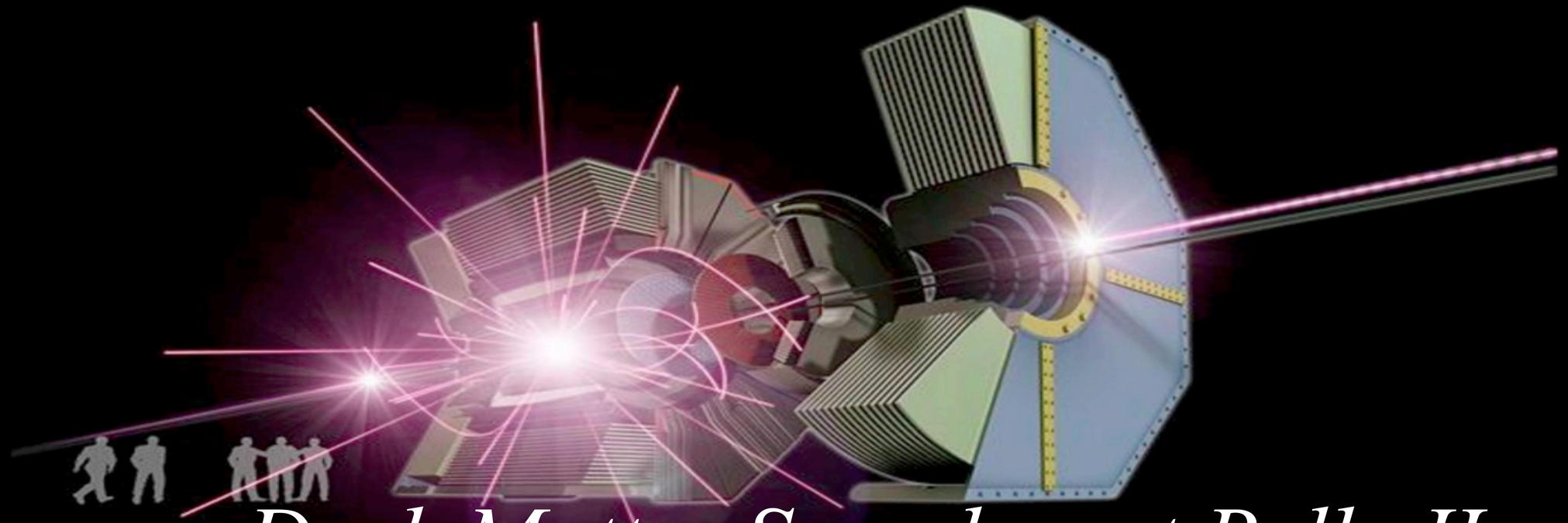


Dark Matter Searches at Belle II

Minakshi Nayak
on behalf of the Belle II Collaboration
IISc, Bangalore

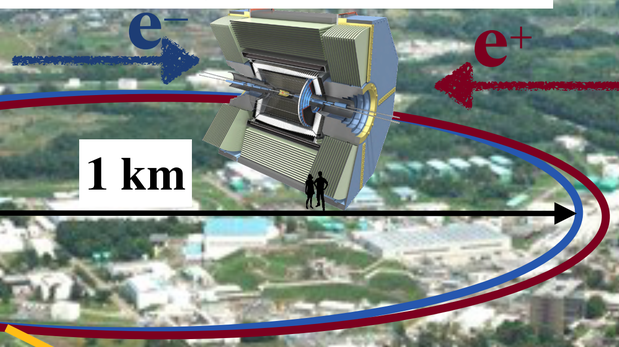
Belle II @ Super-KEKB

Intensity Frontier Flavor Factory Experiment

@ World's Highest-Luminosity Electron Positron Collider

KEK Tsukuba Campus

Successor to Belle at KEKB (1999-2010)



7 GeV e^- ★ 4 GeV e^+

E_{CM} : $\Upsilon(4S) = 10.58$ GeV + scans

$\sigma(e^+e^- \to \Upsilon(4S) \to B\bar{B}) = 1.1$ nb

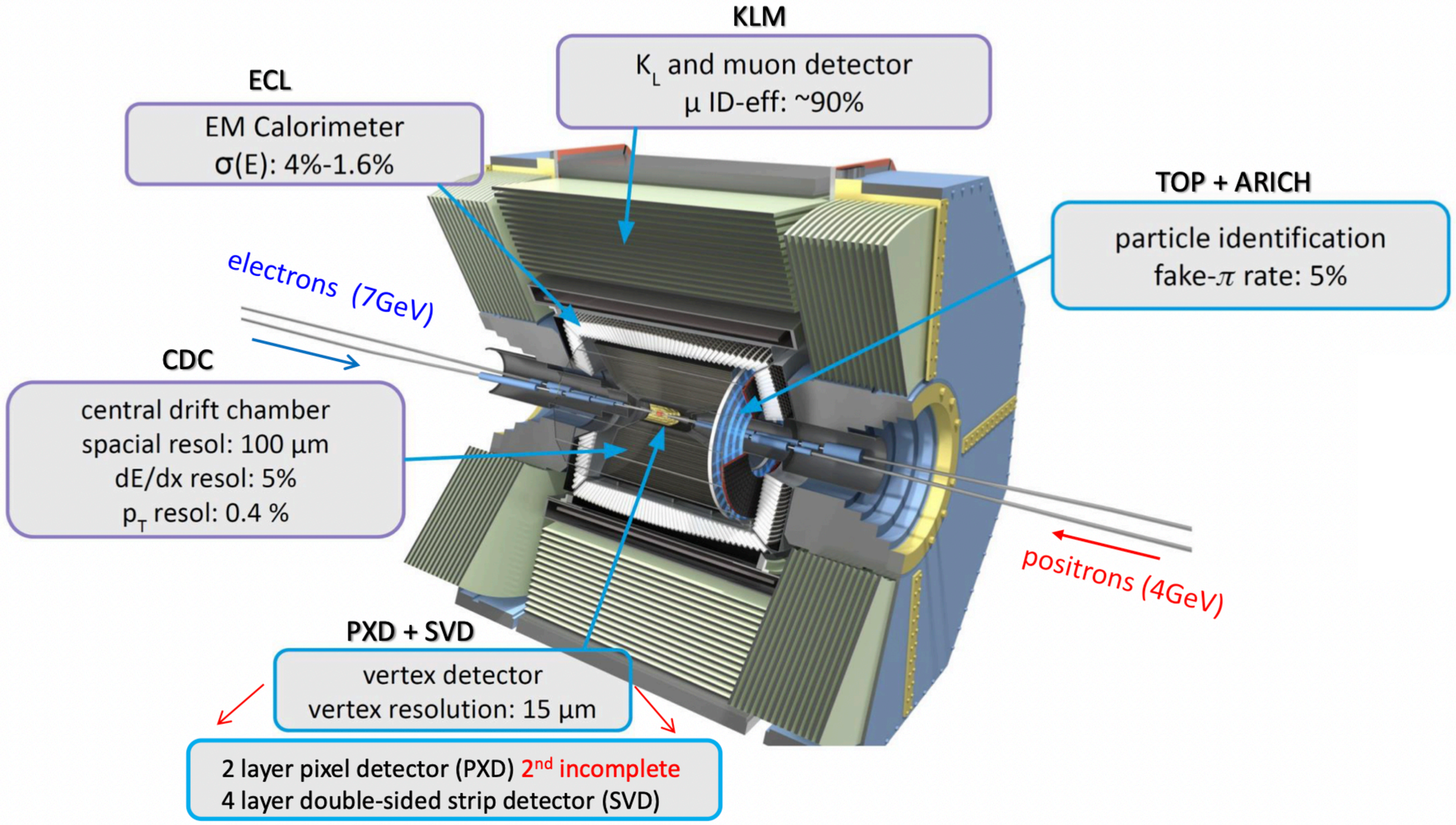
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb

$\sigma(e^+e^- \to \tau^+\tau^-) = 0.9$ nb

Super B (+charm + τ) Factory

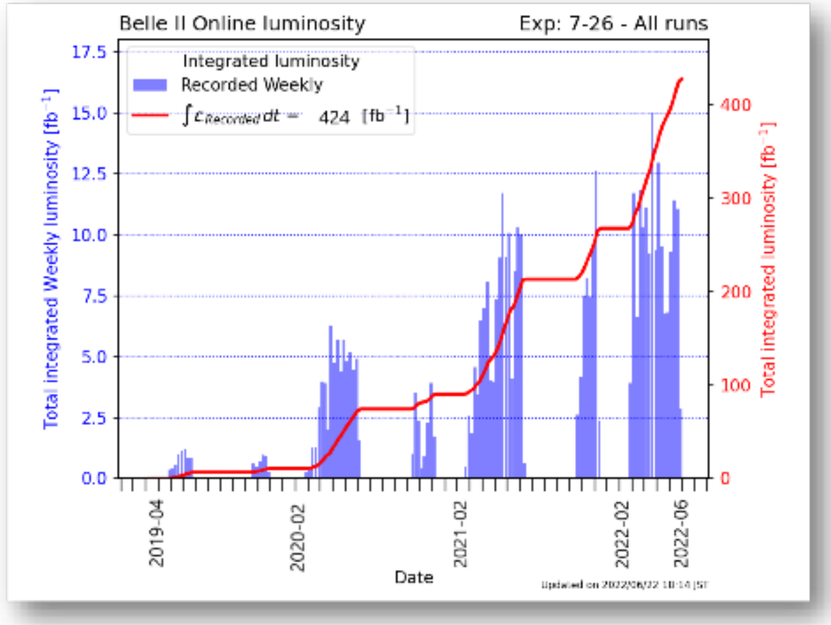
~1100 researchers 123 institutions
26 countries and regions

Belle II detector

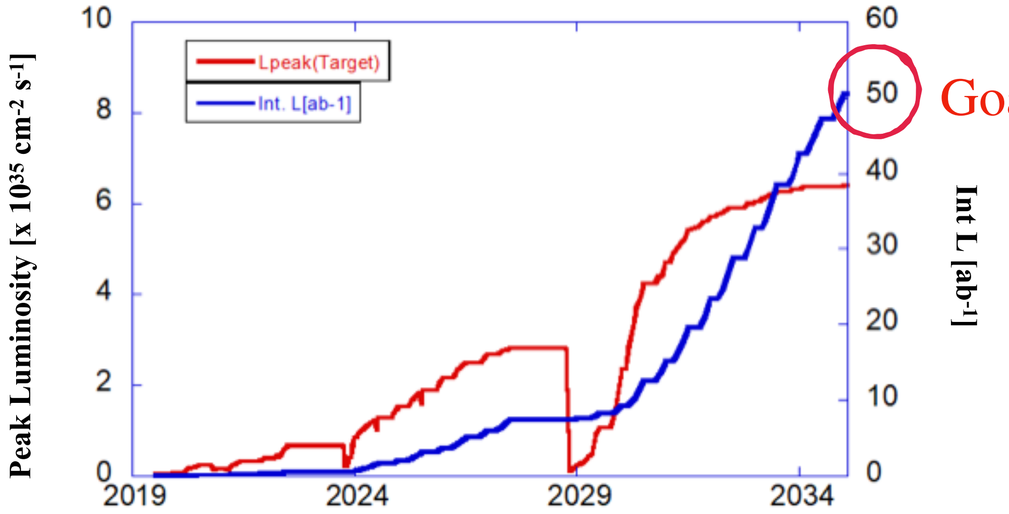


Hermetic detector and Well known initial condition	Low background	Excellent PID	Dedicated triggers for Low Multiplicity events

Luminosity Status and projection

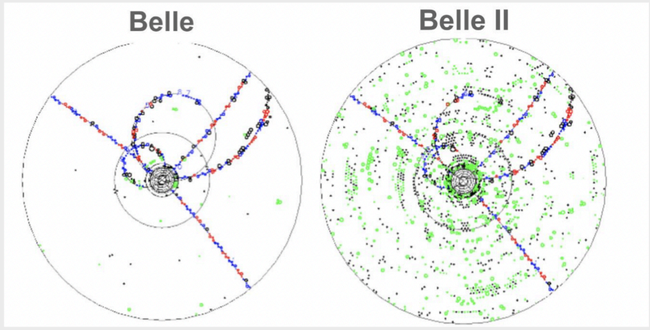


- So far $L_{\text{int}} = 424\ \text{fb}^{-1}$ (~ BaBar, ~1/2 Belle)
- first long shutdown (LS1) mid 2022 - end 2023
  - Install two-layer pixel detector
  - significant improvements made to the accelerator and detector
- Run 2 starts soon in about a month
- Goal: $L_{\text{int}} = 50\ \text{ab}^{-1}$ ($50 \times$ Belle)
  - World record: $L_{\text{peak}} = 4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - Target: $L_{\text{peak}} = 6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$



Goal: 50 ab^{-1}

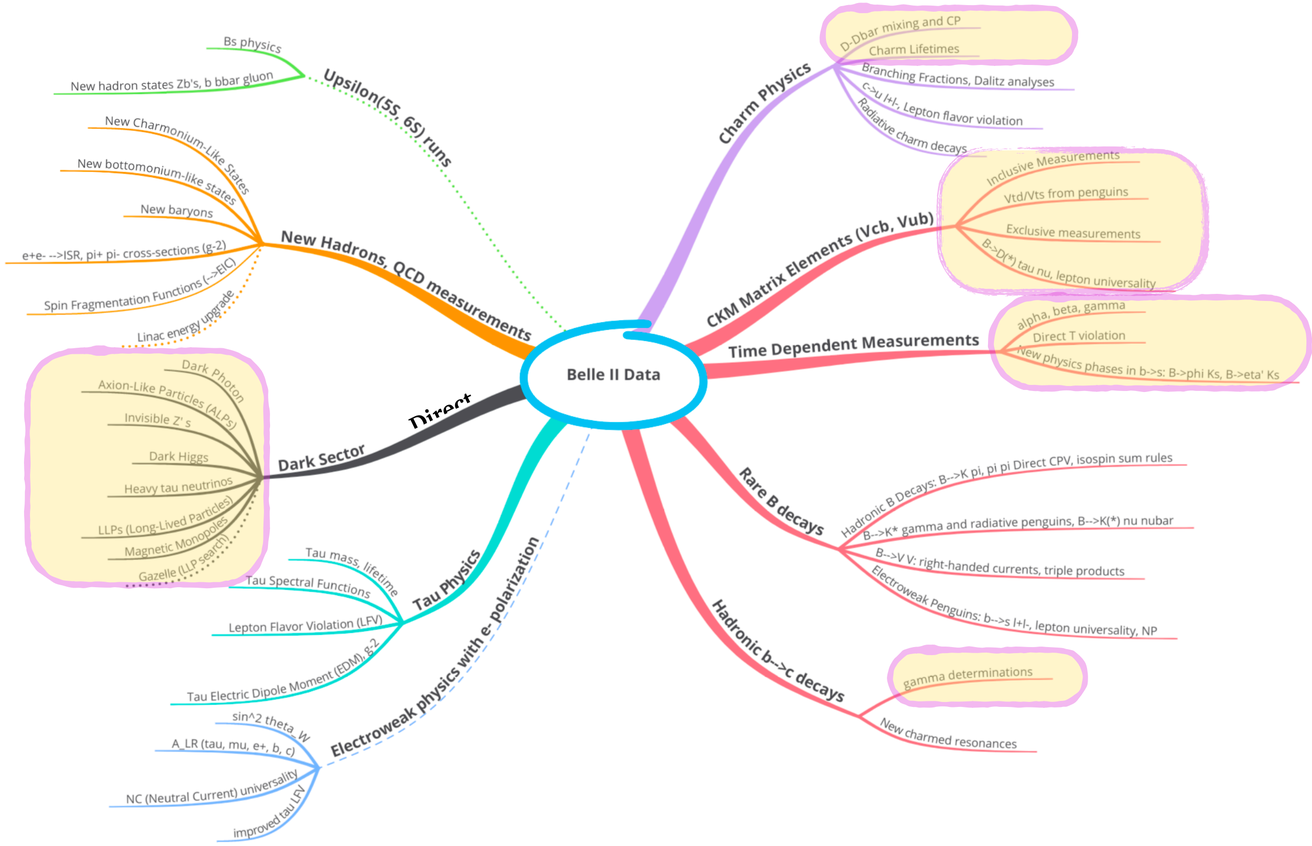
- Increased beam backgrounds
  - ➔ upgraded trigger system with dedicated low multiplicity lines



A diversified Physics Program

Snowmass white paper

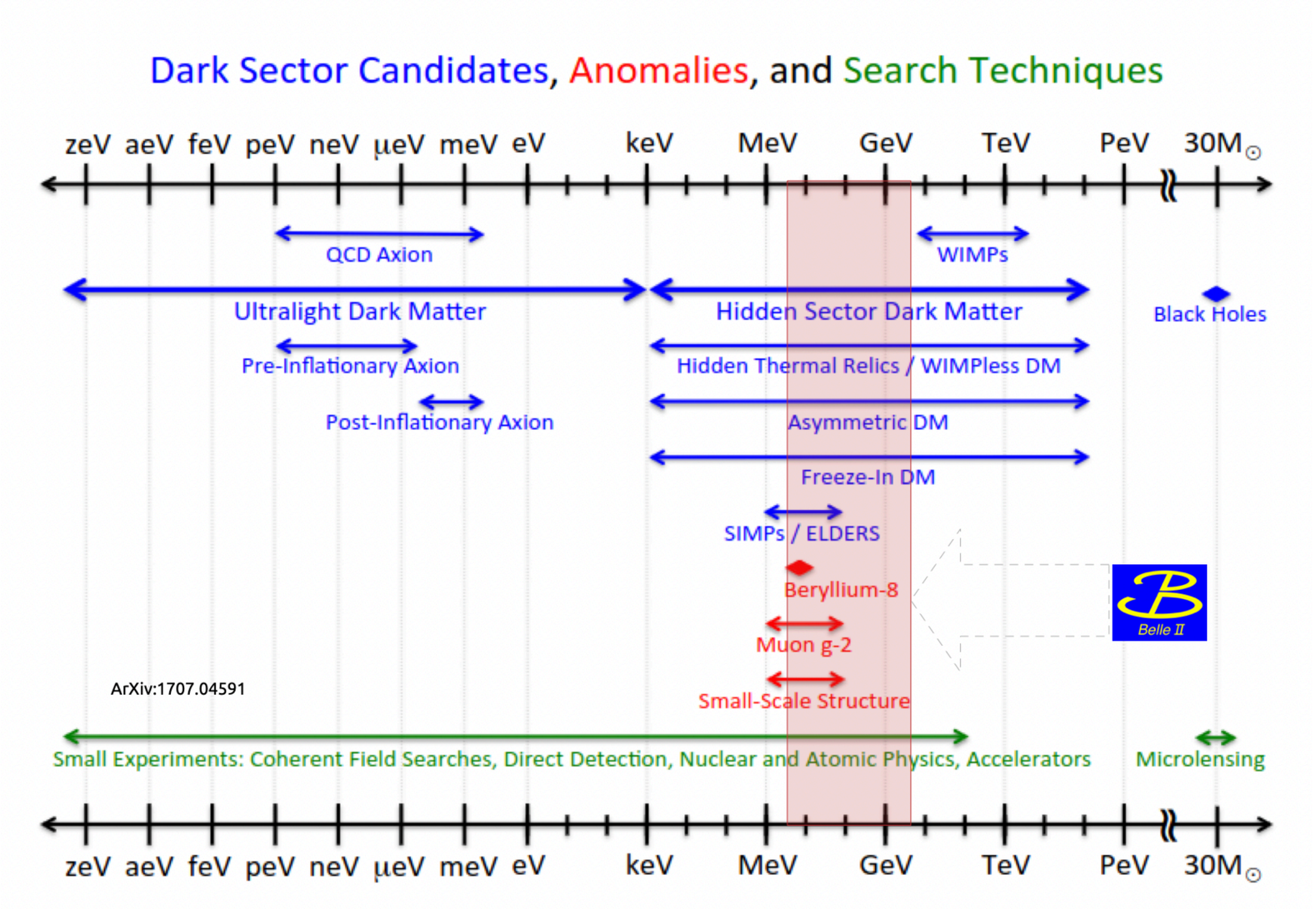
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CP violation)
  - Time dependent CP violation
- BSM Physics
  - Rare decays
  - NP in loop in $b \to s\gamma$, $b \to sll$
  - Tests for LFU such as $R(D^{(*)})$
  - radiative, semi-(leptonic) modes
- Charm Physics
- τ Physics
- Hadron Spectroscopy
- **Dark Sector**
  - Z', Axion, Dark Photon, HNL, LLP



https://confluence.desy.de/display/BI/Journal+Publications

September 2023 – 26 Belle II submissions + 16 in CWR1 or beyond

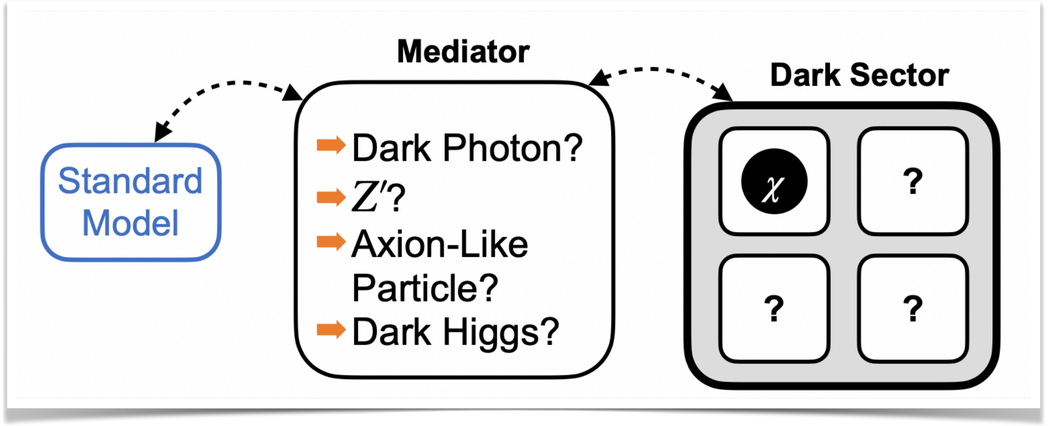
Light Dark Matter



Why Dark sector at Belle II?

In recent years the possibility that both DM and the particles mediating its interactions to the Standard Model (SM) have a mass at or below the GeV–scale has gained much attraction.

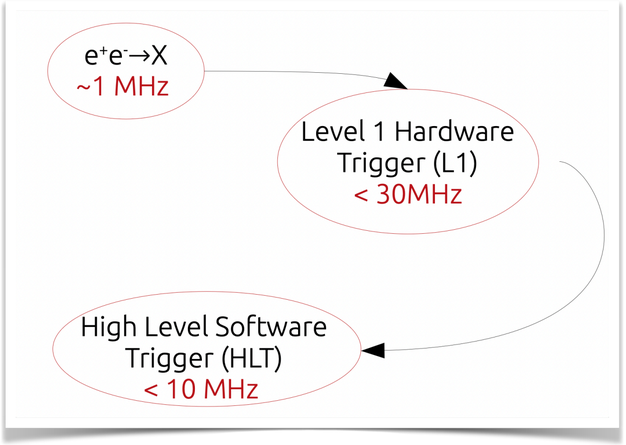
- Belle II has unique sensitivity to dark matter via missing energy decays.
- Belle II is sensitive to direct production of MeV to GeV scale Mediators between Standard Model and Dark Sectors
- Precise determination of missing energy/momentum
- Special Dark Sector Triggers enabled:

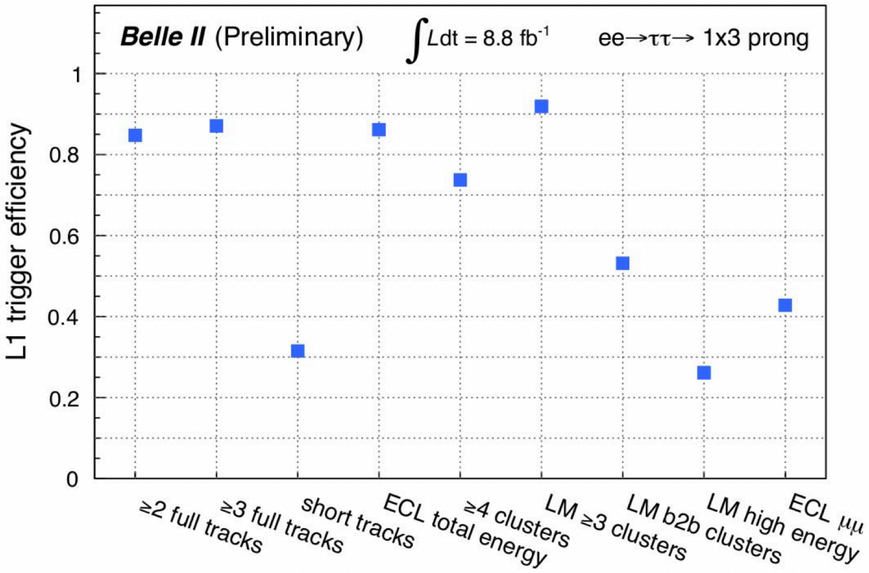


1. Vector portal (Dark Photons, Z' bosons)
2. Pseudo-scalar portal (Axion Like Particles)
3. Scalar portal (Dark higgs/Scalars)
4. **Neutrino portal** (Heavy neutral lepton)

Trigger System

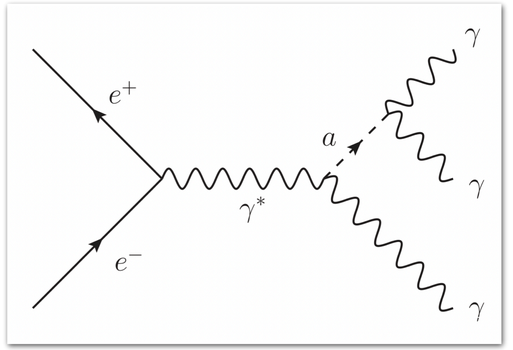
- Two-tier trigger system
  - Hardware based low level trigger (L1)
  - Software based high level trigger (HLT)
- Reduce effects from beam backgrounds (Touschek effect, beam-gas scattering, radiative Bhabha, …)
- L1 trigger
  - Maximum trigger rate 30KHz
  - Combines 4 sub-detector triggers; **Drift Chamber, Cherenkov detectors, Muon System, Electromagnetic Calorimeter**
- Dedicated trigger lines for dark sector and low-multiplicity physics (not available in Belle):
  - Single photon / track
  - Multi track triggers
    - **2 full tracks with opening angle requirement used in dark higgsstrahlung/invisible Z' searches**
    - **Logical OR of a three-track trigger and a single-muon trigger used in X searches in $e^+e^- \to \mu^+\mu^-(X \to \tau^+\tau^-)$ and $e^+e^- \to \mu^+\mu^-(X \to \mu^+\mu^-)$ decays**
  - 3D neural trigger





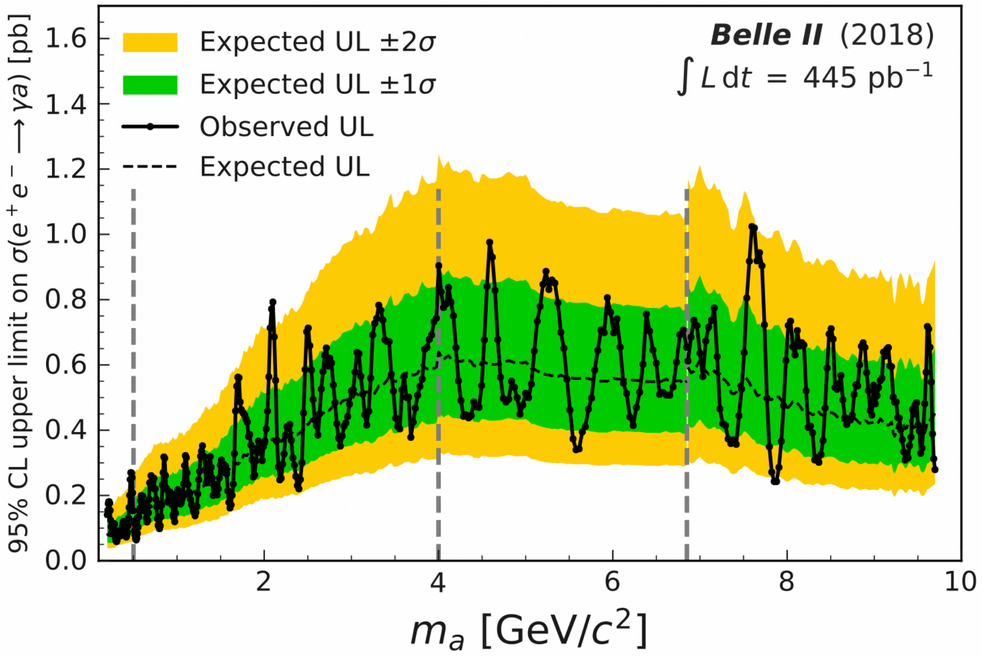
Search for Axion-like Particle (ALP) in $e^+e^- \to \gamma a, a \to \gamma\gamma$

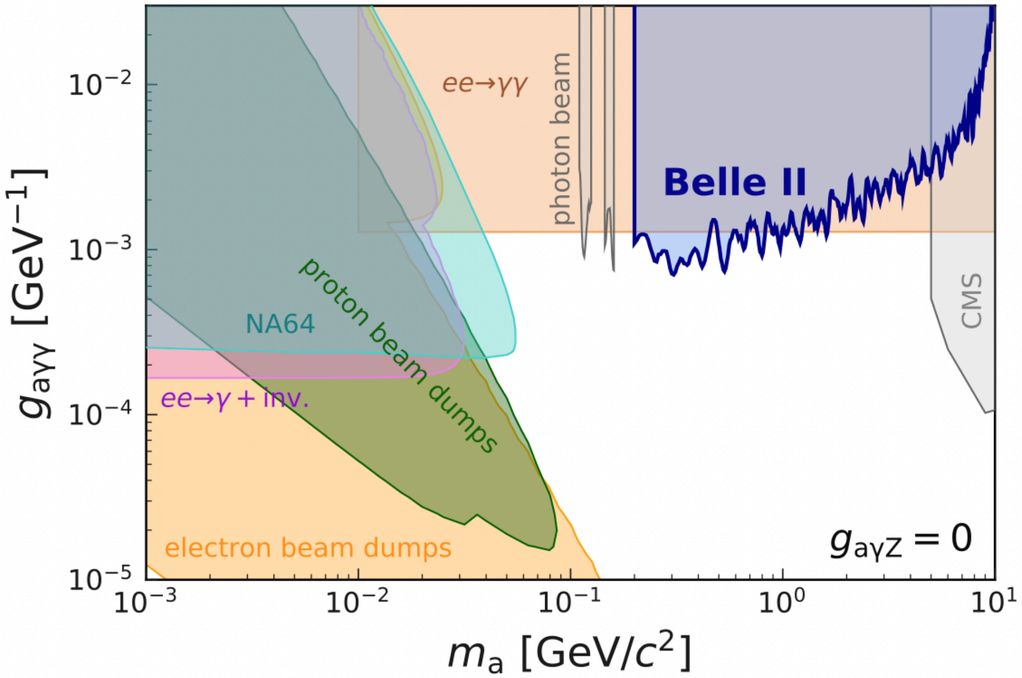
- Search conducted with 445 pb^{-1} of data
  - No excess observed (Largest local significance 2.8σ)
- 98% CL UL on $g_{a\gamma\gamma}$
- Already competitive with **preliminary data** (we now have $\times$ 1000 data)
- Belle II has a unique area of sensitivity



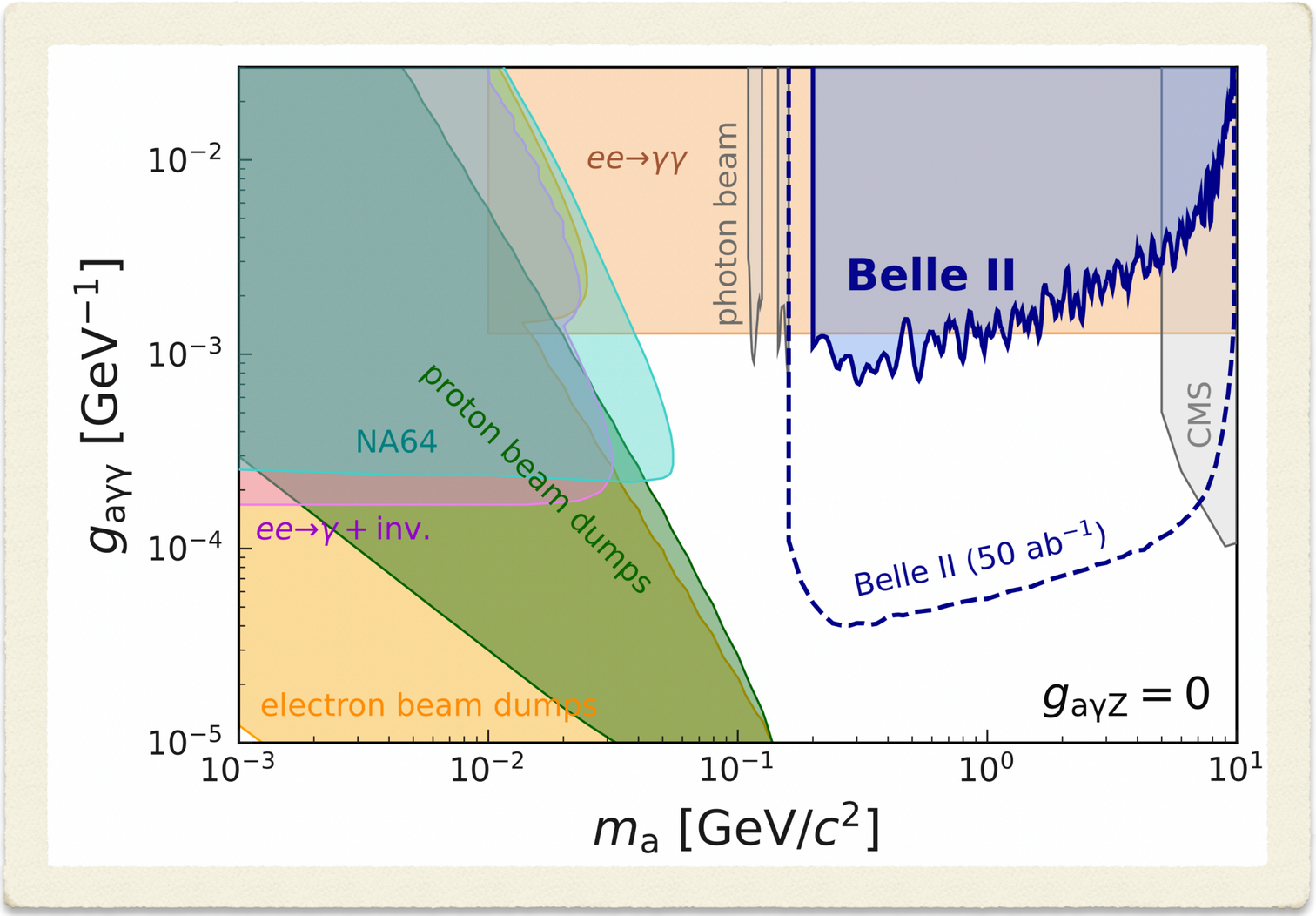
ALP Strahlung

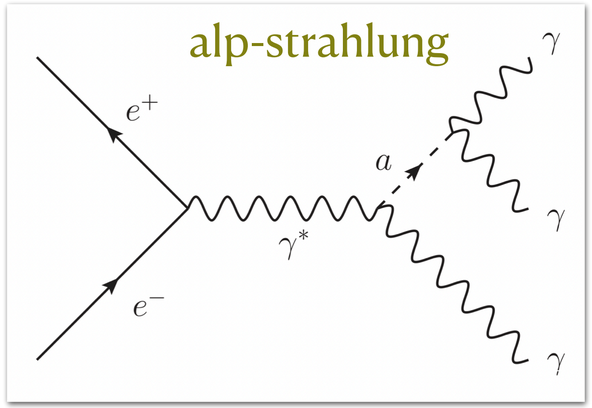
Phys. Rev. Lett. 125, 161806





Search for Axion-like Particle (ALP) overview: projections





Belle II physics reach @ Snowmass
ArXiv: 2207.06307

Recent Dark Sector searches overview

$L_\mu - L_\tau$

$Z' \to$ invisible

$Z' \to \mu\mu$

$Z' \to \tau\tau$

Dark Higgsstrahlung

$A'h'$

$A' \to \mu\mu, h' \to$ invisible

LLP dark scalar in B decays

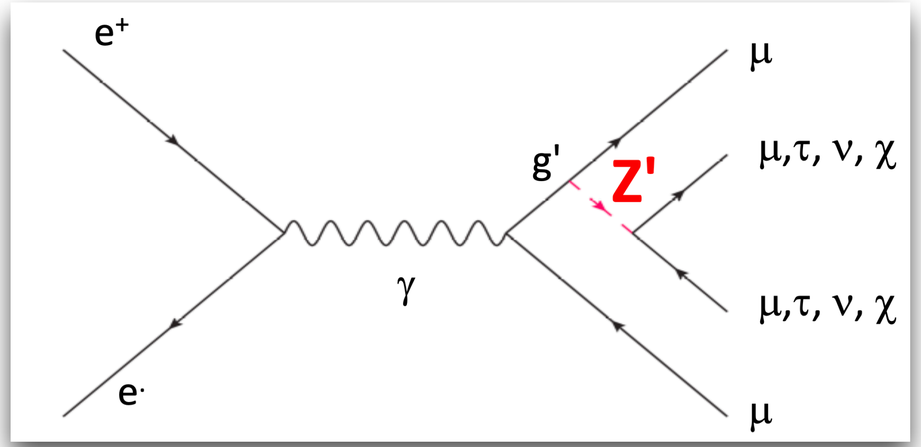
$B \to KS(\to ee, \mu\mu, \pi\pi, KK)$

Invisible boson in τ decays

$\tau \to e\alpha, \mu\alpha$

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

- Model gauges $L_\mu - L_\tau$, the difference of μ and τ lepton numbers
- Z' couples to SM only through $\mu, \tau, \nu_\mu, \nu_\tau$ with coupling g'
- It may solve
  - **Dark matter puzzle** → Sterile ν's / Light Dirac fermions
  - $(g-2)_\mu$
  - **tensions in flavor observables reported by the LHCb, Belle, and BABAR**



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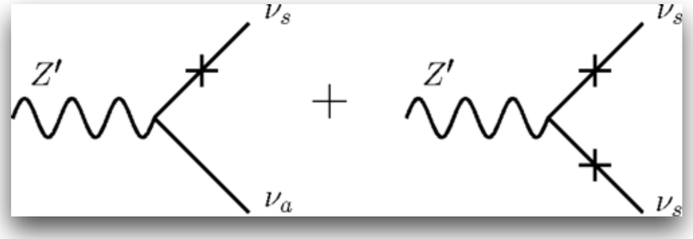
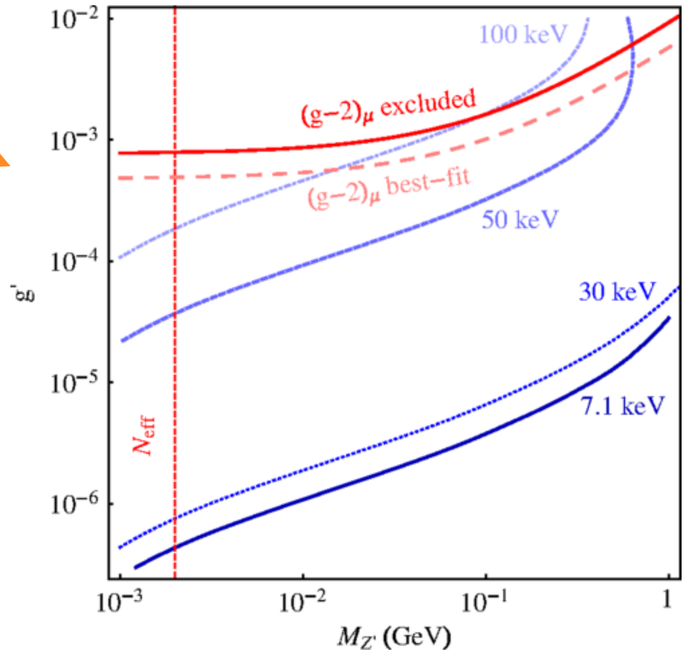


sterile neutrino abundance through Z' decay



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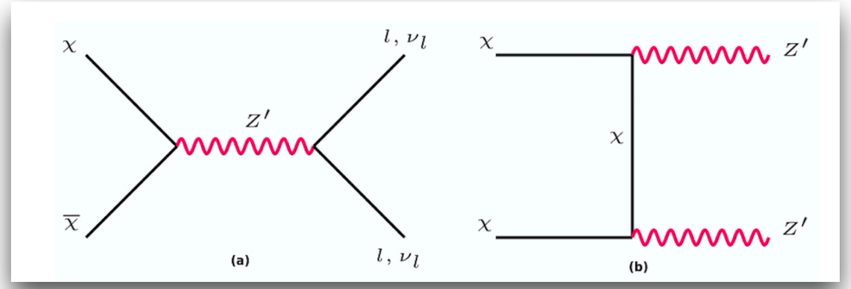
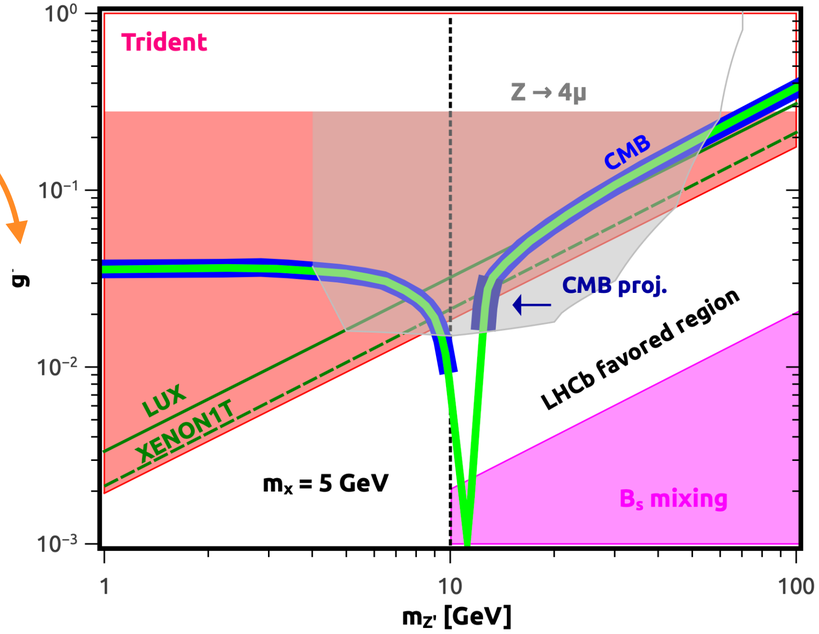


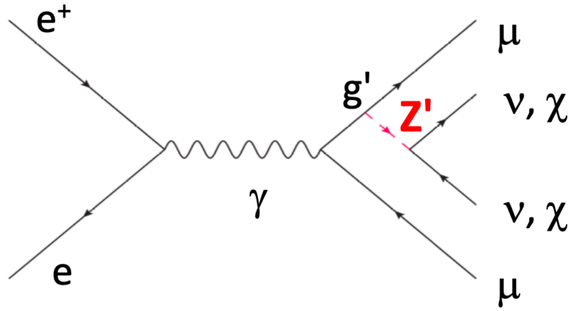
Annihilation diagram

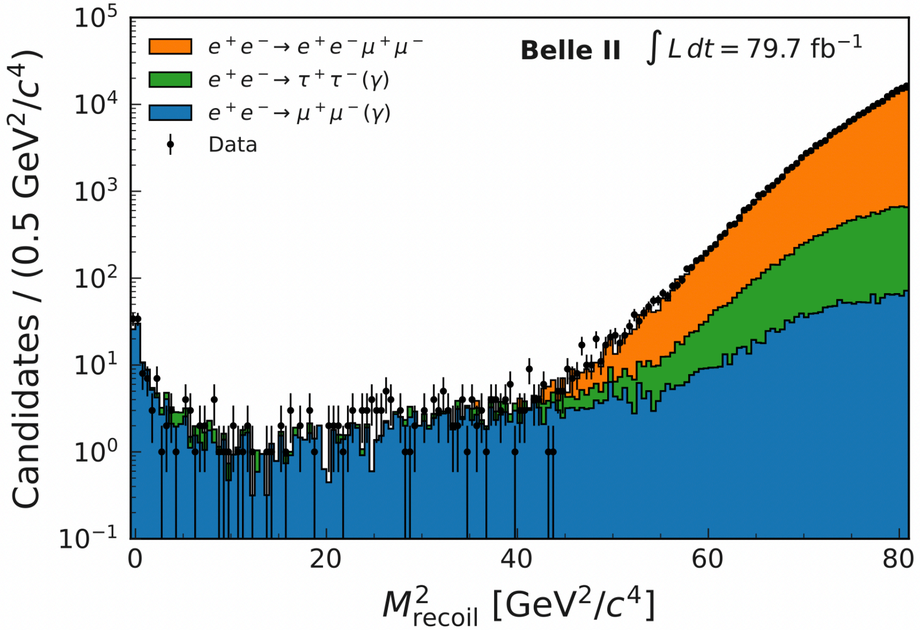


Search for an invisible Z'

PRL 130, 231801 (2023)

- Search for the process: $e^+e^- \to \mu^+\mu^- Z' \to$ invisible
  - Two possible interpretations:
    1. Vanilla, $BF(Z' \to \nu\bar{\nu}) \sim 33 - 100\,\%$
    2. Full invisible , $BF(Z' \to \chi\bar{\chi}) \sim 100\,\%$
- Look for a narrow peak **in the recoil mass against a $\mu^+\mu^-$ pair** in events where nothing else is detected
- Dominant background radiative QED processes:
  1. $e^+e^- \to e^+e^-\mu^+\mu^-$
  2. $e^+e^- \to \tau^+\tau^-(\gamma)$
  3. $e^+e^- \to \mu^+\mu^-(\gamma)$

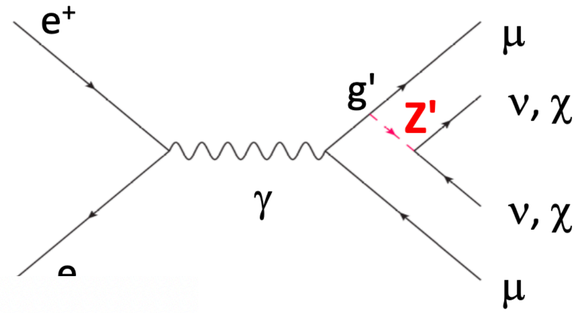




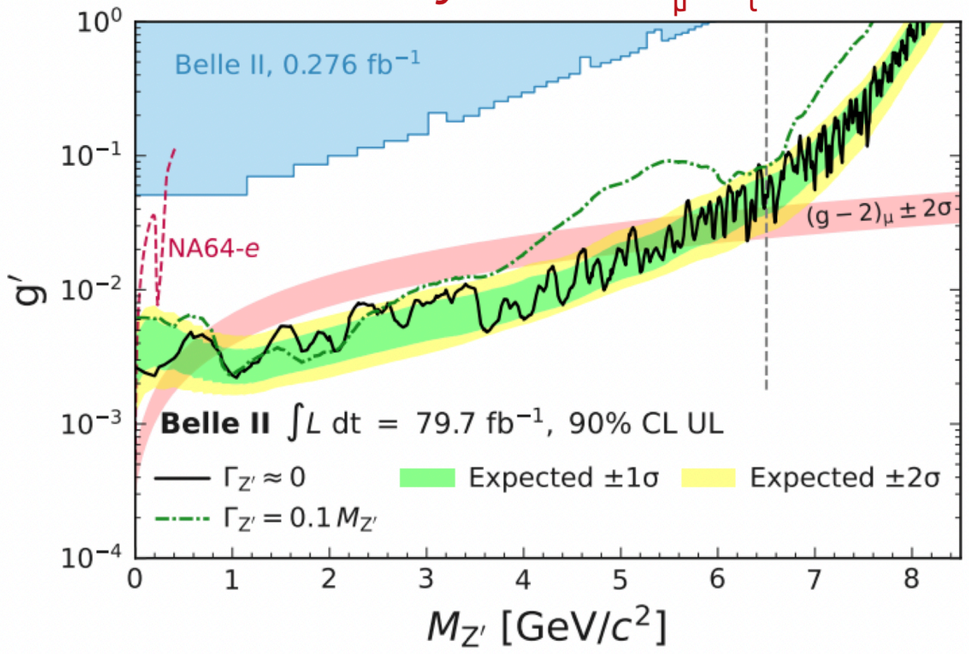
Search for an invisible Z': Results

PRL 130, 231801 (2023)

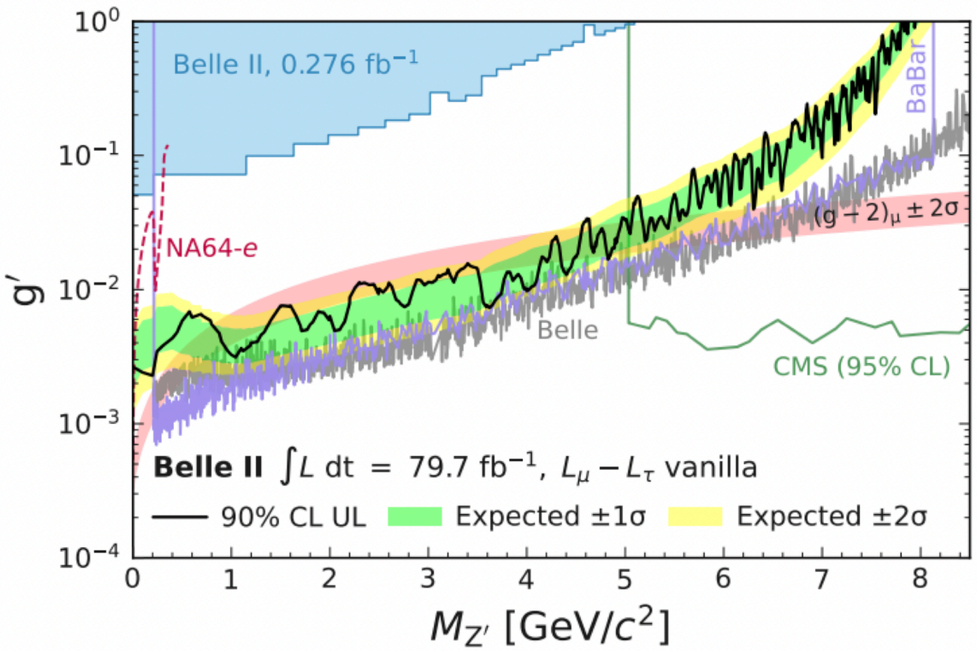
- **No excess found in** 79.7 fb^{-1}
  - 90% CL upper limits on $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \text{invisible})$ and on g'



Fully invisible $L_\mu - L_\tau$



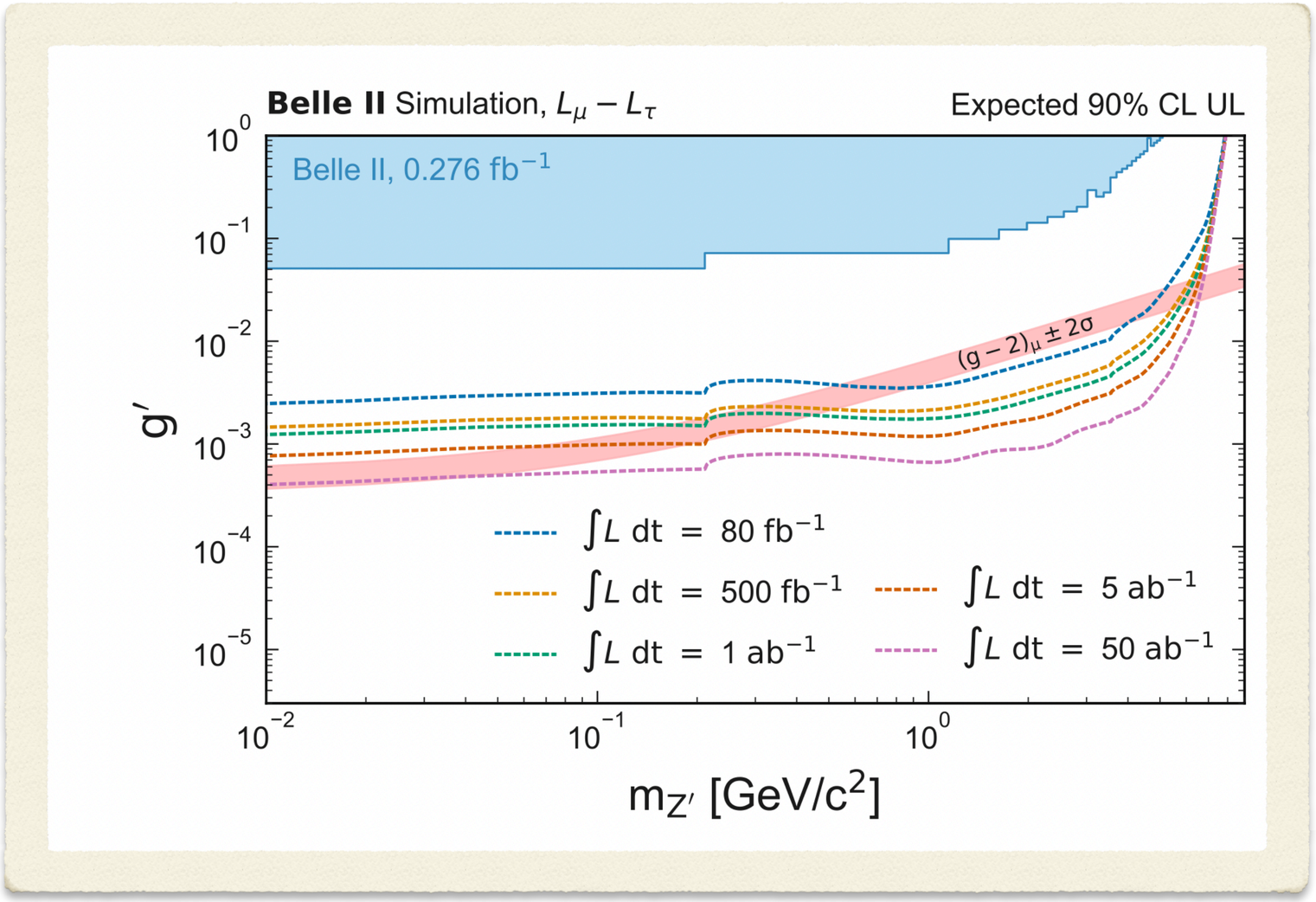
Vanilla

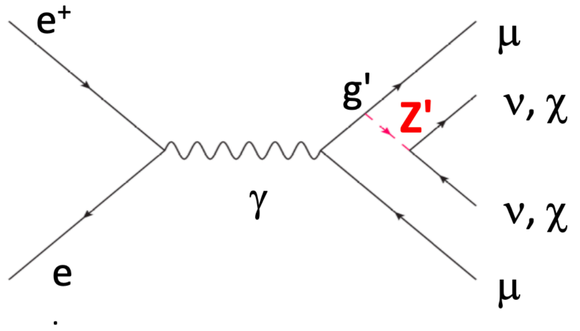


fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Search for invisible Z': projections

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



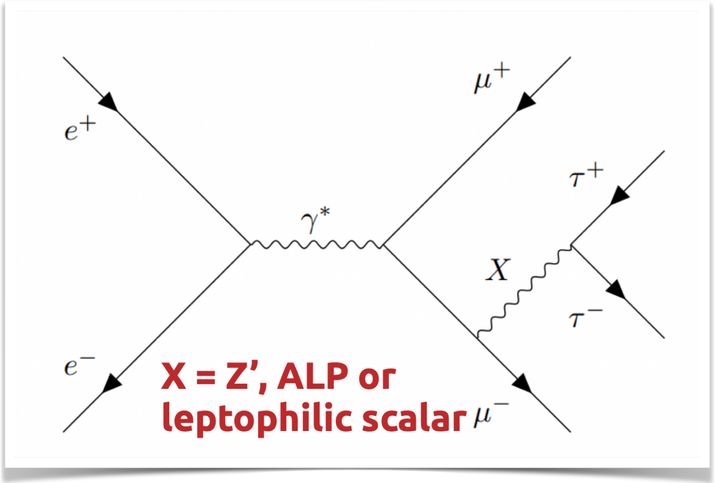


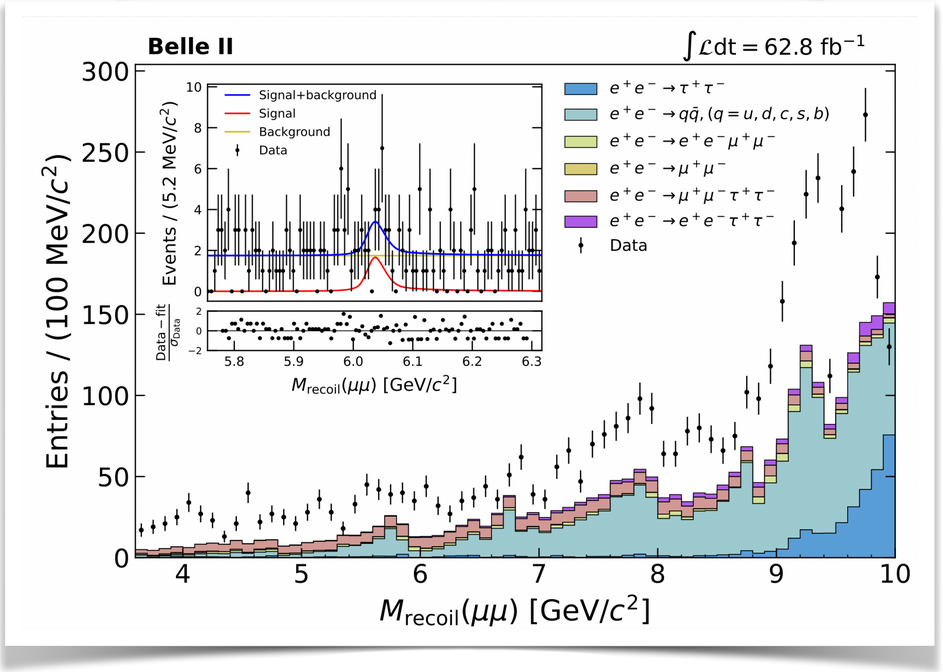
Belle II physics reach @ Snowmass
ArXiv: 2207.06307

Search for $Z' \to \tau^+\tau^-$

Phys. Rev. Lett. 131, 121802

- Search for a **di-tau resonance in** $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ as a peak in the recoil against two muons
- Reconstruct τ **decays to one-charged particle** $(+nh^0)$
  - Select **four-track events** with at least two tracks identified as muons
  - **M(4tracks) < 9.5 GeV/c²** to suppress the four-lepton backgrounds that peak at them c.m. energy
- **Background suppression exploits features of kinematic variables in the signal**
- Discrepancies between data and simulation due to contributions from non-simulated/unmodeled processes

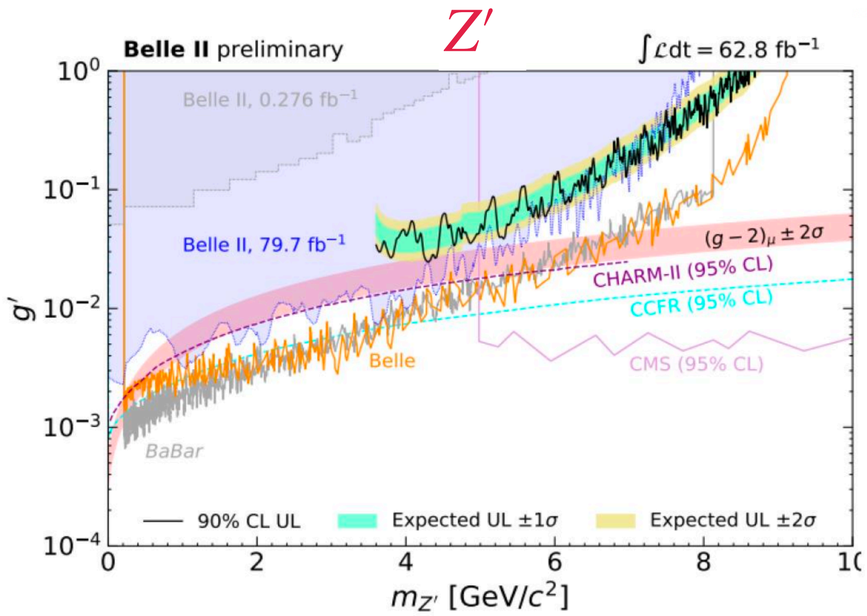


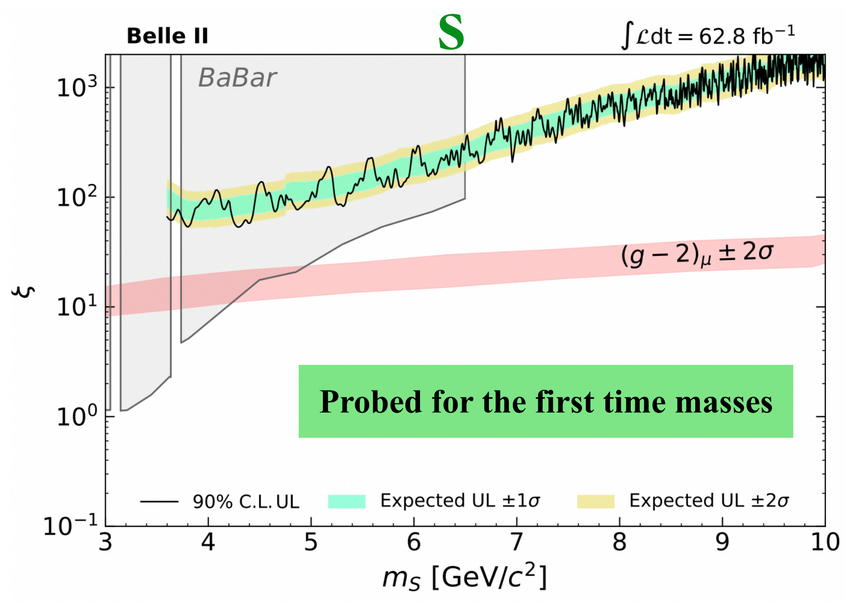


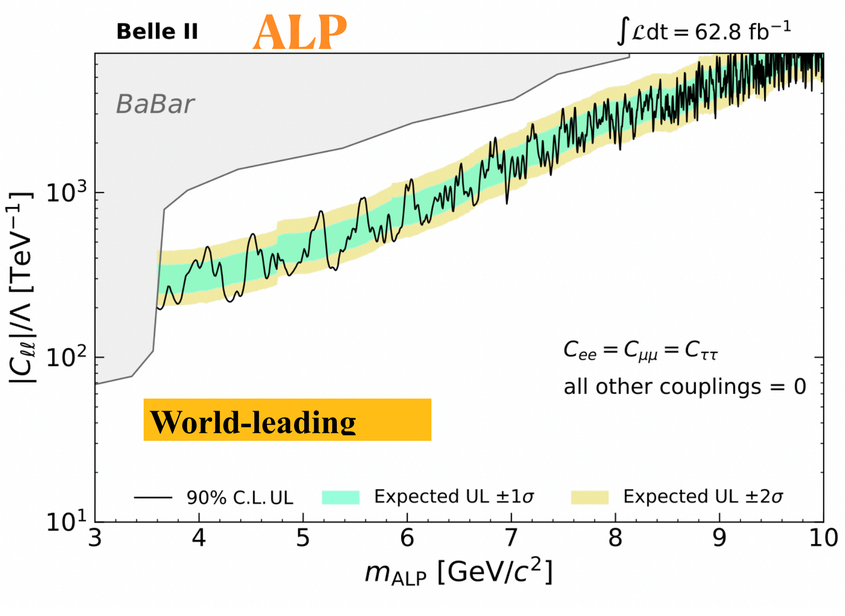
Search for $Z' \to \tau^+\tau^-$: Results

Phys. Rev. Lett. 131, 121802

- **No significant excess observed in** 62.8 fb^{-1}
  - 90% CL upper limits on $\sigma(e^+e^- \to \mu^+\mu^-(X \to \tau^+\tau^-)$, with $X = Z', S$, ALP
- Exclusion limits on the couplings for three different models (Z', leptophilic scalar (S), and ALP) are derived:

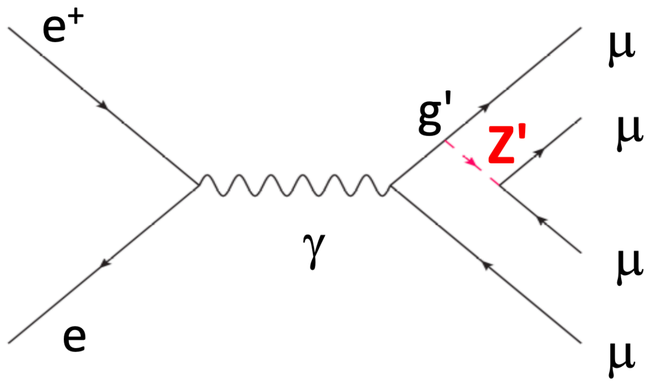






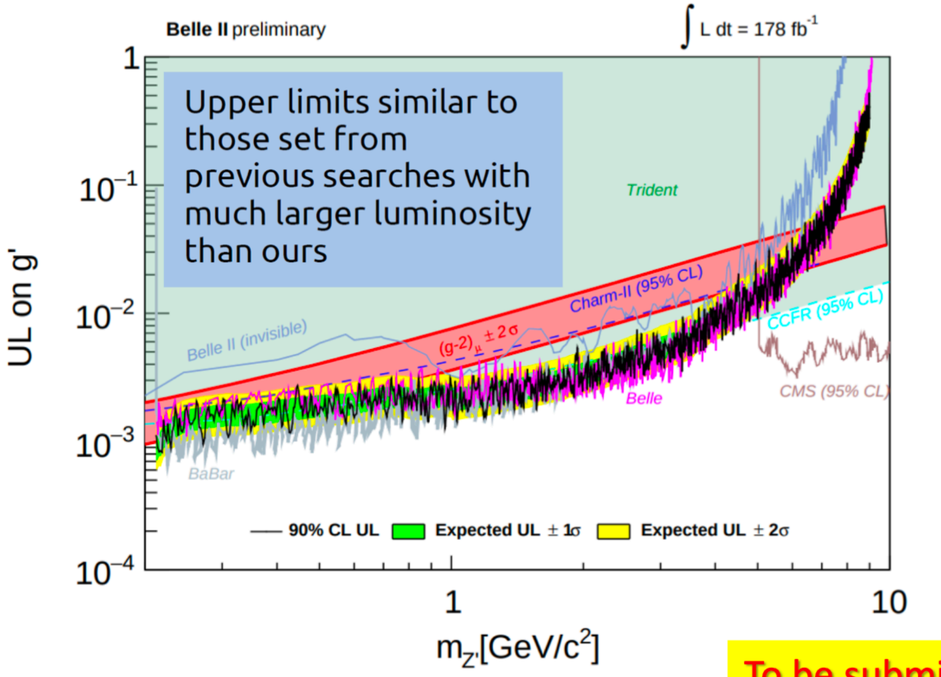
Search for $Z' \to \mu^+\mu^-$: Results

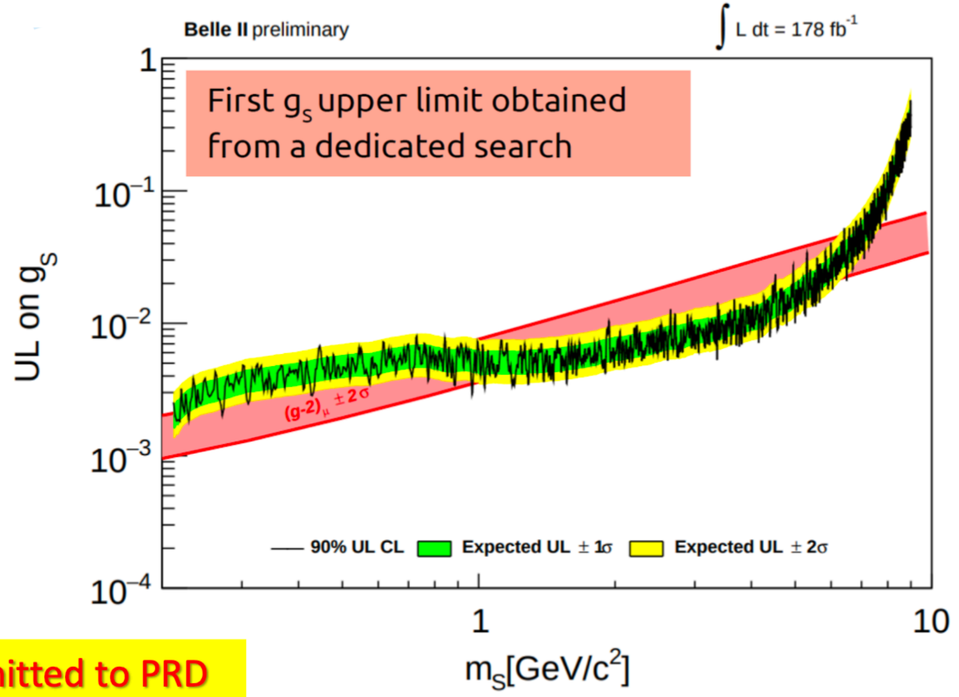
$$e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$$



Reinterpreted also as

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



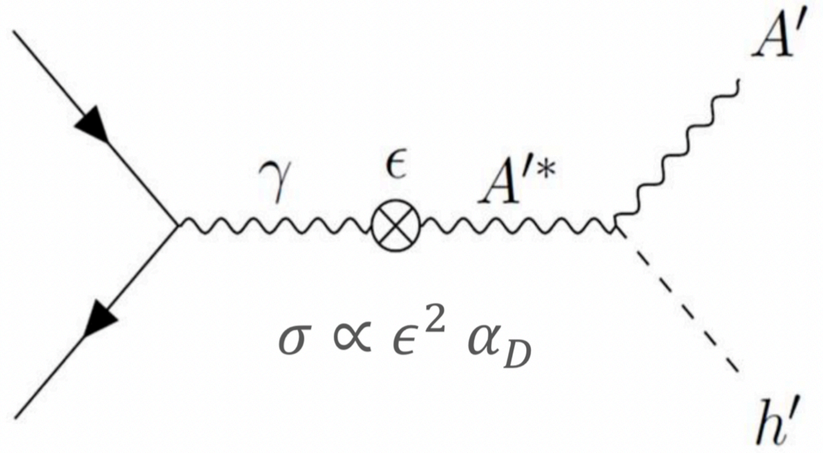


To be submitted to PRD

Search for Dark Higgsstrahlung

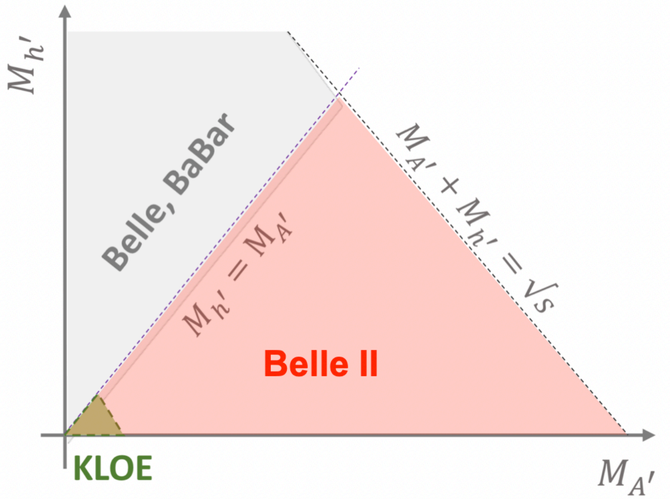
Next to minimal dark photon model

- Dark photon (A') couples to SM photon via kinetic mixing parameter ϵ
- A' mass can be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson (h') to the theory.
  Phys. Rev. D 79, 115008 (2009)
- No dark Higgs mixing with SM Higgs.
- Both particles can be produced via dark Higgsstrahlung process.



Mass hierarchy scenarios

- $M_{h'} > M_{A'} : h' \rightarrow A' \rightarrow 4l, 4\text{had}, 2l + 2\text{had} \implies$ 6charged tracks
  - Searches conducted by Belle (2015) and BaBar (2012)
- $M_{h'} < M_{A'}$: h' is long-lived and so invisible $\implies$ 2 charged tracks
  - Partially constrained by KLOE (2015)



Exploring unconstrained regions at Belle II !

Search for Dark Higgsstrahlung: Analysis Strategy

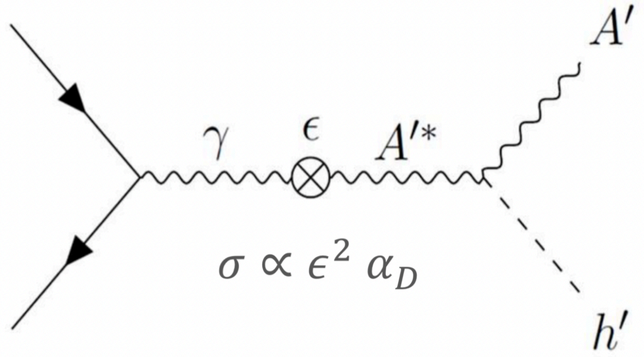
Data sample: 2019 dataset $\Longrightarrow$ 8.34 fb^{-1}

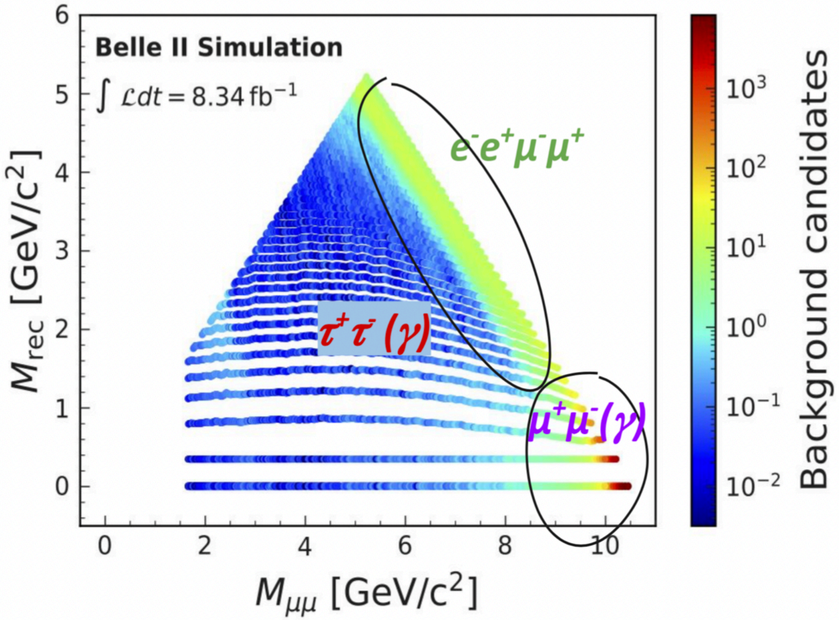
Detector signature

- Looking for invisible h' with
  $A' \to \mu^+\mu^- \Longrightarrow \mu\mu +$ missing energy
- 2D peak in $M_{\mu\mu} < M_{rec}$
  M_{rec} = invariant mass of the system recoiled against $\mu\mu$.

Surviving backgrounds:

- Main contributions:
  $\mu^+\mu^-\gamma$ (79%)
  $\tau^+\tau^- \to \mu^+\mu^-, 4\nu$ (18%)
  $e^+e^-\mu^+\mu^-$ (3%)
- Mostly localised near the kinematic limit, especially for $M_{\mu\mu} > 9$ GeV



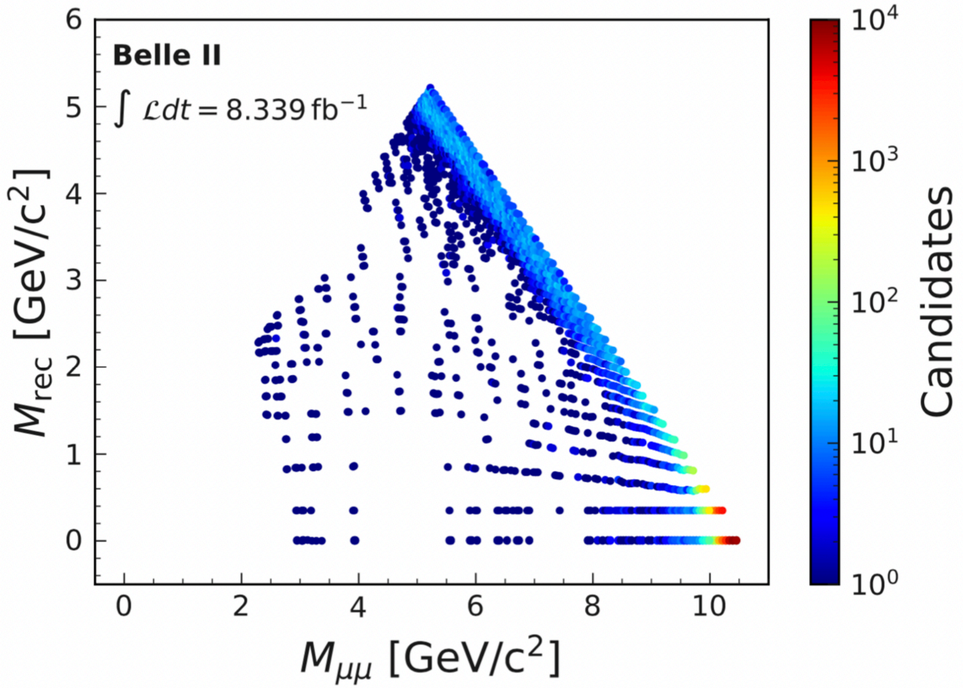


Search for Dark Higgsstrahlung: Results

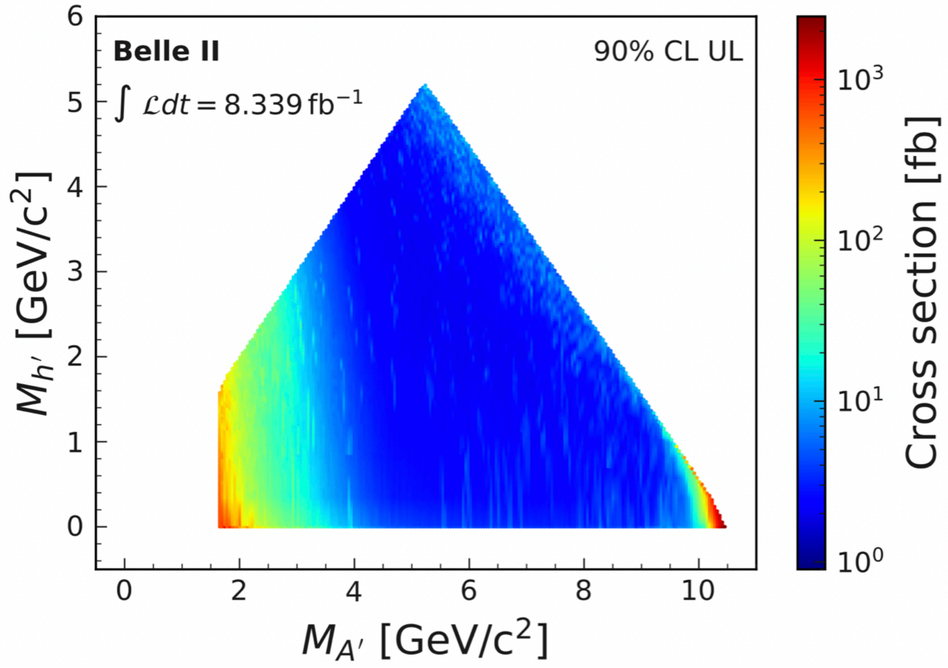
Phys. Rev. Lett. 130, 071804

Search for excesses above expected background independently in the ~9k search windows

- Event counts in a single window interpreted as: $N = \epsilon_{sig} \times L \times \sigma_{DH} + B$ with systematic uncertainties taken into account.



- Find no significant excess above background.
- 90% upper limits computed in a Bayesian approach on the cross section from 1.65 - 10.51 GeV in $M_{A'}$ ($M_{h'} < M_{A'}$)

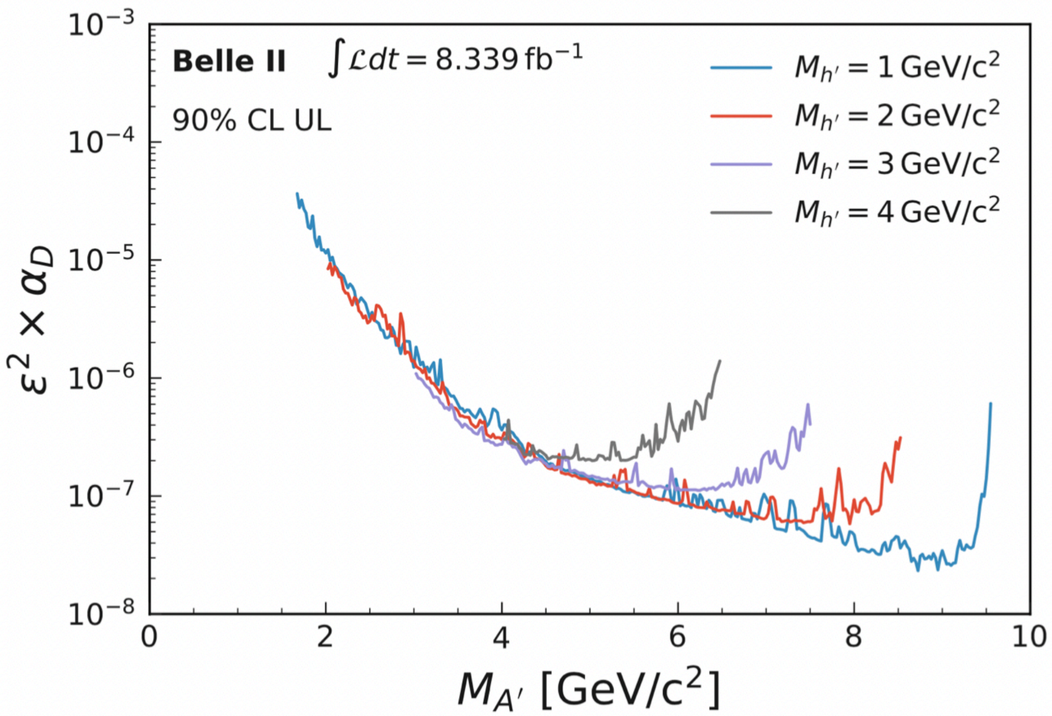


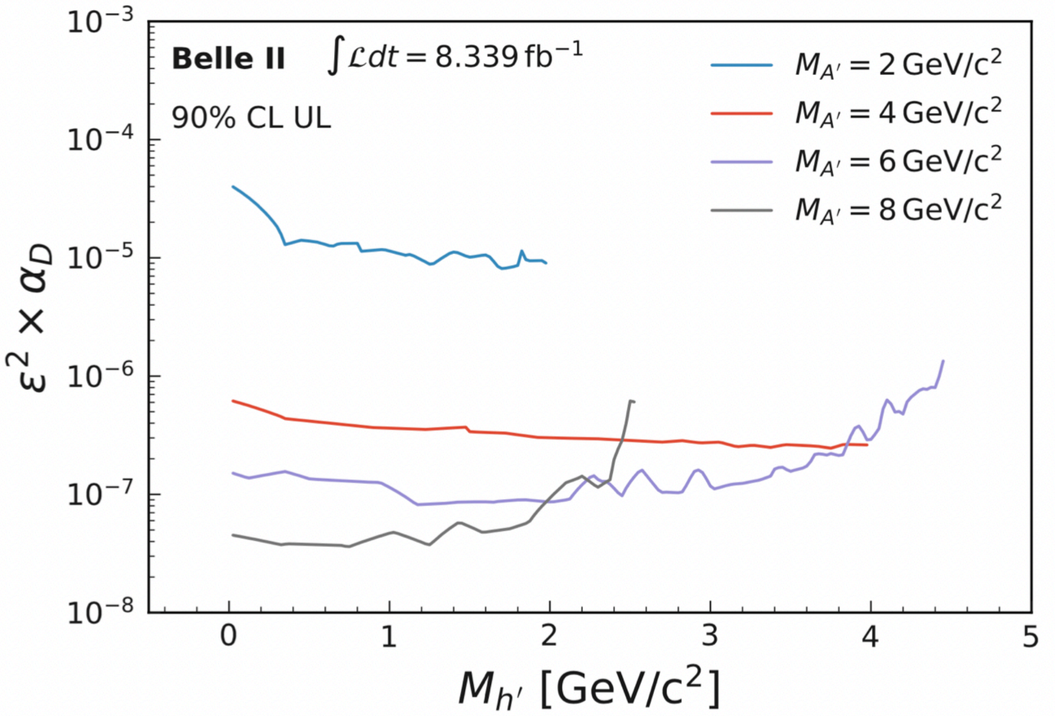
World leading ULs in previously unexplored regions !

Search for Dark Higgsstrahlung: Results

Phys. Rev. Lett. 130, 071804

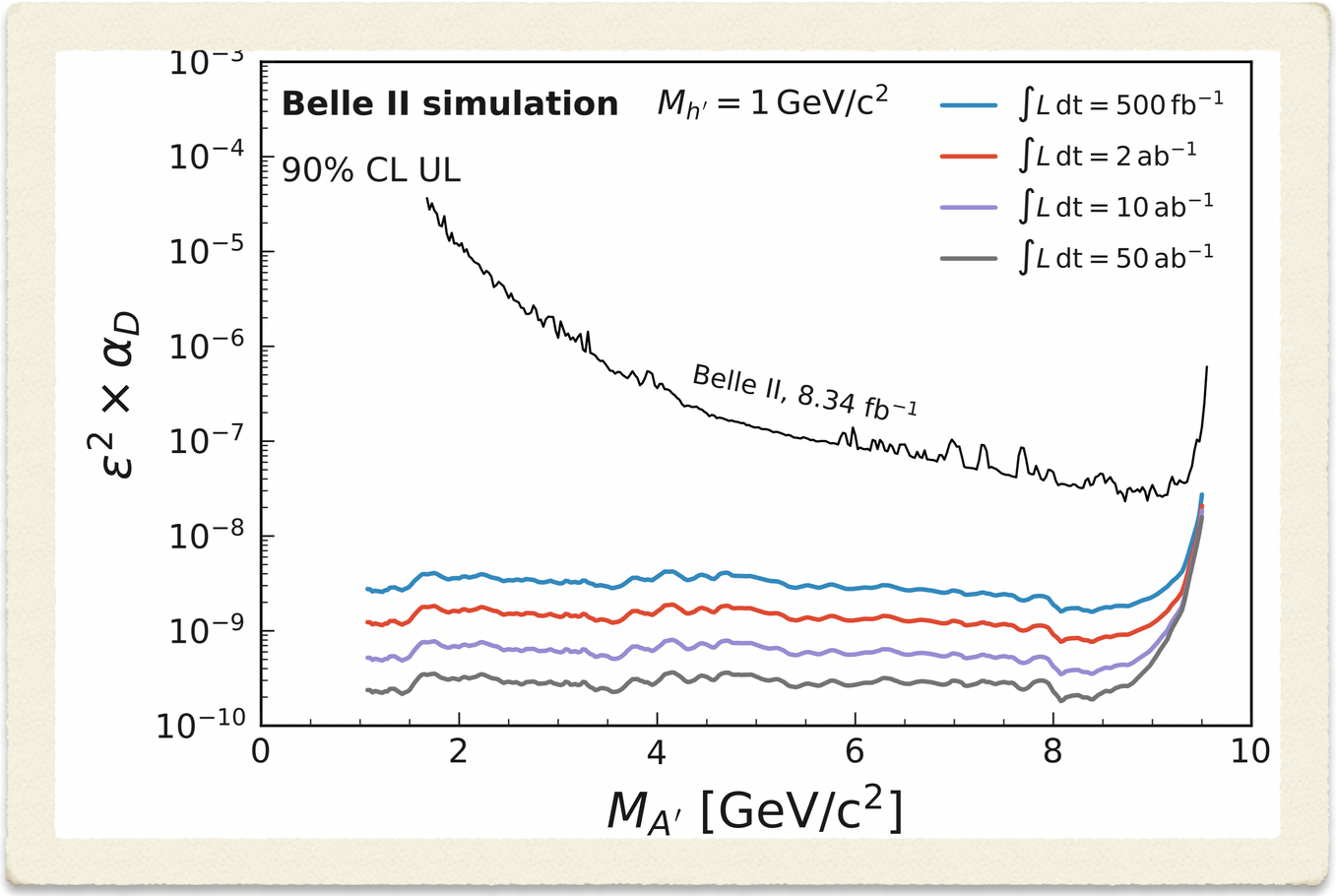
Upper limits also computed in terms of the effective coupling:

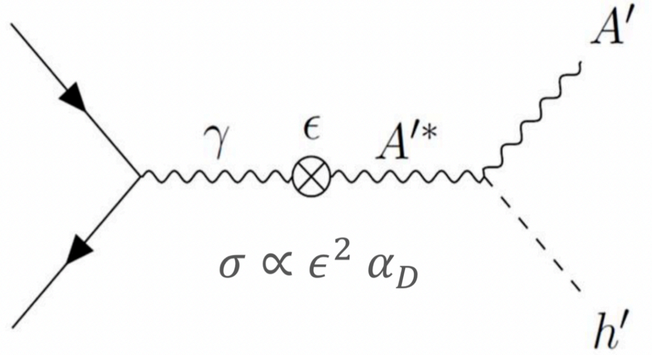




World leading ULs in previously unexplored regions !

Search for Dark Higgsstrahlung: Projections





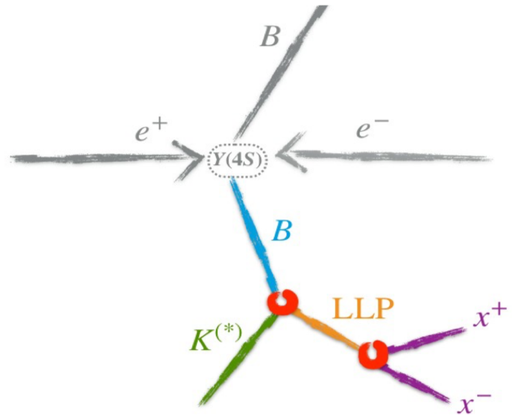
Belle II physics reach @ Snowmass

ArXiv: 2207.06307

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

Motivation:

- **First model-independent** search in rare $b \to s$ transition
- Possible missing with SM Higgs with mixing angle θ_s
- For $M_S < M_B$, decay to **DM** kinematically forbidden by relic density constraint
- Look for S decays into SM final states in 8 exclusive channels
  - $B^+ \to K^+ S(\to ee/\mu\mu/\pi\pi/KK)$
  - $B^0 \to K^{*0}(\to K^+\pi^-) S(\to ee/\mu\mu/\pi\pi/KK)$



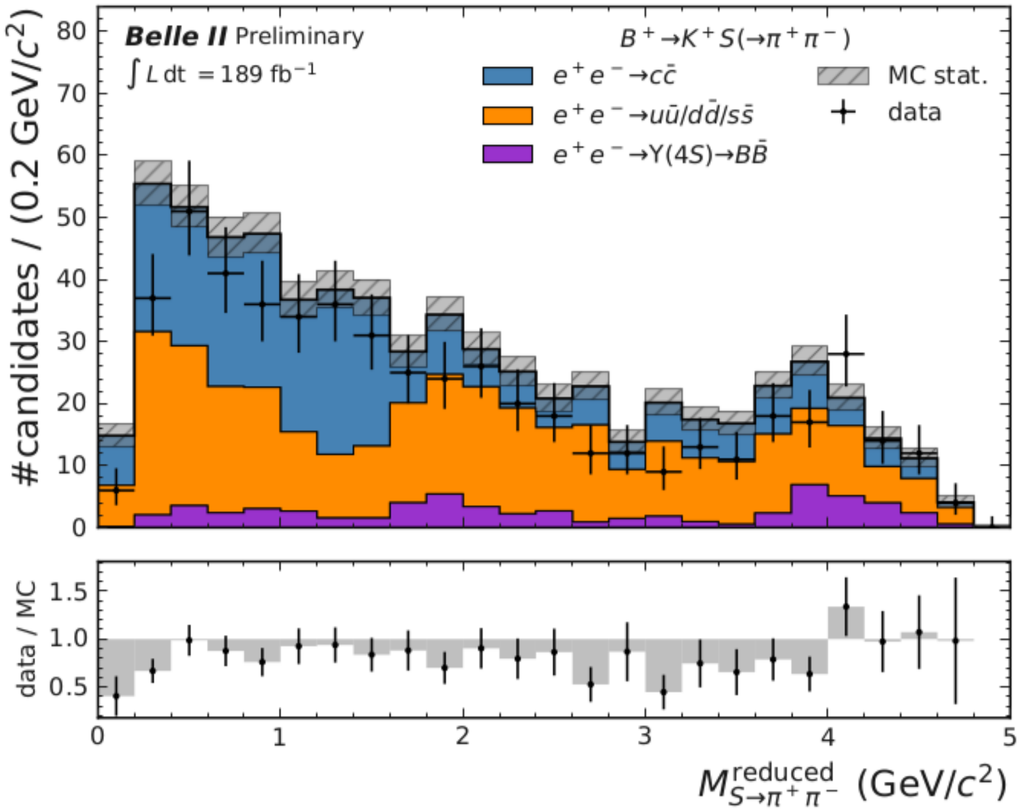
Analysis Overview:

- B-meson kinematics to reject combinatorial $e^+e^- \to q\bar{q}$ background
- Veto region/Control sample: K_S^0 mass region → excellent control sample in data to evaluate LLP performance (efficiencies, shapes)
- Further peaking backgrounds suppressed by tighter displacement selection

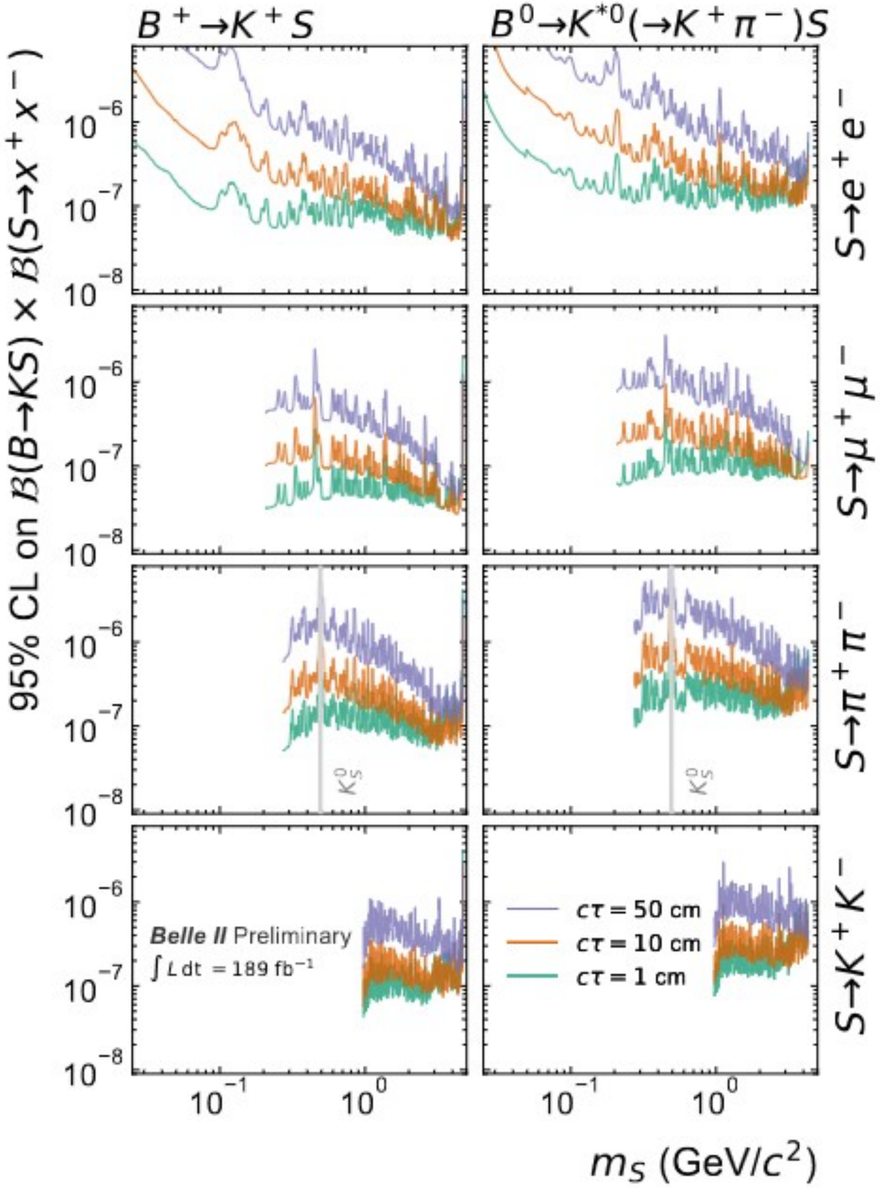
Search for a long-lived (pseudo)scalar: signal extraction

Submitted to PRL, arXiv:2306.02830

- Bump hunt with unbinned maximum likelihood fit to the modified mass $M'(x^+x^-) = \sqrt{M^2(x^+x^-) - 4m_x^2}$
- Background determined directly in data (robust against un-modelled non-peaking background)



Search for a long-lived (pseudo)scalar: Results

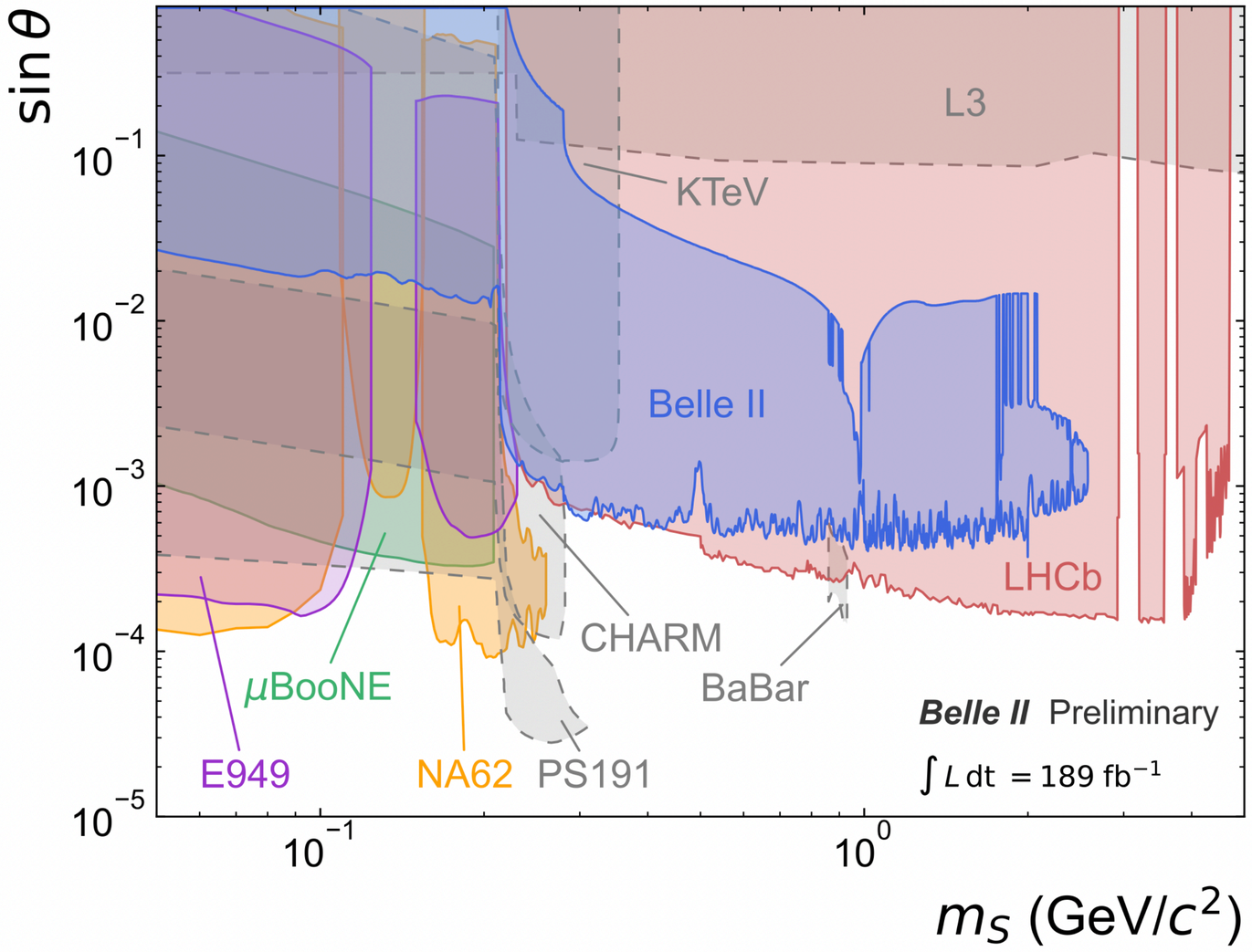


Submitted to PRL, arXiv:2306.02830

- No significant excess found in **189 fb-1**

Search for a long-lived (pseudo)scalar: Results

Submitted to PRL, arXiv:2306.02830

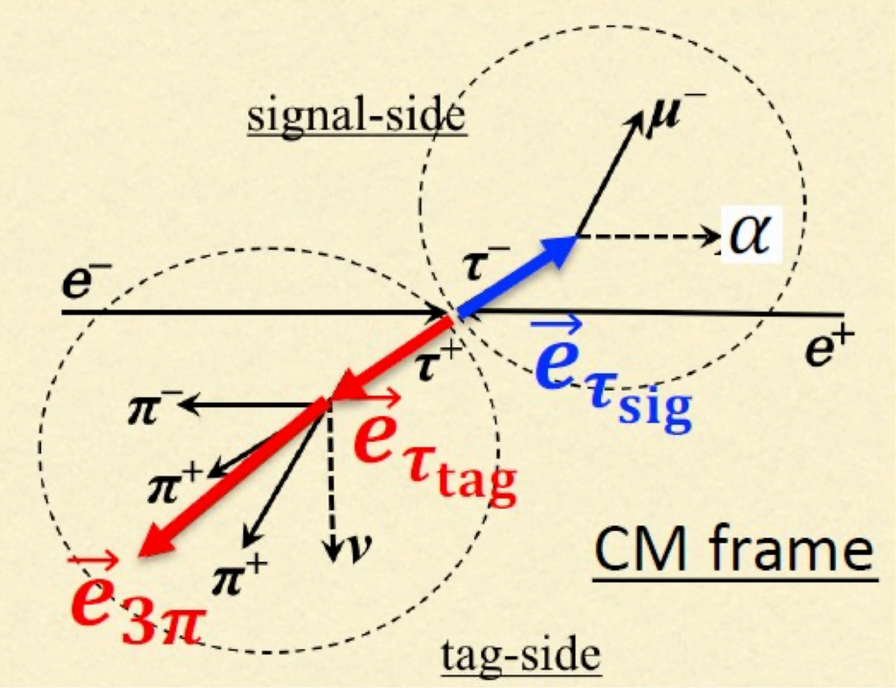


Search for invisible boson in lepton-flavor violating τ decays

- α is a spin-0 non-detected (invisible) particle
  - e.g. an ALP
- Interesting mass range from 100 MeV - 1.6 GeV not covered by other searches
- Previous limits from ARGUS (1995): $10^{-2} - 10^{-3}$ with α mass in the $(0 - 1.6)$ GeV/c^2 range
- We report a search for LFV $\tau \to l\alpha$ decay

Analysis Strategy

- Data sample: 63 fb^{-1}
- Tag with $\tau \to h^-h^+h^-\nu_\tau$ $(h = \pi, K)$ with π^0 veto
- Similar visible topology from background from $\tau \to l\nu\nu$ as signal $\tau \to l\alpha$ $(l = e, \mu)$
  - Use two body (signal) vs 3-body kinematics (background) to isolate signal
- Construct τ pseudo rest frame using
  - $p^{\tau}_{\text{sig}} \approx -\overrightarrow{p}_{3h}/|\overrightarrow{p}_{3h}|$
  - $E^{\text{signal}}_{\tau} = \sqrt{s}/2$



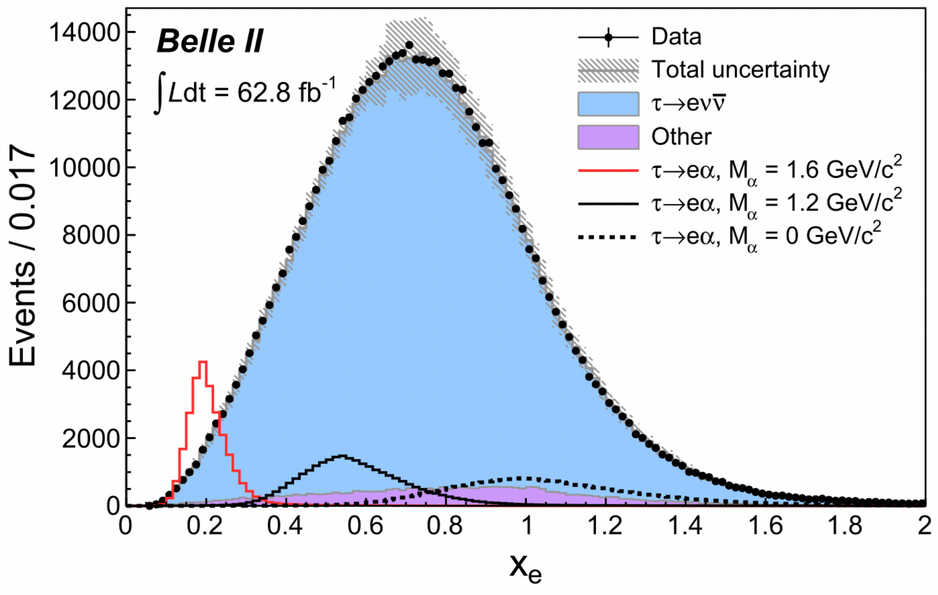
Signal extraction

- Use normalized lepton energy $x_l \equiv \dfrac{E_l^*}{m_\tau c^2/2}$

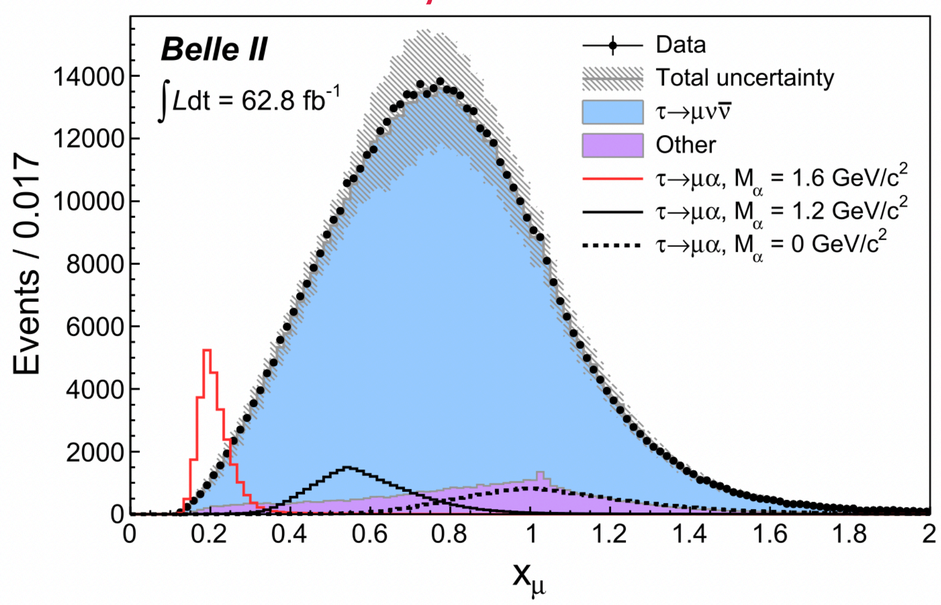
  where E_l^* is the lepton energy in τ pseudo rest frame

- Signal signature: Excess above the $\tau \to l\nu\nu$ background spectra of x_l
- Simulation derived templates fit for different α mass hypotheses

$\tau \to e\alpha$ search



$\tau \to \mu\alpha$ search

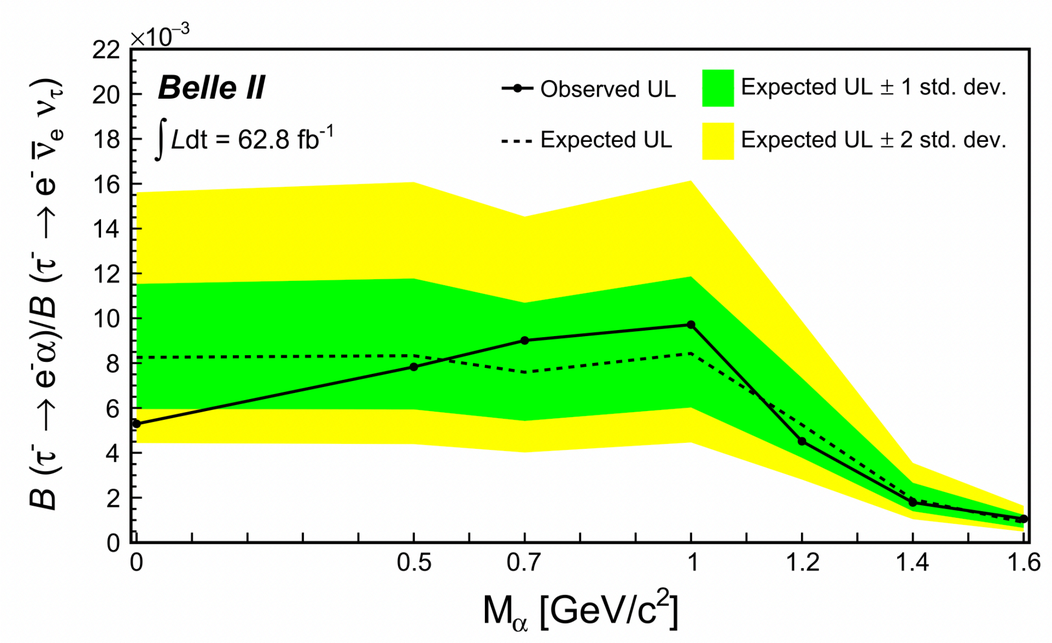


Signal results

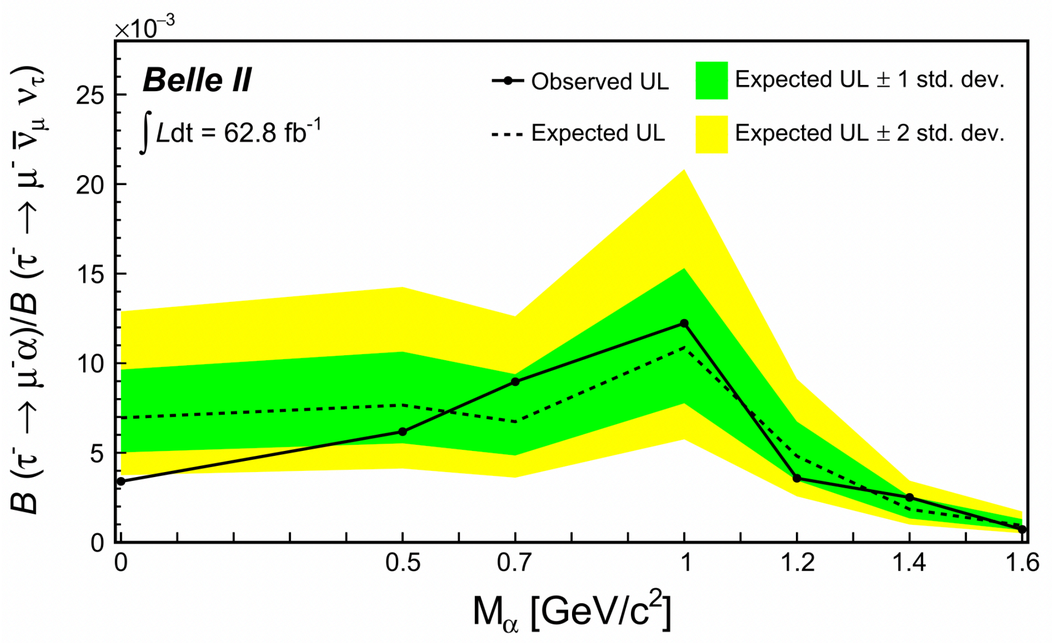
Phys. Rev. Lett. 130, 181803

- 95% C.L. branching fraction limits for M_α from 0 to 1.6 GeV
- 2 to 14 times more stringent than ARGUS

$\tau \to e\alpha$ search



$\tau \to \mu\alpha$ search



Big Picture

- The SM is very successful but leaves unanswered questions
- Belle II/SuperKEKB is a **unique environment** to search for **light dark matter or mediators**
- **Excellent sensitivity** for dark sector searches
- **World leading results** are obtained with a subset of the full available data
- Look forward to new results in physics from Belle II!

Thank you