

Tau Physics at Belle II



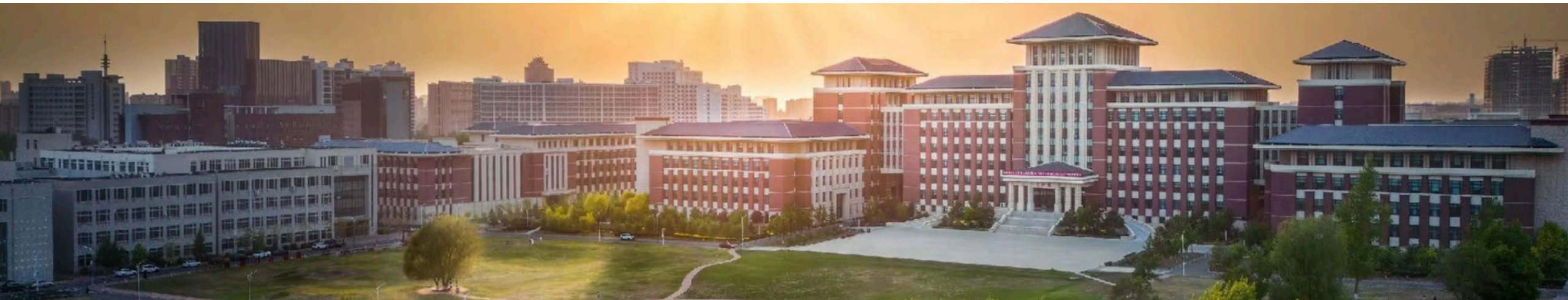
NAGOYA UNIVERSITY



Kobayashi-Maskawa
Institute

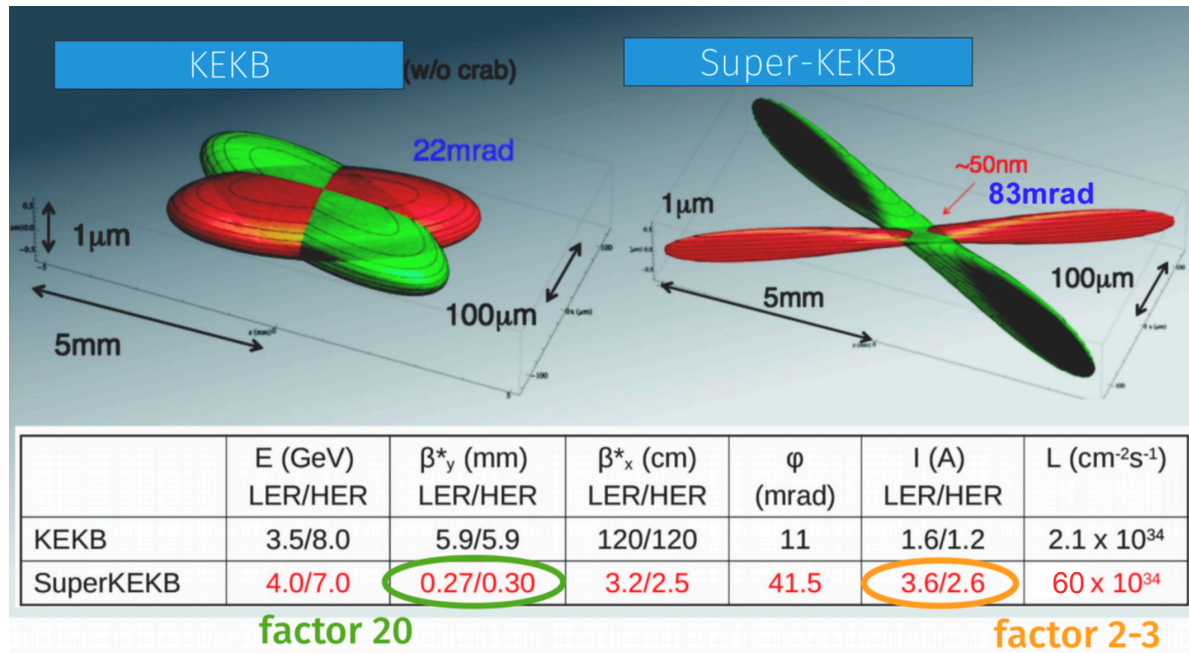
Petar Rados
KMI, Nagoya University

Workshop on Tau Physics at Belle II & STCF
Jilin University in Changchun, China
31 August 2026



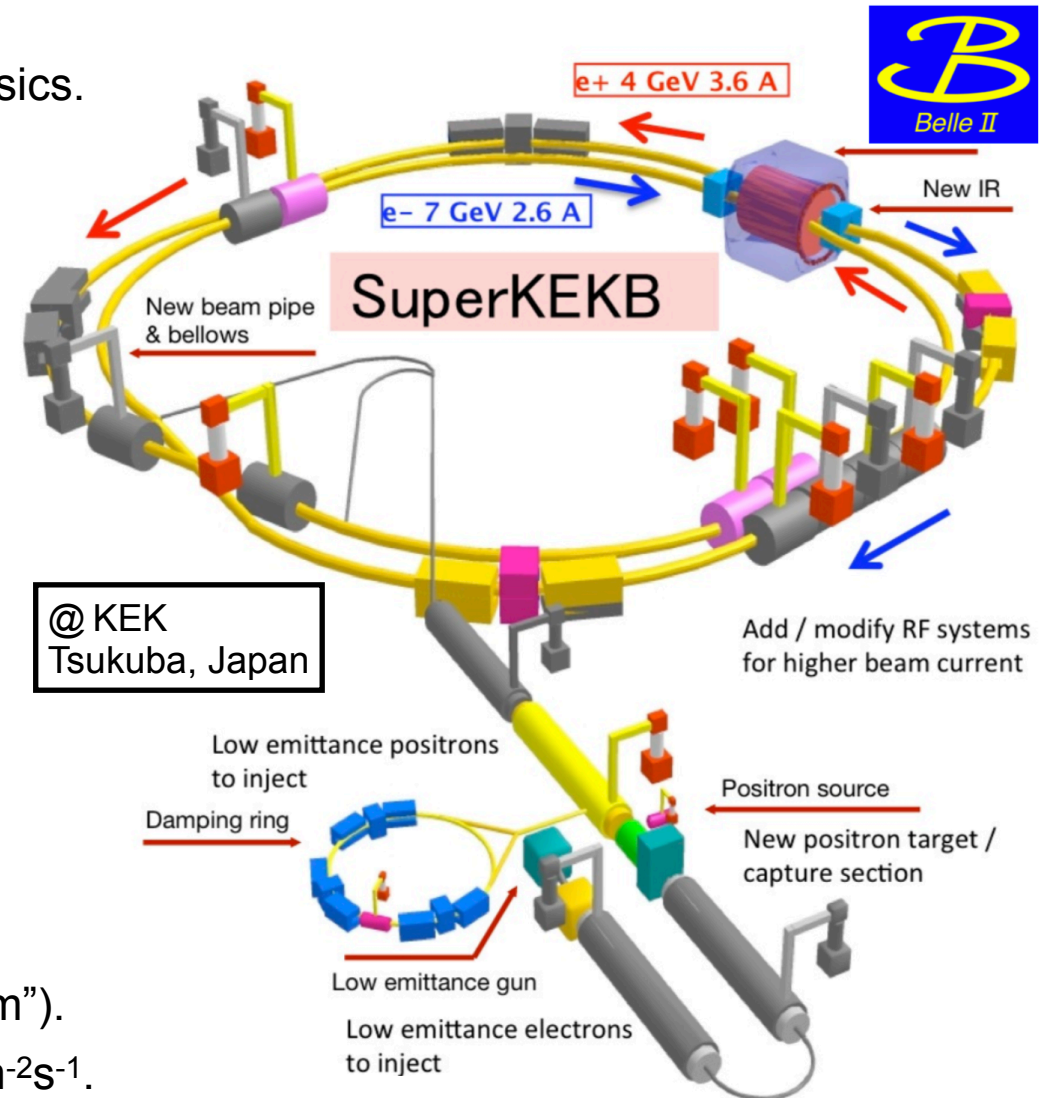
SuperKEKB Accelerator

- Asymmetric energy e^+e^- collisions at or near $\sqrt{s} \approx 10.58$ GeV.
B-factory + rich program of tau, dark sector & low-multiplicity physics.

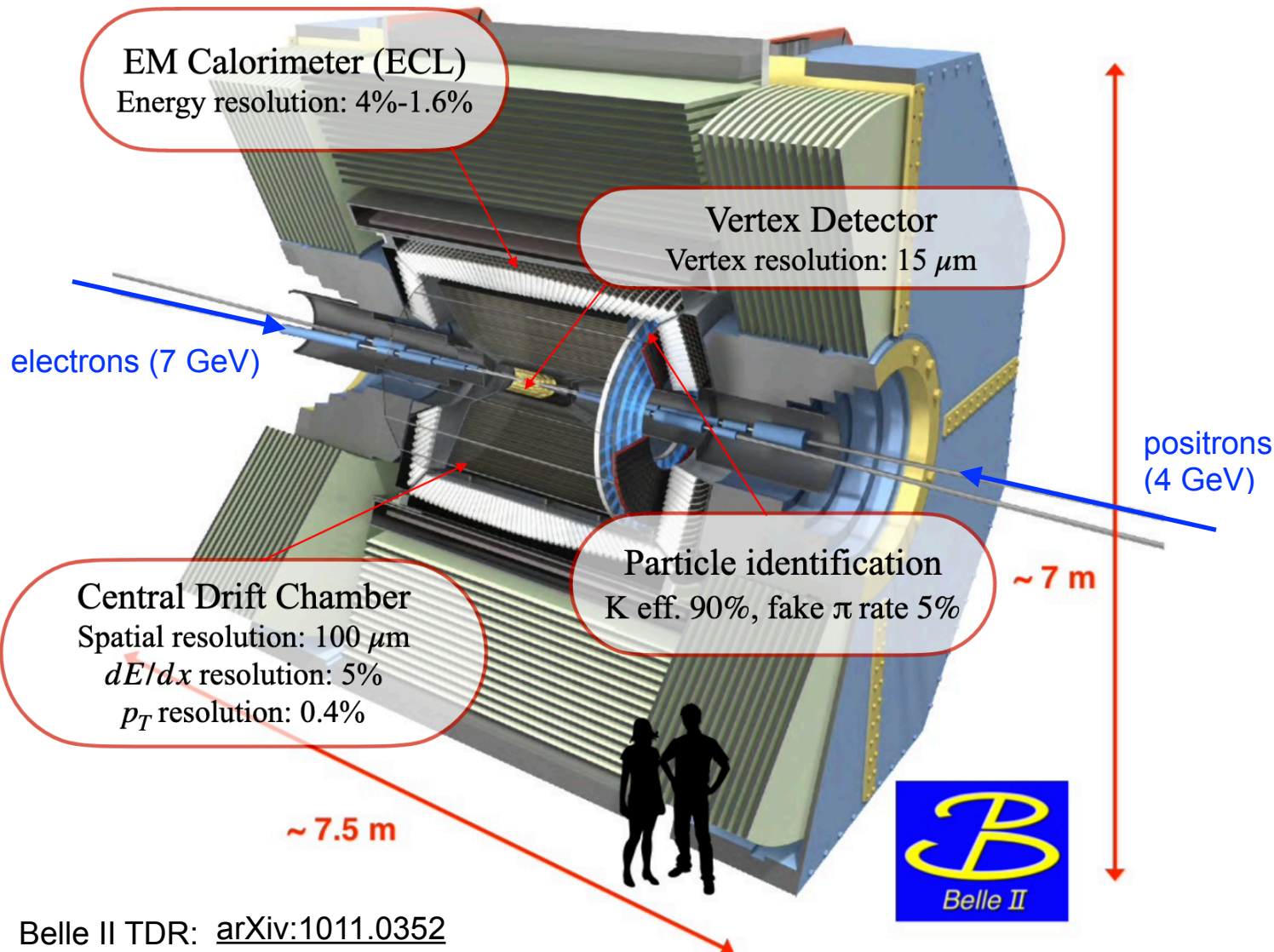


- KEKB** → **SuperKEKB** accelerator

- 2x beam currents, 50nm vertical beam spot size (“nano beam”).
- Unprecedented design luminosity: $2.1 \times 10^{34} \rightarrow \sim 6.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.



Belle II Detector



- **Belle** $\rightarrow$ **Belle II** detector

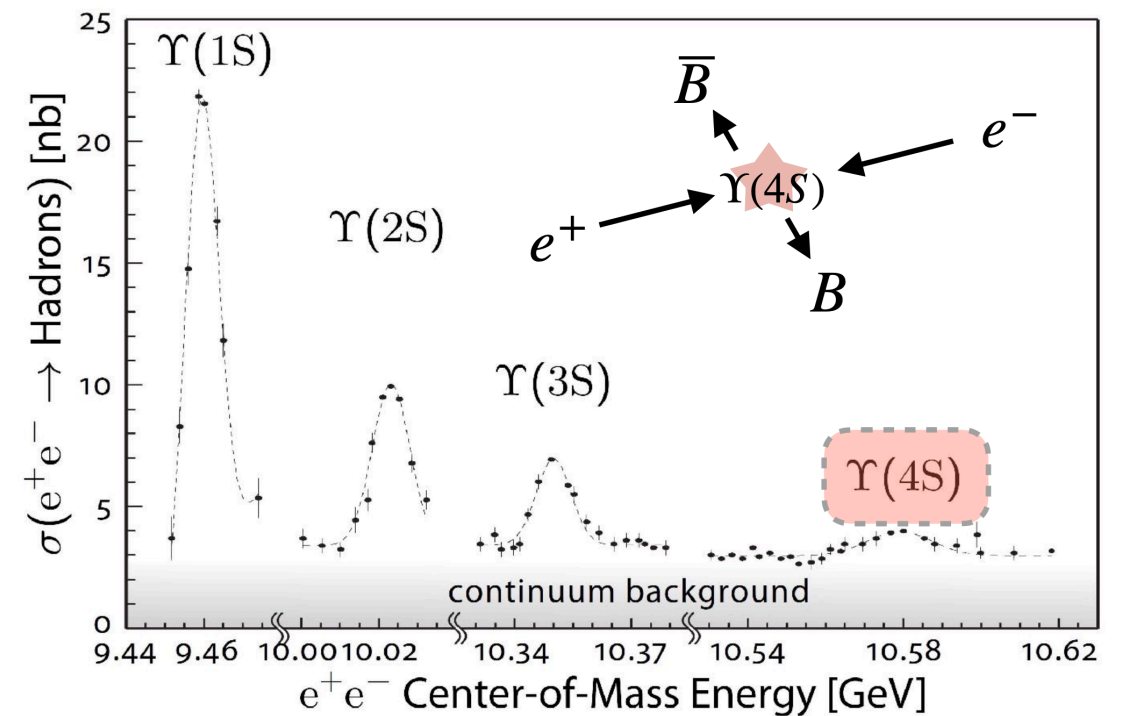
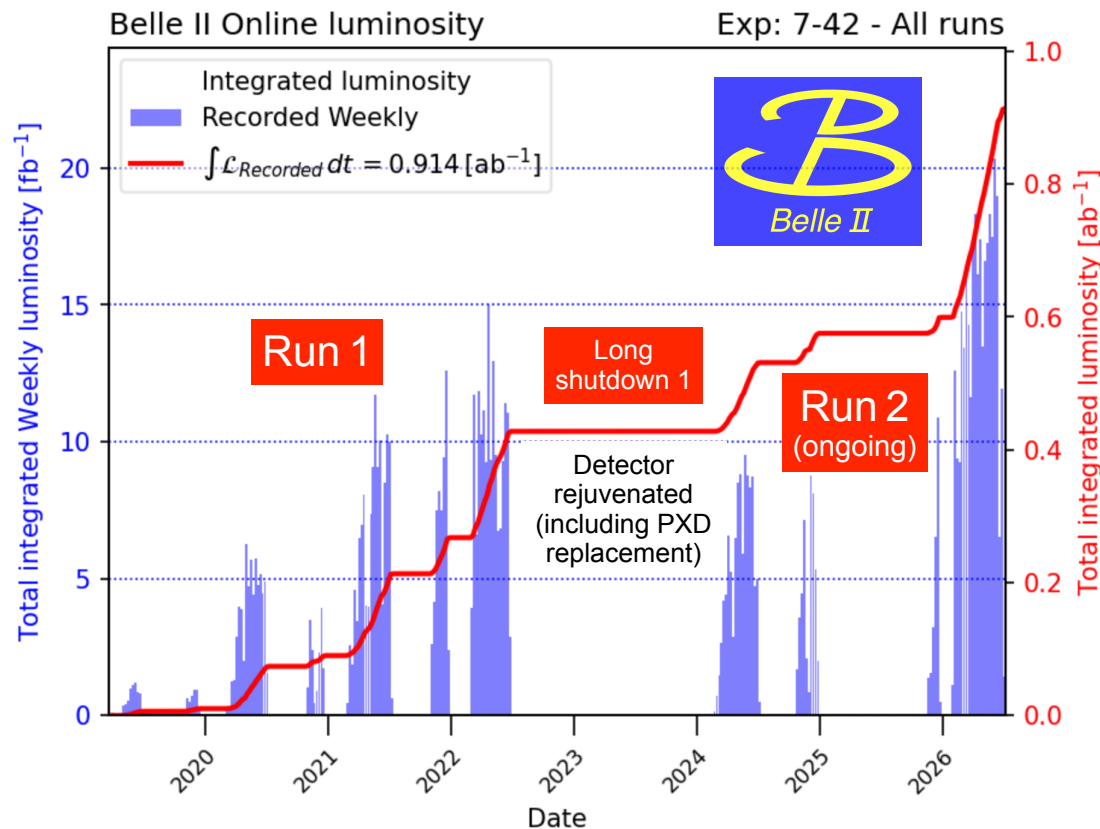
- ▶ 2-layer Pixel Detector (**PXD**) with first layer at 1.4cm, significantly improves vertexing.
- ▶ 4-layer Silicon Vertex Detector (**SVD**) with larger acceptance.
- ▶ Central Drift Chamber (**CDC**) with larger outer radius.
- ▶ Improved particle ID: **TOP** + new **ARICH** (K/ π separation). **KLM** (μ , K_L)
- ▶ Improved **trigger** and faster electronics.

- Ideal for **τ physics**

- ▶ Clean environment with high efficiency trigger lines not present at Belle.
- ▶ Hermetic detector with well-known initial state $\rightarrow$ neutrino energy can be determined precisely.
- ▶ Efficient reconstruction of neutrals (γ , π^0 , η) & excellent charged PID capabilities (e , μ , π , K).
- ▶ Excellent track momentum & vertex resolution (e.g. for τ lifetime).

Performance to date

- Belle II explores the **intensity frontier** at SuperKEKB
 - Peak luminosity world record ($5.32 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$).
 - Accumulated world's largest $\Upsilon(4S)$ dataset, surpassing Belle.
 - 808 fb^{-1} at $\Upsilon(4S)$ and 914 fb^{-1} overall.
 - Aiming to collect 50 ab^{-1} over next ~10 years (50x Belle dataset)

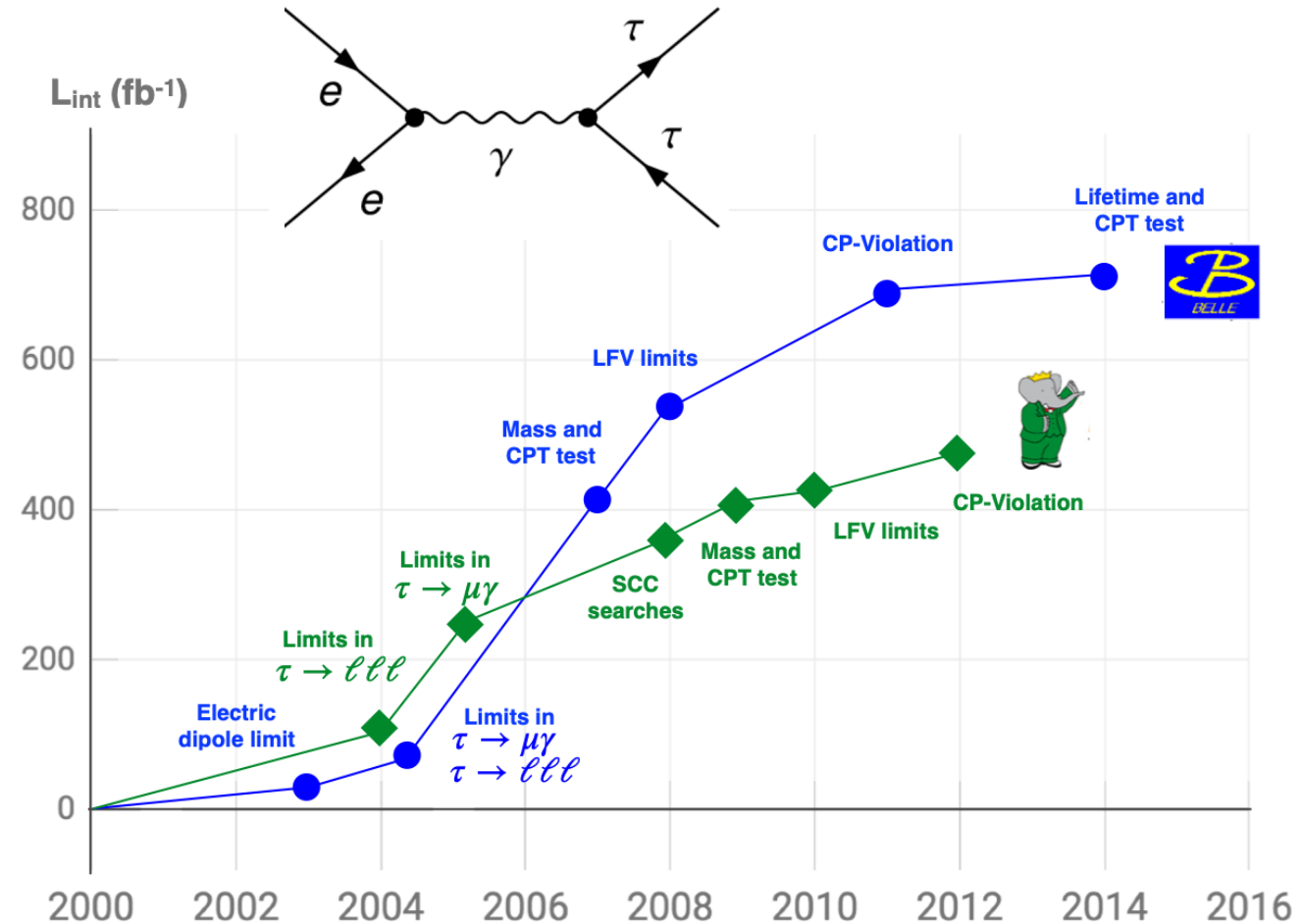


Belle II as a τ factory

- **B-factories are also τ -factories!**
 - $\sigma(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}) = 1.05 \text{ nb}$
 - $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb}$
- Last generation B-factories (Belle, BABAR) provided a variety of very interesting τ physics results over the last two decades
- Over its lifetime Belle II will deliver an enormous sample of $\sim 4.6 \times 10^{10}$ τ -pair events



a unique environment to study τ physics with high precision!



Tau Physics Program

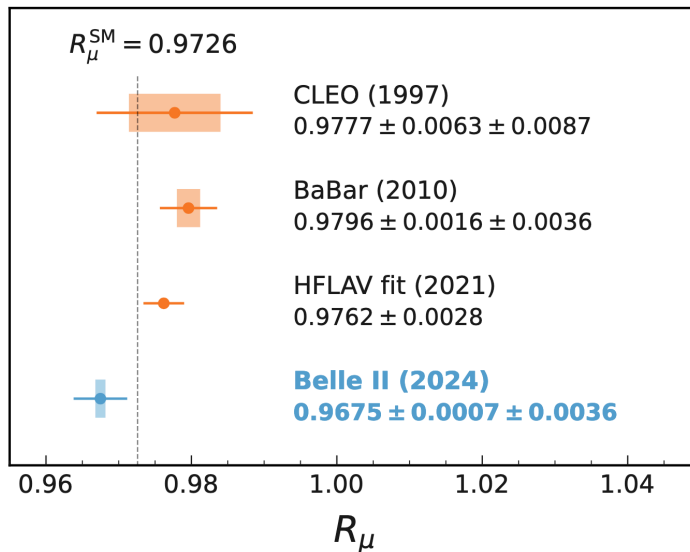
Precision SM measurements.

Indirect hints of New Physics in SM deviations.

- ♦ τ properties (mass, lifetime), couplings (e- μ universality, V_{us}), CP violation, Michel parameters $\Rightarrow$ see Denis' talk), + more.
- ♦ Often sub-% measurements: systematics are usually the dominant error source.

e.g. e- μ universality

JHEP 2024, 205 (2024)



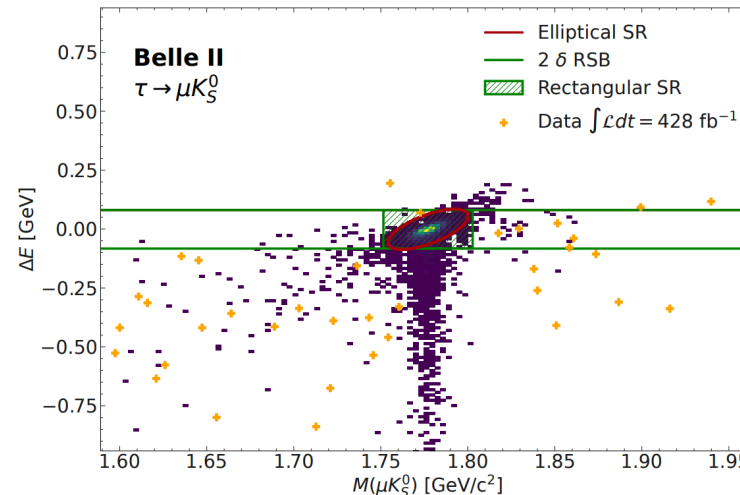
Search for rare or forbidden processes.

Direct observation would be unambiguous sign of NP.

- ♦ Mostly Lepton Flavor Violating (LFV) τ decays. Often very little to no background.
- ♦ Need to be smart to beat limits from Belle with less data.
 - Requires high reconstruction efficiencies.
 - Machine learning techniques, inclusive tagging.

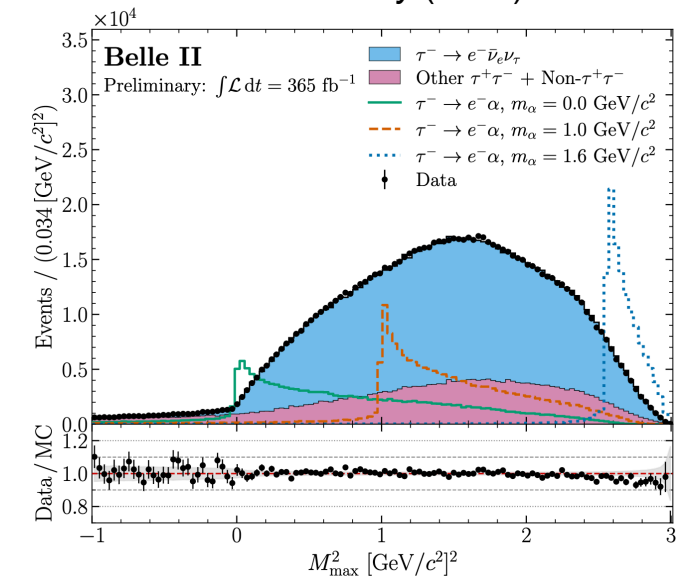
e.g. $\tau \rightarrow \ell K_S^0$

JHEP 2025, 092 (2025)



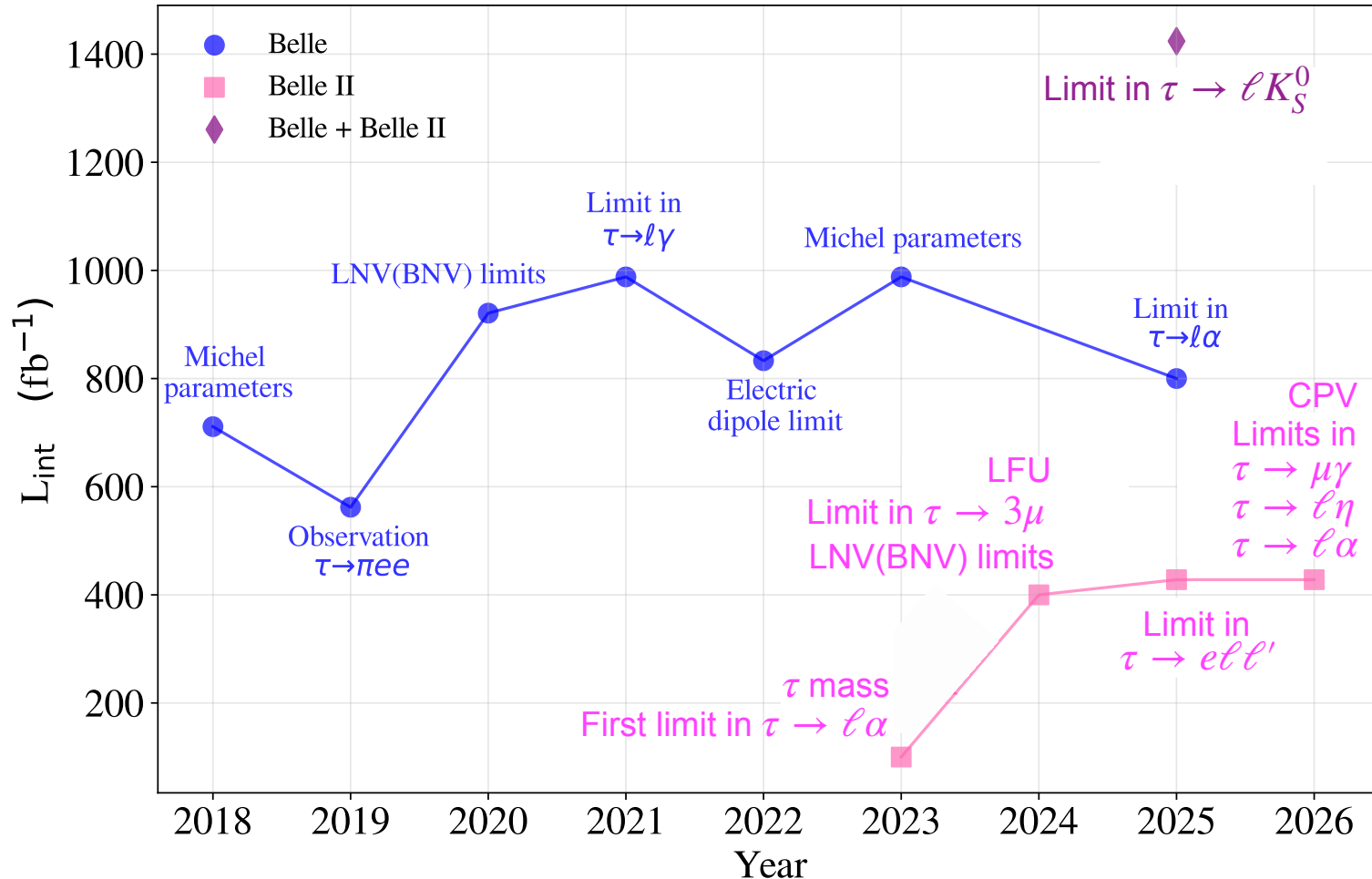
$\tau \rightarrow \ell \alpha$ (invisible)

Preliminary (2026)



Tau Physics Program

- **Belle II already having a major impact** with its growing data sample, improved analysis techniques and reduced systematic uncertainties.



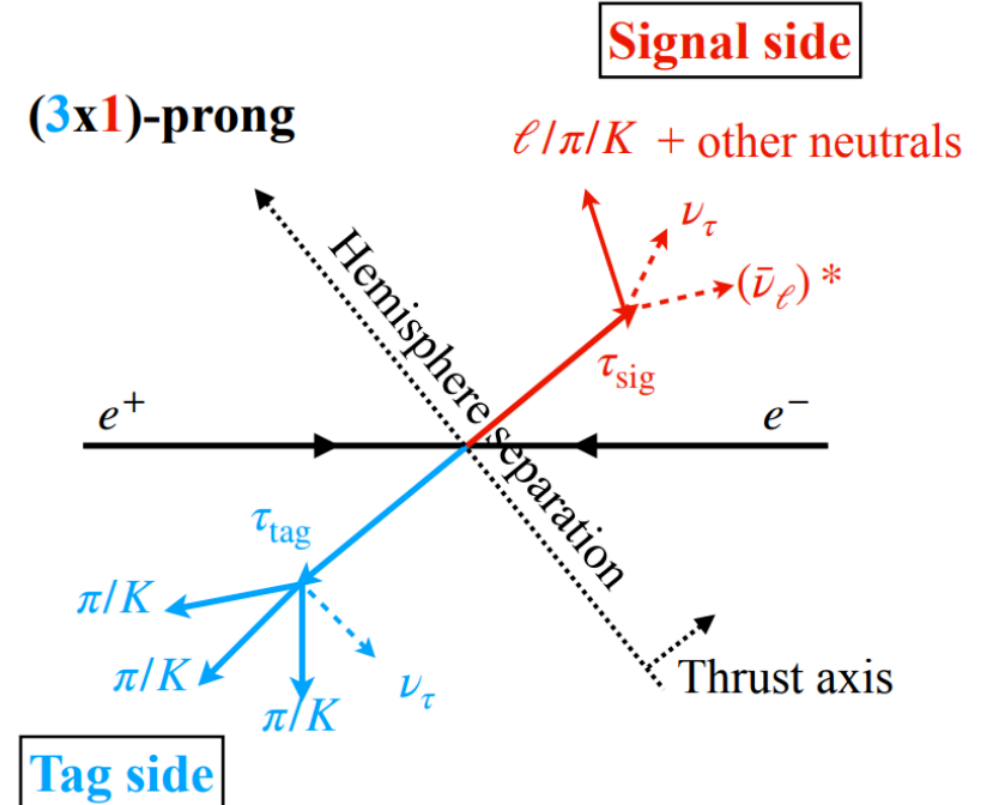
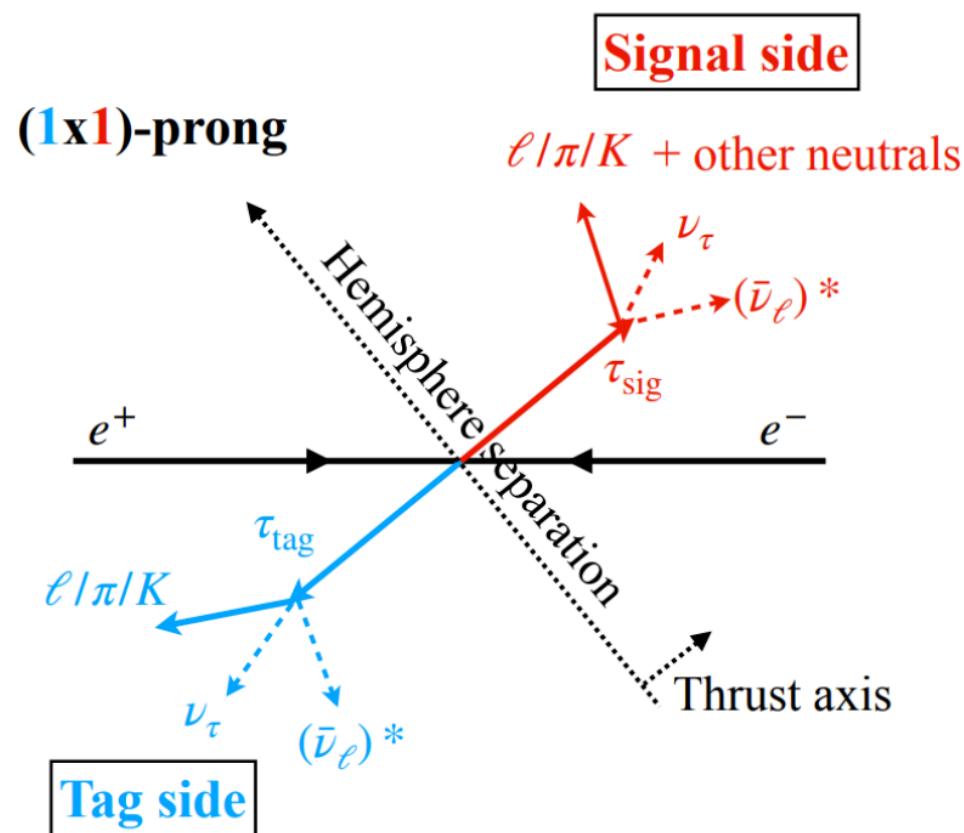
- World-leading results in precision SM measurements
 - τ mass PRD 108, 032006
 - Test of LFU JHEP 2024, 205
 - CPV in $\tau \rightarrow \pi K_S^0 \nu$ *Preliminary*
- & direct searches for New Physics
 - $\tau \rightarrow \ell \alpha$ (3x1) PRL 130, 181803
 - $\tau \rightarrow \mu \mu \mu$ JHEP 2024, 62
 - $\tau \rightarrow \Lambda \pi$ PRD 110, 112003
 - $\tau \rightarrow \ell K_S^0$ JHEP 2025, 092
 - $\tau \rightarrow e \ell \ell'$ JHEP 2025, 169
 - $\tau \rightarrow \mu \gamma$ *Preliminary*
 - $\tau \rightarrow \ell \eta$ *Preliminary*
 - $\tau \rightarrow \ell \alpha$ (1x1) *Preliminary*

+ much more in the pipeline!

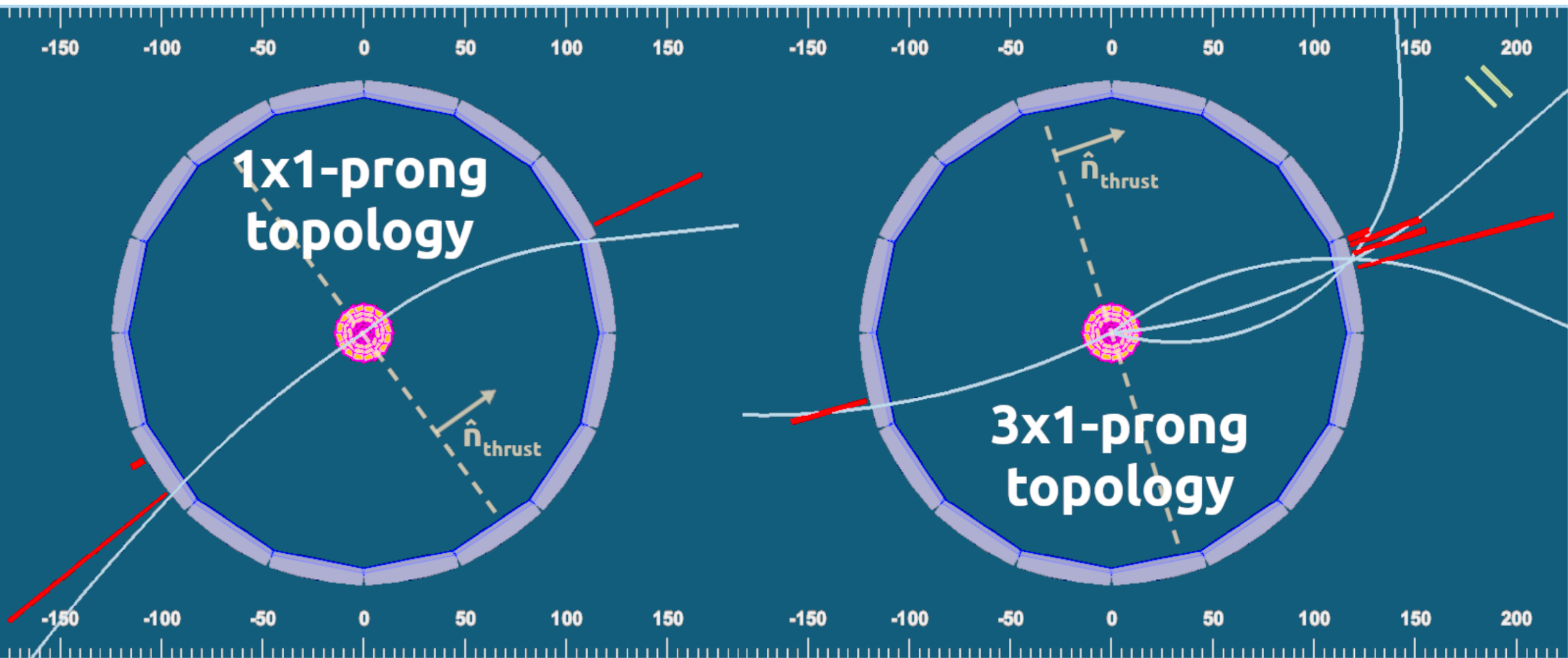
Decay topology

- $e^+e^- \rightarrow \tau^+\tau^-$ events are split across **thrust axis** into two hemispheres:
signal side and **tag side**.
- At Belle II we mainly study the **1x1** and **3x1 prong** topologies.
- Pros & cons: 1x1 is more abundant (73% vs 25%), but with larger backgrounds & lower trigger efficiency.

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



Decay topology



Tau Mass Measurement

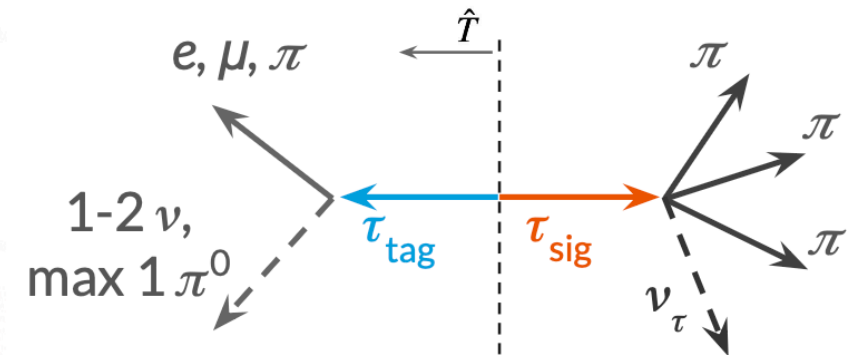
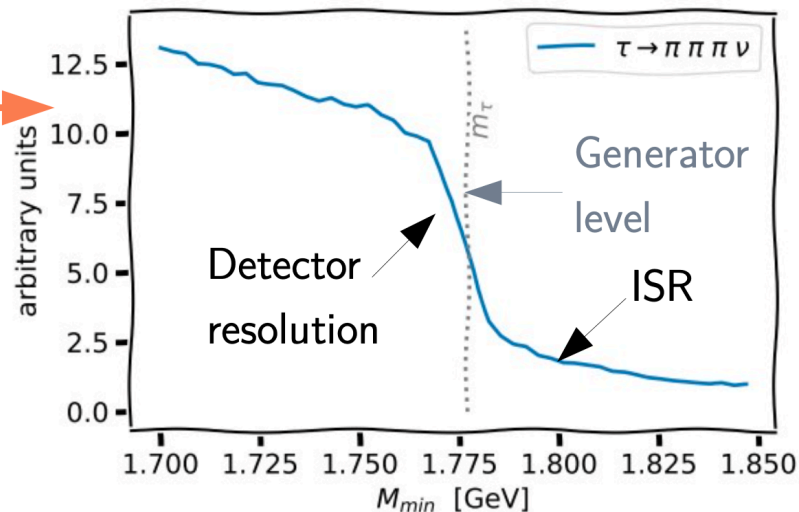
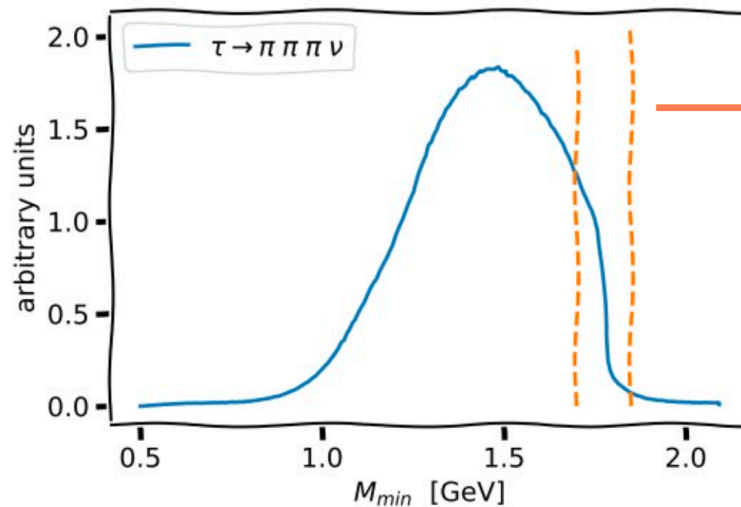
- Lepton masses (and lifetimes) are fundamental parameters of the SM.

For taus the uncertainties are by far the largest!

	electron	muon	tau
$\delta m/m$	6×10^{-9}	2×10^{-8}	$7 \times 10^{-5} \dagger$
$\delta \tau/\tau$	n/a	1×10^{-6}	2×10^{-3}

$\dagger$ prior to Belle II

- Reconstruct 3x1 prong topology with **inclusive tag** and $\tau_{\text{signal}} \rightarrow 3\pi\nu$
- Access m_τ via pseudo-mass M_{min} :
$$\sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$$
- Fit to end point distribution with an empirical function within **1.7-1.85 GeV**



- Sharp threshold behaviour near m_τ
- Smeared edge due to **detector resolution effects** and larger **tails because of ISR**

Tau Mass: precision challenge

- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_{\tau}$

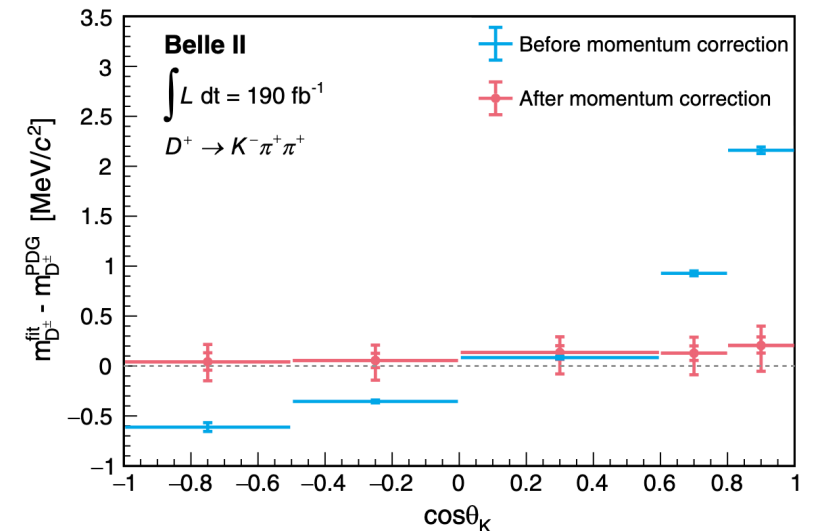
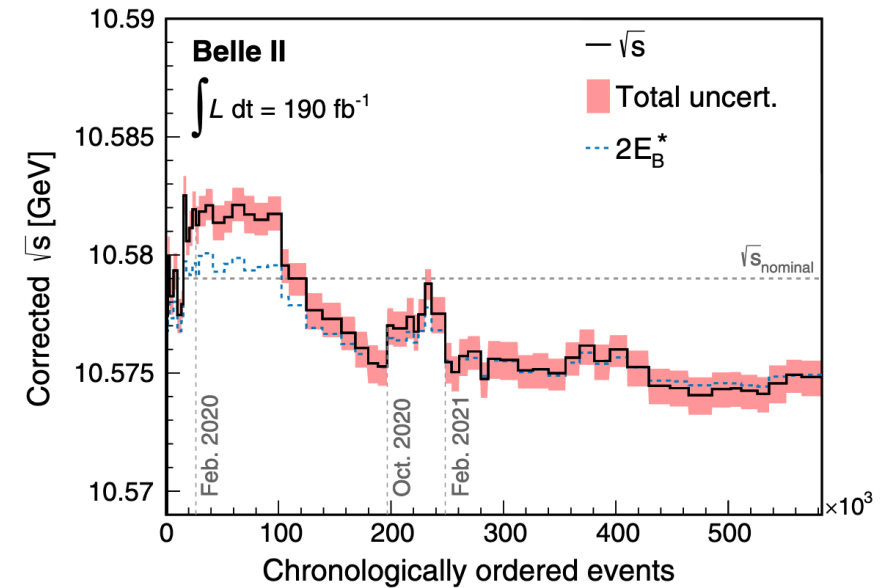
Source	Uncertainty [MeV/c ²]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence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

Beam energy calibration

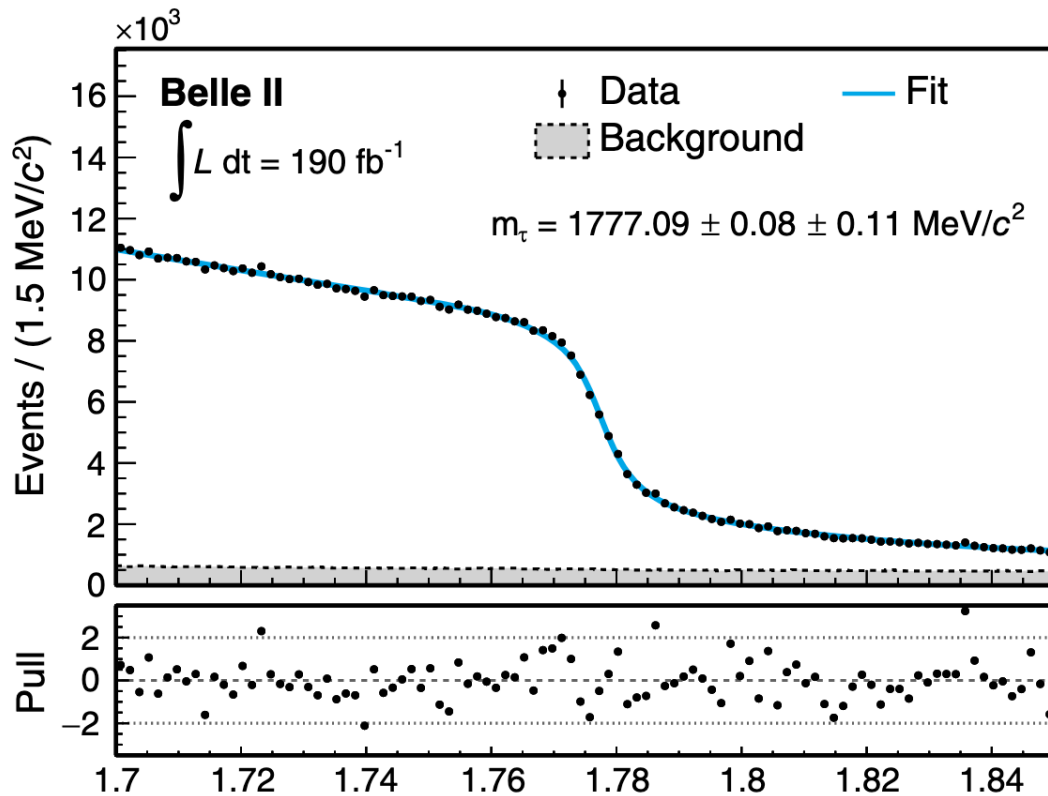
with B-meson hadronic decays method and Y(4S) lineshape measurement to get $\sqrt{s}$

Momentum scale factor

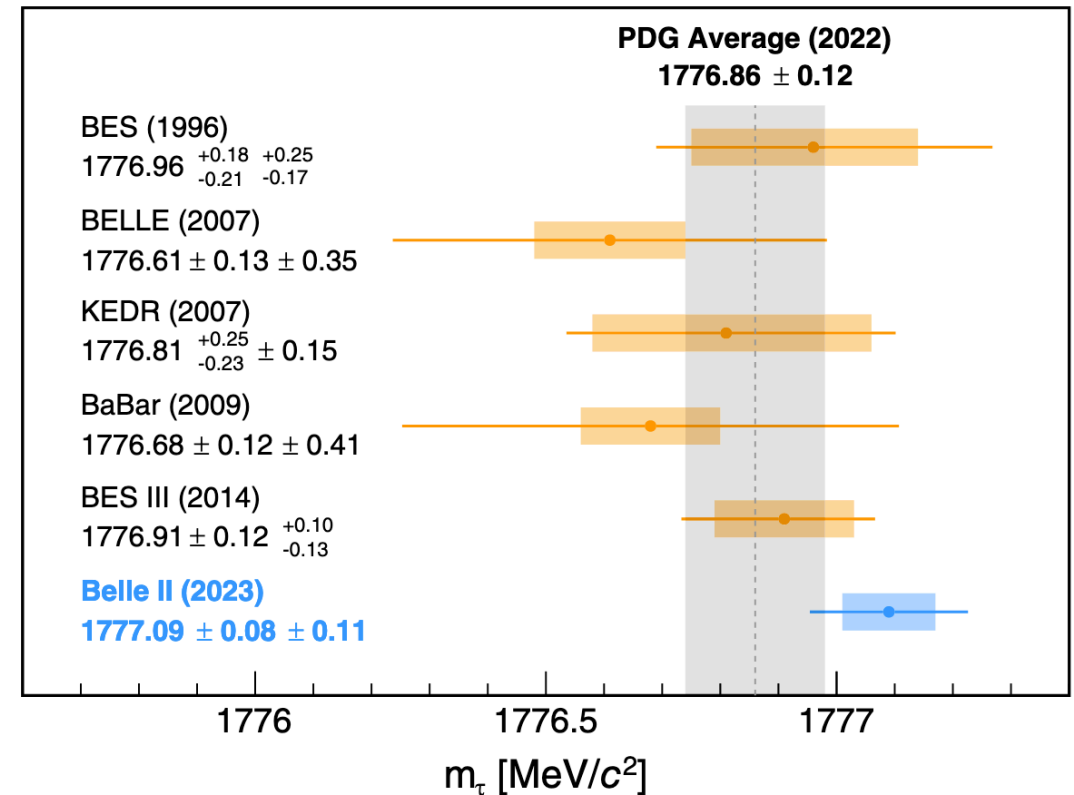
cures the bias due to imperfect B-field: extract corrections dependent on $\cos\theta_{\text{track}}$ by comparing $D^0 \rightarrow K\pi$ mass peak w.r.t PDG mass.



- Analysis performed on part of the on-resonance Run 1 data (190 fb^{-1}).
- **Achieve world's most precise measurement:** $m_\tau = 1777.09 \pm 0.08_{\text{stat}} \pm 0.11_{\text{sys}} \text{ MeV}/c^2$
 $\Rightarrow$ **Demonstration of the high precision capability of Belle II!**

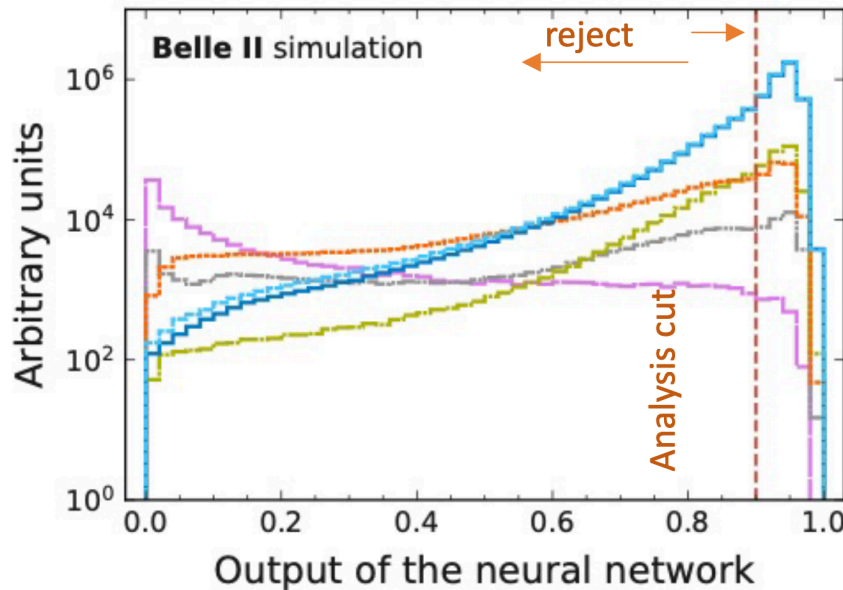
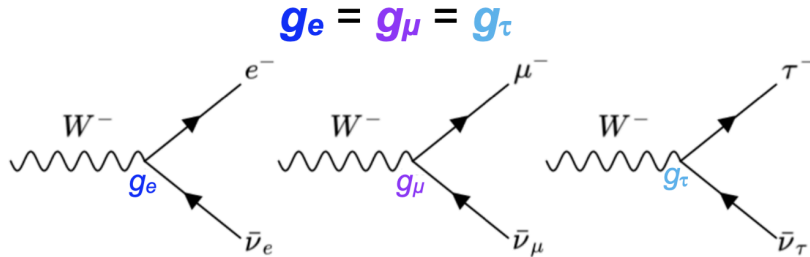


Phys. Rev. D 108, 032006 (2023)



Lepton Flavour Universality

- LFU $\Rightarrow$ couplings of leptons to W bosons is flavour independent

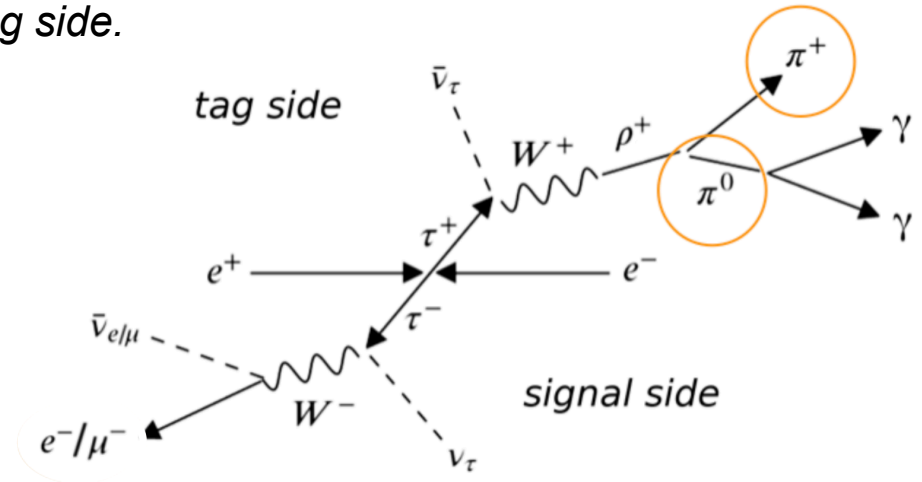


- In τ decays, testing LFU is in principle simple: compare the rates of $\tau \rightarrow \mu \nu \nu$ VS $\tau \rightarrow e \nu \nu$

$$R_\mu = \frac{BF[\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau]}$$

- Goal: measure R_μ at Belle II in Run1 data (362 fb⁻¹).

- 1x1 prong topology with ρ tag, with **charged hadron** & **at least one π^0** on the *tag side*.



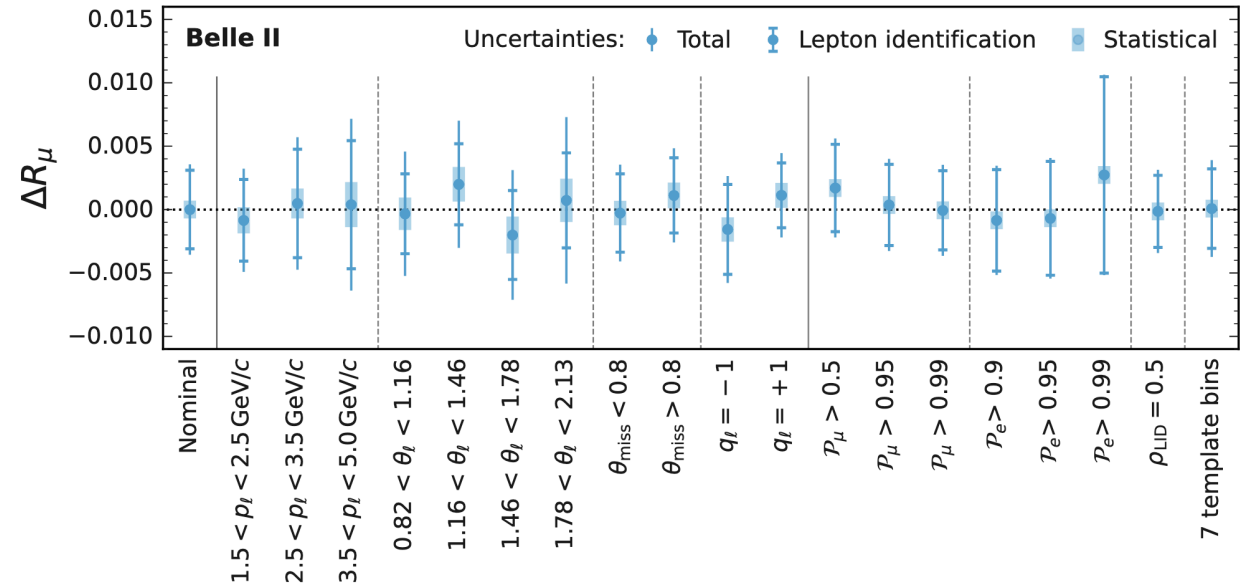
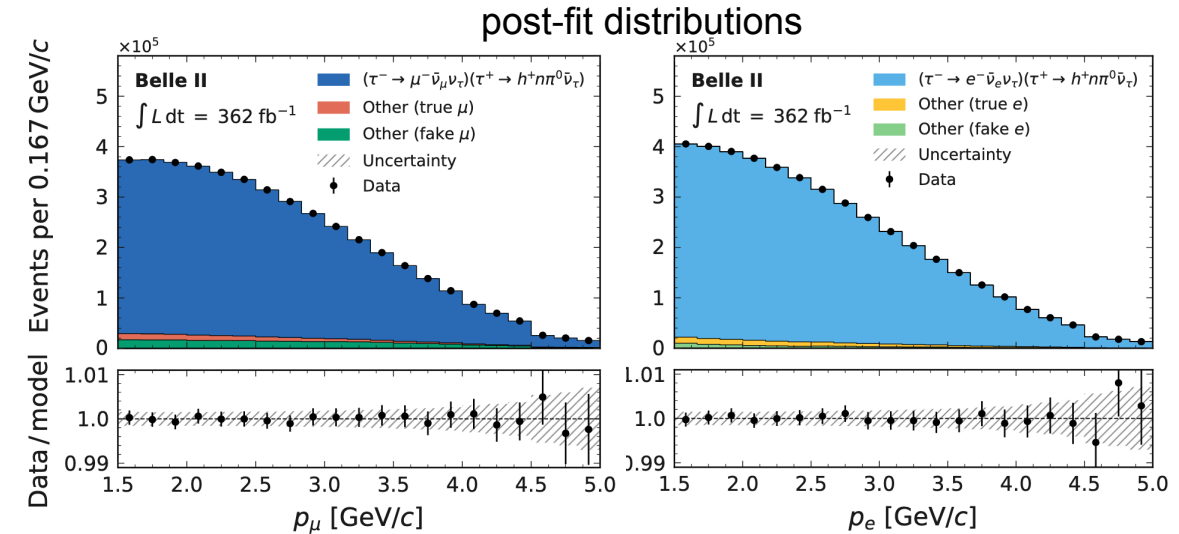
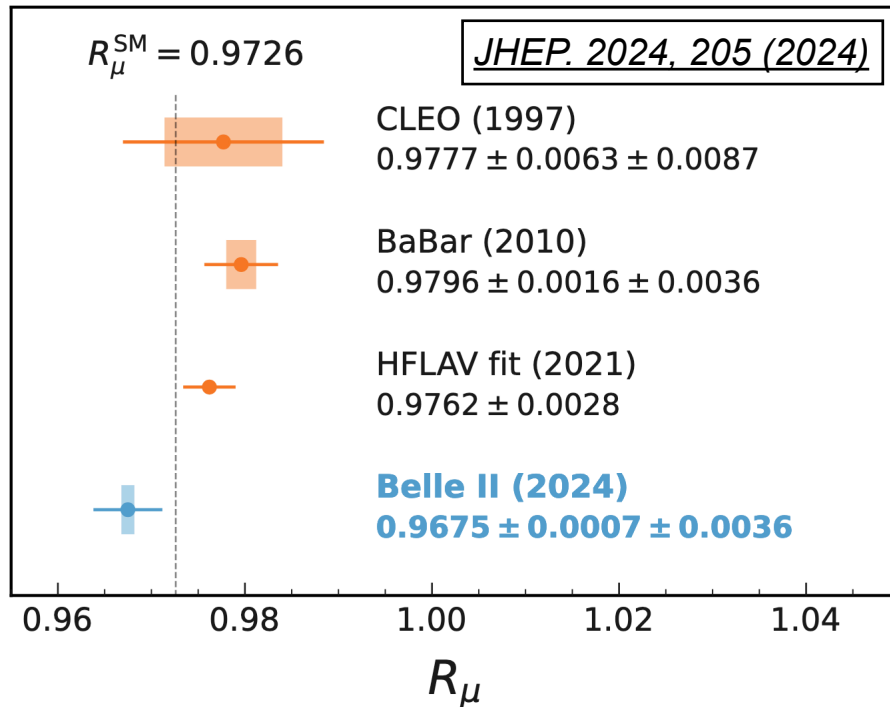
Analysis strategy:

- Neural network to suppress backgrounds (94% purity @ 9.6 efficiency).
- Restrict to barrel region & $1.5 < p < 5$ GeV, to reduce PID systematics.
- R_μ extracted via binned ML template fit to e/ μ momentum distributions.

LFU result

- Big effort within the Performance Group of Belle II to get **lepton ID efficiency and fake-rate systematics** under control (0.32%).
- Before unblinding, confirmed **good agreement b/w different sub-regions** of kinematic variables, charge, data-taking periods, and particle ID requirements.

Belle II achieved the world's most precise test of LFU in τ decays! Consistent with SM at 1.4σ

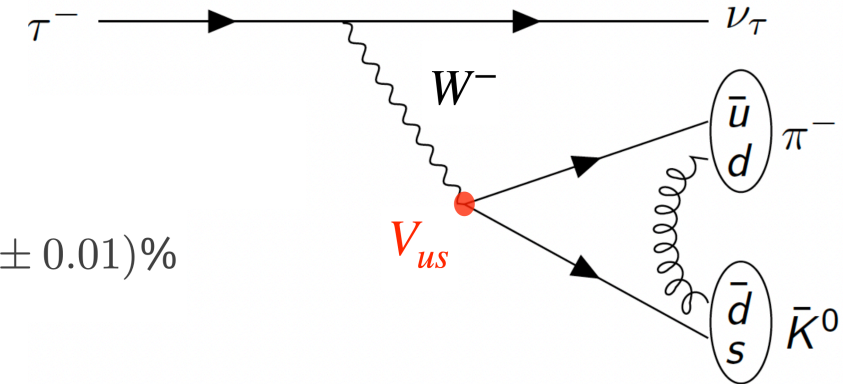


CPV in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$

- Certain τ decays involving a neutral kaon can exhibit nonzero CP-violating decay-rate asymmetry due to $K^0 - \bar{K}^0$ mixing. Provides **unique insight into leptonic sector**. Largely unexplored territory.

- SM predicts a small but nonzero value:

$$A_{CP}^{SM} = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)} \simeq (0.33 \pm 0.01)\%$$



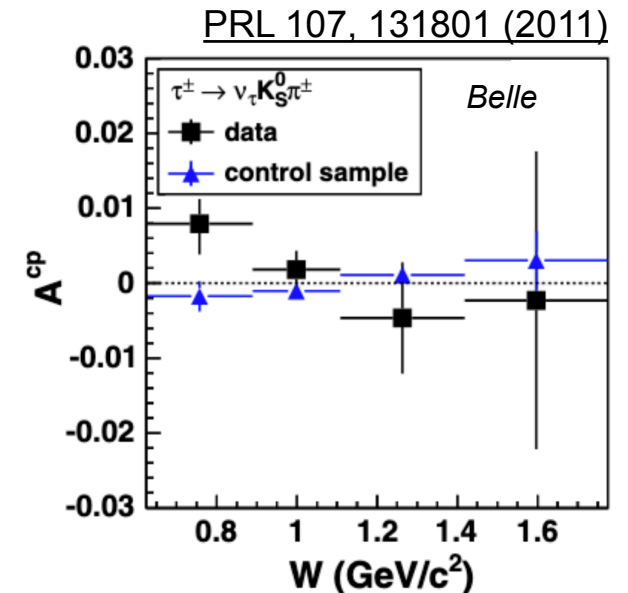
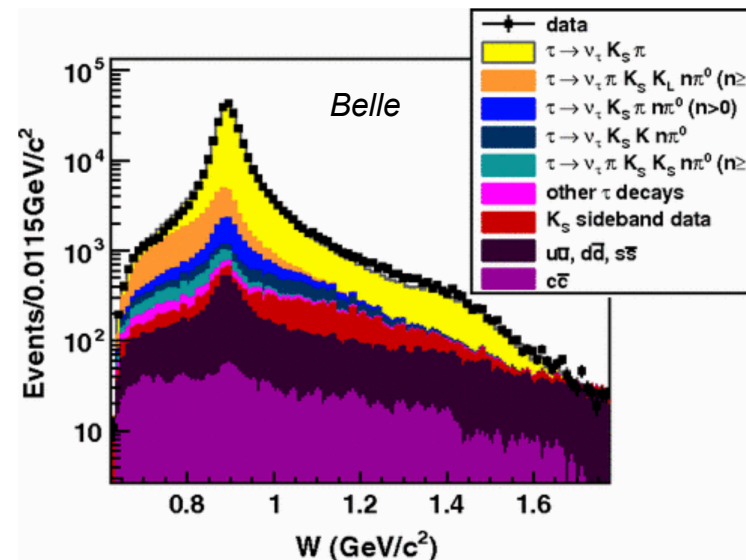
- BABAR** (476 fb⁻¹) measured it to be **2.8σ away from the SM expectation**.
- Whereas **Belle** (699 fb⁻¹) performed an angular analysis, measuring A_{CP} in four bins of $K_S \pi$ invariant mass. Consistent with zero A_{CP} within a precision of $\mathcal{O}(10^{-2})$...but lacked stat precision to confirm/exclude BaBar excess.



Puzzle remains after ~15 years...

PRD 85, 031102(R) (2012)

$$A_{CP}^{BaBar} = (-0.36 \pm 0.23(\text{stat}) \pm 0.11(\text{syst}))\%$$

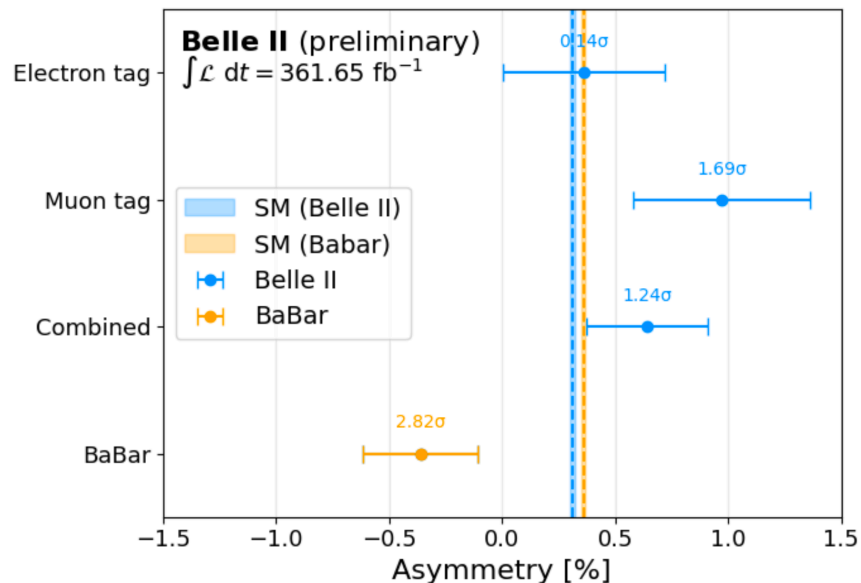


CPV Result

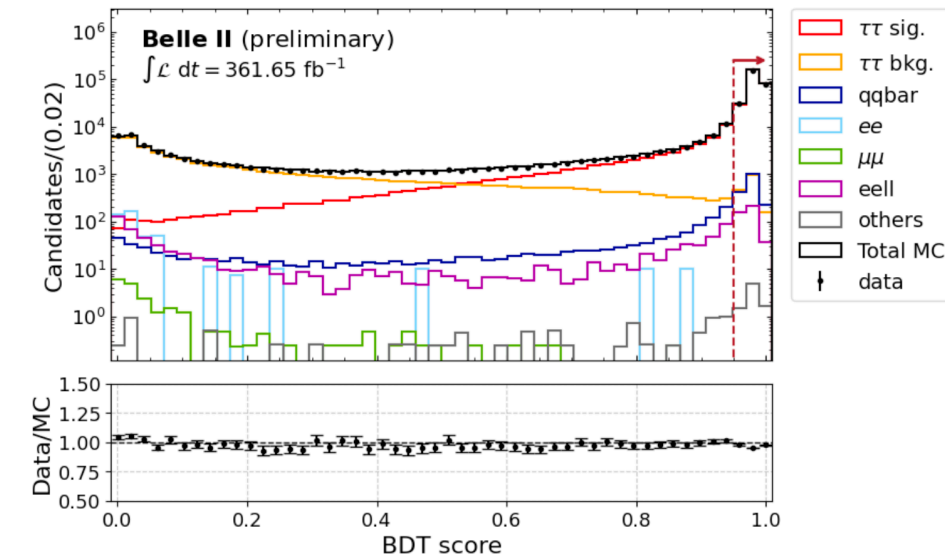
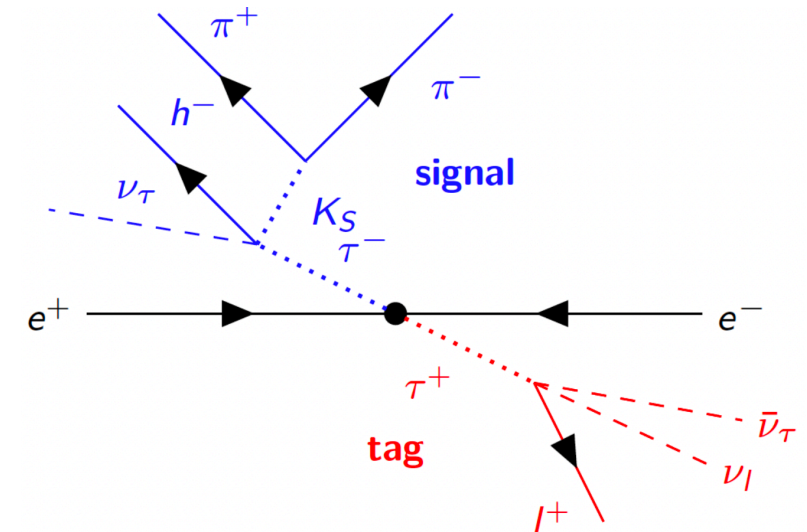
- Recent Belle II measurement with Run1 data using 3x1 topology & **leptonic tag**.
- Achieve ~98% signal purity using two Boosted Decision Trees.
BDT1 to suppress $e^+e^- \rightarrow q\bar{q}$ & BDT2 to suppress $e^+e^- \rightarrow \tau^+\tau^-$ backgrounds.
- Measure pure CP-violating quantity after careful subtraction of production dynamics and detector-induced effects.

$$A_{CP}^{Belle II} = 0.64 \pm 0.26 \text{ (stat)} \pm 0.06 \text{ (sys)} \%$$

In agreement with SM within 1.24σ . No confirmation of BaBar tension.



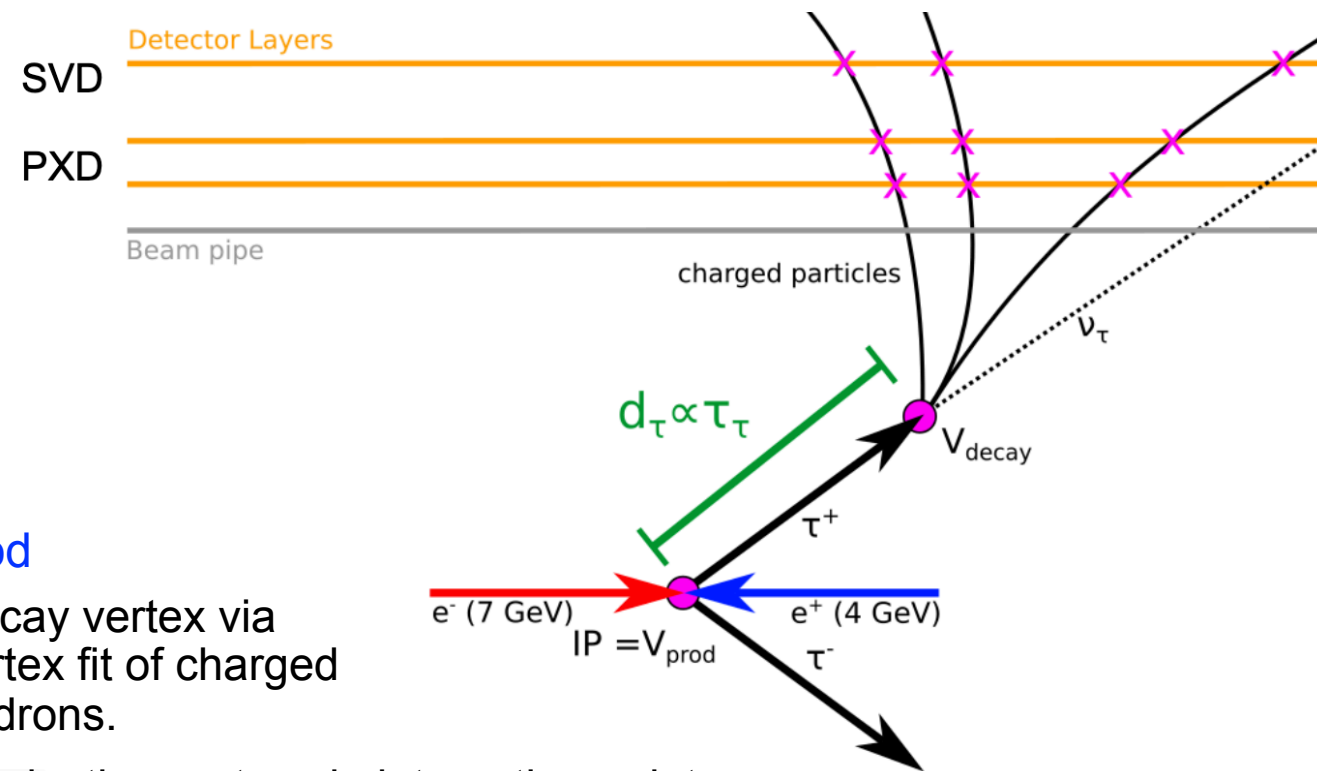
- Comparable statistical precision to BaBar (despite ~30% less data).
- ~Half the systematic uncertainty of BaBar (largest uncertainty mostly driven by control sample statistics, which bodes well for future measurements).



Next precision challenge: tau lifetime

See Fabian's talk for more details!

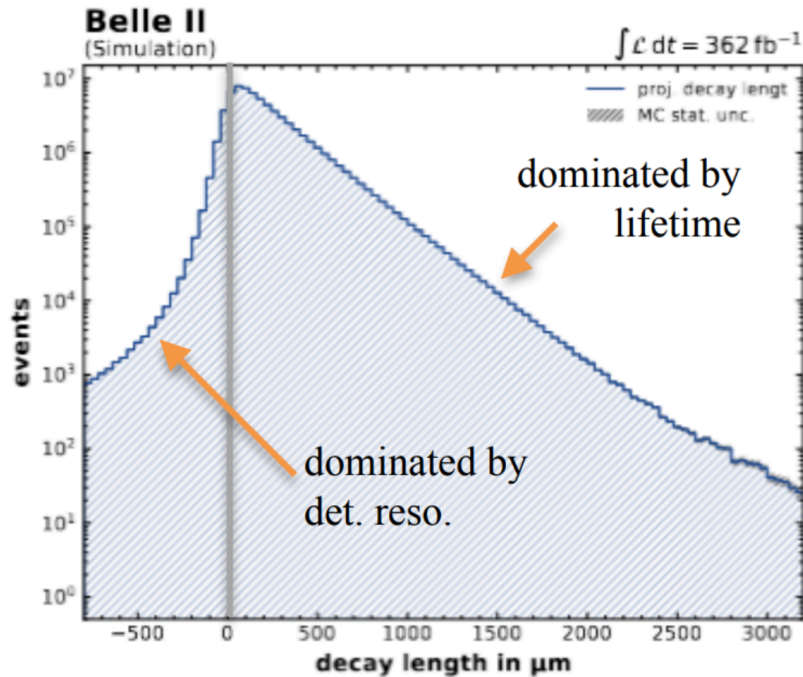
- World's best measurement from **Belle** (711 fb^{-1}) using **3x3 topology** [[PRL.112.031801](#) (2014)].
- Belle II** measurement is underway!
 - Small SuperKEKB beam spot enables use of **3x1 topology** for the first time with **13x BR!**
 - Improved vertex reconstruction (PXD).



Method

- Decay vertex via vertex fit of charged hadrons.
- Production vertex via interaction point.
- Project decay length on transverse momentum of the three hadron system $\rightarrow$ negative tail purely from detector resolution effects.
- Template fit to extract lifetime.

Belle II can deliver a world-leading measurement with the current data



Tau lifetime: Belle II measurement coming soon!

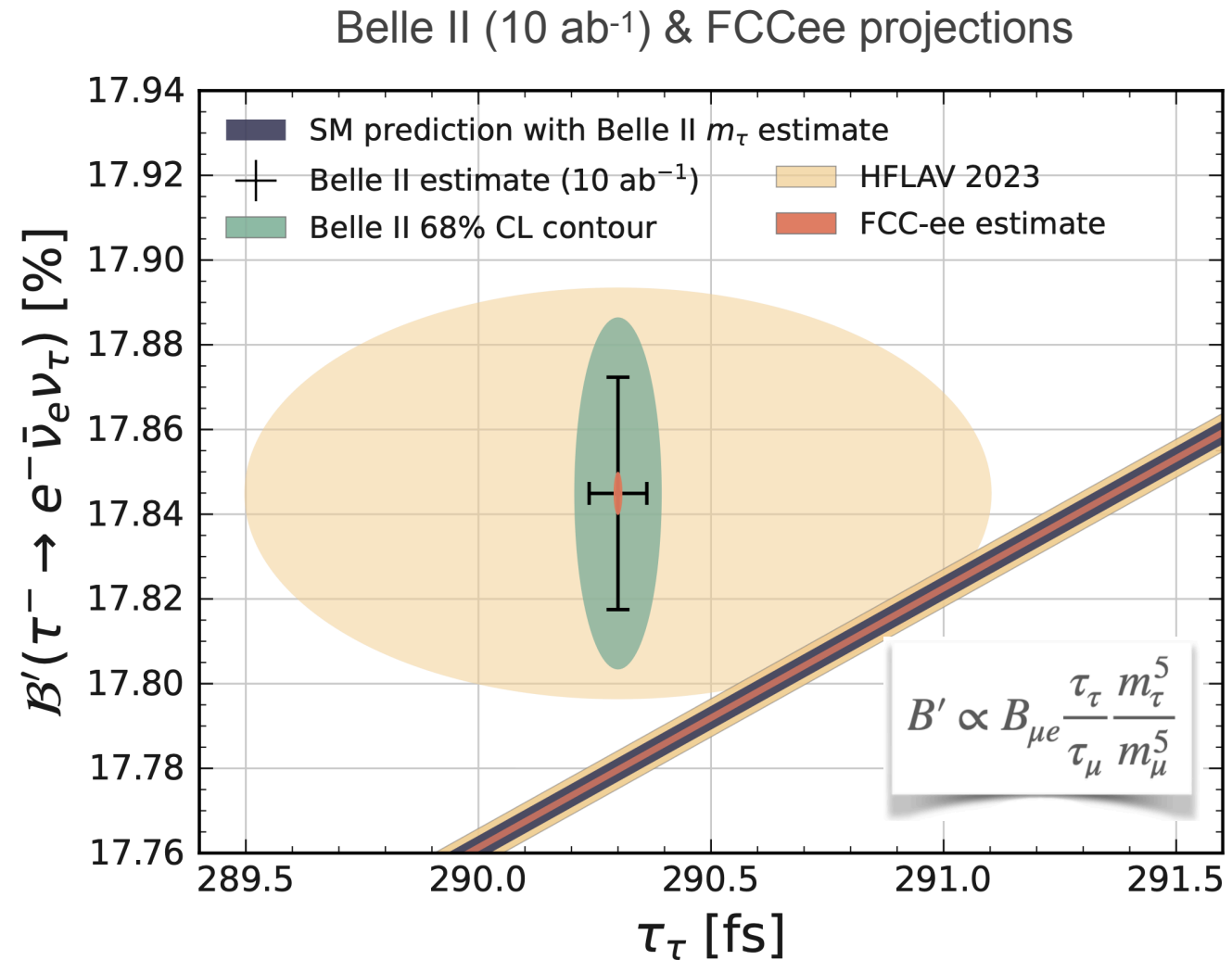
- ▶ Nano-beam scheme + excellent vertex resolution
→ first ever use of 3x1 topology!

Improved tau mass measurement with more data

- ▶ Better control of beam energy and track momentum scale corrections.
- ▶ Possibility to test CPT conservation measuring τ^+ and τ^- separately.

Improved test of e- μ universality with more data

- ▶ More precise particle ID corrections and reduced trigger systematics.
- ▶ Complementary measurement in 3x1 topology.
- ▶ Possibility to measure absolute BFs, whose measurements are still dominated by LEP experiments from 1990s (ALEPH, DELPHI, etc.).



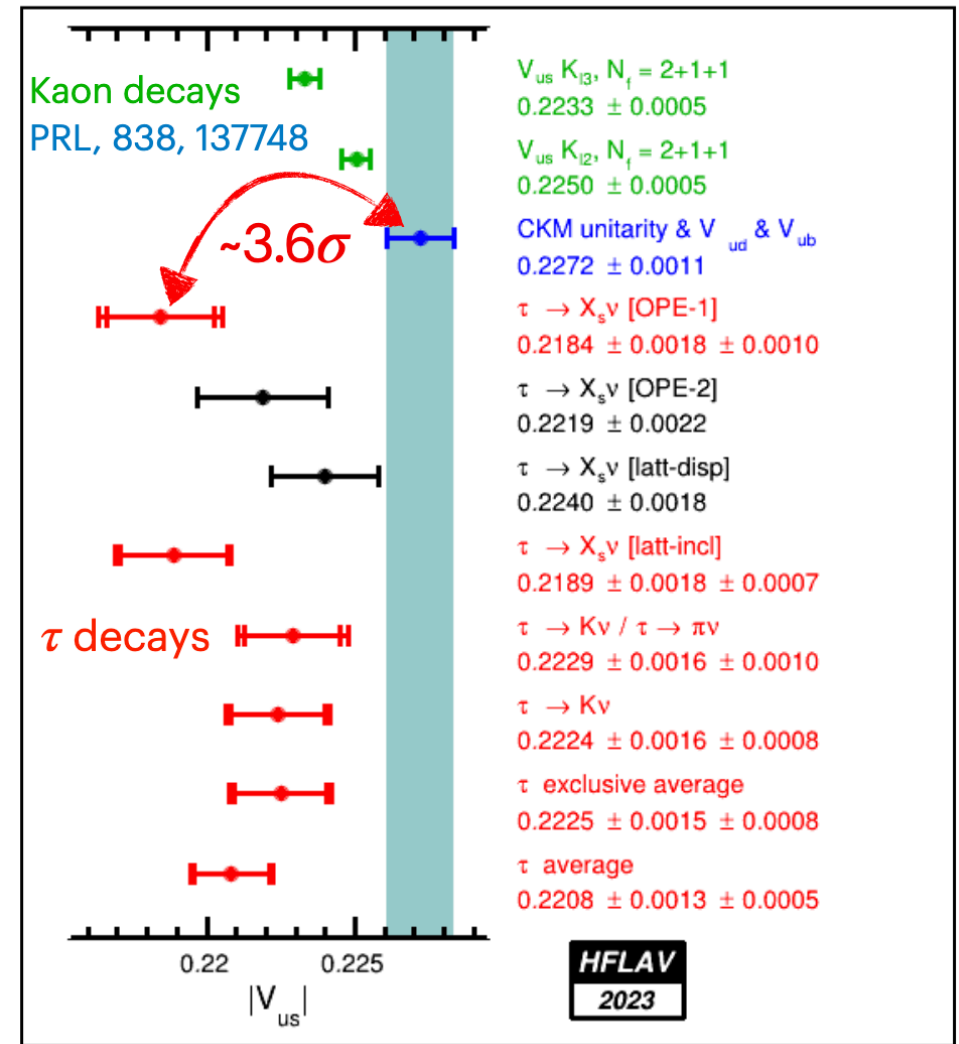
Tackling the V_{us} anomaly

HFLAV23

- **Persistent $>3\sigma$ tension** between V_{us} from CKM unitarity and from sum of exclusive BF's of $\tau \rightarrow X_s \nu$.



- What can Belle II do to help resolve this?

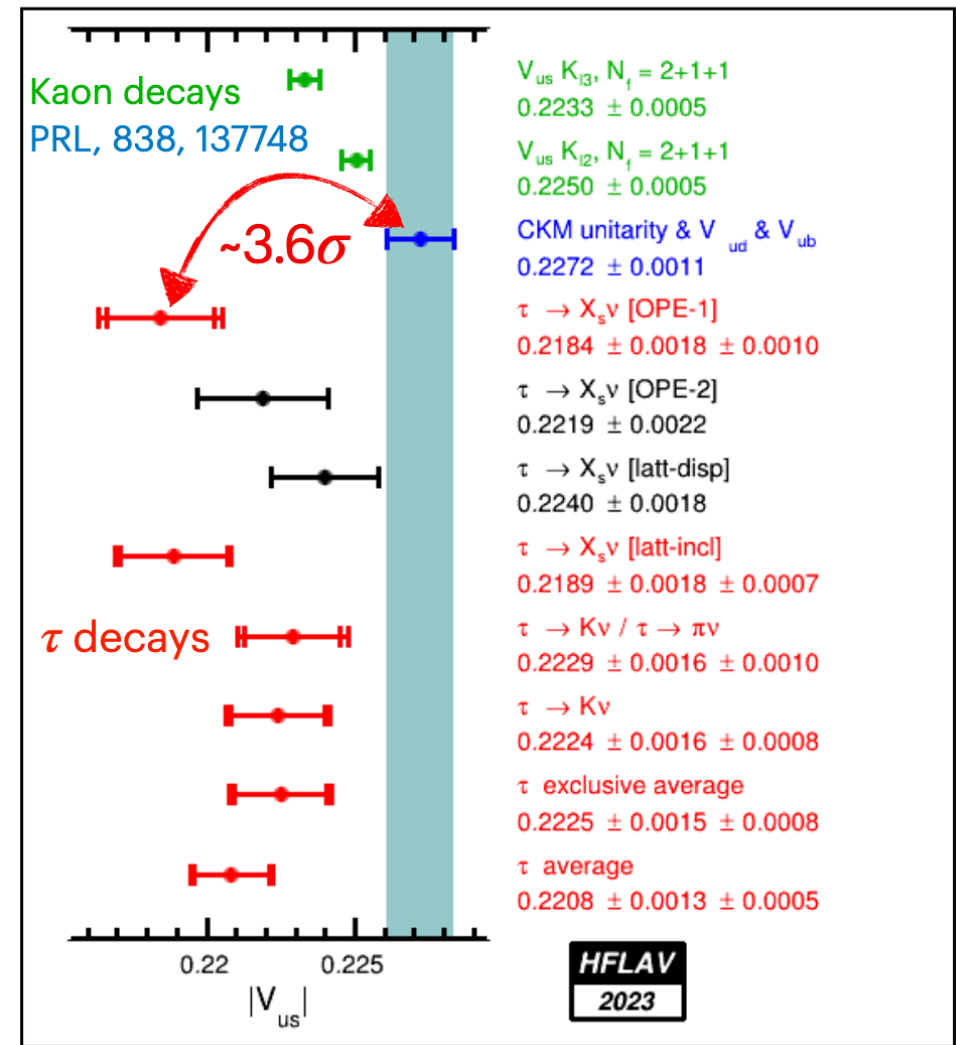


Tackling the V_{us} anomaly

HFLAV23

- Belle II is tackling this from three directions:

(1) Measuring inclusive $\mathcal{B}(\tau \rightarrow X_s \nu)$ to have
first direct inclusive V_{us} measurement
 with a total uncertainty of $\sim 1\%$.
See talk from Michele!



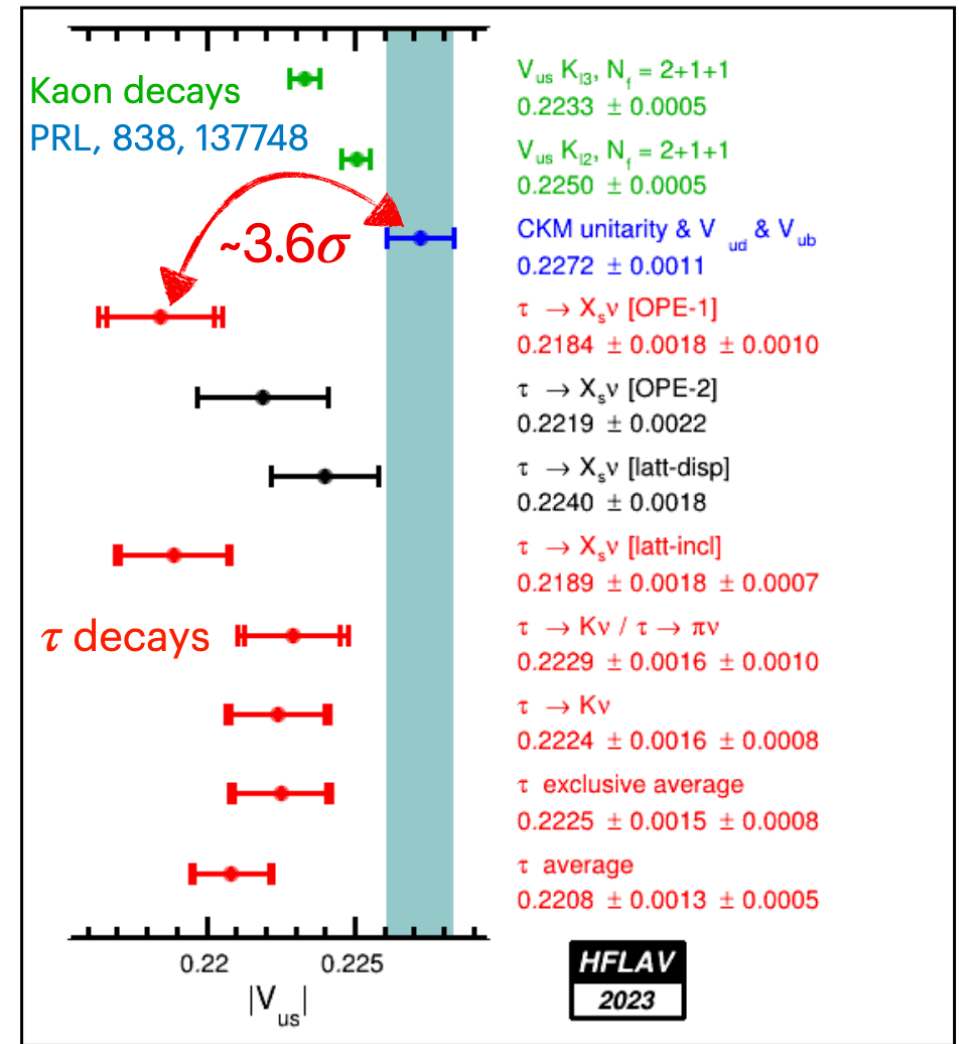
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(2) **Exclusive measurement of V_{us} through $R_{K/\pi}$** ,
 which is also an important test of LFU.
See talk from Michele!



Tackling the V_{us} anomaly

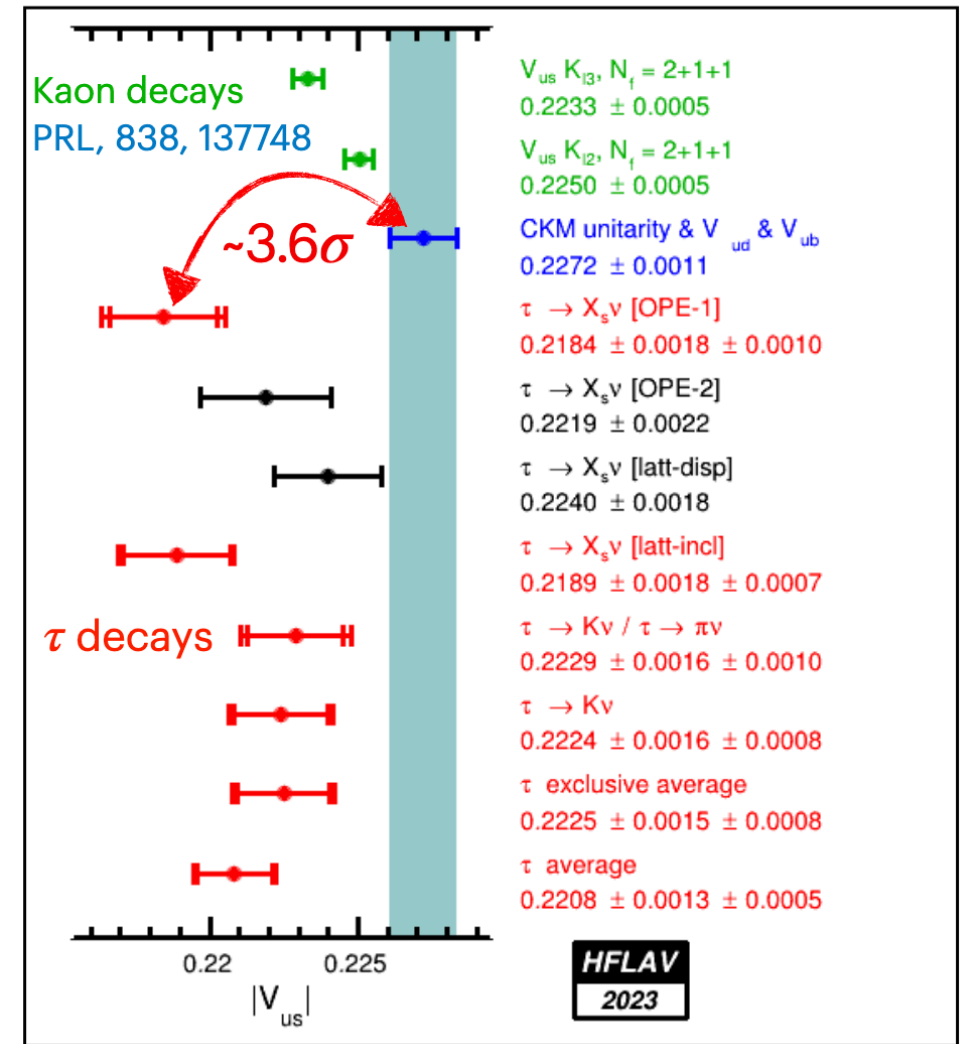
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See talk from Michele!

(3) Study **decay channels with open strangeness** $\tau \rightarrow K X \nu$ which are also important inputs for V_{us} .



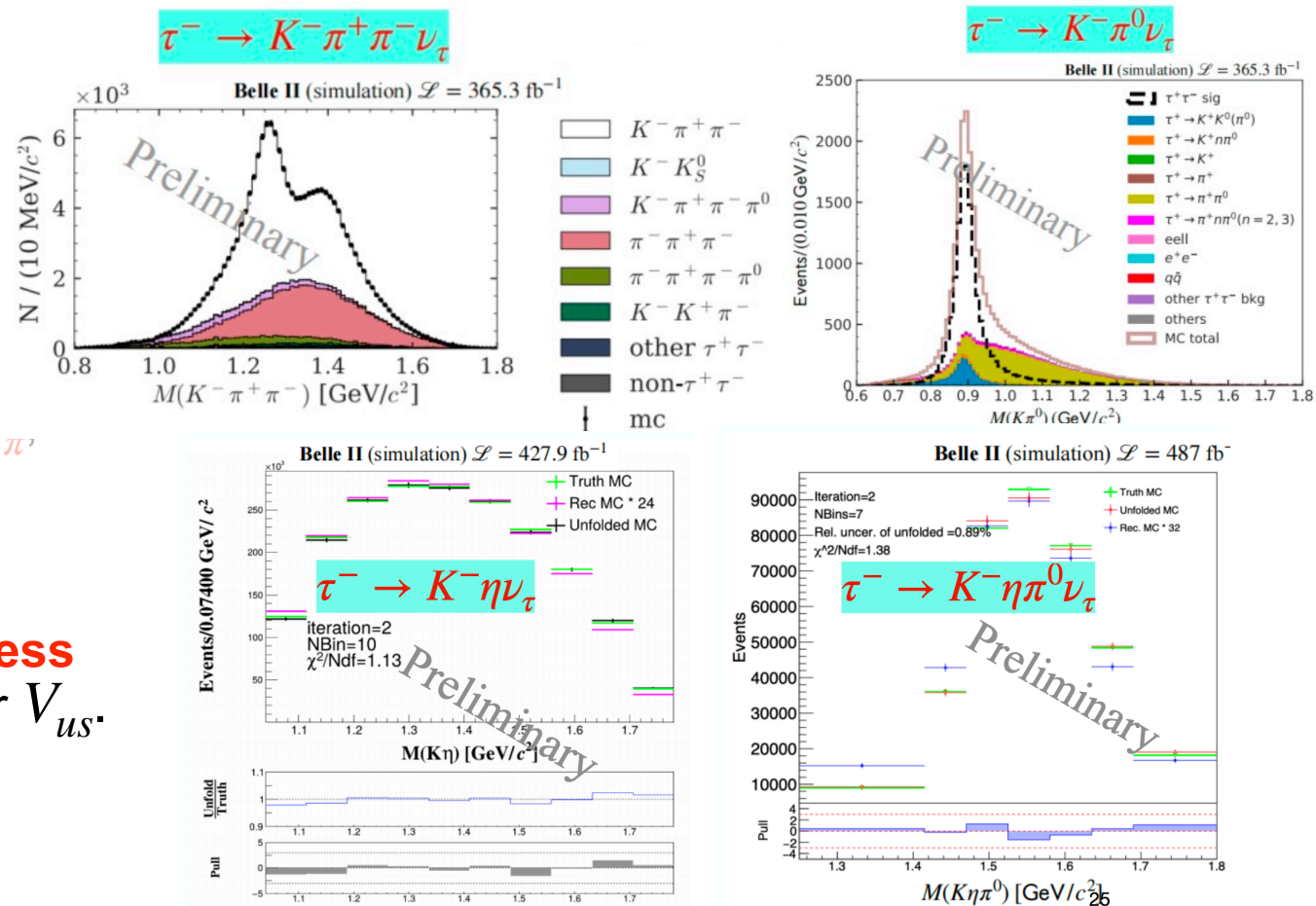
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See talk from Michele!

(3) Study **decay channels with open strangeness** $\tau \rightarrow K X \nu$ which are also important inputs for V_{us} .
 Several BF & spectral function measurements (via unfolding techniques) are coming soon.



+ more are underway!

e.g. $\tau^- \rightarrow \pi^- \pi^0 \nu$, $[K \bar{K}(\pi)]^- \nu$, ...

Lepton Flavour Violating τ decays

- In the SM, LFV decays of charged leptons via neutrino oscillation are highly suppressed & immeasurably small.

$$Br(\ell_1 \rightarrow \ell_2 \gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 \sim 10^{-54} - 10^{-49}$$

⇒ **Observation would be clear signature of New Physics!**

- $\tau \rightarrow e/\mu$ transitions have significantly weaker constraints.
Could 3rd lepton generation preferentially couple to NP?

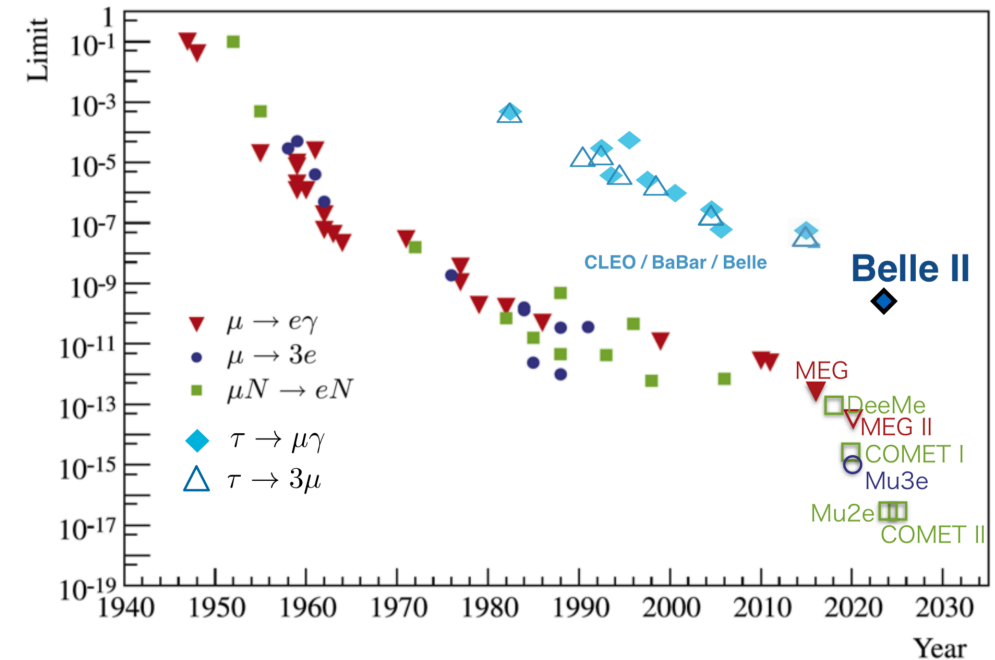
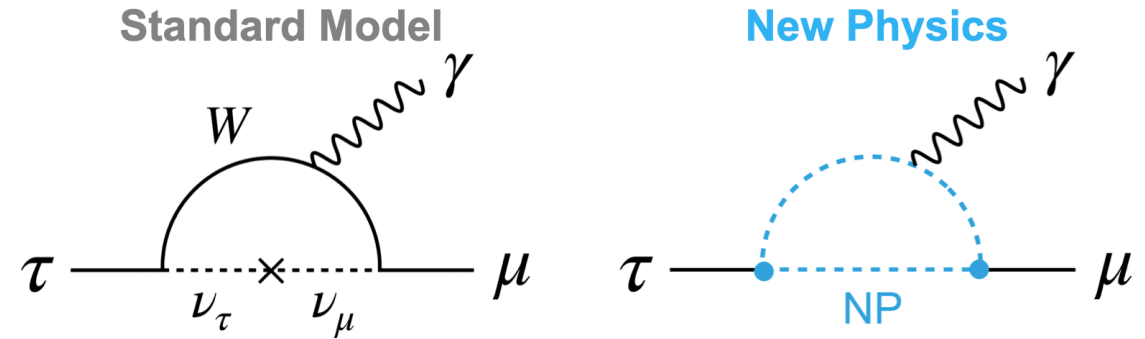
More than 52 LFV τ decays to explore, with the best sensitivity typically coming from *B*-factory experiments.

e.g. $\tau \rightarrow \mu \gamma$

- Various NP models can enhance to the 10^{-8} - 10^{-10} level, just below current experimental sensitivity.

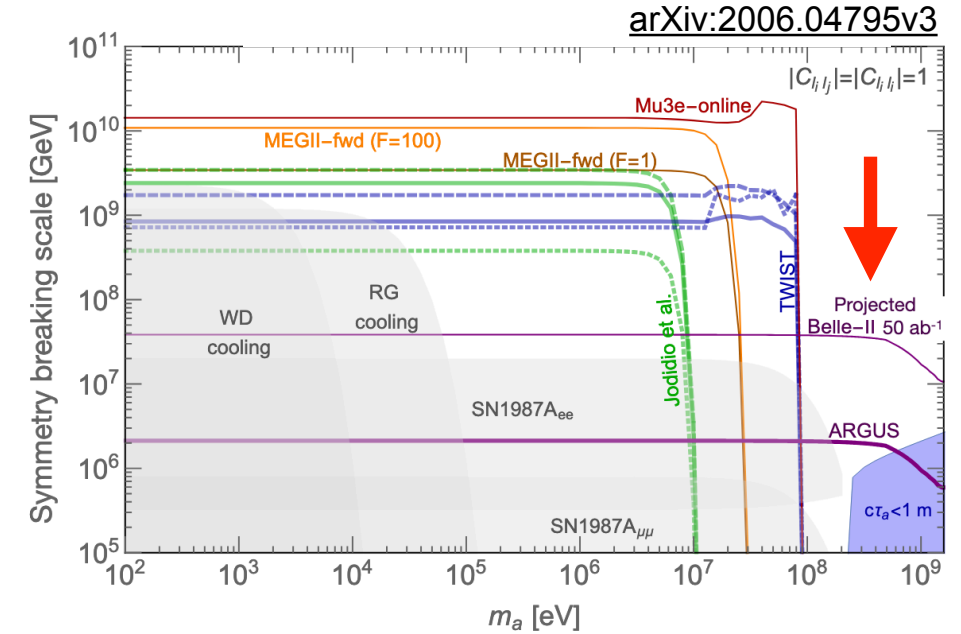
SUSY Higgs	10^{-10} [ref]
Little Higgs	10^{-10} [ref]
SM + seesaw	10^{-9} [ref]
Non-universal Z'	10^{-9} [ref]
SUSY SO(10)	10^{-8} [ref]

⇒ **Belle II is in a unique position to probe LFV τ decays with unprecedented sensitivity!**

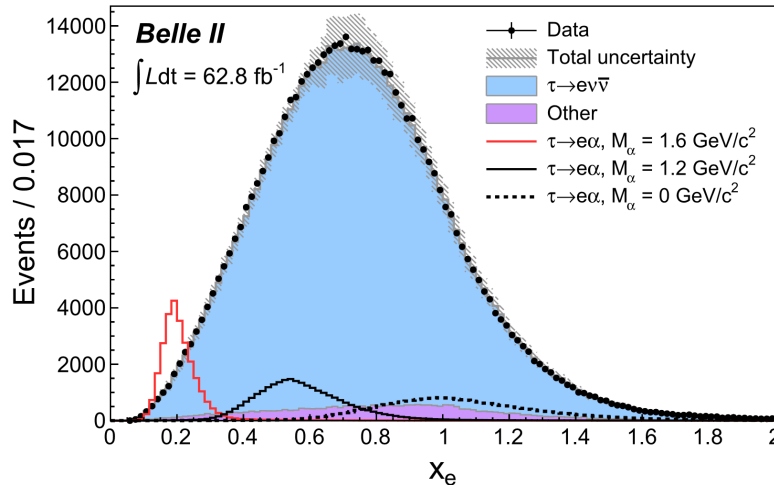


Searches for LFV $\tau \rightarrow \ell \alpha$

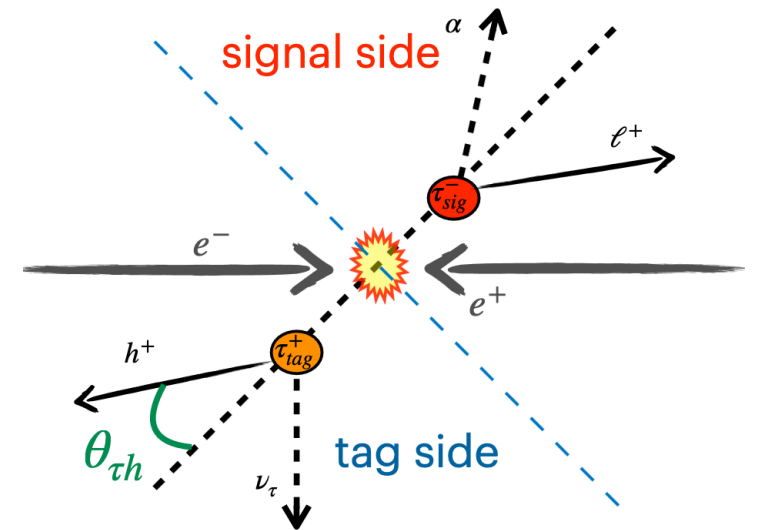
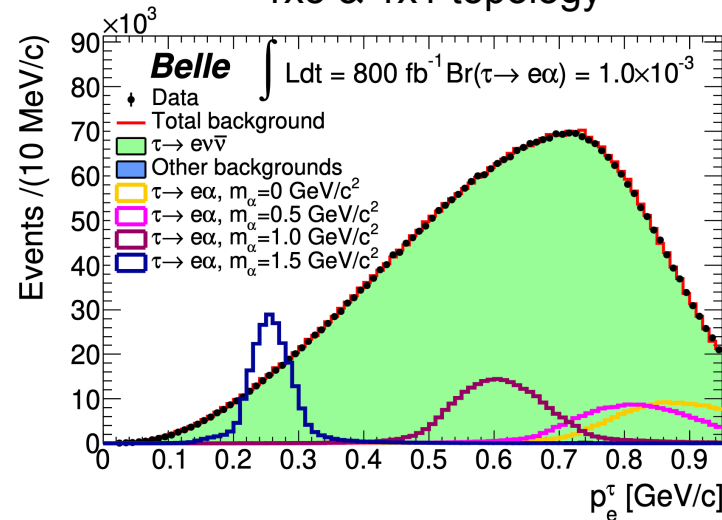
- Search for beyond SM particle (α) assumed to be light, invisible spin-0 boson.
e.g. ALPs $\rightarrow$ **unique mass reach of B -factories**.
- First search at B -factory by **Belle II** in 2023 [PRL 130, 181803].
 - Discriminate signal/background using lepton momentum in τ rest frame.
- Superseded last year with larger **Belle** dataset [JHEP 2025, 155].
 - Considering both 1x3 & 1x1 topologies.
 - Improved momentum resolution via selection on angle between tag-side τ & hadron.



Belle II (2023, 62.8 fb⁻¹)
1x3 topology

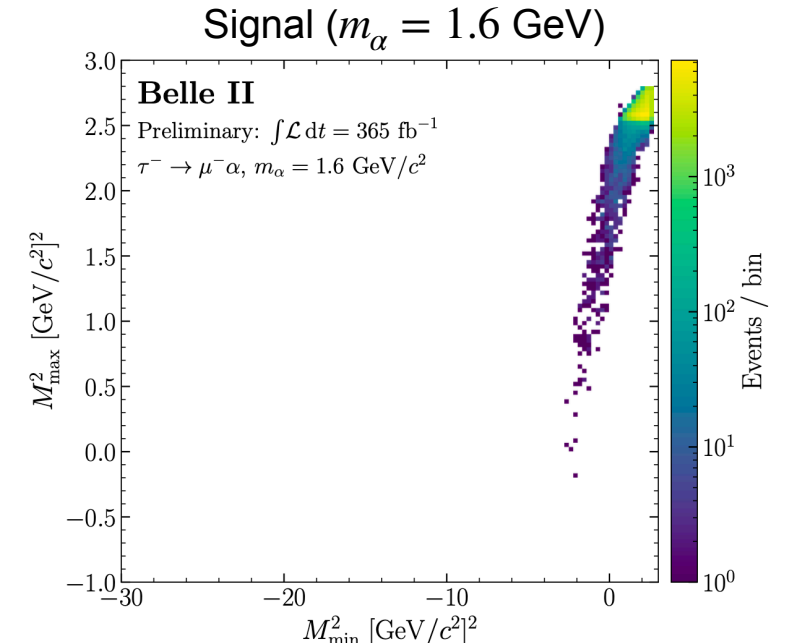
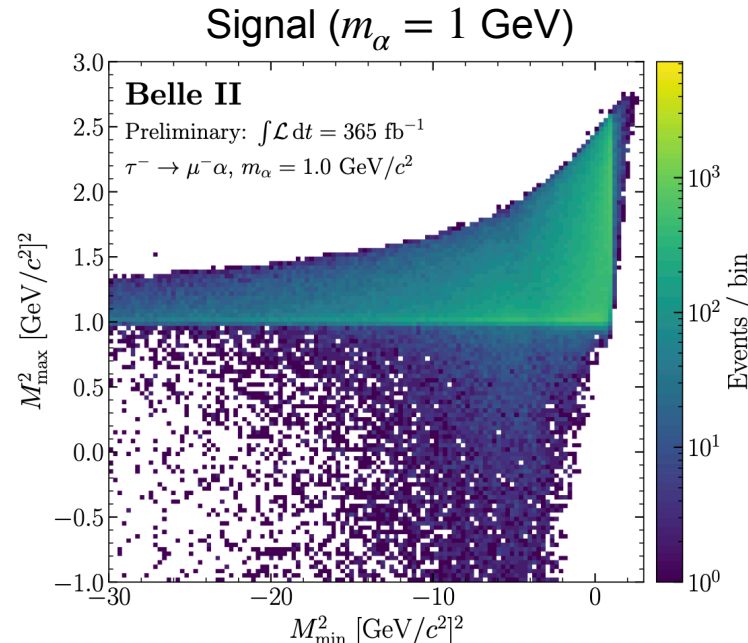
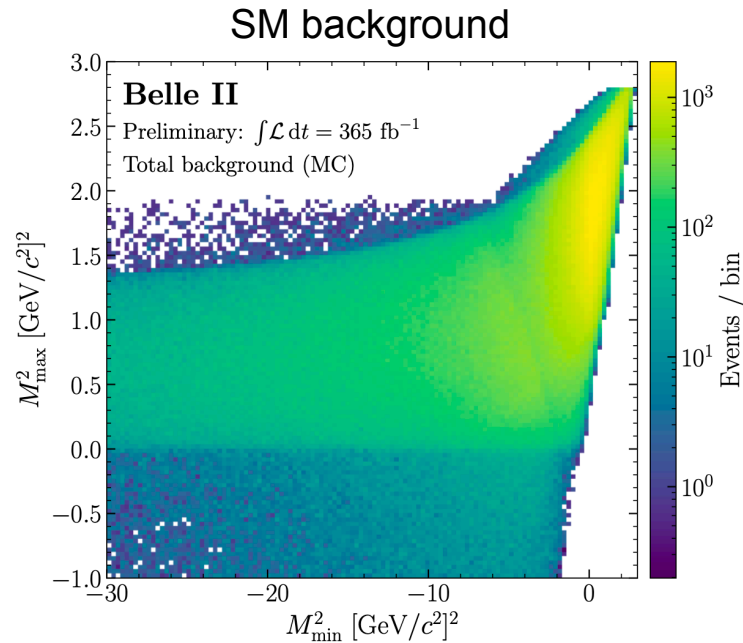


Belle (2025, 800 fb⁻¹)
1x3 & 1x1 topology



- Using Belle II data (365 fb⁻¹) with 1x1 topology.
- Online**: CDC-based with 99.1% (96.9%) trigger efficiency in the electron (muon) channel.
Offline: selections on ten variables to achieve τ -pair purity of 98.8% (99.6%).
- Main improvement:
 - Careful consideration of kinematic constraints yields two new variables M_{min}^2, M_{max}^2 with **upper / lower endpoints** at m_α^2 [PRD.102.115001].
⇒ **significantly enhanced signal/background separation**.
 - 2D binned maximum likelihood fit for signal extraction.

Variable	$\tau^- \rightarrow e^- \alpha$	$\tau^- \rightarrow \mu^- \alpha$
$\cos \theta_{th}$	[-0.92, 0.44]	[-0.84, 1.00]
E_{vis}^*	[2.86, 7.70]	[3.60, 8.40]
p_{mis}^*	[0.84, 5.64]	[0.96, 4.80]
θ_{mis}^*	[0.63, 2.20]	[0.69, 2.39]
M_{mis}^2	[1.16, 55.24]	[1.16, 40.68]
$p_{T,mis}^*$	[0.40, 5.00]	[0.40, 5.00]
$p_{T,max}^*$	[1.43, 5.10]	[1.94, 5.10]
E_{sig}^{clus}	[0.00, 6.23]	[0.00, 3.74]
p_{tag}	[0.39, 6.11]	[0.39, 6.50]
θ_{tag}	[0.29, 2.62]	[0.29, 2.62]



New search for $\tau \rightarrow \ell \alpha$

NEW from
ICHEP2026!

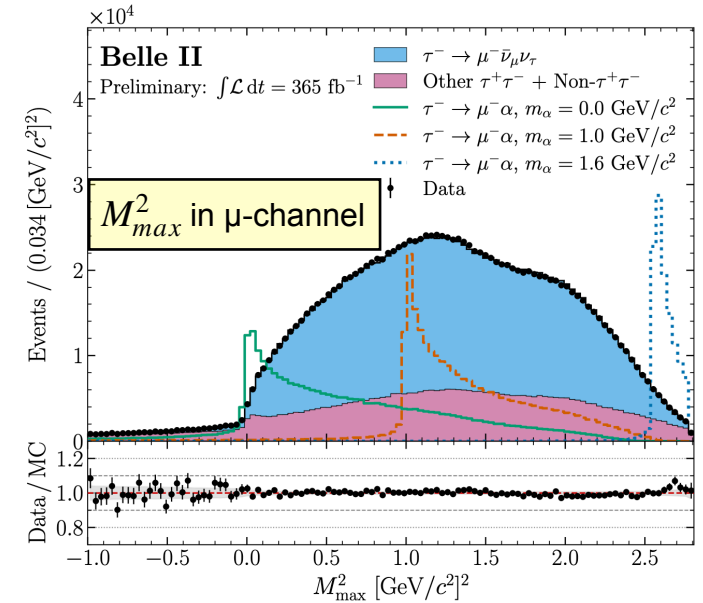
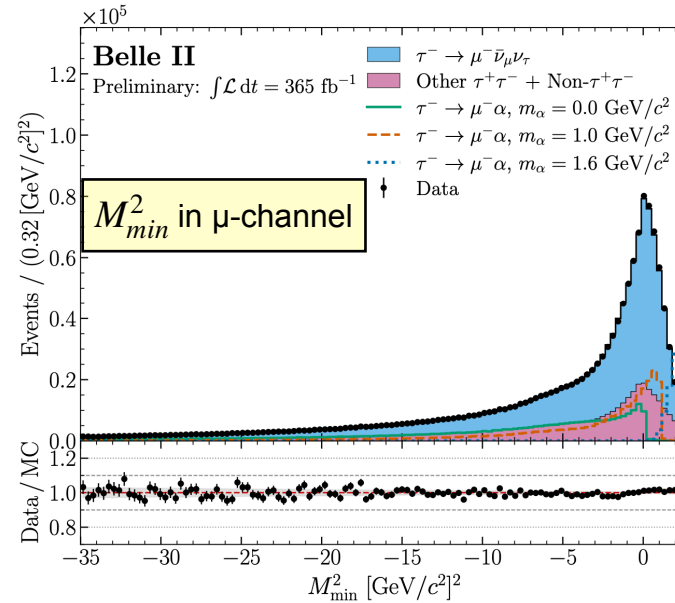
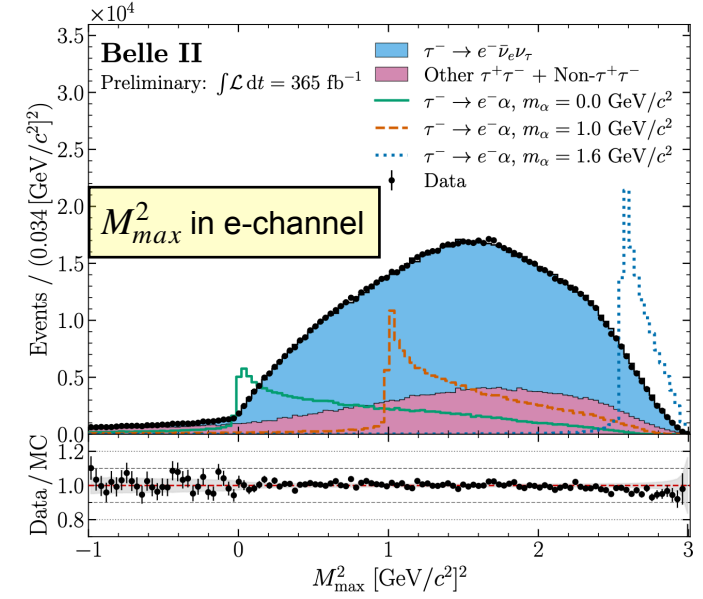
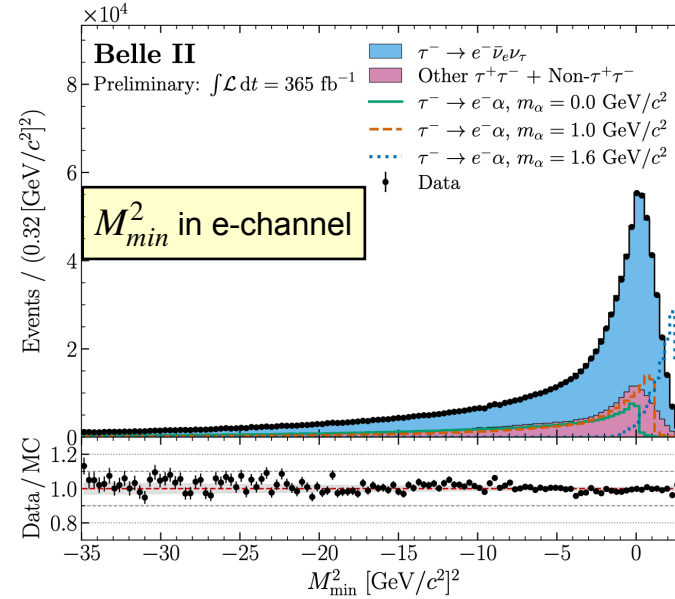
- Detailed validation of MC simulation prior to opening the box:
 - Control sample ($\tau \rightarrow \rho \nu$): all variables.
 - Signal region: variables insensitive to signal.

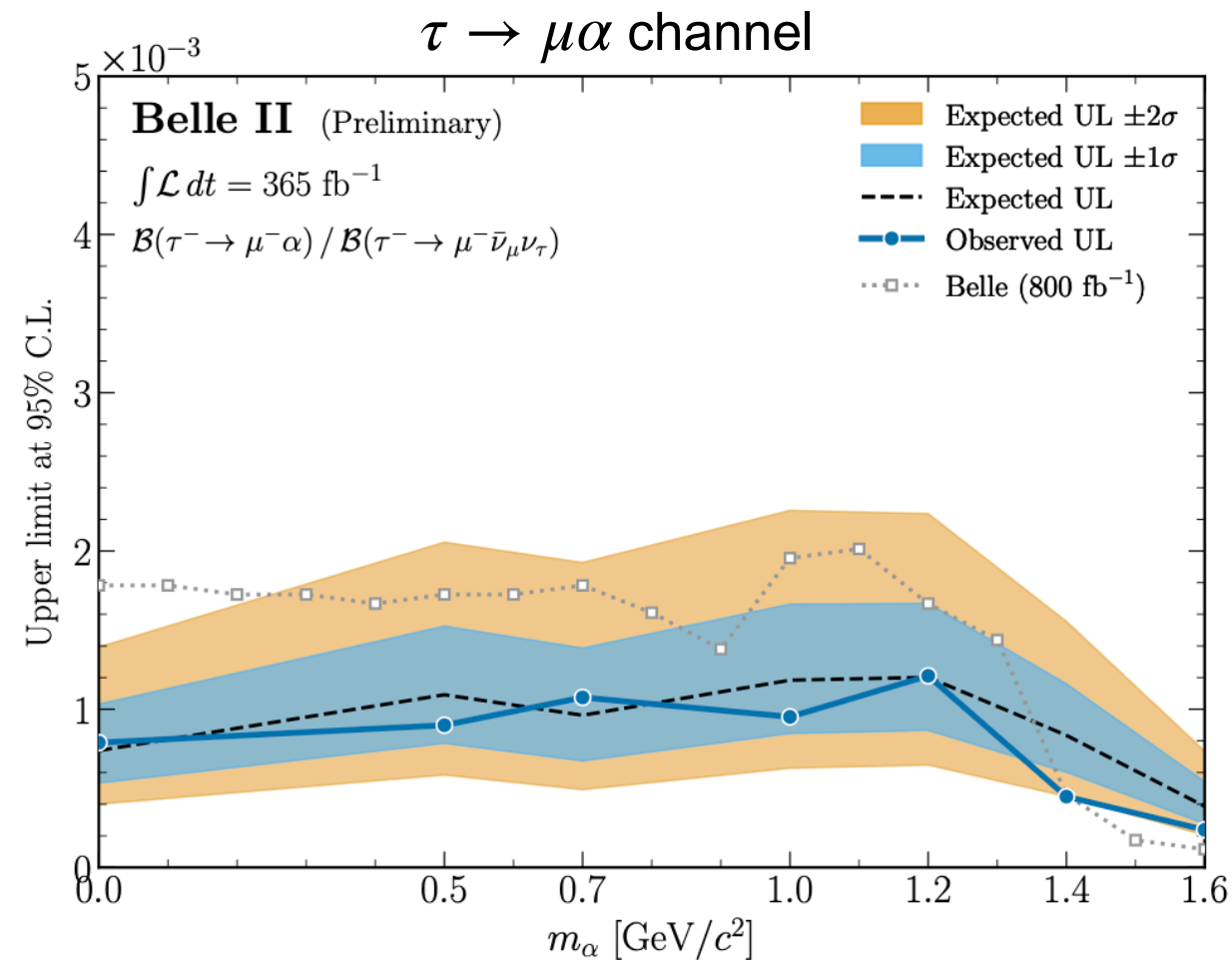
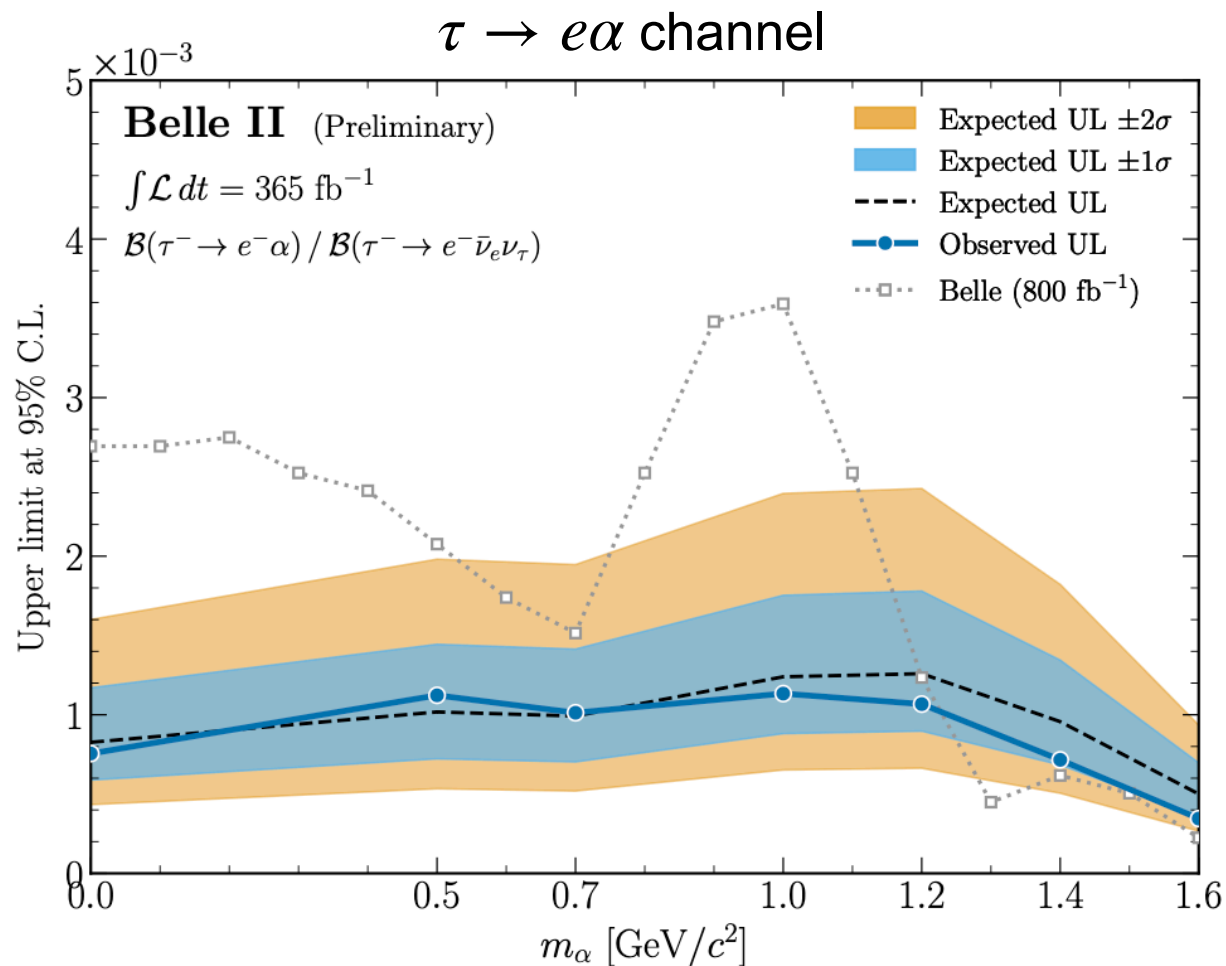
- Observe no statistically significant signal and set upper limits on the relative BF:

$$\mathcal{B}(\tau^- \rightarrow \ell^- \alpha) / \mathcal{B}(\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau)$$

- Largest systematics associated to particle ID and γ reconstruction efficiency (e-channel).

Source	Electron (%)	Muon (%)
Lepton identification	2.23	0.56
$\pi^\pm$ identification	0.66	1.97
$\pi^\pm$ misidentified as ℓ	0.09	1.66
Photon efficiency	1.35	0.16
ℓ misidentified as $\pi^\pm$	0.31	0.35
Trigger efficiency	0.26	0.29
π^0 efficiency	0.11	0.07





World's best upper limits for $m_\alpha \leq 1.2$ (1.4) GeV in the electron (muon) channel.
(despite using ~50% less data than Belle, and using the 1x1 topology alone)

Search for $\tau \rightarrow \ell \eta$

- Beyond SM mediators (Z' , h' , $\widetilde{H}$) could enhance LFV rates to pseudo-scalar mesons to observable levels.
Previous best limits from Belle with 401 fb⁻¹ of data [PLB 648 (2007) 341].

• New search from Belle II with 428 fb⁻¹

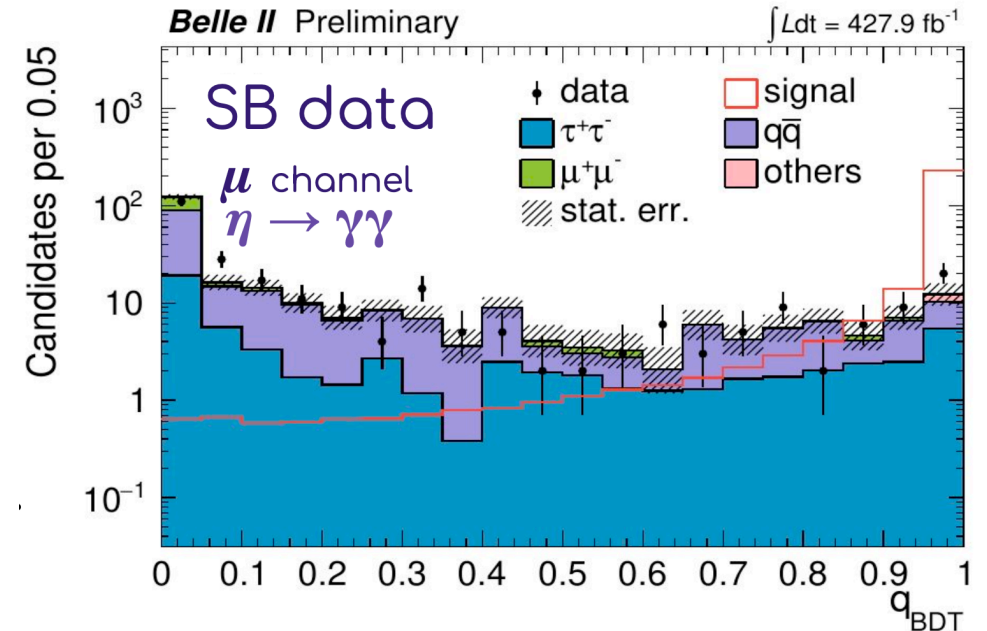
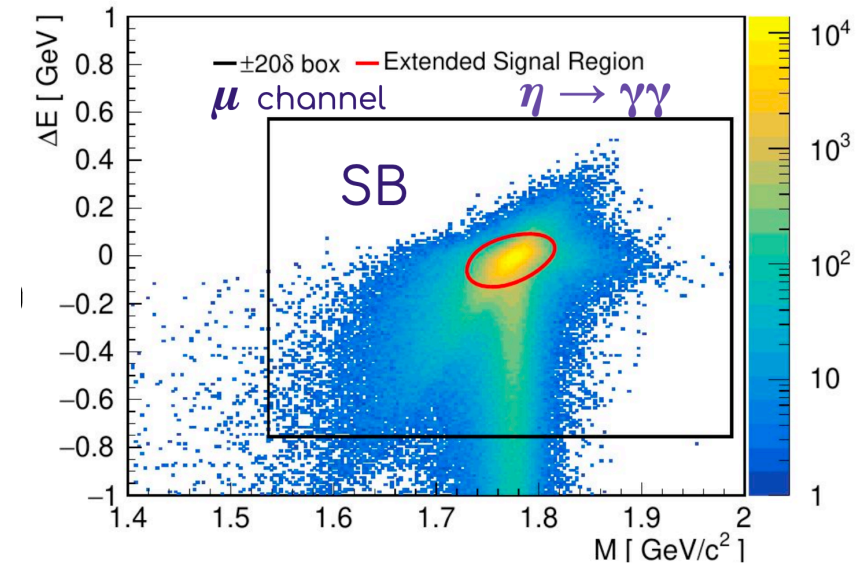
- 4 orthogonal $\tau \rightarrow \ell \eta$ searches: $(e, \mu) \times \eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi\pi\pi^0$.
- Define signal & sideband regions using $(M_\tau, \Delta E = E_\tau^{CM} - \sqrt{s}/2)$ plane. Expect signal peak at $M_\tau \sim 1.7$ GeV and $\Delta E \sim 0$ GeV.
- Background estimation using sideband data.

$$\eta \rightarrow \gamma\gamma$$

Background dominated by Bhabha events.
Suppression through Boosted Decision Tree (BDT).
Background estimation by counting based method.

$$\eta \rightarrow \pi\pi\pi^0$$

Lower backgrounds wrt $\eta \rightarrow \gamma\gamma$.
Suppression through dedicated cut-based selection.
Background estimation by 2D unbinned fit in $(M_\tau, \Delta E)$



$\tau \rightarrow \ell \eta$ Results

⇒ **No significant signal observed.**
Upper limits are set on BRs.

$$\mathcal{B}(\tau \rightarrow e \eta) < 9.21 \times 10^{-8} @ 90\% \text{ CL}$$

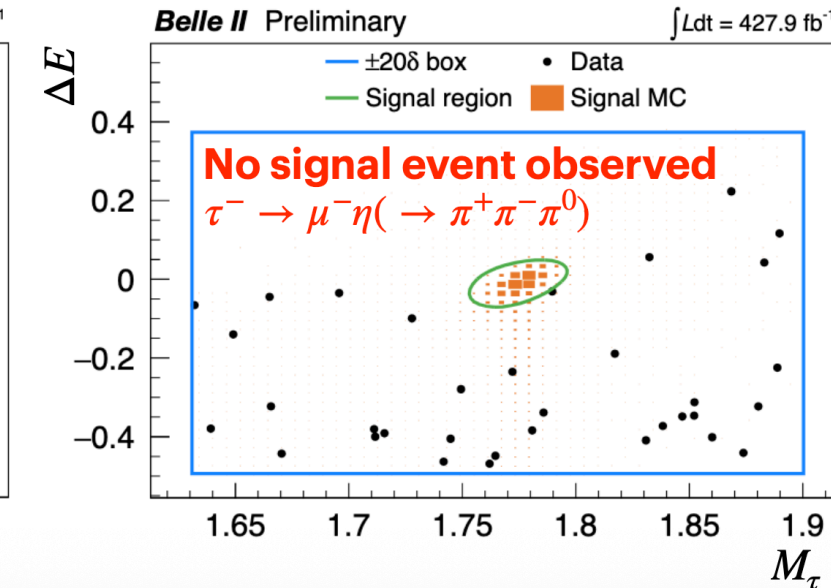
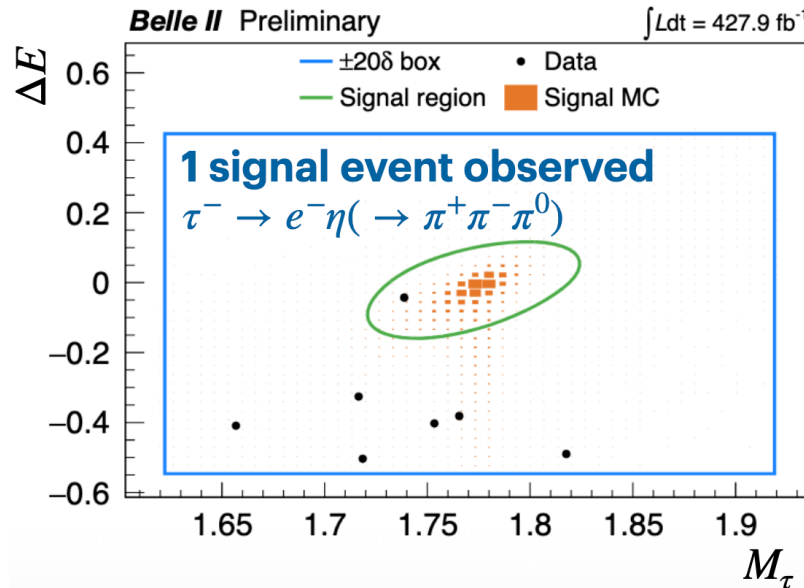
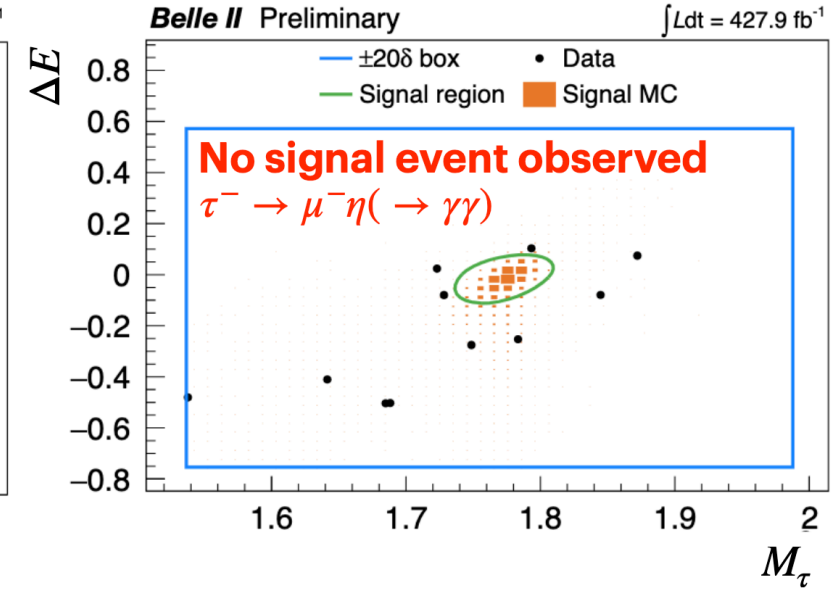
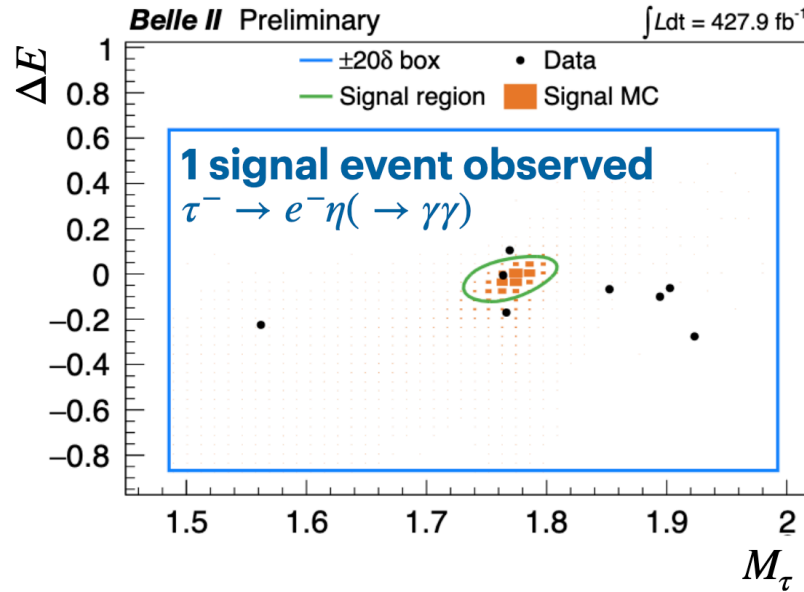
Comparable with previous Belle result
(although expected UL @ Belle II is superior)

$$\mathcal{B}(\tau \rightarrow \mu \eta) < 4.23 \times 10^{-8} @ 90\% \text{ CL}$$

Most stringent constraint to date!

See Laura's talk for more details,
including more LFV searches:

- $\tau \rightarrow \mu \mu \mu$
- $\tau \rightarrow e \ell \ell'$
- $\tau \rightarrow \ell K_S^0$
- $\tau \rightarrow \mu \gamma$
- + teasers for $\tau \rightarrow 3\mu$ with displ. vertex
and $\tau \rightarrow e \gamma$.

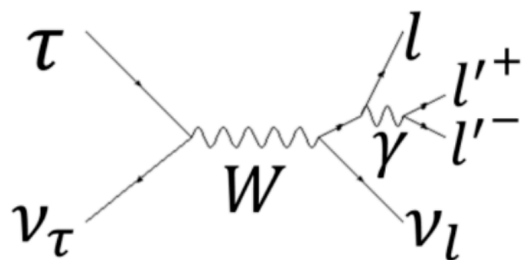


5-lepton decays

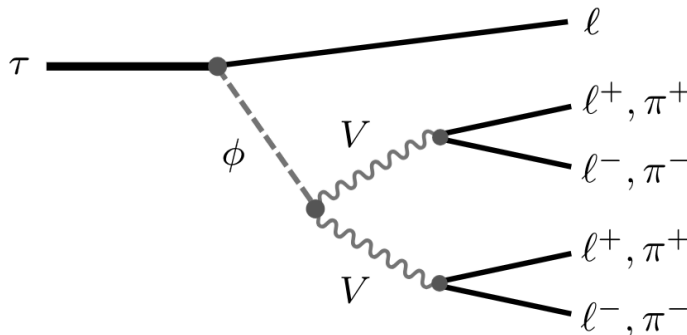
- **Rare multilepton cascades** can probe Dark Sector scenarios beyond standard τ LFV searches. See recent [talk](#) by Maxim Pospelov at the Belle II & Theory Workshop.

- **We are strongly encouraged to search for all kinds of 5-lepton signatures!**

- e.g. $\tau \rightarrow \ell \ell \ell \nu \bar{\nu}$ analyses are already underway at Belle II!



- e.g. $\tau \rightarrow 5\mu$ from on-shell new mediator offers a strong detectable signature!



Goals (with current data):

- Improve $\tau \rightarrow e e e \nu \bar{\nu}$ from CLEO: $(2.8 \pm 1.5) \times 10^{-5}$
- First observation of $\tau \rightarrow \mu e e \nu \bar{\nu}$ (CLEO set UL)
- First UL on $\tau \rightarrow \ell \mu \mu \nu \bar{\nu}$.

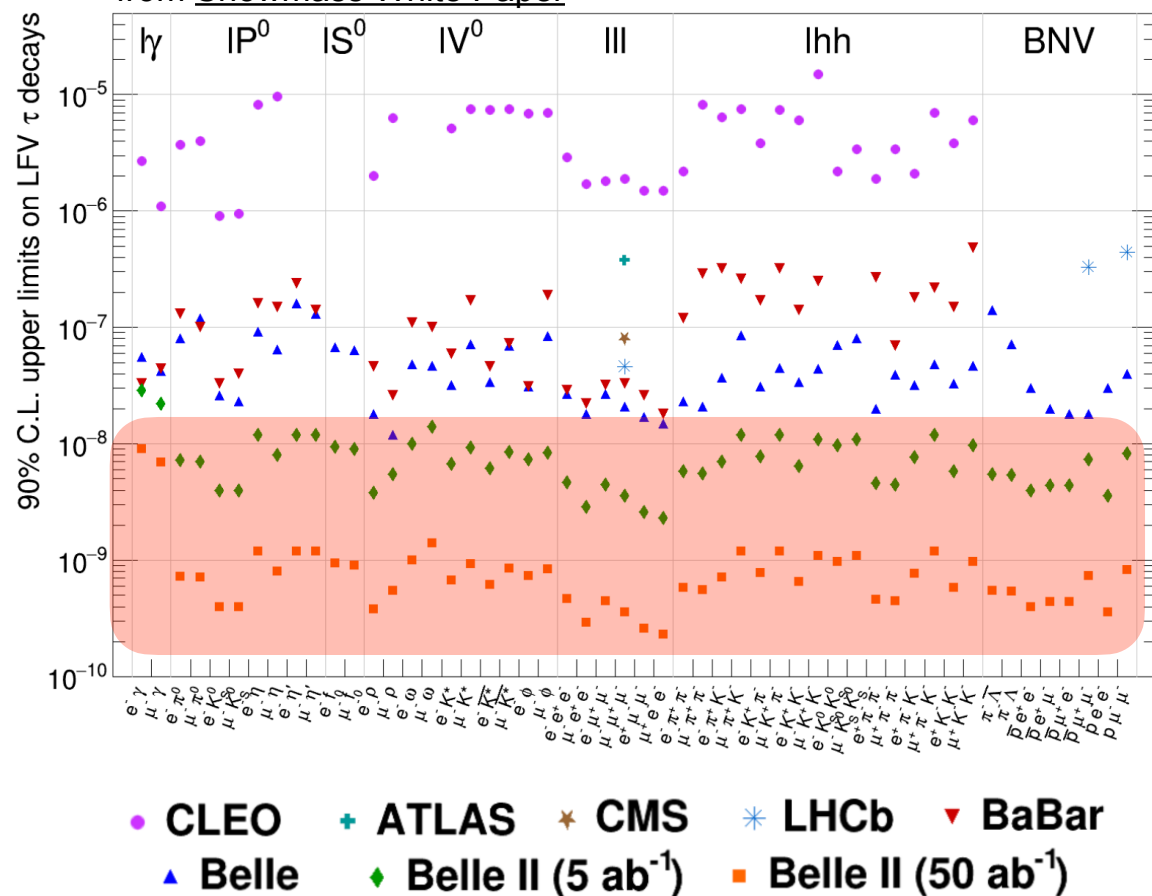
- **+ much more to explore!**

$\cancel{E}$	τ decay	Search
$\cancel{E} = 0$	$\tau \rightarrow 5\mu$	[56]*
	$\tau \rightarrow 4\mu e$	X
	$\tau \rightarrow 3\mu 2e$	X
	5 leptons $\tau \rightarrow 2\mu 3e$	X
	$\tau \rightarrow \mu 4e$	X
	$\tau \rightarrow 5e$	X
$\cancel{E} > 0$	$\tau \rightarrow 3\mu 2\nu$	X
	$\tau \rightarrow 2\mu e 2\nu$	[57]
	5 leptons $\tau \rightarrow \mu 2e 2\nu$	X
	$\tau \rightarrow \mu 4\nu$	X
	$\tau \rightarrow 3e 2\nu$	[57]
	$\tau \rightarrow e 4\nu$	X

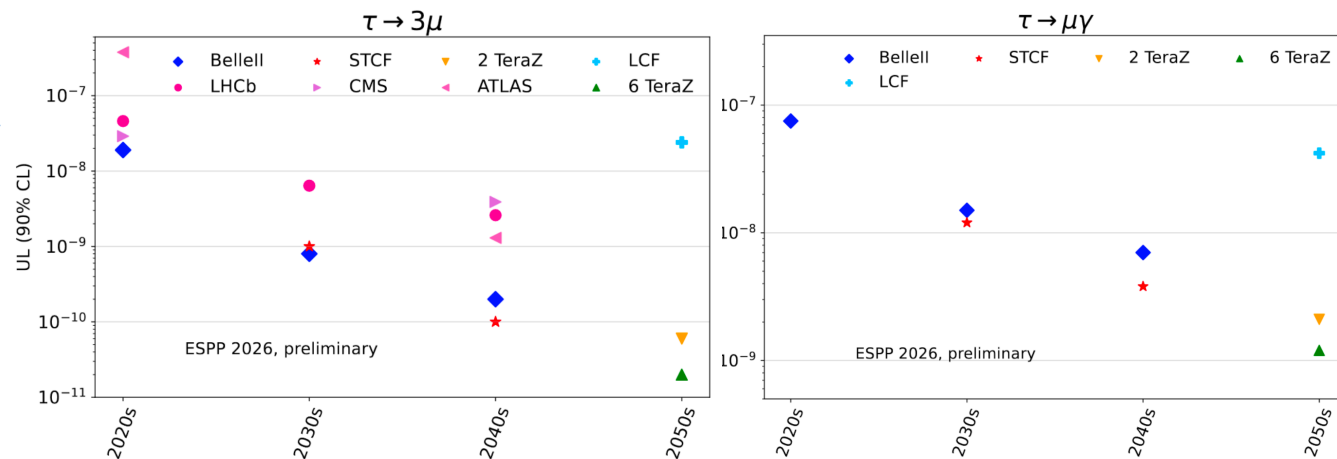
Looking to the future

- Wide variety of decays to study: *radiative* ($\tau \rightarrow \ell \gamma$), *leptonic* ($\tau \rightarrow \ell \ell \ell$), *semileptonic* ($\tau \rightarrow \ell h(h)$) + more.
- Over 60 modes to be studied at Belle II over the coming years.

from Snowmass White Paper



Belle II is expected to probe LFV in many channels $\approx \mathcal{O}(10^{-9})$ to $\mathcal{O}(10^{-10})$ with 50 ab^{-1}



- Belle II & STCF will provide best limits for the next ~20 years, until Tera-Z experiments enter the game in 2050s.

Summary

- **Belle II is having a major impact in τ physics** with its growing data sample, improved analysis techniques and reduced systematic uncertainties wrt Belle/BaBar.
- We saw some highlights in this talk:
 - World's most precise measurement of the τ mass.
 - World's most precise test of LFU in $\tau \rightarrow \ell \nu \bar{\nu}$ decays.
 - Long awaited test of CPV in $\tau \rightarrow \pi K_S^0 \nu$, in agreement with SM.
 - Most stringent upper limits to date in many forbidden decay modes.
e.g. recent results in searches for LFV $\tau \rightarrow \ell \alpha$, $\ell \eta$ + much more!
- Stay tuned for upcoming precision results (e.g. τ lifetime) & searches for many more forbidden modes.

⇒ **Exciting times ahead!**

BACKUP SLIDES

Tau Mass Impact

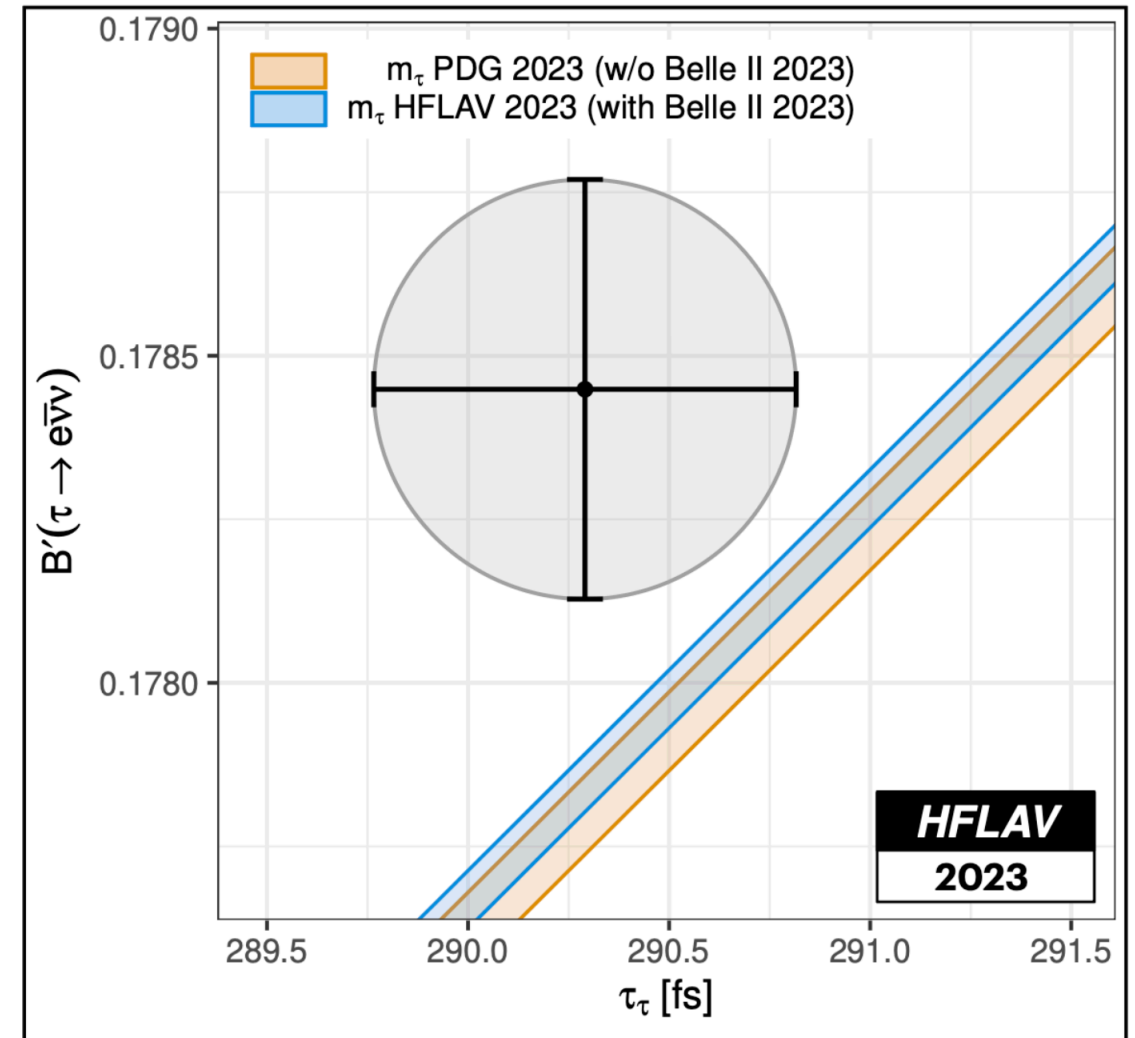
- A precise τ mass (and lifetime) measurement is an important input for **lepton-flavour-universality tests of SM**.
- SM prediction for the relationship b/w **τ mass, lifetime**, and the average of the **BF for $\tau \rightarrow e\nu\bar{\nu}$** and the value predicted from $\tau \rightarrow \mu\nu\bar{\nu}$ assuming lepton universality:

$$B' \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

- **The mild tension is slightly reduced by the Belle II τ mass measurement.**

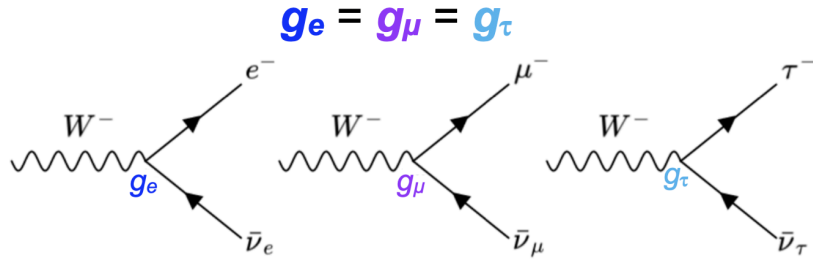
We eagerly await the τ lifetime measurement from Belle II.

A. Lusiani for HFLAV TAU2023



Lepton Flavour Universality

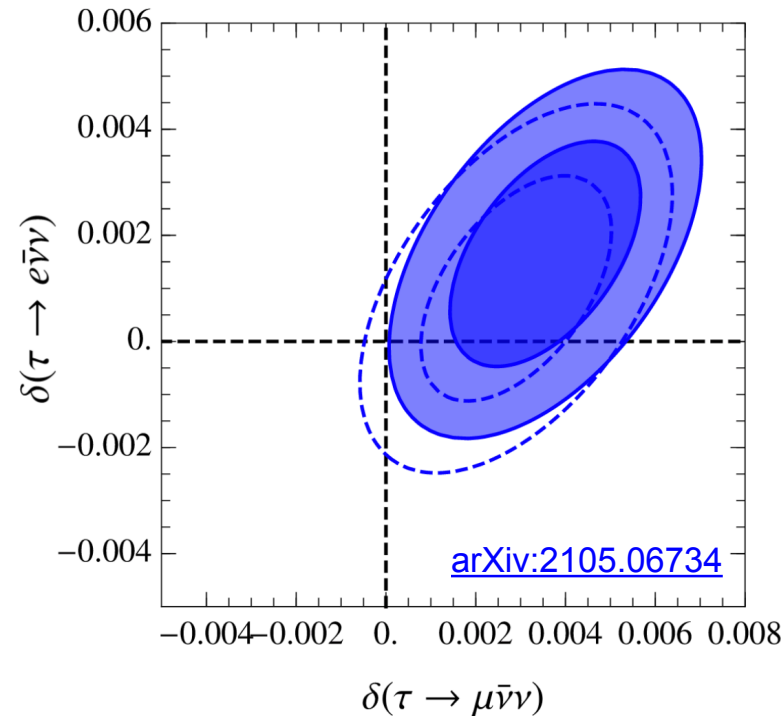
- LFU $\Rightarrow$ couplings of leptons to W bosons is flavour independent



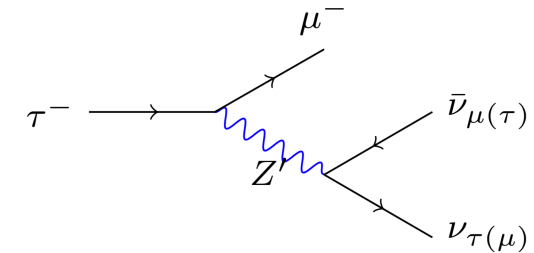
- In τ decays, testing LFU symmetry is in principle simple: compare the rates of $\tau \rightarrow \mu \nu \bar{\nu}$ vs $\tau \rightarrow e \nu \bar{\nu}$

$$R_\mu = \frac{BF[\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau]}$$

- Global fit to $\tau \rightarrow \ell \bar{\nu} \nu$ and $\mu \rightarrow e \bar{\nu} \nu$ ratios (latter well constrained by EW data) $\Rightarrow$ **2 σ tension with SM**



- New Physics could enter in a variety of ways:
 - LFUV charged current
 - LFV neutral currents (Phys. Lett. B 2016 09 046)

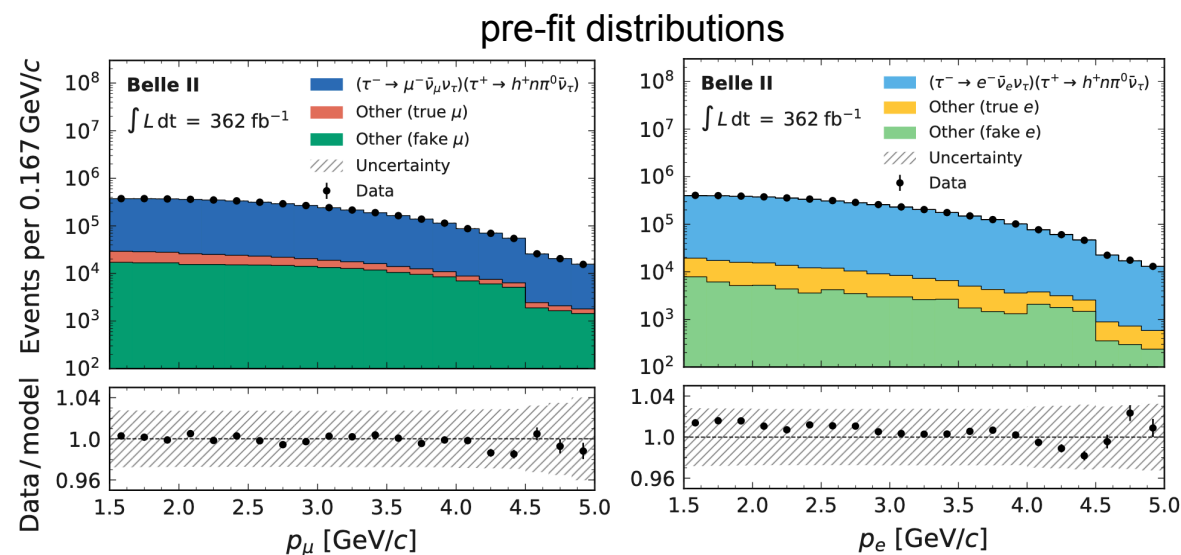
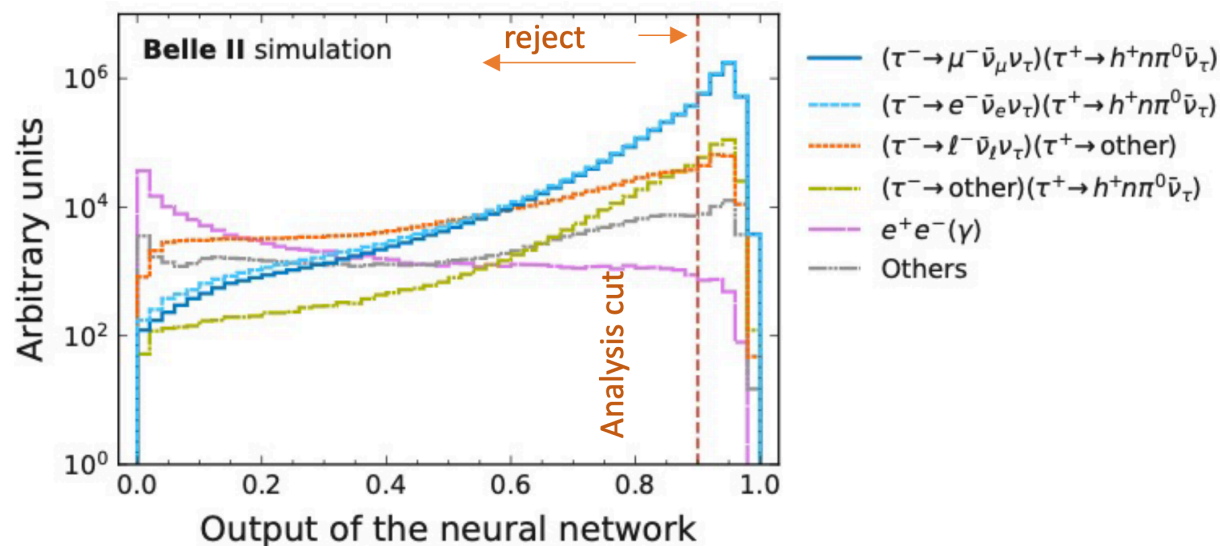
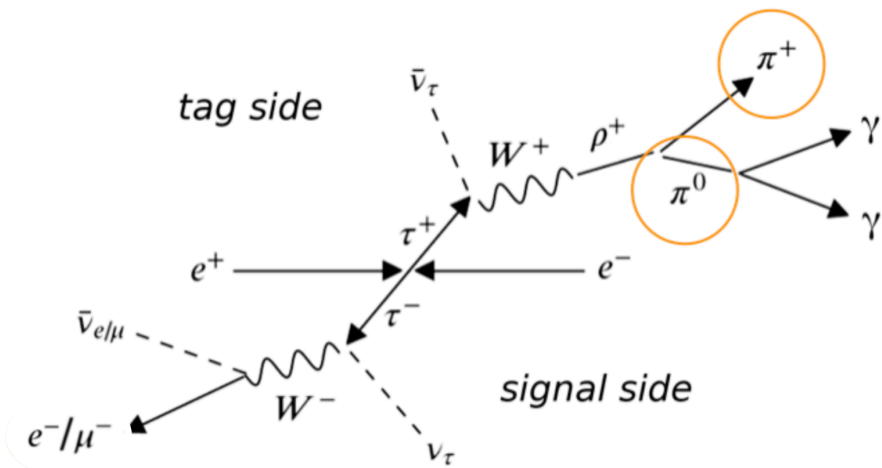


Will this mild tension become more significant with better precision on R_μ ?

Only Belle II can provide answers!

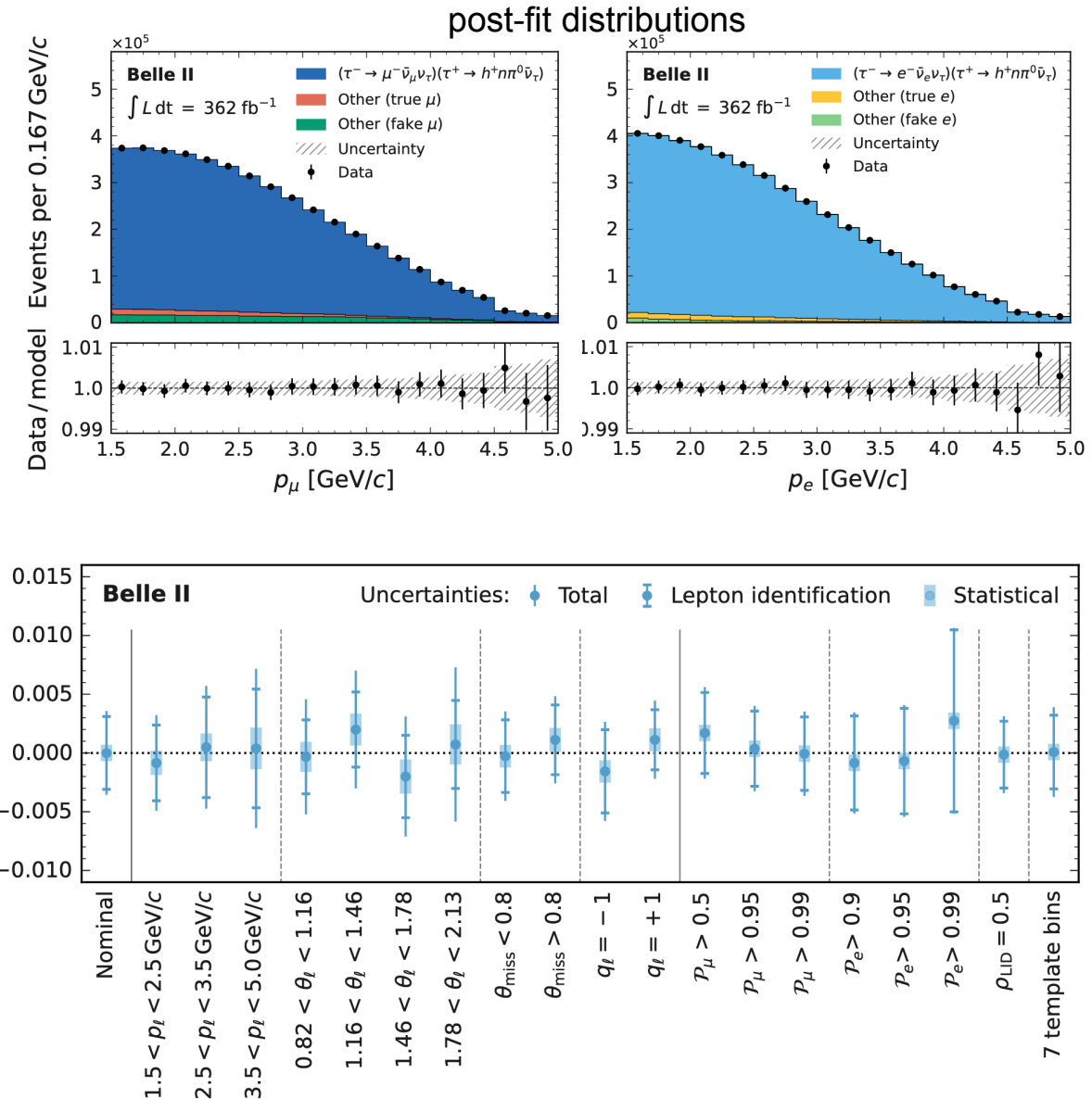
LFU in τ decays

- Measurement of R_μ using the full on-resonance Run1 data (362 fb⁻¹)
- Consider 1x1 prong topology with focus on the ρ tag, with a **charged hadron** and **at least one π^0** on the *tag side*.
 $\Rightarrow$ large BF(35%), low backgrounds, high trigger efficiency
- Event selections:
 - Restrict to barrel region, $1.5 < p < 5$ GeV (to reduce PID systematics).
 - Rectangular cuts + neural networks to remove backgrounds.
 - 94% purity with 9.6% signal efficiency for combined e+ μ samples



R_μ extraction

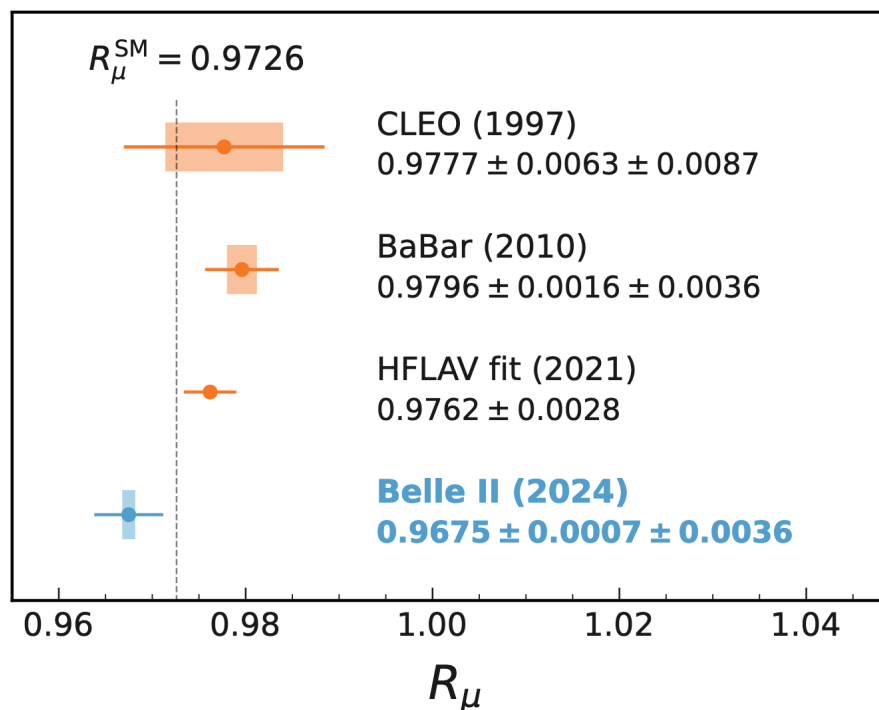
- Measure R_μ with a binned maximum likelihood fit using the *pyhf* library OSS 6 (2021) 2823
 - 21 bins over lepton momentum from 1.5 - 5 GeV
 - systematics included with (constrained) nuisance parameters
- 3 templates for μ and e channel
 - signal decays
 - background with correct lepton on the signal side
 - background with misidentified particle on the signal side
- Checked for consistency of the result before unblinding
 - sub-regions for different kinematic variables (momentum, polar angle, missing momentum, charge)
 - data-taking periods
 - different requirements for PID
- Good agreement between the measured values**



LFU in τ decays: Result

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

- Big effort within the Performance Group of Belle II to get **lepton ID efficiency and fake-rate systematics** under control (**0.32%**).
- Several calibration samples were used.
 - Efficiencies: $J/\psi \rightarrow \ell^+\ell^-$, $e^+e^- \rightarrow \ell^+\ell^-\gamma$, $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$
 - Fake rates: $K_S^0 \rightarrow \pi^+\pi^-$, $e^+e^- \rightarrow \tau^+\tau^-$

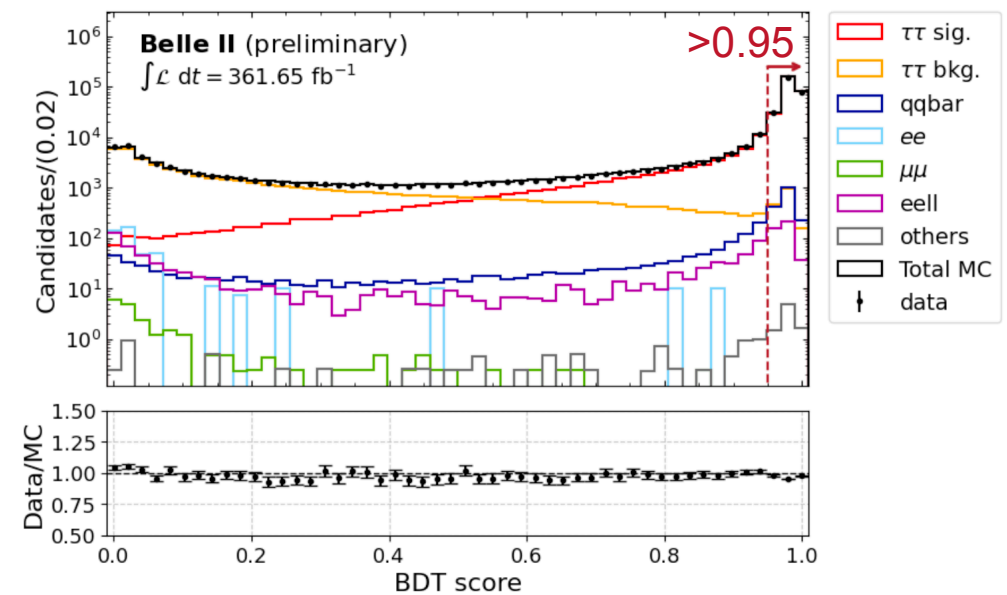
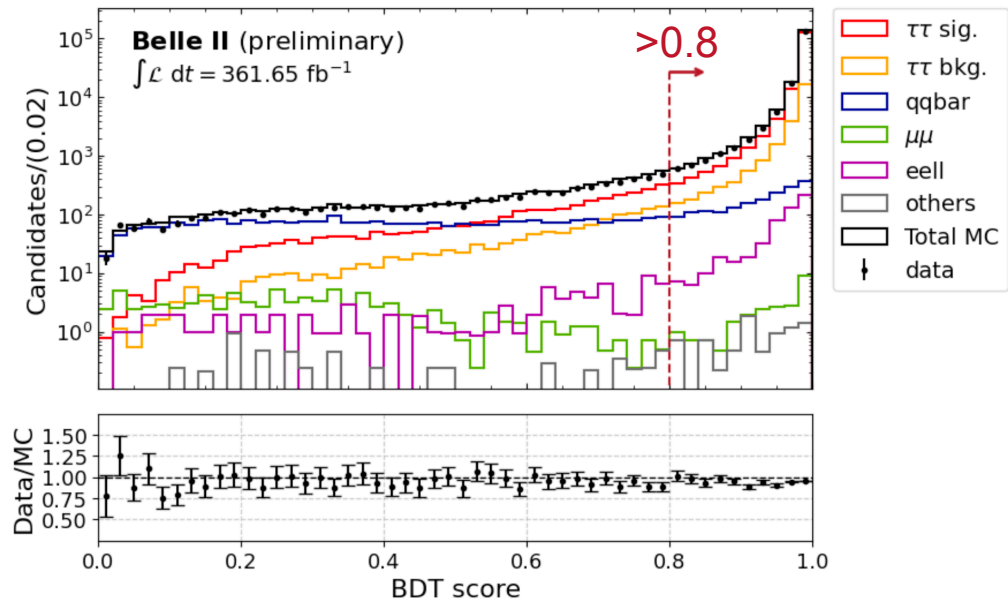
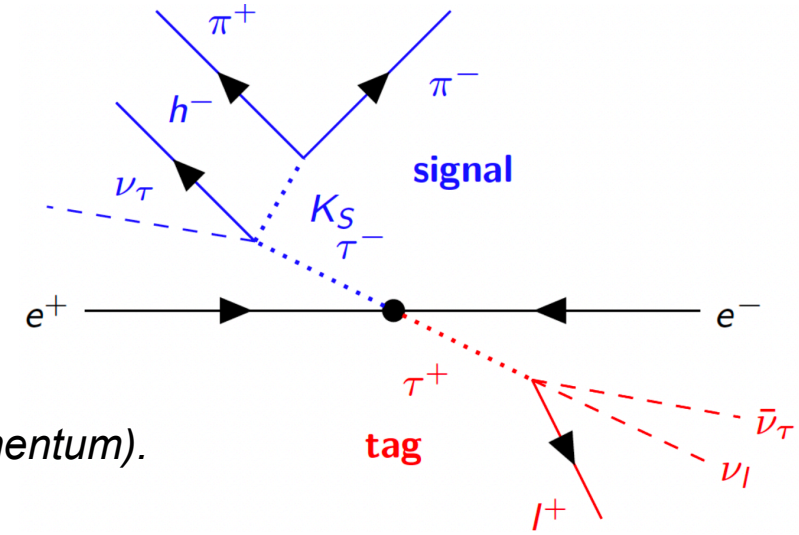


JHEP. 2024, 205 (2024)

- **Belle II achieved the world's most precise test of LFU in τ decays!** Consistent with SM expectation at 1.4σ

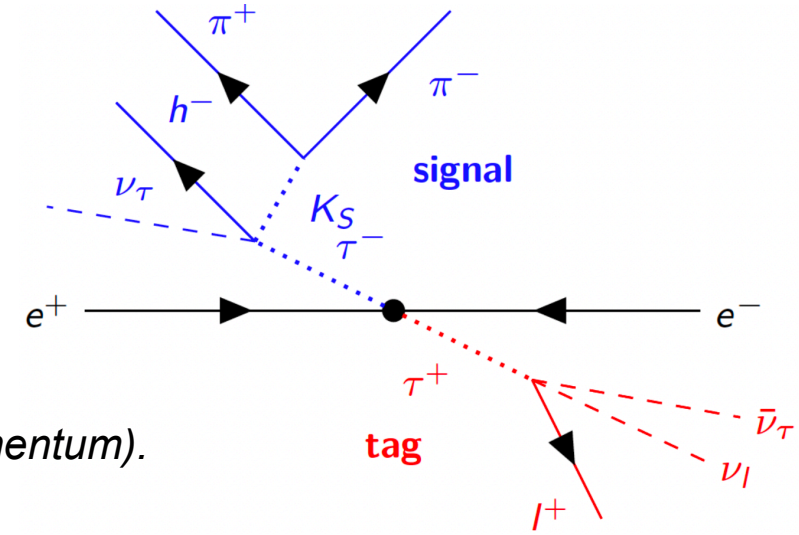
CPV in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$

- Recent Belle II measurement of the CP-violating decay-rate asymmetry using 362 fb⁻¹ of data, for $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ (with ≥ 0 π^0) events. Targeting the 3x1 prong topology with **leptonic tag**.
- Achieve ~98% signal purity using **two Boosted Decision Trees**.
 - BDT1** trained on event-shape/kinematic variables (e.g. thrust, total E_{visible}). Suppress the dominant $e^+e^- \rightarrow q\bar{q}$ background.
 - BDT2**: trained on K_S^0 topology and kinematics (e.g. decay vertex position & momentum). Separate signal from other τ -pair decays.



CPV in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$

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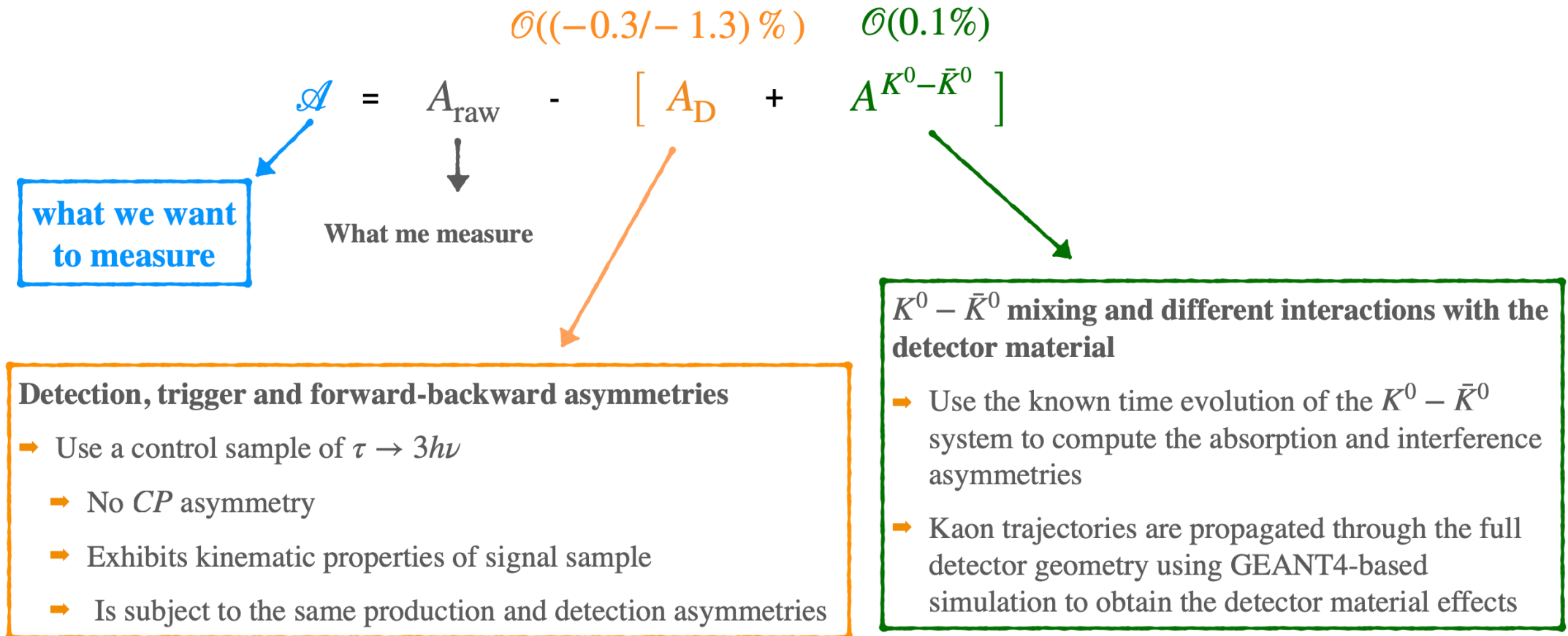
	e -tagged sample [%]	μ -tagged sample [%]
Overall signal purity		
$\tau^- \rightarrow h^- K_S^0 (\geq 0\pi^0) \nu_\tau$	98.74 ± 0.18	98.32 ± 0.19
Fractional composition of selected signal		
1 $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$	77.86 ± 0.15	76.63 ± 0.16
2 $\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$	2.68 ± 0.02	2.73 ± 0.02
3 $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 (\geq 0\pi^0) \nu_\tau$	18.20 ± 0.06	18.98 ± 0.07

“Dilution factor” for
1 estimated from
 MC simulation

From A_{raw} to A_{CP}

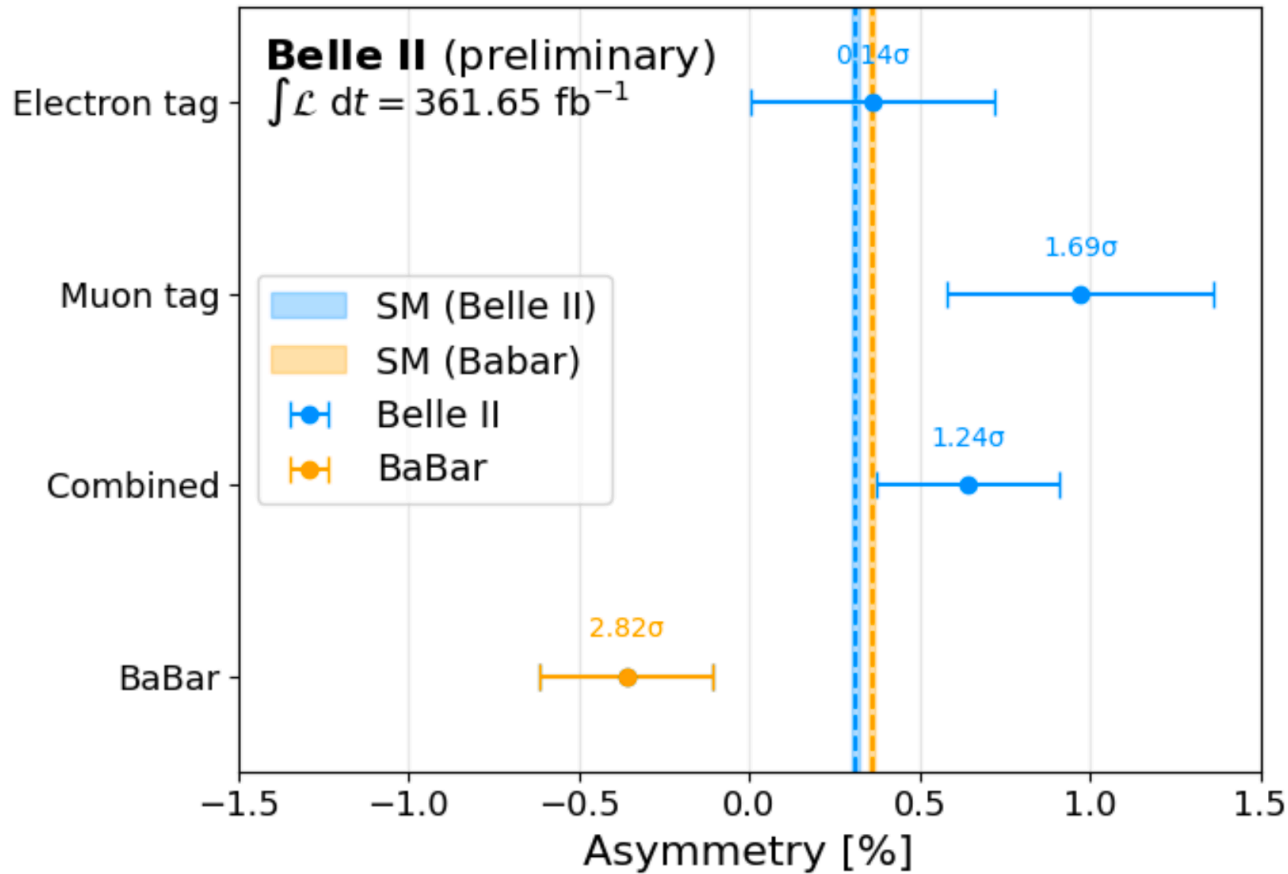
$$A_{\text{raw}} \equiv \frac{N(\tau^+ \rightarrow h^+ K_S^0 (\geq 0\pi^0) \bar{\nu}_\tau) - N(\tau^- \rightarrow h^- K_S^0 (\geq 0\pi^0) \nu_\tau)}{N(\tau^+ \rightarrow h^+ K_S^0 (\geq 0\pi^0) \bar{\nu}_\tau) + N(\tau^- \rightarrow h^- K_S^0 (\geq 0\pi^0) \nu_\tau)}$$

- This is not a pure CP-violating quantity. To get A_{CP} we must subtract contributions from production dynamics and detector-induced effects.



Belle II result

$$A_{CP}^{Belle II} = 0.64 \pm 0.26 \text{ (stat)} \pm 0.06 \text{ (sys) } \%$$



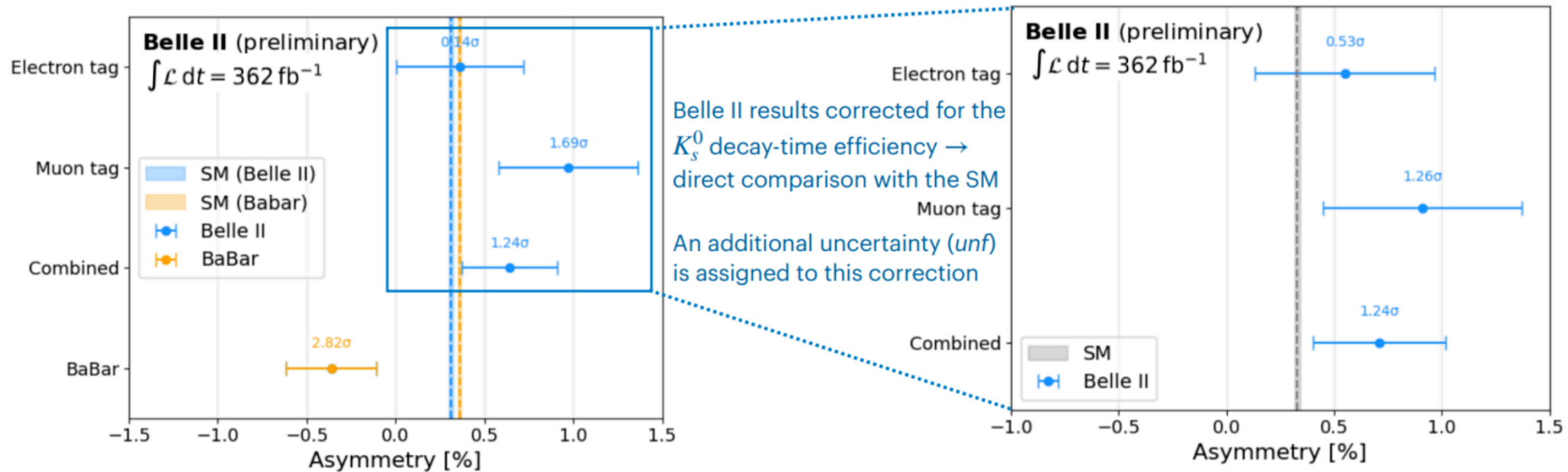
- **In agreement with the SM prediction within 1.24σ .** No confirmation of BaBar tension.

- ▶ Comparable statistical precision to BaBar (with ~30% less data).
- ▶ ~Half the systematic uncertainty of BaBar (**largest systematic uncertainty** mostly driven by control sample statistics).

Source	Uncertainty (%)	
	<i>e</i> -tagged	<i>μ</i> -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 - $\bar{K}^0$	0.01	0.01
Total	0.08	0.09

Belle II result

- A_{CP} depends on the K_S^0 decay-time efficiency: a non-uniform proper-time acceptance modifies the relative contributions of the $K^0/\bar{K}^0$ components. A_{SM} prediction is affected as well $\rightarrow$ correction required.



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

Measurement statistically limited, consistent with SM expectation within 1.24σ

- SM rate far below any present/future experimental sensitivity $\Rightarrow$ any observation a clear indication of New Physics!

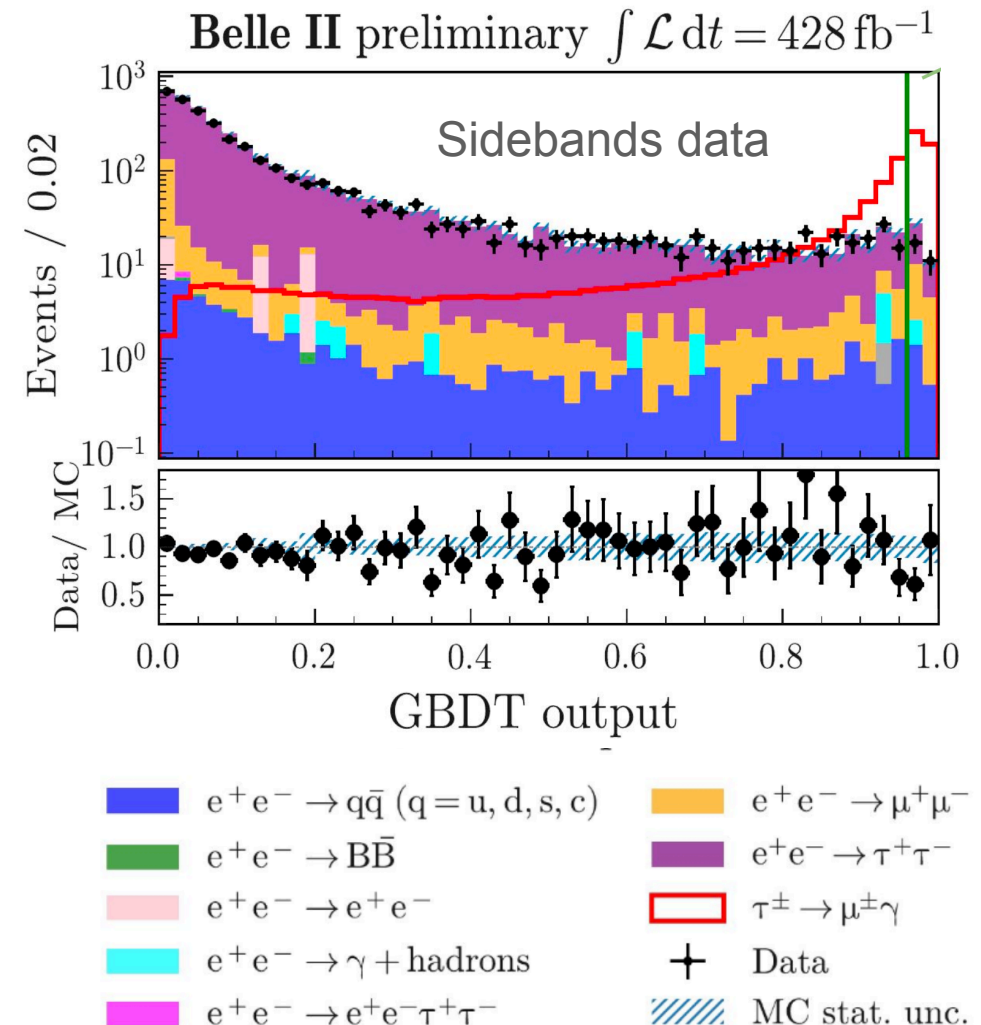
World's best UL from Belle (988 fb⁻¹): $\mathcal{B}(\tau \rightarrow \mu\gamma) < 4.2 \times 10^{-8}$
[JHEP 10, 019 (2021)]

- New search from Belle II with 428 fb⁻¹**

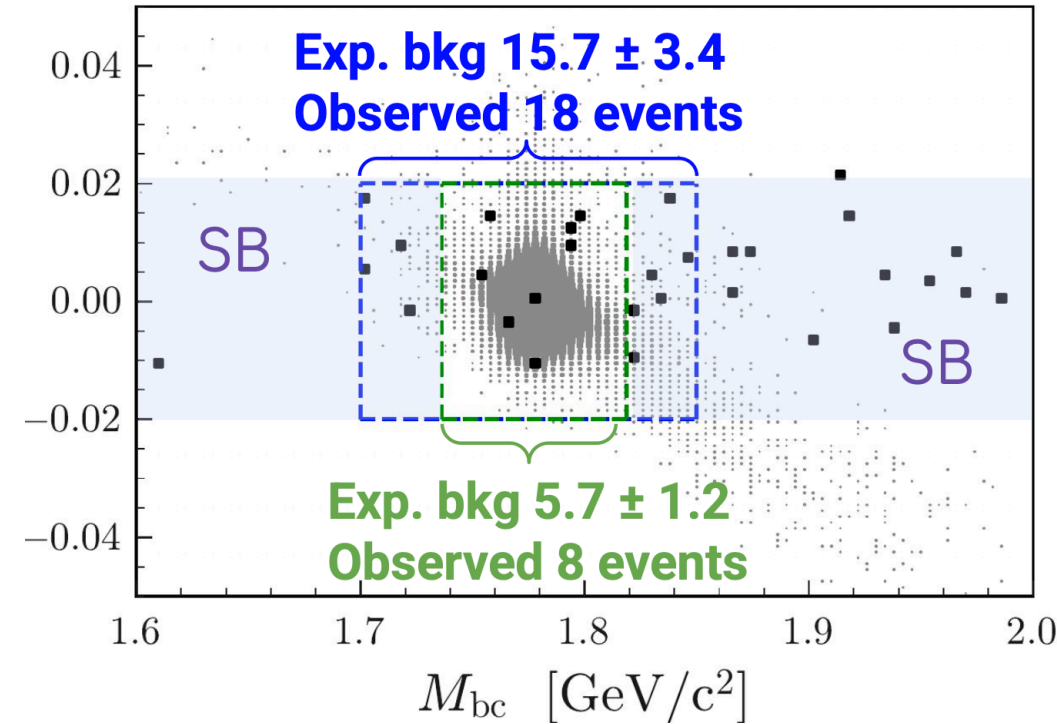
- 1x1 prong topology: signal side ($\mu\gamma$), tag side (e , π or ρ).
- Dominant backgrounds: $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow \mu^+\mu^-$.
- Background reduction via **Gradient Boost Decision Tree** (GBDT).
40% $\uparrow$ signal efficiency and **80% $\downarrow$ backgrounds** wrt Belle.
- Sidebands: derive expected background yields in signal region.
- Search using 2D plane in:

$$M_{bc} = \sqrt{\left(E_{\text{beam}}^*\right)^2 - \left(\vec{p}_{\mu\gamma}^*\right)^2} \quad \text{and} \quad \Delta E' = \frac{\Delta E}{\sqrt{s}} = \frac{E_{\mu\gamma}^* - E_{\text{beam}}^*}{\sqrt{s}}$$

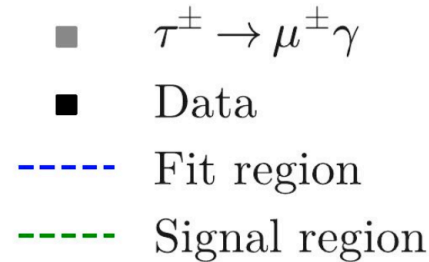
- Signal extraction: unbinned maximum likelihood fit in $(M_{bc}, \Delta E')$.



Belle II preliminary $\int \mathcal{L} dt = 428 \text{ fb}^{-1}$



- Fit result for signal is consistent with zero.
- So we set **upper limit**.



$$\mathcal{B}(\tau \rightarrow \mu\gamma) = (2.8_{-2.6}^{+4.4}) \times 10^{-8}$$

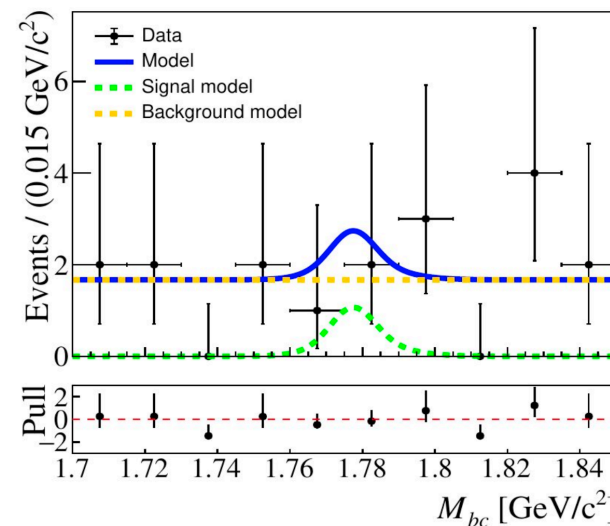
$$\mathcal{B}(\tau \rightarrow \mu\gamma)_{\text{post-fit}}^{\text{exp}} < 7.6 \times 10^{-8}$$

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

Approaching but not yet at the level of Belle (4.2×10^{-8})

- We anticipate world-leading upper limit after including all the currently available data (914 fb^{-1}).
(40%↑ efficiency, 80%↓ backgrounds wrt Belle)

1D projections



Belle II preliminary $\int L dt = 428 \text{ fb}^{-1}$

