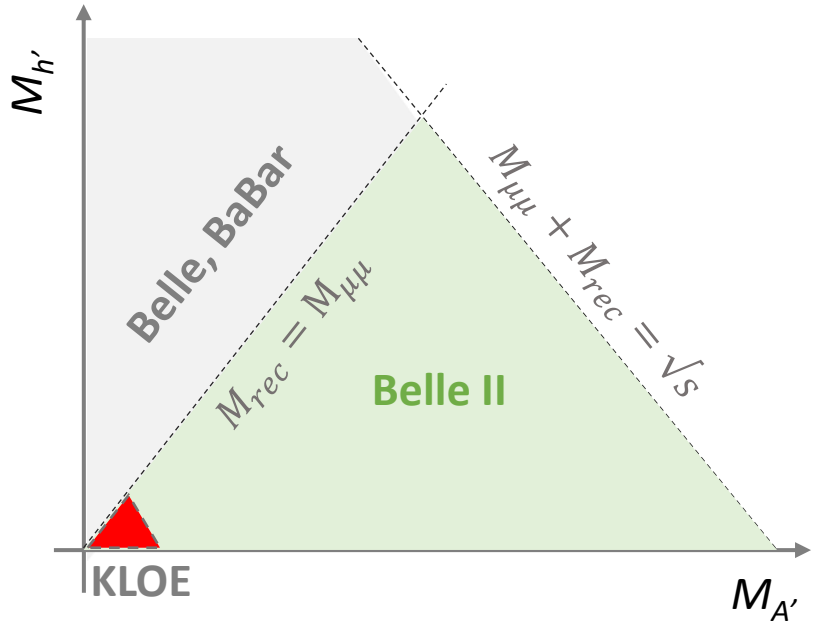
Phys. Rev D79, 115008 (2009)



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

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

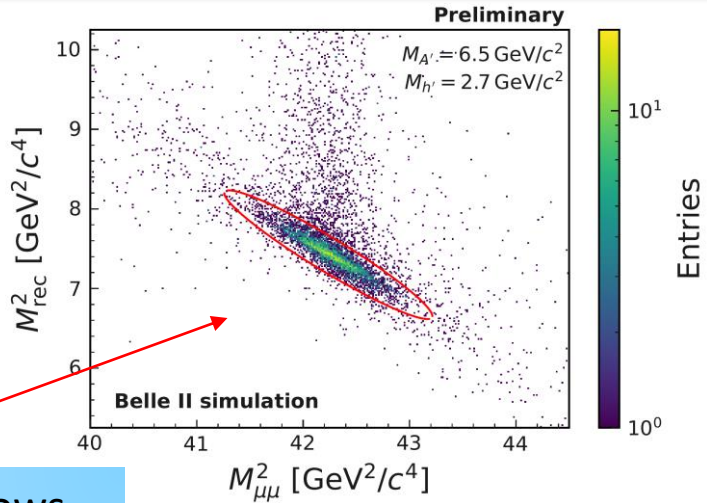


Dark Higgsstrahlung: analysis

Moriond

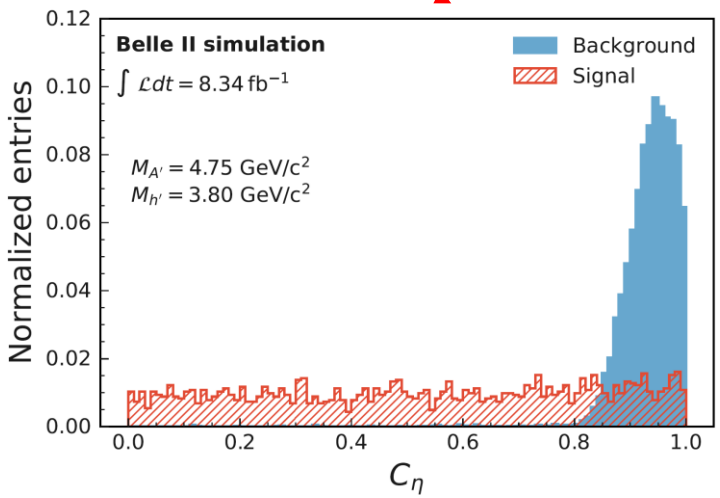
8.34 fb^{-1} (2019)

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

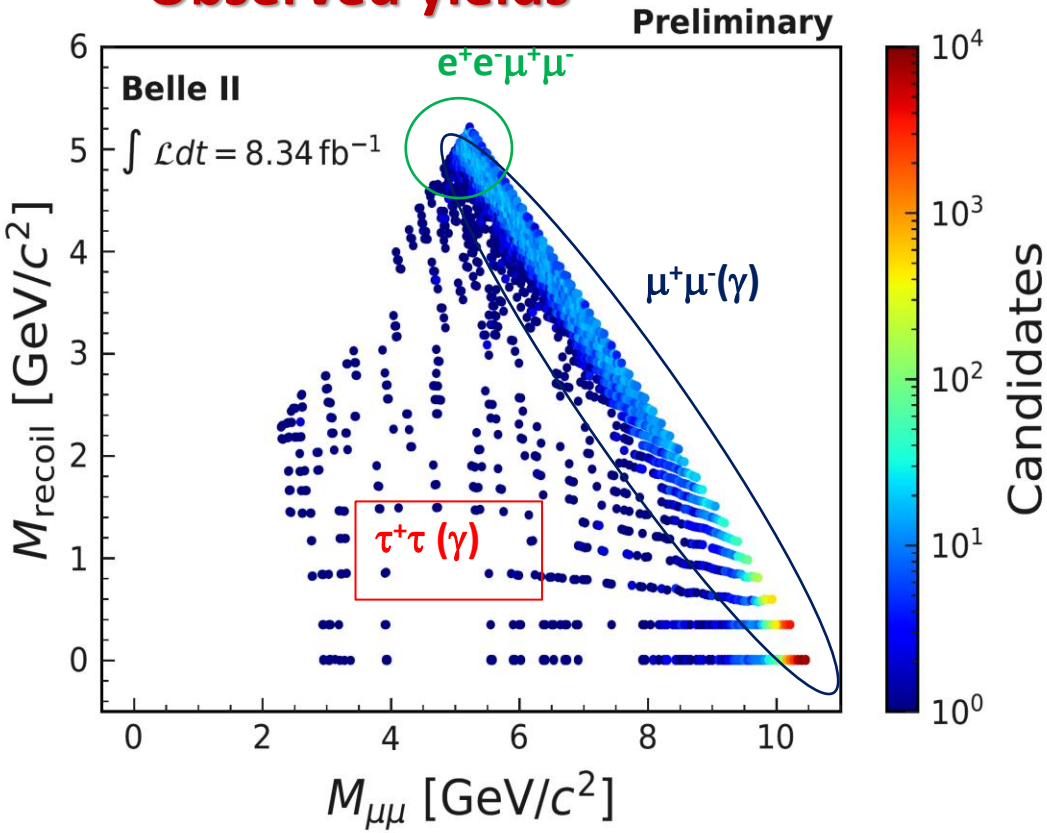
Helicity angle



Backgrounds

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

Observed yields

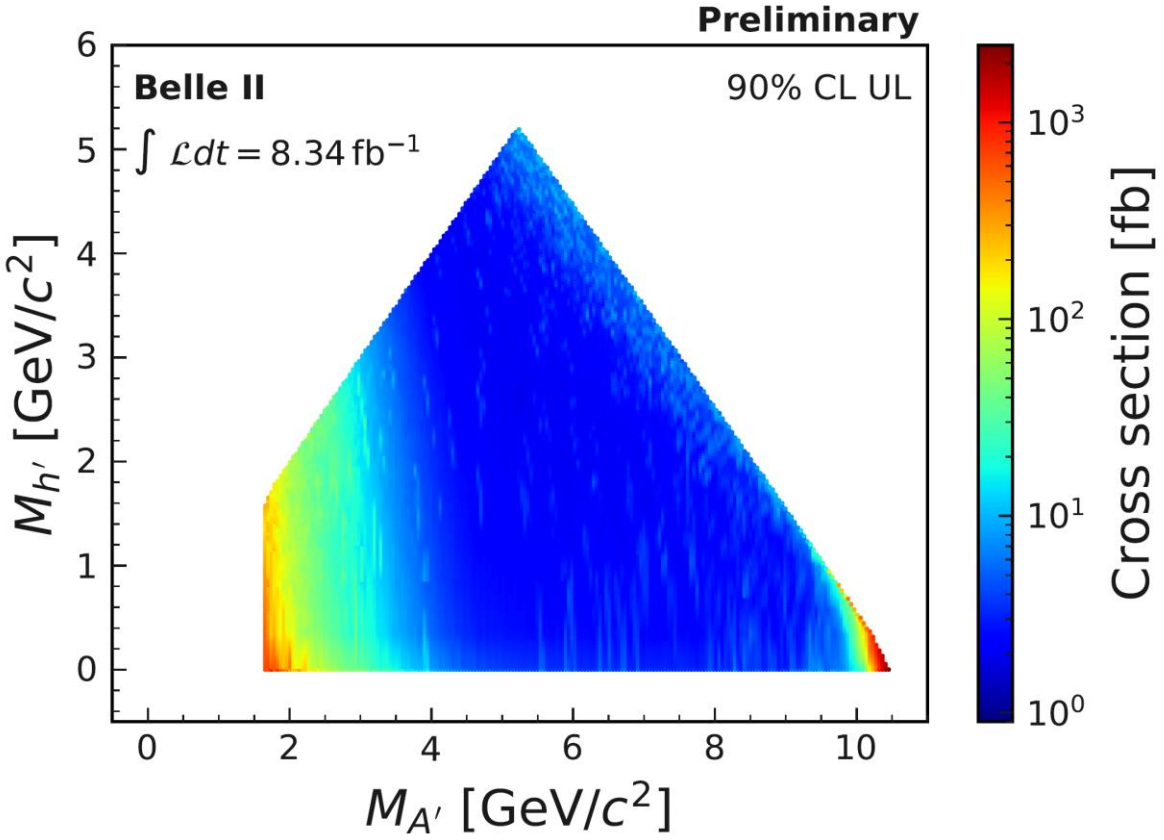


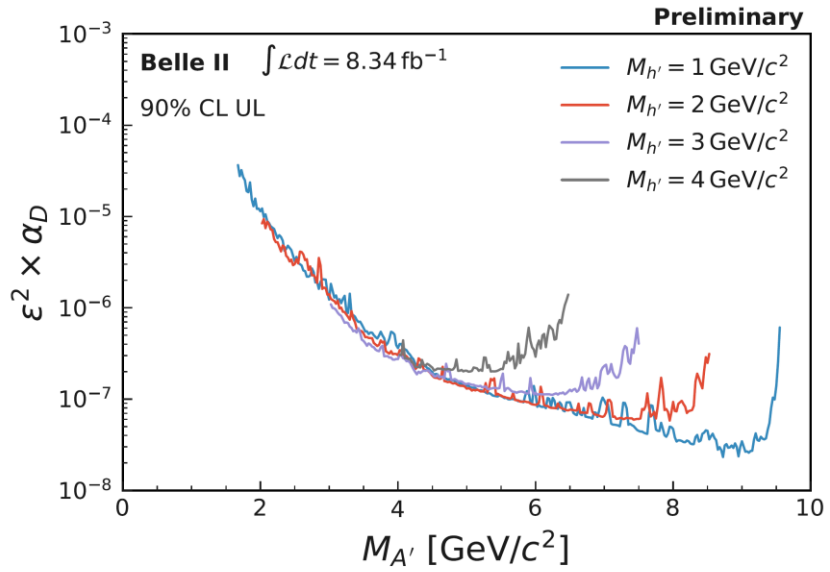
Dark Higgsstrahlung: results

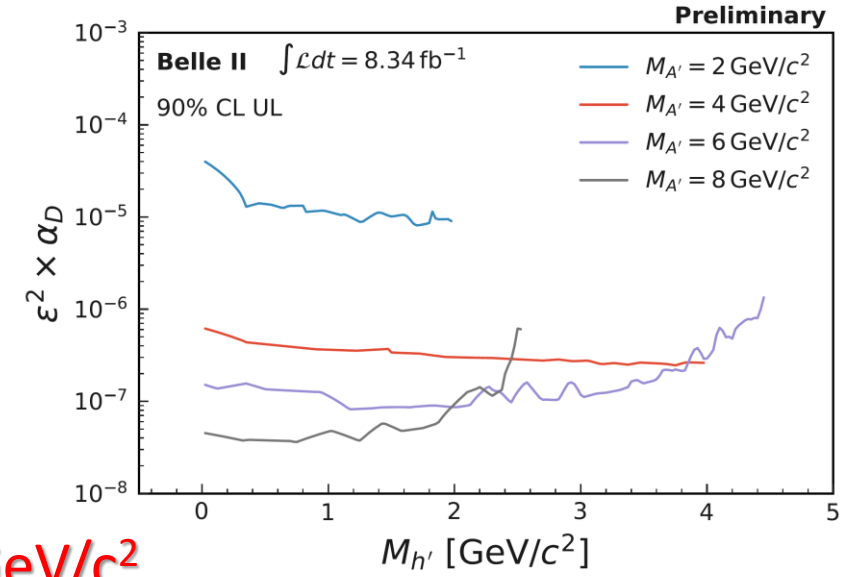
Moriond

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

arXiv:2207.00509
submitted to PRL



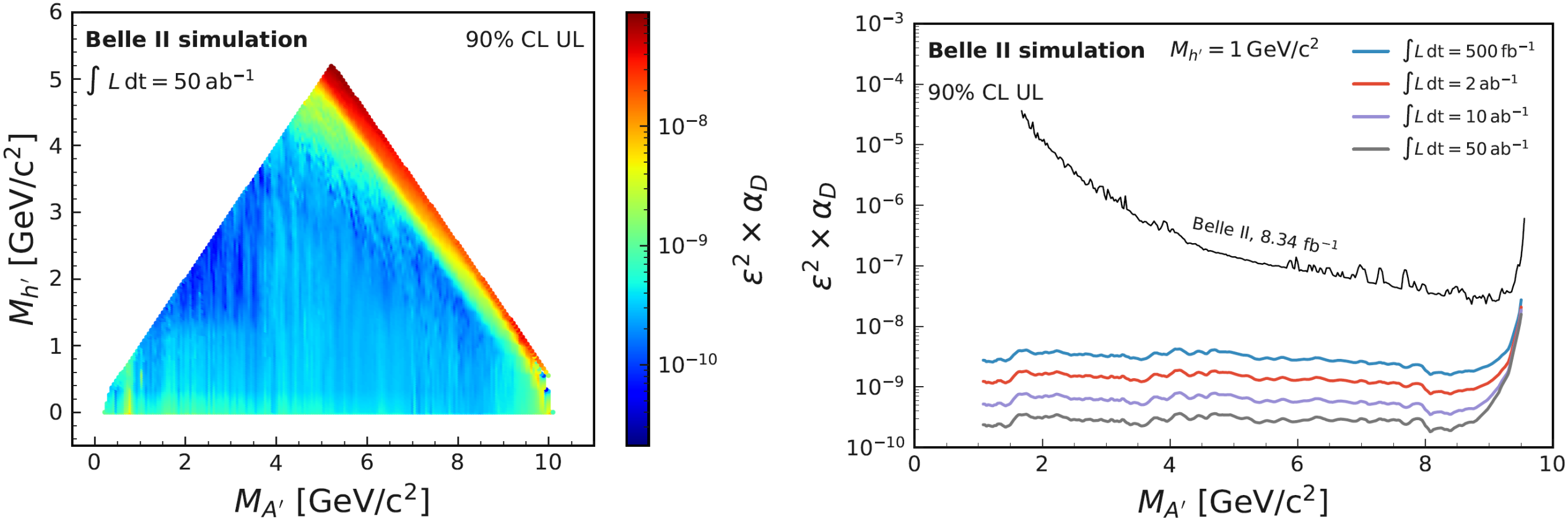




World first for $1.65 < M_{A'} < 10.51$ GeV/c^2

Dark Higgsstrahlung: luminosity projections

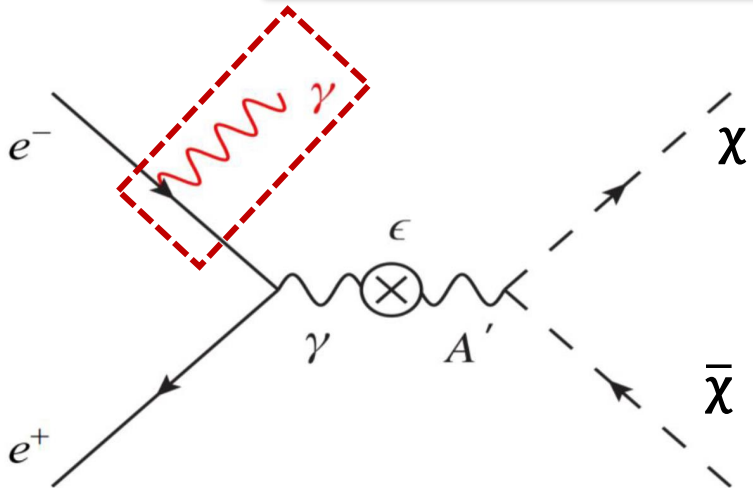
arXiv: 2207.06307v1



Planned searches: projections

- ✓ Belle II and a light dark sector
- ✓ Search of
  - ➢ ALP→$\gamma\gamma$
  - ➢ Z' to invisible
  - ➢ Z', S, ALP →$\tau\tau$
  - ➢ Dark Higgsstrahlung A'h'
  - ➢ A' visible + invisible
  - ➢ LLP signatures
- ✓ Perspectives & Summary

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

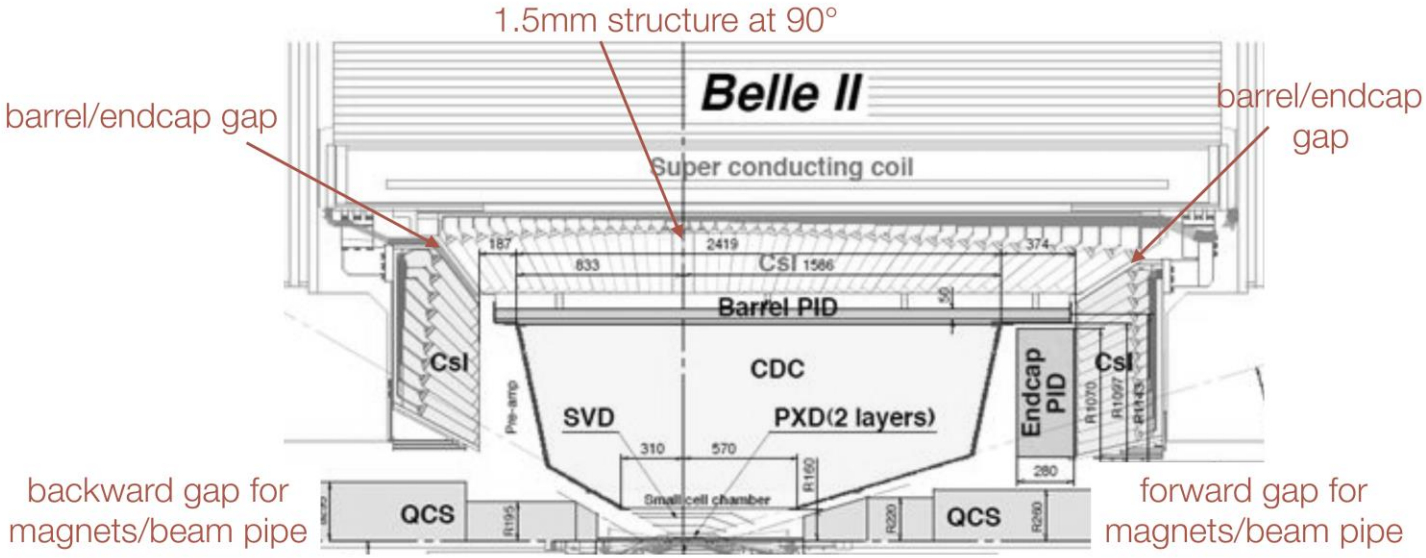
Backgrounds

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

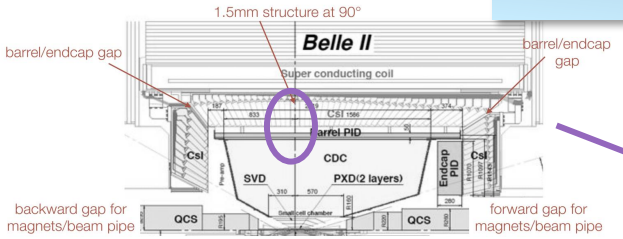
$e^+e^- \to \gamma\gamma(\gamma)$ → low $M_{A'}$ region

Cosmics

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



Invisible dark photon: background

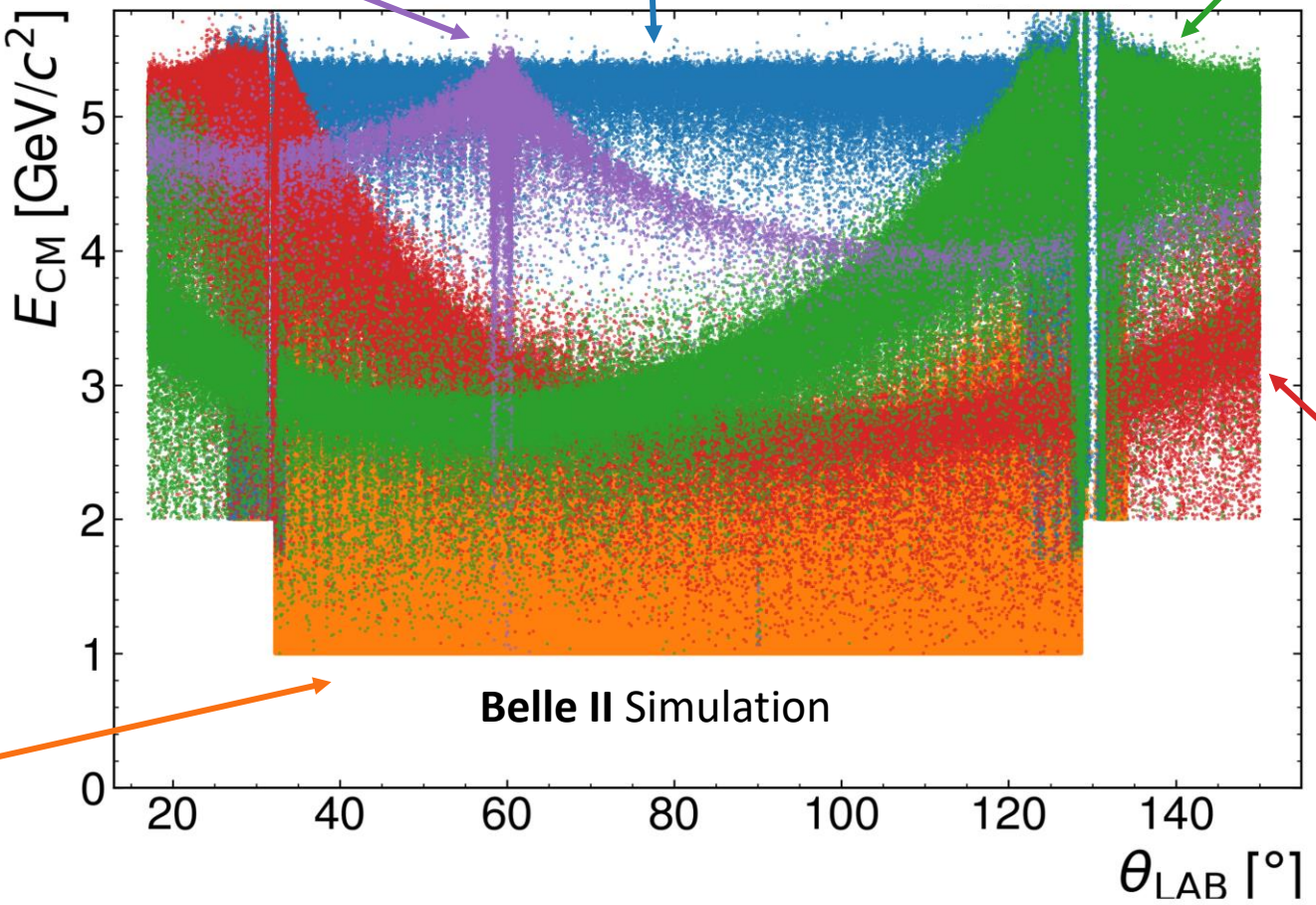


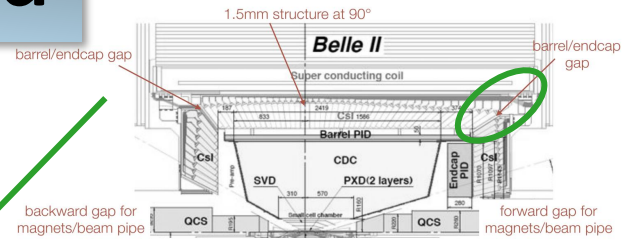
$e^+e^- \to \gamma\gamma\gamma$

1 γ in 90^0 gap

1 γ out of ECL acceptance

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





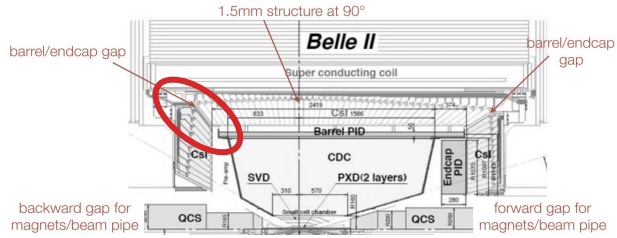
$e^+e^- \to \gamma\gamma\gamma$

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

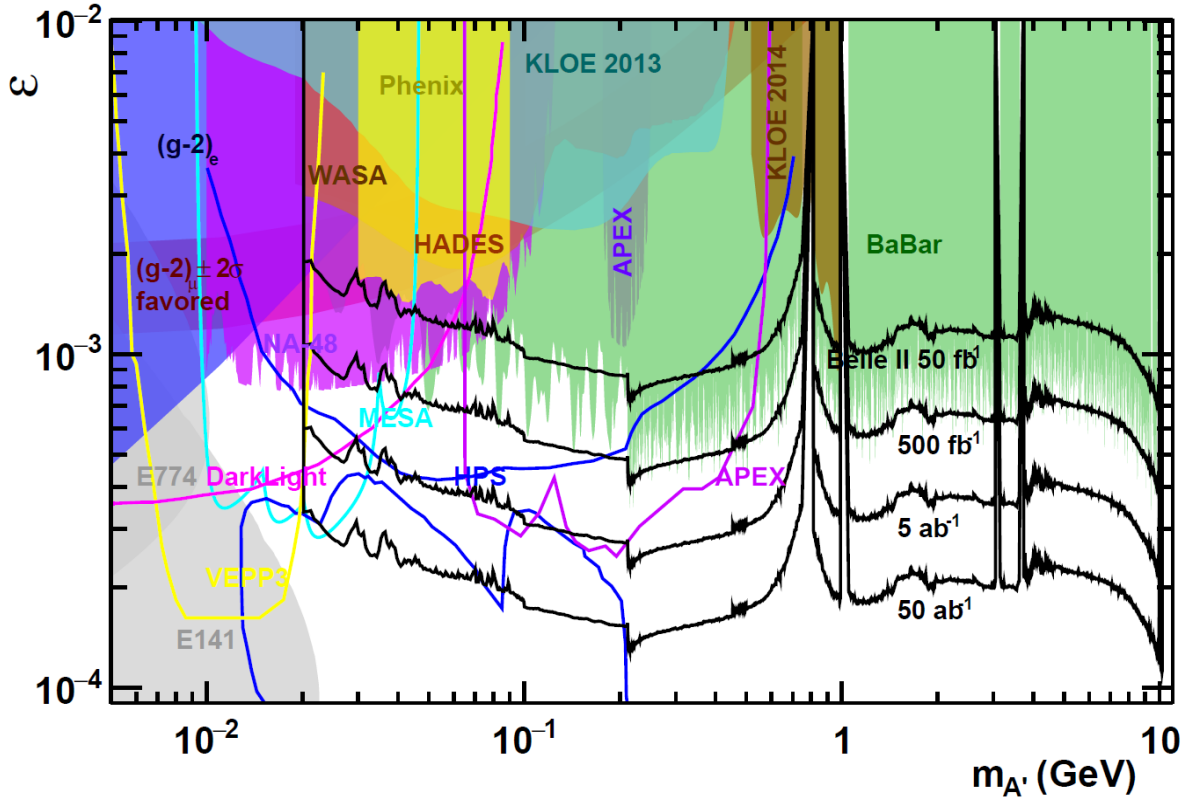
1 γ out of ECL acceptance

Crucial usage of KLM to veto photons in ECL gaps

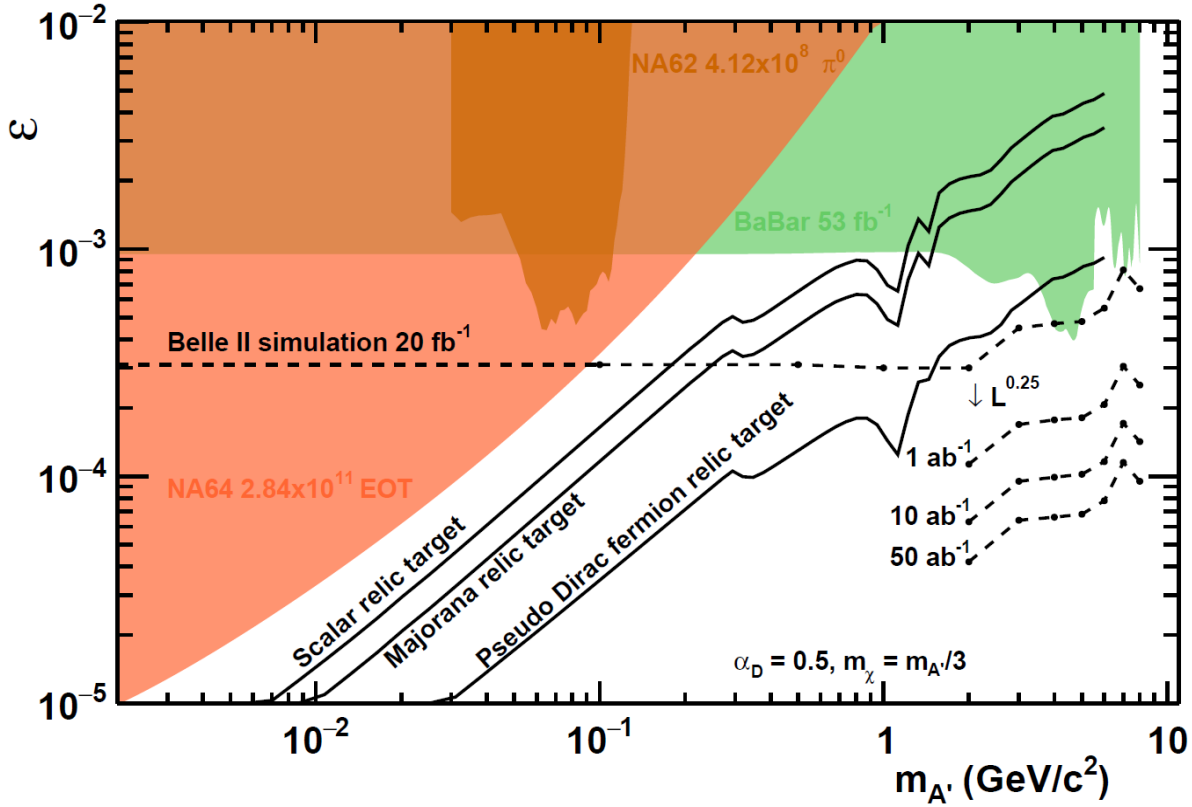
Dark photon: luminosity projections

arXiv: 2207.06307v1

Visible



Invisible



Belle II vs BaBar

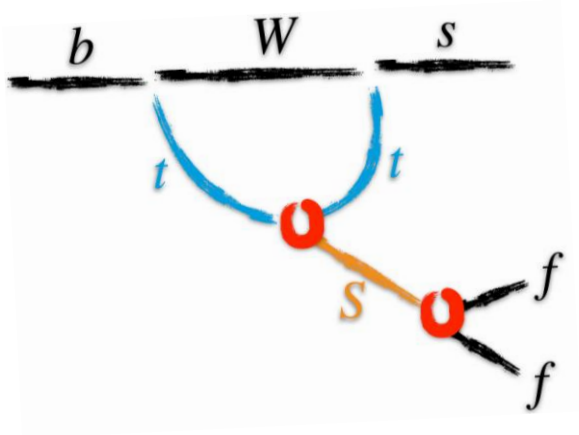
- ✓ Calorimeter with no projective cracks in ϕ
- ✓ Larger acceptance
- ✓ KLM veto

Dark scalar S in b→s transitions

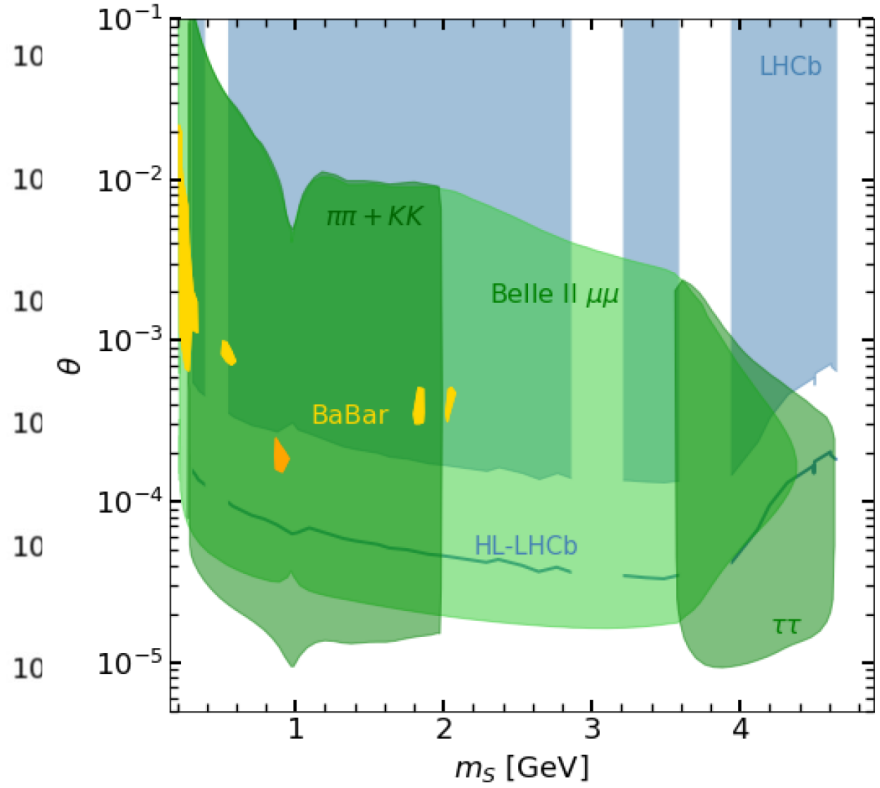
Phys. Rev. D 101, 095006 (2020)

- New scalar field ϕ and a dark fermion χ
- After Electroweak SSB, ϕ mixes with the Higgs to generate a scalar S
- Small mixing → **large lifetimes**
- S inherits Yukawa type couplings to SM fermions
- Produced in Belle II via **b→s transitions**
- Large τ_S limit or decay to DM → same topology as B →Kνν

arXiv: 2207.06307v1



LLP signature



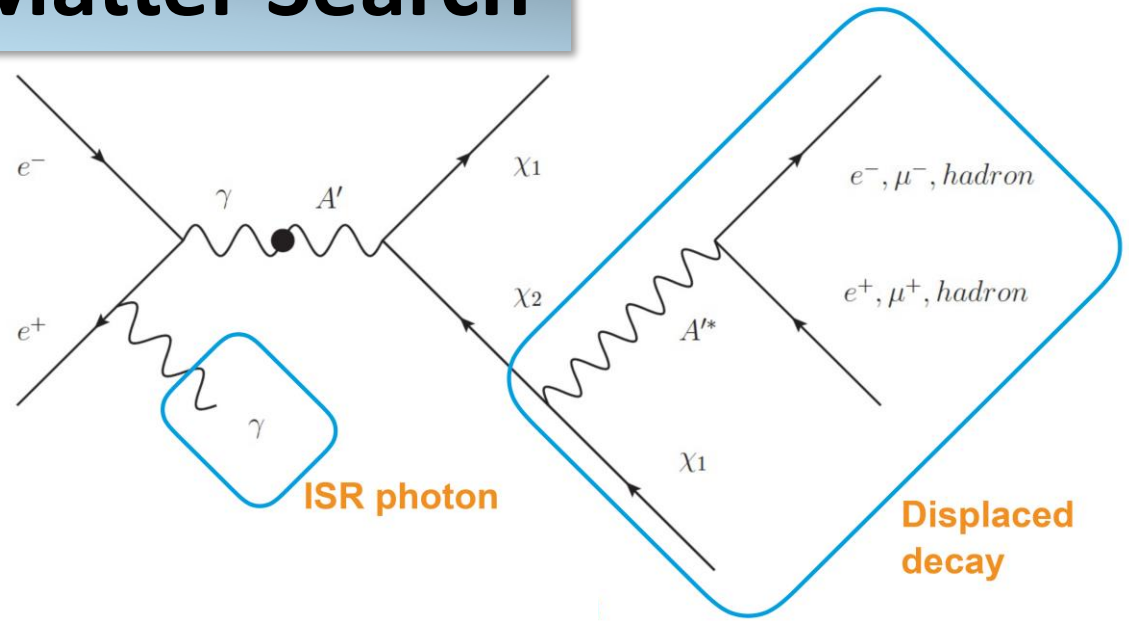
S → $\mu^+\mu^-$ / $\pi^+\pi^-$ / K^+K^- / ($\tau^+\tau^-$)

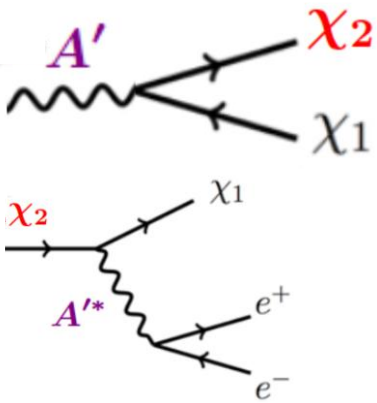
Inelastic Dark Matter Search

- Originally proposed to explain the DAMA anomaly
- Almost hidden to direct detection experiments

- Two dark matter states χ_1, χ_2 with $\Delta = m_{\chi 2} - m_{\chi 1}$
- χ_1 is the relic candidate, χ_2 is long lived
- Background suppressed by LLP signature

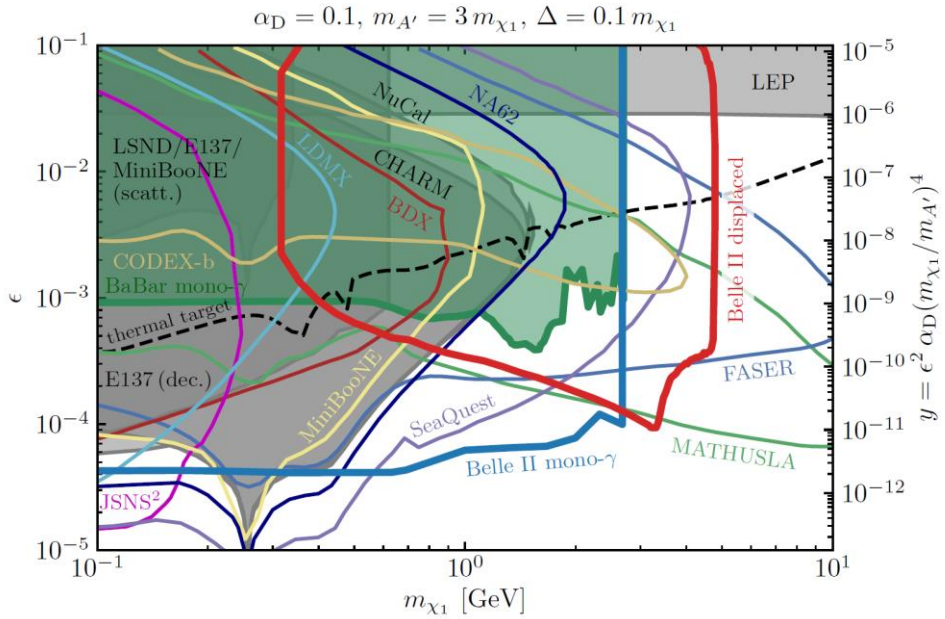
- Similar signatures in SIMP DM models





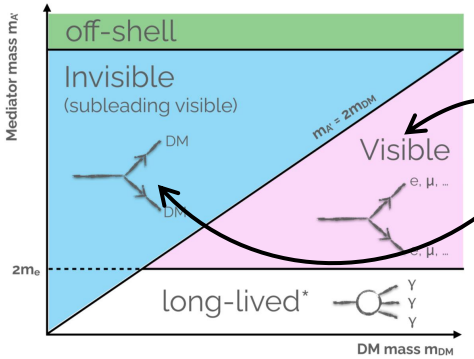
LLP signature

arXiv: 2207.06307v1



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



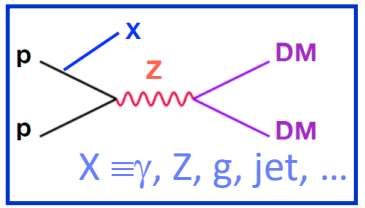
ll (γ) (+missing)

Visible minimal and non minimal dark photons, ALP→ff

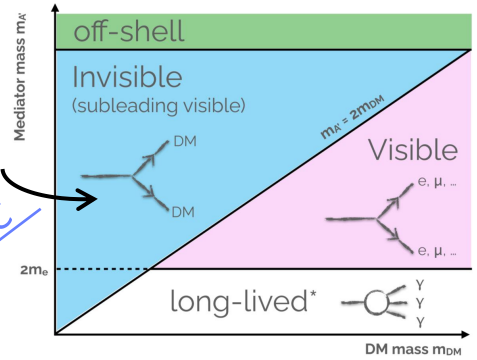
Invisible dark photon, Z'

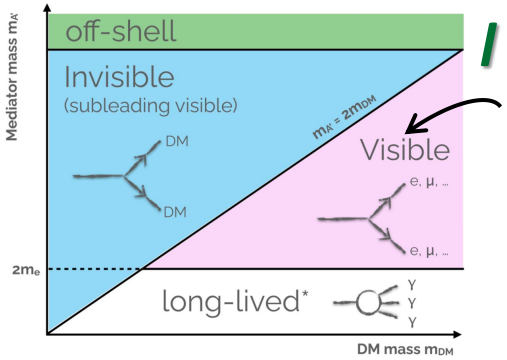
Single γ

Invisible dark photon, ALP →χχ, iDM, LLP



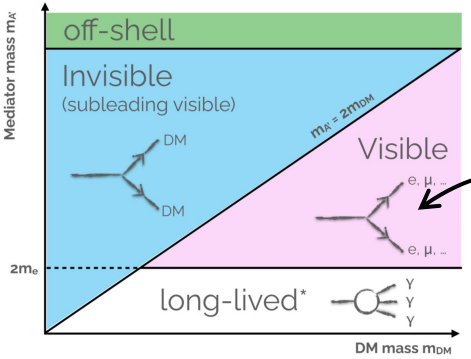
LHC





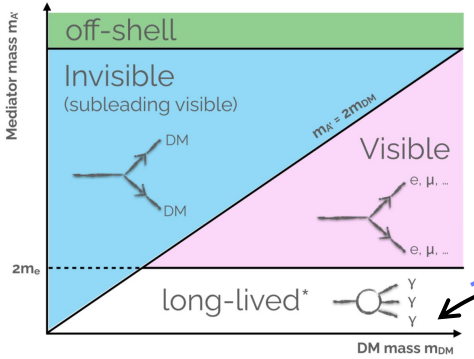
l l l' l'

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



γγ

Visible ALP → γγ



LLP

LHC

Hot topic

A', ALP→χχ, iDM, scalars

Summary

- Negative results from LHC and direct search experiments → light dark sector scenario more and more attractive
- Belle II at SuperKEKB has great potential thank's to low-background collisions, hermeticity, dedicated triggers
- **Belle II** started the physics run in 2019: 424 fb^{-1} collected up to now
- We expect to lead the light dark sector searches in the next decade

Published 0.5 fb^{-1}	Submitted / ~accepted	Close to submission	Next / planned
invisible Z' ALP → $\gamma\gamma$	Dark Higgsstrahlung	invisible Z' ALP, S, Z' → $\tau\tau$	Z'→$\mu\mu$ B→kS with S LLP IDM Heavy QCD axion Invisible A' Visible A' Dark showers …

SPARE SLIDES

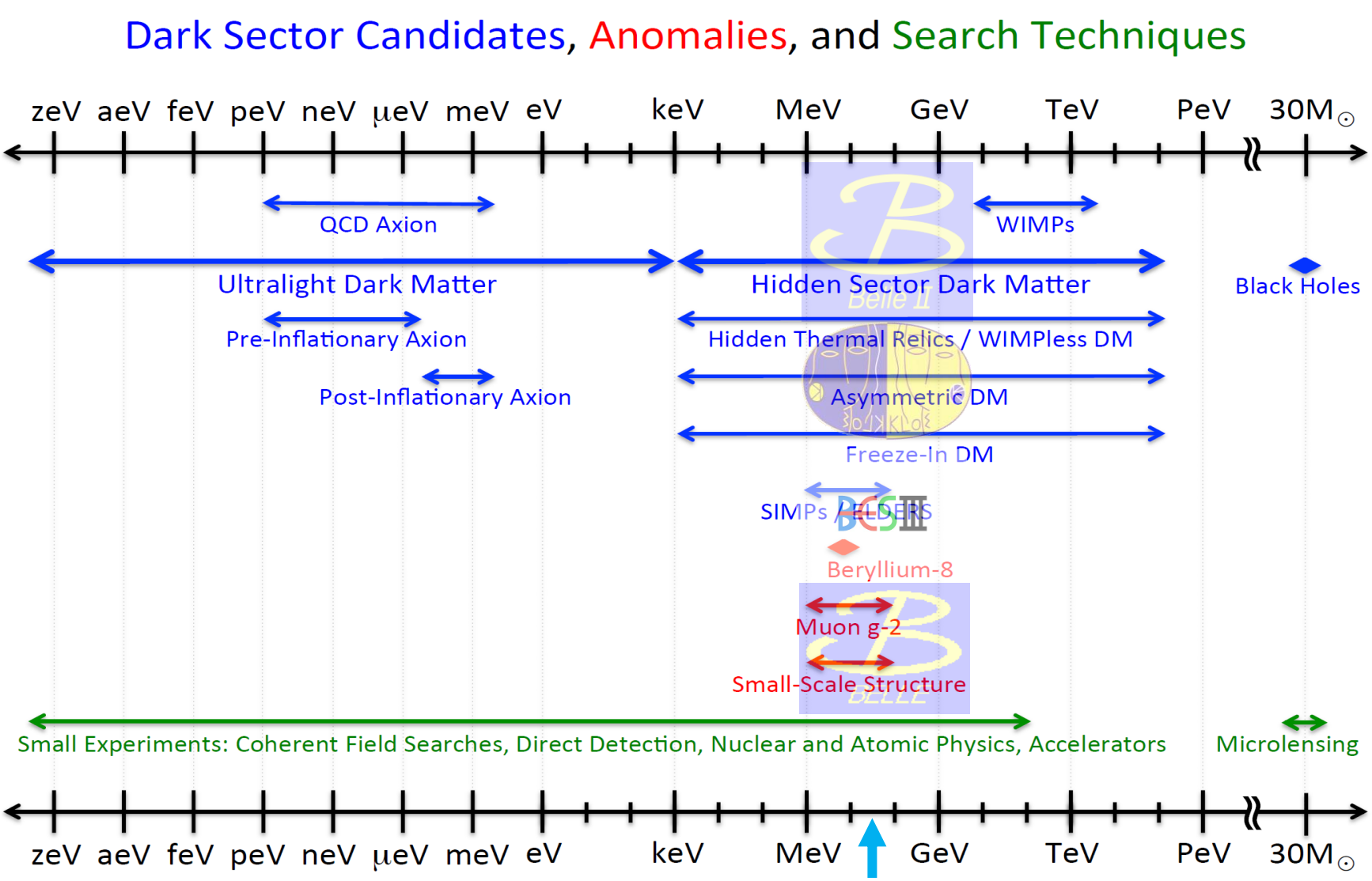
What can we do at B-factories that we can't at the LHC?

- Closeness to the light region
- Clean, low background, «energy conserving» environment, closed kinematics
- 3d momentum conservation, as opposed to p_T
- Easiness of tag & probe techniques
- Full Event Interpretation
- Less model dependency

- Low multiplicity signatures
- Missing energy channels
- Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessibility

- Cleanliness and luminosity sometimes compensate for cross section → competition

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

Belle II trigger

Dark sector physics
- Low multiplicity signatures
- Huge backgrounds from beam, Bhabha, two-photon

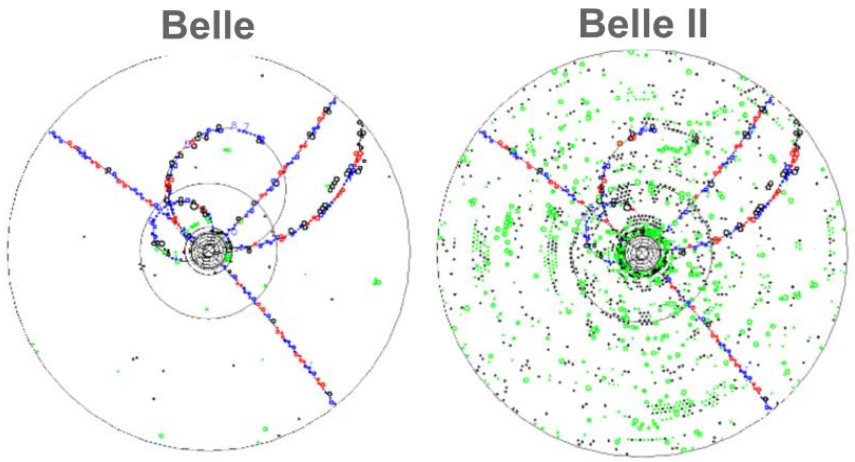
Level 1 hardware-based combines info from CDC, ECL, KLM
- Tracks, clusters, muons

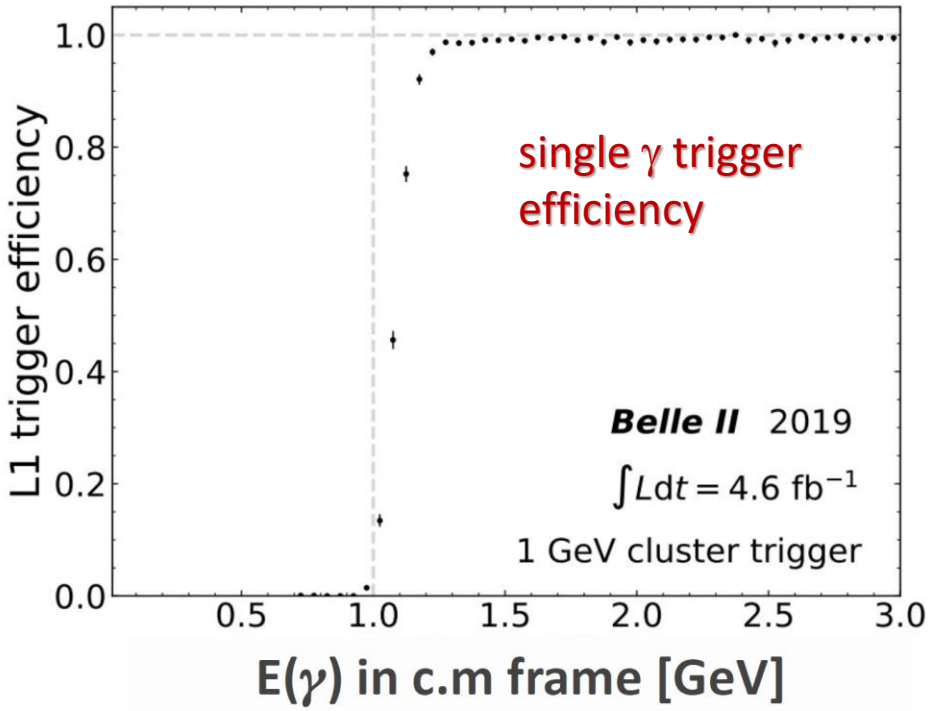
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV





Dark Higgsstrahlung: systematics

2 control samples

$\mu\mu\gamma$ $\mu\mu(\gamma)$ background
$e\mu$ $\tau\tau$ background

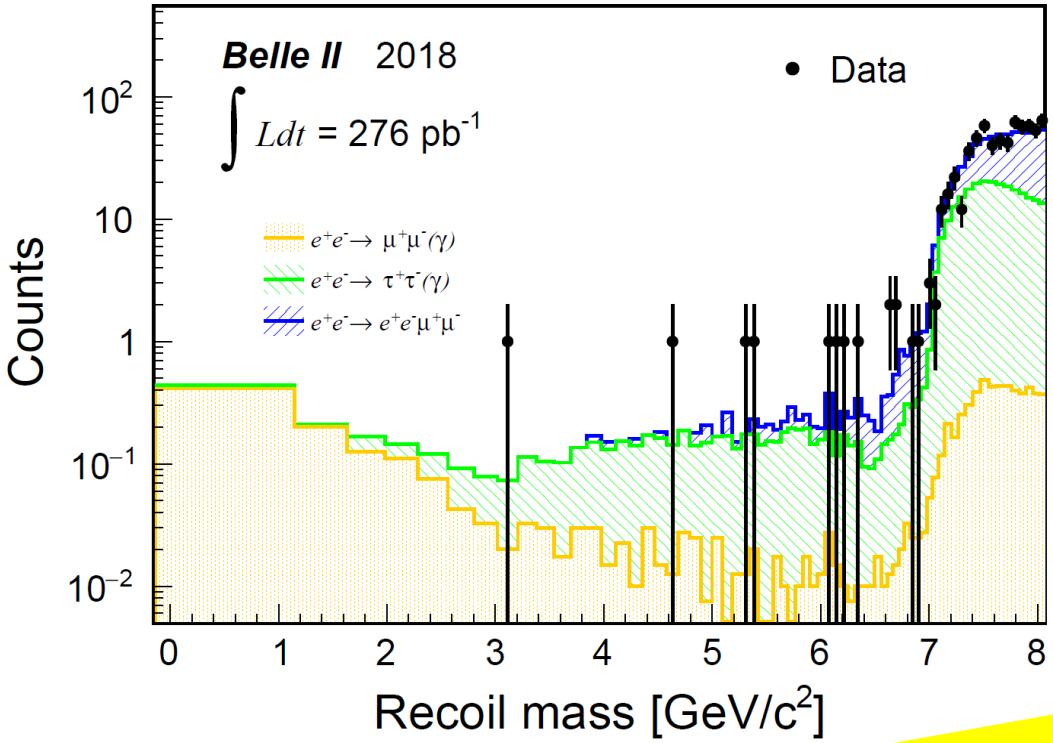
Split mass plane into orthogonal macroregions
- Each dominated by a single background source
- Data/MC normalization + shape

source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

- Negligible effect on Uls (~1%)
- Exception is $M_{A'} > 9$ GeV/c^2 (~25%)

Z’ to invisible: previous result

Pilot run physics results

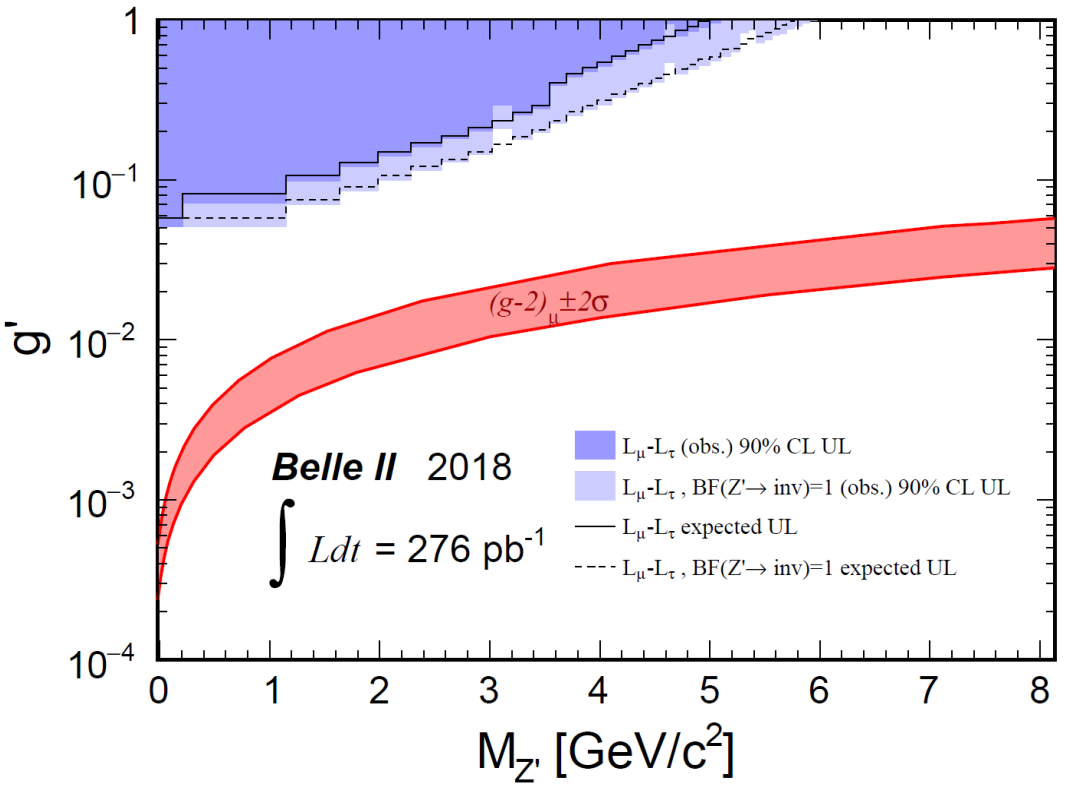


First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

Source	Error
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
Background before τ suppression	2%
τ suppression (background)	22%
Discrepancy in μμ yield (signal)	12.5%

will decrease with new data



Z' to invisible: analysis

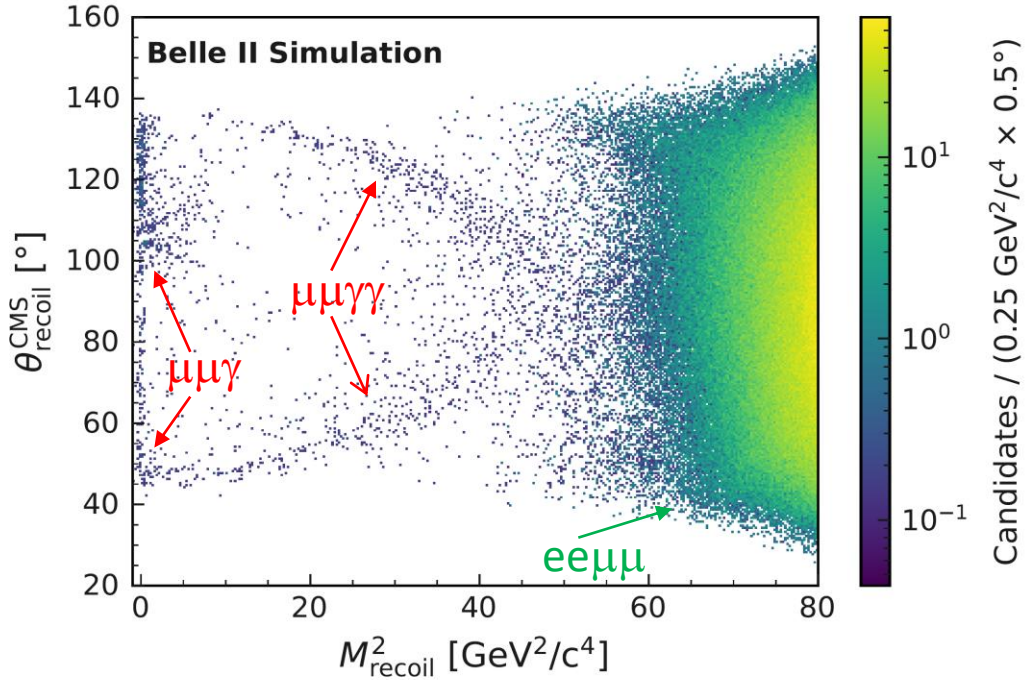
ICHEP

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

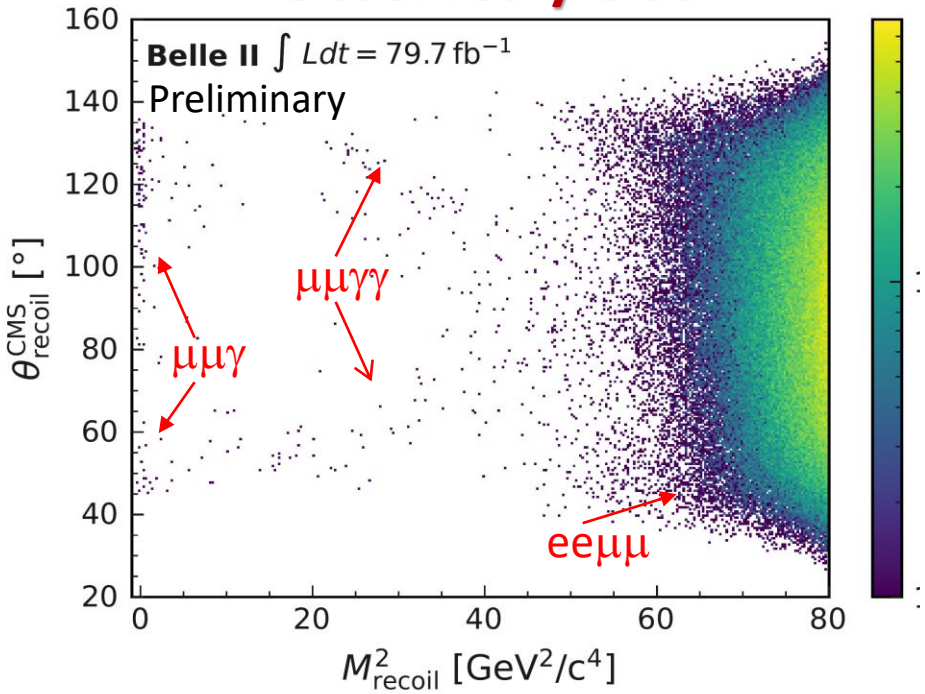
3 control samples

$\mu\mu\gamma$	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}



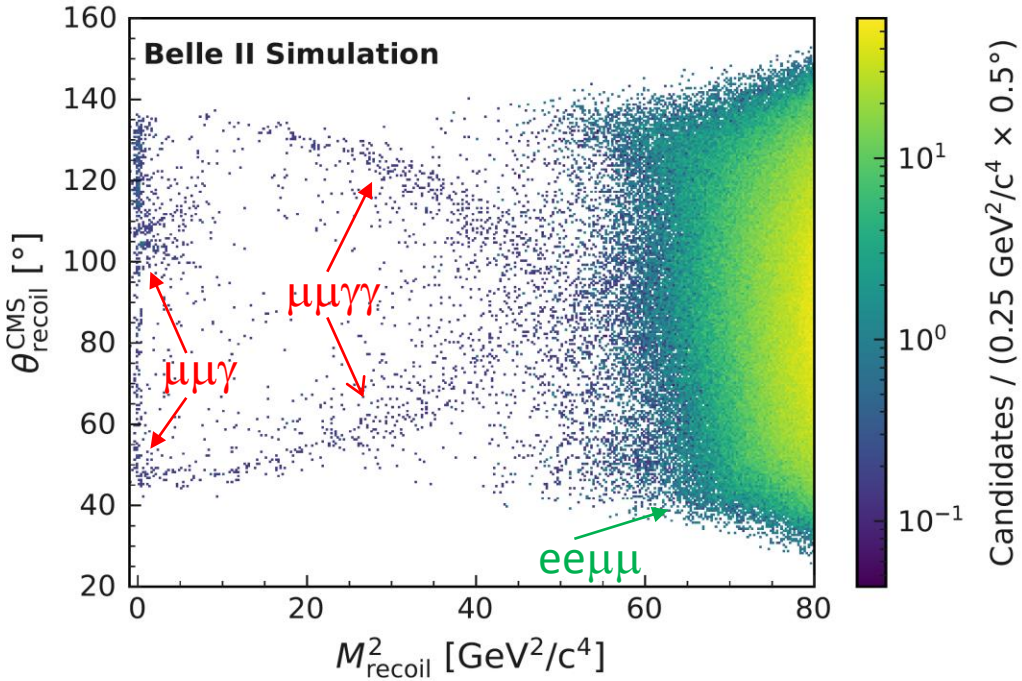
Observed yields



Z' to invisible: systematics

NEW

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



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

3 control samples

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

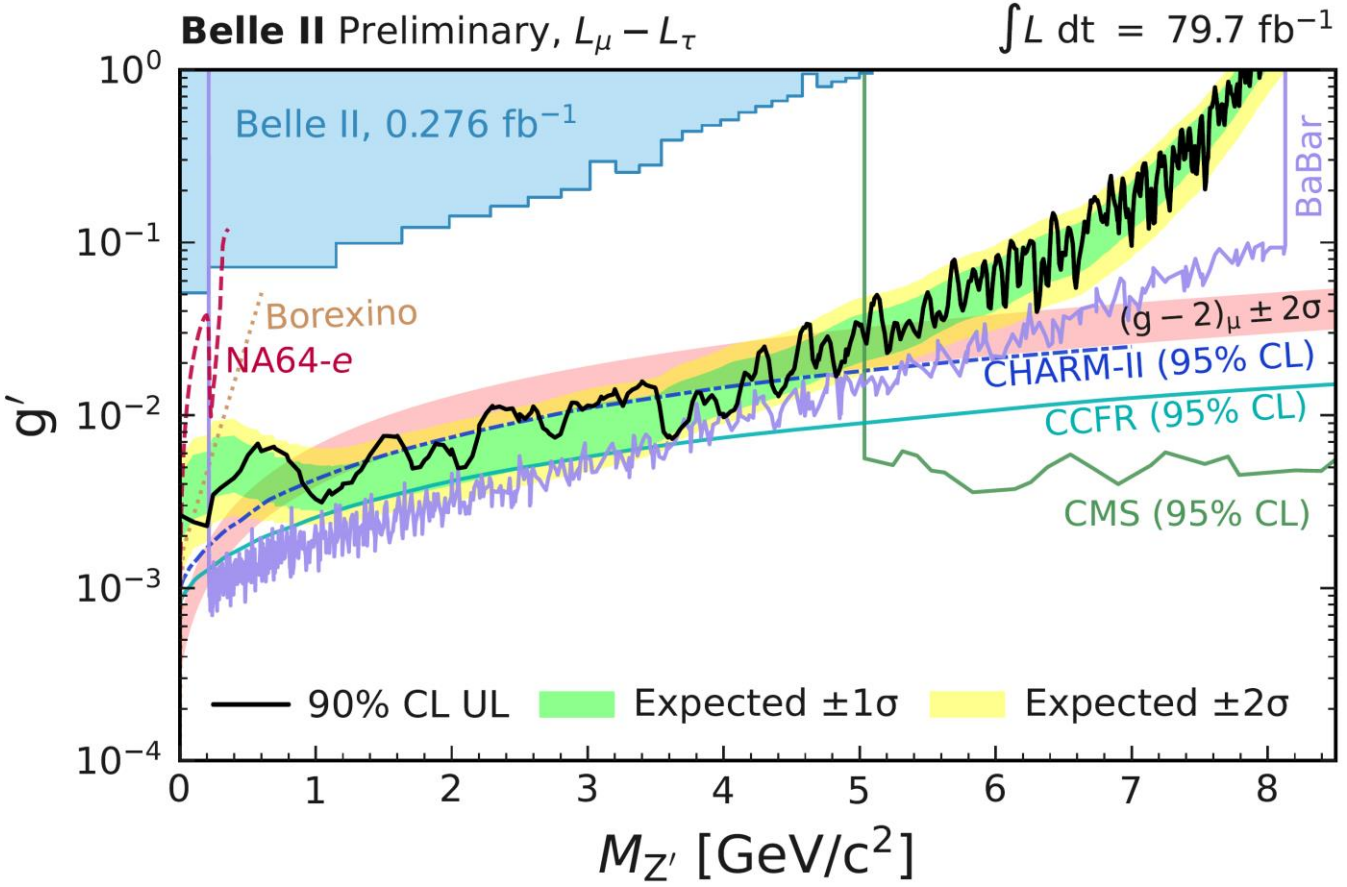
Systematics

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

Z’ to invisible results

NEW

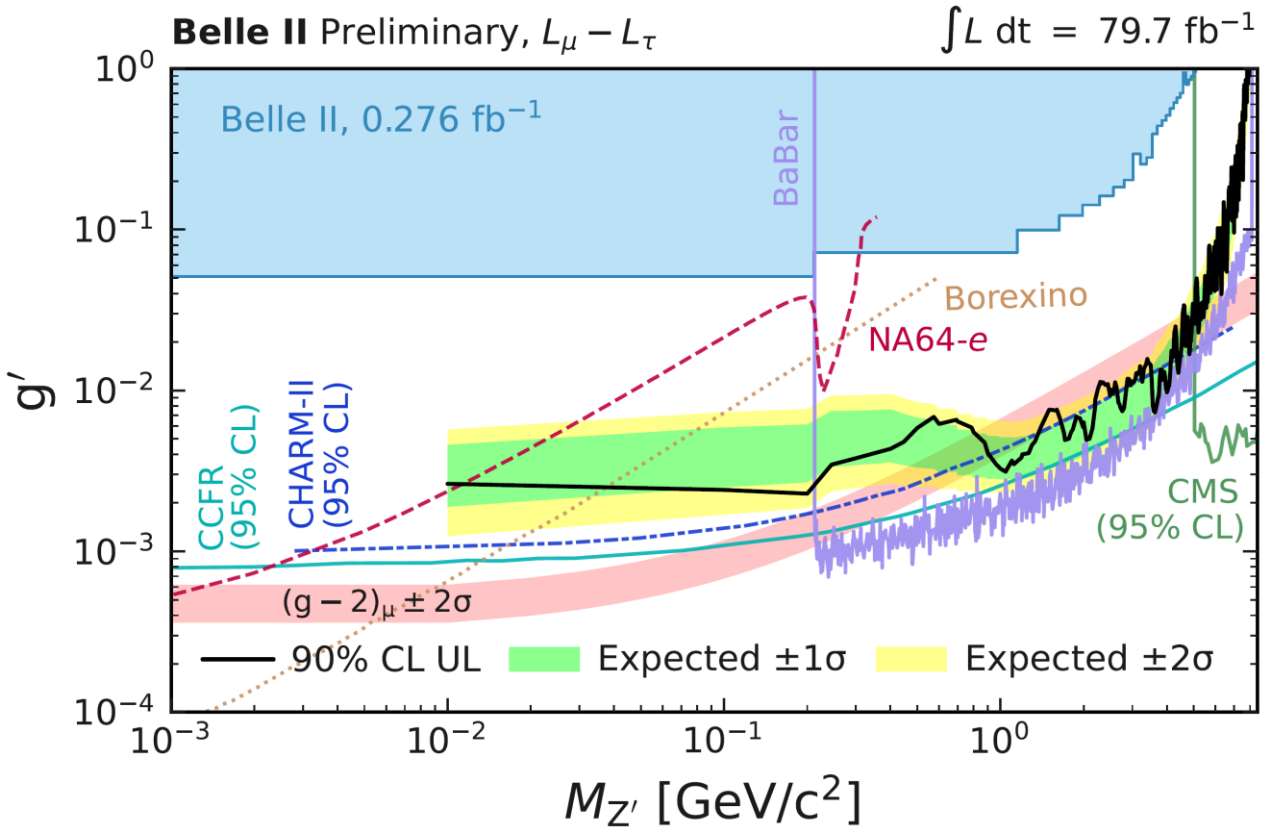
Vanilla model invisible Z’



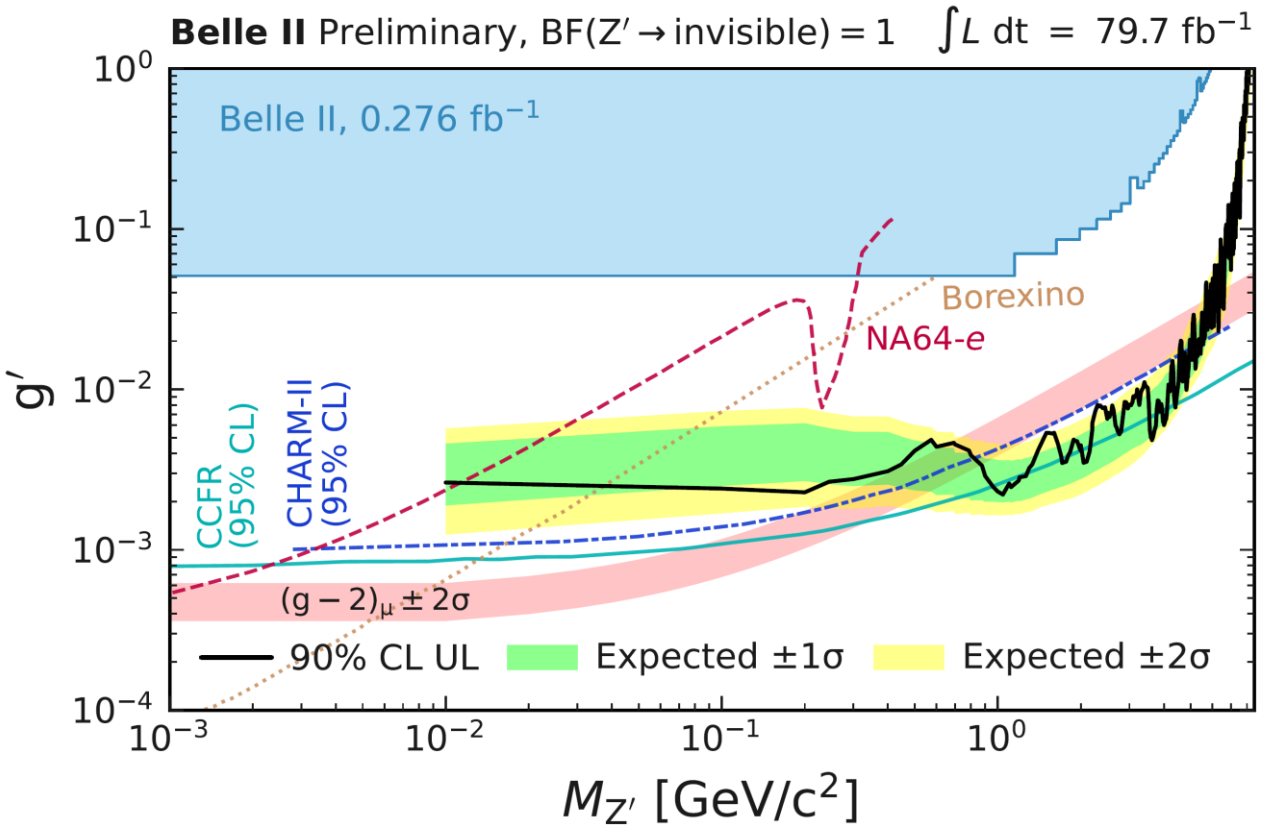
Z’ to invisible results

NEW

Vanilla model invisible Z’



Fully invisible Z’

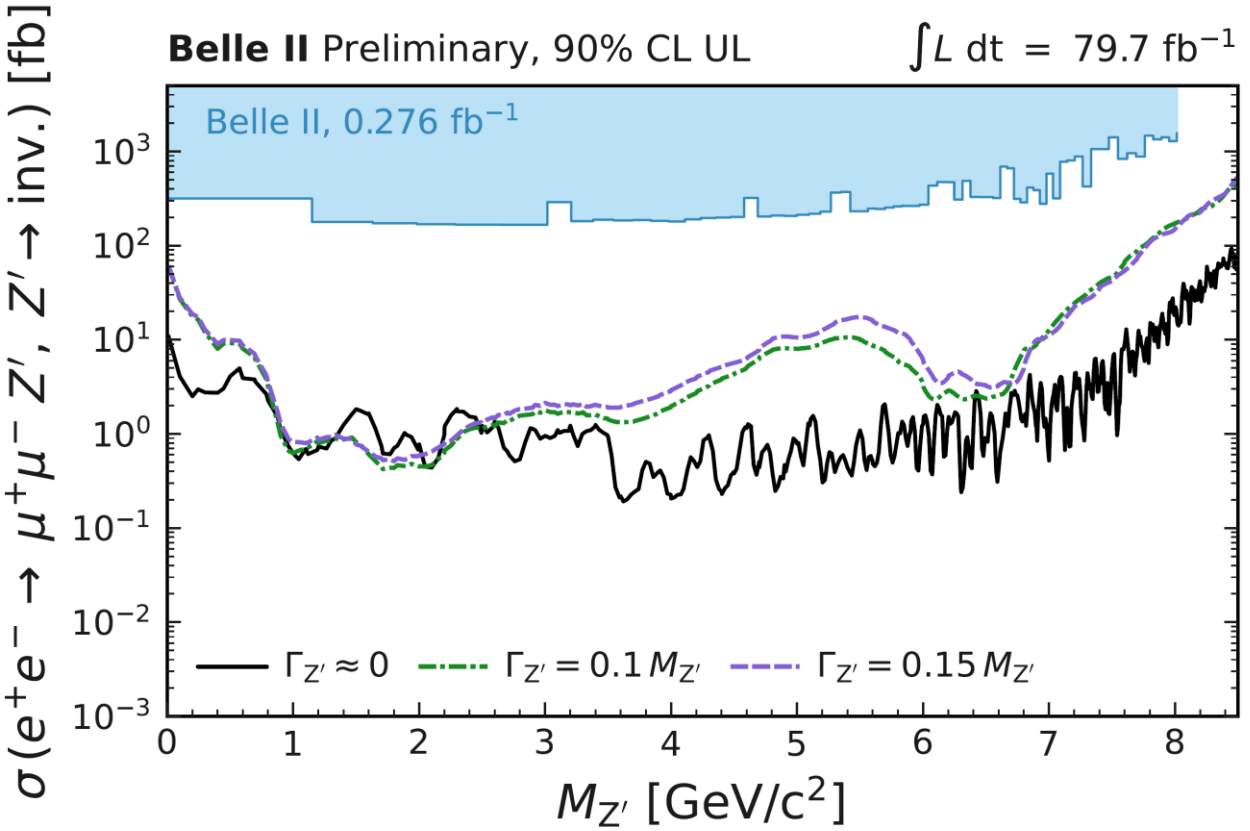


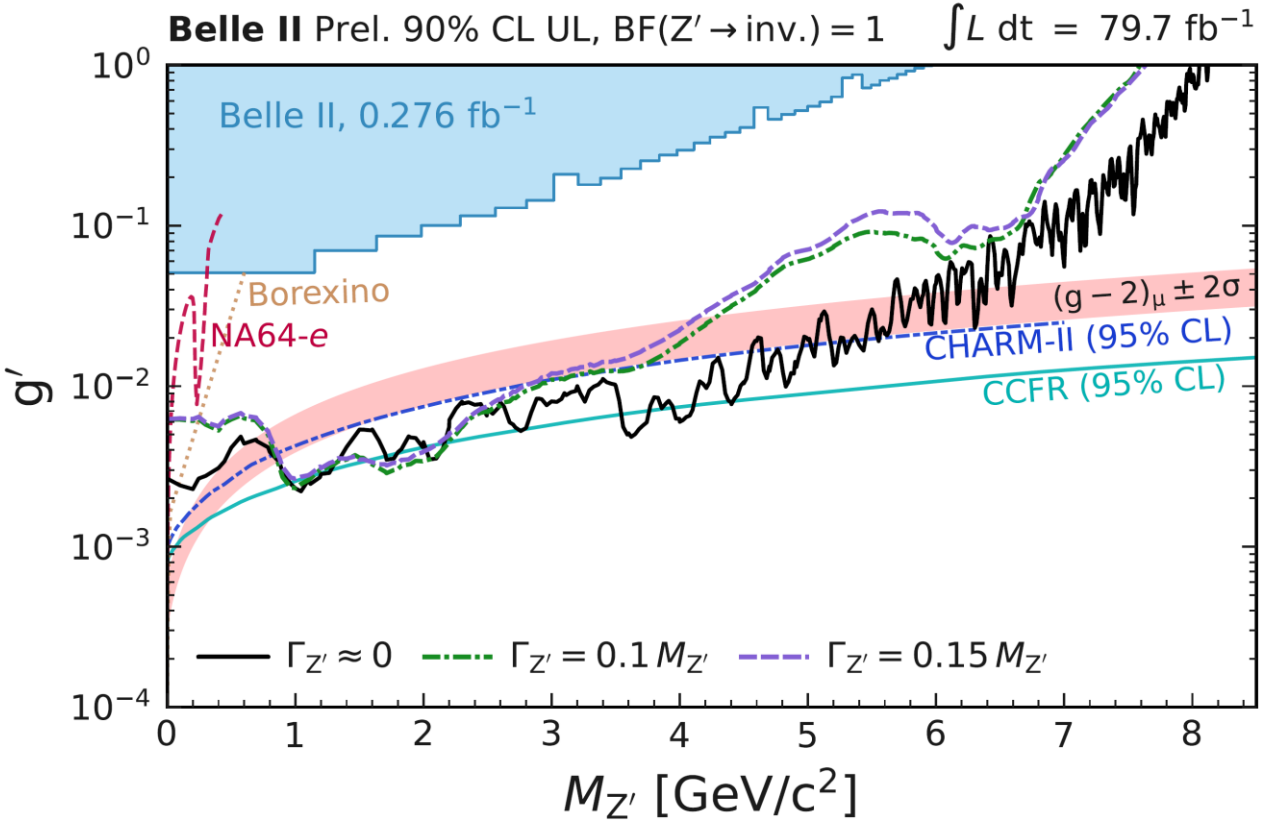
Z’ to invisible results

NEW

- Invisible Z’ with non negligible intrinsic width

- $\Gamma_{Z'} = 0.1\ M_{Z'}$, $0.15\ M_{Z'}$





Z', S, ALP → ττ: systematics

NEW

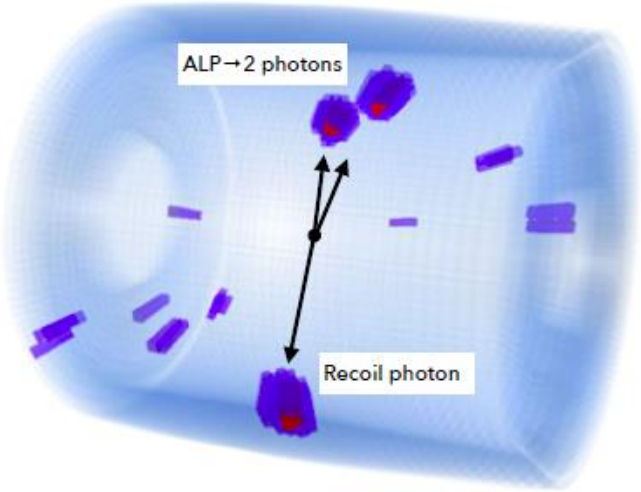
source	Uncertainty (%)
trigger	2.7
Particle ID	3.9-6.2
Tracking	3.6
Fit bias	4
MLP selection	2.8
Mass resolution	3
Efficiency interpolation	2.5
Luminosity	1
other	1
Total	**8.8-9.9**

Negligible effect on sensitivity and Uls → 1%

ALP →γγ : signature

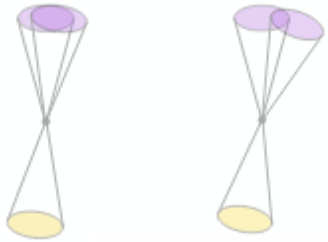
2020

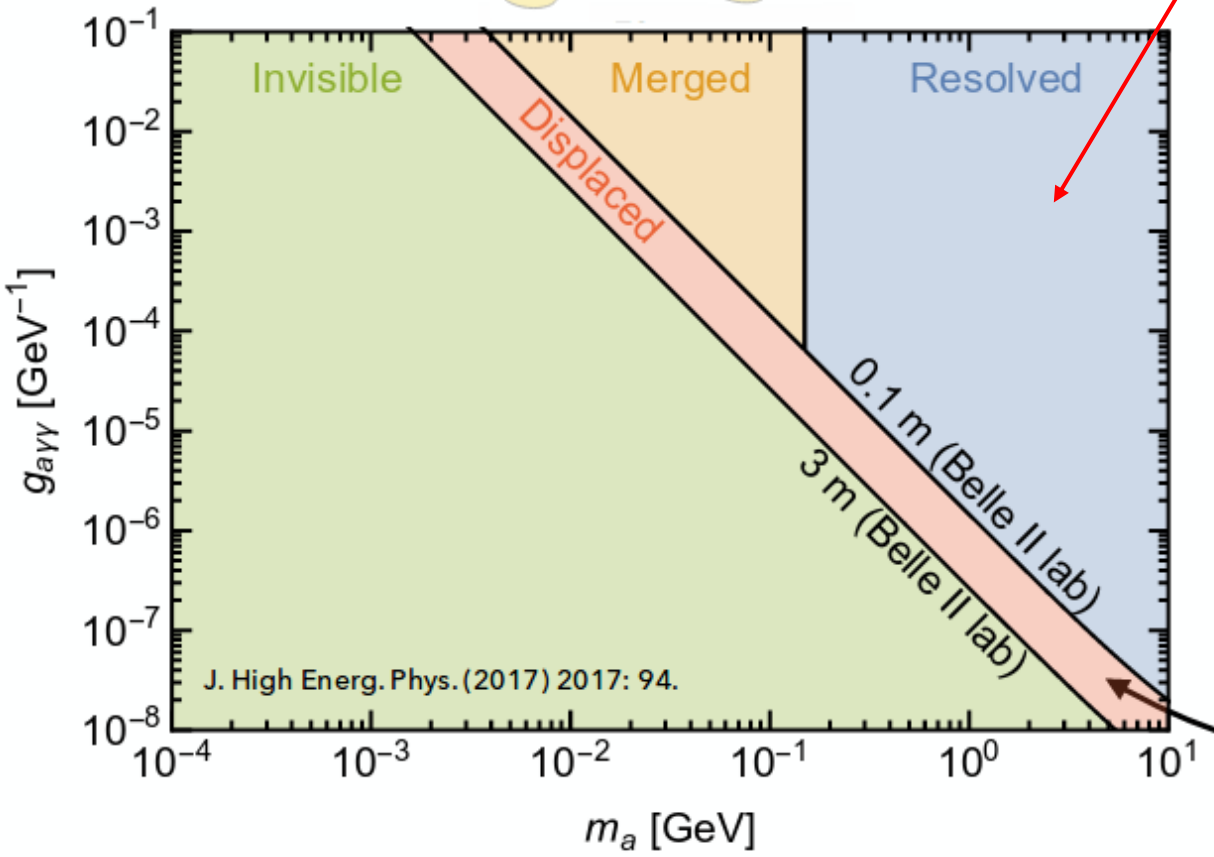
3 γ topology, but…



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

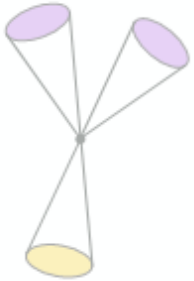
Two of the photons overlap or **merge**.





Belle II

Three **resolved**, high energetic photons.



The searches for invisible and visible ALP decays veto this region.

ALPs can also decay to DM → single photon topology

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.
Good conditions to perform the measurement as soon as possible.