Tau Physics at Belle II

Chunhua Li
Nanjing Normal University
2026.07.16

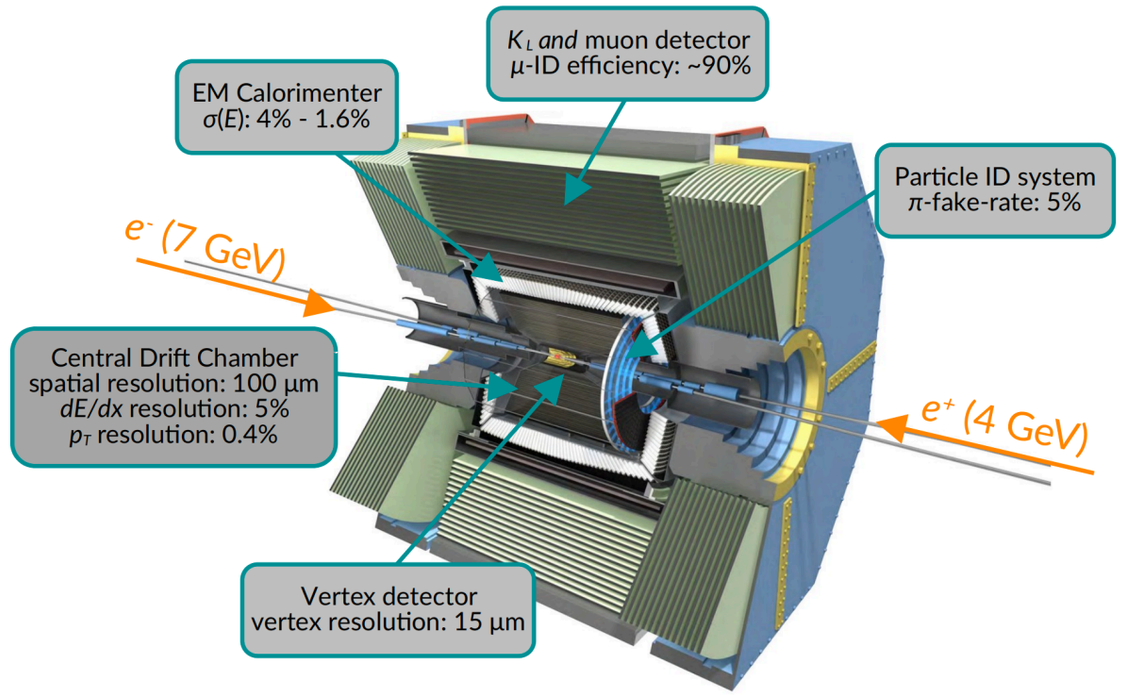
τ Physics at Belle II

Recorded Luminosity

427.8 fb^{-1} (Run1 (offline)) + 151.4 fb^{-1} (2024abc (offline)) + 338.5 fb^{-1} (2025c, 2026ab (online)) = 917.7 fb^{-1}

365 fb^{-1} **~444 fb^{-1}** **=> Tot. 809 fb^{-1} at $\Upsilon(4S)$**

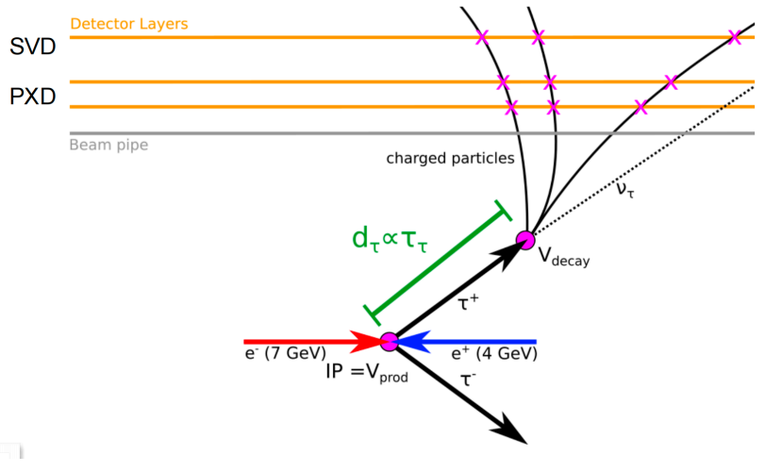
Belle 711 fb^{-1}



- σ(ee→τ⁺τ⁻)=0.92 nb @Υ(4S)
  - ≈740M τ τ pairs with 809 fb^{-1}
  - ≈4600M τ τ pairs with 5 ab^{-1}

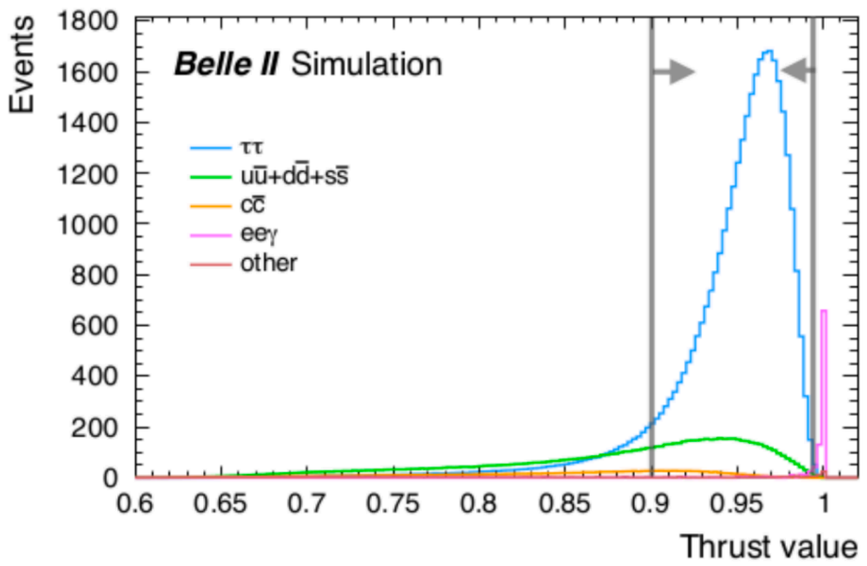
  →Precision τ measurements

- Belle → Belle II
  - PXD+SVD vertex detectors → better vertex resolution
  - better PID system
  - dedicated low multiplicity triggers → significantly improved trigger efficiency and enable new measurements

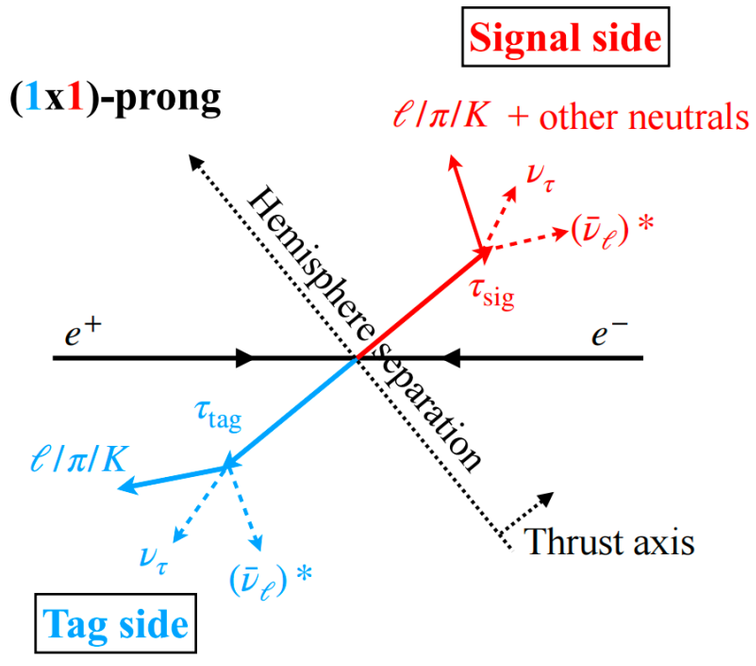


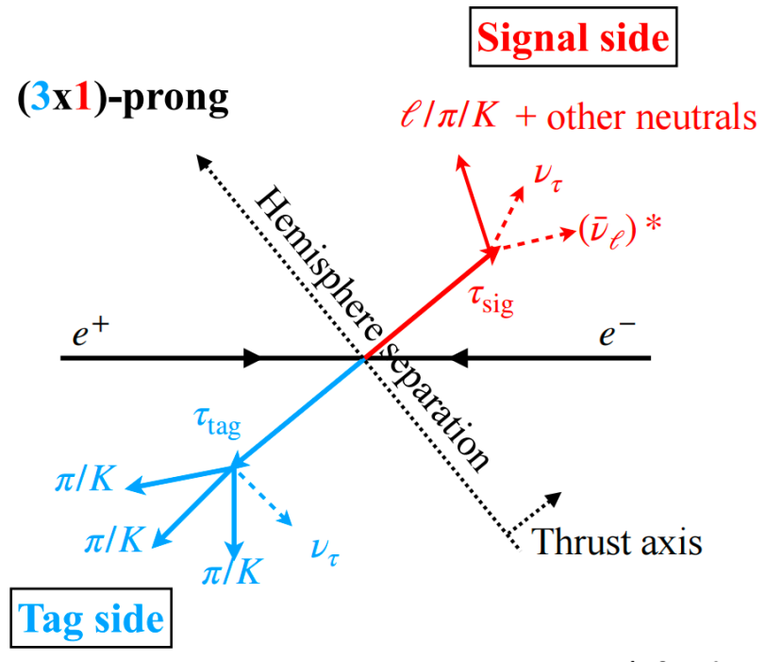
τ Reconstruction at Belle II

- decays mostly into one (1-prong) or three (3-prong) charged particles with at least two neutrinos in the final states
- separate ττ signals from qqbar (q= u,d,s,c,b) and other events by the **thrust** (T) axis



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





τ Physics at Belle II

- Precision measurements
  - τ mass *[PRD 108,032006(2023)]*, *new measurement in progress*
  - τ lifetime, *internal review*

  - μ-e lepton flavor university test, *[JHEP 08, 205(2024)]*
  - Branching fractions and spectral functions of hadronic decays, many in progress
  - $|V_{us}|$ inclusive/exclusive measurements, in progress

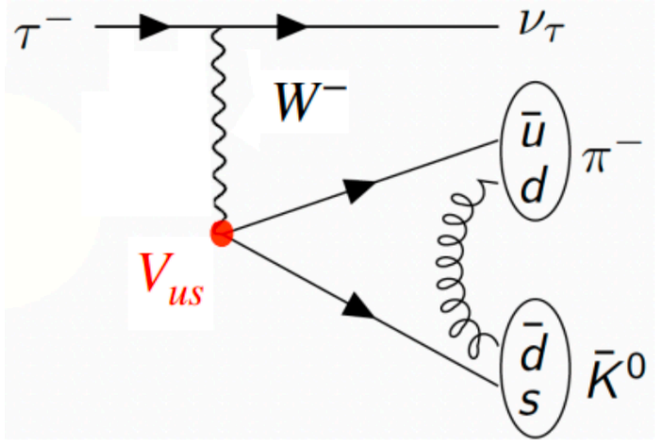
- New physics
  - Lepton flavor violation: many publications, many in progress
  - CP violation, in progress

Search for CPV in $\tau^- \to \pi^- K_S \nu (\geq 0\pi^0)$ decays

preliminary

- no CPV in the charged lepton sectors in SM
- τ decays involving a K_s in the final state exhibit a non-zero decay-rate asymmetry originate from CP violation in the neutral kaon sector
- Search for CPV in $\tau^- \to \pi^- K_S \nu (\geq 0\pi^0)$ decays

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



- SM predicts $A_{CP} \sim (0.33 \pm 0.01)\%$
- any significant deviation from the SM expectation could indicate the new physics
- previous measurements

Belle
PRL 107, 131801 (2011)
No significant CPV

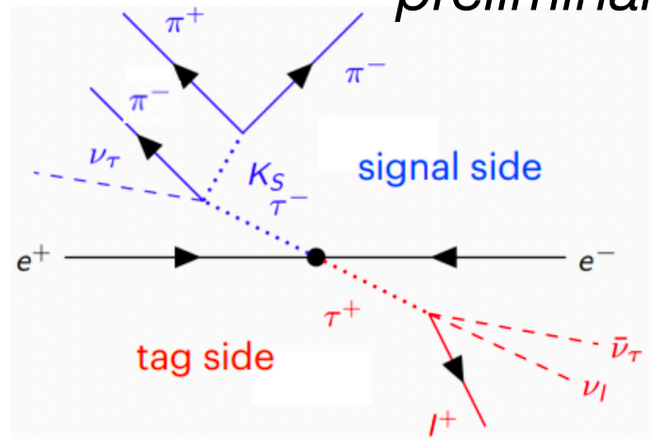
Babar
PRD 85, 031102(R) (2012)
Acp =(-0.36±0.23(stat)±0.11(syst))%
2.8σ deviation from SM

Search for CPV in $\tau^- \to \pi^- K_S \nu (\geq 0\pi^0)$ decays

preliminary

Analysis strategy

- (3x1)-prong topology: leptonic tag
- two-steps BDT to suppress qqbar and tau backgrounds
- >98% of signal purity



- raw asymmetry in data $A_{raw} \rightarrow A_{CP}$

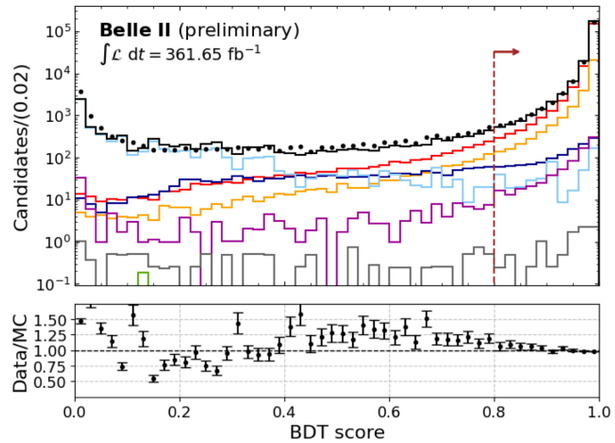
$$A_{\text{raw}} = A_{\text{D(det/trig/FB)}} + A_{\text{abs/int}} + A_{\text{CP}}$$

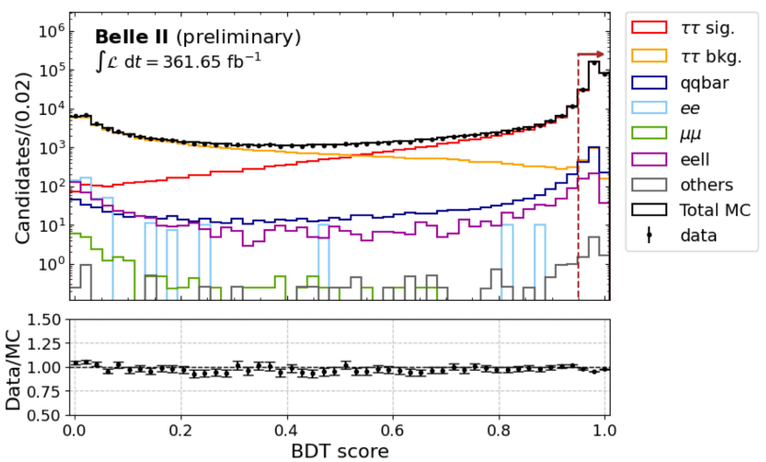
What we measure

Detection, trigger, and forward-backward production asymmetries. **Estimated using the $\tau \to 3\pi\nu_\tau$ control sample**

Absorption due to different $K^0/\bar{K}^0$ cross sections in the detector materials; Interference between absorption and CP mixing. Estimated using numerical calculation*

The goal of this work

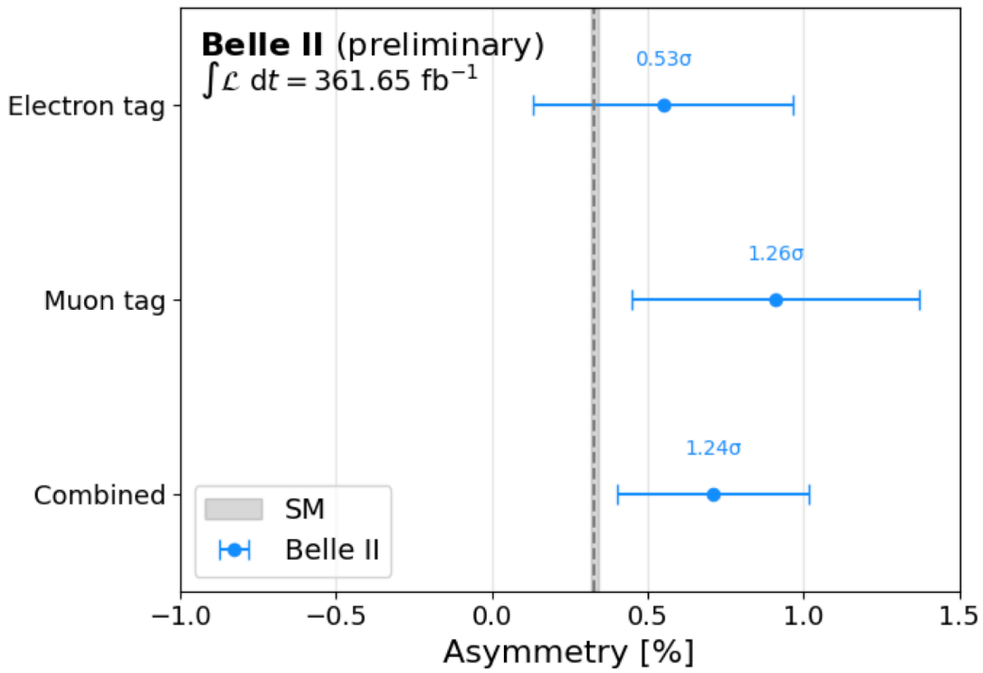




Search for CPV in $\tau^- \to \pi^- K_S \nu (\geq 0\pi^0)$ decays

preliminary

- results



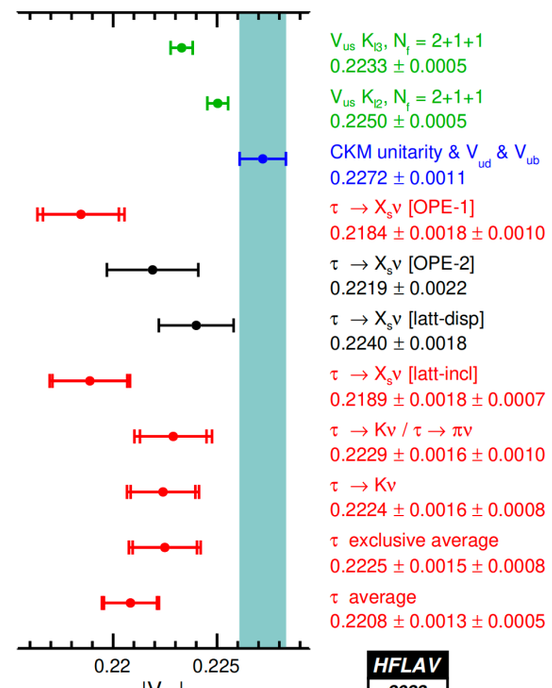
$$A_{CP}^{BelleII} = 0.71 \pm 0.26(\text{stat}) \pm 0.06(\text{syst}) \pm 0.15(\text{unf})$$

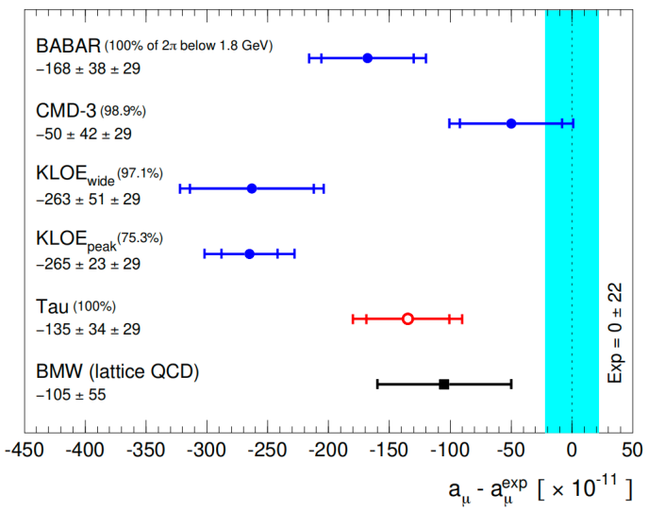
Measurement statistically limited, consistent with SM expectation within 1.24σ

- future measurement with larger data samples will improve both statistical and systematic precision

Precision measurement of τ hadronic decays

- Precision measurements of τ hadronic decays BF and spectral functions (SF) provide important input for $|V_{us}|$ and a_μ^{had}
- Measurements of $|V_{us}|$
  - Discrepancies between CKM unitarity prediction and τ decays
    - inclusive determination 3.7σ lower
    - exclusive determination 2.0σ lower
  - the first $|V_{us}|$ measurement via inclusive τ decay is in progress
- a_μ^{had}
  - τ→2π,4π as independent inputs via conserved vector current relations
- Systematics are challenging



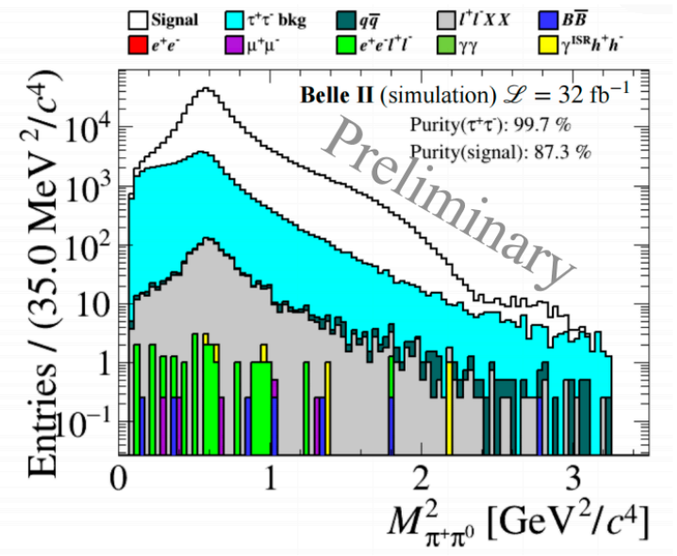


DHLMZ 2023

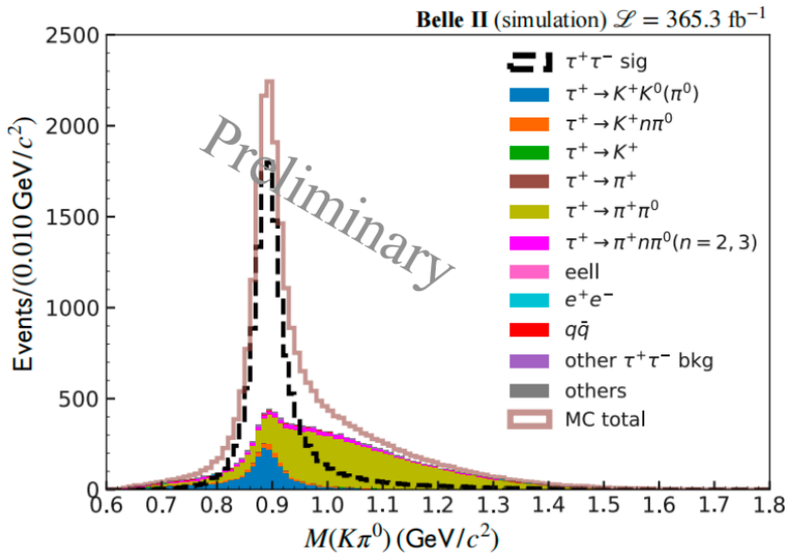
Precision measurement of τ hadronic decays

preliminary

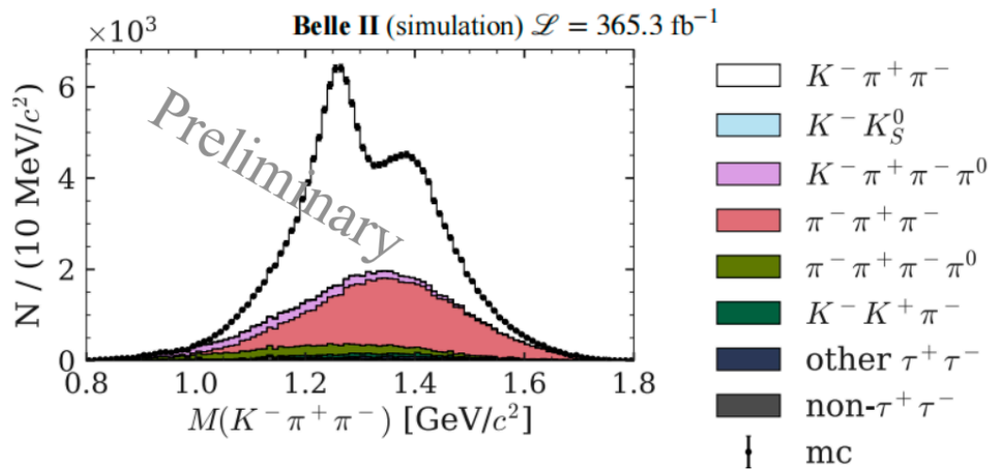
$\tau^- \to \pi^-\pi^0\nu_\tau$

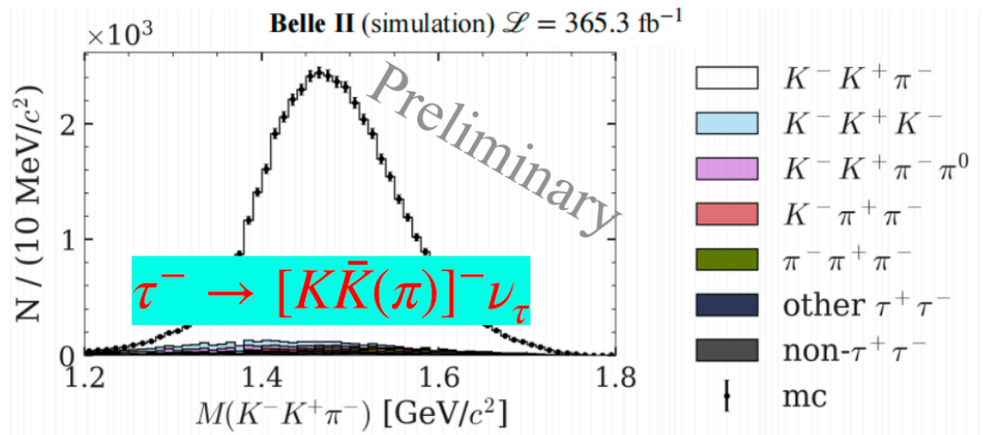


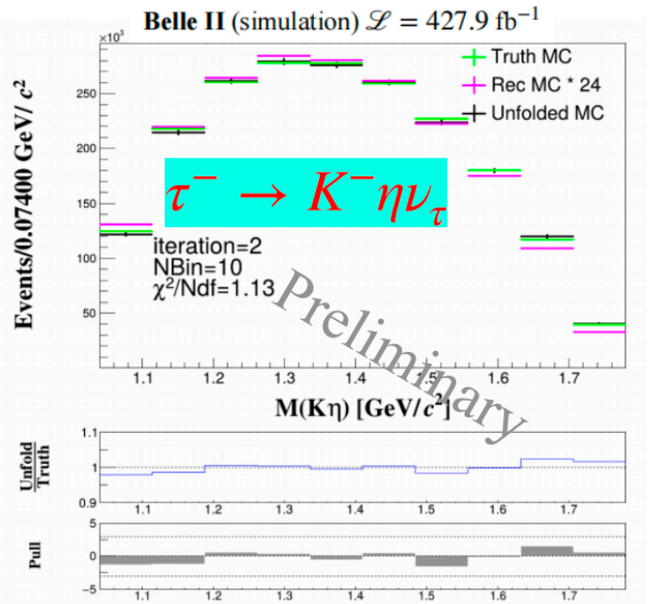
$\tau^- \to K^-\pi^0\nu_\tau$

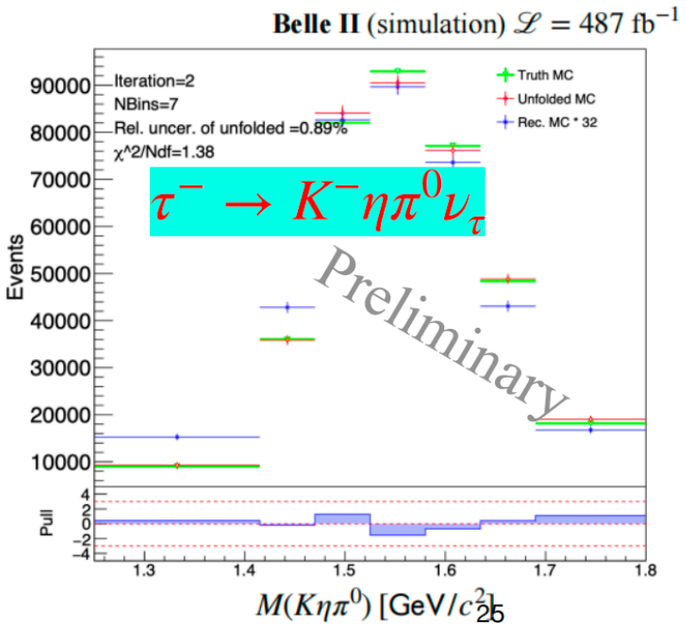


$\tau^- \to K^-\pi^+\pi^-\nu_\tau$





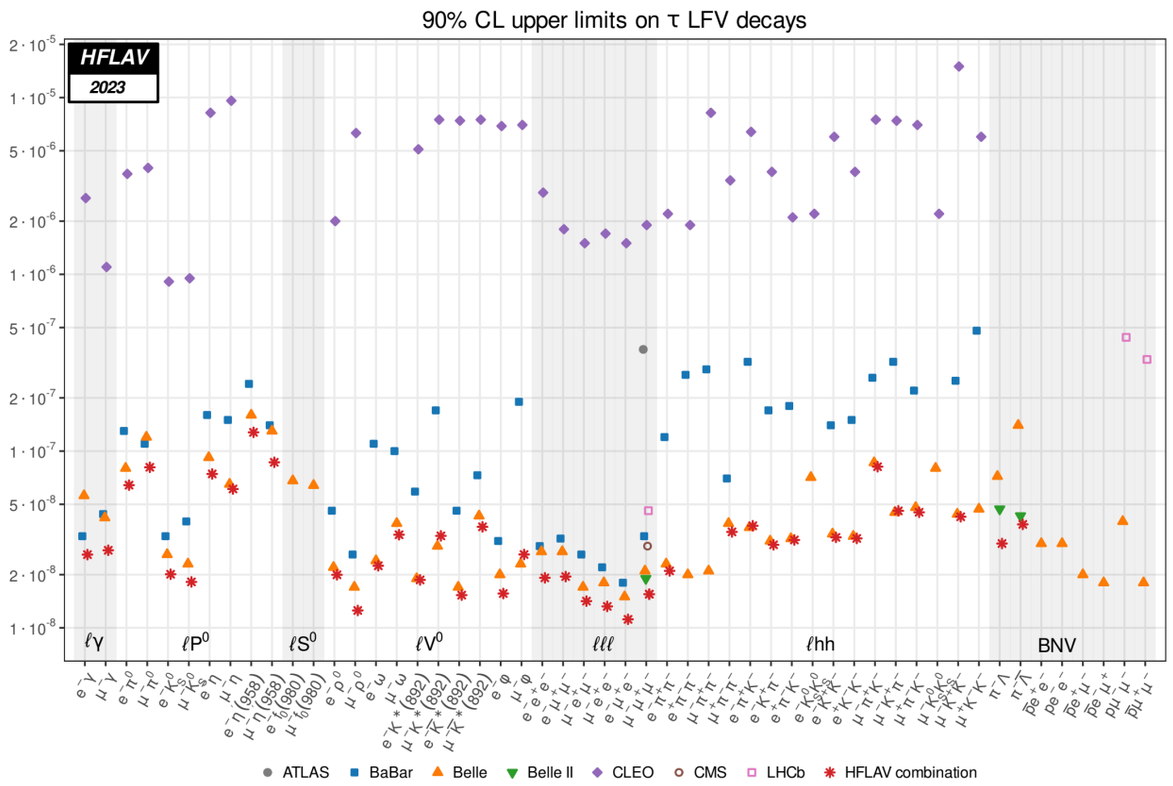




- Many ongoing studies
- Here, **Preliminary with MC samples**
- Measure BF with $\mathscr{B}_x/\mathscr{B}_{\tau\to\ell}$ ratio
- Measure SF with unfolding

Search for LFV in τ decays

- The branching fractions of LFV τ decays are extremely small ($<10^{-50}$) in SM
- SM extensions
  - supersymmetric models, supersymmetric models with a see-saw mechanism, grand unified theories, the Littlest Higgs models……
  - predicate LFV τ decay rates at 10^{-10}-10^{-8}
- Search for LFV τ decays
  - radiative decays: $\tau \to \ell\gamma$
  - leptonic decays: $\tau \to \ell_\alpha \ell_\beta \ell_\beta$。
  - semileptonic decays： $\tau \to \ell(P_0,S_0,V_0)$, $P_0=\pi^0$, η, η’, $S_0=f_0(980)$, $V_0=\rho^0$, K*(892), ϕ, ω



Search for LFV in τ decays

- radiative decay $\tau^- \to \mu\gamma$
  - Belle, Babar, CLEO all made search for this decay
  - most stringent upper limit at 90% C.L. by Belle with 988 fb^{-1} *[JHEP 10 (2021) 19]*

    $\mathcal{B}(\tau^- \to \mu^-\gamma) < 4.2 \times 10^{-8}$

Channel	$\mathcal{O}(\mathcal{B}_{\text{pred}})$	Model
$\tau^- \to \mu^-\gamma$	10^{-10}	SUSY Higgs [1]
	10^{-10}	Littlest Higgs [2]
	10^{-9}	SM + seesaw [3]
	10^{-9}	Non-universal Z' [4]
	10^{-8}	SUSY SO(10) [5]
$\tau^- \to \ell\eta$	10^{-8}	Littlest Higgs [6]
	10^{-8}	Leptoquark [7]
	10^{-8}	type-III seesaw [8]

- $\tau \to \ell\eta$
  - best limit at 90% by Belle with 401 fb^{-1} *[PLB 648, 341 (2007)]*

    $\mathcal{B}(\tau \to e\eta) < 9.2 \times 10^{-8}$
    $\mathcal{B}(\tau \to \mu\eta) < 6.5 \times 10^{-8}$

Search for LFV in $\tau^- \to \mu\gamma$ decays

preliminary

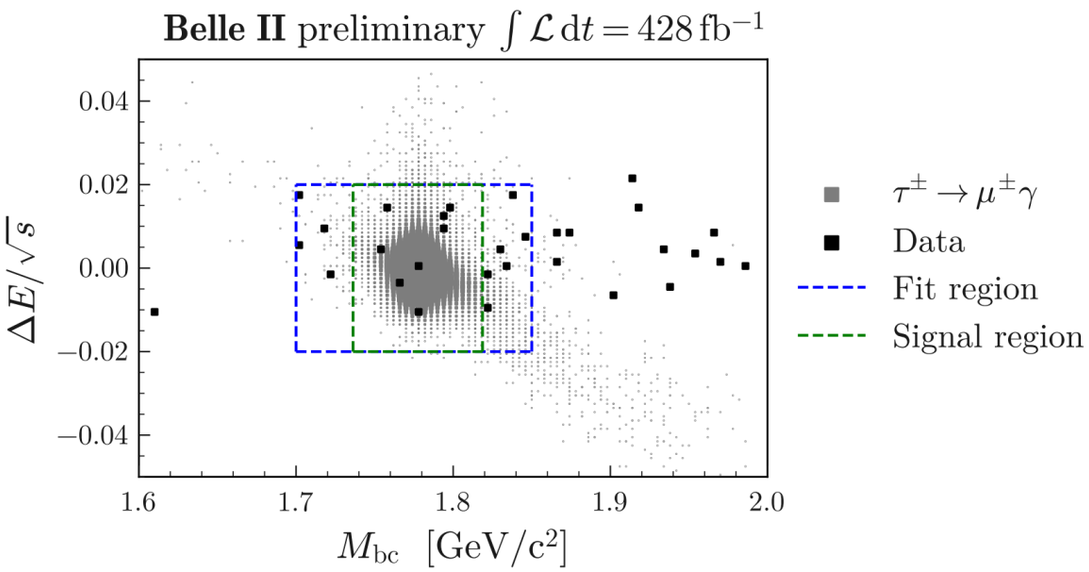
- Make the search with 428 fb^{-1} data
- 1x1 prong topology, tag: $\tau^- \to e^- \nu\nu$, $\pi^- \nu$,$\pi^- \pi^0 \nu$
- Fit to 2D plane (M_{bc}, ΔE)

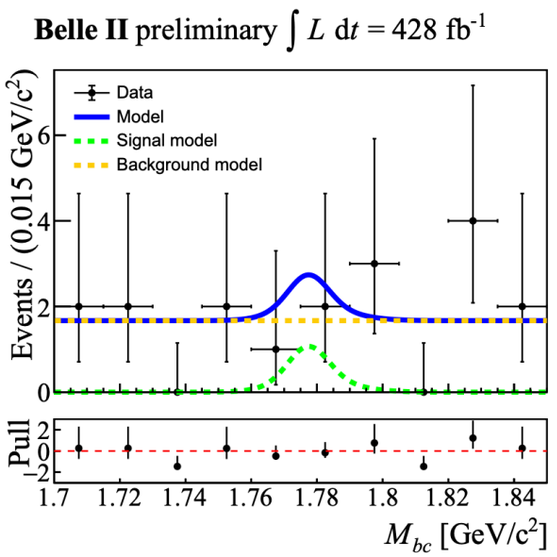
$$M_{bc} = \sqrt{(E^*_{\text{beam}})^2 - (\vec{p}^*_{\mu\gamma})^2}$$

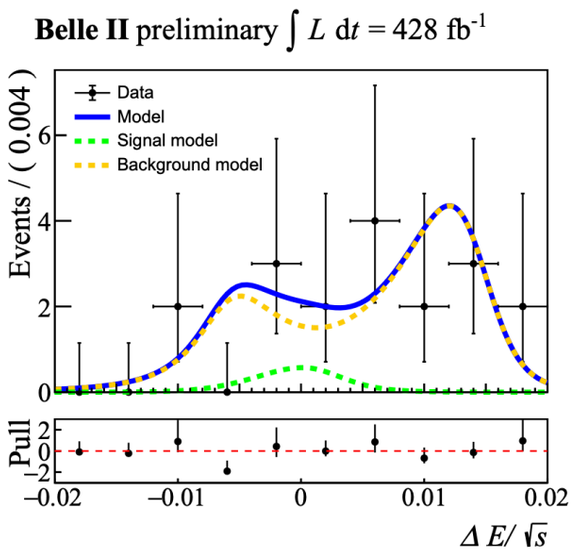
$$\Delta E' = \frac{\Delta E}{\sqrt{s}} = \frac{E^*_{\mu\gamma} - E^*_{\text{beam}}}{\sqrt{s}}$$

$$\mathcal{B}(\tau^- \to \mu^- \gamma)^{\text{obs}} < 9.5\ (12.2) \times 10^{-8}$$

at 90% (95%) C.L.







Search for LFV in $\tau \to \ell\eta$ decays

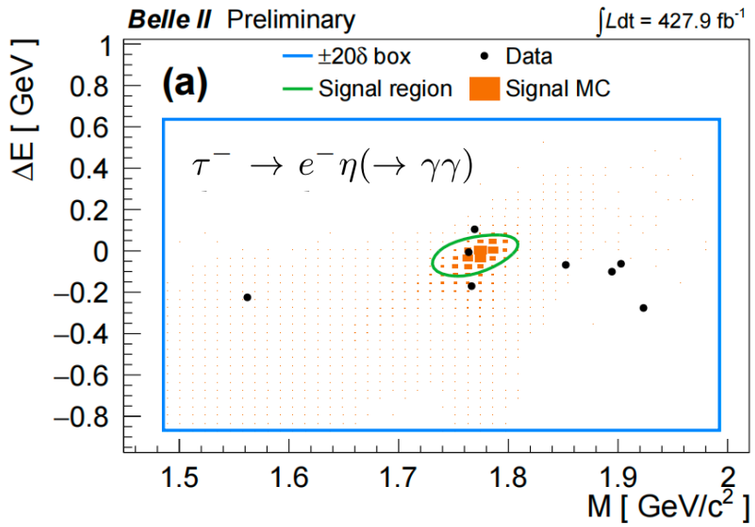
preliminary

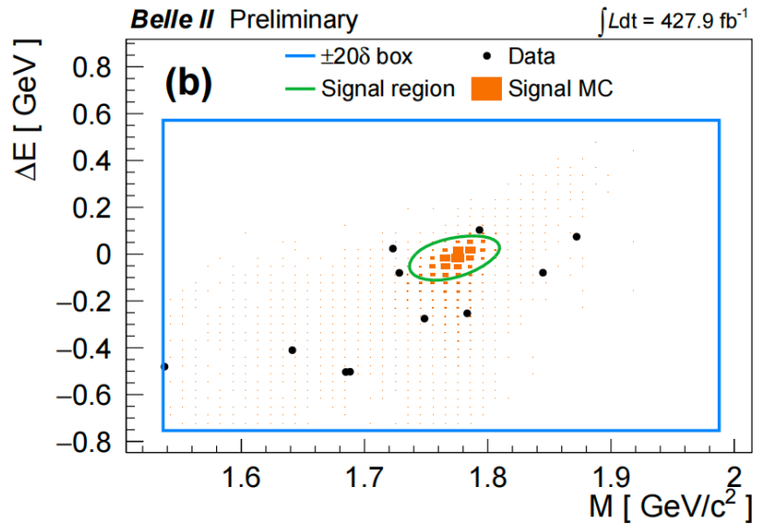
- Make the search with 428 fb^{-1} data
- 1x1 prong topology, tag: $\tau^- \to \pi^- \nu, \pi^- \pi^0 \nu$

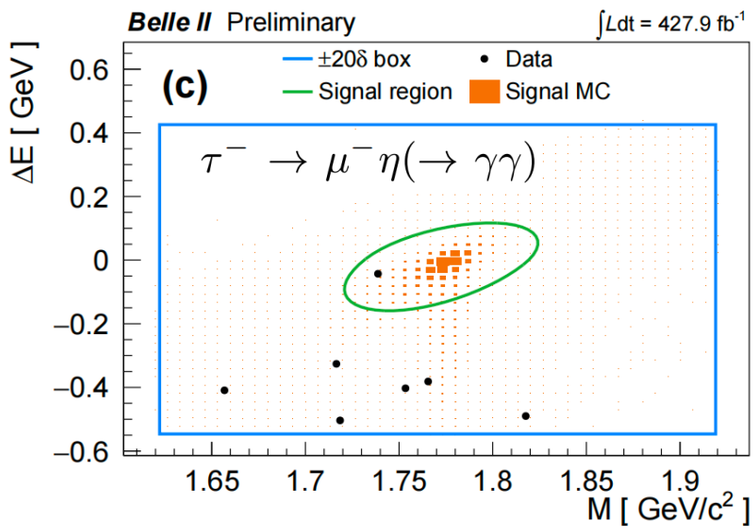
$$\mathcal{B}(\tau^- \to e^- \eta) < 9.21 \times 10^{-8}$$

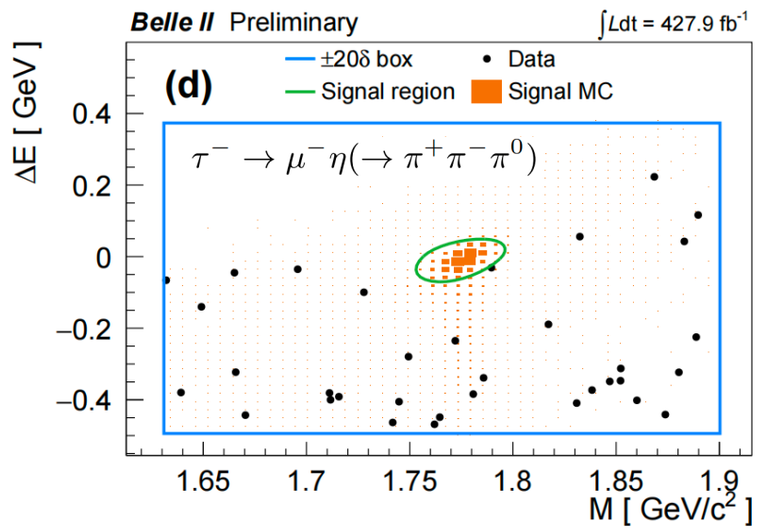
$$\mathcal{B}(\tau^- \to \mu^- \eta) < 4.23 \times 10^{-8}$$

at 90% C.L.





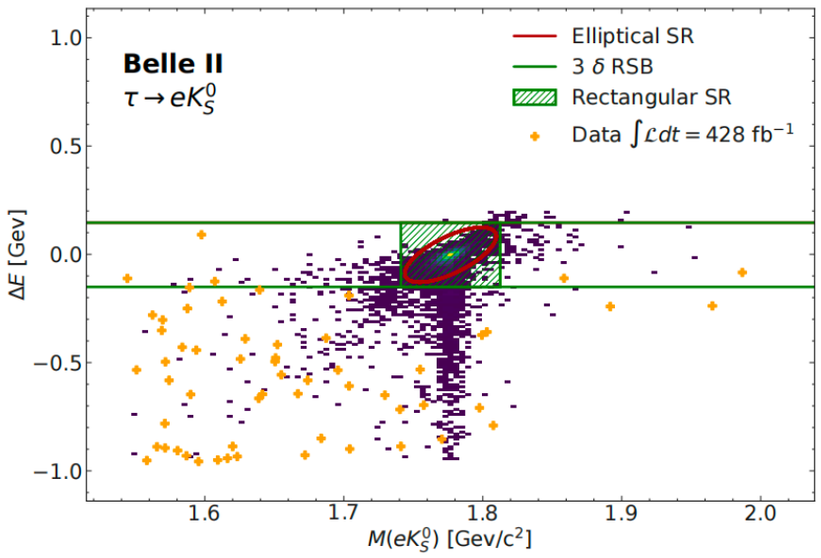


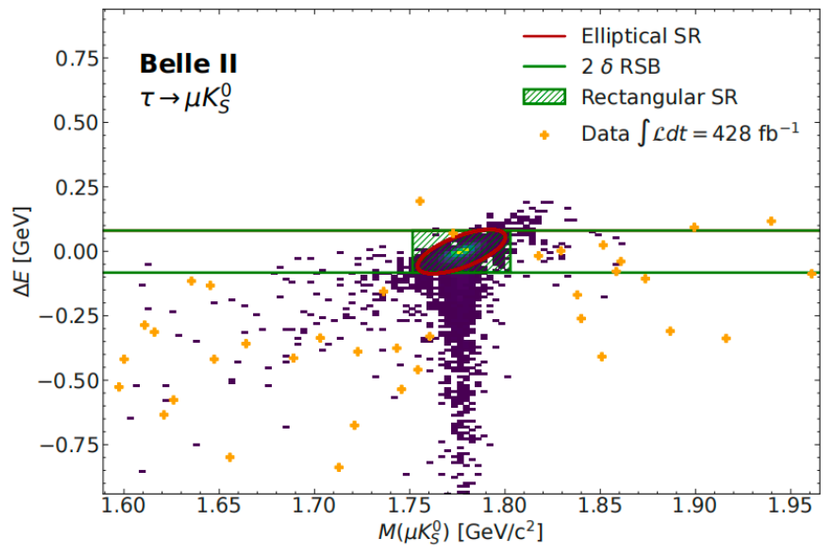


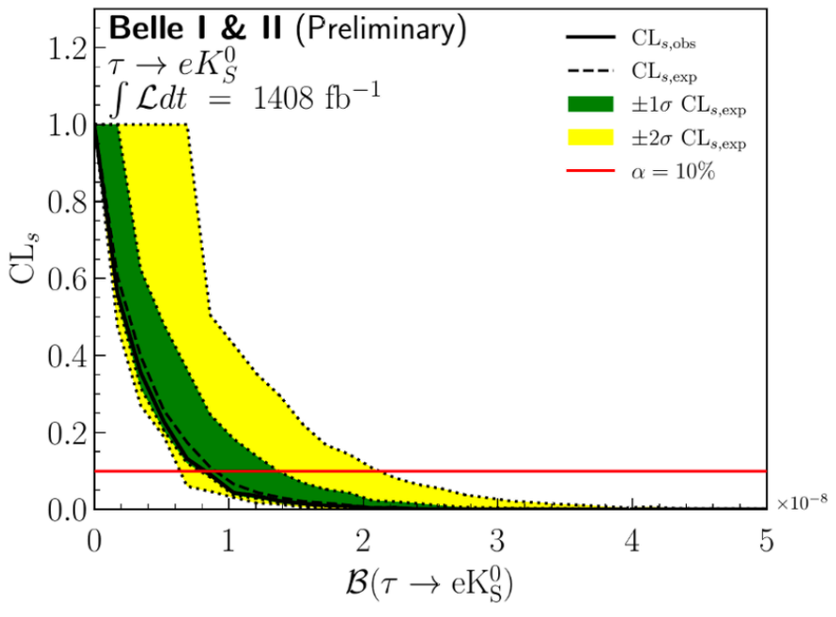
Search for LFV in $\tau \to \ell K_S$ decays

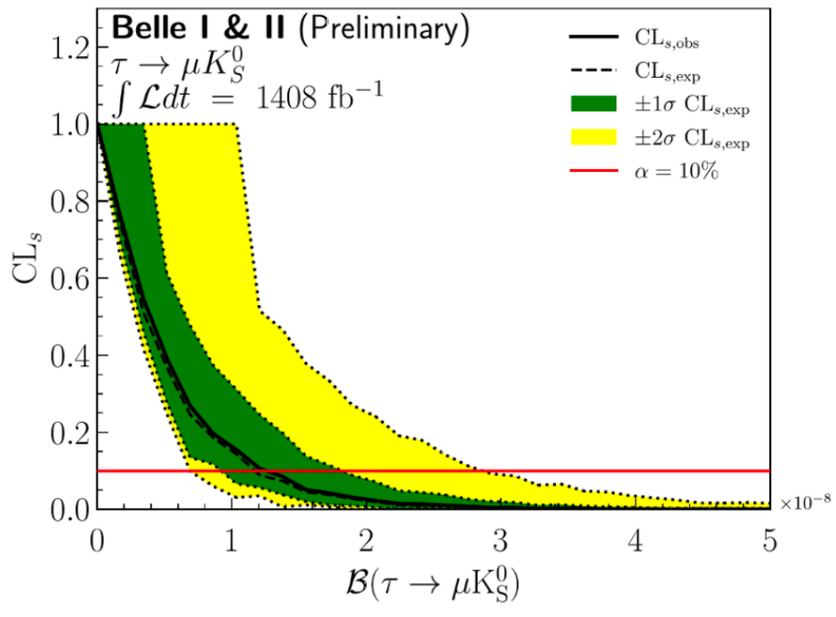
JHEP08 (2025) 092

- Belle 980fb^{-1} + Belle II 428 fb^{-1} data
- 1x1 prong topology, tag: $\tau^- \to \pi^- \nu, \pi^- \pi^0 \nu, \ell \nu$







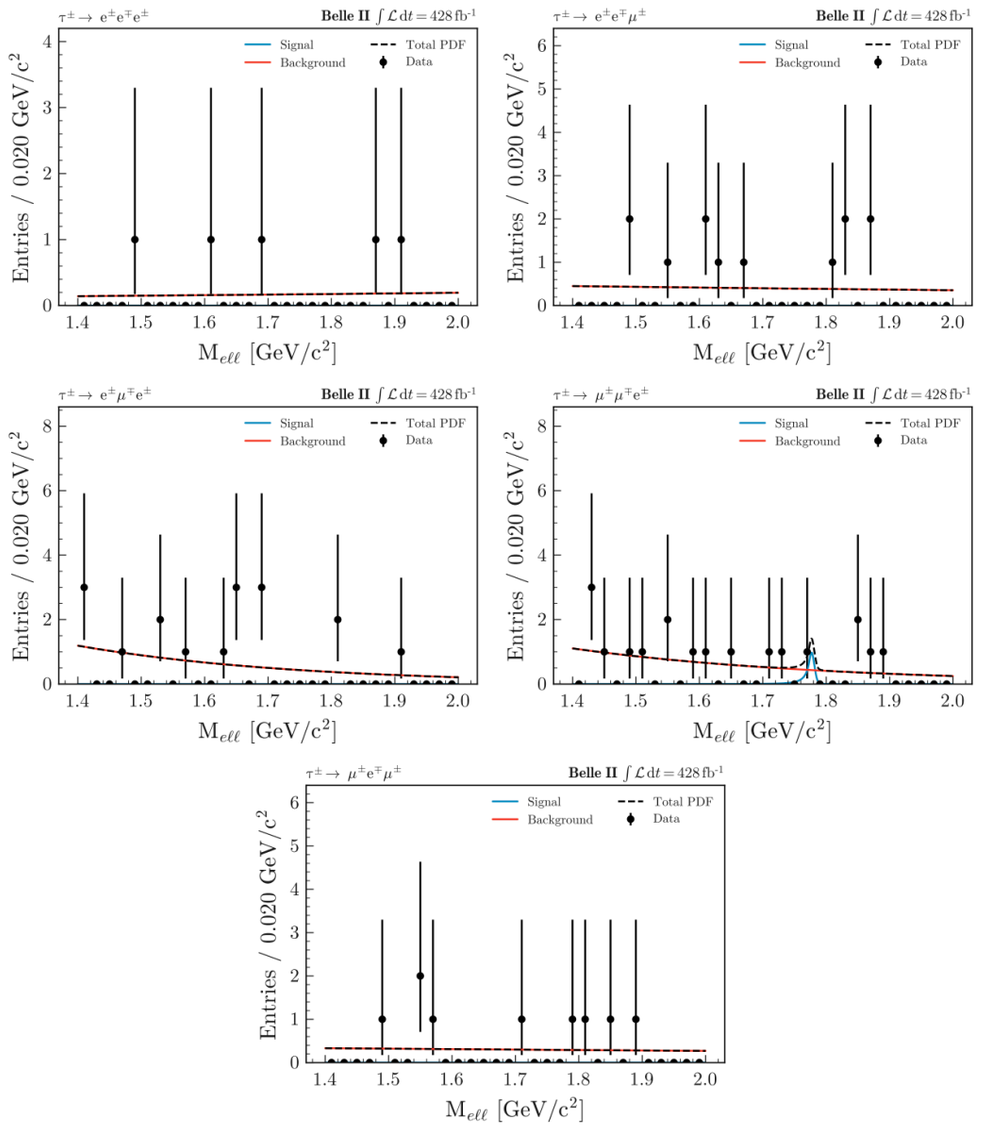


Search for LFV in $\tau \to e\ell\ell$ decays

JHEP12 (2025) 169

- Belle II 428 fb^{-1} data
- Inclusive tag reconstruction

	$N_{\rm exp}$	$N_{\rm obs}$	$\mathcal{B}$ (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	2.7	2.5
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	0	2.1	1.6
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$0.48^{+0.90}_{-0.48}$	1.6	2.4
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	0	1.4	1.3

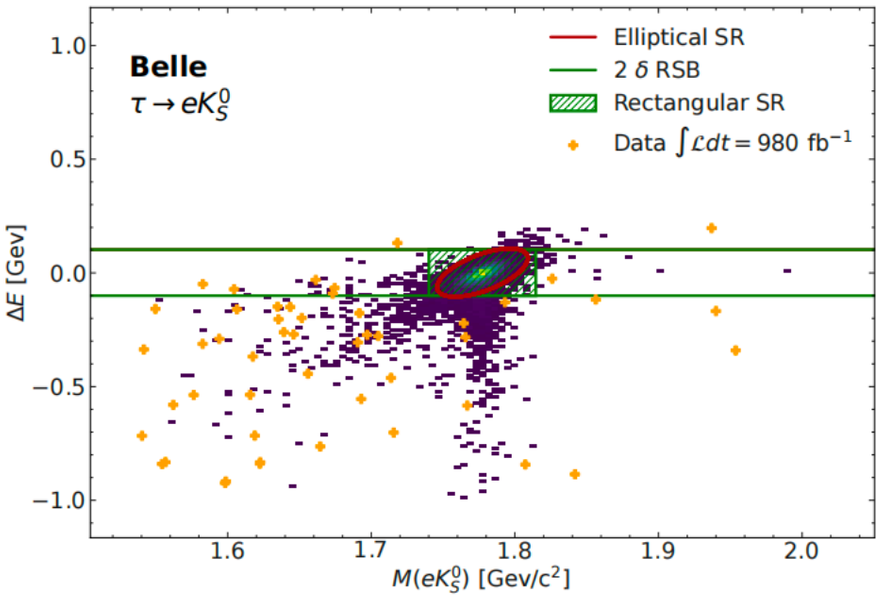


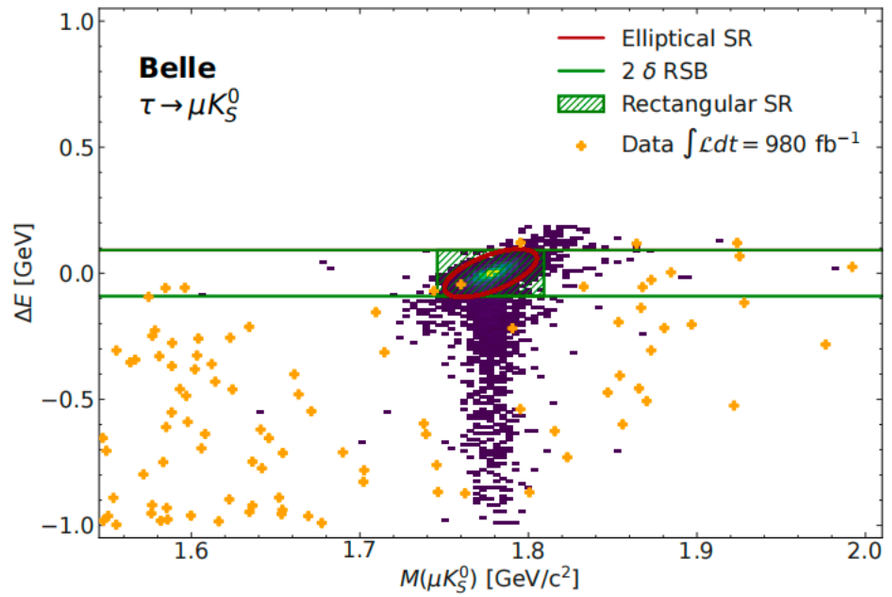
Summary

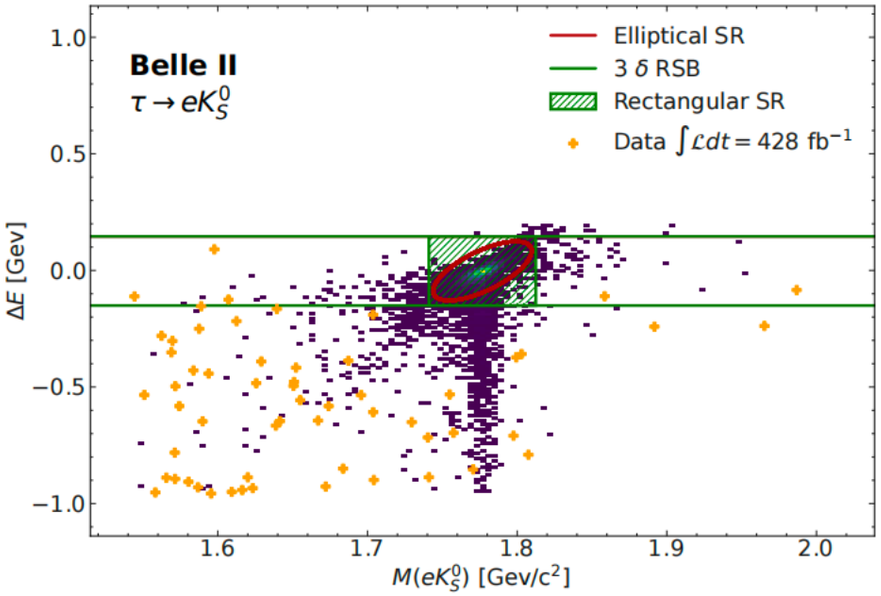
- Belle II is also a τ-factory, a unique
  - Search for CPV in $\tau^- \to \pi^- K_S \nu (\geq 0\pi^0)$

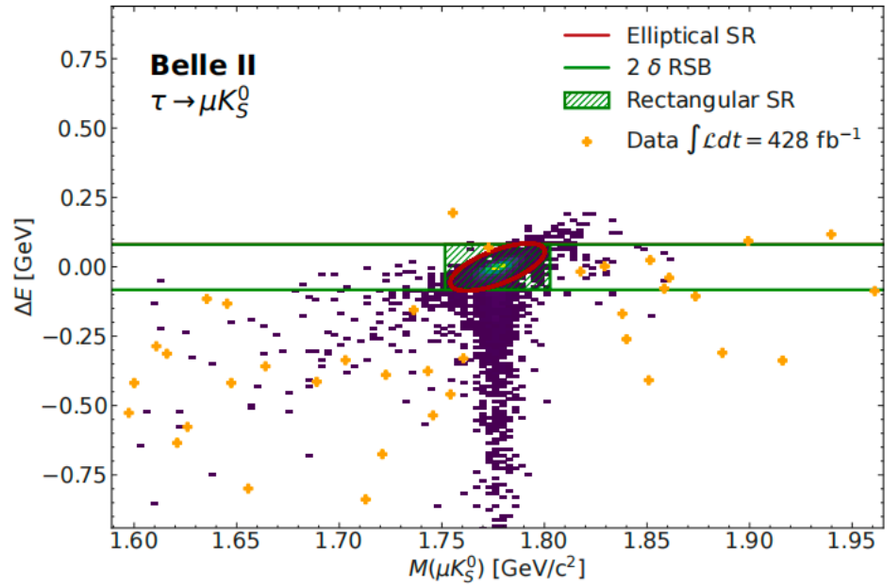
    $A_{cp} = (0.71 \pm 0.26 \pm 0.06 \pm 0.15)$, 1.2σ from SM
  - Search for LFV in $\tau^- \to \mu\gamma$, $\ell\eta$, ℓK_S, $e\ell\ell$
  - Precision measurements of BF and SF of hadronic decays
- Many results will come in the future.

Backup


Belle
$\tau \to eK^0_S$
Elliptical SR
2 δ RSB
Rectangular SR
Data $\int \mathcal{L}dt = 980$ fb^{-1}
ΔE [Gev]
$M(eK^0_S)$ [Gev/c^2]


Belle
$\tau \to \mu K^0_S$
Elliptical SR
2 δ RSB
Rectangular SR
Data $\int \mathcal{L}dt = 980$ fb^{-1}
ΔE [GeV]
$M(\mu K^0_S)$ [GeV/c^2]


Belle II
$\tau \to eK^0_S$
Elliptical SR
3 δ RSB
Rectangular SR
Data $\int \mathcal{L}dt = 428$ fb^{-1}
ΔE [Gev]
$M(eK^0_S)$ [Gev/c^2]


Belle II
$\tau \to \mu K^0_S$
Elliptical SR
2 δ RSB
Rectangular SR
Data $\int \mathcal{L}dt = 428$ fb^{-1}
ΔE [GeV]
$M(\mu K^0_S)$ [GeV/c^2]