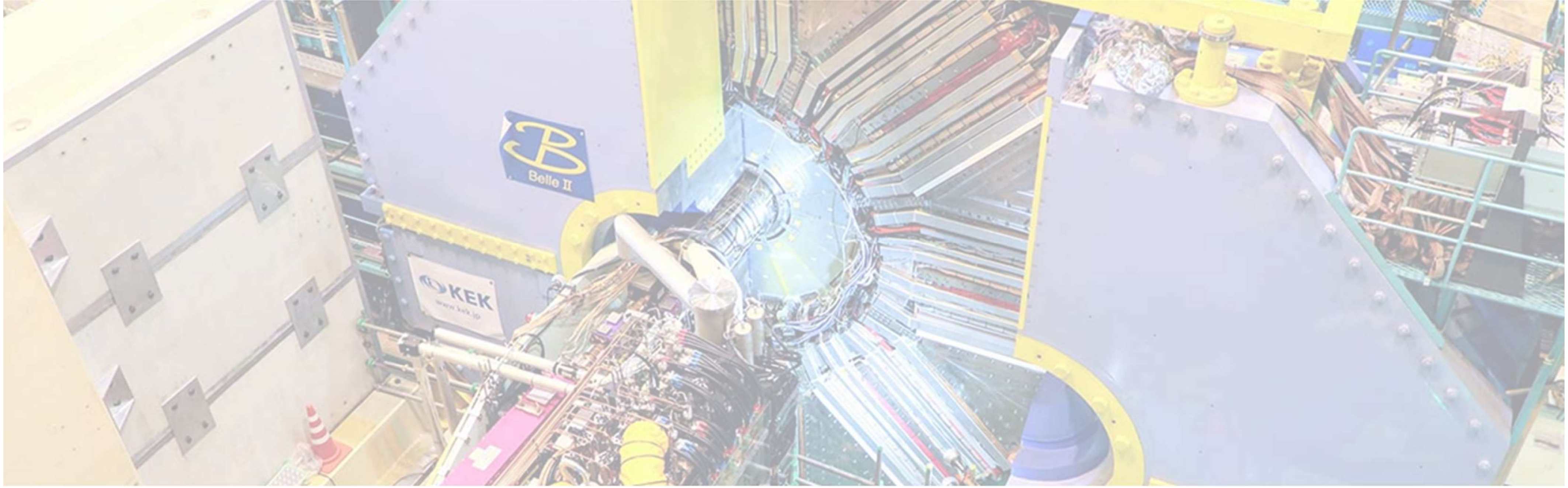

Searches for lepton-flavor violation in τ decays at Belle II

FLASY, June 30 – July 4, 2025, Roma

Laura Salutari – INFN Roma 3, on behalf of the Belle II collaboration
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τ physics: motivation and challenges

τ pairs produced in e^+e^- collisions are a unique laboratory to **test** the standard model (SM) through precision measurements and **search** for non-SM physics (BSM)

Precision physics

- Study allowed processes to test SM
  τ mass, lifetime, lepton flavor universality (LFU)
- **High statistics**
- Mainly dominated by **systematic uncertainties**
- Detector performances must be well understood (tracking, particle identification, calorimeter ..)

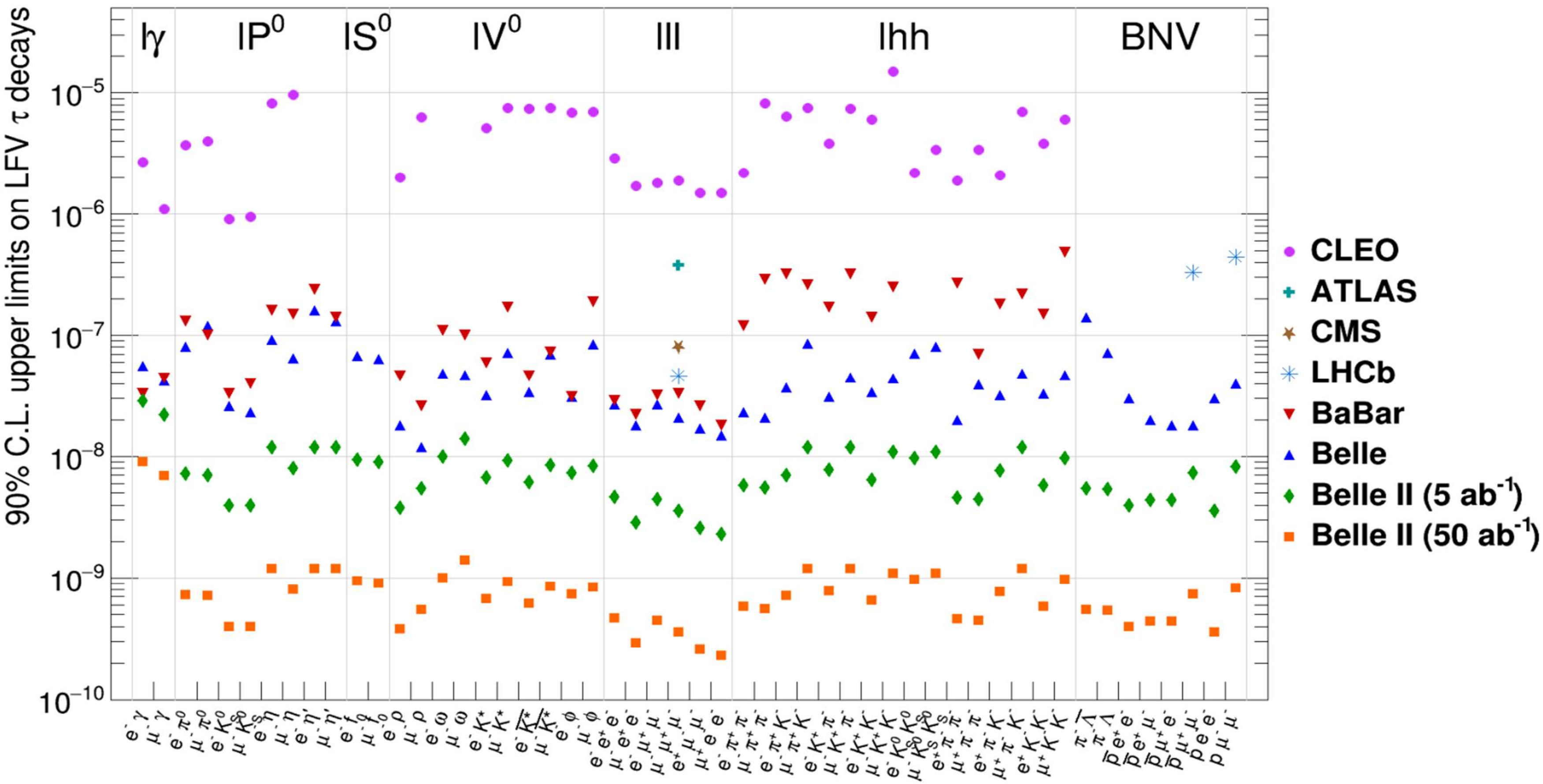
New physics

- Study rare or forbidden processes to probe BSM
- **Low statistics**
- **Need high luminosity** to collect suitable data set
- Develop techniques to mantain good signal /background ratio

τ physics: lepton flavor violation

- Allowed due to neutrinos oscillation
- Predicted rates at level of 10^{-50} , far from any experiment sensitivity
- **any LFV observation indicates new physics**!

Plot from
Belle II
Snowmass
arXiv:2207.06307



Belle II: experiment and detector

B-factory at SuperKEKB

- Asymmetric e^+e^- beams colliding at $\Upsilon(nS)$ ($b\bar{b}$ bound state)
  - Mainly at $\Upsilon(4S)$: $\sqrt{s}$ = 10.58 GeV

Main production cross sections:

$$\sigma(e^-e^+ \to b\bar{b}) \cong 1.1 \text{ nb}$$

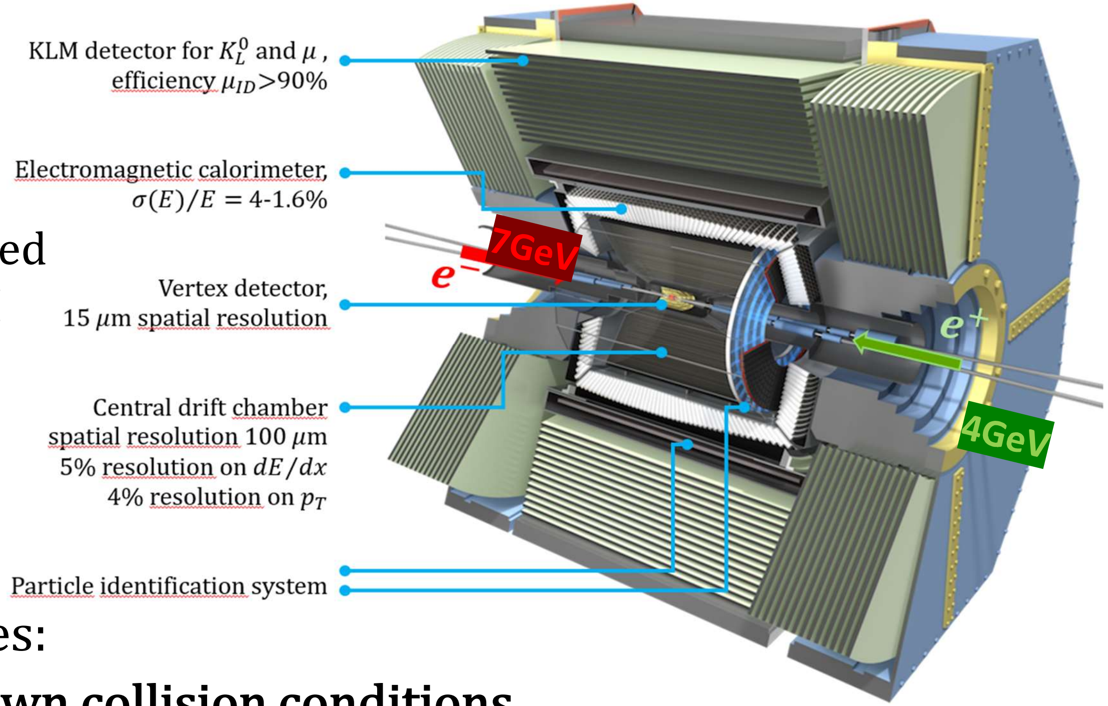
$$\boldsymbol{\sigma(e^-e^+ \to \tau^-\tau^+) \cong 0.9 \text{ nb}}$$

World record $\mathcal{L}$: 5.1 x 10^{34} $cm^{-2}s^{-1}$

- Target $\mathcal{L}$: 6 x 10^{34} $cm^{-2}s^{-1}$
- Target $\int \mathcal{L}$ = **50 ab^{-1}**

Belle II @ superKEKB: collected more than 575 fb^{-1} between run1 (2018-2023) and run2 (ongoing since feb. 2024)

Roughly $500 \cdot 10^6$ τ pairs collected from Belle II



Key features:

- Well **known collision conditions**
- Low multiplicity collisions
- **Hermetic detector**
- Trigger lines specific for low multiplicity event

excellent reconstruction of events even with missing energy & low multiplicity

τ physics at BelleII

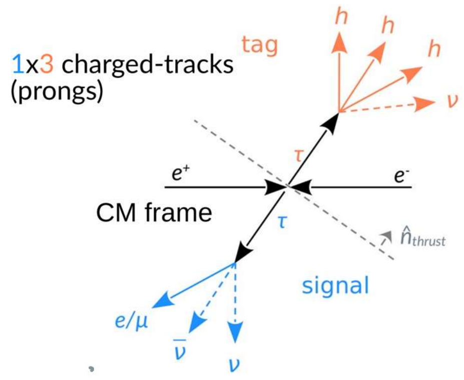
- Pair production is collinear in the center of mass frame (CM)
- Presence of neutrinos (missing energy) in the final state → impossible to reconstruct exactly the flight direction

Study methodology:

- Characterize the τ flight direction with the Thrust (T) vector

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

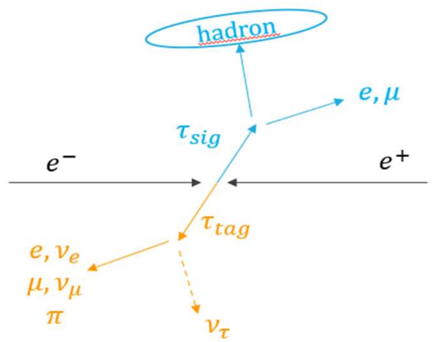
- Separate the event in two distinct hemispheres: tag & signal
- Reconstruct different topologies of events «3x1» o «1x1» to suppress background



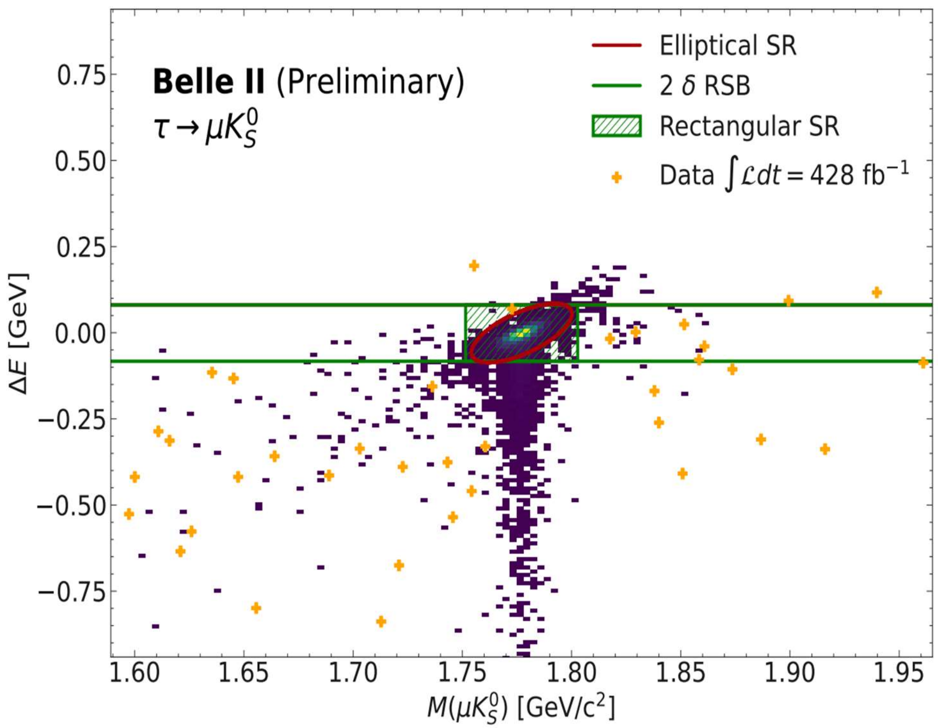
- In many **LFV channels**, the signal side has **no missing energy**:
  - invariant mass of decay products $\boldsymbol{M_{inv}}$ coincide with M_τ
  - decay products energy are half of the available energy in CM frame: $\Delta \boldsymbol{E} = \boldsymbol{E^{CM}_{inv}} - \frac{\sqrt{s}}{2}$ **peaks at 0**
  - these analyses exploit the 2D plane given by M_{inv} and $\Delta \boldsymbol{E}$ to **minimize background**

Search for $\tau \to K_s^0 \ell$

arXiv.2504.15745 , accepted from JHEP



- New leptoquark mediators could enhance decay rate
- First LFV search with joint **Belle (980 fb^{-1})** and **Belle II (428 fb^{-1})**
- $1.6 \cdot 10^9$ τ pairs analyzed in **two final states $\tau \to eK_s^0$ and $\tau \to \mu K_s^0$**



- Tag side: one prong
- Signal side: combination of one charged lepton and a candidate K_s^0 from $\pi^+\pi^-$

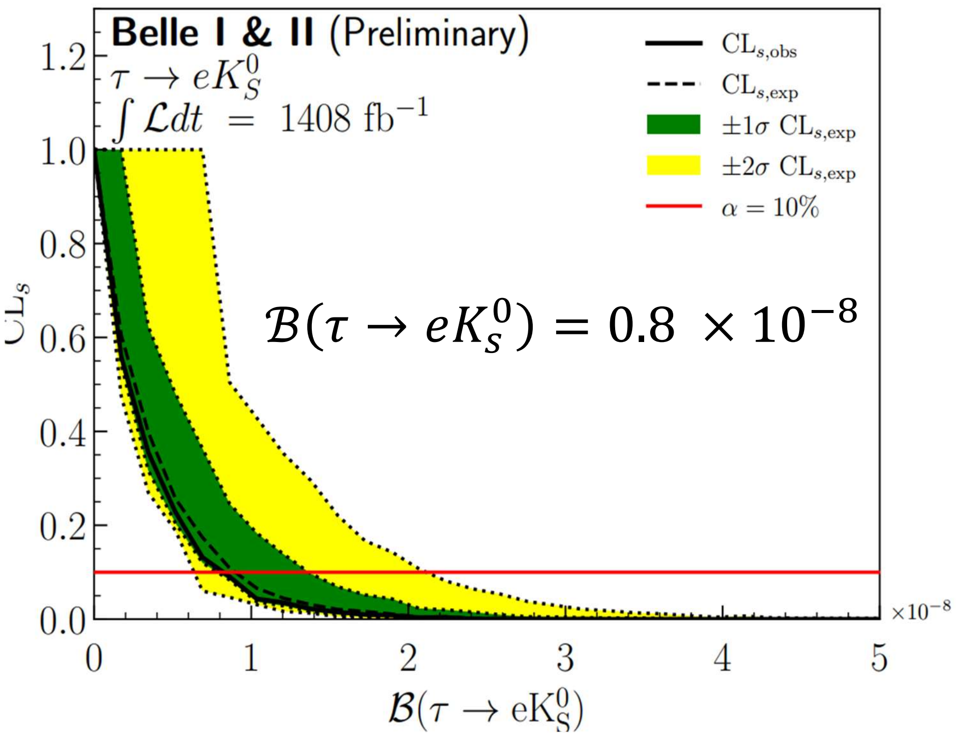
- Main background: $e^+e^- \to q\bar{q}$, rejected with a boosted decision tree (BDT) based selection
- More than 10% efficiency in both channels for both dataset

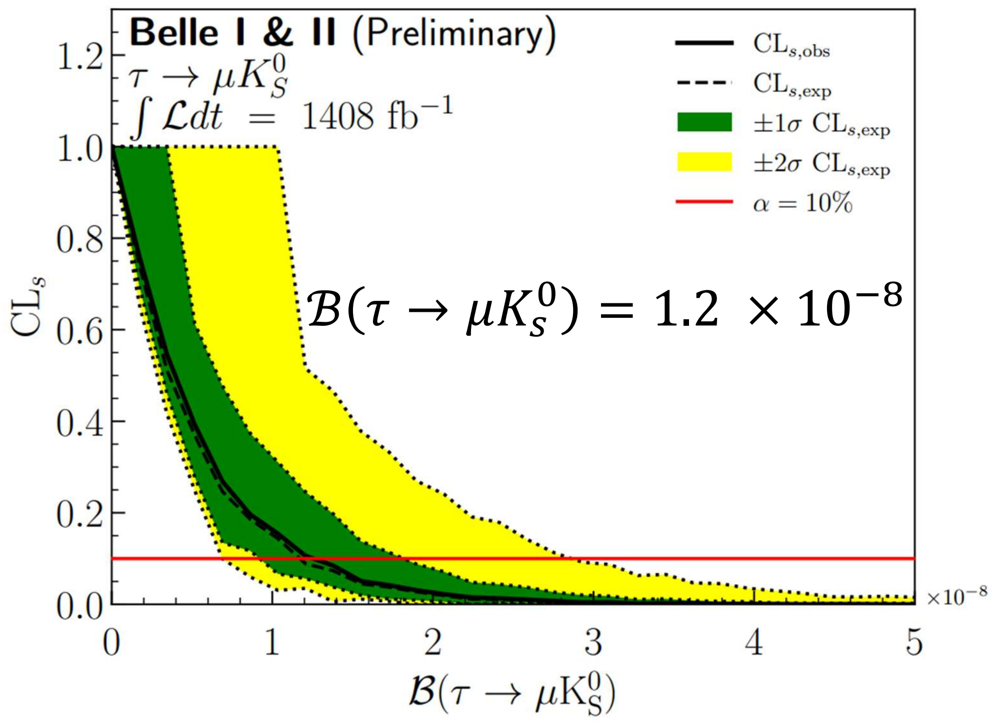
- Define elliptical signal region (SR) for signal extraction; and a sideband region (RSB) for data validation
  - Estimate expected events in SR from a fit in the RSB

Search for $\tau \to K_S^0 \ell$

arXiv.2504.15745 , accepted from JHEP

- Cut and count approach $\mathcal{B}(\tau \to \ell K_S^0) = \frac{N_{obs} - N_{exp}}{2\varepsilon\mathcal{L}\sigma_{\tau\tau}}$
- No significant signal observed, derived 90% CL upper limits
- **Most stringent** up to date for the two considered channels,
    - 3 times and 2 times more stringent than previous best limits from Belle results [Phys. Lett. B 692 (2020) 4]





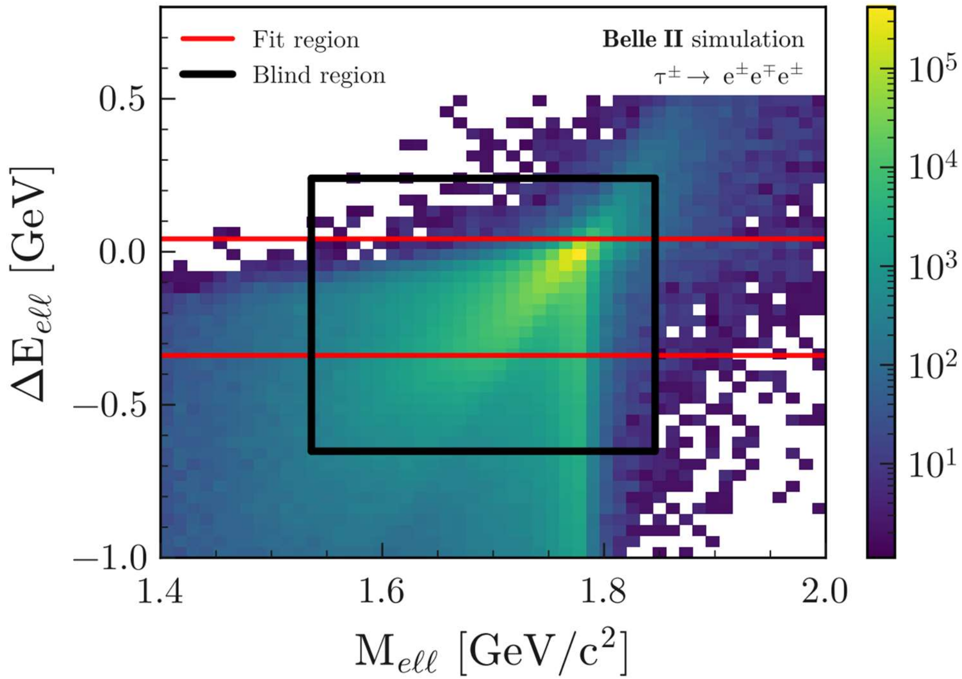
Search for $\tau^- \to e^{\mp}\ell^{\pm}\ell^-$

preliminary, shown at Moriond

check also $\tau \to \mu\mu\mu$ results
JHEP 09 (2024) 062
most stringent limits!

- Several models (new Z ′ , charged Higgs boson..) could enhance rates up to $\mathbf{10^{-10} - 10^{-8}}$
- Analysis with **Belle II ($\mathbf{428\ fb^{-1}}$)** dataset

- $e^-e^+e^-, e^+e^-\mu^+, e^-\mu^-\mu^+$ single violation
- $e^+\mu^-\mu^-, e^-e^-\mu^+$ double violation



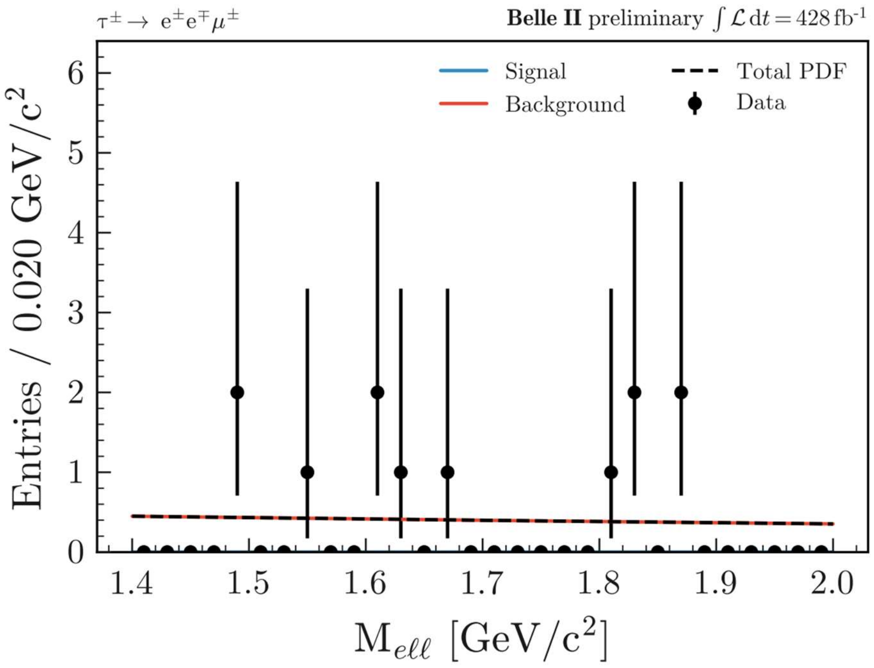
- Signal side: combine an identified e and two ℓ with net charge ± 1 and belonging to the same hemisphere
- Tag side: untagged (no topology request), to increase statistics
- **Heavyly relies on PID**

- Main background from $ee \to \ell\ell(\gamma), ee \to 4\ell$
  - Tighten PID requests
  - Remaining bkg rejected with a BDT trained on data (not from fit region)

Search for $\tau^- \to e^{\mp}\ell^{\pm}\ell^-$

preliminary, shown at Moriond

Overall signal efficiency from 15% to 23% for all channels → up to 3 times higher than previous analysis [*]



Fit to the $M_{e\ell\ell}$ and extract the branching fraction $\mathcal{B}(\tau \to e\ell\ell)$

For all channels no excess found, 90%CL upper limits are derived

$\boldsymbol{\mathcal{B}(\tau^- \to e^{\mp}\ell^{\pm}\ell^-)}$ **in the range of 1.3 – 2.5** $\boldsymbol{\times 10^{-8}}$

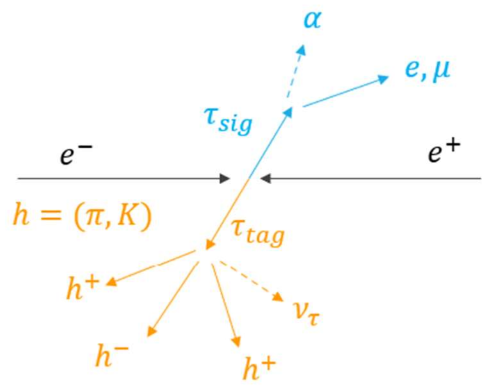
For all channels these represent the **lowest limit**

- except the $e^- e^- \mu^+$ final state

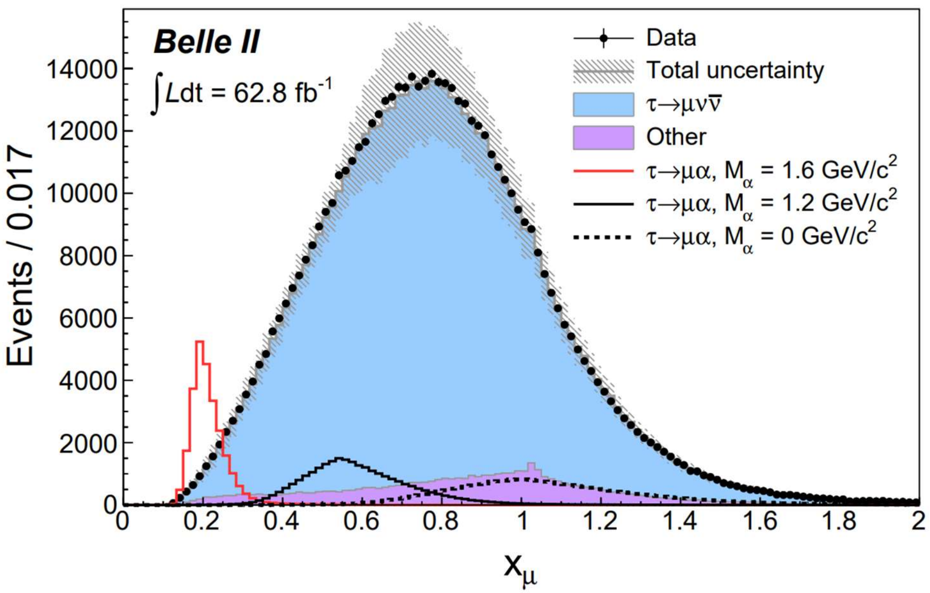
[*] Belle Phys. Lett. B 687 (2010) 139

Search for $\tau^- \to \ell^- \alpha$

Phys. Lett. Rev 130 (2023) 181803



- With $\boldsymbol{\alpha}$ **as neutral spin-0 boson**, the process is not allowed in SM, but present in many Beyond SM models (such as ALPs [*])
- Belle II analysis with 62.8 fb^{-1} and mass hypothesis $\boldsymbol{m_\alpha}$ **from 0 to 1.6GeV/$\boldsymbol{c^2}$**



- Event is reconstructed asking for exactly four tracks and net charge 0 in a 3x1 topology
- Irreducible background: $\tau \to \ell\nu\bar{\nu}$
- Examine the relative ratio $\mathcal{R} = \frac{\mathcal{B}(\tau\to\ell\alpha)}{\mathcal{B}(\tau\to\ell\nu\bar{\nu})}$

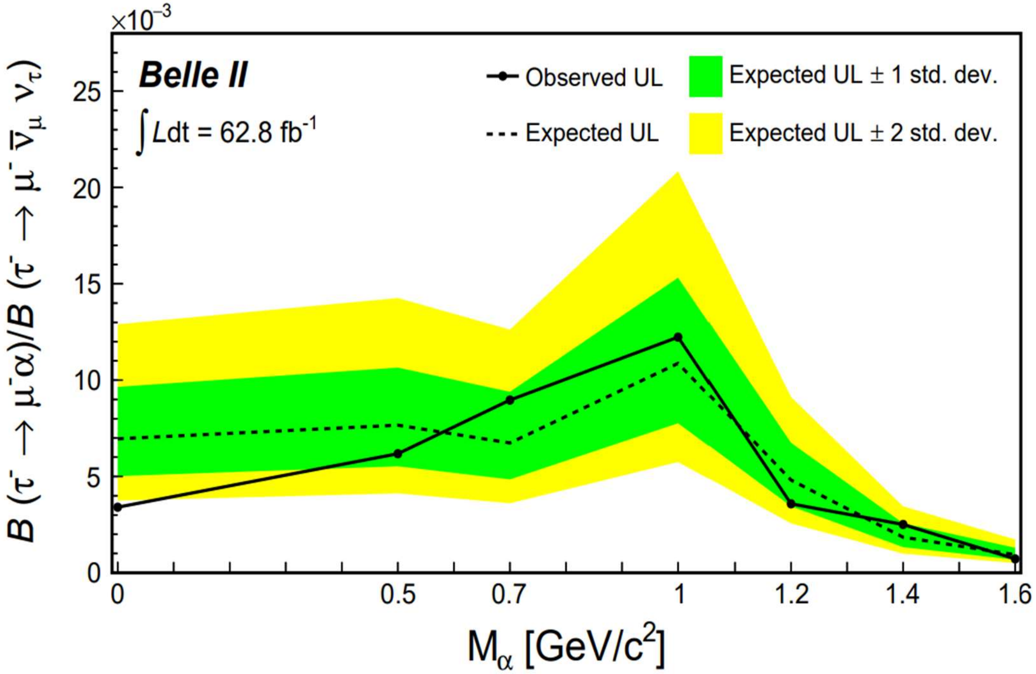
- Exploit **2-body decay of signal**: perform a boost in the ***pseudo-rest frame*** of τ via the Thrust vector, and study the **energy spectrum of the lepton:** $x_\ell = \frac{2E_\ell^*}{m_\tau}$

[*] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

Search for $\tau^- \to \ell^- \alpha$

Phys. Lett. Rev 130 (2023) 181803

- With no excess found, the 95%C.L. limits on the ratio are derived:
$\frac{\mathcal{B}(\tau\to\ell\alpha)}{\mathcal{B}(\tau\to\ell\nu\bar{\nu})} \leq 10^{-3} - 10^{-2}$



- Non-monotonical variation with m_α due to both signal resolution and shape of the irreducible $\tau \to \ell\nu\bar{\nu}$ background
- Between 2 to 14 times more stringent than the previous limits from ARGUS [*]

New analysis from Belle on arXiv 2503.22195v2
Performed with **800 fb^{-1}**
$\mathcal{B}(\tau \to e\alpha) < (0.3 - 6.0) \times 10^{-3}$
$\mathcal{B}(\tau \to \mu\alpha) < (0.1 - 3.3) \times 10^{-3}$

Lower than absolute limits from Belle II

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

Summary & outlook

Belle II provides an ideal environment to explore τ physics

- High statistics
- Clean collisions
- Dedicated low multiplicity triggers

→ Unique dataset

We present leading results in rare τ decay channels:

- $\tau \to \ell K$
- $\tau \to 3\ell$
- $\tau \to \ell\alpha$

Many More LFV searches ongoing, expected to be even more competitive

→ Check out Belle II Snowmass arXiv:2207.06307

In parallel, Belle II reached world-leading precision measurements:

- Tau mass
- Lepton flavor universality test

Backup slides

Search for $\tau \to \mu\mu\mu$

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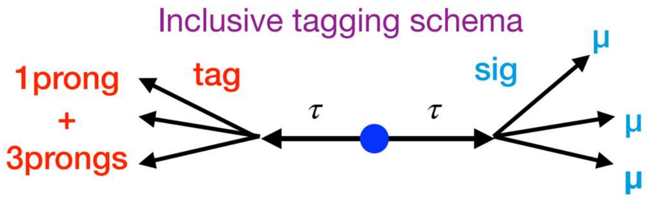
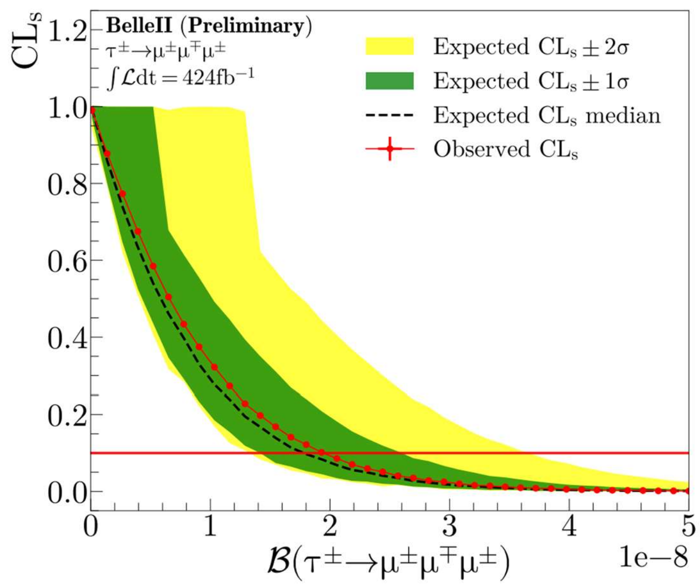
Belle II analysis with
424 fb^{-1} :

- *Signal*: three μ
- *Tag*: inclusive-tag



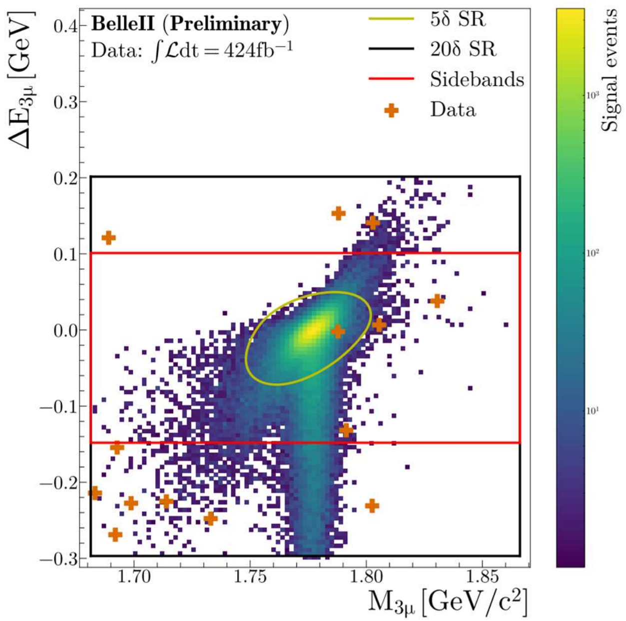


- $\varepsilon_{sig} = 20.42\% \pm 0.06\%$

- Expected events $0.5^{+1.4}_{-0.5}$ estimate from sidebands

- BTD to reject bkg

- $\boldsymbol{Br(\tau \to \mu\mu\mu) =}$ $\boldsymbol{3.1^{+8.7}_{-3.6}\,(stat)\ \pm 0.1\,(syst)}$

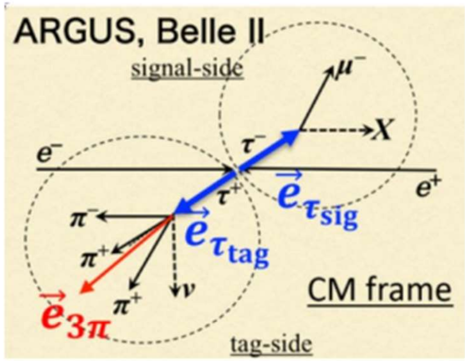


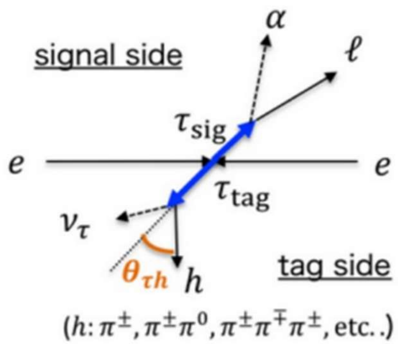
Previous limits:
LHCb: 4.6×10^{-8} $(2.0 fb^{-1})$
BaBar: $3.3 \times 10^{-8}$$(468\ fb^{-1})$
CMS: $2.9 \times 10^{-8}$$(131\ fb^{-1})$
Belle: 2.1×10^{-8} $(782\ fb^{-1})$
Belle II: $1.9 \times 10^{-8}$$(424 fb^{-1})$

Belle search for $\tau^- \rightarrow \ell^- \alpha$

[arXiv 2503.22195v2]

- Room for improvement at Belle with more statistics (800 fb^{-1}) and improved estimate of τ_{sig} direction





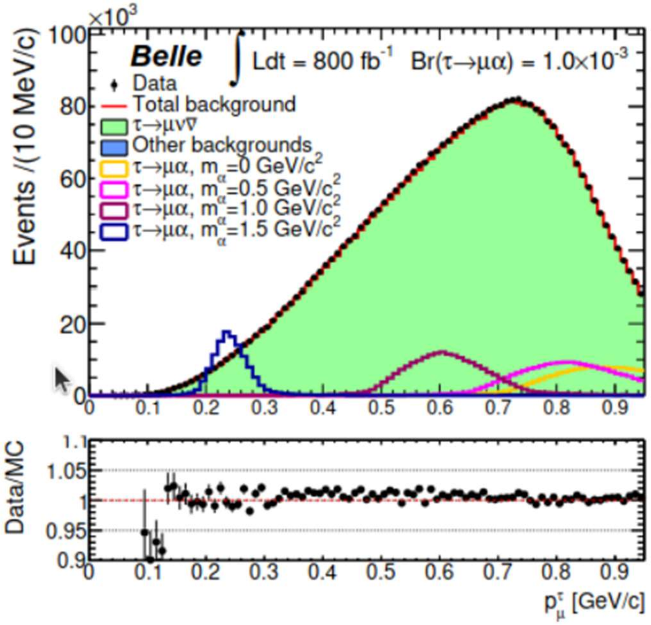
$$\theta_{\tau h} = \arccos\left(\frac{|\vec{p}_{\tau_{\rm tag}}^{\,\rm c.m.}|^2 + |\vec{p}_{h_{\rm tag}}^{\,\rm c.m.}|^2 - (\sqrt{s}/2 - E_{h_{\rm tag}}^{\rm c.m.})^2}{2|\vec{p}_{\tau_{\rm tag}}^{\,\rm c.m.}||\vec{p}_{h_{\rm tag}}^{\,\rm c.m.}|}\right)$$

Credit to K. Uno

- Requiring the τ_{sig} aligned with the hadronic system ($|\theta_{\tau-h}| < 4$) improves the resolution on the signal lepton momentum $p_\ell \rightarrow$ better sensitivity in the signal extraction

- Selections are independent from the α mass: ε_{sig} ranges in [0.3 -1.5]%

- Signal and background yields extracted from binned max likelihood fits to the signal lepton momenta $p_\ell \rightarrow$ shape modeling from MC distributions



Lepton Flavor Universality

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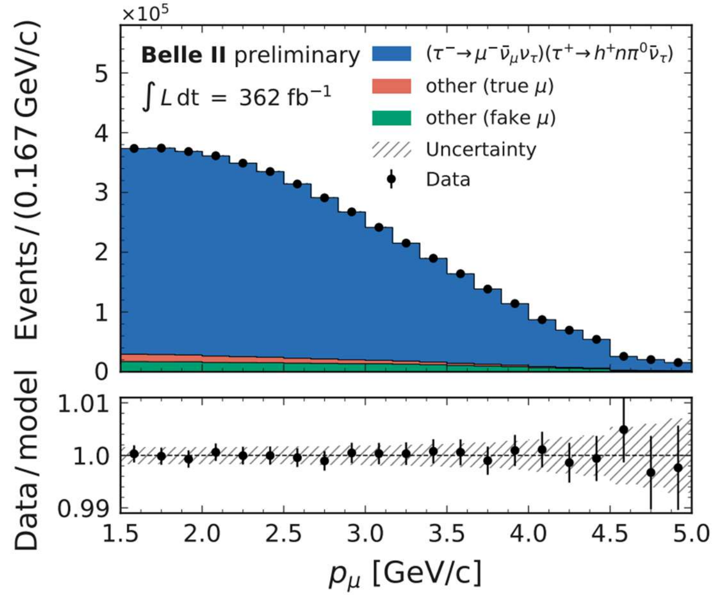
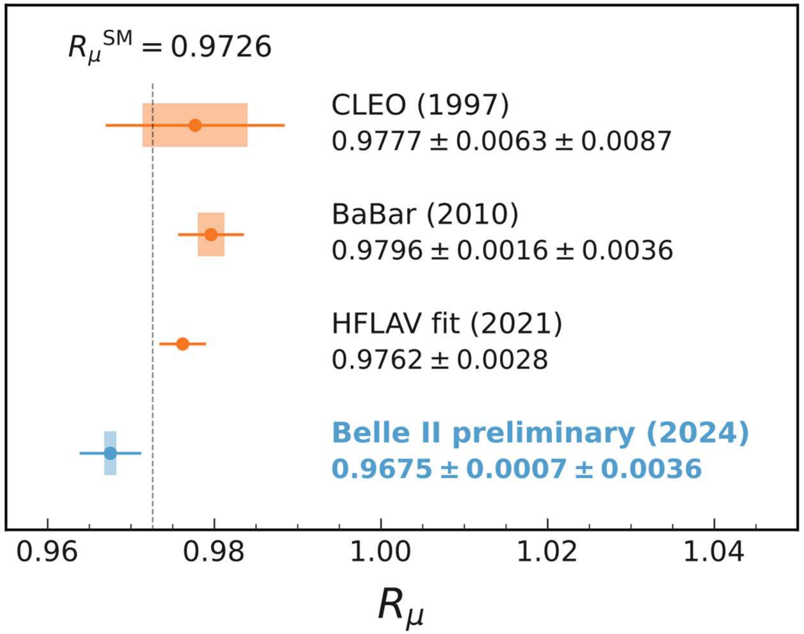
Test the **coupling strength of the electron and muon to the W** using decays

$$R_\mu = \frac{Br(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{Br(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \qquad R_\mu^{SM} = 0.9726$$



- Measured using **1x1-prong topology** with on the tag side
- 94% purity and 9.6% efficiency obtained using rectangular selections and a neural network
- Dominant **systematics** from PID (0.32%) and trigger (0.10%)



- **Most precise determination** of and in decays from a single measurement
- In **agreement with SM** prediction at the level of 1.4

Pseudo rest frame

Cannot determine the τ momentum from the observed particles directly

Approximate its energy: $E_\tau^* \sim \sqrt{s}/2$ in the center of mass frame (neglecting ISR)

Approximate τ direction as opposite to the three hadrons on the tag side:
$\widehat{p_\tau} \simeq -\vec{p}_{3h}/|\vec{p}_{3h}|$