Dark Sector Physics at Belle II

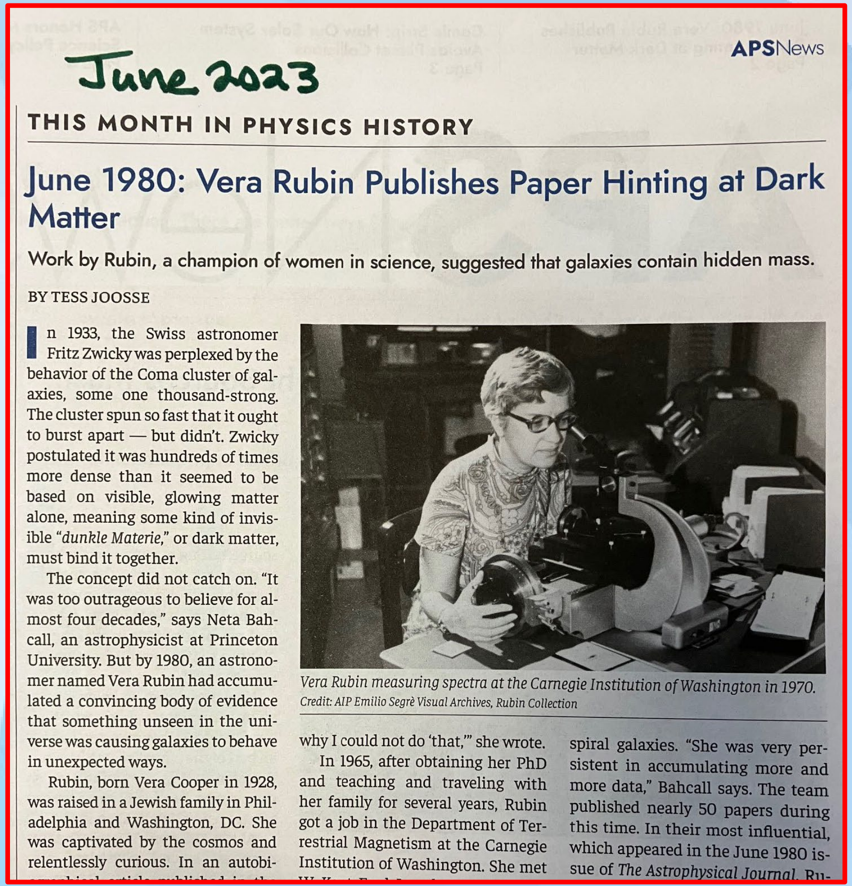
- ➢ Landscape / Belle II
- ➢ Recent Belle II Analyses*
- ➢ It's what's Happening!

W. W. Jacobs
Indiana University / CEEM
Belle II Summer Workshop
Duke University, 24-28 July, 2023

U.S. DEPARTMENT OF ENERGY | Office of Science

* Selected content from many slides "borrowed, thanks!

June 1980: Vera Rubin Publishes Paper Hinting at Dark Matter



June 2023

APSNews

THIS MONTH IN PHYSICS HISTORY

June 1980: Vera Rubin Publishes Paper Hinting at Dark Matter

Work by Rubin, a champion of women in science, suggested that galaxies contain hidden mass.

BY TESS JOOSSE

In 1933, the Swiss astronomer Fritz Zwicky was perplexed by the behavior of the Coma cluster of galaxies, some one thousand-strong. The cluster spun so fast that it ought to burst apart — but didn't. Zwicky postulated it was hundreds of times more dense than it seemed to be based on visible, glowing matter alone, meaning some kind of invisible "*dunkle Materie*," or dark matter, must bind it together.

The concept did not catch on. "It was too outrageous to believe for almost four decades," says Neta Bahcall, an astrophysicist at Princeton University. But by 1980, an astronomer named Vera Rubin had accumulated a convincing body of evidence that something unseen in the universe was causing galaxies to behave in unexpected ways.

Rubin, born Vera Cooper in 1928, was raised in a Jewish family in Philadelphia and Washington, DC. She was captivated by the cosmos and relentlessly curious. In an autobi-

Vera Rubin measuring spectra at the Carnegie Institution of Washington in 1970.

Credit: AIP Emilio Segrè Visual Archives, Rubin Collection

why I could not do 'that,'" she wrote.

In 1965, after obtaining her PhD and teaching and traveling with her family for several years, Rubin got a job in the Department of Terrestrial Magnetism at the Carnegie Institution of Washington. She met

spiral galaxies. "She was very persistent in accumulating more and more data," Bahcall says. The team published nearly 50 papers during this time. In their most influential, which appeared in the June 1980 issue of *The Astrophysical Journal*, Ru-

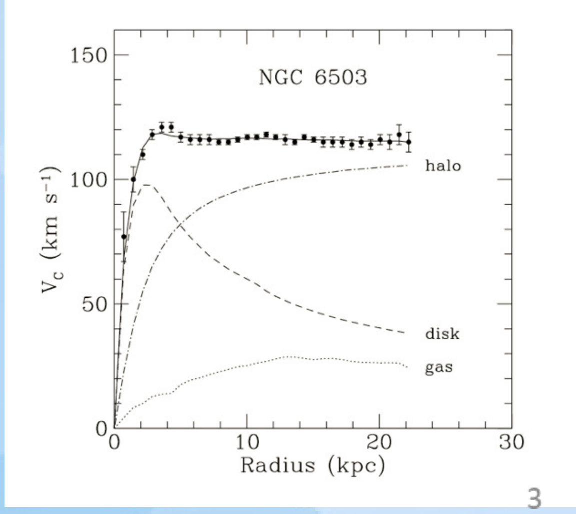
1933:

Swiss astronomer Fritz Zwicky was perplexed by the behavior of the Coma cluster of galaxies … the custer spun so fast that it ought to burst apart - but didn't. Zwicky postulated it was hundreds of times more dense than it seemed to be … meaning some kind of invisible *"dunkleMaterie,"* or dark matter, must bind together.

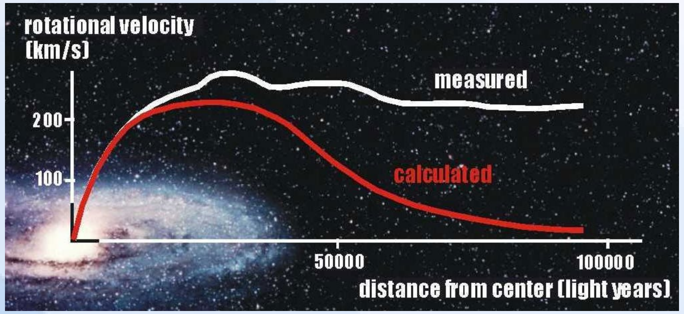
The concept did not catch on. "It was too outrageous to believe for al most four decades," says Neta Bah call, an astrophysicist at Princeton University.

1980:

an astronomer named Vera Rubin had accumulated a convincing body of evidence that something unseen in the universe was causing galaxies to behave in unexpected ways.

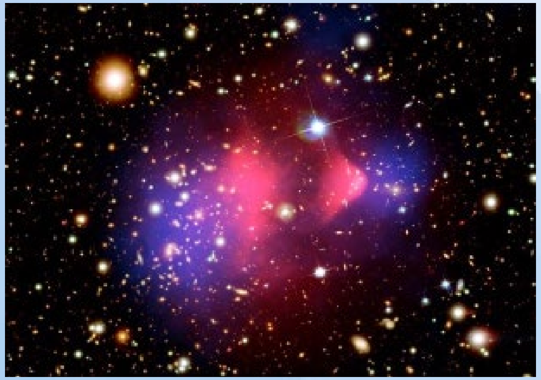


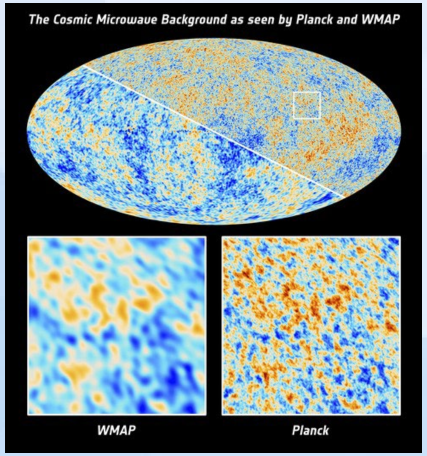
Dark Matter Puzzle: Astrophysical Evidence and Other

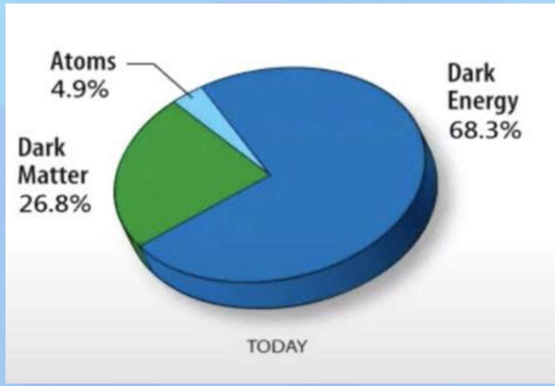


Existence of dark matter (DM : χ) has been established in astrophysics [1]

- Rotation curve of a disk galaxy
- Spatial distributions of luminous baryonic matter (with X-ray) and total matter (with gravitational lens) in a collision of galaxy clusters
- CMB (fluctuations from DM in very early universe)
- And more …







We know the DM density in the Universe
$\Omega h^2 = 0.1188 \pm 0.0010$
27% of total energy

New and very interesting is the role played by dark matter in galaxy formation in the early universe .. stay tuned for the latest from the James Webb Space Telescope!

[1] Albada et al., Astrophysical Journal (1985)

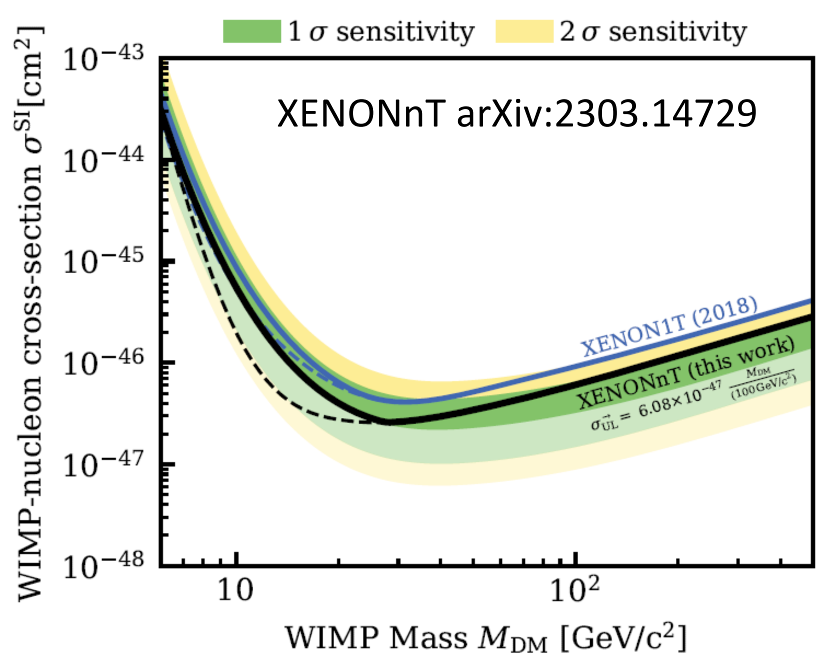
The WIMP "Miracle" … and Ensuing Dark Matter Landscape

- Super Symmetric model particle predictions ….
- Assuming the thermal relic, WIMP with mass around O(100) GeV can explain the relic density.
- WIMP miracle !!

$$\Omega h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

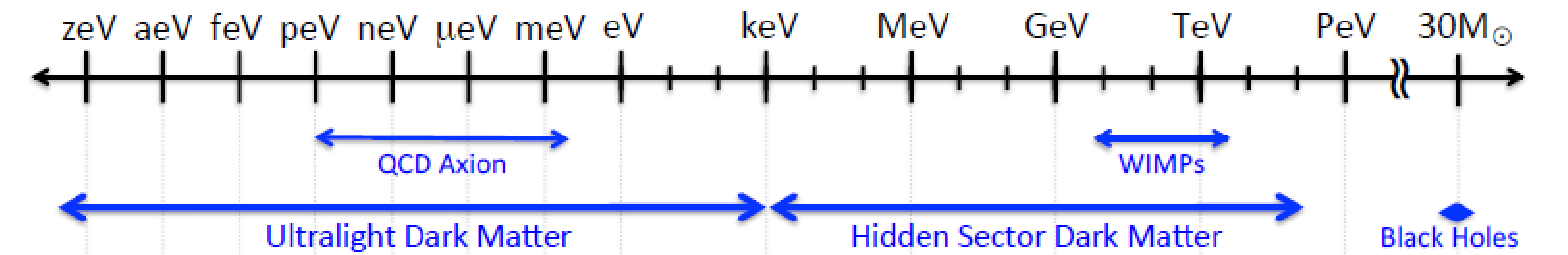
self annihilation xsec to produce DM relic (from thermal origin)

$$10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq 10^{-9}\ \mathrm{GeV}^{-2} \sim \frac{g_2^4}{4\pi} \frac{1}{m_{\mathrm{DM}}^2}$$



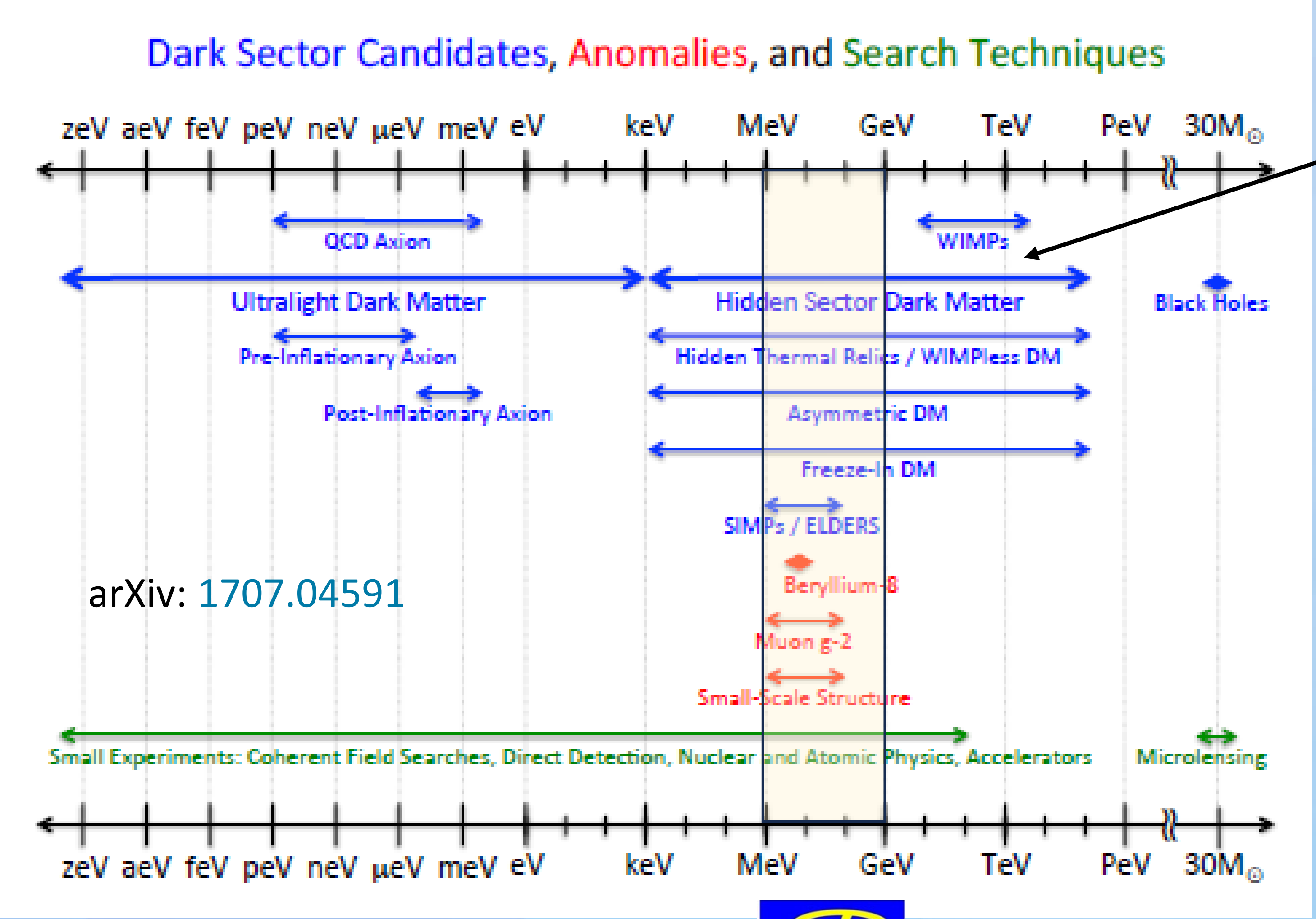
WIMPs not (yet) observed at the energy frontier collider, or in direct and indirect experiments.

Opens the possibility for a wide variety of DM scenarios; Dark sector (DS) is one of the important ones!



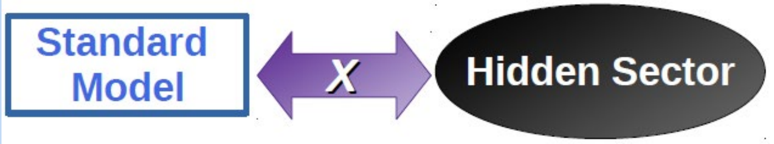
Dark Matter and Light Dark Sectors Accessible with Belle II

Dark matter is one of the most compelling reasons for new physics!



Plausible sub-GeV scale scenario:

- *light DM feebly interacting with* SM through [1] a limited number of light *mediators ('portals')*



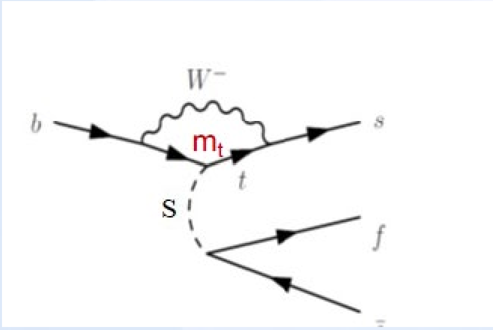
- Vector portal → **Dark Photons, Z' bosons**
- Pseudo-scalar portal → **Axion Like Particles (ALPs)**
- Scalar portal → **Dark Higgs/Scalars**
- Neutrino portal → Sterile Neutrinos

[1] Essig et al., arXiv:1311.0029 (2013)

Dark Scalar S search in $b \rightarrow s$

Minimal SM extension with light scalar **S** that mixes with the SM Higgs boson:

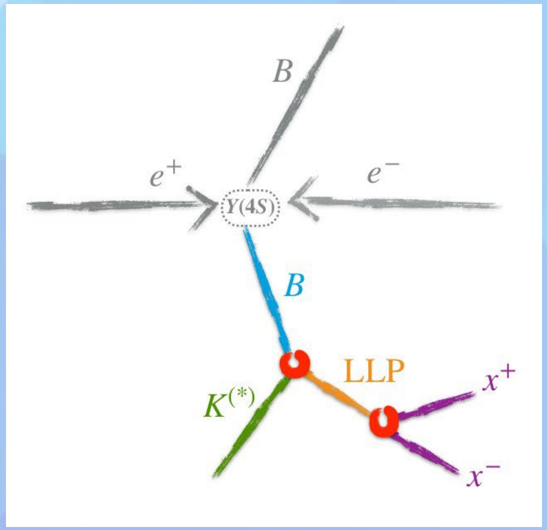
Search for a long-lived scalar in b → s transitions



- S could mix with SM Higgs boson w/ mixing angle angle θ_S
  - S naturally long-lived for $\theta_S << 1$
  - $M_s < 2M_\chi$, region where S -> χχ could explain relic density already ruled out

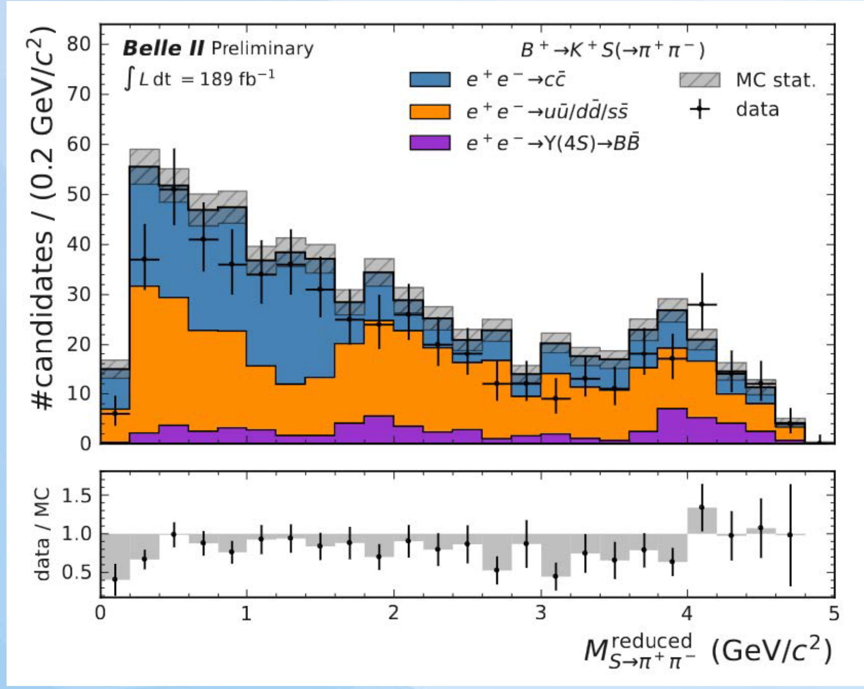
First Belle II Long-Lived Particle (LLP) search

- Look for S decays into SM final states in **8 exclusive visible channels:**
  - $B^+ \to K^+ S$ and $B^0 \to [K^{*0} \to K^+\pi^-] S$
  - $S \to ee/\mu\mu/\pi\pi/KK$
- Search for signal as narrow enhancement in the invariant mass M_S



- Displaced tracks for S vertex with $d_v > 0.05$ cm
- Dominant backgrounds are combinatorial ee->cc, ee->uu,dd,ss, ee->Υ(4S)->BB
- M_{inv} selections reject peaking backgrounds (D^0, J/ψ, ψ(2S), ϕ, …) from B decays
- Bump hunt with extended max likelihood fits
- Long-lived K_S^0 used as good control sample

Distribution of M′(π⁺π⁻)

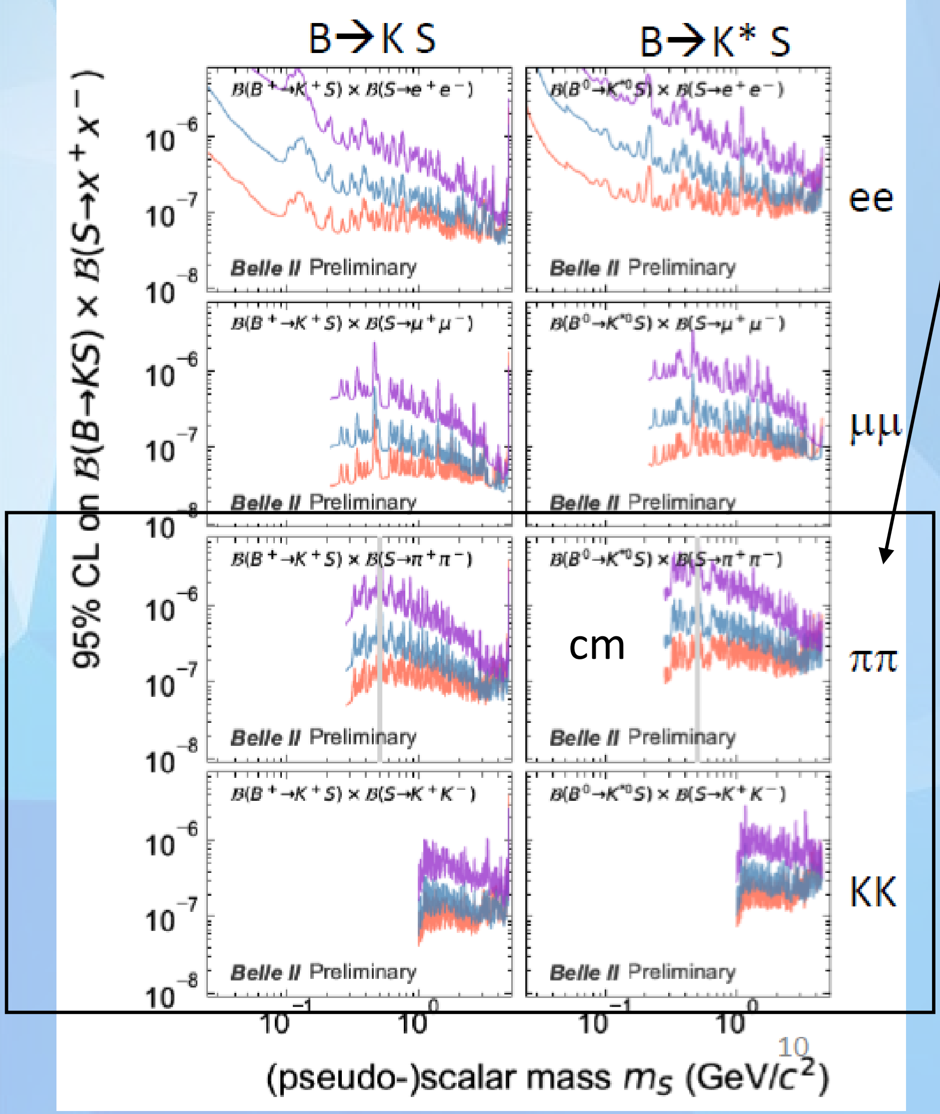


$$M^{reduced}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - (2m_x)^2}$$

Search for a long-lived (pseudo-)scalar in $b \to s$ results

Model-independent 95% upper limits on pseudo-scalar LLP Branching Fraction

submitted to PRL
arXiv:22306.02830

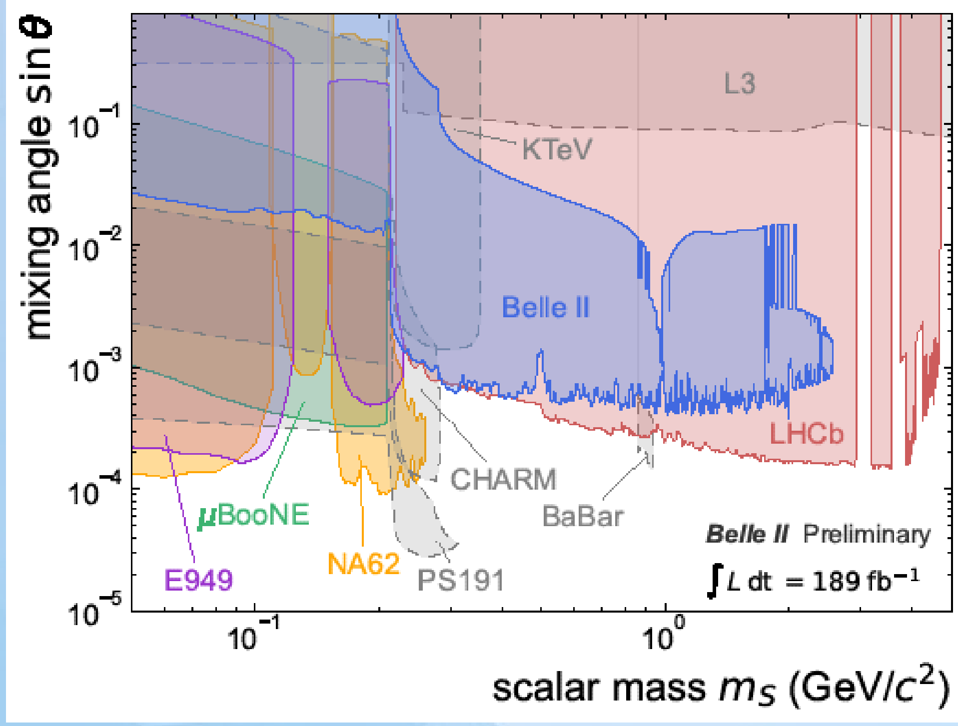


- As functions of ct and Scalar mass for 8 decay modes
- First limit on S decaying to hadrons
- probing lifetimes between 0.001 < cτ < 400

ct=100cm
ct=10cm
ct=1cm

Dark Higgs-like scalar S model interpretation [1]

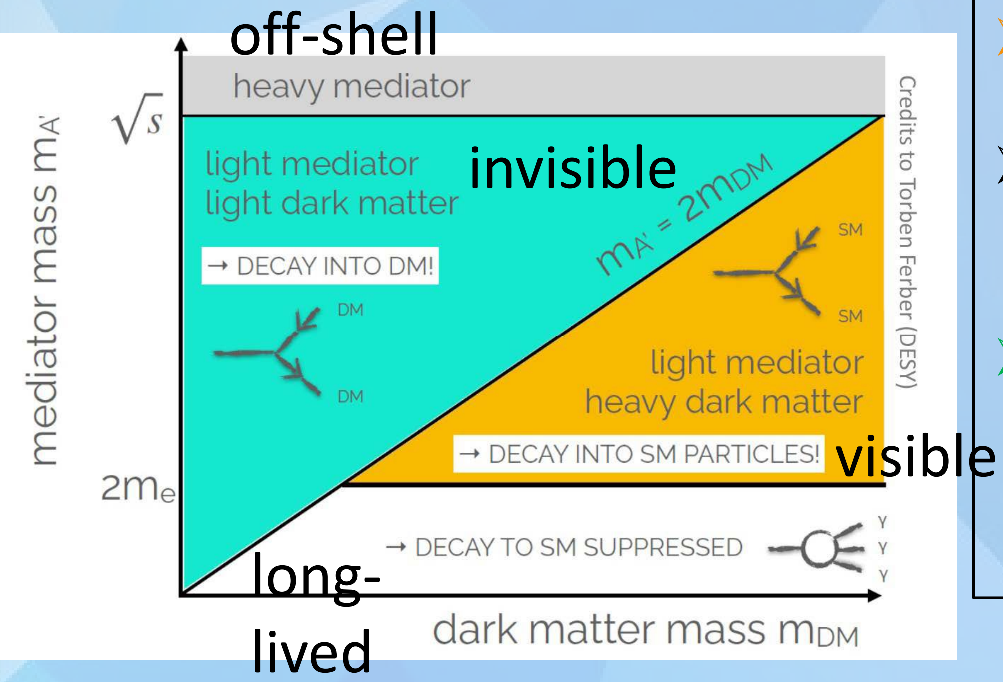
- Translate into 95% CL model-dependent limits on scalar mass vs. sin θ
- Dark Higgs mixing with the SM Higgs
- Strongest limits using e^+e^- mode



[1] Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006

Further Aspects of Light Dark Matter Searches

Different signatures/topologies depending on DM & mediator mass relation and lifetimes



- Prompt decay to SM:
  - visible signature -> invariant mass bump
- Long lived:
  - decay-length < O(1)m: visible signature -> displaced vertex
  - decay-length > O(1)m: invisible signature -> missing momentum
- Decay to DM particle:
  - invisible signature -> missing momentum
  - Decay to SM + DM particles:
  - partially visible signature -> displaced vertex not pointing to IP

Advantages of Belle II / e^+-e^- collider searches

- Mostly "clean" low multiplicity signatures w/ nearly hermetic detector
- Can investigate missing energy channels; Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessible

Additional benefits

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, ...)
- Explanation of the $(g-2)_\mu$ effect
- Explain some flavour anomalies (LHCB, Belle, ...)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

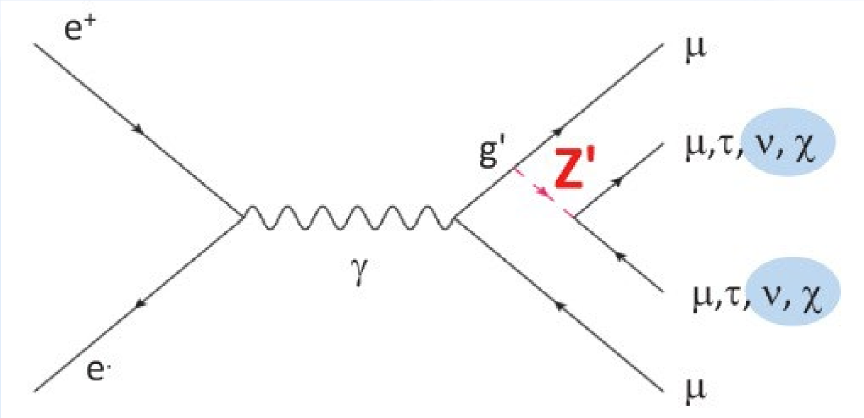
Decay of Z' to Invisible

The $L_\mu - L_\tau$ Gauge Boson and Search for Invisible Decaying Z'

- Vector boson *Z'* with a coupling *g'* only to the 2nd and 3rd lepton family as introduced by the $L_\mu - L_\tau$ model [1] …

$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$

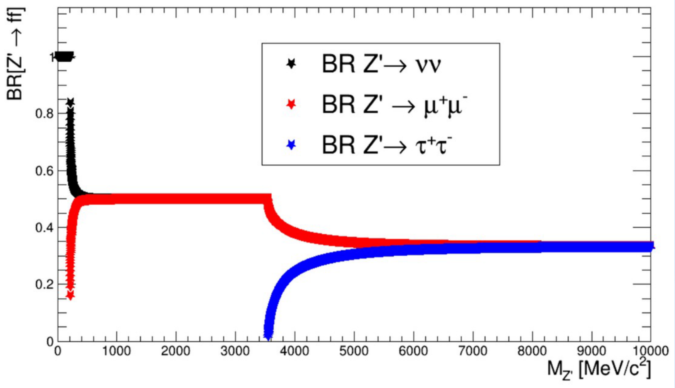
θ =+1 if *l* = μ
θ =-1 if *l* = τ



- $m_{Z'}$ and g' in a two-parameter model
- Could explain DM abundance and muon $(g-2)_\mu$ anomaly
- May also help explain anomalies seen in rare B decays, e.g., $R_{D(*)}$, etc.

Search for the process $e^+e^- \to \mu^+\mu^- Z'$

- $\mathcal{BR}(Z' \to \nu\bar{\nu}) \sim 33 - 100\%$
- $\mathcal{BR}(Z' \to \chi\bar{\chi}) \sim 100\%$ if this decay is kinematically accessible
- **Study the system recoiling against the $\mu^+\mu^-$ pair**
- Dominate backgrounds are from radiative QED processes



BR has dependence on Z' mass

[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014); Altmannshofer et al., JHEP 106 (2016)

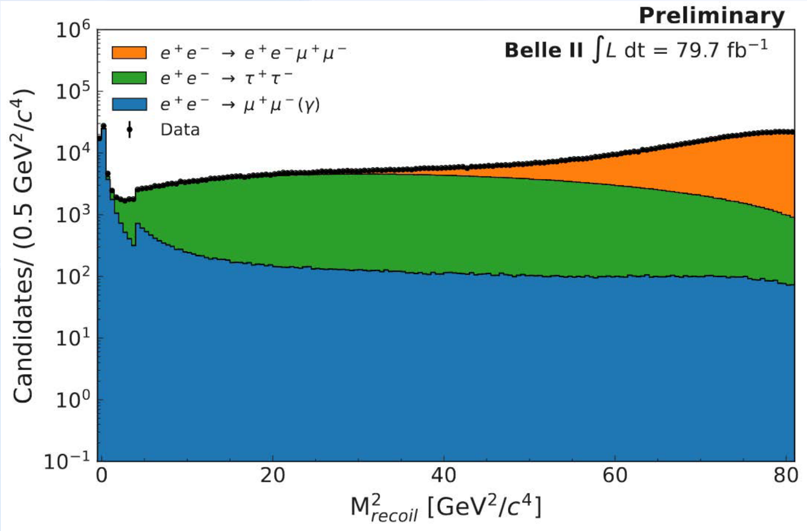
Analysis issues: Search for an Invisibly Decaying Z′ Boson

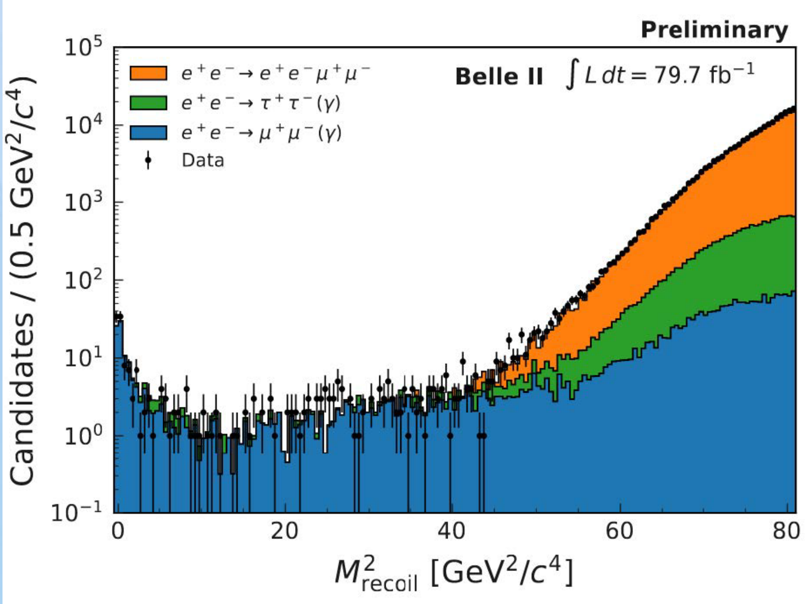
- Analysis of 2019-2020 Belle II data (79.7 fb^{-1})
- Signal: $\mu^+\mu^-$ + missing energy

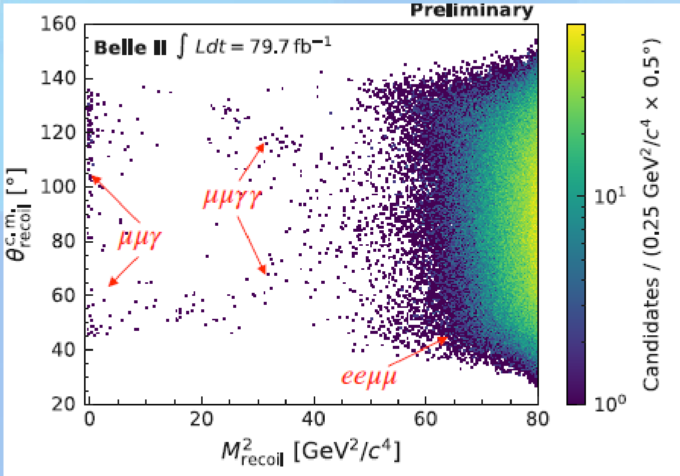
$$M^2_{recoil}(\mu\mu) = s + M(\mu\mu)^2 - \sqrt{s}(E^{CM}_{\mu^+} + E^{CM}_{\mu^-})$$

- Selection:
  - two track w/ muons, p_T > 0.4 GeV/c
  - trigger veto to suppress Bhabha scattering
  - opening angles between muons in c.m. frame < 179° to suppress $\mu^+\mu^-$(gamma)

Punzi-net artificial neural network [1], optimizes FOM for all Z′ mass hypotheses simultaneously.







- Backgrounds:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \mu^+\mu^-e^+e^-$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$, both $\tau \to \mu\nu\bar{\nu}$

  outside accept-ance

- Search: narrow peak in:

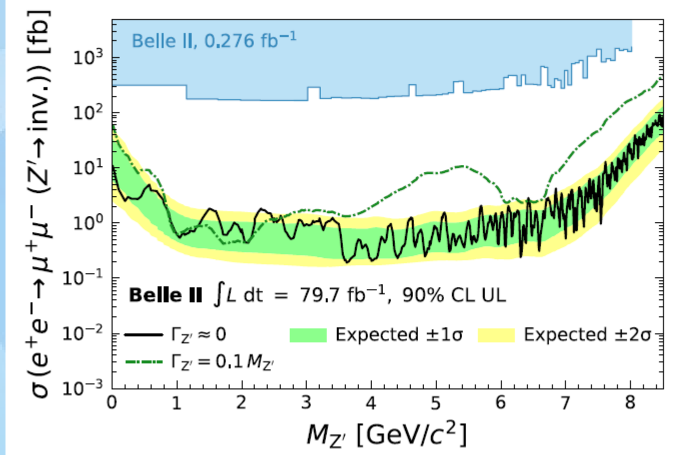
  2D fit M^2_{recoil} vs. θ^{CM}_{recoil}

[1] Eur. Phys. J. C 82, 121 (2022)

Belle II Results: Search for an Invisibly Decaying Z′ with 79.7 fb^{-1}

Phys. Rev. Lett. **130**, 231801 (2023)

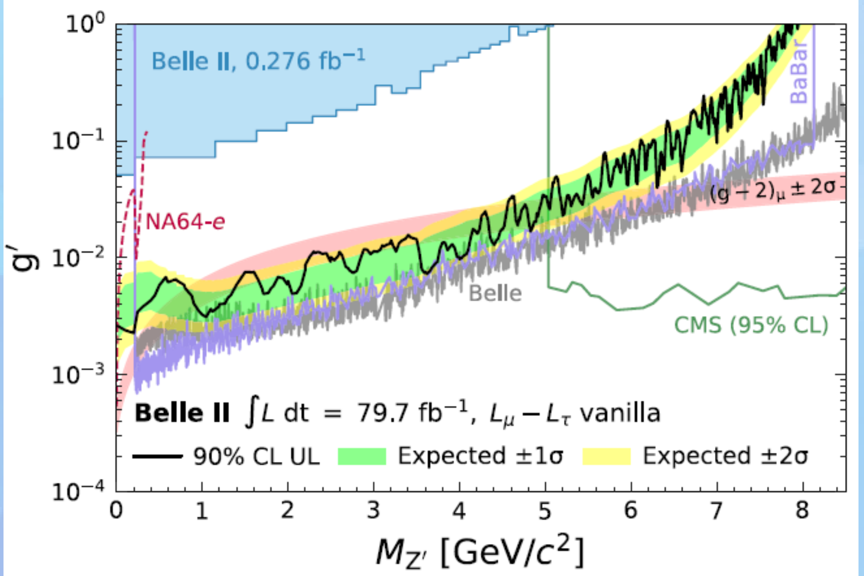
Cross Section



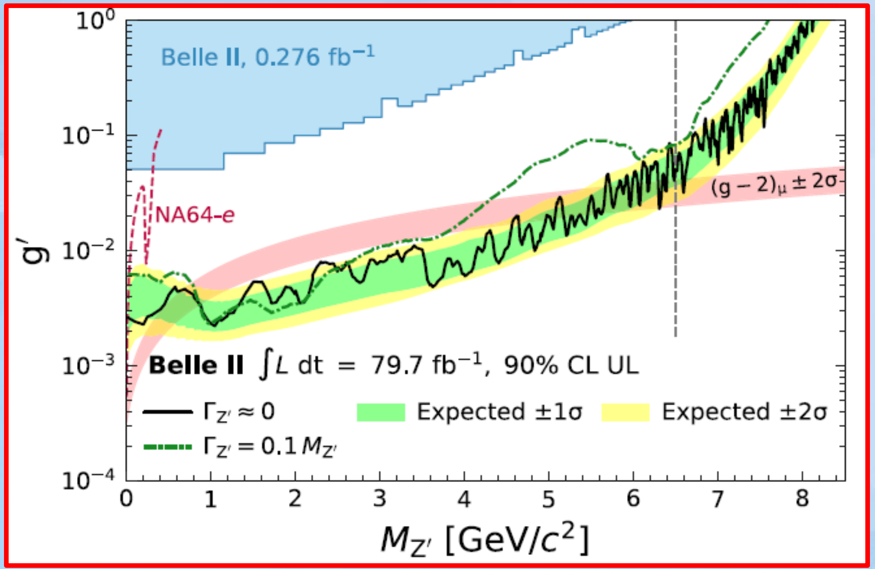
$$\sigma(\mathbf{e^+e^-} \to \mu^+\mu^-\mathbf{Z'}, \mathbf{Z'} \to \mathbf{invisible})$$

- Fit performed in different mass windows with flat backgrounds → no significant signal excess found.
- Set 90% CL exclusion limits on cross section and coupling (g′)
  1. If Z′ only decays to SM particles (vanilla)
  2. For BR(Z′ → invisible) =1

Z′ → SM only



Z′ → invisible



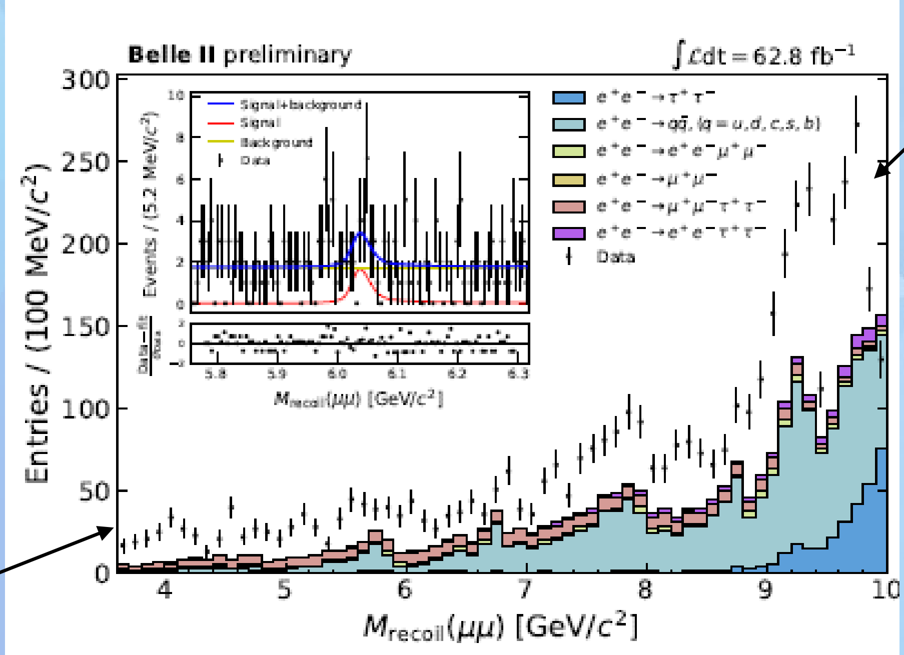
Invisible Z′ as origin of (g-2) anomaly excluded for 0.8 < MZ′ < 5.0 GeV/C2

NB: ongoing analysis w/ x300 dataset

Search for Tau Resonance
(Z' / S / ALP → Tau Tau)

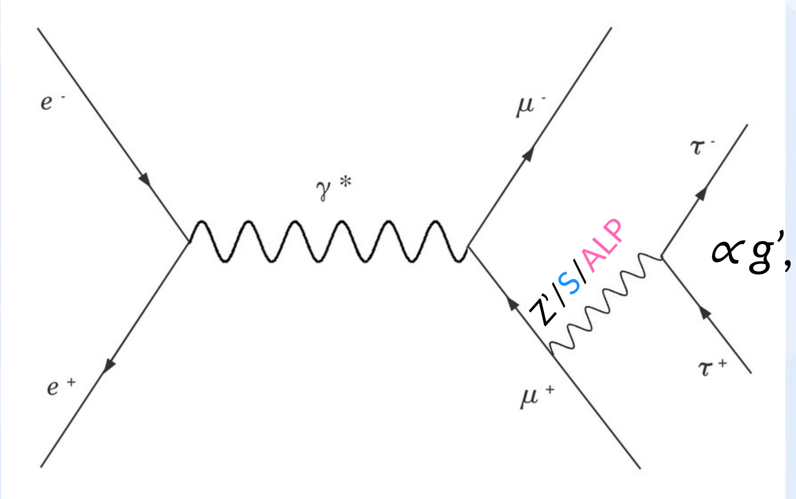
Search for $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

- Extend Z' search to permit additional visible particles in the final state:
  - Four track final-state (restrict tau decay to one ch'gd particle)
  - **Challenging backgrounds** in final-state with neutrinos
    - Missing energy of $Mf_{4\ tracks} < 9.5$ GeV (suppress 4-lepton bkgd)
    - Eight MLP classifiers in different mass regions
  - **Neural net** trained to identify distinctive signal kinematics →



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

not simulated
$e+e- \to \gamma 4\ell_{+/-}$



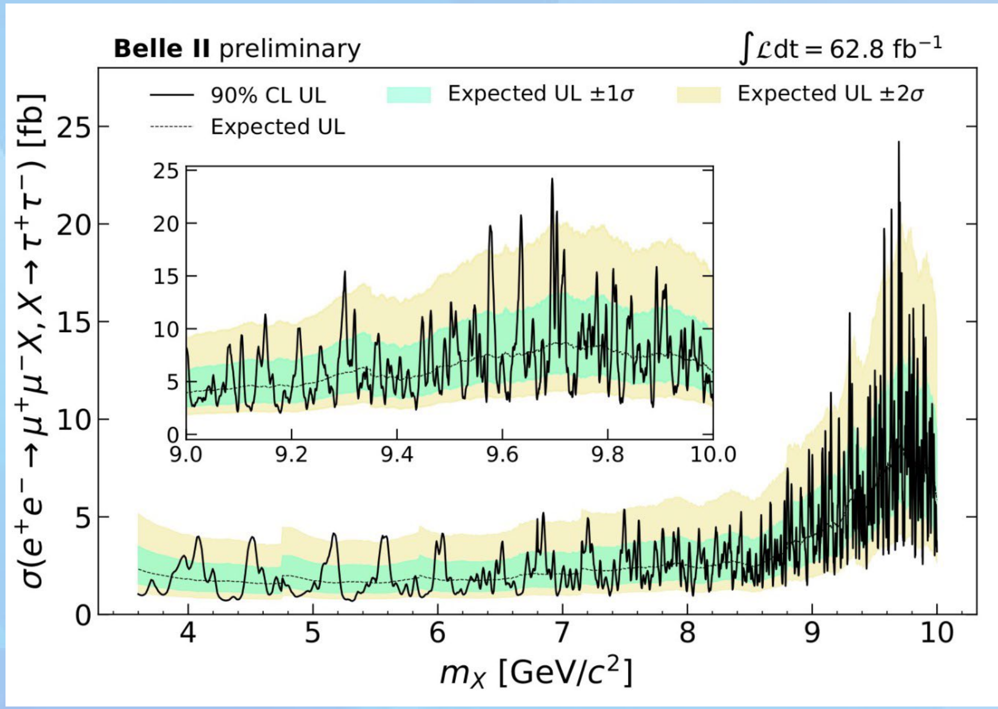
$\propto g'$, ξ, $c_{\tau\tau}$

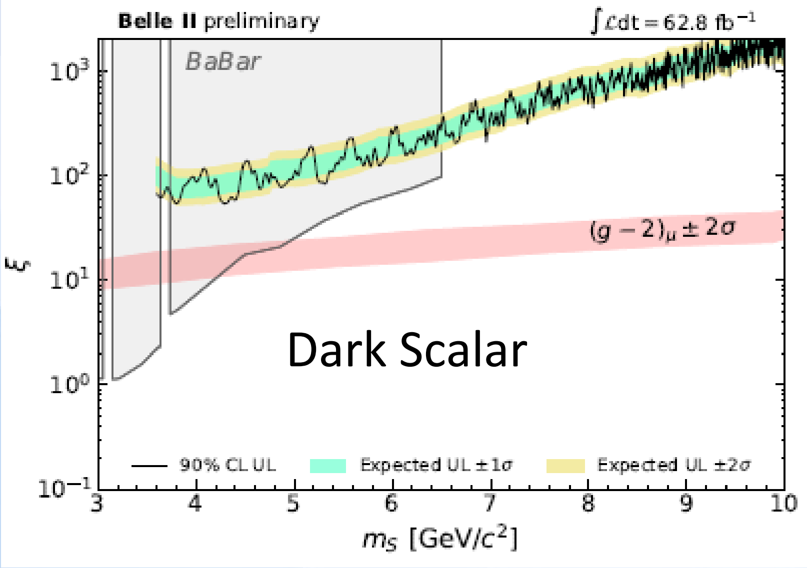
- Substantial backgrounds from continuum di-lepton production and four-lepton processes
- Signal extracted in fits to $M_{recoil}(\mu\mu)$ w/ locally flat bkgrd (e.g., insert in figure)
- Analyse 3 different mediator scenarios ... "in one go"
- Based on 62.8 fb^{-1} integrated luminosity

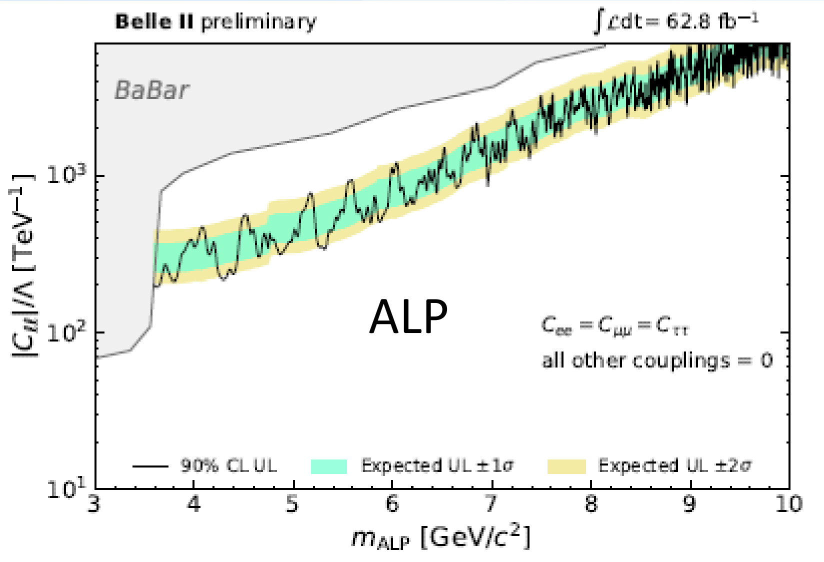
Search for Z', S, ALP → $\tau\tau$ at Belle II

Submitted to PRL, arXiv:2306.12294

- No excess compatible with a signal found
  → Set 90% CL UL on cross section and couplings







note: coupling normalized to global symmetry breaking scale Λ

- **First constraints on S for $M_S > 6.5$ GeV/c^2**
- **First direct constraints for *ALP* → ττ**

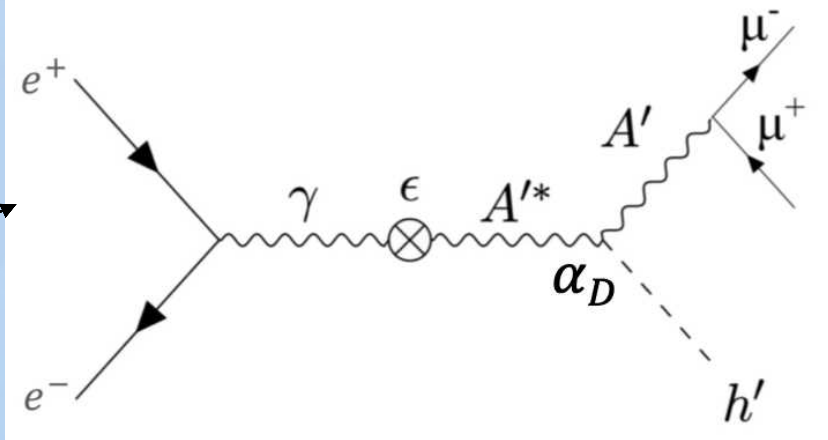
Dark Higgsstrahlung

Dark Sector Higgs and Dark Photon (invisible h' + A' search)

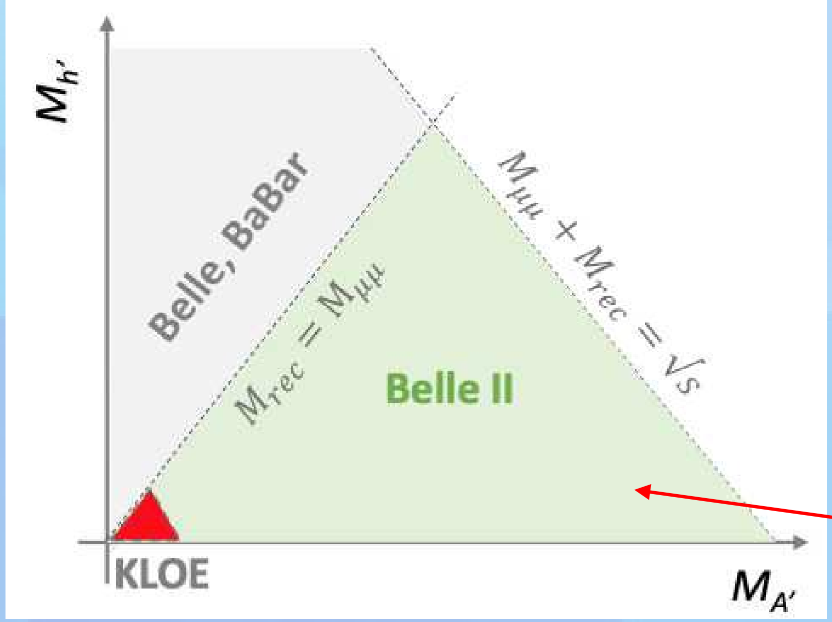
The dark sector could contain a dark Higgs h'

- Dark Higgs **h'** can give mass to the dark photon **A'** through SSB mechanism [1}
- No mixing of **h'** with the SM Higgs
- Dark photon A' kinetic mixing **ε** to SM
- **h'** coupling to A' is $\alpha_\mathbf{D}$ so overall **Higgsstrahlung** process depends on $\epsilon^\mathbf{2} \times \alpha_\mathbf{D}$

$$e^+e^- \to A'^* \to h'A'$$



$$e^+e^- \to \mu^+\mu^- + \text{missing energy}$$



Experimental signature depends on the mass hierarchy

- $M_{h'} > M_{A'}$
  - h'→A'A'
  - Signature: 6 charged tracks
  - Investigated by BaBar (2012) and Belle(2015)

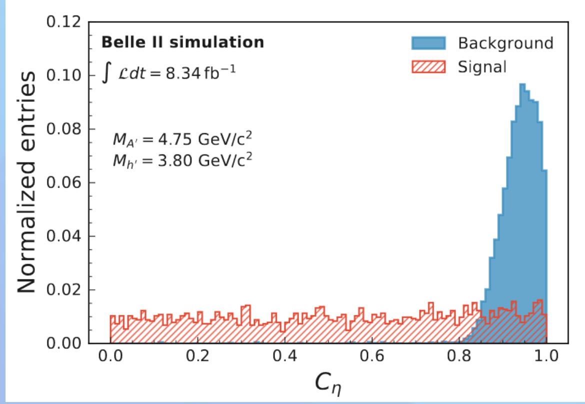
- $M_{h'} < M_{A'}$
  - h' is long-lived -> invisible
  - Signature: 2 tracks and missing energy
  - Probed by KLOE (2015)
  - Largely unconstrained

this analysis

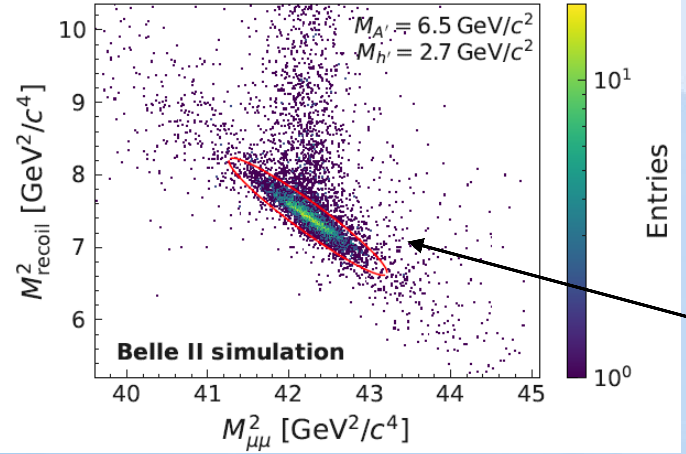
[1] B. Batell, *et al.* , PRD **79**, 115008 (2009)

Dark Sector Higgs and Dark Photon (invisible h' + A' search) -II

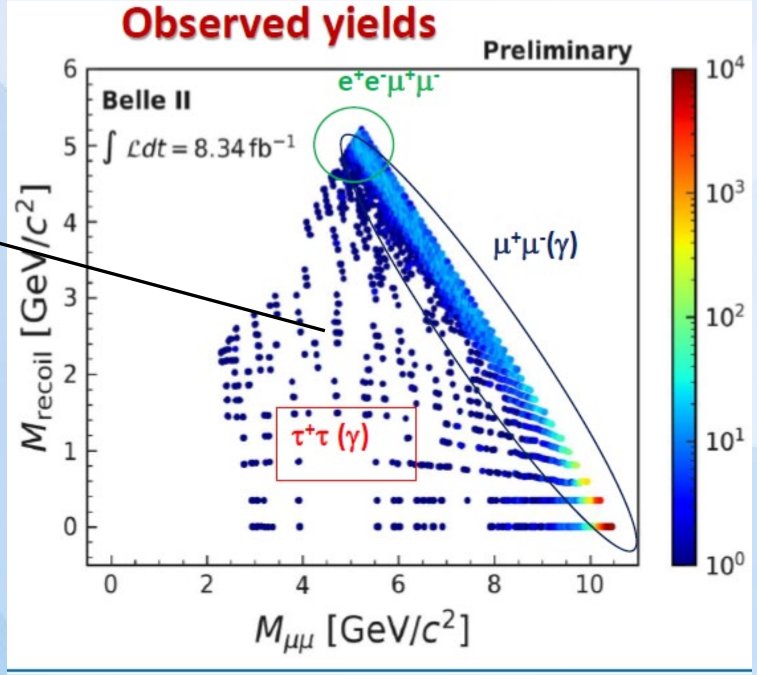
- Signature: Two opposite sign muons + missing energy
- Event selection:
  - Two opposite sign muons, $p_T\mu > 0.1$GeV/c
  - Recoil points to barrel ECL, no nearby photon
  - Low activity in the calorimeter
  - Final suppression exploiting helicity angle* $C_\eta = |\cos(\theta_{helicity})|$ flat for signal, peak at 1 for bkg



initial state radiation



Search performed with 2019 data -> 8.34 fb-1 !



- Analysis Strategy:
  - 2D peak in $M^2_{\mu\mu}$ vs M^2_{recoil}: scan for excess in search windows ~ 9000 2D overlapping elliptical windows, then merge
  - Merge results from neighboring windows

Backgrounds

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

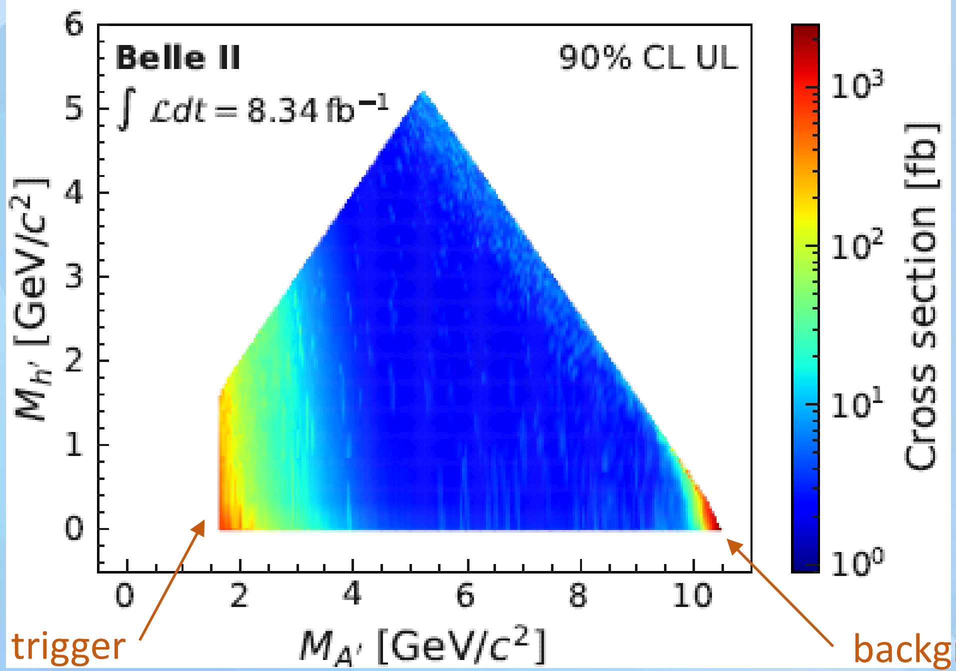
*angle in the dimuon rest frame between the c.m. direction and the μ^-

Dark Higgsstralung: Belle II Results

PRL, 130, 071804 (2023)
arXiv:2207.00509

No significant excess above background is observed

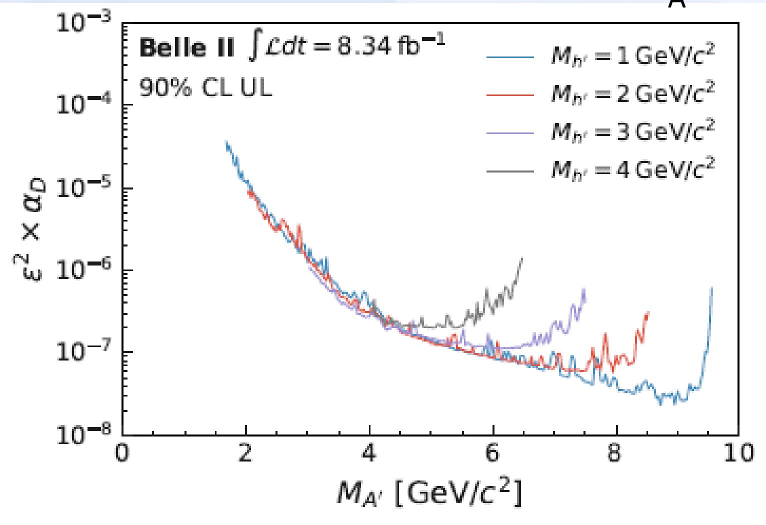
- 90% CL upper limits on cross sections and $\epsilon^2 \times \alpha_D$



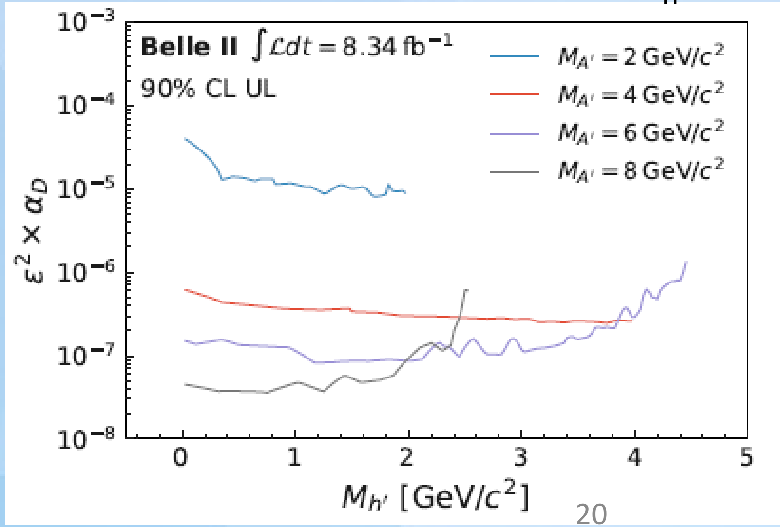
drop in trigger efficiency

backgrounds

$\epsilon^2 \times \alpha_D$ as a function of $M_{A'}$



$\epsilon^2 \times \alpha_D$ as a function of $M_{h'}$



upper limit on $\epsilon^2 \times \alpha_D$ down to 1.7 x 10^{-8} in most sensitive regions

First world limit for 1.65 < $M_{A'}$ < 10.51 GeV/c^2

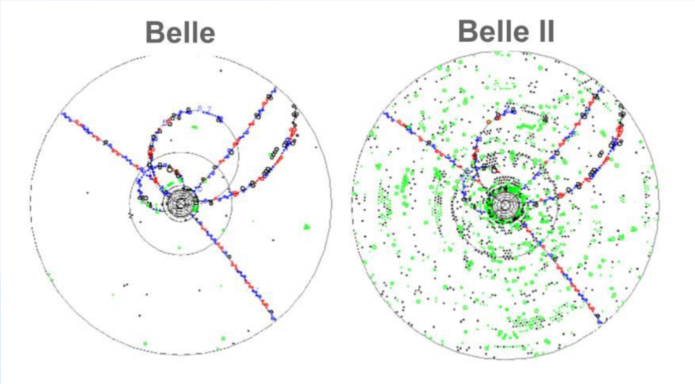
- Next update: much more data; good trigger efficiency at low mass

Triggering for Dark Sector (and Low Multiplicity)

Belle II (Low Multiplicity)Triggering for Dark/Tau

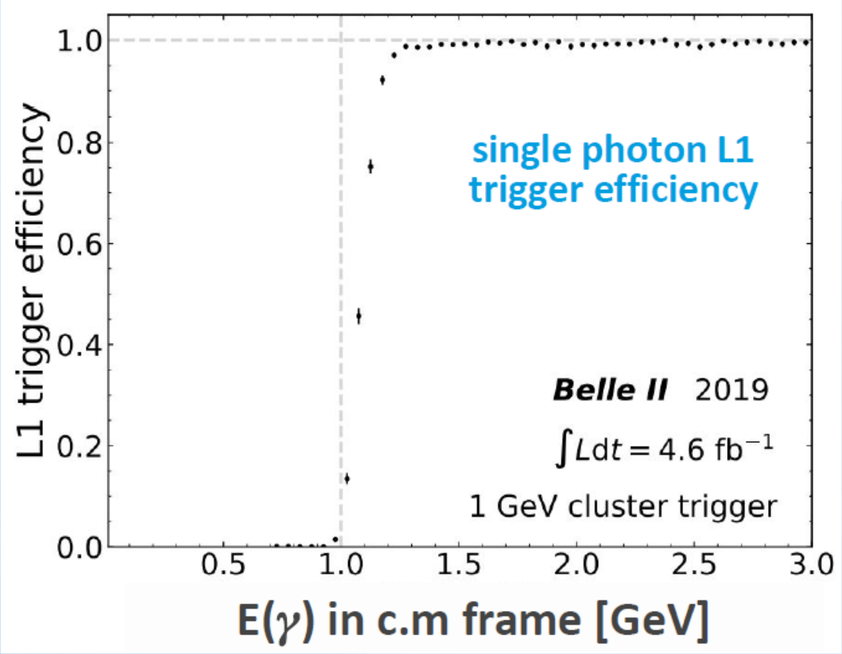
Dark-sector Physics

- Low-multiplicity signatures from tacks and EM Calo energy deposits
- Large/huge backgrounds → radiative Bhabha and two-photon processes … and beam backgrounds!



Some Dedicated Low-Mult/Dark triggers:

- **Single muon trigger**
  - Combine drift chamber & muon detector response
- **Single track trigger**
  - Use a neural-net based hardware trigger
- **Single photon trigger**
  - New, high efficiency for E(γ) > 1 GeV



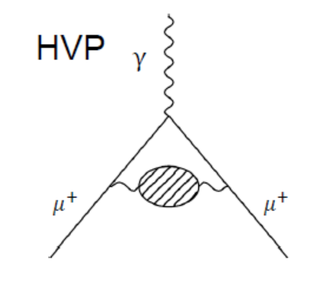
NB: Single-photon trigger → dataset collected is world-unique
- Unavailable to Belle; BABAR sample is ~10x smaller

- Current discussion: strategy for prescales, and reducing L1 rate w/ increasing luminosity

Measurements of $e+e-\to\pi+\pi-\pi^0\gamma$ to constrain theoretical g-2

- Connection to low multiplicity/DM group
  - Ongoing Measurements re: vacuum hadronization correction to g-2

Yuki Sue, Toru Iijima and Boris Shwartz
BELLE2-NOTE-PH-2022-038

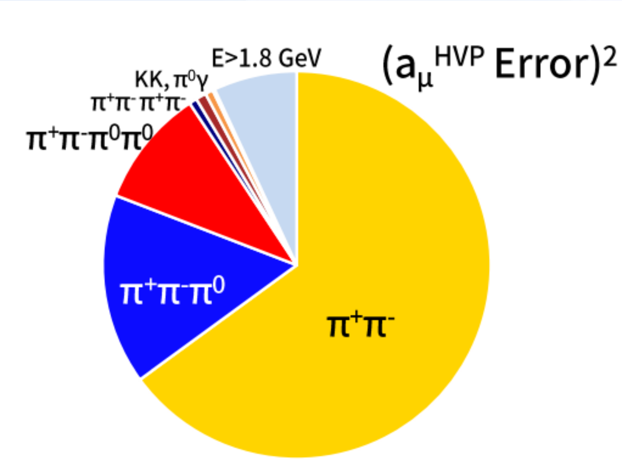


8/5/2023
PHYSICS GENERAL MEETING
21

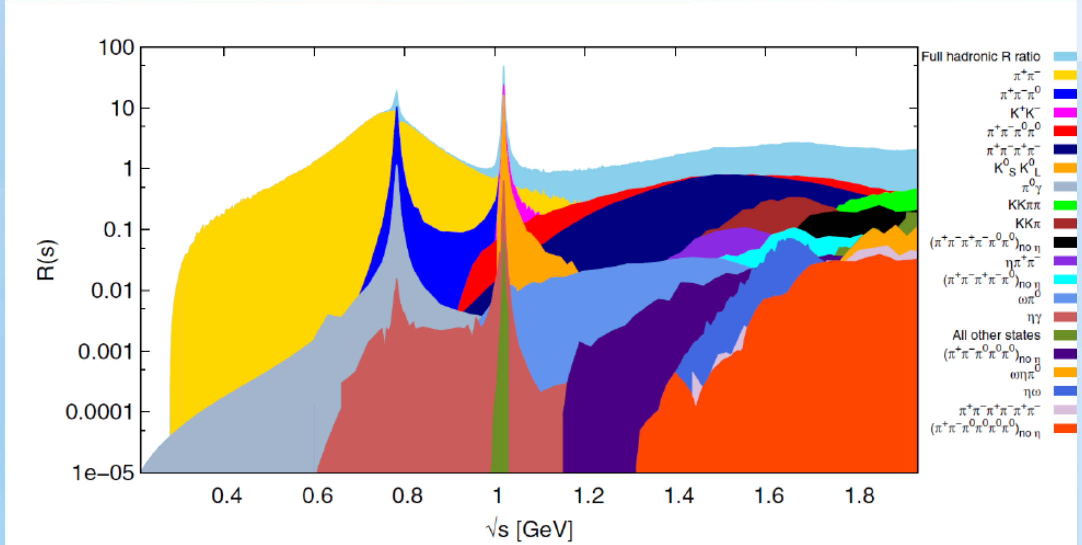
PRD **101**, 014029 (2020)

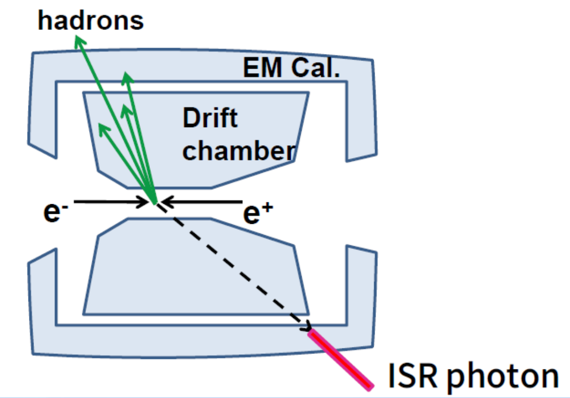
Uncertainty on hadronic vacuum polarization dominates non-lattice prediction of $a_\mu=(g-2)_\mu$
→ 82% of error budget

$e^+e^-\to\pi^+\pi^-\pi^0\gamma$ 2nd largest contribution to HVP



- Use "radiative return" method for new precise measurements at Belle II





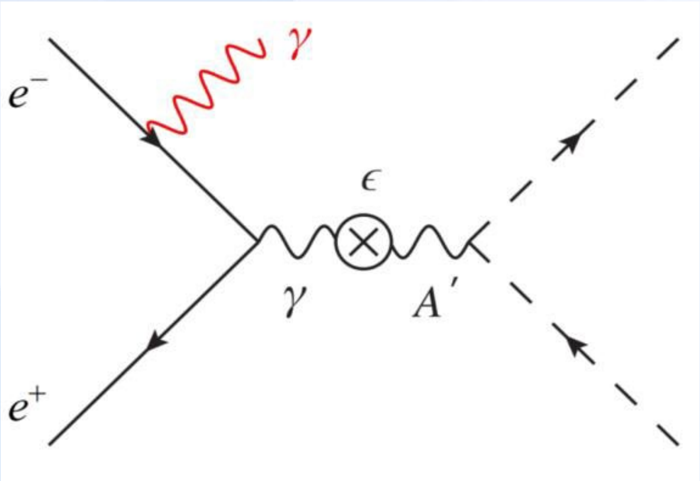
- Scan the energy of hadronic system at fixed energy using ISR
  - Access to the entire hadronic mass range with single dataset
  - Boosted final hadrons

Ongoing Analyses & Prospects

Invisible Dark Photon search @ Belle II

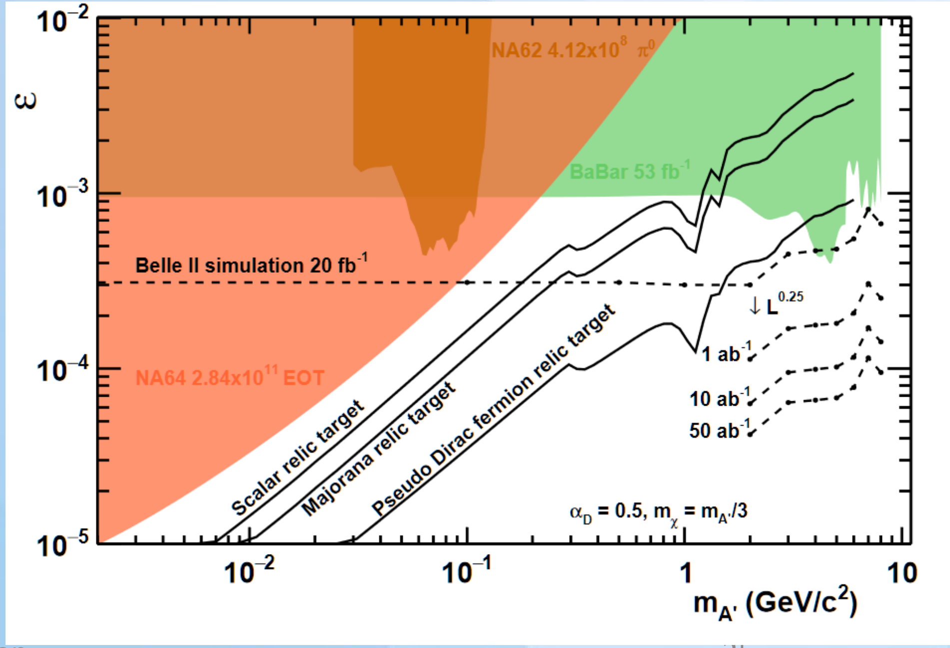
- Of fundamental importance is the simplest case: on-shell production of a dark photon A′ via initial-state radiation. Will decay to dark matter if kinematically allowed. "Single photon" analysis.

BPAC Report Feb 2320: This will be a very important analysis for which the Belle II has unique capabilities



- Signature: only one mono-chromatic high-E photon $\boldsymbol{\gamma_{ISR}}$
  - If DM kinematically accessible expect $BR\ A' \to \chi\chi\ = 1$
  - Requires single photon trigger; "bump" in the photon energy

Belle II Snowmass white paper 2207.06307



- Challenge is to reduce/quantify backgrounds:
  - $e^+e^- \to \gamma\gamma$
  - $e^+e^- \to \gamma\gamma\gamma$
  - $e^+e^- \to \gamma e^+e^-$
  - cosmic rays
  - single beam (non-luminosity)

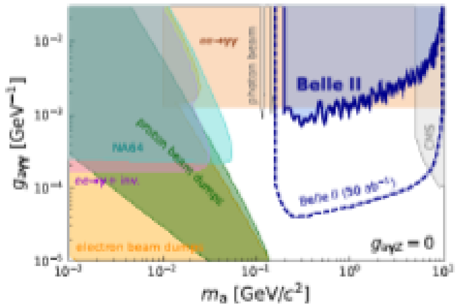
all but one γ out of acceptance or missed

- Current Issues (working through solutions delay publ ~ 1 year)
  - simulation too optimistic (photon detection inefficiency)
  - unexpected cosmic and beam backgrounds
  - ECL clustering software bug

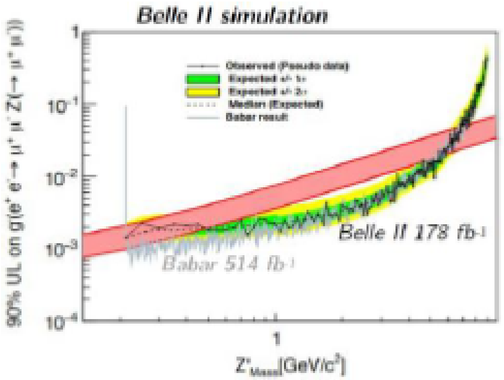
} ?

Many searches are possible at Belle II and in pipeline w/ more data

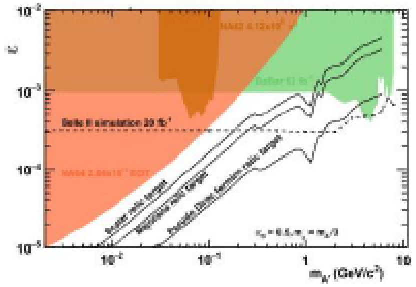
ALPs → diphoton



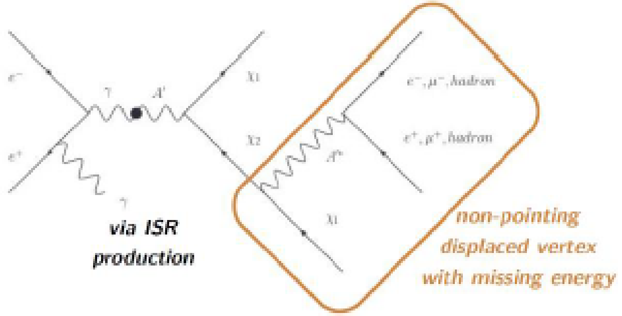
Visible Z′ in L_μ-L_τ



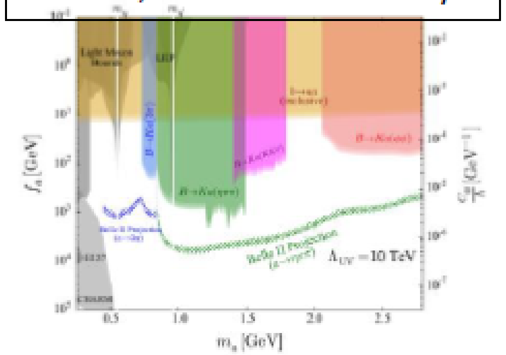
Invisible dark photon



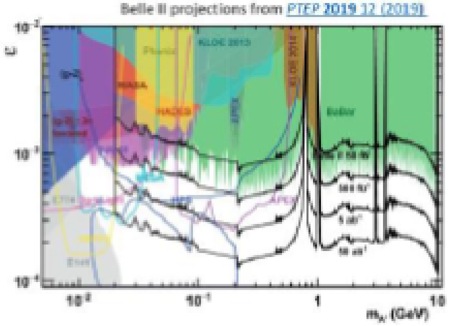
Inelastic DM



Heavy QCD axion in
B→Ka, hadronic a decays



Visible dark photon



ALPs in B→Ka, a→γγ

Sterile neutrino in B decays

Singlino in Υ(1S) decays

ATOMKI dark photon

20230329

Sterile neutrino in τ decays

Dark Higgs in Υ(1S) decays

Dark shower

Displaced jets

Last word from the BPAC

- The Belle II Collaboration is encouraged to seek the help of dark-sector experts to optimise the physics reach of the current and future program. Many dark sector analyses can lead to world-leading results already now; therefore, more manpower is crucially needed in this area.

Group information

Weekly meeting alternates

- Thursday 1830 JST/1130 CET
- Wednesday 1700 CET/0000 JST + 1 day

Web page (out of date): here*

Subscribe: physics-dark-low-multiplicity@belle2.org

Conveners: libby@iitm.ac.in akimasa.ishikawa@kek.jp

*https://confluence.desy.de/pages/viewpage.action?pageId=107058843

Summary and Projections for Belle II Dark Sector

- Dark Sector Physics at Belle II is happening/active
- Several early important results published using just initial data
- Many possibilities for DM and mediator searches in the Dark Sector
- Much more to come! **Expect significant progress with obtainable data sets in the next years!**

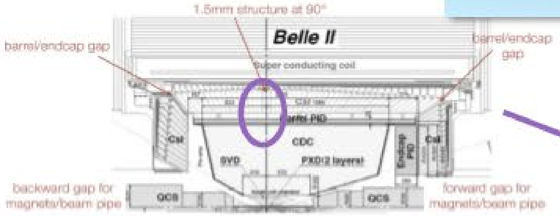
Thank you!

Some links:

- Dark Sector Physics at High-Intensity Experiments (RF6 Snowmass Topical Group) – arXiv:2209.04671
- Snowmass White Paper: Belle II physics reach and plans: https://arxiv.org/abs/2207.06307
- Belle II Executive Summaryhttps://arxiv.org/pdf/2203.10203.pdf
- Physics reach of a long-lived particle detector at Belle II https://arxiv.org/pdf/2105.12962.pdf
- Snowmass page https://snowmass21.org/submissions/rf?s[]=belle

BACKUP SLIDES

Invisible dark photon: background

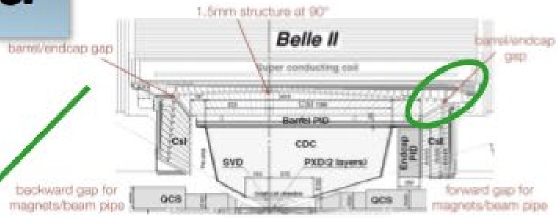


$e^+e^- \to \gamma\gamma\gamma$

1 γ in 90⁰ gap

1 γ out of ECL acceptance

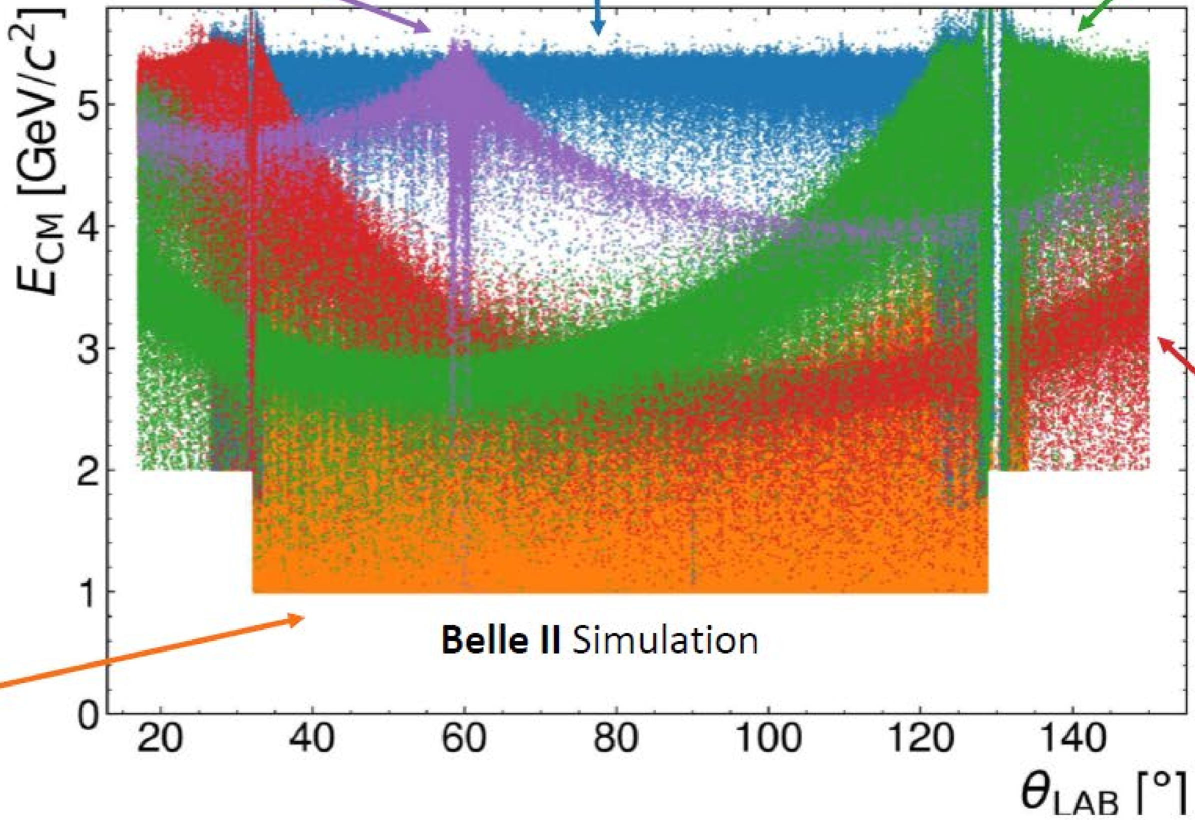
$e^+e^- \to \gamma\gamma$

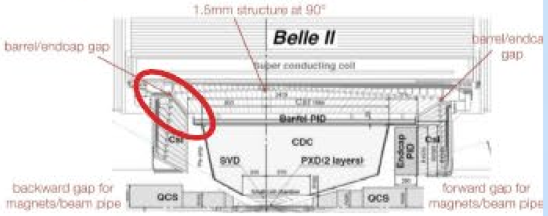


$e^+e^- \to \gamma\gamma\gamma$

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

E. Graziani – Dark sector in Belle II - eeFACT2022 26