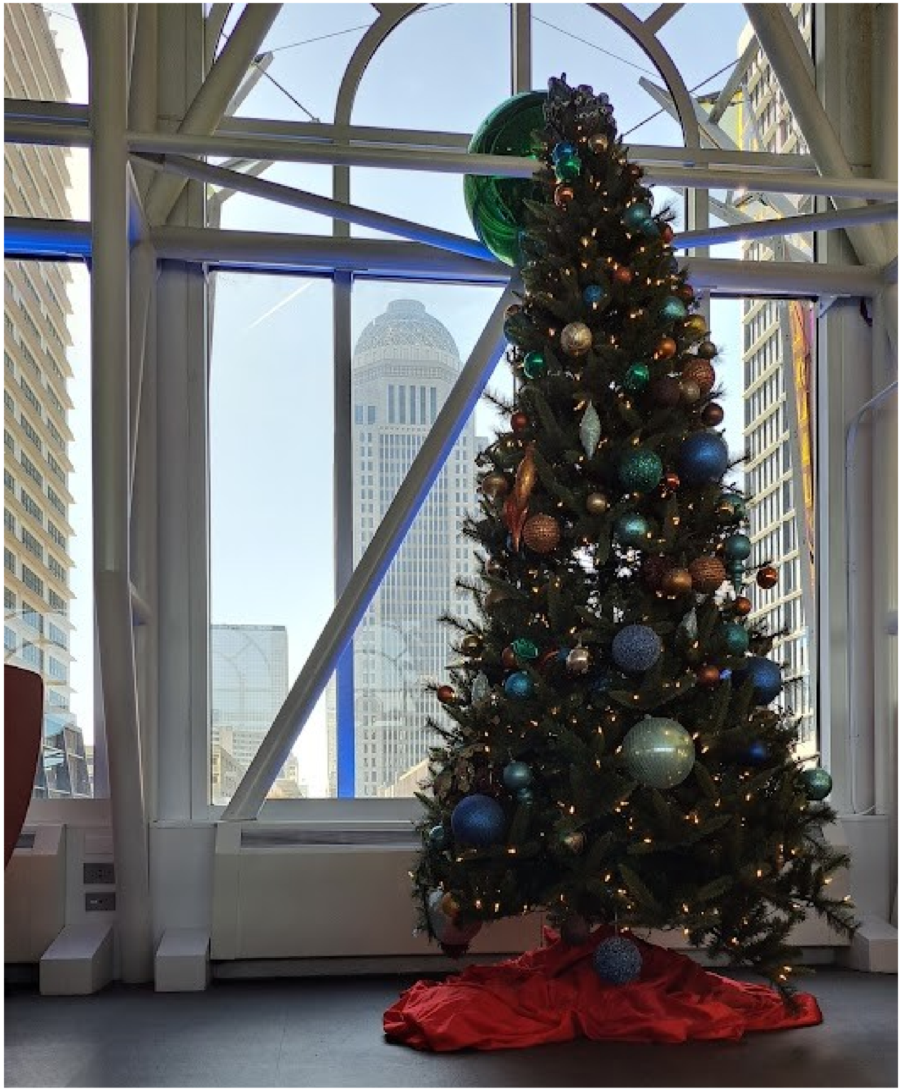
The 17th International Workshop on Tau Lepton Physics (TAU2023)



Wishlist of τ results for τ2025

08/12/2023
Gianluca Inguglia

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

InterLeptons

erc European Research Council
Established by the European Commission

Disclaimer

This is a personal selection of important topics that might not fully include all aspects for the development of the field

so...if I missed your (expected) results, apologies!

Disclaimer II

I am (proudly) a member of Belle II, but will not talk on its behalf

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In principle, I could just provide you with a list of items that I select as wishlist for 2025 and end the talk here.

I will try to instead tell you first why these items are important.

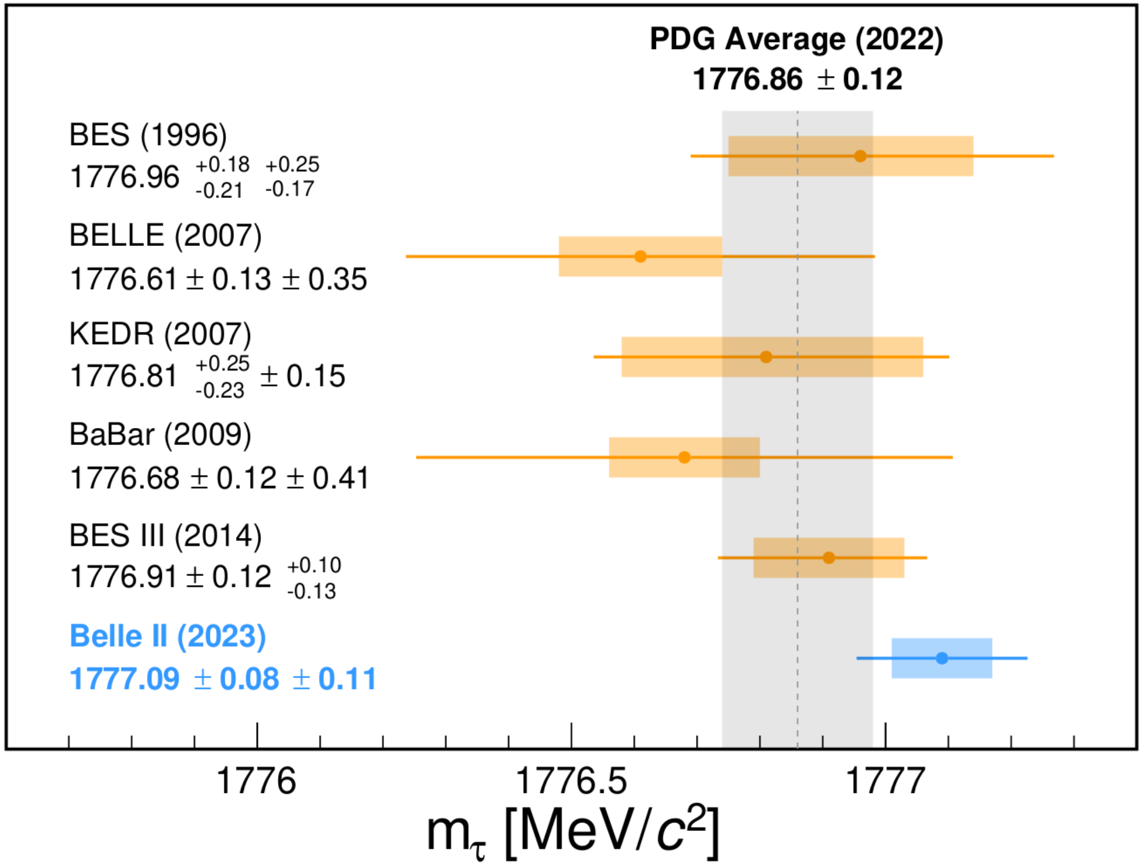
τ mass, it's not just for the sake to know its mass..

- τ mass poorly known compared to *e* or μ (a few orders of magnitude less precise)

M_e= 0.51099895000±0.00000000015 MeV/c²

M_μ= 105.6583755±0.0000023 MeV/c²

M_τ= 1776.86±0.12 MeV/c²



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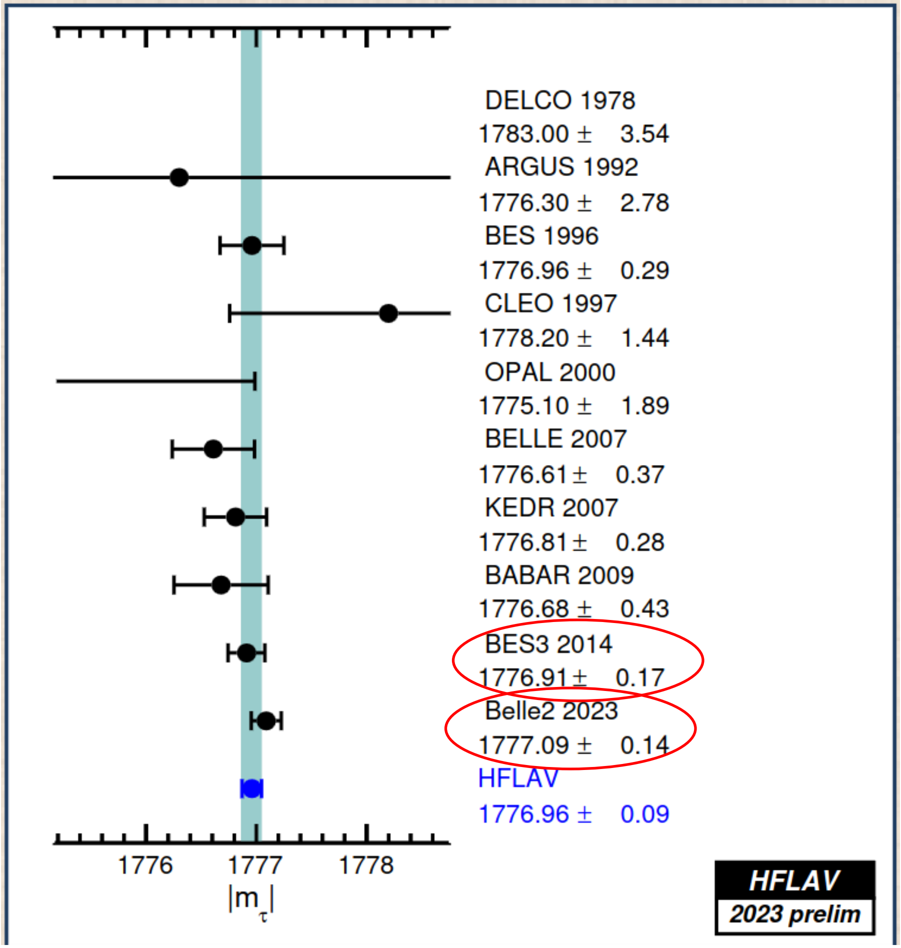
M_τ= 1776.86±**0.09** MeV/c²

See Alberto Lusiani's slides



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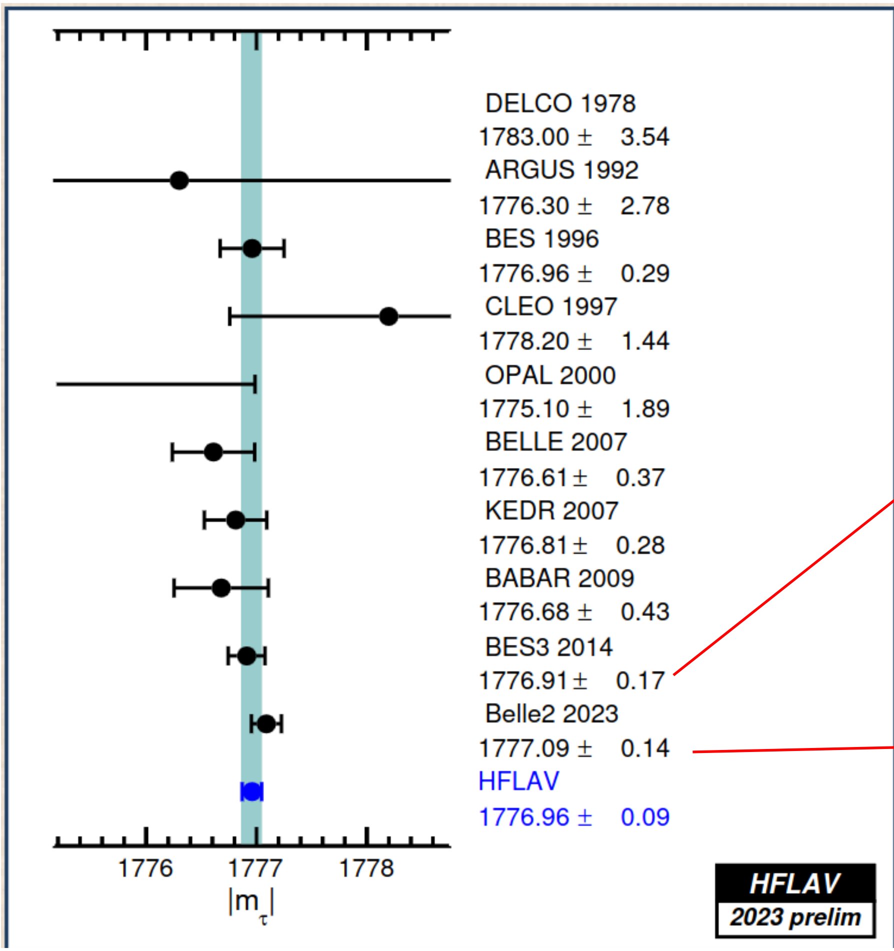

Phys. Rev. D 90, 012001

TABLE VIII: Summary of the τ mass systematic errors.

Source	Δm_τ (MeV/c^2)
Theoretical accuracy	0.010
Energy scale	$^{+0.022}_{-0.086}$
Energy spread	0.016
Luminosity	0.006
Cut on number of good photons	0.002
Cuts on PTEM and acoplanarity angle	0.05
mis-ID efficiency	0.048
Background shape	0.04
Fitted efficiency parameter	$^{+0.038}_{-0.034}$
Total	$^{+0.094}_{-0.124}$

Energy scan

Phys. Rev. D 108, 032006

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

Pseudo-mass

- Both BES III (~x5) and Belle II (~x2) have accumulated more data in the past, can we imagine to have a more precise determination of the τ mass by 2025?

Experimental absolute leptonic Bf determination

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$ Γ_3/Γ

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
17.39 ±0.04 OUR FIT					
17.33 ±0.05 OUR AVERAGE					
17.319±0.070±0.032	54k	[1] SCHAEL	05C	ALEP	1991-1995 LEP runs
17.34 ±0.09 ±0.06	31.4k	ABBIENDI	03	OPAL	1990-1995 LEP runs
17.342±0.110±0.067	21.5k	[2] ACCIARRI	01F	L3	1991-1995 LEP runs
17.325±0.095±0.077	27.7k	ABREU	99X	DLPH	1991-1995 LEP runs
• • • We use the following data for averages but not for fits. • • •					
17.37 ±0.08 ±0.18		[3] ANASTASSOV	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$ Γ_5/Γ

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
17.82 ±0.04 OUR FIT					
17.82 ±0.05 OUR AVERAGE					
17.837±0.072±0.036	56k	[1] SCHAEL	05C	ALEP	1991-1995 LEP runs
17.806±0.104±0.076	24.7k	[2] ACCIARRI	01F	L3	1991–1995 LEP runs
17.81 ±0.09 ±0.06	33.1k	ABBIENDI	99H	OPAL	1991–1995 LEP runs
17.877±0.109±0.110	23.3k	ABREU	99X	DLPH	1991–1995 LEP runs
17.76 ±0.06 ±0.17		[3] ANASTASSOV	97	CLEO	E^{ee}_{cm}= 10.6 GeV

- Some of you weren't even born when the last measurements of the absolute leptonic Bf took place.
- What were you doing, say, in 1990?
- Anyone else thinking it's time for an update?

Mean lifetime of tau lepton

VALUE (10^{-15} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
290.3 ± 0.5 OUR AVERAGE					
290.17 ± 0.53 ± 0.33	1.1M	BELOUS	14	BELL	711 fb^{-1} E^{ee}_{cm}=10.6 GeV
290.9 ± 1.4 ± 1.0		ABDALLAH	04T	DLPH	1991-1995 LEP runs
293.2 ± 2.0 ± 1.5		ACCIARRI	00B	L3	1991–1995 LEP runs
290.1 ± 1.5 ± 1.1		BARATE	97R	ALEP	1989–1994 LEP runs
289.2 ± 1.7 ± 1.2		ALEXANDER	96E	OPAL	1990–1994 LEP runs
289.0 ± 2.8 ± 4.0	57.4k	BALEST	96	CLEO	E^{ee}_{cm}= 10.6 GeV

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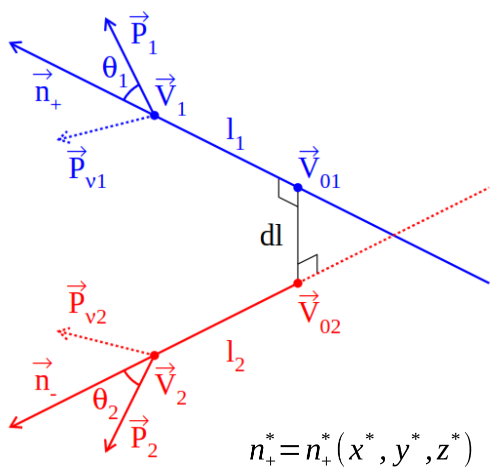
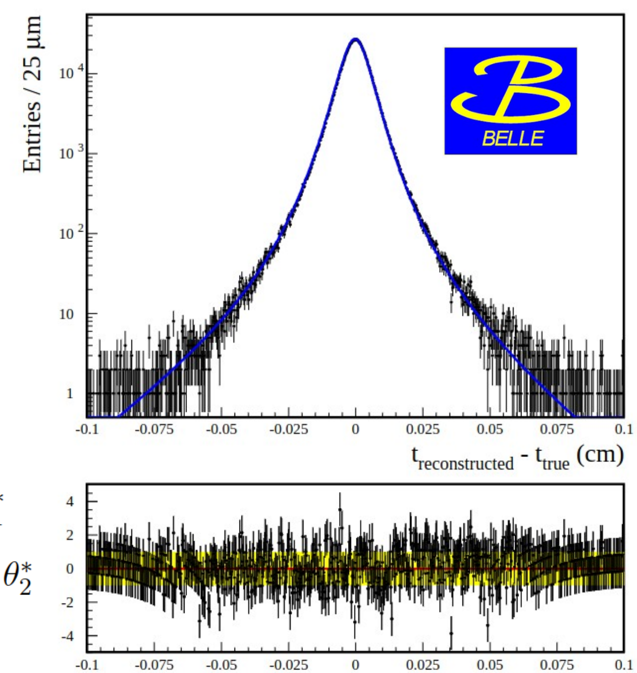
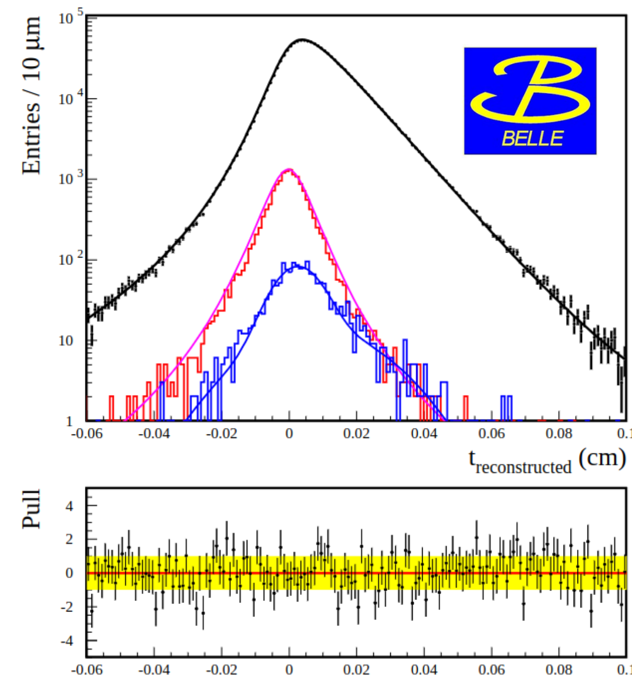
Phys. Rev. Lett. 112, 031801



$n^*_+ = n^*_+(x^*, y^*, z^*)$

$$\begin{cases} x^* \cdot P^*_{1x} + y^* \cdot P^*_{1y} + z^* \cdot P^*_{1z} = |P^*_1| \cos\theta^*_1 \\ x^* \cdot P^*_{2x} + y^* \cdot P^*_{2y} + z^* \cdot P^*_{2z} = -|P^*_2| \cos\theta^*_2 \\ (x^*)^2 + (y^*)^2 + (z^*)^2 = 1 \end{cases}$$





$n^*_\pm$ converted to a 4-momentum using $e^\pm$ beam energy and **τ mass**

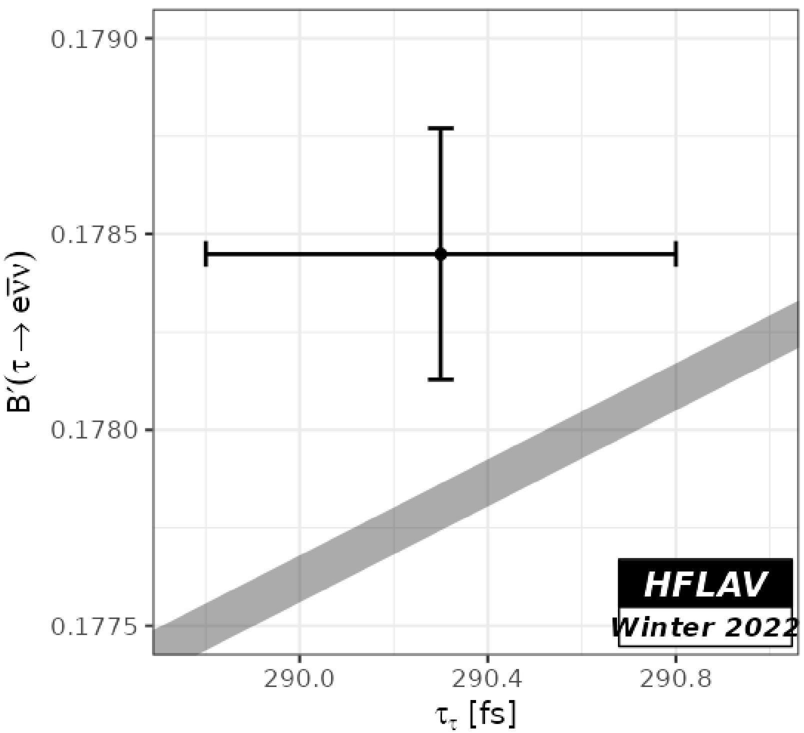
$$|\langle\tau_{\tau^+}\rangle - \langle\tau_{\tau^-}\rangle| / \langle\tau_\tau\rangle < 7.0 \times 10^{-3} \text{ at } 90\% \text{ CL}$$

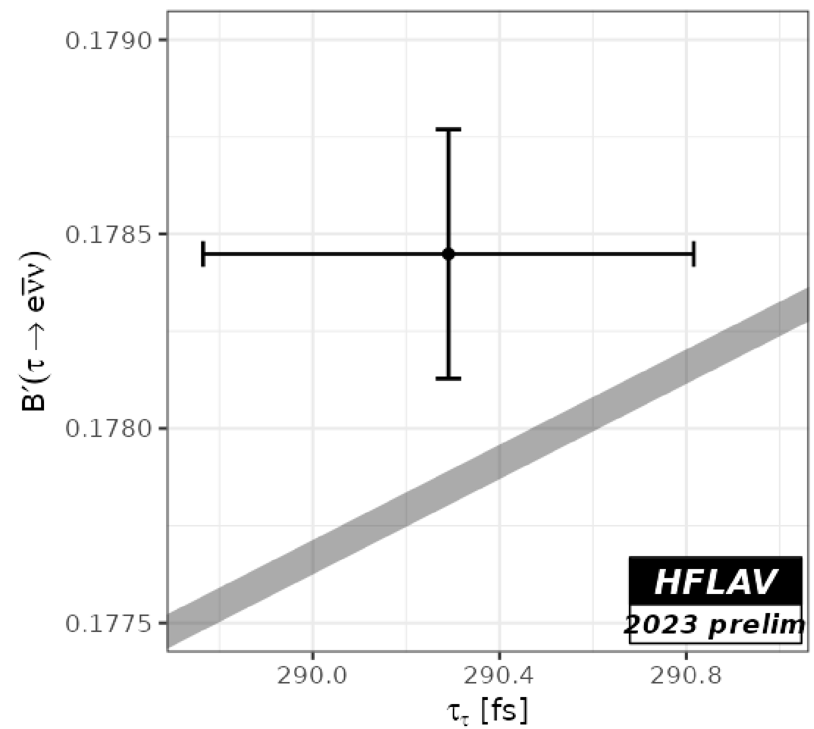
Belle II measured with world's best precision the lifetime of D^0, D^+ and Λ_c, can we expect also the τ lifetime to be measured in the near future?

τ mass, it's not just for the sake to know its mass..

- τ mass poorly known compared to *e* or μ
  (a few orders of magnitude less precise)
- Important parameter in lepton universality tests

$$B^{SM}_{\tau \to l} \propto B_{\mu \to e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$





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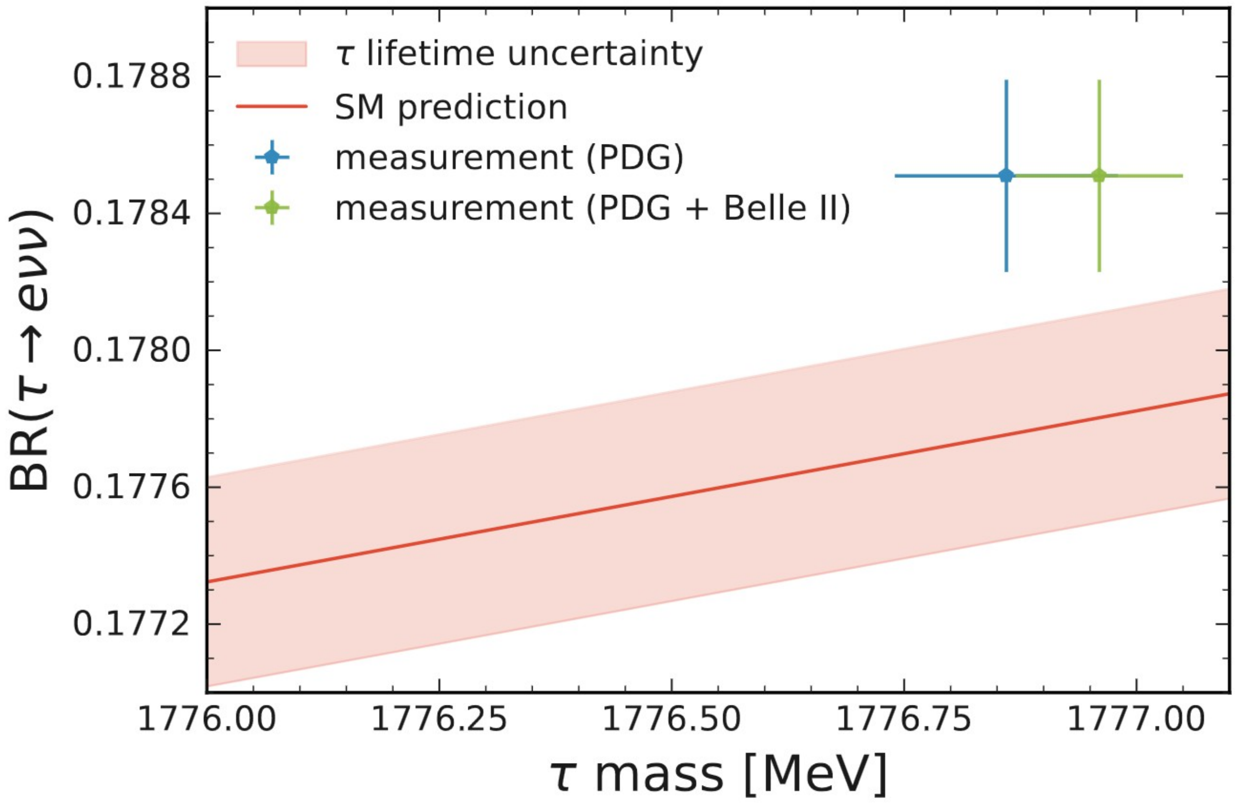


Private plot
Credits: A. Rostomyan, N. Rad et al.

Using τ for LFU tests, LEP and hadron colliders

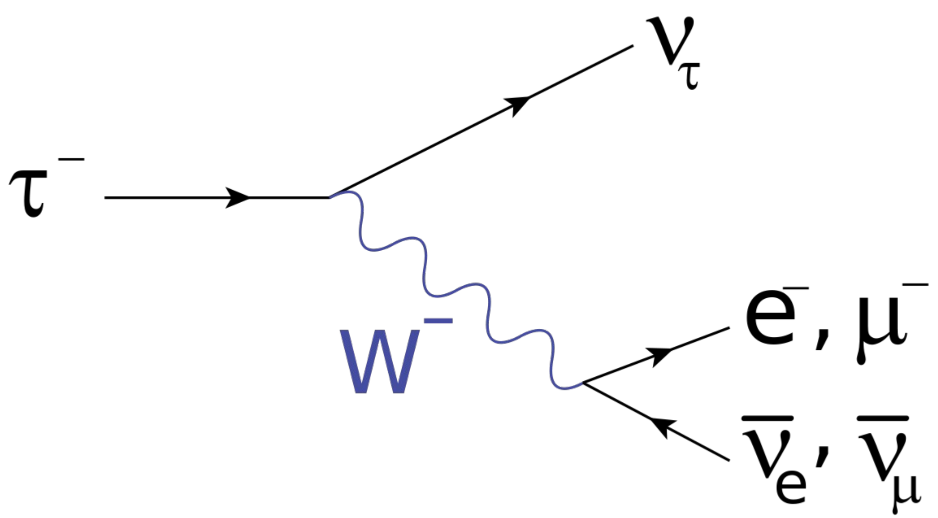
Two reference papers, of experimental measurements and their combinations

ALEPH, DELPHI, L3, OPAL, LEP Electroweak Collaboration, “Electroweak Measurements in electron-positron collisions at W-boson-pair energies at LEP”, Phys. Rept. 532 (2013) 119, doi:10.1016/j.physrep.2013.07.004, arXiv:1302.3415.

Particle Data Group, P. A. Zyla et al., “Review of particle physics”, Prog. Theor. Exp. Phys. 2020 (2020) 083C01, doi:10.1093/ptep/ptaa104.

$$R_{\tau/(e+\mu)} = \frac{2\,\mathcal{B}(W \to \tau\overline{\nu}_\tau)}{\mathcal{B}(W \to e\overline{\nu}_e) + \mathcal{B}(W \to \mu\overline{\nu}_\mu)} = 1.066 \pm 0.025$$

LEP results from W boson decays to leptons indicated a ~2.5σ tension with the predicted value of $R_{\tau/l}$ = 0.9996 (0709.1075, 0005060)



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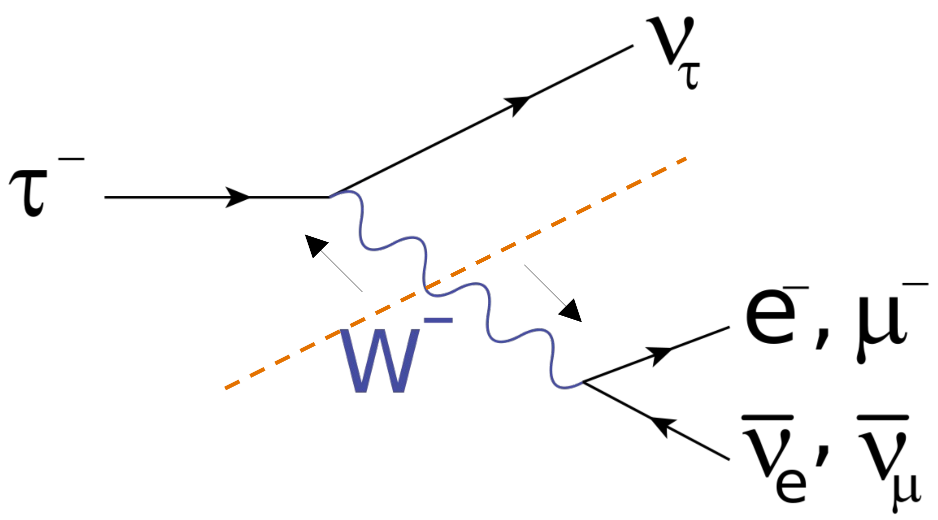

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Table 5: Ratios of different leptonic branching fractions, $R_{\mu/e} = \mathcal{B}(W \to \mu\overline{\nu}_\mu)/\mathcal{B}(W \to e\overline{\nu}_e)$, $R_{\tau/e} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to e\overline{\nu}_e)$, and $R_{\tau/\mu} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to \mu\overline{\nu}_\mu)$, measured here compared with the values obtained by other LEP [8], LHC [13, 16, 17], and Tevatron [14, 15] experiments.

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

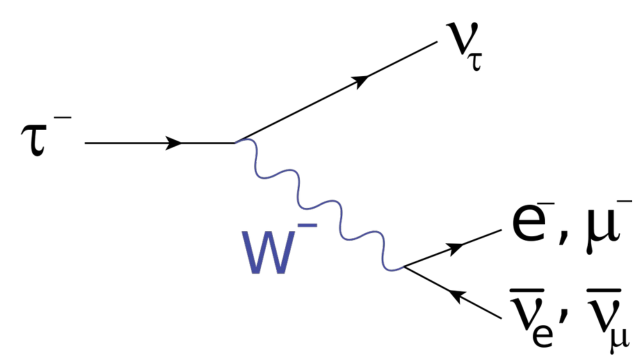
Test of lepton flavour universality

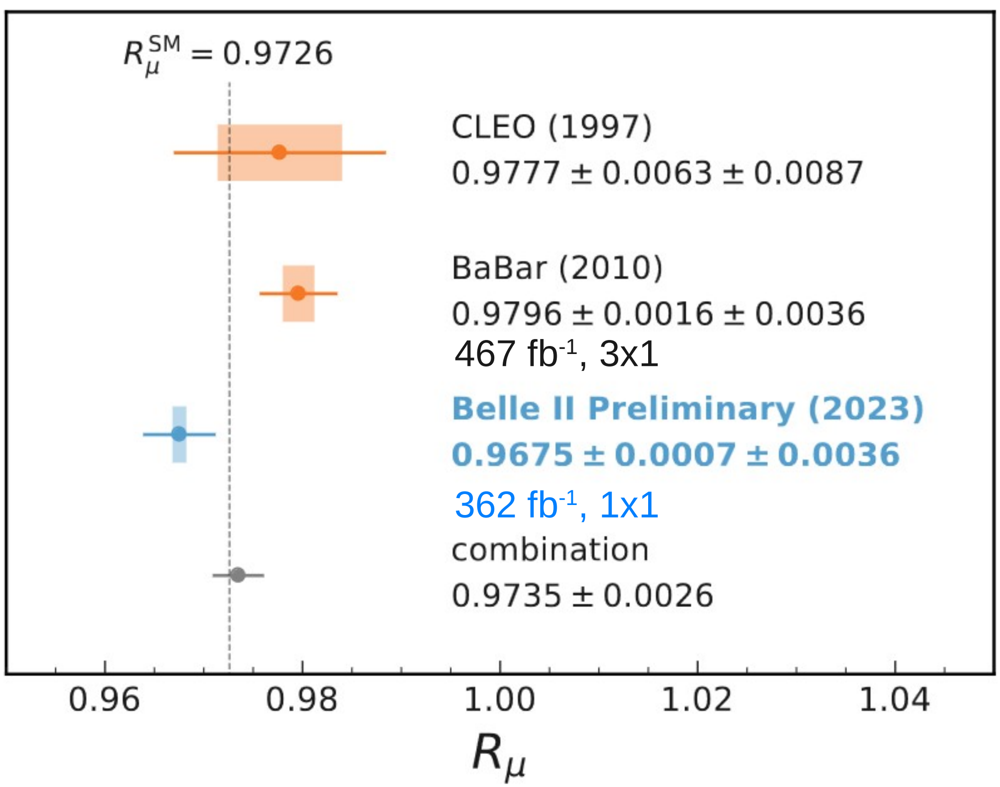
It is in principle it is a very simple test: compare the rates of $\tau \to \mu\nu\nu$ vs $\tau \to e\nu\nu$

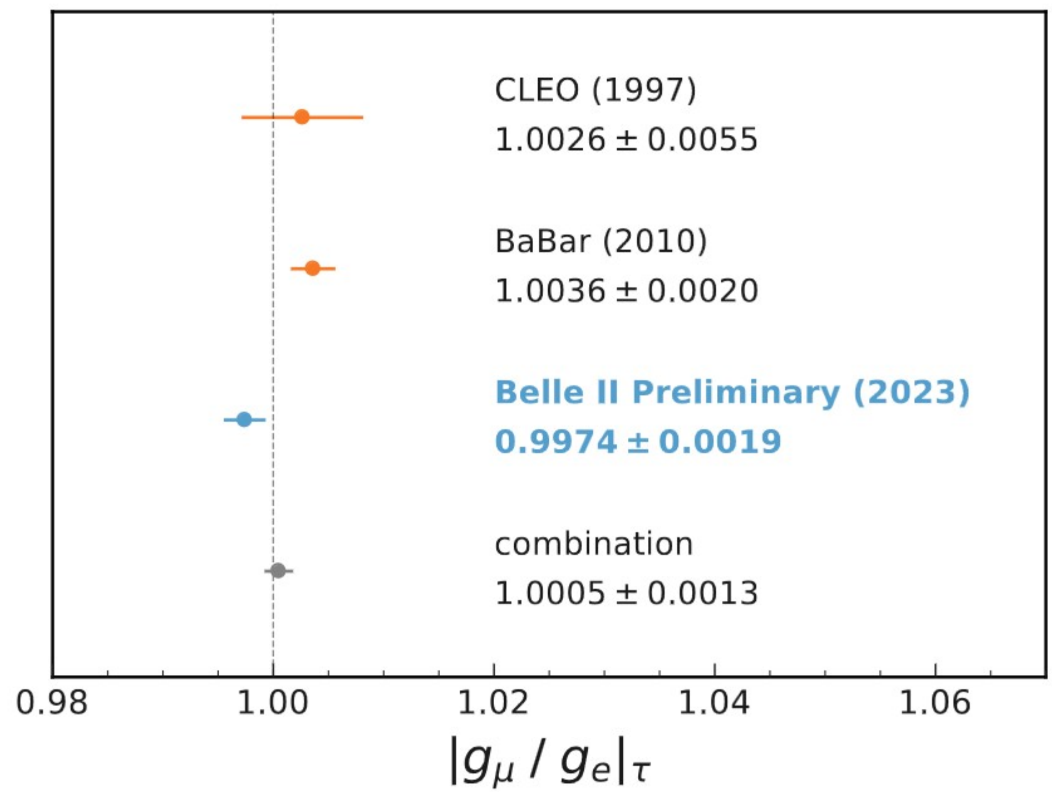
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu_\mu}\nu_\tau]}{BF[\tau^- \to e^- \bar{\nu_e}\nu_\tau]}\,\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu_\mu}\nu_\tau]}{BF[\tau^- \to e^- \bar{\nu_e}\nu_\tau]}$$

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







Details in Paul Feichtinger's slides

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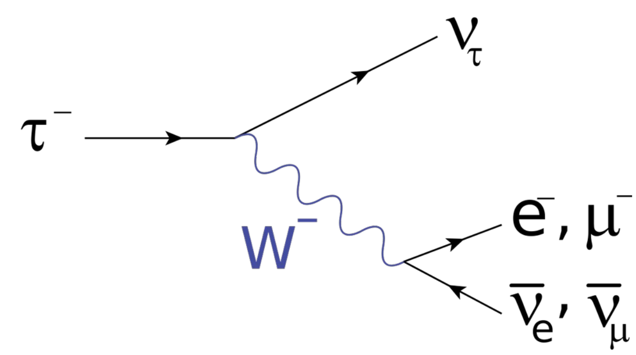

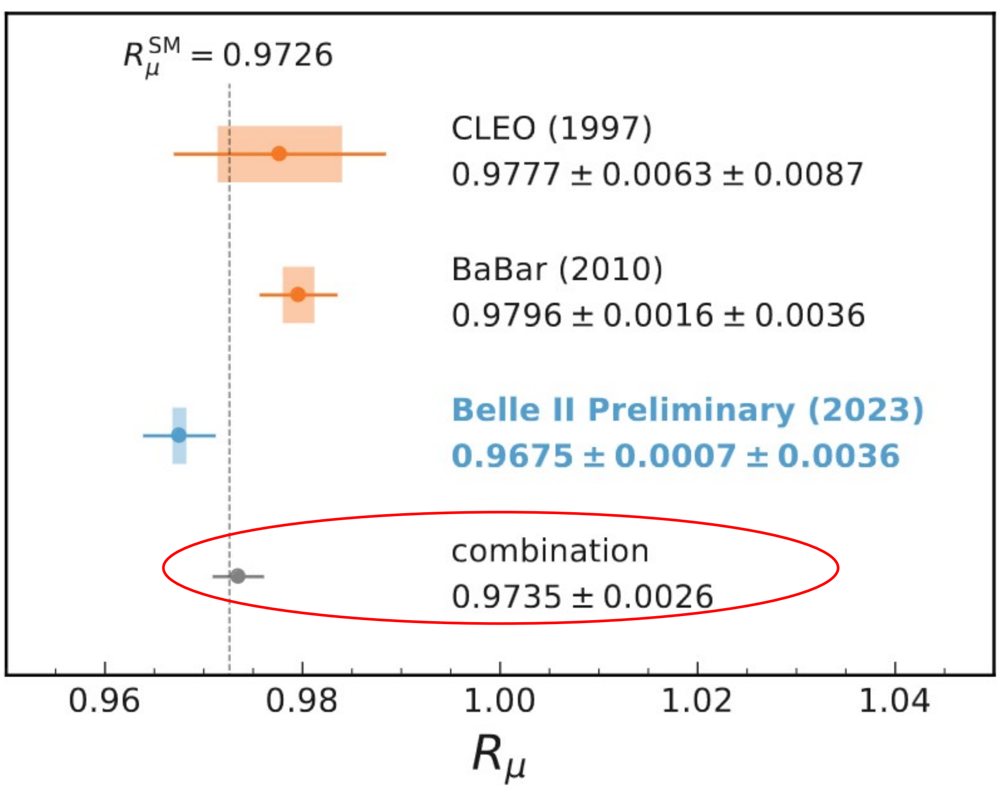

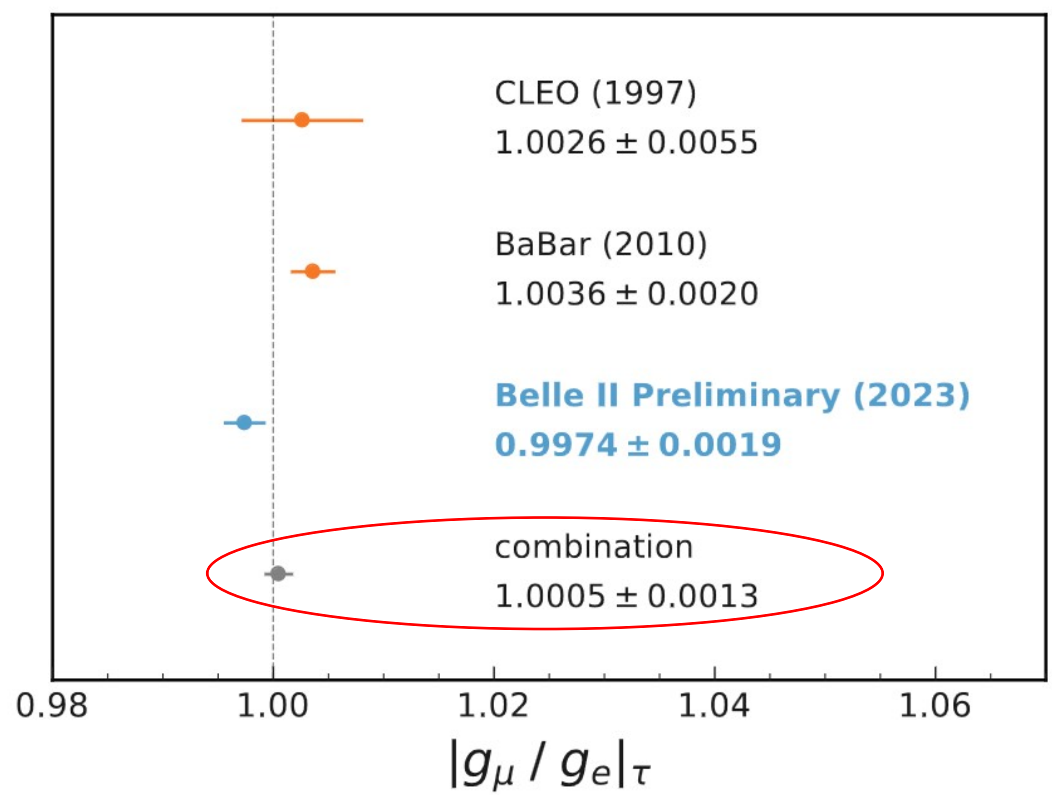

Details in Paul Feichtinger’s slides

LFU tests in tau decays, implications on BSM

https://arxiv.org/pdf/1607.06832.pdf

Phys.Lett. B762 (2016) 389-398

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]
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[2] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
[4] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany and*
[5] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

We discuss a minimal solution to the long-standing $(g-2)_\mu$ anomaly in a simple extension of the Standard Model with an extra Z' vector boson that has only flavor off-diagonal couplings to the second and third generation of leptons, i.e. $\mu, \tau, \nu_\mu, \nu_\tau$ and their antiparticles. A simplified model realization, as well as various collider and low-energy constraints on this model, are discussed. We find that the $(g-2)_\mu$-favored region for a Z' lighter than the tau lepton is totally excluded, while a heavier Z' solution is still allowed. Some testable implications of this scenario in future experiments, such as lepton-flavor universality-violating tau decays at Belle 2, and a new four-lepton signature involving same-sign di-muons and di-taus at HL-LHC and FCC-ee, are pointed out. A characteristic resonant absorption feature in the high-energy neutrino spectrum might also be observed by neutrino telescopes like IceCube and KM3NeT.

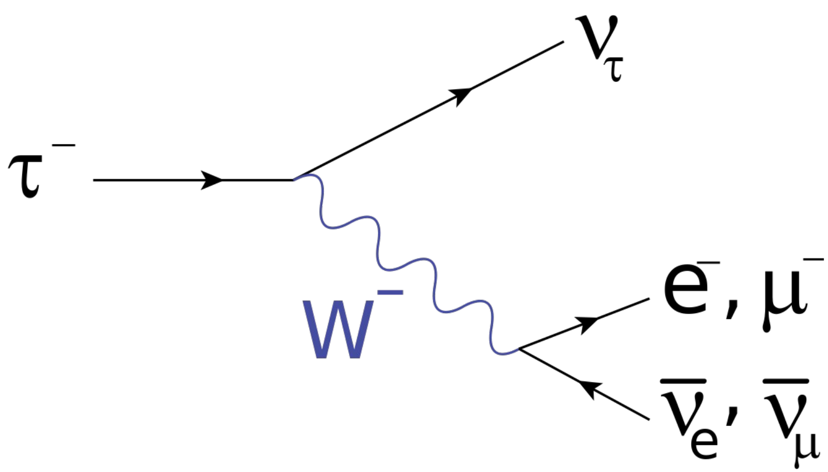
Within this Abelian symmetry, L_μ-L_τ , LFV terms are allowed

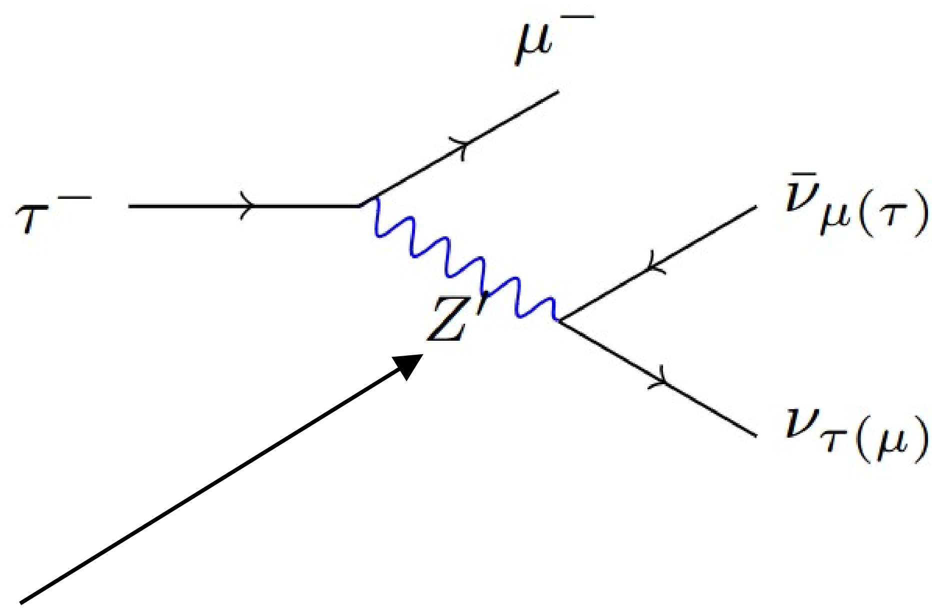
20

LFU tests in tau decays, implications on BSM

https://arxiv.org/pdf/1607.06832.pdf

Phys.Lett. B762 (2016) 389-398





Within this Abelian symmetry, L_μ-L_τ, LFV terms are allowed

LFU tests in tau decays, implications on BSM

$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}$$

$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

A "standard" L_μ-L_τ Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

LFU tests in tau decays, implications on BSM

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$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

$$L_\mu \leftrightarrow L_\tau, \qquad \mu_R \leftrightarrow \tau_R,$$
$$B^\alpha \leftrightarrow B^\alpha, \qquad Z'^\alpha \leftrightarrow -Z'^\alpha$$

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$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}$$

$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

Lepton doublets → $(\nu_l, l)_L$

$$L_\mu \leftrightarrow L_\tau\,,$$

Lepton singlets → l_R

$$\mu_R \leftrightarrow \tau_R\,,$$

$$B^\alpha \leftrightarrow B^\alpha\,,$$

U(1)^Y gauge field

$$Z'^\alpha \leftrightarrow -Z'^\alpha$$

U(1)' gauge field

A "standard" L_μ-L_τ Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

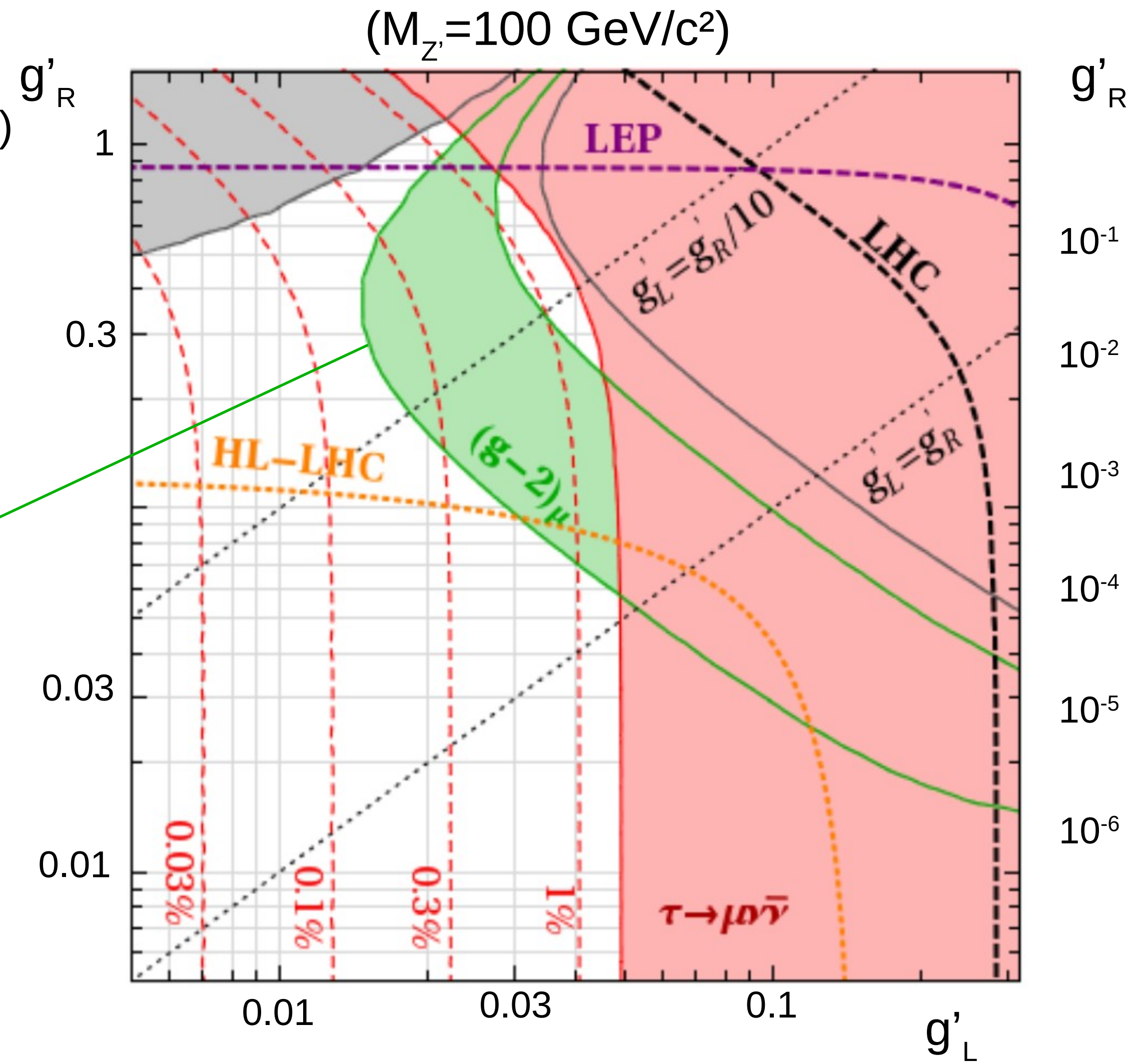
$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

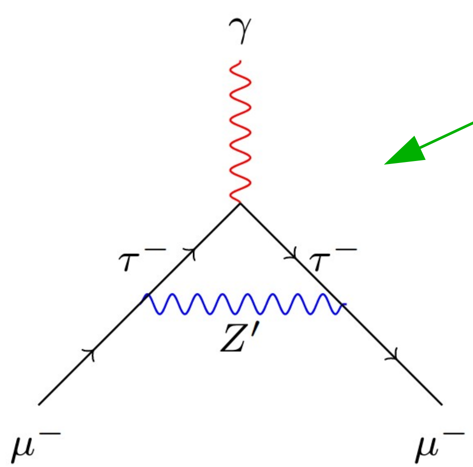
$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

LFU tests in tau decays, implications on BSM

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

BaBar: $R_{\mu e}$=0.976 ± 0.004(=0.0016$_{stat}$ ± 0.0036$_{sys}$)
SM: $R_{\mu e}$=0.972559 ± 0.000005 (see here)
PDG: $R_{\mu e}$=0.979 ± 0.004
$R_{\mu e}^{PDG}/R_{\mu e}^{SM}$-1=0.0064±0.004





Z' contribution to the anomalous magnetic moment of the muon

The sensitivity to a LFV Z' depends on the level of systematics in the test of LFU in tau decays.

LFU tests in tau decays, implications on BSM

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

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

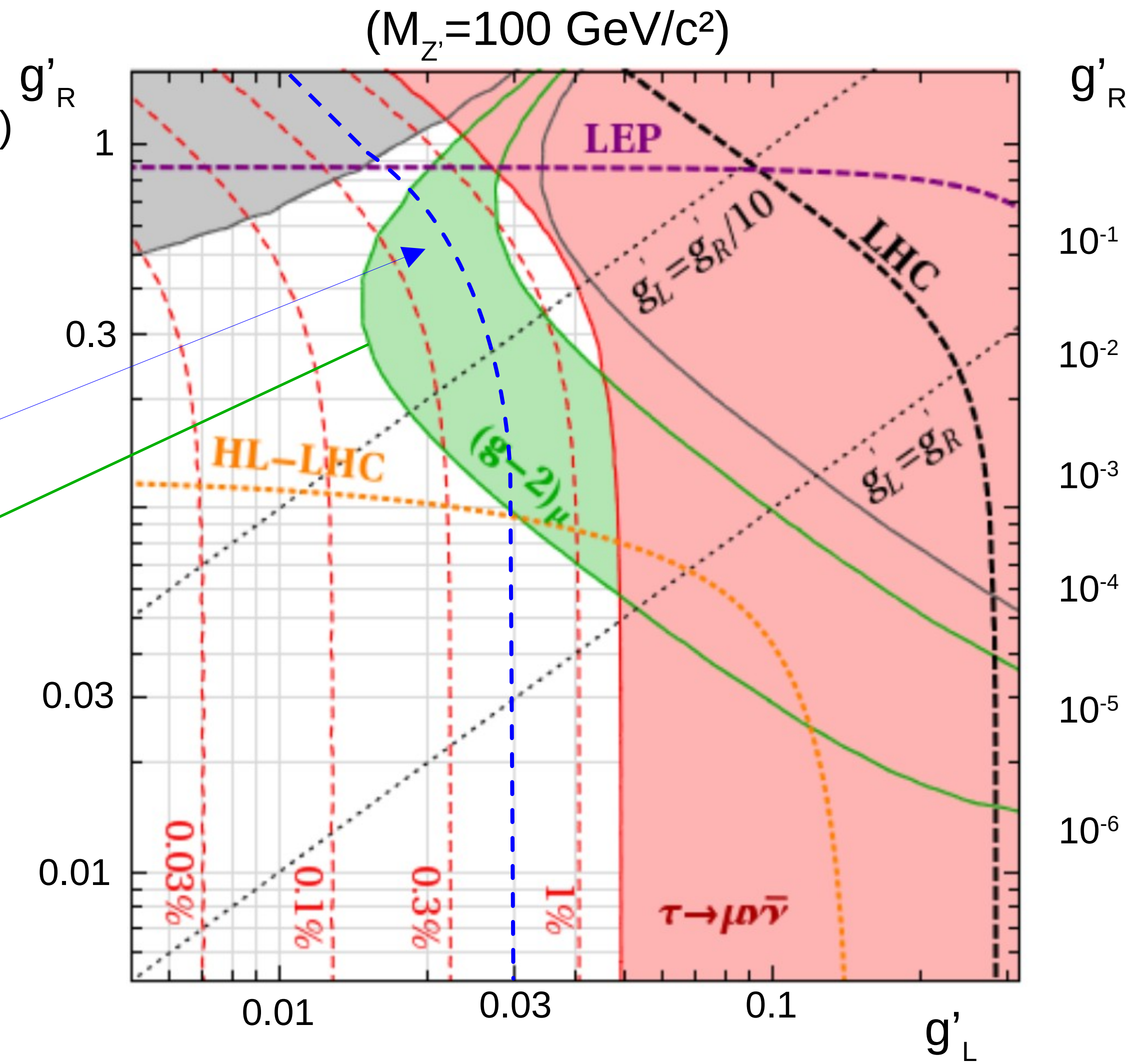
SM: $R_{\mu e}=0.972559 \pm 0.000005$ (see here)

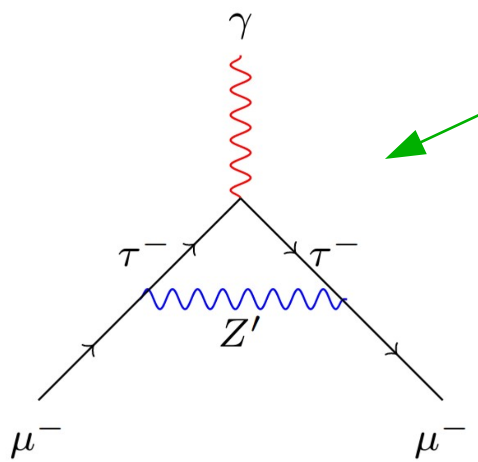
PDG: $R_{\mu e}=0.979 \pm 0.004$

$R_{\mu e}^{PDG}/R_{\mu e}^{SM}-1=0.0064\pm0.004$

Using Belle II new average: **$R_{\mu e}=0.935\pm0.0026$**

$R_{\mu e}^{2023}/R_{\mu e}^{SM}-1=0.00097\pm0.0027$ Preliminary!



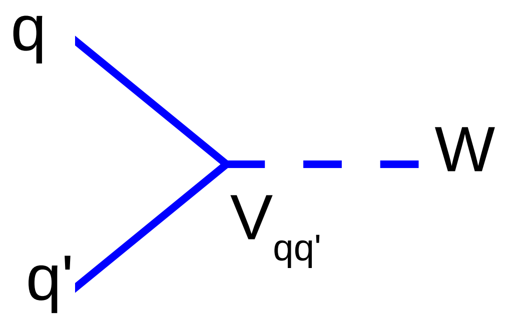


Z' contribution to the anomalous magnetic moment of the muon

The sensitivity to a LFV Z' depends on the level of systematics in the test of LFU in tau decays.

Transitions between quarks: the CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



With probability proportional to $|V_{qq'}|^2$

A 3x3 matrix is defined by 18 parameters, however

→ V_{CKM} is a unitary matrix $VV^{\dagger}=V^{\dagger}V=I$: 9 unitarity conditions..

Only 9 parameters are "free", and these are 3 angles and 6 phases, however

→ 5 phases are non-physical (unobservable)

→ V_{CKM} can be parametrised by 4 parameters: 3 Euler angles and 1 complex phase. The complex phase in V_{CKM} violates *CP*.

CKM matrix and the unitarity relations

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk}$$ **Column orthogonality**

$$\sum_j V_{ij} V_{kj}^* = \delta_{ik}$$ **row orthogonality**

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

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$$

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$$

$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$$

$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

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$$V_{ud} V^*_{us} + V_{cd} V^*_{cs} + V_{td} V^*_{ts} = 0$$

$$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$

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$$\sum_j V_{ij} V^*_{kj} = \delta_{ik}$$ **row orthogonality**

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

Cabibbo Angle Anomaly

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$
- 3 sigma tension with SM!
- This is the CAA

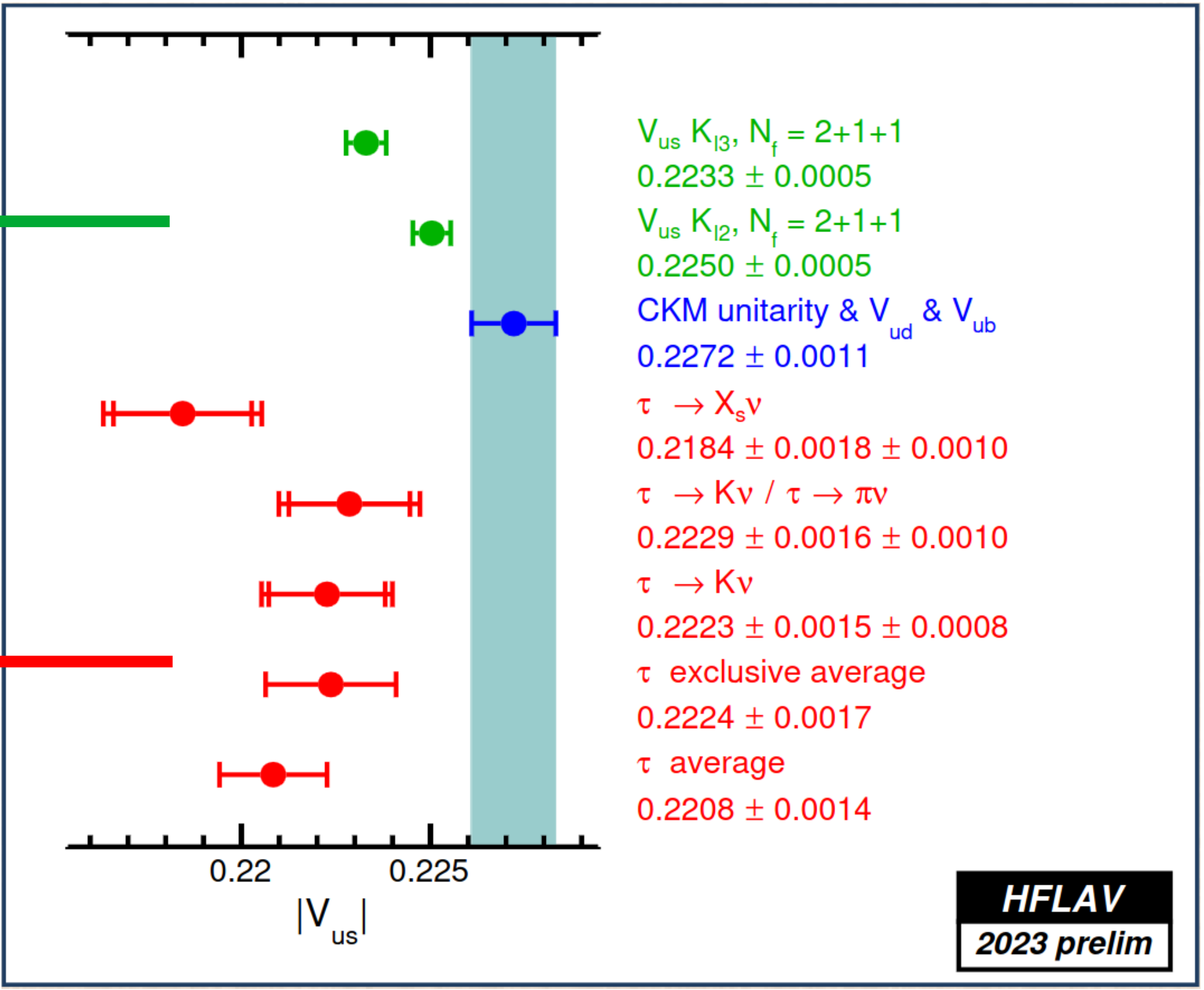
See Matthew Kirk slides at Anomalies and precision in the Belle II era workshop

Or Andreas Crivellin, explaining the Cabibbo Angle Anomaly, 2207.02507

CKM matrix element, tension from different determinations?

Kaon decays provide a very precise determination of V_{us} and indicate a tension with CKM unitarity

Hadronic τ decays provide a less precise determination of V_{us}, but its an independent approach that provides a consistency check indicate a tension with CKM unitarity



See Alberto Lusiani's slides

LFU in $\tau \rightarrow h\nu$ and V_{us}

BaBar has performed a precision test using hadronic τ decays Phys. Rev. Lett.105 051602

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

where the radiative corrections are $\delta_\pi = (0.16 \pm 0.14)\%$ and $\delta_K = (0.90 \pm 0.22)\%$ [23]. Using the world averaged mass and lifetime values and meson decay rates [3], we determine $\left(\frac{g_\tau}{g_\mu}\right)_{\pi(K)} = 0.9856 \pm 0.0057\ (0.9827 \pm 0.0086)$ and $\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$ when combining these results; this is 2.8σ below the SM expectation and within 2σ of the world average.

	μ	π	K
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

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

$|V_{us}| = 0.2193 \pm 0.0032$

$$R_{K/\pi} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \frac{\left(1 - \frac{m_K^2}{m_\tau^2}\right)^2}{\left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2} (1 + \delta_{LD}),$$

$|V_{us}| = 0.2255 \pm 0.0024$

Systematic uncertainties here are much larger than in the case of leptonic decays.
Is it foreseeable that by 2025 we see an update of these measurements, from Belle II?

New physics? → https://arxiv.org/pdf/2102.02825.pdf

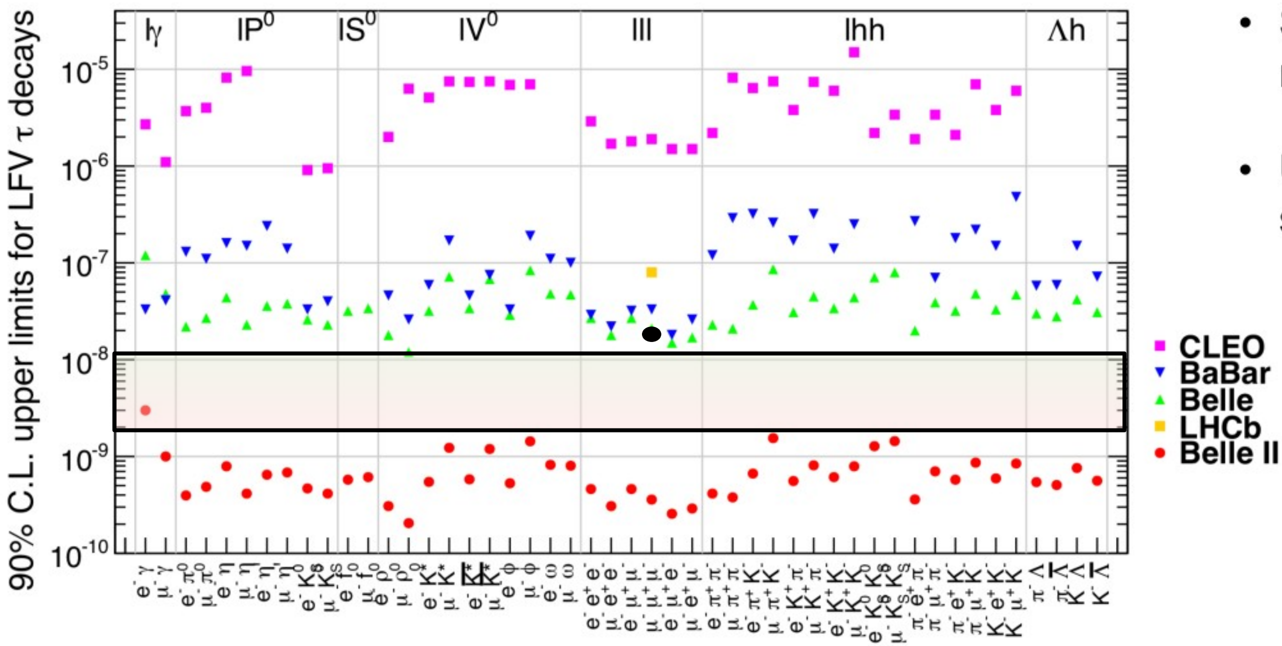
https://arxiv.org/abs/2002.07184

Lepton flavour violation

See Alberto Martini's slides

- Due to their large mass, τ leptons provide a wide variety of LFV (and LNV) decay modes to study:
  - radiative: $\tau \to \ell\gamma$
  - leptonic: $\tau \to \ell\ell\ell$
  - semileptonic: $\tau \to \ell h(h)$

  - "golden channels" for discovery: τ→μγ, τ→μμμ
  - complementary: semileptonic modes allow us to test LFV couplings b/w quarks and leptons, and better discriminate b/w NP models



- So far, searches for τ LFV decays mostly occurred at last-gen *B* factories
- Upper limits had approached the regime sensitive to NP (10^{-10}-10^{-7})

arXiv:1808.10567

Extrapolating from Belle results (50 ab^{-1}):

Belle II will push the current bounds forward by at least one order of magnitude!

While luminosities are integrated, could we know something in between?
@Belle, what about the ~2ab^{-1} of Belle+Belle II data expected by next summer?

see here, from P. Rados

CP violation in τ decays

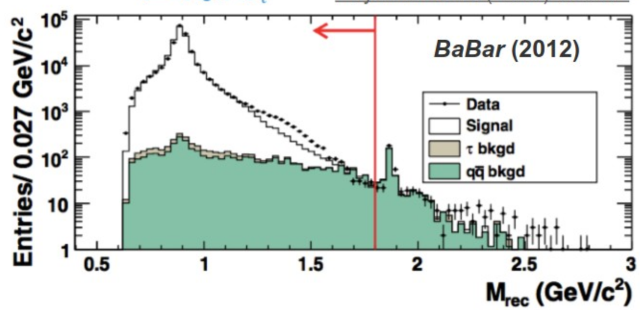
- Due to CP violation in the kaon sector, $\tau \to K_S \pi^\pm \nu_\tau$ decays in the SM have a nonzero decay-rate asymmetry:

$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

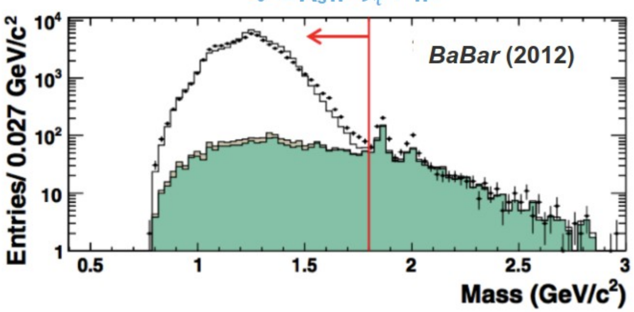
  - SM prediction: $(3.6 \pm 0.1) \times 10^{-3}$
  - BaBar measurement: $(-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$ (2.8σ)

- **An improved A_τ measurement is a priority at Belle II**

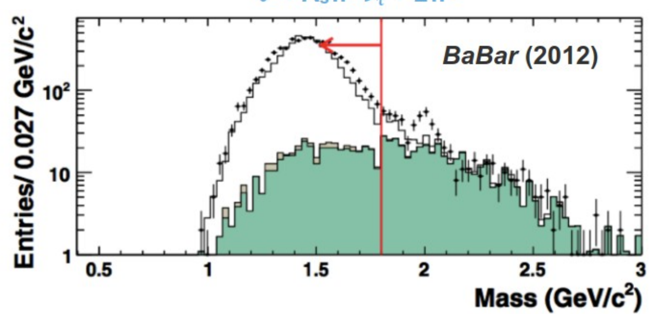
$\tau \to K_S \pi^\pm \nu_\tau$ Phys.Rev D85 (2012) 031102



$\tau \to K_S \pi^\pm \nu_\tau + \pi^0$



$\tau \to K_S \pi^\pm \nu_\tau + 2\pi^0$

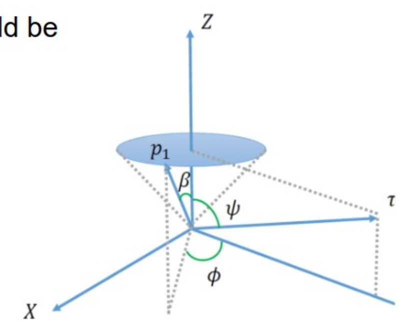


- Two different analysis techniques adopted by BaBar and Belle.
- BaBar looked at the asymmetry in decays to a specific final state (and reported the observation of CP violation with a significance of 2.8 σ)
- Belle looked instead into possible effects in angular distributions (and reported basically no CP violation)
- What about Belle II? A measurement to be presented at τ2025?

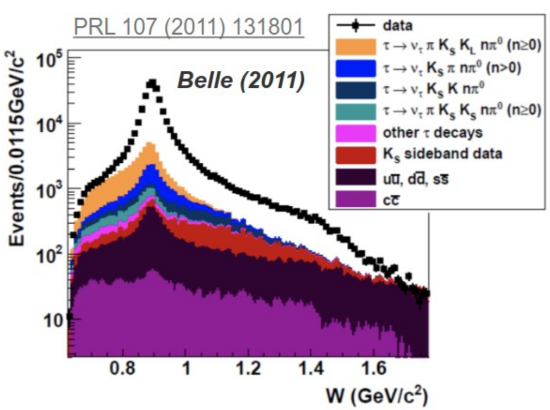
- CP violation could also arise from a charged scalar boson exchange. It would be detected as a difference in the decay angular distributions:

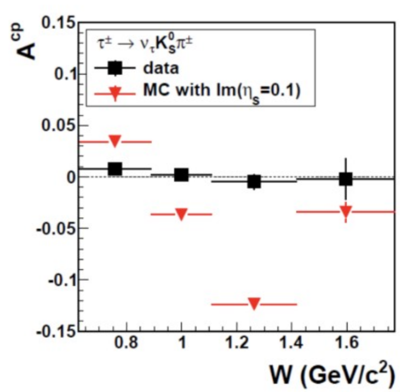
$$A_i^{CP} = \frac{\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \cos\beta\cos\psi\left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega}{\frac{1}{2}\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega} \simeq \langle\cos\beta\cos\psi\rangle^i_{\tau^-} - \langle\cos\beta\cos\psi\rangle^i_{\tau^+},$$

$$d\omega = dQ^2 d\cos\theta d\cos\beta$$



PRL 107 (2011) 131801





- With 50 ab⁻¹ of data, Belle II is expected to provide a x70 more precise measurement:

$|A_{CP}| < (0.5\text{-}3.8) \times 10^{-4}$

(assuming central value $A^{CP} = 0$)

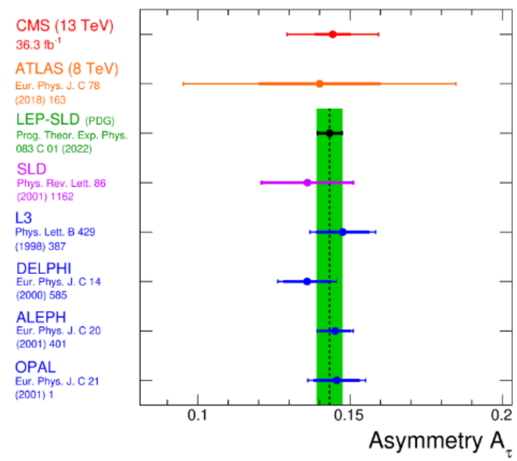
see here, from P. Rados

Polarization measurements

Measurement of the tau lepton polarisation in Z boson decays by CMS detector

- Polarization of τ^- leptons in the decay of Z bosons produced in pp collisions using CMS detector is presented to an integrated luminosity of 36.3 fb^{-1}.
- The measured τ^- lepton polarization, **$\mathcal{P}_\tau$ (Z) = −0.144 ±0.015**, is in good agreement with the SLD, LEP and ATLAS results.
- The measured polarization constrains the effective couplings of τ^- leptons to the Z boson and determines the effective weak mixing angle to be **$\sin^2\theta^{eff}_W = 0.2319 \pm 0.0019$**
- No deviation from SM! Improving the sensitivity requires both more data and more importantly, better understanding/reducing the systematics.

Abdollah Mohammadi



Left, CMS, used only partial data samples, much more data available that might help shrinking Systematics → hope for better precision by 2025

Below, BaBar new tau polarimetry technique allowed to measure "nothing" with good precision! Can you try to measure "nothing" at Belle II by 2025?

Caleb Miller

Conclusions

Measurement of beam polarization at an e^+e^- B-Factory with a new tau polarimetry technique

- *BaBar* has implemented the first application of the new Tau Polarimetery technique to measure the PEP-II average beam polarization

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} + 0.0029_{\text{sys}}$$

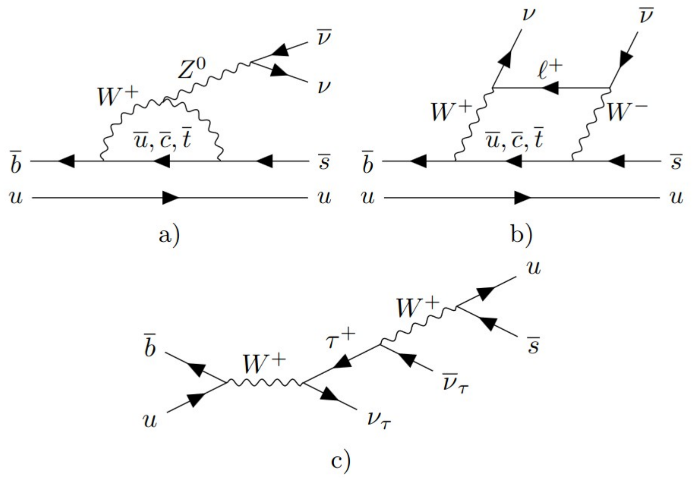
- Identified 21 sources of systematic uncertainty
- Modelling/Understanding of neutral processes dominates the largest systematics
- Tau Polarimetry could be applied at other e^+e^- colliders interested in polarization
- Final uncertainty exceeds Chiral Belle assumptions suggesting the experiment could make even more precise measurements

B decays involving missing energy

- Flavour-changing neutral currents forbidden at tree-level proceeds via loops

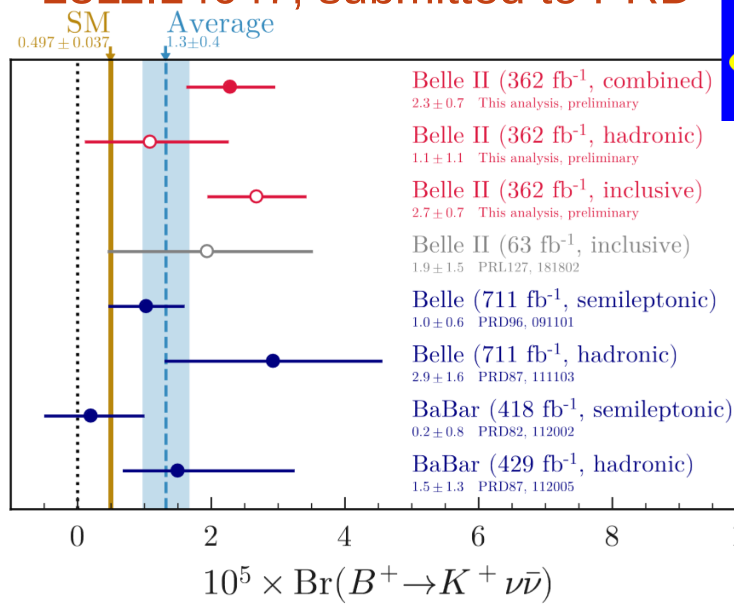
- Belle II studied

$B^+ \to K^+ \nu\bar{\nu}$



and reported the observation of the process with a significance of 3.5 σ, and a tension with SM predictions at the level of 2.8 σ.

2311.14647, submitted to PRD



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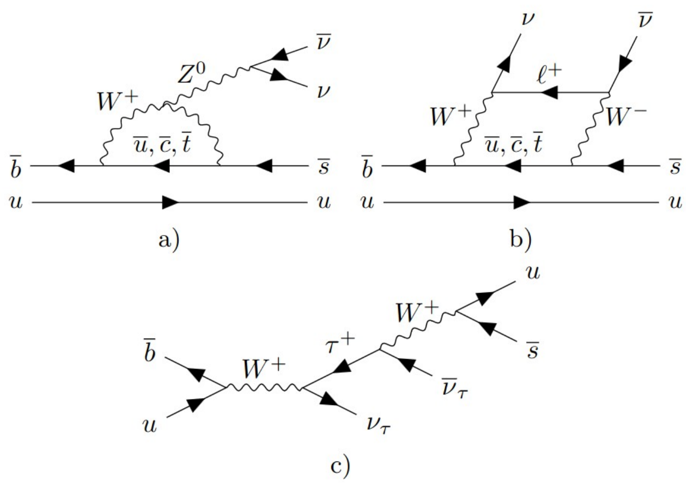

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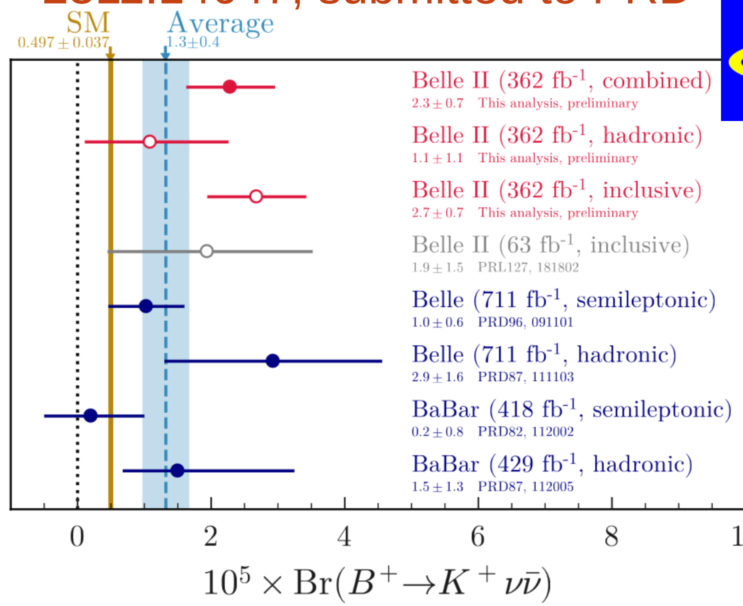
- How does this relate to τ?
  → because some models (ex. 2309.0005) assuming heavy NP, would predict enhancements of other channels, such us:

$B \to K^{(*)} \tau \tau \qquad B_s \to \tau \tau \qquad B \to K^{(*)} \tau l$

2311.14647, submitted to PRD



See this presentation for details

Decay	BF U.L. @ 90% CL			
$B_s \to \tau\tau$	5.2×10^{-3}	LHCb	$3\,fb^{-1}$	PRL 118.251802 (2017)
$B^+ \to K^+\tau\tau$	2.3×10^{-3}	BABAR	$424\,fb^{-1}$	PRL 118.031802 (2017)
$B^0 \to K^{*0}\tau\tau$	3.1×10^{-3}	Belle	$711\,fb^{-1}$	2110.03871

Can we expect some updates (LHCb), or maybe a measurement from Belle II, by 2025?

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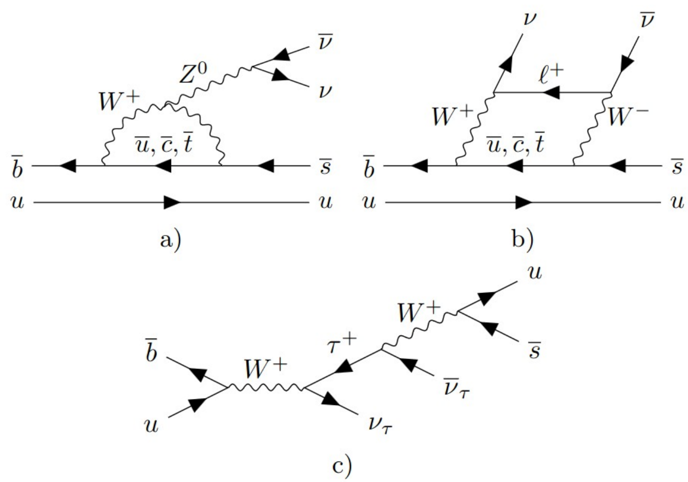

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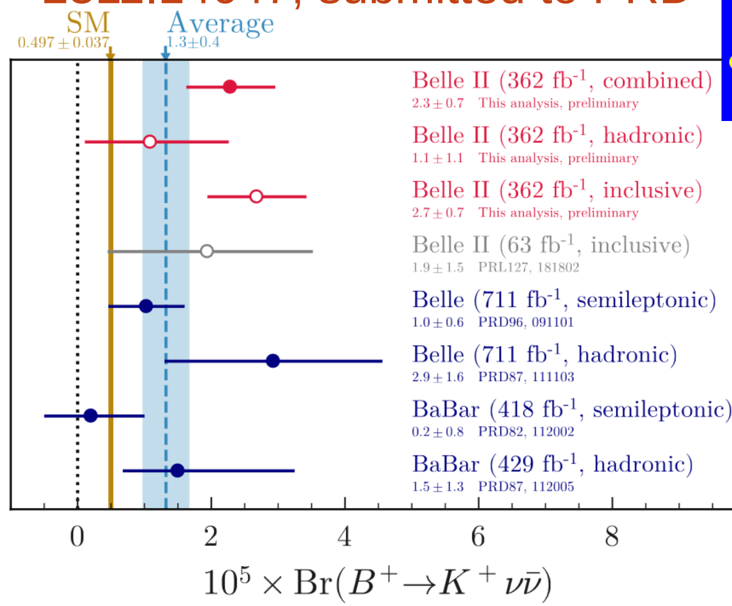

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Light New Physics in $B \to K^{(*)} \nu\bar{\nu}$?

Wolfgang Altmannshofer, Andreas Crivellin, Huw Haigh, Gianluca Inguglia, Jorge Martin Camalich

2311.14629, submitted to PRD

Can we expect some updates (LHCb), or maybe a measurement from Belle II, by 2025?

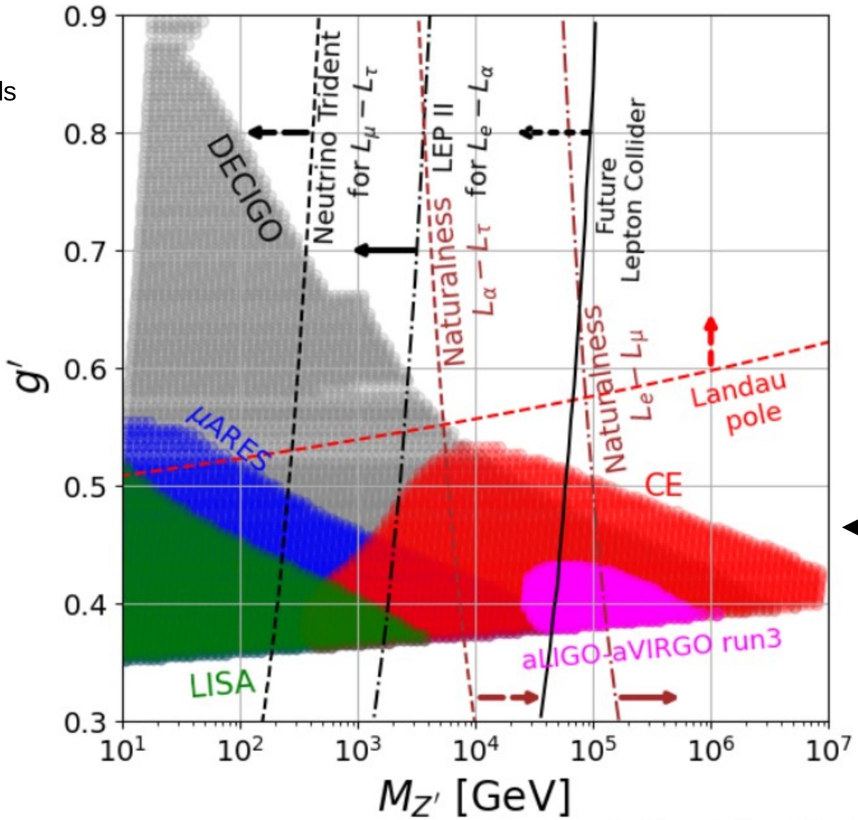
Gravitational waves probing fundamental physics, leptophilic Z’

Leptophilic Dark Portals

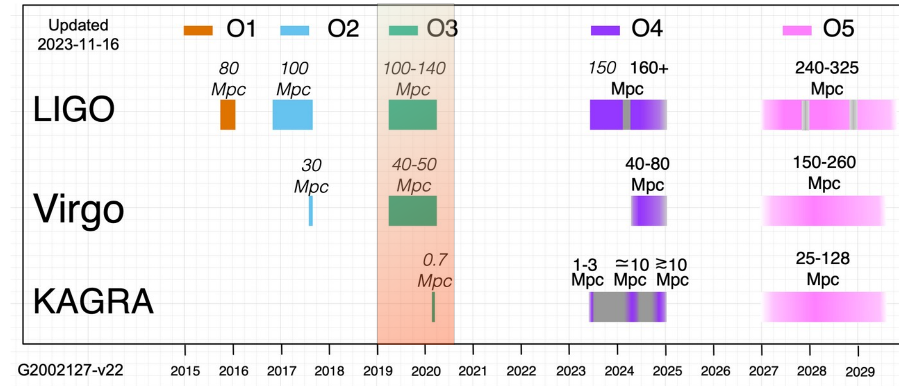
Bhupal Dev

First-order phase transition if scalar sector is conformally invariant:

$$V_{\rm tree} = \lambda_H (H^\dagger H)^2 + \lambda(\Phi^\dagger \Phi)^2 - \lambda'(\Phi^\dagger \Phi)(H^\dagger H)\,.$$



[Dasgupta, BD, Han, Padhan, Wang, Xie, 2308.12804 (JHEP ’23)]



This data used

We are here

Enhanced sensitivity with already available new set of data

- Heavy boson fields might be responsible for phase transitions, strong enough to generate gravitational waves → stochastic, not observed so far → set upper limits
- New, complementary, way with respect to typical HEP measurements with even more accessible parameter space.
- More analysis methodologies and results can be expected in the very near future.

Take home message, my wishlist for 2025

- Understanding the properties of τ is a fundamental step towards gaining a more complete understanding of the standard model and beyond.

- Many players: hadron colliders, high/middle/low-energy electron-positron colliders.

- The τ mass is being measured with higher precision using different techniques, but absolute Bf and lifetime need an update.
  - Current understanding is based on measurements performed in the 90s. Facilities that could update these measurements should do so.
  - Also new CP violation tests are needed.

- Precision tests of the SM from τ processes (i.e. LFU, CKM, LFV, EDM, etc.) can be used to discover or constrain new physics. It's not always about adding more data, but we need to understand better the data $\rightarrow$ lower systematics should be a priority.

- If the excess reported by @Belle II in $B^+ \rightarrow K^+ \nu \bar{\nu}$ is due to NP, then we might observe something also in rare B decays involving τ, updates would be welcome.

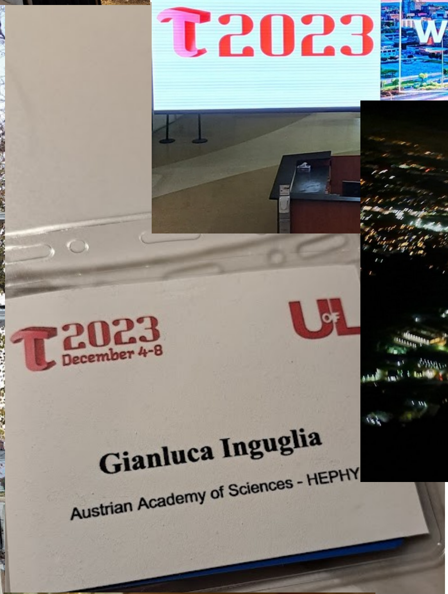
- Unconventional ways to study fundamental physics are being developed (gravitational waves, first-order phase transitions), let's keep an eye on that and see what O4 brings that could be relevant to us.

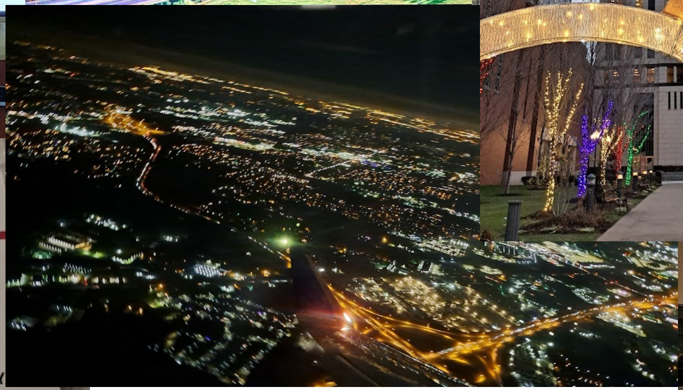

The GALT
NO STOPPING ANY TIME
GALT HOUSE


LOUISVILLE
MUHAMMAD ALI
INTERNATIONAL AIRPORT
τ2023
WELCOME TO LOUISVILLE


the old spaghetti factory


HOTEL
THE HAUNTED HOTEL

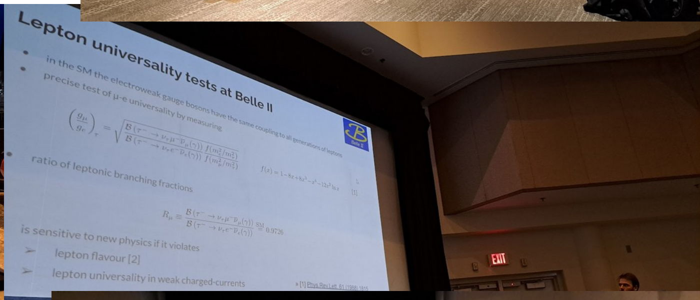

τ2023
December 4-8
Gianluca Inguglia
Austrian Academy of Sciences - HEPHY

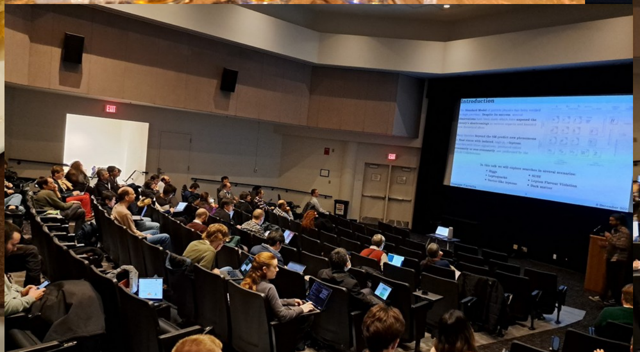


Thank you!!


FOURTH STREET
Live!


OLD FORESTER
1870
OLD FORESTER
1897
OLD FORESTER
1920


Lepton universality tests at Belle II
ratio of leptonic branching fractions
is sensitive to new physics if it violates
lepton flavour [2]
lepton universality in weak charged currents



$\Upsilon(nS) \to \tau\mu$ decays at Belle 2

Lepton flavor violating quarkonium decays

Derek E. Hazard and Alexey A. Petrov

https://arxiv.org/pdf/1607.00815.pdf

Phys. Rev. D 94, 074023 – Published 17 October 2016

"Any new physics model that incorporates flavor and involves flavor-violating interactions at high energy scales can be cast in terms of the effective Lagrangian of Eq. (1) at low energies. We argued that Wilson coefficients of this Lagrangian could be effectively probed by studying decays of quarkonium states with different spin-parity quantum numbers, providing complementary constraints to those obtained from tau and mu decays"

	Leptons	Initial state (quark)				
Wilson coefficient (GeV^{-2})	$\ell_1\ell_2$	$\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	ϕ (s)
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\lvert C_{VL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\lvert C_{VR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\lvert C_{TL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\lvert C_{TR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}