Tau (τ) lepton physics at Belle (II)

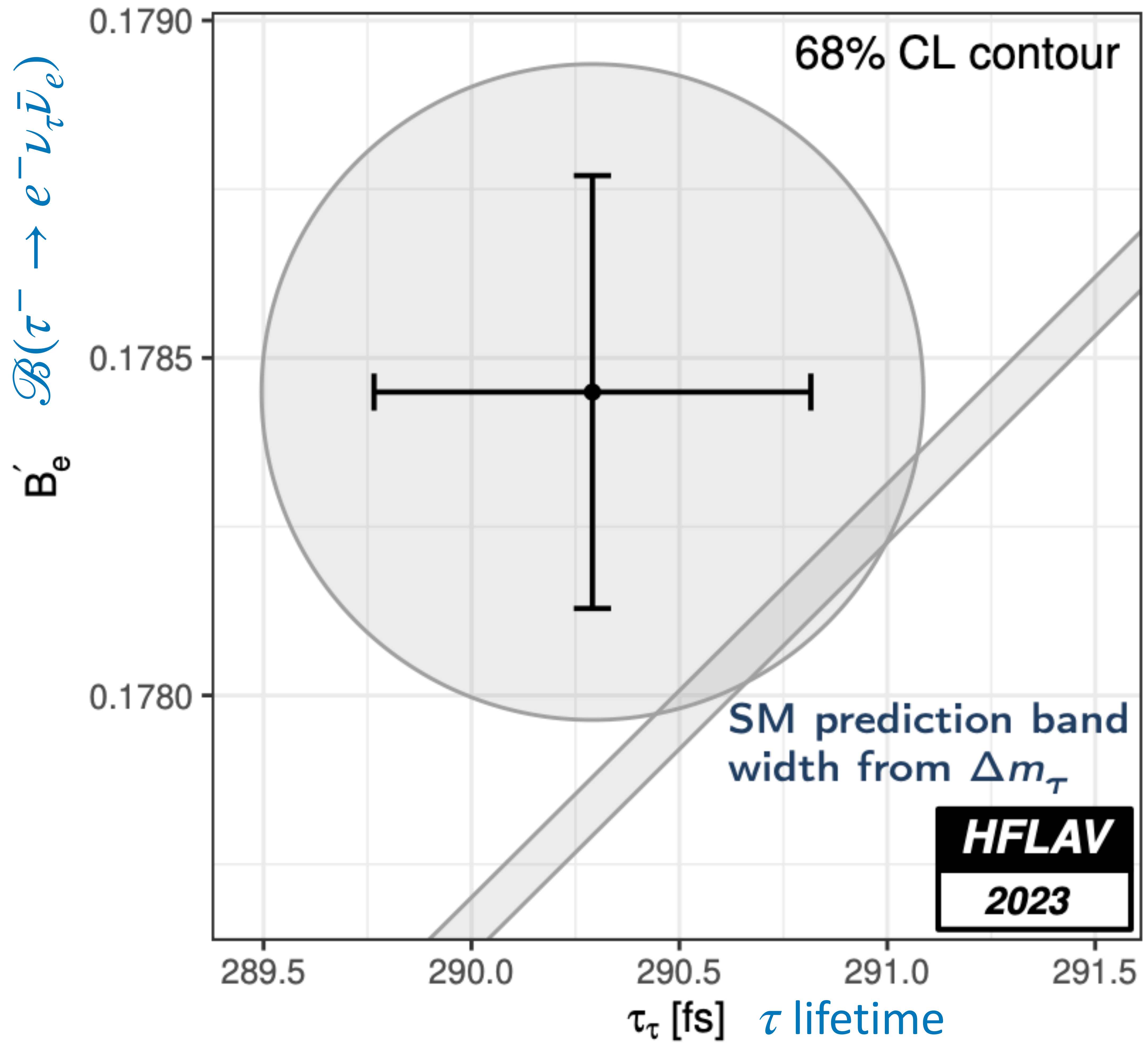
Yipu Liao
Institute of High Energy Physics, CAS, Beijing
On behalf of the **Belle and Belle II Collaborations**

14th International Workshop on e^+e^- collisions from Phi to Psi (**PhiPsi26**)
@ Pisa, Italy
2026.06.08

Introduction of τ physics

- The heaviest lepton in the Standard Model (SM)
- Properties of τ (mass, lifetime, EDM …) → precise test on electroweak part of SM
- τ decays (leptonic, hadronic, LFV …)
  - 252 decay modes listed in PDG 2025
  - The only one lepton can decay to hadrons
  - A unique tool for the precision study of low energy QCD and search for New Physics

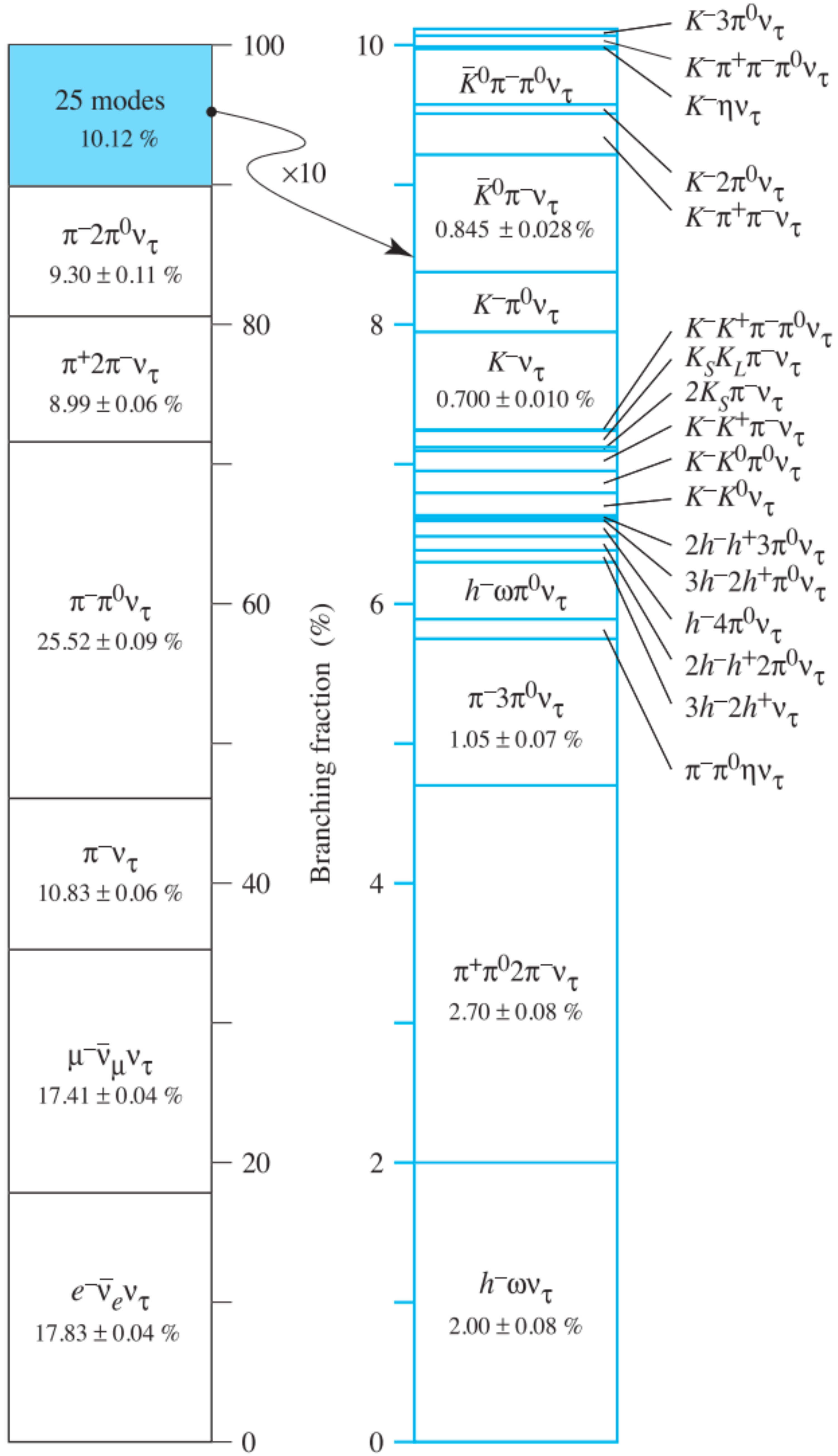
A. Lusiani, TAU2025



Introduction of τ physics

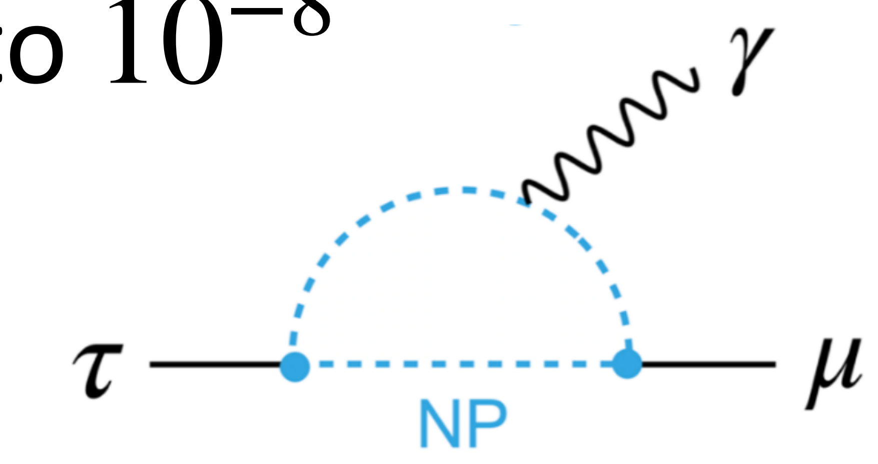
- The heaviest lepton in the Standard Model (SM)
- Properties of τ (mass, lifetime, EDM …) → precise test on electroweak part of SM
- τ decays (leptonic, hadronic, LFV …)
  - 252 decay modes listed in PDG 2025
  - The only one lepton can decay to hadrons
  - A unique tool for the precision study of low energy QCD and search for New Physics

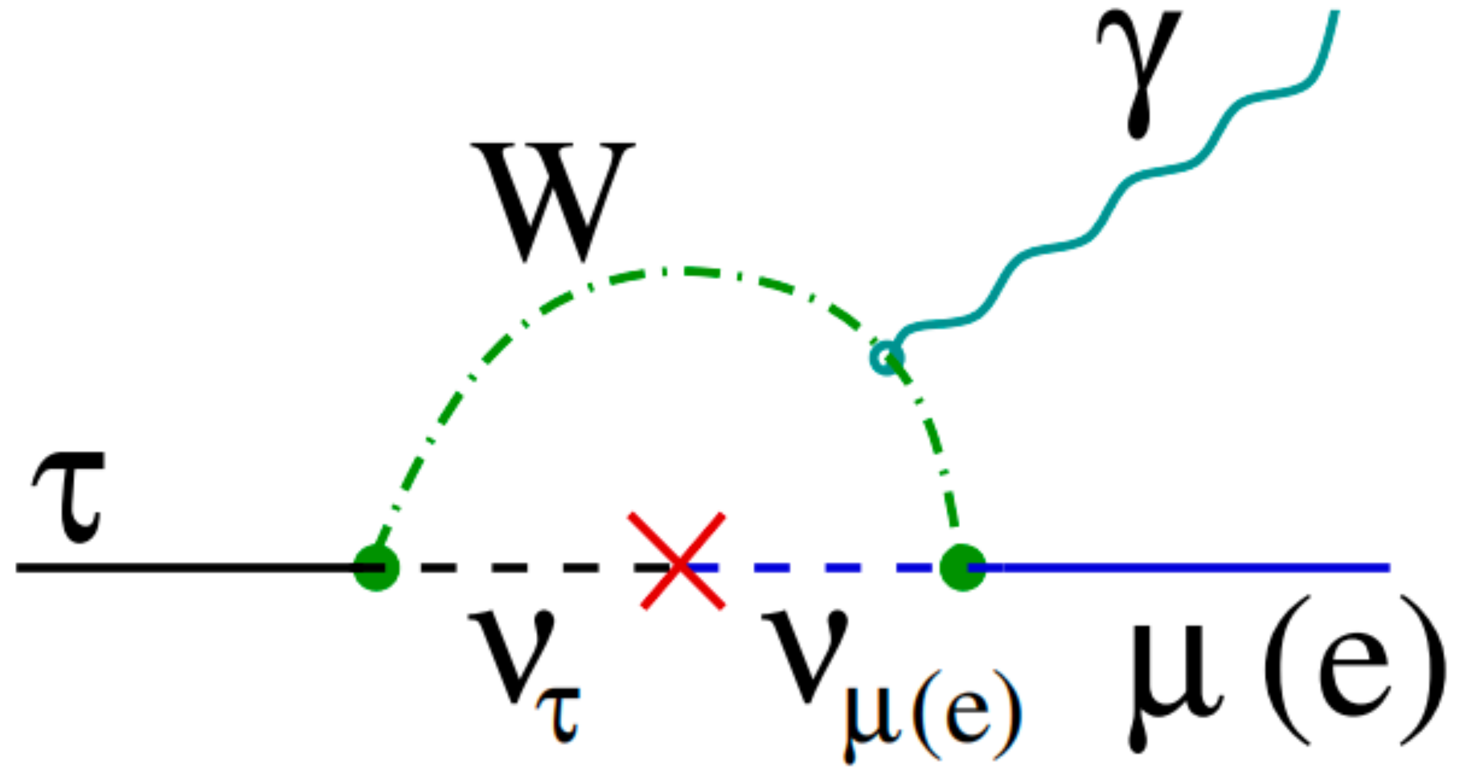
Plot from PDG 2015



New physics search in present τ physics

- The lepton-flavor-violating (LFV) τ decays are extremely small in SM, $\mathscr{B}(\tau \to \ell\nu) \sim (\frac{\Delta m_\nu^2}{m_W^2}) < 10^{-54}$
  - Many models beyond the SM predict LFV decays with branching fractions up to 10^{-8}





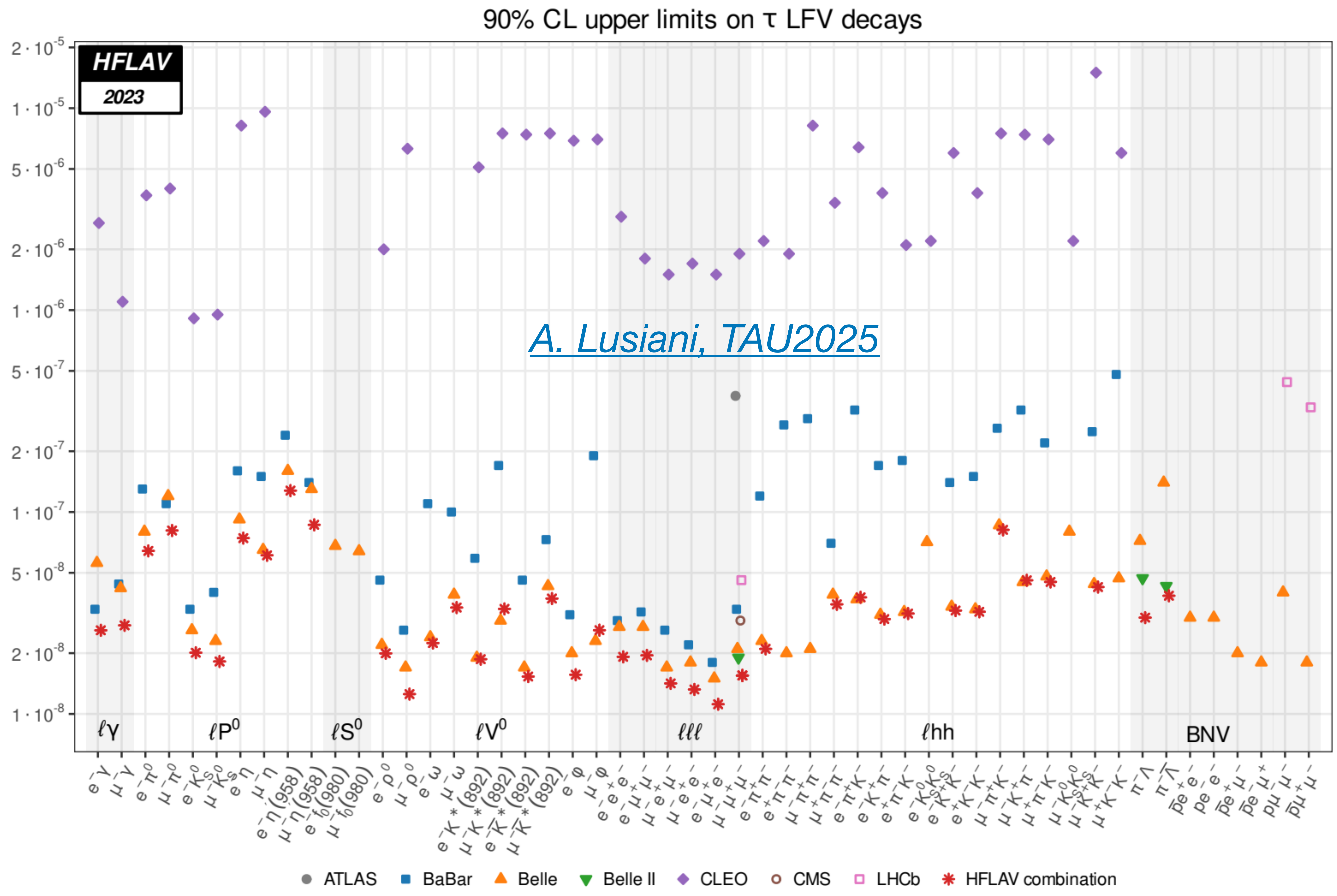
Standard Model

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]

Refs. [1-8] can be found in backup

New physics search in present τ physics

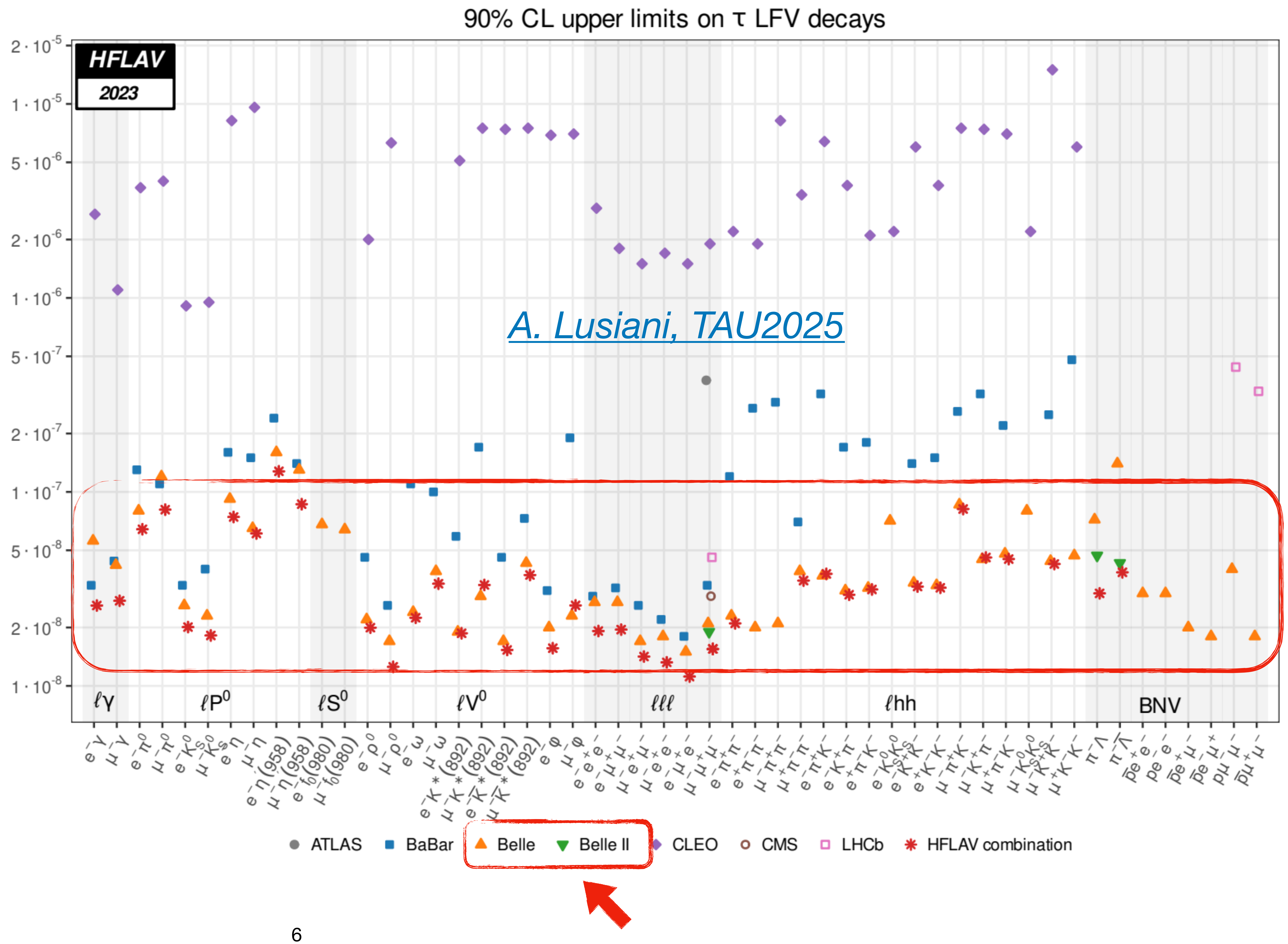
- Some results of τ LFV decays have already achieved $\mathcal{O}(10^{-8})$ precision
  - More can be tested
- Belle (II) contribute a lot in τ LFV searches



New physics search in present τ physics

- Some results of τ LFV decays have already achieved $\mathcal{O}(10^{-8})$ precision
  - More can be tested

- Belle (II) contribute a lot in τ LFV searches



Anomaly in present τ-related physics

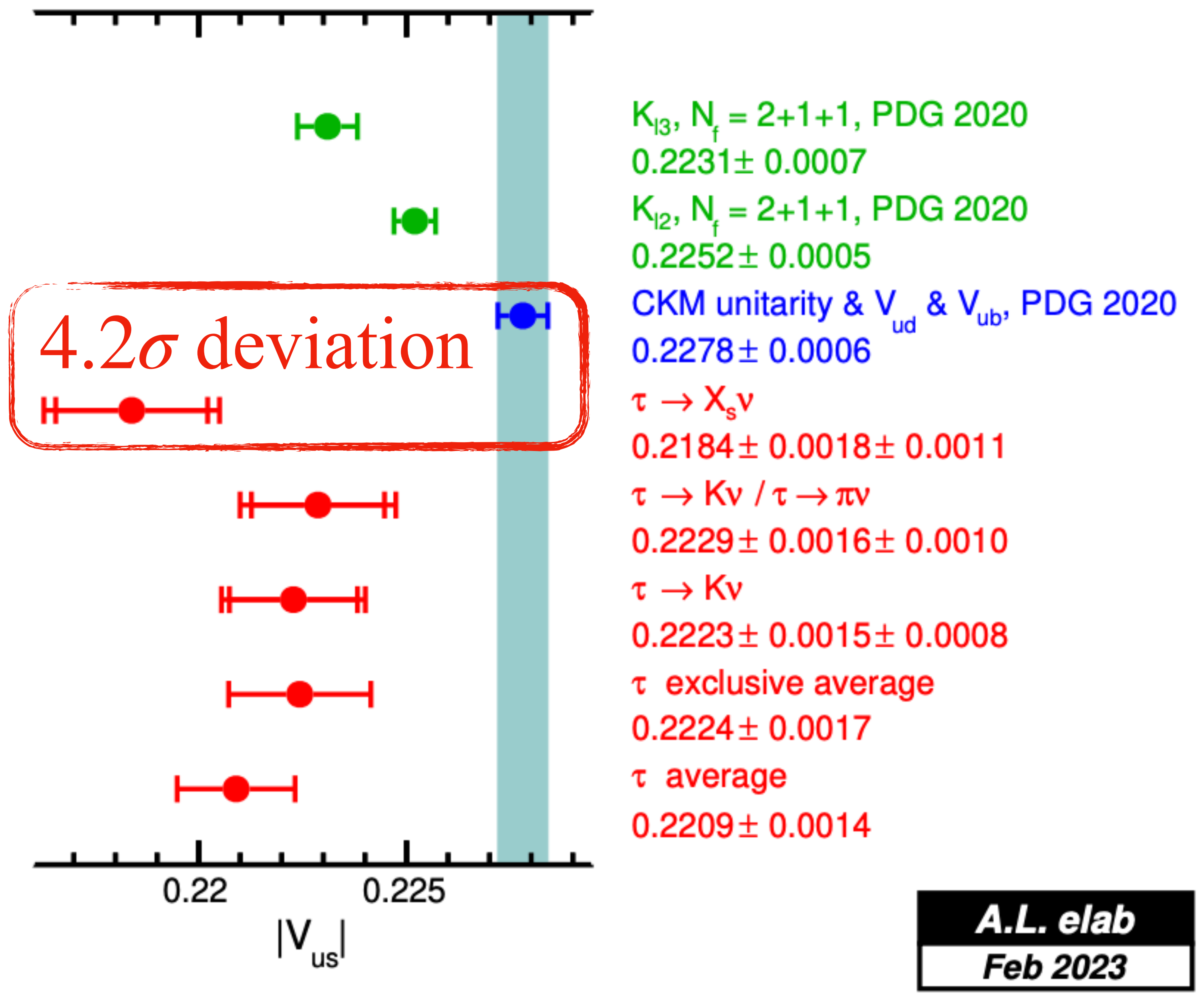
- Many anomalies still exists in present τ-related physics

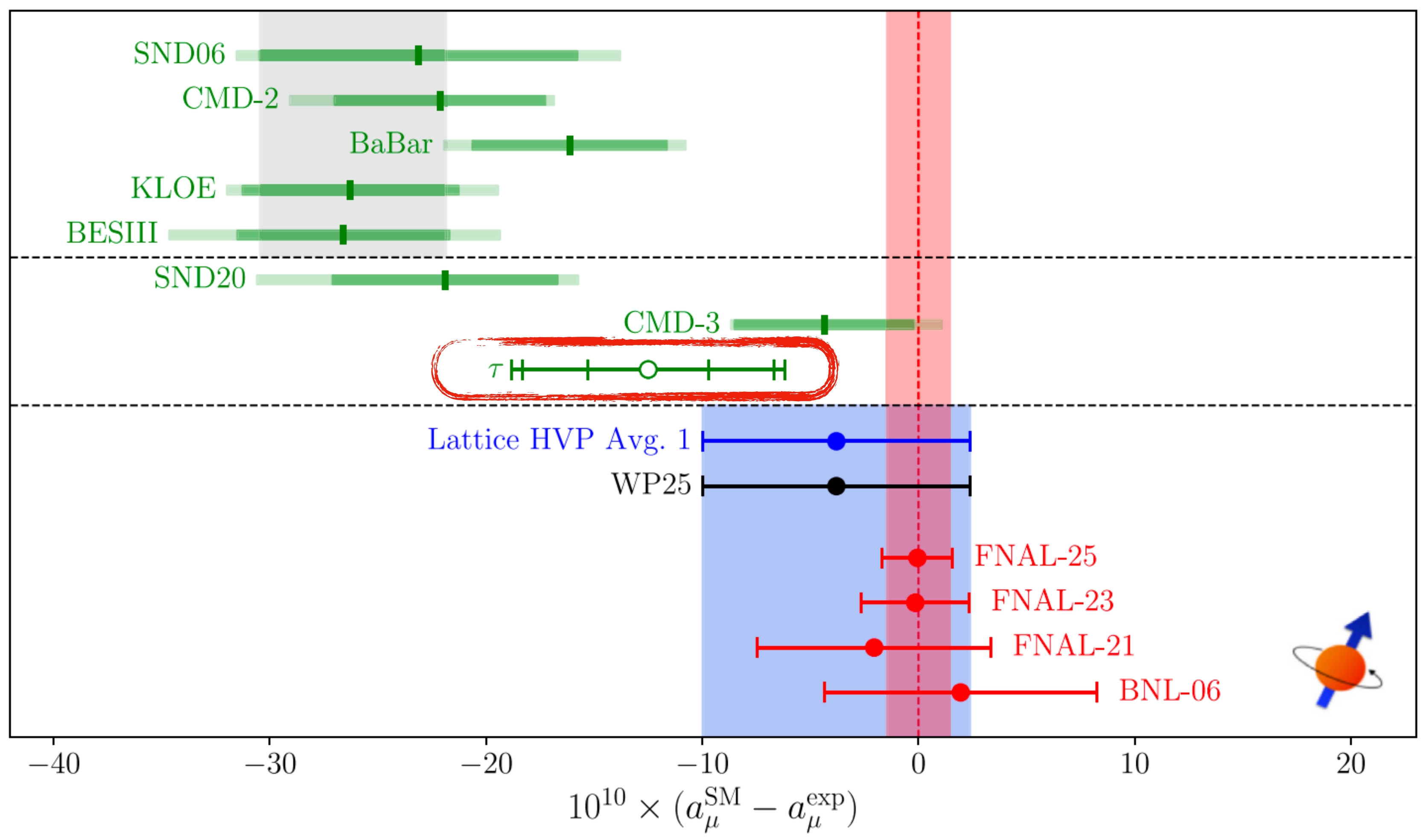
$$A_{CP} = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

$$A_{\rm CP}^{\rm SM} \sim (0.33 \pm 0.01)\,\%$$

$$A_{\rm CP}^{\rm BaBar} = (-0.36 \pm 0.23 \pm 0.11)\,\%$$

2.8σ deviation





Wrong sign puzzle in τ CPV

Cabibbo angle anomaly

Inconsistent between e^+e^- data and direct measurement on a_μ

BaBar, PRD 85.031102 (2012)

A. Lusiani, TAU2025

WP25, Physics Report 1143, 1 (2025)

τ physics at three main c.m. energy types of experiments

Threshold: $3.55 \sim 3.68$ **GeV**, below $\psi(2S)$ peak (KEDR, BESIII)

- τ almost static, $\sigma(e^+e^- \to \tau^+\tau^-) = 0 \sim 2.5$ nb
- Good neutral performance from control samples under ψ peak
- Limited data samples; hard to control $q\bar{q}$ background

B factories: 10.58 GeV (BaBar, Belle, Belle II)

- $\sigma(e^+e^- \to \tau^+\tau^-) \sim 0.92$ nb
- High luminosity and huge statistics
- Background level higher

Z **pole: 91 GeV** (experiments at LEP)

- Large Lorentz boost, $\tau^+\tau^-$ back-to-back, $\sigma(e^+e^- \to \tau^+\tau^-) \sim 1.5$ nb
- Very high efficiency, background level low
- Limited statistics in previous experiments

* c.m.: center-of-mass

τ physics at three main c.m. energy types of experiments

Threshold: $3.55 \sim 3.68$ **GeV**, below $\psi(2S)$ peak (KEDR, BESIII)

- τ almost static, $\sigma(e^+e^- \to \tau^+\tau^-) = 0 \sim 2.5$ nb
- Good neutral performance from control samples under ψ peak
- Limited data samples; hard to control $q\bar{q}$ background

B factories: 10.58 GeV (BaBar, Belle, Belle II)

- $\sigma(e^+e^- \to \tau^+\tau^-) \sim 0.92$ nb   S. Banerjee et al., PRD, 77, 054012 (2008)
- High luminosity and huge statistics
- Background level higher

BELLE

Belle II

Z **pole: 91 GeV** (experiments at LEP)

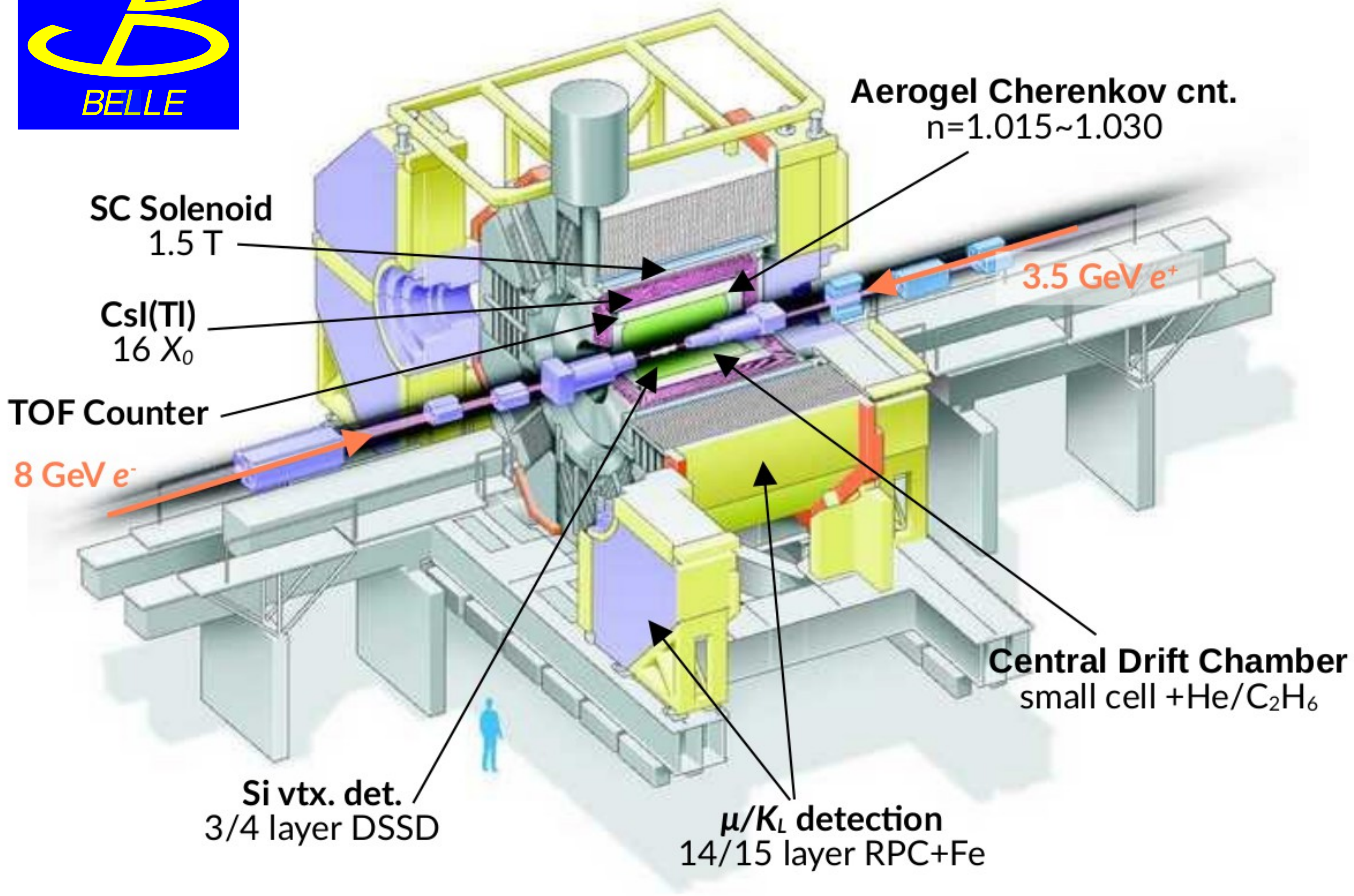
- Large Lorentz boost, $\tau^+\tau^-$ back-to-back, $\sigma(e^+e^- \to \tau^+\tau^-) \sim 1.5$ nb
- Very high efficiency, background level low
- Limited statistics in previous experiments

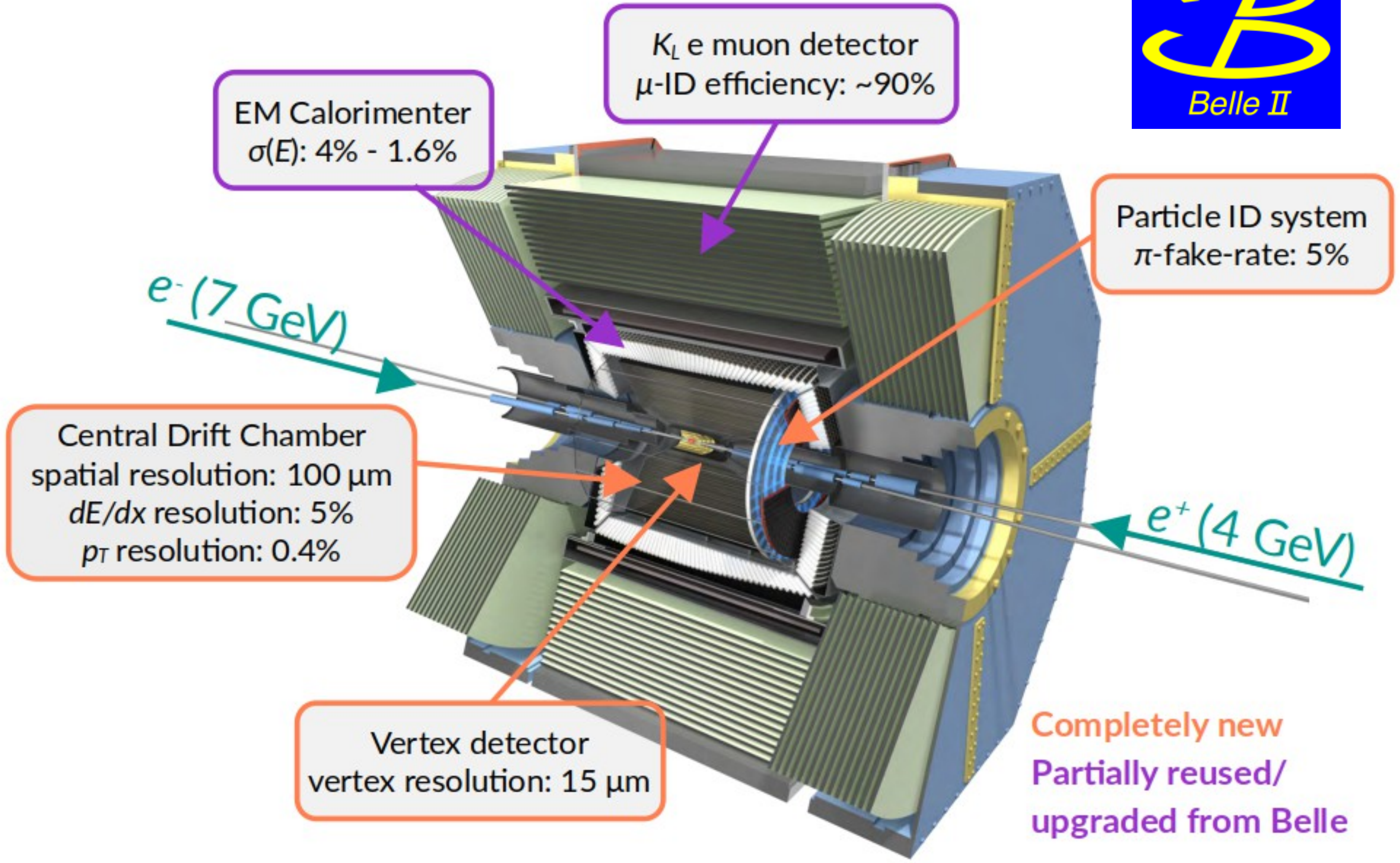
* c.m.: center-of-mass

Belle and Belle II

$\sigma(e^+e^- \to b\bar{b}) \sim 1.0$ nb
$\sigma(e^+e^- \to \tau\tau) \sim 0.9$ nb

- **Belle** (1999-2010) and **Belle II** (2018-now) operate as B-factories
  - **Asymmetric e^+e^- colliders** optimized for the $B\bar{B}$ production, collisions at and near $Y(4S)$
  - B-factories are also **τ- factories**!



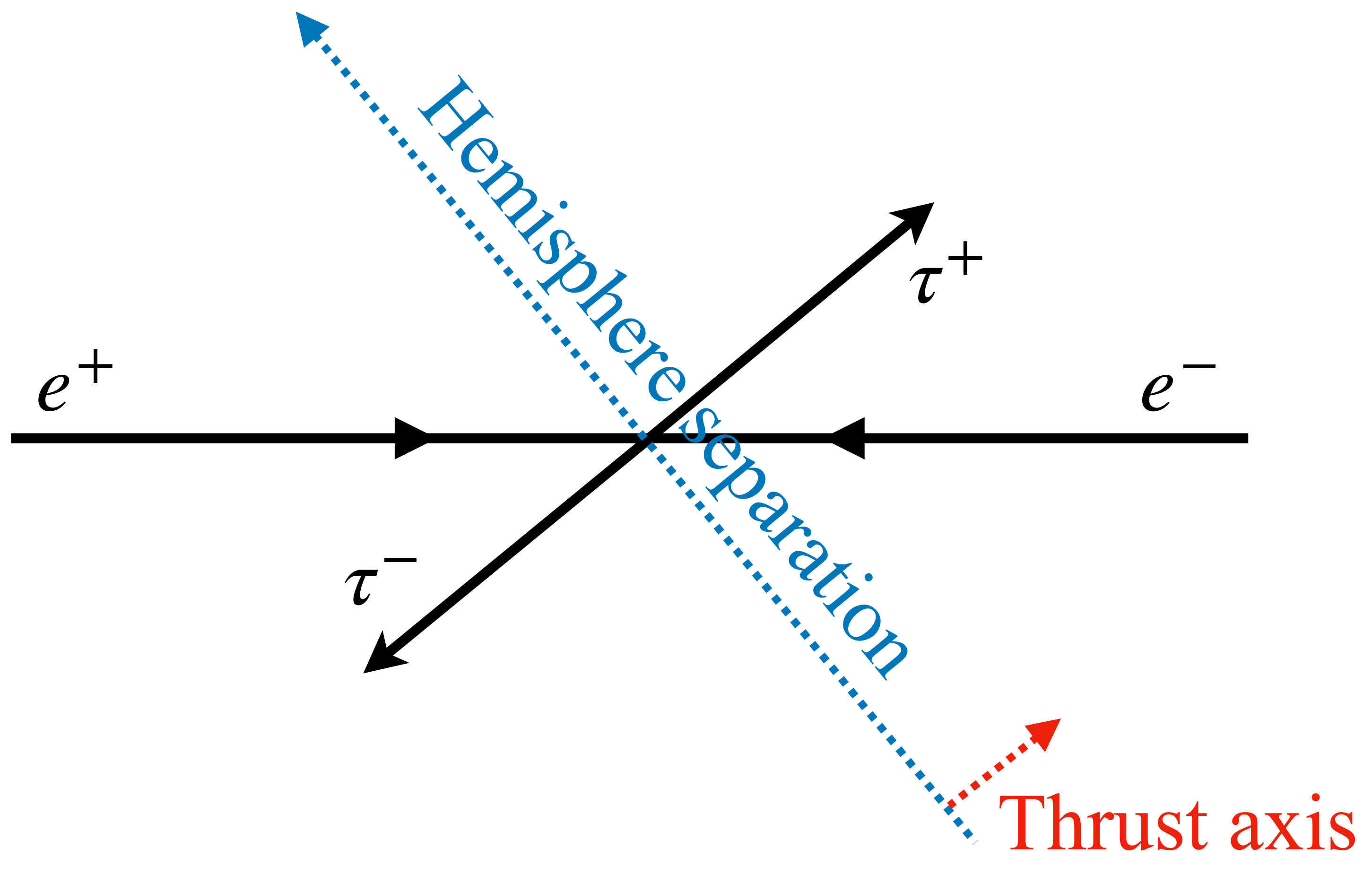


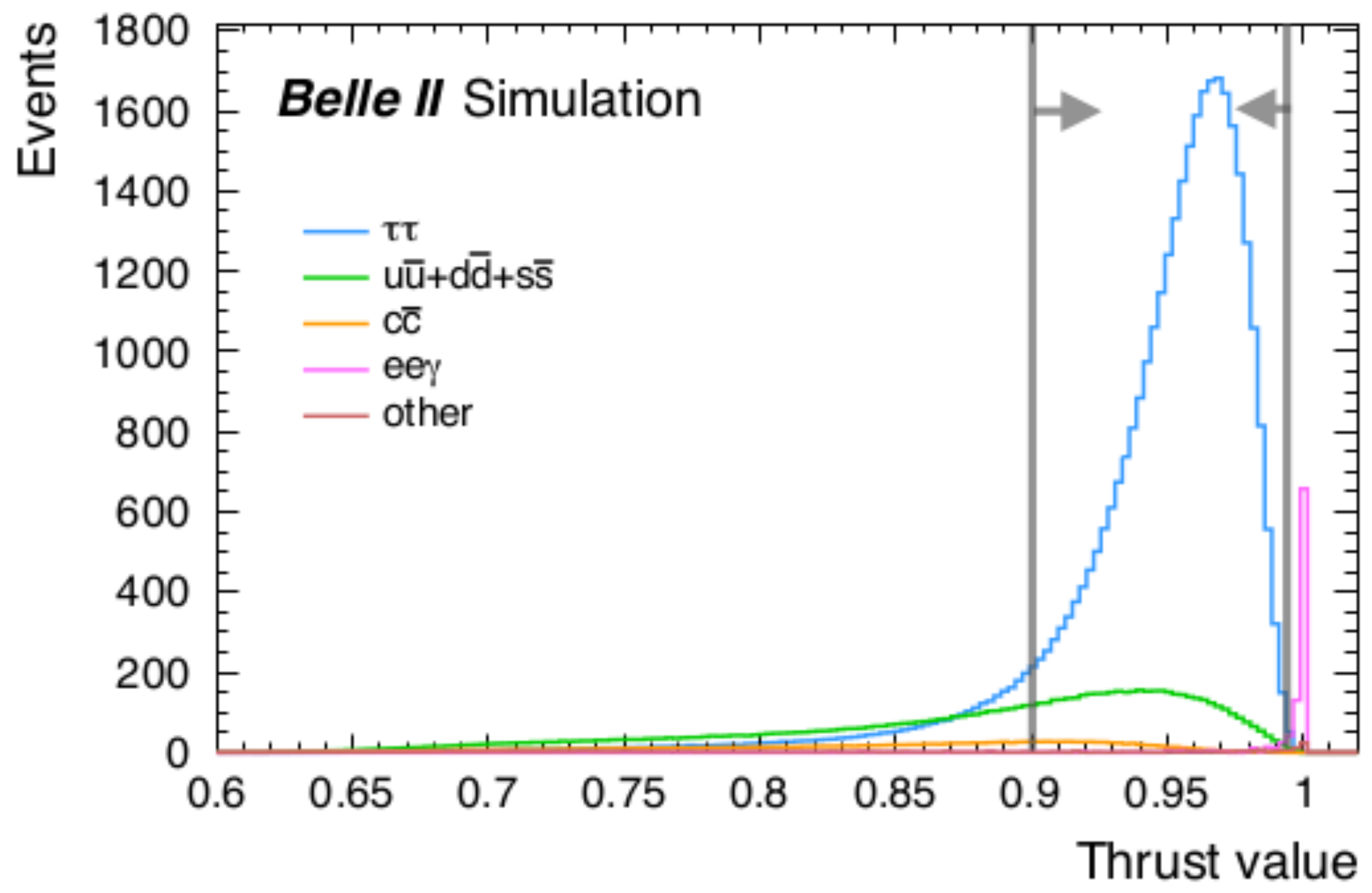
Belle @ KEKB, recorded $\sim 1\ \text{ab}^{-1}$

Belle II @ SuperKEKB, recorded $\sim 0.8\ \text{ab}^{-1}$ up to now

τ reconstruction at Belle (II)

- At least two missing neutrinos from τ SM decays → cannot fully reconstructed
- Separate $\tau^+\tau^-$ signals from $q\bar{q}$ $(q = u, d, s, c, b)$ and other events by the **thrust** (T) axis
- Some of common $\tau^+\tau^-$ reconstruction by number of charged tracks (**prong**) from τ decays
  - (1x1)-prong, (3x1)-prong, (3x3)-prong, Inclusive tagging method[†] …

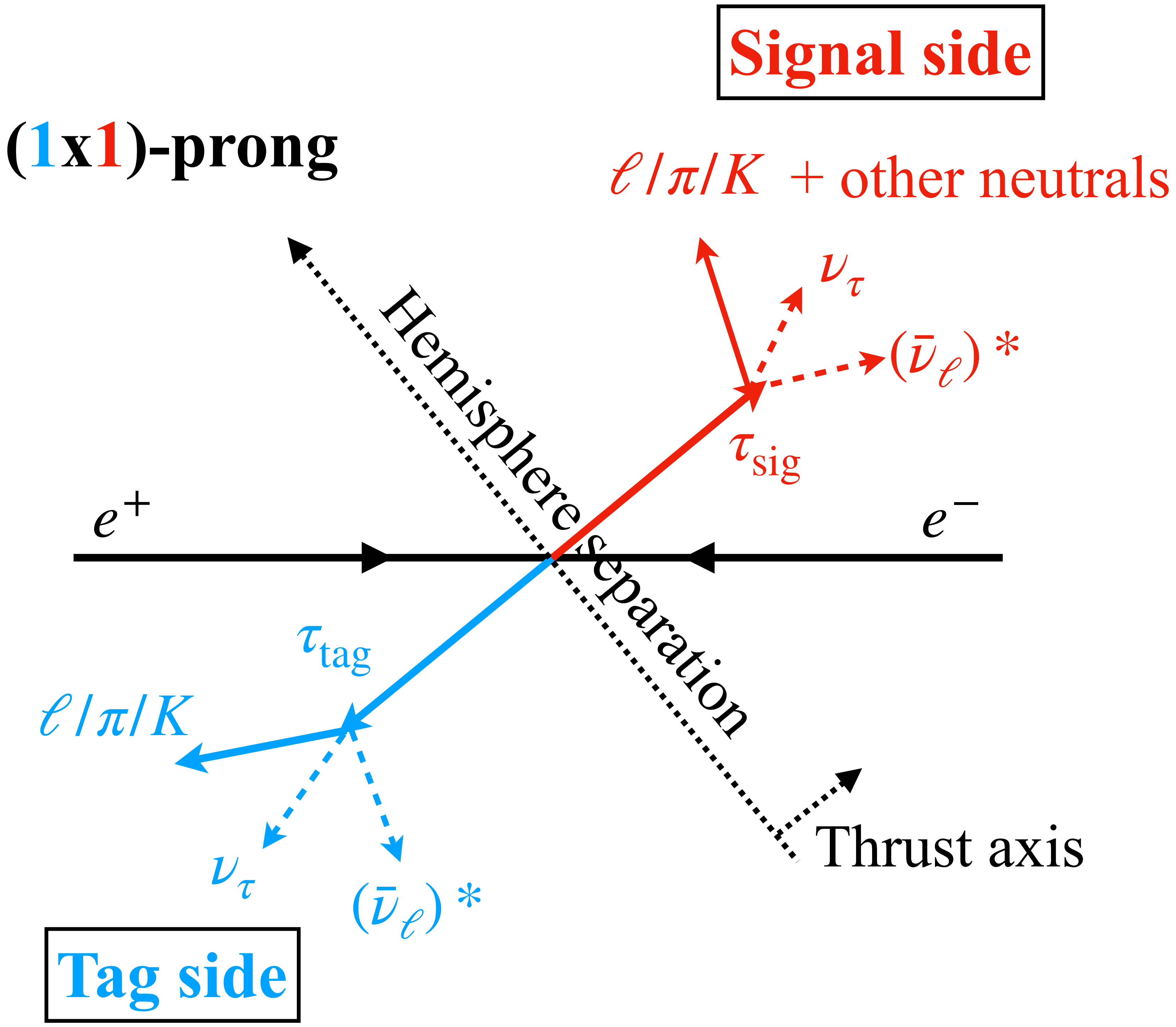


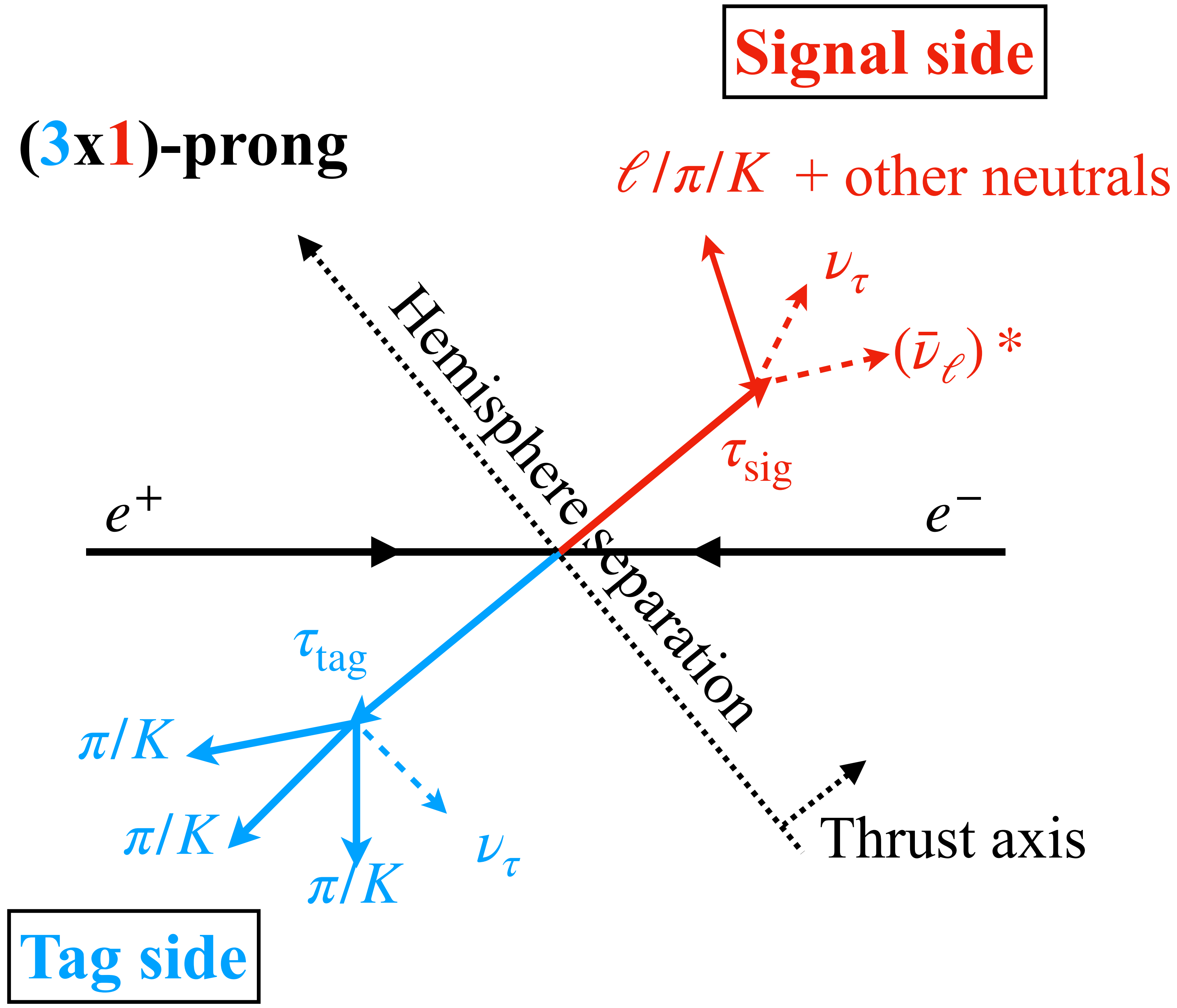


$$T = \max_{\hat{n}_T}\left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|}\right)$$

τ reconstruction at Belle (II)

- At least two missing neutrinos from τ SM decays $\rightarrow$ cannot fully reconstructed
- Separate $\tau^+\tau^-$ signals from $q\bar{q}$ $(q = u, d, s, c, b)$ and other events by the **thrust** (T) axis
- Some of common $\tau^+\tau^-$ reconstruction by number of charged tracks (**prong**) from τ decays
  - (1x1)-prong, (3x1)-prong, (3x3)-prong, Inclusive tagging method† …





* for leptonic decays

† used in Belle II, JHEP 09, 062 (2024)

Some of τ physics results at Belle (II)

BELLE Belle II

Tau mass: [Belle, PRL 99, 011801 (2007)] + [Belle II, PRD 108, 032006 (2023)]

Tau lifetime: [Belle, PRL 112, 031801 (2014)]

Tau LFU test ($\tau \to \ell \nu_\tau \bar{\nu}_\ell$): [Belle II, JHEP 08, 205 (2024)]

Tau electric dipole moment (EDM): [Belle, JHEP 04, 110 (2022)]

Tau Michel Parameter:

$\bar{\eta}$ & $\xi\kappa$ [Belle, PTEP 2018, 2, 023C01]; ξ' [Belle, PRL 131, 021801 (2023) + RPD]

Tau LFV search (part):

$\tau \to \ell\alpha$ [Belle II, PRL 130, 181803 (2023)] + [Belle, JHEP 08, 155 (2025)];

$\tau \to \mu\mu\mu$ [Belle II, JHEP 09, 062 (2024)]; $\tau \to \Lambda(\bar{\Lambda})\pi$ [Belle II, PRD 110, 112003 (2024)];

$\tau \to e\ell\ell$ [Belle II, JHEP 12, 169 (2025)]; $\tau \to \ell K_S^0$ [Belle+Belle II, JHEP 08, 092 (2025)]

Tau hadronic decay:

$\tau \to \pi\pi^0\nu_\tau$ [Belle, PRD 78, 072006 (2008)]; $\tau \to hhh\nu_\tau$ [Belle, PRD 81, 113007 (2010)];

$\tau \to K_S^0\nu_\tau + X$ [Belle, PRD 89, 072009 (2014)]; $\tau \to \pi K_S^0\nu_\tau$ CPV [Belle, PRL 107, 131801 (2011)]

Selected progress of τ physics at Belle II

Search for CPV in the $\tau \to \pi K_S^0 \nu_\tau$ decays

Consistent with SM within 1.2σ

To be submitted to JHEP

Search for LFV in the $\tau \to \mu\gamma$ decays

$\mathscr{B}(\tau^\pm \to \mu^\pm\gamma) < 9.5 \times 10^{-8}$ **at 90% C.L.**

To be submitted to JHEP

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

$\mathscr{B}(\tau^- \to e^-\eta) < 9.2 \times 10^{-8}$ **at 90% C.L.**

$\mathscr{B}(\tau^- \to \mu^-\eta) < 4.2 \times 10^{-8}$ **at 90% C.L.**

To be submitted to PRD

Precise measurement of τ hadronic decay

MC study and systematics on Branching Fraction and Spectral Function

Ongoing study

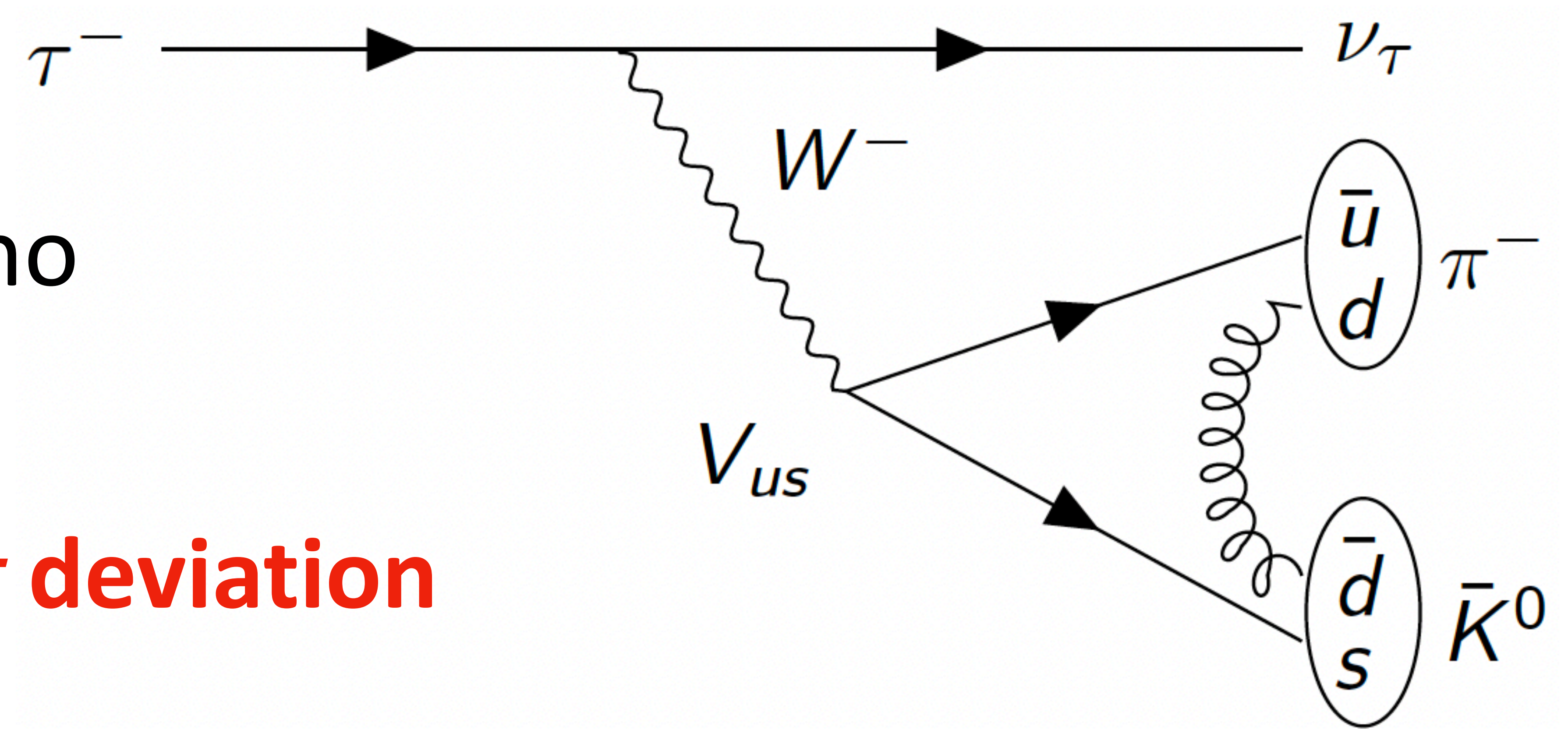
Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Motivation

- Charge-Parity Violation (CPV) in τ decays **remains far less unexplored** compared to the K^0, B, D, and baryon sectors
  - Sensitive probe for new CP-Violating phases
- Search for the direct CPV in the $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays with known $K^0 - \bar{K}^0$ mixing

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

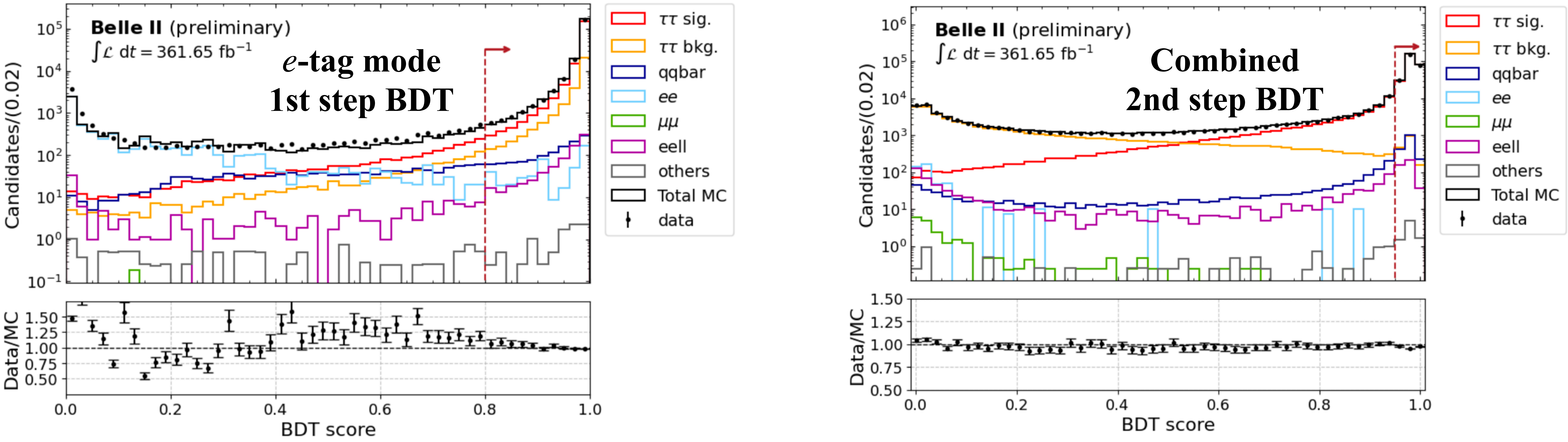
- The SM predicts $A_{CP}^{SM} \sim (0.33 \pm 0.01)\,\%$
- The Belle measured the A_{CP} using angular analysis, but no significant A_{CP}^{Belle} were reported: $|\mathrm{Im}(\eta_s)| < 0.026$
- The BaBar result: $A_{CP}^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\,\%$, **2.8$\sigma$ deviation from SM expectation**
- **A new measurement at Belle II is needed!**



Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Strategy

- (1x3)-prong topology: $\tau^-_{\text{sig}} \to \pi^-[K_S^0 \to \pi^+\pi^-]\nu_\tau(\geq 0\pi^0)$ with $\tau^+_{\text{tag}} \to \ell^+\nu_\ell\bar{\nu}_\tau$
- Obtain >98% of signal purity using a two-step Boosted Decision Tree (BDT) method to suppress background (continuum and $\tau\tau$ events)
- Raw asymmetry in data (A_{raw}) corrected for different factors to get true A_{CP}



Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Strategy

- (1x3)-prong topology: $\tau_{\rm sig}^- \to \pi^-[K_S^0 \to \pi^+\pi^-]\nu_\tau(\geq 0\pi^0)$ with $\tau_{\rm tag}^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$
- Obtain >98% of signal purity using a two-step Boosted Decision Tree (BDT) method to suppress background (continuum and $\tau\tau$ events)
- Raw asymmetry in data ($A_{\rm raw}$) corrected with different factors to get true $A_{\rm CP}$

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

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*

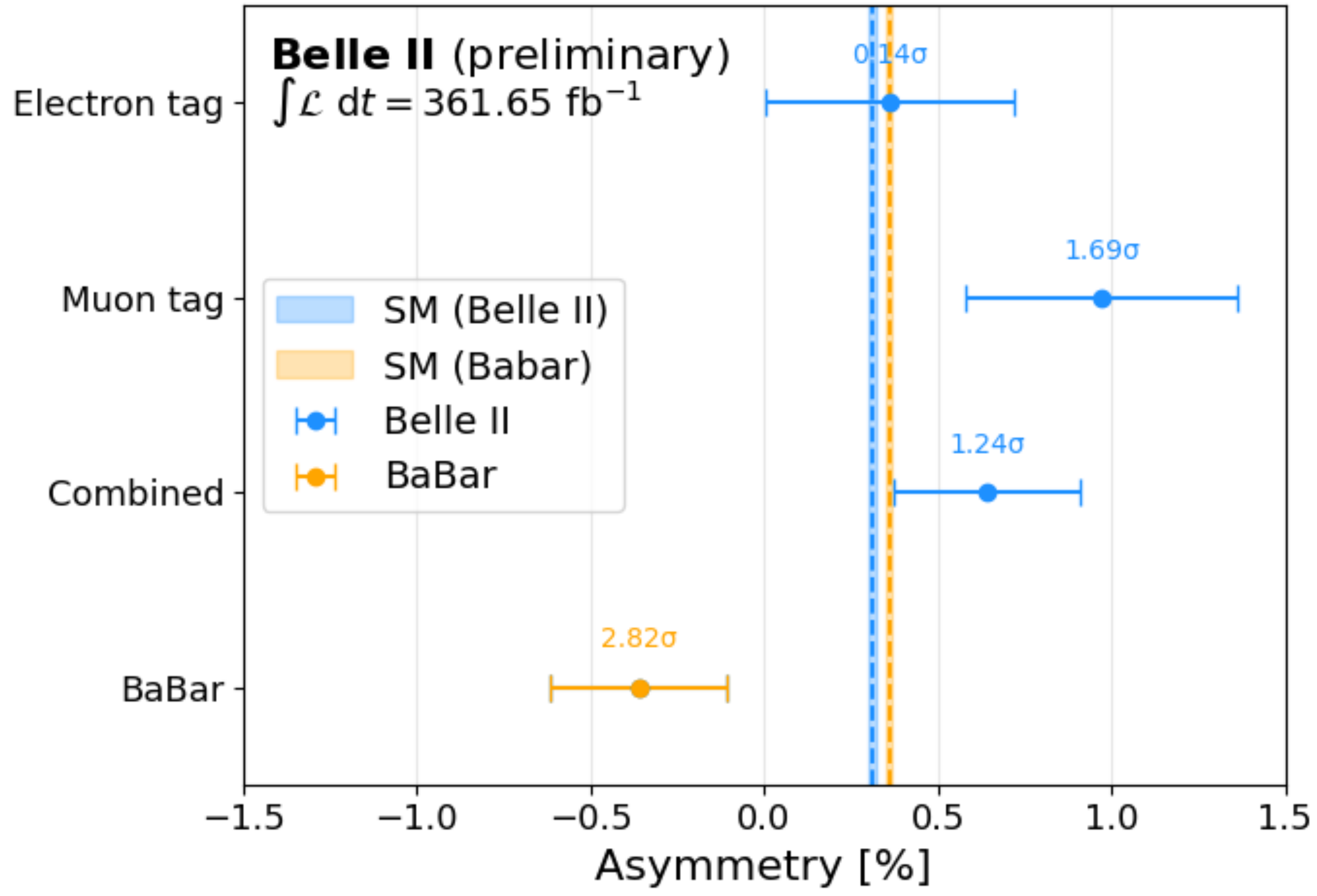
The goal of this work

* *Y. Grossman et al, JHEP 04, 179 (2026)*

Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Results

- Final $A_{\rm CP}$ depends on the K_S^0 decay-time efficiency* $\to$ correction required!
  - A non-uniform proper-time acceptance is modified
  - $A_{\rm CP}^{\rm SM}$ prediction is affected as well

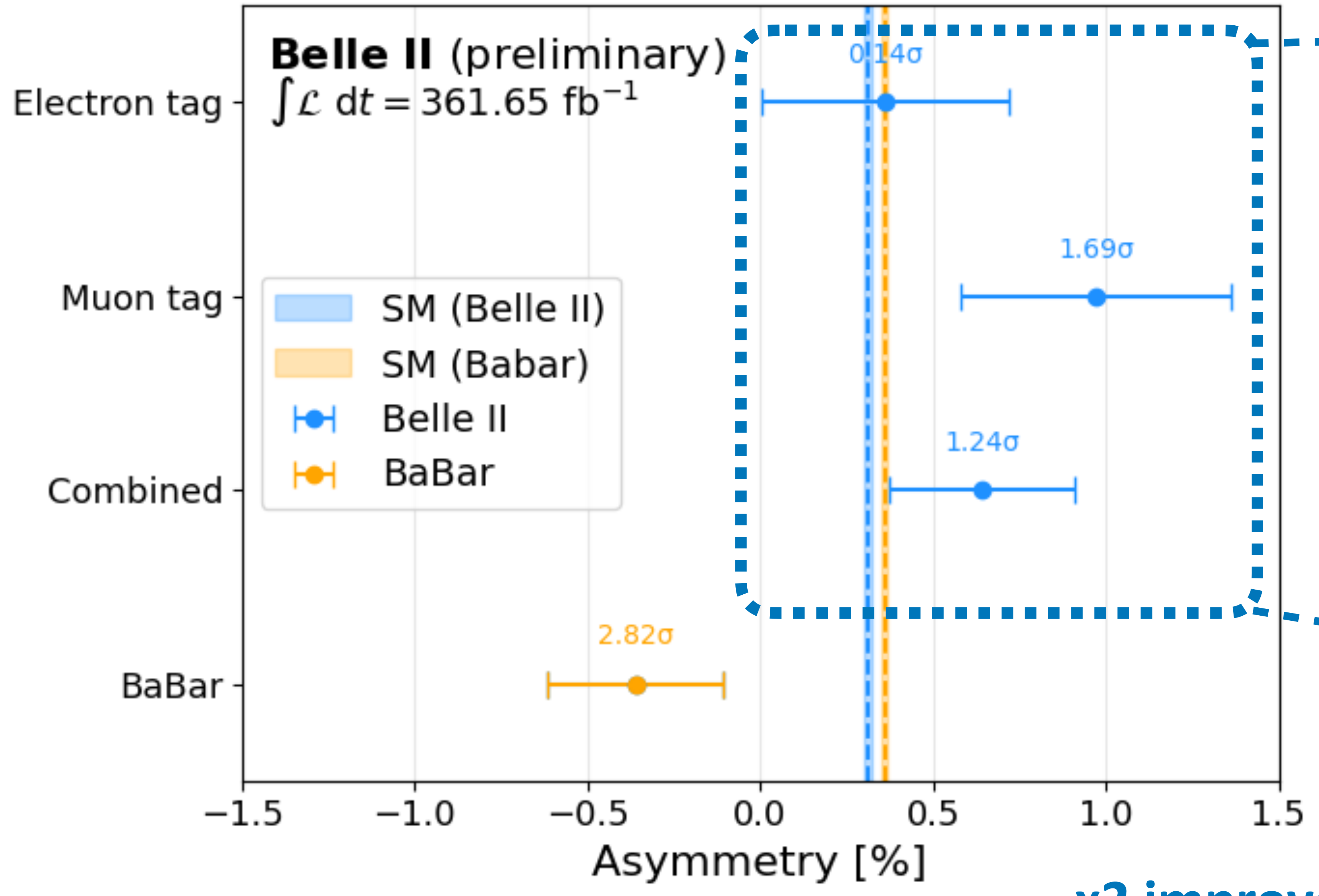


* *Y. Grossman et al, JHEP 04, 002 (2012), JHEP 04, 179 (2026)*

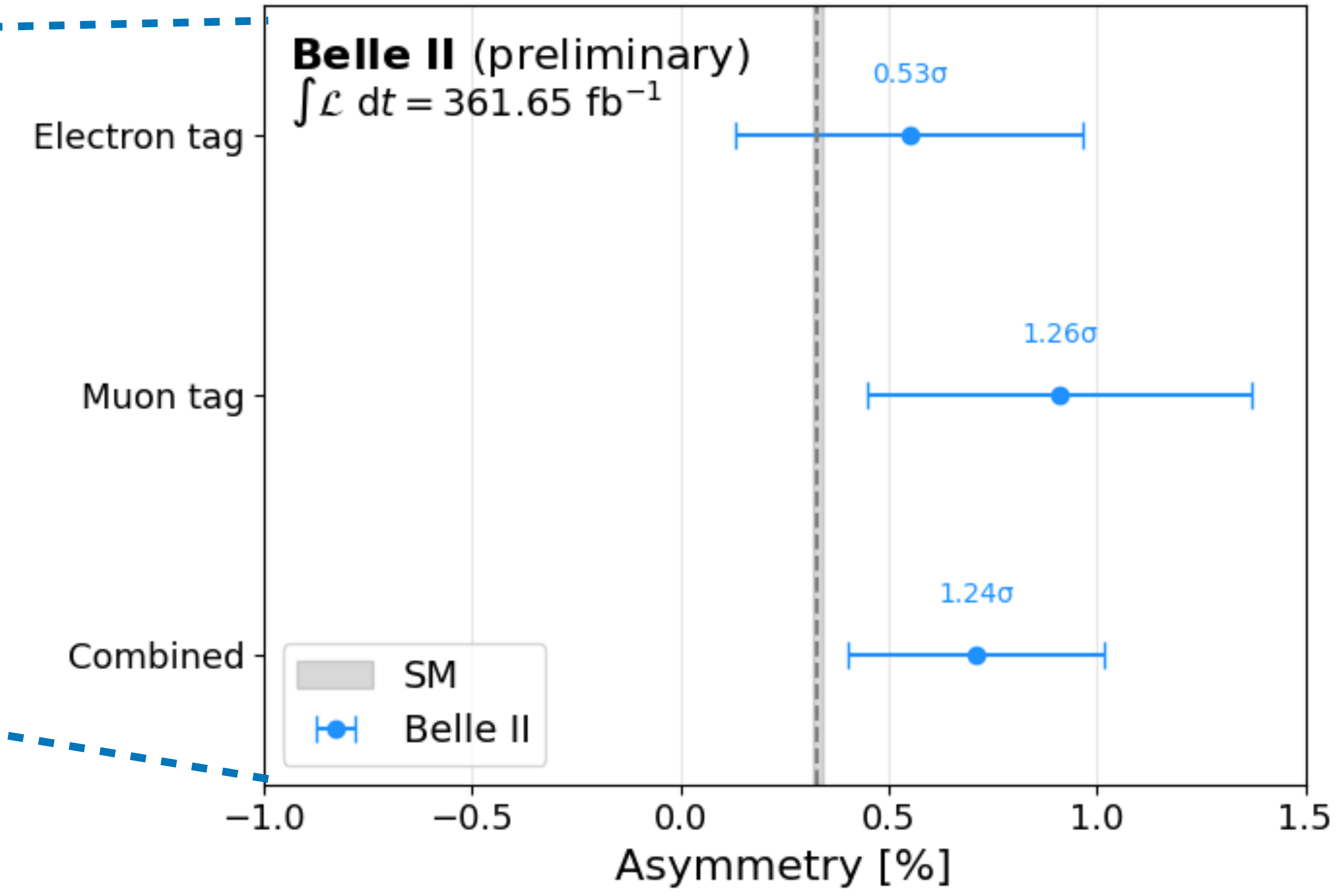
Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Results

- Final $A_{\rm CP}$ depends on the K_S^0 decay-time efficiency* $\to$ correction required!
  - A non-uniform proper-time acceptance is modified
  - $A_{\rm CP}^{\rm SM}$ prediction is affected as well



Belle II results corrected with considering the K_S^0 decay-time efficiency; so it can be compared with SM directly



x2 improvement in syst.

$$A_{\rm CP}^{\rm Belle\ II} = (0.71 \pm 0.26_{\rm stat} \pm 0.06_{\rm syst} \pm 0.15_{\rm corr})\ \%$$

Consistent with SM prediction within **1.24σ**

To be submitted to JHEP

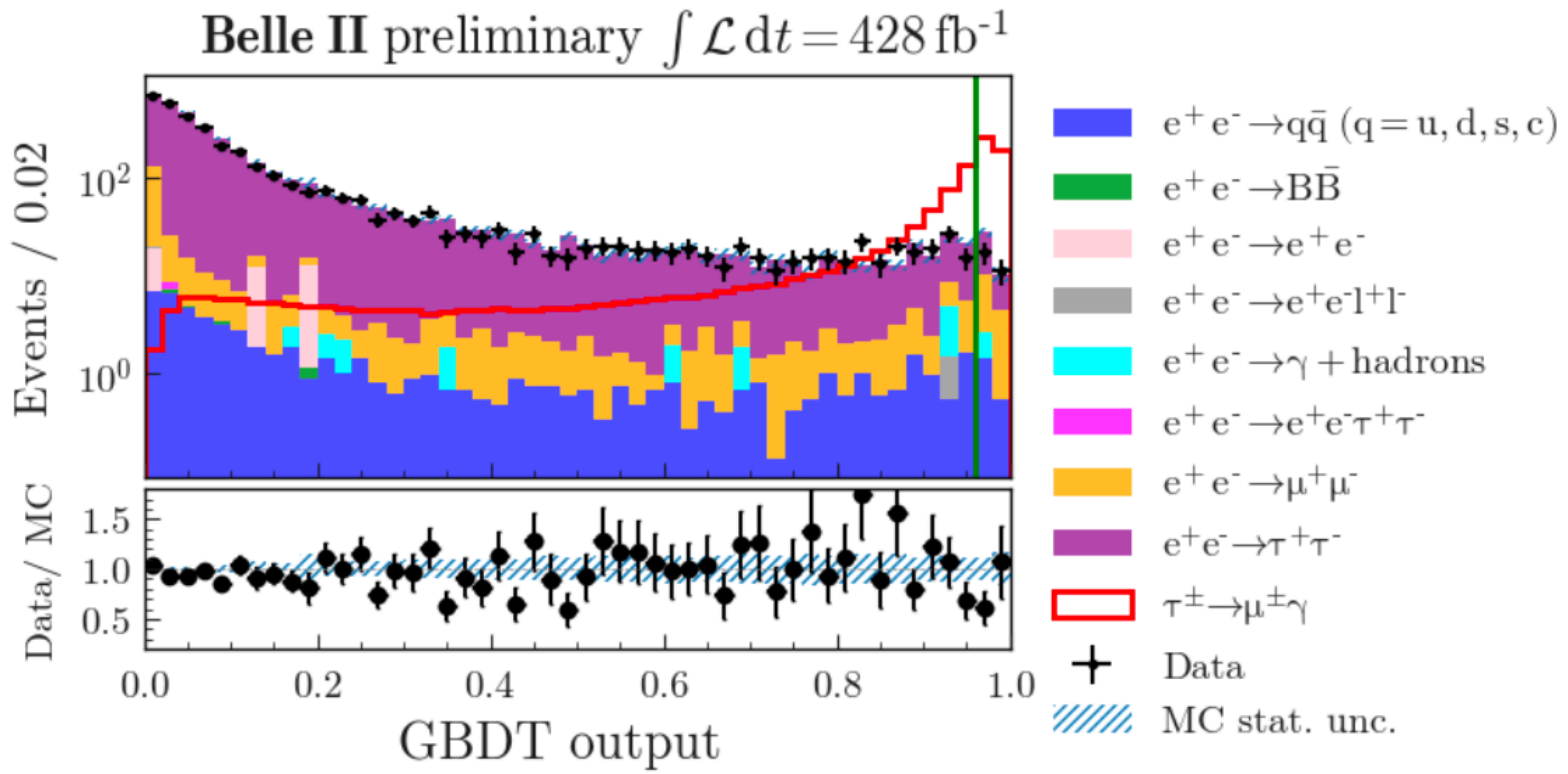
* *Y. Grossman et al, JHEP 04, 002 (2012), JHEP 04, 179 (2026)*

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

- World's best upper limit from Belle with $988\ \text{fb}^{-1}$*: $\mathscr{B}(\tau^- \to \mu^-\gamma) < 4.2 \times 10^{-8}$

- (1x1)-prong topology: $\tau^-_{\text{sig}} \to \mu^-\gamma$ with $\tau^+_{\text{tag}} \to \ell^+\nu_\ell\bar{\nu}_\tau$ and $\tau^+_{\text{tag}} \to \pi^+\pi^0\bar{\nu}_\tau$
- Background suppression with Gradient BDT: $50\ \%$ increase in signal efficiency and 80% decrease in background level

- Search signal in 2D plane of:
  - $M_{bc} = \sqrt{(E^*_{\text{beam}})^2 - (\vec{p}^{\,*}_{\mu\gamma})^2}$
  - $\Delta E' = \frac{\Delta E}{\sqrt{s}} = \frac{E^*_{\mu\gamma} - E^*_{\text{beam}}}{\sqrt{s}}$
  - * means e^+e^- c.m. frame



* Belle, JHEP 10, 019 (2021)

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

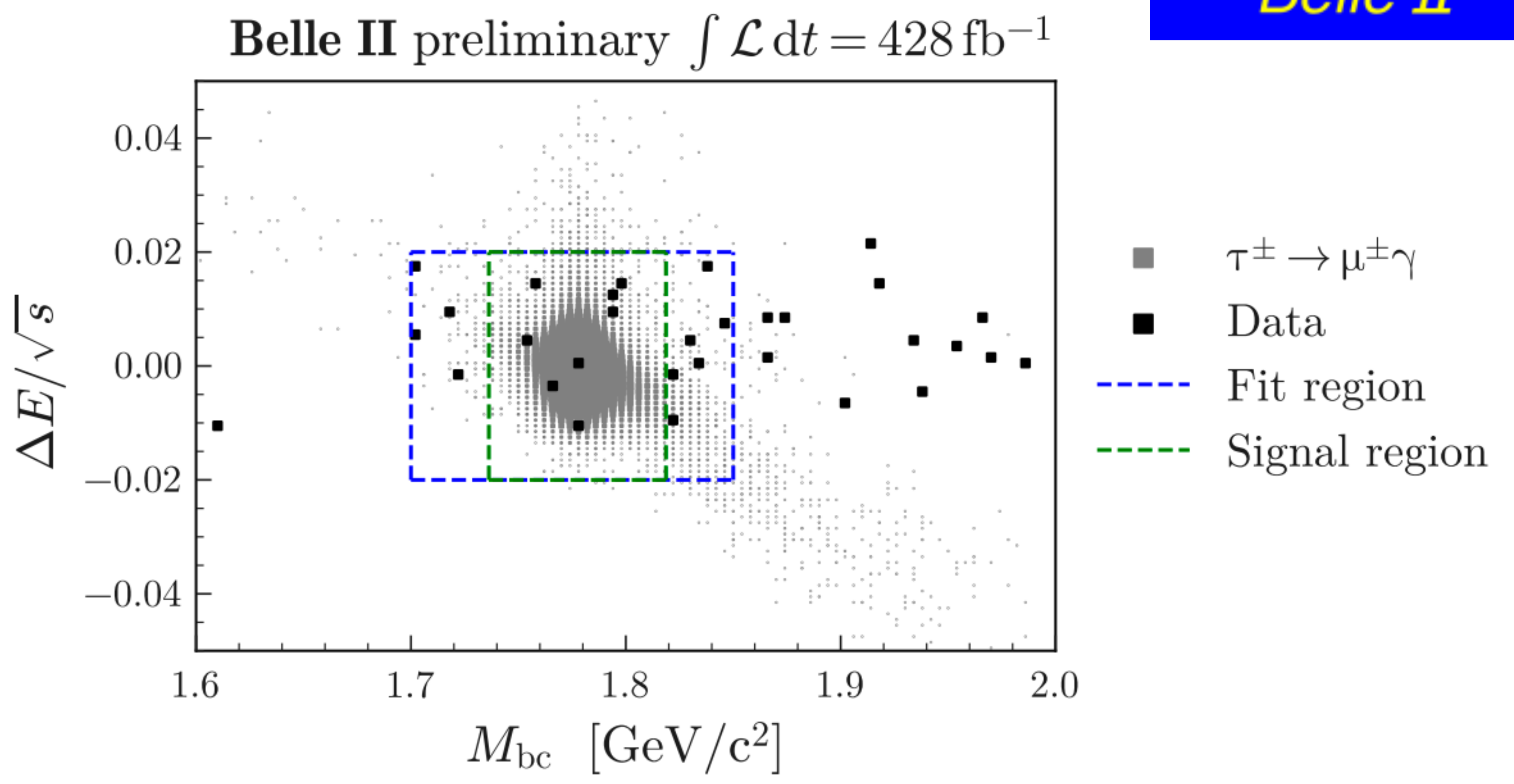
- Use unbinned maximum likelihood fits on (M_{bc}, $\Delta E'$)
  - Expected events from sideband events: 15.7 ± 3.4
  - Observed events in signal region: 18

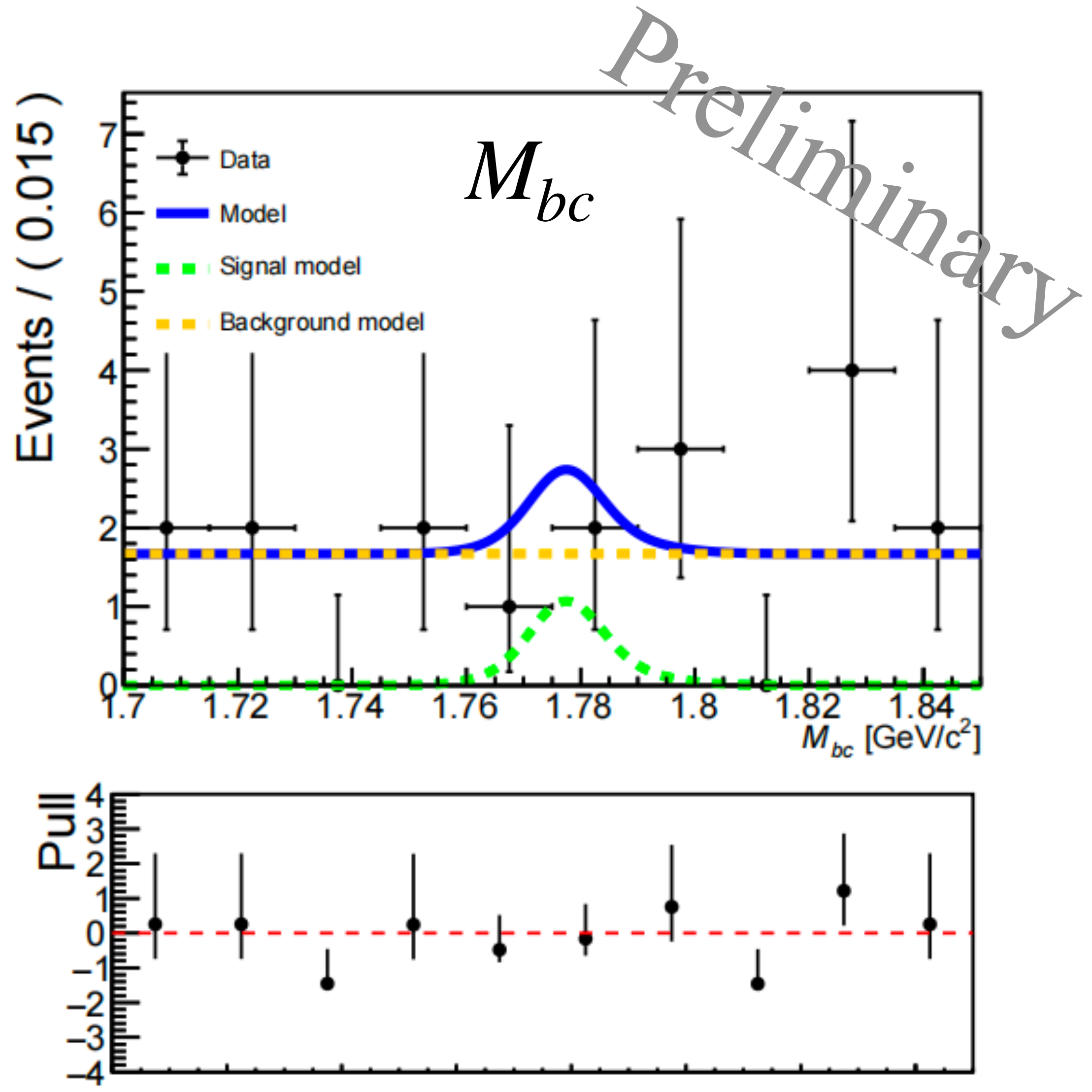
- Fit result of signal yield is consistent with 0
  - Upper limit set at 90% C.L.:

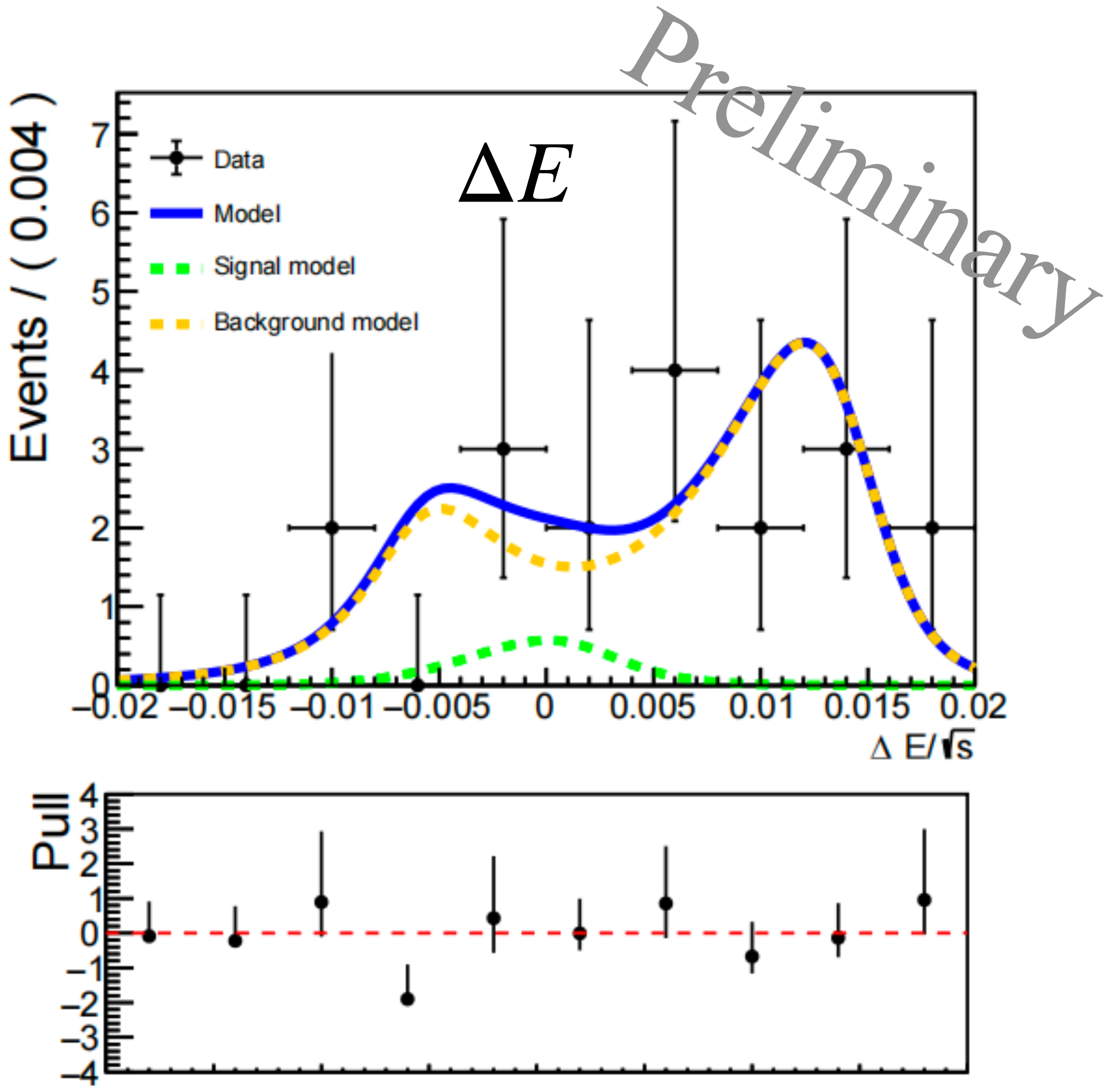
$$\mathscr{B}(\tau^- \to \mu^-\gamma)^{\mathrm{exp}} < 5.8 \times 10^{-8}$$

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

- Consistent with previous Belle result
- **Belle II with same statistics is expected to be better than Belle thanks to higher efficiency and lower background**







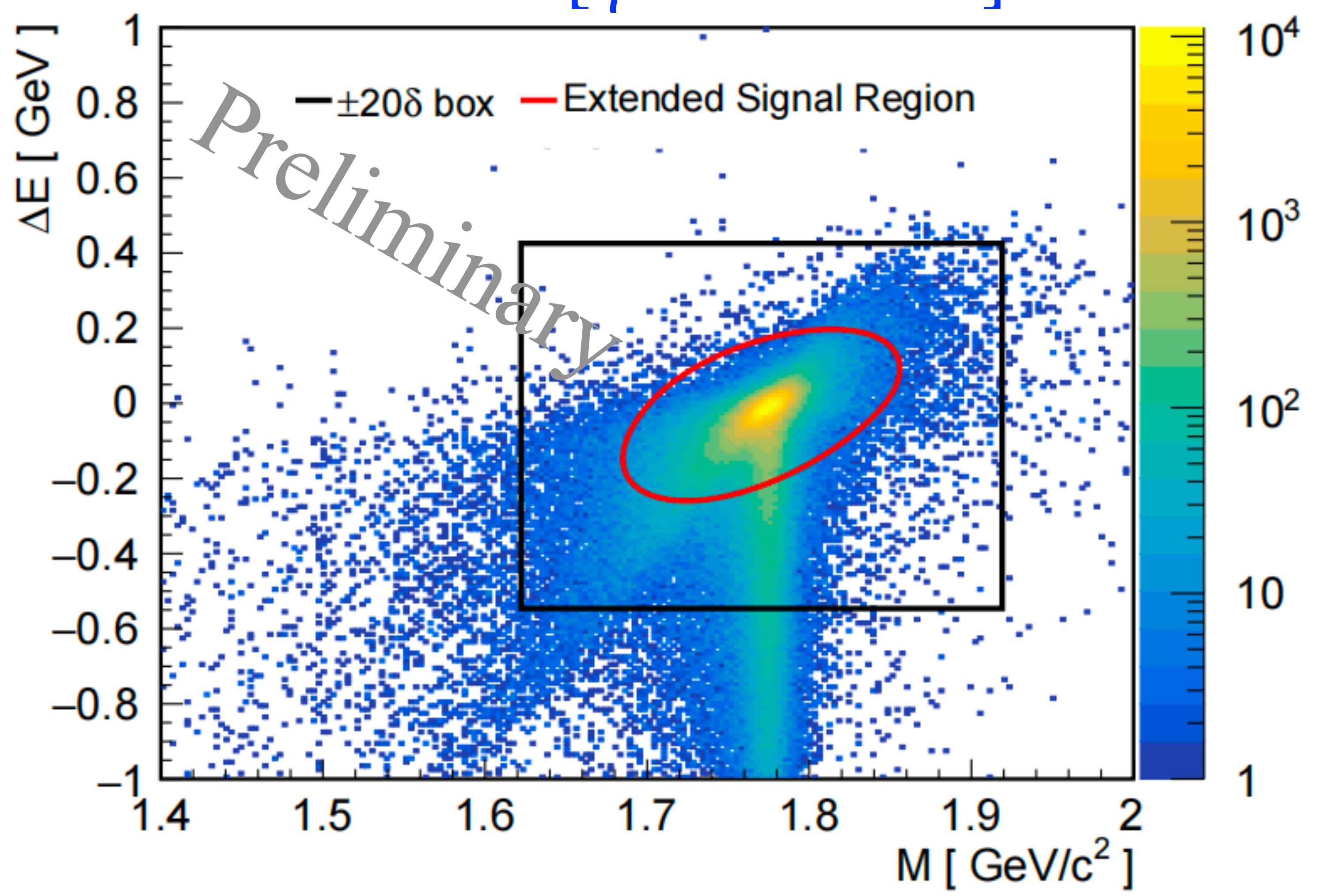
To be submitted to JHEP

* Belle, JHEP 10, 019 (2021)

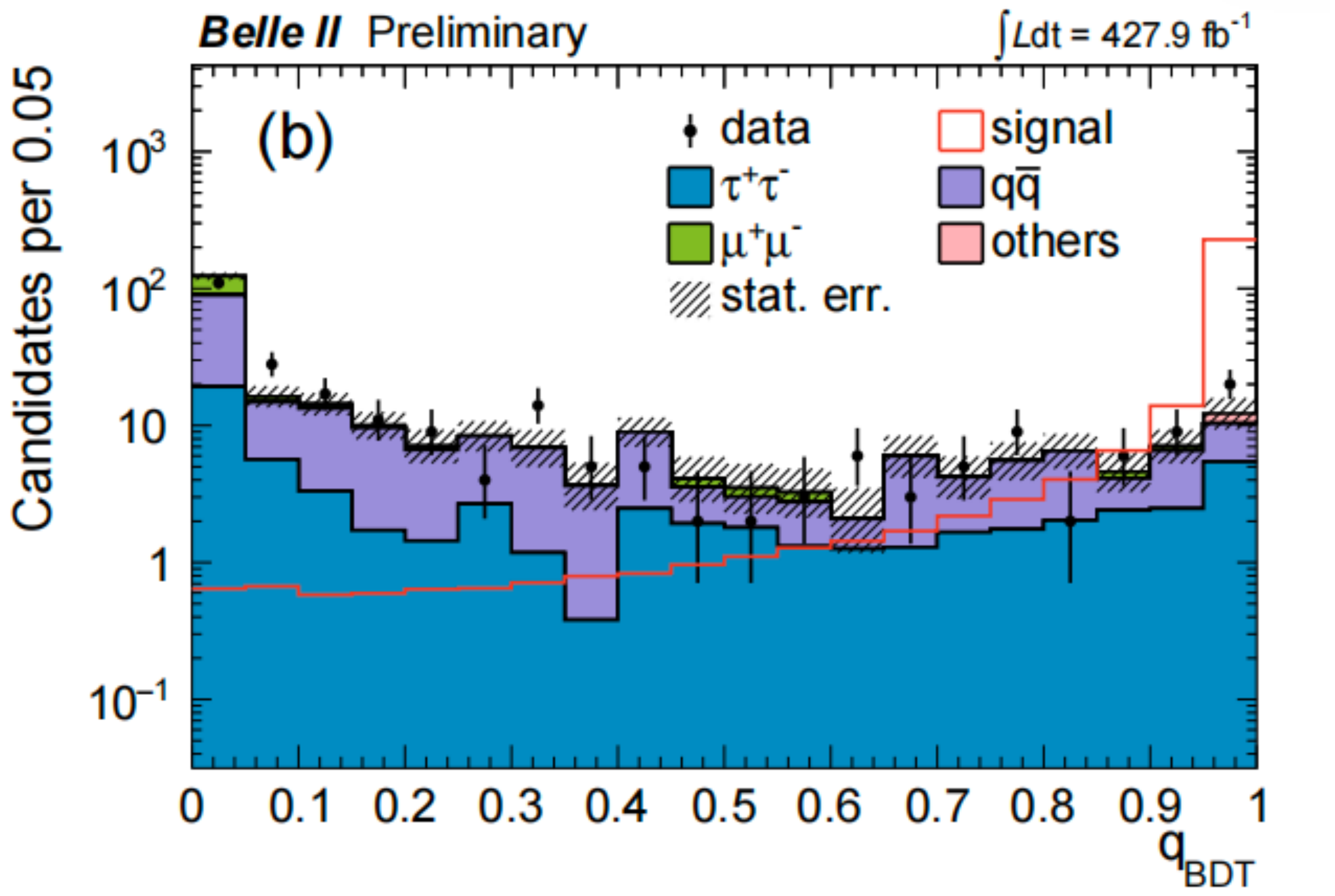
Search for LFV in $\tau^- \to \ell^-\eta$ decays at Belle II

- World's best upper limit from Belle with $401\ \mathrm{fb}^{-1}$*:
  - $\mathscr{B}(\tau^- \to e^-\eta) < 9.2 \times 10^{-8}$ and $\mathscr{B}(\tau^- \to \mu^-\eta) < 6.5 \times 10^{-8}$
- [1x1(3)]-prong topology: $\tau^-_{\mathrm{sig}} \to \ell^-[\eta \to \gamma\gamma/\pi^+\pi^-\pi^0]$ with $\tau^+_{\mathrm{tag}} \to$ a single charged track
- Background suppression with BDT method for $\eta \to \gamma\gamma$ mode and cut-based method for $\eta \to \pi^+\pi^-\pi^0$ mode
- Search signal in 2D plane of:
  - $M = \sqrt{(\vec{p}_\ell + \vec{p}_\eta)^2}$
  - $\Delta E = E_\tau^{\mathrm{c.m.}} - \sqrt{s}/2$

$\tau^- \to e^-[\eta \to \pi^+\pi^-\pi^0]$



$\tau^- \to \mu^-[\eta \to \gamma\gamma]$, Sideband region



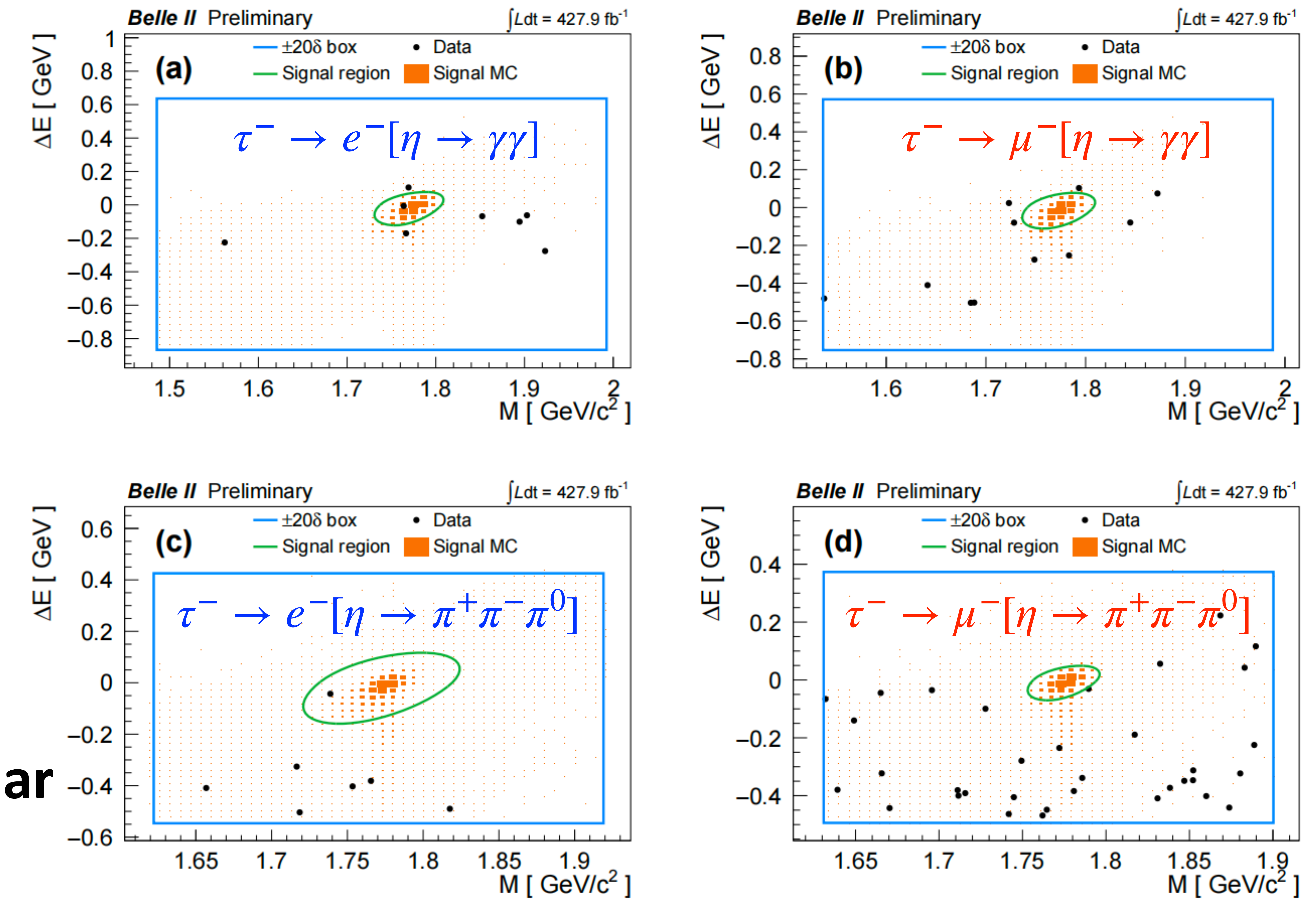
* Belle, PLB 648, 341 (2007)

Search for LFV in $\tau^- \to \ell^- \eta$ decays at Belle II

- Use unbinned maximum likelihood fits on $(M, \Delta E)$

$$\mathcal{L}_i(\mu, \boldsymbol{\theta}|N_i) = (\mu s_i + b_i)^{N_i} \times \frac{e^{-(\mu s_i + b_i)}}{N_i!} \times f(\boldsymbol{\theta})$$

Channel	Observed	Expected
$e^-\eta(\to \gamma\gamma)$	1	$0.22^{+0.54}_{-0.18}$
$\mu^-\eta(\to \gamma\gamma)$	0	$0.36^{+0.83}_{-0.28}$
$e^-\eta(\to \pi^+\pi^-\pi^0)$	1	$0.06^{+0.09}_{-0.04}$
$\mu^-\eta(\to \pi^+\pi^-\pi^0)$	0	$0.28^{+0.09}_{-0.08}$



- Fit result of signal yield is consistent with 0
  - Upper limit set at 90% C.L.:

$$\mathscr{B}(\tau^- \to e^-\eta)^{\text{exp (obs)}} < 4.6\ (9.2) \times 10^{-8}$$

$$\mathscr{B}(\tau^- \to \mu^-\eta)^{\text{exp (obs)}} < 4.4\ (4.2) \times 10^{-8}$$

- Consistent with previous Belle results
- **World-leading result in muon channel, similar precision to Belle in electron channel**

To be submitted to PRD

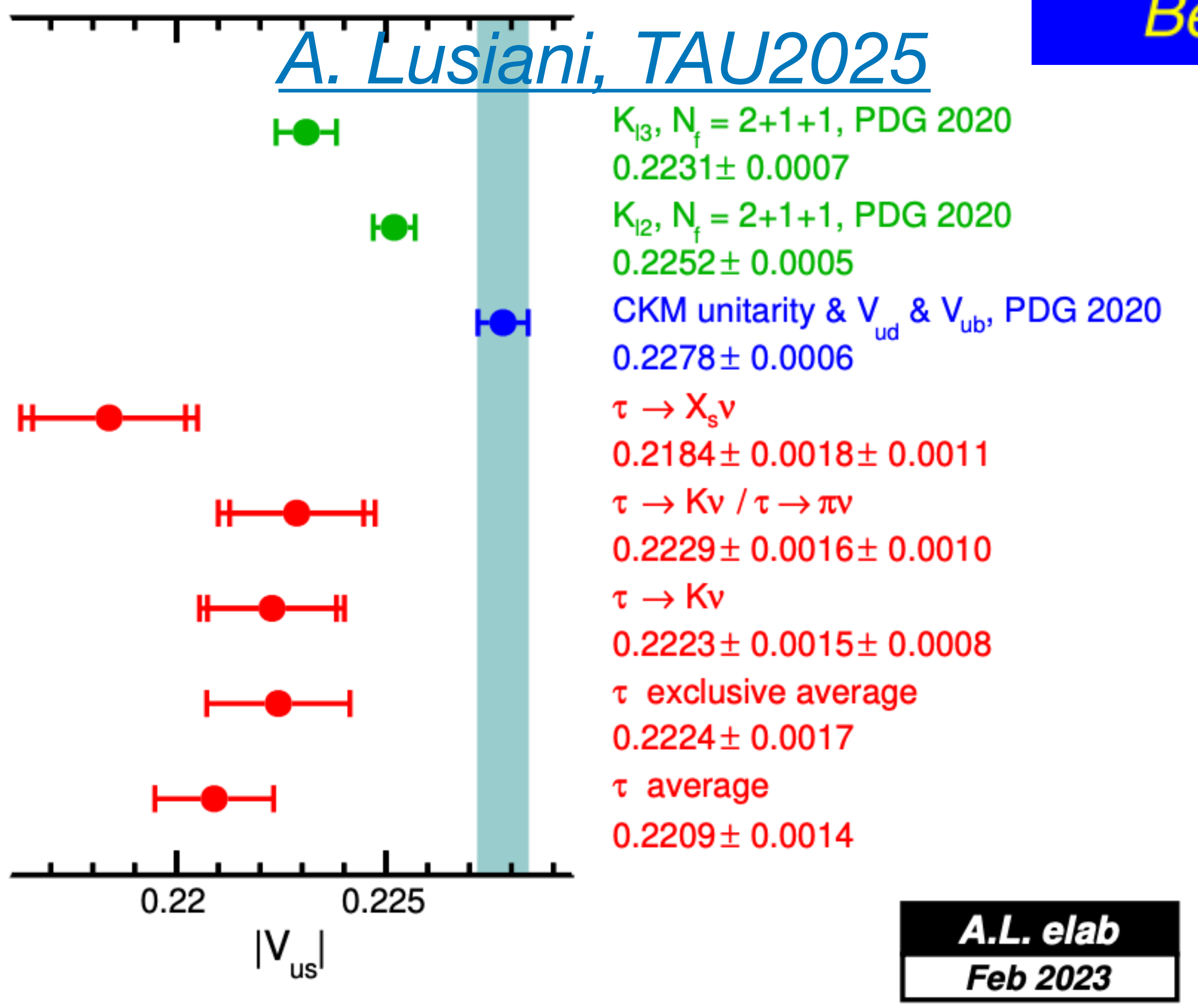
Precise measurement of τ hadronic decay at Belle II

- Branching fractions (BF) and spectral functions (SF) of τ hadronic decays provide important input for $|V_{us}|$, $|V_{ud}|$ and a_μ^{had}
  - Persistent >3σ discrepancy exists in $|V_{us}|$ between τ measurements and unitary expectation
  - Persistent discrepancy exists between $a_\mu^{e^+e^-}$ and a_μ^{exp}, $\tau \to 2\pi/4\pi\nu_\tau$ via conserved vector current* relation can contribute

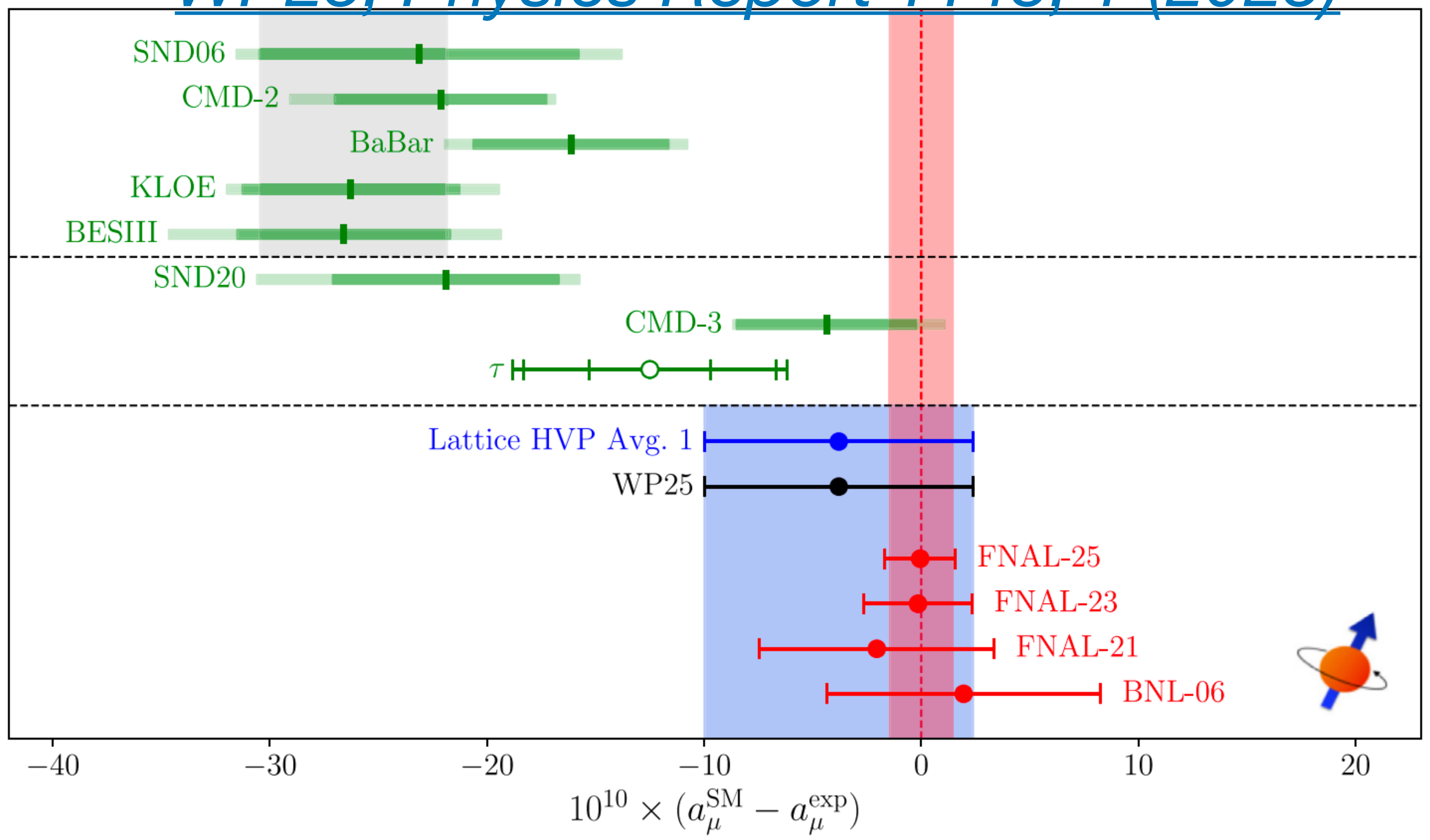
* *ADH, EPJC 2, 123 (1998)*

- Precise results on BF from LEP (ALEPH mainly)
  - Belle II can perform an independent measurement!
- Precise results on SF from BaBar and Belle
  - Belle II can provide more statistics!

A. Lusiani, TAU2025

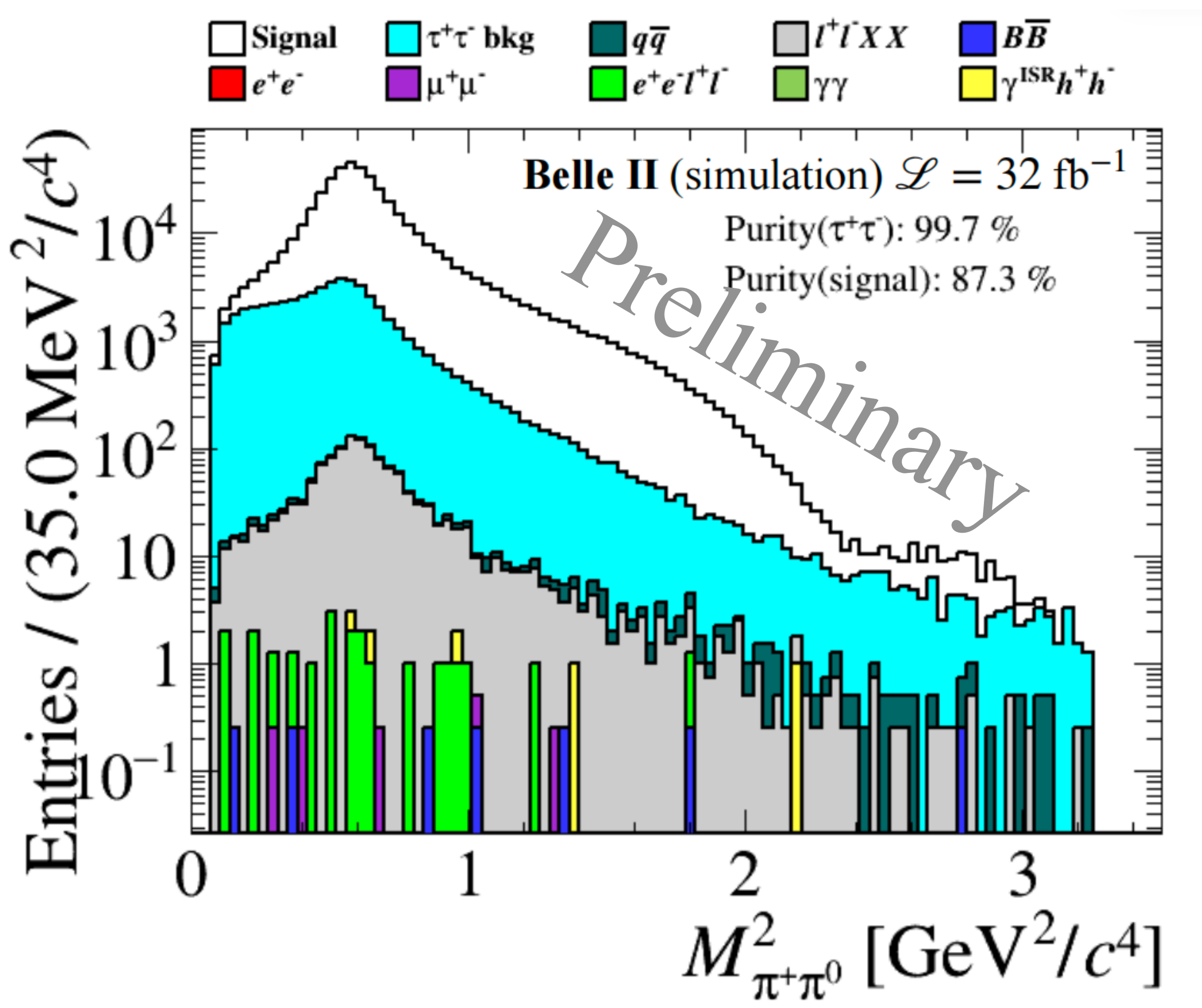


WP25, Physics Report 1143, 1 (2025)

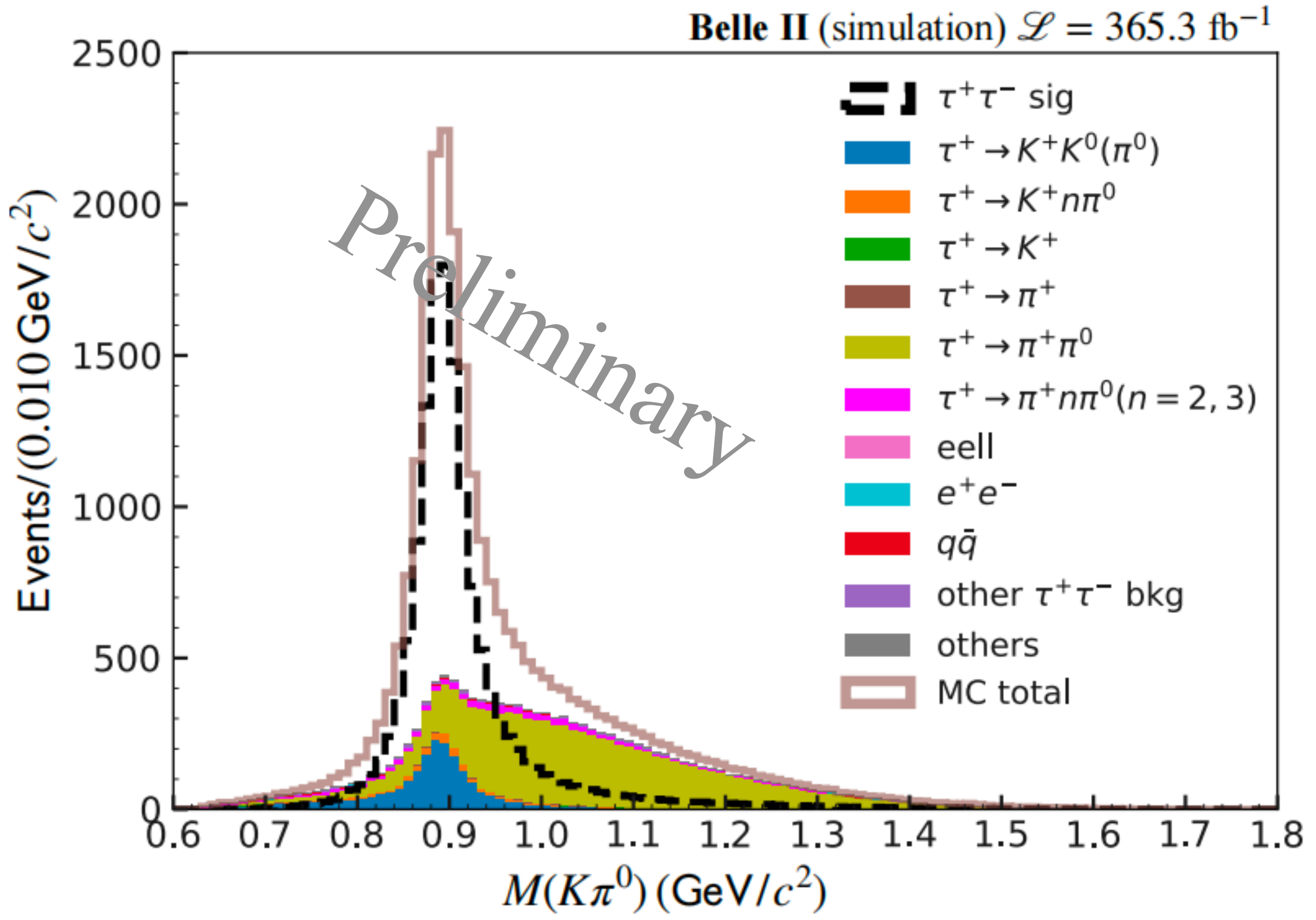


Precise measurement of τ hadronic decay at Belle II

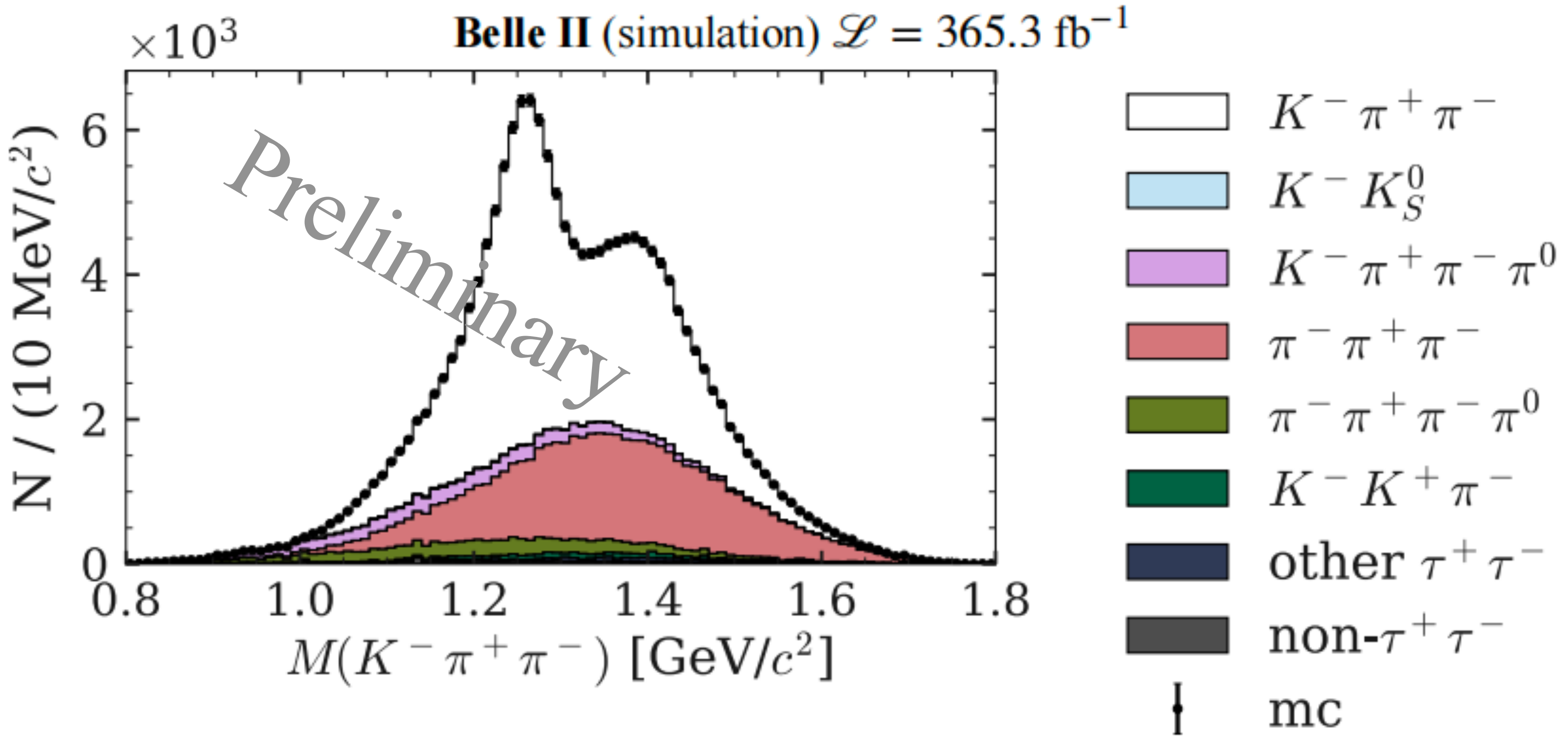
$\tau^- \to \pi^-\pi^0\nu_\tau$

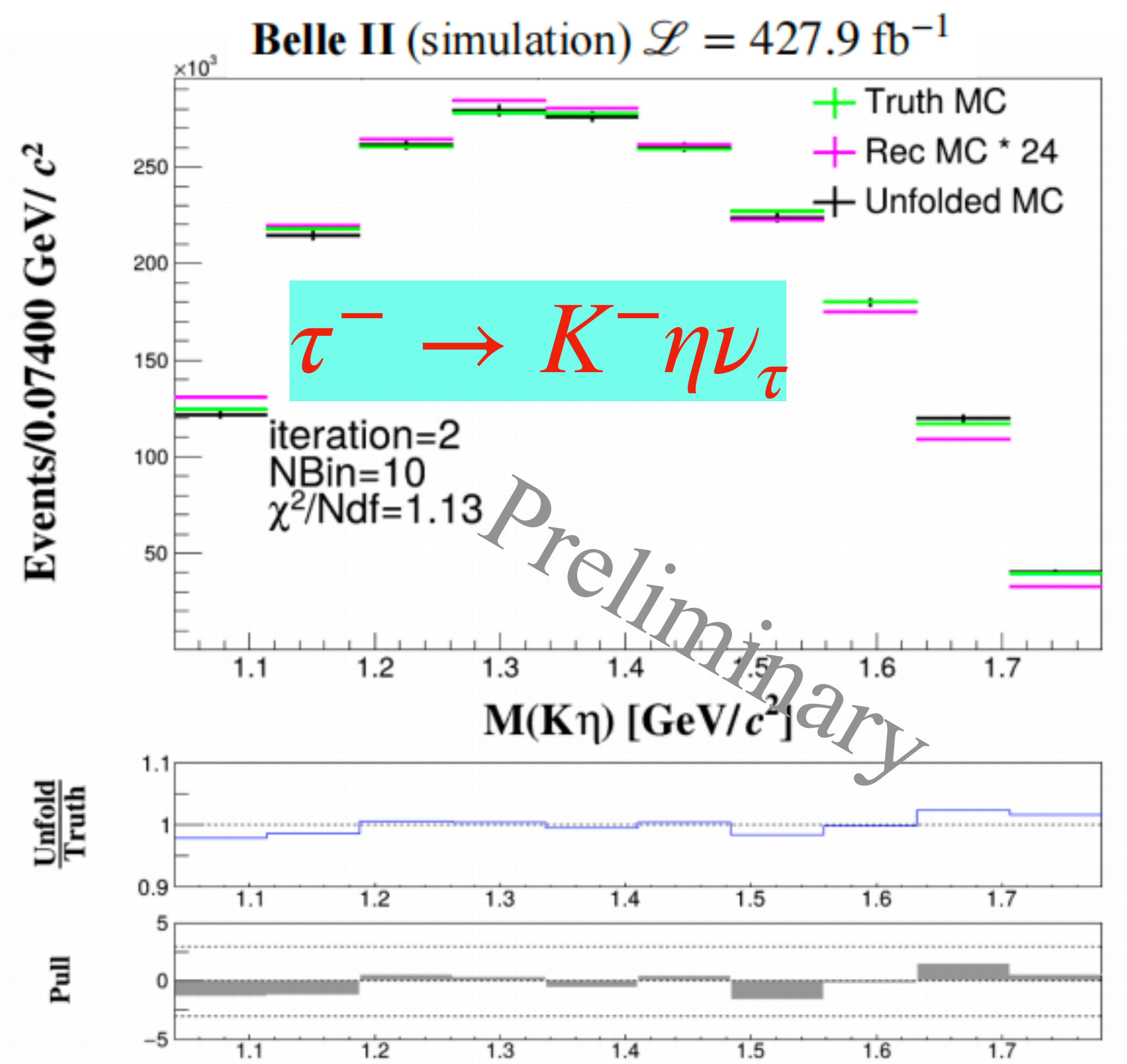


$\tau^- \to K^-\pi^0\nu_\tau$

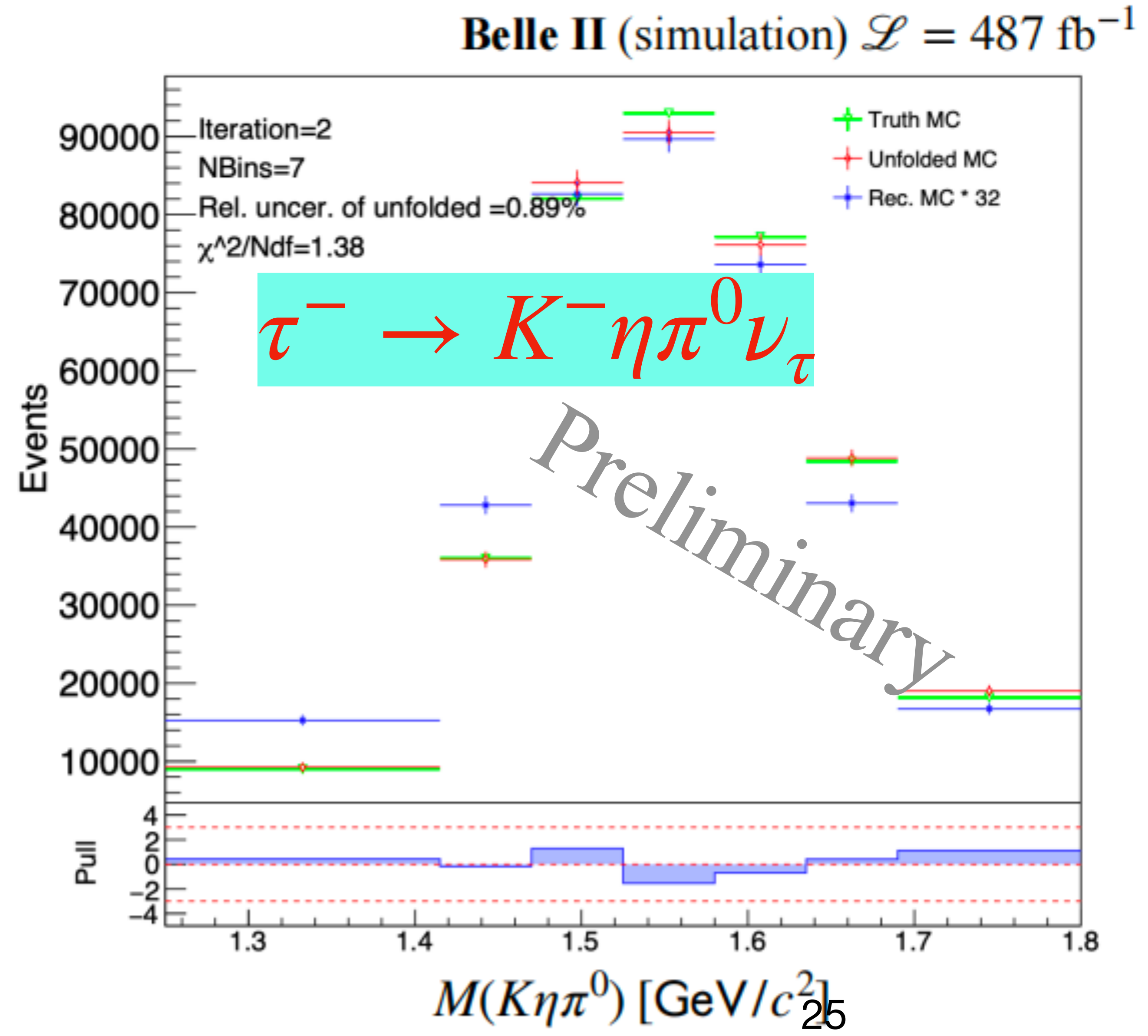


$\tau^- \to K^-\pi^+\pi^-\nu_\tau$

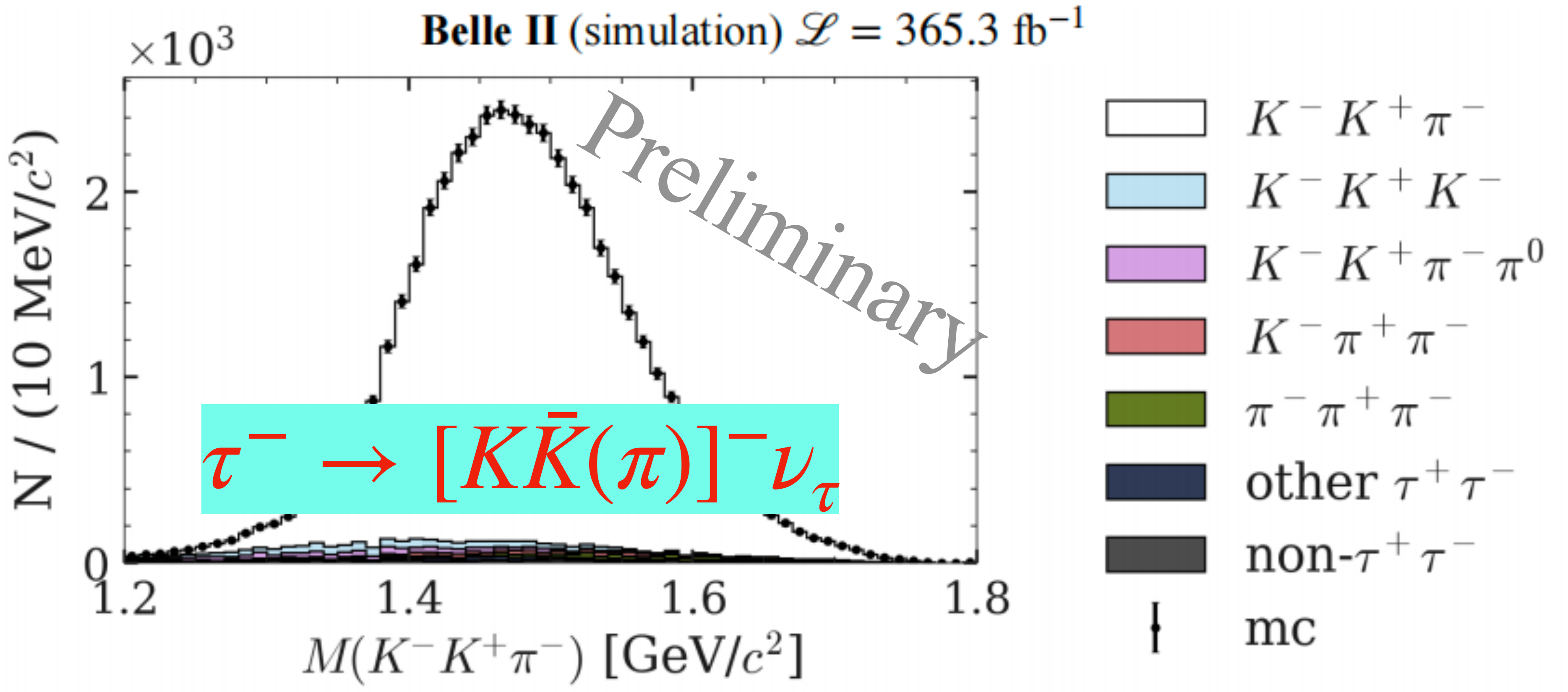




$\tau^- \to K^-\eta\nu_\tau$



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



$\tau^- \to [K\bar{K}(\pi)]^-\nu_\tau$

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

Uncertainties in τ hadronic decay at Belle II

- The measurements on BF and SF are mainly dominant by systematic uncertainties at Belle II
- $\pi \leftrightarrow K$ and other misidentification (misID)
  - Lower misID rates lead to smaller systematic uncertainty (Belle II particle identification (PID) performance is much better than Belle and BaBar)
- π^0/γ reconstruction efficiency
  - **Has a leading impact on modes with π^0 (already improved at Belle II to around 1.4%)**
  - One of the leading impact on all modes for γ vetos
- K_S^0 reconstruction efficiency
  - One of the leading impact on modes with K_S^0
- Backgrounds from poorly studied decays (shape is also important)
  - Depends on mode (in most analysis at Belle II, data-driven corrections are obtained)
- Normalization Channel
  - **Reduce a lot of systematics** including luminosity, cross section, tracking and so on

Summary

- Belle and Belle II, as B-factories, are also τ-factories with a huge $\tau^+\tau^-$ statistics
- Searches for LFV and CPV in τ decays offer a unique window onto New Physics; many anomalies still exist in present τ-related physics
  - Belle (II) can contribute, and we already do
- More results of τ properties and decays will come in the future!

Yipu Liao (廖一朴)
IHEP, CAS, Beijing
liaoyp@ihep.ac.cn

Thank you for listening!

Reference of New Physics prediction on LFV τ decays

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]

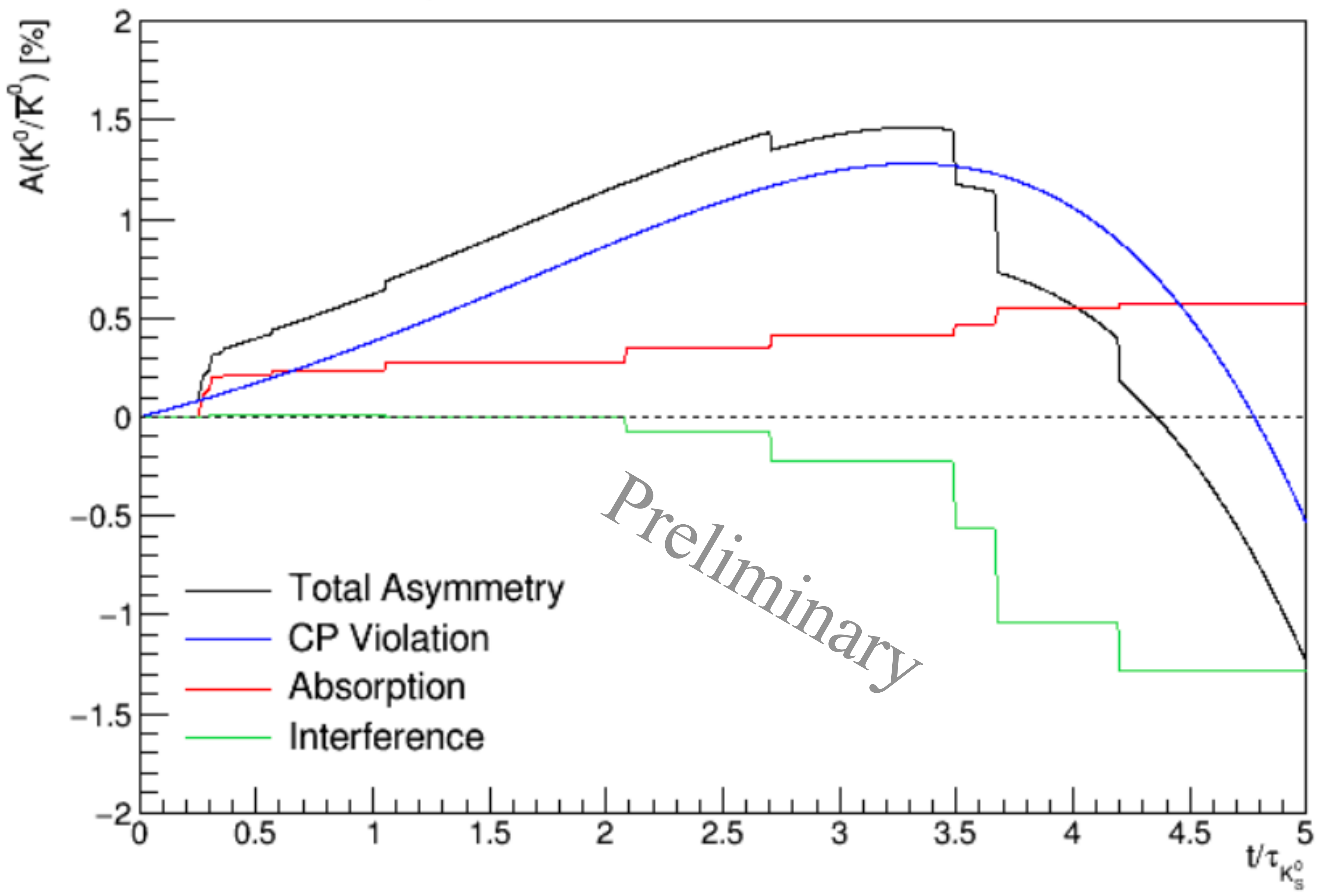
[1] A. Brignole and A. Rossi, Phys. Lett. B 566, 217 (2003)
[2] M. Blanke et al, JHEP 05, 013 (2007)
[3] T. Fukuyama et al, Phys. Rev. D 68, 033012 (2003)
[4] C. X. Yue et al, Phys. Lett. B 566, 217 (2003)
[5] A. Masiero et al, Nucl. Phys. B 649, 289 (2003)
[6] M. Blanke et al, Acta Phys. Polon. B 41, 657 (2010)
[7] R. Benbrik and C. H. Chen, Phys. Lett. B 672, 172 (2009)
[8] A. Arhrib, RB, CHC, Phys. Rev. D 81, 113003 (2010)

Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

Table 6: Systematic uncertainties in A_1 asymmetry measurement.

Source	**Uncertainty (%)**	
	e-tagged	μ-tagged
Production and detection asymmetry correction	0.07	0.08
Background correction	0.03	0.03
Dilution factor	0.02	0.03
Detection asymmetry of K^0-$\overline{K}^0$	0.01	0.01
Total	0.08	0.09

Preliminary



Search for CPV in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ decays at Belle II

Implementation	Feature	Description
`thrust`	thrust	mathematically defined in Eq.(5), corresponds to the measurement of the collimation or alignment of final-state particles produced in a collision
`visibleEnergyOfEvent_CMS`	$E_{\text{visible}}^{\text{CM}}$	visible energy in the CMS, equal to the sum of the energy of every input particle.
`missingMass2OfEvent`	m_{missing}^2	missing mass squared
`missingMomentumOfEventCMS`	$p_{\text{missing}}^{\text{CM}}$	missing momentum in the CMS, calculated by subtracting the sum of the momentum in CMS of all particles in the input from the sum of the beam momenta in CMS.
`missingMomentumOfEventCMS_theta`	$\theta_{\text{missing}}^{\text{CM}}$	polar angle of the missing momentum in the CMS
`track_1prong_p`	$p_{\text{1-prong}}$	momentum of the track in the tag side
`track_1prong_theta`	$\theta_{\text{1-prong}}$	polar angle of the track in the tag side

1st step BDT for continuum suppression

Features used as input of BDTs

Search for CPV in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays at Belle II

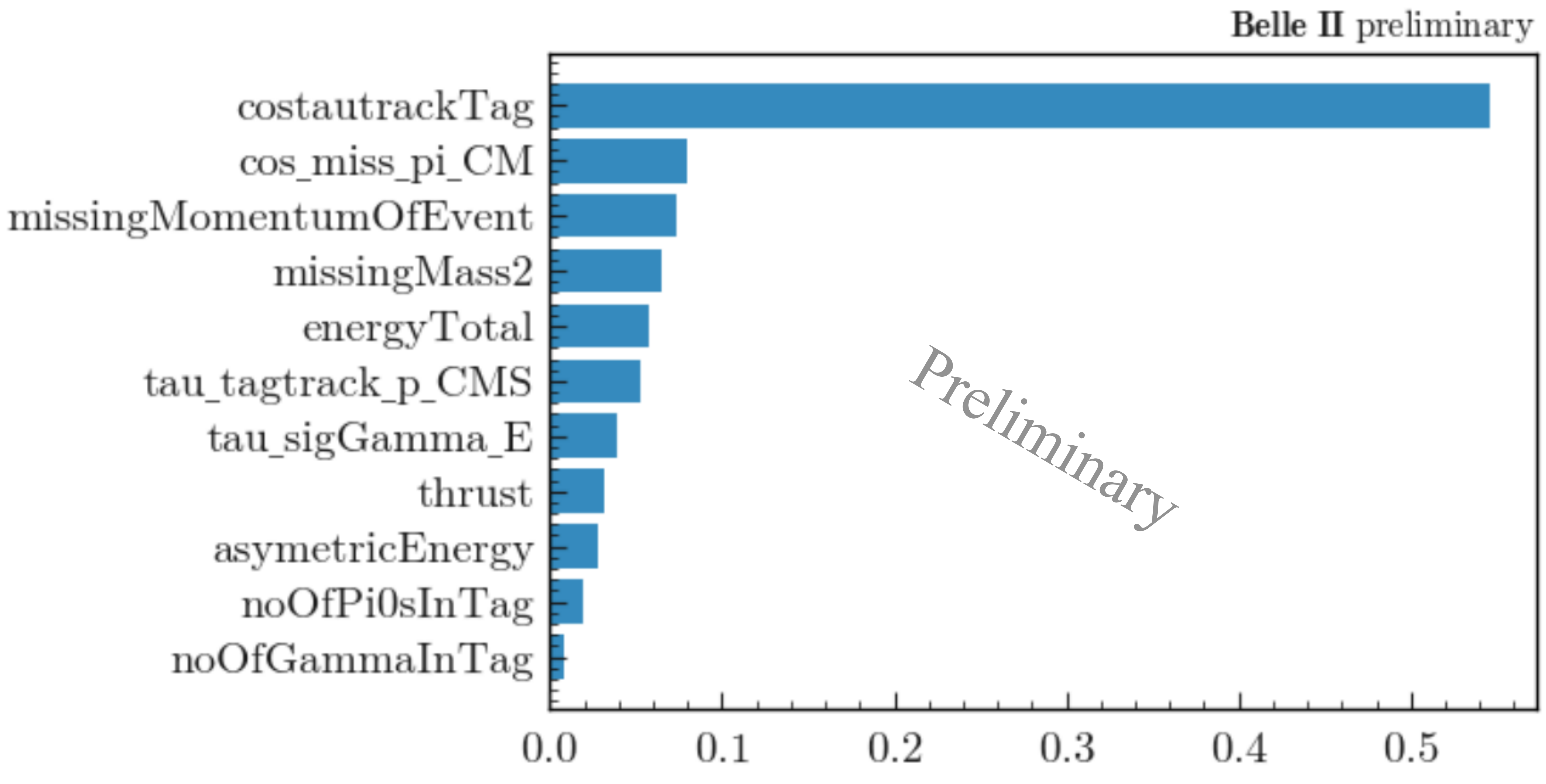
Implementation	Feature	Description
track_kshort_p, track_kshort_pt, track_kshort_theta	$p_{K_S^0}$, p_{t,K_S^0}, $\theta_{K_S^0}$	momentum, transverse momentum and polar angle of the K_S^0
track_pi_kshort_p, track_pi_kshort_pt, track_pi_kshort_theta	$p_{\pi(\mathrm{sig})}$, $p_{t,\pi(\mathrm{sig})}$, $\theta_{\pi(\mathrm{sig})}$	momentum, transverse momentum and polar angle of the prong track in the signal side
kshort_track1_p, kshort_track1_pt, kshort_track1_theta	p_{track1}, $p_{t,\mathrm{track1}}$, θ_{track1}	momentum, transverse momentum and polar angle of the first track (positive/negative charged track with highest momentum for positive/negative events) coming from K_S^0 decay
kshort_track2_p, kshort_track2_pt, kshort_track2_theta	p_{track2}, $p_{t,\mathrm{track2}}$, θ_{track2}	momentum, transverse momentum and polar angle of the second track (negative/positive charged track for postive/negative events) coming from K_S^0 decay
kshort_track_leadpt, kshort_track_subpt	$p_{t,\mathrm{lead}}$, $p_{t,\mathrm{sub}}$	leading and subleading transverse momentum of the two tracks coming from K_S^0 decay
track_kshort_significanceOfDistance, track_kshort_flightDistance, track_kshort_distance	$S_{K_S^0}^{\mathrm{distance}}$, $d_{K_S^0}^{\mathrm{flight}}$, $d_{K_S^0}^{\mathrm{3D}}$	significance of distance, flight distance and 3D distance between the IP and the K_S^0 decay vertex.
track_kshort_daughter1DecayAngle, track_kshort_daughter2DecayAngle	$\theta_{K_S^0-track1}$, $\theta_{K_S^0-track2}$	angle in the K_S^0's rest frame between the reverted CMS momentum vector and the direction of the i-th daughter

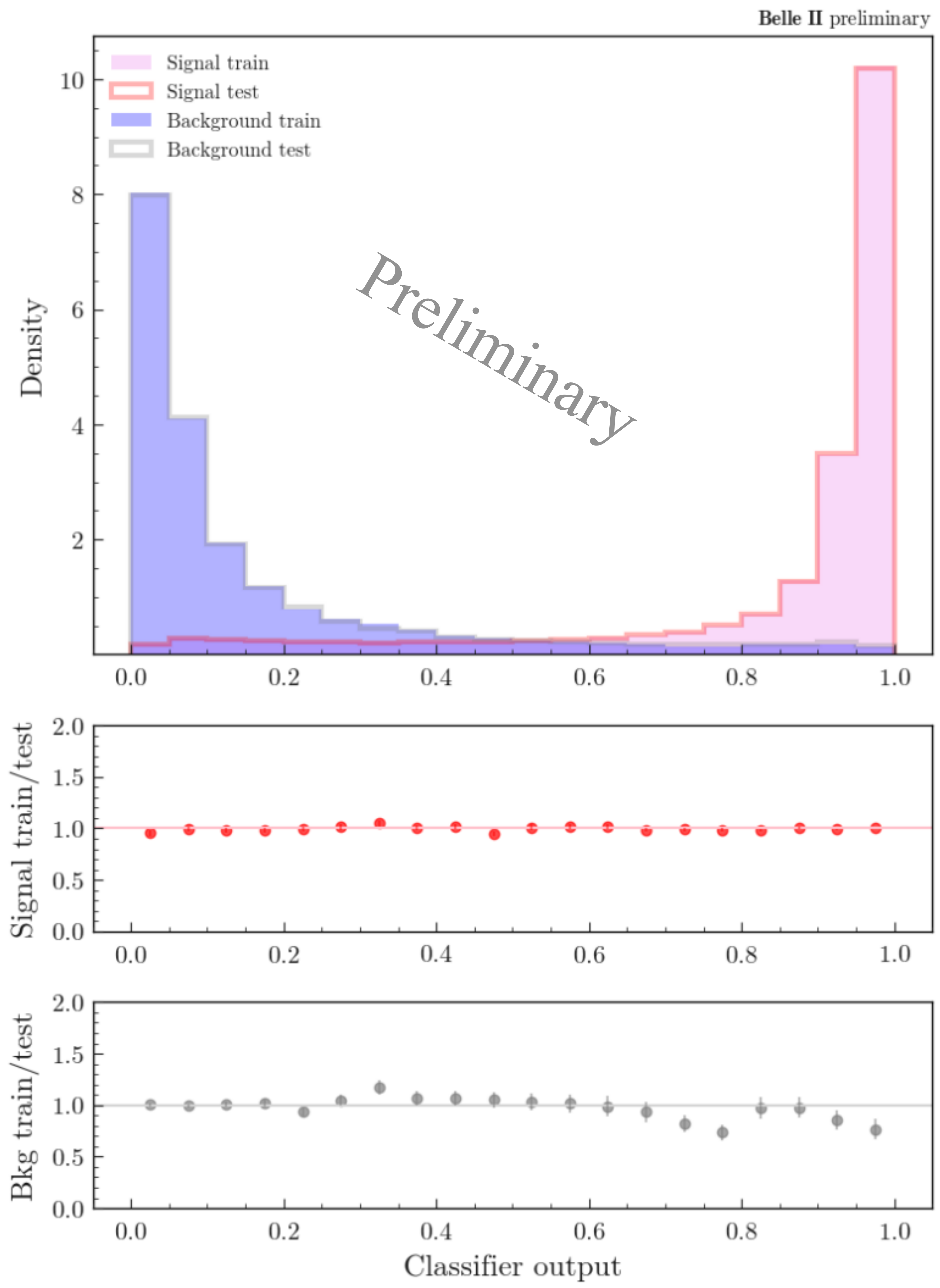
Implementation	Feature	Description
track_kshort_cosHelicityAngleMomentum	$\cos\theta_h^p$	cosine of the angle between the line defined by the momentum difference of the two daughters in the frame of the K_S^0 and the momentum of the K_S^0 in the lab frame.
kshort_track1_dr, kshort_track1_dz, kshort_track2_dr, kshort_track2_dz	dr_{track1}, dz_{track1}, dr_{track2}, dz_{track2}	absolute value of the distance to the point-of-closest-approach (POCA) in the $r-\phi$ plane and POCA in the z direction with respect to IP for the i-th track coming from K_S^0 decay

2nd step BDT for $\tau\tau$ background suppression

Features used as input of BDTs

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





Features used as input of BDTs

Search for LFV in $\tau^- \to \ell^-\eta$ decays at Belle II

Implemented Name	Expression	Definition
foxWolframR2	R_2	the ratio between fox-Wolfram second moment and zeroth moment
normalized_missP_CMS	$P^{\rm CM}_{\rm miss}/\sqrt{s}$	Total missing momentum CM frame divided by CM energy $[c^{-1}]$
cos_miss_thrust	$\cos\theta^{\rm CM}_{\rm miss-thrust}$	Cosine angle between thrust axis and missing momentum
missingMass2OfEvent	M^2_{miss}	The square of missing mass of system $[\mathrm{GeV}^2/\mathrm{c}^4]$
nGammaSig	$N^{\rm sig}_\gamma$	the number of photon in signal side hemisphere
tau_sig_flightTime_Significance	$t_\tau/\Delta t_\tau$	The ratio of flight time of signal τ and its error
ell_CMS_cosTheta	$\cos\theta^{\rm CM}_\ell$	Cosine angle between lepton in CM frame and z axis
eta_CMS_cosTheta	$\cos\theta^{\rm CM}_\eta$	Cosine angle between η in CM frame and z axis
cos_miss_ell	$\cos\theta^{\rm CM}_{\ell-\rm miss}$	Cosine angle between lepton and missing momentum in CM frame
cos_eta_lepton_CMS	$\cos\theta^{\rm CM}_{\ell\eta}$	Cosine angle between lepton and η meson in CM frame
normalized_eta_CMS_E	$E^{\rm CM}_\eta/\sqrt{s}$	The η meson energy in CM frame divided by CM energy
normalized_eta_gamma_E_low_high	$E^{\rm low,CM}_\gamma$	Low energy γ in CM frame divided by CM energy
eta_angleBetweenGammas	$\theta^{\rm CM}_{\gamma\gamma}$	3D angle between two γs
nGammaTag	$N^{\rm tag}_\gamma$	the number of photon in tagside hemisphere
normalized_totalGammaETag_CMS	$\sum_i E^{\rm tag,CM}_{i,\gamma}/\sqrt{s}$	Energy sum of gammas in tagside hemisphere divided by CM energy
cos_miss_tag	$\cos\theta^{\rm CM}_{\rm tag-miss}$	Cosine angle between tagside track and missing momentum in CM frame
tagside	$\mathcal{L}_{\ell/h}$	0 for leptonic tagside and 1 for hadronic tagside

Features used as input of BDTs

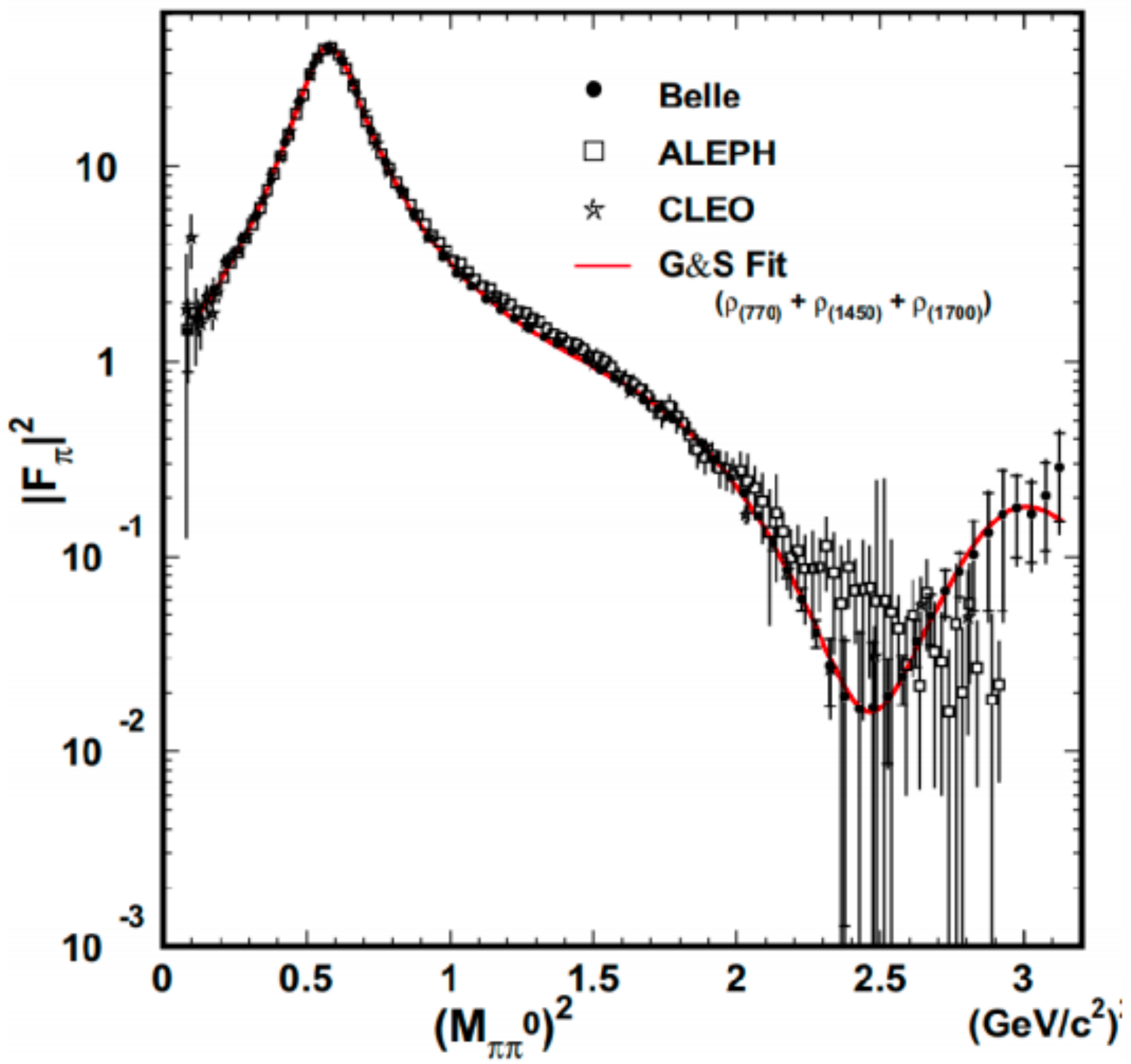
Precise measurement of τ hadronic decay at Belle II

- Hard to compete with LEP in BF precision
- SF can be improved with larger statistics

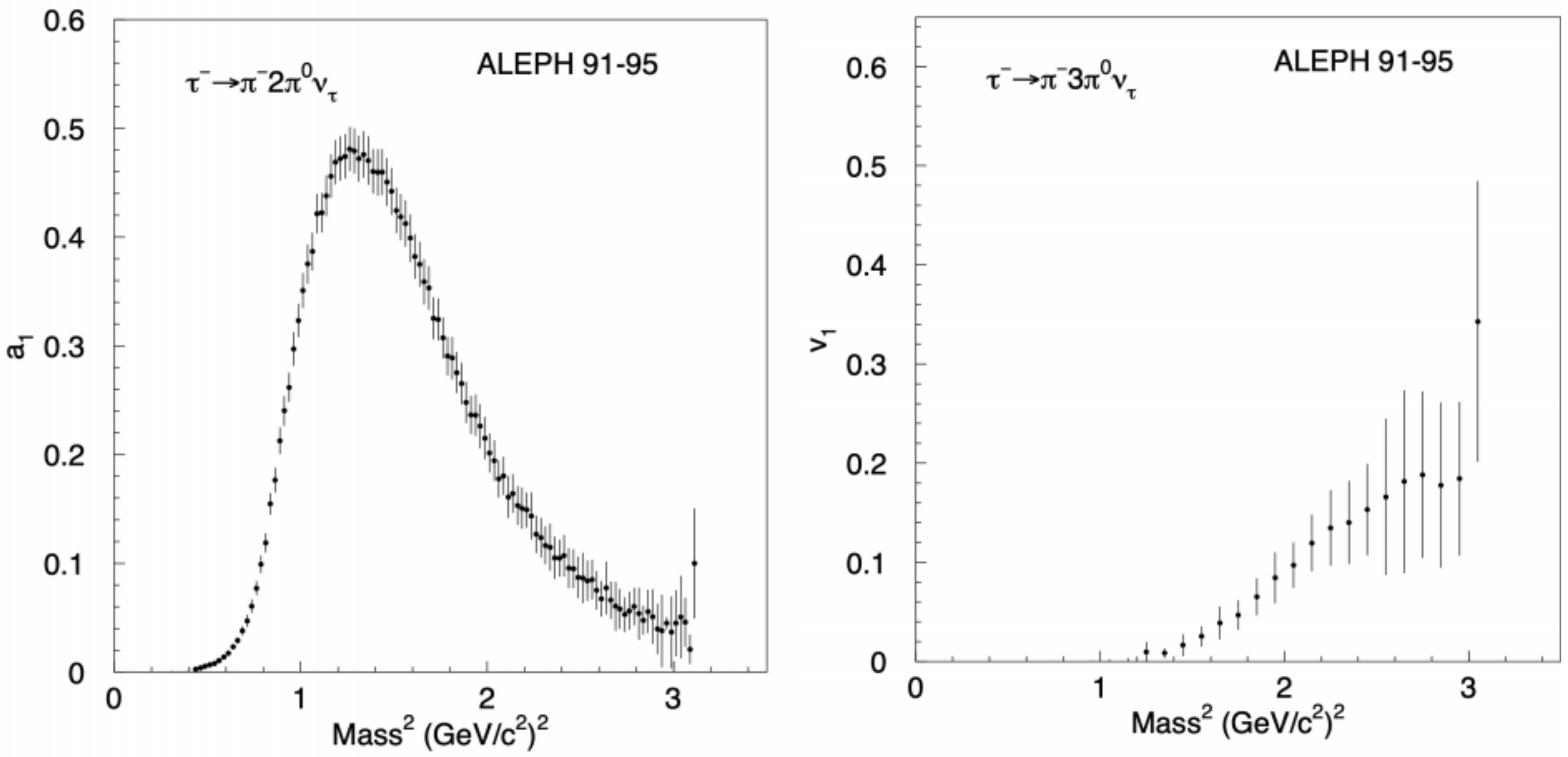
Final state	Belle, %	BaBar, %
$\tau^- \to \pi^- \nu_\tau$	–	$10.59 \pm 0.03 \pm 0.11$
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$8.42 \pm 0.00^{+0.26}_{-0.25}$	$8.83 \pm 0.01 \pm 0.13$
$\tau^- \to \pi^- \pi^+ \pi^- 3\pi^0 \nu_\tau$	–	$[2.07 \pm 0.18 \pm 0.37] \times 10^{-2}$

Final state	ALEPH, %	PDG, %
$\tau^- \to \pi^- \nu_\tau$	$10.828 \pm 0.070 \pm 0.078$	10.82 ± 0.05
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$25.471 \pm 0.097 \pm 0.085$	25.49 ± 0.09
$\tau^- \to \pi^- 2\pi^0 \nu_\tau$	$9.239 \pm 0.086 \pm 0.090$	9.26 ± 0.10
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	$0.977 \pm 0.069 \pm 0.058$	1.04 ± 0.07
$\tau^- \to \pi^- 4\pi^0 \nu_\tau$	$0.112 \pm 0.037 \pm 0.035$	0.11 ± 0.04
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$9.041 \pm 0.060 \pm 0.076$	9.02 ± 0.05
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	$4.590 \pm 0.057 \pm 0.064$	4.49 ± 0.05
$\tau^- \to \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$	$0.392 \pm 0.030 \pm 0.035$	–

Phys.Rev.D 78 (2008) 072006

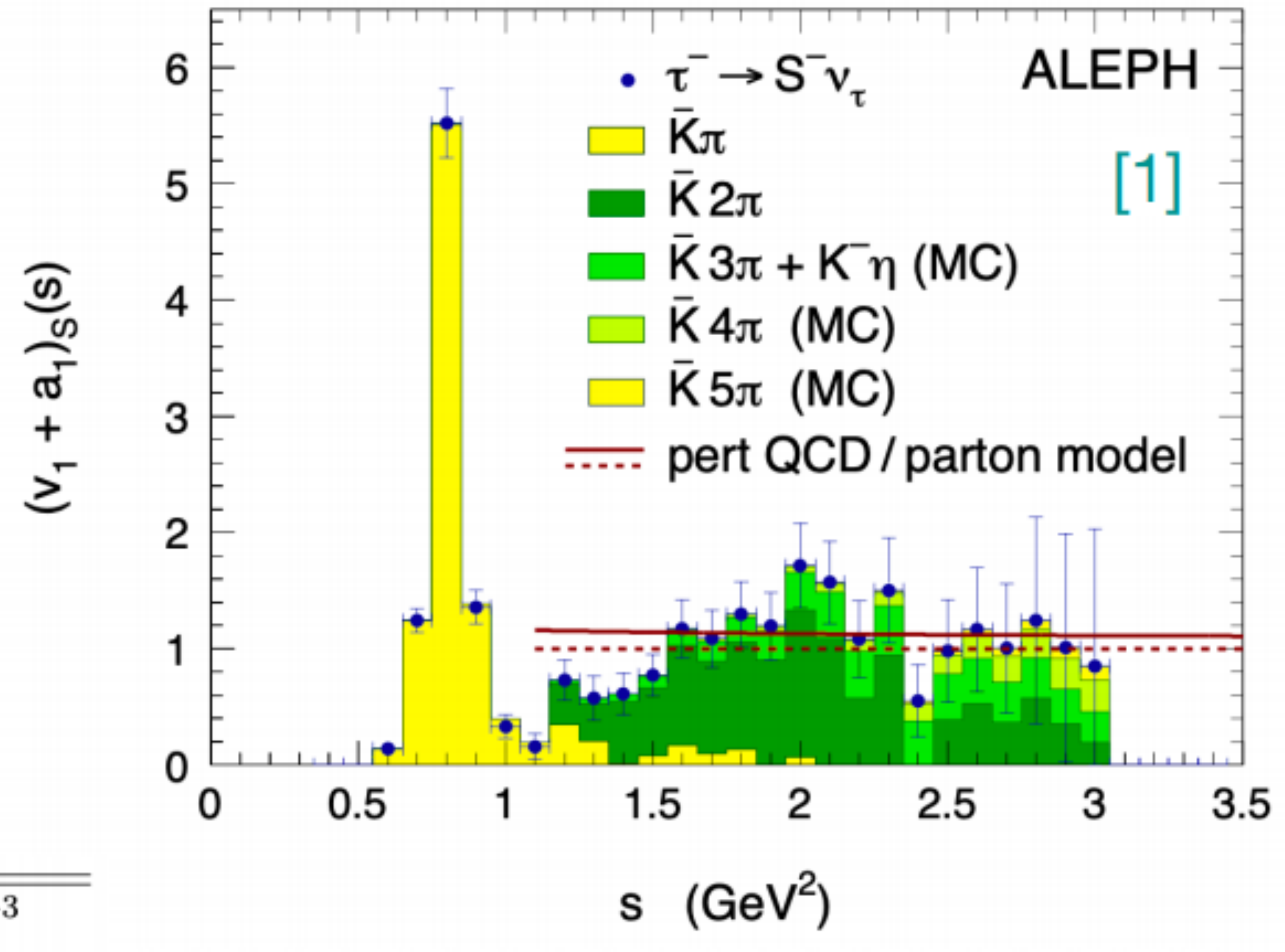


Phys.Rept. 421 (2005) 191

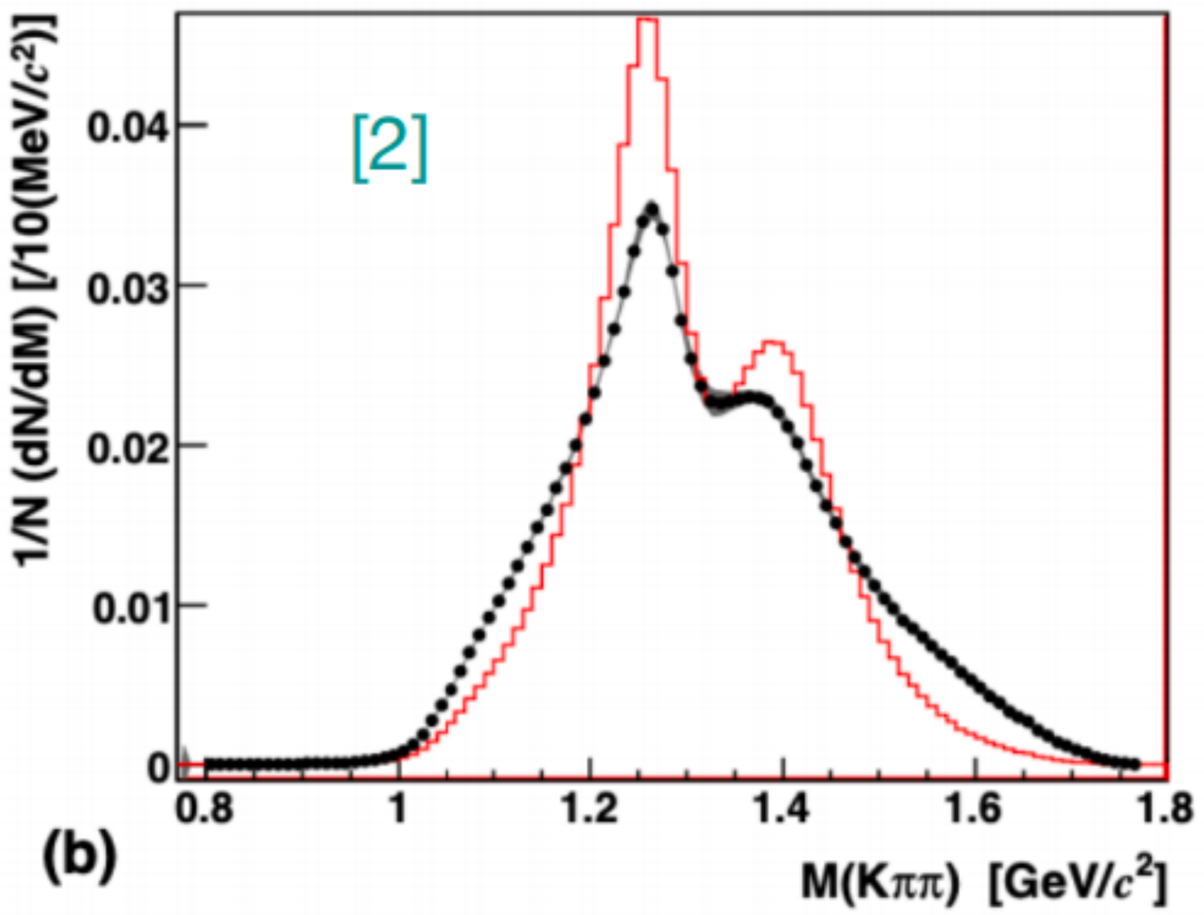


Precise measurement of τ hadronic decay at Belle II

- Consistent study of $\tau^- \to [KX]^- \nu_\tau$ with extraction of spectral functions were done only by LEP experiments with limited statistics
- B factories measured only branching fractions
- In $\tau^- \to h'^- h^+ h^- \nu_\tau$ decay, B factories also measured spectral functions, but Belle and BaBar results are inconsistent



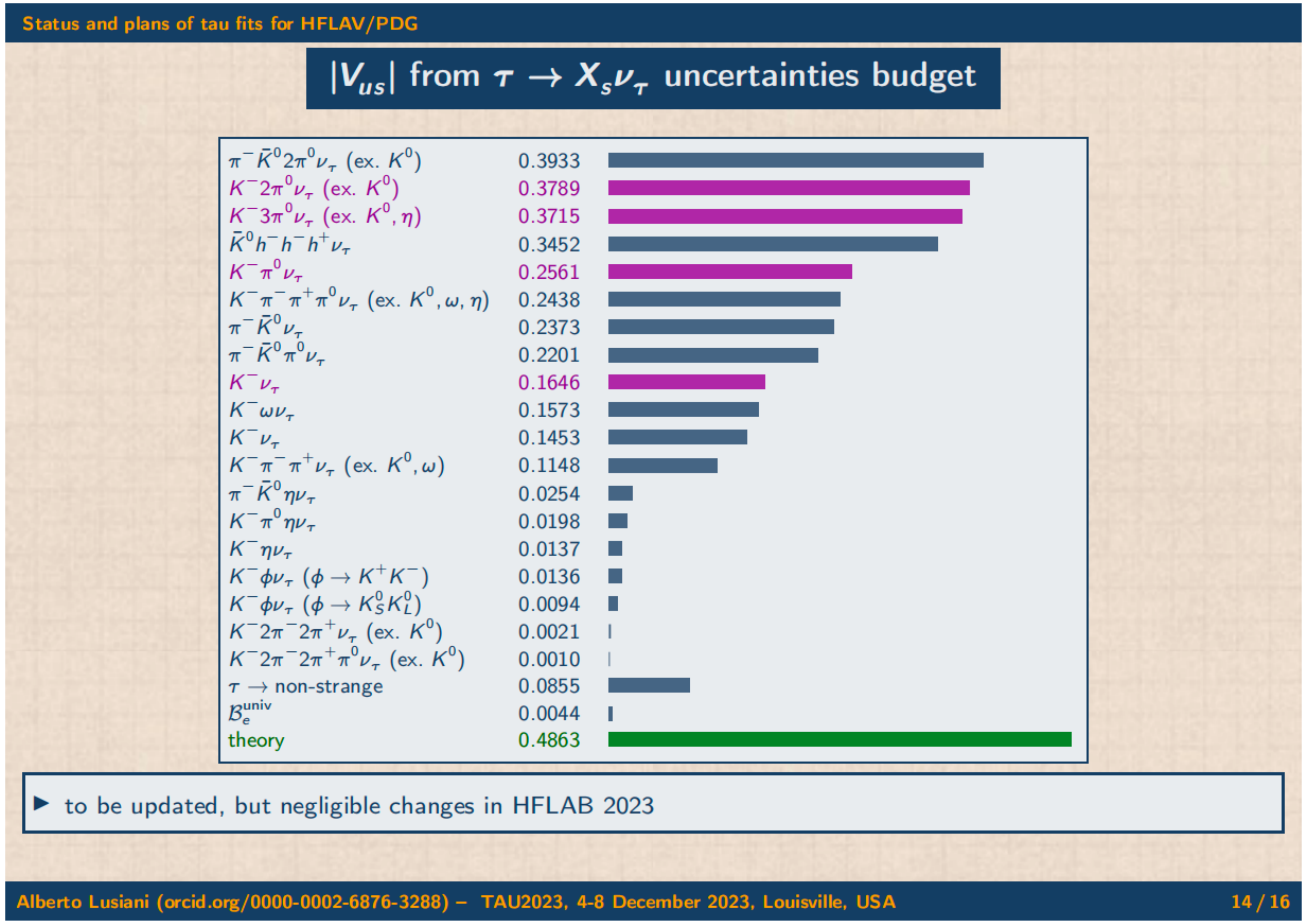
Final state	Belle $\times 10^{-3}$	BaBar $\times 10^{-3}$	PDG $\times 10^{-3}$
$\tau^- \to K^-\nu_\tau$	–	$6.92 \pm 0.06 \pm 0.10$	6.97 ± 0.10
$\tau^- \to K^-\pi^0\nu_\tau$	–	$4.16 \pm 0.03 \pm 0.18$	4.33 ± 0.15
$\tau^- \to K^0_S\pi^-\nu_\tau$	$4.16 \pm 0.01 \pm 0.08$	–	4.19 ± 0.07
$\tau^- \to K^-\pi^0\pi^0\nu_\tau$	–	–	0.65 ± 0.22
$\tau^- \to K^-\pi^+\pi^-\nu_\tau$	$3.30 \pm 0.01^{+0.16}_{-0.17}$	$2.73 \pm 0.02 \pm 0.09$	2.93 ± 0.07
$\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$	$1.93 \pm 0.02 \pm 0.07$	–	1.91 ± 0.07
$\tau^- \to K^-\pi^0\pi^0\pi^0\nu_\tau$	–	–	0.48 ± 0.21
$\tau^- \to K^-\pi^+\pi^-\pi^0\nu_\tau$	–	–	0.39 ± 0.14
$\tau^- \to K^0_S\pi^-\pi^0\pi^0\nu_\tau$	–	–	0.26 ± 0.23
$\tau^- \to K^0_S h^- h^+ h^-\nu_\tau$	–	–	0.25 ± 0.20
$\tau^- \to K^-\eta\nu_\tau$	$0.158 \pm 0.005 \pm 0.009$	$0.142 \pm 0.011 \pm 0.007$	0.155 ± 0.008
$\tau^- \to K^-\eta\pi^0\nu_\tau$	$0.046 \pm 0.011 \pm 0.004$	–	0.048 ± 0.012
$\tau^- \to K^0_S\eta\pi^-\nu_\tau$	$0.044 \pm 0.007 \pm 0.003$	–	0.047 ± 0.008
$\tau^- \to K^-\omega\nu_\tau$	–	–	0.41 ± 0.09



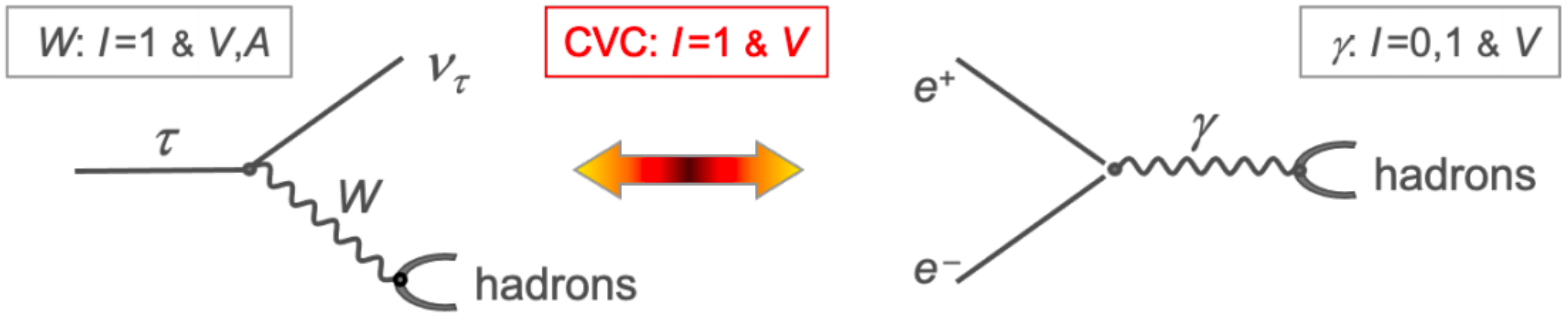
[1] Eur.Phys.J.C 11 (1999) 599
[2] Phys.Rev.D 81 (2010) 113007

$|V_{us}|$ determination with $\tau \to X_s \nu_\tau$

Sources of uncertainty in $|V_{us}|$



CVC



- CVC implies using τ decays to calculate HVP
- Hadronic physics factorizes in Spectral Functions (SF)
- Isospin symmetry connects $I = 1$ e^+e^- cross section to vectors τ spectral functions:

$$\sigma^{(I=1)}(e^+e^- \to \pi^+\pi^-) = \frac{4\pi\alpha^2}{s} v(\tau^- \to \pi^-\pi^0\nu_\tau),$$

- where

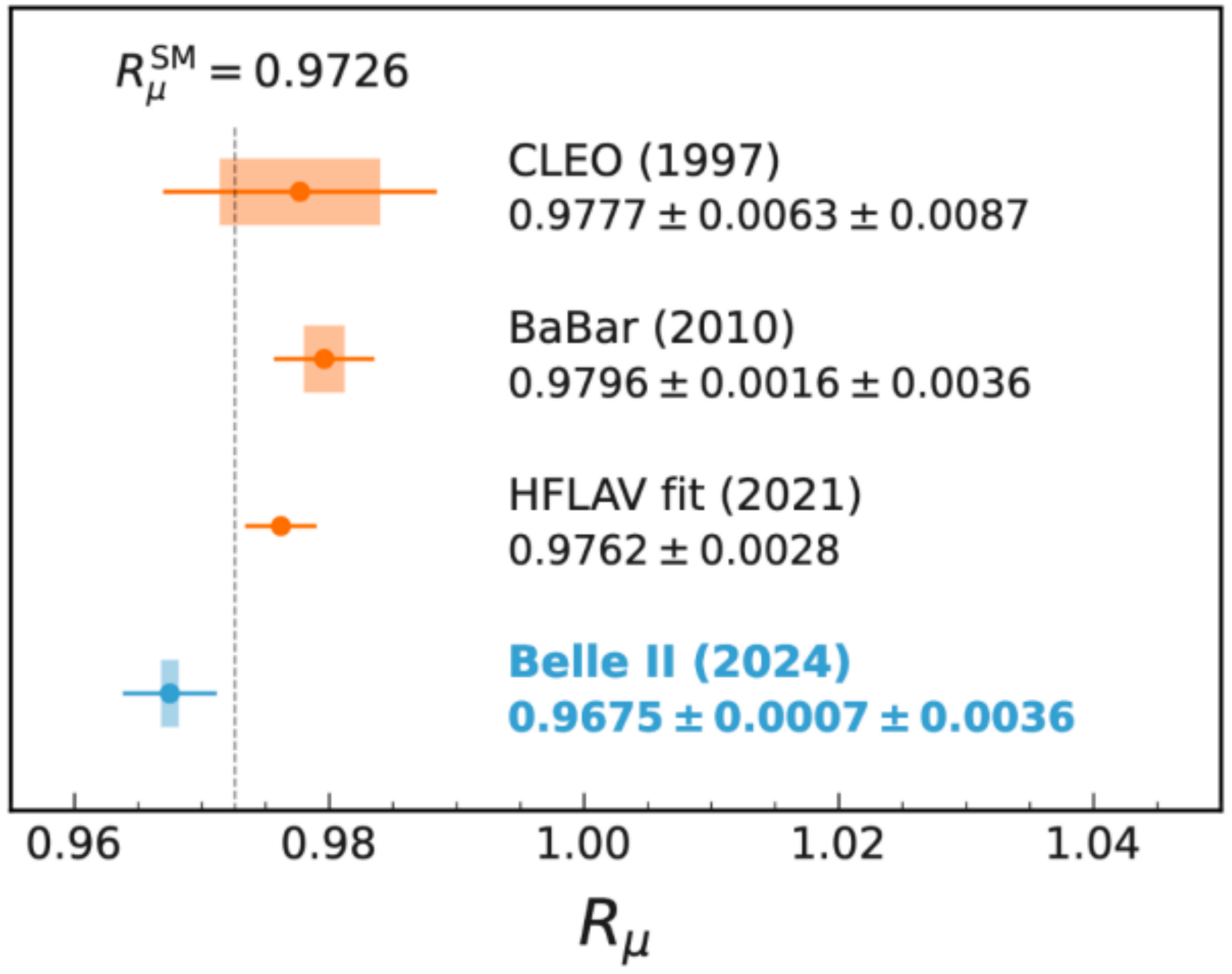
$$v_1(s) = \frac{m_\tau^2}{6|V_{ud}|^2 S_{EW}} \frac{Br(\tau^- \to V^-\nu_\tau)}{Br(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \frac{dN_V}{N_V ds} \left[\left(1 - \frac{s}{m_\tau^2}\right)^2 \left(1 + \frac{2s}{m_\tau^2}\right)\right]^{-1}$$

LFU test in τ leptonic decays at Belle II

Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Imperfections of the simulation:	0.14
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Trigger	0.10
Size of the simulated samples	0.06
Luminosity	0.01
Total	0.37

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

[JHEP 2024, 205] (2024)



→ **world's most precise test of LFU in τ decays**

- consistent with SM at 1.4σ

τ mass measurement at Belle II

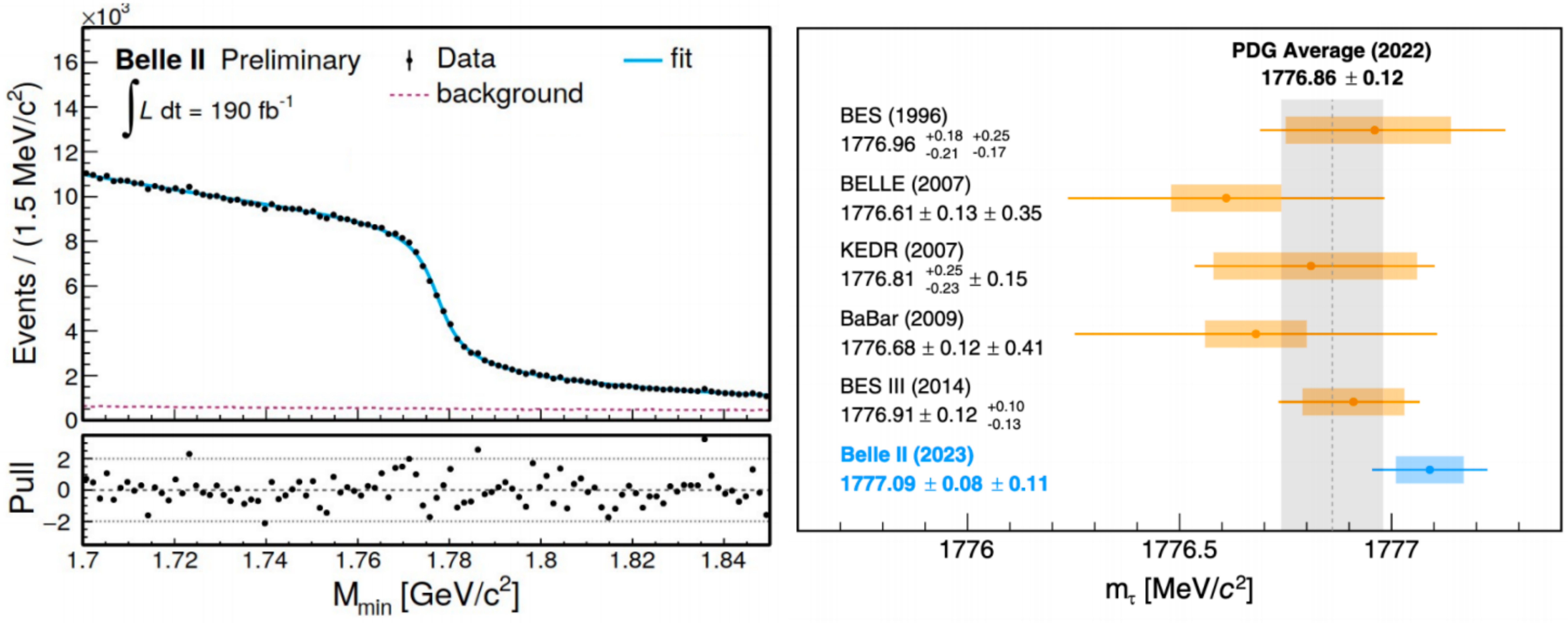
» **Analysis performed on part of the on-resonance Run 1 data ($190\ \mathrm{fb}^{-1}$)**
→ **world's most precise measurement**

SM

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

→ **Demonstration of the high precision capability of Belle II!**

[PRD 108, 032006] (2023)



τ lifetime measurement at Belle

» **Current world-leading measurement from Belle** ($711\ \mathrm{fb}^{-1}$)

- $3{\times}3$-prong topology, both tau leptons decaying to $3\pi\nu$

  $\tau_\tau = 290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst})\ \mathrm{fs}$

Belle II analysis

» **5× large signal sample** despite less luminosity

- thanks to the 1-prong tag

» **2× better proper decay time resolution**