Latest τ and dark sector results from Belle and Belle II

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Max Planck Institute for Physics

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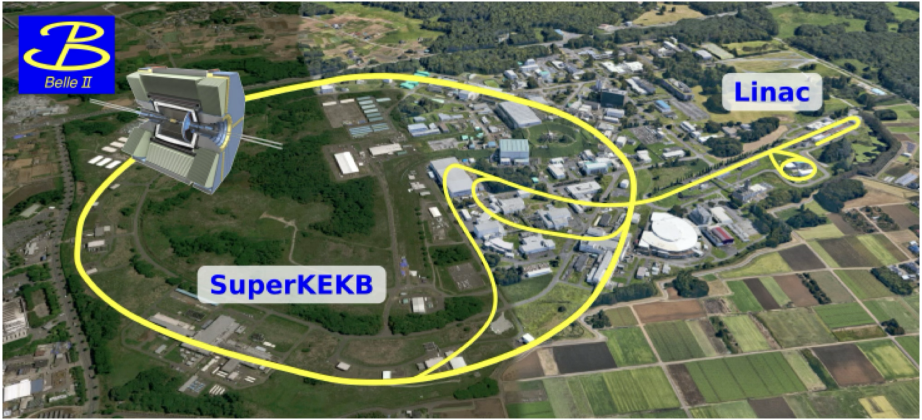
The Belle and Belle II Experiments

- B factories at KEK (Tsukuba/Japan): e^+e^- collider at E_{CM} around $\Upsilon(4S)$ mass



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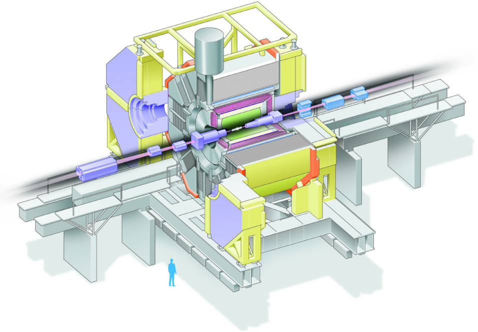
Belle at KEKB accelerator (1999–2010)

- Collected integrated luminosity of about $1000\,\mathrm{fb}^{-1}$

Belle II at SuperKEKB accelerator (2019–)

- Goals
  - $50\times$ Belle data-sample size by increasing luminosity
  - Renewed detector, trigger, analysis techniques, …
- Run 1 (2019–2022)
  - Collected about $1/2\times$ Belle data-sample size
    $1\times$ BaBar data-sample size
- Run2 started in spring 2024
  - Upgraded detector
  - World-record luminosity: $5.1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



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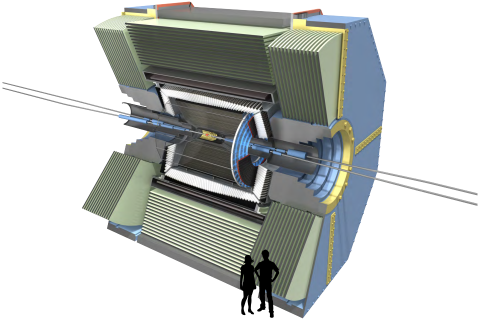

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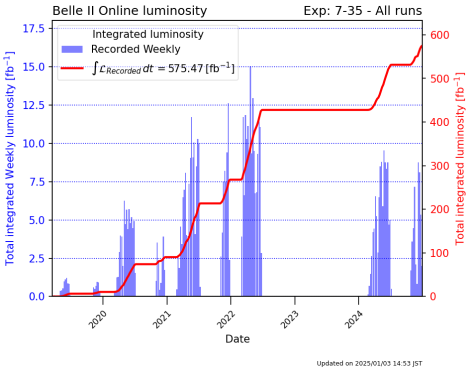
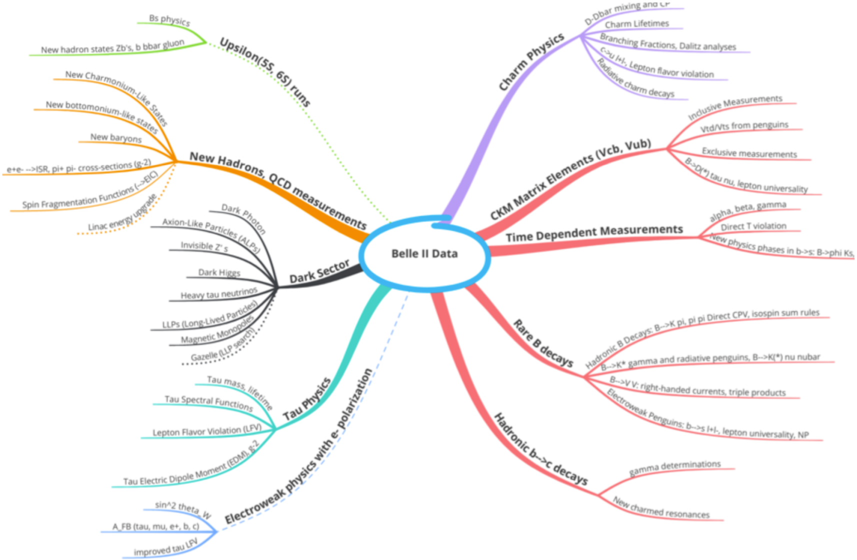


The Belle and Belle II Experiments

Unique environment for high-precision measurements and New Physics searches

[Snowmass White Paper]



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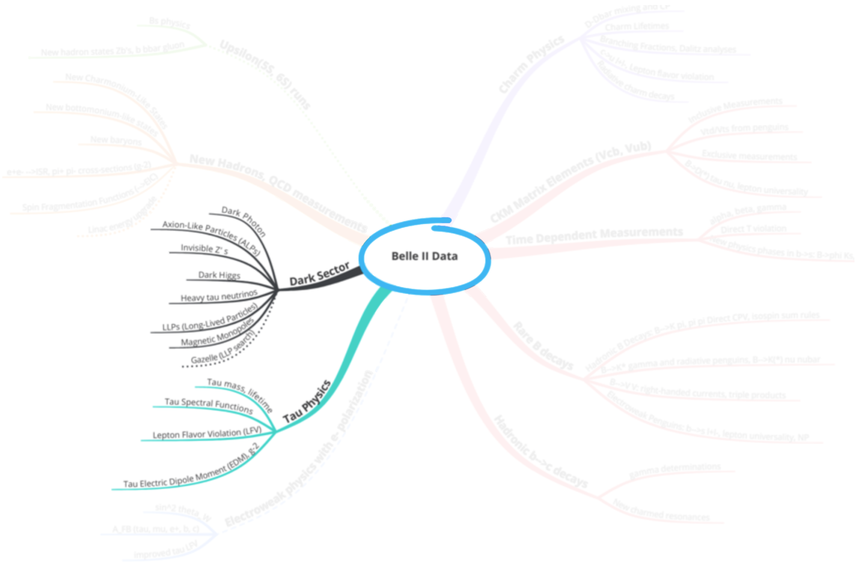

- Precision studies of the weak interaction
- τ lepton decays potentially sensitive to Beyond Standard Model physics
- Unique and clean environment to study hadronic decays
- Precision measurement of τ requires τ factory
  - Belle : 900 M τ pairs produced ($\mathcal{L} \approx 1\,\mathrm{ab}^{-1}$)
  - Belle II: 400 M τ pairs produced ($\mathcal{L} \approx 0.4\,\mathrm{ab}^{-1}$)
- Production of τ pairs separated in signal and tag hemispheres

[Particle Zoo]

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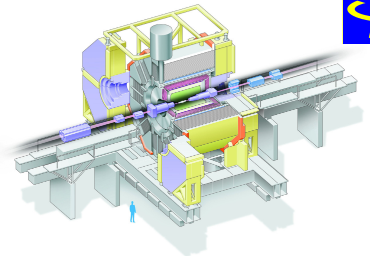

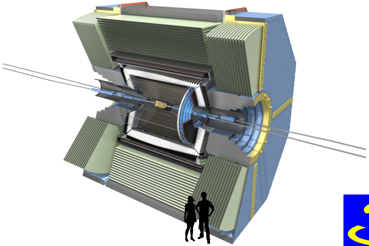

BELLE

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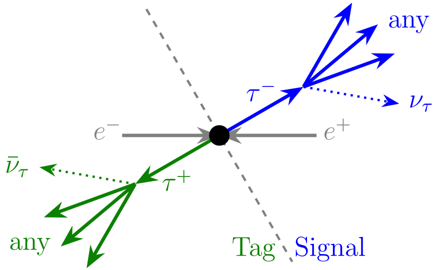
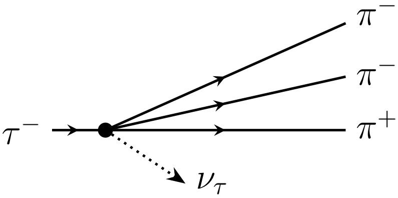


τ Mass Measurement at Belle II

- Fundamental physics parameter and important input, e.g. for lepton-universality tests
- Pseudomass method in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
  - M_{min} distribution ends at m_τ
  - Smeared by resolution and initial and final state radiation
- Accuracy determined by
  - Beam energy $\sqrt{s}/2$
    - Calibrated using $B\bar{B}$ events
  - Final-state particle momentum
    - Calibrated using $D^0 \to K\pi$ standard candle
- Belle II provides World's most precise result



190 fb^{-1}

[PRD 108 (2023) 032006]

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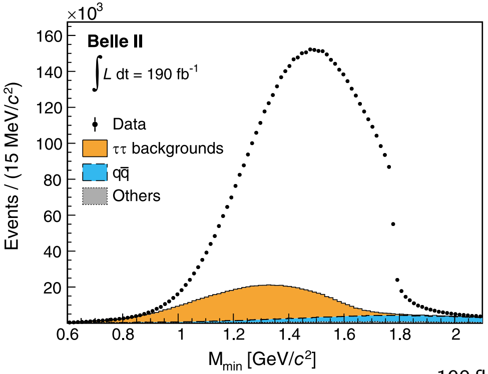

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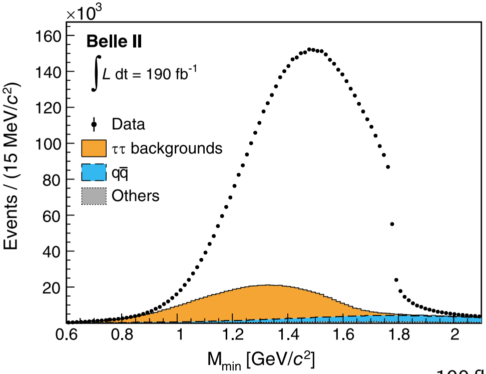

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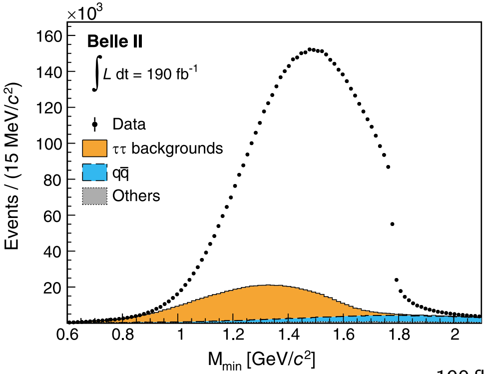

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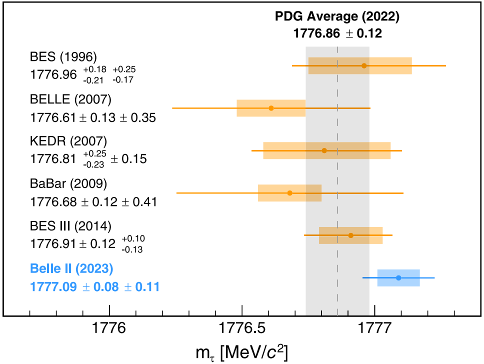

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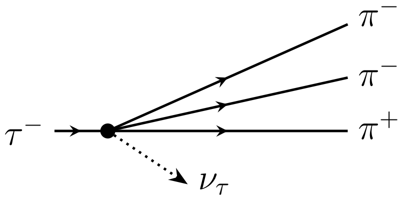
[PRD 108 (2023) 032006]

- $\pi^-\pi^-\pi^+$ system forms meson resonances
- Dominated by $a_1(1260)^- \to \rho^0\pi^-$ decay
  - Parameters of $a_1(1260)$ poorly known
    - CLEO II measured twice larger width in τ decays compared to other experiments
  - Also other contributions possible
    - $a_1(1420)$ resonance observed only by COMPASS in scattering data
- Perform amplitude analysis to separate contributions of partial waves with well-defined quantum numbers
  - Fit partial-wave model to 7-dimensional angular and mass distribution
- Studied to far only by ARGUS and CLEO in partial-wave analysis [PLB 349 (1995) 576], [PRD 61 (1999) 012002]



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BELLE

[τ 2023, Hadron 2023, ICHEP 2022]

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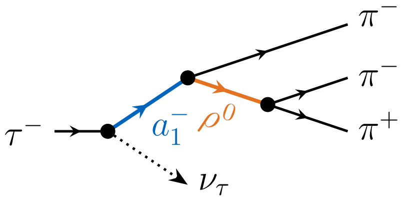

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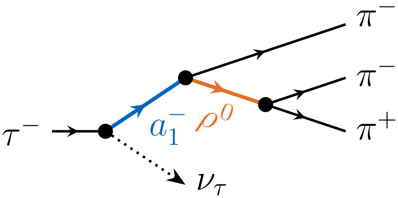

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- Clear $a_1(1260)$ signal in $1^{++}[\rho(770)\pi]_S$ wave
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- Narrow $a_1(1420)$ signal in intensity of $1^{++}[f_0(980)\pi]_P$ wave
  - ➡ First confirmation of COMPASS measurement
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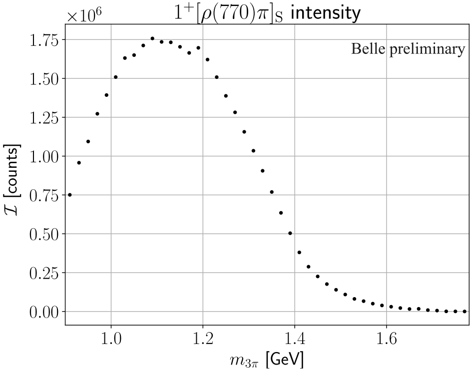

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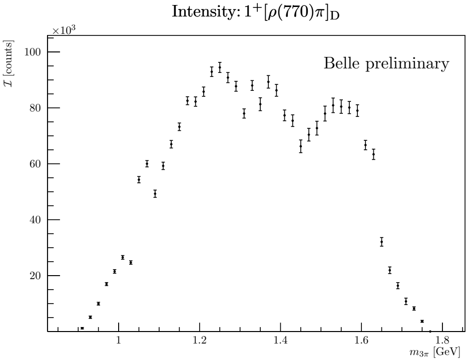

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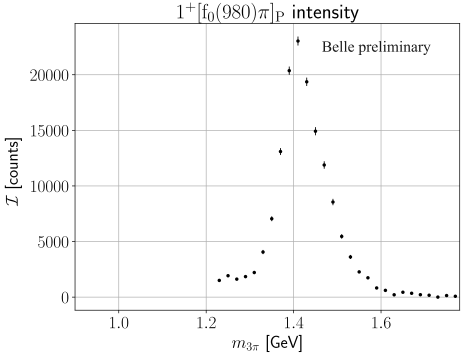

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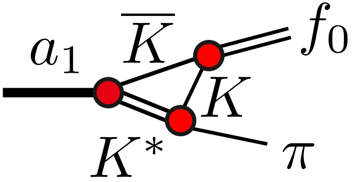

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BELLE

[τ 2023, Hadron 2023, ICHEP 2022]

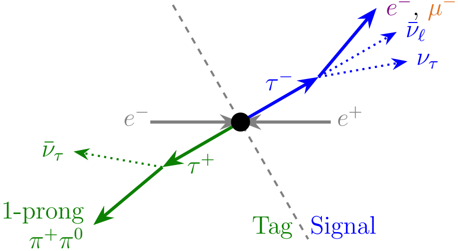
- Ratio of leptonic branching fractions

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

  is sensitive to new physics
- Measured in 1×1 prong topology with $\pi^- + n\pi^0$ tag
- Most precise test of μ-e universality in τ decays
  - Consistent with Standard Model at 1.4σ

$$R_\mu = 0.9675 \pm 0.0007\,(\text{stat.}) \pm 0.0036\,(\text{sys.})$$

- Main systematic uncertainty from particle identification and trigger



362 fb^{-1}

[JHEP 08 (2024) 205]

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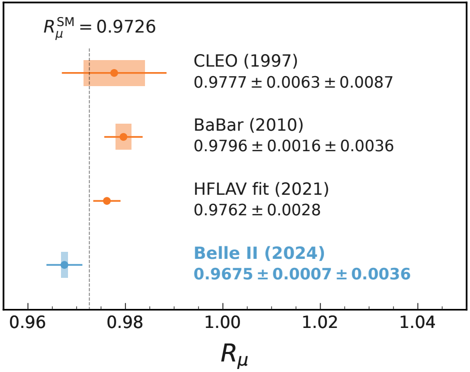

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[JHEP 08 (2024) 205]

Lepton-Flavor Violation (LFV) in τ Decays

- Lepton Flavor Violation (LVF) is negligibly small in Standard Model $+ \nu$ mixing (below 10^{-50})
- Various new-physics models predict branching fractions in the range 10^{-7} – 10^{-10}
  - ➥ Search for lepton flavor violating τ decays without ν

Lepton-Flavor Violation (LFV) in τ Decays

$\tau^- \to \ell^- V^0$

- Search for decays $\tau^- \to \ell^- V^0$, $V^0 = \rho^0, \phi, \omega, K^{*,0}$
- Consider 1-prong and 3-prong decays on tag side
- Multivariate analysis (BDT) to select signal
- Signal region defined by
  - $M_{\ell V^0} = m_\tau$ due to missing neutrino
  - $\Delta E = E^*_{\ell V^0} - \sqrt{s}/2 = 0$ upon radiative effects
- World's best upper limit for 8/10 channels (90 % confidence level)
  - $B(\tau^- \to e^- V^0) < (1.7\text{–}2.4) \times 10^{-8}$
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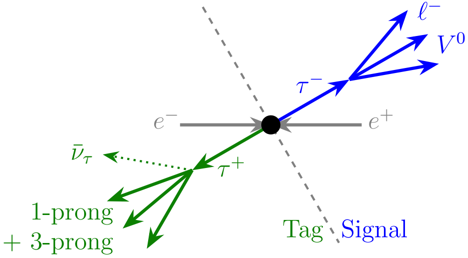

980 fb^{-1}

[JHEP 06 (2023) 11]

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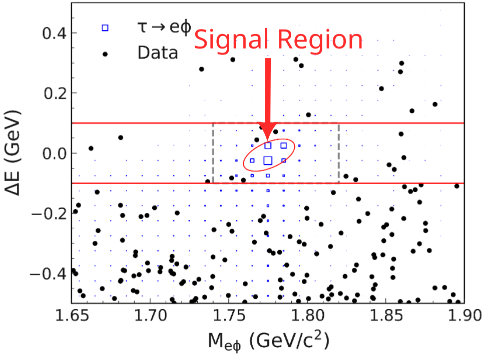

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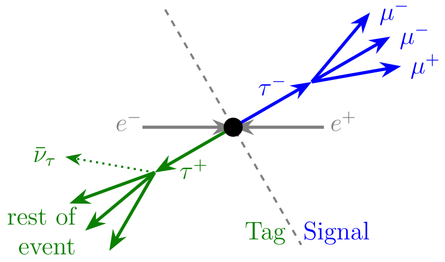
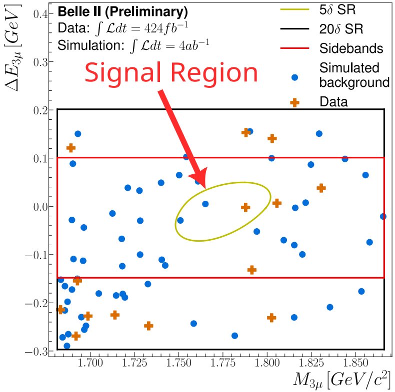
[JHEP 06 (2023) 11]

$\tau \to \mu\mu\mu$

- Untagged: Inclusively use rest of event
- Multivariate selection yields 3× larger efficiency compared to Belle
- Upper limit
  - $B(\tau^- \to \mu^-\mu^-\mu^+) < 1.9 \times 10^{-8}$
- World's most stringent limit





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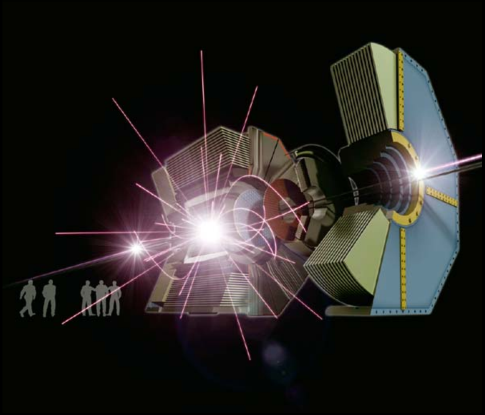
Belle II

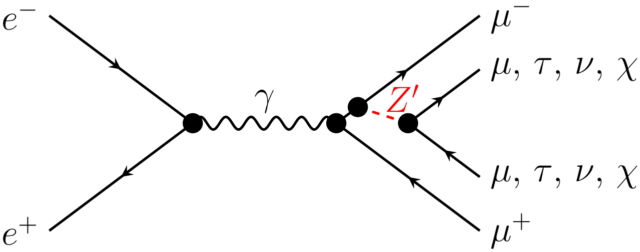
[JPHE 09 (2024) 062]

Dark Sector Searches at Belle II

- Dark sector physics
  - ➥ Low multiplicity events
- Well known initial condition and special trigger important for dark sector searches
- Belle II is sensitive to direct production of MeV to GeV mediators

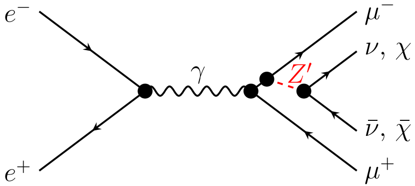


Searches for the $L_\mu - L_\tau$ Gauge Boson Z'

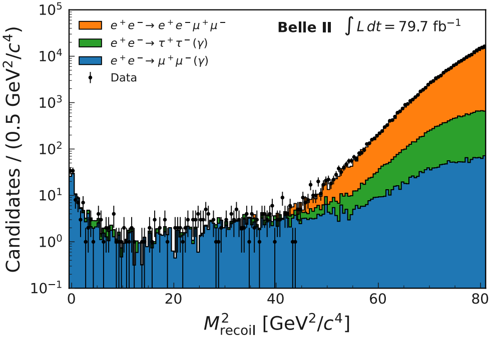


- New gauge boson Z' couples only to 2nd and 3rd generation of leptons ($L_\mu - L_\tau$)
- Coupling to μ, τ, ν_μ, ν_τ with strength g'
  - Decays visibly and invisibly
  - Decays to dark matter χ could be dominant

Dark Sector Searches in $Z' \to$ invisible



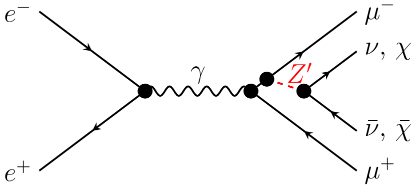
- Search for peak in mass of recoil system against $\mu\mu$
- Neural network for background suppression trained on full $M_{Z'}$ range of Z'
- No significant excess observed
- $(g-2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5\,\mathrm{GeV}/c^2$ for a fully invisible Z'



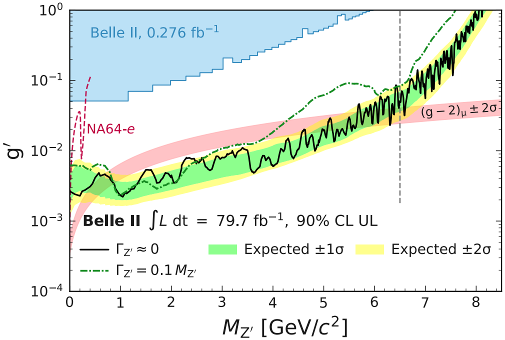
79.7 fb^{-1}

[PRL (2023) 231801]

Dark Sector Searches in $Z' \to$ invisible



- Search for peak in mass of recoil system against $\mu\mu$
- Neural network for background suppression trained on full $M_{Z'}$ range of Z'
- No significant excess observed
- $(g-2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5\,\mathrm{GeV}/c^2$ for a fully invisible Z'



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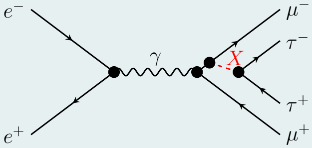
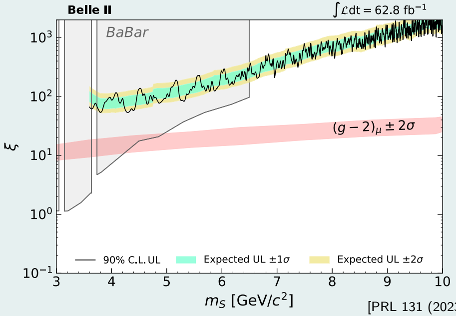
Belle II

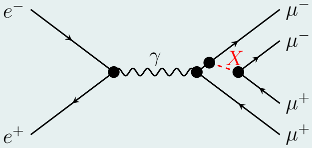
[PRL (2023) 231801]

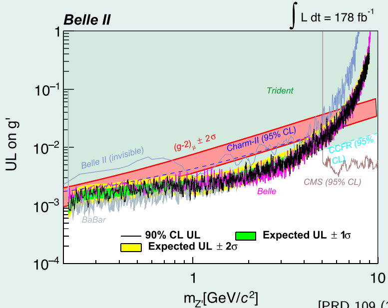
Dark Sector Searches in $Z' \to \tau\tau$ and $Z' \to \mu\mu$





[PRL 131 (2023) 121802]





[PRD 109 (2024) 112015]

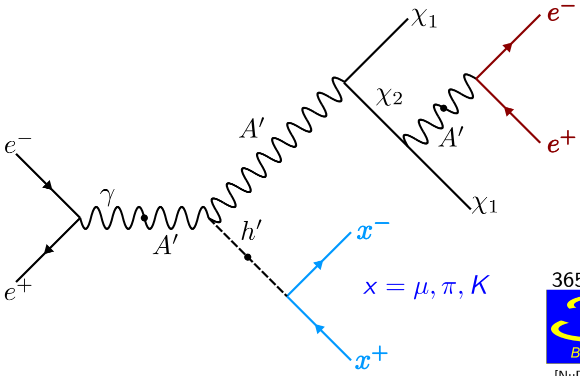
- Leptophilic scalar probed above 6.5 GeV/c^2
- World-leading limits for ALPs

- Exclude Z' and muophilic scalar explanations for $(g-2)_\mu$ over wide mass range

Searches for Inelastic Dark Matter with a Dark Higgs

- 4 final-state tracks
  - 2 forming pointing displaced vertex
  - 2 forming non-pointing displaced vertex
- Missing energy

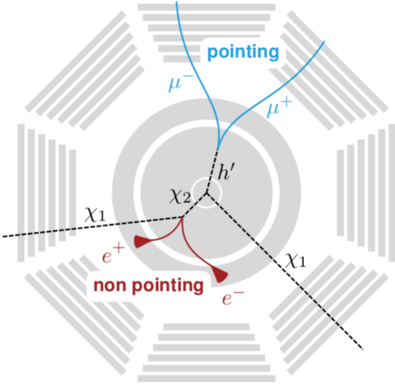
- Challenging for tracking and trigger
- Almost zero-background analysis



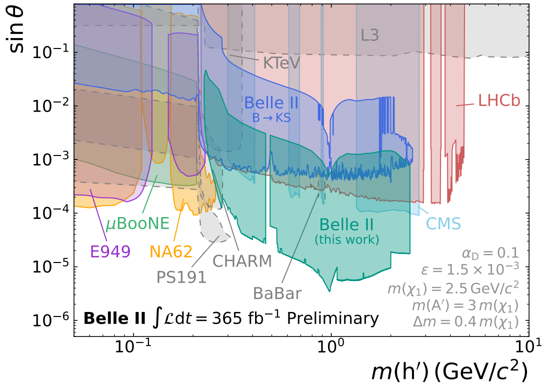
365 fb^{-1}

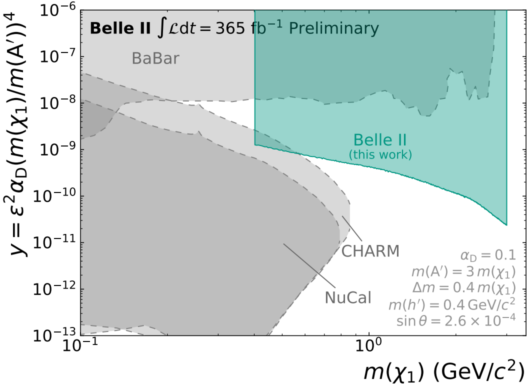
Belle II

[NuDM2024]



- Expected background estimated in data from sidebands to not rely on simulation
- No significant excess in $m_{h'}(xx)$ spectrum found
  - ➥ 95 % CL upper limits on model parameters





Summary

- Belle and Belle II are leading τ and dark sector searches
  - Precision measurements of τ properties
  - Various studies of Standard Model parameters
  - Searches for Beyond Standard Model physics
- Many frontiers of improvement
  - Data sample size
  - Improved analysis techniques and reduced systematic uncertainties
  - Accurate physics models

Further analysis in τ physics

BII	Baryon/lepton num. viol. in $\tau^- \to \overset{(-)}{\Lambda}\pi^-$	[PRD 110 (2024) 112003]
BII	Lepton-flavor violation in $\tau^- \to \ell^- \phi$	[arXiv:2305.04759]
BII	Lepton-flavor violation in $\tau^- \to \ell^- \alpha$	[PRL 130 (2023) 181803]
B	Michell Parameters in $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	[PRL 131 (2023) 021801]
B	Electric Dipole Moment of the τ	[JHEP 04 (2022) 110]

Further dark-sector searches

B	Heavy neutral lepton in $\nu_h \to \pi^+ \ell^-$	[PRL 131 (2023) 21180]
B	Leptophilic scalar in association with $\tau^- \tau^+$	[PRD 109 (2024) 032002]
BII	Long-lived spin-0 mediator in $b \to s$	[PRD 108 (2023) L111104]
BII	Dark Photon and Higgs in $\mu^+ \mu^-$	[PRL 130 (2023) 071804]
BII	Axionlike particle decaying to $\gamma\gamma$	[PRL 125 (2020) 161806]

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  - Precision measurements of τ properties
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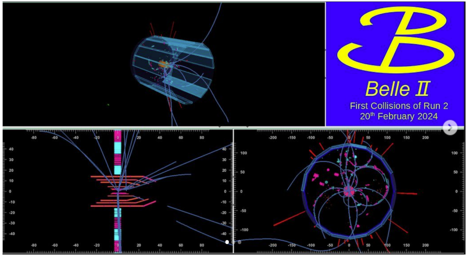


Backup

Outline

[JHEP 08 (2024) 205]

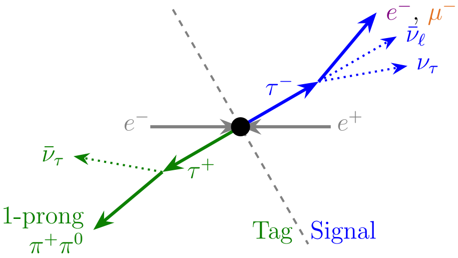
- Ratio of leptonic branching fractions

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

  is sensitive to new physics
- Measured in 1×1 prong topology with $\pi^- + n\pi^0$ tag
- Event yields extracted via p_ℓ template fit
- Most precise test of μ-e universality in τ decays
  - Consistent with Standard Model at 1.4σ

$$R_\mu = 0.9675 \pm 0.0007\,(\text{stat.}) \pm 0.0036\,(\text{sys.})$$

- Main systematic uncertainty from particle identification and trigger
- Detailed stability tests



362 fb^{-1}

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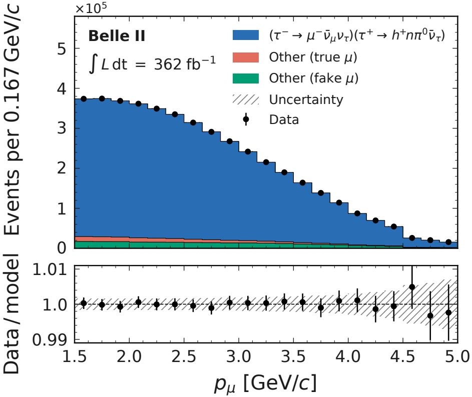

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Test of Lepton-Flavor Universality (LFU) in τ Decays

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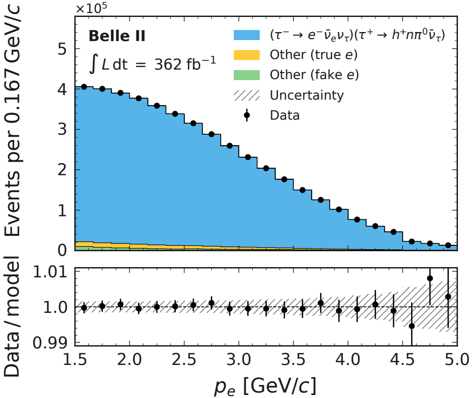

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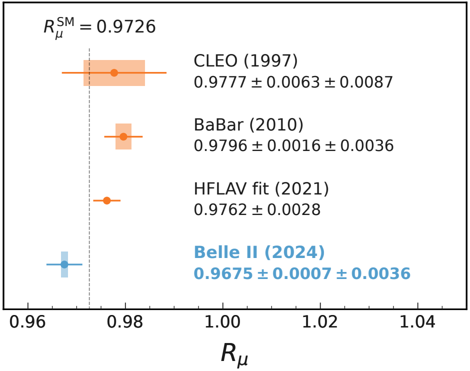

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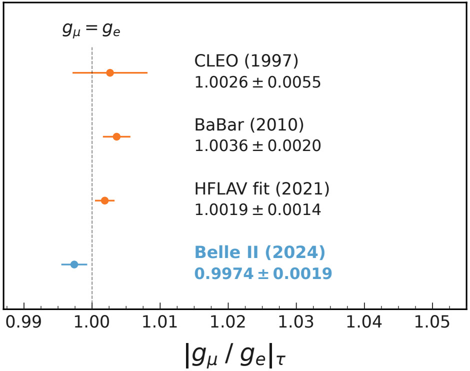

362 fb^{-1}

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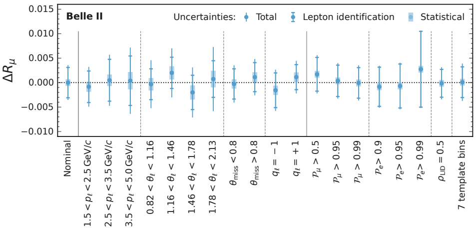
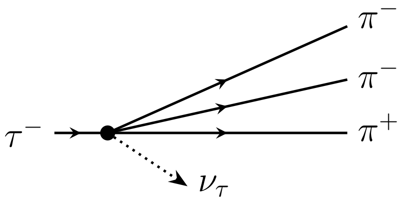


$362\ \text{fb}^{-1}$

- $\pi^-\pi^-\pi^+$ system forms meson resonances
- Dominated by $a_1(1260)^- \to \rho^0\pi^-$ decay
  - Parameters of $a_1(1260)$ poorly known
    - CLEO II measured twice larger width in τ decays compared to other experiments
  - Also other contributions possible
    - $a_1(1420)$ resonance observed only by COMPASS
- Perform amplitude analysis to separate contributions of partial waves with well-defined quantum numbers
  - Fit partial-wave model to 7-dimensional angular and mass distribution
- CLEO-II performed the only amplitude analysis [PRD 61 (1999) 012002]



980 fb^{-1}

BELLE

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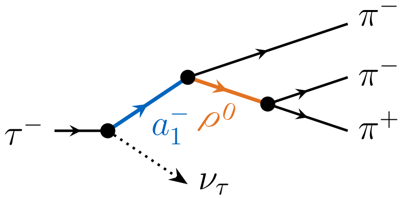

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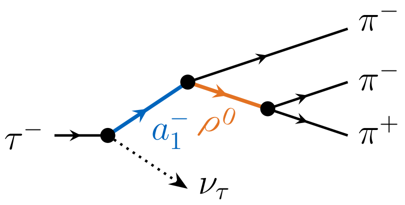
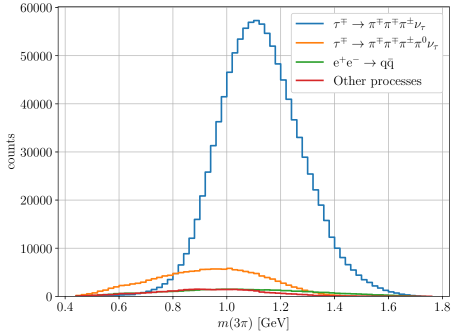


980 fb^{-1}

- 1-prong decays on tag side
- Achieve high efficiency: 32 %
- Maintain low impurity: 18 %
  - Main background from $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$

Simulated $m_{3\pi}$ spectrum



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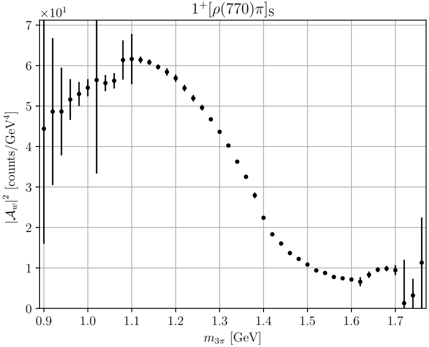
$$J_\mu = \sum_a c_a \, J_a^\mu$$

- Fit 17 partial waves to the data
- 10 waves representing $J^P = 1^+$
  - Various ρ, f_0, f_2, and ω decay modes
- 4 waves representing $J^P = 0^-$
  - $\rho(770)$, f_0 and $f_2(1270)$ decay modes
- 3 waves representing $J^P = 1^-$
  - $\rho(770)$, $f_2(1270)$, $\omega(782)$ decay modes
- CLEO used only 7 waves representing only $J^P = 1^+$

- Dominant $a_1(1260)$ signal in $1^{++}[\rho(770)\pi]_S$ wave
- Narrow $a_1(1420)$ signal in intensity of $1^{++}[f_0(980)\pi]_P$ wave
  - ➥ First confirmation of COMPASS measurement
- Novel “freed-isobar” method not requiring knowledge of isobar resonance
  - Allows to measure also amplitude of $\pi\pi$ subsystem
  - Clear $\rho(770)$ signal
    - ➥ Precision measurement of $\rho(770)$ in clean environment



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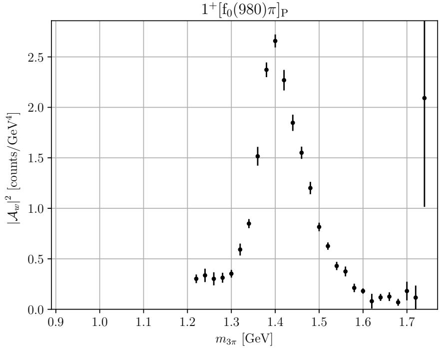

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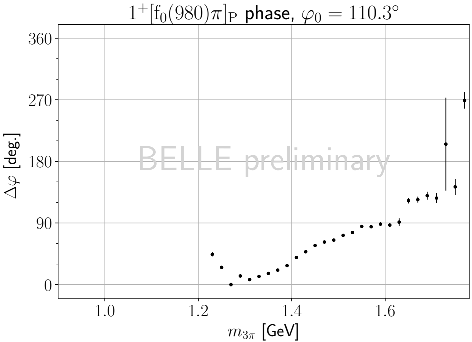

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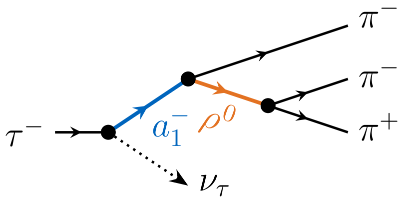

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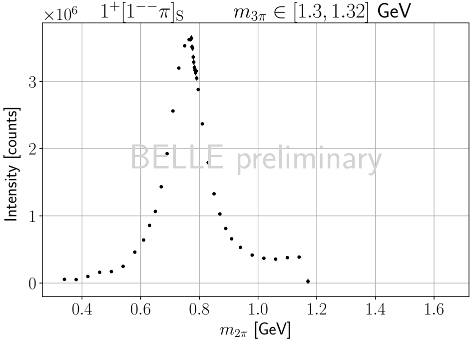
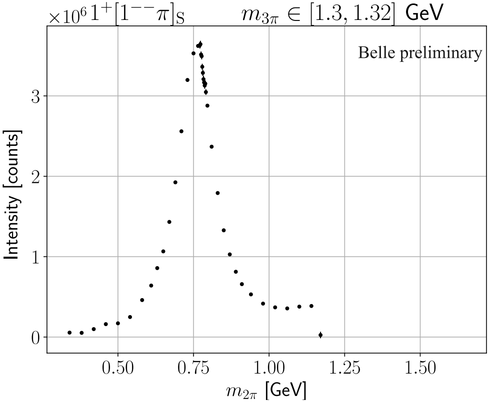


980 fb^{-1}

$[\pi\pi]_P$ amplitudes from $J^P = 1^+$ partial wave

- $G_{\pi\pi} = + \Rightarrow \rho$-like state
- Clear peak from $\rho(770)$ resonance
- Accompanied by rising phase



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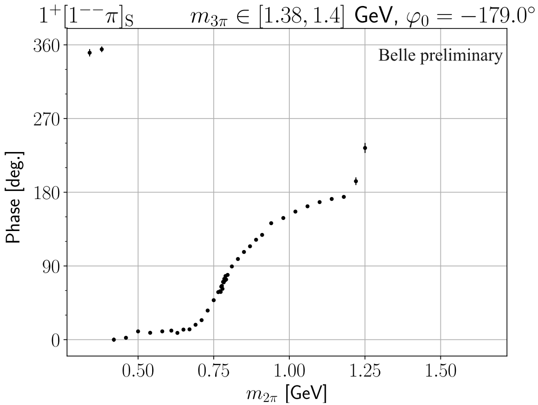
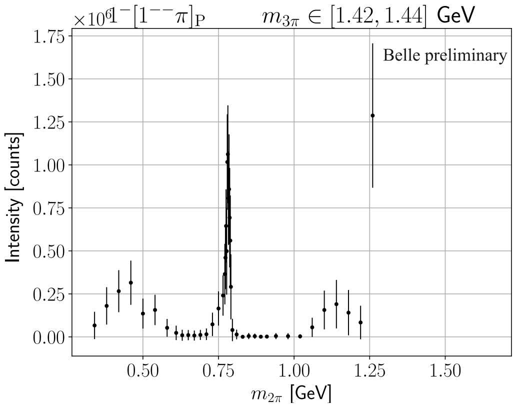


$[\pi\pi]_P$ amplitudes from $J^P = 1^-$ partial wave

- $G_{\pi\pi} = - \;\Rightarrow\; \omega$-like state
- Clear peak from $\omega(782)$ resonance



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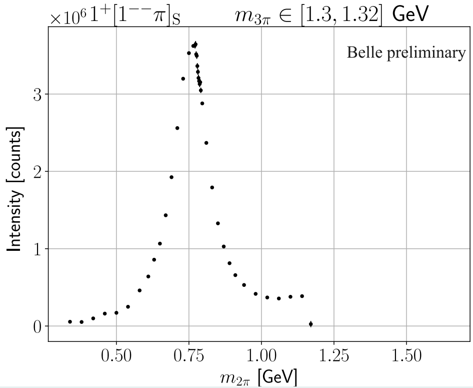

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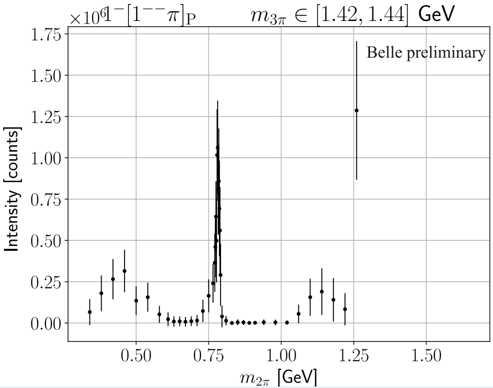


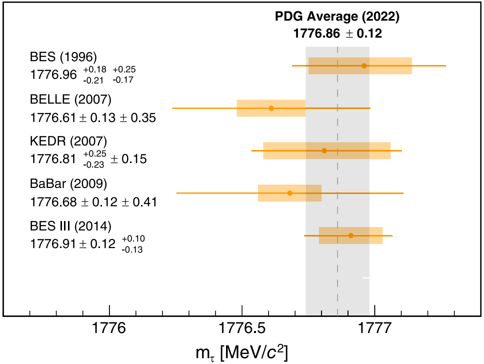
- Different signals when changing parity of $\pi^-\pi^-\pi^+$ system
  - ➥ Verifies observation of G violation $\omega(782) \to \pi^-\pi^+$ decay

τ Mass Measurement at Belle II

[Phys. Rev. D 108 (2023) 032006]

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

- Fundamental physics parameter and important input, e.g. for lepton-universality tests
- Pseudomass method in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
  - $M_{\min}$ distribution ends at m_τ
  - Smeared by resolution and initial and final state radiation
- Accuracy determined by
  - Beam energy $\sqrt{s}/2$
    - Calibrated using $B\bar{B}$ events
  - Final-state particle momentum
    - Calibrated using $D^0 \to K\pi$ standard candle
- Fit to $M_{\min}$ distribution
- Belle II provides World's most precise result



$190\ \text{fb}^{-1}$

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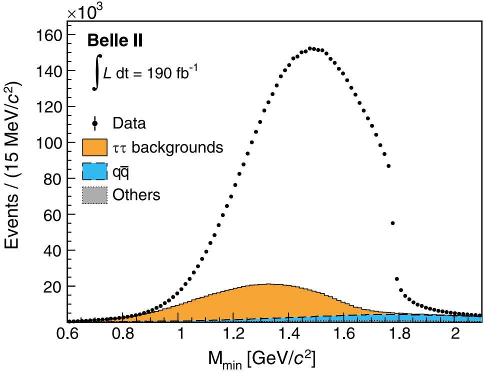
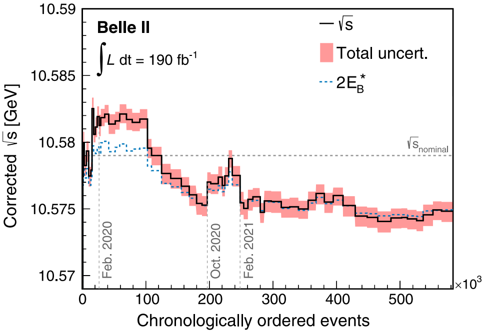


190 fb^{-1}

τ Mass Measurement at Belle II

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

- Fundamental physics parameter and important input, e.g. for lepton-universality tests
- Pseudomass method in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
  - $M_{\min}$ distribution ends at m_τ
  - Smeared by resolution and initial and final state radiation
- Accuracy determined by
  - Beam energy $\sqrt{s}/2$
    - Calibrated using $B\bar{B}$ events
  - Final-state particle momentum
    - Calibrated using $D^0 \to K\pi$ standard candle
- Fit to $M_{\min}$ distribution
- Belle II provides World's most precise result



190 fb^{-1}

τ Mass Measurement at Belle II

[Phys. Rev. D 108 (2023) 032006]

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

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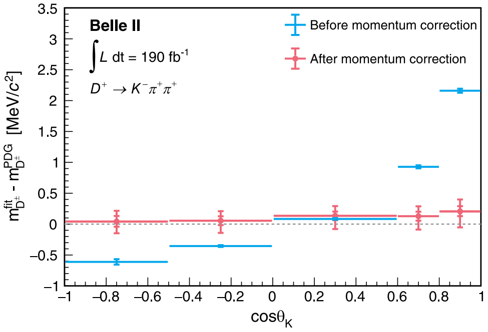

190 fb^{-1}

Belle II

[Phys. Rev. D 108 (2023) 032006]

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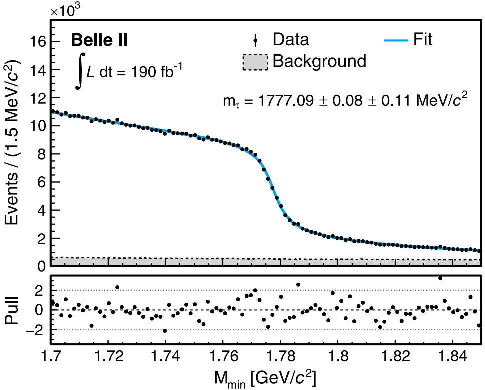

190 fb^{-1}

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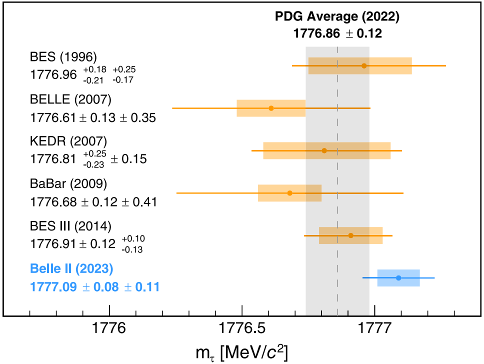
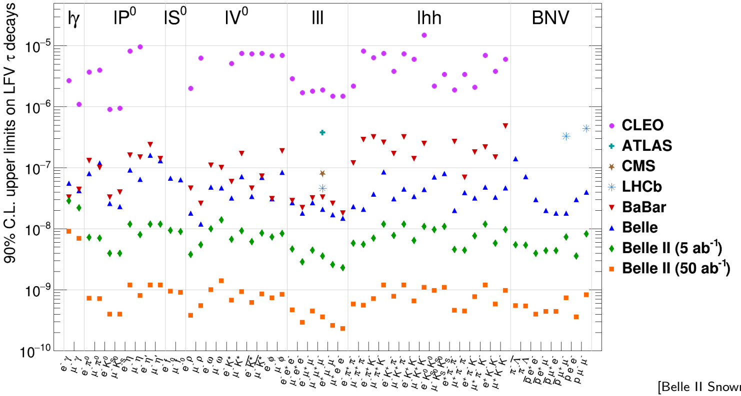


190 fb^{-1}

- Lepton Flavor Violation (LVF) is negligibly small in Standard Model + ν mixing (below 10^{-50})
- Various new-physics models predict branching fractions in the range $10^{-7} - 10^{-10}$
  - ➥ Search for lepton flavor violating decay channels

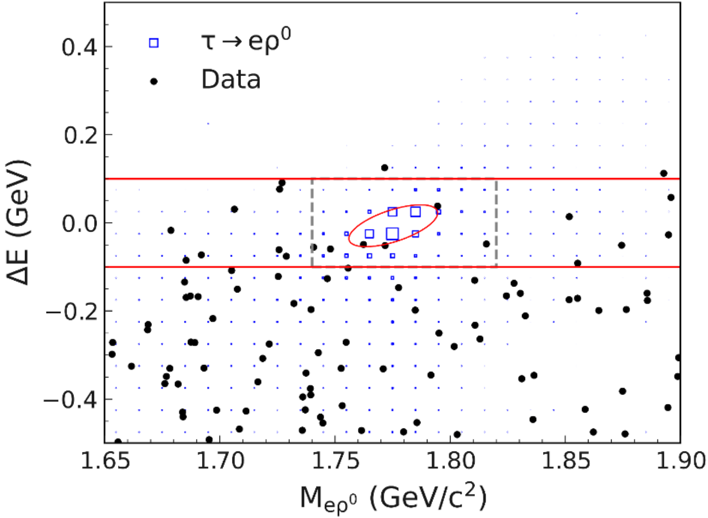


[Belle II Snowmass Paper]

Lepton-Flavor Violation (LFV) in τ Decays

$\tau^- \to \ell^- V^0$

[J. High Energ. Phys. 2023, 118 (2023)]



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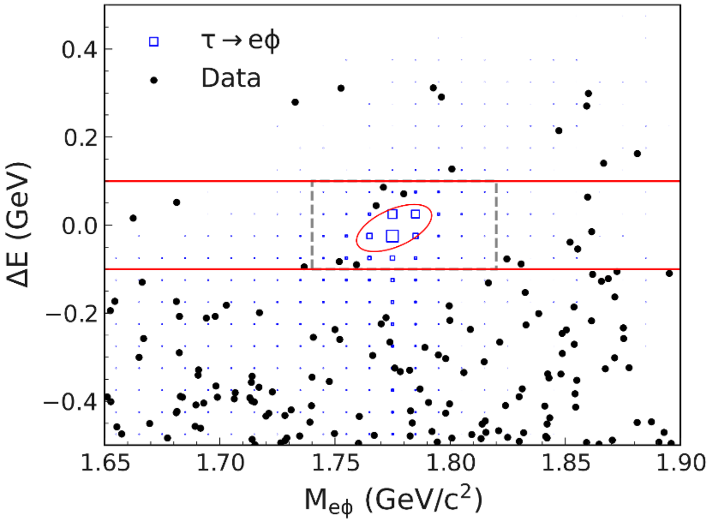

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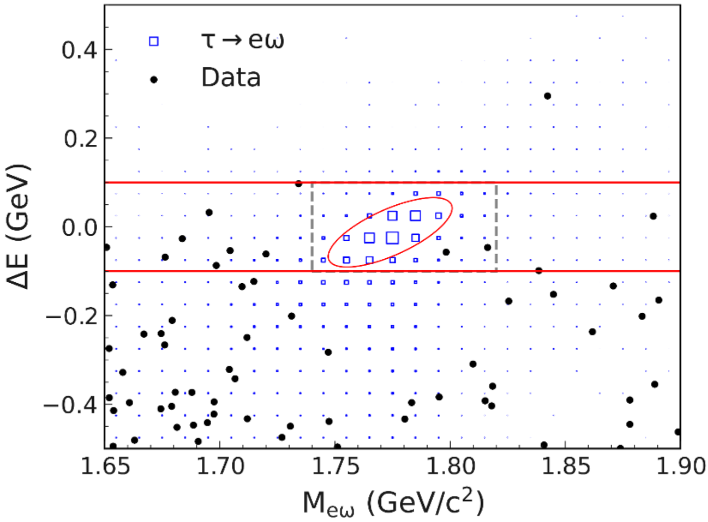
[J. High Energ. Phys. 2023, 118 (2023)]



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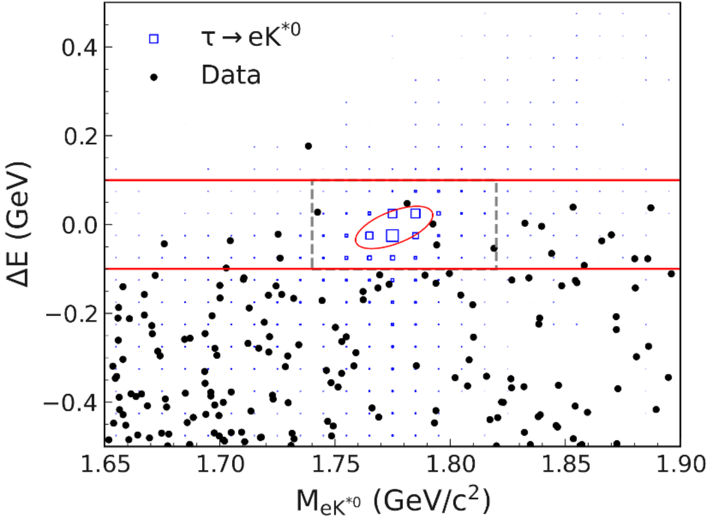

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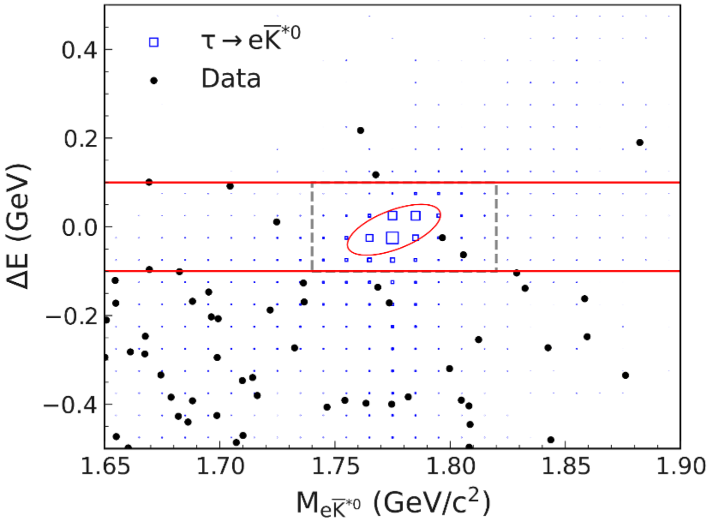
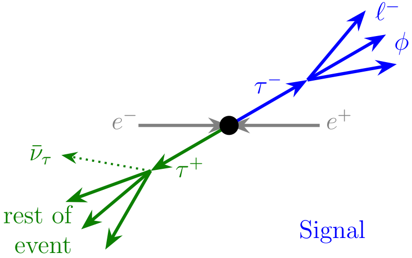
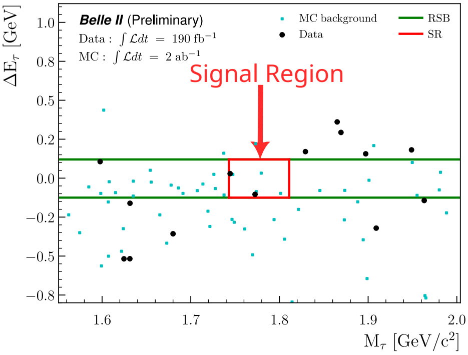
[J. High Energ. Phys. 2023, 118 (2023)]



$\tau \to \ell\phi$

- Similar strategy as $\tau^- \to \ell V^0$ measurement at Belle
- First application of untagged approach
  - Fully inclusive on tag side
- Upper limits
  - $B(\tau^- \to e^-\phi) < 23 \times 10^{-8}$
  - $B(\tau^- \to \mu^-\phi) < 9.7 \times 10^{-8}$

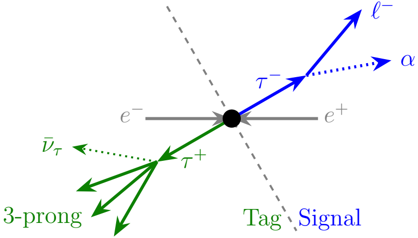


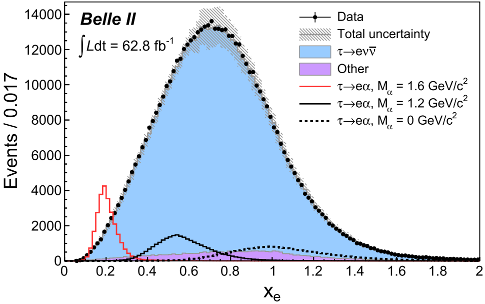


190 fb^{-1}

$\tau \to \ell\alpha$, where α is an invisible particle

- Fixed kinematic of two-body decay for given m_α characteristic for signal
- Normalized lepton energy X_ℓ in τ^- rest frame
  - $\tau^- \to \ell^-\alpha$ yields fixed X_ℓ
    - Broadened by approximation of τ^- rest frame from hadronic tag system
  - $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ yields broad peak
- 2–14 times more stringent limit than ARGUS





62.8 fb^{-1}

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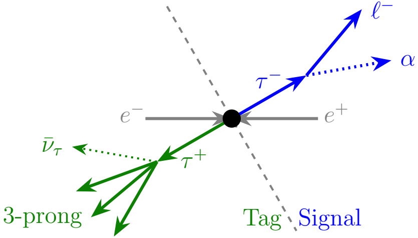

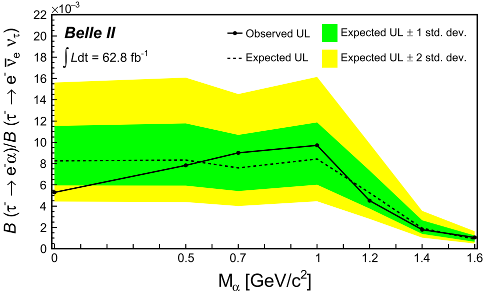

62.8 fb^{-1}

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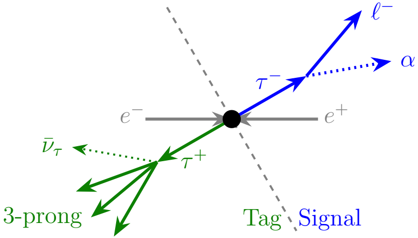

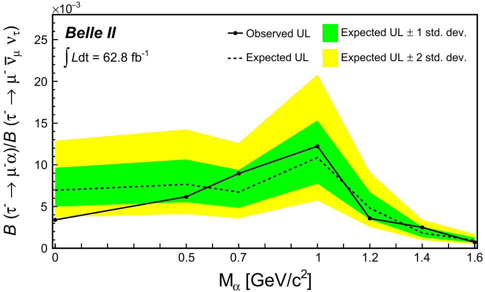

62.8 fb^{-1}

[PRL 130 (2023) 181803]

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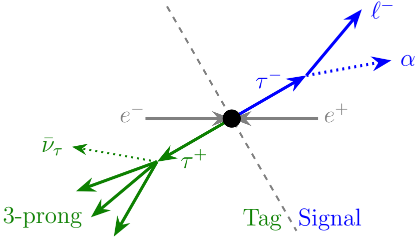
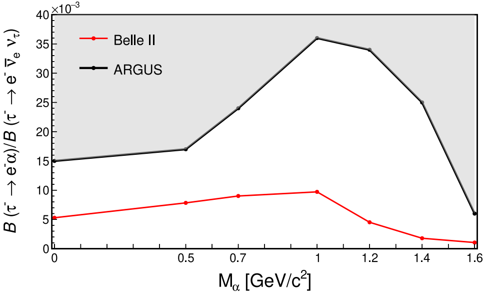
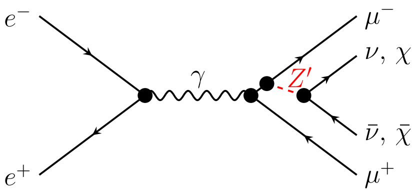




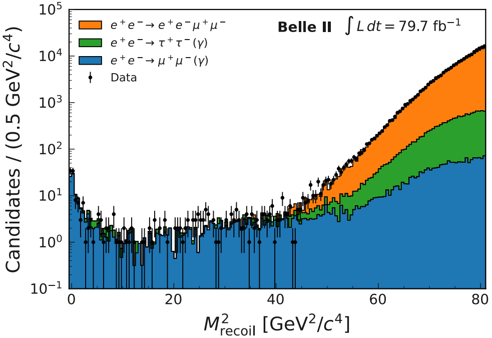
62.8 fb^{-1}

Dark Sector Searches in $Z' \to$ invisible

[Phys. Rev. Lett. 130 (2023) 231801]



- Search for peak in mass of recoil system against $\mu\mu$
- Neural network for background suppression trained on Z' signal and background
- No significant excess observed
- $(g-2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5\,\mathrm{GeV}/c^2$ for a fully invisible Z'



79.7 fb^{-1}

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[Phys. Rev. Lett. 130 (2023) 231801]

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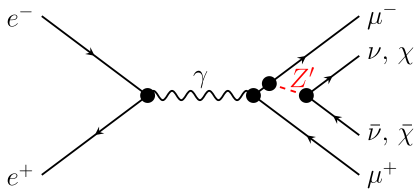
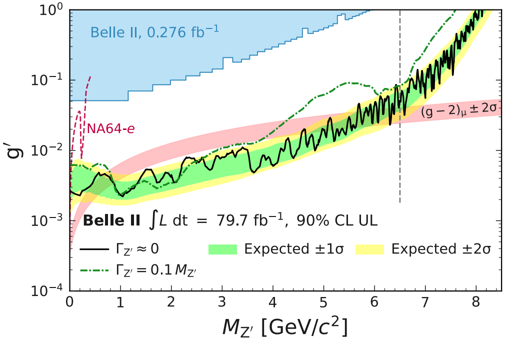
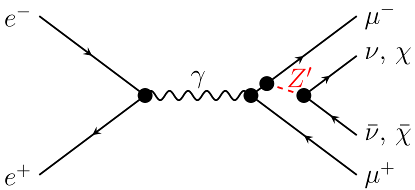




[Phys. Rev. Lett. 130 (2023) 231801]



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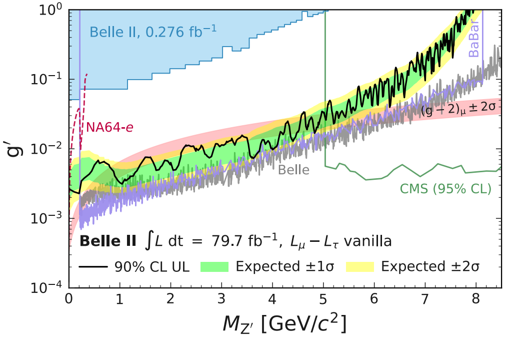
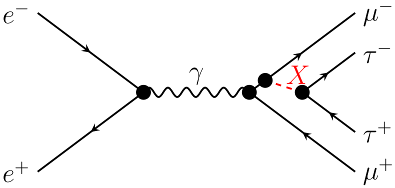


79.7 fb^{-1}

Belle II



- Search for peak in mass of recoil system against $\mu\mu$
- τ decays to single charged particle + neutrals
  - ➥ Suppress background using characteristic kinematics
- Exclusion limits on couplings for three models: Z', Axion-like particle (ALP), and leptophilic scalar (S)
  - m_S probed for the first time above 6.5 GeV/c^2
  - World-leading limits for ALPs

62.8 fb^{-1}

Dark Sector Searches in $Z' \to \tau\tau$

[PRL 131 (2023) 121802]

- Search for peak in mass of recoil system against $\mu\mu$
- τ decays to single charged particle + neutrals
  - ➥ Suppress background using characteristic kinematics
- Exclusion limits on couplings for three models: Z', Axion-like particle (ALP), and leptophilic scalar (S)
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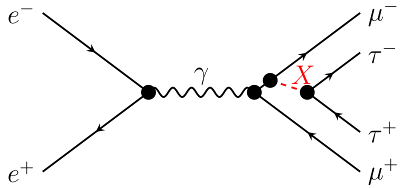
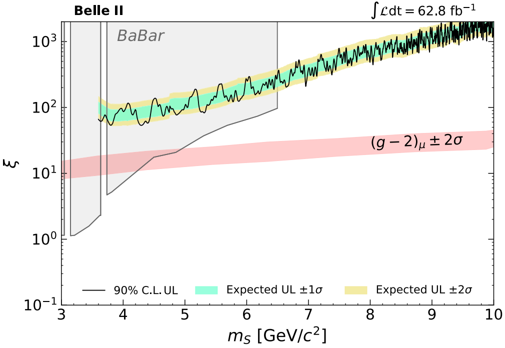
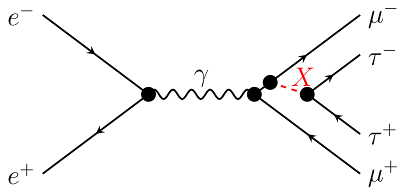
62.8 fb^{-1}







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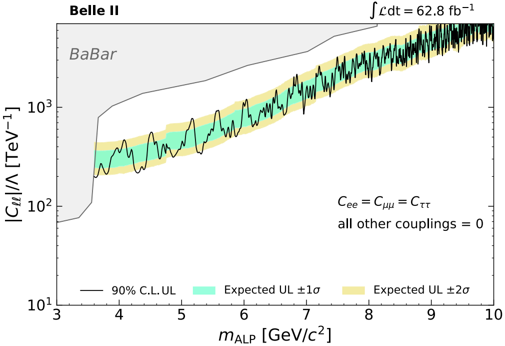
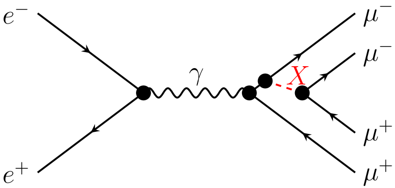
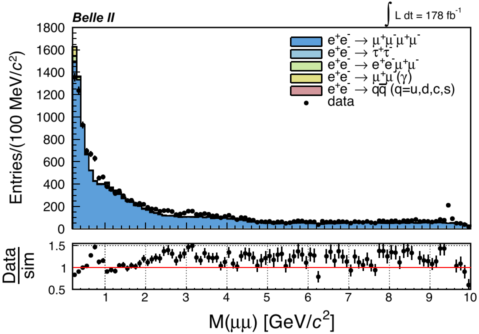


Dark Sector Searches in $Z' \to \mu\mu$

[PRD 109 (2024) 112015]

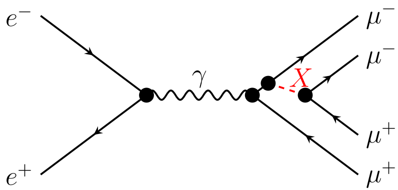
- Search for peak in opposite-charge di-muon mass
- First upper limit for muonic scalar model from a explicit search
- Upper limits on Z' already competitive
  - Due to improved background suppression
- Exclude Z' and scalar explanations for $(g-2)_\mu$ over wide mass range





178 fb^{-1}

Dark Sector Searches in $Z' \to \mu\mu$



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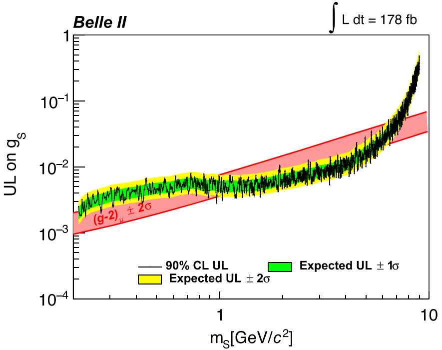

178 fb^{-1}

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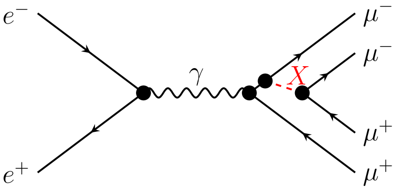
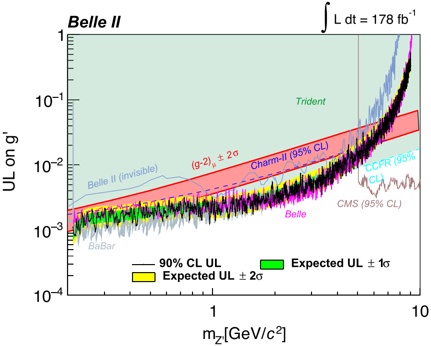
178 fb^{-1}





[PRD 109 (2024) L111102]

Searches for heavy neutral letpons (N or ν_h)

- Can interact with $\nu_{\rm SM}$ via $N \leftrightarrow \nu_{\rm SM}$ mixing
- Long lifetime
- Probe $m_N < m_\tau$ in $\tau^- \to \pi^- N$ decays

Heavy lepton in $N \to \mu^+\mu^-\nu_\tau$ decays

- Signature: prompt π^- and displaced $\mu^+\mu^-$ vertex
  - Allows direct measurement of m_N
- Observation in agreement with background expectation
- Set 95 % C.L. upper limits on mixing parameter

915 fb^{-1}

BELLE

Searches for heavy neutral letpons (N or ν_h)

- Can interact with ν_{SM} via $N \leftrightarrow \nu_{\mathrm{SM}}$ mixing
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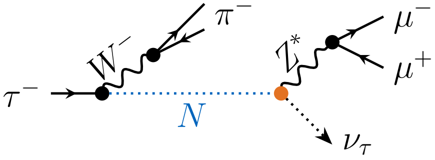

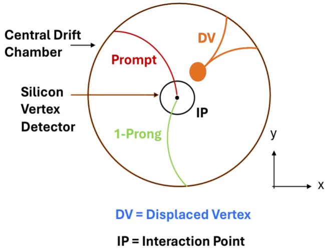

915 fb^{-1}

Searches for a Heavy Neutral Lepton (N or ν_h) in τ Decays

[PRD 109 (2024) L111102]

Searches for heavy neutral letpons (N or ν_h)

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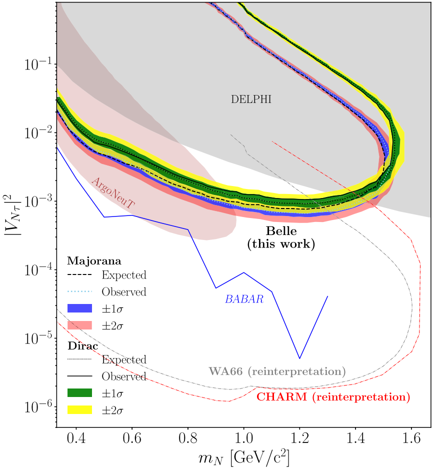
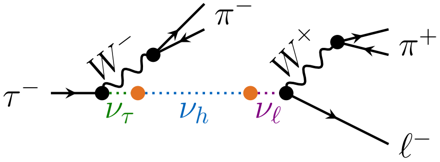
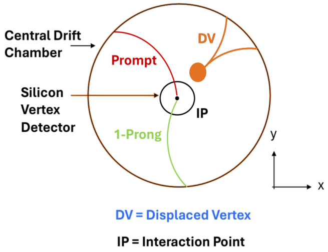


915 fb^{-1}



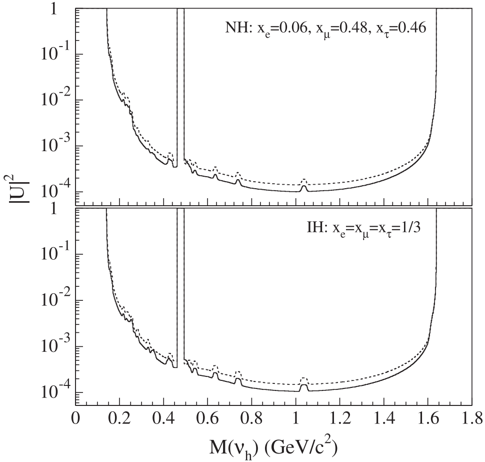
Heavy neutrino in $\nu_h \to \pi^+\ell^-$ decays

- Signature: prompt π^- and displaced $\pi^+\ell^-$ vertex
- Final state fully reconstructed
- No significant excess observed
- Set 95 % C.L. upper limits on $|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$



988 fb^{-1}

[PRL 131 (2023) 211802]



Heavy neutrino in $\nu_h \to \pi^+\ell^-$ decays

- Signature: prompt π^- and displaced $\pi^+\ell^-$ vertex
- Final state fully reconstructed
- No significant excess observed
- Set 95 % C.L. upper limits on $|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$

988 fb^{-1}

BELLE

NH: Normal hierarchy; IH: Inverted hierarchy

Searches for a Heavy Neutral Lepton (N or ν_h) in τ Decays

Searches for heavy neutral letpons (N or ν_h)

- Can interact with ν_{SM} via $N \leftrightarrow \nu_{\mathrm{SM}}$ mixing
- Long lifetime
- Probe $m_N < m_\tau$ in $\tau^- \to \pi^- N$ decays

Heavy lepton in $N \to \mu^+\mu^-\nu_\tau$ decays

- Signature: prompt π^- and displaced $\mu^+\mu^-$ vertex
  - Allows direct measurement of m_N
- Observation in agreement with background expectation
- Set 95 % C.L. upper limits on mixing parameter

915 fb^{-1}

BELLE

[PRD 109 (2024) L111102]

Searches for heavy neutral letpons (N or ν_h)

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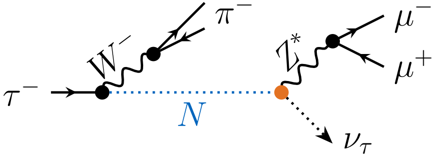

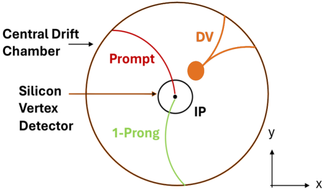

DV = Displaced Vertex

IP = Interaction Point

915 fb^{-1}

[PRD 109 (2024) L111102]

Searches for a Heavy Neutral Lepton (N or ν_h) in τ Decays

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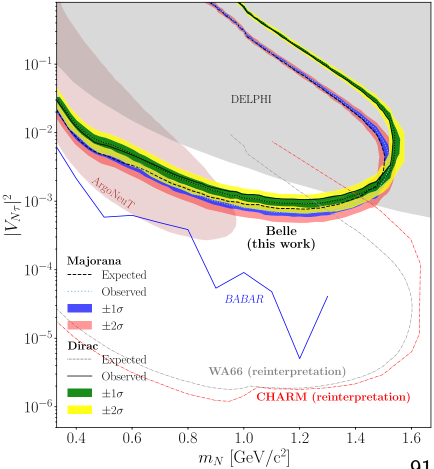

915 fb^{-1}

[PRD 109 (2024) L111102]

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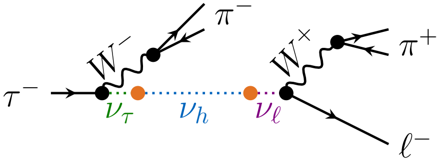

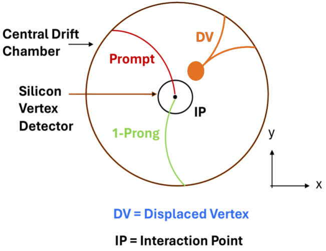

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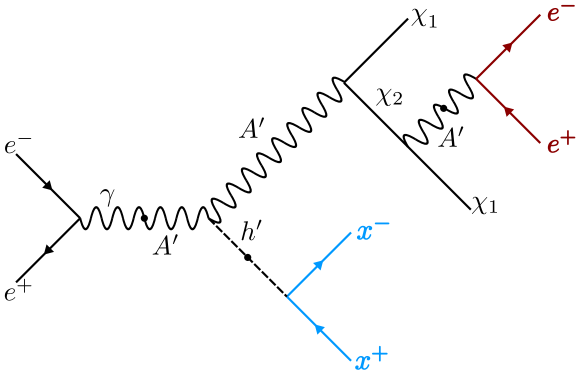
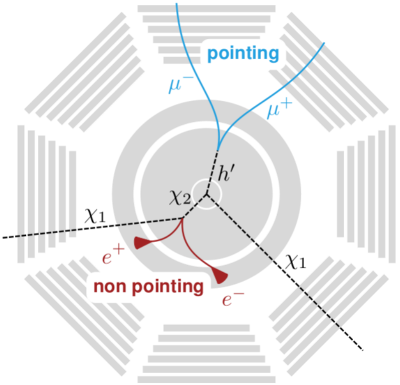
[PRL 131 (2023) 21180]

Searches for Inelastic Dark Matter with a Dark Higgs

- 4 final-state tracks
  - 2 forming pointing displaced vertex
  - 2 forming non-pointing displaced vertex
- Missing energy

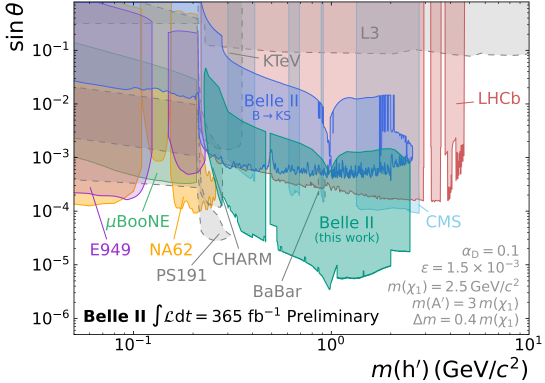
- Challenging for tracking and trigger
- Almost zero-background analysis

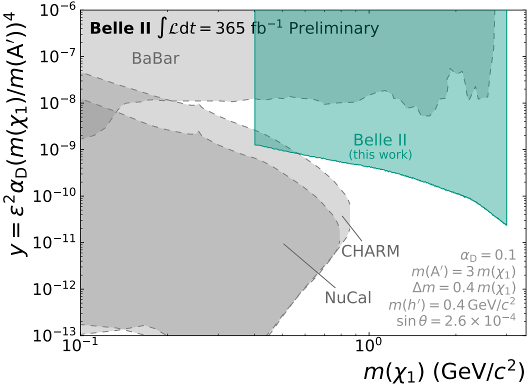




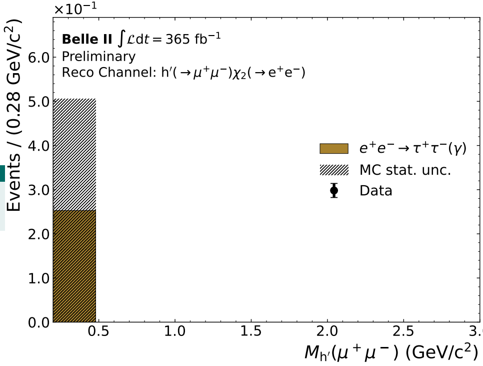
Searches for Inelastic Dark Matter with a Dark Higgs

- Expected background estimated in data from sidebands to not rely on simulation
- No significant excess in m_{xx} spectrum found
  - ➥ 95 % CL upper limits on model parameters



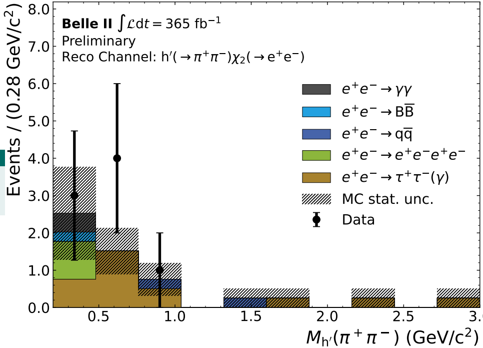


- Mass distribution

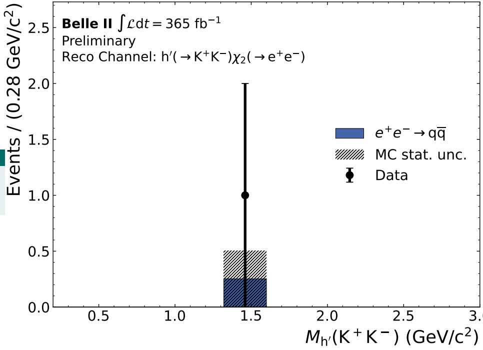


Searches for Inelastic Dark Matter with a Dark Higgs

- Mass distribution



- Mass distribution



Searches for Inelastic Dark Matter with a Dark Higgs

- Stable dark matter χ_1 (relict candidate)
- Long-lived dark matter χ_2
- Dark photon A'
  - Focused on $m_{A'} > m_{\chi_1} + m_{\chi_2}$
    - $A' \to \chi_1\chi_2$ favored with α_D
  - Mixes with SM γ with ε
- Dark Higgs h'
  - Mixing with SM Higgs θ
  - Provides mass to A'
- 7 parameters: ε, θ, α_D, $m_{A'}$, $m_{h'}$, m_{χ_1}, Δm_χ