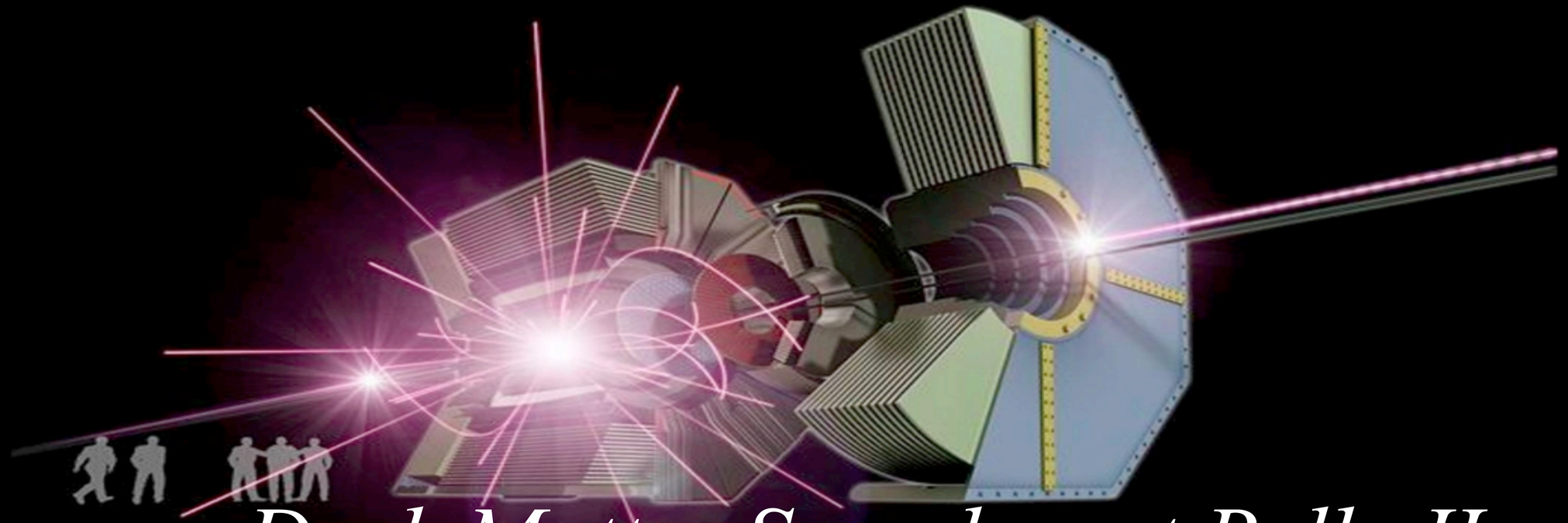


Dark Matter Searches at Belle II

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

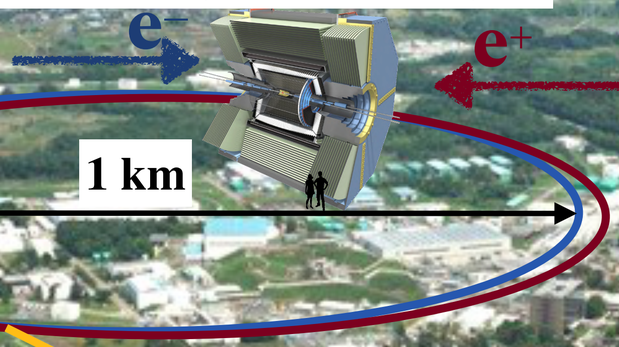
Belle II @ Super-KEKB

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

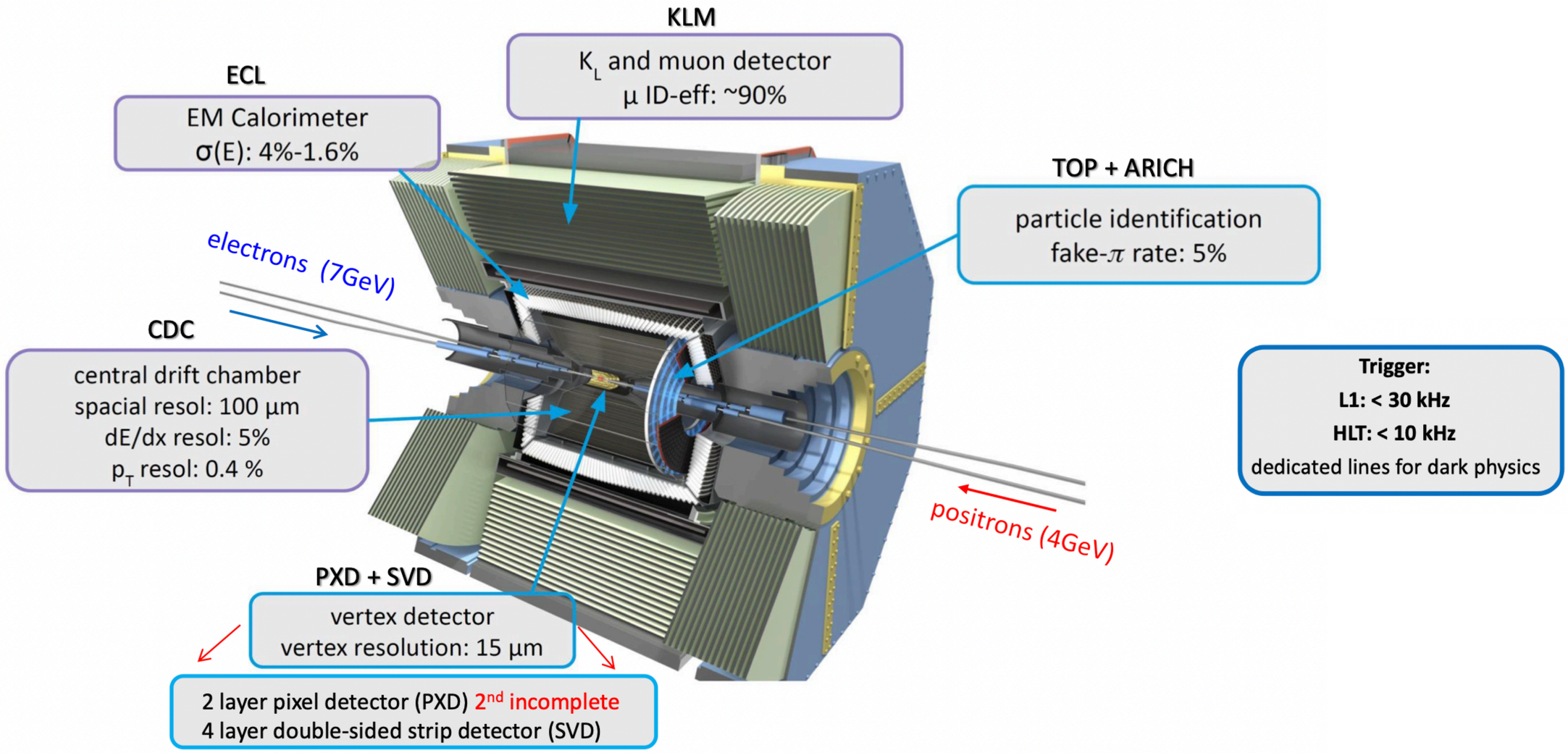
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb

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

Super B (+charm + τ) Factory

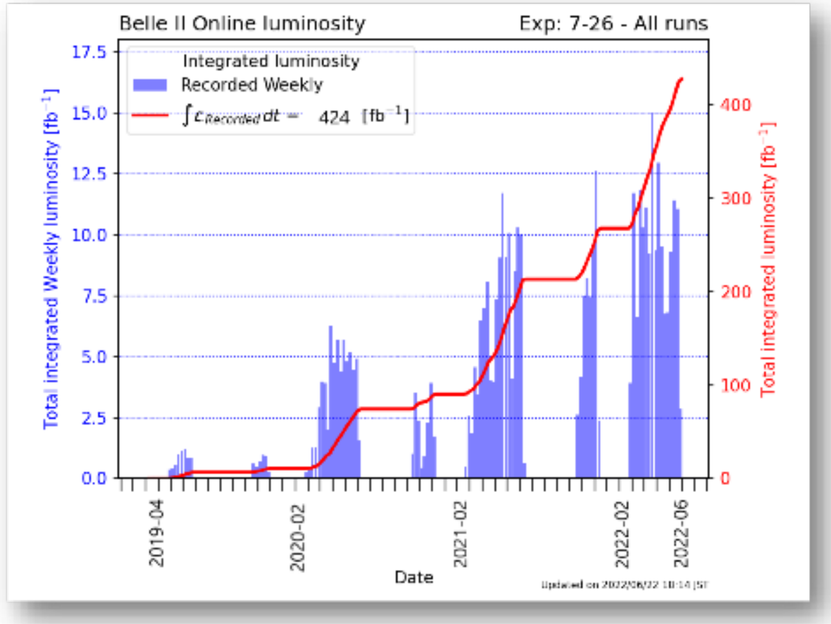
~1100 researchers 123 institutions
26 countries and regions

Belle II detector

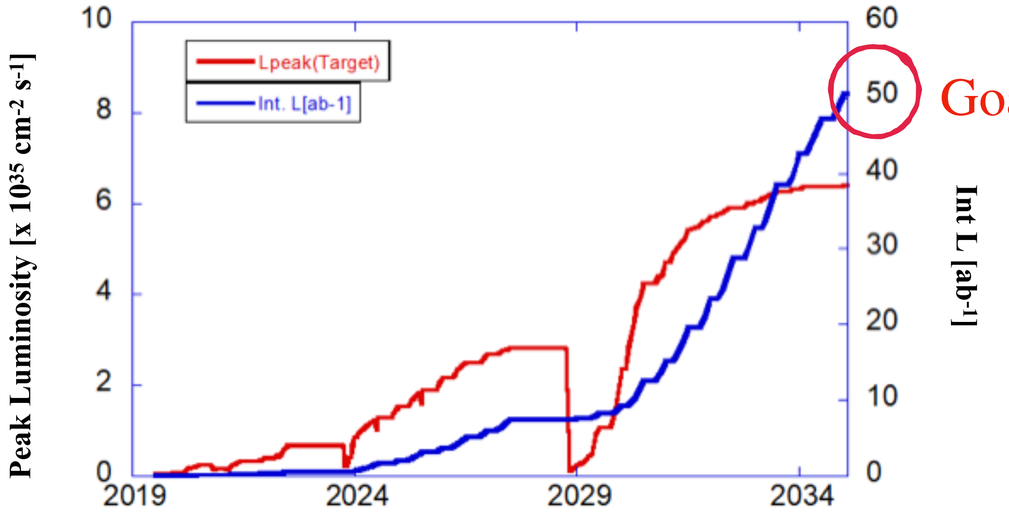


Hermetic detector and Well known initial condition	Low background	Excellent PID	Dedicated triggers for Low Multiplicity events

Luminosity Status and projection

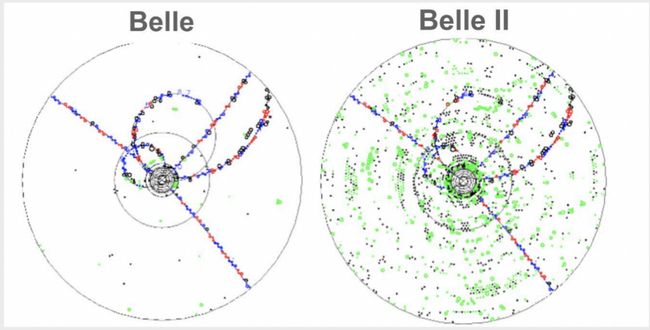


- So far $L_{\text{int}} = 424\ \text{fb}^{-1}$ (~ BaBar, ~1/2 Belle)
- first long shutdown (LS1) mid 2022 - end 2023
  - Install two-layer pixel detector
  - significant improvements made to the accelerator and detector
- Run 2 starts soon in about a month
- Goal: $L_{\text{int}} = 50\ \text{ab}^{-1}$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

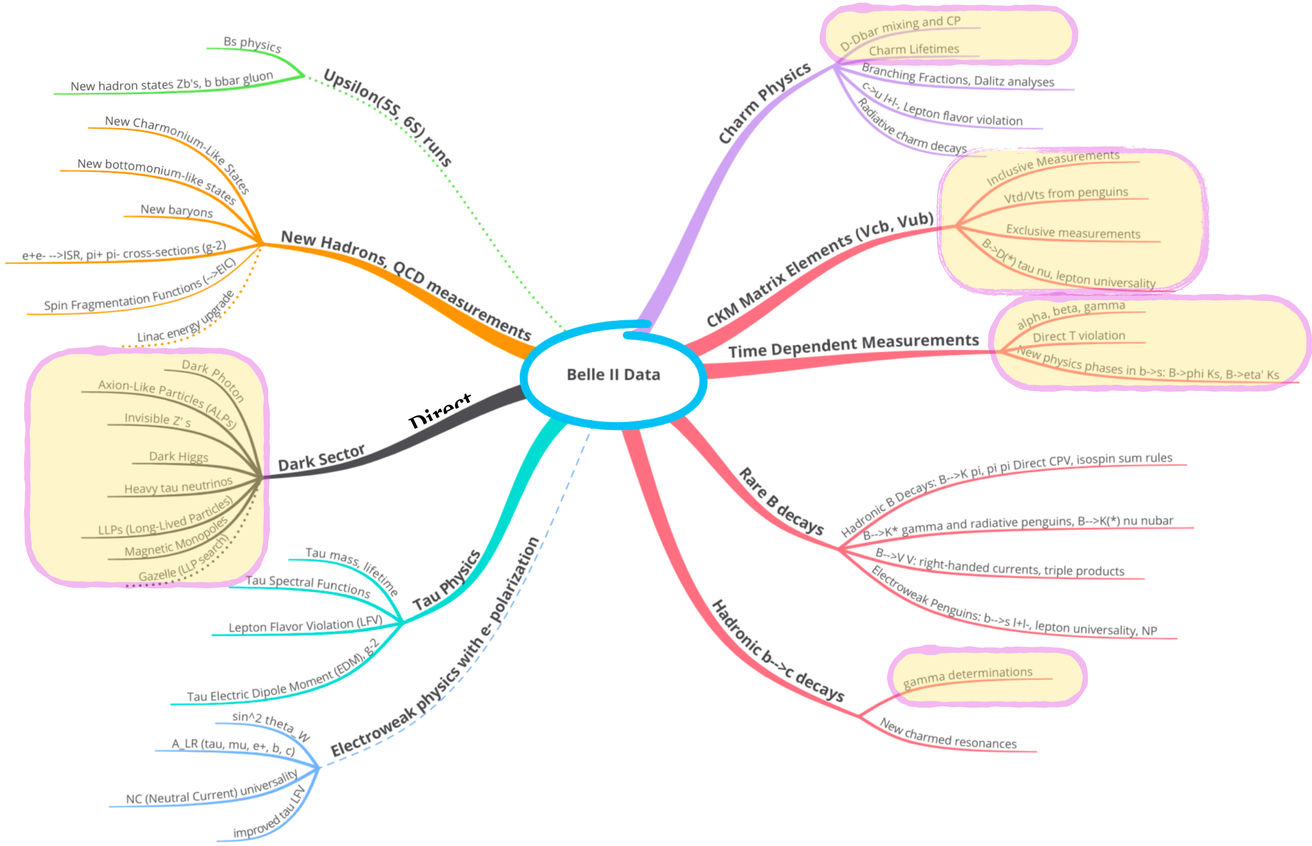
- Increased beam backgrounds
  - ➔ upgraded trigger system with dedicated low multiplicity lines



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

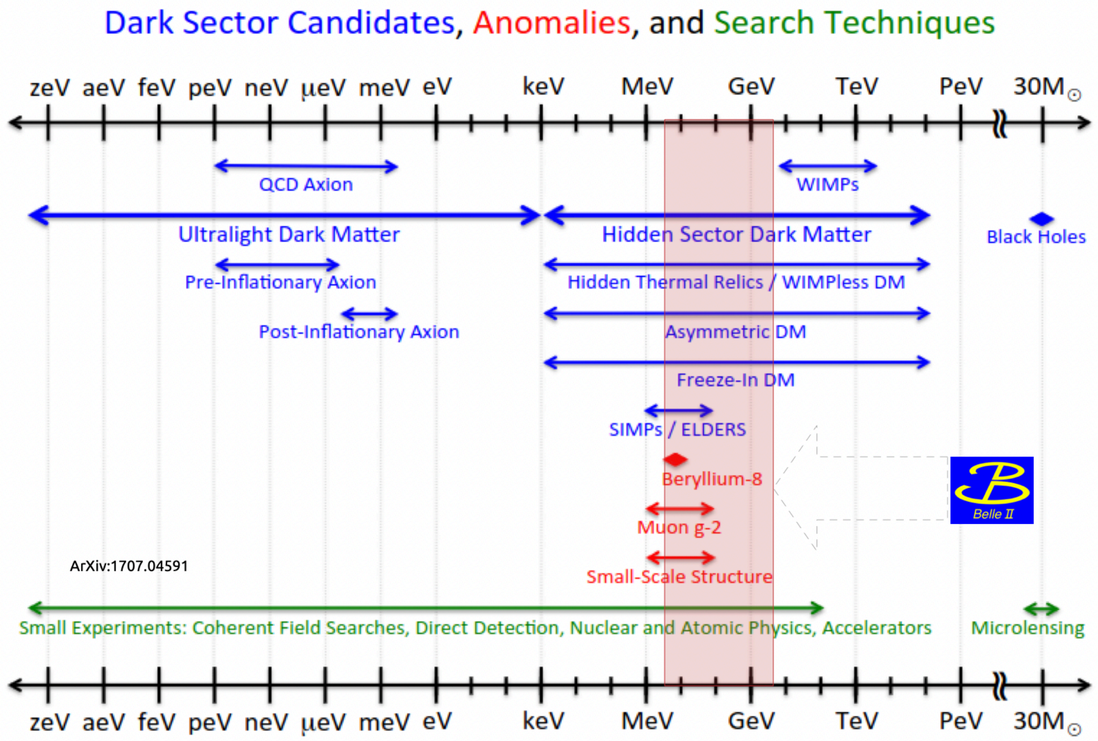


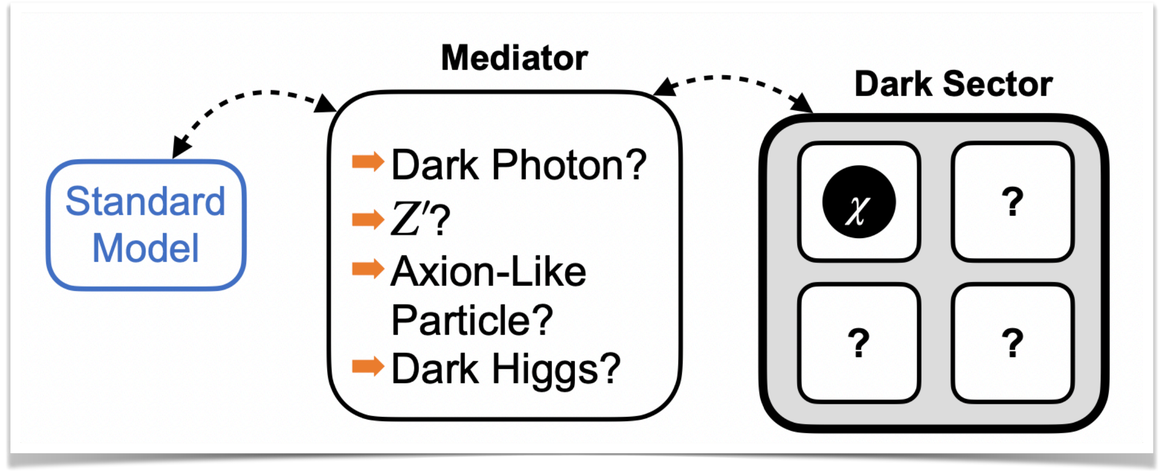
https://confluence.desy.de/display/BI/Journal+Publications

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

Light Dark Matter 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.

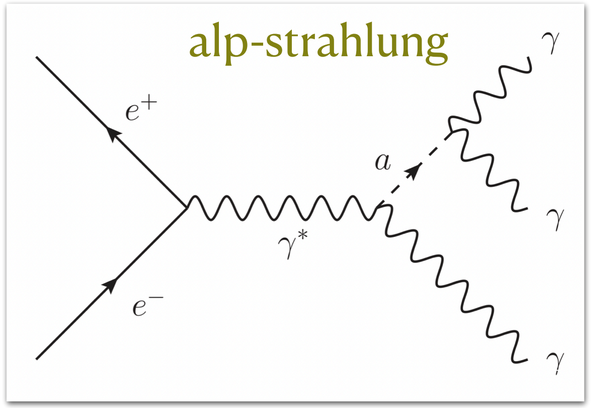




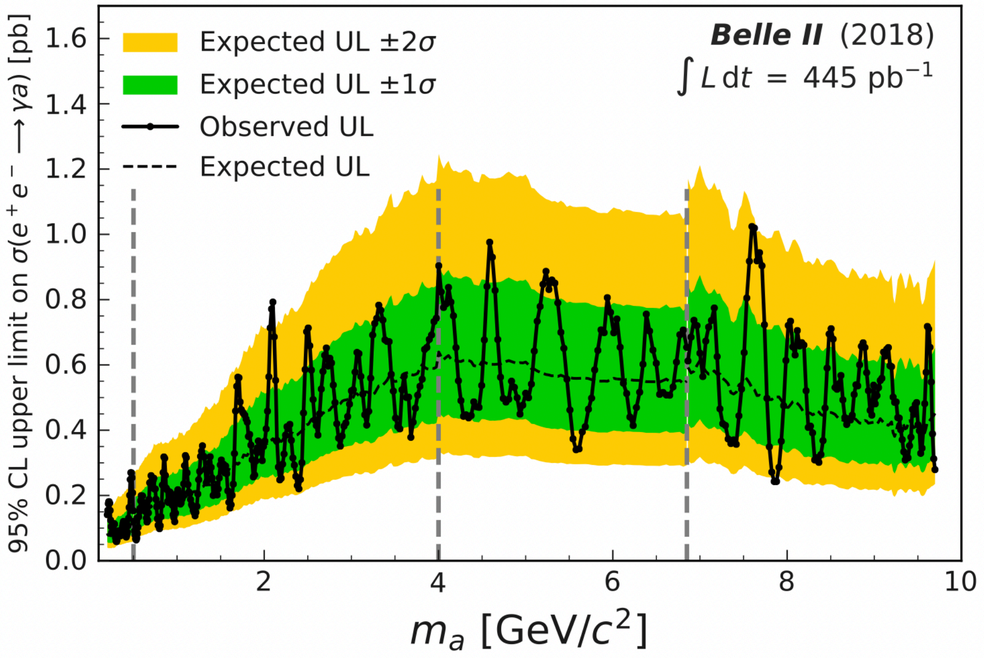
- Belle II is sensitive to direct production of MeV to GeV scale Mediators between SM and Dark Sectors
- Precise determination of missing energy/momentum
- Special Dark Sector Triggers enabled

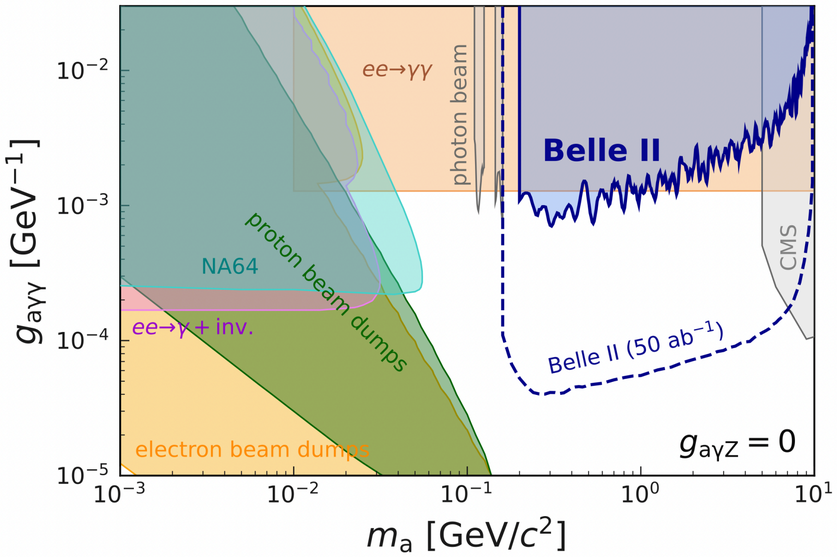
Search for Axion-like Particle (ALP) in $e^+e^- \to \gamma a, a \to \gamma\gamma$

- 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



Phys. Rev. Lett. 125, 161806





Belle II physics reach @ Snowmass

ArXiv: 2207.06307

Belle II limits are more restrictive than previous limits

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

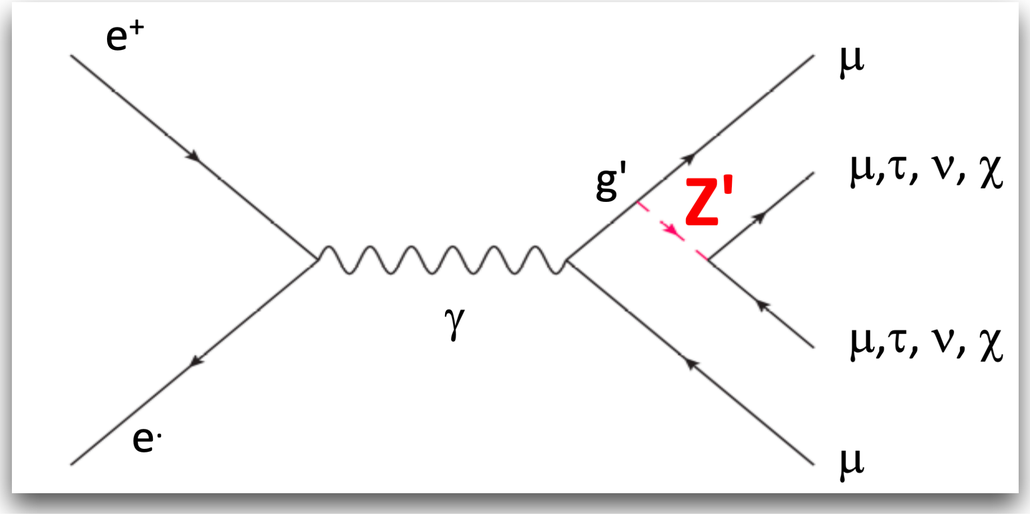
$B \to KS(\to ee, \mu\mu, \pi\pi, KK)$

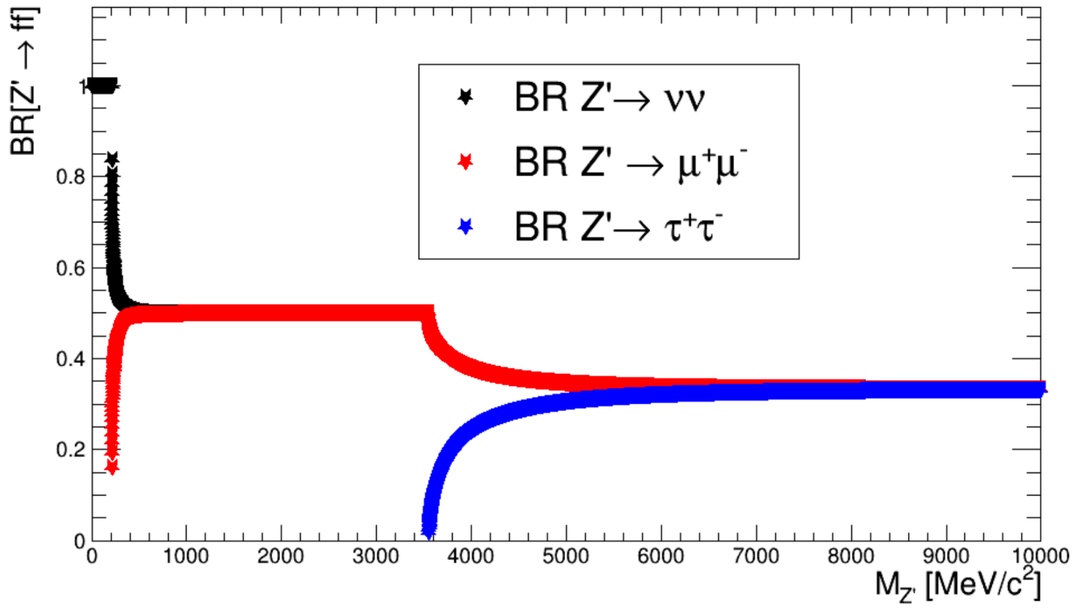
Invisible boson in τ decays

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

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

- New gauge boson Z' coupling only to the **2nd** and **3rd** generation of leptons $L_\mu - L_\tau$ may explain
  - Dark matter puzzle
  - $(g-2)_\mu$
- Z' couples to SM only through $\mu, \tau, \nu_\mu, \nu_\tau$ with coupling g'
- Decays both visibly and invisibly

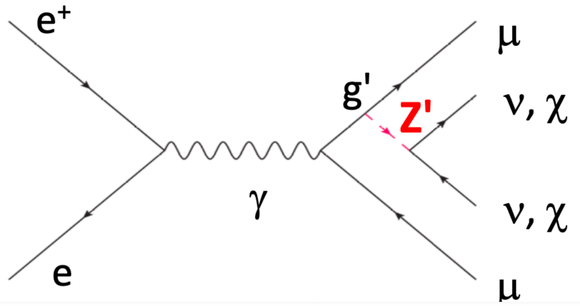


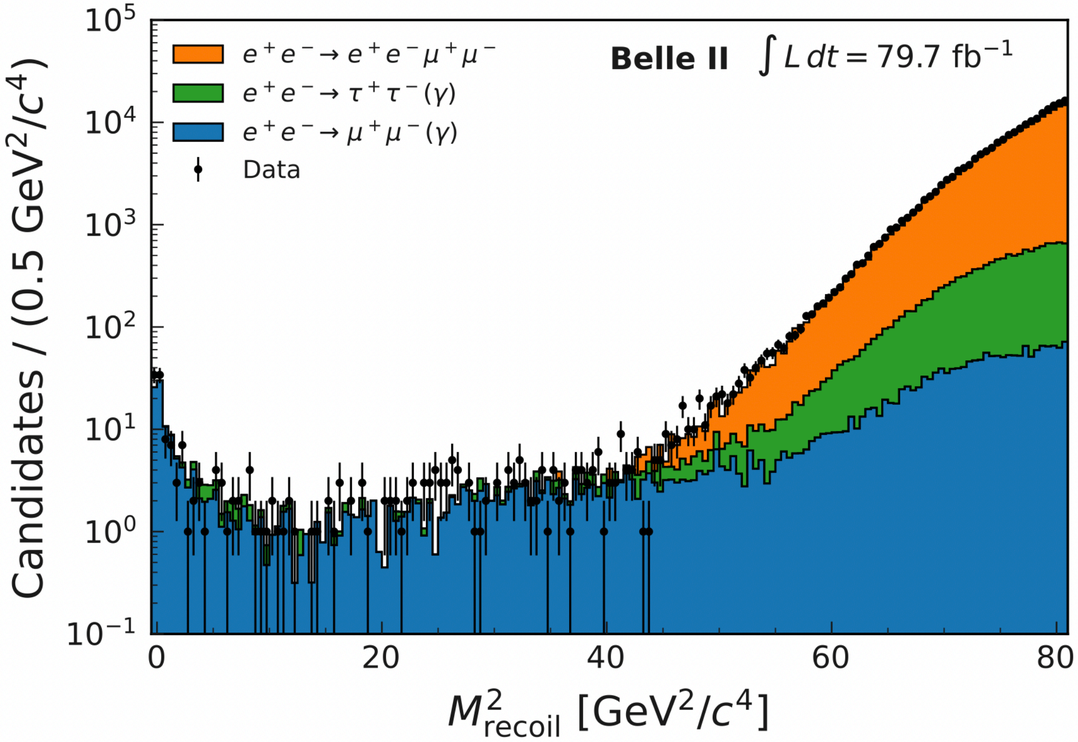


Search for an invisible Z'

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. $e^+e^- \to \mu^+\mu^-(\gamma)$

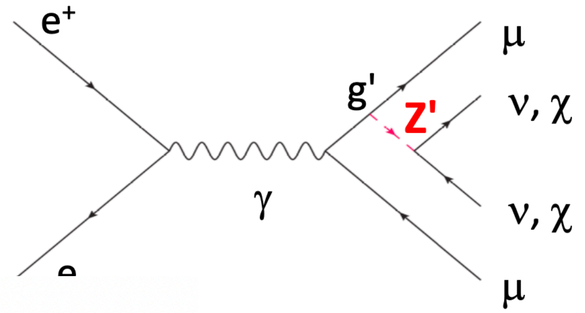


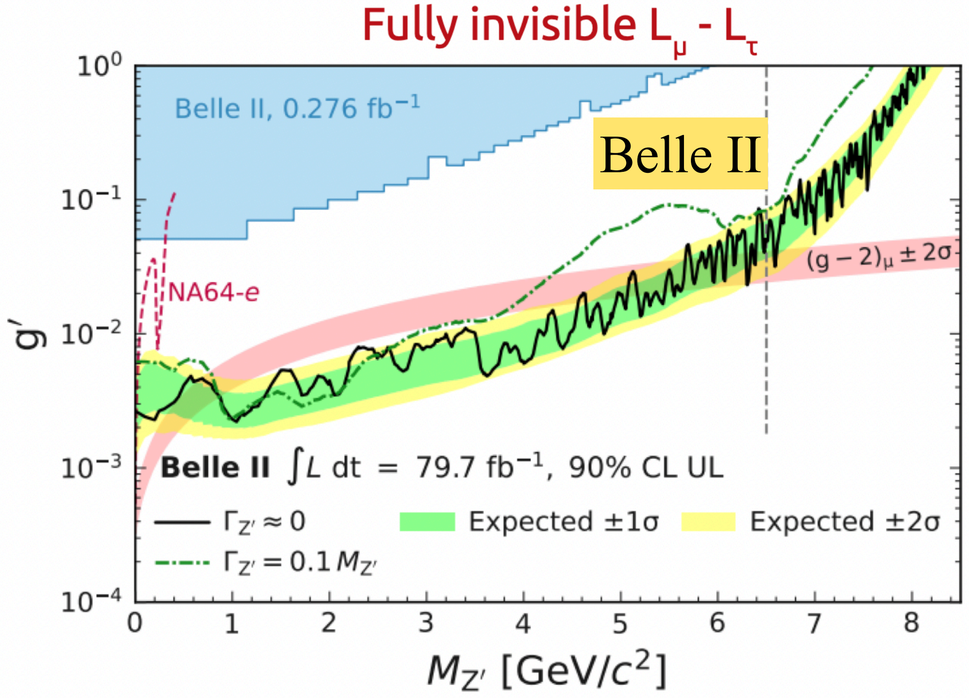


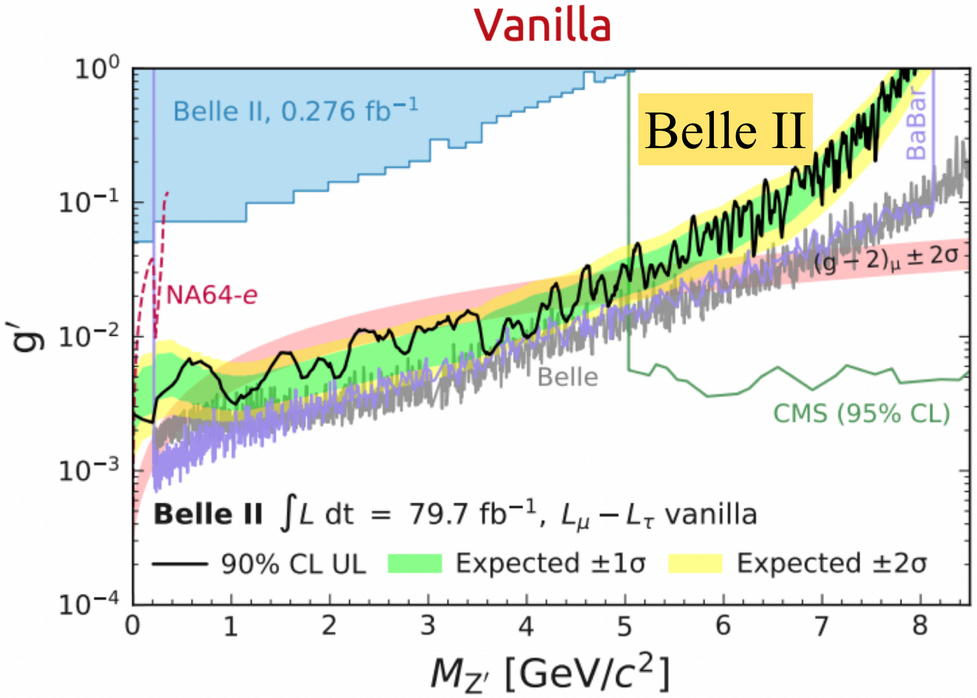
Search for an invisible Z': Results

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'



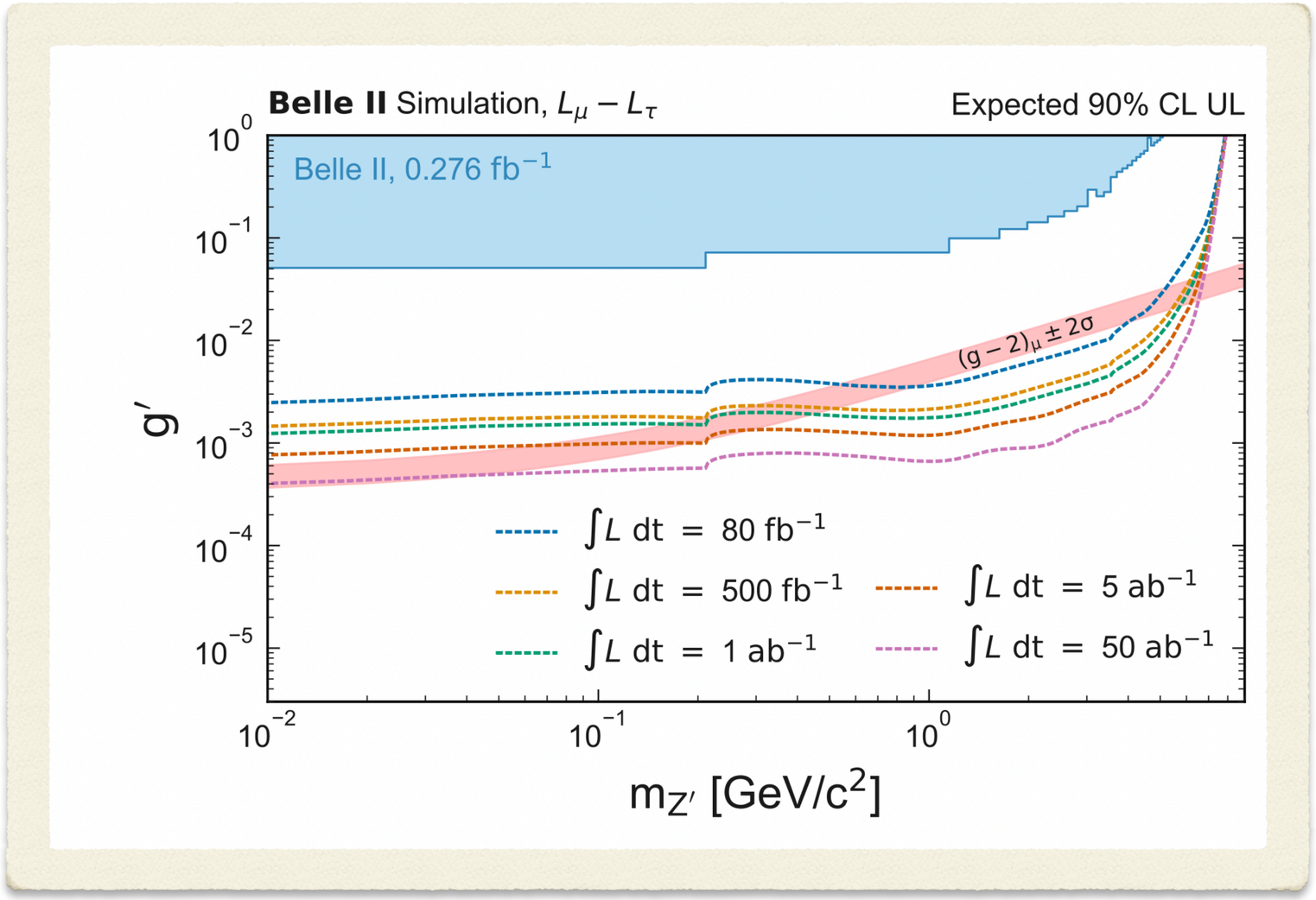


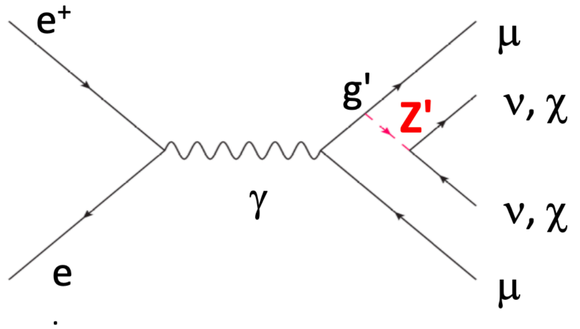


fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Search for invisible Z': projections

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



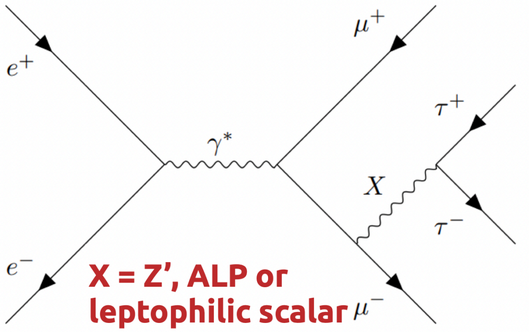


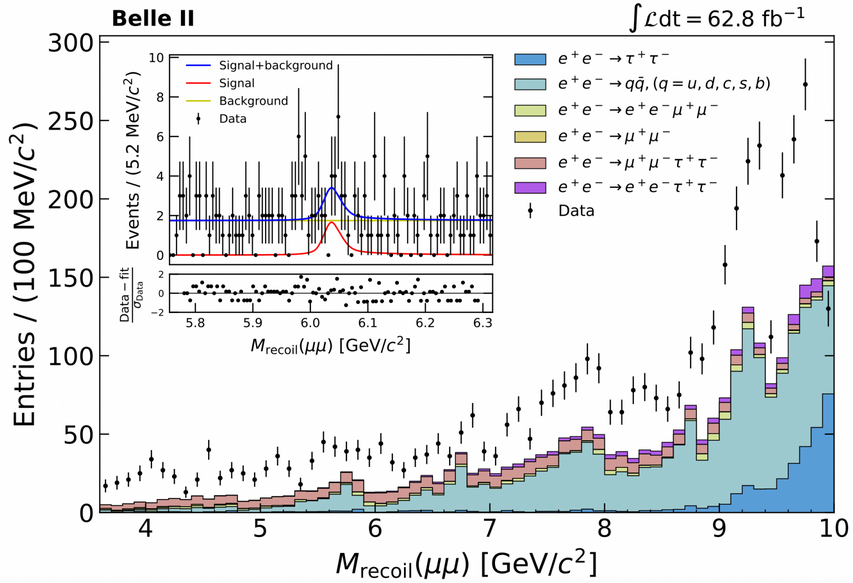
Belle II physics reach @ Snowmass
ArXiv: 2207.06307

Search for a $\tau^+\tau^-$ resonance

Phys. Rev. Lett. 131, 121802

- Search for the process $e^+e^- \to \mu^+\mu^- X$, with $X \to \tau^+\tau^-(X = Z', S, \text{ALP})$
  - Look for a narrow peak in di-muon mass distribution in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events
- 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 using kinematic variables in the signal
- Data-MC discrepancies due to contributions from non-simulated/unmodeled processes
  - lack of ISR effects paper in $M_{\text{recoil}}(\mu\mu) < 6$ GeV/c^2
  - For $M_{\text{recoil}}(\mu\mu) > 9$ GeV/c^2 the discrepancies are from nonsimulated two-photon processes
  - Additional contributions come from the process $e^+e^- \to \mu^+\mu^-\pi^+\pi^-$

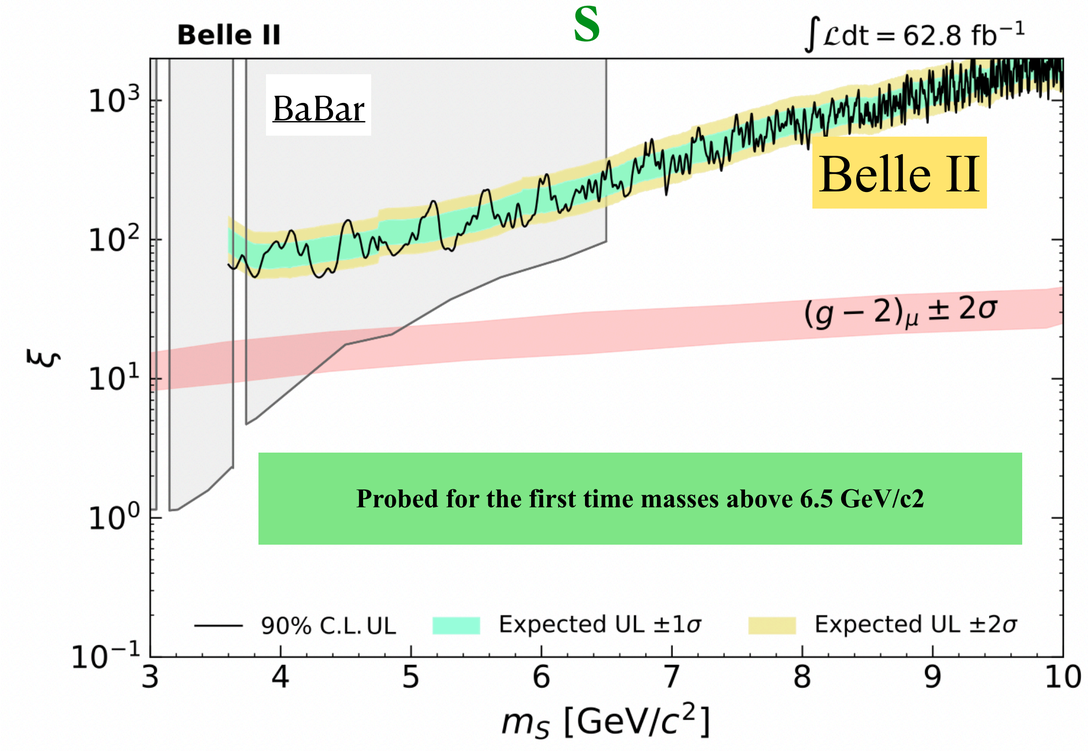


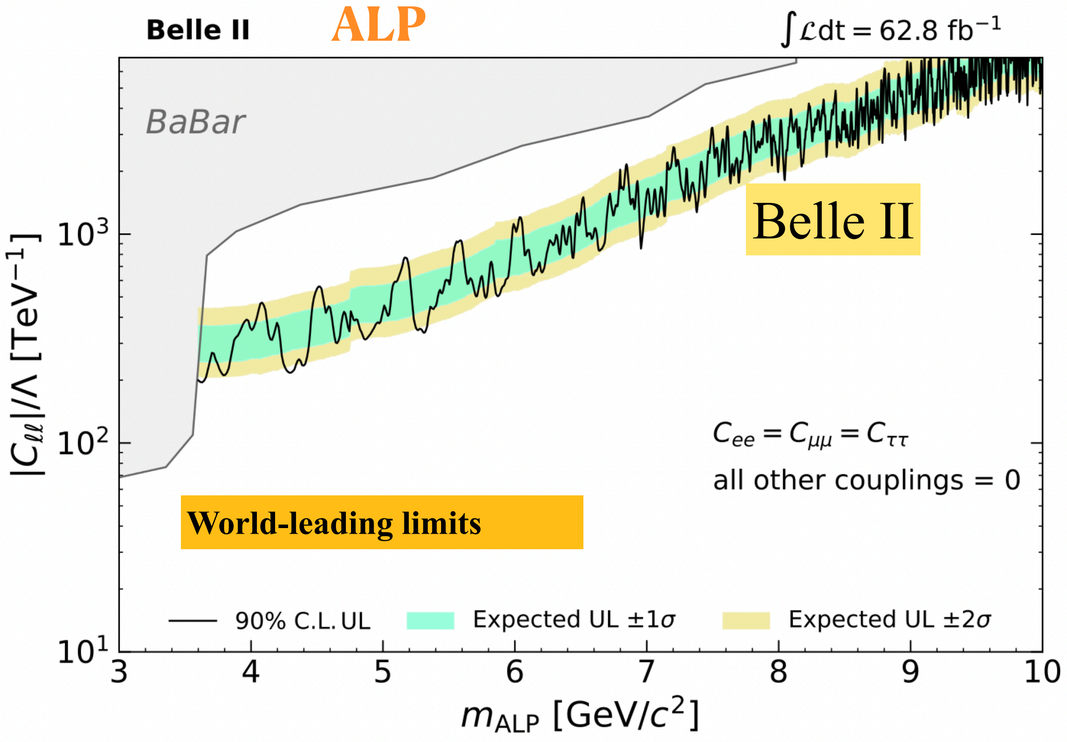


Search for a $\tau^+\tau^-$ resonance: results

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:





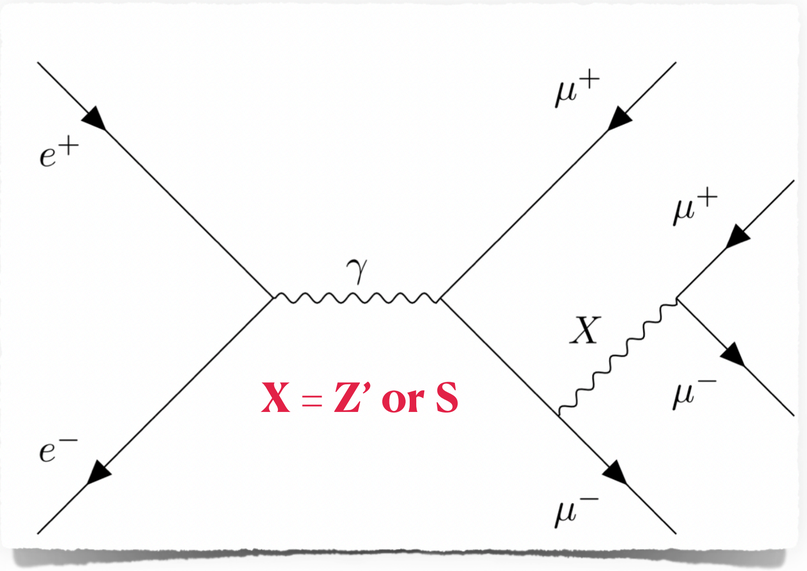
Search for a $\mu\mu$ resonance

- Search for the process $e^+e^- \to \mu^+\mu^- X$,with $X \to \mu^+\mu^-(X = Z', S)$

  ➡ Look for a peak in the opposite charge di-muon mass distribution in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events

- $(L_\mu - L_\tau)$ model used as a benchmark and then performances are checked for the **Muonphilic dark scalar (S)**

- Z' reinterpreted as **S** couple to muons through Yukawa-like interaction (g_S).



Scalar particle coupling to muons through Yukawa-like interaction

Mainly proposed as a way to solve the muon $(g-2)_\mu$ anomaly

$\mathcal{L} \supset g_S S\bar{\mu}\mu$

Coupling constant: induces a shift in $\Delta a_\mu = a_\mu^{exp} - a_\mu^{theory}$

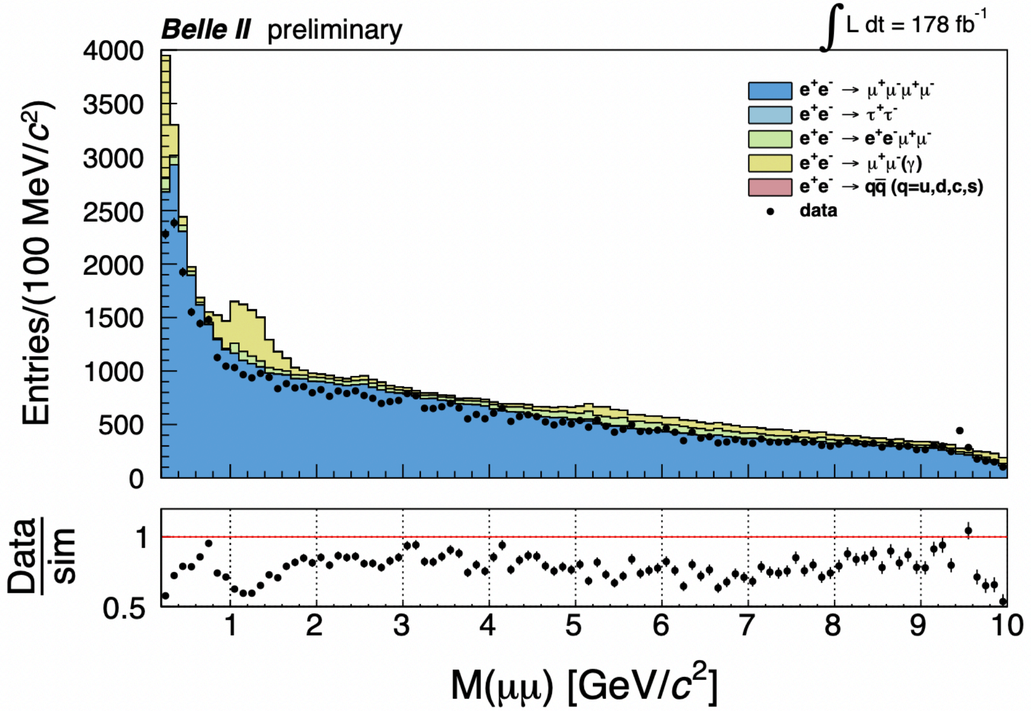
If $m_S > 2m_\mu$ the only tree-level decay channel is $S \to \mu\mu$
($S \to \nu\bar{\nu}$, $\gamma\gamma$ also are possible at one loop level, but highly suppressed)

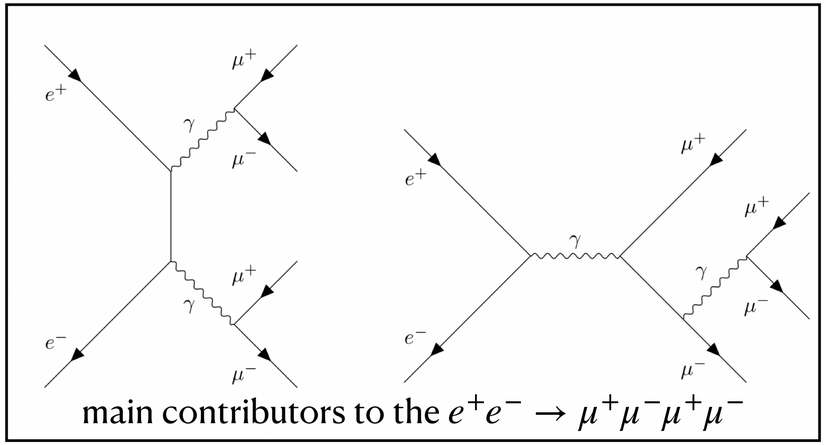
Search for a $\mu\mu$ resonance

- Event selected have 4 charged particles:
  - zero charge
  - at least three identified as muons
  - M(4tracks) ~ $\sqrt{s}/c^2$
  - No extra energy

- Main SM background contributions:
  1. $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  2. $e^+e^- \to e^+e^-\mu^+\mu^-$
  3. $e^+e^- \to \mu^+\mu^-\gamma$

- **Multi-Layer Perceptron (MLP)-based background suppression**
- Signal over background discrimination relying on a few variables sensitive the signal features:
  A. Presence of a μμ resonance
  B. Production mechanism





main contributors to the $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

Search for a $\mu\mu$ resonance

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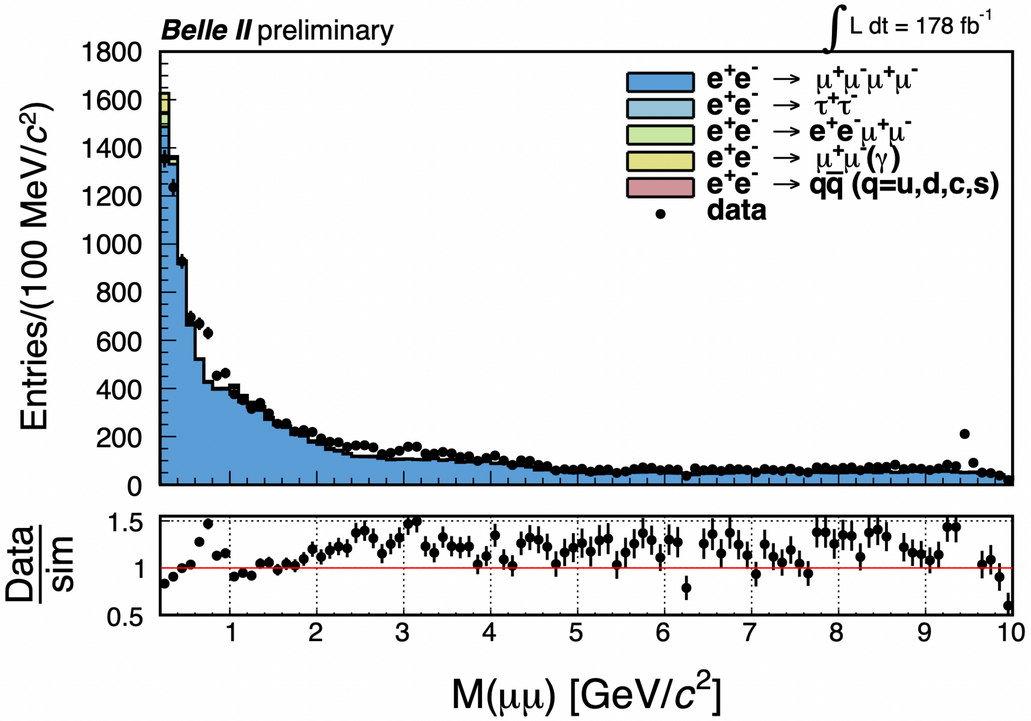
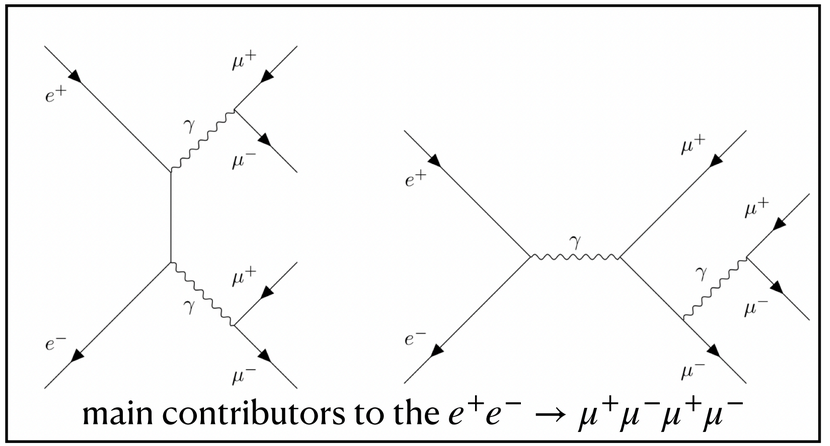
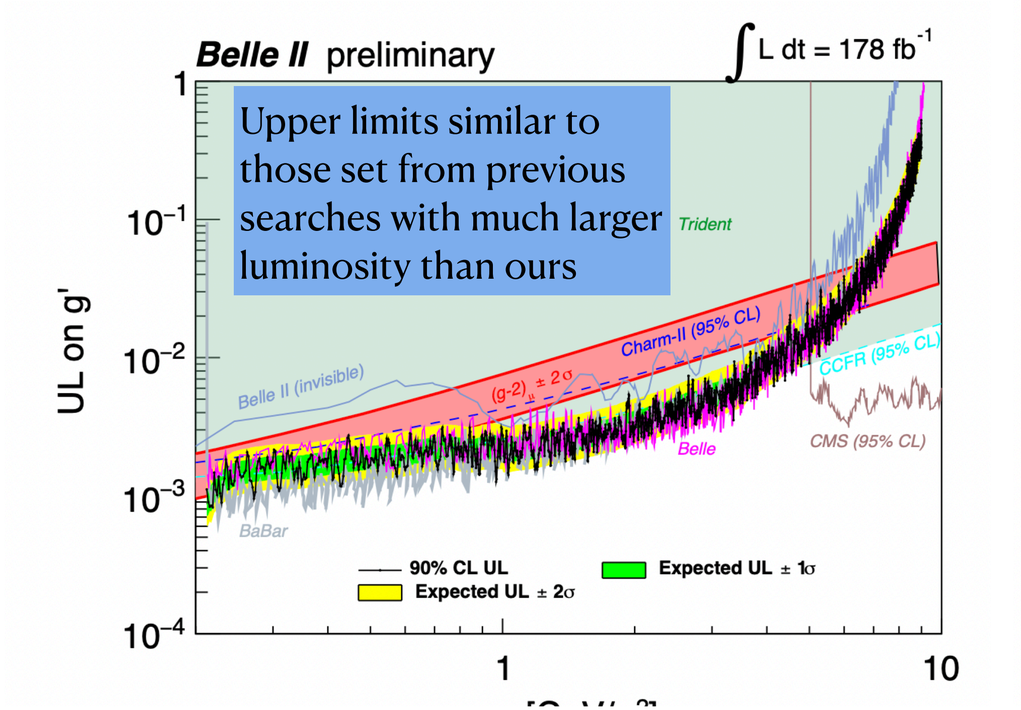




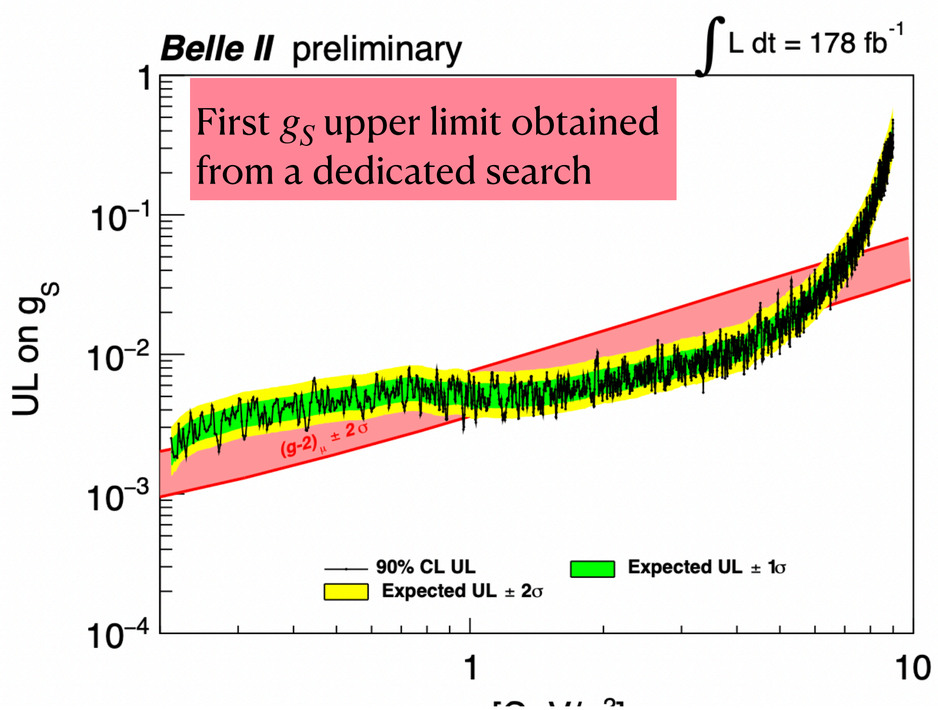
main contributors to the $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

Search for a $\mu\mu$ resonance: Results

- **No significant excess observed in** 178 fb^{-1}
  - 90% CL upper limits on $\sigma(e^+e^- \to \mu^+\mu^-(X \to \mu^+\mu^-)$, with $X = Z', S$
- Cross section limits are translated into upper limits on the g' coupling constant for the $(L_\mu - L_\tau)$ model and on the g_S coupling constant for the muonphilic dark scalar S



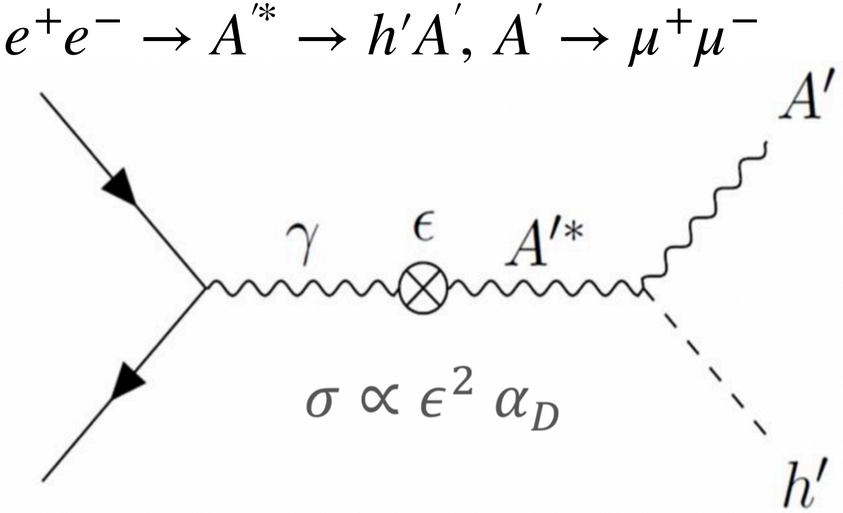
$Z' \to \mu\mu$ **as origin of** $(g-2)_\mu$ **excluded for** $0.8 < M_{Z'} < 4.9$ **GeV/c²**



$S \to \mu\mu$ **as origin of** $(g-2)_\mu$ **excluded for** $2.9 < M_S < 3.5$ **GeV/c²**

Search for Dark Higgsstrahlung

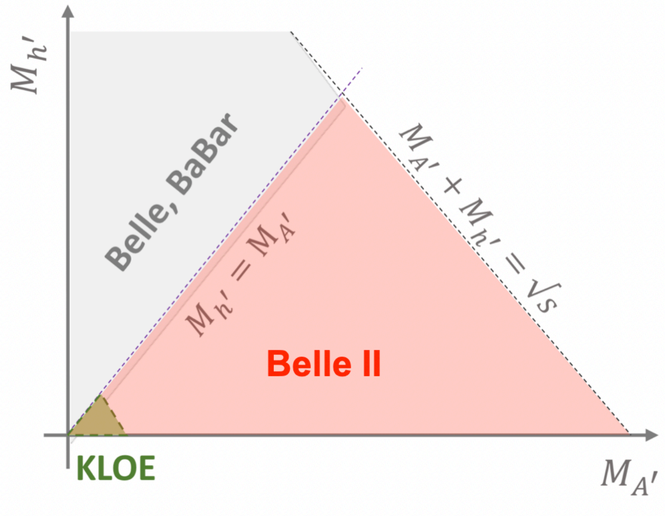
- Dark photon (A') couples to SM photon via kinetic mixing parameter ϵ
- $M_{A'}$ can be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson (h') to the theory. Phys. Rev. D 79, 115008 (2009)
- No h' mixing with SM Higgs.
- Both particles can be produced via dark Higgsstrahlung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



Mass hierarchy scenarios

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

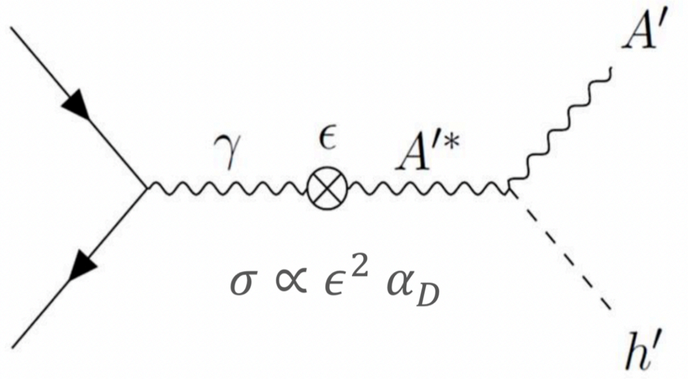
Exploring unconstrained regions at Belle II !



Search for Dark Higgsstrahlung: Analysis Strategy

Detector signature

- invisible h' with $A' \to \mu^+\mu^- \implies \mu\mu + \text{missing energy}$
- a peak in two dimensional distribution of recoiling mass vs dimuon mass



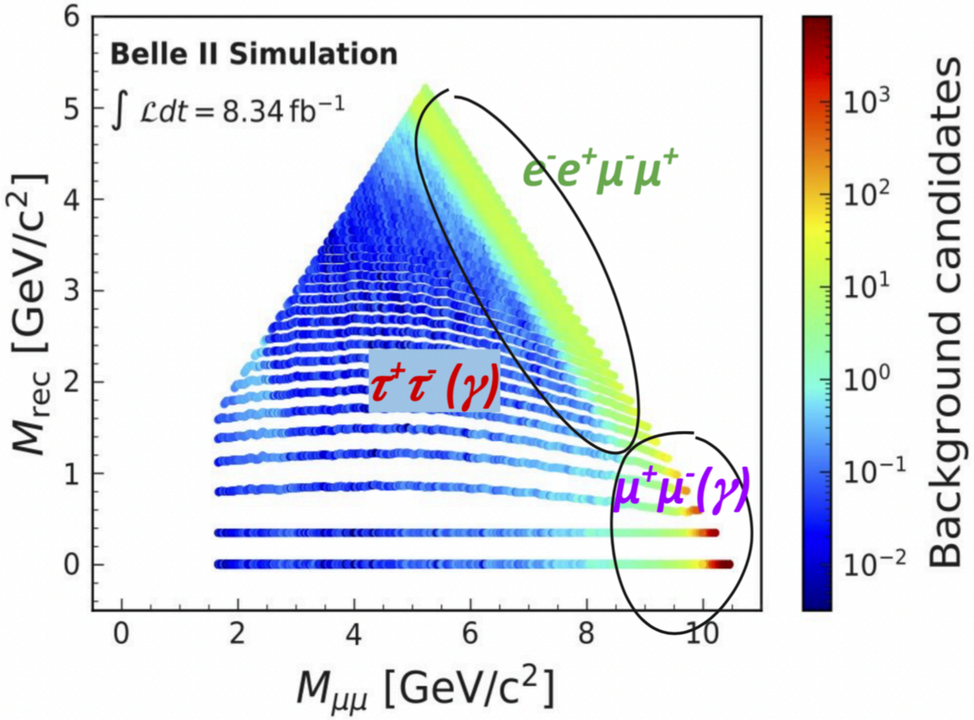
Main contributions:

- $\mu^+\mu^-\gamma$ (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

Main challenge: measurement strategy

- scan+count in elliptical mass windows
- continuous grid of 9k (overlapping) ellipses

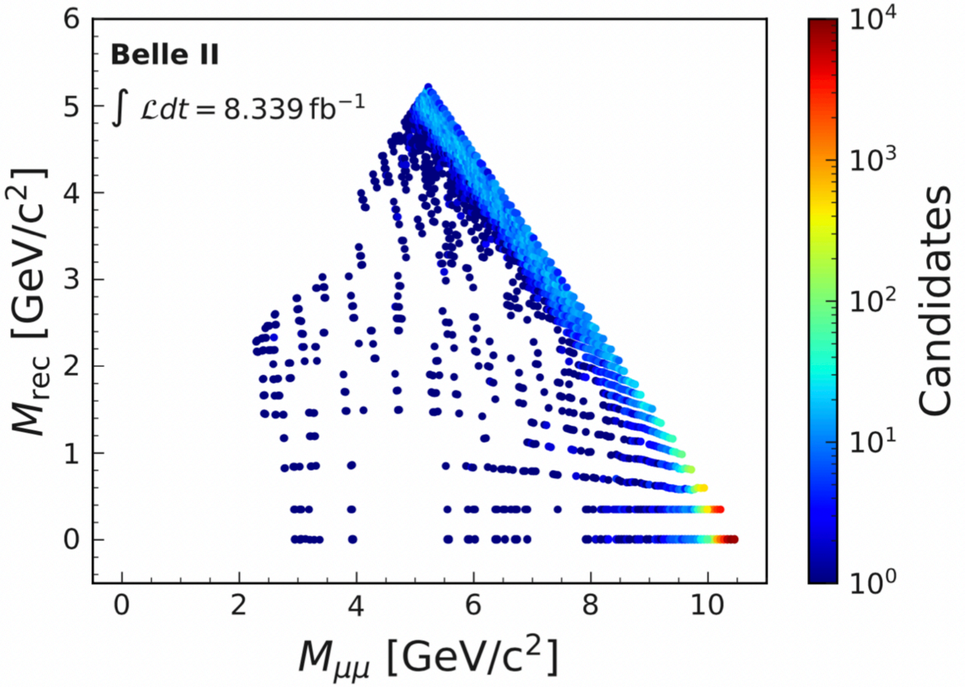


Search for Dark Higgsstrahlung: Results

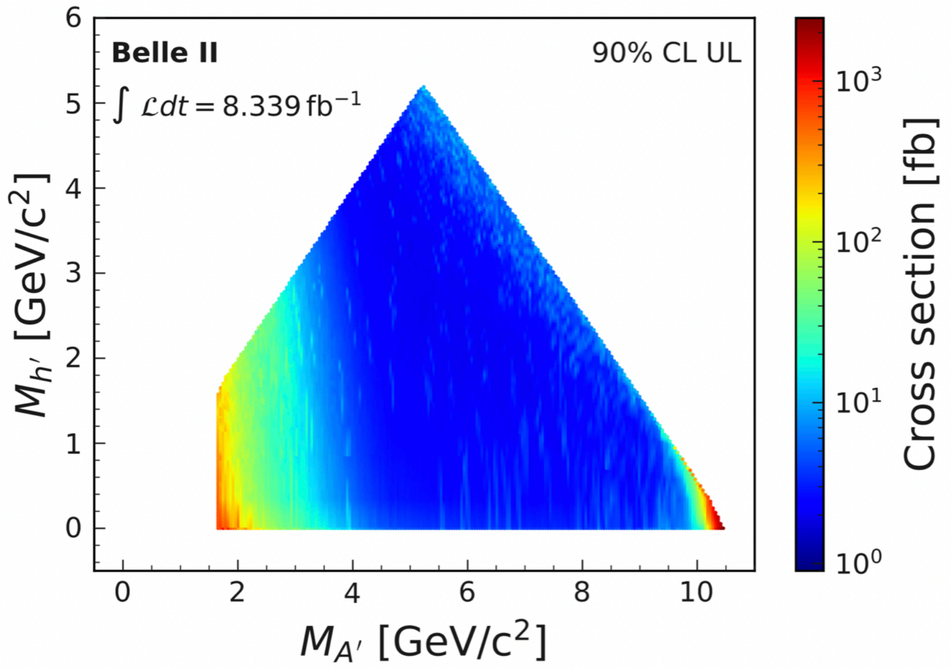
Phys. Rev. Lett. 130, 071804

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.



- Very promising results even with 9 fb^{-1}
- 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 $M_{A'}$ ($M_{h'} < M_{A'}$)

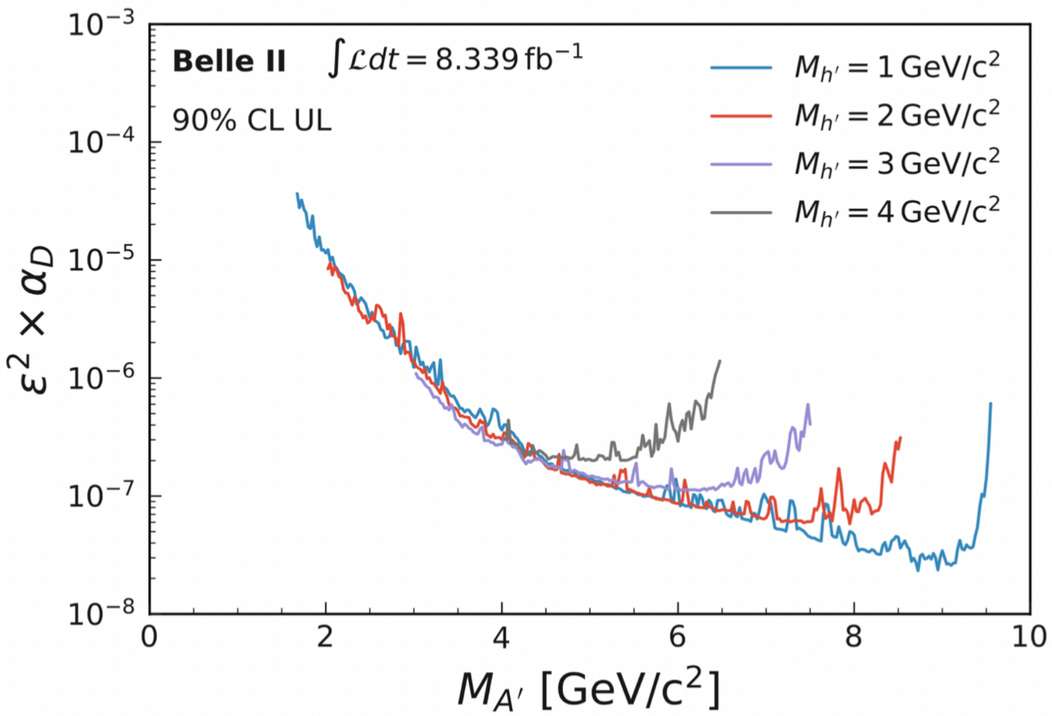


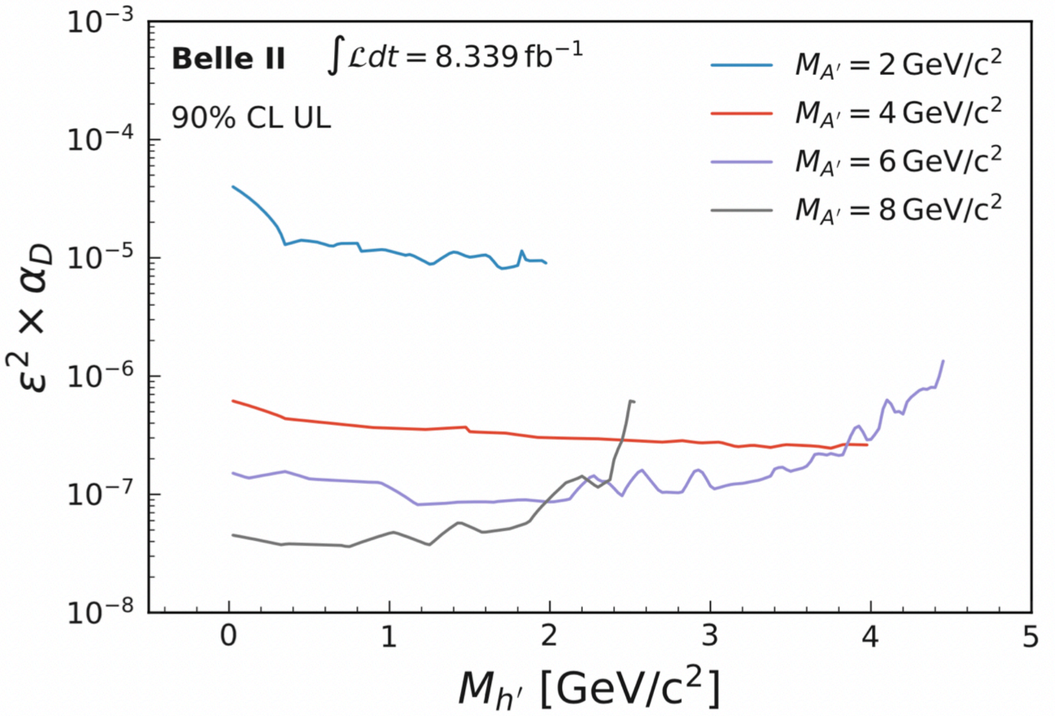
World leading ULs in previously unexplored regions !

Search for Dark Higgsstrahlung: Results

Phys. Rev. Lett. 130, 071804

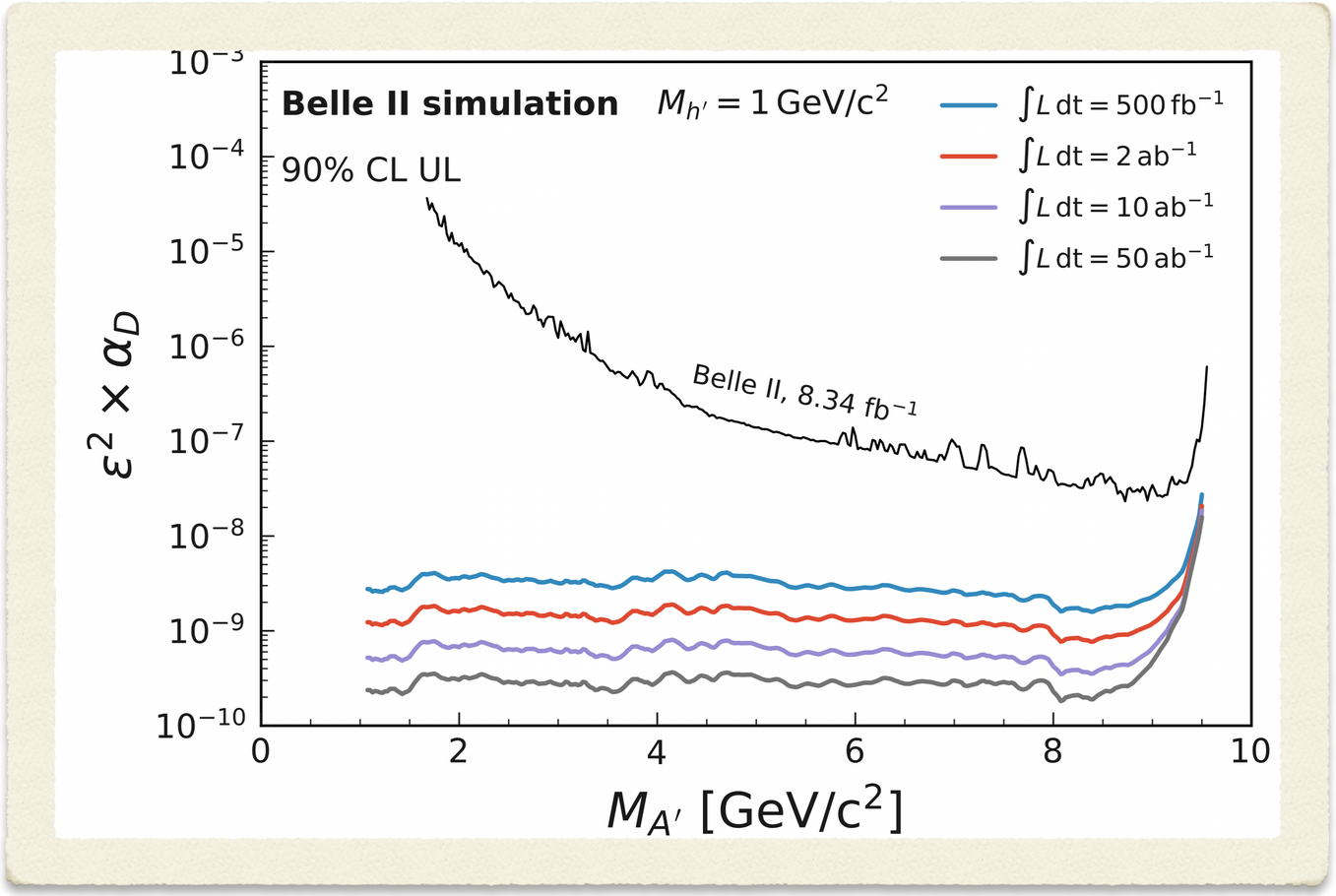
Upper limits also computed in terms of the effective coupling:

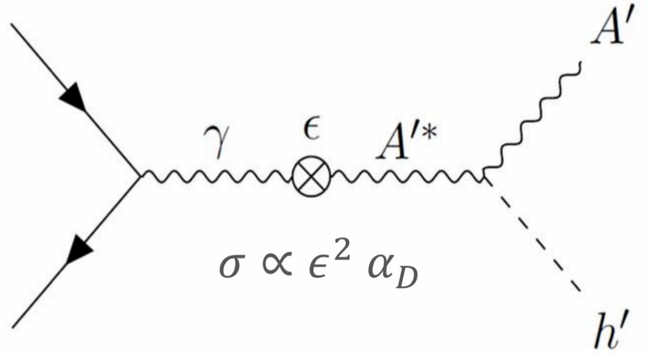




World leading ULs in previously unexplored regions !

Search for Dark Higgsstrahlung: Projections



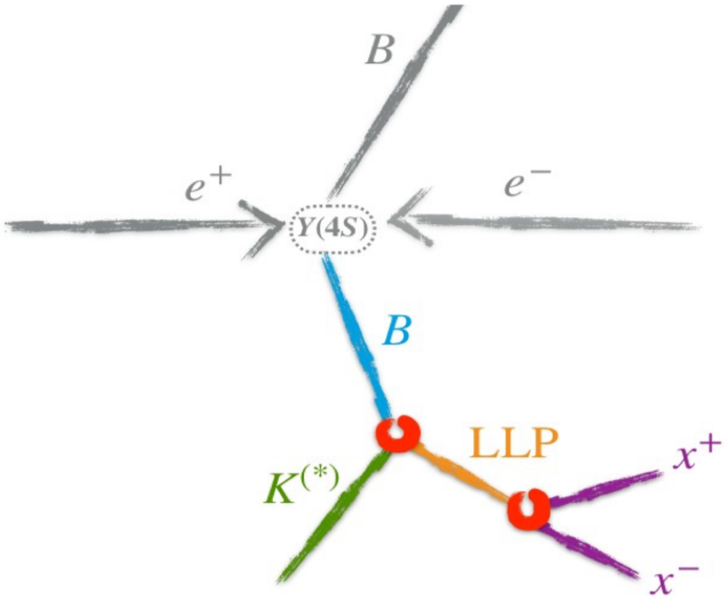


Belle II physics reach @ Snowmass

ArXiv: 2207.06307

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

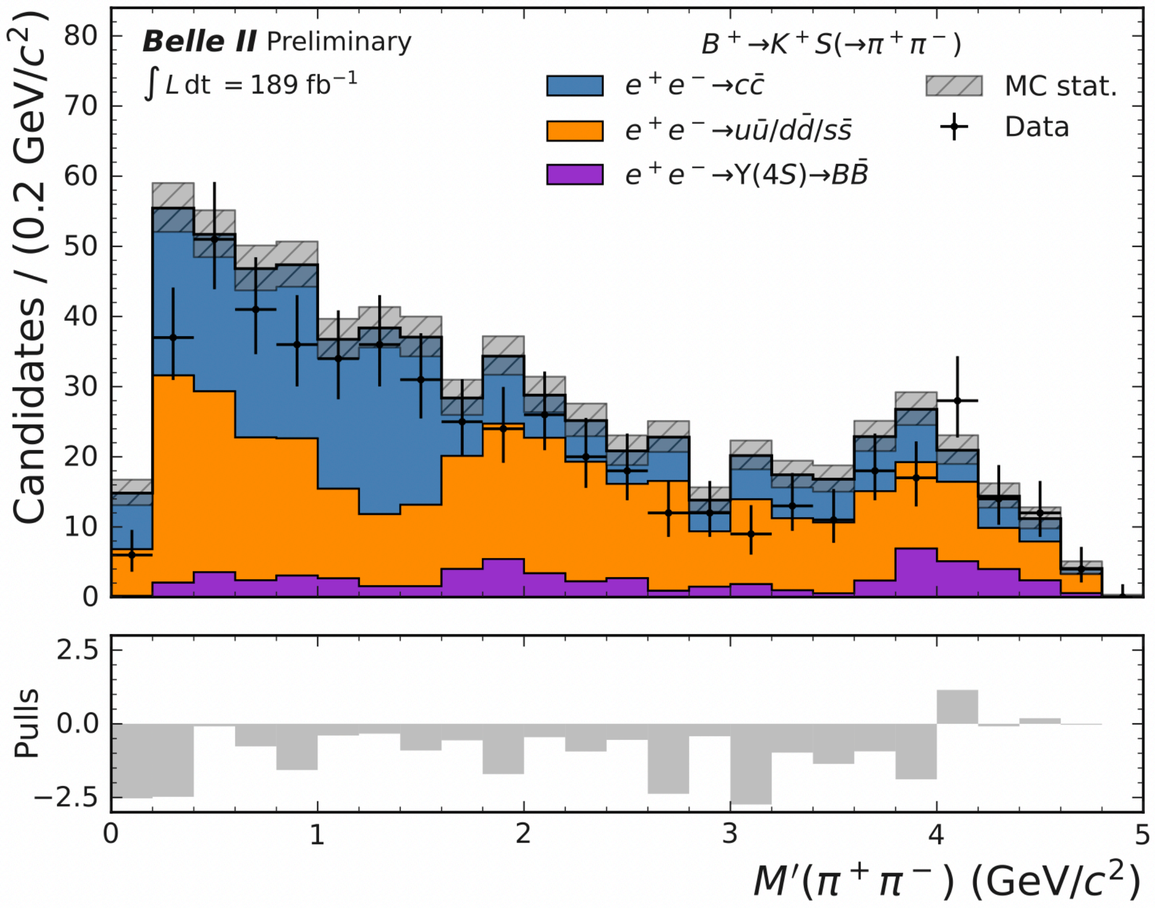
- First model-independent search in rare b→s transition
- Possible mixing with SM Higgs with mixing angle θ_s
- For $M_S < M_B$, decay to DM kinematically forbidden by relic density constraint
- Look for S decays into SM final states in 8 exclusive channels
  - $B^+ \to K^+ S(\to ee/\mu\mu/\pi\pi/KK)$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



- 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

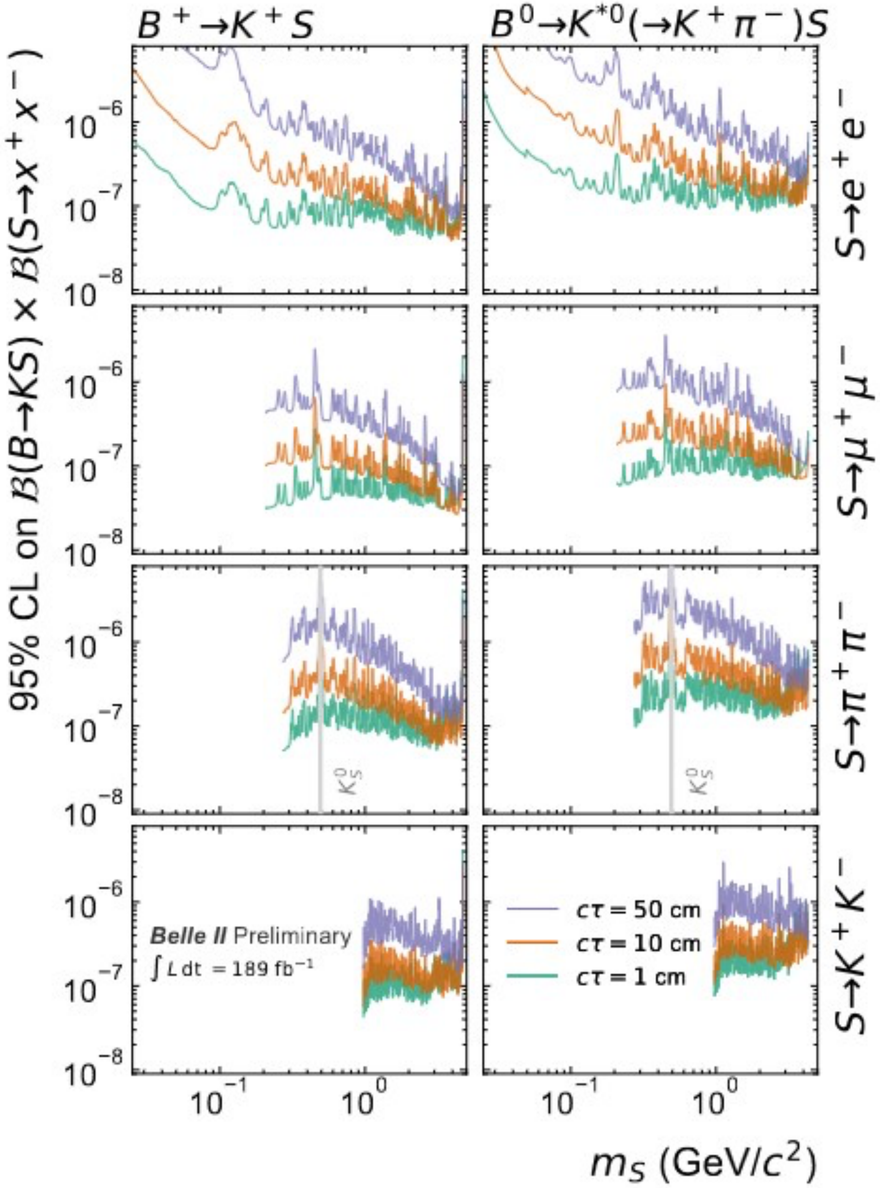
Search for a long-lived (pseudo)scalar: signal extraction

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

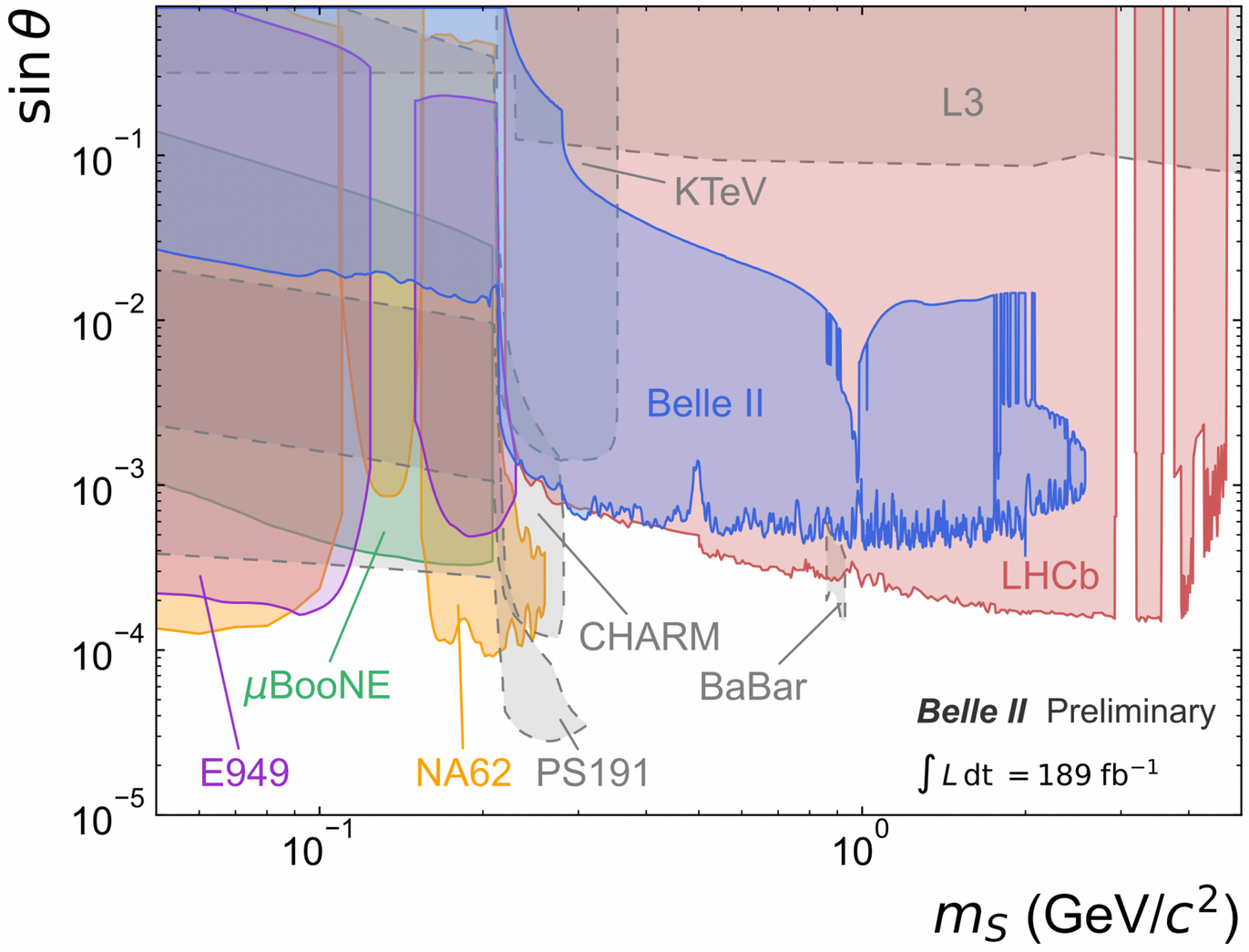


Submitted to PRL, arXiv:2306.02830

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

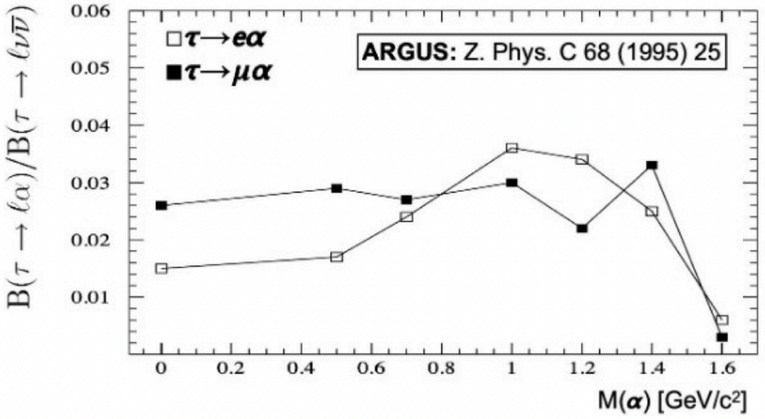
Search for a long-lived (pseudo)scalar: Results

Submitted to PRL, arXiv:2306.02830

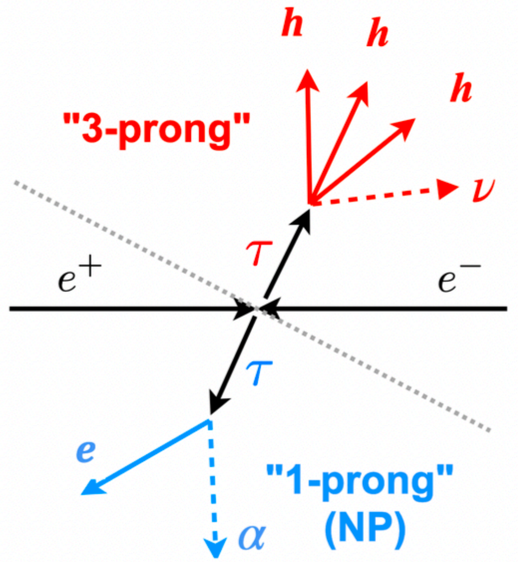


Search for invisible boson in lepton-flavor violating τ decays

- τ decays to new LFV bosons decaying invisibly predicted in many models, possible **ALPs candidates**
- Previously at **ARGUS** (~ 0.5 fb^{-1}) → Belle II analysis relies on **120 x luminosity**
- We report a search for LFV $\tau \to l\alpha$ decay



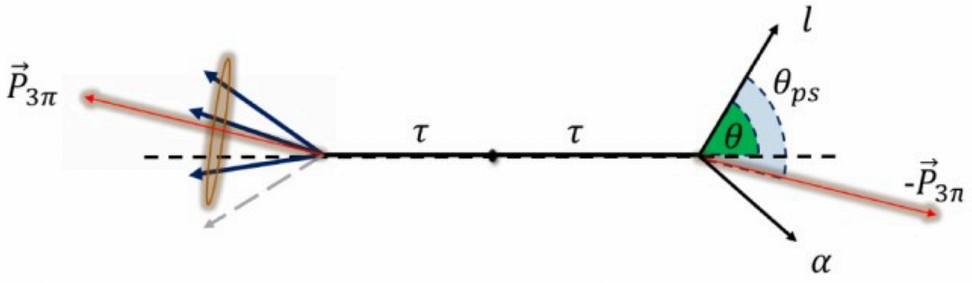
- Split events in two hemispheres based on the ***thrust axis:***
  - Tag with $\tau \to (3h)^{\pm}\nu_{\tau}$ $(h = \pi, K)$ with π^0 veto
- Similar visible topology from background $\tau \to l\nu\nu$ as signal $\tau \to l\alpha$ $(l = e, \mu)$
  - Use 2-body (signal) vs 3-body kinematics (background) to isolate signal



Signal extraction

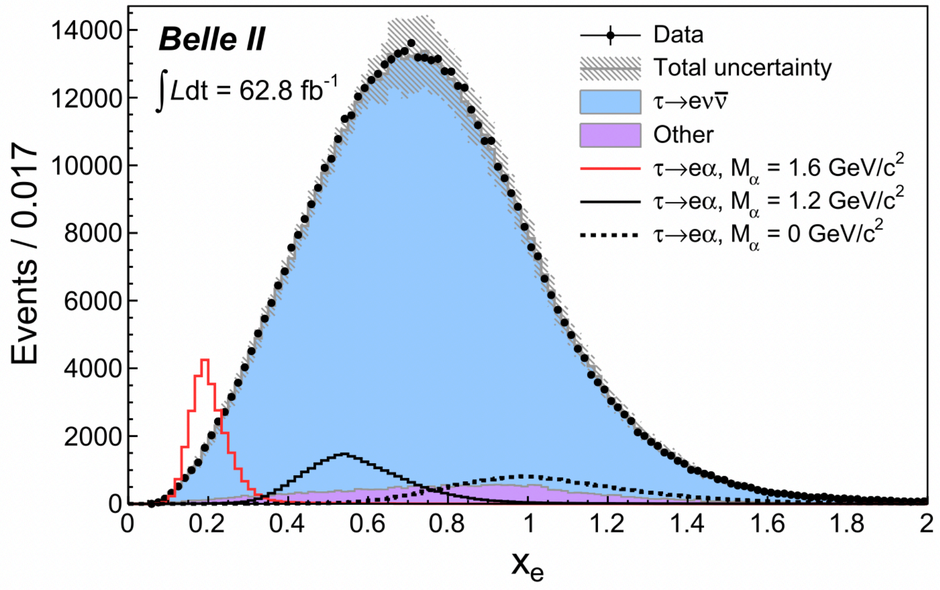
- Construct τ pseudo rest frame using
  - $p^{\tau}_{\mathrm{sig}} \approx -\vec{p}_{3h}/|\vec{p}_{3h}|$
  - $E^{\mathrm{signal}}_{\tau} = \sqrt{s}/2$

$$x_l \equiv \frac{E_l^*}{m_\tau c^2/2}$$

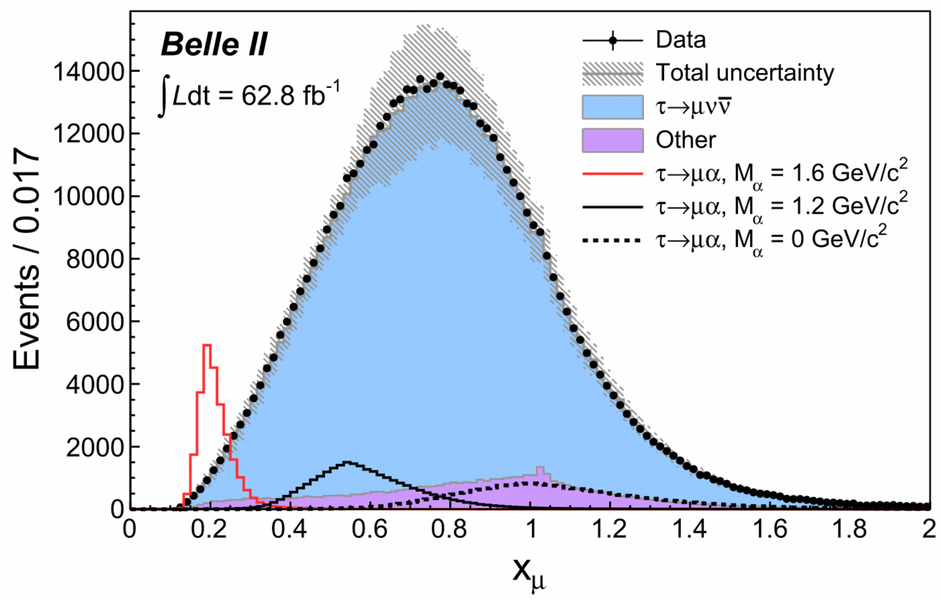


- Discriminating variable: **normalized lepton energy** x_l
- Signal signature: Excess above the $\tau \to l\nu\nu$ background spectrum

$\tau \to e\alpha$ search



$\tau \to \mu\alpha$ search

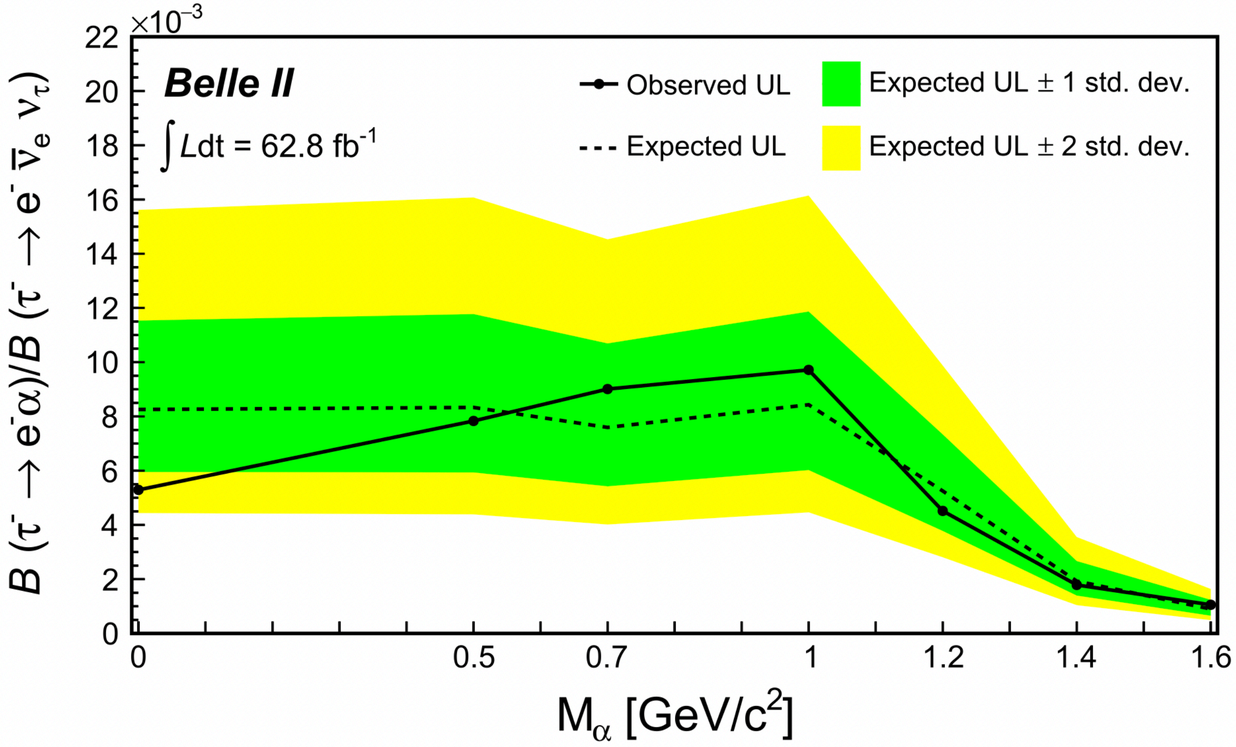


Signal results

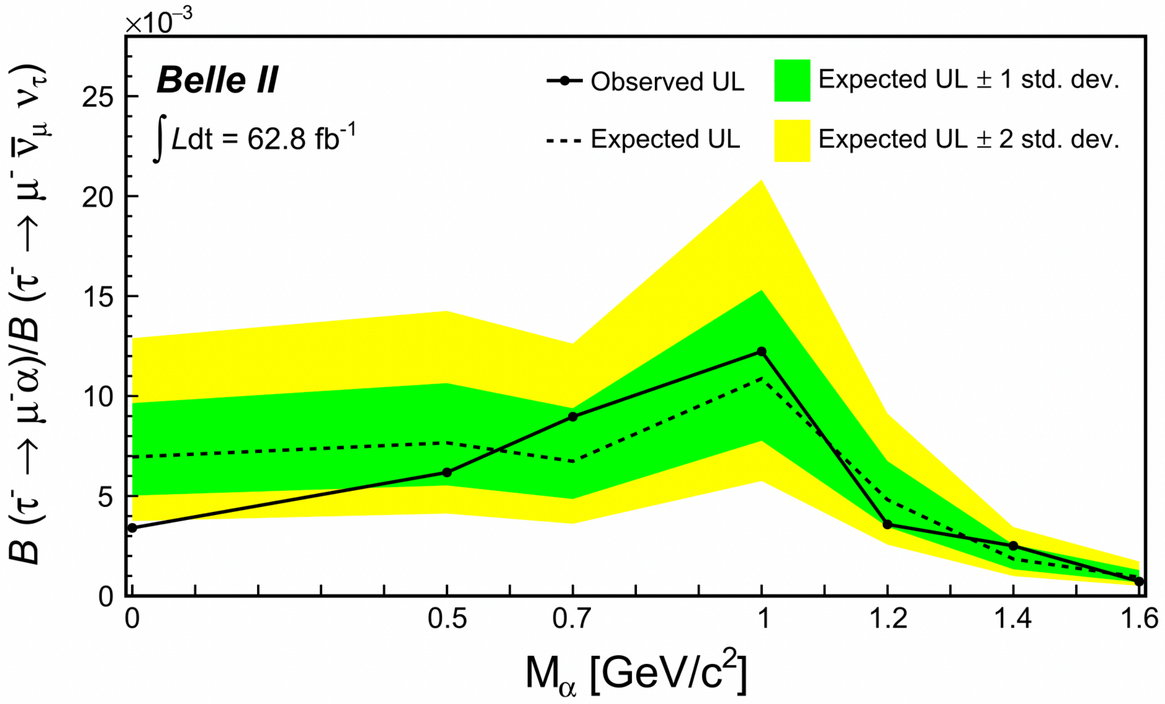
Phys. Rev. Lett. 130, 181803

- No significant excess found in 63 fb^{-1}
- Set 95% C.L. BF ratios for M_α from (0 - 1.6) GeV

$\tau \to e\alpha$ search



$\tau \to \mu\alpha$ search



2 to 14 times more stringent than ARGUS

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
- A lot of dark sector searches are in progress
- In the next years Belle II is expected to lead the light dark matter field!

Thank you

Trigger System

- Two-tier trigger systems
  - 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