Hot topic at Belle and Belle II: τ physics

Jim Libby on behalf of Belle and Belle II

Indian Institute of Technology Madras

Outline

1. Not the only hot topic
    - a trailer for other Belle and Belle II talks
2. Why τ physics? Why Belle and Belle II?
3. Recent results
    1. Beyond-the-standard-model physics: lepton-flavour violation
    2. Precision measurement: τ mass
4. More to come: a further trailer

1) Belle (II)@HQL

Seven other talks with physics results – hot topics for all!

1. Wed. 12:10: **LFU tests and searches for new physics in charged current decays at Belle II** – Henrik Junkerkalefeld
2. Wed, 15:00: **Recent spectroscopy results from Belle II** – Renu Garg
3. Wed. 17:20: **New LFV results from e^+e^- colliders** – Devendar Kumar
4. Fri. 10:10: **Rare decays from Belle and Belle II** - Seema Choudhuri
5. Fri. 12:00: **Time-dependent *CP* violation in B^0 decay** - Seema Bahinipati
6. Sat. 09:30: **Search for $B \to K\nu\nu$ decay** – Roberta Volpe
7. Sat. 10.35: ***CP* violation in charmless B decays** – Luka Santlej

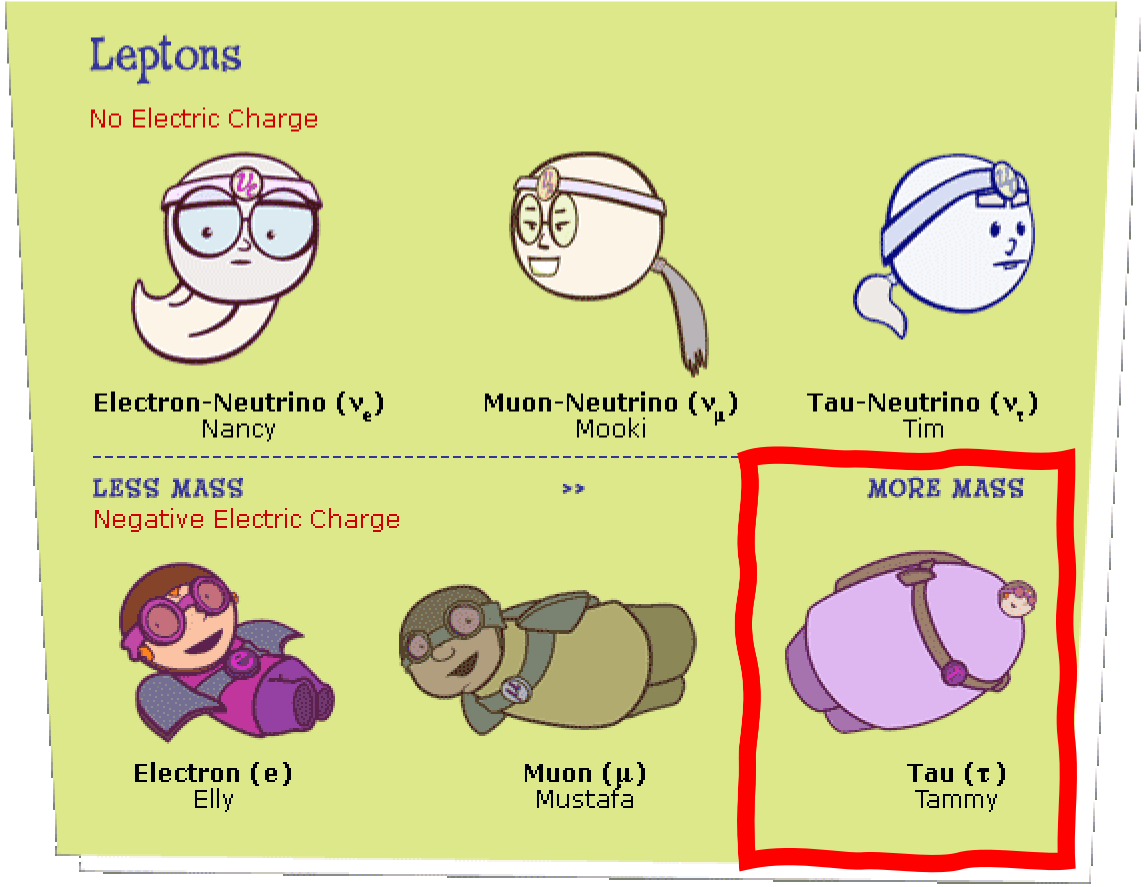
1) Belle (II)@HQL

Seven other talks with physics results – hot topics for all!

1. Wed. 12:10: **LFU tests and searches for new ph… …arged current decays at Belle II** – Henrik Junkerkalefeld…
2. Wed, 15:00: **Recent spectrosc… …om Belle II** – Renu Garg
3. Wed. 17:20: **New LFV… … e^+e^- colliders** – Devendar Kumar
4. Fri. 10:10: **R… …om Belle and Belle II** - Seema Choudhuri
5. Fri. … **…-dependent *CP* violation in B^0 decay** - Seema Bahinipati
6. …:30: **Search for $B \rightarrow K\nu\nu$ decay** – Roberta Volpe
7. Sat. 10.35: ***CP* violation in charmless B decays** – Luka Santlej

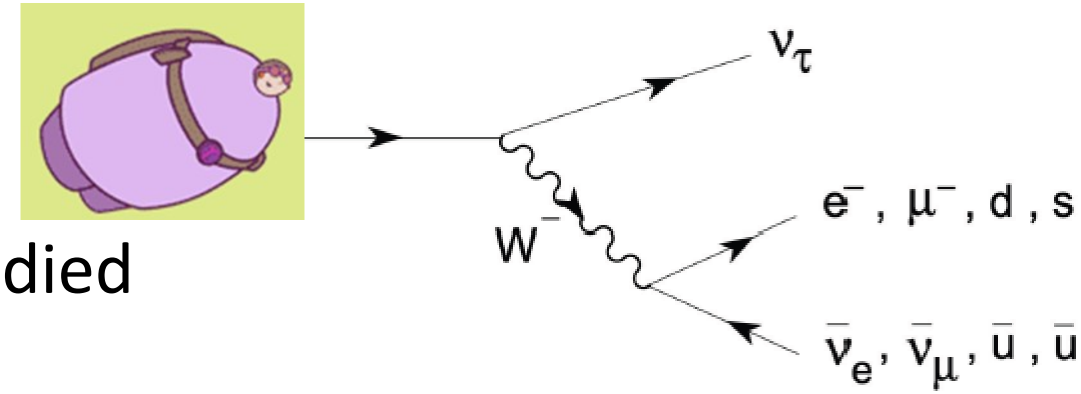
But all heavy quarks.....what about the heavy leptons?

https://www.quarked.org/



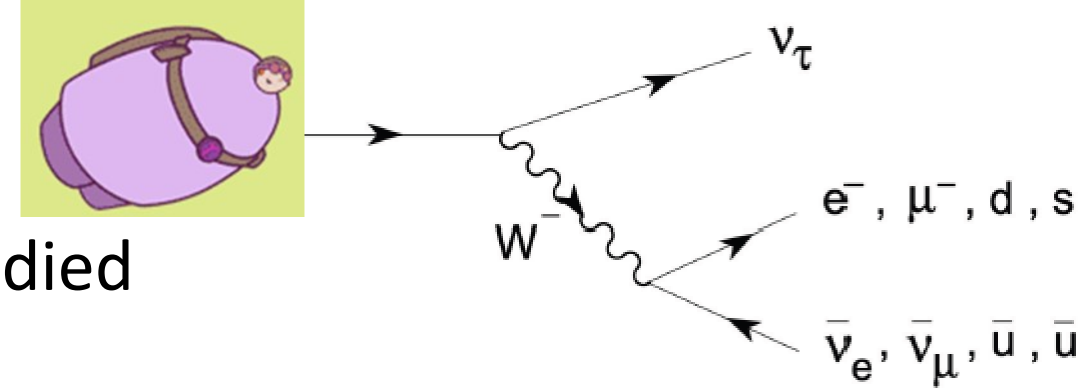
2) Why τ? Why Belle (II)?

Tau physics motivation I

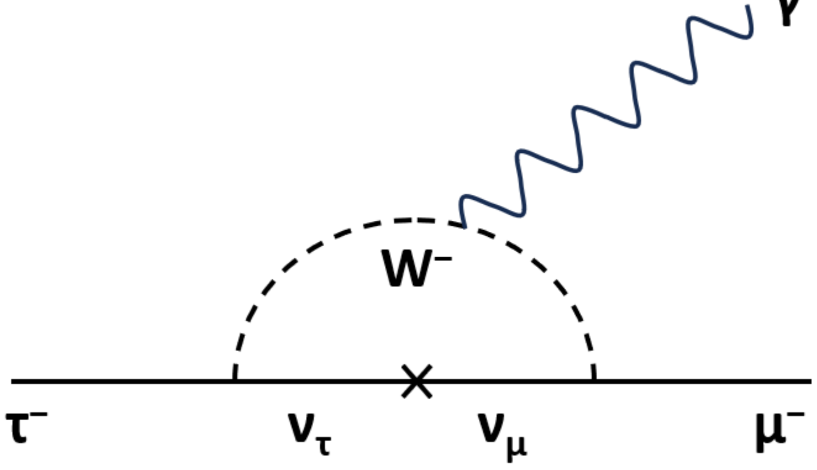


- 185 standard model decay modes studied
  - **principally hadronic final states**
- Unique laboratory to study weak interaction

Tau physics motivation I



- 185 standard model decay modes studied
  - **principally hadronic final states**
- Unique laboratory to study weak interaction
- Third-generation therefore beyond-SM-sensitivity anticipated
  - Any observation of lepton-flavour violation in $\tau \to 3\mu$, $\tau \to \mu\gamma$, $\tau \to l\phi$ etc **new physics**
  - SM highly suppressed
- Connections to g-2 and lepton universality violation in b decay



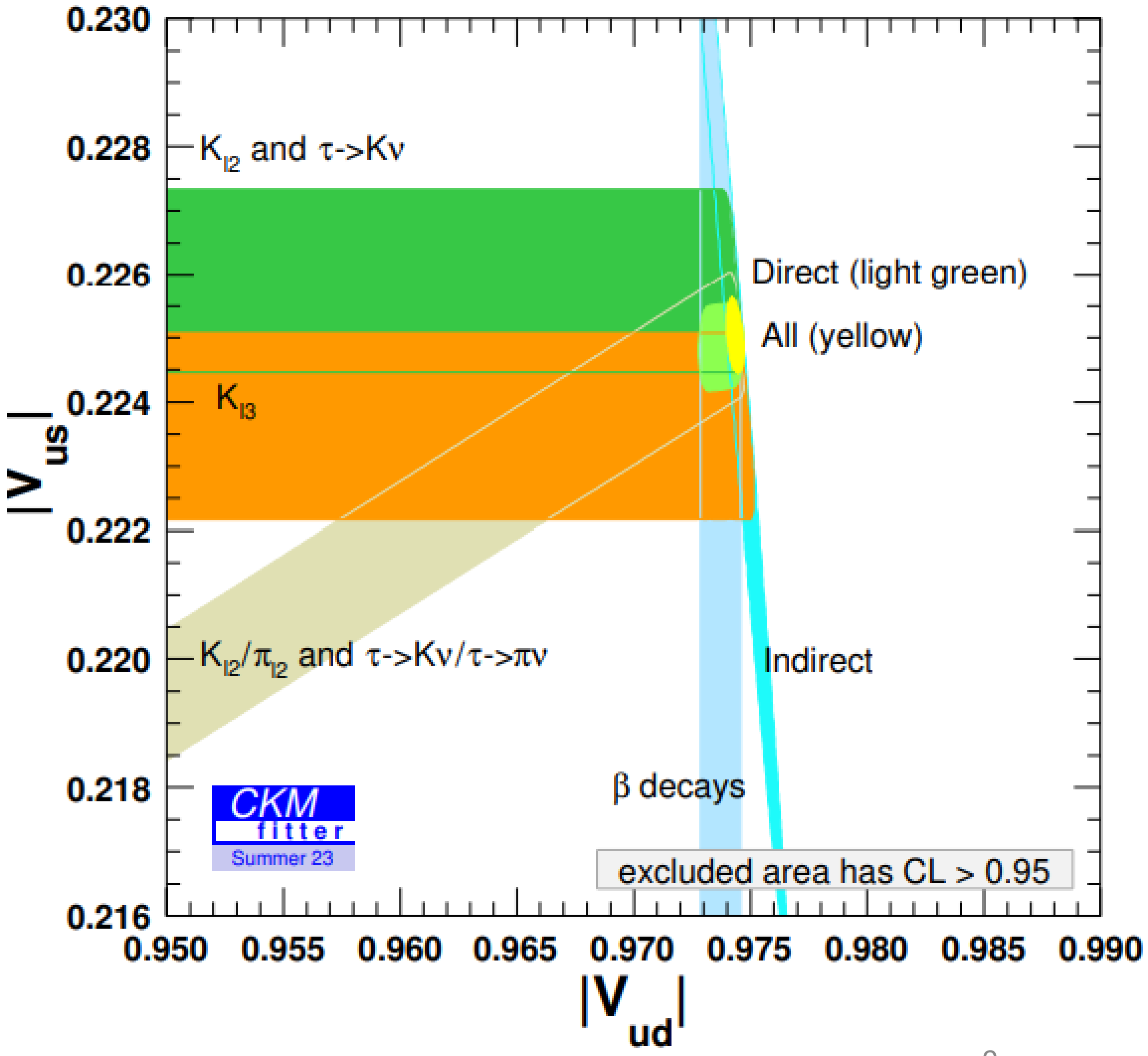
Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact

Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact
- Example:
  - first row unitarity of CKM matrix – 'Cabibbo angle anomaly'
  - B(τ→Kν)/B(τ→πν) proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint

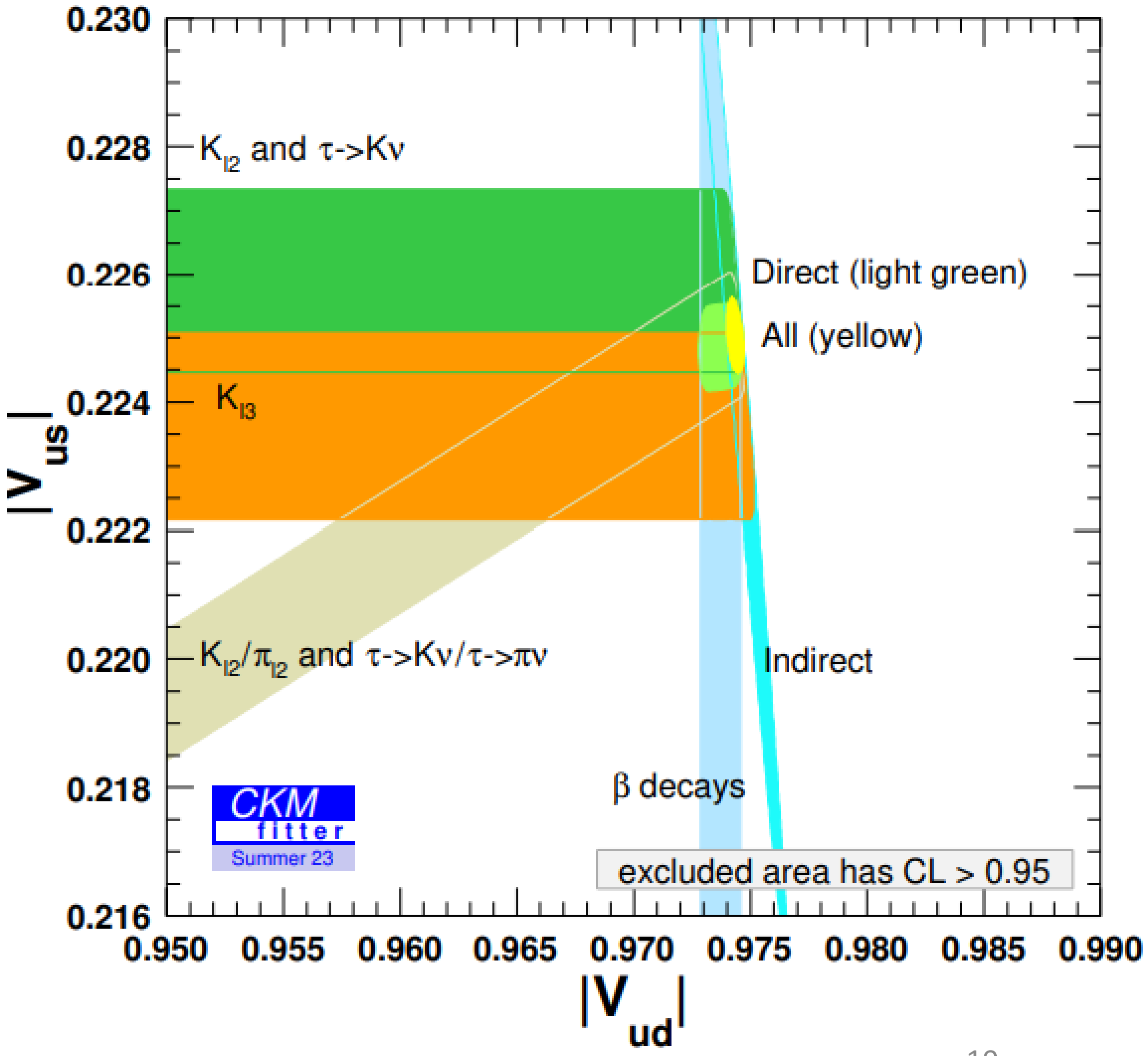
Luiz Vale Silva (CKM 2023)



Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact
- Example:
  - first row unitarity of CKM matrix – ‘Cabibbo angle anomaly’
  - $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint
- Additionally, lepton-flavour universality and dipole moments
- **Mass** and lifetime important inputs to these calculations

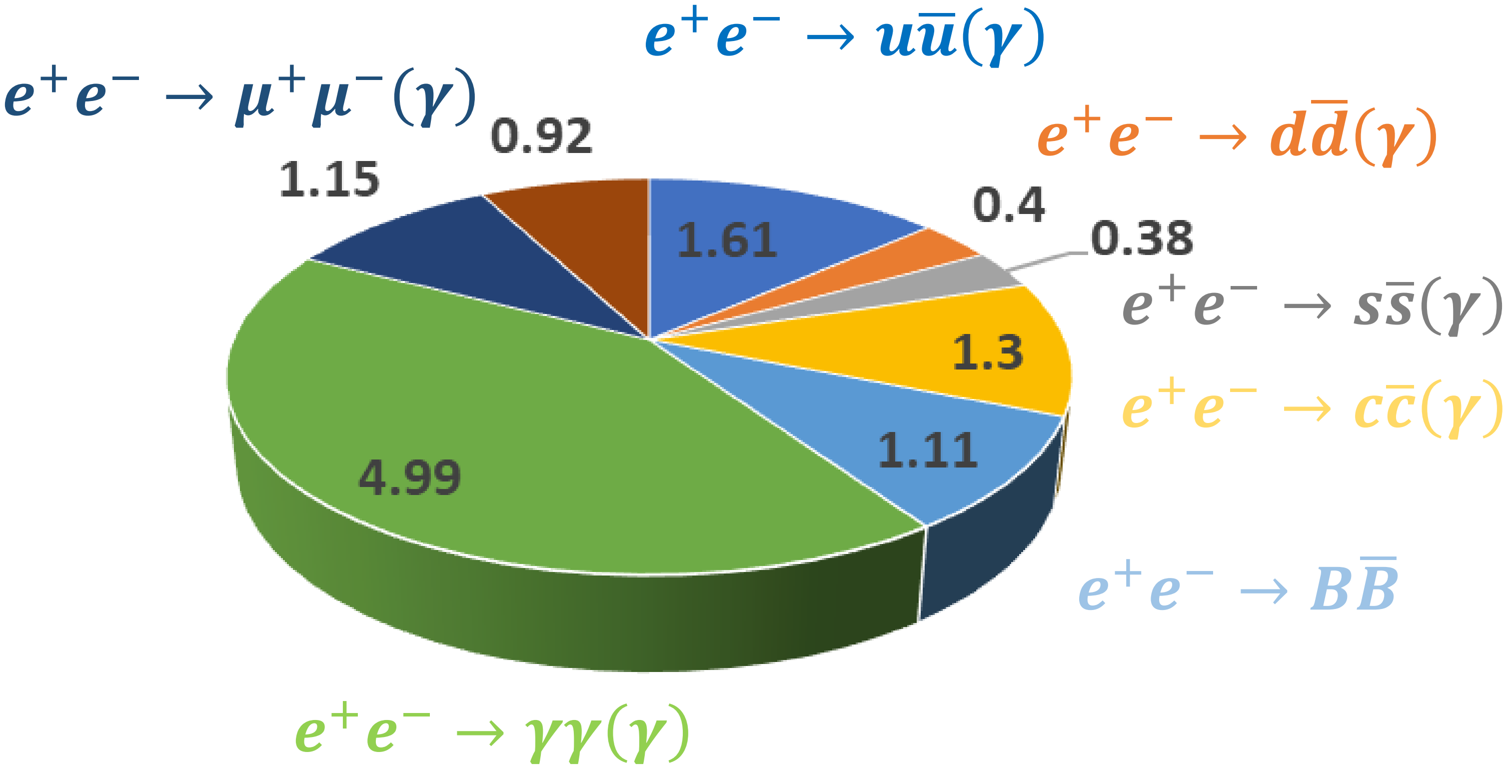
Luiz Vale Silva (CKM 2023)



Why τ physics at the Υ(4S)?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum

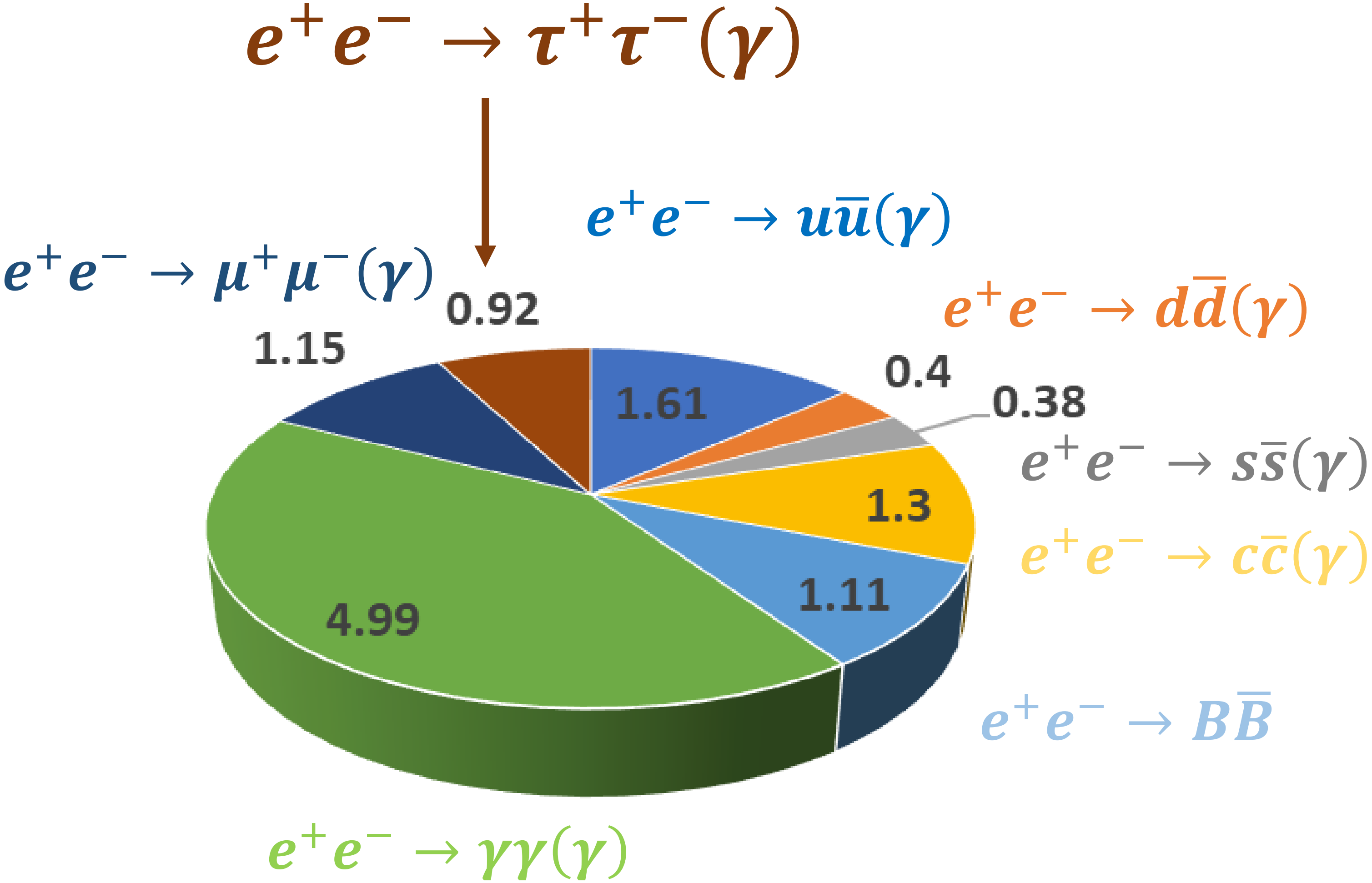
Non Bhabha cross section in nb



Why τ physics at the Υ(4S)?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum
- Similar cross section for $e^+e^- \to \tau^+\tau^-$
- 920 million tau pairs per ab^{-1} of integrated luminosity
- **A HQL-factory!**

Non Bhabha cross section in nb



Detectors and data samples

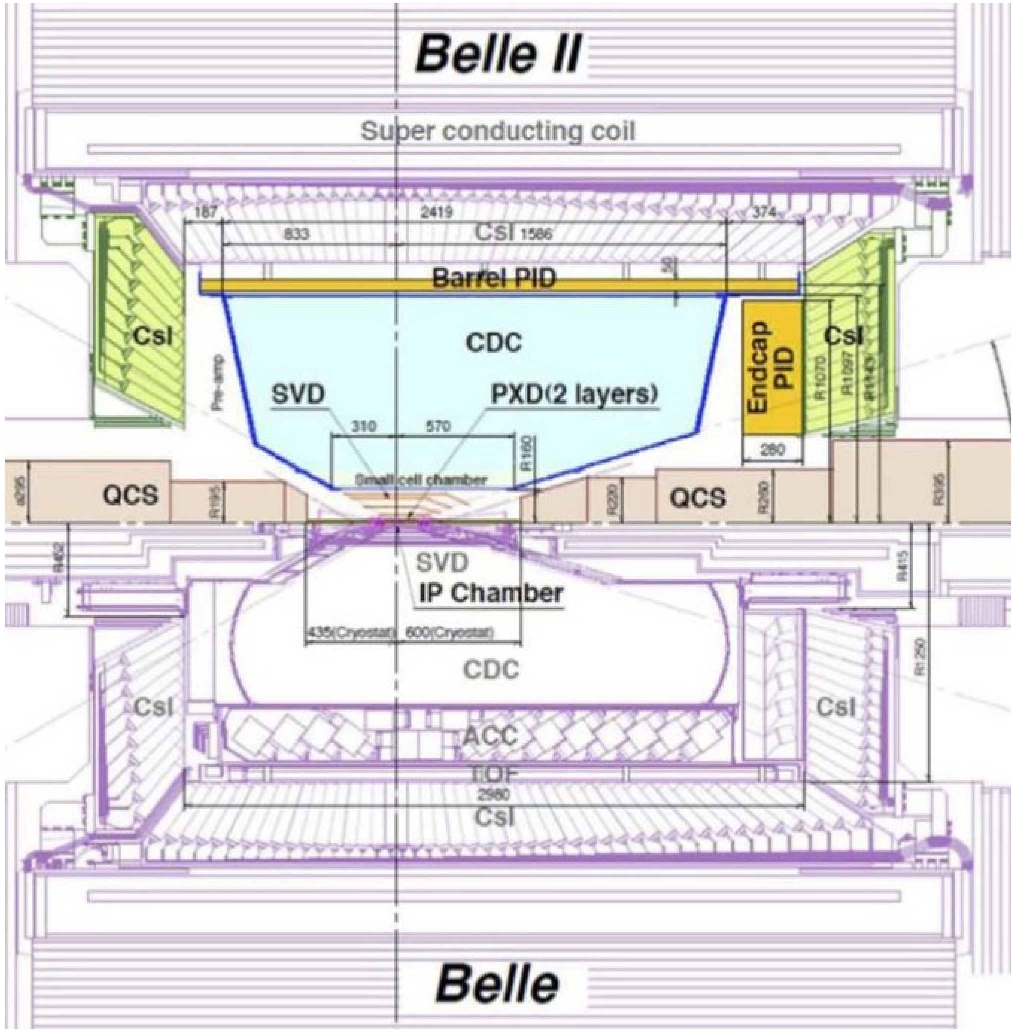
- Belle: ~1 ab^{-1}
  - Many achievements:
    confirmation of KM mechanism,
    $b \rightarrow c\tau\nu$, direct CPV in B decay

Detectors and data samples

- Belle: ~1 ab^{-1}
  - Many achievements:
    confirmation of KM mechanism,
    $b \to c\tau\nu$, direct CPV in B decay
- SuperKEKB + Belle II
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record 4.7×10^{34} $cm^{-2}s^{-1}$**
  - Target 6×10^{35} $cm^{-2}s^{-1}$
  - So far 424 fb^{-1}

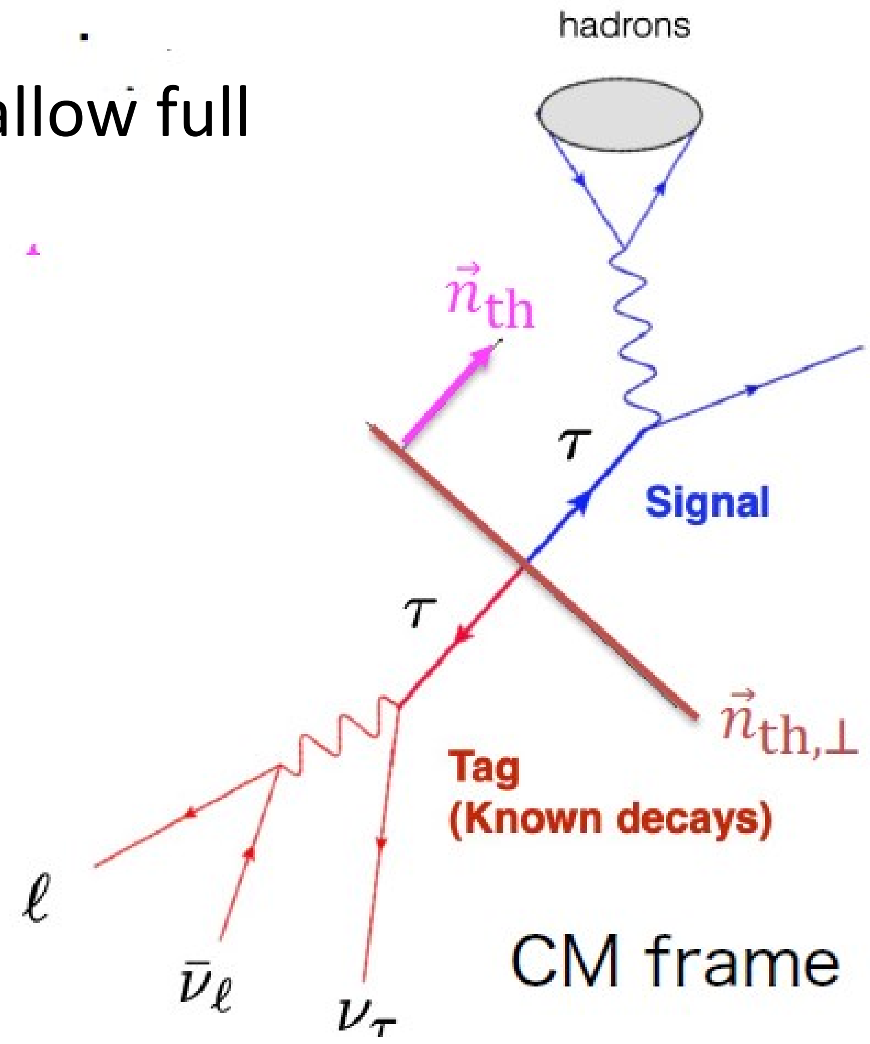
Detectors and data samples

- Belle: ~1 ab^{-1}
  - Many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decay
- SuperKEKB + Belle II
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record 4.7×10^{34} $cm^{-2}s^{-1}$**
  - Target 6×10^{35} $cm^{-2}s^{-1}$
  - So far 424 fb^{-1}

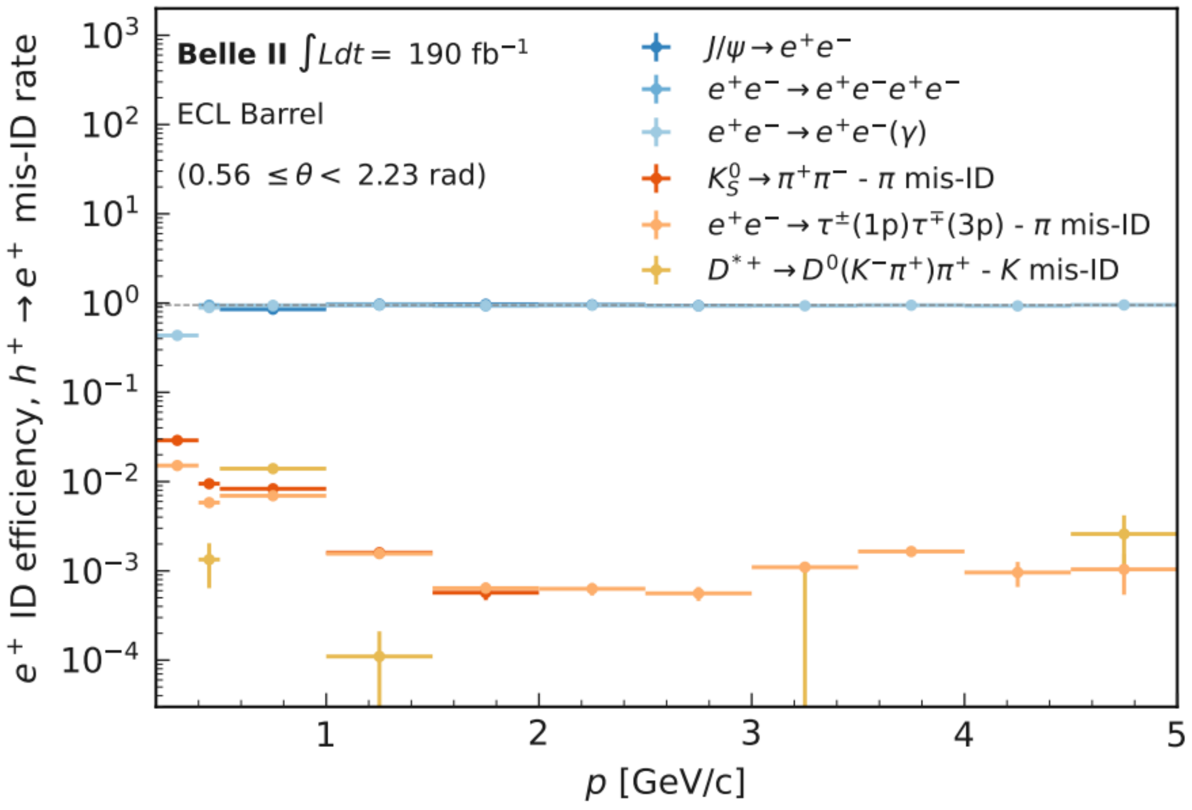


How to reconstruct a τ lepton at Belle (II)

- Missing energy from neutrinos does not allow full reconstruction
  - Identify using the thrust axis $\vec{n}_{\text{th}}$
    - maximizes the momentum projection
  - Divide event into two hemispheres
- Signal side
  - e.g. $\tau \to \nu$ + hadrons
- Tag side: a standard model decay
  - single prong: $\tau \to l\nu\nu$ or $\tau \to \pi\nu + n\pi^0$
  - three prong decay: $\tau \to 3\pi\nu + n\pi^0$

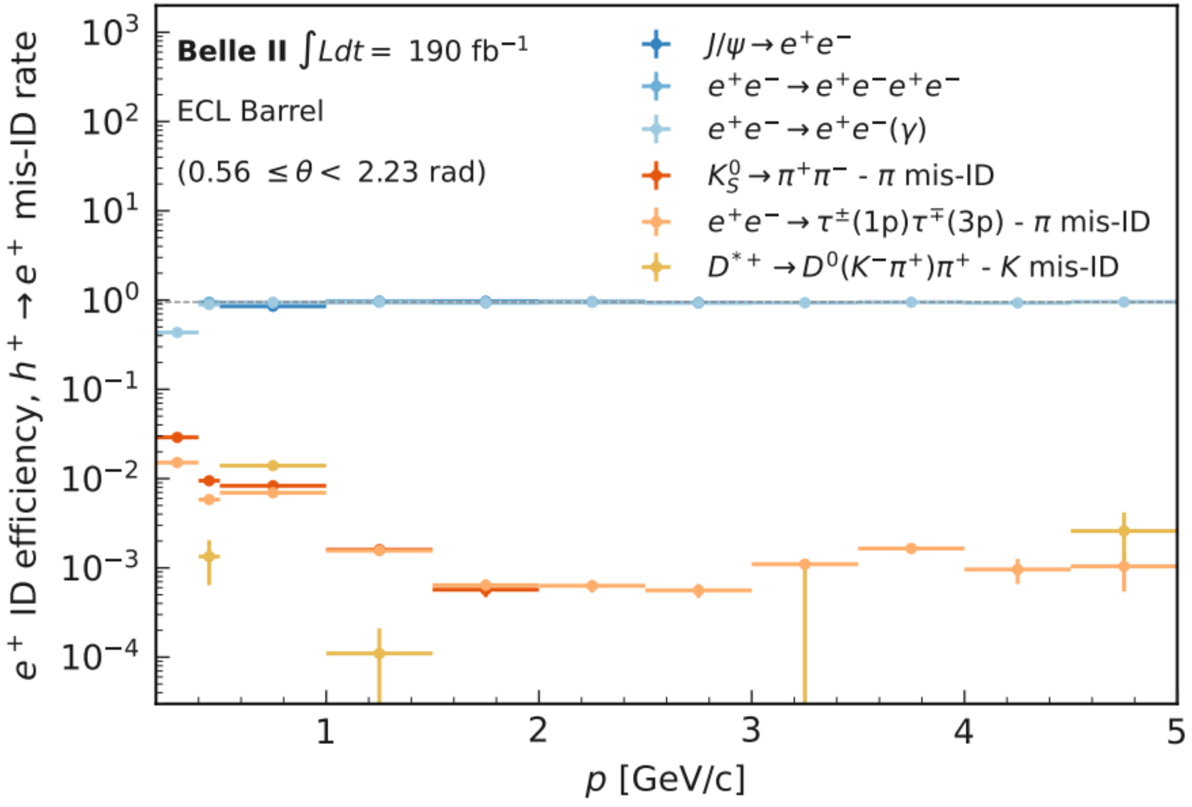


Performance for τ lepton physics

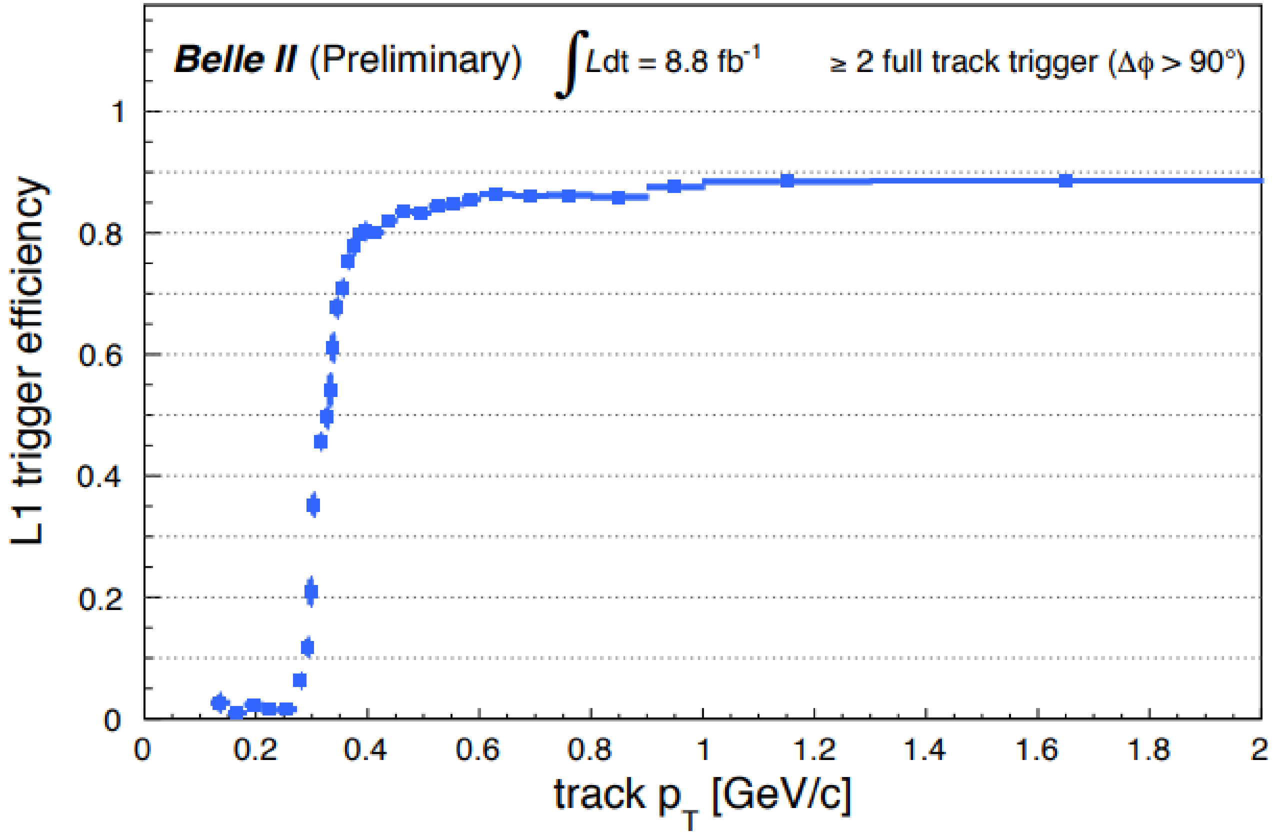


Electron ID: efficiency and mis-ID

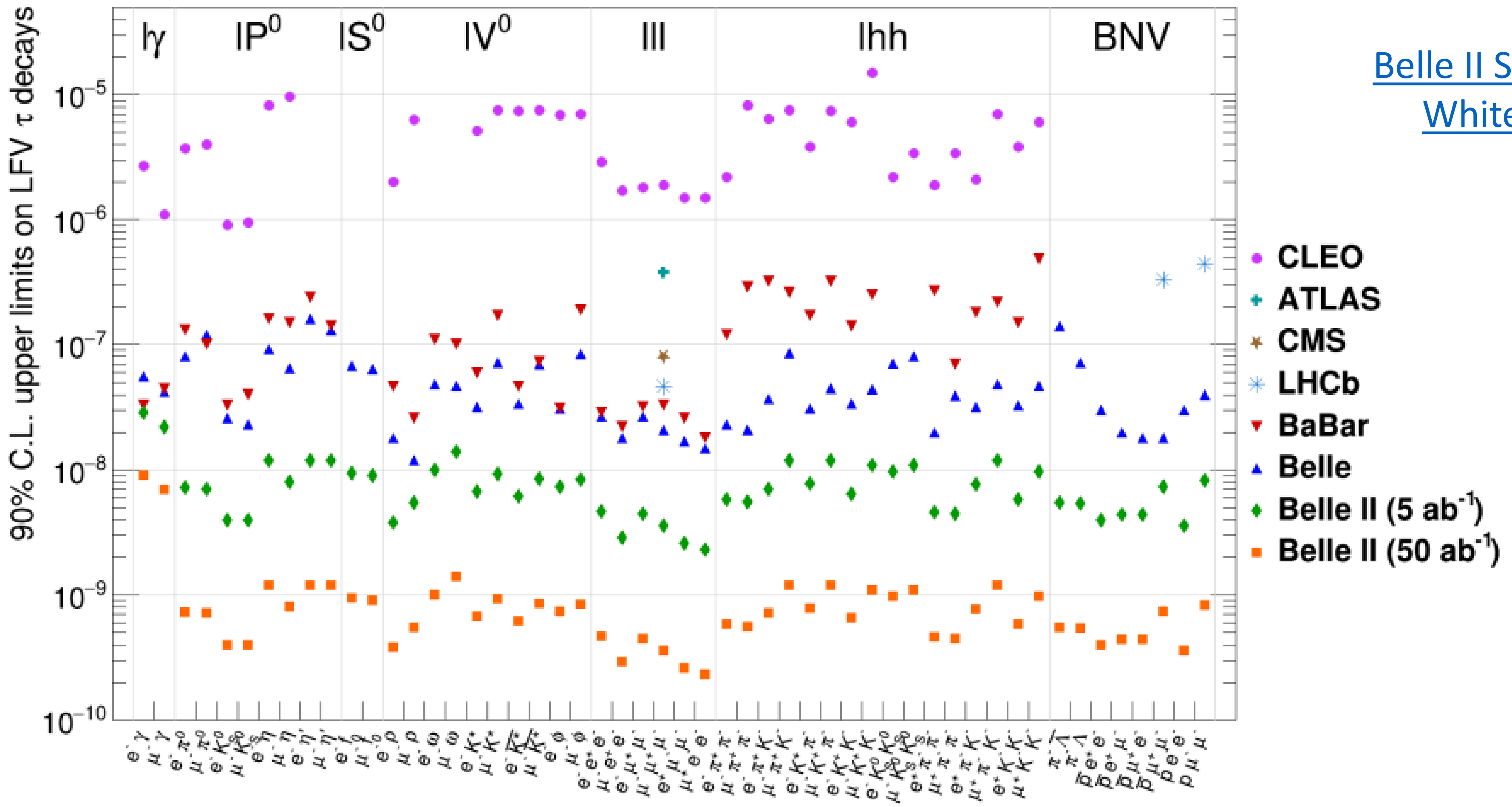
Performance for τ lepton physics



Electron ID: efficiency and mis-ID



L1: trigger for 1x1 tau pairs (min p_t)



[Belle II Snowmass White Paper]

3.1) Lepton-flavour violating searches

LFV: $\tau \to lV^0$ ($V^0=\rho, \omega, \phi, K^*$)

- Forbidden in SM but enhanced many leptoquark models, c.f., R(D(*))

- $V^0=\rho, \omega, \phi, K$
- Full data set of 980 fb^{-1}
- 3 and 1 prong tag: $3\pi\nu$, $l\nu\nu$, $\pi\nu$+up to $2\pi^0$
- Background suppression with BDT
- JHEP **06** (2023) 118

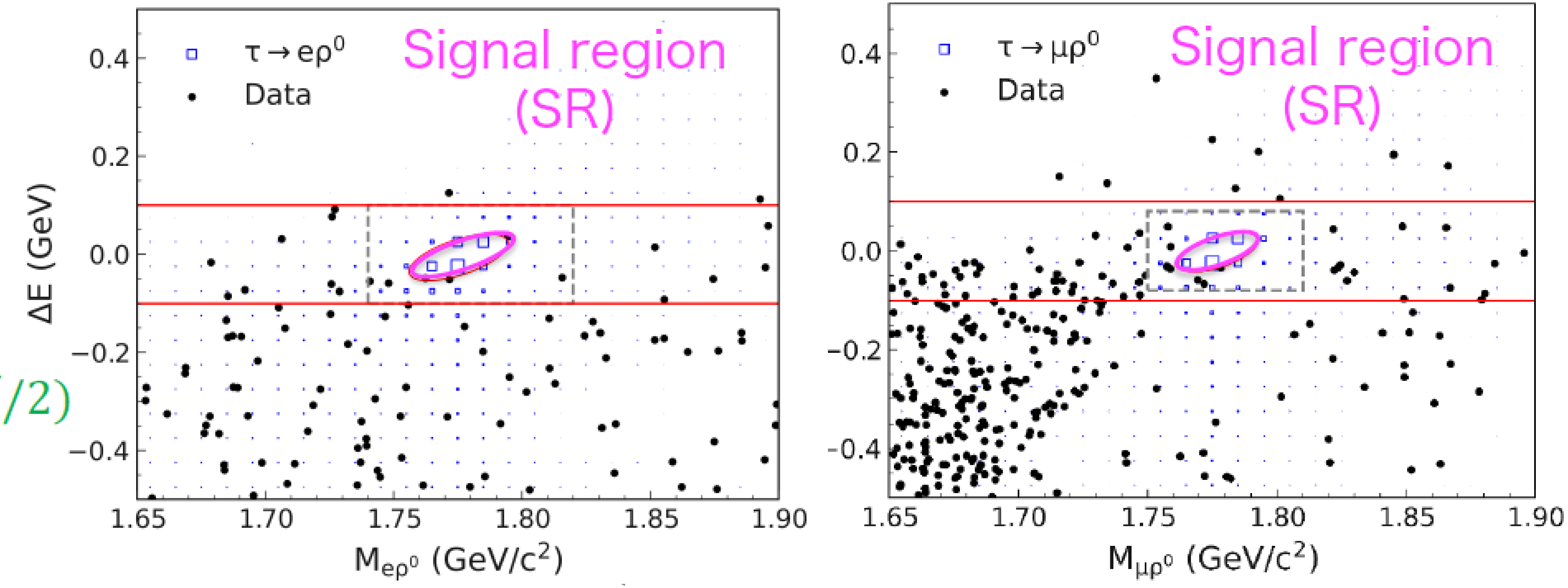
- $V^0= \phi$
- Data set of 190 fb^{-1}
- **Inclusive tag**
- Background suppression with BDT
- arXiv:2305.04759

High efficiency key for best sensitivity: multivariate selection and inclusive tagging

LFV: Belle $\tau \to lV^0$ ($V^0 = \rho, \omega, \phi, K^*$) approach

- Tagged with 1-prong or 3-prong decay
- Background from $\tau \to 3\pi\nu$ and $ee \to qq$ suppressed with a boosted decision tree (BDT)
- Prepared separate BDT classifier for each lV^0 mode

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



LFV: Belle $\tau \to lV^0$ ($V^0 = \rho, \omega, \phi, K^*$) results

No significant excess in all ℓV^0 modes

World leading results

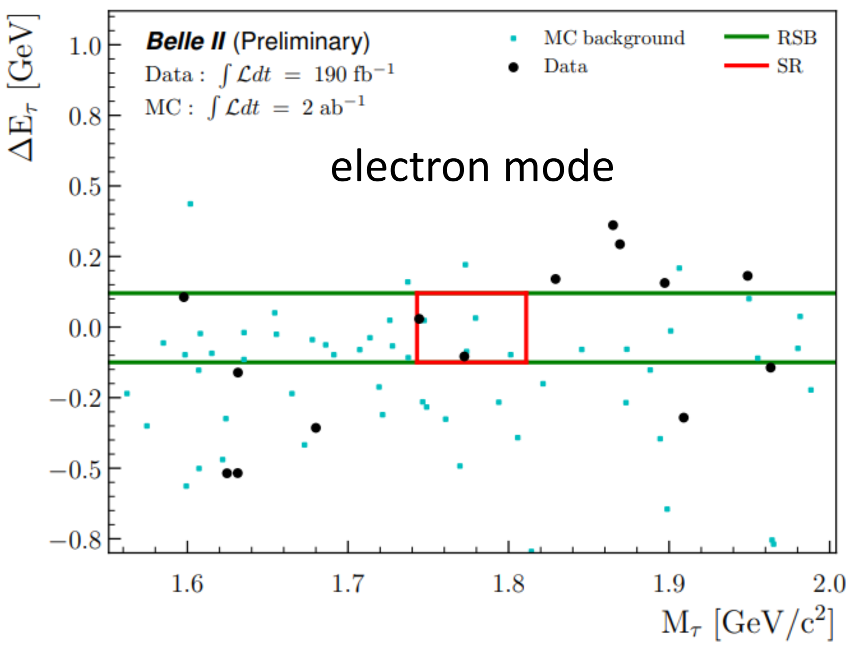
Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±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 *

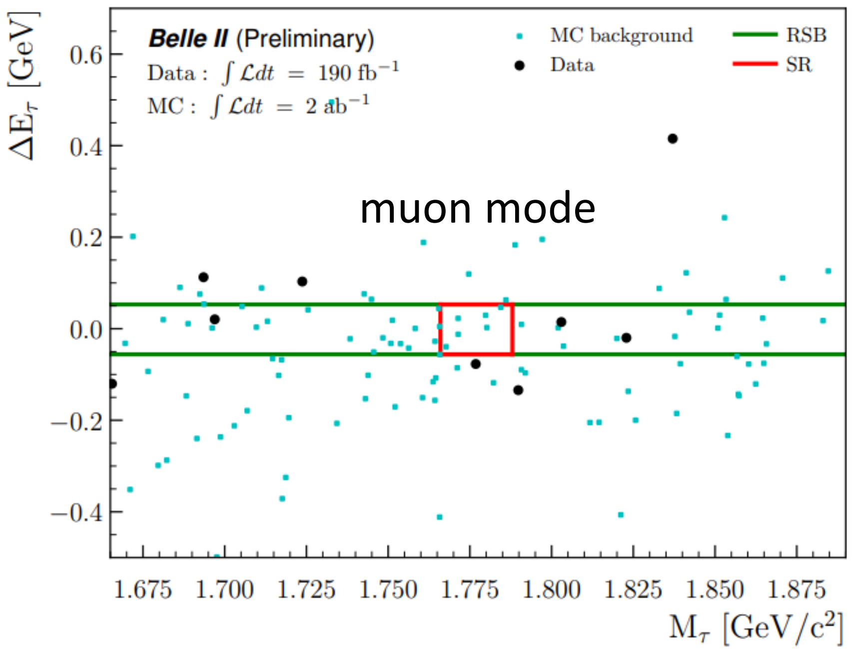
Counting method 90% confidence levels

30% improvement over previous measurements

LFV: Belle II τ→lϕ approach

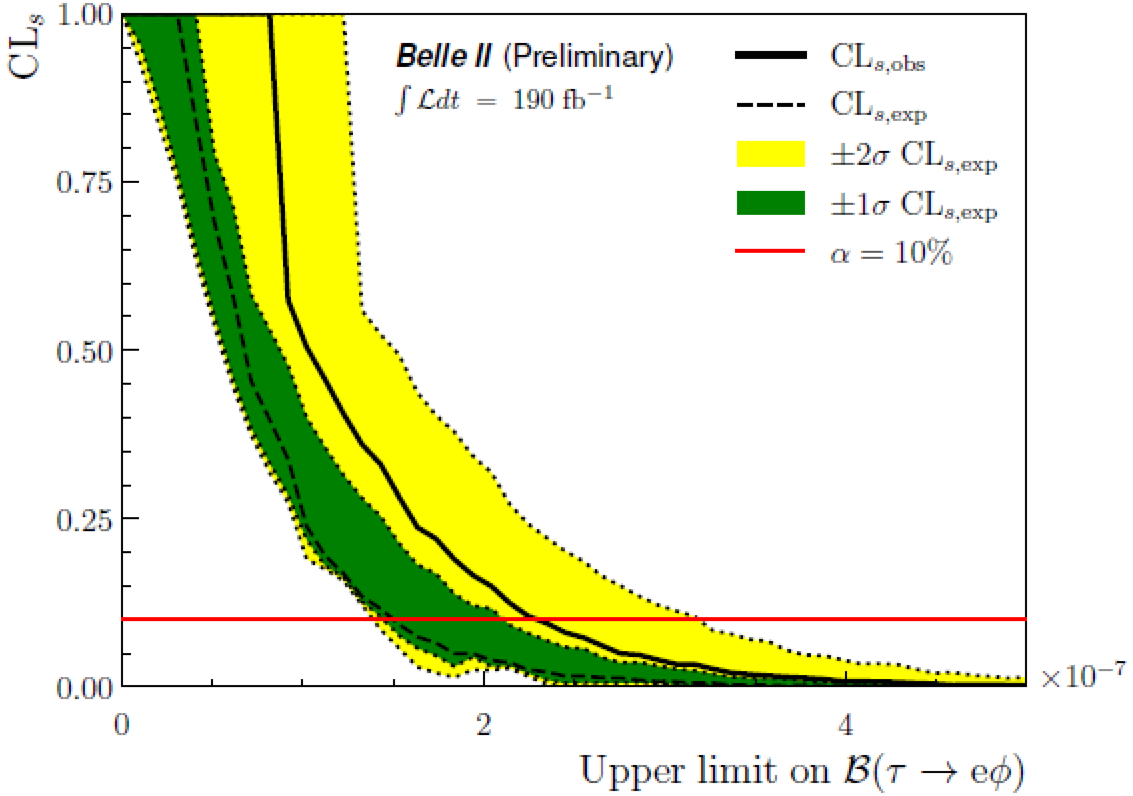
- Untagged: train BDT inclusively to discriminate from background
  - event shape variables, signal kinematics, ϕ mass and rest-of-the-event, i.e., tracks and clusters not used to reconstruct signal
  - 6% efficiency – twice Belle

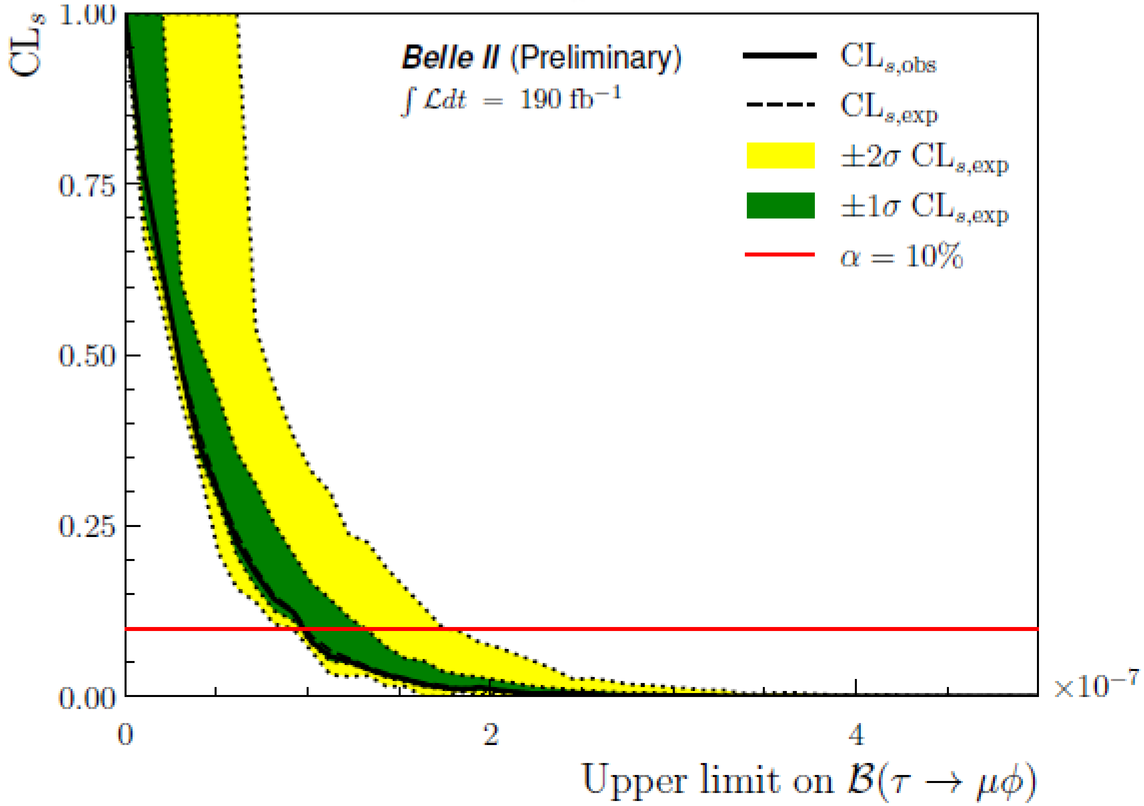




LFV: Belle II τ→lϕ results

Not competitive with the Belle results
But first application of the inclusive tag



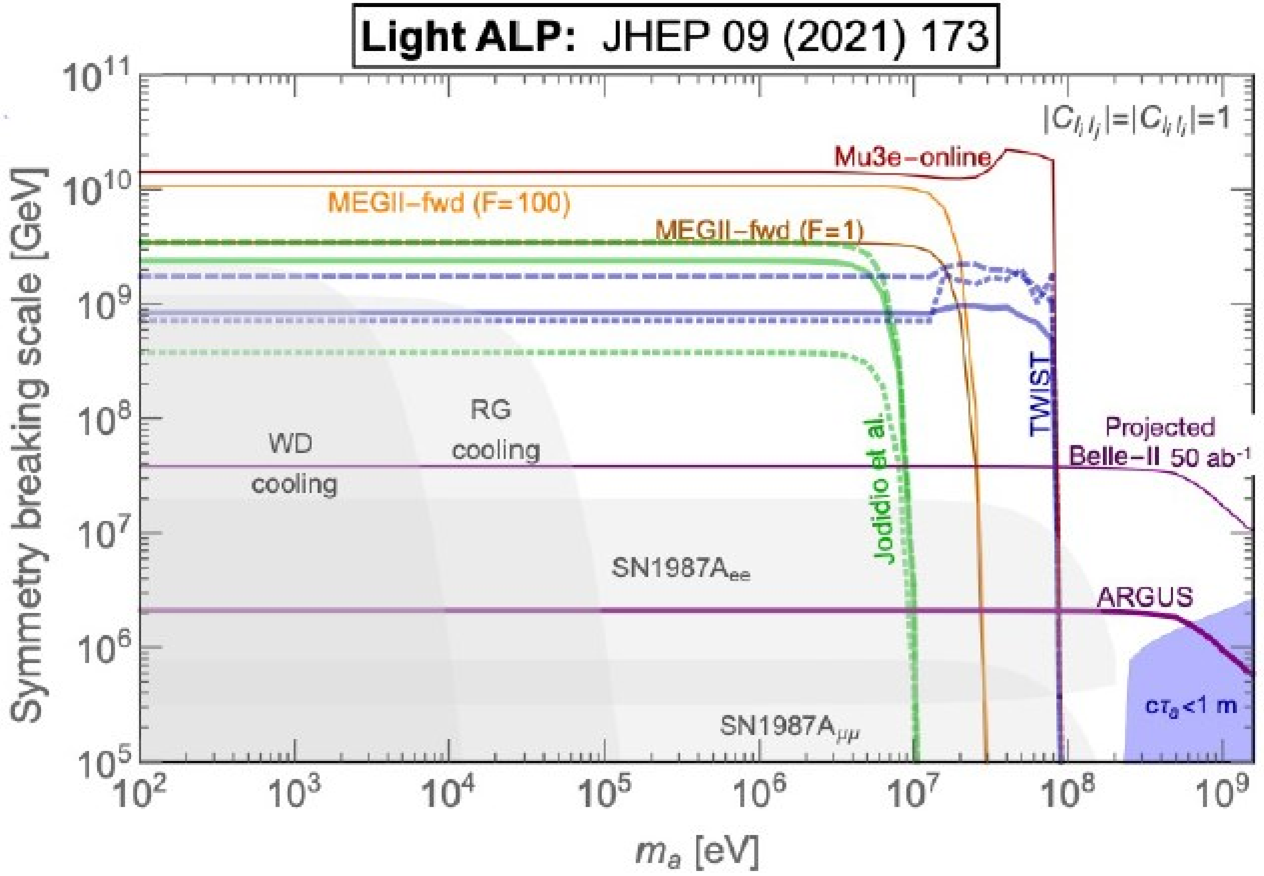


Obs. $B_{\mathrm{UL}}(\tau \to e\phi) = 23{\times}10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to e\phi) = 15{\times}10^{-8}$

Obs. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.7{\times}10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.9{\times}10^{-8}$

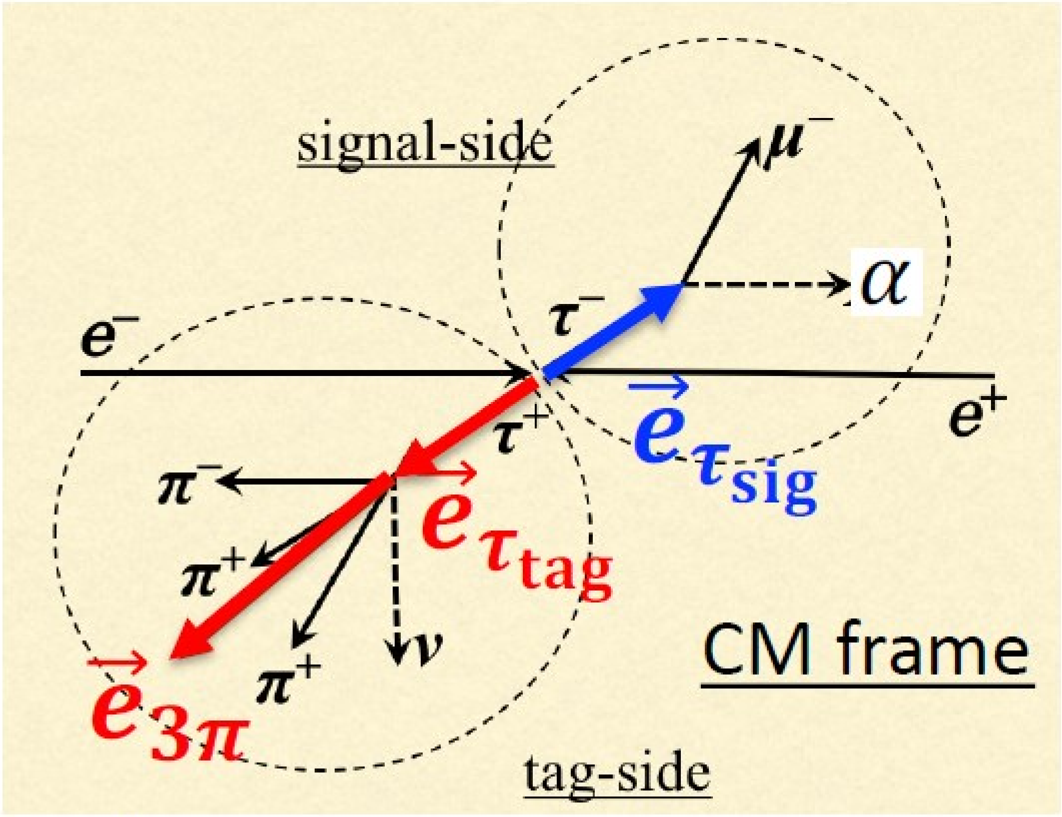
LFV: Belle II τ→lα motivation

- α is a non-detected (invisible) particle
  - e.g, an axion-like particle (ALP)
- Interesting mass range from 100 MeV-1.6 GeV not covered by other searches
- Previous limits from [ARGUS (1995)](ARGUS) – 10^{-2} to 10^{-3} with masses from zero to 1.6 GeV
  - Only 0.5 fb^{-1} of data



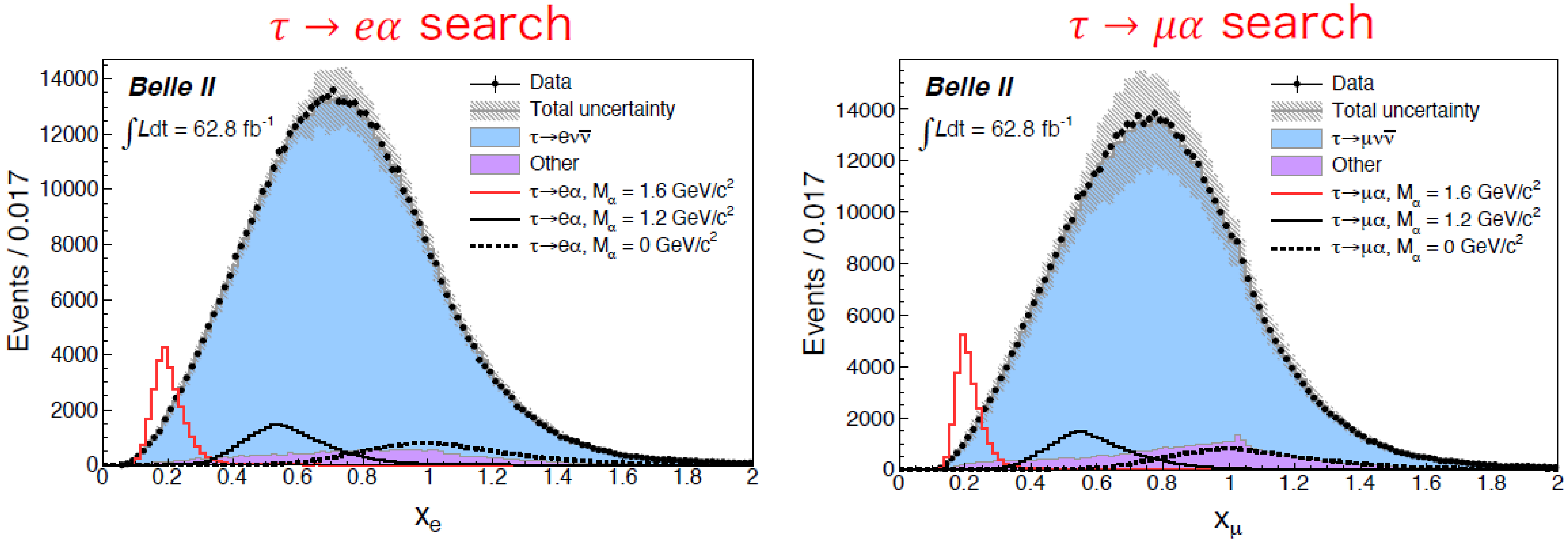
LFV: Belle II $\tau \to l\alpha$ approach

- Using 63 fb^{-1} of data
- Tag with $\tau \to 3\pi\nu$ with π^0 veto
- Background from $\tau \to l\nu\nu$
  - Use difference in two-body (signal) and three-body kinematics (background) to isolate signal
- Workout lepton momentum in **pseudo tau rest frame**
  - Assume signal direction opposite 3π direction and tau energy is $\sqrt{s}/2$



LFV: Belle II τ→lα signal extraction

- Use $x_l = 2E_l^*/m_\tau$ where lepton energy is in pseudo rest frame
  - signal would be monochromatic in rest frame – broaden by the approximations
- Simulation derived templates fit for different α mass hypotheses

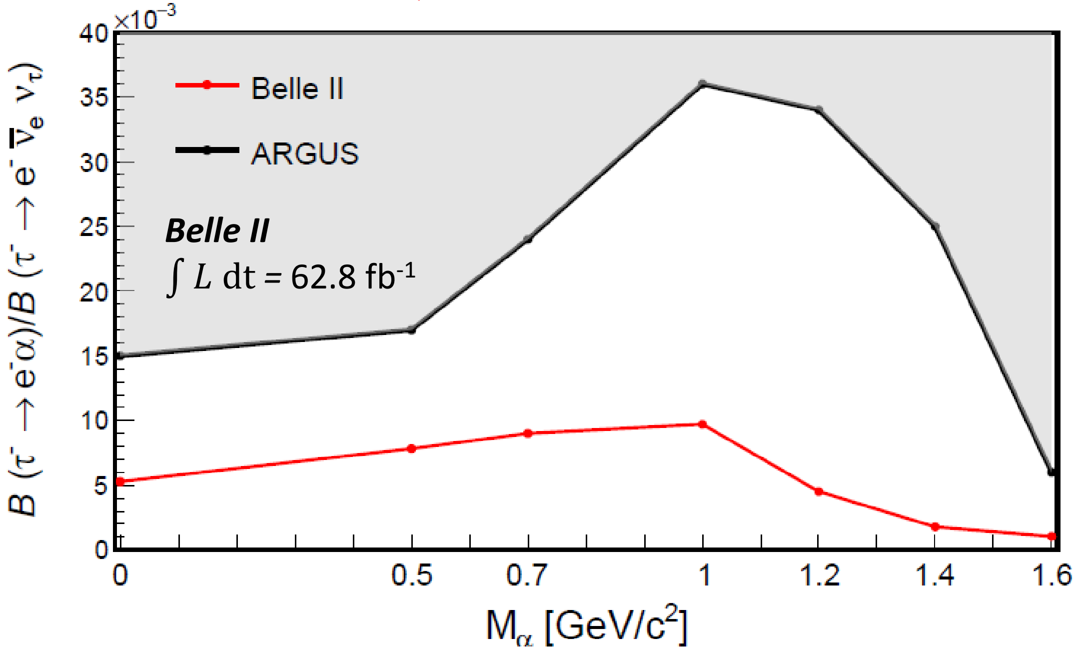


PRL **130**, 181803 (2023)

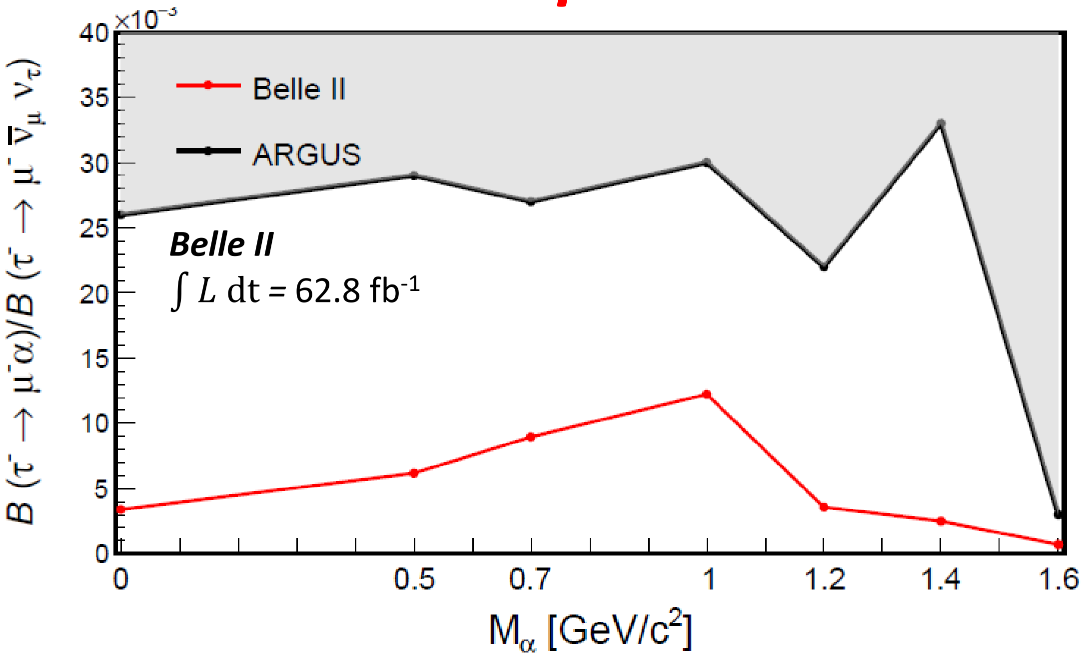
LFV: Belle II $\tau \rightarrow l\alpha$ signal results

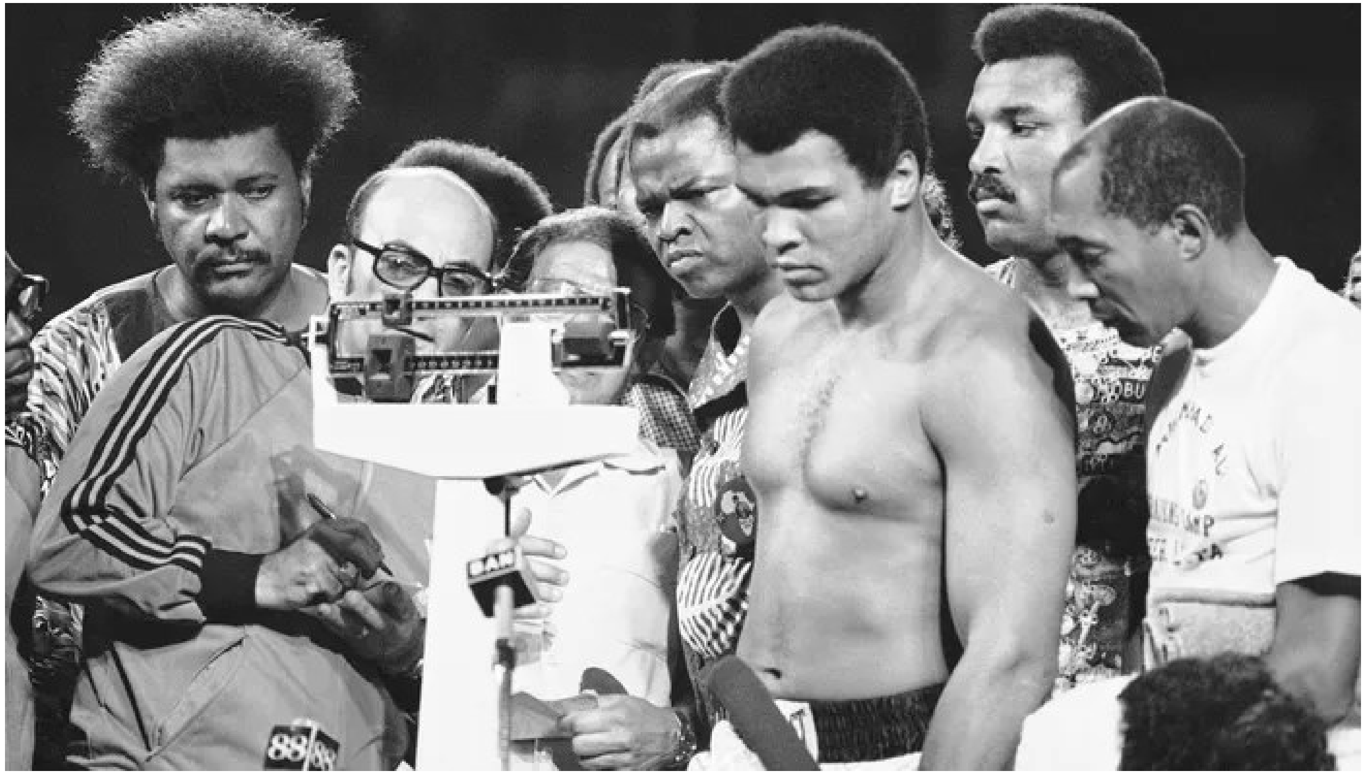
- 95% C.L. branching fraction limits for M_α from 0 to 1.6 GeV
- **2 to 14 times more stringent than ARGUS**

τ→αe search



τ→αμ search





“Ali’s weight was announced as 206 pounds. He had not been so low in years: 216 pounds came through as the correction. A miscalculation of the kilos. A whistle from the press. He was four to eight pounds heavier than he said he would be, a poor prospect for his ability to dance and run”, *The Fight*, Norman Mailer

3.2) Heavyweight weigh-in: τ mass measurement:

Phys. Rev. D **108**, 032006 (2023)

τ mass measurement

- Fundamental parameter of the standard model
  - Important input to lepton-flavour-universality tests

$$R_e = \frac{\mathcal{B}[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}{\mathcal{B}[\mu^- \to e^- \bar{\nu}_e \nu_\mu]} \qquad \left(\frac{g_\tau}{g_\mu}\right)_e = \sqrt{R_e \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^3}{m_\tau^3} (1+\delta_W)(1+\delta_\gamma)}$$

(δs are radiative corrections)

Phys. Rev. D **108**, 032006 (2023)

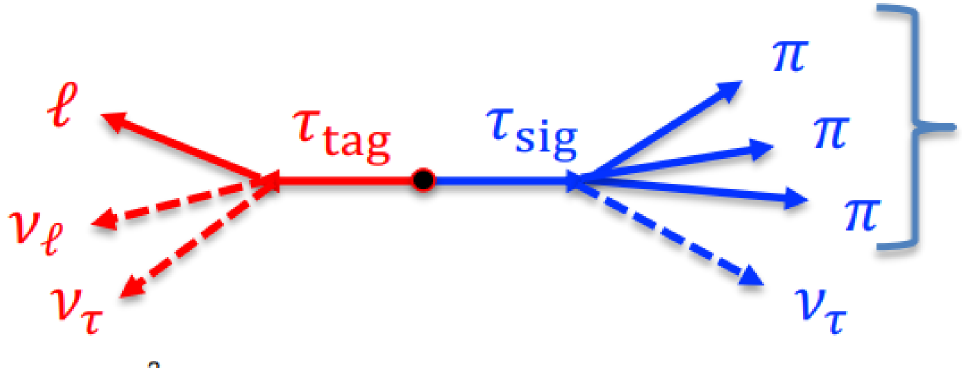
τ mass measurement

- Fundamental parameter of the standard model
  - Important input to lepton-flavour-universality tests

$$R_e = \frac{\mathcal{B}[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}{\mathcal{B}[\mu^- \to e^- \bar{\nu}_e \nu_\mu]} \qquad \left(\frac{g_\tau}{g_\mu}\right)_e = \sqrt{R_e \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^3}{m_\tau^3} (1+\delta_W)(1+\delta_\gamma)}$$

(δs are radiative corrections)

- We use the pseudomass variable to determine mass

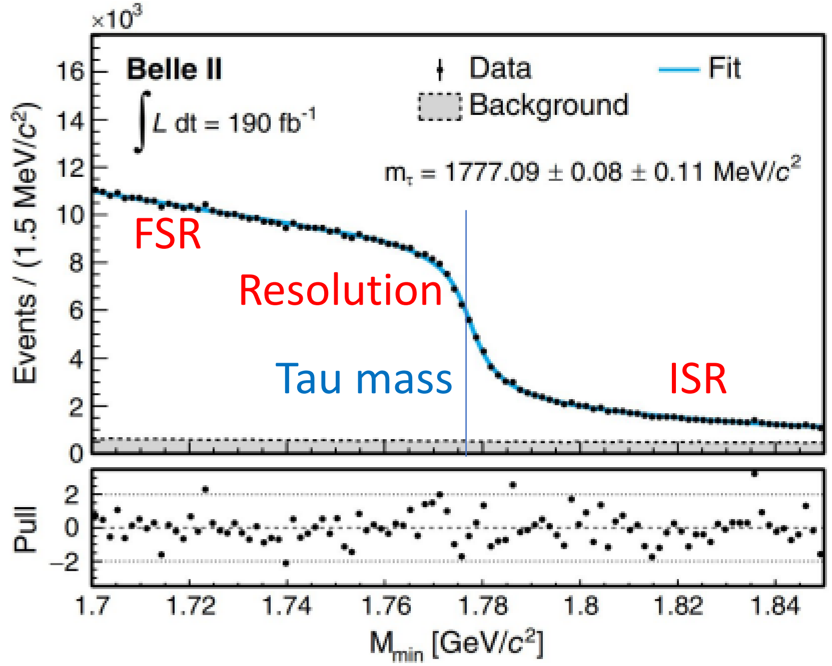


$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$$

Phys. Rev. D **108**, 032006 (2023)

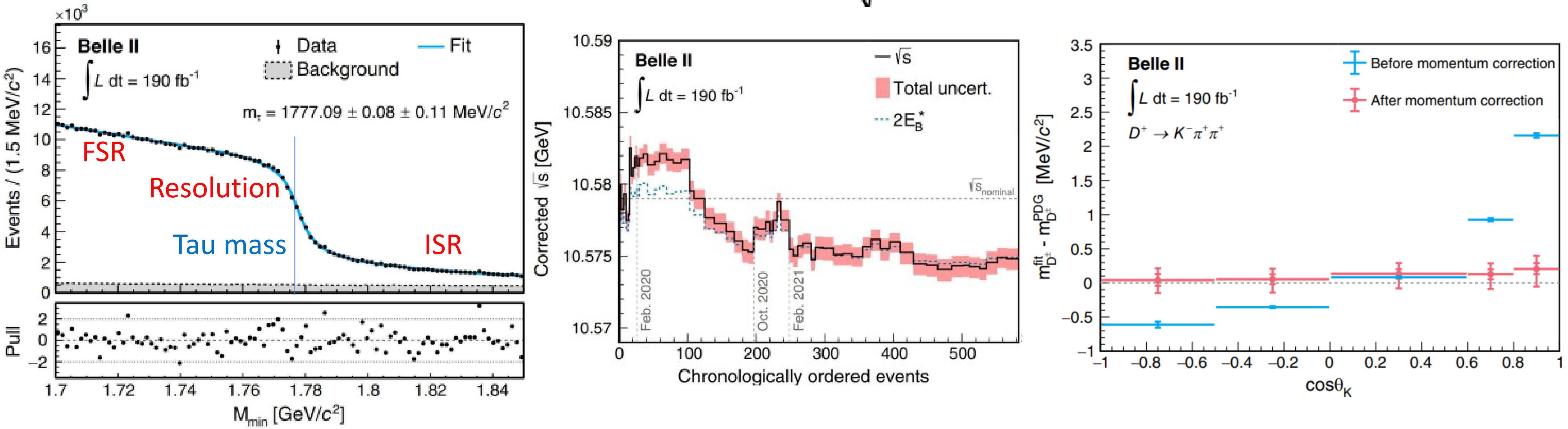
τ mass measurement

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



- Fit to distribution with analytic form that accounts for ISR and resolution

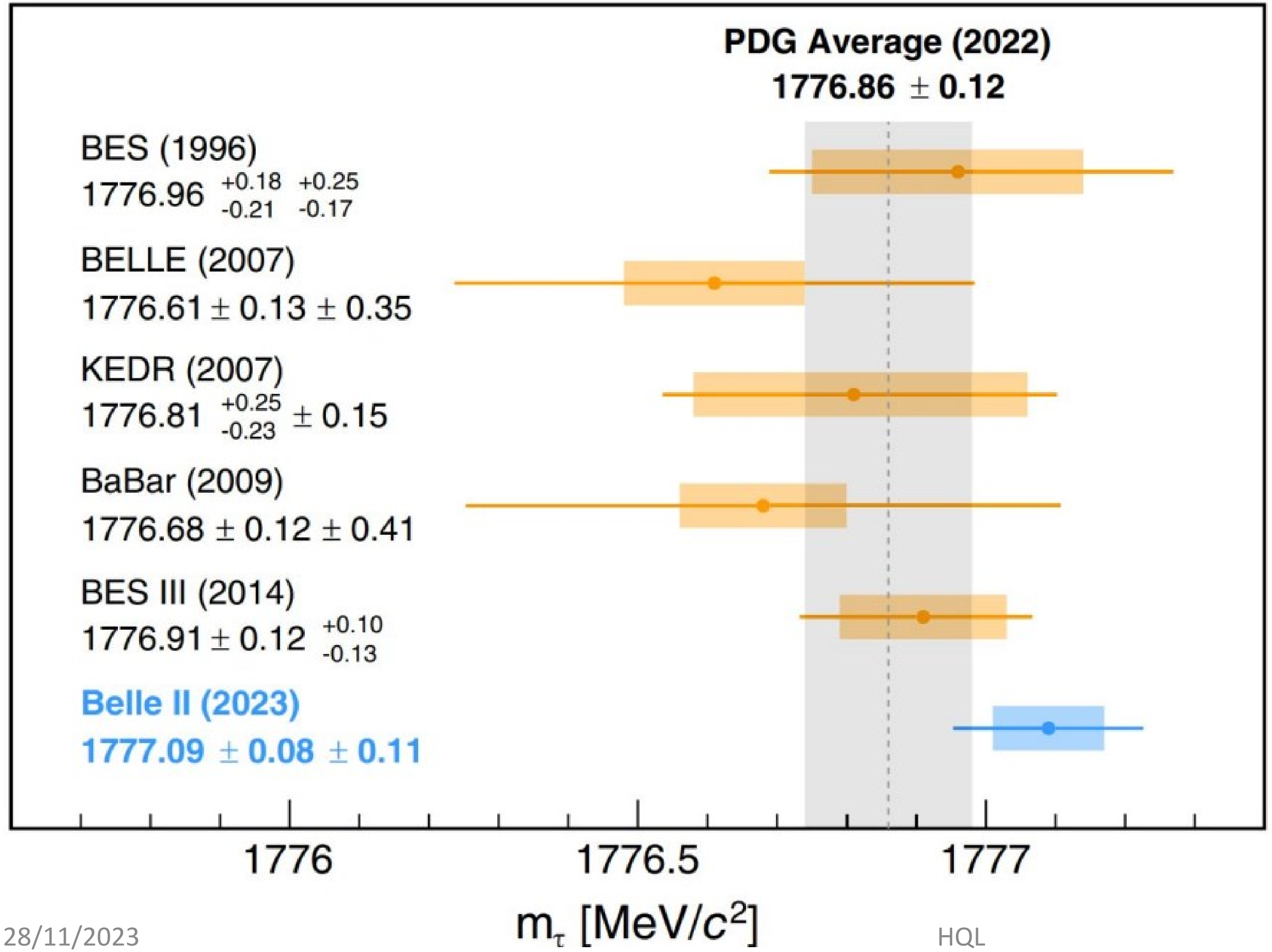
τ mass measurement $M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$



- Fit to distribution with analytic form that accounts for ISR/FSR and resolution
- Knowing the scale key:
  - beam energy (from E_B*) and
  - momentum (from D mass)

Phys. Rev. D **108**, 032006 (2023)

τ mass measurement

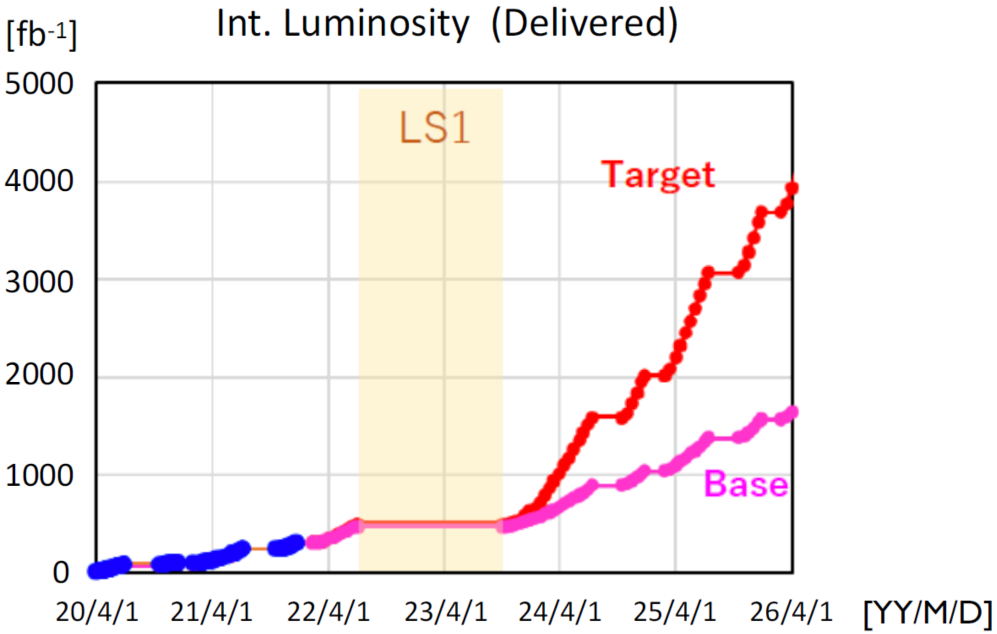


World's most precise measurement to date - dominant systematics from beam energy and momentum scale

5) Prospects and conclusion

Belle II: after current shutdown

- We have not collected the sample size planned to date
  - Beam conditions
- Since summer 2022 shutdown for accelerator upgrades to mitigate background and increase luminosity
- Detector upgrades too
  - two-layer pixel detector installed
- Restart of SuperKEKB in January
- **Path to 2×10^{35} cm $^{-2}$s^{-1} but new final focus to go beyond**
- **Proposed upgrade from 2027**
  - **Wed 18:00: Belle II upgrade programme – Peter Lewis**



More results coming v. soon

Conclusion

- Belle and Belle II will be leading the way in investigating properties of the tau lepton
  - Searches for beyond-the-SM physics
  - Precision measurements of tau properties and SM parameters
- A lot more to come once we enter the “10^{35} era”
- Upgrade plans for reaching the 10s of ab^{-1}