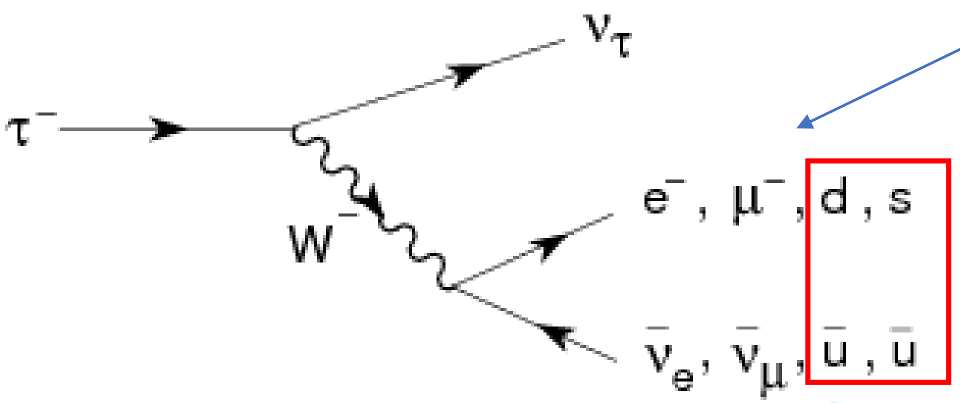
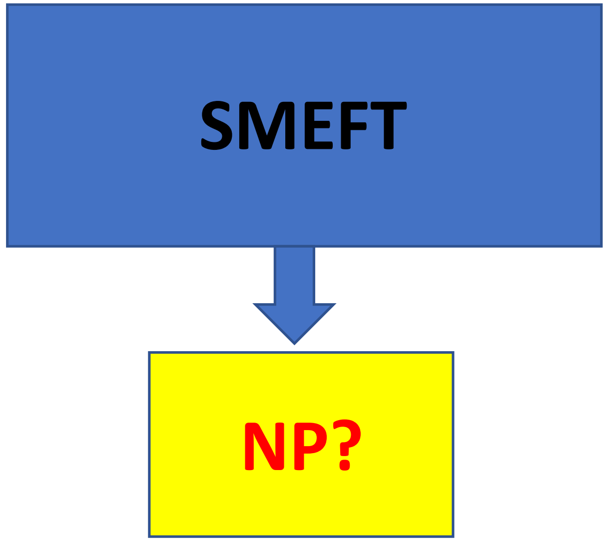
Semileptonic tau decays: Powerful probes of non-standard charged current weak interactions

LHC, EWPO



Pablo Roig

Cinvestav (Mexico City)

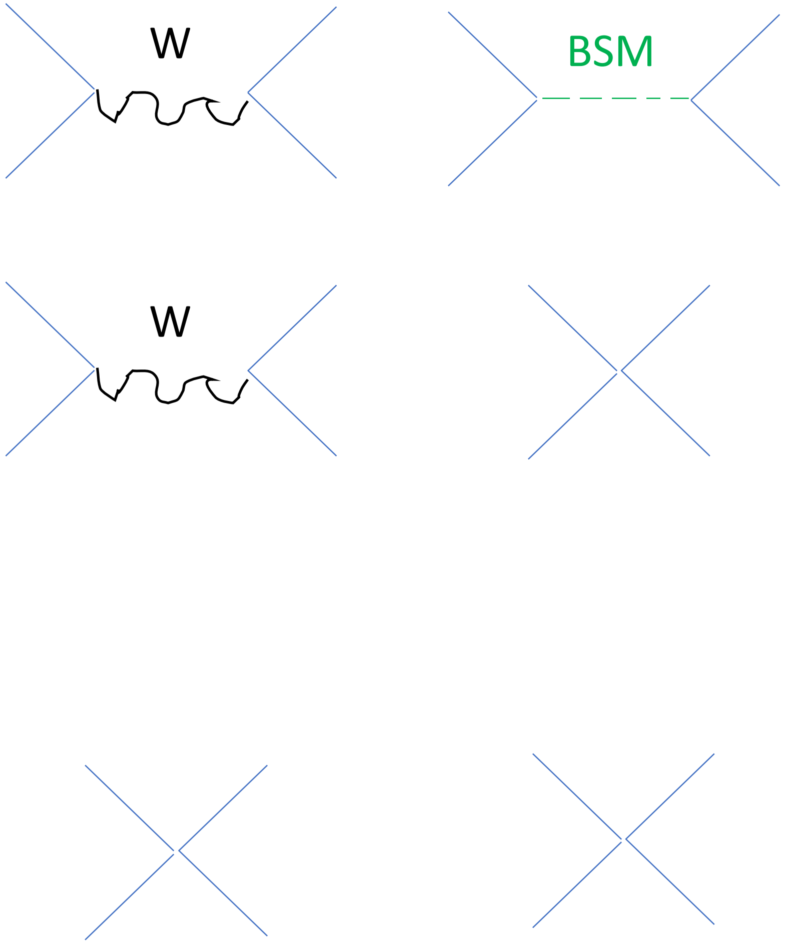


(Related discussion in all other talks in the session)

K decays
$0^+ \rightarrow 0^+$

12th International Workshop on e+e- Collisions From Phi to Psi, Feb. 25-March 1, 2019, Budker INP & Novosibirsk State University

Introduction: EFT application



10 TeV — SM + BSM — D=4

(Buchmuller & Wyler ’86, Grzadkowski et al. ‘10)

1 TeV — SMEFT — D=4+6+...

QCDxEW

$\boxed{M_Z}$

QCDxEM

RGE+matching @ M_Z
(Alonso et al. ‘14; González-Alonso et al. 17+Cirigliano et al. ’10)

2 GeV — Light fields — D=6+...

Pablo Roig

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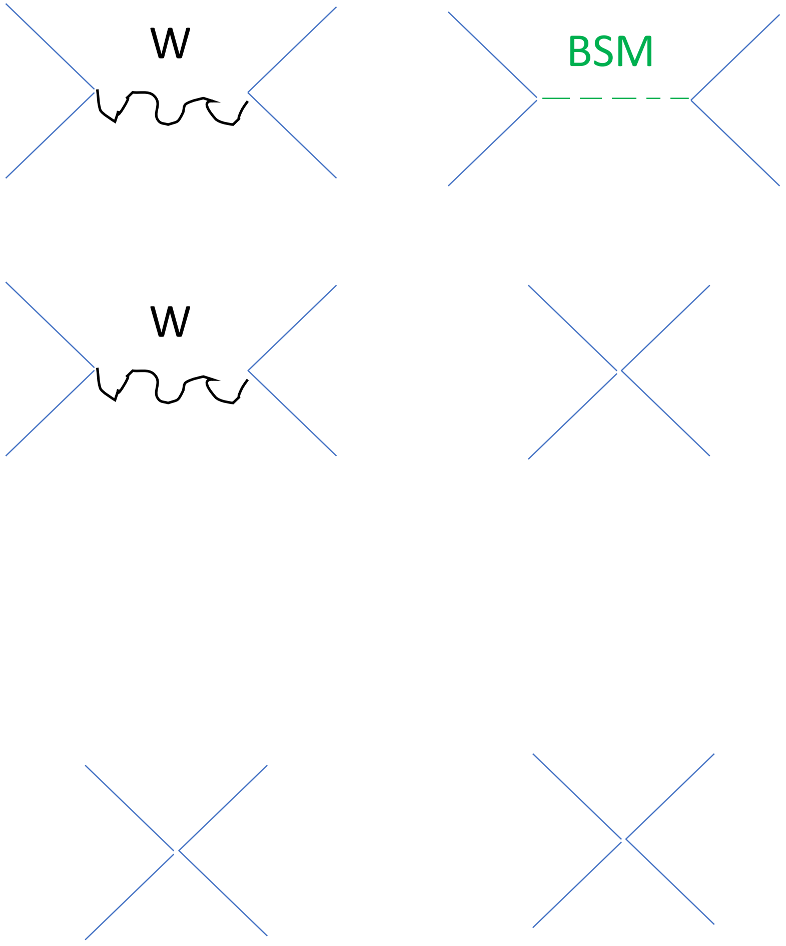

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$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i$$

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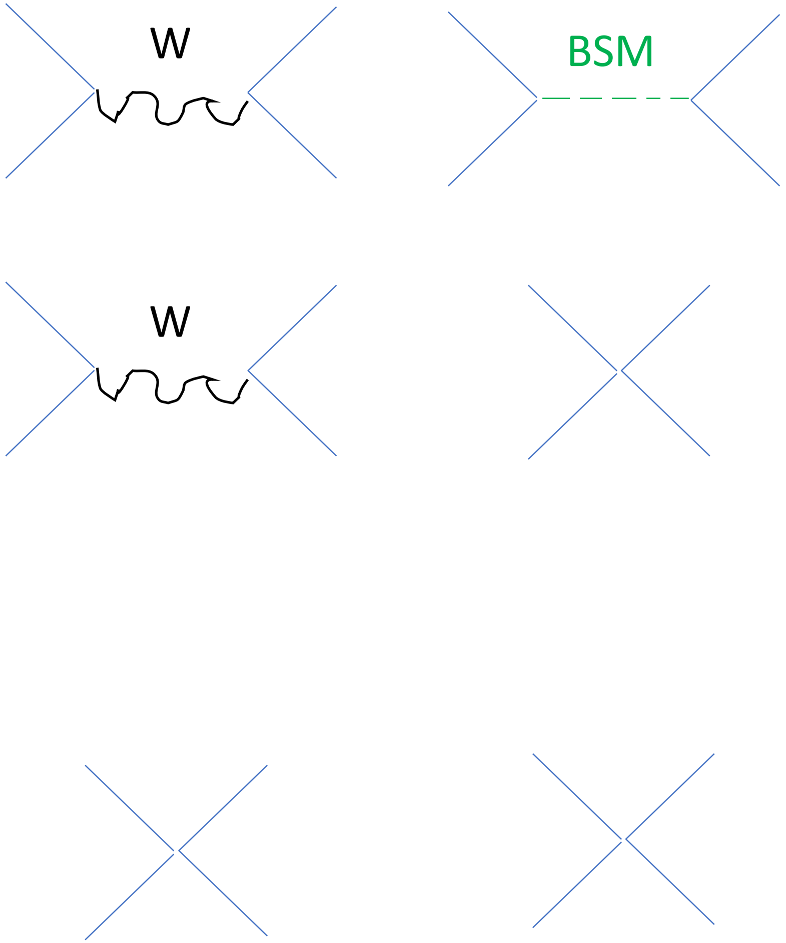

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QCDxEM

2 GeV | Light fields | D=6+...

$$\mathcal{L}_{CC} = -\frac{G_F}{\sqrt{2}} V_{ud}(1+\epsilon_L+\epsilon_R)\{\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau\,\bar{u}[\gamma^\mu-(1-2\hat{\epsilon}_R)\gamma^\mu\gamma^5]d$$
$$+\bar{\tau}(1-\gamma^5)\nu_\tau\,\bar{u}(\hat{\epsilon}_S-\hat{\epsilon}_P\gamma^5)d$$
$$+2\hat{\epsilon}_T\bar{\tau}\sigma_{\mu\nu}(1-\gamma^5)\nu_\tau\,\bar{u}\sigma^{\mu\nu}d\}+h.c.,$$

*(Similarly with **d<-->s**)*
*(It may not be convenient to factor our **1+ε_L+ε_R**)*
*(See González-Alonso et al. papers for **use outside τ decays**)*

Use of the EFT in semileptonic tau decays: $\tau \to \pi \nu_\tau$

The effective NP interactions modify the SM prediction for $\tau \to \pi \nu_\tau$, allowing to bind (Cirigliano et al., '18)

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{B_0}{m_\tau}\epsilon_P^\tau = (-1.5 \pm 6.7) \cdot 10^{-3}$$

(RadCors & lattice evaluation of f_π included)

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$$B_0 = m_\pi^2/(m_u + m_d)$$

One can also take the ratio with the π decay to cancel the dependence on f_π

$$\epsilon_L^\tau - \epsilon_L^\mu - \epsilon_R^\tau + \epsilon_R^\mu - \frac{B_0}{m_\tau}\epsilon_P^\tau + \frac{B_0}{m_\mu}\epsilon_P^\mu = (-3.8 \pm 2.7) \cdot 10^{-3}$$

Use of the EFT in semileptonic tau decays: $\tau \to \pi\,\pi\,\nu_\tau$

1st Strategy: Rely on calculated isospin-breaking corrections relating τ and e^+e^- data (Cirigliano et al., '18)

2nd Strategy: Rely on dispersive representations of form factors fitted to data (Miranda & Roig '18)

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(Cirigliano et al. & Davier et al. '01-'10)

Key: Heavy NP contributions to $e^+e^- \to \pi^+\pi^-$ at low energies are negligible.

$$\frac{a_\mu^\tau - a_\mu^{ee}}{2\,a_\mu^{ee}} = \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e + 1.7\,\epsilon_T^\tau = (8.9 \pm 4.4)\cdot 10^{-3}$$

(**Davier et al.**'s evaluations are used for both a_μ values)

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→ Since the g-2 kernel is saturated at low energies, the previous observable is very sensitive to NP effects at low $\pi\pi$ invariant masses (where the isospin breaking is more reliable).

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→ Since the g-2 kernel is saturated at low energies, the previous observable is very sensitive to NP effects at low $\pi\pi$ invariant masses (where the isospin breaking is more reliable).

→ One could compare the energy-dependence of both spectral functions, but different sets of e^+e^- data are inconsistent.

(This has been largely discussed during this workshop)

Use of the EFT in semileptonic tau decays: $\tau \to \pi\,\pi\,\nu_\tau$

2nd Strategy: Rely on dispersive representations of form factors fitted to data (Miranda & Roig '18)

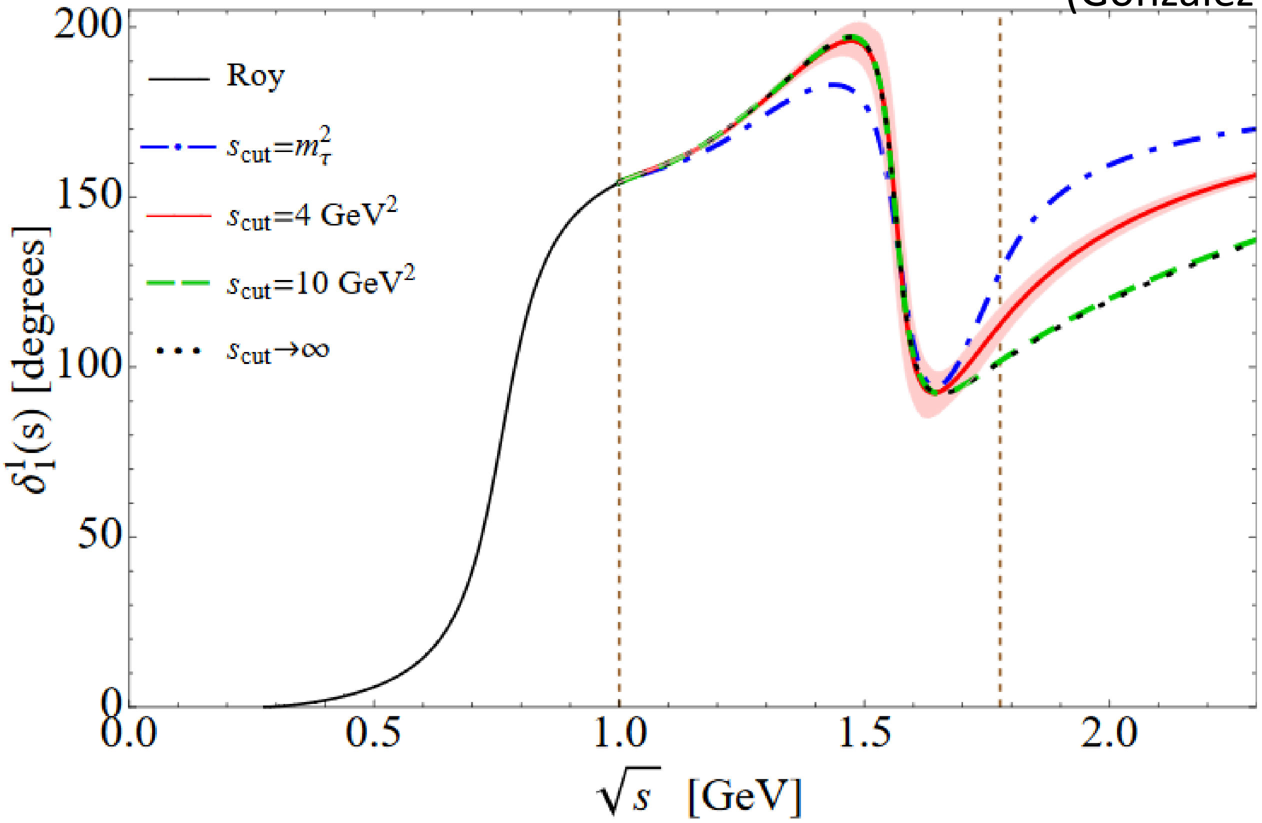
(*Previous talks by José Ramón Peláez & Gilberto Colangelo*)

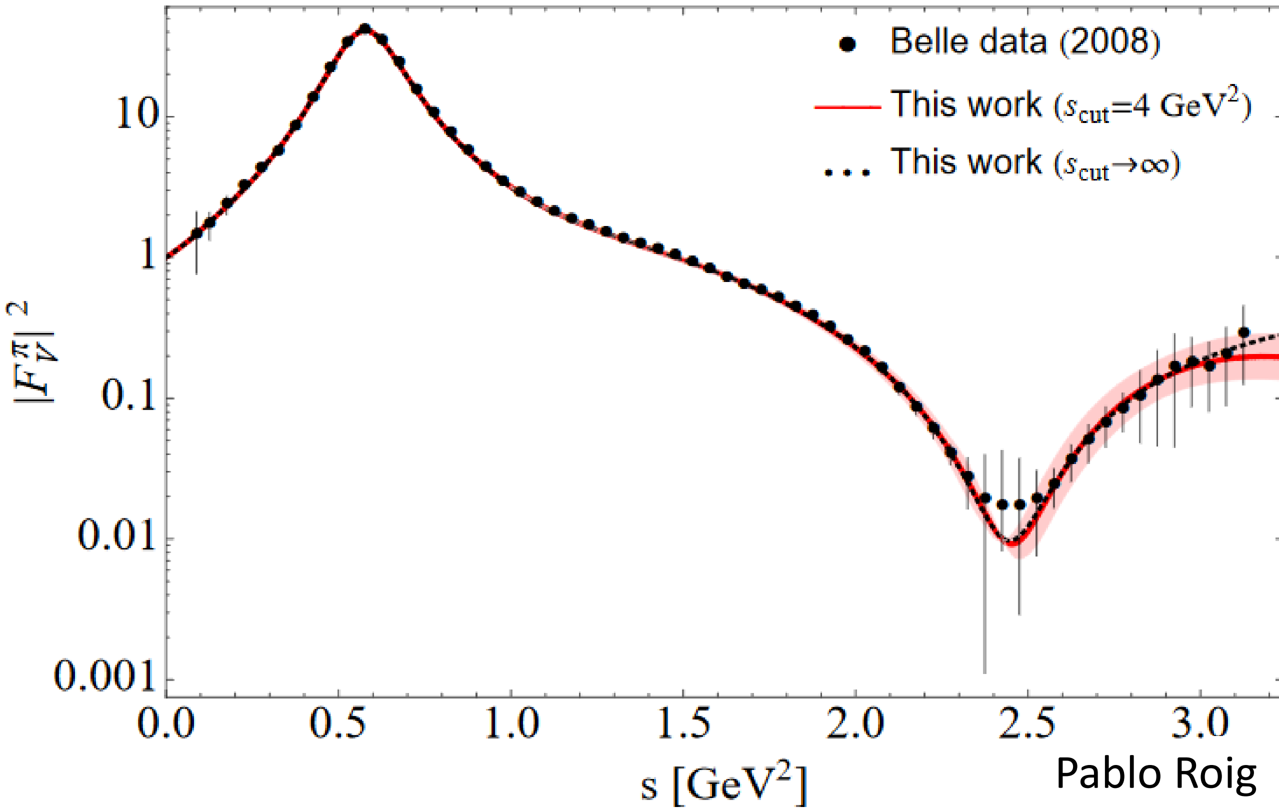
See Emilie Passemar & Sergi Gonzàlez-Solís' talks

VFF from Dumm & Roig '13 (DR)
SFF from Descotes-Genon & Moussallam '14 (DR)
TFF normalization from Baum et al. '12 (lattice QCD)

$\pi\pi$ VFF

(González-Solís & Roig '19)





Pablo Roig

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A fit to Belle's $\pi\pi$ invariant mass distribution and branching ratio measurement yields

$$\boxed{\hat{\epsilon}_T = \left(-1.3^{+1.5}_{-2.2}\right) \cdot 10^{-3}}$$

(provided we restrict $|\hat{\epsilon}_S| < 0.8 \times 10^{-2}$)

Cirigliano et al. '12 (updated values in González-Alonso et al. '18)

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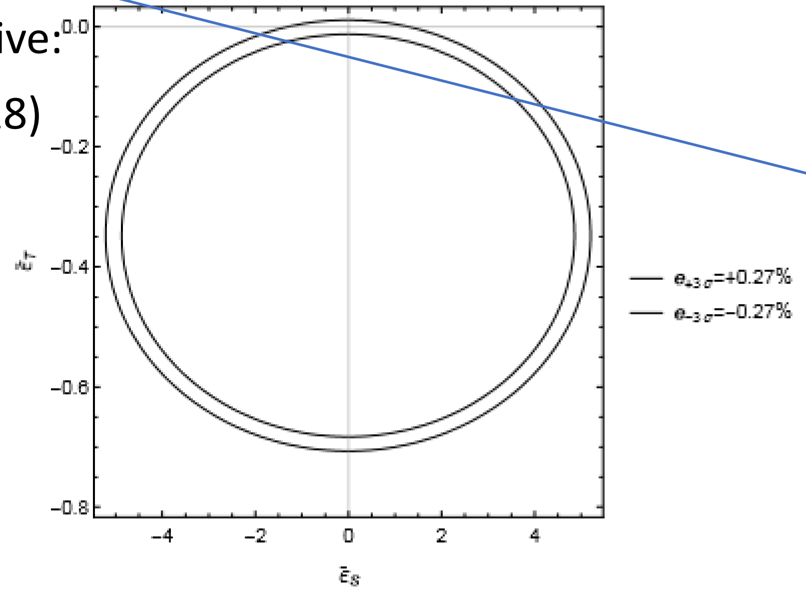
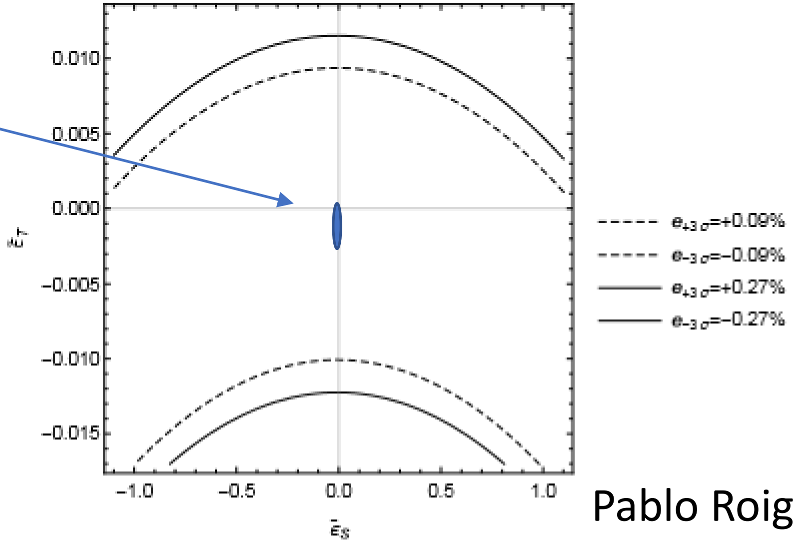
Using only the BR, the limits are not so restrictive:

(Miranda & Roig '18)





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Use of the EFT in semileptonic tau decays: $\tau \to \eta \pi \nu_\tau$

In this case only one possible strategy: Rely on dispersive representations of form factors fitted to data (Garcés et al. '17)

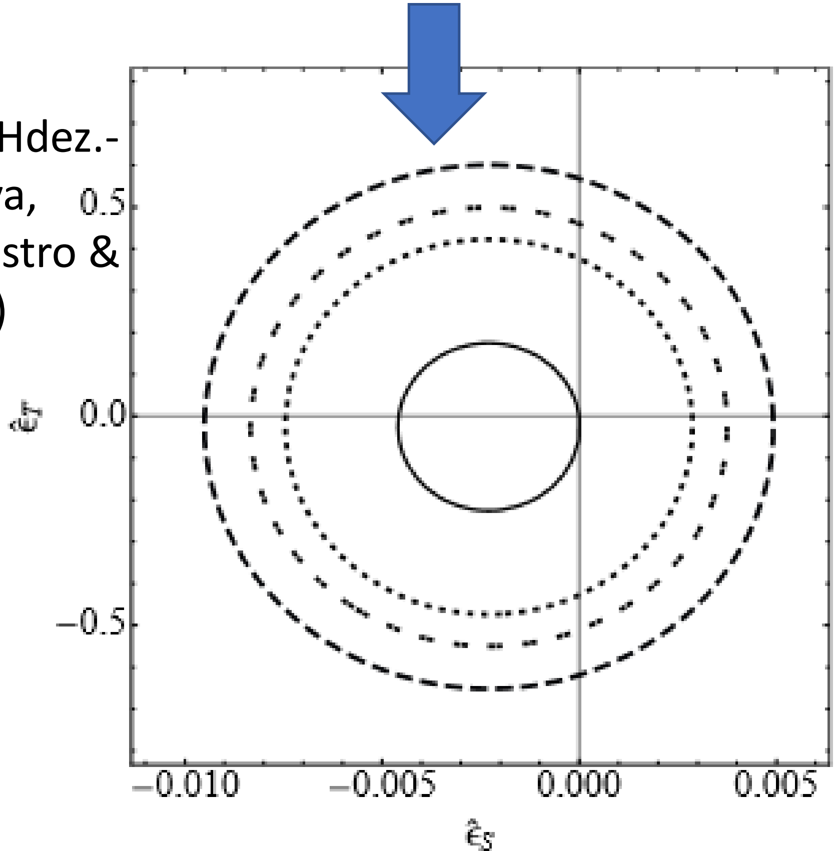
See Emilie Passemar & Sergi Gonzàlez-Solís' talks

- VFF from Dumm & Roig '13 (DR)
- SFF from Escribano et al. '16+ Guo-Oller'12 (DR)
- TFF normalization from Baum et al. '12

This decay mode has a very large scalar form factor contribution, almost unsuppressed by meson mass differences (Escribano et al., '16). As a result, there is a strong sensitivity (although theory error is large) to ε_S:

$$\Gamma_{exp} \approx \Gamma_{SM}\left(1 + 700\,\epsilon_S^\tau + 1.6\times 10^5\,\epsilon_S^{\tau\,2}\right)$$

(Garcés, Hdez.-Villanueva, López-Castro & Roig, '17)



From inner to outer ellipse: SM prediction, Belle, BaBar & CLEO upper limits

For realistically small ε_T, we find $\boxed{-0.83\ 10^{-2} \le \varepsilon_S \le 0.37\ 10^{-2}}$

Using the same hadronic input as we do, Cirigliano et al. '18 found

$$\epsilon_S^\tau = (-6 \pm 15)\times 10^{-3}$$

Use of the EFT in semileptonic ΔS=0 tau decays

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From $\pi\pi$ channel: $\hat{\epsilon}_T = (-1.3^{+1.5}_{-2.2}) \cdot 10^{-3}$ (Miranda & Roig '18)

Limits from Cirigliano et al. '18:

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_S^\tau \\ \epsilon_P^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 1.0 \pm 1.1 \\ 0.2 \pm 1.3 \\ -0.6 \pm 1.5 \\ 0.5 \pm 1.2 \\ -0.04 \pm 0.46 \end{pmatrix} \cdot 10^{-2}$$

Global analysis

Constraints from V+A spectral function:

$$\epsilon_{L+R}^\tau - \epsilon_{L+R}^e - 0.78\epsilon_R^\tau + 1.71\epsilon_T^\tau = (4 \pm 16) \cdot 10^{-3} \,,$$
$$\epsilon_{L+R}^\tau - \epsilon_{L+R}^e - 0.89\epsilon_R^\tau + 0.90\epsilon_T^\tau = (8.5 \pm 8.5) \cdot 10^{-3} .$$

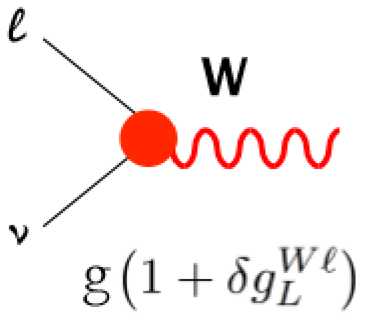
Constraints from V-A spectral function:

$$\epsilon_{L+R}^\tau - \epsilon_{L+R}^e + 3.1\epsilon_R^\tau + 8.1\epsilon_T^\tau = (5.0 \pm 50) \cdot 10^{-3} \,,$$
$$\epsilon_{L+R}^\tau - \epsilon_{L+R}^e + 1.9\epsilon_R^\tau + 8.0\epsilon_T^\tau = (10 \pm 10) \cdot 10^{-3} .$$

Connection to SMEFT:

(See additional material)

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



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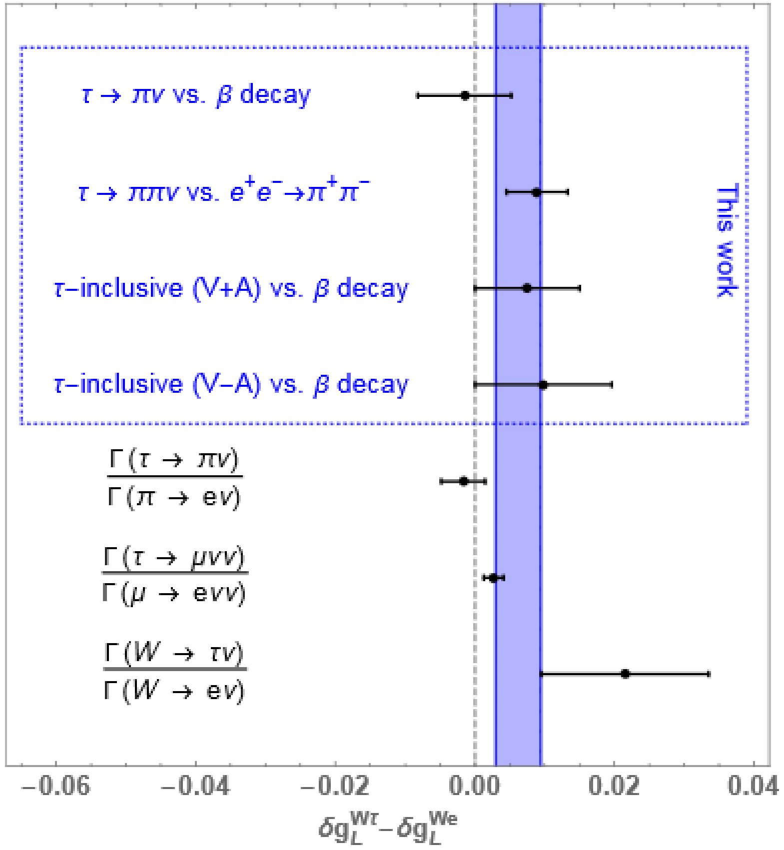

Coefficient	ATLAS $\tau\nu$	τ decays	τ and π decays
$[c_{\ell q}^{(3)}]_{\tau\tau 11}$	$[0.0, 1.6]$	$[-12.6, 0.2]$	$[-7.6, 2.1]$
$[c_{\ell equ}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-8.4, 4.1]$	$[-5.6, 2.3]$
$[c_{\ell edq}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-3.5, 9.0]$	$[-2.1, 5.8]$
$[c_{\ell equ}^{(3)}]_{\tau\tau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

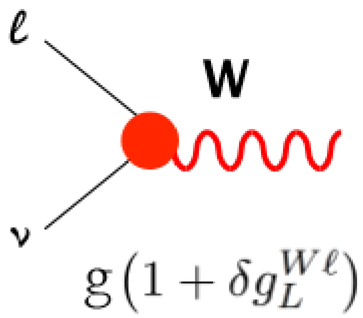

TABLE I. 95% CL intervals (in 10^{-3} units) at $\mu = 1$ TeV, assuming one Wilson coefficient is present at a time.

Use of the EFT in semileptonic ΔS=0 tau decays

From ηπ channel: $\boxed{-0.83\ 10^{-2} \leq \varepsilon_S \leq 0.37\ 10^{-2}}$ (Garcés et al. '17)

From ππ channel: $\boxed{\hat{\epsilon}_T = \left(-1.3^{+1.5}_{-2.2}\right)\cdot 10^{-3}}$ (Miranda & Roig '18)

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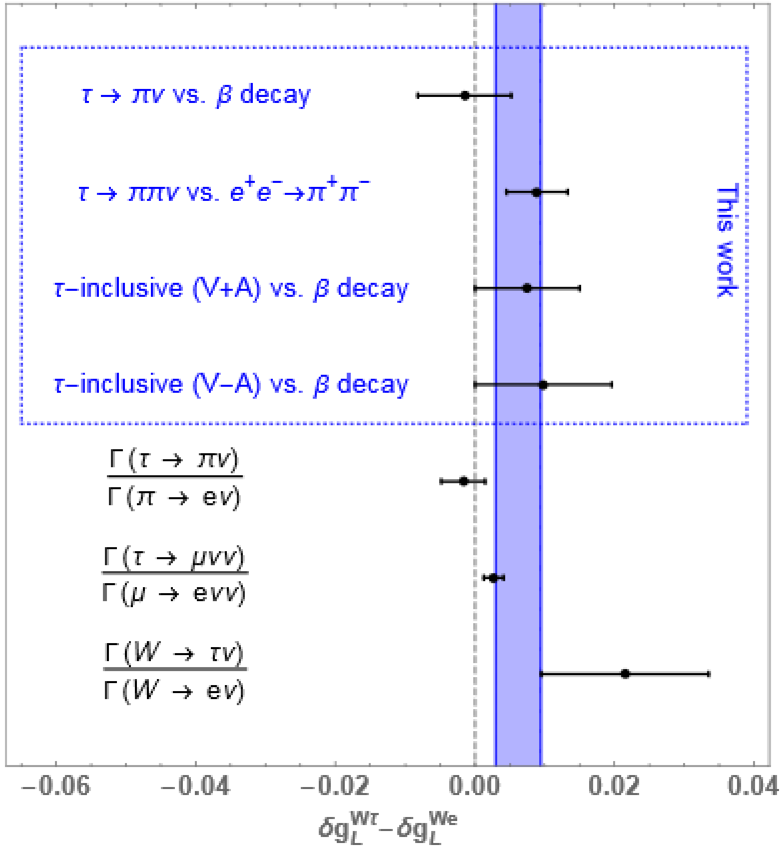

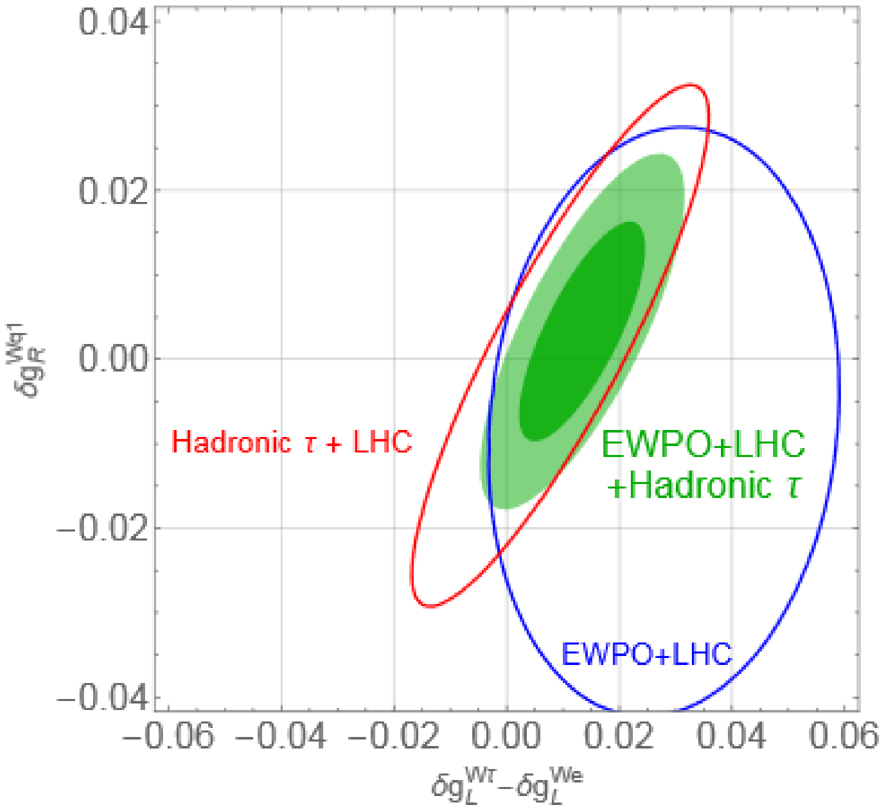

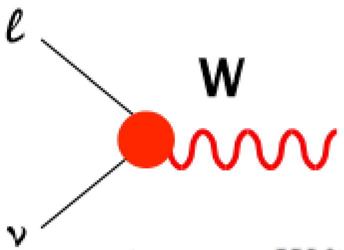

$g\left(1 + \delta g_L^{W\ell}\right)$

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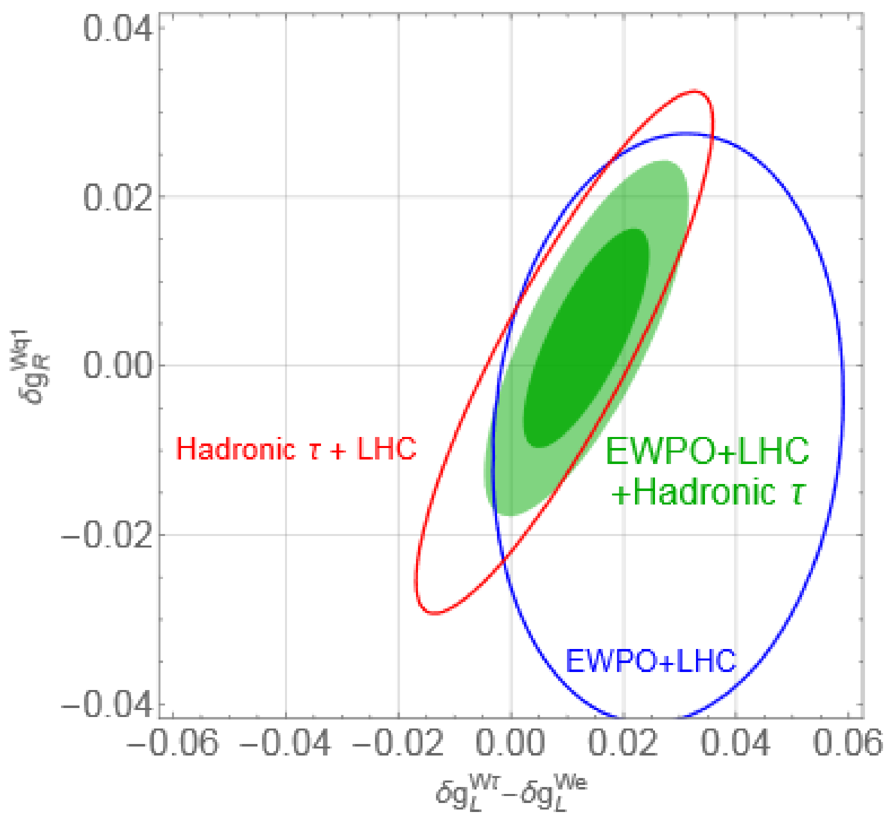
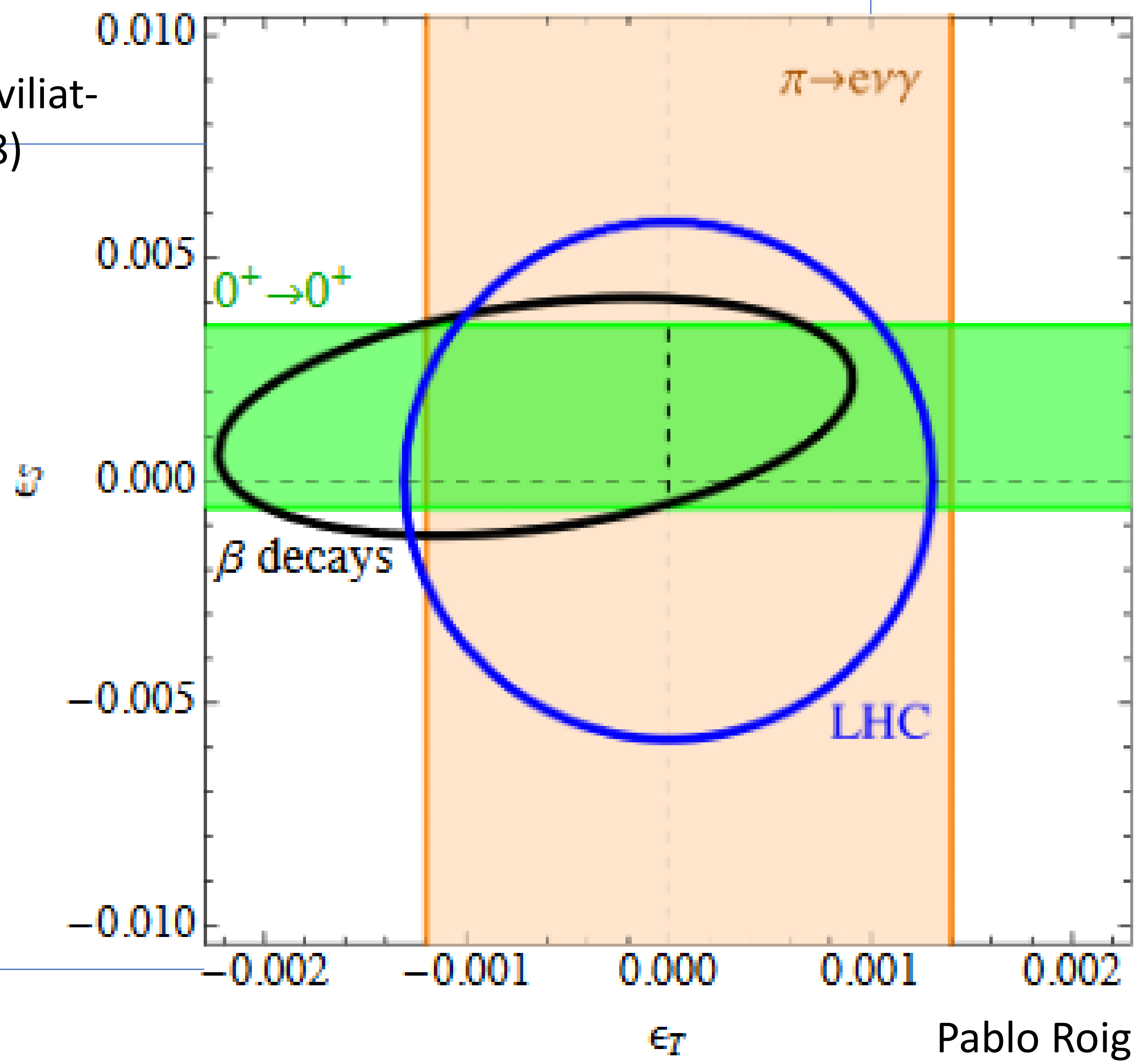


(González-Alonso, Naviliat-Cuncic & Severijns '18)

$\boxed{\Lambda \approx [5,6]\mathrm{TeV}}$

Non-trivial constraints from τ decay!!

$\Lambda \approx v\, (V_{ud}\, \varepsilon_{S,T})^{-1/2}$



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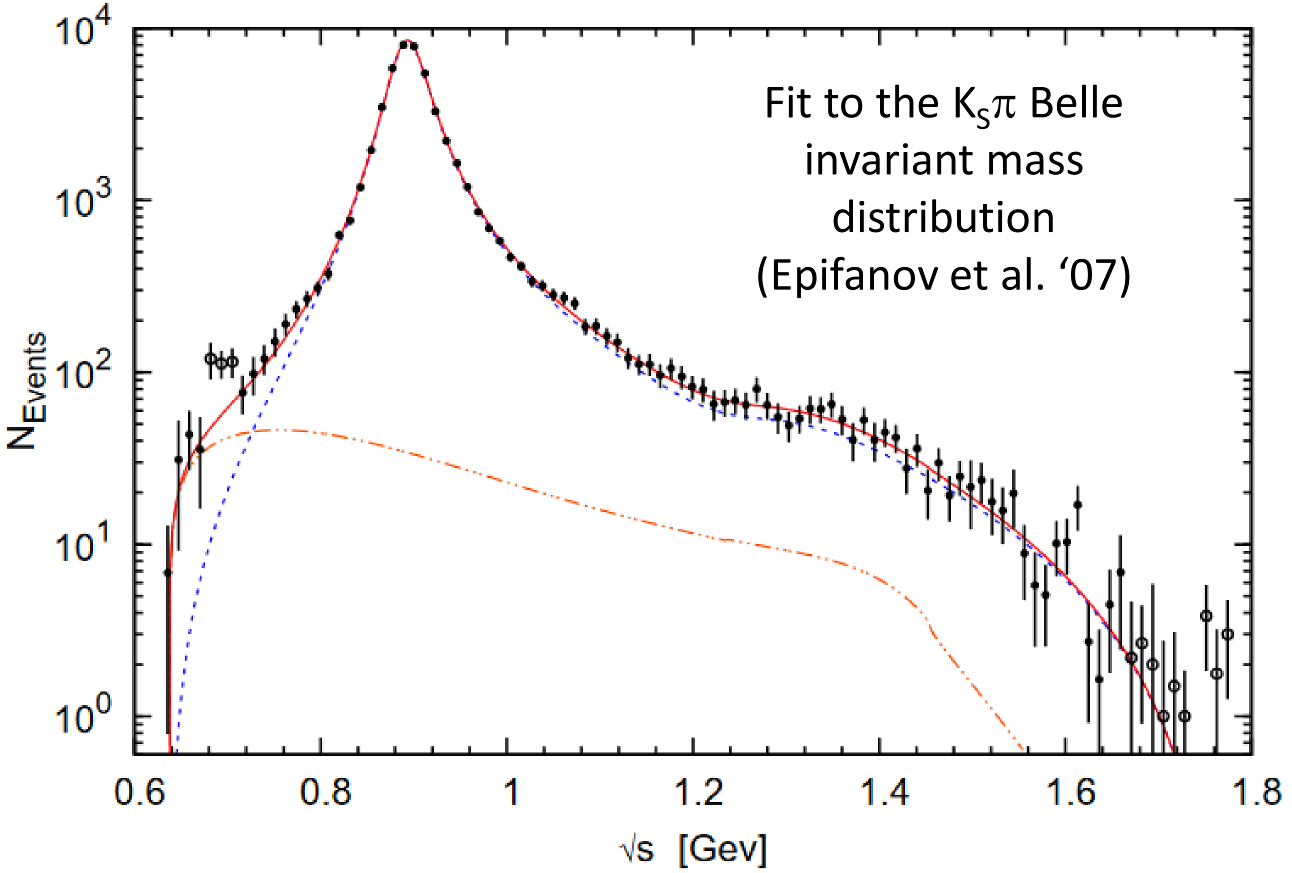
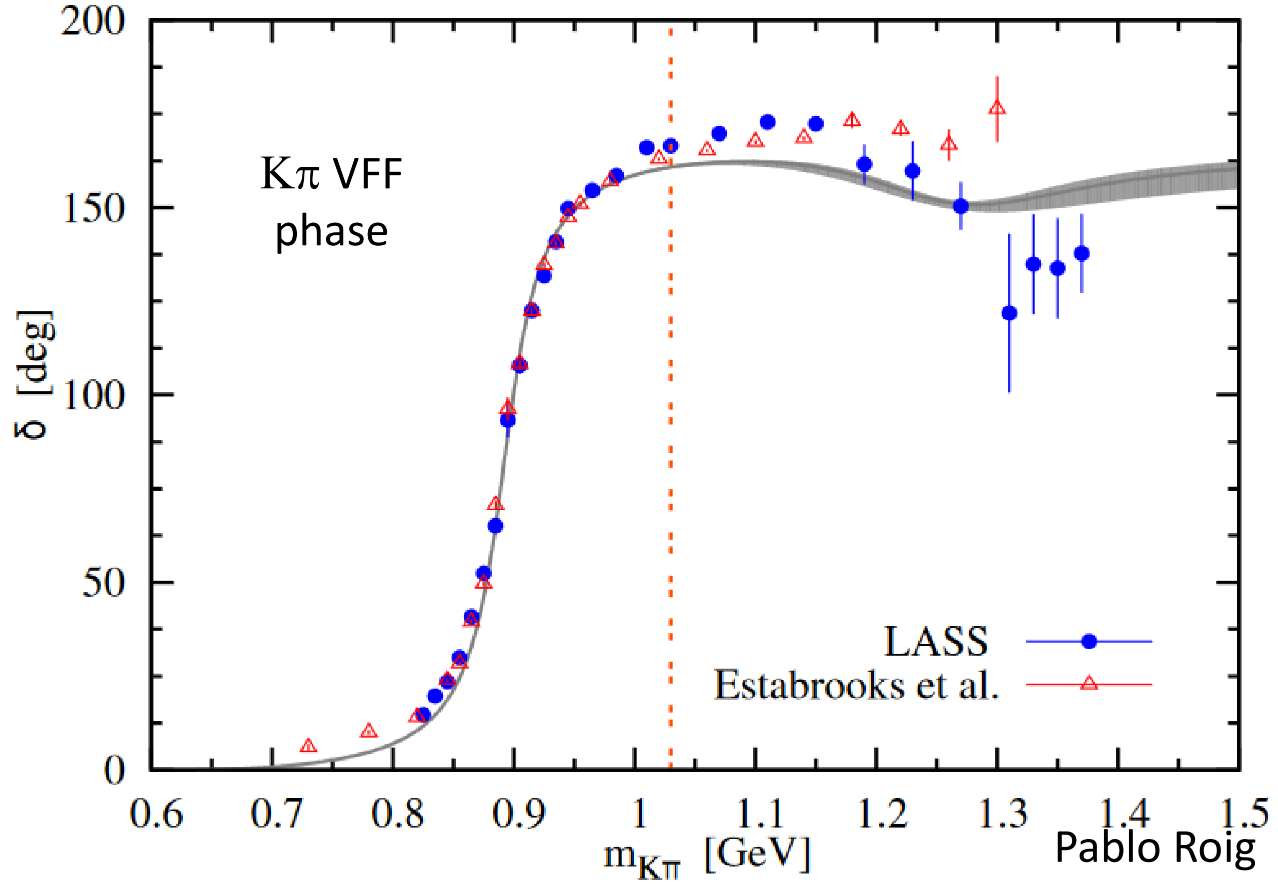
In this case only one possible strategy: Rely on dispersive representations of form factors fitted to data (Rendón, Roig & Toledo ‘19)

See Emilie Passemar & Sergi Gonzàlez-Solís’ talks

VFF from Boito et al. ‘08 (DR)
SFF from Jamin-Oller-Pich ‘06 (DR)
TFF normalization from Baum et al. ’12 (lattice QCD)

(Boito et al. ‘08,…)





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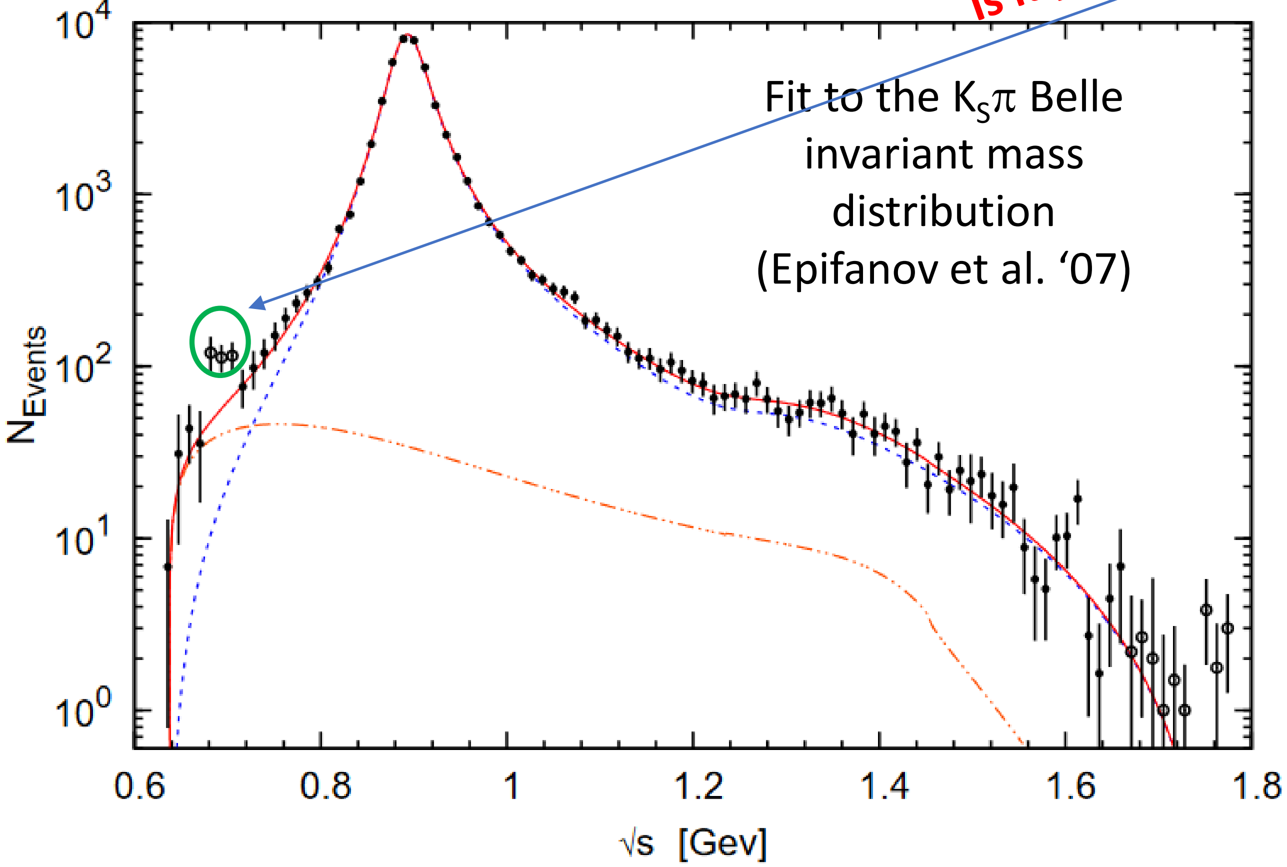
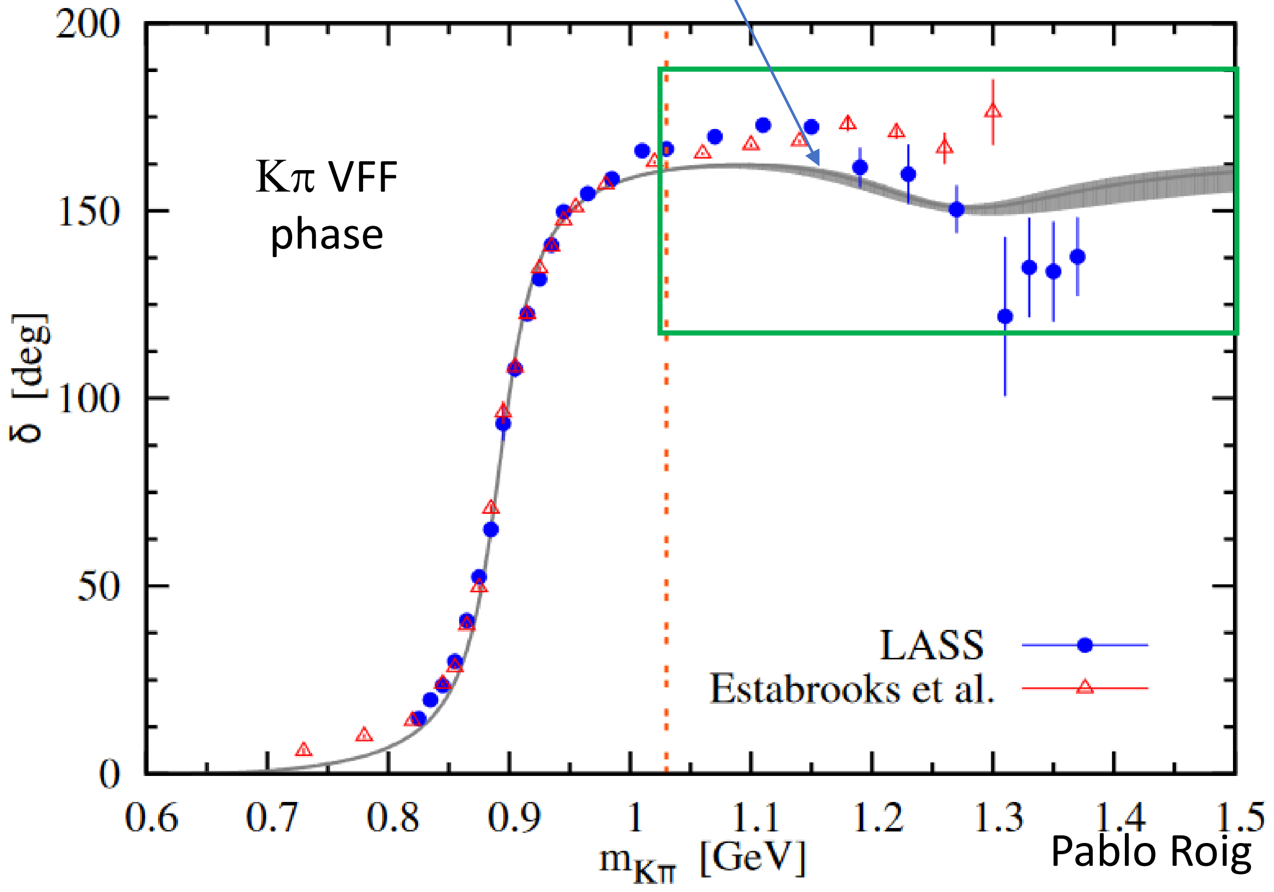
Is it possible that these data points are due to NP?

E-dependence is important for computing A_{CP} later on!!

(Boito et al. '08,…)





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

BaBar measurement: $A_{CP} = -3.6(2.3)(1.1) \times 10^{-3}$

(inclusive in π^0's)

SM prediction (Grossman & Nir, ...): $A_{CP}^{SM} = 3.6(1) \times 10^{-3}$

But the corresponding Belle binned asymmetry (from angular analysis) is consistent with the null SM value expected with permille level precision & Cirigliano et al. '18 derived a no-go theorem for heavy NP explanation of the BaBar result.

What is the UL for A_{CP}^{BSM} taking all FF uncertainties into account?

Are the limits on ε_S, ε_T competitive with those from Kaon & hyperon decays?

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NO

Best fit values	$\hat{\epsilon}_S$	$\hat{\epsilon}_T$	χ^2	χ^2 in the SM
Excluding $i = 5, 6, 7$ bins	$(1.3 \pm 0.9) \times 10^{-2}$	$(0.7 \pm 1.0) \times 10^{-2}$	$[72, 73]$	$[74, 77]$
Including $i = 5, 6, 7$ bins	$(0.9 \pm 1.0) \times 10^{-2}$	$(1.7 \pm 1.7) \times 10^{-2}$	$[83, 86]$	$[91, 95]$

(86 data points)

What is the UL for A_{CP}^{BSM} taking all FF uncertainties into account?

Are the limits on ε_S, ε_T competitive with those from Kaon & hyperon decays?

Use of the EFT in semileptonic tau decays: $\tau \to K \pi \nu_\tau$

In this case only one possible strategy: Rely on dispersive representations of form factors fitted to data (Rendón, Roig & Toledo '19)

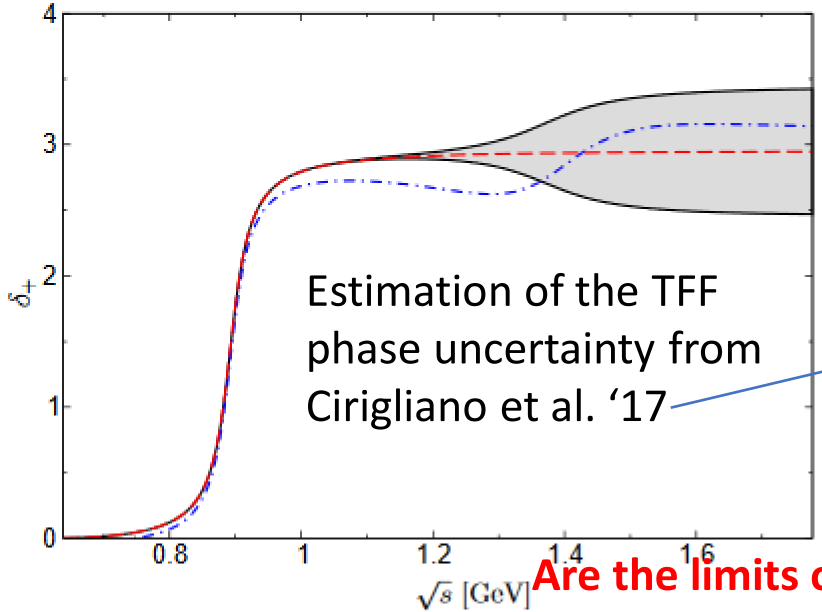
Is it possible that the i=5,6,7 data points are due to heavy NP?

NO

What is the UL for A_{CP}^{BSM} taking all FF uncertainties into account?

$$A_{CP} = \frac{A_{CP}^{SM} + A_{CP}^{BSM}}{1 + A_{CP}^{SM} \times A_{CP}^{BSM}} ,$$

$$A_{CP}^{BSM} = \frac{2\sin\delta_T^W |\hat{\epsilon}_T| G_F^2 |V_{us}|^2 S_{EW}}{256\pi^3 M_\tau^2 \Gamma(\tau \to K_S \pi \nu_\tau)} \int_{s_{\pi K}}^{M_\tau^2} \mathrm{d}s |f_+(s)||F_T(s)| \sin\left(\delta_+(s) - \delta_T(s)\right) \frac{\lambda^{3/2}(s, m_\pi^2, m_K^2)(M_\tau^2 - s)^2}{s^2}$$



Estimation of the TFF phase uncertainty from Cirigliano et al. '17

$$\sin\delta_T^W |\hat{\epsilon}_T| \sim \Im m[\hat{\epsilon}_T]$$

$$2\Im m[\hat{\epsilon}_T] \lesssim 10^{-5}$$

We find $A_{CP}^{BSM} \lesssim 8 \cdot 10^{-7}$

Compared to $A_{CP}^{BSM} \lesssim 3 \cdot 10^{-7}$ In Cirigliano et al. '17

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What is the UL for A_{CP}^{BSM} taking all FF uncertainties into account?

$$A_{CP}^{BSM} \lesssim 8 \cdot 10^{-7}$$ (**See, however, 1902.09561**)

BaBar measurement: $A_{CP} = -3.6(2.3)(1.1) \times 10^{-3}$

SM prediction (Grossman & Nir, …): $A_{CP}^{SM} = 3.6(1) \times 10^{-3}$

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Are the limits on ε_S, ε_T competitive with those from Kaon & hyperon decays?

They are better than hyperon decays but cannot compete with (semi)leptonic Kaon decays

Best fit values	$\hat{\epsilon}_S$	$\hat{\epsilon}_T$	χ^2	χ^2 in the SM
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The previous limits correspond to $\Lambda \approx [2,5]$ TeV, while **Kaon Physics may reach O(500) TeV** (González-Alonso et al. '15, '16, '17)

$$\Lambda \sim v(V_{us}\hat{\epsilon}_{S,T})^{-1/2}$$

Use of the EFT in |ΔS| =1 tau decays

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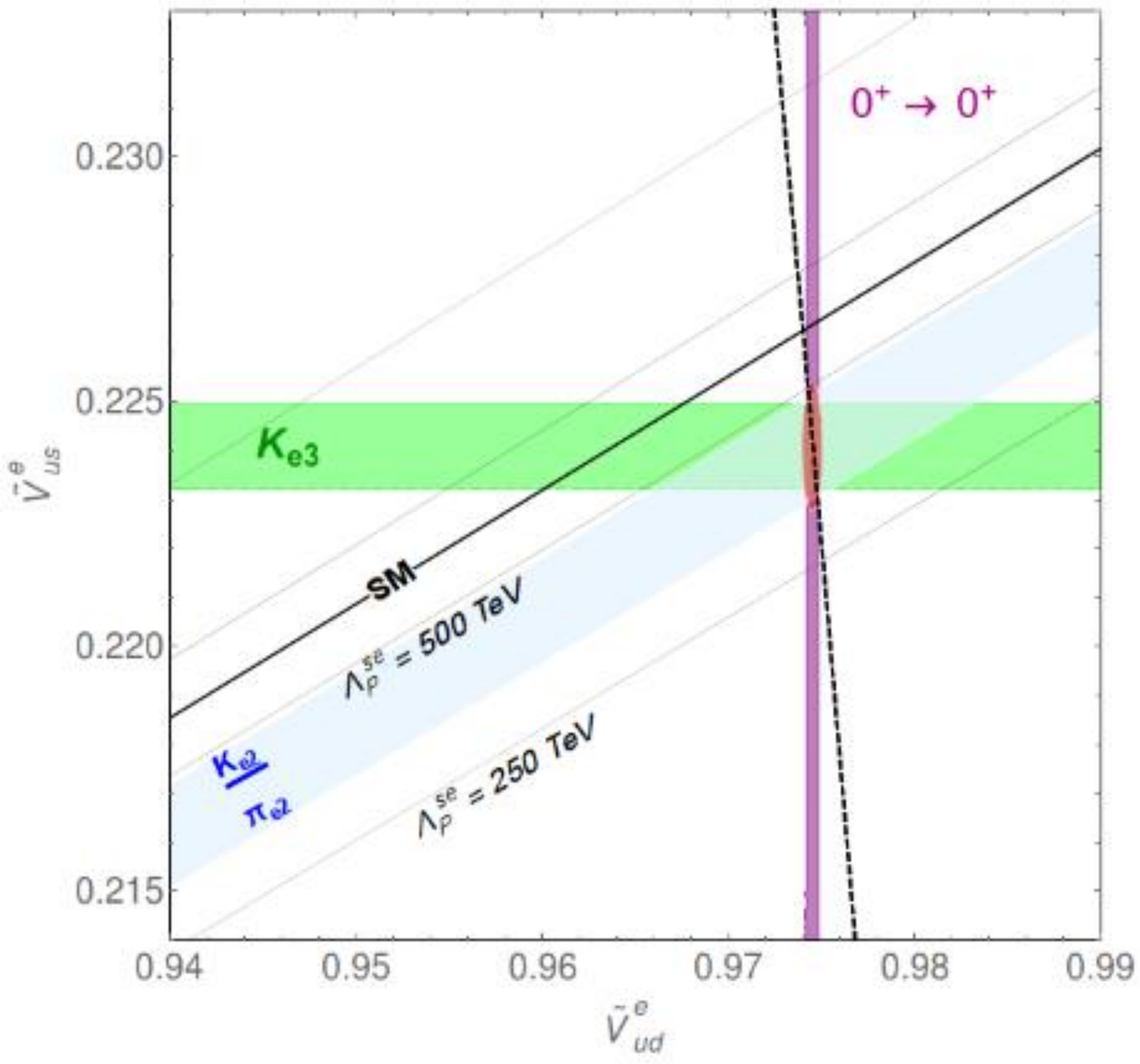

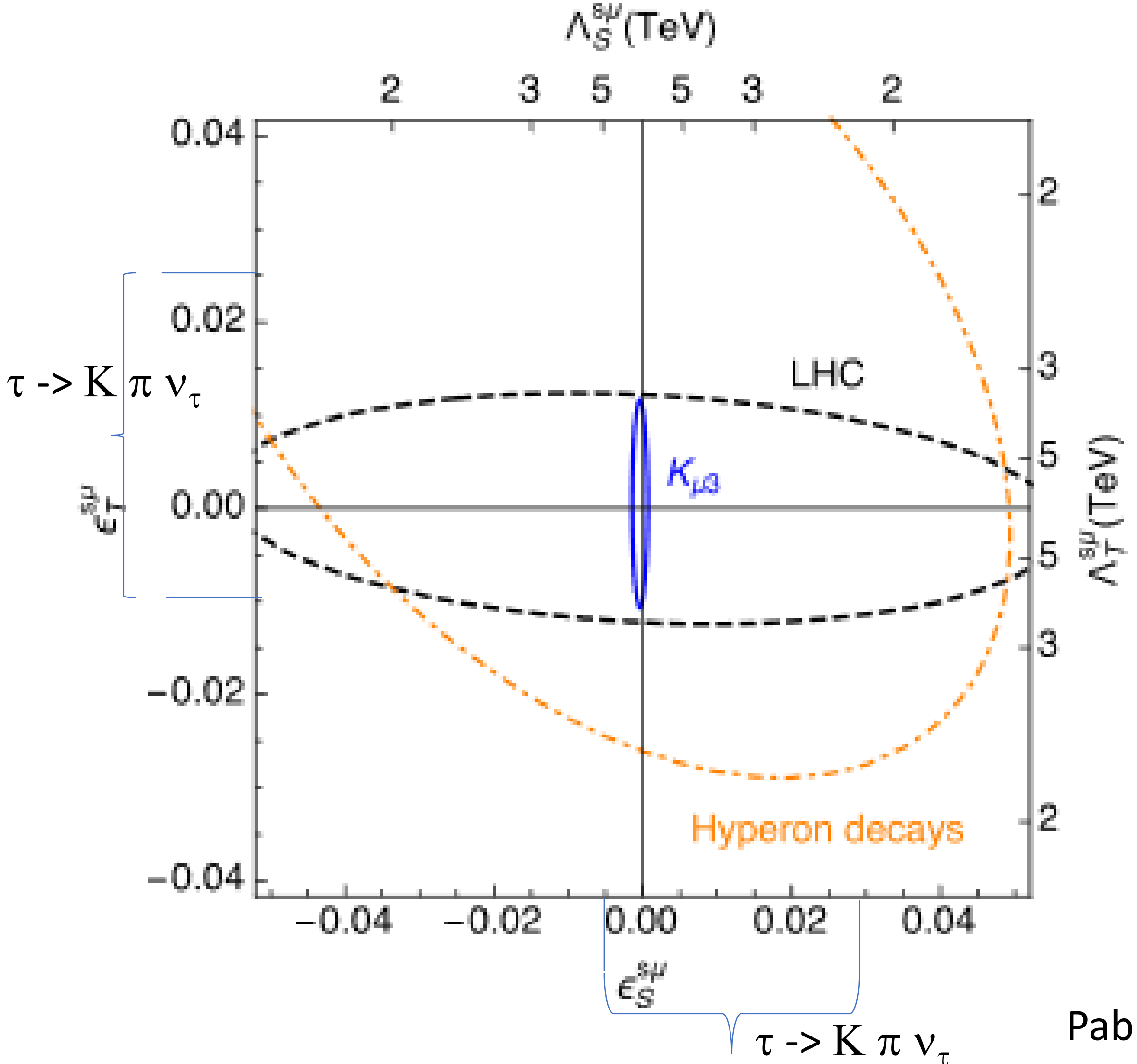

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Plenty of interesting measurable observables for hadron τ decays in our papers

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Belle-II can improve the τ-based limits drastically!!

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ADDITIONAL MATERIAL

SMEFT Lagrangian

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} W_\mu^+ \left[\delta g_R^{W q_1} \bar{u}\gamma_\mu P_R d + \left(1 + \delta g_L^{W\ell}\right) \bar{\ell}\gamma_\mu P_L \nu_\ell\right] + \mathrm{h.c.}$$

$$\begin{aligned}\mathcal{L} \supset \Big(& [c_{lq}^{(3)}]_{\tau\tau 11} (\bar{l}\gamma_\mu \sigma^i P_L l)(\bar{q}\gamma_\mu \sigma^i P_L q) \\ & + [c_{lequ}]_{\tau\tau 11} (\bar{l} P_R e)(\bar{q} P_R u) \\ & + [c_{ledq}]_{\tau\tau 11} (\bar{l} P_R e)(\bar{d} P_L q) \\ & + [c_{lequ}^{(3)}]_{\tau\tau 11} (\bar{l}\sigma_{\mu\nu} P_R e)(\bar{q}\sigma_{\mu\nu} P_R u)\ \Big) \frac{1}{v^2}\end{aligned}$$

1902.09561 Dighe, Ghosh, Kumar & Roy

$$\mathcal{L} \supset \frac{K}{\Lambda^4} \left[(\bar{\ell}_3 H^\dagger)\sigma_{\mu\nu}\tau_R\right] \left[(\bar{q}_2 H)\sigma^{\mu\nu} u_R\right] + \text{h.c.} \, ,$$

They argue that exclusive determination of Vus (in agreement with CKM unitarity) is not spoilt if the operator is such that

$$\langle K\nu_\tau | \mathcal{O}_{\rm NP} | \tau\rangle = \langle K | \mathcal{O}_{\rm NP}^{\rm had} | 0\rangle \, \langle \nu_\tau | \mathcal{O}_{\rm NP}^{\rm lep} | \tau\rangle = 0 \, .$$

But, if this is to bring the V_{us} determination from τ data (0.2216(15)) into agreement with CKM unitarity (0.2257), then it would produce a **quite large V_{us}** (around 0.2270) obtained **from K_{l3} decays** (that is 0.2231(8) before any modification).

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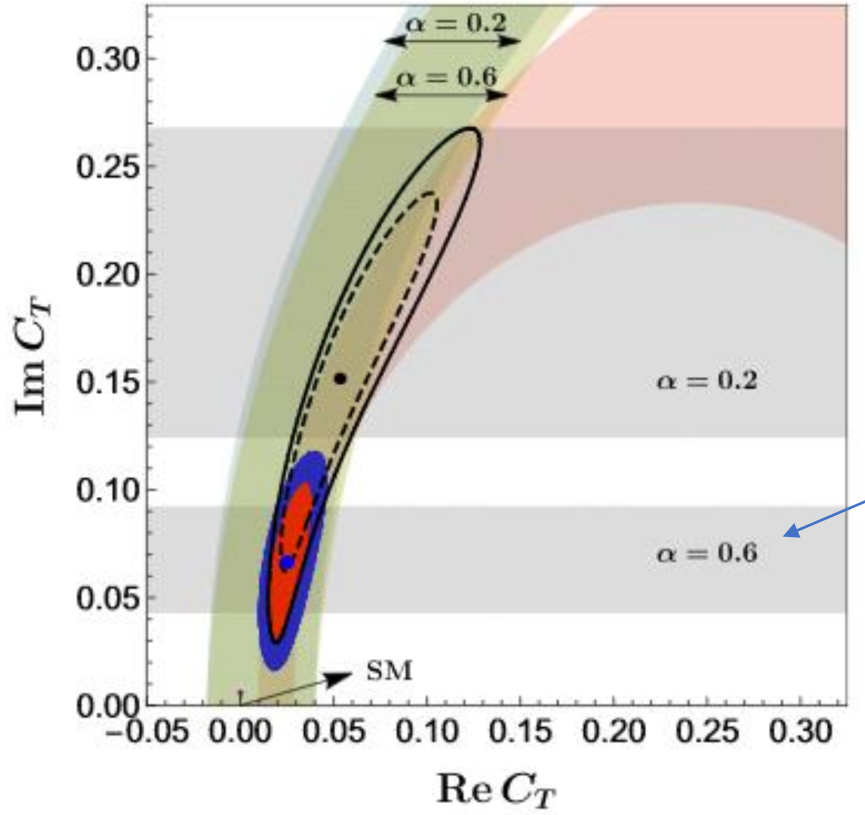
1902.09561 Dighe, Ghosh, Kumar & Roy

$$\mathcal{L} \supset \frac{K}{\Lambda^4}\left[(\bar{\ell}_3 H^\dagger)\sigma_{\mu\nu}\tau_R\right]\left[(\bar{q}_2 H)\sigma^{\mu\nu}u_R\right] + \text{h.c.}\ ,$$

The effective coupling that should be compared to $C_T = 2\,\varepsilon_T$ is $Kv^2/2\Lambda^4$ (Relative suppression factor ≤ 0.03)



Conflict with the EFT counting: The global analysis of Kaon decays yields $|C_T| \leq 1.2\ 10^{-2}$. Then, one would expect that their induced $|C_T| \leq 3.6\ 10^{-5}$, which is much smaller than their solutions (they need $\mathrm{Im}[C_T] \geq 0.1$ for realistic α).

They also argue that NP would modify $K\pi$ but not KK, $KK\pi$ (bkg) channels.

Probably too large value

(Inelasticities)

$$\delta_T(s) - \delta_+(s) = \alpha \times \mathrm{Arg}[\mathrm{BW}(K^*(1410))]$$

FIG. 1. The 1σ allowed regions from A^T_{CP} (grey), BR of $\tau \to K_s\pi\nu_\tau$ (light blue, light green) and, the V_{us} anomaly (pink). The combined 1σ and 90% C.L. regions for $\alpha = 0.2$ (unfilled ovals) and $\alpha = 0.6$ (filled ovals) are also shown.

A no-go theorem for non-standard explanations of the $\tau \to K_S \pi \nu_\tau$ CP asymmetry

Vincenzo Cirigliano,[1] Andreas Crivellin,[2] and Martin Hoferichter[3]

$$\mathcal{L}_T = C_{abcd}\, \bar{L}^i_{La} \sigma_{\mu\nu} e_{Rb}\, \epsilon^{ij}\, \bar{q}^j_{Lc} \sigma^{\mu\nu} u_{Rd} \; + \; \text{h.c.},$$

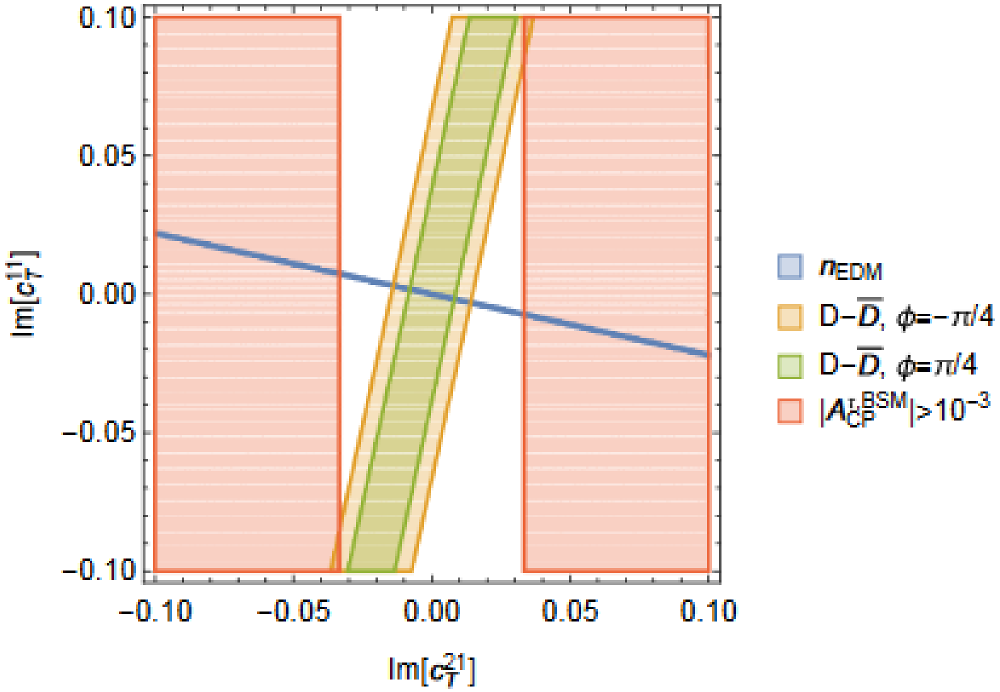
$$\mathcal{L}_T = C_{3321}\Big[(\bar{\nu}_\tau \sigma_{\mu\nu} R \tau)(\bar{s}\sigma^{\mu\nu} R u) - V_{us}(\bar{\tau}\sigma_{\mu\nu} R\tau)(\bar{u}\sigma^{\mu\nu} R u)\Big] \; + \; \text{h.c.},$$

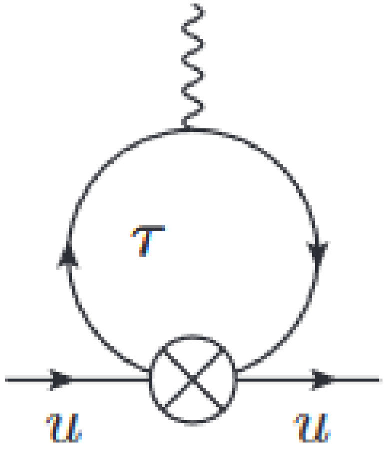
$$C_{3321} = -\sqrt{2} G_F V_{us} c_T = -V_{us}\frac{c_T}{v^2}$$

RGE

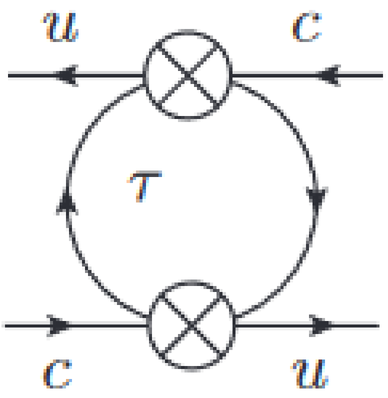
Up quark EDM => n EDM

$$\mathcal{L}_{\mathrm{D}} = -\frac{i}{2} d_u(\mu) \bar{u}\sigma^{\mu\nu}\gamma_5 u F_{\mu\nu}$$





EDM



$\overline{\text{D}}$-D mixing

(These contributions are avoided in 1902.09561 by the presence of the two Higgs doublets)

Pablo Roig