

# Non-standard interactions in

$$\tau^- \rightarrow (\pi^-\pi^0, \pi^-\eta)\nu_\tau$$

**Gabriel López Castro (Cinvestav, México)**

- E. Garcés, Hernández-Villanueva, GLC, P. Roig, JHEP 1712, (2017) 027;
- J. A. Miranda and P. Roig, 1806.09547 [hep-ph]

See talks by M. Hoferichter and M. González-Alonso

# Interest of non-standard currents in tau decays

“Beyond a QCD laboratory, hadronic tau decays are competitive NP probes due to very precise measurements and SM calculations”  
(Cirigliano et al, 1809.01161)

- Second Class Currents (SCC) in tau decays- not observed yet (**S & PT**)  
(Weinberg 1958, Leroy and Pestieau 1978, ....)
- CP violation in angular & hadronic mass distributions (**S & T**)  
(Belle, Babar, Cleo searches)
- CP rate asymmetry of CP violation in  $\tau \rightarrow K\pi\nu_\tau$  (**T**)  
(Delepine, Faisel, Khalil, GLC, PRD 2006; Devy, Dargyal, Sinha PRD 2014;  
Cirigliano, Crivellin, Hoferichter, PRL 2018)

$$\begin{aligned}\tau^- &\rightarrow \pi^-\eta^{(')}\nu_\tau \longrightarrow \text{sensitive to scalar} \\ \tau^- &\rightarrow \pi^-\pi^0\nu_\tau \longrightarrow \text{sensitive to tensor}\end{aligned}$$

**Dim 6, LF conserving,  $\tau^- \rightarrow \pi^-(\pi^0, \eta, \eta')\nu_\tau$  decays**

$$\begin{aligned} \mathcal{L}_{eff} = & -\sqrt{2}G_F V_{ud}(1 + \epsilon_L + \epsilon_R) \left\{ \bar{\tau}_L \gamma_\mu \nu_L \cdot \bar{u} \gamma^\mu \left( 1 - (1 - 2\hat{\epsilon}_R)\gamma_5 \right) d \right. \\ & \left. + \bar{\tau}_R \nu_L \cdot \bar{u} \left( \hat{\epsilon}_S - \hat{\epsilon}_P \gamma_5 \right) d + 2\hat{\epsilon}_T \bar{\tau}_R \sigma_{\mu\nu} \nu_L \cdot \bar{u} \sigma^{\mu\nu} d \right\} + \text{h.c.} \end{aligned}$$

**Cirigliano, Jenkins & González-Alonso 2010**

$$\hat{\epsilon}_i \equiv \epsilon_i / (1 + \epsilon_L + \epsilon_R)$$

# Dim 6, LF conserving, $\tau^- \rightarrow \pi^-(\pi^0, \eta, \eta')\nu_\tau$ decays

$$\begin{aligned} \mathcal{L}_{eff} = & -\sqrt{2}G_F V_{ud}(1 + \epsilon_L + \epsilon_R) \left\{ \bar{\tau}_L \gamma_\mu \nu_L \cdot \bar{u} \gamma^\mu \left( 1 - (1 - 2\hat{\epsilon}_R) \gamma_5 \right) d \right. \\ & \left. + \bar{\tau}_R \nu_L \cdot \bar{u} \left( \hat{\epsilon}_S - \hat{\epsilon}_P \gamma_5 \right) d + 2\hat{\epsilon}_T \bar{\tau}_R \sigma_{\mu\nu} \nu_L \cdot \bar{u} \sigma^{\mu\nu} d \right\} + \text{h.c.} \end{aligned}$$

Cirigliano, Jenkins & González-Alonso 2010

$$\hat{\epsilon}_i \equiv \epsilon_i / (1 + \epsilon_L + \epsilon_R)$$

$$0 = \pi^0, \eta, \eta'$$

induced (genuine) scalar

$$\begin{aligned} \mathcal{M} = & \frac{G_F V_{ud} \sqrt{S_{EW}}}{\sqrt{2}} (1 + \epsilon_L + \epsilon_R) \left\{ L_\mu \cdot \left[ F_+^{0\pi^-}(s) Q^\mu + \frac{\Delta_{0\pi^-}}{s} q^\mu F_0^{0\pi^-}(s) \right] + \hat{\epsilon}_S L \cdot F_S^{0\pi^-}(s) \right. \\ & \left. + 2i\hat{\epsilon}_T F_T^{0\pi^-}(s) L_{\mu\nu} \cdot \left( p_0^\mu p_-^\nu - p_0^\nu p_-^\mu \right) \right\} \end{aligned}$$

$$q = p_{\pi^-} + p_0, \quad s = q^2, \quad Q_\mu = (p_0 - p_{\pi^-})_\mu - \frac{\Delta_{0\pi^-}}{s} q_\mu, \quad \Delta_{ij} = m_i^2 - m_j^2$$

# Only three form factors are relevant (div.vector current)

$$F_0(s) \rightarrow F_0(s) \left( 1 + \frac{s\hat{\epsilon}_S}{m_\tau(m_d - m_u)} \right)$$

grows with  $s$ ,  
 $O(0)$  in  $IB$

# Only three form factors are relevant (div.vector current)

$$F_0(s) \rightarrow F_0(s) \left( 1 + \frac{s\hat{\epsilon}_S}{m_\tau(m_d - m_u)} \right)$$

grows with  $s$ ,  
 $O(0)$  in  $IB$

$$\frac{d\Gamma}{ds} = \frac{\hat{G}_F^2 S_{EW} m_\tau^3 |V_{ud} F_+^{0\pi^-}(0)|^2}{192\pi^3 \sqrt{s}} \left( 1 - \frac{s}{m_\tau^2} \right)^2 |\mathbf{p}_{\pi^-}| [X_{VA+S} + \hat{\epsilon}_T X_T + \hat{\epsilon}_T^2 X_{T^2}]$$

$$X_{VA+S} = 4 \left[ \left| \tilde{F}_+^{0\pi^-}(s) \right|^2 \left( 1 + \frac{2s}{m_\tau^2} \right) \frac{|\mathbf{p}_{\pi^-}|^2}{s} + \frac{3\Delta_{0\pi^-}^2}{4s^2} \left| \tilde{F}_0^{0\pi^-}(s) \right|^2 \left( 1 + \frac{s\tilde{\epsilon}_S}{m_\tau(m_d - m_u)} \right)^2 \right]$$

$$X_T = -\frac{24\sqrt{2}\text{Re}[\tilde{F}_+^{0\pi^-}(s)]\tilde{F}_T^{0\pi^-}}{m_\tau} |\mathbf{p}_{\pi^-}|^2$$

$$X_{T^2} = 16 \left| \tilde{F}_T^{0\pi^-}(s) \right|^2 \left( 1 + \frac{s}{2m_\tau^2} \right) |\mathbf{p}_{\pi^-}|^2$$

$$\widehat{G}_F \equiv G_F(1 + \epsilon_L + \epsilon_R)$$

$$\widetilde{F}_i(s) = F_i(s)/F_+^{0\pi^-}(0)$$

$$(m_{\pi^-} + m_0)^2 \leq s \leq m_\tau^2$$

# $\tau^- \rightarrow \pi^- \eta^{(')} \nu_\tau$ and Scalar Second Class Currents (SCC)

- \* G-Parity states (Lee, Yang 1956);

$$G = Ce^{i\pi I_2}$$

- \* Classification of currents according to  $G$  (Weinberg, 1958)

FirstCC :  $J^{PG}[V_\mu] = 1^{-+}$ ,  $J^{PG}[A_\mu] = 1^{+-}$

SecondCC :  $J^{PG}[S] = 0^{+-}$ ,  $J^{PG}[(PT)_{\mu\nu}] = 1^{++}$

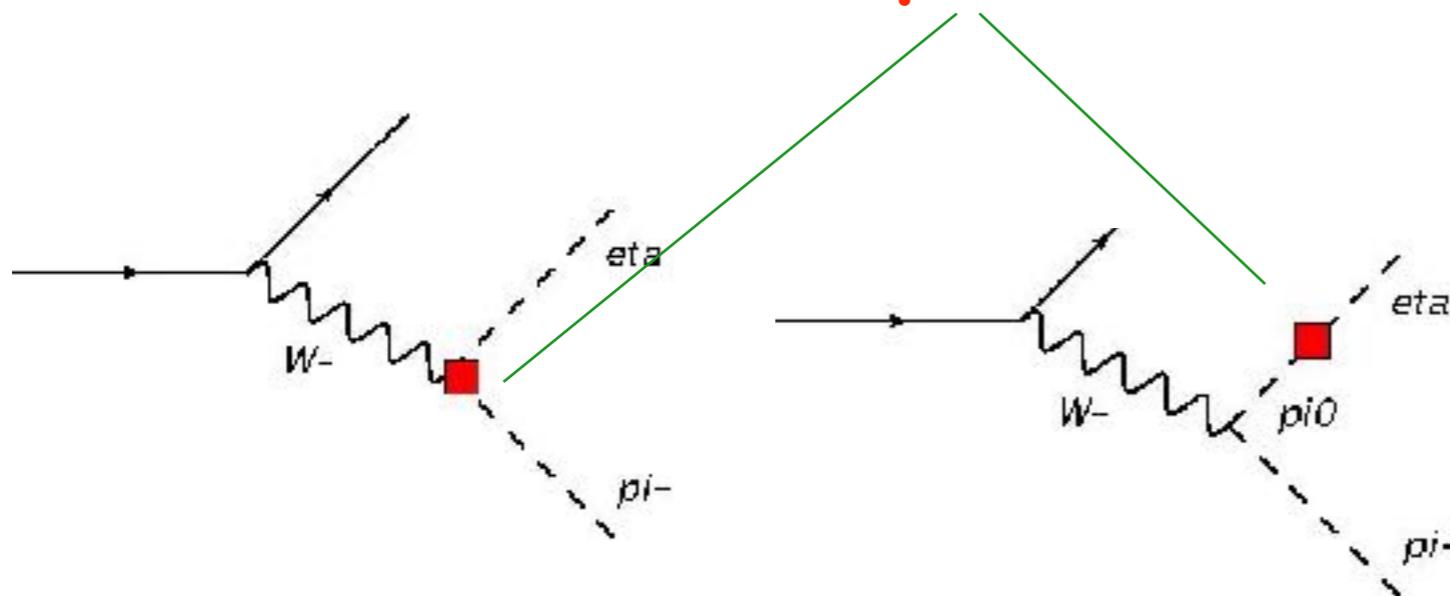
- \* SCC exist if the following occurs (Leroy, Pestieau 1978):

$$\tau^- \rightarrow a_0^-(980) \left[ \rightarrow \eta^{(')} \pi^- \right] \nu_\tau, \quad J^{PG} = 0^{+-}$$

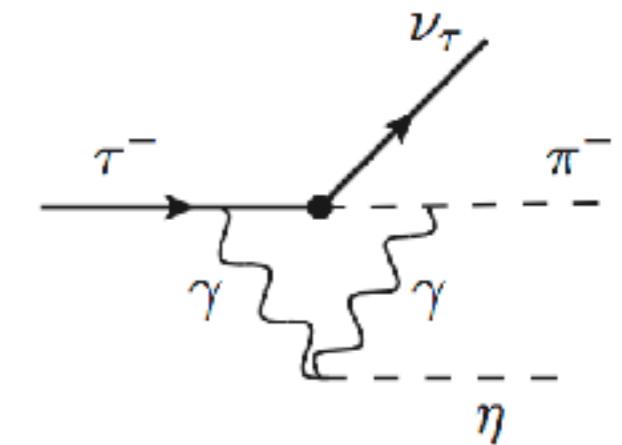
$$\rightarrow b_1^-(1235) \left[ \rightarrow \omega \pi^- \right] \nu_\tau, \quad J^{PG} = 1^{++}$$

**Isospin is good but not exact → suppressed rates**

# SM contributions: **isospin violation**



$$B_{SM}^{IB}(\eta\pi^-) \sim (\epsilon_{\pi\eta})^2 \sim 10^{-5}$$



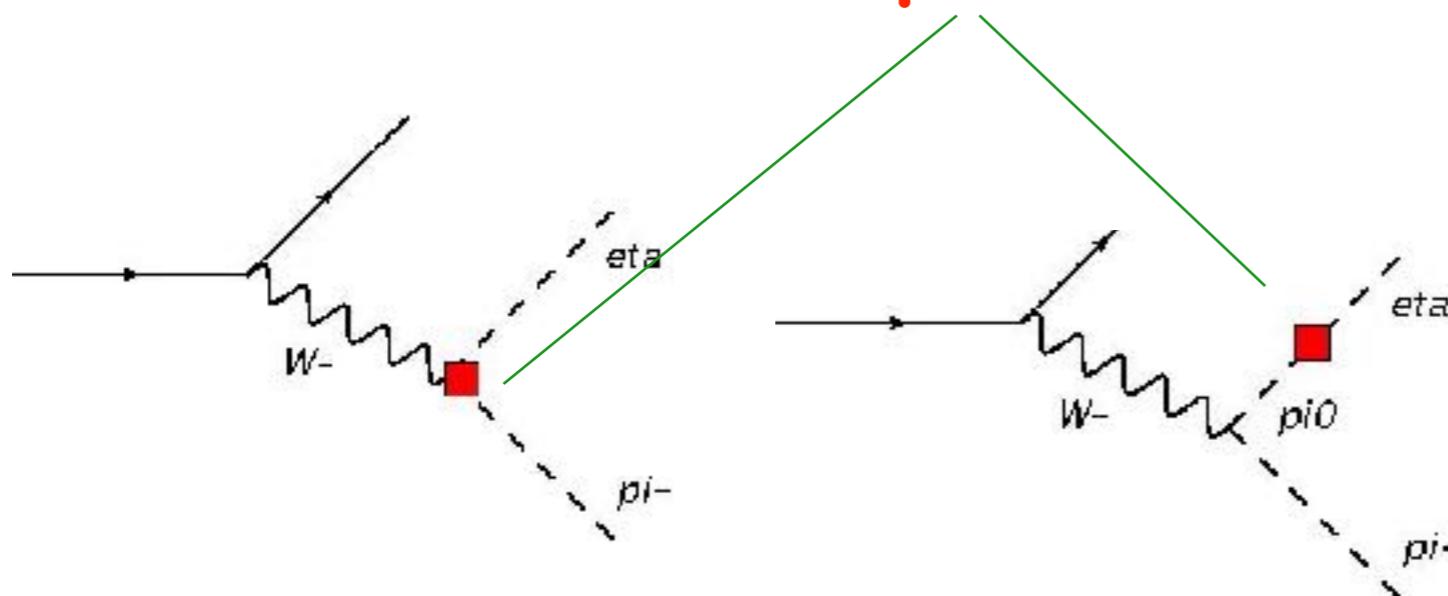
$$B_{SM}^{\gamma\gamma}(\eta\pi^-) \sim 10^{-13}$$

$$BR(\eta\pi^-\gamma)_{E_\gamma \geq 0.1 \text{ GeV}} \sim O(10^{-6})$$

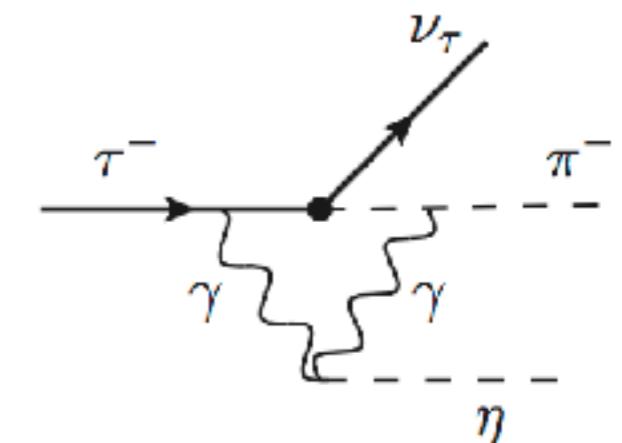
$$\epsilon_{\pi\eta}^{LO} = \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \hat{m}}$$

Hernandez-Tome, Roig, GLC, PRD96, 2017  
Guevara, Roig, GLC, PRD95, 2017

# SM contributions: **isospin violation**



$$B_{SM}^{IB}(\eta\pi^-) \sim (\epsilon_{\pi\eta})^2 \sim 10^{-5}$$



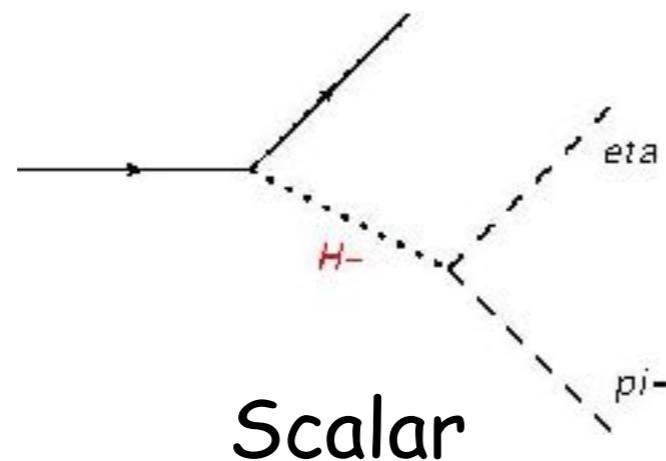
$$B_{SM}^{\gamma\gamma}(\eta\pi^-) \sim 10^{-13}$$

$$BR(\eta\pi^-\gamma)_{E_\gamma \geq 0.1 \text{ GeV}} \sim O(10^{-6})$$

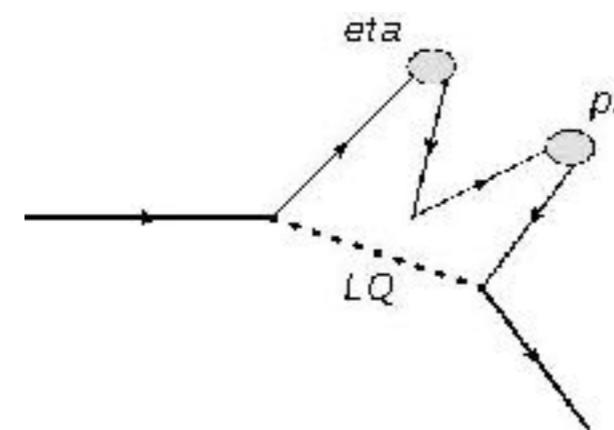
$$\epsilon_{\pi\eta}^{LO} = \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \hat{m}}$$

Hernandez-Tome, Roig, GLC, PRD96, 2017  
Guevara, Roig, GLC, PRD95, 2017

Examples  
of New  
Physics  
contributions



Scalar



Scalar & tensor

$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{NP}$$

**Suppressed**

# Some recent predictions for $\tau \rightarrow \pi \eta \nu_\tau$

Recent calcs. of branching ratios for  $\tau \rightarrow \pi \eta \nu_\tau$  (in units 10<sup>-5</sup>)

BRv	BRs	BRv+s	Model/Reference	eta-pi mixing (10 <sup>-2</sup> )
0.36	1.0	1.36	VMD, 1 resonance [1]	
0.33~0.47	1.73~3.33	2.1~3.8	VMD, 2 resonances [2]	1.34
0.44	0.04	0.48	Nambu-Jona-Lasinio[3]	1.55
0.13	0.20	0.33	FF+Analit/Unitarity [4]	1.56
0.26	1.41	1.67	SFF 3 coupled channel [5]	0.98
0.11	$0.37^{+0.30}_{-0.20}$	$0.48^{+0.30}_{-0.20}$	FF Dispersive eval. [6]	1.49

[1] S. Nussinov +A. Soffer PRD78 (2008);

[2] N. Paver + Riazuddin, PRD82, (2010);

[3] N. Volkov and Kostunin, PRD86, (2012);

[4] S. Descotes-Genon and B. Moussallam, EPJC74, (2014);

[5] R. Escribano, S. González-Solis and P. Roig, PRD94 (2016);

[6] S. Descotes-Genon E. Kou & B. Moussallam,NPB-PS, (2014)

$$BR^{\text{exp}}(\tau^- \rightarrow \pi^- \eta \nu) < 9.9 \times 10^{-5} \quad (CL = 95\%)$$

Babar Collab,  
PRD83, 032002 (2011)

# Form factor inputs

$$F_+^{\eta\pi^-}(s) = \epsilon_{\eta\pi} \tilde{F}_+^{\pi^0\pi^-}(s)$$

D. Gómez-Dumm and P. Roig, EPC73, 2528 (2013)  
 R. Escribano, S. Gonzalez P. Roig, PRD94, (2016)

$$F_0^{\eta\pi^-}(s) = \epsilon_{\eta\pi} \tilde{F}_0^{\pi^0\pi^-}(s)$$

Tensor form factor:

$$\mathcal{L}^{O(p^4)} = \Lambda_1 \langle t_+^{\mu\nu} f_+^{\mu\nu} \rangle - i \Lambda_2 \langle t_+^{\mu\nu} u_\mu u_\nu \rangle$$

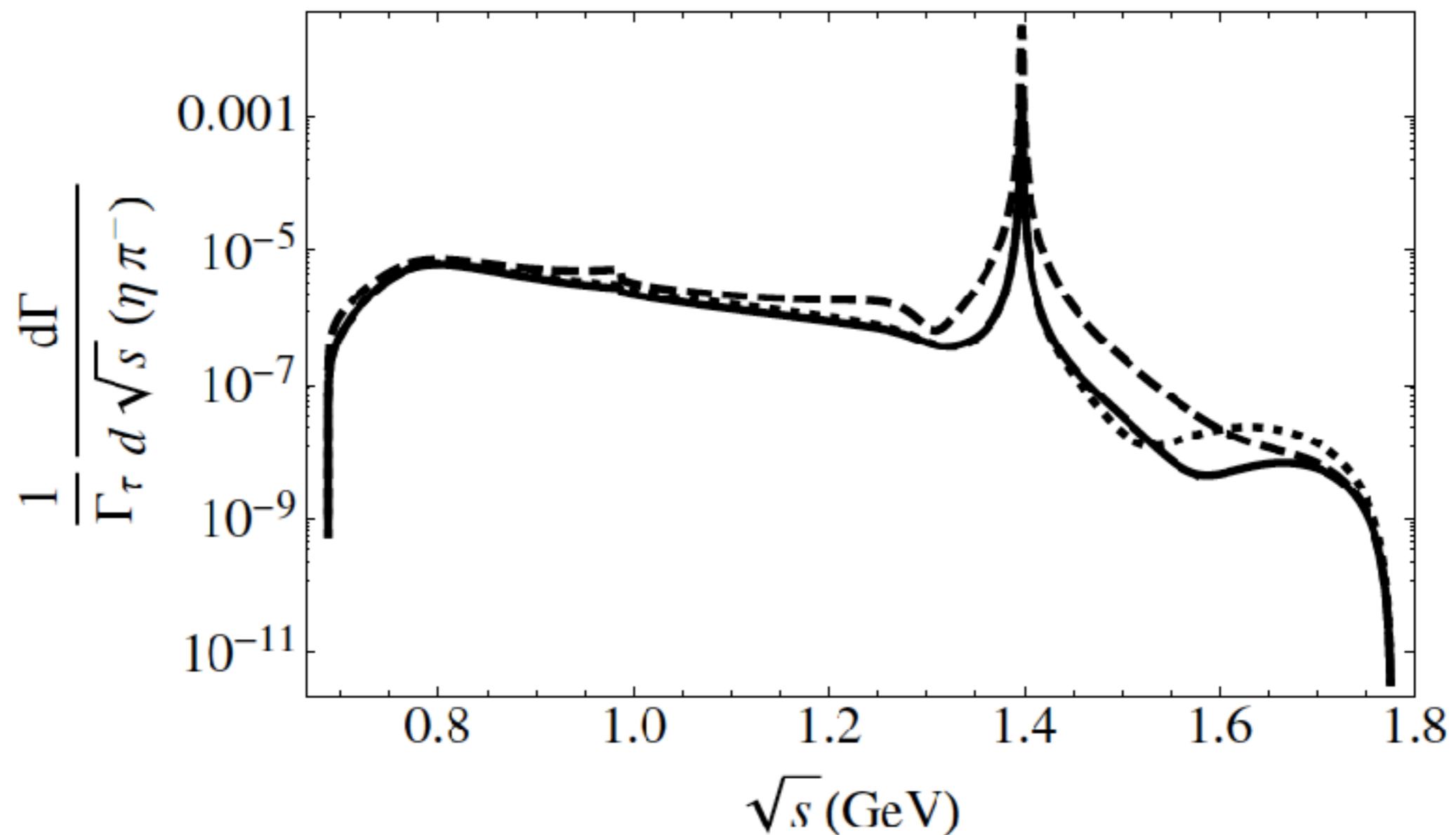
O. Catá, V. Mateu,  
 JHEP 09, 078 (2007)

$$f_+^{\mu\nu} = u F_L^{\mu\nu} u^\dagger + u^\dagger F_R^{\mu\nu} u; \quad u_\mu = i \left[ u^\dagger (\partial_\mu - ir_\mu) u - u (\partial_\mu - i\ell_\mu) u^\dagger \right]; \quad u = \exp[i\phi/\sqrt{2}F]$$

$$F_T^{\eta\pi^-}(s) = \epsilon_{\pi\eta} \frac{\sqrt{2}\Lambda_2}{F^2} = \begin{cases} \leq 9.4 \times 10^{-2} \text{ GeV}^{-1}, \text{ our estimate } * \\ (1.96 \pm 0.11) \times 10^{-2} \text{ GeV}^{-1}, \text{ Lattice } \dagger \end{cases}$$

\* E. Garcés et al, JHEP 12, (2017)

† I. Baum et al PRD84, (2011)



—

SM

$$\dots \quad \hat{\epsilon}_S = 0, \quad \hat{\epsilon}_T = 0.6$$

● - - ●  $\hat{\epsilon}_S = 0.004$ ,  $\hat{\epsilon}_T = 0$

E. Garcés et al, JHEP (2017)

Decay rates are the most sensitive (other observables studied: Dalitz plot, pi- angular distribution, spectrum)

E. Garcés et al, JHEP (2017)

$$\Delta \equiv \frac{\Gamma - \Gamma^0}{\Gamma^0} = \alpha \hat{\epsilon}_S + \beta \hat{\epsilon}_T + \gamma \hat{\epsilon}_S^2 + \delta \hat{\epsilon}_T^2$$

$$\Gamma^0 = \Gamma(\hat{\epsilon}_S = \hat{\epsilon}_T = 0)$$

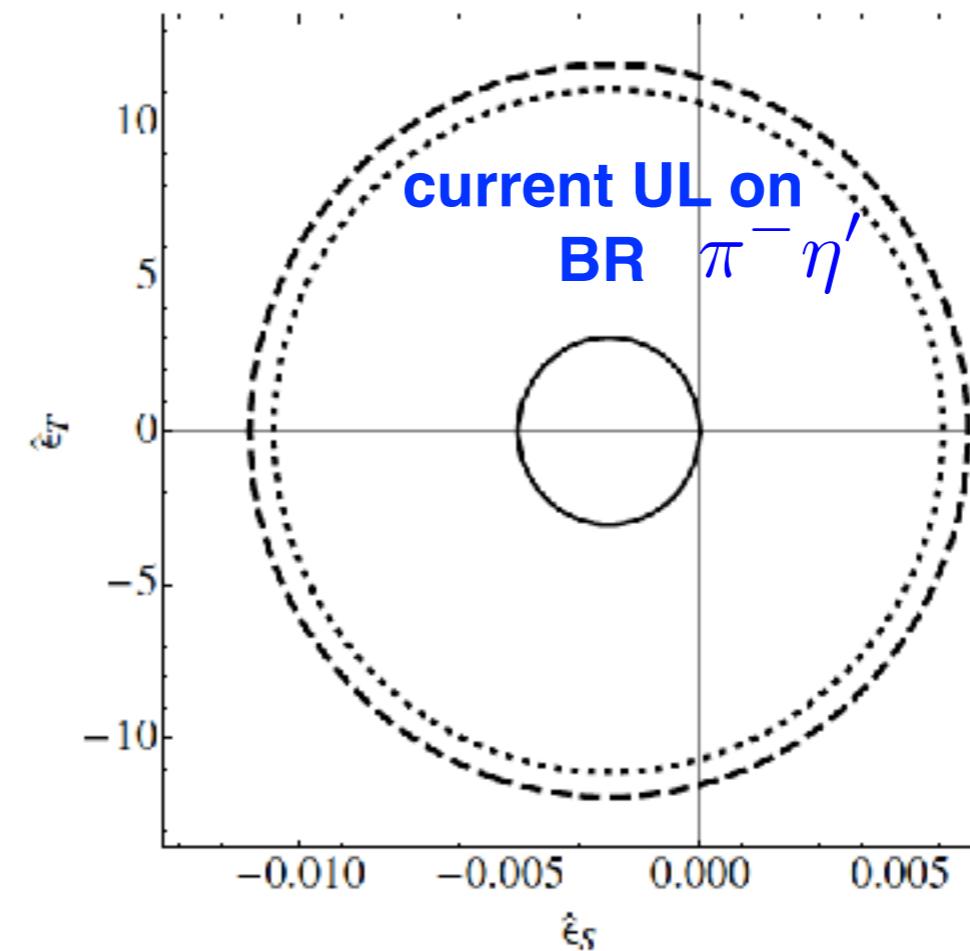
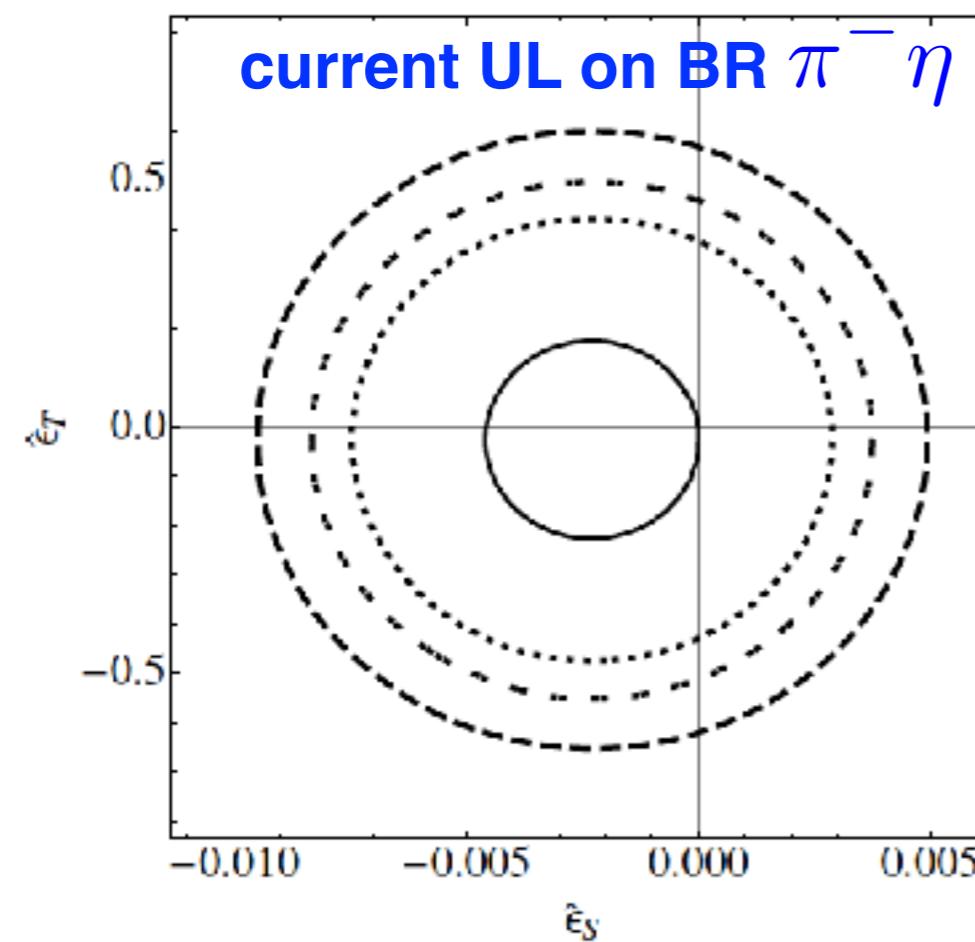
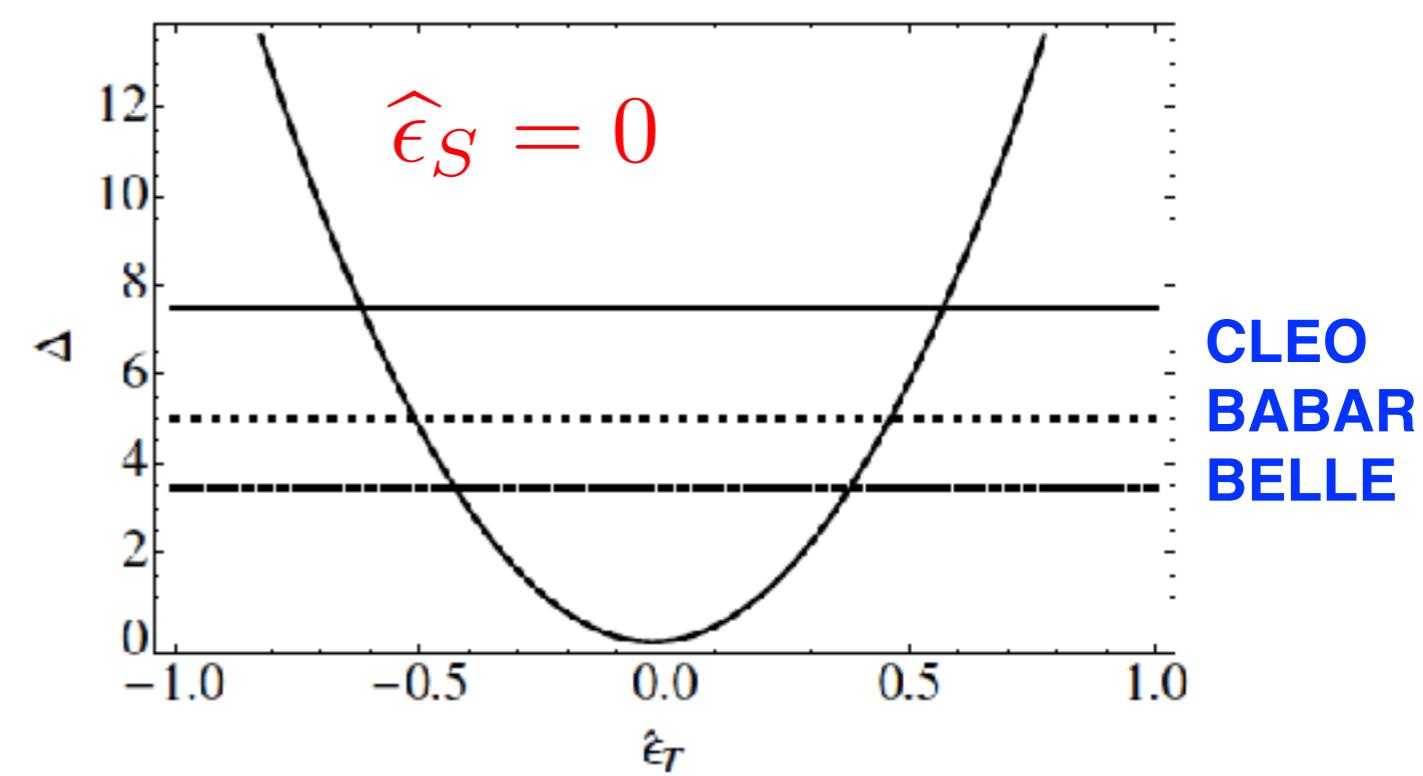
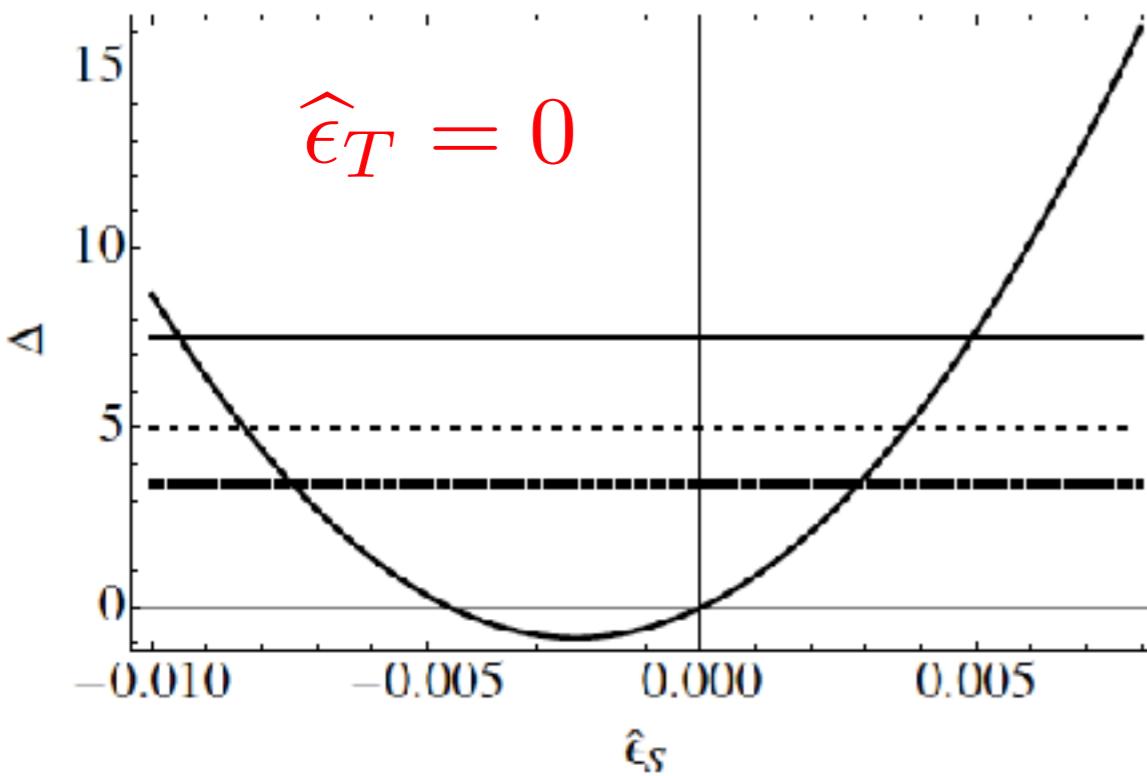
Escribano et al, PRD94 (2016)

channel	$\alpha$	$\beta$	$\gamma$	$\delta$
$\pi^- \eta^*$	$7.0 \times 10^2$	1.1	$1.6 \times 10^5$	21
$\pi^- \eta'$	$9.0 \times 10^2$	$-8.0 \times 10^{-4}$	$1.9 \times 10^5$	0.1
$\pi^- \pi^0$	$3.5 \times 10^{-4}$	$3.3^{+0.6}_{-0.4}$	$2.2 \times 10^{-2}$	$4.7^{+2.0}_{-1.0}$

- \* Theoretical errors not included, but they are for the pi-pi channel
- \* (see J. Miranda and P. Roig, 1806.09547)

$\tau^- \rightarrow \pi^- \eta \nu_\tau$ 

E. Garcés et al, JHEP (2017)



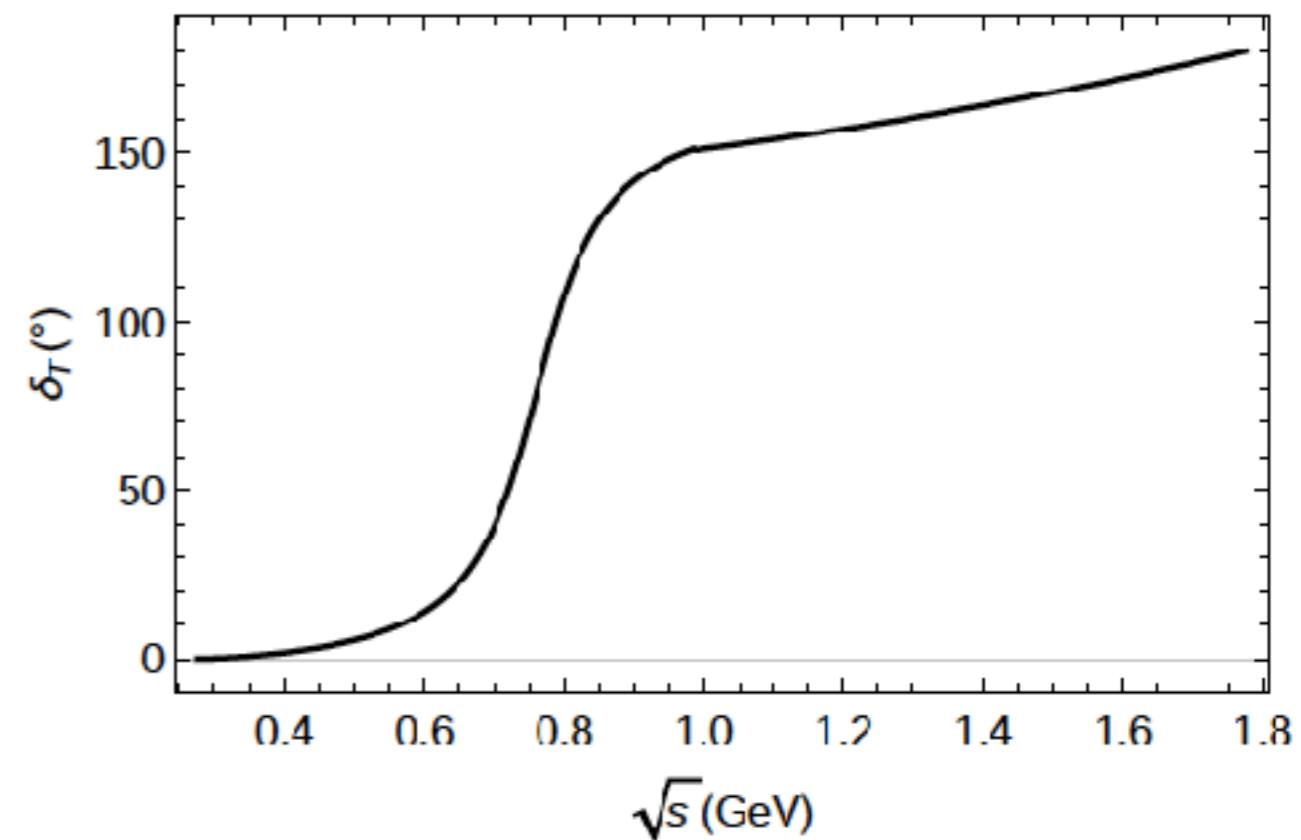
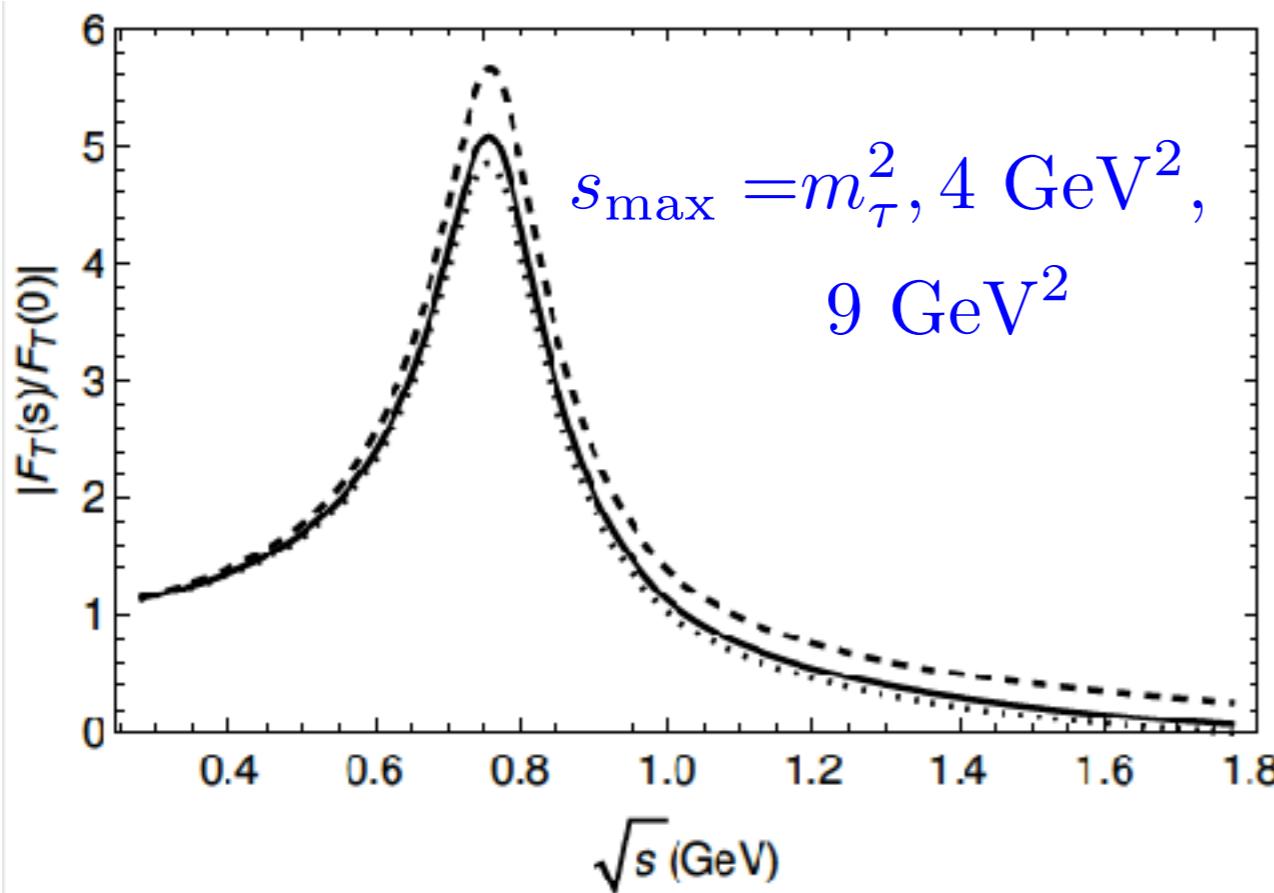
# $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ and tensor interactions

$$F_T^{\pi^0 \pi^-}(s) = \frac{\sqrt{2}\Lambda_2}{F^2} \exp \left\{ \frac{s}{\pi} \int_{4m_\pi^2}^{\infty} ds' \frac{\delta_T(s')}{s'(s' - s - i\epsilon)} \right\}$$

J. Miranda and P. Roig,  
1806.09547

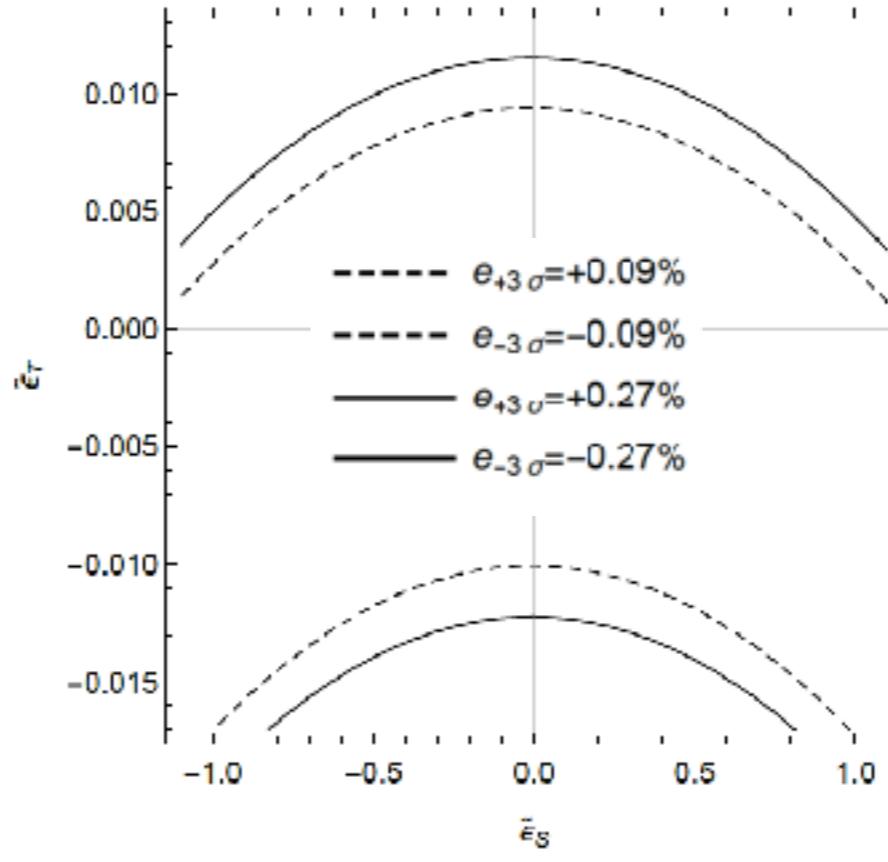
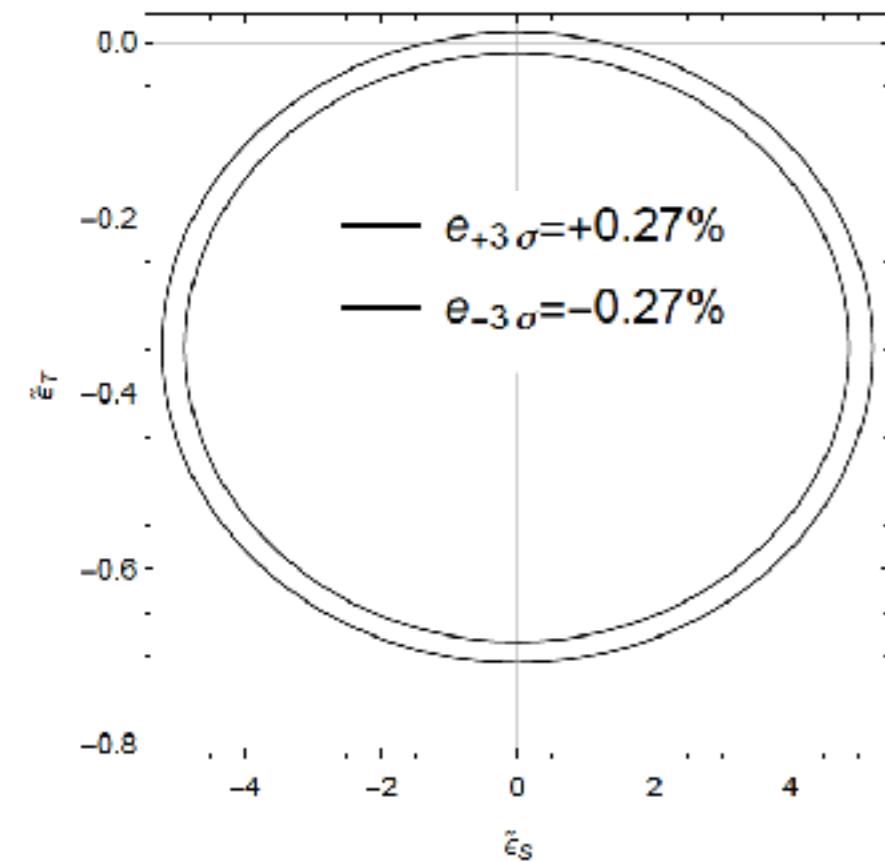
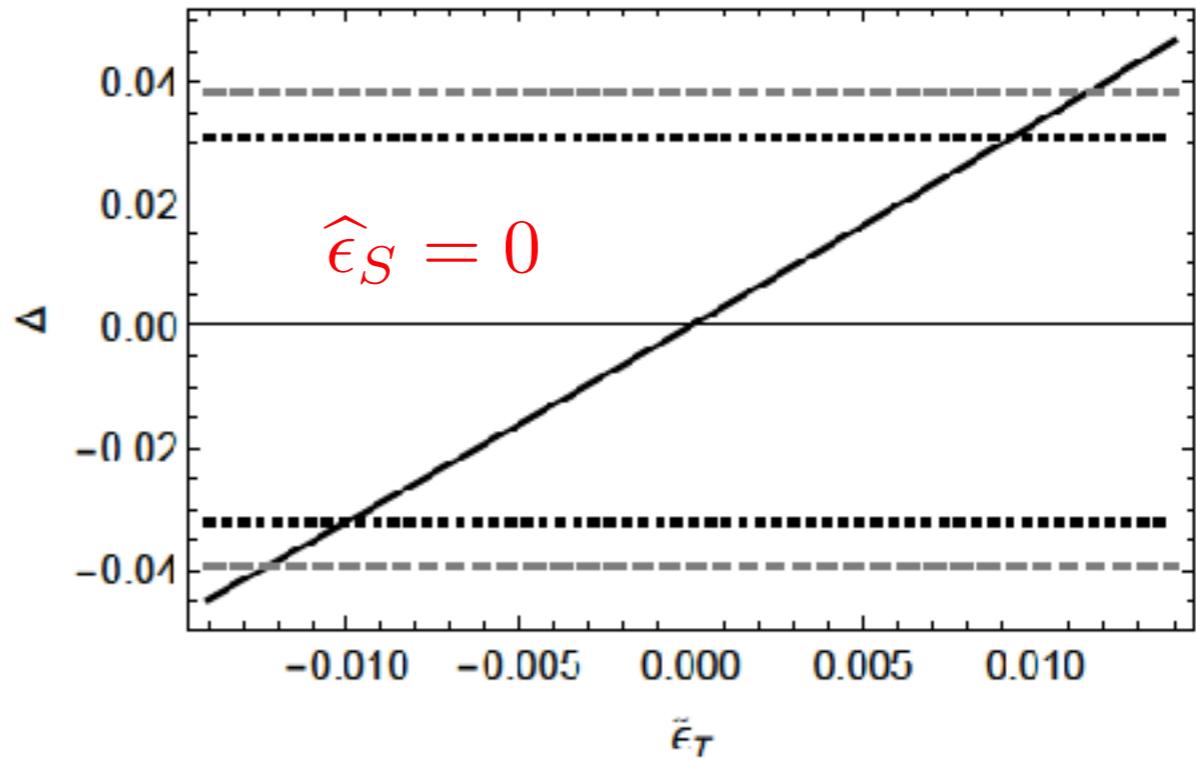
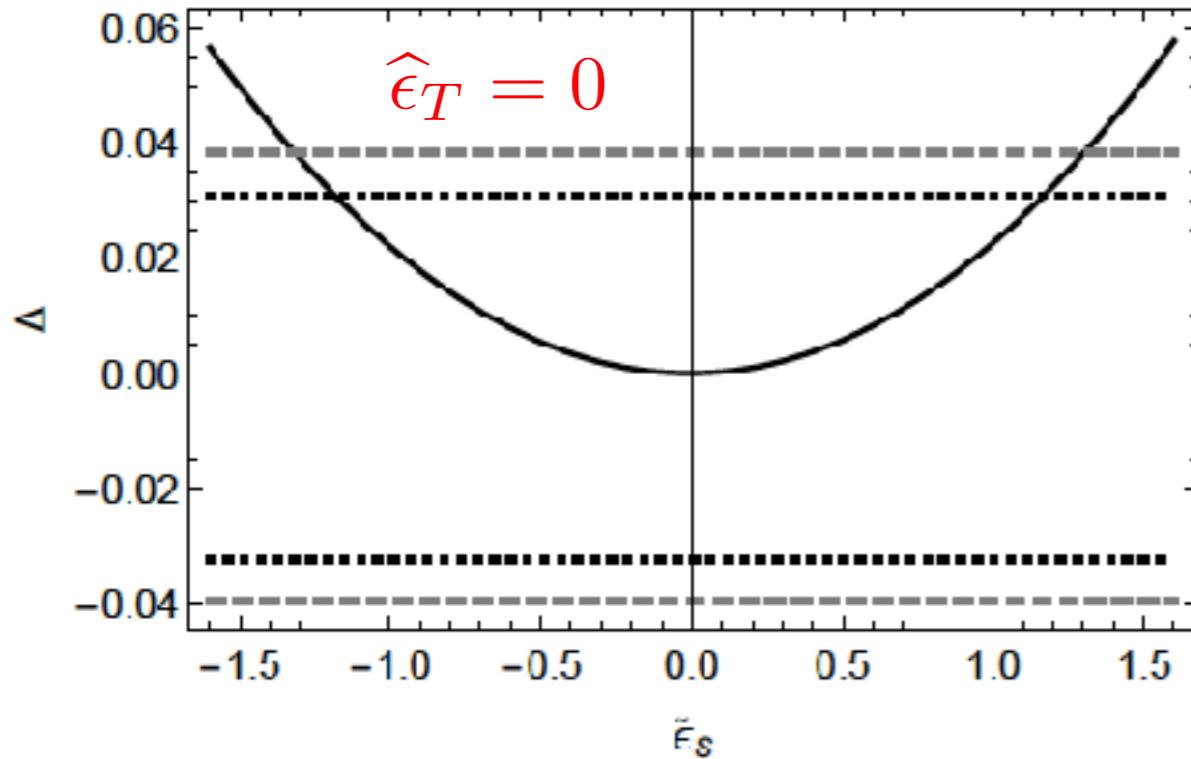
$$F_T^{\pi^- \pi^0}(0) = (2.0 \pm 0.1) \text{ GeV}^{-1}$$

I. Baum et al, PRD84, 2011



$$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$$

J. Miranda and P. Roig, 1806.09547



Fit to pi-pi Belle spectrum imposing  
 $|\hat{\epsilon}_S| < 0.8 \times 10^{-2}$   
gives

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

# Summary:

Channel	$\hat{\epsilon}_S$	$\hat{\epsilon}_T$	Source
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	(-5.2, 5.2)	(-0.79, 0.013)	BR Belle *
	$< 8 \cdot 10^{-3}$	$(-1.3^{+1.5}_{-2.2}) \cdot 10^{-3}$	$\pi\pi$ spectrum Belle *
$\tau^- \rightarrow \pi^- \eta \nu_\tau$	$(-8.3, 3.7) \cdot 10^{-3}$	(-0.55, 0.50)	BR Babar UL †
	$(-6 \pm 15) \cdot 10^{-3}$	-	arXiv 1809.01161
semileptonic $\tau$	-	$(-0.4 \pm 4.6) \cdot 10^{-3}$	arXiv 1809.01161
$\frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$	$< 8 \times 10^{-2}$	$< 10^{-3}$	Cirigliano et al JHEP 2013

\* E. Garcés et al, JHEP 12, (2017)

† J. Miranda and P. Roig, 1806.09547

Improved searches/measurements at Belle II, can provide stronger constraints from semileptonic tau decays.

**Conclusions:** NP effects of non-standard weak interactions can be constrained from  $\tau^- \rightarrow (\pi^- \pi^0, \pi^- \eta) \nu_\tau$

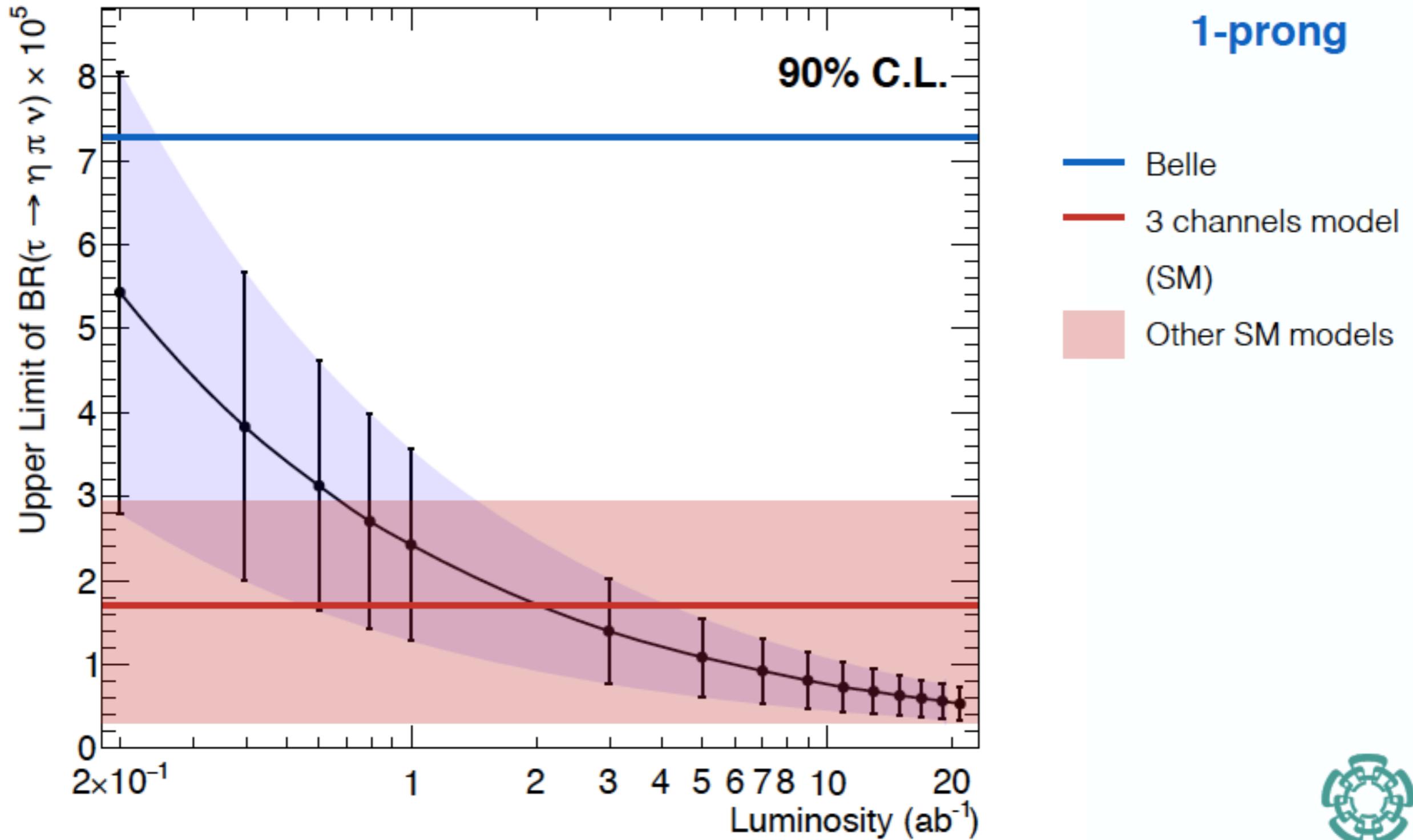


# Constraints on S and T couplings from the decay rate of $\tau^- \rightarrow \pi^- \eta^{(')} \nu_\tau$

$\Delta$	$\widehat{\epsilon}_S(\widehat{\epsilon}_T = 0)$	$\widehat{\epsilon}_T(\widehat{\epsilon}_S = 0)$	$\widehat{\epsilon}_S$	$\widehat{\epsilon}_T$
$\pi\eta$				
Babar	$[-8.3, 3.9] \cdot 10^{-3}$	[-0.43,0.39]	$[-0.83, 0.37] \cdot 10^{-2}$	[-0.55,0.50]
Belle	$[-7.7, 2.9] \cdot 10^{-3}$	[-0.51,0.47]	$[-0.75, 0.29] \cdot 10^{-2}$	[-0.48,0.43]
CLEO	$[-9.5, 5.0] \cdot 10^{-3}$	[-0.62,0.57]	$[-0.95, 0.49] \cdot 10^{-2}$	[-0.66,0.60]
Belle II	$([-4.8, 2.0] \cdot 10^{-3}$	[-0.12,0.08]	$[-4.9, -4.3] \cdot 10^{-3} \cup$ $[-2.6, 3.0] \cdot 10^{-4}$	$[-0.20, -0.25] \cup$ [0.15,0.20]
$\pi\eta'$				
Babar	$[-1.13, 0.68] \cdot 10^{-2}$	$ \widehat{\epsilon}_T  < 11.4$	$[-1.13, 0.67] \cdot 10^{-2}$	[-11.9,11.9]
Belle	$[-1.07, 0.60] \cdot 10^{-2}$	$ \widehat{\epsilon}_T  < 10.6$	$[-1.06, 0.61] \cdot 10^{-2}$	[-11.0,11.0]
Belle II	$[-4.8, 2.3] \cdot 10^{-3}$	[-1.35,1.41]	$[-4.8, -4.3] \cdot 10^{-3} \cup$ $[-2.4, 2.4] \cdot 10^{-4}$	$[-3.4, -2.7] \cup$ [2.7,3.3]

# Estimated upper limits at Belle II

Michel Hernandez  
Villanueva



$$H=\langle\pi^0\pi^-|\bar{d}u|0\rangle\equiv F_S(s),$$

$$H^\mu = \langle\pi^0\pi^-|\bar{d}\gamma^\mu u|0\rangle = C_V Q^\mu F_+(s) + C_S \left(\frac{\Delta_{\pi^-\pi^0}}{s}\right) q^\mu F_0(s),$$

$$H^{\mu\nu} = \langle\pi^0\pi^-|\bar{d}\sigma^{\mu\nu} u|0\rangle = iF_T(s)(P_{\pi^0}^\mu P_{\pi^-}^\nu - P_{\pi^-}^\mu P_{\pi^0}^\nu)\,.$$

## Vector form factors

$$f_+(s) = \frac{\epsilon_{\pi\eta}}{1 + \beta_\rho} \left\{ BW_\rho(s) + \beta_\rho BW_{\rho'}(s) \right\}$$

Paver-Riazuddin (2010)

$$f_+(s) = \epsilon_{\pi\eta} \widetilde{F}_+^{\pi^-\pi^0}(s) \quad \text{Tau data from Belle}$$

Escribano et al (2016)

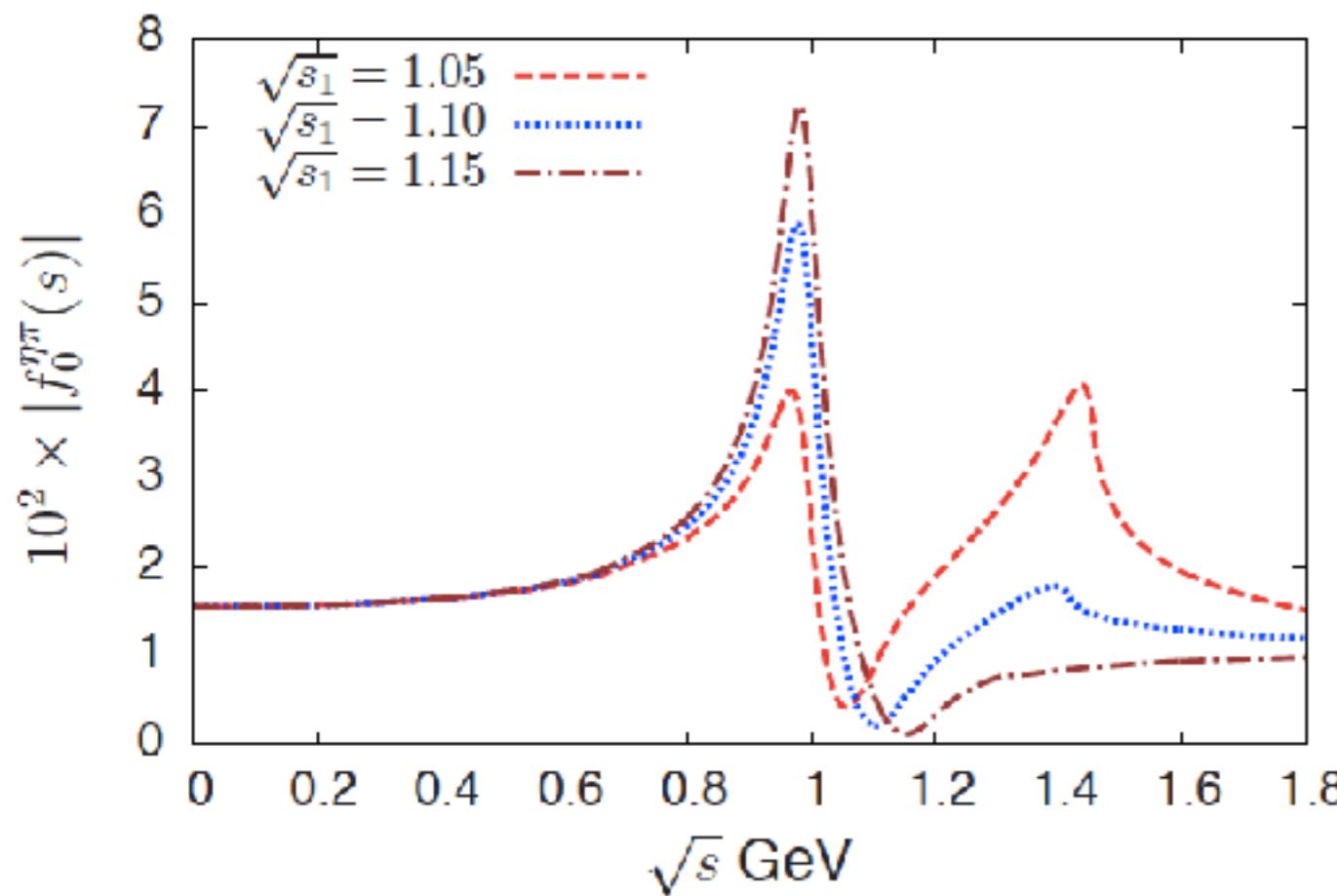
## Scalar form factors

$$f_0(s) = \frac{\epsilon_{\pi\eta}}{1 + \beta_a} \left\{ BW_{a_0}(s) + \beta_a BW_{a'_0}(s) \right\}$$

Paver & Riazuddin (2010)

# Scalar form factors

Descotes-Genon and Moussallam (2014)



Escribano et al (2016)

