1.777 GeV/c²
-1
½ τ
tau

Physics

… personal selection
(with more focus on Belle II)

Aglia tau, the tau emperor, is a moth of the family Saturniidae

Ami Rostomyan
Jeniffer Summer School
26 July 2021

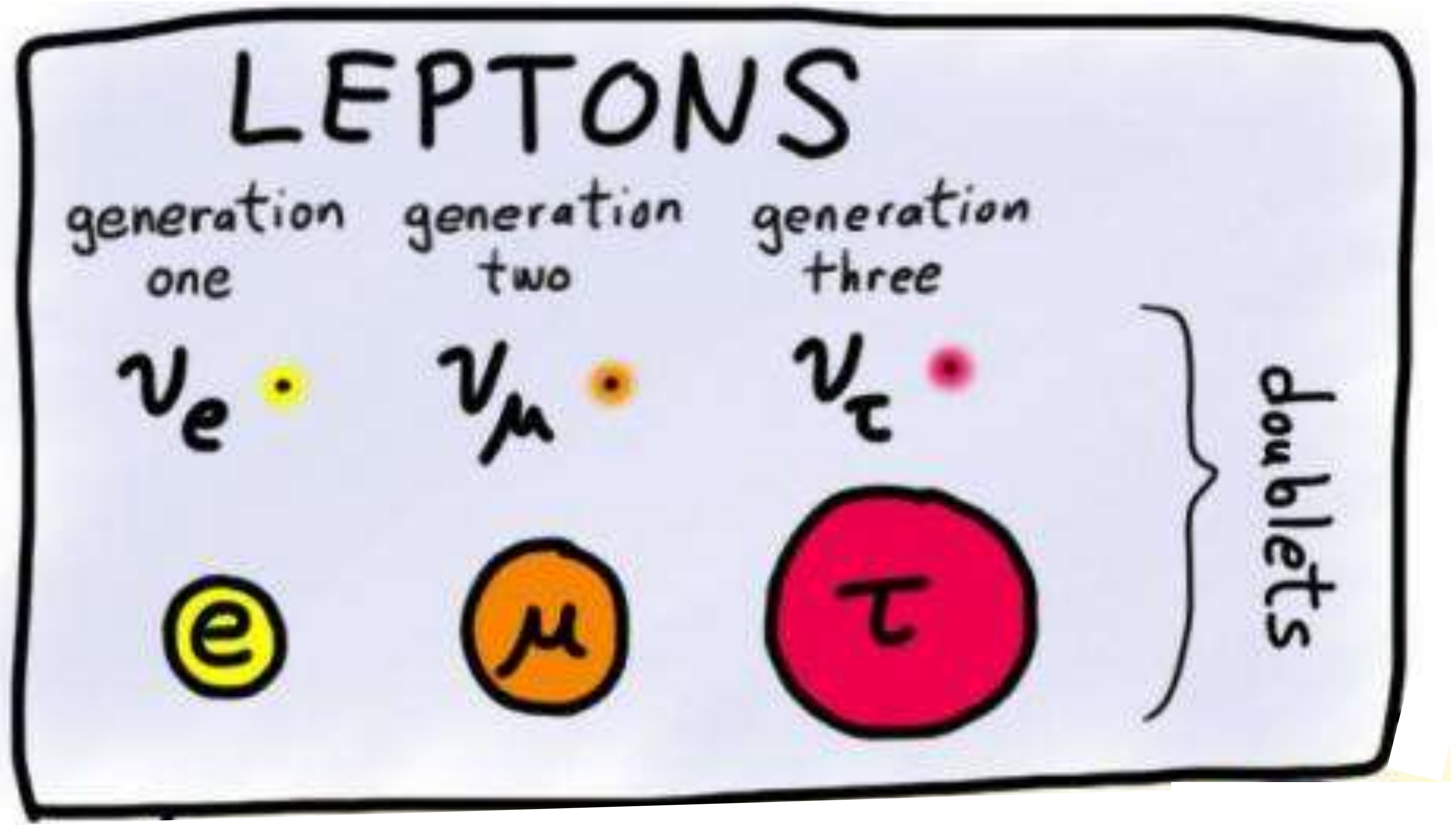
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

The third charged lepton - τρίτον

First observed in 1974 at SPEAR in SLAC as an anomalous decay in e^+e^- collisions

> We have discovered 64 events of the form
>
> $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + at least two undetected particles
>
> for which we have no conventional explanation.



SLAC-PUB-1626
LBL-4228
August 1975
(T/E)

EVIDENCE FOR ANOMALOUS LEPTON PRODUCTION IN $e^+ - e^-$ ANNIHILATION*

ABSTRACT

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing energy and missing momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

Proposal:

- these events were the production and subsequent decay of a new particle pair:

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu$$

- The mass and spin of the τ was established at DESY with the Double Arm Spectrometer (DASP), and at SLAC-Stanford with the SPEAR Direct Electron Counter (DELCO).

The τ lepton

Very massive:

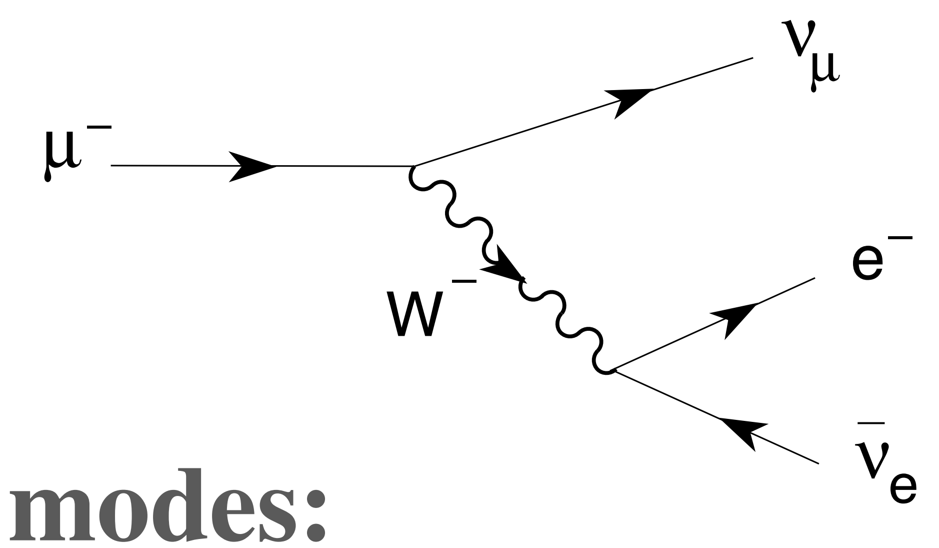
- ~3500 times more massive than electron

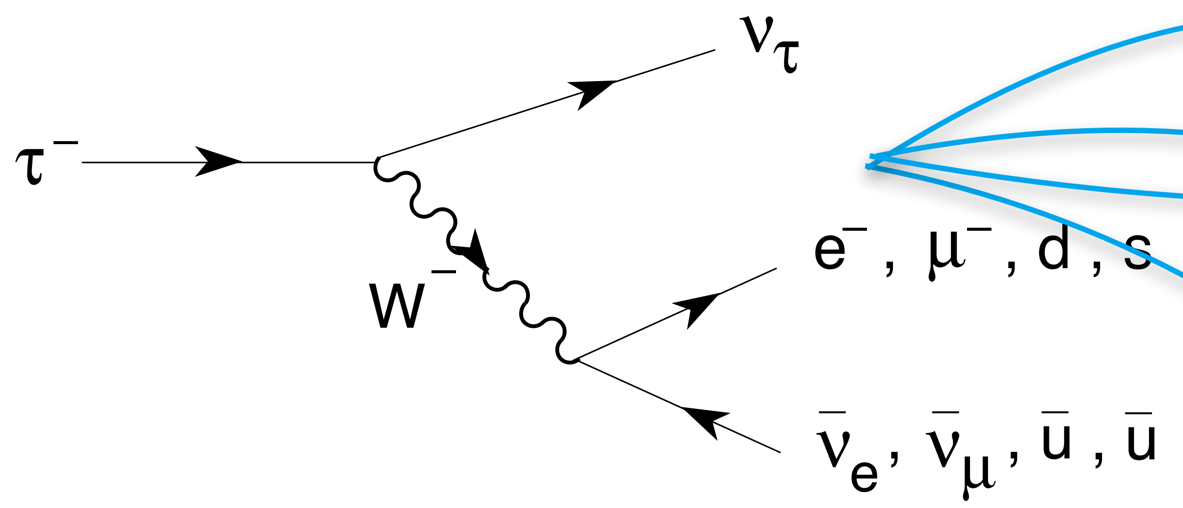
Short lifetime:

- ~1.3*10^{-7} times smaller lifetime than muon

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\tau$$

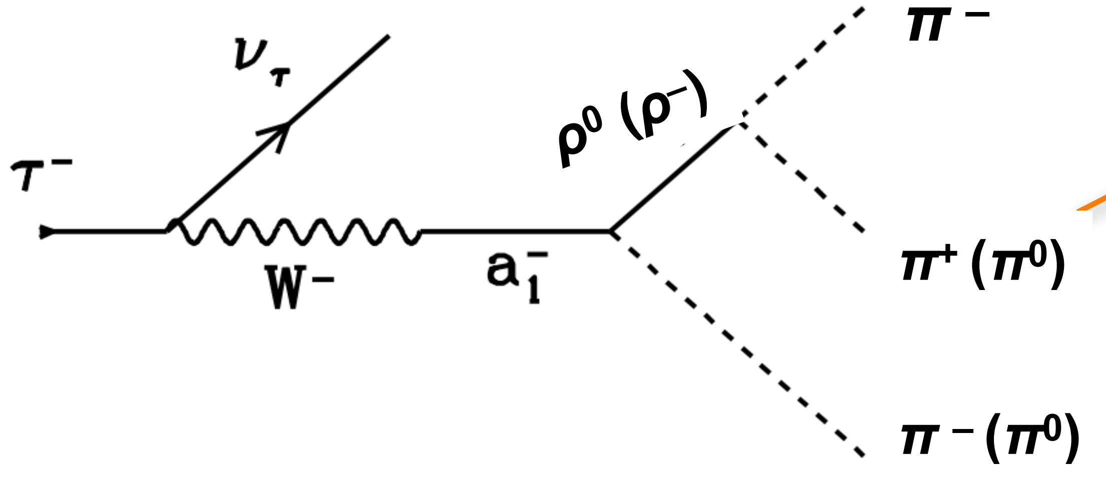
$$\tau^- \rightarrow X\nu_\tau \; (X = e^-\bar{\nu}_e\,,\, \mu^-\bar{\nu}_\mu\,,\, d\bar{u}\,,\, s\bar{u}\,,\, \ldots)$$

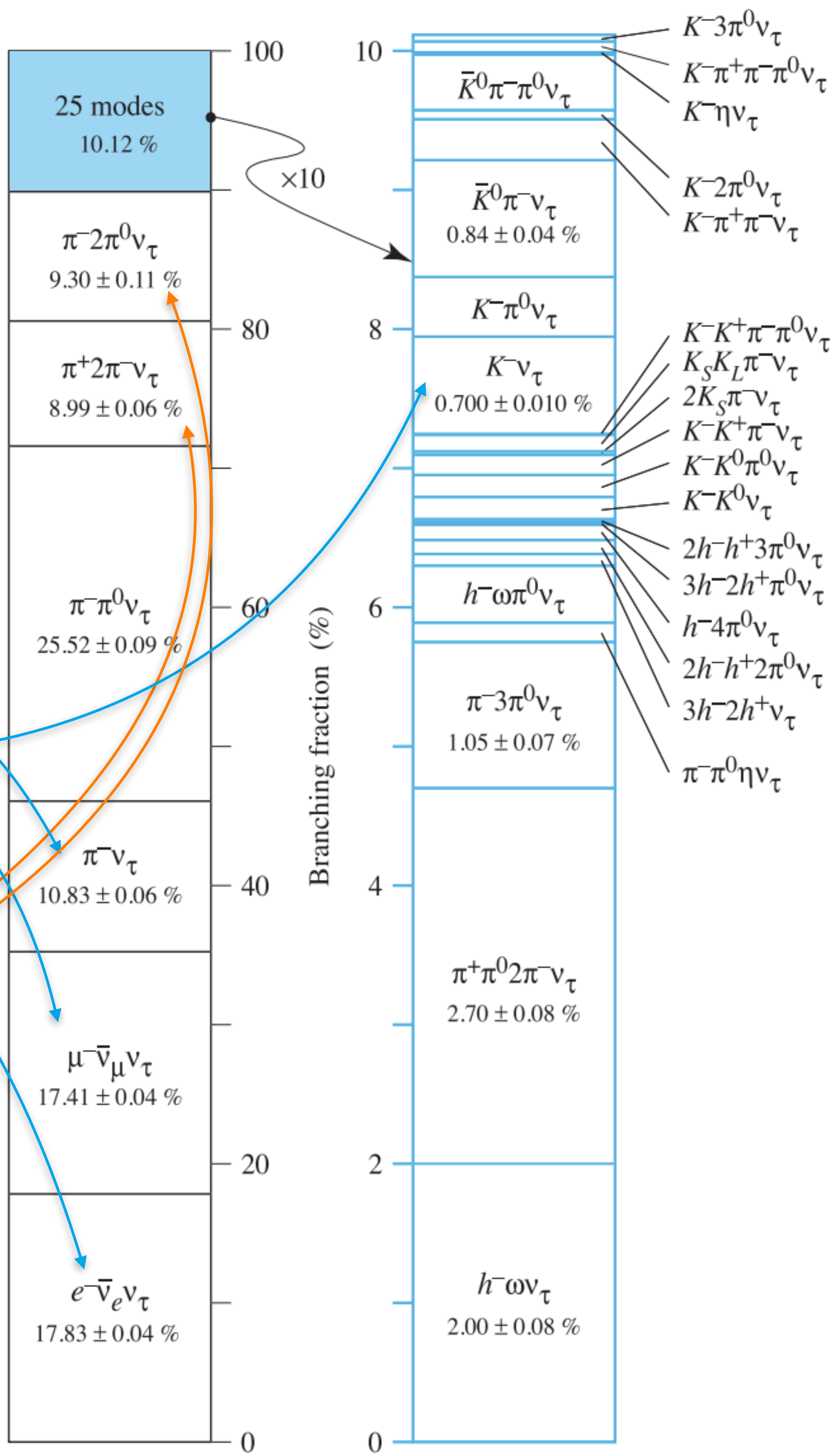




Decay modes:

- ~ 250 decay modes in PDG
- τ → e or μ (~35%)
- heavy enough to decay to hadrons





Laboratory to test the structure of the weak currents, the universality of their coupling to the gauge bosons and the low-energy aspects of strong interactions.

B factories

Not just B-Factories but also τ factories!

- Collision energy at Υ(nS)
  - e.g. E_{CMS} = 10.58 GeV
  - BR(Υ(4S)→ $B\bar{B}$) > 96%
- Asymmetric beam energies

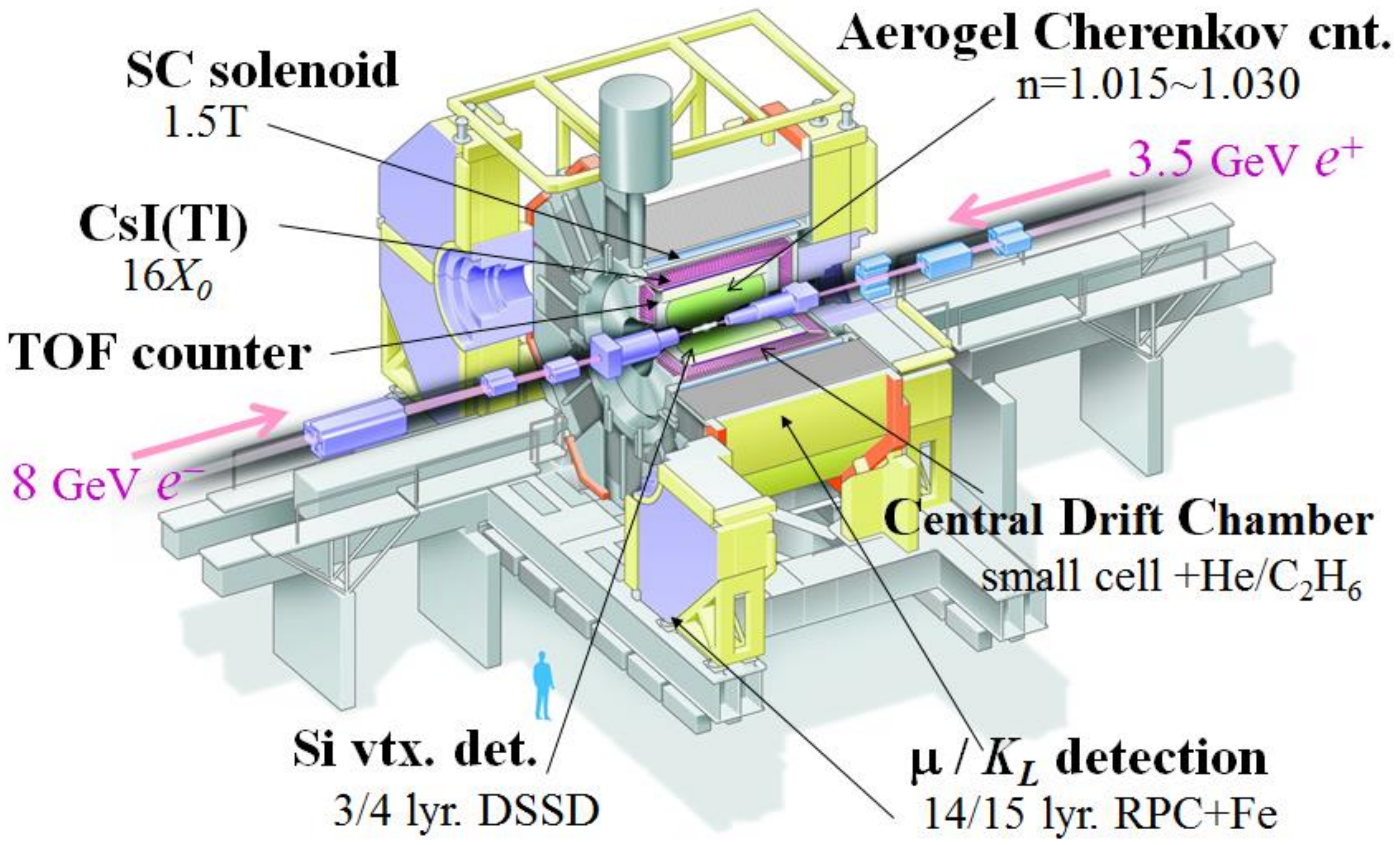
  Belle: 8.0 GeV (e^-) / 3.5 GeV (e^+)

  BaBar: 9.1 GeV (e^-) / 3.0 GeV (e^+)
  - Boosted $B\bar{B}$ pairs
- High luminosities

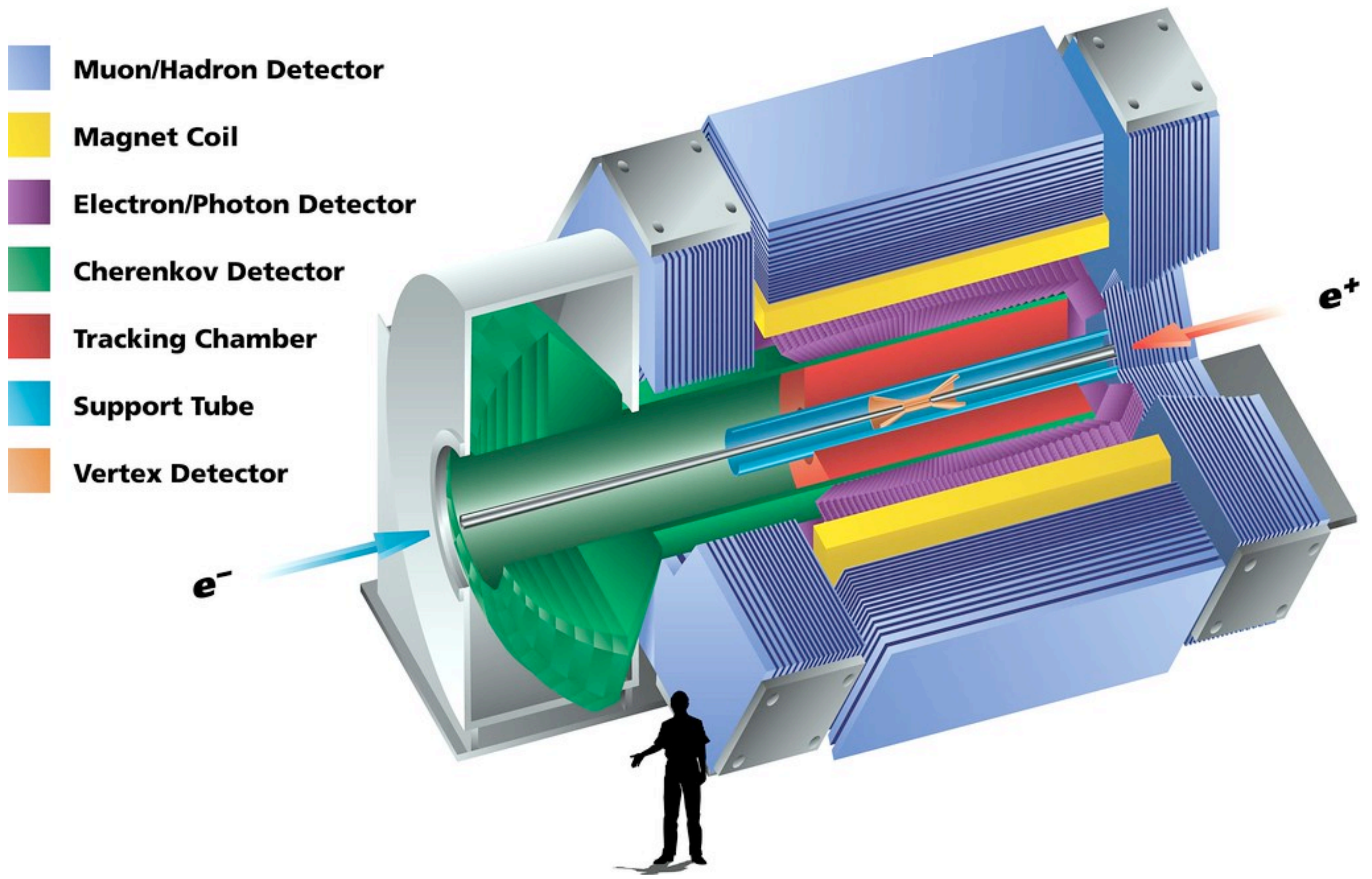
  ~Belle: 710 fb^{-1} @ Υ(4S)

  ~ BaBar: 424 fb^{-1} @ Υ(4S)

Belle@KEKB

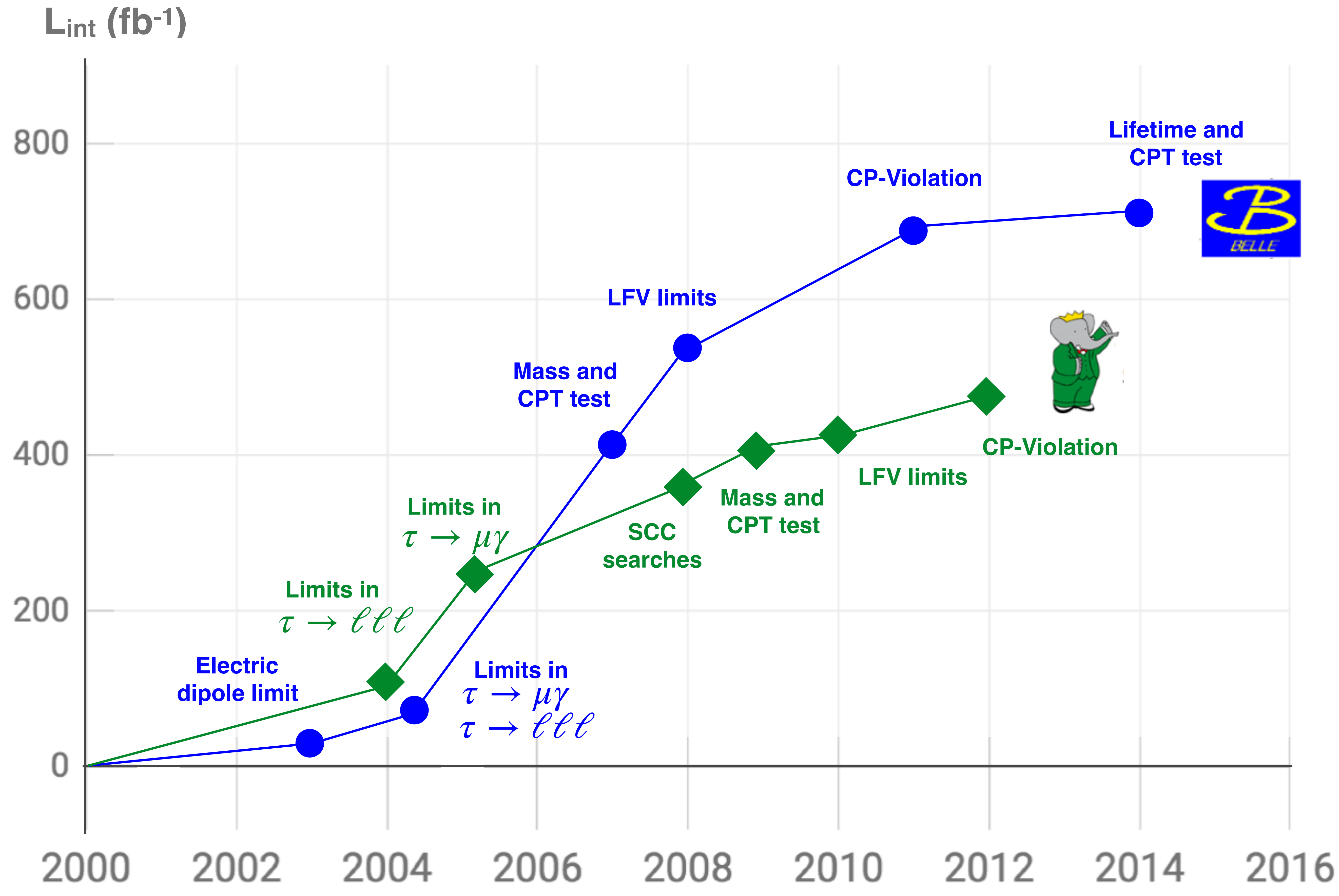


BaBar@PEP-II

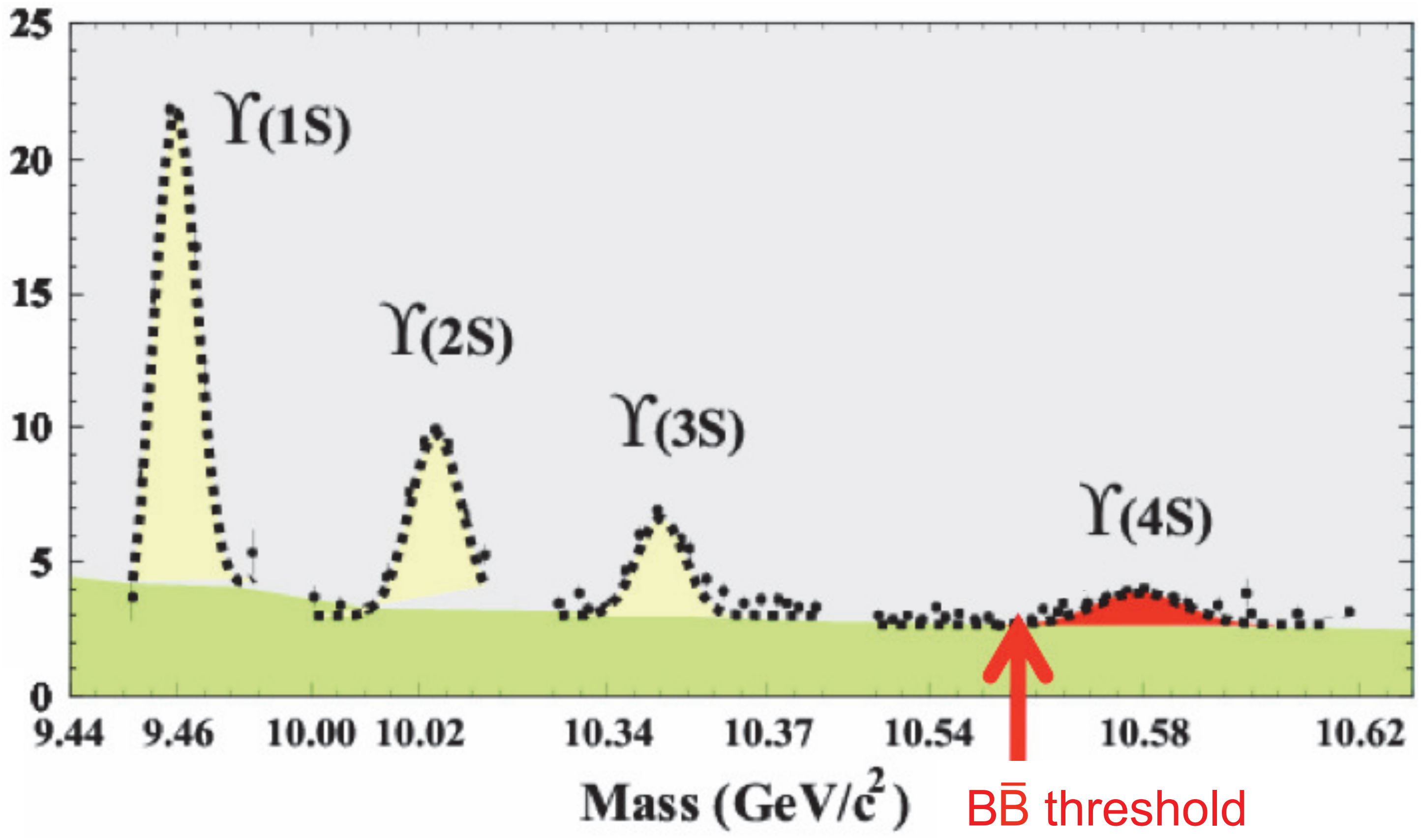


τ physics program @ B factories

Historically B-factories provided a variety of very interesting results in the last two decades.



B-factories: Belle@KEKB and BaBar@PEP-II

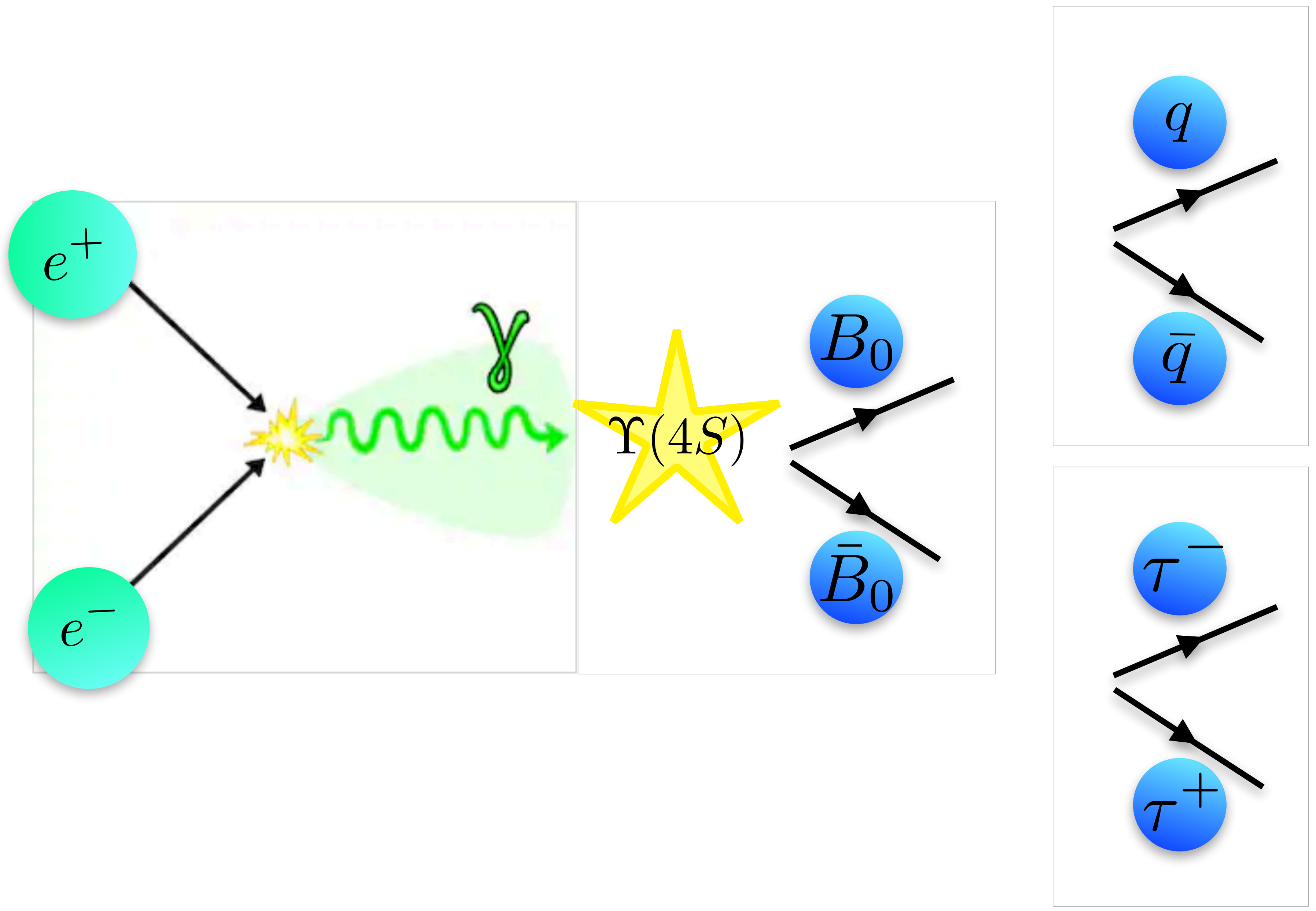


Wide range of observables to confront theory

- ➡ Precision SM measurement
- ➡ CP asymmetries
- ➡ Rare decays, forbidden decays
- ➡ Angular distributions

B-Factories

Not just B-Factories but also τ factories!



$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = 1.05\ [\mathrm{nb}]$$
$$\sigma\left(e^+e^- \to q\bar{q}\right) = 3.69\ [\mathrm{nb}]$$
$$\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.919\ [\mathrm{nb}]$$

Clean environment

- the kinematics of the initial state is precisely known
- the neutrino energy can be determined precisely

Hermetic detectors with

- high track reconstruction efficiency
- good kinematic and vertex resolution
- excellent PID capability
- excellent γ and π^0 reconstruction

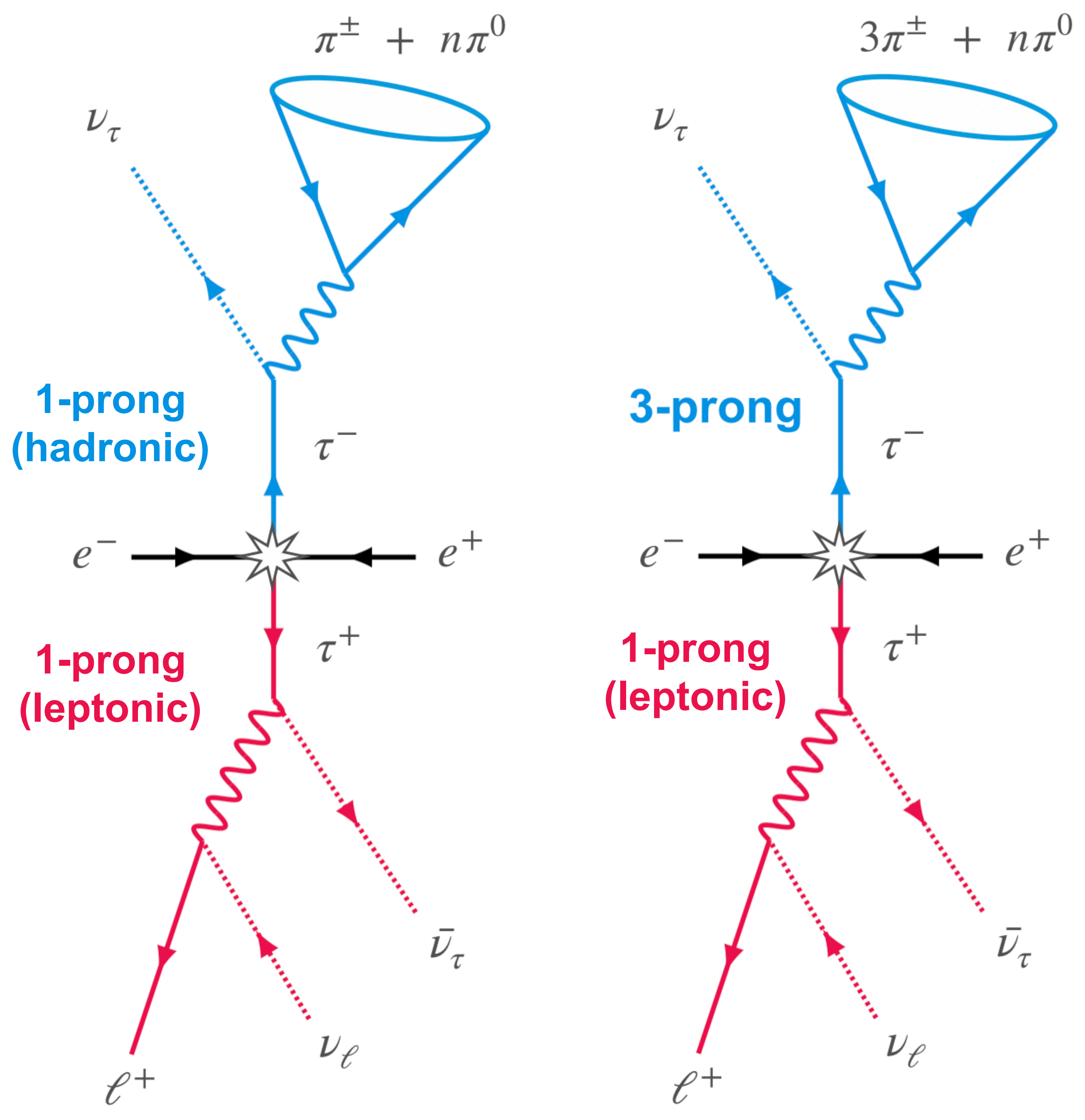
Wide physics program

- precision measurements of time-dependent CPV and CKM parameters
- searches for lepton flavor/universality/number violations
- …

$e^+e^- \to \tau^+\tau^-$

e^+e^- annihilation data is ideal for missing energy channels

- ➡ the neutrino energy can be determined precisely



** "prong" is the number of charged tracks in the decay*

Reconstruct 1-prong*, 3-prong τ decays in various channels

- ➡ wide variety of signatures involving tracks (e, μ, π, K) and neutrals

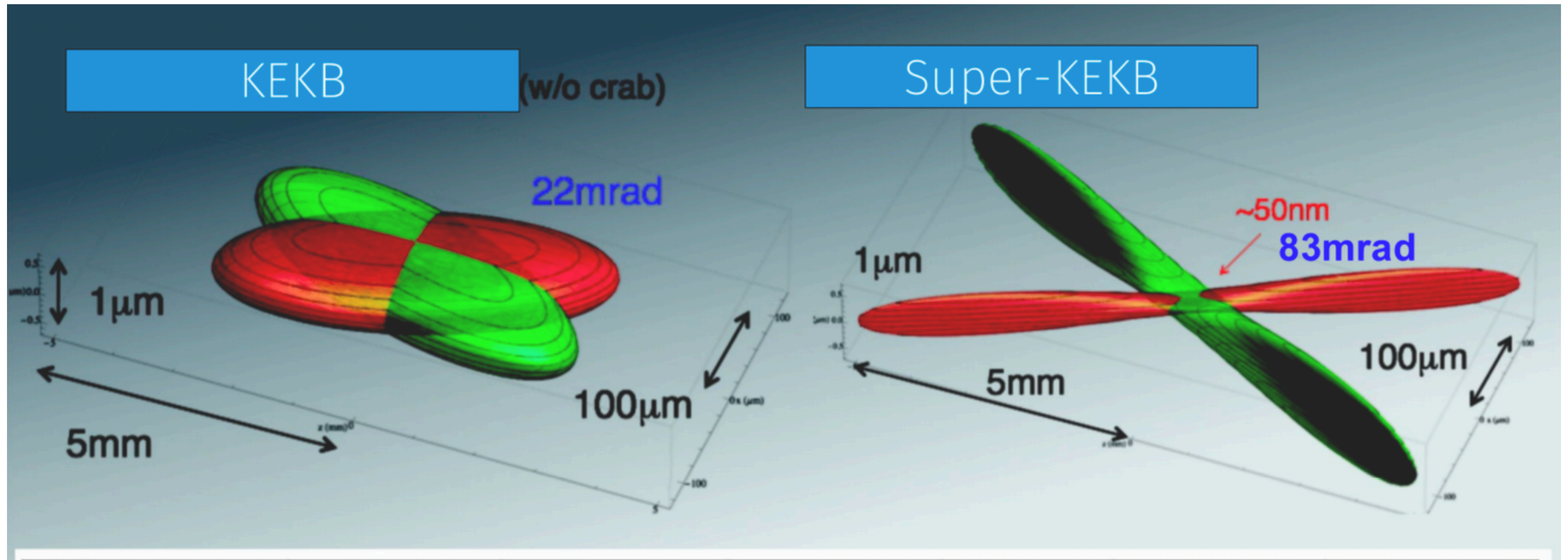
Precise tests of SM & NP searches

- ➡ τ mass and lifetime measurements
- ➡ Lepton universality tests
- ➡ V_{us} measurement
- ➡ Electric Dipole Moment (CP/T violation)
- ➡ CP violation $\tau \to K_S \pi \nu$
- ➡ LFV and LNV decays
- ➡ …

Belle II @ SuperKEKB

Next generation B-factory

Unprecedented design luminosity of ~6×10^{35} cm^{-2}s^{-1}



	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	80 x 10^{34}

factor 20 factor 2-3

SuperKEKB – major upgrade of the KEKB

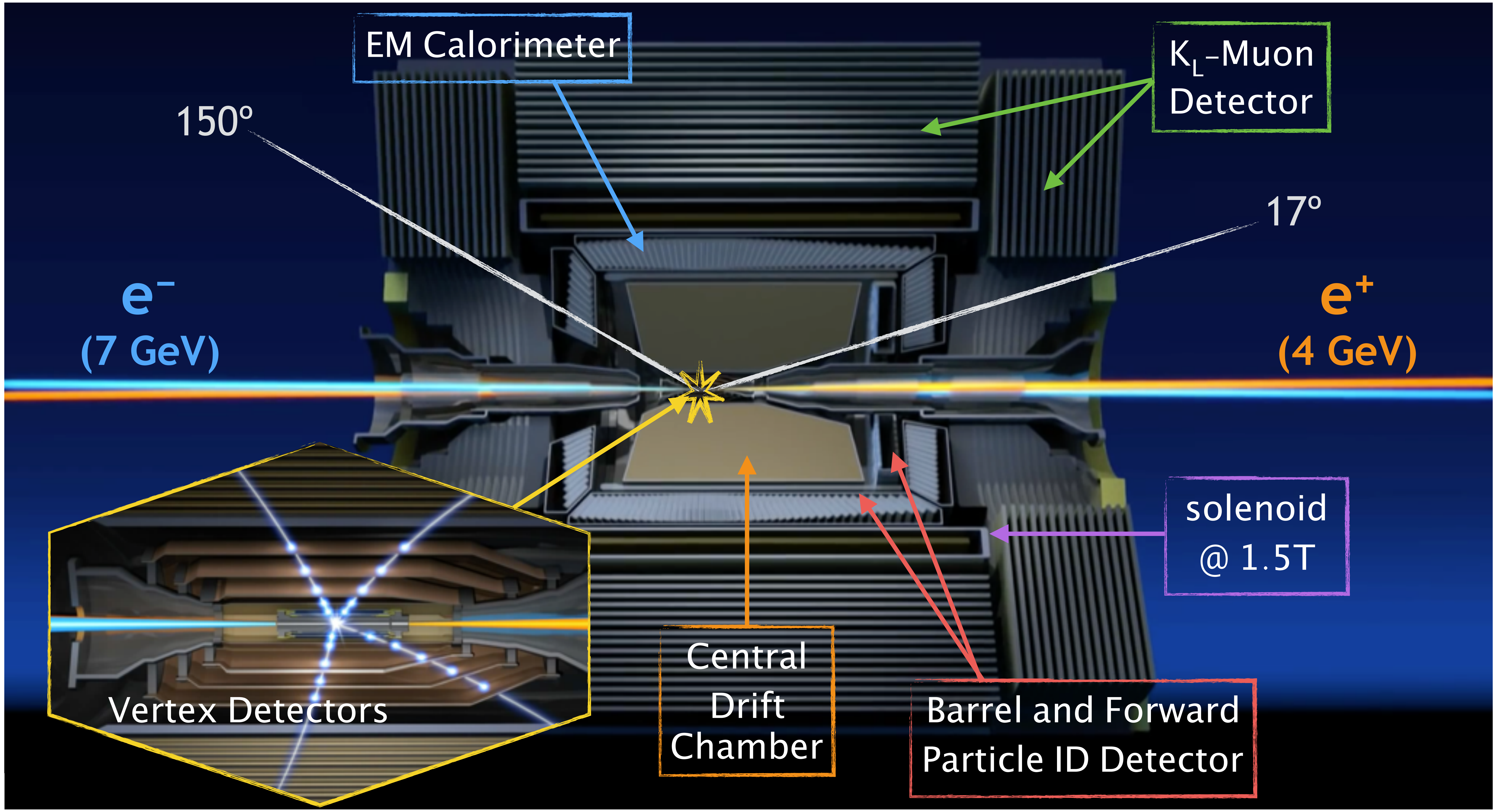
- ➡ an asymmetric electron-positron collider
  7.0 GeV (e$^-$) / 4.0 GeV (e$^+$)
- ➡ smaller interaction point
- ➡ increased currents

First beams and commissioning in 2016

Broke the world lumi record in June 2020!

Belle II @ SuperKEKB

Belle II detector – upgraded Belle detector



- ➡ improved tracking efficiency
- ➡ improved particle identification
- ➡ smarter software
- ➡ more precise algorithms
- ➡ rolled in April 2017

First recorded events in April 2018

Important for τ analysis: discriminate between e, μ, π, K; reconstruct neutrals!

The Belle II Collaboration

New facility to search for physics beyond the SM by studying B, D and τ decays

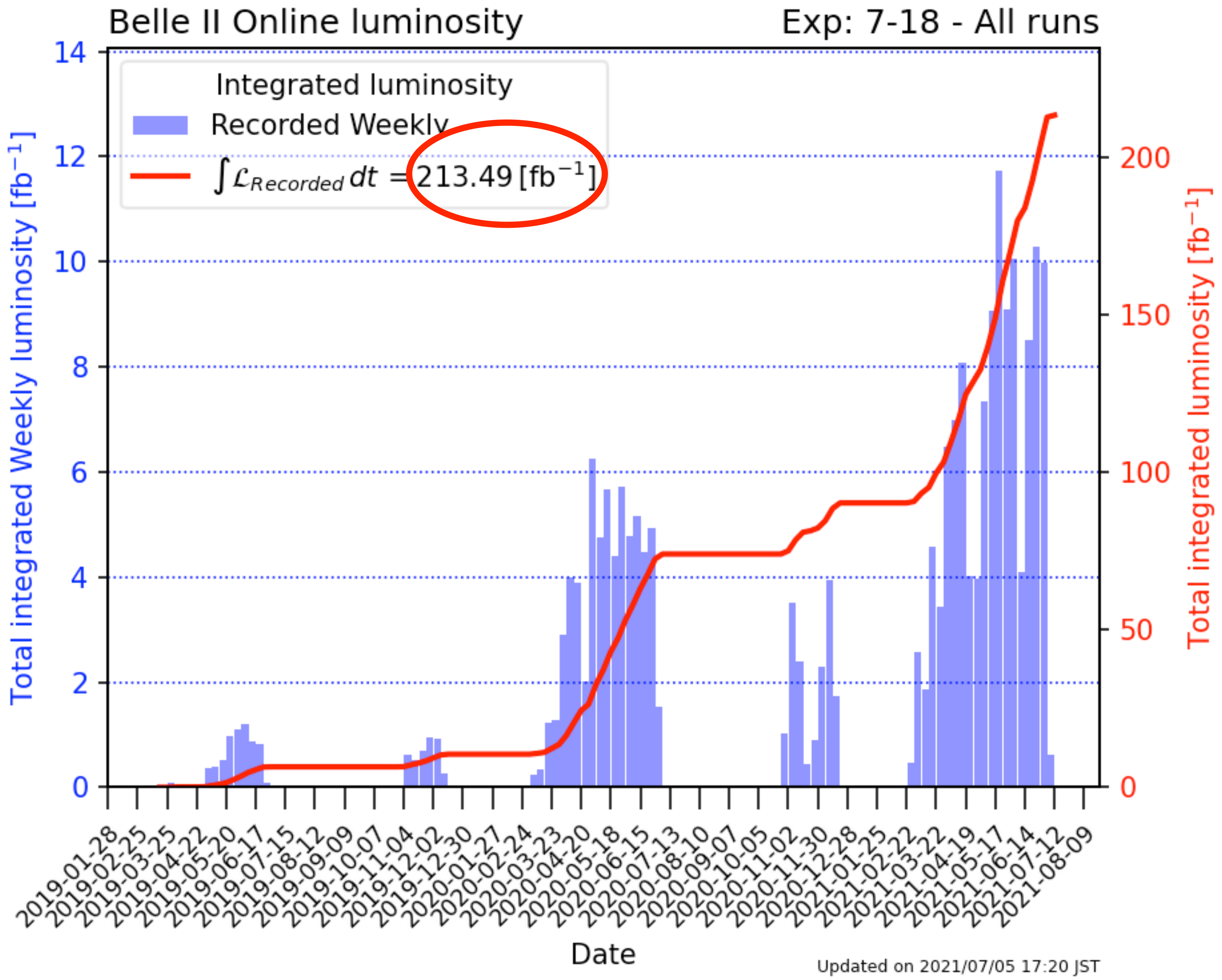
The world largest set of $e^+e^- \rightarrow \tau^+\tau^-$ for τ physics with high precision.

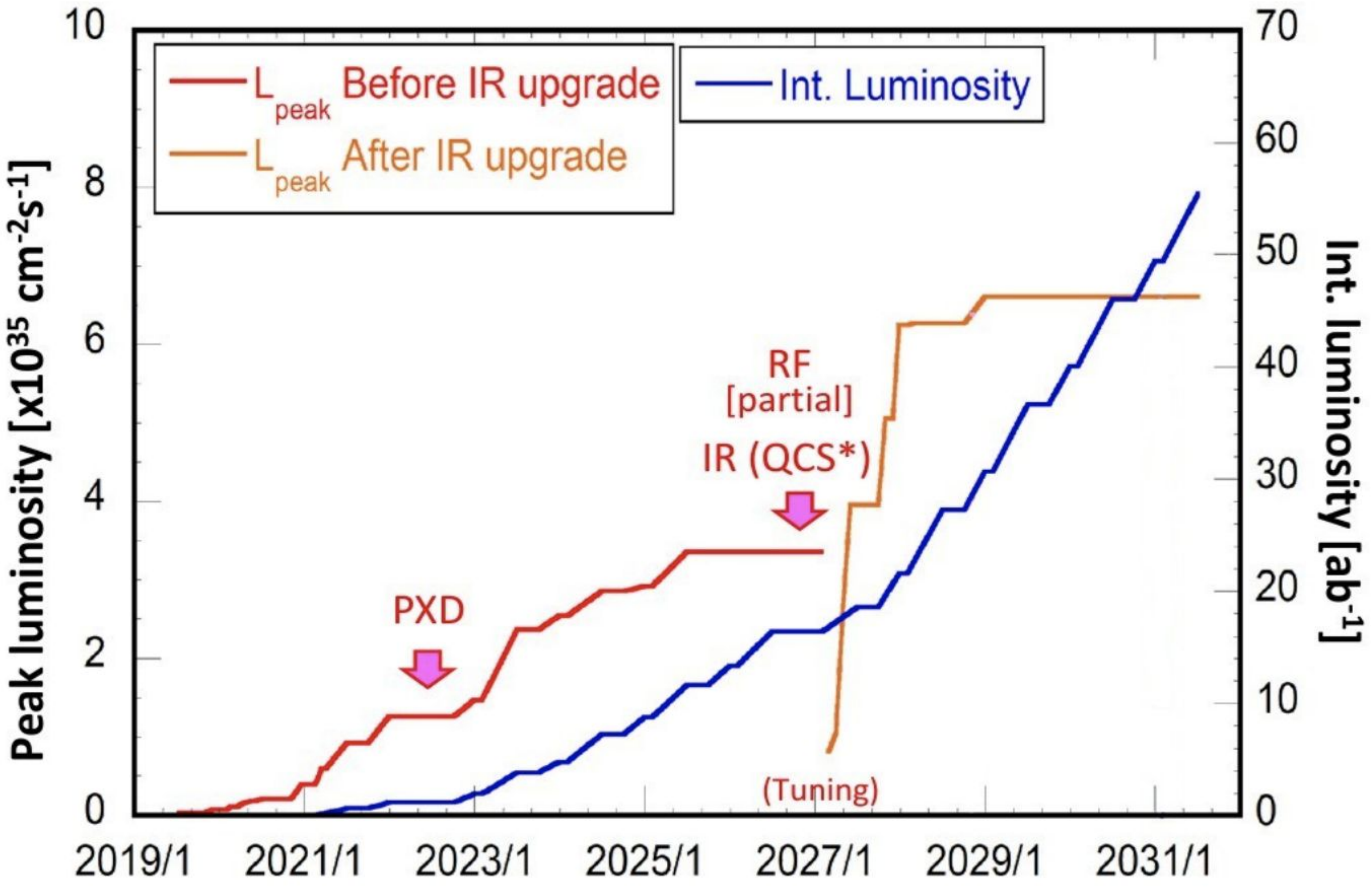
Luminosity status and plans

~ 200/fb of data already collected since 2019

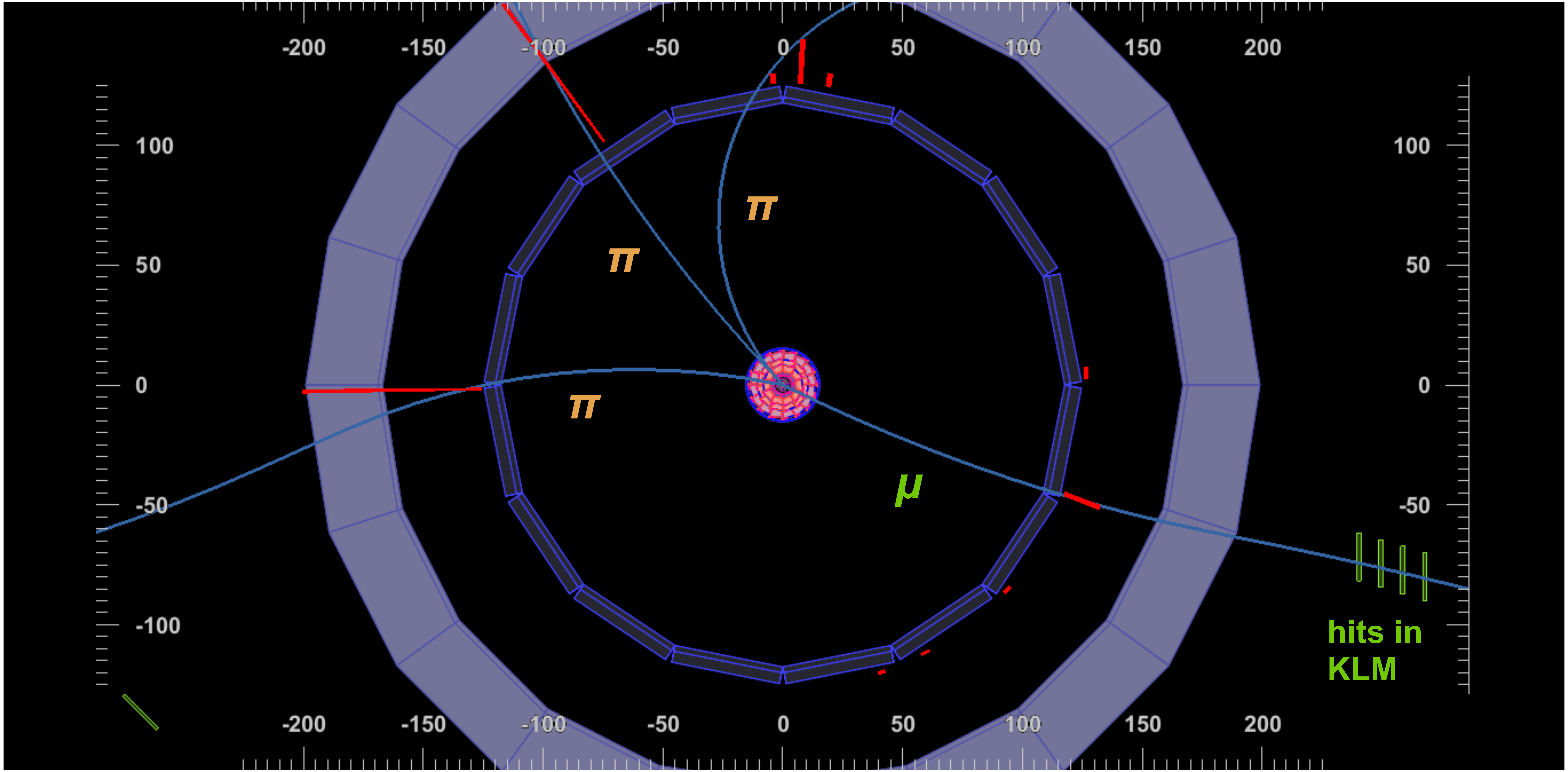
Data taking is

- ➡ challenging in the pandemic
- ➡ however efficiency largely unaffected
- ➡ similar data sample as at 1st generation B-factories by 2022





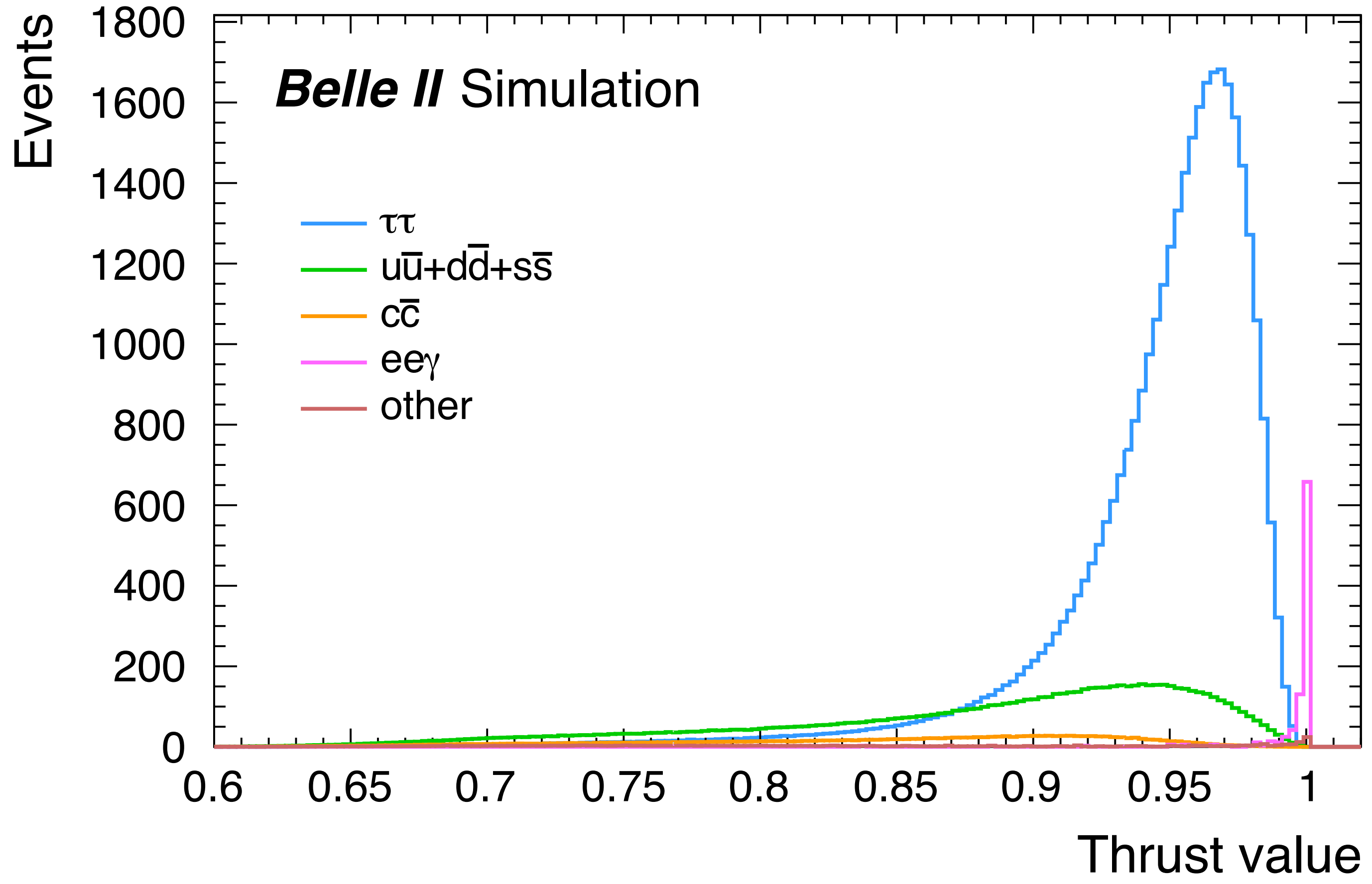
τ leptons @ Belle II



$e^+e^- \to \tau^+\tau^-$: An example of 3x1 topology

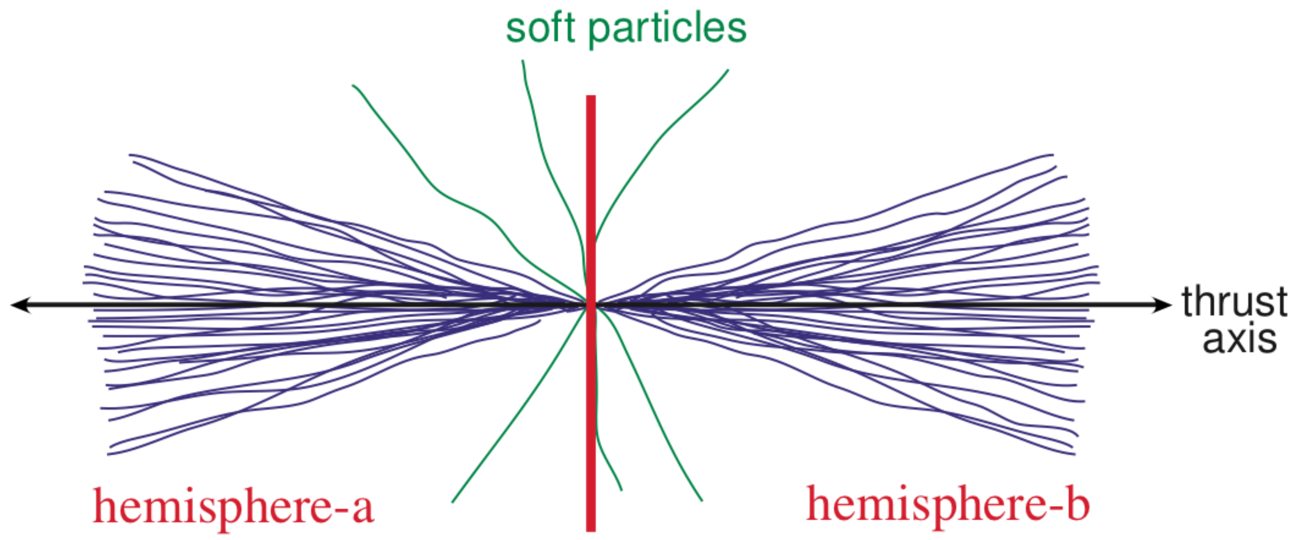
Event topology and kinematics crucial to observe τ leptons

- relatively mild deviation of the τ decay particles from the primary trajectory

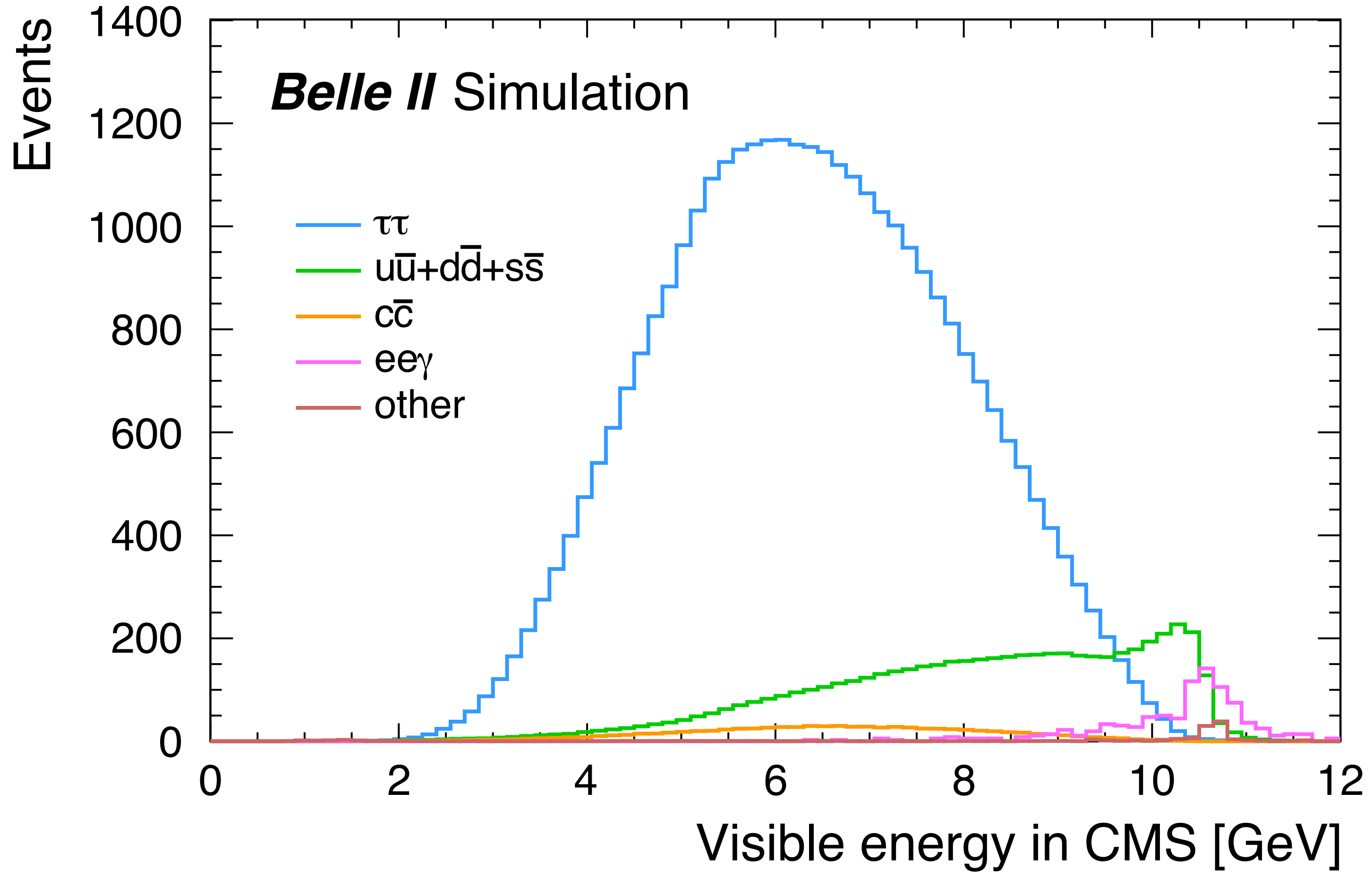


Thrust axis ($\boldsymbol{T}$) is maximising the event shape variable

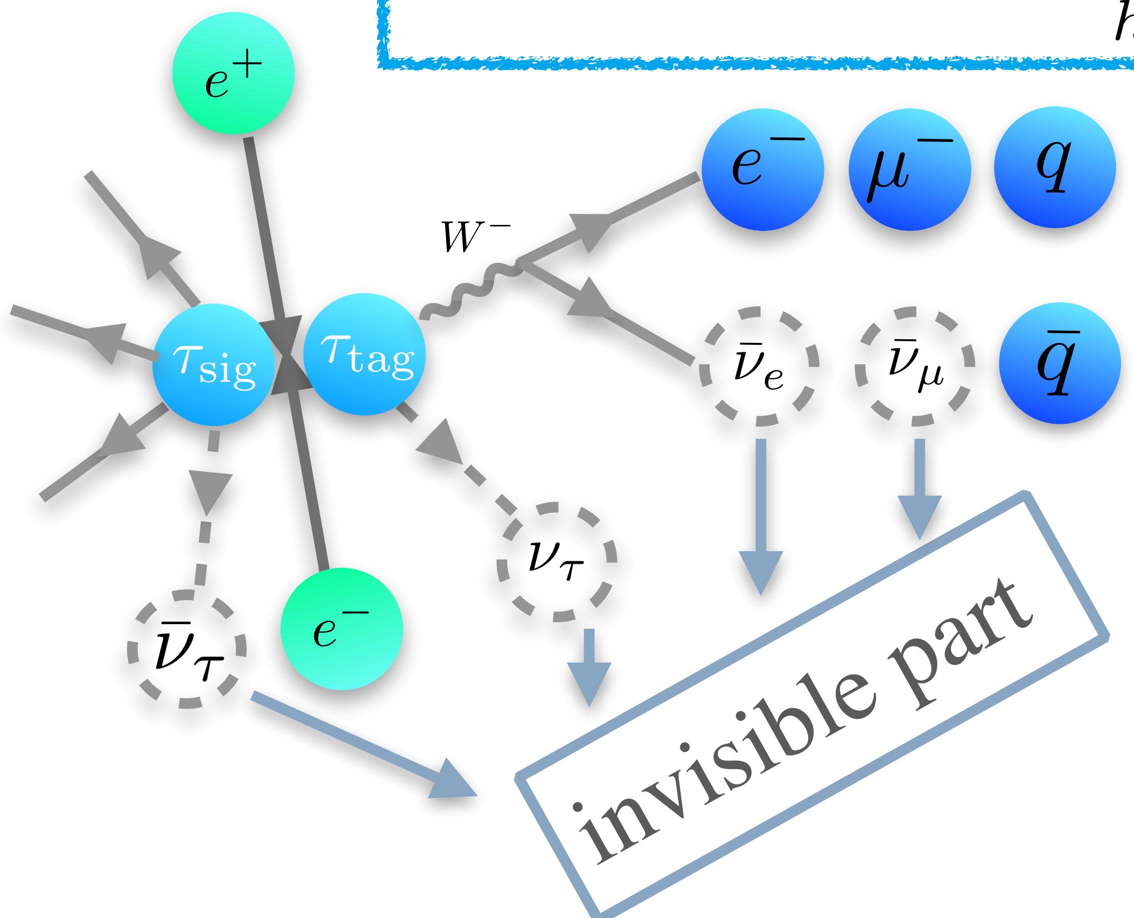
$$\text{thrust value} = \sum_h \frac{\vec{p}_h \cdot \hat{T}}{|p_h|}$$



- undetected neutrinos in τ events



$$\text{visible energy} = \sum_h E_h$$



Outline of my lecture: SM & BSM

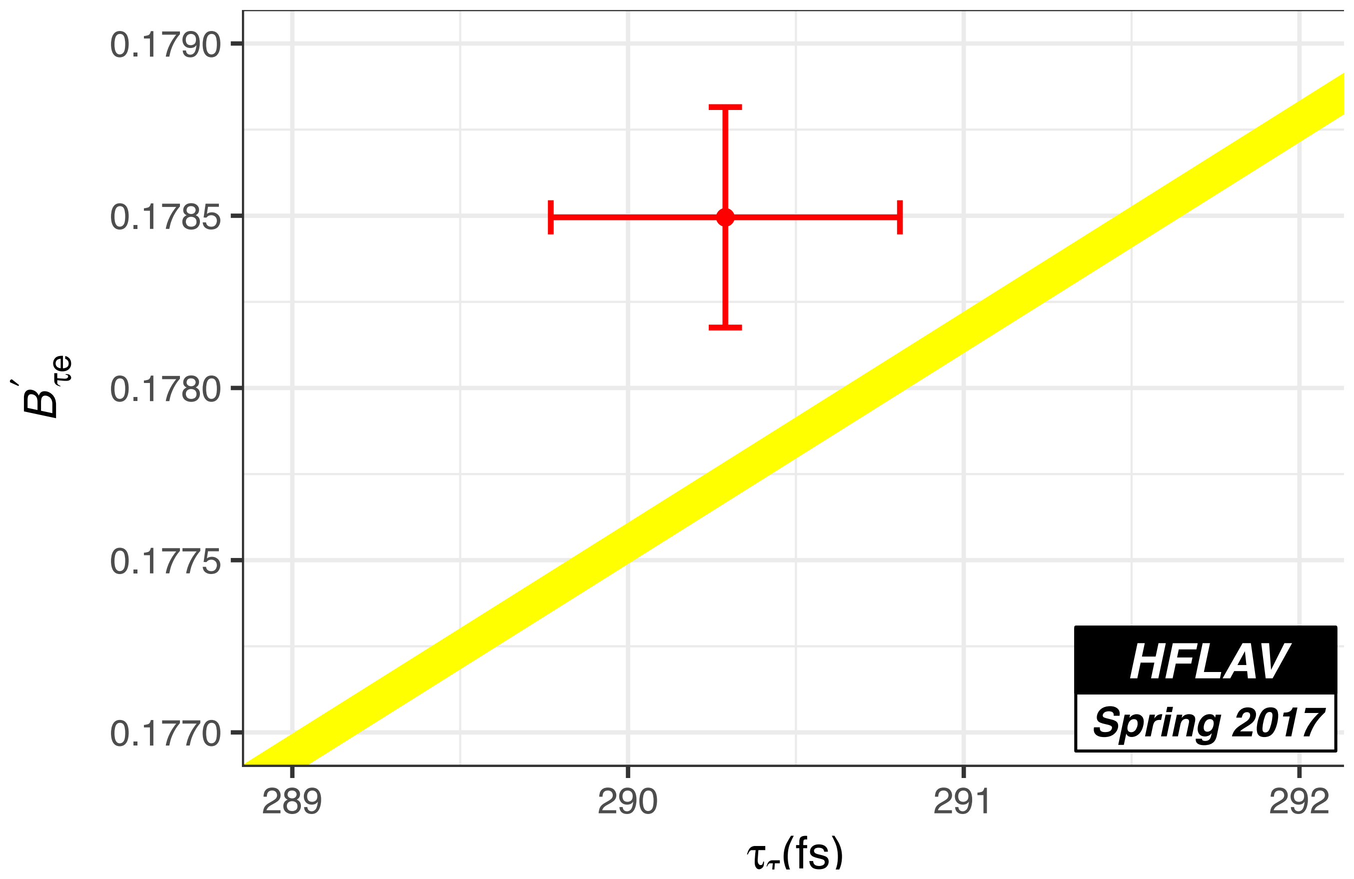
Does NP couple to 3rd generation strongly?

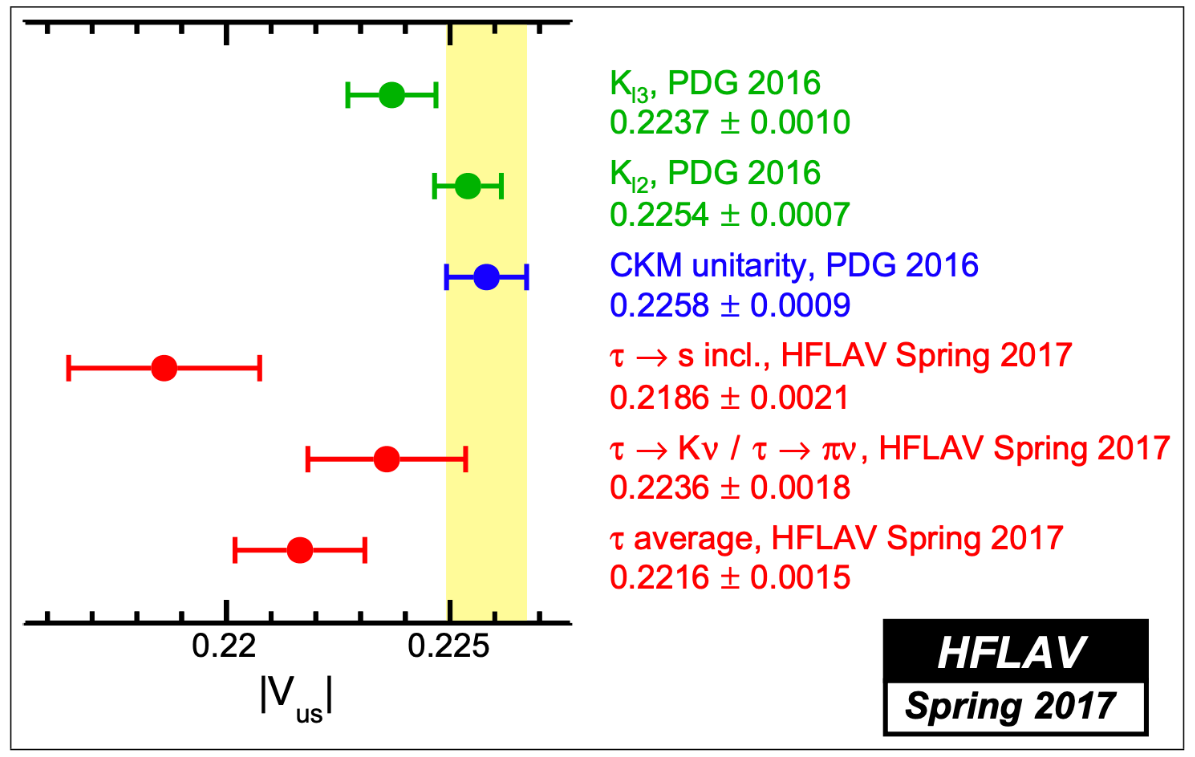
Precision measurements or indirect search of BSM

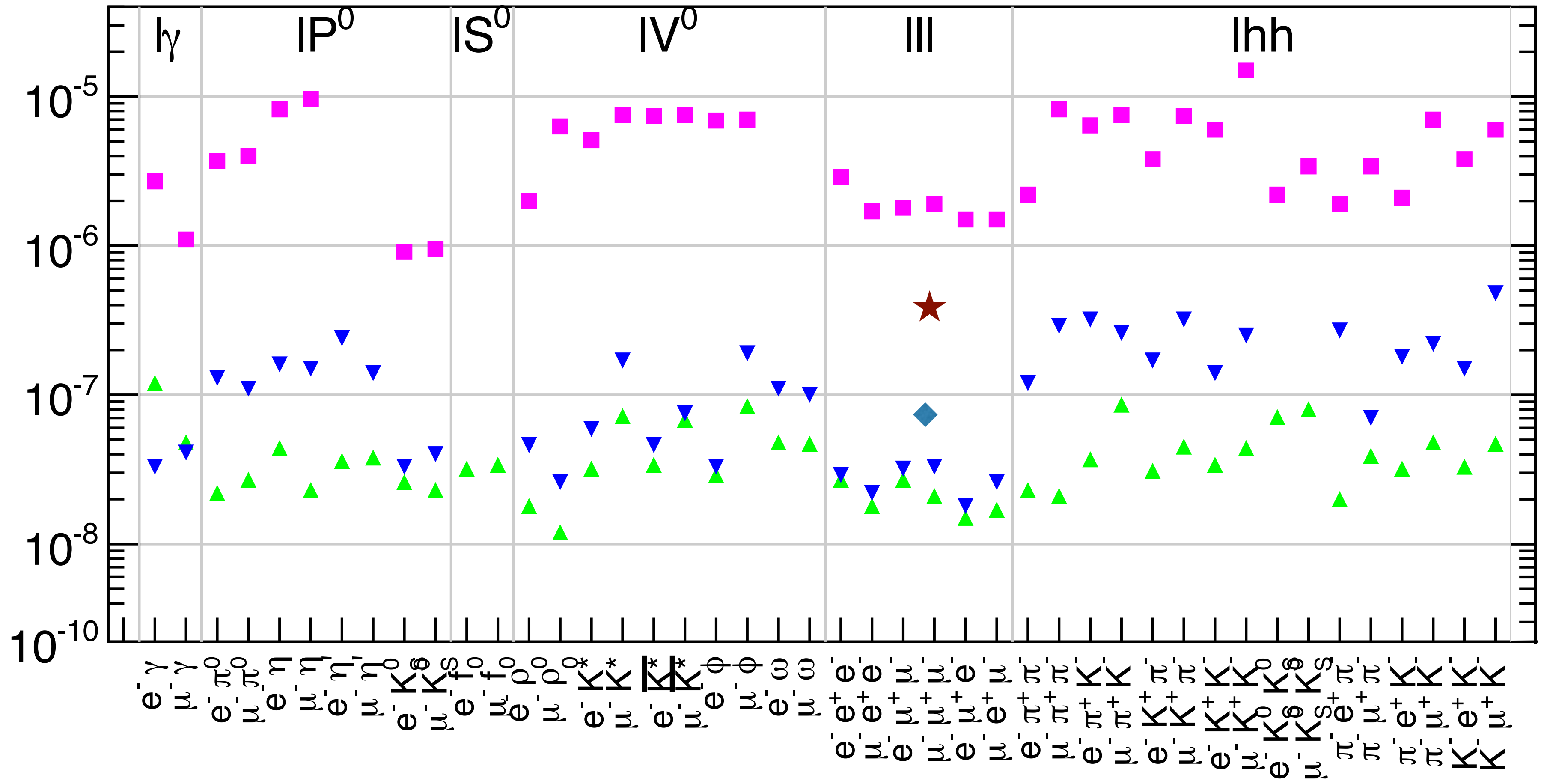
- elementary particles ***talk*** to each other through loops and boxes
  - learn about ***new particles*** by making precision measurements of the ***"talking"*** particle's properties
- 1-prong τ decays probe the SM predictions of charged current **lepton universality** and the **unitarity** relation of the first row of the **CKM** quark mixing matrix.
- ***significant deviations from SM*** are unambiguous signatures of NP

Direct search of BSM

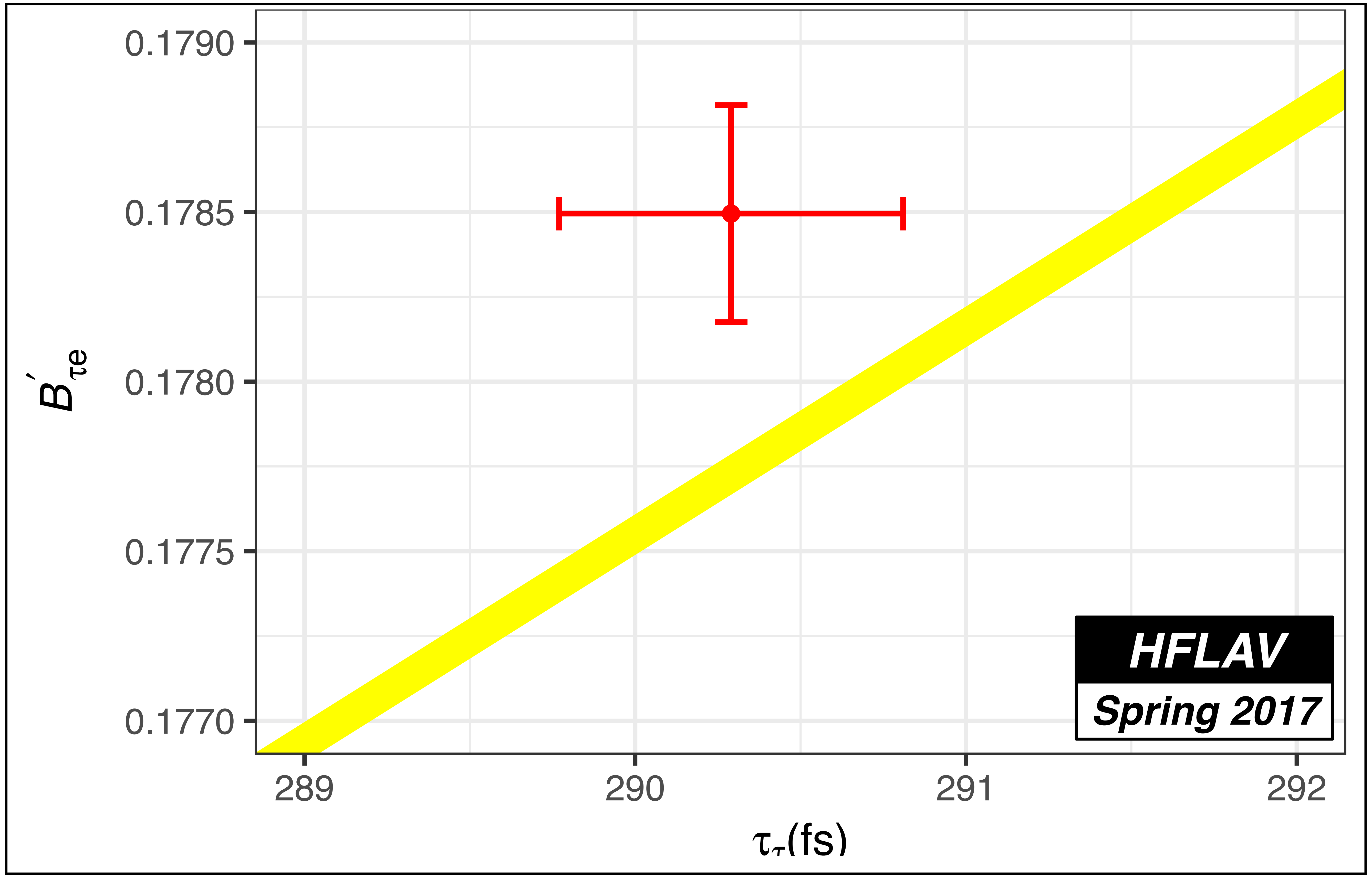
- search of forbidden decays
  - **LFV** and **LNV** decays
- **any signal** is unambiguous signature of NP







The mass, lifetime and leptonic decays of τ

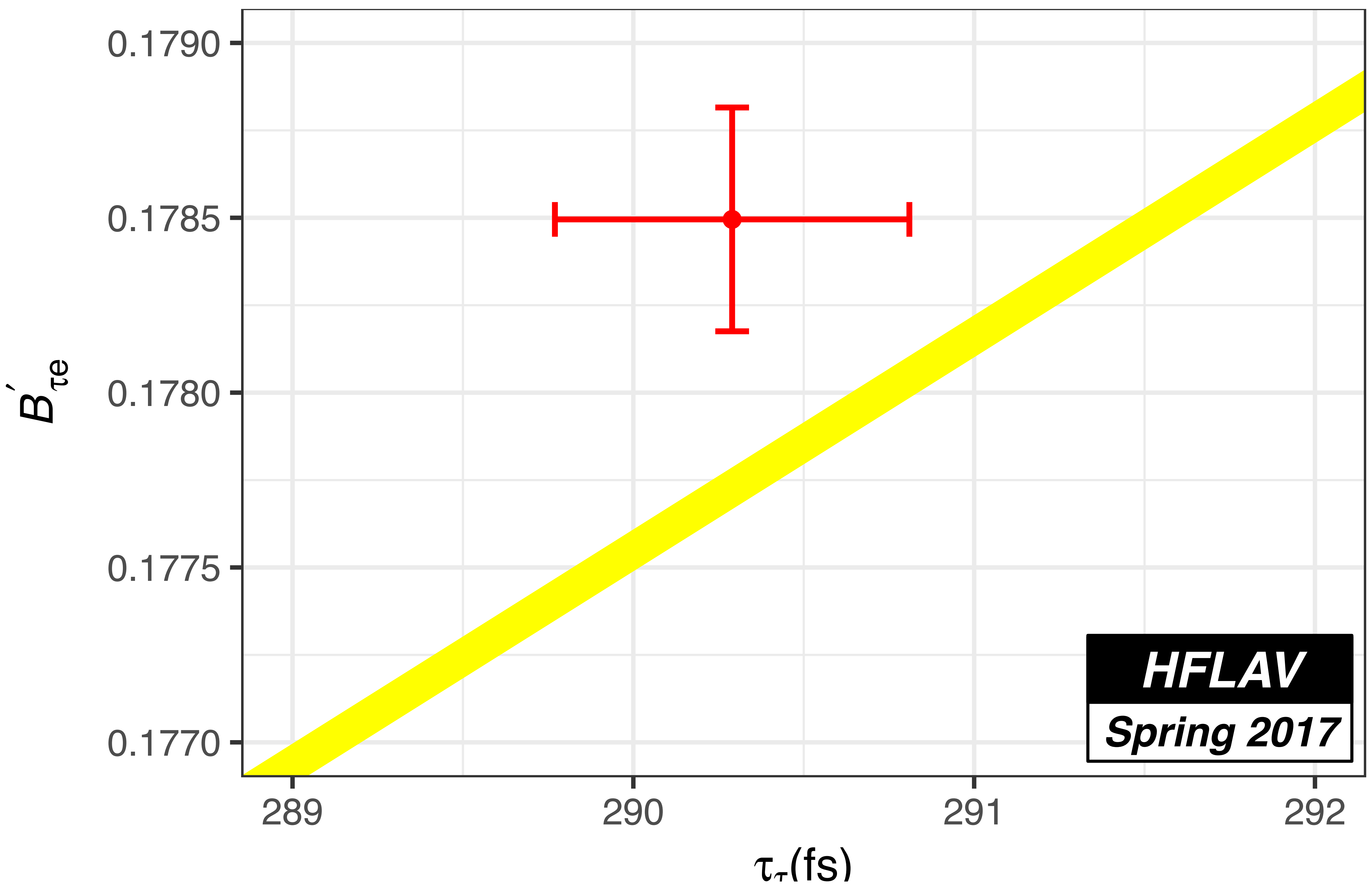


The mass, lifetime and leptonic decays of τ

Lepton masses and lifetimes are fundamental parameters of SM!

- A precise tau mass and lifetime measurements are crucial for lepton universality tests of SM
- Possibility to test CPT conservation measuring τ^- and τ^+ lifetimes and masses separately.

A. Lusiani et al: arXiv:1804.08436



Lepton Masses (MeV):

- m_e= 0.5109989461 ± 0.0000000031 $\delta m/m \sim 6*10^{-9}$
- m_μ= 105.6583745 ± 0.0000024 $\delta m/m \sim 2*10^{-8}$
- m_τ= 1776.86 ± 0.12 $\delta m/m \sim 7*10^{-5}$

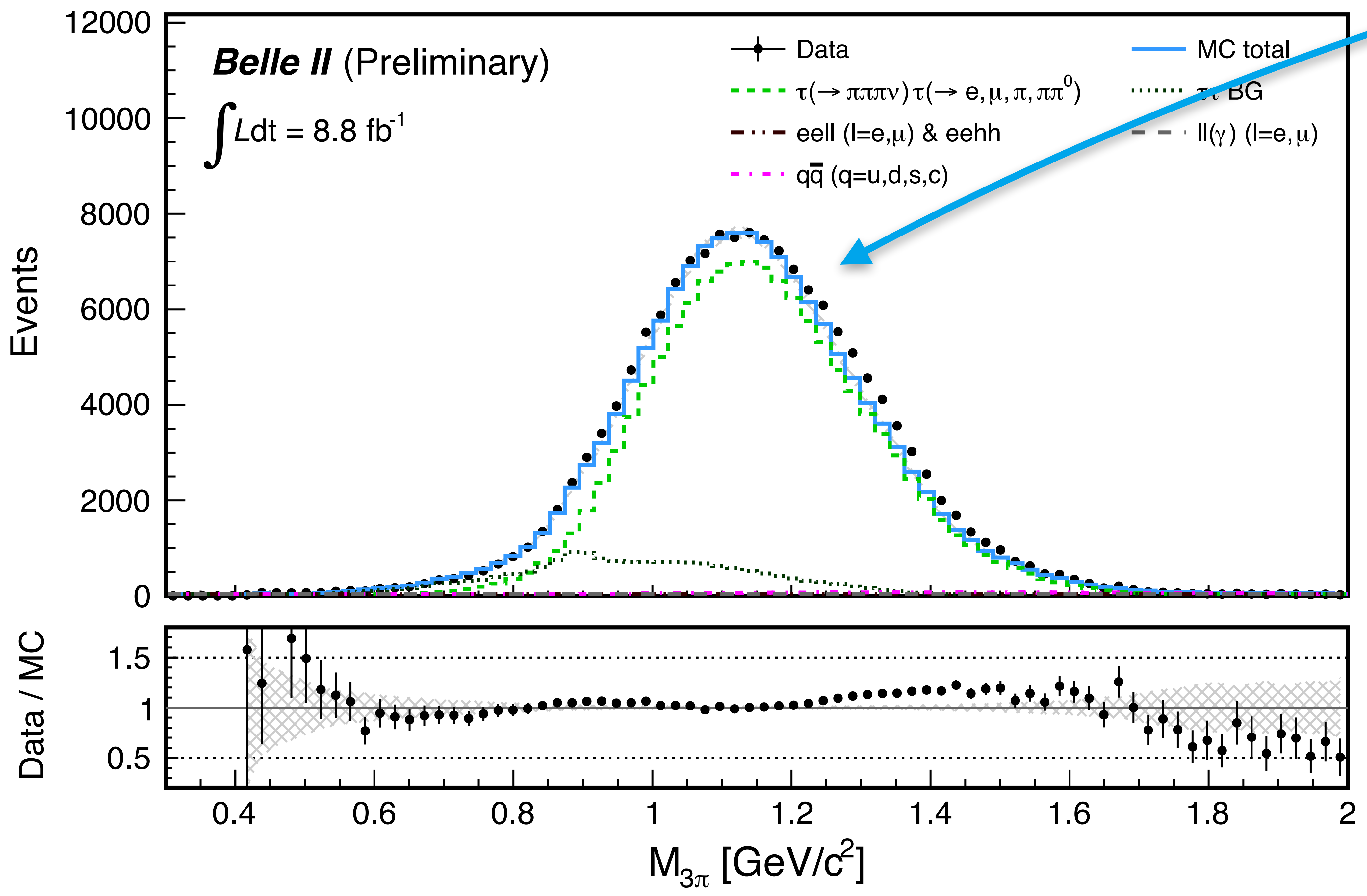
$$B_{\tau l} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

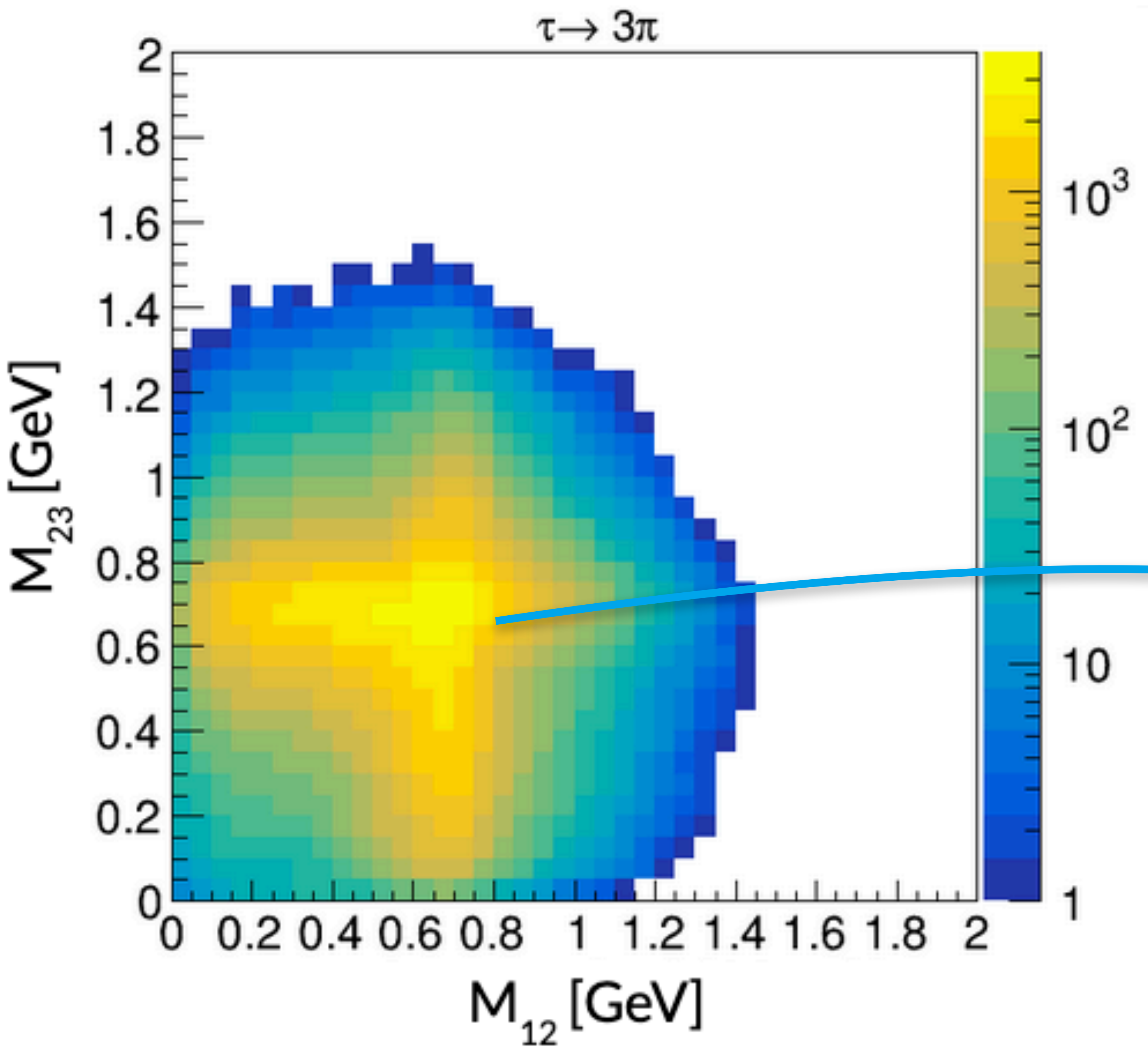
Similar situation for lifetime

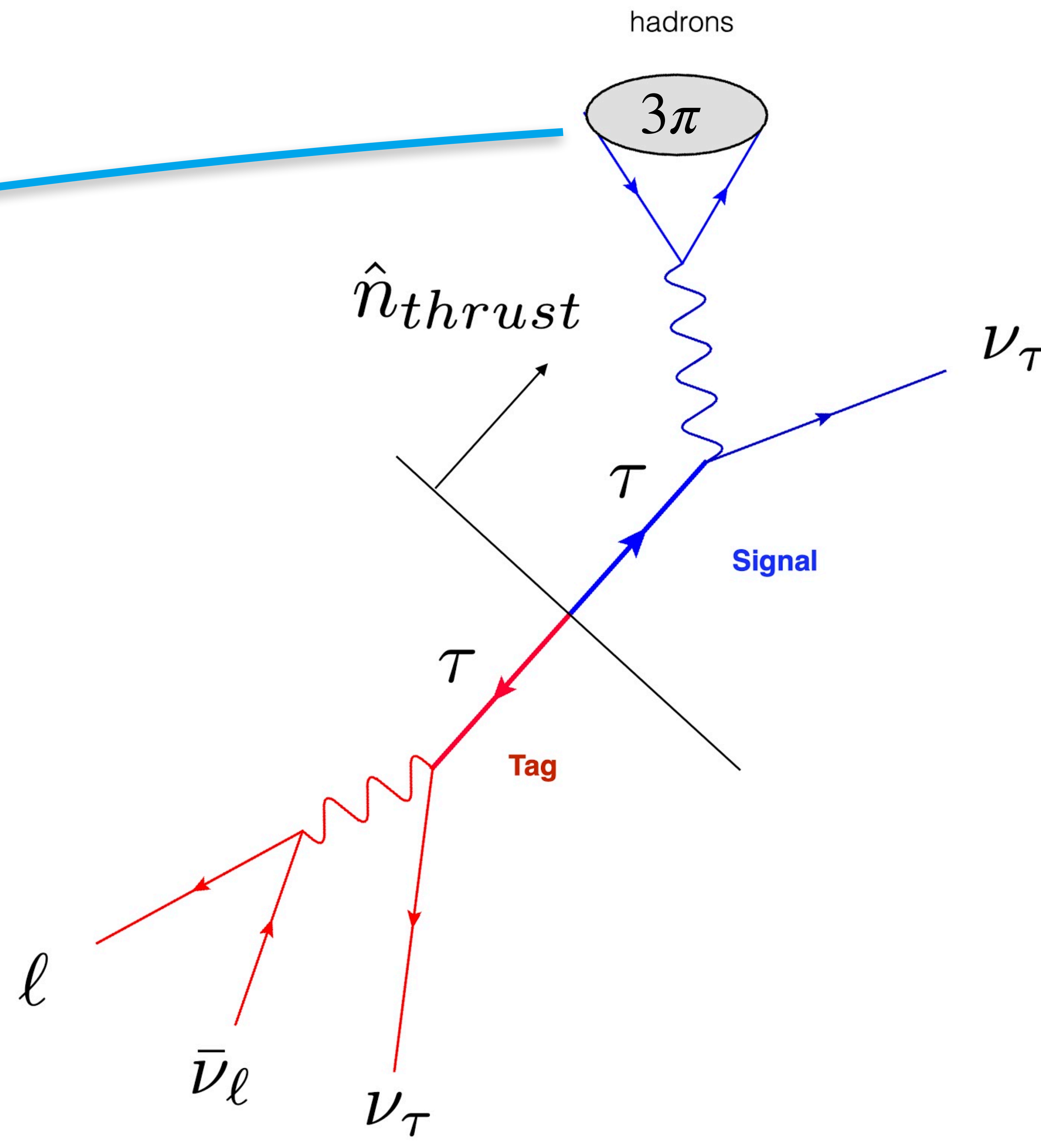
τ mass measurement

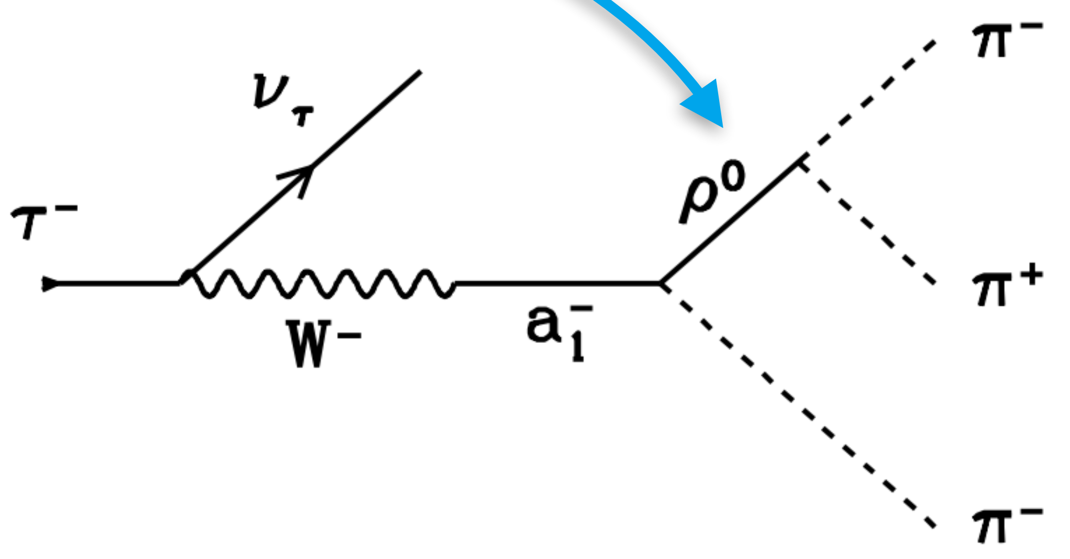
The τ mass cannot be measured directly

➡ neutrinos in the final state









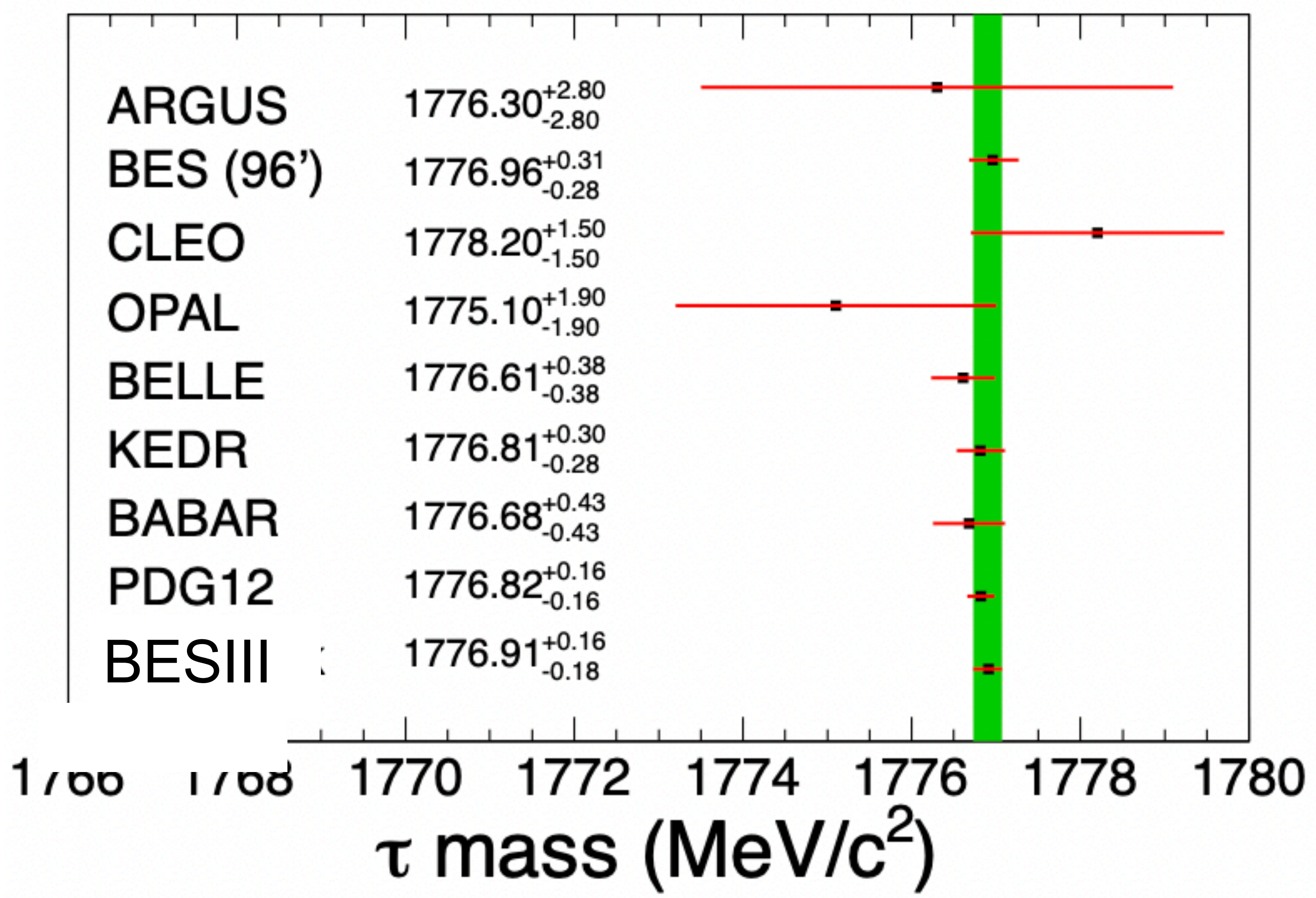
Why important to have a precise measurement of τ mass?

Threshold scan method

- DELCO, BES, KEDR, BESIII
- exploits the threshold behaviour of the τ-pair production cross section in e^+e^- collisions

Pseudomass technique

- ARGUS, OPAL, BELLE, BABAR
  - relies on the reconstruction of the invariant mass and energy of the hadronic system in the hadronic τ decay



- SM prediction for the relationship between the τ lifetime, mass, $B(\tau \to e\nu\bar{\nu})$ and weak coupling constant

$$\frac{B(\tau \to e\nu\nu)}{\tau_\tau} = \frac{g_\tau^2 m_\tau^5}{192\pi^3}$$

- violated before the first precise mass measurement by BES

BES - PRL V69 (1992) 3021 -

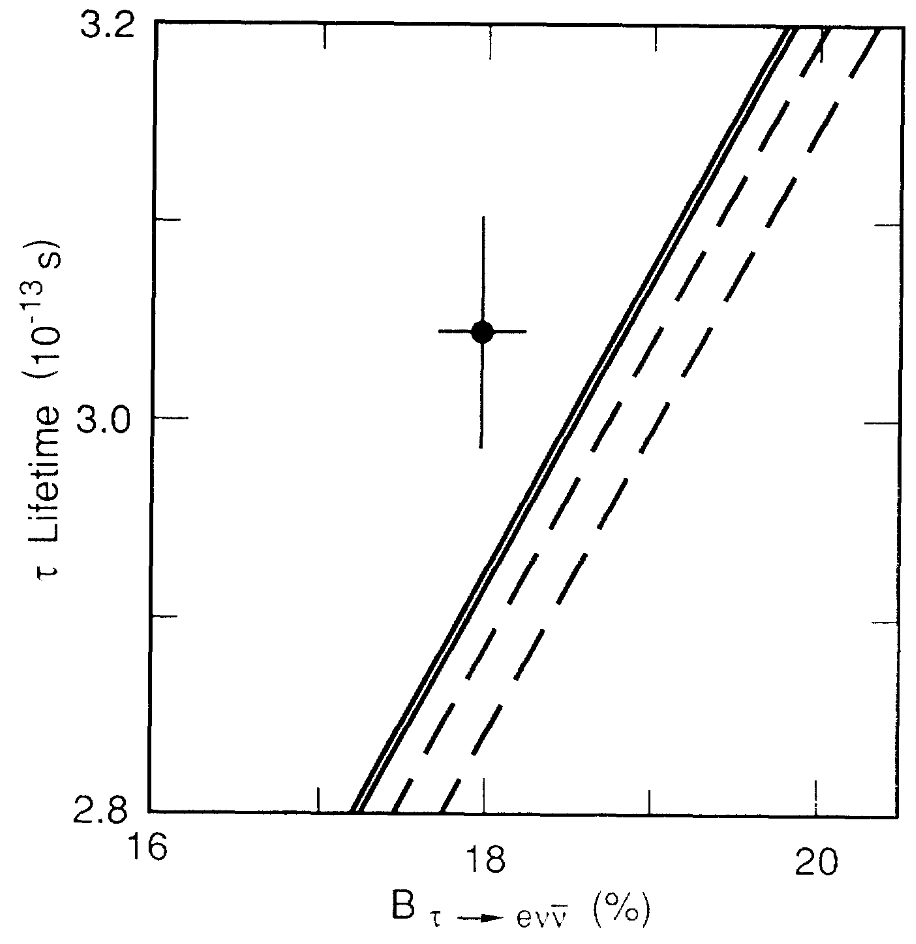


FIG. 3. The variation of τ_τ with B_τ^e, given by Eq. (1) under the assumption of lepton universality; the $\pm 1\sigma$ bands obtained using m_τ from this experiment (solid lines) and using the PDG value (dashed lines) are shown in comparison to the point corresponding to the PDG values (1σ error bars).

Threshold scan method

Determination of the beam energy and the beam energy spread precisely is of great importance

- measure the electron and positron beam energies with one laser using Compton backscattering principle

$$E_e = \frac{E_\gamma}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\epsilon_\gamma E_\gamma}}\right]$$

beam energy

energy of the laser beam

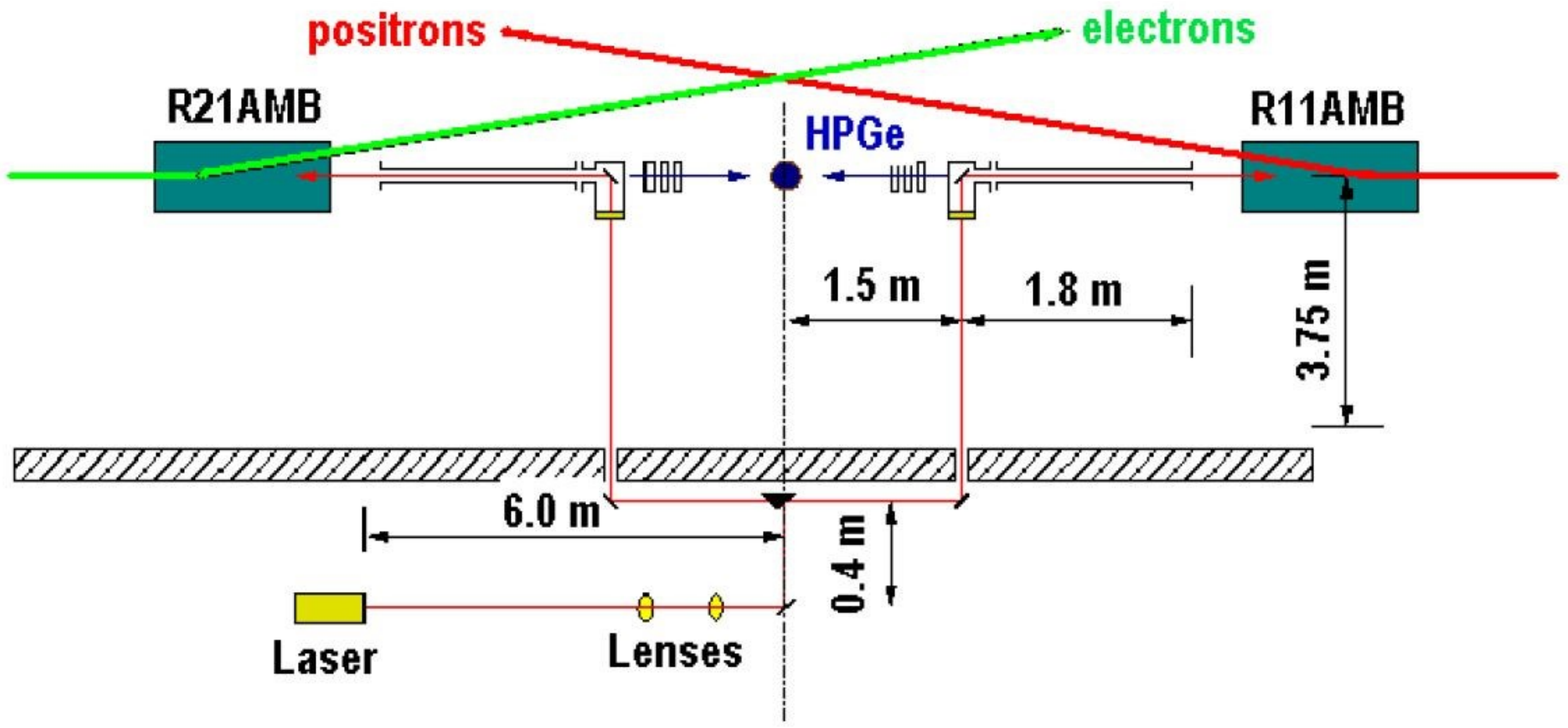
max energy of scattered photon

- E_e accuracy at the level of 10^{-5}.
- data at 4 scan points near τ pair production threshold
  - the first τ scan point is below the mass of τ pair while the other three are above
- Likelihood function to estimate the τ mass

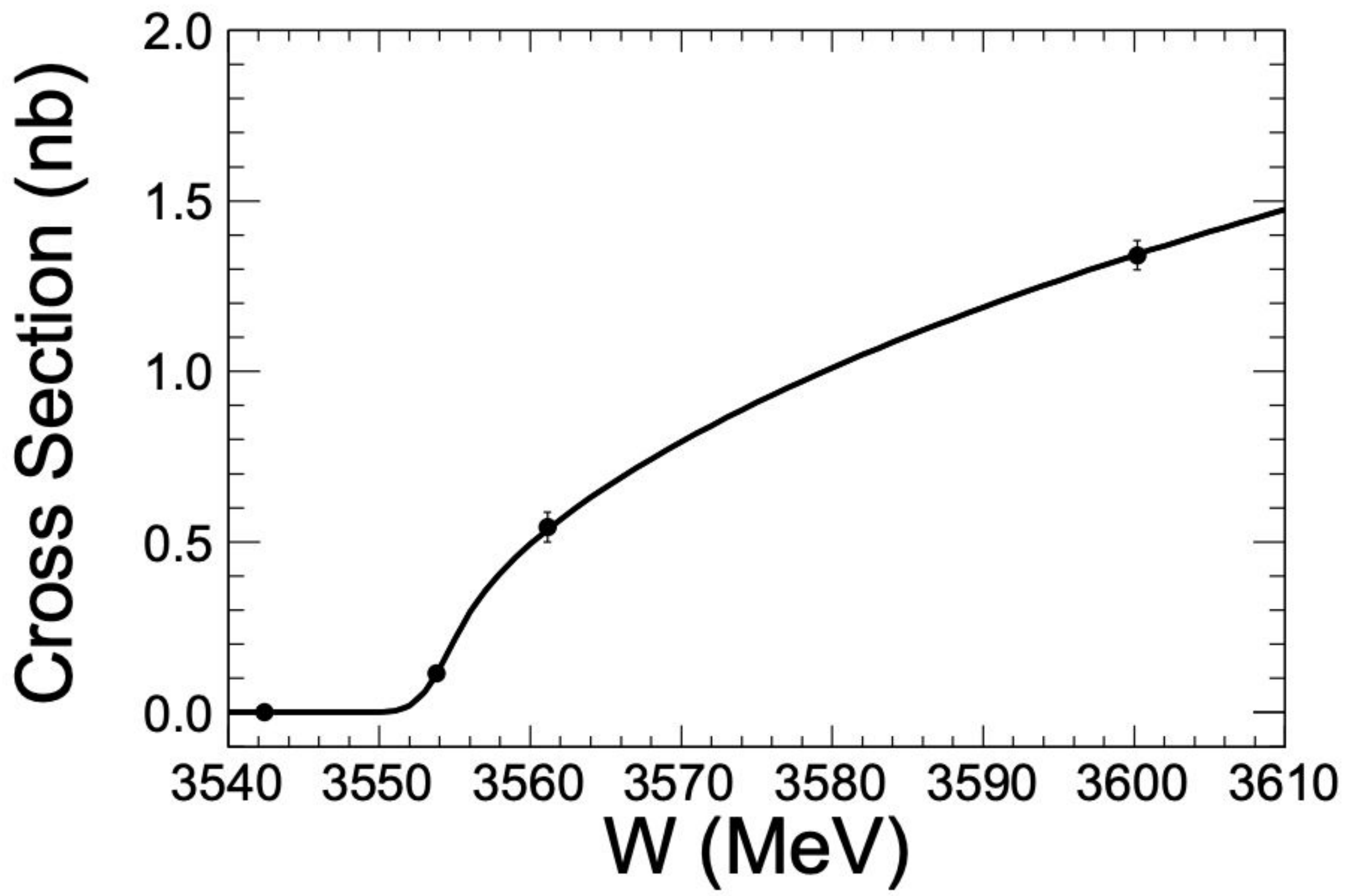
$$L(m_\tau, \mathcal{R}_{Data/MC}, \sigma_B) = \prod_{i=1}^{4} \frac{\mu_i^{N_i} e^{-\mu_i}}{N_i!}$$

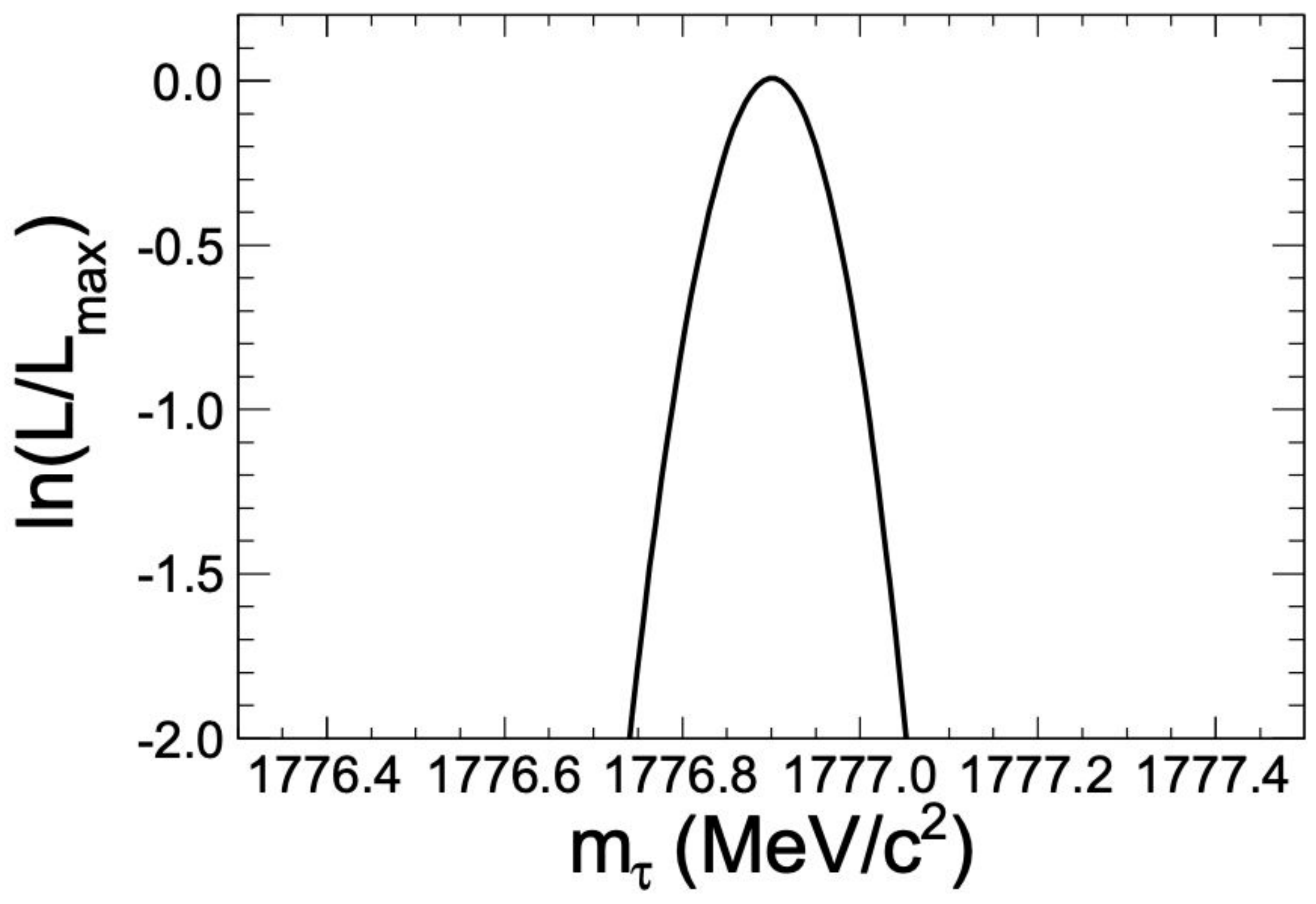
$$\mu_i = [\mathcal{R}_{Data/MC} \times \epsilon_i \times \sigma(E^i_{\mathrm{CM}}, m_\tau) + \sigma_B] \times \mathcal{L}_i.$$

Beam Energy Measurement System



BES III - Phys. Rev. D 90, 012001 (2014)-





Pseudomass technique

Use conservation of momentum and energy:

$$\mathcal{P}_\tau^2 = (\mathcal{P}_\nu + \mathcal{P}_{3\pi})^2$$
$$\Rightarrow m_\tau^2 = m_\nu^2 + m_{3\pi}^2 + 2(E_\nu\ E_{3\pi} - \vec{p_\nu}\cdot\vec{p_{3\pi}}) \quad (1)$$
$$= m_\nu^2 + m_{3\pi}^2 + 2(E_\nu\ E_{3\pi} - p_\nu p_{3\pi}\cos\theta)$$

Use:

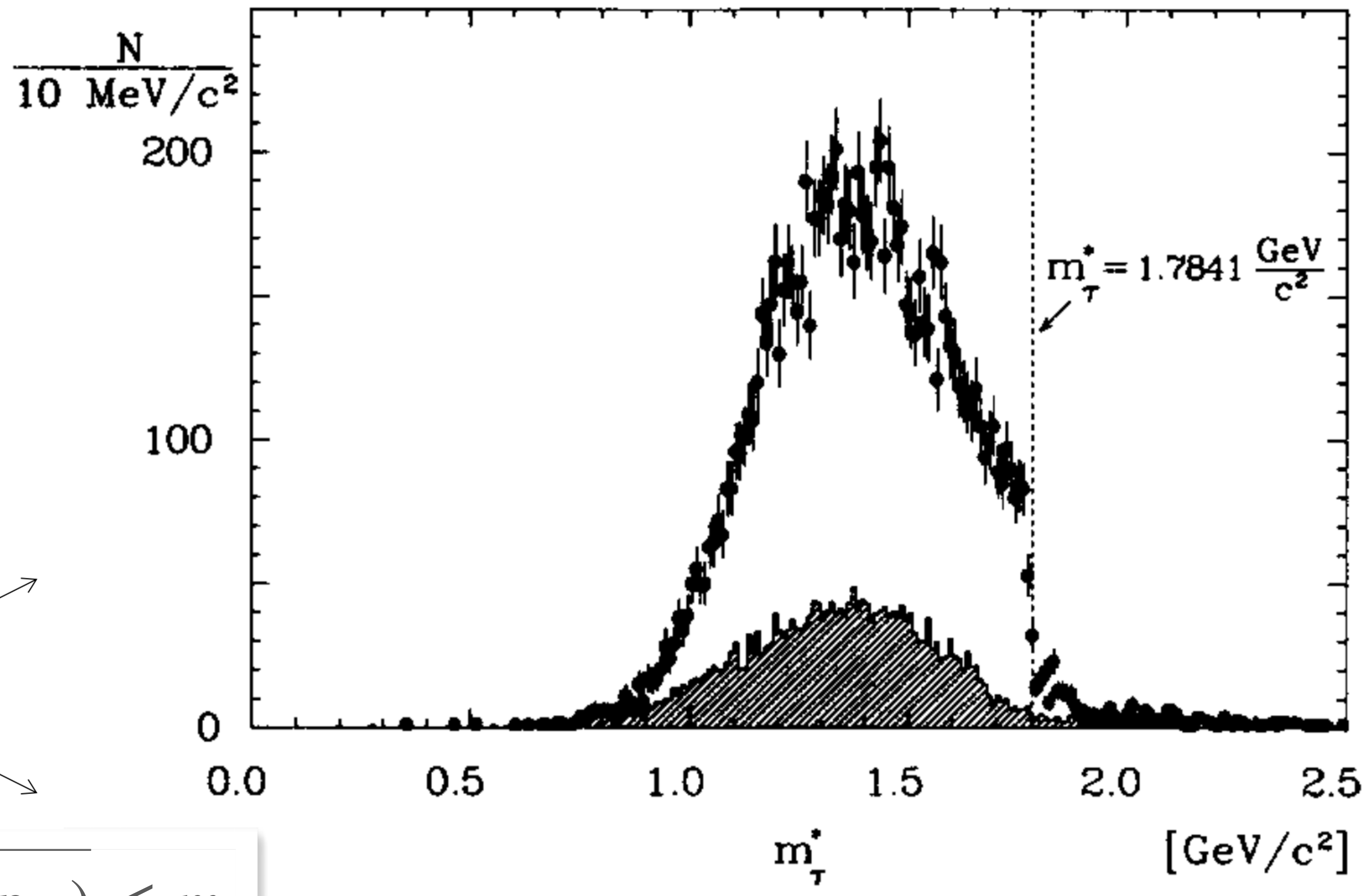
$$E_\nu = E_\tau - E_{3\pi}, and$$
$$p_\nu = \sqrt{E_\nu^2 - m_\nu^2} = E_\nu = E_\tau - E_{3\pi} \quad (2)$$

To get:

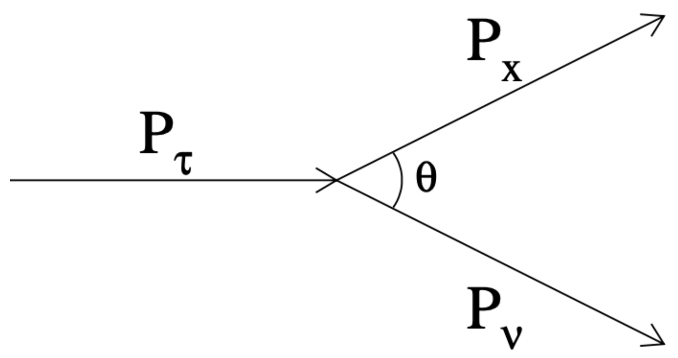
$$m_\tau^2 = m_{3\pi}^2 + 2\Big((E_\tau - E_{3\pi})\ E_{3\pi} - (E_\tau - E_{3\pi})p_{3\pi}\cos\theta_{\nu,3\pi}\Big) \quad (3)$$
$$= m_{3\pi}^2 + 2(E_\tau - E_{3\pi})(E_{3\pi} - p_{3\pi}\cos\theta_{\nu,3\pi})$$

The distribution has a kinematic edge around the τ mass

- a sharp threshold behaviour in the region close to the nominal value of the τ mass
- first used by ARGUS in 1992, later by Opal, BELLE and now by BELLEII



- in the centre of mass $E_\tau = E_{beam} = \sqrt{s}/2$
- the equation has a minimum when $\cos\theta_{\nu,3\pi} = 1$



This is called pseudomass

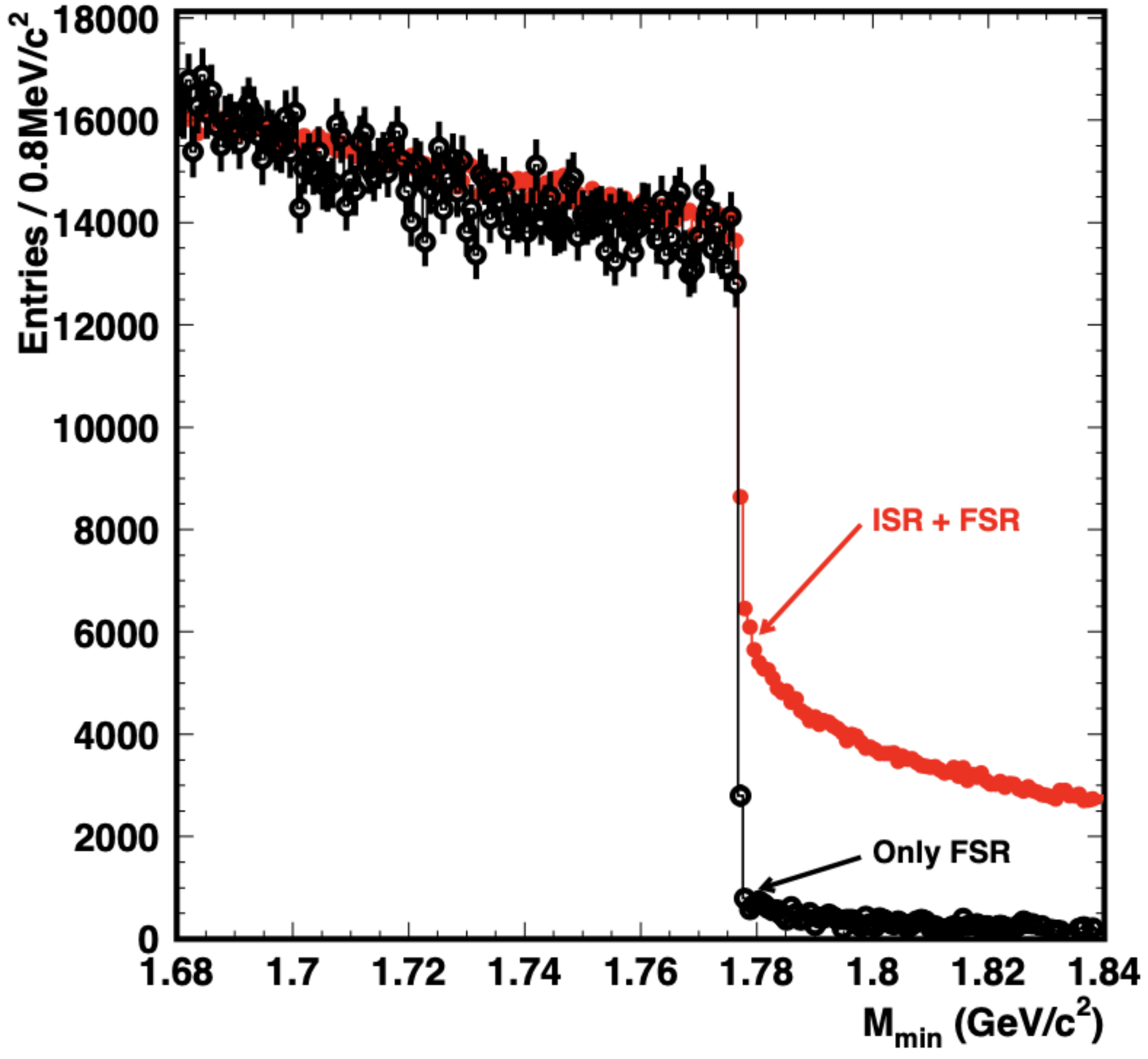
$$m_{\min} = \sqrt{m_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - p_{3\pi})} \leq m_\tau$$

The threshold behaviour

$$m_{\min} = \sqrt{m_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - p_{3\pi})} \leq m_\tau$$

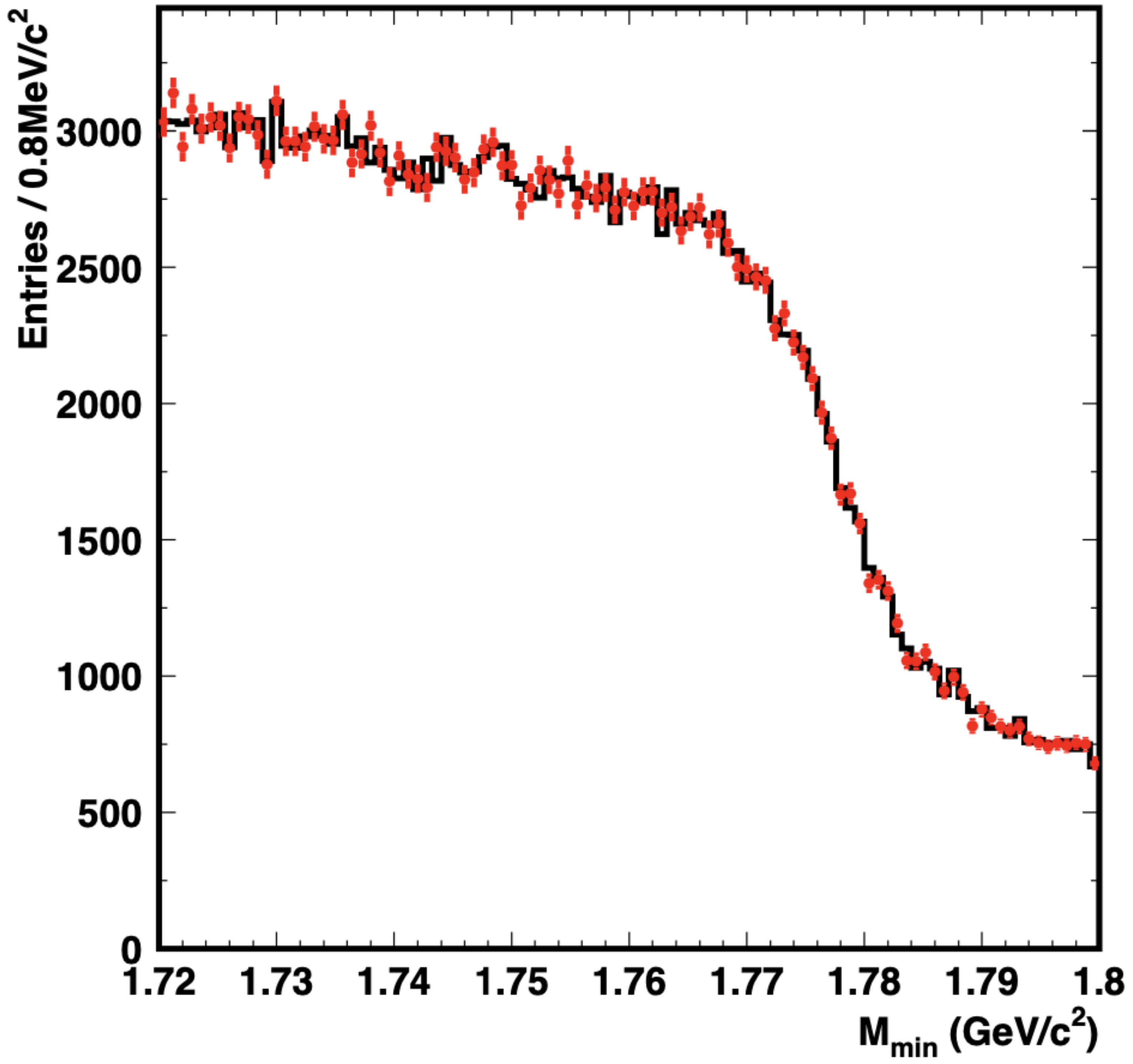
The tails

➡ ISR + FSR



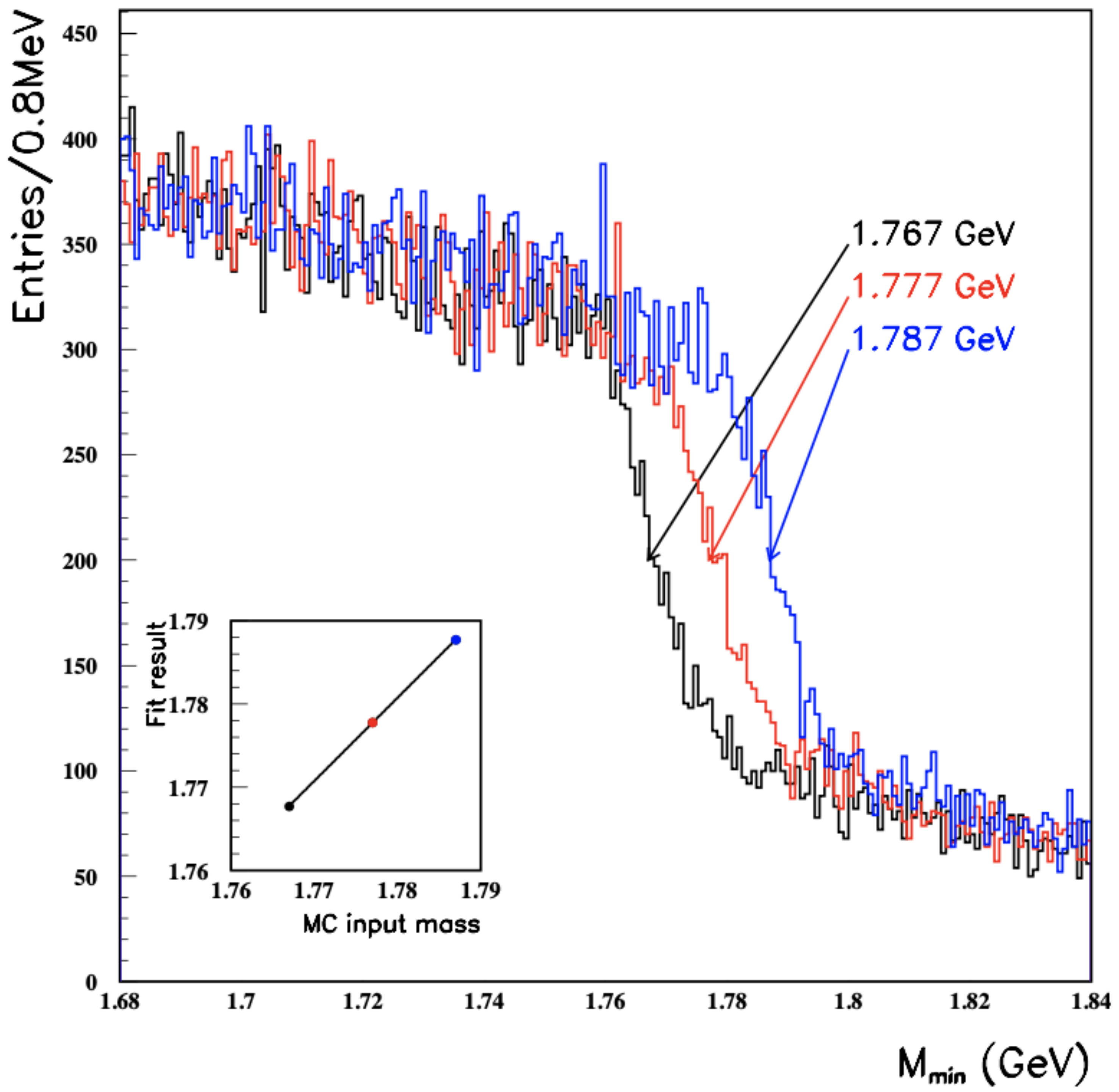
Smearing of the edge

➡ detector resolution



Position of the edge

➡ depends on mass



➡ the edge position can be exploited to extract the mass

The τ lepton mass

High signal purity

- the remaining continuum backgrounds are flat
  - don't impact the shape of the distribution

Mass extraction using ML fit

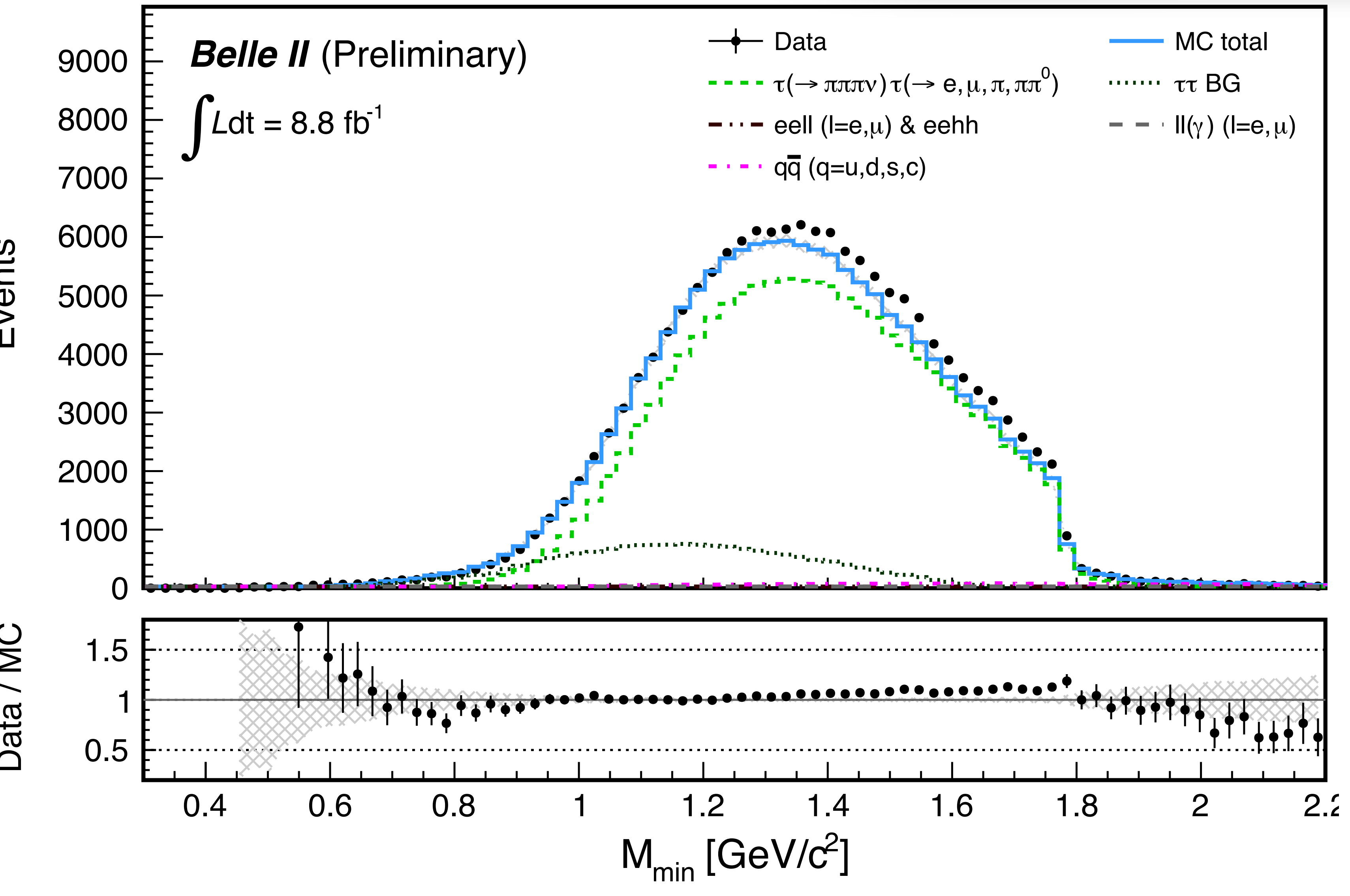
- P1 is an estimator for the τ mass
- with multi/additive components to describe the tails

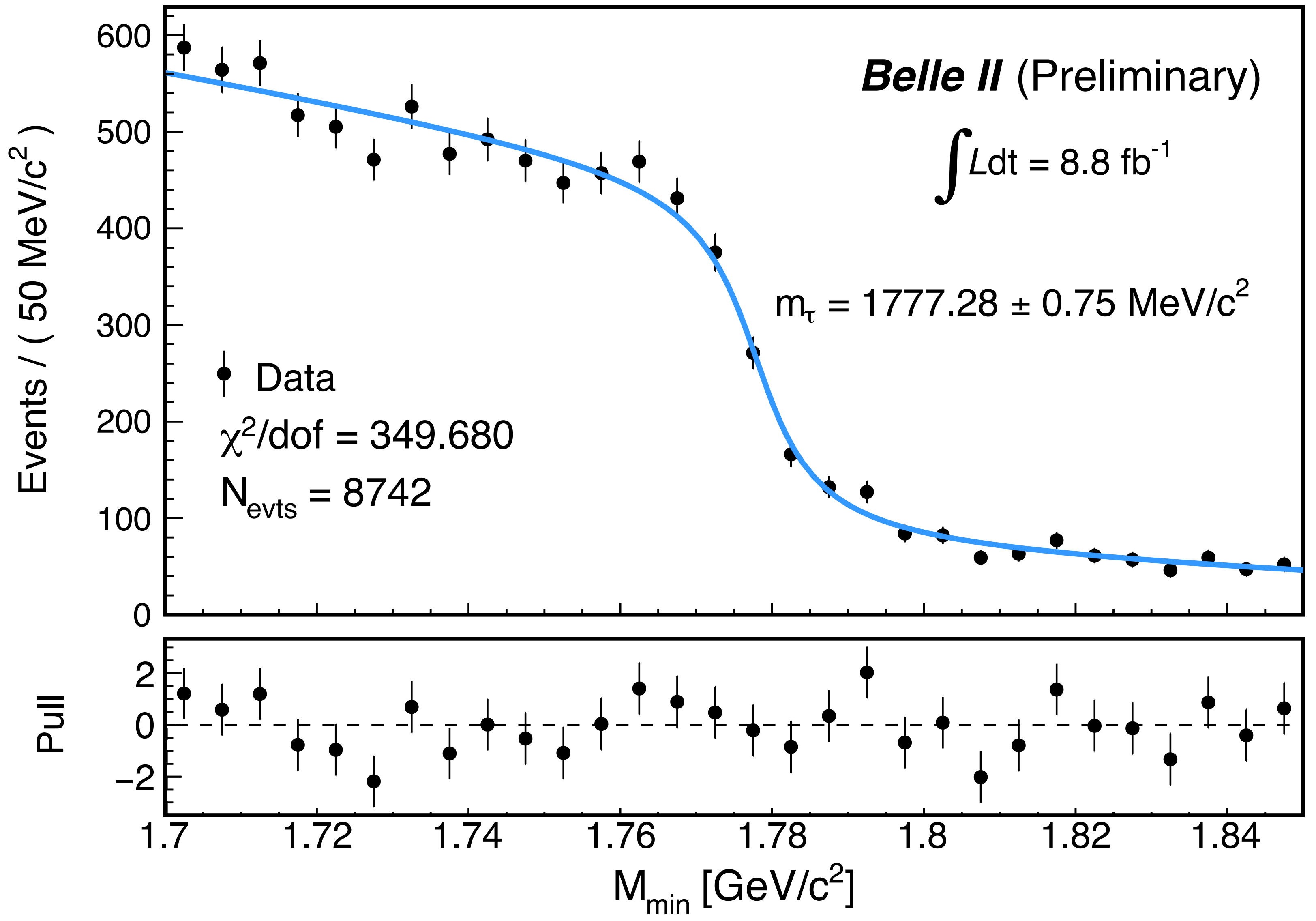
Systematics

- Compatible precision with previous B factory results
- dominated by uncertainty on the track momentum scale
- expected to improve

$$F(M_{min} \,|\, \vec{P}) = (P_3 + P_4 \cdot M_{min}) \cdot \tan^{-1}[(M_{min} - P_1)/P_2] + P_5 \cdot M_{min} + 1$$

BELLE2-NOTE-PH-2020-001



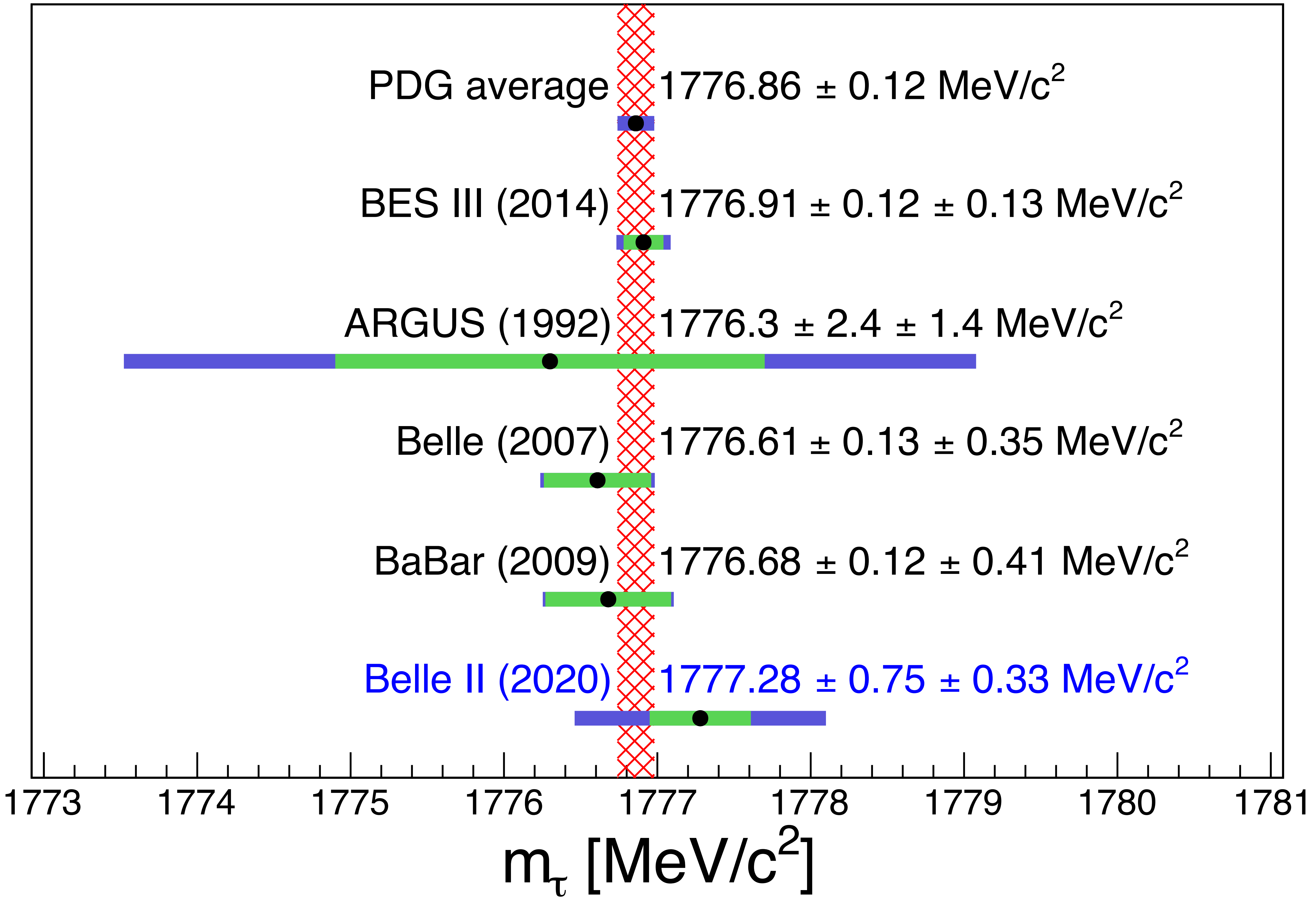


Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

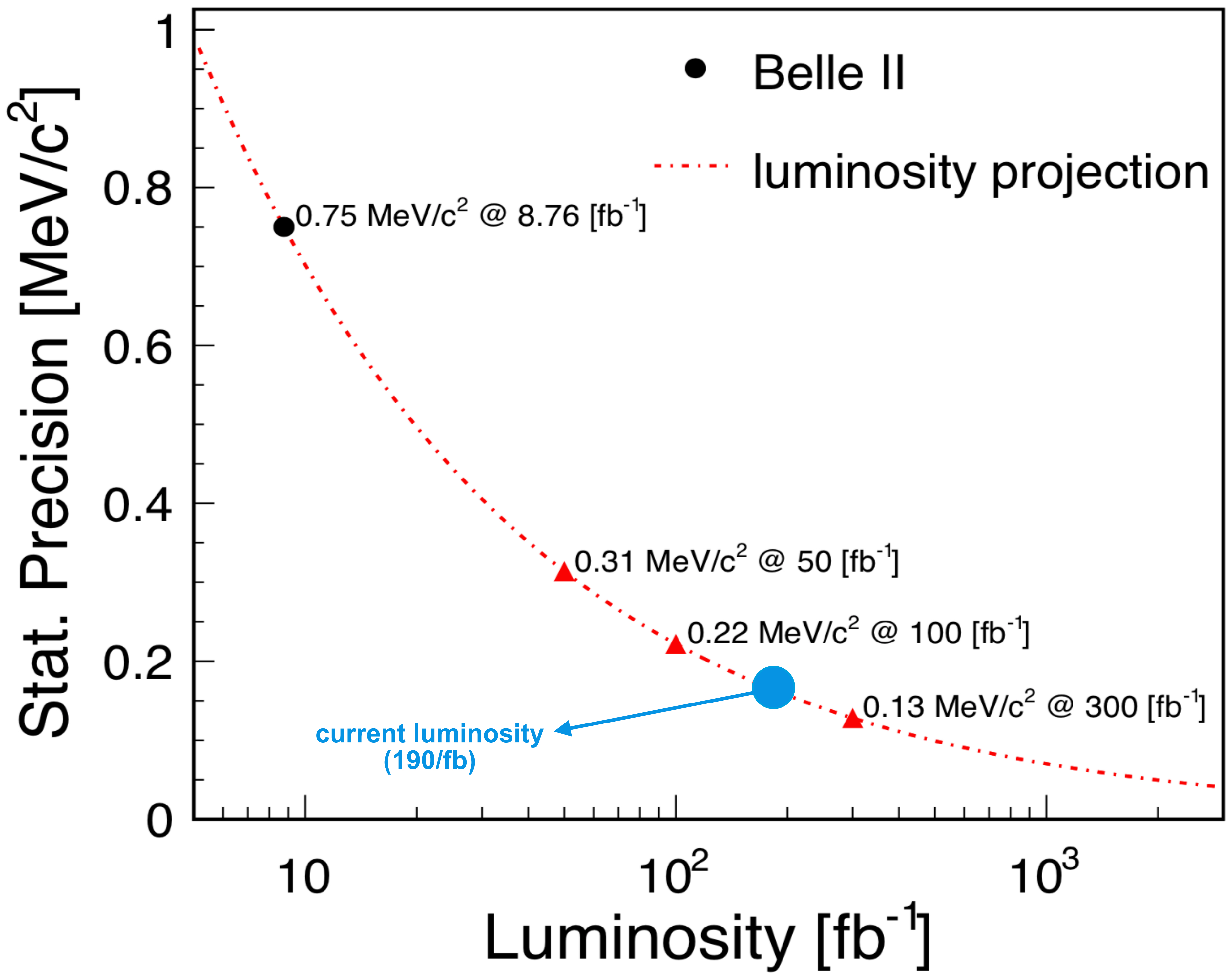
The τ leptons mass

Goal: achieve best precision among pseudomass measurements

- best result from BES III from pair production at threshold energy
- best measurement from pseudomass technique by Belle



- expect to match statistical precision of Belle/BABAR with **~300 fb^{-1}**
- future improvements of systematic uncertainty
- eventually perform CPV test as well



The τ lifetime

The lifetimes of elementary particles are statistical in nature.

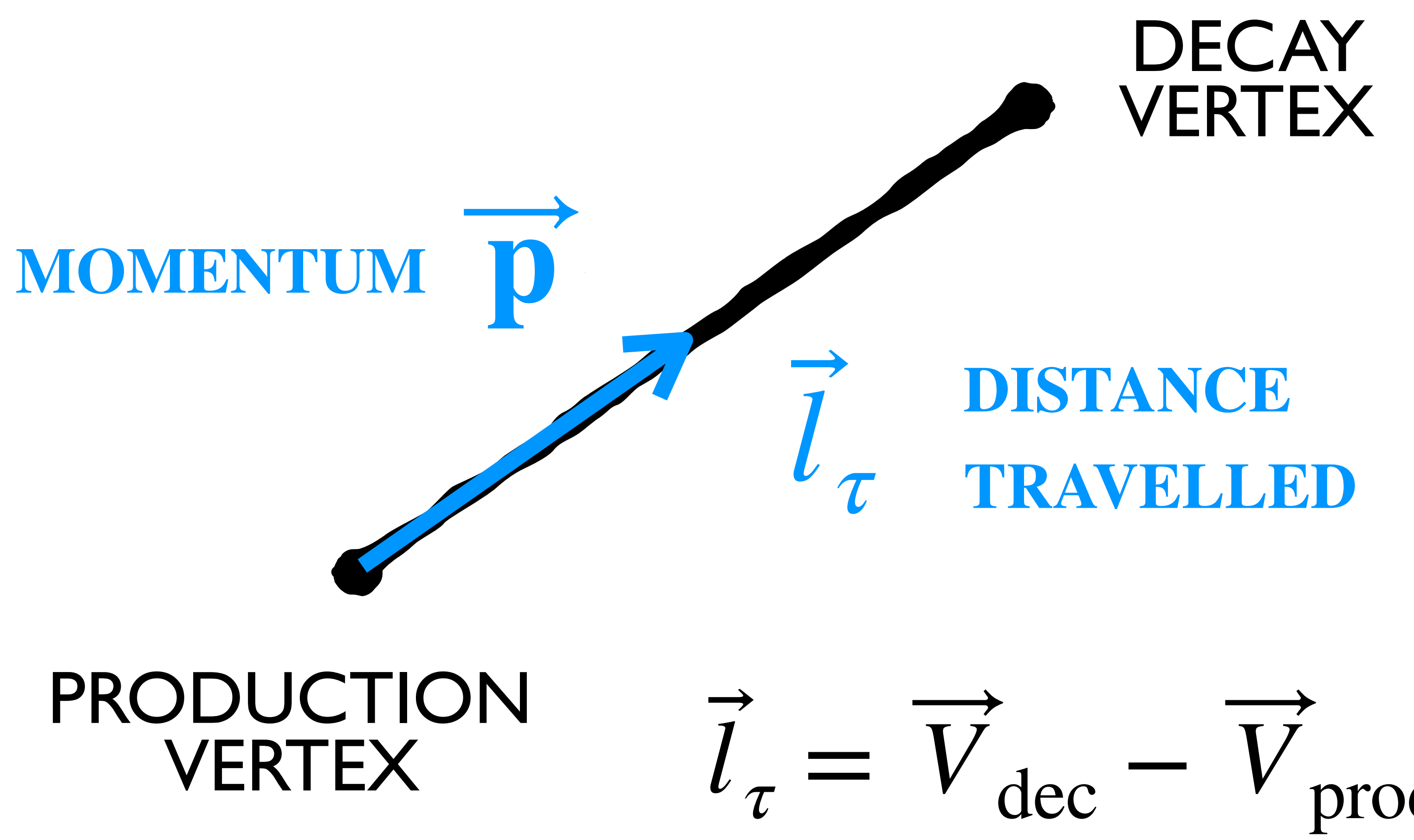
- the lifetime is the time it takes for a sample to decay so that 1/e (~30%) of the sample is left

$$N(t) = N(0)\, e^{-t/\tau}$$

- in an ideal experiment the lifetime τ is extracted with an exponential fit to the proper time distribution $t = t_{\mathrm{dec}} - t_{\mathrm{prod}}$
- the finite resolution of a real experiment has a to be taken into account

$$p(t;\tau) = \frac{1}{\tau} e^{-t/\tau} \times \mathscr{R}(t)$$

← *Proper time resolution*



$$\vec{l}_\tau = \vec{V}_{\mathrm{dec}} - \vec{V}_{\mathrm{prod}}$$

The proper time is measured using the particle's

- flight distance in the lab frame $\vec{l}_\tau$
- momentum $\vec{\mathbf{p}}$ in the lab frame
- $t_{\mathrm{lab}} = l_\tau \,/\, \beta c$
- $t_{\mathrm{lab}} = \gamma\, t_{\mathrm{true}}$

$$t_{\mathrm{true}} = \frac{l_\tau}{\beta\gamma c} = m\frac{l_\tau}{p}$$

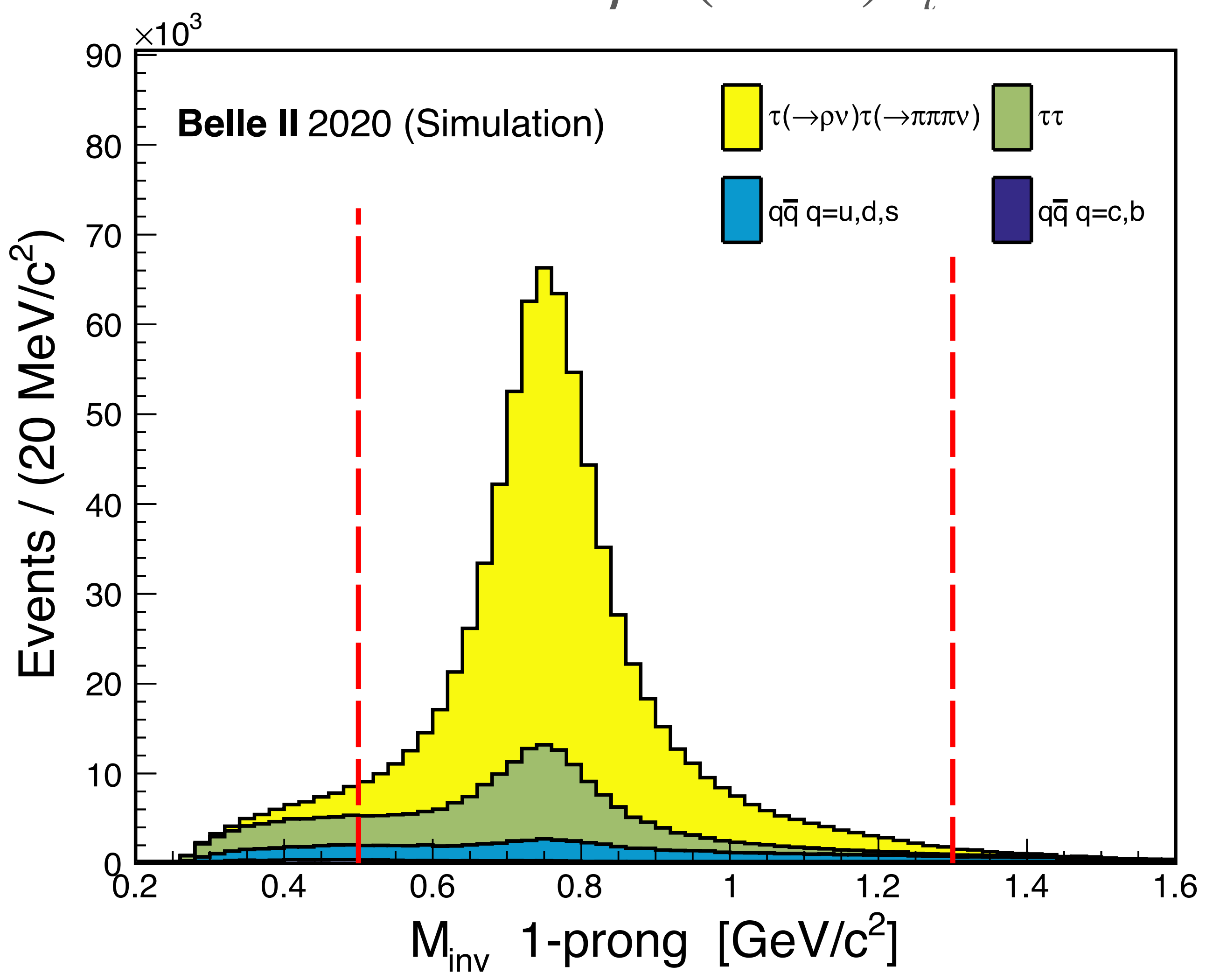
measure these!

Strategy at Belle II

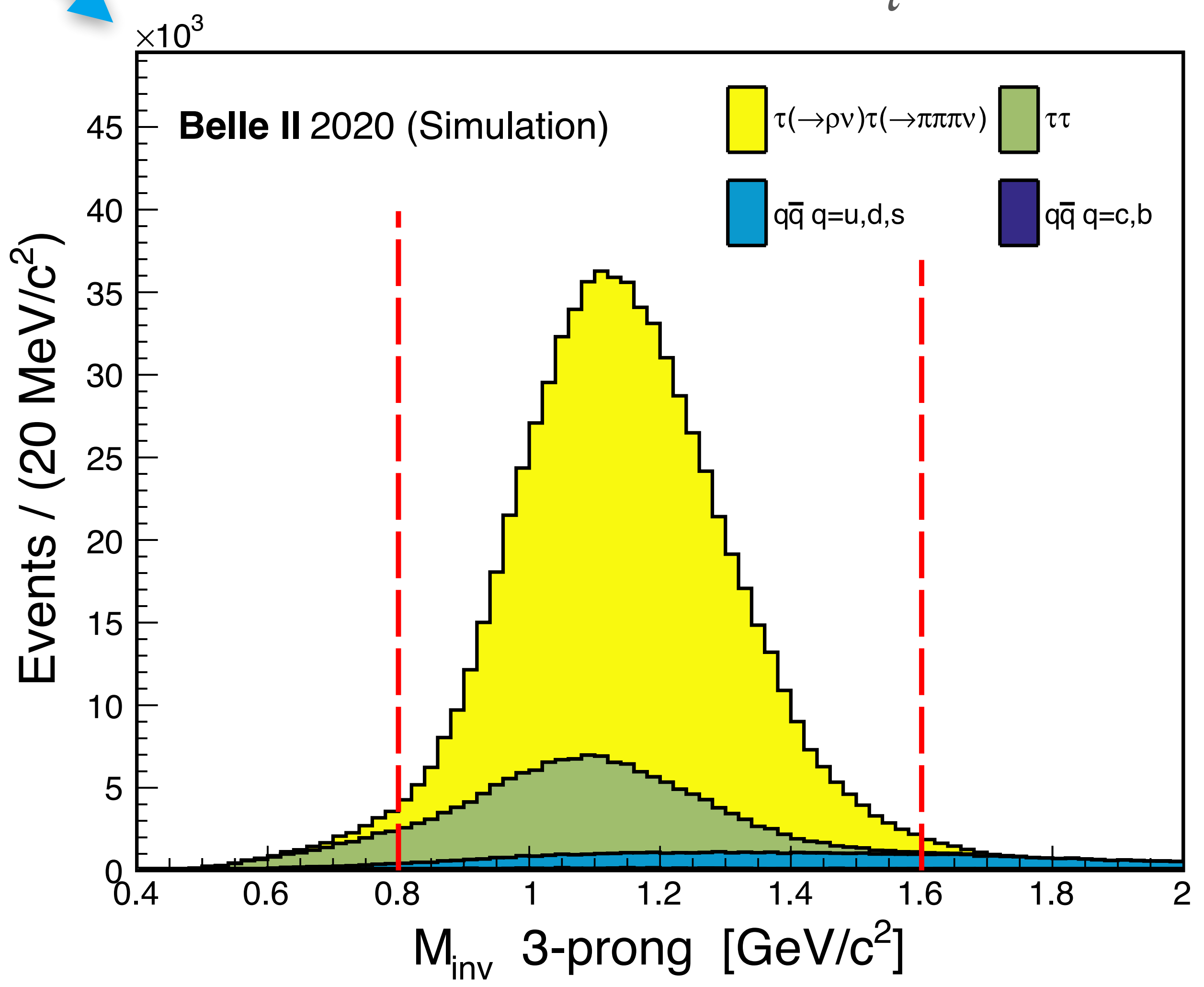
- (1) decay vertex → reconstruct vertex for 3-prong
  - vertex fitting
- (2) estimate τ momentum using τ decay products
  - increase the statistical precision by using 3x1 topology

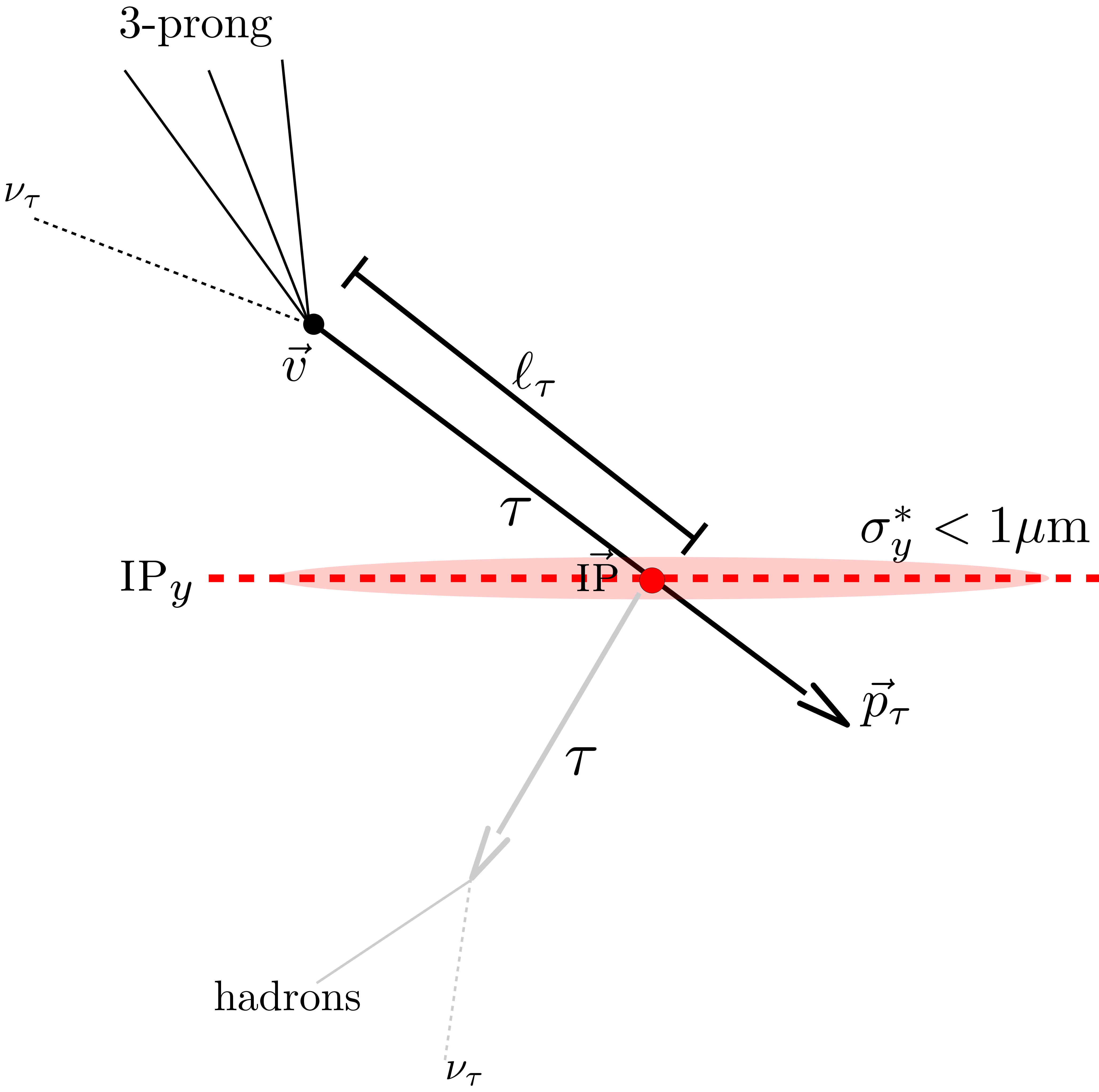
$$e^+e^- \to \tau^+ \; \tau^-$$

$\tau^\pm \to \rho^\pm(\pi^\pm\pi^0)\nu_\tau$



$\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$





- (3) production vertex that is intersection of momentum direction with plane $y = \mathrm{IP_y}$
  - exploits the tiny beam spot size at the interaction

Momentum of τ

$t_{\text{true}} = m\frac{l_\tau}{p}$

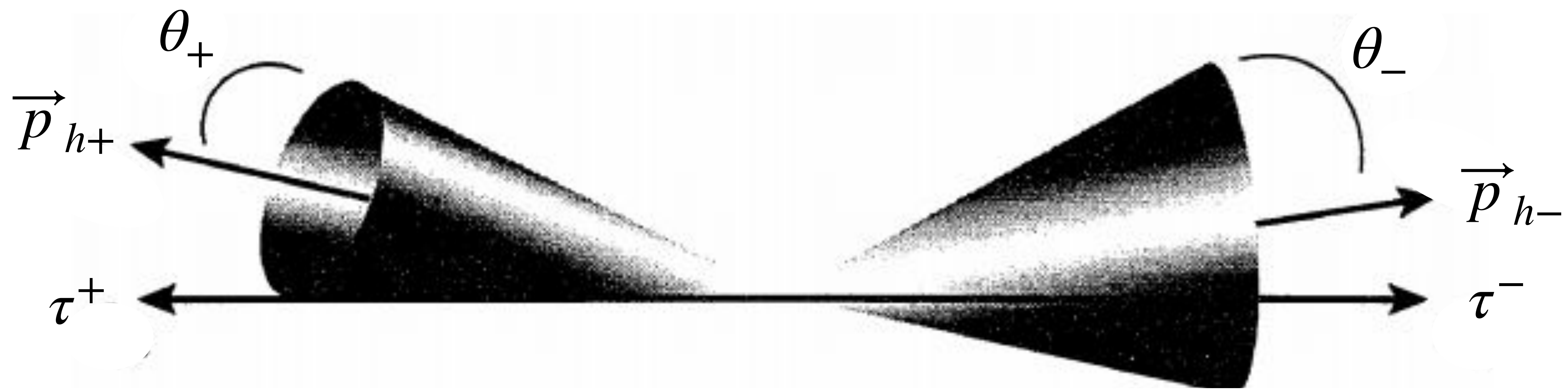
In the CMS the τ^+ (τ^-) direction lies on the surface of a cone with axis $\vec{p}_{h+}$ ($\vec{p}_{h-}$) and opening angle θ_+ (θ_-).

➡ the τ momentum is given by the intersection of the two cones

$$\vec{p}_\tau^{\,CM} = \vec{m} \pm \sqrt{\Delta}(\vec{p}_{h+}^{\,CM} \times \vec{p}_{h-}^{\,CM})$$

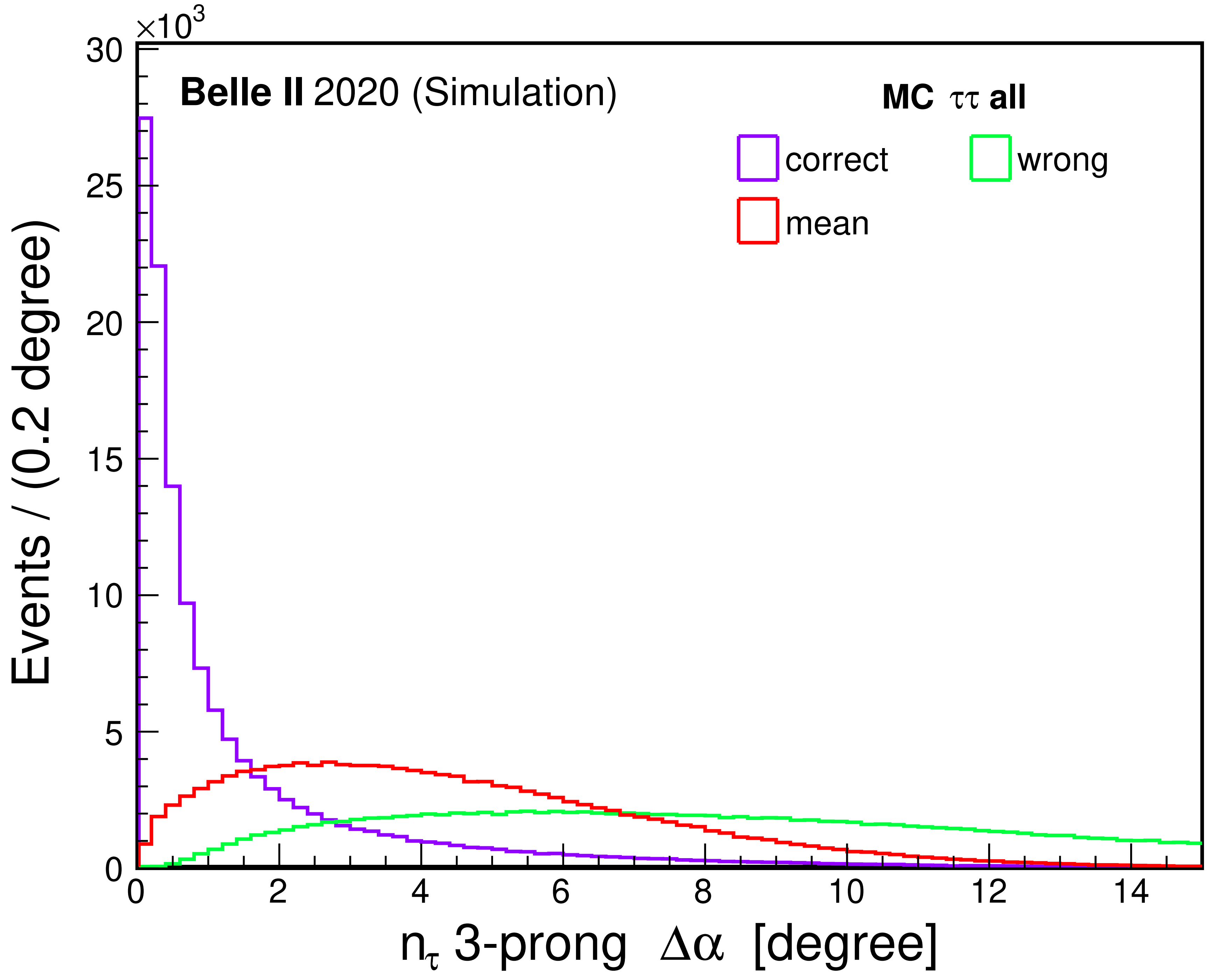
$\vec{m}$ – a linear combination of $\vec{p}_{h\pm}$

Δ – function of $\theta^\pm$



$\vec{p}_{h\pm}$ – the total momentum of visible daughters

$\theta^\pm$ – the angle between $\tau^\pm$ and $\vec{p}_{h\pm}$



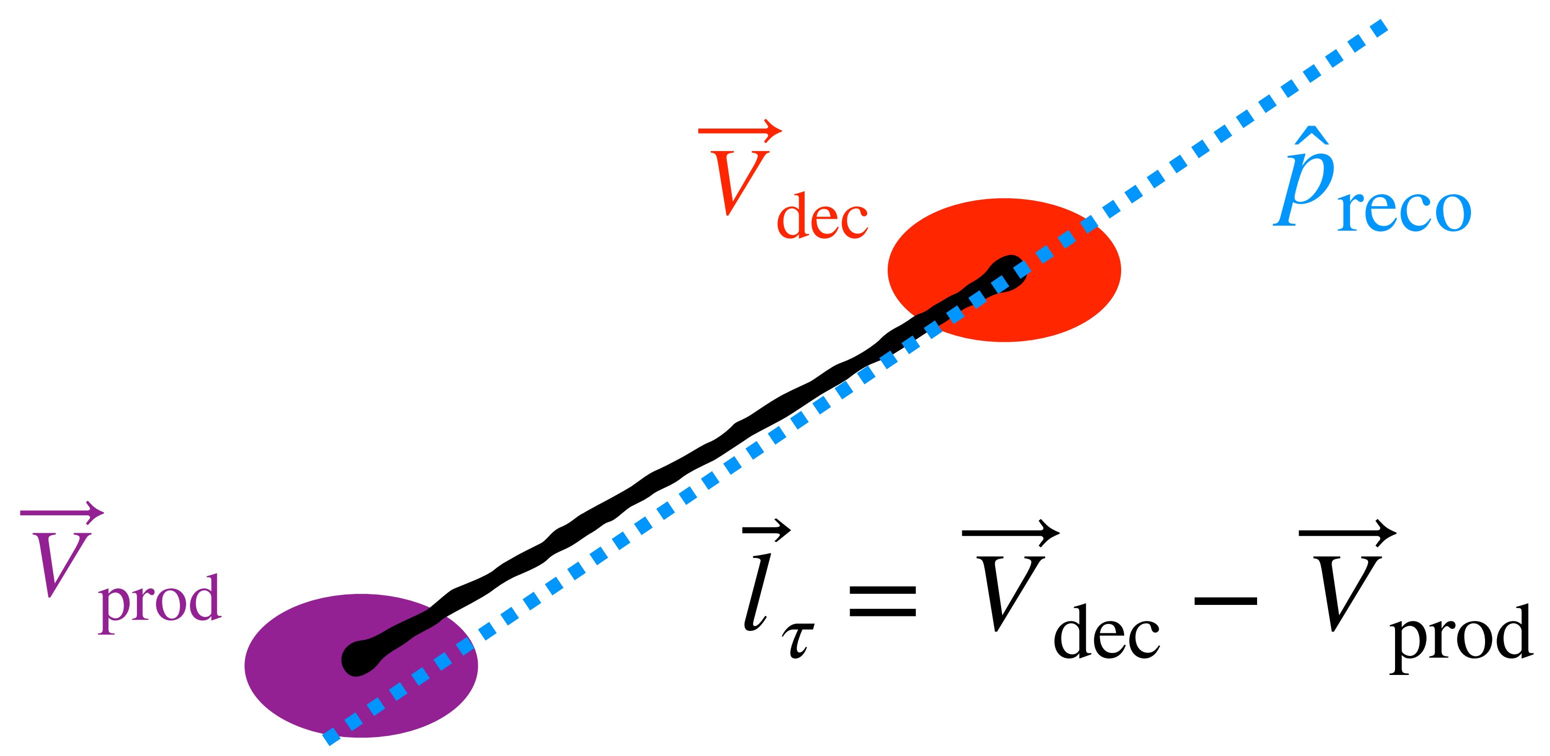
- $\Delta > 0$: there are two distinct real solutions with average $\vec{m}$
- $\Delta = 0$: there is one degenerate real solution $\vec{p}_\tau^{\,CM} = \vec{m}$
- $\Delta < 0$: there are two complex conjugate solutions with average $\vec{m}$

Consider only events having $\Delta \geq 0$

Boost back to lab frame.

Decay length l_τ of τ

$t_{\text{true}} = m\frac{l_\tau}{p}$



The flight distance is determined using the positions of decay and production vertices and the direction of the momentum

- ➡ the direction is better measured by the momentum

$$\vec{l}_\tau \cdot \hat{p}_{reco}$$

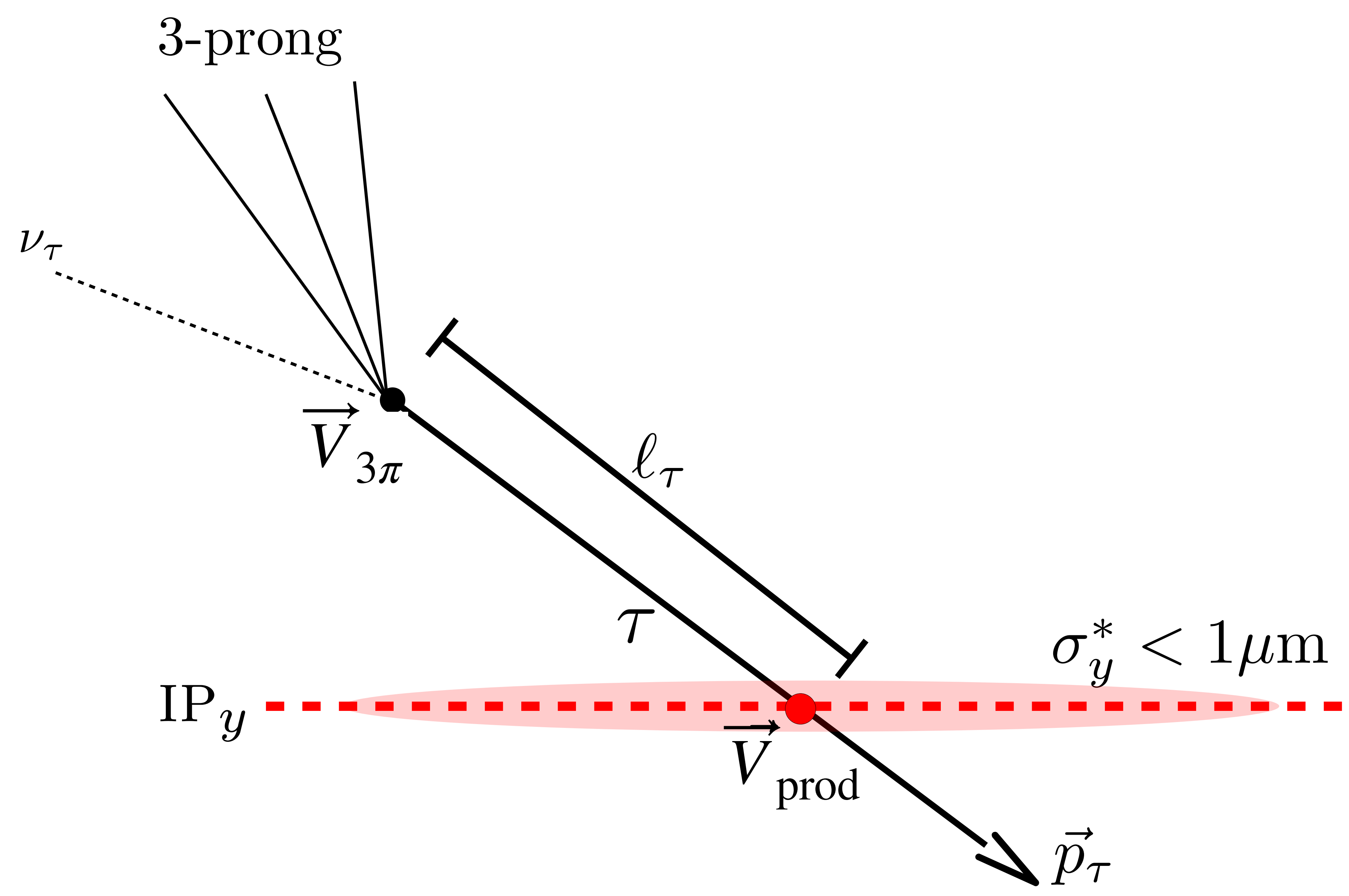
$$\hat{p}_{reco} = \vec{p}_\tau \,/\, |\vec{p}_\tau|$$

The decay length l_τ is extracted minimising a function $F(l_\tau, IP_x, IP_z)$ using

- ➡ beam-spot constraint
- ➡ the relation between τ displacement and production/decay vertices

$$\vec{V}_{\text{prod}} + l_\tau \cdot \hat{p}_{\text{reco}} - \vec{V}_{3\pi} = 0$$

strong constraint on IP_y **3-prong vertex**



$p(t;\tau) = 1/\tau\, e^{-t/\tau} \times \mathscr{R}(t)$

Proper decay time

$$t = m\frac{l_\tau}{p}$$

- computed from the reconstructed decay length l_τ and the estimated momentum p

Proper decay time resolution

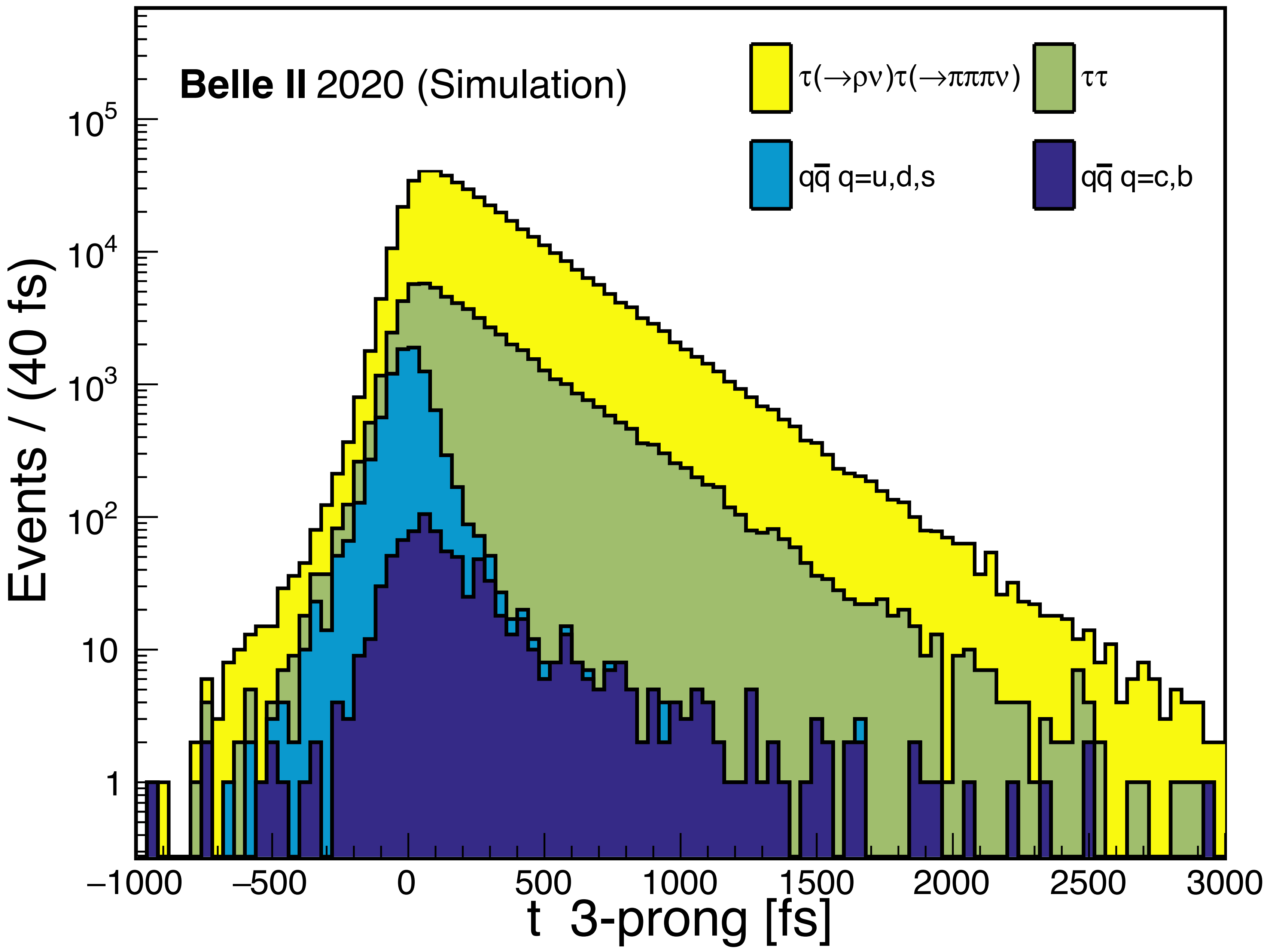
$$\Delta t = t^{rec} - t^{gen}$$

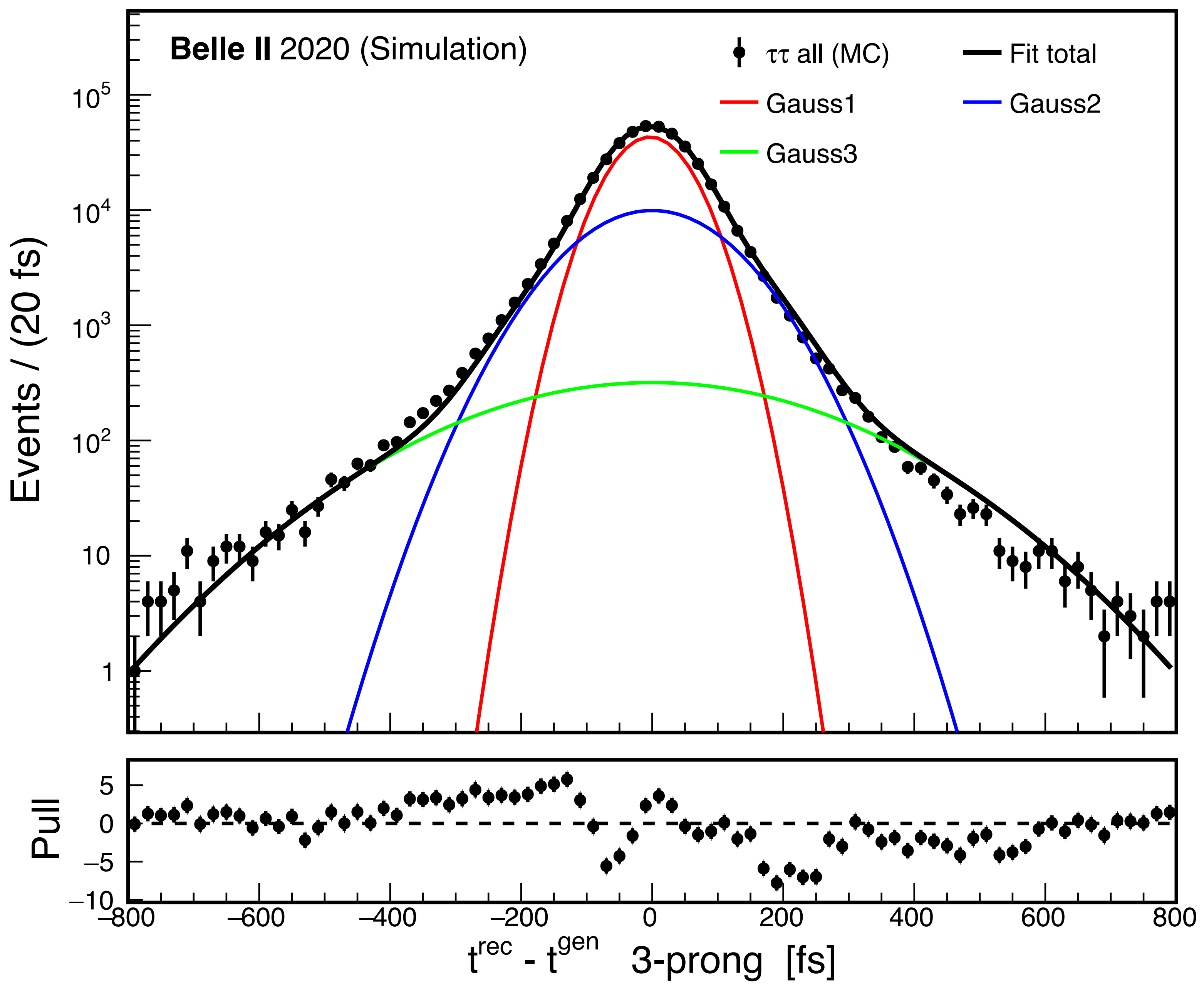
- binned ML fit with 3 Gaussians

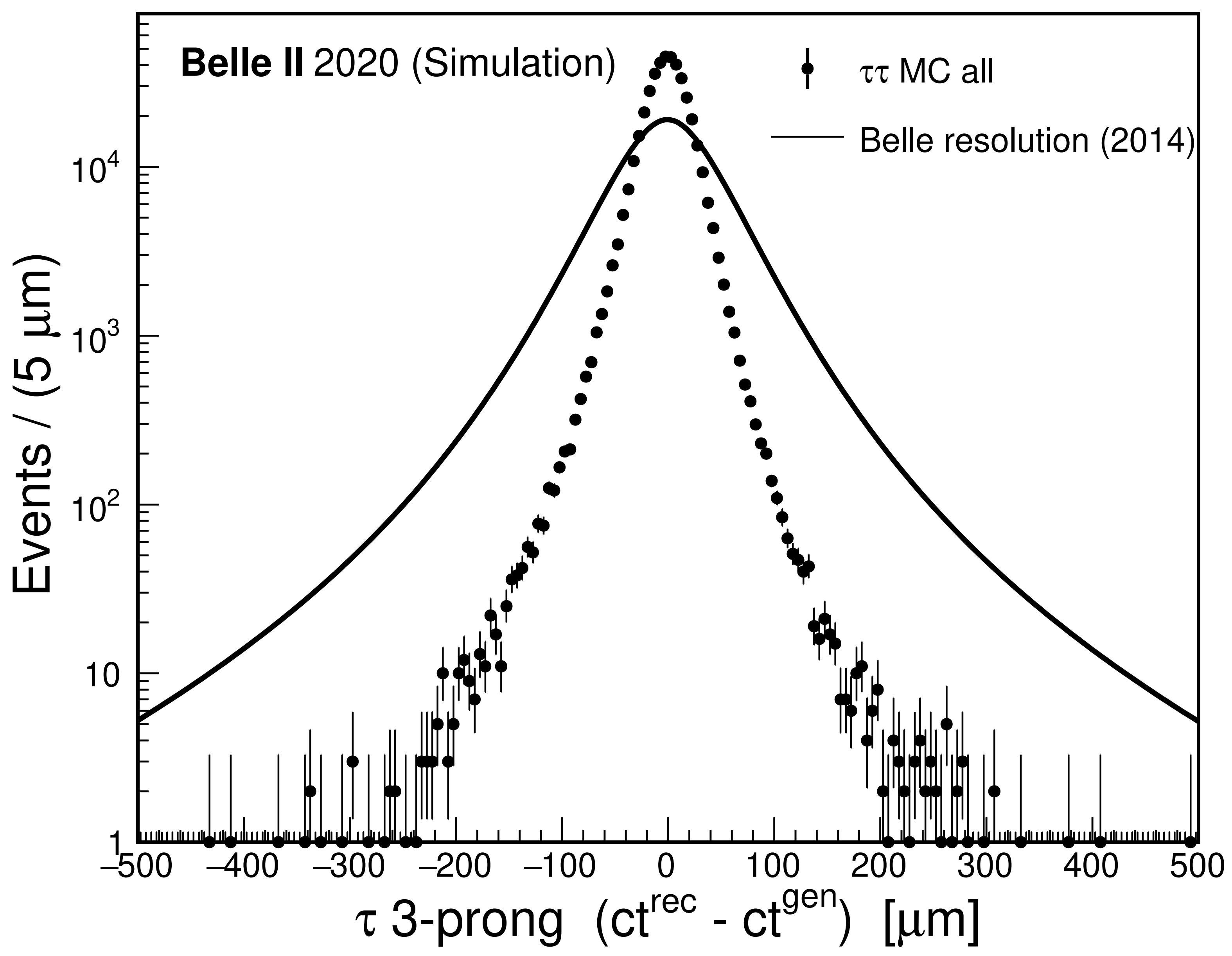
$$\mu[fs] = -3.43 \pm 0.13$$

$$\sigma[fs] = -79.3 \pm 0.7$$

- the resolution @Belle II is nearly x2 narrower than @Belle





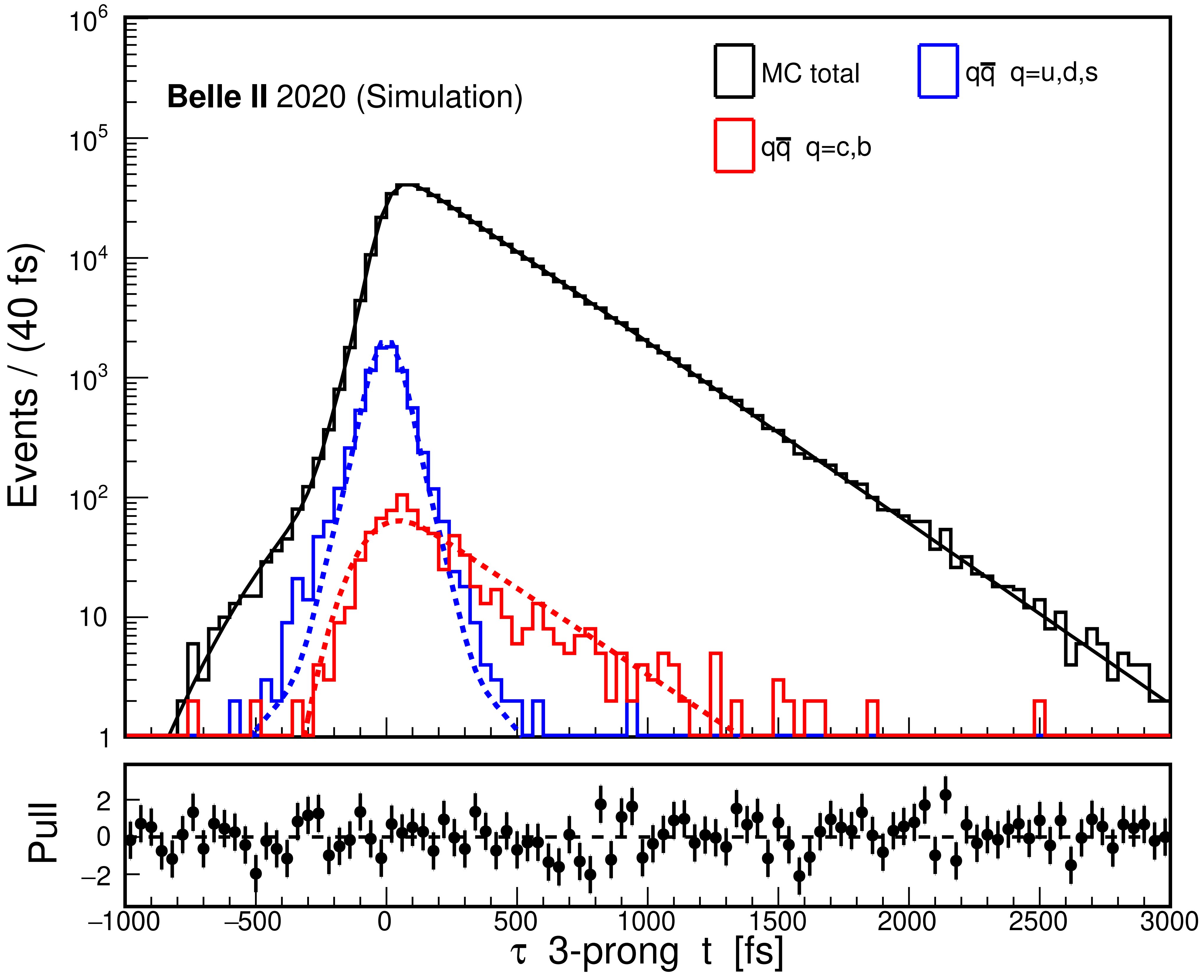


The τ lepton lifetime

Fit the proper time distribution with a convolution of an exponential distribution and resolution function

$$p(t;\tau) = \frac{1}{\tau} e^{-t/\tau} \times \mathscr{R}(t) \longrightarrow \tau = 287.2 \pm 0.5 \text{ fs}$$

BELLE2-NOTE-PH-2020-076



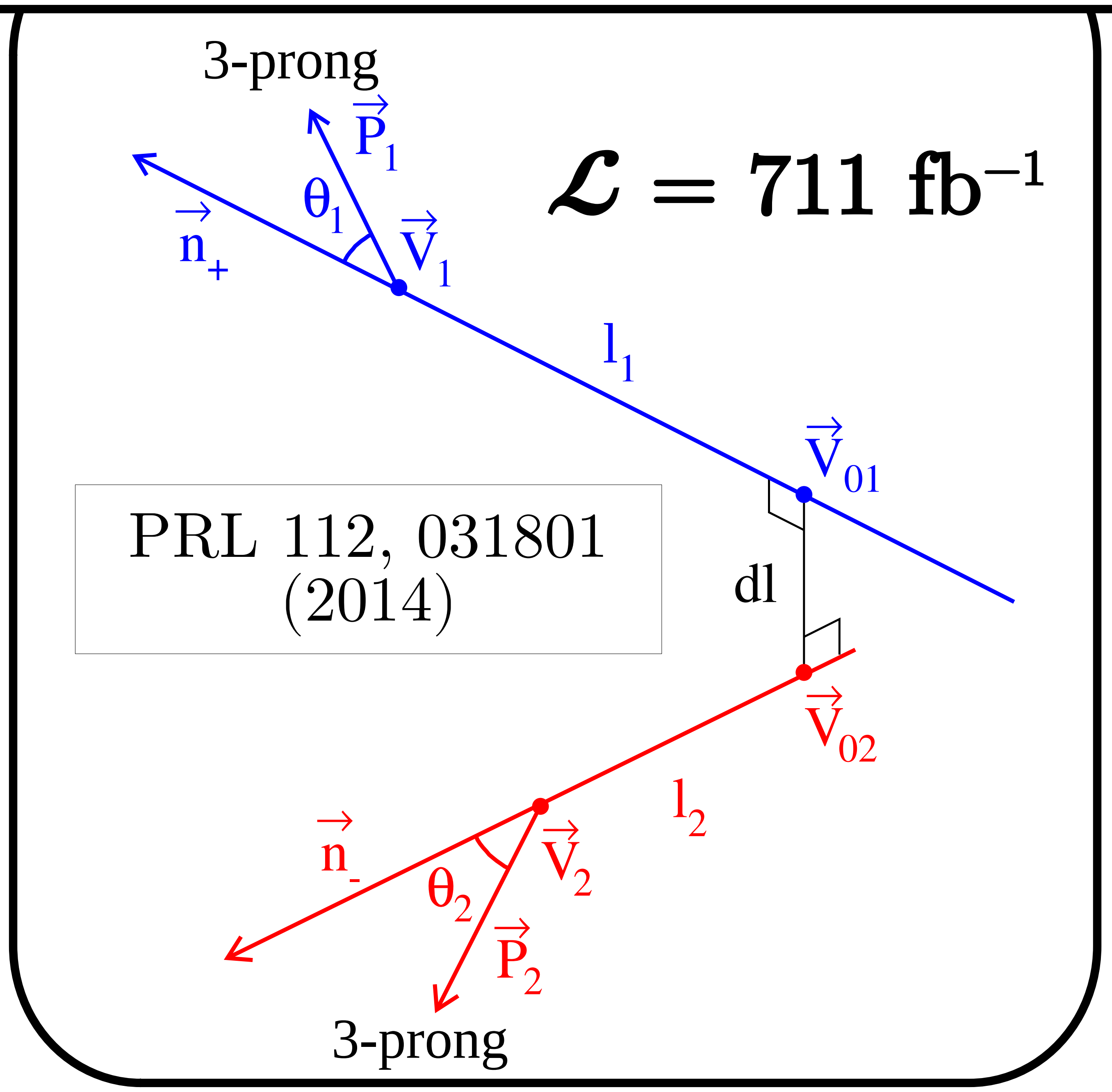
Generated lifetime $\tau = 290.57$ fs

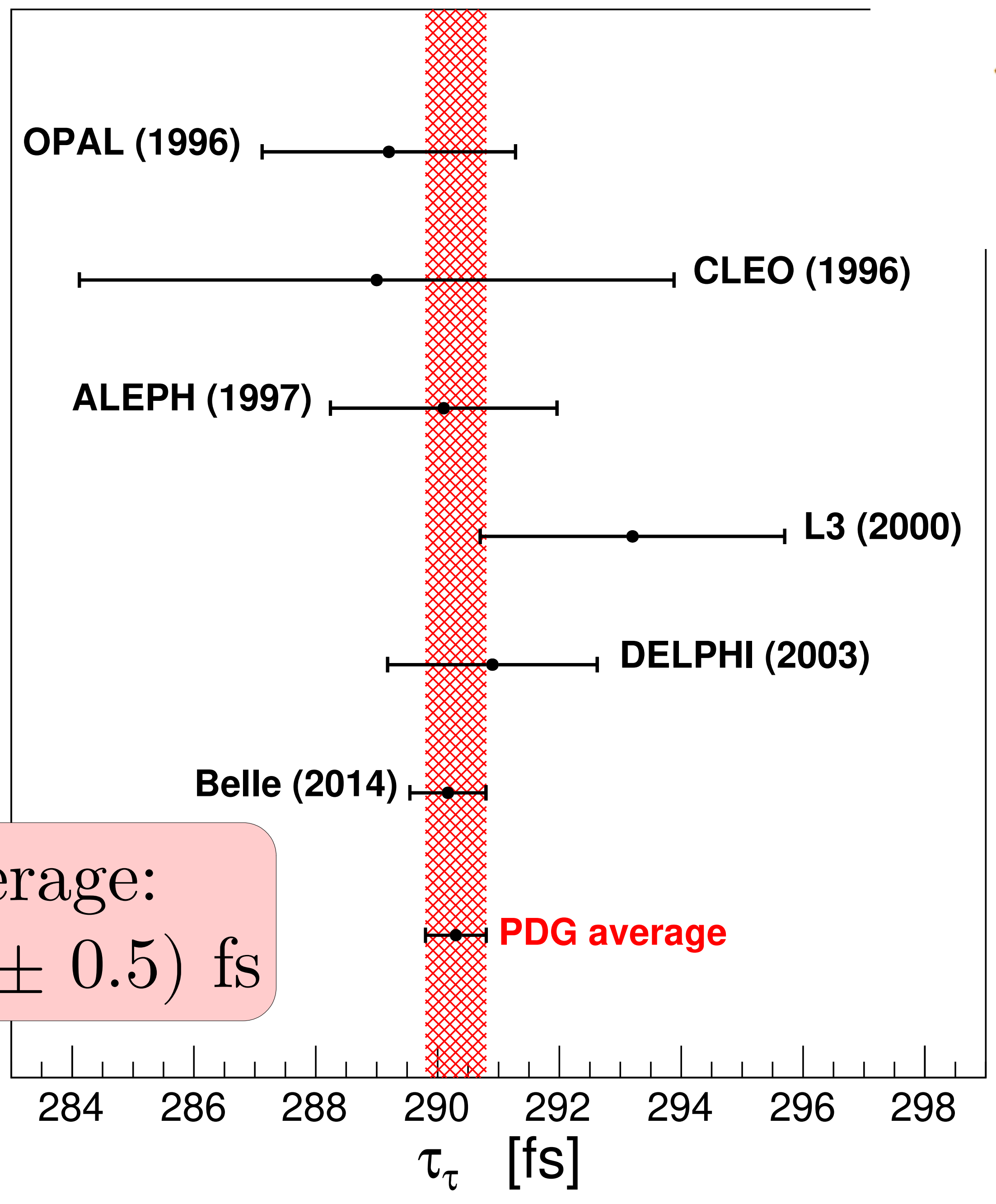
- ~3 fs bias in the measurement
  - ISR/FSR losses
    - overestimation of p_τ results in underestimation of proper time
  - intrinsic bias of the measurement
    - estimate the bias from MC and correct the measurement

Previous measurements of τ lifetime in $e^+e^- \to \tau^+\tau^-$

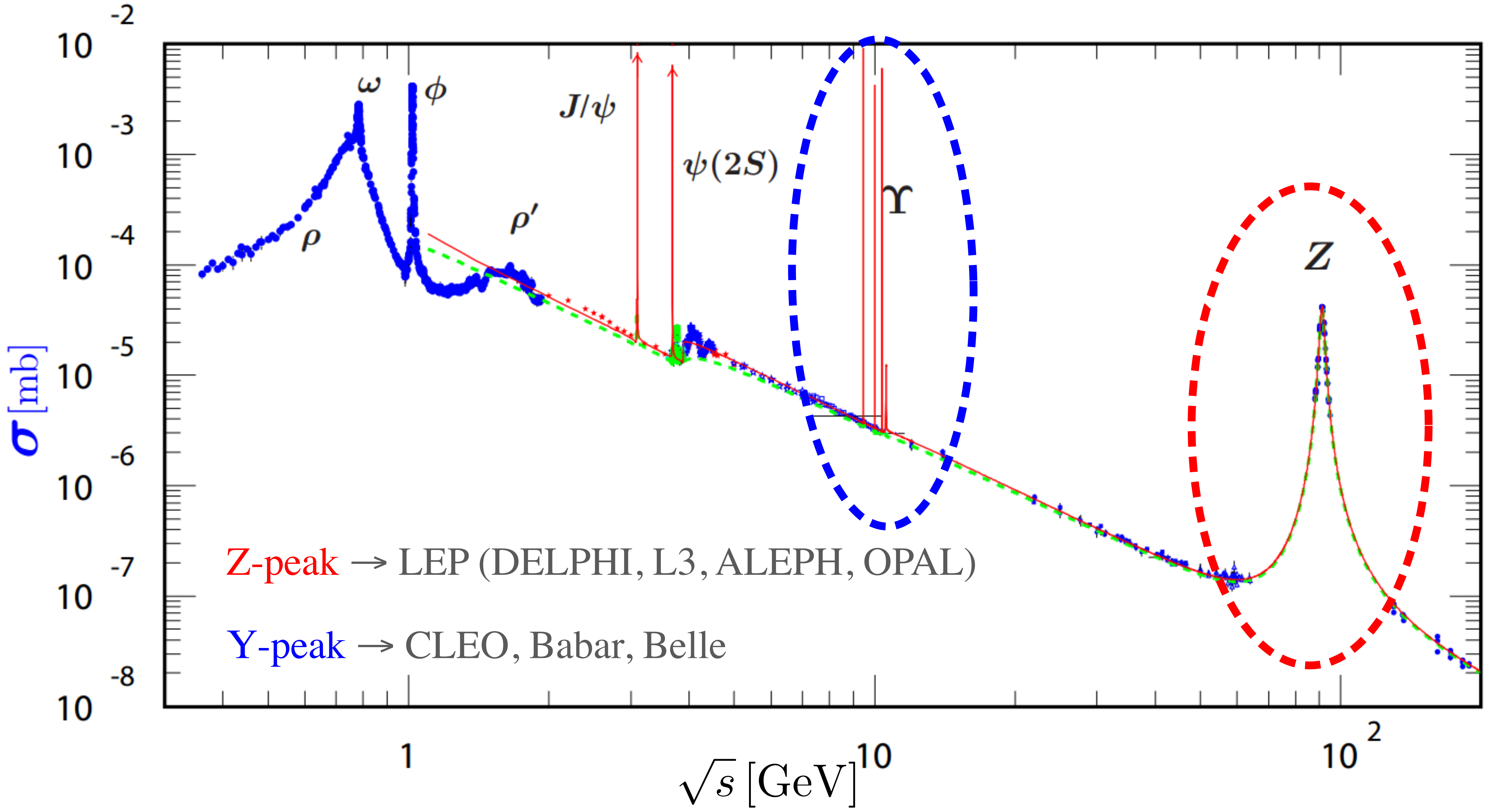
World-best measurement

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





PDG average:
$\tau_\tau = (290.3 \pm 0.5)$ fs



With respect to Belle:

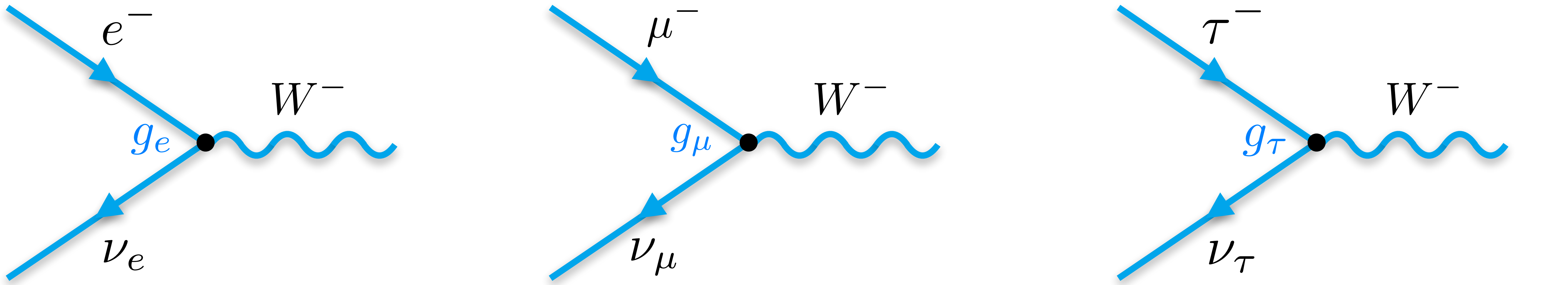
- exploit the tiny beam spot size at the IP
- increase the statistical precision by a factor of 5 using 3x1 topology
- competitive statistical precision can already be reached with 200/fb

e-μ-τ universality

e, μ and τ differ only by

- the mass
- different and separately conserved lepton numbers

The coupling of leptons to W bosons is flavour-independent: $g_e = g_\mu = g_\tau$

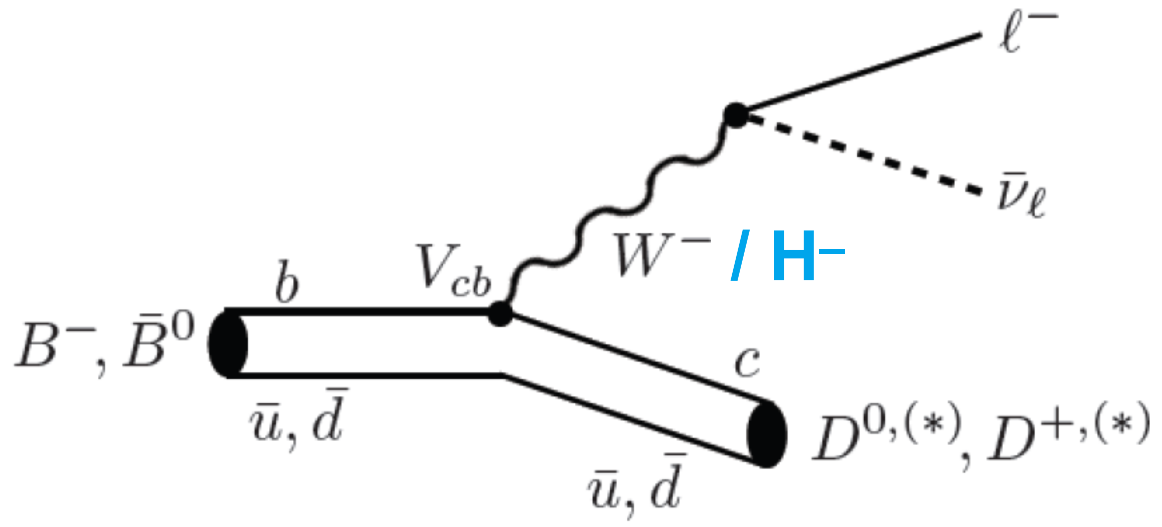


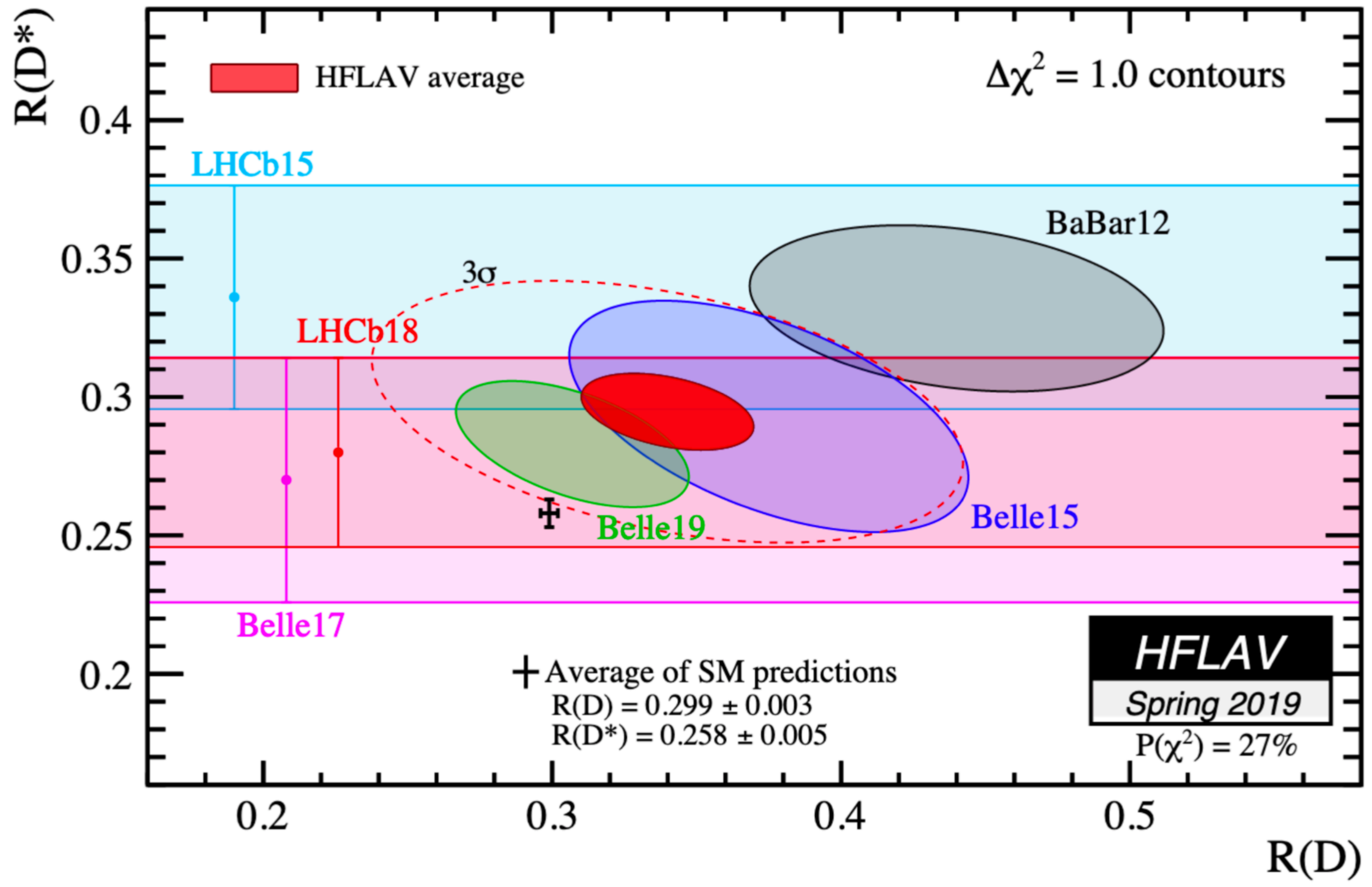
Identical lepton interaction rates involving e, μ or τ

Anomalies in quark sector

- R(D)-R(D*) plane (~3.1σ)
- R(K) (3.1σ), also P_5' in B→$K^*\mu\mu$ (~3.4σ)
- and more…

$$R(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*\ell\nu)} \quad \text{with } \ell = e, \mu$$





Significant tensions in lepton sector

- anomalous magnetic moment of μ (4.2σ) and e (~2.5σ)

Are these hints of a new fundamental interaction that violates LFU?

e-μ-τ universality

If so, then we could also see hints in the **tau sector**

Test of e–μ universality

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}$$

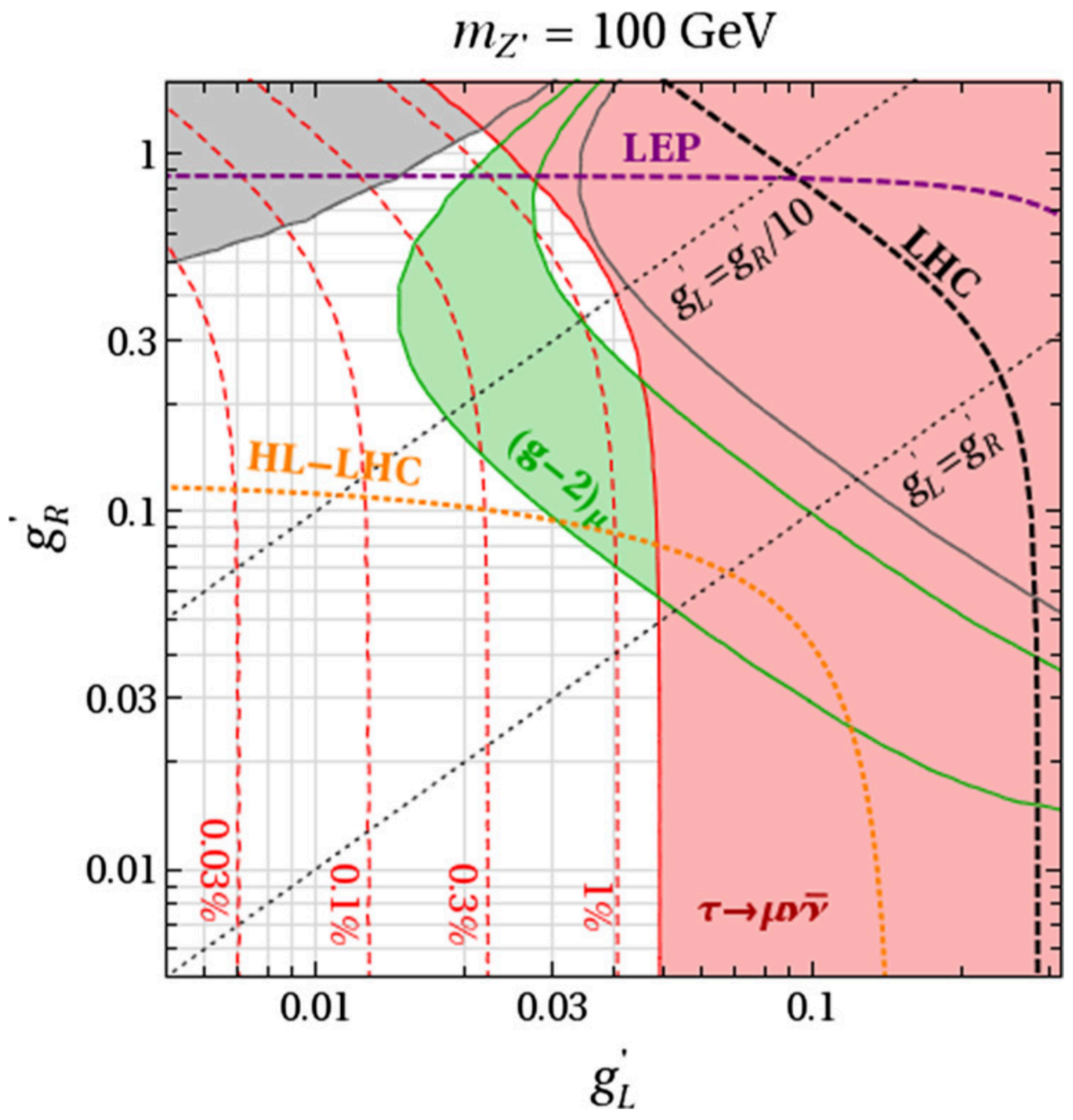
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2\log x$$

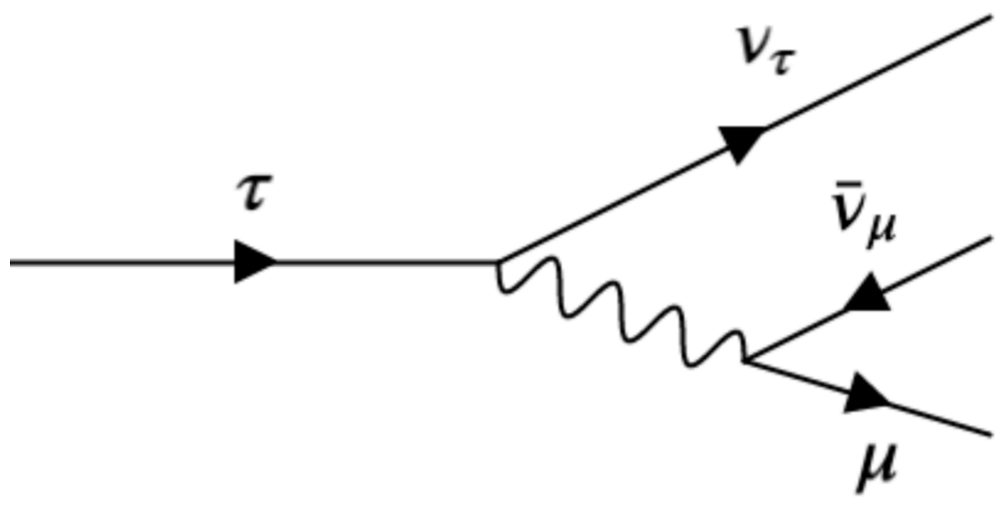
Test of τ–μ universality

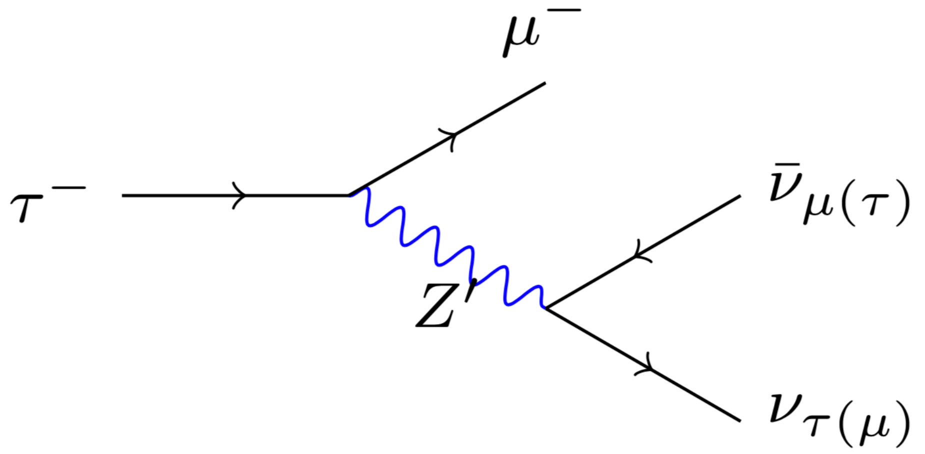
$$\left(\frac{g_\tau}{g_\mu}\right)^2_h \propto \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\nu_\mu)}\frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h)m_\tau^3\tau_\tau}\left(\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}\right)^2$$

Can put strong constraints on lepton flavour violating Z' models

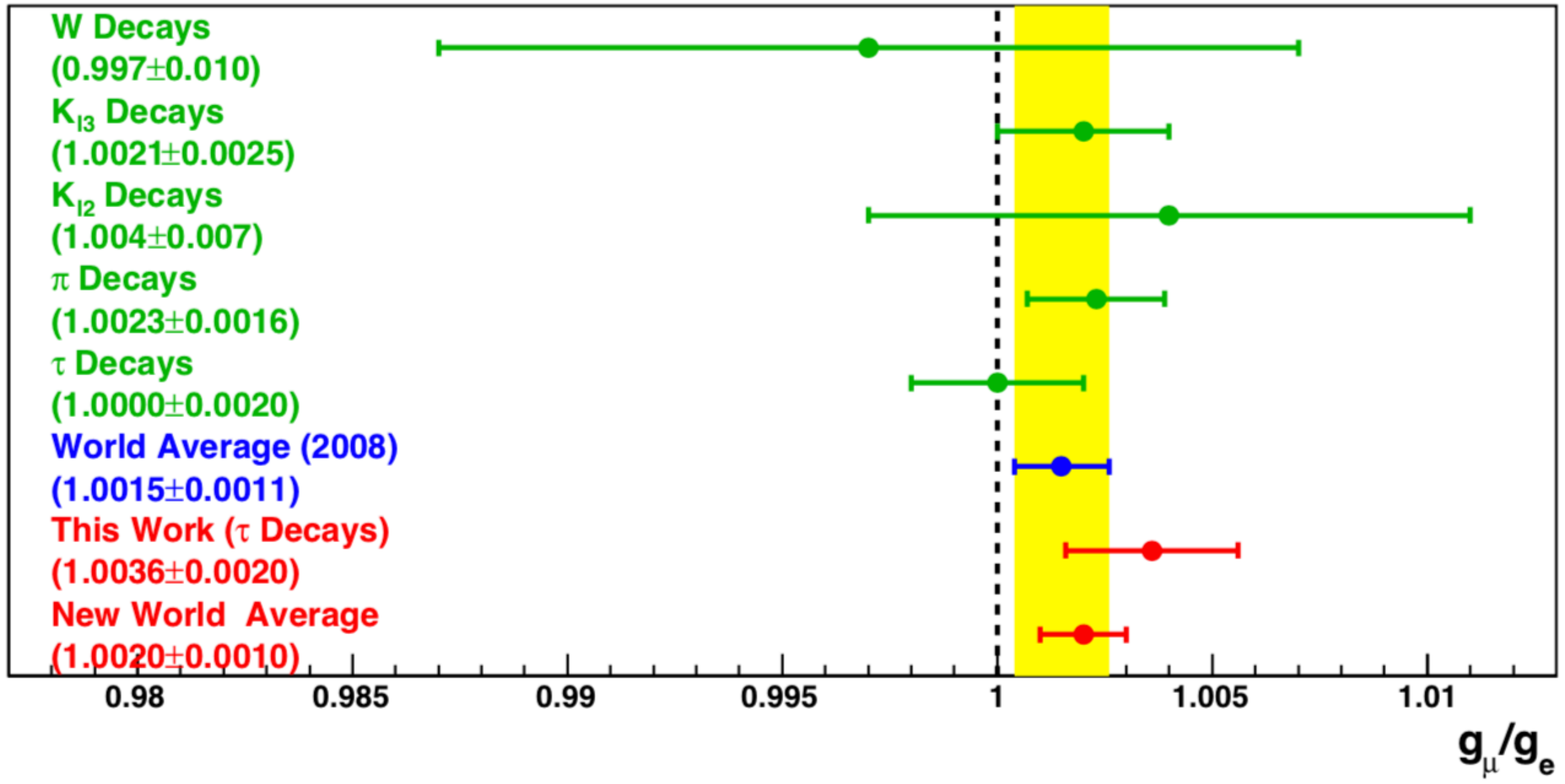
arXiv:1607.06832v1







arXiv:1607.06832v1



e-μ-τ universality

Most precise measurement from BaBar

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020 \qquad \left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$$

- in agreement with SM
- 2.8 σ below the SM expectation

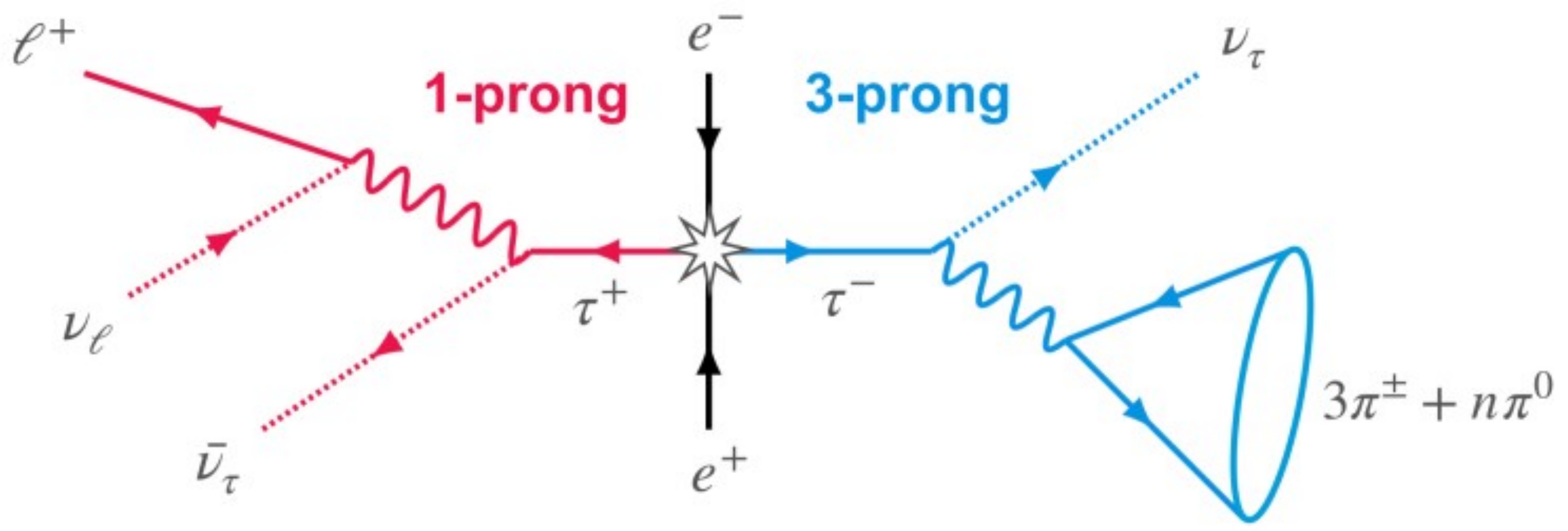
- The BR measurements dominated by systematic uncertainty
  - μ: PID due limited size of data and MC samples
  - h: additional contribution to systematics detector modelling and associated BGs

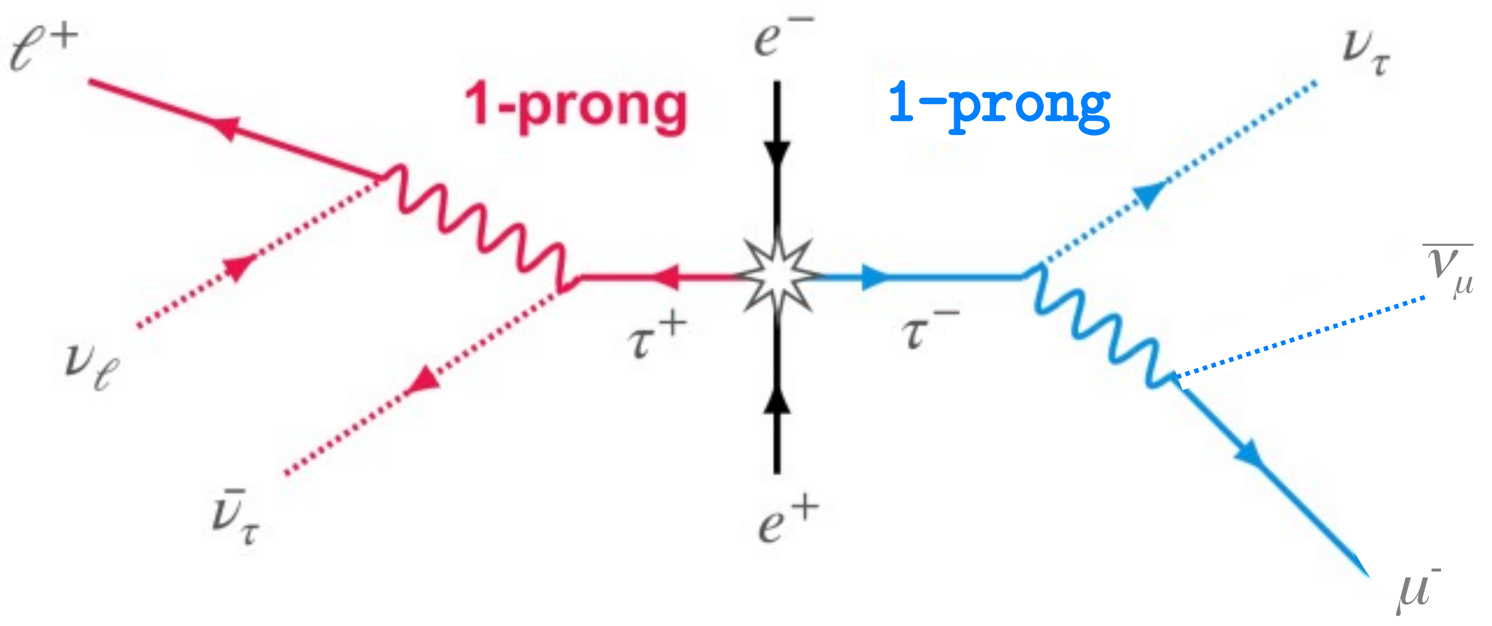
- Phys. Rev. Lett. 105 051602 -

	μ	π	K
$\mathbf{N}^D$	731102	369091	25123
Purity	97.3%	78.7%	76.6%
Total Efficiency	0.485%	0.324%	0.330%
Particle ID Efficiency	74.5%	74.6%	84.6%
Systematic uncertainties:			
Particle ID	0.32	0.51	0.94
Detector response	0.08	0.64	0.54
Backgrounds	0.08	0.44	0.85
Trigger	0.10	0.10	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01	0.07	0.27
Radiation	0.04	0.10	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05	0.15	0.40
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02	0.39	0.20
Total [%]	0.36	1.0	1.5

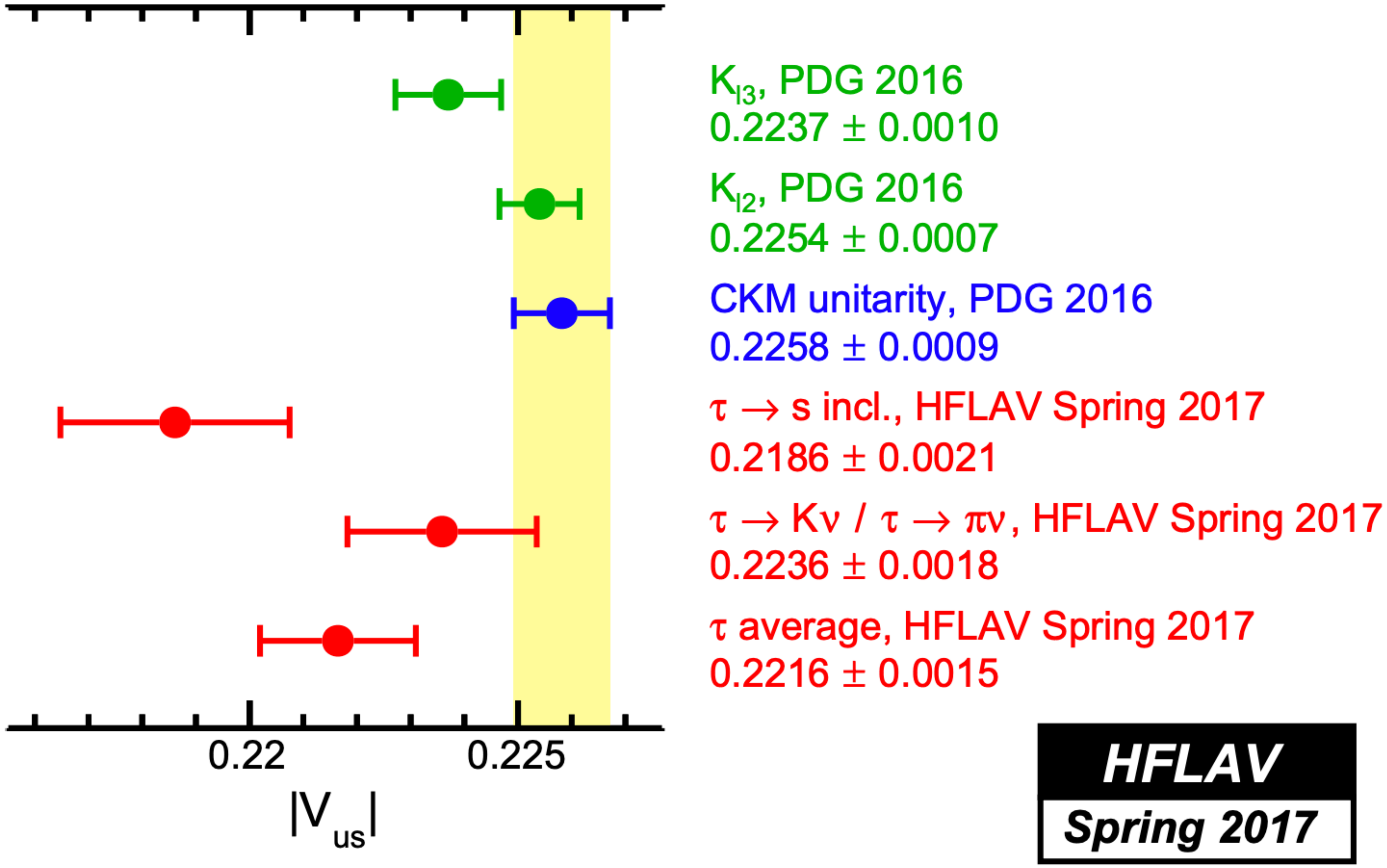
Can Belle II improve this?

- use 3x1 and 1x1 (not used @BaBar) to improve the statistical precision
- work hard to improve the systematics

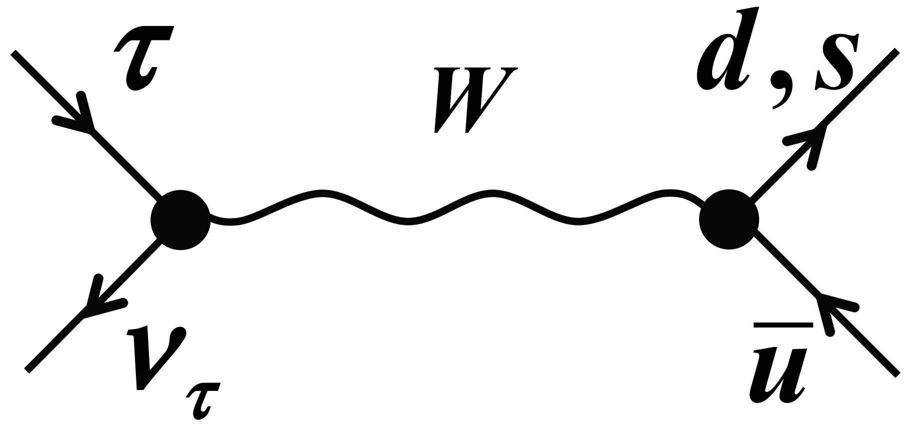




V_{us} from τ decays



Test of unitarity



Unique opportunity for probing the coupling strength of the weak current to the first and second generation of quarks to a very high precision

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak Eigenstates **CKM Matrix** **Mass Eigenstates**

Test of unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 \stackrel{?}{=} 1$$

$0^+ \to 0^+$; $K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$; $K \to \pi\ell\nu$; $\sim 1.6 \cdot 10^{-5}$ **B decays**

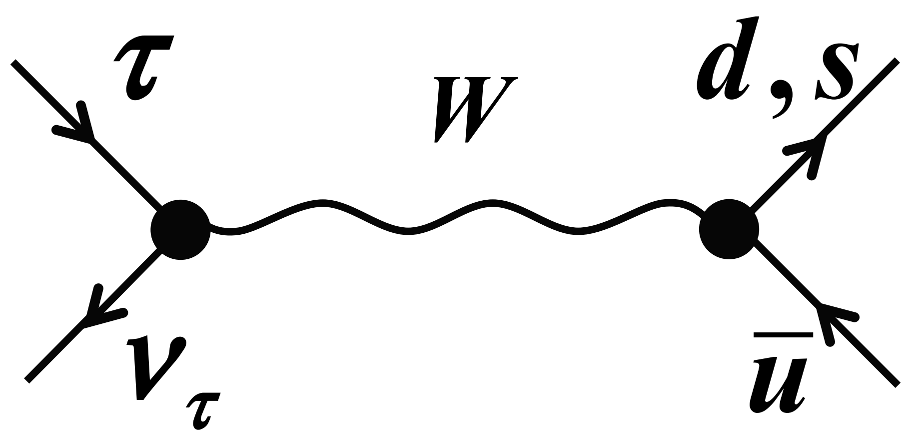
➡ From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi \to \pi e \nu_e$	$n \to p e \nu_e$	$\pi \to \ell \nu_\ell$
V_{us}	$K \to \pi \ell \nu$	$\Lambda \to p e \nu_e$	$K \to \ell \nu_\ell$

➡ From τ decays

V_{ud}	$\tau \to \pi\pi^0\nu_\tau$	$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$	$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$

Two methods of V_{us} from τ decays



Exclusive: compare the BR of $\tau \to \pi\nu$ and $\tau \to K\nu$

- BaBar, Phys. Rev. Lett. 105 051602 -

Fermi constant — *electroweak corrections*

$$B(\tau^- \to K^-\nu_\tau) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi}\left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{\text{EW}}$$

$V_{us} = 0.2193 \pm 0.0032$

➡ within 2σ of the value predicted by the CKM unitarity

$$\frac{B(\tau^- \to K^-\nu_\tau)}{B(\tau^- \to \pi^-\nu_\tau)} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \frac{(m_\tau^2 - m_K^2)^2}{(m_\tau^2 - m_\pi^2)^2}(1 + \delta_{LD})$$

decay constant — *electroweak corrections*

$V_{us} = 0.2255 \pm 0.0024$

➡ consistent with CKM unitarity

Inclusive: compare the BR of $\tau \to (\bar{u}d)\,\nu$ and $\tau \to (\bar{u}s)\,\nu$

fundamental parameters of SM

$(\alpha_s\,,\,|V_{us}|\,,\,m_s\,)$

BR w.r.t. BR($\tau \to e\nu\nu$)

hadrons with S=0 — *hadrons with S=1*

$$\Delta R_{\text{SU(3) breaking}} = \frac{R_{\text{NS}}}{|V_{ud}|^2} - \frac{R_{\text{S}}}{|V_{us}|^2}$$

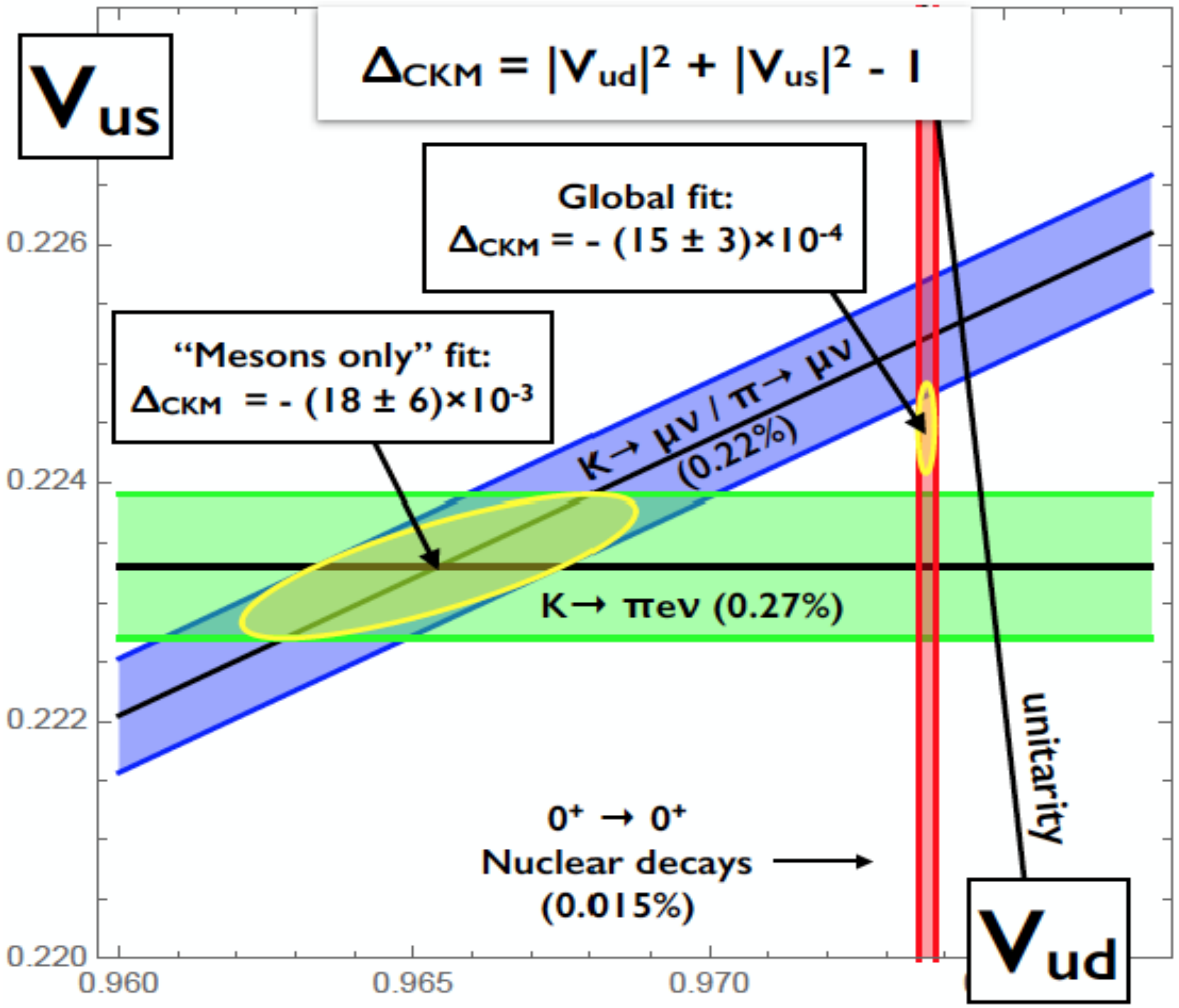
$V_{\text{us}} = 0.2186 \pm 0.0021$

➡ within 3.1σ of the value predicted by the CKM unitarity

V_{us} from τ decays @Belle II

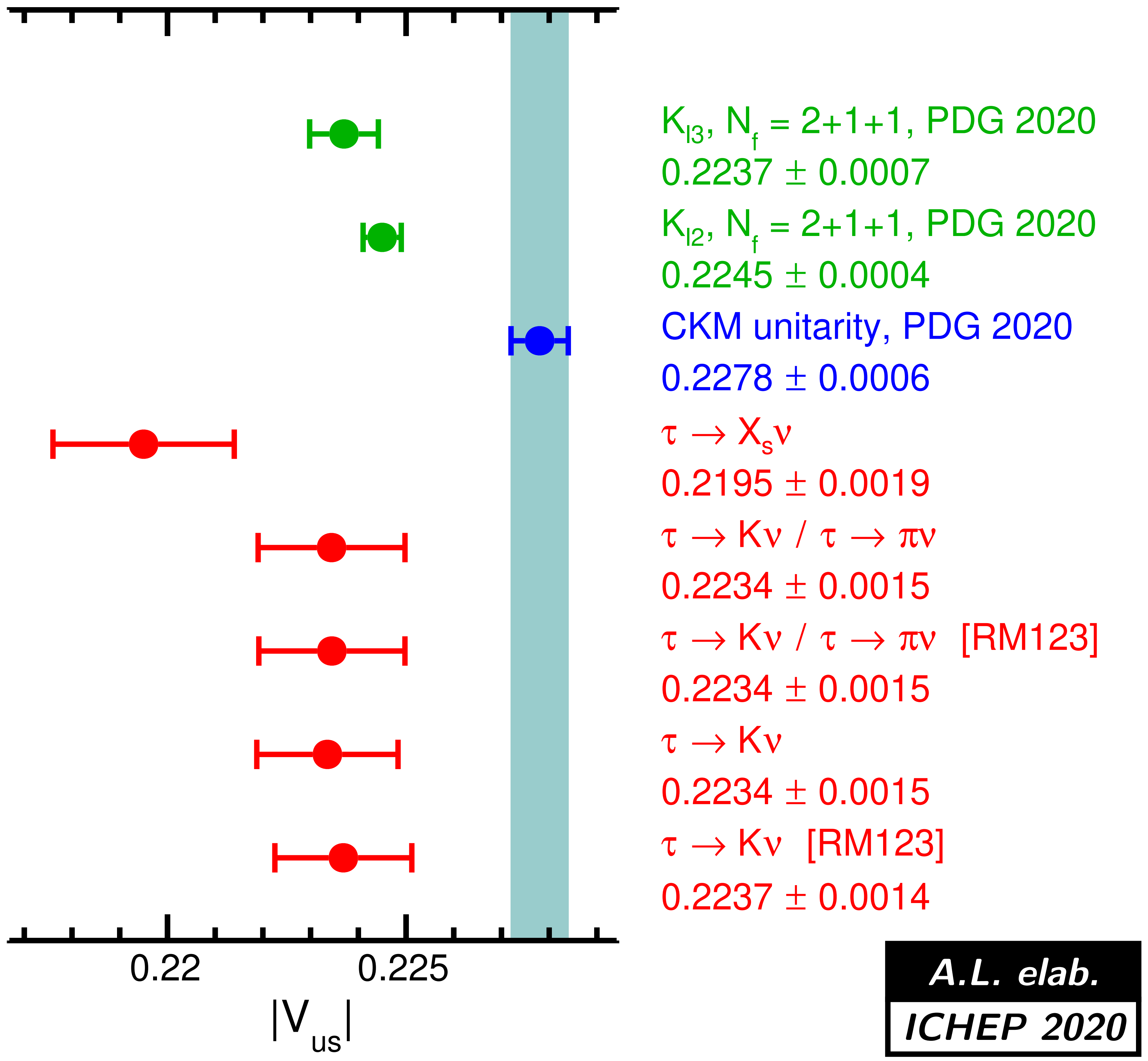
New results with improved theoretical input

- precise determination of V_{us} from kaon and nuclear decays
- discrepancy with CKM unitarity at 4.8 σ



Can τ physics help?

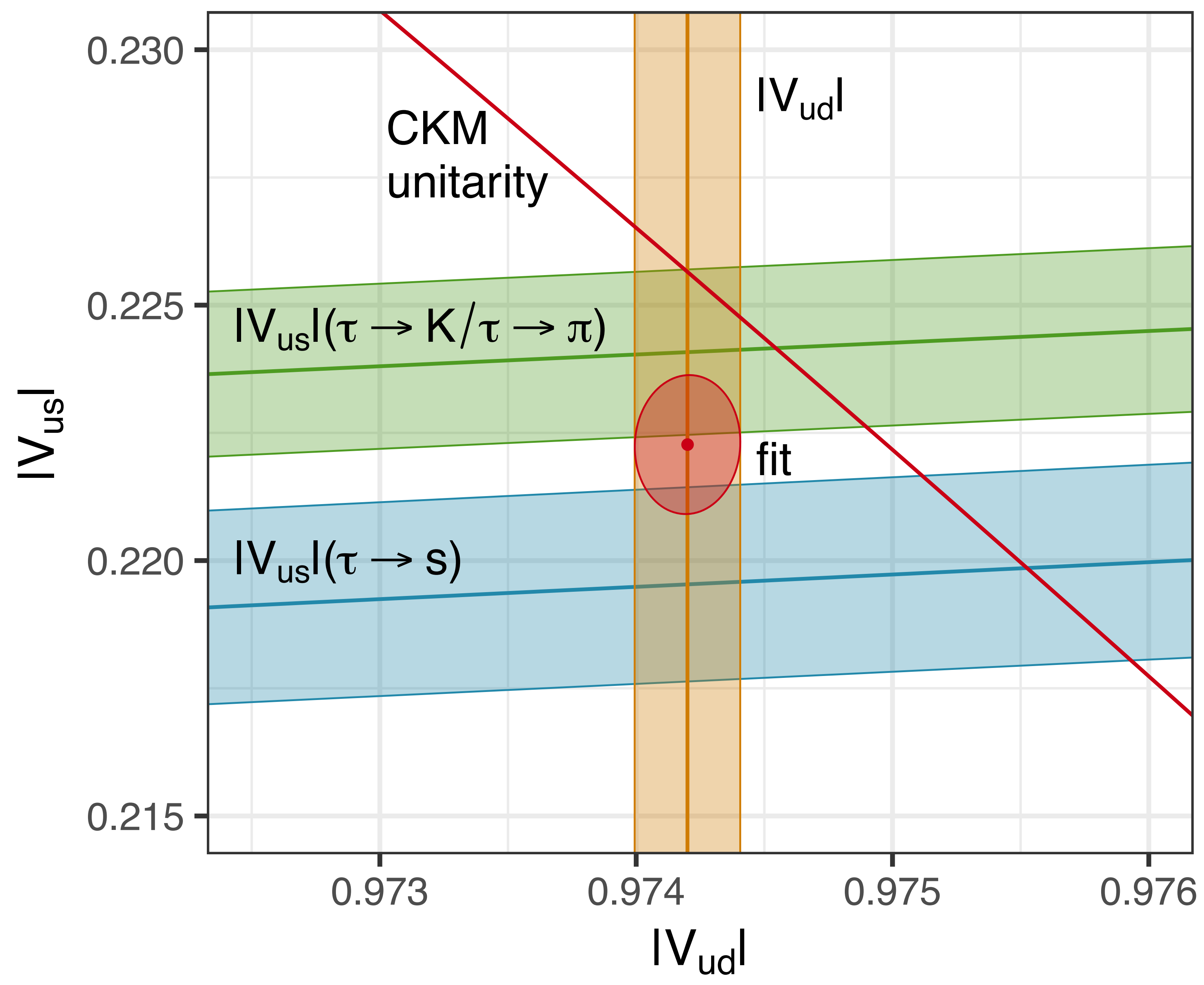
- currently less precise determination of V_{us}
- large PID systematic uncertainties @BaBar
- inclusive measurement not truly inclusive

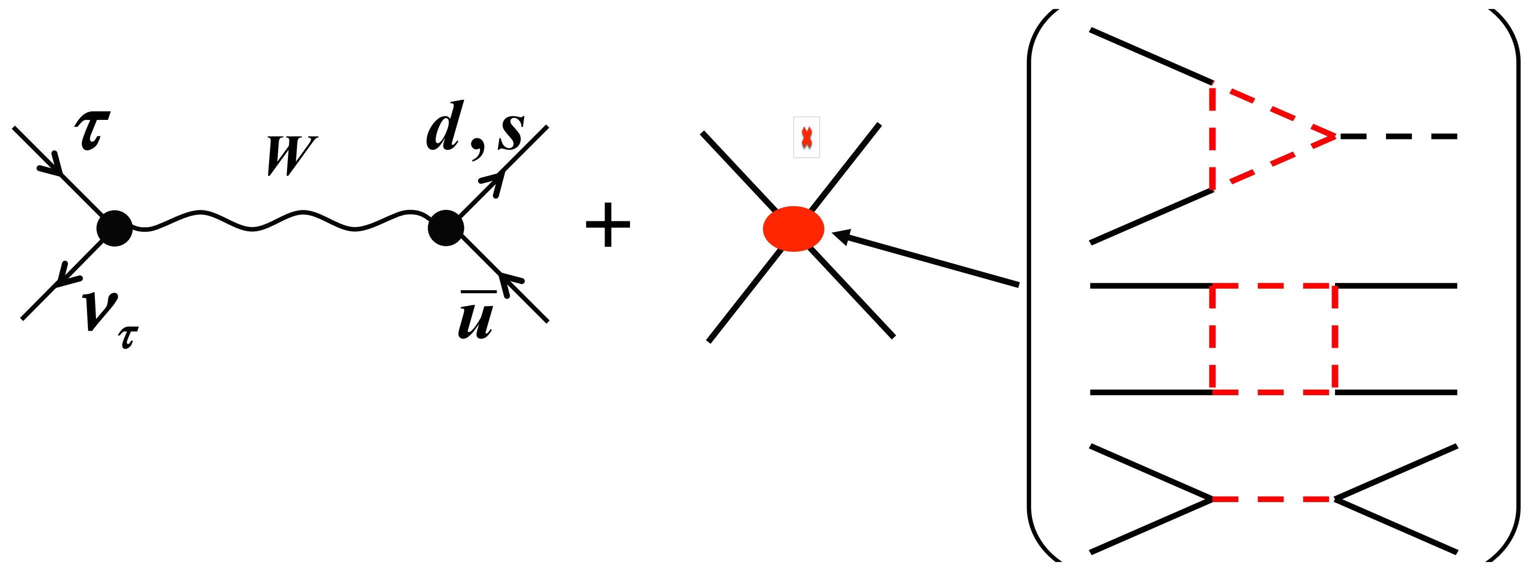


V_{us} from τ decays @Belle II

3σ tension between $|V_{us}|$ from the CKM matrix unitarity and $\tau \to s$.

SciPost Phys. Proc. 1, 001 (2019)

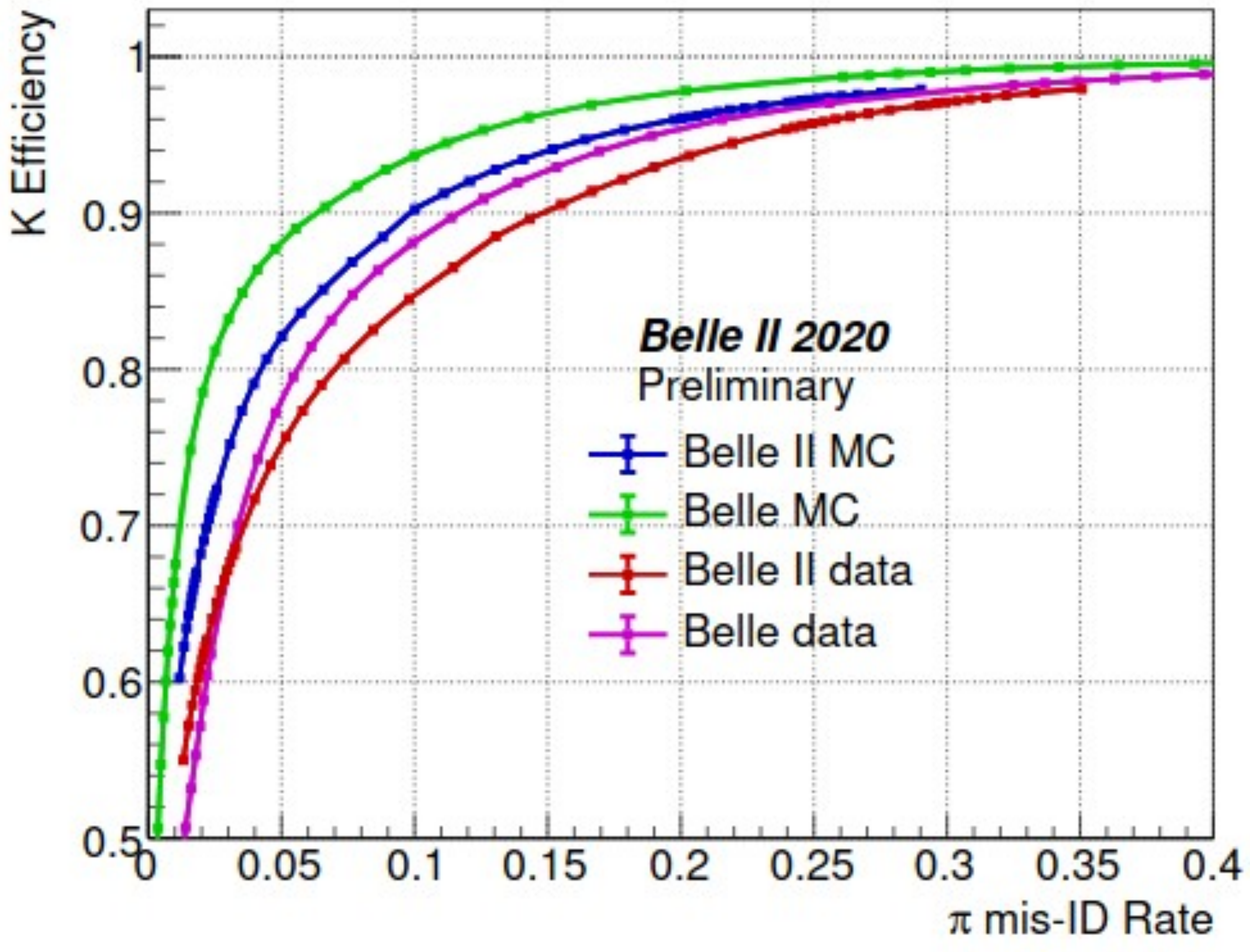




SUSY loops, Leptoquarks, Z', Charged Higgs Right-Handed Currents,….

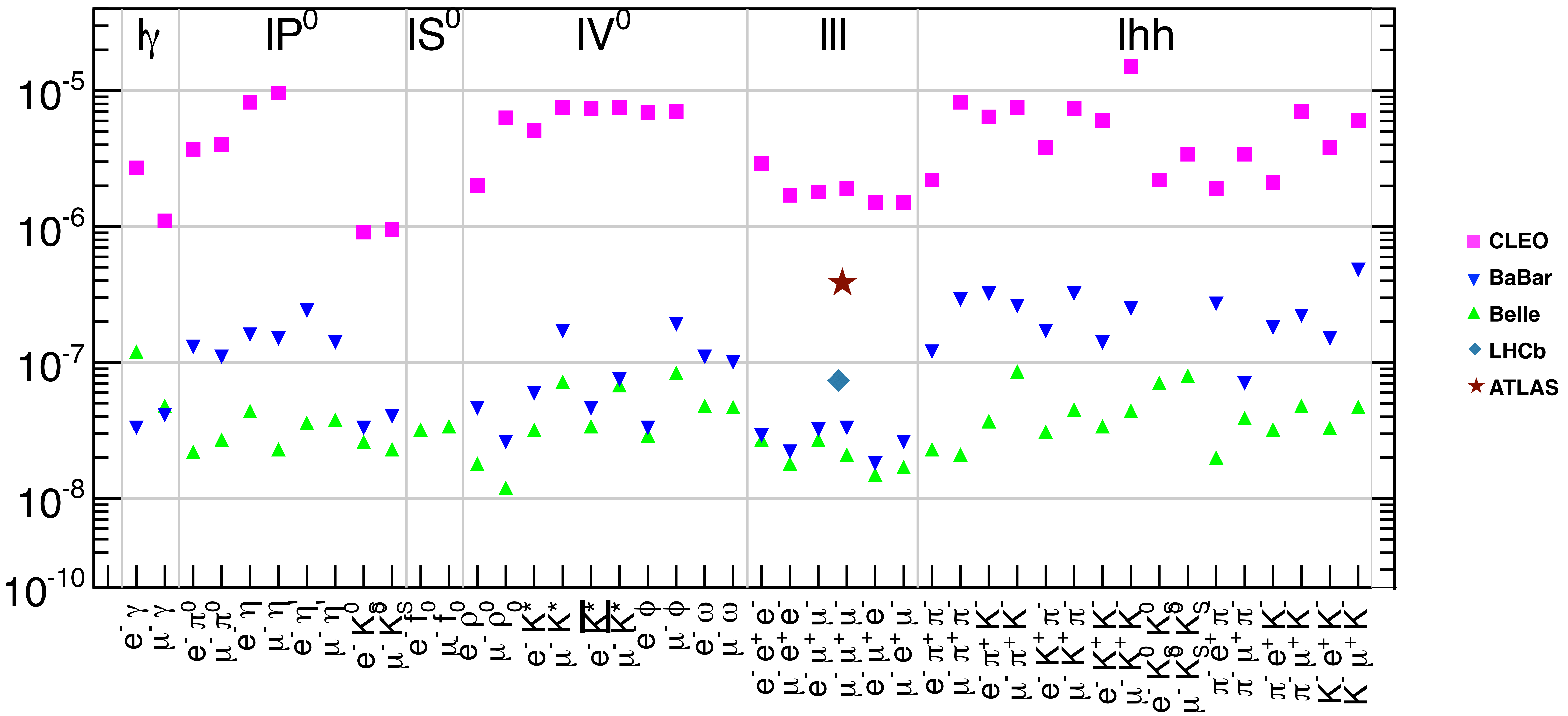
What can we do @BelleII?

- larger data sample will be available
- similar to LFU analysis use 3x1 and 1x1 topologies
- improve the understanding of the detector (PID, trigger, …)



Belle II will improve the experimental precision!

LVF & LNV

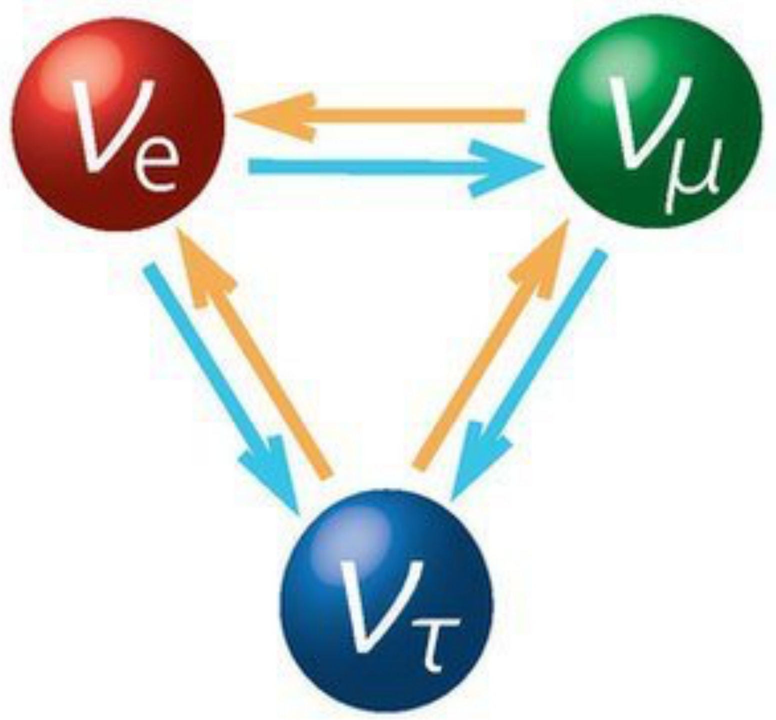


lγ
lP0
lS0
lV0
lll
lhh
10-5
10-6
10-7
10-8
10-10
CLEO
BaBar
Belle
LHCb
ATLAS

Lepton flavour conservation

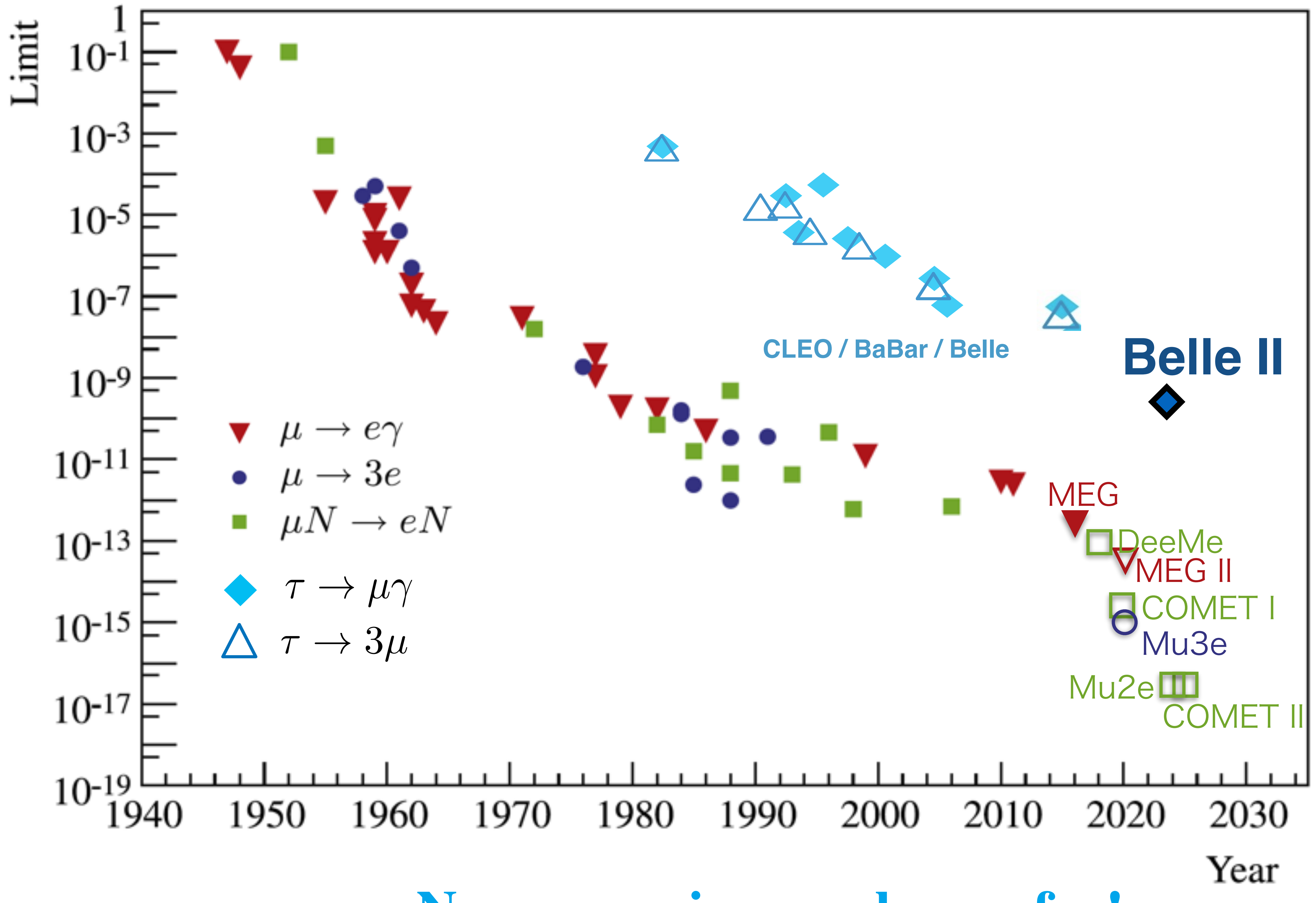
Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$



➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

What about the charged leptons?

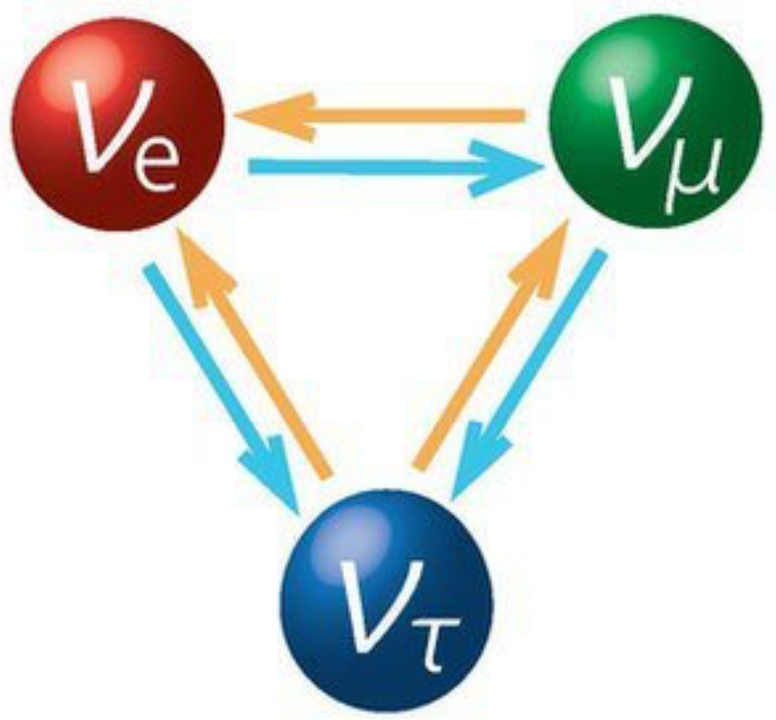


No success in searches so far!

Lepton number conservation

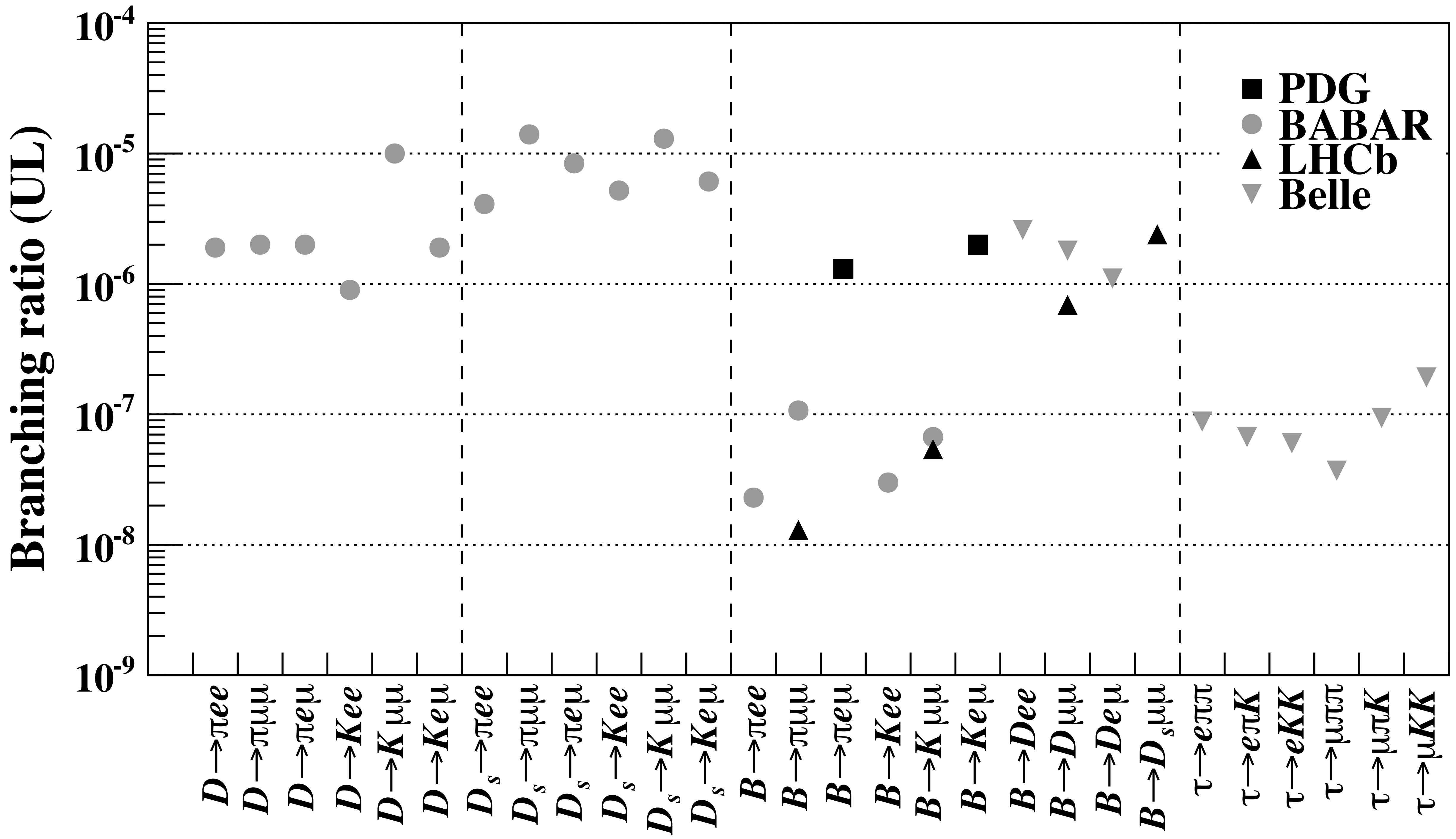
Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$



➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

Are neutrinos Dirac (|ΔL| = 0) or Majorana (|ΔL| = 2) particles?



No answer yet!

Effective field theory approach

No compelling evidence for new particles mediating LFV processes

- ➡ Strong experimental constraints on the scale Λ for new degrees of freedom
- ➡ Parameterise the LFV τ decays via the effective field theory (EFT)
- ➡ Their effect will show up at low energies as a series of non-renormalisable operators:

$$L = L_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- ➡ Each NP model generates a specific pattern of operators
- ➡ Due to the variety of the hadronic final states, the semi-leptonic τ decays probe a larger set of operators

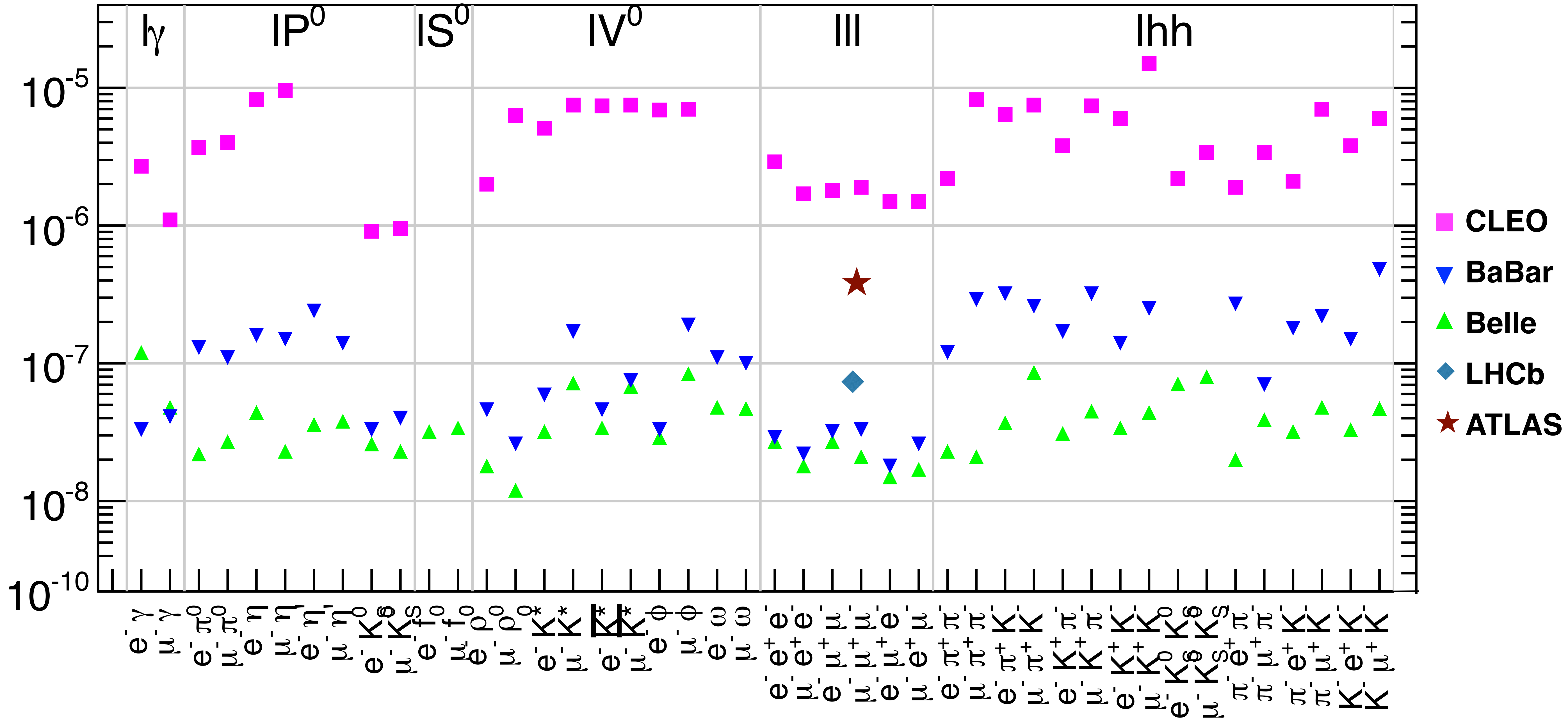
		$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
4-lepton	$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
dipole	O_D	✓	✓	✓	✓	–	–
lepton-quark	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
lepton-quark	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
lepton-quark	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-quark	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-gluon	$O_{G\tilde{G}}$	–	–	–	–	–	✓

- Celis, Cirigliano, Passemar (2014) -

The τ decays offer an opportunity to probe the underlying NP responsible for the LFV.

The progress of τ LFV and LNV searches

… mostly occurred at the B-factories



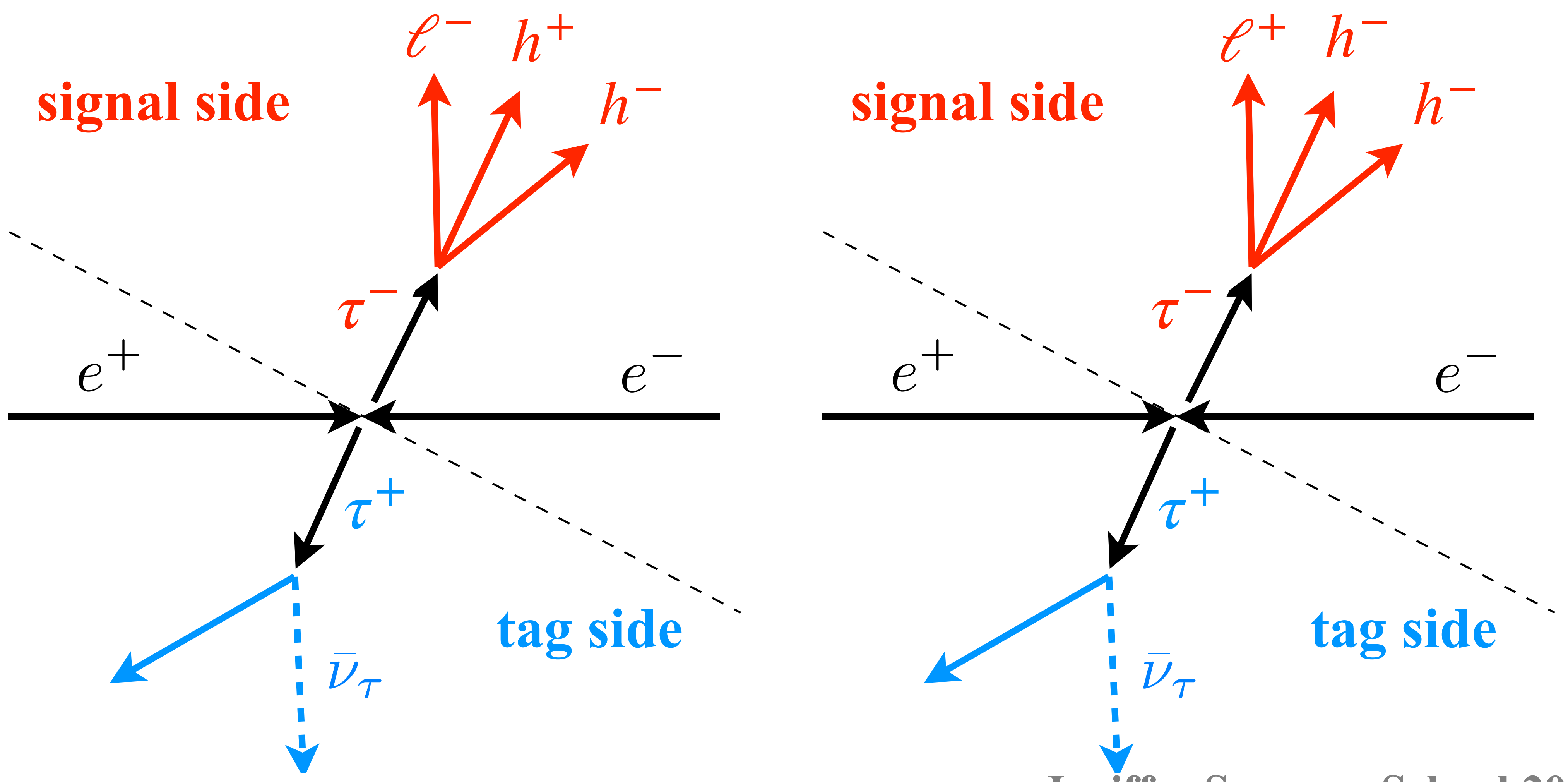
The upper limits reached for τ decays approached the regions sensitive to NP.

Test the SM in a variety of ways

- radiative ($\tau \to \ell\gamma$)
- leptonic decays ($\tau \to \ell\ell\ell$)
- a large variety of LFV and LNV semi-leptonic decays
- τ → μ and τ → e: test of the lepton flavour structure

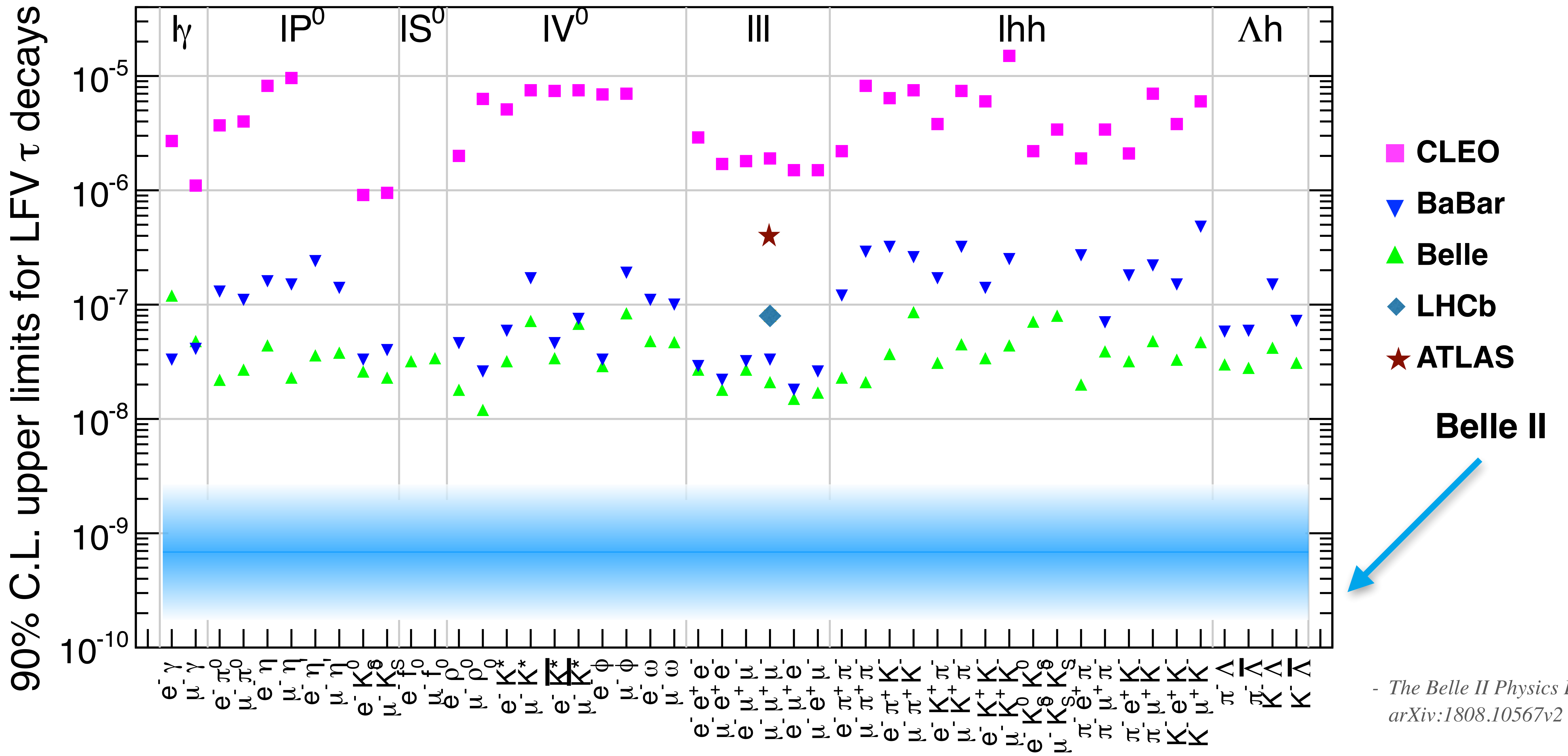
ℓ = *e or μ*

$h^{\pm}$ = *states with no lepton flavour number*



Perspectives at Belle II

… mostly occurred at the B-factories



- *The Belle II Physics Book - arXiv:1808.10567v2*

Test the SM in a variety of ways

- ➡ radiative ($\tau \to \ell\gamma$)
- ➡ leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ a large variety of LFV and LNV semi-leptonic decays
- ➡ τ → μ and τ → e: test of the lepton flavour structure

- ➡ One of the factors pushing up the sensitivity of probes is the increase of the luminosity
- ➡ Equally important is the increase of the signal detection efficiency
  - ➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

The searches at Belle II will push the current bounds further by more than one order of magnitude

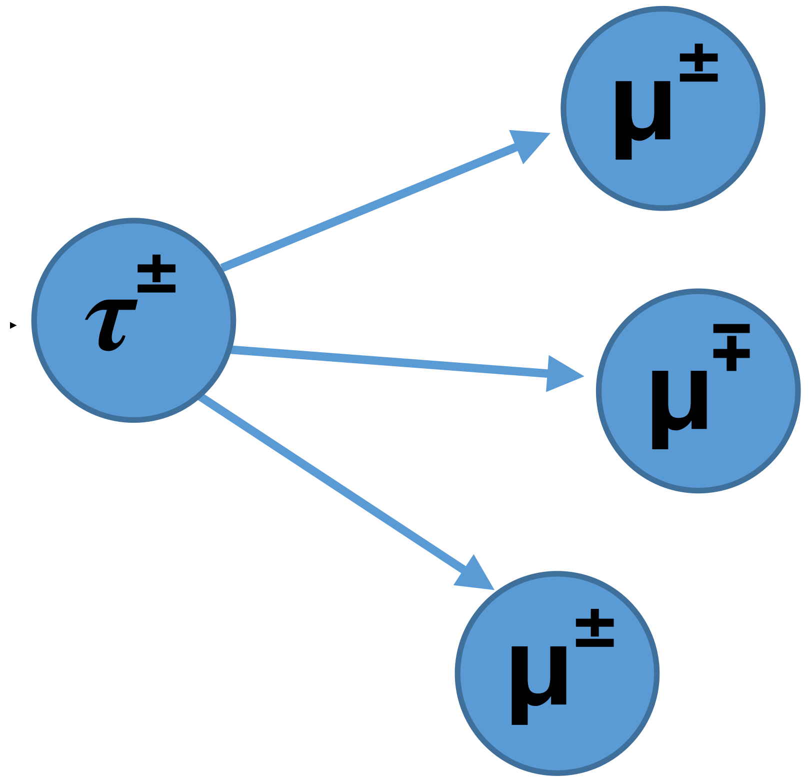
$\tau \to \mu\mu\mu$

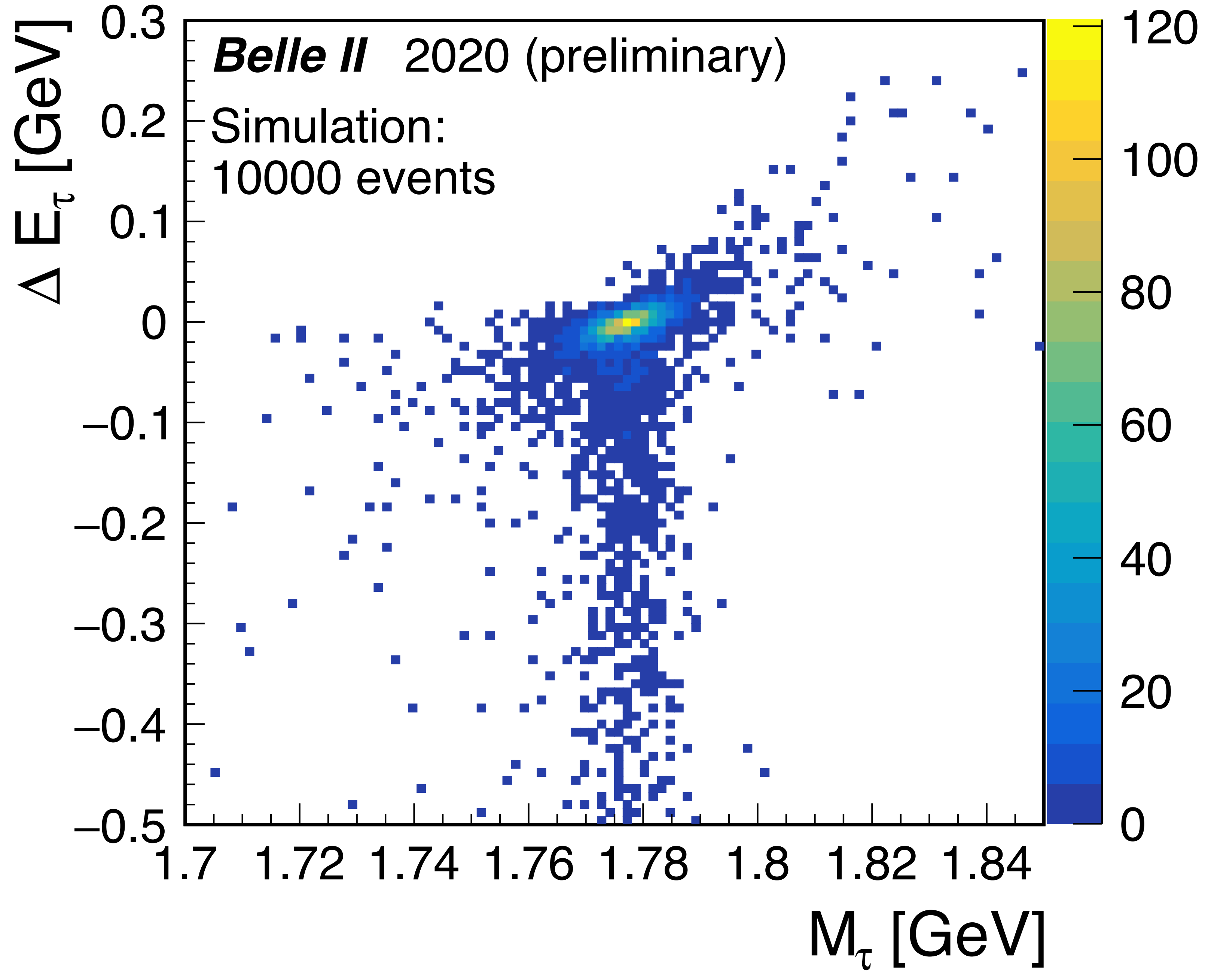
Signal-background discrimination using kinematics of the event

μID - the most powerful discriminating variable

Momentum dependent optimisation of the muID requirement

- $P_\mu < 0.7$ GeV
  - μ do not reach the μ detector (KLM)
- $0.7 < P_\mu < 1$ GeV
  - μ reach KLM but not many layers are crossed
- $P_\mu > 1$ GeV
  - μ reach KLM and many layers are crossed





Other requirement used @Belle but not @Belle II:

- μ veto on tag track
- $P_\mu > 0.6$ GeV

Higher efficiency is foreseen @Belle II than @Belle or @BaBar

Two independent variables:

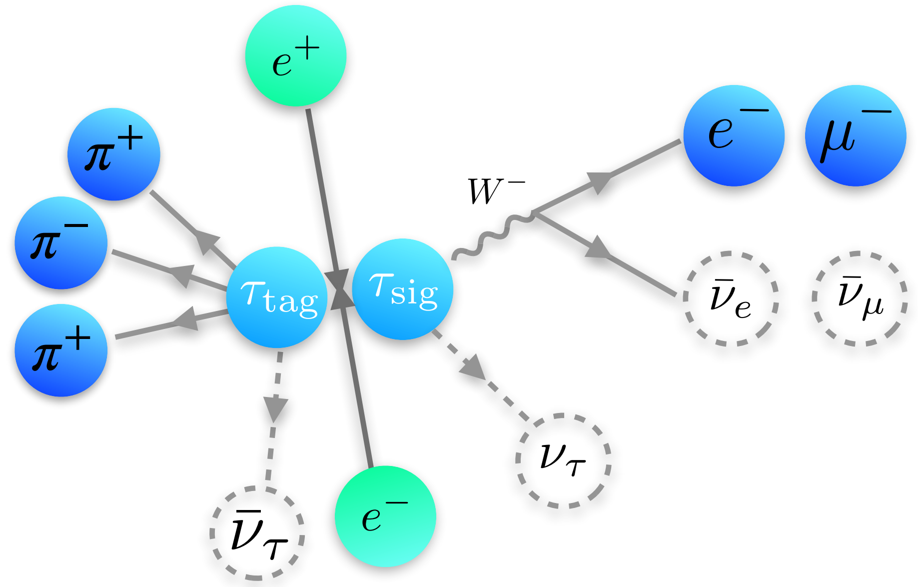
$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

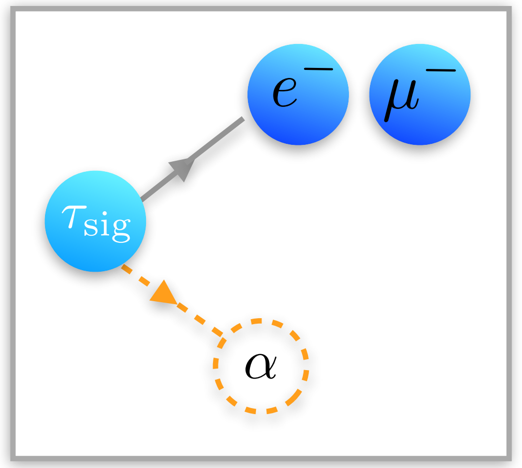
$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

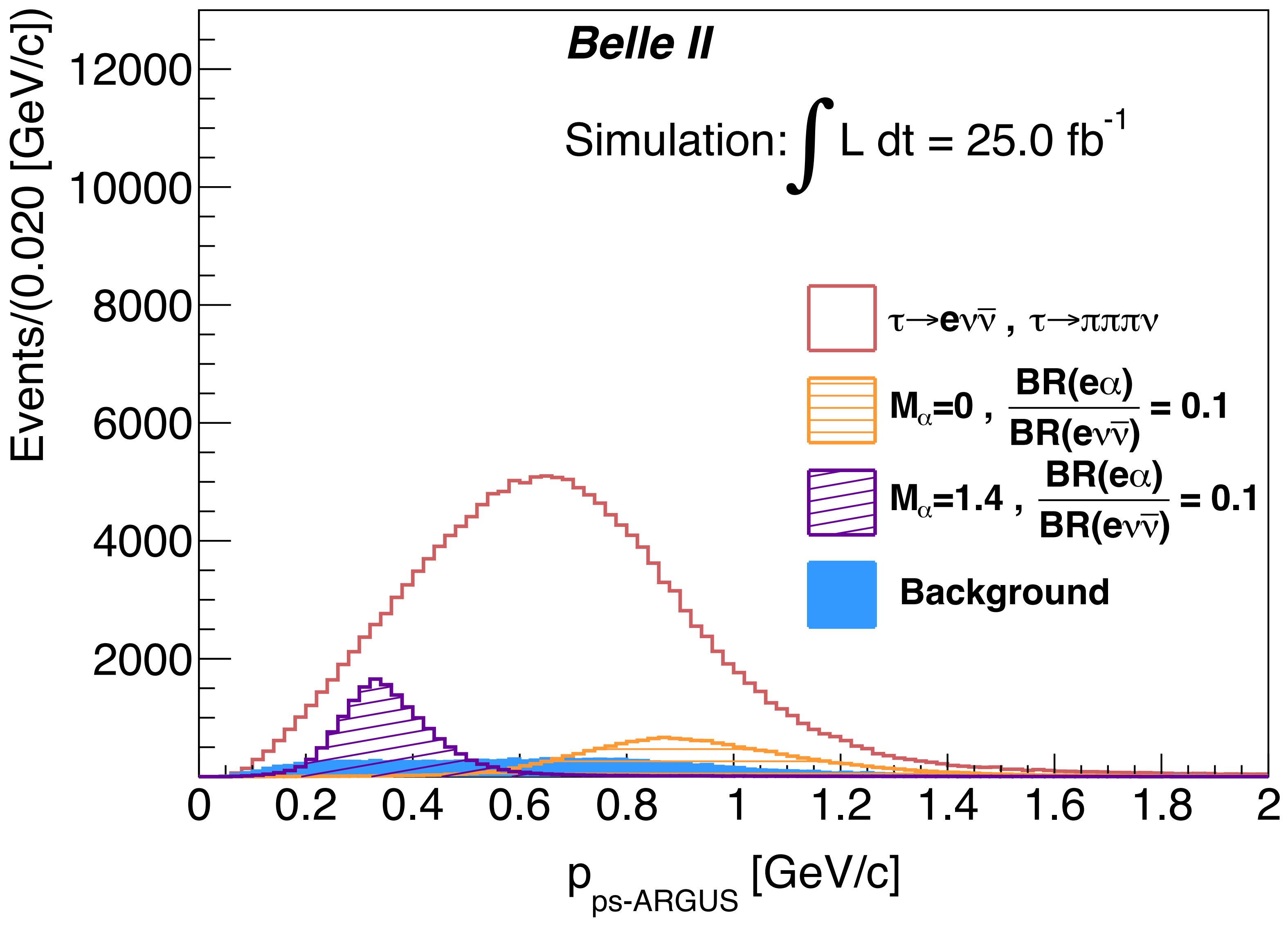
- For signal → ΔE close to 0 and $M_{\mu\gamma}$ close to τ mass

Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

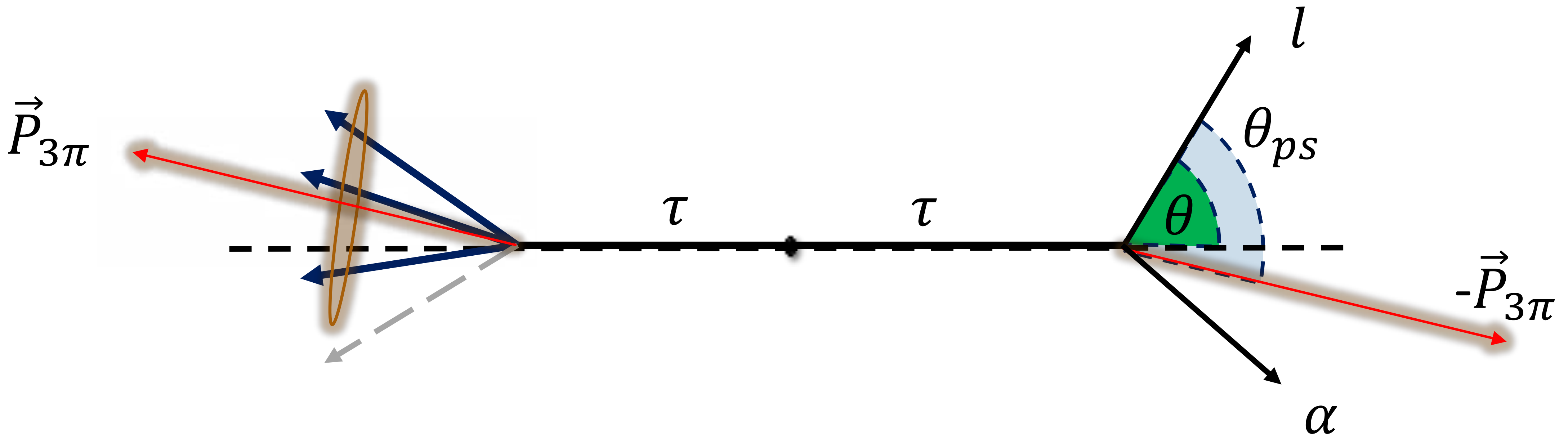
Probe the existence of a new boson α

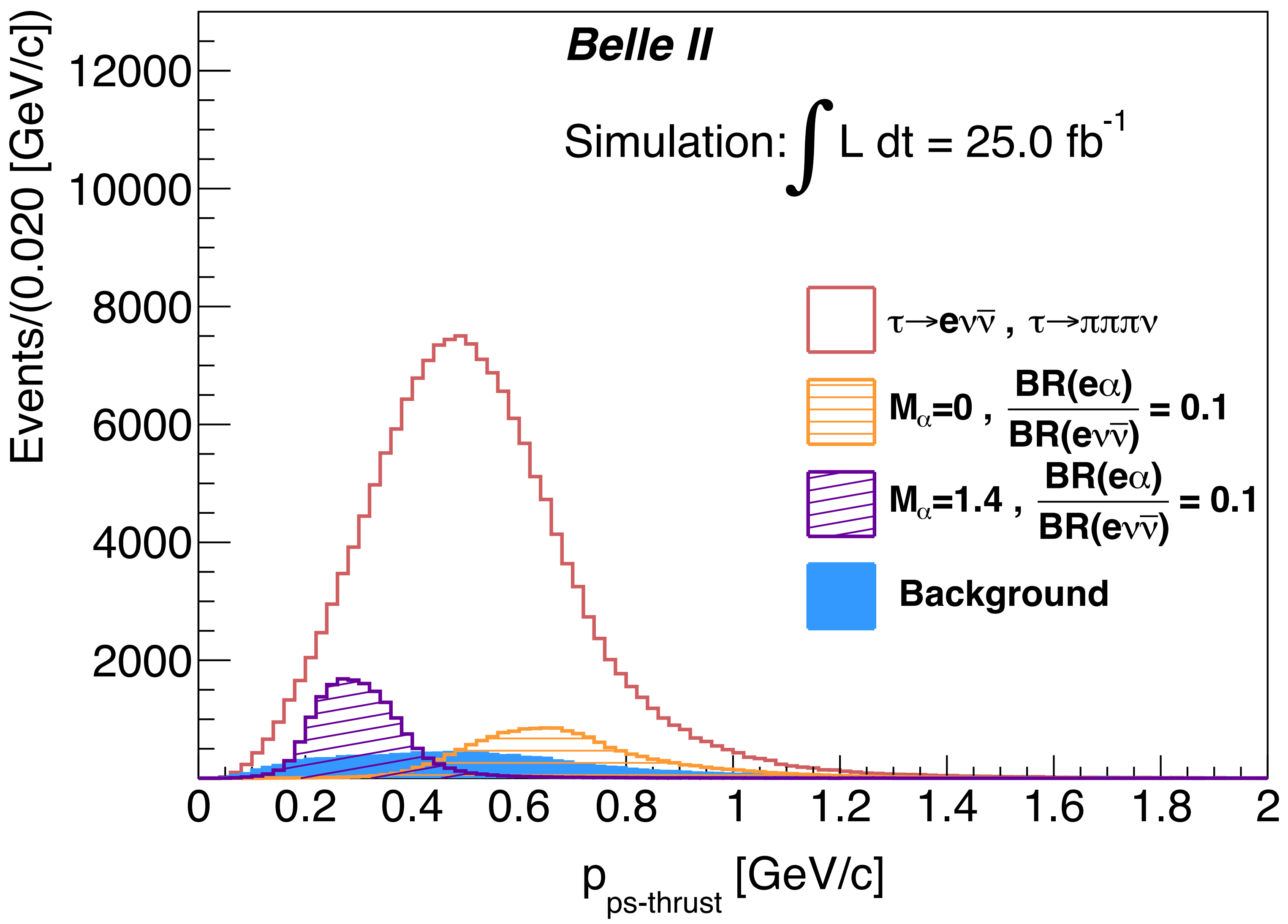






- ➡ previous studied at Mark III (9.4 pb^{-1}) and ARGUS (476 pb^{-1})
- ➡ search for a two body decay spectrum
- ➡ signal will manifest itself as a peak in the τ rest frame





- ➡ cannot access the τ rest frame directly due to the missing neutrino
- ➡ approximate with the following assumptions:

$$E_\tau = \sqrt{s}/2$$

ARGUS method: $\hat{p}_\tau \approx -\hat{p}_{3\pi}$ Thrust method: $\hat{p}_\tau \approx \hat{T}$

Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

UL is provided for the ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$

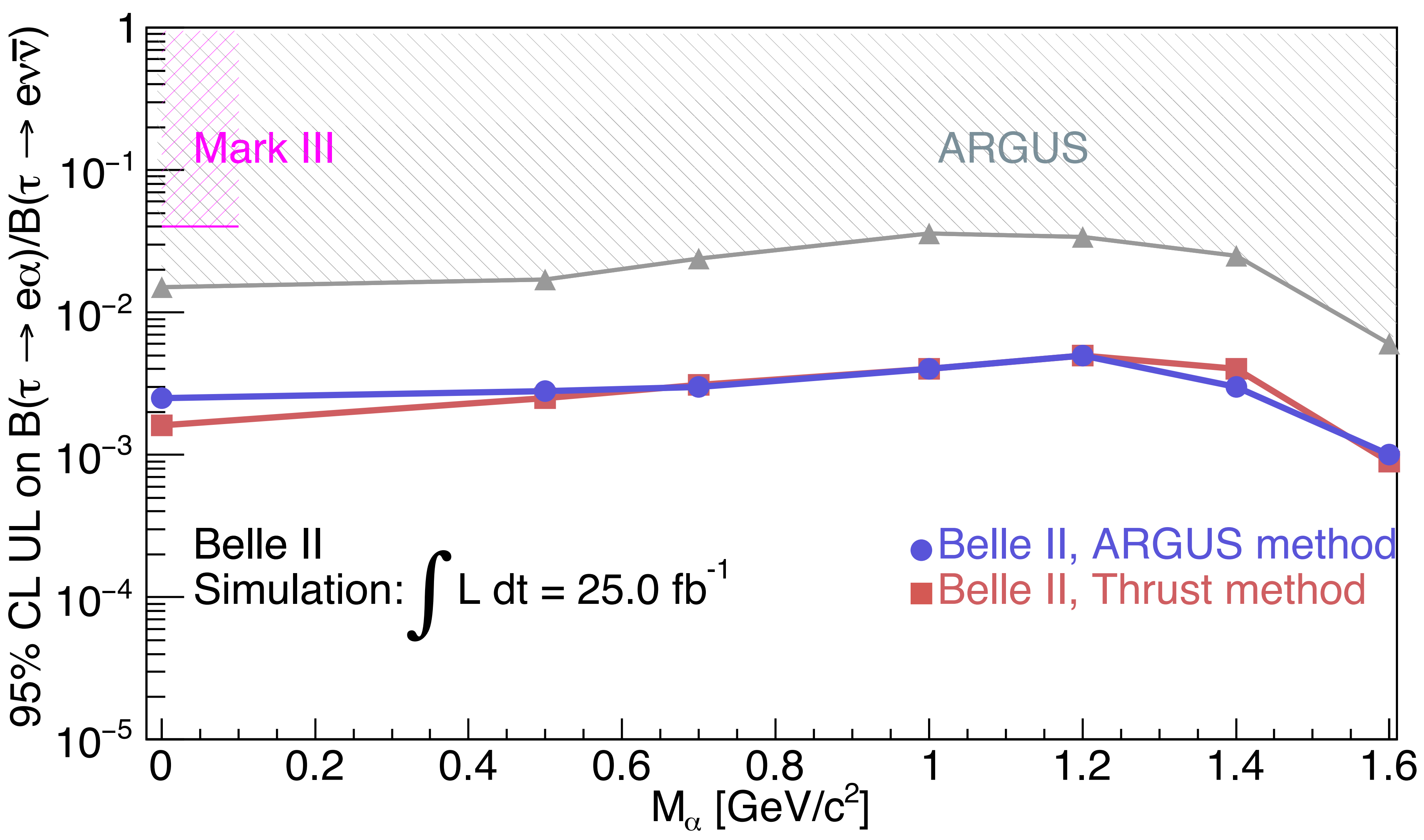
BELLE2-NOTE-PH-2019-009

Status of the analysis:

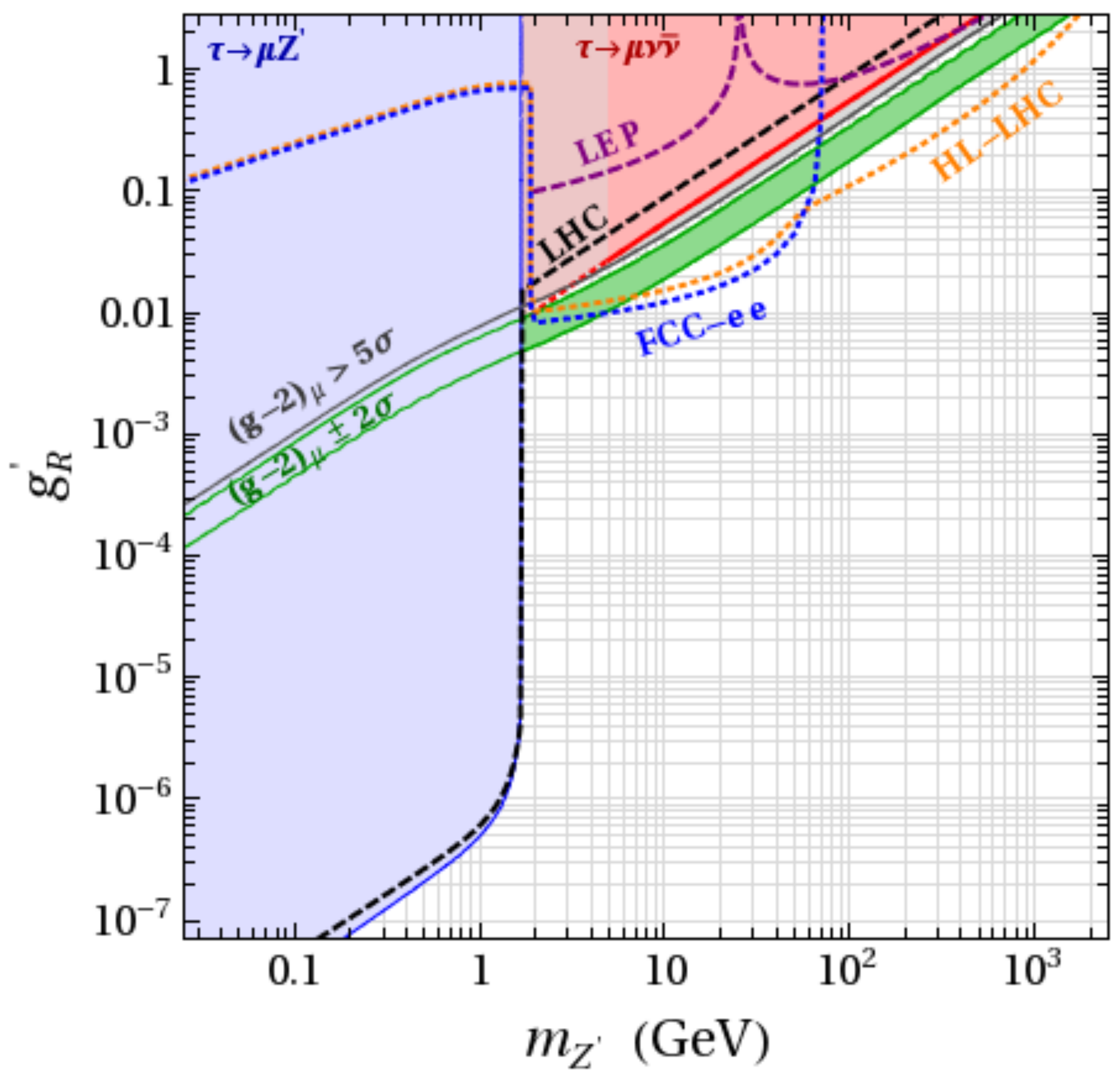
- background suppression already quite effective
- ongoing work to further suppress BG using BDT
- UL estimation using the frequentist profile-likehood method using asymptotic approach
- alternative test using the Bayesian approach

Various NP scenarios:

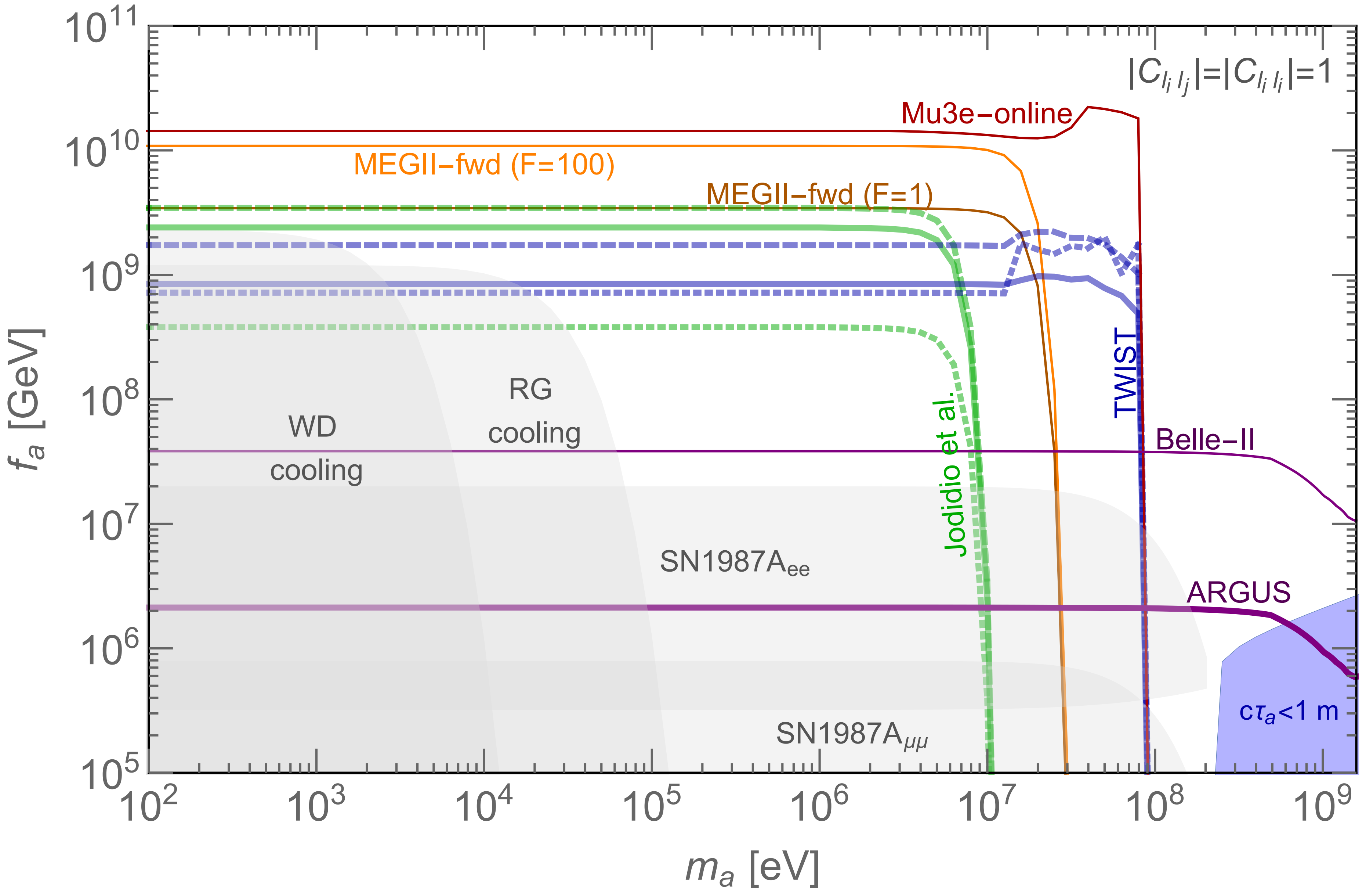
- **LFV Z′**
  - strong bound from ARGUS measurement
- **light ALP *a***
  - exploring regions in parameter space not reachable by other experiments



- W. Altmannshofer, C.Y. Chen, B. Dev, A, Soni -

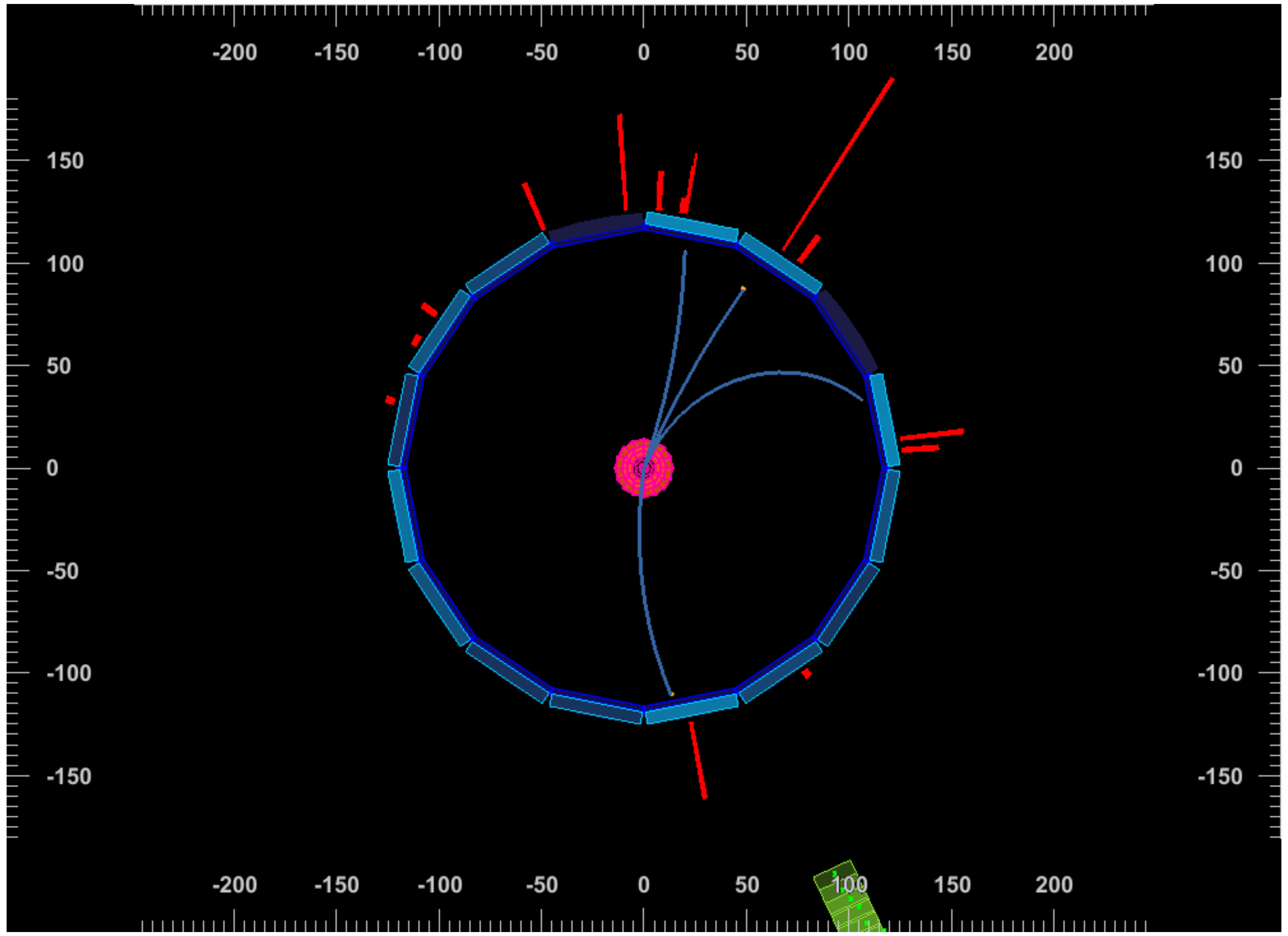


- L. Calibbi, D. Redigolo, R.. Ziegler, J. Zupan -



Summary

e^+e^- annihilation data is ideal for precision measurements and NP searches!



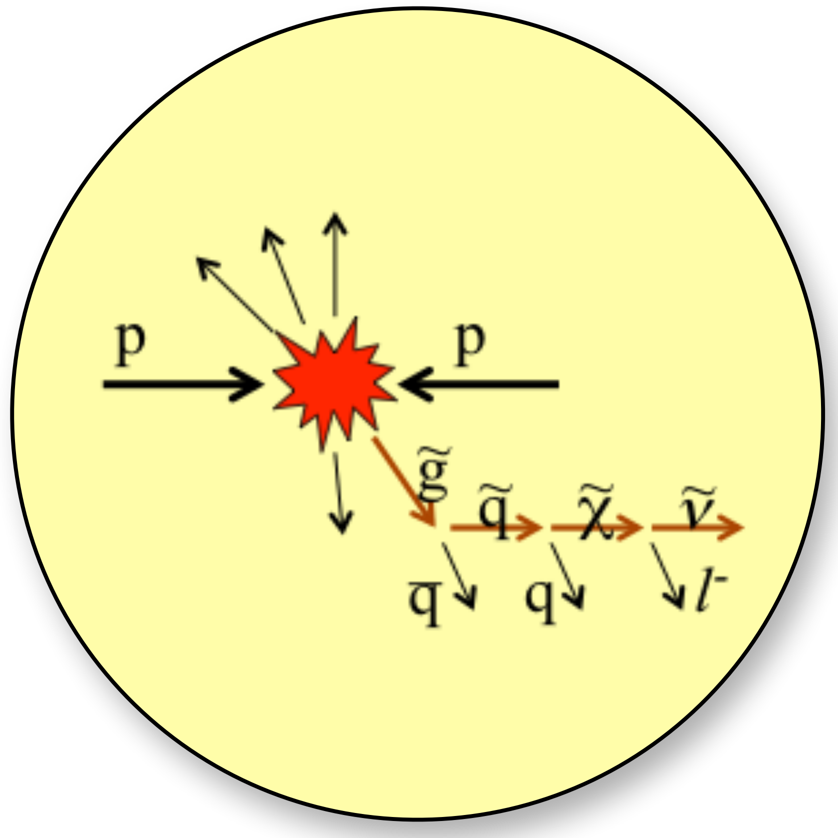
If got interested, join us!
Contact me!

- **Belle II experiment started**
  - Achieved world record luminosity $L = 2.4 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$
  - Accelerator tuning is ongoing; more data will be recorded soon
  - **τ mass** and **lifetime** measurements with the early data are very promising and show the potential of Belle II precision measurements
  - **LFU** and **V_{us}** (exclusive) analysis started
  - **$\tau \rightarrow \mu\mu\mu$** indicates the potential of LFV searches
  - …
- **Belle II will provide the world largest number ($5\text{x}10^{10}$) of $e^+e^- \rightarrow \tau^+\tau^-$ events**
  - τ precision measurements and NP searches will reach higher sensitivity w.r.t. the previous experiments

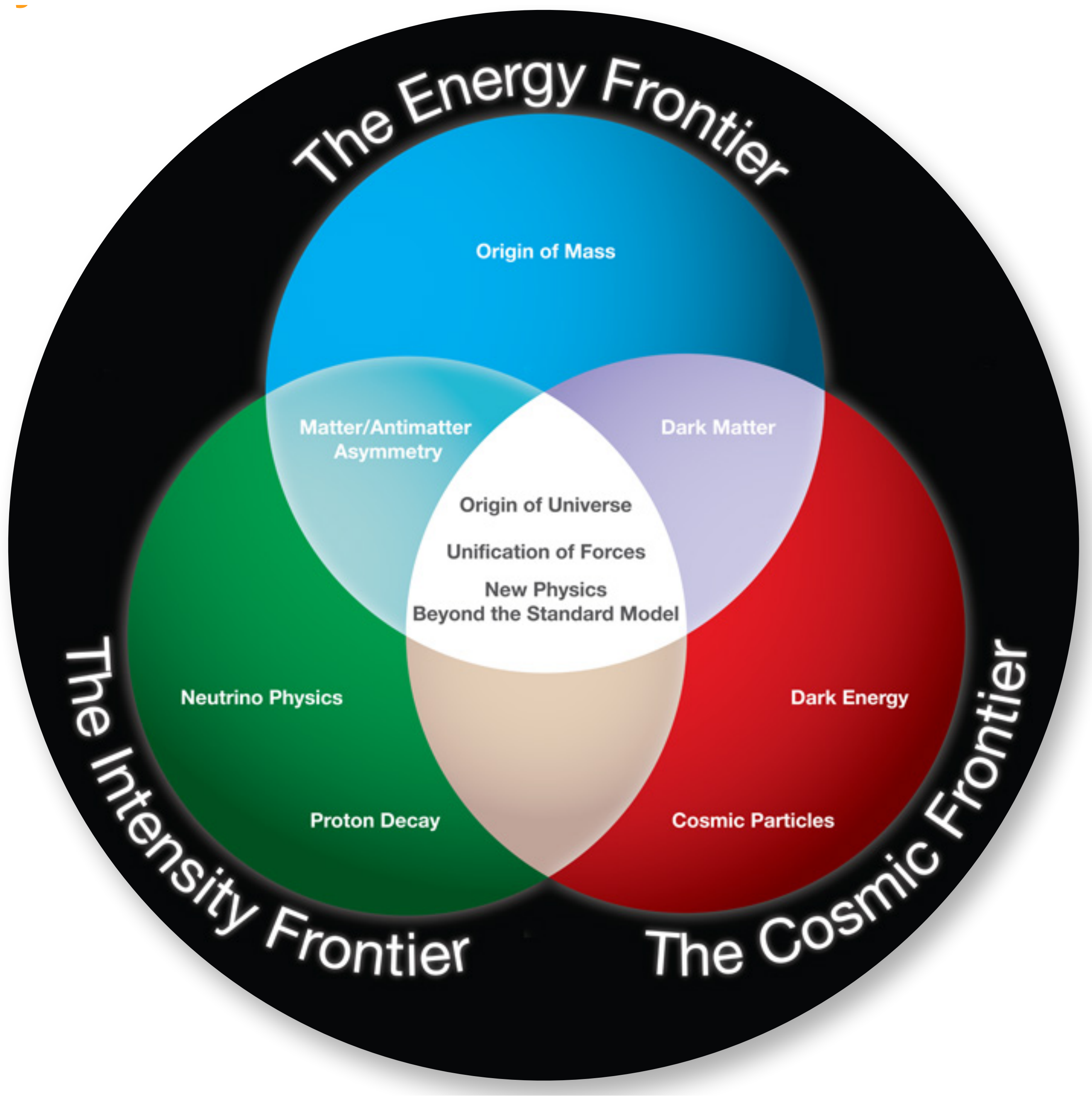
Outlook

Complementary Pathways to New Physics

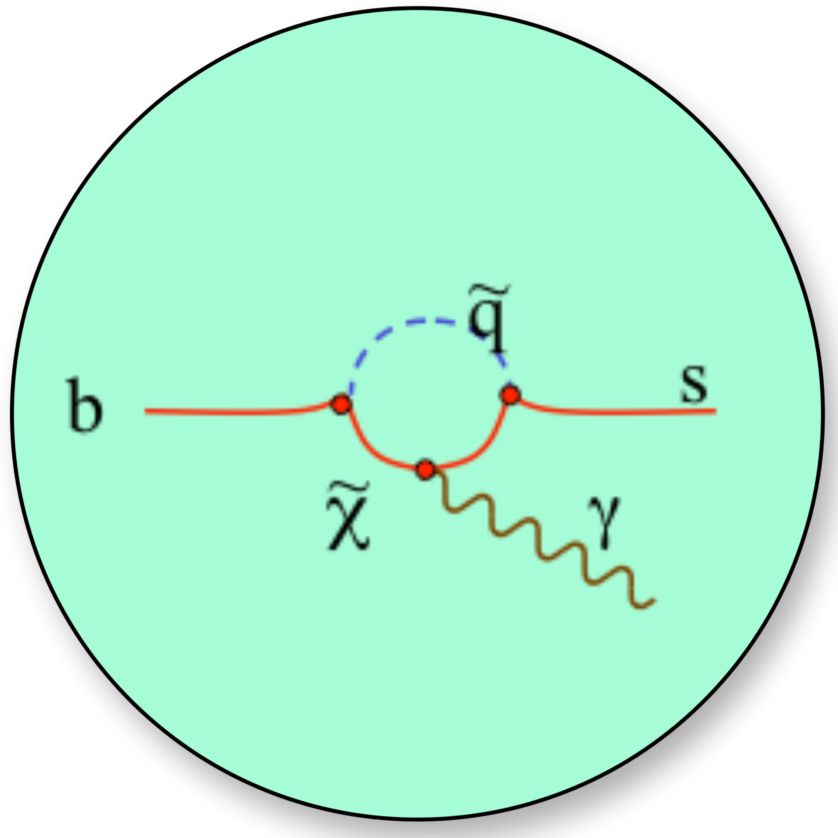
Energy frontier



Direct production of new particles (limited by the beam energy)



Intensity frontier



Indirect sensitivity through loops (probe the energy above 10 TeV)

If NP is seen by one frontier, the confirmation by the other would be important!