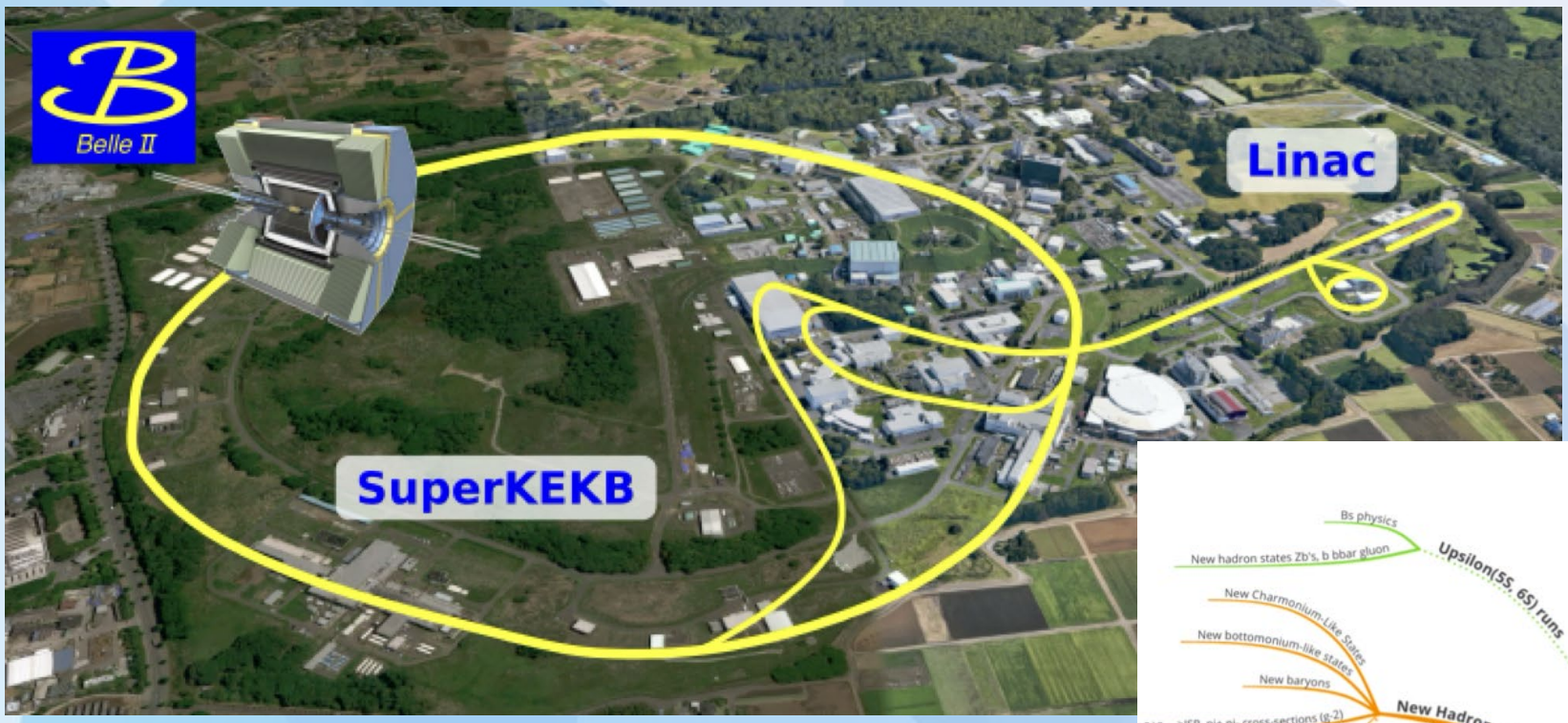
Studies of Tau and Dark Sector Decays at Belle and Belle II

- W. W. Jacobs
- Indiana University / CEEM

- CIPANP25, 8-13 June, 2025

on behalf of the Belle and Belle II Collaborations

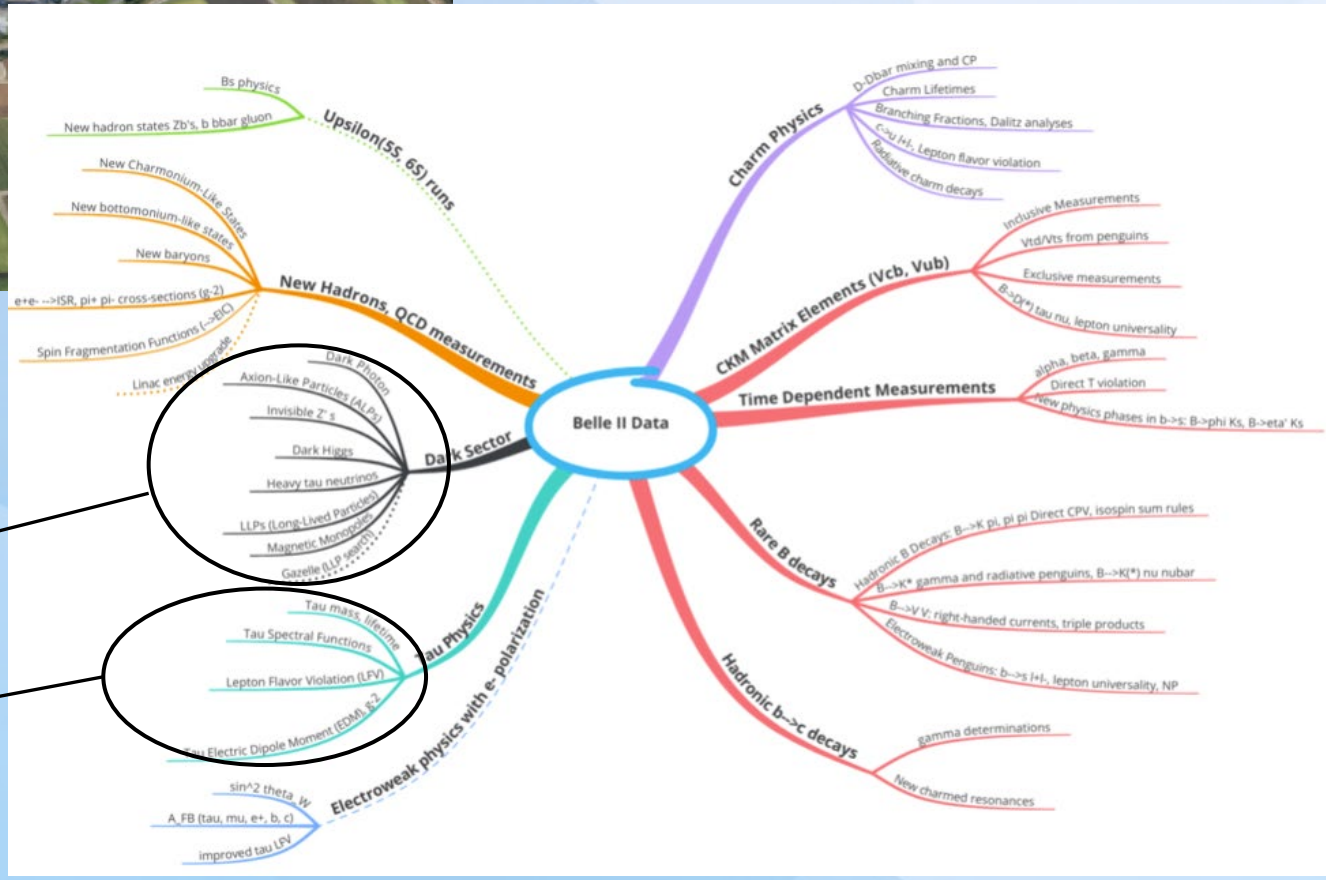


B-Factory: SuperKEKB at KEK **Laboratory** with Belle and Belle II, Tsukuba

Many physics "branches" and interests!

Dark Sector physics

Tau decays / physics



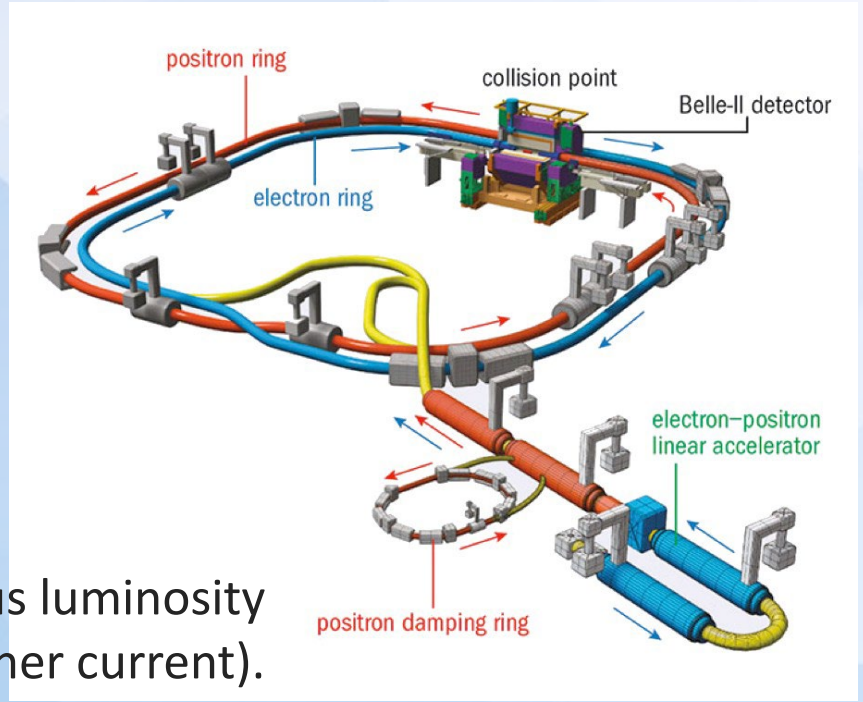
KEK Collider and Belle / Belle II Experiments

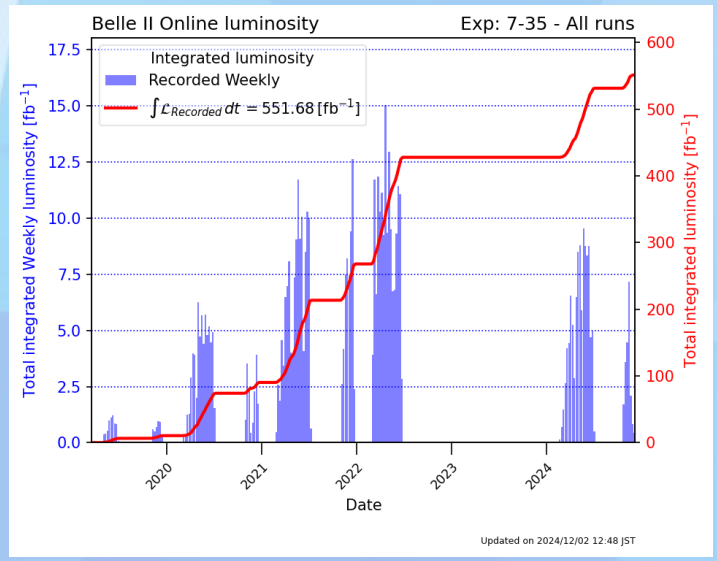
KEKB 1999-2010: e^+ (3.5 GeV) e^- (8 GeV) collider

- collected luminosity ≈ 1 ab^{-1}

SuperKEKB: e^+ (4 GeV) e^+ (7 GeV) collider w/ **major upgrades**

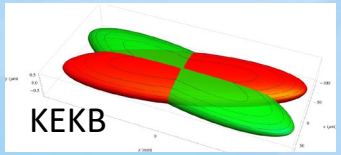
- recorded luminosity = 575 fb^{-1}
- Run 1 = 428 fb^{-1} (365 @ $\Upsilon(4S)$ + 62 off-resonance)
- **World Record instantaneous luminosity = 5.1 x$10^{34} cm^{-2} s^{-1}$**
- plan to collect many ab^{-1} of data!





Design: x **30** increase in instantaneous luminosity

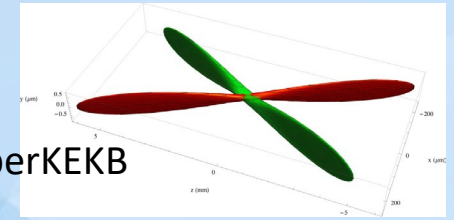
- × 1.5 from upgraded ring (higher current).
- × 20 β* from final focus magnets.



Nano beam scheme works!

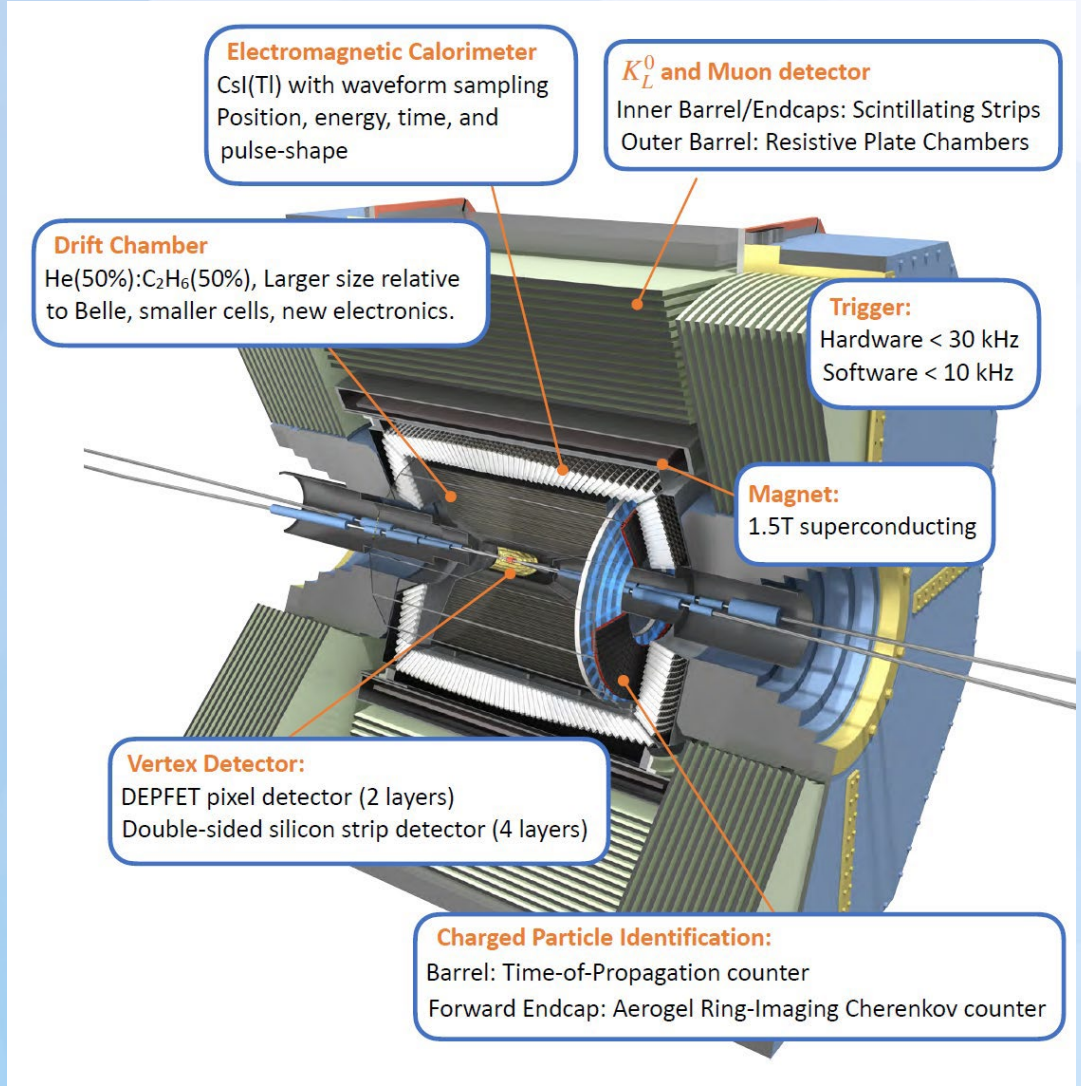
Squeeze vertical beam spot down to ~ 50 nm with super-conducting magnets

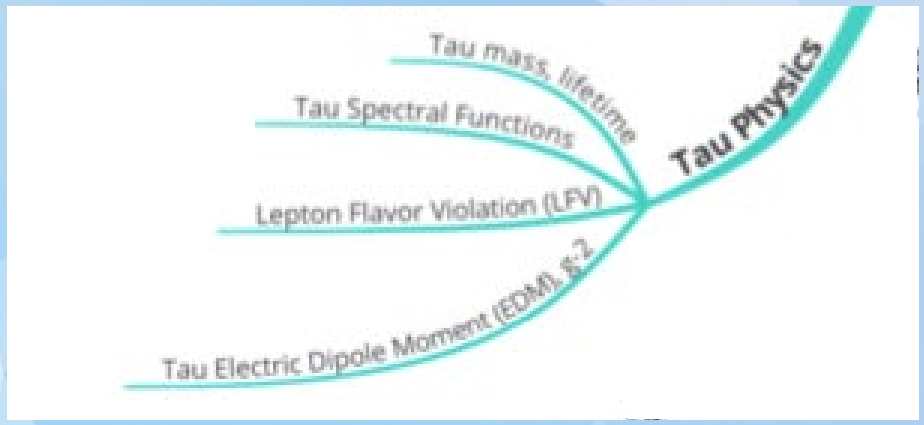
⇨



KEK Collider and Belle / Belle II Experiments

- Belle II is a **major upgrade** of the Belle detector
  - better resolution, particle ID and rate capability (including backgrounds)
- **Excellent capabilities for Tau and Dark Sector physics investigations**
  - **missing energy and neutral reconstruction:**
    - well defined initial state and clean environment
    - precisely known acceptance/efficiencies with nearly hermetic detector
    - good particle identification (lepton ID, π/K separation)
- Improved **vertex resolution;** excellent **tracking and reconstruction efficiency**
- **Special triggers** dedicated to low-multiplicity events (including single photon trigger not available at Belle)
  - allows for signal selection not previously possible
- In combination: can exploit **new analysis approaches**





TAU DECAYS

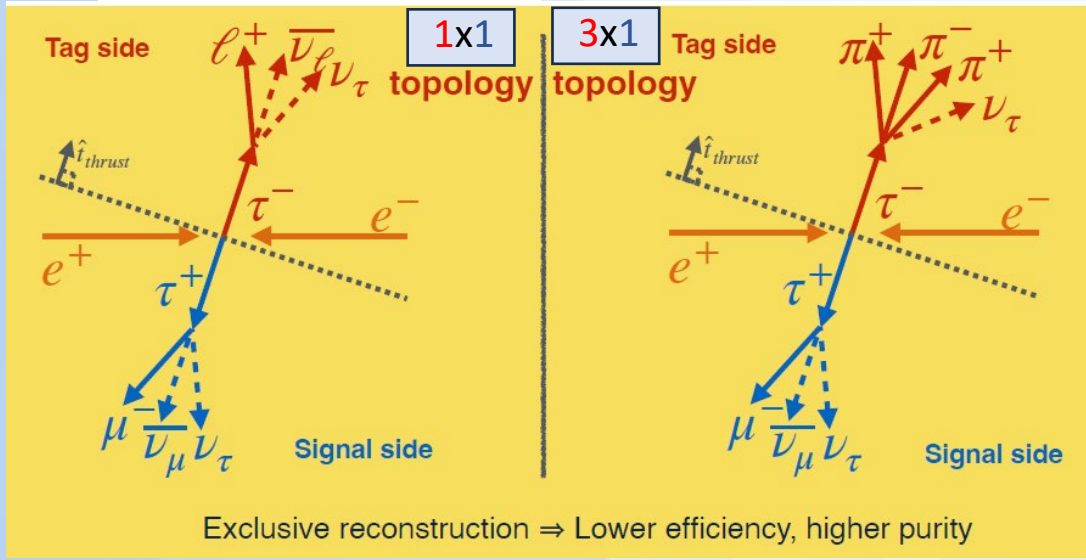
- ❑ Tau mass
- ❑ Lepton Universality
- ❑ Lepton Flavor Violation
- ❑ Baryon Number Violation

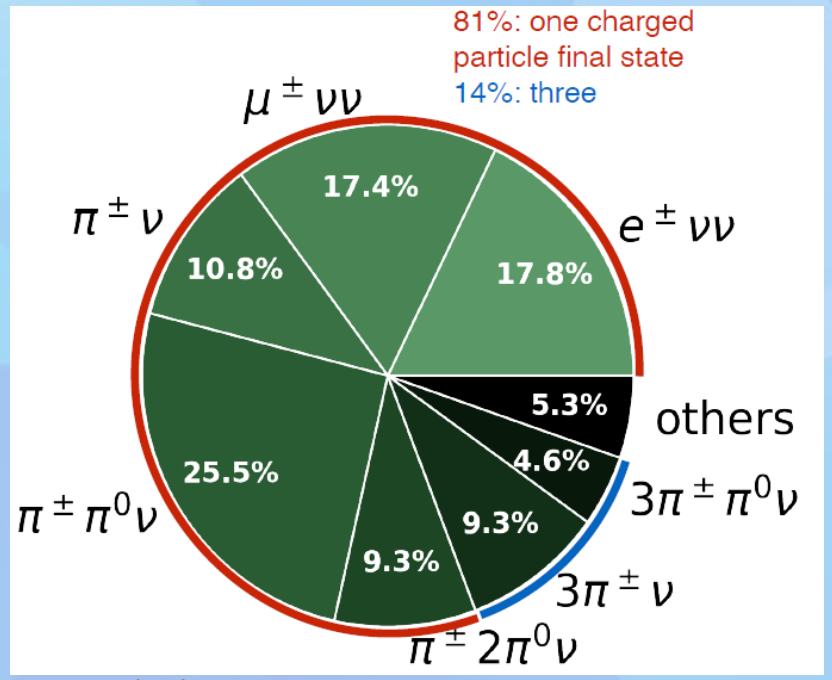
Overview - Tau Physics at Belle and Belle II

- **The τ is the heaviest lepton in the SM:**
  - Tau can decay into leptons and hadrons
  - Decays can involve 1 or 3 charged final-state particles
  - Due to its large mass: sensitive to new physics models
- **B Factories are also τ factories !**

$$\sigma(e^+e^- \to \tau^+\tau^-(B\bar{B})) = 0.92(1.05)nb$$

- **Testbed for SM or rare process searches**

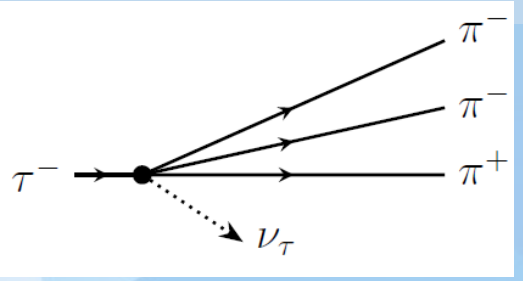




- τ pairs are produced **back-to-back** and boosted in the CM frame
  - **Identification largely topological**
  - Separate into **two opposite hemispheres** via the **thrust axis T**
  - Use either **one charged track (1-prong)** or **three charged tracks (3-prong)**
- One τ **tags the event** … the **signal is reconstructed on the other side**
  - Can also exploit **untagged analyses** to **boost the signal efficiency at the cost of some purity**

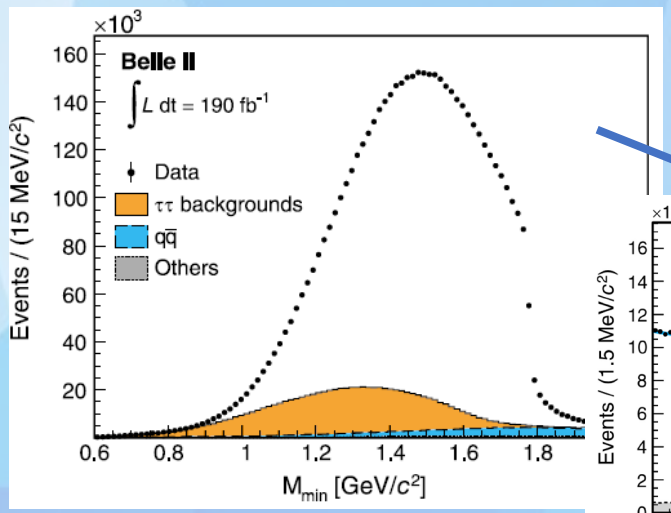
$$T = \max_{\hat{n}_T} \left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|} \right)$$

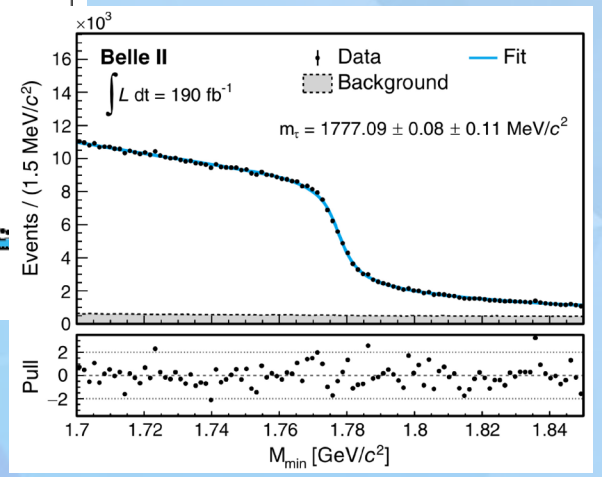
τ Mass Measurement at Belle II



- The Tau Lepton mass is a **fundamental physics parameter**
  - important input, e.g., for lepton-universality tests
- Use the pseudomass analysis method with $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
  - the M_{min} distribution ends at m_τ
  - smeared by resolution and initial and final state radiation

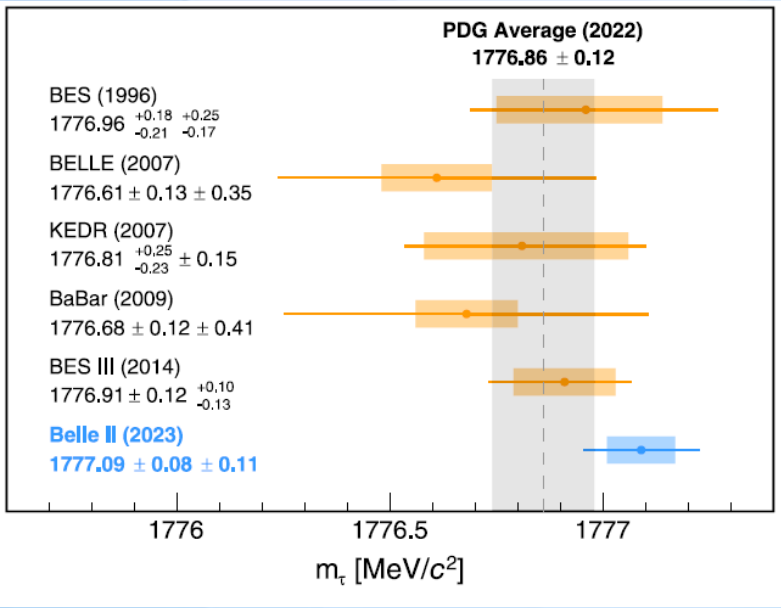
Tag side: ($\varepsilon = 2.3\%, purity\ 90\%$)
$\tau \to e\nu\bar{\nu}, \mu\nu\bar{\nu}, \pi^{\pm}\nu, \pi^{\pm}\pi^0\nu$





- **Accuracy determined by:**
  - Beam energy $\sqrt{s}$ calibrated using $B\bar{B}$ events (and tracked)
  - Final-state particle momentum calibr'ed using the standard candle $D^0 \to K\pi$
  - $190 fb^{-1}$ dataset

PRD 108, 032006 (2023)



$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} < m_\tau$$

Belle II: most precise result!
$m_\tau = 1777.09 \pm 0.08 \pm 0.11 MeV/c^2$

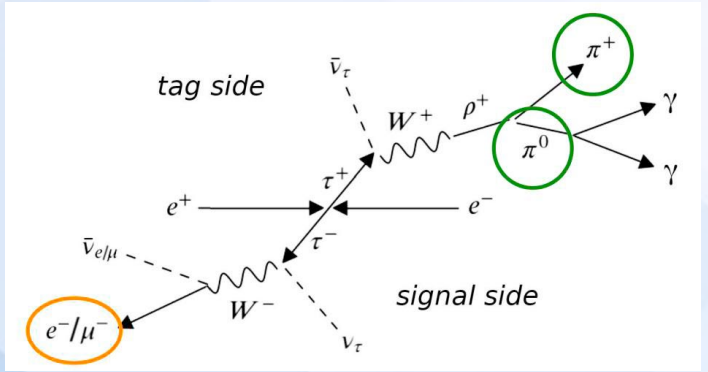
Test of Lepton Flavor Universality (LFU) in τ Decays

- Are the W gauge bosons couplings for the three generations of leptons the same as predicted in the SM?

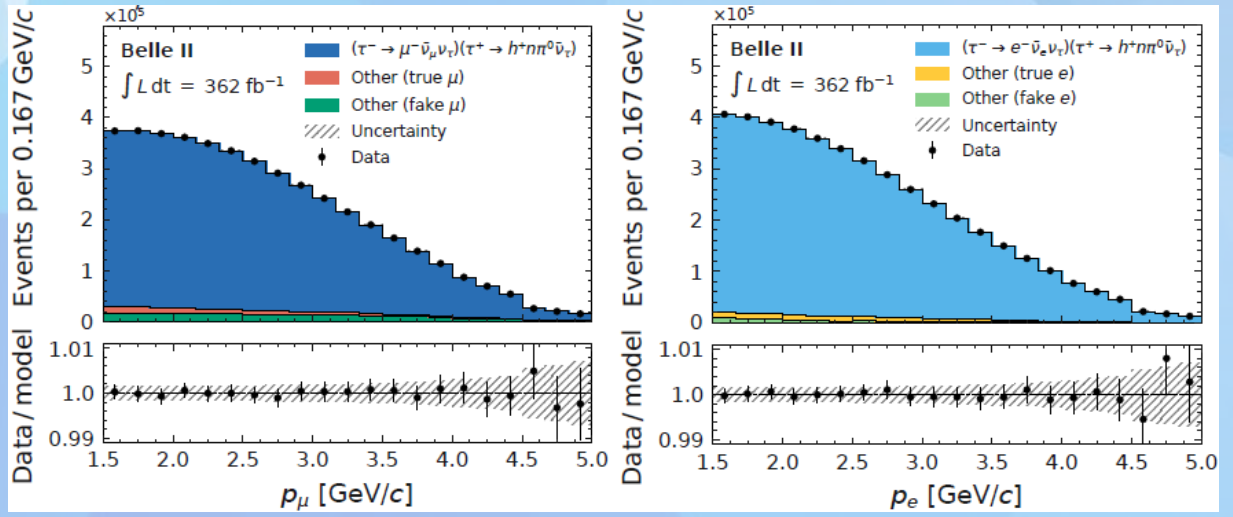
$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1$$

- R_μ measurement in a 1 X 1 prong topology with $\pi^+ + n\pi^0$ tag and 365 fb^{-1} at Belle II

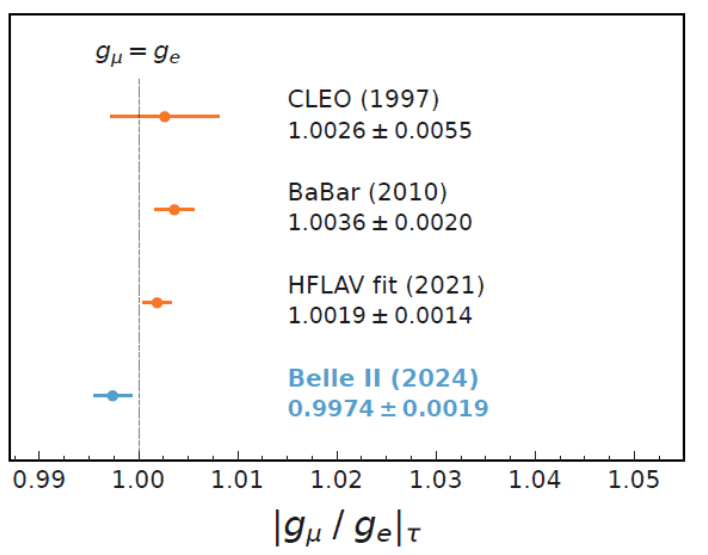
$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{\text{SM}}{=} 0.9726$$



- Event selection is performed with **rectangular cuts** and a **neural network**
  - main systematics are from **PID** (0.32%) and **trigger** (0.1%)
- R_μ is extracted with a **template fit** of the e and μ **momentum distr's**



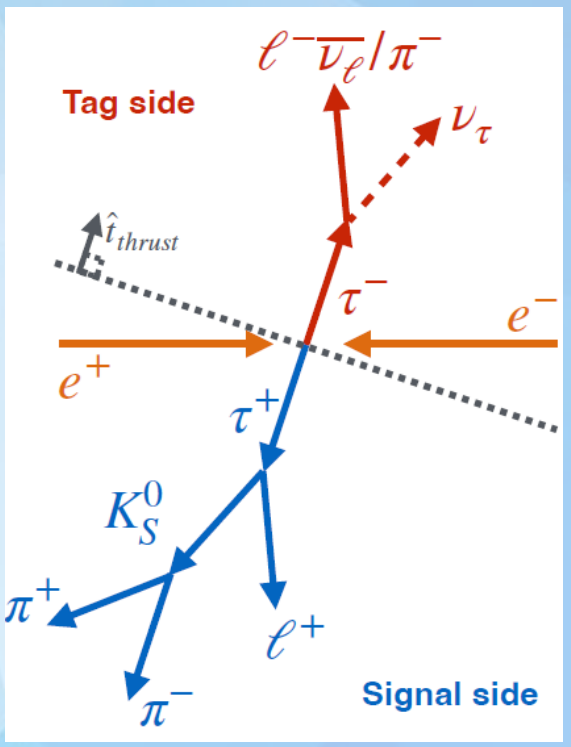
- **No deviation from the SM**
- **Most precise test** from a single Tau decay measurement



$$R_\mu = 0.9675 \pm 0.0007(stat) \pm 0.0036(sys)$$
$$|g_\mu/g_e|_\tau = 0.9974 \pm 0.0019$$

JHEP08(2024)205

New LFV Results: Decay $\tau^- \to \ell^- K_S^0$

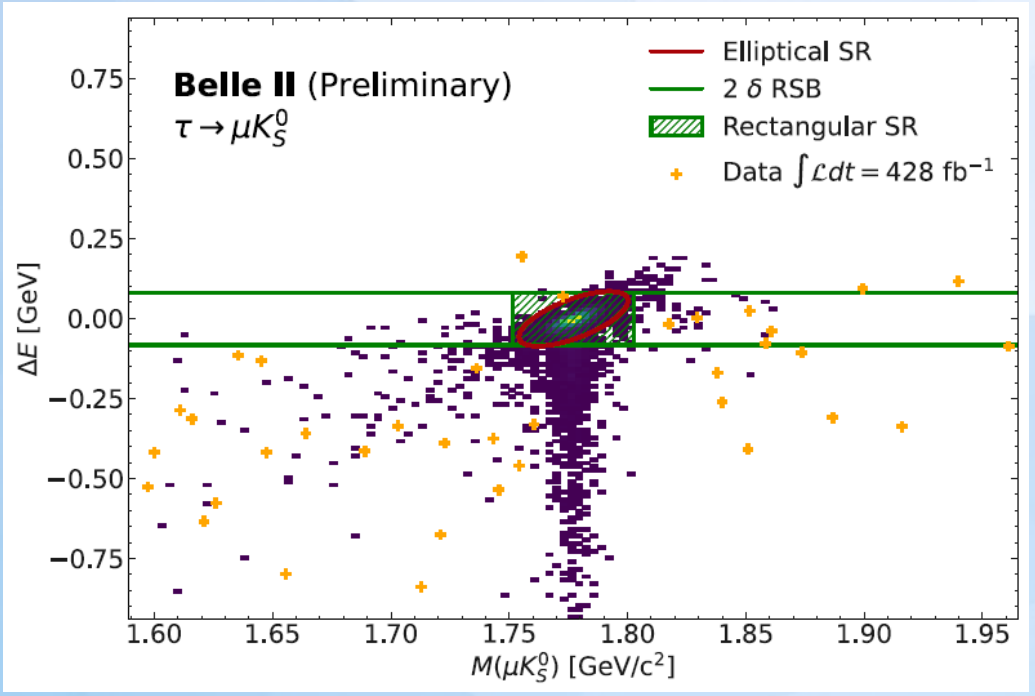


Belle + Belle II search for $\tau^- \to \ell^- K_S^0 (\ell = e, \mu)$

- Require **4 charged particles** with 0 net charge in 3×1-prong topology
  - reconstruct K_S^0 from $\pi^+\pi^-$
  - on the tag side: $\tau \to \ell \bar{\nu}_\ell \nu_\tau / \pi \nu_\tau (\ell = e, \mu)$

arXiv:2504.15745

- Cut-based preselection
- **BDT classifier** trained using
  - track kinematics
  - event shape
  - neutral variables
- Resulting efficiency: 10%
- **Extract signal yield from 2D plane** $(M_\tau, \Delta E = E_\tau - E_{beam})$



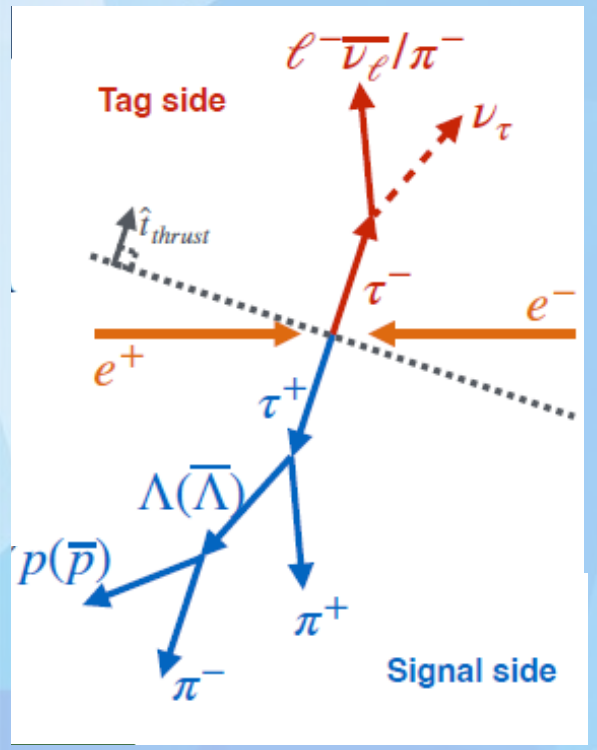
- **No significant signal** observed in 428 fb^{-1} + 980 fb^{-1} (Belle + Belle II)
- Combined 90% CL upper limit on branching ratios:

$$\mathcal{BR}(\tau \to K_S^0 e) < 0.8 \times 10^{-8} \quad \mathcal{BR}(\tau \to K_S^0 \mu) < 1.2 \times 10^{-8} \quad \to \text{ new world-leading upper limits}$$

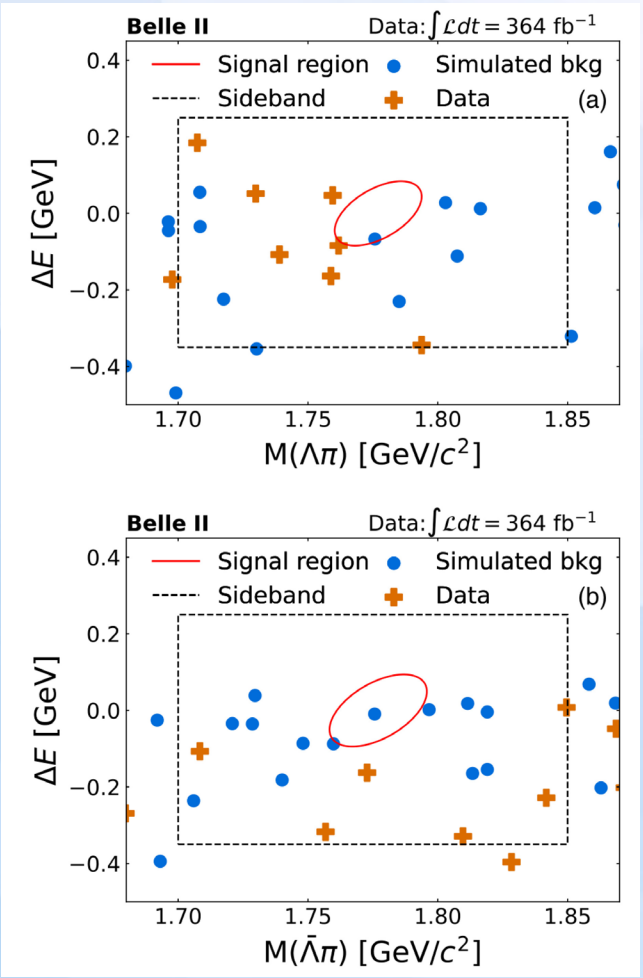
Baryon (and Lepton) Number Violation: $\tau^- \to \Lambda\pi^-$ and $\tau^- \to \bar{\Lambda}\pi^-$

- **BNV plays a key role in helping explain the observed asymmetry of matter**
  - **Many** of the BSM scenarios allow for BNV
  - Baryon and Lepton number violated; some models* allow $|\Delta(B-L)| = 2, 0$

PRD **110, 112003 (2024)**



- Recent analysis and new most stringent limit
  - use a 1 x 3 **topology**
  - reconstruct **4 charged particles** (0 net charge)
  - $\Lambda(\bar{\Lambda})$ reconstructed from $p(\bar{p})$ and π^-
  - background suppression: **loose preselection** plus **gradient BDT**
  - $\epsilon_{sig} \simeq 9.5(9.9)\%$ for $\tau^- \to \Lambda(\bar{\Lambda})\pi^-$
  - **backgrounds** $1.0^{1.3}_{-1.1}(0.5^{0.6}_{-0.6})$ estimated by rescaling sideband data yields in signal region

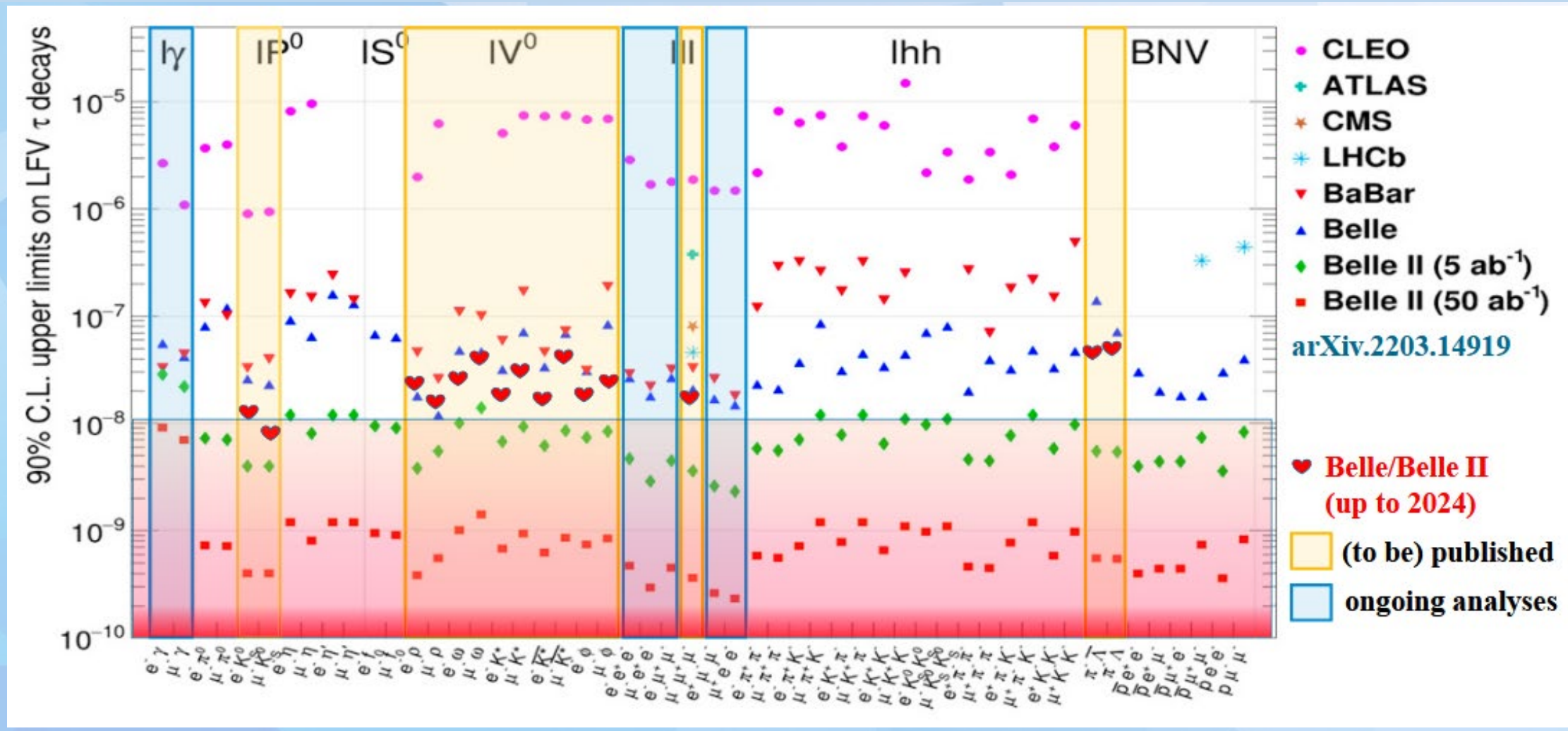


- **No events observed** in signal region with $364 fb^{-1}$ integrated luminosity
- Set 90% CL upper limit on the branching fraction

$$\mathcal{BR}(\tau^- \to \Lambda(\bar{\Lambda}\pi^-) < 4.7(4.3) \times 10^{-8}$$

- PRD **90**,016011 (2014)
  Phys. Lett. **88B**, 311 (1979)

Summary of Searches of LFV, LNV and BNV at Belle / Belle II



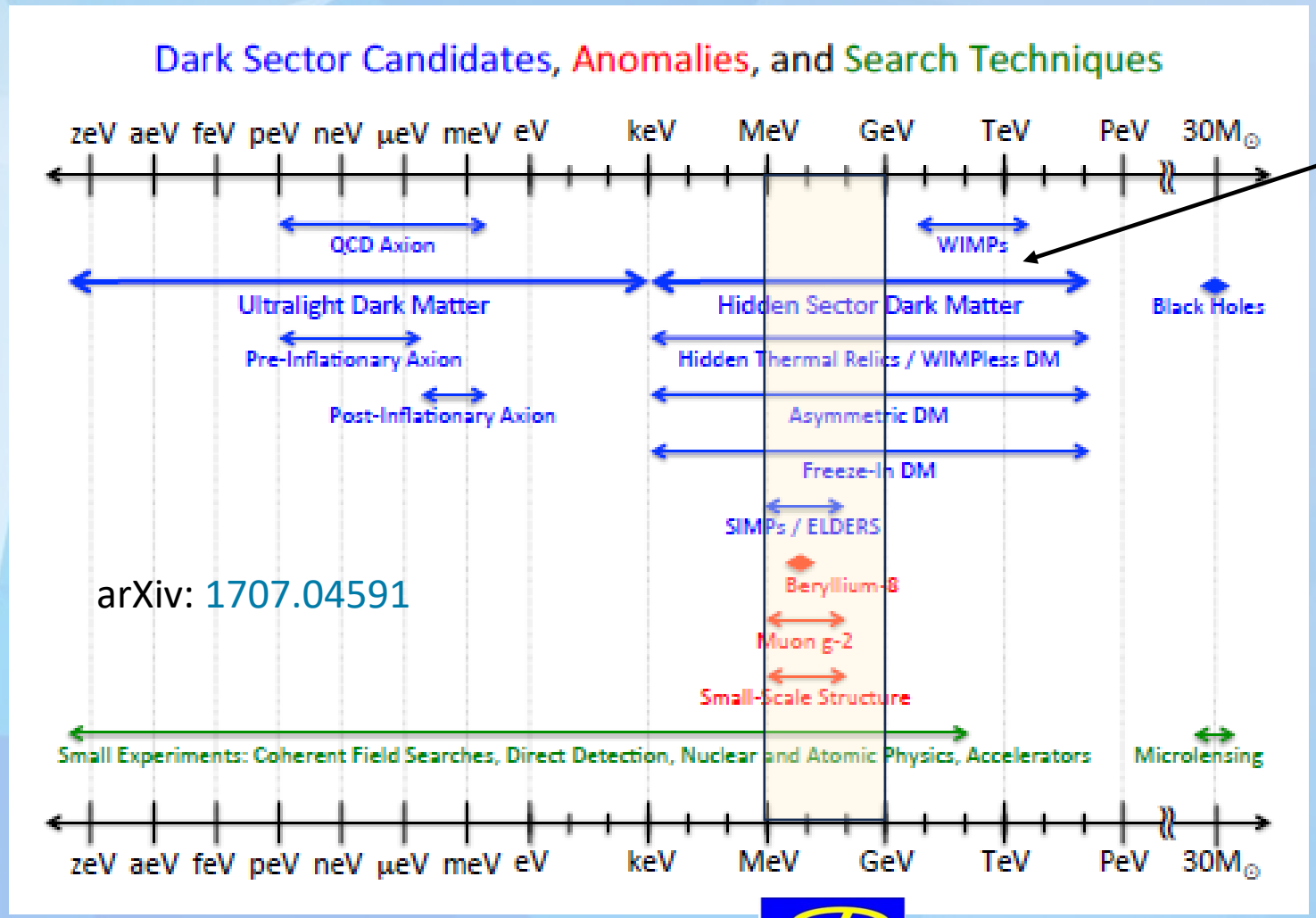
- $\tau \to 3\mu$ **new LFV,** with untagged reconstruction
  - **most stringent result** $1.9 \times 10^{-8} (\mathcal{L} = 424 fb^{-1})$
  - JHEP **2024**, 062 (2024)
- $\tau \to e2\ell$ **new LFV,** with untagged reconstruction
  - extend previous study to 5 more modes
  - **most stringent upper limit** for all modes (prelim)

DARK SECTOR

- Z' boson invisible decay
- $\mu\mu, \tau\tau$ resonant searches for DM Scalar, ALP
- Inelastic DM search
- FCNC B decay and ALP search

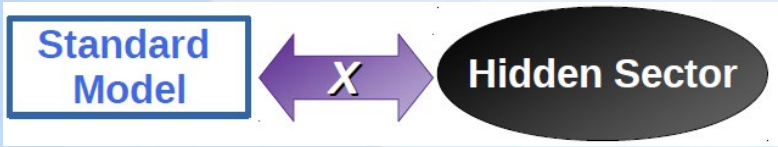
Dark Matter and Light Dark Sectors Accessible with Belle / Belle II

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')*

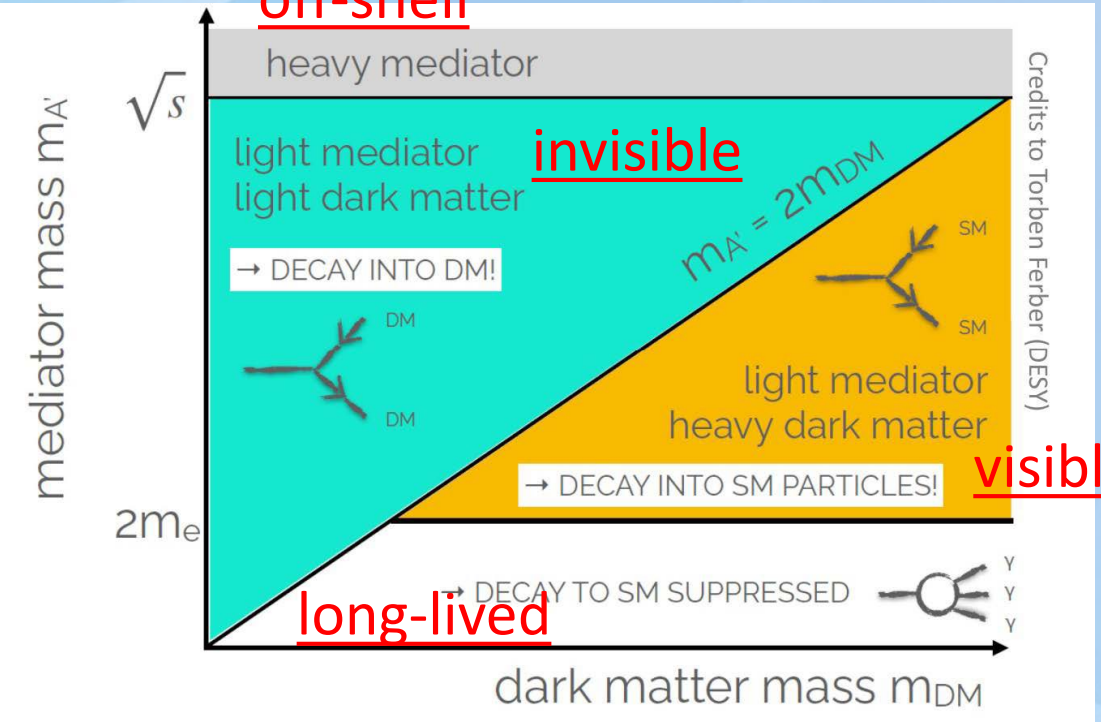


- Vector portal → **Dark Photons, Z' bosons**
- Pseudo-scalar portal → **Axion Like Particles (ALPs)**
- Scalar portal → **Dark Higgs/Scalars**
- Neutrino portal → Sterile Neutrinos

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

Experimental signatures in Dark Sector searches

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



- **Decay to DM particle:**
  - invisible dark photon A', Z', …
  - signature -> missing momentum
  - decay to SM + DM particles:
  - partially visible signature -> displaced vertex not pointing to IP
- **Prompt decay to SM:**
  - visible dark photon A', Z', ALP -> γγ, ALP -> ff …
  - signature -> invariant mass bump search

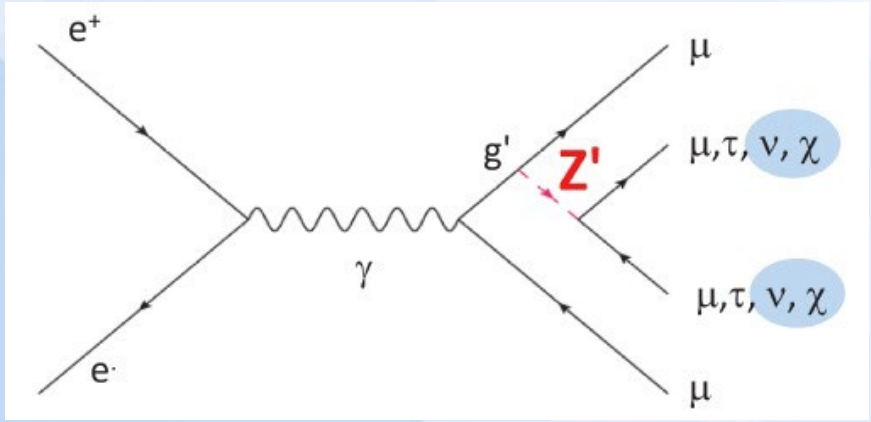
- **Long lived (decay to SM suppressed)**
  - inelastic DM, scalars, h', …
  - decay-length < O(1)m: visible signature -> displaced vertex
  - decay-length > O(1)m: invisible signature -> missing momentum

The $L_\mu - L_\tau$ Gauge Boson: 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] …

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

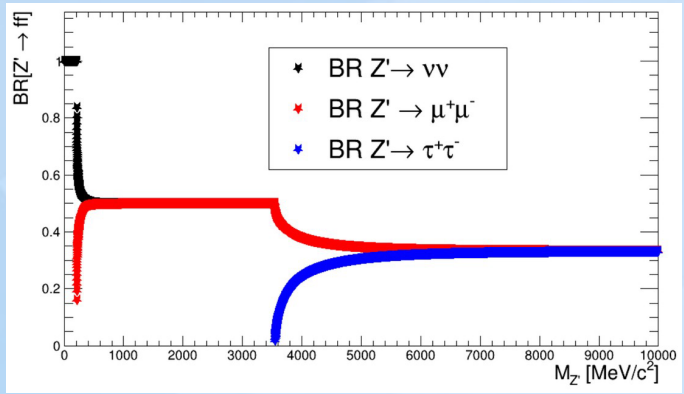
θ =+1 if *l* = μ
θ =-1 if *l* = τ



- $m_{Z'}$ 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 $e^+e^- \to \mu^+\mu^- Z'$ (invisible)

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



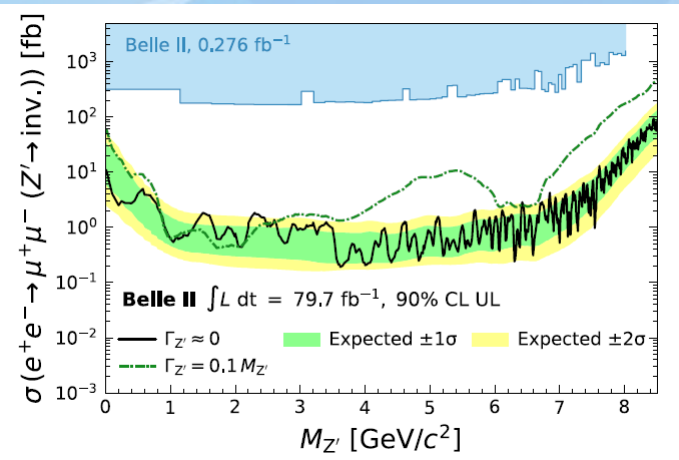
BR has dependence on Z' mass

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

Search for an Invisibly Decaying Z′

PRL **130**, 231801 (2023)

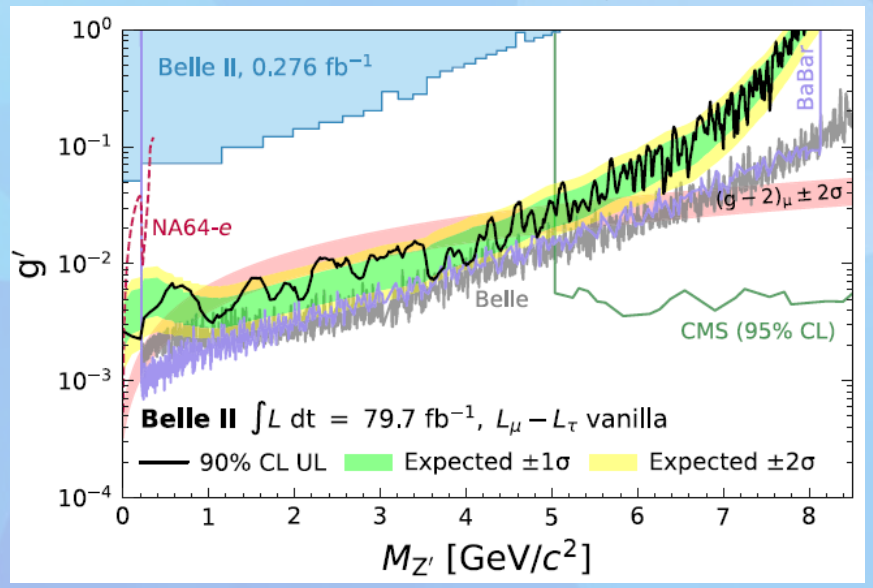
Cross Section



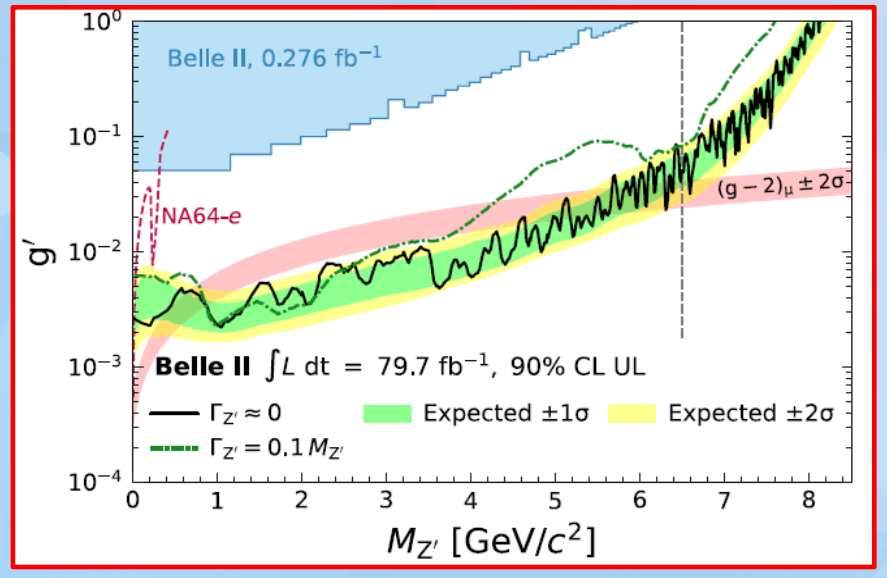
$\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \textbf{invisible})$, using $79.7 fb^{-1}$

- 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



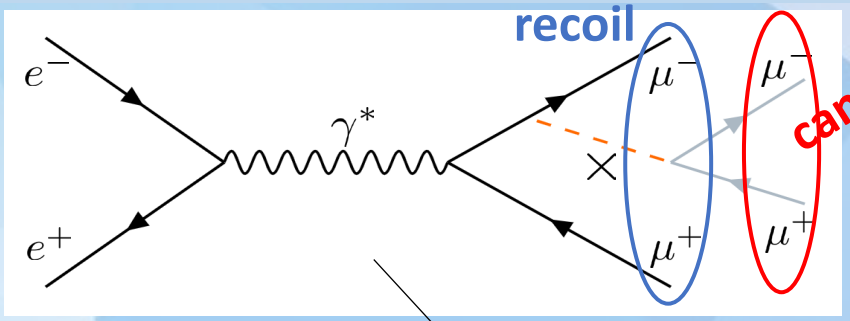
Z′ → invisible



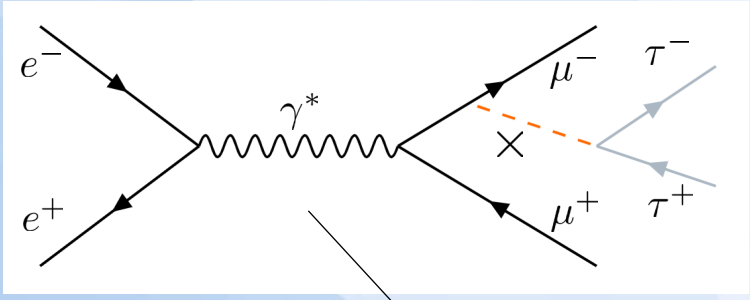
Invisible Z′ as origin of (g-2) anomaly **excluded** for $0.8 < M_{Z'} < 5.0$ GeV/C^2

NB: ongoing analysis w/ x4.6 dataset!

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

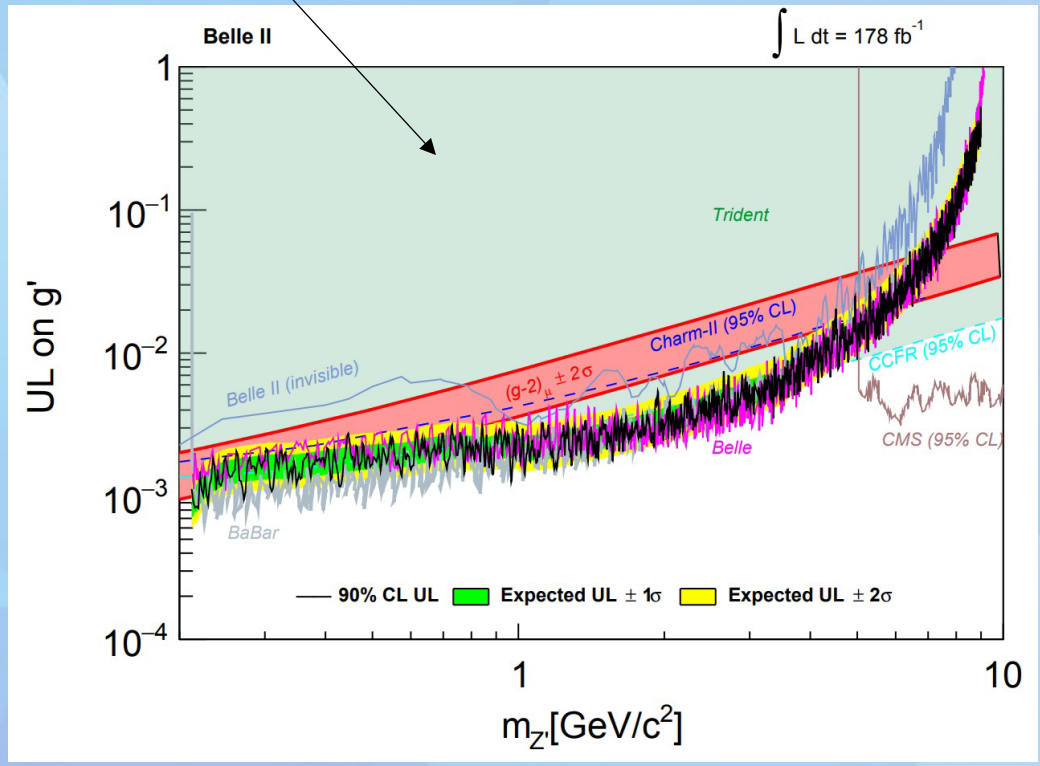


- $3\mu/4$ tracks
- $4\,\mu$ SM bkgd
- opposite-chrg $M(\mu\mu)$ peak

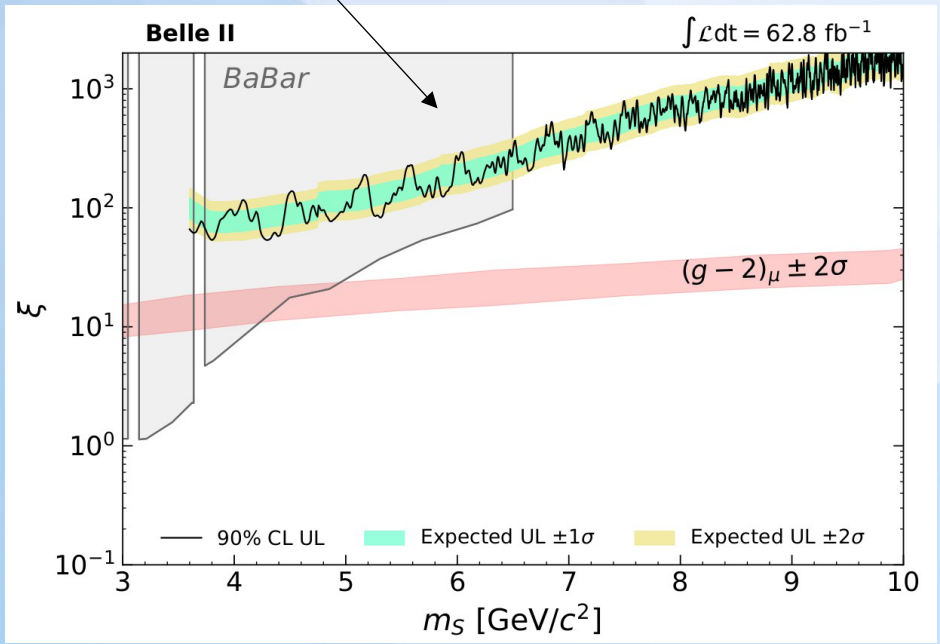


- 4 tracks (ℓ, h)
- recoil $M(\mu\mu)$
- missing energy challenge!

PRD **109**, 112015 (2024)



PRL **131**, 121802 (2023)

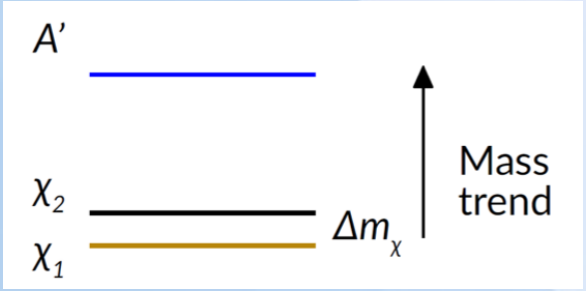


- Exclude Z' (as well as muonphilic dark scalar model) explanations for $(g-2)_\mu$ over a wide mass range
- Leptophilic dark scalar probed above 6.5 GeV/c^2
- Separately, first direct limits on axion-like particle ALP $\to \tau\tau$

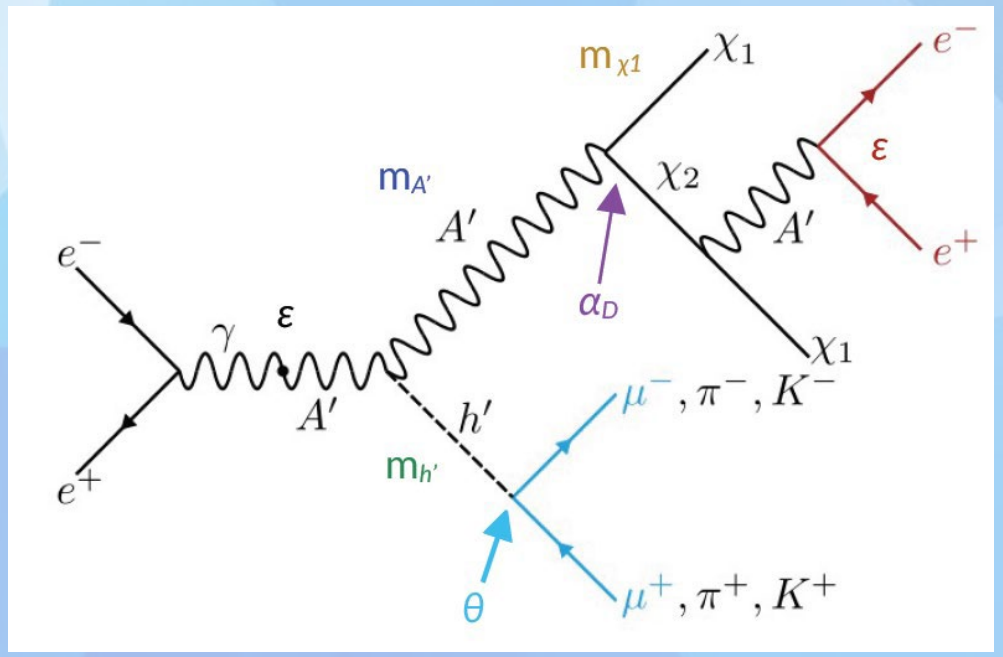
Inelastic Dark Matter with a Dark Higgs

Probing a non-minimal Dark Sector model*

- Model can reproduce relic DM density
- **4 new DS particles**:
  - dark photon: A'
  - dark Higgs: h'
  - two dark states: χ_1, χ_2
- Exploring **3 final states**:
  - $h' \to x^+x^-$, with $x = \mu, \pi, K$
- 7 free parameters:
  - 3 masses
  - 2 mixings
  - 2 couplings



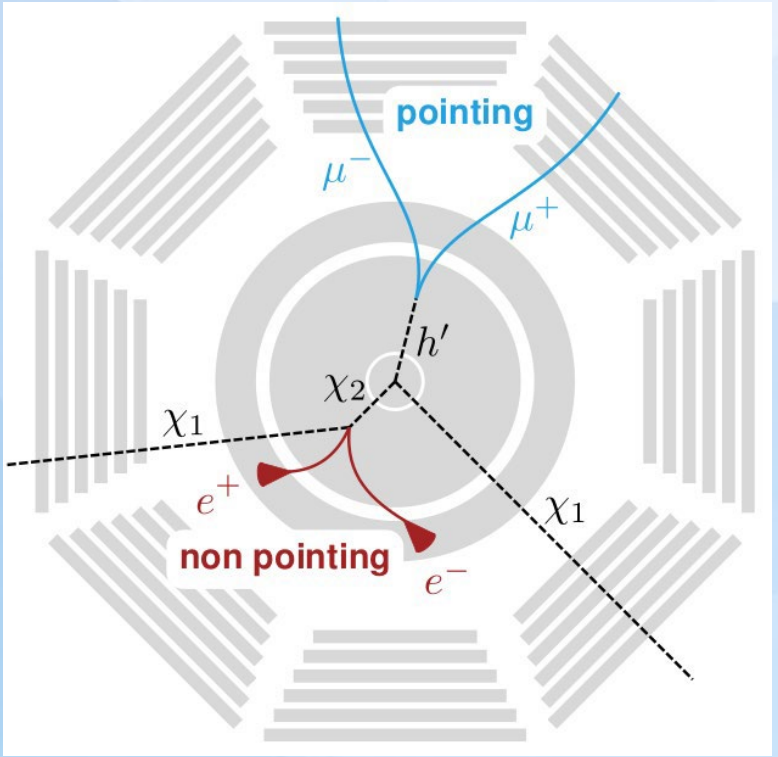
- DM χ_1 stable relic candidate
- χ_2 is generally long-lived
- Focus on: $m(A') > m(\chi_1) + m(\chi_2)$
- Decay $A' \to \chi_1\chi_2$ favored



Looking for simultaneous production of A′ and h′

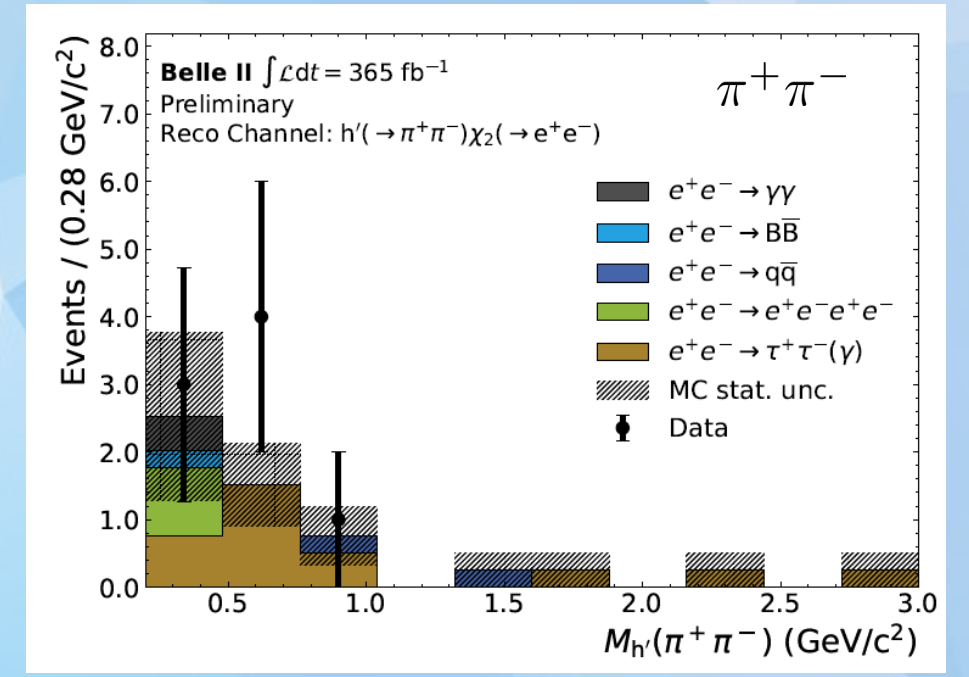
- 4 tracks in final state:
  - 2 forming a pointing displaced vertex
  - other 2 forming a non-pointing displaced vertex
  - missing energy

→ **signature-based analysis challenging for tracking and trigger**

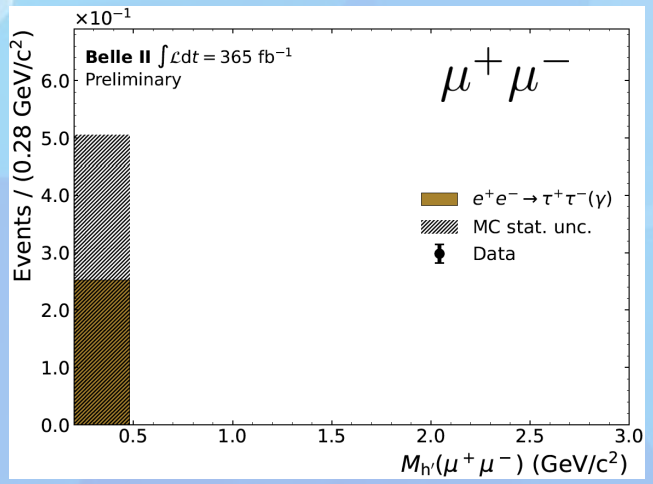


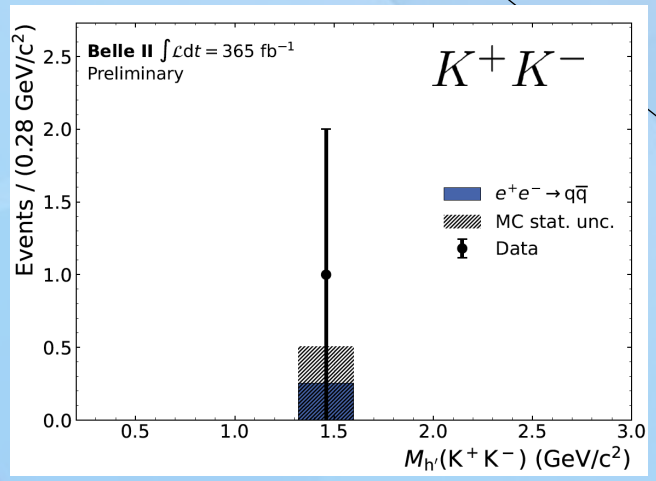
* JHEP04(2021)146

Inelastic Dark Matter with a Dark Higgs



- Search performed analyzing 365 fb^{-1} of Belle II data
- Challenging due to **displaced vertices** and the **trigger**
  - Signal selection:
    - use pointing angles and vertex distance from the interaction point
    - **very low SM background**
  - Signal yield:
    - cut and count strategy in $M_{h'}(x^+x^-)$ distributions
    - **backgrounds estimated from sidebands (data)**



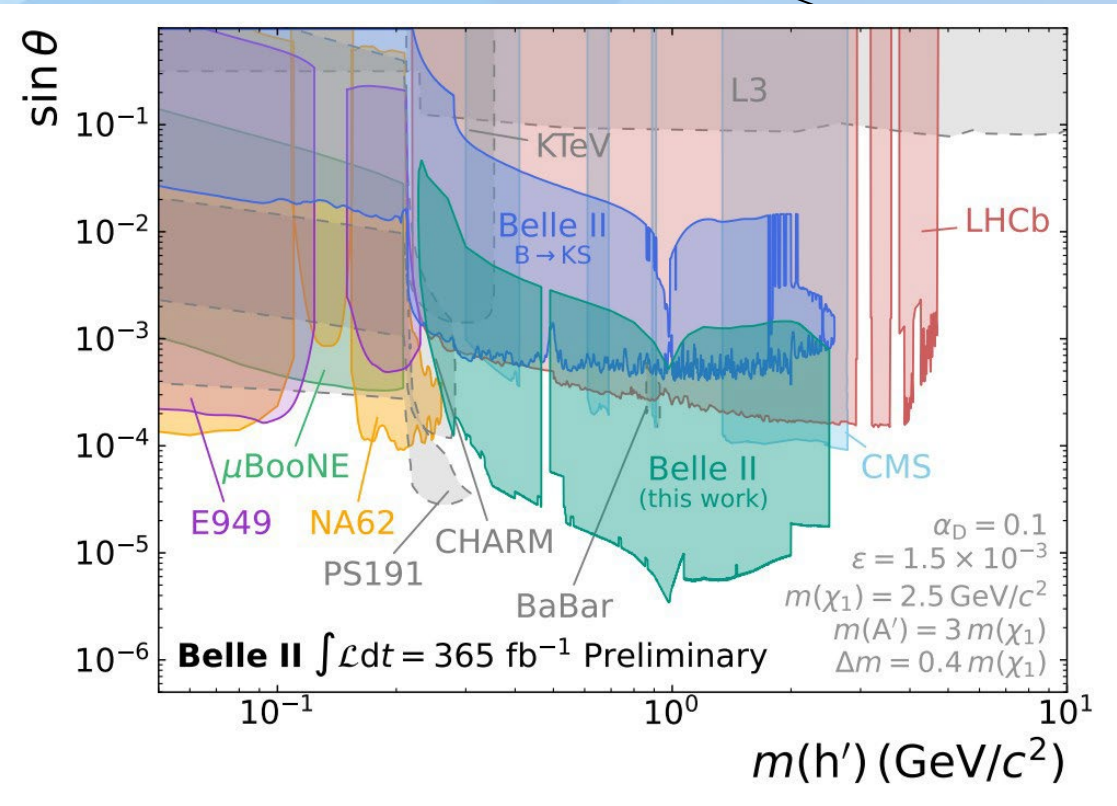


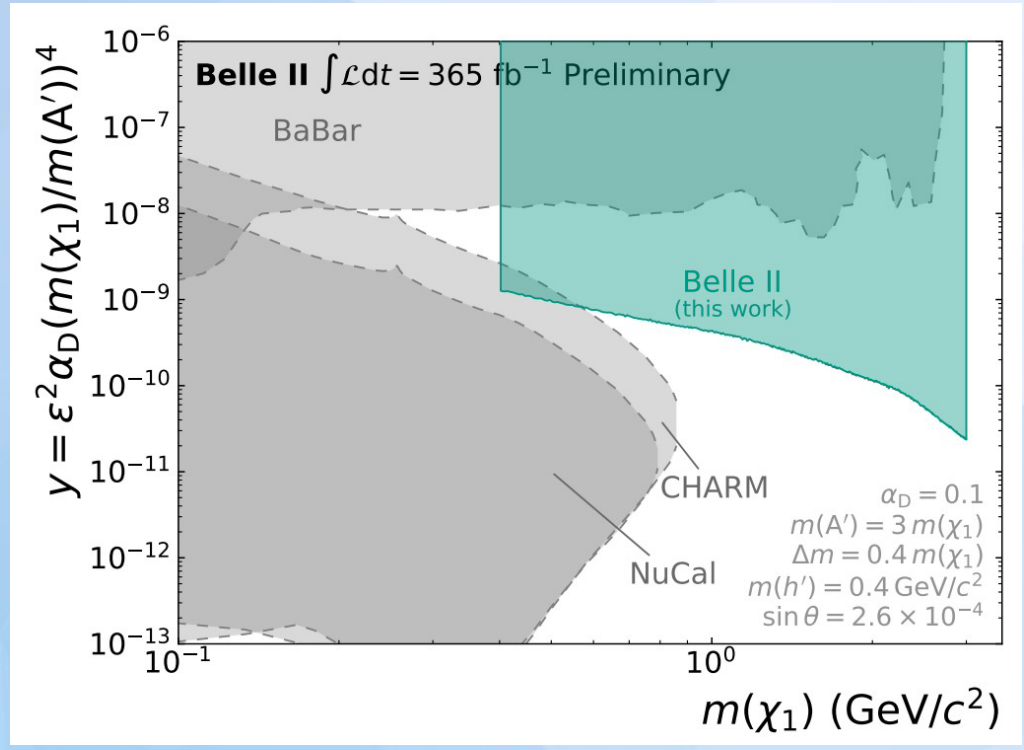
- **No significant excess found** in the individual final states or the combination:
  - for the $\pi^+\pi^-$ channel, of the 9 events observed, 8 are consistent with expected background

Inelastic Dark Matter with a Dark Higgs

arXiv:2505.09705

- Model independent limits on the process cross section
- 95% CL upper limits on $\sigma(e^+e^- \to \chi_1\chi_2 h') \times \mathcal{BR}(\chi_2 \to \chi_1 e^+e^-)[\times \mathcal{BR}(h' \to x^+x^-)]$
- Strong limits on θ and $\epsilon \times \alpha_D$ (h' mixing, A' mixing/coupling), w/ dependency on 5 other parameters





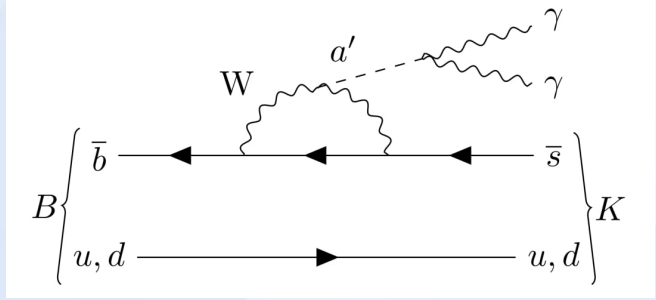
World leading limits, but dependent on the choice of the remaining parameters

→ **Provides interpretation for an additional ~ 30 model parameter configurations**

Search for ALPs in FCNC B decays: $B \to K^{(*)} a'(\to \gamma\gamma)$

New Physics searches in Flavor Changing Neutral Current B decays

- **FCNC heavily suppressed** in the Standard Model; NP can appear at same order

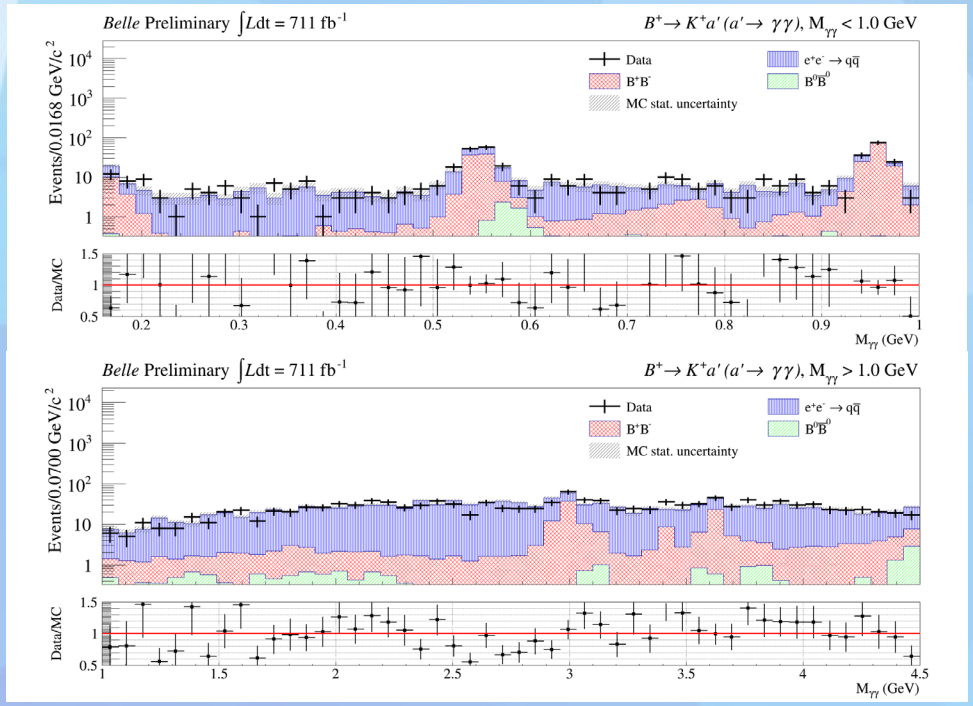


Search for **Axion-Like Particle emission** by W± in $B \to K(^*)a$ decays

- BR($a \to \gamma\gamma$) $\simeq 100\%$ for $M_a \ll M_{W^\pm}$
- Probe range 0.16 – 4.50 GeV/c²; including 4 kaon modes $K^0_S, K^\pm, K^{*0}, K^{*\pm}$; full 711 fb^{-1} Belle dataset

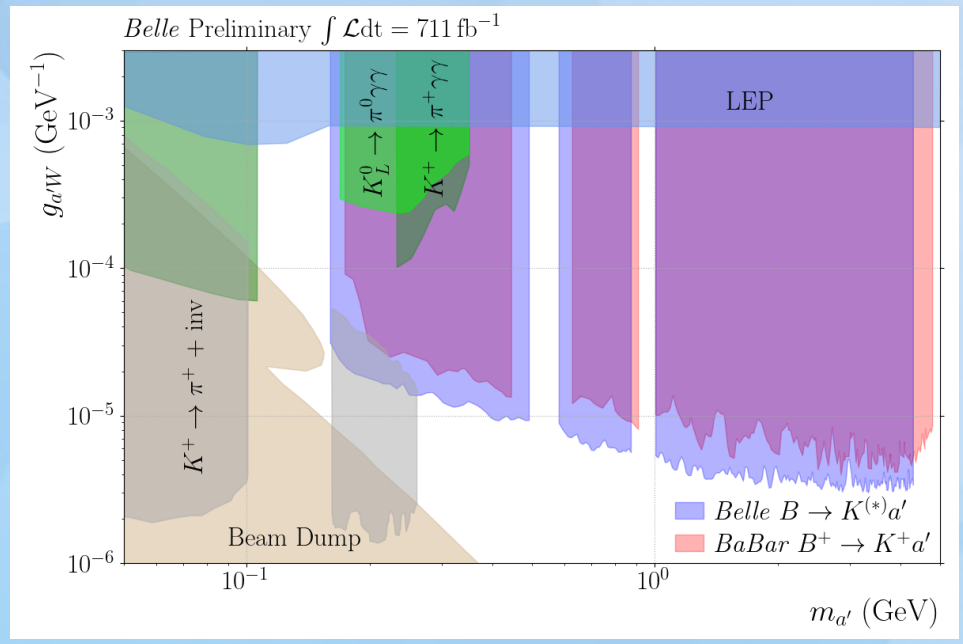
Signal Reconstruction

- Reconstruct B meson from ALP candidate (photon pair) and a Kaon candidate (charged or neutral)



Background suppression

- Energy Main background from continuum $e^+e^- \to q\bar{q}$
- Use **multiple BDTs** exploiting event shape, kinematics and energy cluster info to suppress π^0 backgrounds

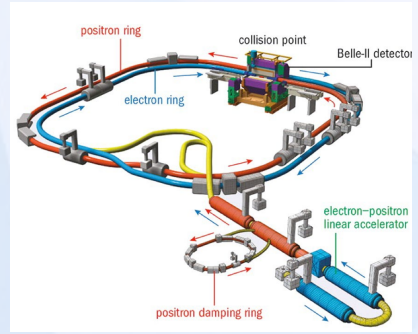


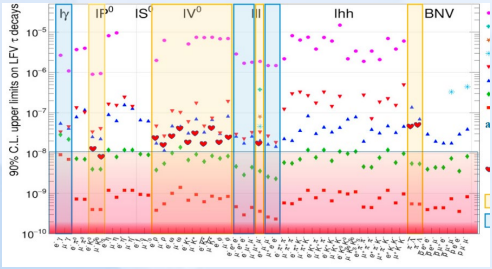
No significant excess observed!

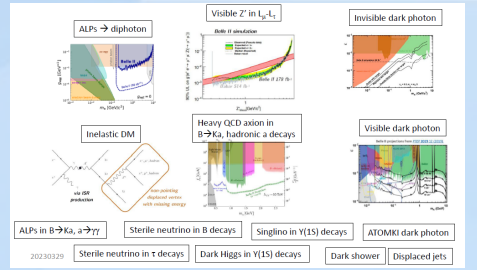
- Simultaneous fit to 4 kaon modes
- **World leading** 90% CL upper limits on $g_{a'W}$

Summary for Belle/Belle II Tau and Dark Sector

- Belle and Belle II are unique facilities and provide an excellent environment for many exciting dark sector and tau studies
  - Precision measurements of tau properties
  - World-leading results on LFU and LFV searches with tau decay
  - New limits from Z' invisible and visible decays; resonance searches put limits on dark scalar models and ALP decay to tau leptons
  - First search for Dark Higgs bosons produced in association with inelastic dark matter
  - Many more tau decay and dark matter searches ongoing and projected







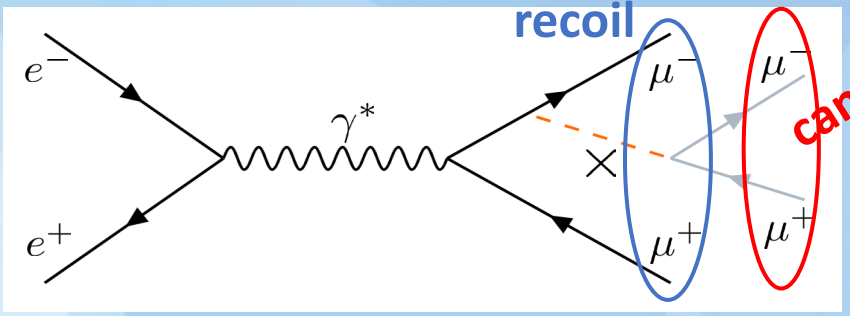
Expect new significant results with the data sets of the next few years!

Thank you!

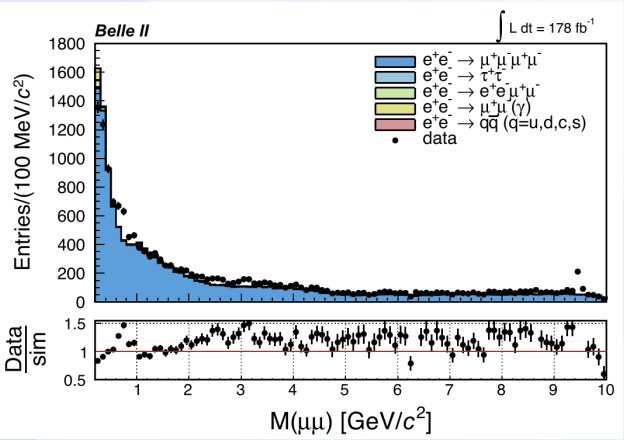
BACKUP SLIDES

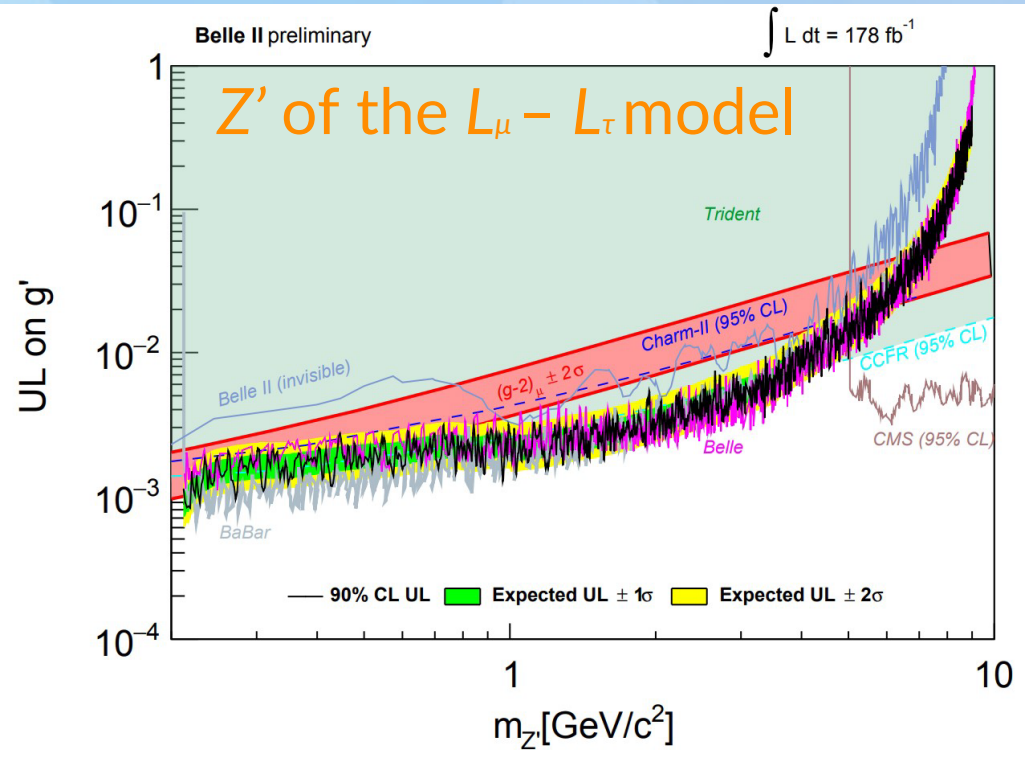
Search for Z', S → $\mu\mu$ at Belle II

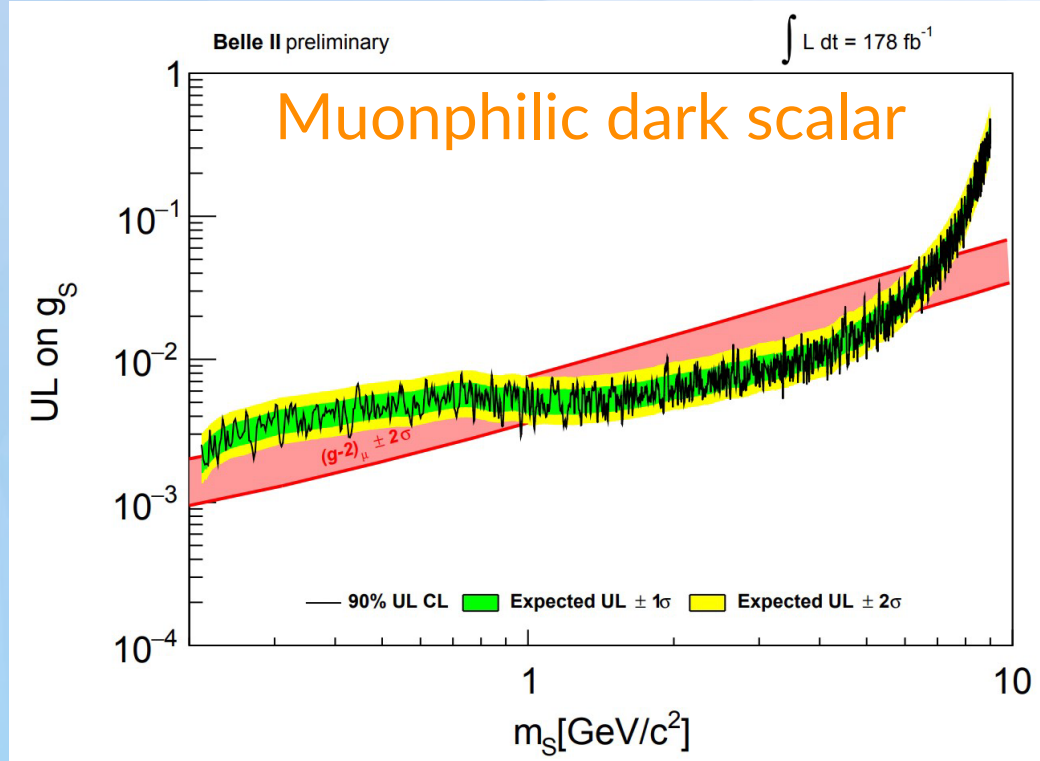
Phys. Rev. D 109, 112015 (2024)



- **Competitive 90% CL upper limits on the *g'* coupling** of the $L_\mu - L_\tau$ model (Z')
- **First 90% CL upper limits on muonphilic scalar model** from a dedicated search



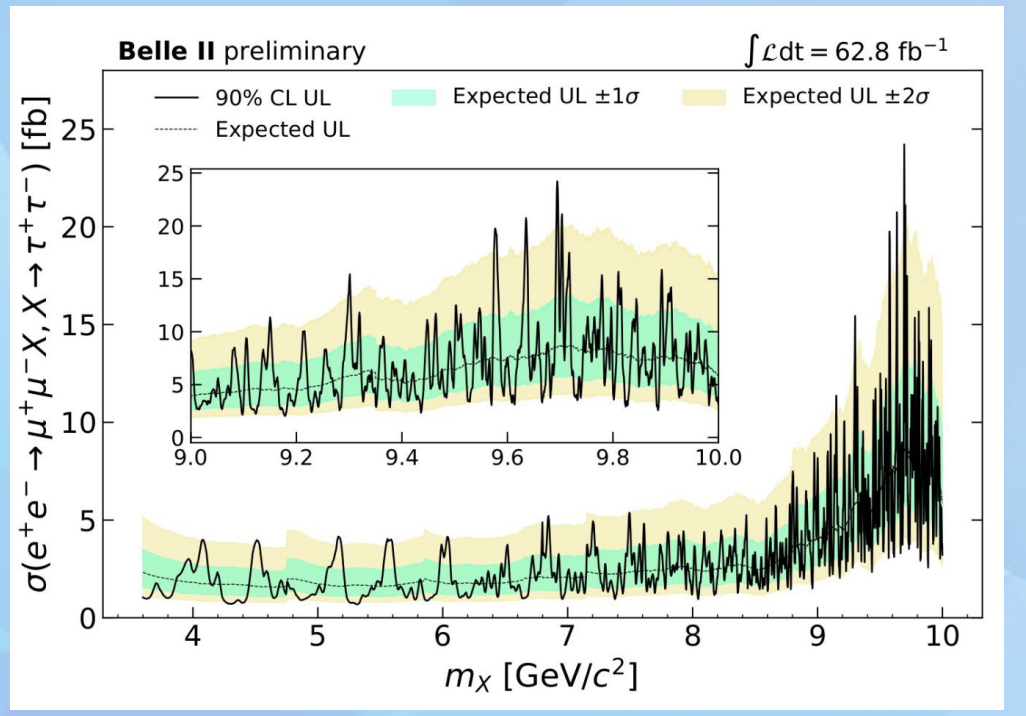


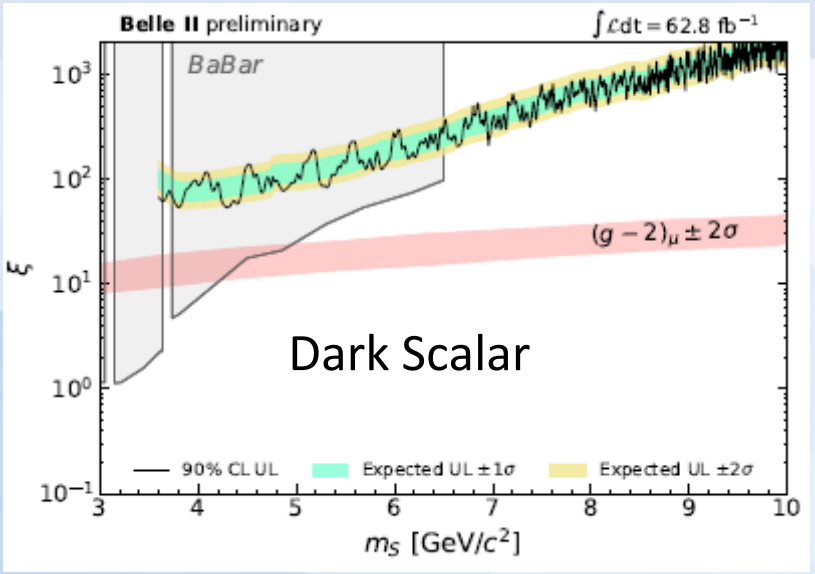


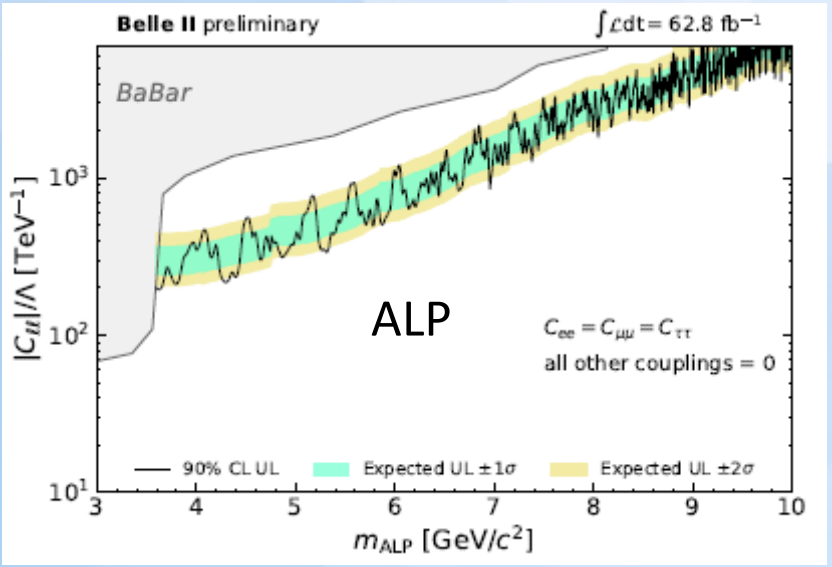
Search for Z', S, ALP → $\tau\tau$ at Belle II

Submitted to PRL, arXiv:2306.12294

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







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

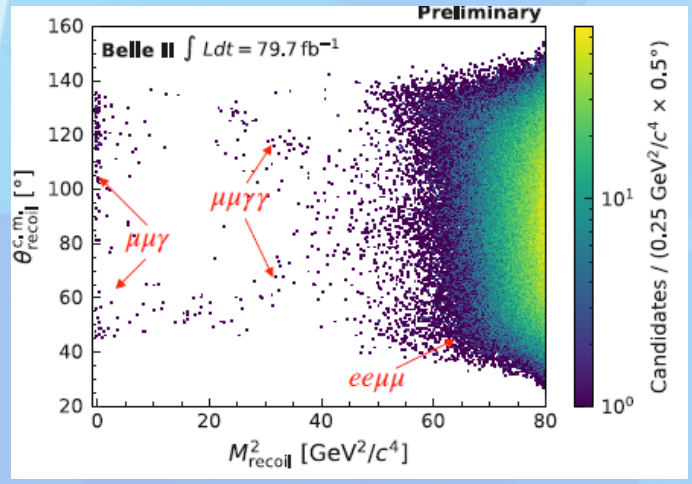
note: coupling normalized to global symmetry breaking scale Λ

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

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

- 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)



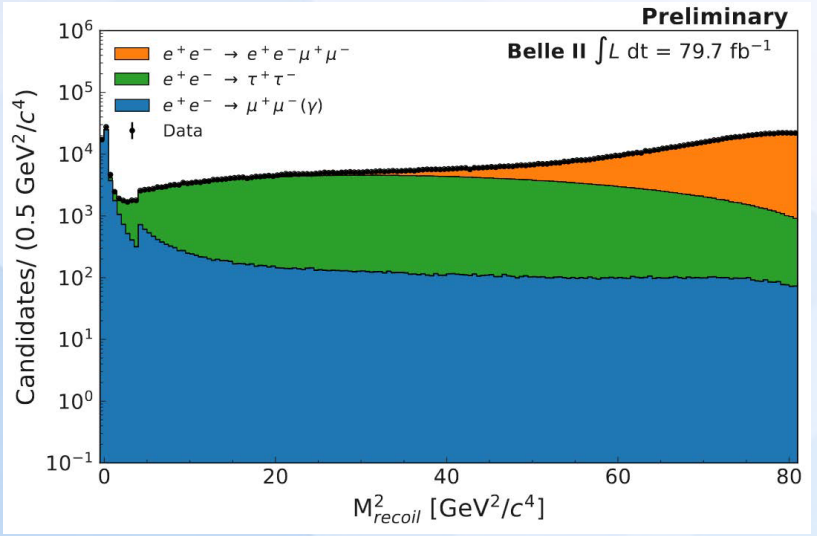
- Backgrounds:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \mu^+\mu^- e^+e^-$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$, both $\tau \to \mu\nu\bar{\nu}$

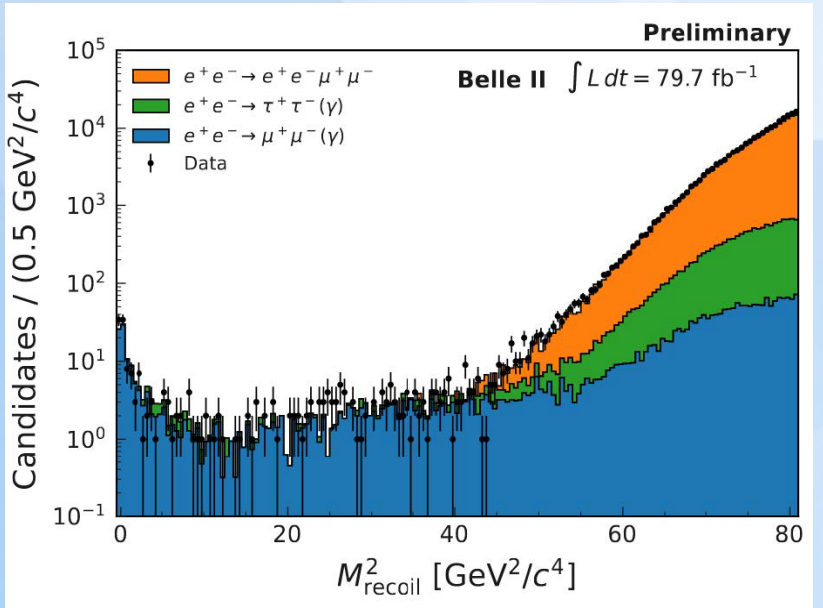
outside accept-ance

- Search: narrow peak in:

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

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





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