Higgs mediated lepton flavour violation

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  AC, Cirigliano, Passemar (1309.3564)

- Prospects for LFV Higgs decays at the LHC

The Higgs boson couplings are not dictated by gauge symmetries.

$$\mathcal{L}_{\mathrm{Y}} = - \sum_{j,k=1}^{3} \left\{ \left(\bar{u}_j, \bar{d}_j\right)_L \left[c_{jk}^{(d)}\, \Phi\, d_{kR} \;+\; c_{jk}^{(u)}\, \tilde{\Phi}\, u_{kR} \right] \right.$$
$$\left. +\;\; \left(\bar{\nu}_j, \bar{l}_j\right)_L\, c_{jk}^{(l)}\, \Phi\, l_{kR} \right\} \;+\; \mathrm{h.c.}$$

Diagonalizing the mass terms after EWSB

$$f_L \to U_L^f\, f_L\,, \qquad f_R \to U_R^f\, f_R$$

$$\mathcal{L}_Y \;=\; -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}\, M_d\, d + \bar{u}\, M_u\, u + \bar{l}\, M_l\, l \right\}$$

Neutral weak current is diagonal in the fermion mass basis.

Charged weak current is non-diagonal in the fermion mass basis

$$\mathcal{L}_{\mathrm{CC}} \;=\; \frac{g}{2\sqrt{2}} \left\{ W_\mu^\dagger \left[\sum_{ij} \bar{u}_i\, \gamma^\mu (1-\gamma_5)\, V_{ij}\, d_j + \sum_l \bar{\nu}_l\, \gamma^\mu (1-\gamma_5)\, l \right] + \mathrm{h.c.} \right\}$$

CKM matrix

In the absence of Yukawa couplings the SM has a global flavour symmetry

$$SU(3)_Q \times SU(3)_U \times SU(3)_D$$

rotations of Q_L^i u_R^i d_R^i

The lepton sector posses a similar flavour symmetry, but in this case it depends on how neutrino masses are implemented

$$G_{\mathrm{LF}} = SU(3)_L \times SU(3)_E$$

Minimal field content

Cirigliano et al. (0507001)

rotations of L_L^i ℓ_R^i

With the discovery of the 126 GeV Higgs boson, we can now access directly the flavour symmetry breaking sources (Yukawa couplings)

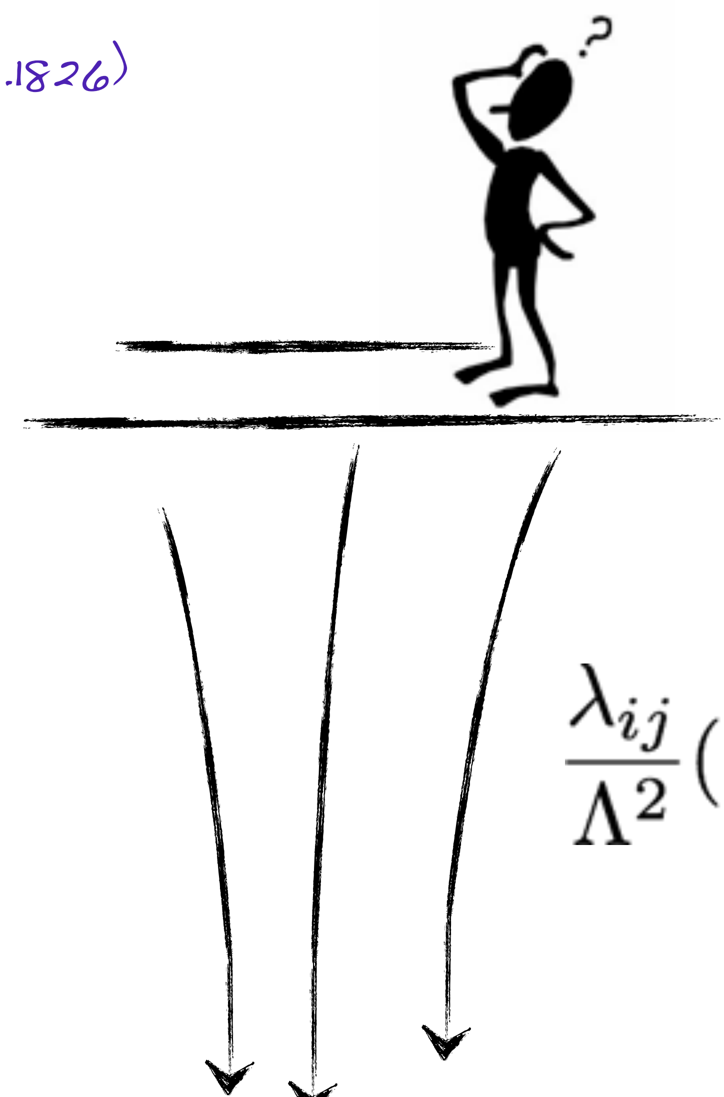
Flavour violation in the Higgs sector

Many scenarios of physics beyond the SM predict rates for charged lepton flavour violating transitions at observable levels

for a long review see: M. Raidal et al. (0801.1826)

Different channels to probe charged LFV at low energy

Important to unravel the origin of LFV



$\mu - e$ conversion in nuclei

$\mu \to e\gamma$

$\mu \to 3e$

$$\frac{\lambda_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H)$$

$\tau \to \ell\gamma$

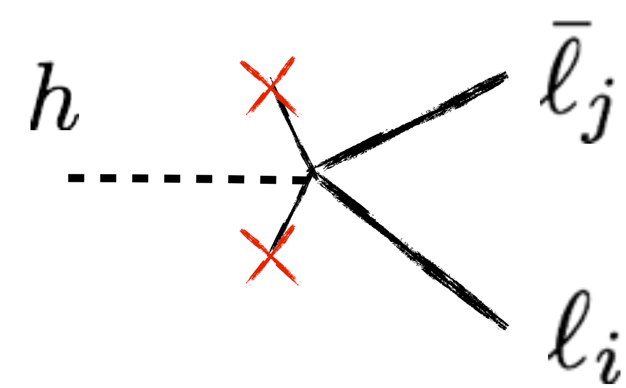
$$H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$\tau \to \ell\ell'\bar{\ell}''$

$\tau \to \ell P$ $\qquad P = \pi, \eta, \eta'$

$\tau \to \ell V$ $\qquad V = \rho(770), f_0(980)$

$\tau \to \ell PP$



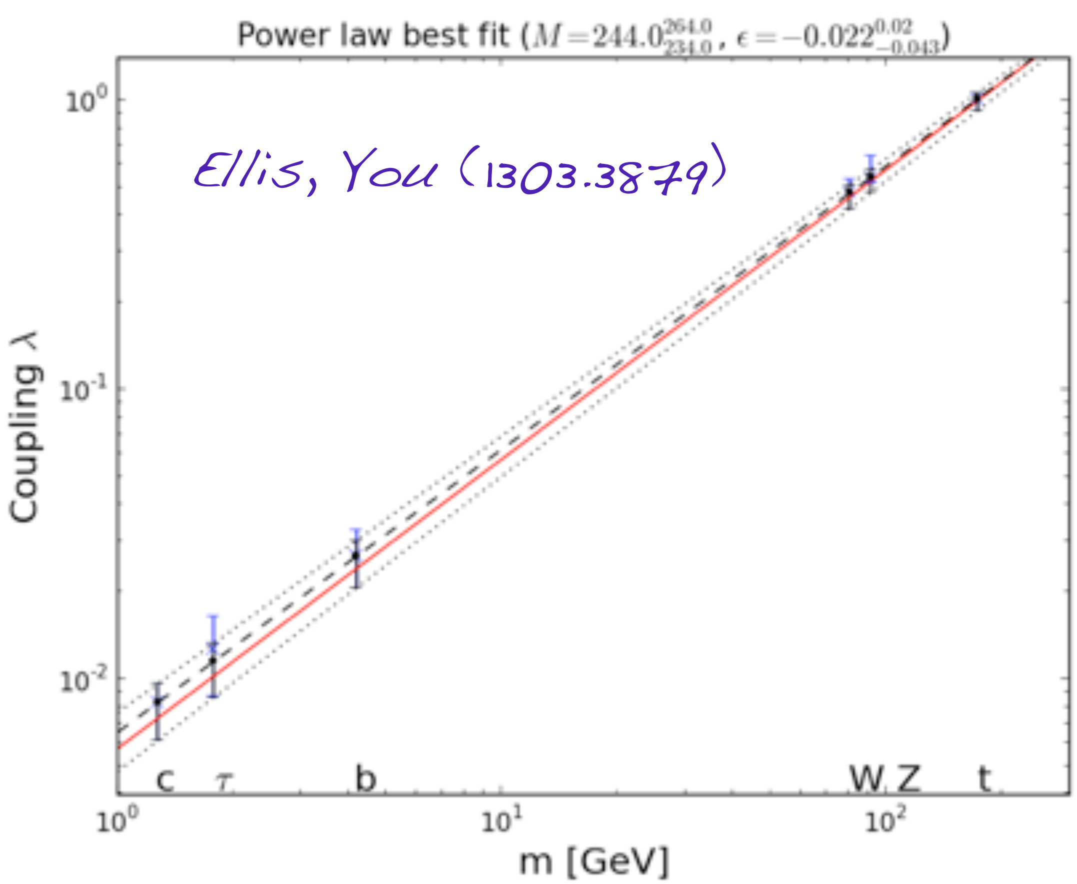
Flavour violation in the Higgs sector

So far, what do we now about the Yukawa couplings of the 126 GeV Higgs?

$$\mathcal{L}_{\mathrm{Y}} = - \sum_{j,k=1}^{3} \left\{ \left(\bar{u}_j, \bar{d}_j\right)_L \left[c_{jk}^{(d)} \, \Phi \, d_{kR} \, + \, c_{jk}^{(u)} \, \tilde{\Phi} \, u_{kR} \right] \right. \\ \left. + \, \left(\bar{\nu}_j, \bar{l}_j\right)_L \, c_{jk}^{(l)} \, \Phi \, l_{kR} \right\} + \, \mathrm{h.c.}$$

LHC data confirms that the relation $Y_{ii} = \dfrac{m_i}{v}$ hold for 3° family fermions

(with still significant uncertainties)



Coupling with vector bosons also SM-like

Not much can be done for 1° and 2° family fermions at the LHC.

High Lum. LHC can probably measure $Y_{\mu\mu}$

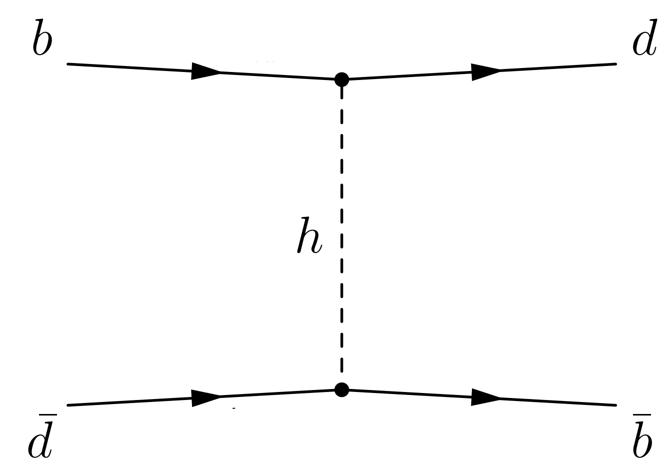
Flavour violation in the Higgs sector

Indirect bonds on flavour changing couplings of the 126 GeV Higgs are already quite strong in most of the cases, putting the relevant decay rates $h \to f_i \bar{f}_j$ beyond the reach of colliders

In the quark sector

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc} Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db} Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2,\ \lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb} Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2),\ \mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2),\ \mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$

Blankenburg, Ellis, Isidori (1202.5704)
Harnik, Kopp, Zupan (1209.1397)



M. Bona et al. (0707.0636)
Isidori, Nir, Perez (1002.0900)

flavour changing Higgs couplings with top are weakly constrained

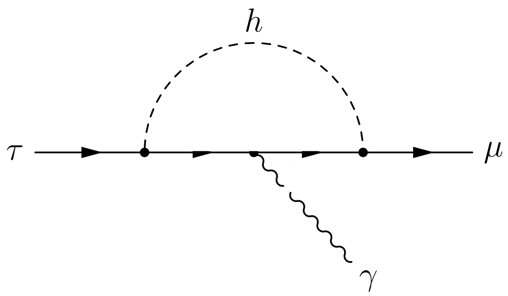
$$t \to hj \qquad \sqrt{|Y_{tq}|^2 + |Y_{qt}|^2} < 0.34\,, \qquad (q = u, c)$$

from CMS multi-lepton search

Harnik, Kopp, Zupan (1209.1397)

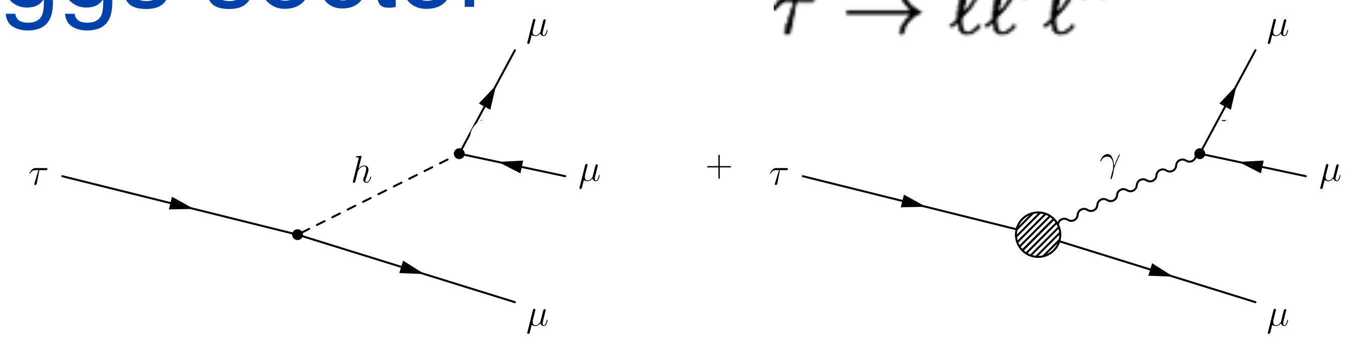
Flavour violation in the Higgs sector

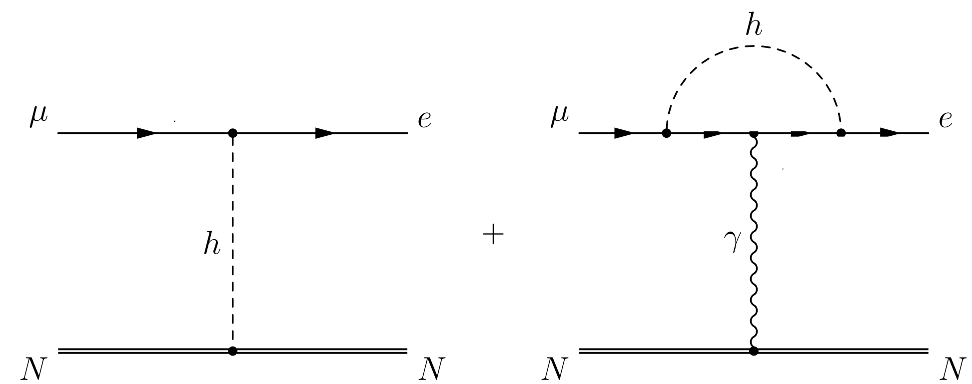
In the lepton sector



$$\tau \to \ell\gamma$$

$$\tau \to \ell\ell'\bar{\ell}''$$





$\mu - e$ conversion in nuclei

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$

$$\mathrm{Br}(h \to e\mu) < 3 \times 10^{-9}$$

Indirect bounds are very weak for tau-mu and tau-e

$$\mathrm{Br}(h \to \tau\ell) \leq 10\%$$

fixing the diagonal couplings to their SM value

Harnik, Kopp, Zupan (1209.1397)

Blankenburg, Ellis, Isidori (1202.5704)

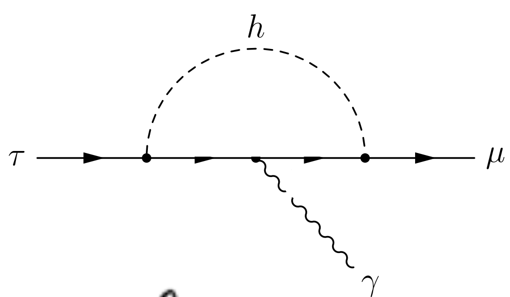
Diaz-Cruz, Toscano (9910233)

LFV radiative decays

A transition dipole moment is generated at the loop level

$$(\bar{\ell}\sigma^{\mu\nu}P_{L,R}\tau)F_{\mu\nu}$$

Dominant contribution from 2-loop diagrams of Barr-Zee type



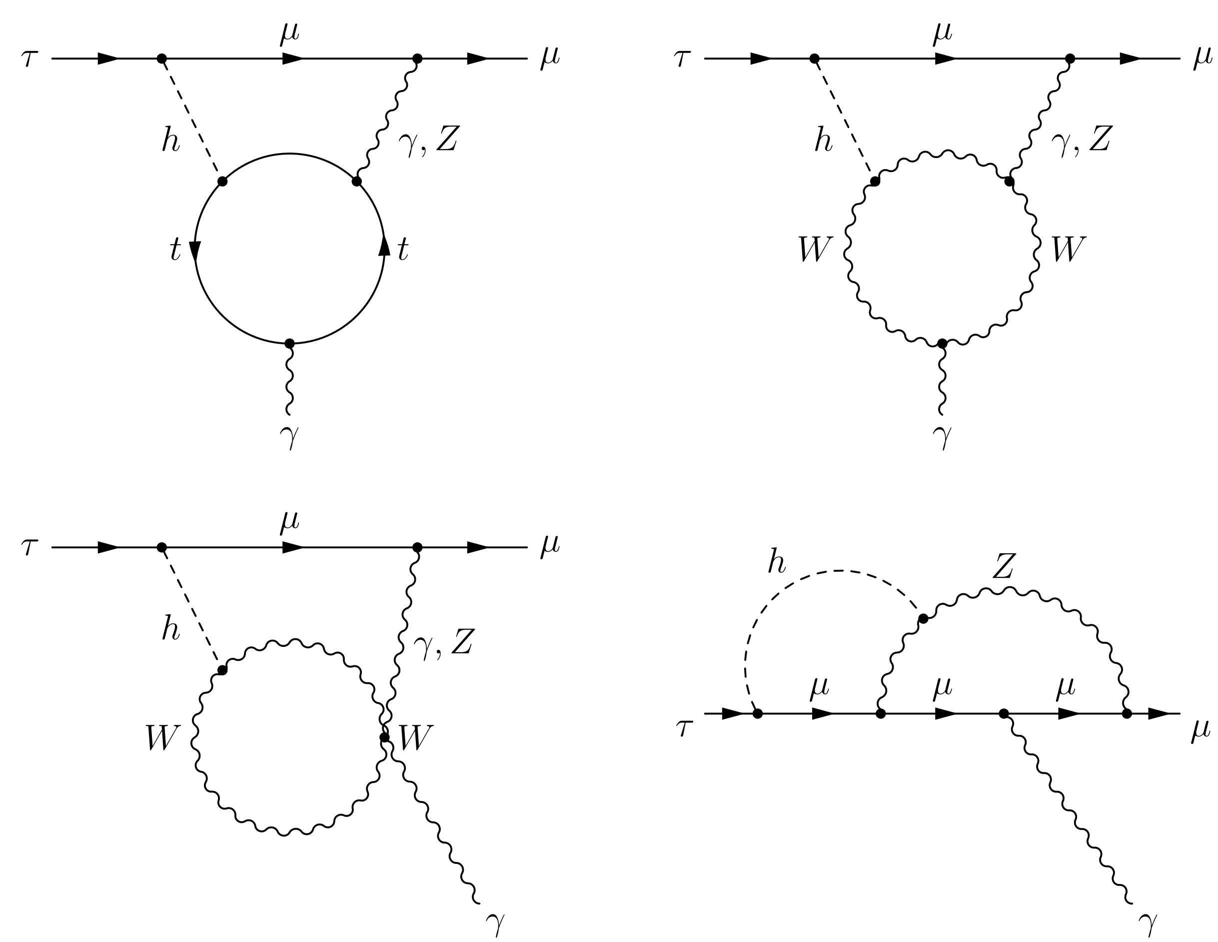
$\tau \to \ell\gamma$

1-loop diagram involve three chirality flips

This is just an accident at the 1-loop level and can be avoided at higher orders

Bjorken, Weinberg (1977)

Chang, Hou, Keung (1993)



diagrams extracted from Harnik, Kopp, Zupan (2012)

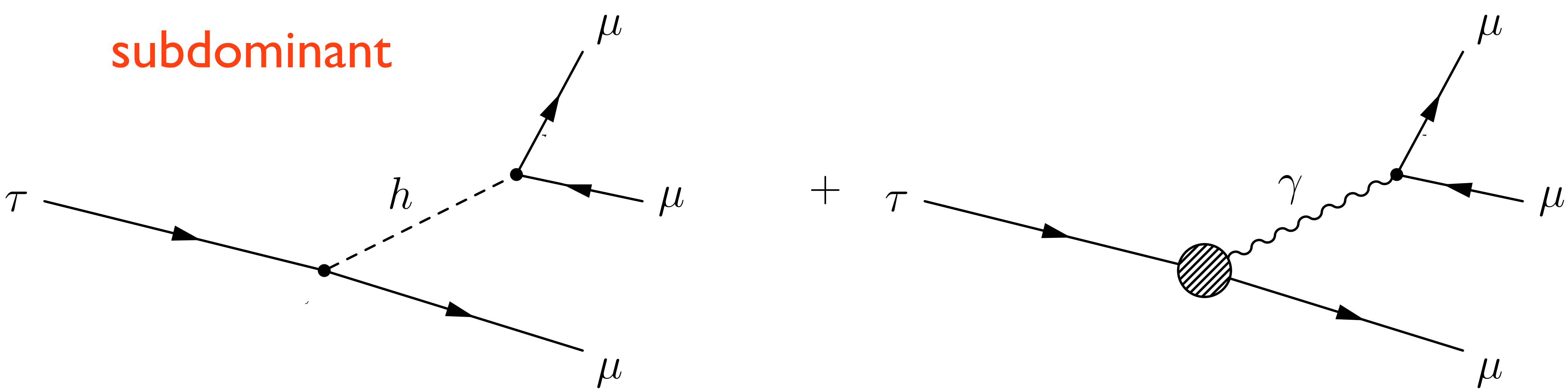
LFV leptonic decays

If LFV leptonic decays are observed at some point, a Dalitz plot analysis would provide a useful handle to disentangle different kinds of new physics

Dassinger, Feldmann, Mannel, Turczyk (0707.0988)

suppressed by small Yukawa $Y_{\mu\mu}$

subdominant



τ^- decay mode	Upper bound on BR (90 % CL)
$e\gamma$	3.3×10^{-8}
$\mu\gamma$	4.4×10^{-8}
$e^-e^+e^-$	2.7×10^{-8}
$e^-\mu^+\mu^-$	2.7×10^{-8}
$e^+\mu^-\mu^-$	1.7×10^{-8}
$\mu^-e^+e^-$	1.8×10^{-8}
$\mu^+e^-e^-$	1.5×10^{-8}
$\mu^-\mu^+\mu^-$	2.1×10^{-8}

additional $\alpha_{\rm em}$ suppression in the decay rate compared with the radiative mode

$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$

diagrams extracted from Harnik, Kopp, Zupan (2012)

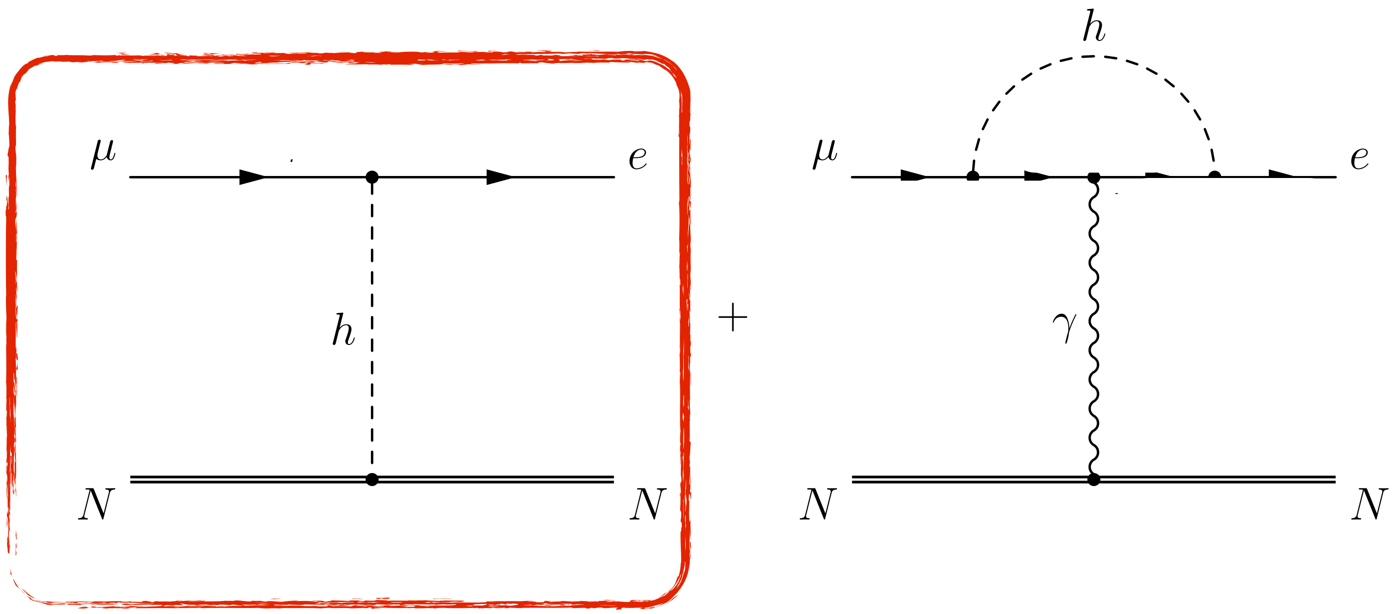
mu-e conversion in nuclei

Cirigliano, Kitano, Okada, Tuzon (0904.0957)

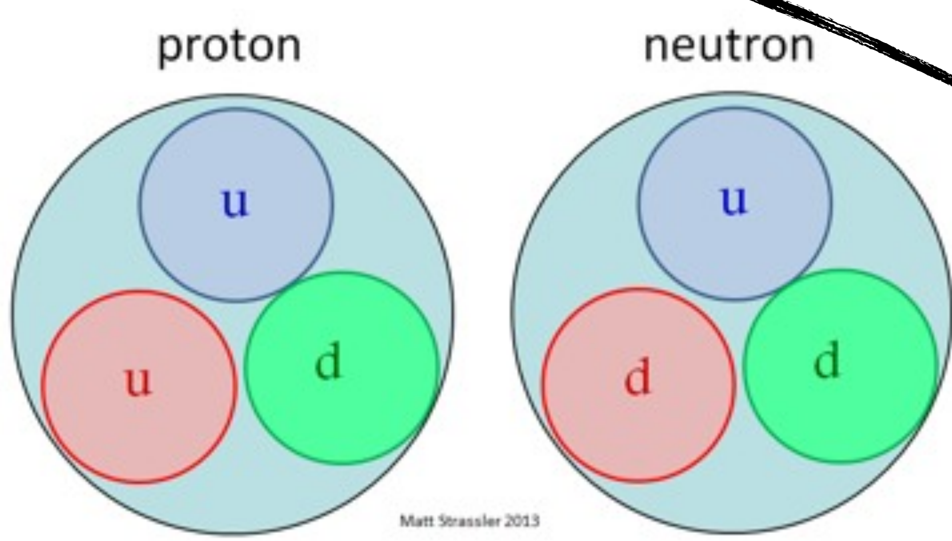
Kitano, Koike, Okada (0203110)

Kuno, Okada, (9909265)

By comparing different target nuclei
one can disentangle different effective operators



plots from Harnik, Kopp, Zupan (2012)



only Higgs coupling to up
and down quarks relevant?

Where does the nucleon mass comes from?

mu-e conversion in nuclei

Volume 78B, number 4 PHYSICS LETTERS 9 October 1978

REMARKS ON HIGGS-BOSON INTERACTIONS WITH NUCLEONS

M.A. SHIFMAN, A.I. VAINSHTEIN and V.I. ZAKHAROV
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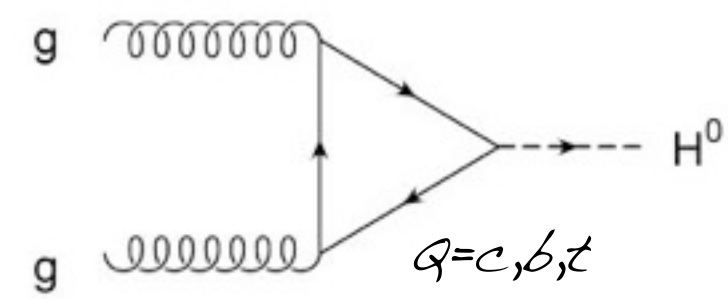
Received 15 April 1978



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

$$\langle N|\theta^\mu_\mu|N\rangle = m_N \langle N|\bar{\psi}_N \psi_N|N\rangle$$

trace of the energy-momentum tensor

(at zero momentum transfer)

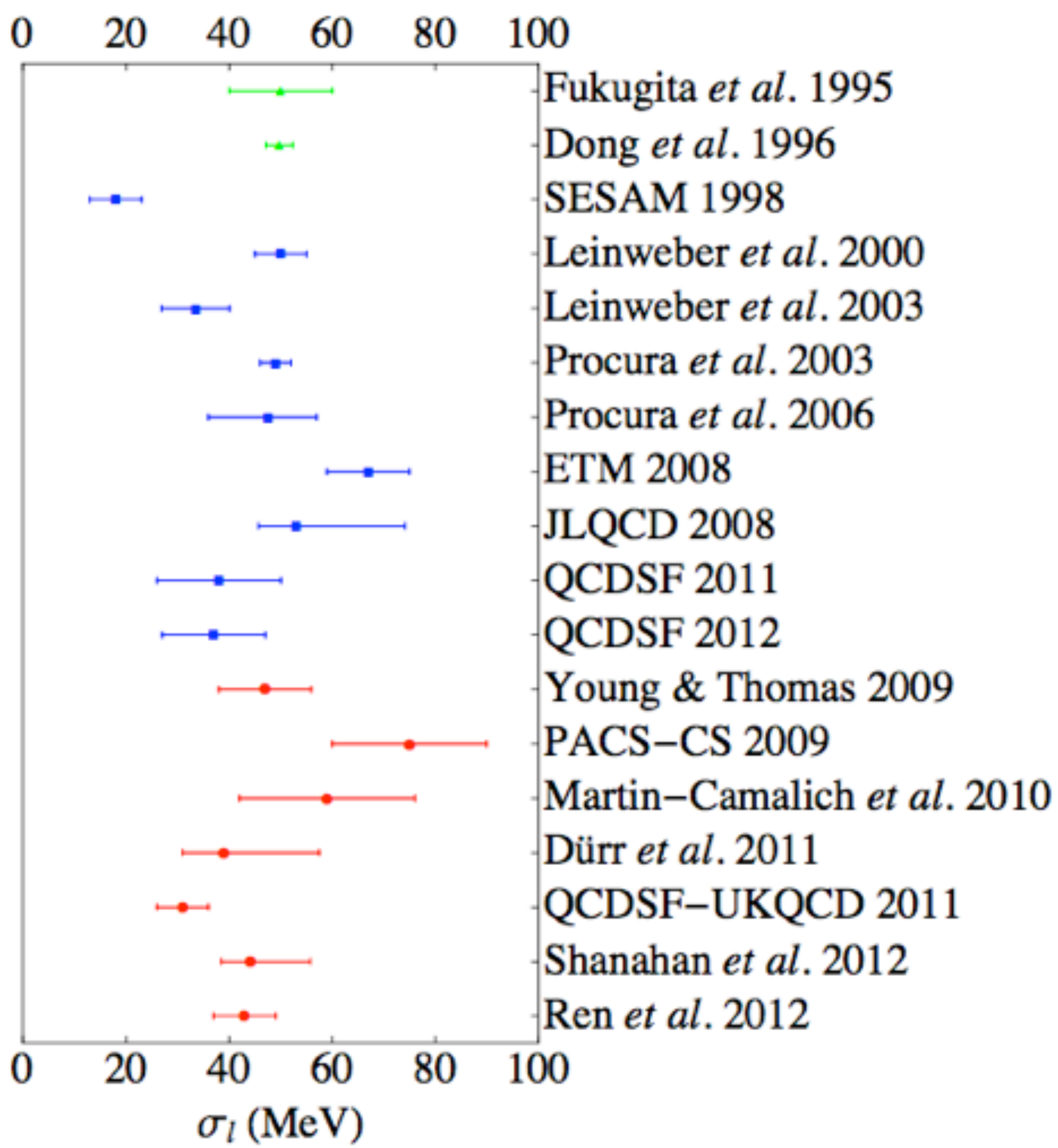
$$\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q} q$$

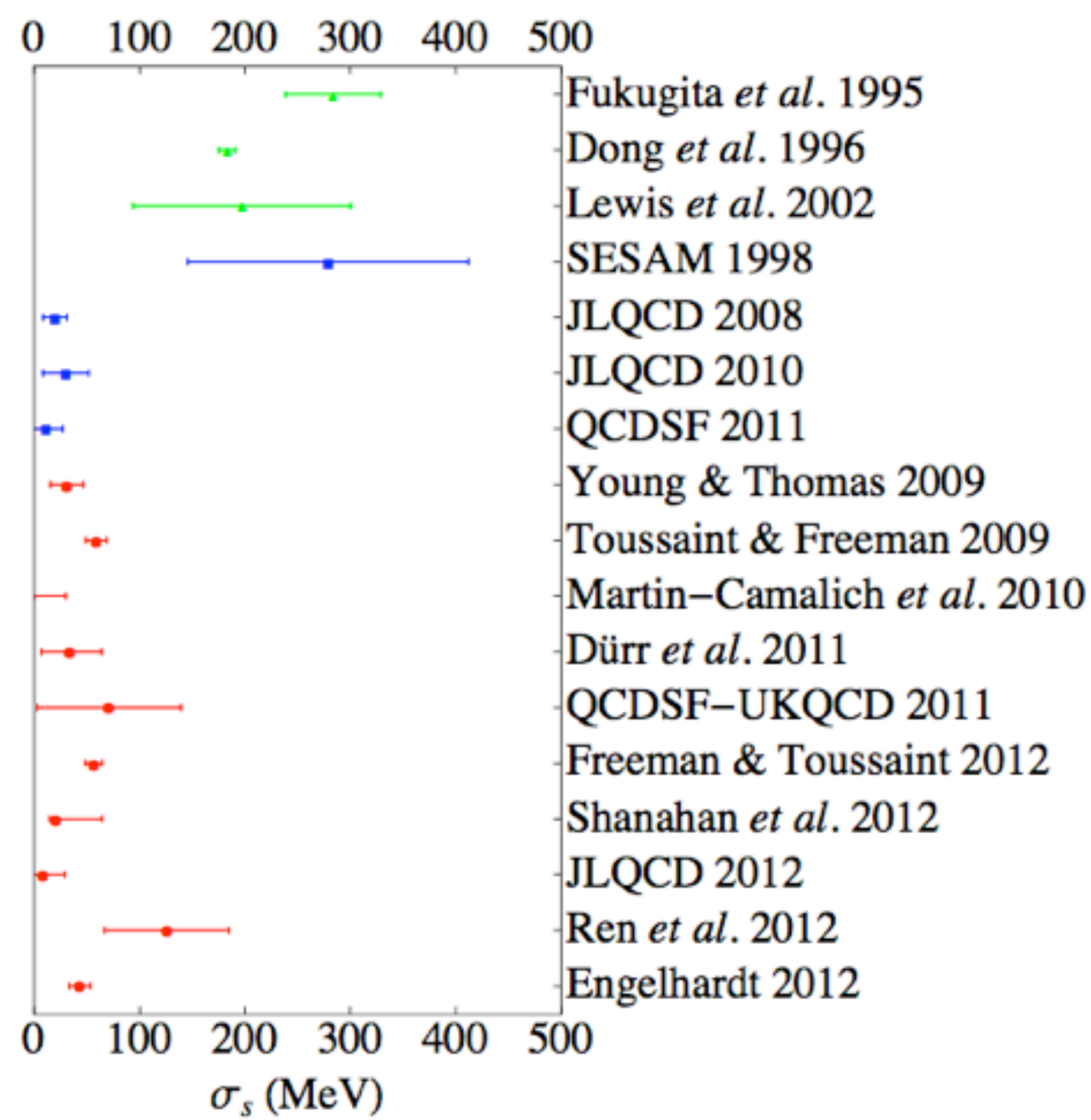
from triangle anomaly

A long-standing problem, how large is the strange quark content in the nucleon?

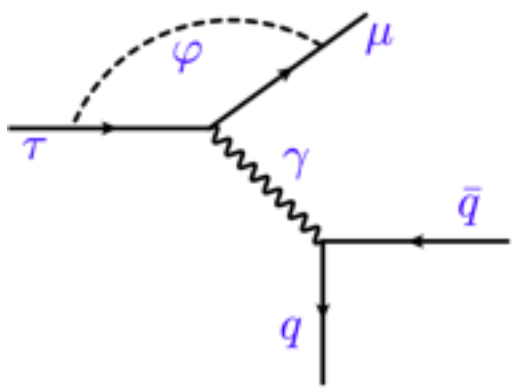
$$\sigma_l = m_l \langle N|\bar{u}u + \bar{d}d|N\rangle \qquad \sigma_s = m_s \langle N|\bar{s}s|N\rangle$$

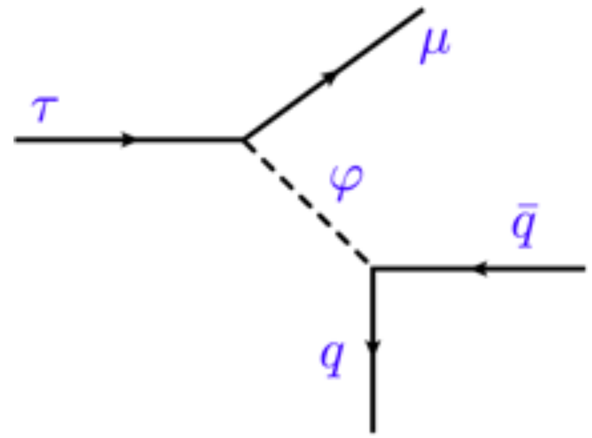
from a recent review with state of the art Lattice calculations R. D. Young, 1301.1765

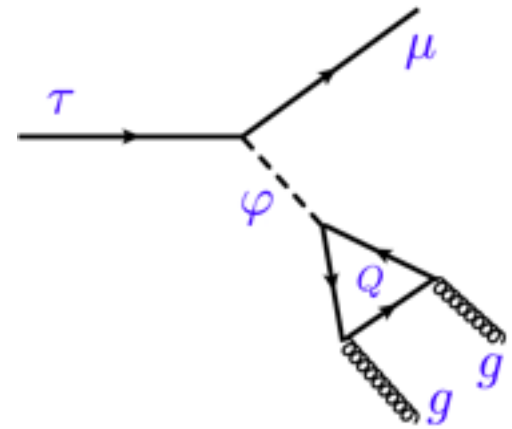




Recent progress on $\tau \to \ell\pi\pi$ decays







Important points:

- Need to consider the Higgs coupling with strange quarks and the effective Higgs-gluon interaction induced by heavy quarks

- Need a proper description of the hadronic matrix elements up to invariant masses of the pion pair of ~1GeV *J. T. Daub et al. (1212.4408)*

$$\sqrt{s} \leq m_\tau - m_\mu \qquad s = (p_{\pi^+} + p_{\pi^-})^2$$

These two points were not being addressed in the literature !!

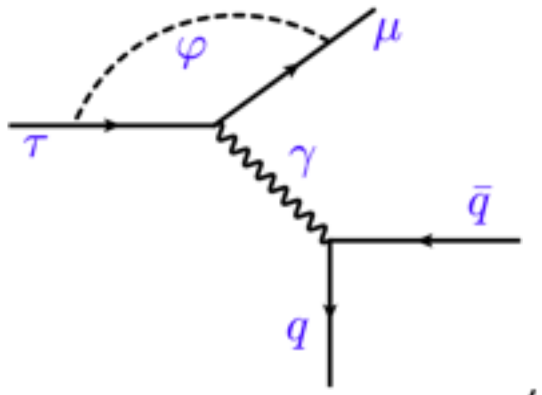
First consideration of these points for Higgs mediated $\tau \to \ell\pi\pi$ decays

AC, Cirigliano, Passemar (1309.3564)

Interestingly, the problem was solved years ago in the context of very light Higgs decays

Donoghue, Gasser, Leutwyler (1990)

Photon mediated contributions require the pion vector form factor



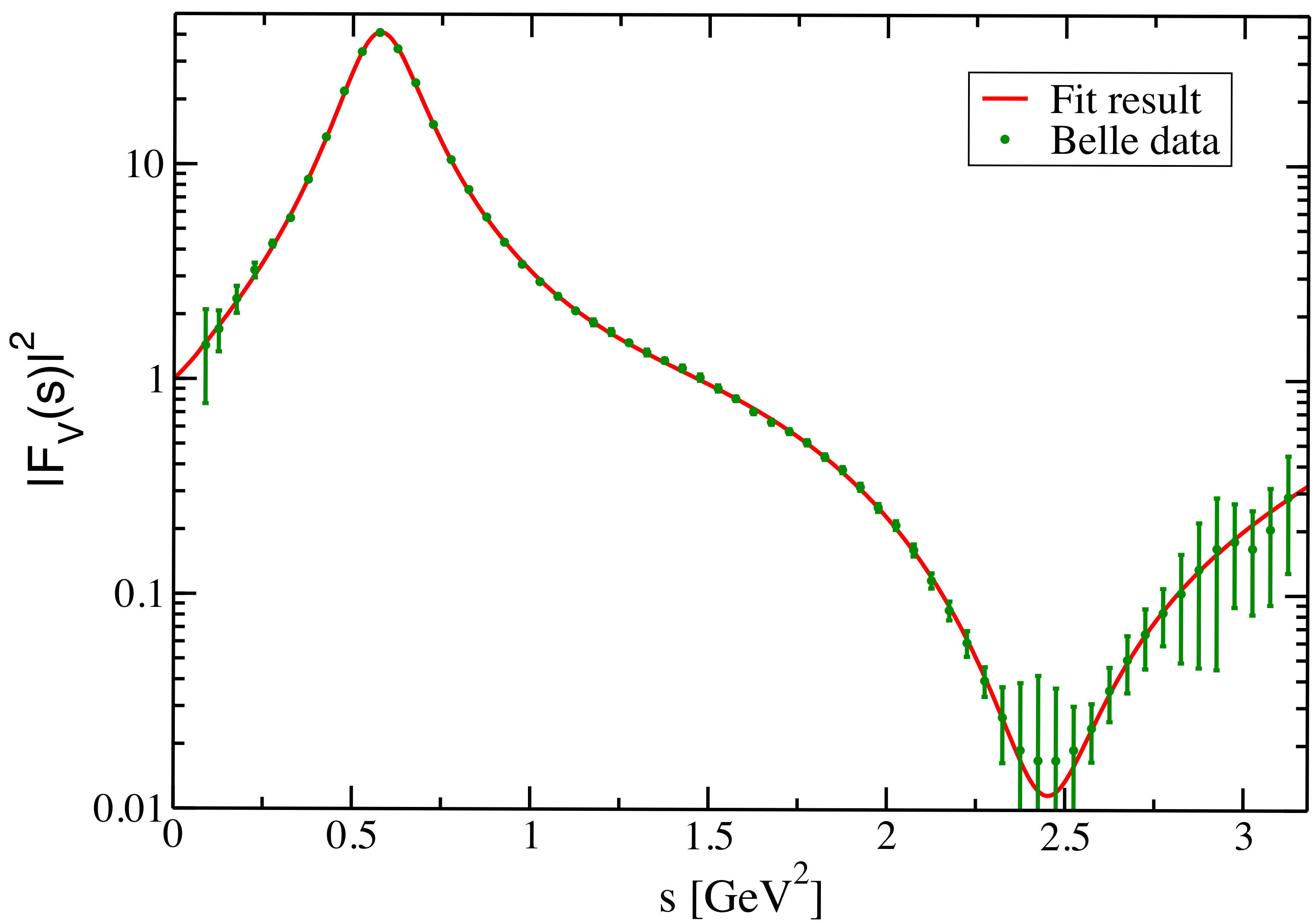
$$\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-}) \big| \tfrac{1}{2}(\bar{u}\gamma^\alpha u - \bar{d}\gamma^\alpha d) \big| 0 \rangle \equiv F_V(s)(p_{\pi^+} - p_{\pi^-})^\alpha$$

Theoretically: decay very well described by resonances

Dispersive parametrization following the properties of analyticity and unitarity of the FF

Determined from a fit to the $\tau^- \to \pi^0 \pi^- \nu_\tau$ Belle data

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



AC, Cirigliano, Passemar (1309.3564)

The other hadronic matrix elements were determined in previous works about $H \to \pi\pi$

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

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

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

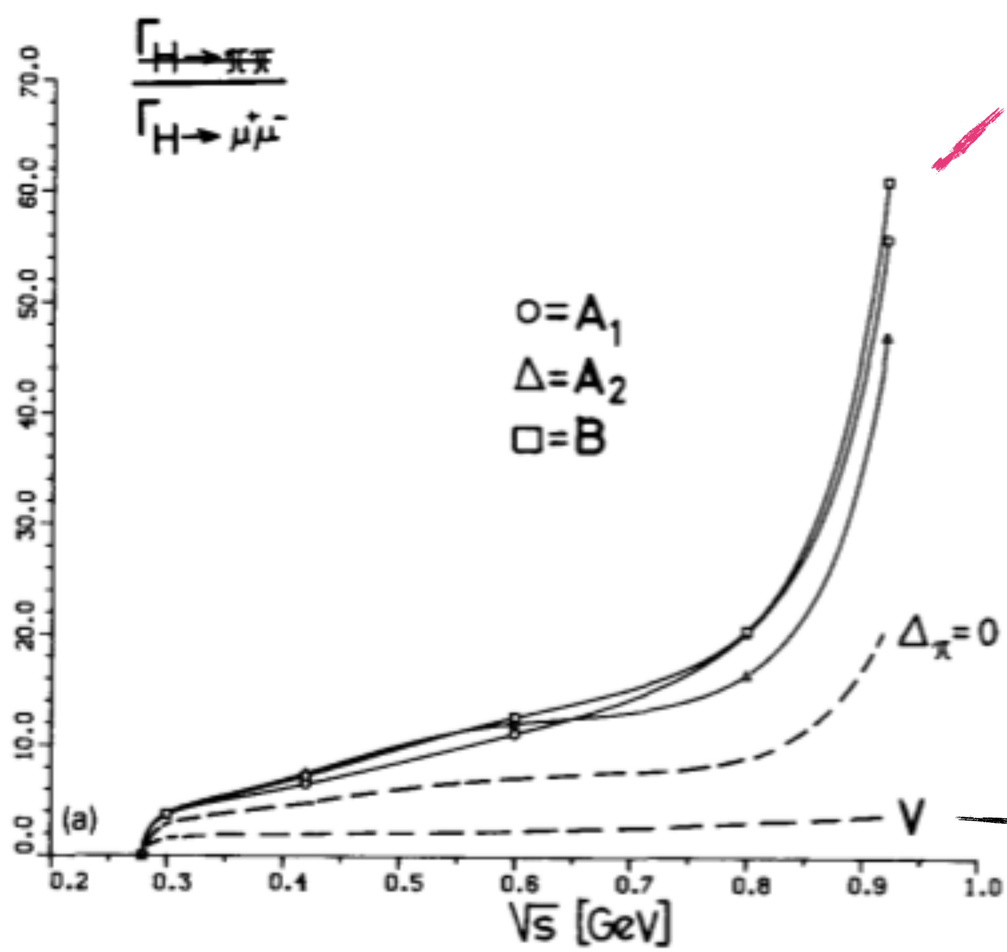
$$\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q}q$$

Using leading-order chiral perturbation theory

$$\theta_\pi(s) = s + 2m_\pi^2 + \mathcal{O}(p^4)$$ Voloshin (1985)

extracted from Donoghue, Gasser, Leutwyler (1990)

J.F. Donoghue et al. / Decay of a light Higgs boson



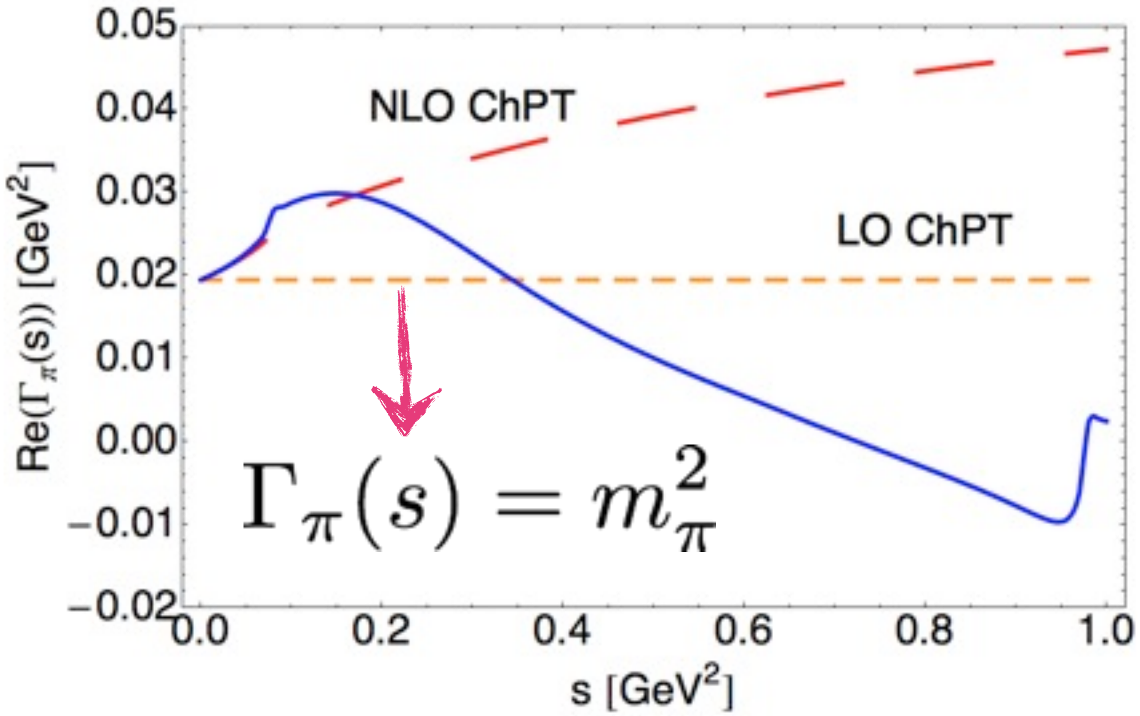
Using the triple constraints of chiral symmetry, analyticity, and unitarity, together with exp. input pi-pi scattering, etc

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 (1985)

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



$$\Gamma_\pi(s) = m_\pi^2$$

Previous studies have been considering only

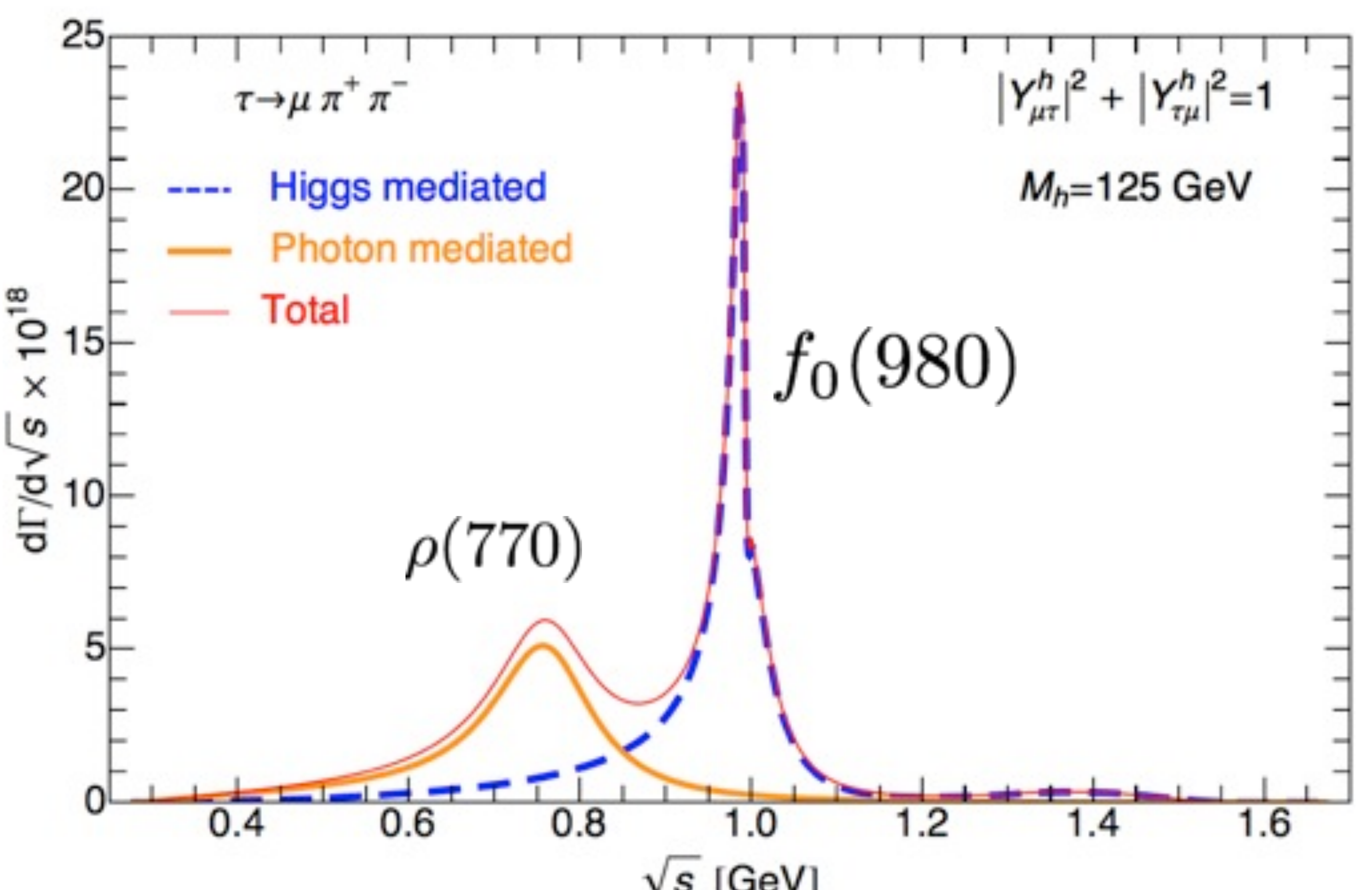
$$\Gamma_\pi(s) = m_\pi^2$$

(LO-ChPT)

Equivalent to the naive estimate

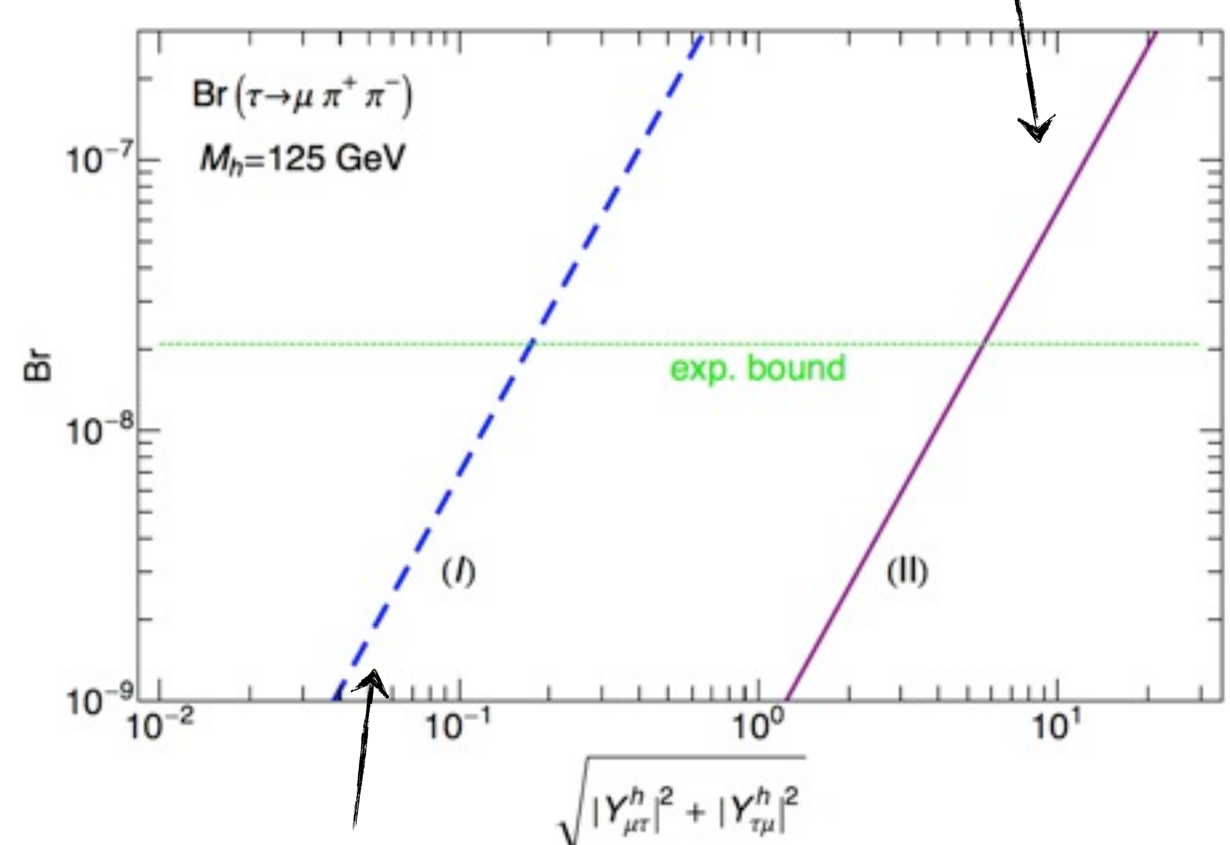
$$\frac{\Gamma(h \to \mu^+\mu^-)}{\Gamma(h \to \pi^+\pi^-)} \sim \frac{m_\mu^2}{m_\pi^2}$$

Impact of hadronic matrix elements on $\tau \to \mu\pi^+\pi^-$

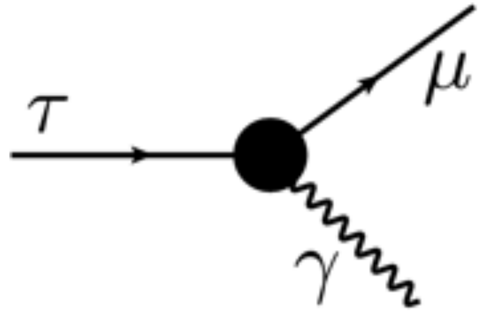


$f_0(980)$

$\rho(770)$



AC, Cirigliano, Passemar (1309.3564)



$\mathrm{BR} < 4.4 \times 10^{-8}$

$$\longrightarrow \quad \mathrm{Br}(h \to \tau\mu, \tau e) \lesssim 0.1$$

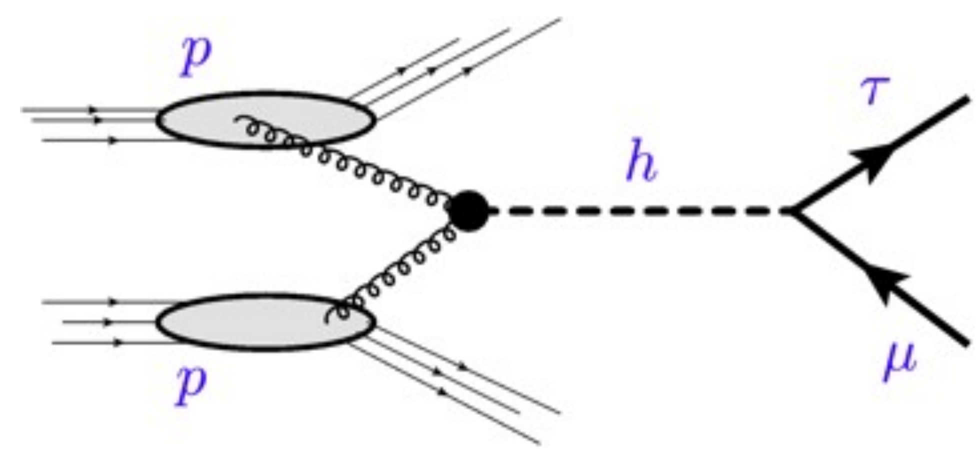
LHC would provide stronger constraints, even with present data

Harnik, Kopp, Zupan (1209.1397)

Davidson, Verdier (1211.1248)

Estimated sensitivity of the LHC with 20 fb^- of data

$$pp(gg) \to h \to \tau\mu$$



$$\mathrm{BR}(h \to \tau\mu) < 4.5 \times 10^{-3}$$

Davidson, Verdier (1211.1248)

PDG 201X

h(126) properties

Decay Modes	$\mathrm{Fraction}(\Gamma_i/\Gamma)$	Confidence Level
$h \to \tau\mu$	$< 10^{-X}$	$\mathrm{CL} = 95\%$
...		

Summary of main points discussed

Higgs interaction with nucleons and where does the nucleon mass comes from?

Recent progress on $\tau \to \ell\pi\pi$ decays

J. T. Daub et al. (1212.4408)

AC, Cirigliano, Passemar (1309.3564)

rely on techniques developed for the problem of calculating the decay width of a ~1 GeV Higgs into two pions, hot topic back in the late 80´s and 90´s

Direct search for $H \to \tau\ell$ decays
at the LHC can probe flavour violating Higgs couplings beyond the limits set by LFV tau decays

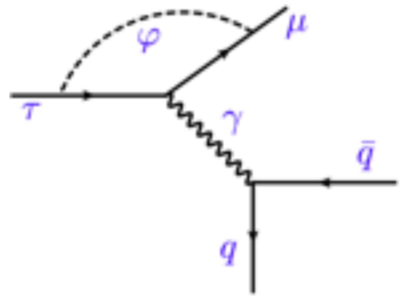
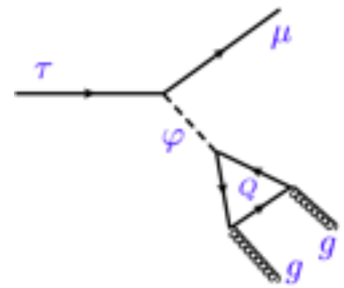
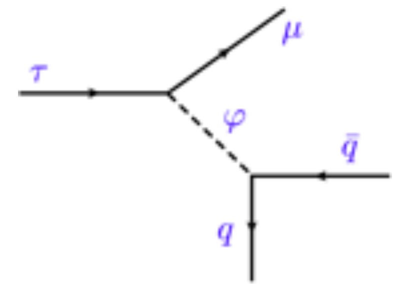
Back-up

Richard Thompson

LFV semileptonic tau decays

Precise knowledge of hadronic states involved provides important information

(neglecting Z penguins)

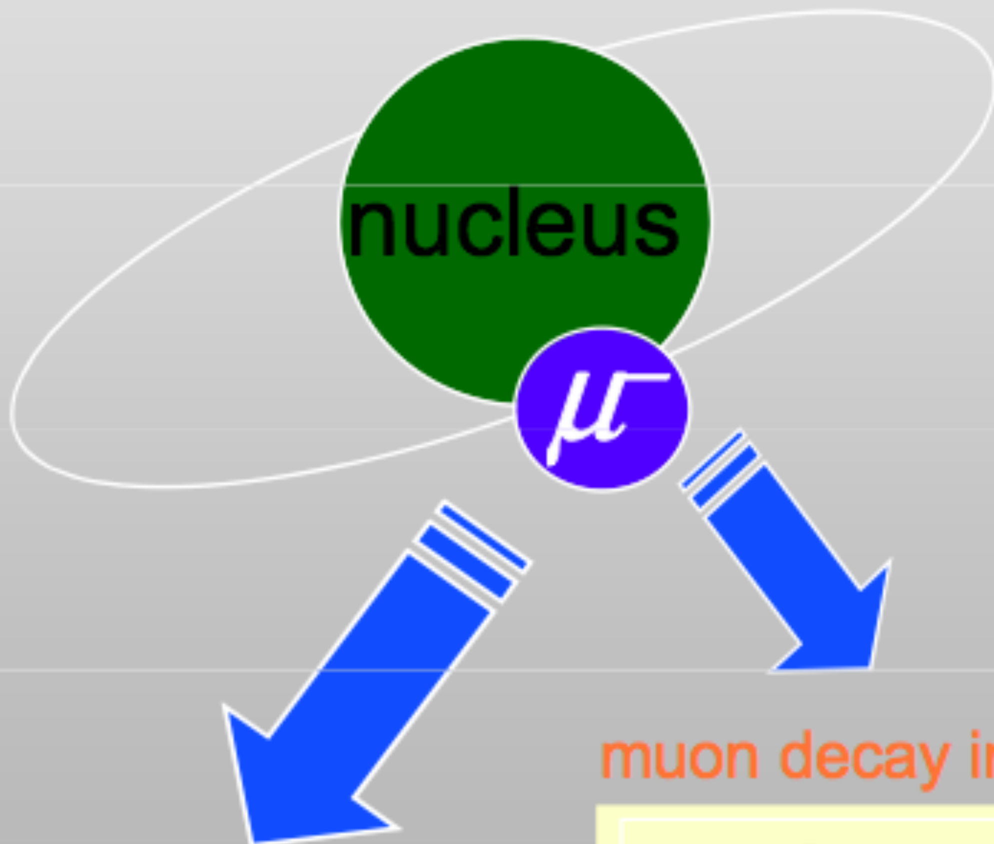
				$\varphi - CP$
$\tau \to \ell \pi^+ \pi^-$	✓	✓	✓	-----
$\boxed{\tau \to \ell \pi^0 \pi^0}$	✗	✓	✓	even
$\tau \to \ell \eta$	✗	✓	✓	odd

Possible to isolate CP-even and CP-odd Higgs exchange in semileptonic decays

From S. Mihara

What is a μ-e Conversion ?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

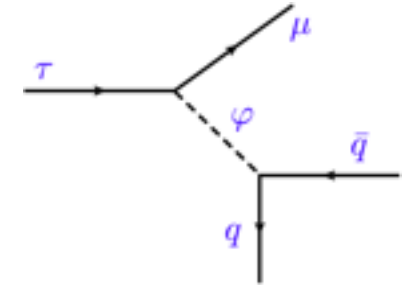
Neutrino-less muon nuclear capture (=μ-e conversion)

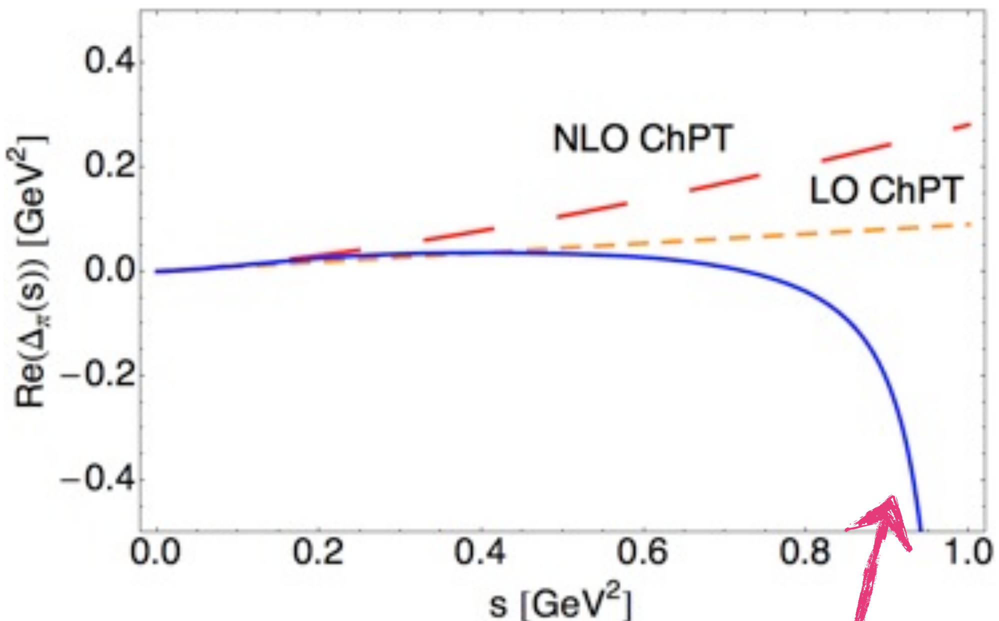
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

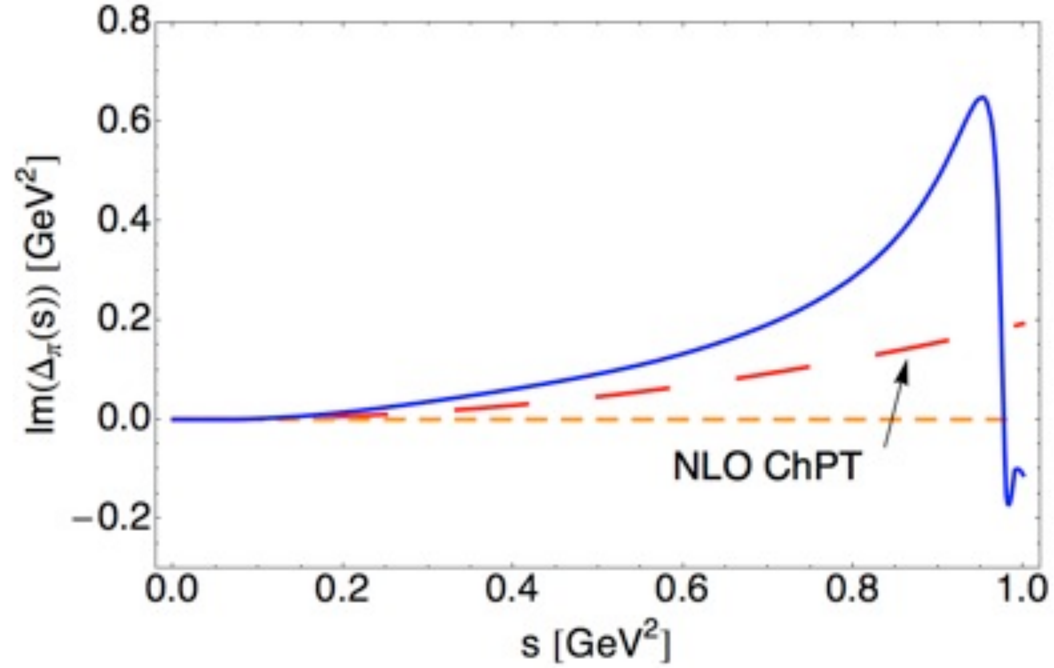
lepton flavors changes by one unit

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

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

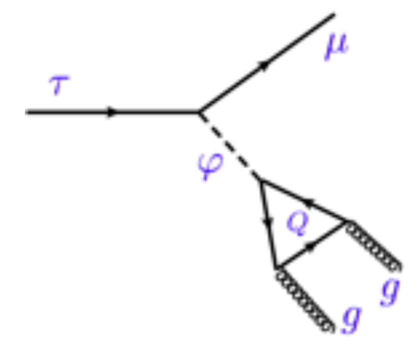


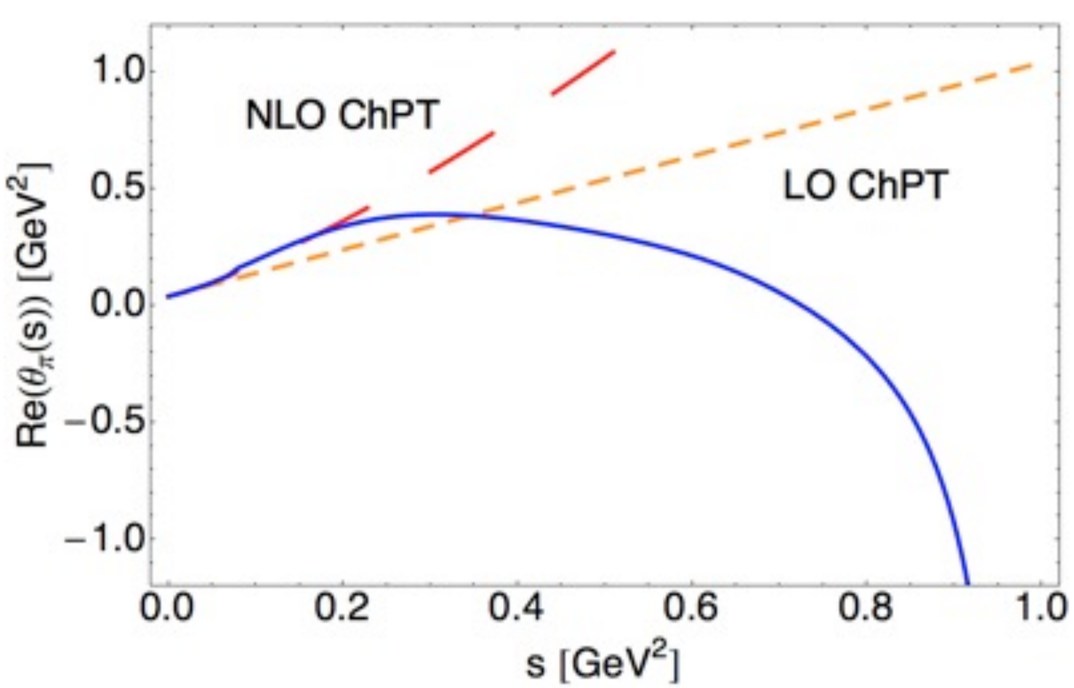


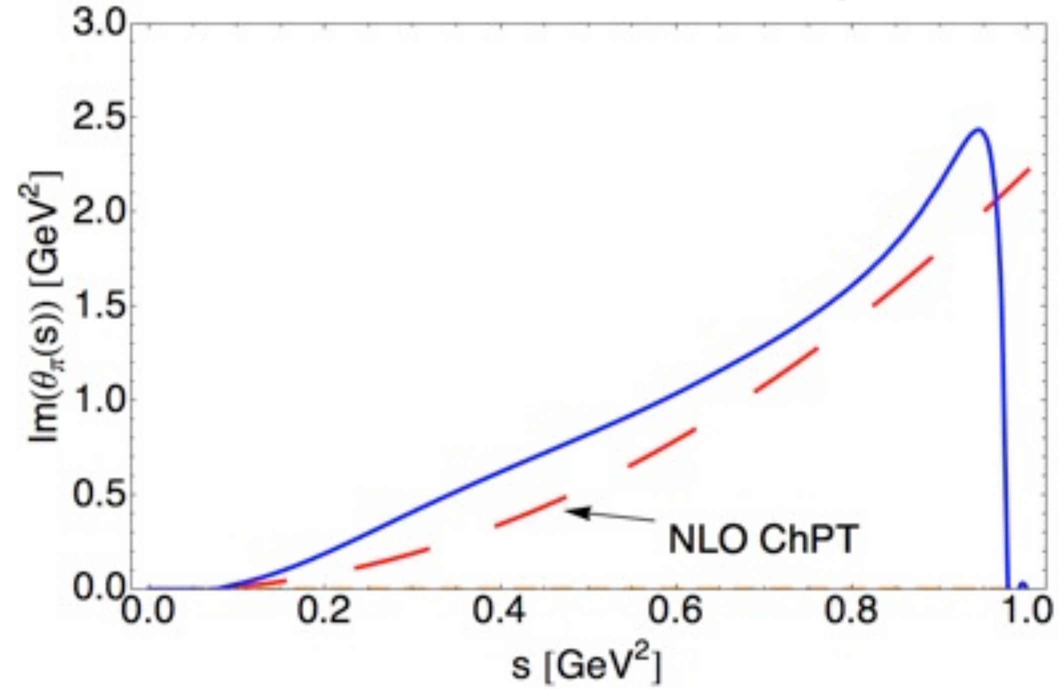


following DGL

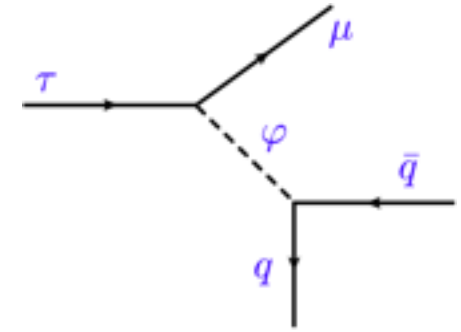
$$\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})|\theta^\mu_\mu|0\rangle \equiv \theta_\pi(s)$$

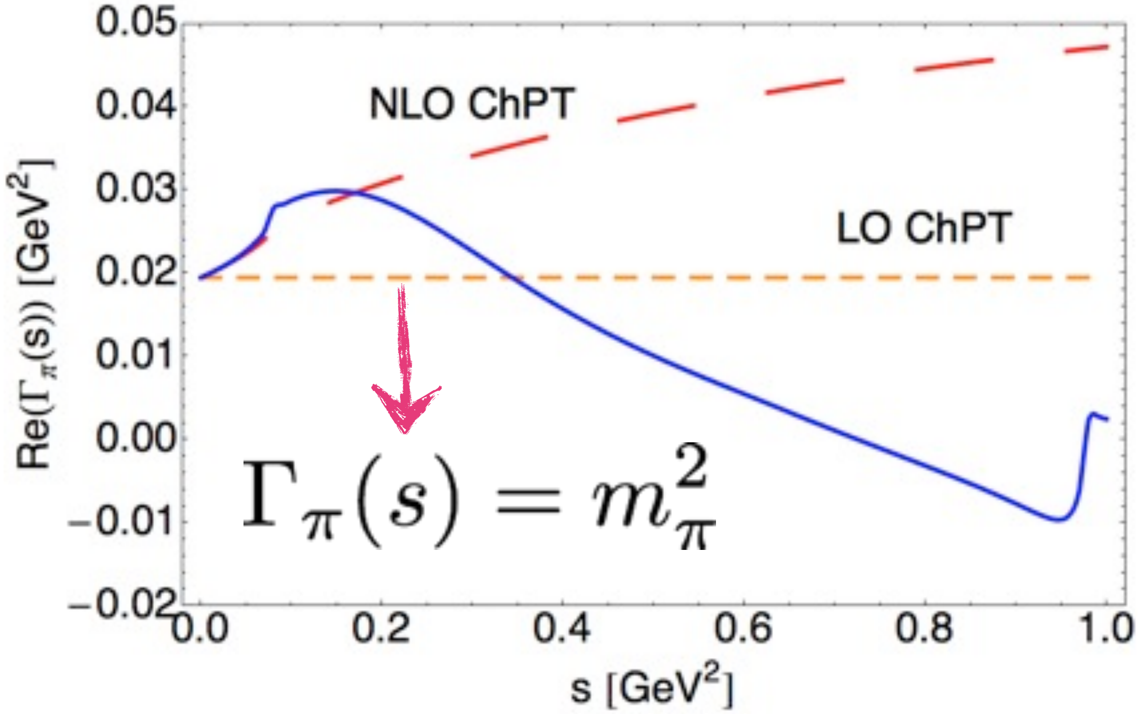


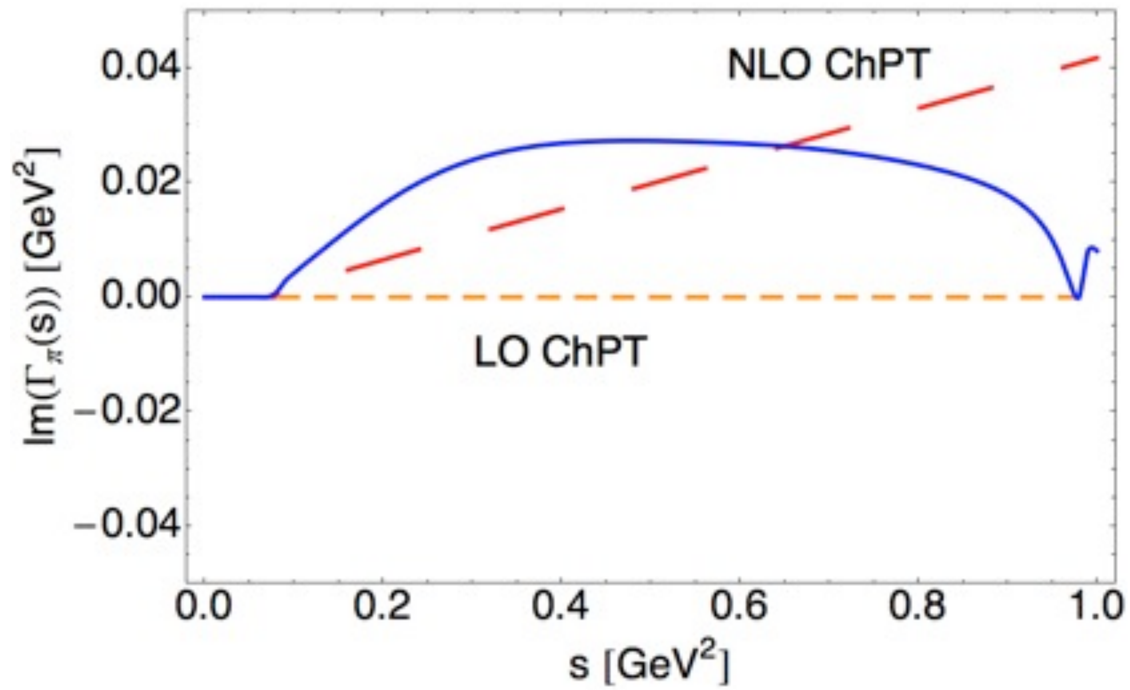




$$\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})\big|m_u\bar{u}u + m_d\bar{d}d\big|0\rangle \equiv \Gamma_\pi(s)$$







Higgs to two pions proceeds mostly through the Higgs-gluon coupling and the Higgs-strange quark coupling.

but pions have u,d valence quarks ¿? $\longrightarrow$ Violation of the OZI rule (Okubo-Zweig-Iizuka)