1.777 GeV/$c^2$
-1
½
tau

# τ Physics

… a very personal selection

Anomalies and Precision in the Belle II Era
Vienna, 6-8 September 2021

Belle II

Ami Rostomyan
(on behalf of the Belle II collaboration)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

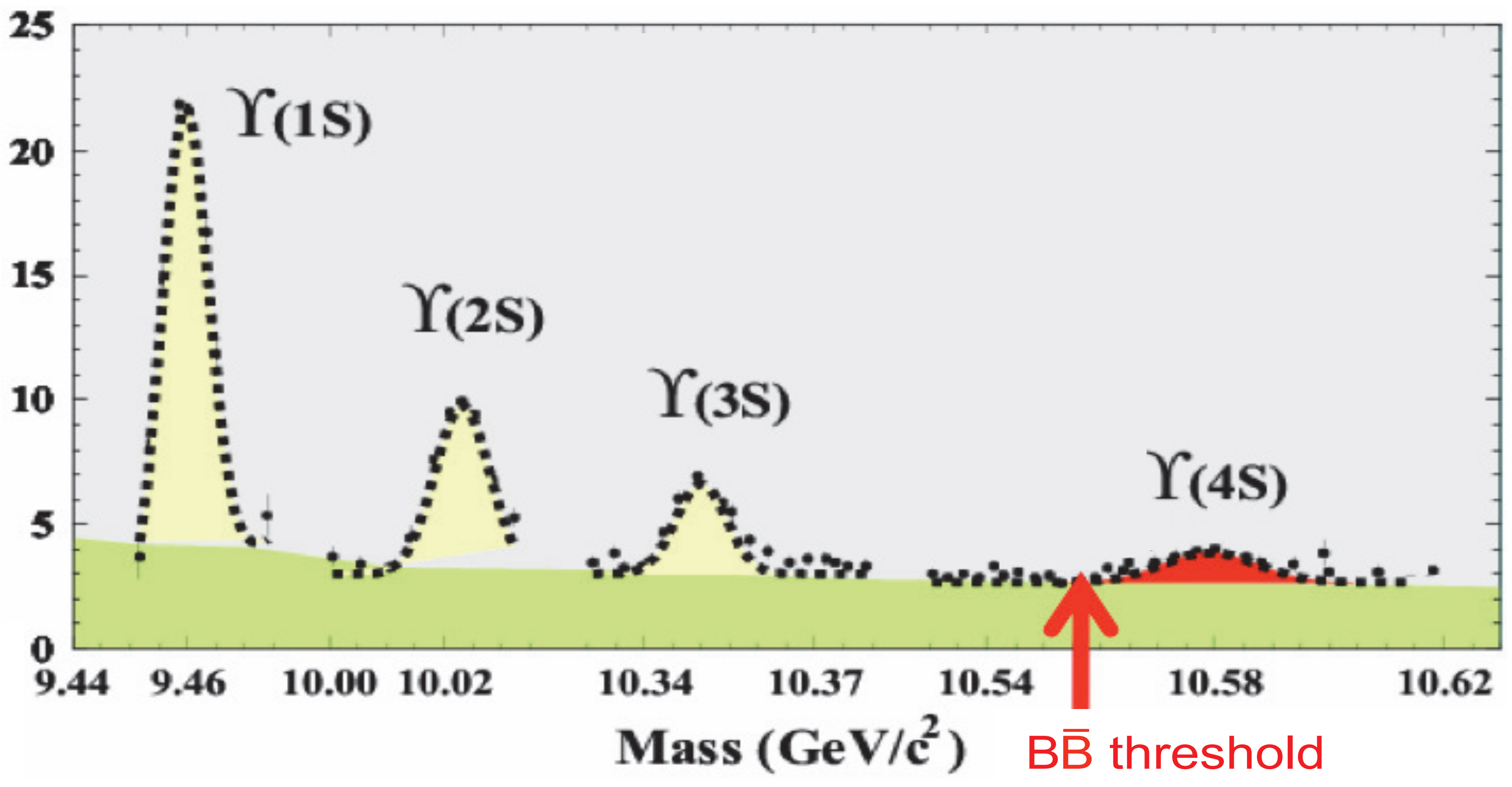
DESY.

# $\tau$ 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**

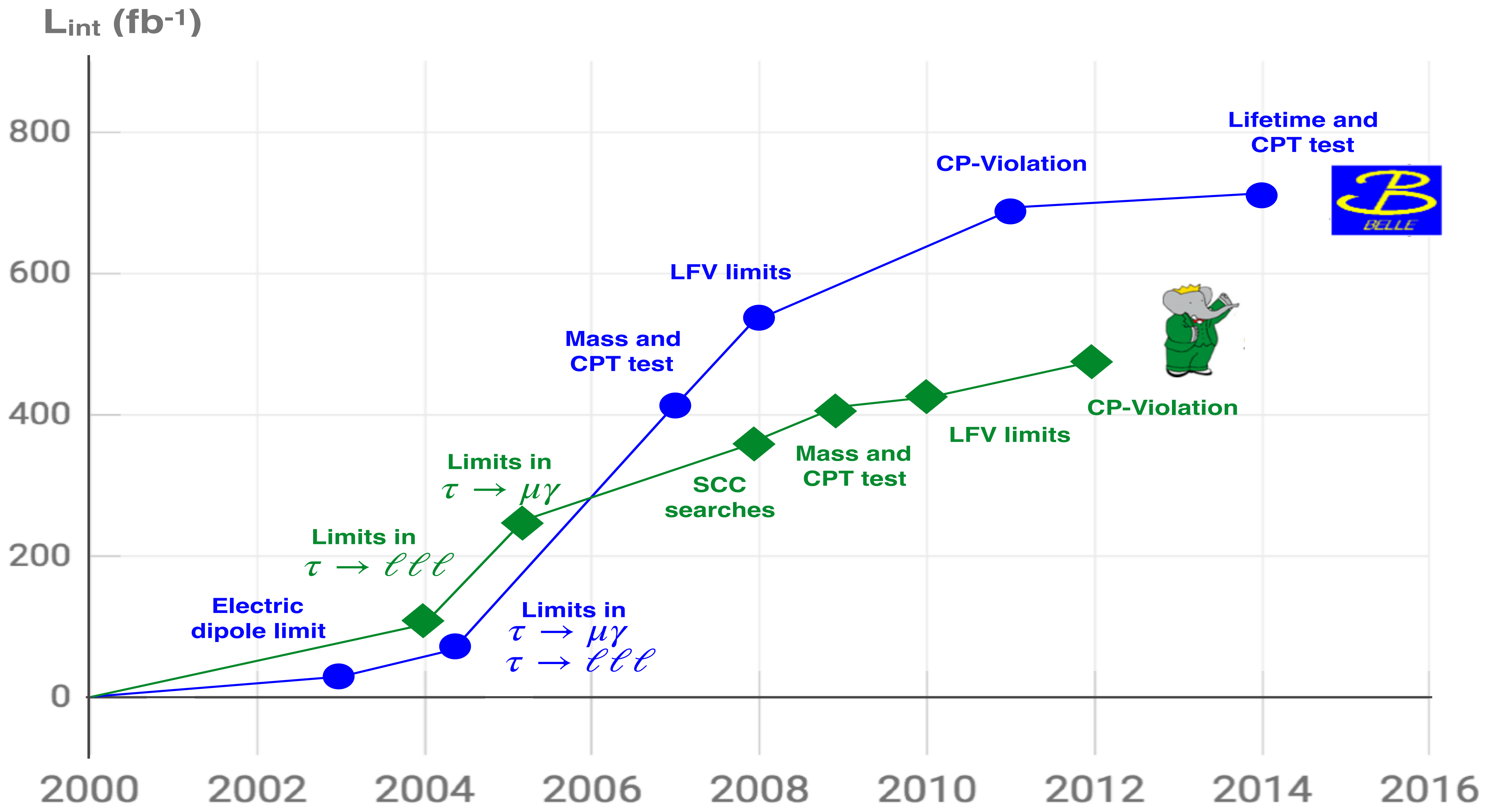
- Collision energy at $\Upsilon(nS)$
  - $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$



- Asymmetric beam energies
  - Boosted $B\bar{B}$ pairs
- High luminosities

~Belle: 710 fb$^{-1}$ @ $\Upsilon(4S)$

~ BaBar: 424 fb$^{-1}$ @ $\Upsilon(4S)$

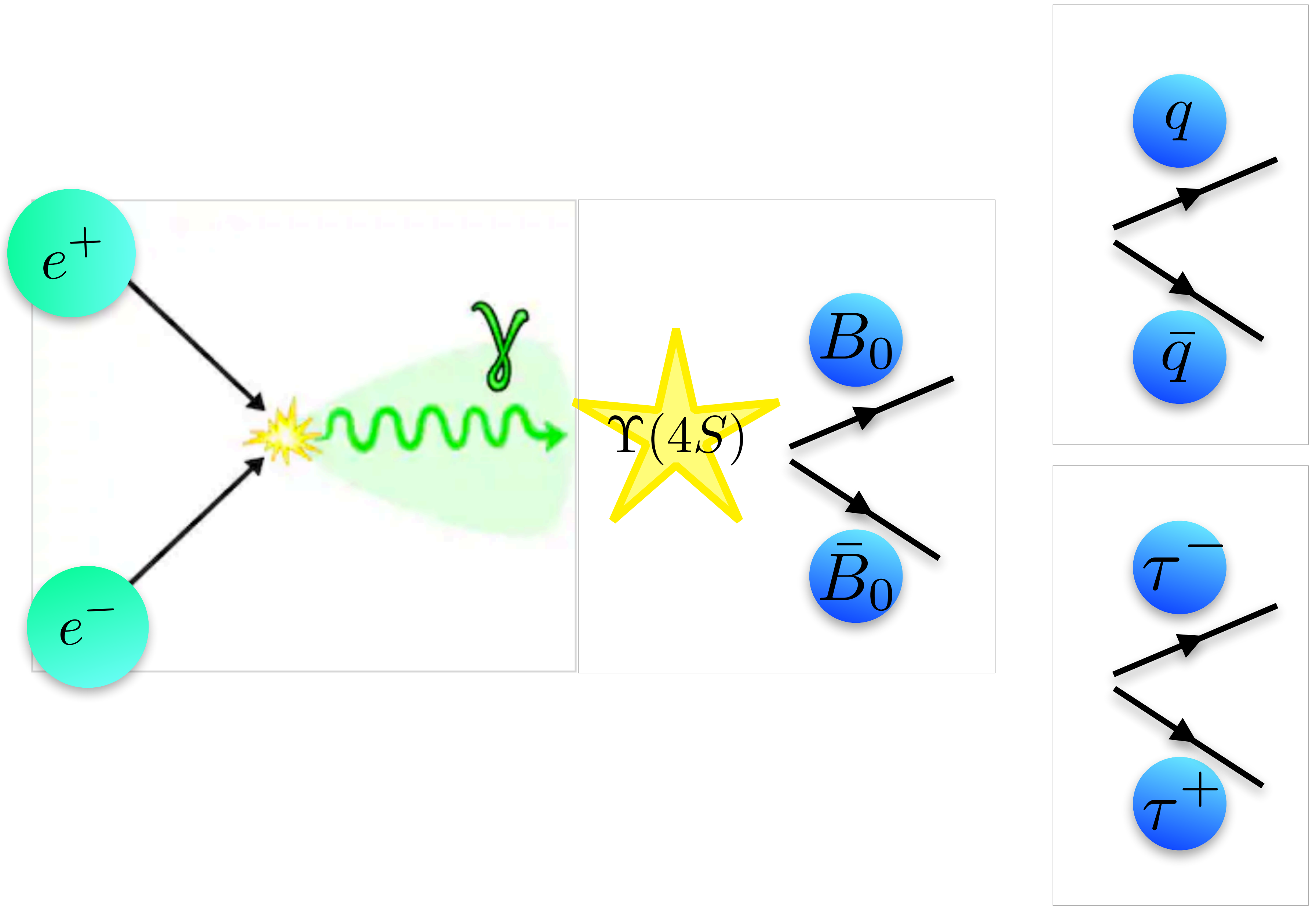


**Wide physics program**

- Precision SM measurement
- CP asymmetries
- Angular distributions
- Searches for lepton flavor/universality/number violations
- …

# B-Factories

**Not just B-Factories but also τ factories!**



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

**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 & γ & $\pi^0$ reconstruction capabilities

**Wide range of observables in τ sector to confront theory!**

**Does NP couple to 3rd generation strongly?**

**Precision measurements or indirect search of BSM**

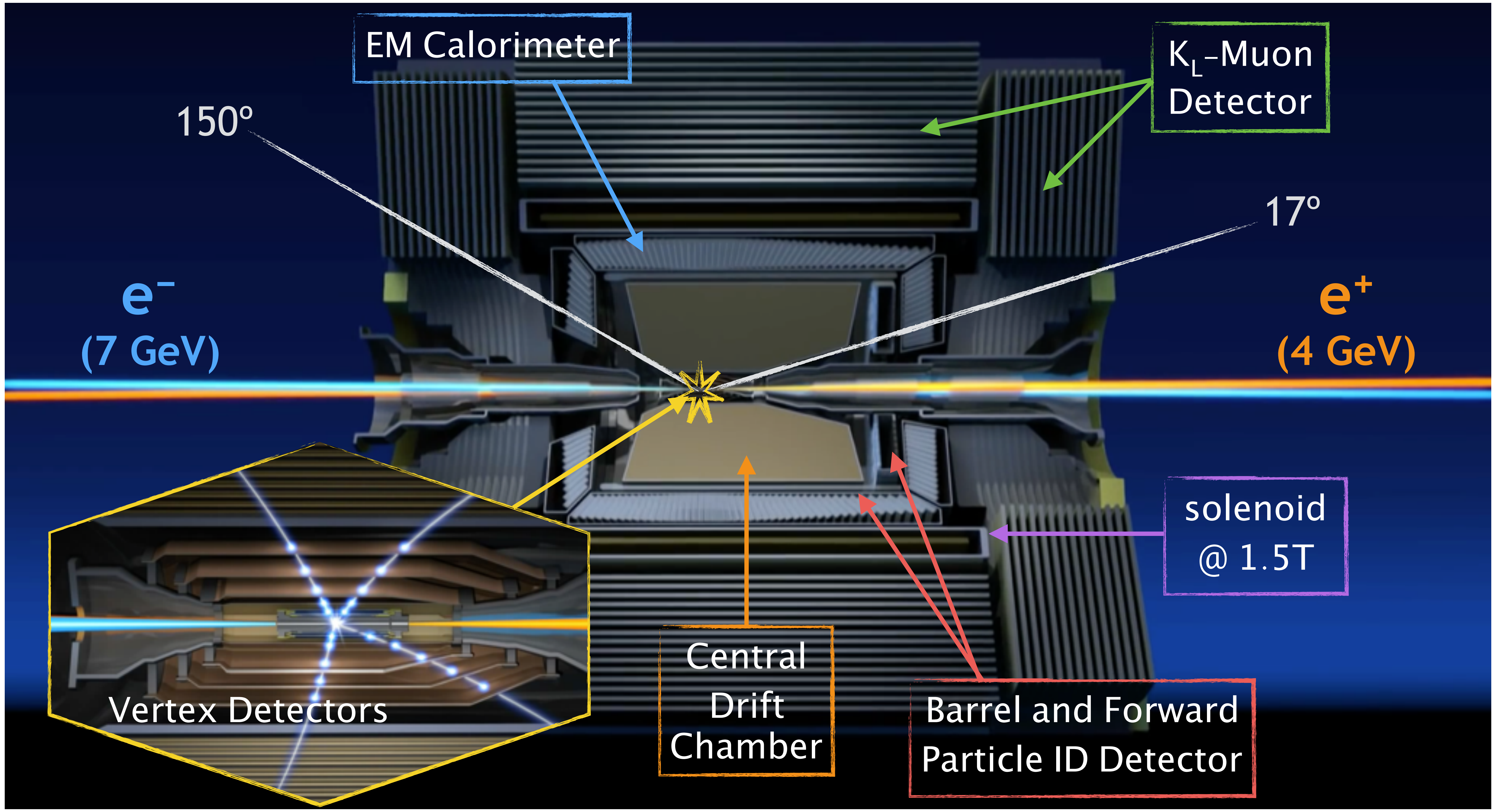
- ➡ ***significant deviations from SM*** are unambiguous signatures of NP

**Direct search of forbidden decays**

- ➡ ***any signal*** is unambiguous signature of NP

# Belle II @ SuperKEKB

## Belle II detector – upgraded Belle detector



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

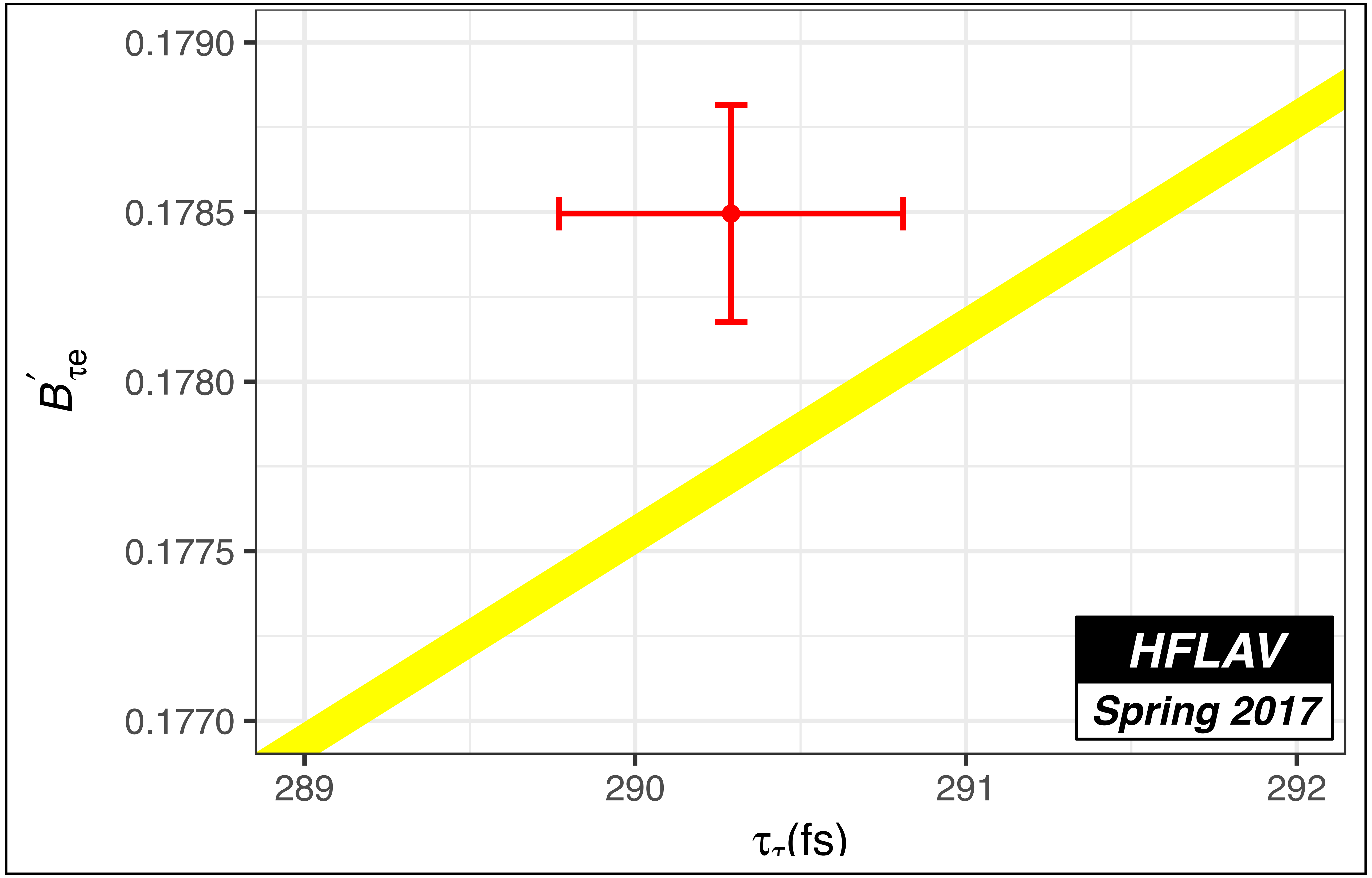
**First recorded events in April 2018**

**~ 200/fb of data already collected**

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

# The mass, lifetime and leptonic decays of τ

A. Lusiani et al: arXiv:1804.08436



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

# 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 $\tau^-$ and $\tau^+$ lifetimes and masses separately.

## Lepton Masses (MeV):

- $m_e = 0.5109989461 \pm 0.0000000031$   $\delta m/m \sim 6*10^{-9}$
- $m_\mu = 105.6583745 \pm 0.0000024$   $\delta m/m \sim 2*10^{-8}$
- $m_\tau = 1776.86 \pm 0.12$   $\delta m/m \sim 7*10^{-5}$

## Similar situation for lifetime

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

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

- violated before the first precise mass measurement by BES

*BES - PRL V69 (1992) 3021 -*

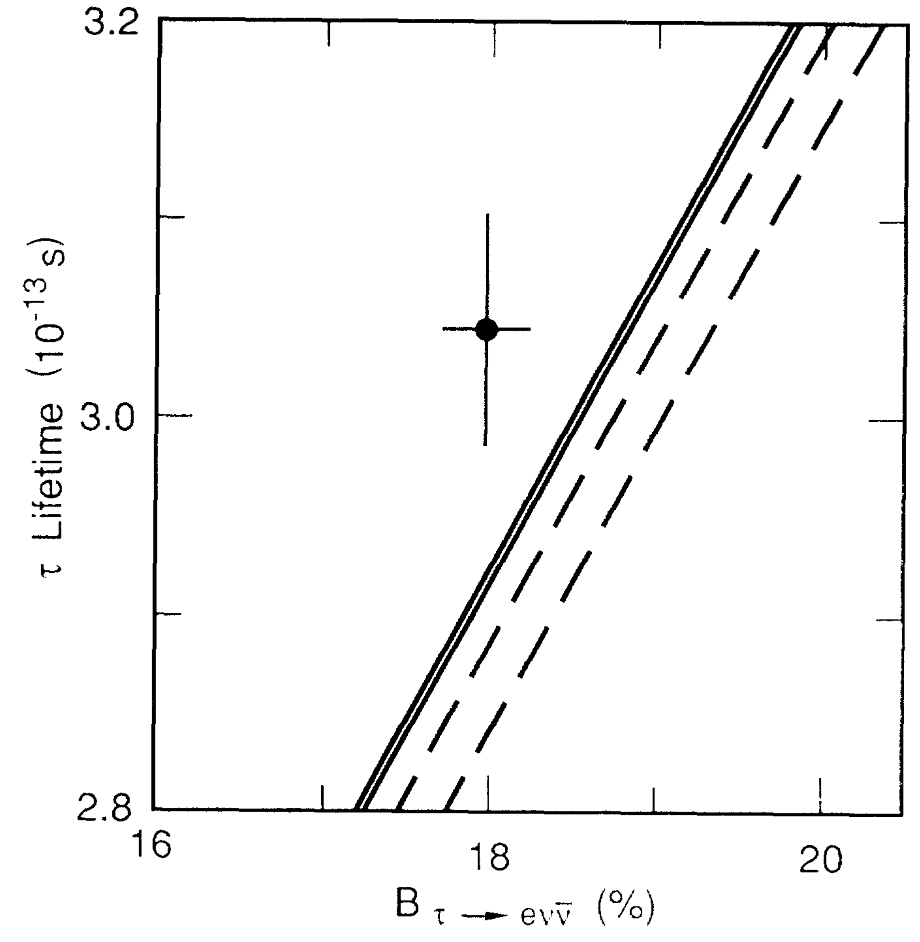
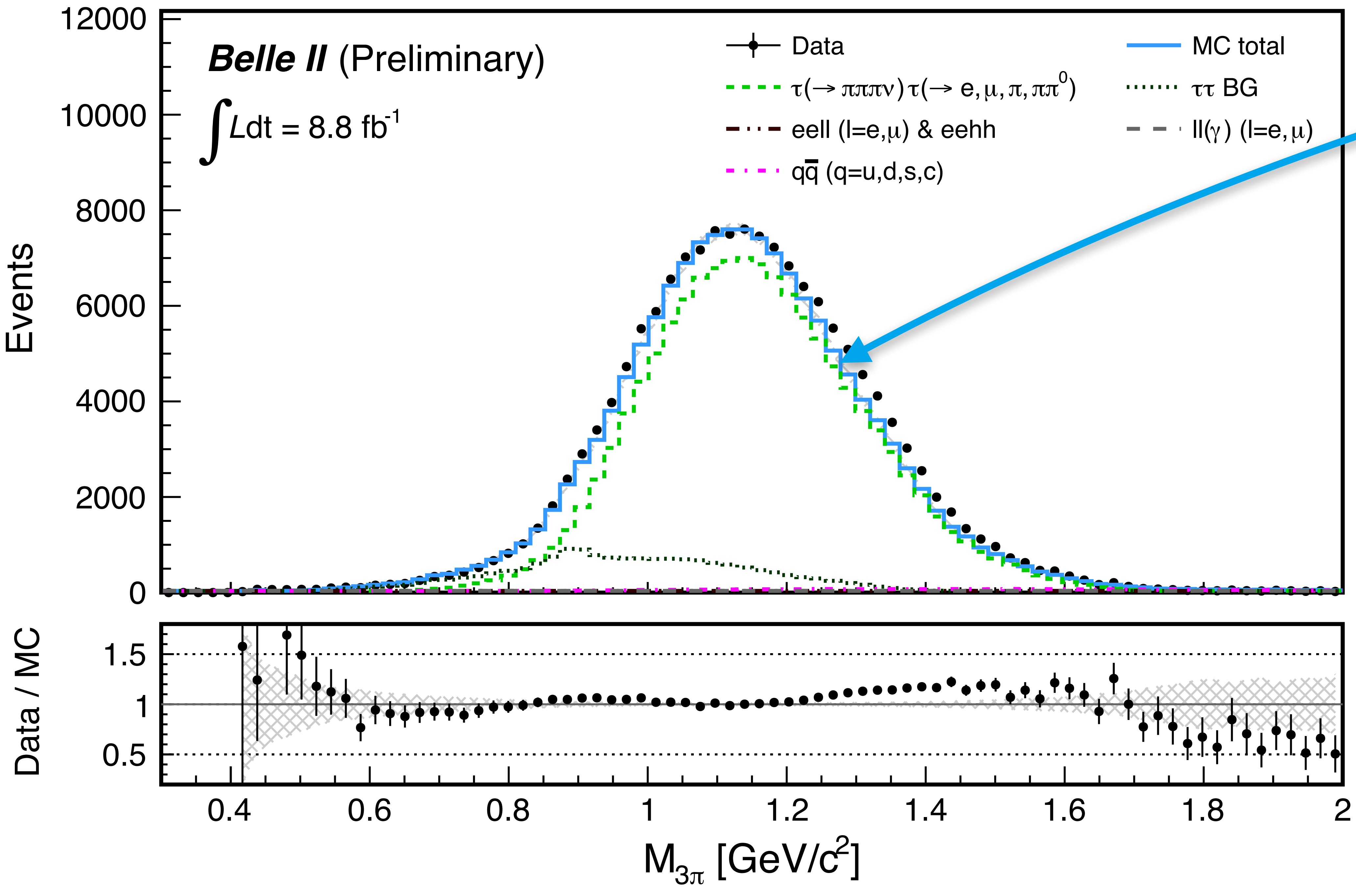


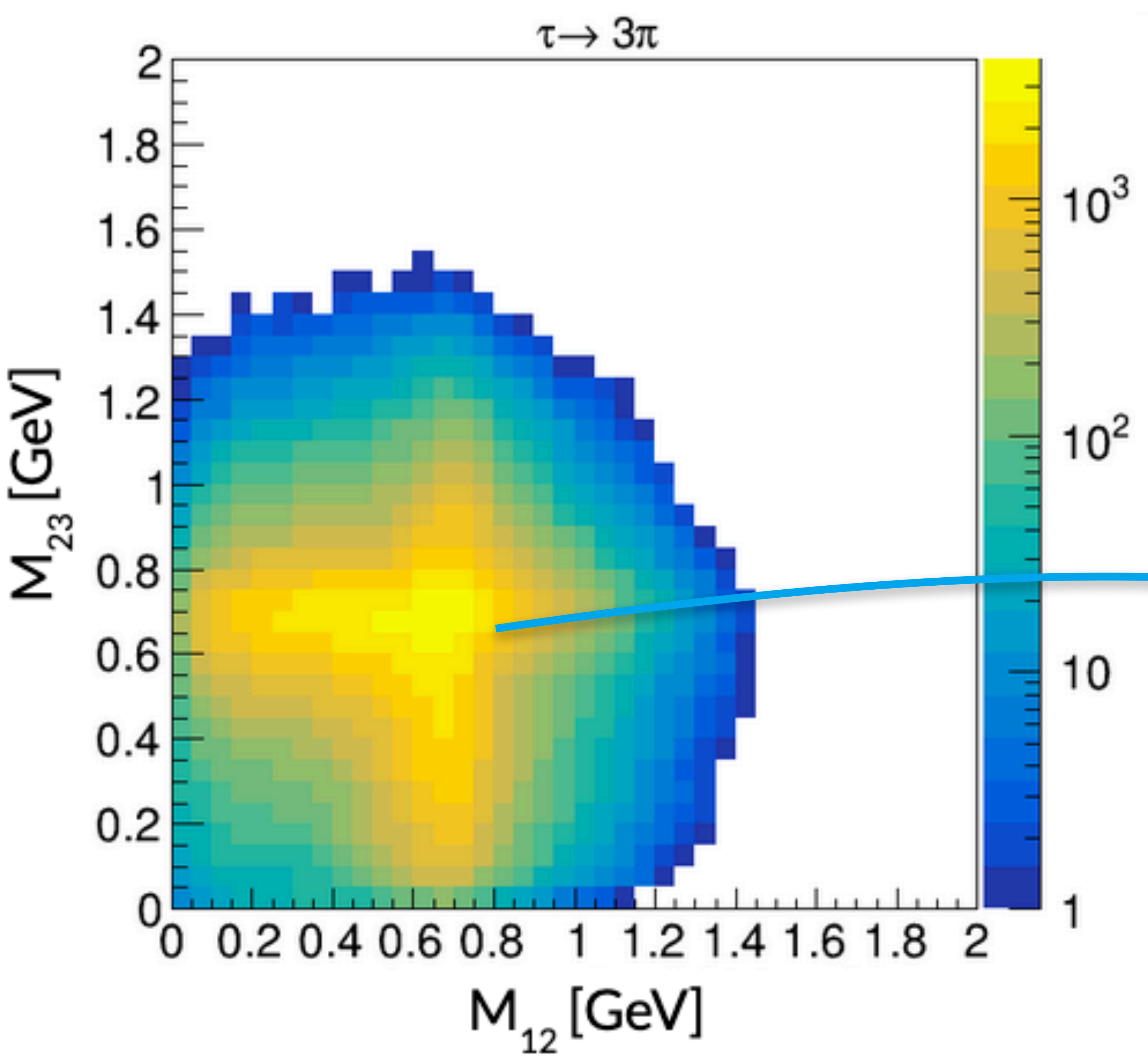
FIG. 3. The variation of $\tau_\tau$ with $B_\tau^e$, given by Eq. (1) under the assumption of lepton universality; the $\pm 1\sigma$ bands obtained using $m_\tau$ from this experiment (solid lines) and using the PDG value (dashed lines) are shown in comparison to the point corresponding to the PDG values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

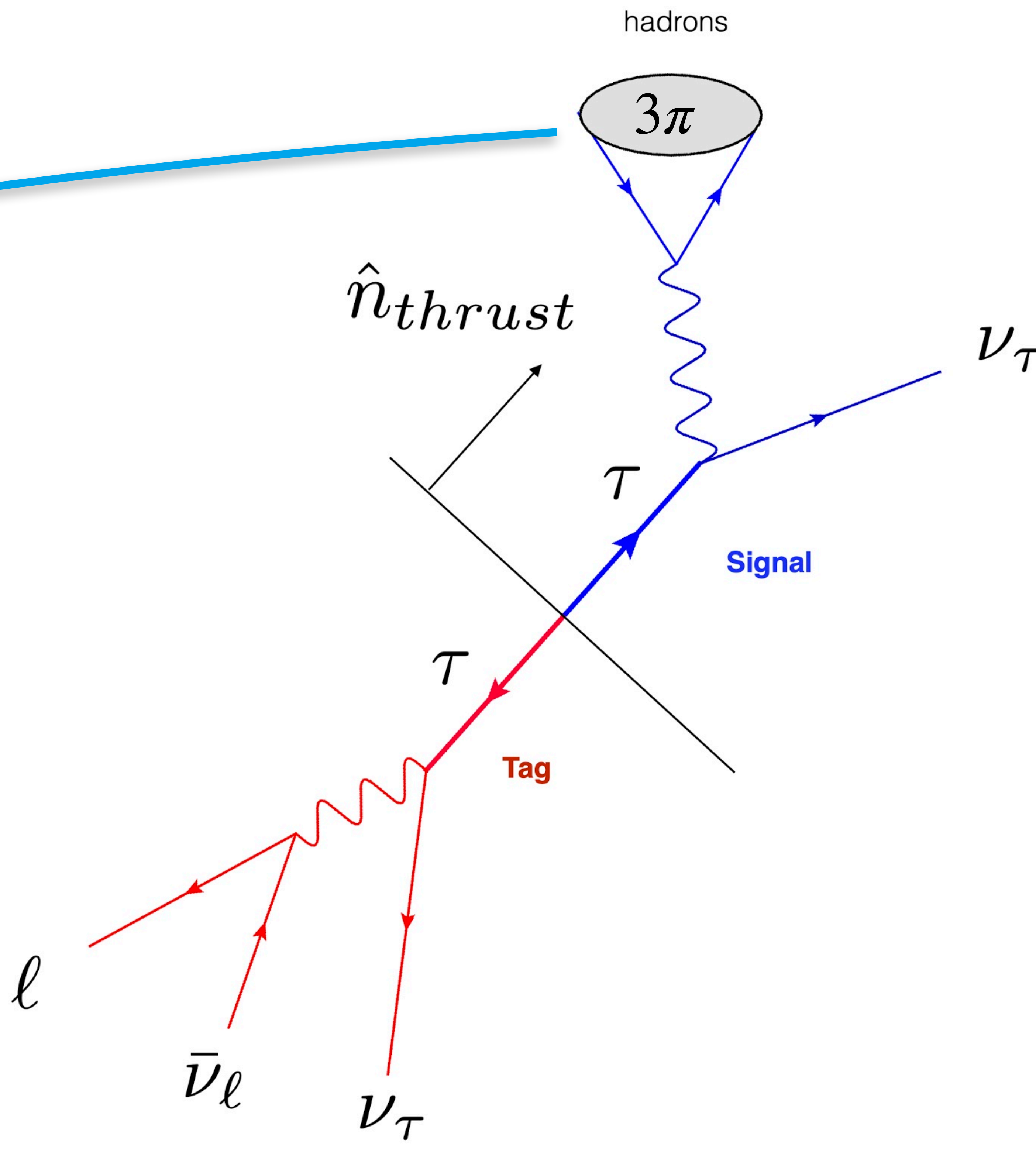
# τ mass measurement

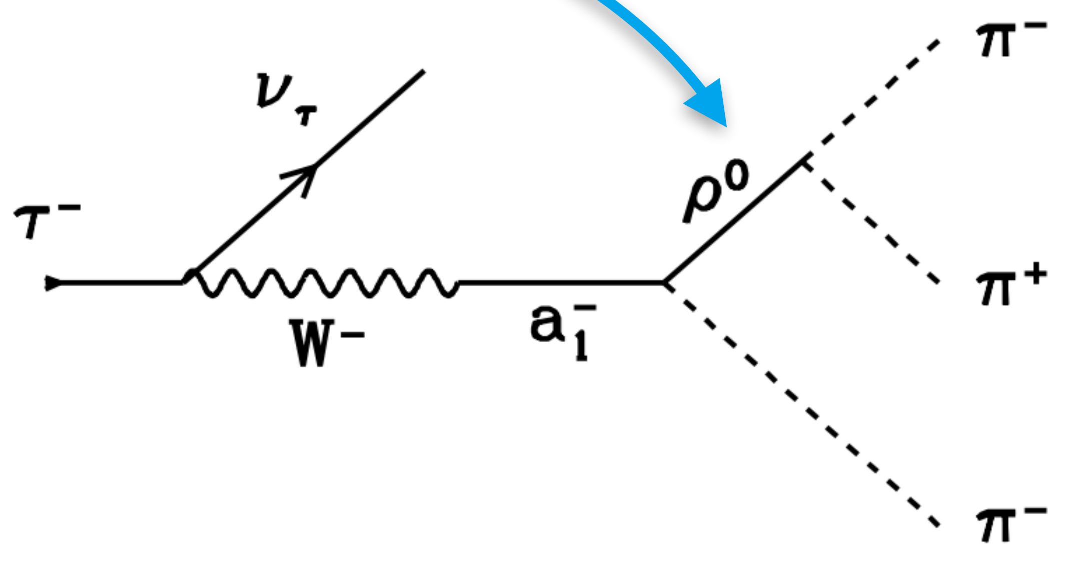
## The τ mass cannot be measured directly

➡ neutrinos in the final state









# Pseudomass technique

**Use conservation of momentum and energy:**

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

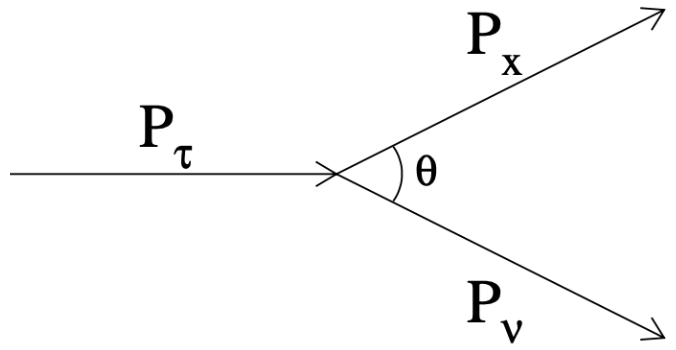
Use:

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

To get:

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

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

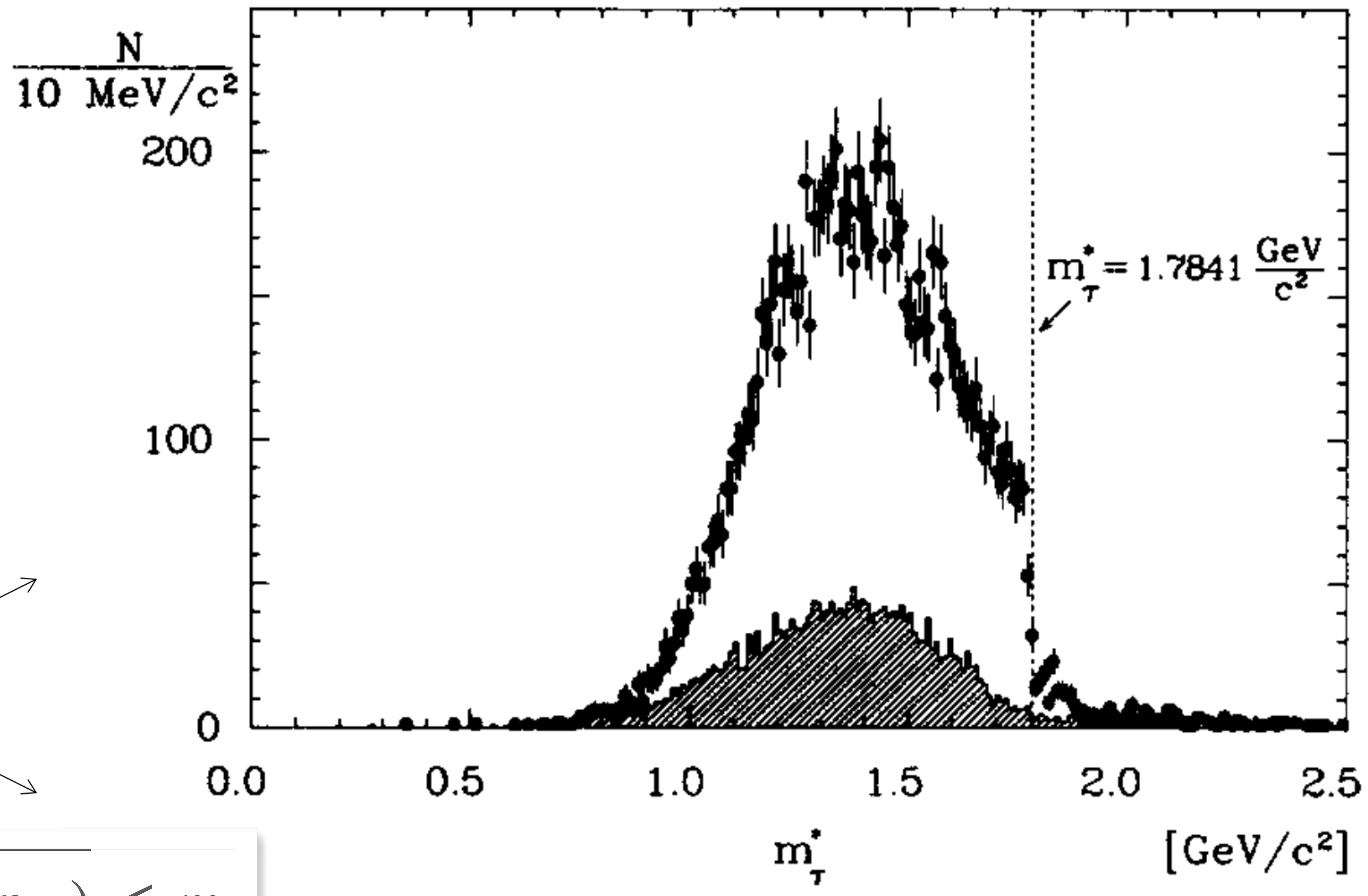


**This is called pseudomass**

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

**The 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, BaBar and now by BELLE II



# 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

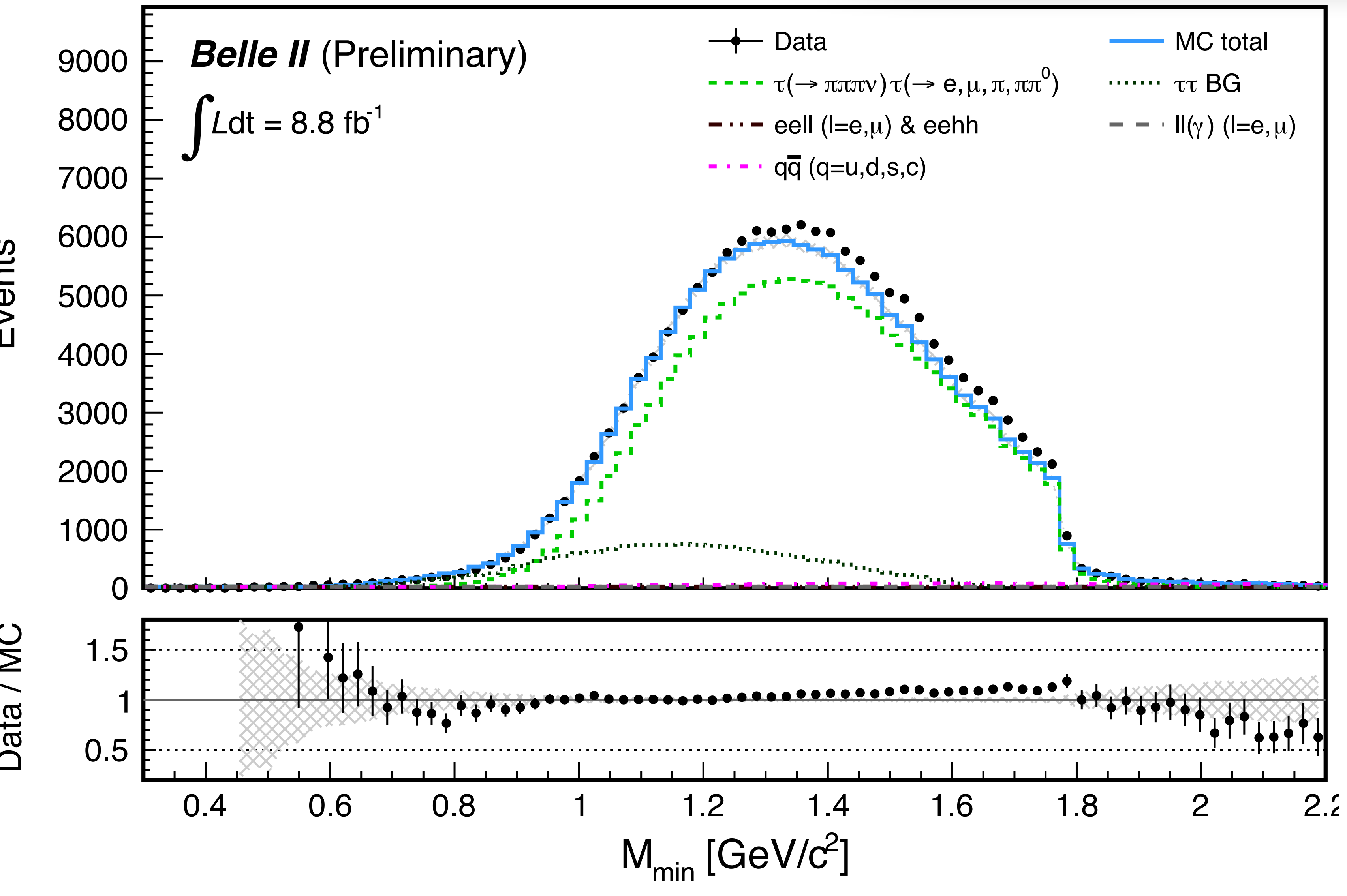
- P1 is an estimator for the τ mass
- with multi/additive components to describe the tails

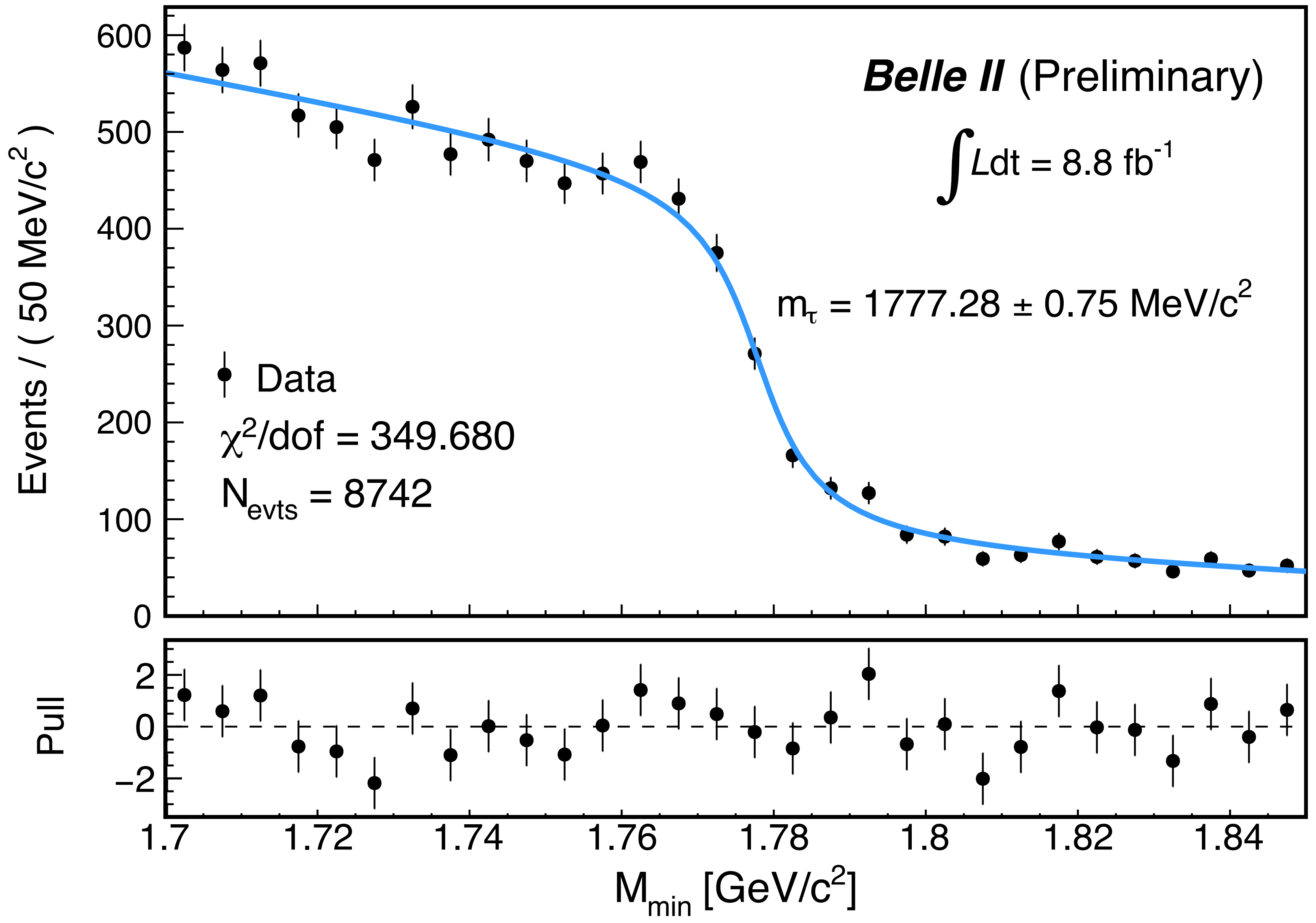
## Systematics

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

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

arXiv:2008.04665



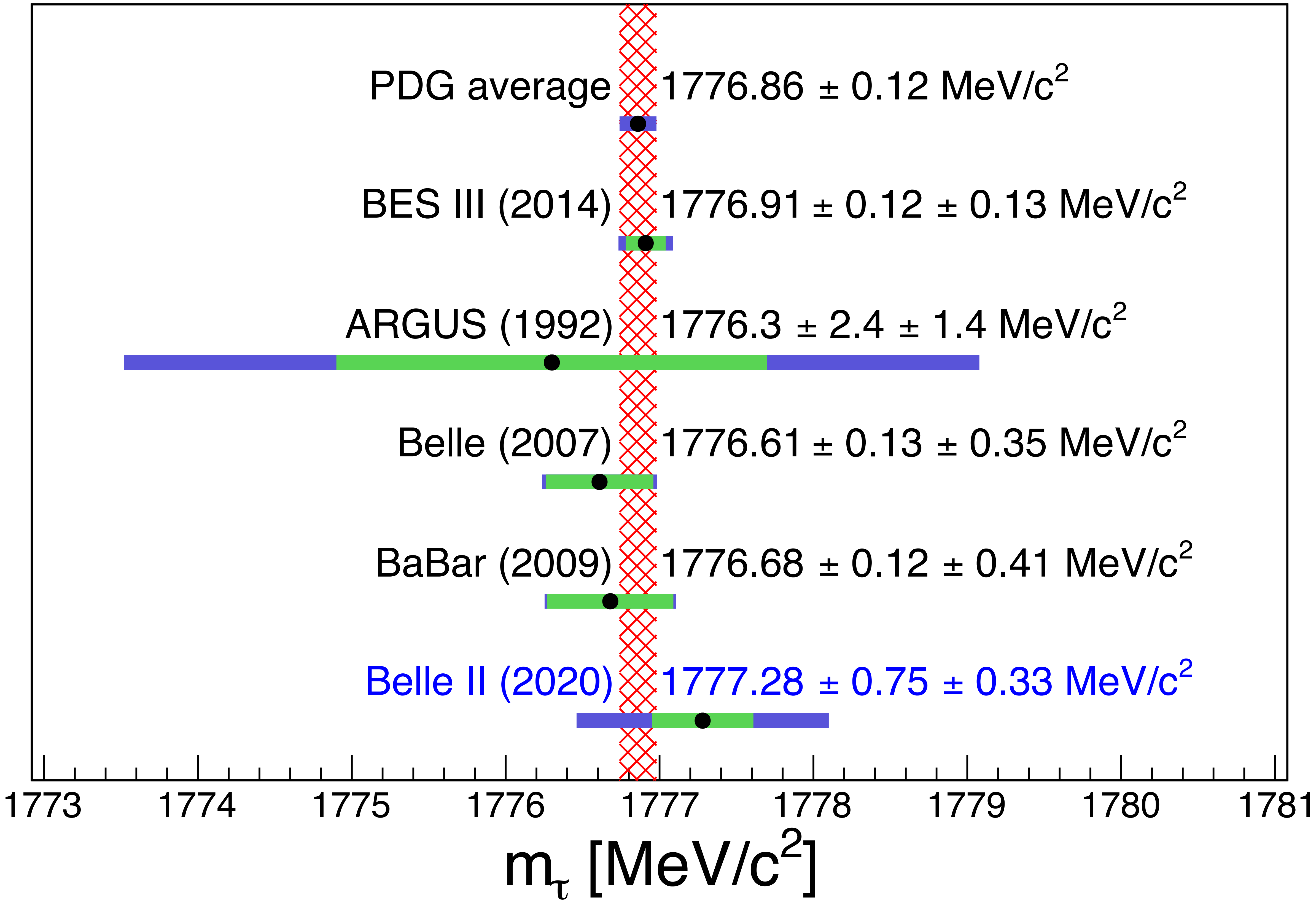


| Systematic uncertainty | MeV/$c^2$ |
|---|---|
| Momentum shift due to the B-field map | 0.29 |
| Estimator bias | 0.12 |
| Choice of p.d.f. | 0.08 |
| Fit window | 0.04 |
| Beam energy shifts | 0.03 |
| Mass dependence of bias | 0.02 |
| Trigger efficiency | $\leq 0.01$ |
| Initial parameters | $\leq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

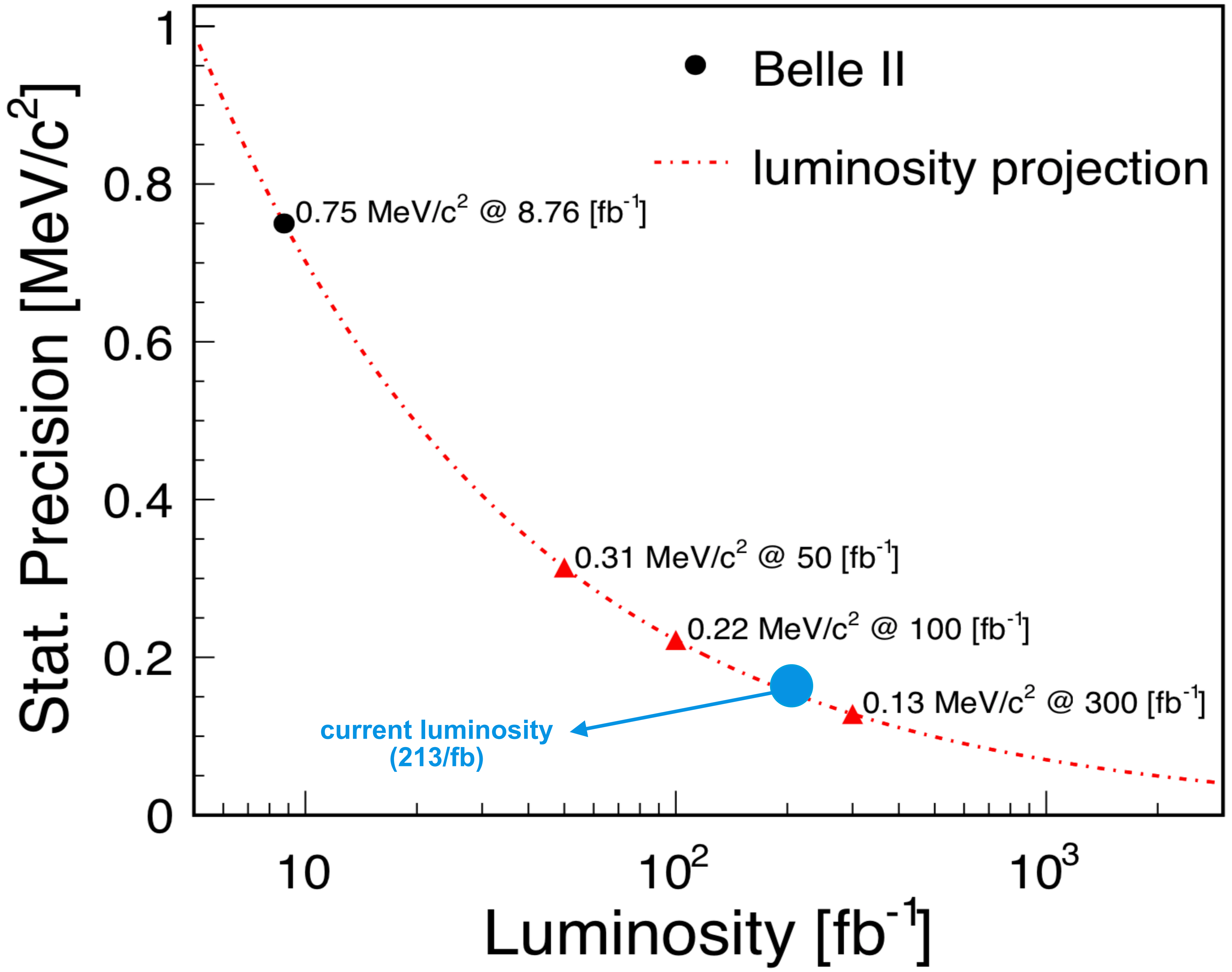
# The τ leptons mass

## 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



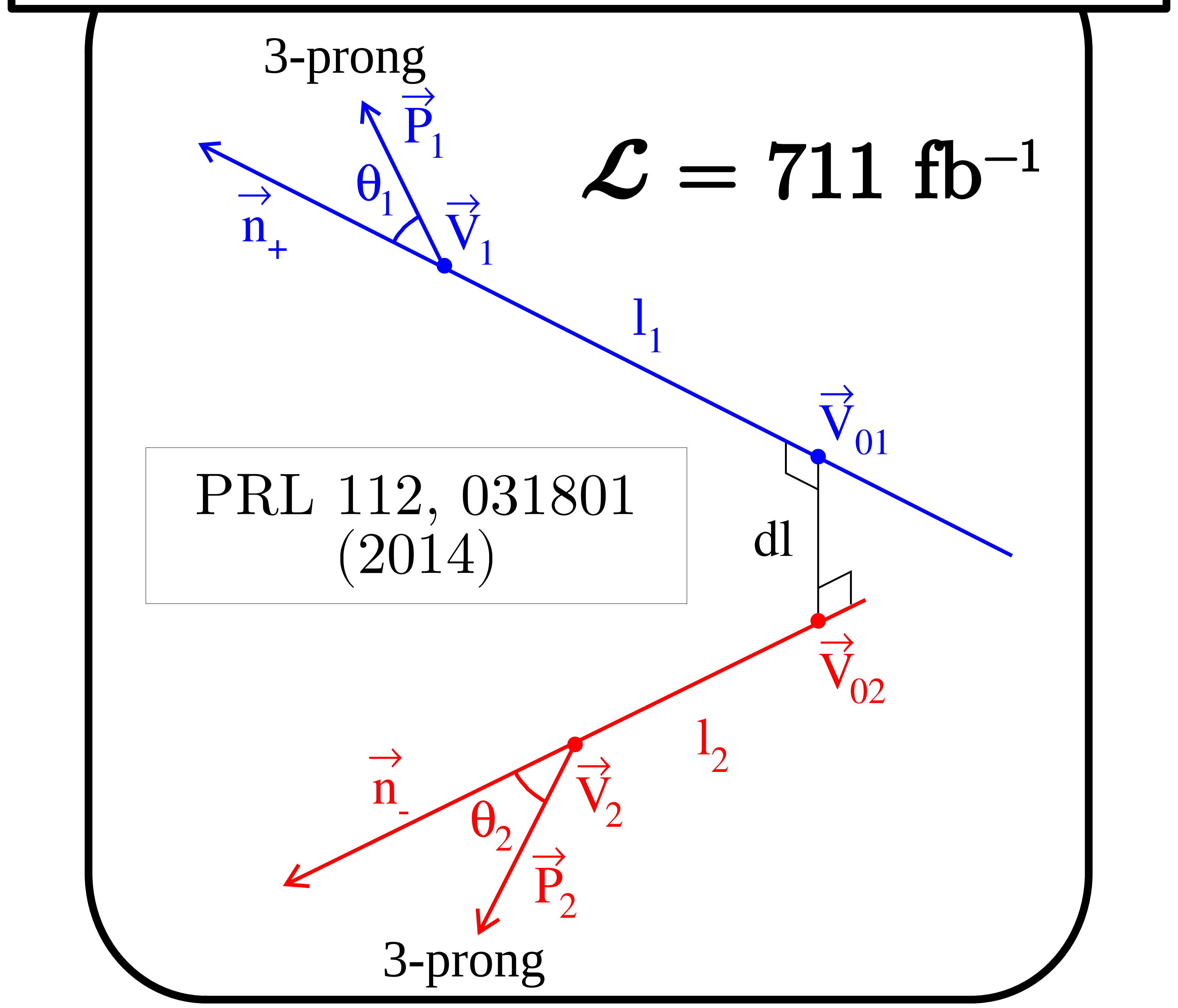
- expect to match statistical precision of Belle/BABAR with ~300 fb$^{-1}$
- future improvements of **reconstruction efficiency** and **systematic uncertainty**
- eventually perform CPV test



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

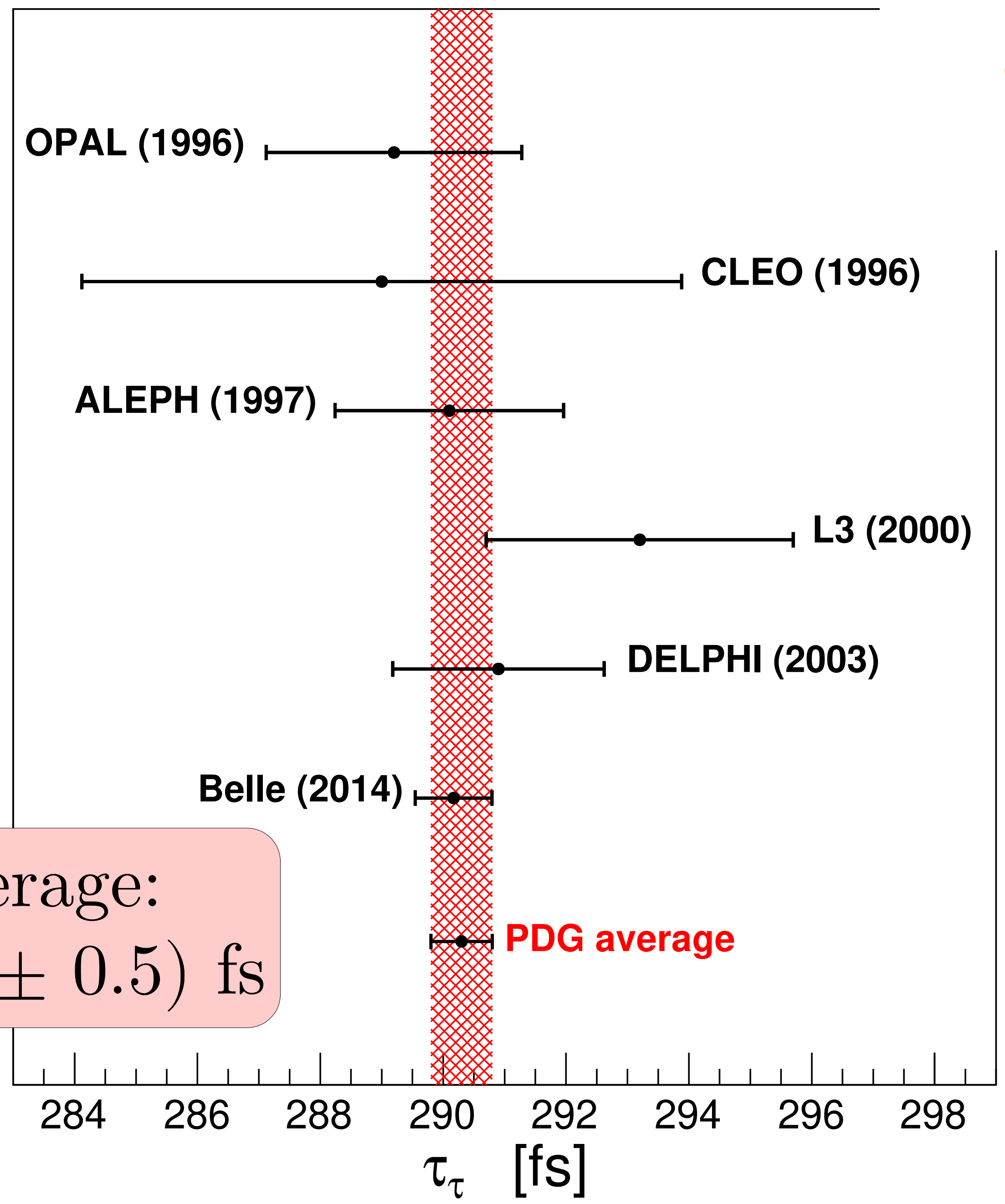
**World-best measurement**

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

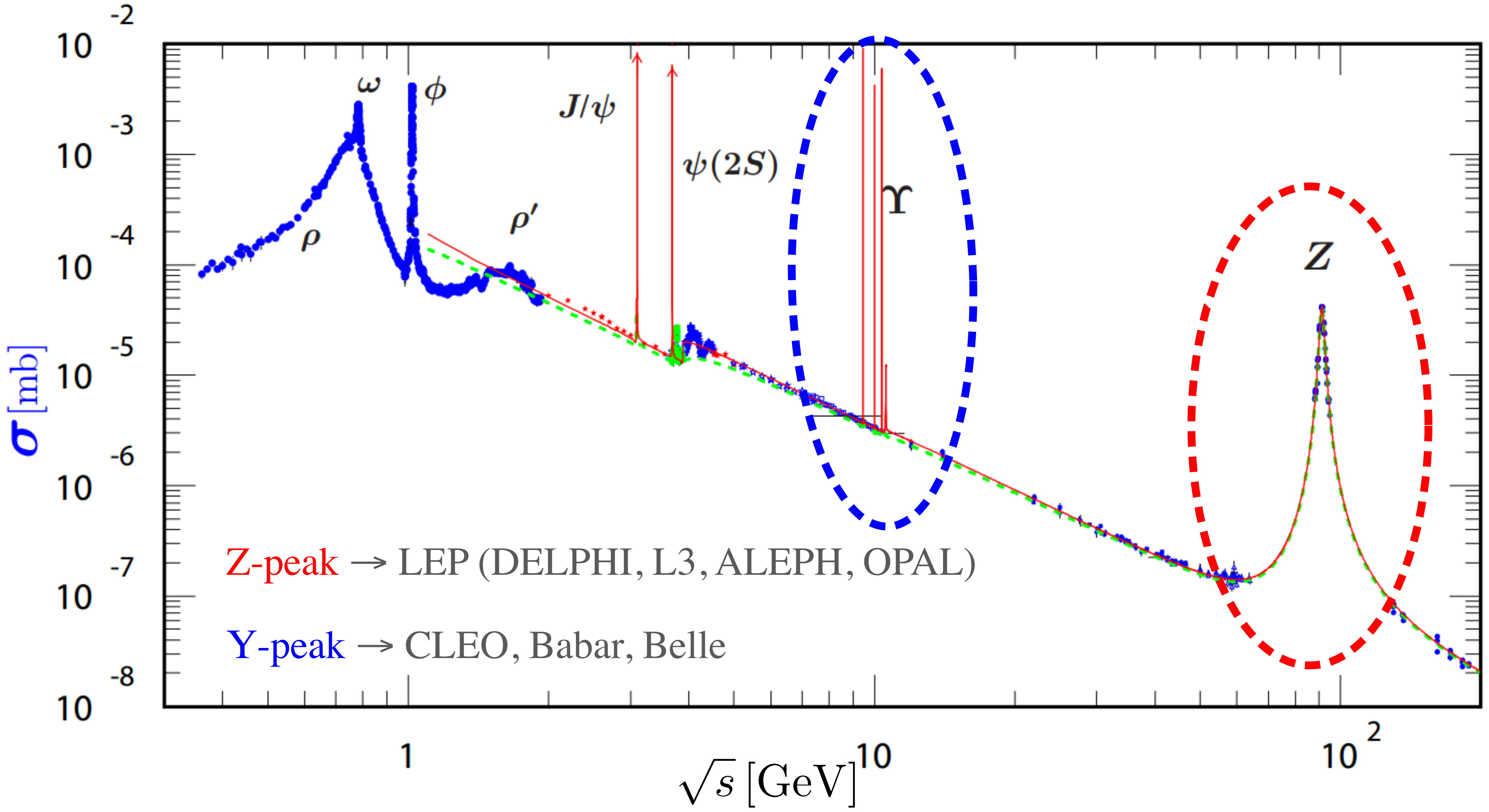


$\mathcal{L} = 711\ \text{fb}^{-1}$

PRL 112, 031801 (2014)



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



Z-peak → LEP (DELPHI, L3, ALEPH, OPAL)

Y-peak → CLEO, Babar, Belle

**Belle II w.r.t. Belle: exploit**

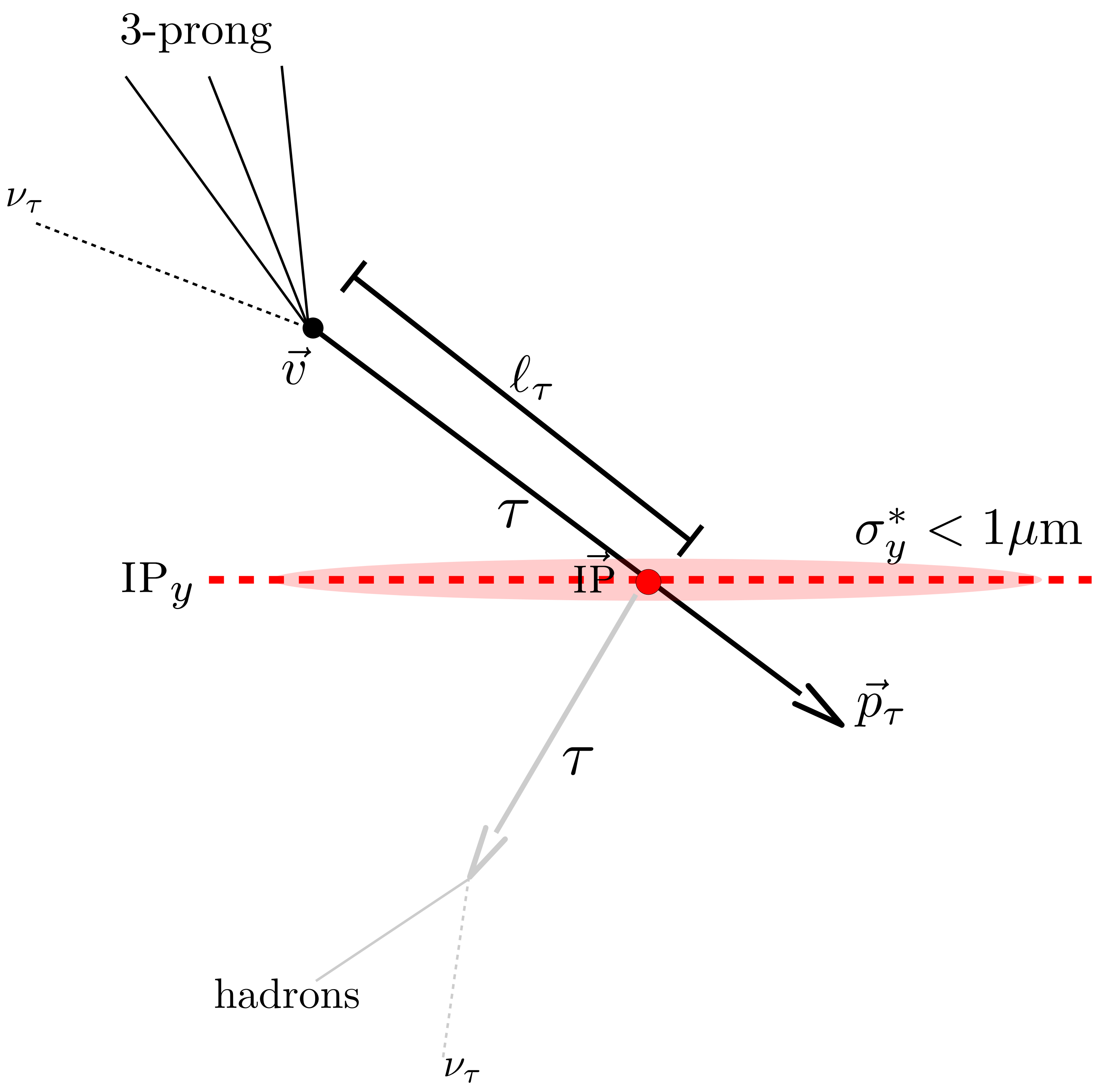
- the tiny beam spot size at the IP
- the 3x1 event topology to increase the statistical precision of the measurement

# Strategy at Belle II

**The proper time is measured using the particle's**

- flight distance in the lab frame $\vec{l}_\tau$
- momentum $\overrightarrow{\mathbf{p}}$ in the lab frame

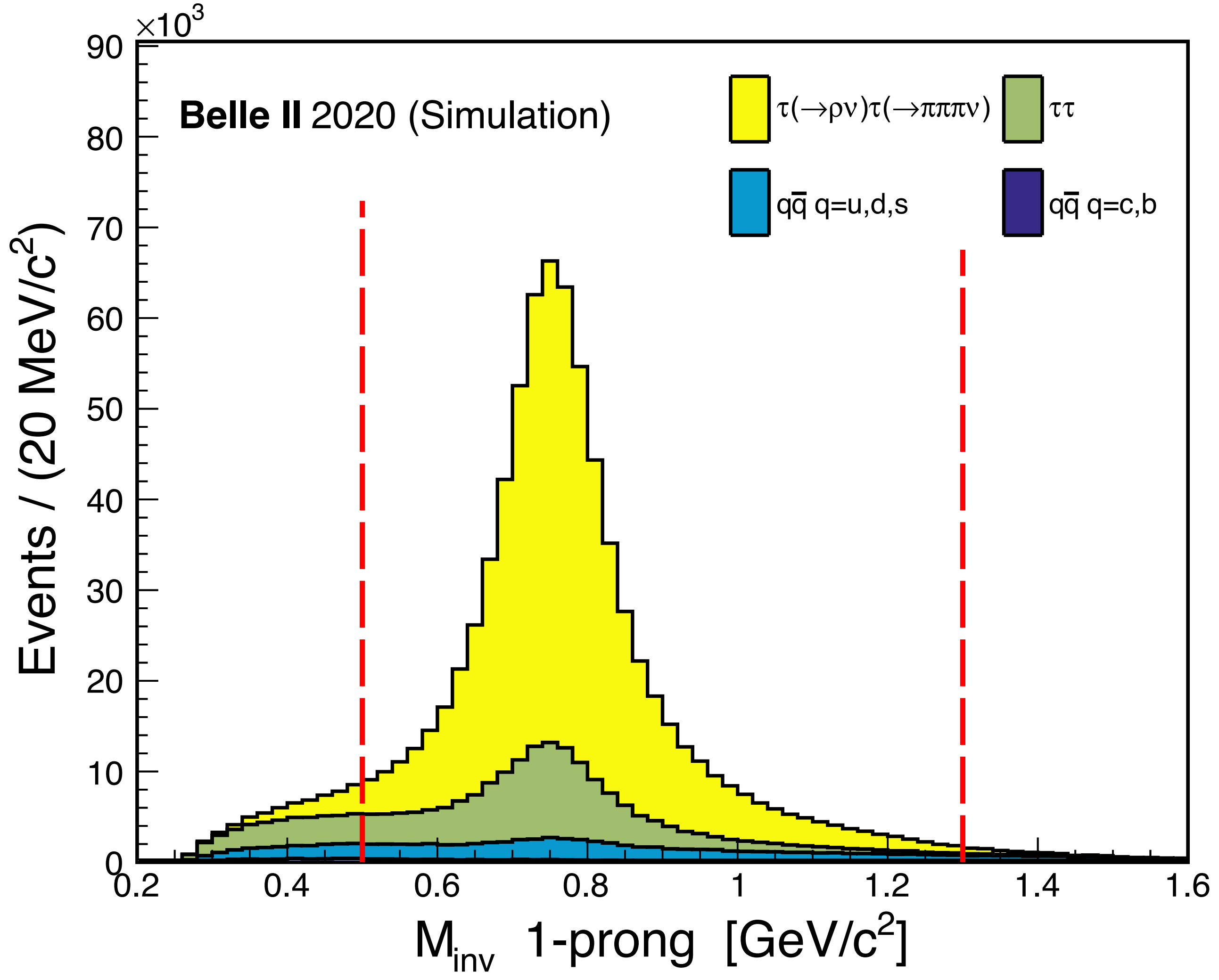
$$t_{\text{true}} = \frac{l_\tau}{\beta\gamma c} = m\frac{l_\tau}{p}$$



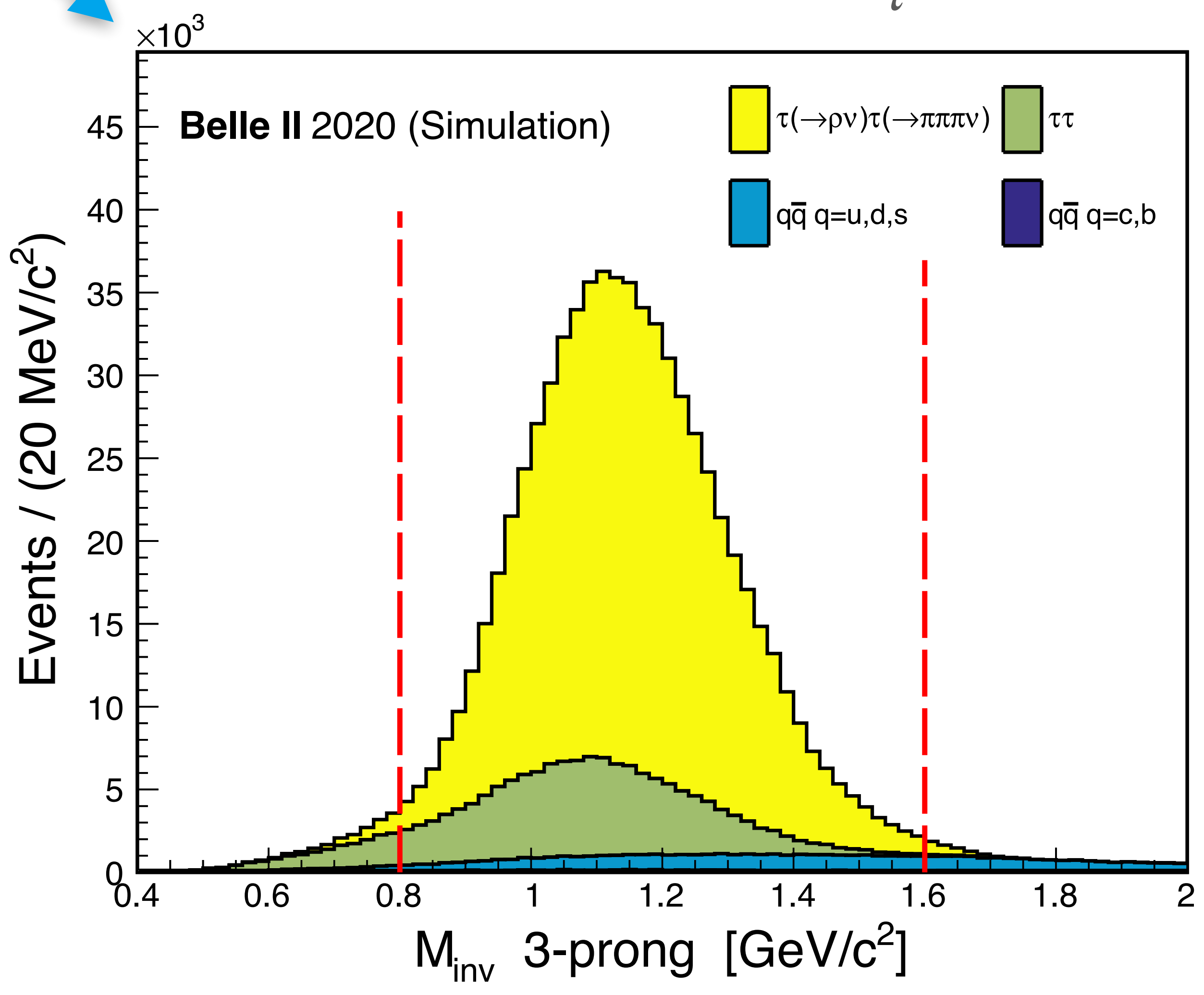
- (1) decay vertex → reconstruct vertex for 3-prong
  - vertex fitting
- (2) estimate τ momentum using τ decay products
  - increase the statistical precision by using 3x1 topology

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

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



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



- (3) production vertex that is intersection of momentum direction with plane $y = \text{IP}_\text{y}$

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

## Proper decay time

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

- ➡ computed from the reconstructed decay length $l_\tau$ and the estimated momentum $p$

## Proper decay time resolution

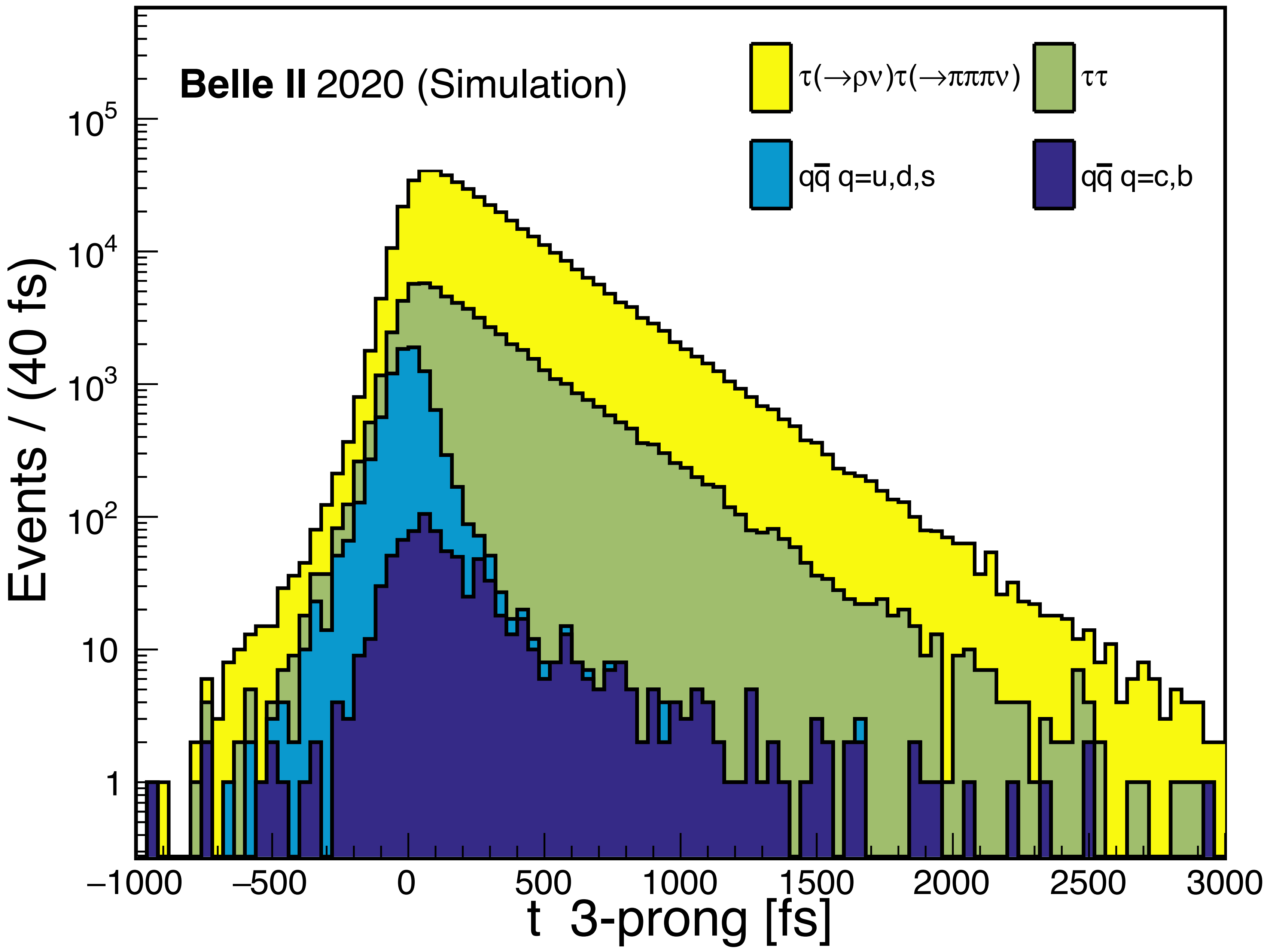
$$\Delta t = t^{rec} - t^{gen}$$

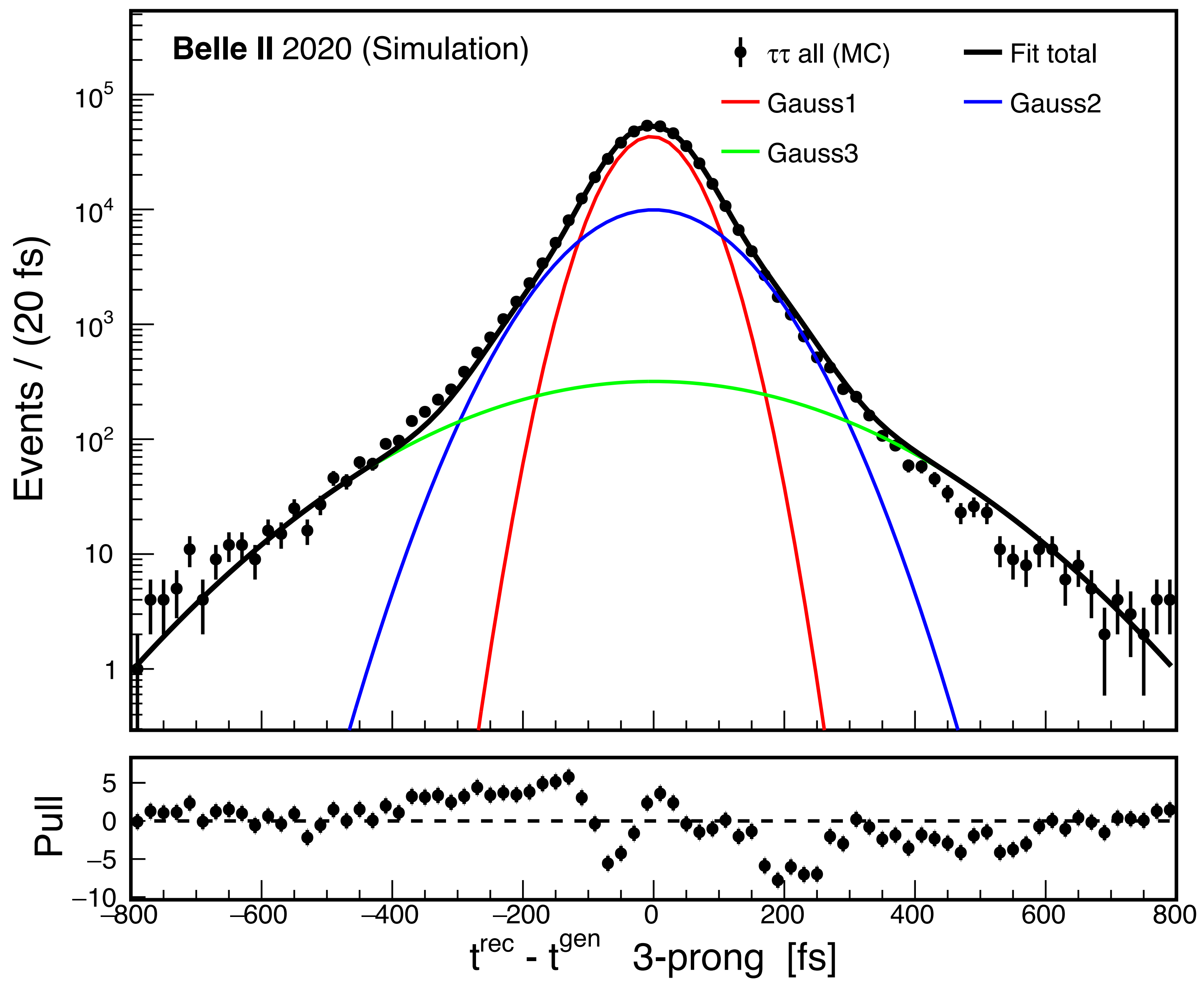
- ➡ binned ML fit with 3 Gaussians

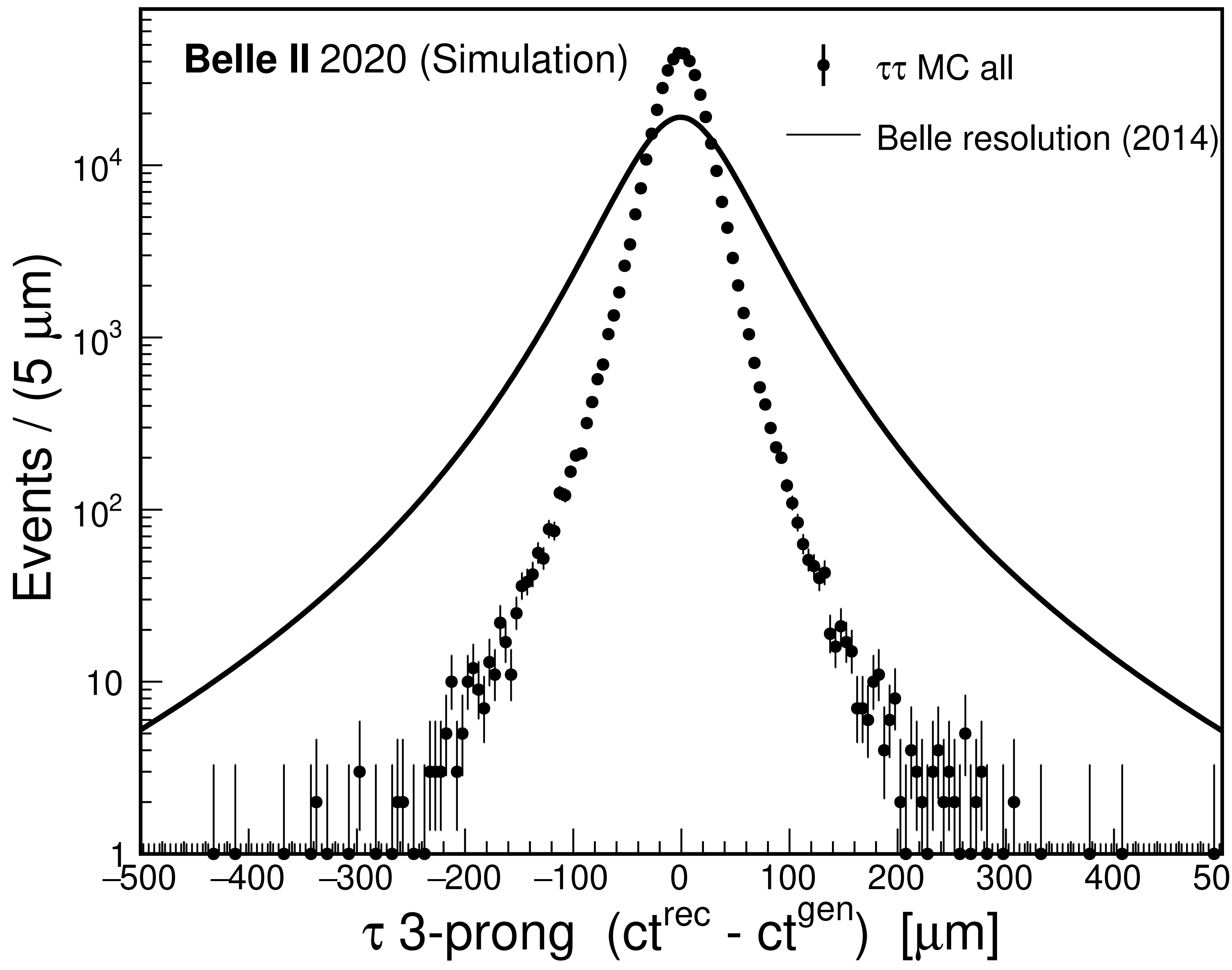
$$\mu[fs] = -3.43 \pm 0.13$$

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

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



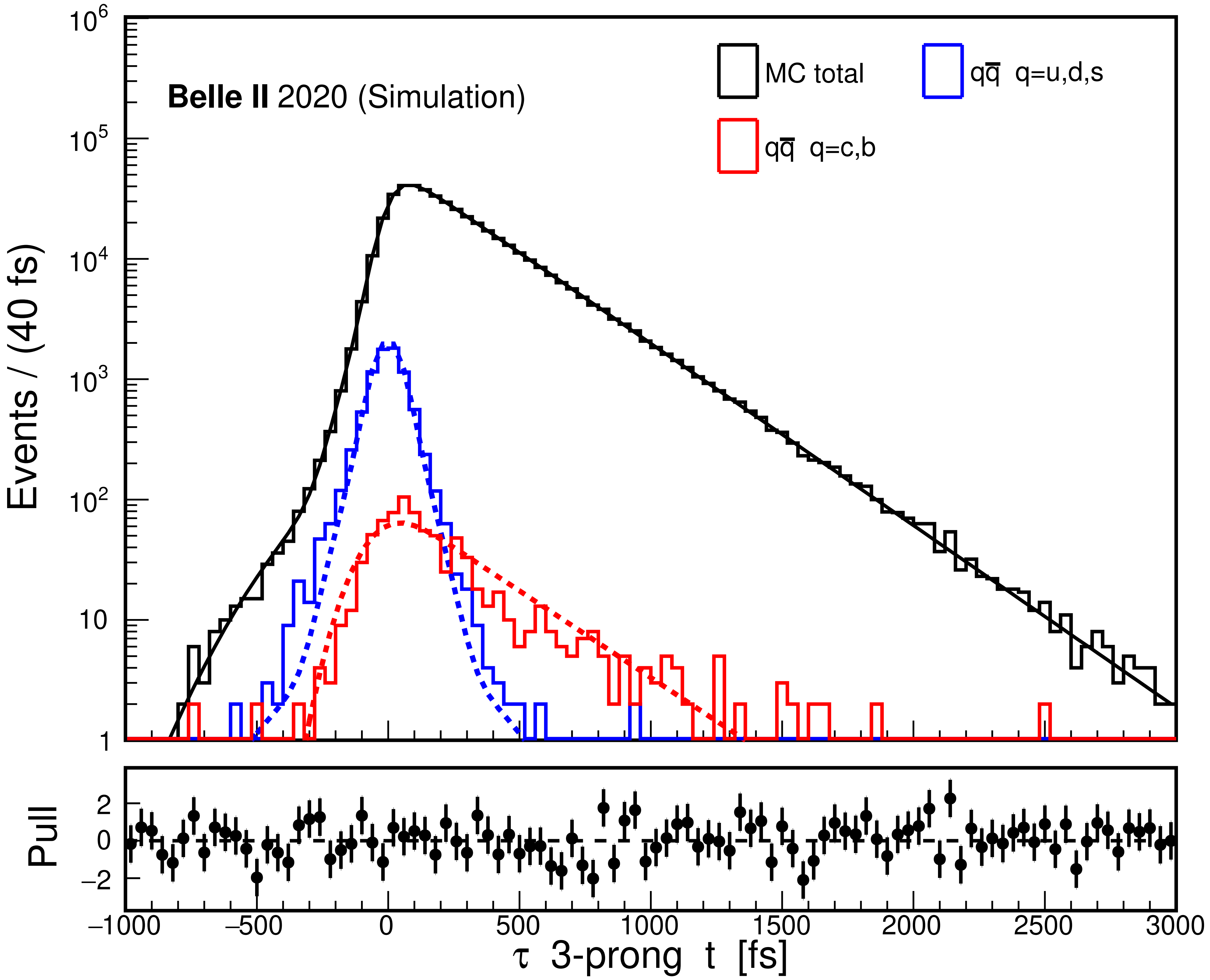




# The τ lepton lifetime

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

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



**Generated lifetime** $\tau = 290.57$ fs

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

**With respect to Belle:**

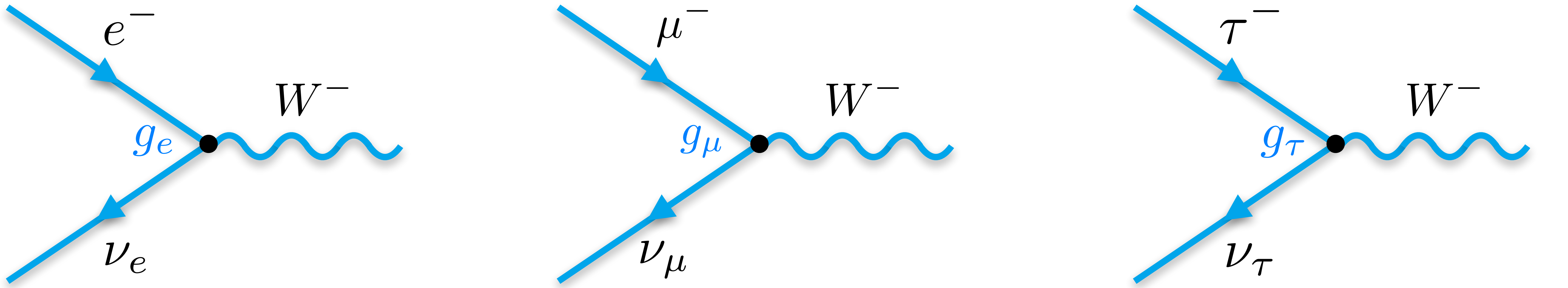
- competitive statistical precision can already be reached with 200/fb

# e-μ-τ universality

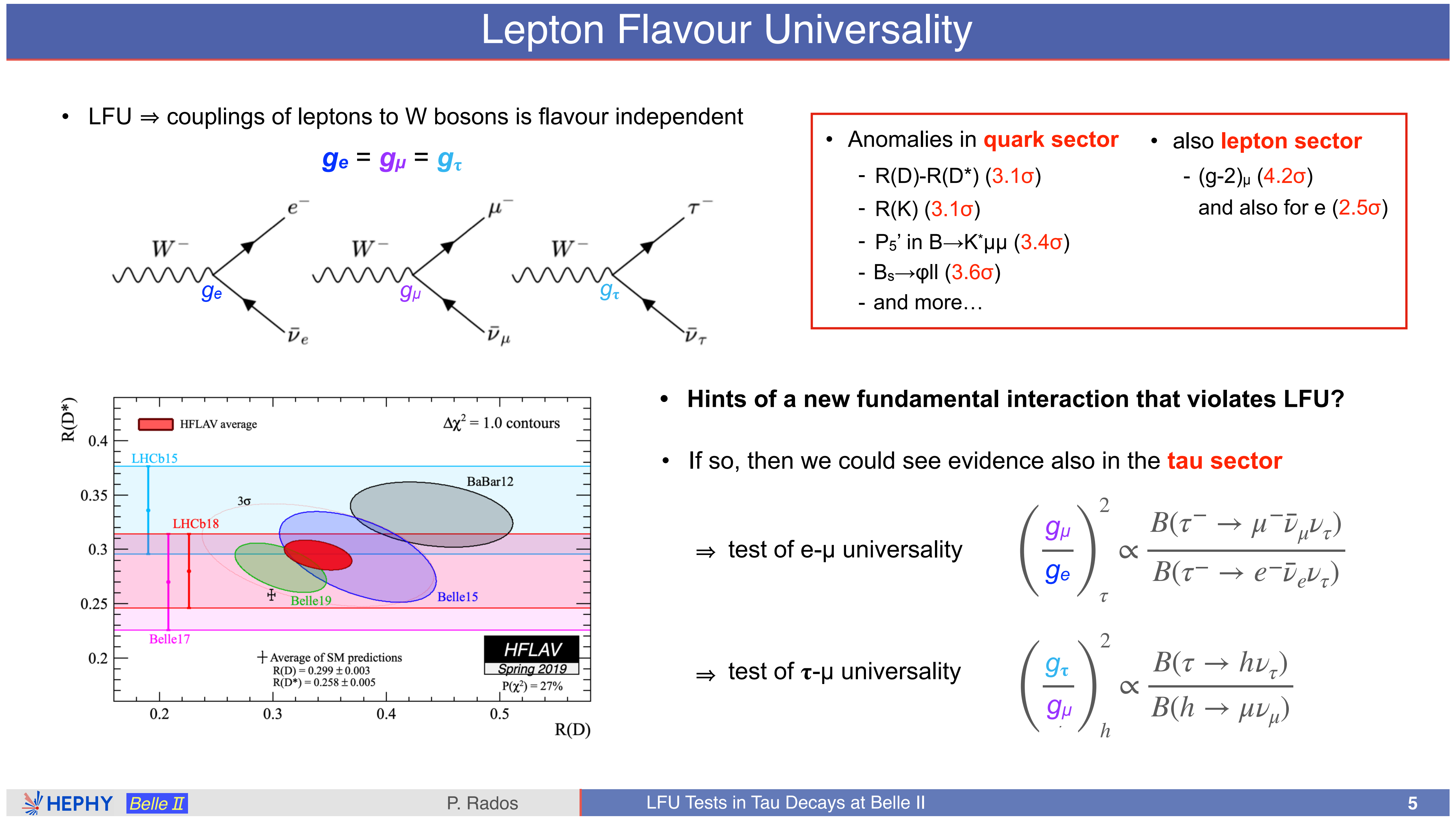
## e, μ and τ differ only by

- ➡ 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**



## Lepton Flavour Universality

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

  $g_e = g_\mu = g_\tau$

- Anomalies in **quark sector**
  - R(D)-R(D*) (3.1σ)
  - R(K) (3.1σ)
  - $P_5'$ in $B \to K^* \mu\mu$ (3.4σ)
  - $B_s \to \varphi ll$ (3.6σ)
  - and more…
- also **lepton sector**
  - $(g-2)_\mu$ (4.2σ)

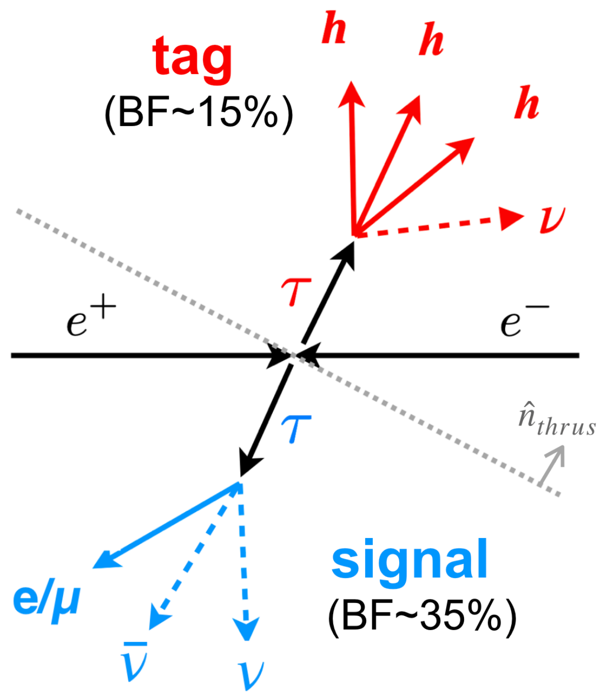
    and also for e (2.5σ)

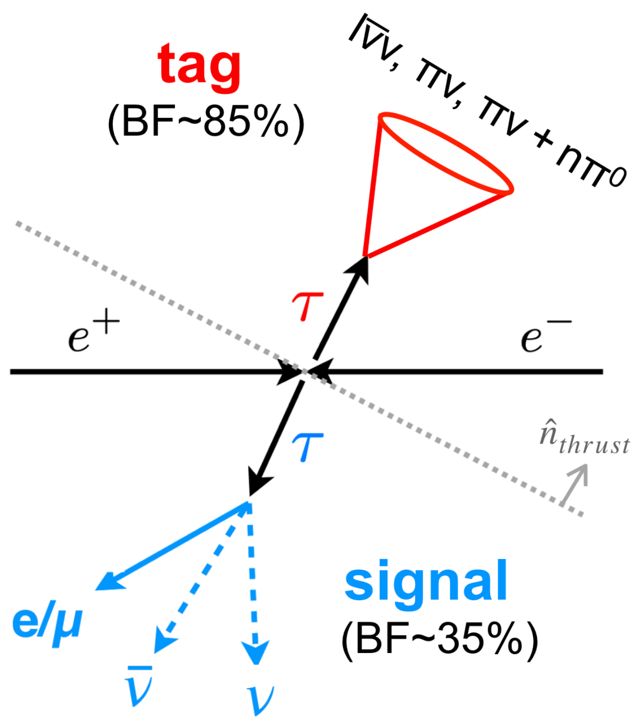
- **Hints of a new fundamental interaction that violates LFU?**
- If so, then we could see evidence also in the **tau sector**

⇒ test of e-μ universality $\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$

⇒ test of τ-μ universality $\left(\frac{g_\tau}{g_\mu}\right)^2_h \propto \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\nu_\mu)}$

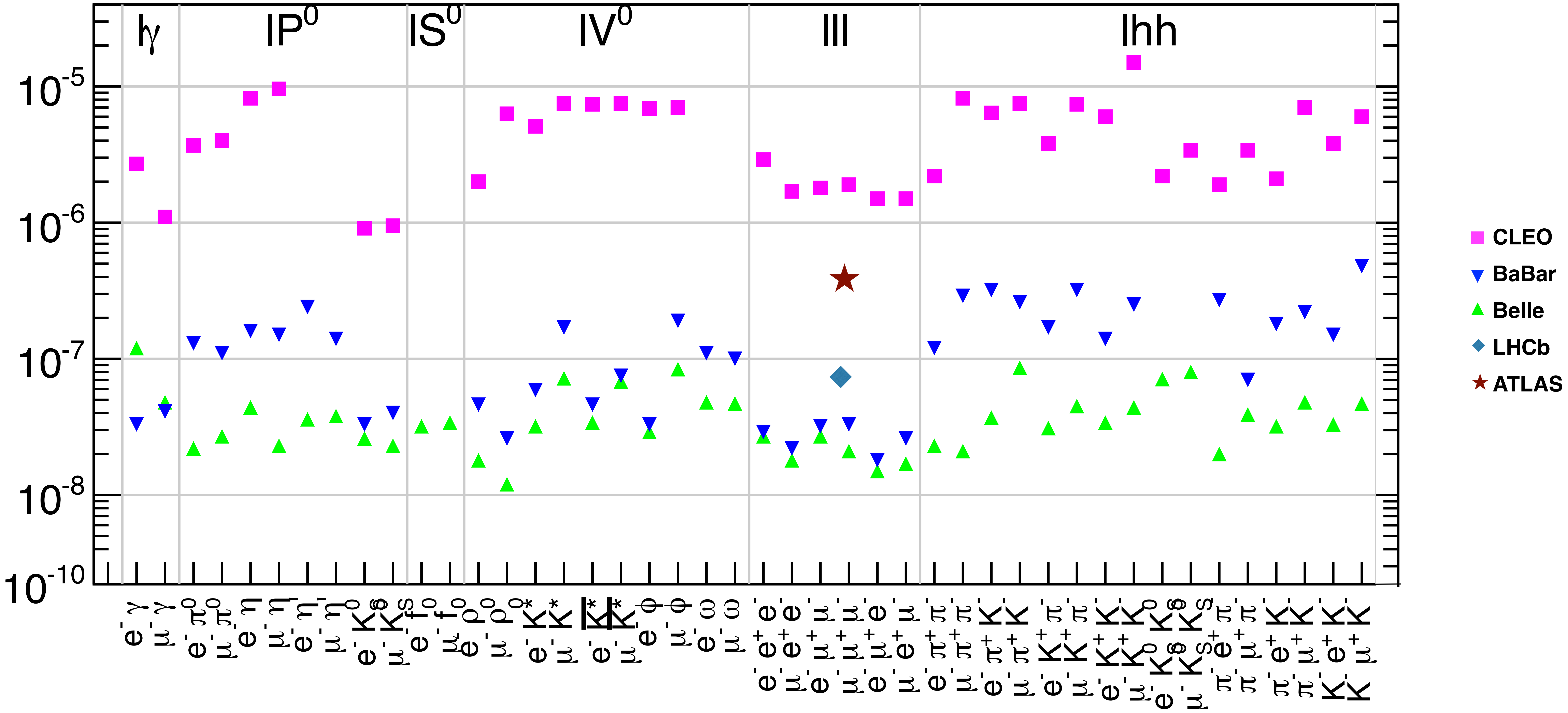
HEPHY Belle II P. Rados LFU Tests in Tau Decays at Belle II 5





**See Petar Rados' slides for Belle II prospects on LFU**

# LVF & LNV

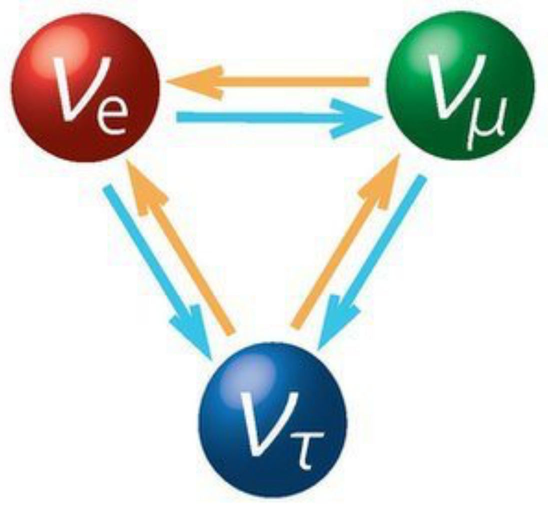


$l\gamma$
$lP^0$
$lS^0$
$lV^0$
$lll$
$lhh$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-10}$
$e^-\gamma$
$\mu^-\gamma$
$e^-\pi^0$
$\mu^-\pi^0$
$e^-\eta$
$\mu^-\eta$
$e^-\eta'$
$\mu^-\eta'$
$e^-K_S^0$
$\mu^-K_S^0$
$e^-f_0$
$\mu^-f_0$
$e^-\rho^0$
$\mu^-\rho^0$
$e^-K^*$
$\mu^-K^*$
$e^-\bar{K}^*$
$\mu^-\bar{K}^*$
$e^-\phi$
$\mu^-\phi$
$e^-\omega$
$\mu^-\omega$
$e^-e^+e^-$
$\mu^-e^+e^-$
$e^-\mu^+\mu^-$
$\mu^-\mu^+\mu^-$
$e^-\mu^+e^-$
$\mu^-e^+\mu^-$
$e^-\pi^+\pi^-$
$\mu^-\pi^+\pi^-$
$e^-\pi^+K^-$
$\mu^-\pi^+K^-$
$e^-K^+\pi^-$
$\mu^-K^+\pi^-$
$e^-K^+K^-$
$\mu^-K^+K^-$
$e^-K_S^0K_S^0$
$\mu^-K_S^0K_S^0$
$\pi^-e^+\pi^-$
$\pi^-\mu^+\pi^-$
$\pi^-e^+K^-$
$\pi^-\mu^+K^-$
$K^-e^+K^-$
$K^-\mu^+K^-$
CLEO
BaBar
Belle
LHCb
ATLAS

# Lepton flavour and number conservation

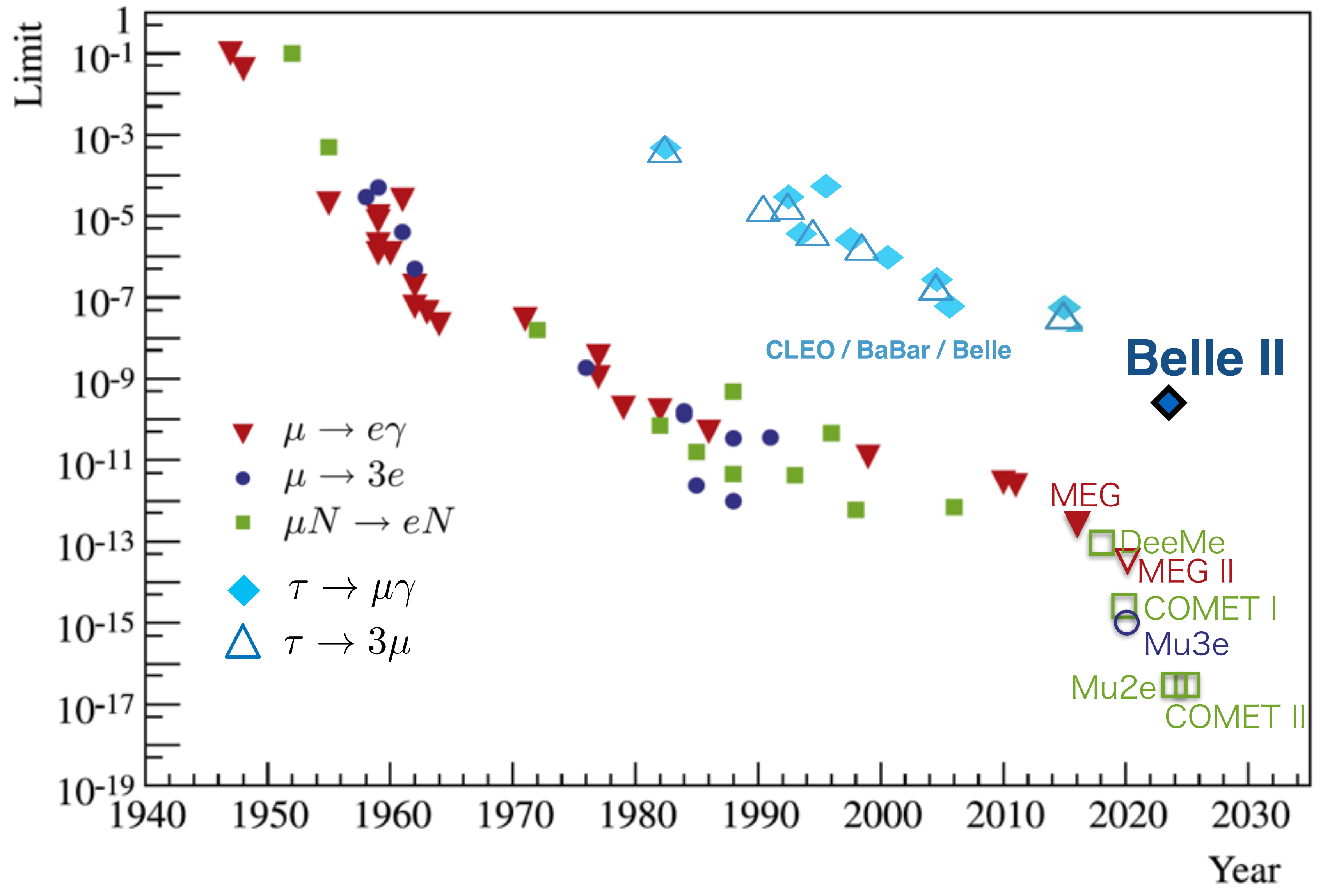
**Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)**

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

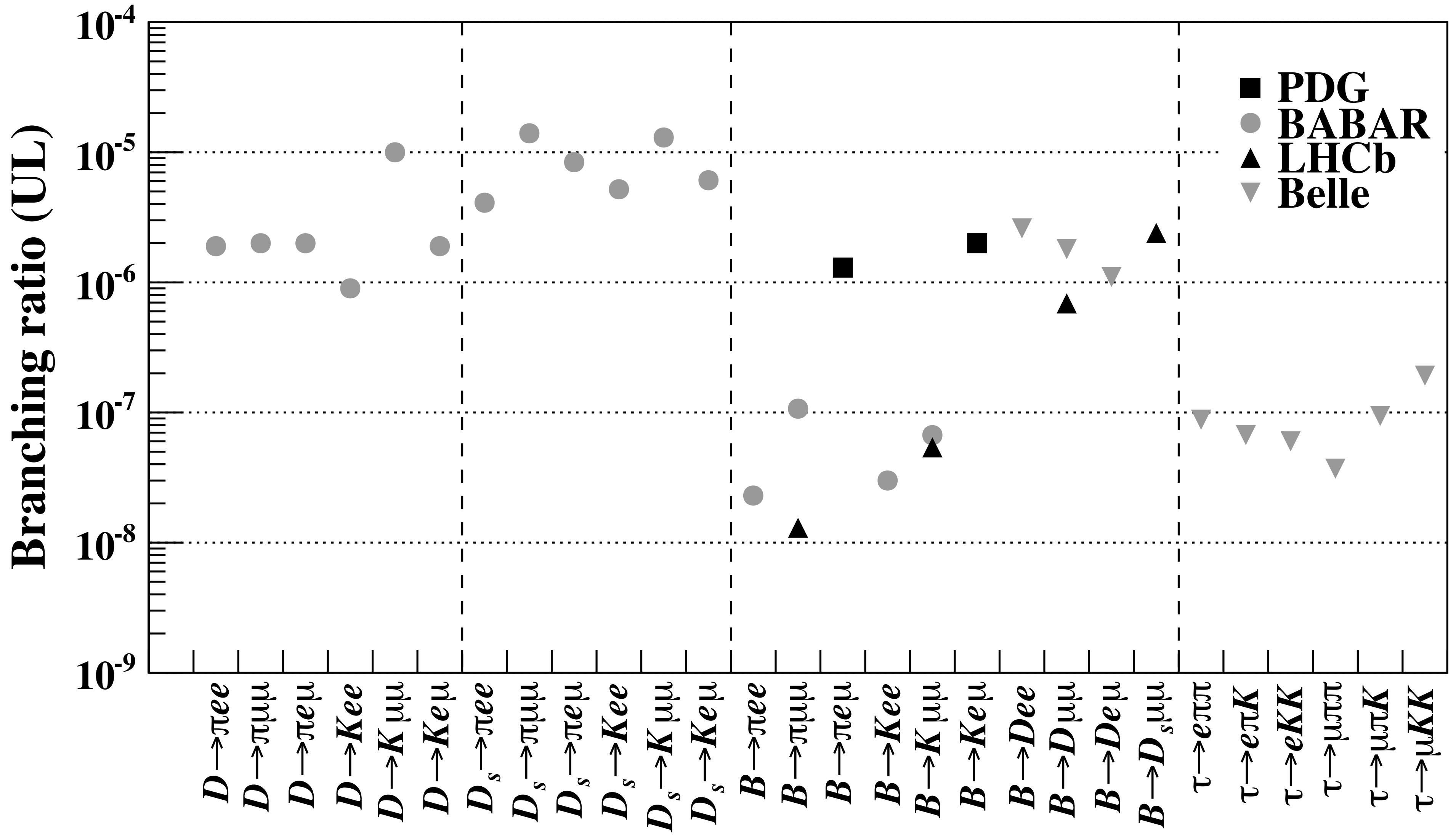


- ➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

**What about the charged leptons?**



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

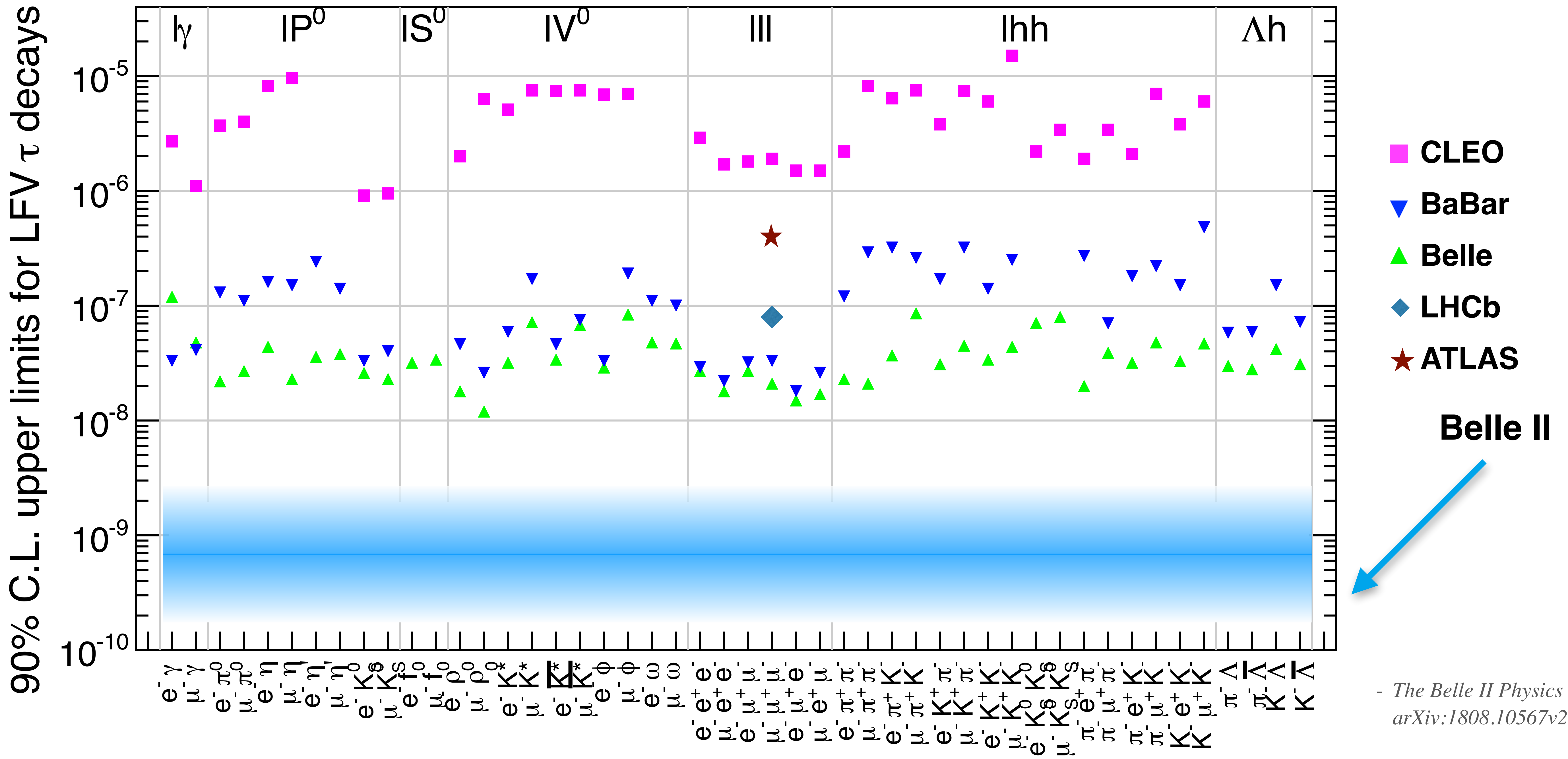


**No success in searches so far!**

**Observation of LFV or LNV will be a clear signature of the NP!**

# 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**

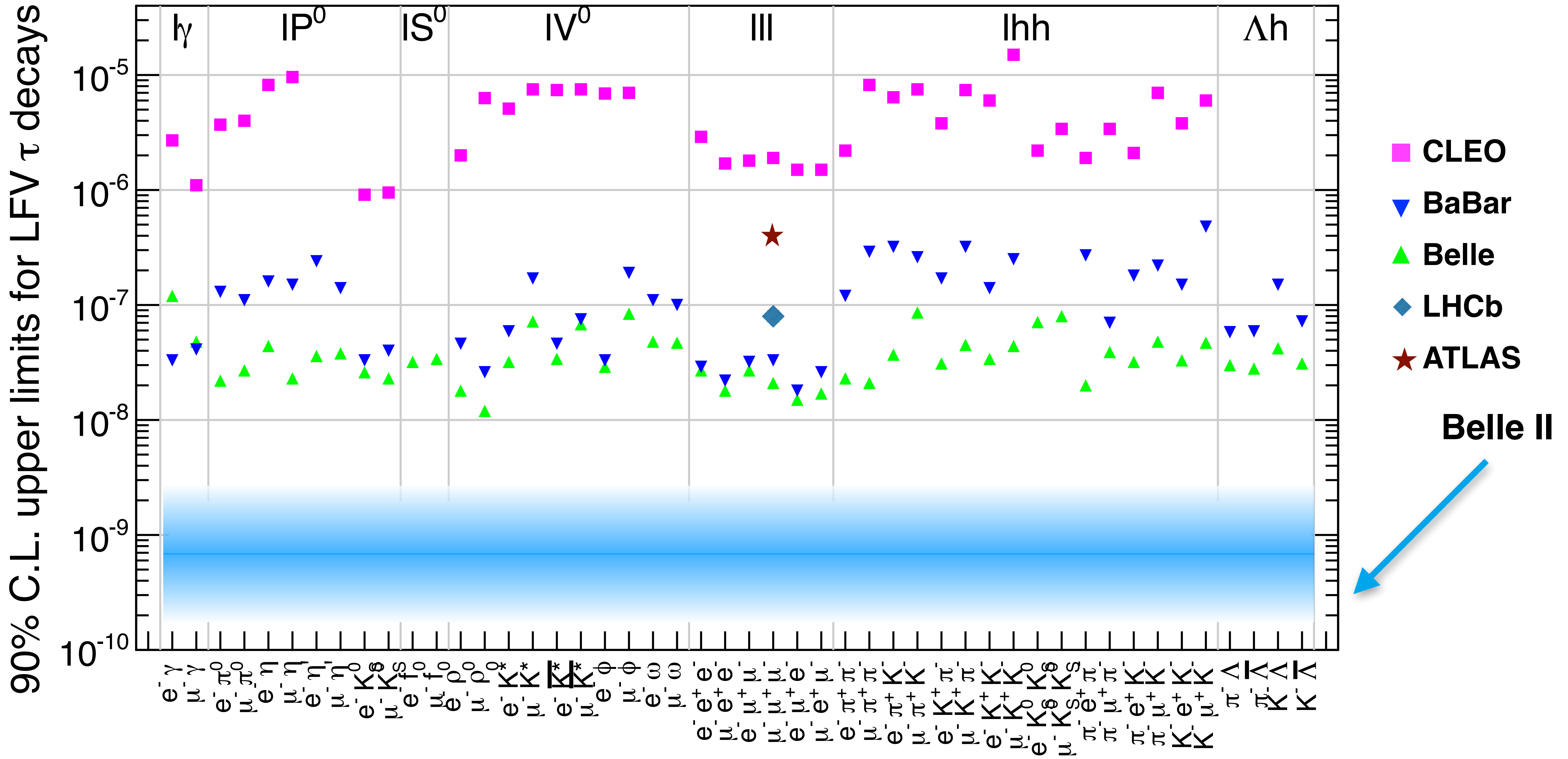
- ➡ radiative ($\tau \to \ell\gamma$)
- ➡ leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ a large variety of LFV and LNV semi-leptonic decays
- ➡ $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour structure

- ➡ 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**

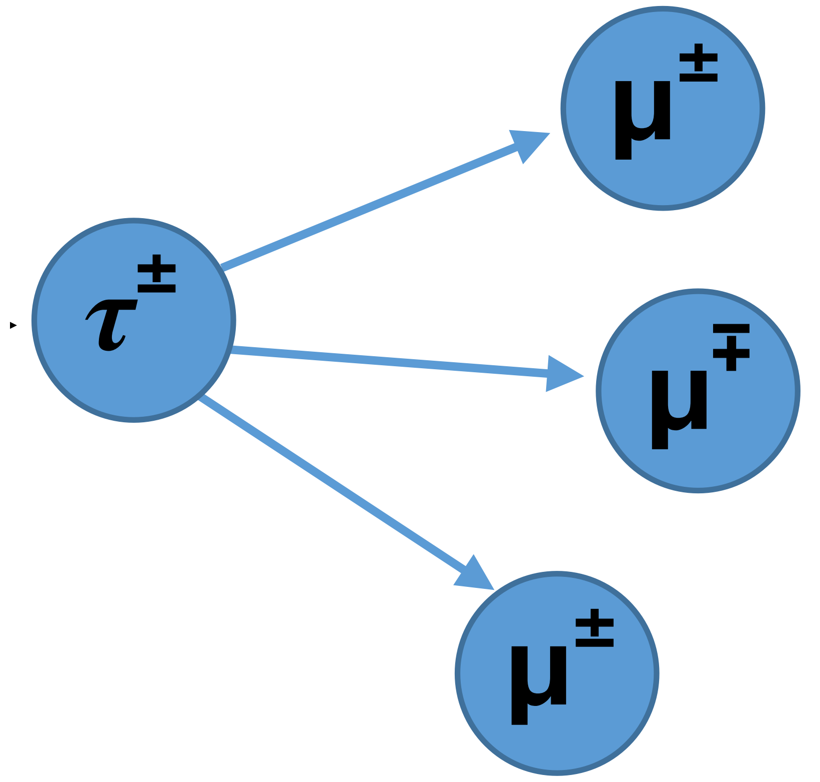
# Perspectives at Belle II

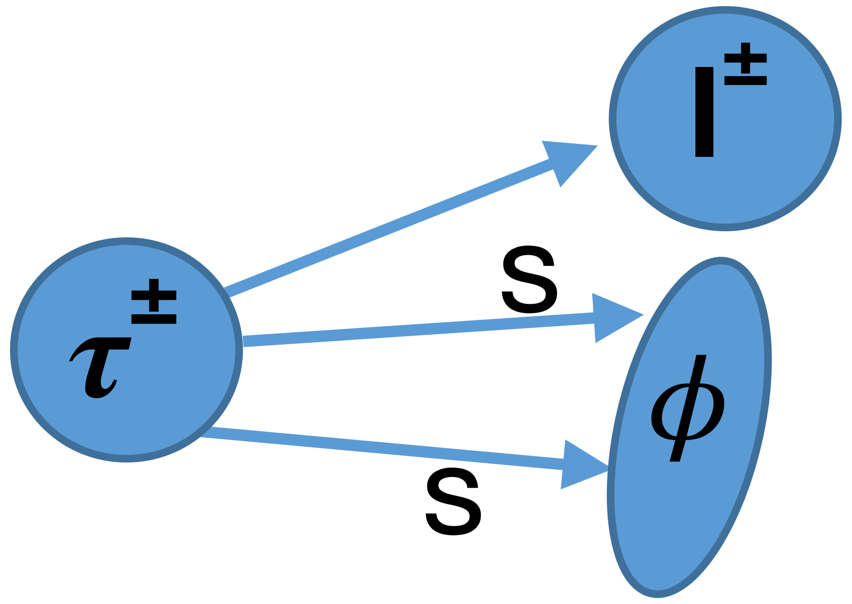
## … mostly occurred at the B-factories



**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

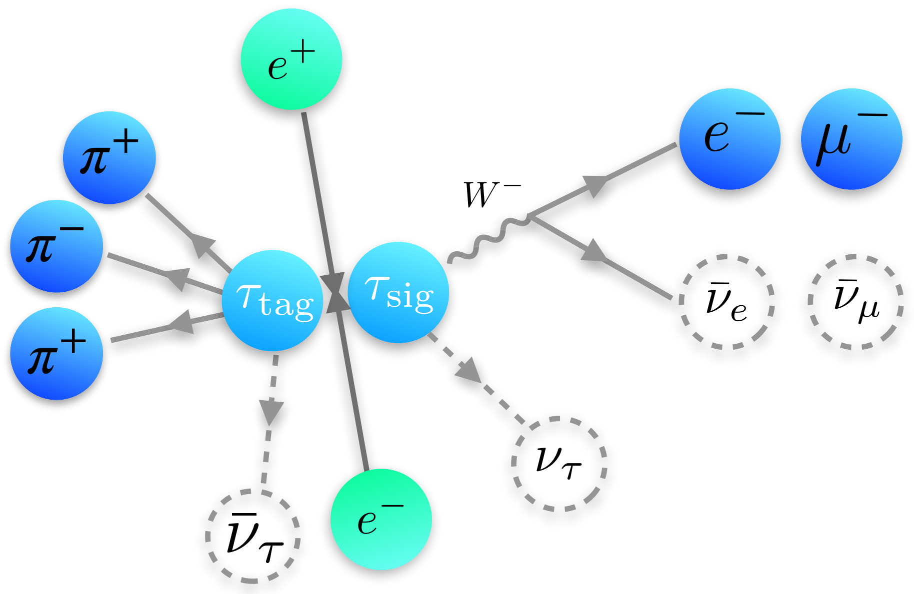


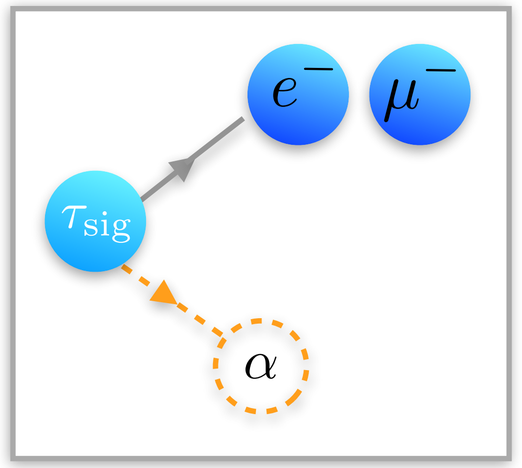


See Alberto Martini's slides for Belle II prospects on LFV

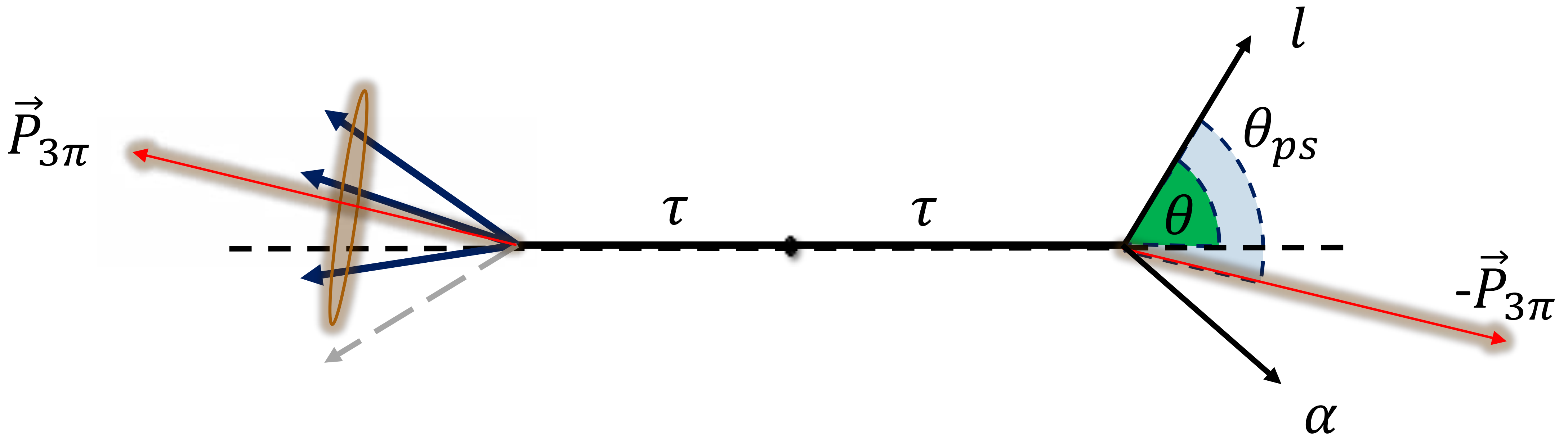
# Search for LFV $\tau \rightarrow \ell\alpha$ ($\alpha \rightarrow$ invisible)

## Probe the existence of a new boson α





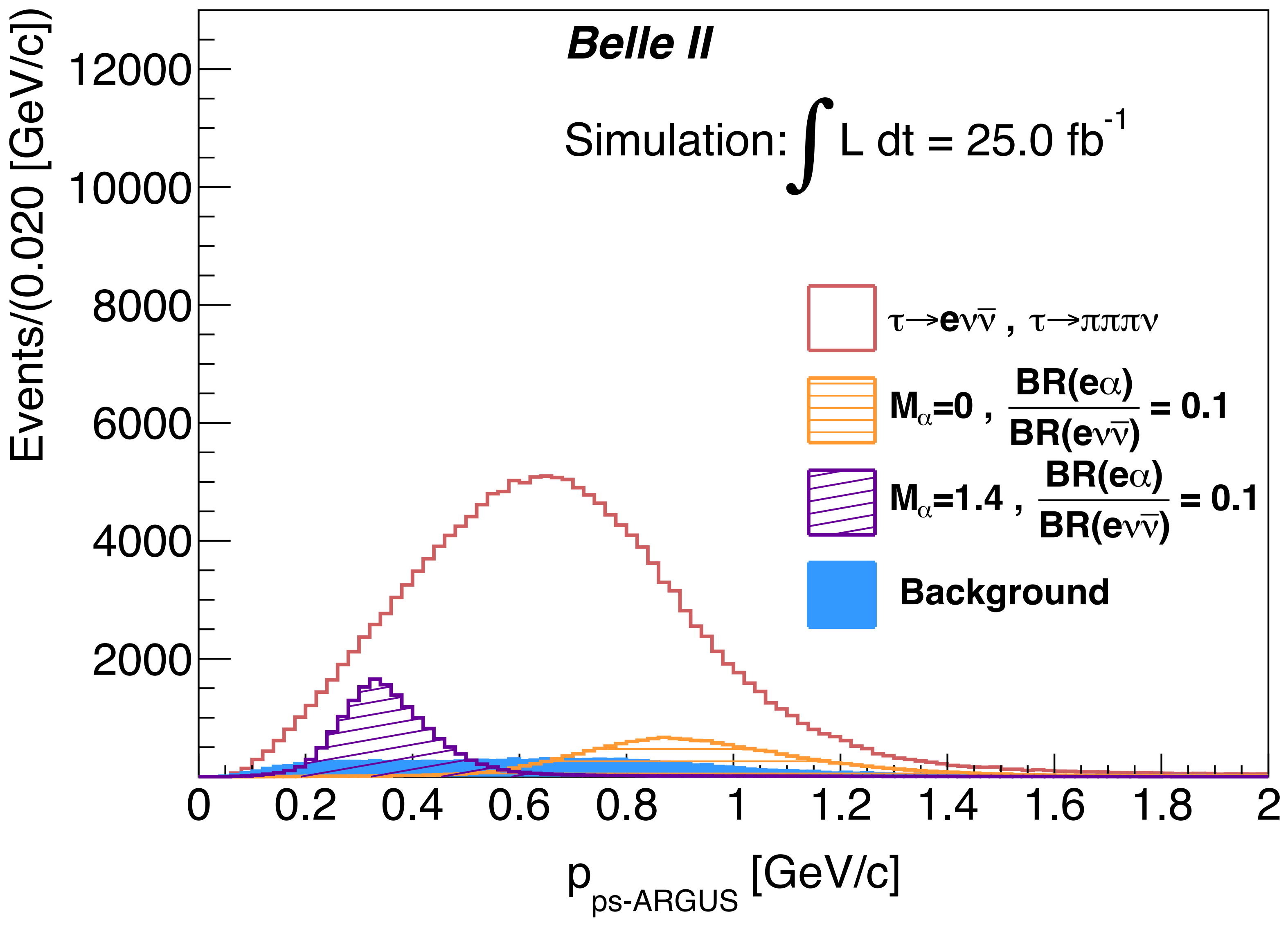
- ➡ previous studied at Mark III (9.4 $\text{pb}^{-1}$) and ARGUS (476 $\text{pb}^{-1}$)
- ➡ search for a two body decay spectrum
- ➡ signal will manifest itself as a peak in the τ rest frame

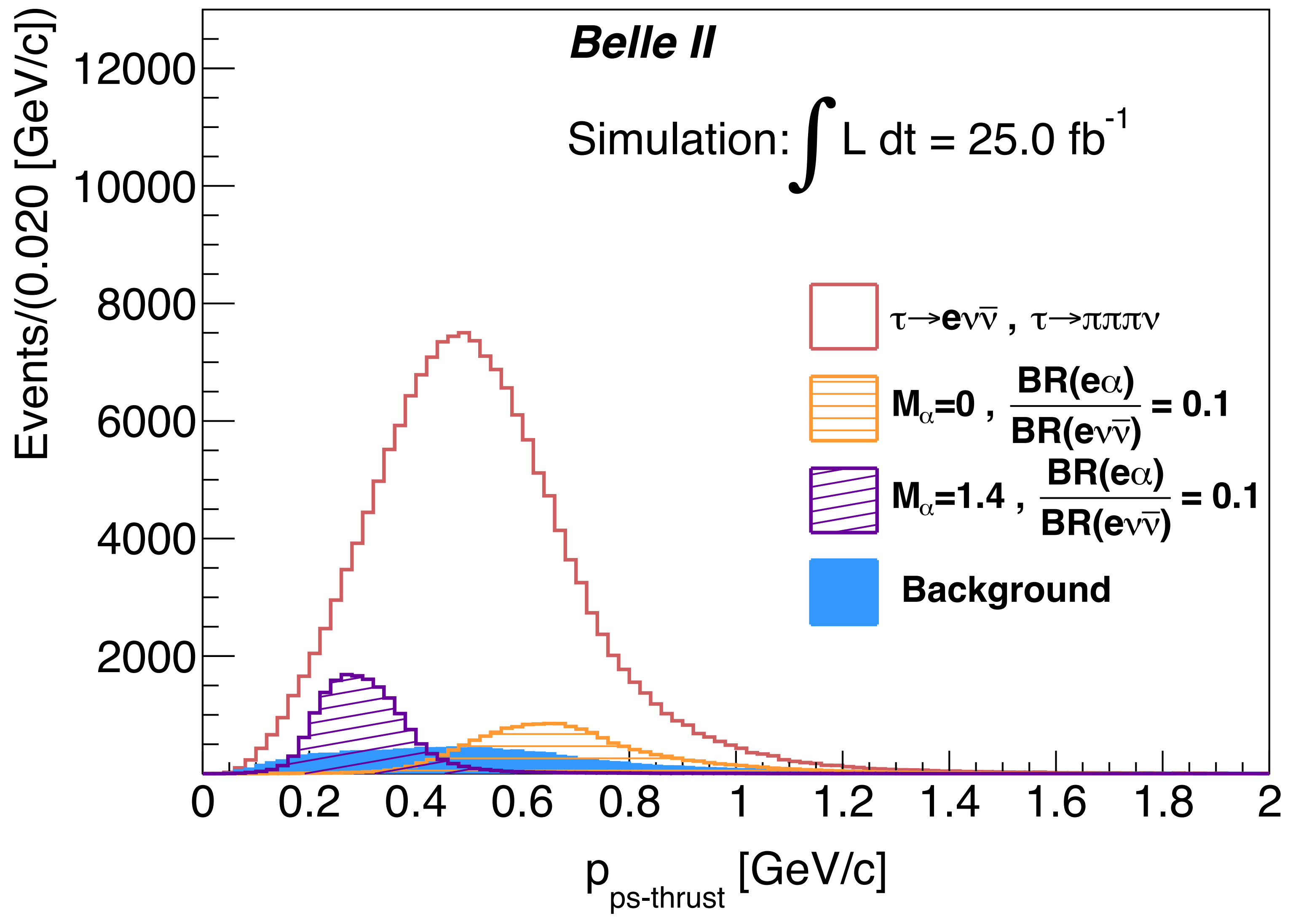


- ➡ cannot access the τ rest frame directly due to the missing neutrino
- ➡ approximate with the following assumptions:

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

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)

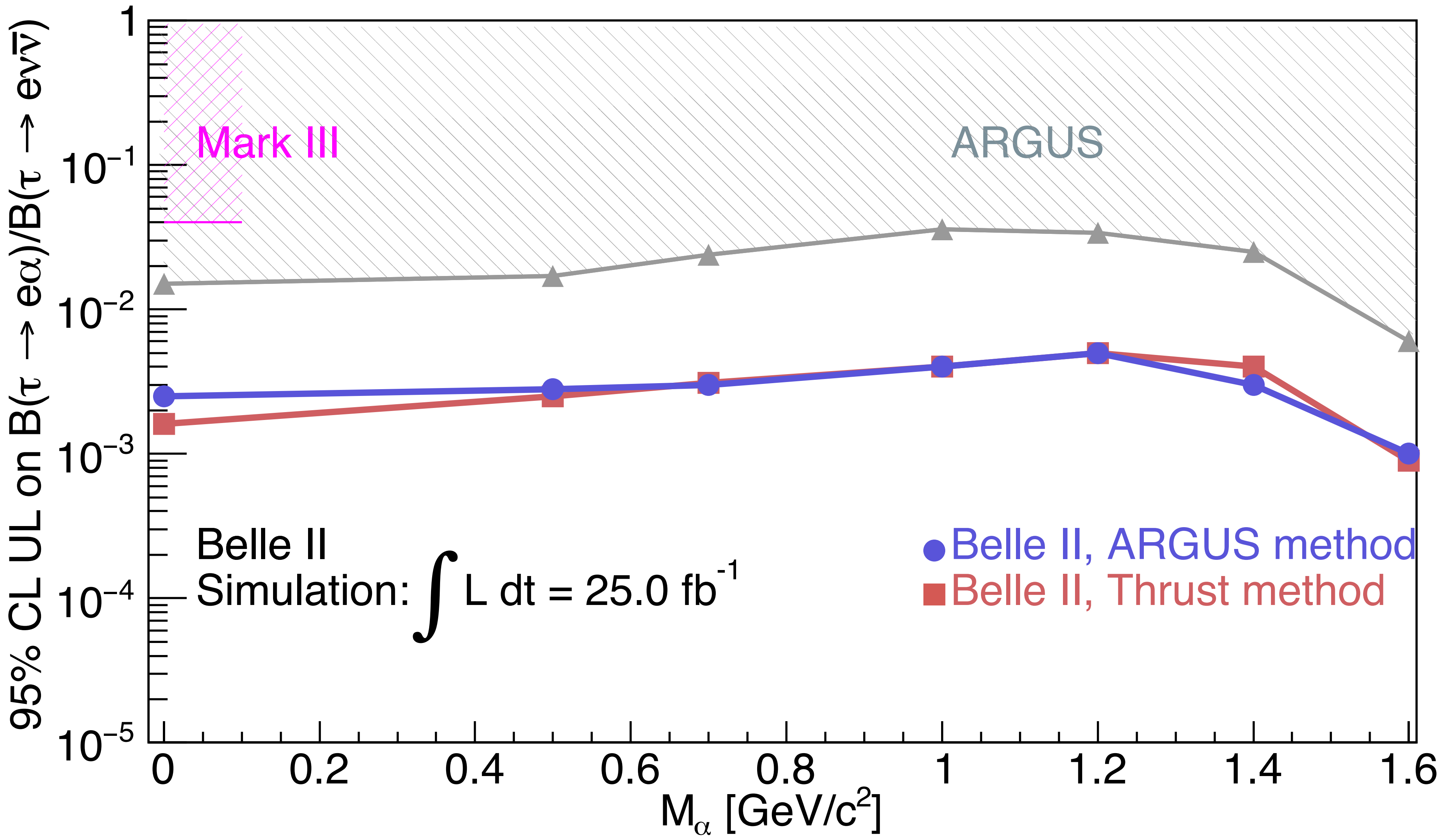
## UL is provided for the ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$

**Status of the analysis:**

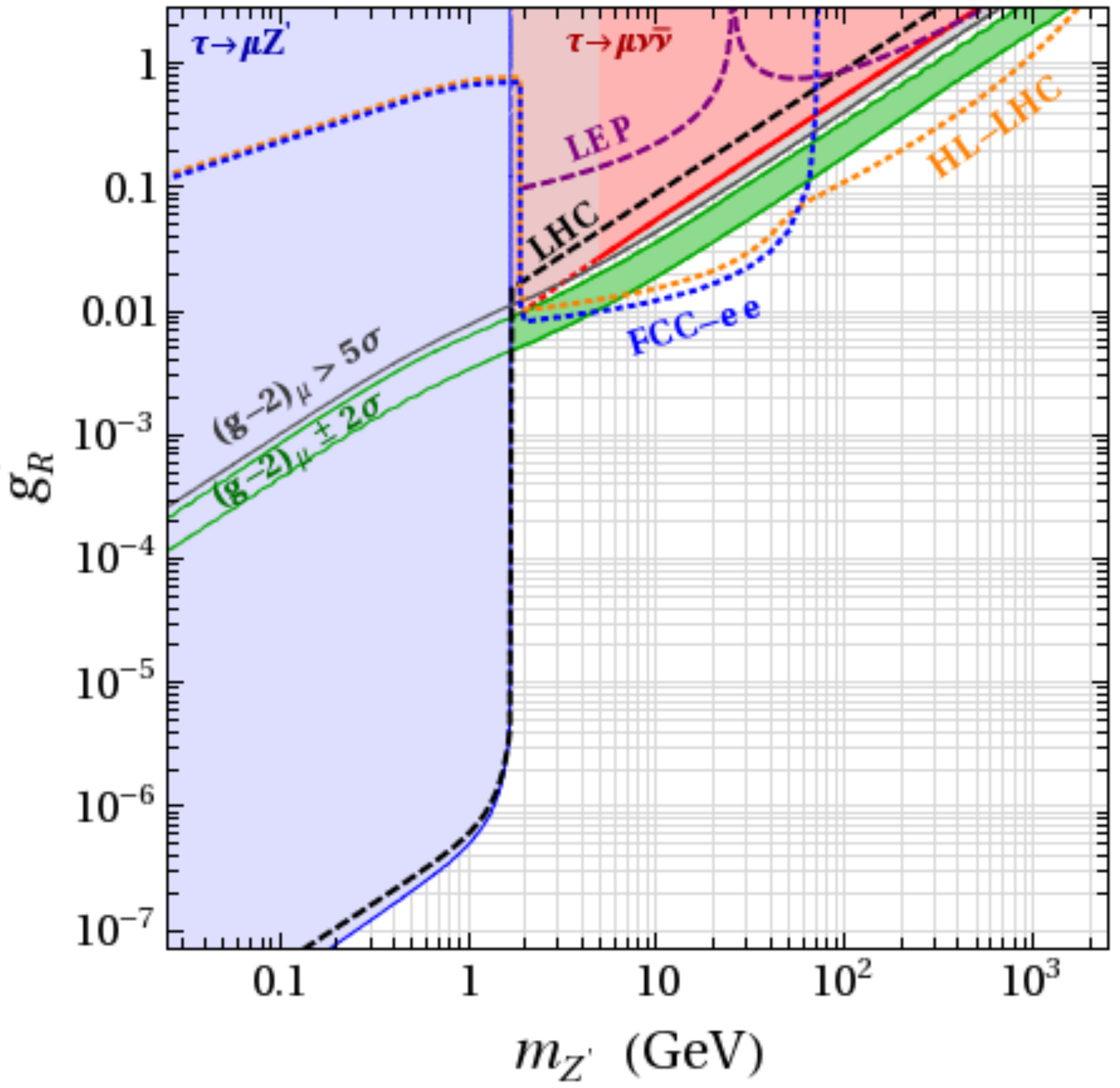
- background suppression already quite effective
- UL estimation using the frequentist profile-likehood method using asymptotic approach

**Various NP scenarios:**

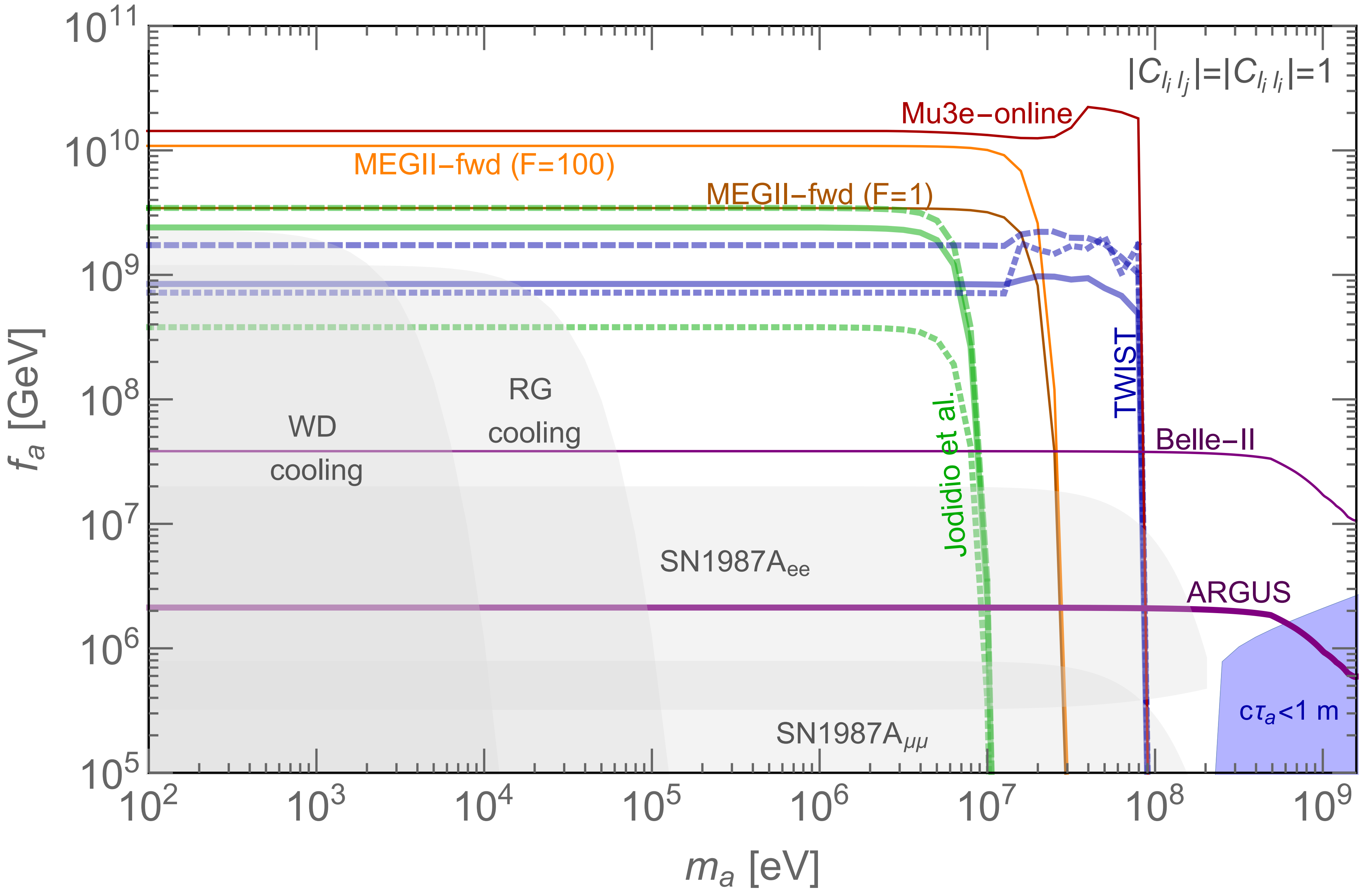
- **LFV Z′**
  - strong bound from ARGUS measurement
- **light ALP *a***
  - exploring regions in parameter space not reachable by other experiments



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

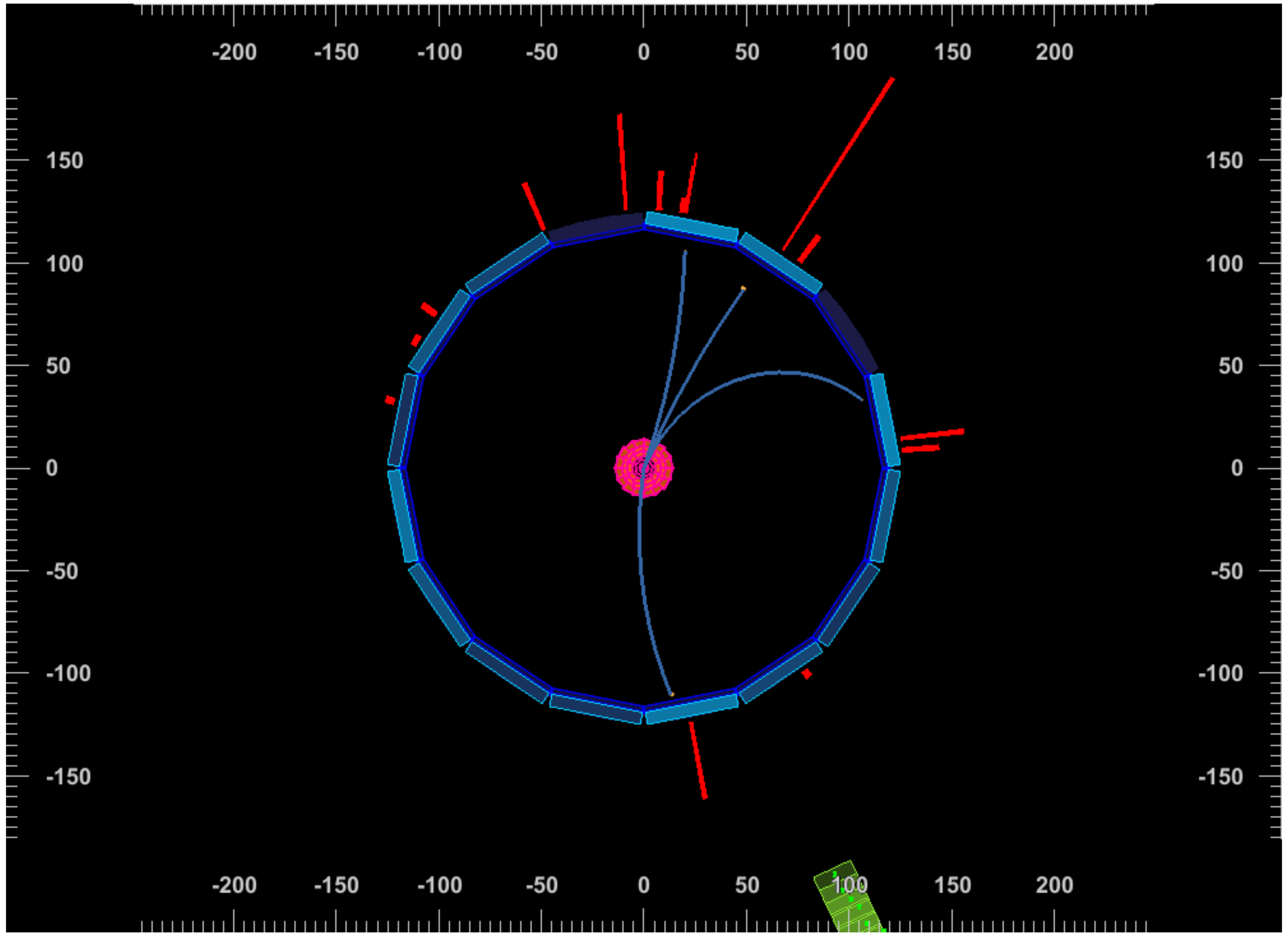


*- L. Calibbi, D. Redigolo, R.. Ziegler, J. Zupan -*



# Summary

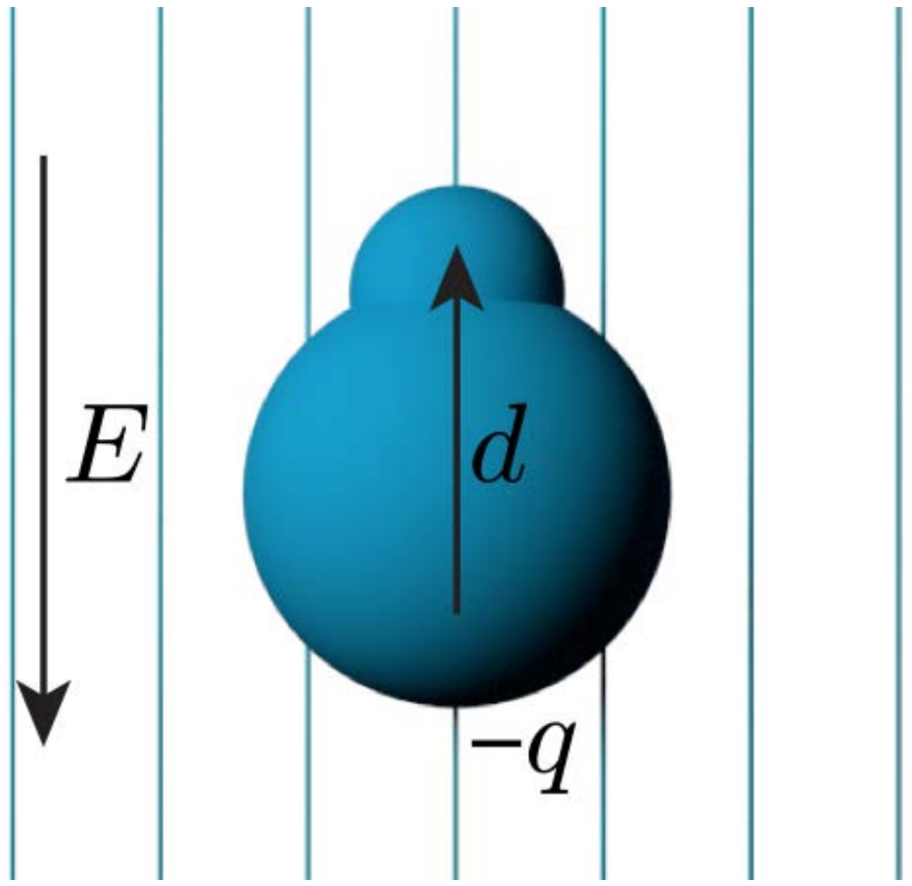
$e^+e^-$ **annihilation data is ideal for precision measurements and NP searches!**

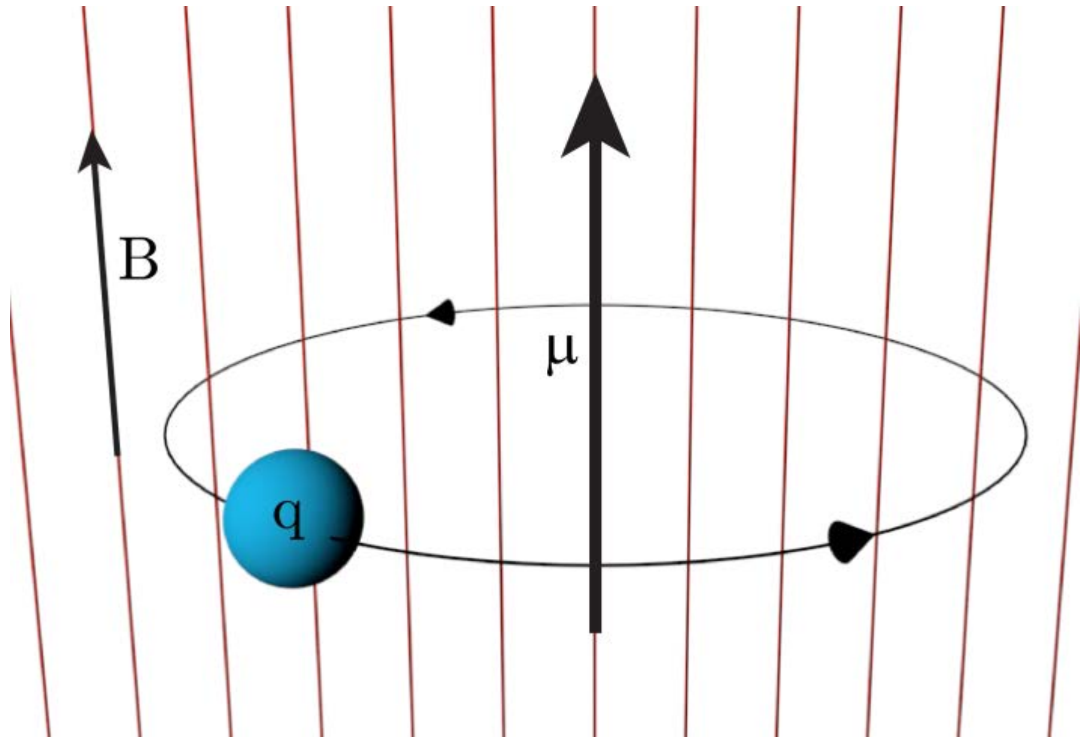


- **Belle II experiment started**
  - Achieved world record luminosity $L = 3.1 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Accelerator tuning is ongoing; more data will be recorded soon
  - **τ mass** and **lifetime** measurements with the early data are very promising and show the potential of Belle II precision measurements
  - **LFU** and **$V_{us}$** analysis ongoing
  - **τ EDM & MDM** analysis progressing
  - **τ → μμμ** indicates the potential of LFV searches
  - …
- **Belle II will provide the world largest number ($5 \times 10^{10}$) of** $e^+e^- \to \tau^+\tau^-$**events**
  - τ precision measurements and NP searches will reach higher sensitivity w.r.t. the previous experiments

# Backup slides

# τ Electric and Magnetic Dipole Moments





**Unveil or constrain NP effects**

- ➡ NP contribution expected $\propto \dfrac{m_\ell}{\Lambda^2}$
- ➡ NP contribution expected $\propto \dfrac{m_\ell^2}{\Lambda^2}$

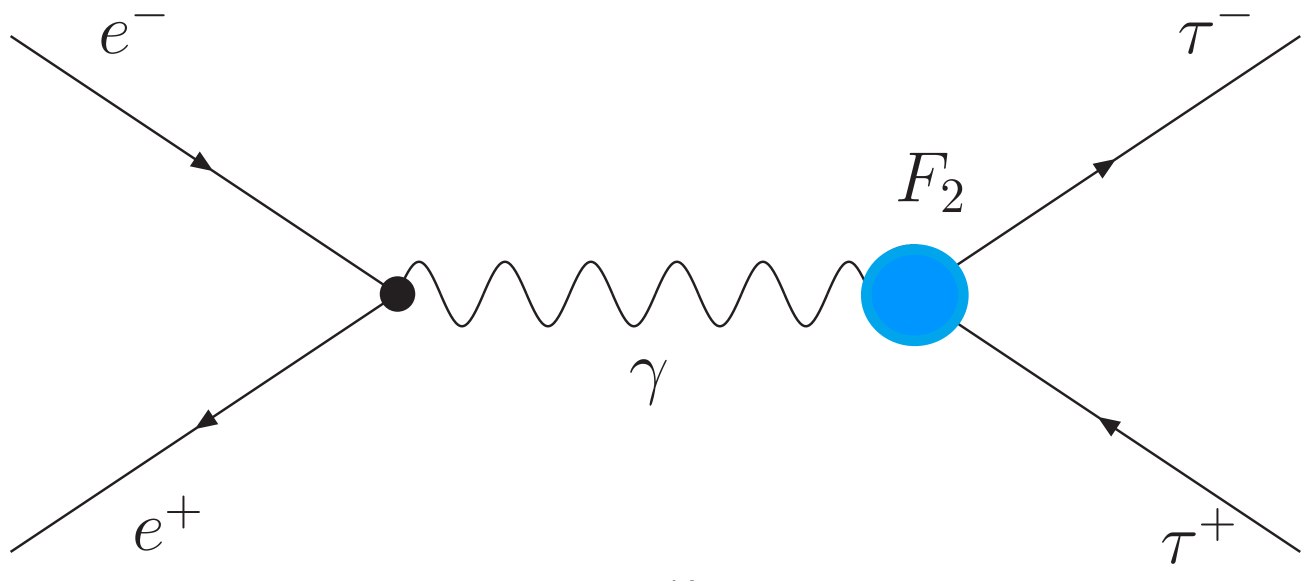
# EDM & MDM

## Interactions between $\tau$ and photon

$$\Gamma^\mu(q^2) = -ieQ_\tau\left\{\gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}\left(iF_2(q^2) + F_3(q^2)\gamma_5\right)\right\}$$

- ➡ $F_1(q^2)$: Dirac form factor $F_1(0) = 1$
- ➡ $F_2(q^2)$: Pauli form factor (MDM) $F_2(0) = a_\tau$
- ➡ $F_3(q^2)$: electric dipole moment (EDM) $F_3(0) = d_\tau \cdot 2m_\tau\ /\ eQ_\tau$

**When NP exists in the loop diagrams of the $\gamma$-$\tau$ interaction vertex, τ can possess extra EDM and/or MDM.**



**EDM is a fundamental parameter that parameterises T- or CP- violation at the $\gamma\tau\tau$ vertex.**

- ➡ SM prediction for EDM: $d_\tau = 10^{-37}ecm$
- ➡ NP models predict $d_\tau = 10^{-19}ecm$
- ➡ World best measurement from Belle *- arXiv:2108.11543 -*

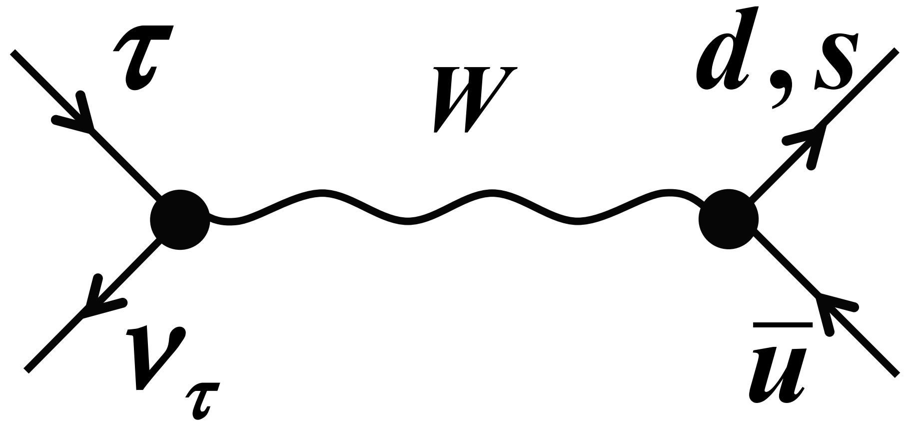
$$-1.85\times10^{-17} < \mathscr{R}(\tilde{d}_\tau) < 0.61\times10^{-17}ecm\ (95\,\%\,\text{CL})$$

$$-1.03\times10^{-17} < \mathfrak{I}(\tilde{d}_\tau) < 0.23\times10^{-17}ecm\ (95\,\%\,\text{CL})$$

**The experimental measurement of MDM of the fast-decaying τ is very different from that of the stable or relatively long-lived $e$ and $\mu$.**

- ➡ SM prediction:
  $a_\tau^{\text{SM}} = a_\tau^{\text{QED}} + a_\tau^{\text{EW}} + a_\tau^{\text{HLO}} + a_\tau^{\text{HHO}} = 117\,721(5)\times10^{-8}$
- ➡ World best measurement from DELPHI *- EPJ.C 35:159, 2004 -*
  $-0.0052 < \tilde{a}_\tau < 0.013(95\,\%\,\text{CL})$
- ➡ Every deviation assumed to stem from $a_\tau$

# Test of unitarity

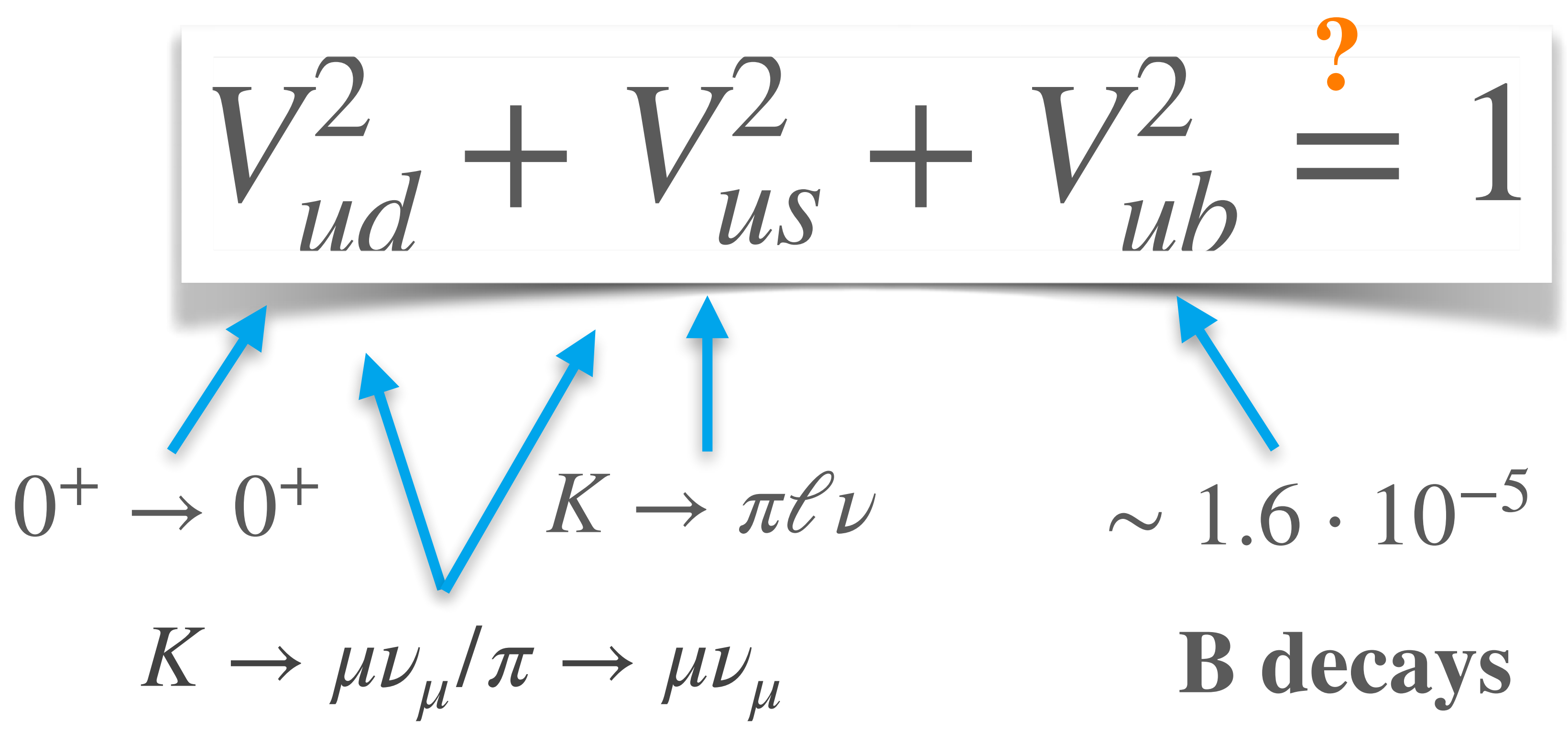


**Unique opportunity for probing the coupling strength of the weak current to the first and second generation of quarks to a very high precision**

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

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

## Test of unitarity



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

$0^+ \to 0^+$

$K \to \pi \ell \nu$

$K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$

$\sim 1.6 \cdot 10^{-5}$

**B decays**

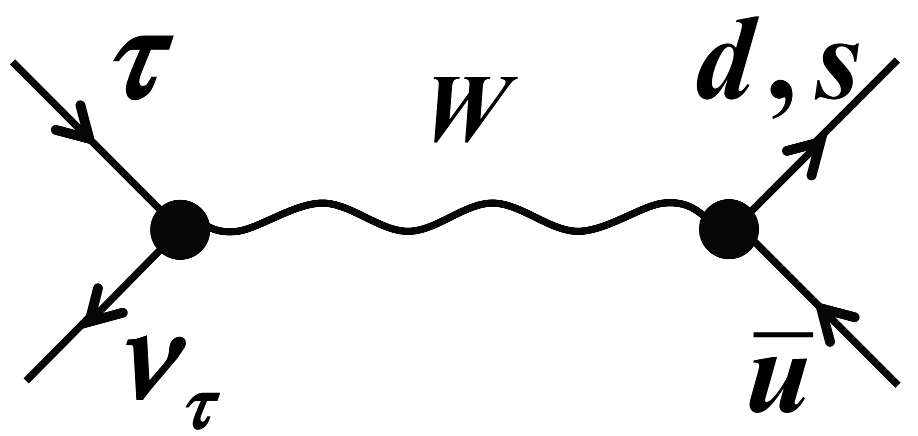
➡ From kaon, pion, baryon and nuclear decays

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

➡ 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*

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

$V_{us} = 0.2193 \pm 0.0032$

➡ 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*

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

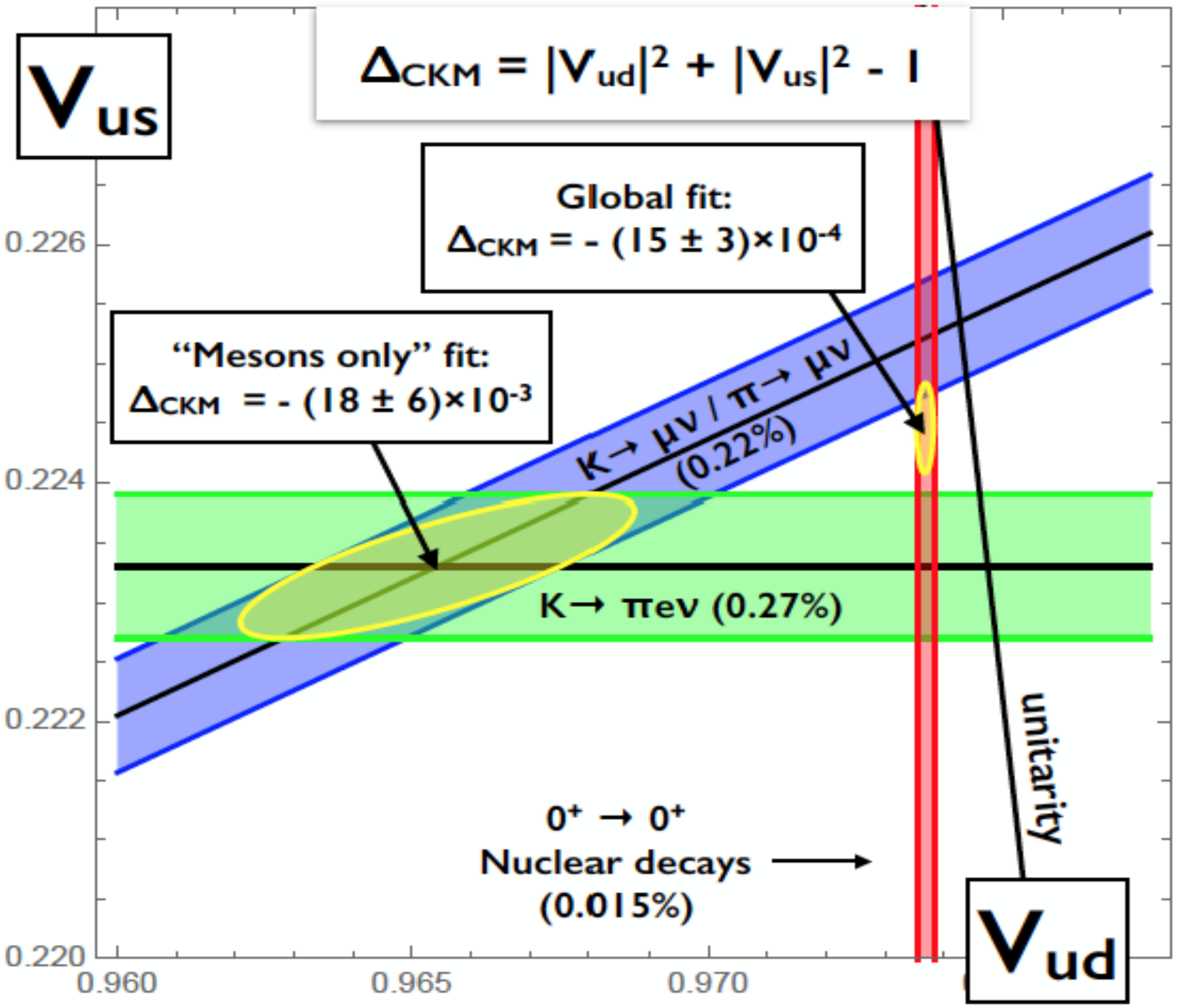
$V_{\mathrm{us}} = 0.2186 \pm 0.0021$

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

# $V_{us}$ from τ decays @Belle II

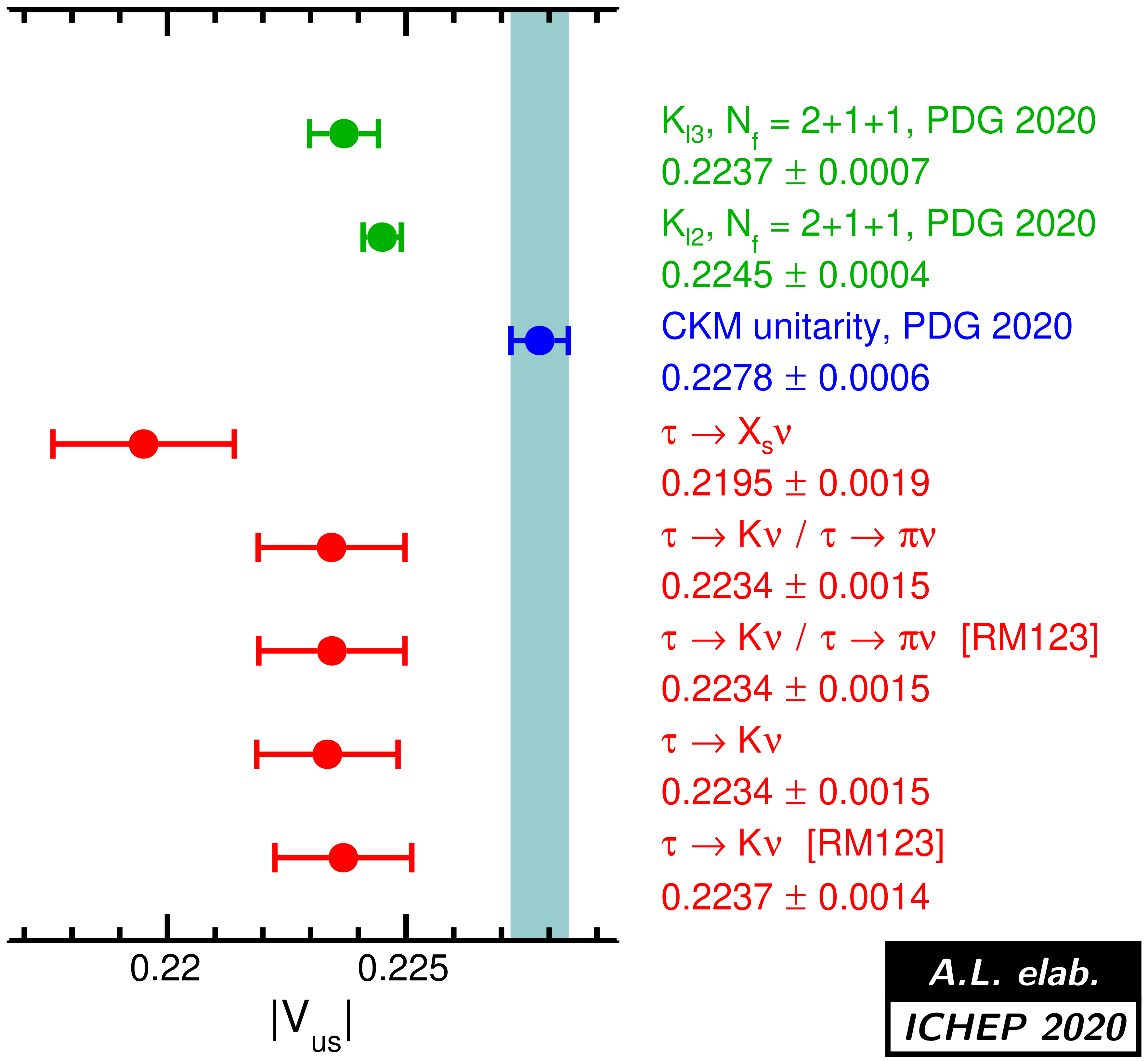
## New results with improved theoretical input

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



## Can τ physics help?

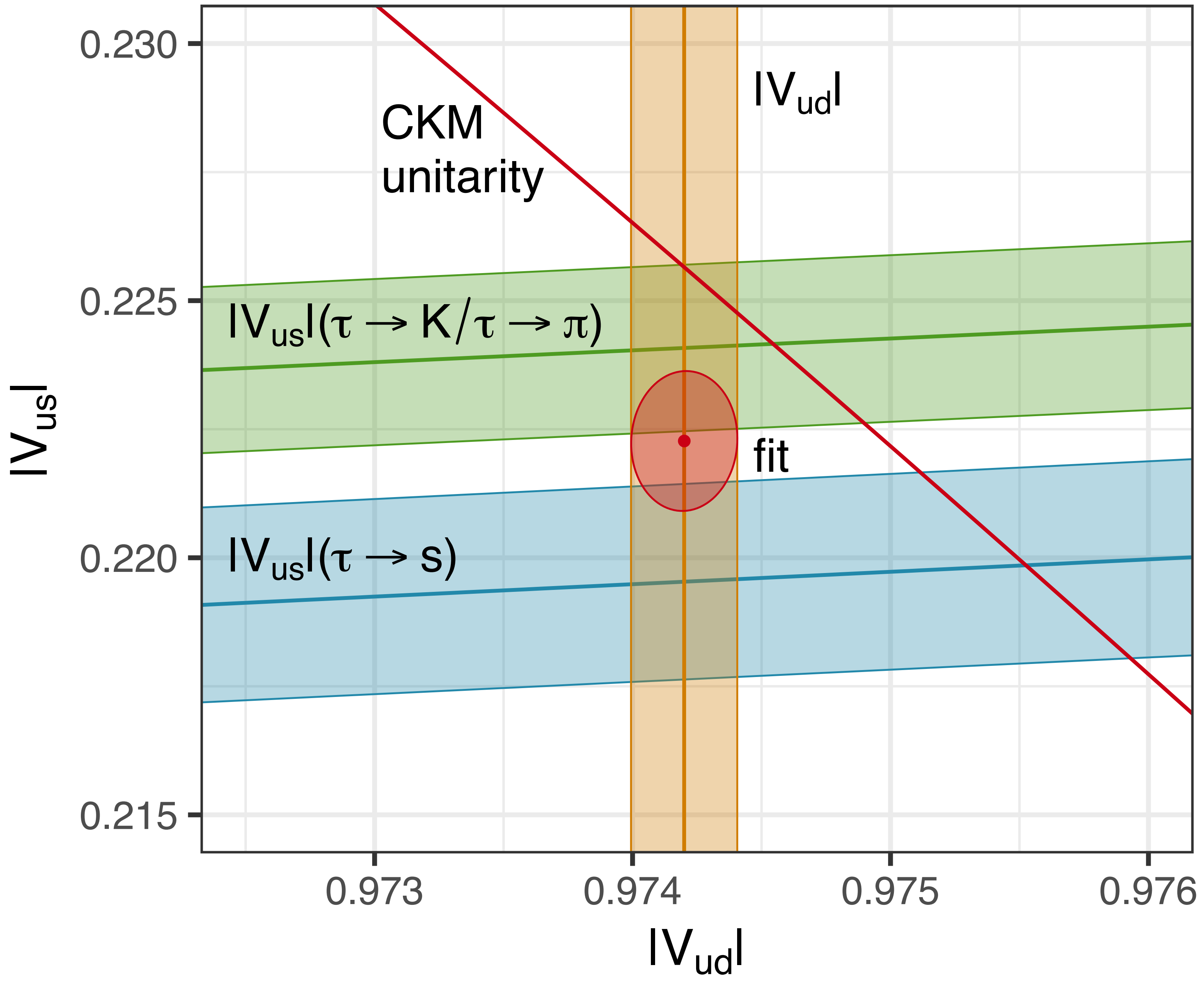
- currently less precise determination of $V_{us}$
- large PID systematic uncertainties @BaBar
- inclusive measurement not truly inclusive

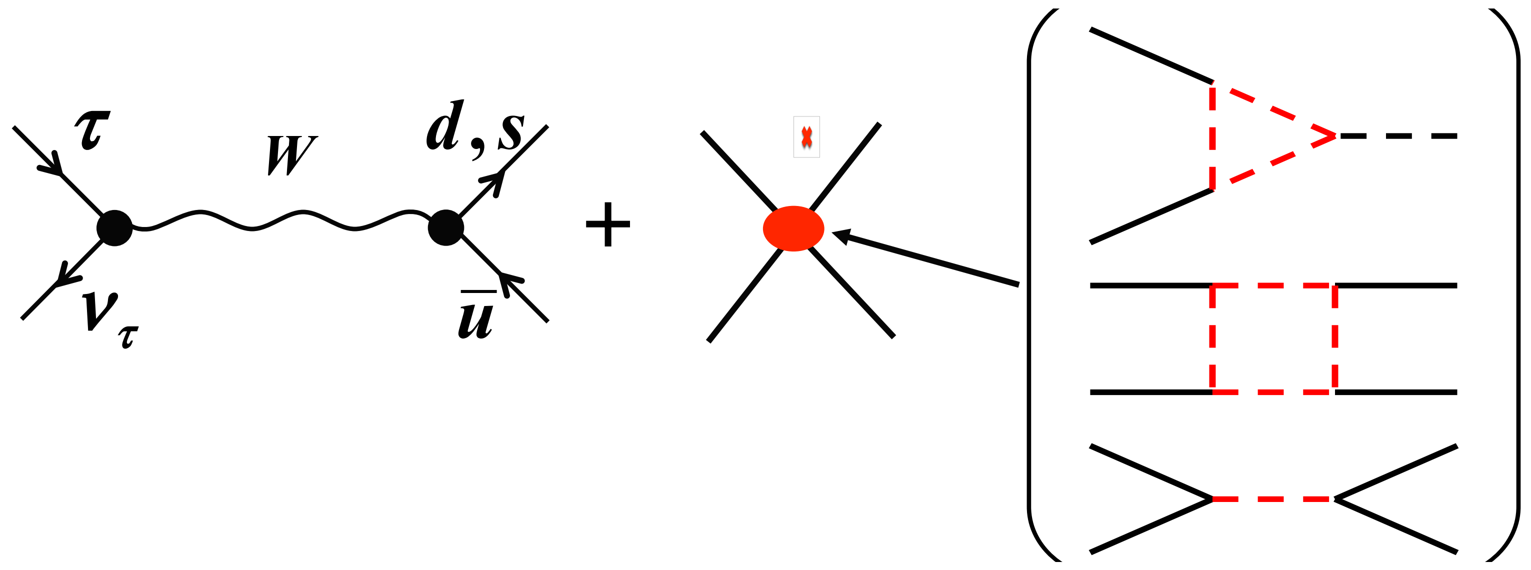


# $V_{us}$ from τ decays @Belle II

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

*SciPost Phys. Proc. 1, 001 (2019)*

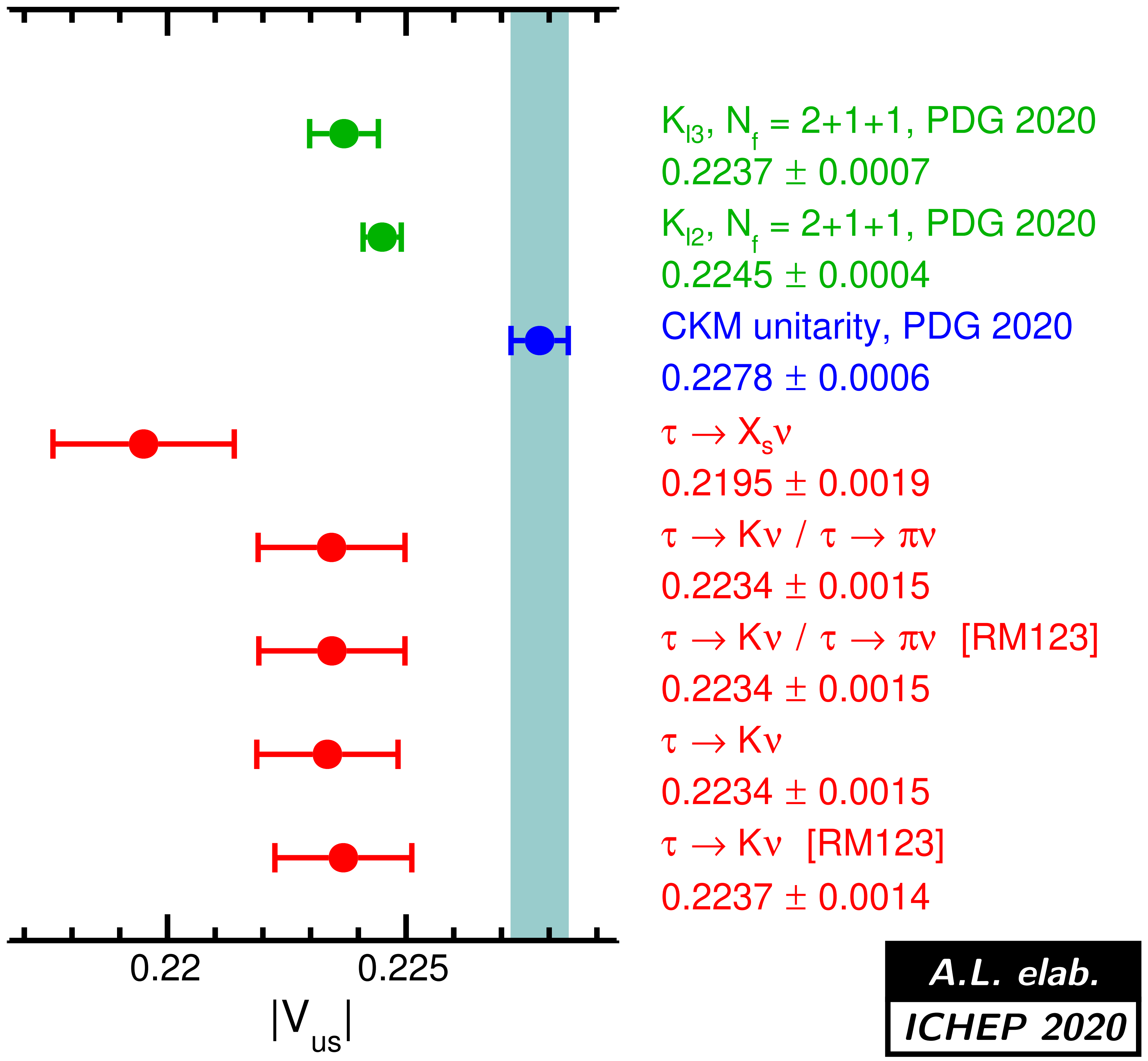




SUSY loops,
Leptoquarks,
Z', Charged Higgs
Right-Handed
Currents,….

## 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, … )

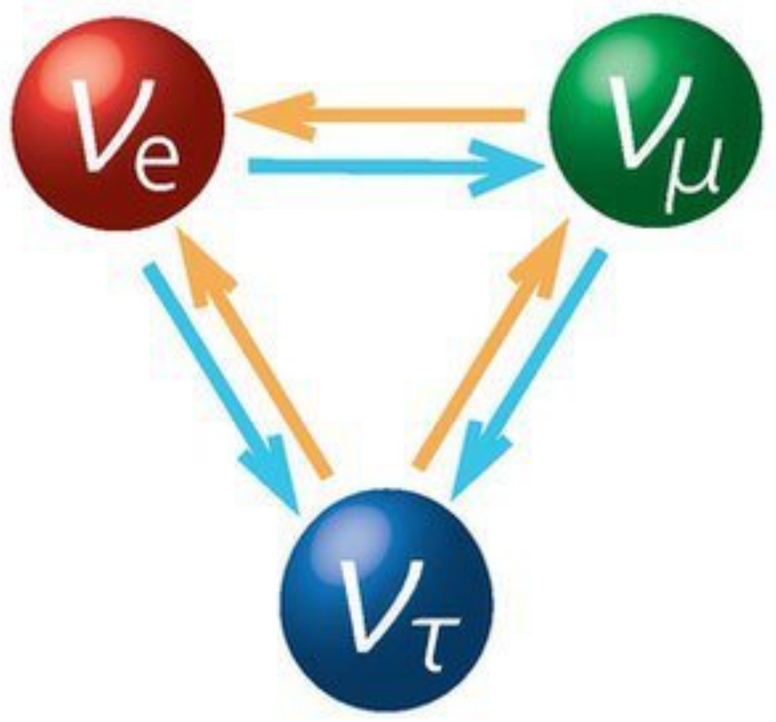


**A.L. elab.**
**ICHEP 2020**

# Lepton flavour conservation

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

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



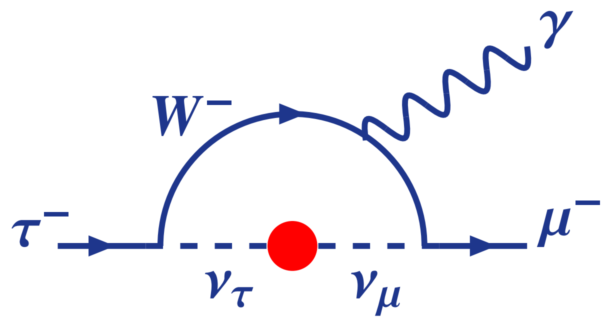
- ➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

**What about the charged leptons?**

- ➡ The charged LFV processes can occur through oscillations in loops
- ➡ Unmeasurable small rates ($10^{-54}$-$10^{-49}$) for all the LFV μ and τ decays

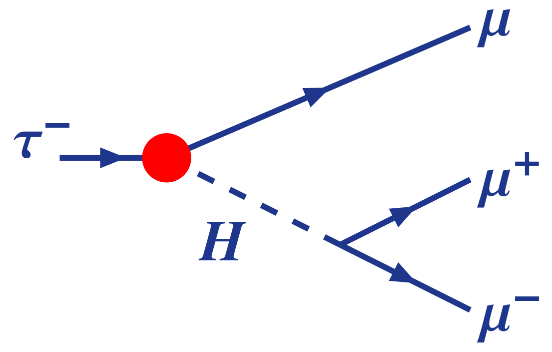
$$\mathcal{B}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\ell_1 i}U_{\ell_2 i}\enclose{circle}{\frac{\Delta m^2_{i1}}{M_W^2}}\right|^2$$

LFV from ν mixing

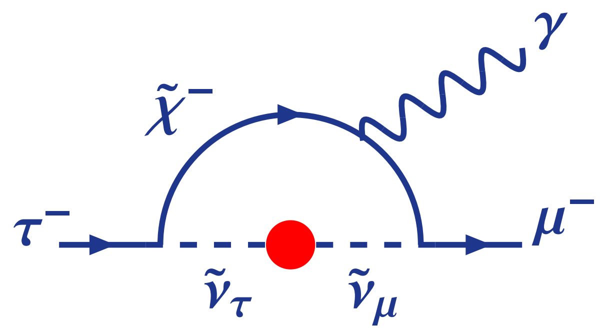


**Observation of LFV will be a clear signature of the NP!**

Higgs mediated LFV



s-lepton mixing

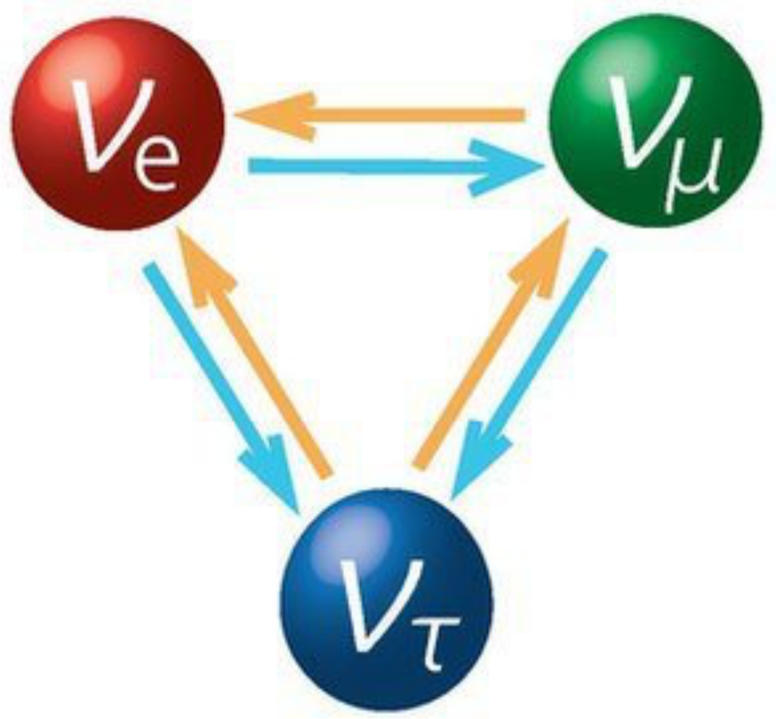


- ➡ Charged LFV enhanced in many NP models ($10^{-10}$ - $10^{-7}$)

# Lepton flavour conservation

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

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



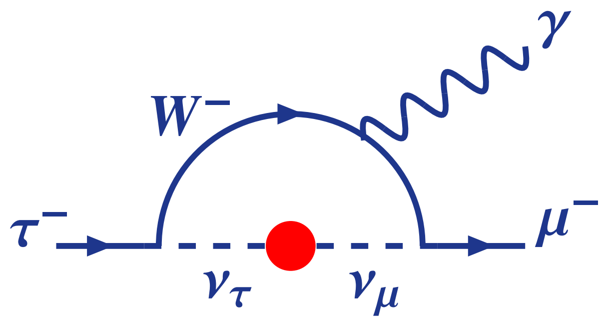
- ➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

**What about the charged leptons?**

- ➡ The charged LFV processes can occur through oscillations in loops
- ➡ Unmeasurable small rates ($10^{-54}$-$10^{-49}$) for all the LFV μ and τ decays

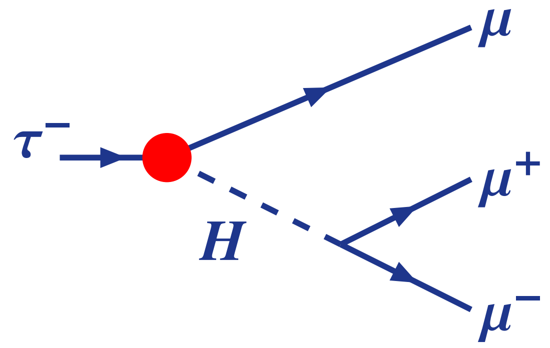
$$\mathcal{B}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\ell_1 i}U_{\ell_2 i}\boxed{\frac{\Delta m^2_{i1}}{M_W^2}}\right|^2.$$

**LFV from ν mixing**

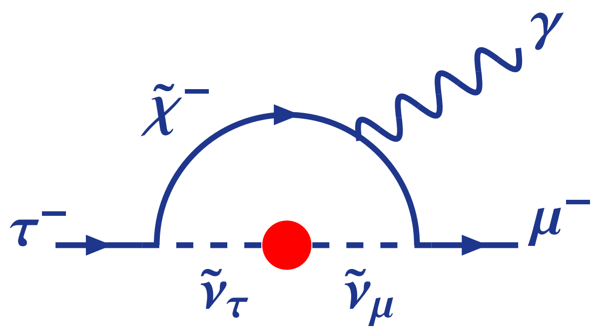


**Observation of LFV will be a clear signature of the NP!**

**Higgs mediated LFV**



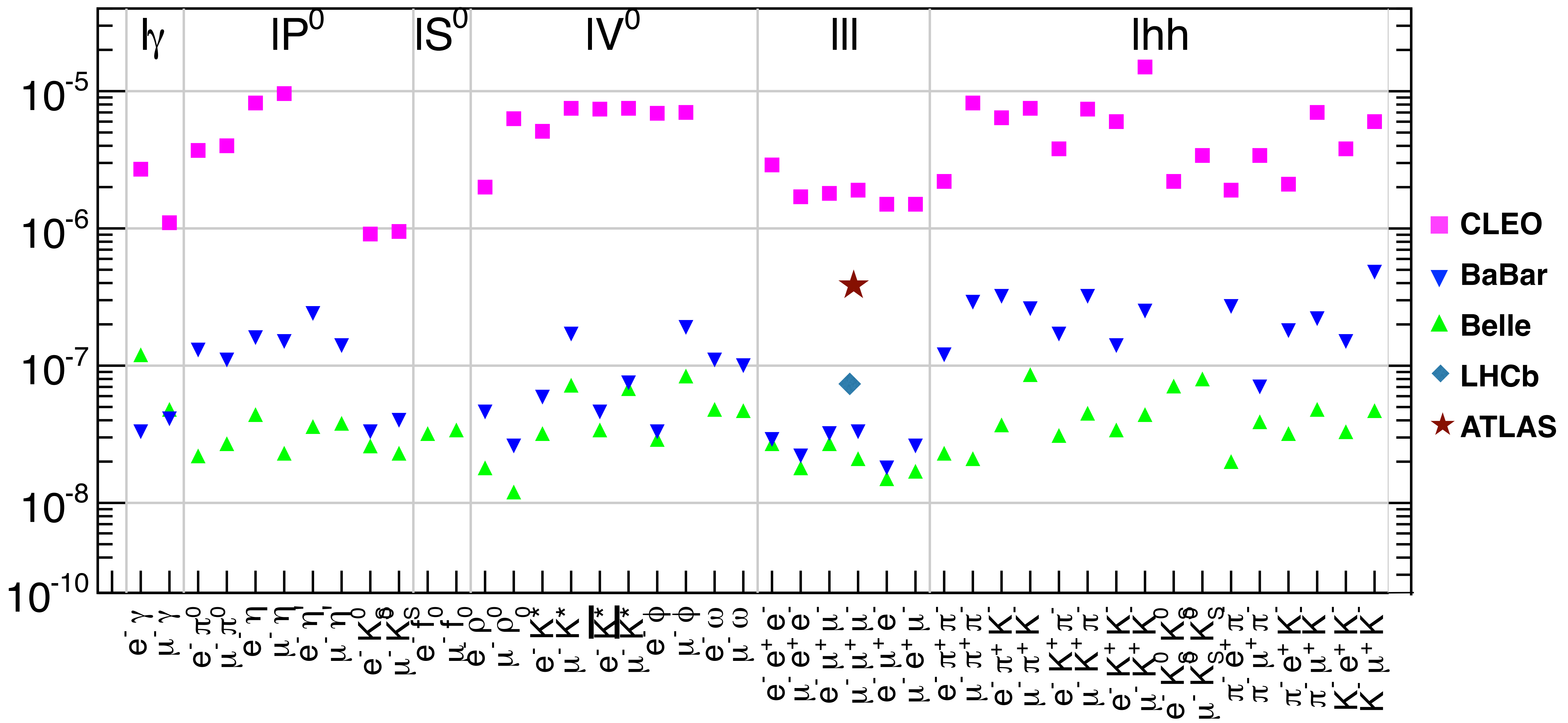
**s-lepton mixing**



- ➡ Charged LFV enhanced in many NP models ($10^{-10}$ - $10^{-7}$)

# The progress of τ LFV and LNV searches

**… mostly occurred at the B-factories**



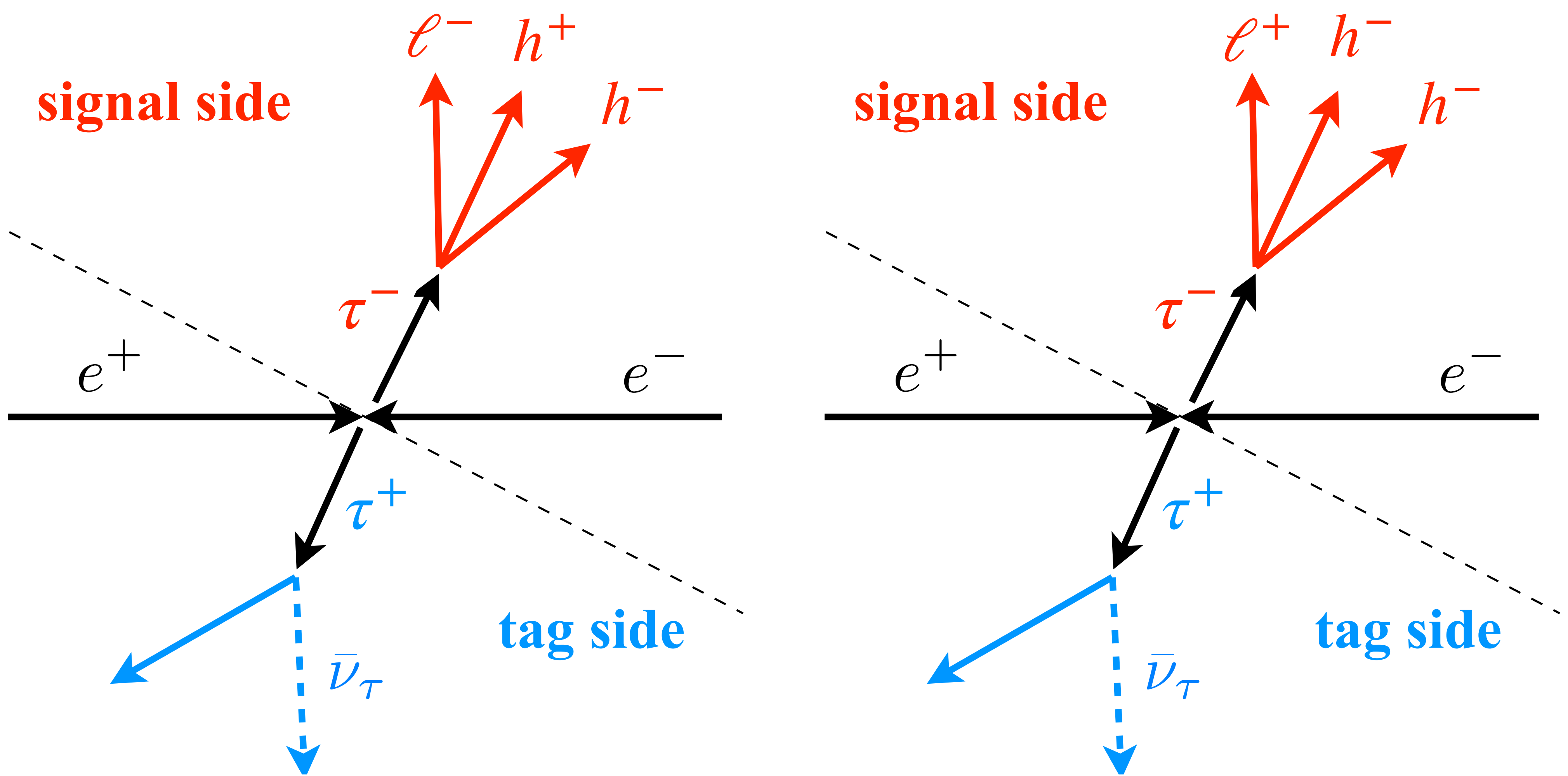
**The upper limits reached for τ decays approached the regions sensitive to NP.**

**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
- ➡ $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour structure

*$\ell$ = e or μ*

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



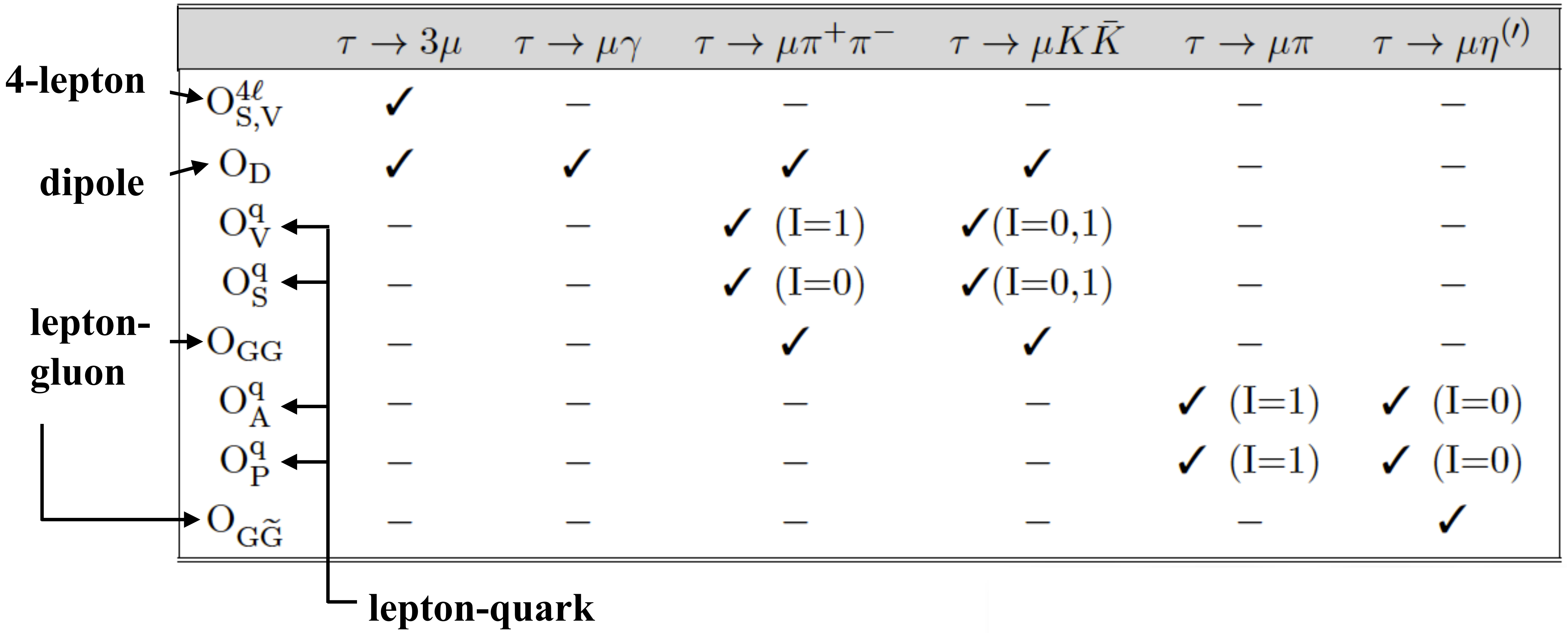
# Effective field theory approach

## 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



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

*- Celis, Cirigliano, Passemar (2014) -*

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