Recent Dark Sector and Tau Physics Results at Belle II

Lepton Photon 2023

July 18 2023

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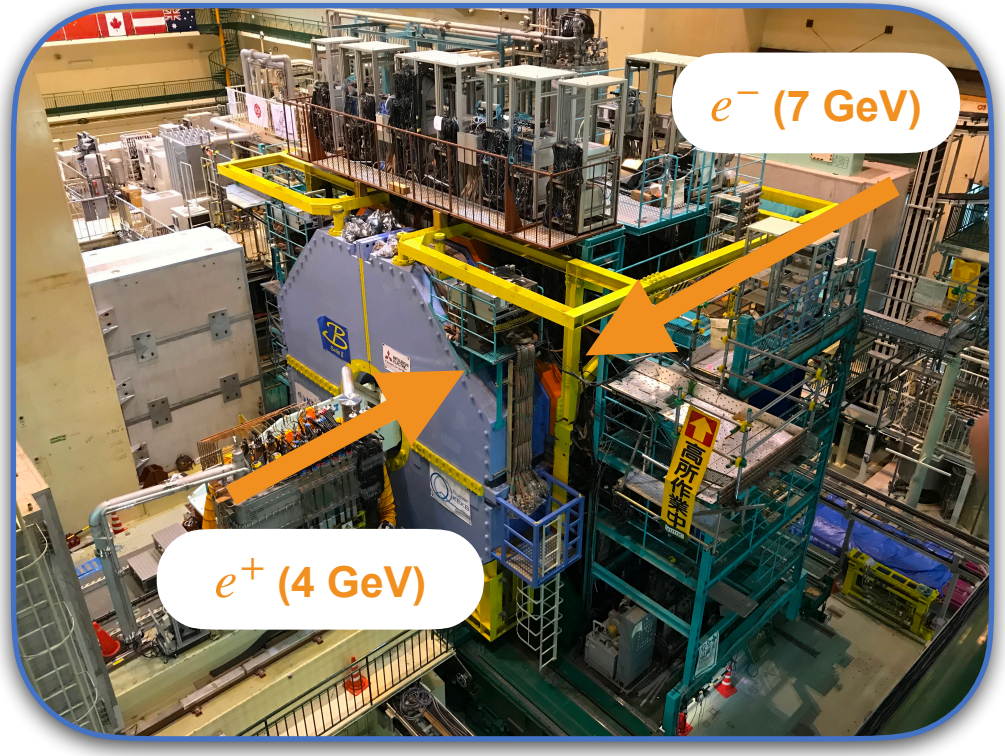
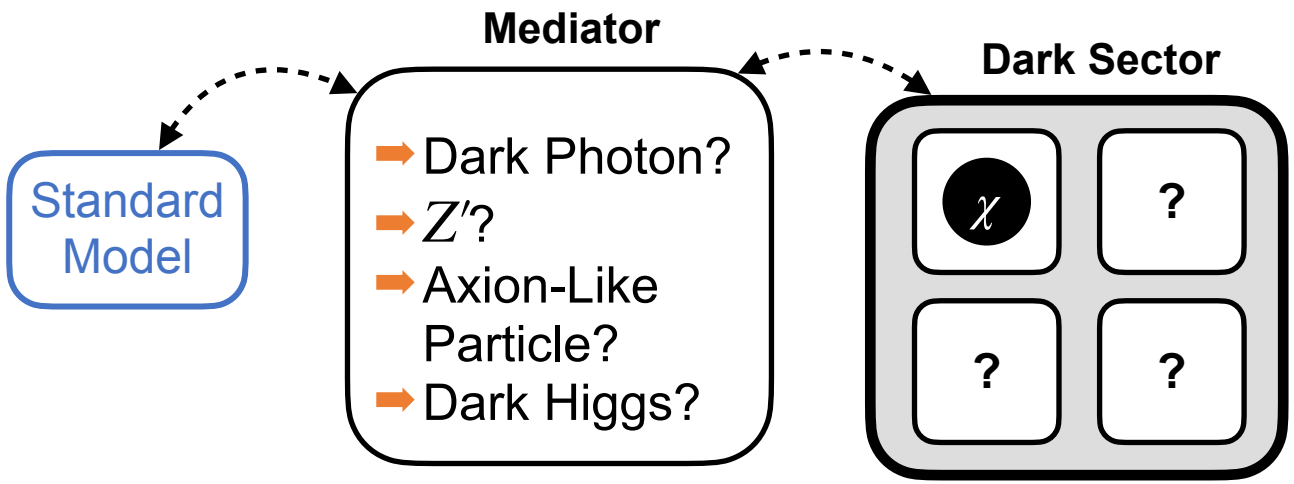
Dark Sector and τ Physics at Belle II

- Next generation B/τ-Factory operating at the SuperKEKB asymmetric-energy e^+e^- collider
  - ➡ Collisions at or near $\Upsilon(4S)$ ($\sqrt{s}$ around 10.6 GeV)
  - ➡ World's highest luminosity particle collider
- Targets 50 ab^{-1} over experiment lifetime (Belle ~ 1 ab^{-1}, BaBar ~ 0.5 ab^{-1})
- Sensitive to direct production of MeV to GeV scale mediators between Standard Model and Dark Sectors
- $\sigma(e^+e^- \to \tau^+\tau^-) \sim 0.9$ nb enables extensive τ physics program





Precise determination of missing energy/momentum via:

- ✓ Minimal collision pile-up
- ✓ Well-known initial conditions
- ✓ Hermetic detector with high detection efficiency for charged and neutral particles.

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Belle II Detector and Dataset

- Substantial detector upgrade from Belle
- Total dataset to-date is 424 fb^{-1}
- Specialized **Dark Sector Triggers** enabled:

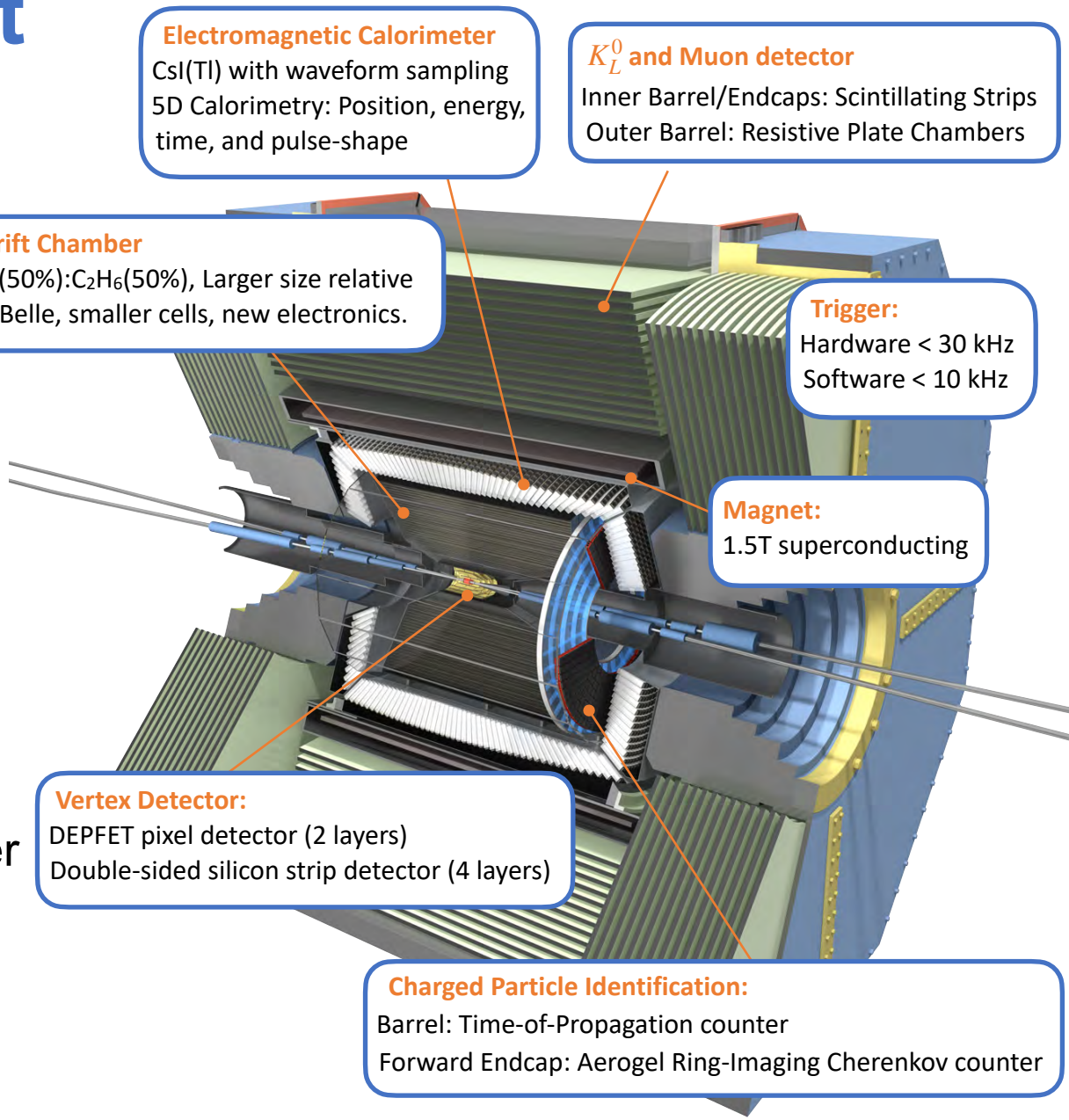
✓**Single muon trigger** using KLM

✓**3D track reconstruction at L1** using neural networks

✓**Single photon trigger** operational for entire dataset

- Not present at Belle.
- 53 fb^{-1} recorded by BaBar with single photon trigger

✓**Displaced vertex trigger** in development.



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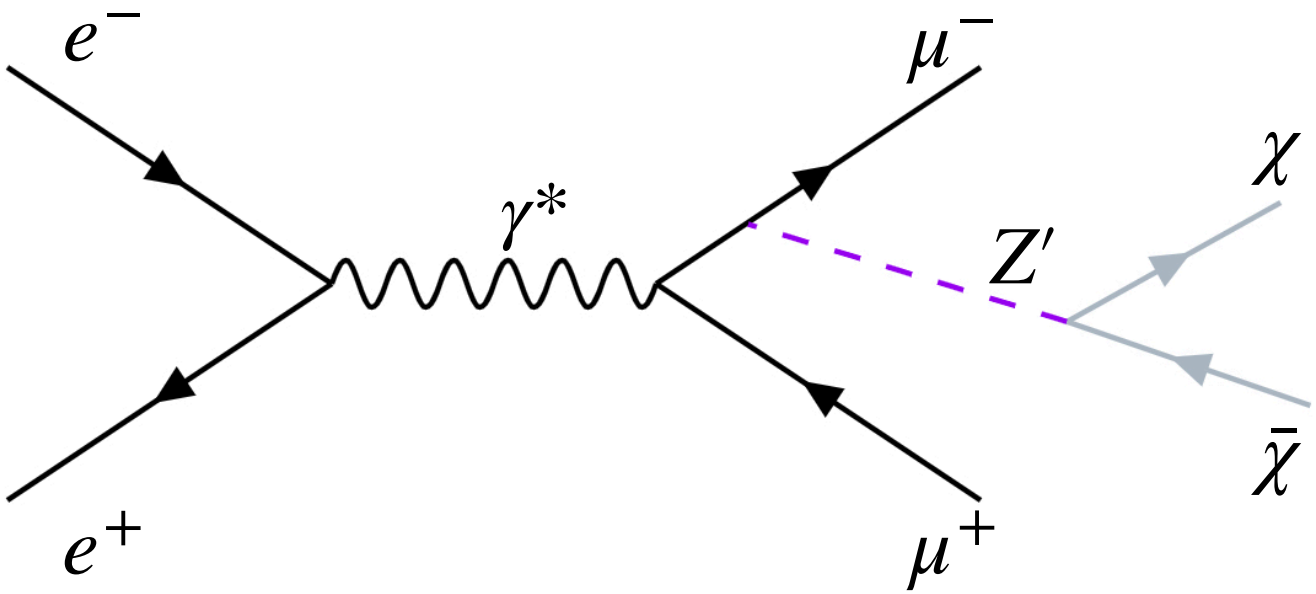
Search for Invisible Z'

- Search for massive Z' vector boson with coupling to only particles having muon and tau lepton number ($L_\mu - L_\tau$ extension of SM)
  - Could explain current muon $g-2$ tension and mediate interactions between SM and dark matter

B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. Lett. 113, 091801 (2014).
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, J. High Energy Phys. 12 (2016) 106.

- Search performed at Belle II via $e^+e^- \to \mu^+\mu^- Z', Z' \to$ Invisible

BF($Z' \to \nu\bar{\nu}$) ~ 33 - 100%
BF($Z' \to \chi\bar{\chi}$) ~ 100% if kinematically allowed



Detected muons used to compute recoil mass that peaks for Z' signal

Takes advantage of capabilities for precision determination of missing energy!

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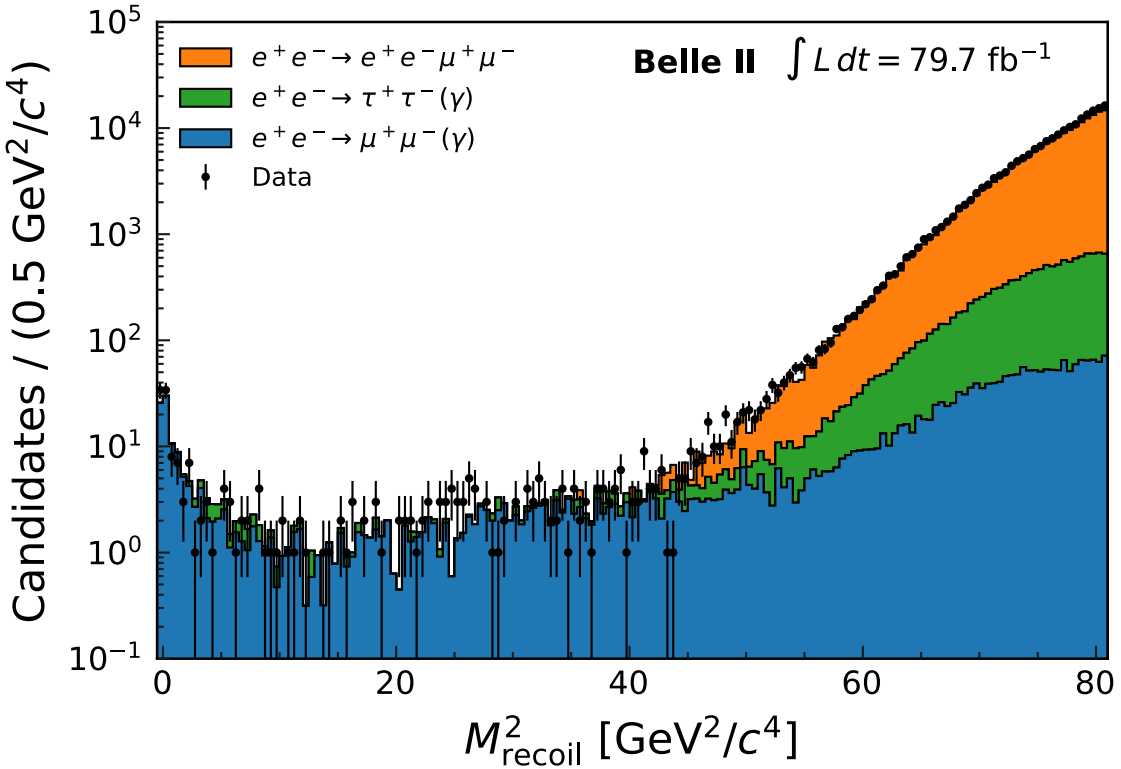
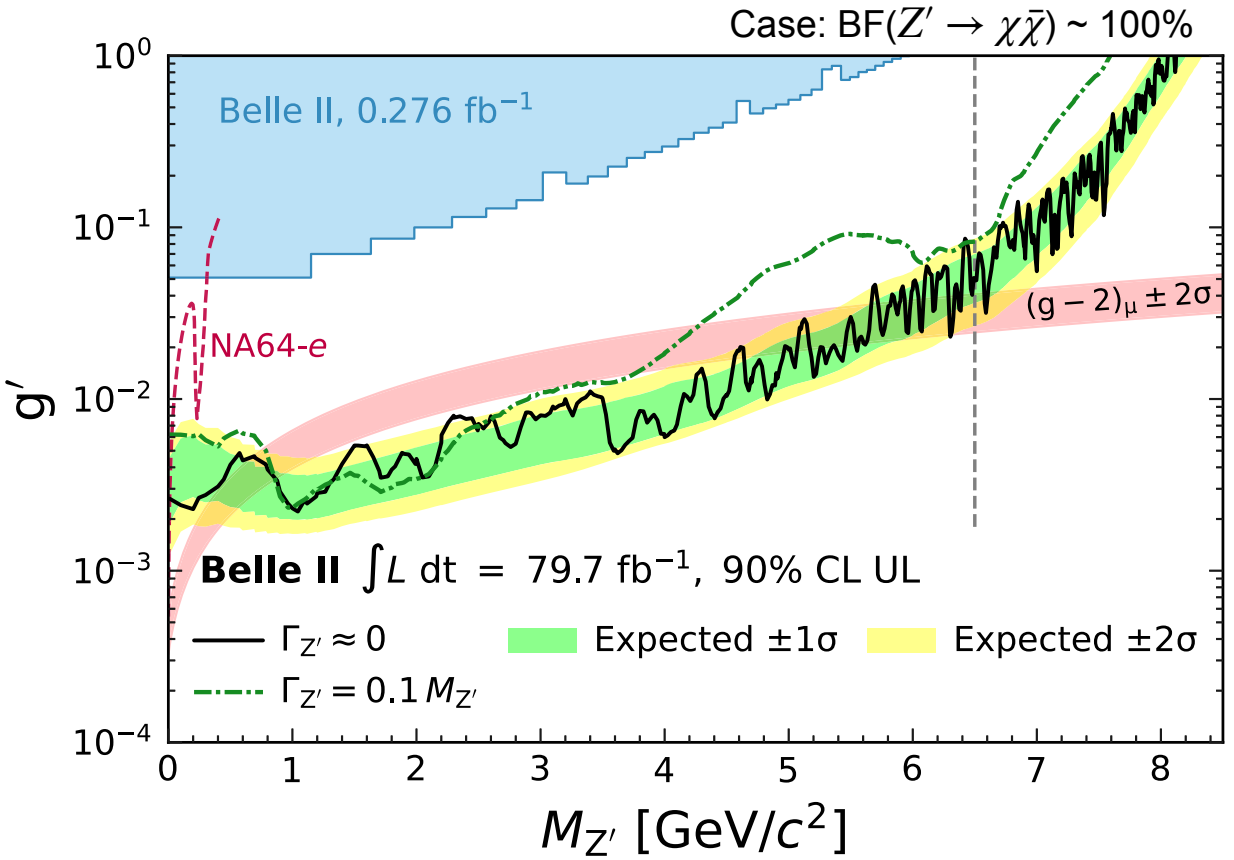
Search for Invisible Z'

Belle II Collaboration Phys. Rev. Lett. 130, 231801 (2023)

- Backgrounds arise from:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$ where photon is not reconstructed
  - $e^+e^- \to \tau^+\tau^-(\gamma)$ neutrinos escape detector
  - $e^+e^- \to e^+e^-\mu^+\mu^-$ with e^+e^- not in acceptance



- No significant excess observed in 79.7 fb^{-1}
- Excluded part of Z' parameter space, which could explain muon $g-2$ tension



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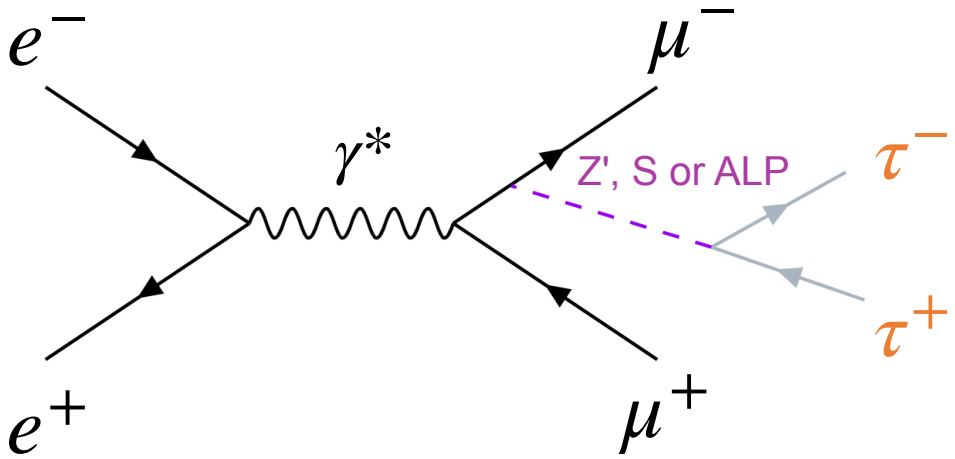
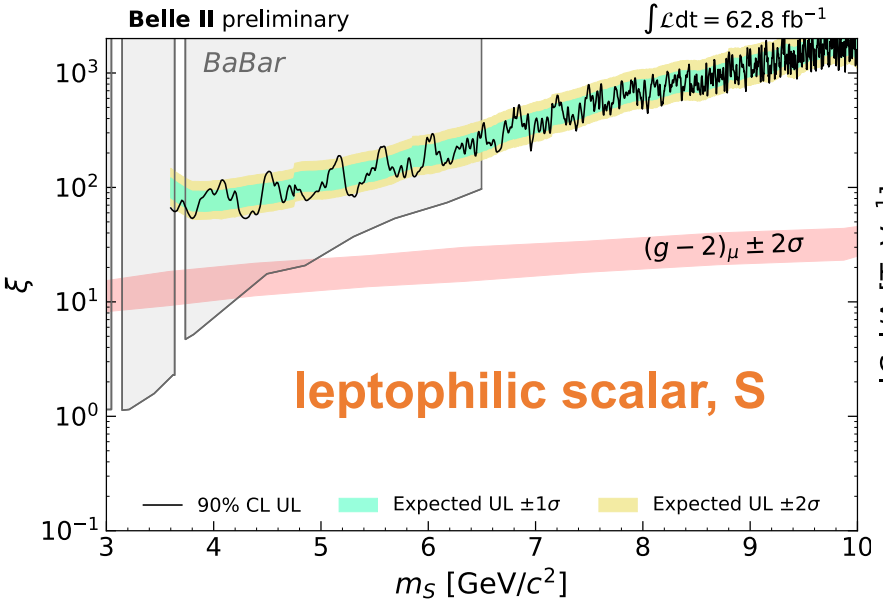
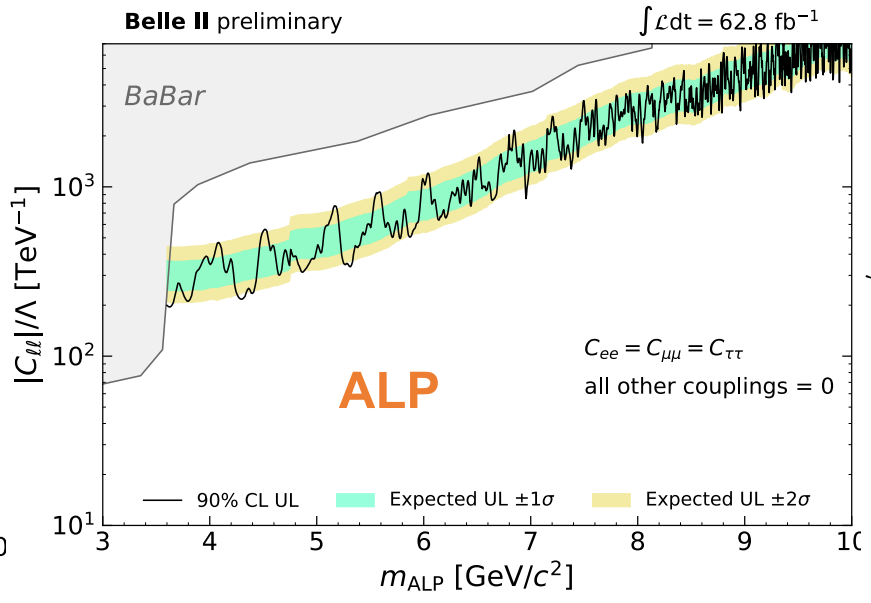
Search for $\tau\tau$ resonance in $e^+e^- \to \mu\mu\tau\tau$

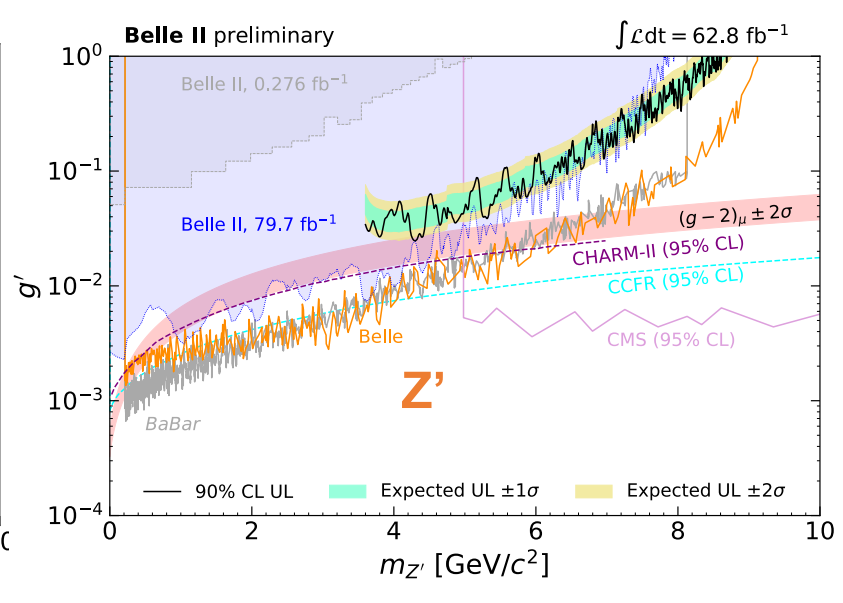


- Selects taus decaying via $\tau^- \to \ell^- \nu\nu$ or $\tau^- \to \pi^- \nu n \pi^0$
- Event signature is four tracks with missing energy
- Muons used to compute recoil mass that peaks for signal
- No significant excess observed in 62.8 fb^{-1}
- Cross section limits for $e^+e^- \to X(\to \tau^+\tau^-)\mu^+\mu^-$ translated to limits on leptophilic scalar, Z', and ALP mediator interpretations

Submitted to PRL arXiv:2306.12294







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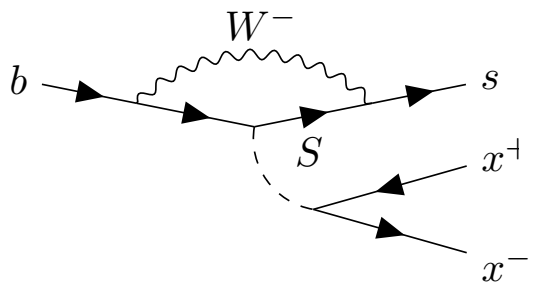
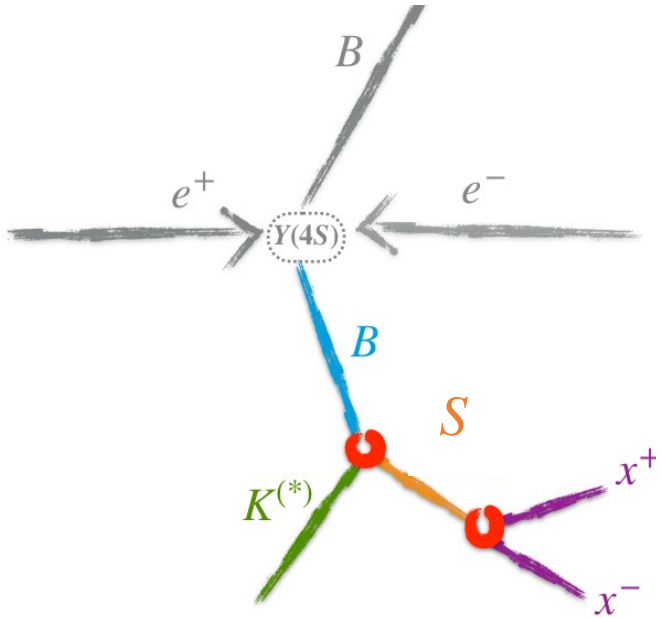
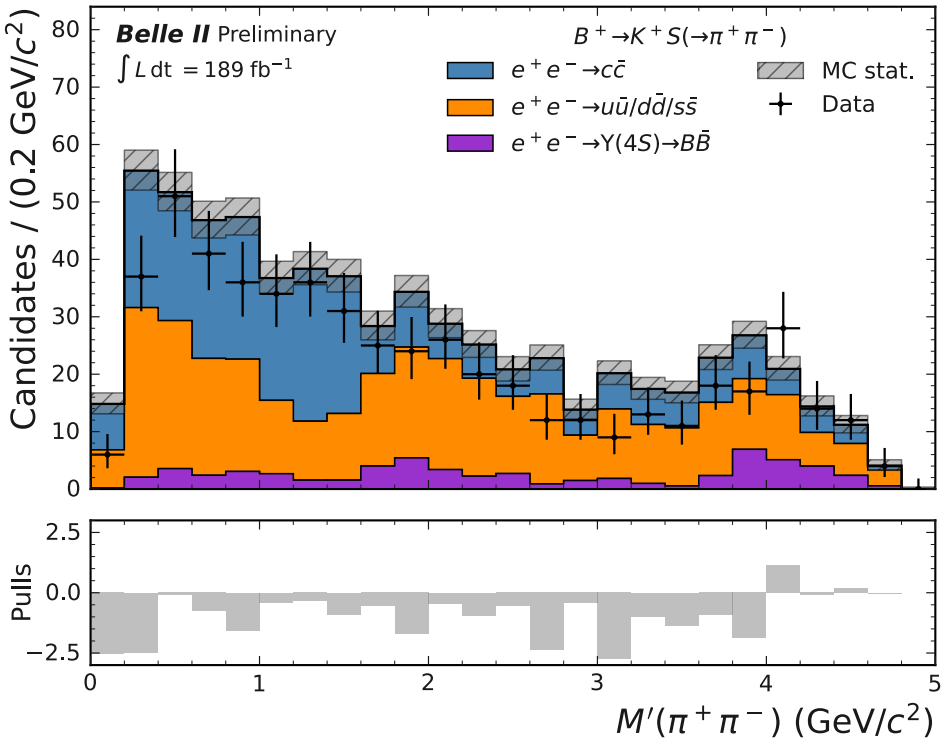
Search for a Long-lived Spin-0 Mediator in B-meson Decays

- Extensions of SM predict dark matter mass generation via light spin-0 (scalar) S that mixes with SM Higgs (mixing angle θ)
- S is long-lived particle (LLP) at small mixing angles
- Could be produced at Belle II via $b \to s$ transitions







- Eight decay channels considered:

$$B^+ \to K^+ S$$

$$B^0 \to K^{*0}(\to K^+\pi^-) S$$

$$S \to x^+x^-, x = e, \mu, \pi, K$$

Explore S lifetime range from $0.001 < c\tau < 100$ cm

- Require signal B to be fully reconstructed for background rejection
- Search for localized excess in reduced mass:

$$M'(x^+x^-) = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$$

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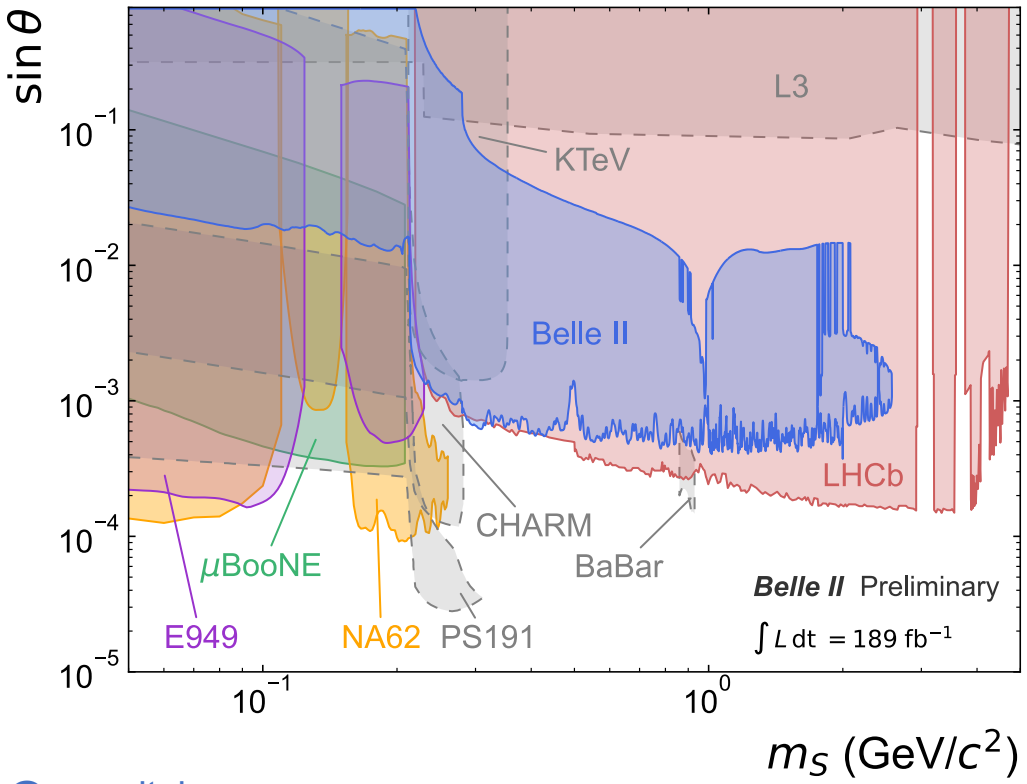
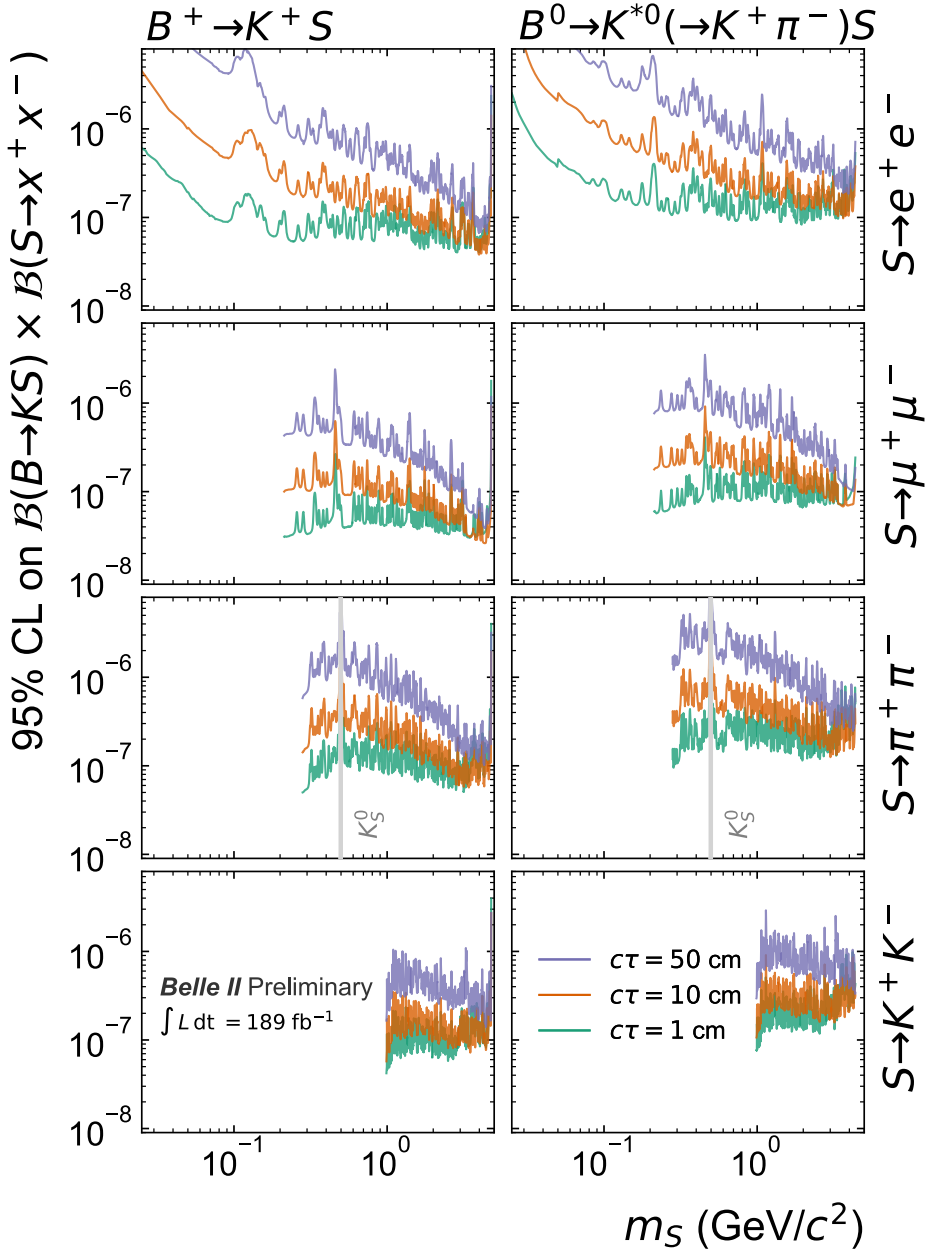
Search for a Long-lived Spin-0 Mediator in B-meson Decays

- No significant excess observed in 189 fb^{-1}
- Analysis sets first model-independent limits for eight exclusive final states (right)
- Dark Higgs-like scalar interpretation shown on bottom left

Submitted to PRL arXiv:2306.02830





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Search for τ Decays to a Lepton and an Invisible (pseudo) scalar

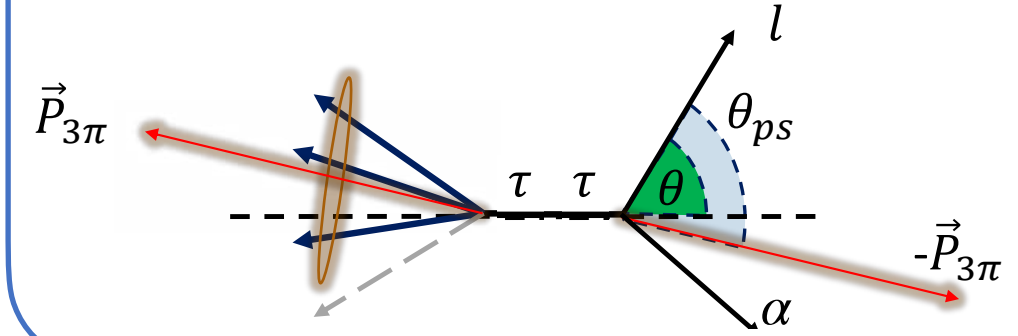
- Search for invisible (pseudo) scalar with τ coupling

$$\tau \to \ell^{\pm}\alpha \qquad \ell = e, \mu \qquad \alpha = \text{Invisible boson}$$

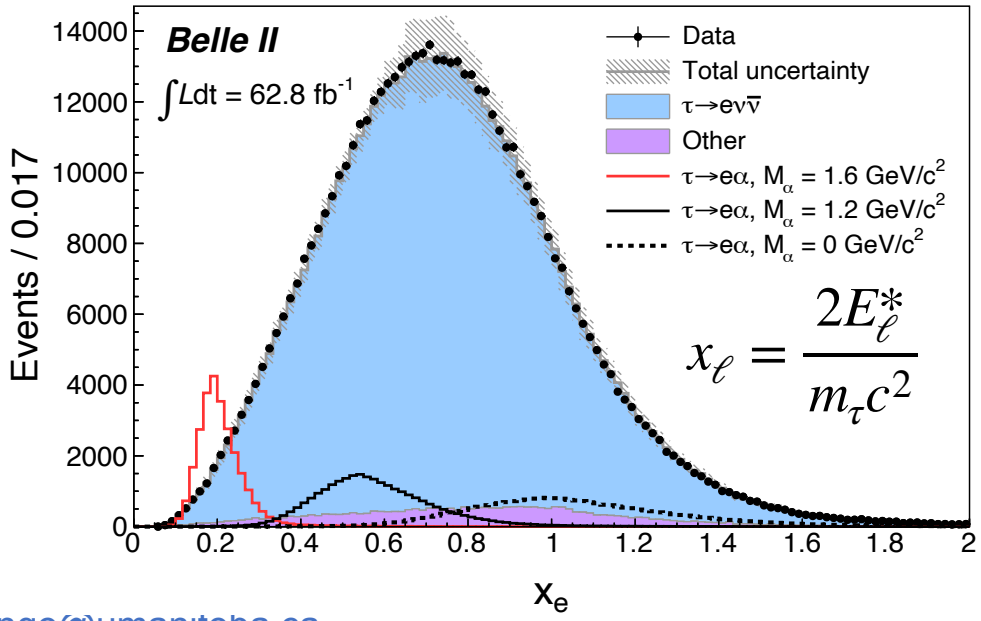
- Two-body decay causes ℓ energy to peak in τ rest-frame
- Select $e^+e^- \to \tau^+\tau^-$ events with one τ decaying as $\tau \to 3h\nu_\tau$
- No significant excess observed with 62.8 fb^{-1}
- Limits 2.2 - 14 times more stringent than the best previous limits by ARGUS

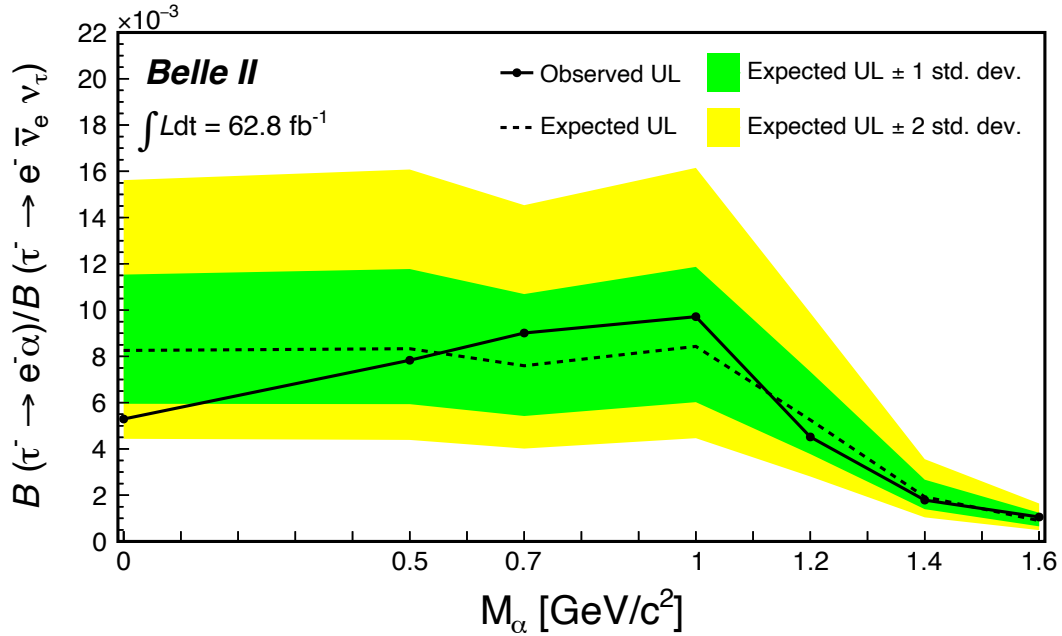
τ "pseudo rest-frame"

$$E_\tau \approx E_{CM}/2 \qquad \hat{p}_\tau \approx -\vec{p}_{3h}/|\vec{p}_{3h}|$$



Belle II Collaboration Phys. Rev. Lett. 130, 181803 (2023)





ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

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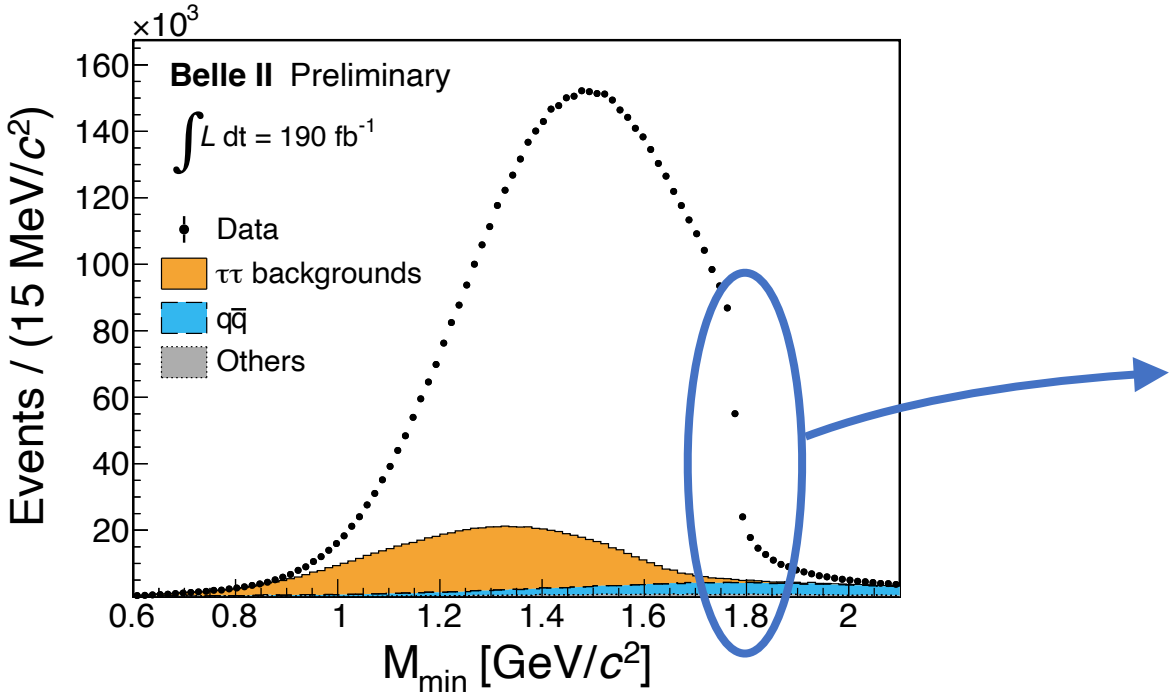
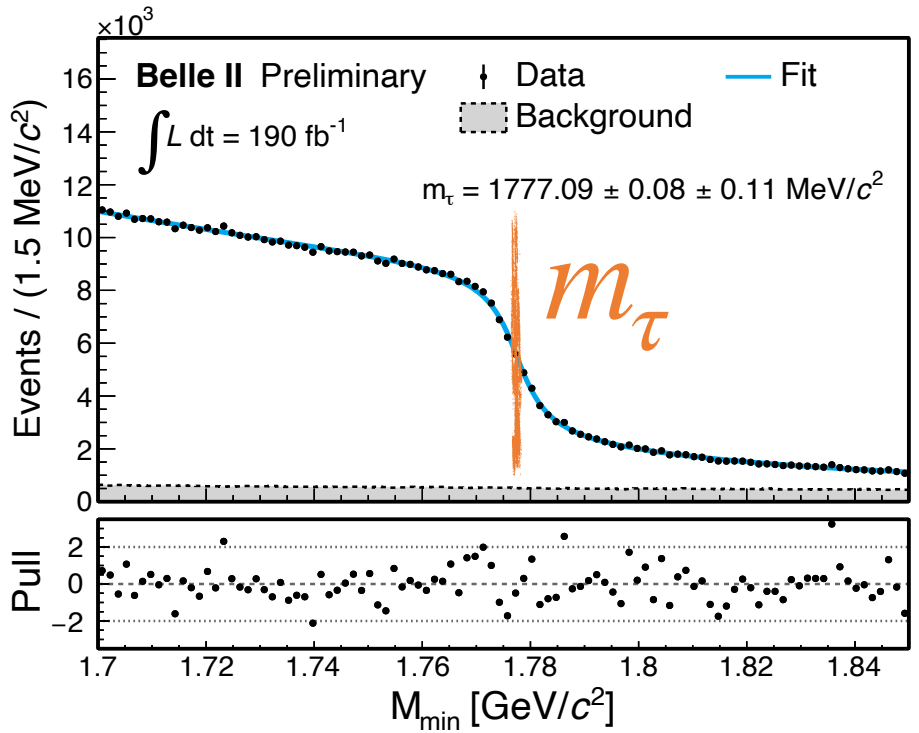
Precise Measurement of the τ Mass

- τ mass enters in precision tests of Lepton Flavour Universality, predictions of τ branching fractions, and α_s measurements at τ-mass scale
- Analysis selects $e^+e^- \to \tau^+\tau^-$ events containing decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- Assume neutrino co-linear with $\overrightarrow{p}_{3\pi}$ to obtain: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$
- τ mass extracted from threshold of this distribution measured using fit to empirical function





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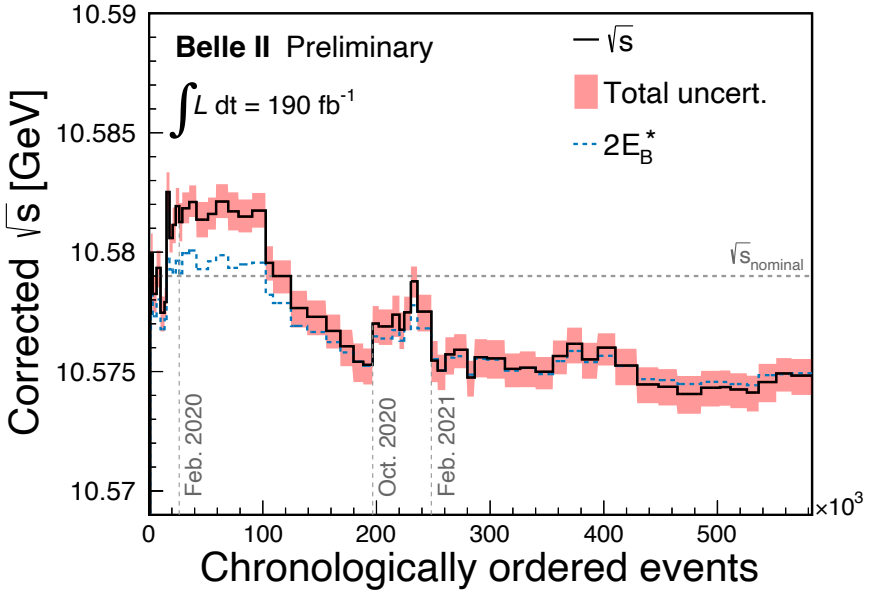
Precise Measurement of the τ Mass

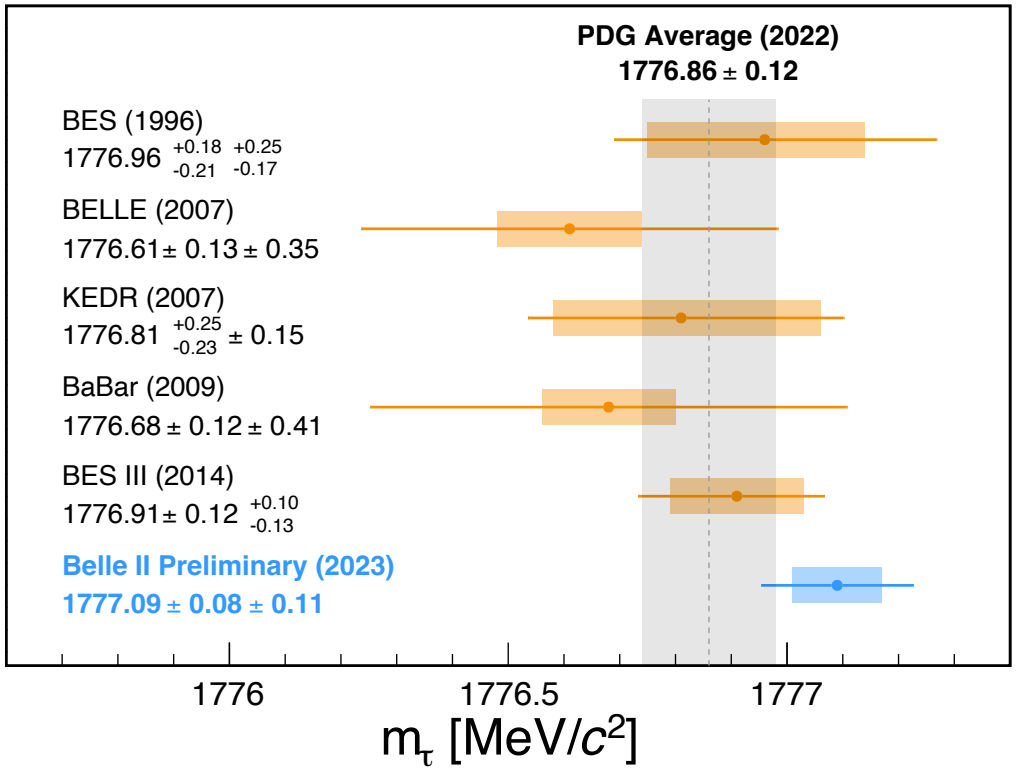
- Precise knowledge of beam energy and track momentum scale required for measurement
- Result is most precise measurement to-date of the τ mass

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

Submitted to Phys. Rev. D arXiv:2305.19116



Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11



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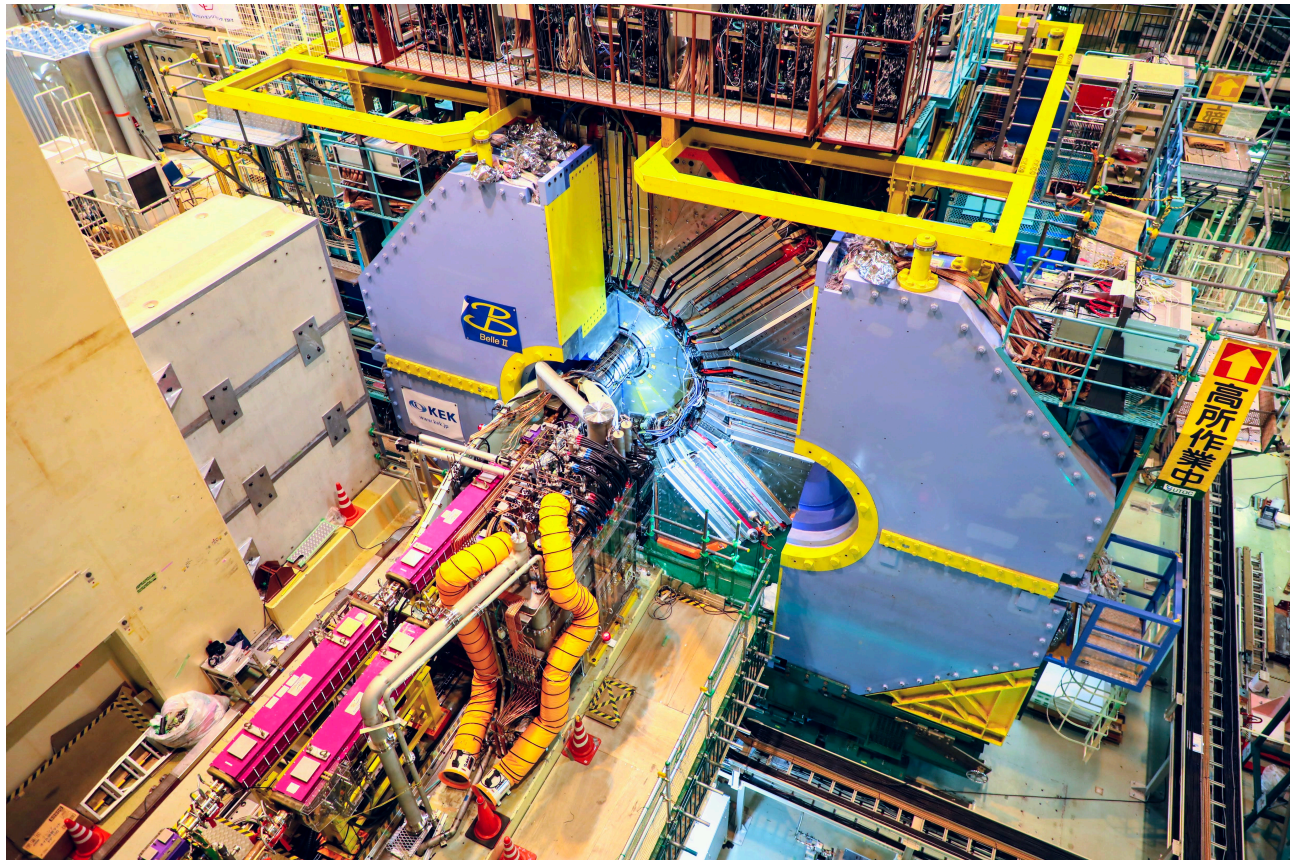
Conclusion

- Belle II is a unique facility with many exciting dark sector and tau physics opportunities
- Multiple world-leading dark sector and tau results achieved using subset of total data recorded
- Luminosity and physics output expected to continue to ramp up with next data-taking period planned to start in late 2023/early 2024



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Extra Slides

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Tau Mass Systematics

- Collision energy is slightly above kinematic threshold for $B\bar{B}$ pairs
- E_B^* computed with fully-reconstructed neutral and charged B-meson decays
- $e^+e^- \to B\bar{B}$ cross-section is:

$$\frac{d^2\sigma}{dx\, d\sqrt{s'}} = G(\sqrt{s'} - \sqrt{s}, \sigma_{\sqrt{s}})\, W(s', x)\, \sigma_0(s'(1-x))$$

$$E_B^* = \frac{1}{2}\sqrt{s'(1-x)}$$

- x is fraction of energy carried by the ISR photon
- Use simulation to computing mapping from E_B^* to $\sqrt{s}$

- Momentum scale correction for tau mass measurement performed with $D^0 \to K^-\pi^+$
- $D^\pm$ consistency check shown below