τ Physics

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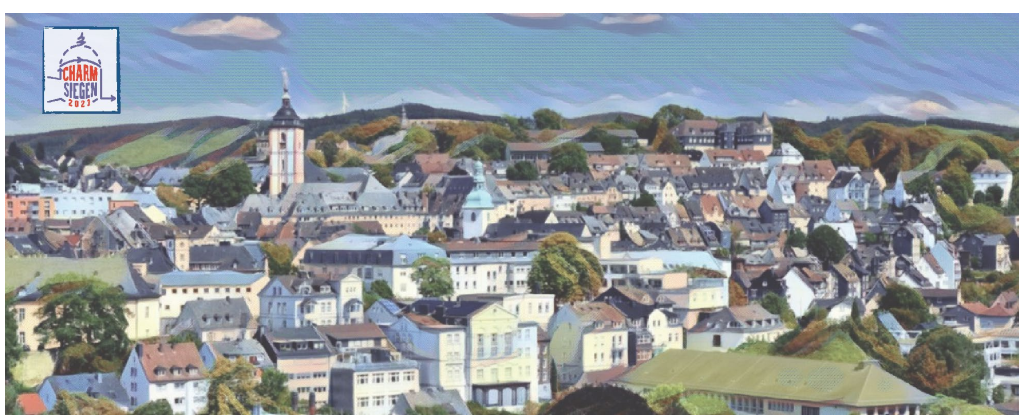
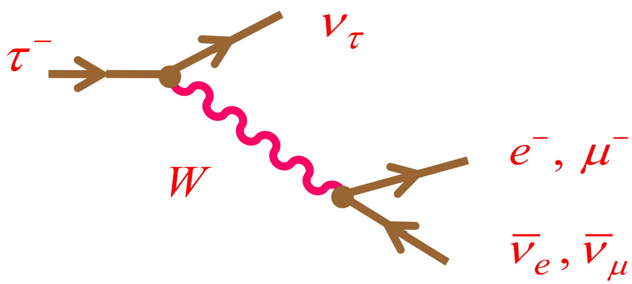


CHARM 2023
Siegen, Germany
17-21 July 2023

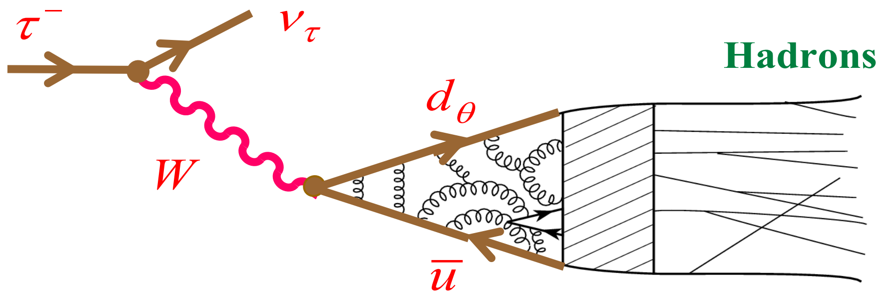
A.P., Prog. Part. Nucl. Phys. 75 (2014) 41

τ Physics

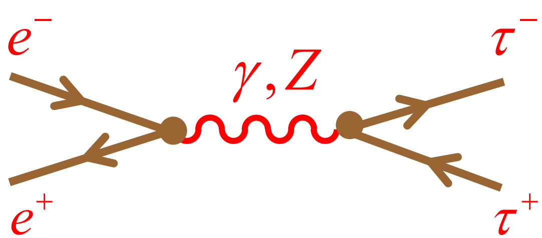
Decay



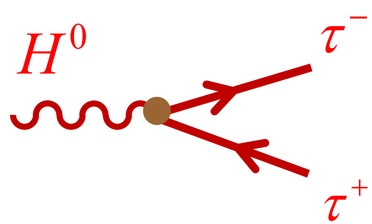
QCD

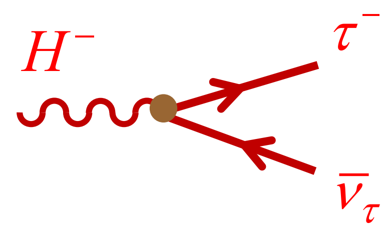


Production

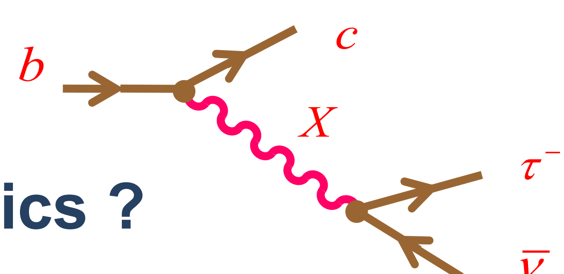


Higgs Interactions

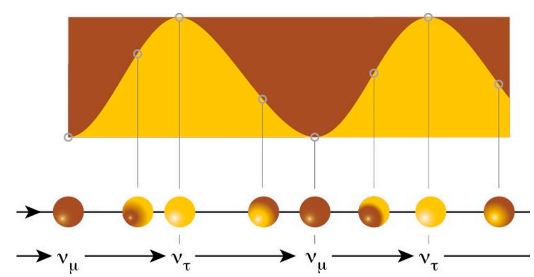




?



New Physics ?



Neutrinos

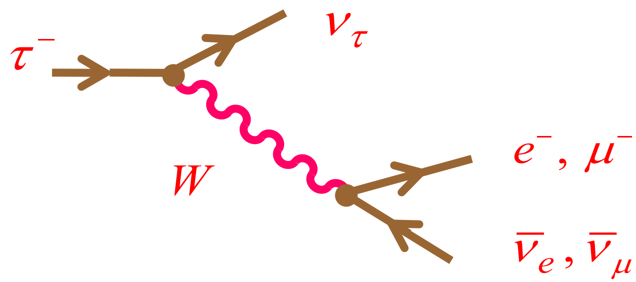
τ Data Samples

ALEPH:	$3.3\cdot 10^5$ reconstructed τ decays	
BaBar / Belle:	$1.4\cdot 10^9$ $\tau^+\tau^-$ pairs	
Belle-II:	$4.6\cdot 10^{10}$ $\tau^+\tau^-$ pairs	
sτcF:	$2.1\cdot 10^{10}$ $\tau^+\tau^-$ pairs	(10^8 near threshold)
Tera-Z:	$1.7\cdot 10^{11}$ $\tau^+\tau^-$ pairs	

Luminosity is important. Systematics & backgrounds also!

Different experimental conditions at different energies
($\tau^+\tau^-$ threshold, ψ, Υ, Z)

LEPTONIC DECAYS

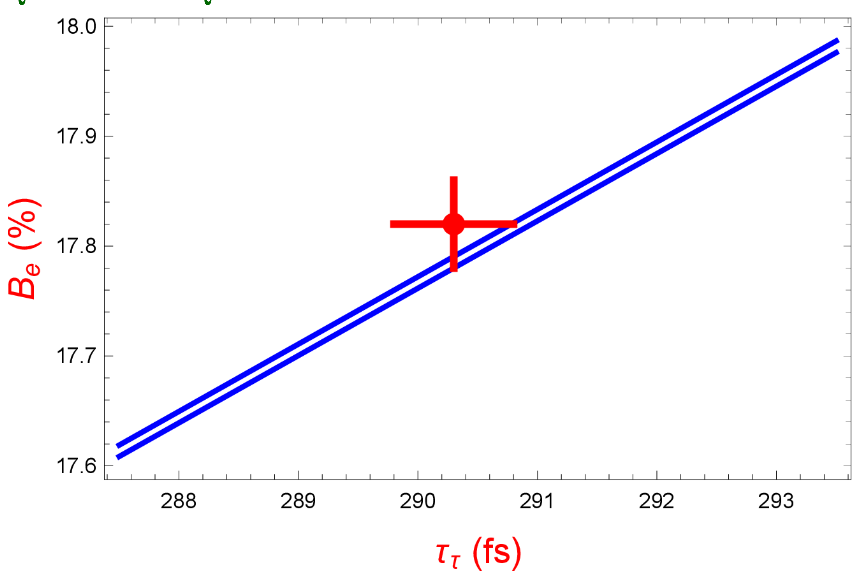


$$\Gamma(\tau \to \nu_\tau\, l\, \bar{\nu}_l) = \frac{G_F^2\, m_\tau^5}{192\,\pi^3}\, f(m_l^2/m_\tau^2)\, \left(1 + \delta_{\rm RC}\right)$$

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

$$B_e = \frac{B_\mu}{0.972564 \pm 0.000003} = \frac{\tau_\tau}{(1632.3 \pm 0.5) \times 10^{-15}\,\text{s}}$$

τ_τ (Belle), m_τ (BesIII, BelleII)



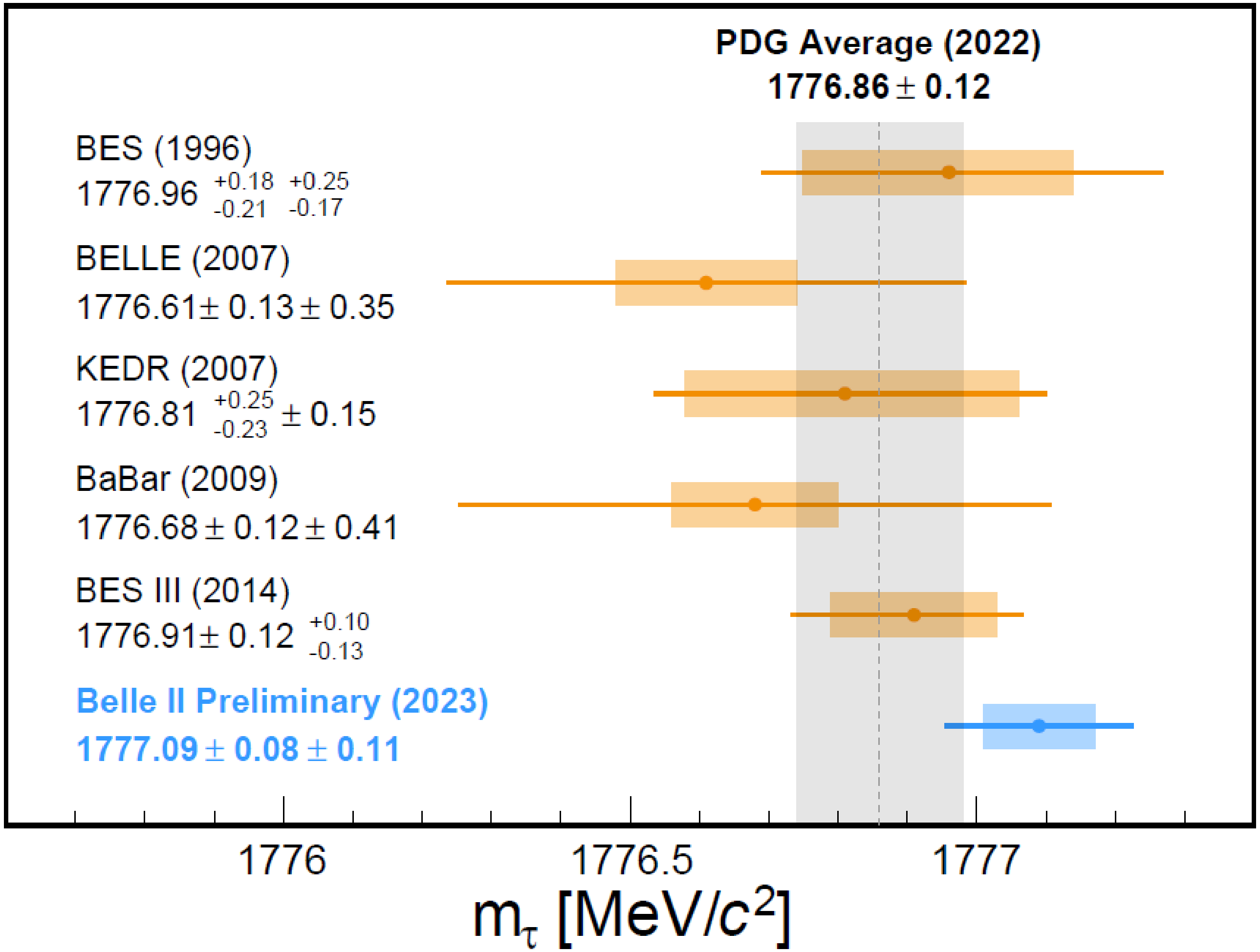
$$\left(B_\mu / B_e\right)_{\rm exp} = 0.9762 \pm 0.0028$$

Non-BF: 0.9725 ± 0.0039

BaBar '10: 0.9796 ± 0.0039

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

Preliminary Belle-II measurement of m_τ

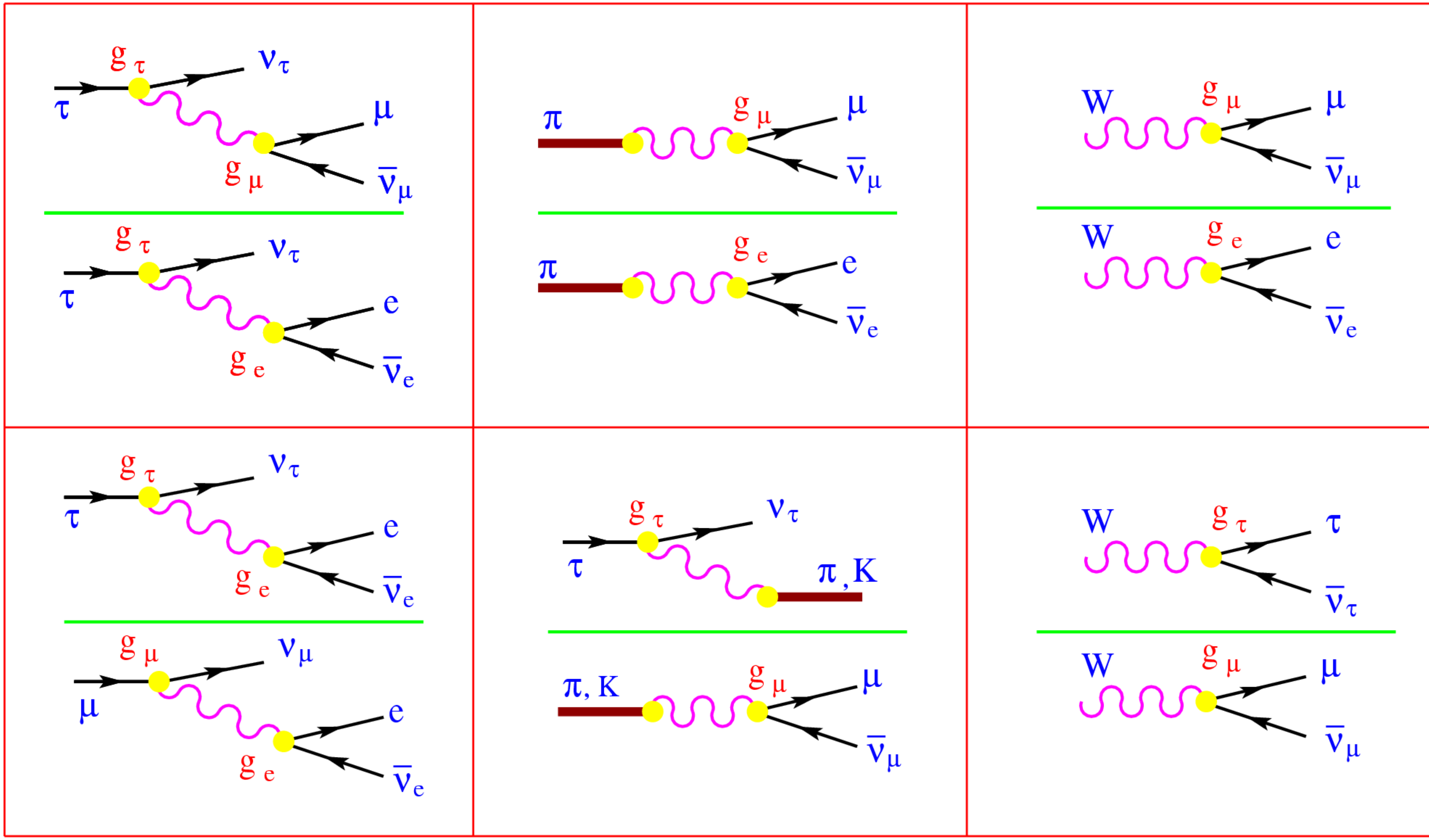


$m_\tau = (1776.96 \pm 0.09)$ MeV

Lepton Universality

$\frac{g_\mu}{g_e}$

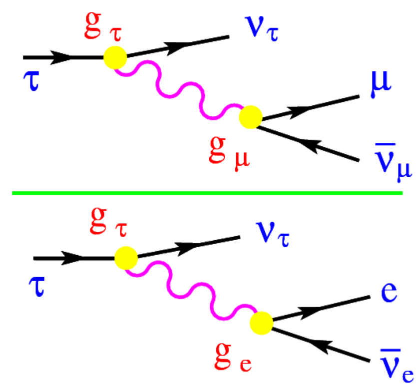
$\frac{g_\tau}{g_\mu}$

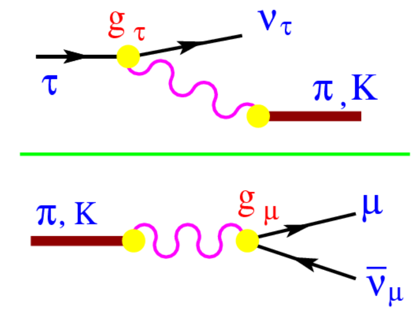


Lepton Universality

$$\left| g_\mu / g_e \right|$$

$B_{\tau\to\mu} / B_{\tau\to e}$	1.0019 ± 0.0014
$B_{\pi\to\mu} / B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu} / B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu} / B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu} / B_{W\to e}$	1.001 ± 0.003





$$\left| g_\tau / g_e \right|$$

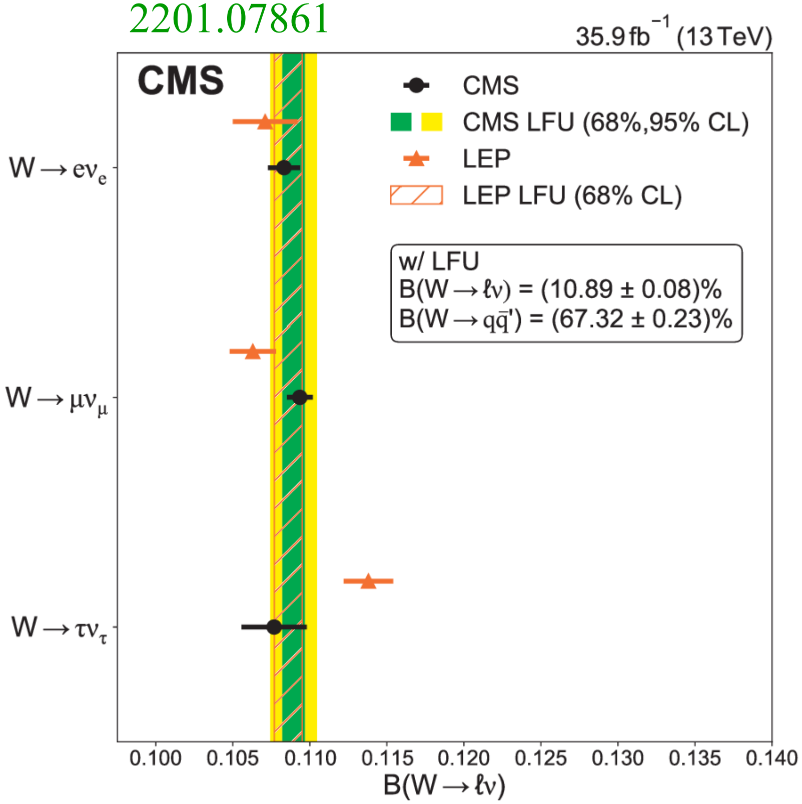
$B_{\tau\to\mu}\; \tau_\mu / \tau_\tau$	1.0027 ± 0.0014
$B_{W\to\tau} / B_{W\to e}$	1.007 ± 0.010

$$\left| g_\tau / g_\mu \right|$$

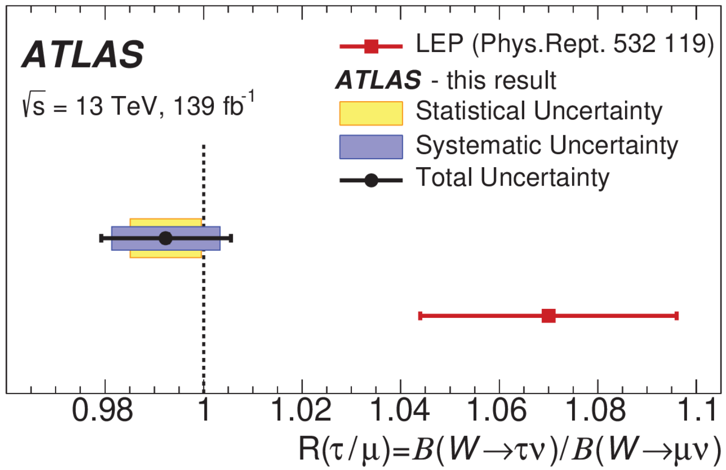
$B_{\tau\to e}\; \tau_\mu / \tau_\tau$	1.0009 ± 0.0014
$\Gamma_{\tau\to\pi} / \Gamma_{\pi\to\mu}$	0.9959 ± 0.0038
$\Gamma_{\tau\to K} / \Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau} / B_{W\to\mu}$	1.001 ± 0.010

Lepton Universality in W decays

2201.07861



2007.14040

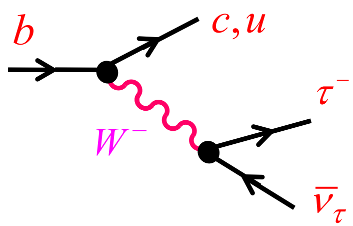


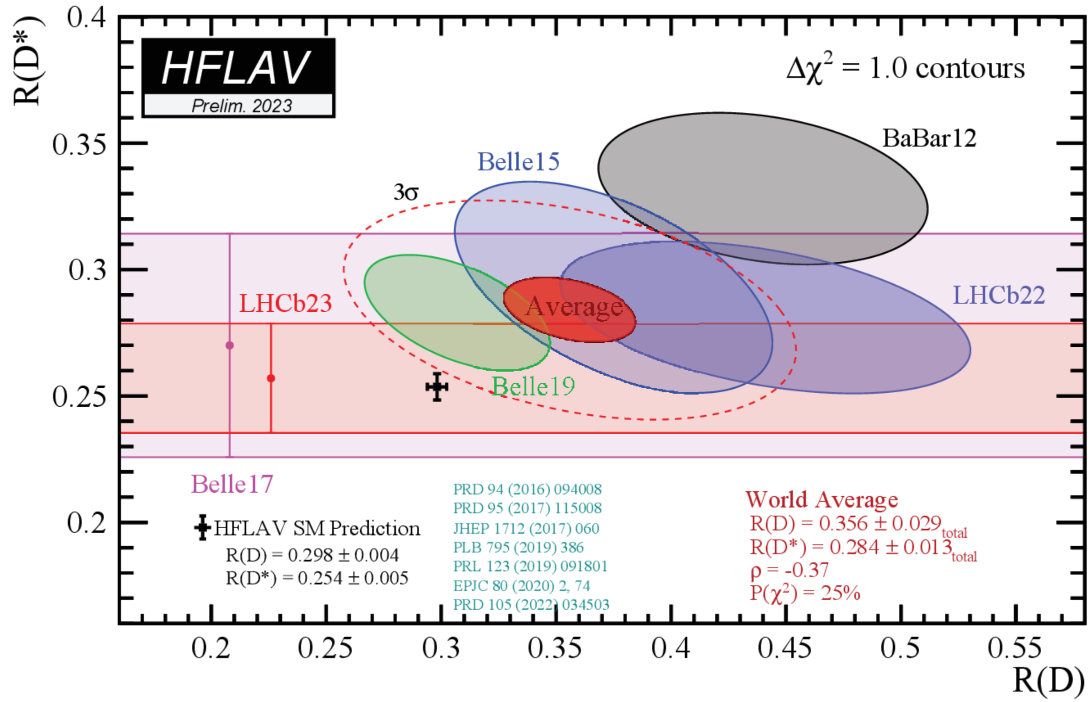
	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

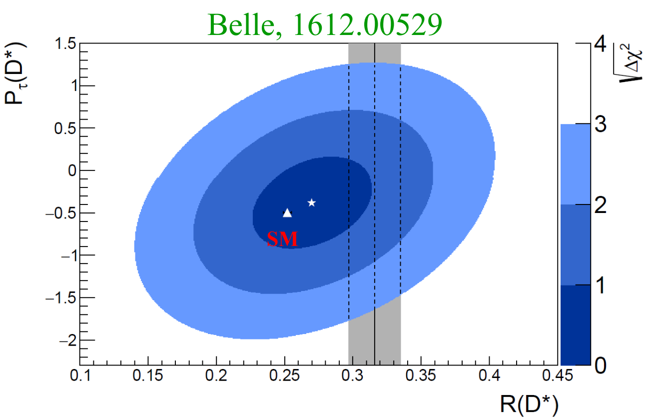
Flavour Anomaly

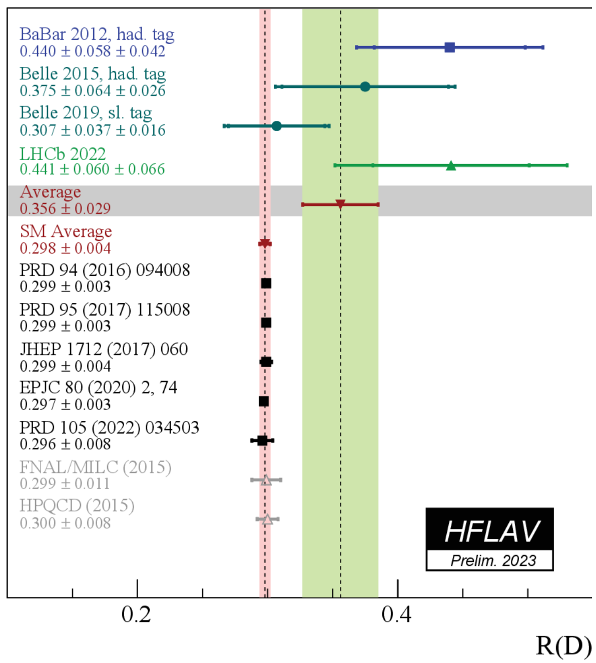
3.2 σ discrepancy

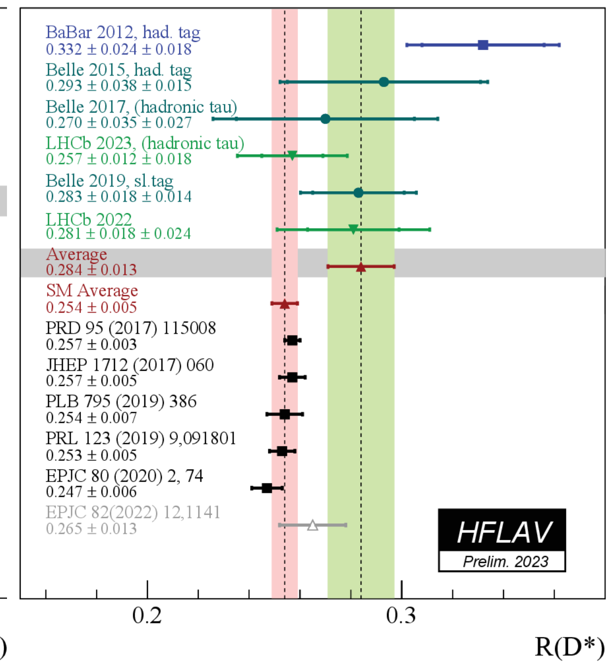
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$











$$\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18 \qquad (1.7\,\sigma)$$

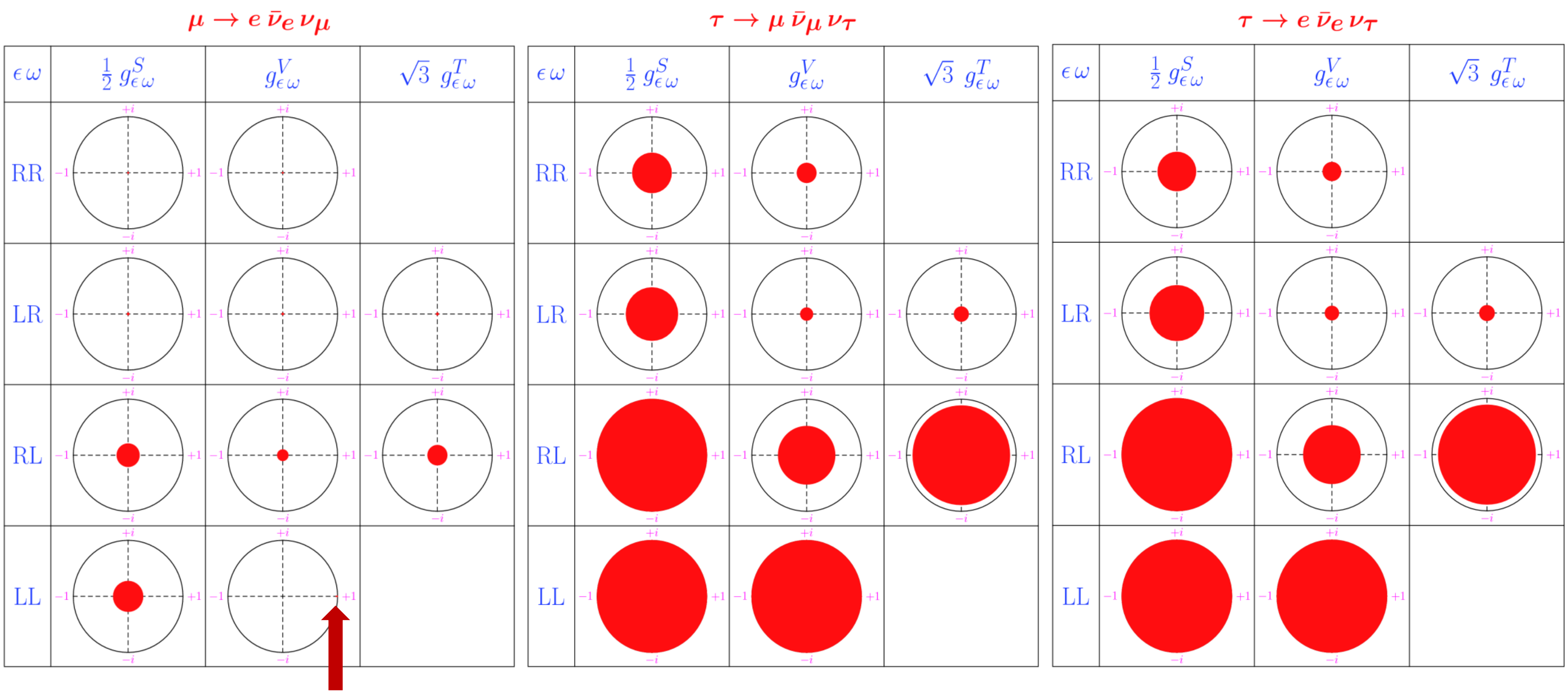
$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04 \qquad (1.6\,\sigma)$$

$$\mathcal{R}^{\mathrm{SM}}_{J/\psi} \approx 0.26 - 0.28 \qquad F^{D^*}_{L,\mathrm{SM}} = 0.455 \pm 0.003$$

Lorentz Structure: $\ell^- \to \ell'^- \bar{\nu}_{\ell'} \nu_\ell$

Effective Hamiltonian: $$\mathcal{H} = 4\,\frac{G_{\ell'\ell}}{\sqrt{2}} \sum_{n,\epsilon,\omega} g^n_{\epsilon\omega} \left[\overline{\ell'_\epsilon}\Gamma^n(\nu_{\ell'})_\sigma\right] \left[\overline{(\nu_\ell)_\lambda}\Gamma_n \ell_\omega\right]$$

Normalization: $$\Gamma \propto \frac{1}{4}\left(|g^S_{RR}|^2 + |g^S_{RL}|^2 + |g^S_{LR}|^2 + |g^S_{LL}|^2\right) + 3\left(|g^T_{RL}|^2 + |g^T_{LR}|^2\right) + \left(|g^V_{RR}|^2 + |g^V_{RL}|^2 + |g^V_{LR}|^2 + |g^V_{LL}|^2\right) \equiv 1$$



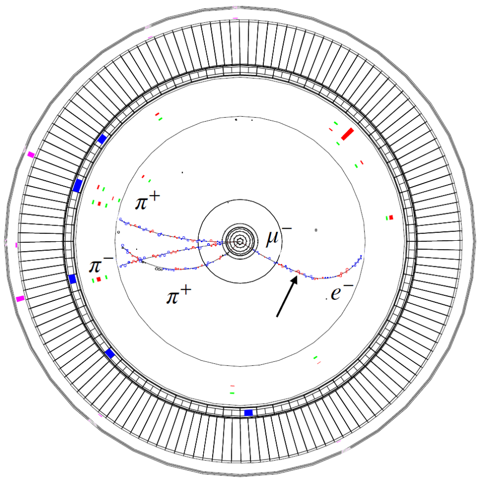
$|g^V_{LL}| > 0.960$ (90% CL)

High-precision τ data needed!

μ^- Longitudinal Polarization in $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

Probability to decay into a right-handed muon:

$$Q_{\mu_R} = Q_{RR} + Q_{RL} = \frac{1}{4}\left(|g^S_{RR}|^2 + |g^S_{RL}|^2\right) + 3\,|g^T_{RL}|^2 + |g^V_{RR}|^2 + |g^V_{RL}|^2 = \frac{1}{2}\left(1 - \xi'\right)$$



MC $\tau^+\tau^-$ event

Belle, 2303.10570

Tiny probability of muon decaying inside the detector compensated by huge statistics

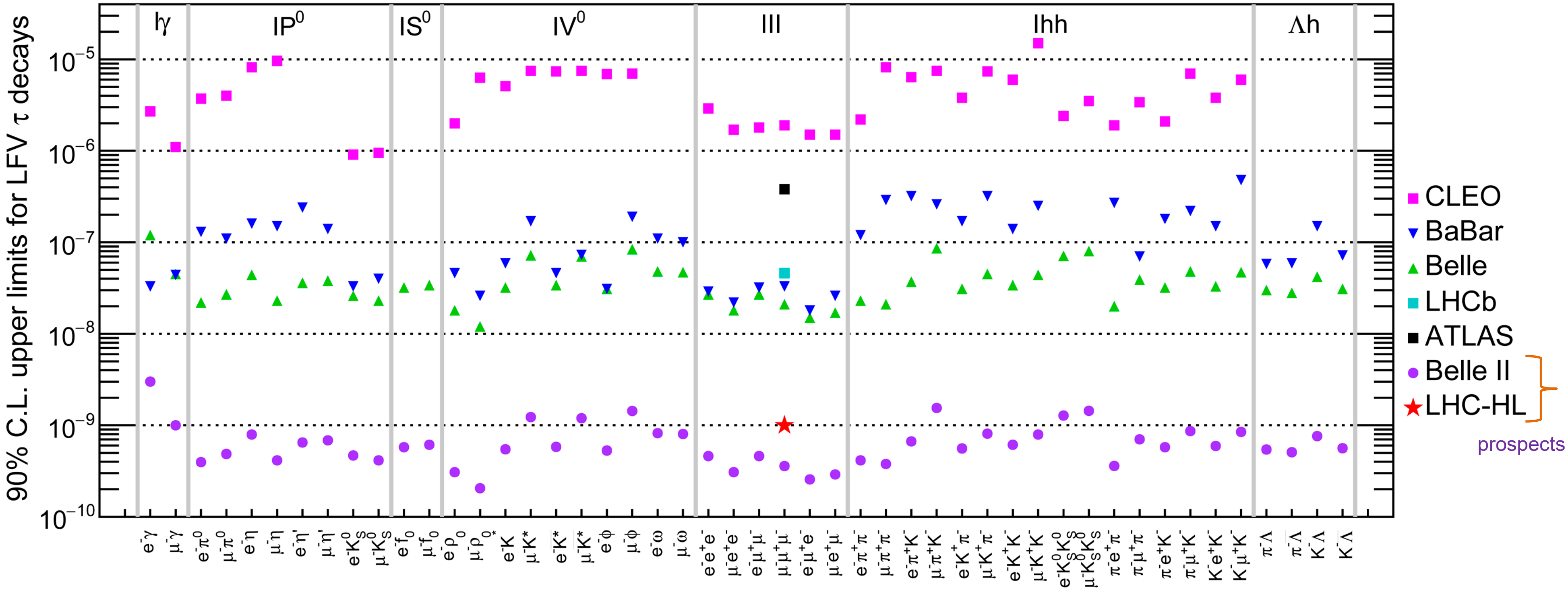
$$\xi' = 0.22 \pm 0.94 \pm 0.42$$

$$Q_{\mu_R} \le 1.23 \quad (90\%\ \mathrm{CL})$$

Not yet constraining. Error dominated by statistics…

Bounds on Lepton Flavour Violation

τ Decays (90% CL)



$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (MEG, 90% CL) , $\mathrm{Br}(\mu \to 3e) < 1.0 \times 10^{-12}$ (SINDRUM, 90% CL)

$\mathrm{Br}(K_L \to \mu e) < 4.7 \times 10^{-12}$ (BNL-E871, 90% CL) , $\mathrm{Br}(K^+ \to \pi^+\mu^+e^-) < 1.3 \times 10^{-11}$ (BNL-E865, 90% CL)

$\mathrm{Br}(B^0 \to e\mu) < 1.0 \times 10^{-9}$ (LHCb, 90% CL) , $\mathrm{Br}(D^0 \to e\mu) < 1.3 \times 10^{-8}$ (LHCb, 90% CL)

$\mathrm{Br}(Z^0 \to e\mu) < 7.5 \times 10^{-7}$ (ATLAS, 95% CL) , $\mathrm{Br}(H \to e\mu) < 6.1 \times 10^{-5}$ (ATLAS, 95% CL)

$\mathrm{Br}(Z^0 \to e\tau) < 5.0 \times 10^{-6}$ (ATLAS, 95% CL) , $\mathrm{Br}(H \to e\tau) < 2.2 \times 10^{-3}$ (CMS, 95% CL)

$\mathrm{Br}(Z^0 \to \mu\tau) < 6.5 \times 10^{-6}$ (ATLAS, 95% CL) , $\mathrm{Br}(H \to \mu\tau) < 1.5 \times 10^{-3}$ (CMS, 95% CL)

CP Asymmetry

$$A_\tau \equiv \frac{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)} = (-3.6 \pm 2.3 \pm 1.1) \cdot 10^{-3}$$

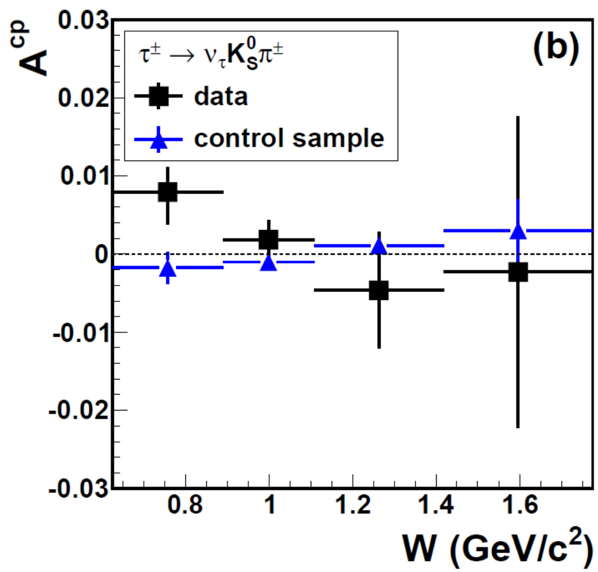
BaBar'11 $(\geq 0\,\pi^0)$

$$A_\tau^{\mathrm{SM}}\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) = (3.6 \pm 0.1) \cdot 10^{-3}$$

Bigi-Sanda, Grossman-Nir

2.8 σ discrepancy

Belle does not see any asymmetry at the 10^{-2} level



$$A_i^{\mathrm{CP}} \simeq \langle \cos\beta \cos\psi \rangle_i^{\tau^-} - \langle \cos\beta \cos\psi \rangle_i^{\tau^+}$$

bins (i) of $W = \sqrt{Q^2}$

$\beta = K_S$ direction in hadronic rest frame

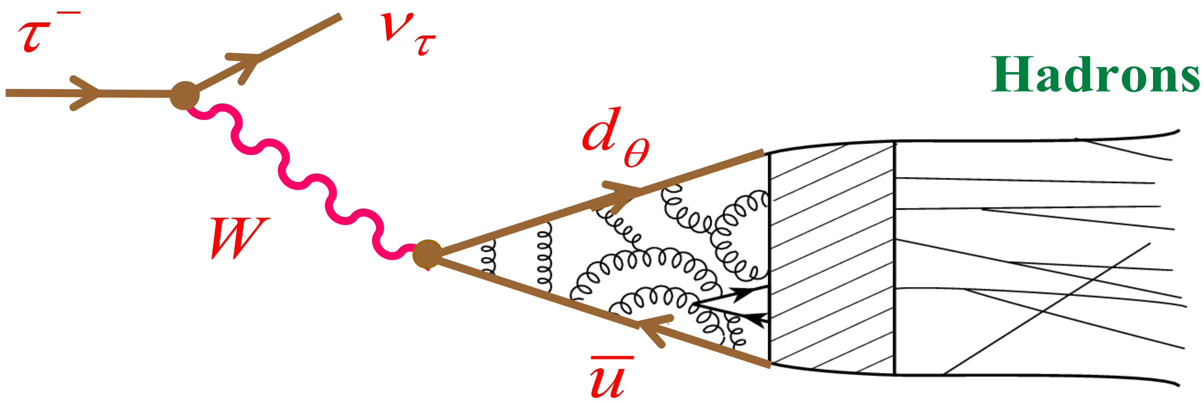
$\psi = \tau$ direction

BaBar signal incompatible (with EFT) with other sets of flavour data

Cirigliano-Crivellin-Hoferichter, 1712.06595

Rendón-Roig-Toledo, 1902.08143

HADRONIC TAU DECAY



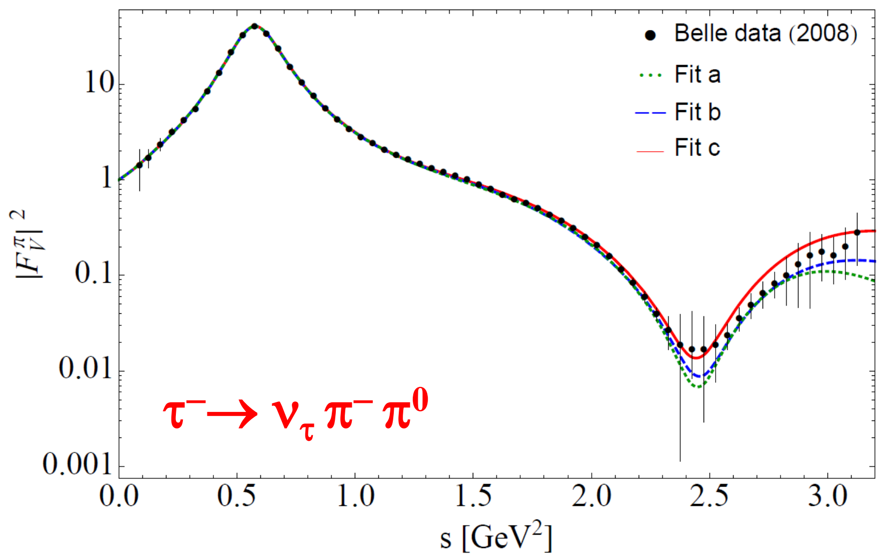
$$d_\theta = V_{ud}\, d + V_{us}\, s$$

Only lepton massive enough to decay into hadrons

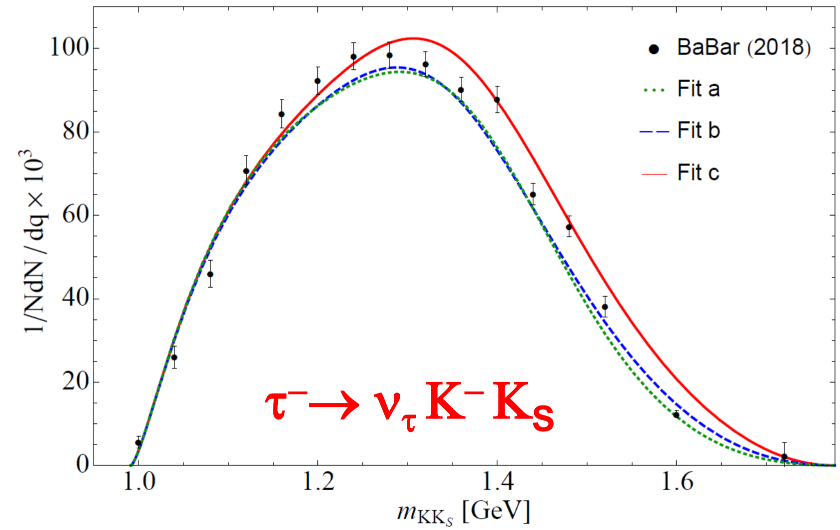
$$R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{Hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau\, e^- \overline{\nu}_e\right)} \approx N_C \qquad ; \qquad R_\tau = \frac{1 - B_e - B_\mu}{B_e^{\text{univ}}} = 3.6381 \pm 0.0075$$

$$R_\tau = \frac{1}{B_e^{\text{univ}}} - 1.972564 = 3.6417 \pm 0.0070 \qquad ; \qquad R_\tau = \frac{\text{Br}\left(\tau^- \to \nu_\tau + \text{Hadrons}\right)}{B_e^{\text{univ}}} = 3.6343 \pm 0.0082$$

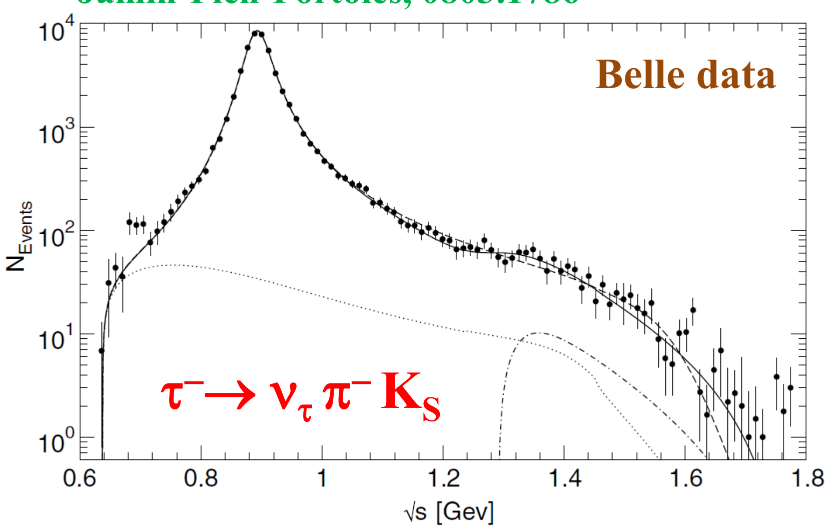
Invariant Mass Spectra



Gónzàlez-Solís – Roig, 1902.02273



Jamin-Pich-Portolés, 0803.1786



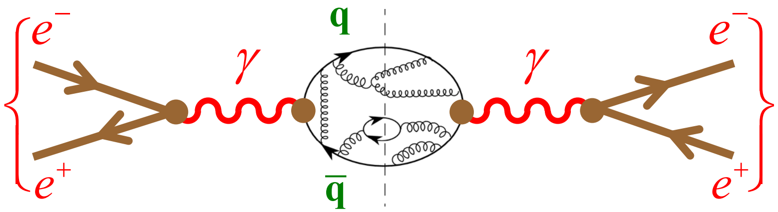
Useful tests of QCD Dynamics

Form Factors

Non-perturbative parameters

Resonance Chiral Theory (RχT)

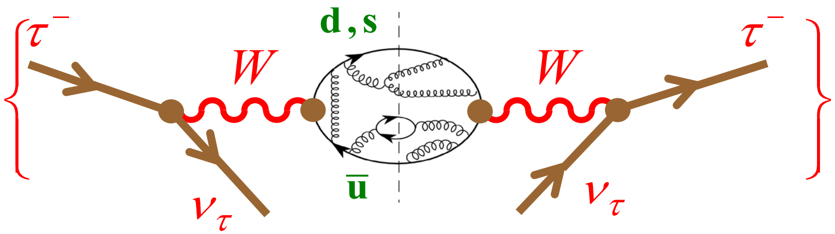
$\sigma \sim \mathrm{Im}$



$$\frac{\sigma(e^+e^-\to \mathrm{had})}{\sigma(e^+e^-\to \mu^+\mu^-)} = 12\pi\ \mathrm{Im}\,\Pi_{\mathrm{em}}(s)$$

$$\Pi^{\mu\nu}_{\mathrm{em}}(q) \equiv i\int d^4x\ e^{iqx}\,\langle 0|T[J^\mu_{\mathrm{em}}(x)\,J^\nu_{\mathrm{em}}(0)]|0\rangle = \left(-g^{\mu\nu}q^2+q^\mu q^\nu\right)\Pi_{\mathrm{em}}(q^2)$$

$\Gamma_{\tau\to\nu_\tau+\mathrm{had}} \sim \mathrm{Im}$



$$R_\tau \equiv \frac{\Gamma(\tau^-\to\nu_\tau+\mathrm{had})}{\Gamma(\tau^-\to\nu_\tau e^-\bar{\nu}_e)} = 12\pi\int_0^{m_\tau^2}\frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2\left[\left(1+2\frac{s}{m_\tau^2}\right)\mathrm{Im}\,\Pi^{(1)}(s)+\mathrm{Im}\,\Pi^{(0)}(s)\right]$$

$$\Pi^{(J)}(s) \equiv |V_{ud}|^2\left[\Pi^{(J)}_{ud,V}(s)+\Pi^{(J)}_{ud,A}(s)\right] + |V_{us}|^2\left[\Pi^{(J)}_{us,V}(s)+\Pi^{(J)}_{us,A}(s)\right]$$

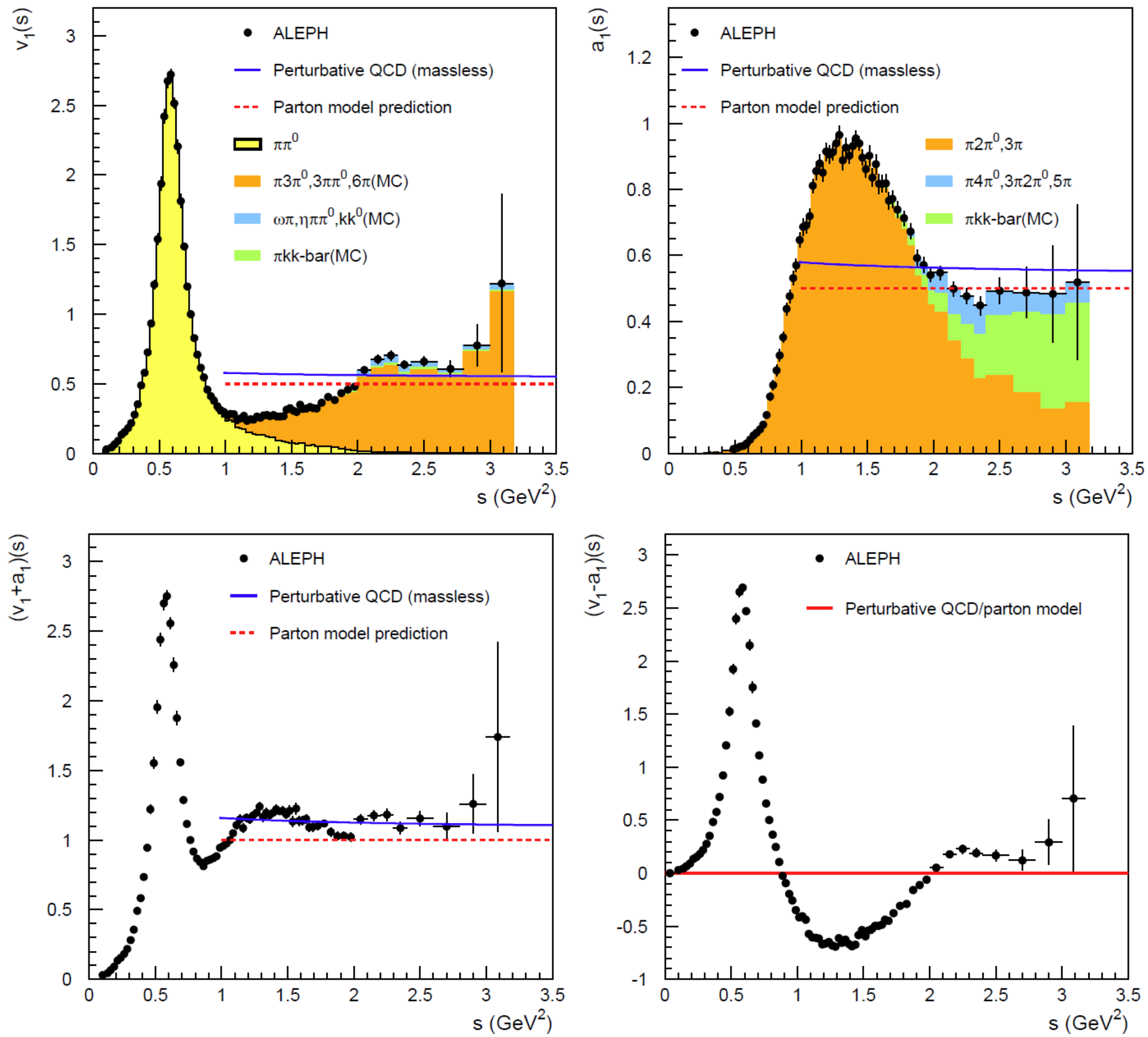
$$\Pi^{\mu\nu}_{ij,J}(q) \equiv i\int d^4x\ e^{iqx}\,\langle 0|T[J^\mu_{ij}(x)\,J^\nu_{ij}(0)^\dagger]|0\rangle = \left(-g^{\mu\nu}q^2+q^\mu q^\nu\right)\Pi^{(1)}_{ij,J}(q^2) + q^\mu q^\nu\ \Pi^{(0)}_{ij,J}(q^2)$$

SPECTRAL FUNCTIONS

Davier et al, 1312.1501

$$v_1(s) = 2\pi\, \mathrm{Im}\, \Pi^{(0+1)}_{ud,V}(s)$$

$$a_1(s) = 2\pi\, \mathrm{Im}\, \Pi^{(0+1)}_{ud,A}(s)$$



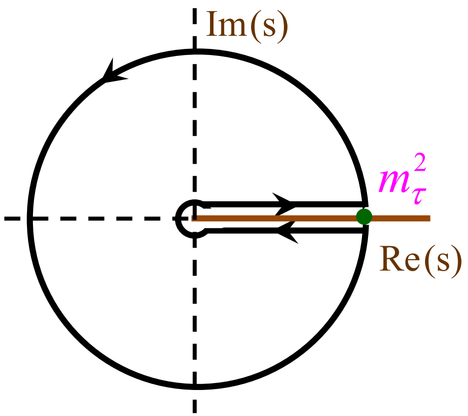
Better data needed

QCD Prediction of R_τ

Braaten-Narison-Pich'92

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{had})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = 12\pi \int_0^1 dx\,(1-x)^2 \left[(1+2x)\,\text{Im}\,\Pi^{(1)}(x m_\tau^2) + \text{Im}\,\Pi^{(0)}(x m_\tau^2)\right]$$

$x \equiv s/m_\tau^2$



$$R_\tau = 6\pi i \oint_{|x|=1} dx\,(1-x)^2 \left[(1+2x)\,\Pi^{(0+1)}(x m_\tau^2) - 2x\,\Pi^{(0)}(x m_\tau^2)\right]$$

$$\Pi^{(J)}(s) = \sum_{D=2n} \frac{C_D^{(J)}(s,\mu)\,\langle O_D(\mu)\rangle}{(-s)^{D/2}}$$

OPE

$$R_\tau = N_C\, S_{\text{EW}} \left(1 + \delta_{\text{P}} + \delta_{\text{NP}}\right) = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$$

$S_{\text{EW}} = 1.0201\,(3)$; $\delta_{\text{NP}} = -0.0064 \pm 0.0013$

Marciano-Sirlin, Braaten-Li, Erler — **Fitted from data (Davier et al)**

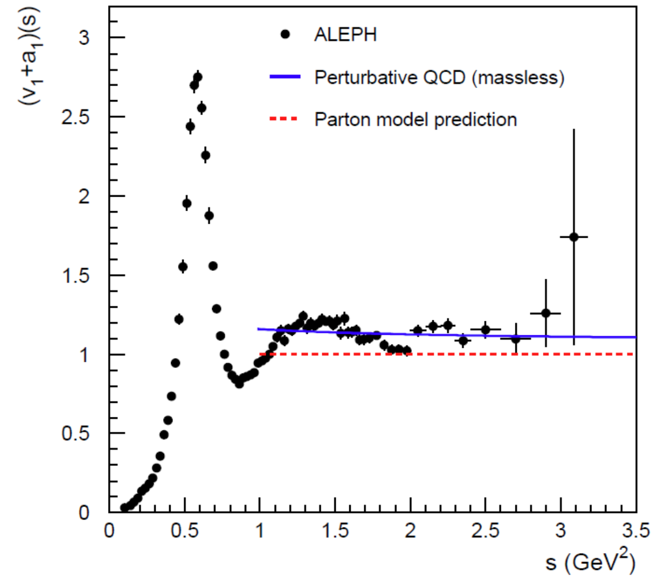
$\delta_{\text{P}} = a_\tau + 5.20\, a_\tau^2 + 26\, a_\tau^3 + 127\, a_\tau^4 + \ldots \approx 20\%$; $a_\tau \equiv \alpha_s(m_\tau)/\pi$

Baikov-Chetyrkin-Kühn

Spectral Function Distribution

Moments:

$$R_\tau^{kl}(s_0) \equiv \int_0^{s_0} ds \left(1-\frac{s}{s_0}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_\tau}{ds}$$



Sensitivity to power corrections (k,l)

The non-perturbative contribution to R_τ can be obtained from the invariant-mass distribution of the final hadrons

Detailed analyses by ALEPH, CLEO and OPAL

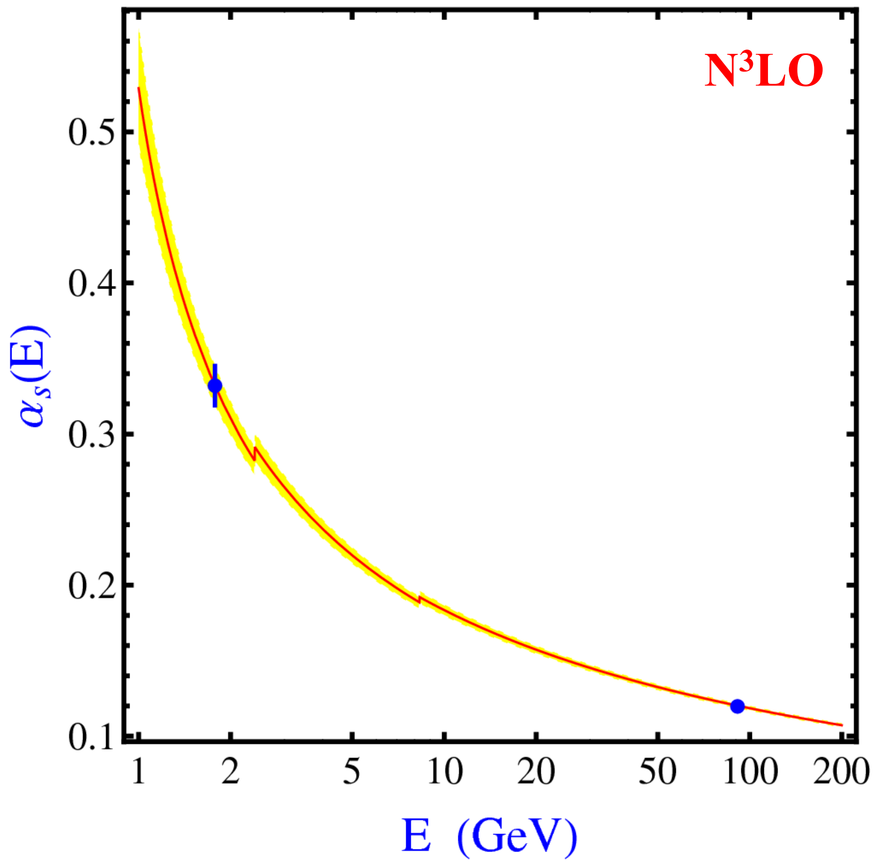
$$\delta_{\mathrm{NP}} = -0.0064 \pm 0.0013$$

$$\alpha_s(m_\tau^2) = 0.332 \pm 0.005_{\mathrm{exp}} \pm 0.011_{\mathrm{th}}$$

Davier et al., 1312.1501
(ALEPH data)

α_s at N³LO from τ and Z

Rodríguez-Sánchez, Pich, 1605.06830



$$\alpha_s(m_\tau^2) = 0.328 \pm 0.013$$

$$\alpha_s(M_Z^2) = 0.1197 \pm 0.0015$$

$$\alpha_s(M_Z^2)_{Z\,\text{width}} = 0.1199 \pm 0.0029$$

Very precise test of Asymptotic Freedom

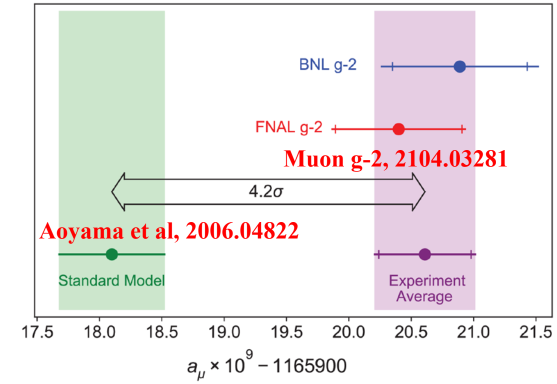
$$\alpha_s^\tau(M_Z^2) - \alpha_s^Z(M_Z^2) = 0.0002 \pm 0.0015_\tau \pm 0.0029_Z$$

Improved spectral function data ➡ Better control of non-perturbative contributions

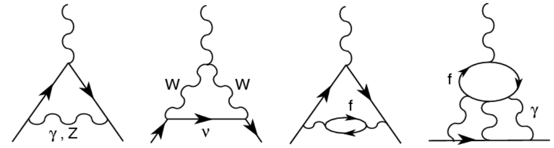
Rodríguez-Sánchez, Pich, 2205.07587

Better theoretical understanding of higher-order perturbative corrections needed
(CIPT / FOPT, K_5, renormalons…) Hoang et al, Golterman et al…

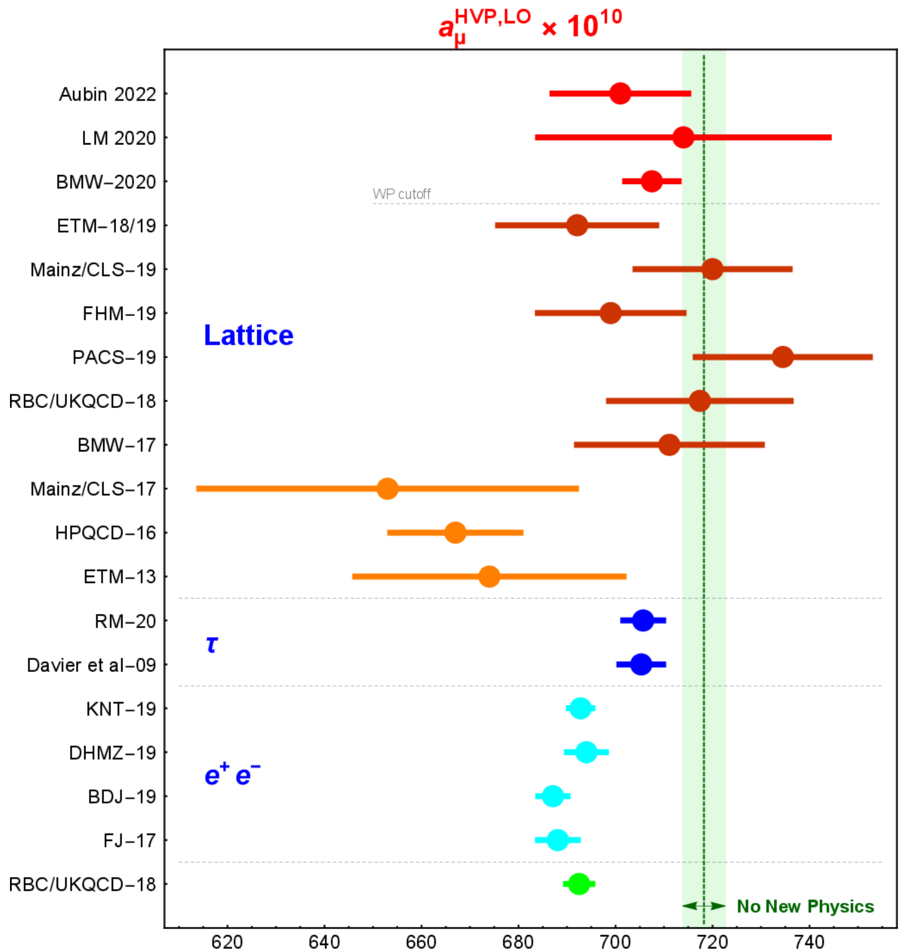
μ Anomalous Magnetic Moment

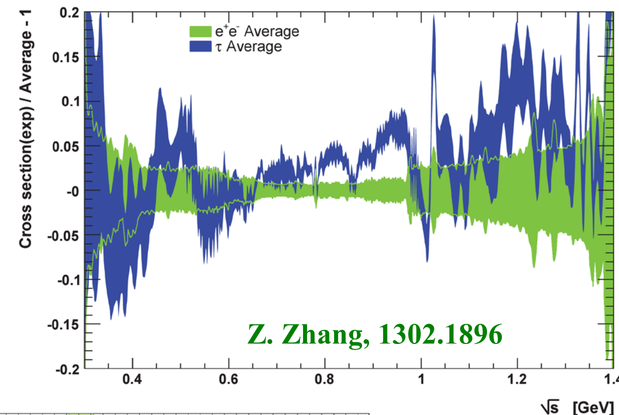


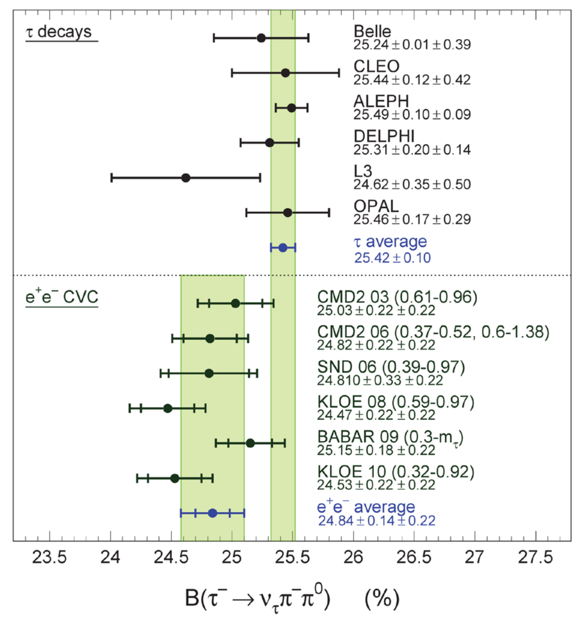
$$a_\mu^{\rm HVP,LO} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{s_{\rm th}}^{\infty} \frac{ds}{s^2}\, \hat{K}(s)\, R(s)$$



Dominated (75%) by 2π

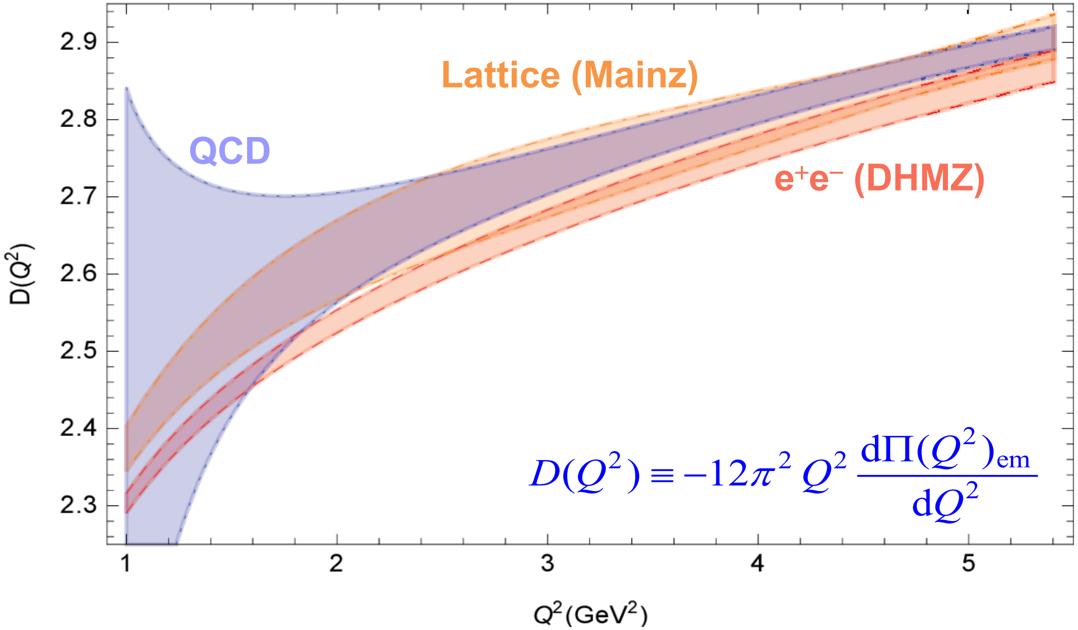






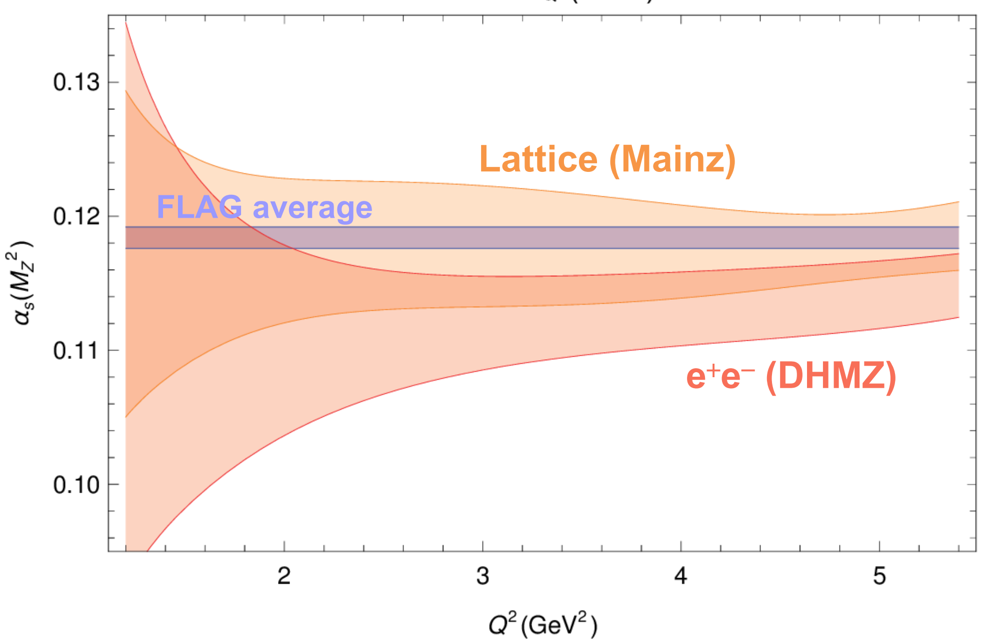
M. Davier
Tau 10

Euclidean Adler Function $(Q^2 = -q^2)$



M. Davier, D. Díaz-Calderón, B. Malaescu, A. Pich, A. Rodríguez-Sánchez, Z. Zhang, 2302.01359

2σ discrepancy between e^+e^- data & QCD

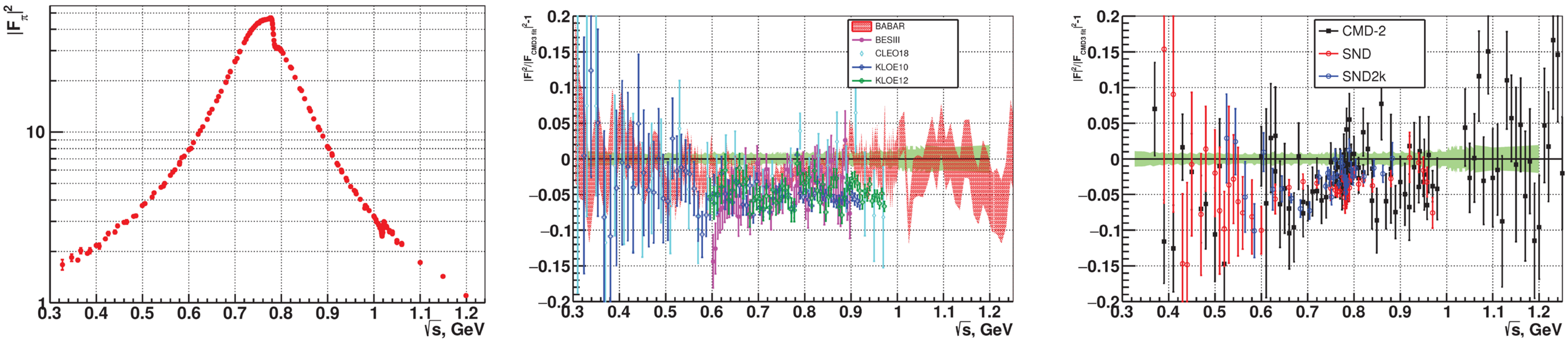


FLAG average: $\alpha_s(M_Z^2) = 0.1184 \pm 0.0008$

$$\alpha_s(M_Z^2) = \begin{cases} 0.1136 \pm 0.0025 & (e^+e^- \text{ data}) \\ 0.1179 \pm 0.0025 & (\text{Lattice}) \end{cases}$$

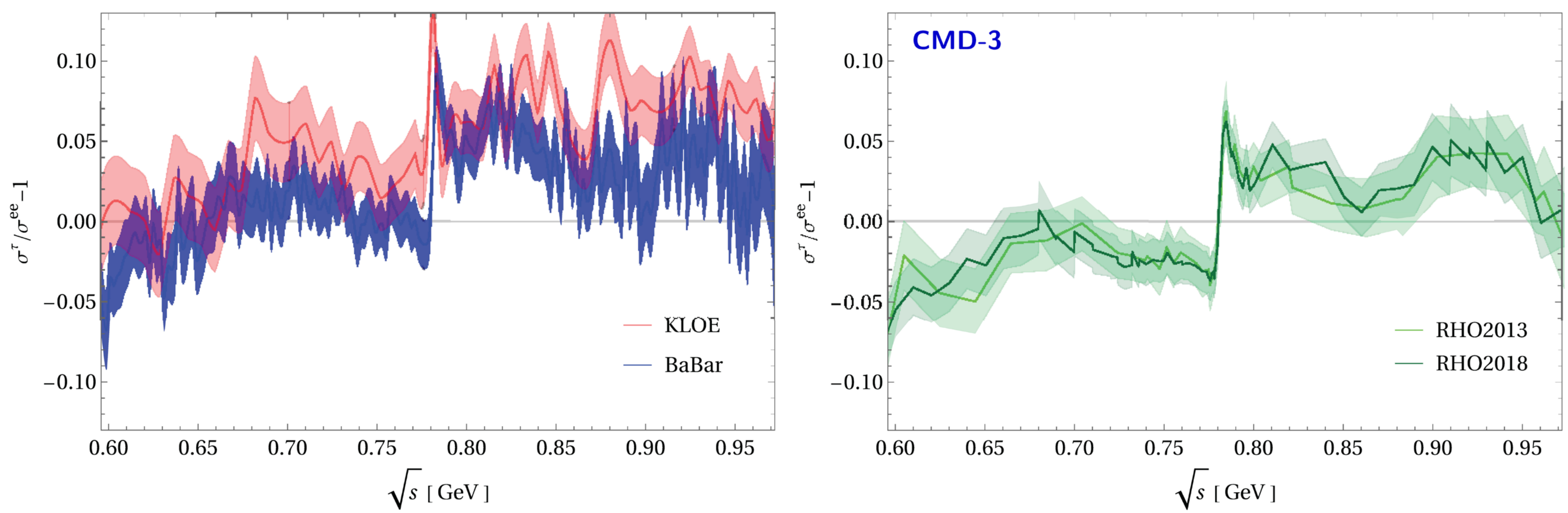
2023 CMD-3 $e^+e^- \to \pi^+\pi^-$ Data

2302.08834

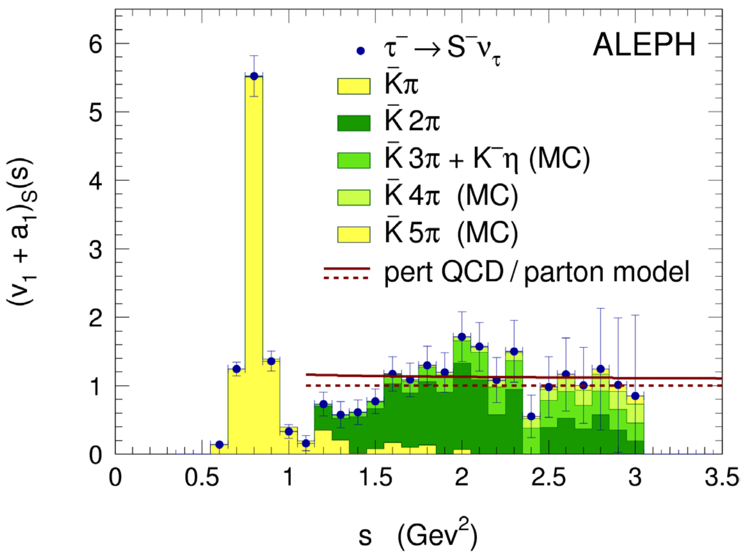


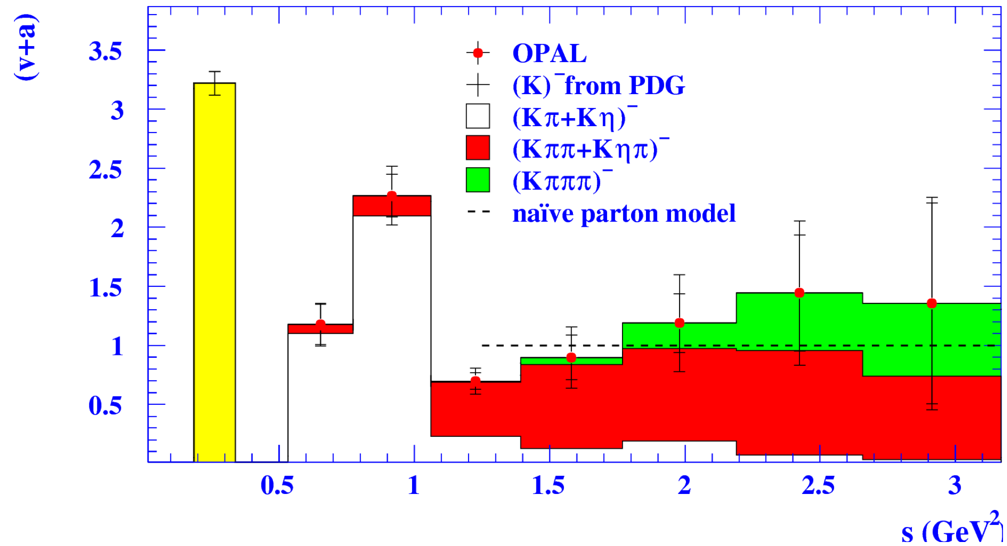
$\tau \to 2\pi\nu_\tau$ & $e^+e^- \to 2\pi$ Spectral Functions

Masjuan-Miranda-Roig 2305.20005



Strange Spectral Function





Very low statistics. Large experimental uncertainties

Sensitive to SU(3) breaking: m_s , V_{us}

V_{us} Determination

Gámiz-Jamin-Pich-Prades-Schwab '03

$$|V_{us}|^2 = \frac{R_{\tau,us}}{\frac{R_{\tau,ud}}{|V_{ud}|^2} - \delta R_{\tau,\text{th}}}$$

$$\delta R_{\tau,\text{th}} \approx 24\, \frac{m_s^2(m_\tau^2)}{m_\tau^2}\, \Delta(\alpha_s)$$

$$\delta R_{\tau,\text{th}} \equiv \underbrace{0.1544\,(37)}_{J=0} + \underbrace{0.084\,(33)}_{m_s(2\text{ GeV}) = 93.0\,(8.5)\text{ MeV}} = 0.238\,(33)$$

$$R_{\tau,uq} = \Gamma\left(\tau^- \to \nu_\tau \bar{u} q\right) / \Gamma\left(\tau^- \to \nu_\tau \bar{\nu}_e e^-\right)$$

HFLAV 2022:

$$\text{Br}\left(\tau^- \to \nu_\tau \bar{u}\, s\right) = (2.908 \pm 0.048)\%$$

$$\text{Br}\left(\tau^- \to \nu_\tau \bar{u}\, d\right) = (61.83 \pm 0.10)\%$$

$$\text{Br}\left(\tau^- \to \nu_\tau \bar{\nu}_e e^-\right)_{\text{univ}} = (17.812 \pm 0.022)\%$$

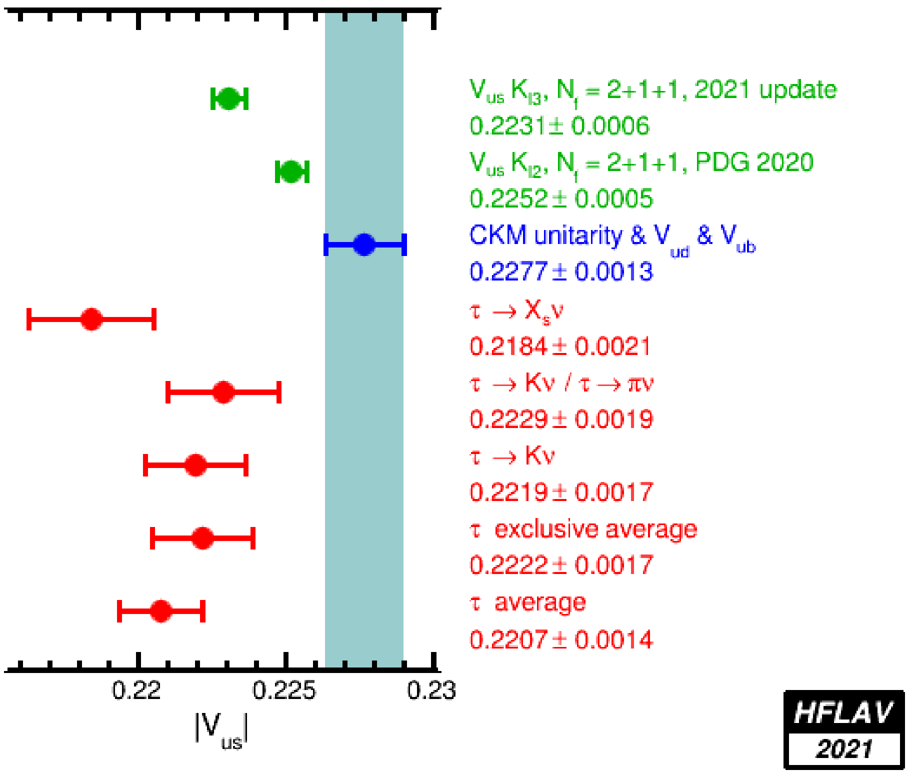
$$V_{ud} = 0.97373 \pm 0.00031$$

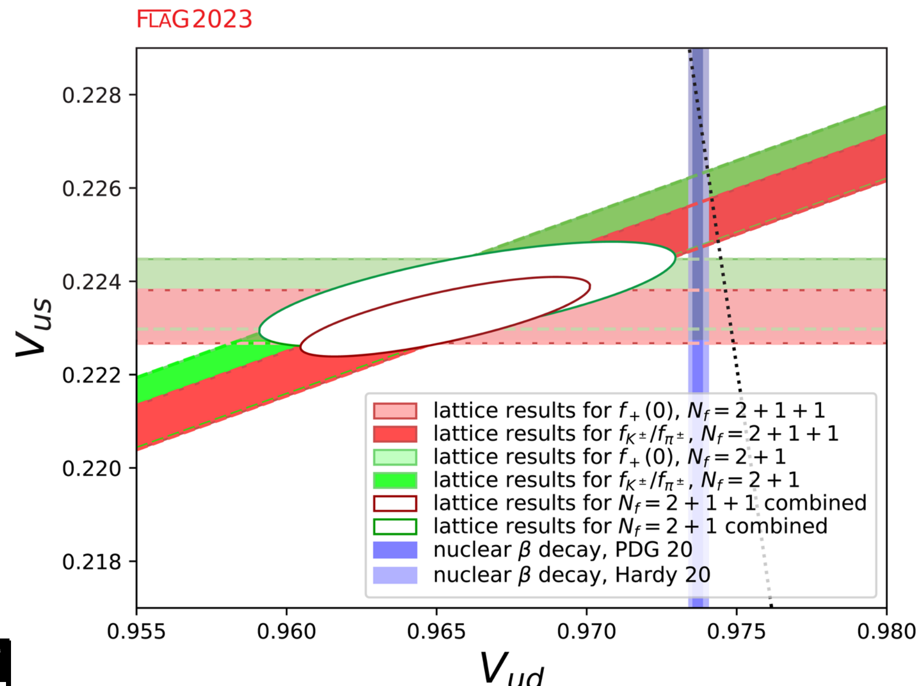
$\Rightarrow$ $$|V_{us}| = 0.2184 \pm 0.0018_{\text{exp}} \pm 0.0011_{\text{th}}$$

K_{l3}: $|V_{us}| = 0.2232 \pm 0.0006$ $\qquad [f_+(0) = 0.9698 \pm 0.0017]$ $\qquad$ FLAG 2021

Sizeable discrepancy. Improvements needed

V_{us} & V_{ud} Cabibbo Anomaly





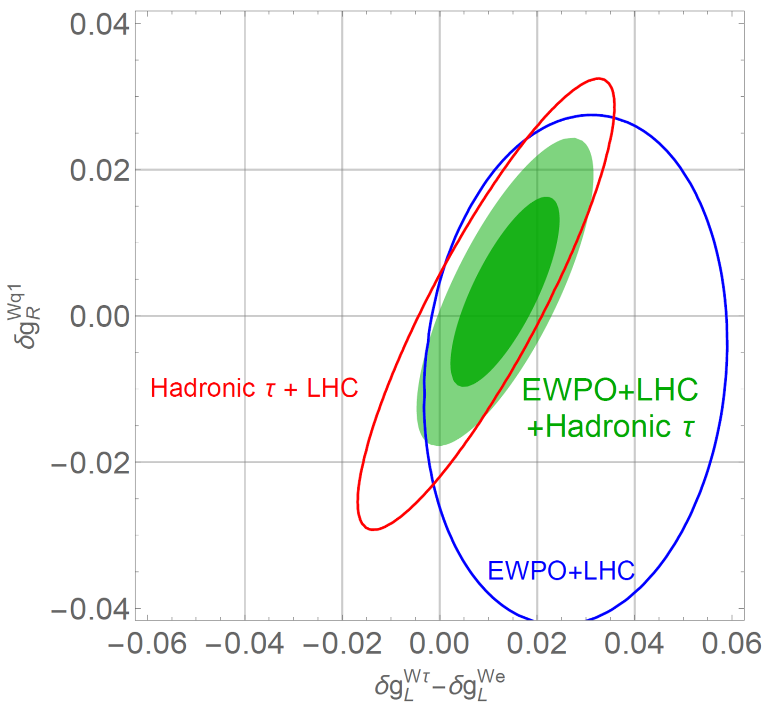
Sizeable violation of CKM unitarity

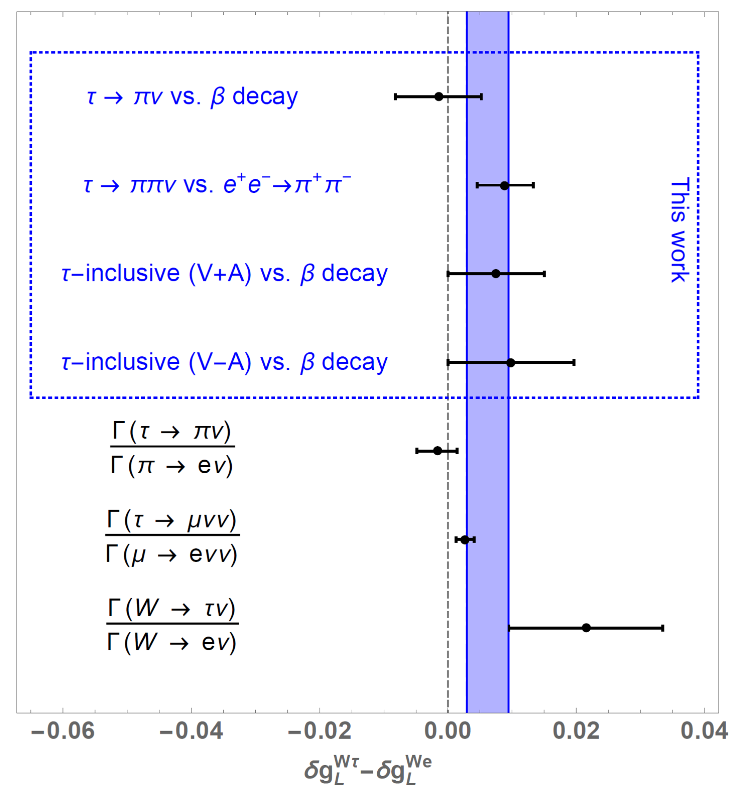
Hadronic τ Decay & New Physics

$$\mathcal{L}_{\rm eff} = -\frac{G_F V_{ud}}{\sqrt{2}} \Bigg[\Big(1+\epsilon_L^\tau\Big) \bar\tau\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar u \gamma^\mu (1-\gamma_5) d \; + \; \epsilon_R^\tau \; \bar\tau\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar u \gamma^\mu (1+\gamma_5) d$$
$$+ \; \bar\tau(1-\gamma_5)\nu_\tau \cdot \bar u \Big[\epsilon_S^\tau - \epsilon_P^\tau\gamma_5\Big] d \; + \; \epsilon_T^\tau \, \bar\tau\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau \cdot \bar u \sigma^{\mu\nu}(1-\gamma_5) d \Bigg] + \text{h.c.}$$

Cirigliano, Falkowski, González-Alonso, Rodríguez-Sánchez, 1809.01161

$$\epsilon_L^\tau - \epsilon_L^e = \delta g_L^{W\tau} - \delta g_L^{We} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + [c_{\ell q}^{(3)}]_{ee11} \qquad \epsilon_{S,P}^\tau = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^*_{\tau\tau 11}$$
$$\epsilon_R^\tau = \delta g_R^{Wq_1}, \qquad \epsilon_T^\tau = -\frac{1}{2}[c_{lequ}^{(3)}]^*_{\tau\tau 11} \; ,$$

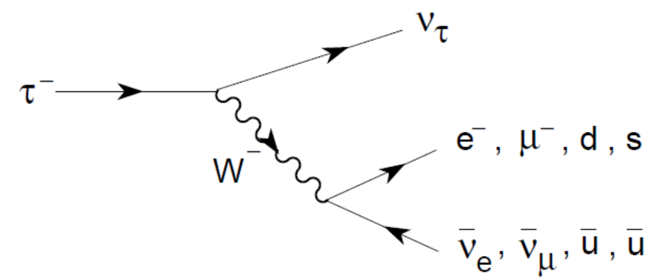




95% CL $\qquad$ 10^{-3} units

Coefficient	ATLAS $\tau\nu$	τ decays	τ and π decays
$[c_{\ell q}^{(3)}]_{\tau\tau 11}$	$[0.0, 1.6]$	$[-12.6, 0.2]$	$[-7.6, 2.1]$
$[c_{lequ}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-8.4, 4.1]$	$[-5.6, 2.3]$
$[c_{ledq}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-3.5, 9.0]$	$[-2.1, 5.8]$
$[c_{lequ}^{(3)}]_{\tau\tau 11}$	$[-3.3, 3.3]$	$[-10.4, -0.2]$	$[-8.6, 0.7]$

SUMMARY



Many interesting τ topics

- ❑ Tests of QCD and the Electroweak Theory
- ❑ Looking for Signals of New Phenomena
- ❑ Superb Tool for New Physics Searches

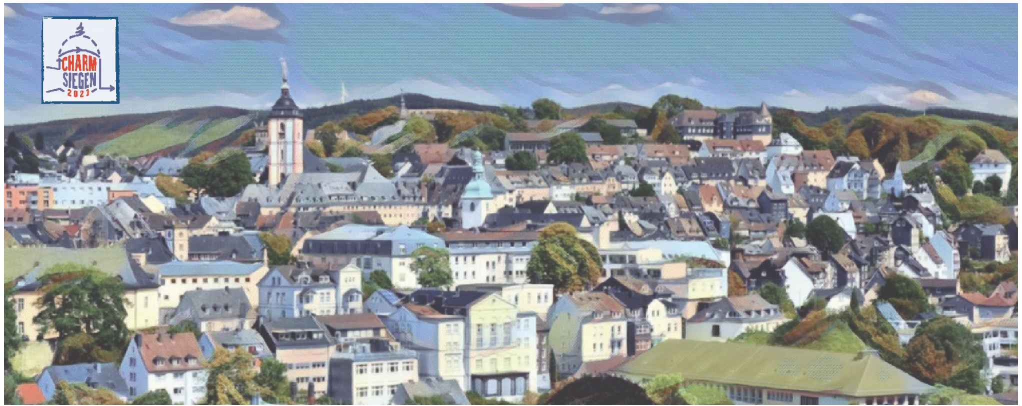
Better data samples needed

Lots of data will be produced @ Belle-II & sτcF

& TeraZ…

Improving systematics brings a great reward

Backup



CHARM 2023
Siegen, Germany
17-21 July 2023

LORENTZ STRUCTURE

$$\mathcal{H} = 4 \frac{G_{l'l}}{\sqrt{2}} \sum_{n,\epsilon,\omega} g^n_{\epsilon\omega} \left[\overline{l'_\epsilon} \Gamma^n (\nu_{l'})_\sigma\right] \left[\overline{(\nu_l)_\lambda} \Gamma_n l_\omega\right]$$

90% CL — Fetscher-Gerber, PDG2020

$\mu \to e \bar{\nu}_e \nu_\mu$

$\lvert g^S_{RR}\rvert < 0.035$	$\lvert g^V_{RR}\rvert < 0.017$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.050$	$\lvert g^V_{LR}\rvert < 0.023$	$\lvert g^T_{LR}\rvert < 0.015$
$\lvert g^S_{RL}\rvert < 0.420$	$\lvert g^V_{RL}\rvert < 0.105$	$\lvert g^T_{RL}\rvert < 0.105$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$
$\lvert g^S_{LR} + 6g^T_{LR}\rvert < 0.143$	$\lvert g^S_{RL} + 6g^T_{RL}\rvert < 0.418$	
$\lvert g^S_{LR} + 2g^T_{LR}\rvert < 0.108$	$\lvert g^S_{RL} + 2g^T_{RL}\rvert < 0.417$	
$\lvert g^S_{LR} - 2g^T_{LR}\rvert < 0.070$	$\lvert g^S_{RL} - 2g^T_{RL}\rvert < 0.418$	
$Q_{RR} + Q_{LR} < 8.2 \times 10^{-4}$		

95% CL — Stahl, PDG2020

$\tau \to e \bar{\nu}_e \nu_\tau$

$\lvert g^S_{RR}\rvert < 0.70$	$\lvert g^V_{RR}\rvert < 0.17$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.99$	$\lvert g^V_{LR}\rvert < 0.13$	$\lvert g^T_{LR}\rvert < 0.082$
$\lvert g^S_{RL}\rvert < 2.01$	$\lvert g^V_{RL}\rvert < 0.52$	$\lvert g^T_{RL}\rvert < 0.51$
$\lvert g^S_{LL}\rvert < 2.01$	$\lvert g^V_{LL}\rvert < 1.005$	$\lvert g^T_{LL}\rvert \equiv 0$

$\tau \to \mu \bar{\nu}_\mu \nu_\tau$

$\lvert g^S_{RR}\rvert < 0.72$	$\lvert g^V_{RR}\rvert < 0.18$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.95$	$\lvert g^V_{LR}\rvert < 0.12$	$\lvert g^T_{LR}\rvert < 0.079$
$\lvert g^S_{RL}\rvert < 2.01$	$\lvert g^V_{RL}\rvert < 0.52$	$\lvert g^T_{RL}\rvert < 0.51$
$\lvert g^S_{LL}\rvert < 2.01$	$\lvert g^V_{LL}\rvert < 1.005$	$\lvert g^T_{LL}\rvert \equiv 0$

$\tau \to \pi \nu_\tau$

$\lvert g^V_R\rvert < 0.15$ $\quad \lvert g^V_L\rvert > 0.992$

$\tau \to \rho \nu_\tau$

$\lvert g^V_R\rvert < 0.10$ $\quad \lvert g^V_L\rvert > 0.995$

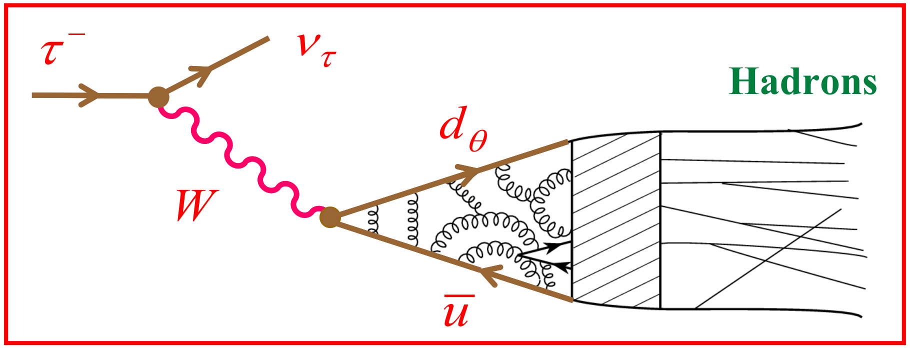
$\tau \to a_1 \nu_\tau$

$\lvert g^V_R\rvert < 0.16$ $\quad \lvert g^V_L\rvert > 0.987$

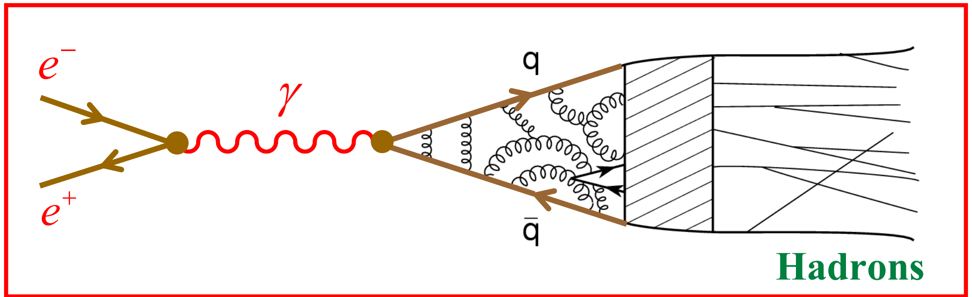
Only Lepton Massive Enough to Decay into Hadrons

$\tau^- \to \nu_\tau H^-$ probes the hadronic V-A current

$\langle H^- | \bar{d}_\theta \gamma^\mu (1-\gamma_5) u | 0 \rangle$



$e^+e^- \to H^0$ probes the hadronic electromagnetic current



$\langle H^0 | \sum_q Q_q \, \bar{q} \gamma^\mu q | 0 \rangle$

Isospin: $$\frac{\Gamma(\tau^- \to \nu_\tau V^-)}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = \frac{3\cos^2\theta_C}{2\pi\alpha^2} S_{\mathrm{EW}} \int_0^1 dx \, (1-x)^2 (1+2x) \, x \; \sigma^{I=1}_{e^+e^- \to V^0}(x m_\tau^2)$$

Perturbative $(m_q=0)$

$$-s\,\frac{d}{ds}\,\Pi^{(0+1)}(s) = \frac{1}{4\pi^2}\sum_{n=0} K_n \left(\frac{\alpha_s(-s)}{\pi}\right)^n$$

$$K_0 = K_1 = 1 \quad , \quad K_2 = 1.63982 \quad , \quad K_3 = 6.37101 \quad , \quad K_4 = 49.07570$$

Baikov-Chetyrkin-Kühn '08

$$\delta_{\mathrm{P}} = \sum_{n=1} K_n\; A^{(n)}(\alpha_s) = a_\tau + 5.20\; a_\tau^2 + 26\; a_\tau^3 + 127\; a_\tau^4 + \cdots$$

Le Diberder- Pich '92

$$A^{(n)}(\alpha_s) \equiv \frac{1}{2\pi i}\oint_{|x|=1}\frac{dx}{x}\,(1-2x+2x^3-x^4)\left(\frac{\alpha_s(-s)}{\pi}\right)^n = a_\tau^n + \cdots \qquad ; \qquad a_\tau \equiv \alpha_s(m_\tau)/\pi$$

Power Corrections

$$\Pi^{(0+1)}_{\mathrm{OPE}}(s) \approx \frac{1}{4\pi^2}\sum_{n\geq 2}\frac{C_{2n}\langle O_{2n}\rangle}{(-s)^n}$$

Braaten-Narison-Pich '92

$$C_4\langle O_4\rangle \approx \frac{2\pi}{3}\langle 0|\alpha_s G^{\mu\nu}G_{\mu\nu}|0\rangle$$

$$\delta_{\mathrm{NP}} \approx \frac{-1}{2\pi i}\oint_{|x|=1} dx\;(1-3x^2+2x^3)\sum_{n\geq 2}\frac{C_{2n}\langle O_{2n}\rangle}{(-x m_\tau^2)^n} = -3\,\frac{C_6\langle O_6\rangle}{m_\tau^6} - 2\,\frac{C_8\langle O_8\rangle}{m_\tau^8}$$

Suppressed by m_τ^6 **[additional chiral suppression in** $C_6\langle O_6\rangle^{V+A}$ **]**

Exhaustive Analysis of ALEPH Data

Rodríguez-Sánchez, Pich, 1605.06830

Method (V + A)	$\alpha_s(m_\tau^2)$		
	CIPT	FOPT	Average
ALEPH moments [1]	$0.339\,^{+0.019}_{-0.017}$	$0.319\,^{+0.017}_{-0.015}$	$0.329\,^{+0.020}_{-0.018}$
Mod. ALEPH moments [2]	$0.338\,^{+0.014}_{-0.012}$	$0.319\,^{+0.013}_{-0.010}$	$0.329\,^{+0.016}_{-0.014}$
$A^{(2,m)}$ moments [3]	$0.336\,^{+0.018}_{-0.016}$	$0.317\,^{+0.015}_{-0.013}$	$0.326\,^{+0.018}_{-0.016}$
s_0 dependence [4]	0.335 ± 0.014	0.323 ± 0.012	0.329 ± 0.013
Borel transform [5]	$0.328\,^{+0.014}_{-0.013}$	$0.318\,^{+0.015}_{-0.012}$	$0.323\,^{+0.015}_{-0.013}$
Combined value	$\mathbf{0.335 \pm 0.013}$	$\mathbf{0.320 \pm 0.012}$	$\mathbf{0.328 \pm 0.013}$

→ $$\alpha_s(M_Z^2) = 0.1197 \pm 0.0015$$

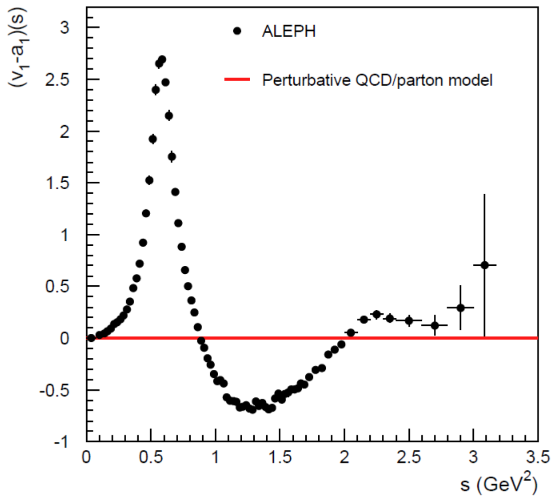
1) $\omega_{kl}(x) = (1+2x)\,(1-x)^{2+k}\,x^l$ $\qquad (k,l) = (0,0),\ (1,0),\ (1,1),\ (1,2),\ (1,3)$

2) $\tilde{\omega}_{kl}(x) = (1-x)^{2+k}\,x^l$ $\qquad (k,l) = (0,0),\ (1,0),\ (1,1),\ (1,2),\ (1,3)$

3) $\omega^{(2,m)}(x) = (1-x)^2 \sum_{k=0}^{m} (k+1)\,x^k = 1-(m+2)\,x^{m+1} + (m+1)x^{m+2}$, $\qquad 1 \leq m \leq 5$

4) $\omega^{(2,m)}(x)$ $\qquad 0 \leq m \leq 2$, 1 single moment in each fit

5) $\omega_a^{(1,m)}(x) = (1-x^{m+1})\,\mathrm{e}^{-ax}$ $\qquad 0 \leq m \leq 6$



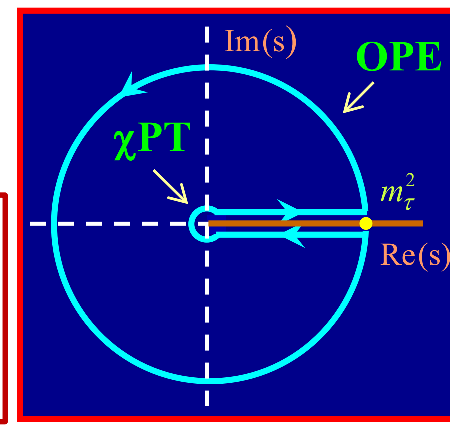
Chiral Sum Rules

$\Pi(s) \equiv \Pi_{VV}(s) - \Pi_{AA}(s)$ **Pure non-perturbative quantity**

$$\lim_{s\to\infty} s^2\,\Pi(s) = 0 \quad\rightarrow\quad \Pi^{\rm OPE}(s) = -\frac{O_6}{s^3} + \frac{O_8}{s^4} - \cdots$$

χPT (s→0): $$\Pi(s) = \frac{2F^2}{s} - 8\,L_{10}^r(\mu^2) + \frac{1}{16\pi^2}\left(\frac{5}{3} - \ln\frac{-s}{\mu^2}\right) + 16\,C_{87}^r(\mu^2)\,\frac{s}{F^2} + \cdots$$

$$\int_{s_{\rm th}}^{s_0} ds\;\omega(s)\,\frac{1}{\pi}\,{\rm Im}\,\Pi(s) + \frac{1}{2\pi i}\oint_{|s|=s_0} ds\;\omega(s)\,\Pi(s) \;=\; 2\,f_\pi^2\,\omega(m_\pi^2) + {\rm Res}[\omega(s)\Pi(s),\,s=0]$$



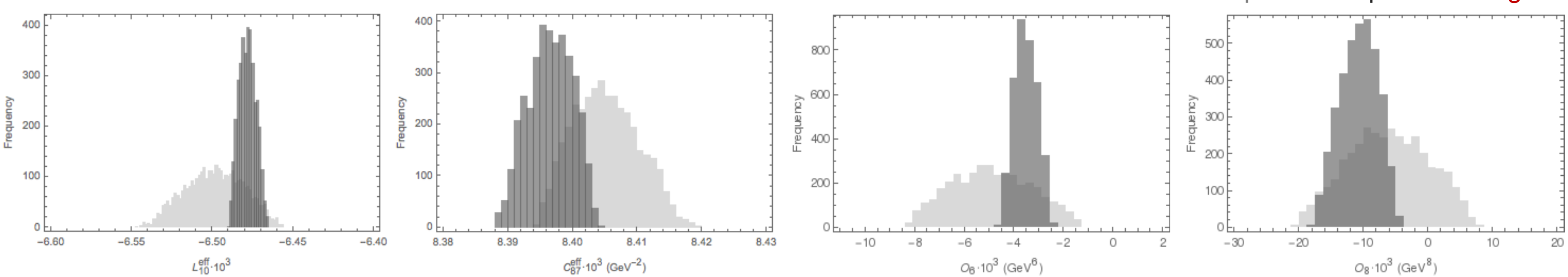
Statistical analysis:

González-Pich-Rodríguez, 1602.06112

$$C_{87}^{\rm eff} = (8.40 \pm 0.18)\cdot 10^{-3}\ {\rm GeV}^{-2} \qquad O_6 = (-3.6 \pm 0.7)\cdot 10^{-3}\ {\rm GeV}^6$$

$$L_{10}^{\rm eff} = (-6.48 \pm 0.05)\cdot 10^{-3}\ . \qquad O_8 = (-1.0 \pm 0.4)\cdot 10^{-2}\ {\rm GeV}^8$$

Non-pinched & pinched weights



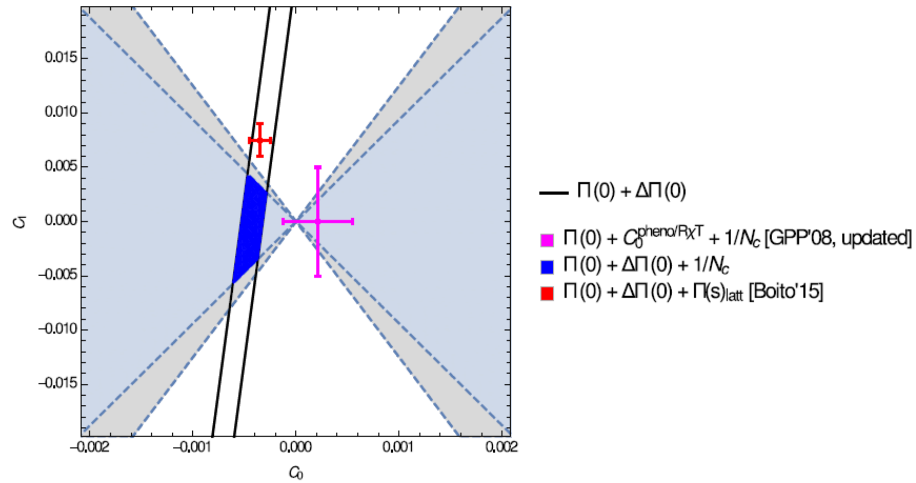
• χPT Parameters:

González-Alonso, Pich, Rodríguez-Sánchez, 1602.06112

$$L_{10}^{\rm eff} = L_{10}^r - 0.00126 + \mathcal{O}(p^6)$$

$$L_{10}^{\rm eff} = 1.53\, L_{10}^r + 0.263\, L_9^r - 0.00179 - \frac{1}{8}\left(\mathcal{C}_0^r + \mathcal{C}_1^r\right) + \mathcal{O}(p^8)$$

$$C_{87}^{\rm eff} = C_{87}^r + 0.296\, L_9^r + 0.00155 + \mathcal{O}(p^8)$$



➡

- $\mathcal{O}(p^4)$ analysis: $\quad L_{10}^r(M_\rho) = -(5.22 \pm 0.05)\cdot 10^{-3}$
- $\mathcal{O}(p^6)$ analysis: $\quad L_{10}^r(M_\rho) = -(4.1 \pm 0.4)\cdot 10^{-3}$

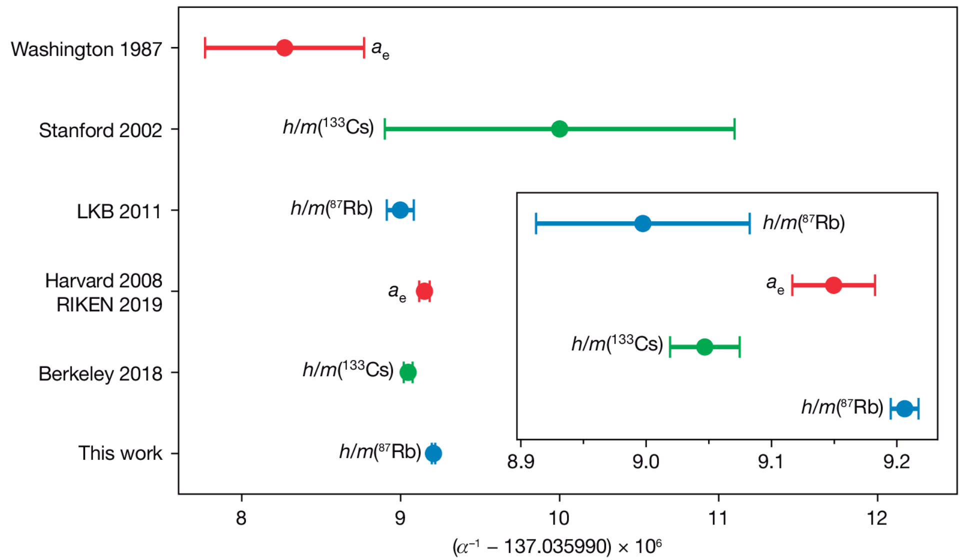
  $C_{87}^r(M_\rho) = (5.10 \pm 0.22)\cdot 10^{-3}\ \mathrm{GeV}^{-2}$

• $\varepsilon'_K/\varepsilon_K$: $\mathcal{O}_6$ ➡ $\langle(\pi\pi)_{I=2}|Q_8|K^0\rangle$ ➡ e.m. penguin contribution

$$\left(\varepsilon'_K/\varepsilon_K\right)^{I=2}_{\rm EWP} = (-4.5 \pm 1.8)\cdot 10^{-4}$$

Pich-Rodríguez, 2102.09308

Electron Anomalous Magnetic Moment



Morel et al, Nature 588 (2020) 61

New measurement of α

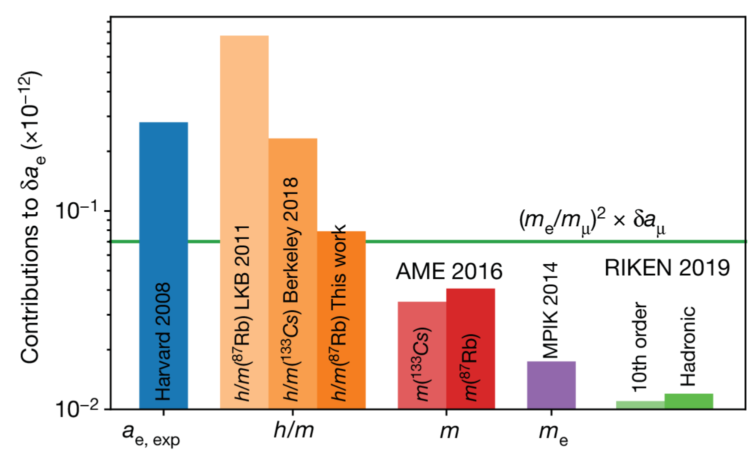
$$\alpha^{-1}(\mathrm{Rb}) = 137.035\,999\,206\;(11)$$

8.1×10^{-11} accuracy

$5.8\,\sigma$ discrepancy with Cs experiment

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}}$$

$$= \begin{cases} (-8.8 \pm 3.6) \cdot 10^{-13} & (\mathrm{Cs},\ -2.4\sigma) \\ (+4.8 \pm 3.0) \cdot 10^{-13} & (\mathrm{Rb},\ +1.6\sigma) \end{cases}$$



τ Anomalous Magnetic Moment

Difficult to measure! $a_\tau^{\exp} = (-0.018 \pm 0.017)$ **DELPHI**

$-0.007 < a_\tau^{\text{New Phys}} < 0.005$ **González-Springer, Santamaria, Vidal '00** **(LEP/SLD data)**

Eidelman, Passera

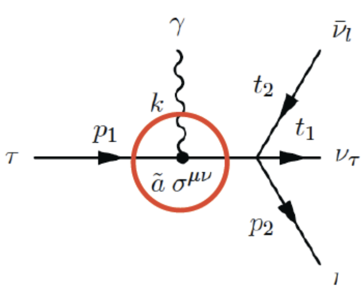
$$
\begin{aligned}
10^8 \cdot\ a_\tau^{\text{th}} = &\ 117\,324 \pm 2 && \text{QED} \\
&+ 47.4 \pm 0.5 && \text{EW} \\
&+ 337.5 \pm 3.7 && \text{hvp} \\
&+ 7.6 \pm 0.2 && \text{hvp NLO} \\
&+ 5 \pm 3 && \text{light-by-light} \\
&= \mathbf{117\,721 \pm 5}
\end{aligned}
$$

Enhanced sensitivity to new physics: $(m_\tau/m_\mu)^2 = 283$

	Electron	Muon	Tau
a^{EW}/a^{HAD}	1/56	1/45	1/7
$a^{EW}/\delta a^{HAD}$	1.6	3	10

Essentially unknown

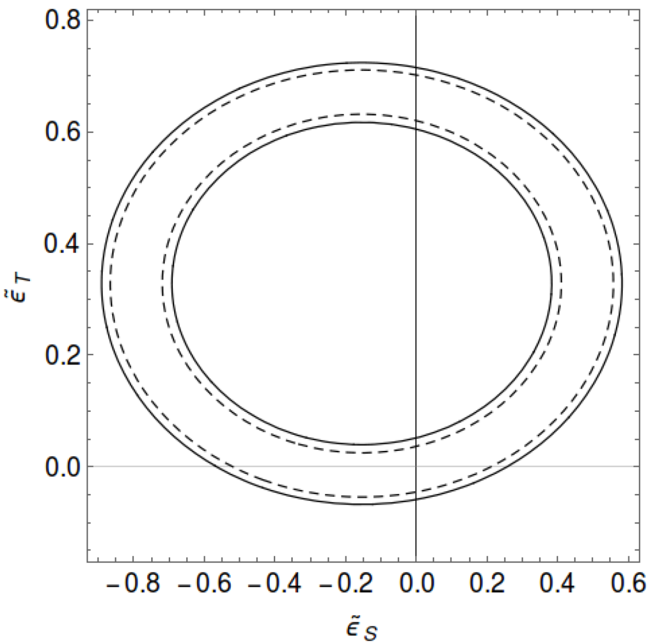
May be accessible at BFs through radiative leptonic decays **(Fael et al)** or with a polarized e⁻ beam **(Crivellin et al)**



EFT analysis of $\tau \to \nu_\tau K\pi$

Rendón-Roig-Toledo, 1902.08143

$$\mathcal{L}_{cc} = -\frac{G_F V_{us}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\Big[\bar\tau\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar u[\gamma^\mu - (1-2\hat\epsilon_R)\gamma^\mu\gamma_5]s$$
$$+\bar\tau(1-\gamma_5)\nu_\ell \cdot \bar u[\hat\epsilon_s - \hat\epsilon_p\gamma_5]s + 2\hat\epsilon_T\bar\tau\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar u\sigma^{\mu\nu}s\Big] + \text{h.c.}$$



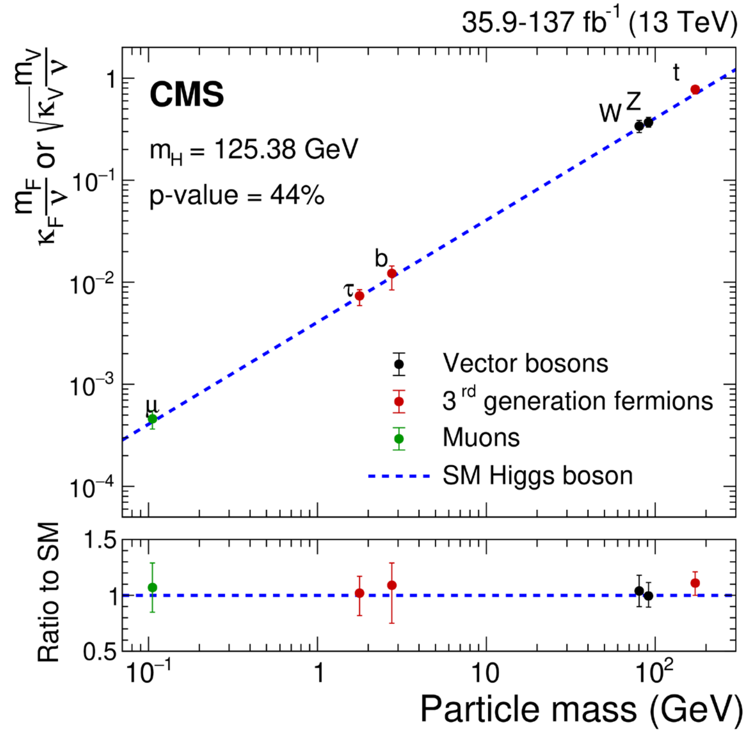
Best fit values	$\hat\epsilon_S$	$\hat\epsilon_T$	χ^2	χ^2 in the SM
Excluding $i=5,6,7$ bins	$(1.3\pm0.9)\times10^{-2}$	$(0.7\pm1.0)\times10^{-2}$	$[72,73]$	$[74,77]$
Including $i=5,6,7$ bins	$(0.9\pm1.0)\times10^{-2}$	$(1.7\pm1.7)\times10^{-2}$	$[83,86]$	$[91,95]$

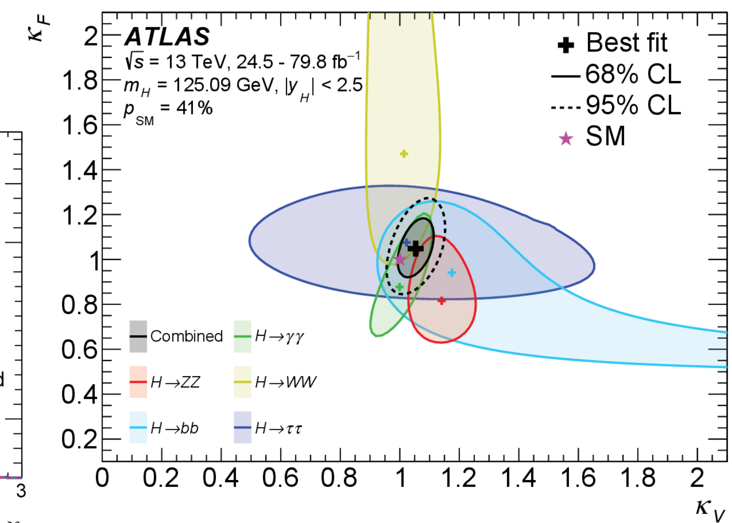
$\Rightarrow$ $\Lambda_{NP} \geq 2-5$ TeV

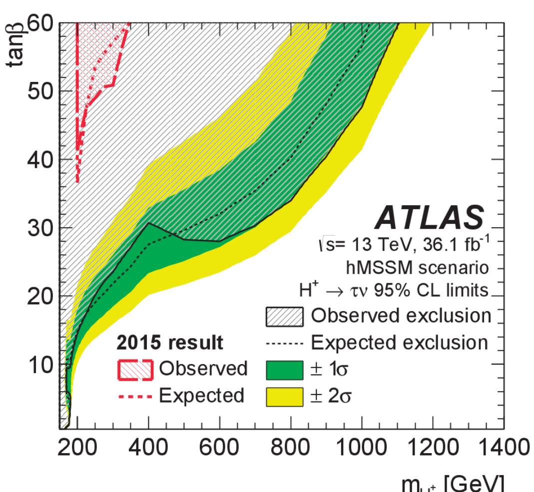
Complementary to kaon and hyperon data analyses

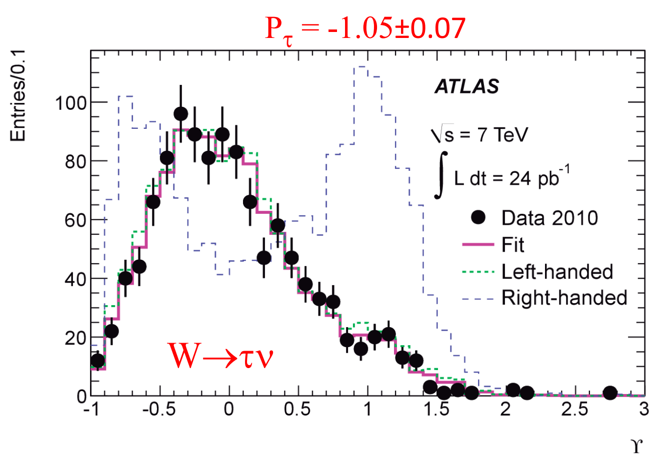
τ's @ LHC

- **Excellent signature to probe New Physics**
  Difficult to identify light objects (Z,$W^{\pm}$) with only Jets
  QCD Jets orders of magnitude larger
  Must rely on leptons
- **LHC produces high-momenta τ's**
  Tightly collimated decay products (mini-jet like)
  Momentum reconstruction possible
- **Low multiplicity.** Good tagging efficiency
- **Heaviest lepton coupling to the Higgs** (4th H Br)
- **Polarization information**





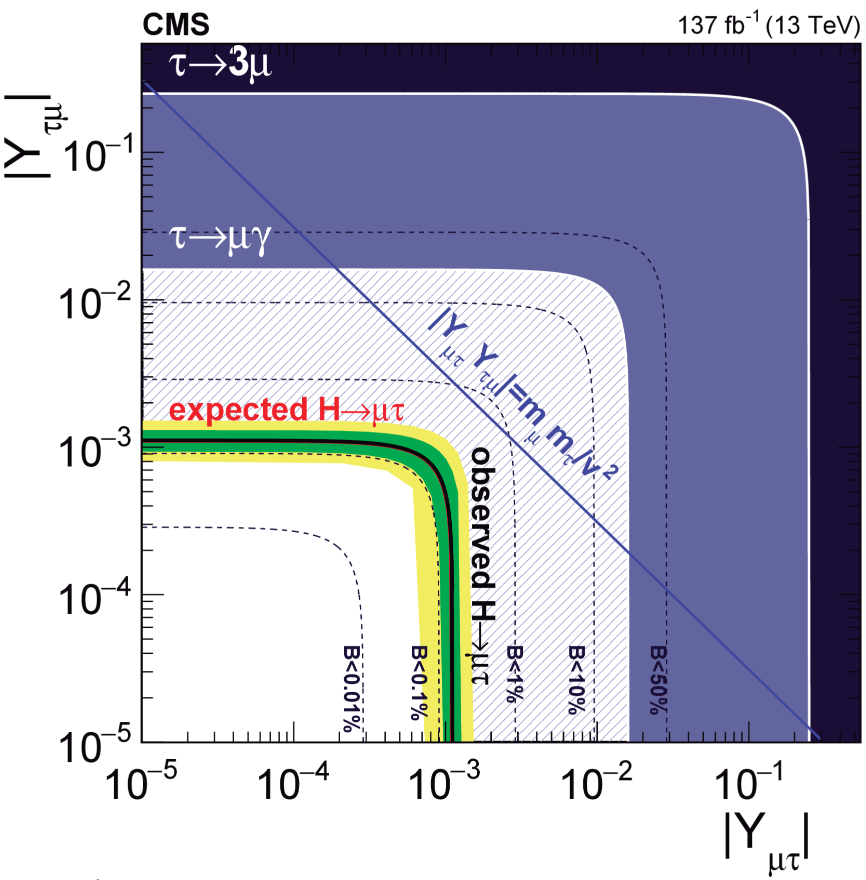




Flavour-Violating Higgs Couplings

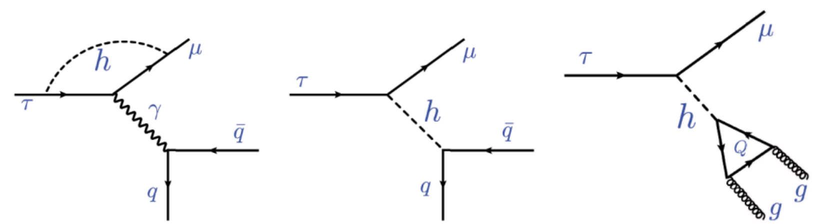
$$\mathcal{L} = -H\ \{ Y_{e\mu}\, \bar{e}_L \mu_R + Y_{e\tau}\, \bar{e}_L \tau_R + Y_{\mu\tau}\, \bar{\mu}_L \tau_R + \cdots \}$$

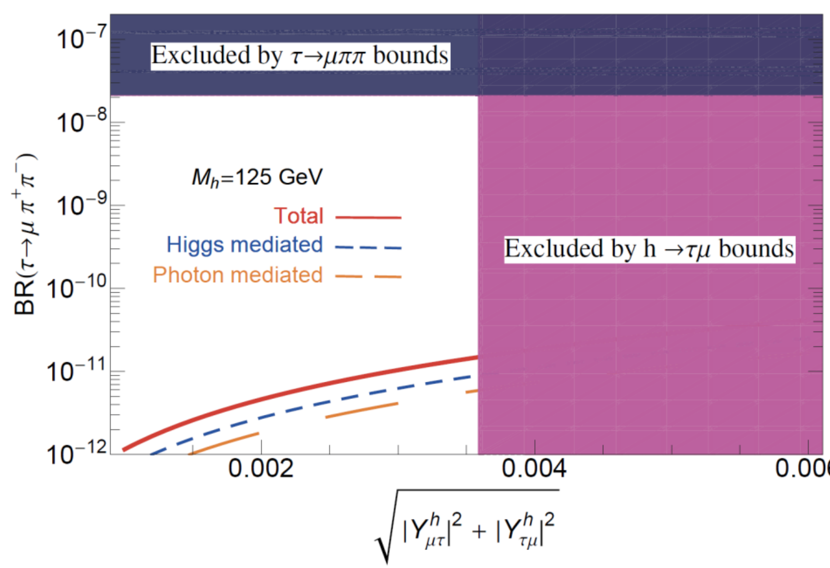
$$\mathrm{Br}\left(H \to \mu\tau\right) < 0.15\% \quad (95\%\ \mathrm{CL})$$



$\tau \to \mu\, \pi^+ \pi^-$

Celis et al., 1409.4439

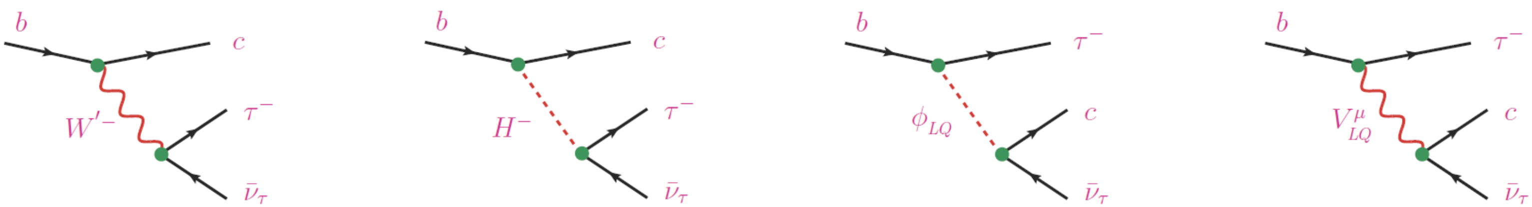




Effective Field Theory Analysis

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_L})\, \mathcal{O}_{V_L} + C_{V_R} \mathcal{O}_{V_R} + C_{S_R} \mathcal{O}_{S_R} + C_{S_L} \mathcal{O}_{S_L} + C_T \mathcal{O}_T \right] + \text{h.c.}$$

$$\mathcal{O}_{V_{L,R}} = (\bar c\, \gamma^\mu b_{L,R})\, (\bar\ell_L \gamma_\mu \nu_{\ell L})\,, \qquad \mathcal{O}_{S_{L,R}} = (\bar c\, b_{L,R})\, (\bar\ell_R \nu_{\ell L})\,, \qquad \mathcal{O}_T = (\bar c\, \sigma^{\mu\nu} b_L)\, (\bar\ell_R \sigma_{\mu\nu} \nu_{\ell L})$$



C_{V_L} $\qquad$ $C_{S_L},\ C_{S_R} \quad (C_T)$ $\qquad$ $C_{V_L},\ C_{S_L},\ C_T$ $\qquad$ $C_{V_L},\ C_{S_R}$

Many analyses (usually with single operator/mediator and partial data information)

Freytsis et al, Bardhan et al, Cai et al, Hu et al, Celis et al, Datta et al, Bhattacharya et al, Alonso et al, ...

Global fit to all data

(q^2 distributions included)

Murgui-Peñuelas-Jung-Pich, 1904.09311

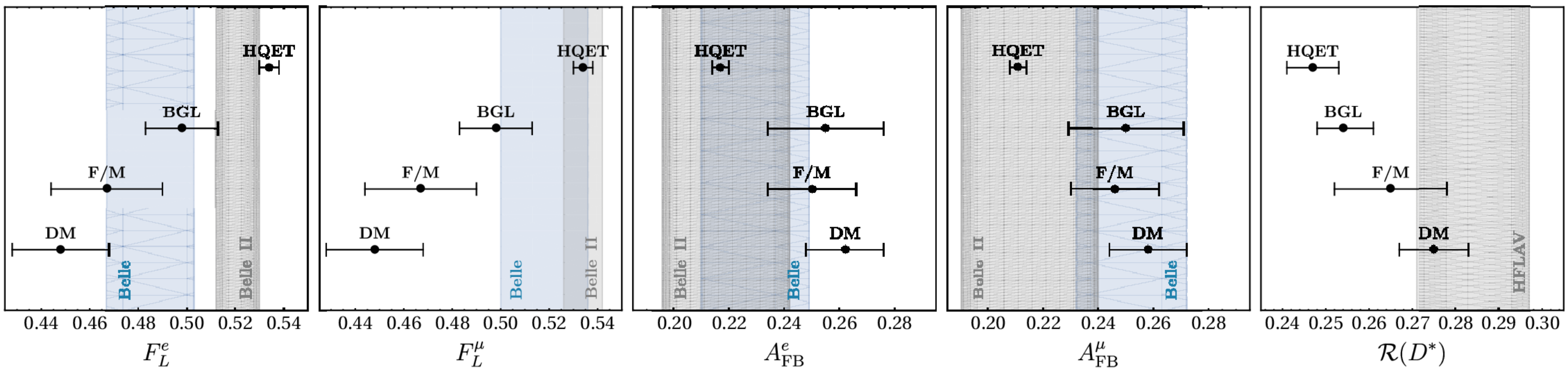
$F_L^{D^*},\ \mathcal{B}_{10}$	Min 1	Min 2
$\chi^2/\text{d.o.f.}$	$37.4/54$	$40.4/54$
C_{LL}^V	$0.09\,^{+0.13}_{-0.12}$	$0.34\,^{+0.05}_{-0.07}$
C_{RL}^S	$0.09\,^{+0.12}_{-0.61}$	$-1.10\,^{+0.48}_{-0.07}$
C_{LL}^S	$-0.14\,^{+0.52}_{-0.07}$	$-0.30\,^{+0.11}_{-0.50}$
C_{LL}^T	$0.008\,^{+0.046}_{-0.044}$	$0.093\,^{+0.029}_{-0.030}$

$\mathcal{B}(B_c \to \tau\bar\nu) < 10\%$

$F_L^{D^*}$ included

$B\to D^*\ell\nu$ Observables with different FFs

Fedele et al 2305.15457



Smaller [larger] discrepancy on R(D*) [R(D)] would bring back a possible new-physics scalar explanation

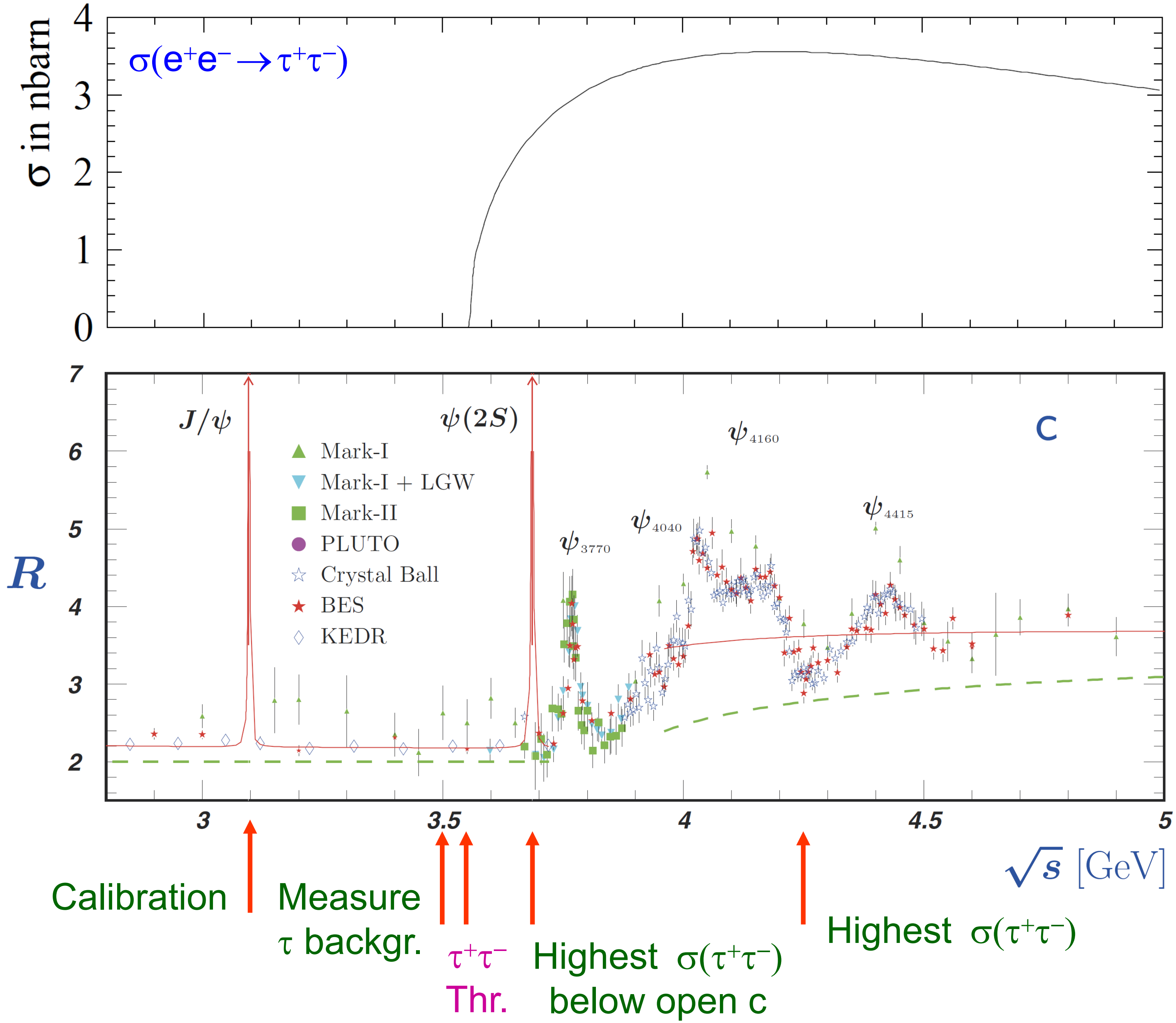
τ Data Samples

ALEPH:	$3.3 \cdot 10^5$	reconstructed τ decays
BaBar / Belle:	$1.4 \cdot 10^9$	$\tau^+\tau^-$ pairs
Belle-II:	$4.6 \cdot 10^{10}$	$\tau^+\tau^-$ pairs
sτcF:	$2.1 \cdot 10^{10}$	$\tau^+\tau^-$ pairs (10^8 near threshold)

Luminosity (10^{35} cm^{-2} s^{-1}) is important. Systematics also!

Advantages of the threshold región:

- Ability to measure backgrounds (running below threshold)
- Free of heavy quark backgrounds
- Single-Tagging ➡ Precise measurement of absolute branching fractions
- Monochromatic spectra for two-body decays (π, K)


σ in nbarn
σ(e⁺e⁻ → τ⁺τ⁻)
R
J/ψ
ψ(2S)
ψ3770
ψ4040
ψ4160
ψ4415
c
Mark-I
Mark-I + LGW
Mark-II
PLUTO
Crystal Ball
BES
KEDR
√s [GeV]
Calibration
Measure τ backgr.
τ⁺τ⁻ Thr.
Highest σ(τ⁺τ⁻) below open c
Highest σ(τ⁺τ⁻)