INDIANA UNIVERSITY
BLOOMINGTON

Jefferson Lab

Lepton Flavour Violation: Theory Overview

Emilie Passemar

Indiana University/Jefferson Laboratory

Flavour Physics and CP Violation 2015
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Outline

1. Introduction and Motivation

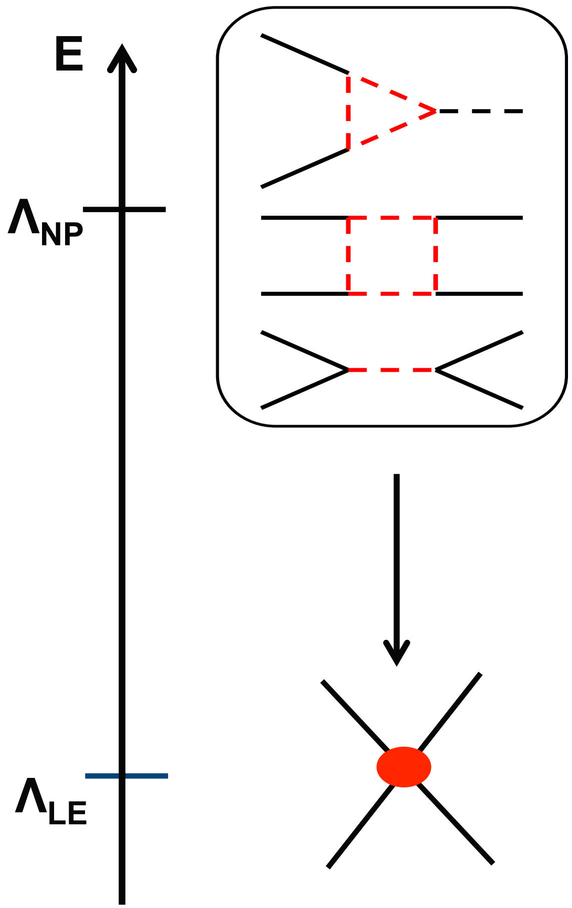
2. Low energy probes: The reach and model discriminating power of
   - muon decays
   - tau decays

3. High energy probes: Higgs LFV

4. Conclusion and Outlook

1. Introduction and Motivation

Why study charged leptons?

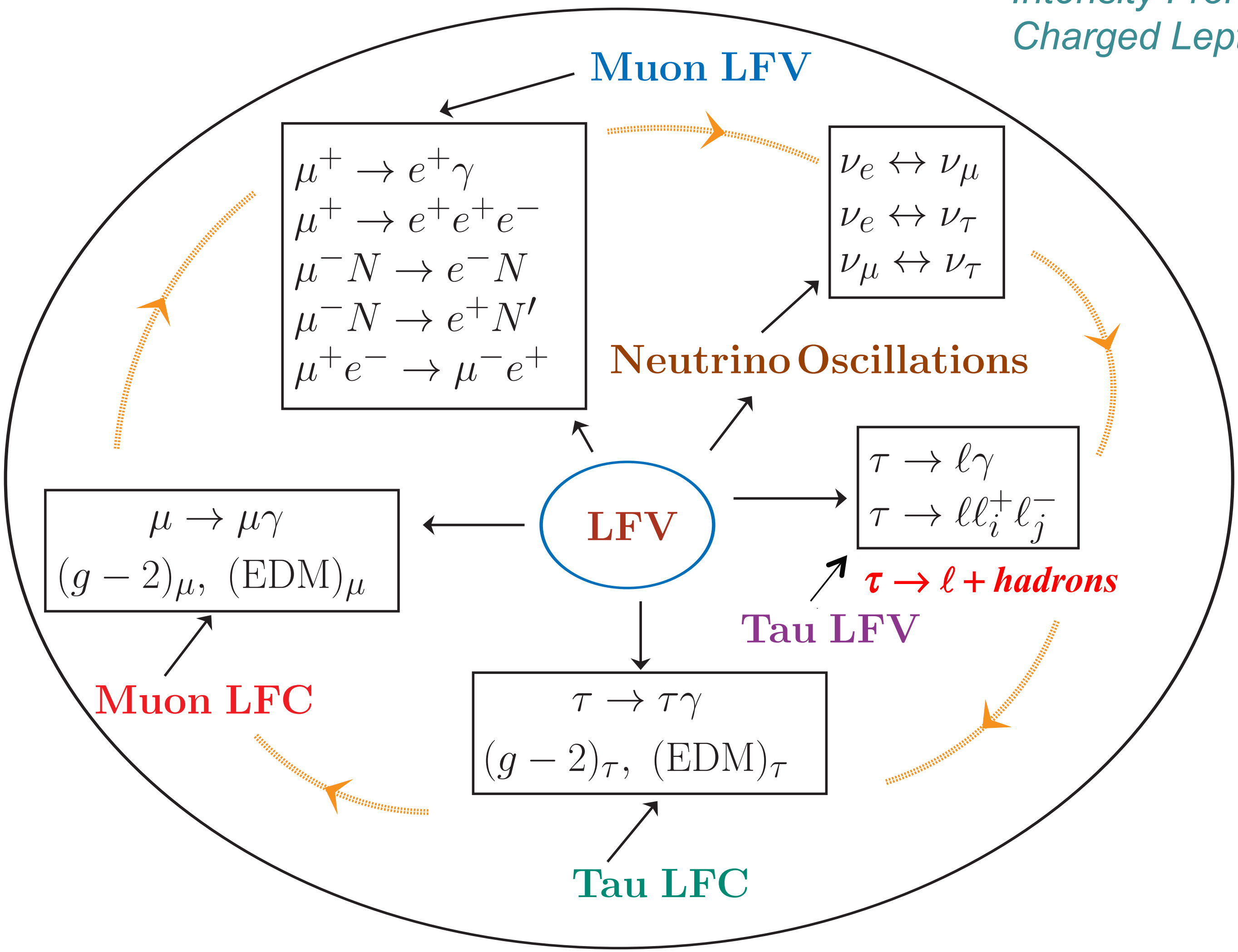


- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: $\boxed{\frac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^5 \text{ TeV}}$
    [ε_K]
  - Charged Leptons: $\boxed{\frac{\mu\bar{e}f\bar{f}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^4 \text{ TeV}}$
    [$\mu \rightarrow e\gamma$]
- 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*!

The Program

Intensity Frontier Charged Lepton WG'13



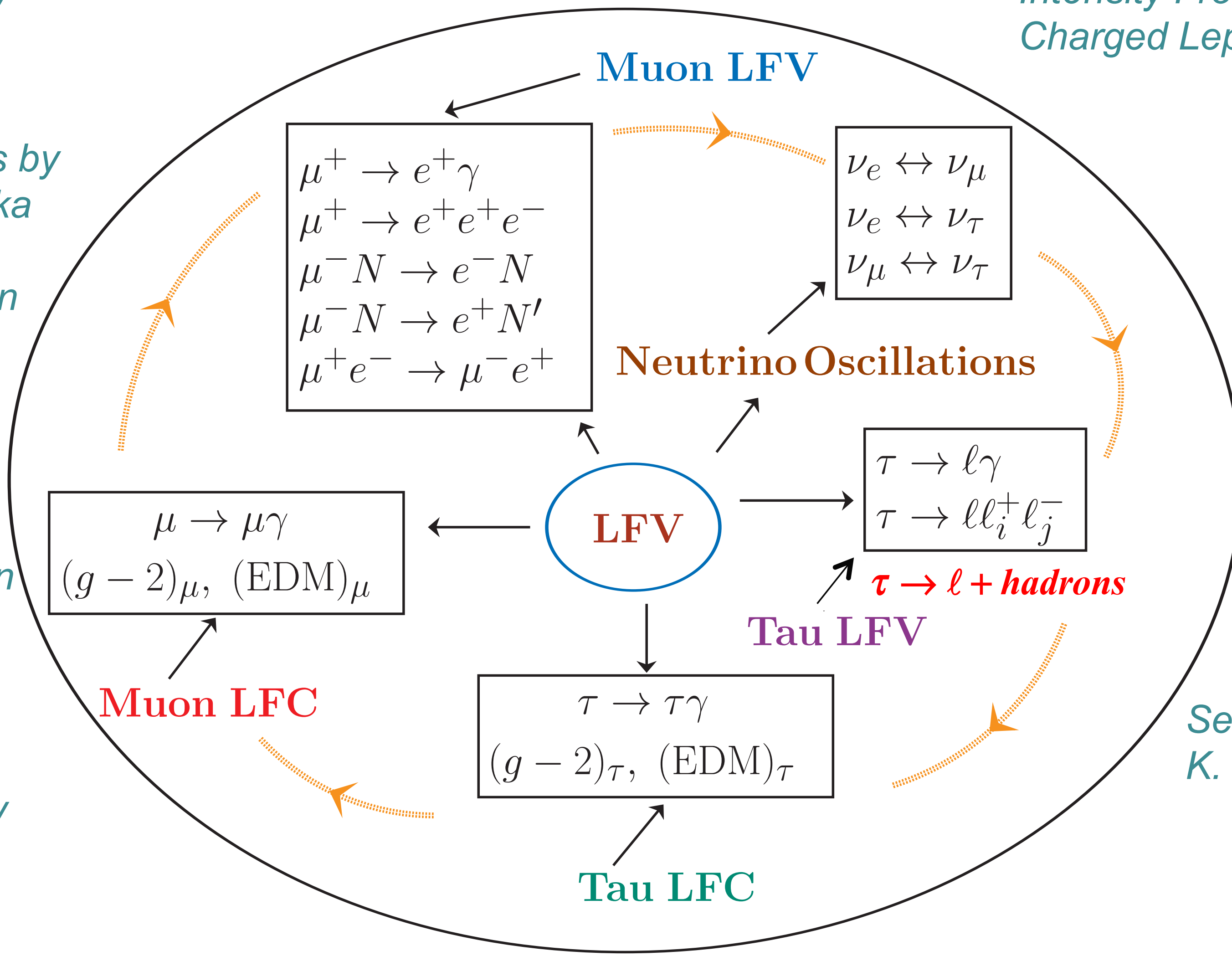
The Program

See talks by
S. Mihara
A. Sato

See Posters by
M. Yamanaka
Y. Uesaka
M. Roehrken
S. Ogawa
K. Oshida
T. Wong
N. Yu,
M. Wong
T.M, Nguyen
N.Teshima
T. Nagao

See talks by
B. Garry
M. Eads

Intensity Frontier
Charged Lepton WG'13



See talk by
K. Hayasaka

2. Charged Lepton-Flavour Violation

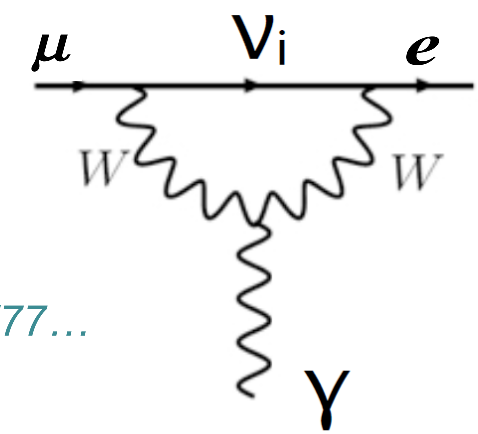
2.1 Introduction and Motivation

- Neutrino oscillations are the first evidence for lepton flavour violation

- How about in the charged lepton sector?

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

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



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

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

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

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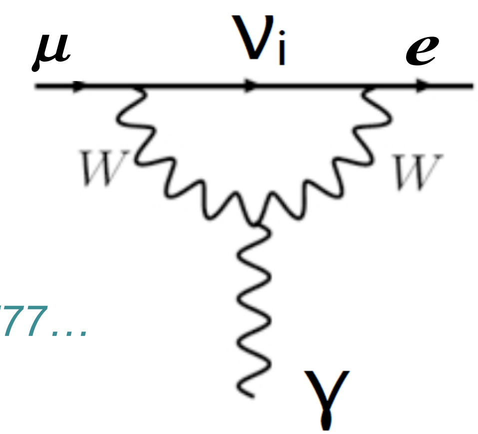


Petcov'77, Marciano & Sanda'77, Lee & Shrock'77…

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

- Extremely *clean probe of beyond SM physics*

2.1 Introduction and Motivation

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

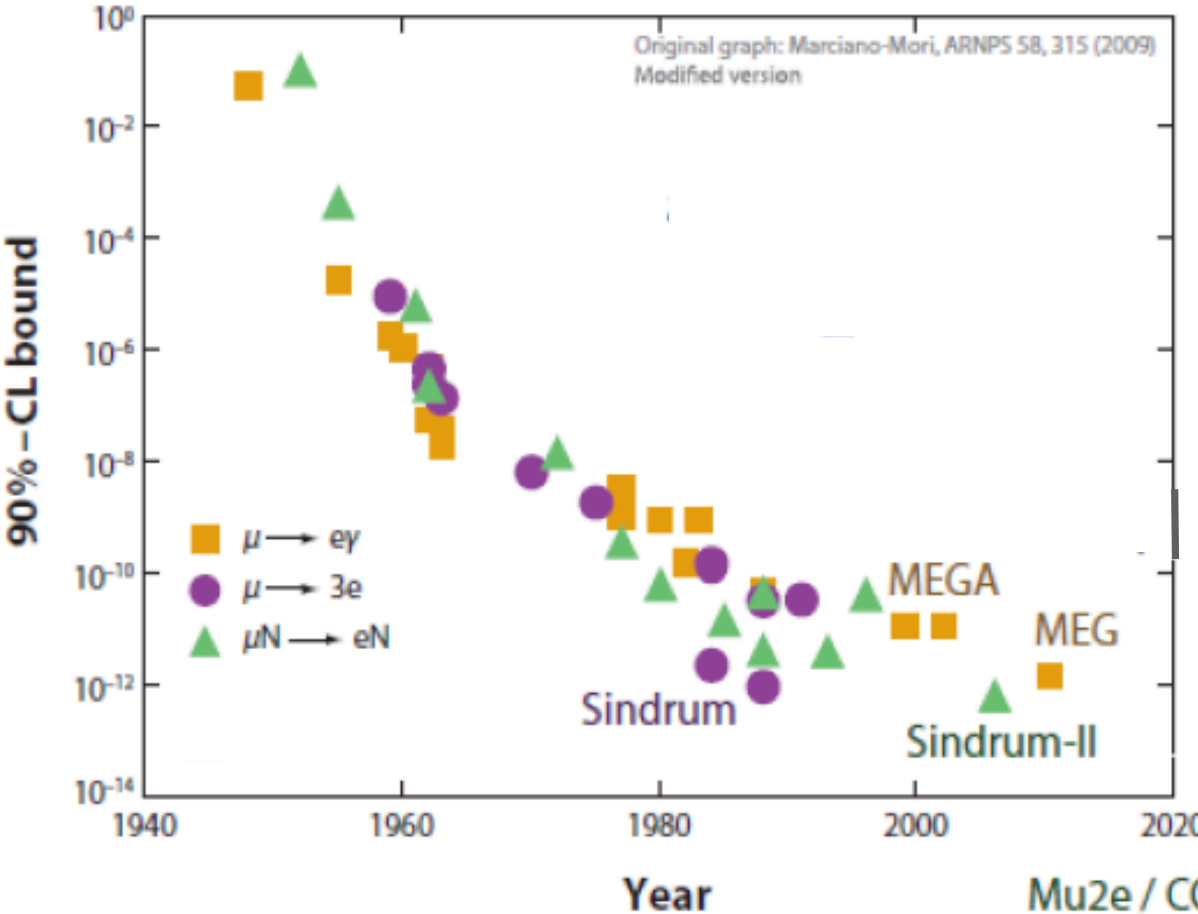
Talk by D. Hitlin @ CLFV2013

		$\tau \to \mu\gamma$	$\tau \to \ell\ell\ell$
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: muon decays

- Several processes: $\mu \to e\gamma,\ \mu \to e\bar{e}e,\ \mu(A,Z) \to e(A,Z)$



MEG'13

$$\boxed{BR(\mu \to e\gamma) < 5.7 \times 10^{-13}}$$

$\Rightarrow$ 10^{-14}

Talk by S. Mihara

Posters by S. Ogawa, K. Oshida

PSI/Mu3e

$$\boxed{BR(\mu \to eee) < 1.0 \times 10^{-12}}$$

$\Rightarrow$ $10^{-15} - 10^{-16}$

Talk by S. Mihara

Mu2e/COMET

$$\boxed{BR^{Ti}_{\mu-e} < 4.3 \times 10^{-12}}$$

Mu2e / COMET $\Rightarrow$ $10^{-16} - 10^{-17}$

Talk by A. Sato

- Proposal for search of CLFV in $\mu^- e^- \to e^- e^-$

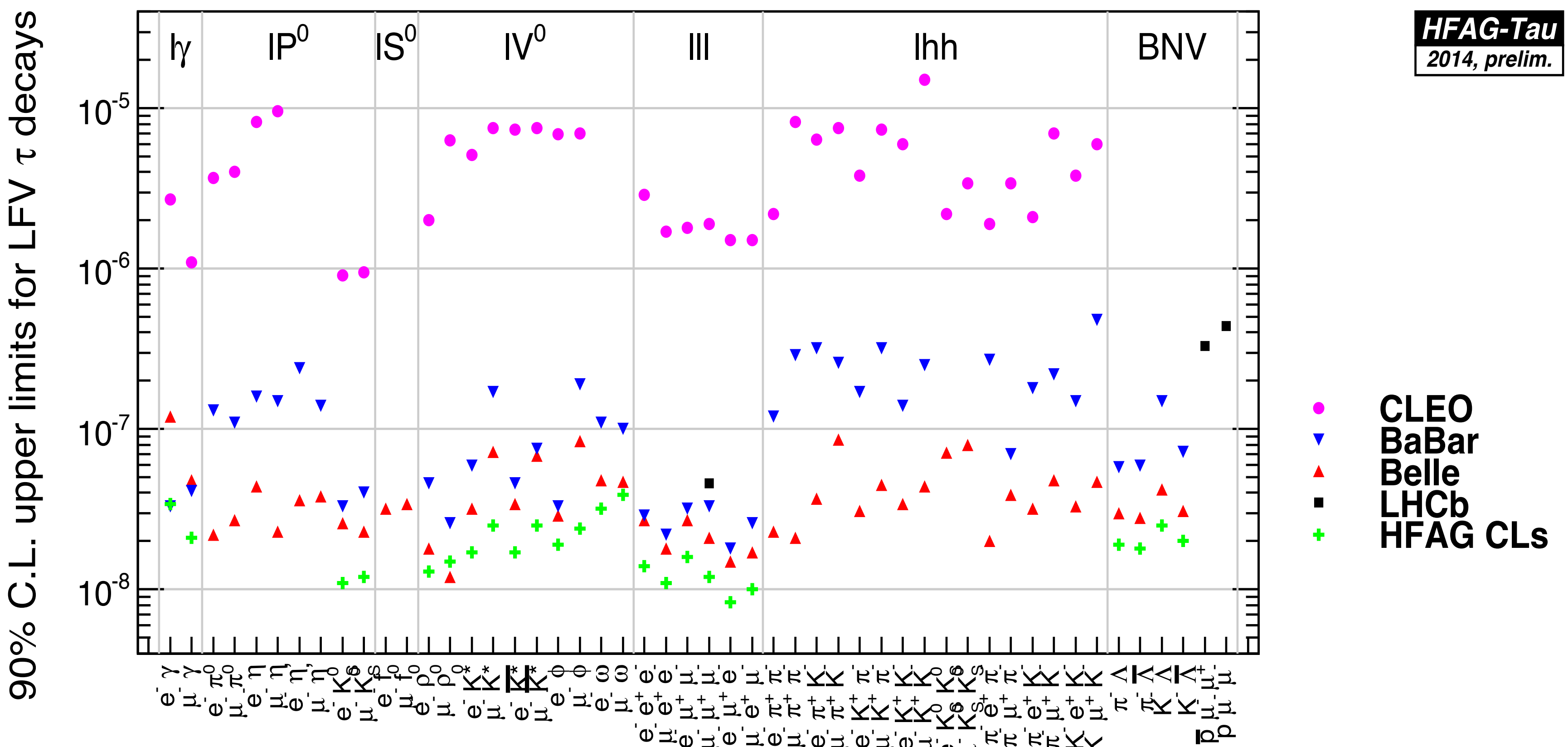
Koike et al'10 $\Rightarrow$ *Poster by Y. Uesaka*

DeeMe

Posters by M. Roehrken, T. Wong, N. Yu, M. Wong, T. M, Nguyen, N.Teshima, T. Nagao

2.2 CLFV processes: tau decays

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



- 48 LFV modes studied at Belle and BaBar

2.2 CLFV processes: tau decays

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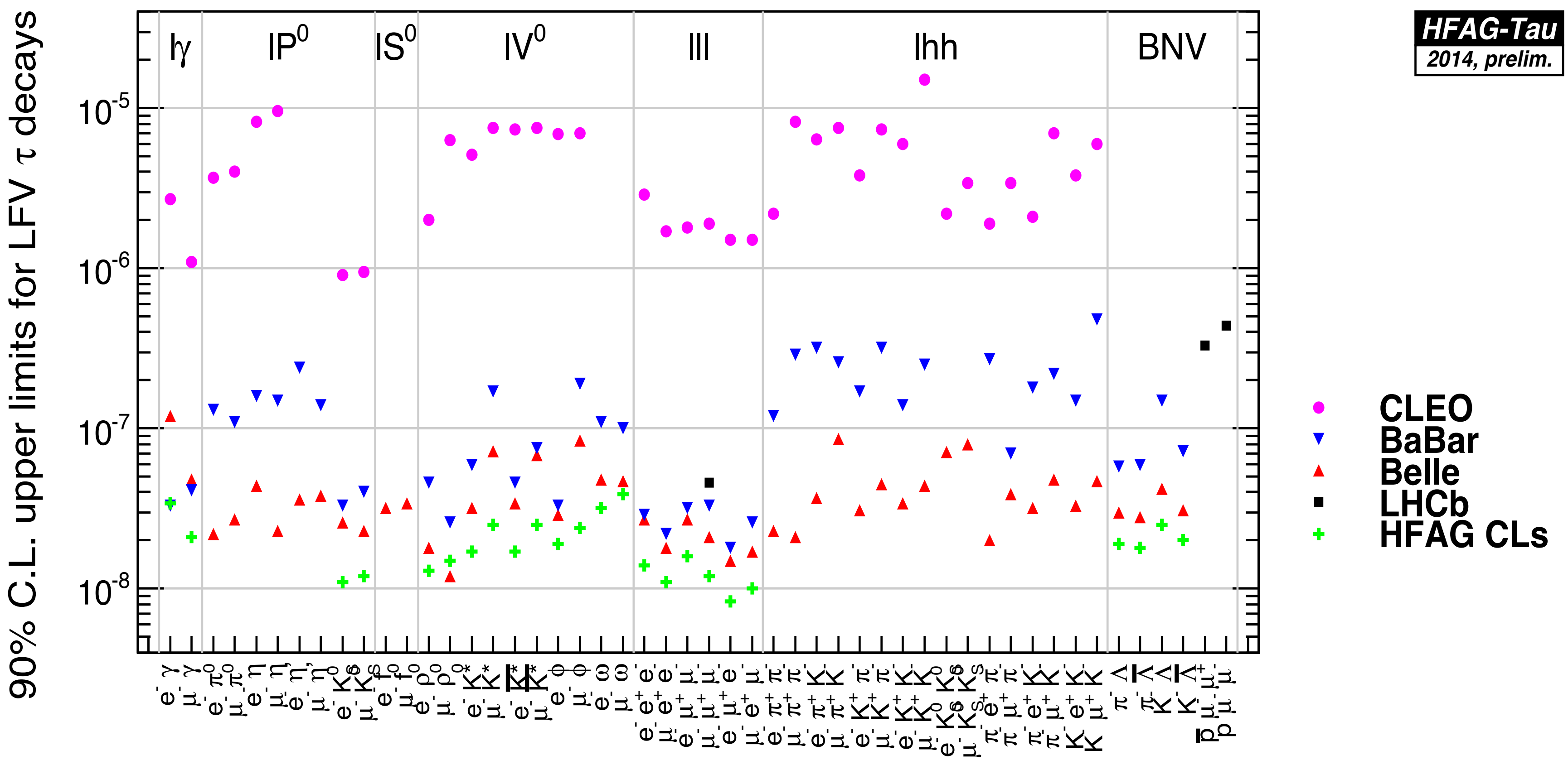


- Expected sensitivity 10^{-9} or better at *LHCb, Belle II?*

2.3 Effective Field Theory approach

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

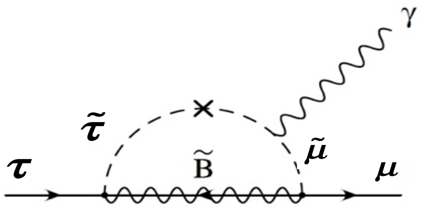
See e.g.
Black, Han, He, Sher'02
Brignole & Rossi'04
Dassinger et al.'07
Matsuzaki & Sanda'08
Giffels et al.'08
Crivellin, Najjari, Rosiek'13
Petrov & Zhuridov'14
Cirigliano, Celis, E.P.'14

- Build all D>5 LFV operators:
  - Dipole
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector)
  - Lepton-gluon (Scalar, Pseudo-scalar)
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector)

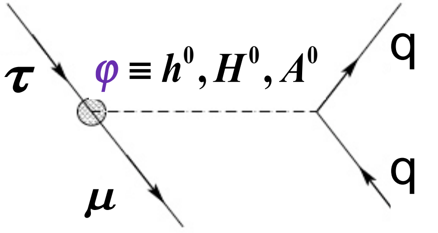
- Each UV model generates a *specific pattern* of them

2.3 Effective Field Theory approach

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

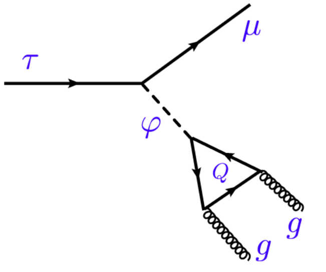


- Scalar (Pseudo-scalar) : $\boxed{\mathcal{L}_{eff}^{S} \supset -\frac{C_S}{\Lambda^2} m_\tau m_q G_F \underbrace{\bar{\mu} P_{L,R}\tau\, \bar{q}q}_{O_S^q}}$



Integrating out heavy quarks generates *gluonic operator:*

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

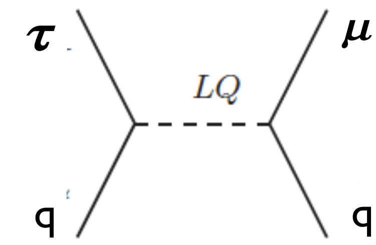


Importance of this operator emphasized in *Petrov & Zhuridov'14*

2.3 Effective Field Theory approach

- Vector (Axial-vector) : $\boxed{\mathcal{L}_{eff}^{V} \supset -\frac{C_V^q}{\Lambda^2}\, \bar{\mu}\gamma^{\mu} P_{L,R}\tau\; \bar{q}\gamma_{\mu} q}$

O_V^q

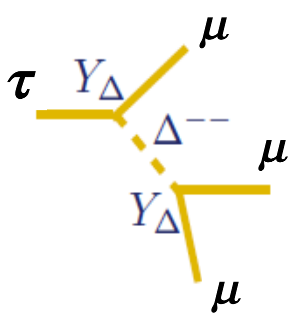


- 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector) :

$$\boxed{\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2}\, \bar{\mu}\, \Gamma P_{L,R}\tau\; \bar{\mu}\, \Gamma P_{L,R}\mu}$$

$O_{S,V}^{4\ell}$

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



2.4 Model discriminating power of muon processes

- Summary table:

Cirigliano@Beauty2014

	$\mu \to 3e$	$\mu \to e\gamma$	$\mu \to e$ conversion
$O^{4\ell}_{S,V}$	✓	–	–
O_D	✓	✓	✓
O^q_V	–	–	✓
O^q_S	–	–	✓

- 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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Cirigliano@Beauty2014

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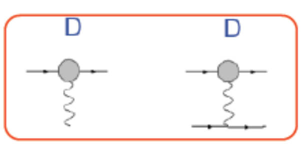
O_D	✓	✓	✓
O^q_V	–	–	✓
O^q_S	–	–	✓

- $\mu \to e\gamma$ vs. $\mu \to 3e$ ⇨ relative strength between *dipole* and *4L* operators

$$\frac{\Gamma_{\mu\to 3e}}{\Gamma_{\mu\to e\gamma}} = \frac{\alpha}{4\pi} I_{\rm PS} \left(1 + \sum_i \frac{c_i^{\rm (contact)}}{c^{\rm (dipole)}} \right)$$



6×10^{-3}

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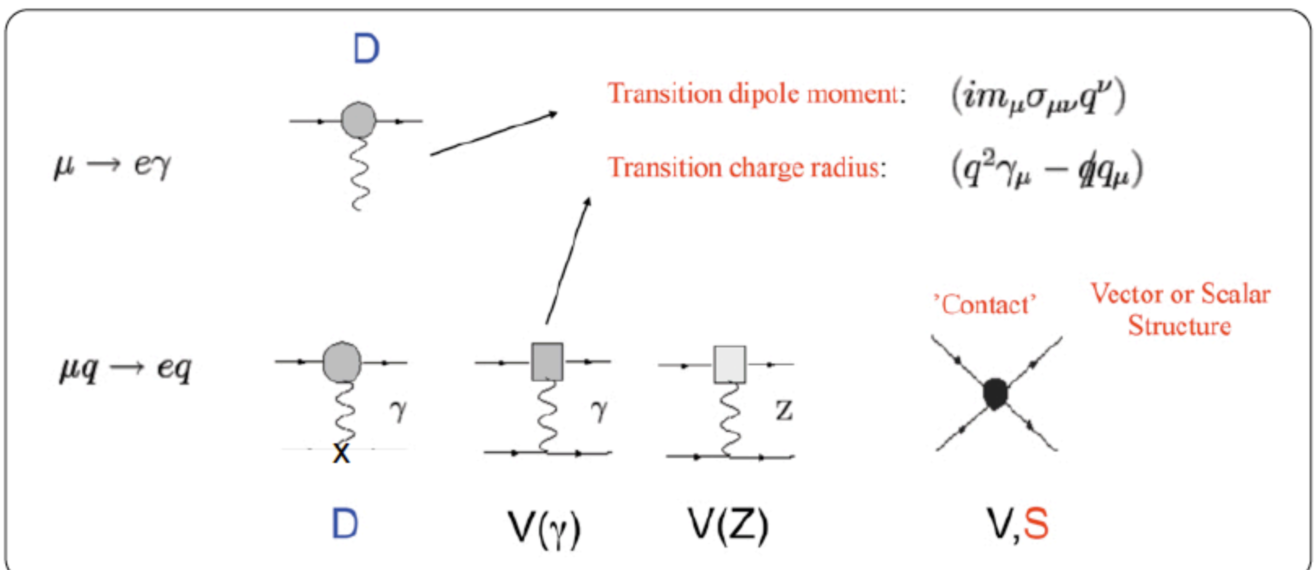
	$\mu \to 3e$	$\mu \to e\gamma$	$\mu \to e$ conversion
$O_{S,V}^{4\ell}$	✓	–	–
O_D	✓	✓	✓
O_V^q	–	–	✓
O_S^q	–	–	✓

- *$\mu \to e\gamma$* vs. *$\mu \to e$ conversion* ⇒ relative strength between *dipole* and *quark* operators



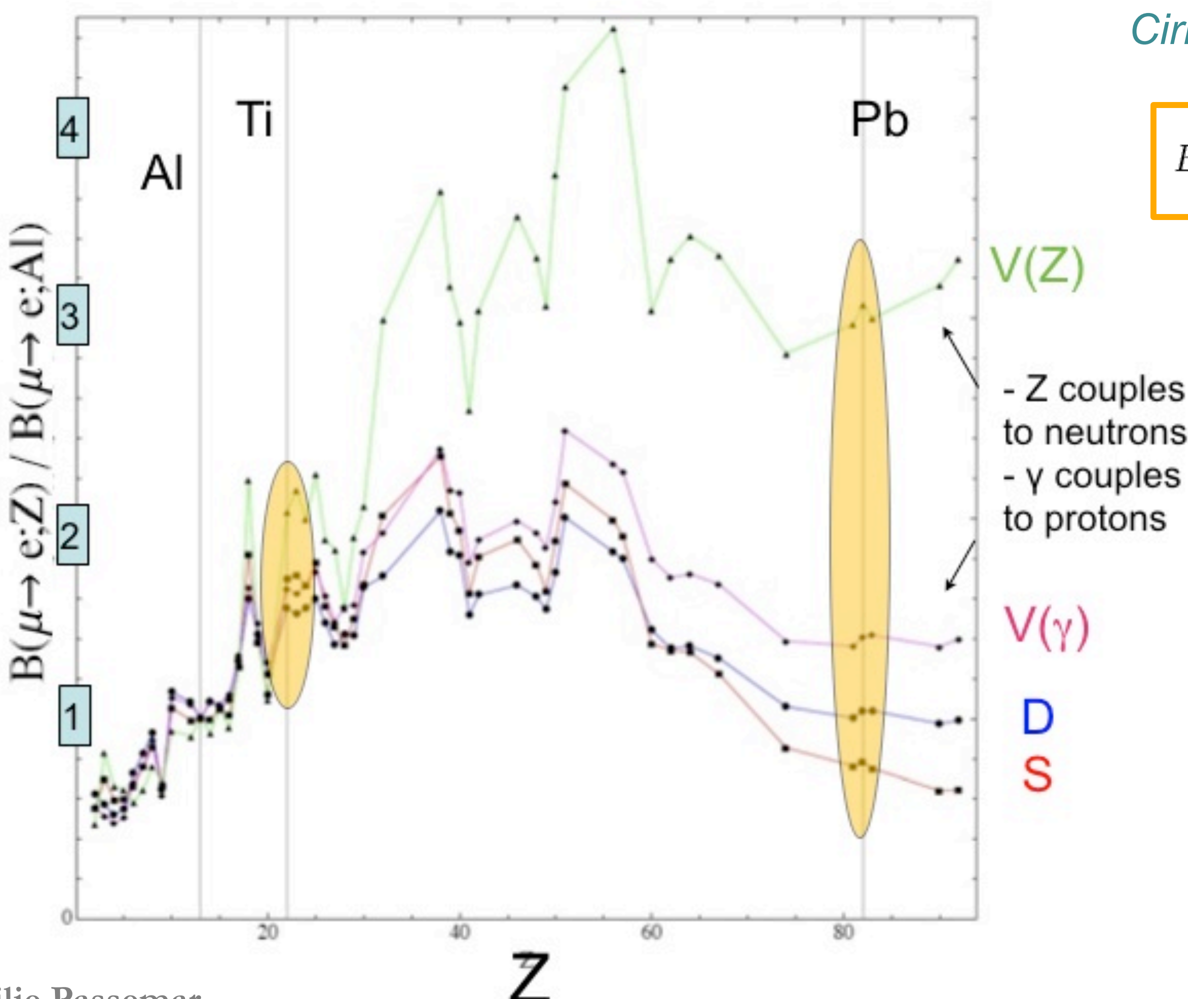
Discriminating power of μ→ e conversion

- For *$\mu \to e$ conversion,* target dependence of the amplitude is different for V, D or S models

Kitano, Koike, Okada'06

Cirigliano, Kitano, Okada, Tuzon'09

$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$



Ratio: hadronic uncertainties cancel

Discrimination: need
~*5%* measure of *Ti/Al*
~*20%* measure of *Pb/Al*

2.5 Model discriminating power of Tau processes

- Summary table:

Celis, Cirigliano, E.P.'14

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

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Summary table:

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$\mathrm{O}_{\mathrm{S,V}}^{4\ell}$	✓	–	–	–	–	–
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)
$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

- 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 Model discriminating power of Tau processes

- Summary table: *Celis, Cirigliano, E.P.'14*

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$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- Recent progress in $\tau \to \mu(e)\pi\pi$ using *dispersive techniques* *Daub et al'13* *Celis, Cirigliano, E.P.'14*

- Hadronic part: $\boxed{H_\mu = \langle \pi\pi | \left(V_\mu - A_\mu\right) e^{iL_{QCD}} | 0 \rangle = \left(\textit{Lorentz}\ \text{struct.}\right)^i_\mu F_i(s)}$ with $s = \left(p_{\pi^+} + p_{\pi^-}\right)^2$

- Form factors determined by solving 2-channel unitarity condition, with I=0 s-wave $\pi\pi$ and KK scattering data as input

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

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

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- 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
  - Spectra for > 2 bodies in the final state:

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

2.6 Model discriminating of BRs

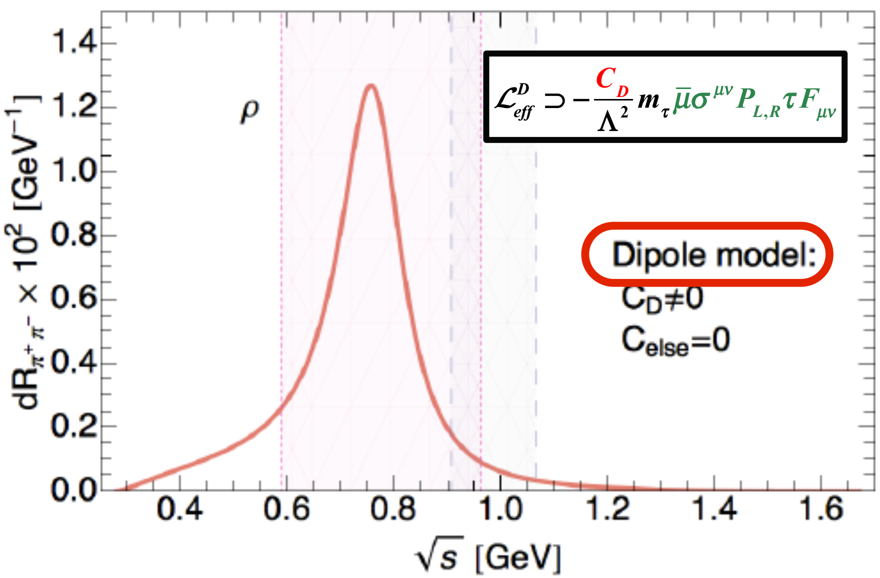
- Studies in specific models *Buras et al.'10*

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\mathrm{Br}(\mu^-\to e^-e^+e^-)}{\mathrm{Br}(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{\mathrm{Br}(\tau^-\to e^-e^+e^-)}{\mathrm{Br}(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{\mathrm{Br}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathrm{Br}(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{\mathrm{Br}(\tau^-\to e^-\mu^+\mu^-)}{\mathrm{Br}(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{\mathrm{Br}(\tau^-\to \mu^-e^+e^-)}{\mathrm{Br}(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{\mathrm{Br}(\tau^-\to e^-e^+e^-)}{\mathrm{Br}(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{\mathrm{Br}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathrm{Br}(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{\mathrm{Br}(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

⇨ Disentangle the *underlying dynamics* of NP

2.7 Model discriminating of Spectra: τ→μππ

Celis, Cirigliano, E.P.'14



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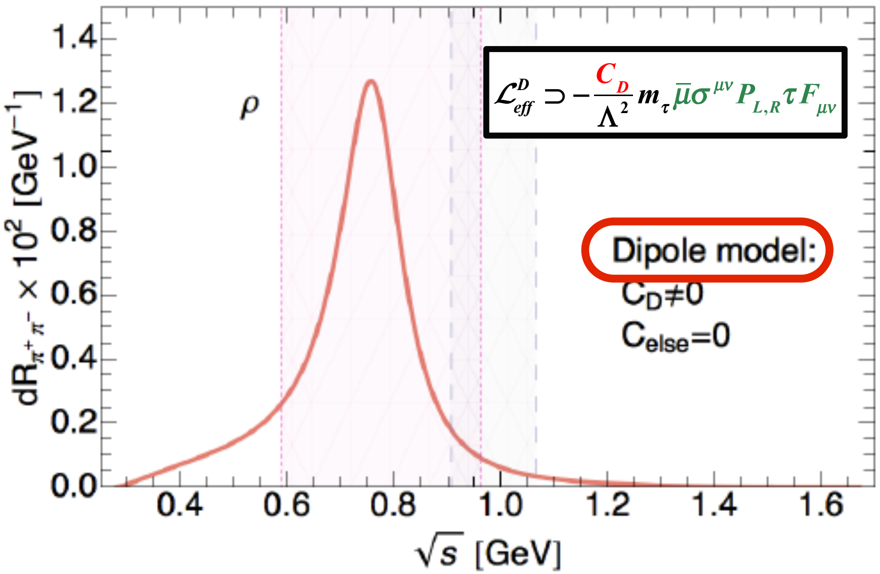

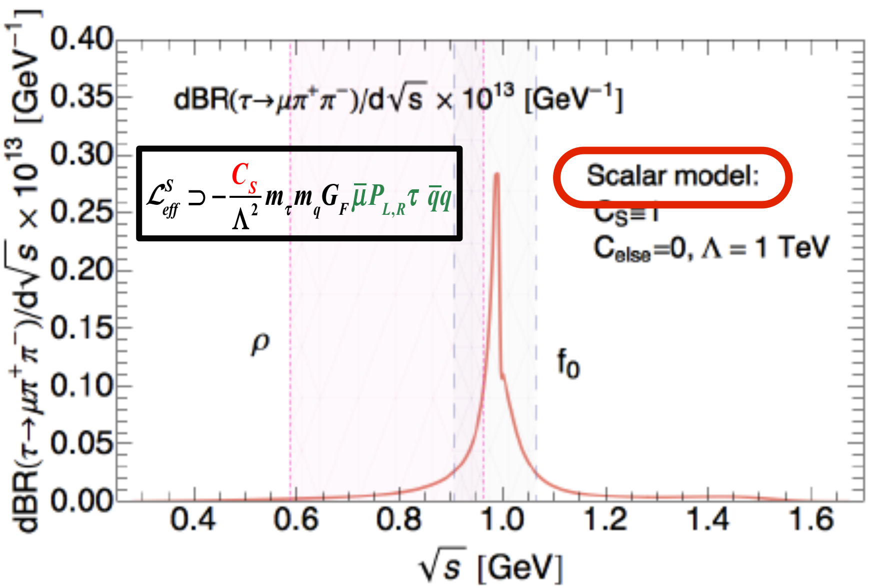

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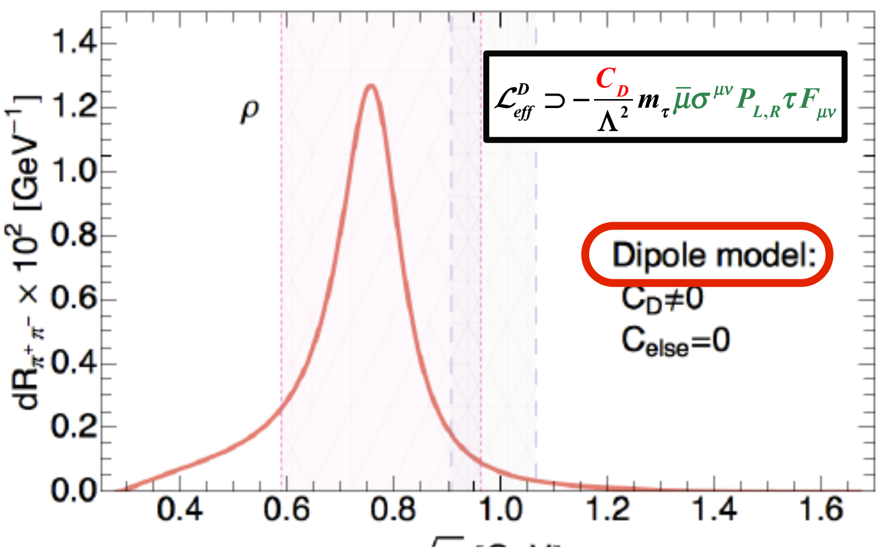
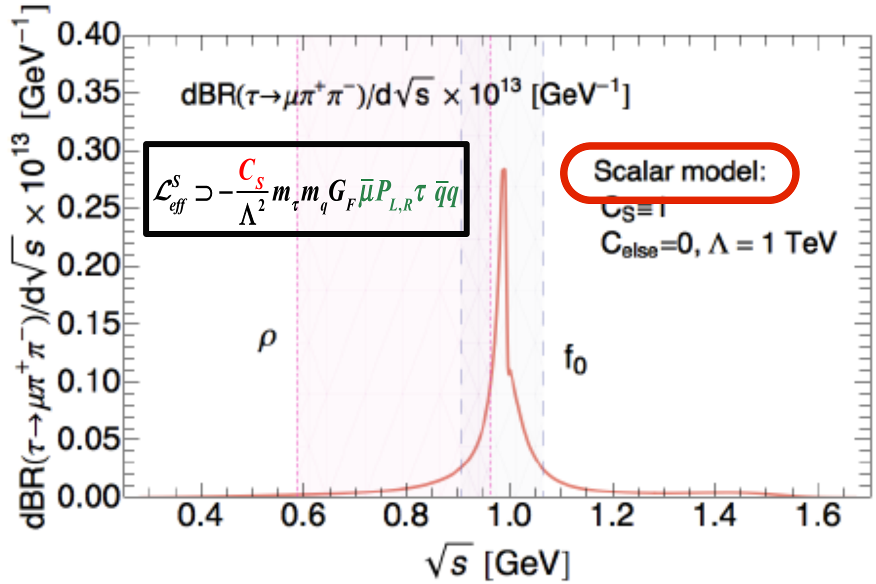
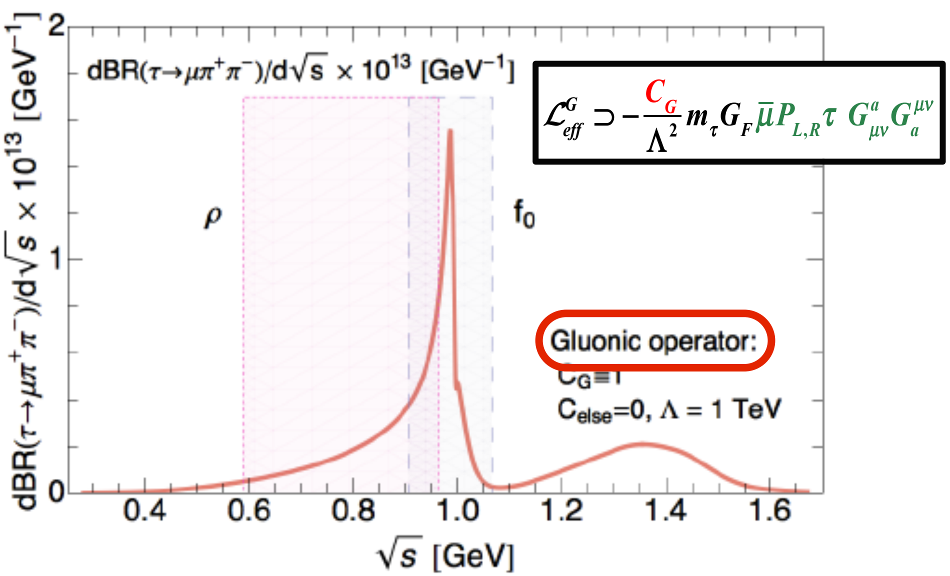


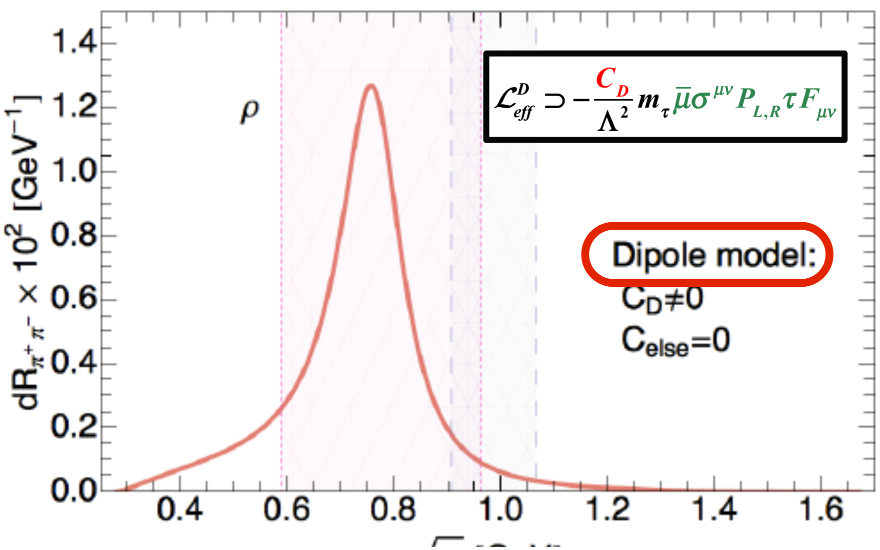


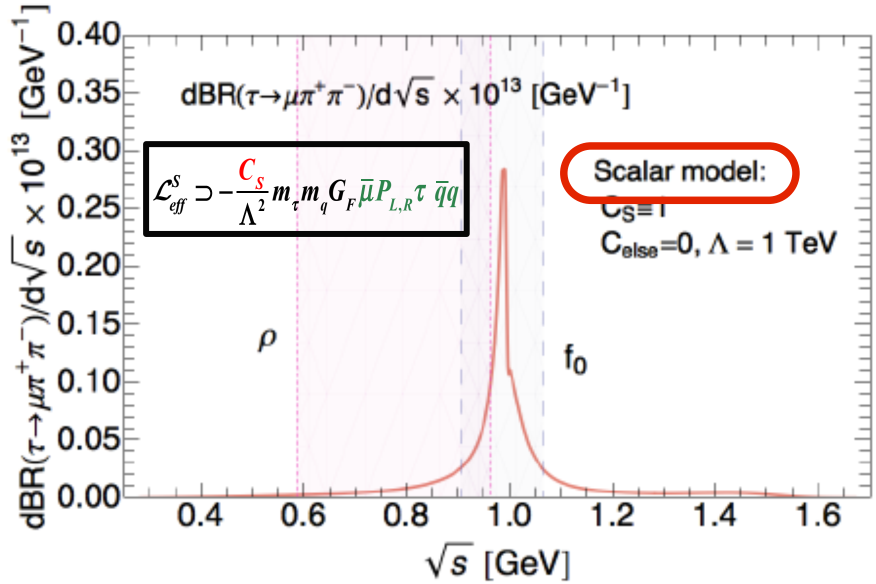


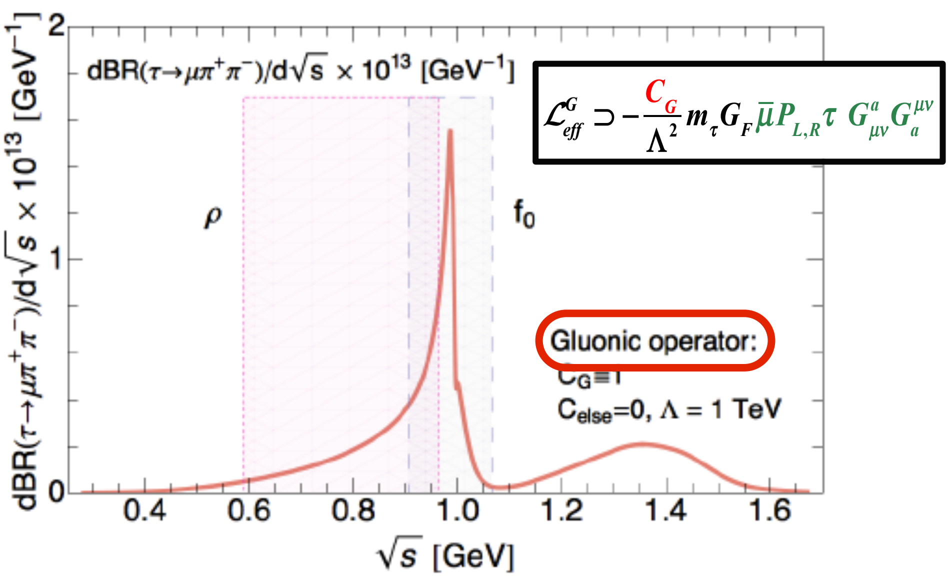
Very different distributions according to the *final hadronic state!*

2.7 Model discriminating of Spectra: $\tau \to \mu\pi\pi$

Celis, Cirigliano, E.P.'14







Very different distributions according to the *final hadronic state!*

NB: See also Dalitz plot analyses for $\tau \to \mu\mu\mu$

Dassinger et al.'07

3. Charged Lepton-Flavour Violation and Higgs Physics

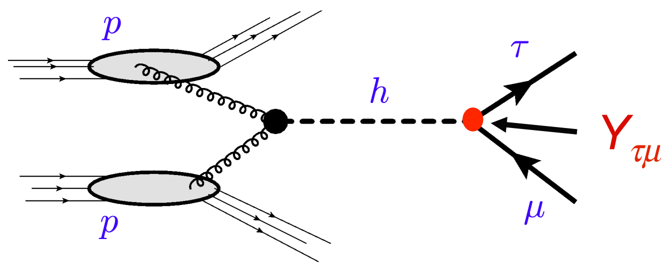
3.1 Non standard LFV Higgs coupling

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

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

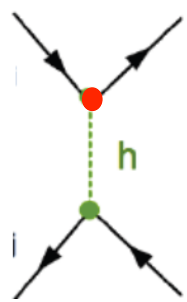
In the SM: $Y_{ij}^{h_{SM}} = \frac{m_i}{\mathrm{v}}\delta_{ij}$

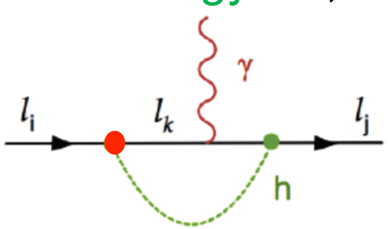
- High energy : LHC

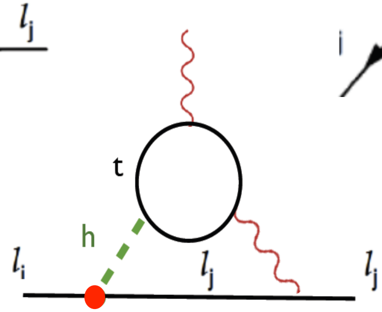


Hadronic part treated with perturbative QCD

- Low energy : D, S operators







3.1 Non standard LFV Higgs coupling

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

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

Goudelis, Lebedev, Park'11
Davidson, Grenier'10
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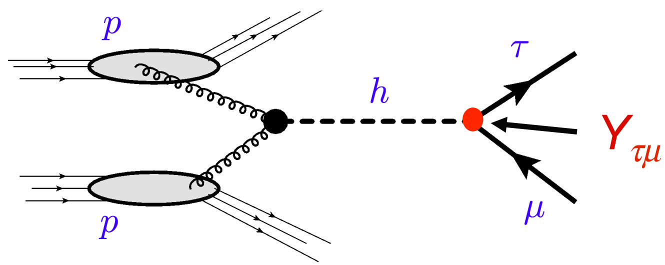
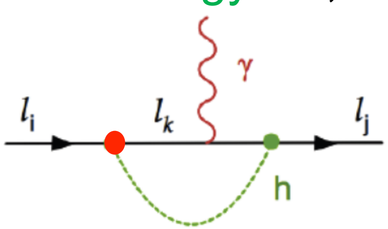
- High energy : LHC

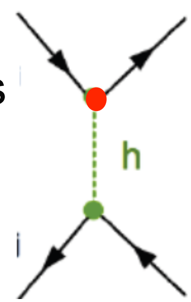


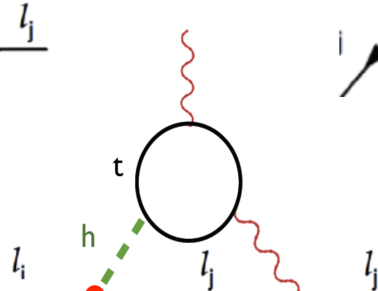
Hadronic part treated with perturbative QCD

Reverse the process

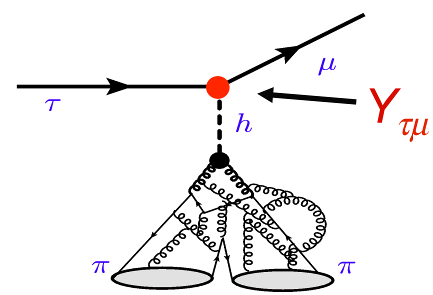
- Low energy : D, S, G operators







+

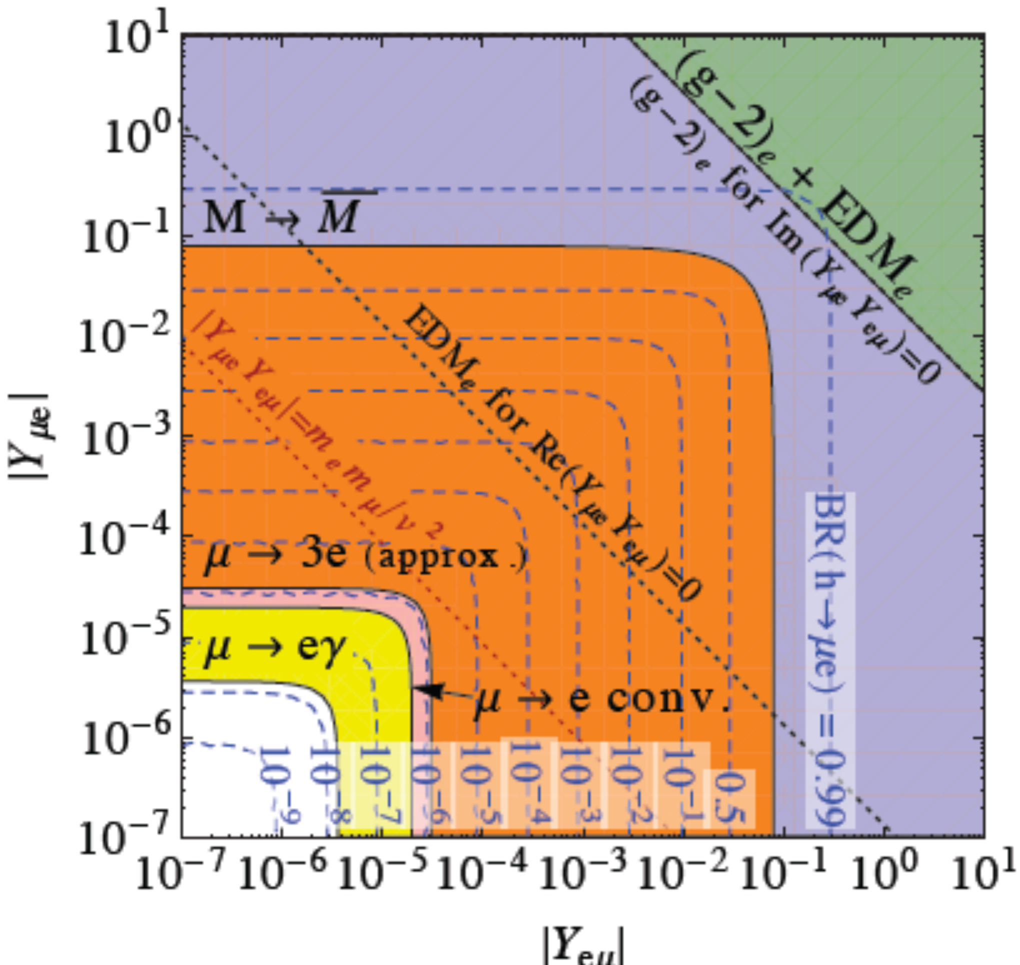


Hadronic part treated with non-perturbative QCD

3.2 Constraints in the μe sector

- Constraints from Higgs decay (LHC) vs. low energy LFV and LFC observables

Harnik, Kopp, Zupan'12



- Best constraints coming from low energy: $\mu \to e\gamma$

MEG'13

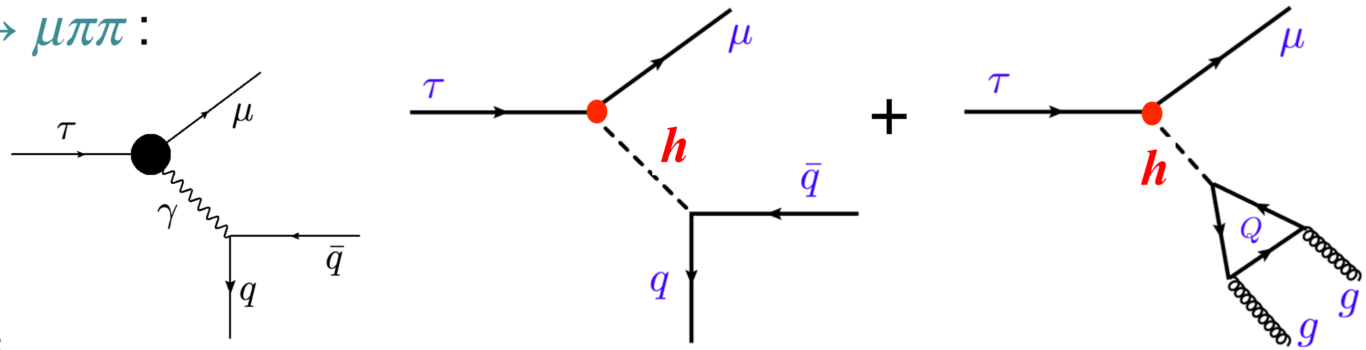
$$BR\left(\mu \to e\gamma\right) < 5.7\ 10^{-13}$$

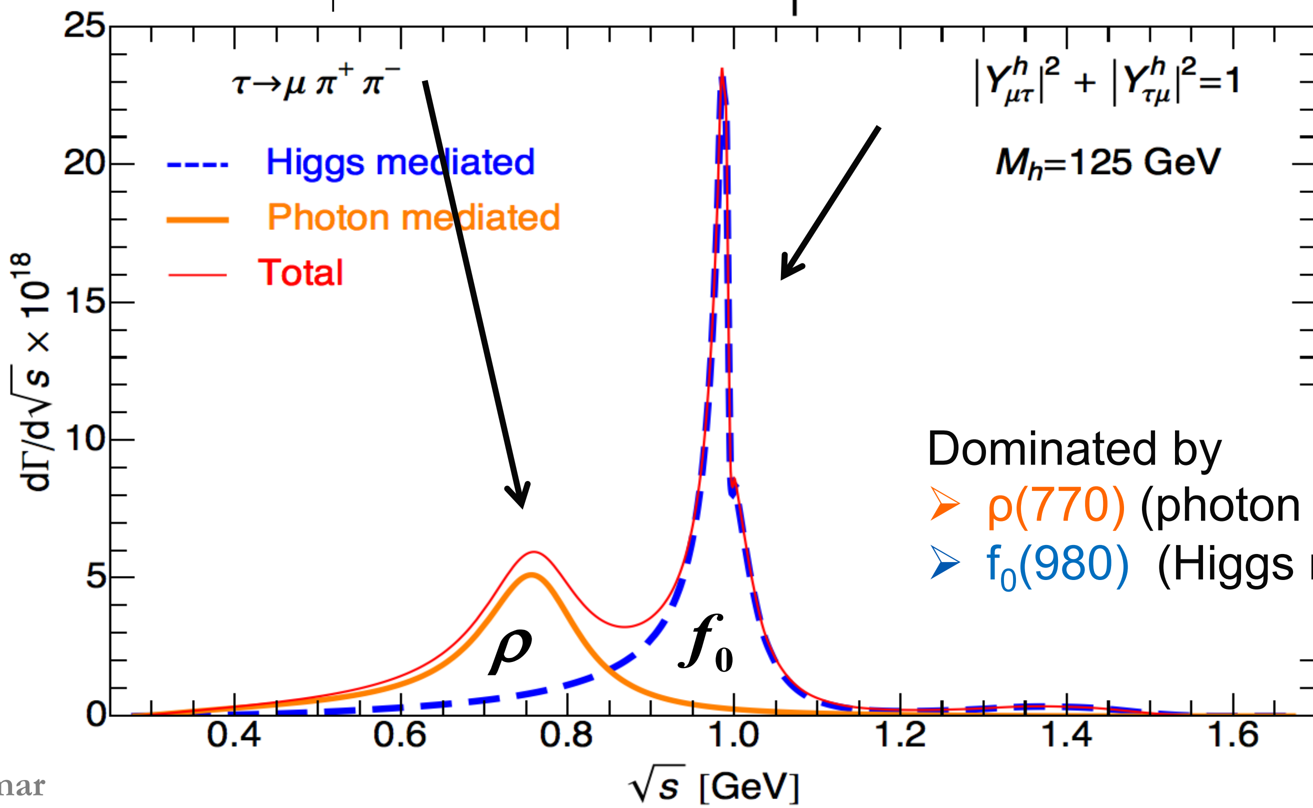
$$\Rightarrow \quad BR\left(h \to \mu e\right) < 10^{-7}$$

NB: Diagonal couplings set to SM value

3.3 Constraints in the τμ sector

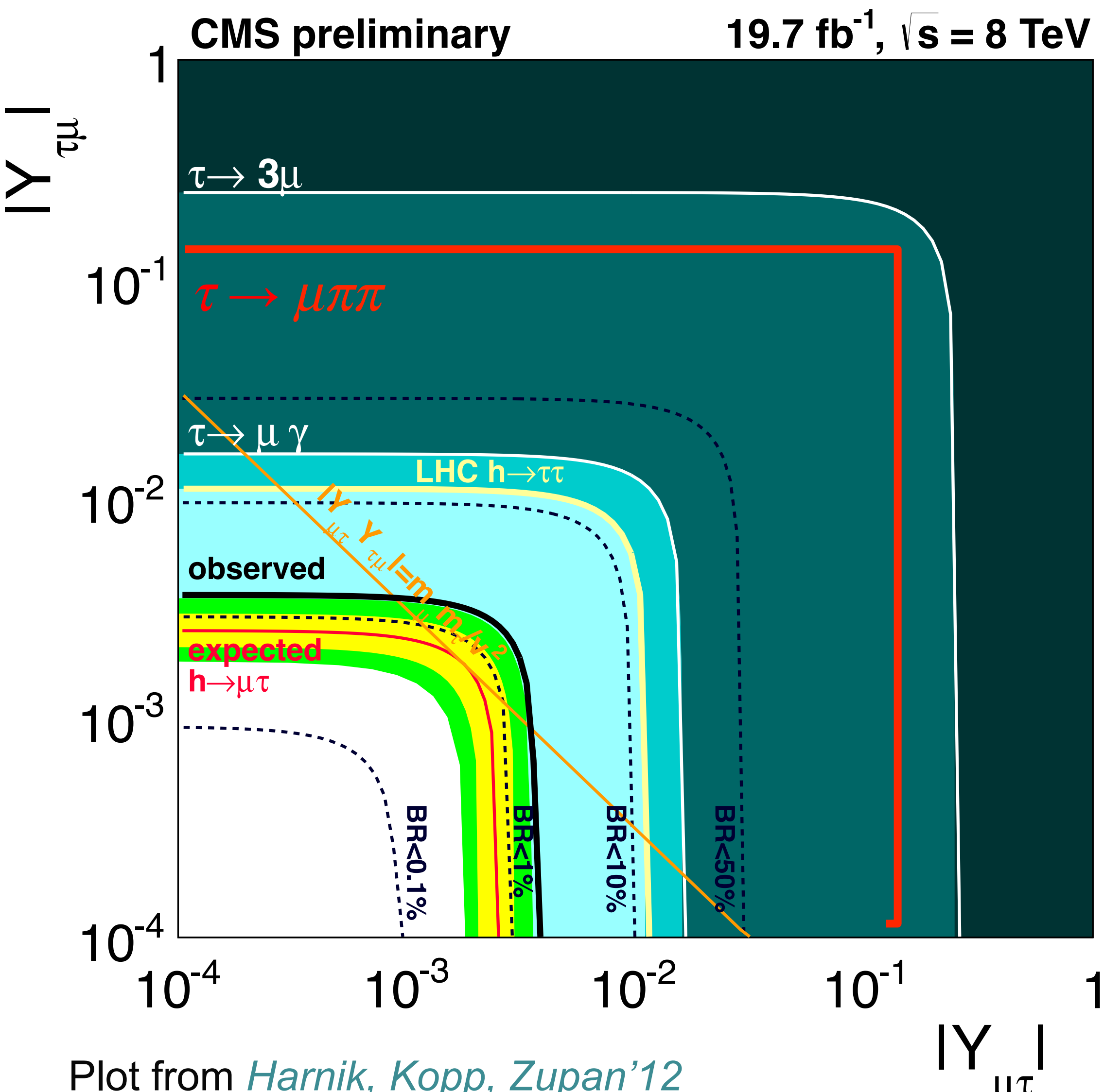
- At low energy
  - $\tau \to \mu\pi\pi$:





Dominated by
- ρ(770) (photon mediated)
- $f_0(980)$ (Higgs mediated)

3.3 Constraints in the τμ sector



Plot from *Harnik, Kopp, Zupan'12*
updated *by CMS* ⇨ *Talk by P. Onyisi*

- 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

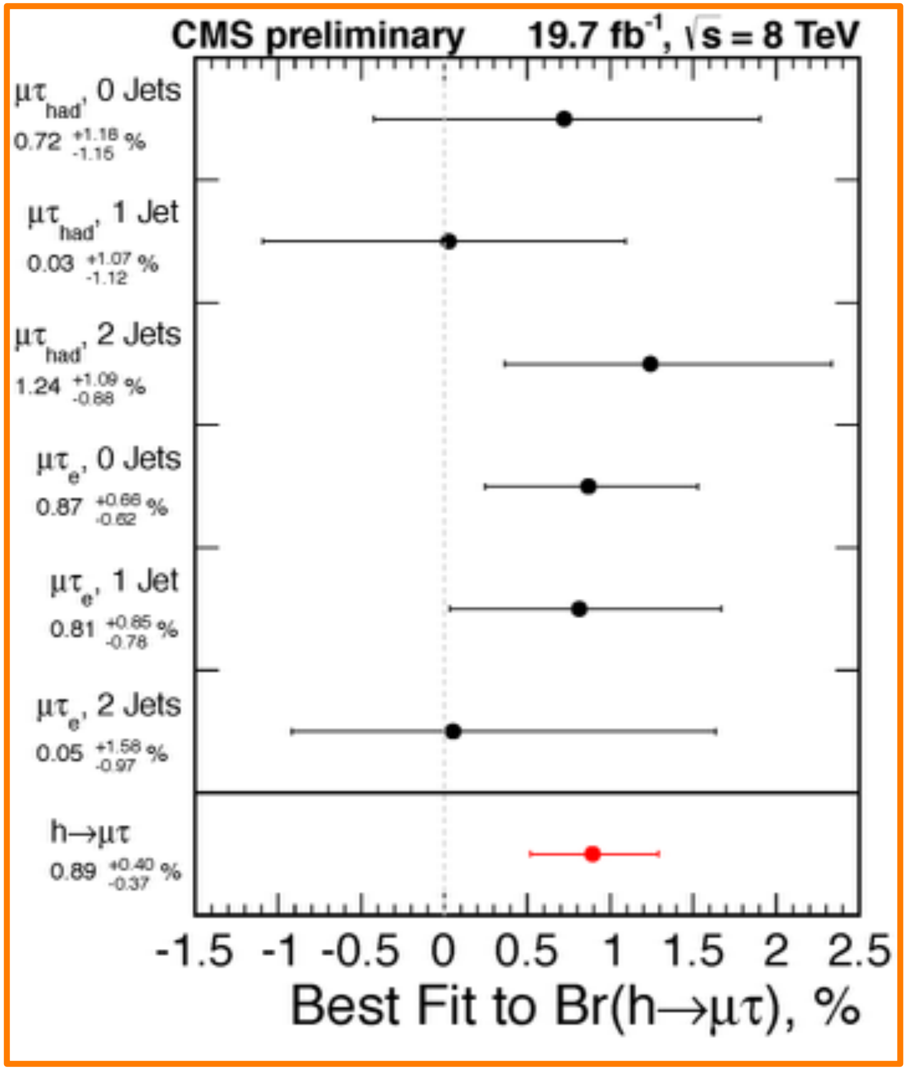
⇨ $BR(\tau \to \mu\gamma) < 2.2 \times 10^{-9}$

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

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

CMS'14

See talk by P. Onyisi

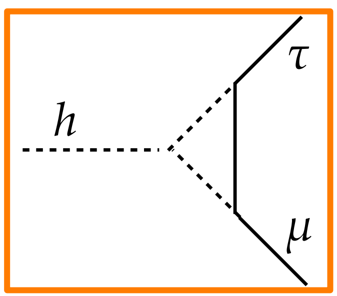


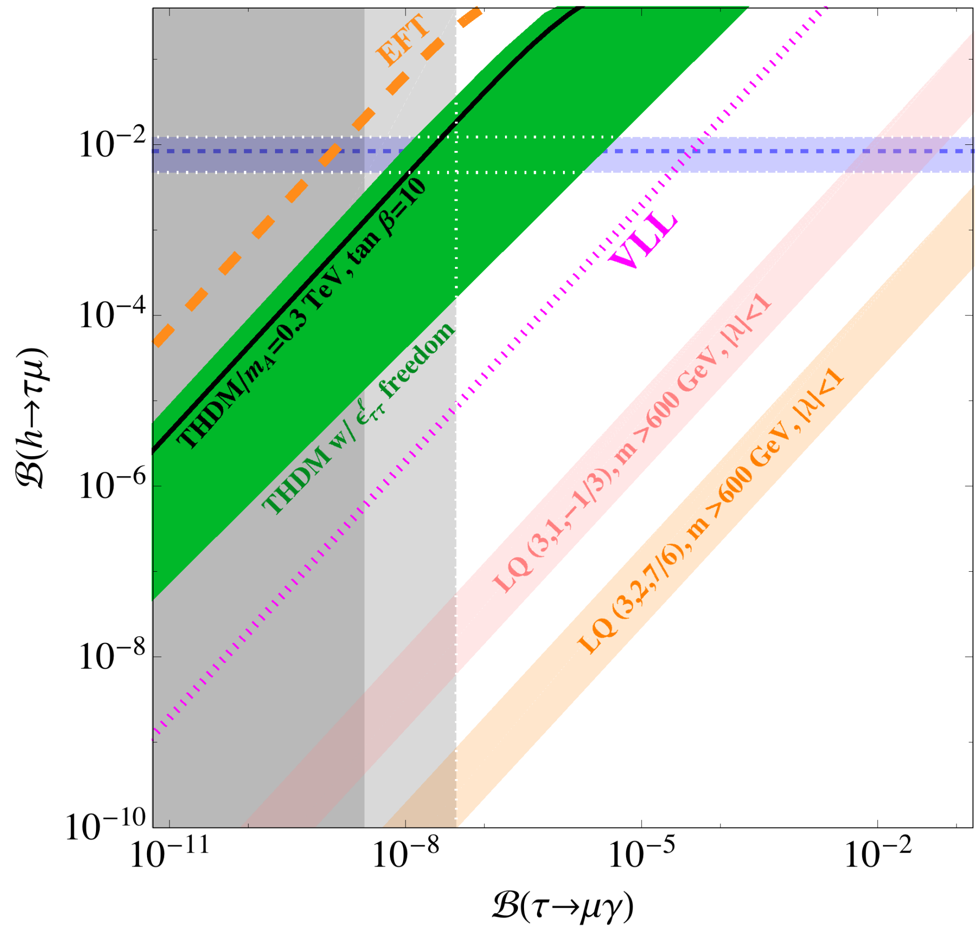
3.5 Interplay between LHC & Low Energy

Dorsner et al.'15

- If real what type of NP?

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





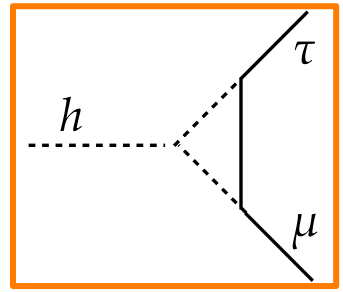
- h → τμ possible to explain if extra scalar doublet:

  ⇨ *2HDM of type III*

3.5 Interplay between LHC & Low Energy

- If real what type of NP?

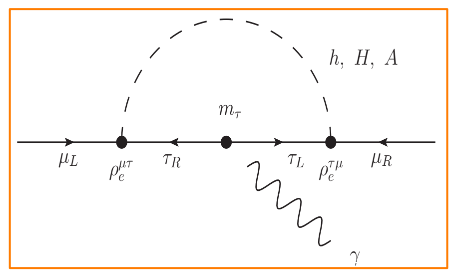
- If $h \to \tau\mu$ due to loop corrections:
  - extra charged particles necessary
  - $\tau \to \mu\gamma$ too large



Dorsner et al.'15

- $h \to \tau\mu$ possible to explain if extra scalar doublet ⇨ *2HDM of type III*

- *Type III 2HDMs* with tree level FCNCs in lepton sector
  ⇨ explain also g-2



Omhura, Senaha, Tobe '15
See Poster by K. Tobe

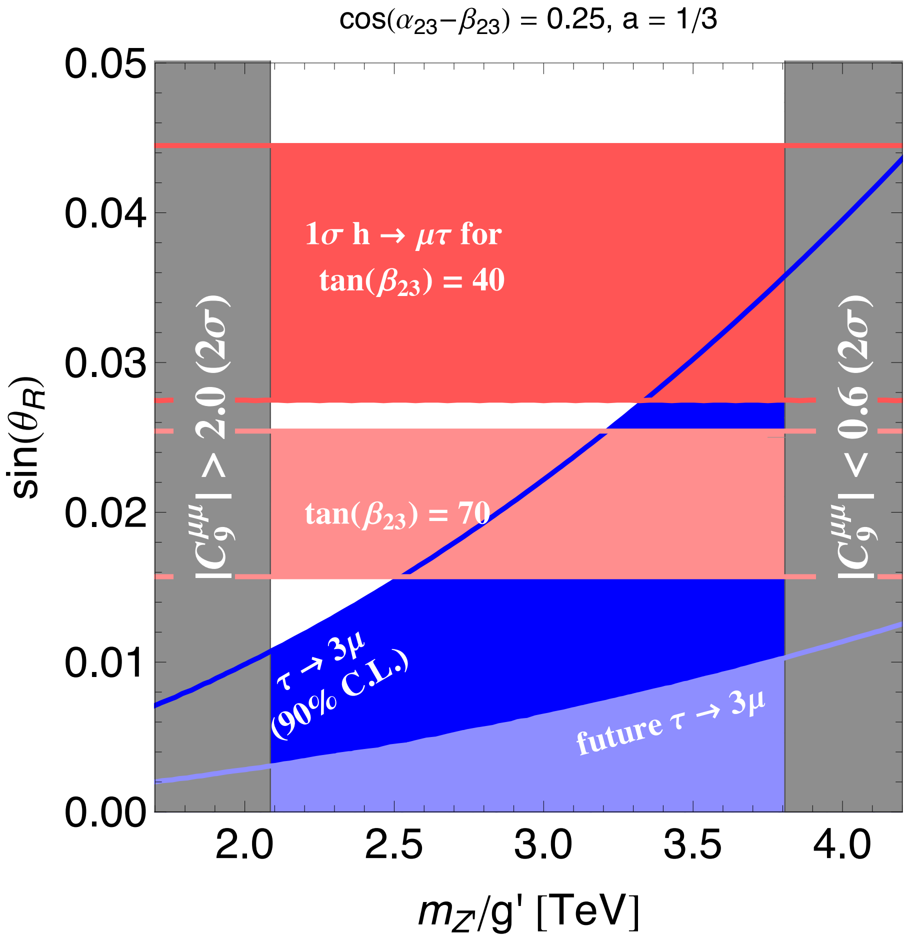
- *2HDMs* with gauged $L_\mu - L_\tau$ ⇨ Z', explain anomalies in
  - $h \to \tau\mu$
  - $B \to K^*\mu\mu$
  - $R_K = B \to K\mu\mu / B \to Kee$

Crivellin, D'Ambrosio, Heeck.'15

See also: *Aristizabal-Sierra&Vicente'14, Lima et al'15*

3.5 Interplay between LHC & Low Energy

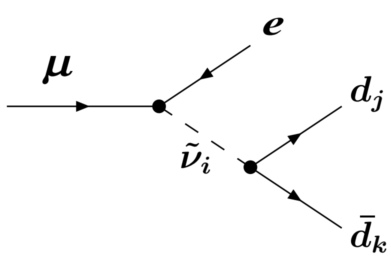
- *2HDMs* with gauged $L_\mu - L_\tau$ *Crivellin, D'Ambrosio, Heeck.'15*

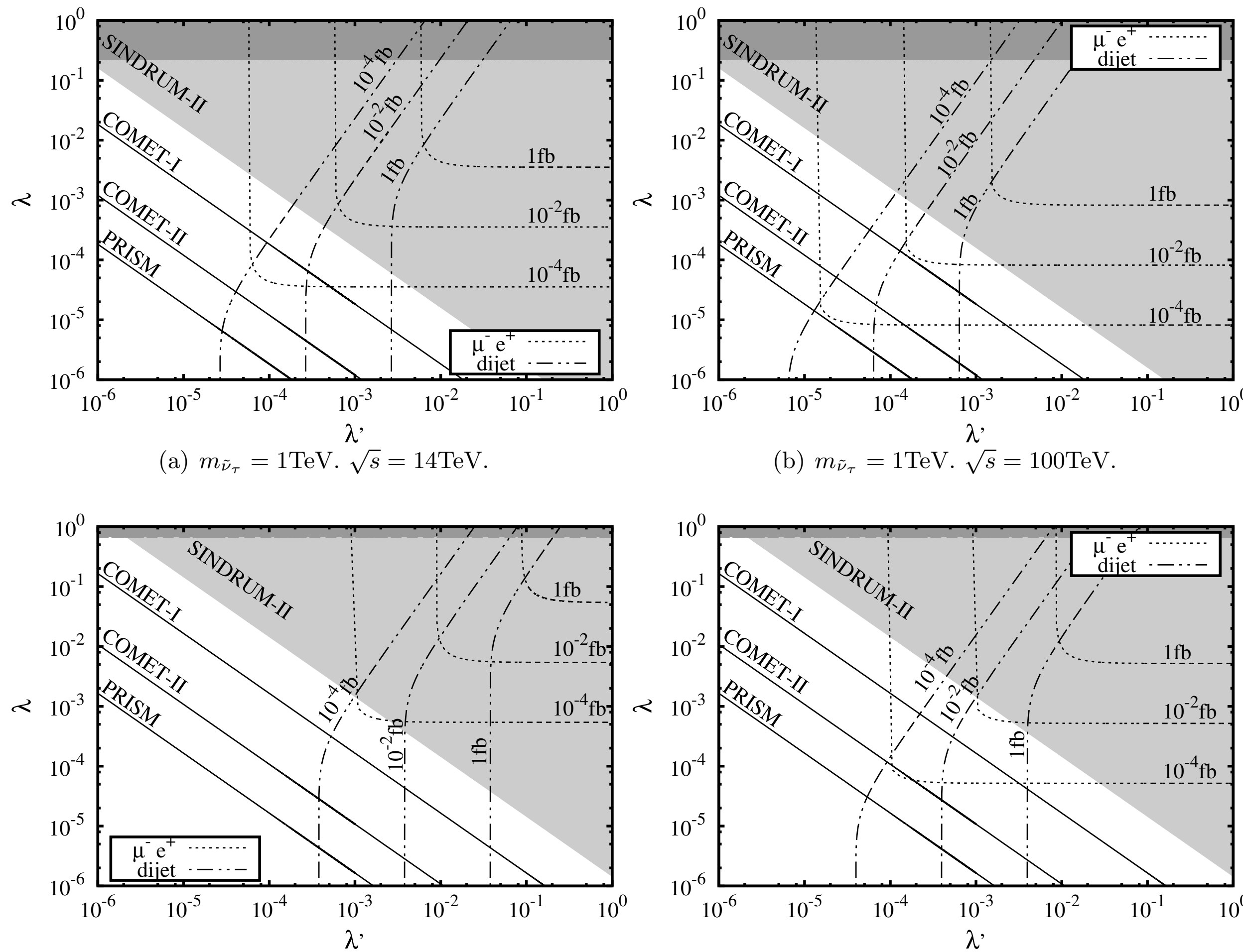


3.5 Interplay between LHC & Low Energy

Sato & Yamanaka'15
See poster by M. Yamanaka

- In the muon sector:
  Ex: R-parity violating SUSY operators with no signals in $\mu \to e\gamma$ and $\mu \to 3e$:





(a) $m_{\tilde{\nu}_\tau} = 1\text{TeV}$. $\sqrt{s} = 14\text{TeV}$.

(b) $m_{\tilde{\nu}_\tau} = 1\text{TeV}$. $\sqrt{s} = 100\text{TeV}$.

(c) $m_{\tilde{\nu}_\tau} = 3\text{TeV}$. $\sqrt{s} = 14\text{TeV}$.

(d) $m_{\tilde{\nu}_\tau} = 3\text{TeV}$. $\sqrt{s} = 100\text{TeV}$.

4. Conclusion and Outlook

Summary

- Direct searches for new physics at the TeV-scale at LHC by ATLAS and CMS ⇨ energy frontier

- Probing new physics orders of magnitude beyond that scale and helping to decipher possible TeV-scale new physics requires to work hard on the *intensity* and *precision frontiers*

- *Charged leptons* offer an important spectrum of possibilities:
  - ➢ LFV measurement has SM-free signal
  - ➢ Current experiments and mature proposals promise orders of magnitude sensitivity improvements
  - ➢ We show how CLFV decays offer an excellent model discriminating tools giving indications on
    - the *mediator* (operator structure)
    - the *source of flavour breaking* (comparison $\tau\mu$ vs. τe vs. μe)

Summary

- Direct searches for new physics at the TeV-scale at LHC by ATLAS and CMS ⇨ energy frontier

- Probing new physics orders of magnitude beyond that scale and helping to decipher possible TeV-scale new physics requires to work hard on the *intensity* and *precision frontiers*

- *Charged leptons* offer an important spectrum of possibilities:
  - ➢ We show how CLFV decays offer an excellent model discriminating tools giving indications on
    - the *mediator* (operator structure)
    - the *source of flavour breaking* (comparison $\tau\mu$ vs. τe vs. μe)

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

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

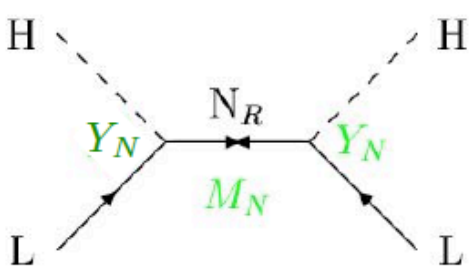
  ⇨ New physics models usually strongly correlate these sectors

5. Back-up

CLFV in see-saw models

Type I:
Fermion singlet

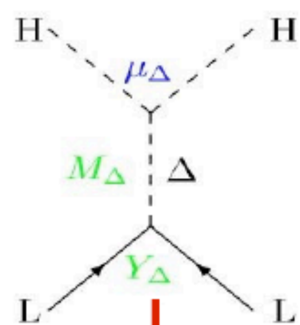
N_{R_i}



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Type II:
Scalar triplet

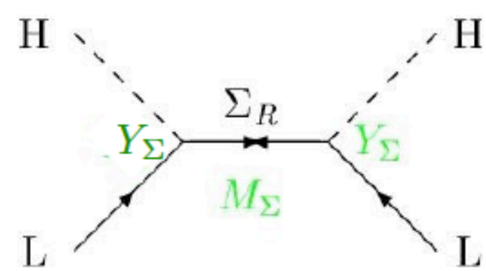
$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Type III:
Fermion triplet

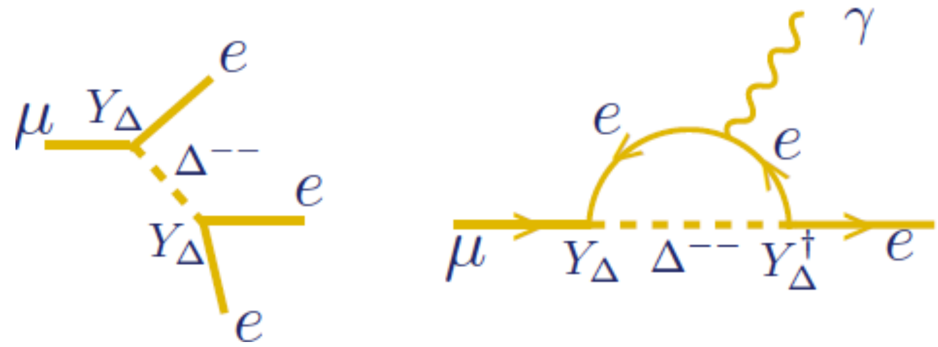
$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

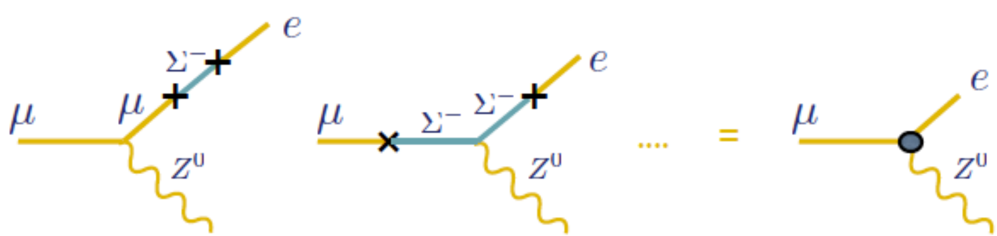
- Observable CLFV if see-saw scale low (with protection of LN)
- Each model leads to specific CLFV pattern

- CLFV in Type II seesaw: tree-level 4L operator (D,V at loop) → 4-lepton processes most sensitive



- CLFV in Type III seesaw: tree-level LFV couplings of Z ⇒

  μ →3e and μ →e conversion at tree level, μ →eγ at loop



Abada-Biggio-Bonnet-Gavela-Hambye '07, '08

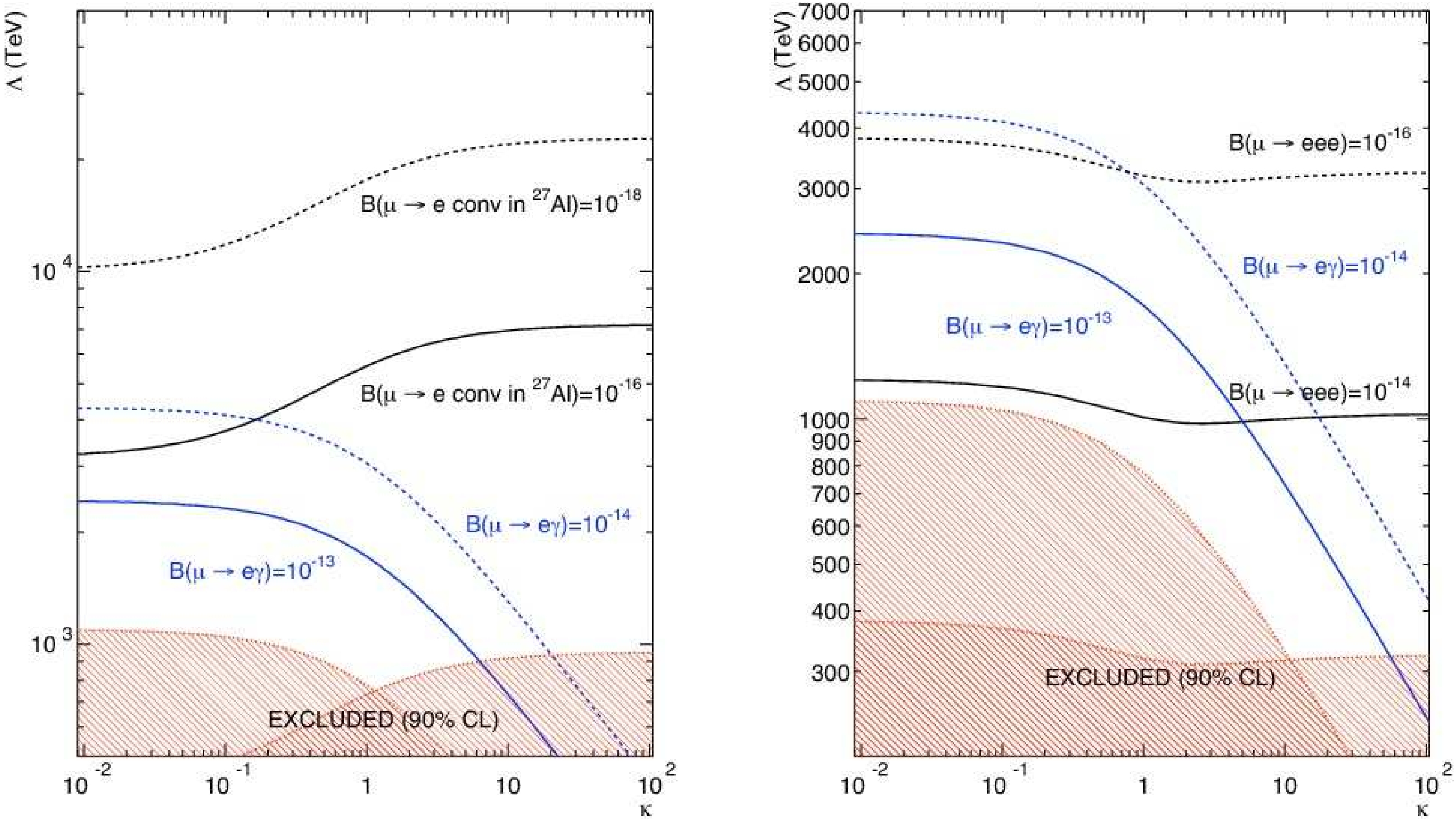
- Ratios of 2 processes with same flavor transition are fixed

$$\begin{aligned}
Br(\mu \to e\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\mu \to eee) = 3.1 \cdot 10^{-4} \cdot R^{\mu\to e}_{Ti} \\
Br(\tau \to \mu\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\tau \to \mu\mu\mu) \\
Br(\tau \to e\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\tau \to eee)
\end{aligned}$$

2.4 Model discriminating power of muon processes

- Dependence: NP scale Λ versus ratio of two operators $\kappa = \frac{C_1}{C_2}$

DeGouvea & Vogel'13



2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- 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: $C_{GG} \neq 0$, $C_{else} = 0$

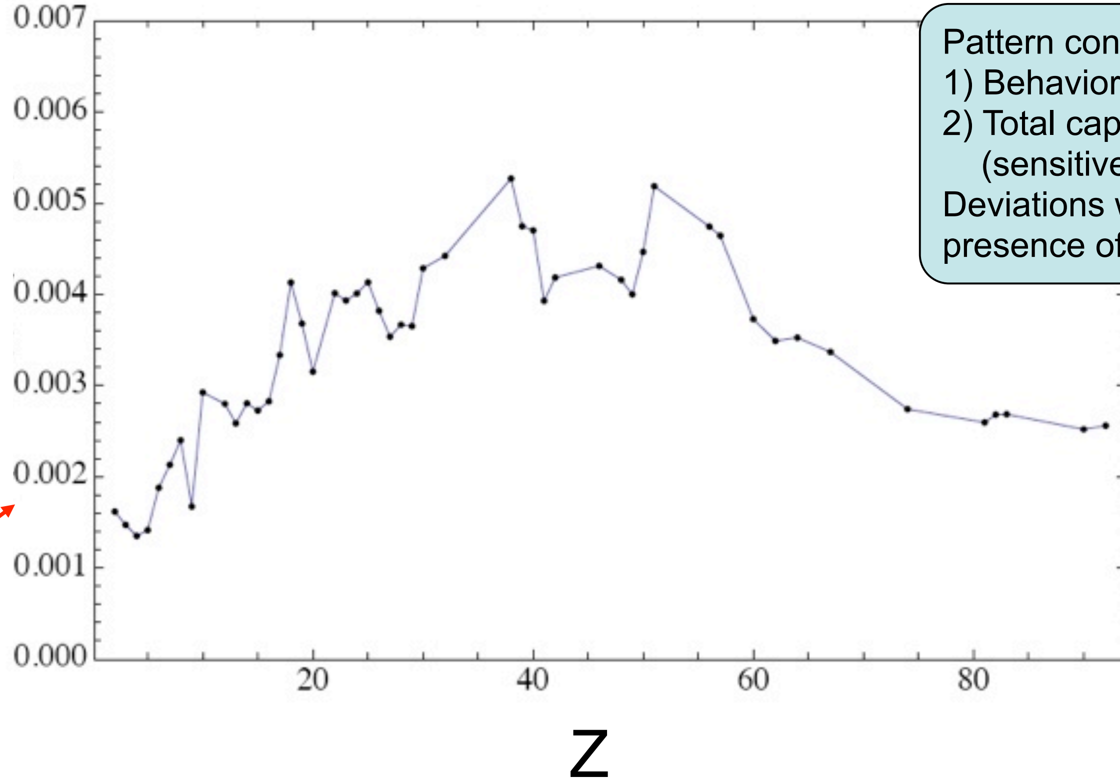
μ→e vs μ→eγ

- Assume dipole dominance:

$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

Kitano-Koike-Okada '02
VC-Kitano-Okada-Tuzon '09

$$\boxed{\frac{B(\mu \to e, Z)}{B(\mu \to e\gamma)}}$$



O(α/π)

Pattern controlled by:
1) Behavior of overlap integrals
2) Total capture rate
(sensitive to nuclear structure)
Deviations would indicate presence of scalar / vector terms

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

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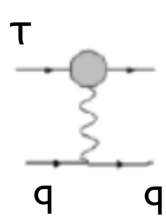
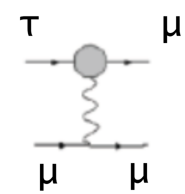
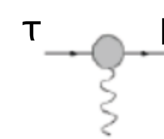
  - Branching ratios: $\boxed{R_{F,M} \equiv \dfrac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}}$ with F_M dominant LFV mode for model M

		$\mu\pi^+\pi^-$	$\mu\rho$	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:

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

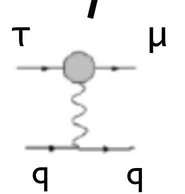
2.5 Model discriminating power of Tau processes

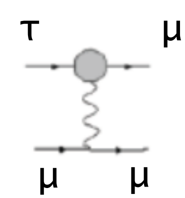
Celis, Cirigliano, E.P.'14

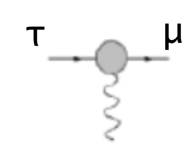
- Two handles:
  - Branching ratios: $\boxed{R_{F,M} \equiv \frac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}}$ with F_M dominant LFV mode for model M

		$\mu\pi^+\pi^-$	$\mu\rho$	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	$< 2.1 \times 10^{-8}$	$< 8.6 \times 10^{-9}$	$< 8.6 \times 10^{-9}$	-	-

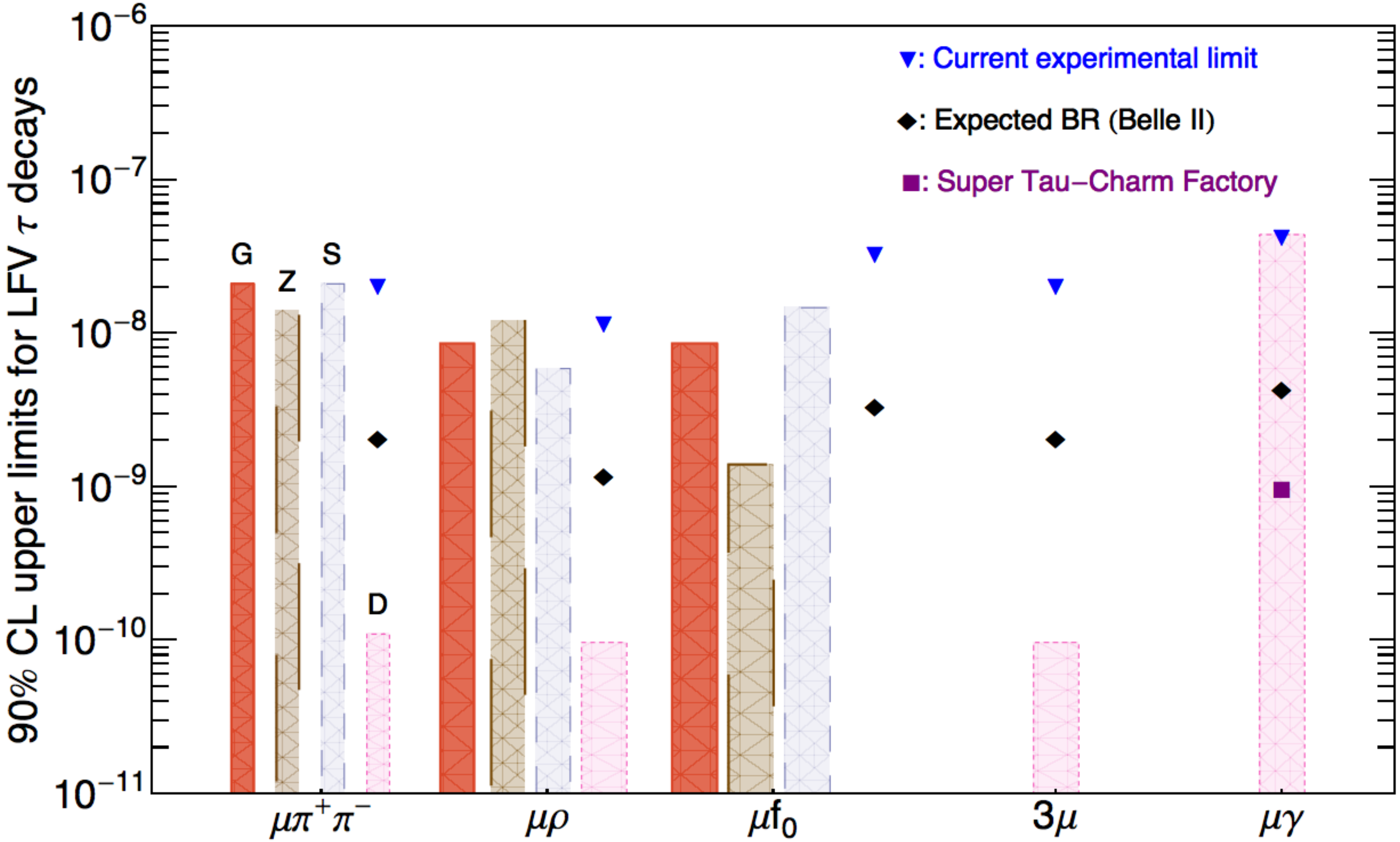
Benchmark







4.2 Prospects:

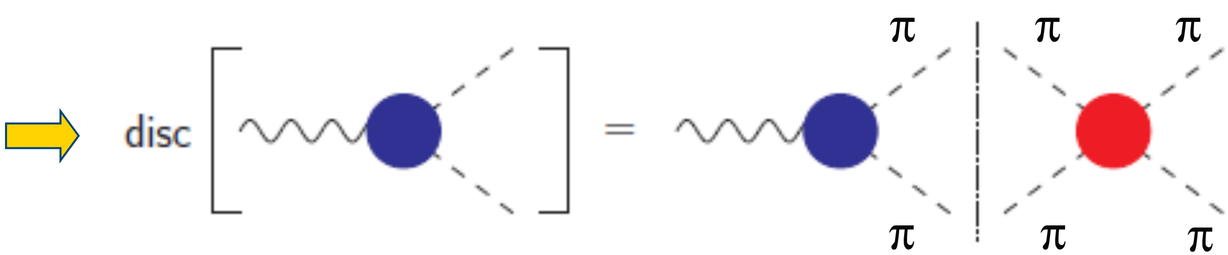


3.4.2 Dispersion relations: Method

- Unitarity ⇨ the discontinuity of the form factor is known

$$\boxed{\frac{1}{2i}\, disc\; F_{\pi\pi}(s) = \mathrm{Im}\, F_{\pi\pi}(s) = \sum_n F_{\pi\pi\to n}\left(\mathrm{T}_{n\to\pi\pi}\right)^*}$$

- Only one channel n = ππ



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

ππ scattering phase
known from experiment

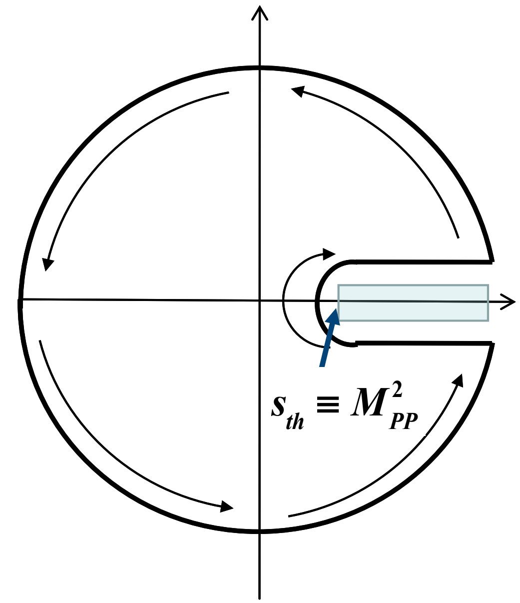
Watson's theorem

3.4.2 Dispersion relations: Method

- Knowing the discontinuity of F ⇨ write a dispersion relation for it

- Cauchy Theorem and Schwarz reflection principle

$$F(s) = \frac{1}{\pi}\oint \frac{F(s')}{s'-s}ds' \Rightarrow \frac{1}{2i\pi}\int_{M_{PP}^2}^{\infty} \frac{disc\left[F(s')\right]}{s'-s-i\varepsilon}ds'$$



- If F does not drop off fast enough for $|s| \to \infty$
  ⇨ subtract the DR

$$\boxed{F(s) = P_{n-1}(s) + \frac{s^n}{\pi}\int_{M_{PP}^2}^{\infty} \frac{ds'}{s'^n}\frac{\mathrm{Im}\left[F(s')\right]}{\left(s'-s-i\varepsilon\right)}}$$

$P_{n-1}(s)$ polynomial

3.4.2 Dispersion relations: Method

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

➡ Omnès representation : $F_I(s) = \underbrace{P_I(s)}_{\text{polynomial}}\ \underbrace{\Omega_I(s)}_{\text{Omnès function}}$

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

- Polynomial: $P_I(s)$ not known but determined from a matching to experiment or to ChPT at low energy

3.4.3 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 $F_V(s)$

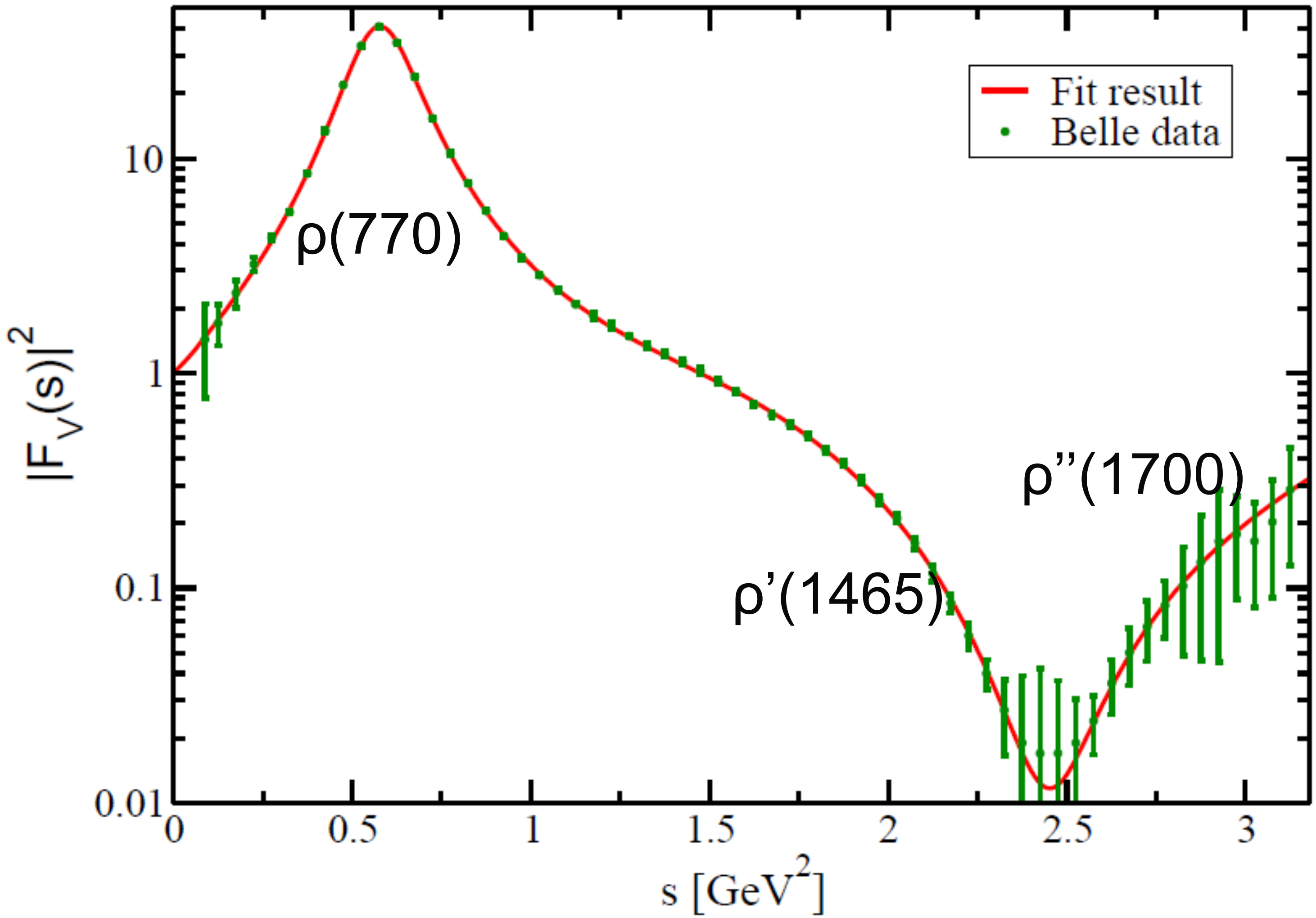
Guerrero, Pich'98, Pich, Portolés'08
Gomez, Roig'13

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

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* $\tau^- \to \pi^0\pi^-\nu_\tau$

3.4.3 Determination of $F_V(s)$

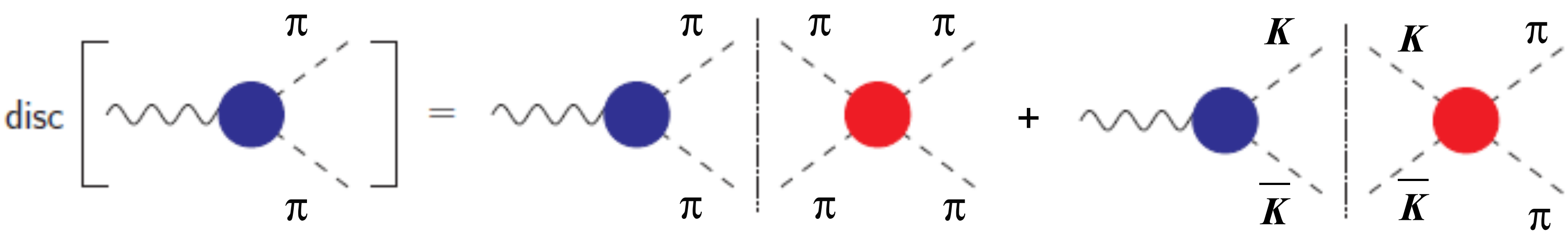


Determination of $F_V(s)$ thanks to precise measurements from Belle!

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

- No experimental data for the other FFs up to $\sqrt{s}\sim 1.4$ GeV
  Inputs: I=0, S-wave $\pi\pi$ and $K\bar{K}$ data
  → *Coupled channel analysis*
  Donoghue, Gasser, Leutwyler'90
  Moussallam'99
  Daub et al'13

- Unitarity:

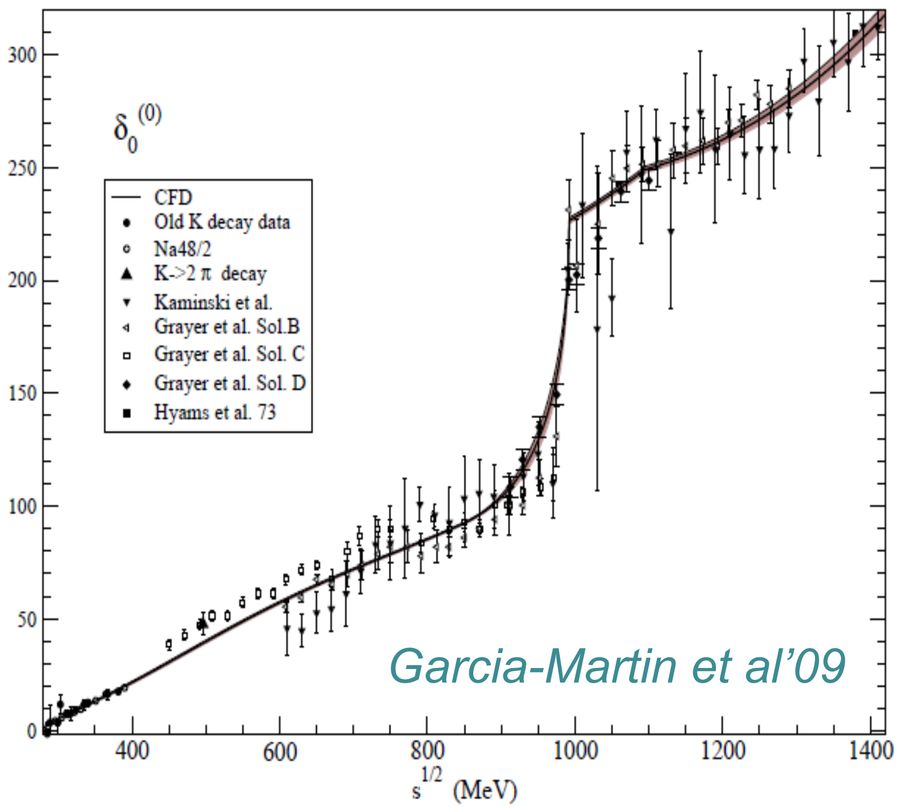


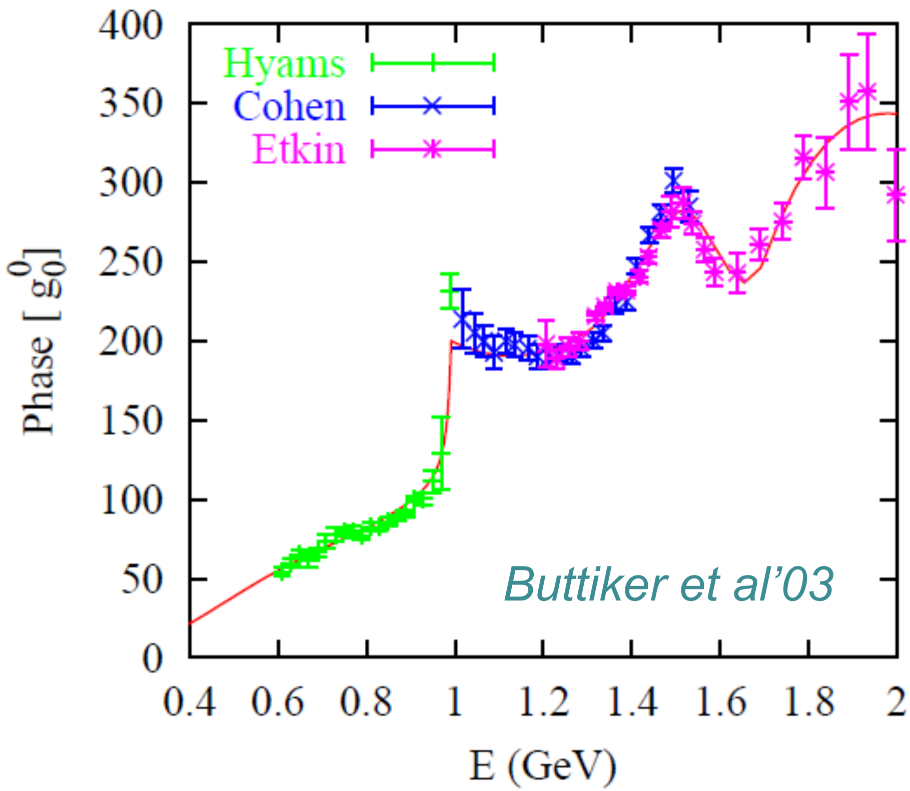
$$\Rightarrow \quad \boxed{\mathrm{Im} F_n(s) = \sum_{m=1}^{2} T^*_{nm}(s)\sigma_m(s)F_m(s)} \qquad n = \pi\pi, K\bar{K}$$

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

Celis, Cirigliano, E.P.'14

- Inputs : $\pi\pi \to \pi\pi, KK$





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

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

- General solution:

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

Canonical solution

Polynomial determined from a matching to ChPT + lattice

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

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

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

Determination of the polynomial

- General solution

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

- Fix the polynomial with requiring $F_P(s) \to 1/s$ (*Brodsky & Lepage*) + ChPT:

  Feynman-Hellmann theorem: ⇨

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

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

- At LO in ChPT:

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

⇨

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

Determination of the polynomial

- General solution

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

- At LO in ChPT:

$$\begin{aligned} M^2_{\pi^+} &= (m_u + m_d)\, B_0 + O(m^2) \\ M^2_{K^+} &= (m_u + m_s)\, B_0 + O(m^2) \\ M^2_{K^0} &= (m_d + m_s)\, B_0 + O(m^2) \end{aligned} \Rightarrow \begin{aligned} P_\Gamma(s) &= \Gamma_\pi(0) = M_\pi^2 + \cdots \\ Q_\Gamma(s) &= \frac{2}{\sqrt{3}}\Gamma_K(0) = \frac{1}{\sqrt{3}} M_\pi^2 + \cdots \\ P_\Delta(s) &= \Delta_\pi(0) = 0 + \cdots \\ Q_\Delta(s) &= \frac{2}{\sqrt{3}}\Delta_K(0) = \frac{2}{\sqrt{3}}\left(M_K^2 - \frac{1}{2}M_\pi^2\right) + \cdots \end{aligned}$$

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

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

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

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

Determination of the polynomial

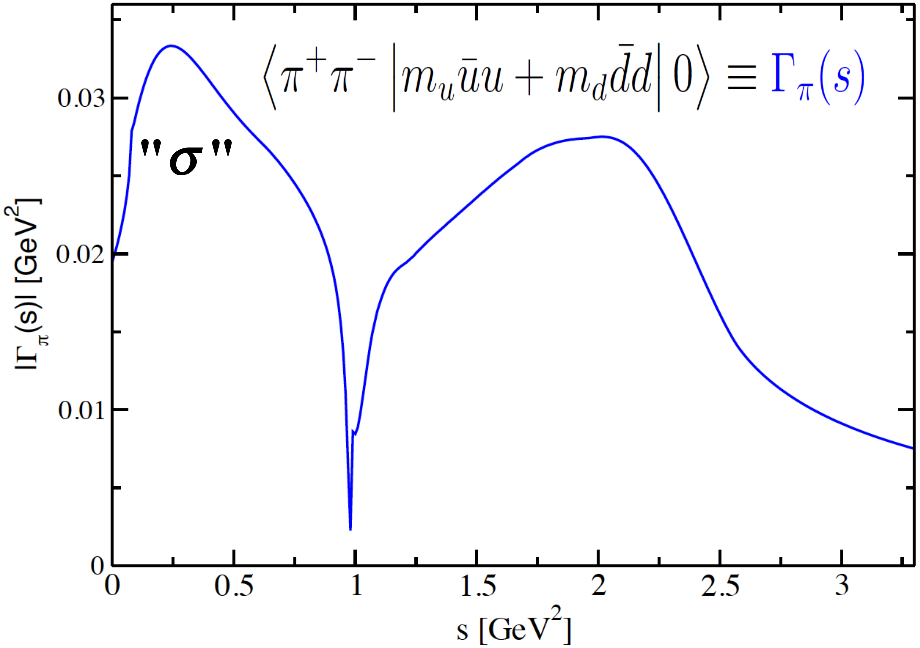
- General solution

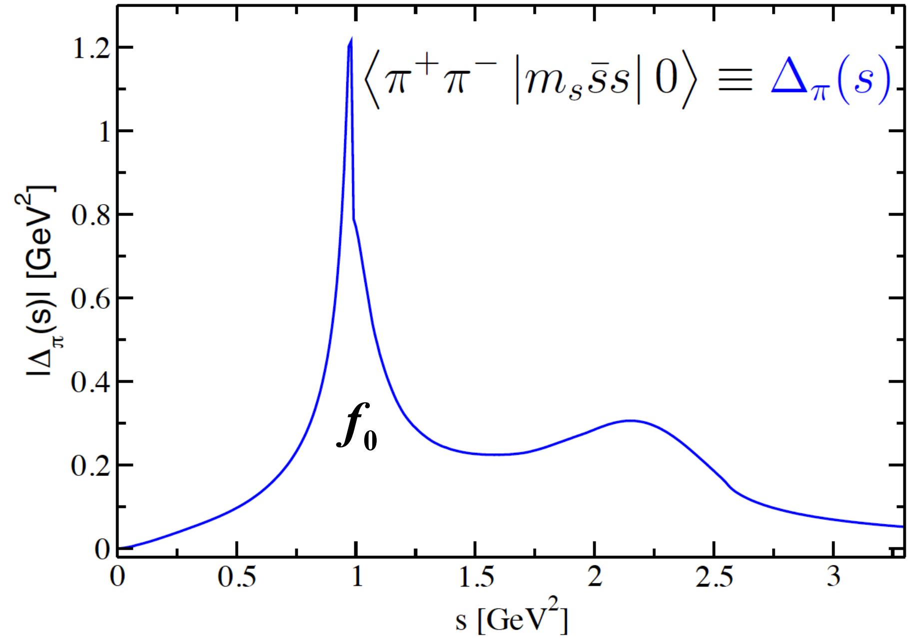
$$\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}$$

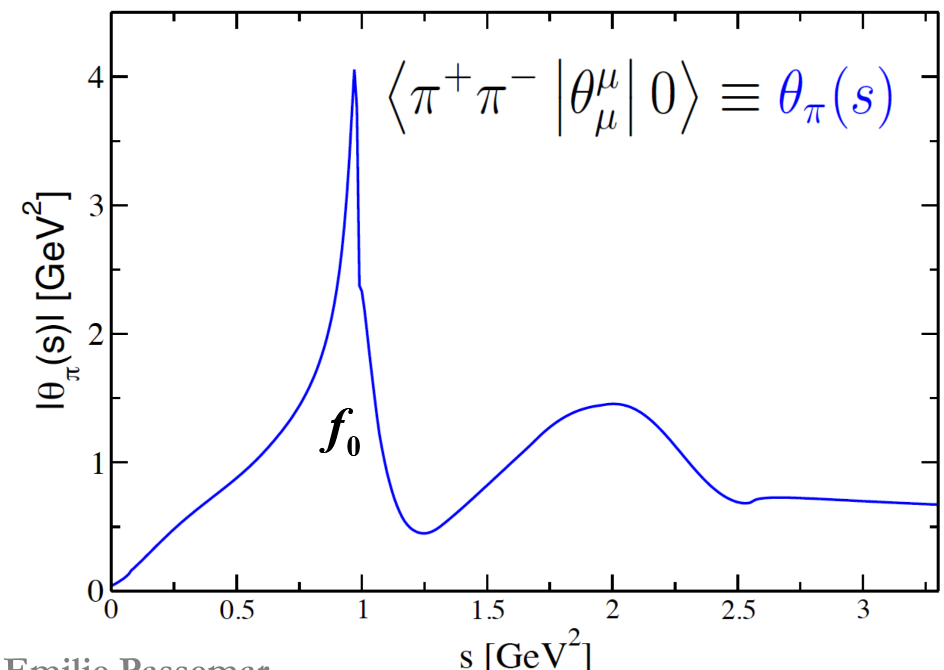
- For θ_P enforcing the asymptotic constraint is not consistent with ChPT
  The unsubtracted DR is not saturated by the 2 states

⇨ Relax the constraints and match to ChPT

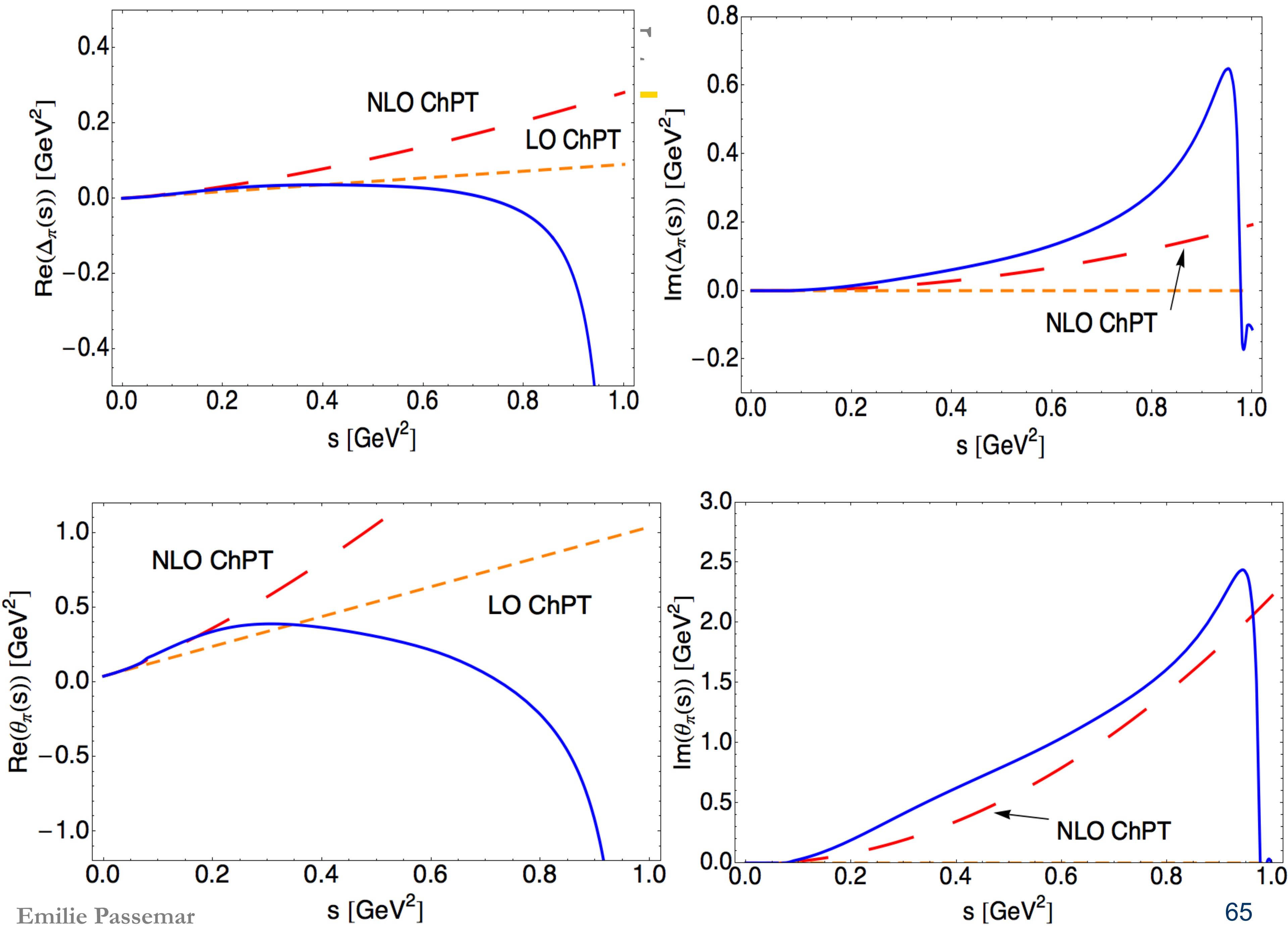
$$\begin{aligned} P_\theta(s) &= 2M_\pi^2 + \left(\dot{\theta}_\pi - 2M_\pi^2 \dot{C}_1 - \frac{4M_K^2}{\sqrt{3}} \dot{D}_1\right) s \\ Q_\theta(s) &= \frac{4}{\sqrt{3}} M_K^2 + \frac{2}{\sqrt{3}} \left(\dot{\theta}_K - \sqrt{3} M_\pi^2 \dot{C}_2 - 2M_K^2 \dot{D}_2\right) s \end{aligned}$$



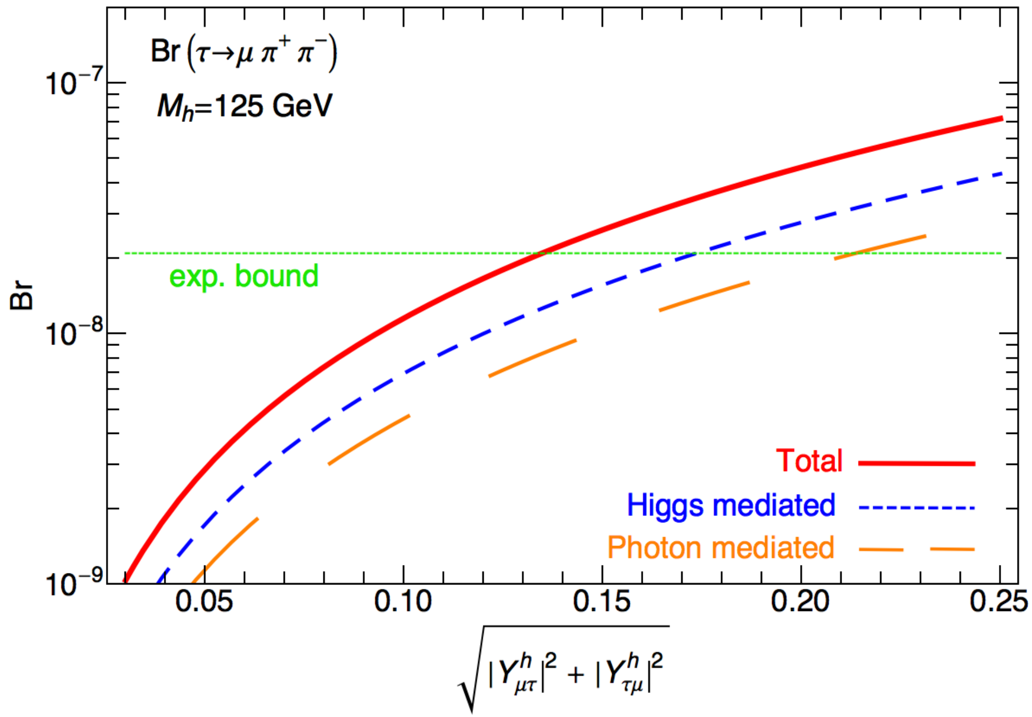




Dispersion relations:
Model-independent method,
based on first principles
that extrapolates ChPT
based on data


NLO ChPT
LO ChPT
Re(Δ_π(s)) [GeV²]
s [GeV²]
Im(Δ_π(s)) [GeV²]
NLO ChPT
Re(θ_π(s)) [GeV²]
Im(θ_π(s)) [GeV²]

3.5 Results



Bound:

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

Process	(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
$\tau\to\mu\pi^0\pi^0$	$<1.4\times10^3$ [87]	<6.3	Scalar, Gluon

Less stringent but more robust handle on LFV Higgs couplings

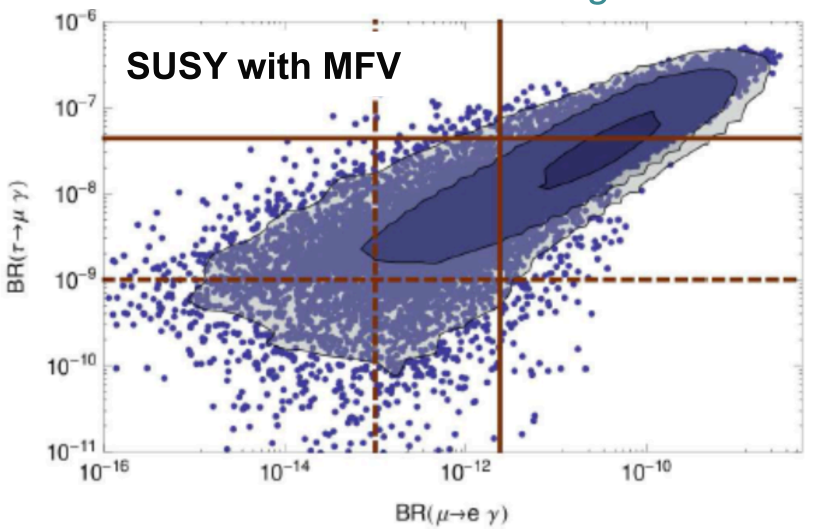
?

Belle'08'11'12 except last from *CLEO'97*

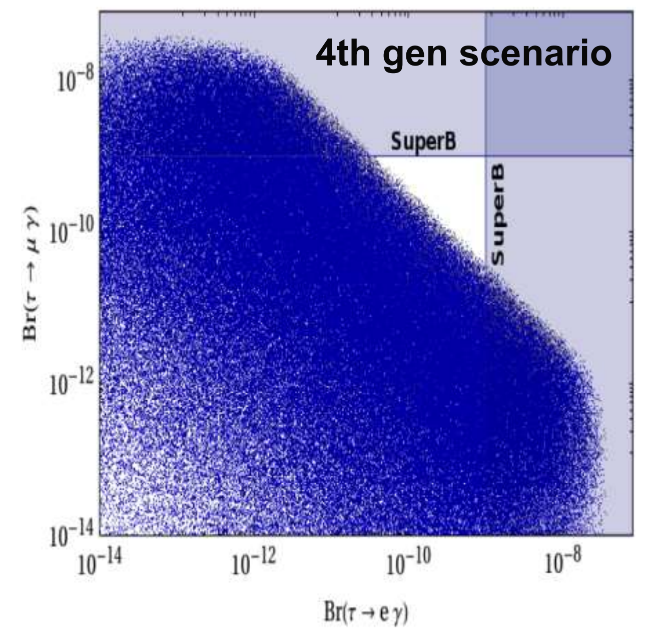
2.5 Model discriminating power of Tau processes

- Depending on the UV model different correlations between the BRs

Blankerburg et al.'12



Buras et al.'10

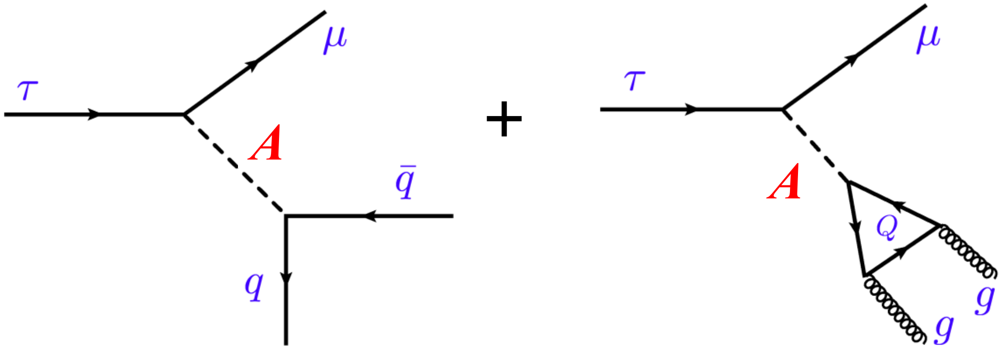


➡ Interesting to study to determine the underlying dynamics of NP

4. CP-odd Higgs with LFV

4.1 Constraints from $\tau \to 1P$

- Tree level Higgs exchange



- L_Y ⇒ $$\boxed{\mathcal{L}_{eff}^{A} \simeq -\frac{A}{v}\left(\sum_{q=u,d,s} y_q^A\, m_q\, \bar{q} i\gamma_5\, q - \sum_{q=c,b,t} y_q^A\, \frac{\alpha_s}{8\pi}\, G_{\mu\nu}^a\, \widetilde{G}_{\mu\nu}^a\right)}$$

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

- Mediate only one pseudoscalar meson ⇒ very characteristic!

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 :

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

4.2 Results

- $\tau \longrightarrow \mu P$

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

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

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

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

4.2 Results

- $\tau \longrightarrow eP$

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

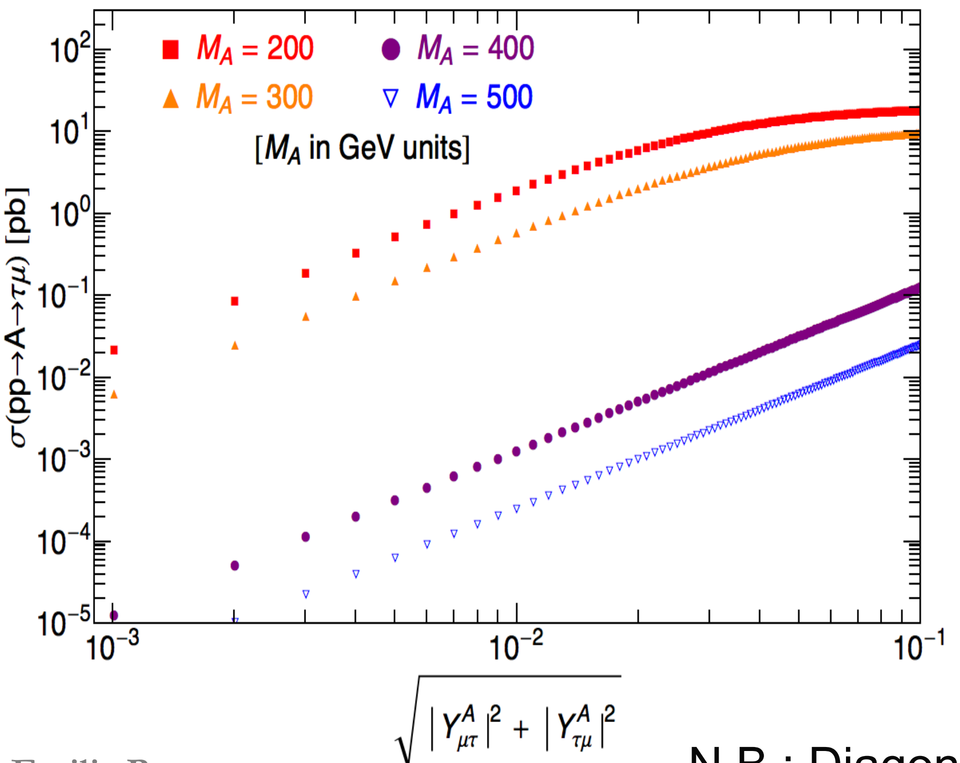
N.B.: Diagonal couplings $\left|y^A_f\right| = 1$

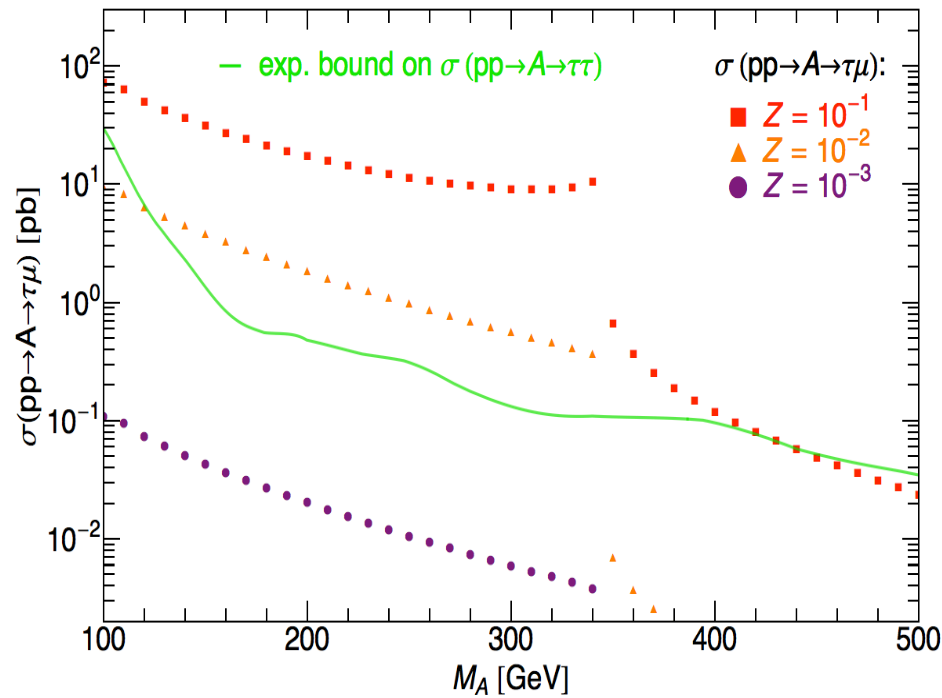
4.3 Prospects at LHC

see also e.g., Assamagan, Deandrea, Delsart'03
Davidson & Verdier'12
Arana-Catania, Arganda, Herrero'14

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

  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 couple to WW, ZZ at tree level. Results :



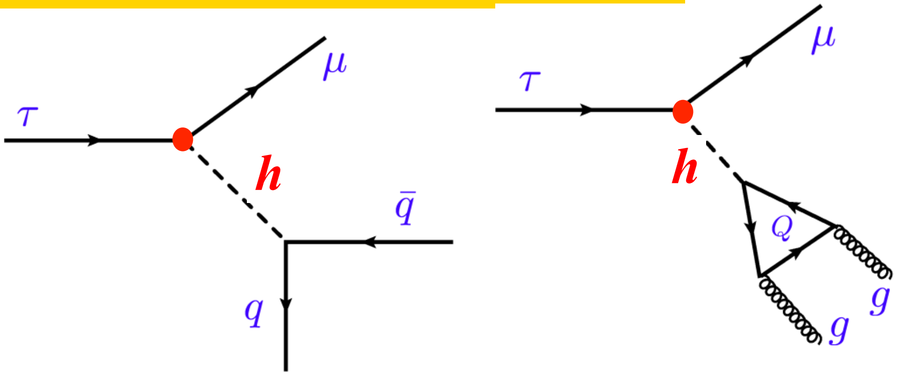


N.B.: Diagonal couplings $\left|y_f^A\right| = 1$

3.5 What if $\tau \to \mu(e)\pi\pi$ observed?
Reinterpreting *Celis, Cirigliano, E.P'14*

Talk by J. Zupan @ KEK-FF2014FALL

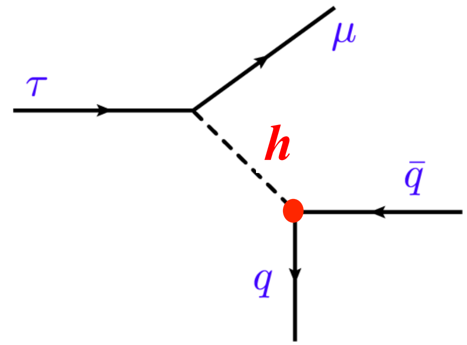
- $\tau \to \mu(e)\pi\pi$ sensitive to $Y_{\mu\tau}$

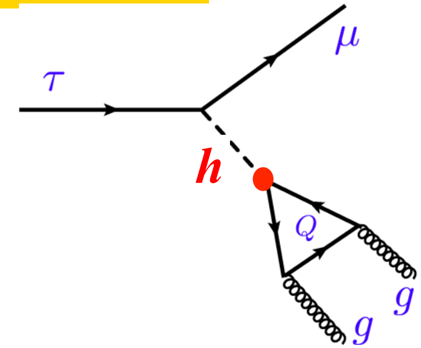


3.5 What if $\tau \to \mu(e)\pi\pi$ observed?
Reinterpreting *Celis, Cirigliano, E.P'14*

Talk by J. Zupan @ KEK-FF2014FALL

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





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

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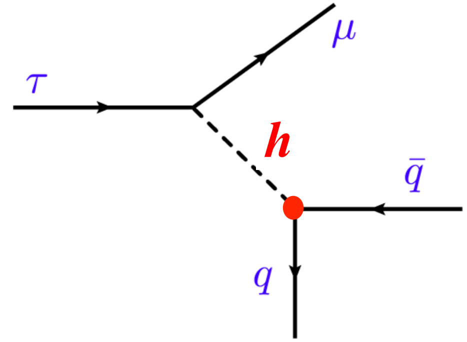
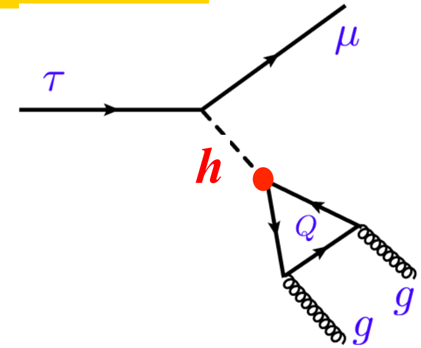
Talk by J. Zupan @ KEK-FF2014FALL





- $\tau \to \mu(e)\pi\pi$ sensitive to $Y_{\mu\tau}$ but also to $Y_{u,d,s}$!
- $Y_{u,d,s}$ 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 ⇨ among other things *upper limit* on $Y_{u,d,s}$*!*

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