Lepton Flavour Violation in Extended Higgs sectors

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Just posted on ArXiv, will appear on Tuesday

Outline :

1. Introduction and Motivation
2. CP-even Higgs with LFV
3. CP-odd Higgs with LFV
4. Conclusion and Outlook

1. Introduction and Motivation

1.1 Introduction

- Discovery of a 125 GeV scalar particle :
  Standard Higgs? ⇒ Need to study its property

- Consider the possibility of non-standard LFV couplings of the Higgs
  ⇒ arise in several models

Goudelis, Lebedev,Park'11
Davidson, Grenier'10

- Conveniently parametrized by effective interaction

$$\boxed{\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}\left(\bar{f}_L^i f_R^i\right)\varphi + h.c. + \ldots}$$

Harnick, Koop, Zupan'12
Blankenburg, Ellis, Isidori'12
McKeen, Pospelov, Ritz'12
Arhrib, Cheng, Kong'12

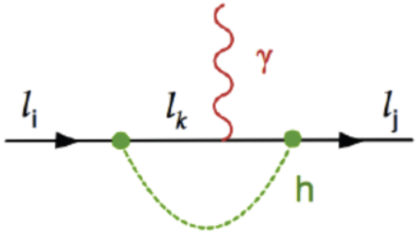
- In the SM : $Y_{ij}^{h_{SM}} = \frac{m_i}{v}\delta_{ij}$

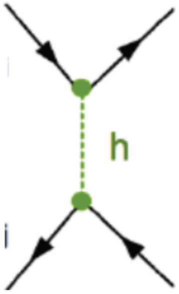
- In full generality parametrization of the Yukawas
  - $Y_{ii}^{\varphi} = y_i^{\varphi}\frac{m_i}{v}$
  - Assumption: CP conservation ⇒ Y_{ij}^{φ}
    - → *real* for $\boxed{\varphi \equiv h}$ CP-even Higgs
    - → *Imaginary* for $\boxed{\varphi \equiv A}$ CP-odd Higgs

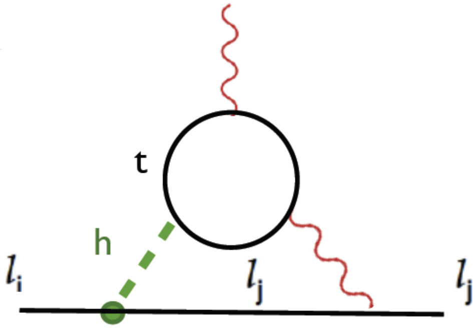
1.1 Introduction

- $\mathcal{L}_Y \xrightarrow{\text{EFT}} \boxed{\mathcal{L}_{d=6} = -\frac{\lambda_\ell^{'ij}}{\Lambda^2}\left(\bar{f}_L^i f_R^j\right) H \left(H^\dagger H\right) + h.c. + \ldots}$

- $\mathcal{L}_Y$ mediates LFV Higgs and generates at low energy
  - 4 fermions operators
  - Dipole (loops)







1.2 Constraints on LFV Higgs couplings

Harnick, Koop, Zupan'12

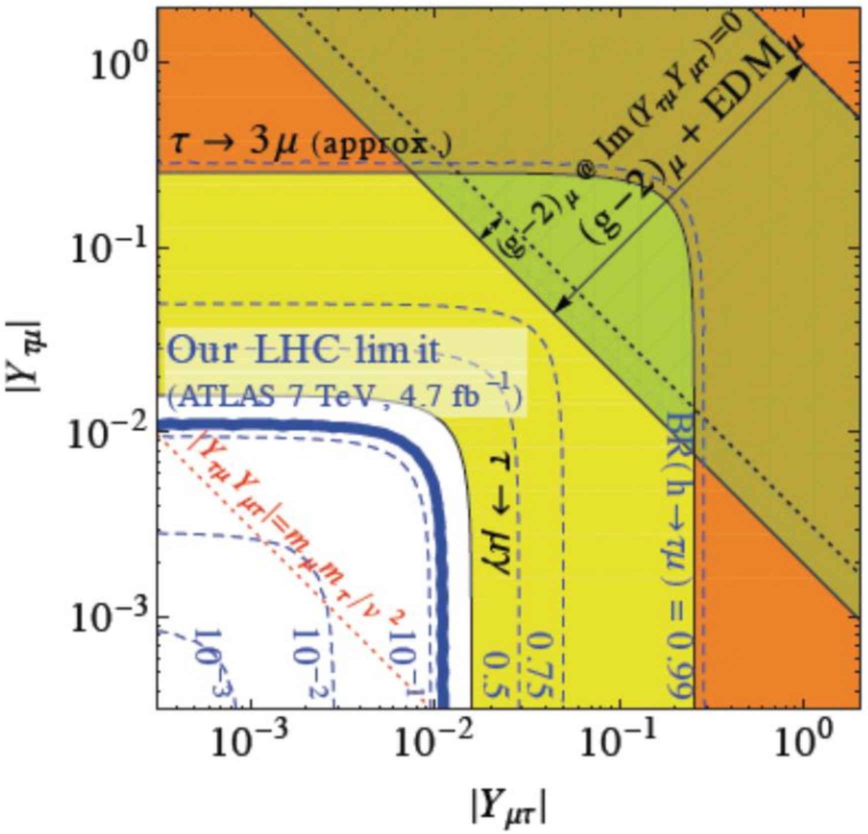
- Results :

Channel	BR 90% CL	$\sqrt{\lvert Y^h_{ij}\rvert^2 + \lvert Y^h_{ji}\rvert^2}$
$\mu \to e\gamma$	$< 2.4 \times 10^{-12}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$< 1 \times 10^{-12}$	$\lesssim 3.1 \times 10^{-5}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	< 0.014
$\tau \to 3e$	$< 2.7 \times 10^{-8}$	$\lesssim 0.12$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	< 0.016
$\tau \to 3\mu$	$< 2.1 \times 10^{-8}$	$\lesssim 0.25$

- Bounds from flavour factories : *MEG*, *Belle*, *Babar* and *LHCb* for $\tau \to 3\mu$

- Strong constraint from $\tau \to \mu\gamma$
  loop induced process, very sensitive to UV completion ⇨ Model dependent

- From LHC : best constraints on $h \to \tau\mu$, $h \to \tau e$

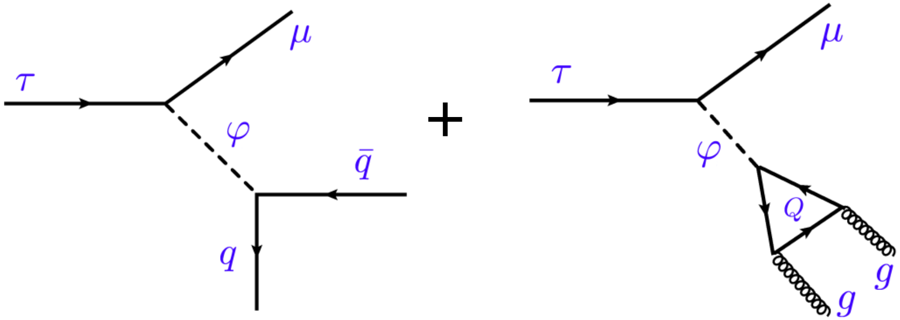


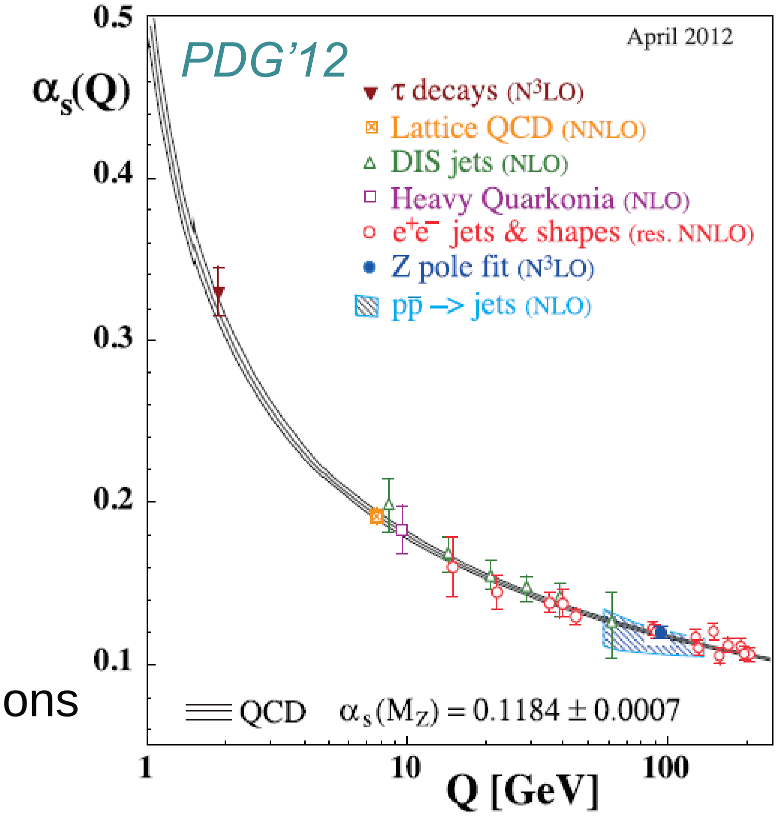
N.B.: Diagonal couplings set to the SM values

1.3 Constraints from hadronic τ decays ($\tau \rightarrow \mu\pi\pi$)

- Most of the time not taken into account but important because tree level Higgs exchange ⇨ less sensitive to UV completion

- Contribution from tree level Higgs exchange





- Complementary analysis between *LHC* and *flavour physics* : *crossed channel*!

  ⇨ two different energy scales :

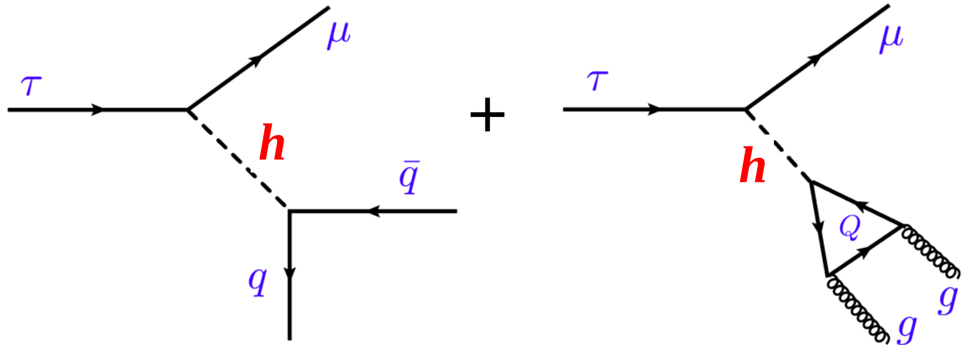
  - LHC: perturbative QCD
  - Flavour factories: intermediate energy, use of ChPT + dispersion relations

⇨ Very interesting processes to look at!

2. CP-even Higgs with LFV

2.1 Constraints from τ → μππ

- Tree level Higgs exchange



- $\mathcal{L}_Y$ ⇨ $$\boxed{\mathcal{L}^h_{eff} \simeq -\frac{h}{v}\left(\sum_{q=u,d,s} y^h_q\, m_q\, \bar{q}\, q - \sum_{q=c,b,t} \frac{\alpha_s}{12\pi}\, y^h_q\, G^a_{\mu\nu} G^{\mu\nu}_a\right)}$$

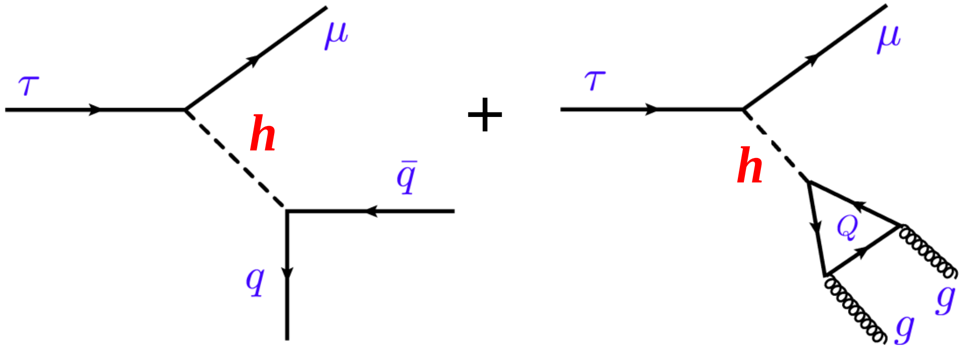
- Problem : Have the hadronic part under control, ChPT not valid at these energies!

⇨ Use *form factors* determined with *dispersion relations* matched at low energy to *CHPT*

Dreiner, Hanart, Kubis, Meissner'13

2.1 Constraints from τ → μππ

- Tree level Higgs exchange



$$\frac{d\Gamma(\tau\to\mu\pi^+\pi^-)}{d\sqrt{s}} = \frac{(m_\tau^2-s)^2\sqrt{s-4m_\pi^2}}{256\pi^3 m_\tau^3}\frac{\left(|Y^h_{\tau\mu}|^2+|Y^h_{\mu\tau}|^2\right)}{M_h^4 v^2}\left|\mathcal{K}_\Delta\Delta_\pi(s)+\mathcal{K}_\Gamma\Gamma_\pi(s)+\mathcal{K}_\theta\theta_\pi(s)\right|^2$$

$$f\left(y_q^h\right)$$

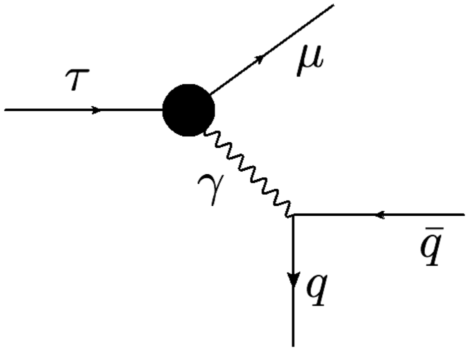
with the form factors:

$$\left\langle \pi^+\pi^- \left| m_u\bar{u}u + m_d\bar{d}d \right| 0 \right\rangle \equiv \Gamma_\pi(s)$$

$$\left\langle \pi^+\pi^- \left| m_s\bar{s}s \right| 0 \right\rangle \equiv \Delta_\pi(s) \qquad \left\langle \pi^+\pi^- \left| \theta_\mu^\mu \right| 0 \right\rangle \equiv \theta_\pi(s)$$

2.1 Constraints from $\tau \to \mu\pi\pi$

- Contribution from dipole diagrams



$$\boxed{\mathcal{L}_{eff} = c_L Q_{L\gamma} + c_R Q_{R\gamma} + h.c.}$$

with the dim-5 EM penguin operators :

$$\boxed{Q_{L\gamma,R\gamma} = \frac{e}{8\pi^2} m_\tau \left(\mu \sigma^{\alpha\beta} P_{L,R} \tau\right) F_{\alpha\beta}}$$

- $$\boxed{\frac{d\Gamma(\tau \to \ell\pi^+\pi^-)}{d\sqrt{s}} = \frac{\alpha^2 |F_V(s)|^2 \left(|c_L|^2 + |c_R|^2\right)}{768\pi^5\, m_\tau} \frac{(s - 4m_\pi^2)^{3/2} (m_\tau^2 - s)^2 (s + 2m_\tau^2)}{s^2}}$$

with the vector form factor :

$$\boxed{C_{L,R} = f\left(Y_{\tau\mu}\right)}$$

$$\left\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-}) \middle| \tfrac{1}{2}(\bar{u}\gamma^\alpha u - \bar{d}\gamma^\alpha d) \middle| 0 \right\rangle \equiv F_V(s)(p_{\pi^+} - p_{\pi^-})^\alpha$$

- Diagram only there in the case of $\tau^- \to \mu^-\pi^+\pi^-$ absent for $\tau^- \to \mu^-\pi^0\pi^0$
  ⇒ neutral mode more model independent

2.2 Determination of the form factors : $F_V(s)$

- Vector form factor

  - Precisely known from experimental measurement $e^+e^- \to \pi^+\pi^-$ and $\tau^- \to \pi^0\pi^-\nu_\tau$ (isospin rotation)

  - Theoretically: decay very well described by resonances
    Following properties of *analyticity* and *unitarity* of the FF

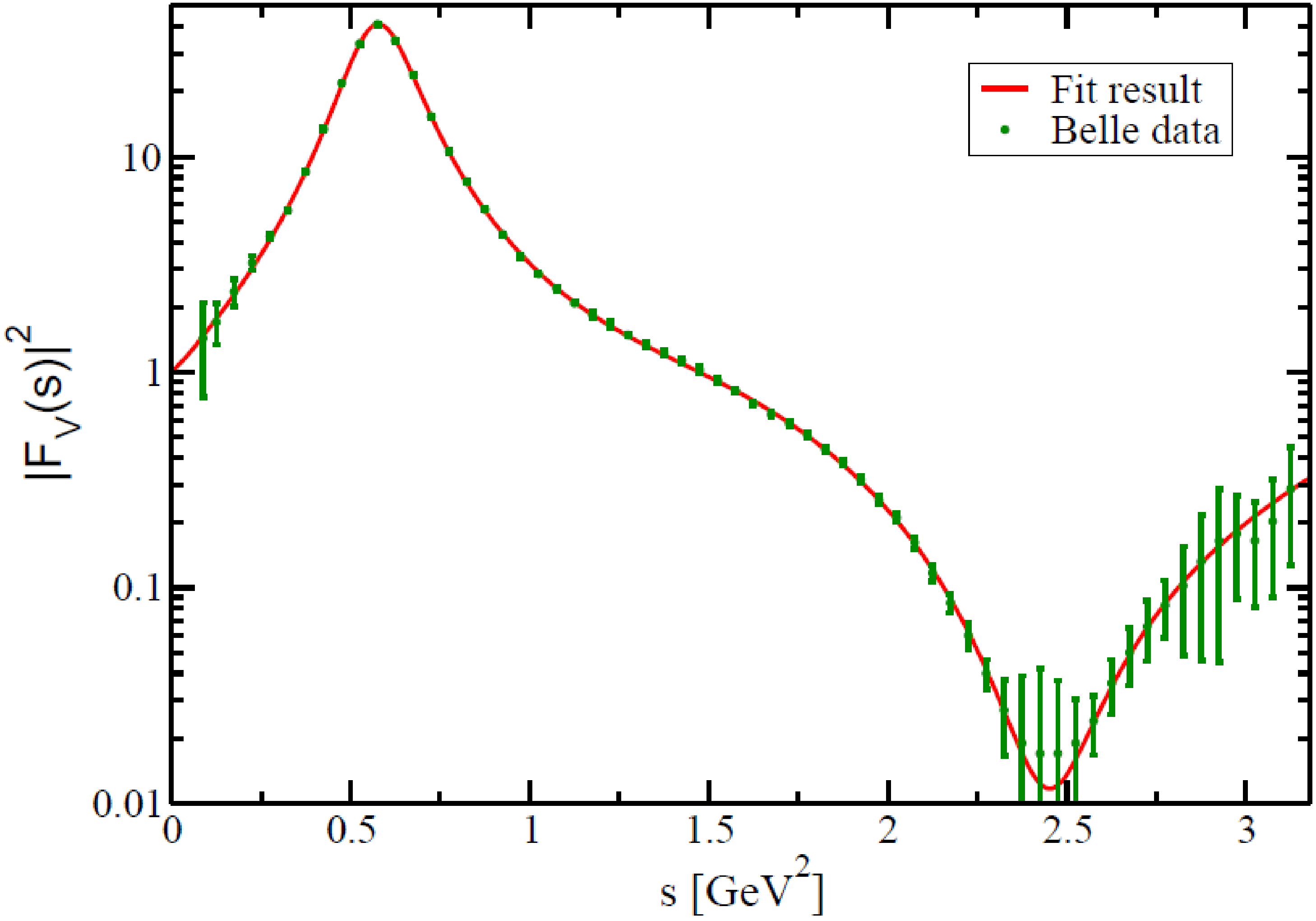
    ⇨ Dispersive parametrization for $F_V(s)$ to fit the Belle data on $\tau^- \to \pi^0\pi^-\nu_\tau$

Guerrero, Pich'98, Pich, Portolés'08
Gomez, Roig'13

$$\boxed{F_V(s) = \exp\left[\lambda'_+ \frac{s}{m_\pi^2} + \frac{1}{2}\left(\lambda''_V - \lambda'^2_V\right)\left(\frac{s}{m_\pi^2}\right)^2 + \frac{s^3}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'}{s'^3} \frac{\phi_V(s')}{(s' - s - i\varepsilon)} \right]}$$

Extracted from a model including
3 resonances ρ(770) , ρ'(1465)
and ρ''(1700) fitted to the data

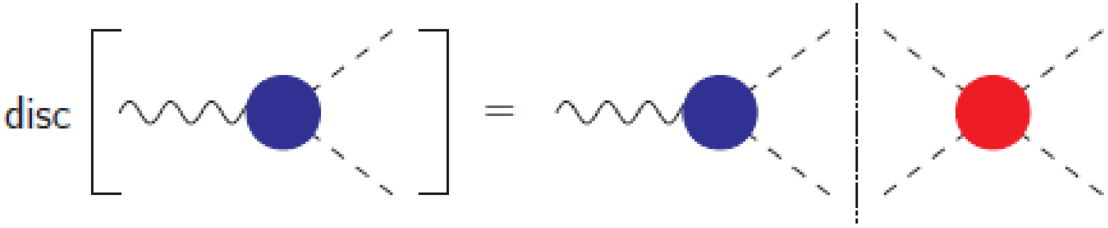
2.2 Determination of the form factors : $F_V(s)$



Very precise determination of $F_V(s)$ thanks to very precise measurements of Belle!

2.2 Determination of the form factors : $\Gamma_\pi(s)$, $\Delta_\pi(s)$, $\theta_\pi(s)$

- With one channel, in the energy region $\pi\pi \to \pi\pi$ unitarity ⇨ the discontinuity of the form factor is known

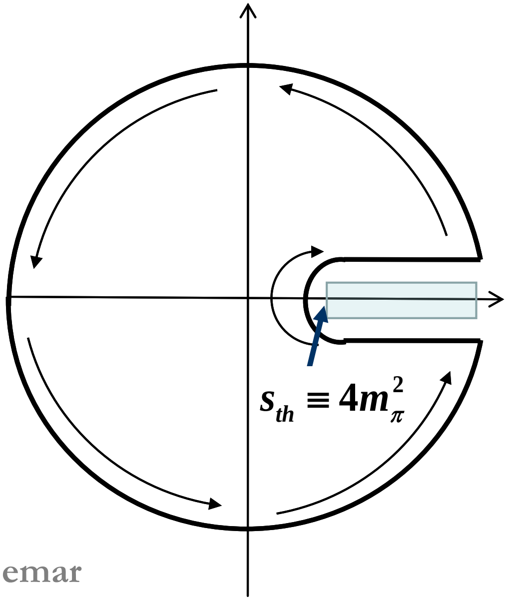


Phase of the FF is
$\pi\pi$ scattering phase
Known from experiment

Watson's theorem

$$\boxed{\frac{1}{2i}\, disc\; F_I(s) = \text{Im}\, F_I(s) = F_I(s)\;\; \sin\delta_I(s) e^{-i\delta_I(s)}}$$

- Use analyticity to reconstruct the form factor in the entire space:



Omnès representation: $F_I(s) = \underset{\text{polynomial}}{P_I(s)}\; \underset{\text{Omnès function}}{\Omega_I(s)}$

$$\boxed{\Omega_I(s) = \exp\left[\frac{s}{\pi}\int_{s_{th}}^{\infty}\frac{ds'}{s'}\,\frac{\delta_I(s')}{s'-s-i\varepsilon}\right]}$$

$P_I(s)$ not known but determined from a matching to CHPT at low energy

2.2 Determination of the form factors : $\Gamma_\pi(s)$, $\Delta_\pi(s)$, $\theta_\pi(s)$

- $\tau \to \mu\pi\pi \Rightarrow \boxed{4m_\pi^2 < s < \left(m_\tau - m_\mu\right)^2 \sim \left(1.77\ \text{GeV}\right)^2}$

  Two channels contribute $\pi\pi$ and $K\bar{K}$

Donoghue, Gasser, Leutwyler'90
Moussallam'99

- Generalisation of the previous method :

  Unitarity $\Rightarrow$ $$\Gamma_m^\star(s) = \sum_n \{\delta_{mn} + 2\,i\,T_{mn}(s)\,\sigma_n(s)\}^\star\,\Gamma_n(s)$$

  Scattering matrix $\pi\pi \to \pi\pi$, $\pi\pi \to K\bar{K}$
  $K\bar{K} \to \pi\pi$, $K\bar{K} \to K\bar{K}$

- Solve the dispersive integral equations iteratively starting with Omnès functions

$$\boxed{\mathrm{Im}X_n^{(N+1)}(s) = \sum_{m=1}^{2} \mathrm{Re}\left\{T_{nm}^*\sigma_m(s)X_m^{(N)}\right\}} \longrightarrow \boxed{\mathrm{Re}X_n^{(N+1)}(s) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'}{s'-s}\mathrm{Im}X_n^{(N+1)}}$$

- According to *Muskhelishvili*, 2 sets of solutions $\{C_1(s), D_1(s)\}$, $\{C_2(s), D_2(s)\}$

  FFs linear combinations : $\boxed{\Gamma_n(s) = P_\Gamma(s)C_n(s) + Q_\Gamma(s)D_n(s)}$

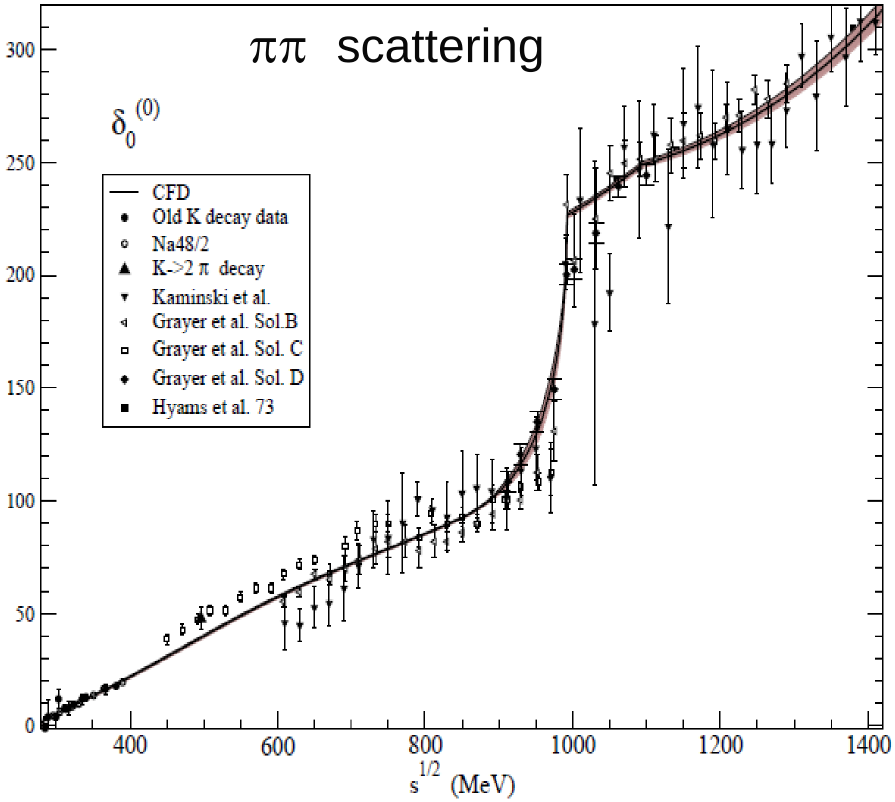
  Determined from a matching to ChPT

2.2 Determination of the form factors : $\Gamma_\pi(s)$, $\Delta_\pi(s)$, $\theta_\pi(s)$

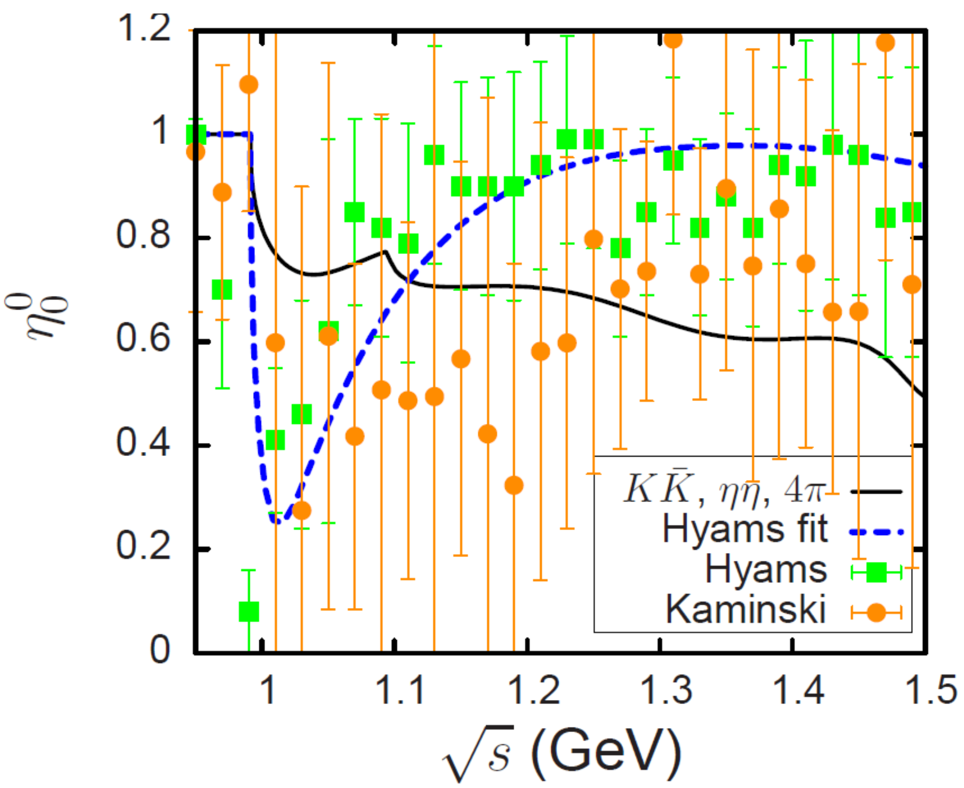
- Inputs : Several inputs ⇨ solve the Roy-Steiner equations

Ananthanarayan et al'01, Colangelo et al'01

Buettiker, Descotes, Moussallam '02

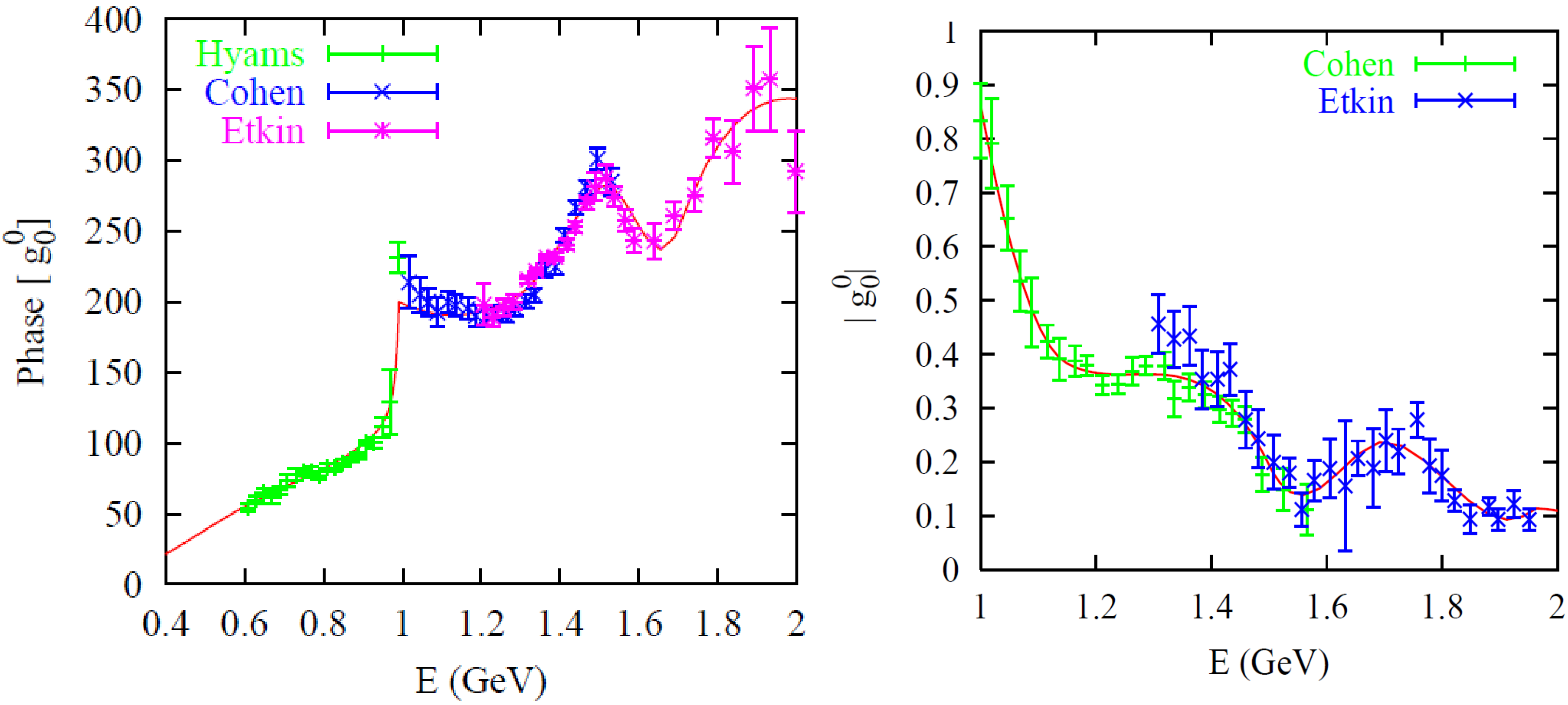

$\pi\pi$ scattering

Inelasticity

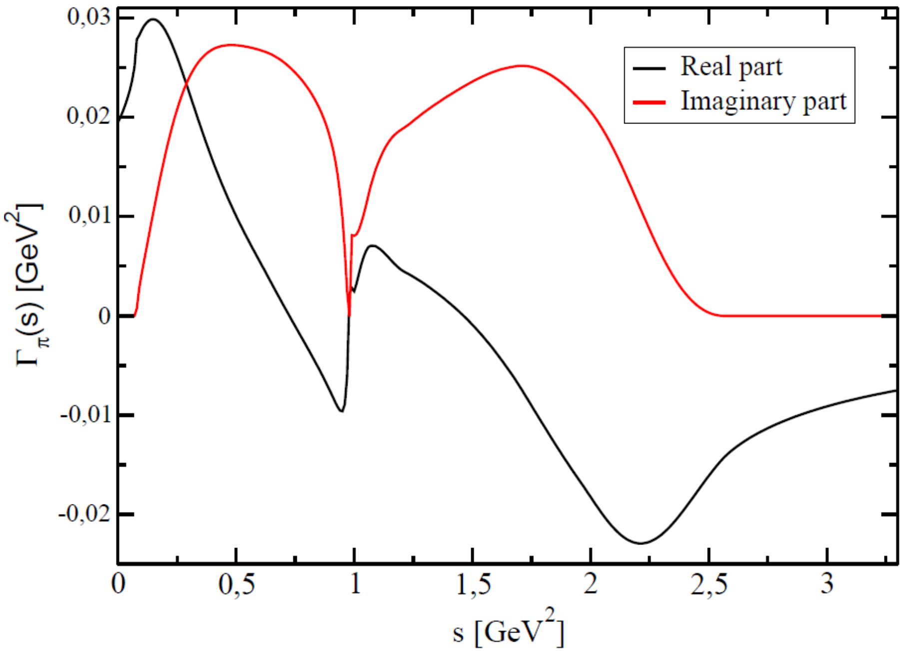


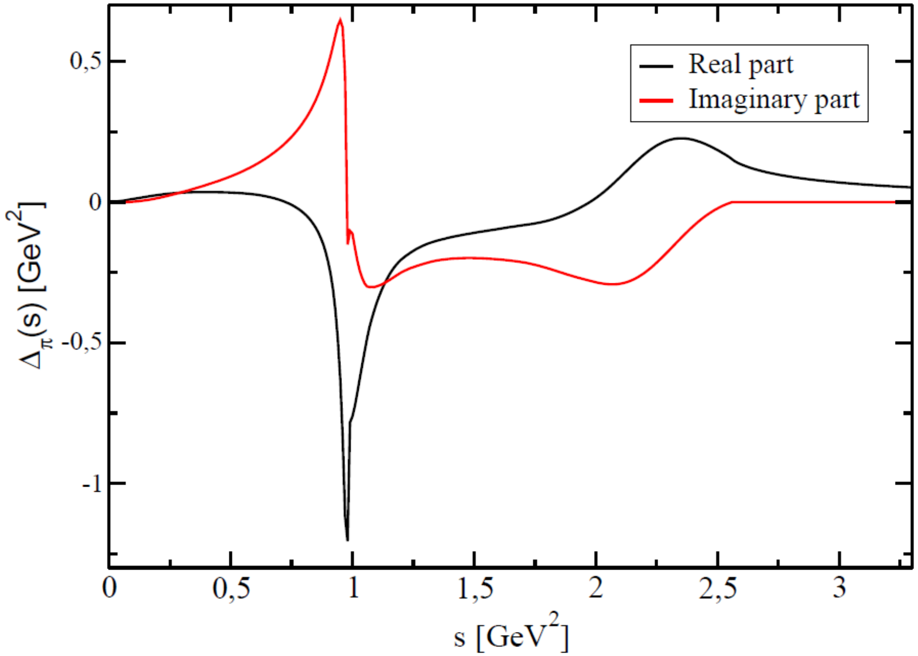
2.2 Determination of the form factors : $\Gamma_\pi(s)$, $\Delta_\pi(s)$, $\theta_\pi(s)$

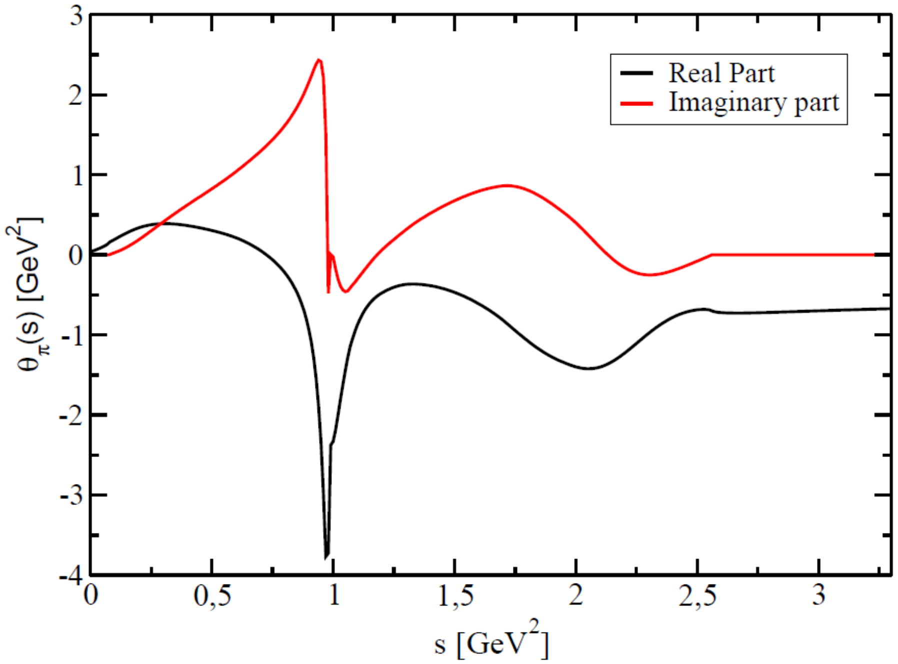
- Inputs : $\pi\pi \rightarrow \boldsymbol{K\bar{K}}$



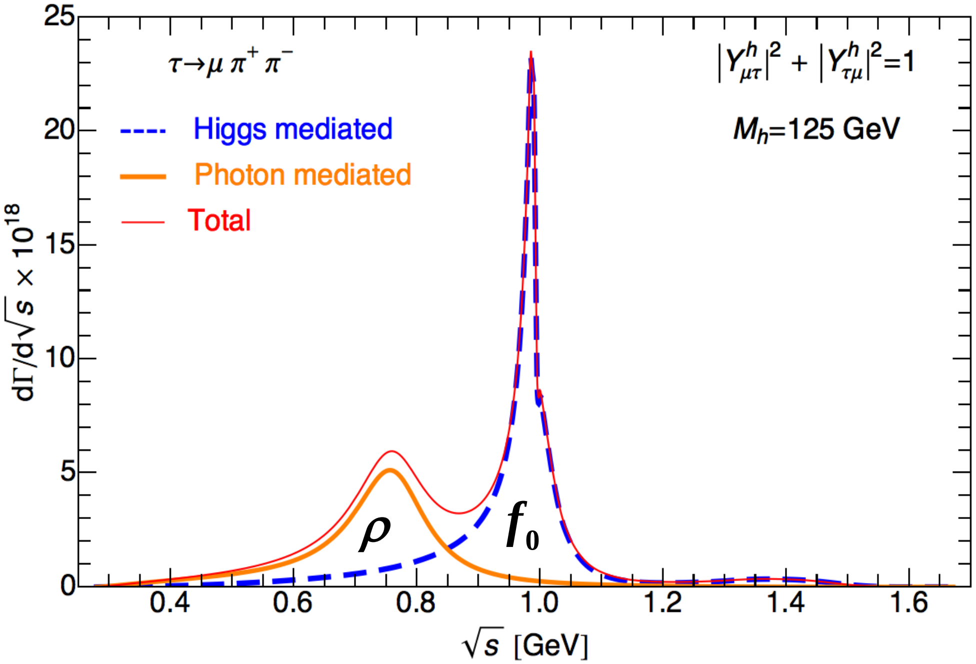
- A large number of theoretical analyses *Descotes-Genon et al'01, Kaminsky et al'01, Garcia-Martin et al'09, Colangelo et al.'11* and all agree
- 3 inputs: $\delta_\pi(s)$, $\delta_K(s)$, η from *B. Moussallam* ⇨ *reconstruct T matrix*


$\Gamma_\pi(s)$ [GeV^2]
0,03
0,02
0,01
0
-0,01
-0,02
0
0,5
1
1,5
2
2,5
3
s [GeV^2]
Real part
Imaginary part


$\Delta_\pi(s)$ [GeV^2]
0,5
0
-0,5
-1
0
0,5
1
1,5
2
2,5
3
s [GeV^2]
Real part
Imaginary part


$\theta_\pi(s)$ [GeV^2]
3
2
1
0
-1
-2
-3
-4
0
0,5
1
1,5
2
2,5
3
s [GeV^2]
Real Part
Imaginary part

2.3 Results

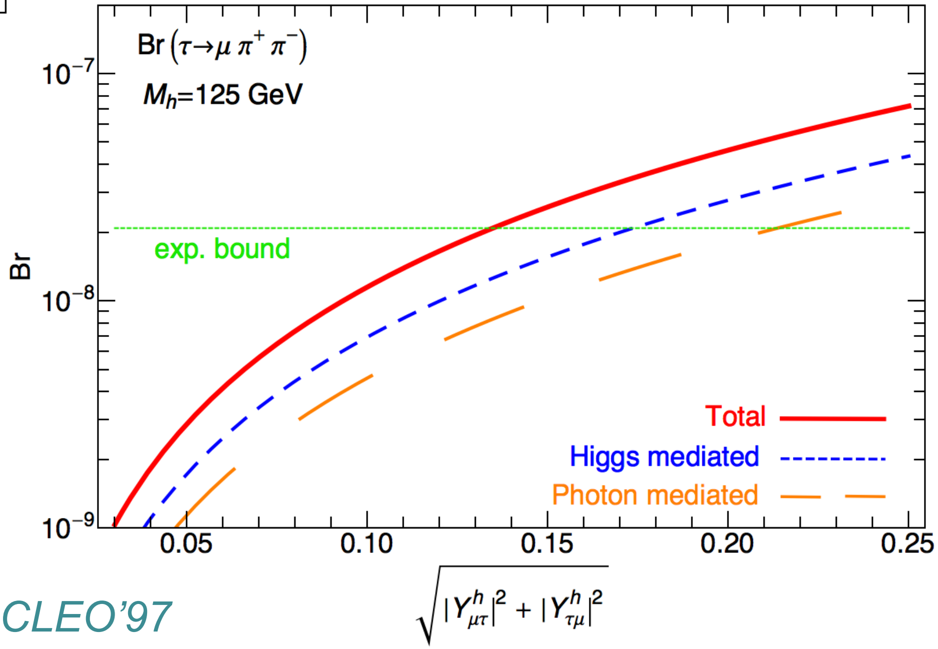


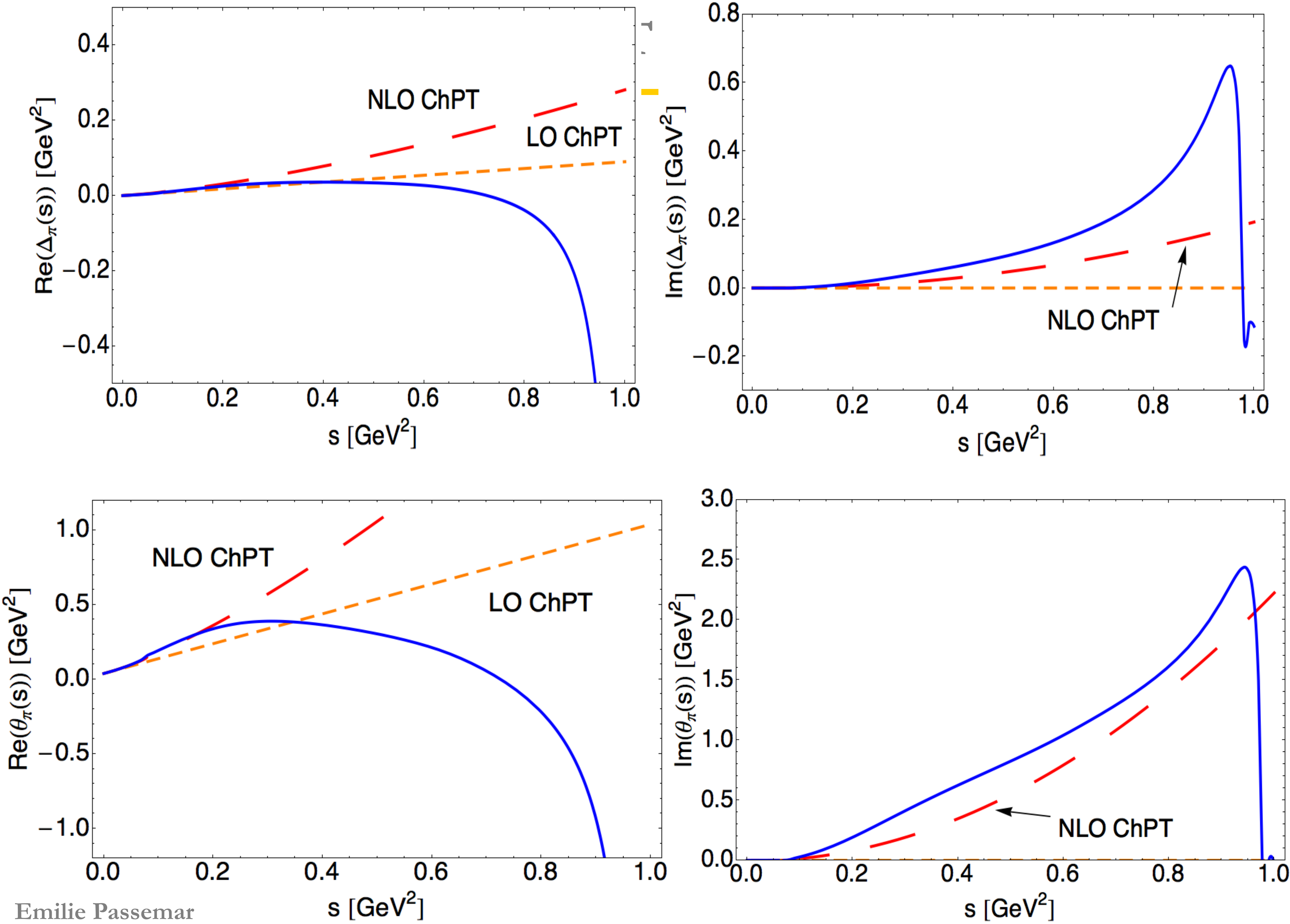
Dominated by

- $\rho(770)$ (photon mediated)
- $f_0(980)$ (Higgs mediated)

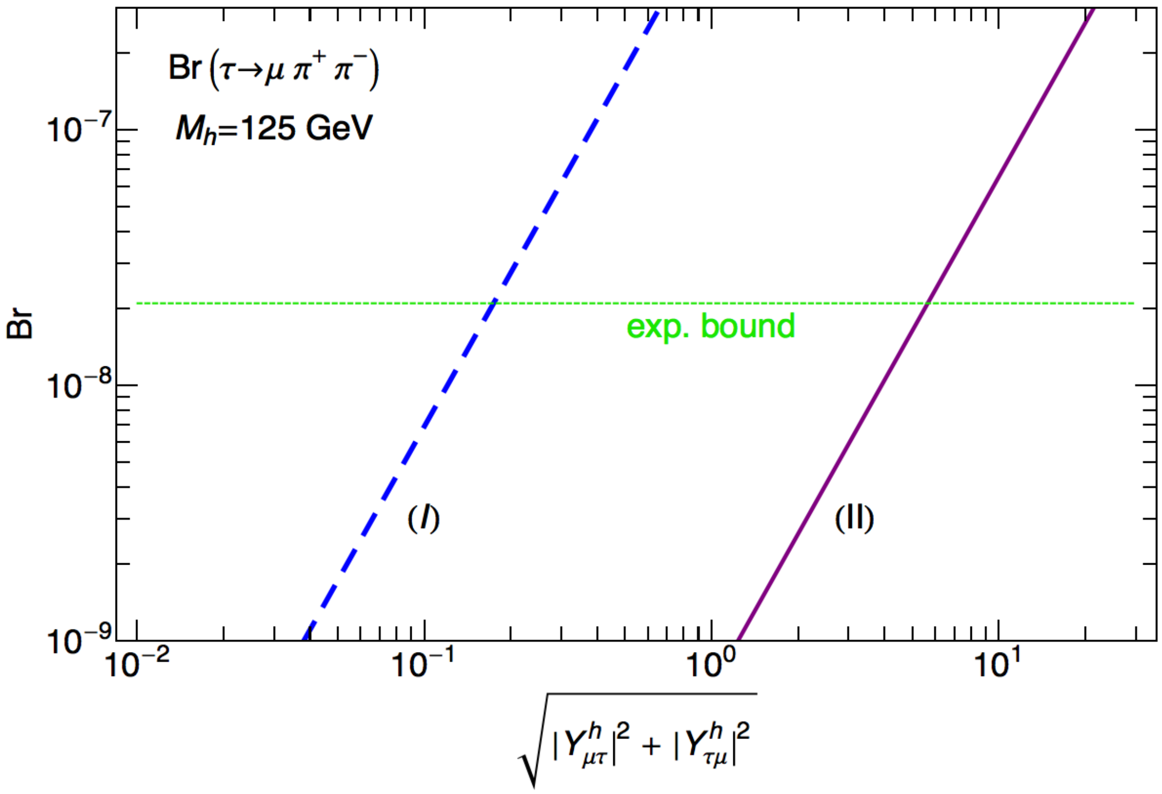
Channel	BR 90% CL	$\sqrt{\lvert Y^h_{ij}\rvert^2 + \lvert Y^h_{ji}\rvert^2}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	< 0.016
$\tau \to 3\mu$	$< 2.1 \times 10^{-8}$	$\lesssim 0.25$
$\tau \to \mu\pi^+\pi^-$	$< 2.1 \times 10^{-8}$	< 0.13
$\tau \to \mu\rho$	$< 1.2 \times 10^{-8}$	< 0.13
$\tau \to \mu\pi^0\pi^{0(*)}$	$< 1.4 \times 10^{-5}$	< 6.3

Belle'08'11'12 except for * *CLEO'97*




NLO ChPT
LO ChPT
$\mathrm{Re}(\Delta_\pi(s))$ [GeV^2]
0.4
0.2
0.0
−0.2
−0.4
0.0
0.2
0.4
0.6
0.8
1.0
s [GeV^2]
$\mathrm{Im}(\Delta_\pi(s))$ [GeV^2]
0.8
0.6
0.4
0.2
0.0
−0.2
NLO ChPT
0.0
0.2
0.4
0.6
0.8
1.0
s [GeV^2]
NLO ChPT
LO ChPT
$\mathrm{Re}(\theta_\pi(s))$ [GeV^2]
1.0
0.5
0.0
−0.5
−1.0
0.0
0.2
0.4
0.6
0.8
1.0
s [GeV^2]
$\mathrm{Im}(\theta_\pi(s))$ [GeV^2]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
NLO ChPT
0.0
0.2
0.4
0.6
0.8
1.0
s [GeV^2]

2.4 Comparison with ChPT



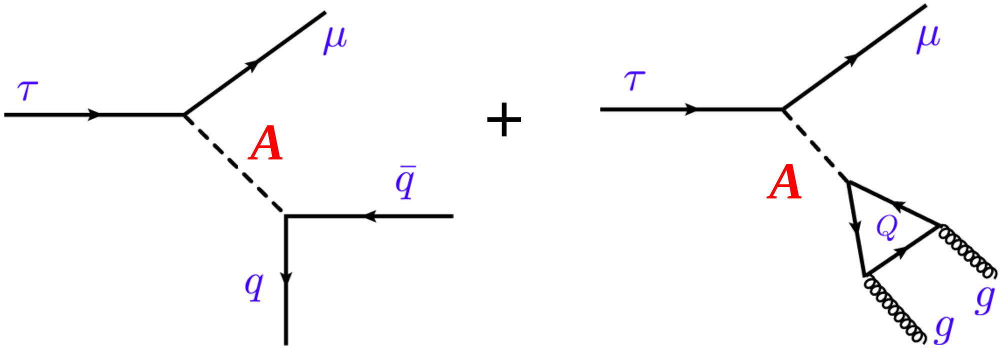
- Rigorous treatment of hadronic part ⇨ bound reduced by one order of magnitude! ⇨ Very *robust bounds*!

- ChPT, EFT only valid at low energy for $\boxed{\mathbf{p} \ll \Lambda = 4\pi f_\pi \sim 1\ \mathbf{GeV}}$
  ⇨ *not valid up to* $E=(m_\tau - m_\mu)$!

3. CP-odd Higgs with LFV

3.1 Constraints from $\tau \to 1P$

- Tree level Higgs exchange



- $\mathcal{L}_Y$ ⇨ $$\boxed{\mathcal{L}^A_{eff} \simeq -\frac{A}{v}\left(\sum_{q=u,d,s} y^A_q\, m_q\, \bar{q} i\gamma_5\, q - \sum_{q=c,b,t} y^A_q\, \frac{\alpha_s}{8\pi}\, G^a_{\mu\nu}\, \widetilde{G}^a_{\mu\nu}\right)}$$

$$\widetilde{G}^a_{\mu\nu} = \frac{1}{2}\,\epsilon_{\mu\nu\alpha\beta}\, G^a_{\alpha\beta}$$

- Mediate only one pseudoscalar meson ⇨ very characteristic!

3.1 Constraints from $\tau \rightarrow 1P$

- Tree level Higgs exchange
  - ➢ η, η’

$$\Gamma\left(\tau \to \ell\eta^{(\prime)}\right) = \frac{\bar\beta\,(m_\tau^2 - m_\eta^2)\left(|Y^A_{\mu\tau}|^2 + |Y^A_{\tau\mu}|^2\right)}{256\,\pi\, M_A^4\, v^2\, m_\tau}\left[(y_u^A + y_d^A) h^q_{\eta'} + \sqrt{2} y_s^A h^s_{\eta'} - \sqrt{2} a_{\eta'} \sum_{q=c,b,t} y_q^A\right]^2$$

with the decay constants :

$$\langle \eta^{(\prime)}(p)|\bar q\,\gamma_5\, q|0\rangle \;=\; -\frac{i}{2\sqrt{2}m_q}\, h^q_{\eta^{(\prime)}} \qquad \langle \eta^{(\prime)}(p)|\bar s\,\gamma_5\, s|0\rangle \;=\; -\frac{i}{2m_s}\, h^s_{\eta^{(\prime)}}$$

$$\langle \eta^{(\prime)}(p)|\frac{\alpha_s}{4\pi}\, G_a^{\mu\nu}\widetilde{G}^a_{\mu\nu}|0\rangle = a_{\eta^{(\prime)}}$$

➢ π :

$$\Gamma(\tau \to \ell\pi^0) \;=\; \frac{f_\pi^2\, m_\pi^4\, m_\tau}{256\pi M_A^4\, v^2}\left(|Y^A_{\tau\mu}|^2 + |Y^A_{\mu\tau}|^2\right)\left(y_u^A - y_d^A\right)^2$$

3.2 Results

- $\tau \to \mu P$

Process	BR 90% CL	$M_A = 200$ GeV	$M_A = 500$ GeV	$M_A = 700$ GeV
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	$Z < 0.018$	$Z < 0.040$	$Z < 0.055$
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	$Z < 0.28$	$Z < 0.60$	$Z < 0.85$
$^{(*)}$ $\tau \to \mu\pi$	$< 11 \times 10^{-8}$	$Z < 41$	$Z < 257$	$Z < 503$
$^{(*)}$ $\tau \to \mu\eta$	$< 6.5 \times 10^{-8}$	$Z < 0.52$	$Z < 3.3$	$Z < 6.4$
$^{(*)}$ $\tau \to \mu\eta'$	$< 13 \times 10^{-8}$	$Z < 1.1$	$Z < 7.2$	$Z < 14.1$
$\tau \to \mu\pi^+\pi^-$	$< 2.1 \times 10^{-8}$	$Z < 0.25$	$Z < 0.54$	$Z < 0.75$
$\tau \to \mu\rho$	$< 1.2 \times 10^{-8}$	$Z < 0.20$	$Z < 0.44$	$Z < 0.62$

BaBar'06'10 , Belle'10'11'13

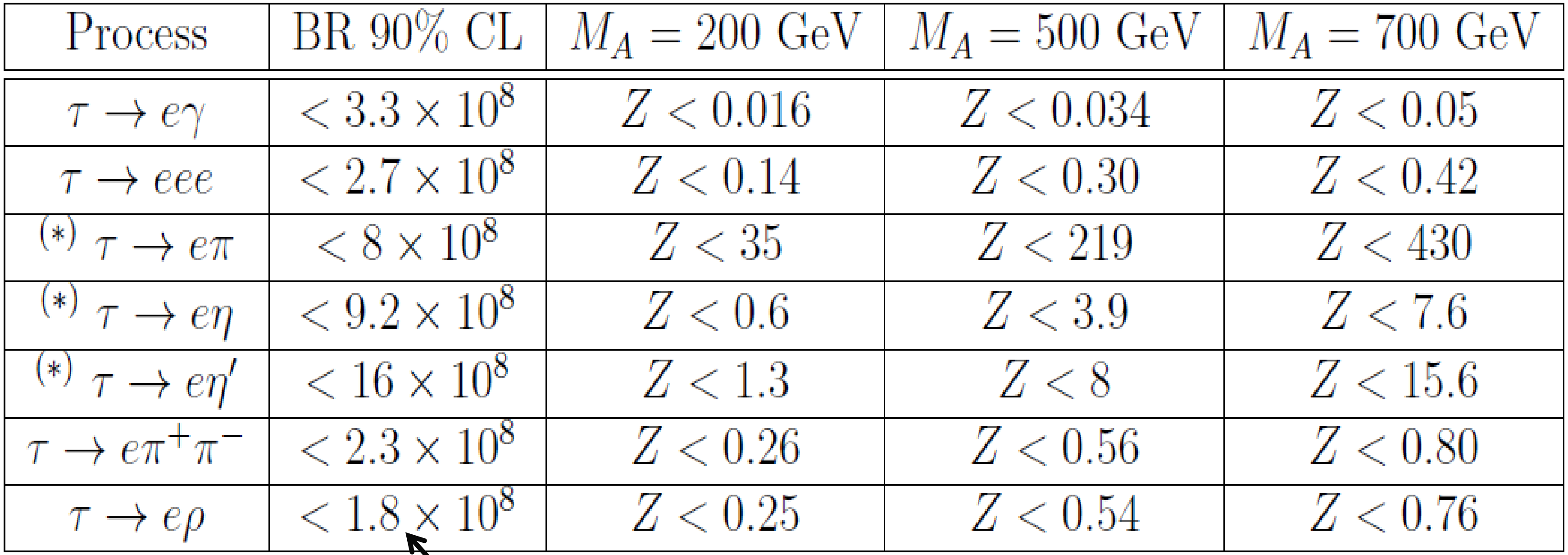
$$\boxed{Z = \sqrt{\left|Y^A_{\mu\tau}\right|^2 + \left|Y^A_{\tau\mu}\right|^2}}$$

(*) : No contribution from effective dipole operator or CP-even Higgs

N.B.: Diagonal couplings $\left|y^A_f\right| = 1$

3.2 Results

- $\tau \to e\boldsymbol{P}$



Process	BR 90% CL	$M_A = 200$ GeV	$M_A = 500$ GeV	$M_A = 700$ GeV
$\tau \to e\gamma$	$< 3.3 \times 10^8$	$Z < 0.016$	$Z < 0.034$	$Z < 0.05$
$\tau \to eee$	$< 2.7 \times 10^8$	$Z < 0.14$	$Z < 0.30$	$Z < 0.42$
$^{(*)}$ $\tau \to e\pi$	$< 8 \times 10^8$	$Z < 35$	$Z < 219$	$Z < 430$
$^{(*)}$ $\tau \to e\eta$	$< 9.2 \times 10^8$	$Z < 0.6$	$Z < 3.9$	$Z < 7.6$
$^{(*)}$ $\tau \to e\eta'$	$< 16 \times 10^8$	$Z < 1.3$	$Z < 8$	$Z < 15.6$
$\tau \to e\pi^+\pi^-$	$< 2.3 \times 10^8$	$Z < 0.26$	$Z < 0.56$	$Z < 0.80$
$\tau \to e\rho$	$< 1.8 \times 10^8$	$Z < 0.25$	$Z < 0.54$	$Z < 0.76$

BaBar'06'10 , Belle'10'11'13

$$\boxed{Z = \sqrt{\left|Y^A_{e\tau}\right|^2 + \left|Y^A_{\tau e}\right|^2}}$$

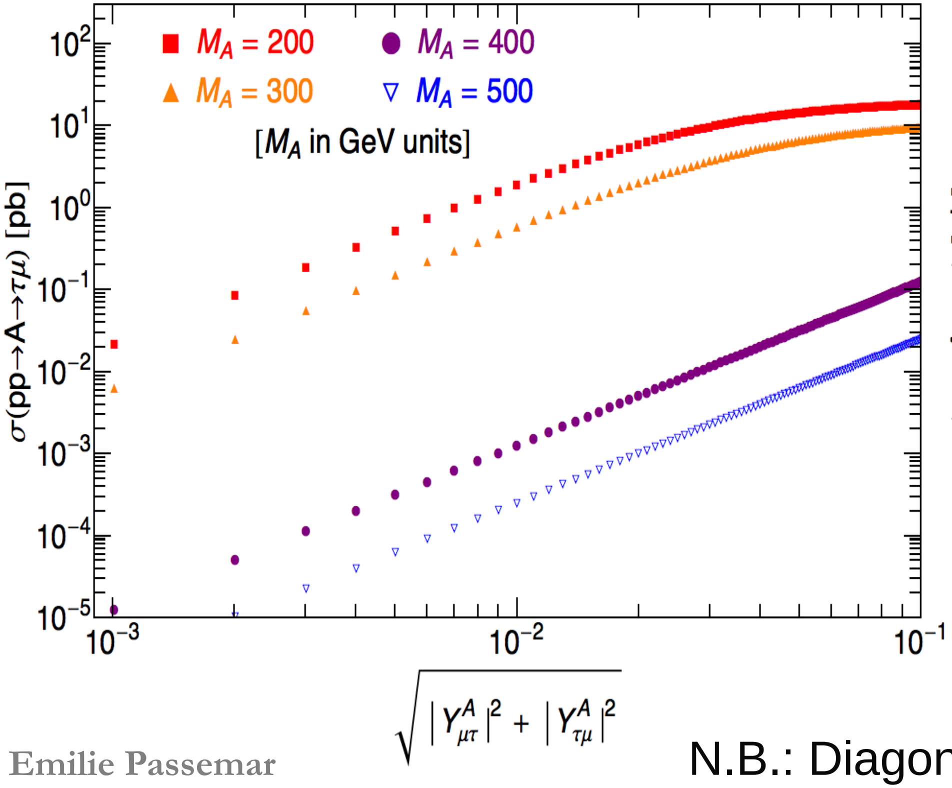
(*) : No contribution from effective dipole operator or CP-even Higgs

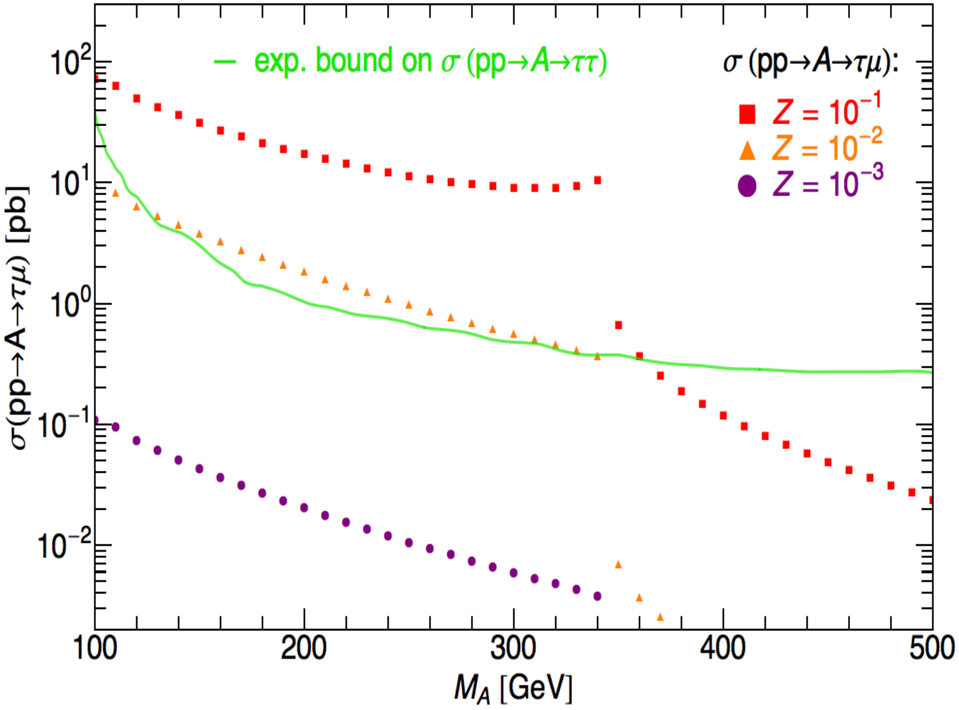
N.B.: Diagonal couplings $\left|y^A_f\right| = 1$

3.3 Prospects at LHC

- Decay width : $$\boxed{\Gamma(A \to \tau^+\mu^- + \tau^-\mu^+) \equiv \Gamma(A \to \tau\mu) = \frac{M_A\left(|Y^A_{\tau\mu}|^2 + |Y^A_{\mu\tau}|^2\right)}{8\pi}}$$

  Assumption : only SM channels ($A \to gg, b\bar{b}, c\bar{c}, \tau\tau \ldots$) are important
- Large BR for $\boxed{A \to \tau\mu}$ can be expected since A does not decay in WW, ZZ
- Results :





N.B.: Diagonal couplings $\left|y^A_f\right| = 1$

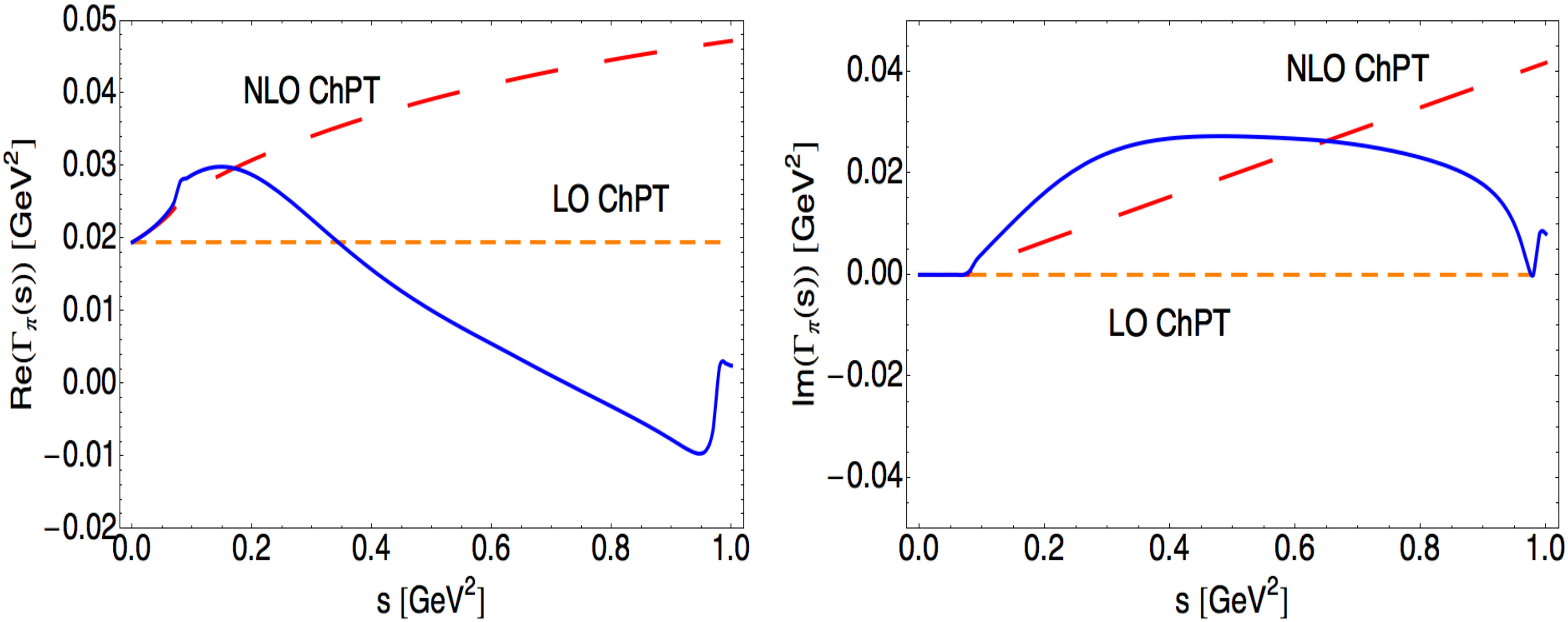
4. Conclusion and Outlook

- Conclusion:
  - We have studied the LFV mode $\tau \to \mu\pi\pi$ for constraining LFV couplings of the Higgs
  - Very interesting and important :
    - The more model-independent (tree level exchange of Higgs)
    - Same process can be studied at LHC and at the flavour factories with totally different experimental and theoretical conditions
    - Very little hadronic uncertainties: using form factors and dispersion relations + ChPT ⇨ *More robust bounds!*
  - Phenomenology of CP-odd Higgs, very peculiar pattern ⇨ decays through $\tau \to lP$, *clear signature*

- Outlook:
  - The more model independent process is $\boxed{\tau^- \to \mu^- \pi^0 \pi^0}$ no loop induced processes but the only experimental bound from *CLEO* and weak ~10^{-5} ⇨ need to be remeasured
  - Dedicated experimental analyses
  - The form factors can be used for EFT analysis of LFV

5. Back-up

2.4 Comparison with ChPT



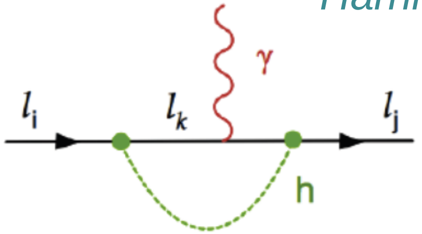
2.2 Constraints on LFV Higgs couplings

Harnick, Koop, Zupan'12

- Constraints from τ → μγ (τ → eγ, μ → eγ)
  - Interactions through loop diagrams

$$\boxed{\Gamma(\tau\to\mu\gamma)=\frac{\alpha m_\tau^5}{64\pi^4}\left(|C_L|^2+|C_R|^2\right)}$$

$$\boxed{C_{L,R}=f\left(Y_{\tau\mu}\right)}$$



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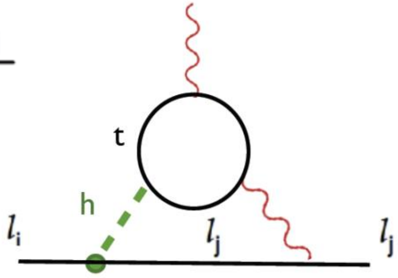
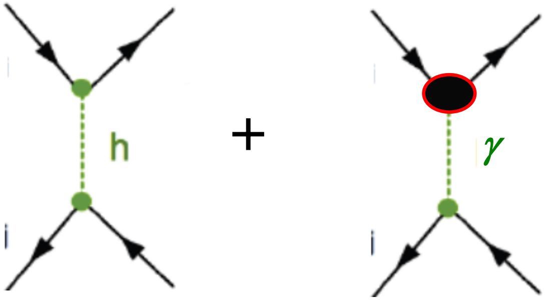


  - Strong bounds from flavour factories especially for μ→eγ

- Constraints from τ → 3μ
  - Tree level contribution subdominant, mainly dominated by loops



$$\boxed{\Gamma(\tau\to3\mu)=\frac{\alpha^2m_\tau^5}{72(2\pi)^5}\left[12\log\frac{m_\mu^2}{m_\tau^2}+29+6\log4\right]\left(|C_L|^2+|C_R|^2\right)}$$

  - Bounds from flavour factories + LHCb