Dark matter search at Belle II

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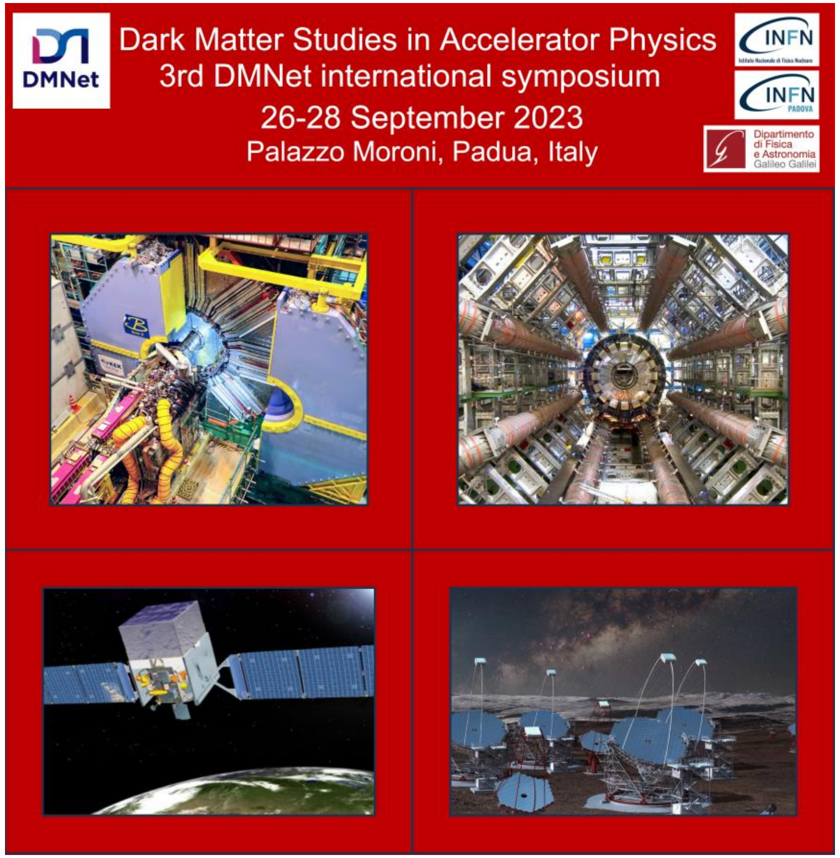
INFN – Roma 3

on behalf of the Belle II Collaboration



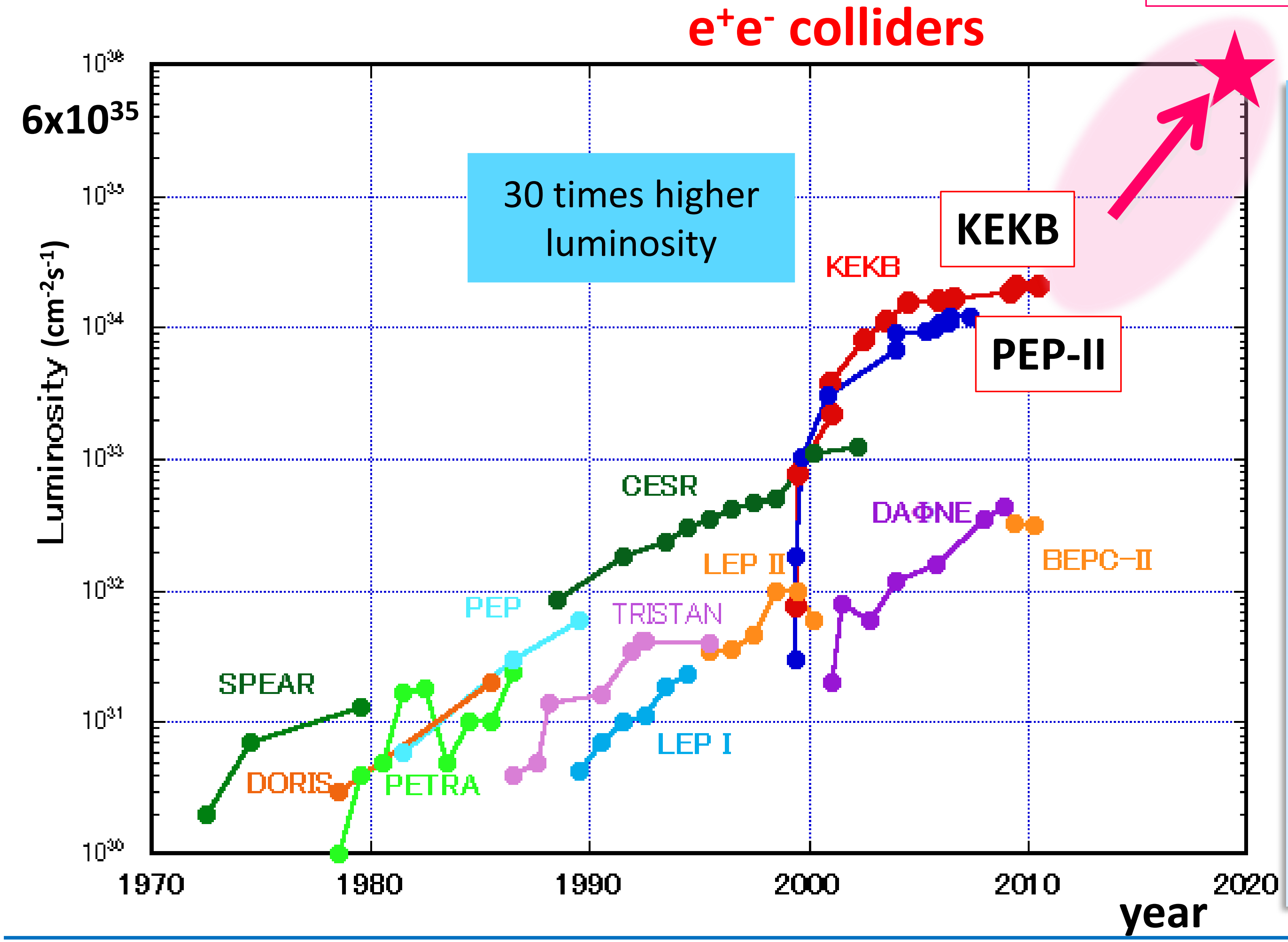
OUTLINE OF THE TALK

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

Peak luminosity trend

SuperKEKB

Final goal: L= 50 ab^{-1}



Very rich physics program

Flavour physics

- CKM matrix
- CPV in B deacys

see S.Robertson's talk

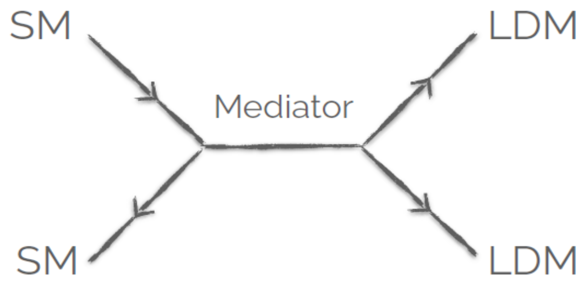
BSM physics

- 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

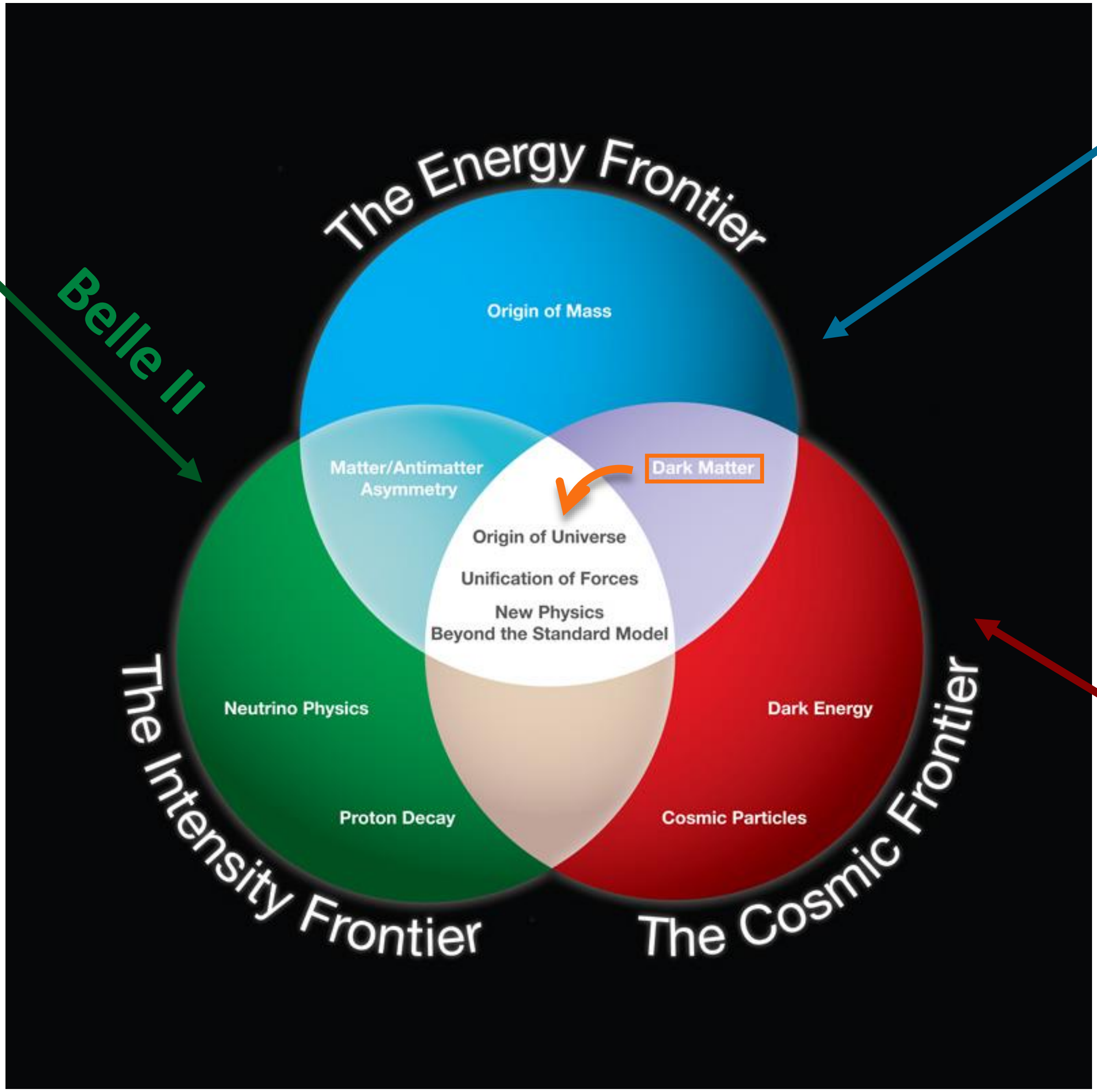
Dark matter hunt



LDM → Light Dark Matter
Mediators → portals

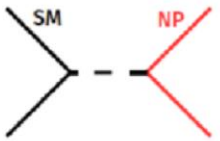
⇓

The possibility of LDM make intensity machines genuine discovery machines



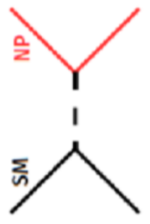
Energy frontier

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



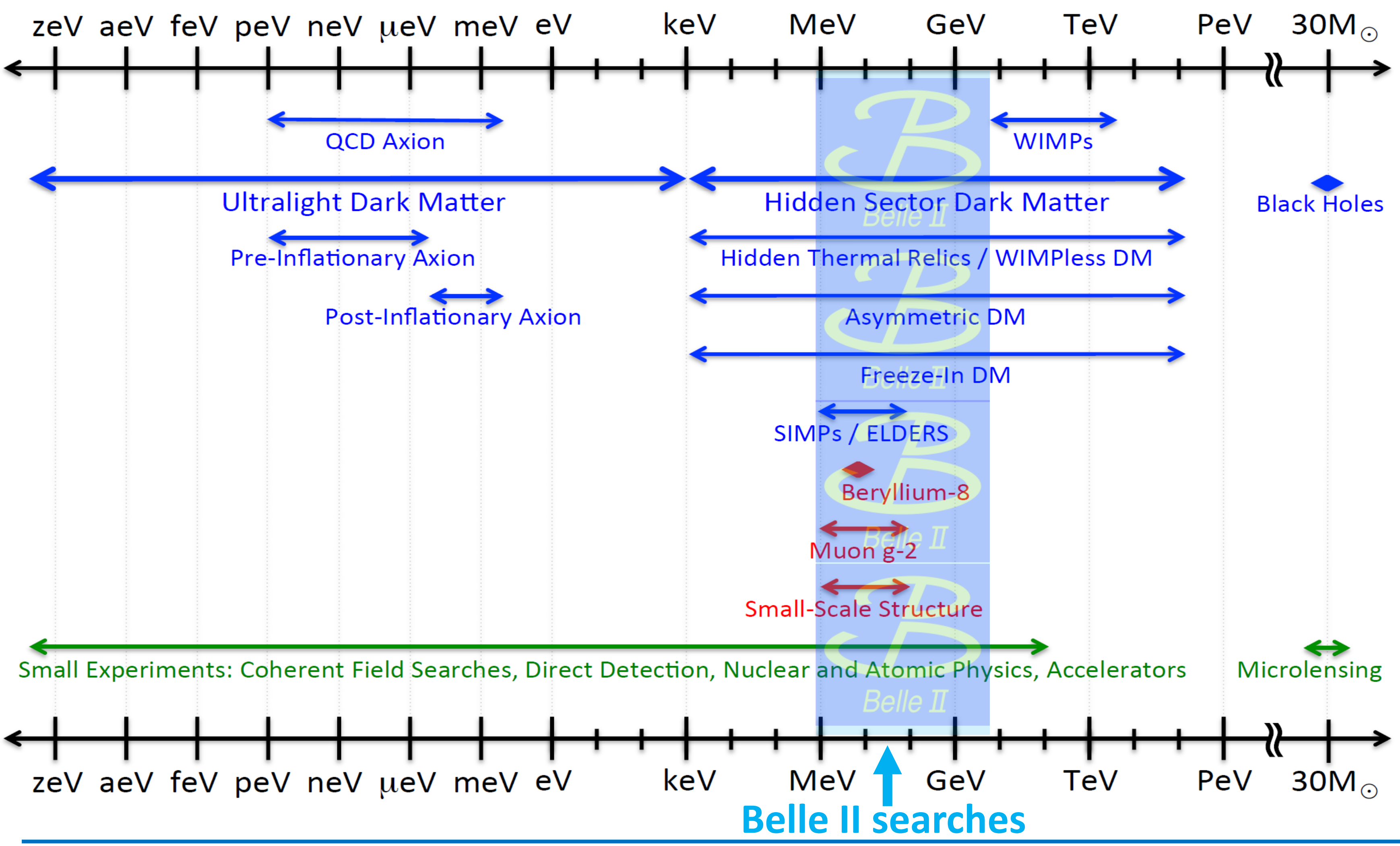
Cosmic frontier

Direct effect search in (mostly) underground experiments



Searching for dark matter

Dark Sector Candidates, Anomalies, and Search Techniques



Dark matter/mediators

Vector portal
Dark photon, Z', …

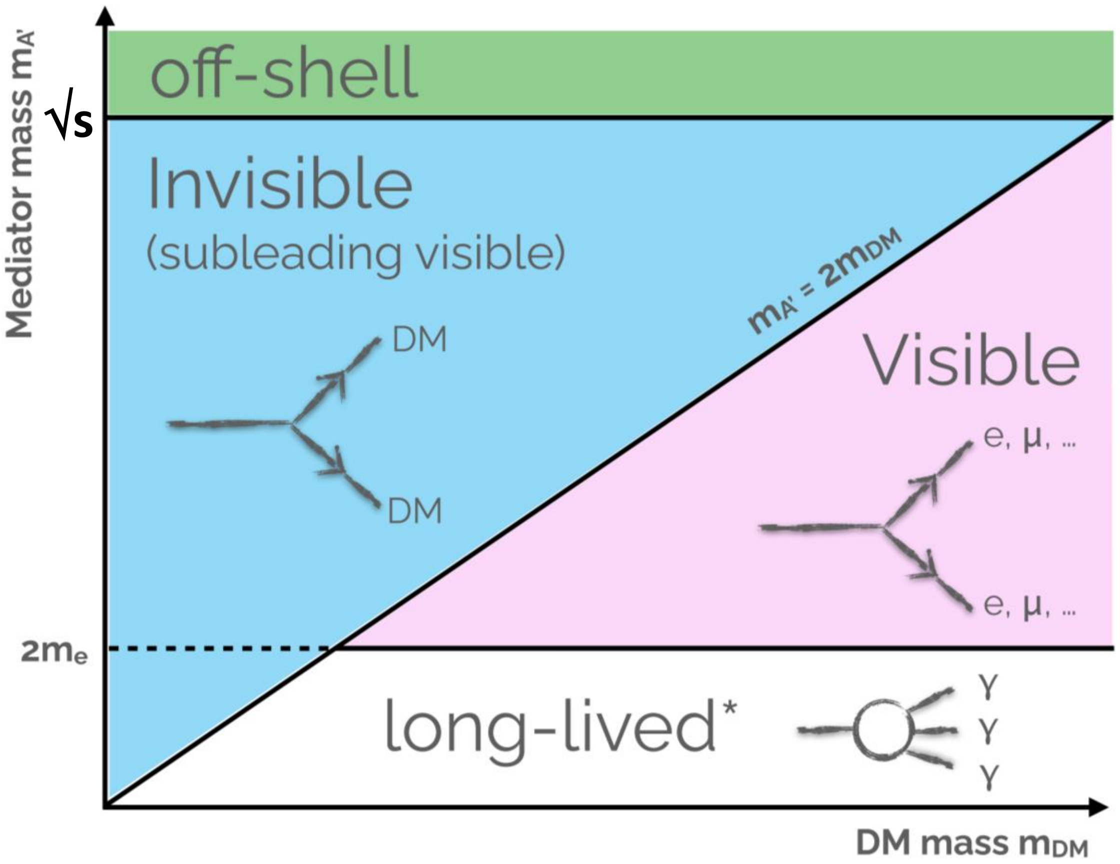
Pseudoscalar portal
Axions, **ALPs**, …

Scalar portal
Dark Higgs, scalars

Neutrino portal
Sterile neutrino

Light dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

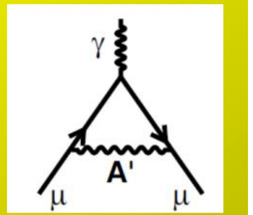


Probability of interaction of LDM detectors is negligible

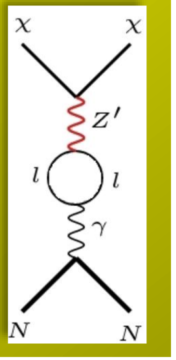
- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

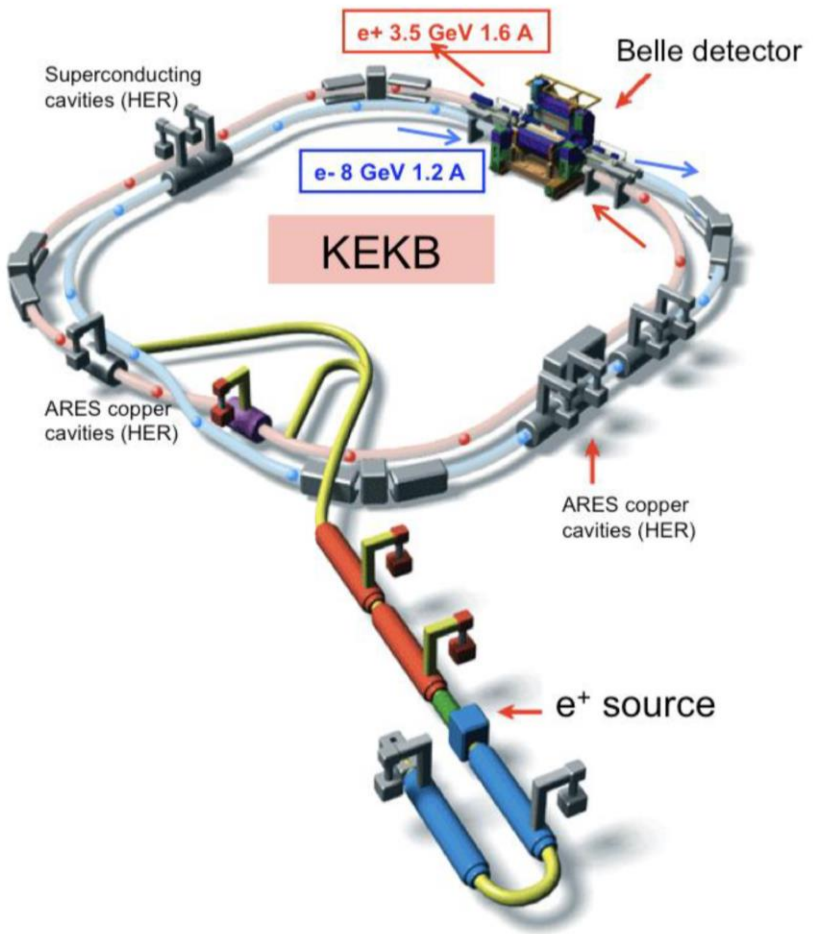
- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)

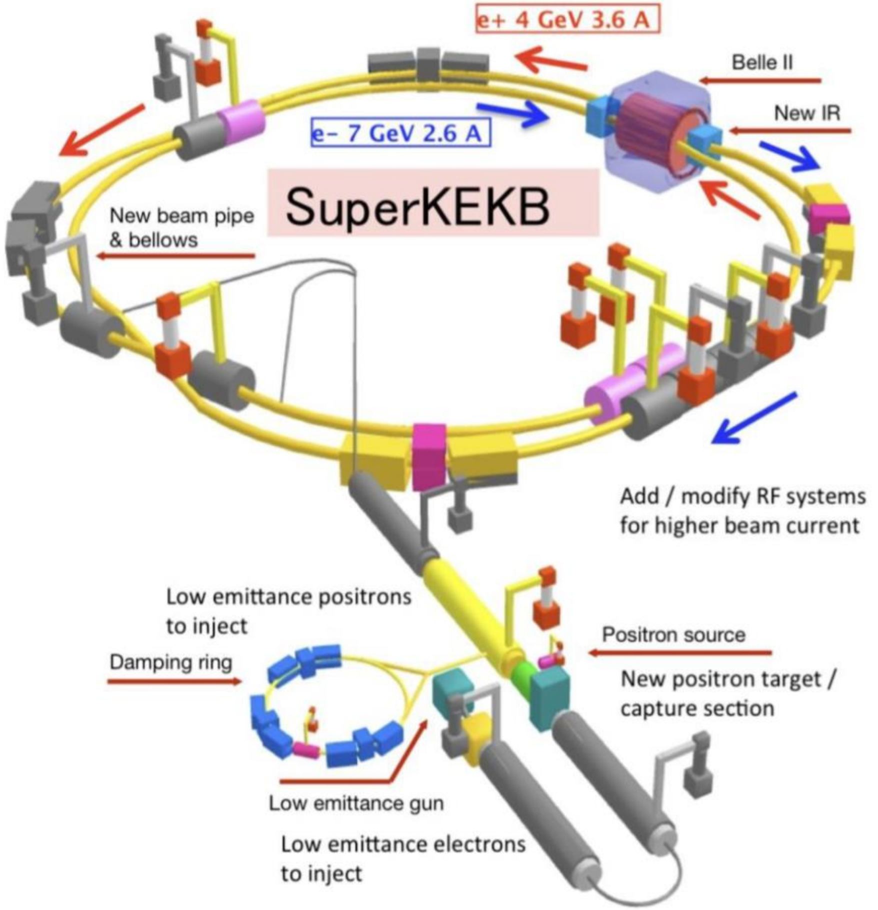


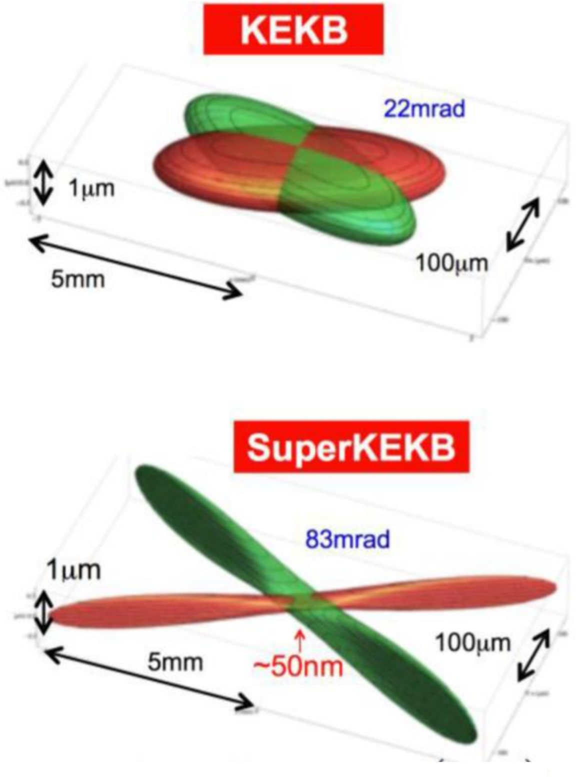
- Explanation of the $(g\text{-}2)_\mu$ effect
- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits



From KEKB to SuperKEKB







Nano-Beam scheme

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

From KEKB to SuperKEKB

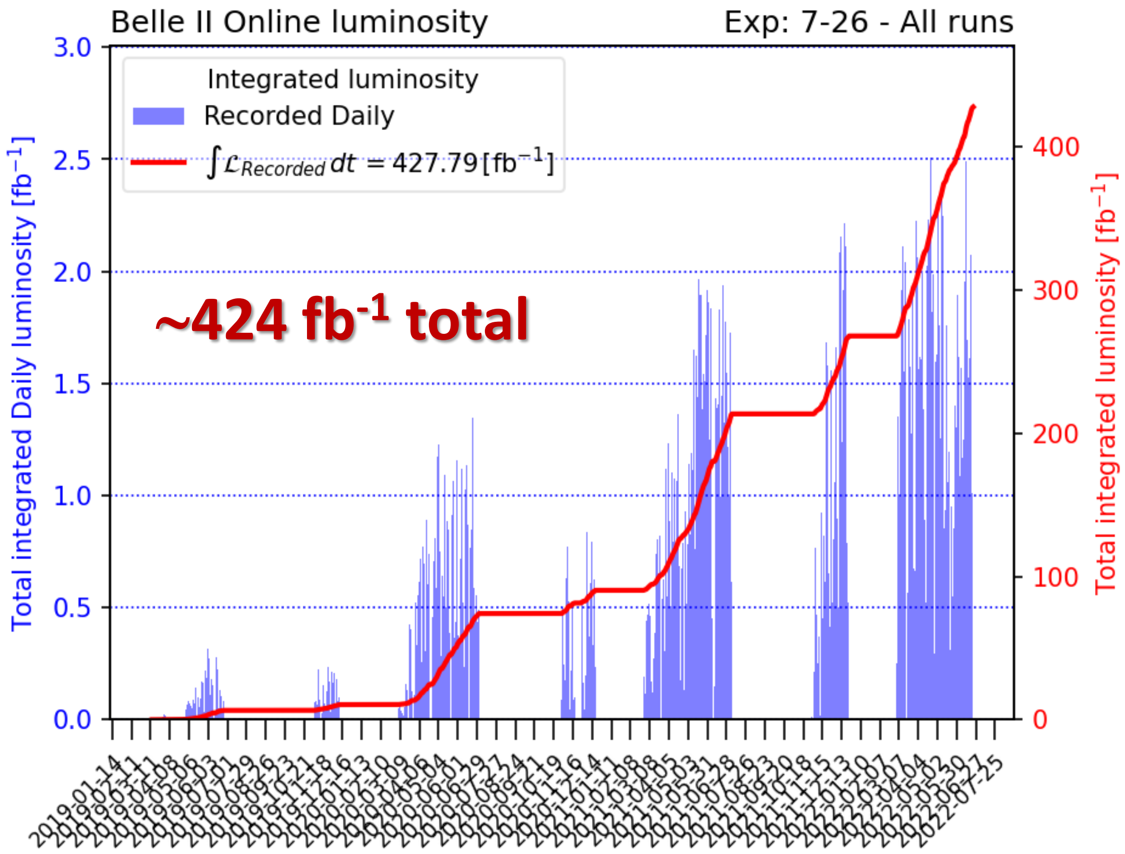
- **Upgraded rings**
  - New e^+ Damping Ring
  - Increased currents
- **Nano-beam scheme**
  - New Final Focus magnets (QCS)
  - Large crossing angle

x20 **x30**

Final goal : 50 ab^{-1}

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

Collected luminosity up to now: 2019-2022



Currently in shutdown LS1 since July 2022

Restart run in December 2023

Belle II detector

ECL

EM Calorimeter
$\sigma(E)$: 4%-1.6%

KLM

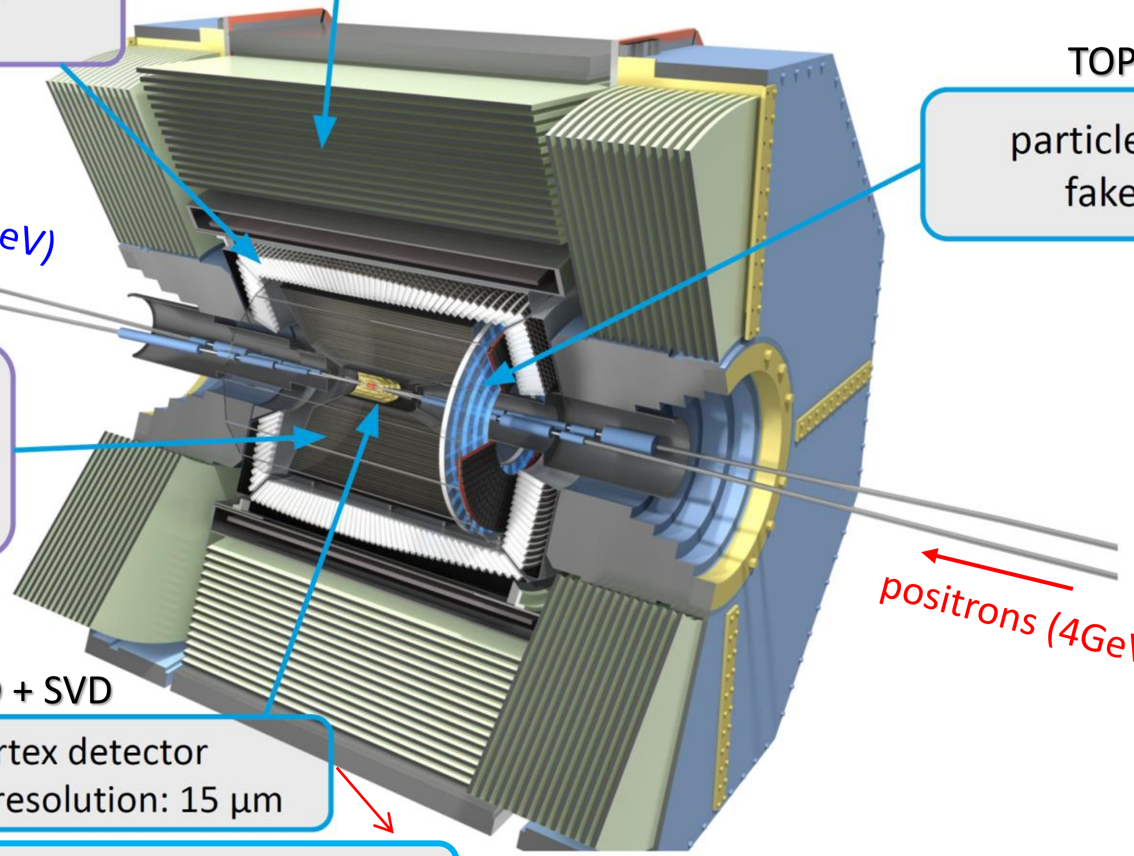
K_L and muon detector
μ ID-eff: ~90%

TOP + ARICH

particle identification
fake-π rate: 5%

CDC

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



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

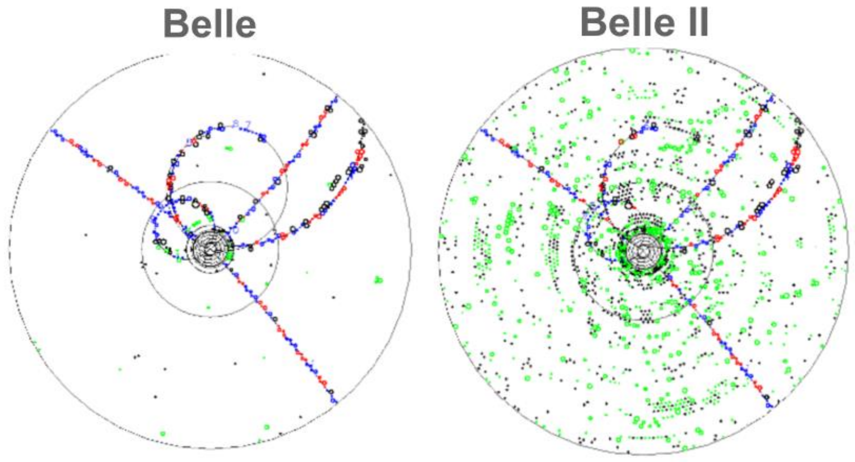
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

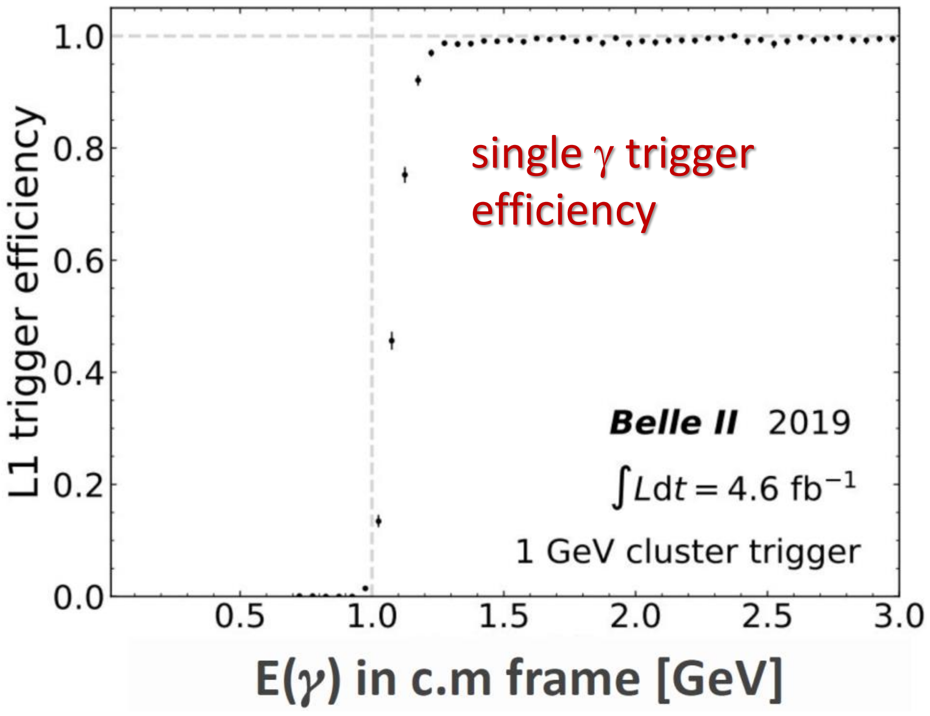
Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- $E_{\gamma} > 0.5, 1, 2$ GeV

Displaced-vertex trigger
- Under study





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

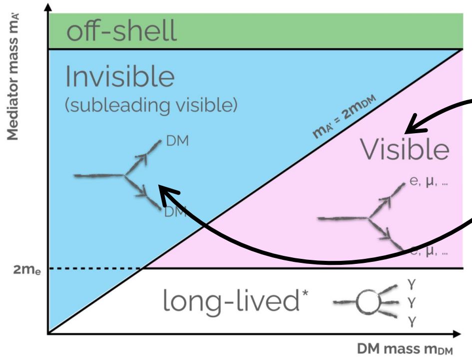
- Closeness to the light region
- Clean, low background, «energy conserving» environment, closed kinematics
- 3d momentum conservation, as opposed to p_T
- Easiness of tag & probe techniques
- Full Event Interpretation

- 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

Search overview: models ↔ signatures ↔ topologies

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



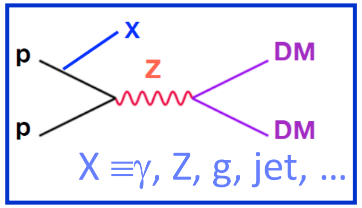
ll (γ) (+missing)

Visible minimal and non minimal dark photons, ALP→ff

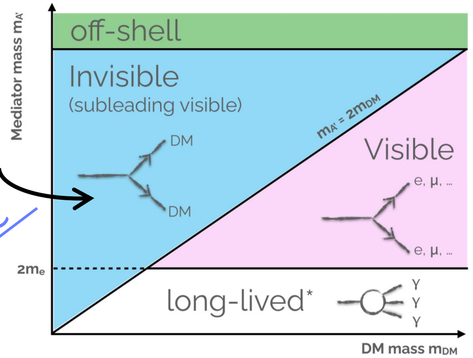
Invisible dark photon, Z'

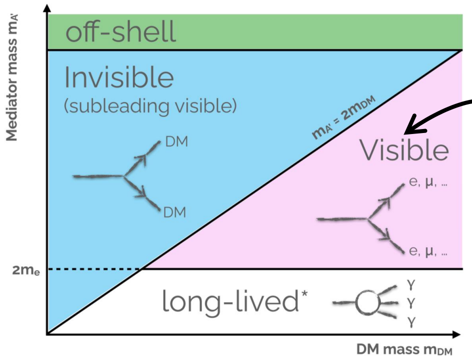
Single γ

Invisible dark photon, ALP →χχ, iDM, LLP



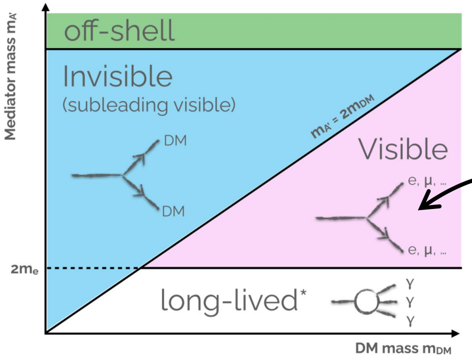
LHC





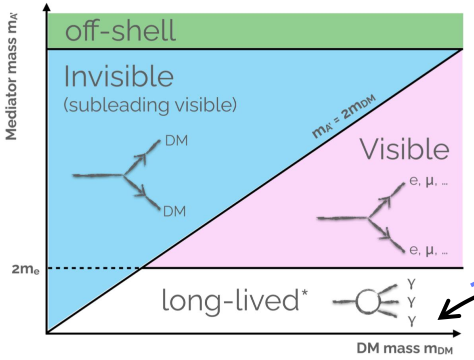
l l l' l'

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



γγ

Visible ALP → γγ



LLP long-lived particles

LHC

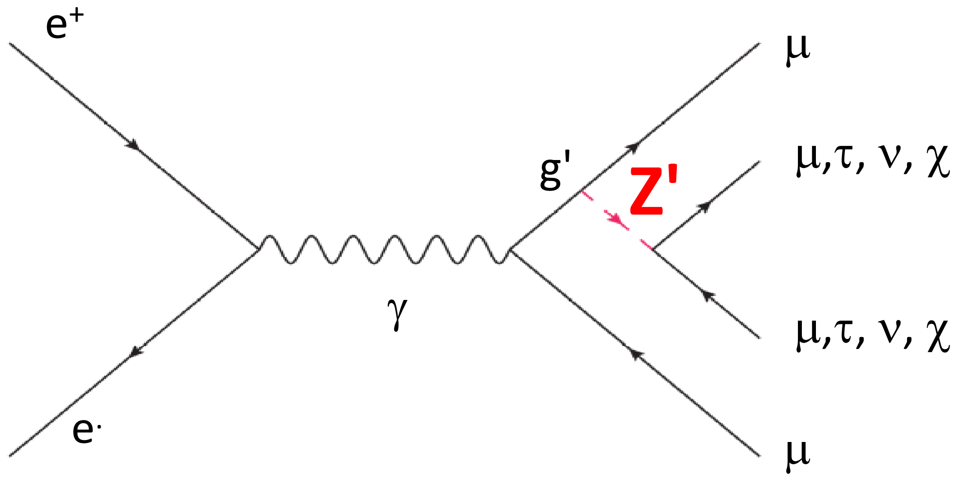
Hot topic

A', ALP→χχ, iDM, scalars

Z’: L_μ - L_τ model

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

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



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  - **dark matter puzzle** → **Sterile ν's**, Light Dirac fermions
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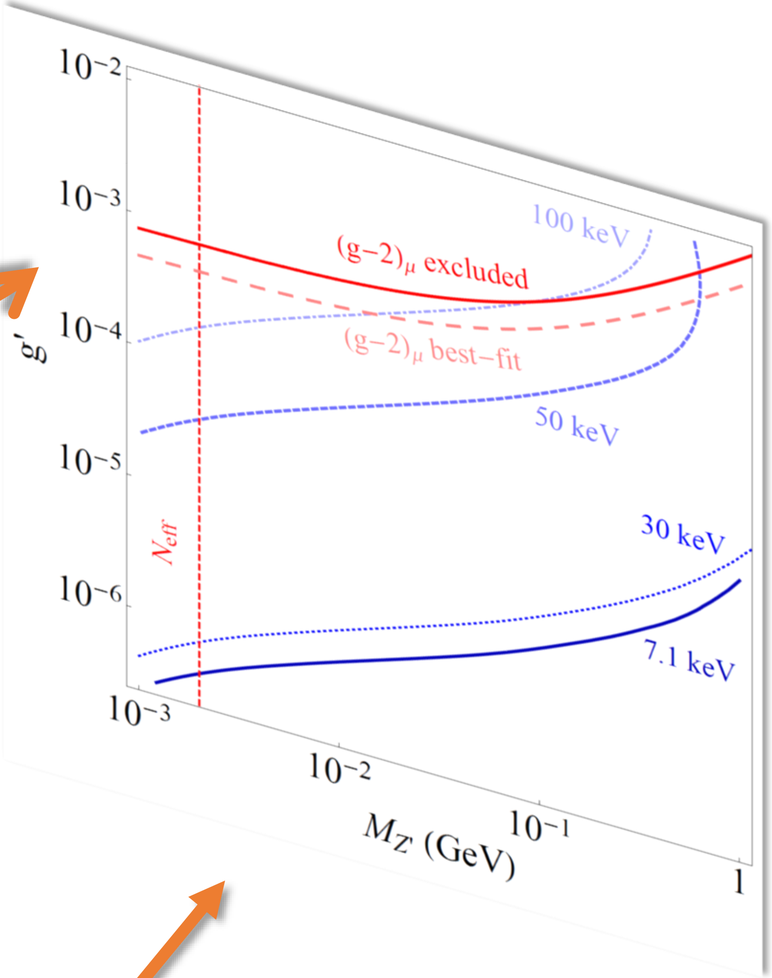

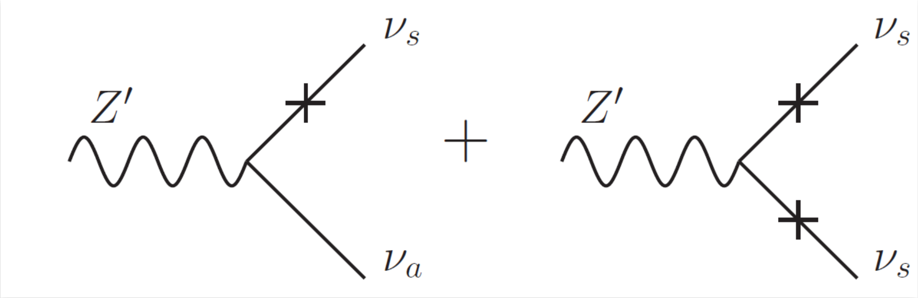

Sterile neutrino abundance

Z': L_μ - L_τ model

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- 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**

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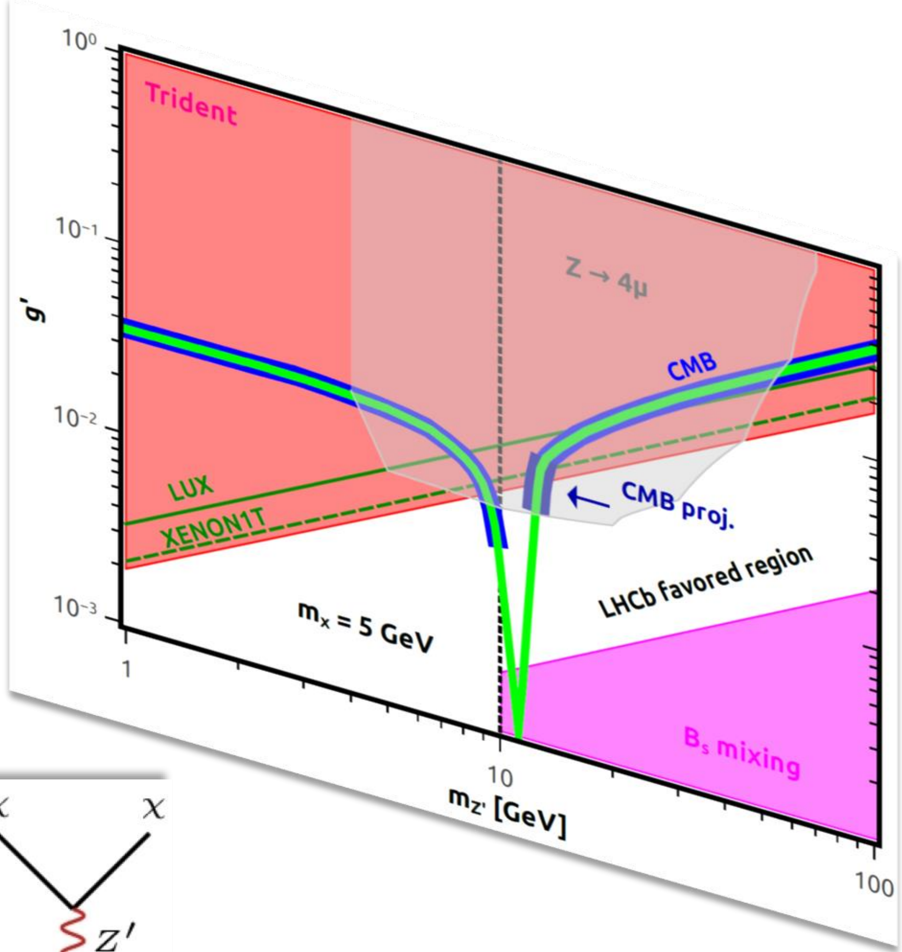
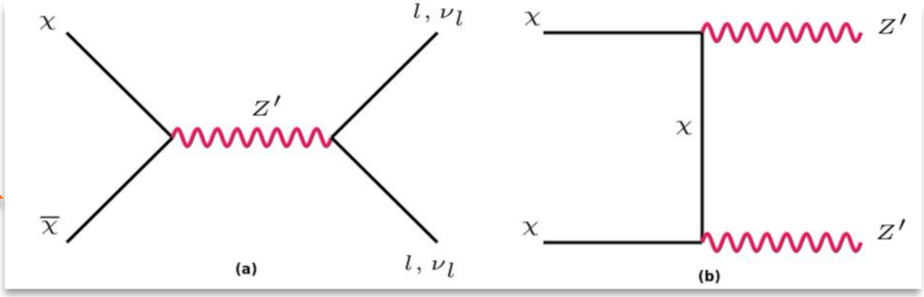
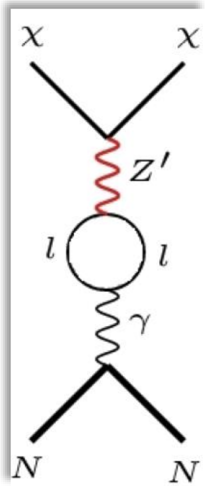


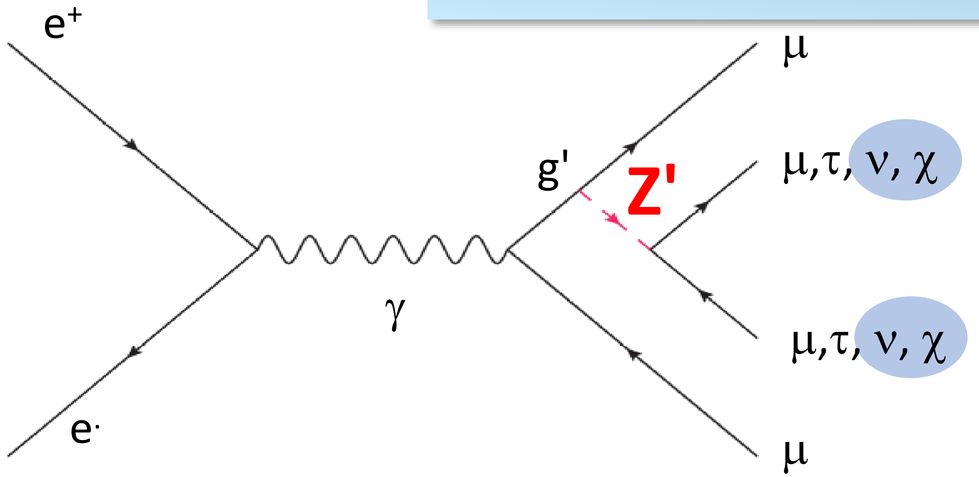
Annihilation





Direct detection

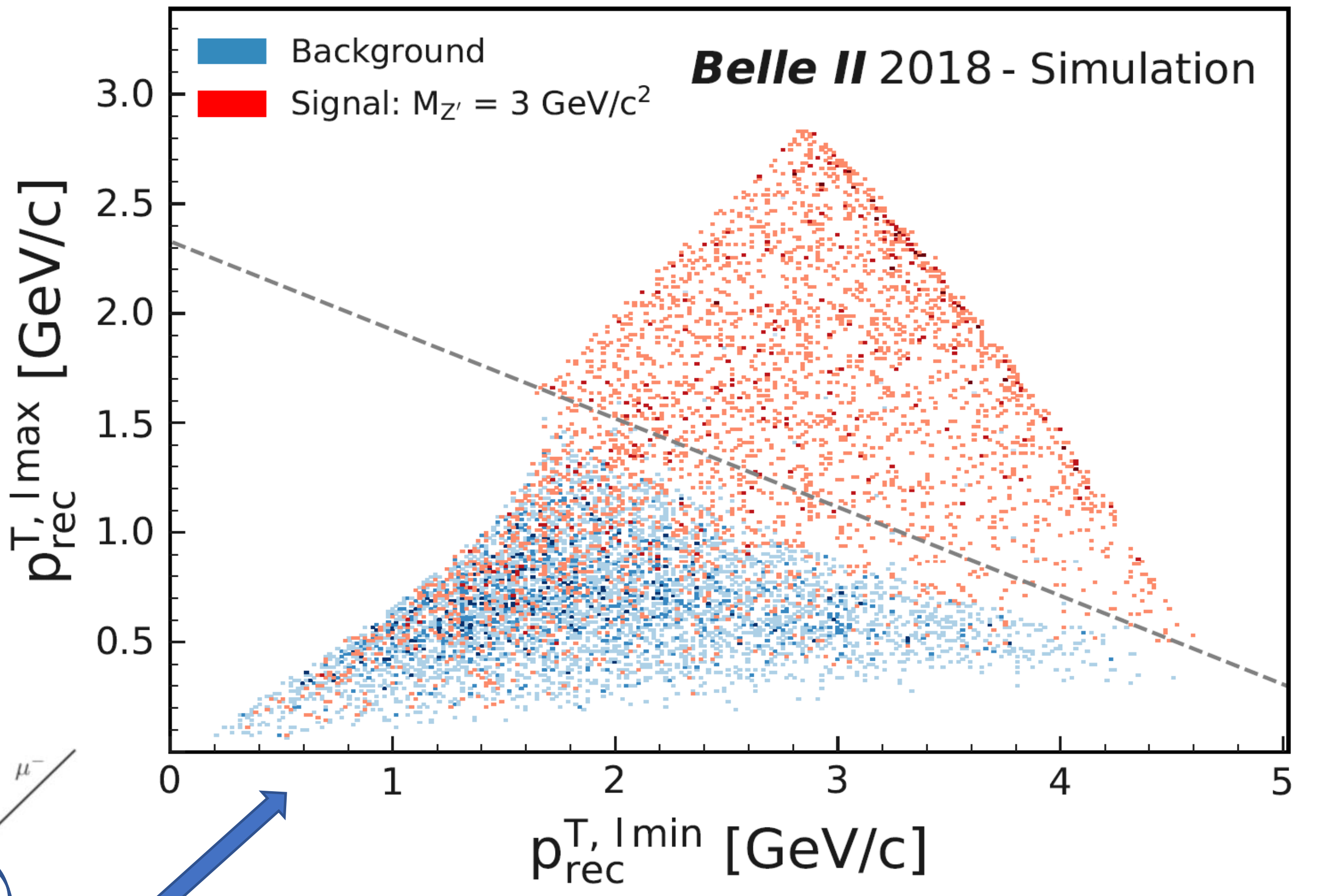
Z’ to invisible: first Belle II physics result



Explored for the first time

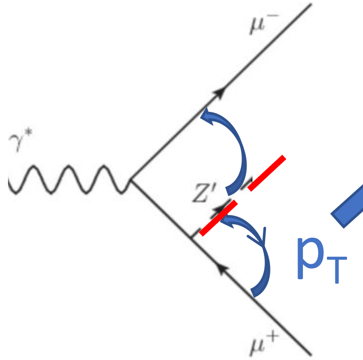
$e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*

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



Main backgrounds:

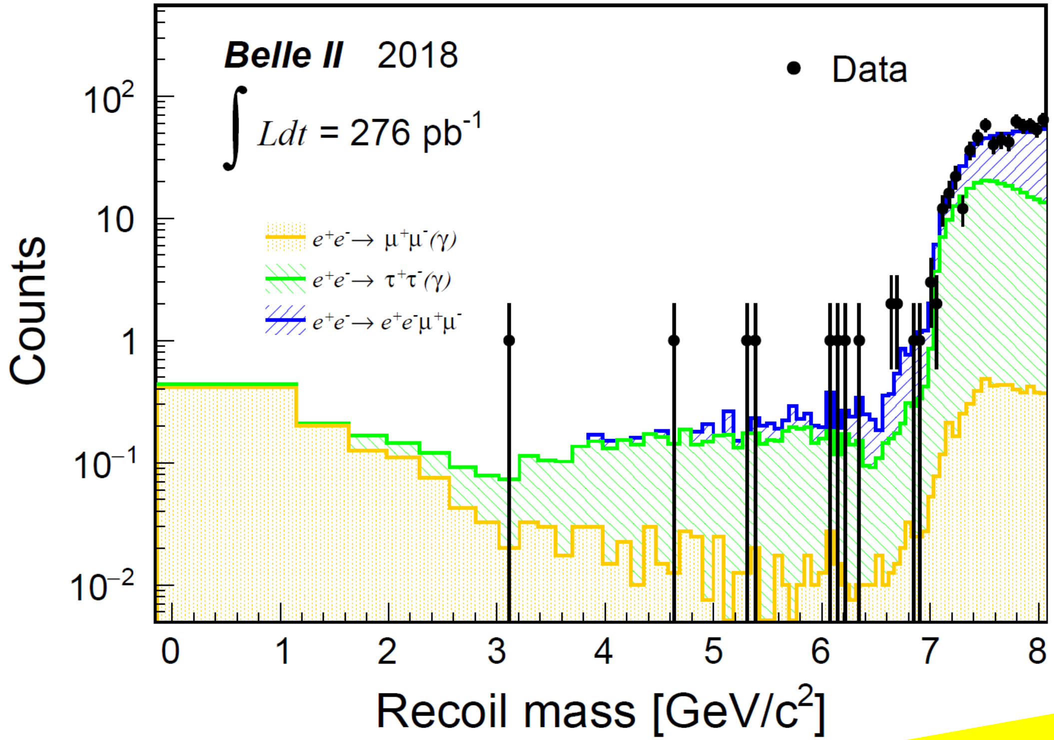
$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$
$e^+e^- \rightarrow \tau^+\tau^- (\gamma),\ \tau^\pm \rightarrow \mu^\pm\nu\nu$
$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$



FSR vs ISR + τ decay

Z' to invisible: first result

Pilot run physics results

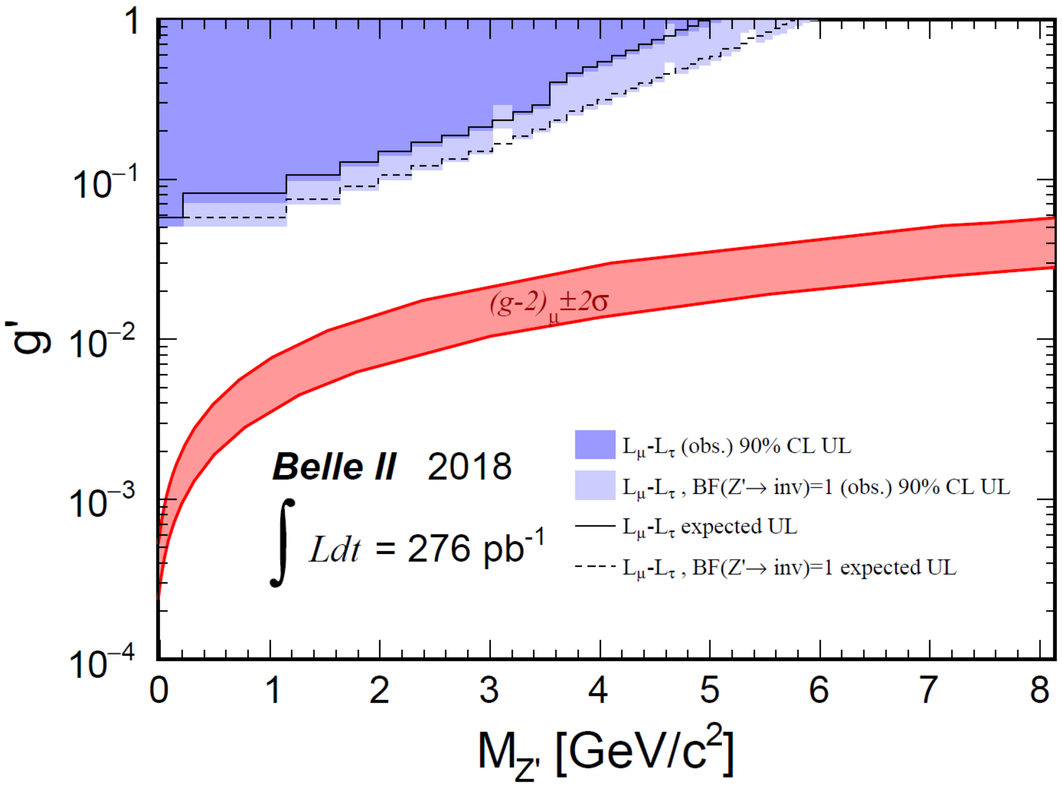


First physics paper by Belle II
PRL 124 (2020), 141801

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 $\mu\mu$ yield (signal)	12.5%

will decrease with new data



Belle II dark sector search overview: results

L_μ-L_τ
Z' → invisible
Z' → $\mu\mu$
Z' → $\tau\tau$

Axion like particles
ALP→$\gamma\gamma$

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

LLP dark scalar in B decays
B→kS   S→ee, $\mu\mu$, $\pi\pi$, kk

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

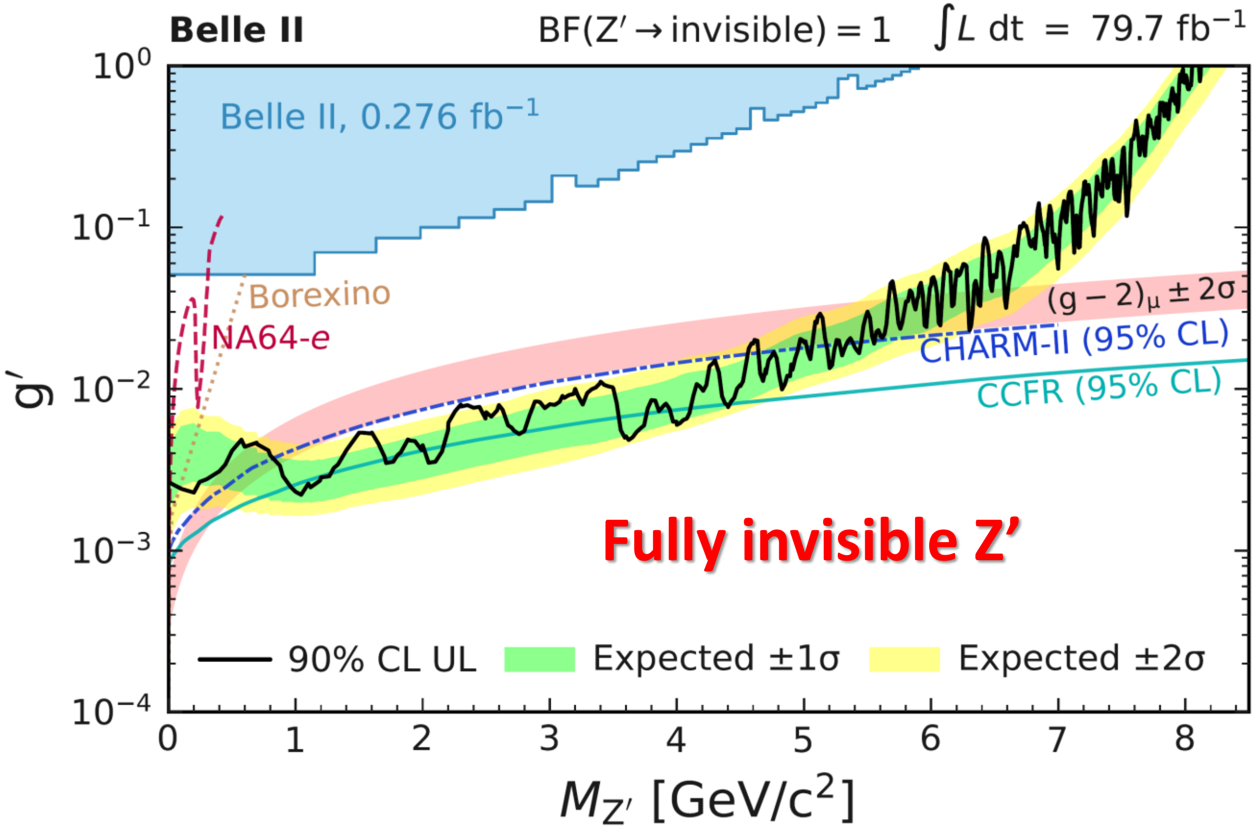
In progress

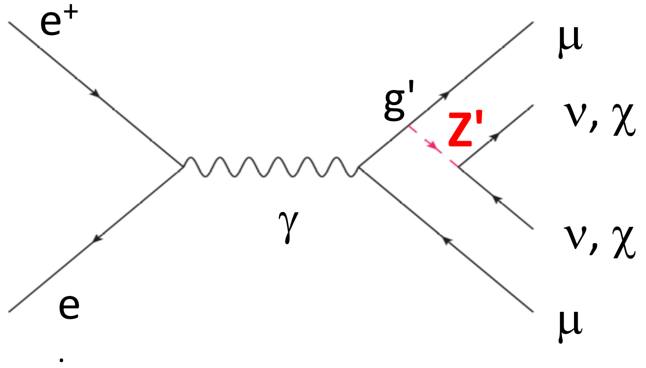
LLP Dark Higgsstrahlung with IDM
A'h' A'→$\chi_1\chi_2$, h'→$\mu\mu$, $\pi\pi$, kk

Invisible dark photon
γA'   A'→$\chi\chi$

Belle II dark sector search overview: results

L_μ-L_τ
Z' → invisible





see M.Laurenza's talk

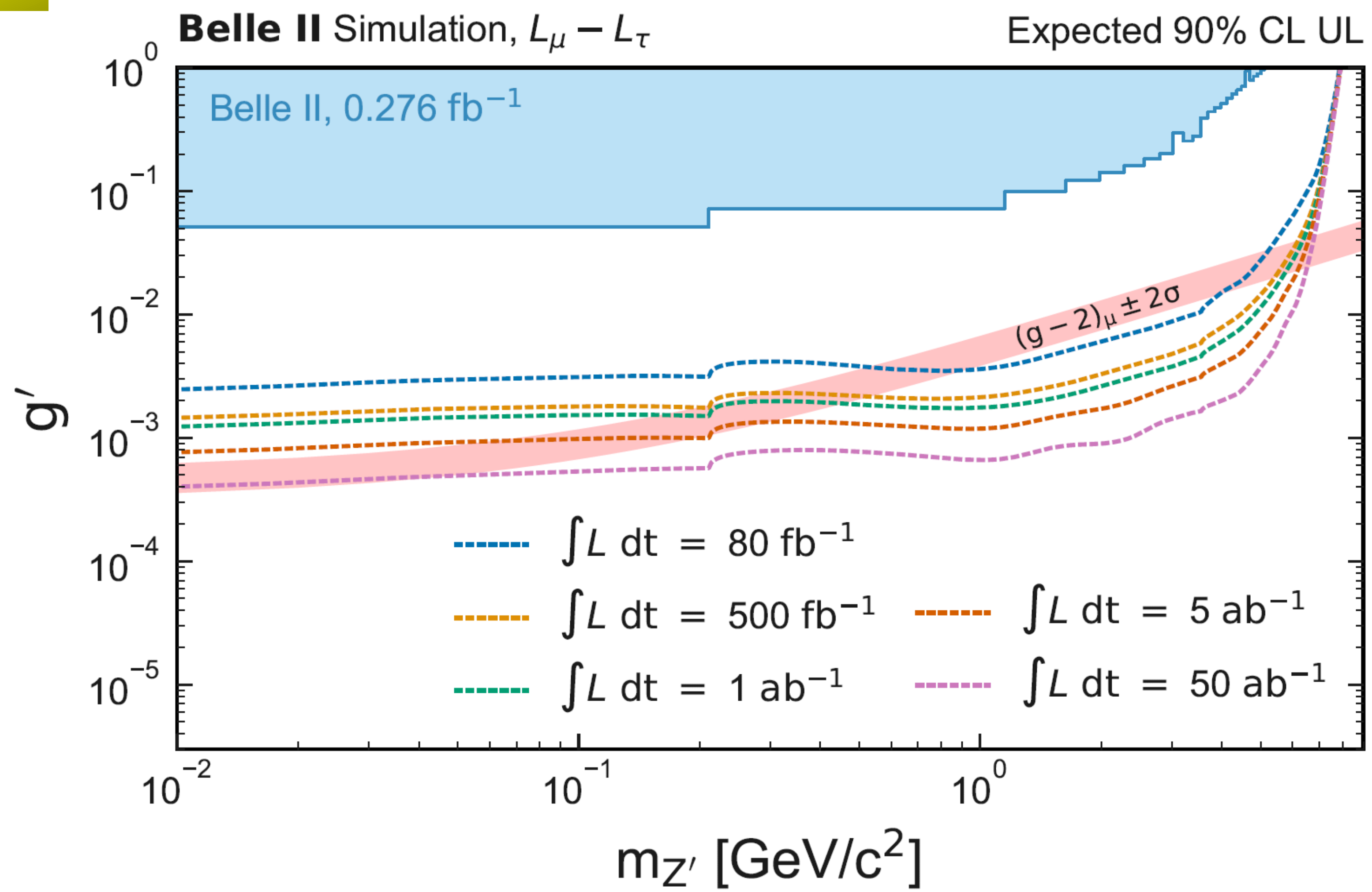
PRL 130, 231801 (2023)

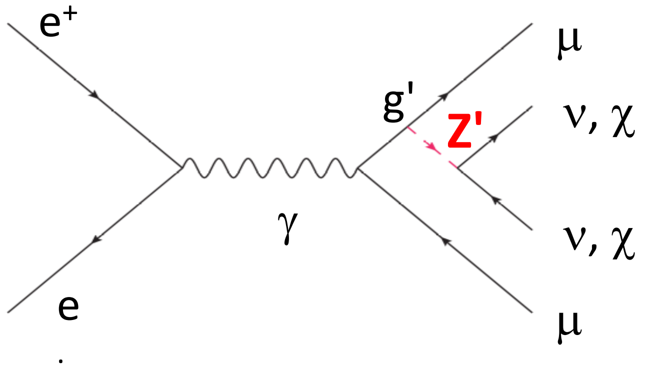
fully invisible Z' as origin of $(g\text{-}2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Belle II dark sector search overview: projections

L_μ-L_τ
Z' → invisible

Belle II physics reach @ Snowmass
arXiv: 2207.06307v1



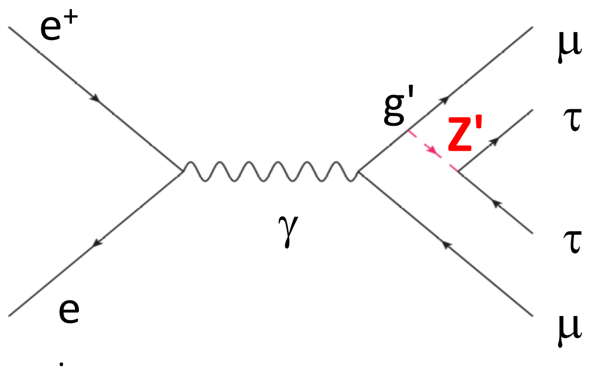


Belle II dark sector search overview: results

L_μ-L_τ

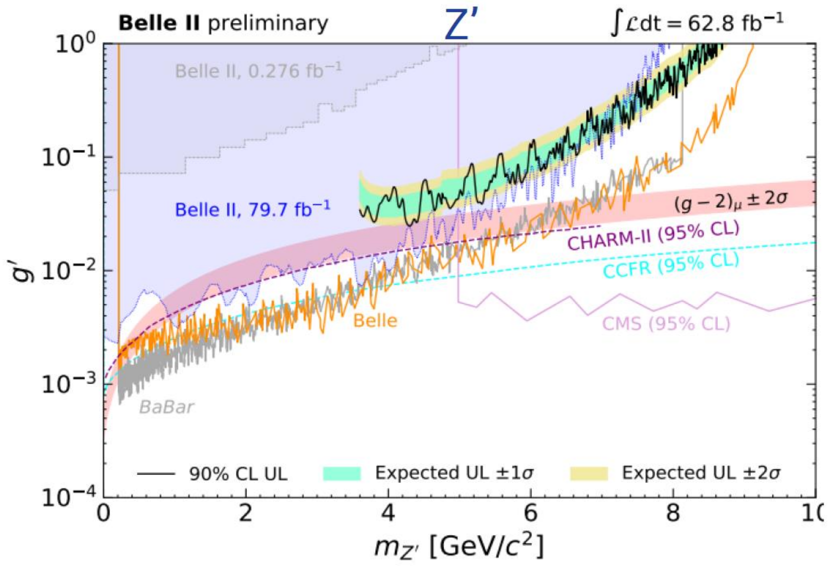
$Z' \rightarrow \tau\tau$

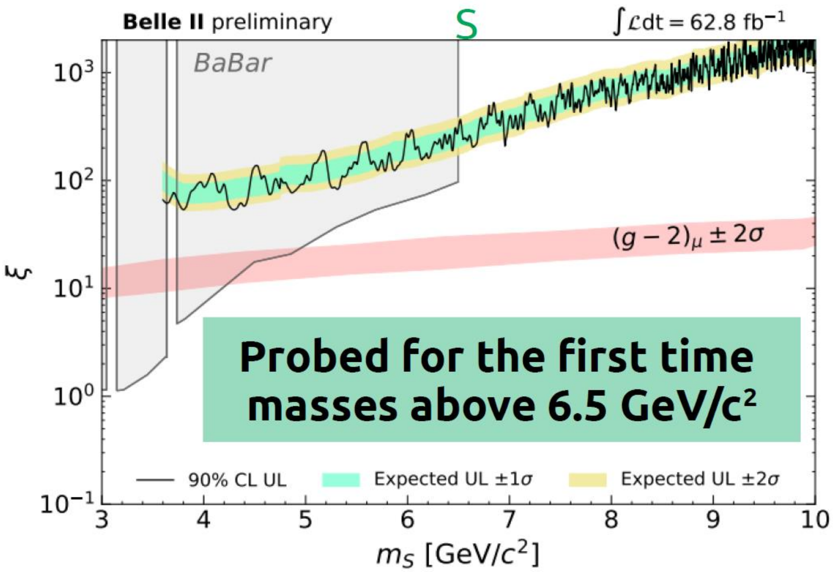
Reinterpreted also as
- Leptophilic dark scalar S → $(g\text{-}2)_\mu$
- ALP with τ coupling

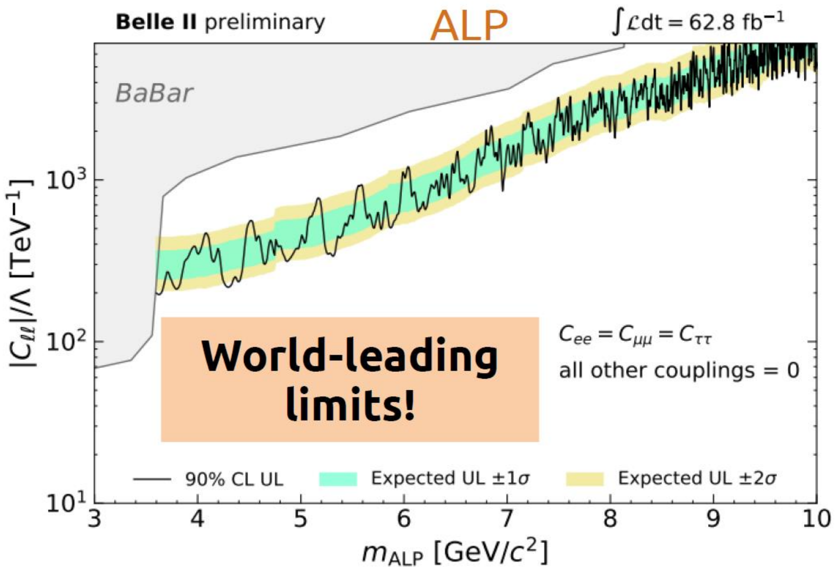


see M.Laurenza's talk

PRL 131, 121802 (2023)





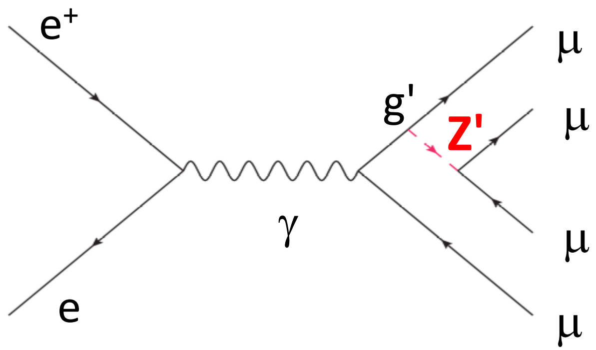


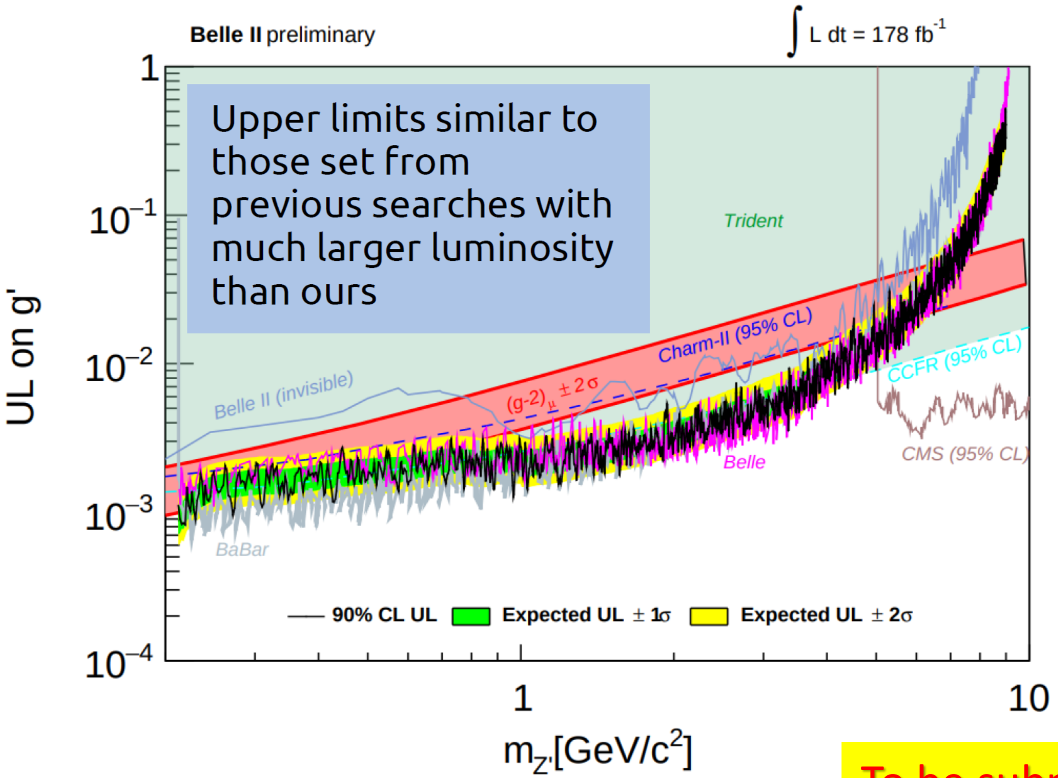
Belle II dark sector search overview: results

L_μ-L_τ
$Z' \to \mu\mu$

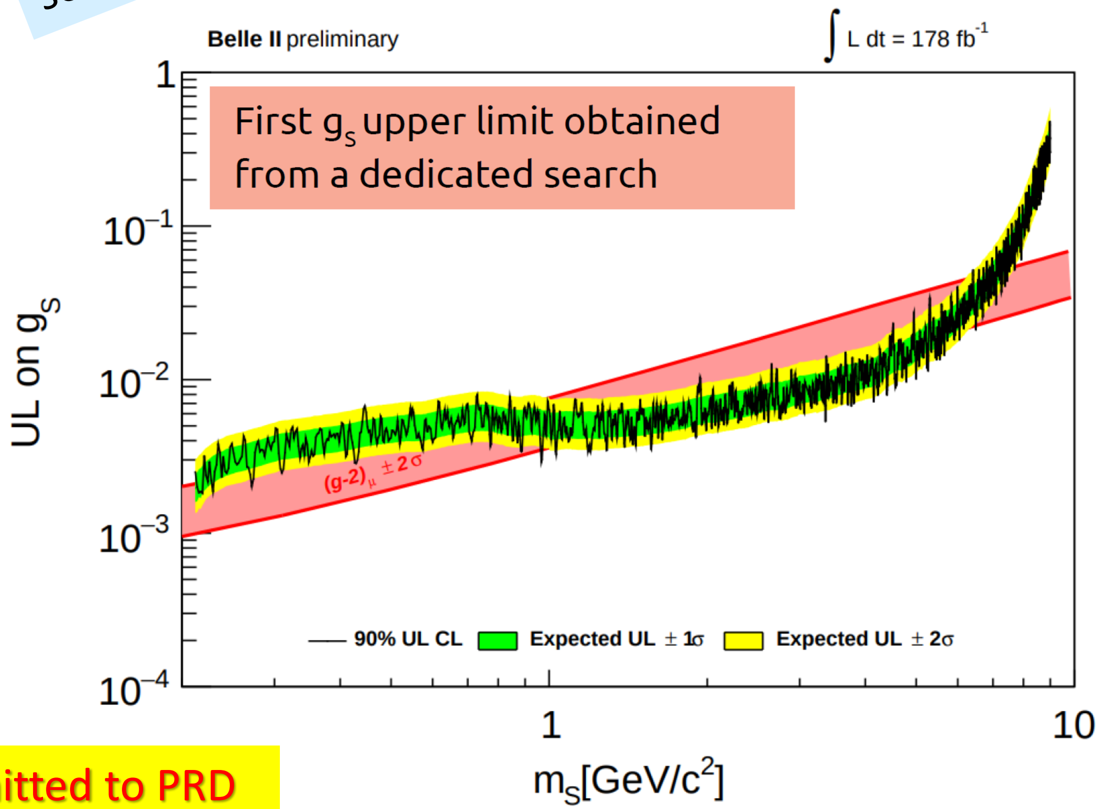
Reinterpreted also as
- Muonphilic dark scalar $S \to (g\text{-}2)_\mu$

see M.Laurenza's talk





Upper limits similar to those set from previous searches with much larger luminosity than ours



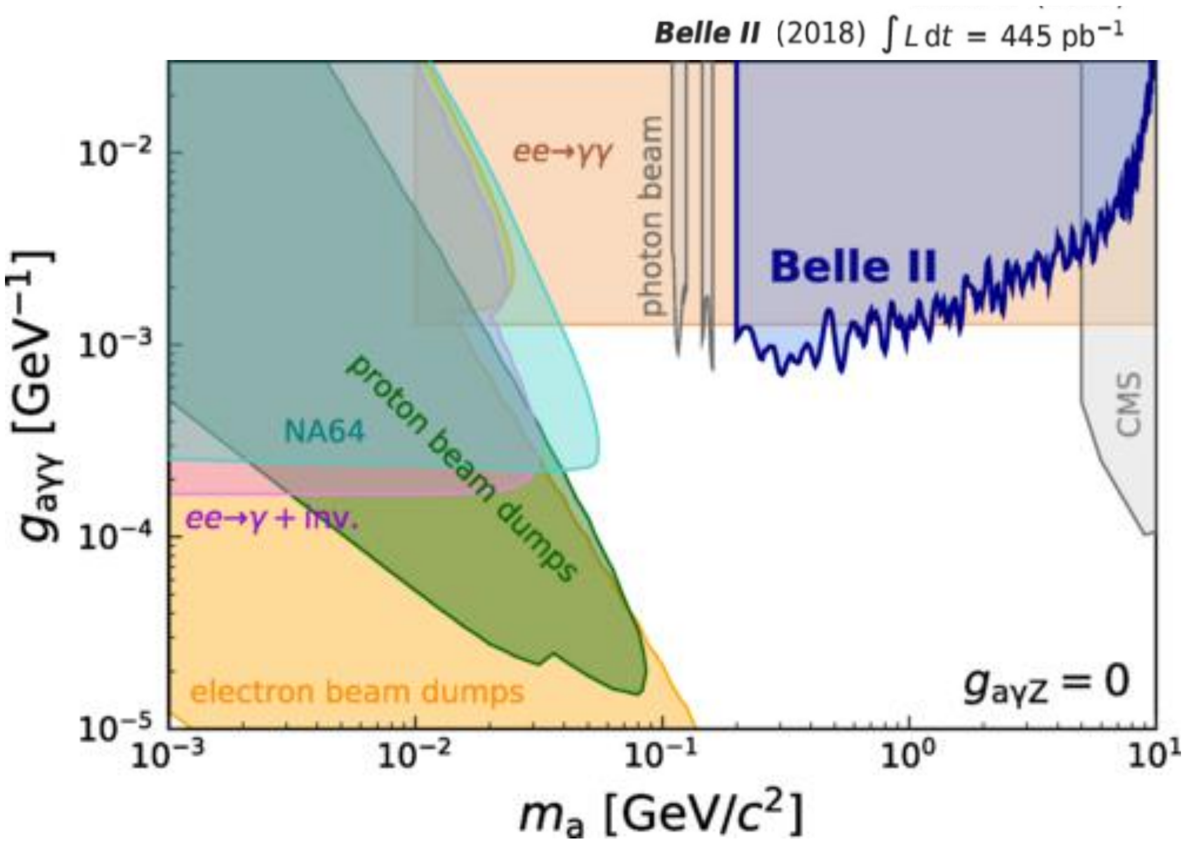
First g_s upper limit obtained from a dedicated search

To be submitted to PRD

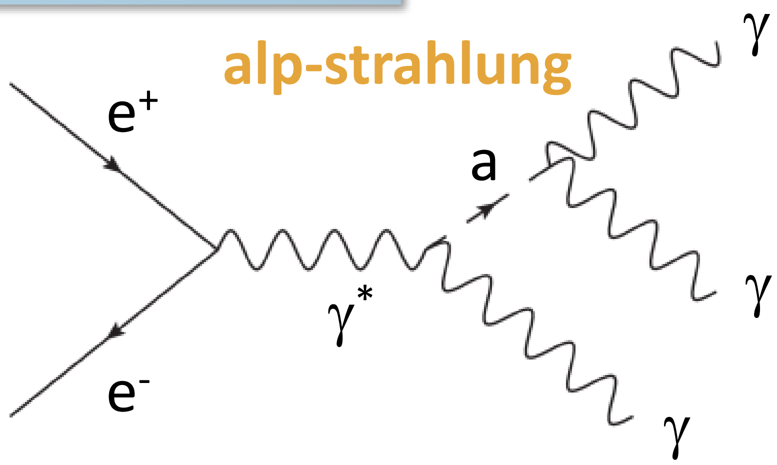
Belle II dark sector search overview: results

Axion like particles
ALP→$\gamma\gamma$

Pilot run physics results



alp-strahlung

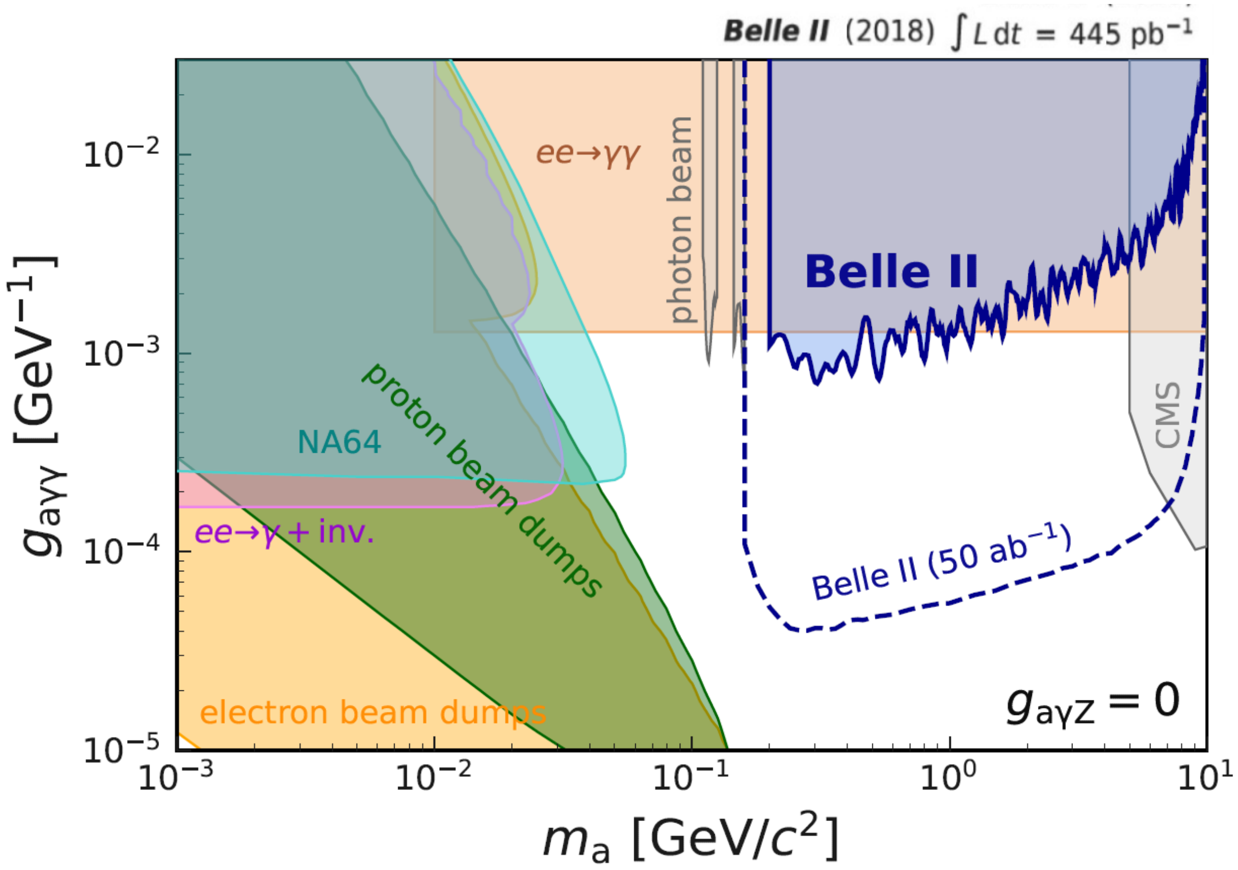


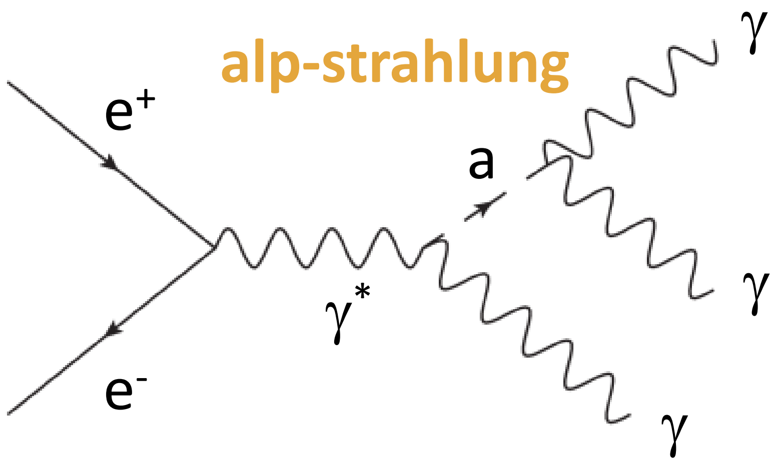
see L.Zani's talk

PRL 125, 161806 (2020)

Belle II dark sector search overview: projections

Axion like particles
ALP→$\gamma\gamma$





Belle II physics reach @ Snowmass

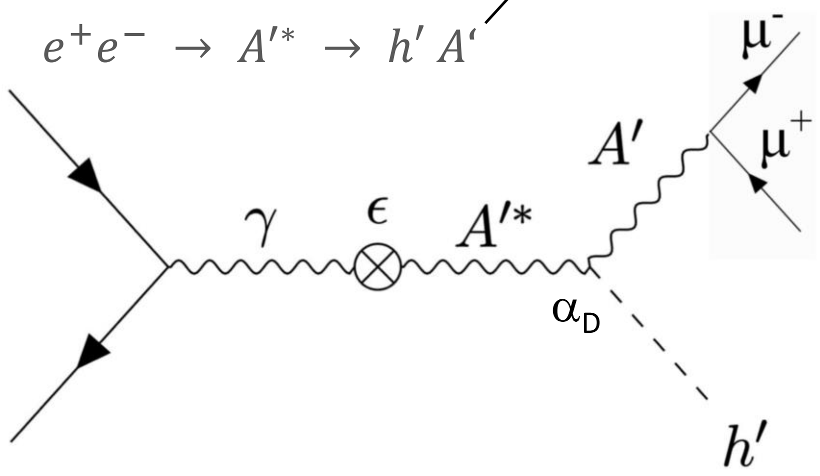
arXiv: 2207.06307v1

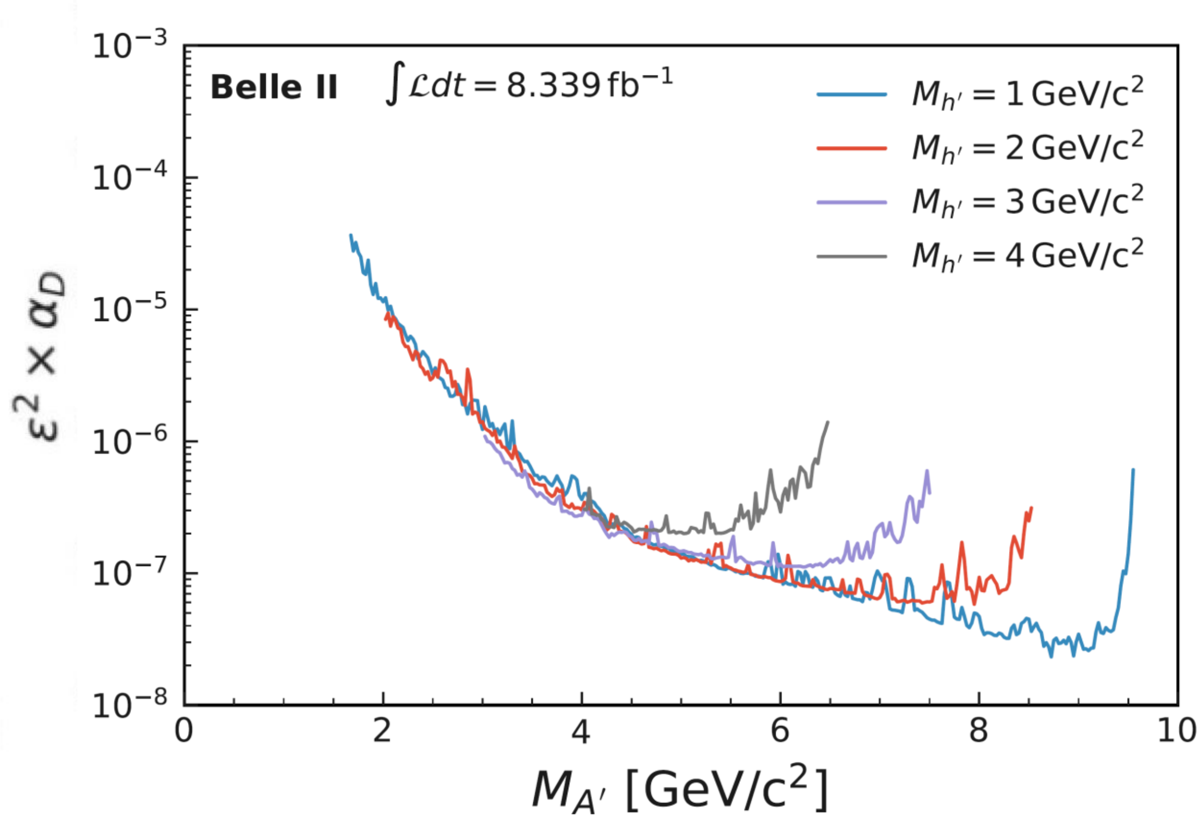
Belle II dark sector search overview: results

Dark Higgsstrahlung

A'h'   A'→μμ, h' invisibile

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





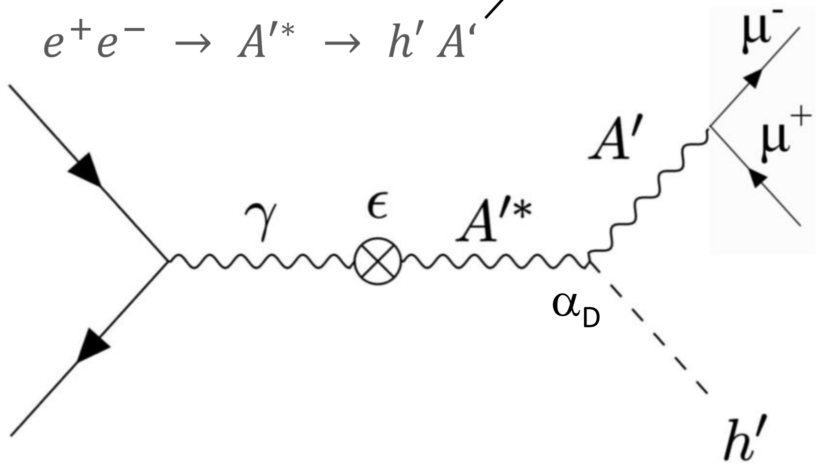
see L.Zani's talk

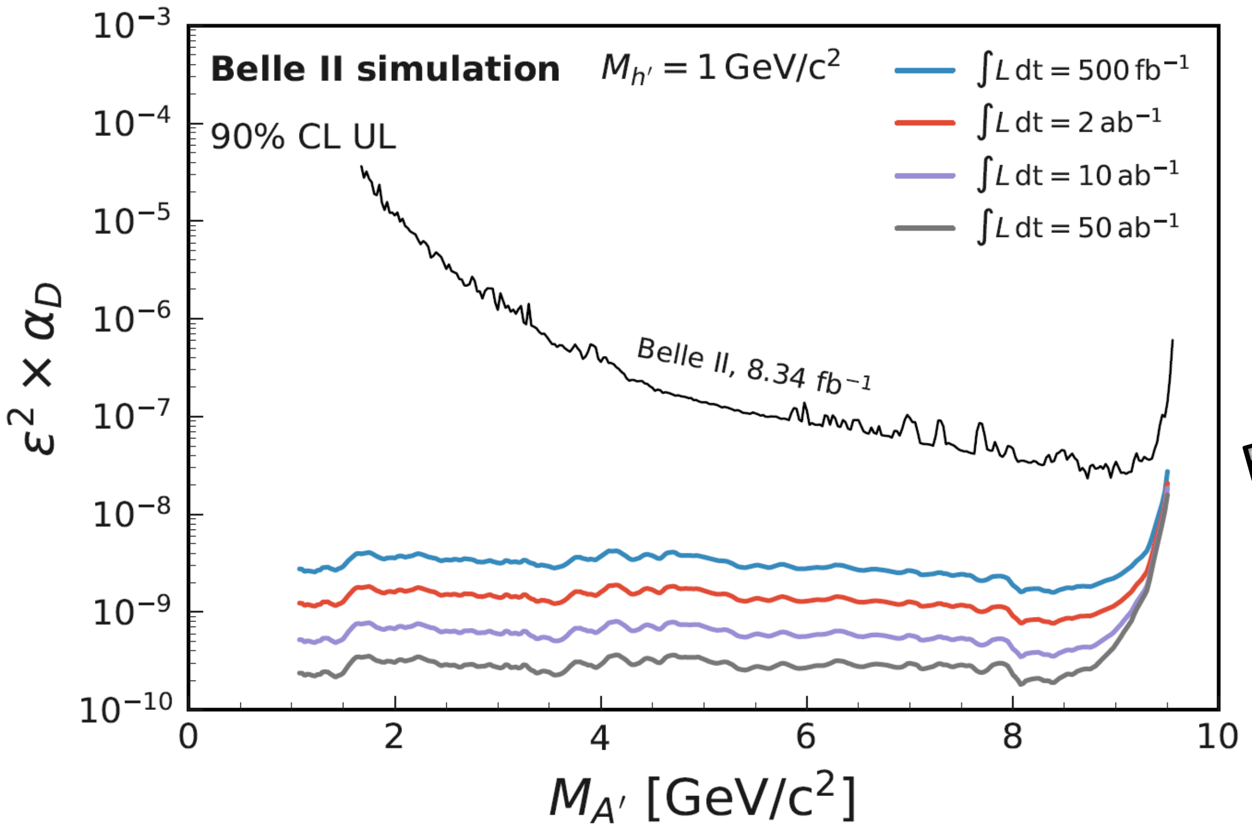
PRL 130, 071804 (2023)

Belle II dark sector search overview: projections

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

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





Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

Belle II dark sector search overview: results

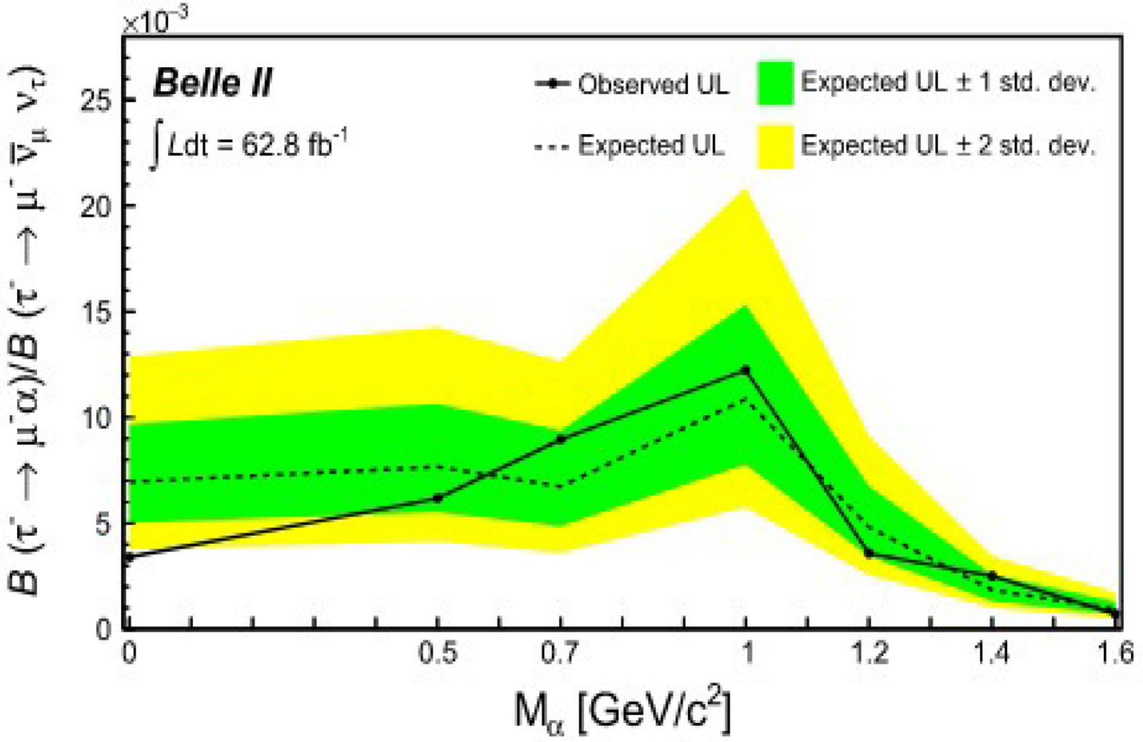
Invisible α in τ decays

$\tau \to l\alpha \quad l=e,\mu$

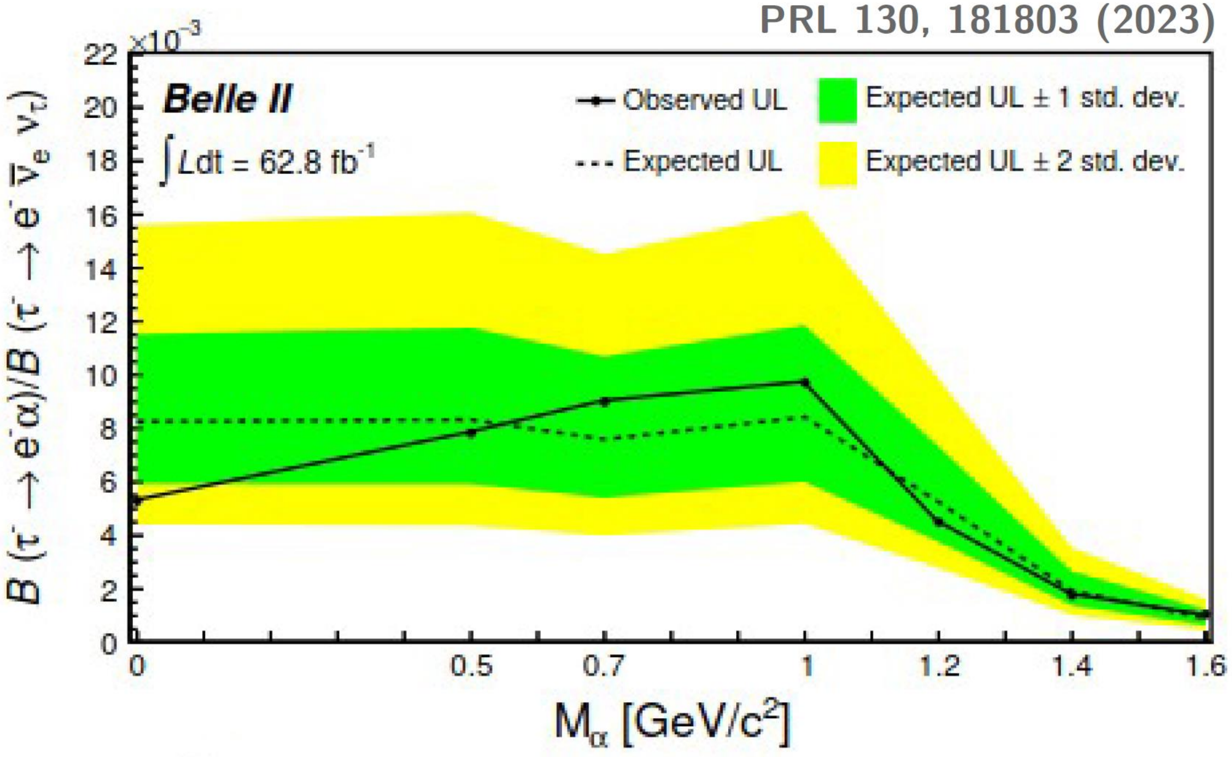
LFV, possible ALP candidate

PRL 130, 181803 (2023)

see L.Zani's talk



PRL 130, 181803 (2023)

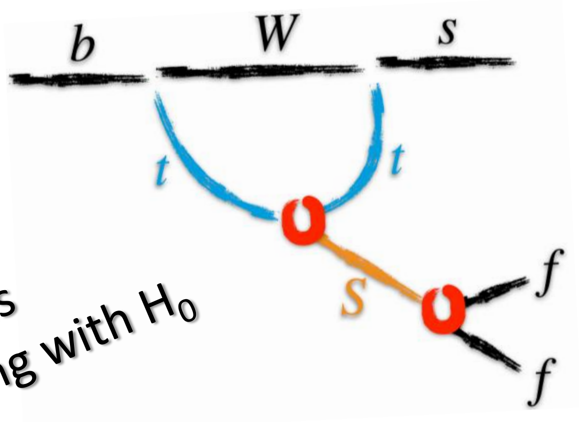


Belle II dark sector search overview: results

see L.Zani's talk

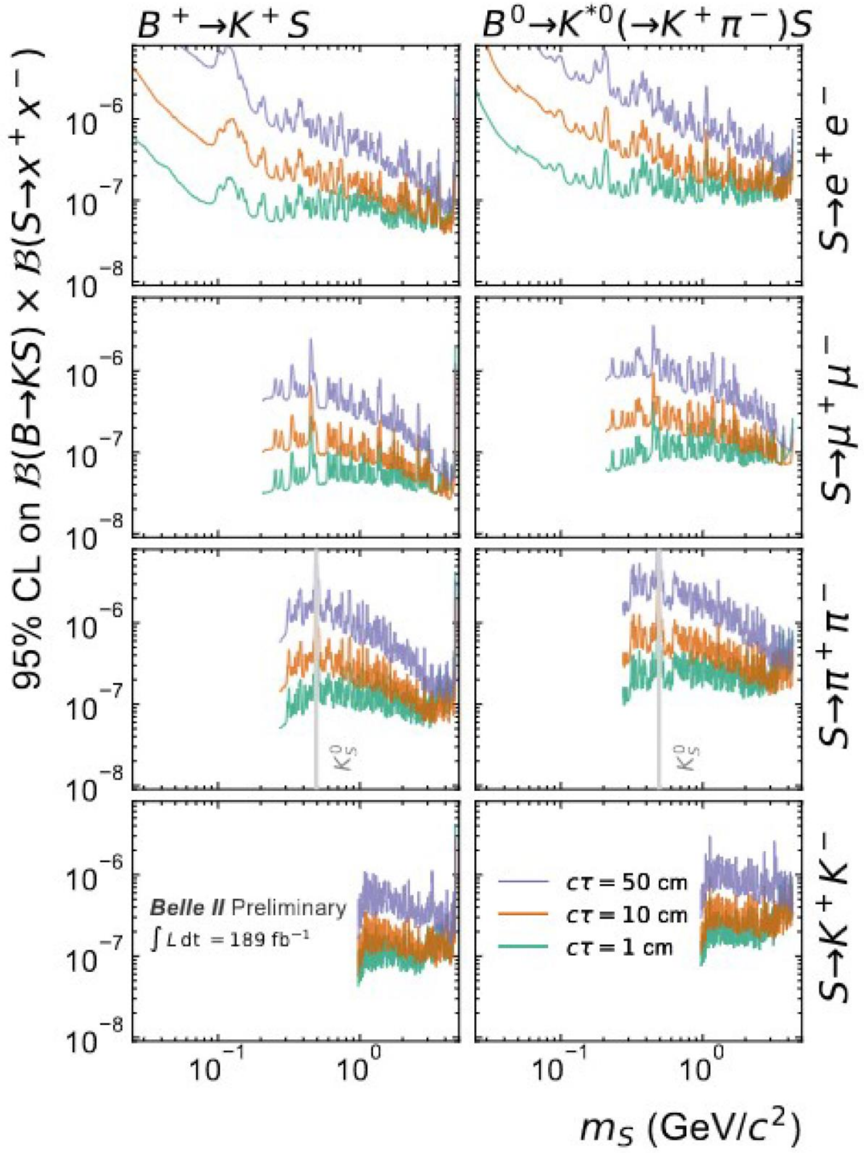
LLP dark scalar in B decays

B→kS S→ee, μμ, ππ, kk



b→s transitions
Possible mixing with H_0
LLP signature

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



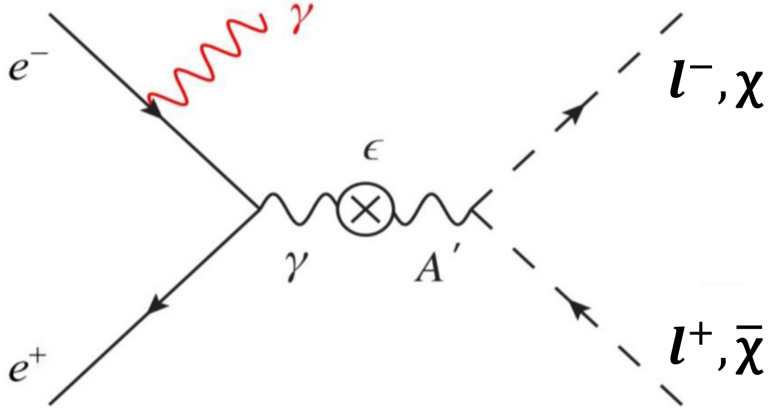
Submitted to PRL
arXiv:2306.02830

In progress Belle II dark searches

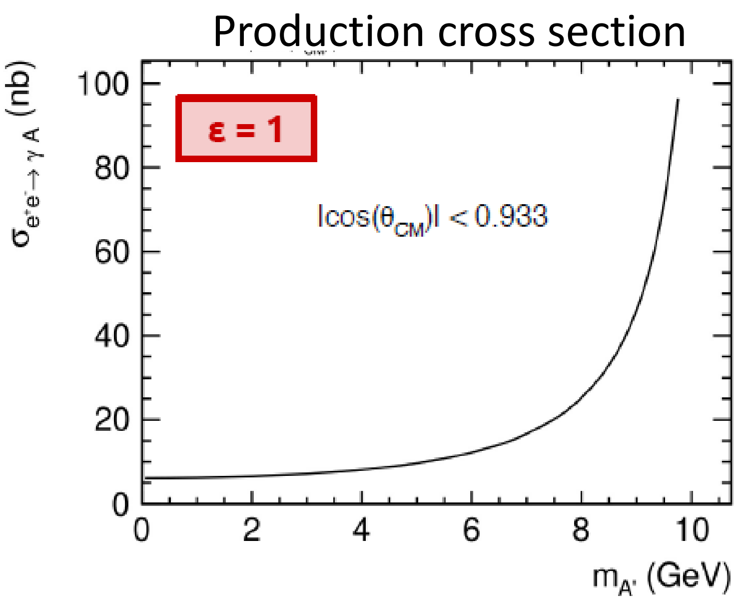
Dark photon: introduction

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



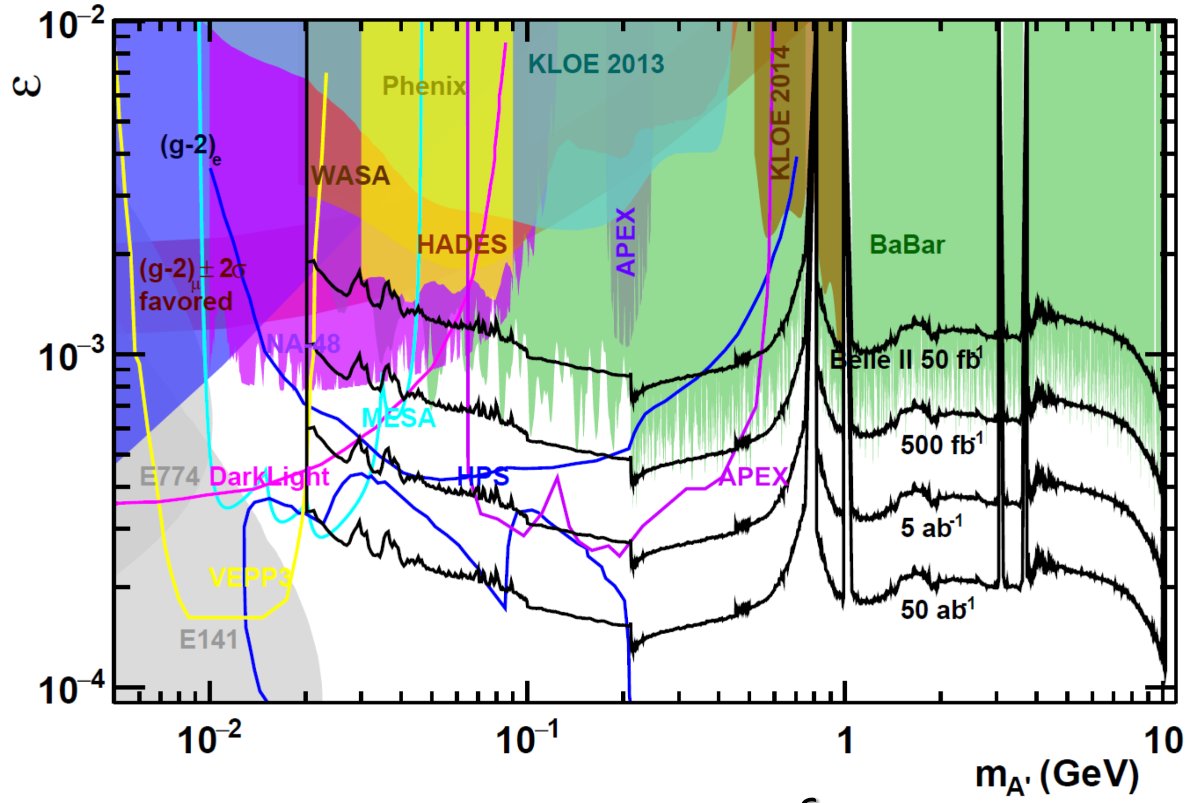
two basic scenarios depending on A′ vs χ DM mass relationship

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

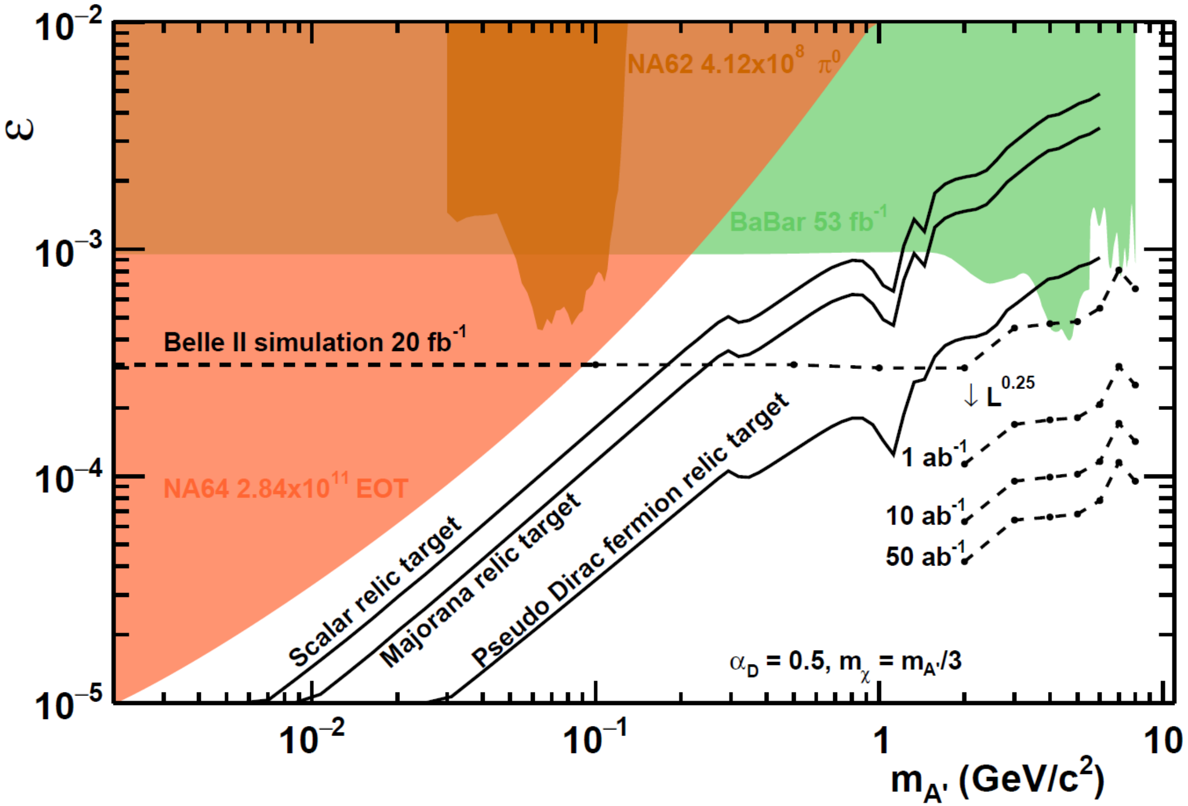
$m_{A'} > 2m_\chi \Rightarrow$ A’ decays ≈100% invisibly to DM particles

Dark photon: luminosity projections

Visible



Invisible



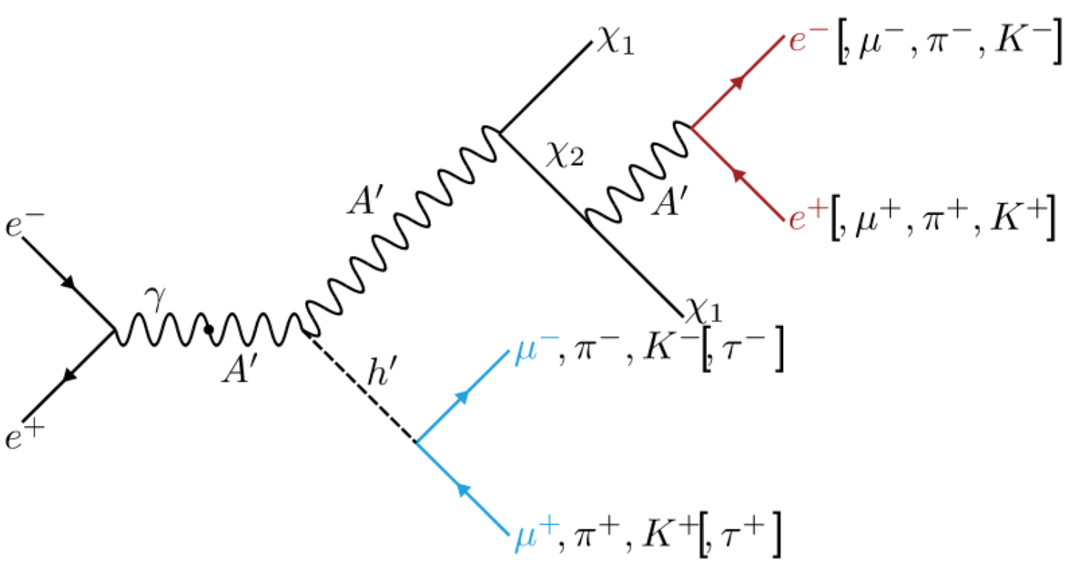
Belle II physics reach @ Snowmass
arXiv: 2207.06307v1

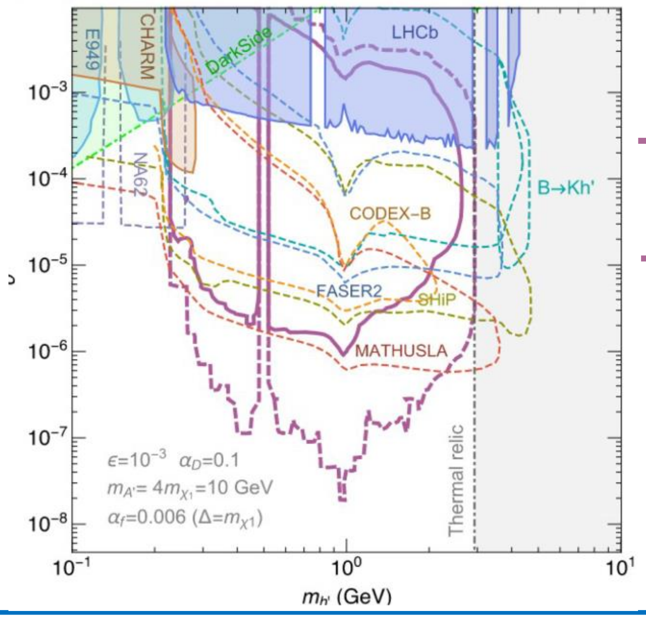
Belle II vs BaBar

- ✓ 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

see L.Zani's talk

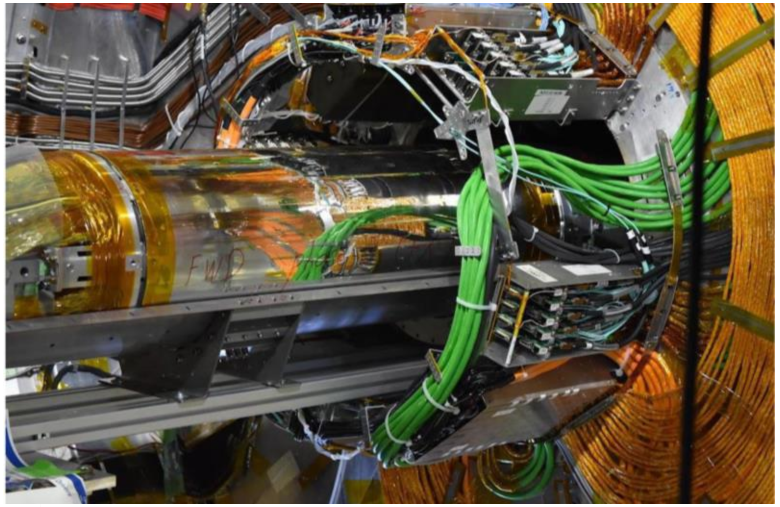
JHEP 04 (2021), arXiv:2012.08595

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

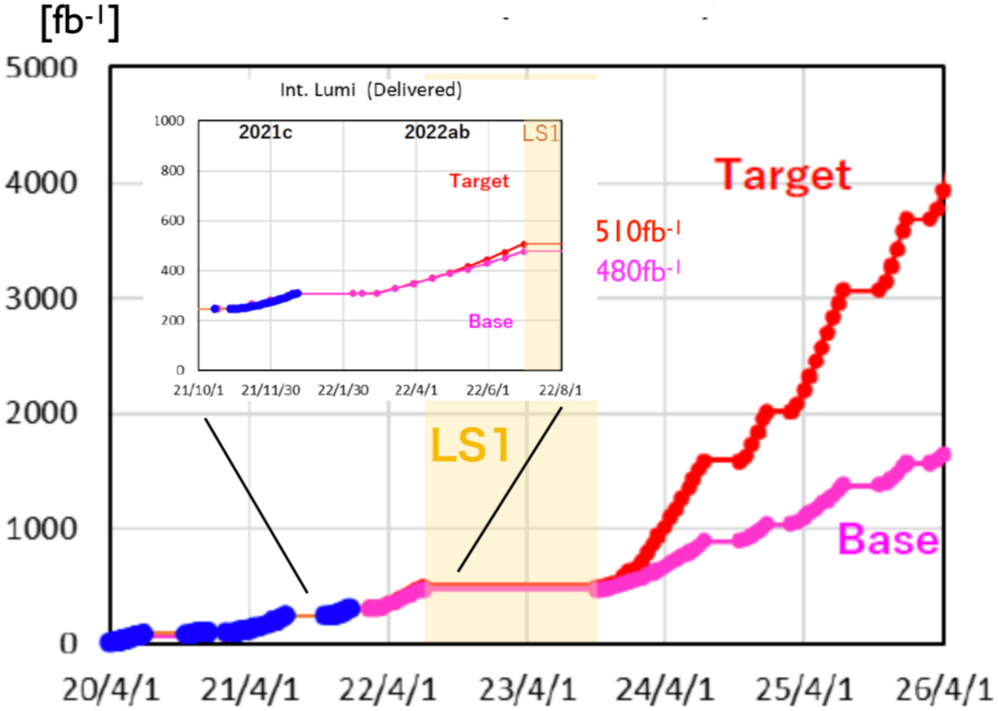
- Restart SuperKEKB in December 2023 and physics beginning of 2024

- 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)

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

Short term

- 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

see M.Laurenza's talk

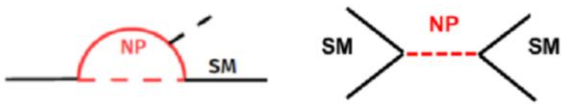
see L.Zani's talk

SPARE SLIDES

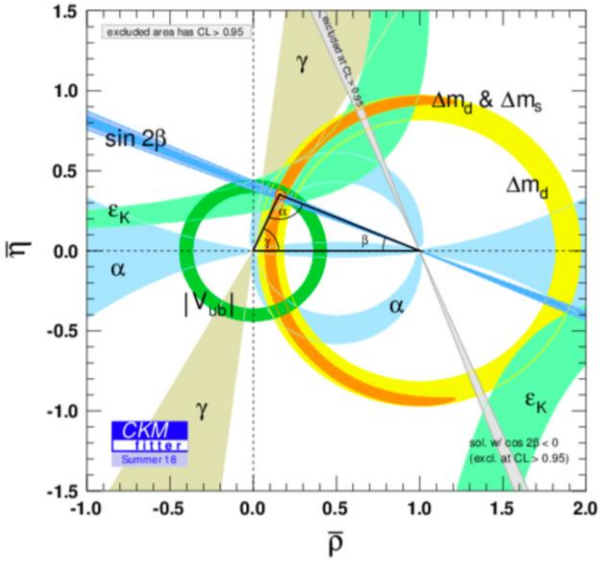
Dark matter hunt: «classical» approach

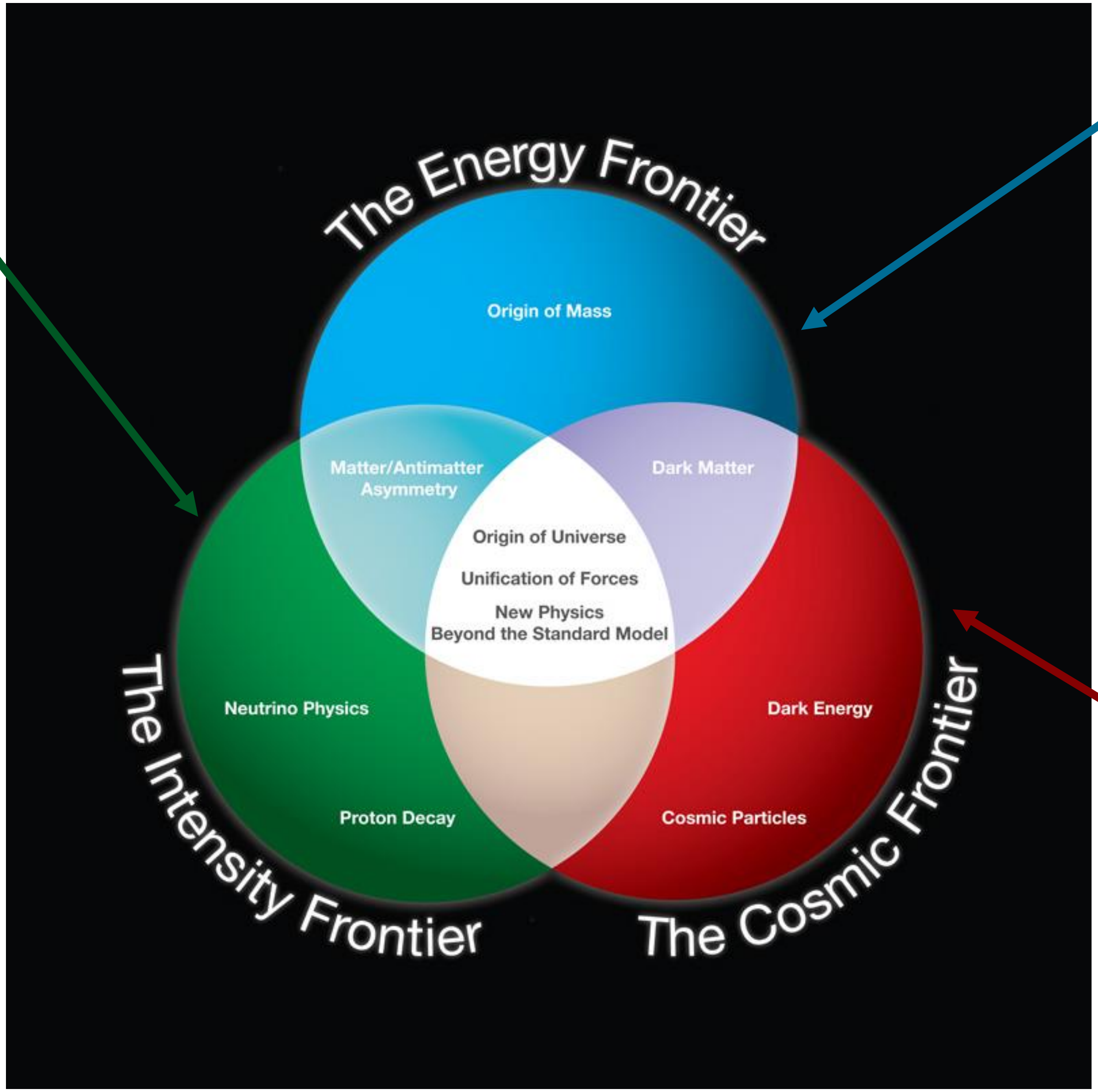
Intensity / precision frontier

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



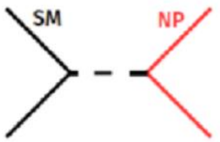
If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays





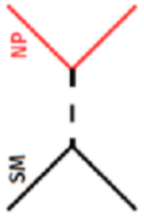
Energy frontier

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

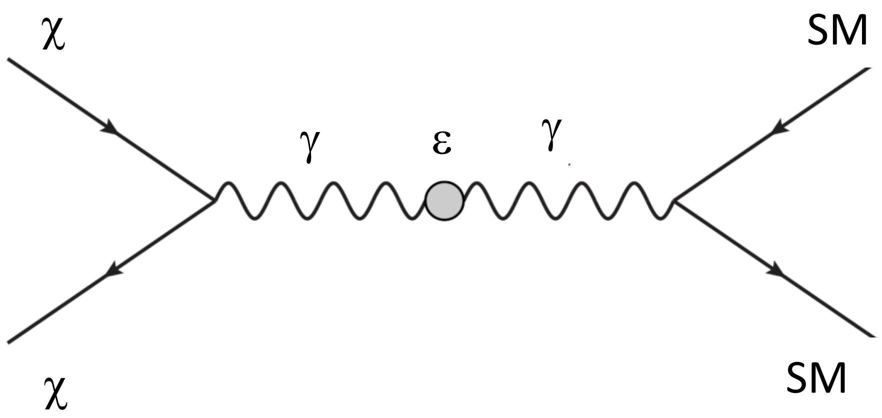
It modeled decades of direct search experiment design

$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_\chi^2 & \text{for } m_\chi \ll m_W \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W \end{cases} \Rightarrow \text{few GeV} < m_\chi < \text{few TeV}$$

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



From KEKB to SuperKEKB

Super KEKB uest for BSM

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

Beam-beam parameter

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

Lorentz factor

Beam current

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

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

Classical electron radius

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

Vertical beta function@IP

x30

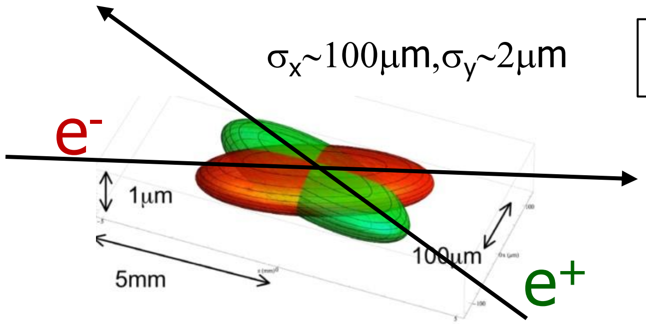
β^*_y=0.30/0.30 mm

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

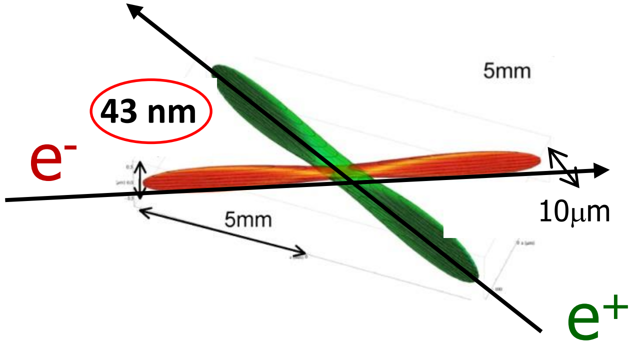
(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

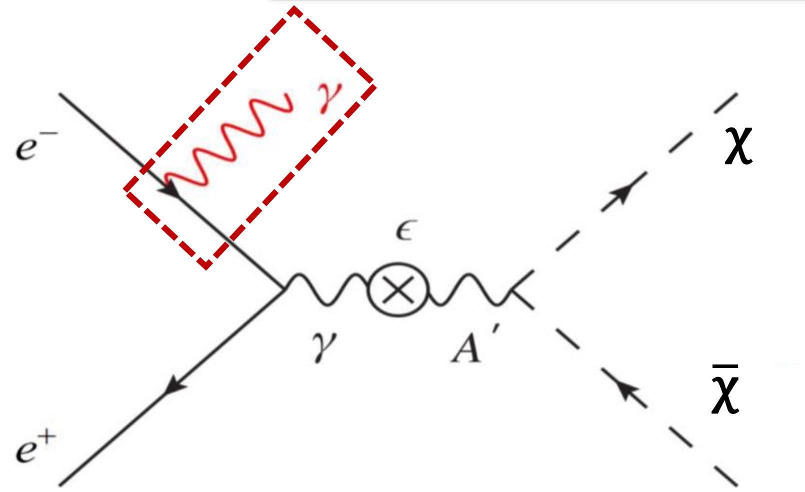


Nano-Beam scheme



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

Invisible dark photon: experimental signature



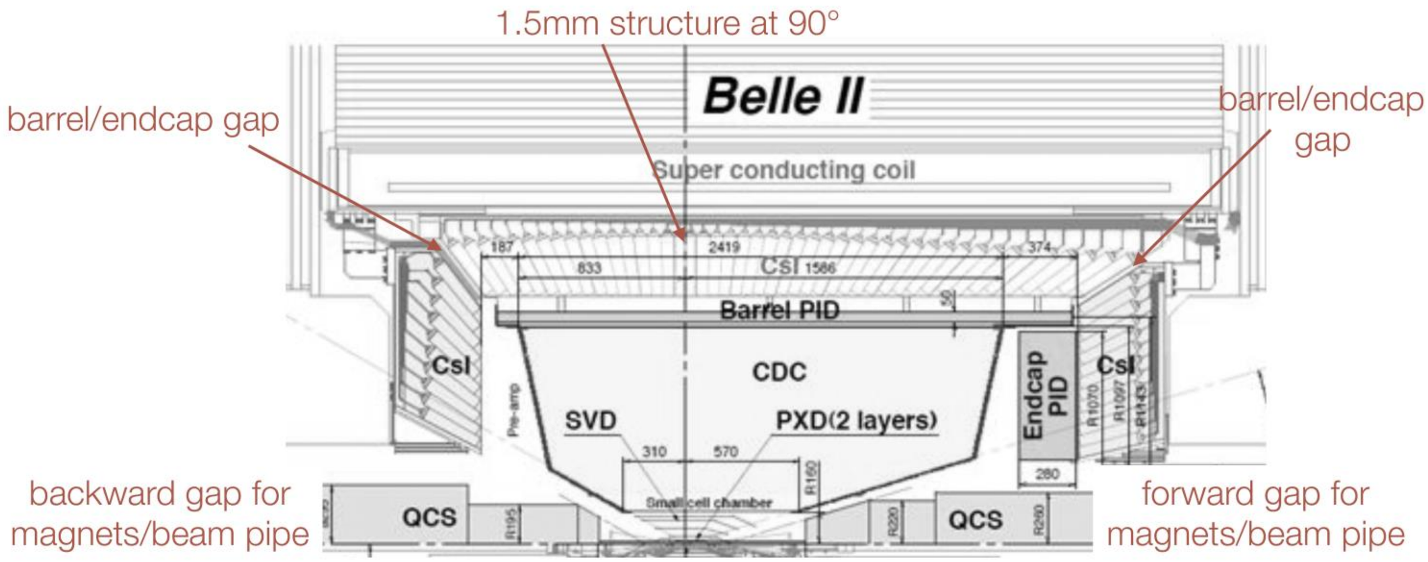
Only **one photon** in the detector

Needs a **single photon trigger**
(*not available in Belle, ≈ 10% of data in BaBar*)

Needs an excellent knowledge of the **detector acceptance**

$$\boxed{E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}} \rightarrow$$

Bump in recoil mass or photon energy

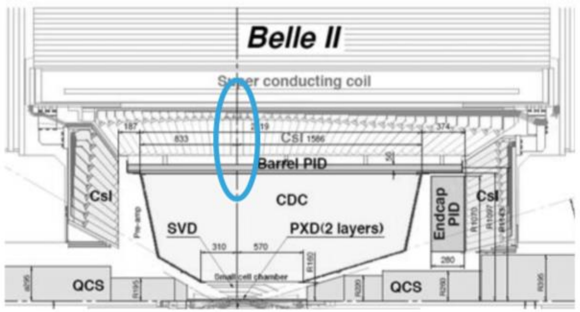


Backgrounds

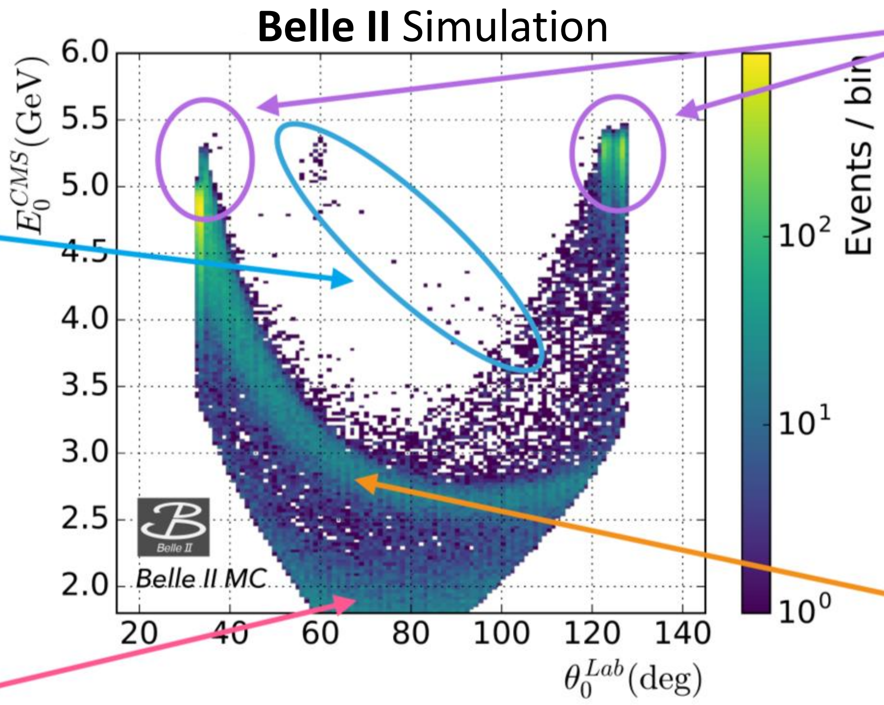
$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ → high $M_{A'}$ region
$e^+e^- \rightarrow \gamma\gamma(\gamma)$ → low $M_{A'}$ region

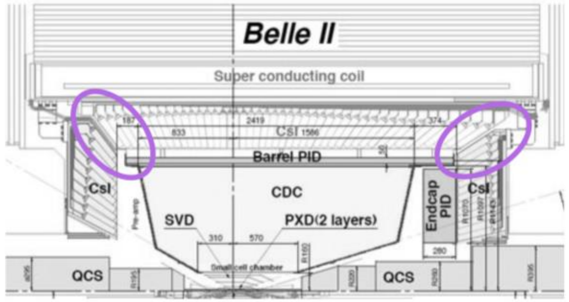
Cosmics
$e^+e^- \rightarrow \gamma\nu\nu$

Invisible dark photon: background

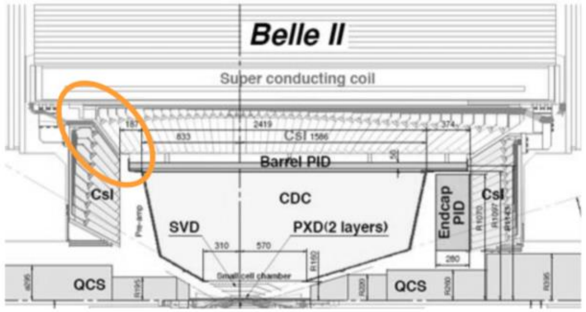


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

Crucial usage of KLM to veto photons in ECL gaps