Recent tau physics at Belle II

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01 Tau leptons at B-factories

- B-factories are also τ-factories

  At $\sqrt{s} = 10.58$ GeV: $\sigma(e^+e^- \to \Upsilon(4S) \to B\bar{B}) \cong 1.1$ nb

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

- Last generation B-factories (Belle, BABAR) provided a variety of important tau physics results over the last two decades

- Tau leptons at Belle II

  500M tau-pairs at 575 fb^{-1} (current)

  34 billion at 50 ab^{-1} (goal)

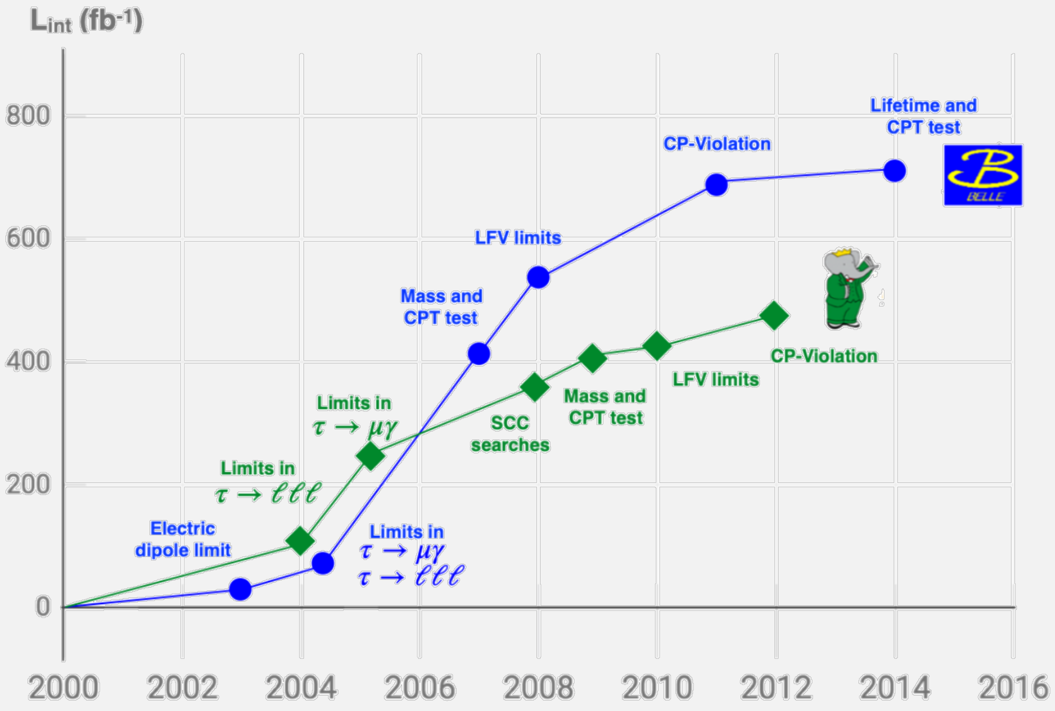
- Advantages

  Clean physics environment

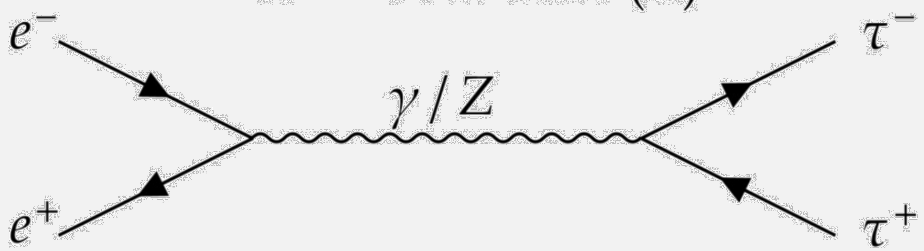
  Known initial state

  Missing energy reconstruction

  High trigger efficiency



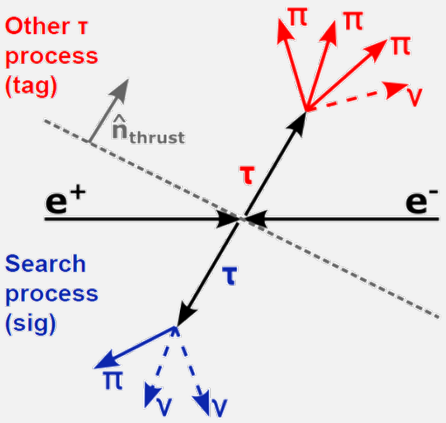
$ee \to \tau\tau$ at Belle (II)



03 Tau events reconstruction

Tau topologies and signatures

- Tau leptons in e^+e^- collisions are mostly produced in pairs, back to back, in center-of-mass system.
- At Belle II we mainly study 1×1 and 3×1-prong topologies.
- Separation into two hemispheres defined by the plane perpendicular to the thrust axis $\hat{n}_{thrtst}$.
- Use one tau to tag the event and reconstruct signal in the other hemisphere
- Even using new method: untagged



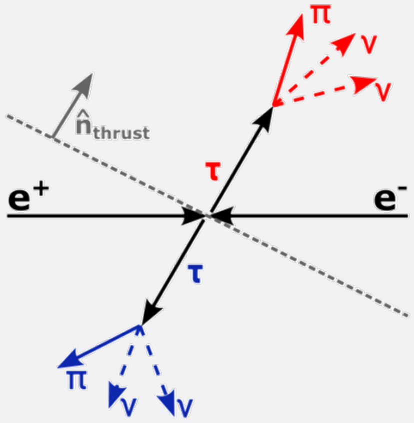
Use different topologies:

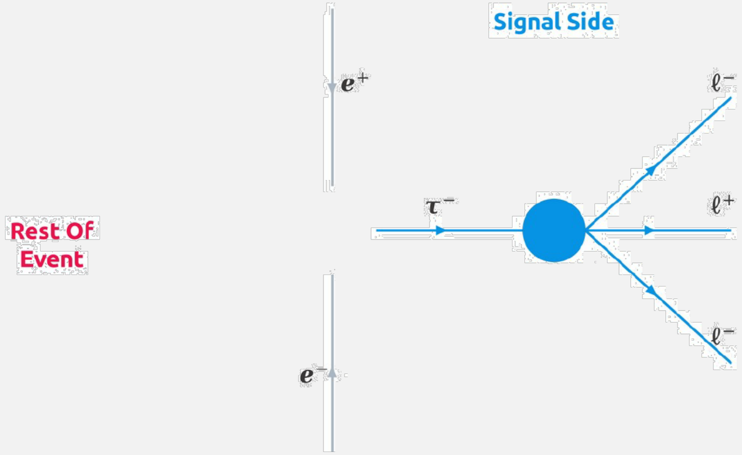
(1x3) vs (1x1)

Define best topologies for each analysis, e.g., to suppress background

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

$\hat{n}_{thrust}$, the best approximation of the τ flight direction

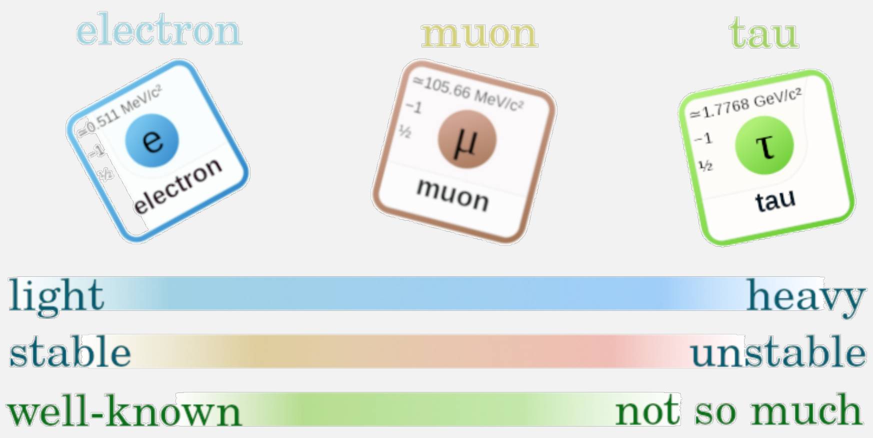




04 Tau physics program at Belle II

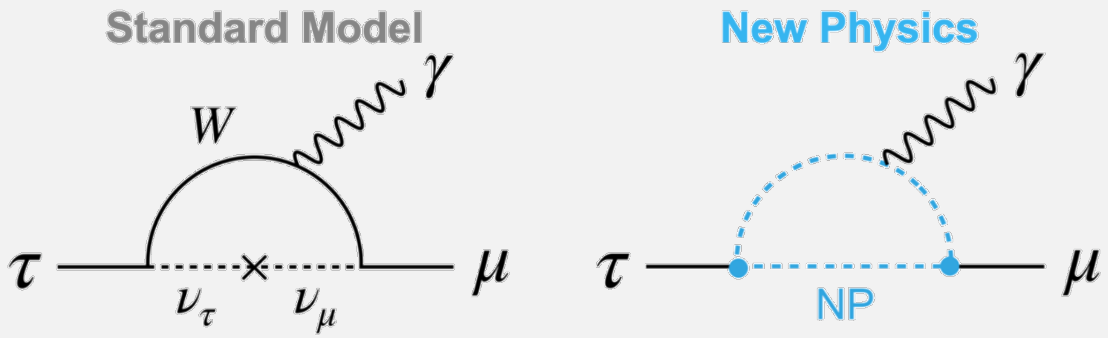
Precision SM measurements

- Tau properties are know with much worse precision compared to e and μ. (e.g. tau mass, lifetime, couplings, etc)
- Impact on the precision of SM parameters (e.g. test of LFU).



Search for rare and forbidden processes

- Lepton Flavour Violating (LFV) tau decays
  - very little to no background
- Innovative approaches to set world-leading limits
  - High reconstruction efficiency, MVA techniques, inclusive tagging

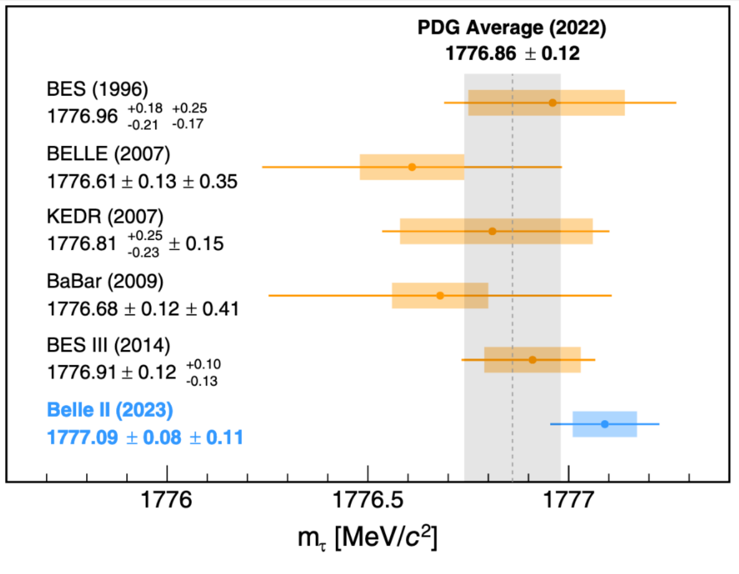


Tau mass: [PRD 108, 032006] (2023)

- 3×1-prong topology ($\tau_{\mathrm{sig}} \to 3\pi\nu$, τ_{tag} inclusive).
- Using the 190 fb^{-1} dataset collected by Belle II.
- Obtain the world's most precise measurement.

$$M_\tau = 1777.09 \pm 0.08(\mathrm{stat}) \pm 0.11(\mathrm{sys})\ \mathrm{MeV}/c^2$$

- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking.

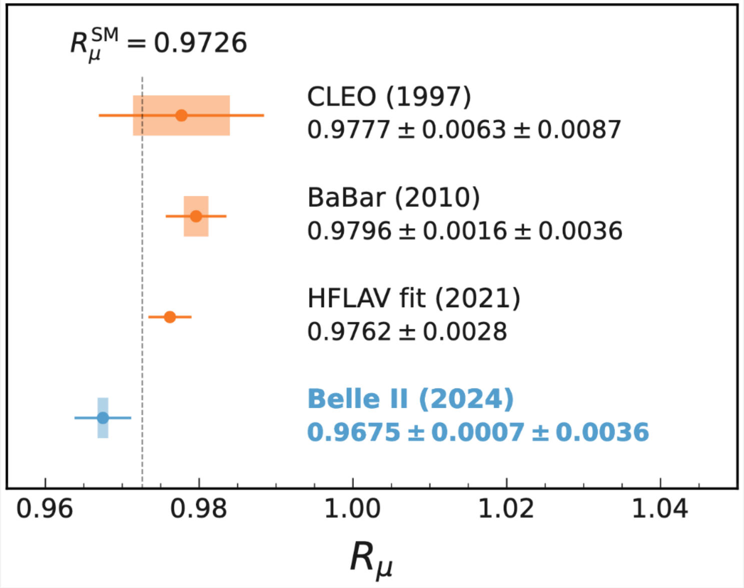


LFU test: [JHEP 2024, 205] (2024+update)

- 1×1-prong topology ($\tau_{\mathrm{sig}} \to l\nu\nu$, $\tau_{\mathrm{tag}} \to \rho\nu$).
- Using the 362 fb^{-1} dataset collected by Belle II.
- Obtain the world's most precise test of LFU in tau decays, consistent with SM at 1.4σ.

$$R_\mu = 0.9675 \pm 0.0007(\mathrm{stat}) \pm 0.0036(\mathrm{sys})$$

- Update: evaluate the R_μ using 3×1-prong events, aim at combining the 1×1 and 3×1-prong results to improve the R_μ precision even further.

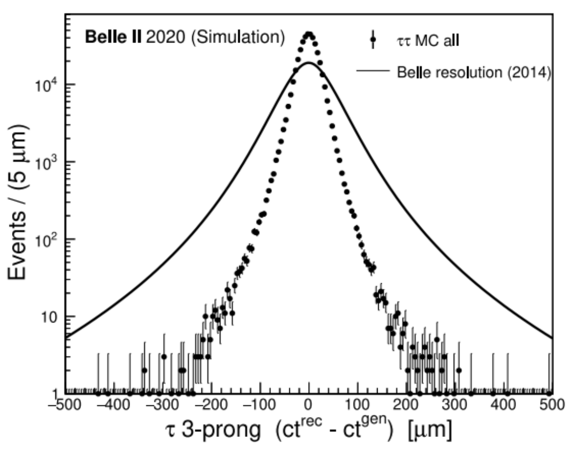


Tau lifetime: ongoing

- Measure using proper decay time relation to flight distance and momentum in lab frame.
- 3×1-prong topology ($\tau_{\text{sig}} \to 3\pi\nu$, $\tau_{\text{tag}} \to \rho\nu$).
- Reconstruct 3-prong vertex and estimate p_τ from decay produces.
- This method is possible exclusively at Belle II, due to the very high requirements for vertex detectors.
- $2 \times$ better proper decay time resolution in Belle II (Preliminary Study).

$$t = \frac{l_\tau}{\beta\gamma c} = m\frac{l_\tau}{p_\tau}$$

measure these

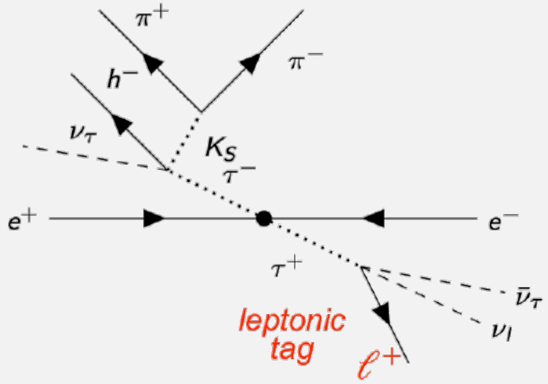


CPV test in kaon sector: ongoing

- Charge asymmetry in $\tau \to K_s\pi\nu$, CP violation in the kaon sector.

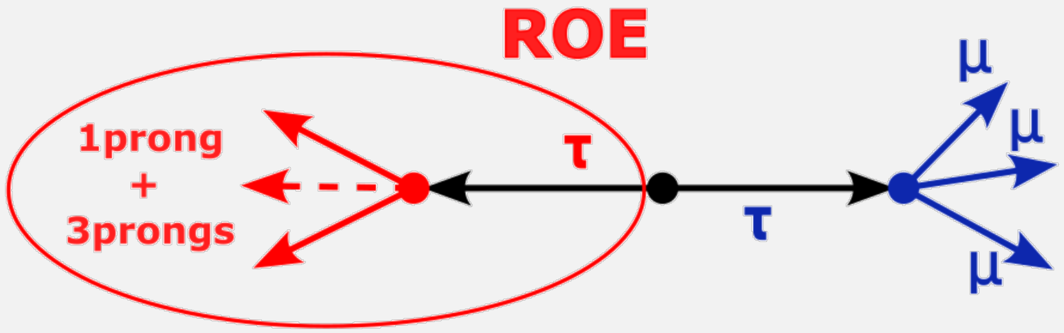
$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

- SM prediction: $A_\tau^{\text{SM}} = (3.6 \pm 0.1) \times 10^{-3}$
- Current most precise result from BaBar: $A_\tau^{\text{BaBar}} = (-0.36 \pm 0.23 \pm 0.11) \times 10^{-3}$, 2.8σ deviation from the SM.
- An improved A_τ measurement is a priority at Belle II (Stay tuned).



LFV decay $\tau \to \mu\mu\mu$: [JHEP 2024, 062]

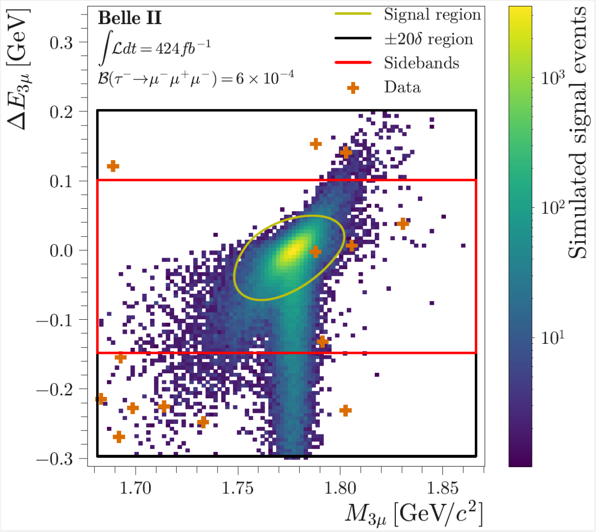
- One of the "golden channel" for LFV search using tau leptons
  - Clean channel, low SM background

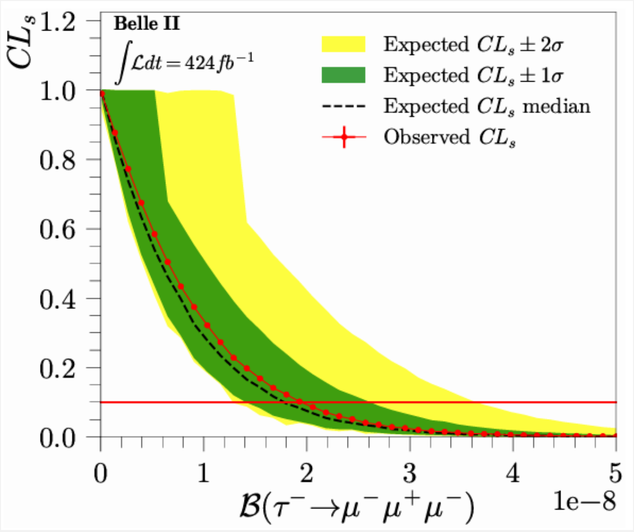


- Signal efficiency: 20.4% (2.7 × Belle)
  - untagged approach
  - Reject $ll\gamma$ and $4l$ with data-driven selection
  - BDT classifier to suppress $q\bar{q}$

- Belle II with 424 fb^{-1} could set world's best upper limit
  - 1 event observed, 0.5 bkg expected
  - No significant excess observed
  - Upper limits computed at 90% CL with CLs approach

$$\mathcal{B}^{UL}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$$

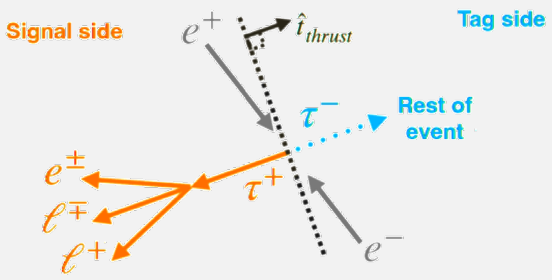


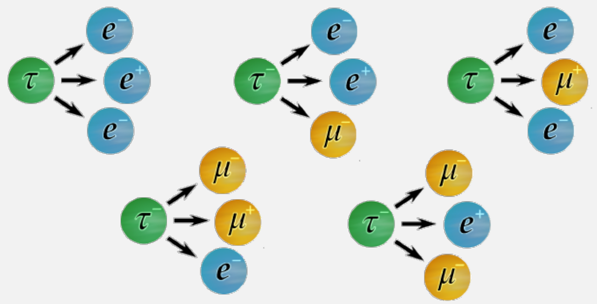


Search for forbidden decays

LFV decay $\tau \to ell$: [arXiv:2507.18236] (submitted JHEP)

- Extending the $\tau \to 3\mu$ study, Studying 5 more channels





- Higher background contamination than $\tau \to 3\mu$ channel
- Data-driven BDT classifier
  - Trained on sideband data
  - Relies on ROE & kinematic variables
  - Rejecting main $4l$ background

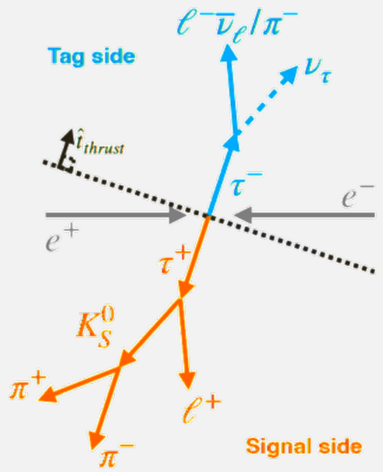
- Signal efficiency 15%~24%

- No significant excess in 428 fb^{-1} observed
  - Upper limits at 90% CL computed with CLs approach
  - world's best result

	$N_{\rm exp}$	$N_{\rm obs}$	$C_{\rm bg}$	$\mathcal{B}$ (10^{-8})	$\mathcal{B}^{UL}_{\rm exp}$ (10^{-8})	$\mathcal{B}^{UL}_{\rm obs}$ (10^{-8})
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	$-2.90^{+1.48}_{-1.54}$	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$-2.50^{+1.45}_{-1.52}$	$0.48^{+0.90}_{-0.48}$	1.6	2.4
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	$-0.34^{+1.93}_{-1.94}$	0	1.4	1.3

06 Search for forbidden decays

LFV decay $\tau \to lK_S^0$: [JHEP 2025, 092]

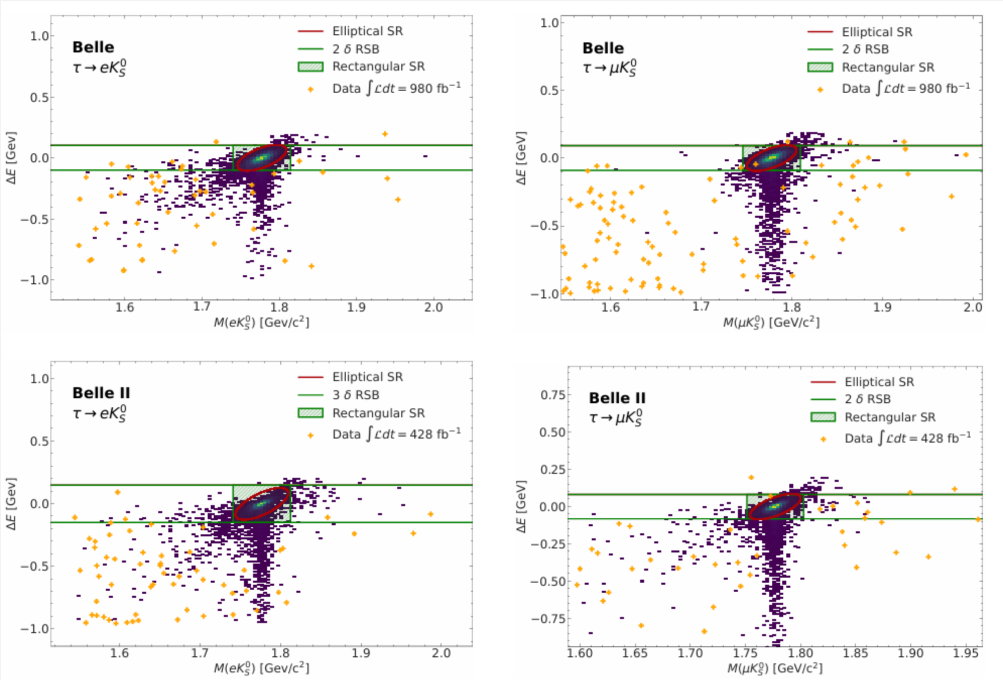


- First LFV search using the combined data set Belle + Belle II (1408 fb^{-1})
- Require 4 charged particle with 0 net charge in 3×1-prong topology
  - Signal side: reconstruct K_S^0 from $\pi^+\pi^-$
  - Tag side: $\tau \to l\bar{\nu}_l\nu_\tau / \pi\nu_\tau \;\; (l = e, \mu)$

- Signal efficiency >10%
  - Cut-based preselection
  - BDT trained using track kinematics, event shape and neutral variables

- No significant excess observed
  - Upper limits at 90% CL computed with CLs approach
  - world's best result:

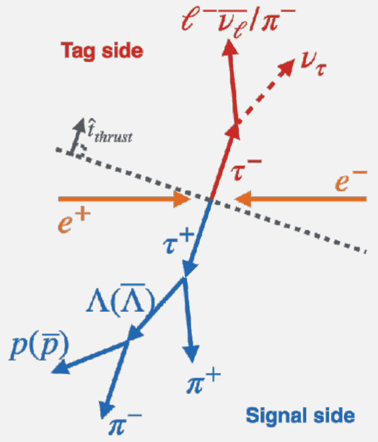
$$\mathcal{B}^{UL}(\tau \to e(\mu)K_S^0) < 0.8(1.2) \times 10^{-8}$$

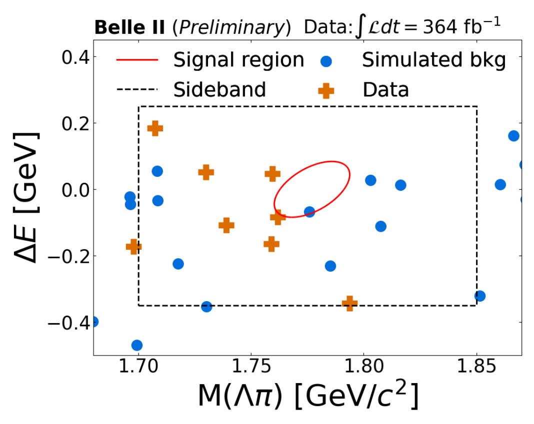


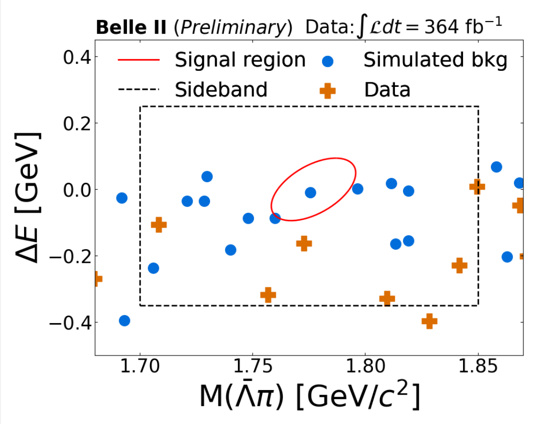
LNV and BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$: [PRD 110, 112003]

- Require 4 charged particle with 0 net charge in 3×1-prong topology
  - Signal side: reconstruct $\Lambda(\bar{\Lambda})$ from $p(\bar{p})$ and π
  - Tag side: $\tau \to l\bar{\nu}_l\nu_\tau/\pi\nu_\tau\ (l = e, \mu)$
- Signal efficiency ≈10%
  - Λ flight significance is most discriminant in background suppresion
  - BDT trained using event kinematics, event shape and extra photon informations
- Belle II with 364 fb^{-1} could set world's best upper limit
  - 0 (0) event observed, 1 (0.5) background expected
  - No significant excess observed
  - Upper limits at 90 CL computed with count approach

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





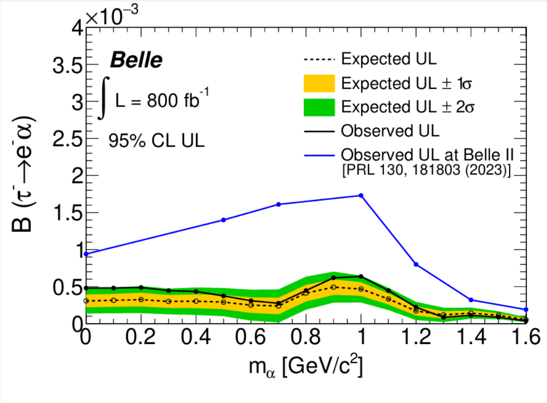


Search for forbidden decays

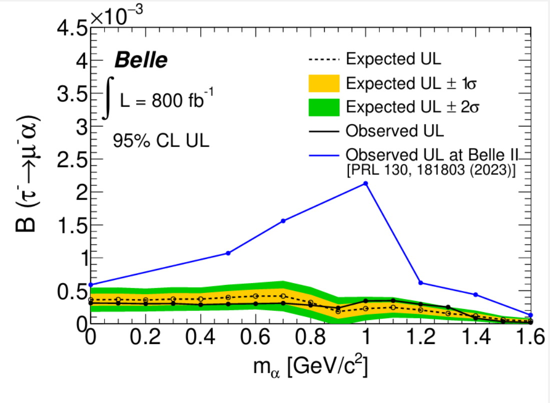
Invisible scalar boson $\tau \to l\alpha$: [PRL 130, 181803] + [JHEP 2025, 155] + update

- First paper: published by Belle II (62.8 fb^{-1})
  - No signal observed and 95% CL UL set on $\mathcal{B}(\tau^- \to \ell^- \alpha)/\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$
  - Ratio allows for partial cancellation of systematics
- Recently superseded by follow up study with Belle data (800 fb^{-1})
  - Better sensitivity in the final fits thanks to improved lepton momentum resolution

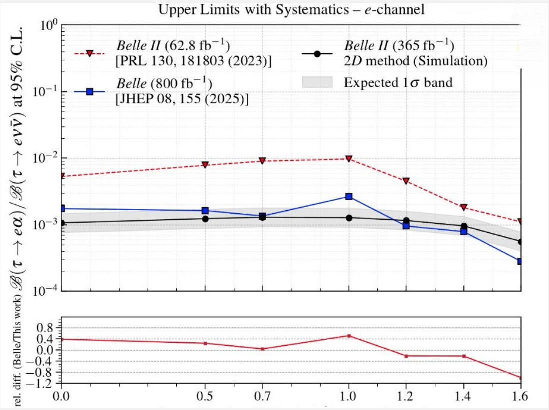
- Belle II is working on an updated analysis
  - Sensitivity studies indicate an order of magnitude improvement in UL [PRD 102, 115001]

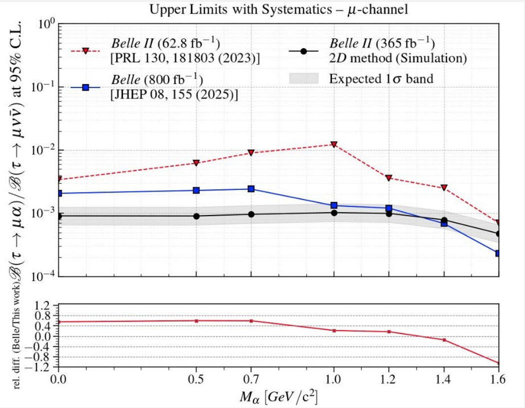


(a) $\tau^- \to e^-\alpha$.

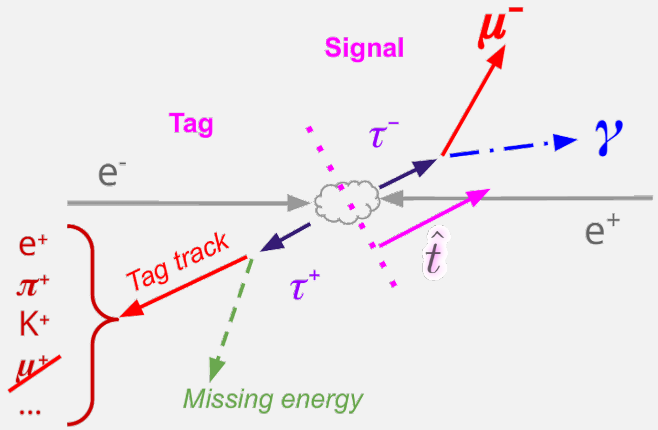


(b) $\tau^- \to \mu^-\alpha$.





LFV decay $\tau \to \mu\gamma$: To be submitted to JHEP



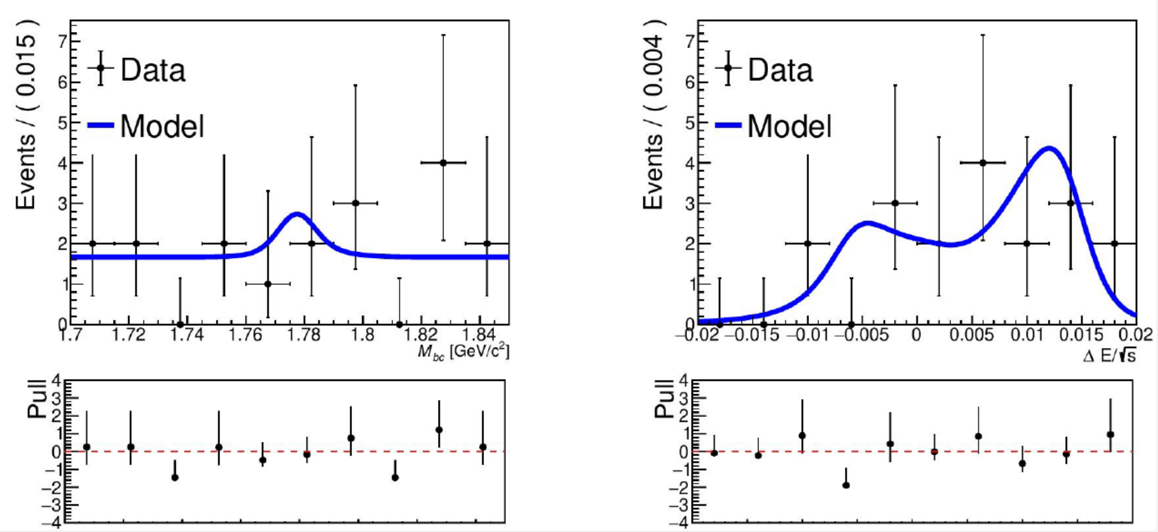
- Using 427.9 fb^{-1} data
- Require 2 charged particle with 0 net charge in 1×1-prong topology
  - Signal side: muID>0.95
  - Tag side: muID<0.1

- Signal efficiency 5.21%
  - Data-driven pre-selection
  - BDT trained using track kinematics and event shape variables

- Upper limits at 90% CL computed with CLs technique

$$\mathcal{B}(\tau \to \mu\gamma)^{exp} < 5.8 \times 10^{-8}$$

$$\mathcal{B}(\tau \to \mu\gamma)^{obs} < 9.5 \times 10^{-8}$$



07 Summary

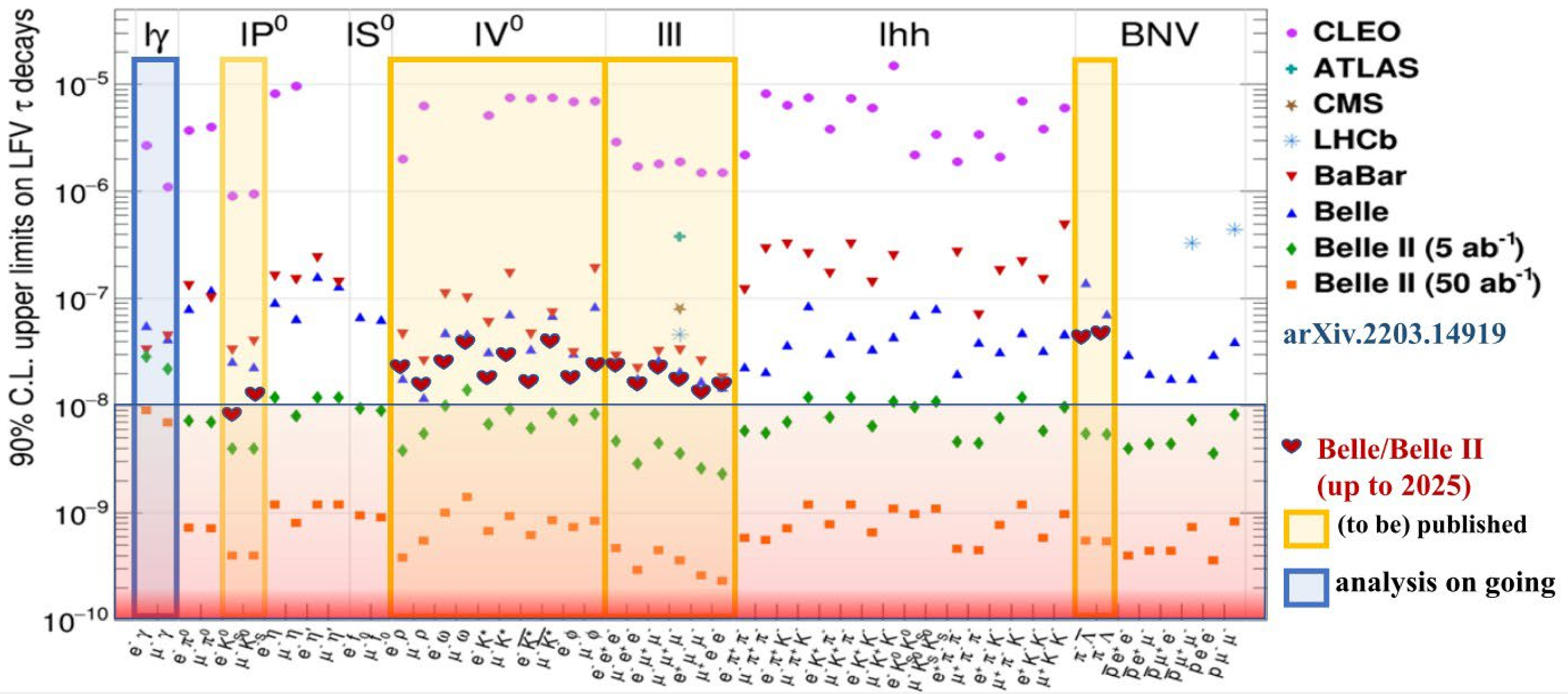
- Belle II provides a unique environment for tau physics studies, providing world's most precise measurements, as well as setting world-leading in LFV searches

- Recent highlights from precision SM measurements and forbidden decay searches:
  - **Tau mass:** [PRD 108, 032006]
  - **LFU test:** [JHEP 2024, 205]
  - $\boldsymbol{\tau \to l\alpha}$: [PRL 130, 181803] + [JHEP 2025, 155]
  - $\boldsymbol{\tau \to \mu\mu\mu}$: [JHEP 2024, 062]
  - $\boldsymbol{\tau \to e2l}$: [arXiv:2507.18236]
  - $\boldsymbol{\tau \to lK_S^0}$: [JHEP 2025, 092]
  - $\boldsymbol{\tau \to \Lambda(\bar{\Lambda})\pi}$: [PRD 110, 112003]
  - $\boldsymbol{\tau \to \mu\gamma}$: **To be submitted to JHEP**
  - And more to come!
  - Tau lifetime, CPV in kaon sector, LFU test and $\tau \to l\alpha$ search updates

- Stay tuned for more exciting tau physics results from Belle & Belle II

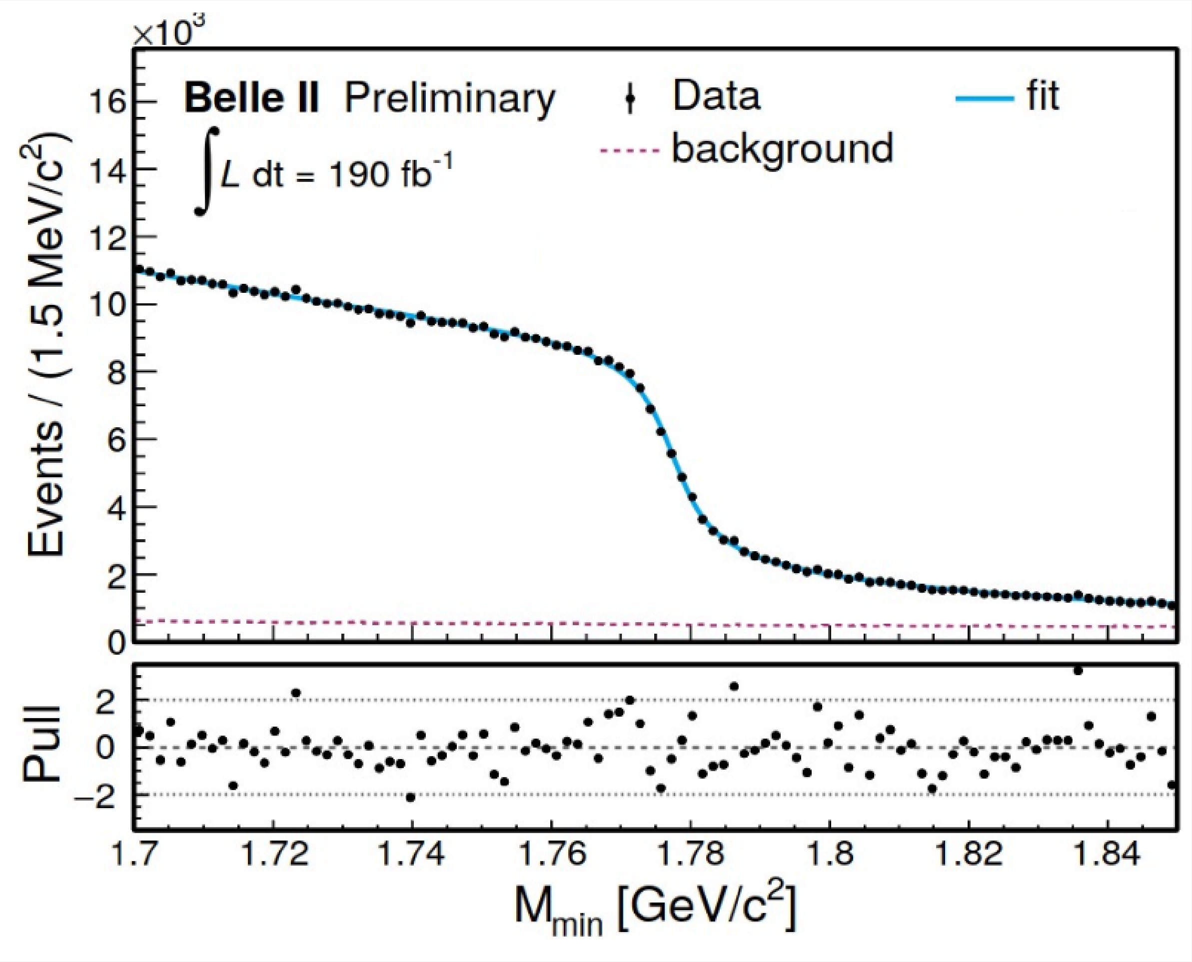
THANKS

Status of LFV search in τ sector at Belle/Belle II



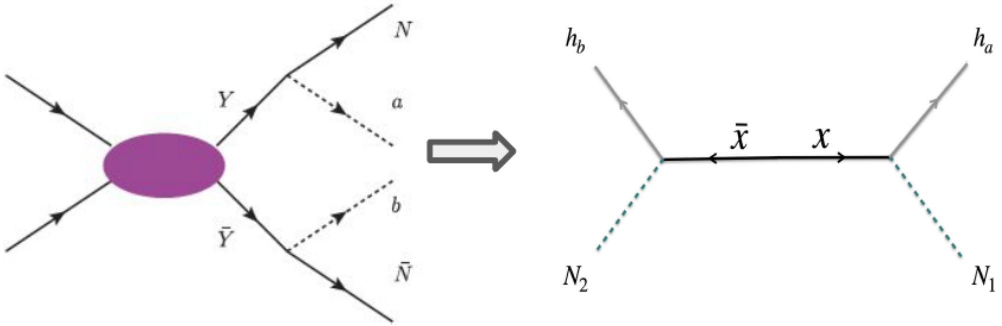
08 Back up

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



Belle II New Analysis Strategy: Increasing sensitivity

New method



$$X\overline{X} \to (h_a + N_1)(h_b + \overline{N}_2)$$

Suitable for leptonic colliders

h_a, h_b: could be a bunch of detectable particles

N_1, N_2: couple of particles that evade the detector

This generalization allows to study $X\overline{X}$ pair decays with BSM processes in one decay, and SM processes with missing particle in the complementary decay.

$$A_0(\mu_\alpha^2)^2 + B_0\mu_\alpha^2 + C_0 \leq 0,$$

$$A_0 = A_1,$$
$$B_0 = -B_1 + C_1 - (2A_1 + A_3)\mu_\tau^2,$$
$$C_0 = (A_1 + A_2 + A_3)\mu_\tau^4 + (B_1 + B_2)\mu_\tau^2 + D_1.$$

Discriminating variables

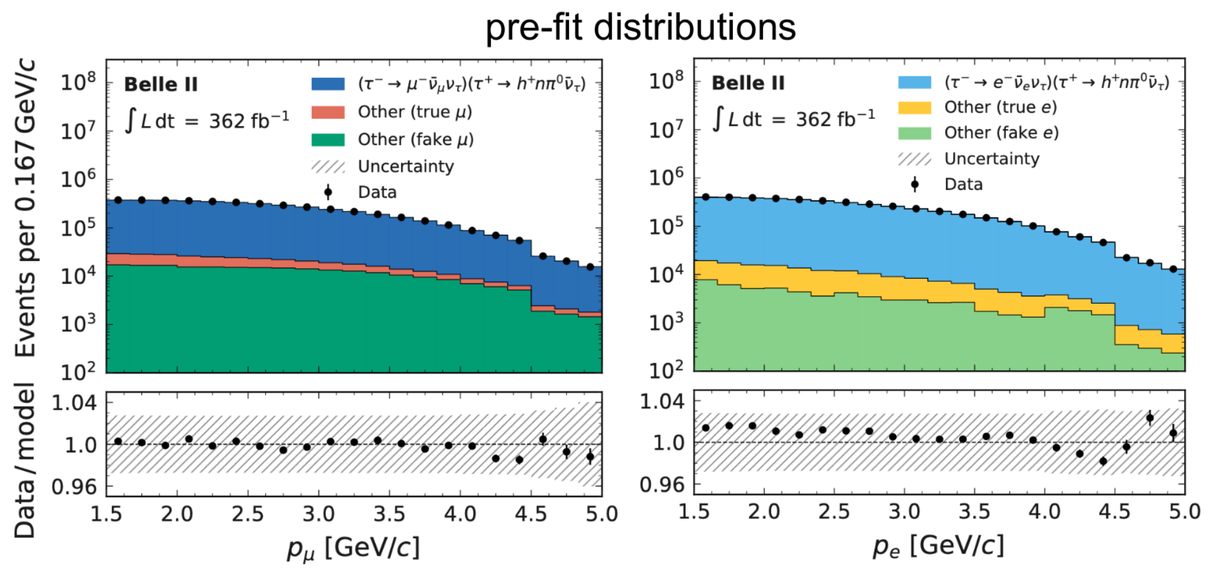
$$M_{min}^2 = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 - \sqrt{B_0^2 - 4A_0D_0}}{2A_0}\right),$$

$$M_{max}^2 = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 + \sqrt{B_0^2 - 4A_0D_0}}{2A_0}\right).$$

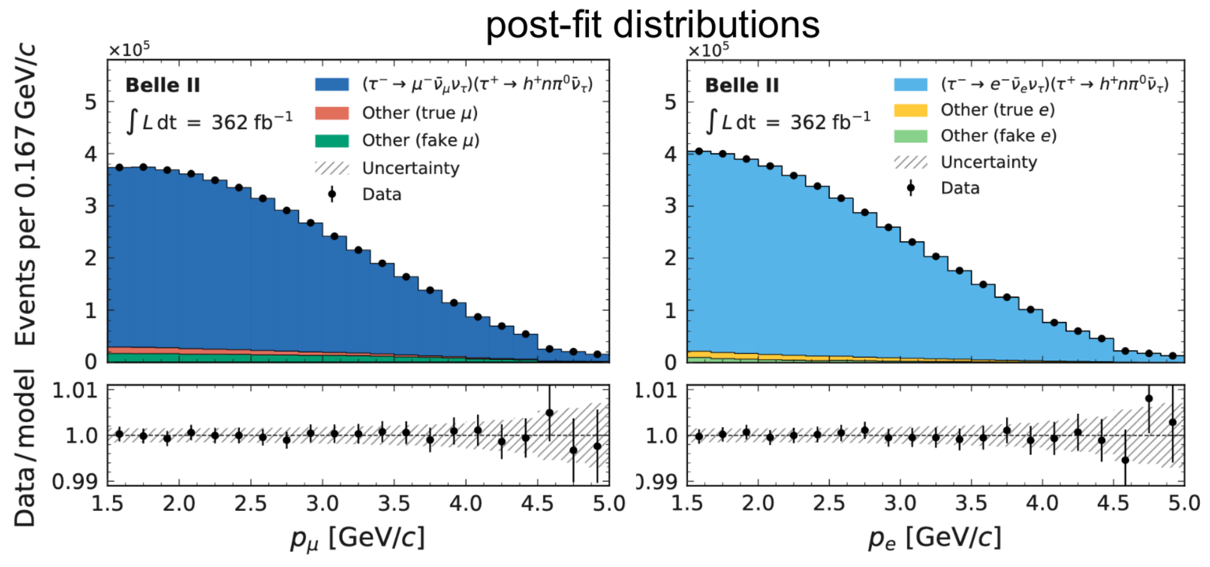
$$M_{min}^2 \leq m_\alpha^2 \leq M_{max}^2;$$

Phys. Rev. D 102, 115001

08 Back up



pre-fit distributions
Belle II
$\int L\,dt = 362\ \text{fb}^{-1}$
$(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)(\tau^+ \to h^+ n\pi^0\bar{\nu}_\tau)$
Other (true μ)
Other (fake μ)
Uncertainty
Data
Events per 0.167 GeV/c
Data / model
p_μ [GeV/c]
$(\tau^- \to e^-\bar{\nu}_e\nu_\tau)(\tau^+ \to h^+ n\pi^0\bar{\nu}_\tau)$
Other (true e)
Other (fake e)
p_e [GeV/c]



post-fit distributions
$\times 10^5$
Belle II
$\int L\,dt = 362\ \text{fb}^{-1}$
$(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)(\tau^+ \to h^+ n\pi^0\bar{\nu}_\tau)$
Other (true μ)
Other (fake μ)
Uncertainty
Data
Events per 0.167 GeV/c
Data / model
p_μ [GeV/c]
$(\tau^- \to e^-\bar{\nu}_e\nu_\tau)(\tau^+ \to h^+ n\pi^0\bar{\nu}_\tau)$
Other (true e)
Other (fake e)
p_e [GeV/c]