Petar Rados (KMI, Nagoya University)
on behalf of the Belle II Collaboration

KMI2025
Nagoya, Japan
6 March 2025

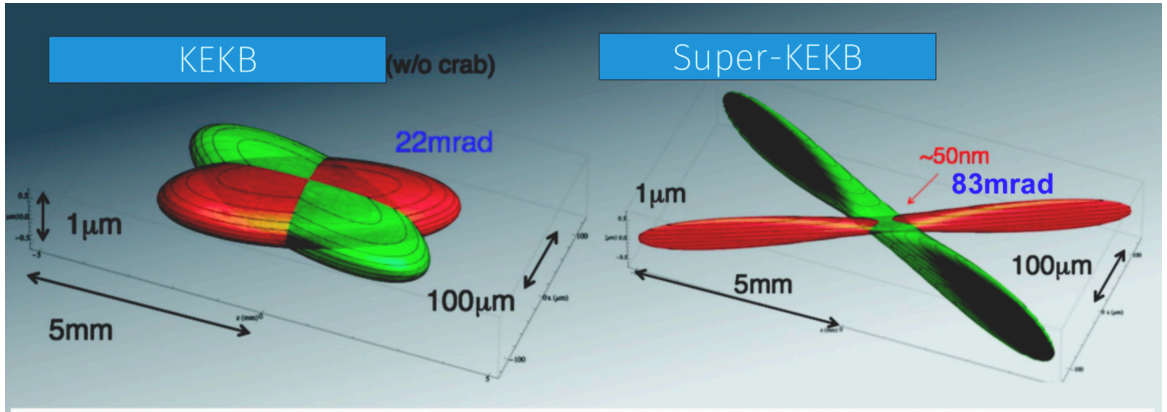
Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

名古屋大学
NAGOYA UNIVERSITY

Belle II

SuperKEKB Accelerator

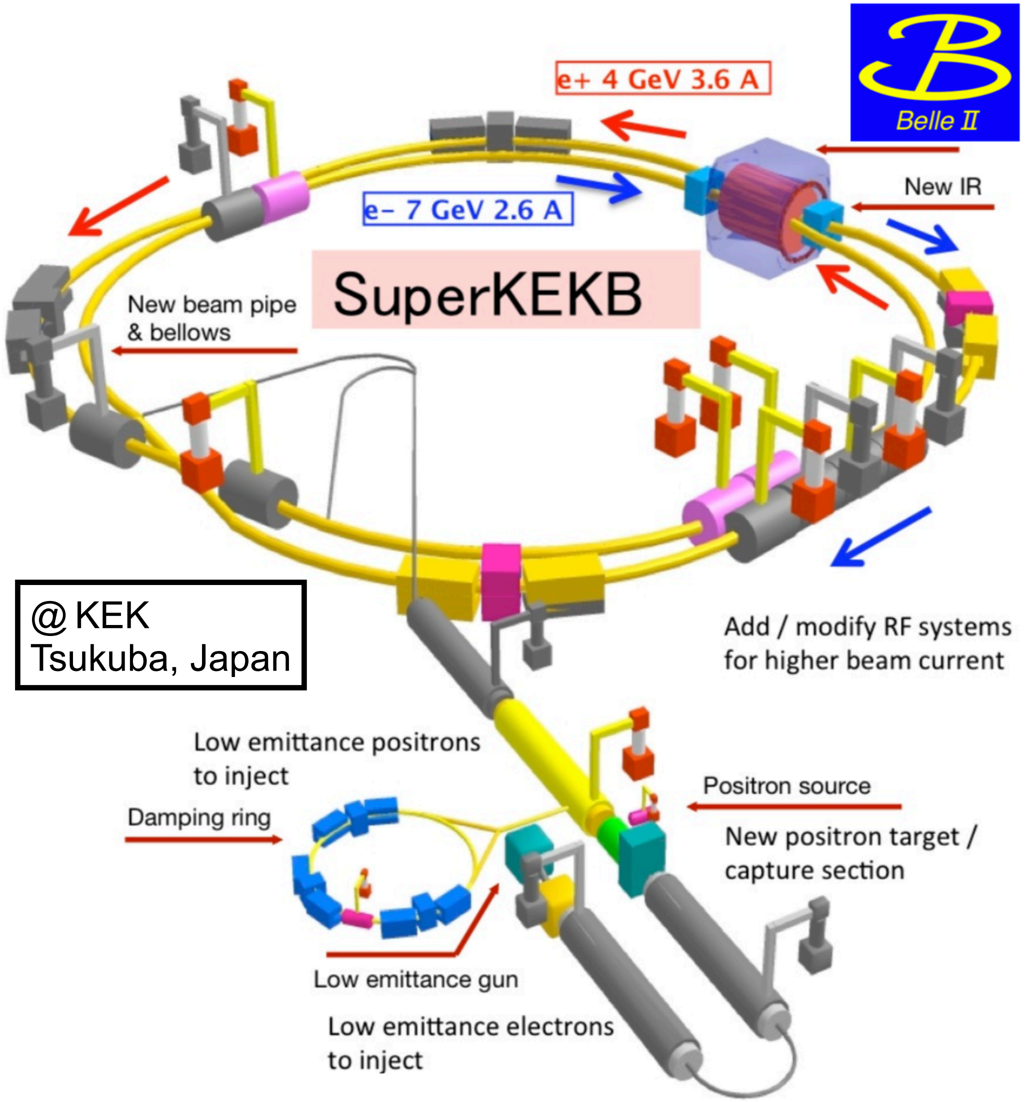
- Next generation B-factory: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, $\sqrt{s} \approx 10.58$ GeV
  + rich program of tau, dark sector and other low-multiplicity physics.



	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	6 x 10^{34}

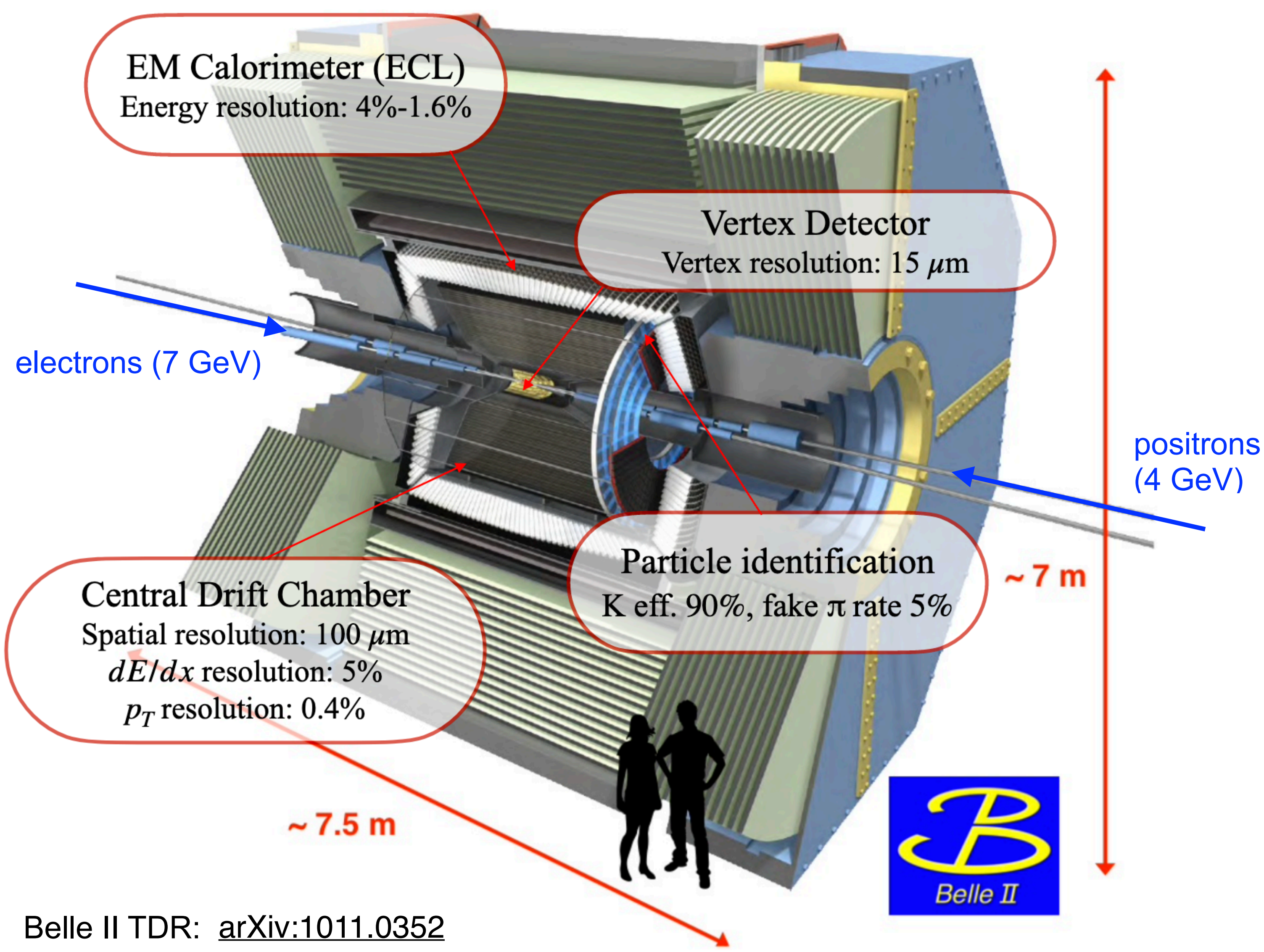
factor 20

factor 2-3



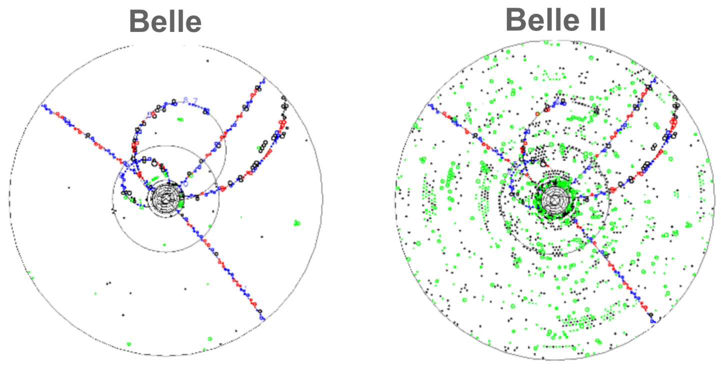
- 50 nm vertical beam spot size → “nano beam”.
- Unprecedented design luminosity of ~6×10^{35} cm^{-2}s^{-1} (30x KEKB)

Belle II Detector



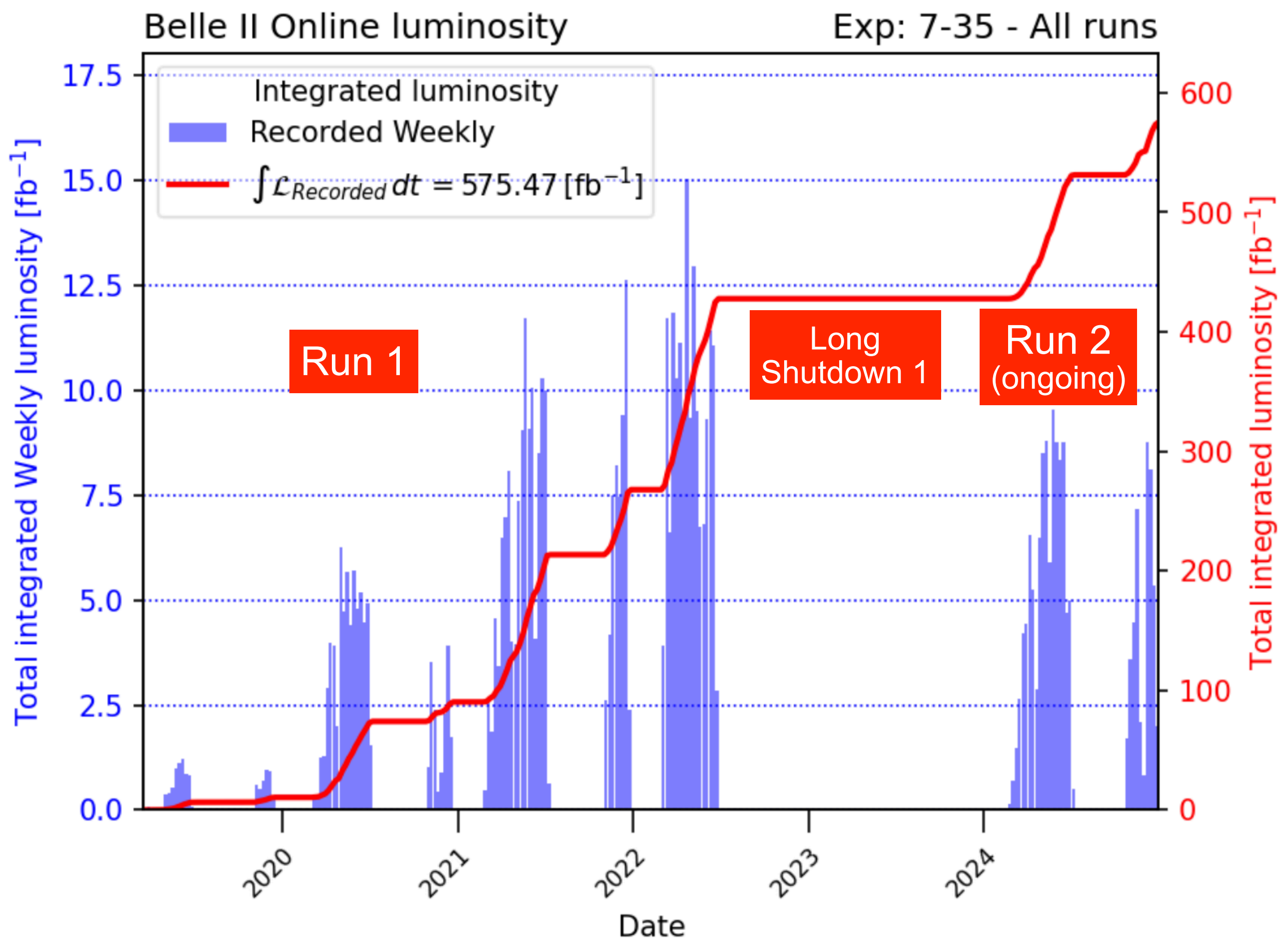
Belle II TDR: arXiv:1011.0352

- Consequently Belle II has higher beam backgrounds and event rates.



- Major upgrade of the Belle 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).
  - Improved trigger, and faster electronics in general.

Performance to date



Peak instantaneous luminosity

5.1×10^{34} cm^{-2} s^{-1}

(new world record in 2024)

Integrated luminosity: 573 fb^{-1}

495 fb^{-1} recorded at $\Upsilon(4S)$

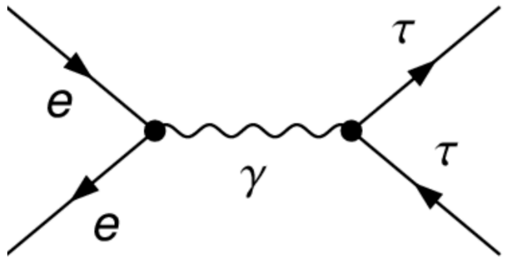
59 fb^{-1} at 60 MeV below $\Upsilon(4S)$, for background studies

19 fb^{-1} at 10.75 GeV, for exotic hadron searches

Aiming to collect **50 ab^{-1}** over the next ~10 years (x50 Belle)

Belle II as a τ factory

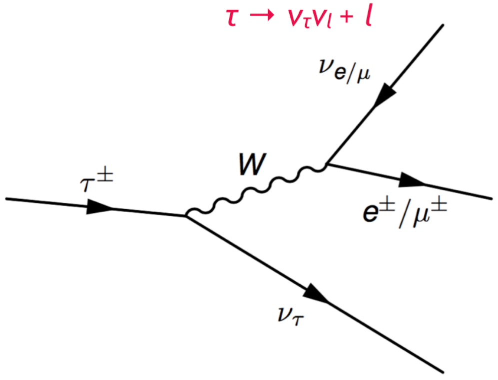
- The τ is the charged lepton of the third generation. They are produced in pairs.



- Only lepton massive enough to decay into hadrons (>200 hadronic channels).

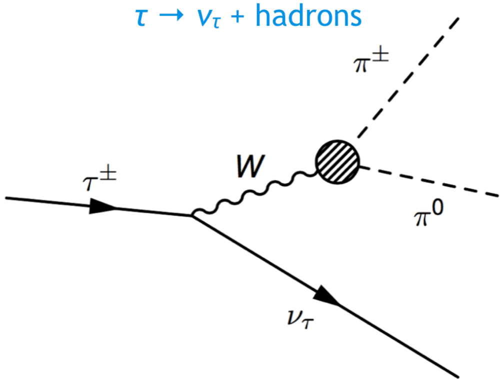
leptonic decays (BF~35%)

$\tau \to \nu_\tau \nu_l + l$



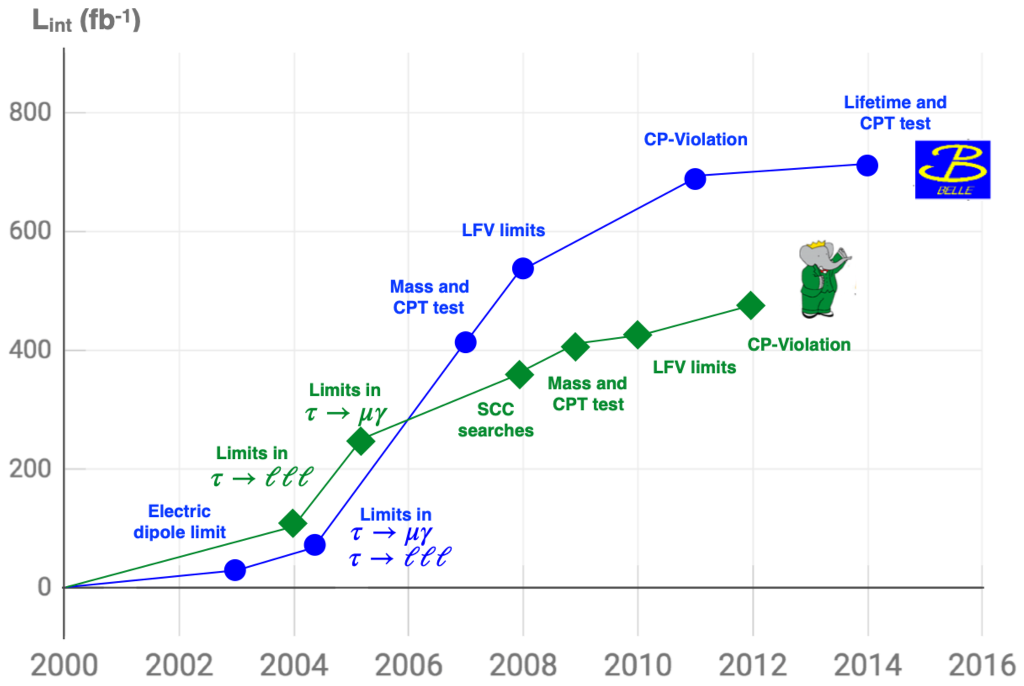
hadronic decays (BF~65%)

$\tau \to \nu_\tau$ + hadrons



- **B-factories are also τ-factories**

  $\sigma(e^+e^- \to \Upsilon(4s))$ = 1.05 nb *vs.* $\sigma(e^+e^- \to \tau^+\tau^-)$ = 0.92 nb

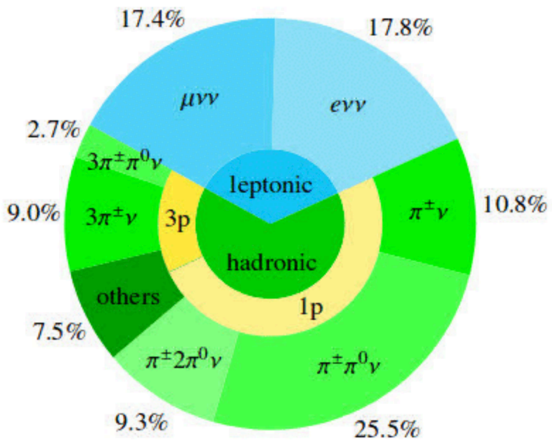


- Over its lifetime Belle II will deliver an enormous sample of ~4.6×10^{10} τ-pair events

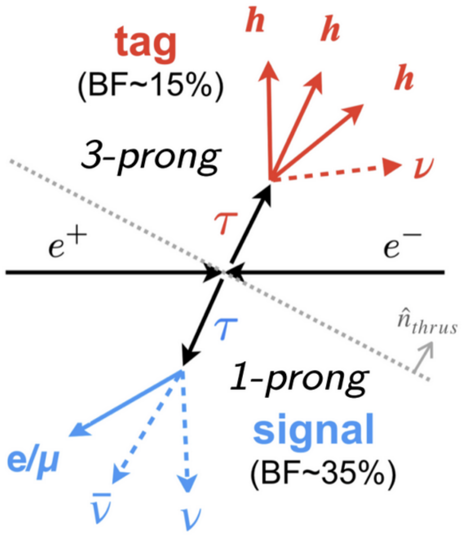
A unique environment to study τ physics with high precision!

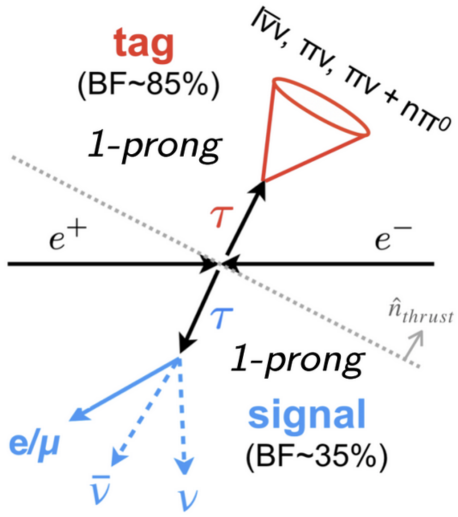
Tau Physics at Belle II

- Each τ will subsequently decay into final states containing mostly one (**1-prong**) or three (**3-prong**) charged particles.



- We mainly study **3x1 prong** and **1x1 prong** topologies.





Split event into two hemispheres across thrust axis

$$\vec{T} = max\left(\sum_i \frac{\vec{p}_i \cdot \hat{T}}{|p_i|}\right)$$

- Tau physics program follows two strategies:

(1) Precision SM measurements.
Indirect hints of NP in SM deviations.

✦ τ properties (mass, lifetime), couplings (e-μ universality, V_{us}), CP violation, etc

✦ Often sub-% measurements: systematics are usually the dominant error source.

(2) 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 ½ data.
- Requires high reconstruction efficiencies
- Machine learning techniques, inclusive tagging

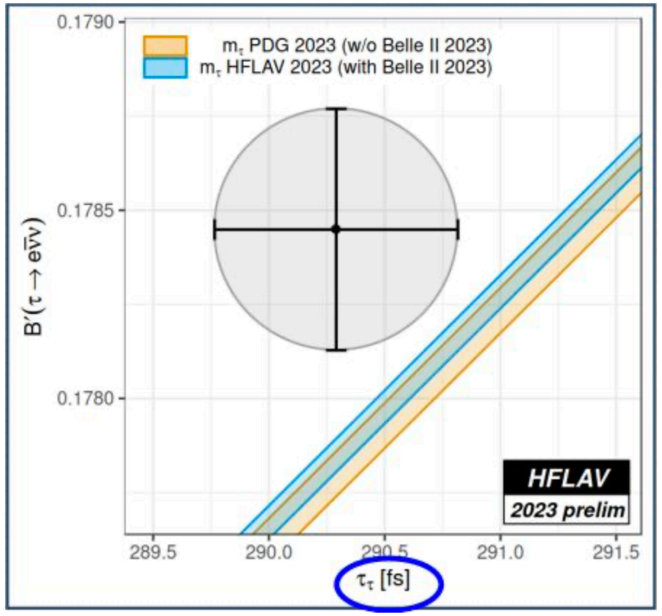
Tau Mass

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

  For taus the uncertainties are by far the largest!

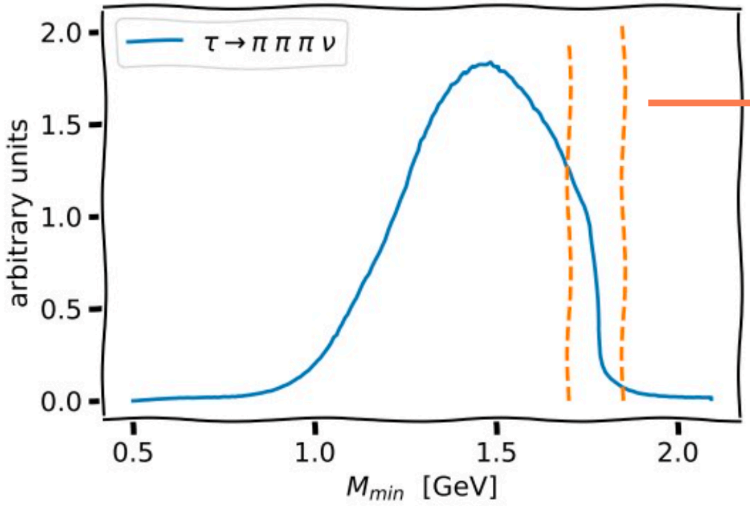
	electron	muon	tau
δm/m	6×10-9	2×10-8	**7×10-5** †
δτ/τ	n/a	1×10-6	**2×10-3**

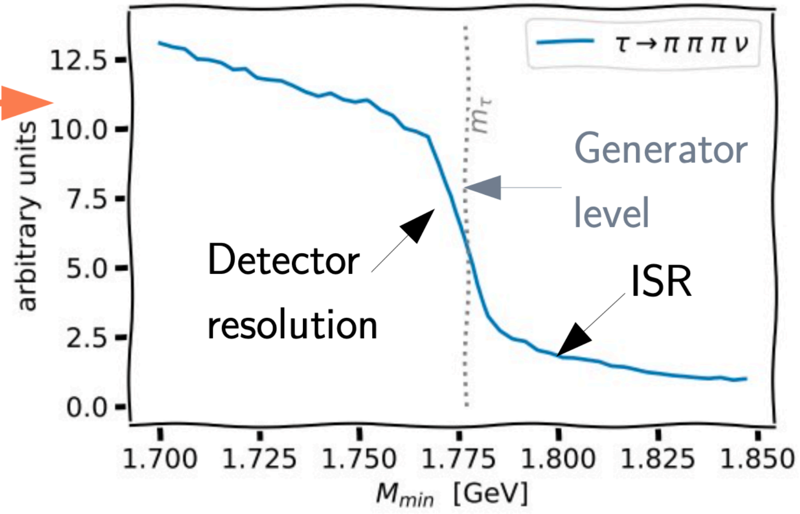
† prior to Belle II



$$B^{SM}_{\tau\ell} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

- Reconstruct 3x1 prong topology with inclusive tag and $\tau_{signal} \rightarrow 3\pi\nu$
- Access m_τ via pseudo-mass M_{min}: $\sqrt{M^2_{3\pi} + 2(\sqrt{s}/2 - E^*_{3\pi})(E^*_{3\pi} - P^*_{3\pi})} \leq M_\tau$
- 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***

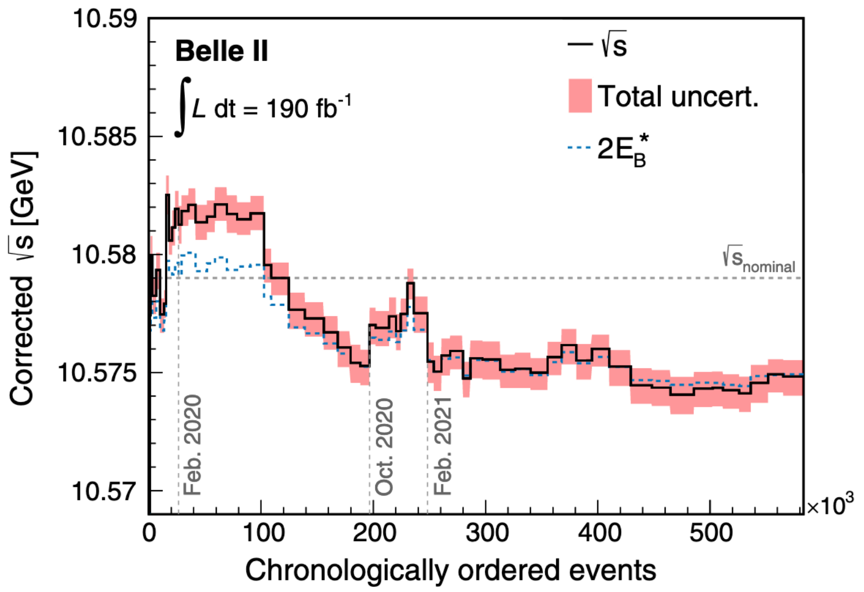
Tau Mass: precision challenge

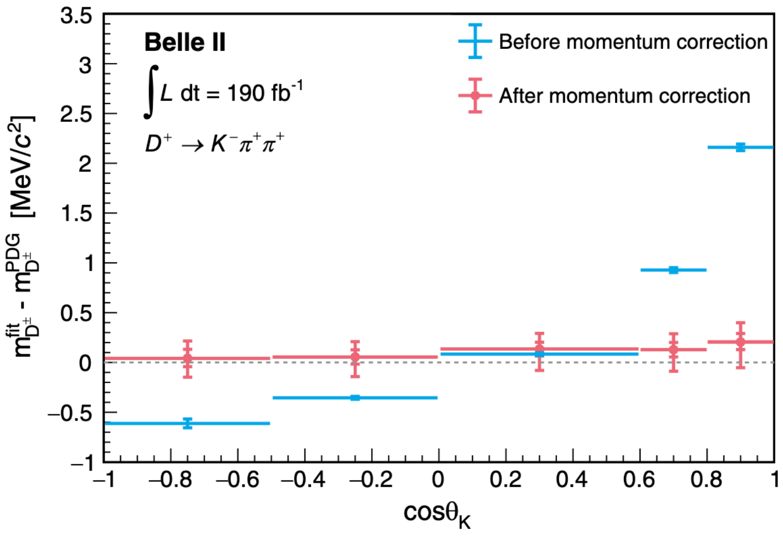
- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 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	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	$\leq$ 0.01
Neutral particle reconstruction efficiency	$\leq$ 0.01
Tracking efficiency correction	$\leq$ 0.01
Trigger efficiency	$\leq$ 0.01
Background processes	$\leq$ 0.01
Total	0.11

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

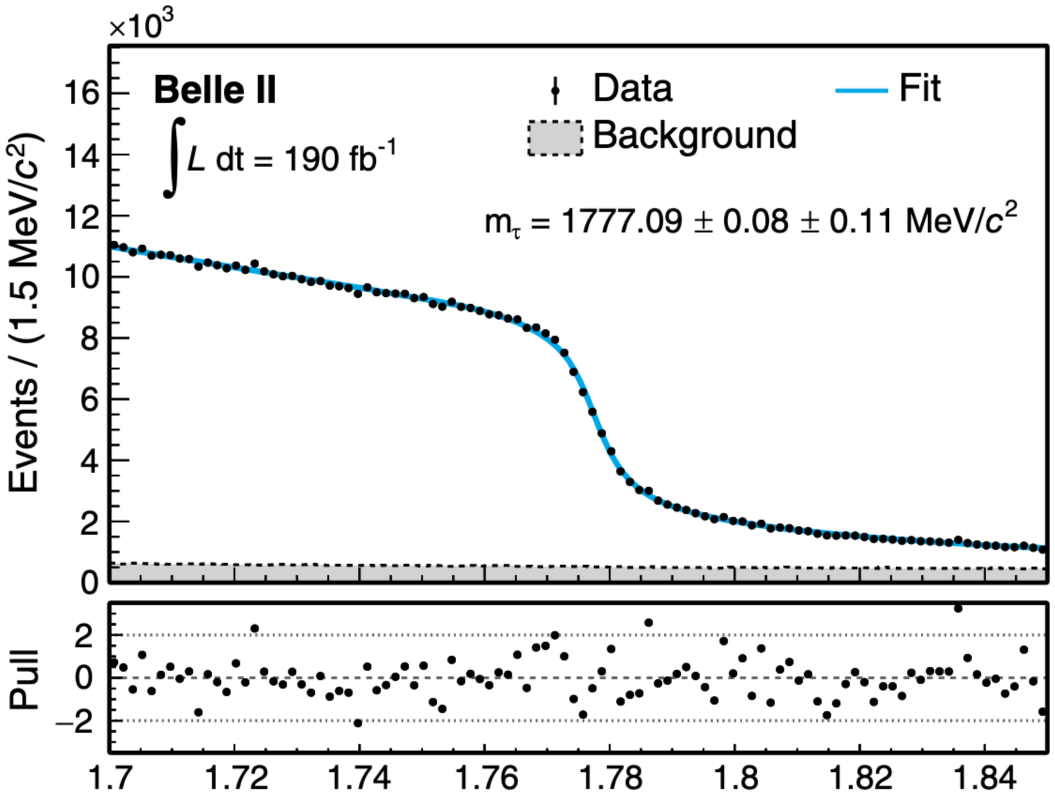
Momentum scale factor cures the bias due to imperfect B-field: extract corrections dependent on $\cos\theta_{track}$ by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass.



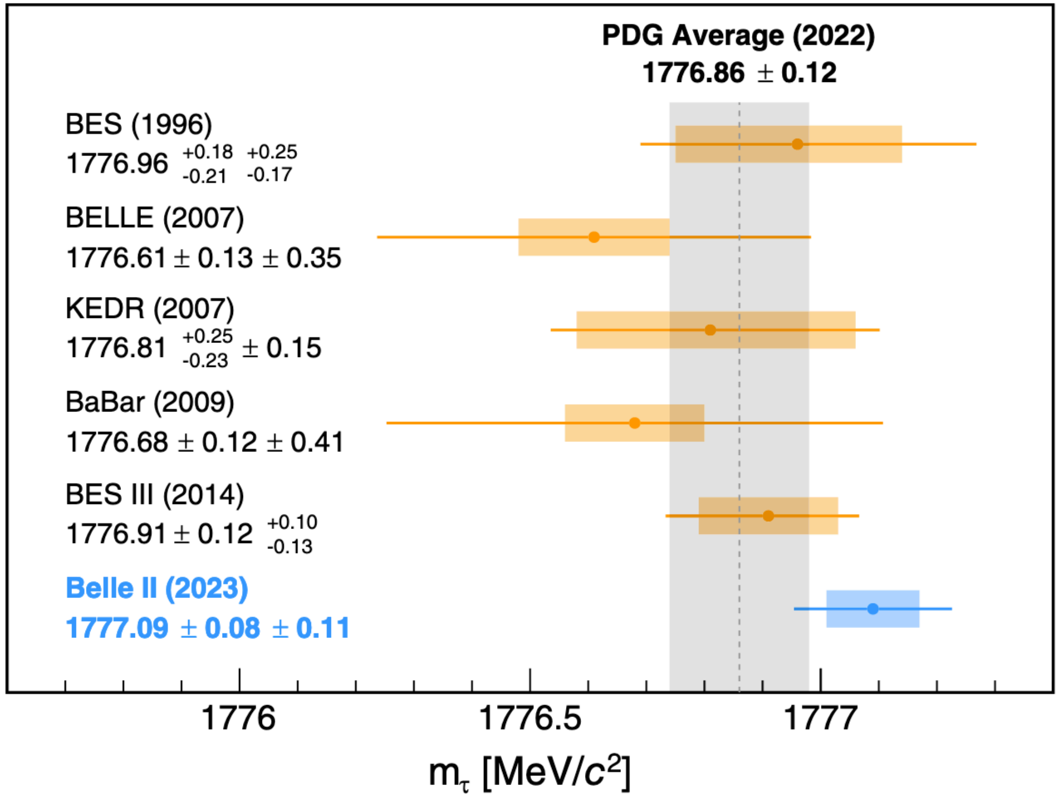


- Analysis performed on part of the on-resonance Run 1 data (190 fb^{-1})
- **Achieve world's most precise measurement**: $m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}\ MeV/c^2$

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



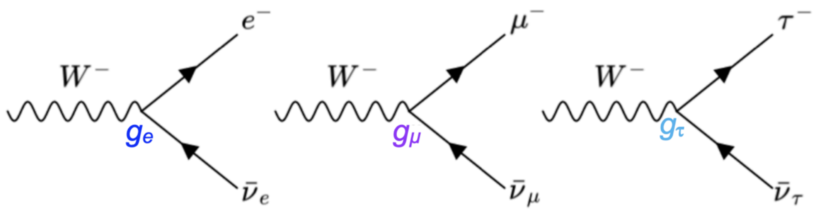
Phys. Rev. D 108, 032006 (2023)



Lepton Flavour Universality

- LFU ⇒ couplings of leptons to W bosons is flavour independent

$g_e = g_\mu = g_\tau$

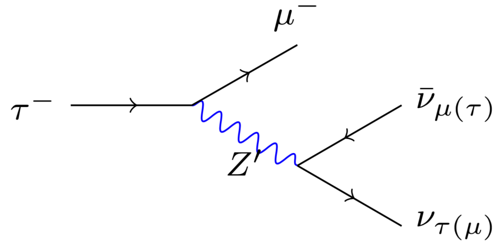


- Precision test of of e-μ universality in τ decays

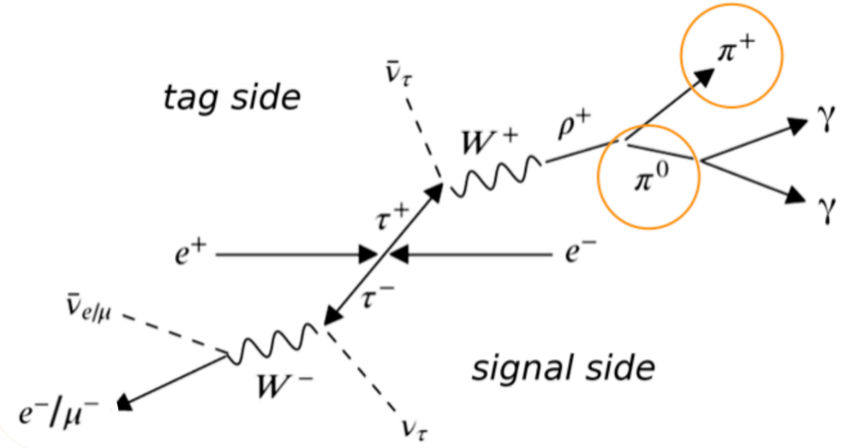
$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu_\mu} \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu_e} \nu_\tau]}$$

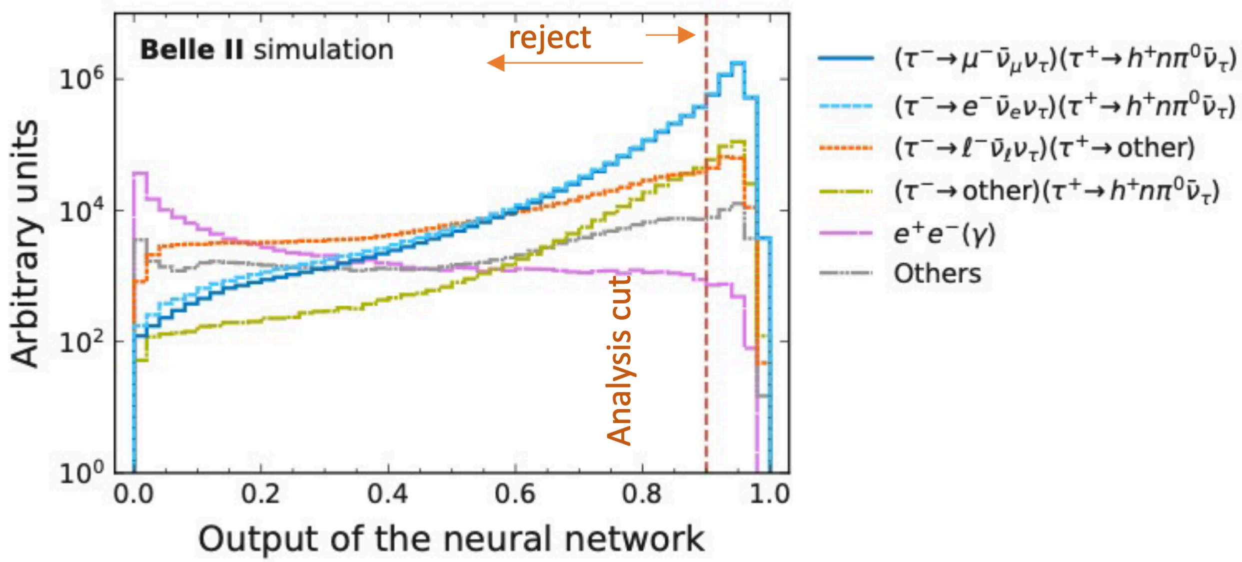
- New Physics could enter in many ways, e.g. LFV neutral current.

Phys. Lett. B 2016 09 046)



- Belle II analysis on the full on-resonance Run 1 data (362 fb^{-1}). Considering the 1x1 prong topology with ρ **tag**.
- Restrict to barrel region, 1.5 < p < 5 GeV (↓ PID systematics).
- Rectangular cuts + neural networks to remove backgrounds.
- Achieve 94% purity with 9.6% signal efficiency (e+μ)

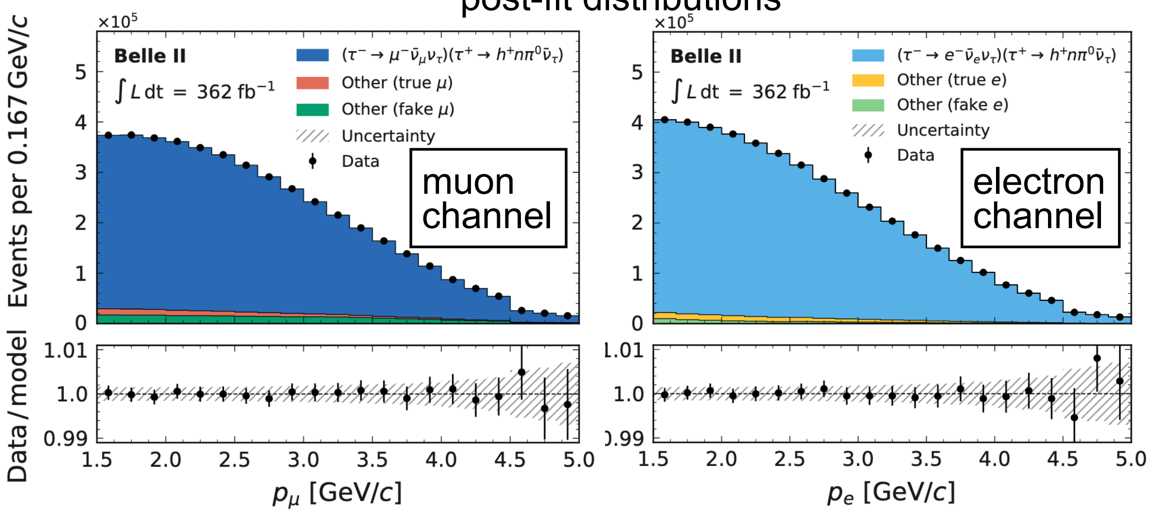




Lepton Flavour Universality

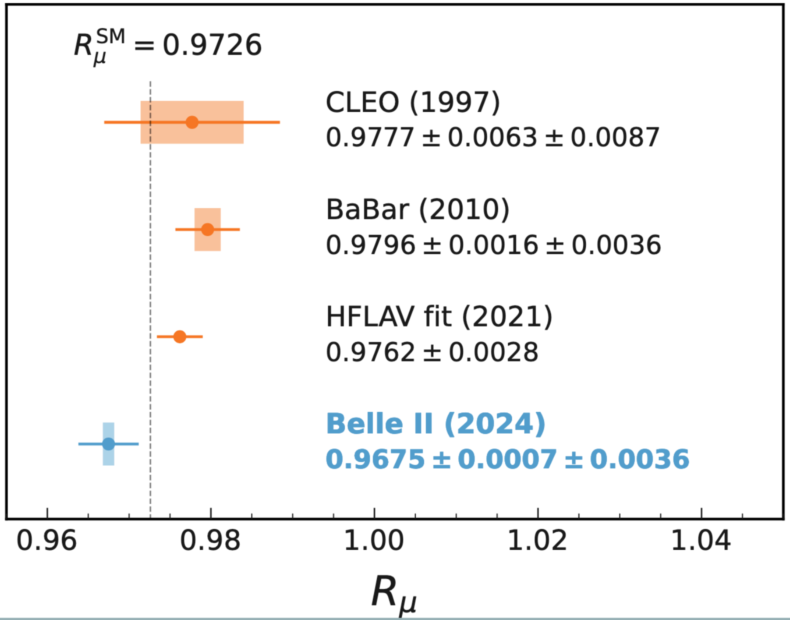
- Measure R_μ with a binned maximum likelihood fit using the *pyhf* library OSS 6 (2021) 2823
  - 21 bins over lepton momentum from 1.5 - 5 GeV
  - systematics included with (constrained) nuisance parameters
  - 3 templates for the μ & e channels (signal decay, background w/wo correct particle on signal side)

post-fit distributions



- Huge effort within Belle II to get lepton ID efficiency and fake-rate systematics under control.

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
Trigger	0.10
Size of the simulated samples	0.06
Luminosity	0.01
Total	0.37



JHEP. 2024, 205 (2024)

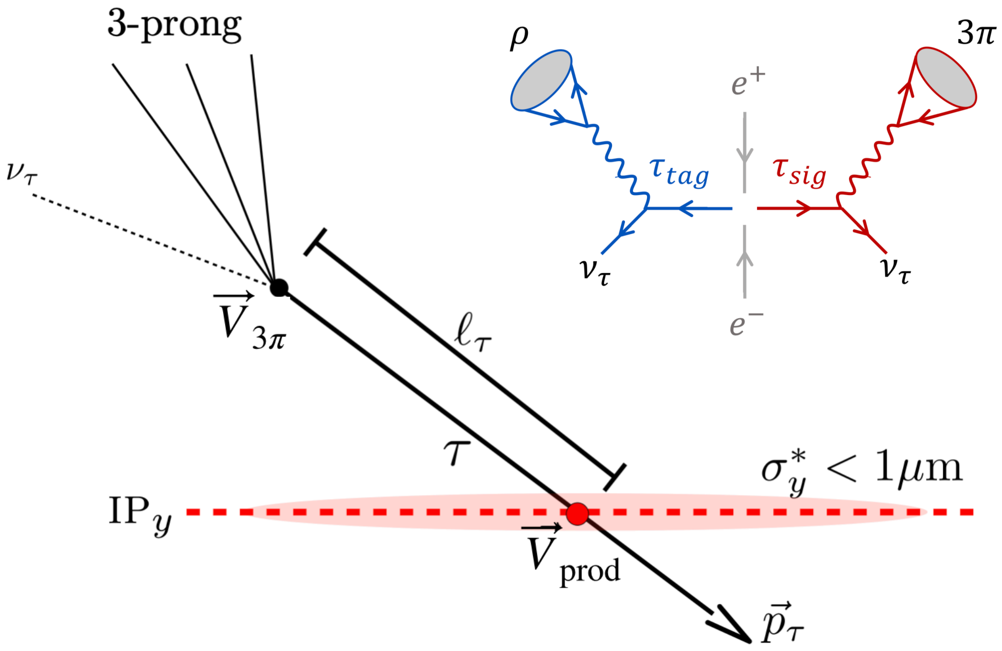
World's most precise test of LFU in τ decays!

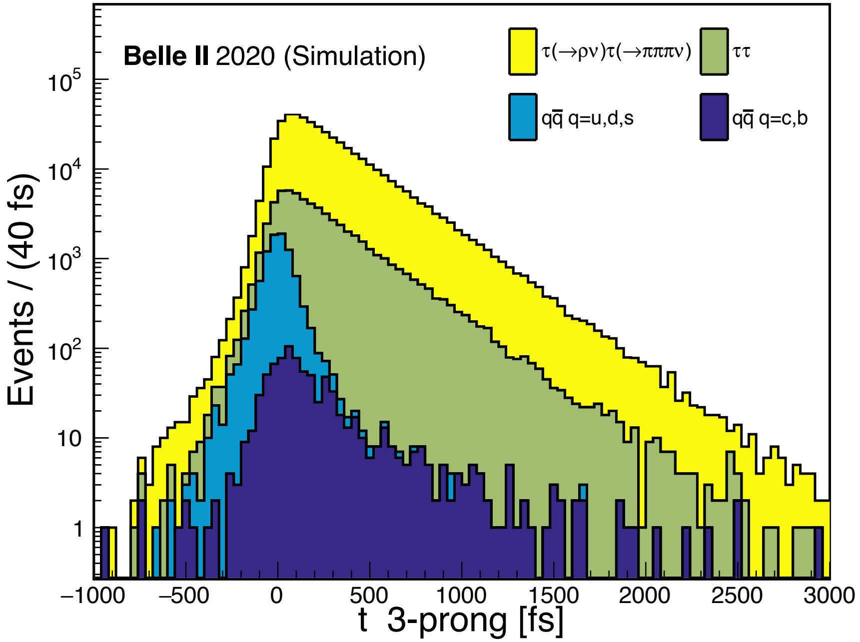
Consistent with SM at 1.4σ

Next precision challenge: tau lifetime

- Can relate proper decay time to flight distance and momentum in lab frame: $t = \frac{l_\tau}{\beta\gamma c} = m\frac{l_\tau}{p_\tau}$ → measure these!
- Reconstruct 3-prong vertex and estimate p_τ using decay products
- Exploit the tiny beam spot size near the IP ⇒ estimate production vertex as the intersection of p-direction with vertical plane of IP

This method is only possible at Belle II!





- Current world-best measurement from Belle (711 fb^{-1}) using 3x3 prong topology.

  τ_τ = 290.1 ± 0.53 (stat) ± 0.33 (sys) fs Phys. Rev. Lett. 112, 031801

- Belle II has 5x higher efficiency (1x3 prong), and 2x better proper decay time resolution (where we have PXD)

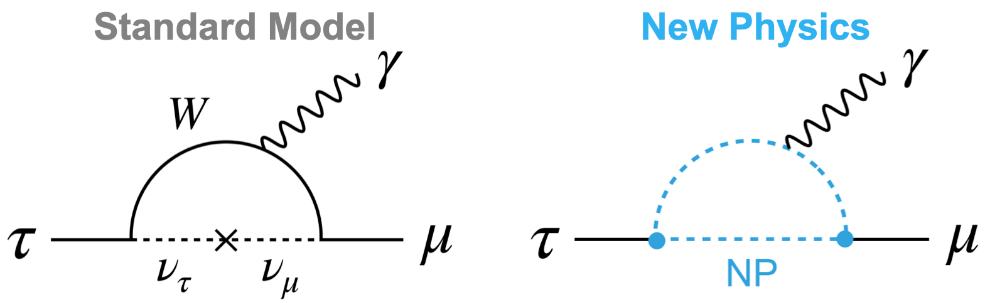
Belle II can deliver a world-leading measurement with the current data

Search for LFV τ decays

- In the SM, charged LFV decays via neutrino oscillation are highly suppressed and immeasurably small:

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

$\Rightarrow$ **Observation would be a clear signature of NP!**



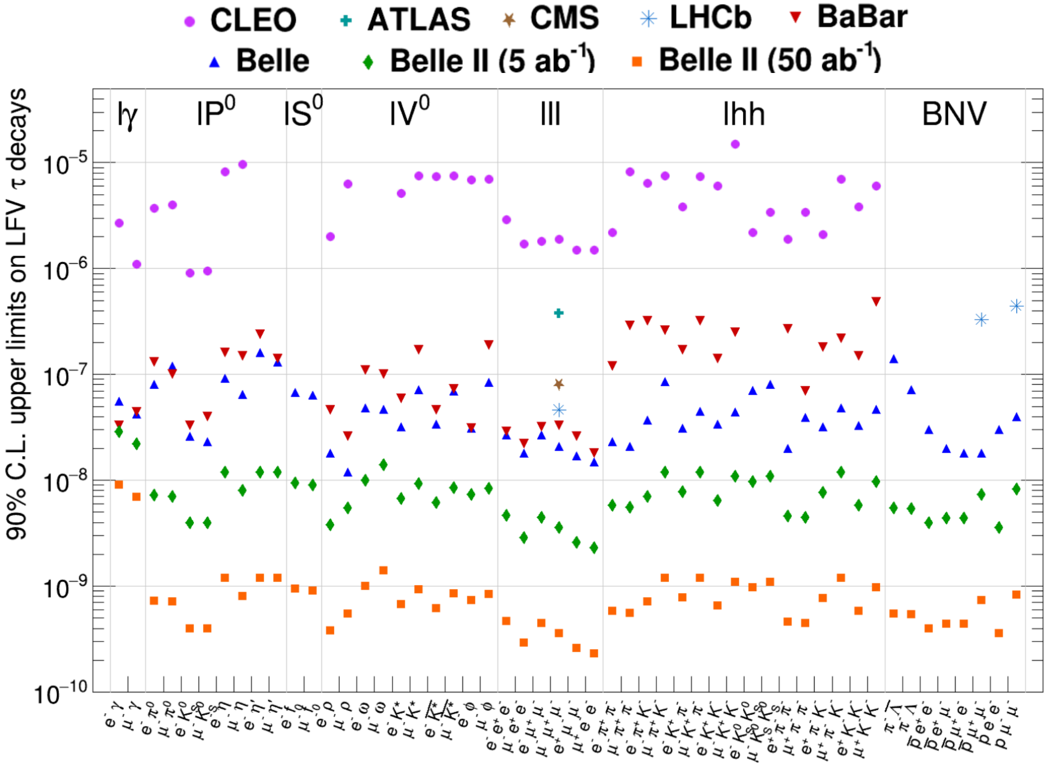
- $\mu \to e$: stringent bounds exist from MEG experiment
- $\tau \to \mu/e$: weaker bounds mainly from Belle & BABAR.

- Wide variety of τ LFV decay modes to study
  - Radiative $\tau \to \ell\gamma$
  - Leptonic. $\tau \to \ell\ell\ell$
  - Semileptonic. $\tau \to \ell h(h)$
  - "Invisible" $\tau \to \ell\alpha$

Golden channels: τ→μμμ, τ→μγ

SL modes can test couplings b/w quarks and leptons, and better discriminate b/w NP models.

Invisible largely unconstrained.



Extrapolating from Belle results (5, 50 ab^{-1}):

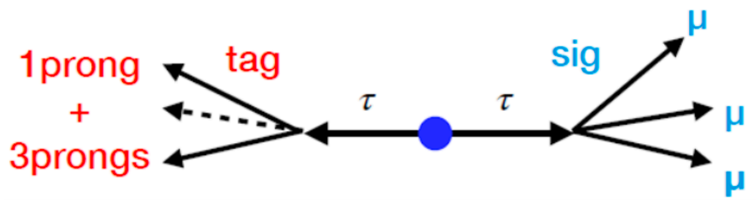
Belle II will push the current bounds forward by at least one order of magnitude!

arXiv:2203.14919

LFV $\tau \to 3\mu$

- One of the "golden channels" for τ LFV. Neutrinoless 3-body decay (3μ).
- Analysis strategy:
  - inclusive tag (3x1 & 3x3 topologies)
  - background rejection using BDT

⇒ **signal efficiency 2.7x Belle**

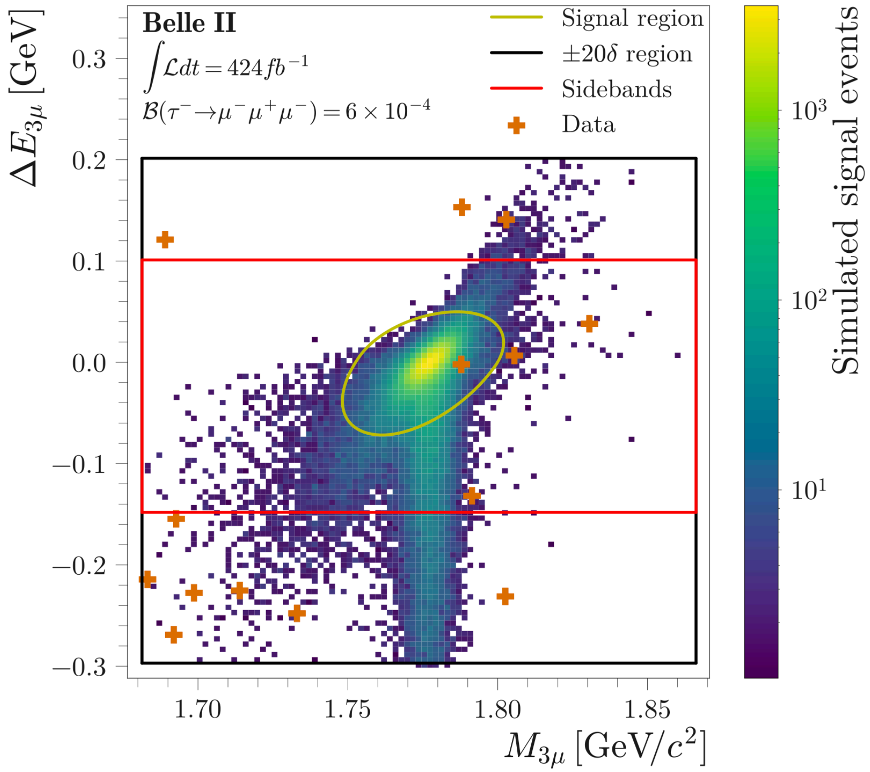


- Extract signal yield in 2D plane:

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$

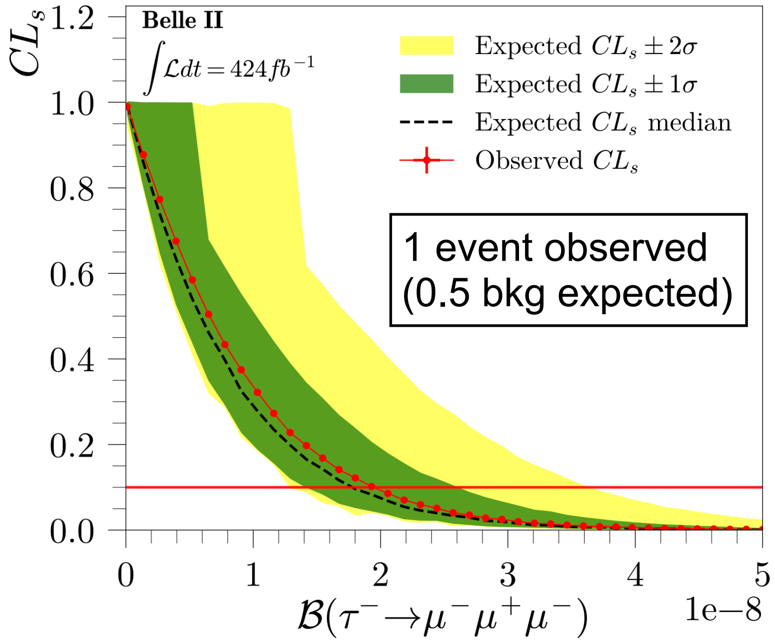
$$\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{\text{beam}}^{CM}$$

- For signal:
  - $\Delta E_{3\mu}$ close to zero, and $M_{3\mu}$ close to τ mass.
  - Tails due to initial and final state radiation.



Belle II with 424 fb[-1] set world's best upper limits!

JHEP09(2024)062



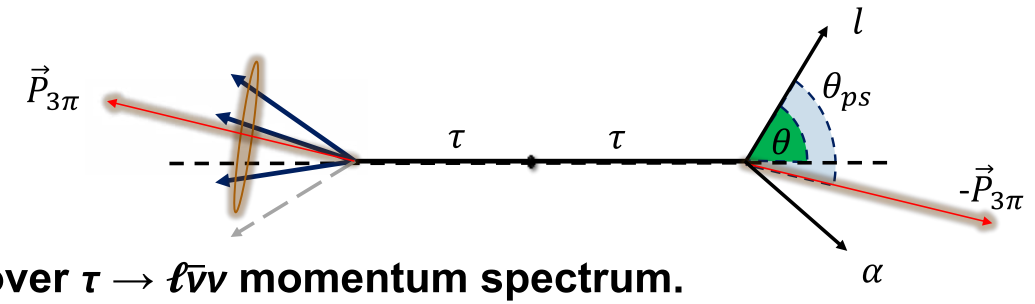
	UL at 90% C.L. on $\mathcal{B}(\tau \to 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L}$ = 20.3 fb^{-1})
LHCb	4.6×10^{-8} ($\mathcal{L}$ = 3.0 fb^{-1})
CMS	2.9×10^{-8} ($\mathcal{L}$ = 131 fb^{-1})
Belle	2.1×10^{-8} ($\mathcal{L}$ = 782 fb^{-1})
BaBar	3.3×10^{-8} ($\mathcal{L}$ = 486 fb^{-1})
Belle II	1.9×10^{-8} ($\mathcal{L}$ = 424 fb^{-1})

- Search for LFV $\tau^- \to \ell^-\alpha$ ($\ell = e, \mu$) where α is an invisible particle.
- α can enter from NP models such as light ALP and many more.

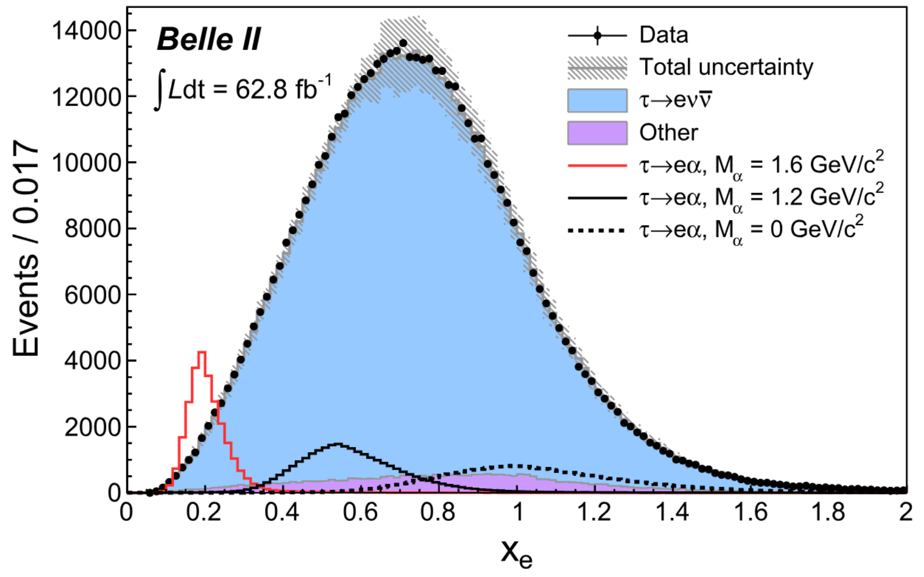
- Cut-based analysis to suppress reducible bkgs ($q\bar{q}$, $\ell\ell\gamma$, 2-photon) and also correctly-tagged $\tau^+\tau^-$ with misidentified signal (e.g $\tau \to \pi\nu$).
- High purity: 96(e)-92(μ)% with ϵ = 9-17% depending on m_α.

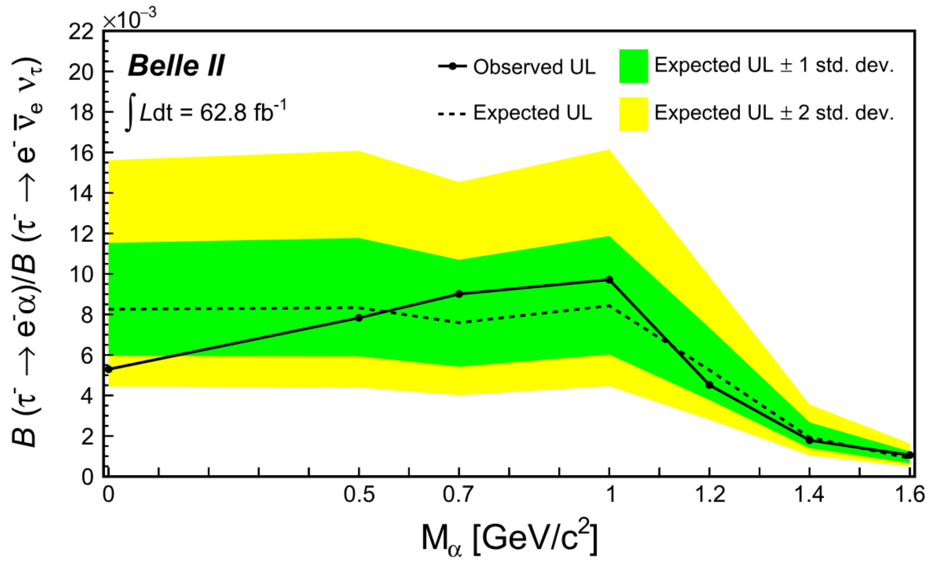
- Cannot boost to the signal τ rest frame due to undetected neutrinos.
- Approximate using *pseudo-rest* frame with two assumptions

1. $E_\tau \approx \sqrt{s}/2$
2. $\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$

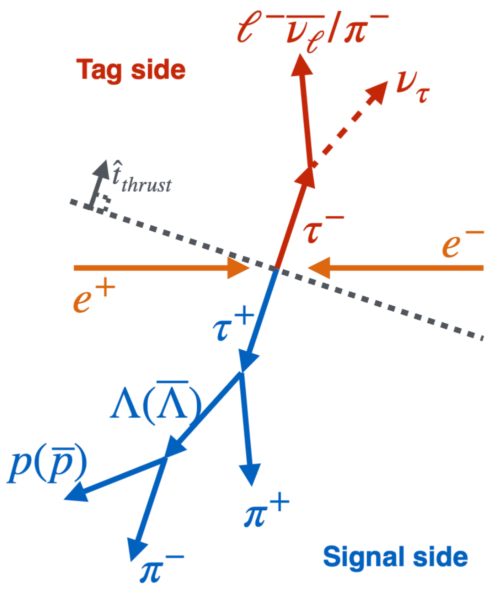


⇒ **Bump search over $\tau \to \ell\bar{\nu}\nu$ momentum spectrum.**



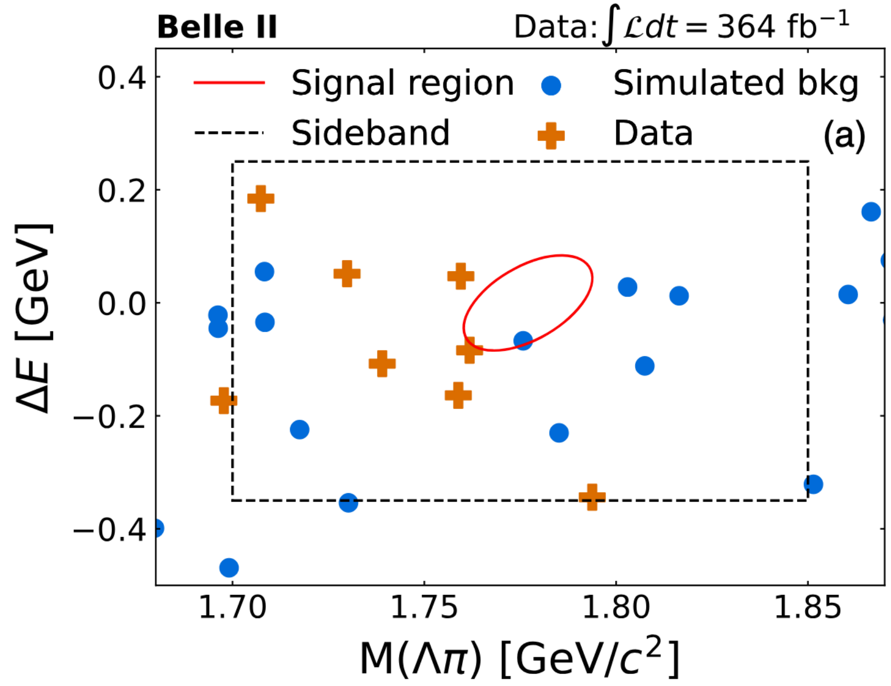


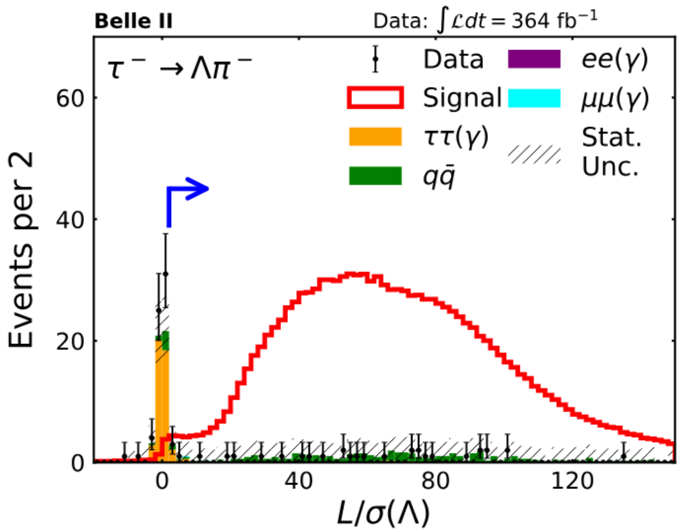
Belle II with 62.8 fb^{-1} set world's best upper limits, 2.2 - 14x better than previous! *PRL 130, 181803 (2023)*

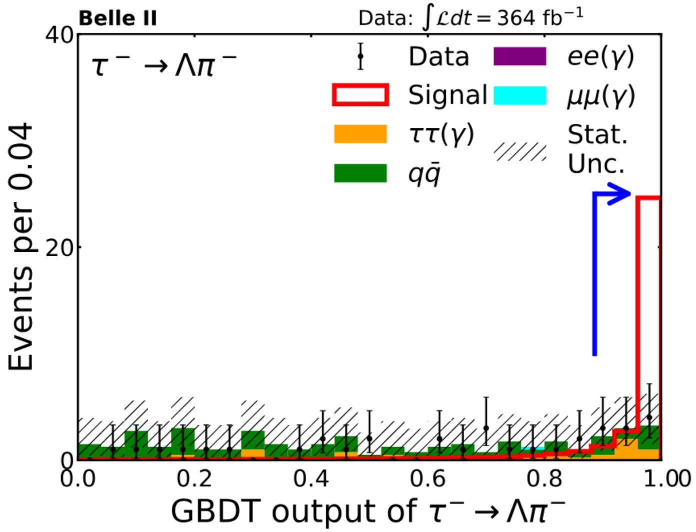


- These decays violate lepton number and baryon number conservation.
  BNV key ingredient to explain asymmetry of matter.
- $\Lambda(\bar{\Lambda})$ reconstructed from $p(\bar{p})$ and π.
- Background suppression:
  Pre-selection (Λ flight distance most discriminate).
  Followed by gradient BDT.
- ϵ_{sig} ~ 9.5% (9.9%) for $\tau \to \Lambda(\bar{\Lambda})\pi$
- Look for an excess within ellipses (ΔE vs mass)

$$\Delta E = E^{CM}_{\Lambda\pi} - \sqrt{s}/2 \qquad M(\Lambda\pi) = \sqrt{E^2_{\Lambda\pi} - P^2_{\Lambda\pi}}$$







- No observed events in 364 fb^{-1}.
  New Belle II limits at 90% CL are:

$$B(\tau \to \Lambda\pi) < 4.7\times10^{-8}$$
$$B(\tau \to \bar{\Lambda}\pi) < 4.3\times10^{-8}$$

World's best limits!

Phys. Rev. D 110 (2024)112003

Summary

- After big efforts to control systematic uncertainties, Belle II is providing **world-leading precision measurements** in the tau sector:
  - τ mass measurement and test of e-μ universality.

- High signal reconstruction efficiency with MVA techniques and inclusive tagging has enabled Belle II to already deliver **world-leading limits on LFV τ decays**:
  - $\tau \to \mu\mu\mu$, $\tau \to \ell\alpha$, and $\tau \to \Lambda(\bar{\Lambda})\pi$ shown today
  - + more (e.g $\tau \to e2\ell$, $\tau \to K_s\ell$)

- Many more results are in the pipeline:
  - Another LFV "golden channel": $\tau \to \mu\gamma$
  - Next precision challenge: τ lifetime
  - Rate and angular CP asymmetries in $\tau \to K_s\pi\nu$, V_{us} measurement, absolute BFs
  - and much more

⇒ **Exciting times ahead!**