Probing New Physics in Lepton Flavour Violating Tau decays

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In collaboration with A. Celis (LMU, Munich), and V. Cirigliano (LANL)
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Outline

1. Introduction and Motivation

2. Charged Lepton-Flavour Violation from tau decays

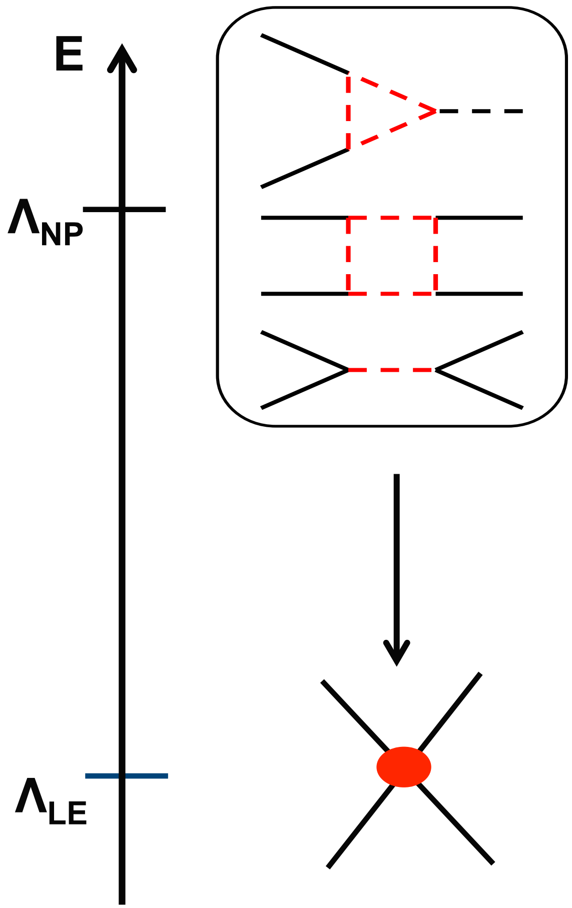
3. Special Role of $\tau \to \mu\pi\pi$: hadronic form factors

4. Results

5. Conclusion and Outlook

1. Introduction and Motivation

1.1 Why study charged leptons?

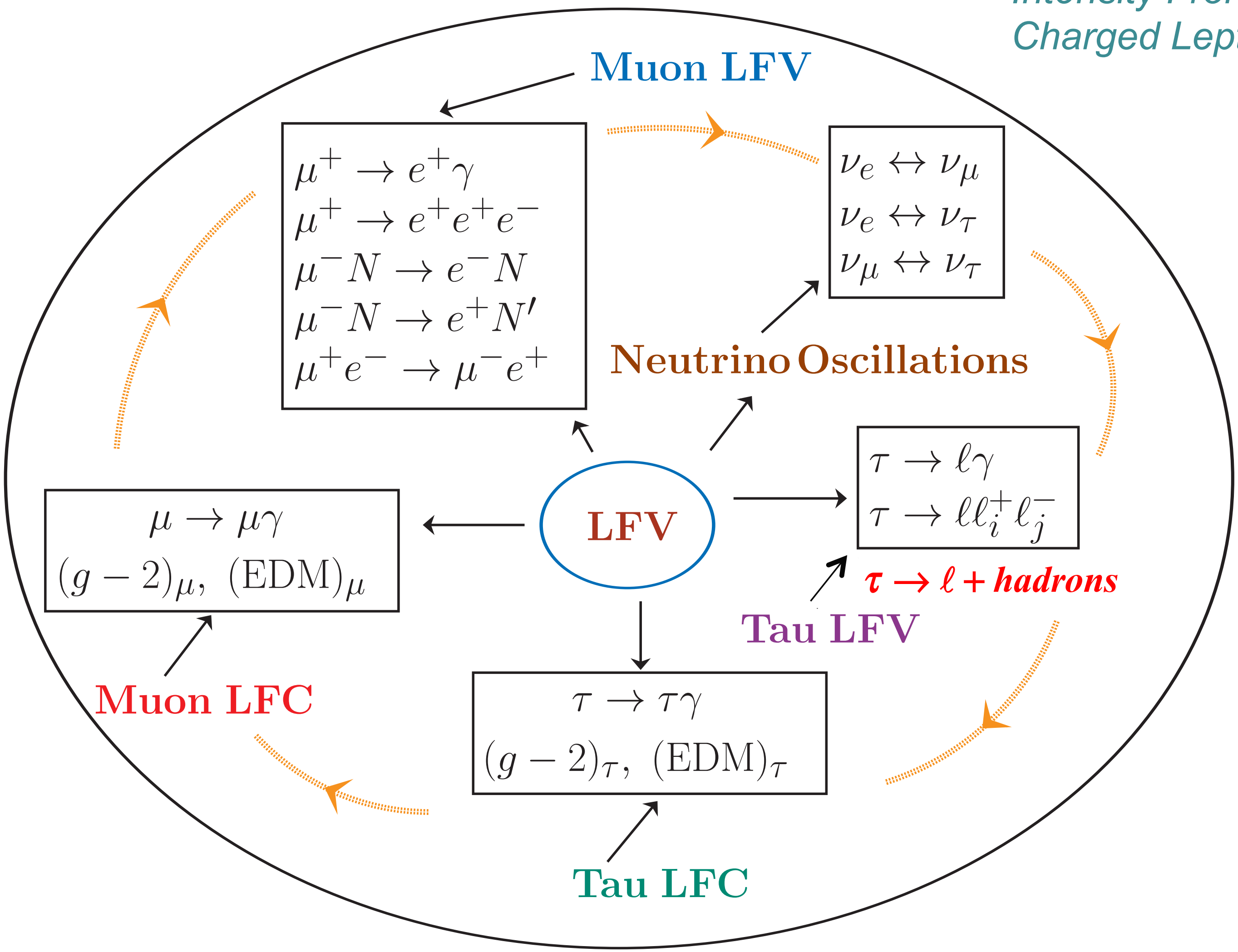


- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: *[ε_K]* $\boxed{\dfrac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^5 \text{ TeV}}$
  - Charged Leptons: *[$\mu \to e\gamma$]* $\boxed{\dfrac{\mu\bar{e}f\bar{f}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^4 \text{ TeV}}$
- At low energy: lots of experiments e.g., *MEG*, *COMET*, *Mu2e*, *E-969, BaBar*, *BelleI-II*, *BESIII, LHCb* huge improvements on measurements and bounds obtained and more expected
- In many cases no SM background: e.g., LFV, EDMs
- For some modes accurate calculations of hadronic uncertainties essential

Charged leptons very important to look for *New Physics*!

1.2 The Program

Intensity Frontier
Charged Lepton WG'13



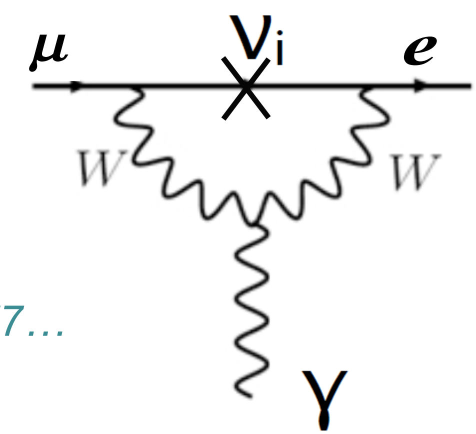
2. Charged Lepton-Flavour Violation

2.1 Introduction and Motivation

- Lepton Flavour Violation is an « accidental » symmetry of the SM (m_ν=0)

- In the *SM* with massive neutrinos effective CLFV vertices are tiny due to GIM suppression ⇨ *unobservably small rates!*

e.g.: $\boxed{\mu \to e\gamma}$



$$\boxed{Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}}$$

Petcov'77, Marciano & Sanda'77, Lee & Shrock'77…

$$\left[Br(\tau \to \mu\gamma) < 10^{-40}\right]$$

- Extremely *clean probe of beyond SM physics*

2.1 Introduction and Motivation

- In New Physics scenarios CLFV can reach observable levels in several channels

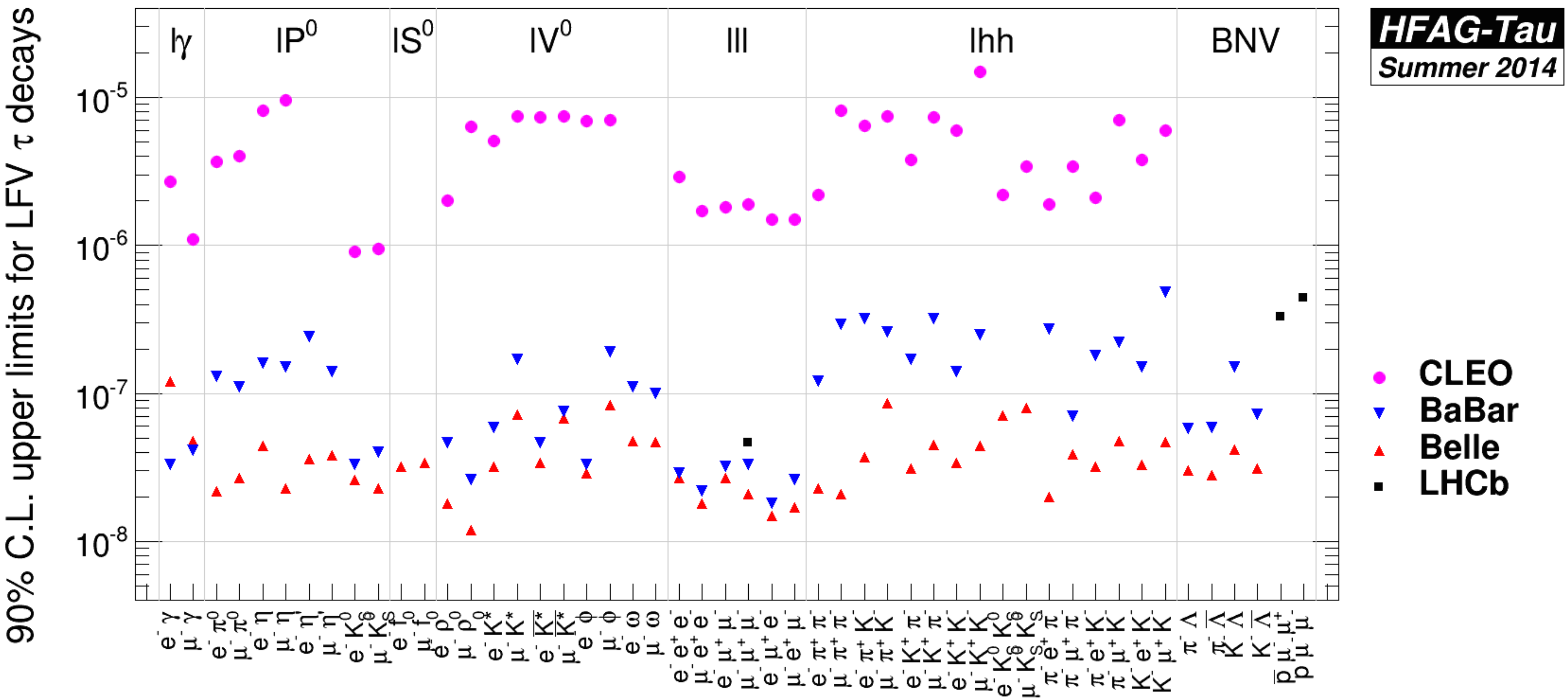
Talk by D. Hitlin @ CLFV2013

		$\tau \to \mu\gamma$	$\tau \to \ell\ell\ell$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908	Undetectable	
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}	10^{-7}
SM + heavy Maj ν_R	Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA + Seesaw	Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319 Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013	10^{-7}	10^{-9}

- But the sensitivity of particular modes to CLFV couplings is model dependent
- Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic

2.2 CLFV processes: tau decays

- Several processes: $\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y$ ↖ $P,\ S,\ V,\ P\bar{P},\ldots$



- 48 LFV modes studied at Belle and BaBar

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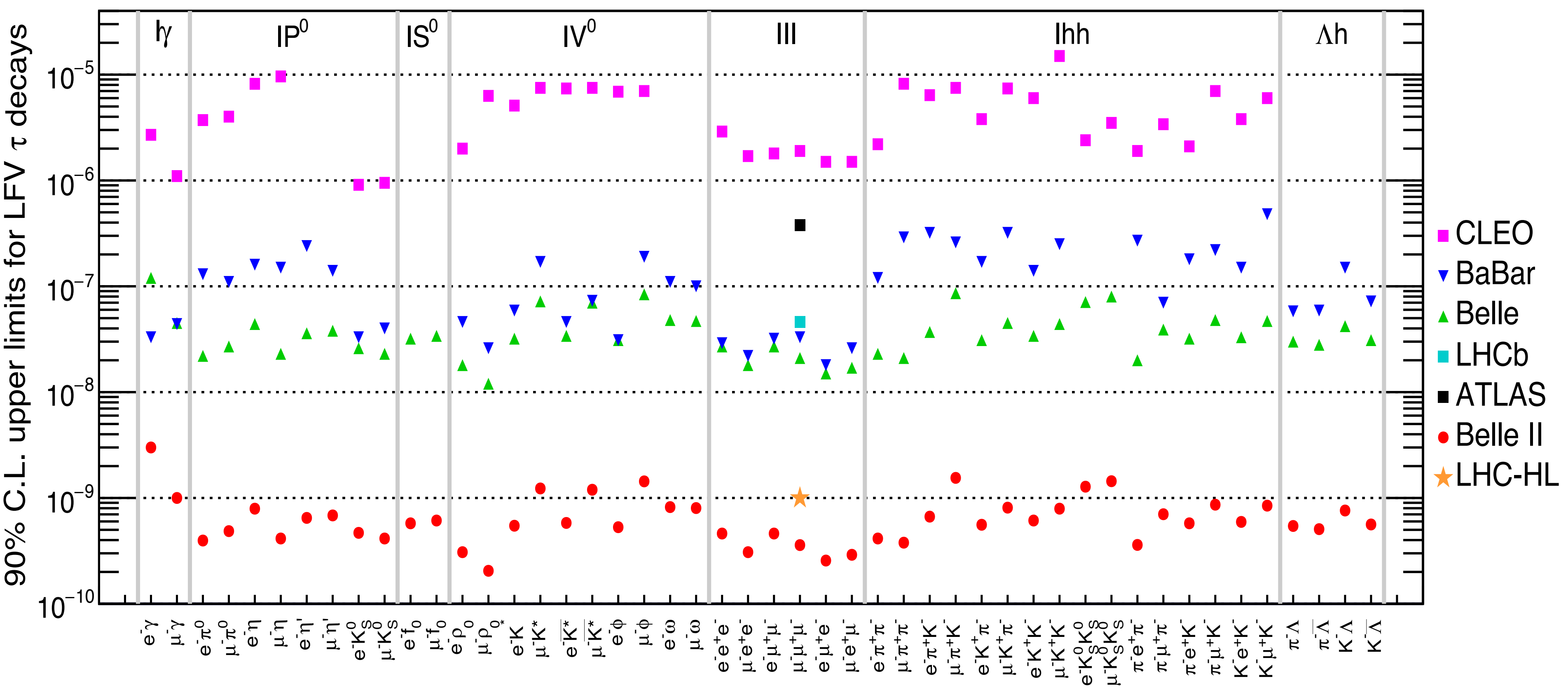


- Expected sensitivity 10^{-9} or better at *LHCb, Belle II, HL-LHC?*

2.3 Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

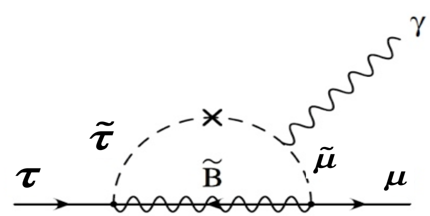
See e.g.
Black, Han, He, Sher'02
Brignole & Rossi'04
Dassinger, Feldmann, Mannel, Turczyk'07
Matsuzaki & Sanda'08
Giffels et al.'08
Crivellin, Najjari, Rosiek'13
Petrov & Zhuridov'14
Cirigliano, Celis, E.P.'14

- Build all D>5 LFV operators:

  - Dipole:

$$\boxed{\mathcal{L}_{eff}^{D} \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu}\sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu}}$$

e.g.



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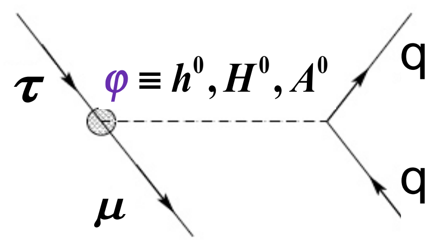
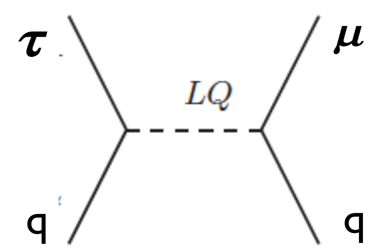
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):

$$\boxed{\mathcal{L}_{eff}^{S,V} \supset -\frac{C_{S,V}}{\Lambda^2} m_\tau m_q G_F \bar{\mu}\, \Gamma P_{L,R} \tau\ \bar{q}\Gamma q}$$

e.g.



$\Gamma \equiv 1$



$\Gamma \equiv \gamma^\mu$

.

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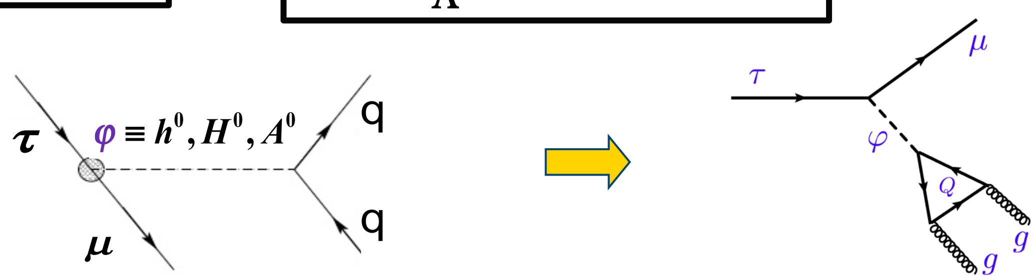
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector): $\boxed{\mathcal{L}_{eff}^{S} \supset -\frac{C_{S,V}}{\Lambda^2} m_\tau m_q G_F \bar{\mu}\, \Gamma P_{L,R}\tau\ \bar{q}\Gamma q}$
  - Integrating out heavy quarks generates *gluonic operator*

$$\boxed{\frac{1}{\Lambda^2}\bar{\mu}P_{L,R}\tau Q\bar{Q}} \rightarrow \boxed{\mathcal{L}_{eff}^{G} \supset -\frac{C_G}{\Lambda^2} m_\tau G_F \bar{\mu} P_{L,R}\tau\ G_{\mu\nu}^{a} G_{a}^{\mu\nu}}$$



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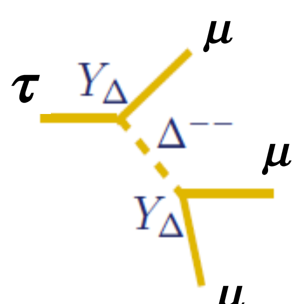
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\boxed{\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu}\, \Gamma P_{L,R} \tau\, \bar{\mu}\, \Gamma P_{L,R} \mu}$

$\boxed{\Gamma \equiv 1, \gamma^\mu}$

e.g.



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  - Lepton-gluon (Scalar, Pseudo-scalar): $\boxed{\mathcal{L}_{eff}^{G} \supset -\frac{C_G}{\Lambda^2} m_\tau G_F \bar{\mu} P_{L,R} \tau\ G_{\mu\nu}^a G_a^{\mu\nu}}$
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\boxed{\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu}\, \Gamma P_{L,R} \tau\ \bar{\mu}\, \Gamma P_{L,R} \mu}$

$\boxed{\Gamma \equiv 1, \gamma^\mu}$

- Each UV model generates a *specific pattern* of them

2.4 Model discriminating power of Tau processes

- Summary table:

Celis, Cirigliano, E.P.'14

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$\mathrm{O}_{\mathrm{S,V}}^{4\ell}$	✓	–	–	–	–	–
O_{D}	✓	✓	✓	✓	–	–
$\mathrm{O}_{\mathrm{V}}^{\mathrm{q}}$	–	–	✓ (I=1)	✓(I=0,1)	–	–
$\mathrm{O}_{\mathrm{S}}^{\mathrm{q}}$	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
$\mathrm{O}_{\mathrm{A}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{P}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

- The notion of "*best probe*" (process with largest decay rate) is *model dependent*

- If observed, compare rate of processes ⇨ key handle on *relative strength* between operators and hence on the *underlying mechanism*

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$\mathrm{O}_{\mathrm{S,V}}^{4\ell}$	✓	–	–	–	–	–
O_{D}	✓	✓	✓	✓	–	–
$\mathrm{O}_{\mathrm{V}}^{\mathrm{q}}$	–	–	✓ (I=1)	✓(I=0,1)	–	–
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O_{GG}	–	–	✓	✓	–	–
$\mathrm{O}_{\mathrm{A}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{P}}^{\mathrm{q}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

- In addition to leptonic and radiative decays, *hadronic decays* are very important ⇨ sensitive to large number of operators!

- But need reliable determinations of the hadronic part: form factors and *decay constants* (e.g. f_η, $f_{\eta'}$)

2.5 Ex: Non standard LFV Higgs coupling

- $$\boxed{\Delta\mathcal{L}_Y = -\frac{\lambda_{ij}}{\Lambda^2}\left(\bar{f}_L^i f_R^j H\right) H^\dagger H} \Rightarrow -Y_{ij}\left(\bar{f}_L^i f_R^j\right) h$$

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

Goudelis, Lebedev, Park'11
Davidson, Grenier'10
Harnik, Kopp, Zupan'12
Blankenburg, Ellis, Isidori'12
McKeen, Pospelov, Ritz'12
Arhrib, Cheng, Kong'12

$$\boxed{\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - h\left(Y_{e\mu}\bar{e}_L\mu_R + Y_{e\tau}\bar{e}_L\tau_R + Y_{\mu\tau}\bar{\mu}_L\tau_R\right) + \ldots}$$

- Arise in several models Cheng, Sher'97, Goudelis, Lebedev,Park'11 Davidson, Grenier'10

Cheng, Sher'97

- Order of magnitude expected $\Rightarrow$ No tuning: $\boxed{|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}}$

- In concrete models, in general further parametrically suppressed

2.5 Ex: Non standard LFV Higgs coupling

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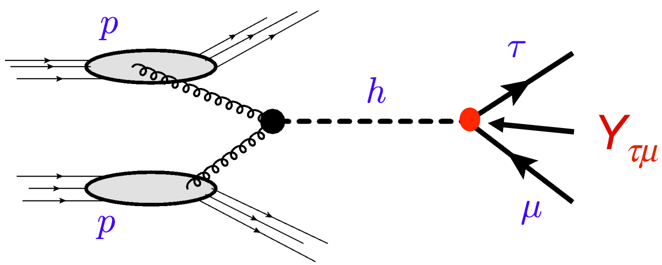
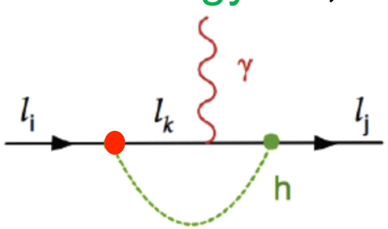
In the SM: $Y_{ij}^{h_{SM}} = \frac{m_i}{\mathrm{v}}\delta_{ij}$

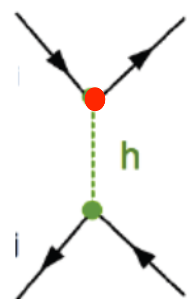
- High energy : LHC

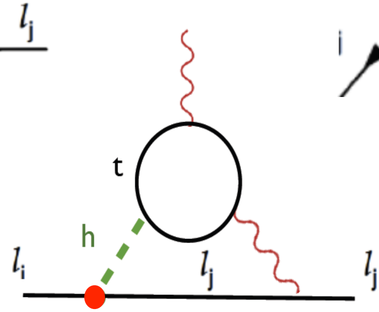


Hadronic part treated with perturbative QCD

- Low energy : D, S operators







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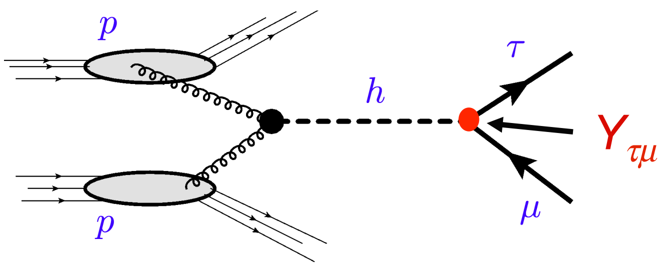
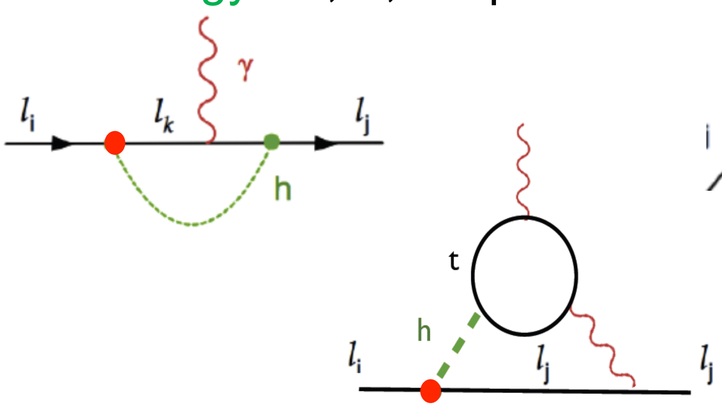
- High energy : LHC

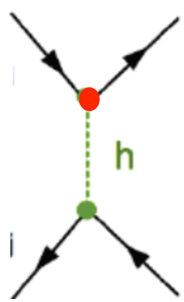


Hadronic part treated with perturbative QCD

Reverse the process

- Low energy : D, S, G operators





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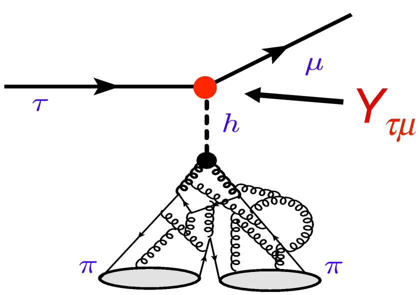
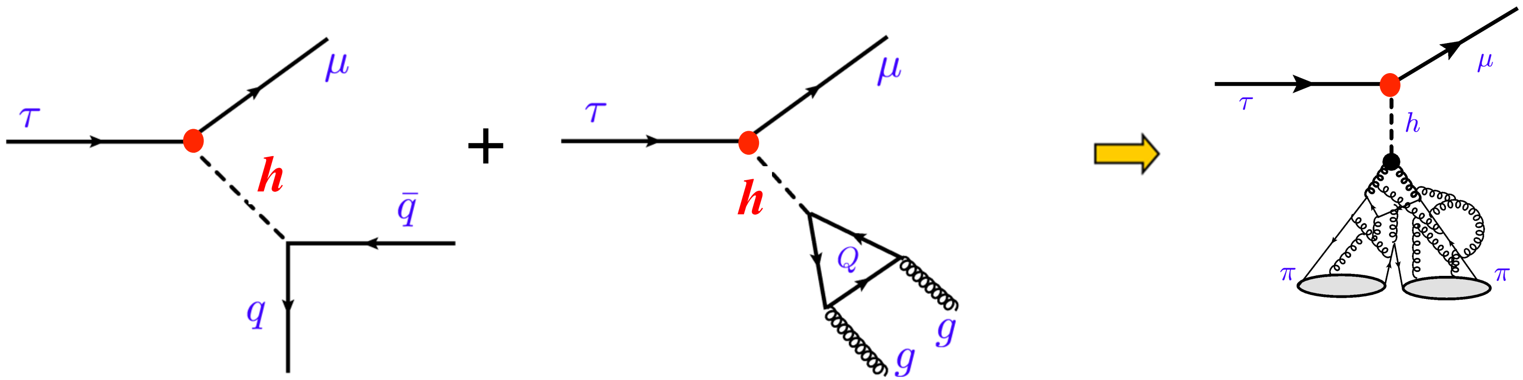


Hadronic part treated with non-perturbative QCD

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

- Tree level Higgs exchange



- 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*

  Daub, Dreiner, Hanhart, Kubis, Meissner'13

  Celis, Cirigliano, E.P.'14

- Dispersion relations: based on unitarity, analyticity and crossing symmetry

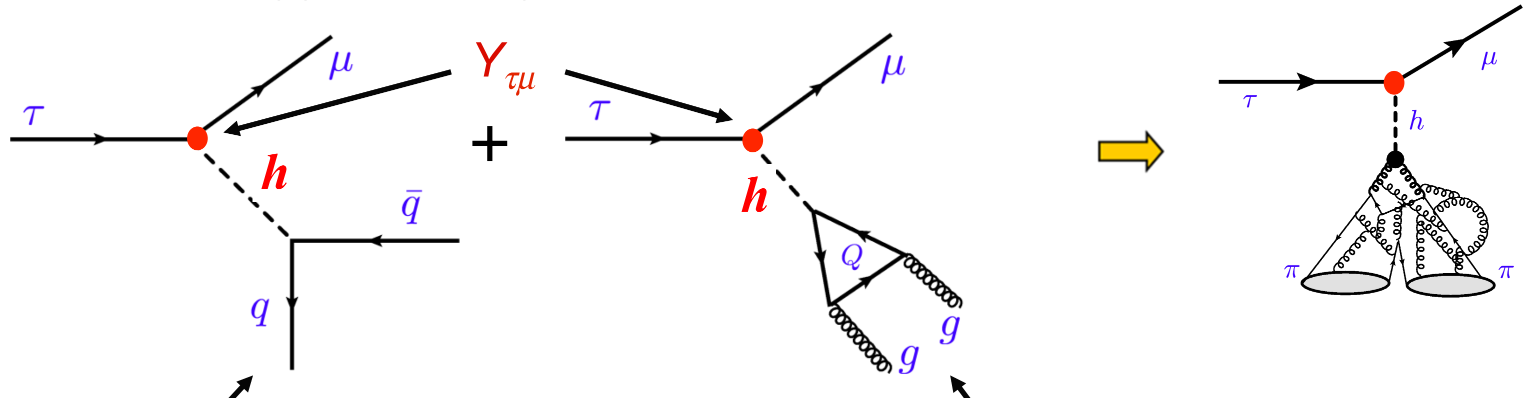
  ⇨ Take *all rescattering* effects into account

  ππ final state interactions important

3. Description of the hadronic form factors

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

- Tree level Higgs exchange



$$s = \left(p_{\pi^+} + p_{\pi^-}\right)^2$$

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

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

$$\boxed{\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q}q}$$

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

$$f\left(y^h_q\right)$$

3.2 How to describe the form factors?

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

$$\langle \pi^+\pi^- | m_s \bar{s}s | 0 \rangle \equiv \Delta_\pi(s)$$

$$\langle \pi^+\pi^- | \theta^\mu_\mu | 0 \rangle \equiv \theta_\pi(s)$$

$$\boxed{\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q}q}$$

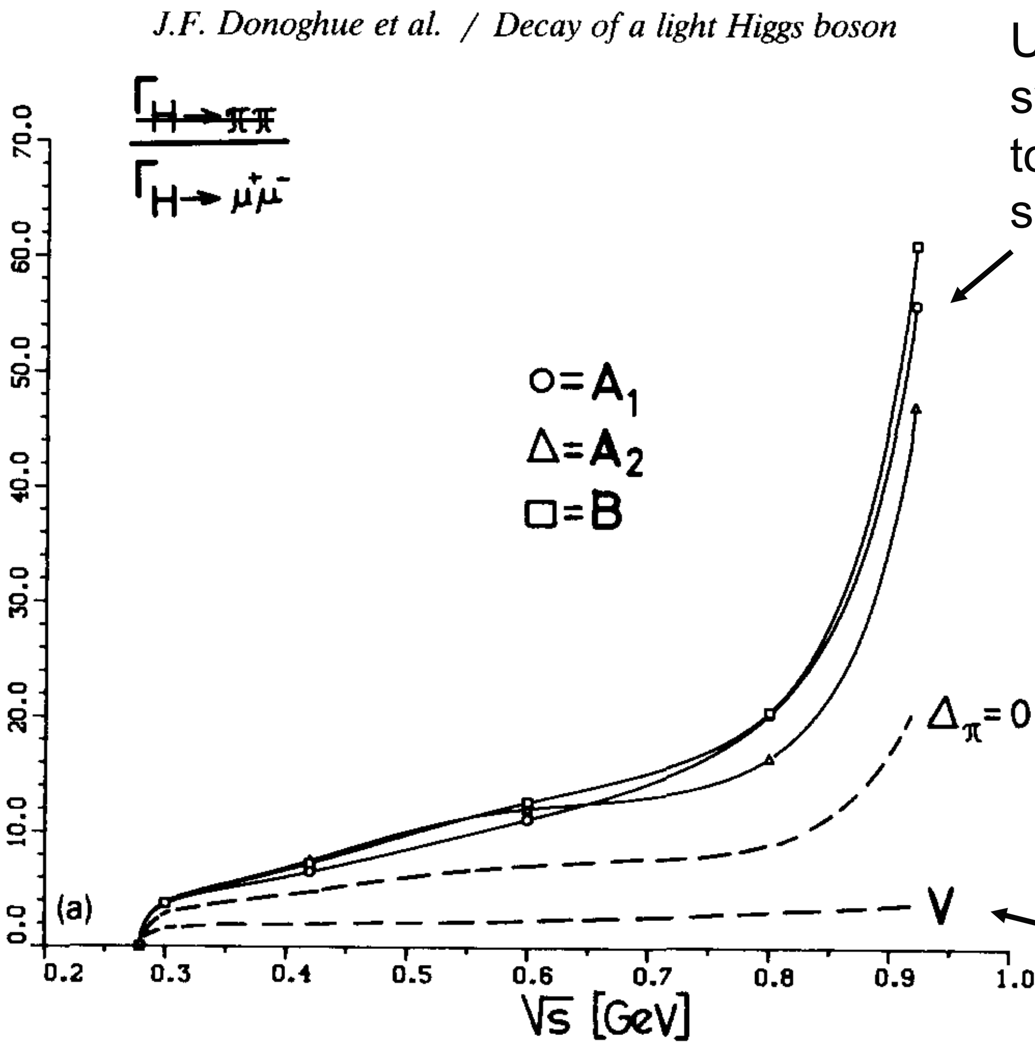
- Using LO ChPT:

$$\Gamma_\pi(s) = m_\pi^2 \qquad \theta_\pi(s) = s + 2m_\pi^2 + \mathcal{O}(p^4)$$

Voloshin'85

3.2 How to describe the form factors?

Donoghue, Gasser, Leutwyler'90



Using the triple constraints of chiral symmetry, analyticity, and unitarity, together with exp. input from pion scattering

very far from the naive expectation

$$\frac{\Gamma(h \to \mu^+\mu^-)}{\Gamma(h \to \pi^+\pi^-)} \sim \frac{m_\mu^2}{m_\pi^2}$$

Voloshin'85

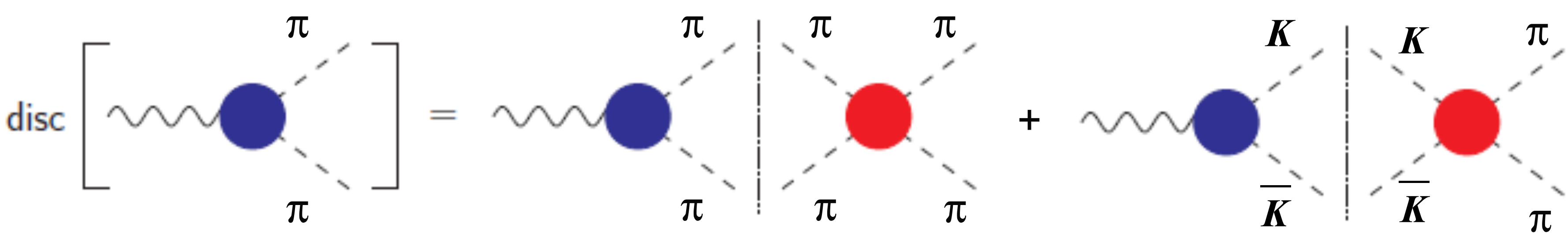
3.3 Unitarity

- Elastic approximation breaks down for the ππ S-wave at $K\bar{K}$ threshold due to the strong inelastic coupling involved in the region of *$f_0(980)$*

⇨ Need to *solve a Coupled Channel Mushkhelishvili-Omnès* problem

Donoghue, Gasser, Leutwyler'90
Osset & Oller'98
Moussallam'99

- Unitarity ⇨ the discontinuity of the form factor is known



⇨ $$\boxed{\mathrm{Im}F_n(s) = \sum_{m=1}^{2} T^*_{nm}(s)\sigma_m(s)F_m(s)}$$

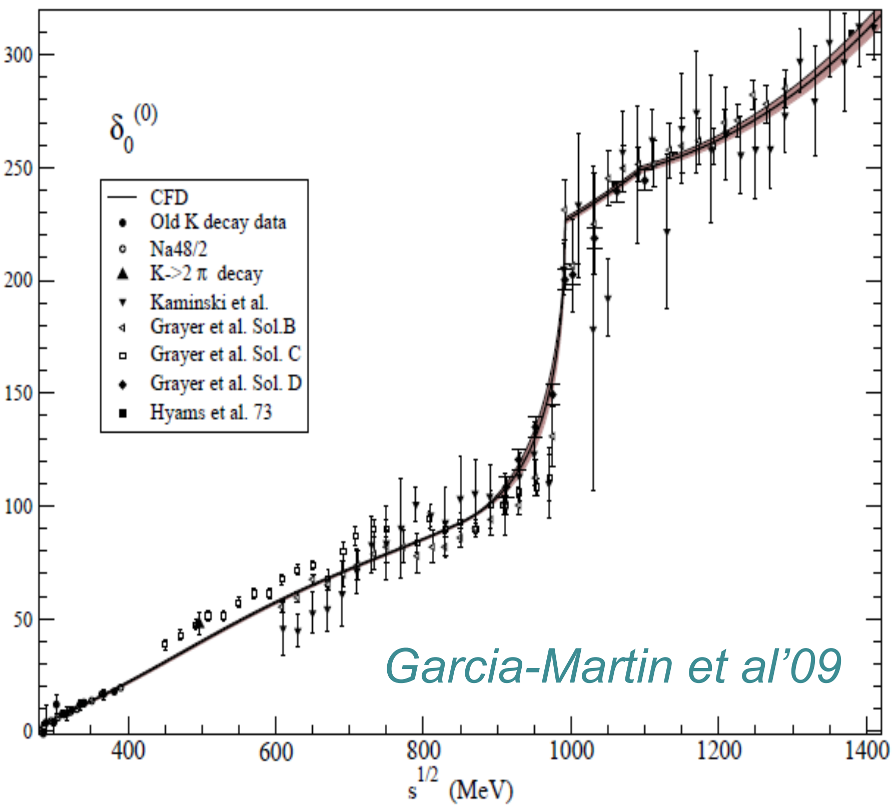
$n = \pi\pi, K\bar{K}$

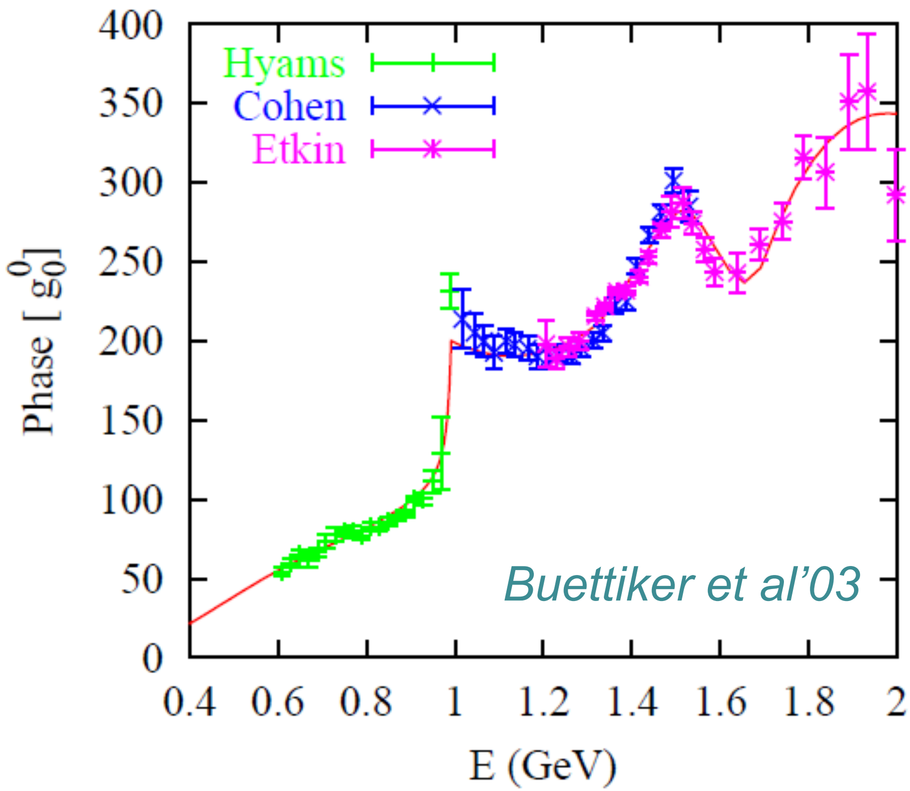
Scattering matrix:

$$\begin{pmatrix} \pi\pi \to \pi\pi, & \pi\pi \to K\bar{K} \\ K\bar{K} \to \pi\pi, & K\bar{K} \to K\bar{K} \end{pmatrix}$$

3.4 Inputs for the coupled channel analysis

- Inputs : $\pi\pi \to \pi\pi, K\bar{K}$





- A large number of theoretical analyses *Descotes-Genon et al'01, Kaminsky et al'01, Buettiker et al'03, 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*

3.5 Dispersion relations

- General solution to *Mushkhelishvili-Omnès* problem:

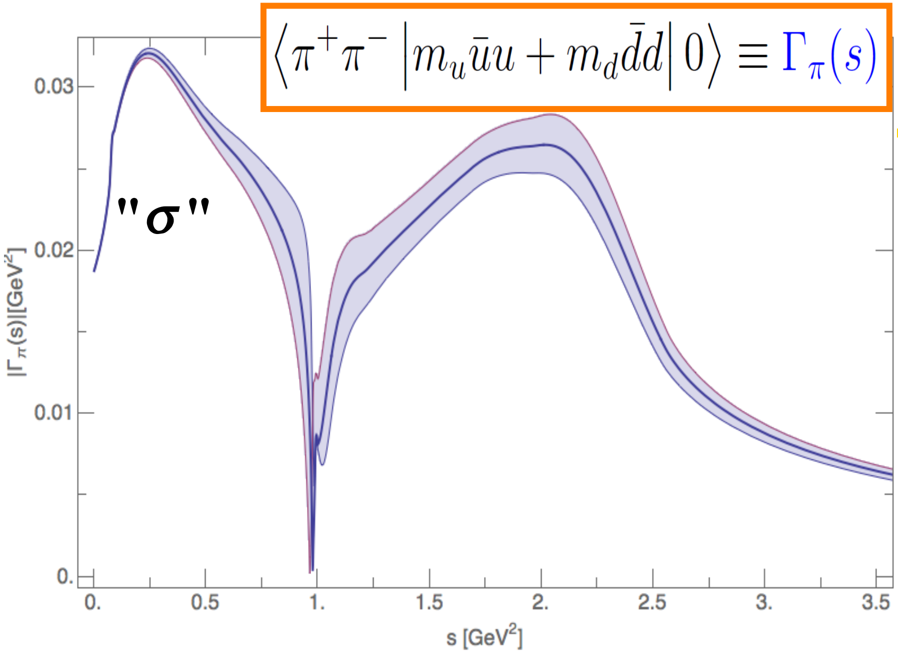
$$\boxed{\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}}$$

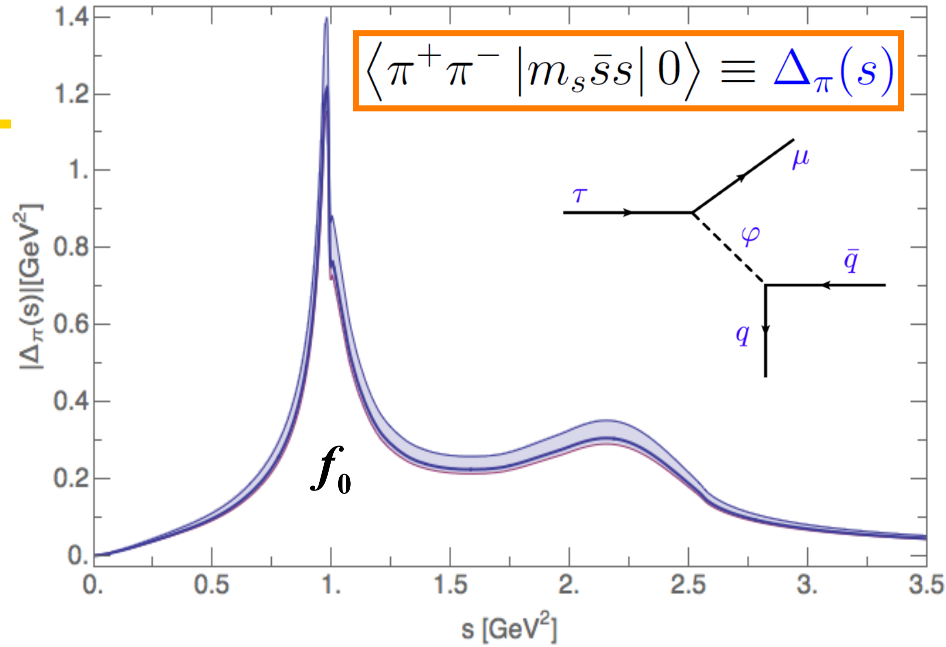
Canonical solution falling as 1/s for large s (obey unsubtracted dispersion relations)

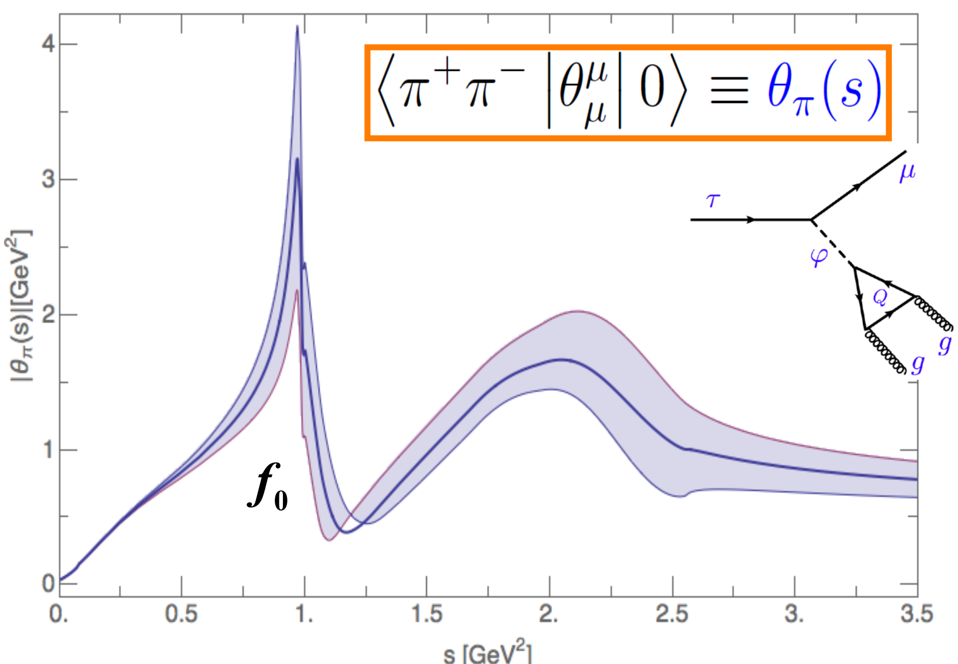
Polynomial determined from a matching to ChPT + lattice

- Canonical solution found by solving dispersive integral equations iteratively starting with *Omnès functions* that are solutions of the one-channel unitary condition

$$\boxed{\Omega_{\pi,K}(s) \equiv \exp\left[\frac{s}{\pi}\int_{4M_\pi^2}^{\infty}\frac{dt}{t}\frac{\delta_{\pi,K}(t)}{(t-s)}\right]}$$

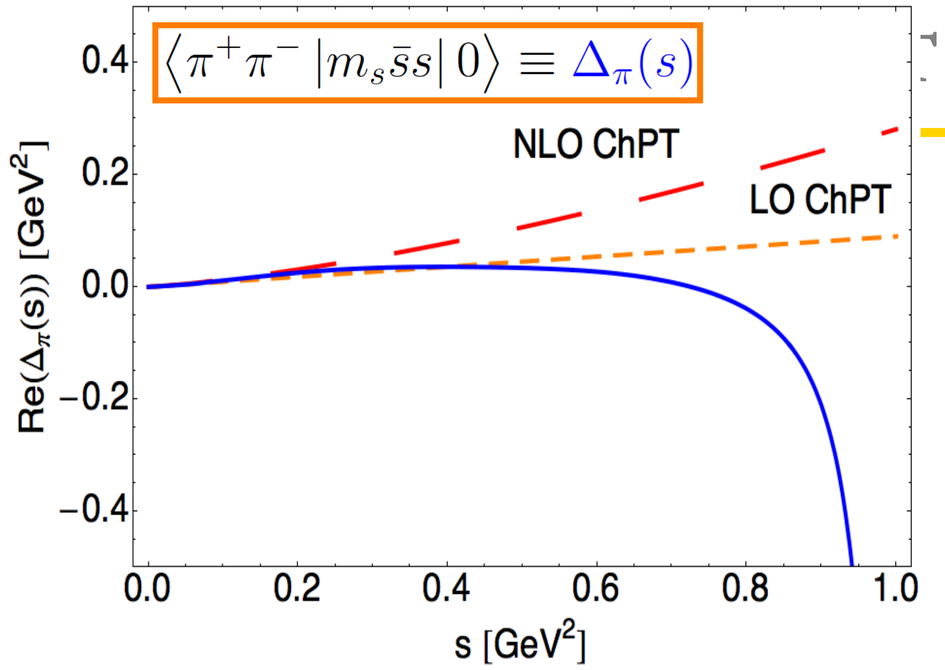


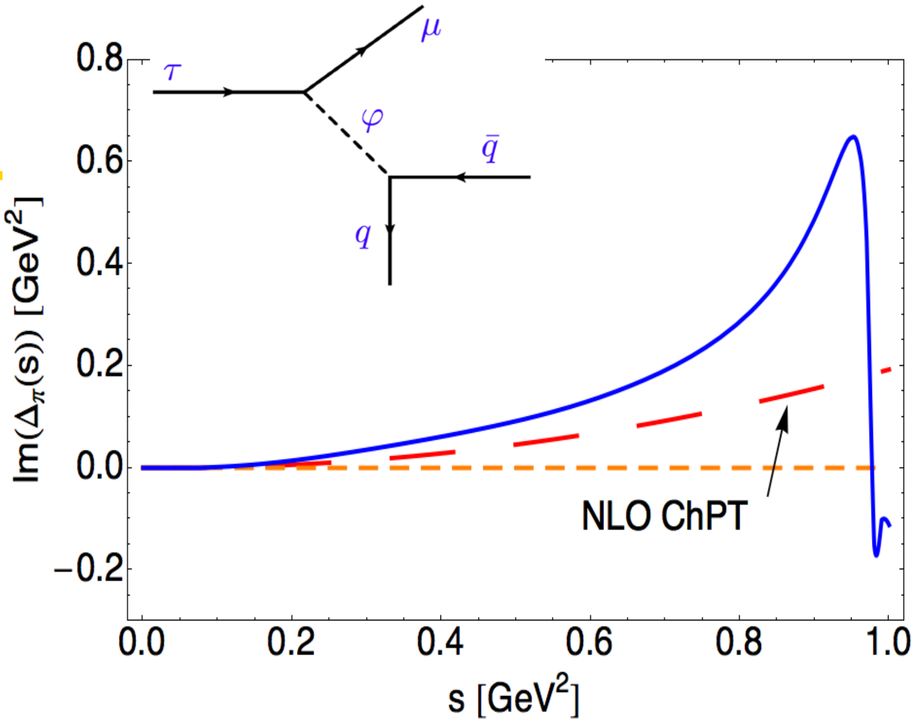


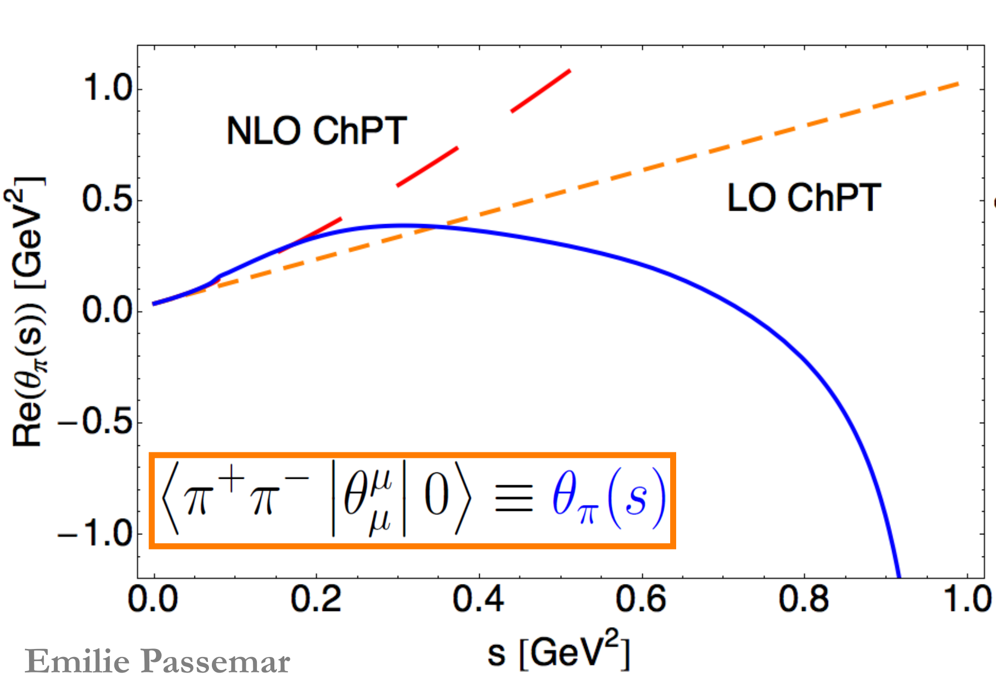


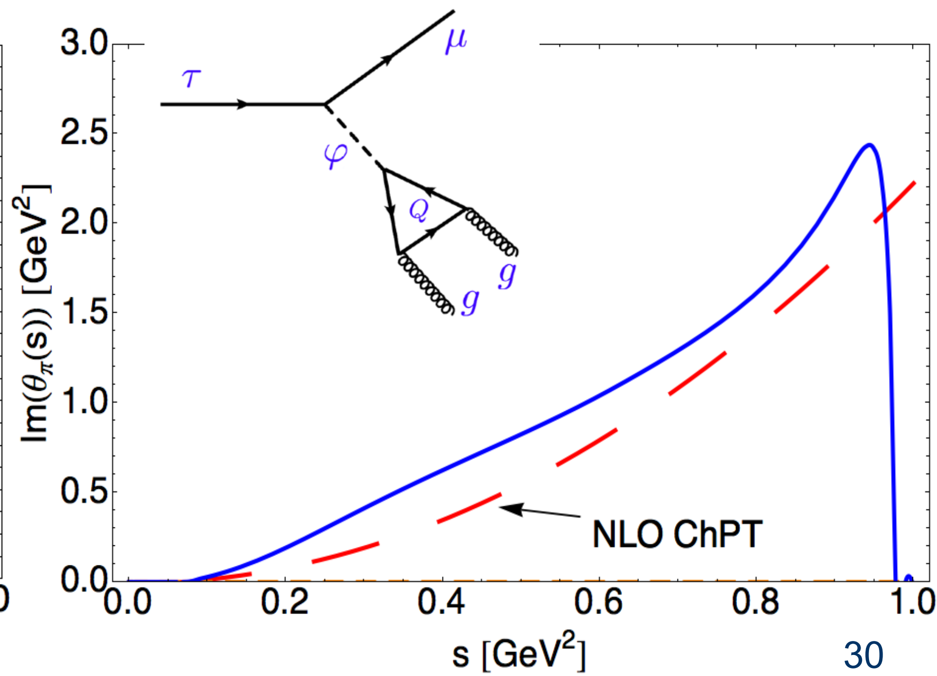
- Uncertainties:
  - Varying s_{cut} (1.4 GeV^2 - 1.8 GeV^2)
  - Varying the matching conditions
  - T matrix inputs

See also *Daub et al.'13*


$\langle \pi^+\pi^- | m_s \bar{s}s | 0 \rangle \equiv \Delta_\pi(s)$
NLO ChPT
LO ChPT
Re(Δ_π(s)) [GeV^2]
s [GeV^2]


τ
μ
φ
$\bar{q}$
q
NLO ChPT
Im(Δ_π(s)) [GeV^2]
s [GeV^2]

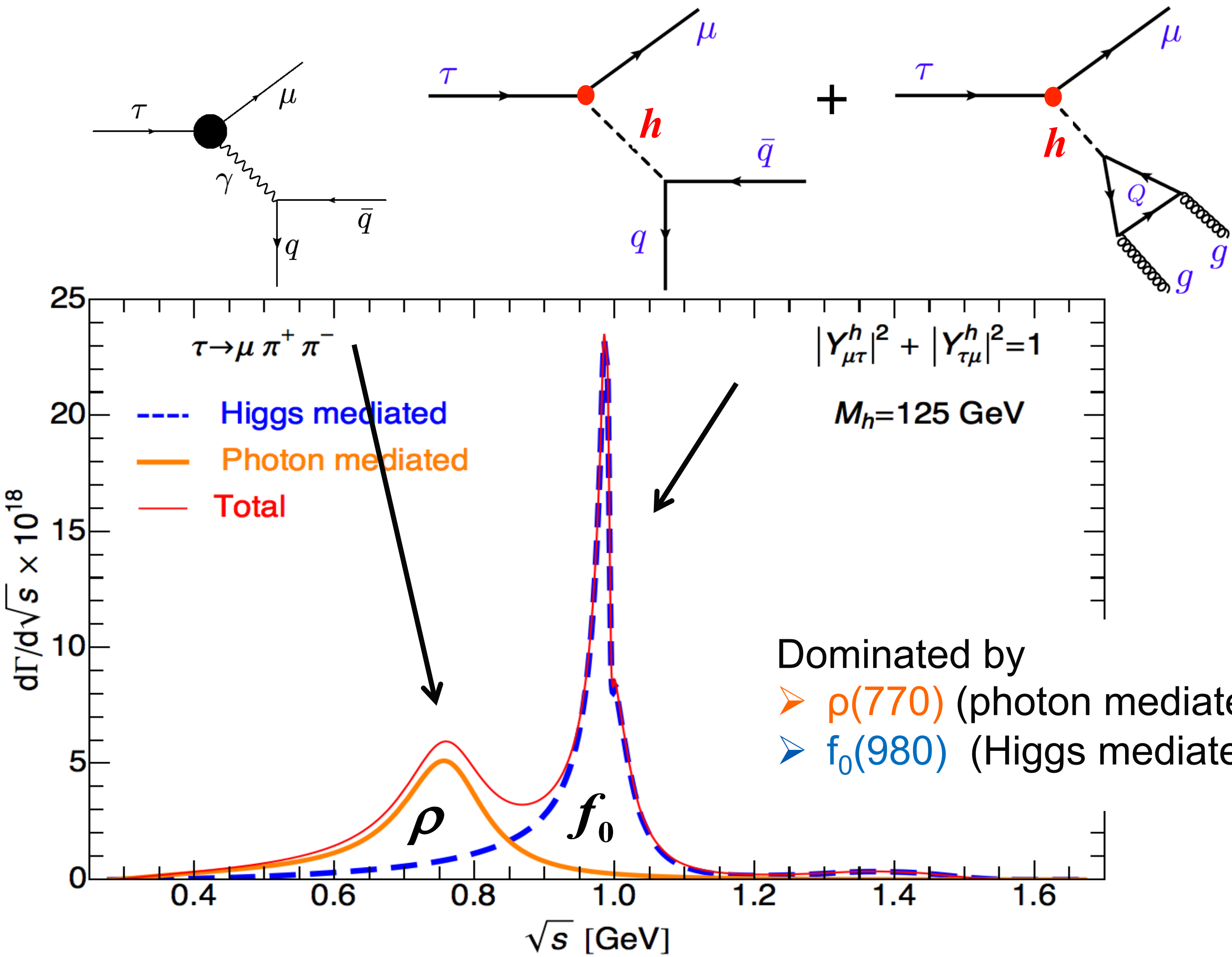

NLO ChPT
LO ChPT
$\langle \pi^+\pi^- | \theta^\mu_\mu | 0 \rangle \equiv \theta_\pi(s)$
Re(θ_π(s)) [GeV^2]
s [GeV^2]


τ
μ
φ
Q
g
g
NLO ChPT
Im(θ_π(s)) [GeV^2]
s [GeV^2]

4. Results

4.1 Spectrum

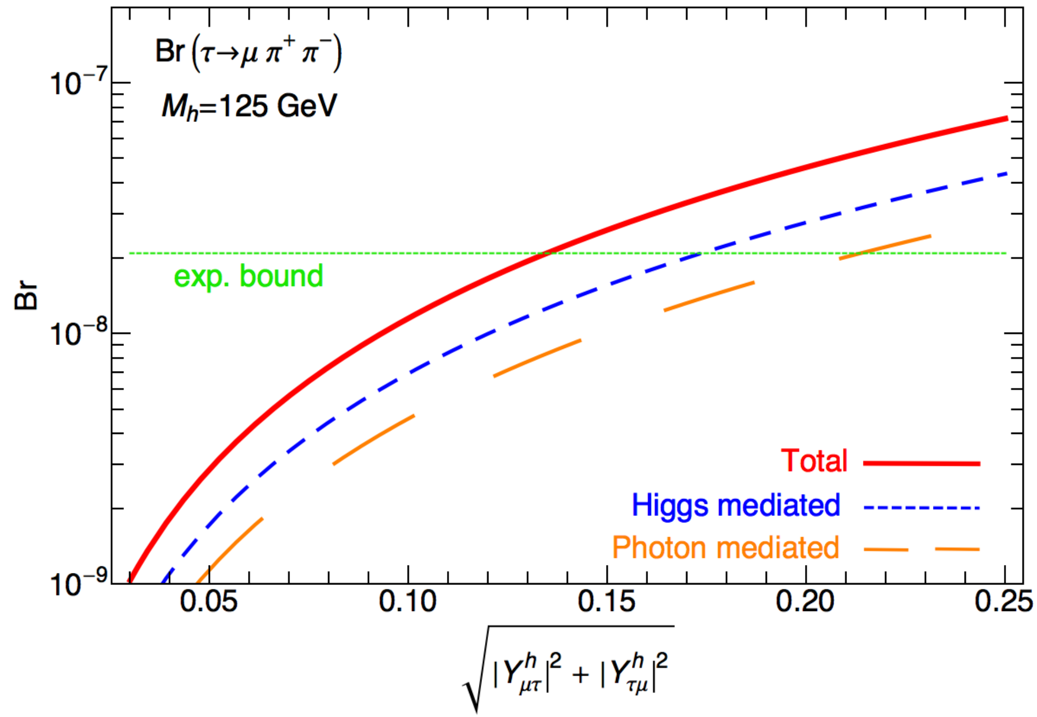
Celis, Cirigliano, E.P.'14



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

4.2 Bounds

Celis, Cirigliano, E.P.'14



Bound:

$$\boxed{\sqrt{\left|Y^h_{\mu\tau}\right|^2 + \left|Y^h_{\tau\mu}\right|^2} \leq 0.13}$$

Process	$(\mathrm{BR} \times 10^8)$ 90% CL	$\sqrt{\lvert Y^h_{\mu\tau}\rvert^2 + \lvert Y^h_{\tau\mu}\rvert^2}$	Operator(s)
$\tau \to \mu\gamma$	< 4.4 [88]	< 0.016	Dipole
$\tau \to \mu\mu\mu$	< 2.1 [89]	< 0.24	Dipole
$\tau \to \mu\pi^+\pi^-$	< 2.1 [86]	< 0.13	Scalar, Gluon, Dipole
$\tau \to \mu\rho$	< 1.2 [85]	< 0.13	Scalar, Gluon, Dipole
$\tau \to \mu\pi^0\pi^0$	$< 1.4 \times 10^3$ [87]	< 6.3	Scalar, Gluon

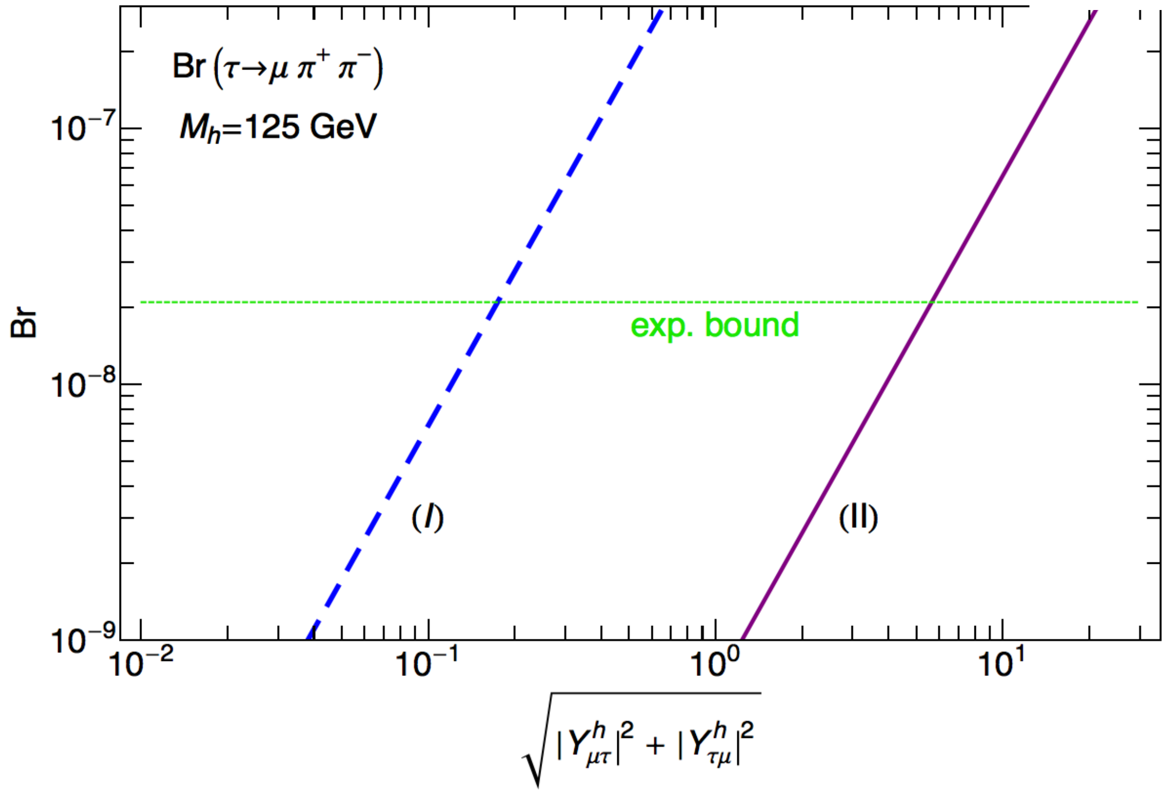
Less stringent but more robust handle on LFV Higgs couplings

?

BaBar'10, Belle'10'11'13 except last from *CLEO'97*

4.3 Impact of our results

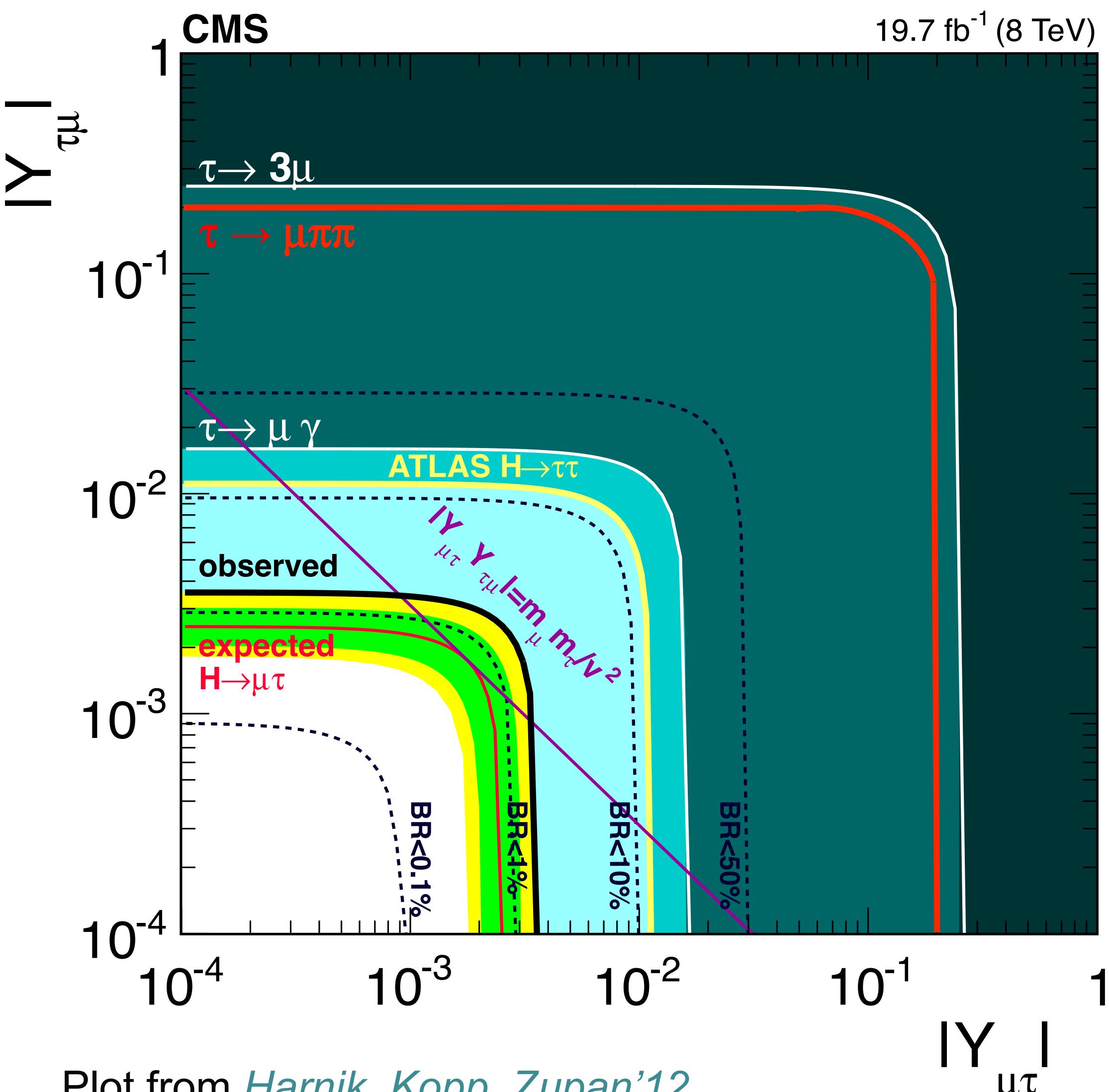
Celis, Cirigliano, E.P.'14



- Dispersive treatment of hadronic part ⇒ bound reduced by one order of magnitude!
- ChPT, EFT only valid at low energy for $\boxed{\mathbf{p \ll \Lambda = 4\pi f_\pi \sim 1\ GeV}}$

  ⇒ *not valid up to* $E = (m_\tau - m_\mu)$!

4.4 Constraints in the τμ sector



Plot from *Harnik, Kopp, Zupan'12*
updated *by CMS'15*

- Constraints from LE:
  - $\tau \to \mu\gamma$: best constraints but loop level
    ➡ sensitive to UV completion of the theory
  - $\tau \to \mu\pi\pi$: tree level diagrams
    ➡ robust handle on LFV
- Constraints from HE:
  LHC wins for τμ!
- Opposite situation for μe!
- For LFV Higgs and nothing else: LHC bound

➡ $BR(\tau \to \mu\gamma) < 2.2 \times 10^{-9}$

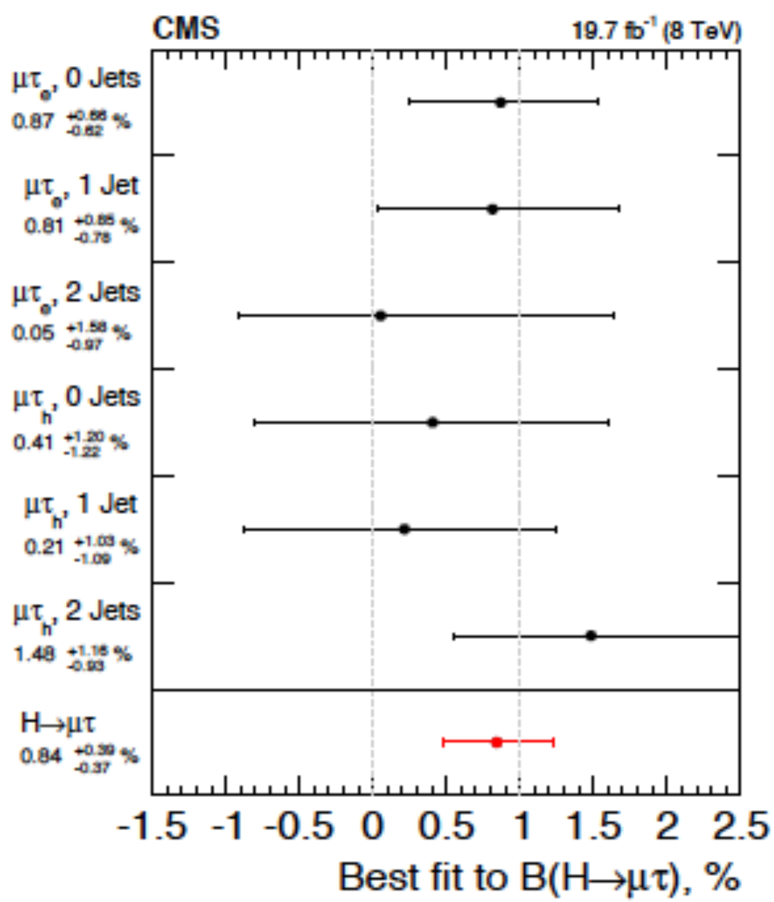
$BR(\tau \to \mu\pi\pi) < 1.5 \times 10^{-11}$

4.5 Hint of New Physics in h → τμ?

$BR\left(h \to \tau\mu\right) = \left(0.84^{+0.39}_{-0.37}\right)\%$

@2.4σ

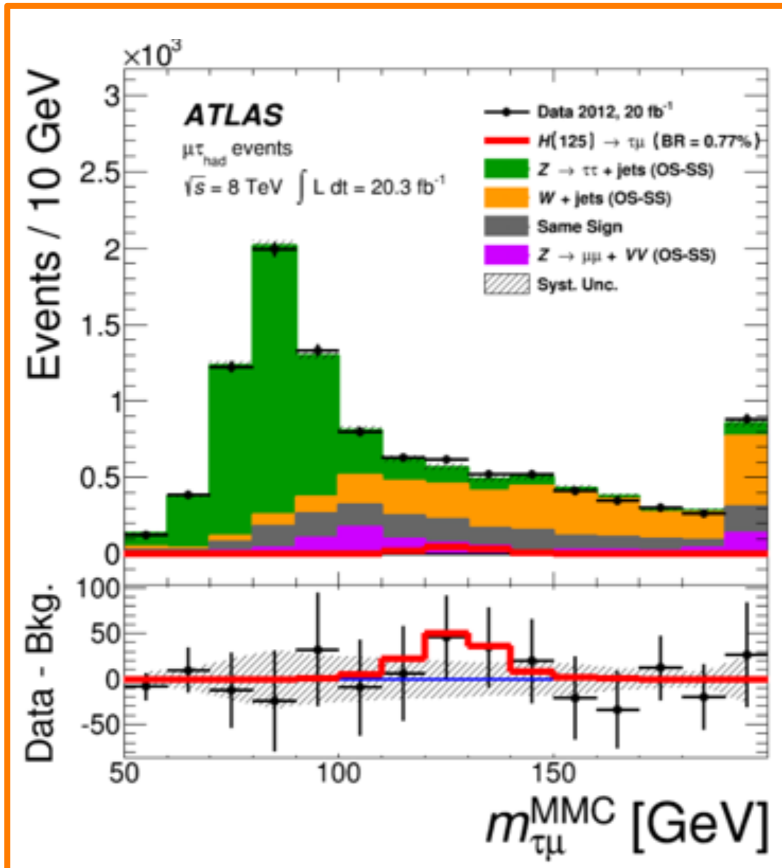
CMS’15



$BR\left(h \to \tau\mu\right) = \left(0.53 \pm 0.51\right)\%$

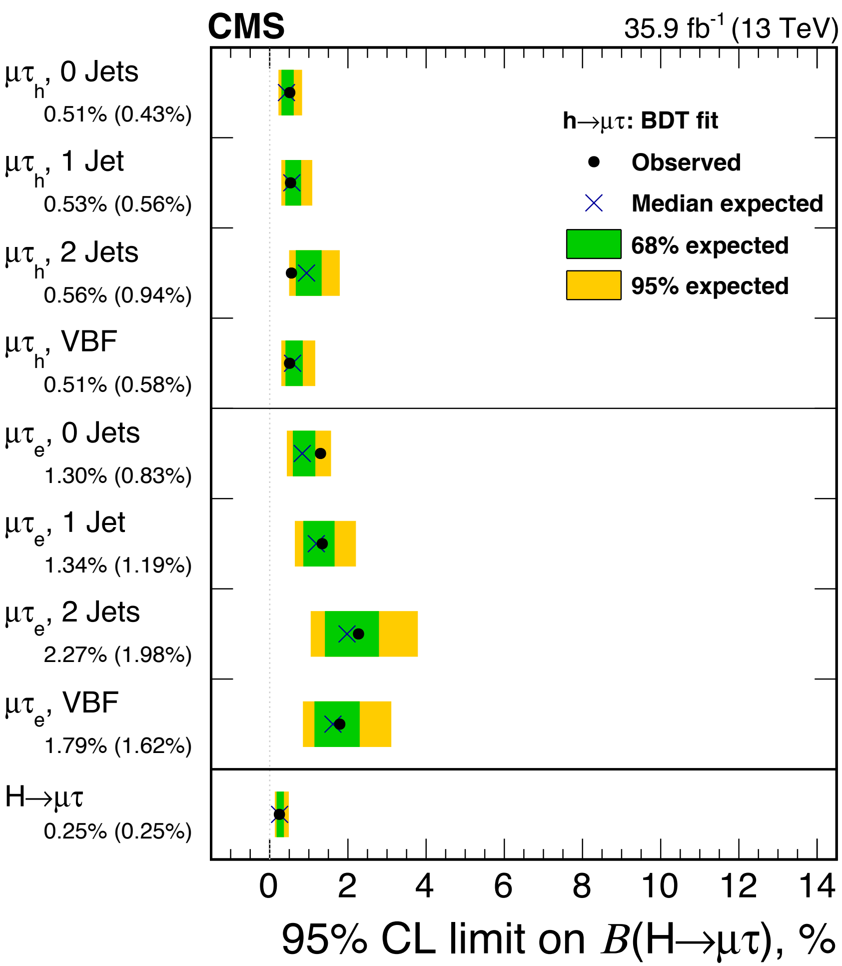
@1σ

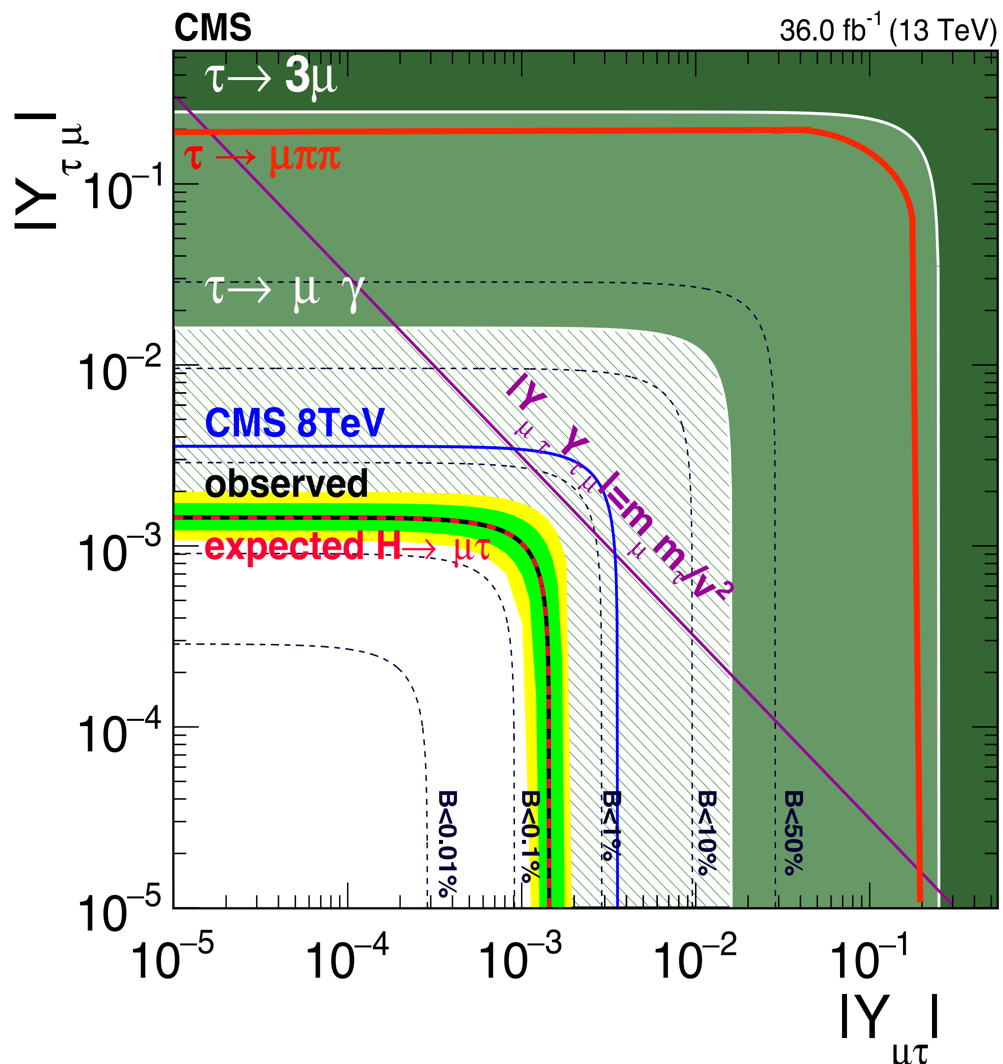
ATLAS’15



4.5 Hint of New Physics in $h \to \tau\mu$?

CMS'17

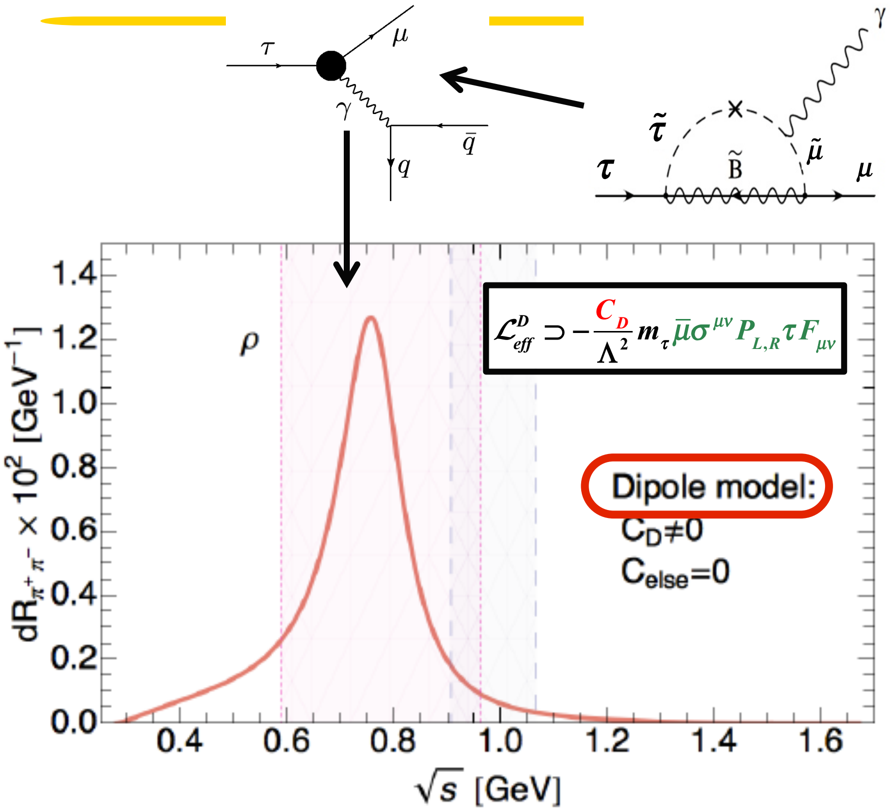




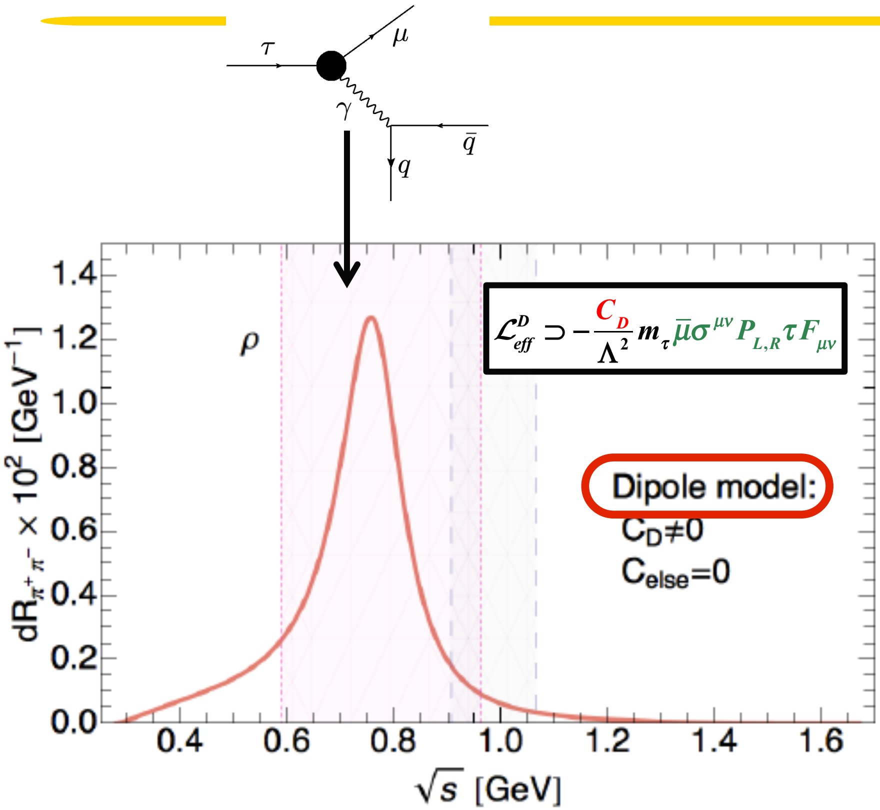
$$BR(h\to\tau\mu) = (0.25 \pm 0.25)\%$$ 13 TeV@CMS CMS'17

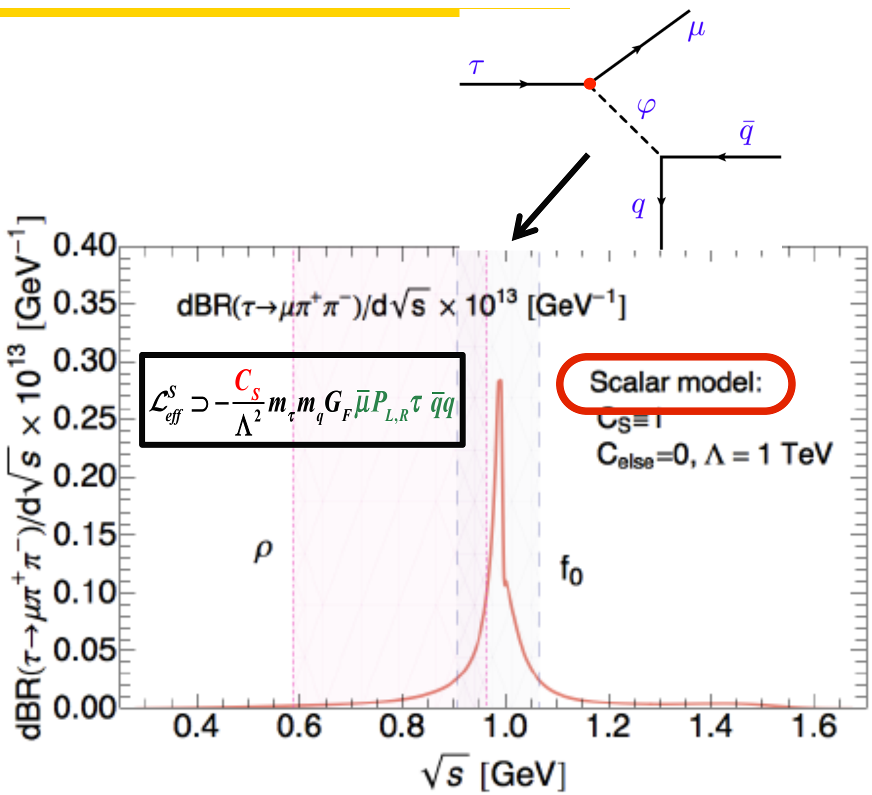
4.6 Discriminating power of $\tau \to \mu(e)\pi\pi$ decays

Celis, Cirigliano, E.P.'14

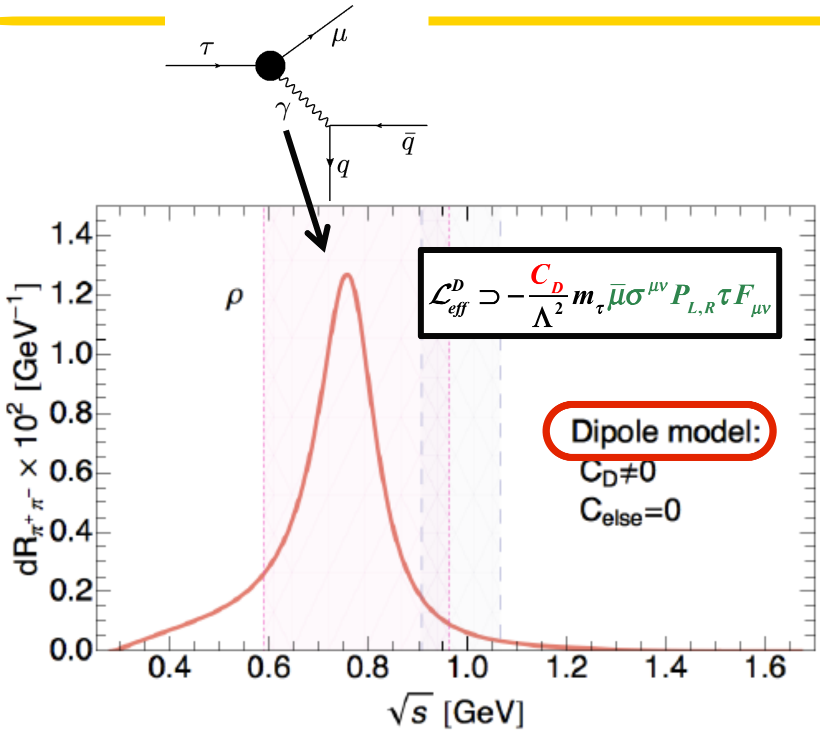


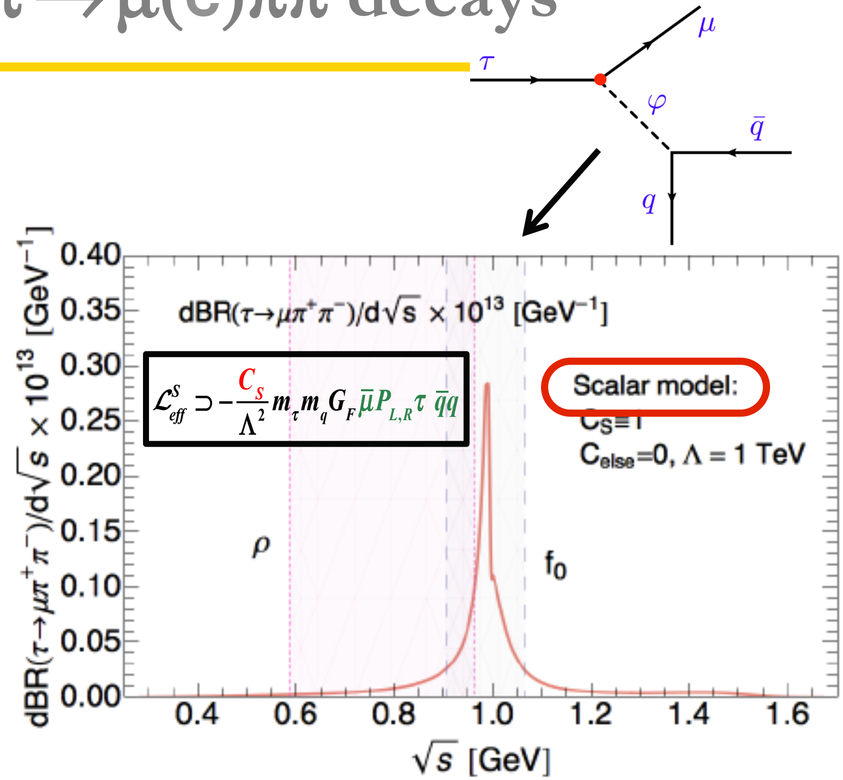
4.6 Discriminating power of τ→μ(e)ππ decays

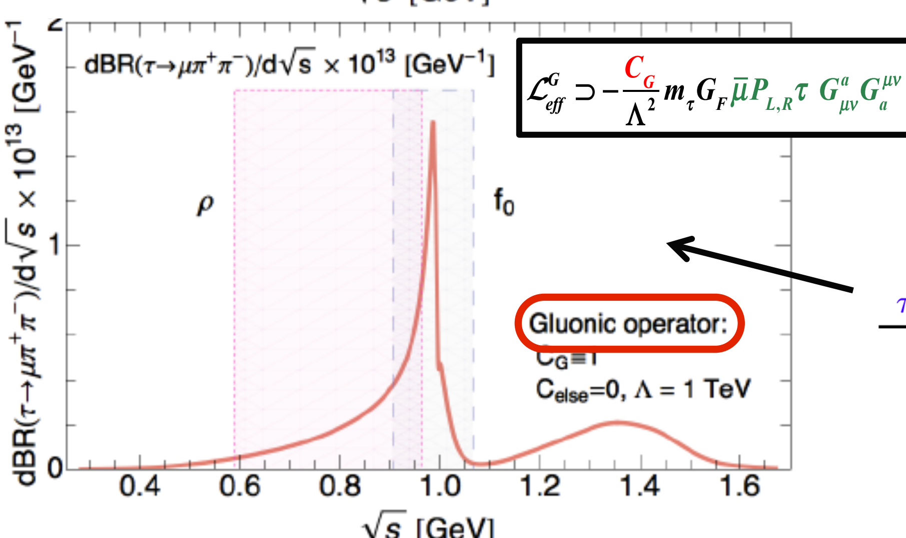




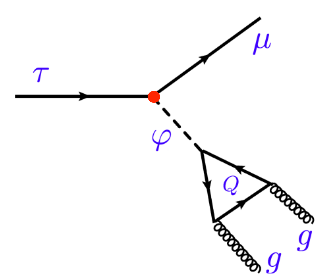
4.6 Discriminating power of τ→μ(e)ππ decays







Different distributions according to the *operator!*



5. Conclusion and Outlook

Summary

- LFV can probe new physics scales much higher than those directly observable at the LHC

- It is possible to observe signals of new physics via *LFV transitions* in the near future, despite the lack of new physics observed so far at the LHC

- Different operators expected at low scales, we need to measure as many processes as possible

  ⇨ *Hadronic decays* such as $\tau \to \mu(e)\pi\pi$ important!

- Use a combination of dispersive methods and ChPT/Lattice QCD in order to determine the relevant hadronic matrix elements in a robust way

- Possible extension $\tau \to \mu(e)K^+K^-$

Summary

- LFV can probe new physics scales much higher than those directly observable at the LHC

- It is possible to observe signals of new physics via *LFV transitions* in the near future, despite the lack of new physics observed so far at the LHC

- Different operators expected at low scales, we need to measure as many processes as possible

  ⇨ *Hadronic decays* such as $\tau \to \mu(e)\pi\pi$ important!

- Possible extension $\tau \to \mu(e)K^+K^-$

- Interplay low energy and collider physics: LFV of the Higgs boson

- Complementarity with LFC sector: EDMs, g-2 and colliders:

  ⇨ New physics models usually strongly correlate these sectors

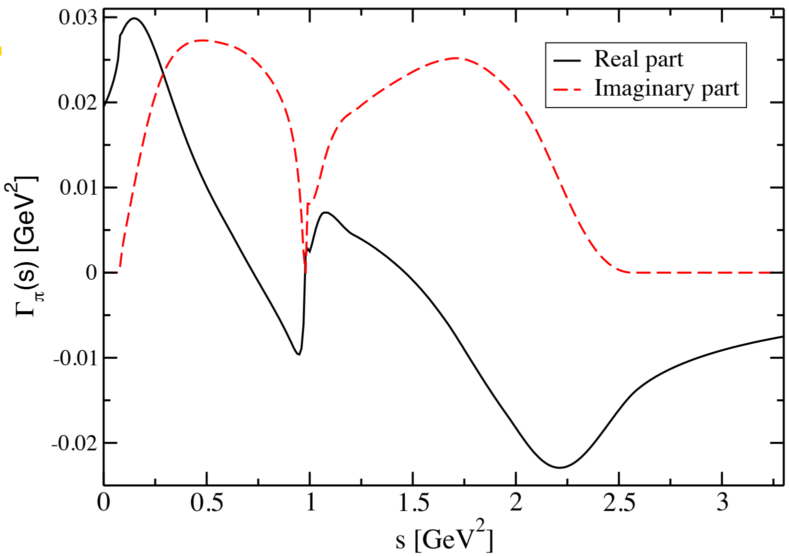
6. Back-up

T matrix parametrization

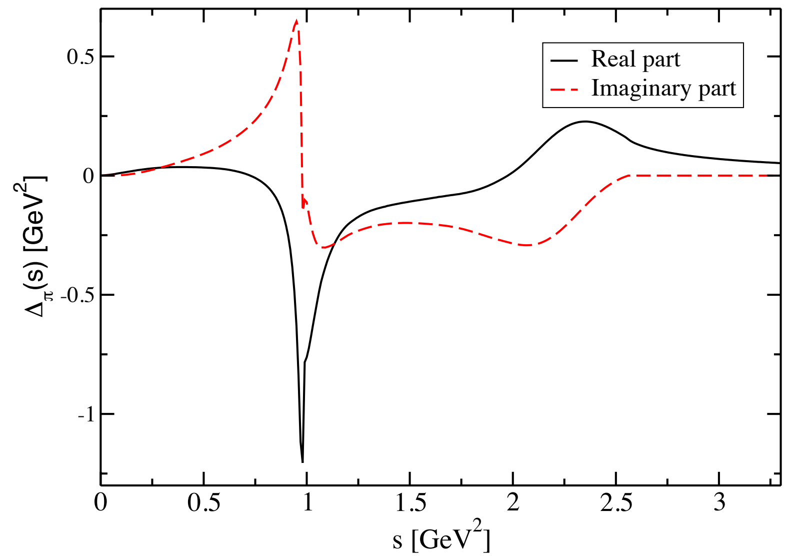
$$S_{mn} = \delta_{mn} + 2i\,\sqrt{\sigma_m \sigma_n}\,T_{mn}$$

$$S = \begin{pmatrix} \cos\gamma\; e^{2i\delta_\pi} & i\,\sin\gamma\; e^{i(\delta_\pi+\delta_K)} \\ i\,\sin\gamma\; e^{i(\delta_\pi+\delta_K)} & \cos\gamma\; e^{2i\delta_K} \end{pmatrix}$$

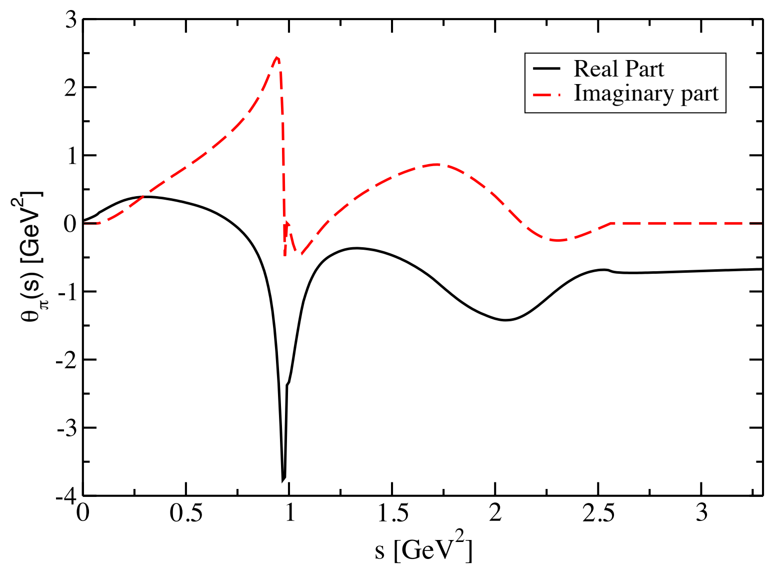
- Inelasticity: $\eta_0^0 \equiv \cos\,\gamma$.
- $\delta_\pi(s)$: ππ S wave phase shift
- $\delta_K(s)$: KK S wave phase shift



Real part
Imaginary part
$\Gamma_\pi(s)$ [GeV^2]
s [GeV^2]



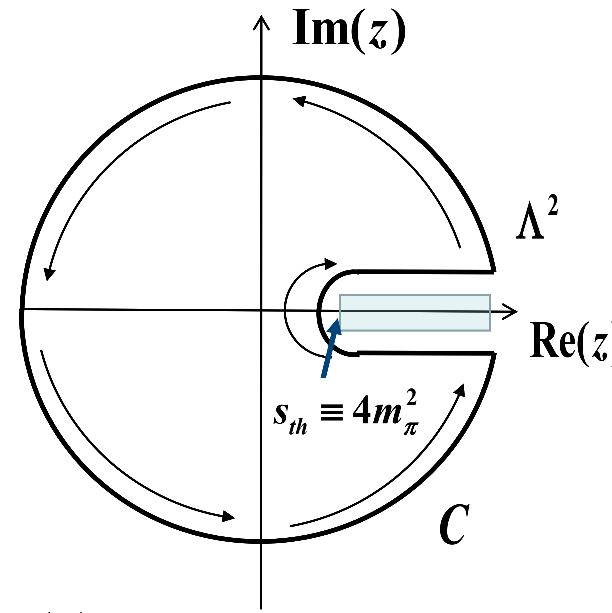
Real part
Imaginary part
$\Delta_\pi(s)$ [GeV^2]
s [GeV^2]



Real Part
Imaginary part
$\theta_\pi(s)$ [GeV^2]
s [GeV^2]

Canonical solution $X(s) = C(s), D(s)$:

- Knowing the discontinuity of X(s) ⇨ write a dispersion relation for it
- Analyticity of the FFs: X(z) is
  - real for $z < s_{th}$
  - has a branch cut for $z > s_{th}$
  - analytic for complex z
- Cauchy Theorem and Schwarz reflection principle:



$$X(s) = \frac{1}{\pi} \oint_C dz \frac{X(z)}{z-s}$$

$$= \frac{1}{2i\pi} \int_{s_{th}=4M_\pi^2}^{\Lambda^2} dz \frac{disc\left[F(z)\right]}{z-s-i\varepsilon} + \frac{1}{2i\pi} \int_{|z|=\Lambda^2} dz \frac{F(z)}{z-s}$$

$\Lambda \to \infty$

⇨ $$\boxed{X(s) = \frac{1}{\pi} \int_{4M_\pi^2}^{\infty} dz \frac{\text{Im}\left[X(z)\right]}{z-s-i\varepsilon}}$$

X(s) can be reconstructed everywhere from the knowledge of ImX(s)

3.4 Dispersion relations

- General solution to *Mushkhelishvili-Omnès* problem:

$$\boxed{\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}}$$

Canonical solution falling as 1/s for large s (obey unsubtracted dispersion relations)

Polynomial determined from a matching to ChPT + lattice

- Canonical solution found by solving the dispersive integral equations iteratively starting with Omnès functions

$$X(s) = C(s), D(s)$$

$$\boxed{\mathrm{Im} X_n^{(N+1)}(s) = \sum_{m=1}^{2} T^*_{mn} \sigma_m(s) X_m^{(N)}(s)} \longrightarrow \boxed{X_n^{(N+1)}(s) = \frac{1}{\pi} \int_{4m_\pi^2}^{\infty} ds' \frac{\mathrm{Im} X_n^{(N+1)}(s')}{s' - s}}$$

Determination of the polynomial

- Fix the polynomial with requiring $\boxed{F_P(s) \to 1/s}$ + ChPT:

  Brodsky & Lepage'80

- Feynman-Hellmann theorem:

$$\boxed{\Gamma_P(0) = \left(m_u \frac{\partial}{\partial m_u} + m_d \frac{\partial}{\partial m_d} \right) M_P^2}$$

$$\boxed{\Delta_P(0) = \left(m_s \frac{\partial}{\partial m_s} \right) M_P^2}$$

- At LO in ChPT:

$$M^2_{\pi^+} = (m_\mathrm{u} + m_\mathrm{d})\, B_0 + O(m^2)$$
$$M^2_{K^+} = (m_\mathrm{u} + m_\mathrm{s})\, B_0 + O(m^2)$$
$$M^2_{K^0} = (m_\mathrm{d} + m_\mathrm{s})\, B_0 + O(m^2)$$

Determination of the polynomial

- Fix the polynomial with requiring $\boxed{F_P(s) \to 1/s}$ + ChPT:

  Brodsky & Lepage'80

- Feynman-Hellmann theorem:

$$\boxed{\Gamma_P(0) = \left(m_u \frac{\partial}{\partial m_u} + m_d \frac{\partial}{\partial m_d} \right) M_P^2}$$

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- At LO in ChPT:

$$M^2_{\pi^+} = (m_u + m_d)\, B_0 + O(m^2)$$
$$M^2_{K^+} = (m_u + m_s)\, B_0 + O(m^2)$$
$$M^2_{K^0} = (m_d + m_s)\, B_0 + O(m^2)$$

$\Rightarrow$

$$\boxed{\begin{aligned} P_\Gamma(s) &= \Gamma_\pi(0) = M_\pi^2 + \cdots \\ Q_\Gamma(s) &= \frac{2}{\sqrt{3}} \Gamma_K(0) = \frac{1}{\sqrt{3}} M_\pi^2 + \cdots \\ P_\Delta(s) &= \Delta_\pi(0) = 0 + \cdots \\ Q_\Delta(s) &= \frac{2}{\sqrt{3}} \Delta_K(0) = \frac{2}{\sqrt{3}} \left(M_K^2 - \frac{1}{2} M_\pi^2 \right) + \cdots \end{aligned}}$$

Determination of the polynomial

- At LO in ChPT:

$$M^2_{\pi^+} = (m_u + m_d)\, B_0 + O(m^2)$$
$$M^2_{K^+} = (m_u + m_s)\, B_0 + O(m^2)$$
$$M^2_{K^0} = (m_d + m_s)\, B_0 + O(m^2)$$

- For the scalar FFs:

$$\boxed{\begin{aligned} P_\Gamma(s) &= \Gamma_\pi(0) = M_\pi^2 + \cdots \\ Q_\Gamma(s) &= \frac{2}{\sqrt{3}}\Gamma_K(0) = \frac{1}{\sqrt{3}}M_\pi^2 + \cdots \\ P_\Delta(s) &= \Delta_\pi(0) = 0 + \cdots \\ Q_\Delta(s) &= \frac{2}{\sqrt{3}}\Delta_K(0) = \frac{2}{\sqrt{3}}\left(M_K^2 - \frac{1}{2}M_\pi^2\right) + \cdots \end{aligned}}$$

- Problem: large corrections in the case of the kaons!
  ⇨ Use lattice QCD to determine the SU(3) LECs

$$\Gamma_K(0) = (0.5 \pm 0.1)\ M_\pi^2$$

$$\Delta_K(0) = 1^{+0.15}_{-0.05}\,(M_K^2 - 1/2 M_\pi^2)$$

Daub, Dreiner, Hanart, Kubis, Meissner'13
Bernard, Descotes-Genon, Toucas'12

Determination of the polynomial

- For θ_P enforcing the asymptotic constraint is not consistent with ChPT
  The unsubtracted DR is not saturated by the 2 states

  ⇨ Relax the constraints and match to ChPT

$$\boxed{\begin{aligned} P_\theta(s) &= 2M_\pi^2 + \left(\dot{\theta}_\pi - 2M_\pi^2\dot{C}_1 - \frac{4M_K^2}{\sqrt{3}}\dot{D}_1\right) s \\ Q_\theta(s) &= \frac{4}{\sqrt{3}}M_K^2 + \frac{2}{\sqrt{3}}\left(\dot{\theta}_K - \sqrt{3}M_\pi^2\dot{C}_2 - 2M_K^2\dot{D}_2\right) s \end{aligned}}$$

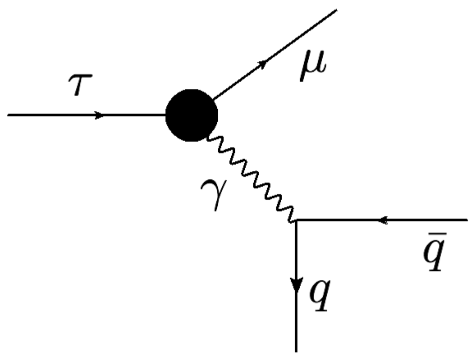
with $\dot{f} = \left(\frac{df}{ds}\right)_{s=0}$

- At LO ChPT: $\dot{\theta}_{\pi,K} = 1$

- Higher orders ⇨ $\boxed{\dot{\theta}_K = 1.15 \pm 0.1}$

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

- Contribution from dipole diagrams



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

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

Determination of $F_V(s)$

- Vector form factor
  - Precisely known from experimental measurements

    $e^+e^- \to \pi^+\pi^-$ and $\tau^- \to \pi^0\pi^-\nu_\tau$ (isospin rotation)

  - Theoretically: Dispersive parametrization for $F_V(s)$

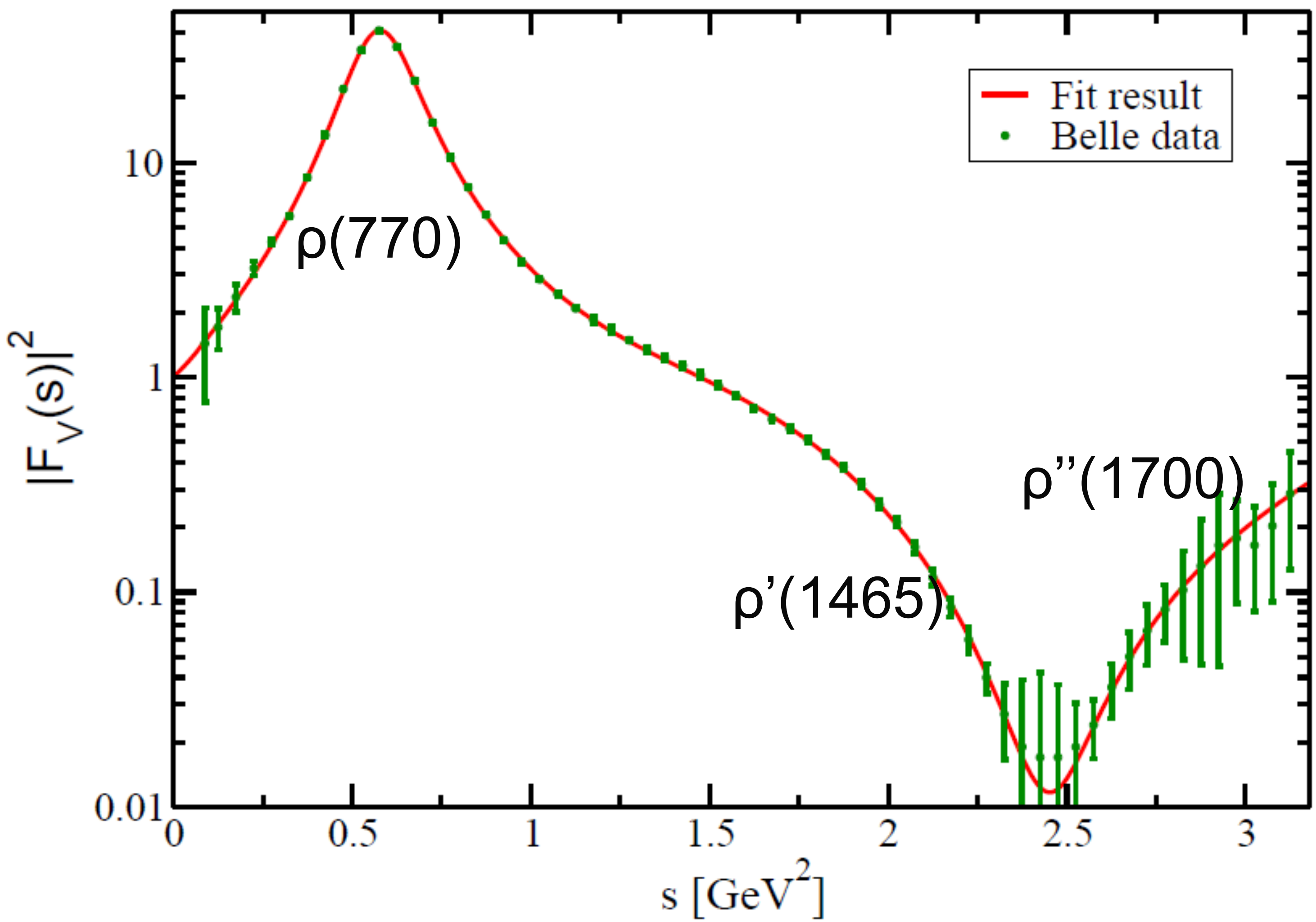
Guerrero, Pich'98, Pich, Portolés'08
Gomez, Roig'13

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

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

  - Subtraction polynomial + phase determined from a *fit* to the *Belle data* $\tau^- \to \pi^0\pi^-\nu_\tau$

Determination of $F_V(s)$

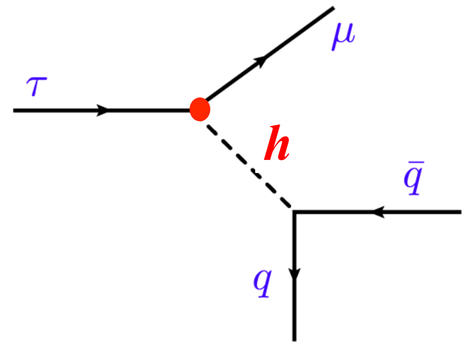


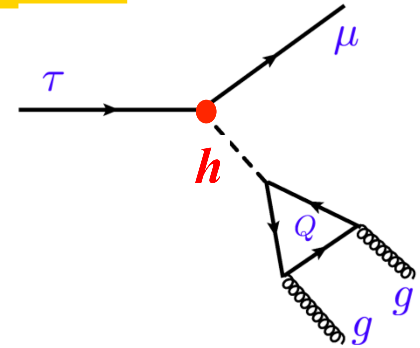
Determination of $F_V(s)$ thanks to precise measurements from Belle!

4.6 What if $\tau \to \mu(e)\pi\pi$ is observed?

Talk by J. Zupan @ KEK-FF2014FALL

- $\tau \to \mu(e)\pi\pi$ sensitive to $Y_{\mu\tau}$

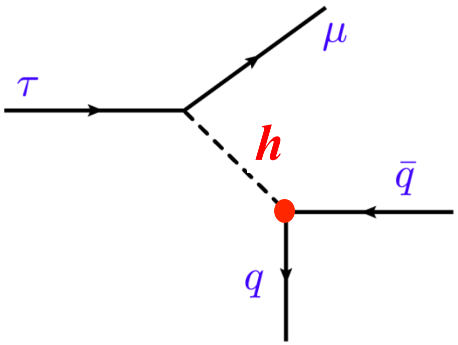


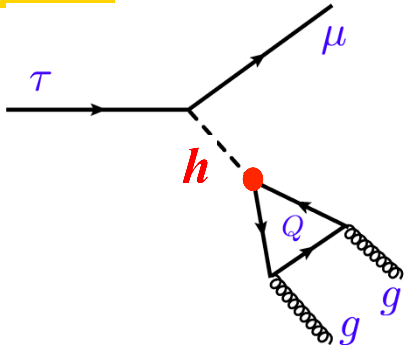


4.6 What if $\tau \rightarrow \mu(e)\pi\pi$ is observed?

Talk by J. Zupan @ KEK-FF2014FALL

- $\tau \rightarrow \mu(e)\pi\pi$ sensitive to $Y_{\mu\tau}$ but also to $Y_{u,d,s}$!





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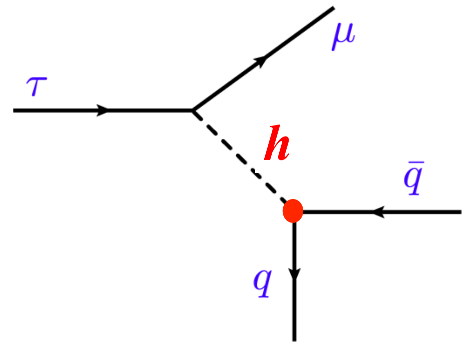
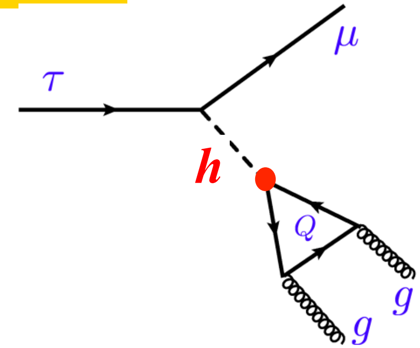




- $Y_{u,d,s}$ poorly bounded

- For $Y_{u,d,s}$ at their SM values :

$$Br(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}, Br(\tau \to \mu\pi^0\pi^0) < 4.6 \times 10^{-12}$$
$$Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-10}, Br(\tau \to e\pi^0\pi^0) < 6.9 \times 10^{-11}$$

- But for $Y_{u,d,s}$ at their upper bound:

$$\boxed{\begin{array}{l} Br(\tau \to \mu\pi^+\pi^-) < 3.0 \times 10^{-8}, Br(\tau \to \mu\pi^0\pi^0) < 1.5 \times 10^{-8} \\ Br(\tau \to e\pi^+\pi^-) < 4.3 \times 10^{-7}, Br(\tau \to e\pi^0\pi^0) < 2.1 \times 10^{-7} \end{array}}$$

below present experimental limits!

- If discovered ⇨ *upper limit* on $Y_{u,d,s}$!

⇨ Interplay between high-energy and low-energy constraints!

3.3 Handles

- Two handles:
  - Branching ratios: $\boxed{R_{F,M} \equiv \frac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}}$ with F_M dominant LFV mode for model M

  - Spectra for > 2 bodies in the final state:

$$\boxed{\frac{dBR(\tau \to \mu\pi^+\pi^-)}{d\sqrt{s}}} \quad \text{and} \quad \boxed{dR_{\pi^+\pi^-} \equiv \frac{1}{\Gamma(\tau \to \mu\gamma)} \frac{d\Gamma(\tau \to \mu\pi^+\pi^-)}{d\sqrt{s}}}$$

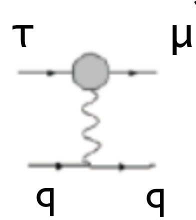
- Benchmarks:
  - Dipole model: $C_D \neq 0$, $C_{else} = 0$
  - Scalar model: $C_S \neq 0$, $C_{else} = 0$
  - Vector (gamma, Z) model: $C_V \neq 0$, $C_{else} = 0$
  - Gluonic model: $C_{GG} \neq 0$, $C_{else} = 0$

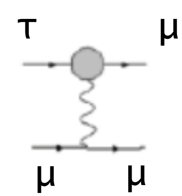
3.3 Branching ratios

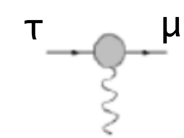
- Two handles:
  - Branching ratios: $\boxed{R_{F,M} \equiv \dfrac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}}$ with F_M dominant LFV mode for model M

		$\mu\pi^+\pi^-$	$\mu\rho$	μf_0	3μ	$\mu\gamma$
D	$R_{F,D}$	0.26×10^{-2}	0.22×10^{-2}	0.13×10^{-3}	0.22×10^{-2}	1
	BR	$< 1.1 \times 10^{-10}$	$< 9.7 \times 10^{-11}$	$< 5.7 \times 10^{-12}$	$< 9.7 \times 10^{-11}$	$< 4.4 \times 10^{-8}$

Benchmark







- ρ (770) resonance ($J^{PC}=1^{--}$): cut in the $\pi^+\pi^-$ invariant mass:

  $$587 \text{ MeV} \leq \sqrt{s} \leq 962 \text{ MeV}$$

- f_0 (980) resonance ($J^{PC}=0^{++}$): cut in the $\pi^+\pi^-$ invariant mass:

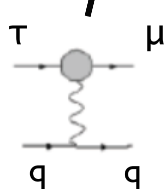
  $$906 \text{ MeV} \leq \sqrt{s} \leq 1065 \text{ MeV}$$

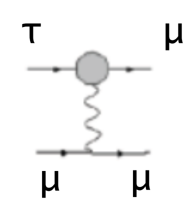
3.3 Branching ratios

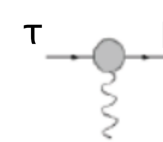
- Two handles:
  - Branching ratios: $\boxed{R_{F,M} \equiv \dfrac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}}$ with F_M dominant LFV mode for model M

		$\mu\pi^+\pi^-$	$\mu\rho$	μf_0	3μ	$\mu\gamma$
D	$R_{F,D}$	0.26×10^{-2}	0.22×10^{-2}	0.13×10^{-3}	0.22×10^{-2}	1
	BR	$< 1.1 \times 10^{-10}$	$< 9.7 \times 10^{-11}$	$< 5.7 \times 10^{-12}$	$< 9.7 \times 10^{-11}$	$< 4.4 \times 10^{-8}$
S	$R_{F,S}$	1	0.28	0.7	-	-
	BR	$< 2.1 \times 10^{-8}$	$< 5.9 \times 10^{-9}$	$< 1.47 \times 10^{-8}$	-	-
$V^{(\gamma)}$	$R_{F,V^{(\gamma)}}$	1	0.86	0.1	-	-
	BR	$< 1.4 \times 10^{-8}$	$< 1.2 \times 10^{-8}$	$< 1.4 \times 10^{-9}$	-	-
Z	$R_{F,Z}$	1	0.86	0.1	-	-
	BR	$< 1.4 \times 10^{-8}$	$< 1.2 \times 10^{-8}$	$< 1.4 \times 10^{-9}$	-	-
G	$R_{F,G}$	1	0.41	0.41	-	-
	BR	$< 2.1 \times 10^{-8}$	$< 8.6 \times 10^{-9}$	$< 8.6 \times 10^{-9}$	-	-

Benchmark







4.1 Constraints from $\tau \to 1P$

- Tree level Higgs exchange
  - η, η'

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

with the decay constants :

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

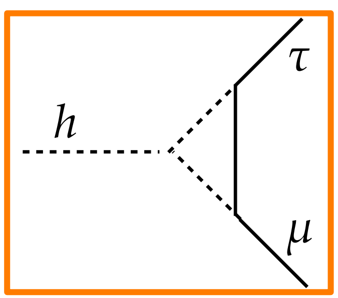
$$\langle \eta^{(\prime)}(p) | \frac{\alpha_s}{4\pi}\, G_a^{\mu\nu} \widetilde{G}^a_{\mu\nu} | 0 \rangle \;=\; a_{\eta^{(\prime)}}$$

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

4.5 Interplay between LHC & Low Energy

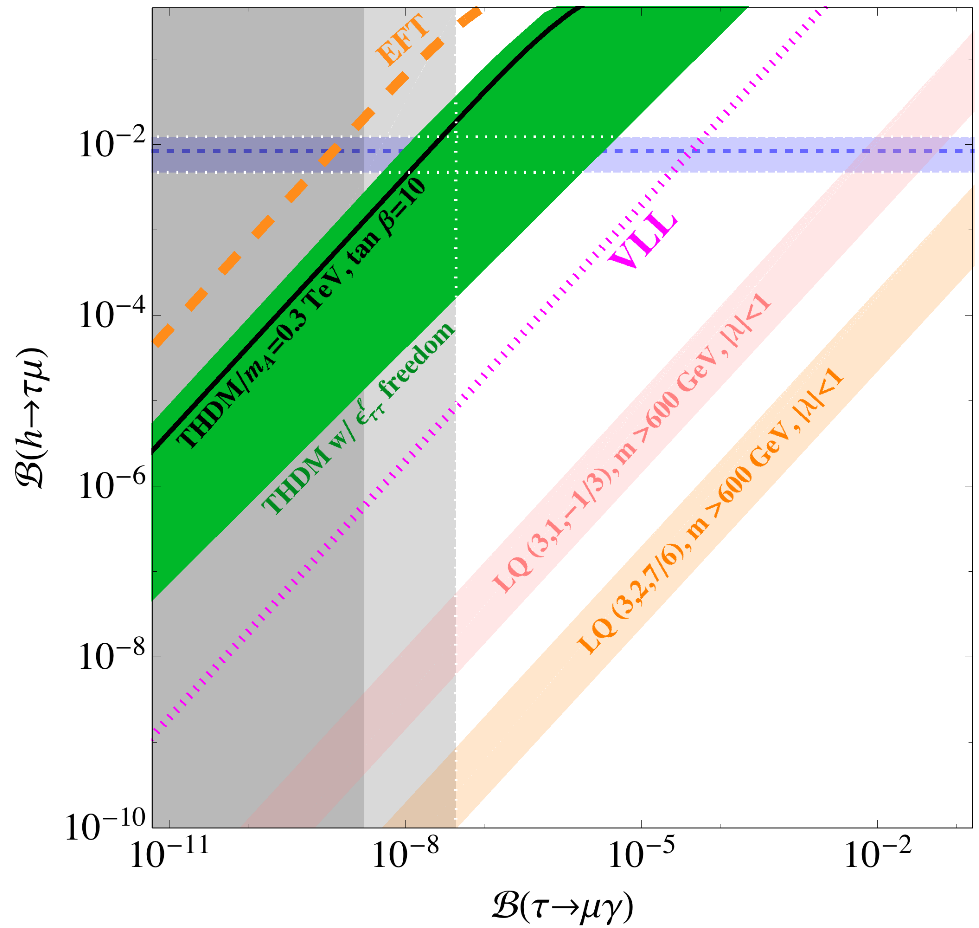
- If real what type of NP?

- If h → τ μ due to loop corrections:
  - extra charged particles necessary
  - τ → μγ too large



- h → τ μ possible to explain if extra scalar doublet:
  ⇨ *2HDM of type III*

Dorsner et al.'15



- Constraints from $\tau \to \mu\gamma$ important! ⇨ *Belle II*

4.5 Interplay between LHC & Low Energy

- *2HDMs* with gauged $L_\mu - L_\tau$
  ⇨ Z', explain anomalies for
  - $h \to \tau\mu$
  - $B \to K^*\mu\mu$
  - $R_K = B \to K\mu\mu / B \to Kee$

- Constraints from $\tau \to 3\mu$ *crucial* ⇨ *Belle II, LHCb*

- See also:
  Aristizabal-Sierra & Vicente'14,
  Lima et al'15,
  Omhura, Senaha, Tobe '15

Altmannshofer & Straub'14, Crivellin et al'15
Crivellin, D'Ambrosio, Heeck.'15