Tau and Low-Multiplicity Decays at Belle and Belle II

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τ Physics at Belle and Belle II

- Unique and clean laboratory to study weak interaction and hadronic systems
- Third-generation lepton potentially sensitive to Beyond Standard Model physics
- 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 ($\mathcal{L} \approx 0.4\,\mathrm{ab}^{-1}$)

[Particle Zoo]

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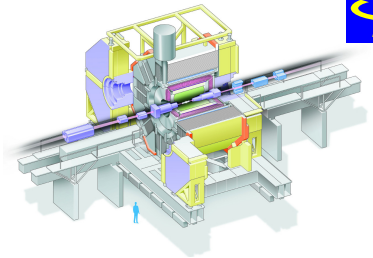
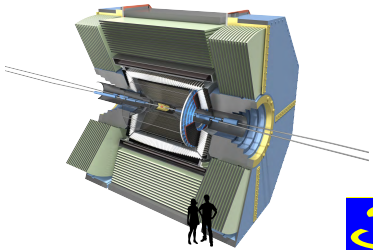
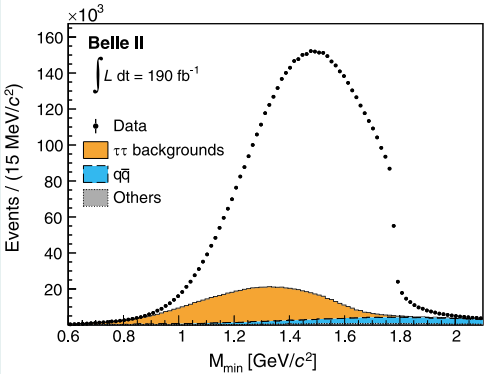




τ Mass Measurement at Belle II

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

- 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
- Belle II provides World's most precise result



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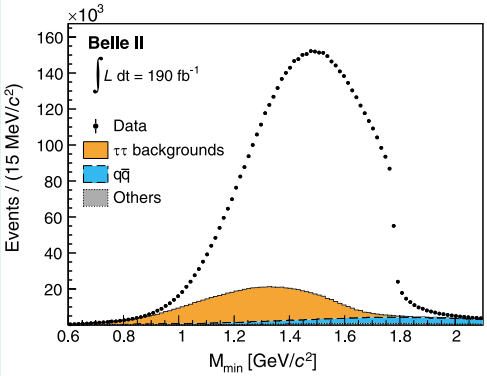

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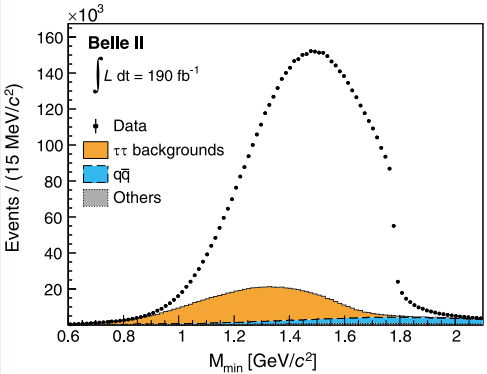

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[Phys. Rev. D 108 (2023) 032006]

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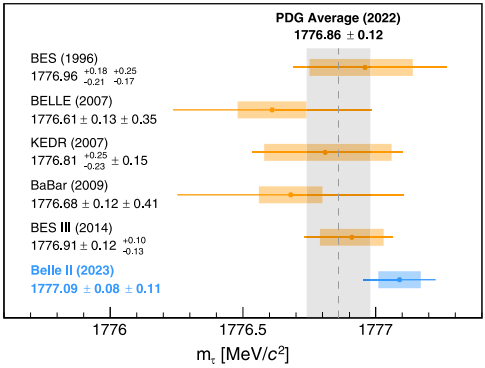

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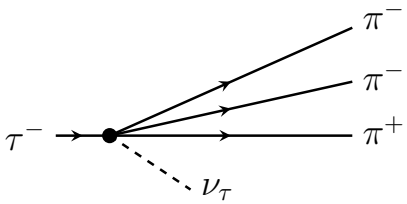
Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ Decays

- $\pi^-\pi^-\pi^+$ 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
- CLEO-II performed the only amplitude analysis [PRD 61 (1999) 012002]



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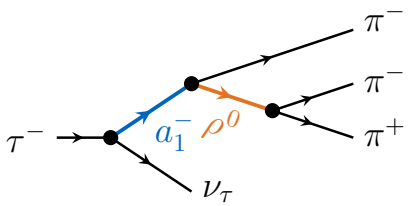

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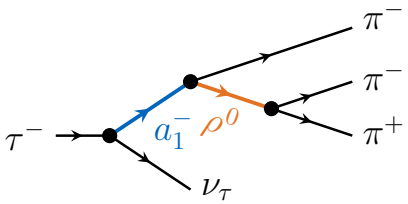

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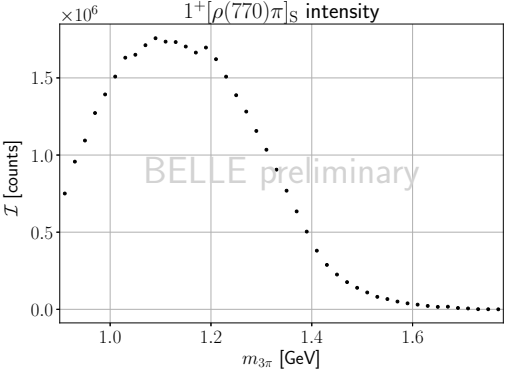
BELLE

Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ Decays

- Clear $a_1(1260)$ 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



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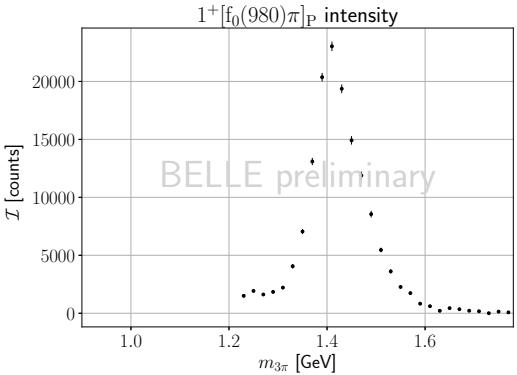

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BELLE

Lepton-Flavor Violation (LFV) in τ Decays

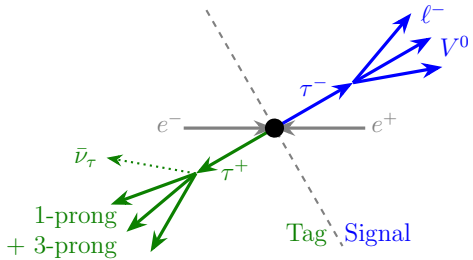
- Lepton Flavor Violation (LVF) is negligibly small in Standard Model + ν mixing (below 10^{-50})
- Various new-physics models predict branching fractions in the range 10^{-7} – 10^{-10}
  - ➥ Search for lepton flavor violating decay channels

Lepton-Flavor Violation (LFV) in τ Decays

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

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

- Search for decays $\tau^- \to \ell^- V^0$, which $V^0 = \rho^0, \phi, \omega, K^{*,0}$
- 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)
  - $B(\tau^- \to e^- V^0) < (1.7\text{–}2.4) \times 10^{-8}$
  - $B(\tau^- \to \mu^- V^0) < (1.7\text{–}4.3) \times 10^{-8}$



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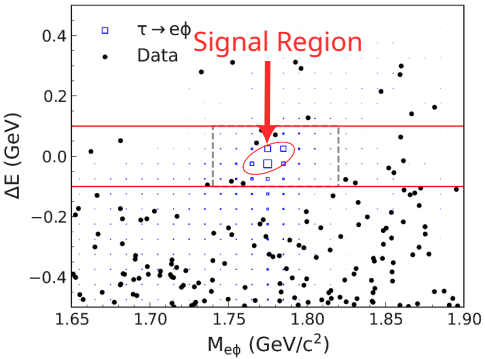

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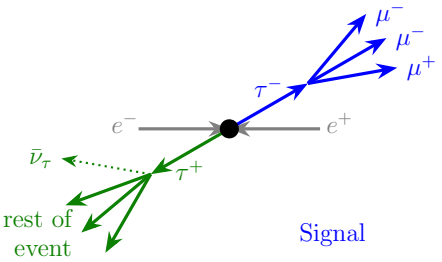
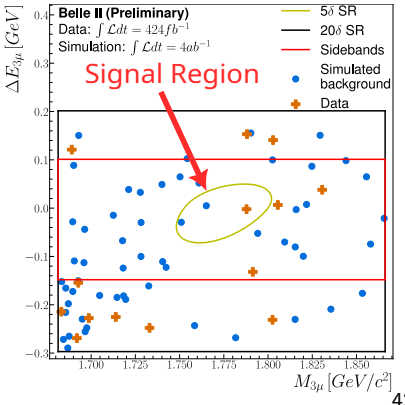
BELLE

Lepton-Flavor Violation (LFV) in τ Decays

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

- 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

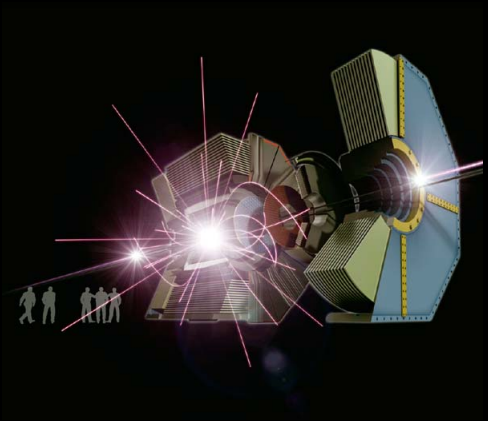




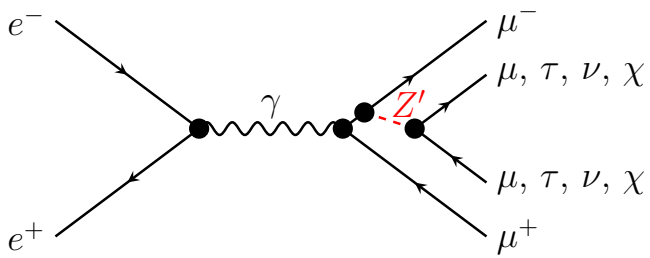
424 fb^{-1}

Dark Sector Searches at Belle II

- Dark sector physics
  - ➥ Low multiplicity events
- L1 trigger for low multiplicity events
  - Single muon, track, photon
  - Displaced-vertex trigger under study
- Well known initial condition at B factories important for dark sector searches
- Belle II is sensitive to direct production of MeV to GeV mediators



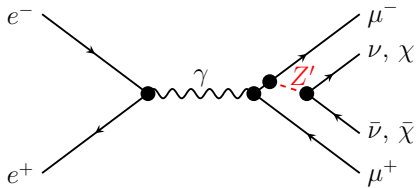
Searches for the $L_\mu - L_\tau$ Gauge Boson Z'



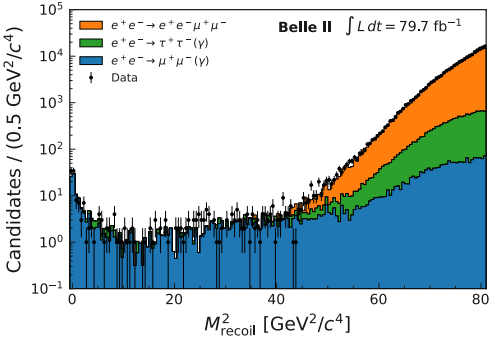
- New gauge boson Z' couples only to 2nd and 3rd generation of leptons ($L_\mu - L_\tau$)
- Coupling to μ, τ, ν_μ, ν_τ with strength g'
  - Decays visibly and invisibly
  - Decays to dark matter χ could be dominant

Searches for $Z' \to$ 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 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'



$79.7\,\mathrm{fb}^{-1}$

Belle II

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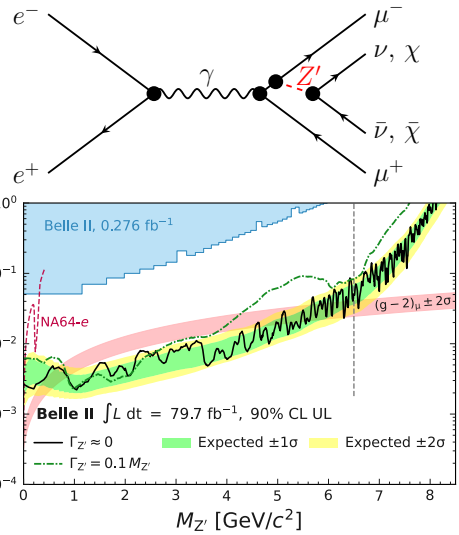

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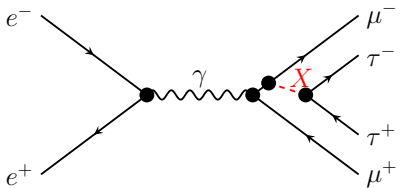
Belle II

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

[Phys. Rev. Lett. 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 leptonic scalar (S)
  - ➥ probe for the first time above 6.5 GeV/c^2
  - ➥ World-leading limits for ALPs

$62.8\,\text{fb}^{-1}$

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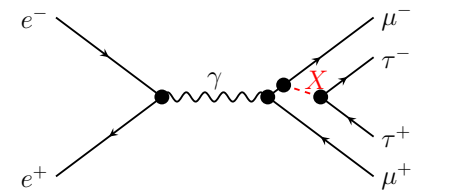

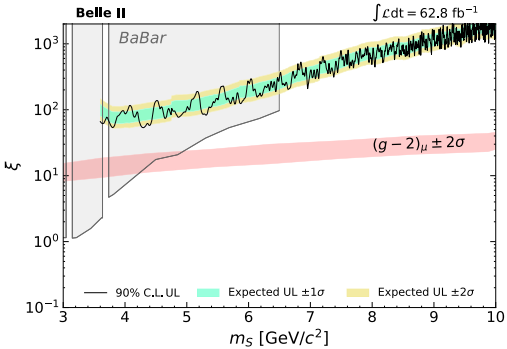

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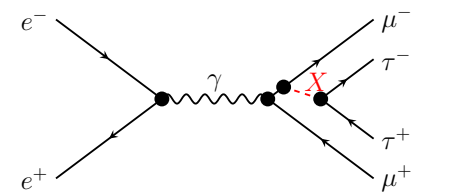

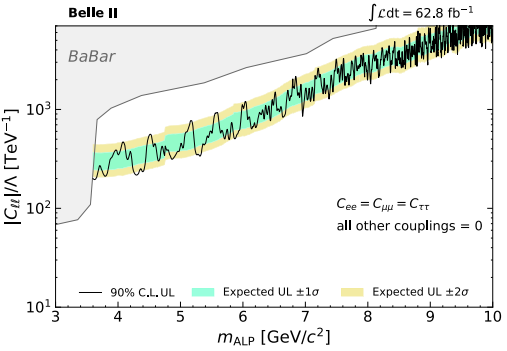

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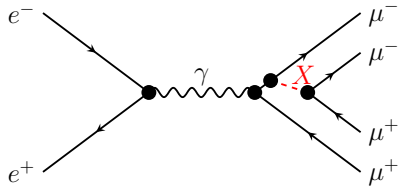
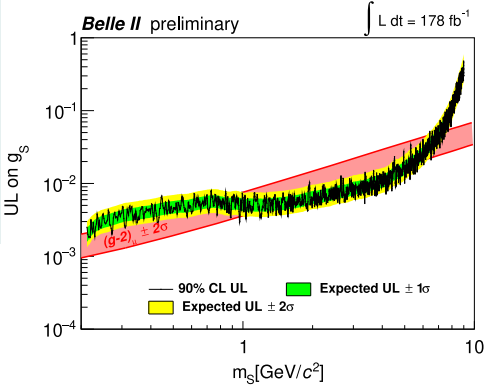
[M. Laurenza, DMMNET 2023]



- 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}

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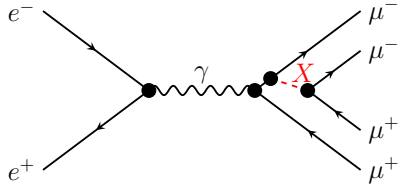

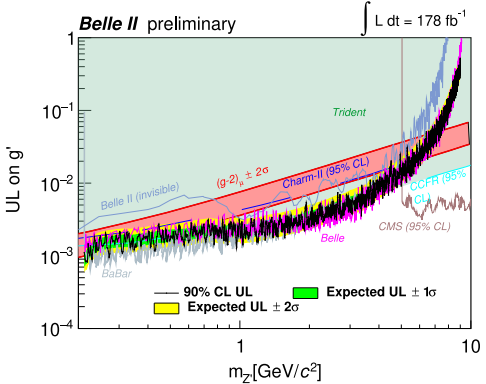

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Belle II

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

- Lepton-flavor violation in $\tau^- \to \ell^- \phi$ [arXiv:2305.04759]
- Lepton-flavor violation in $\tau^- \to \ell^- \alpha$ [PRL 130 (2023) 181803]
- Test lepton-flavor universality in $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ [TAU 2023]
- Searches for heavy neutrino in τ decays [PRL 131 (2023) 211802]
- Michell Parameters in $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ [PRL 131 (2023) 021801]
- Electric Dipole Moment of the τ [JHEP 11 (2022)]

Further dark-sector searches

- Long-lived spin-0 mediator in $b \to s$ [PRD 108 (2023) L111104]
- Dark Higgsstrahlung in $\mu^+\mu^-$ [PRL 130 (2023) 071804]
- Axionlike particle decaying to $\gamma\gamma$ [PRL 125 (2020) 161806]
- Dark leptophilic scalar in association with $\tau^-\tau^+$ [arXiv:2207.07476]

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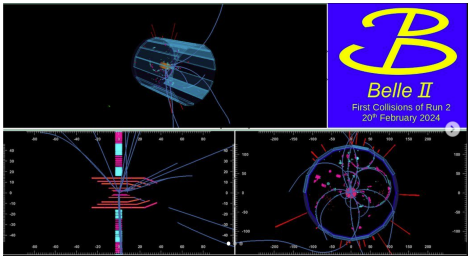
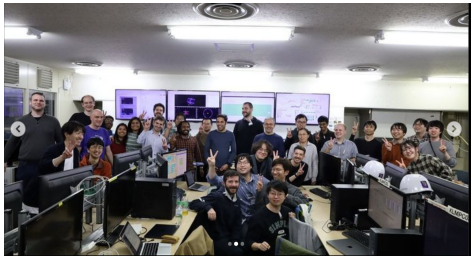




Backup

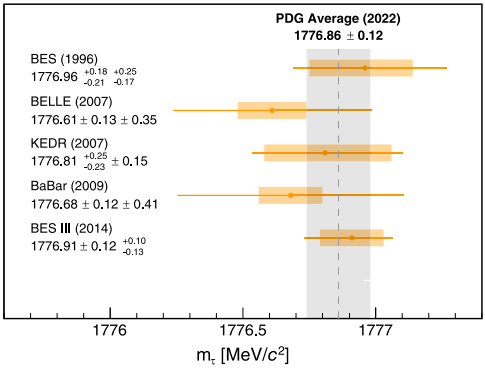
Outline

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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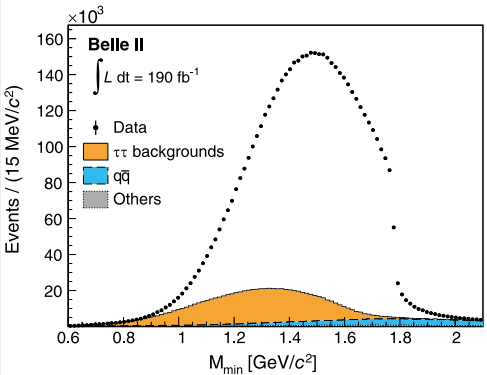

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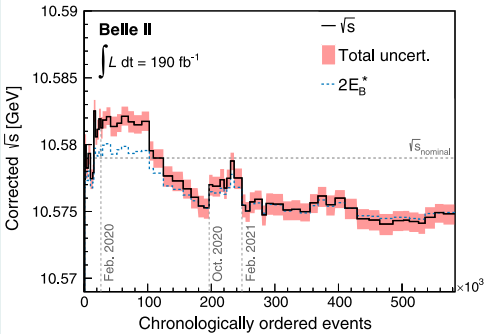

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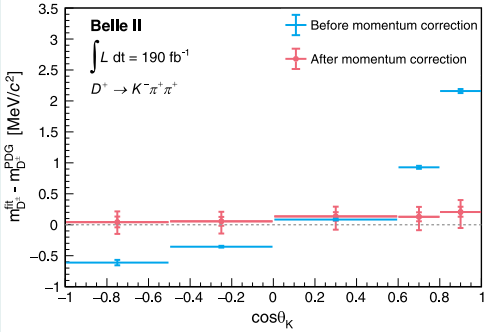

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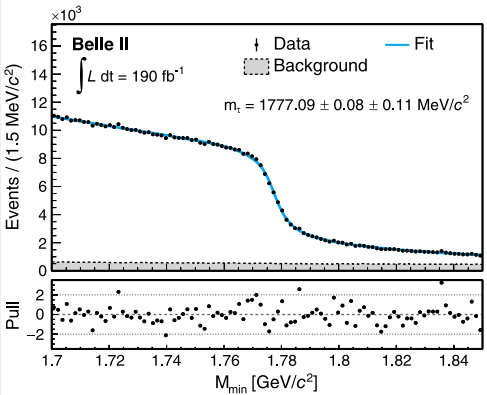

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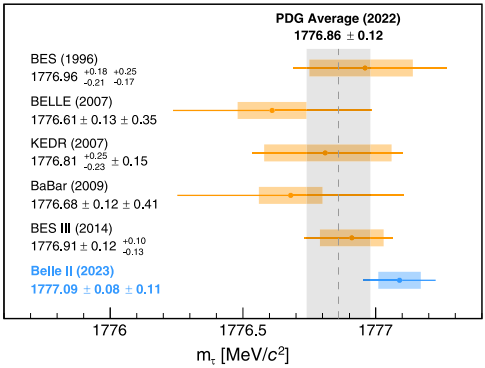
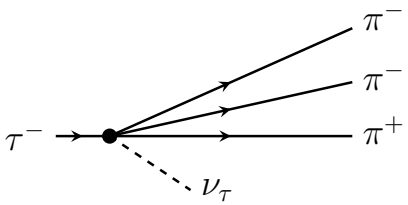


190 fb^{-1}

Belle II

Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ Decays

- $\pi^-\pi^-\pi^+$ 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]



$980\,\text{fb}^{-1}$

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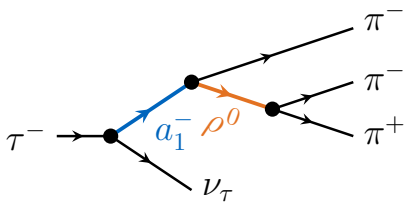

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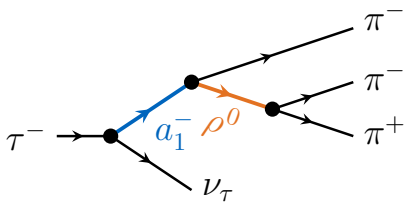


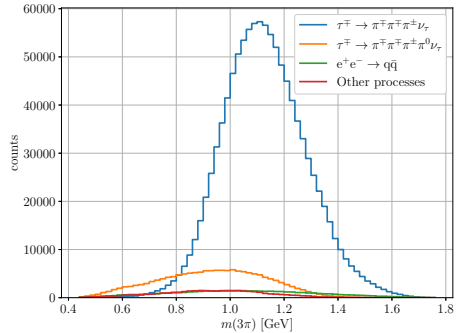
$980\,\text{fb}^{-1}$

BELLE

Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ Decays

- 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

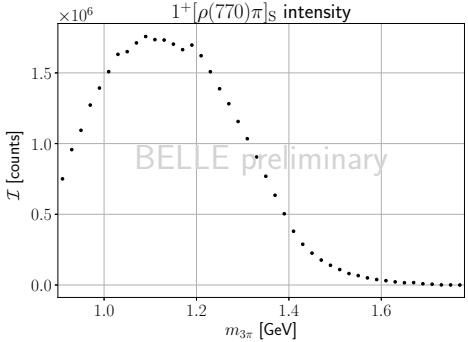


$980\,\text{fb}^{-1}$

BELLE

Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ Decays

- 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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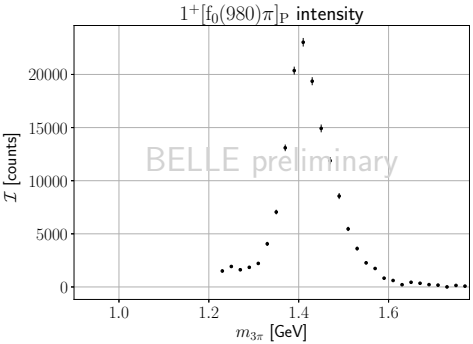

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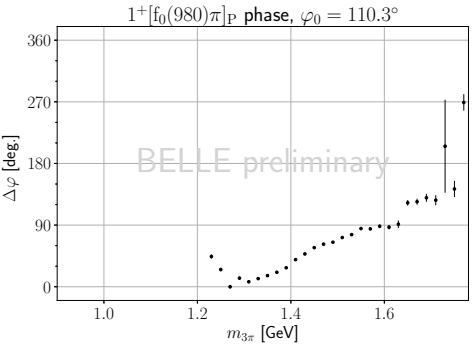

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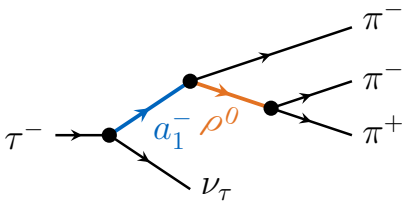

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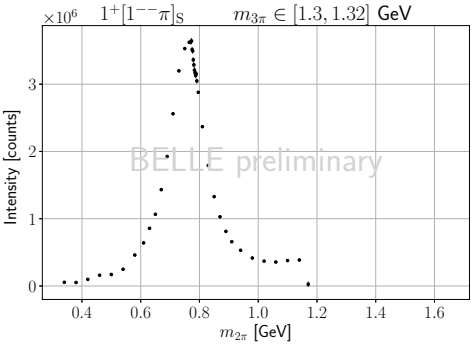
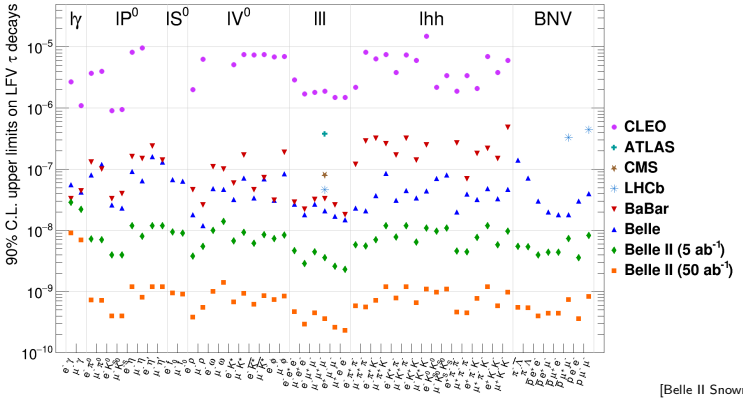


980 fb^{-1}

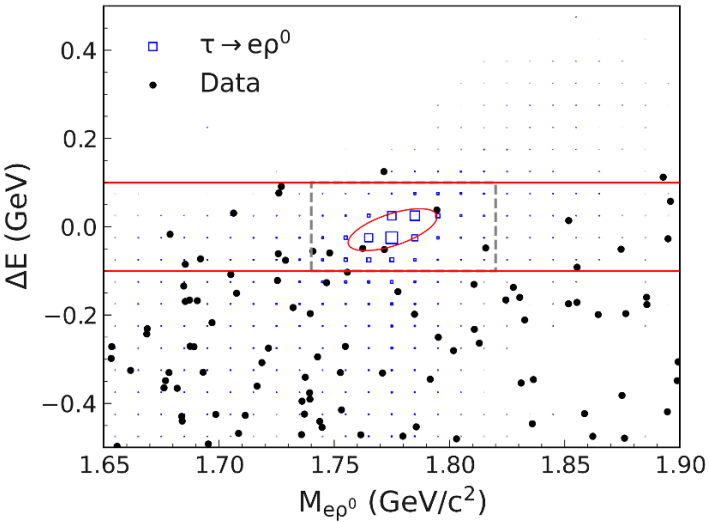
BELLE

Lepton-Flavor Violation (LFV) in τ Decays

- 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]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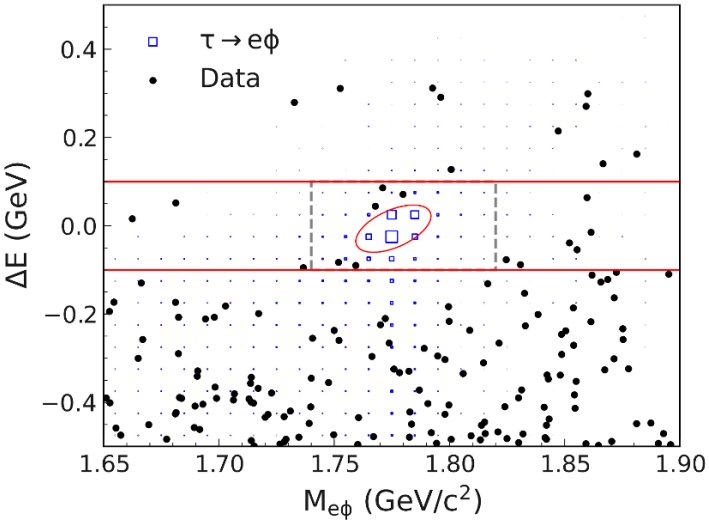
ΔE (GeV)
0.4
0.2
0.0
−0.2
−0.4
1.65
1.70
1.75
1.80
1.85
1.90
M_eρ⁰ (GeV/c²)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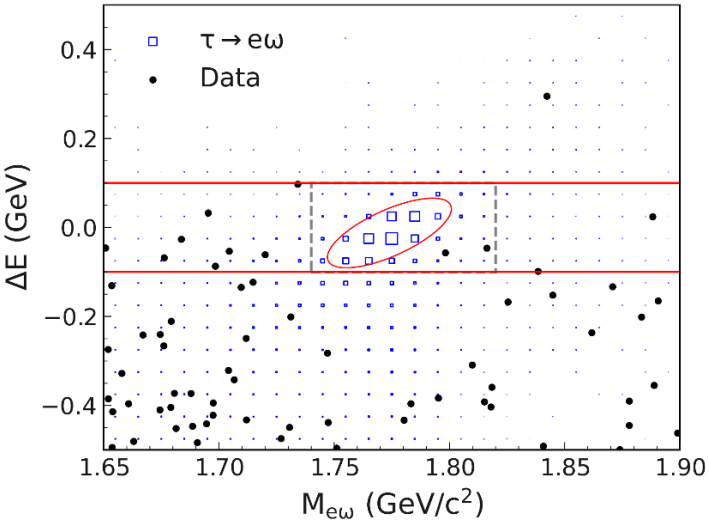
Lepton-Flavor Violation (LFV) in τ Decays

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

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



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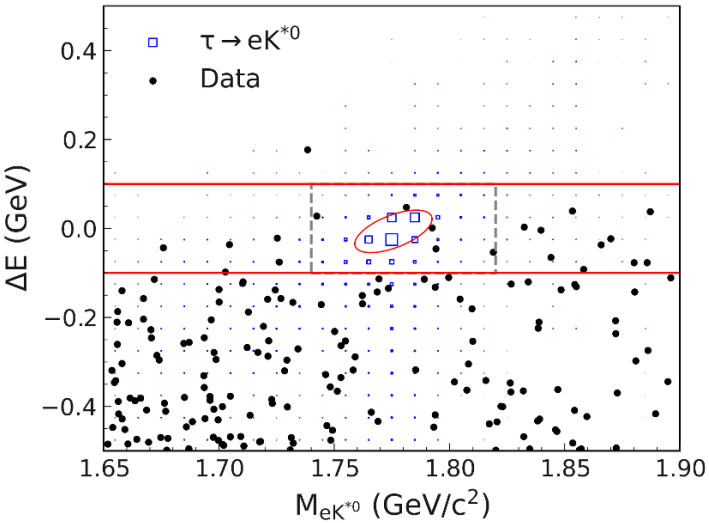
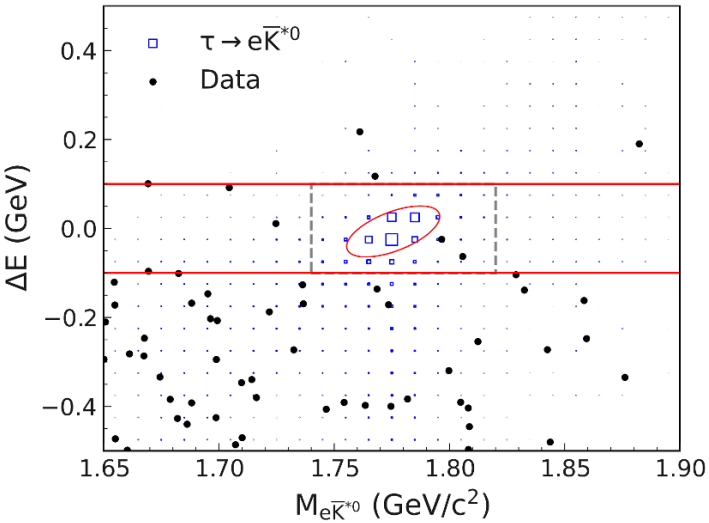
[J. High Energ. Phys. 2023, 118 (2023)]




τ → eK̄*0
Data
ΔE (GeV)
0.4
0.2
0.0
−0.2
−0.4
1.65
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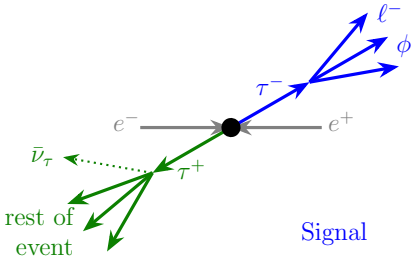
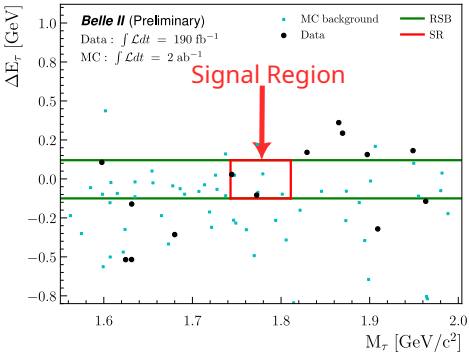
1.75
1.80
1.85
1.90
M eK̄*0 (GeV/c²)

$\tau \to \ell\phi$

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



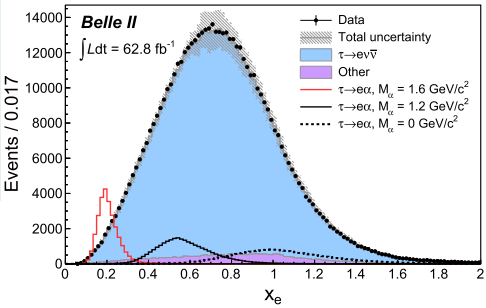


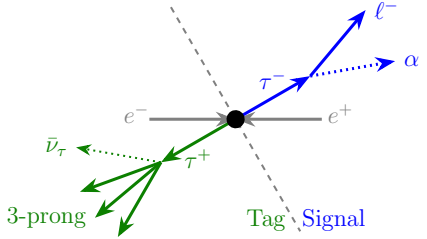
190 fb^{-1}

Belle II

$\tau \to \ell\alpha$, 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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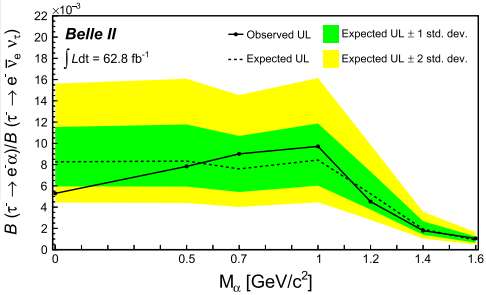

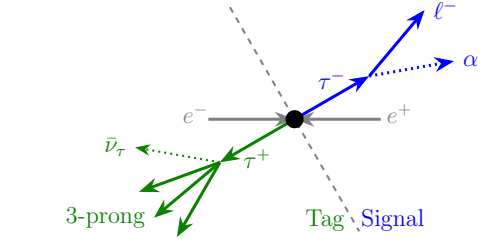

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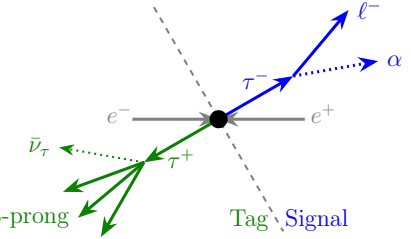
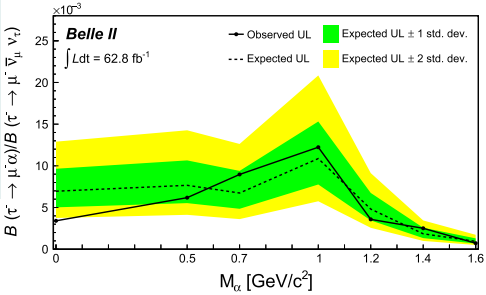


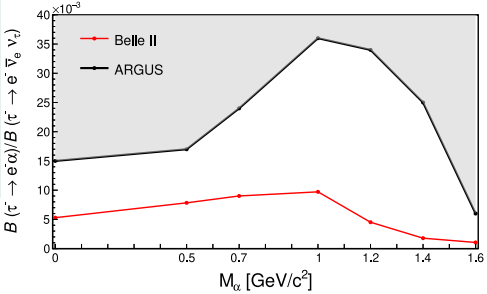


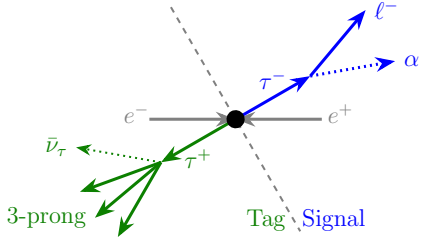
62.8 fb^{-1}

Belle II

$\tau \to \ell\alpha$, 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



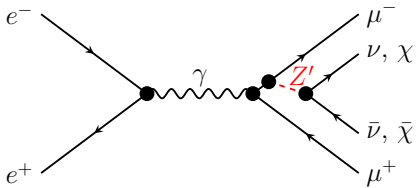


62.8 fb^{-1}

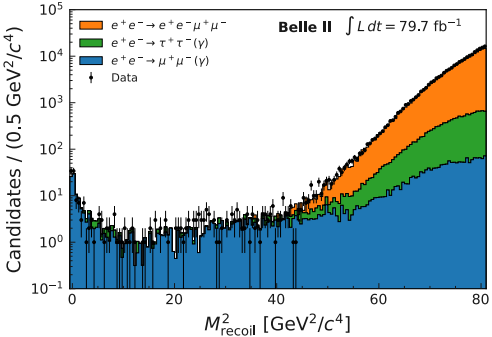
Belle II

Searches for $Z' \to$ 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'



$79.7\,\mathrm{fb}^{-1}$

Belle II

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

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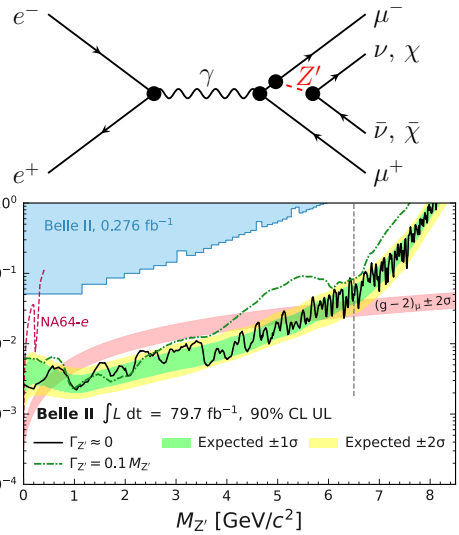

79.7 fb^{-1}

Belle II

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

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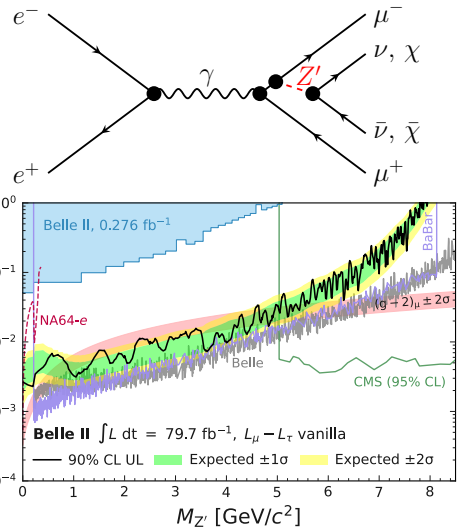

79.7 fb^{-1}

Belle II