Exclusive hadronic tau decays within and beyond the Standard Model

(See Sergi Gonzàlez-Solís' talk at CHARM2020 on this subject)

Thanks to all my collaborators in this topic

Pablo Roig
Cinvestav (Mexico City)
The 16th International Workshop on Tau Lepton Physics (TAU2021) (Indiana, Virtual Edition)

SIMON, R.I.P.

Exclusive hadronic tau decays

Input for $a_\mu^{HVP,LO}$

See J. Miranda talk

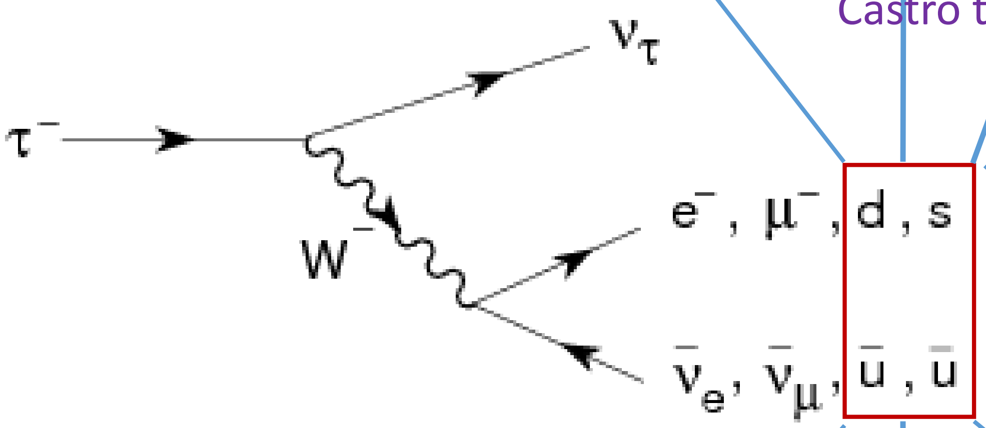
See A. Lusiani talk

V_{us}

LU

See G. López Castro talk

Hadronization of QCD currents



PDG

decay mode	fit result (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.3937 ± 0.0384
$e^-\bar{\nu}_e\nu_\tau$	17.8175 ± 0.0399
$\pi^-\nu_\tau$	10.8164 ± 0.0512
$K^-\nu_\tau$	0.6964 ± 0.0096
$\pi^-\pi^0\nu_\tau$	25.4941 ± 0.0893
$K^-\pi^0\nu_\tau$	0.4328 ± 0.0148
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.2595 ± 0.0964
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0647 ± 0.0218
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.0429 ± 0.0707
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0478 ± 0.0212
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.1118 ± 0.0391
$\pi^-\bar{K}^0\nu_\tau$	0.8384 ± 0.0138
…	…

See Z. H. Guo talk
See F. Noel talk

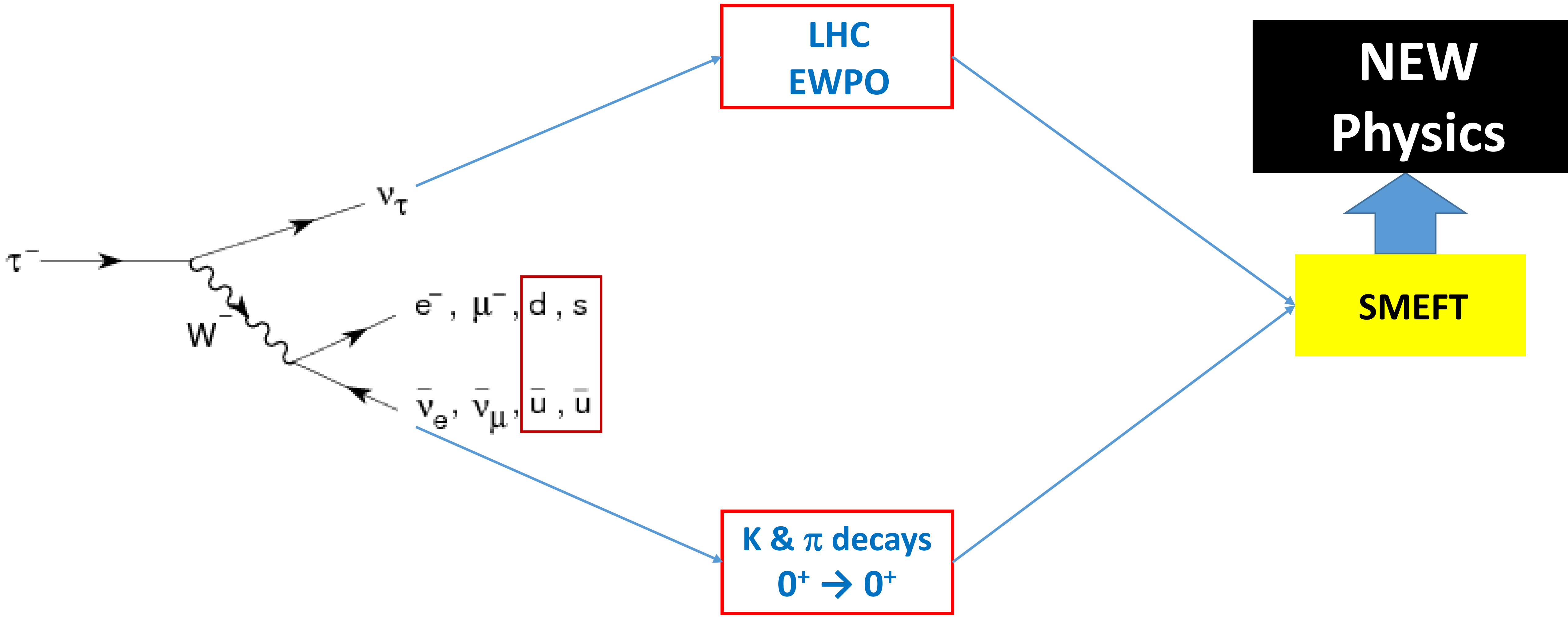
CP & T violation

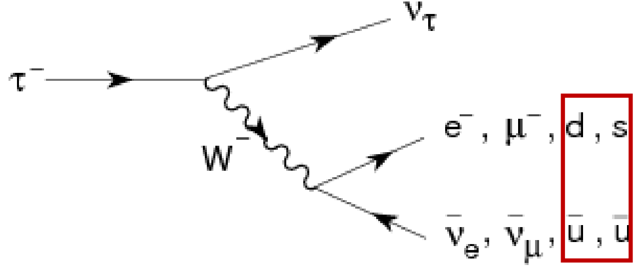
SCCs

See B. Moussallam talk

Resonance (pole) parameters

BSM limits from tau decays





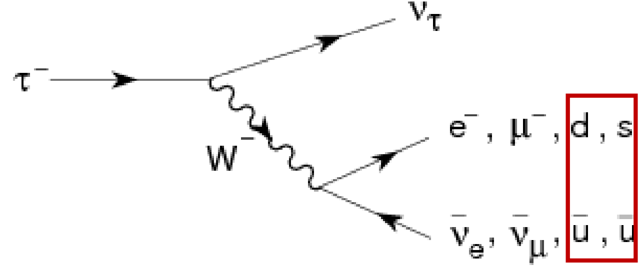
Within the SM

τ **Unique** lepton: Can decay to hadrons! => It has been a clean lab to understand **QCD** hadronization via its semileptonic decays.

Inclusively: Determination of fundamental parameters of the SM (α_S, V_{us}, m_s, χPT LECs, OPE coefficients, DVs, …)

(See M. Davier, A. Hocker & Z. Zhang; and A. Pich reviews)

Exclusively: See next slide.



Within the SM

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{CKM}\, \overline{u}_{\nu_\tau} \gamma^\mu (1-\gamma_5) u_\tau\, \mathcal{H}_\mu$$

$$\mathcal{H}_\mu = \langle\, H \,|\, (\mathcal{V}_\mu - \mathcal{A}_\mu)\, e^{i\mathcal{L}_{QCD}} \,|\, 0 \,\rangle$$

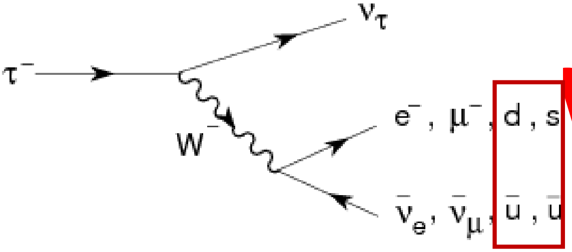
SYMMETRY

$$\mathcal{H}_\mu = \sum_i \underbrace{(\,\ldots\,)^i_\mu}_{Lorentz\ structure} F_i(q^2,\ldots)$$

Alternatively, in terms of structure functions (Kuhn&Mirkes'92)

Chiral symm., analyticity, unitarity, parton dynamics, DATA, …

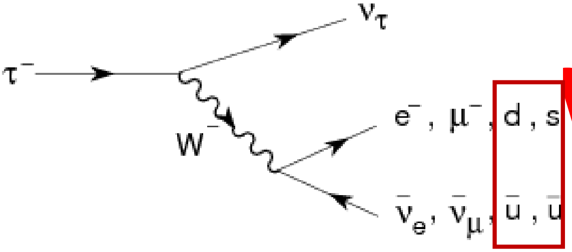
Dispersion relations



Within the SM:1 meson

$$\tau^- \to \nu_\tau \pi^- \text{ and } \tau^- \to \nu_\tau K^-$$

$$\langle \pi^-(p)|\bar{d}\gamma^\mu\gamma_5 u|0\rangle = -i\sqrt{2}\, f_\pi\, p^\mu\,, \qquad \langle K^-(p)|\bar{s}\gamma^\mu\gamma_5 u|0\rangle = -i\sqrt{2}\, f_K\, p^\mu\,,$$



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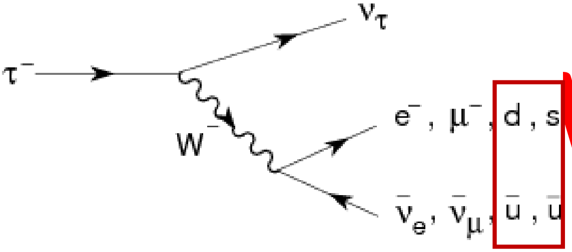
Known from

$$\pi^- \to \mu^- \bar{\nu}_\mu \text{ and } K^- \to \mu^- \bar{\nu}_\mu$$

But, if there is New Physics, $f_{\pi/K}^{QCD}$ is different from $f_{\pi/K}^{exp}$!!

RadCors (real&virtual) are essential (including structure-dependent effects): See **Gabriel**'s talk right after !



Within the SM:2mesons

$$\tau^- \to \nu_\tau P^- P'^0 \qquad \Delta_{PP'} = m^2_{P^-} - m^2_{P'^0}$$

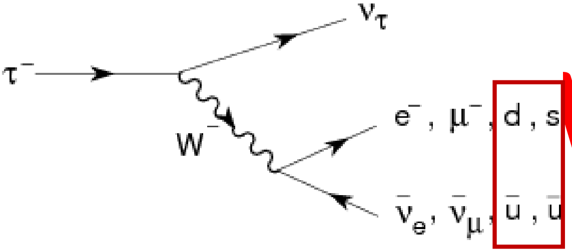
$$\langle P^- P'^0 | \bar{d}_i \gamma^\mu u |0\rangle = C_{PP'} \left\{ \left(p_- - p_0 - \frac{\Delta_{PP'}}{s} q \right)^\mu F_V^{PP'}(s) + \frac{\Delta_{PP'}}{s} q^\mu F_S^{PP'}(s) \right\}$$

$$q^\mu = (p_- + p_0)^\mu \qquad s = q^2$$

$$\frac{d\Gamma}{ds} = \frac{G_F^2 |V_{ui}|^2 m_\tau^3}{768\pi^3} S_{EW}^{\text{had}} C^2_{PP'} \left(1 - \frac{s}{m_\tau^2}\right)^2 \left\{ \left(1 + 2\frac{s}{m_\tau^2}\right) \lambda^{3/2}_{PP'} |F_V^{PP'}(s)|^2 + 3\frac{\Delta^2_{PP'}}{s^2} \lambda^{1/2}_{PP'} |F_S^{PP'}(s)|^2 \right\}$$

$$\lambda_{PP'} \equiv \lambda(s, m^2_{P^-}, m^2_{P'^0})/s^2$$

There is no time to discuss here $\tau \to \nu_\tau (P\,P\,P)^-$ decays. See talks by F. Krinner & M. Mikhasenko later on today.



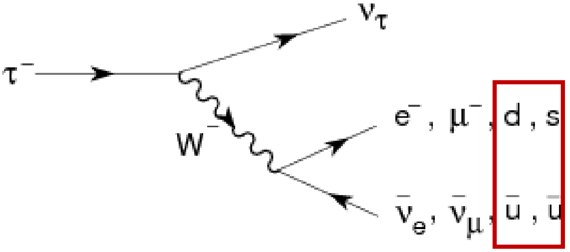
Within the SM:2mesons

$$\tau^- \to \nu_\tau \pi^- \pi^0 \ \textbf{and} \ \tau^- \to K^- K_S \nu_\tau$$

$$F_V^\pi(s) = \exp\left[\alpha_1 s + \frac{\alpha_2}{2} s^2 + \frac{s^3}{\pi}\int_{4m_\pi^2}^{s_{\rm cut}} ds' \frac{\delta_1^1(s')}{(s')^3(s'-s-i0)}\right]$$

S. Gonzàlez-Solís & P. Roig '19,…
(extended list of Refs. in the procs.)

See radiative case in talks by Z. H. Guo & J. A. Miranda.



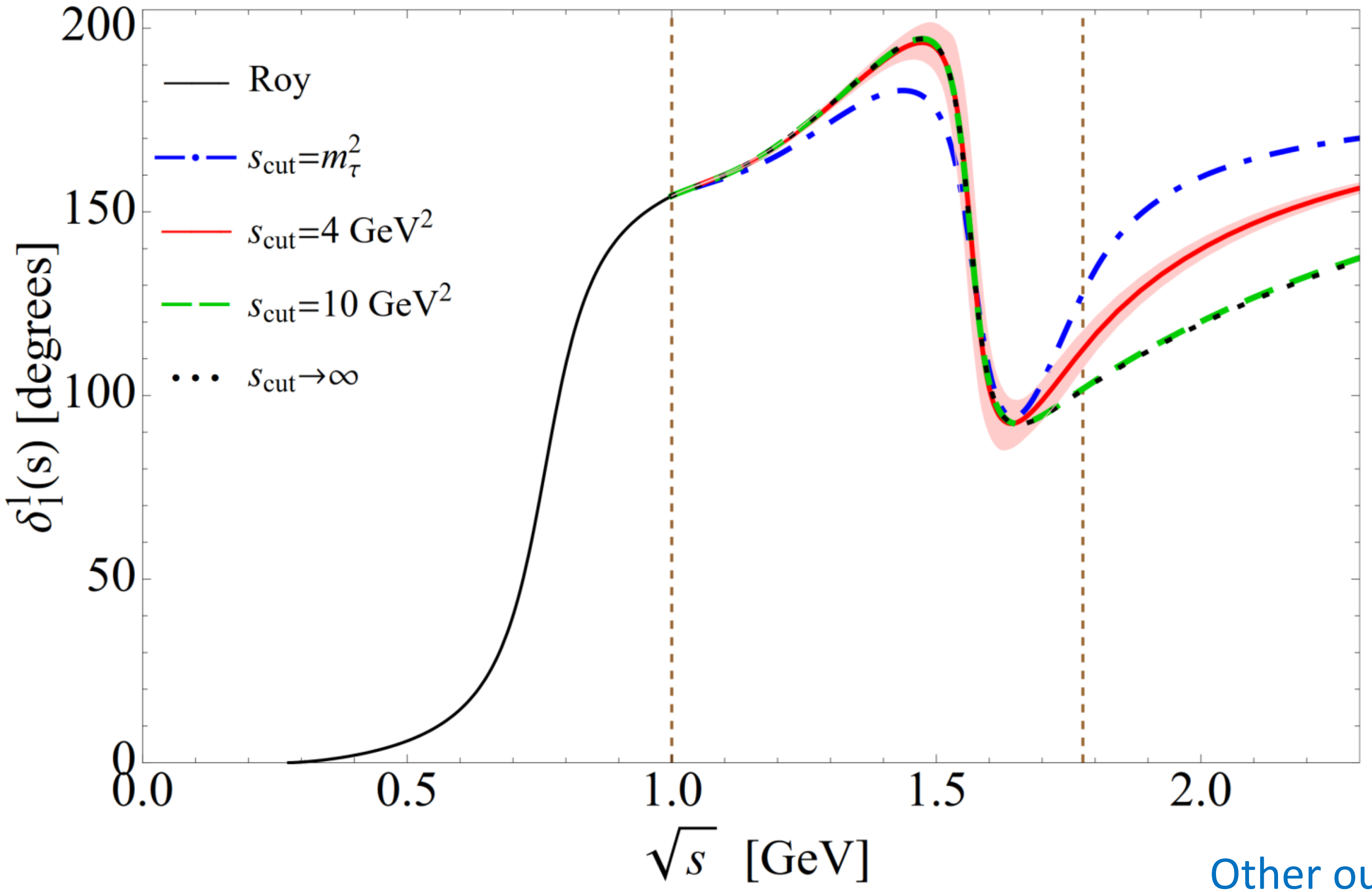
Within the SM:2mesons

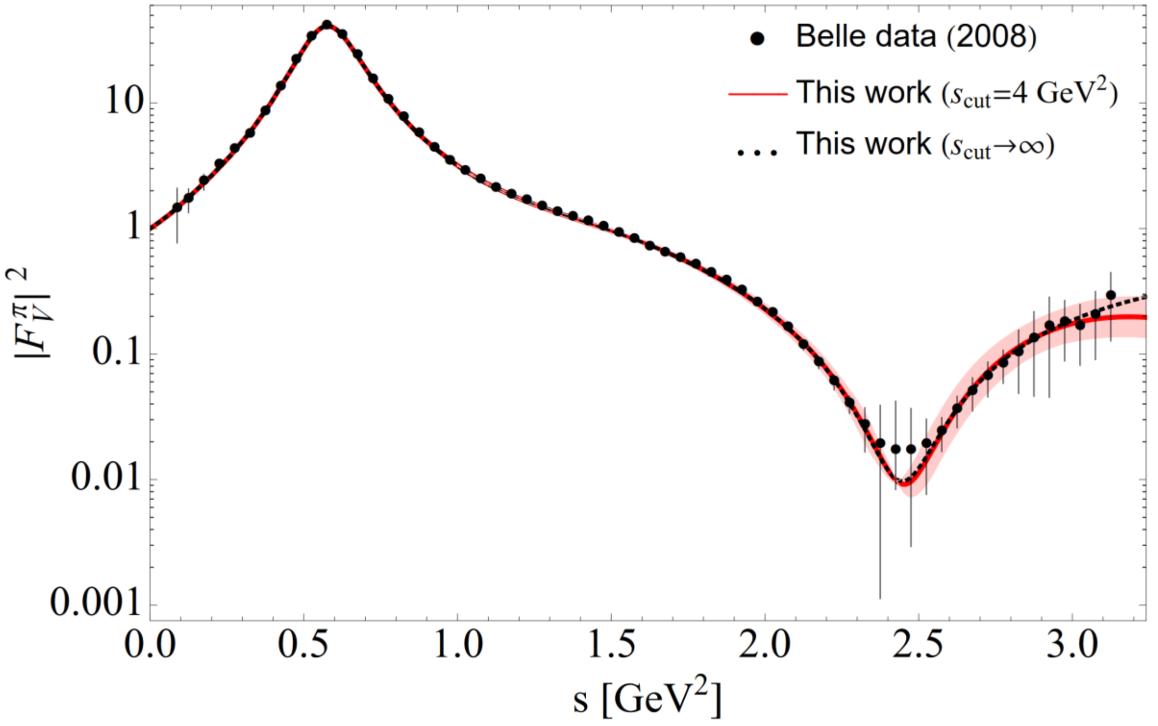
$$\tau^- \rightarrow \nu_\tau \pi^- \pi^0 \textbf{ and } \tau^- \rightarrow K^- K_S \nu_\tau$$

Watson's Th.

As. behaviour

S. Gonzàlez-Solís & P. Roig '19,...
(extended list of Refs. in the procs.)



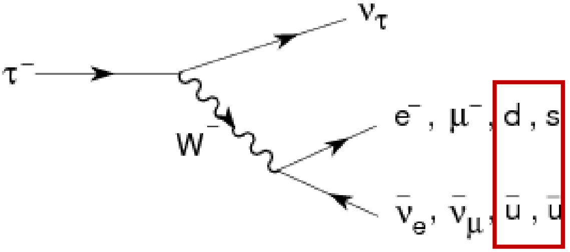


Other outputs: ρ, ρ' & ρ'' pole positions & slope parameters

See radiative case in talks by Z. H. Guo & J. A. Miranda.

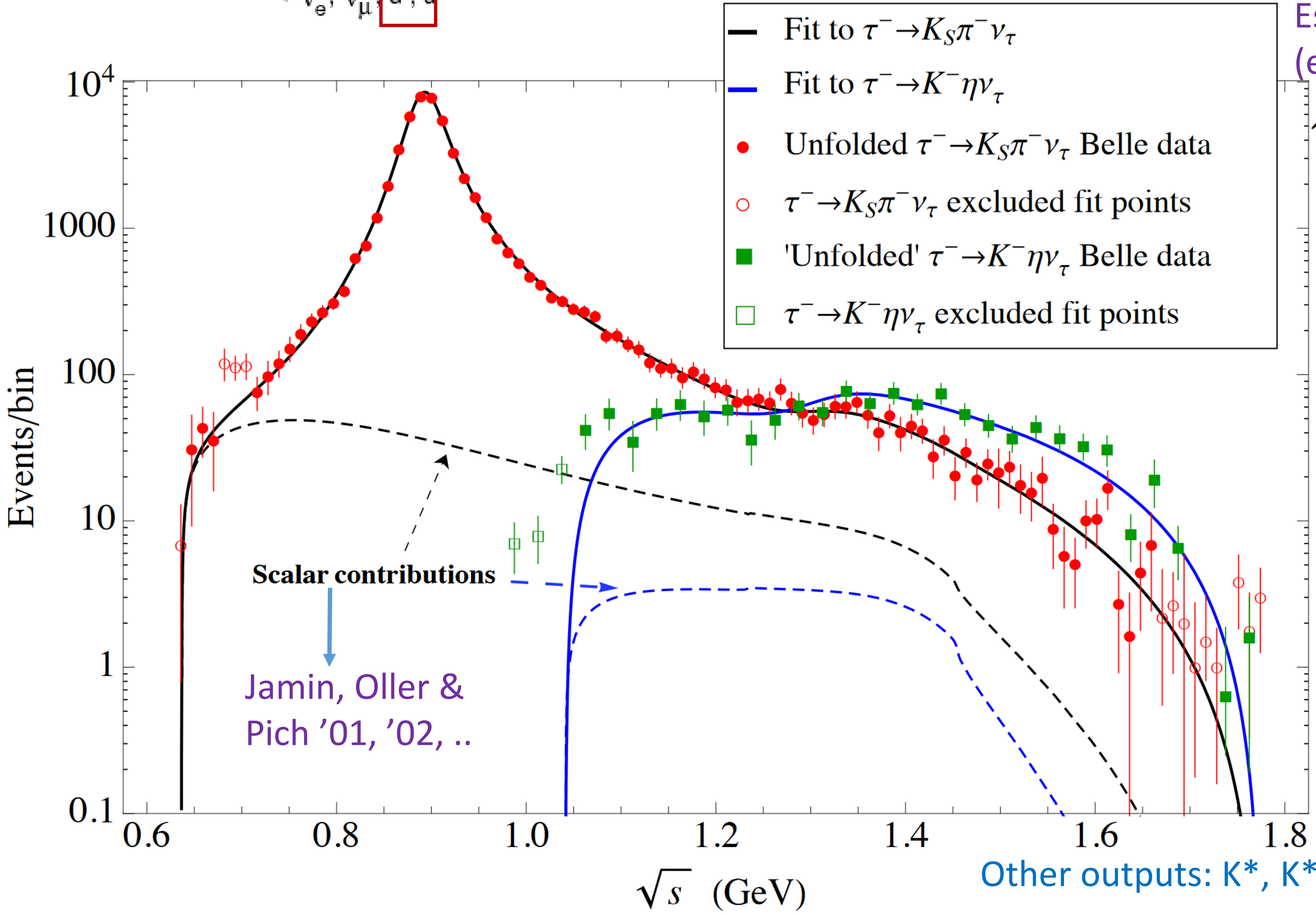
Essential for BSM studies: Model-dependent uncertainties included

Within the SM:2mesons



Escribano, Gonzàlez-Solís, Jamin & P. Roig ’14,…
(extended list of Refs. in the procs.)

$\tau^- \to K_S\pi^-\nu_\tau$ and $\tau^- \to K^-\eta\nu_\tau$



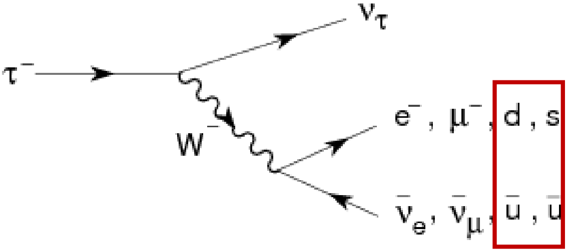
Jamin, Oller & Pich ’01, ’02, ..

Other outputs: K*, K*’ pole positions & slope parameters

Essential for BSM studies: Model-dependent uncertainties included

See F_S in talk by F. Noel.

Within the SM:2mesons



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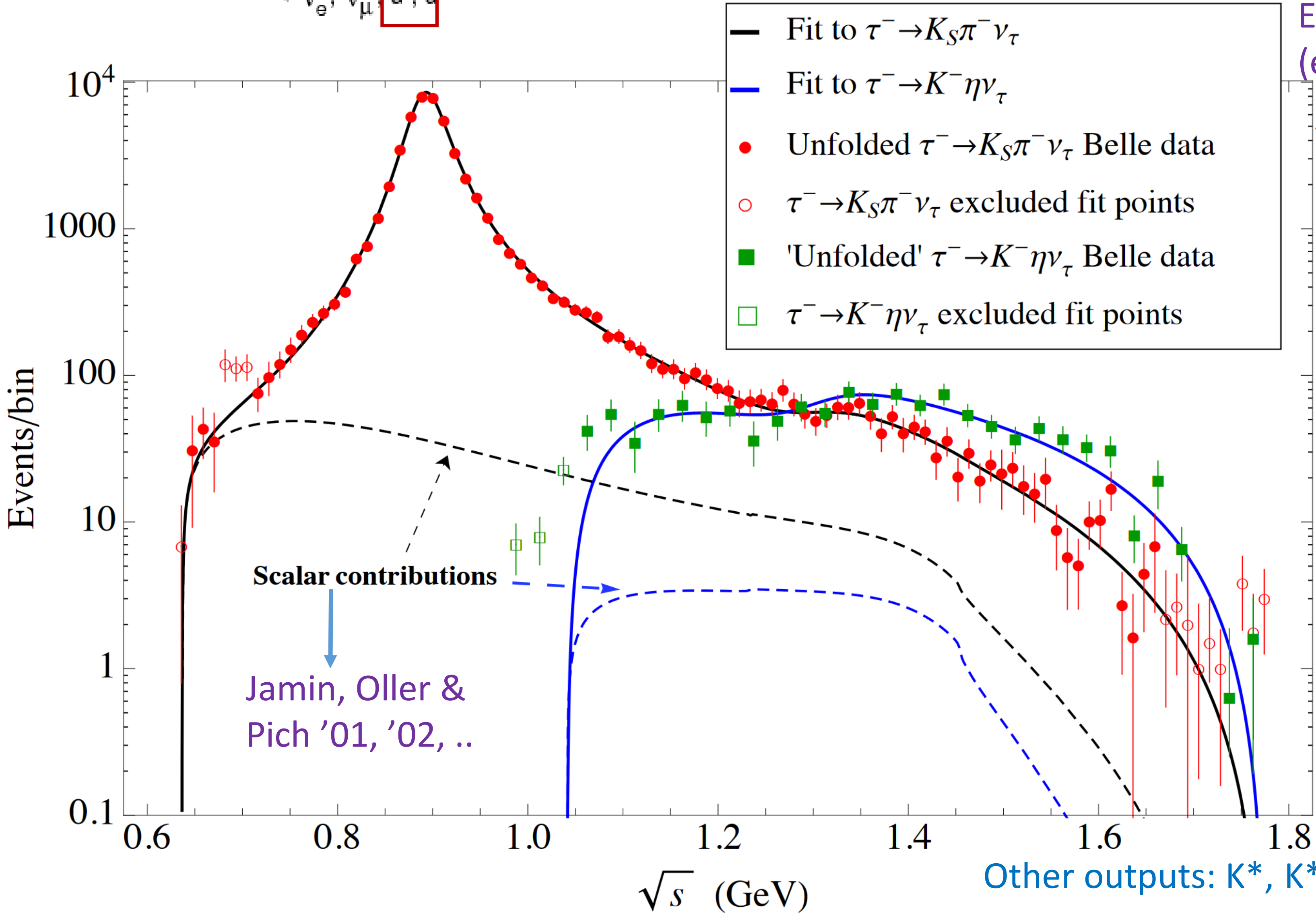
$\tau^- \to K_S \pi^- \nu_\tau$ and $\tau^- \to K^- \eta \nu_\tau$



Jamin, Oller & Pich ’01, ’02, ..

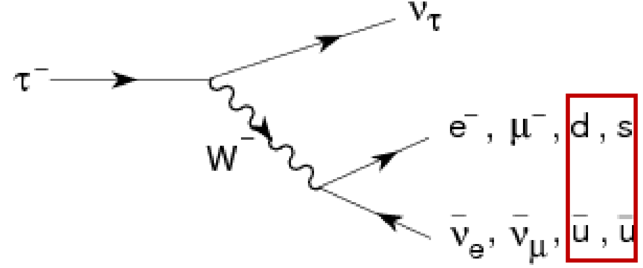
- $\tau \to \pi^- \eta \nu_\tau$ is much more difficult
(Escribano, Gonzàlez-Solís & Roig ’16, …)
(See B. Moussallam’s talk)

- Modes with η’ also included.
(Escribano, Gonzàlez-Solís & Roig ’13, …)

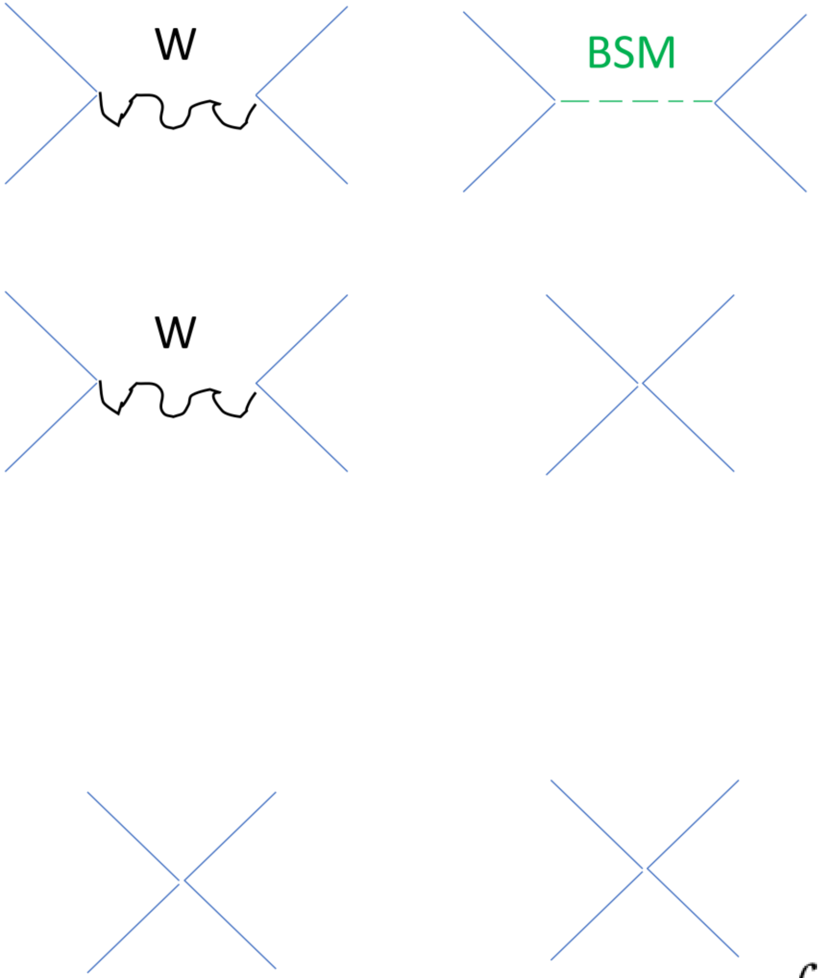
Other outputs: K*, K*’ pole positions & slope parameters

See F_S in talk by F. Noel.

Essential for BSM studies: Model-dependent uncertainties included



Beyond the SM



10 TeV — SM + BSM — D=4

1 TeV — SMEFT — D=4+6+...

QCDxEW

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

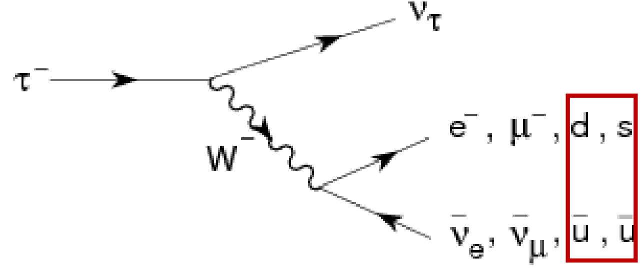
M_Z

RGE+matching @ M_Z

QCDxEM

2 GeV — Light fields — D=6+...

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



Beyond the SM

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

$\tau^- \to \eta^{(\prime)}\pi^-\nu_\tau$ Garcés, Hernández-Villanueva, López-Castro & Roig ‘17

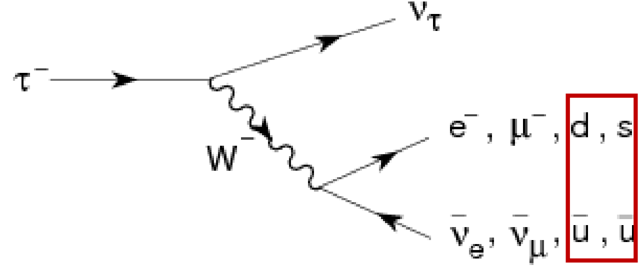
Very sensitive to non-standard scalar interactions:

$$\frac{\Delta^{QCD}_{K^0K^+}}{s}\left[1+\frac{s\hat{\epsilon}_S}{m_\tau(m_d-m_u)}\right]$$

- enhancement of ε_S contribution

- suppression of SM contributions (G-parity)

Only ULs exist (CLEO, BaBar & Belle), which does not allow for fine test (of SM & BSM)



Beyond the SM

$\tau^- \to \eta^{(\prime)}\pi^-\nu_\tau$

Garcés, Hernández-Villanueva, López-Castro & Roig '17

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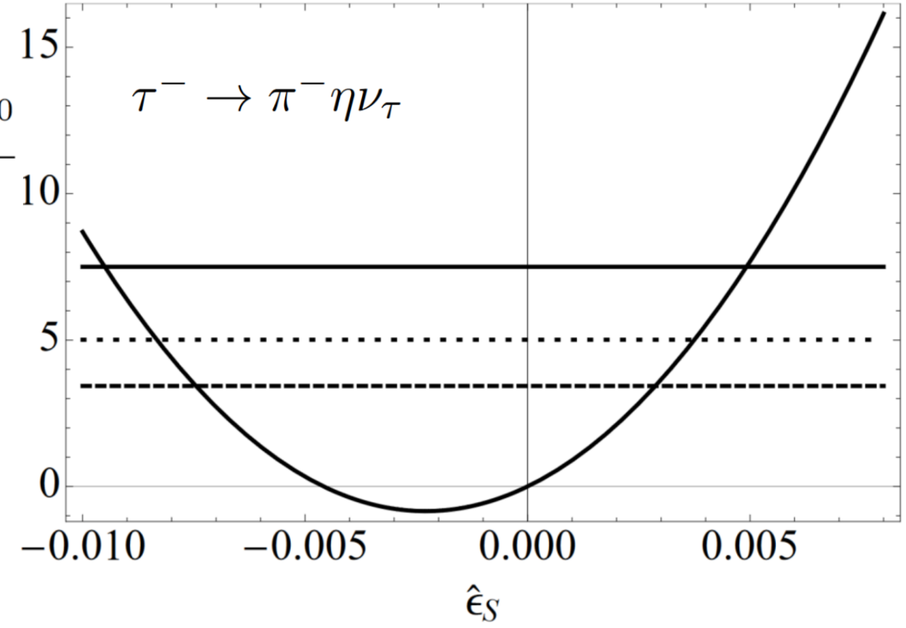
$$\Delta \equiv \frac{\Gamma - \Gamma^0}{\Gamma^0}$$

SM



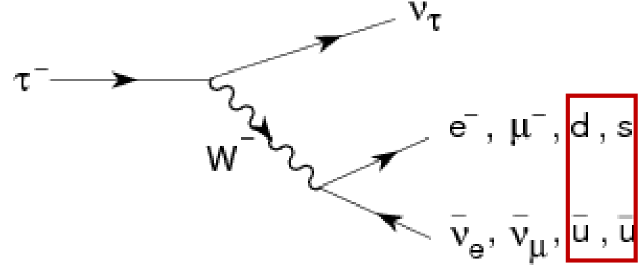
CLEO
BaBar
Belle

Compatible (slightly worse) limits for η' channel

$$\Lambda \sim v\left(V_{uD}\epsilon_i\right)^{-1/2}$$ ~ 3.5 TeV @90%CL

Belle-II data will enable to push NP scale!!

(In all decays we also discuss spectrum, Dalitz plots, etc.)



Beyond the SM

$\tau^- \to \pi^-\pi^0\nu_\tau$ Miranda & Roig '18

Quite sensitive to tensor interactions 

In principle sensitive to NS scalar interactions, but no resonances contribute to F_S at LO in isospin breaking

Very good Belle data 

From a fit to Belle spectrum we get $\hat{\epsilon}_T = \left(-1.3^{+1.5}_{-2.2}\right) \cdot 10^{-3}$ 

Unfortunately, with present data we cannot fit the SM & BSM parameters simultaneously. 

BR restrictions on ε_T are one order of magnitude milder.

$\Lambda \sim v \left(V_{uD}\epsilon_i\right)^{-1/2}$ ~ 3.5 TeV @90%CL

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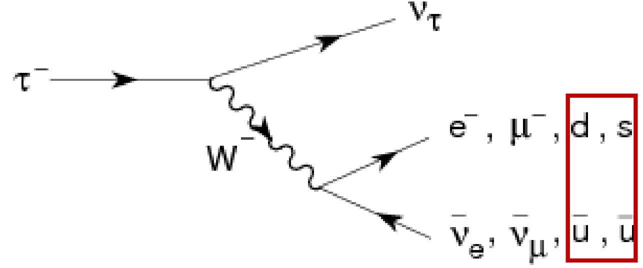


Beyond the SM

$\tau \to K_S \pi \nu_\tau$ CP asymmetry Cirigliano, Crivellin & Hoferichter '18, …

SM SM

$$A_{CP}^{\tau} = \frac{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S \nu_\tau)} \sim A_L = \frac{\Gamma(K_L \to \pi^- \ell^+ \nu_\ell) - \Gamma(K_L \to \pi^+ \ell^- \bar{\nu}_\ell)}{\Gamma(K_L \to \pi^- \ell^+ \nu_\ell) + \Gamma(K_L \to \pi^+ \ell^- \bar{\nu}_\ell)} = 3.32(6) \times 10^{-3}$$

While… $A_{CP}^{\tau,\mathrm{exp}} = -3.6(2.3)(1.1) \times 10^{-3}$

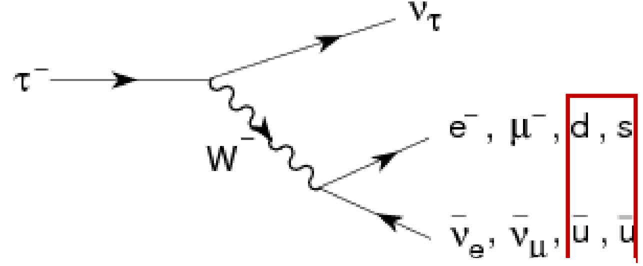
$$A_{CP}^{\tau,\mathrm{BSM}} = \frac{\sin \delta_T^{\mathrm{w}} |c_T|}{\Gamma_\tau \mathrm{BR}(\tau \to K_S \pi \nu_\tau)} \int_{s_{\pi K}}^{m_\tau^2} \mathrm{d}s' \kappa(s') |f_+(s')| |B_T(s')| \sin\left(\delta_+(s') - \delta_T(s')\right)$$

$s_{\pi K} = (M_\pi + M_K)^2$

0 in the elastic region (Watson's Th.)

Tiny, according to D^0-$\bar{D}^0$ mixing & n EDM

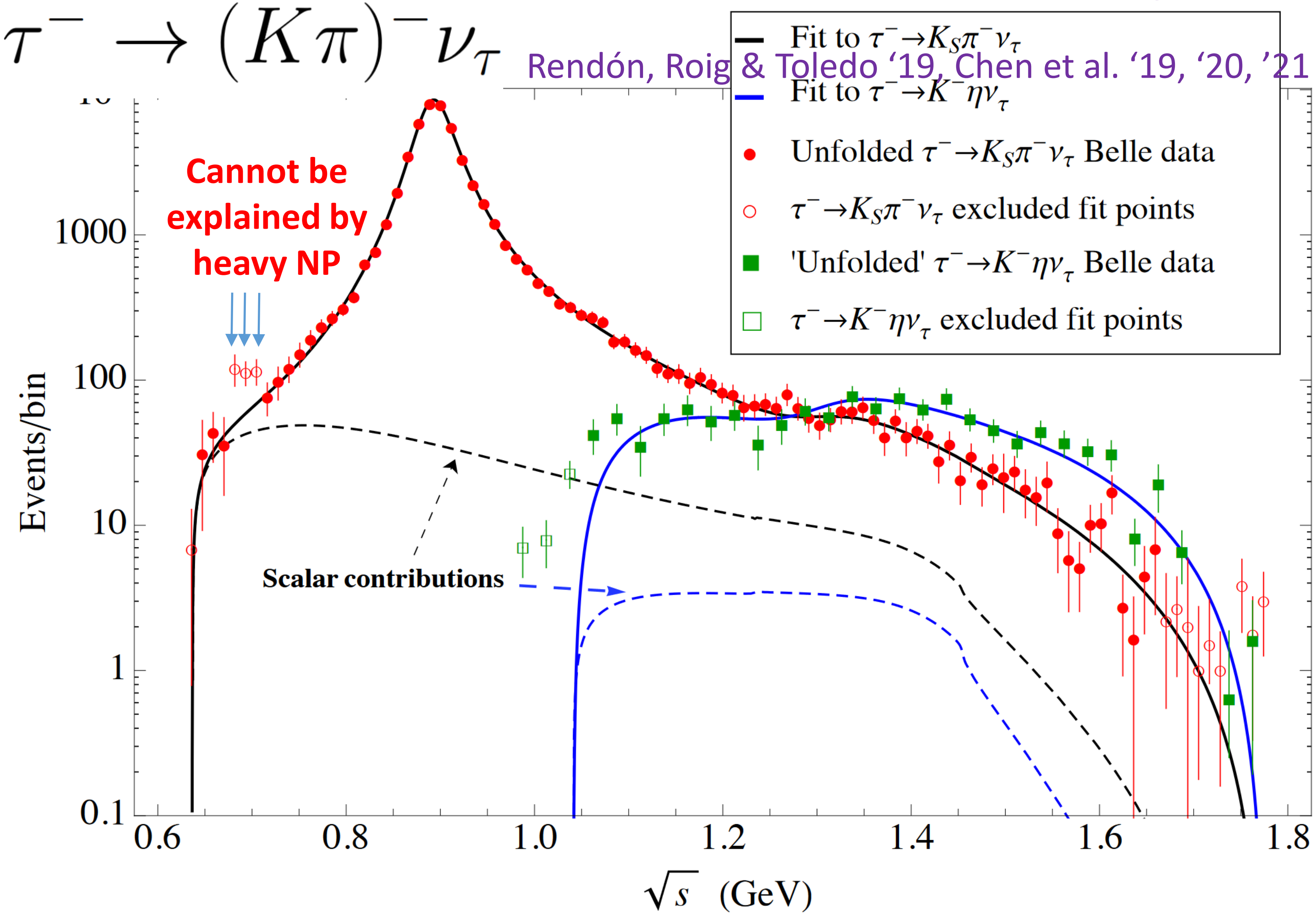
BSM contribution to A^τ_{CP} orders of magnitude smaller than SM one: no-go th. for NS (heavy NP) explanations.

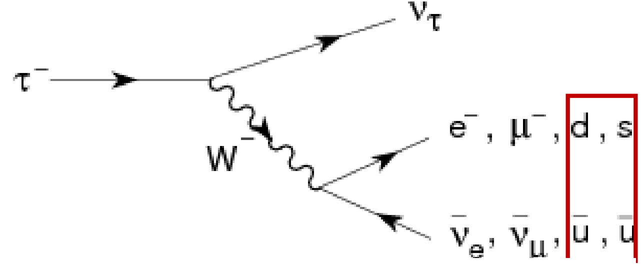


Beyond the SM

(In all decays we also discuss spectrum, Dalitz plots, etc.)

$\tau^- \to (K\pi)^- \nu_\tau$ Rendón, Roig & Toledo '19, Chen et al. '19, '20, '21 …





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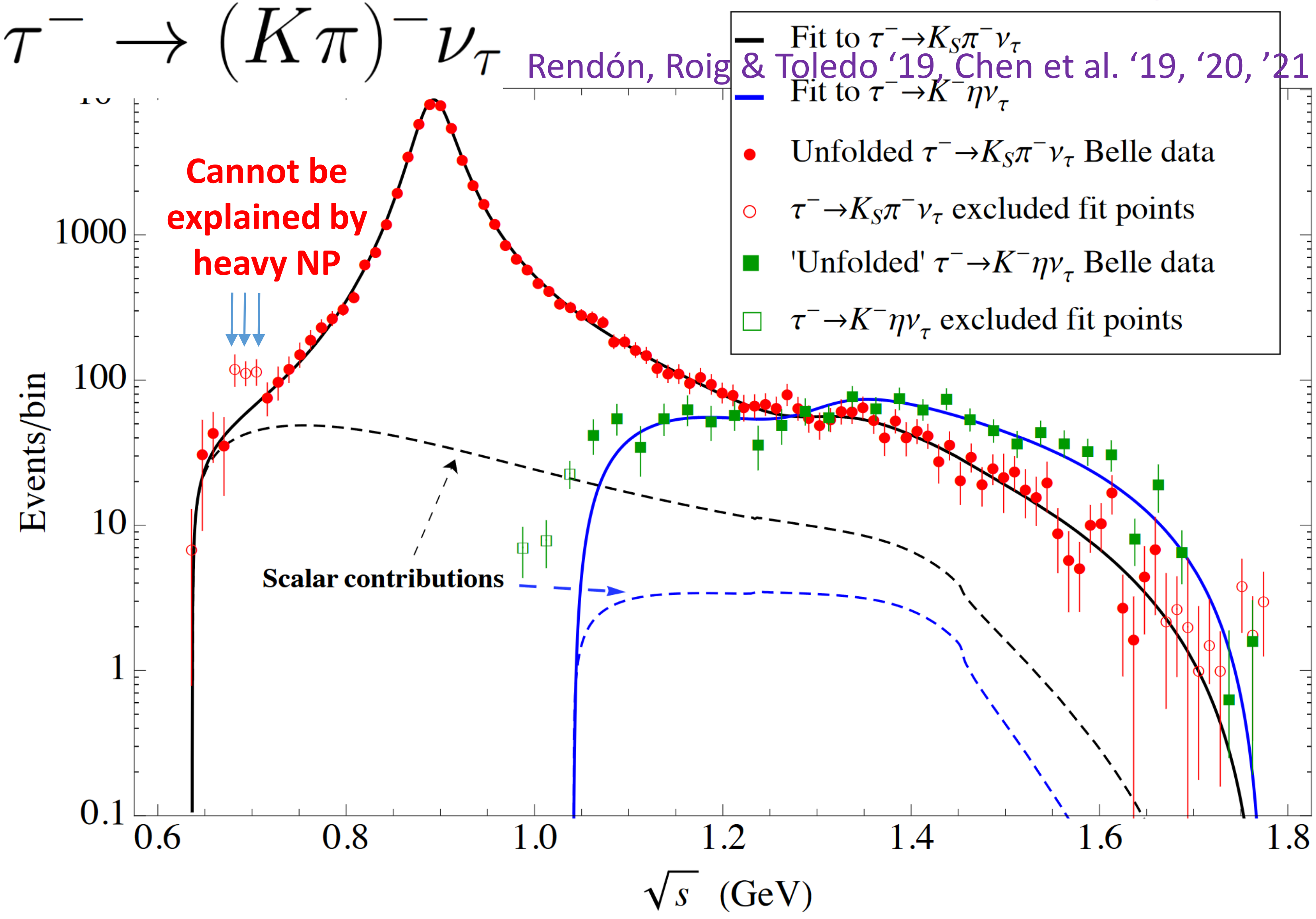


Comparable (good) sensitivities to scalar and tensor interactions.

Good quality Belle data

From a fit to Belle spectrum:

$$\hat{\epsilon}_S = (1.3 \pm 0.9) \times 10^{-2}$$

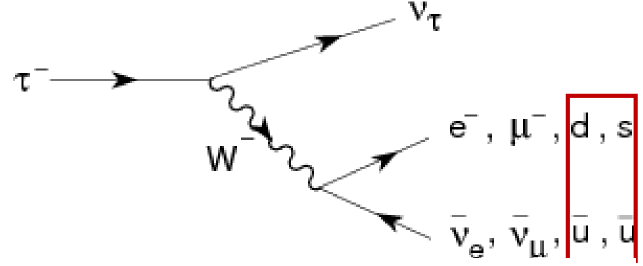
$$\hat{\epsilon}_T = (0.7 \pm 1.0) \times 10^{-2}$$

Joint fit of SM & BSM parameters impossible.

BR bounds 1 order of magnitude worse

$\Lambda \sim v \left(V_{uD} \epsilon_i \right)^{-1/2}$ ~ 3 TeV @90%CL

Belle-II data will enable to push NP scale!!



Beyond the SM

(In all decays we also discuss spectrum, Dalitz plots, etc.)

$$\tau^- \to (K\pi)^- \nu_\tau$$ Rendón, Roig & Toledo ‘19, Chen et al. ‘19, ‘20, ’21 …

See Gonzàlez-Solís, Miranda, Rendón & Roig ‘19 for

$$\tau^- \to K^-(\eta^{(\prime)}, K^0)\nu_\tau$$

(Not as sensitive to NP as those discussed before)

Comparable (good) sensitivities to scalar and tensor interactions.

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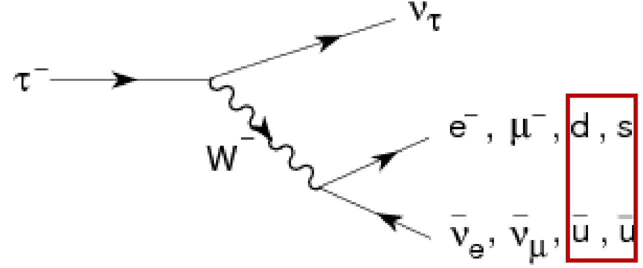
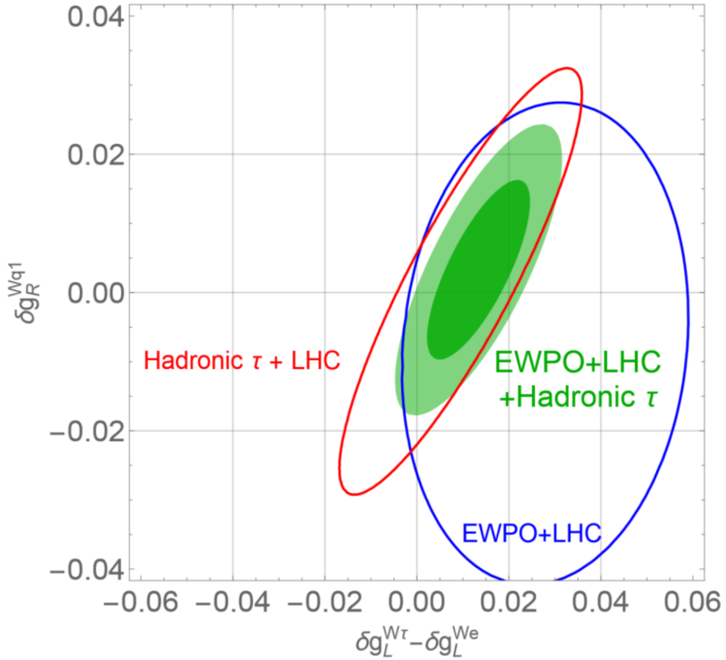


Beyond the SM

Combining inclusive & exclusive semileptonic τ decays, Cirigliano-Falkowski-González Alonso-Rodríguez Sánchez ’19 got

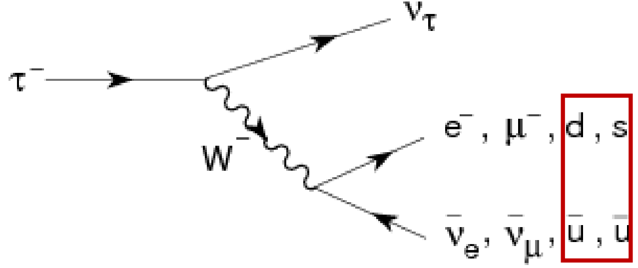
(Only ΔS=0)

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



$$\begin{pmatrix}\epsilon_L^\tau-\epsilon_L^e+\epsilon_R^\tau-\epsilon_R^e\\ \epsilon_R^\tau\\ \epsilon_S^\tau\\ \epsilon_P^\tau\\ \epsilon_T^\tau\end{pmatrix}=\begin{pmatrix}1.0\pm1.1\\ 0.2\pm1.3\\ -0.6\pm1.5\\ 0.5\pm1.2\\ -0.04\pm0.46\end{pmatrix}\cdot10^{-2}$$

$\Lambda\sim v\left(V_{uD}\epsilon_i\right)^{-1/2}$ ~ 2 TeV @90%CL



Beyond the SM

Using only exclusive semileptonic τ decays, González Solís-Miranda-Rendón-Roig '20 got

(Both ΔS=0,1)

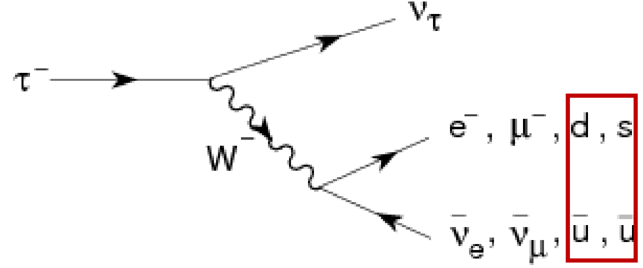
$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_\pi^2}{2m_\tau(m_u+m_d)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 0.6^{+2.3}_{-1.8}{}^{+0.2}_{-0.1} \pm 0.4 \\ 0.3 \pm 0.5^{+1.1}_{-0.9}{}^{+0.1}_{-0.0} \pm 0.2 \\ 9.7^{+0.5}_{-0.6} \pm 21.5^{+0.0}_{-0.1} \pm 0.2 \\ -0.1 \pm 0.2^{+1.1}_{-1.4}{}^{+0.0}_{-0.1} \pm 0.2 \end{pmatrix} \times 10^{-2}$$

ΔS=0

Results for the one-meson modes are slightly updated according to Arroyo Ureña, Hernández Tomé, López Castro, Roig & Rosell '21 (see Gabriel's talk next)

ΔS=1

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_K^2}{2m_\tau(m_u+m_s)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 1.5 \pm 0.3 \\ 0.4 \pm 0.9 \pm 0.2 \\ 0.8^{+0.8}_{-0.9} \pm 0.3 \\ 0.9 \pm 0.7 \pm 0.4 \end{pmatrix} \times 10^{-2}$$



Beyond the SM

Under MFV, using both ΔS=0,1 González Solís-Miranda-Rendón-Roig ’20 got

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 2.9 & \pm 0.6 & {}^{+1.0}_{-0.9} & \pm 0.6 & \pm 0.0 & \pm 0.4 & {}^{+0.2}_{-0.3} \\ 7.1 & \pm 4.9 & {}^{+0.5}_{-0.4} & {}^{+1.3}_{-1.5} & {}^{+1.2}_{-1.3} & \pm 0.2 & {}^{+40.9}_{-14.1} \\ -7.6 & \pm 6.3 & \pm 0.0 & {}^{+1.9}_{-1.6} & {}^{+1.7}_{-1.6} & \pm 0.0 & {}^{+19.0}_{-53.6} \\ 5.0 & {}^{+0.7}_{-0.8} & {}^{+0.8}_{-1.3} & {}^{+0.2}_{-0.1} & \pm 0.0 & \pm 0.2 & {}^{+1.1}_{-0.6} \\ -0.5 & \pm 0.2 & {}^{+0.8}_{-1.0} & \pm 0.0 & \pm 0.0 & \pm 0.6 & \pm 0.1 \end{pmatrix} \times 10^{-2}$$

$$\Lambda \sim v \left(V_{uD} \epsilon_i \right)^{-1/2}$$ ~ O(TeV) @90%CL

Exclusive hadronic tau decays

Input for $a_\mu^{HVP,LO}$

See J. Miranda talk

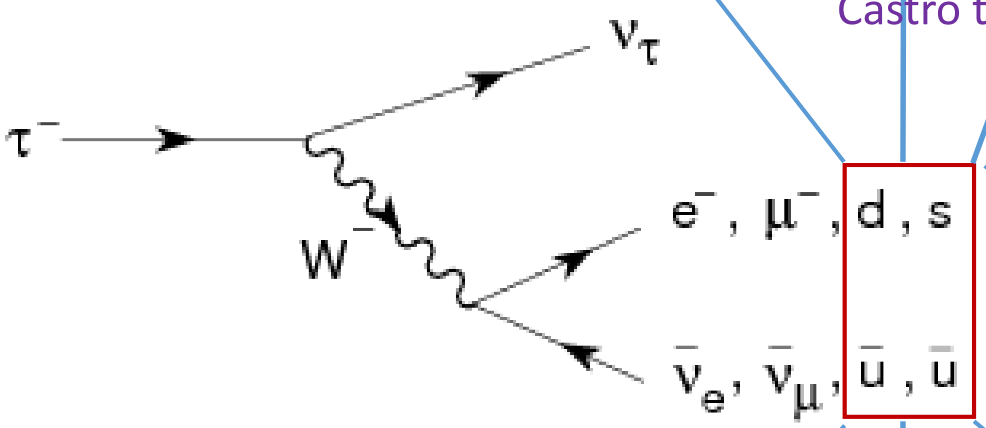
See A. Lusiani talk

V_{us}

LU

See G. López Castro talk

Hadronization of QCD currents



PDG

decay mode	fit result (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.3937 ± 0.0384
$e^-\bar{\nu}_e\nu_\tau$	17.8175 ± 0.0399
$\pi^-\nu_\tau$	10.8164 ± 0.0512
$K^-\nu_\tau$	0.6964 ± 0.0096
$\pi^-\pi^0\nu_\tau$	25.4941 ± 0.0893
$K^-\pi^0\nu_\tau$	0.4328 ± 0.0148
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.2595 ± 0.0964
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0647 ± 0.0218
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.0429 ± 0.0707
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0478 ± 0.0212
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.1118 ± 0.0391
$\pi^-\bar{K}^0\nu_\tau$	0.8384 ± 0.0138
...	...

See Z. H. Guo talk

See F. Noel talk

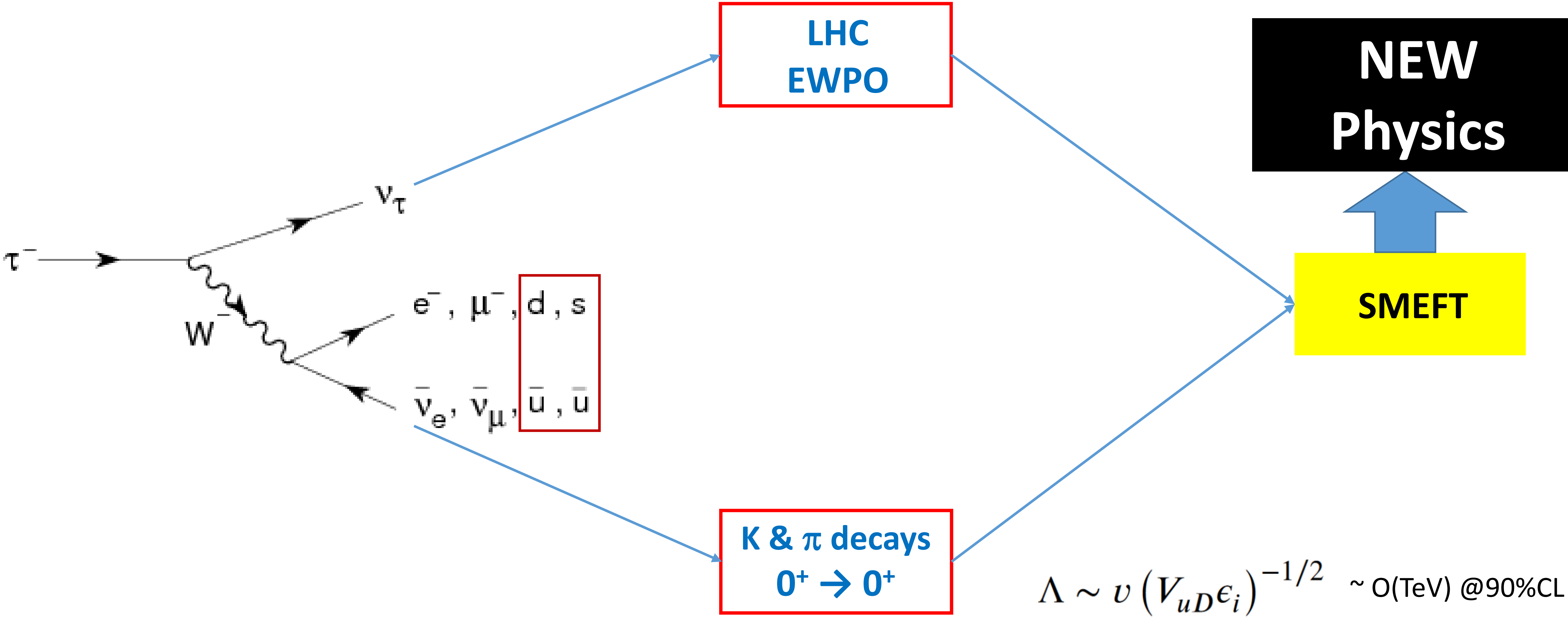
CP & T violation

SCCs

See B. Moussallam talk

Resonance (pole) parameters

BSM limits from tau decays



$\Lambda \sim v\left(V_{uD}\epsilon_i\right)^{-1/2}$ ~ O(TeV) @90%CL