Dark sector searches at Belle II

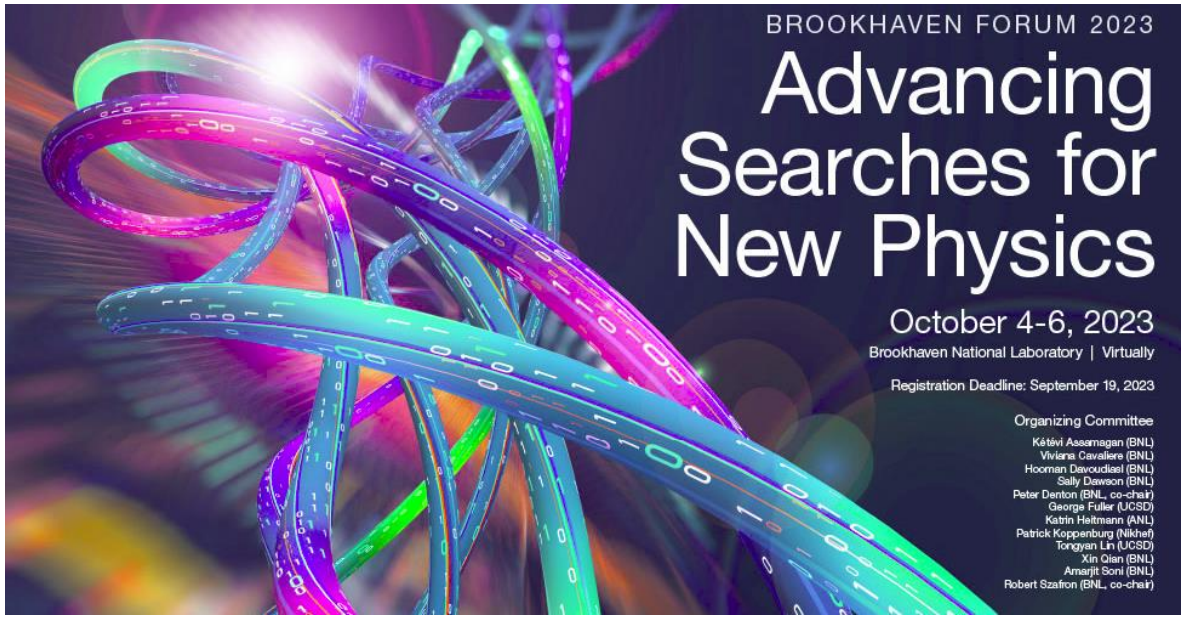
Enrico Graziani

INFN – Roma 3

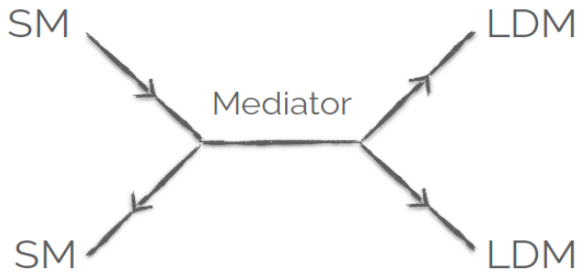
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK

- ✓ Light dark sector models
- ✓ Belle II searches
- ✓ Results
- ✓ Perspectives & Summary



Dark matter hunt with a light sector



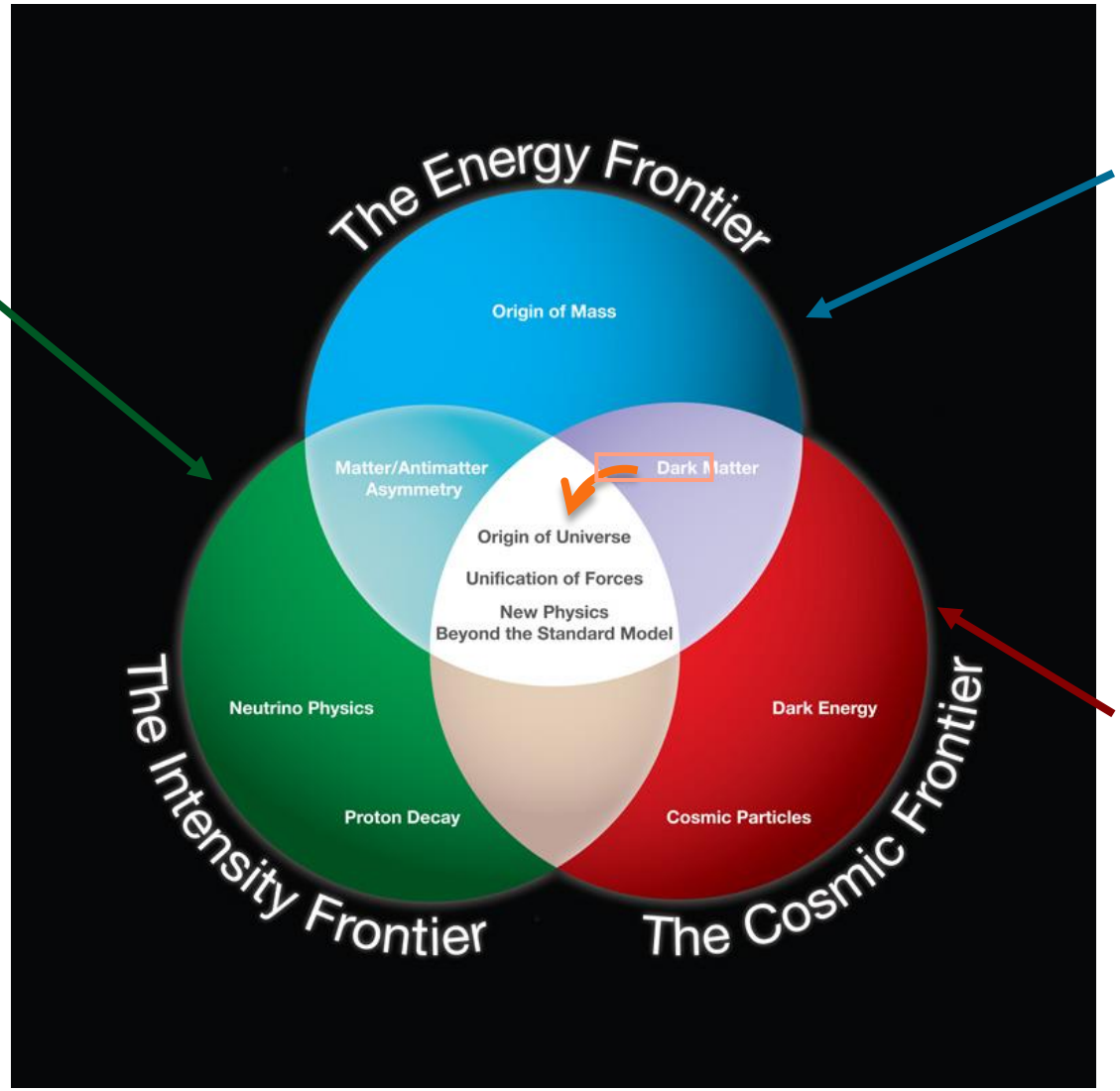
Light Dark Matter Mediators
→ portals

Vector portal
Dark photon, **Z'**, …

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

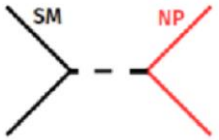
Scalar portal
Dark Higgs, **scalars**

Neutrino portal
Sterile neutrino



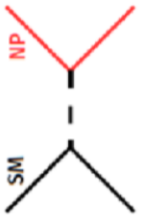
Energy frontier

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



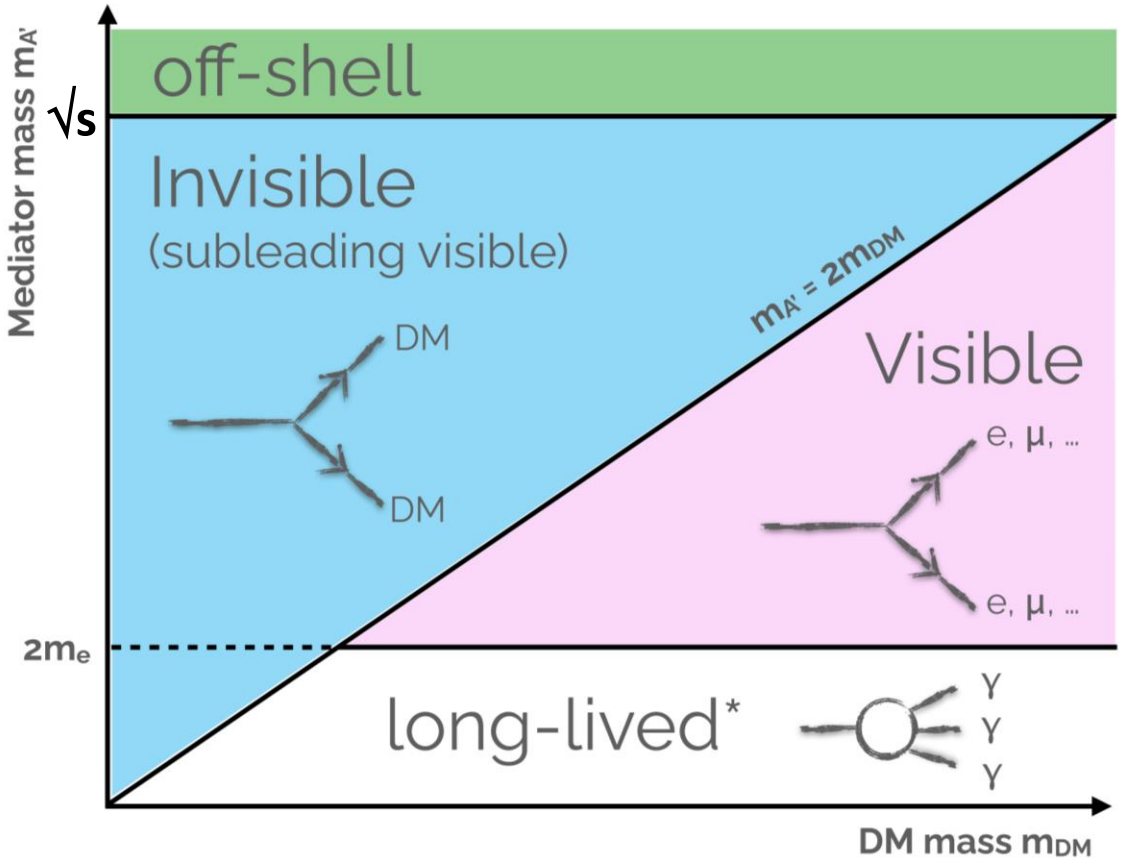
Cosmic frontier

Direct effect search in (mostly) underground experiments



Light dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

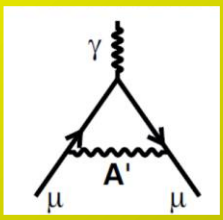


Probability of interaction of LDM detectors is negligible

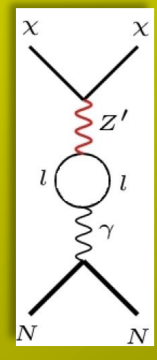
- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)



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



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

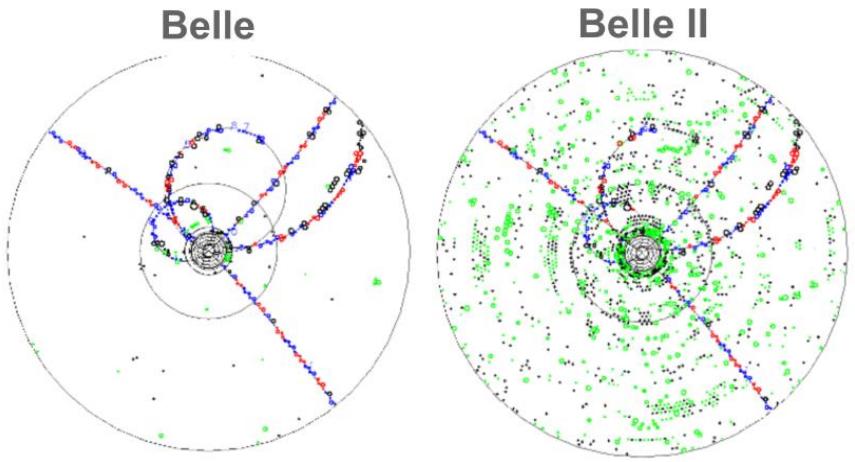
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

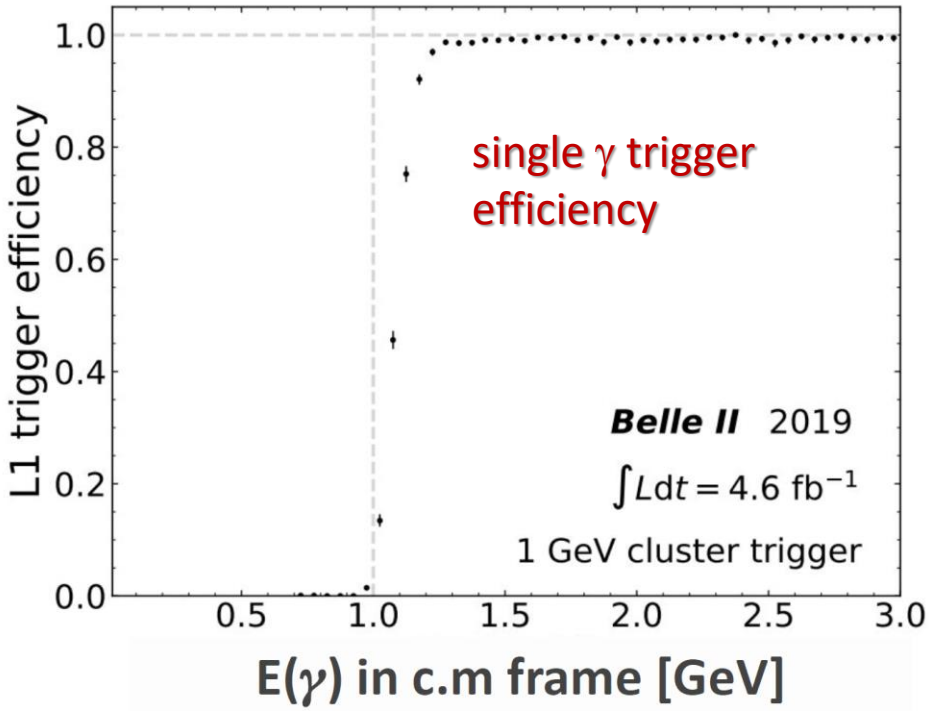
Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

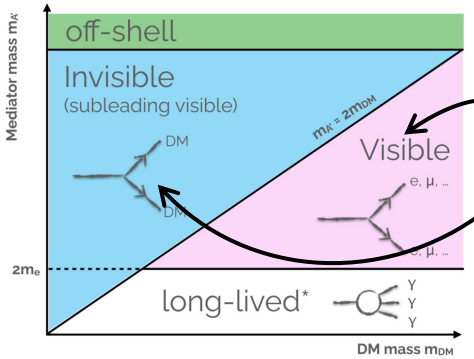
Displaced-vertex trigger
- Under study





Search overview: models ↔ signatures ↔ topologies

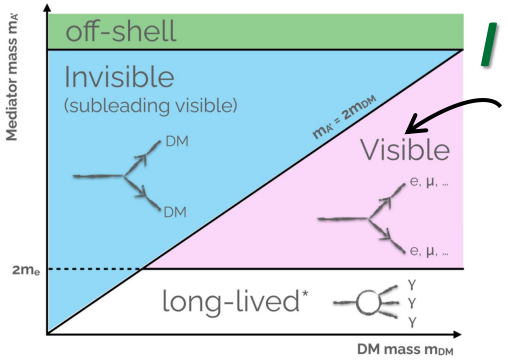
Models are growing up ~ exponentially (a warm thank's to theoreticians to provide us so many ideas). They should be used both to exclude (or confirm!) and as wonderful excuses to search for signatures & topologies as model independently as possible



ll (γ) (+missing)

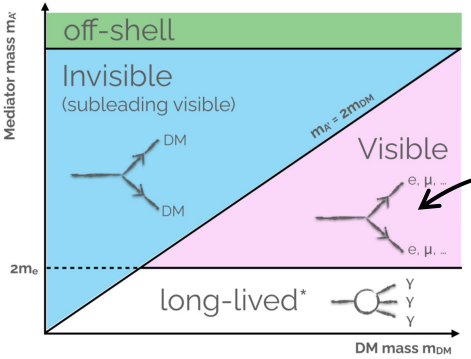
Visible minimal and non minimal dark photons, ALP→ff

Invisible dark photon, Z'



l l l' l'

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

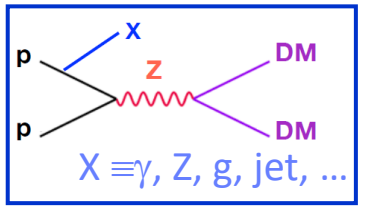


γγ

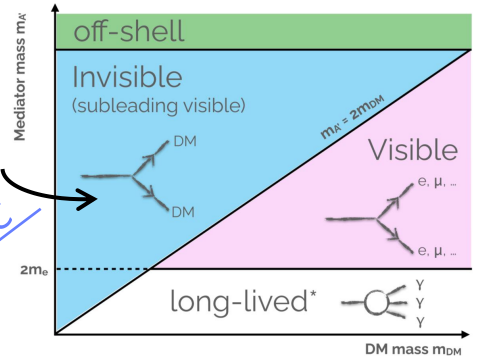
Visible ALP → γγ

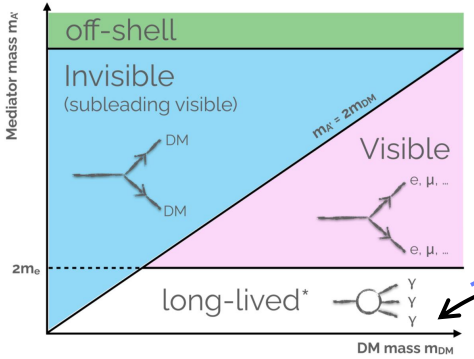
Single γ

Invisible dark photon, ALP →χχ, iDM, LLP



LHC





LLP long-lived particles

Hot topic

LHC

A', ALP→χχ, iDM, scalars

Belle II dark sector search overview: results

Published or publicly shown

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

Axion like particles
ALP→γγ

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

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

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

In progress

Not covered today. Have a look at back up slides

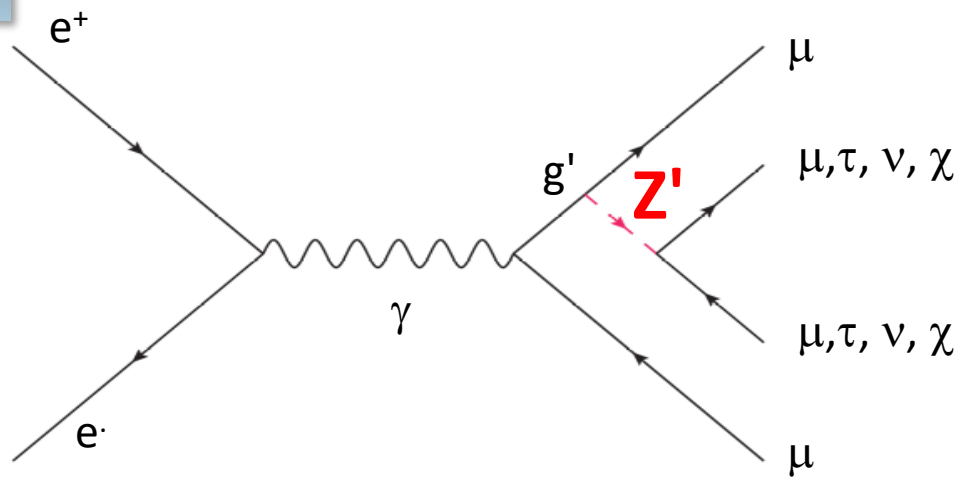
LLP Dark Higgsstrahlung with IDM
A'h' A'→$\chi_1\chi_2$, h'→μμ, ππ, kk

Invisible dark photon
γA' A'→χχ

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

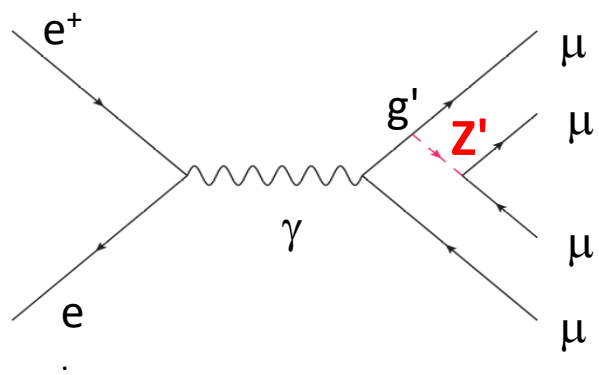


Belle II dark sector search overview: results

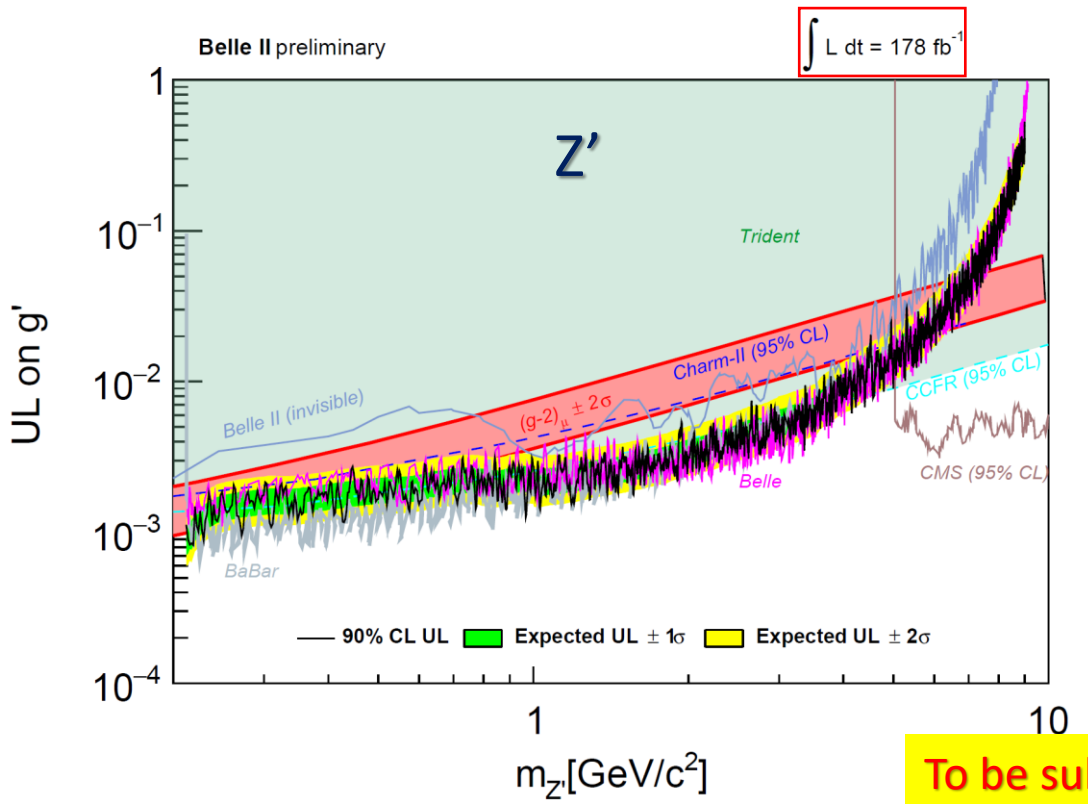
EPS 2023

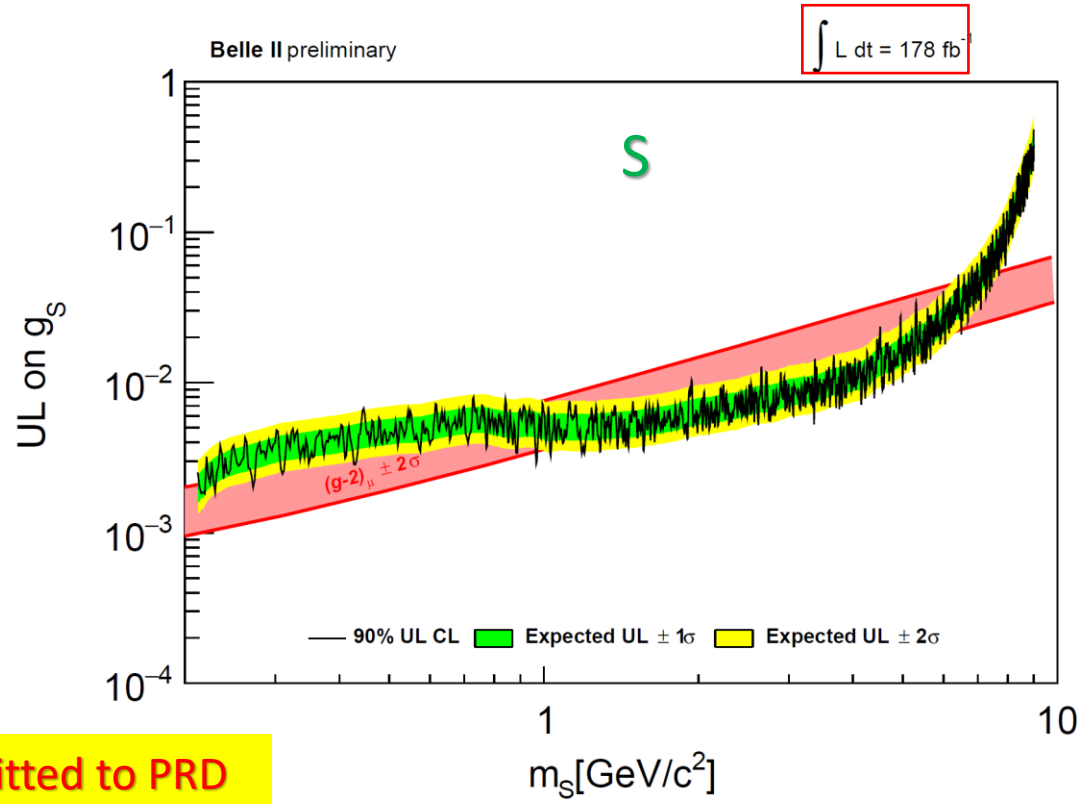
L_μ-L_τ
$Z' \to \mu\mu$

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



- Discovery mode for Z' and S
- Aggressive background suppression
- Exclusions on Z' ~ Babar and Belle, with much less luminosity
- First limits on S with a dedicated search



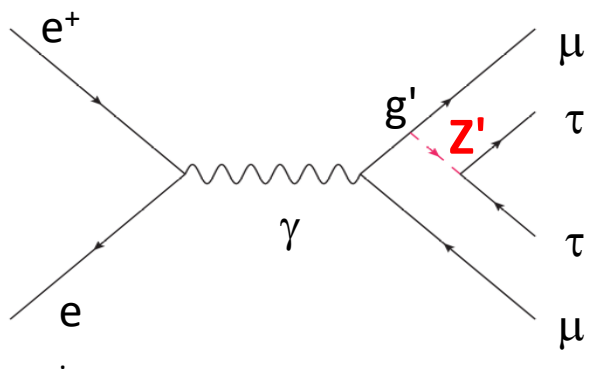


To be submitted to PRD

Belle II dark sector search overview: results

L_μ-L_τ
$Z' \to \tau\tau$

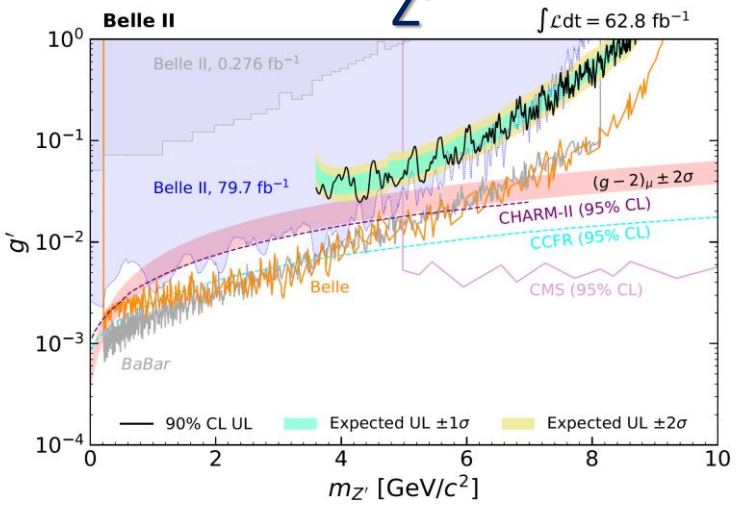
Reinterpreted also as
- Leptophilic dark scalar S → $(g\text{-}2)_\mu$
- ALP with τ coupling



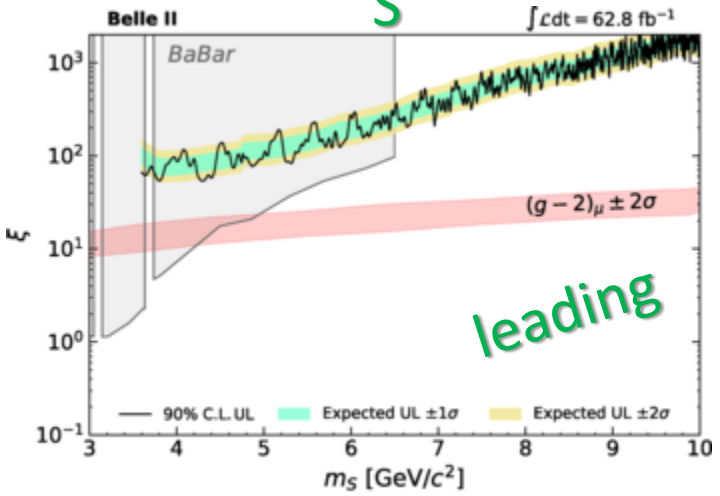
- Aggressive background suppression
- Look for peaks in the system recoiling against μμ

PRL 131, 121802 (2023)

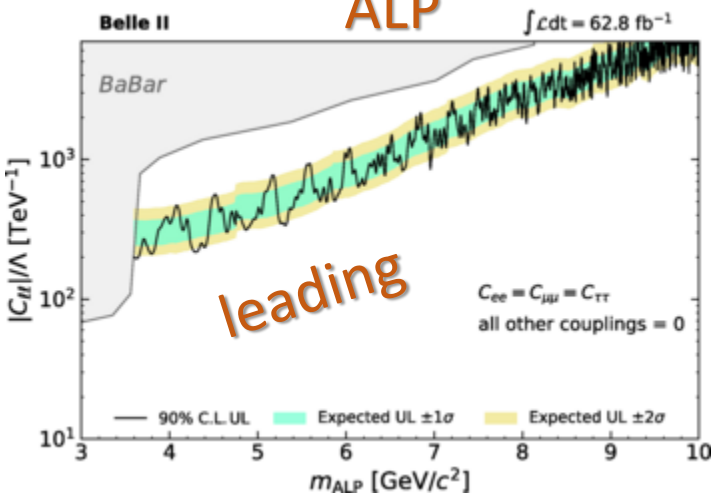
Z'



S



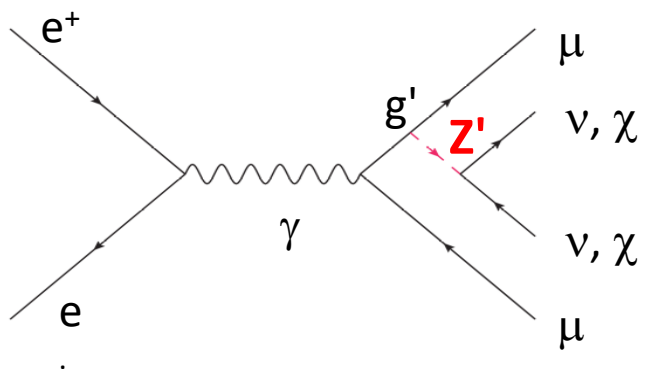
ALP

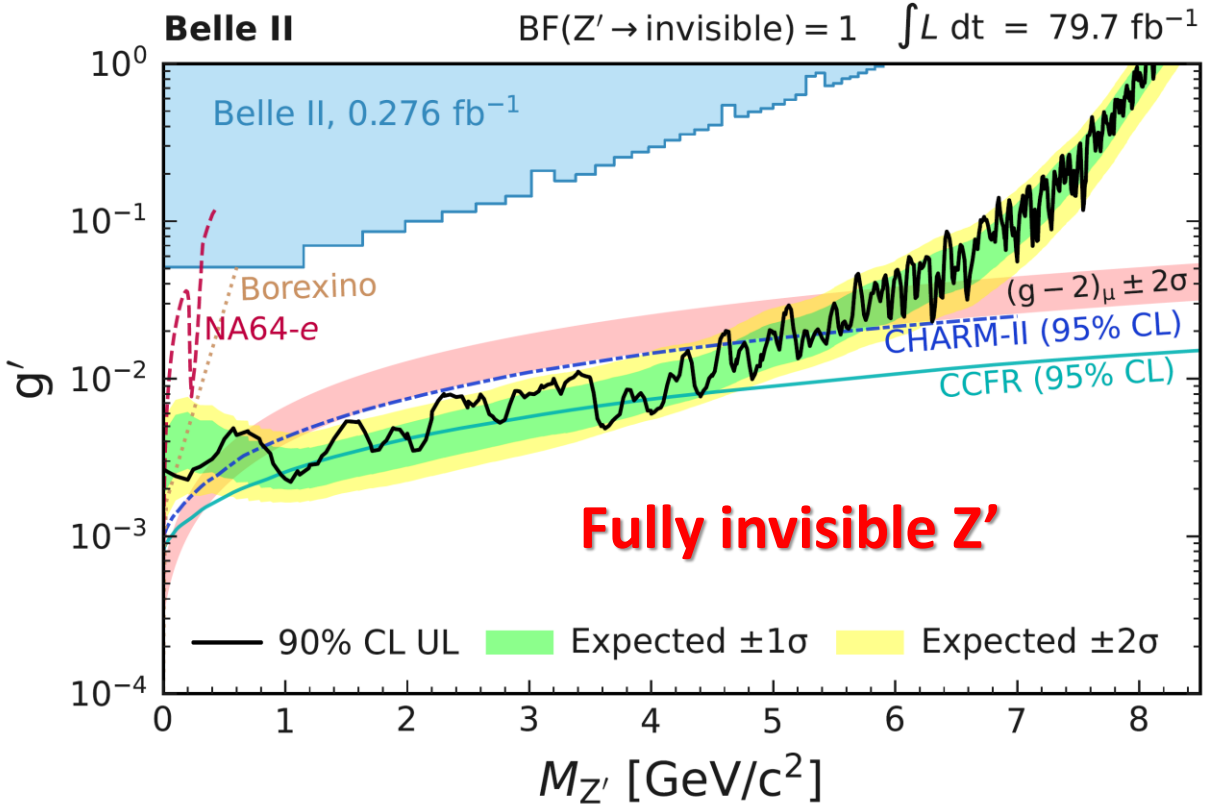


Belle II dark sector search overview: results

L_μ-L_τ
Z' → invisible

- Photon veto
- Aggressive background suppression
- Look for peaks in the system recoiling against μμ





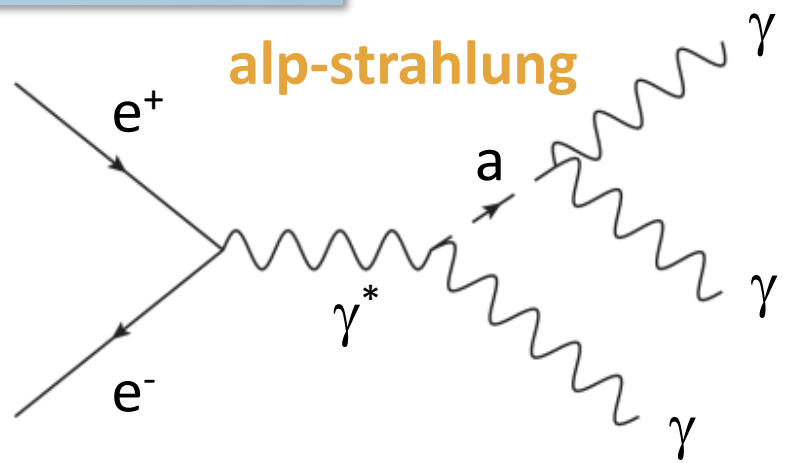
PRL 130, 231801 (2023)

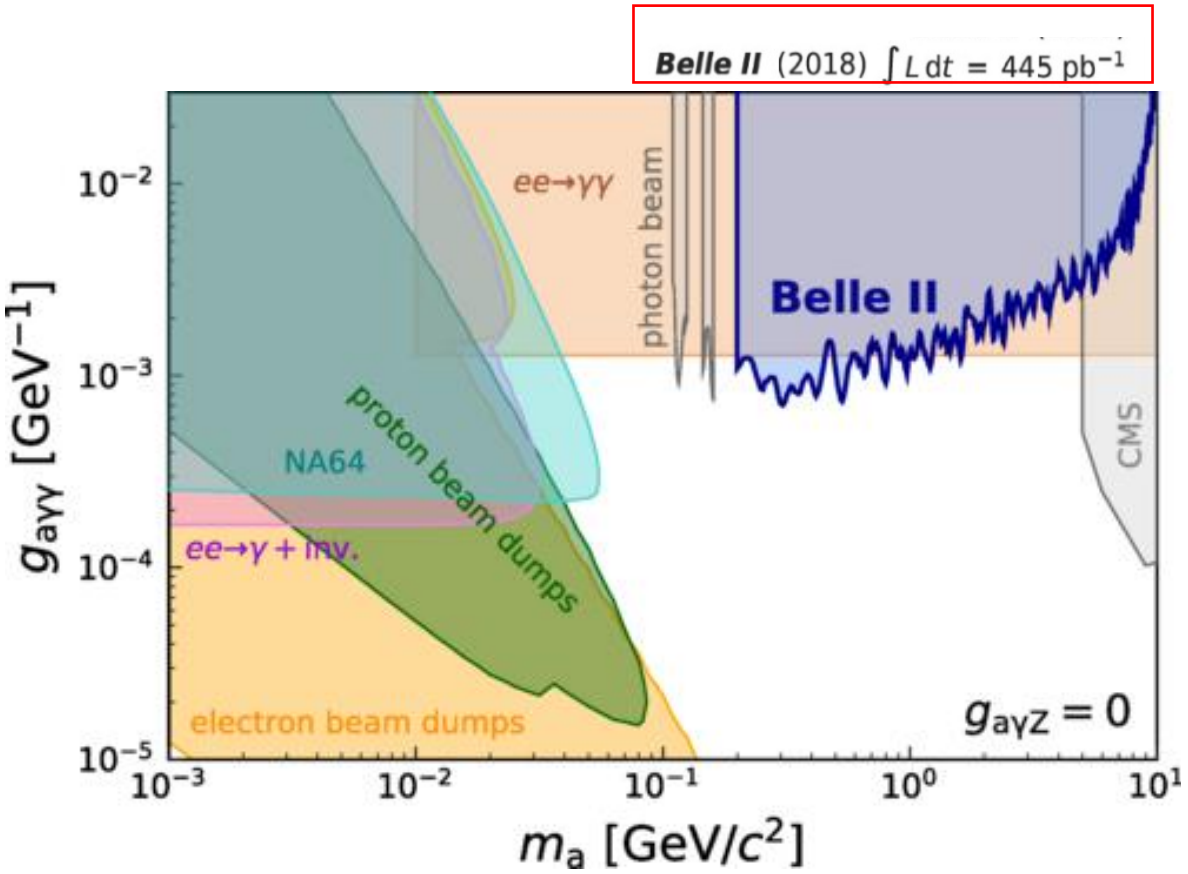
fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Belle II dark sector search overview: results

Axion like particles
ALP→γγ

Look for peaks in γγ mass or in the mass of the system recoiling against an isolated γ



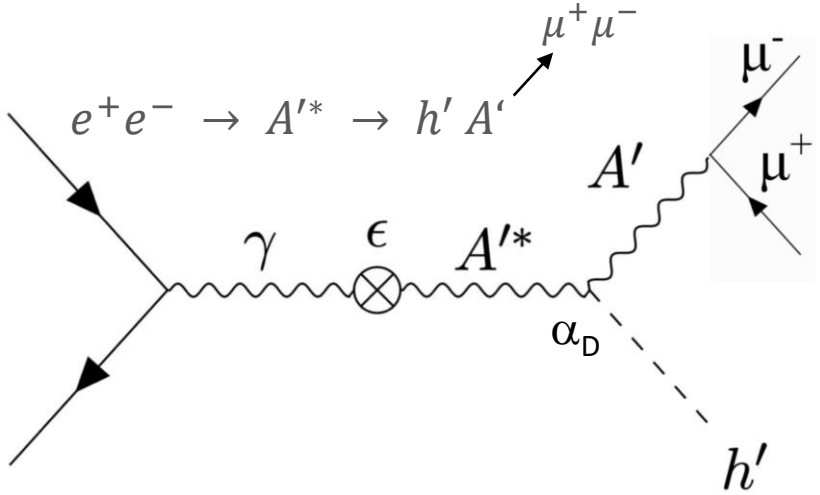


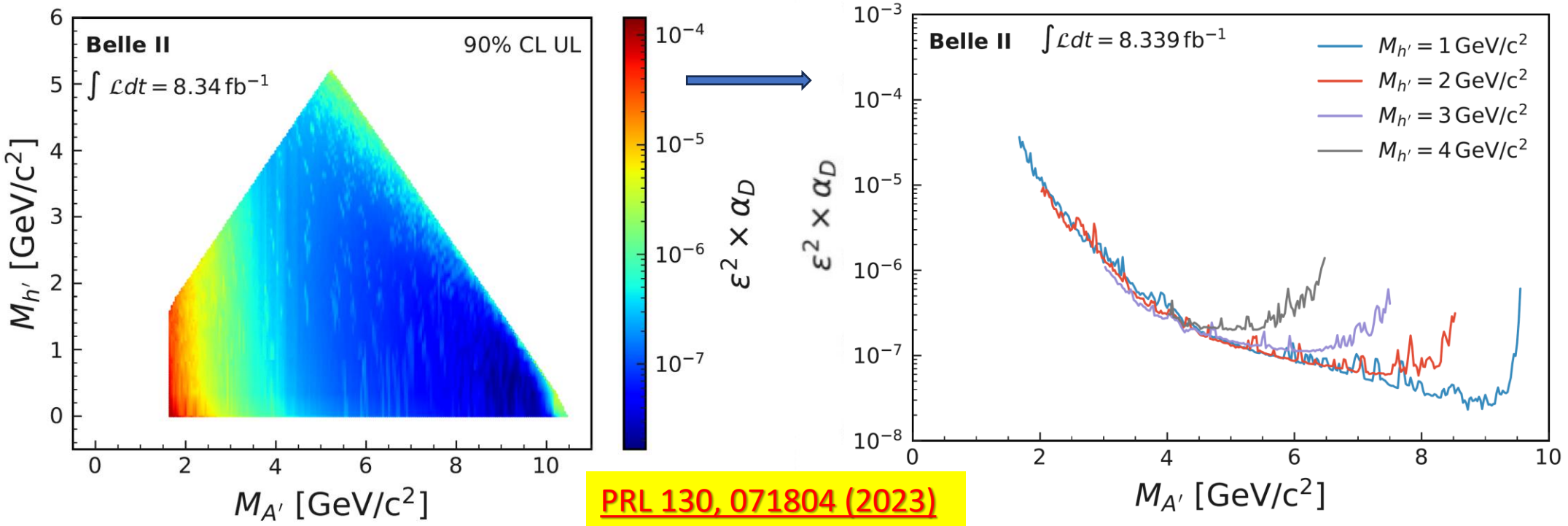
PRL 125, 161806 (2020)

Belle II dark sector search overview: results

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

Look for a double peak in the μμ mass and in the system recoiling against μμ





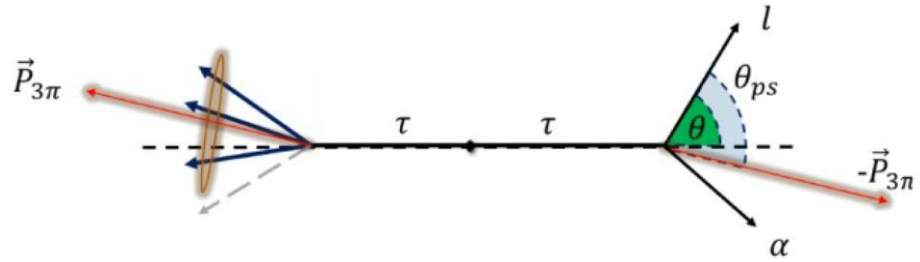
PRL 130, 071804 (2023)

Belle II dark sector search overview: results

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

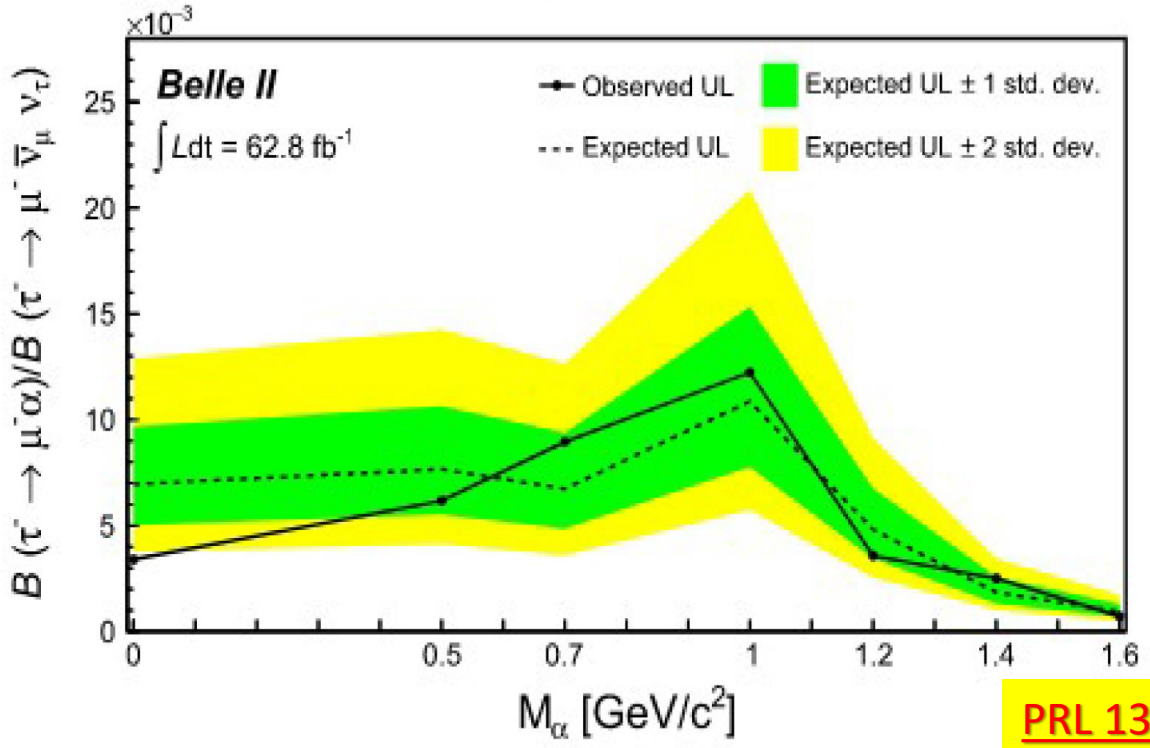
$e^+e^- \to \tau^+\tau^-$

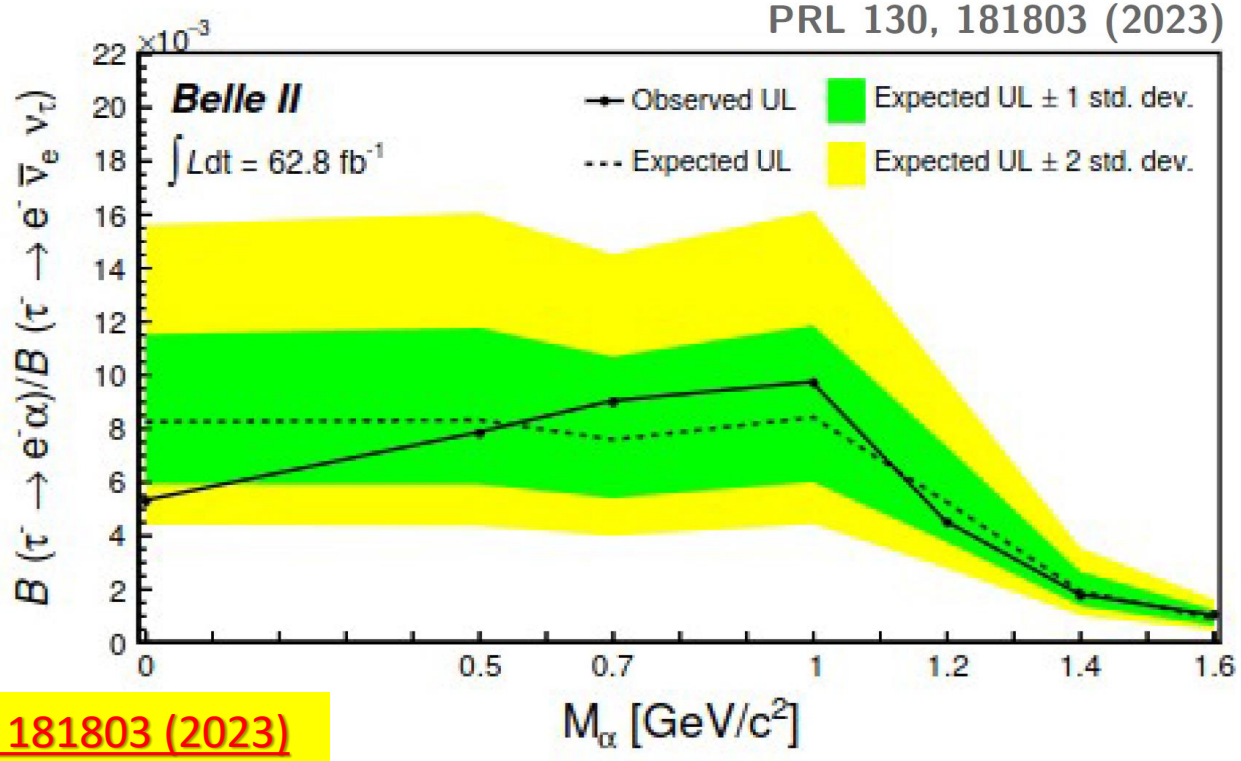
Pseudo-rest-frame from opposite (tag) $\tau \to \pi\pi\pi$



LFV, possible ALP candidate

PRL 130, 181803 (2023)



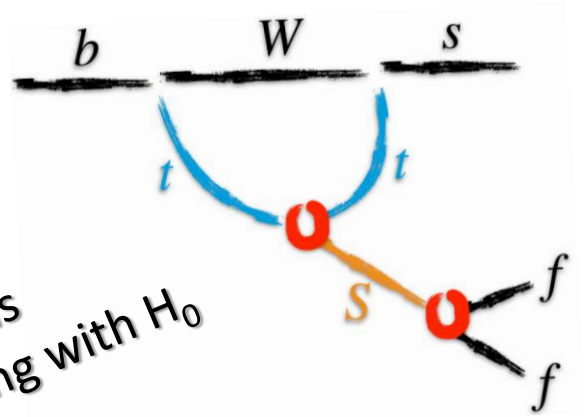


PRL 130, 181803 (2023)

Belle II dark sector search overview: results

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

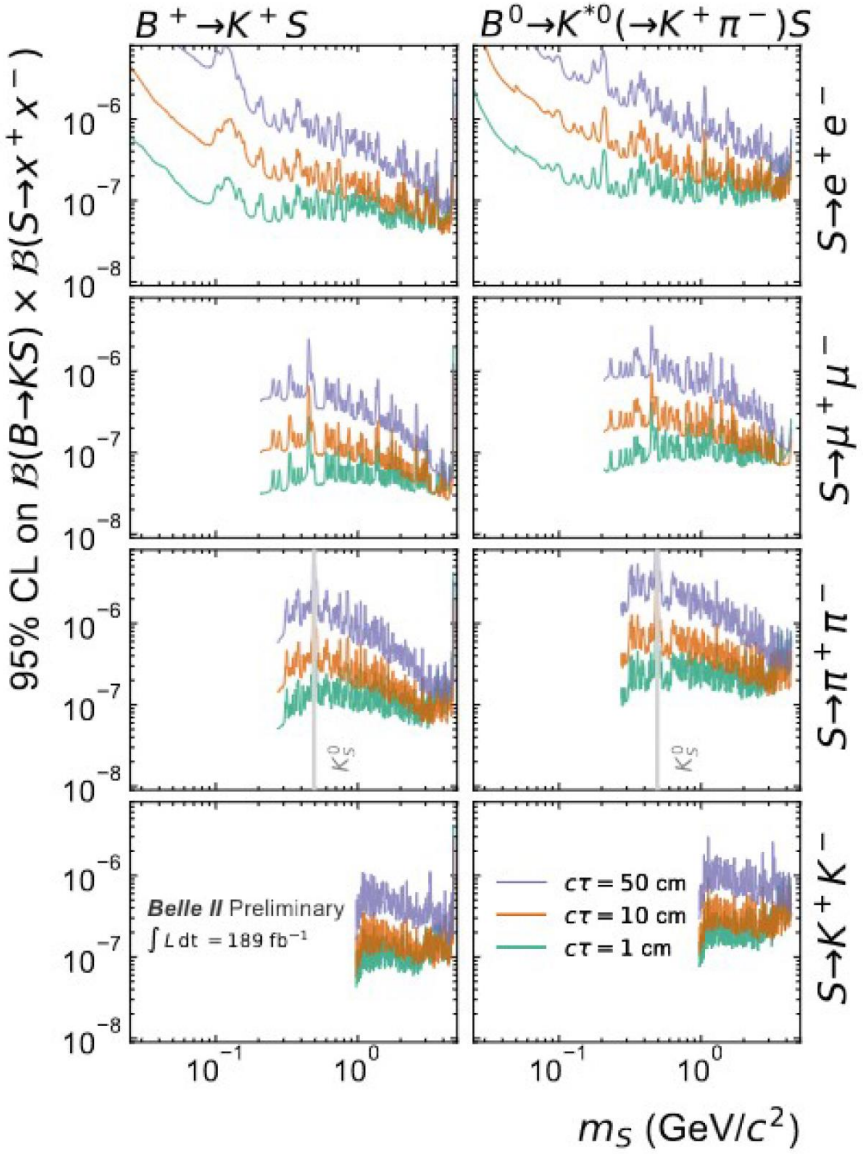
$e^+e^- \to B\bar{B}$



b→s transitions
Possible mixing with H_0
LLP signature

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

Submitted to PRL
arXiv:2306.02830



Dark sector searches in Belle II: future directions

- Align all the searches to the full pre-shutdown luminosity 424 fb^{-1}
- In most cases with improved analysis techniques: second generation searches
- We have already reasonable luminosity projections for some of the analyses (Snowmass)

Short term

- We need to enter the dark photon business: both visible and (especially) invisible

➢ My guess: LLP searches will have a considerable weight in the next years (especially with a new displaced-vtx trigger) 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 on external inputs. My guess: the g-2 focus is moving (has moved?) in the theory field: dispersion relations vs lattice

❑ Luminosity will increase, background will increase as well
❑ Most of the searches have low multiplicity signatures → badly affected by machine background
❑ Best effort to keep the single-object (track, muon, photon) trigger lines in working conditions
❑ Display-vertex trigger needed (efficiency decreases abruptly with lifetime): in preparation

Challenges

❖ We are eager of new dark models. Theorists never disappoint our expectations

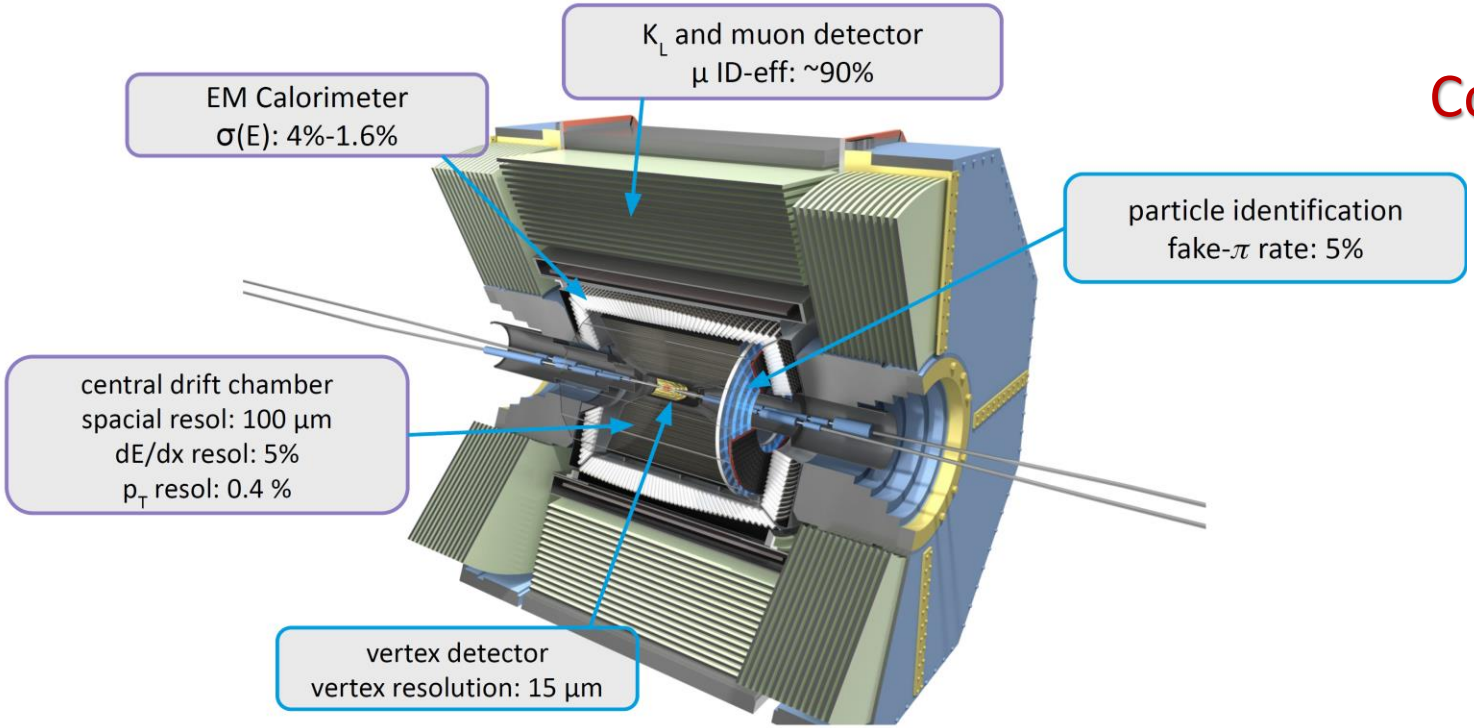
Summary

- The persisting null results from new physics at LHC searches and in direct underground searches make the light dark sector scenario more and more attractive
- **Belle II** started a broad program of searches orthogonal/complementary to LHC
- Will lead the world sensitivity in most of them

BACKUP SLIDES

Belle II detector

Final goal : 50 ab^{-1}



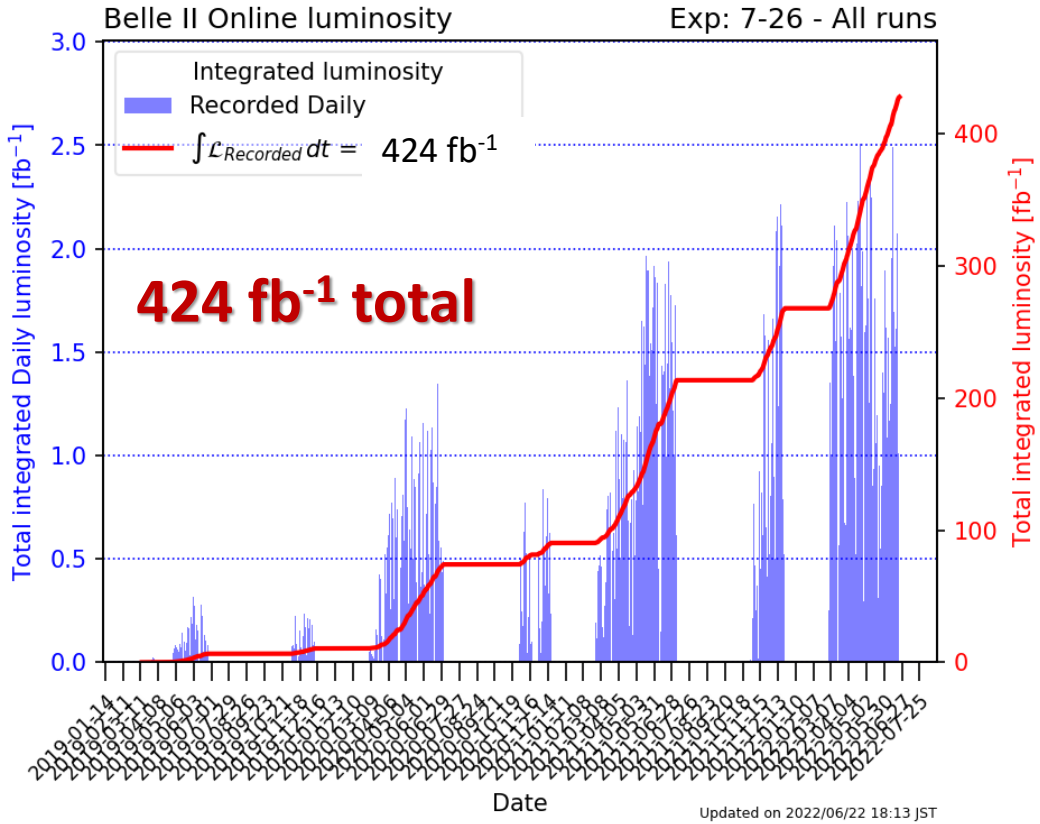
- Two-track trigger
- Three-track trigger
- E_{CAL}> 1 GeV trigger

Single muon
- Drift ch. + μ detector

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

Collected luminosity up to now: 2019-2022



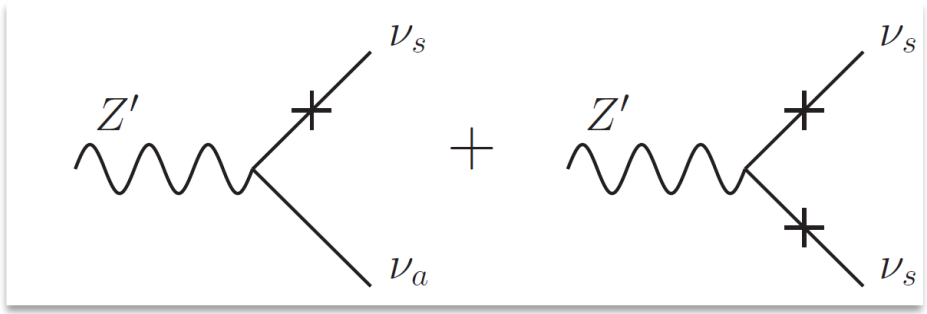
Resume physics run in fall 2023

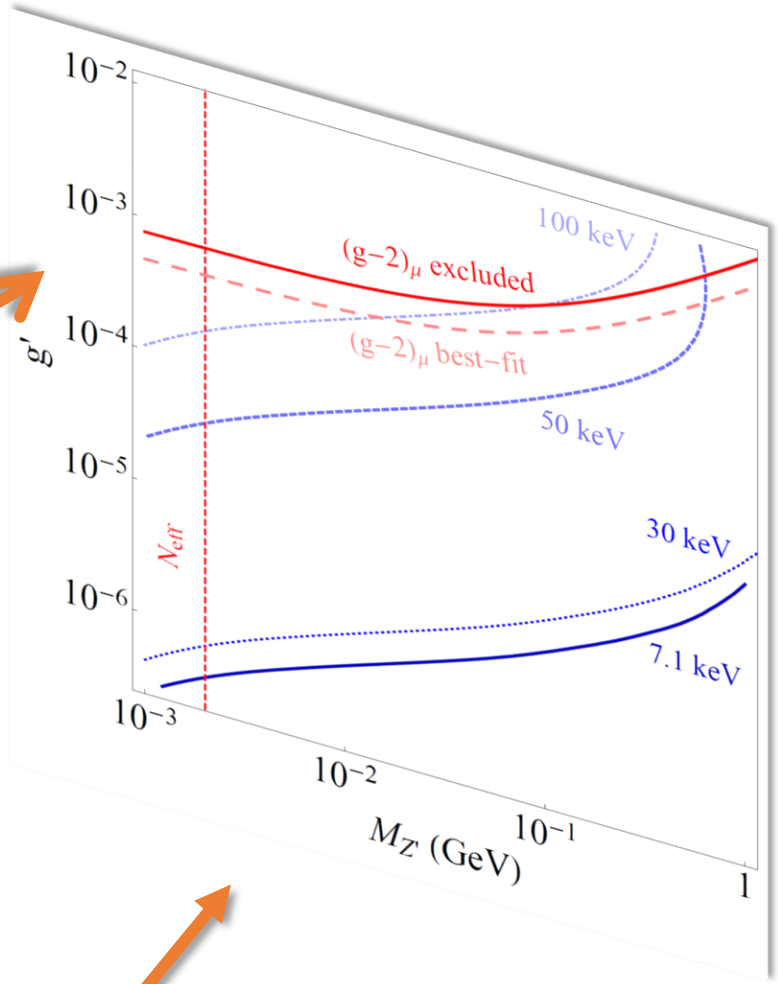
Key factors for dark sector physics: trigger, high backgrounds, precise knowledge of acceptance/vetoes, PID

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



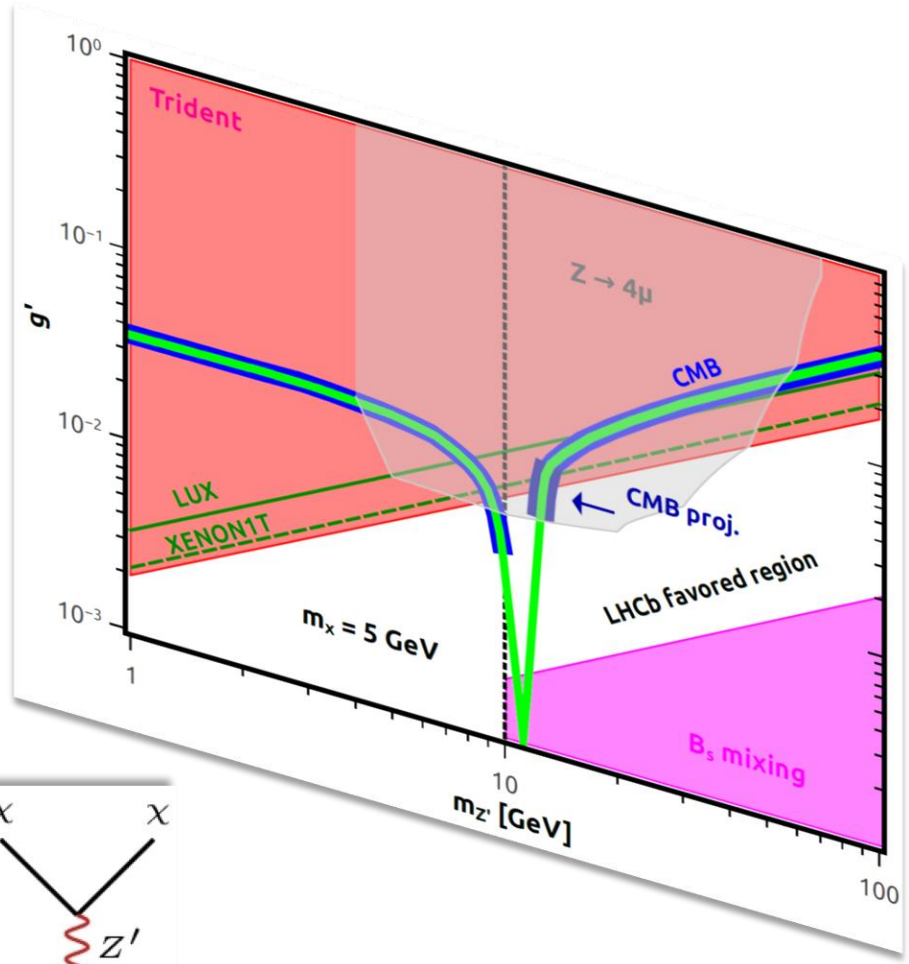


Sterile neutrino abundance

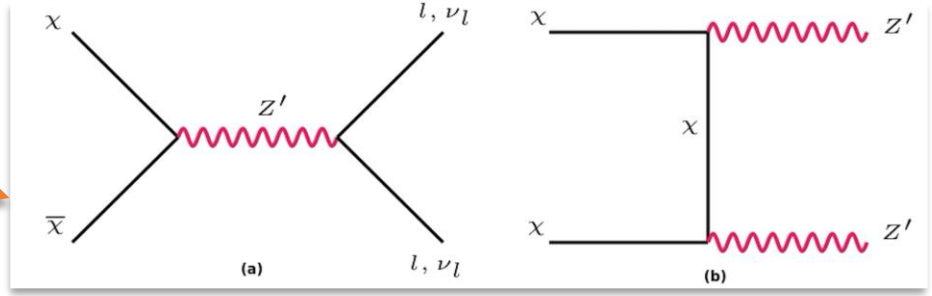
Z': $L_\mu - L_\tau$ model

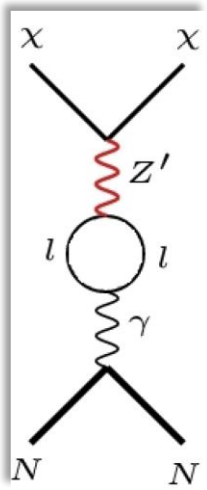
- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / **Light Dirac fermions**
  - **$(g-2)_\mu$**
  - $B \to K^{(*)}\mu\mu$,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

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



Annihilation



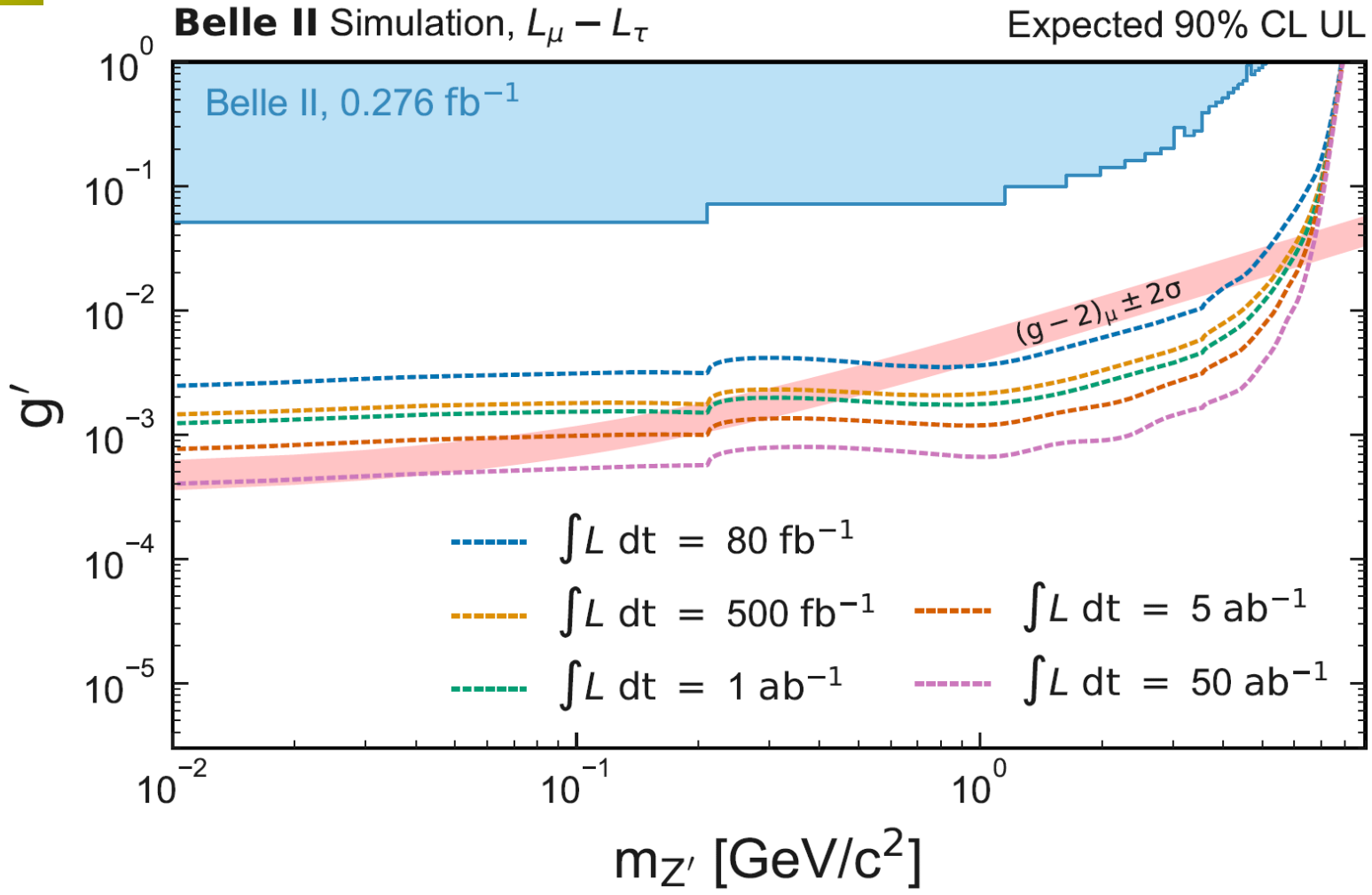


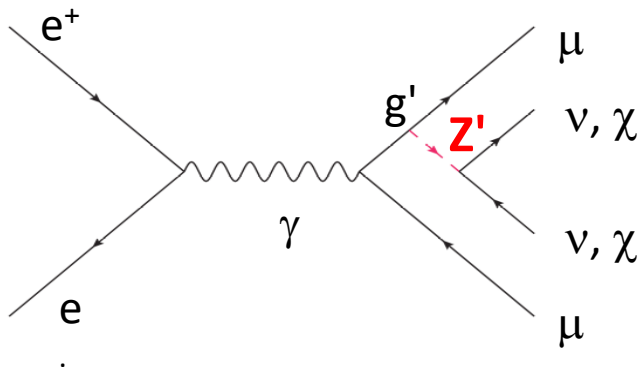
Direct detection

Belle II dark sector search overview: projections

L_μ-L_τ
Z' → invisible

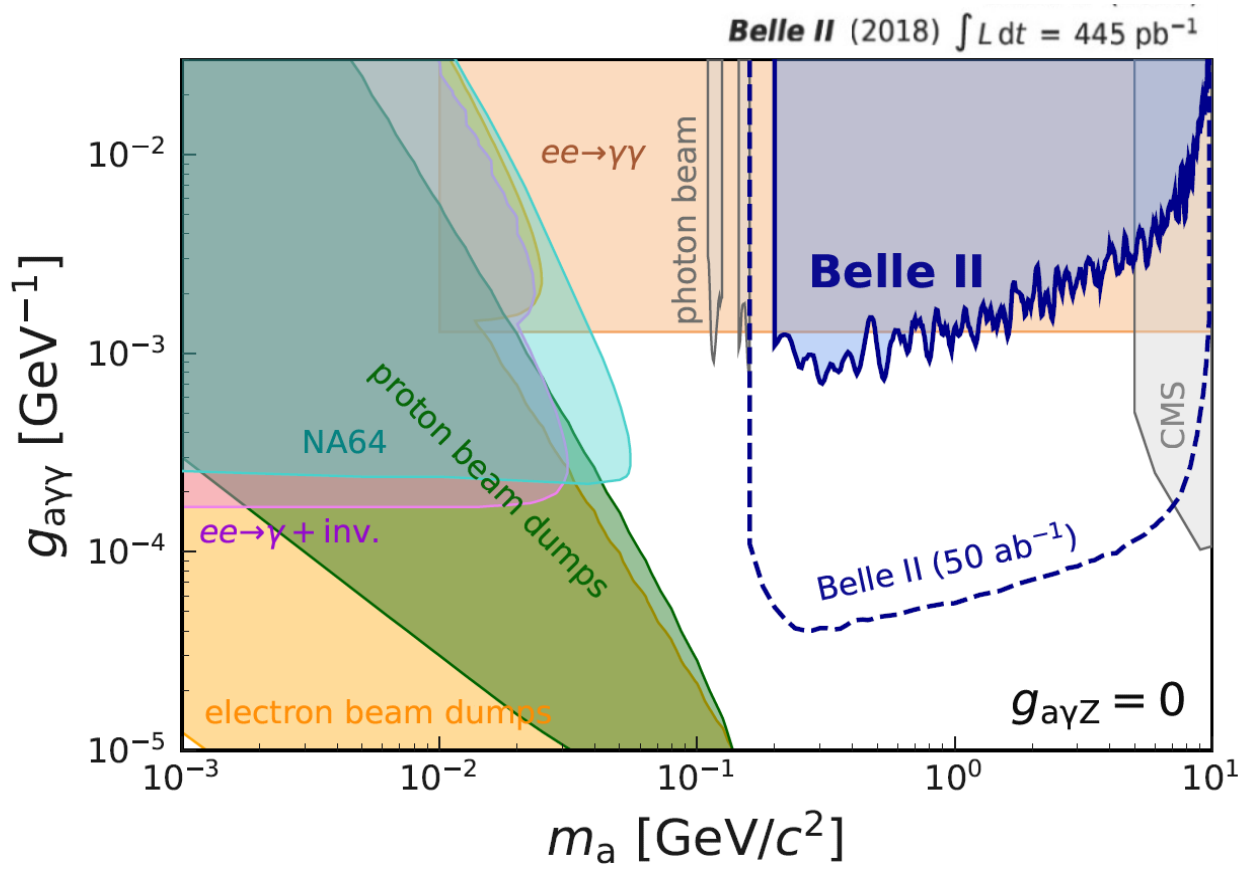
Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

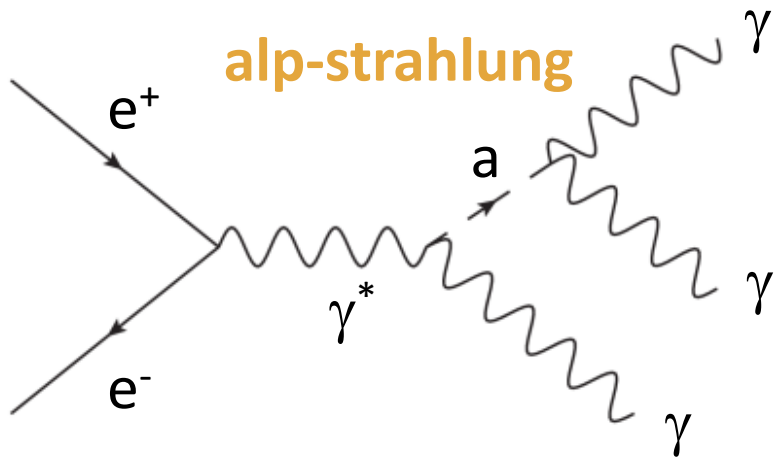




Belle II dark sector search overview: projections

Axion like particles
ALP→γγ

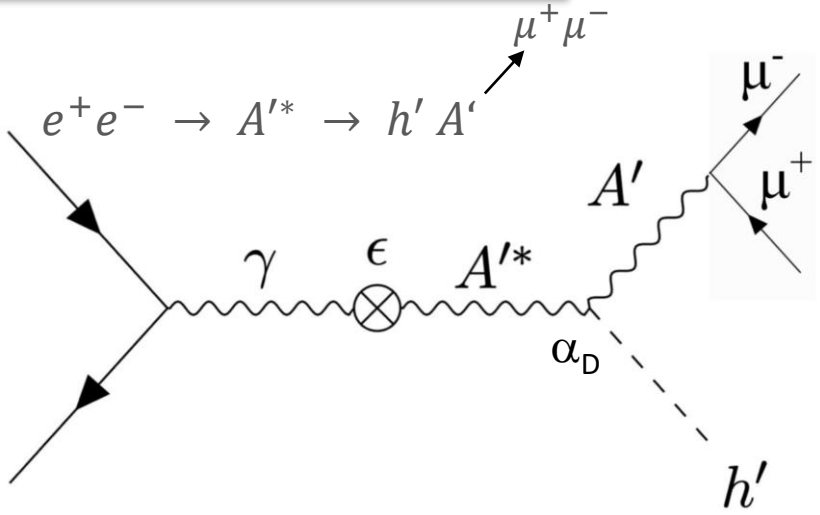


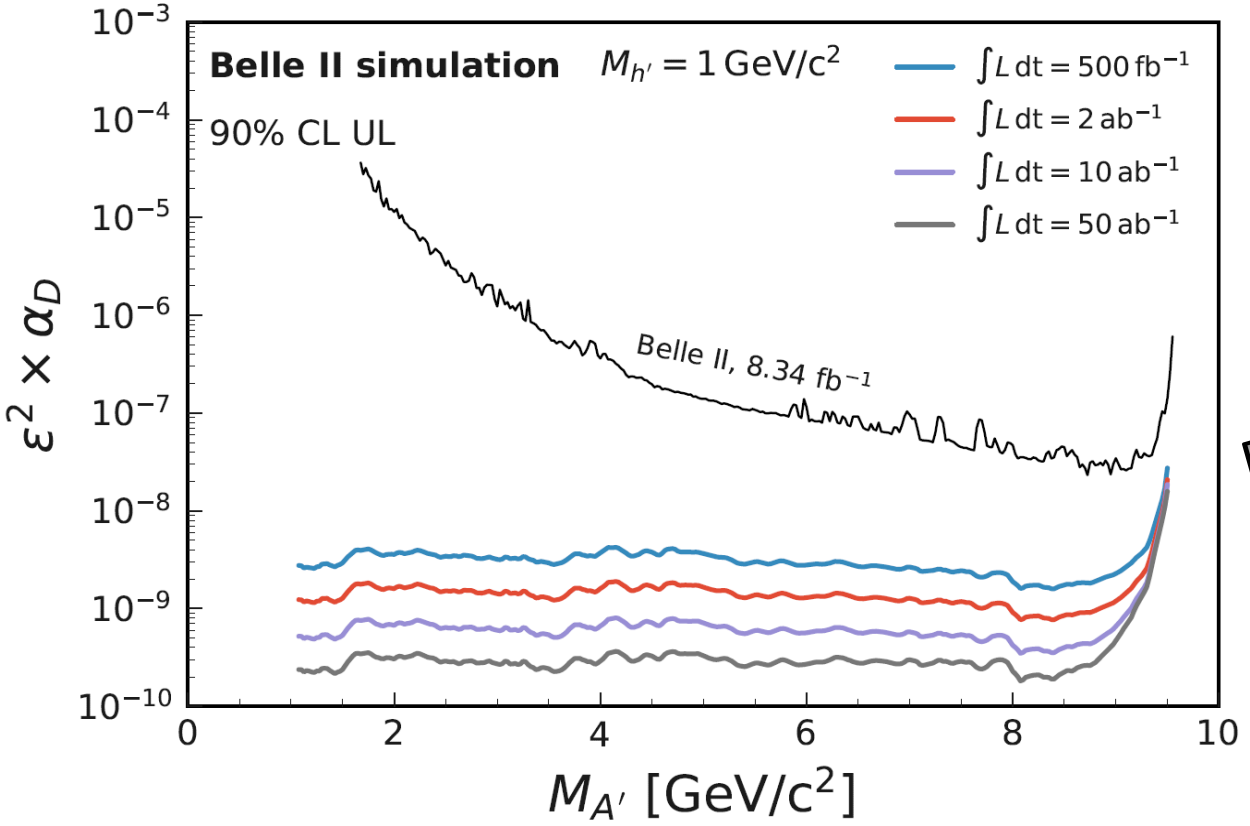


Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

Belle II dark sector search overview: projections

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



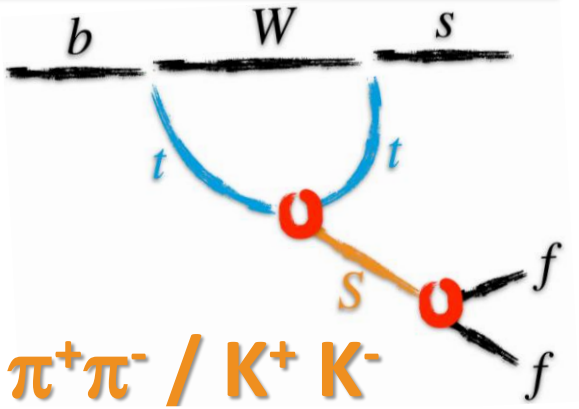


Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

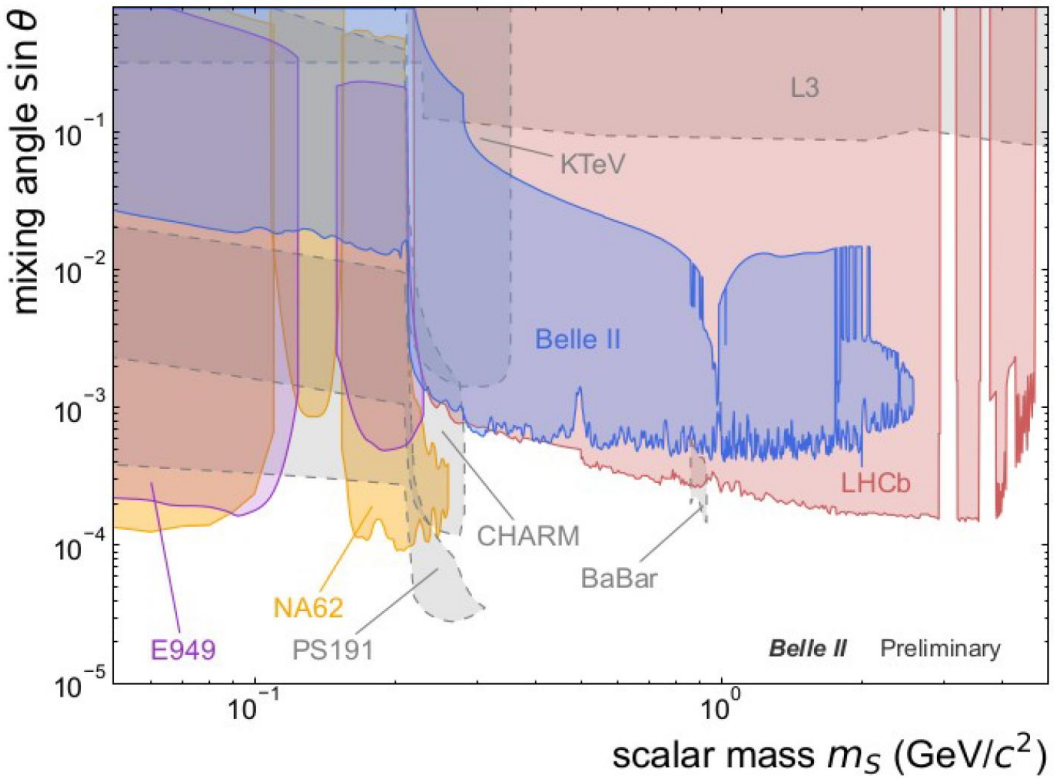
Belle II dark sector search overview: projections

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

b→s transitions
Possible mixing with H_0
LLP signature



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

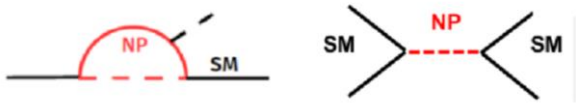


Submitted to PRL
arXiv:2306.02830

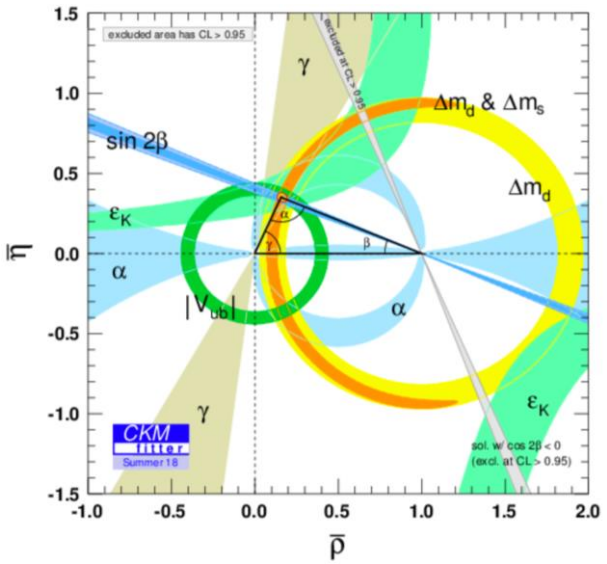
Dark matter hunt: «classical» approach

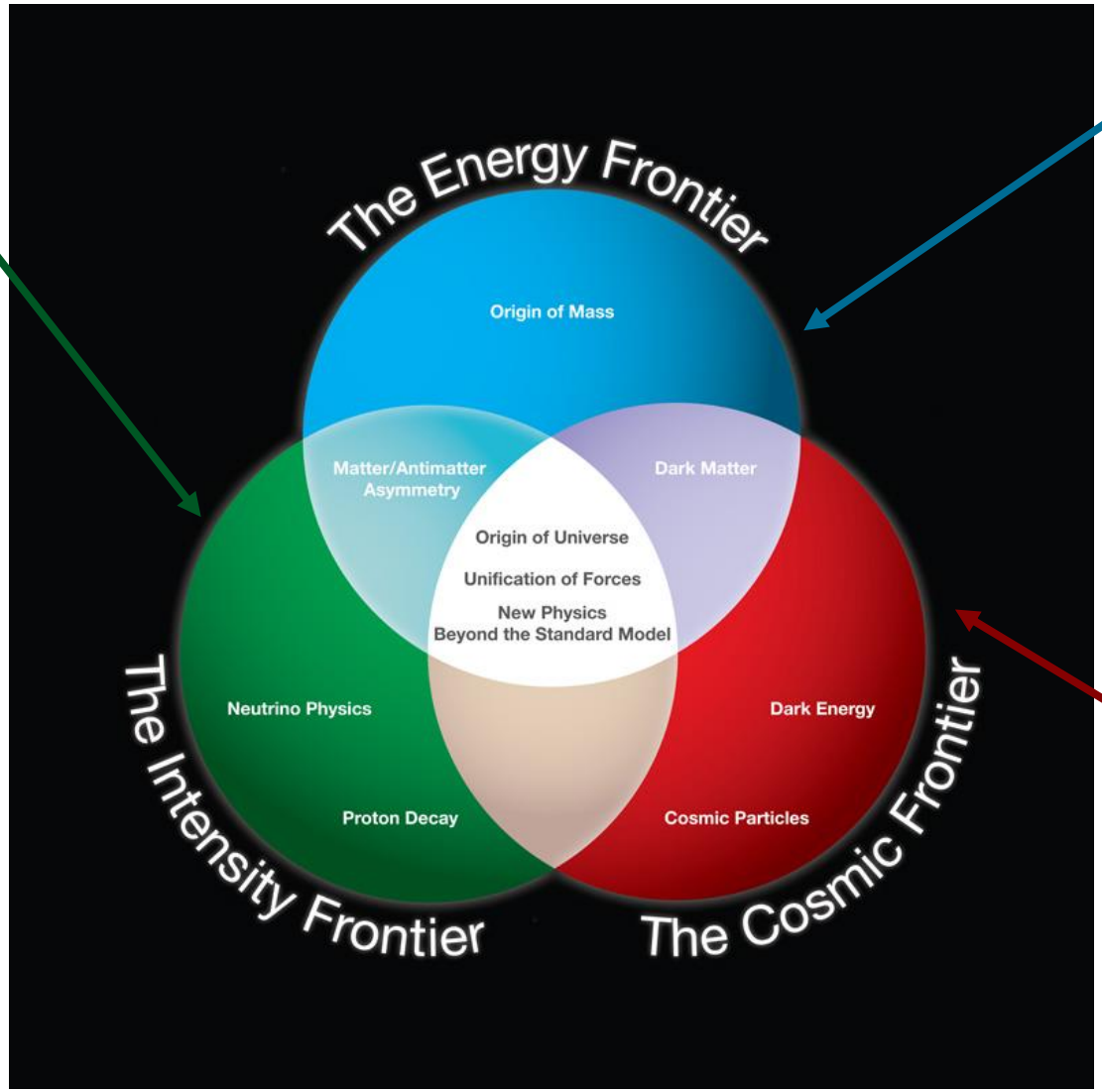
Intensity / precision frontier

New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)



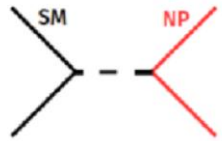
If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays





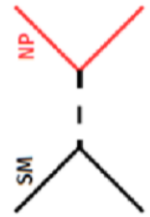
Energy frontier

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



Cosmic frontier

Direct effect search in (mostly) underground experiments

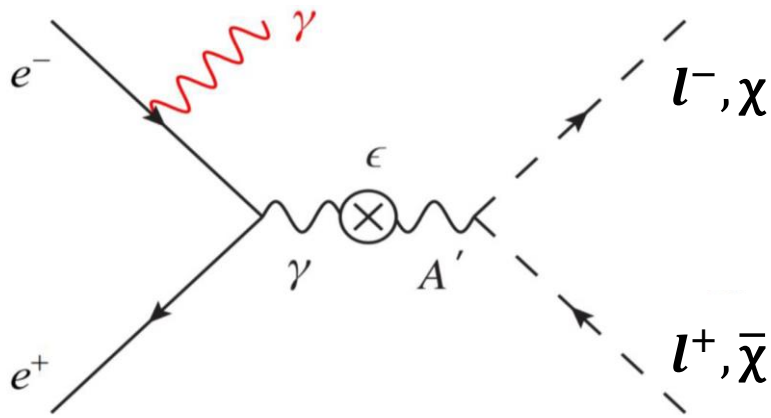


In progress Belle II dark searches

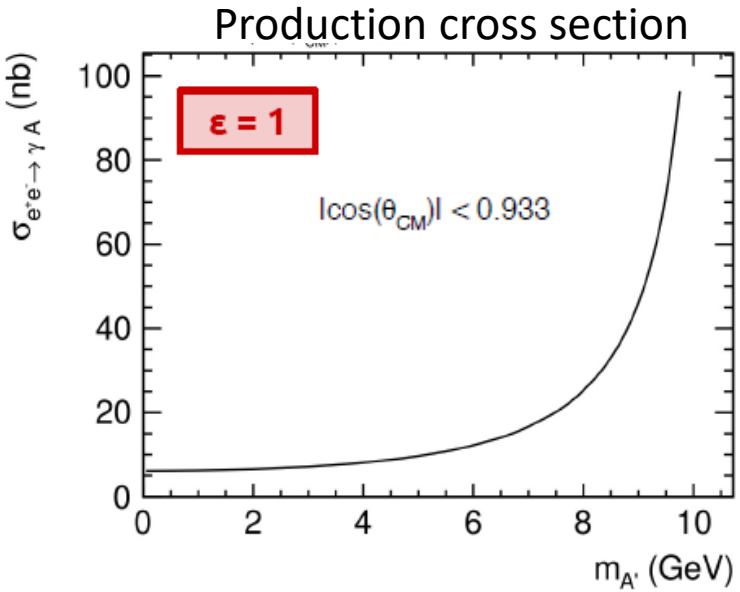
Dark photon: introduction

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



Minimal dark photon



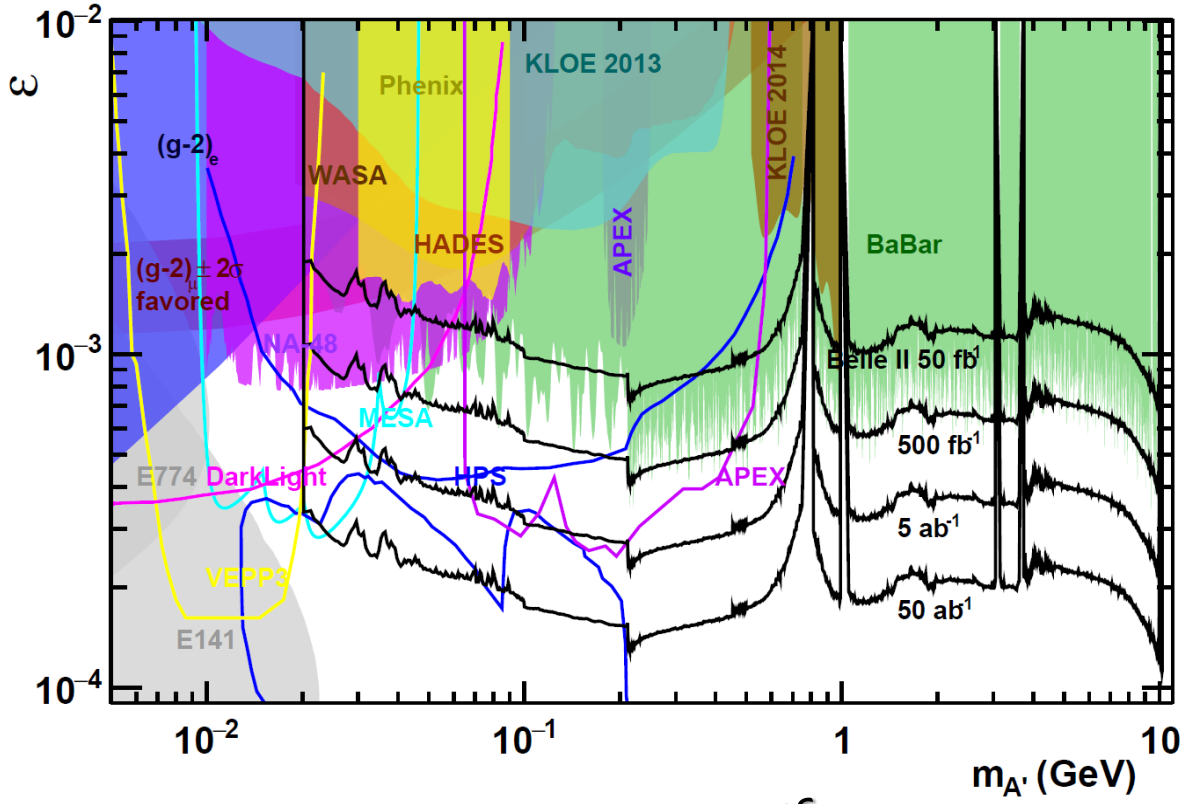
two basic scenarios depending on A′ vs χ DM mass relationship

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

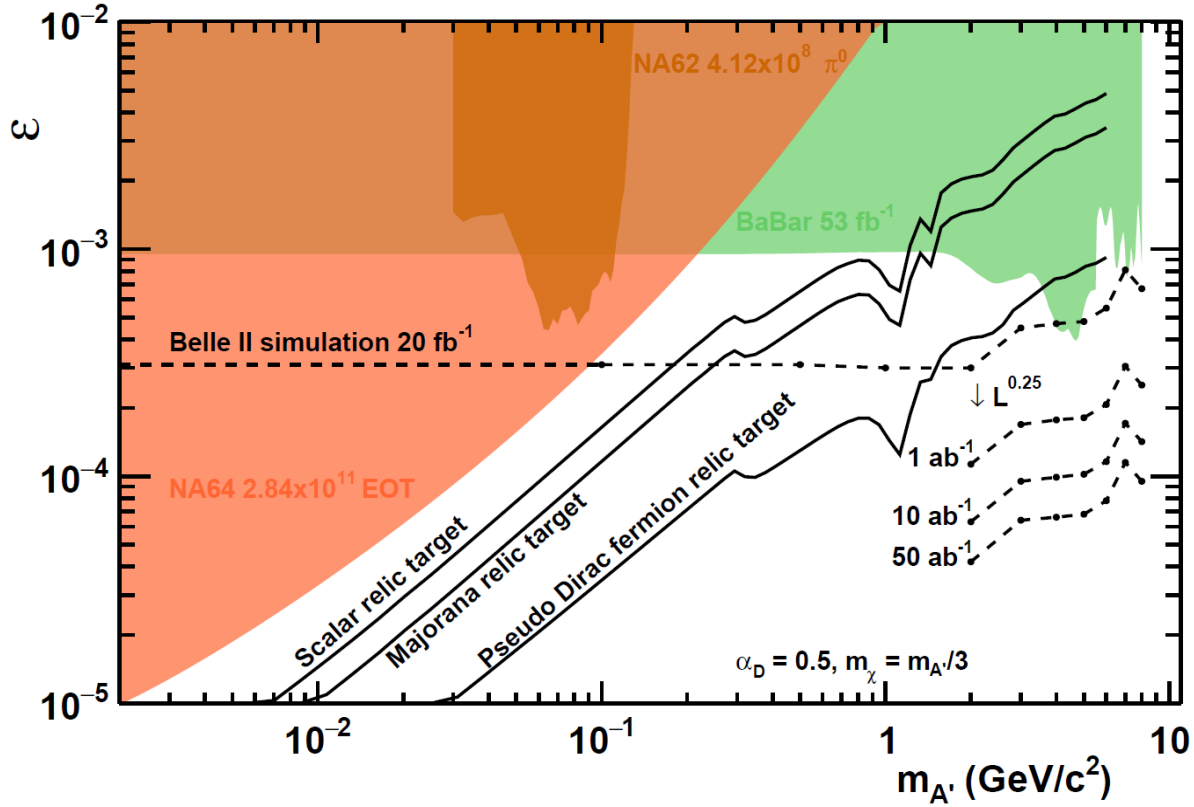
$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

Dark photon: luminosity projections

Visible



Invisible



Belle II physics reach @ Snowmass

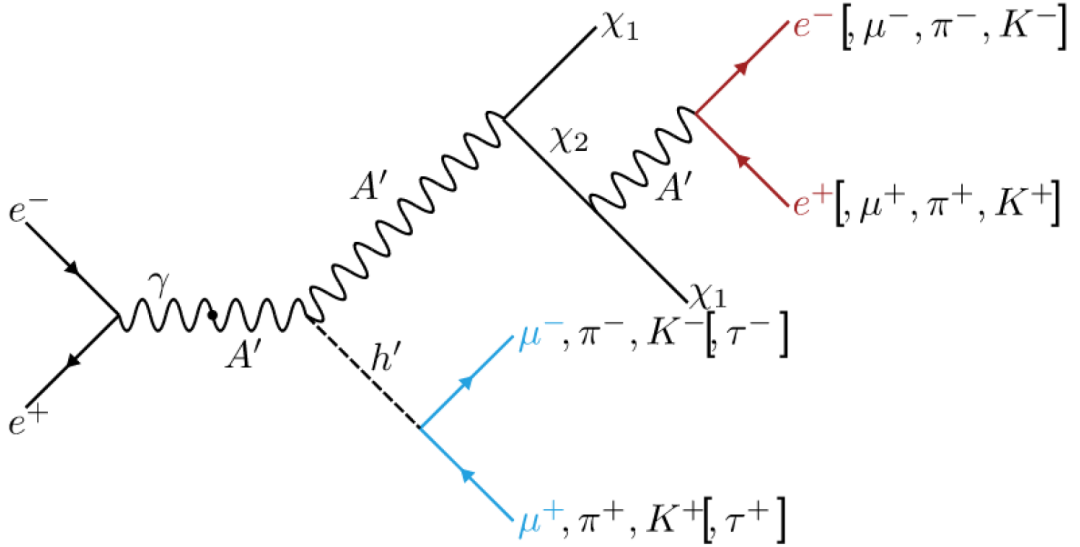
arXiv: 2207.06307v1

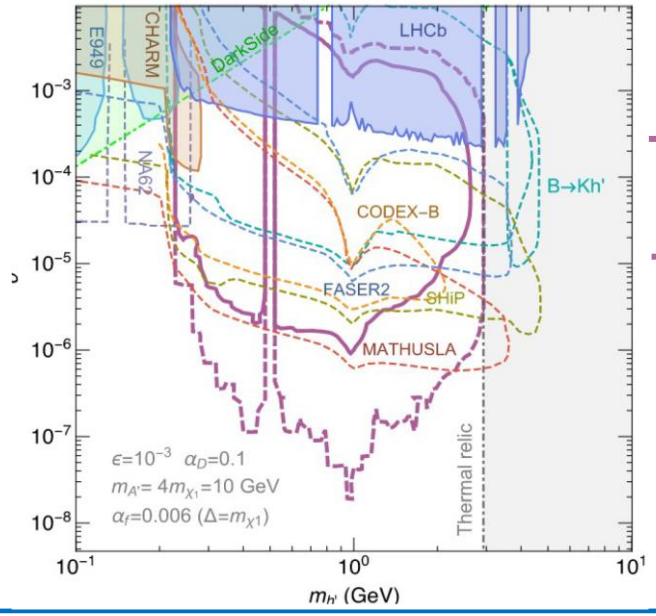
Belle II vs BaBar

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

Inelastic dark matter with dark Higgs

- Dark photon A' and dark Higgs h'
- Two dark matter states χ_1 and χ_2 with a small mass splitting
- χ_1 is stable → dark matter candidate
- χ_2 is generally long-lived
- h' is generally long-lived and mixes with SM H_0
- Signature: up to two displaced vertices





Belle II 100 fb^{-1}

Belle II 50 ab^{-1}

LLP signature

JHEP 04 (2021), arXiv:2012.08595