Tau Physics: hot topics and future prospects

Swagato Banerjee

UNIVERSITY OF LOUISVILLE

Overview of this talk

https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf

Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration

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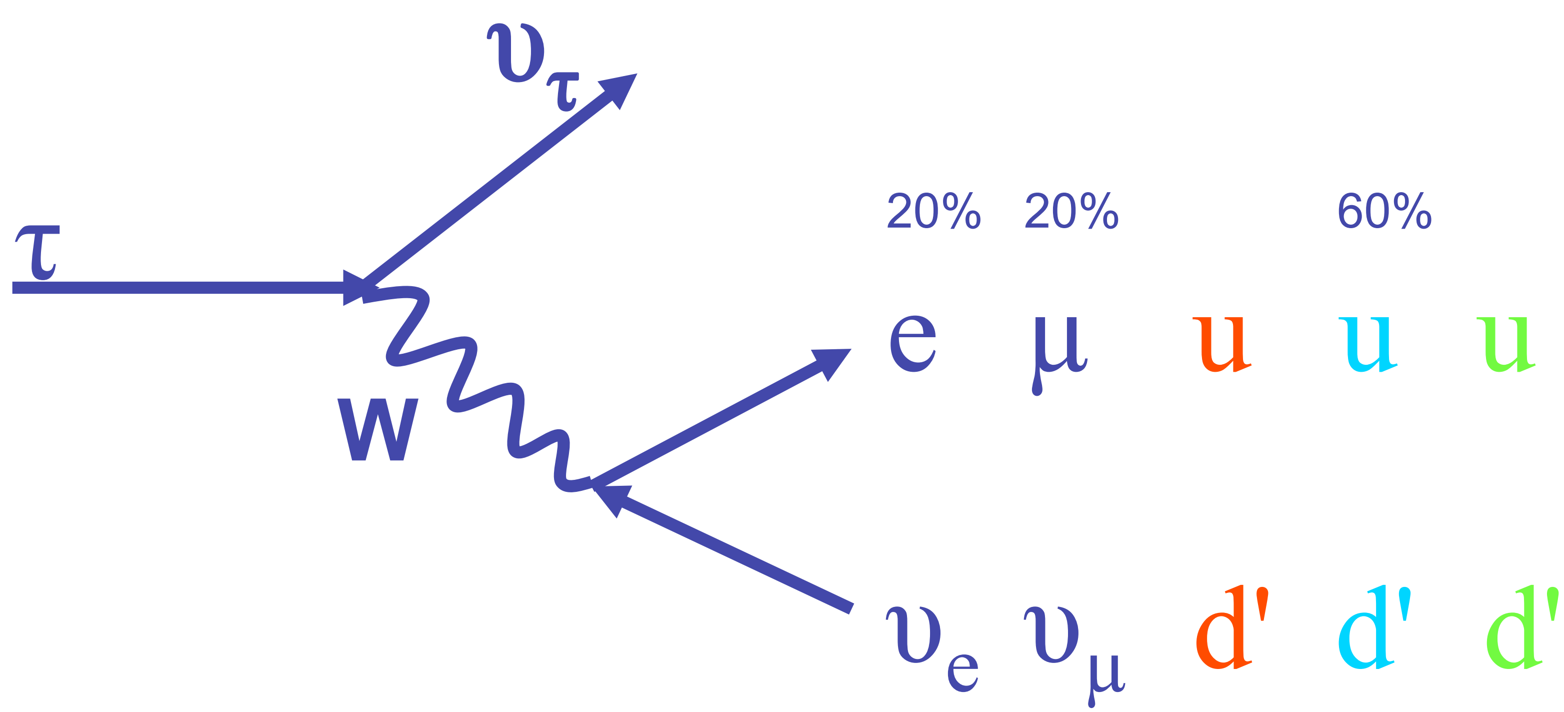
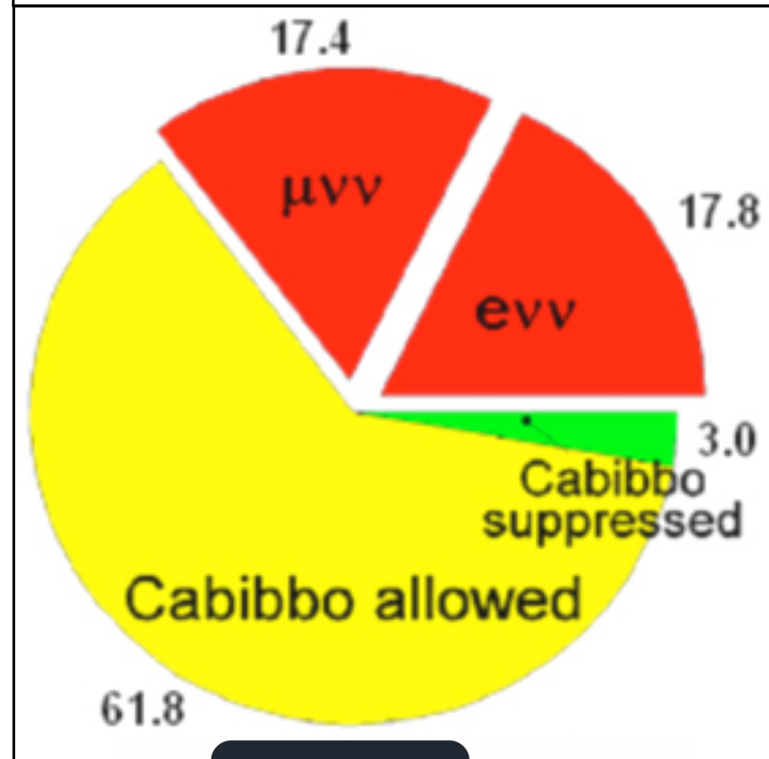
Tau Decays

Naive prediction:



$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

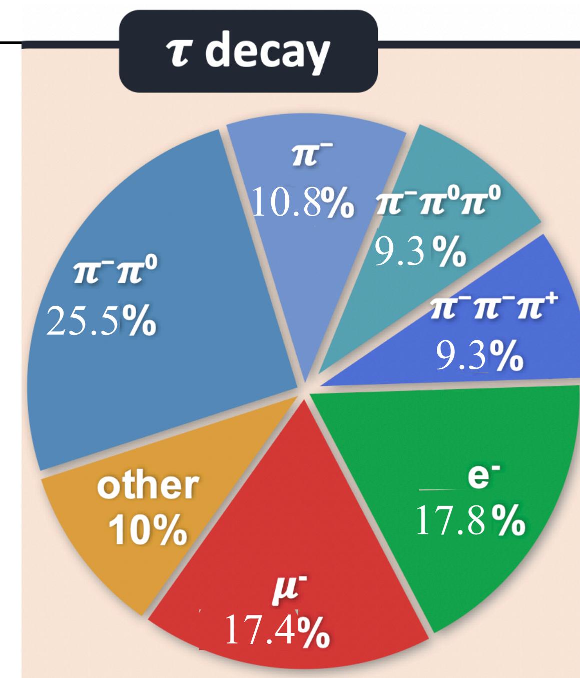
Including QED & QCD corrections:



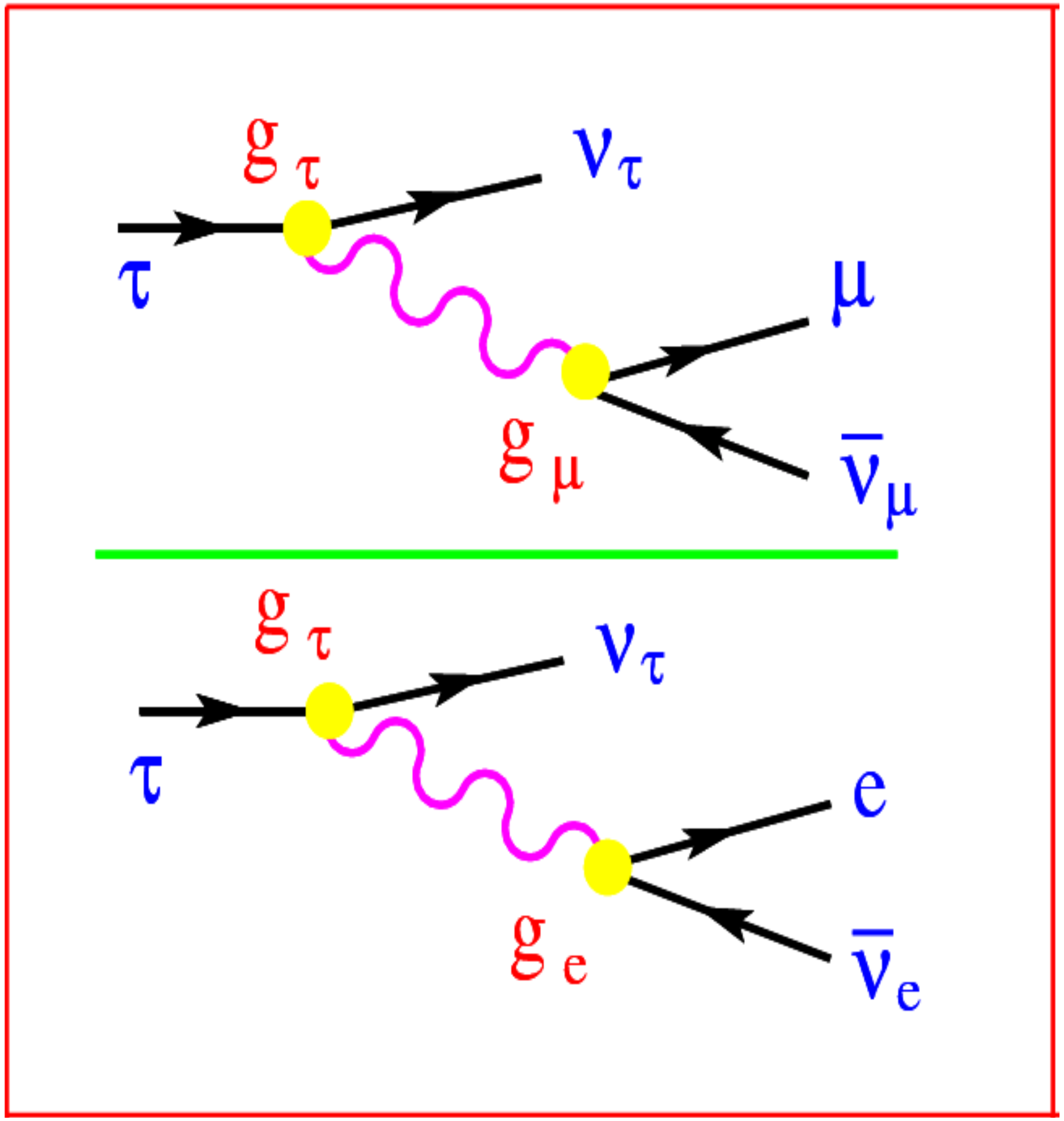
τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^- \geq 0$ neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.24 ± 0.06) %		–
particle$^- \geq 0$ neutrals $\geq 0K^0_L\nu_\tau$		(84.58 ± 0.06) %		–
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.39 ± 0.04) %		885
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e]	(3.67 ± 0.08) × 10^{-3}		885
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.82 ± 0.04) %		888
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e]	(1.83 ± 0.05) %		888
$h^- \geq 0K^0_L\ \nu_\tau$		(12.03 ± 0.05) %		883
$h^-\nu_\tau$		(11.51 ± 0.05) %		883
$\pi^-\nu_\tau$	[g]	(10.82 ± 0.05) %		883
$K^-\nu_\tau$	[g]	(6.96 ± 0.10) × 10^{-3}		820

The Review of Particle Physics (2021)

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.



Lepton Flavor universality: muon vs electron $\left(\frac{g_\mu}{g_e}\right)$



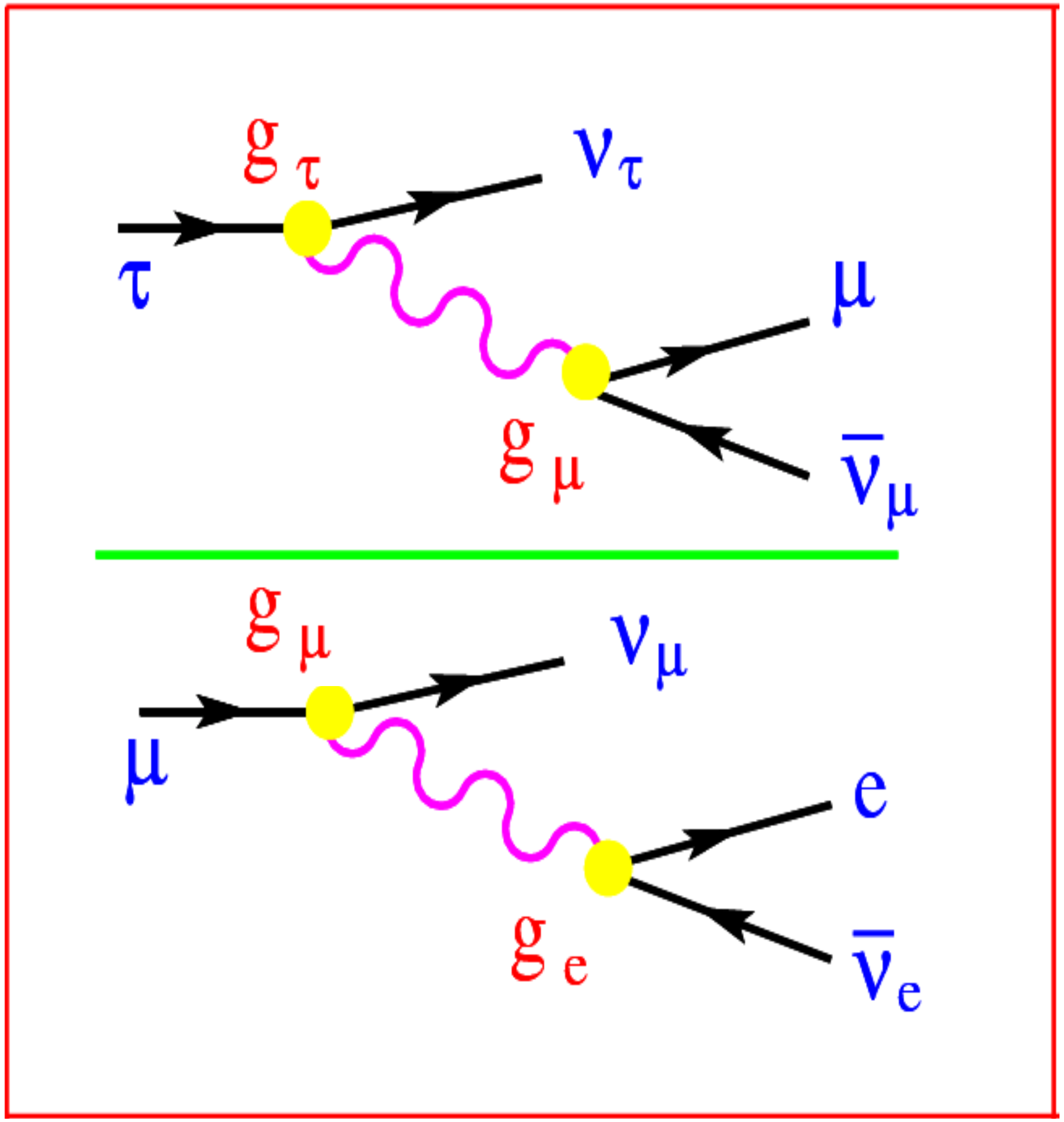
$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}$$

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$ (approximating all $m_\nu = 0$)

Measure:

$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

Lepton Flavor universality: tau vs electron $\left(\frac{g_\tau}{g_e}\right)$



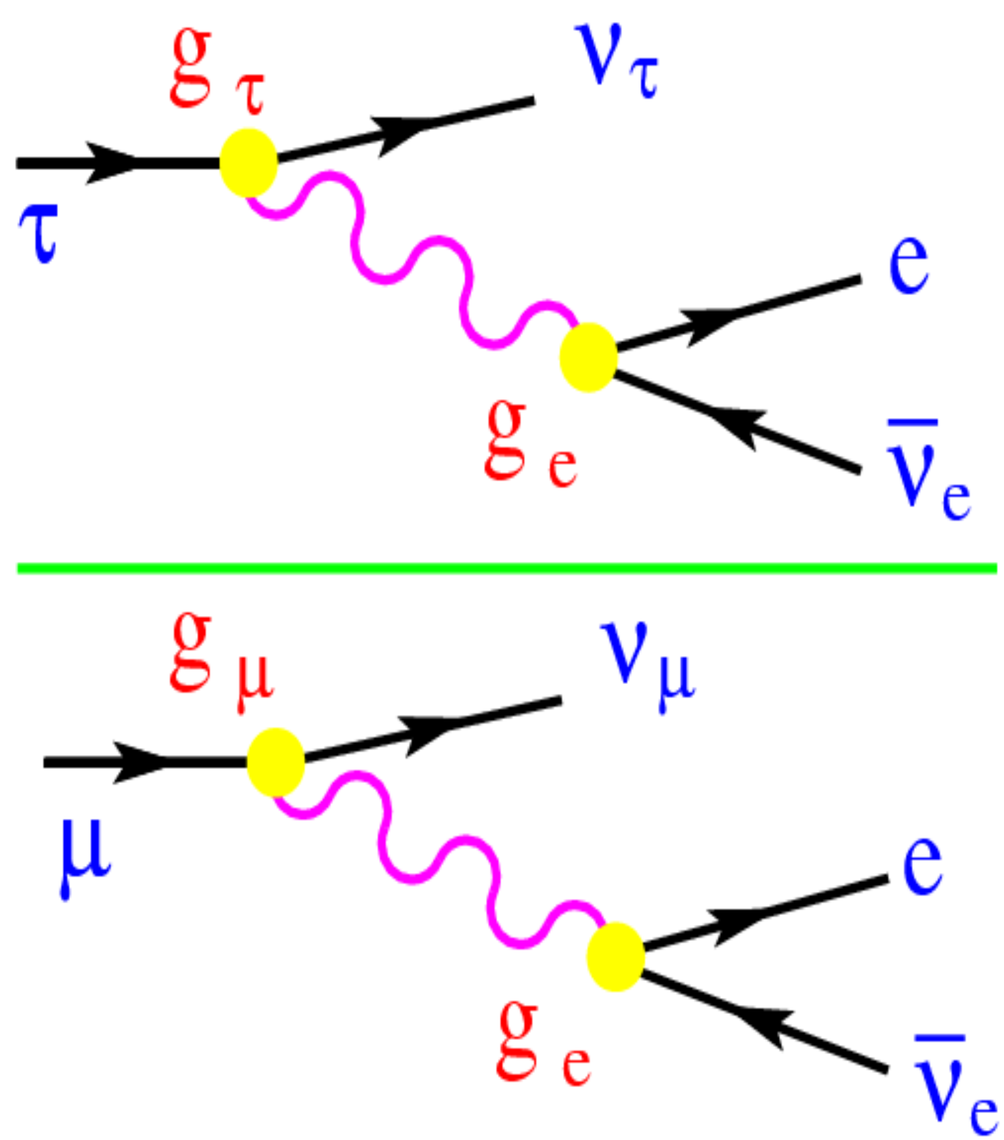
$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r_{EW}^\mu}{f(m_\mu^2/m_\tau^2)r_{EW}^\tau}$$

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$ (approximating all $m_\nu = 0$)

Measure:

$$m_\tau, \tau_\tau, \mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$$

Lepton Flavor universality: tau vs muon $\left(\frac{g_\tau}{g_\mu}\right)$



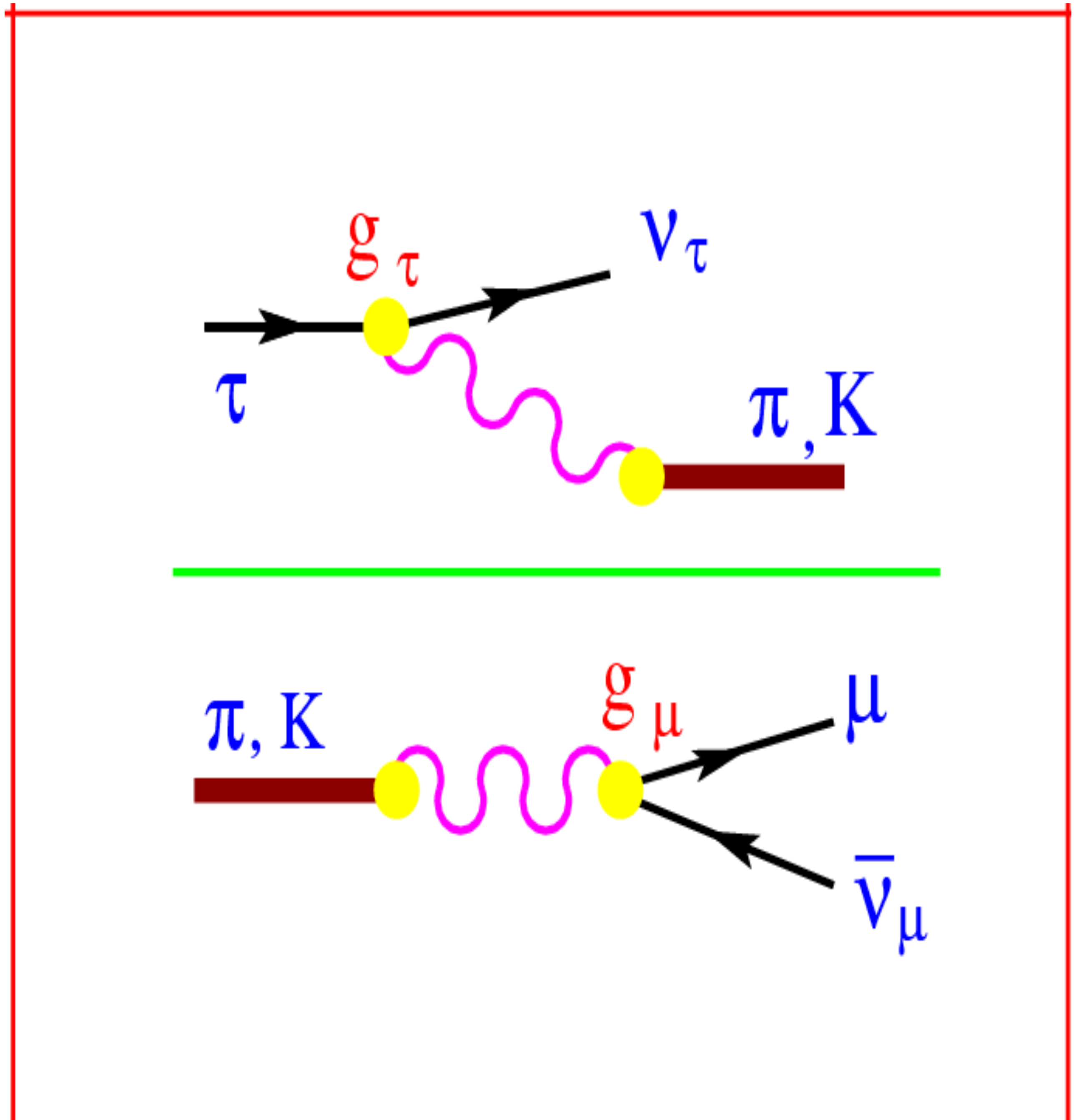
$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r_{EW}^\mu}{f(m_e^2/m_\tau^2)r_{EW}^\tau}$$

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x\ln x$ (approximating all $m_\nu = 0$)

Measure:

$$m_\tau, \tau_\tau, \mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$$

Lepton Flavor universality: tau vs muon $\left(\frac{g_\tau}{g_\mu}\right)$



$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_{\tau/h}) m_\tau^3 \tau_\tau} \frac{\mathcal{B}(\tau^- \to h^- \nu_\tau)}{\mathcal{B}(h^- \to \mu^- \bar{\nu}_\mu)} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2$$

Measure:

$m_\tau, \tau_\tau, \mathcal{B}(\tau^- \to h^- \nu_\tau)\ [h^- = \pi^-/K^-]$

Lepton Flavor universality

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0019 \pm 0.0014 \qquad \left(\frac{g_\tau}{g_e}\right)_\tau = 1.0027 \pm 0.0014$$

$$\left(\frac{g_\tau}{g_\mu}\right)_\tau = 1.0009 \pm 0.0014$$

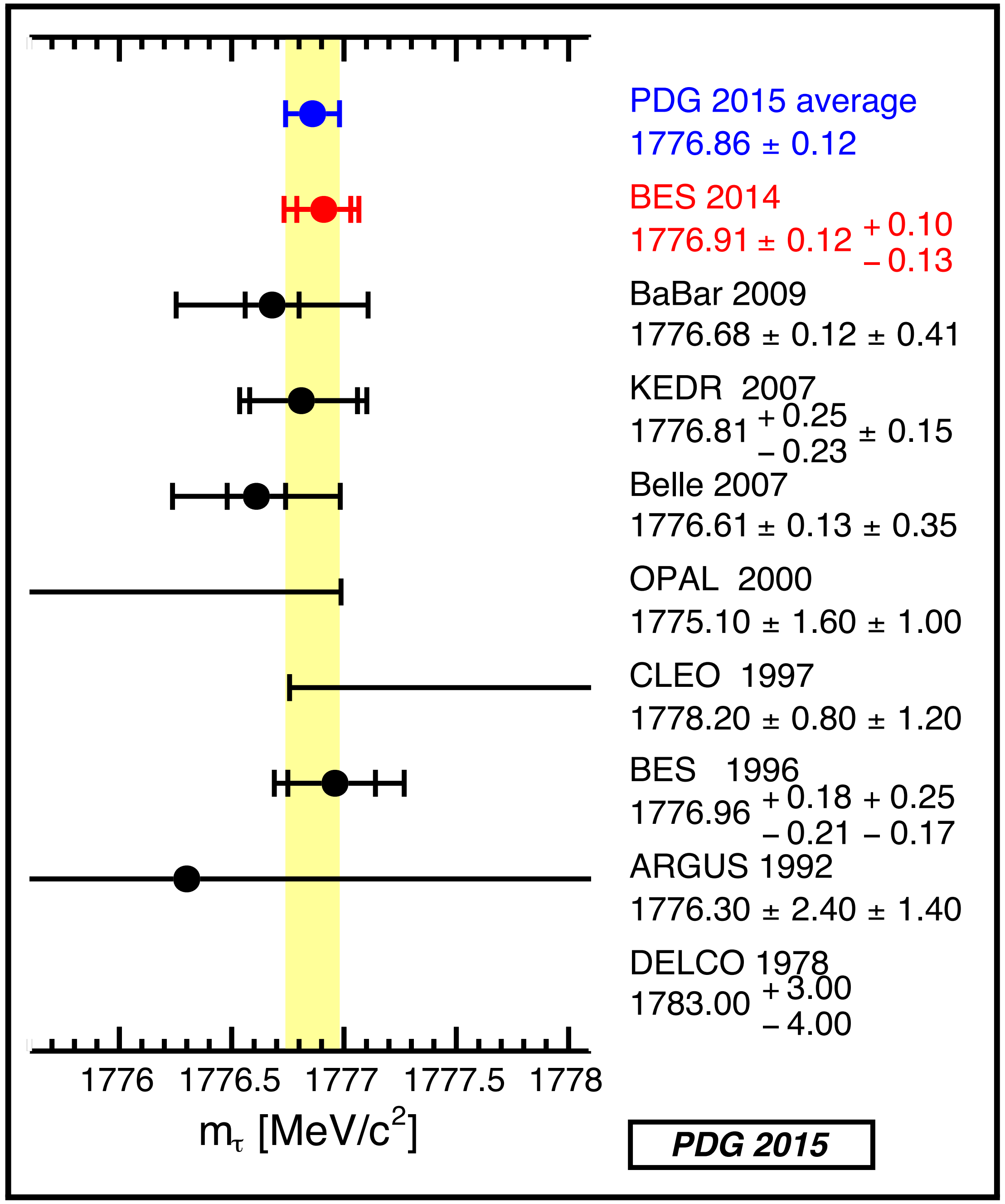
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9959 \pm 0.0038 \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9855 \pm 0.0075$$

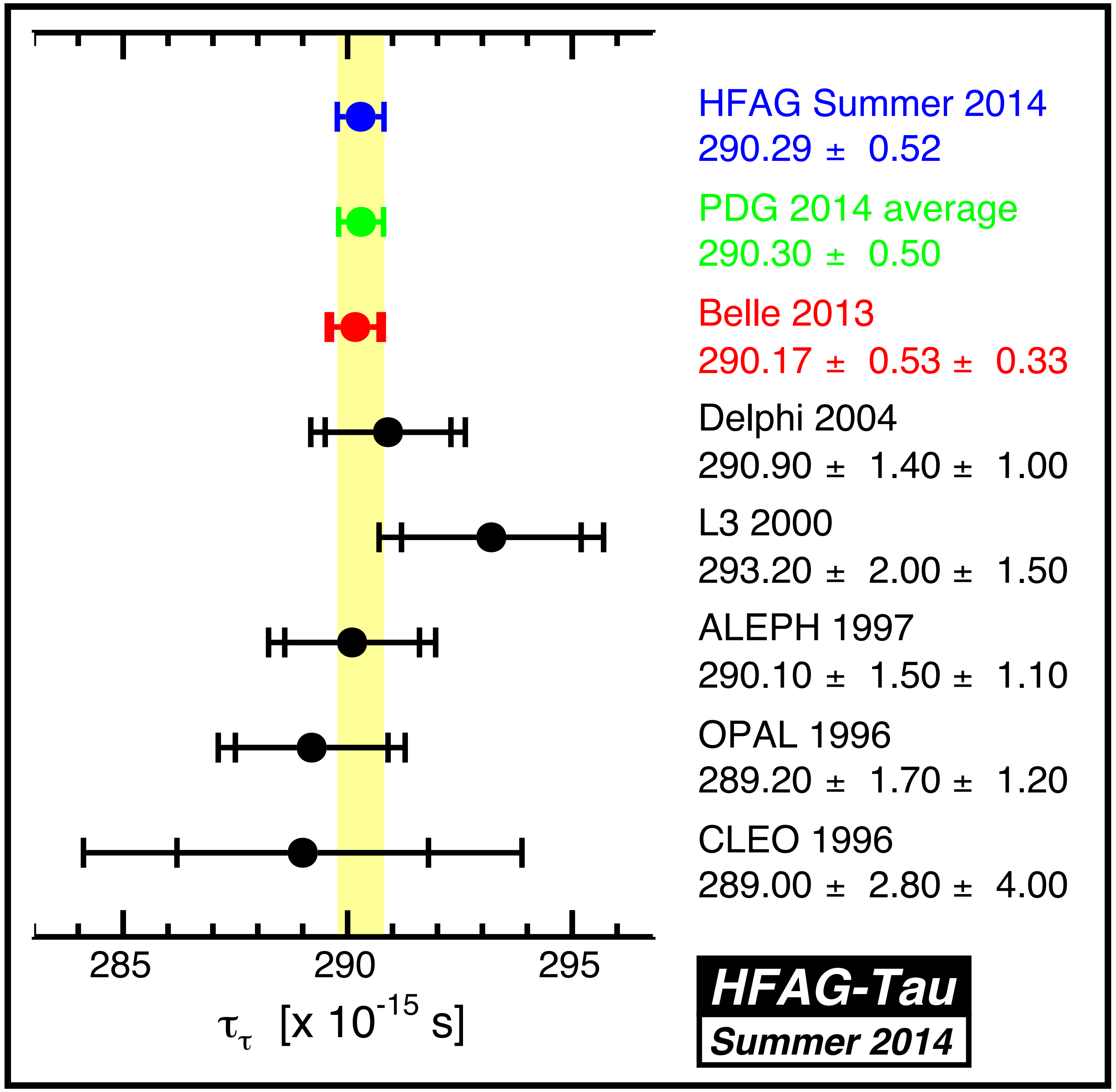
$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0003 \pm 0.0014$$

Table 12: Universality coupling ratios correlation coefficients (%)

$\left(\frac{g_\tau}{g_e}\right)_\tau$	51			
$\left(\frac{g_\mu}{g_e}\right)_\tau$	-50	49		
$\left(\frac{g_\tau}{g_\mu}\right)_\pi$	16	18	1	
$\left(\frac{g_\tau}{g_\mu}\right)_K$	12	11	-1	7
	$\left(\frac{g_\tau}{g_\mu}\right)_\tau$	$\left(\frac{g_\tau}{g_e}\right)_\tau$	$\left(\frac{g_\mu}{g_e}\right)_\tau$	$\left(\frac{g_\tau}{g_\mu}\right)_\pi$

τ mass and lifetime

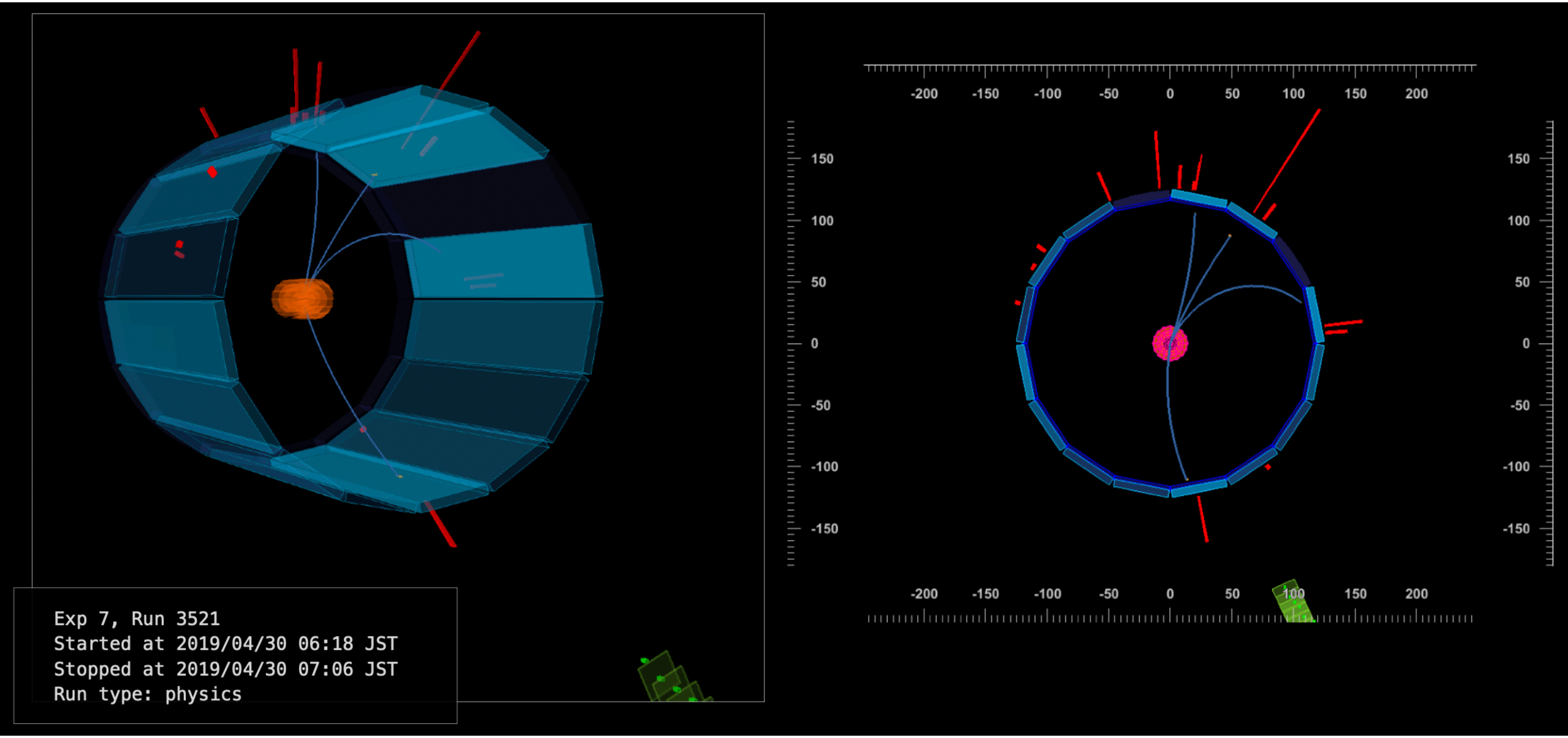




Most precise measurements at $\tau^-\tau^+$ threshold

Most precise measurement by Belle using 3-vs-3 topology

1-vs-3 topology

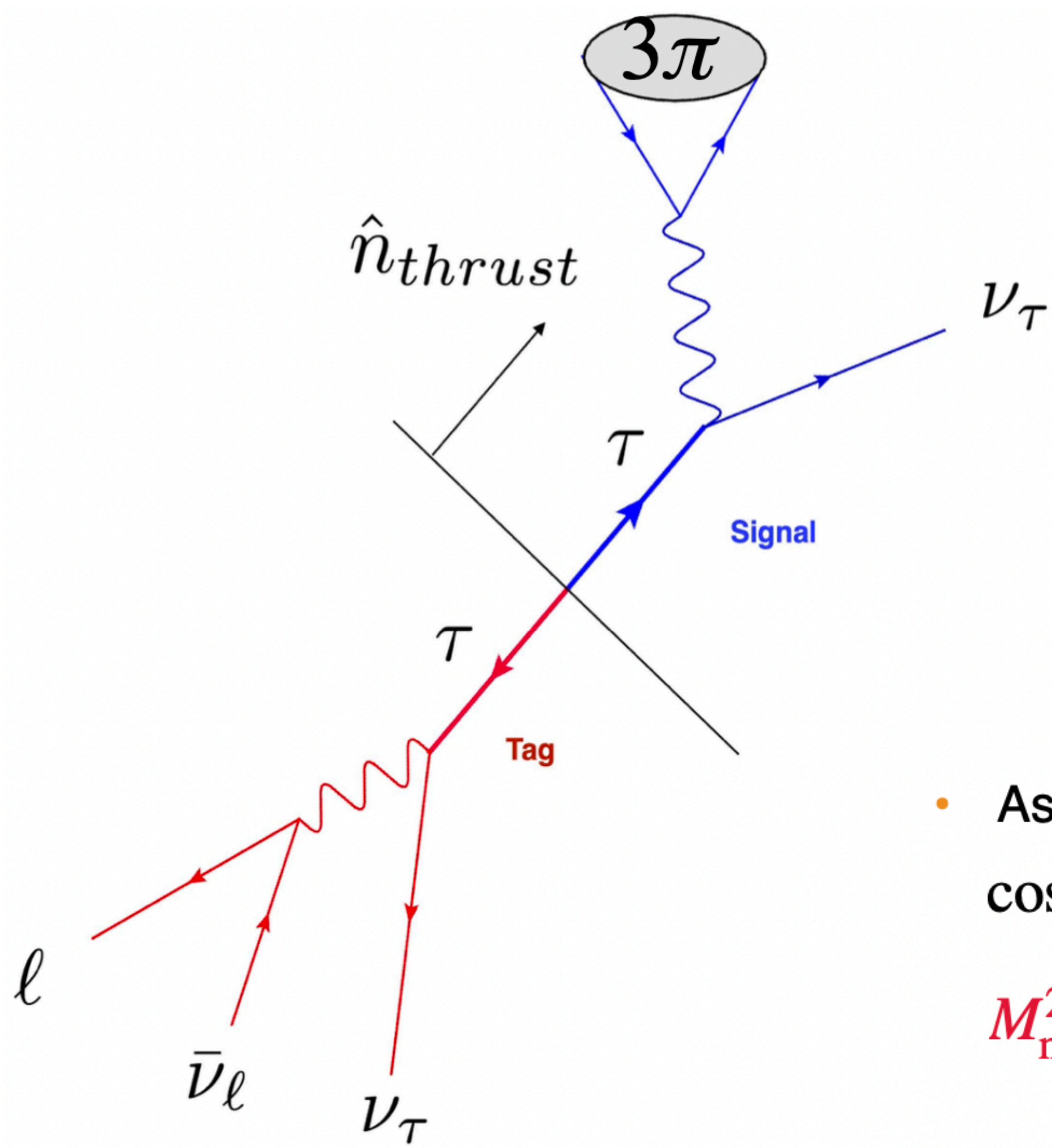


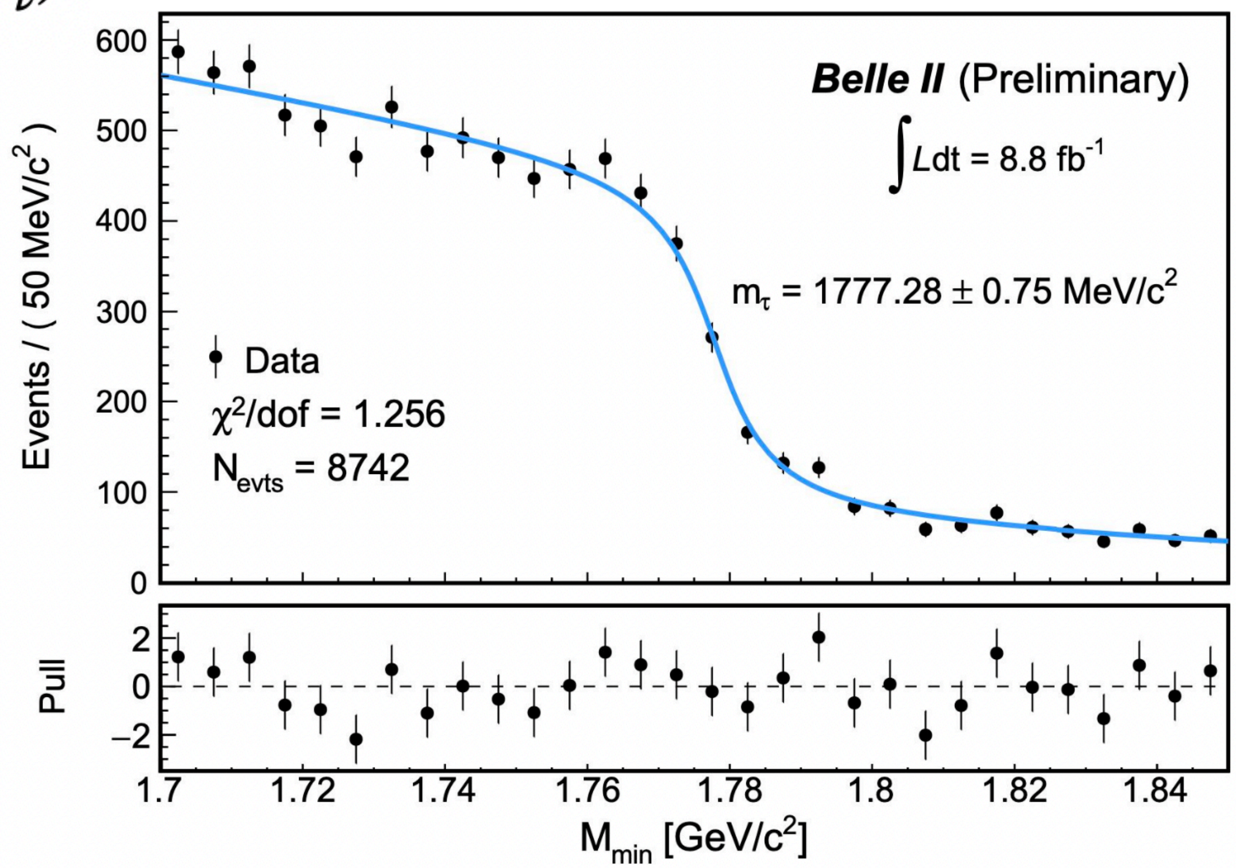
Tau Mass at Belle II

- The tau mass can be calculated as

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ \cos(\vec{p}_h, \vec{p}_\nu)$$

arXiv:2008.04665 [hep-ex]





- As the direction of the neutrino is not known, the approximation $\cos(\vec{p}_\nu, \vec{p}_h) = 1$ is taken, resulting in

$$M^2_{\rm min} = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ < m_\tau^2$$

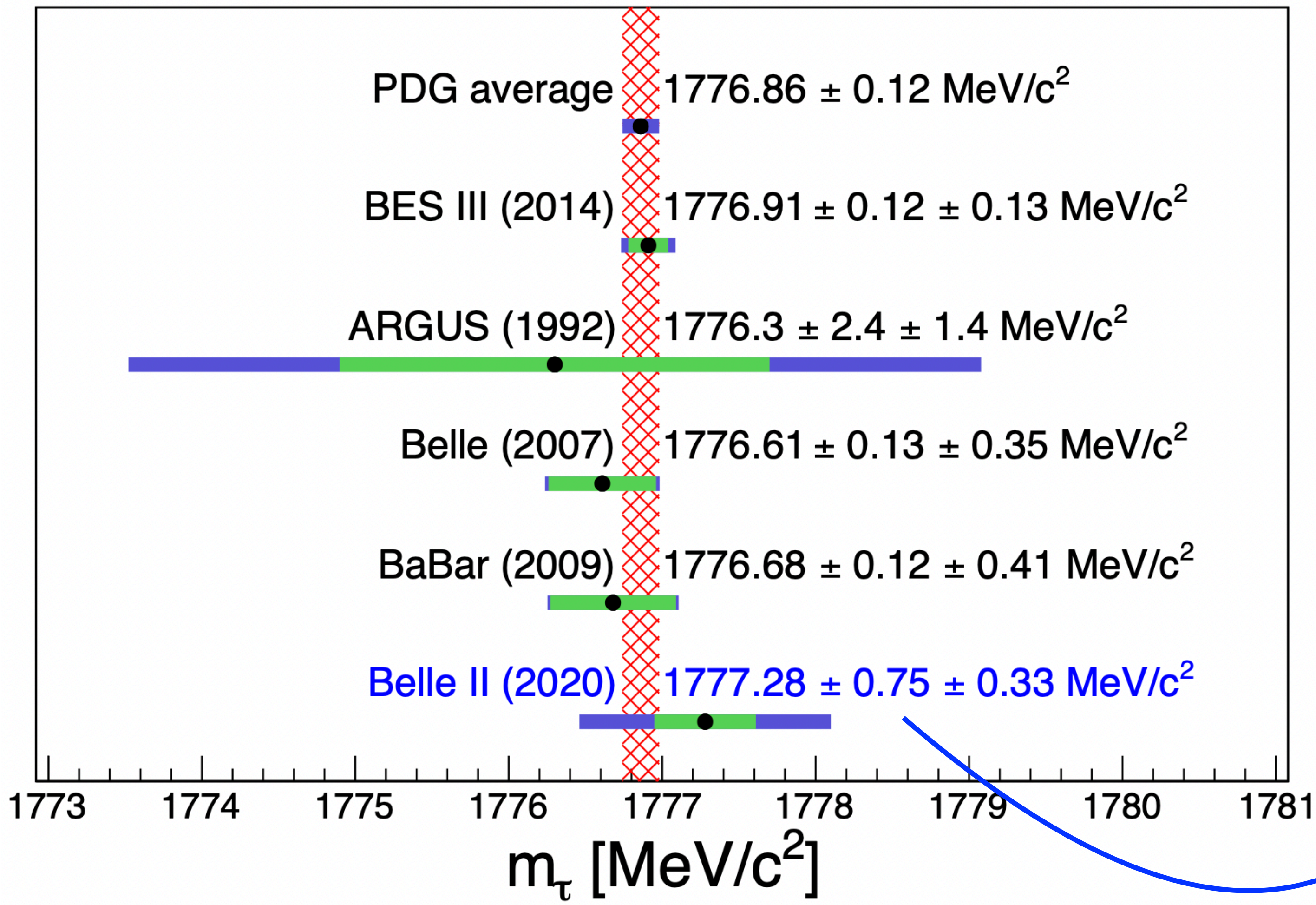
- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass.

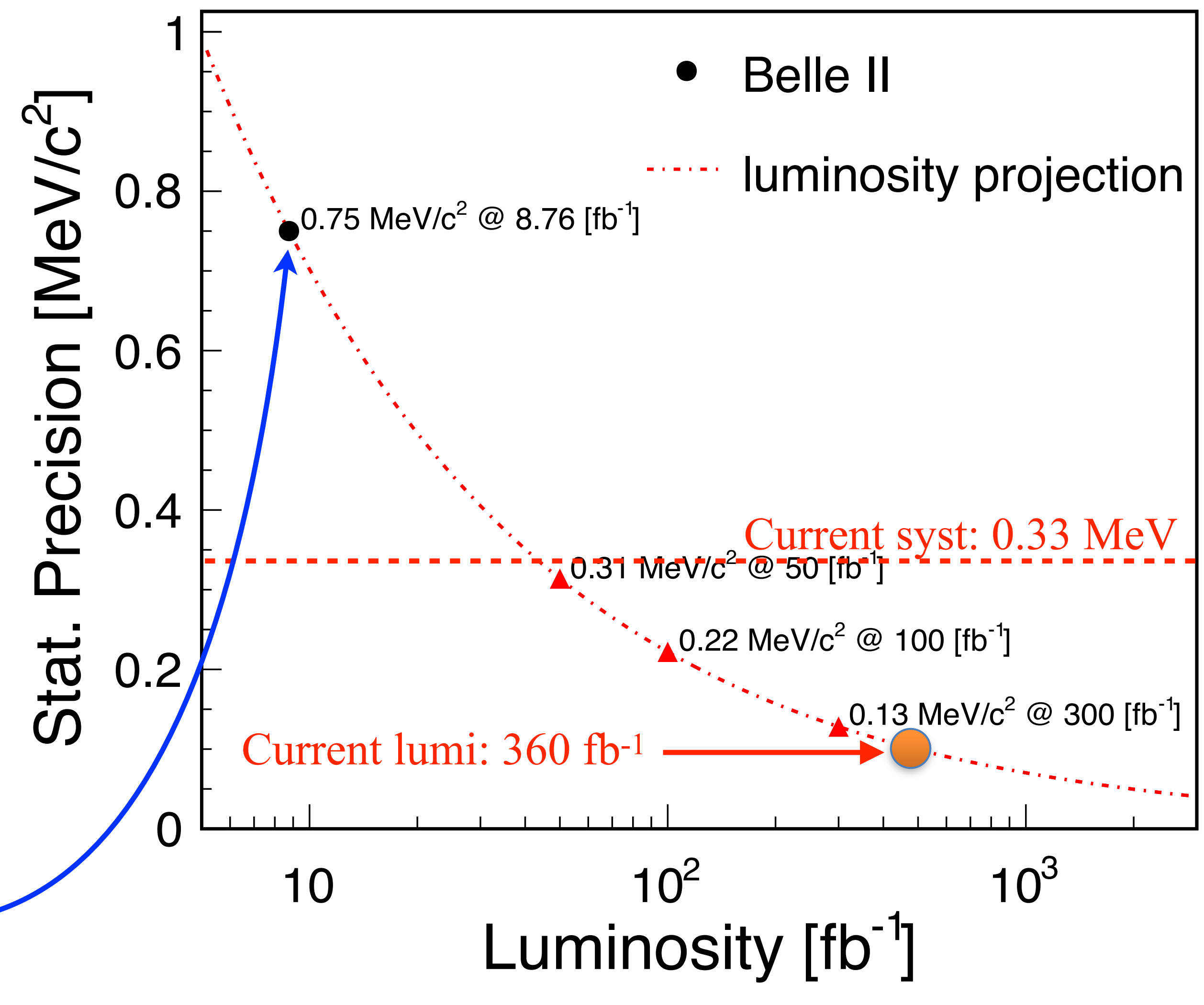
Tau Mass at Belle II

arXiv:2008.04665 **[hep-ex]**

Our result is still dominated by statistical uncertainty, and consistent with previous measurements:

We expect significant reduction in the main systematic uncertainties.





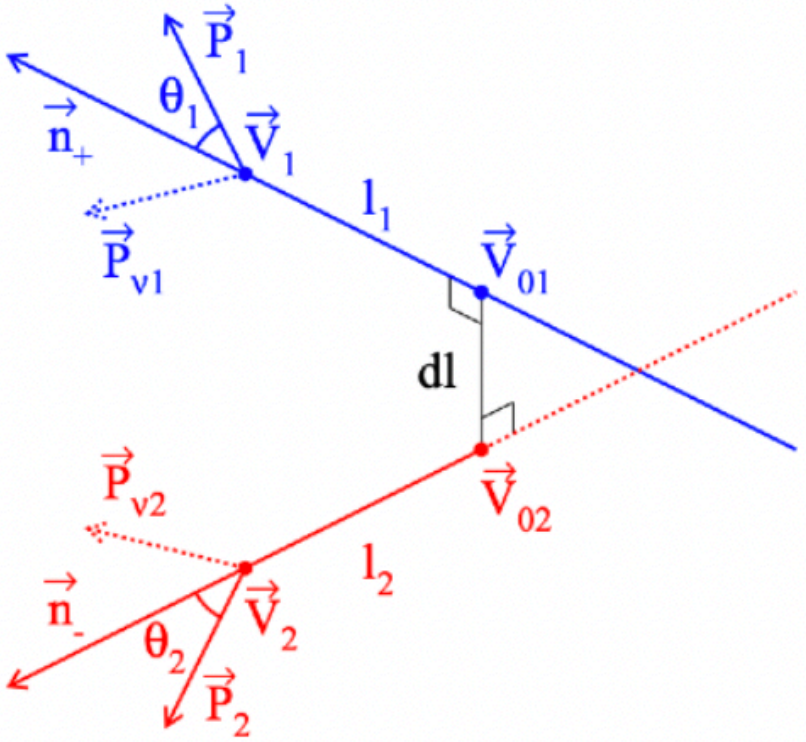
Blue: statistical; **Green: systematic**

Projection towards high luminosity

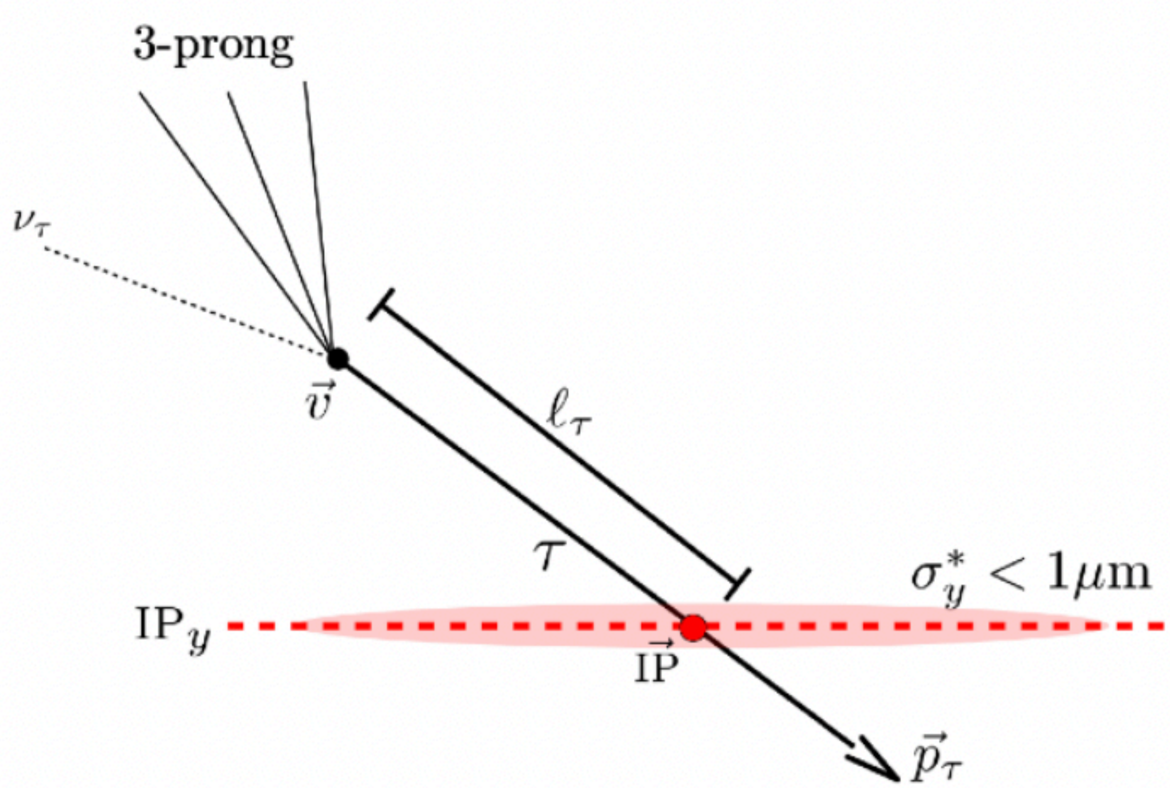
Tau Lifetime at Belle II

- The world-leading measurement by Belle[1] uses a **3x3 topology**, with both tau leptons decaying to $3\pi\nu_\tau$.
  - $\boldsymbol{\tau_\tau}$ **= 290.17 ± 0.53(stat) ± 0.33(syst) fs**

[1] PRL 112, 031801 (2014), arXiv:1310.8503 [hep-ex]



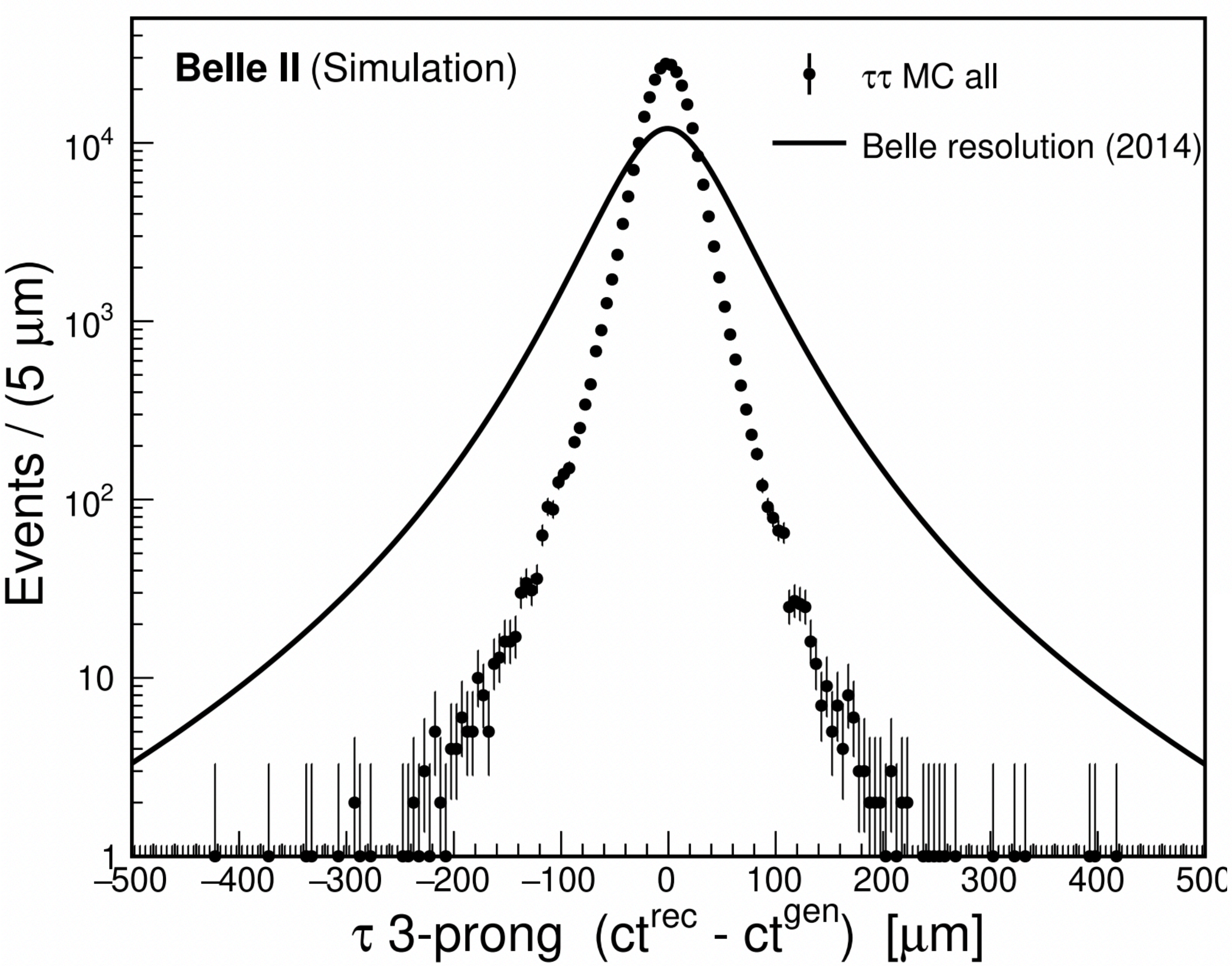
- **Strategy at Belle II:**
  1. Reconstruct vertex for 3-prong τ.
     Only one 3-prong = higher statistics.
  2. Estimate the τ momentum $\overrightarrow{p}_\tau$.
     Hadronic decays in both sides.
  3. Find the production vertex.
     Intersection of $\overrightarrow{p}_\tau$ with the plane IP_y.



Tau Lifetime at Belle II

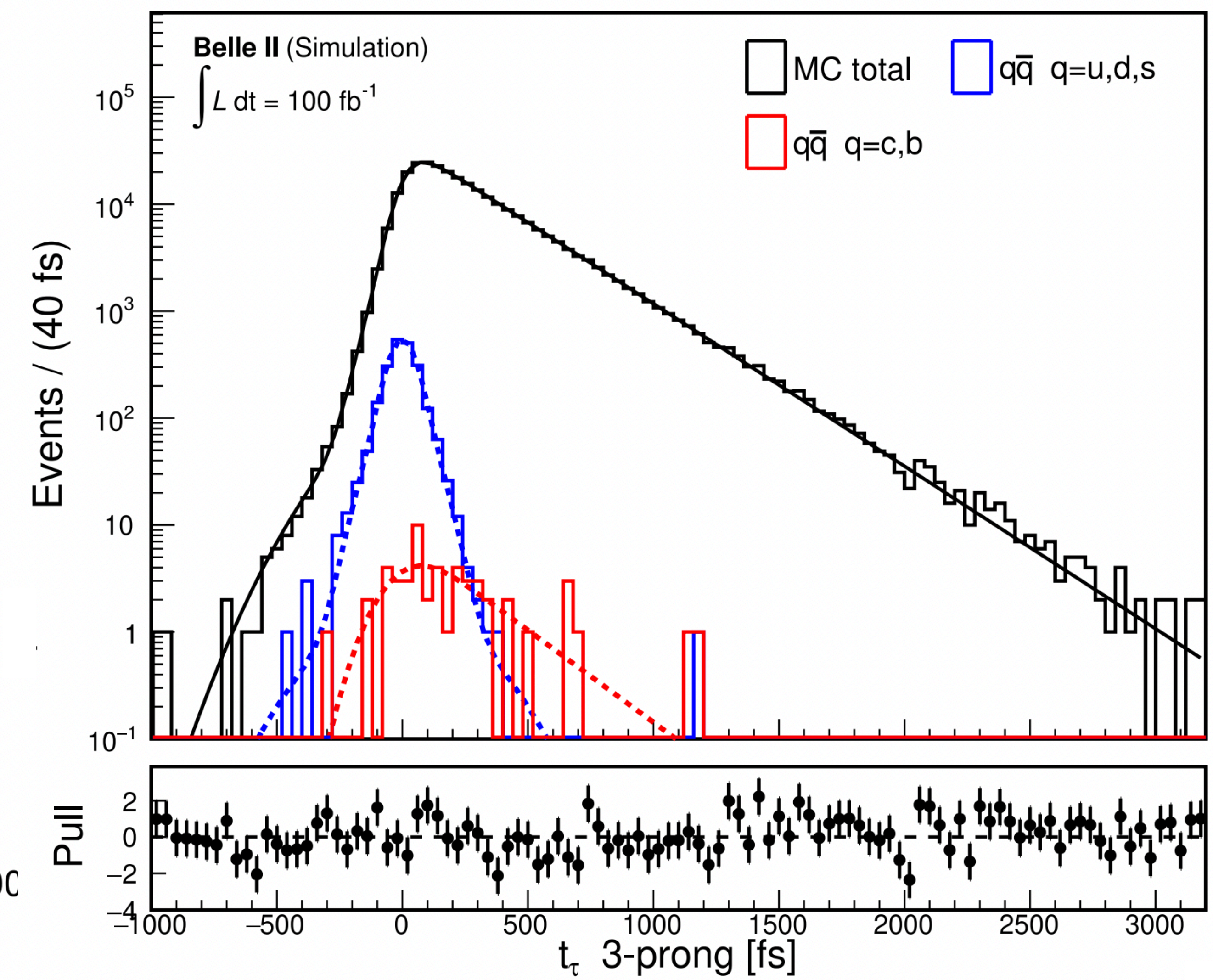
- In MC simulations, the Belle II proper time resolution is **~2x better than Belle.**
  - Due to PXD and smaller beam pipe diameter.

Proper decay time resolution:



Fit proper time distribution, subtracting $q\bar{q}$ backgrounds

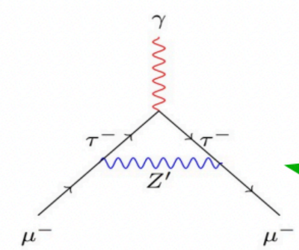
- Lifetime extraction:
  - $\boldsymbol{\tau_\tau}$ **= 287.2 ± 0.5 (stat) fs**
  - Same statistical uncertainty of Belle. (200 fb^{-1} vs 711 fb^{-1})



Lepton Flavor universality at Belle II

Lepton flavor violating Z' explanation of the muon anomalous magnetic moment

Wolfgang Altmannshofer[1], Chien-Yi Chen[2,3], P. S. Bhupal Dev[4], Amarjit Soni[5] arXiv:1607.06832 **[hep-ph]**



Z' contribution to the anomalous magnetic moment of the muon

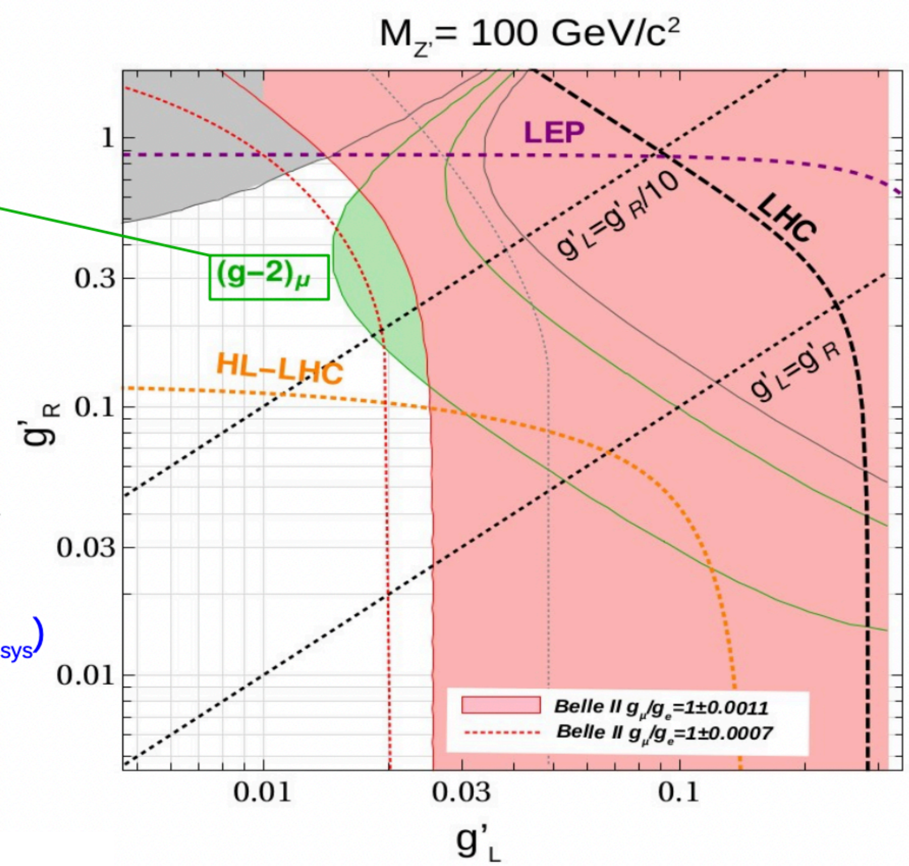
$$\frac{R_{\mu e}}{R_{\mu e}^{\rm SM}} = 1 + \frac{|g'_L|^2}{g_2^2}\frac{4m_W^2}{m_{Z'}^2} + \left(\frac{|g'_L g'_R|^2}{g_2^4} + \frac{|g'_L|^4}{g_2^4}\right)\frac{8m_W^4}{m_{Z'}^4}$$

BaBar: $R_{\mu e}$=0.976 ± 0.004(=0.0016$_{stat}$ ± 0.0036$_{sys}$)

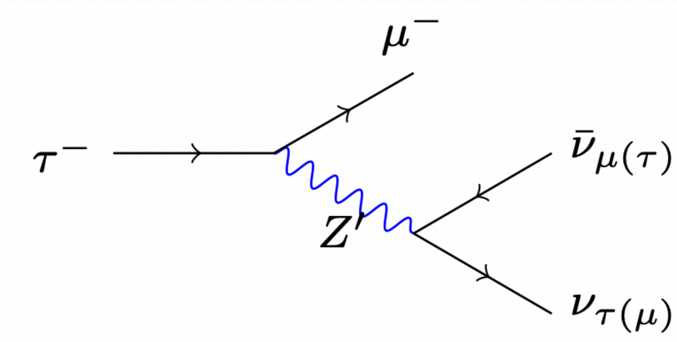
SM: $R_{\mu e}$=0.972559 ± 0.00005 (see here)

PDG: $R_{\mu e}$=0.979 ± 0.004

$R_{\mu e}^{PDG}/R_{\mu e}^{SM}$-1=0.0064±0.004



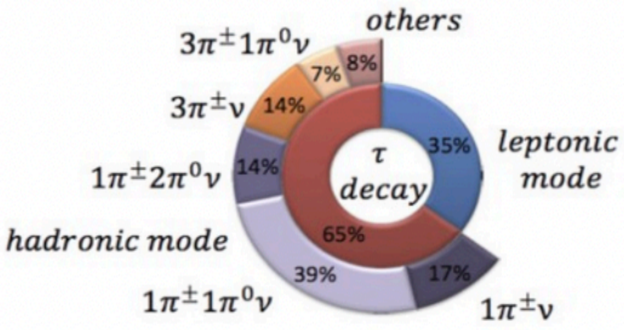
g'_R
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

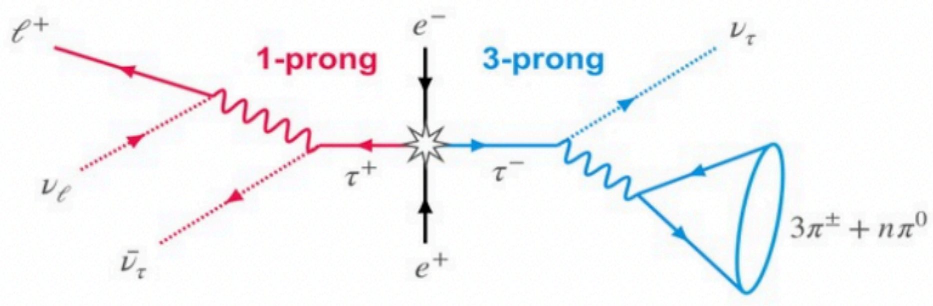


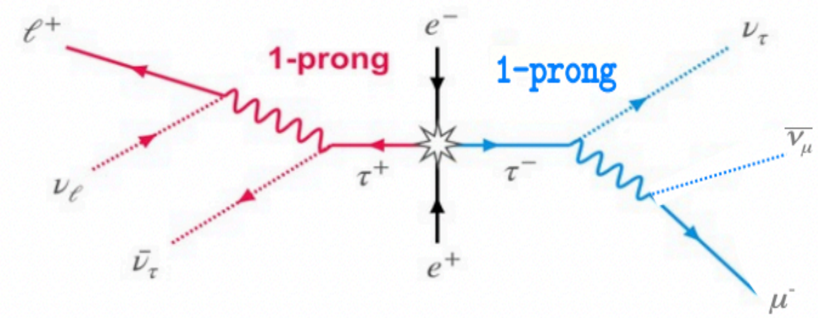
Feynman diagram for the Z' contribution to the lepton flavor universality violating tau decay.

Leptonic branching fractions

We plan to use both 3-prong (LFU+BF) and 1-prong (LFU) tag side







$$R_{\mu} \equiv \frac{\mathscr{B}(\tau^{-} \to \mu^{-}\bar{\nu}_{\mu}\nu_{\tau})}{\mathscr{B}(\tau^{-} \to e^{-}\bar{\nu}_{e}\nu_{\tau})}$$

Belle II will significantly improve the precision on inputs to lepton-flavor universality-violating quantities yielding some of the most stringent constraints on non-SM deviations from charged current lepton universality.

The $|V_{us}|$ element of CKM Matrix

V_{ij}: Mixing between Weak and Mass Eigenstates

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\left|V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 = 1$$

- $|V_{ud}| = 0.97373 \pm 0.00031$ (from nuclear β decays)

  J.C.Hardy & I.S.Towner, PRC 102 (2020) 045501

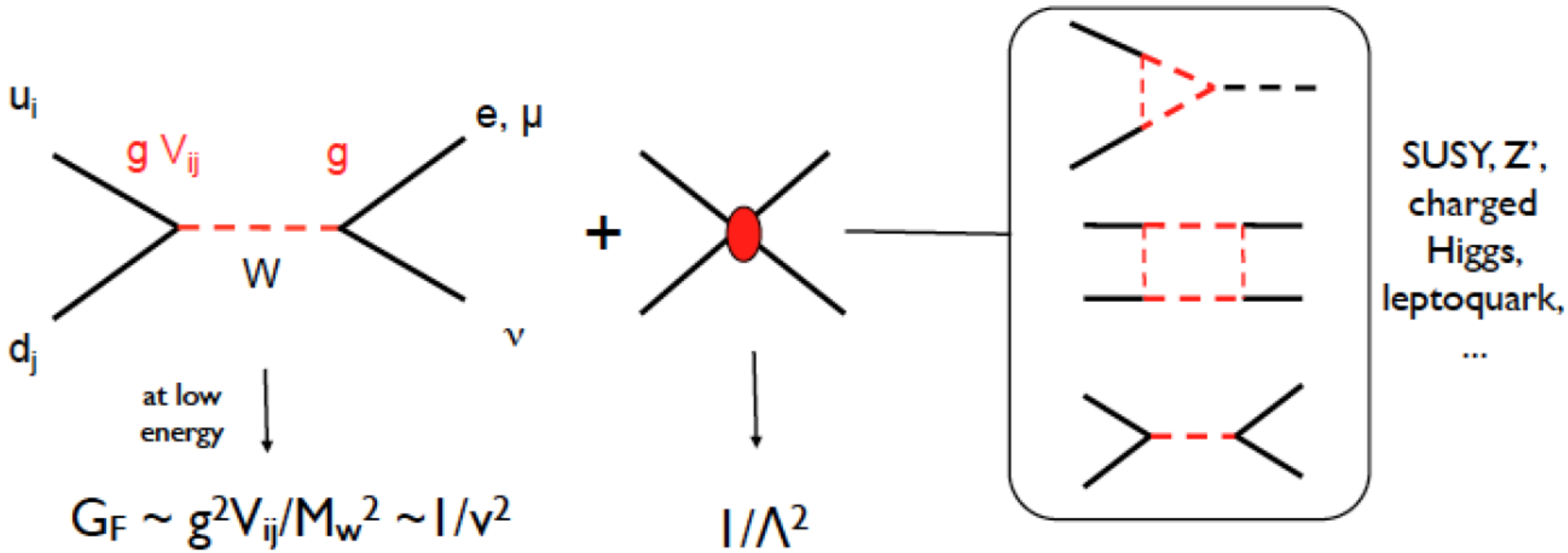
- $|V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$ (from $B \rightarrow X_u\, \ell\, \nu$ decays)

  Particle Data Group 2021

$\Rightarrow |V_{us}|^{CKM} = 0.2277 \pm 0.0013$

Precision measurement of $|V_{us}|$ is a test of CKM unitarity

V-A interaction via W-exchange with quarks have V_{ij}



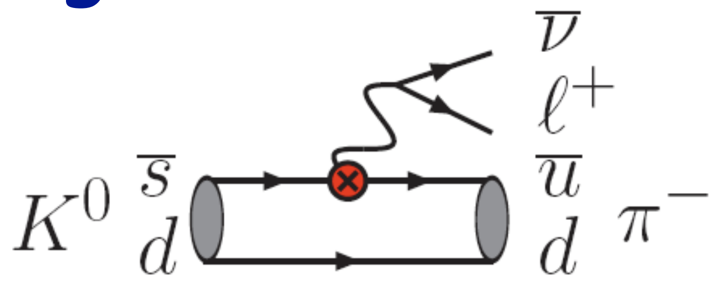
Standard Model

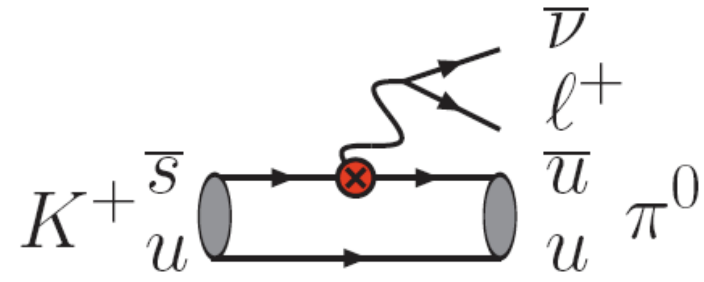
New Physics

$\Delta_{CKM} \sim (v/\Lambda)^2$ sensitive to new physics in large class of models

CKM Unitarity violation: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$

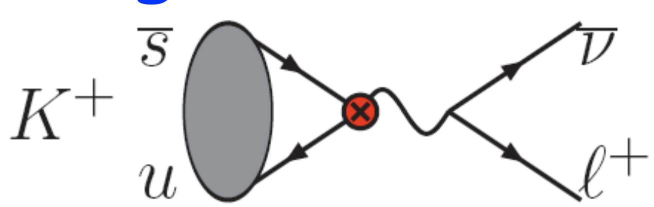
Kl3 decays:

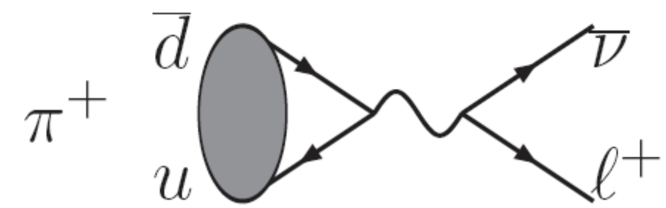




$\Rightarrow |V_{us}| f_+(0)$

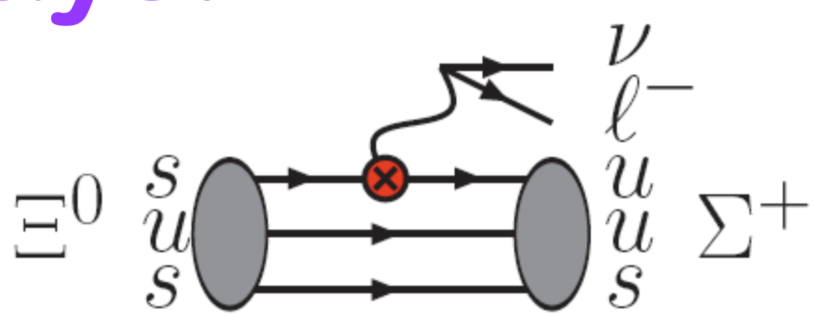
Kl2 decays:





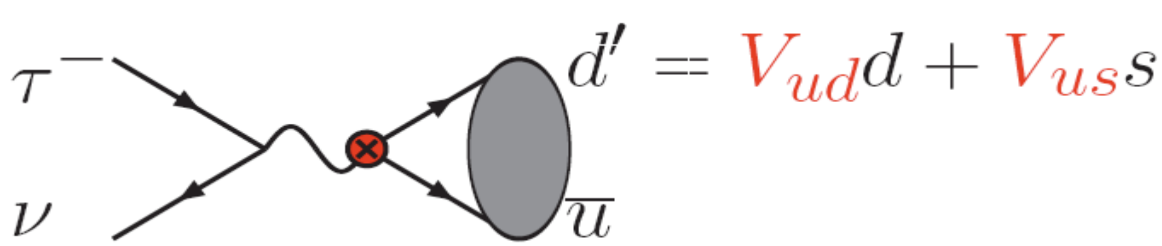
$\Rightarrow \frac{|V_{us}|}{|V_{ud}|} \frac{F_K}{F_\pi}$

Hyperon decays:



$\Rightarrow |V_{us}| f_1(0)$

τ decays:



$\Rightarrow m_s, |V_{us}|$

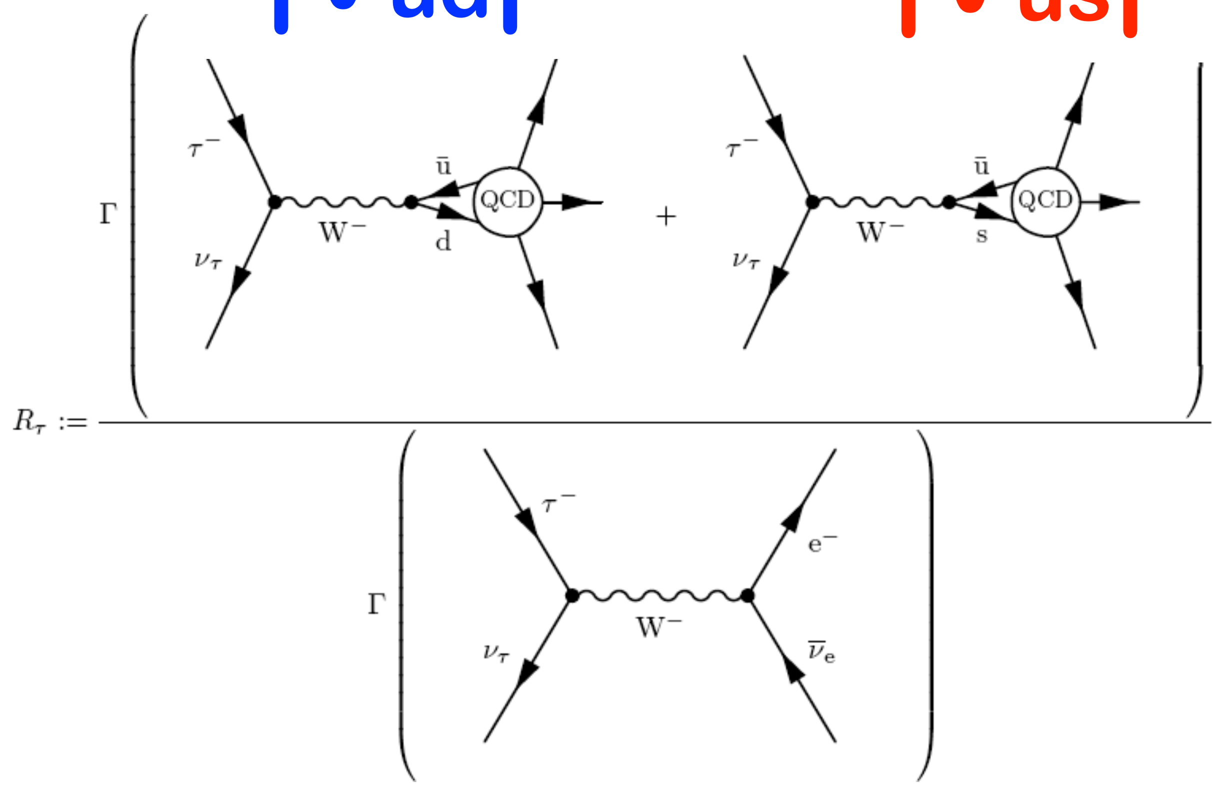
Parton model:

$$R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau e^- \bar{\nu}_e\right)} \approx N_C$$

QCD:

$$R_\tau = R_\tau^{NS} + R_\tau^{S} \approx |V_{ud}|^2 N_C + |V_{us}|^2 N_C$$

$\propto |V_{ud}|^2$ $\propto |V_{us}|^2$



Hadronic width of the τ lepton

QCD corrections : $R_\tau = |V_{ud}|^2 N_C + |V_{us}|^2 N_C + O(\alpha_s)$

Spectral Moments: $R_\tau^{kl} = \int_0^1 dz (1-z)^k z^l \frac{dR_\tau}{dz}, \quad z = \frac{q^2}{m_\tau^2}$

Zeroth order moments are simply the τ branching fractions

Finite energy sum rules ⇒ SU(3) breaking sensitive to m_s :

$$\delta R_\tau^{kl} = \frac{R_{\tau,non-strange}^{kl}}{|V_{ud}|^2} - \frac{R_{\tau,strange}^{kl}}{|V_{us}|^2}$$

$$\delta R_{\tau,\mathrm{th}}^{00} = 0.1544\,(37) + 9.3\,(3.4)\, m_s^2 + 0.0034\,(28) = 0.238 \pm 0.033$$

$$m_s = 93.00 \pm 8.54 \text{ MeV}$$ [PDG2020]

E.Gamiz, M.Jamin, A.Pich, J.Prades & F. Schwab, arXiv 0709.0282 [hep-ph]

Truncation errors studied with QCD lattice inputs in terms of weights:

$$|V_{us}| = \sqrt{R_{V+A;us}^{w}(s_0) / \left[\frac{R_{V+A;ud}^{w}(s_0)}{|V_{ud}|^2} - \delta R_{V+A}^{w,OPE}(s_0) \right]}$$

R. J. Hudspith, R. Lewis, K. Maltman, and J. Zanotti, arXiv:1702.01767 [hep-ph]

$|V_{us}|$ from inclusive strange decays

[Preliminary]

Table 13: HFLAV 2021 τ branching fractions to strange final states.

Branching fraction	HFLAV 2021 fit (%)
$K^-\nu_\tau$	0.6957 ± 0.0096
$K^-\pi^0\nu_\tau$	0.4322 ± 0.0148
$K^-2\pi^0\nu_\tau$ (ex.K^0)	0.0634 ± 0.0219
$K^-3\pi^0\nu_\tau$ (ex.K^0,η)	0.0465 ± 0.0213
$\pi^-\overline{K}^0\nu_\tau$	0.8375 ± 0.0139
$\pi^-\overline{K}^0\pi^0\nu_\tau$	0.3810 ± 0.0129
$\pi^-\overline{K}^0 2\pi^0\nu_\tau$ (ex.K^0)	0.0234 ± 0.0231
$\overline{K}^0 h^- h^- h^+\nu_\tau$	0.0222 ± 0.0202
$K^-\eta\nu_\tau$	0.0155 ± 0.0008
$K^-\pi^0\eta\nu_\tau$	0.0048 ± 0.0012
$\pi^-\overline{K}^0\eta\nu_\tau$	0.0094 ± 0.0015
$K^-\omega\nu_\tau$	0.0410 ± 0.0092
$K^-\phi(K^+K^-)\nu_\tau$	0.0022 ± 0.0008
$K^-\phi(K^0_S K^0_L)\nu_\tau$	0.0015 ± 0.0006
$K^-\pi^-\pi^+\nu_\tau$ (ex.K^0,ω)	0.2924 ± 0.0068
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex.K^0,ω,η)	0.0387 ± 0.0142
$K^-2\pi^-2\pi^+\nu_\tau$ (ex.K^0)	0.0001 ± 0.0001
$K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex.K^0)	0.0001 ± 0.0001
$X_s^-\nu_\tau$	2.9076 ± 0.0478

$$|V_{us}|_{\tau s} = \sqrt{R_s / \left[\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}}\right]}$$

$$B_s = (2.908 \pm 0.048)\%$$

$$B_{VA} = B_{\text{hadrons}} - B_s = (61.83 \pm 0.10)\%$$

To get R, we normalize by

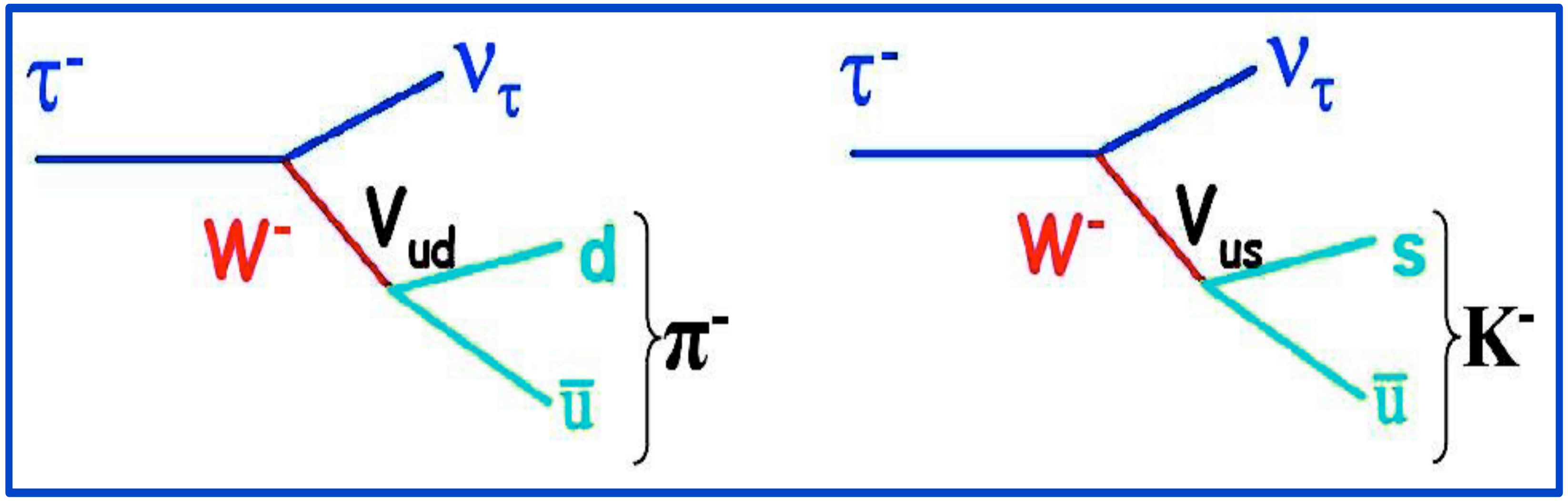
$$(B_e)^{univ} = (17.812 \pm 0.022)\%$$

The error on B_e is improved using lepton universality & improved measurements of mass (m_τ) and lifetime (τ_τ).

$$\Rightarrow |V_{us}| = (0.2184 \pm 0.0021)$$

Dominant contribution to error on $|V_{us}|$ comes from error on the measured B_s. δR_{theory} contributes to $\Delta|V_{us}| = 0.0011$.

$|V_{us}|$ from exclusive τ decays



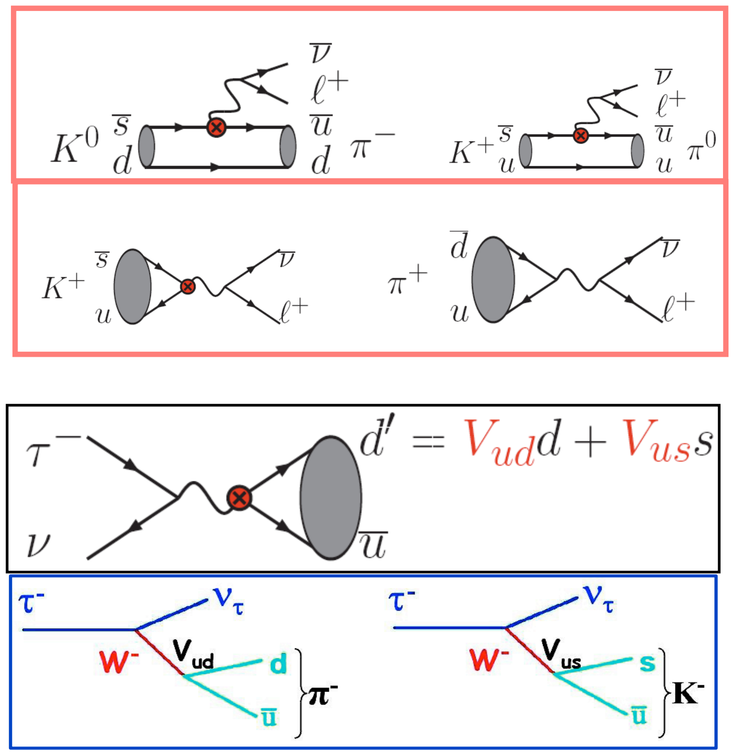
$$\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)} = \frac{f_{K\pm}^2 |V_{us}|^2}{f_{\pi\pm}^2 |V_{ud}|^2} \frac{\left(m_\tau^2 - m_K^2\right)^2}{\left(m_\tau^2 - m_\pi^2\right)^2} (1 + \delta R_{\tau K/\tau\pi})$$

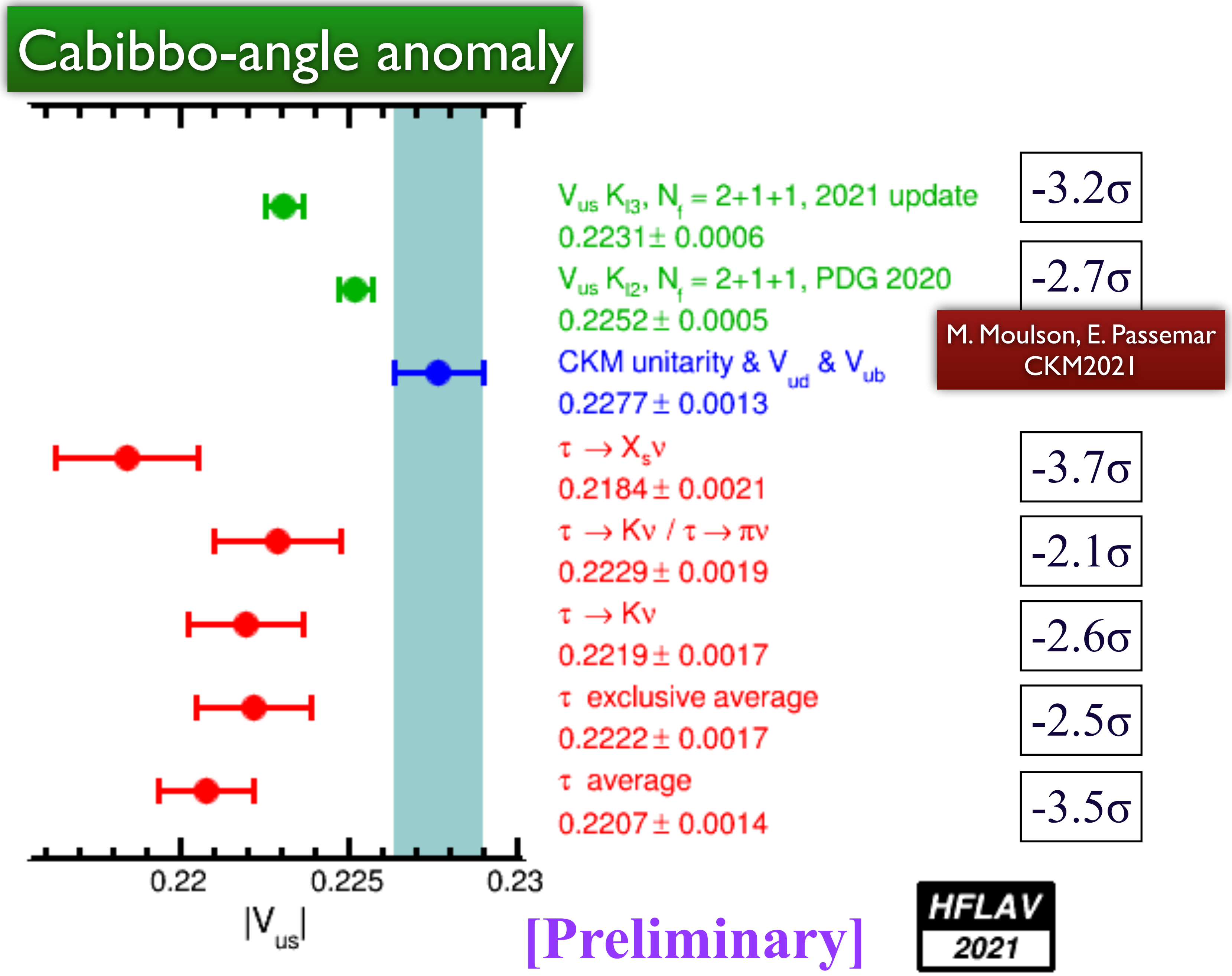
$$\mathcal{B}(\tau^- \to K^- \nu_\tau) = \frac{G_F^2}{16\pi\hbar} f_{K\pm}^2 |V_{us}|^2 \tau_\tau m_\tau^3 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}(1 + \delta R_{\tau K})$$

- Independent of convergence of OPE, as electroweak corrections cancel
- Radiative corrections $S_{EW} = 1.02320 \pm 0.00030$ [Erler 2004]
- Long Distance effects ($R_{\tau K/\tau\pi}$) known [Decker & Finkmeier 1995, Marciano 2004]
- All non-perturbative QCD effects encapsulated as ratio of meson decay constants:

$f_K/f_\pi = 1.1932 \pm 0.0021$, $f_K = 155.7 \pm 0.3$ MeV [FLAG 2019 Lattice Averages]

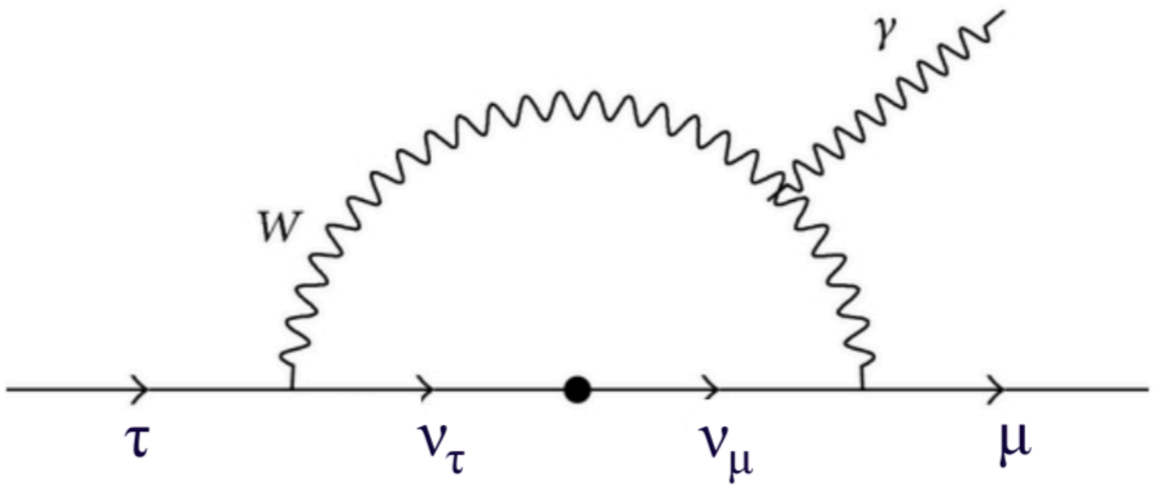
Summary of $|V_{us}|$ results





- $|V_{us}|$ from kaon and tau falls short of CKM unitarity value by ~3σ
- $|V_{us}|$ from inclusive tau decays independent of Lattice errors used for kaons
- New physics affecting 3rd generation only affects $|V_{us}|$ from taus
- Tau decays at Belle II offers unique and complementary insight

Search for lepton number/flavor violation in τ decays



$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$ [Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,{\rm eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,{\rm eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

LNV/LFV is NOT forbidden by any continuous symmetry

⇒ most New Physics (NP) models naturally include such processes

Any observation of LNV/LFV
⇒ unambiguous signature of NP

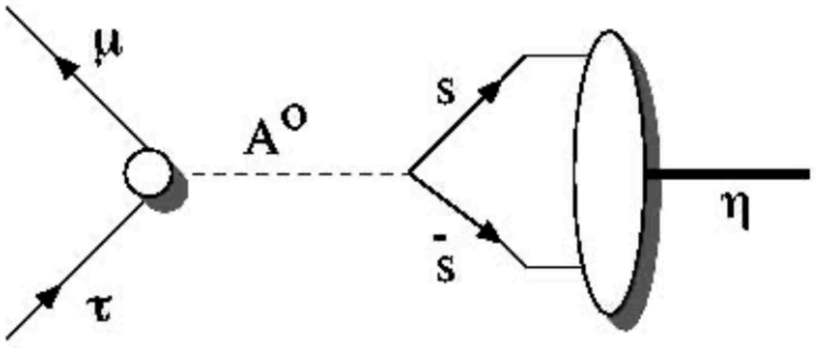
- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons
- Some models predict LFV up to existing experimental bounds
- eg. SUSY models: non-diagonal slepton mass matrix ⇒ LFV
- Normal (Inverted) hierarchy for slepton ⇒ $\tau \to \mu\gamma$ ($\tau \to e\gamma$)

New Physics expectations

- Neutrinoless 2 and 3 body τ decays have different sensitivity

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-8}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-8}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana $\nu_{\rm R}$ (PRD66(2002)034008)	10^{-9}	10^{-10}

- η final state enhanced due to color factor and Higgs-$s\bar{s}$ vertex



- MSSM + seesaw: (M.Sher, PRD66 (2002) 057301)

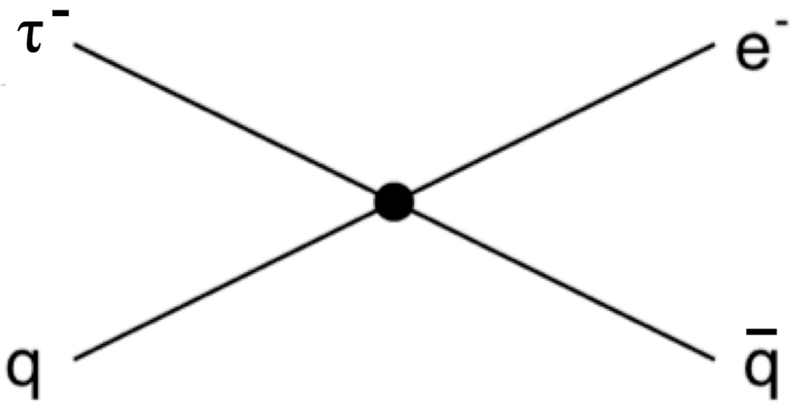
$$\mathcal{B}(\tau \to \mu\eta) = 0.84 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\ \mathrm{GeV}}{m_A}\right)^4$$

where m_A is the pseudoscalar Higgs mass and $\tan\beta = \langle \mathrm{H_u} \rangle / \langle \mathrm{H_d} \rangle$

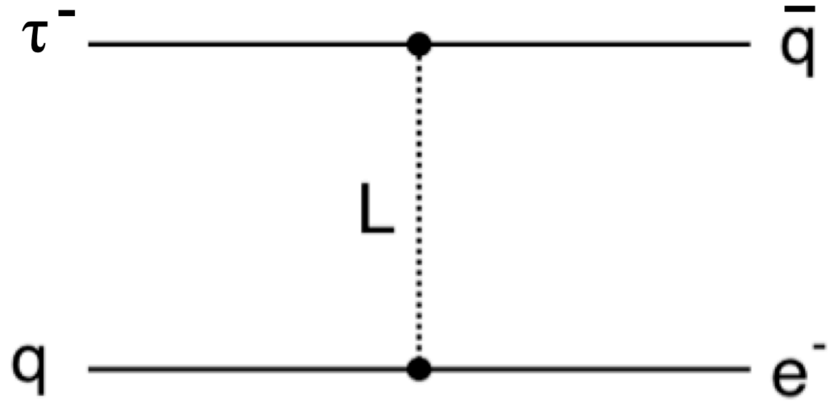
$$\Rightarrow \mathcal{B}(\tau \to \mu\eta) : \mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to \mu\mu\mu) = 8.4 : 1.5 : 1$$

New Physics expectations

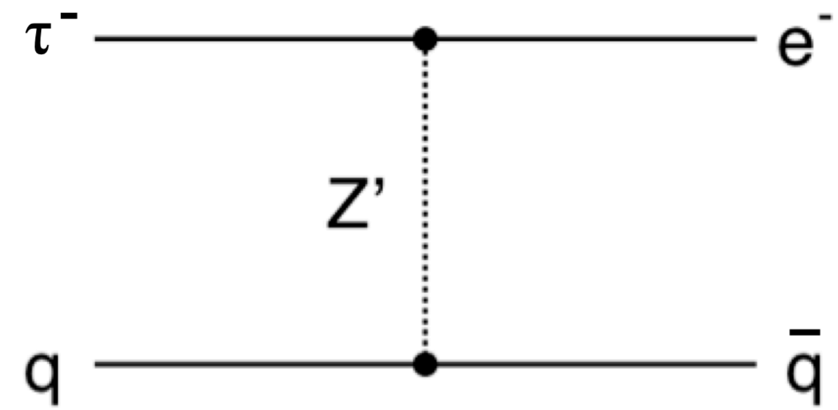
Tree level :



Compositeness

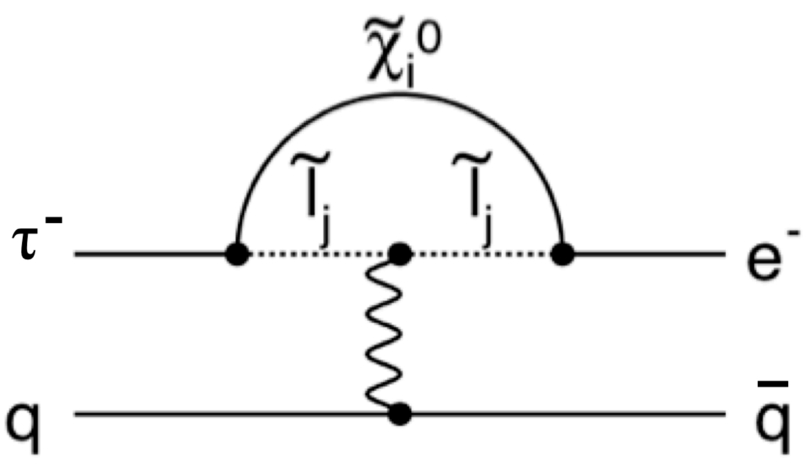


Leptoquarks

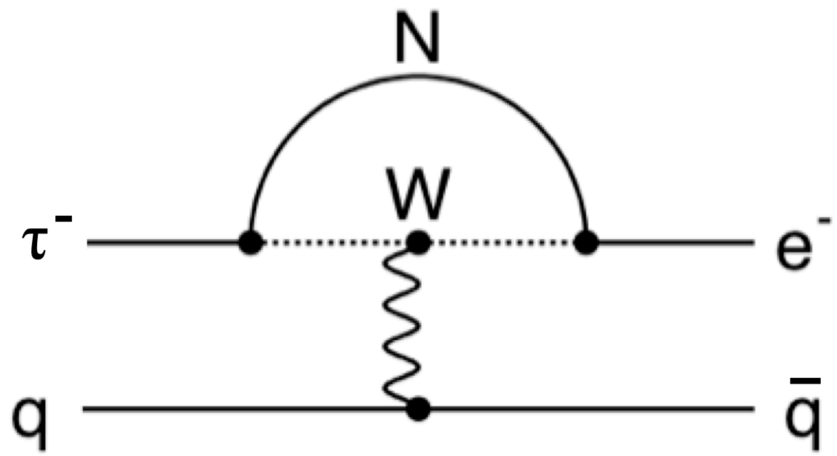


Heavy gauge bosons

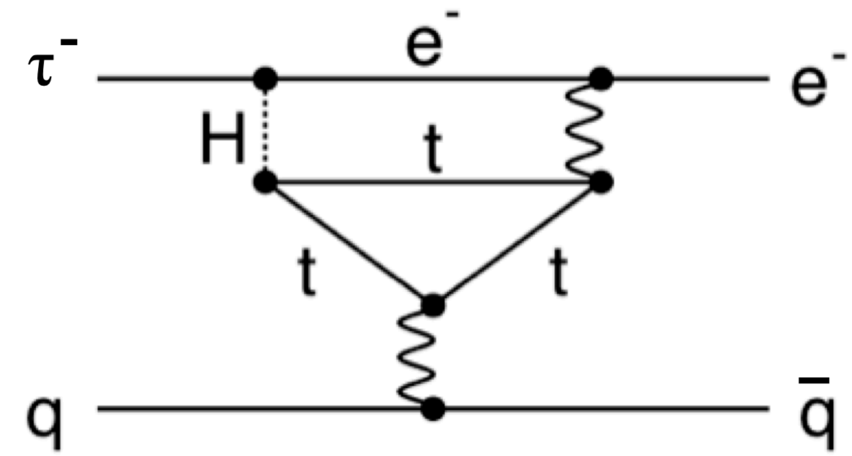
Loop induced :



Supersymmetry



Heavy neutrinos

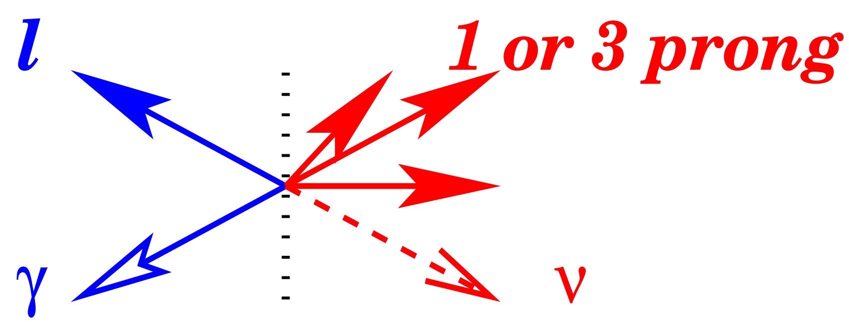


Extended Higgs models

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

- Known initial conditions (beam energy constraint)
- Clean environment (less backgrounds)

$\tau \to \ell\gamma$

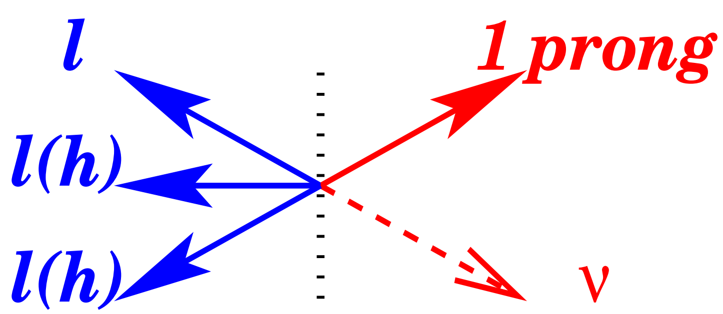


Signal–Side **Tag–Side**

Backgrounds:

- $\tau \to e\gamma$ $(\tau \to \mu\gamma)$:
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}$ (γ)

$\tau \to \ell\ell\ell$ $(\tau \to \ell h h')$



Signal–Side **Tag–Side**

Backgrounds:

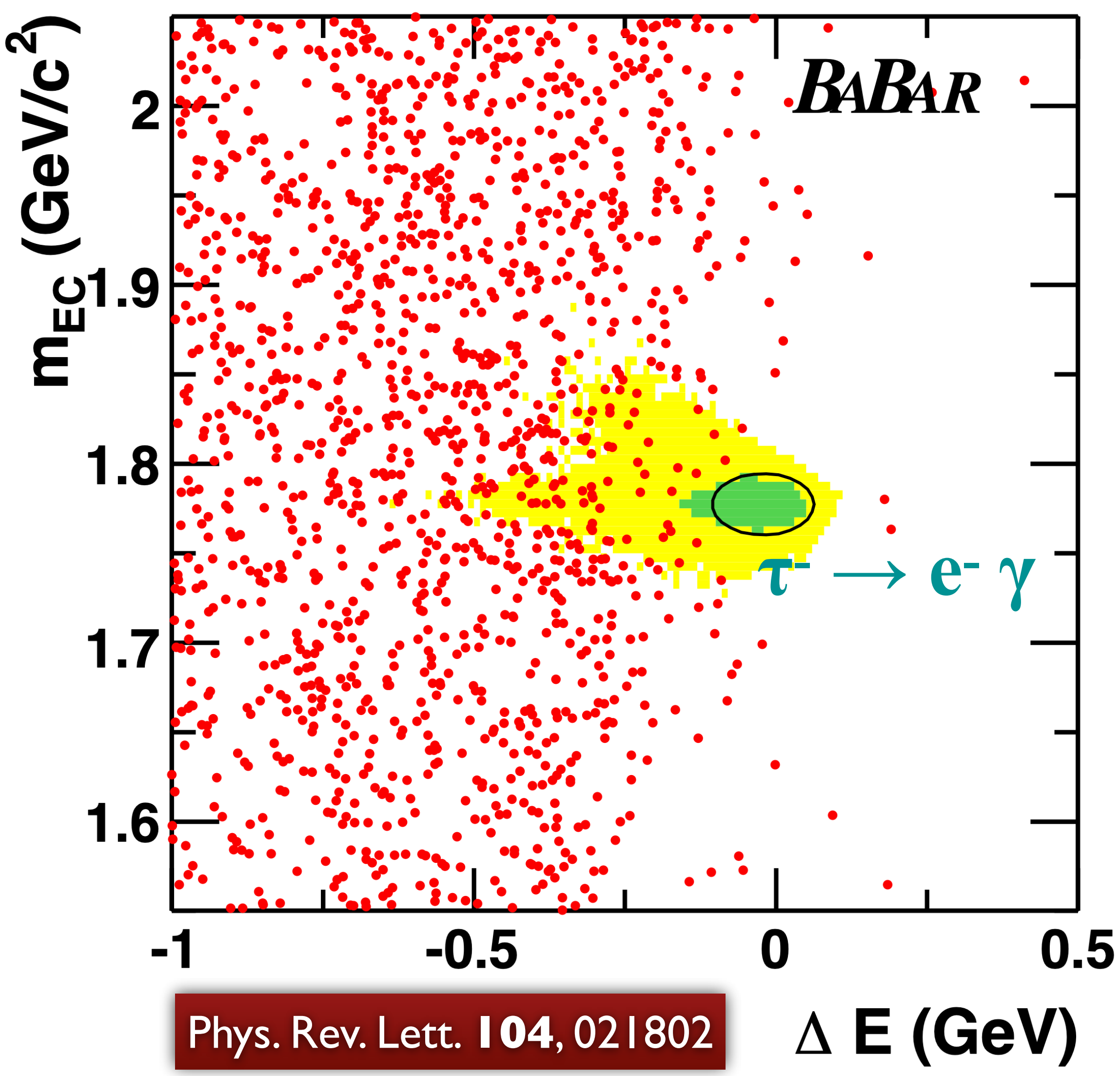
- $\tau^- \to \ell'^- \ell^+ \ell^-$:
  - Bhabha, di-muon
- $\tau^- \to \ell^+ \ell'^- \ell'^-$, $\tau \to \ell h h'$:
  - $\tau^+\tau^-$, $q\overline{q}$

# of ν(s) in Signal-side	Signal: 0	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0
# of ν(s) in Tag-side	Signal: 1-2	$\tau^+\tau^-$: 1-2	Bhabha, di-muon, $q\overline{q}$: 0

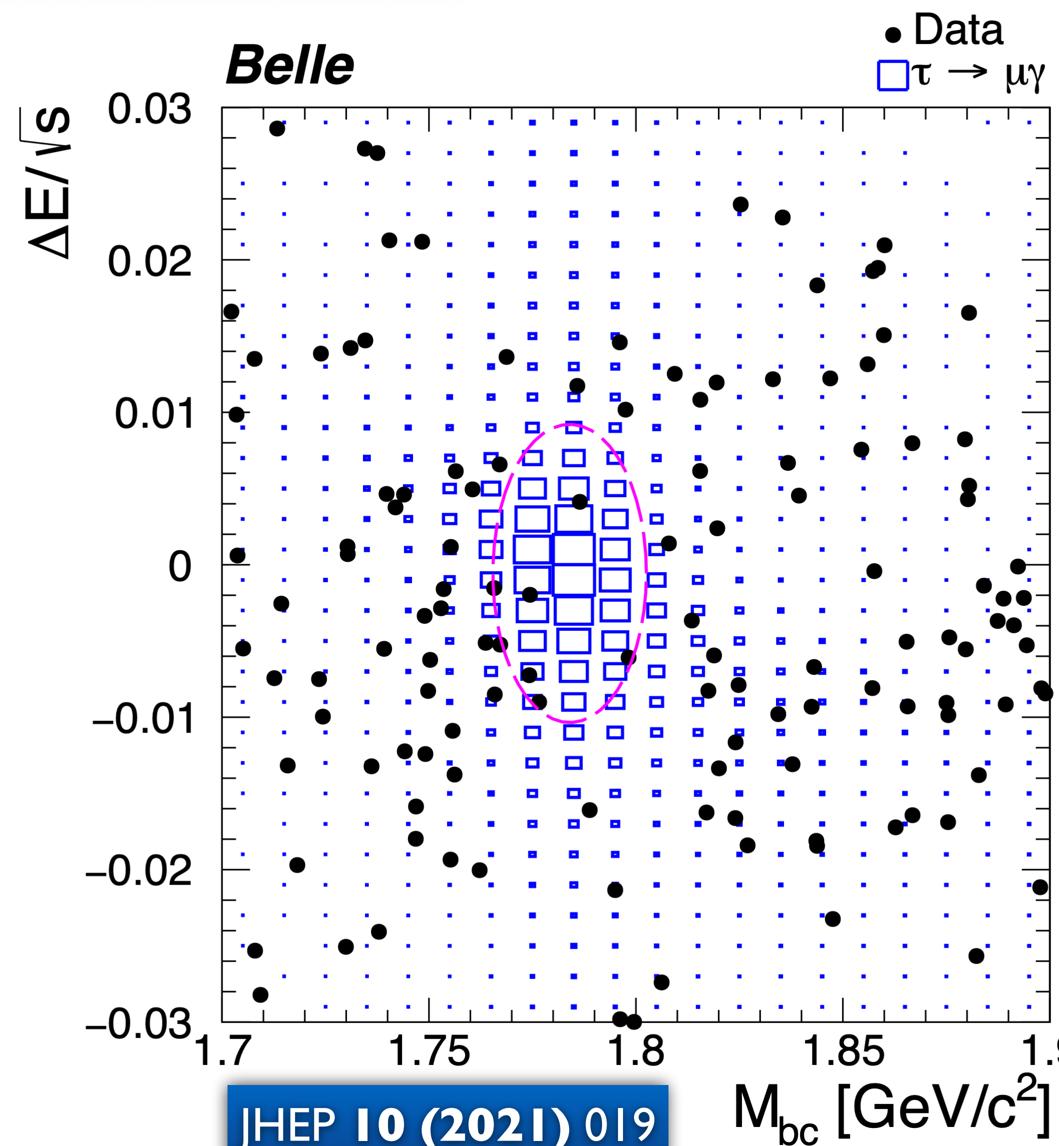
Signal characteristics

$$M_{bc} = \sqrt{(E_{beam}^{CM})^2 - |\vec{p}_{\ell\gamma}^{\,CM}|^2} \simeq m_\tau$$

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



Phys. Rev. Lett. **104**, 021802



JHEP **10 (2021)** 019

Upper limit estimation

$$B_{\rm UL}^{90} = N_{\rm UL}^{90}/(N_\tau \times \varepsilon)$$

- ε: high statistics signal MC simulated for different Data-taking periods

ε = Trigger . Reco . Topology . PID . Cuts . Signal–Box

Trigger	Reco	Topology	PID	Cuts	Signal–Box
90%	70%	70%	50%	50%	50%

Cumulative:

90%	63%	44%	22%	11%	~5%

Decay modes	2σ signal ellipse obs	2σ signal ellipse exp	ε (%)	UL ($\times 10^{-8}$) obs	UL ($\times 10^{-8}$) exp
$\tau^\pm \to e^\pm\gamma$	0	1.6 ± 0.4	3.9 ± 0.3	3.3	9.8
$\tau^\pm \to \mu^\pm\gamma$	2	3.6 ± 0.7	6.1 ± 0.5	4.4	8.2

BABAR

Phys. Rev. Lett. 104 (2010) 021802

$N_\tau = 963$ M

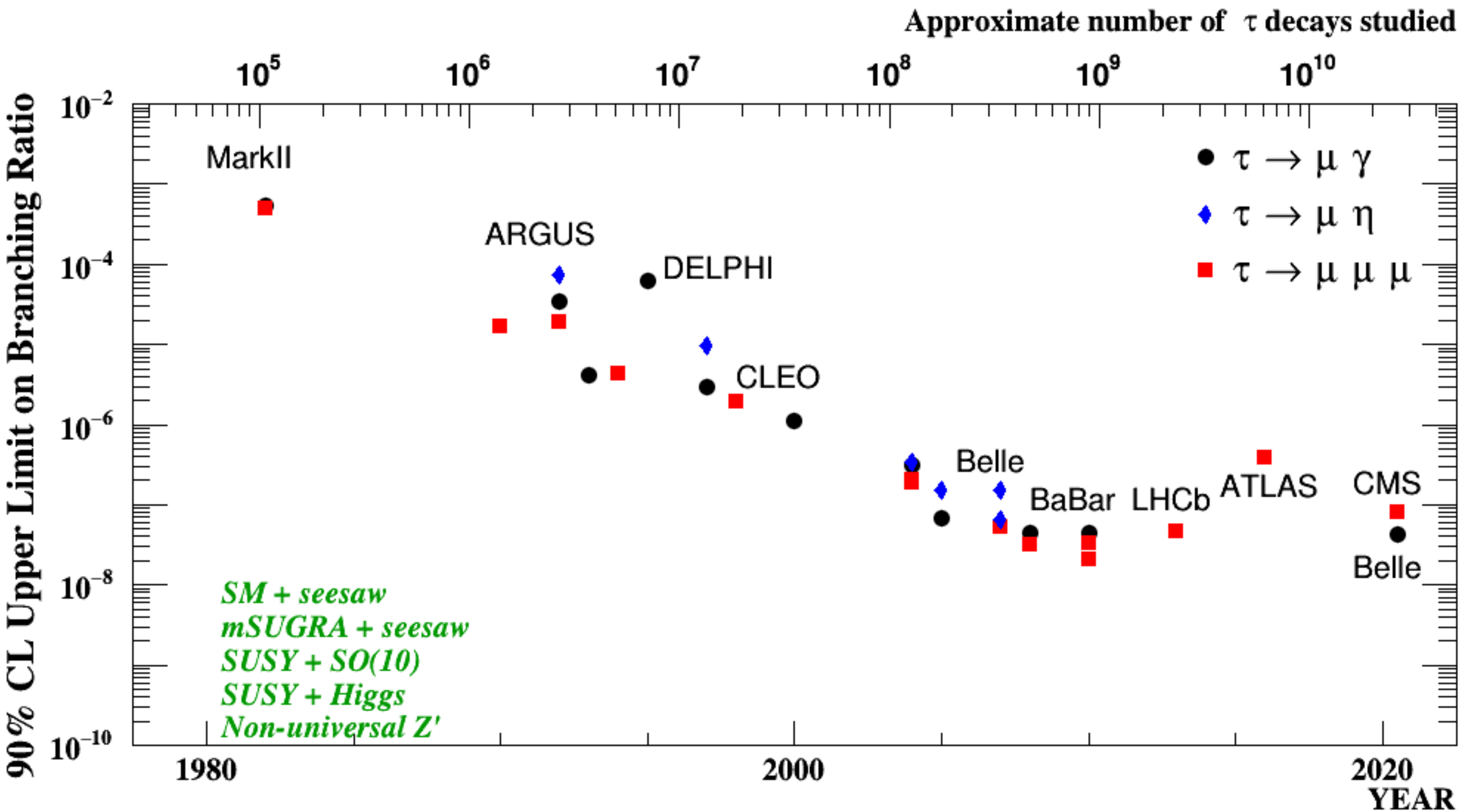
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^-e^+e^-$	6.0	0.21 ± 0.15	9.8	0	< 2.7
$\tau^- \to \mu^-\mu^+\mu^-$	7.6	0.13 ± 0.06	7.4	0	< 2.1
$\tau^- \to e^-\mu^+\mu^-$	6.1	0.10 ± 0.04	9.5	0	< 2.7
$\tau^- \to \mu^-e^+e^-$	9.3	0.04 ± 0.04	7.8	0	< 1.8
$\tau^- \to e^+\mu^-\mu^-$	10.1	0.02 ± 0.02	7.6	0	< 1.7
$\tau^- \to \mu^+e^-e^-$	11.5	0.01 ± 0.01	7.7	0	< 1.5

BELLE

Phys. Lett. B687 (2010) 139

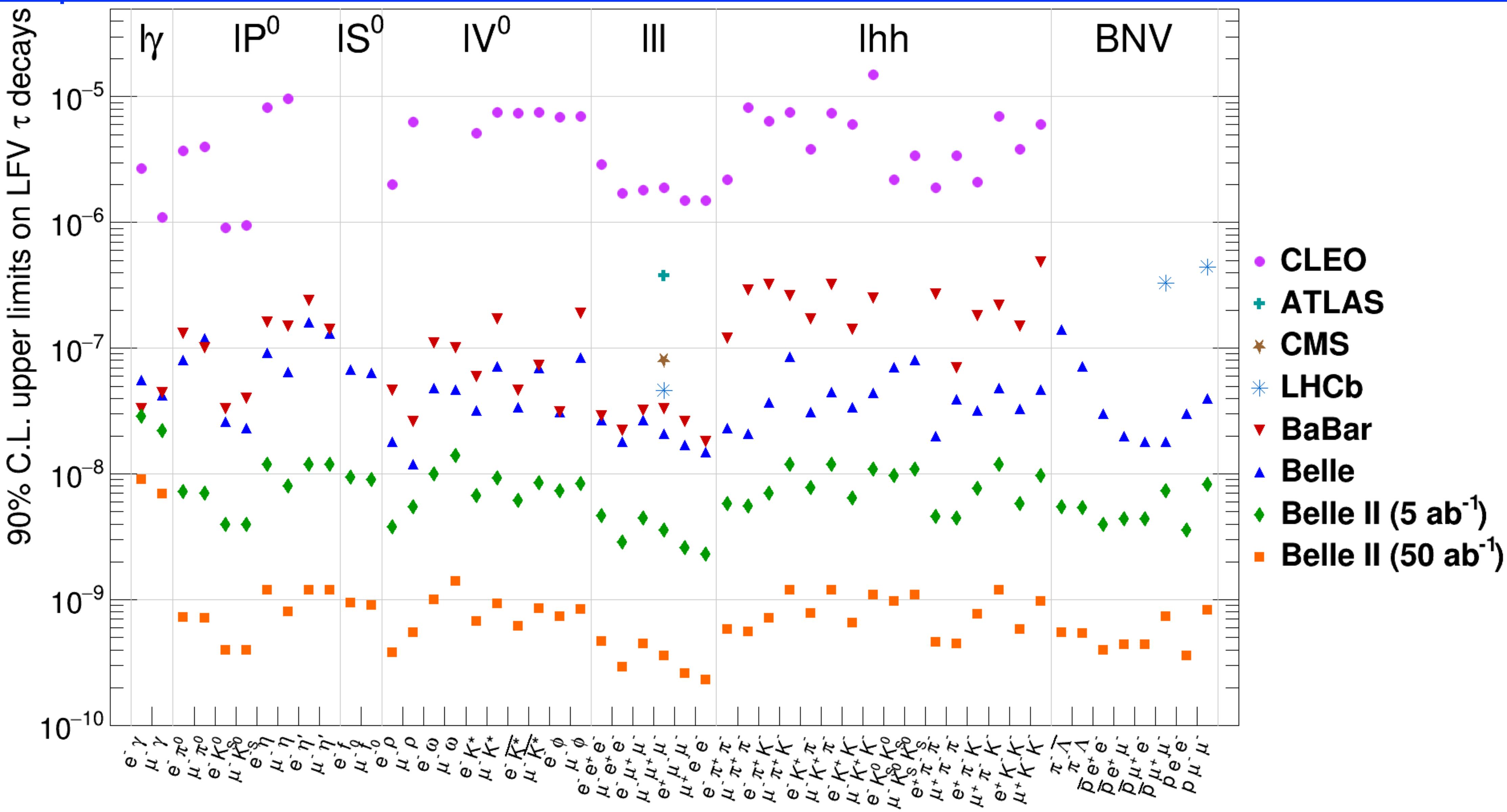
$N_\tau = 1438$ M

Current status of LFV limits



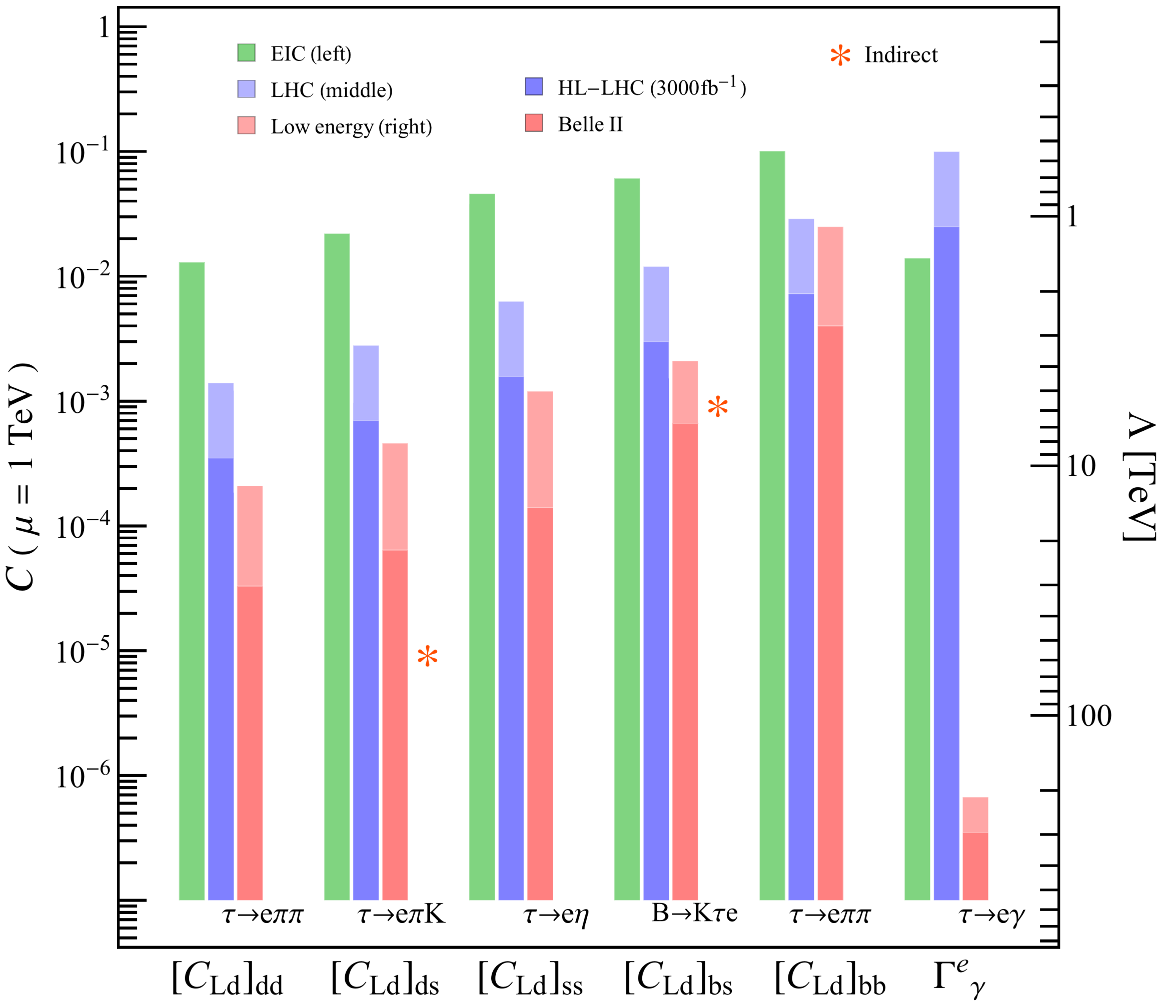
Current and future prospects

	Background limited search	*Background free search*
$N_{\rm UL}^{90}$	$\sqrt{\mathcal{L}}$	2.44 [Feldman – Cousins for $N_{obs} = 0$]
$B_{\rm UL}^{90}$	$\propto 1/\sqrt{\mathcal{L}}$	$\propto 1/\mathcal{L}$

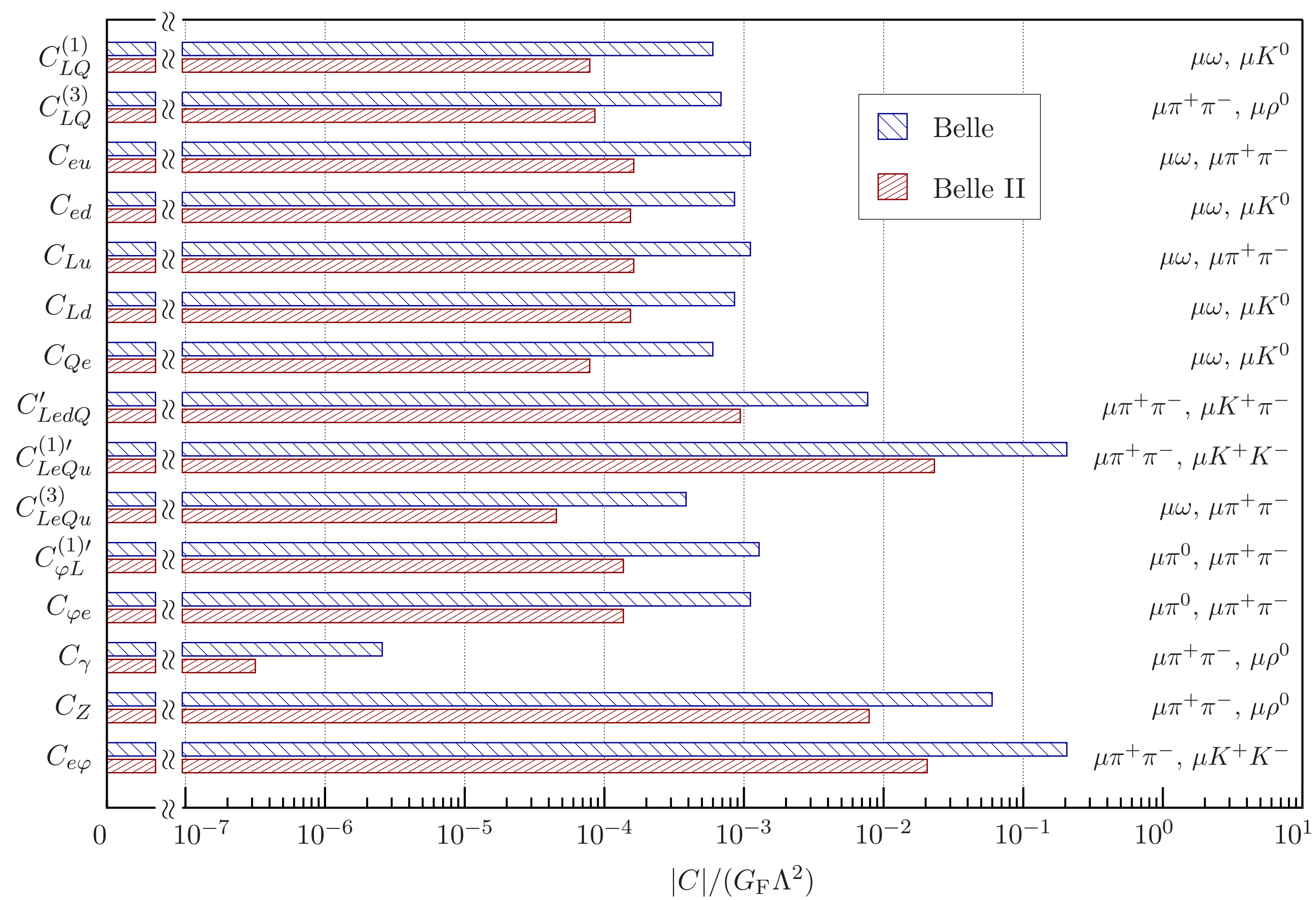


Synergy with other experiments

Model-independent probes of new physics at scale (Λ) encoded as Wilson coefficients (C_n) via EFT approach



Tau to electron transitions

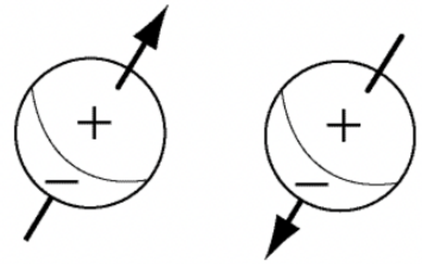


Tau to muon transitions

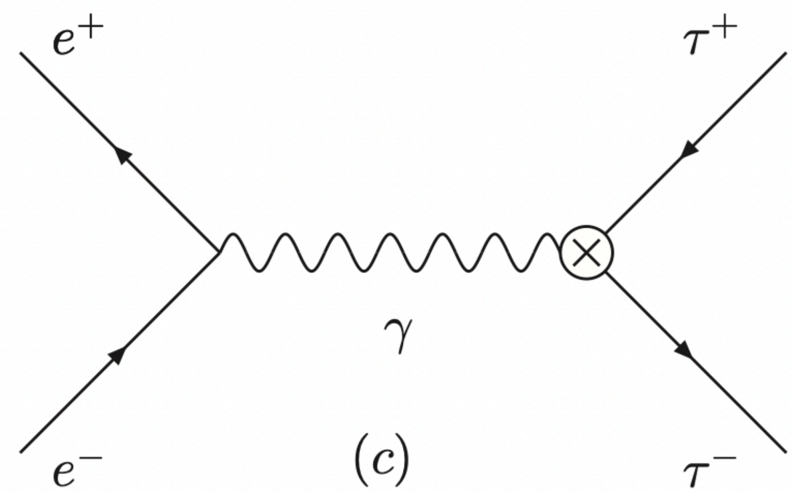
e-Print: 2203.14919 [hep-ph]

Electric dipole moment of τ

- Charge asymmetry along spin direction



- EDM $\neq 0 \Rightarrow$ P, T violation. Search for CP violation in $\tau^-\tau^+\gamma$ vertex.



- SM prediction $\simeq \mathcal{O}(10^{-37} e \cdot cm)$ far below experimental sensitivity
- New Physics contributions in loops can enhance EDM $\simeq \mathcal{O}(10^{-19} e \cdot cm)$

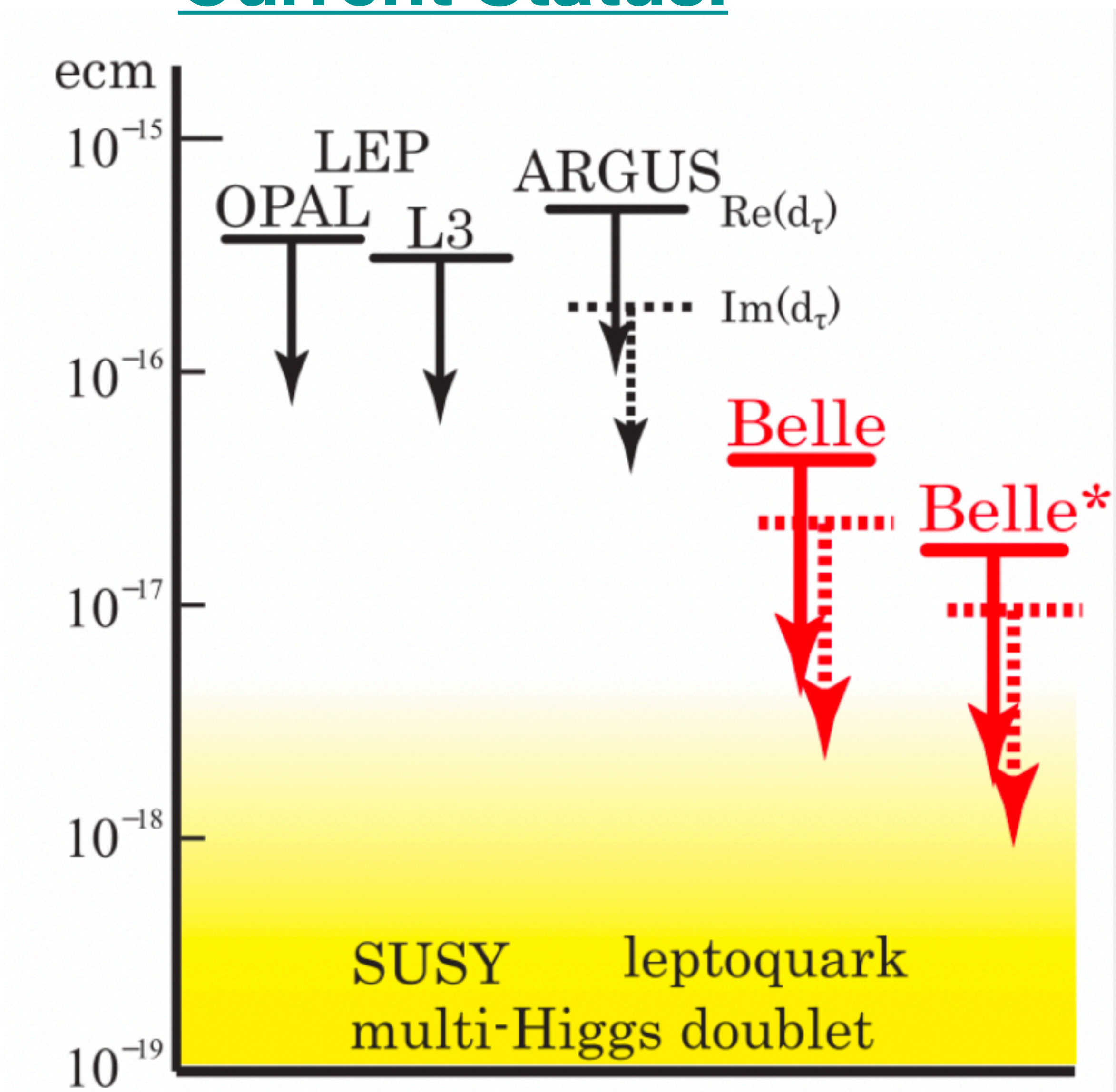
W. Bernreuther, A. Brandenburg, and P. Overmann, Phys. Lett. B 391, 413 (1997).

Huang, W. Lu, and Z. Tao, Phys. Rev. D 55, 1643 (1997).

- EDM $\neq 0 \Rightarrow$ unambiguous signature of New Physics

Electric dipole moment of τ

- **Current Status:**



– Belle; 29.5fb^{-1} data [PLB 551(2003)16]

$$-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\, e\, \mathrm{cm})$$
$$-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\, e\, \mathrm{cm})$$

- Belle; 833 fb^{-1} data (arXiv:2108.11543 **[hep-ex])**

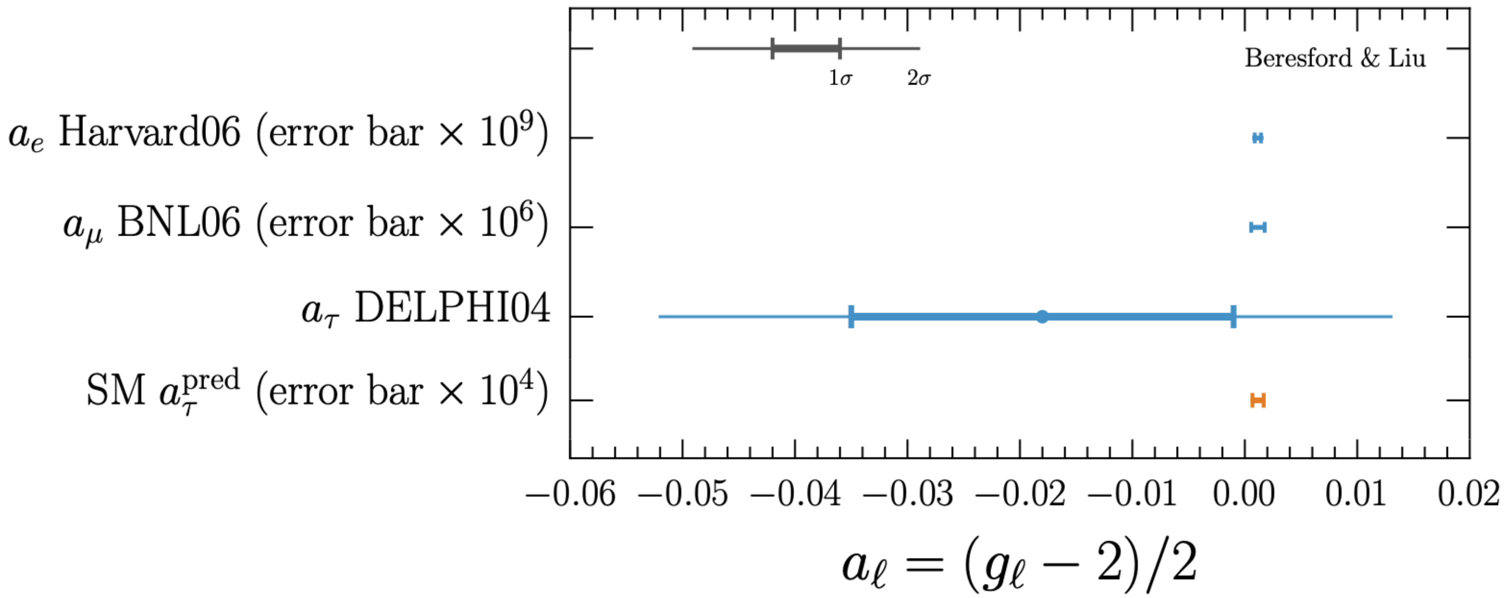
– 95% confidence intervals

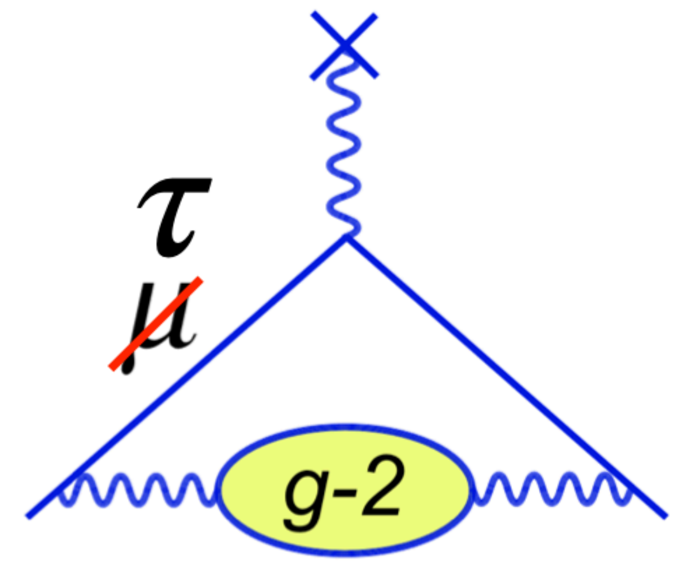
$$-1.85\times 10^{-17} < \mathrm{Re}(d_\tau) < 0.61\times 10^{-17}\ \mathrm{ecm},$$
$$-1.03\times 10^{-17} < \mathrm{Im}(d_\tau) < 0.23\times 10^{-17}\ \mathrm{ecm}.$$

- Consistent with zero EDM
- Systematic errors similar to statistical
- Dominant systematics: Data-MC mismatch in momentum/angular distributions

- **Future Projections:**
  - Preliminary studies at Belle II show much better control of data-MC mismatch
  - After improved control of systematics, extrapolation based on statistical errors only
  - Probe $\simeq \mathcal{O}(10^{-19} e\cdot cm)$ with 50 ab^{-1} data at Belle II.
  - Further improvement expected from proposed upgrade of polarized e- beams.

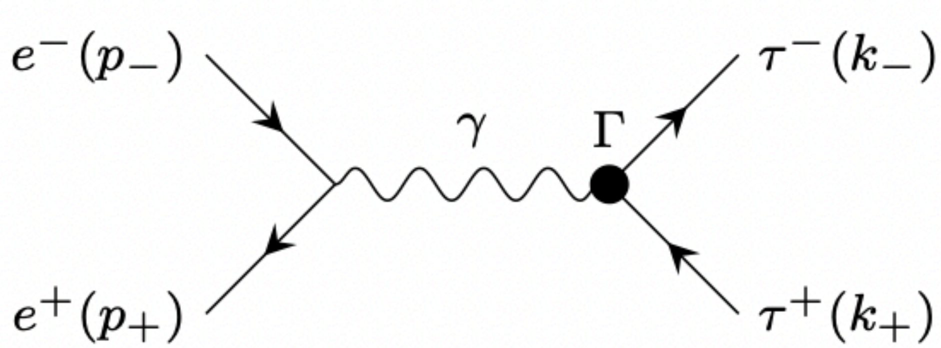
Magnetic dipole moment of τ





- Tensions are seen in electron and muon.
- Current bound in tau ~ 10^{-2} [DELPHI, Eur. Phys. J. C 35, 159 (2004)].
- Belle II will explore $(g\text{-}2)_\tau$. Polarized beam can enhance sensitivity.

EFT Extension for τ-Pair Production



$$q = k_+ + k_-; \quad q^2 \geq 4m_\tau^2 \quad e > 0; \quad \sigma^{\mu\nu} = \frac{\mathrm{i}}{2}[\gamma^\mu, \gamma^\nu]$$

$$\langle \tau^-(k_-), \tau^+(k_+), \mathrm{out} | J^\mu_{\mathrm{em}} | 0 \rangle = -e\bar{u}(k_-)\Gamma^\mu v(k_+)$$

$$\Gamma^\mu = \underbrace{F_1(q^2)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2(q^2)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3(q^2)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

$F_1(q^2)$, $F_2(q^2)$ are called the Dirac and Pauli; $\quad F_1(0) = 1; \quad F_2(0) = a_\tau$

Magnetic dipole moment of τ

4.1. Transverse asymmetry

To get an observable sensitive to the relevant signal define the azimuthal transverse asymmetry as

$$A_T^{\pm} = \frac{\sigma_R^{\pm}|_{\text{Pol}} - \sigma_L^{\pm}|_{\text{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3\pi}{8(3-\beta^2)\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\text{Re}\{F_2\}\right], \quad (29)$$

where

$$\sigma_L^{\pm}|_{\text{Pol}} \equiv \int_{\pi/2}^{3\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\text{Pol}(e^-)}\right]$$
$$= \pm\text{Br}(\tau^+ \to h^+\bar{\nu}_\tau)\,\text{Br}(\tau^- \to h^-\nu_\tau) \times \alpha_{\pm}\frac{(\pi\alpha)^2\beta}{8s}\frac{1}{\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\text{Re}\{F_2\}\right], \quad (30)$$

$$\sigma_R^{\pm}|_{\text{Pol}} \equiv \int_{-\pi/2}^{\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\text{Pol}(e^-)}\right] = -\sigma_L^{\pm}|_{\text{Pol}}. \quad (31)$$

4.2. Longitudinal asymmetry

Then, we define the longitudinal asymmetry as

$$A_L^{\pm} = \frac{\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}} - \sigma_{\text{FB}}^{\pm}(-)|_{\text{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3}{4(3-\beta^2)}\left[|F_1|^2 + 2\,\text{Re}\{F_2\}\right], \quad (34)$$

where

$$\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}} \equiv \int_0^1 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\text{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\text{Pol}(e^-)}$$
$$= \mp\alpha_{\pm}\,\text{Br}(\tau^+ \to h^+\bar{\nu}_\tau)\,\text{Br}(\tau^- \to h^-\nu_\tau)\frac{\pi\alpha^2}{4s}\beta\left[|F_1|^2 + 2\,\text{Re}\{F_2\}\right], \quad (35)$$

$$\sigma_{\text{FB}}^{\pm}(-)|_{\text{Pol}} \equiv \int_{-1}^0 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\text{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\text{Pol}(e^-)} = -\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}}. \quad (36)$$

Tau anomalous magnetic moment form factor at super B/flavor factories

J. Bernabéu [a,b], G.A. González-Sprinberg [c], J. Papavassiliou [a,b], J. Vidal [a,b,*]

Combining Eq. (29) and Eq. (34) one can determine the real part of $F_2(s)$.

$$\text{Re}\{F_2(s)\} = \mp\frac{8(3-\beta^2)}{3\pi\gamma\beta^2}\frac{1}{\alpha_{\pm}}\left(A_T^{\pm} - \frac{\pi}{2\gamma}A_L^{\pm}\right).$$

Nucl.Phys.B790:160-174,2008

TABLE II: Contributions to Re $F_2^{\text{eff}}(s)$ in units of 10^{-6}.

	$s = 0$	$s = (10\,\text{GeV})^2$
1-loop QED	1161.41	−265.90
e loop	10.92	−2.43
μ loop	1.95	−0.34
2-loop QED (mass independent)	−0.42	−0.24
HVP	3.33	−0.33
EW	0.47	0.47
total	1177.66	−268.77

Andreas Crivellin, Martin Hoferichter, J. Michael Roney

arXiv:2111.10378 **[hep-ph]**

Precision $\simeq \mathcal{O}(10^{-5})$ with 40 ab^{-1} of data with polarized beam

Second class currents

Hadronic current in τ decays: $J_h{}^\mu = \langle 0|V^\mu - A^\mu|u\bar{d}\rangle$

Charge Conjugation: $\langle 0|V^\mu|u\bar{d}\rangle \xrightarrow{C} -\langle 0|V^\mu|u\bar{d}\rangle$ $\langle 0|A^\mu|u\bar{d}\rangle \xrightarrow{C} \langle 0|A^\mu|u\bar{d}\rangle$

Isospin Rotation: $R(u\bar{d}) : e^{i\pi I_2}|\pi^+\rangle = (-1)^I|\pi^-\rangle = -|\pi^-\rangle$

G-Parity combines C & R: $\langle 0|V^\mu|u\bar{d}\rangle \xrightarrow{G} \langle 0|V^\mu|u\bar{d}\rangle$ $\langle 0|A^\mu|u\bar{d}\rangle \xrightarrow{G} -\langle 0|A^\mu|u\bar{d}\rangle$

Classification of weak currents according to their G parity

Current Class	Vector	Axial Vector
First	$G = +1$	$G = -1$
Second	$G = -1$	$G = +1$

S. Weinberg, Phys. Rev. 112, 1375 (1958).

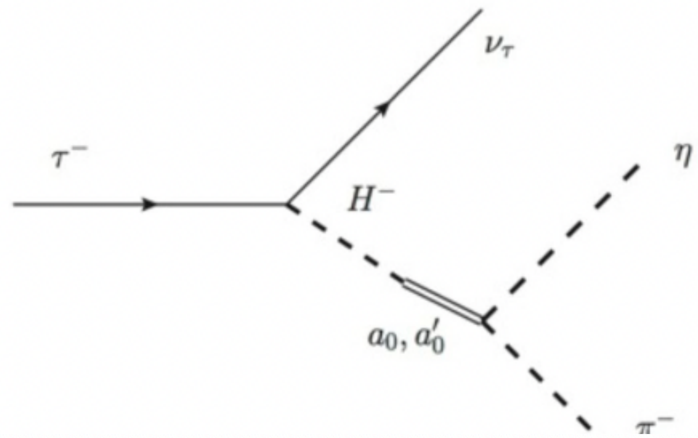
C. Leroy and J. Pestieau, Physics Letters B 72, 398 (1978).

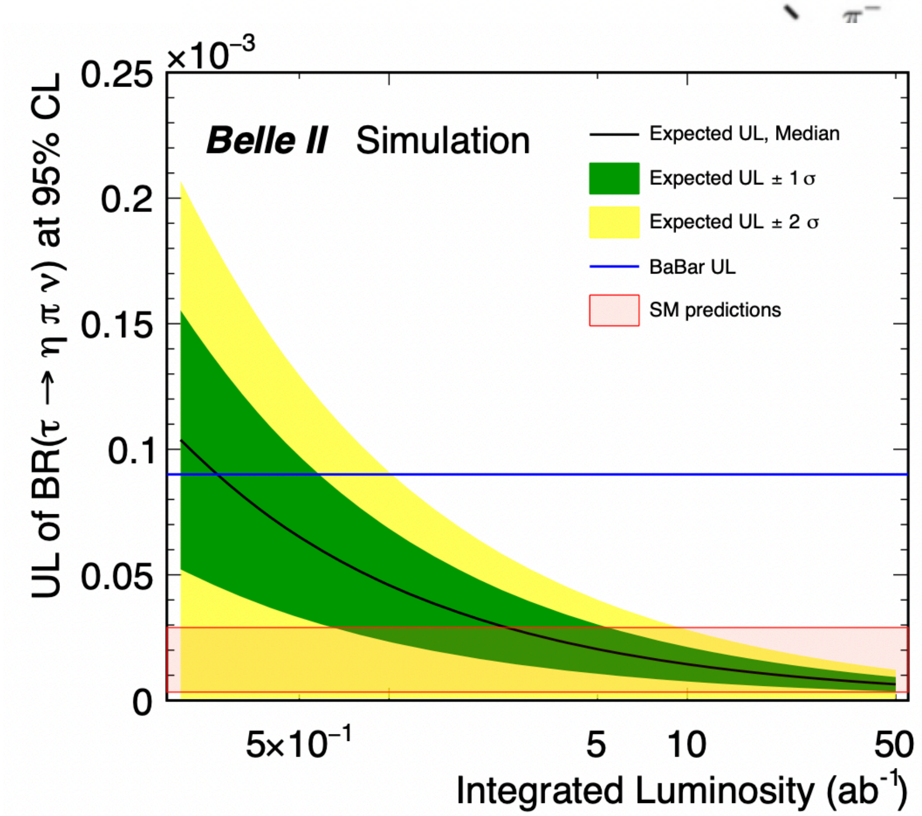
Isospin violating Second Class Current (SCC) in $\tau^- \to \pi^-\eta\nu_\tau$ decays:

- expected at the level of $(m_u - m_d) \sim 10^{-5}$
- enhanced by new physics contributions

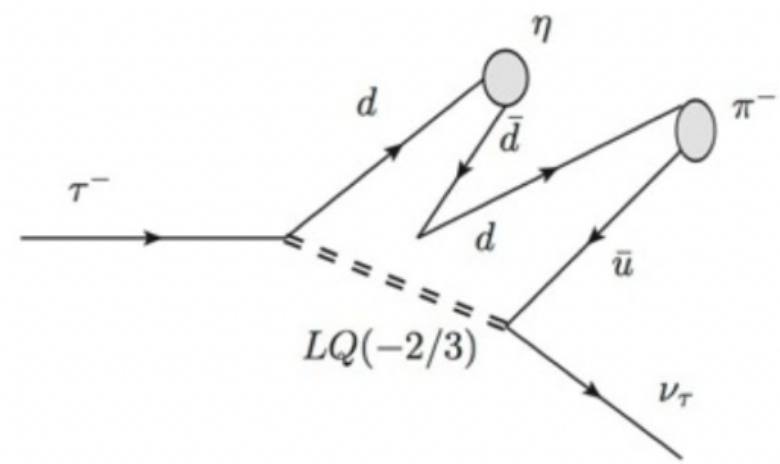
Scalar contributions from extended Higgs/Leptoquark sector

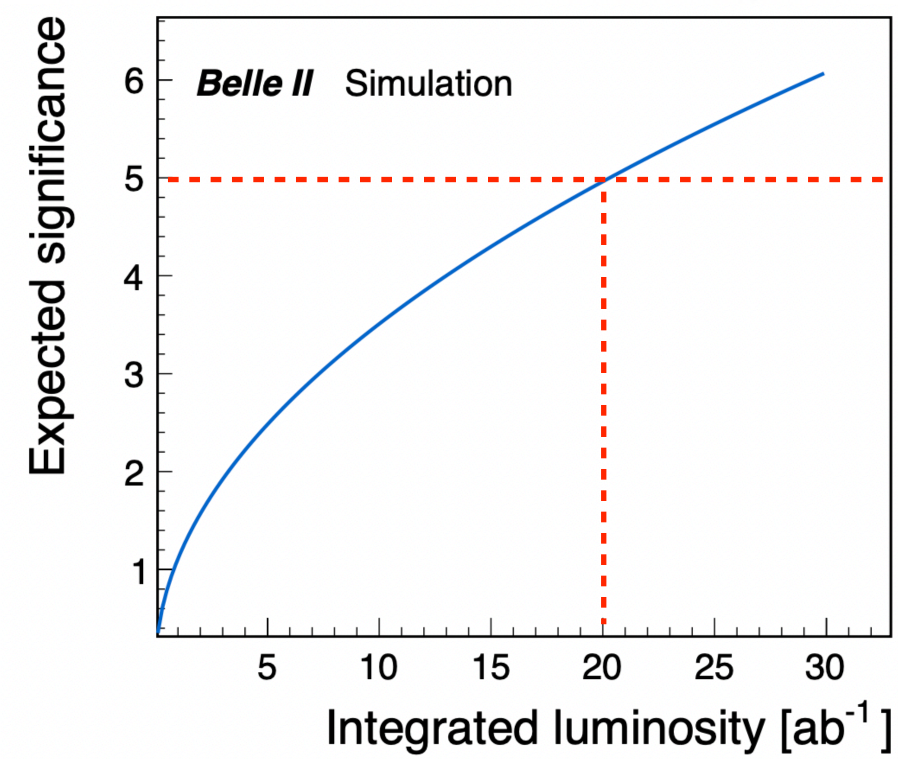
Charged Higgs exchange





Leptoquark exchange





A precision measurement, accompanied by improved theoretical knowledge of the scalar form factor, will set stringent bounds on charged Higgs exchange competitive to those obtained from $B^- \to \tau^- \nu_\tau$ data, even if no excess is seen over second class current predictions.

E. A. Garc´es, M. H. Villanueva, G. L. Castro, and P. Roig, J. High Energy Phys. 12, 027 (2017).

Lots of interesting physics with tau's