Recent tau-lepton results at Belle and Belle II

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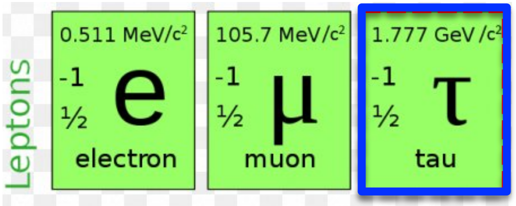
on behalf of the Belle/Belle II collaboration

EPS-HEP2023 conference

21 August 2023

Unravelling the mysteries of matter, life and the universe.

Introduction: τ physics

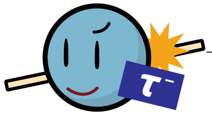


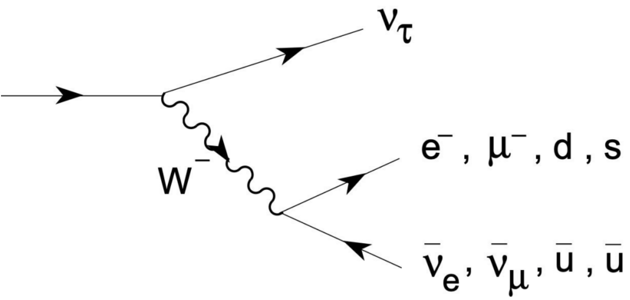
Leptons			
	0.511 MeV/c²	105.7 MeV/c²	1.777 GeV/c²
	-1	-1	-1
	½	½	½
	e	μ	τ
	electron	muon	tau

τ lepton: heaviest lepton in the Standard Model (SM)

- Leptonic and Hadronic decays: > 200 decay channels!

→ Sensitive to new physics





Search for forbidden decays of tau

- Lepton Flavor Violation: $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell, \tau \to \ell V^0$
  - Observation → Clear signs of new physics

Precision measurements of the tau properties

- Lepton Flavor Universality
  - Deviation from the SM → Indirect signs of new physics

Belle, Belle II experiments

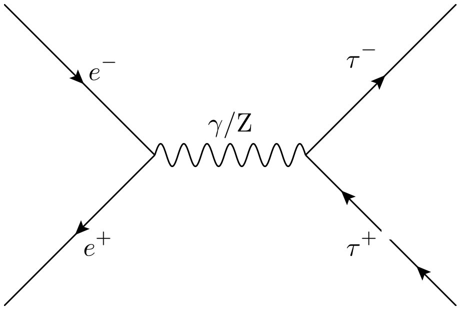
Belle experiment (1999 – 2010)

- 8 GeV e^- and 3.5 GeV e^+
  - Recorded ~1000 fb^{-1} data

Belle II experiment (2018 -)

- 7 GeV e^- and 4 GeV e^+
  - Recorded 424 fb^{-1} data

$e^+e^- \to \tau^+\tau^-$ at Belle (II)



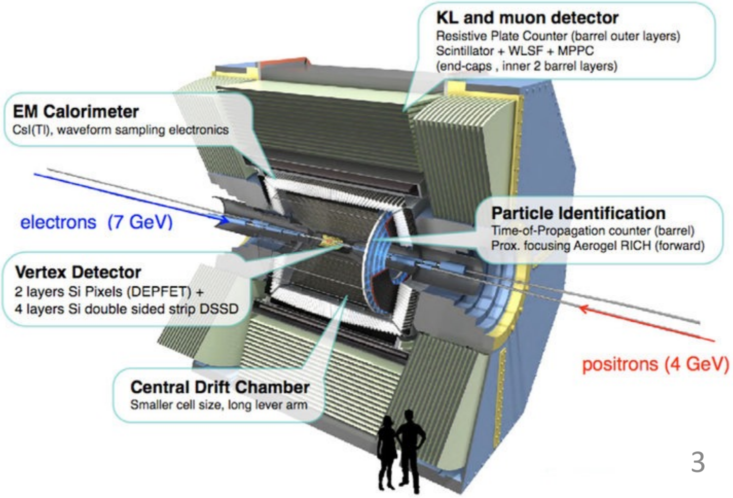
$\sigma(ee \to bb) \sim 1.1\ \mathrm{nb}, \sigma(ee \to \tau\tau) \sim 0.9\ \mathrm{nb}$

τ factory ($N_{\tau\tau} \sim 4.0 \times 10^8$ Belle II)

- Enables high precision studies
- Searches for rare processes

Belle (II) detectors

- Good efficiency of neutral particles (π^0, η)
- Good reconstruction of missing energy
- Specific low-multi triggers at Belle II
  - Eg. single track trigger



How to reconstruct τ at Belle (II)

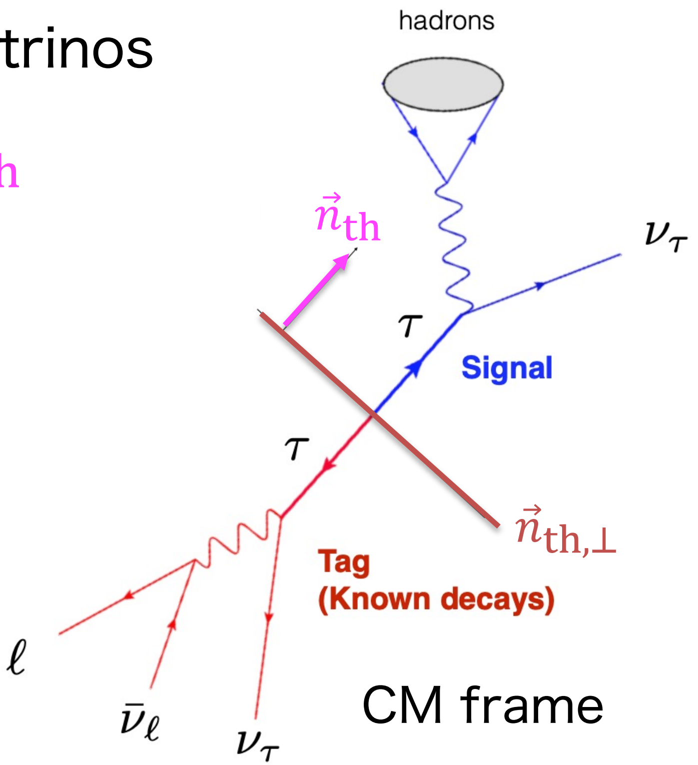
Not fully reconstruct τ in the SM due to neutrinos

→ Identify τ-pair events using thrust axis, $\vec{n}_{\mathrm{th}}$

$\vec{n}_{\mathrm{th}}$ is defined so that V_{th} is maximized

$$V_{\mathrm{th}} = \frac{\sum_i |\vec{p}_i^{\,\mathrm{CM}} \cdot \vec{n}_{\mathrm{th}}|}{\underline{\sum_i} |\vec{p}_i^{\,\mathrm{CM}}|}$$

all the reconstructed particles



τ-pair event is divided into two hemispheres

- Signal-side: Target τ decay, Eg. $\tau \to \ell\gamma, \ell\ell\ell, \ell V^0$ in LFV search
- Tag-side: 1-prong or 3-prong τ decay in the SM

<u>**This method is used in Belle (II) τ analysis to identify an τ event.**</u>

LFV decay: $\tau^{\pm} \to \ell^{\pm} V^{0}$

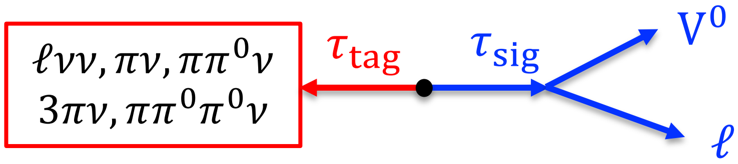
Charged Lepton Flavor Violation

- Forbidden in the SM but possible in several new physics scenarios
  - $\tau \to \ell V^{0}$: sensitive to leptoquark model

    Exotic decay → <u>High signal detection efficiency</u> is crucial!

Belle analysis ($V^{0} = \rho^{0}, \phi, \omega, K^{*}$)

- Use full data (980 fb^{-1})
- Consider 3-prong decay in τ_{tag}
- Event selection by BDT

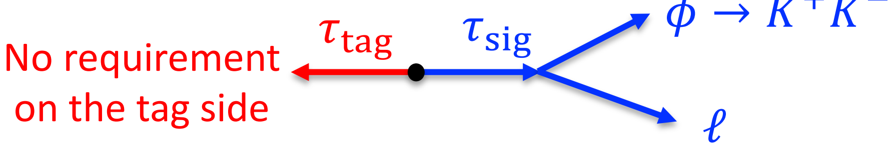


$\ell\nu\nu, \pi\nu, \pi\pi^{0}\nu$
$3\pi\nu, \pi\pi^{0}\pi^{0}\nu$

JHEP06(2023)118

Belle II analysis ($V^{0} = \phi$)

- Use 190 fb^{-1} data
- Untagged reconstruction
- Event selection by BDT



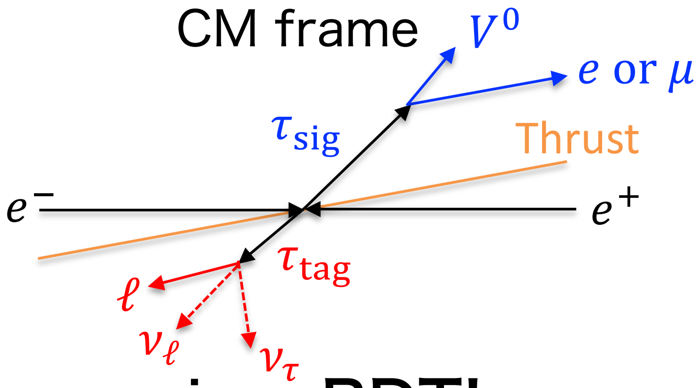
No requirement on the tag side

<u>Signal detection efficiency ~ 2 × Belle</u>

arXiv:2305.04759

Improved the sensitivities by untagged reconstruction and BDT

Belle: Analysis approach



Signal-side: Reconstruct ℓ and V^0

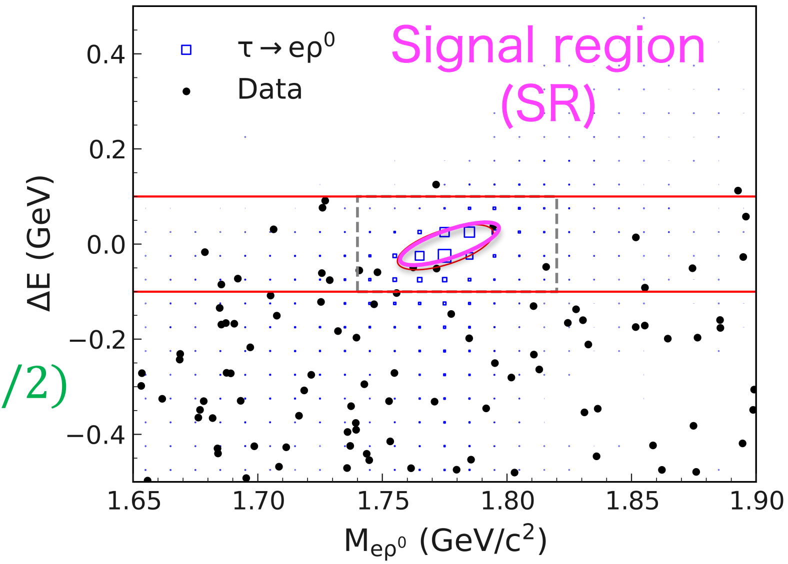
- V^0: $\rho^0, \phi, \omega, K^*(\overline{K}^{*0})$

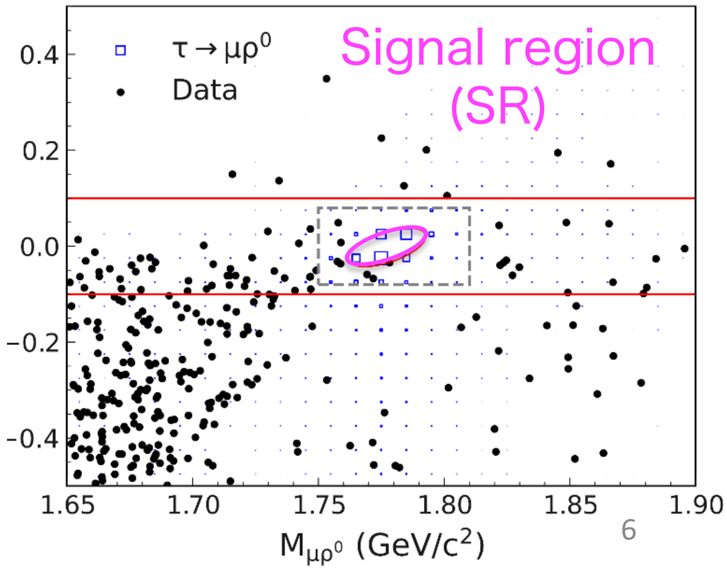
Tag-side: Require 1, 3-prong τ

Background (eg. $\tau \to 3\pi\nu, ee \to q\bar{q}$) suppression: **BDT!**

- Prepare BDT classifier for each ℓV^0 mode
- Training: 11 input variables for $\ell\omega$, 9 input variables for others

$$\Delta E = (E_{\ell V^0}^{\mathrm{CM}} - \sqrt{s}/2)$$





Belle: $\tau^\pm \to \ell^\pm V^0$ results

No significant excess in all ℓV^0 modes

World leading results

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{\mathrm{obs}}$ $(\times 10^{-8})$
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3 *
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0 *
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9 *
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4 *
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9 *
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9 *
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3 *
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7 *

Set ULs at 90% CL by counting approach

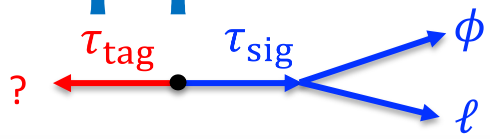
$$\boldsymbol{B(\tau \to eV^0) < (1.7 - 2.4)\times 10^{-8}}$$

$$\boldsymbol{B(\tau \to \mu V^0) < (1.7 - 4.3)\times 10^{-8}}$$

The ULs are improved by ~30% from the previous results

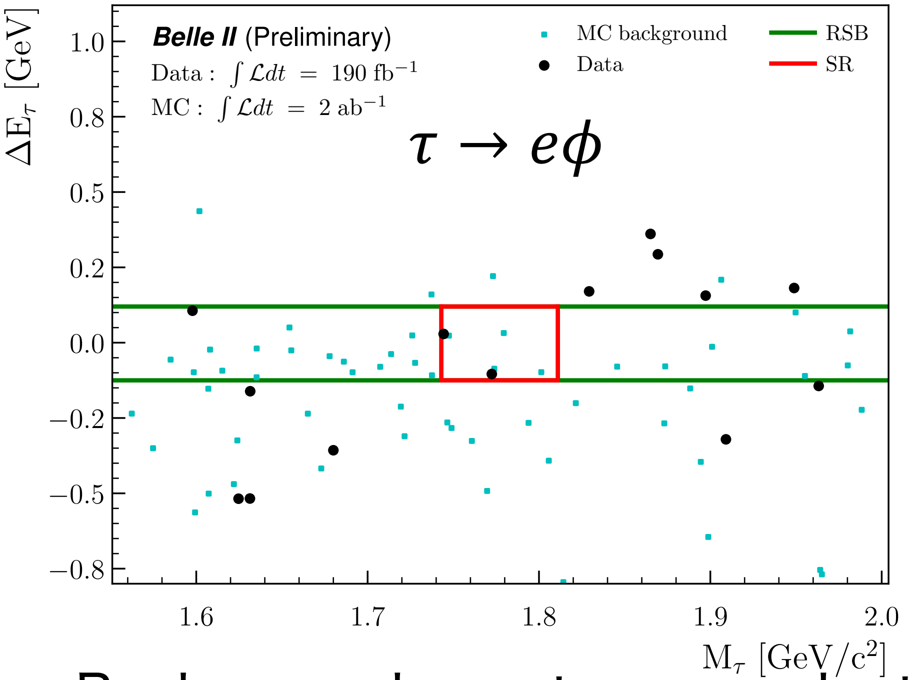
Belle II: Analysis approach

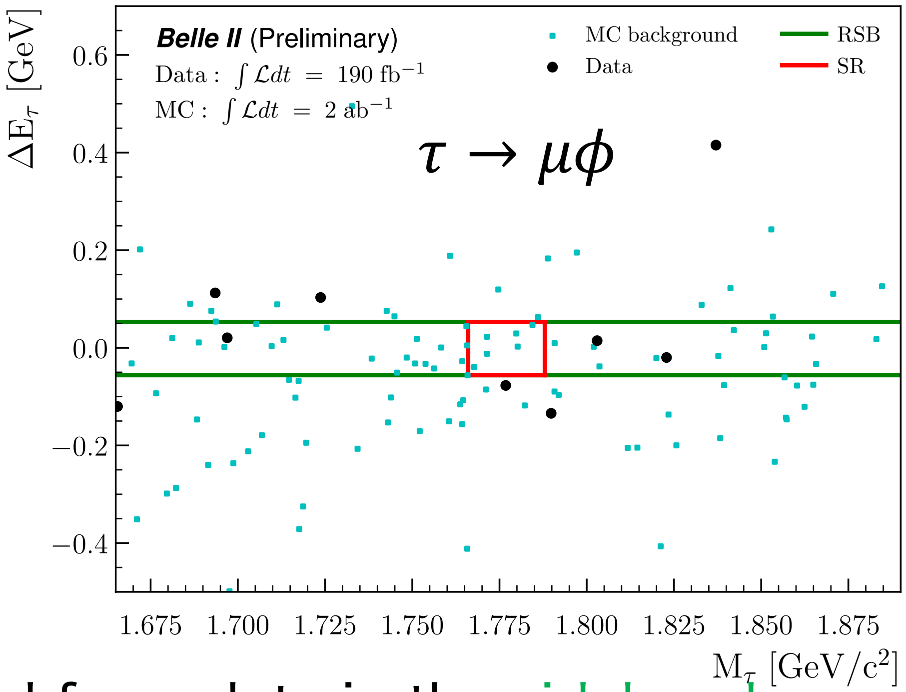
Untagged approach



- Reconstruct $\tau_{\text{sig}} \to \ell\phi$
- SR: $M_{\ell\phi}$ and $\Delta E_\tau = (E^{\text{CM}}_{\ell\phi} - \sqrt{s}/2)$

Result	Region	Mode	
		$e\phi$	$\mu\phi$
N_{exp}	SR	$0.23^{+0.55}_{-0.21}$ stat	$0.36^{+0.39}_{-0.23}$ stat
N_{obs}	SR	$2.0^{+2.6}_{-1.3}$ stat	$0.0^{+1.8}_{-0.0}$ stat

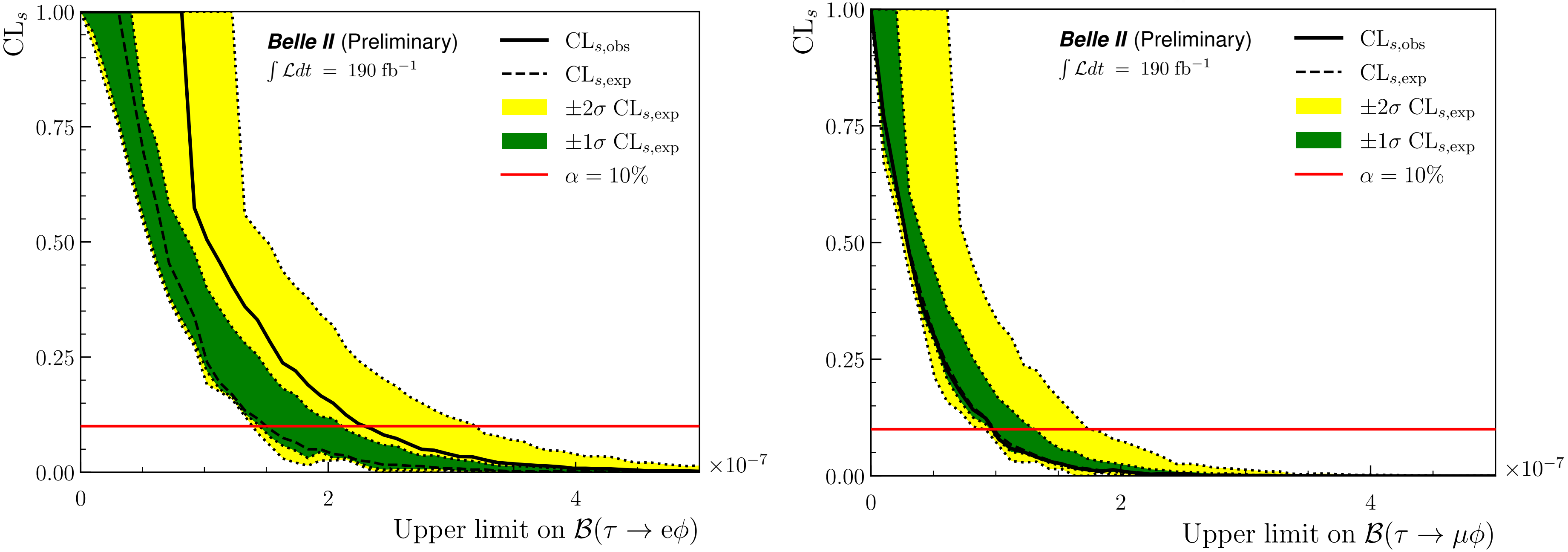




- Background events are evaluated from data in the sidebands
- Perform Poisson counting experiment approach in SR

Belle II: $\tau^{\pm} \to \ell^{\pm}\phi$ results

Set ULs at 90% CL $\mathcal{B}_{\mathrm{UL}}(\tau \to \ell\phi) = \frac{s}{L \times 2\sigma_{\tau\tau} \times \varepsilon_{\ell\phi}}$,



Obs. $B_{\mathrm{UL}}(\tau \to e\phi) = 23\times10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to e\phi) = 15\times10^{-8}$

Obs. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.7\times10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.9\times10^{-8}$

$B_{\mathrm{UL}}(\tau \to e\phi) = 2.0\times10^{-8}$ at Belle

$B_{\mathrm{UL}}(\tau \to \mu\phi) = 2.3\times10^{-8}$ at Belle

Successful first application of untagged approach in τ analysis at Belle II

$\tau^{\pm} \to \ell^{\pm}\alpha$ search at Belle II

Phys.Rev.Lett.130,181803

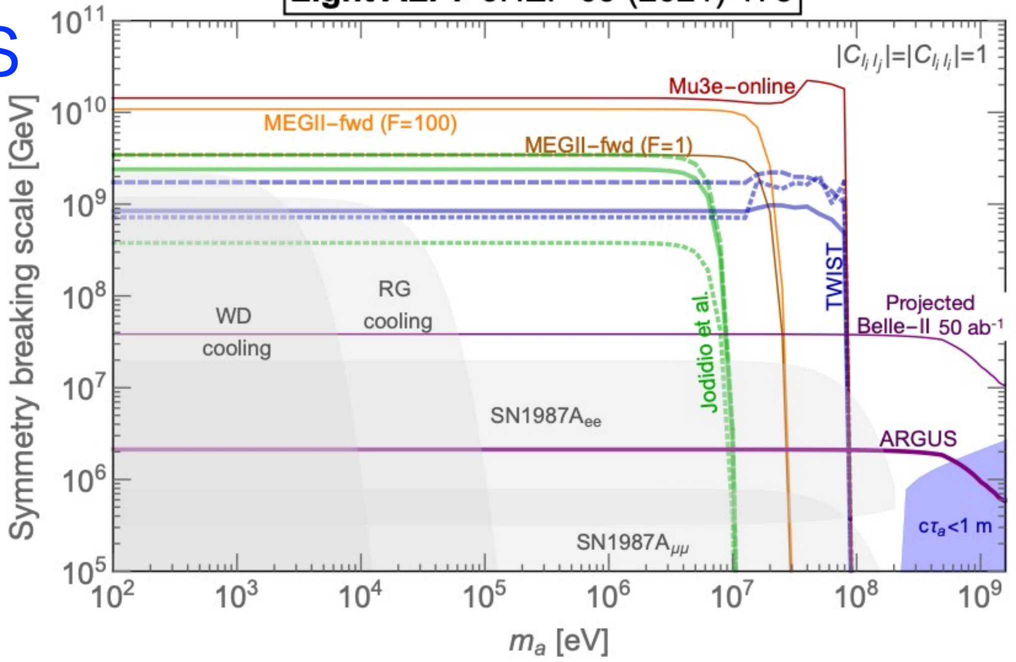
- Search for $\tau \to \ell + \alpha$ (invisible)
  - eg. Axion-like particle (ALP)
- Upper Limit from ARGUS
  - 476 pb^{-1} data (1995)

UL at 95% CL

$$\mathcal{B}(\tau^{\pm} \to e^{\pm}\alpha)/\mathcal{B}(\tau^{\pm} \to e^{\pm}\nu\bar{\nu}) \quad < \quad (0.6-3.4)\times 10^{-2},$$
$$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\alpha)/\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}) \quad < \quad (0.3-3.6)\times 10^{-2},$$

$$0.0 < m_{\alpha} < 1.6 \text{ GeV}$$

Light ALP: JHEP 09 (2021) 173



Belle (II) can set more stringent limits on the invisible boson

$\tau^\pm \to \ell^\pm \alpha$: Analysis approach

- Split event in two hemispheres based on the thrust axis
  - Signal side: 1 lepton track ($\ell = e, \mu$)
  - Tag side: 3-pion ($\tau \to 3\pi\nu$ decay)
  - Veto neutrals to suppress hadronic bkg
- Exploit the shape differences
  - Signals: $\tau \to \ell\alpha$ two-body decays
  - Backgrounds: $\tau \to \ell\nu\nu$ three-body decays

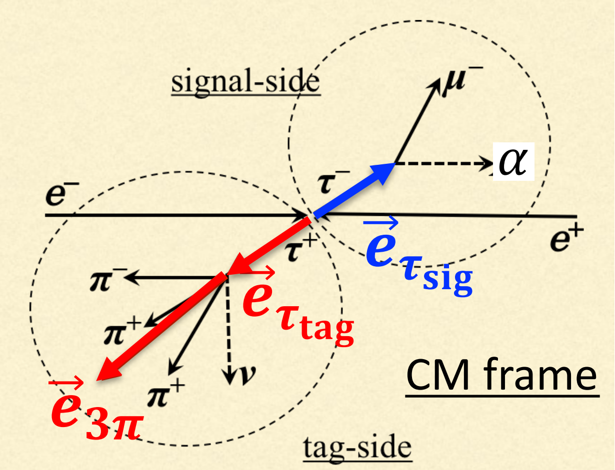
→ p_ℓ, E_ℓ in tau rest frame: monochromatic

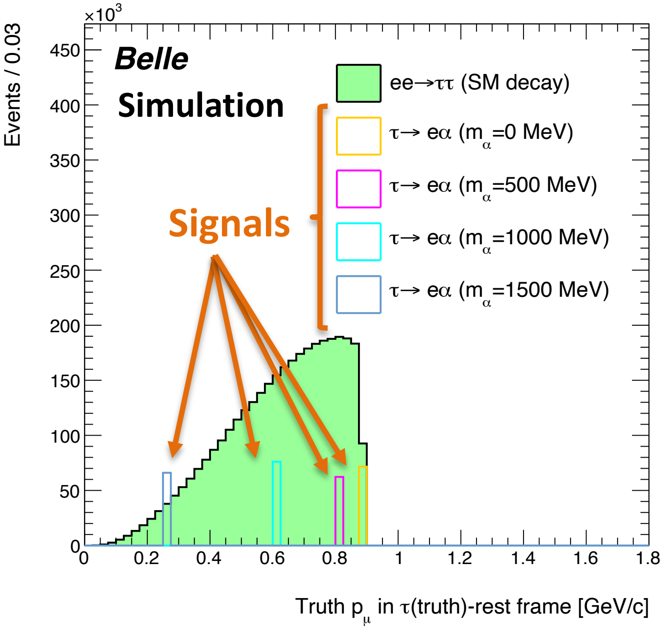
How to obtain tau direction?

- Require $\tau \to a_1(\to 3\pi)\nu$ in tag side

  → $\vec{e}_{\tau_{\text{tag}}} \approx \vec{e}_{3\pi}$

$$m_\tau = 1.78\ \text{GeV}$$
$$m_{a_1} = 1.26\ \text{GeV}$$





Energy in τ pseudo-rest frame

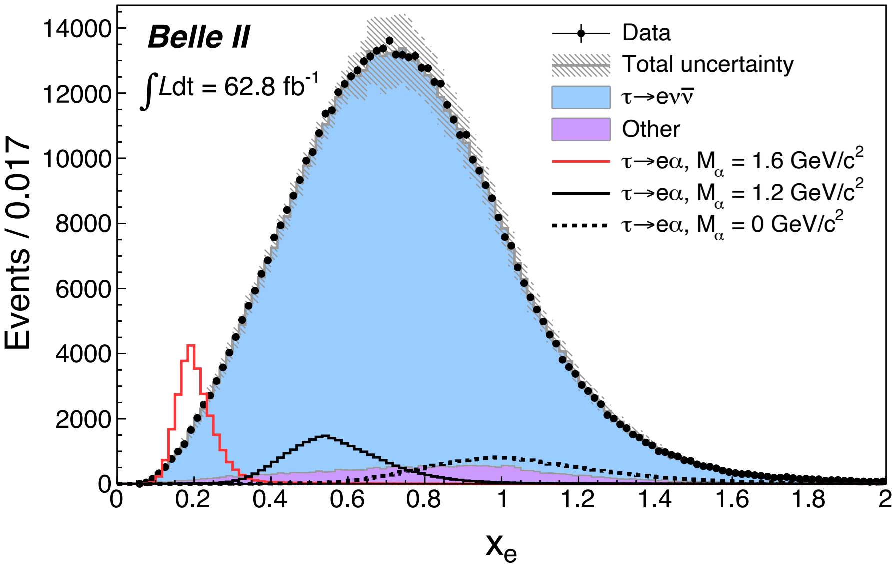
Discriminating variable: normalized lepton energy

$$x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2},$$

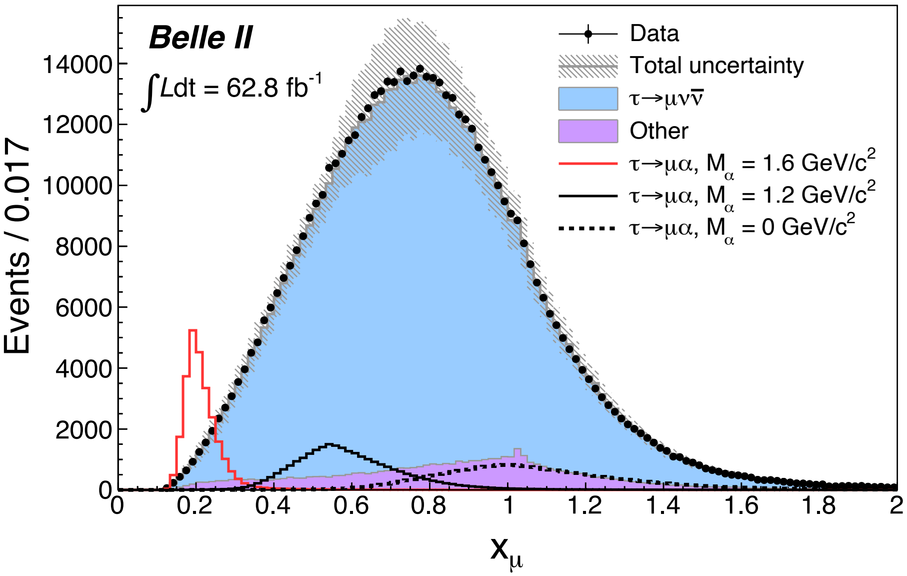
Lepton energy in the τ rest frame

- Bump hunt above broad distribution from $\tau \to \ell\nu\nu$

$\tau \to e\alpha$ search



$\tau \to \mu\alpha$ search



No significant excess over the background predictions..

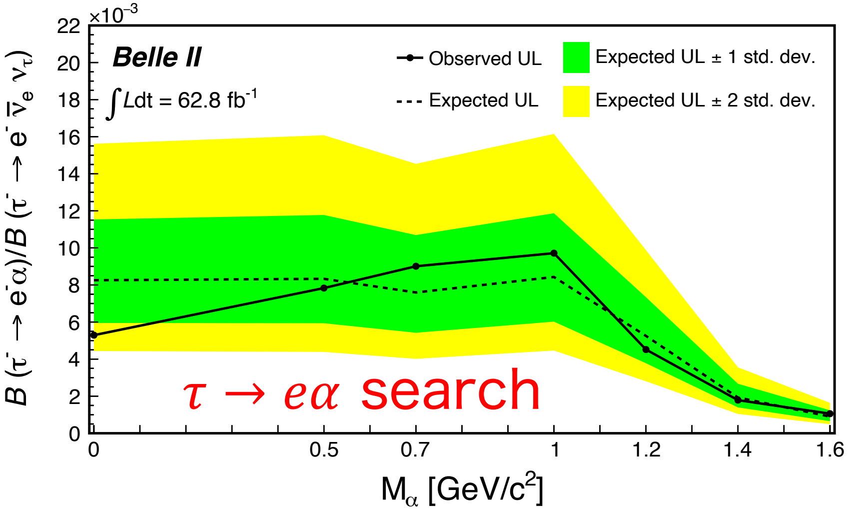
$\tau^{\pm} \rightarrow \ell^{\pm}\alpha$: Upper limits

Perform the maximum likelihood fit

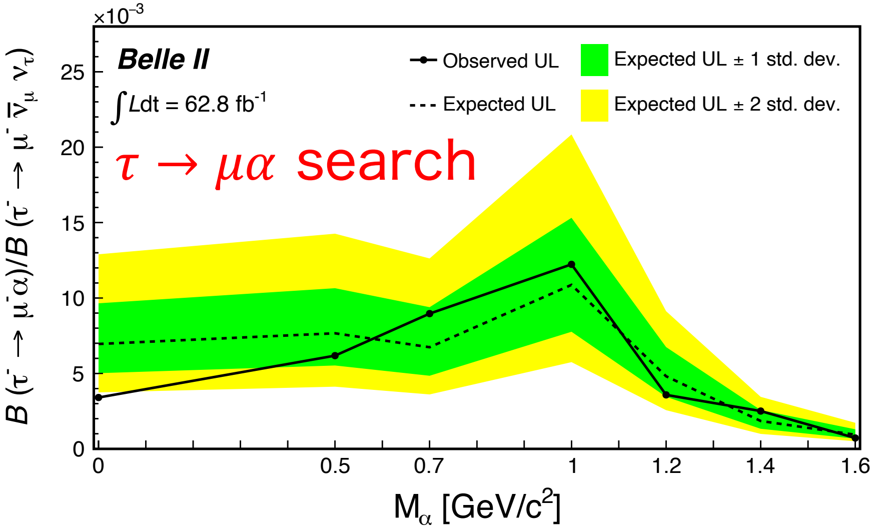
- Use x_ℓ distributions as signal/bkg PDF (MC simulation)

Set upper limits on branching fractions

Dominant syst. unc.: Lepton ID efficiency



$\tau \rightarrow e\alpha$ search



$\tau \rightarrow \mu\alpha$ search

2 – 14 times more stringent limits than ARGUS

Heavy neutrino search in τ decay

Submitted to PRL (arXiv:2212.10095)

Neutrino mass, $m_\nu \neq 0$ → Need a mechanism to establish it

- One approach is to include right-handed neutrino

$\boldsymbol{\tau^\pm \to \pi^\pm \nu_h \; (\nu_h \to \pi^\pm \ell^\mp)}$

ν_h: Majorana neutrino (long-lived)

$\ell = e, \mu$

Signal-side: Require $\pi\pi\ell \; (\ell = e, \mu)$

- $\nu_h \to \pi^\pm \ell^\mp$: π and ℓ with a common vertex

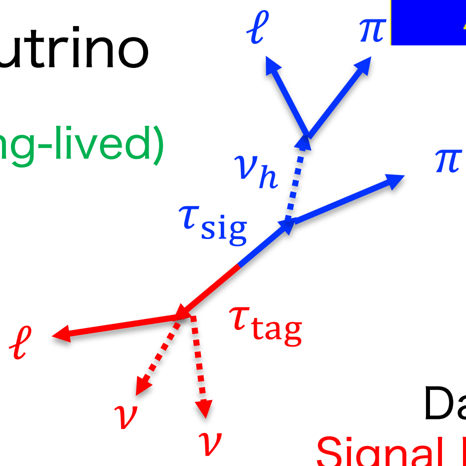
Tag-side: Require 1, 3-prong τ

Background: $ee \to q\bar{q}, \tau\tau, \ell\ell, ee\ell\ell$

→ Suppress the bkgs by $M(\pi\pi\ell)$, ΔE cuts.

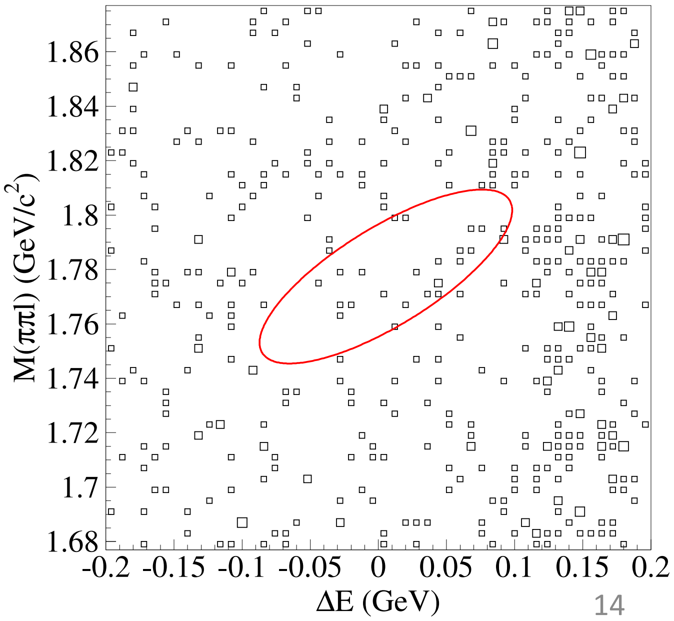
$\Delta E = (E^{\mathrm{CM}}_{\pi\pi\ell} - \sqrt{s}/2)$

Peak search in $m_{\pi\ell}$ distribution



Data

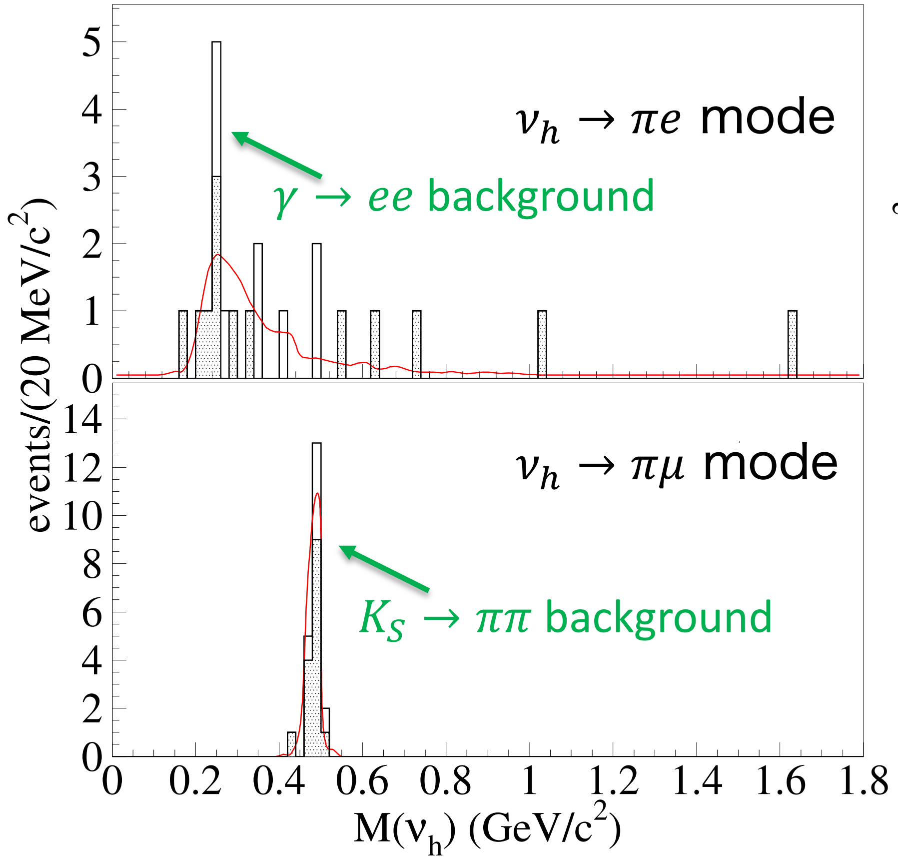
Signal Region



Result: $\nu_h \to \pi\ell$

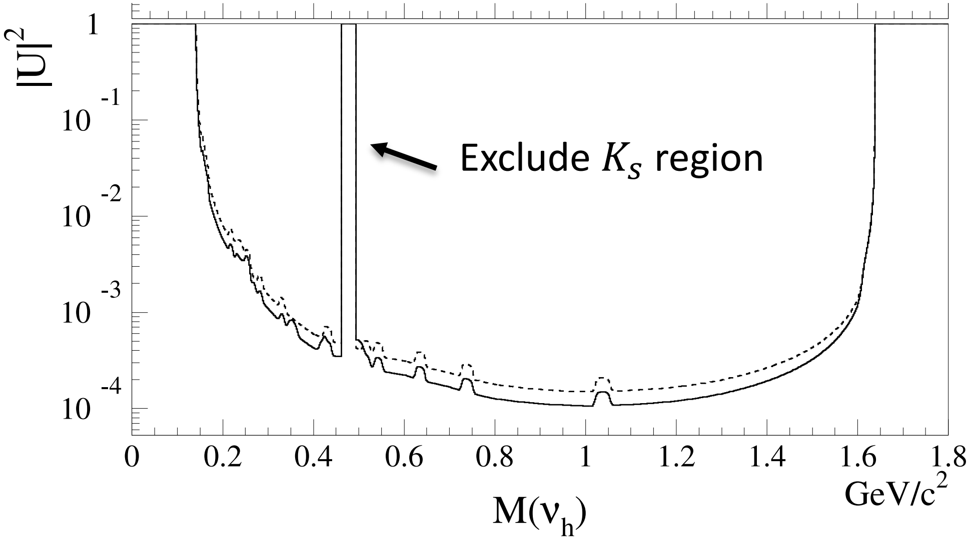
No narrow (signal-like) peak in $M(\nu_h \to \pi\ell)$ distribution

Data, Background only fit



Set ULs at 95% CL on $|U|^2$

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i, \quad \alpha = e, \mu, \tau, ..., \; i = 1, 2, 3, 4, ...$$



ULs on the mixing of heavy neutral leptons to the active neutrinos are set for $0.2 < M(\nu_h) < 1.6$ GeV/c^2

Belle II: m_τ measurement

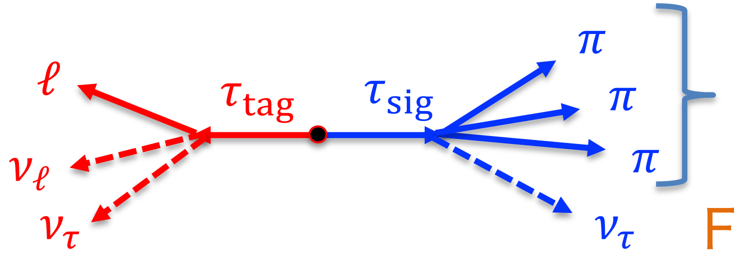
Phys.Rev.D108,032006

m_τ: one of the fundamental parameters of the SM

- Precise measurement is important for tests of LFU (τ vs e/μ)

Belle II: Use Pseudomass endpoint (M_{min}) method

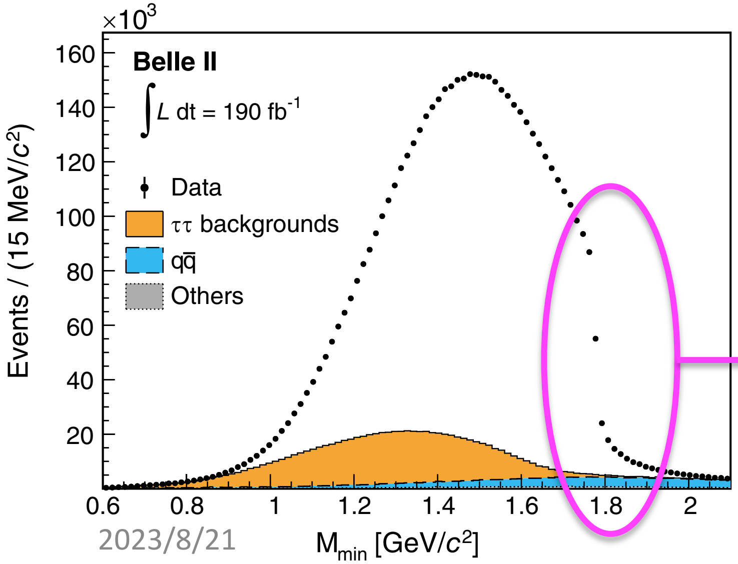
→ Use kinematics edge of M_{min} distribution in $\tau \to 3\pi\nu$ decays

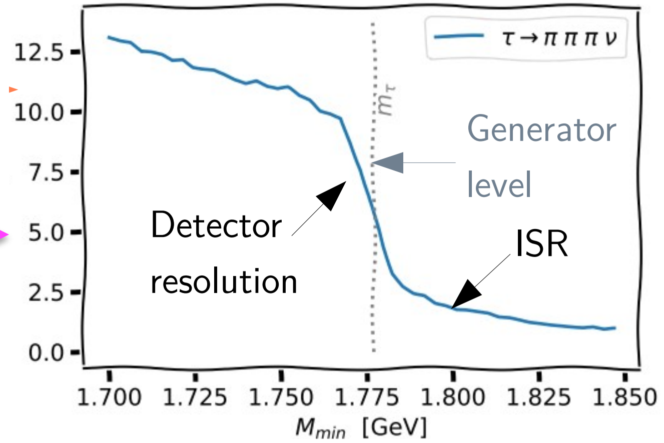


$$M_{\rm min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$$

Fit to the endpoint with empirical function

Smeared edge due to detector resolution/ISR



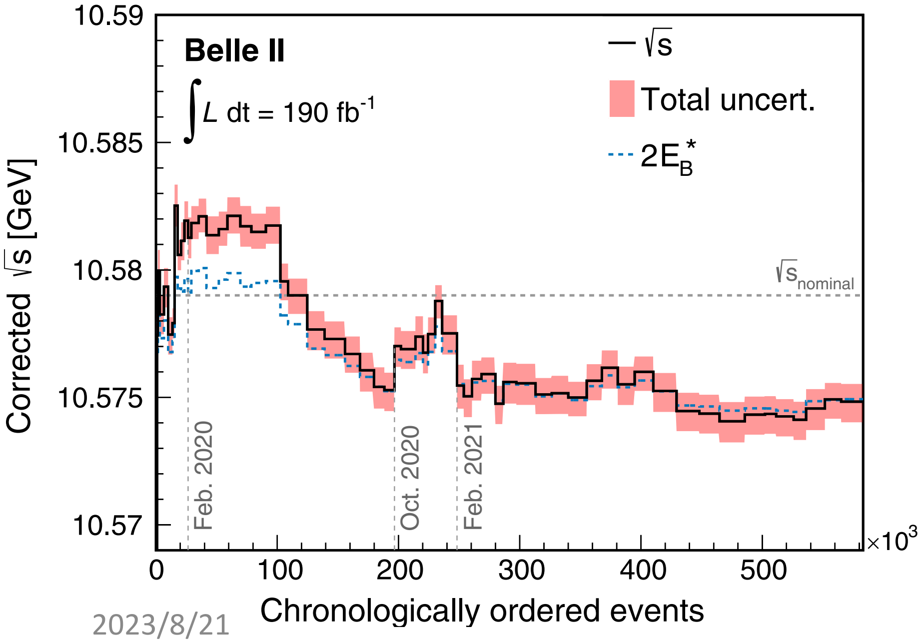


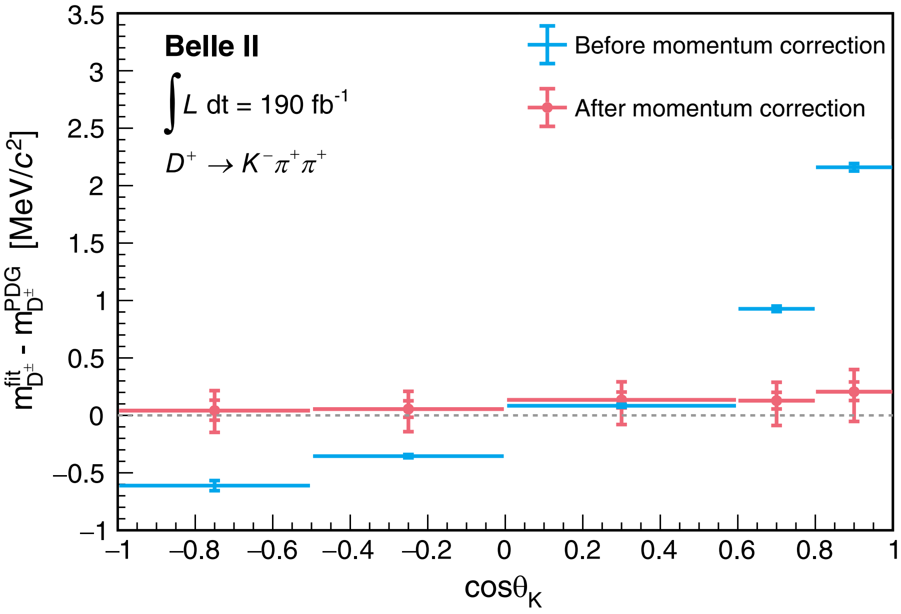
Corrections factors

$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s} - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)}$$

Beam energy calibration and momentum correction are crucial

- Beam energy is corrected using B-meson hadronic decays
- Momentum scale : extract scale factors for K/π using $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$
  - $\vec{p}$ due to imperfect $\vec{B}$, mismodeling in material → bias mass extraction





m_τ measurement: Result

Perform an unbinned maximum likelihood fit

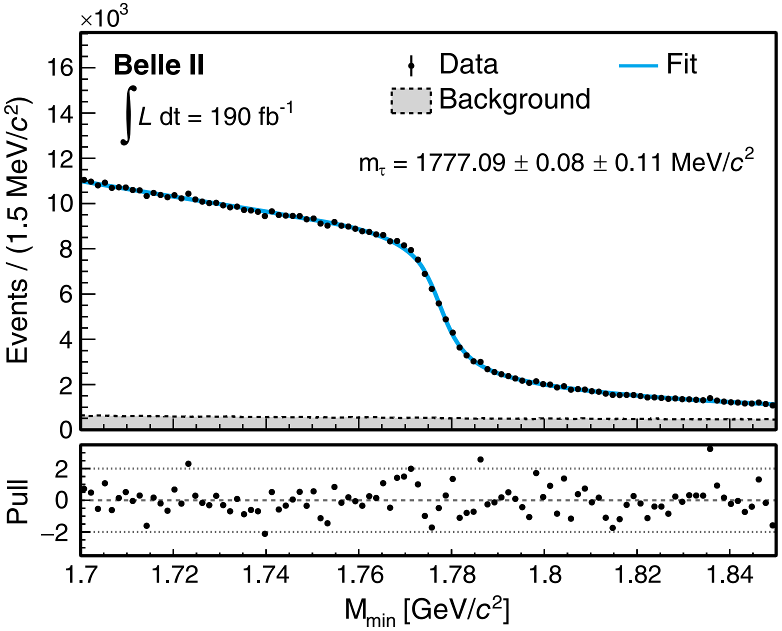
$$F(M_{\min}) = 1 - P_3 \cdot \arctan\left(\frac{M_{\min} - P_1}{P_2}\right) + P_4(M_{\min} - P_1) + P_5(M_{\min} - P_1)^2 \,.$$

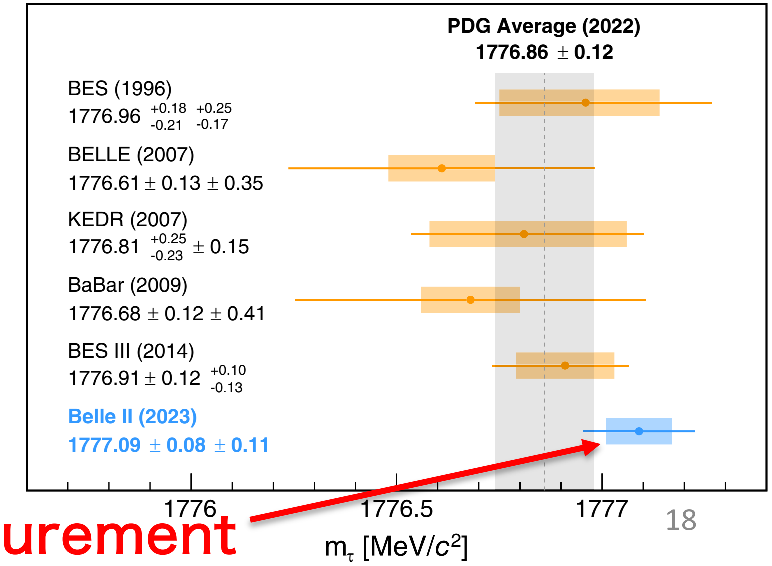
Fit function

$$\boxed{m_\tau = 1777.09 \pm 0.08 \pm 0.11 \ \mathrm{MeV}/c^2}$$

Systematic uncertainties

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
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11





World's most precise measurement

Conclusions and outlook

Belle (II) has an excellent sensitivity for τ physics

- LFV decays, $\tau \to \ell\alpha, \ell V^0$: most stringent BF limit
- World's most precise measurement of τ mass

Statistical uncertainty is still dominant for τ decay searches, eg. LFV

- Now, 424 fb^{-1} at Belle II.
  - Expect more results on larger statistics → Stay tuned!

Backup

Recent tau physics result

Summary of Journal/Conference papers in 2022-2023

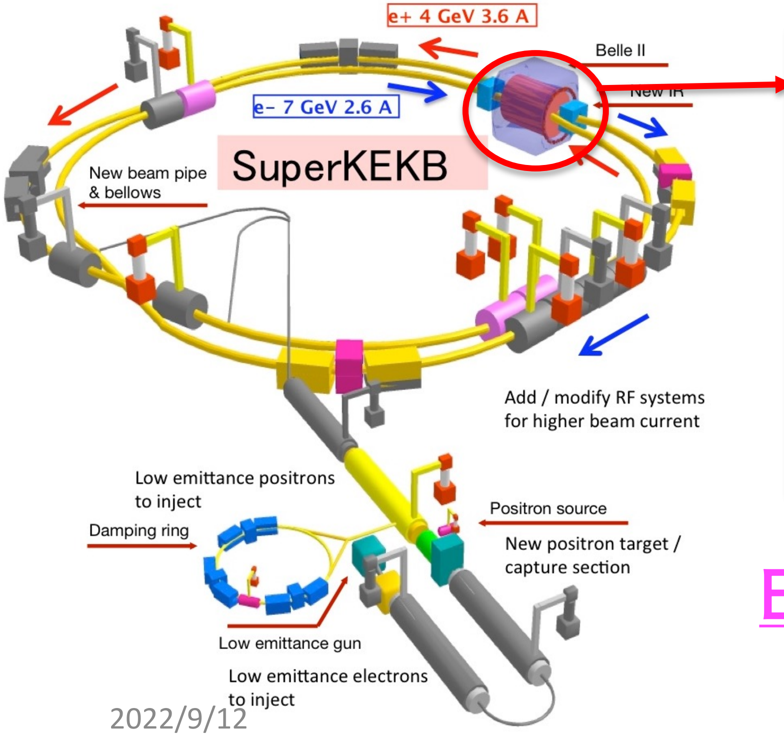
- Belle: 5 papers [Link]
- Belle II: 3 papers [Link]

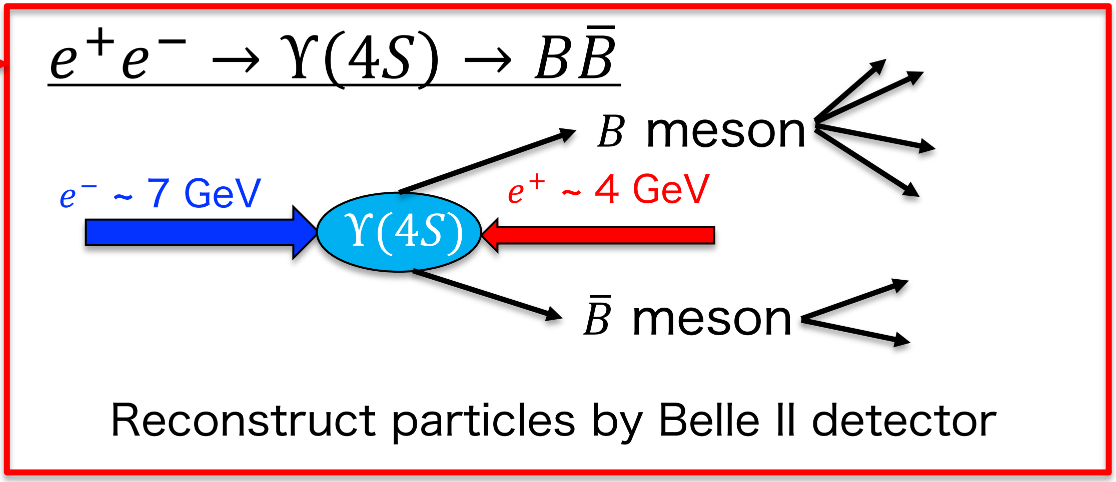
	Short Title	Luminosity	Journal
Belle	Leptophilic search, $ee \to \tau\tau\phi_L$	626 fb^{-1}	Submitted to PRL `arXiv:2207.07476`
	Search for LFV, $\tau \to \ell V_0$	980 fb^{-1}	`JHEP06(2023)118`
	Heavy neutrino search in tau decays	980 fb^{-1}	Submitted to PRL `arXiv:2212.10095`
	Michel parameter measurement in $\tau \to \mu\nu\nu$	980 fb^{-1}	`Phys.Rev.Lett.131,021801`
	Search for τEDM	833 fb^{-1}	`JHEP04(2022)110`
Belle II	τ-lepton mass measurement	190 fb^{-1}	`Phys.Rev.D108,032006`
	Search for LFV, $\tau \to \ell\alpha$	62.8 fb^{-1}	`Phys.Rev.Lett.130,181803`
	Search for LFV, $\tau \to \ell\phi$	190 fb^{-1}	Conference Paper (`arXiv:2305.04759`)

Belle II experiment

Flavor physics experiment to search for new physics

- Asymmetric e^+e^- collider mainly at $\sqrt{s} = 10.58$ GeV
  - Produce B, D, τ, etc..
- Goal: 50 ab^{-1} data in ~10 years
  - 50 × Belle data: $N_{B\bar{B}} \sim 50{\times}10^9$





$$\underline{e^+e^- \to \Upsilon(4S) \to B\bar{B}}$$

B meson

e^- ~ 7 GeV

$\Upsilon(4S)$

e^+ ~ 4 GeV

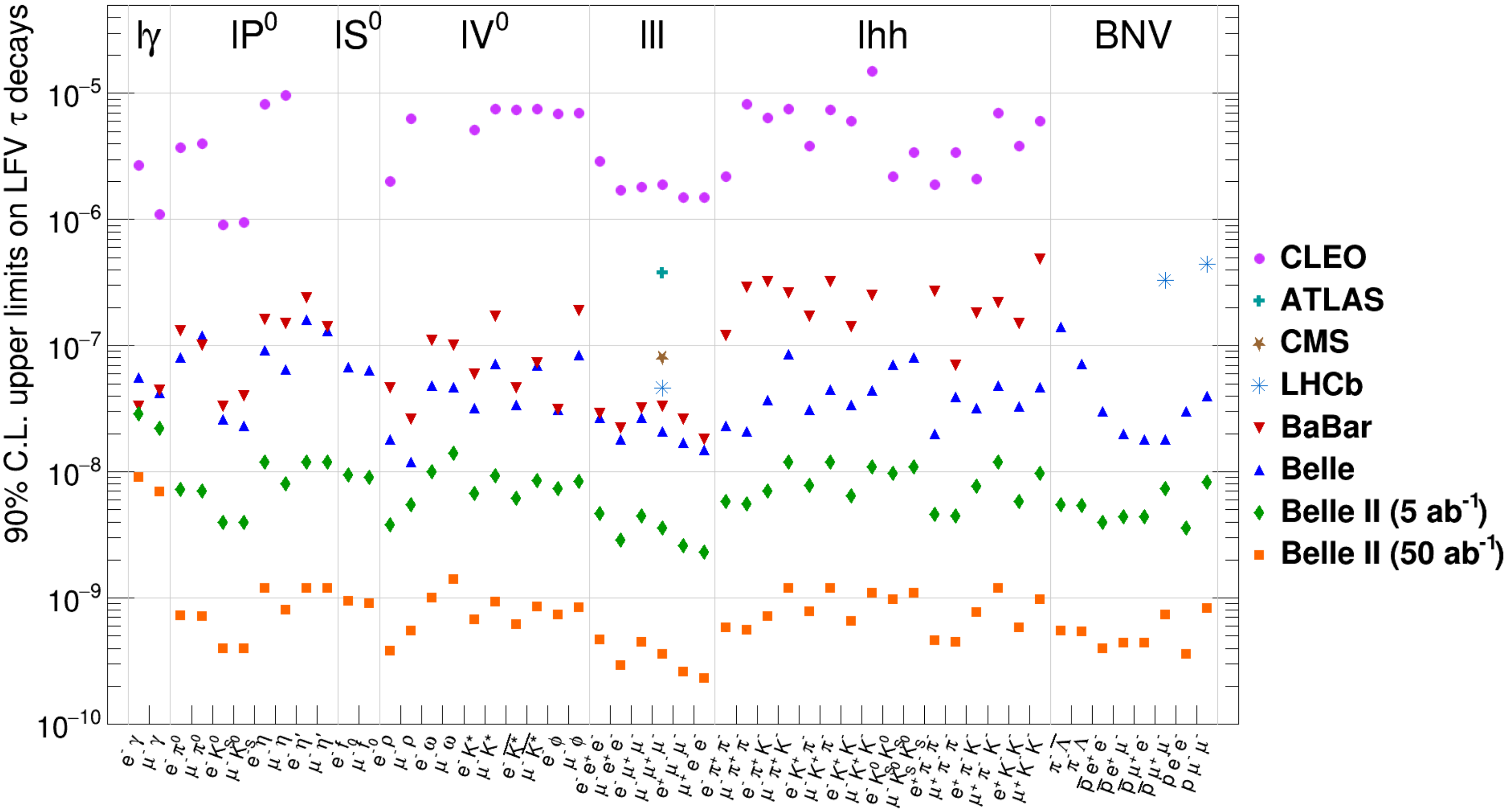
$\bar{B}$ meson

Reconstruct particles by Belle II detector

Belle II operation started in 2019

Summary of LFV in tau decay

[arXiv.2203.14919](https://arxiv.org/abs/2203.14919)

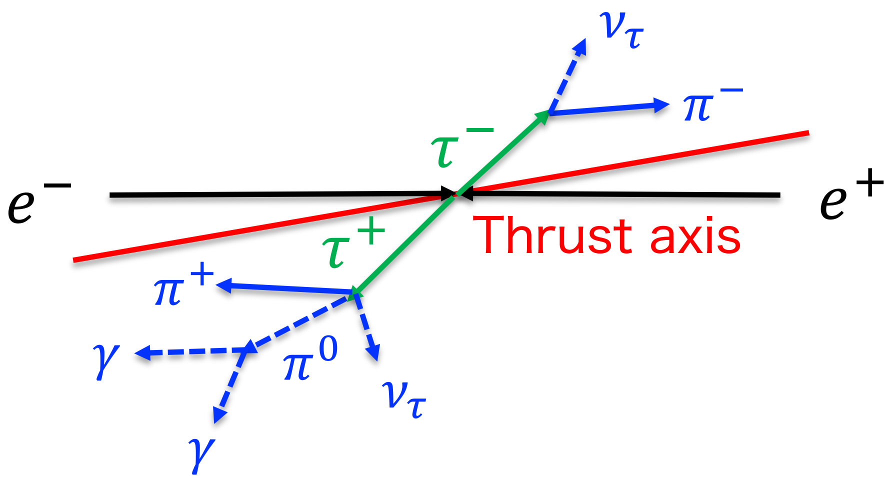


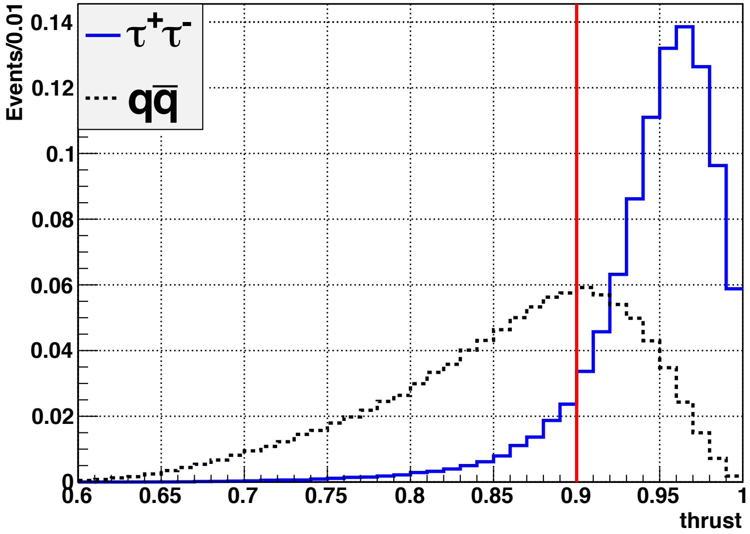
Thrust

- $\boldsymbol{V_{\mathrm{th}}}$ is the magnitude of thrust in the event. The thrust axis, $\hat{n}_{\mathrm{th}}$, is defined so that the value V_{th},

$$V_{\mathrm{th}} = \sum \frac{|\vec{p}_i^{\,\mathrm{CM}} \cdot \hat{n}_{\mathrm{th}}|}{\sum \vec{p}_i^{\,\mathrm{CM}}} \tag{4.3}$$

is maximized. Here, $\vec{p}_i^{\,\mathrm{CM}}$ is the three-momentum of each particle in the CM frame.





$\tau \to \ell V^0$: Belle

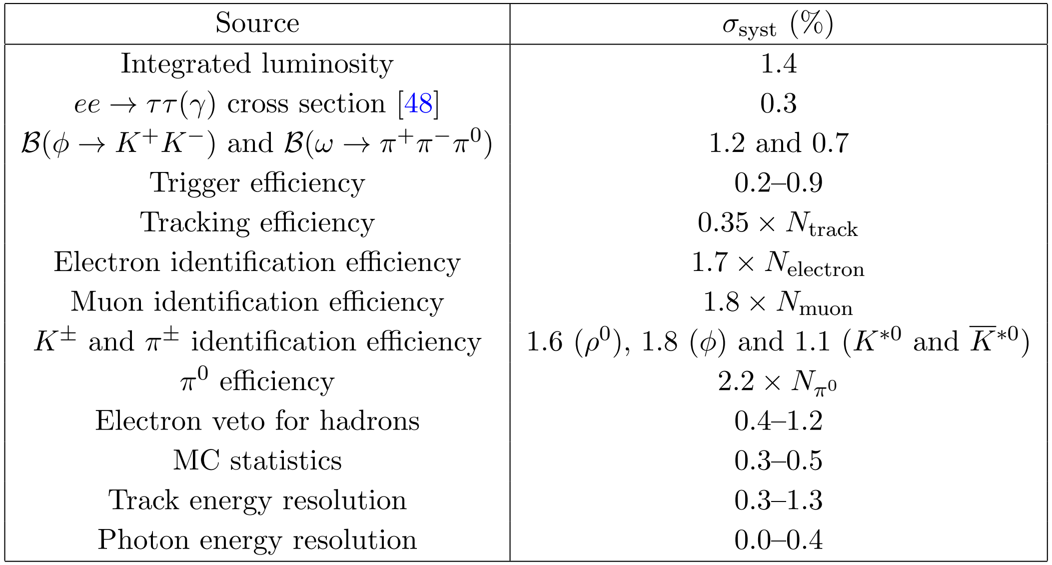
V^0 meson reco.

V^0 meson	ρ^0	ϕ	ω	$K^{*0}(\overline{K}^{*0})$
Decay particles	$\pi^+\pi^-$	K^+K^-	$\pi^+\pi^-\pi^0$	$K^\pm\pi^\mp$
Mass window [GeV/c²]	0.445 – 1.08	1.00 – 1.04	0.7 – 0.9	0.7 – 1.1

BDT: LightGBM library

- M_{V^0}, M_ν^2, $P_\nu^{\mathrm{c.m.}}$, T, P_ℓ^{sig}, $E_{\mathrm{tag}}^{\mathrm{hemi}}$, $\cos\theta_{\mathrm{miss-tag}}^{\mathrm{c.m.}}$
- (categorical variables) τ_{tag} decay mode, collision energy
- (additional for the $\ell\omega$ modes) $P_{\pi^0}^{\mathrm{sig}}$, E_γ^{low},

Systematic uncertainties

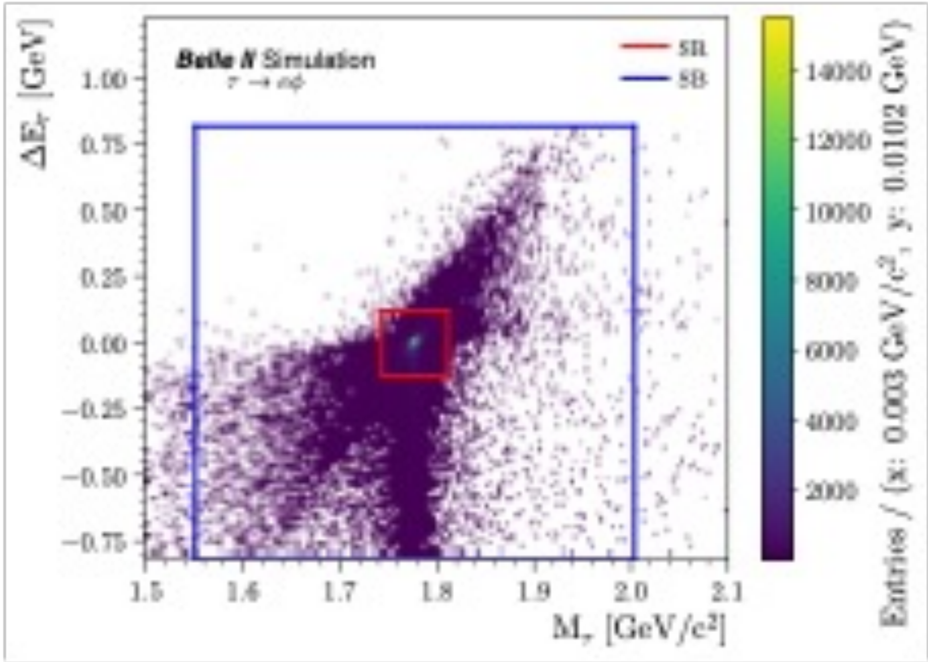


Source	σ_{syst} (%)
Integrated luminosity	1.4
$ee \to \tau\tau(\gamma)$ cross section [48]	0.3
$\mathcal{B}(\phi \to K^+K^-)$ and $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$	1.2 and 0.7
Trigger efficiency	0.2–0.9
Tracking efficiency	$0.35 \times N_{\mathrm{track}}$
Electron identification efficiency	$1.7 \times N_{\mathrm{electron}}$
Muon identification efficiency	$1.8 \times N_{\mathrm{muon}}$
$K^\pm$ and $\pi^\pm$ identification efficiency	1.6 (ρ^0), 1.8 (ϕ) and 1.1 (K^{*0} and $\overline{K}^{*0}$)
π^0 efficiency	$2.2 \times N_{\pi^0}$
Electron veto for hadrons	0.4–1.2
MC statistics	0.3–0.5
Track energy resolution	0.3–1.3
Photon energy resolution	0.0–0.4

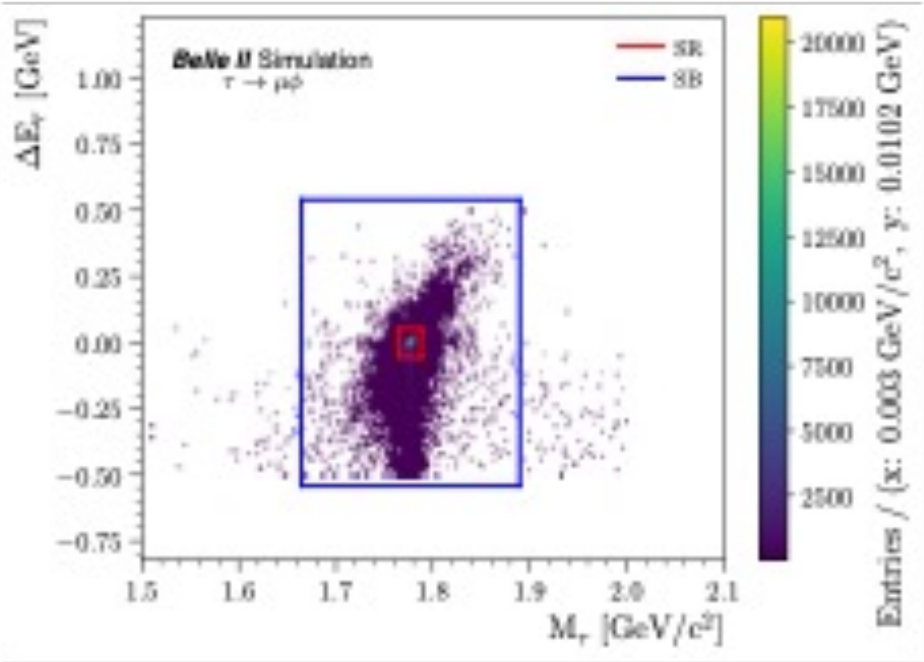
$\tau \to \ell V^0$: Belle II

Signal: $\tau \to \ell\phi(\to KK)$

- $1.014 < m_{KK} < 1.024$ GeV/c²



Bkg: $ee \to q\bar{q}, \tau \to 3\pi\nu$



BDT: XGBoost library

- Event-shape
- Kinematic properties of τ_{sig}, ϕ
- Variables related to the ROE

Affected quantity	Source	Mode	
		$e\phi$	$\mu\phi$
$\varepsilon_{\ell\phi}$	Particle identification	0.8%	0.3%
	Tracking efficiency	0.9%	
	Trigger efficiency	0.4%	0.9%
	Signal variable mismodeling	15.2%	8.5%
N_{exp}	Momentum scale	0.6%	0.4%
L	Luminosity	0.6%	
$\sigma_{\tau\tau}$	Tau-pair cross section	0.3%	

Heavy neutrino

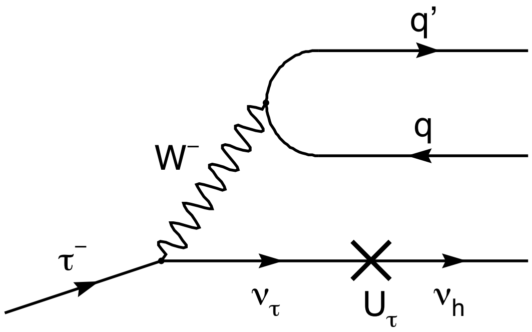
Right handed neutrino (eg. Heavy Neutral Lepton, HNL)

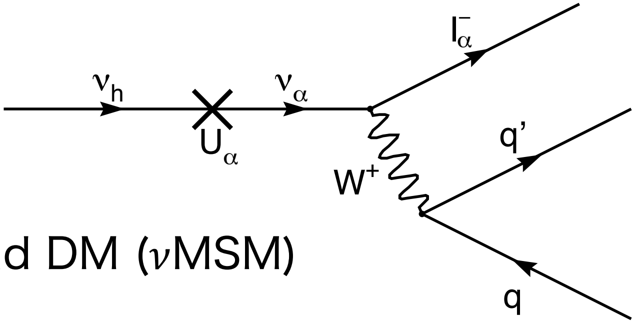
- No strong interaction (it is lepton)
- No weak interaction (it is right-handed)
- No electromagnetic interaction (it is neutral)

→ The only way to interact is to mix with left-handed neutrino:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i, \quad \alpha = e, \mu, \tau, ..., i = 1, 2, 3, 4, ...$$

α: flavor eigenstates, i: mass eigenstates





May also contribute to explanation of baryogenesis and DM (νMSM)

#neutrinos in this method

Particle with a mass m and width Γ has a momentum p, the probability that it travels distance ℓ or greater is

$$P(l) = \exp\left(-\frac{m\Gamma l}{p}\right), \quad \Longrightarrow \quad dP(l) = \frac{m\Gamma}{p}\exp\left(-\frac{m\Gamma l}{p}\right)dl.$$

Estimate $c\tau \sim |U|^{-2} m(\nu_h)^{-5}$

The number of neutrinos detected in the Belle detector is

$$\begin{aligned} n(\nu_h) &= \underline{N_0} \int \varepsilon(m,l)dP(l) \\ &= \underline{2N_{\tau\tau}\ \mathcal{B}(\tau \to \pi\nu_h)\ \mathcal{B}(\nu_h \to \pi\ell)}\ \frac{m\Gamma}{p}\int \exp\left(-\frac{m\Gamma l}{p}\right)\varepsilon(m,l)dl \\ &= |U_\tau|^2 |U_\ell|^2\ 2N_{\tau\tau}\ f_1(m)\ f_2(m)\ \frac{m}{p}\int \exp\left(-\frac{m\Gamma l}{p}\right)\varepsilon(m,l)dl, \end{aligned}$$

$|U_\tau|^2, |U_\ell|^2$coupling come from $B(\tau \to \pi\nu_h), B(\nu_h \to \pi\ell)\Gamma$

To factor out the $|U_\ell|^2$ dependence, we define functions $f_{1,2}(m)$ as

$|U_\tau|^2 f_1(m) = B(\tau \to \pi\nu_h)$ and $|U_\ell|^2 f_2(m) = \Gamma(\nu_h \to \pi\ell) = \Gamma B(\tau \to \pi\nu_h)$

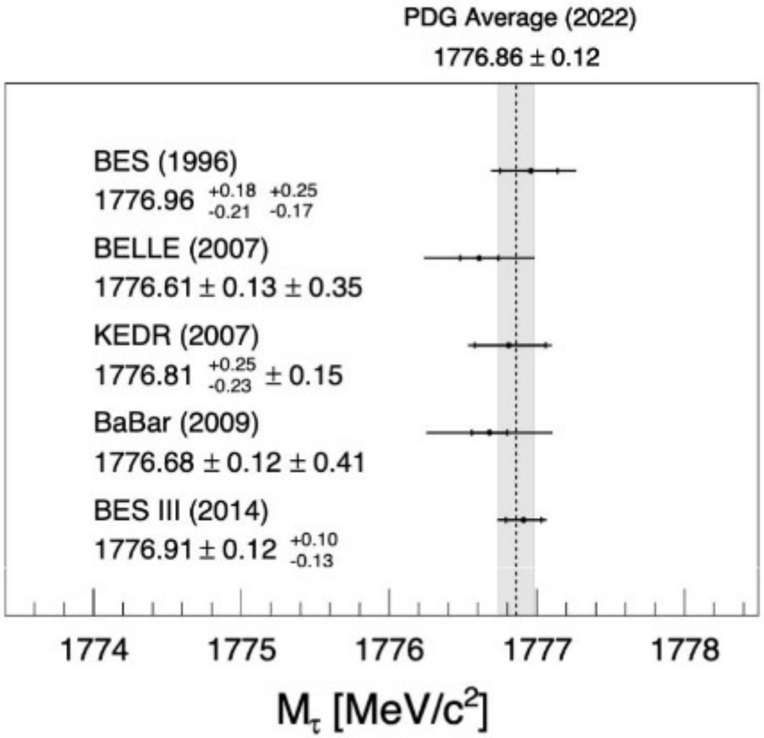
Relative mixing coefficients are different b.t.w normal and inverted hierarchy

$x_\alpha = |U_\alpha|^2/|U|^2\ (\alpha = e, \mu, \tau)$ → $x_e = 0.06, x_\mu = 0.48, x_\tau = 0.46$ from oscillation data

τ mass measurement

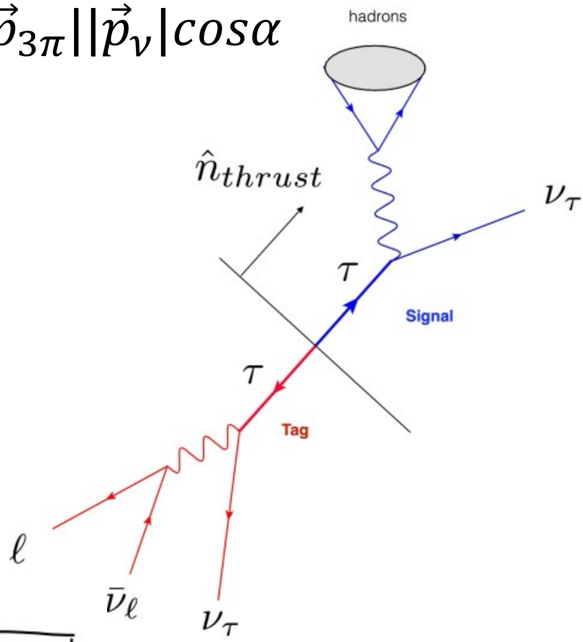
Two possible methods to measure the mass

- Pair-production cross section scan used by BESIII
  - Analyze the $ee \to \tau\tau$ cross-section near the $\tau\tau$ production threshold
- Pseudomass method at Belle, BaBar
  - Exploit the kinematics of the three pions in $\tau \to 3\pi\nu$ decays



τ mass: Psudomass method

Reconstruct $\tau_{\text{sig}} \to 3\pi\nu$ and $\tau_{\text{tag}} \to \ell\nu\nu$



- $m_\tau^2 = (p_{3\pi} + p_\nu)^2 = m_{3\pi}^2 + m_\nu^2 + 2E_{3\pi}(E_\tau - E_{3\pi}) - 2|\vec{p}_{3\pi}||\vec{p}_\nu|cos\alpha$
- $\quad = m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|cos\alpha)$
- $m_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \le m_\tau$

Fit to the end point with an empirical function

- Smeared edge due to detector resolution/ISR