Dark matter search at Belle II

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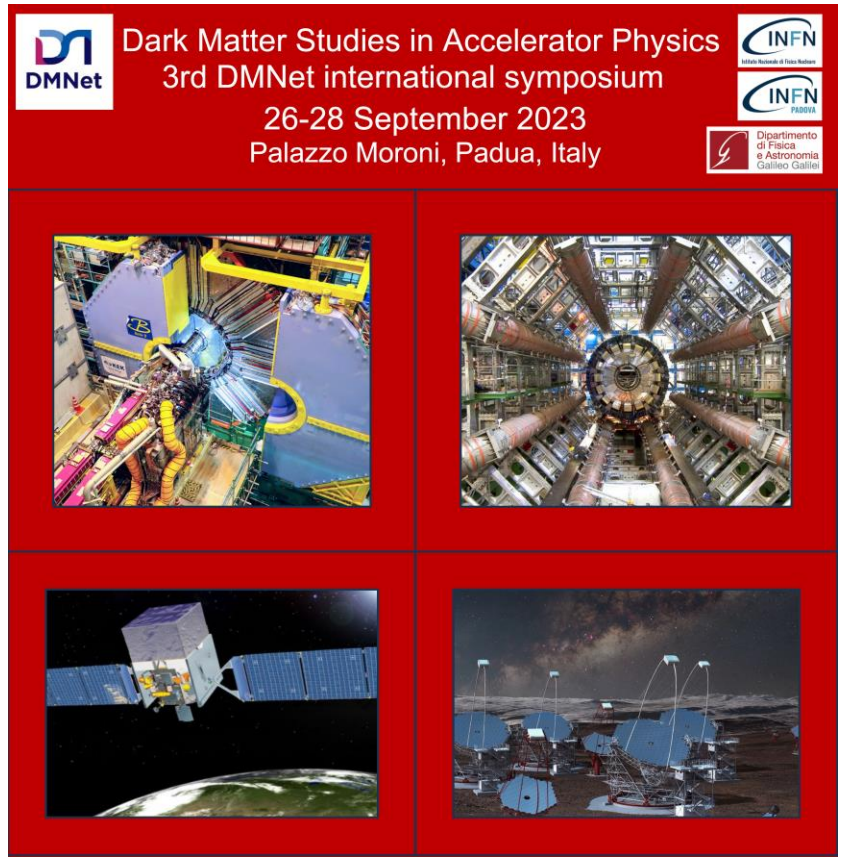
INFN – Roma 3

on behalf of the Belle II Collaboration



OUTLINE OF THE TALK

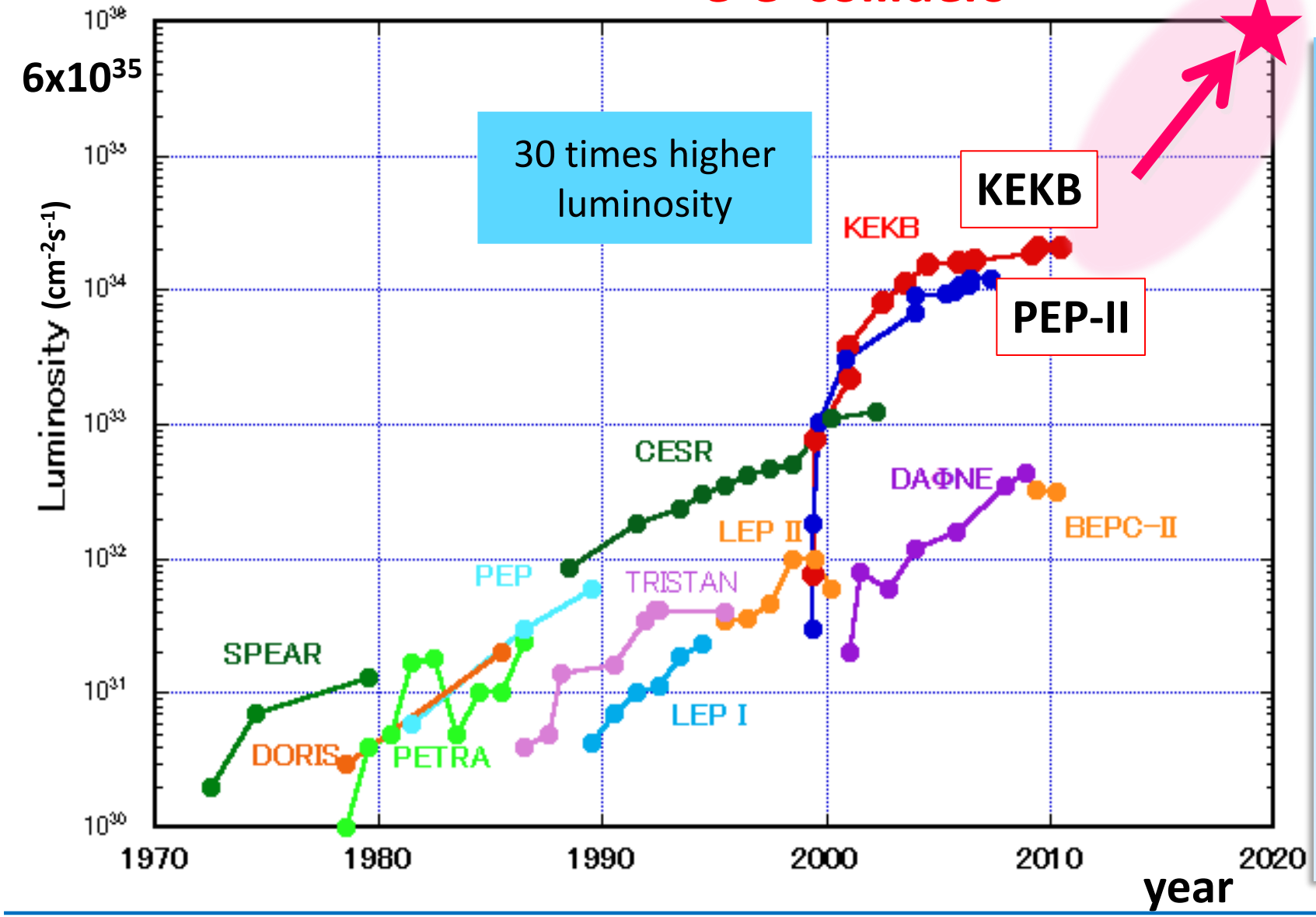
- ✓ Light dark sector models
- ✓ Belle II and SuperKEKB
- ✓ An example: L_μ-L_τ invisible Z'
- ✓ Results
- ✓ Perspectives & Summary

Peak luminosity trend

SuperKEKB

e^+e^- colliders

Final goal: L= 50 ab^{-1} (~ 2030)



Very rich physics program

Flavour physics

- CKM matrix
- CPV in B deacys

BSM physics

see S.Robertson's talk

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

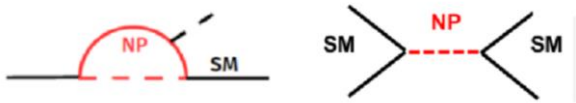
New particles (quarkonium)

Dark sector

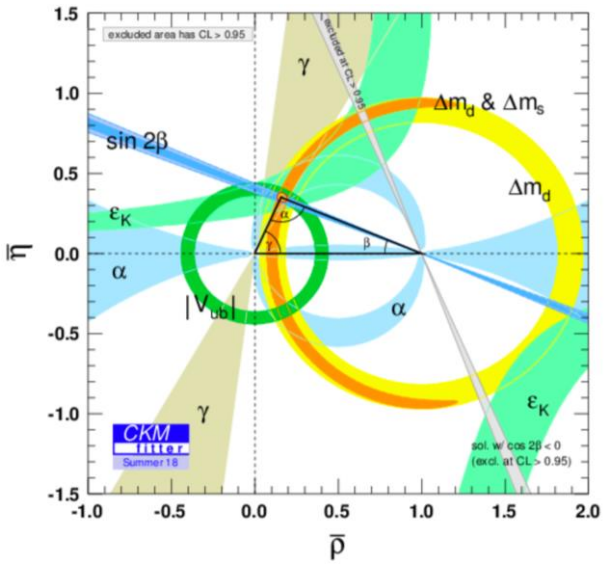
Dark matter hunt: «classical» approach

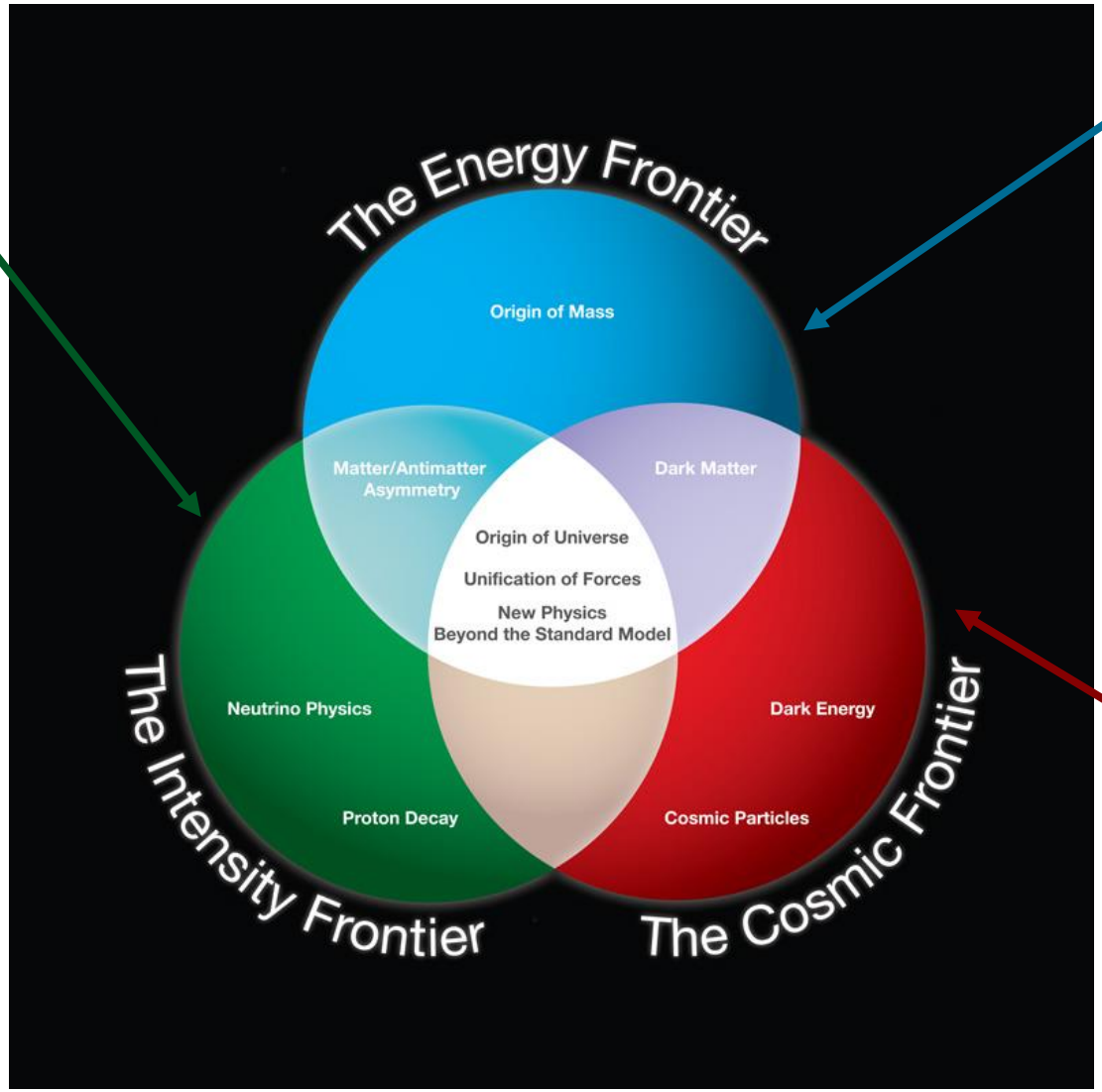
Intensity / precision frontier

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



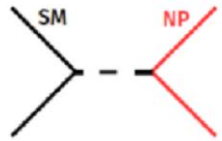
If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays





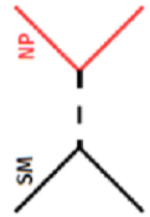
Energy frontier

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



Cosmic frontier

Direct effect search in (mostly) underground experiments



Alternative DM scenario: light WIMPs ⇔ light mediators

Light dark matter not ruled out if dark mediator(s) exist

WIMP paradigm: $\sigma_{ann}(v/c) \approx 1$ pb $\Rightarrow \Omega_{DM} \approx 0.25$

Electroweak mediators ⇒ Lee – Weimberg window

$$\sigma(v/c) \propto \begin{cases} G^2_F\, m^2_\chi & \text{for } m_\chi << m_W \\ 1/\, m^2_\chi & \text{for } m_\chi >> m_W \end{cases}$$

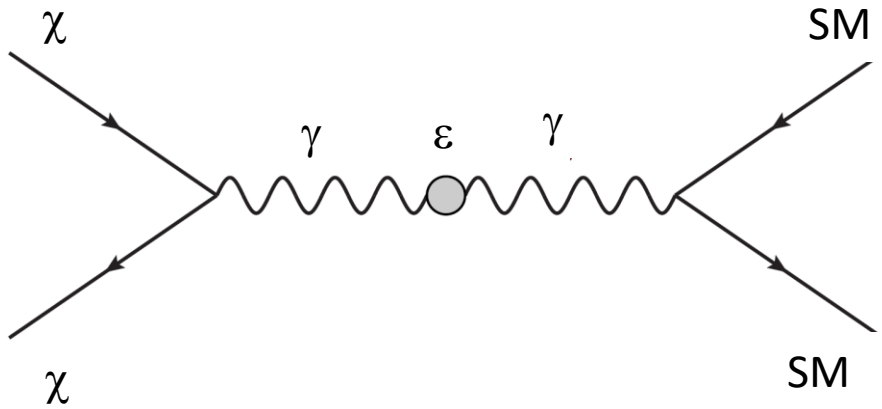
$\Rightarrow$ few GeV < m_χ < few TeV

It modeled decades of direct search experiment design

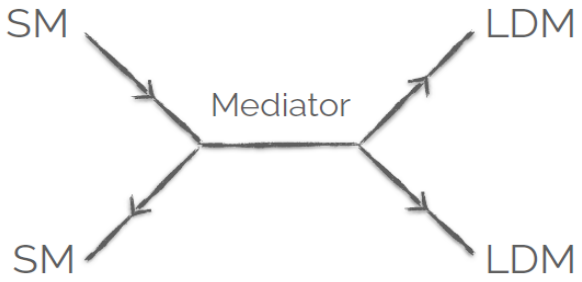
WIMP miracle

If annihilation via a light force carrier, χ can be as light as few MeV

Possibility of Light New Physics, mostly with tiny couplings. Some models are minimal (but UV safe) and show diverse DM fenomenology



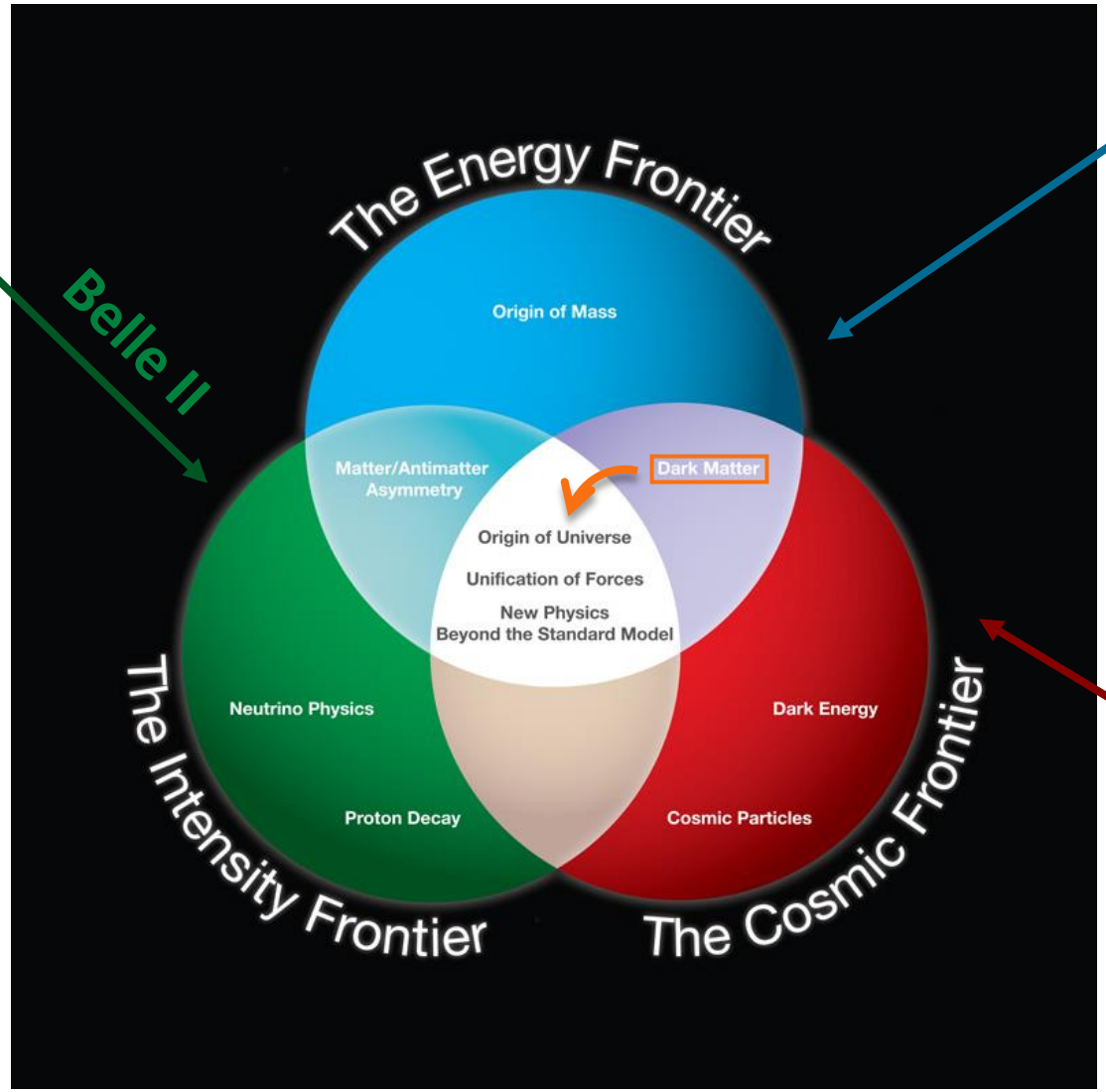
Dark matter hunt: alternative approach



LDM → Light Dark Matter
Mediators → portals

⇓

Light Dark Sector with interactions ~ unsuppressed by a (possibly large) NP scale Λ



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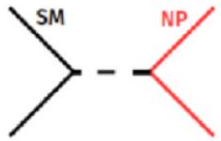

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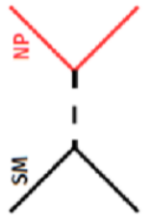


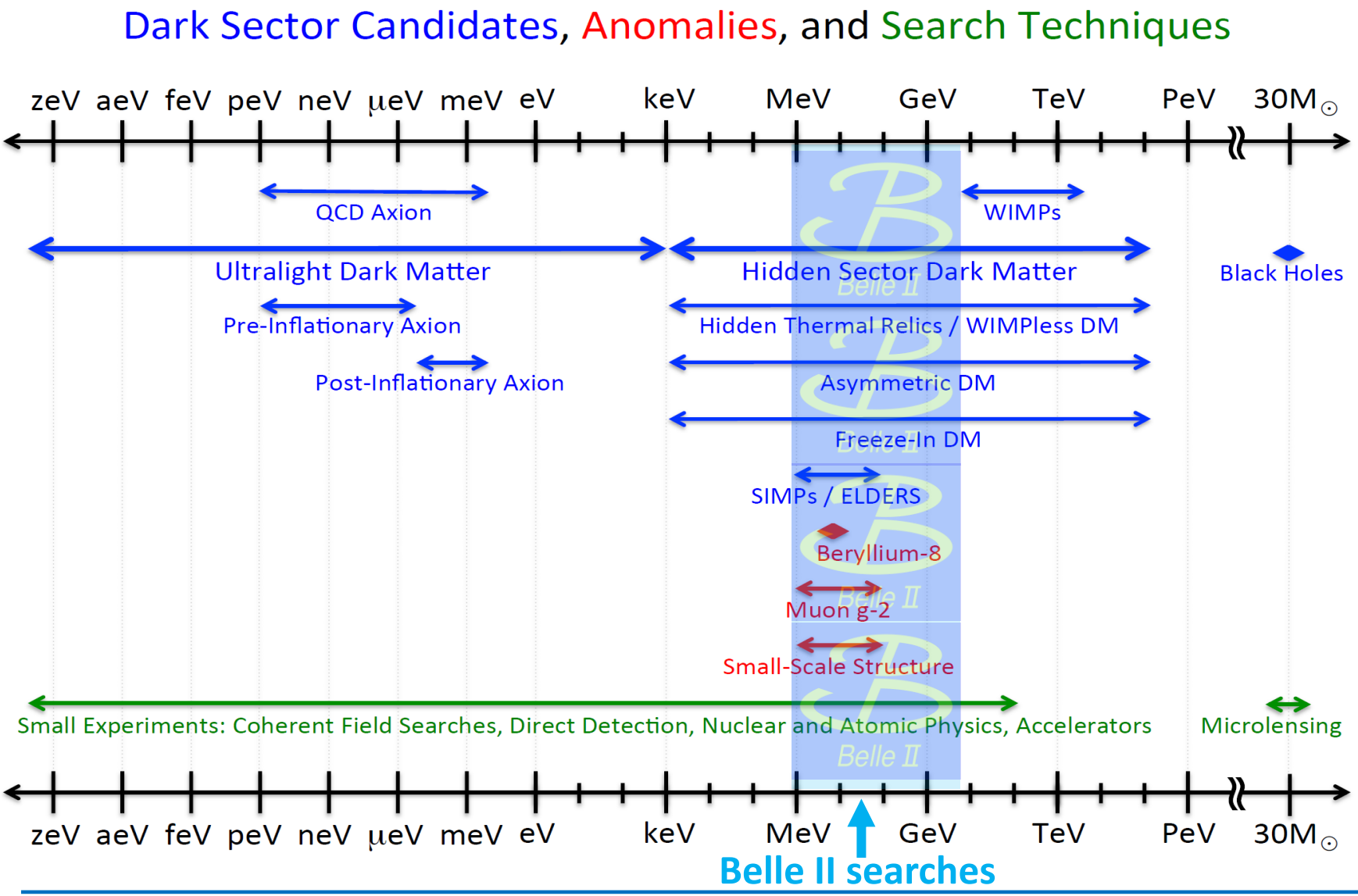
What can we do at B-factories that we can't at the LHC?

- 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

- Low multiplicity signatures
- Missing energy channels
- Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessibility
- Dark sector signatures in B and τ decays

- Cleanliness and luminosity sometimes compensate for cross section → competition

Searching for dark matter



Dark matter/mediators

Vector portal ←
Dark photon, Z', …

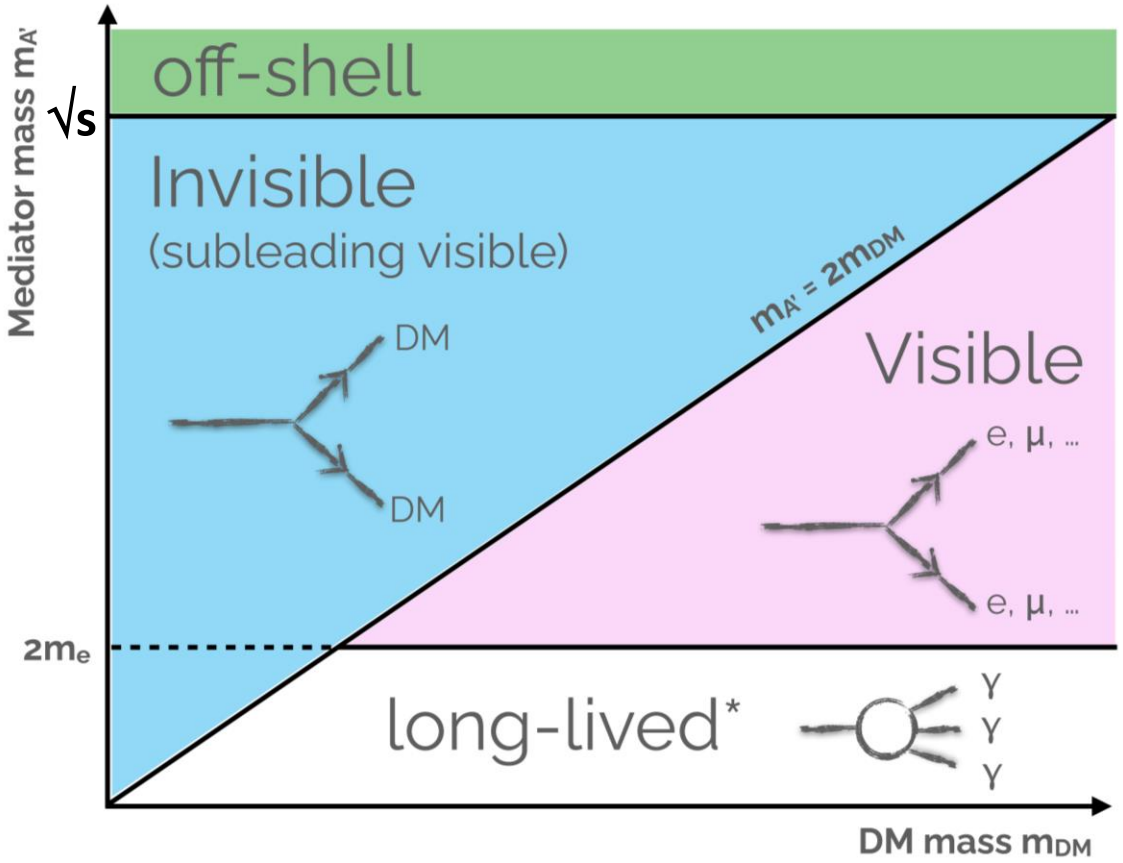
Pseudoscalar portal ←
Axions, **ALPs**, …

Scalar portal ←
Dark Higgs, scalars

Neutrino portal ⇠
Sterile neutrino

Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

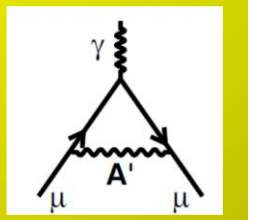


Probability of interaction of LDM detectors is negligible

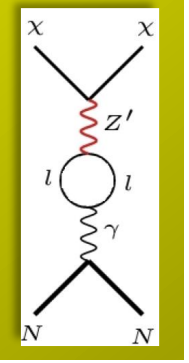
- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

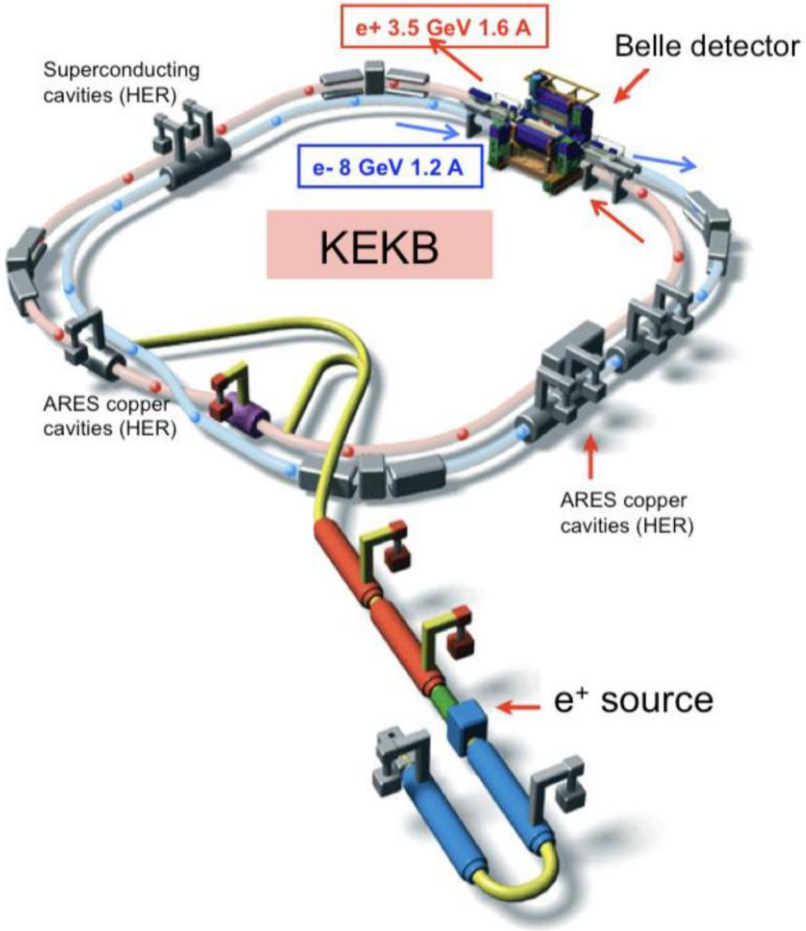
- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)

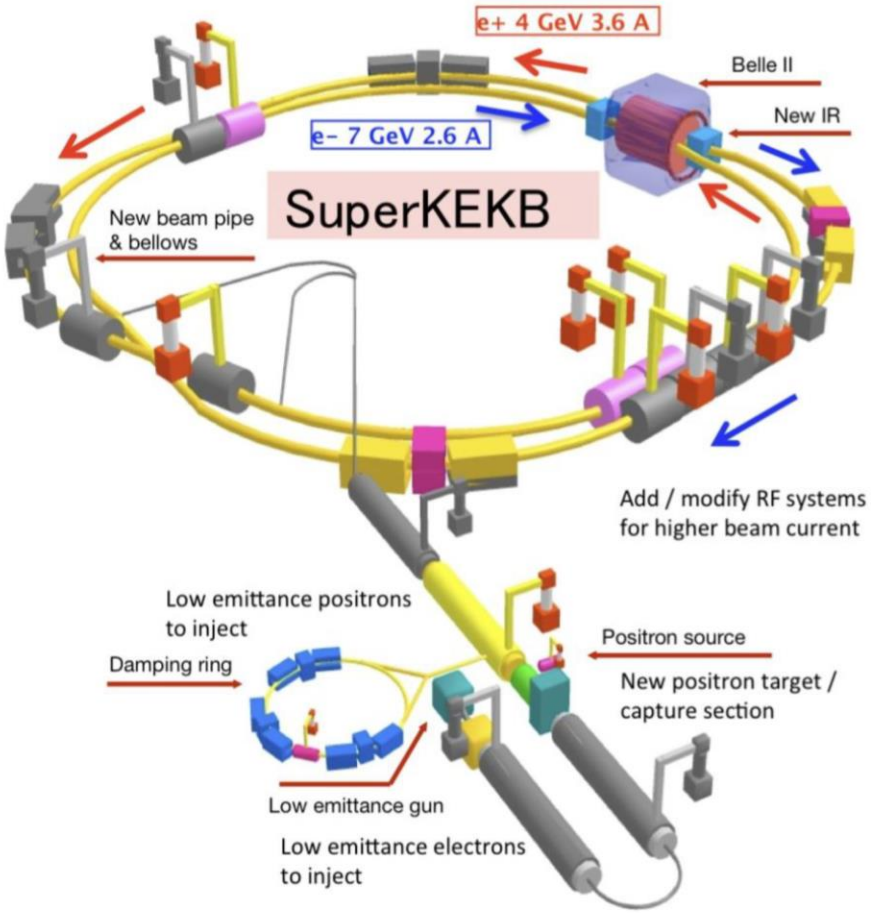


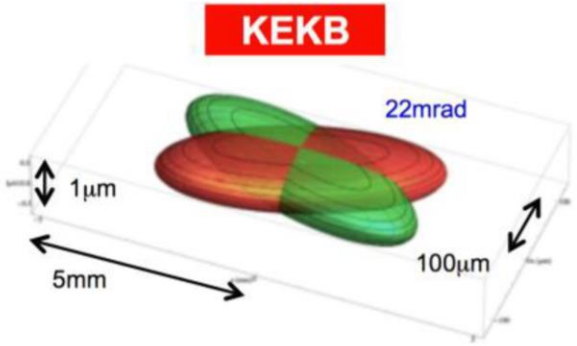
- Explanation of the $(g-2)_\mu$ effect
- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits →

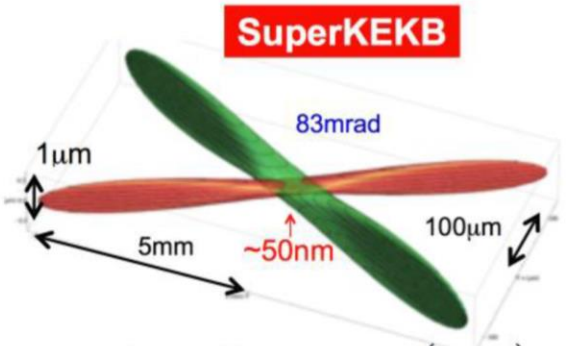


From KEKB to SuperKEKB









Nano-Beam scheme

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

From KEKB to SuperKEKB

- **Upgraded rings**
  - New e^+ Damping Ring
  - Increased currents

x20 → **x30**

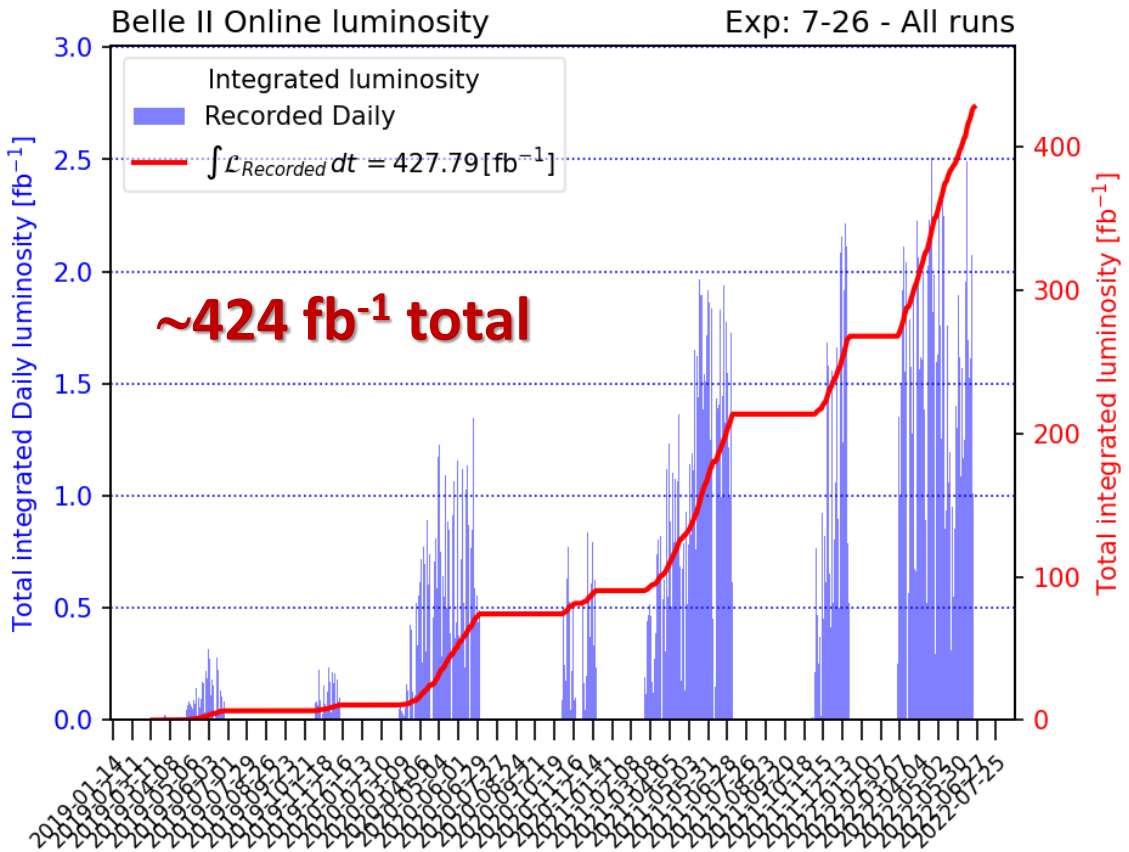
- **Nano-beam scheme**
  - New Final Focus magnets (QCS)
  - Large crossing angle

Final goal : 50 ab^{-1}

Peak luminosity world record: **4.7 x 10^{34} cm^{-2} s^{-1}**

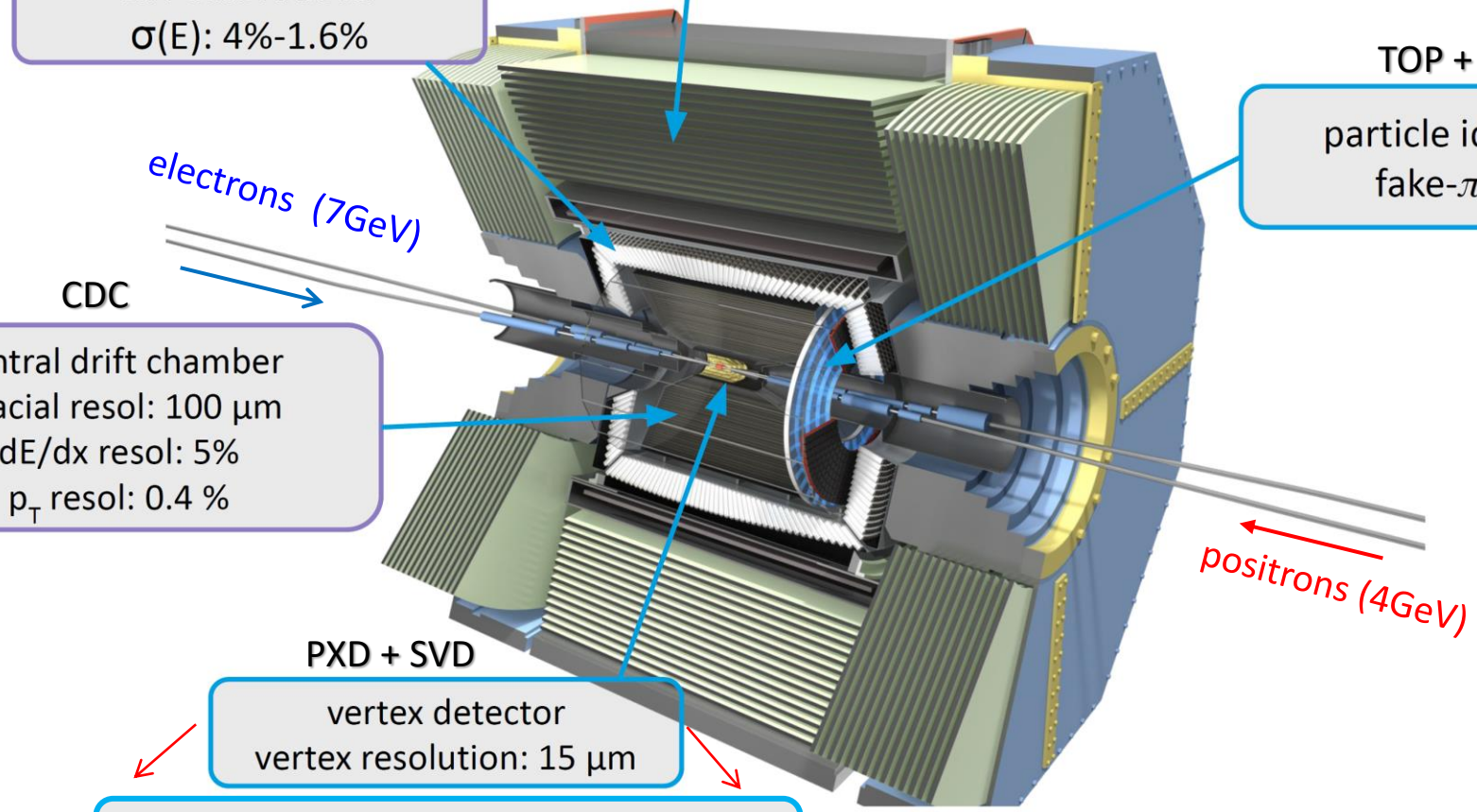
Currently in shutdown LS1 since July 2022

Collected luminosity up to now: 2019-2022



Restart run in december 2023
Resume physics run beginning 2024

Belle II detector



KLM

K_L and muon detector
μ ID-eff: ~90%

ECL

EM Calorimeter
σ(E): 4%-1.6%

TOP + ARICH

particle identification
fake-π rate: 5%

electrons (7GeV)

CDC

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

positrons (4GeV)

PXD + SVD

vertex detector
vertex resolution: 15 μm

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

Trigger:
L1: < 30 kHz
HLT: < 10 kHz
dedicated lines for dark physics

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

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

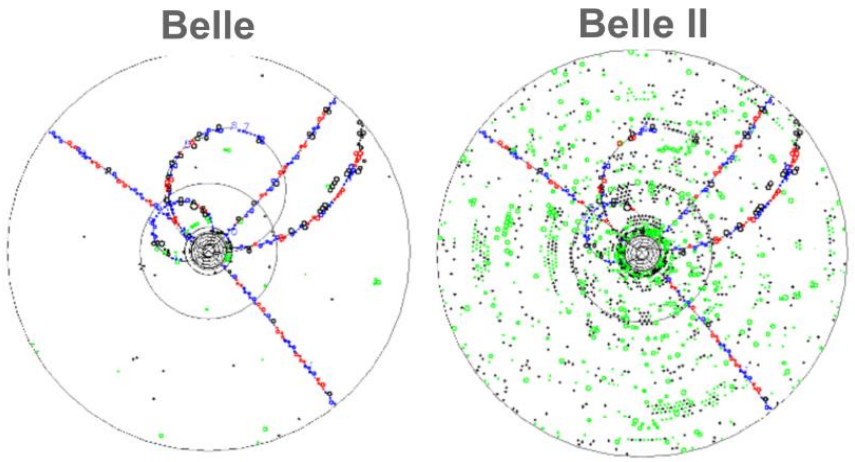
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

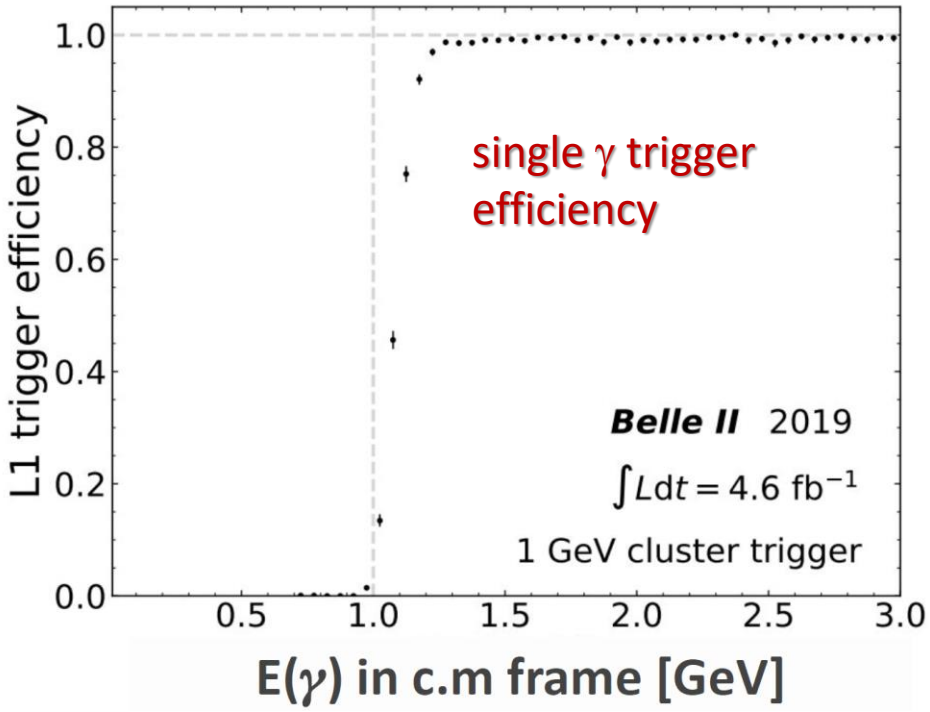
Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV

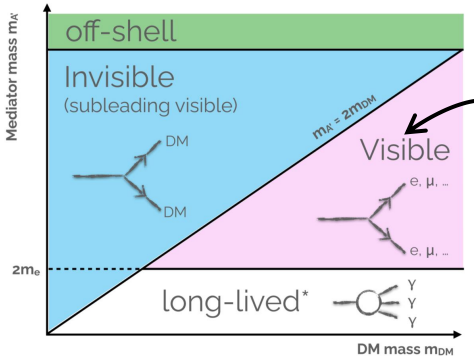
Displaced-vertex trigger
- Under study





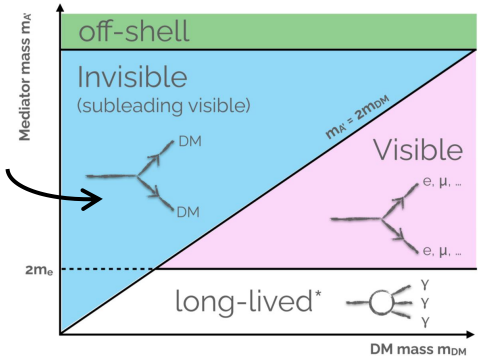
Belle II dark sector search overview

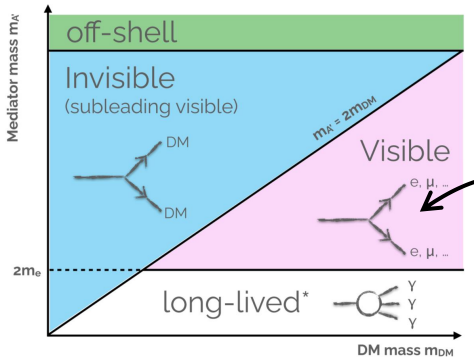
Searches are usually driven by models or proceed according to heuristic approaches



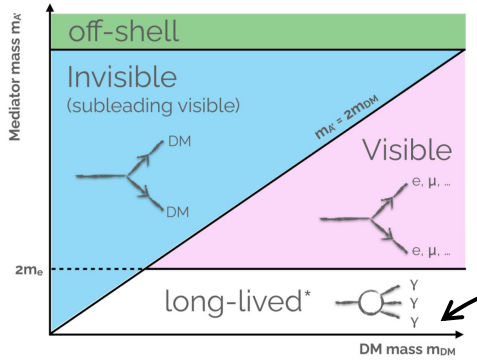
Visible minimal dark photon, Z', ALP→ff

Invisible dark photon, Z'





Visible ALP → γγ

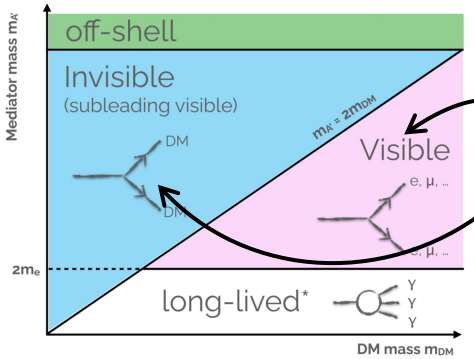


LLP long-lived particles

iDM, scalars

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



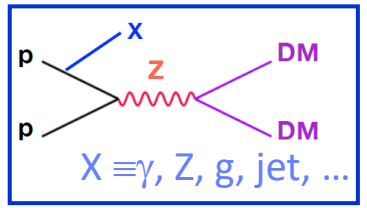
ll (γ) (+missing)

Visible minimal and non minimal dark photons, ALP→ff

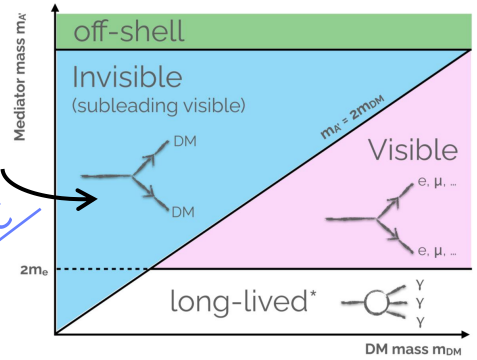
Invisible dark photon, Z'

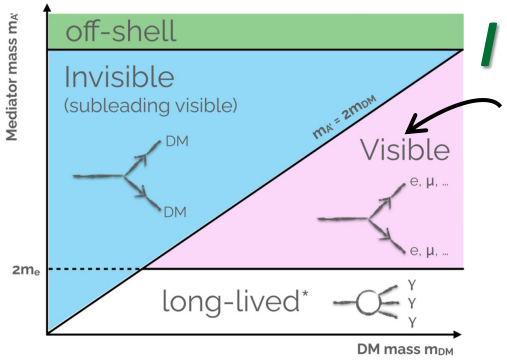
Single γ

Invisible dark photon, ALP →χχ, iDM, LLP



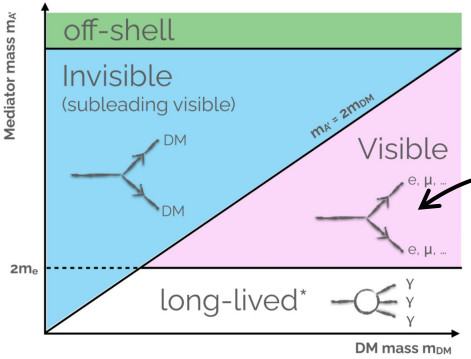
LHC





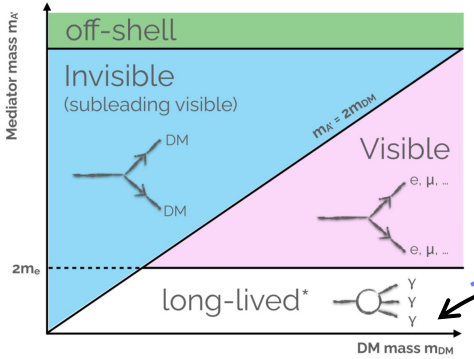
l l l' l'

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



γγ

Visible ALP → γγ



LLP

LHC

Hot topic

A', ALP→χχ, iDM, scalars

Belle II dark sector search overview: results

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

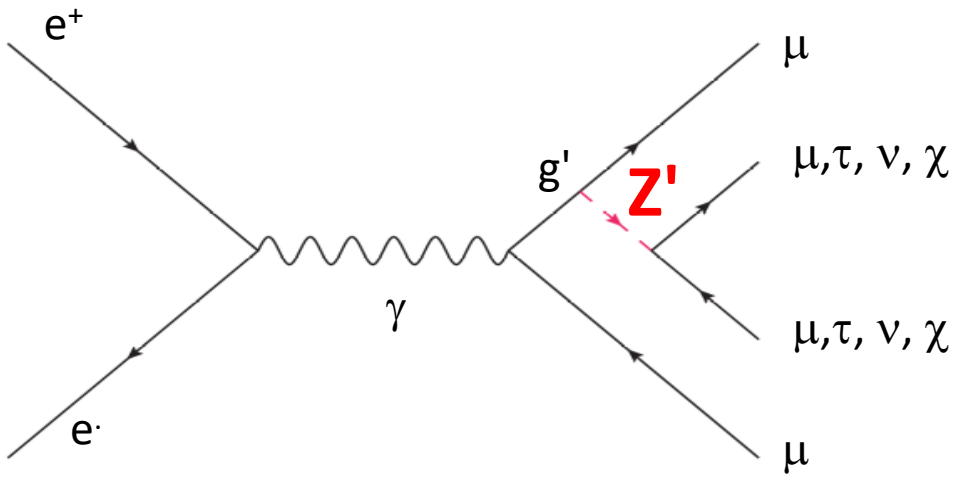
LLP Dark Higgsstrahlung with IDM
A'h' A'→$\chi_1\chi_2$, h'→μμ, ππ, kk

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



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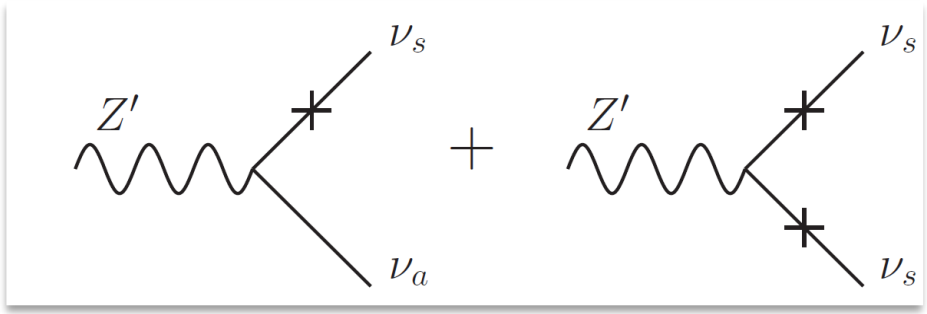

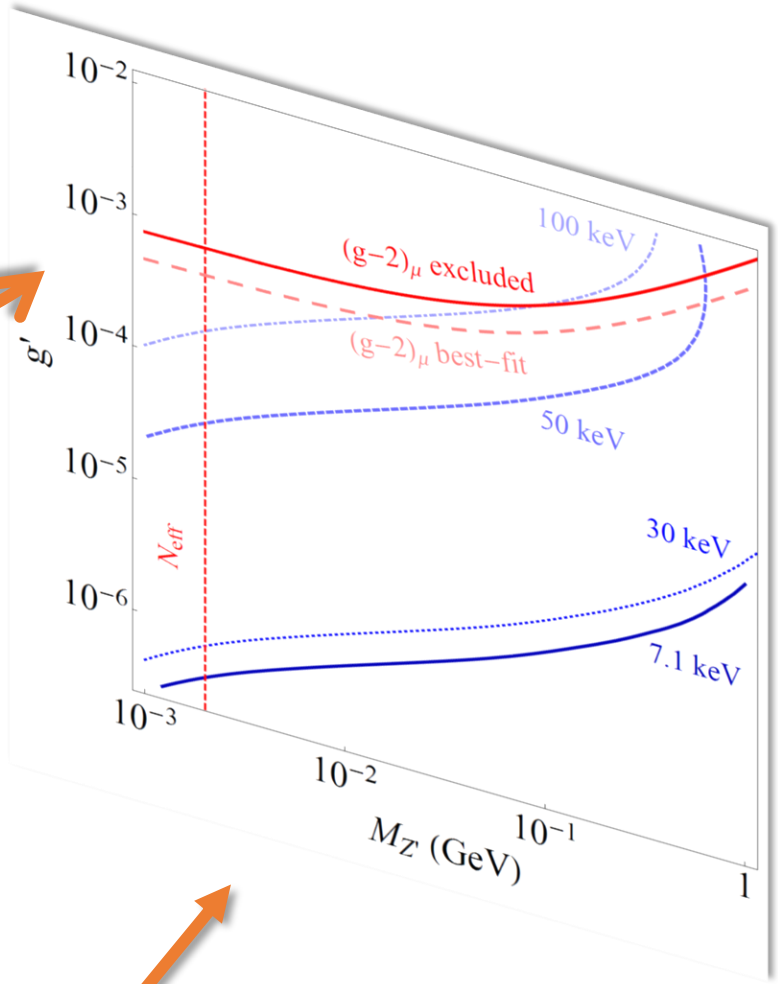

Sterile neutrino abundance

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

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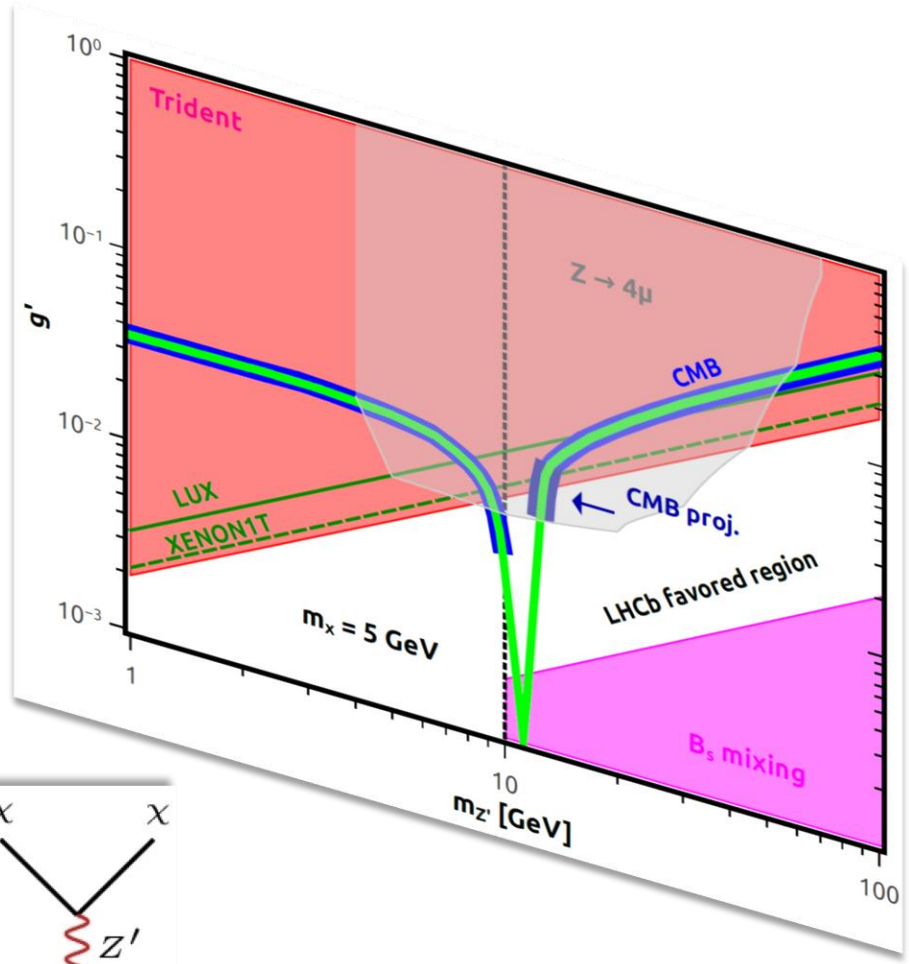
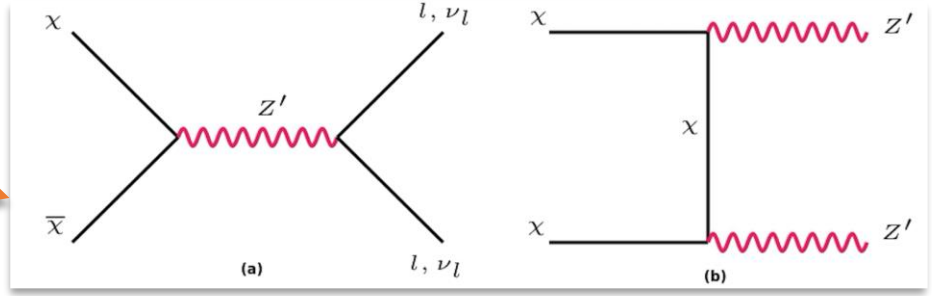
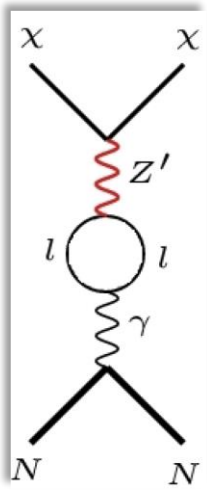


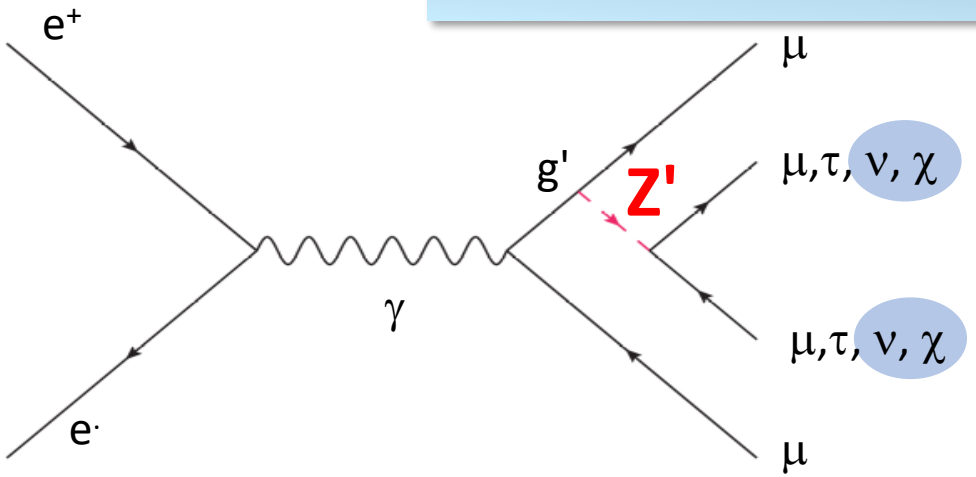
Annihilation





Direct detection

Z' to invisible: first Belle II physics result



Explored for the first time

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

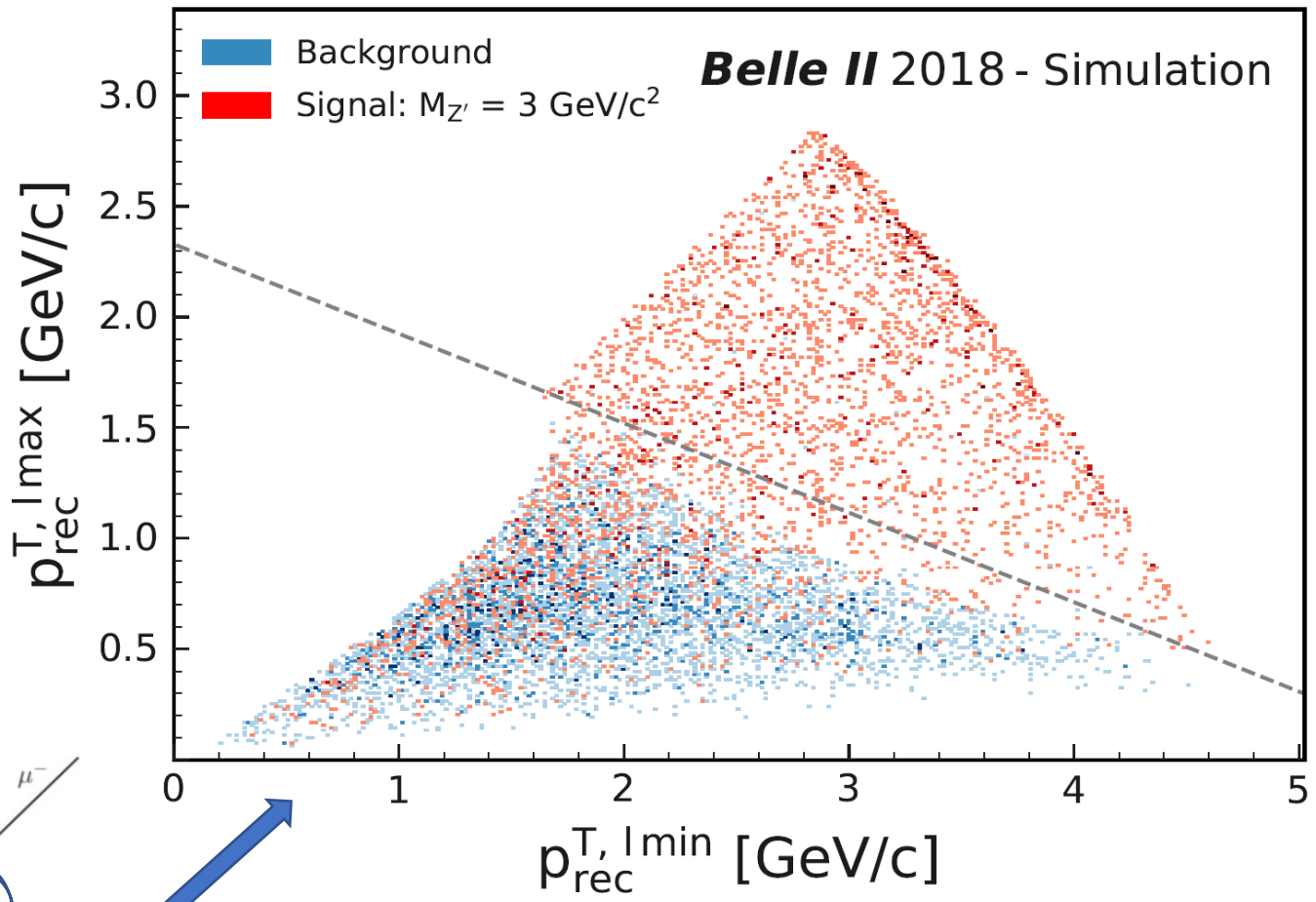
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

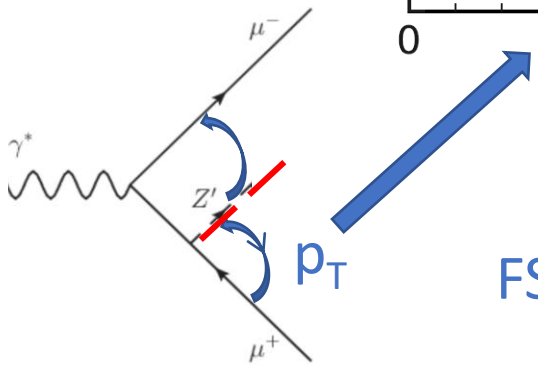
Main backgrounds:

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

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

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

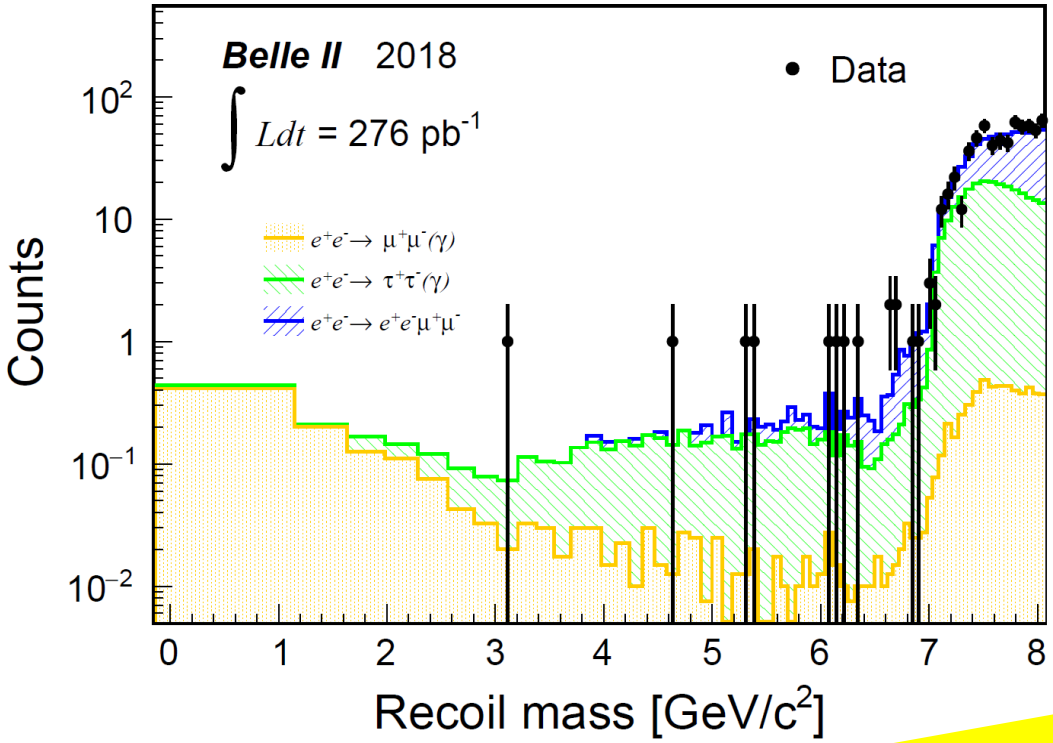




FSR vs ISR + τ decay

Z' to invisible: first result

Pilot run physics results

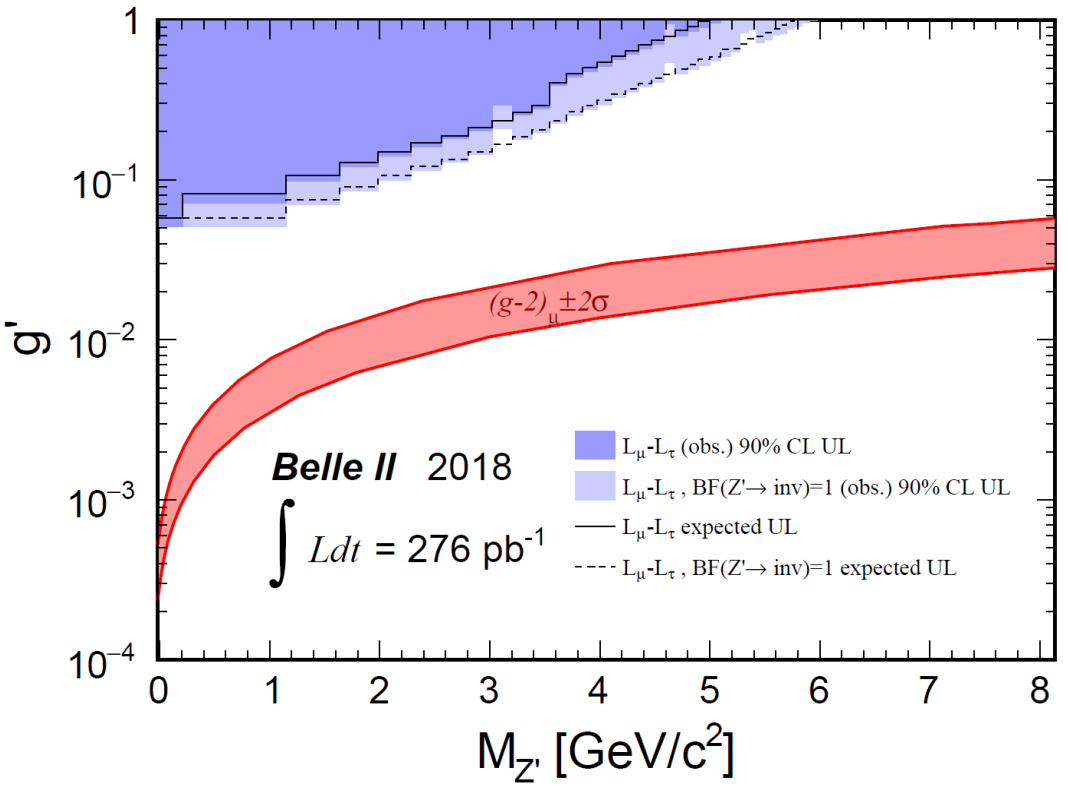


First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

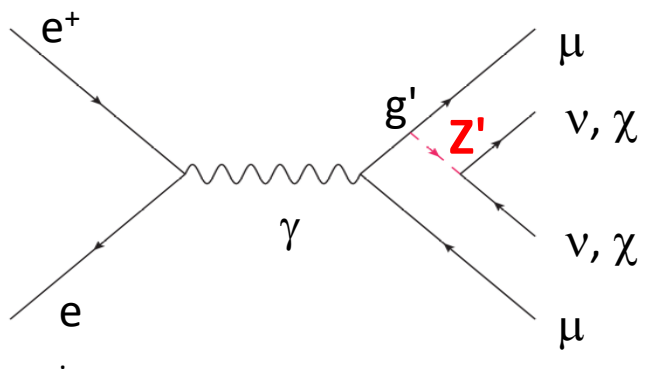
Source	Error
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
Background before τ suppression	2%
τ suppression (background)	22%
Discrepancy in μμ yield (signal)	12.5%

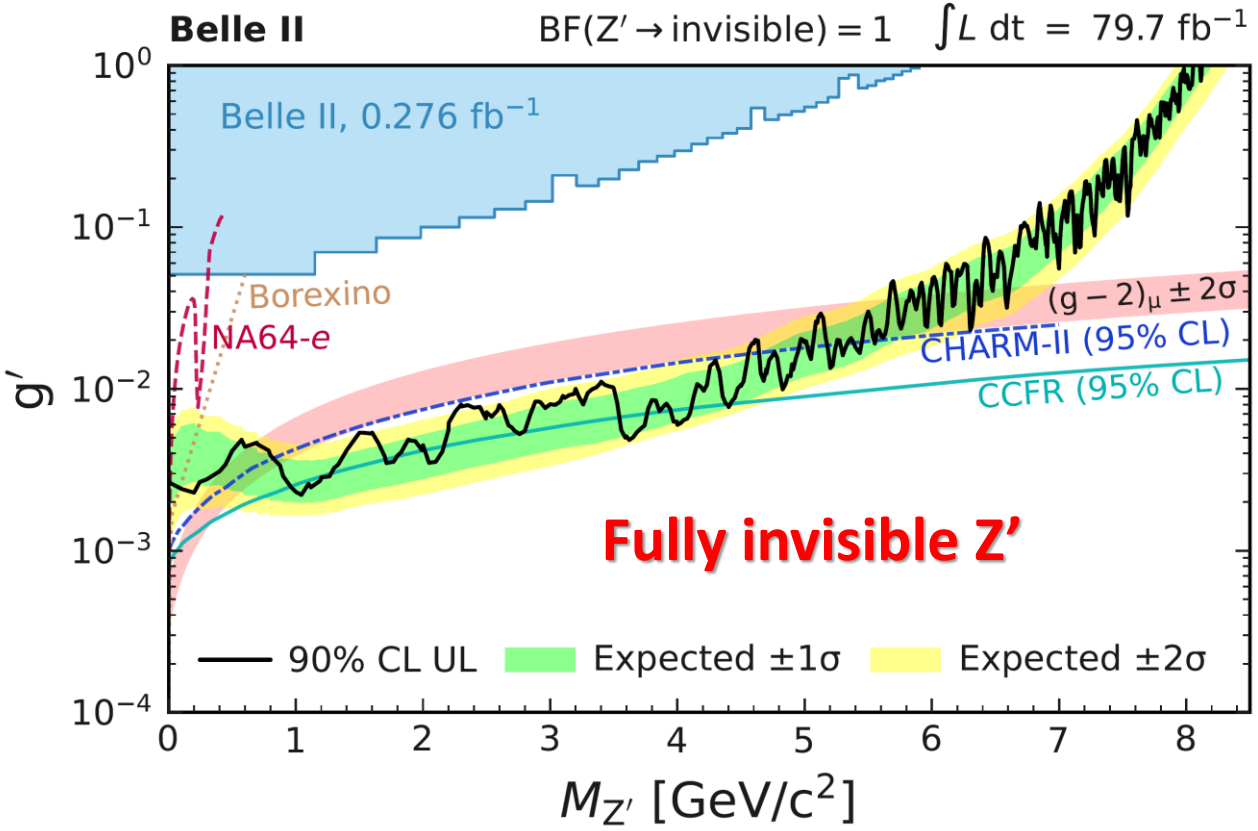
will decrease with new data



Belle II dark sector search overview: results

L_μ-L_τ
Z' → invisible





see M.Laurenza's talk

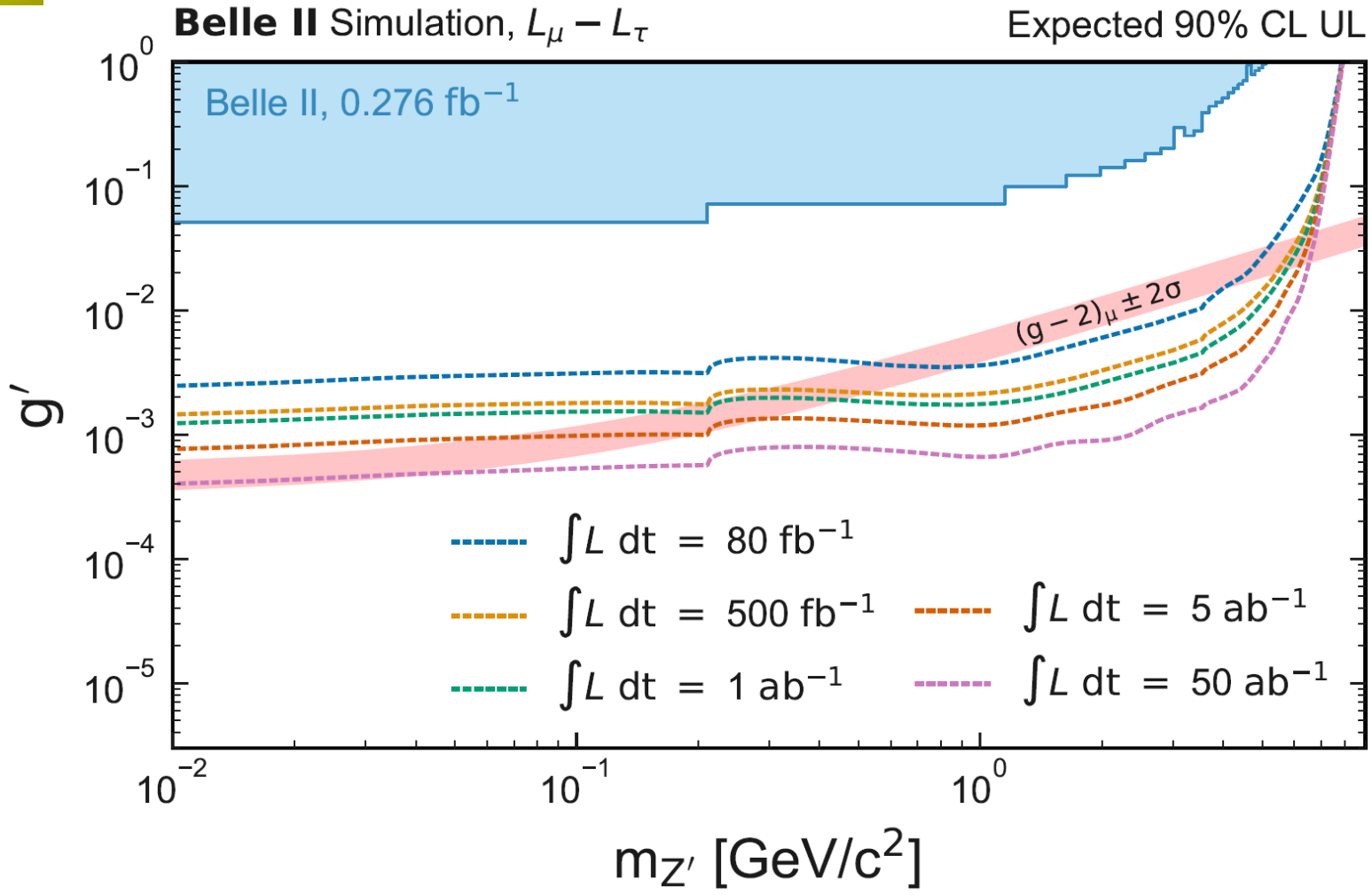
PRL 130, 231801 (2023)

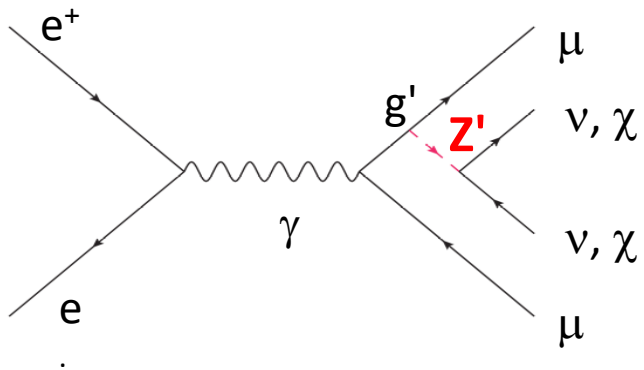
fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Belle II dark sector search overview: results

L_μ-L_τ
Z' → invisible

Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

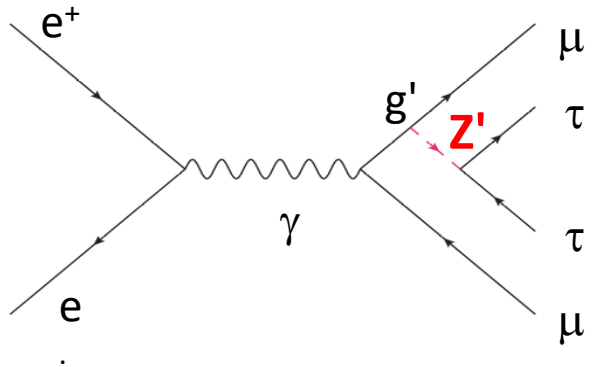




Belle II dark sector search overview: results

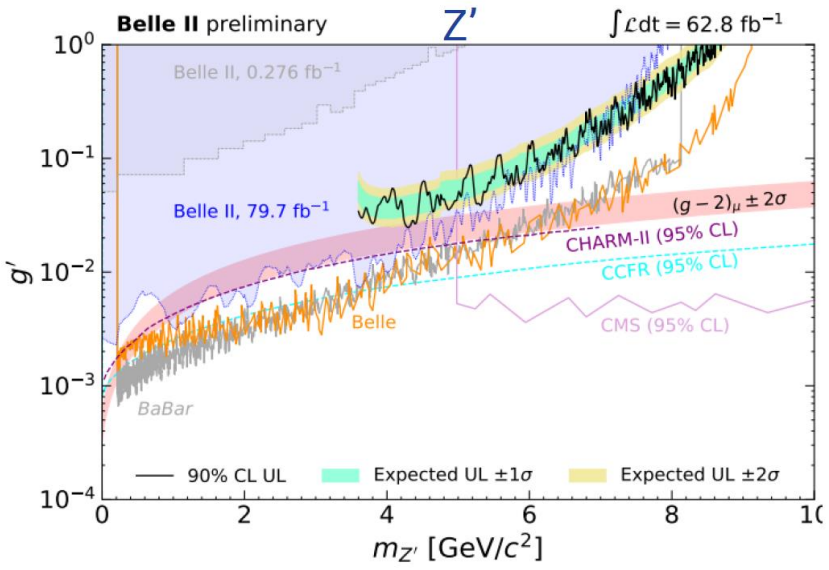
L_μ-L_τ
$Z' \to \tau\tau$

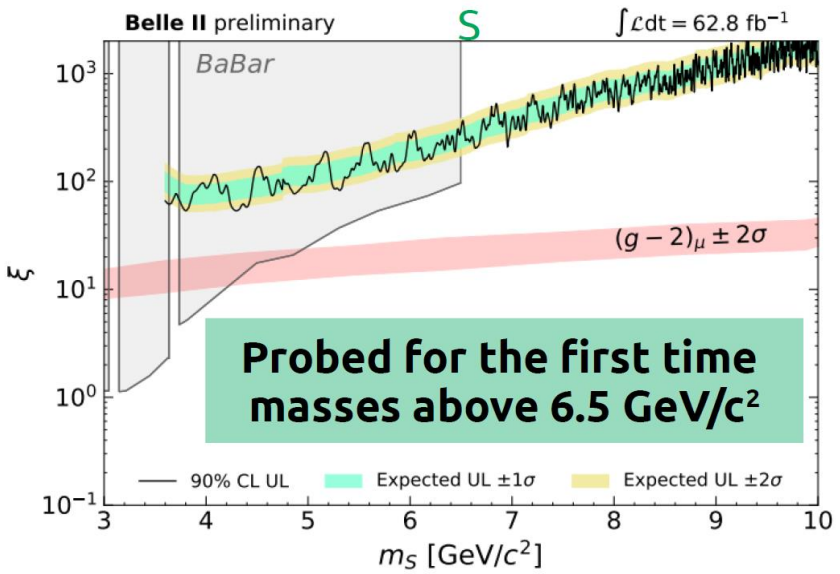
Reinterpreted also as
- Leptophilic dark scalar S → $(g-2)_\mu$
- ALP with τ coupling

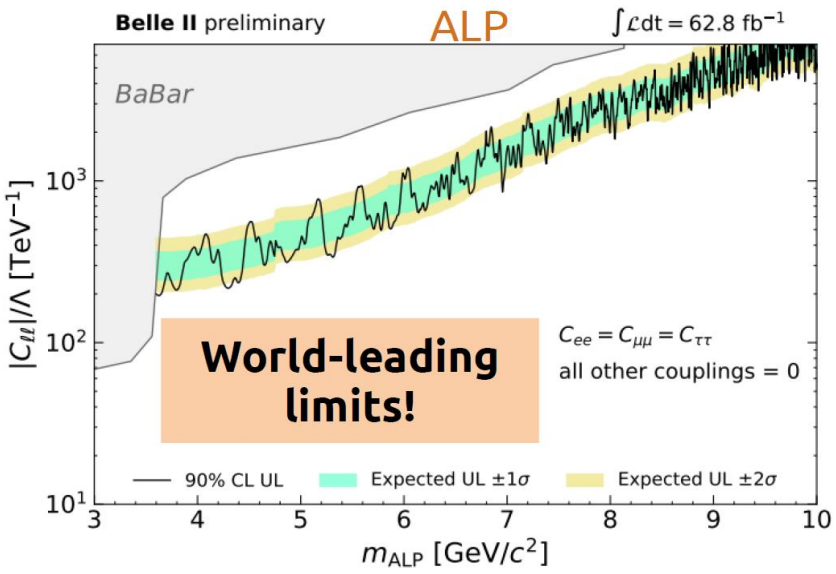


Accepted by PRL
arXiv:2306.12294

see M.Laurenza's talk





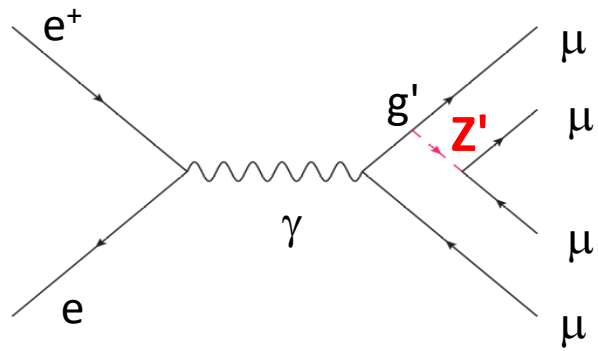


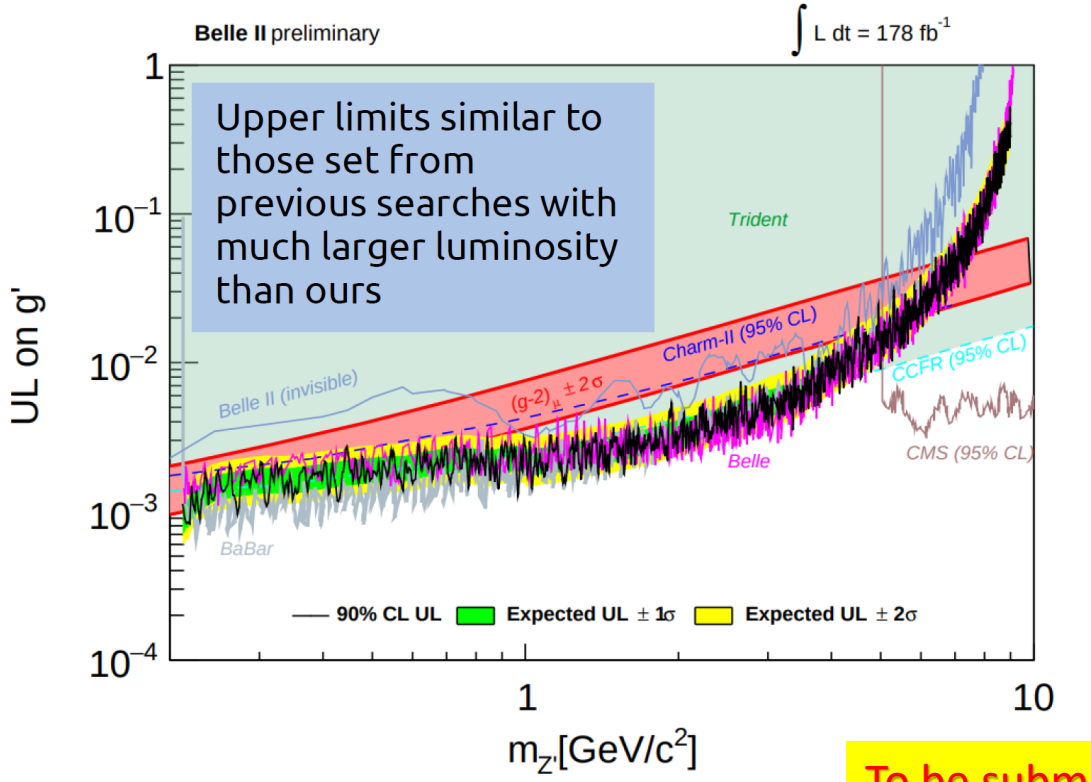
Belle II dark sector search overview: results

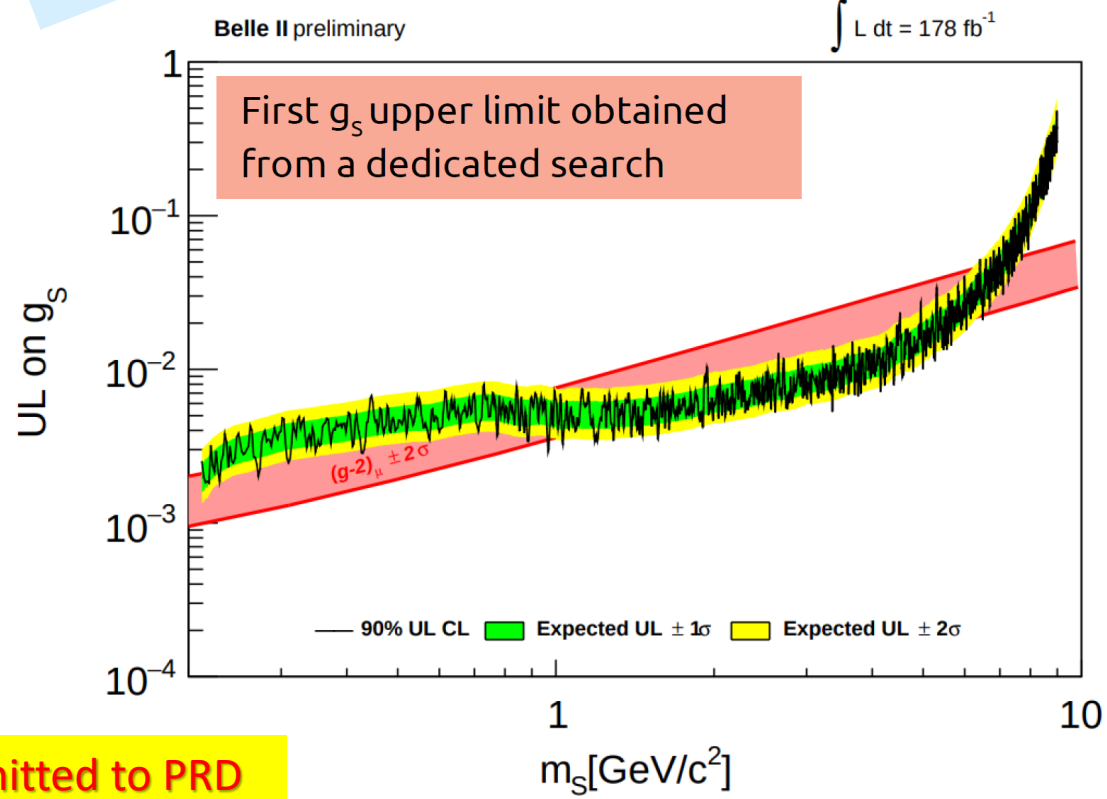
L_μ-L_τ
$Z' \rightarrow \mu\mu$

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

see M.Laurenza's talk





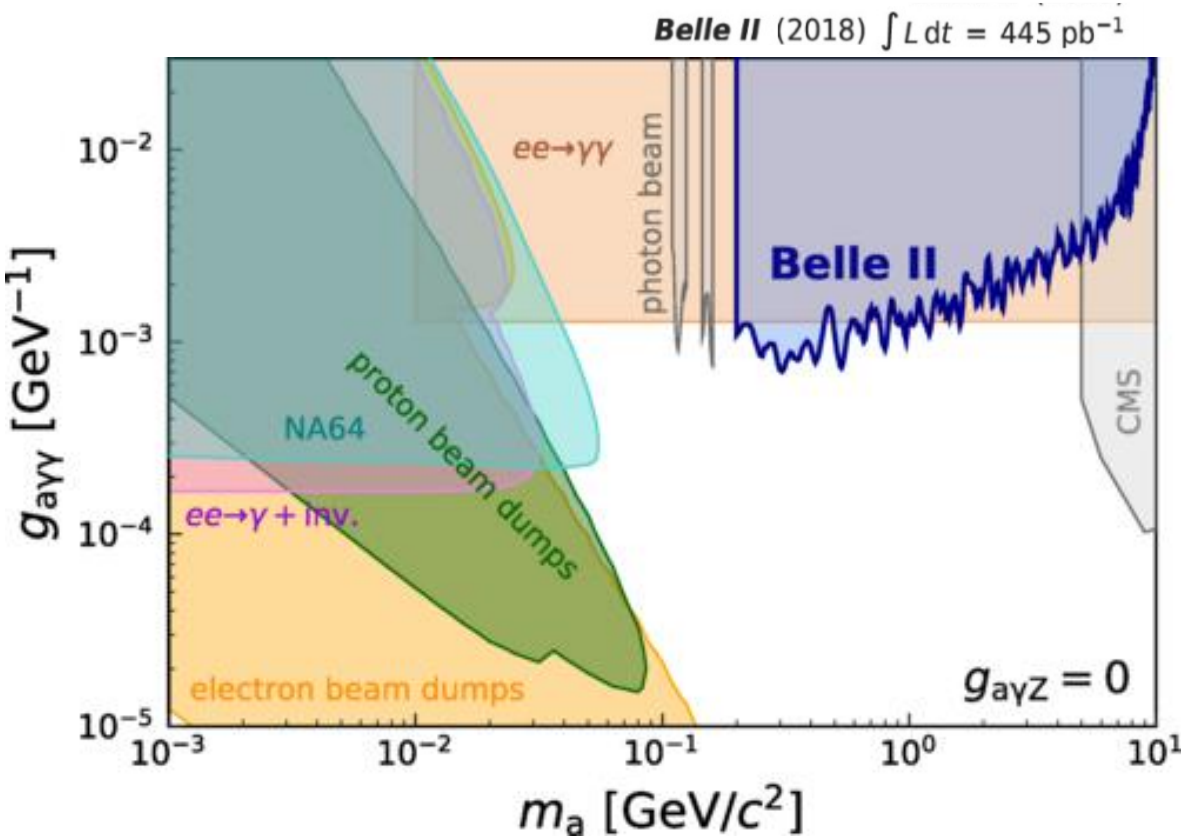


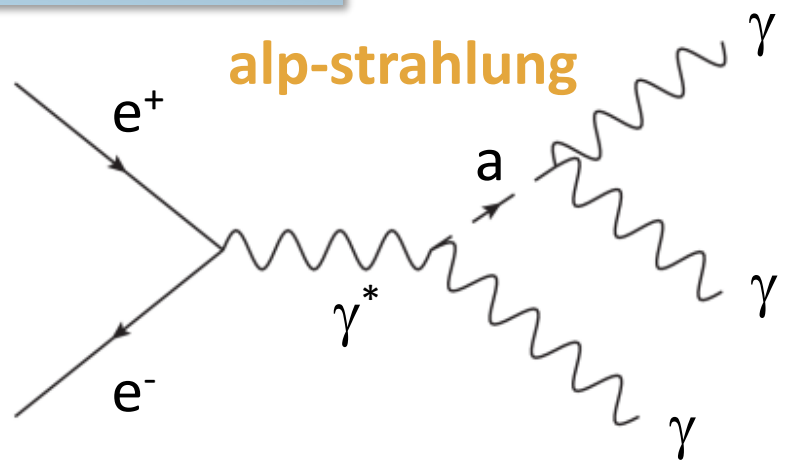
To be submitted to PRD

Belle II dark sector search overview: results

Axion like particles
ALP→γγ

Pilot run physics results



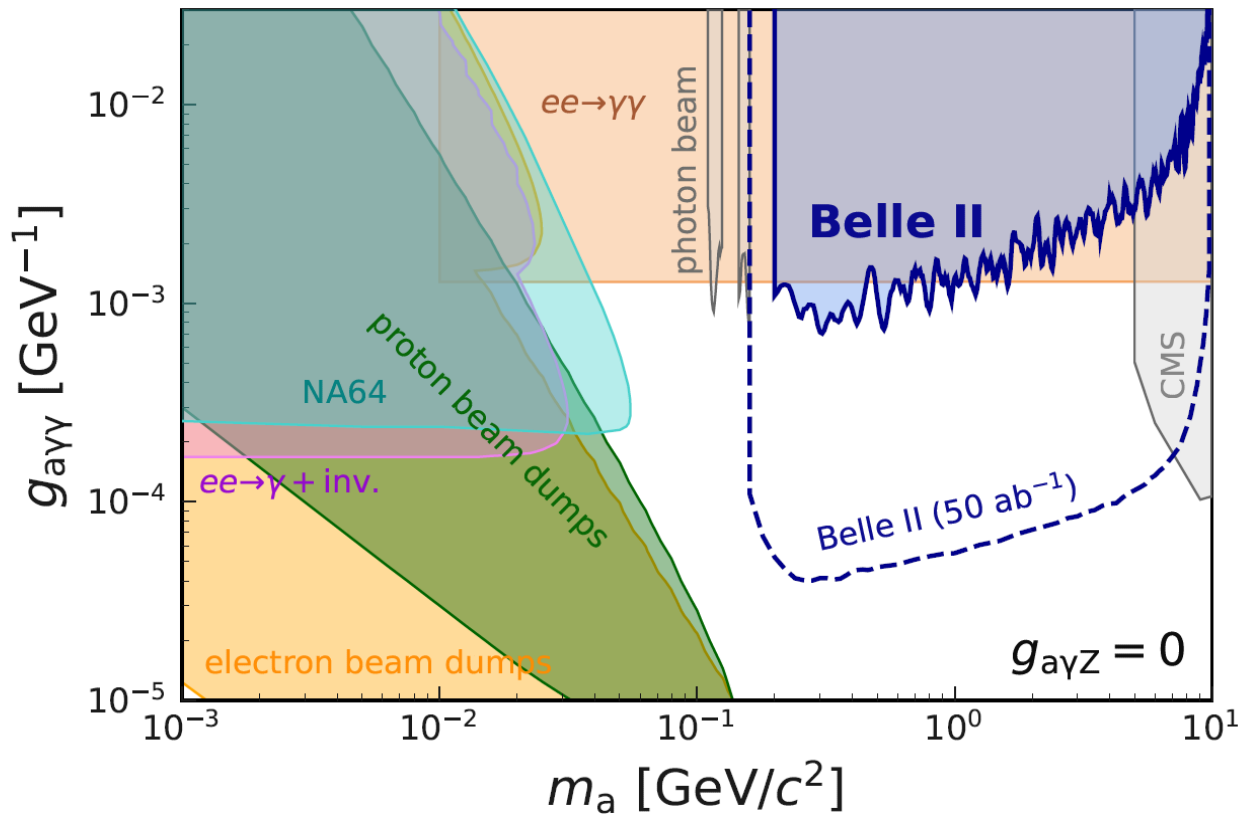


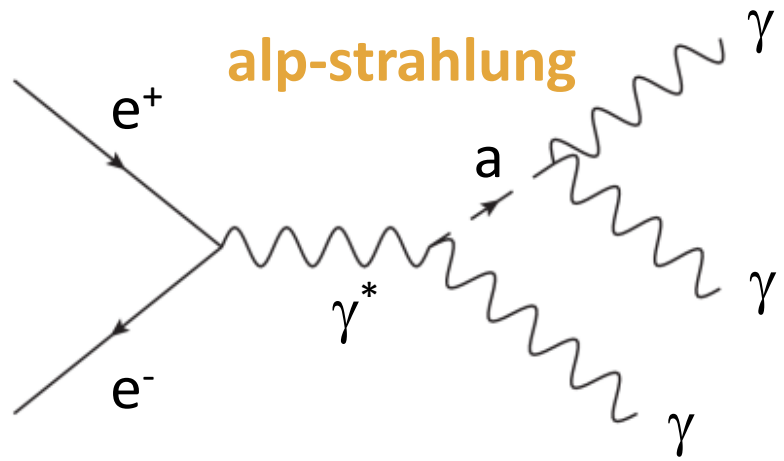
see L.Zani's talk

PRL 125, 161806 (2020)

Belle II dark sector search overview: results

Axion like particles
ALP→γγ



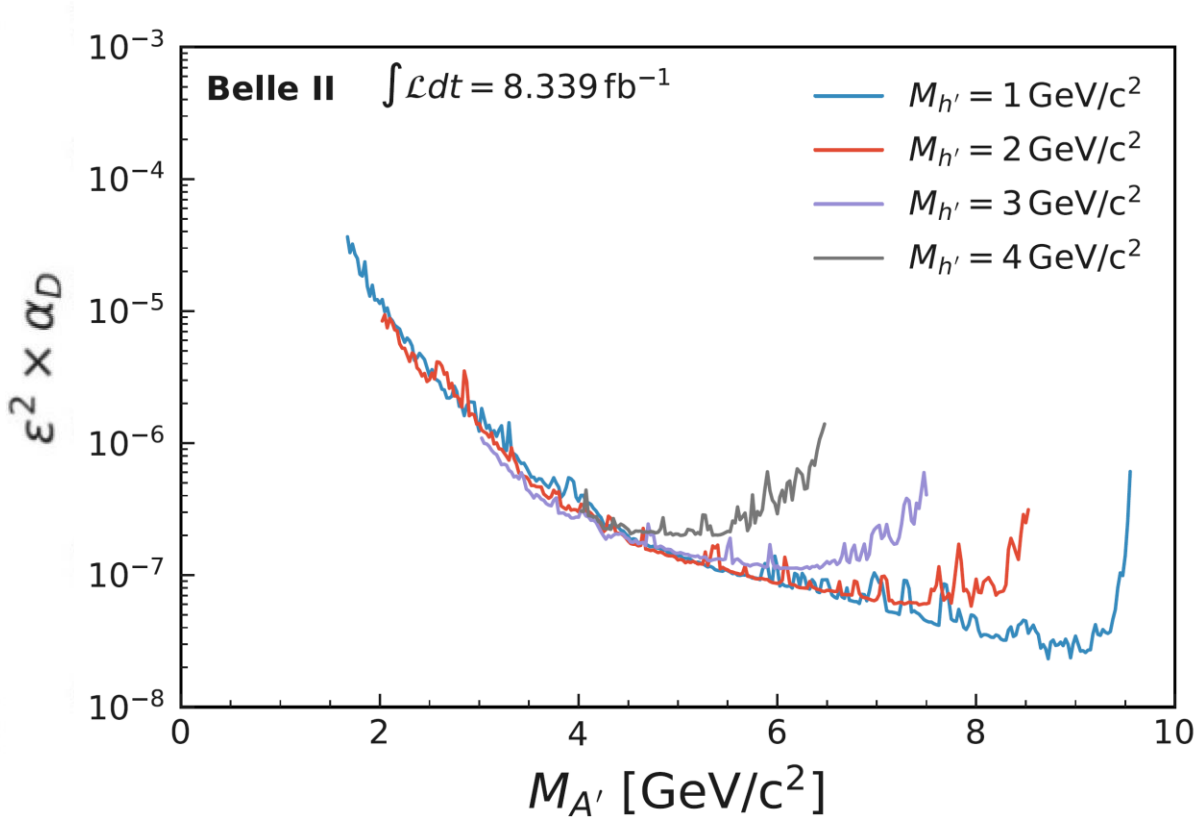


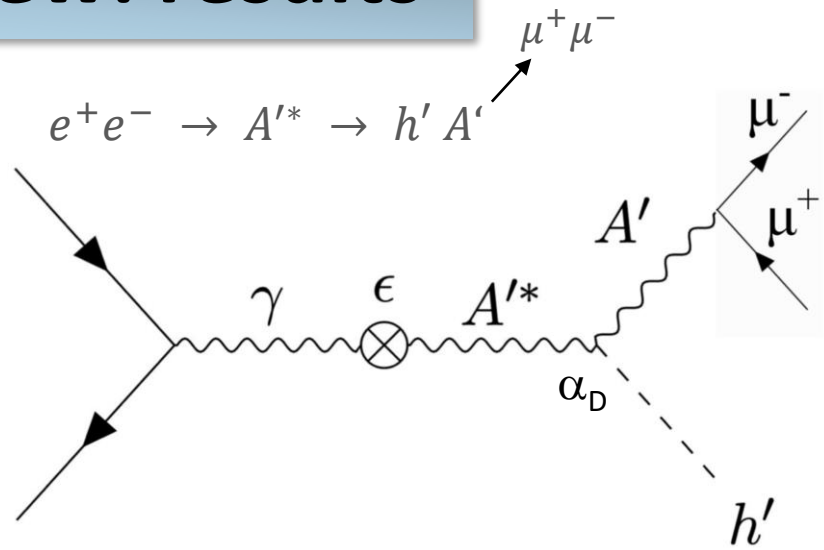
Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

Belle II dark sector search overview: results

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



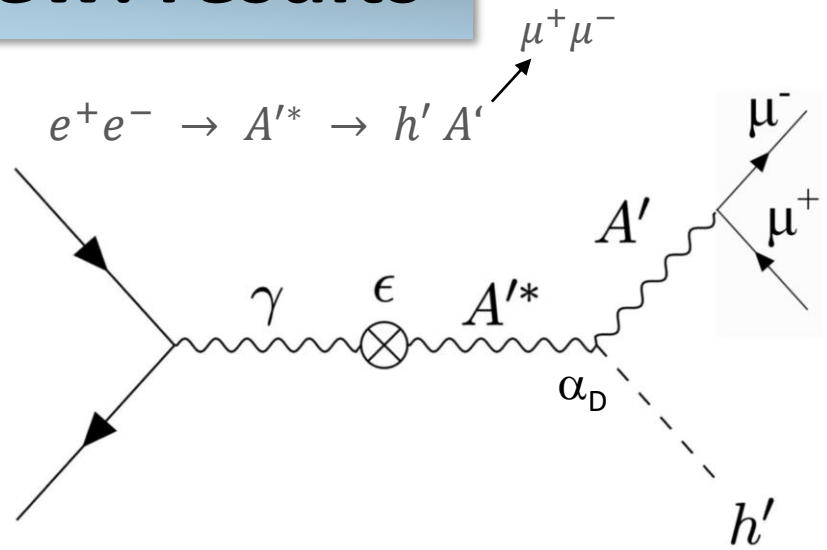


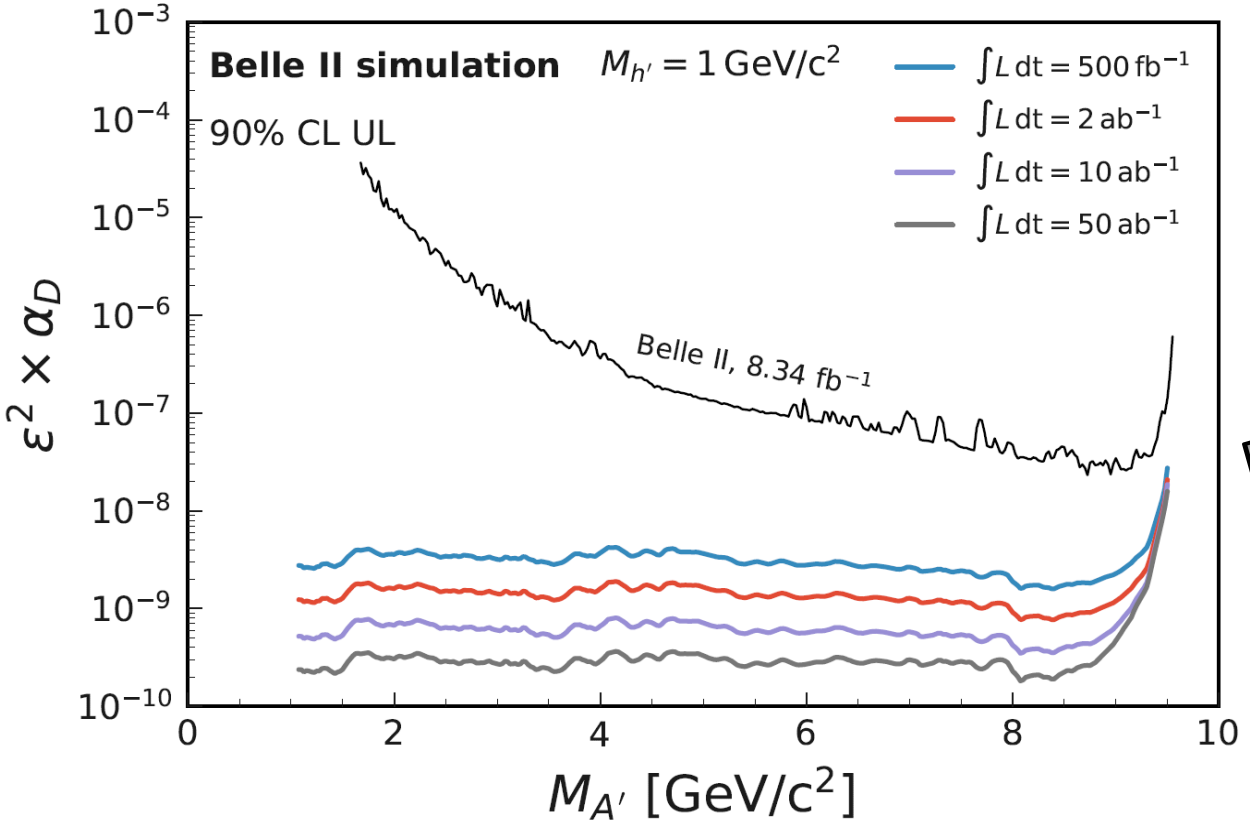
see L.Zani's talk

PRL 130, 071804 (2023)

Belle II dark sector search overview: results

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





Belle II physics reach @ Snowmass

arXiv: 2207.06307v1

Belle II dark sector search overview: results

Invisible α in τ decays

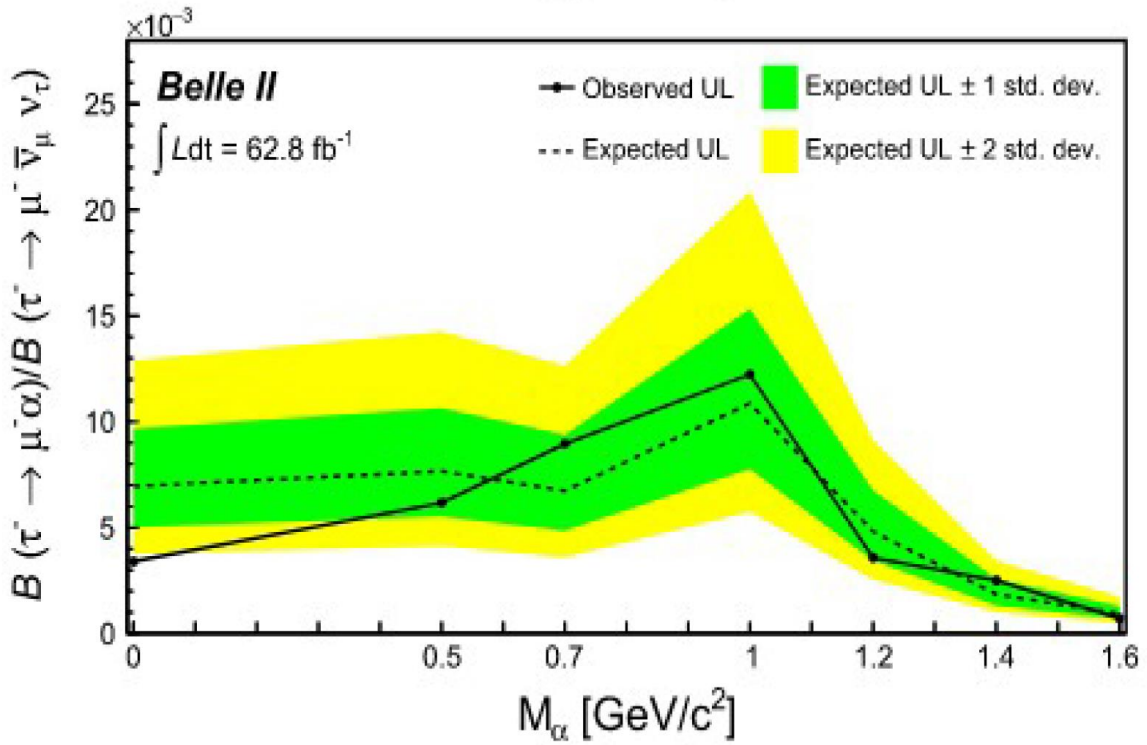
$\tau \to l\alpha$ l=e,μ

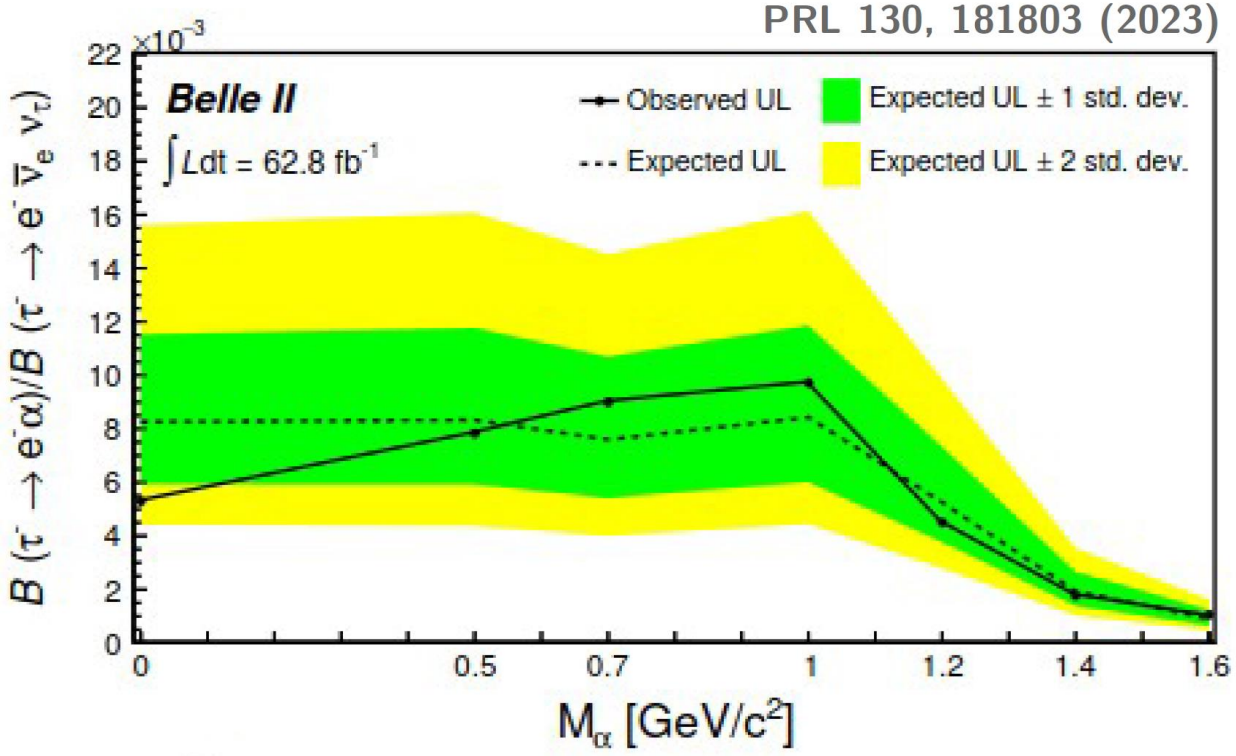
LFV, possible ALP candidate

PRL 130, 181803 (2023)

see L.Zani's talk

PRL 130, 181803 (2023)

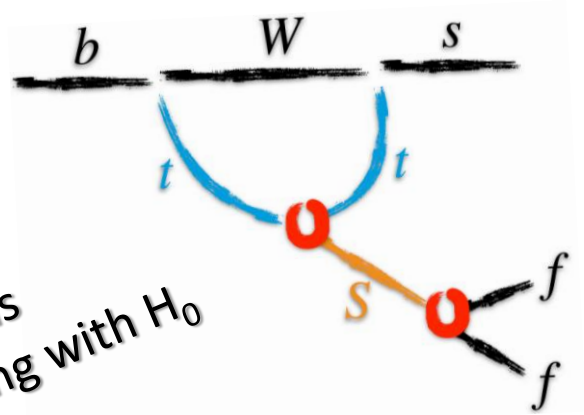




Belle II dark sector search overview: results

see L.Zani's talk

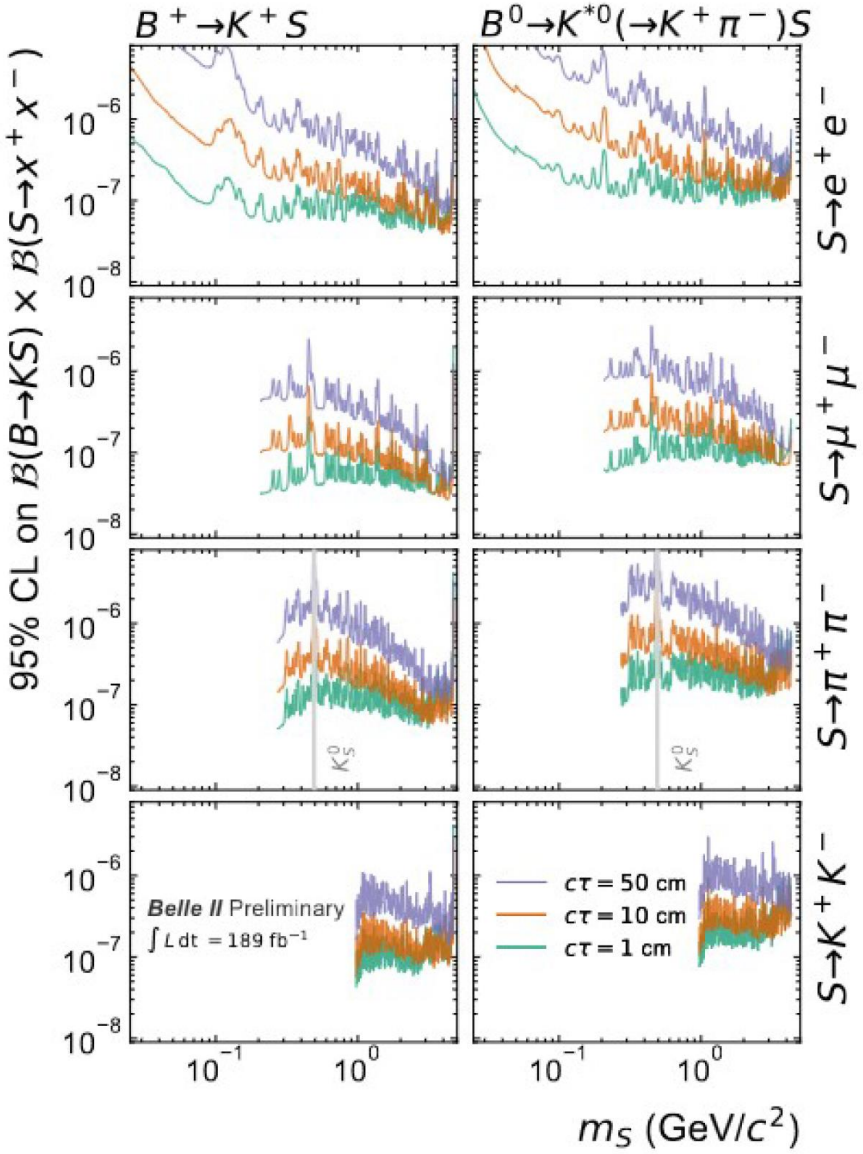
LLP dark scalar in B decays
B→kS S→ee, μμ, ππ, kk



b→s transitions
Possible mixing with H_0
LLP signature

S → μ⁺μ⁻ / π⁺π⁻ / K⁺ K⁻

Submitted to PRL
arXiv:2306.02830

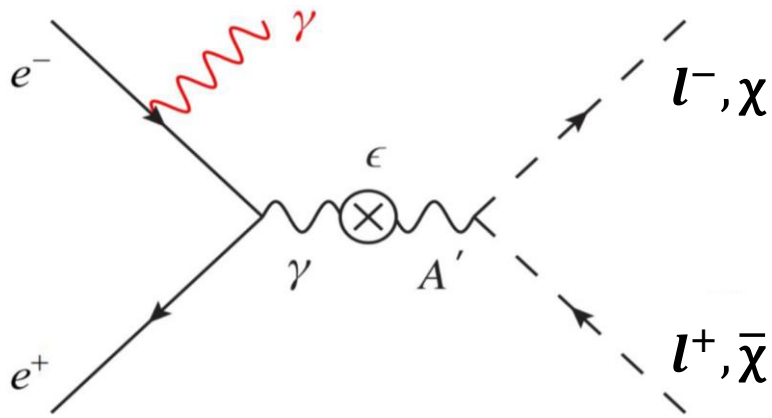


In progress Belle II dark searches

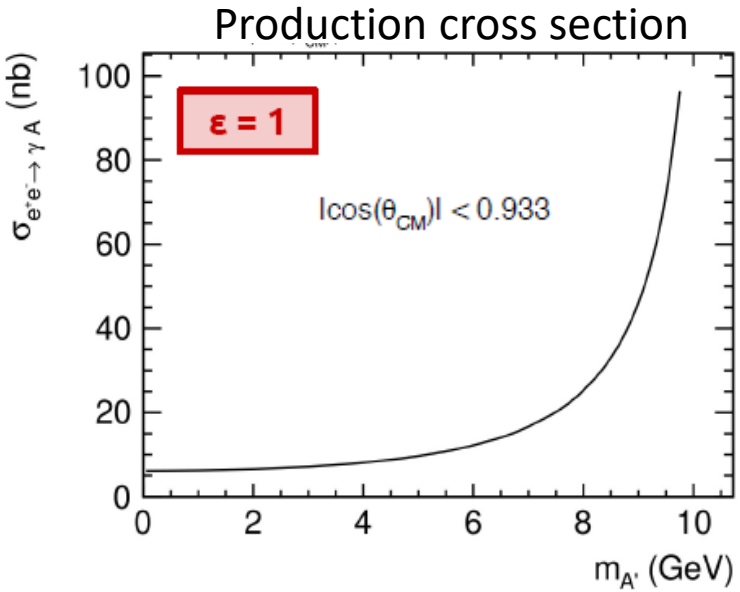
Dark photon: introduction

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



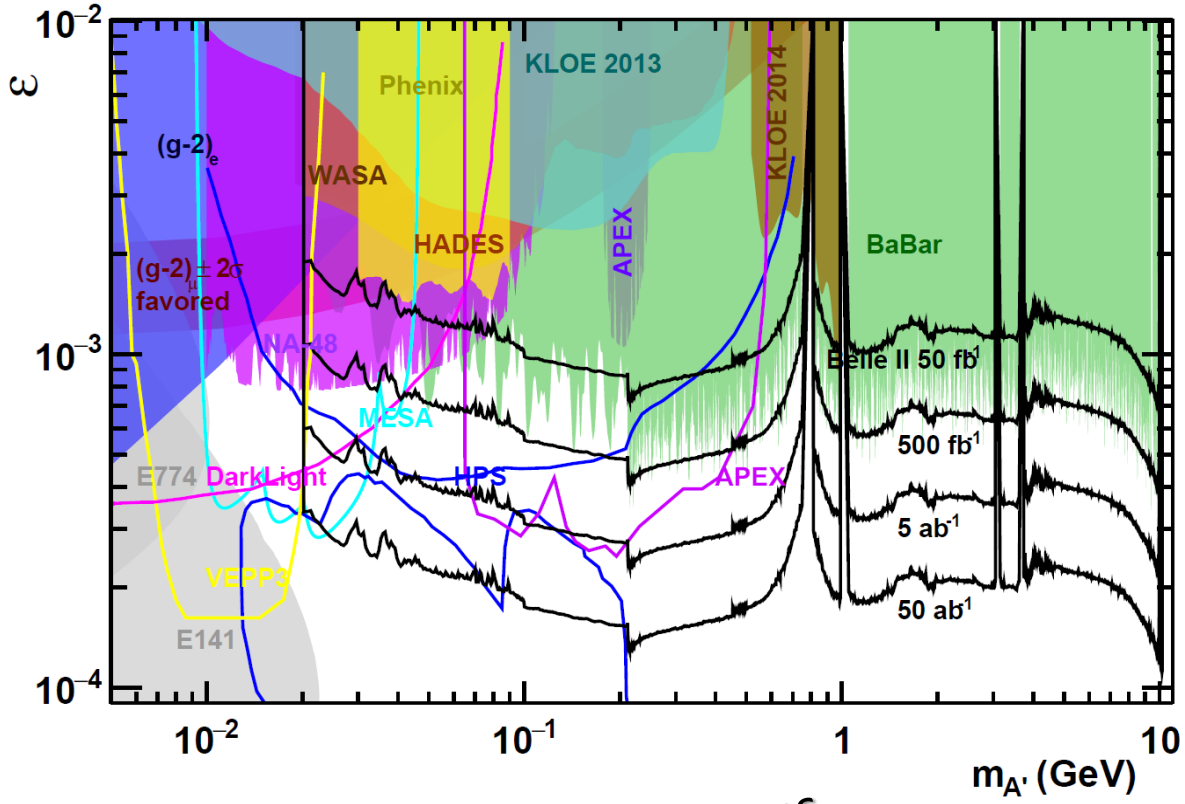
two basic scenarios depending on A′ vs χ DM mass relationship

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

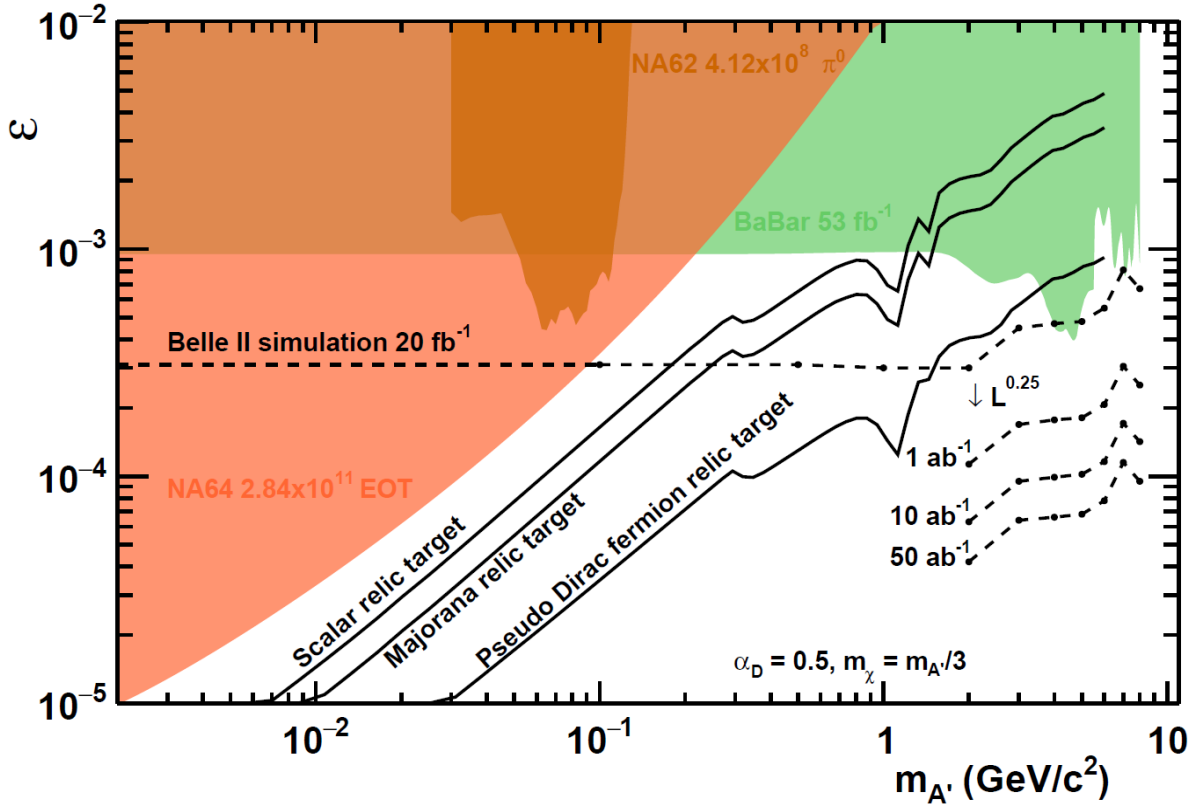
$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

Dark photon: luminosity projections

Visible



Invisible



Belle II physics reach @ Snowmass

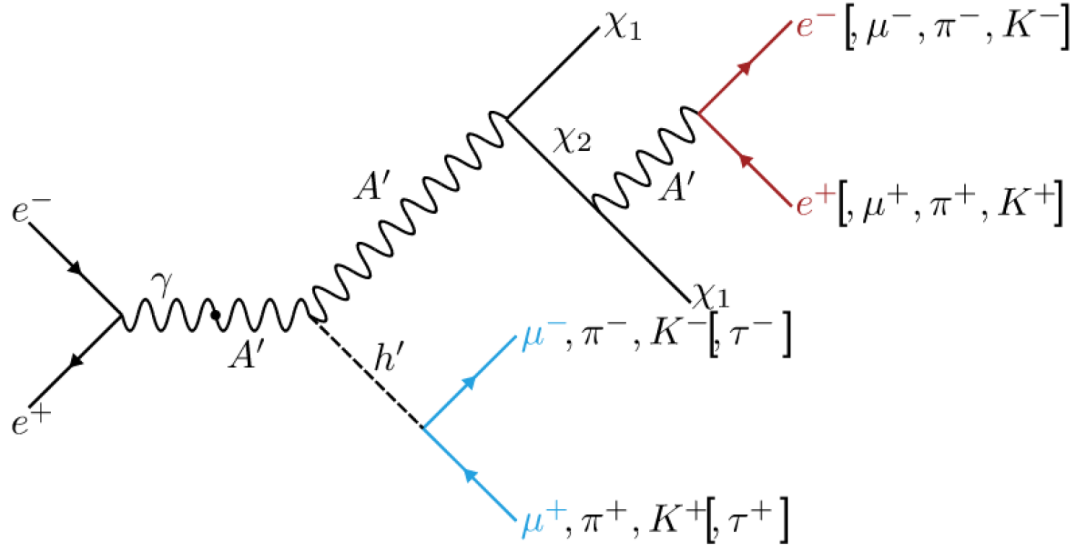
arXiv: 2207.06307v1

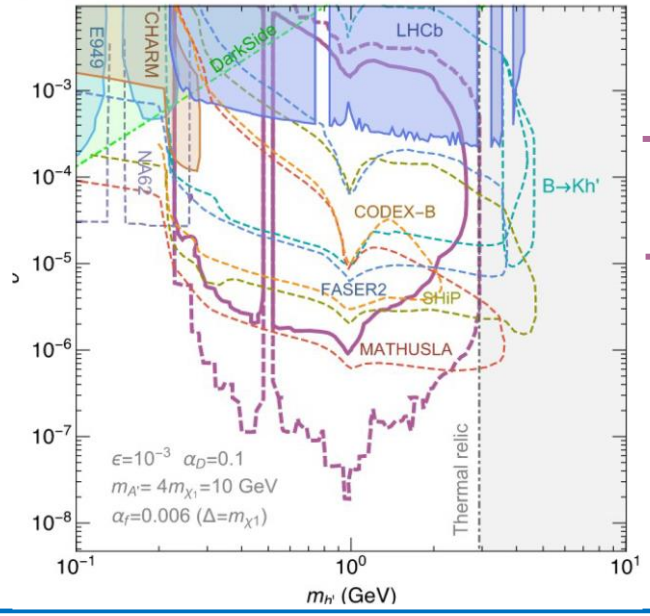
Belle II vs BaBar

- ✓ 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}

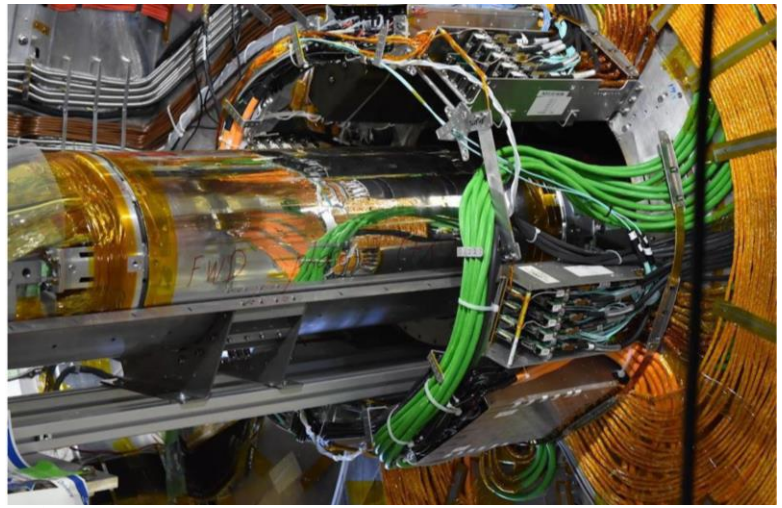
Belle II 50 ab^{-1}

LLP signature

JHEP 04 (2021), arXiv:2012.08595

Belle II and SuperKEKB after shutdown

- Currently in shutdown LS1 since summer 2022
  - Accelerator upgrades: mitigate background and increase luminosity
  - Detector upgrades: two layer pixel detector installed

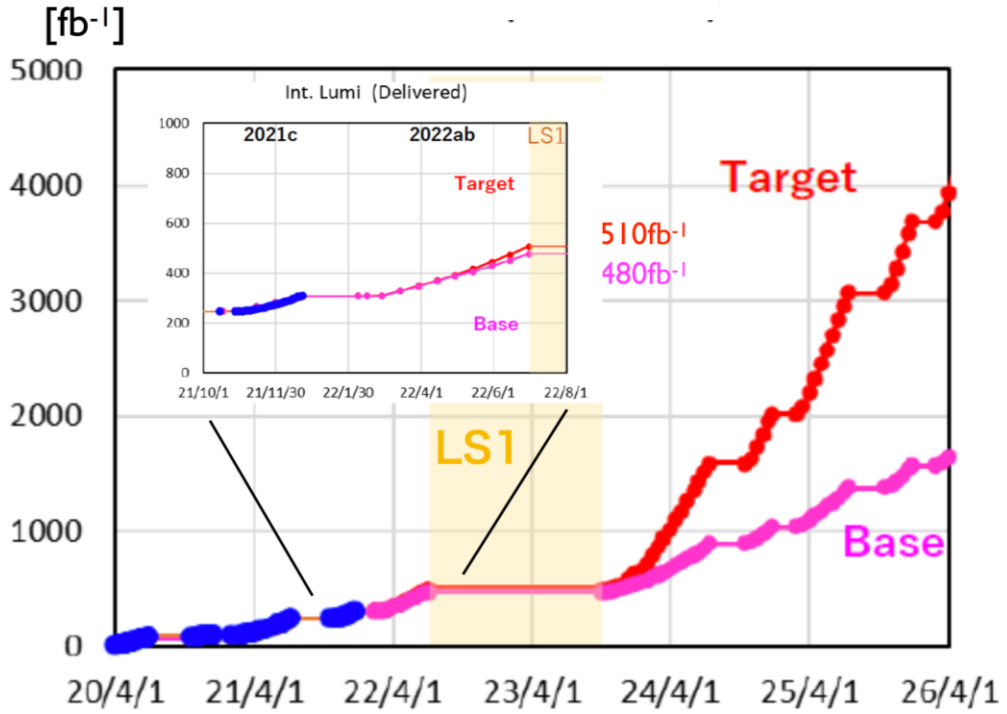


- Restart SuperKEKB in december 2023 and physics beginning of 2024

- Path to $2x10^{35}$ $cm^{-2}s^{-1}$, but new interaction region to go beyond
  - Possible LS2 ~2027
  - Belle II upgrades under study

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



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 g-2 anomaly. Their future may depend by 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