Theory Review of Charged Lepton Flavour Violation

Emilie Passemar
Indiana University/Jefferson Laboratory
epassema@indiana.edu

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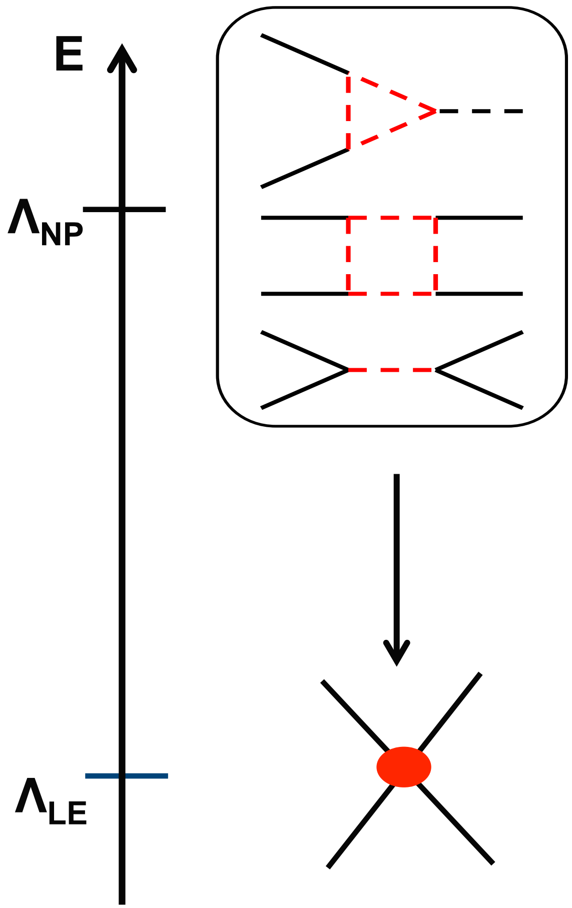
Outline

1. Introduction and Motivation
2. Charged Lepton-Flavour Violation: Model discriminating power of muons and tau channels
3. Ex: Non-Standard LFV couplings of the Higgs boson
4. 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: $\frac{s\bar{d}s\bar{d}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^5$ TeV

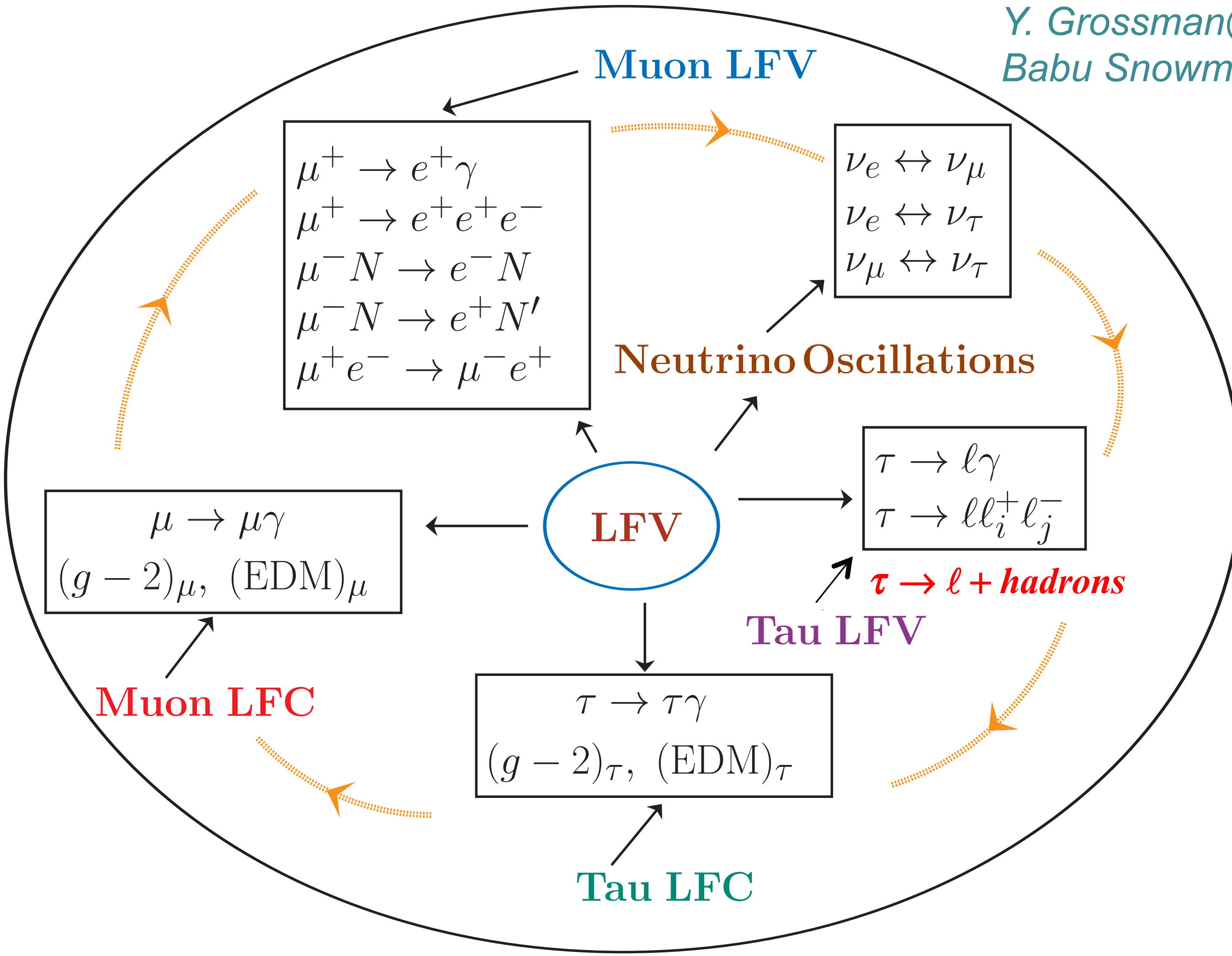
    [ε_K]
  - Charged Leptons: $\frac{\mu\bar{e}f\bar{f}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4$ TeV

    [$\mu \to e\gamma$]
- At low energy: lots of experiments e.g., *MEG*, *Sindrum, Sindrum II, BaBar*, *Belle*, *BESIII, LHCb, ATLAS* ⇒ huge improvements on measurements and bounds obtained and more expected e.g. *MEG, Mu3e, DeeMee, COMET*, *Mu2e, Belle II, LHCb, HL-LHC NA64, EIC, FC-ee, CEPC,STCF*
- In many cases no SM background: e.g., LFV, EDMs
- For some modes accurate calculations of hadronic uncertainties essential (*e.g. talks on g-2 this morning*)

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

1.2 The Program

Adapted from Talk by
Y. Grossman@CLFV2013
Babu Snowmass'13



2. Charged Lepton-Flavour Violation

2.1 Introduction and Motivation

- Neutrino oscillations are the first evidence for lepton flavour violation

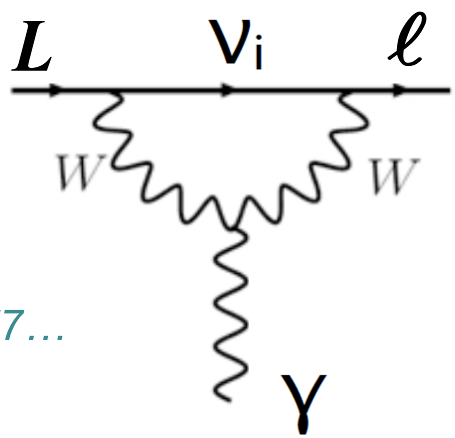
- How about in the charged lepton sector?

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

  E.g.: $\mu \to e\gamma$

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

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



- Extremely *clean probe of beyond SM physics*

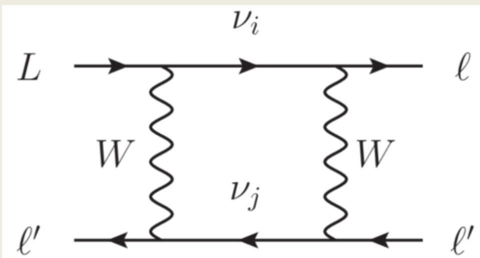
$L \to 3l$

- Claim in *Pham'99* that moving to Physical Limit $m_\nu \ll \mathcal{P} \ll M_W$ ⇨ $Br\left(\tau \to \mu \ell^+ \ell^-\right) \sim 10^{-14}$!

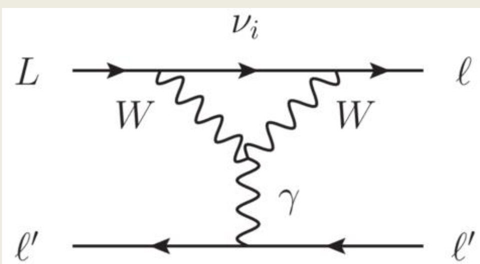
  Could be reachable exp.

⇨ *Incorrect!* *Hernández-Tomé, López Castro & Roig'19, Blackstone, Fael, E.P.'20*

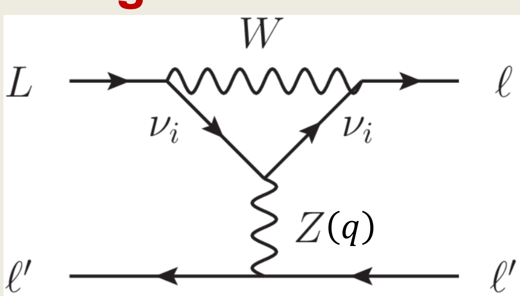
Boxes



γ Penguins



Z Penguins



- Calculation using Method of regions:

$$\Gamma(L \to \ell\ell\ell) = \frac{G_F^2 \alpha^2 m_L^5}{(4\pi)^5} \left| \sum_{i=2}^{3} U_{Li}^* U_{\ell i} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2$$

$$\times \left[\log^2 x_L + 2 \log x_L - \frac{1}{6} \log x_\ell + \frac{19}{18} + \frac{17}{18}\pi^2 - \frac{1}{\sin^2 \theta_W}\left(\log x_L + \frac{11}{12} \right) + \frac{3}{8 \sin^4 \theta_W} \right]$$

	Branching ratio (NO)	
	ZML	PL
$\mu \to eee$	4.1×10^{-54}	2.9×10^{-55}
$\tau \to \mu\mu\mu$	2.0×10^{-53}	5.8×10^{-55}
$\tau \to \mu ee$	1.3×10^{-53}	3.8×10^{-55}
$\tau \to eee$	1.1×10^{-54}	3.3×10^{-56}
$\tau \to e\mu\mu$	7.6×10^{-55}	2.1×10^{-56}

$Br \sim 10^{-56} - 10^{-55}$!

2.2 CLFV probes

- In New Physics scenarios CLFV can reach observable levels in several channels
- But the sensitivity of particular modes to CLFV couplings is model dependent

Probes: *Low energy: decays of μ, τ and mesons

$$\mu \to e\gamma,\ \mu \to e\bar{e}e,\ \mu(A,Z) \to e(A,Z)$$

$$\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y \quad Y = P,\ S,\ V,\ P\bar{P},\ldots$$

$$\pi^0, K_L \to \mu e,\ K \to \pi\mu e,\ B \to K\mu\tau, K\mu e,\ B_S \to \mu\tau, \mu e,\ \ldots$$

Not discussed in this talk

- High energy:

$$pp \to R \to \ell_\alpha \bar{\ell}_\beta + X \quad R = Z', h, \nu$$

$$pp \to \ell_\alpha \bar{\ell}_\beta + X$$

LHC

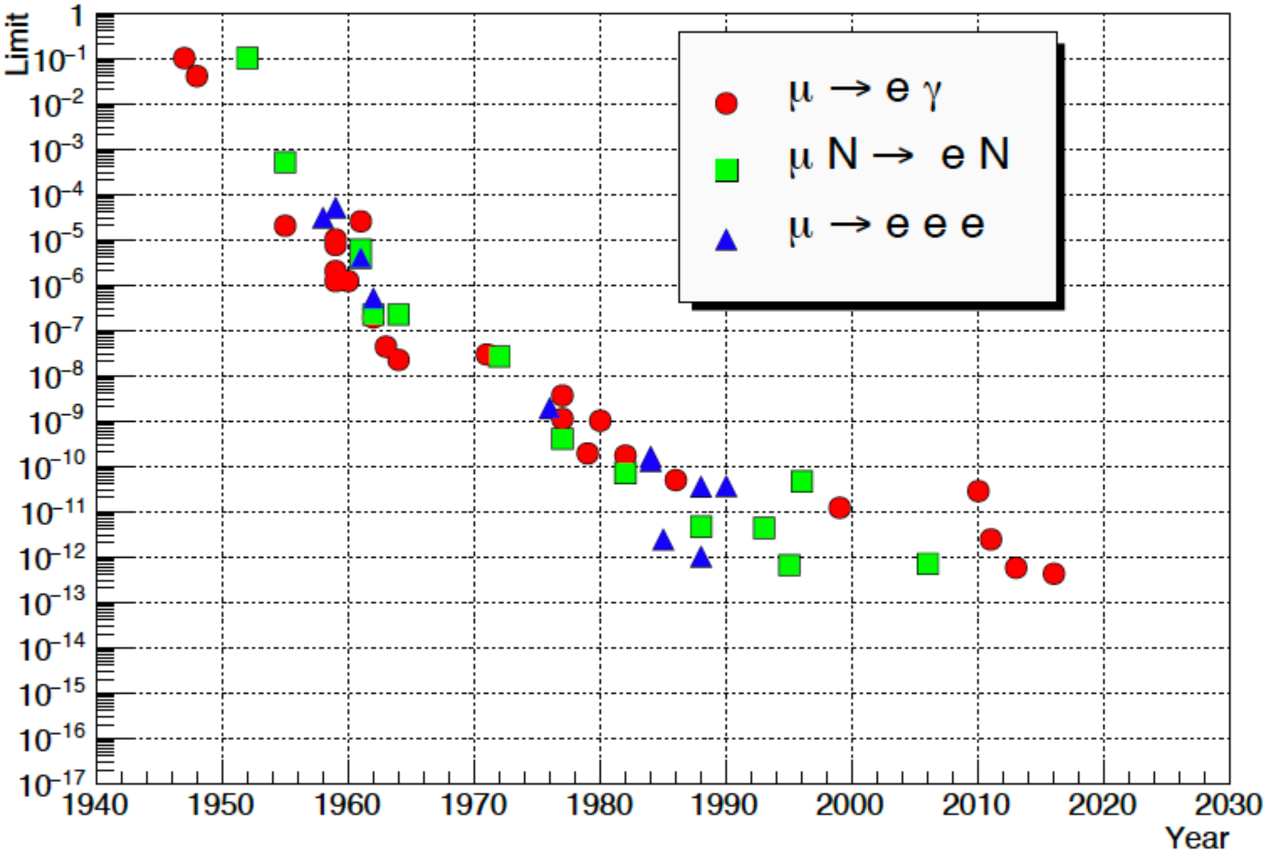
$$ep \to \ell + X$$

HERA, NA64, EIC

2.2 CLFV processes: muon decays

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

Calibbi&Signorelli'17



MEG'16

$$BR(\mu \to e\gamma) < 4.2\times10^{-13}$$

$\Rightarrow$ 6×10^{-14}

Sindrum

$$BR(\mu \to eee) < 1.0\times10^{-12}$$

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

Mu3e

Sindrum II

$$BR^{Ti}_{\mu-e} < 4.3\times10^{-12}$$

$\Rightarrow$ 10^{-14} DeeMee

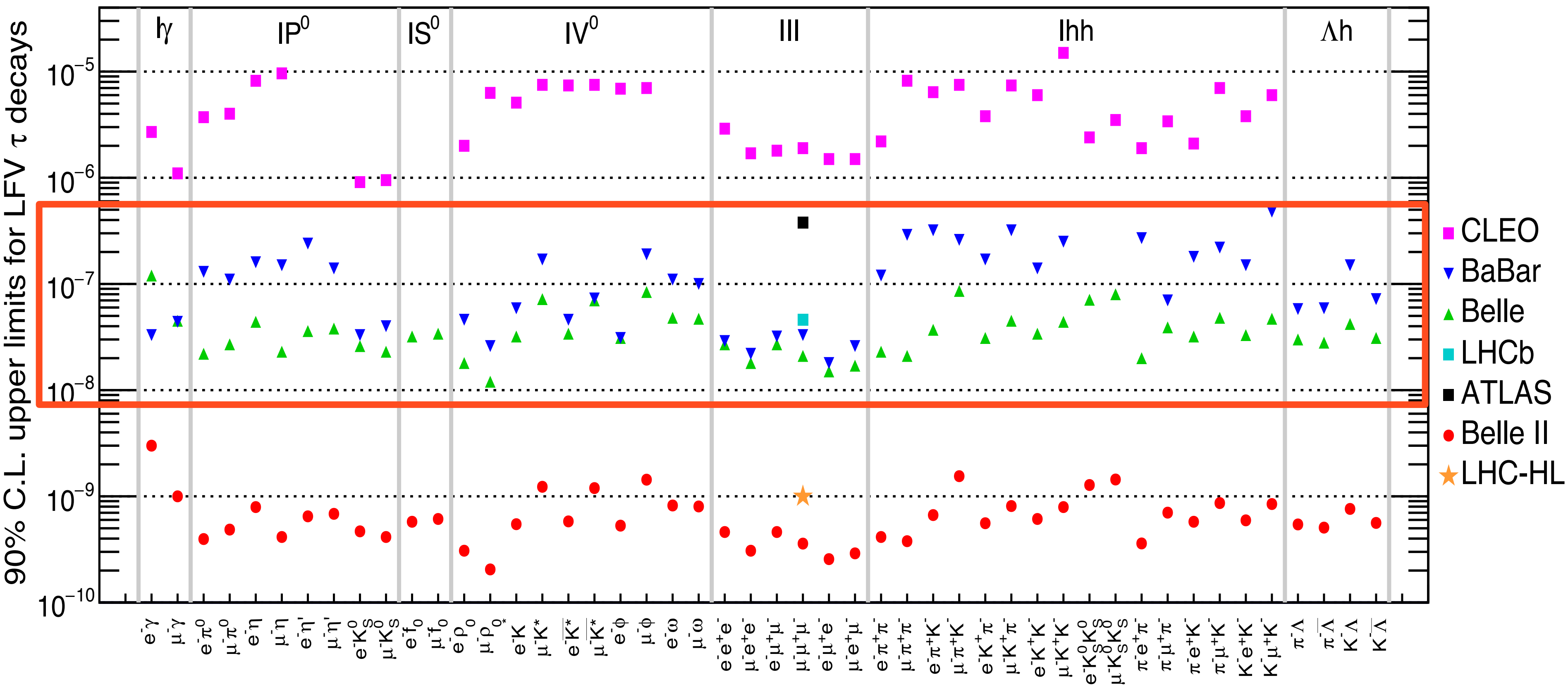
$10^{-16} - 10^{-17}$

Mu2e/COMET

2.2 CLFV processes: tau decays

Belle II Physics Book'18
HL-LHC&HE-LHC'18

- 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 ~10^{-7}-10^{-8}

2.2 CLFV processes: tau decays

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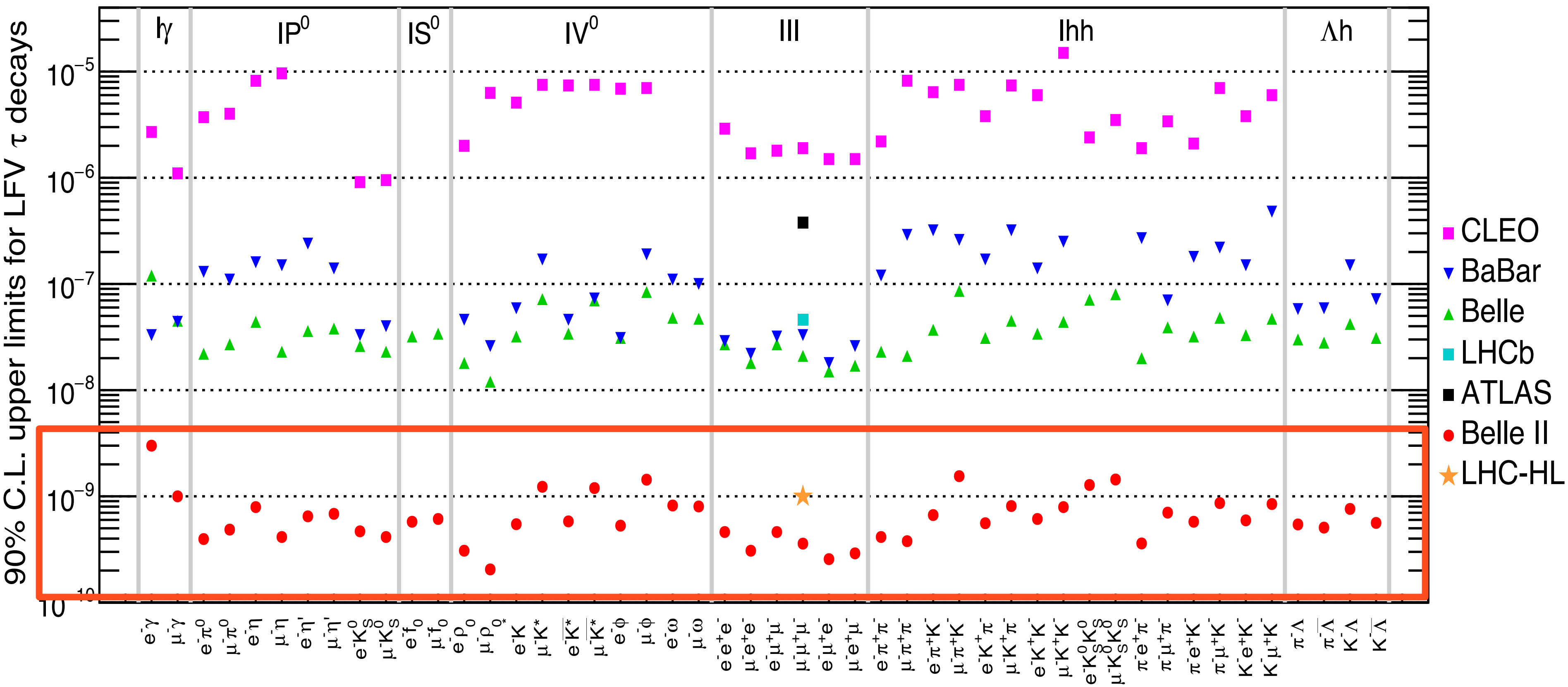
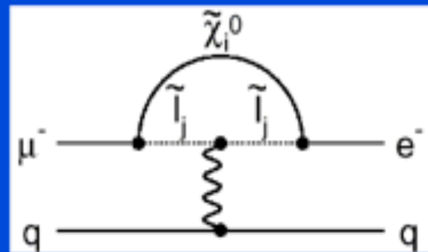


- Expected sensitivity 10^{-9} or better at *Belle II* improvement by 2 order of magnitude!

A multitude of models…

Supersymmetry

Predictions at 10^{-15}

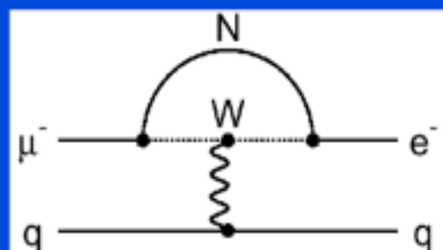


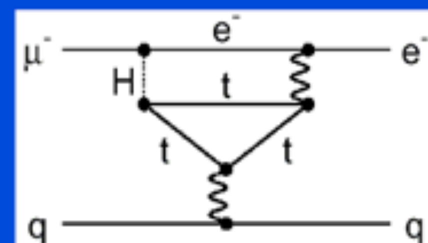
Compositeness

$\Lambda_c = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$





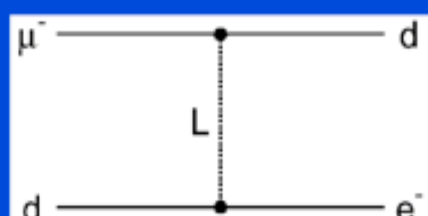
Second Higgs doublet

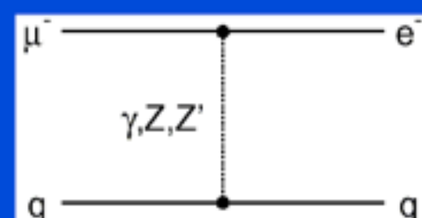
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L =$

$3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

James Miller, 2006

2.3 Effective Field Theory approach

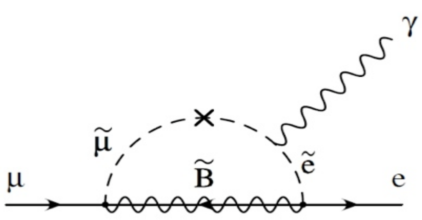
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

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:

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

e.g.



Dominant in SUSY-GUT and SUSY see-saw scenarios

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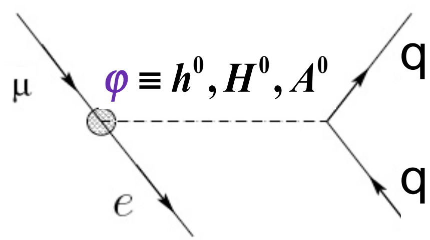
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):

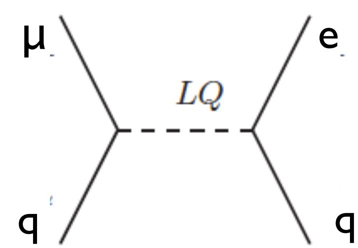
$$\mathcal{L}_{eff}^{S,V} \supset -\frac{C_{S,V}}{\Lambda^2} m_\tau m_q G_F \, \bar{e} \Gamma P_{L,R} \mu \, \bar{q} \Gamma q$$

e.g.



$\Gamma \equiv 1$

Relevant in RPV SUSY and RPC SUSY for large tan(β) and low mA, leptoquarks



$\Gamma \equiv \gamma^\mu$

Enhanced in Type III seesaw (Z), Type II seesaw, LRSM, leptoquarks

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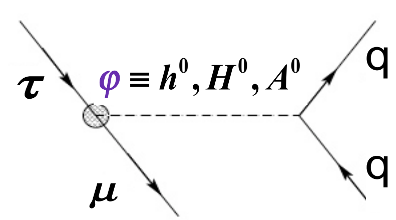
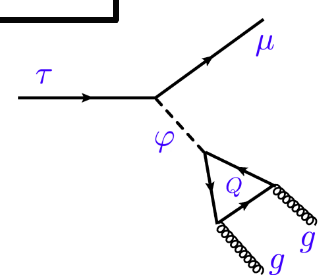
  - Integrating out heavy quarks generates *gluonic operator*

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

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





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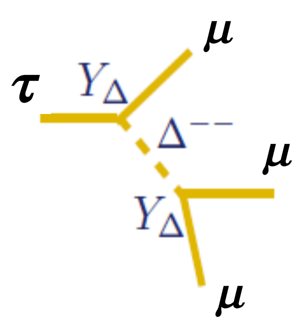
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{e}\, \Gamma P_{L,R} \mu\, \bar{e}\, \Gamma P_{L,R} e$

$\Gamma \equiv 1, \gamma^\mu$

e.g.



Type II seesaw, RPV SUSY, LRSM

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

$\Gamma \equiv 1, \gamma^\mu$

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

2.4 Model discriminating power of muon processes

- Summary table:

From V. Cirigliano

	$\mu \to 3e$	$\mu \to e\gamma$	$\mu \to e$ 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*

2.4 Model discriminating power of muon processes

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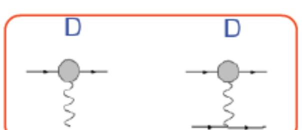
O_D	✓	✓	✓
O^q_V	–	–	✓
O^q_S	–	–	✓

- $\mu \to e\gamma$ 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}

2.4 Model discriminating power of muon processes

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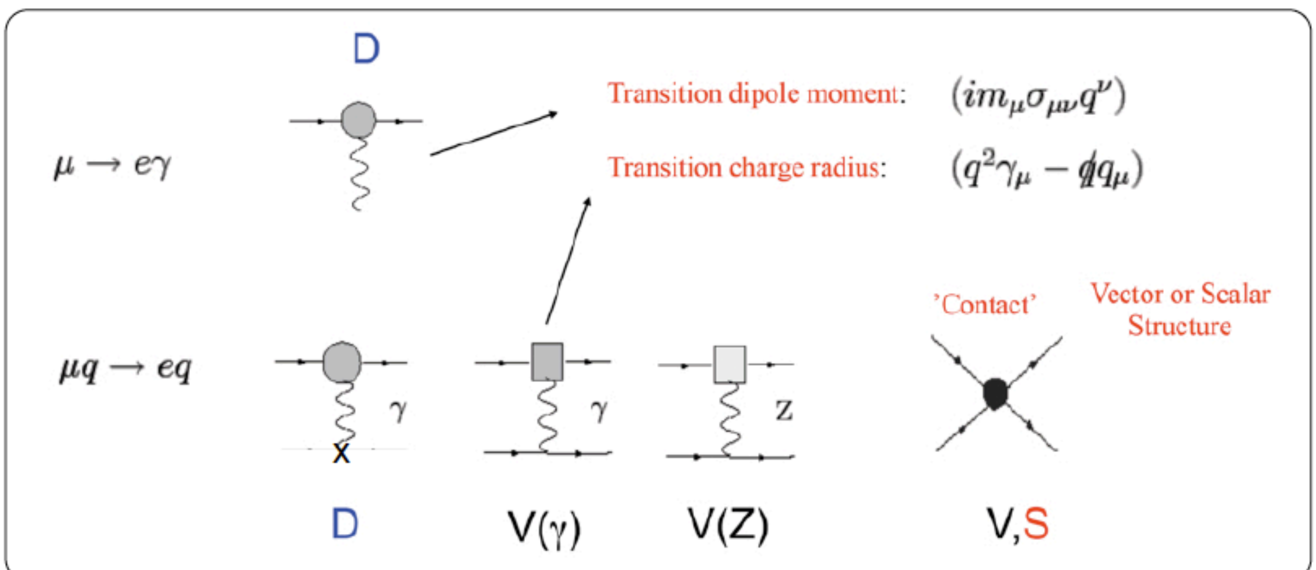
O_D	✓	✓	✓
O^q_V	–	–	✓
O^q_S	–	–	✓

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



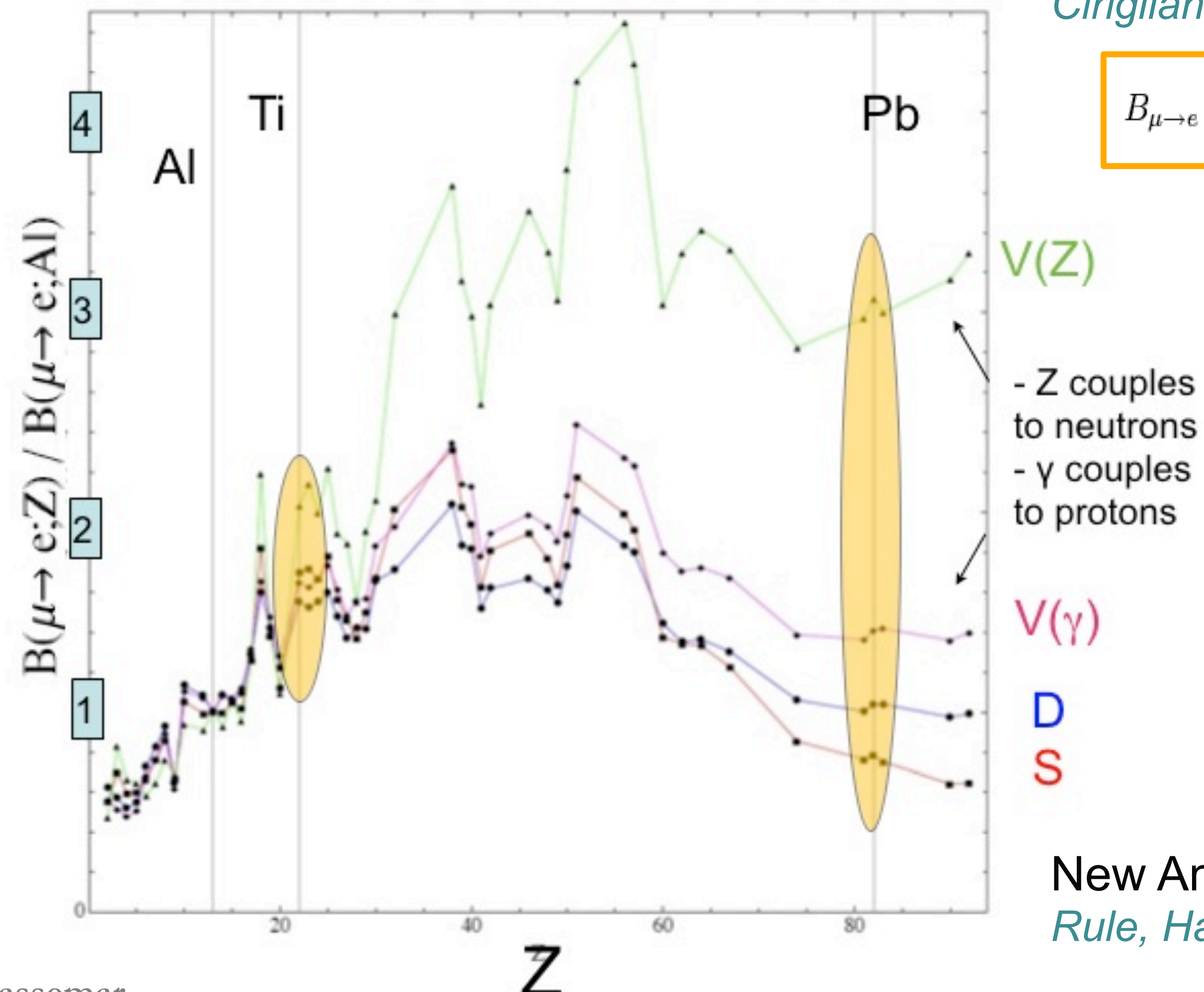
BR for $\mu \to$ e conversion

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

Kitano, Koike, Okada'07

Cirigliano, Kitano, Okada, Tuzon'09

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



New Analysis by
Rule, Haxton, McElvain'21

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Summary table:

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O_{S,V}^{4\ell}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O_V^q	–	–	✓ (I=1)	✓(I=0,1)	–	–
O_S^q	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O_A^q	–	–	–	–	✓ (I=1)	✓ (I=0)
O_P^q	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- 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*

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O_{S,V}^{4\ell}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O_V^q	–	–	✓ (I=1)	✓(I=0,1)	–	–
O_S^q	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O_A^q	–	–	–	–	✓ (I=1)	✓ (I=0)
O_P^q	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- Form factors for $\tau \to \mu(e)\pi\pi$ determined using *dispersive techniques*
- Hadronic part:

Donoghue, Gasser, Leutwyler'90
Moussallam'99
Daub et al'13
Celis, Cirigliano, E.P.'14

$$H_\mu = \langle \pi\pi | \left(V_\mu - A_\mu\right) e^{iL_{QCD}} | 0 \rangle = \left(Lorentz\ \text{struct.}\right)_\mu^i F_i(s)$$

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

- 2-channel unitarity condition is solved with I=0 S-wave ππ and KK scattering data as input

$$\text{Im} F_n(s) = \sum_{m=1}^{2} T_{nm}^*(s)\sigma_m(s)F_m(s)$$

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

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Summary table:

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O_{S,V}^{4\ell}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O_V^q	–	–	✓ (I=1)	✓(I=0,1)	–	–
O_S^q	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O_A^q	–	–	–	–	✓ (I=1)	✓ (I=0)
O_P^q	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- 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*

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Two handles:
  - Branching ratios: $R_{F,M} \equiv \frac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}$ with F_M dominant LFV mode for model M
  - Spectra for > 2 bodies in the final state:

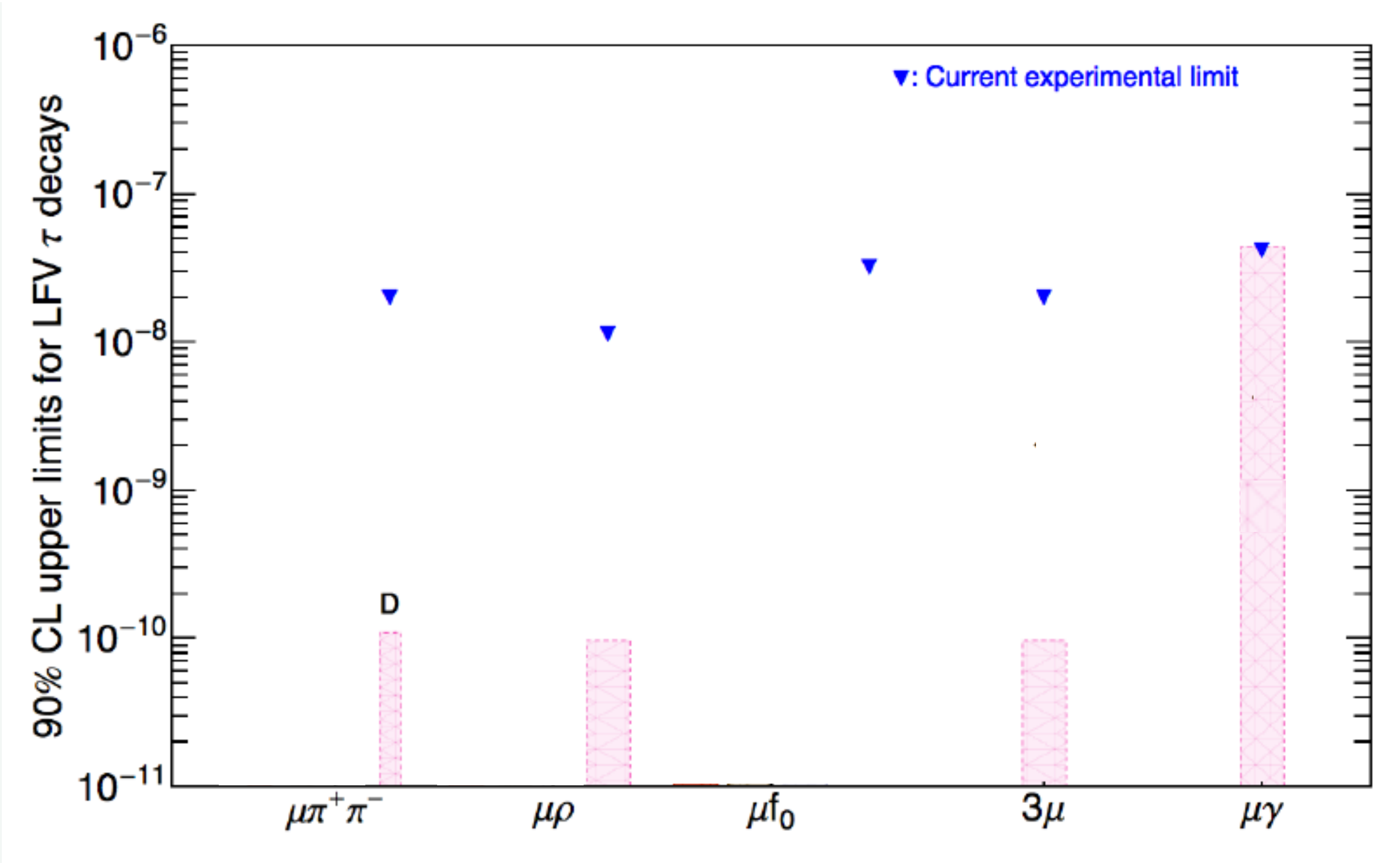
$$\frac{dBR(\tau \to \mu\pi^+\pi^-)}{d\sqrt{s}}$$ and $$dR_{\pi^+\pi^-} \equiv \frac{1}{\Gamma(\tau \to \mu\gamma)} \frac{d\Gamma(\tau \to \mu\pi^+\pi^-)}{d\sqrt{s}}$$

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

2.6 Model discriminating of BRs

- Dipole only:

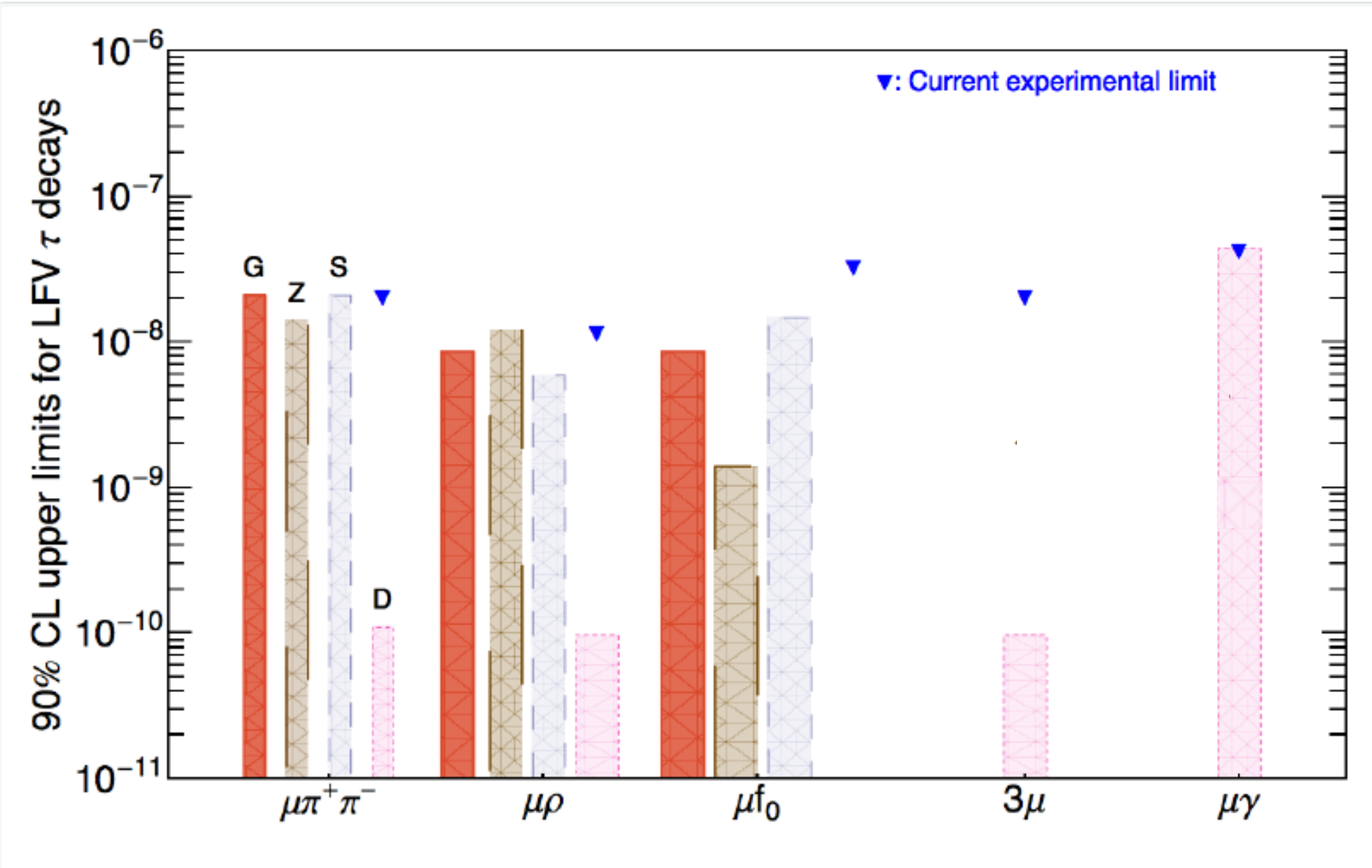
Celis, Cirigliano, E.P.'14



2.6 Model discriminating of BRs

- With Gluon, Vector, Scalar (G, Z, S)

Celis, Cirigliano, E.P.'14



2.6 Model discriminating of BRs

Celis, Cirigliano, E.P.'14

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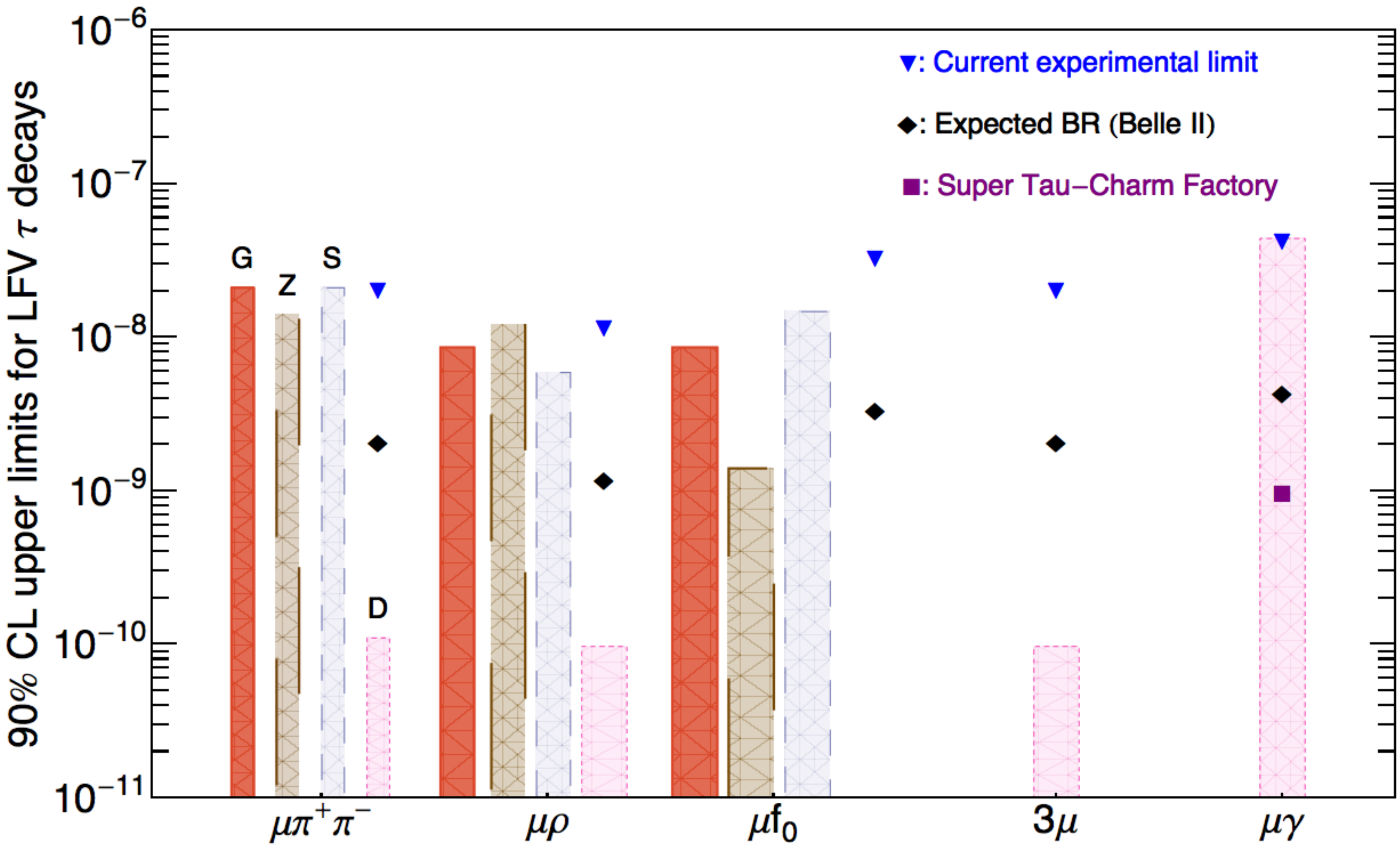
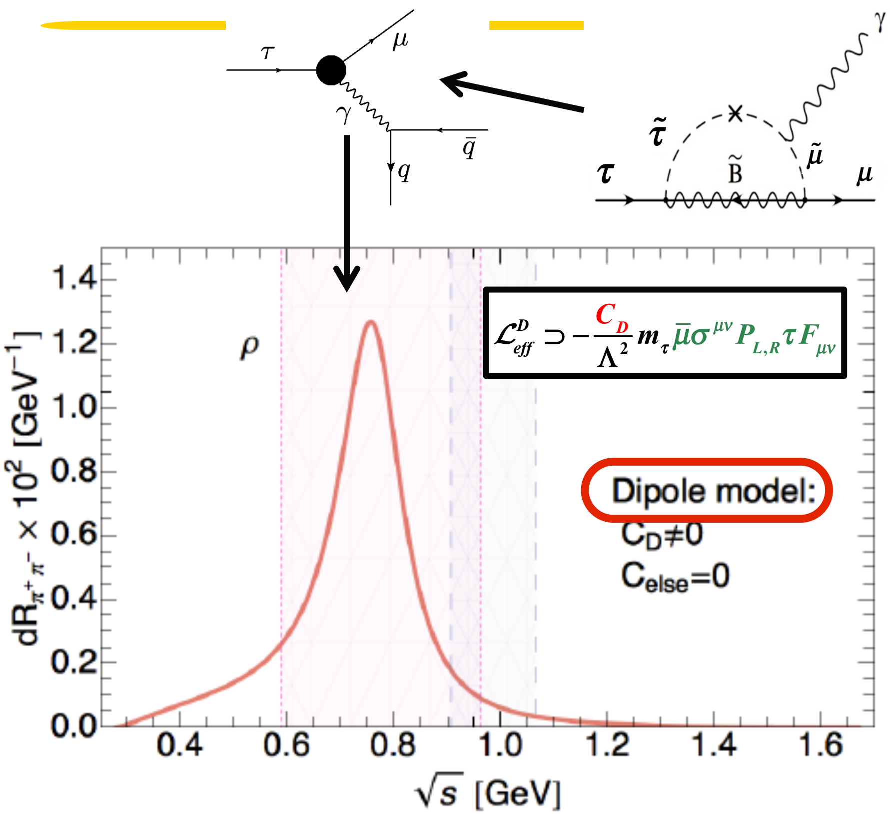
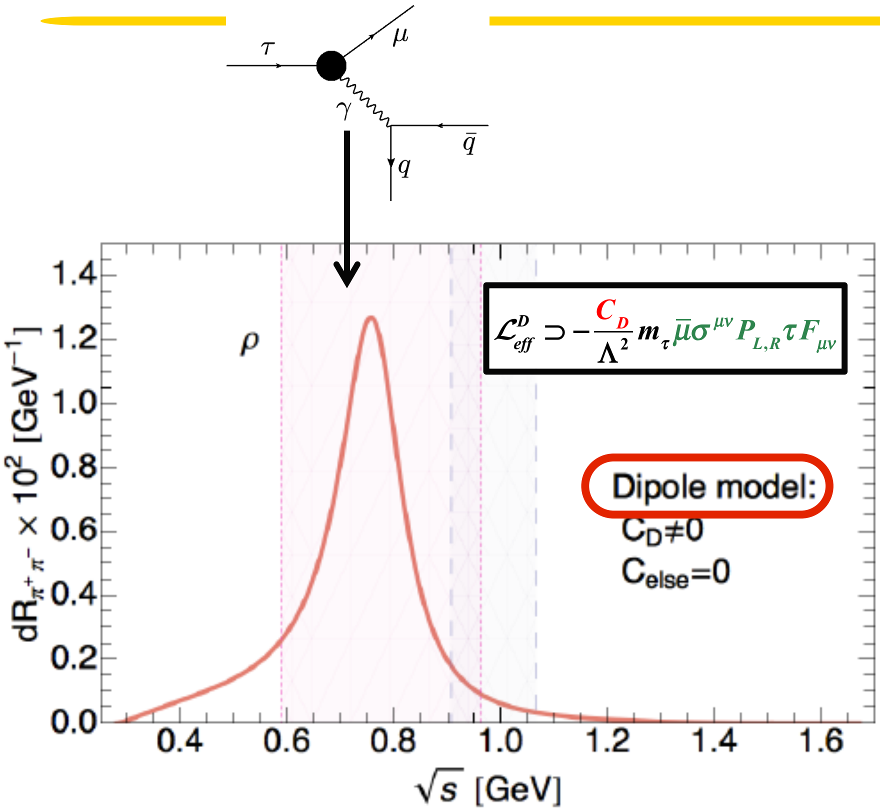


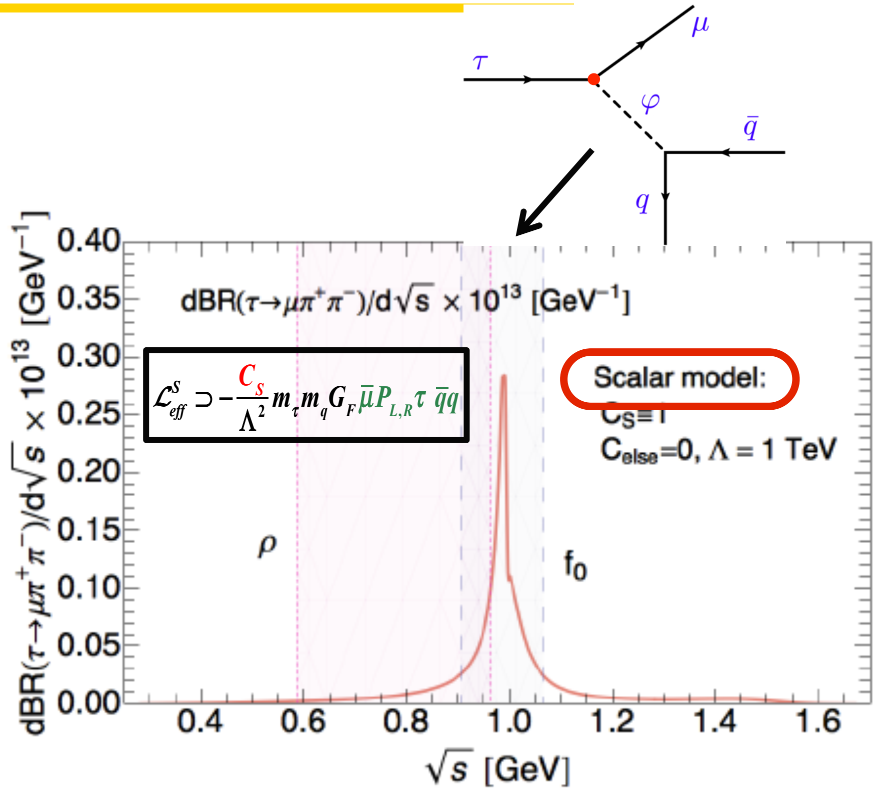
2.7 Differential distributions: τ→μ(e)ππ decays

Celis, Cirigliano, E.P.'14

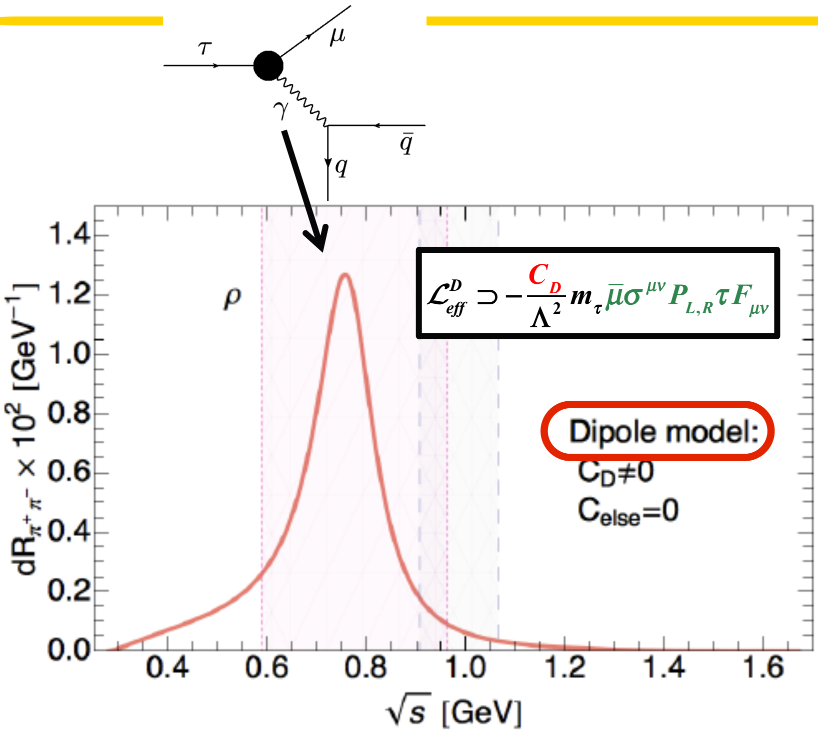


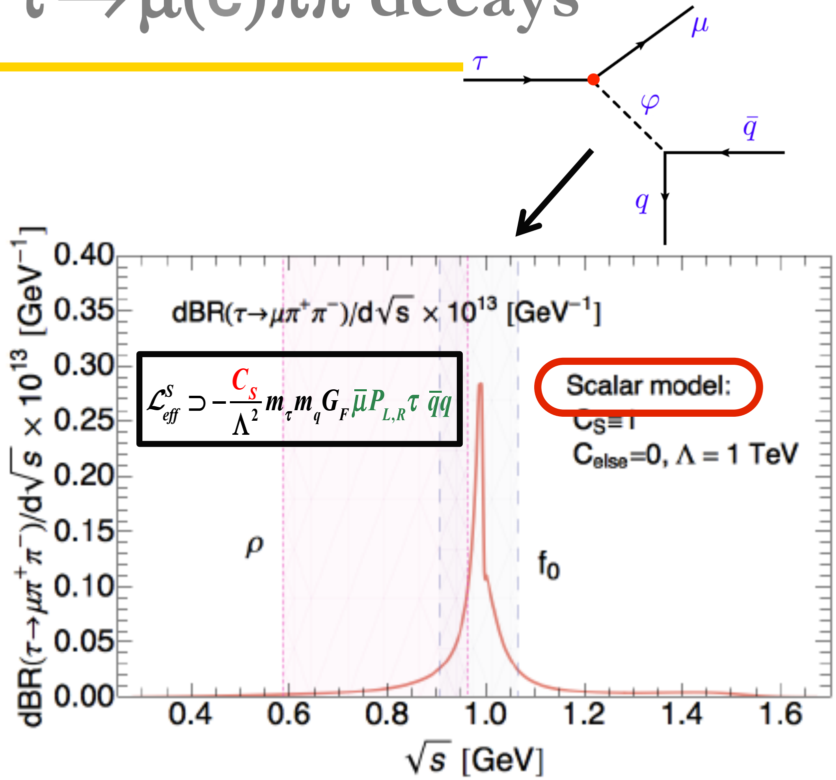
2.7 Differential distributions: τ → μ(e)ππ decays

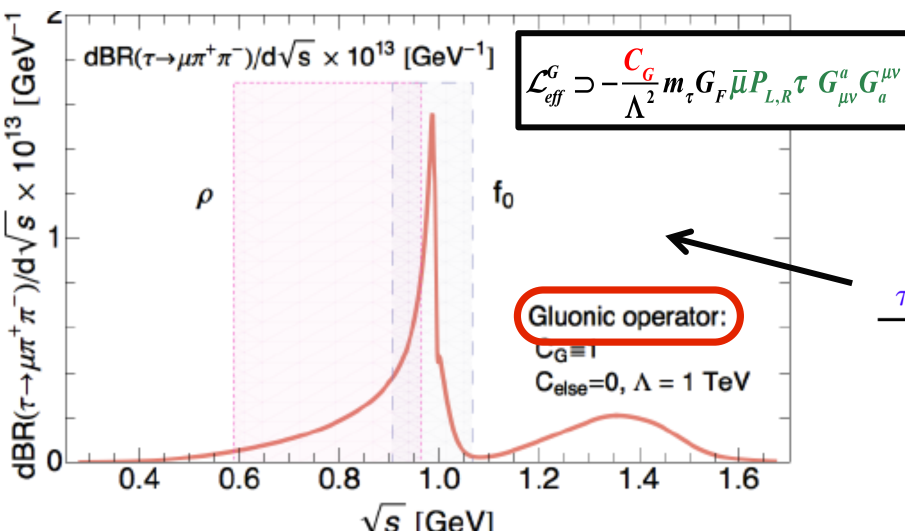


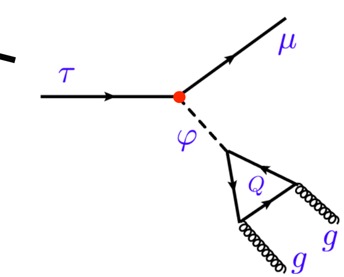


2.7 Differential distributions: $\tau \to \mu(e)\pi\pi$ decays





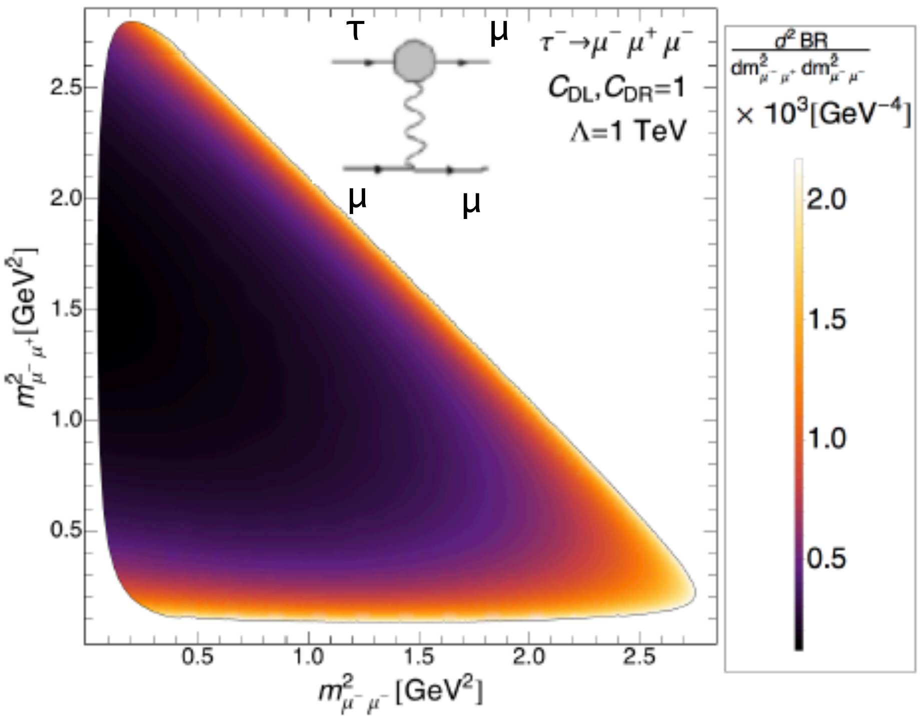




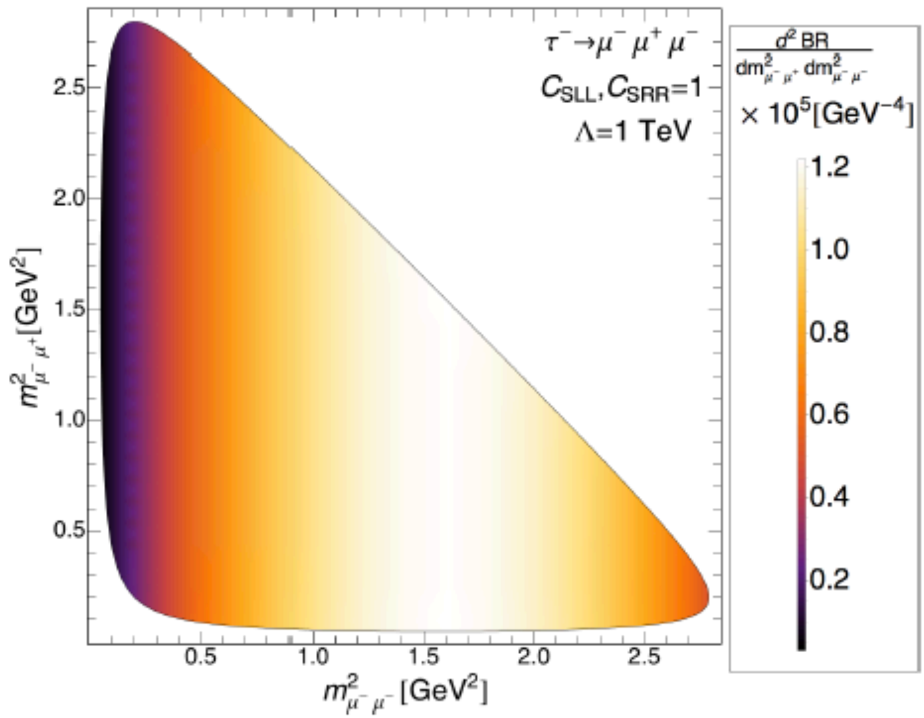
Different distributions according to the *operator!*

2.7 Differential distributions: Dalitz plot of τ→3μ

Dassinger et al.' 07
Matsuzuki&Sanda'07
Celis, Cirigliano, E.P.'14



Dipole operator dominance



Scalar 4-lepton operator dominance

Angular analysis with polarized taus — *Dassinger, Feldman, Mannel, Turczyk' 07*

3. Ex: Charged Lepton-Flavour Violation and Higgs Physics

3.1 Non standard LFV Higgs coupling

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

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

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

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

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

Cheng, Sher'97

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

- In concrete models, in general further parametrically suppressed

3.1 Non standard LFV Higgs coupling

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

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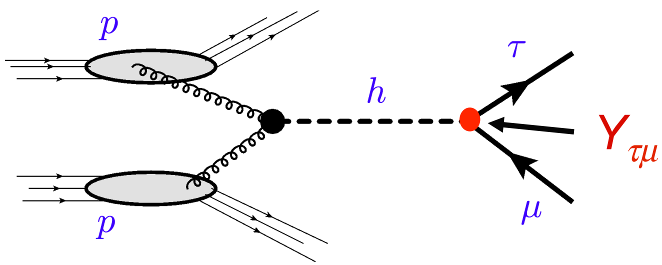
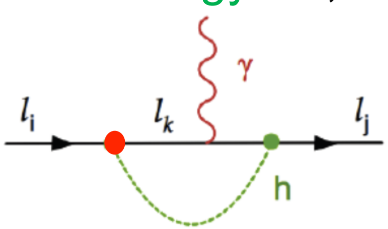
McKeen, Pospelov, Ritz'12
Arhrib, Cheng, Kong'12

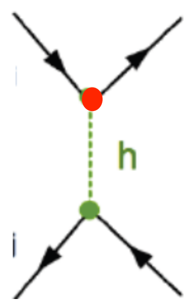
- High energy : LHC

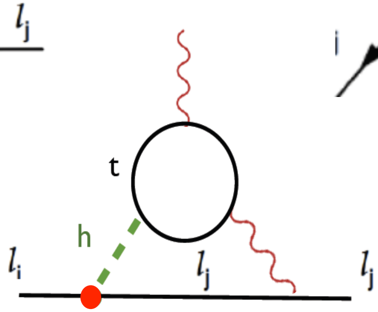


Hadronic part treated with perturbative QCD

- Low energy : D, S operators







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Goudelis, Lebedev, Park'11
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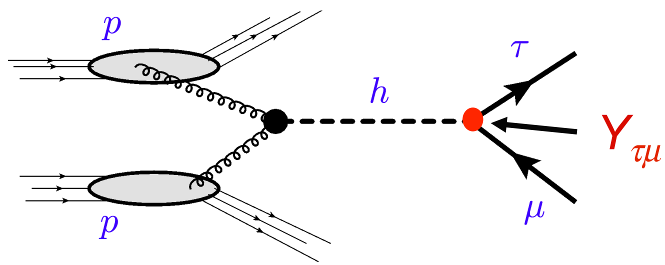
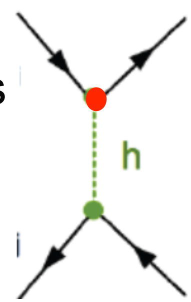
- High energy : LHC

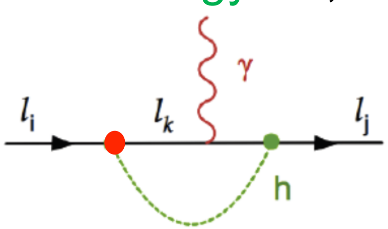


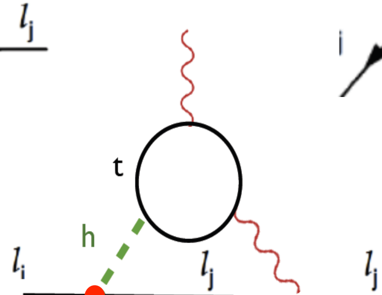
Hadronic part treated with perturbative QCD

Reverse the process

- Low energy : D, S, G operators







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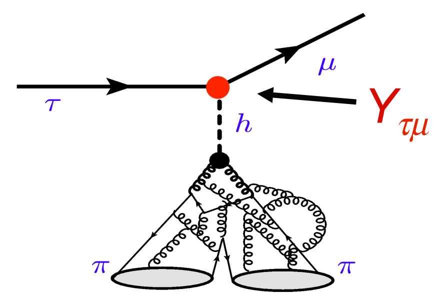
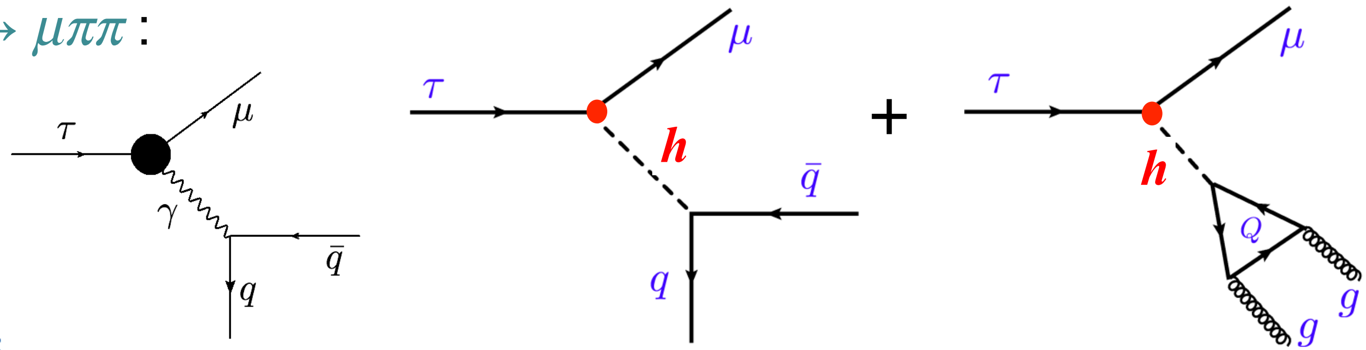
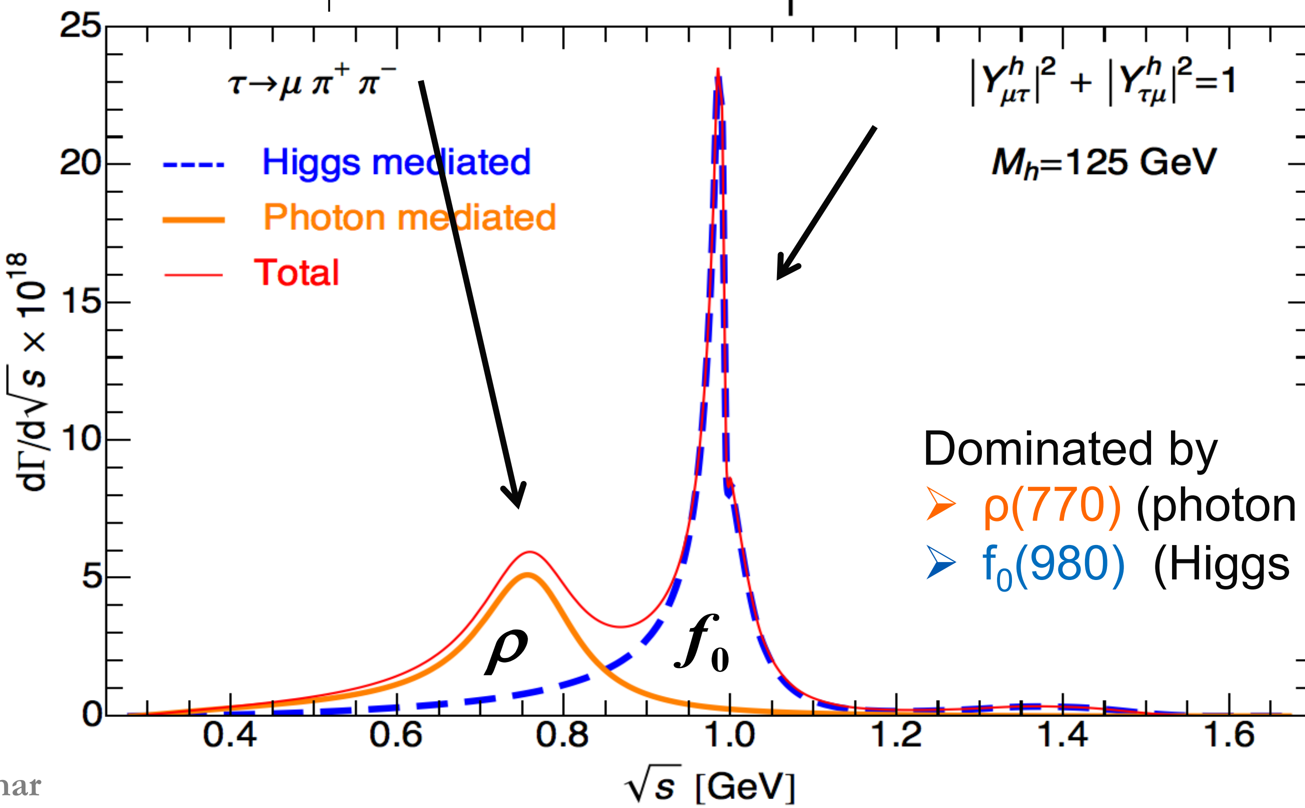


Hadronic part treated with non-perturbative QCD

3.2 Constraints in the τμ sector

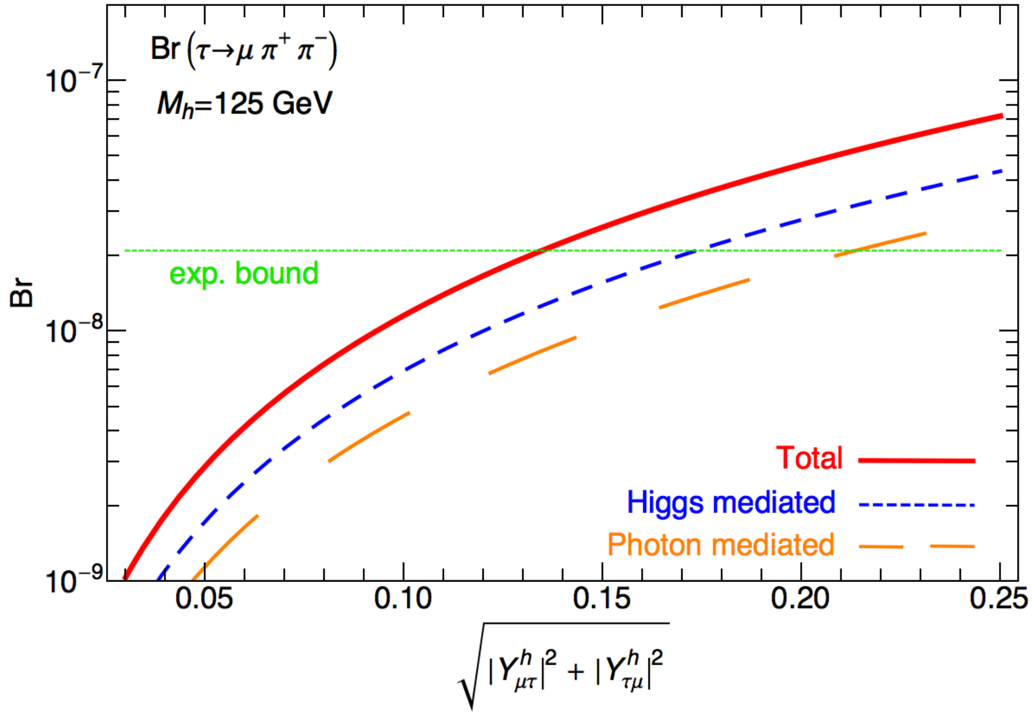
- At low energy
  - $\tau \to \mu\pi\pi$:





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

3.2 Constraints in the τμ sector



Bound:

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

Process	(BR × 10^8) 90% CL	$\sqrt{\vert Y^h_{\mu\tau}\vert^2+\vert Y^h_{\tau\mu}\vert^2}$	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 × 10^3 [87]	< 6.3	Scalar, Gluon

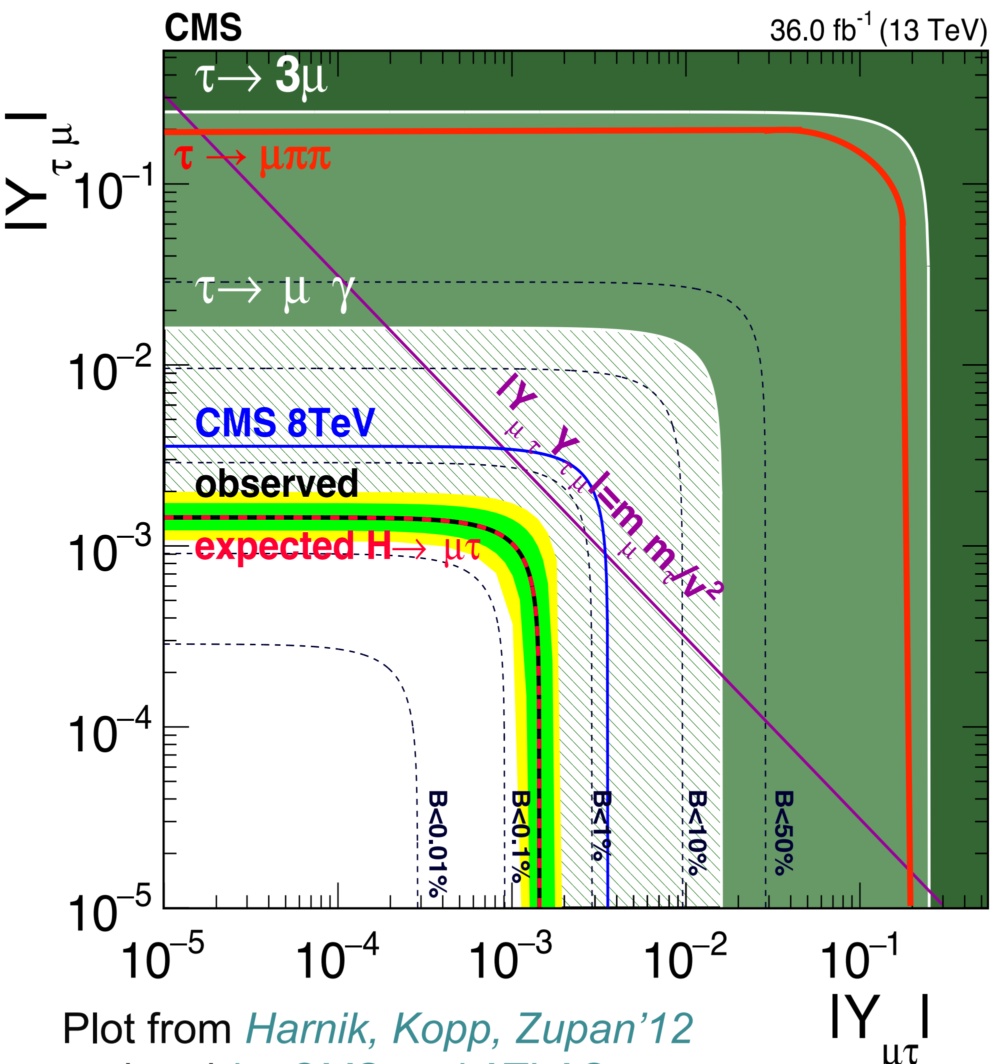
Less stringent but more robust handle on LFV Higgs couplings

?

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

3.2 Constraints in the τμ sector

CMS'17



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

- Constraints from LE:
  - $\tau \to \mu\gamma$: best constraints followed by $\tau \to \mu\pi\pi$ and $\tau \to 3\mu$
- Constraints from HE:

  LHC wins for τμ!

  $BR(h \to \tau\mu) \leq 0.15\%$ *CMS'21*

  $|Y_{\tau\mu}, Y_{\mu\tau}| \leq 0.00111$

  ATLAS'20 $BR(h \to \tau\mu) \leq 0.25\%$
- Opposite situation for μe!
- For LFV Higgs and nothing else: LHC bound

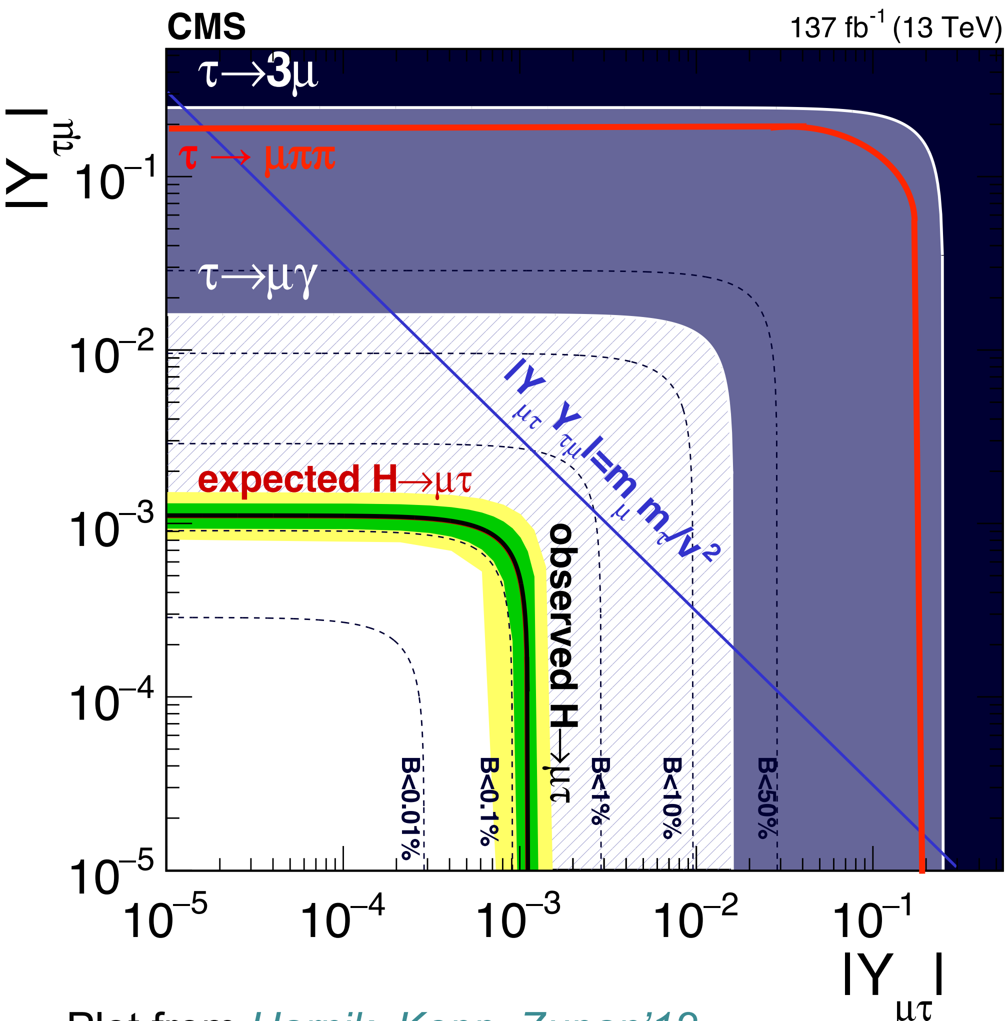
$\Rightarrow$

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

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

3.2 Constraints in the τμ sector

CMS'21



Plot from *Harnik, Kopp, Zupan'12*
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- Constraints from LE:
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  $BR(h \to \tau\mu) \leq 0.15\%$ — *CMS'21*

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- Opposite situation for μe!
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⇒ $BR(\tau \to \mu\gamma) < 2.2 \times 10^{-9}$

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

4. Conclusion and Outlook

Summary

- *Charged LFV* processes are very interesting to look for New Physics
  - LFV measurements have SM-free signal
  - Current impressive experimental bounds in muons and Tau sector but also in meson decays and more to come which promise orders of magnitude sensitivity improvements
  - In addition to leptonic and radiative decays ⇒ hadronic decays important, e.g. $\tau \to \mu(e)\pi\pi, \mu N \to eN$
  - New physics models usually strongly correlate these sectors
  - 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)

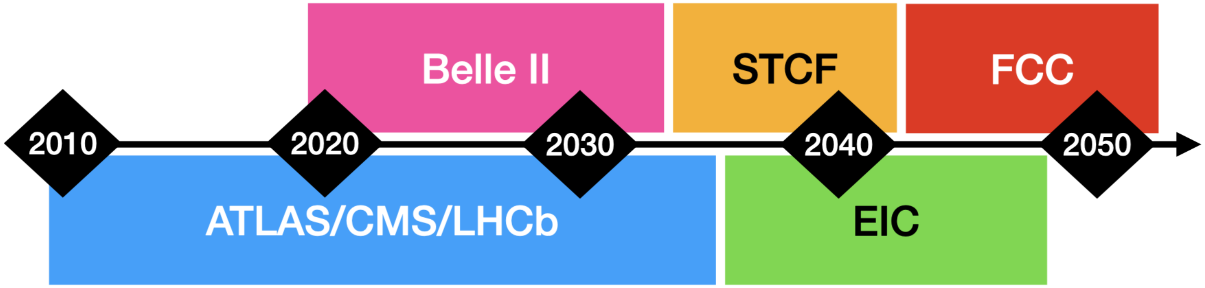
- Interplay low energy and collider physics: LFV of the Higgs boson

Summary

- Several experimental programs:
  MEGII, Mu3e, DeeMee, COMET, *Mu2e*, *Belle II*, *BESIII, LHCb, LHC-HL, EIC, NA64, STCF*

- Theoretical analysis: Global SMEFT analysis, see e.g.
  - For $\mu \rightarrow e$ conversion see e.g. *Davidson & Echenard'22*
  - For NA64 prospects see e.g. *Gninenko et al.'18*
    Husek, Monzalvez-Pozo, Portoles'21
  - For EIC prospects see e.g. *Cirigliano et al.'21*

⇨ Many *Snowmass* papers, see e.g. *Banerjee et al'22*

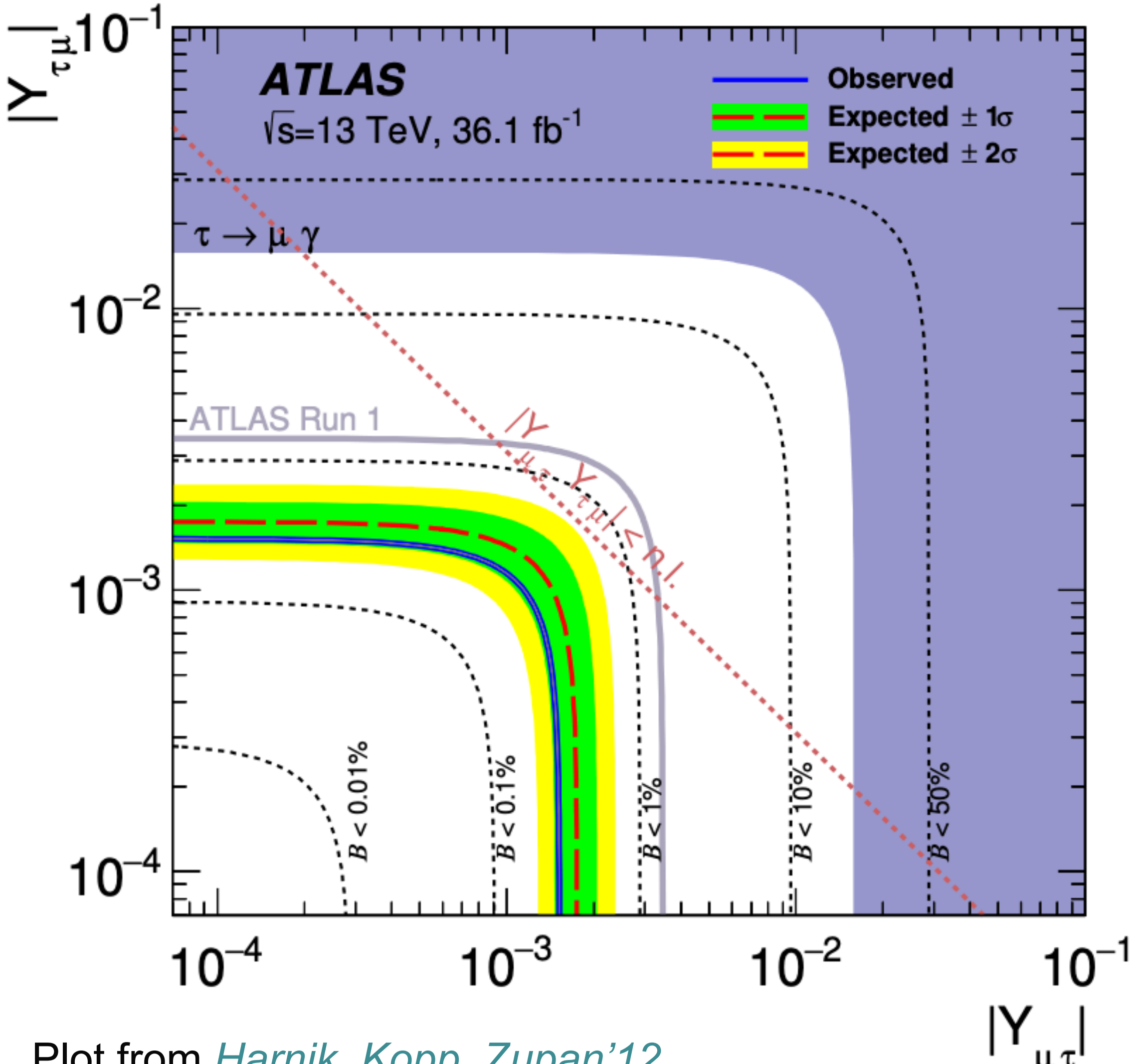


- Go beyond SMEFT to include Gravity ⇨ Bound Lorentz- and CPT-violating effects
  Kostelecky, E.P., Sherrill in progress

5. Back-up

3.2 Constraints in the τμ sector

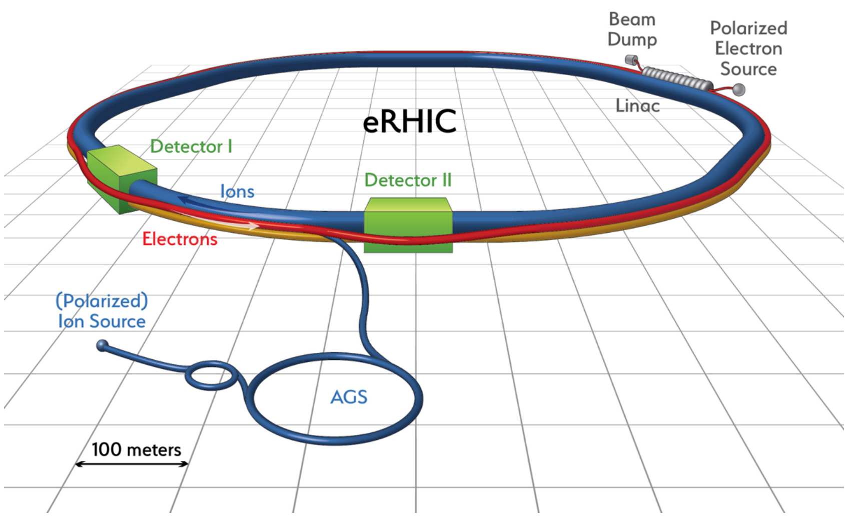
ATLAS'20

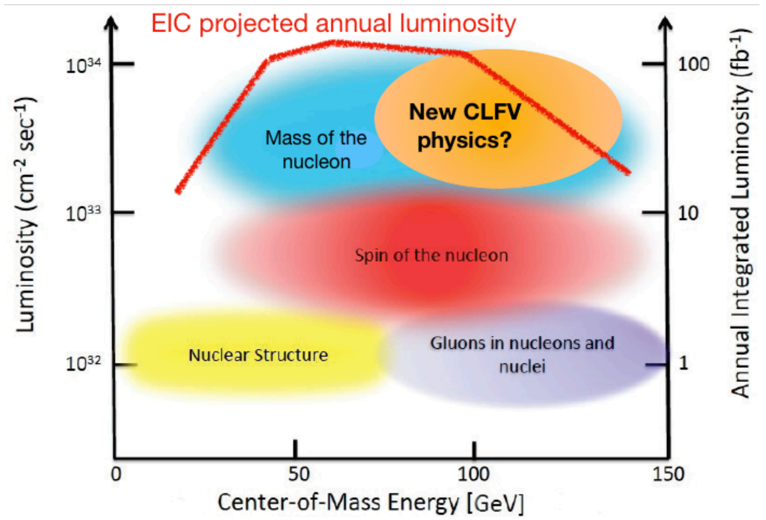


Plot from *Harnik, Kopp, Zupan'12*
updated *by CMS and ATLAS*

From E. Mereghetti

The Electron-Ion Collider: an intensity frontier machine?





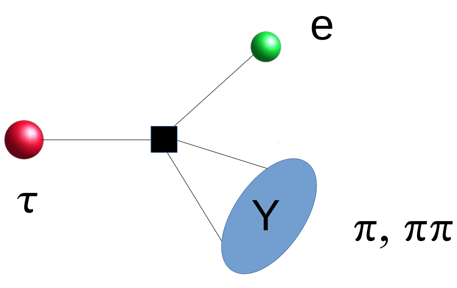
from A. Deshpande, hacked by C. Lee

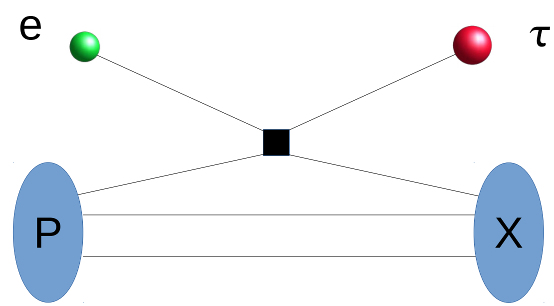
- EIC received CD-1 in Summer ‘21, beginning project design
- can deliver a lot of data!
  1000 times more than HERA
- with additional unique possibility to polarize *e* and proton beams

can we look for rare/BSM processes?

From E. Mereghetti

The Electron-Ion Collider: an intensity frontier machine





E.g. $\tau \leftrightarrow e$ from heavy new physics

$$\mathcal{L} \sim \frac{1}{\Lambda^2} \tau \Gamma e \, \bar{q} \Gamma q \qquad \Lambda \gg 246 \text{ GeV}$$

LFV τ decays at B factories

$$N_\tau^{\text{decay}} = \epsilon_d N_\tau \tau_\tau \Gamma_{\tau \to eY},$$

$$\Gamma_{\tau \to eY} \sim \frac{m_\tau^3 \Lambda_{\text{QCD}}^2}{\Lambda^4}$$

"BSM" τs at the EIC

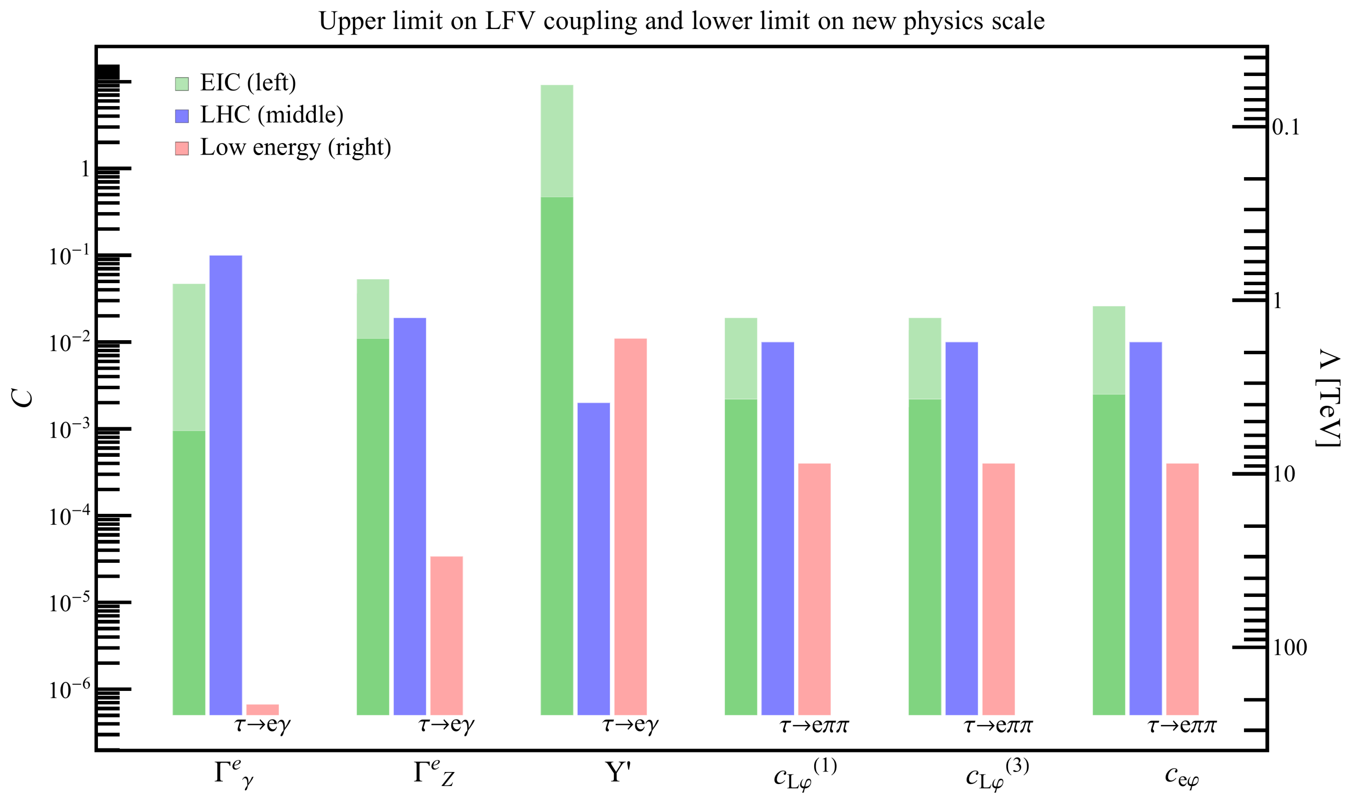
$$N_\tau^{\text{scattering}} = \epsilon_s \mathcal{L} \, \sigma_{ep \to \tau X},$$

$$\sigma_{ep \to \tau X} \sim \frac{S}{\Lambda^4}$$

- to be competitive $N_\tau^{\text{scattering}} = N_\tau^{\text{decay}}$

$$\epsilon_s \mathcal{L} \sim \epsilon_d N_\tau \frac{(4\pi)^3 v^4 \Lambda_{\text{QCD}}^2}{S m_\tau^2} \sim 10^3 \text{ fb}^{-1}$$

High-energy vs low-energy: dipole, Yukawa and Z



- EIC sensitivity with μ analysis (light green) and $\tau \to X_h \nu_\tau$, assuming $\epsilon_0 = 1$ (dark green)
- no competition on γ and Z dipole operators
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

2.5 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Two handles:
  - Branching ratios: $R_{F,M} \equiv \frac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}$ with F_M dominant LFV mode for model M
  - Spectra for > 2 bodies in the final state:

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

- Benchmarks:
  - Dipole model: $C_D \neq 0$, $C_{else} = 0$
  - Scalar model: $C_S \neq 0$, $C_{else} = 0$
  - Vector (gamma,Z) model: $C_V \neq 0$, $C_{else} = 0$
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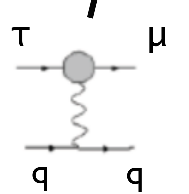
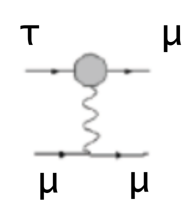
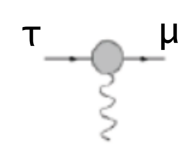
  - Branching ratios: $R_{F,M} \equiv \frac{\Gamma(\tau \to F)}{\Gamma(\tau \to F_M)}$ with F_M dominant LFV mode for model M

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







2.6 Model discriminating of BRs

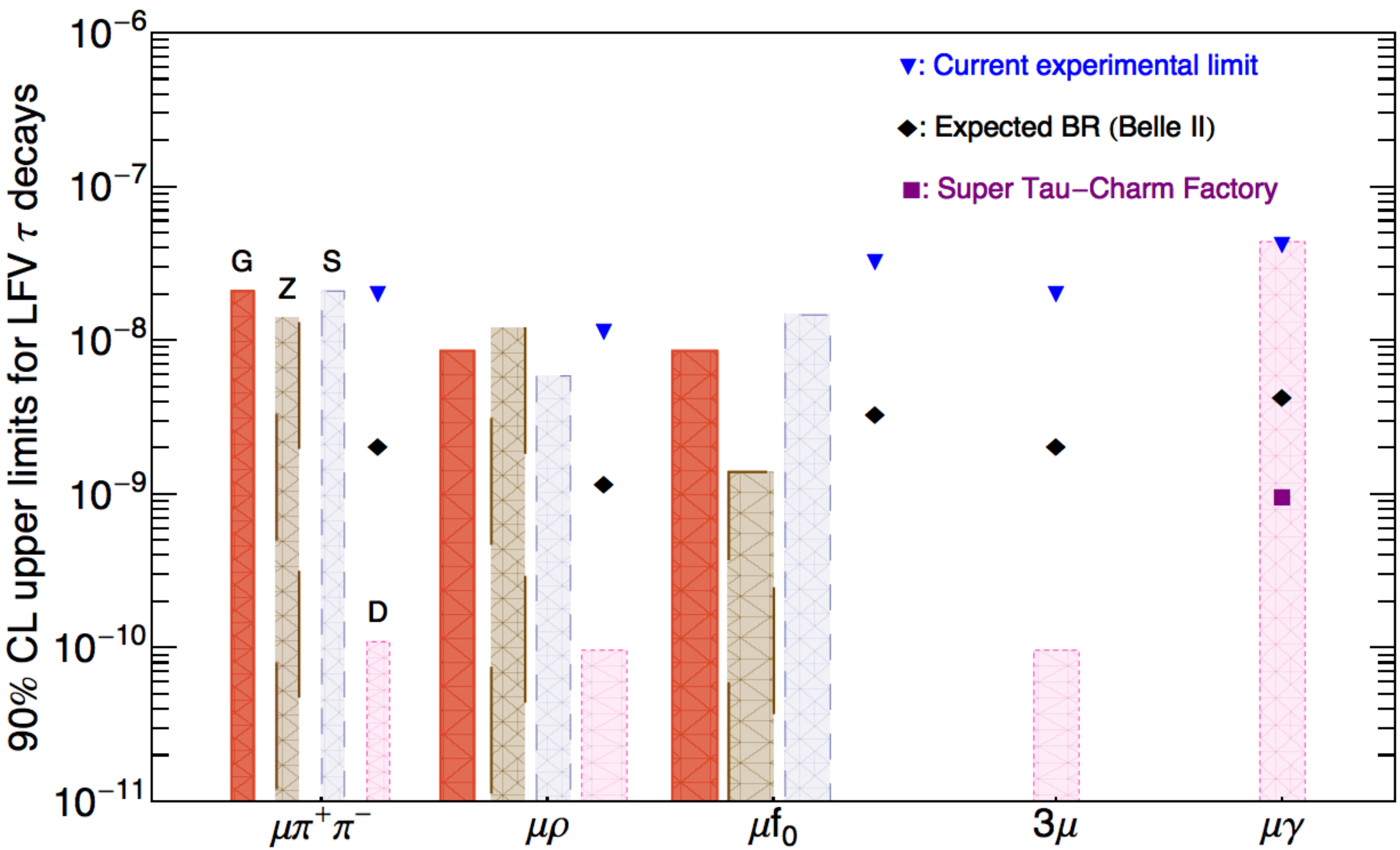
- Studies in specific models

Buras et al.'10

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	$0.06 \ldots 2.2$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.07 \ldots 2.2$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$	$0.06 \ldots 2.2$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$	$0.03 \ldots 1.3$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.04 \ldots 1.4$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2$	~ 5	$0.3 \ldots 0.5$	$1.5 \ldots 2.3$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$	$1.4 \ldots 1.7$
$\frac{R(\mu Ti \to e Ti)}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^2$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$	$10^{-12} \ldots 26$

⇨ Disentangle the *underlying dynamics* of NP

4.2 Prospects:



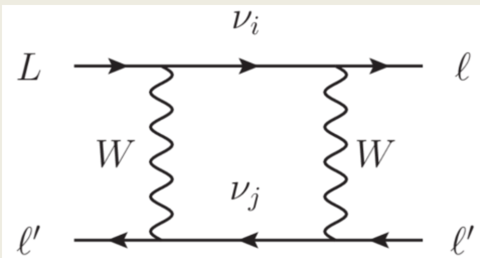
L → 3l

Hernández-Tome, López Castro & Roig'20, Blackstone, Fael, E.P.'21

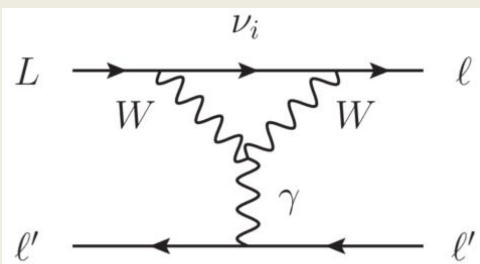
- Claim in *Pham'08* that moving to Physical Limit ⇒ $Br\left(\tau \to \mu \ell^+ \ell^-\right) \geq 10^{-14}$ **!**

$m_\nu \ll \mathcal{P} \ll M_W$

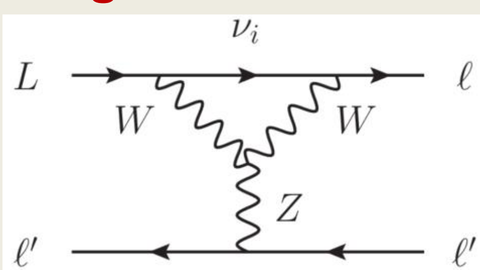
Boxes



γ Penguins



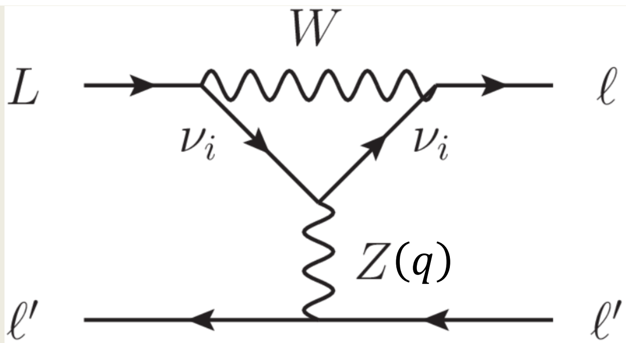
Z Penguins



$L \to 3l$

Hernández-Tome, López Castro & Roig'20, Blackstone, Fael, E.P.'20

- Claim in *Pham'08* that moving to Physical Limit ⇒ $Br\left(\tau \to \mu \ell^+ \ell^-\right) \geq 10^{-14}$ **!**



Claim: Moving to PL generates a log(m_i) divergence in the Z penguin.
This involves an expansion about q^2 = 0:

$$f_0(x_i) + (q^2/M_W^2) f_1(x_i) + \cdots$$
$$f_0(x_i) \sim x_i \log x_i$$
$$f_1(x_i) \sim \mathbf{\log x_i}$$

⇒ *Incorrect!*

Concerns:

1. Non trivial gauge-dependence cancellation — *Buchalla, Buras, Harlander'91*

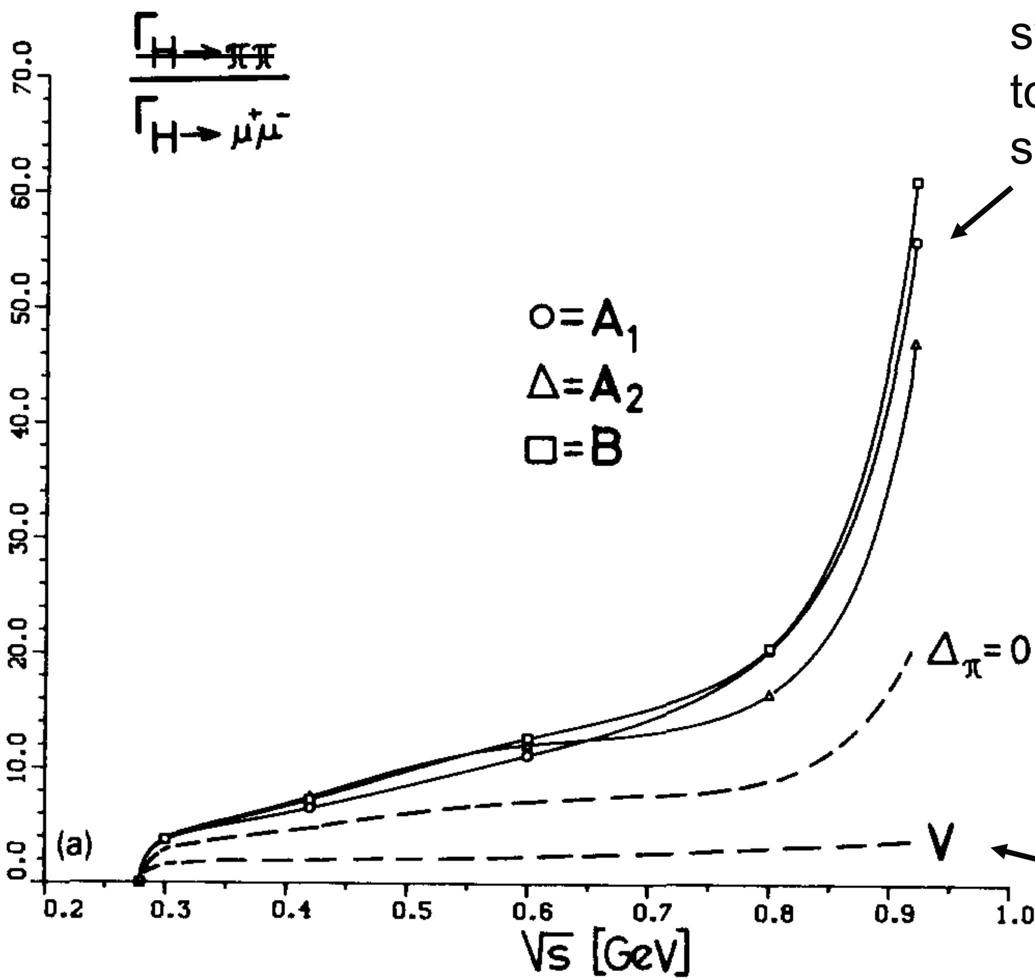
2. q^2 is physically limited by $q^2 \leq 4m_{\ell'}^2$ expansion cannot give correct $m_i \to 0$ behavior

3. When $m_i \to 0$ limit, need to recover the SM without fine-tuning of ratios m_i/m_j

How to describe the form factors?

Donoghue, Gasser, Leutwyler'90

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 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

Unitarity

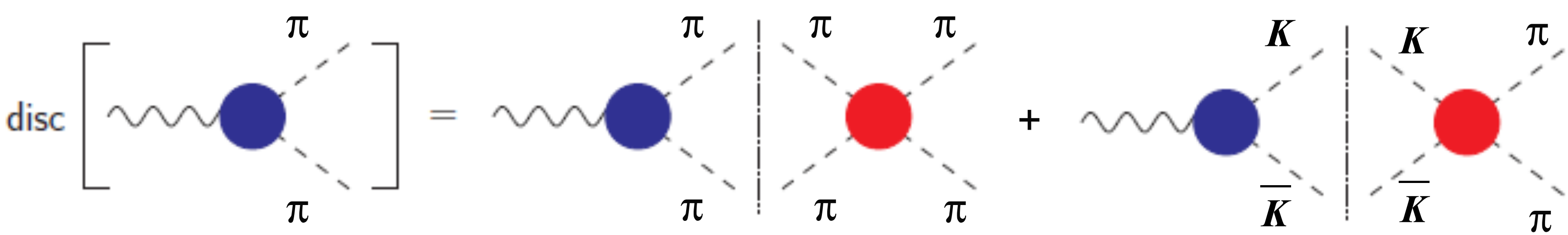
Celis, Cirigliano, E.P.'14

- 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



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

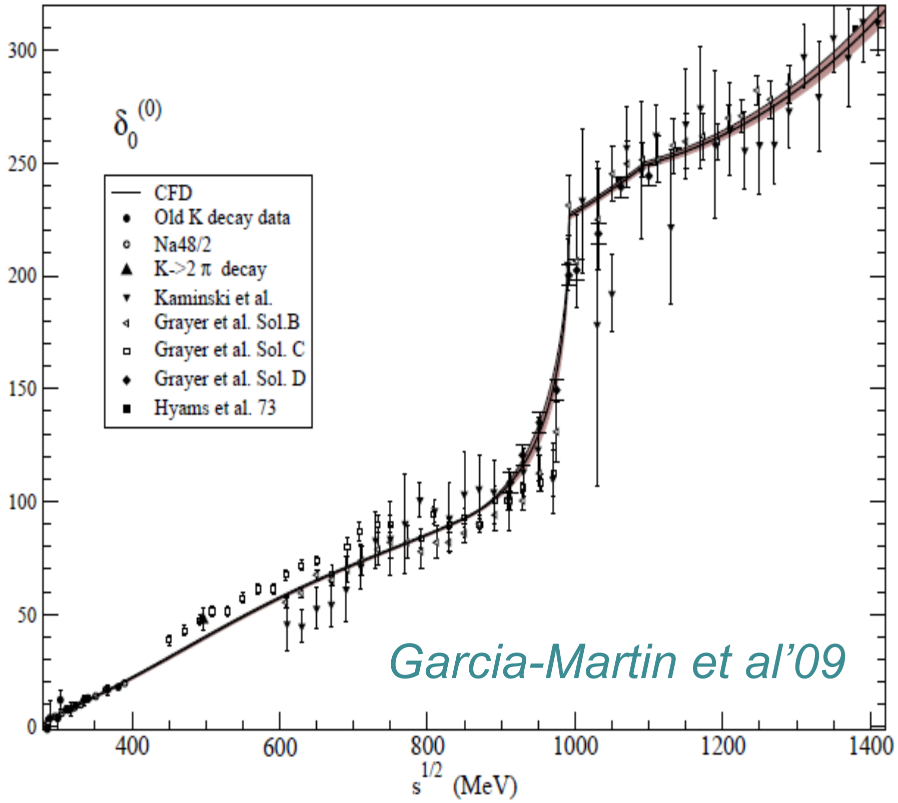
$n = \pi\pi, K\bar{K}$

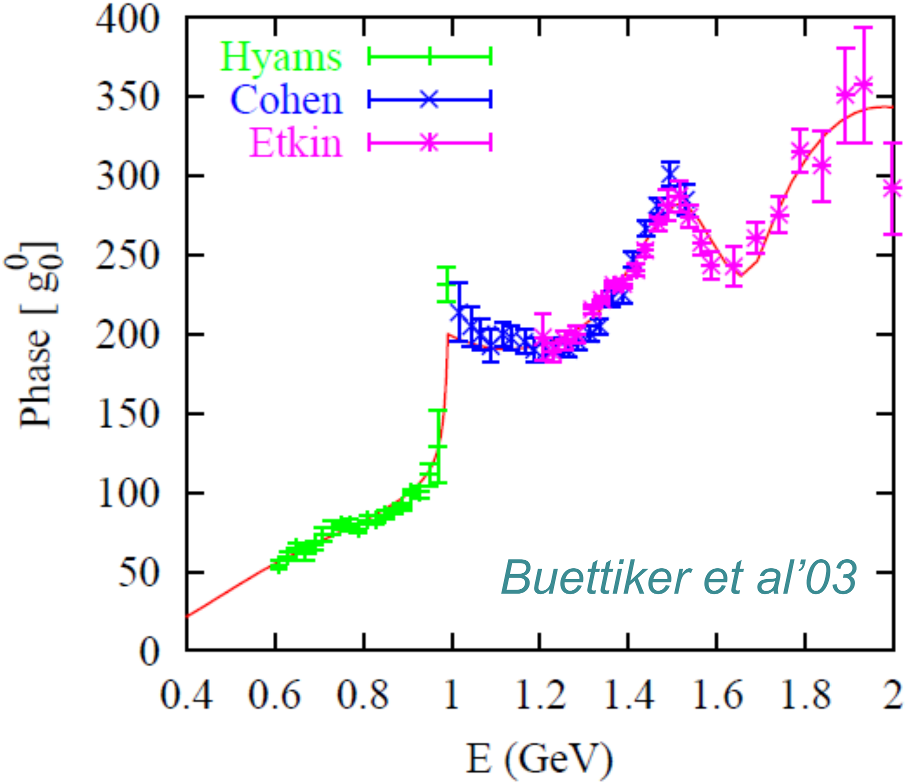
Scattering matrix:

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

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*

Dispersion relations

Celis, Cirigliano, E.P.'14

- General solution to *Mushkhelishvili-Omnès* problem:

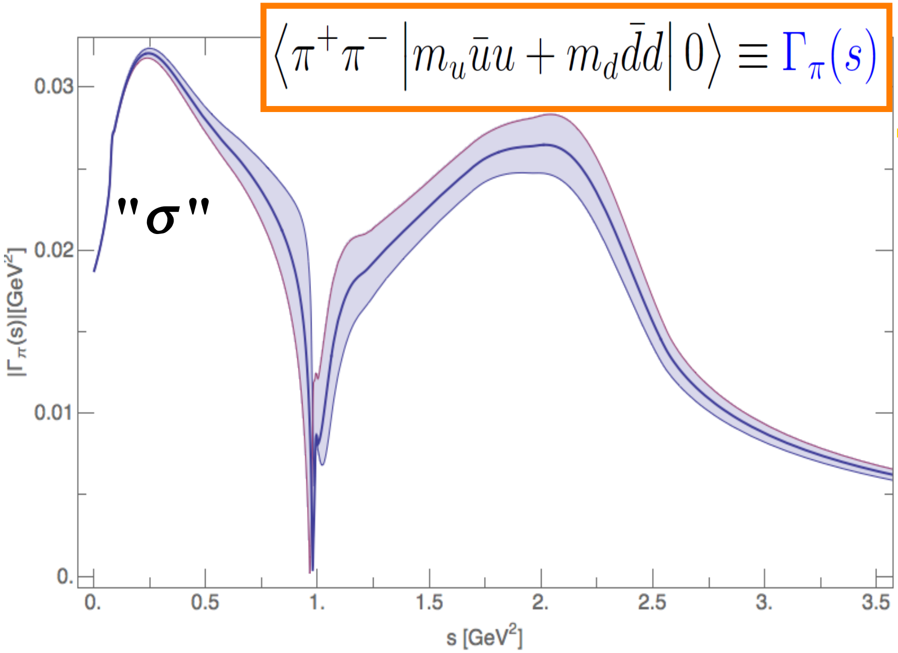
$$\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}$$

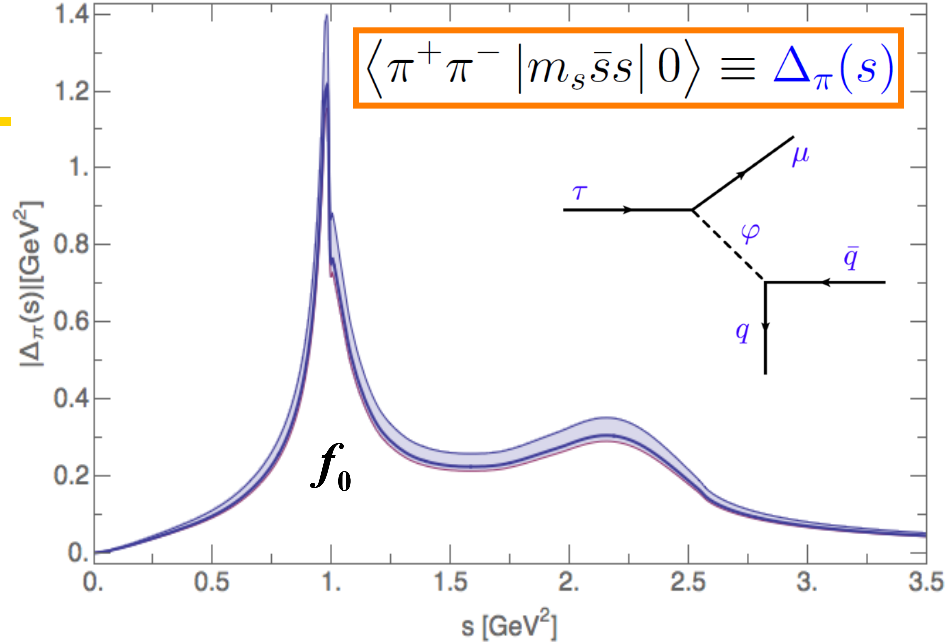
Canonical solution falling as 1/s for large s (obey unsubtracted dispersion relations)

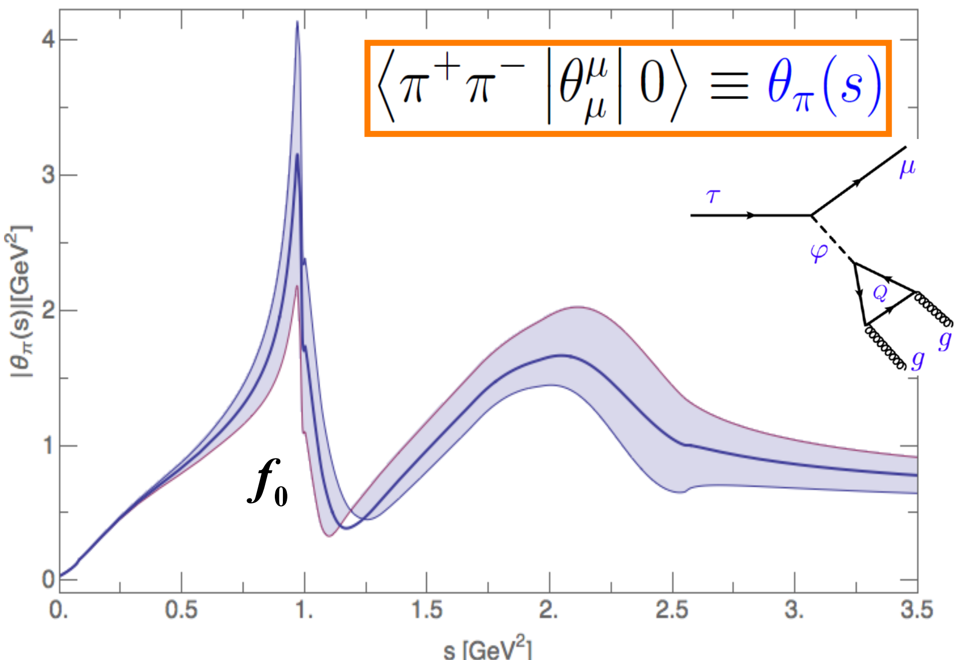
Polynomial determined from a matching to ChPT + lattice

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

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







Celis, Cirigliano, E.P.'14

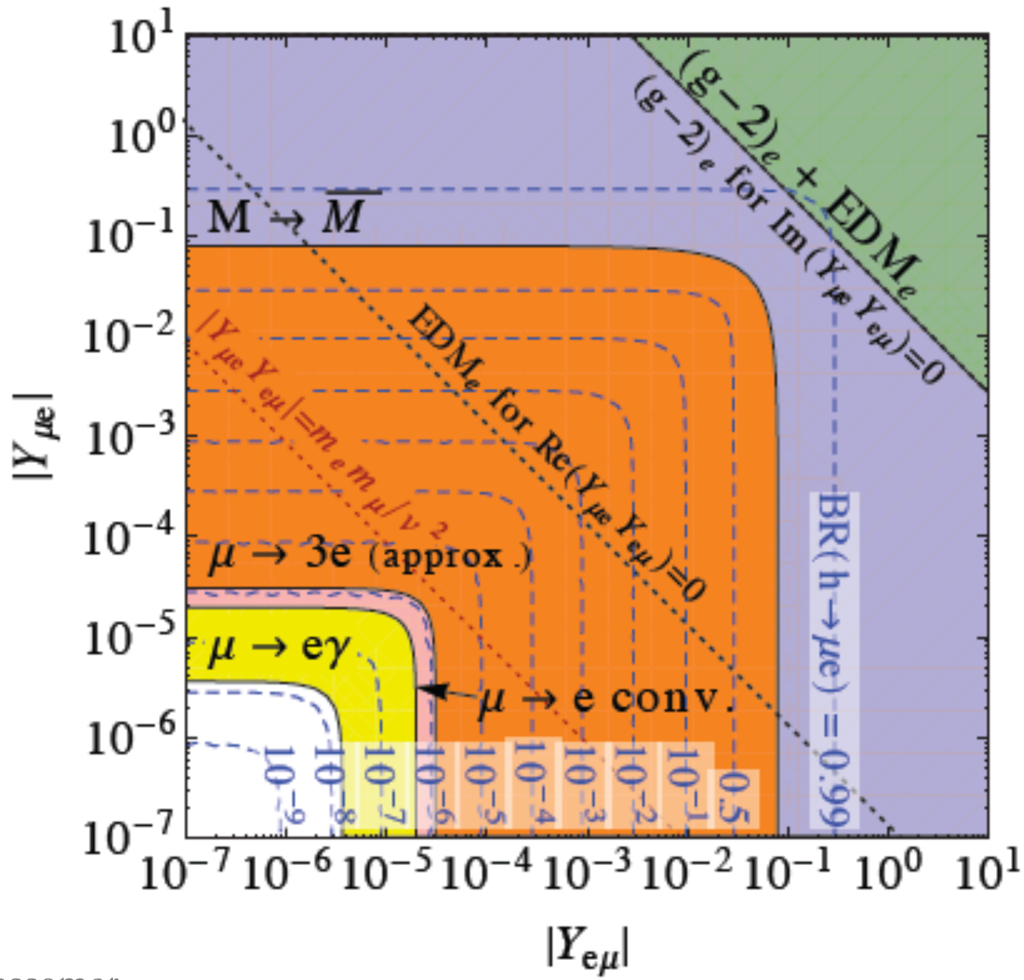
- Uncertainties:
  - Varying s_{cut} (1.4 GeV^2 - 1.8 GeV^2)
  - Varying the matching conditions
  - T matrix inputs

See also *Daub et al.'13*

3.3 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'16

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

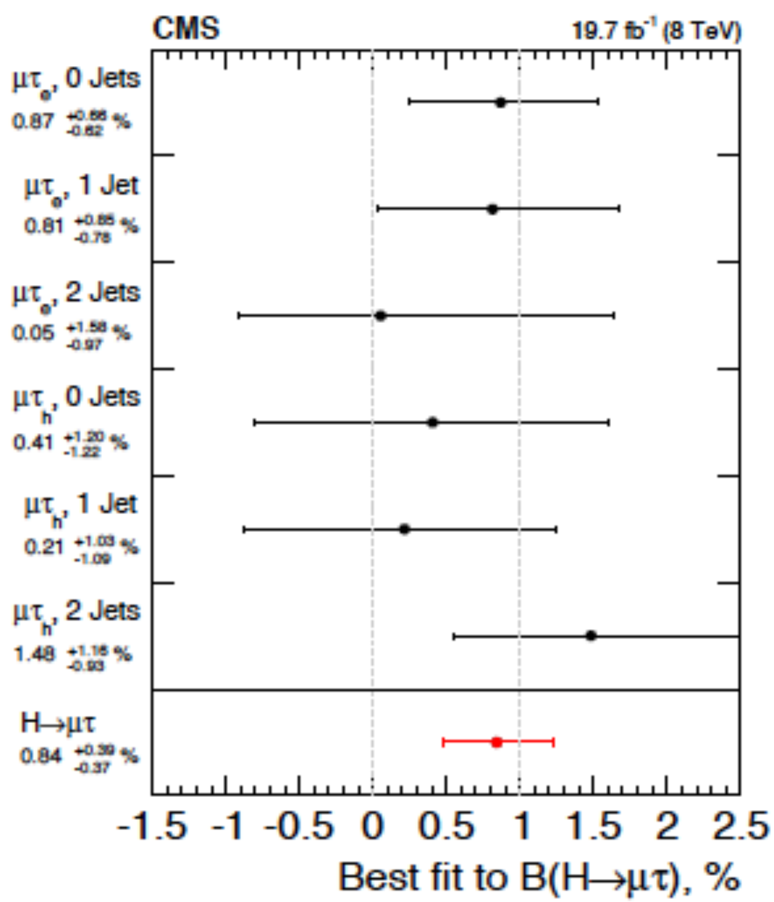
$\Rightarrow$ $BR(h \to \mu e) < 10^{-7}$

3.4 Hint of New Physics in h → τμ?

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

@2.4σ

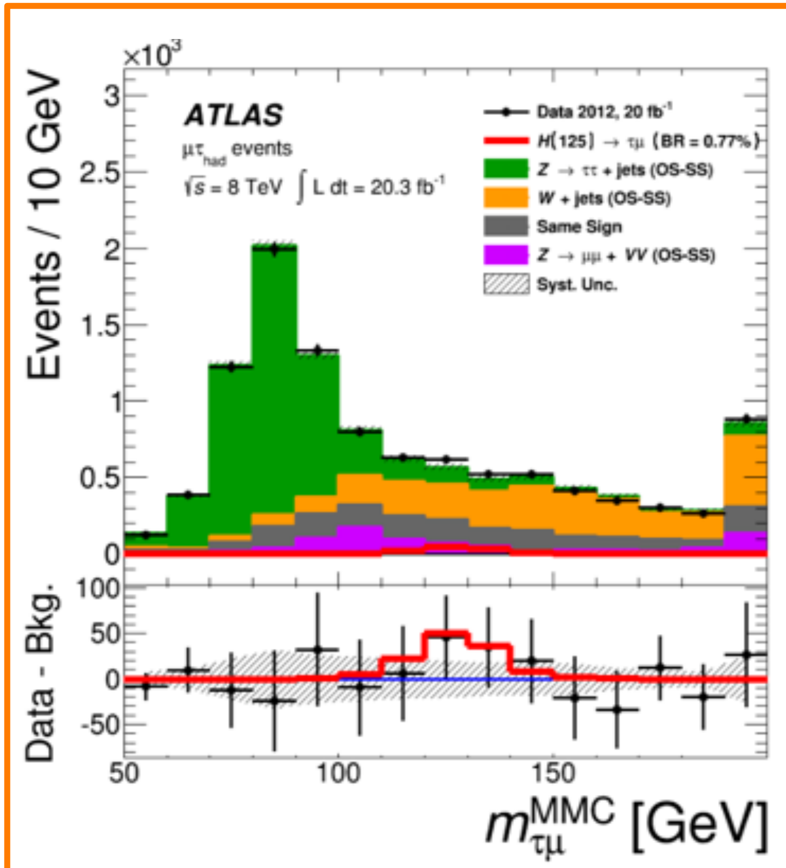
CMS'15



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

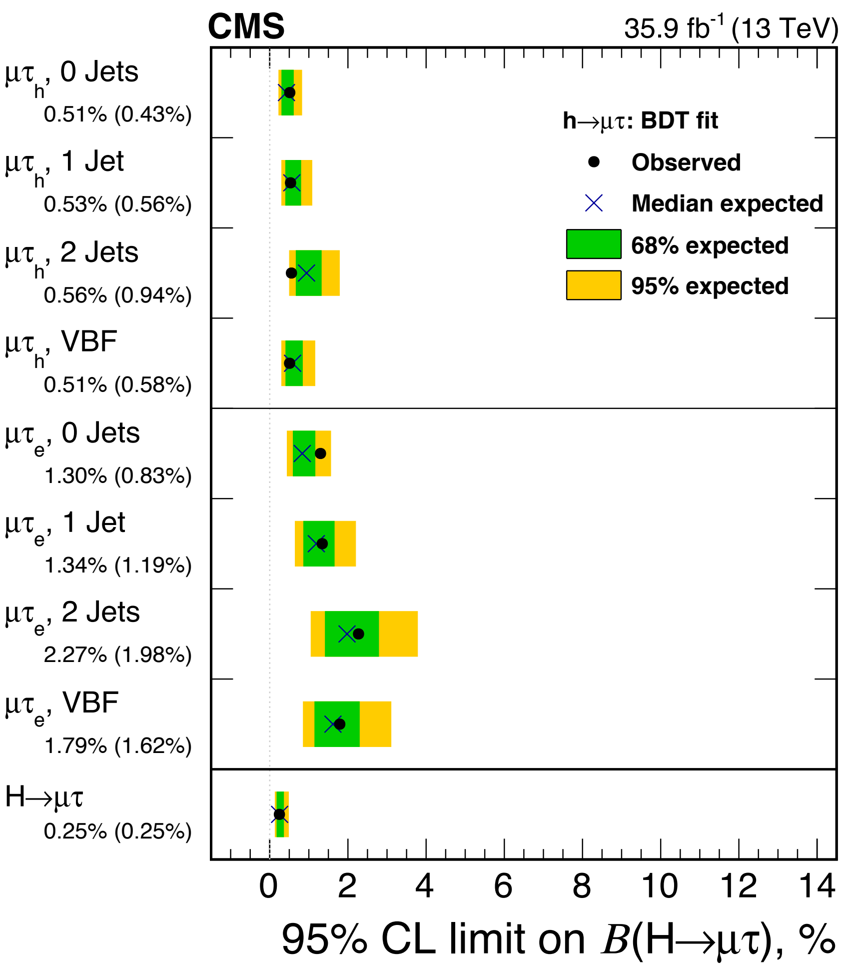
@1σ

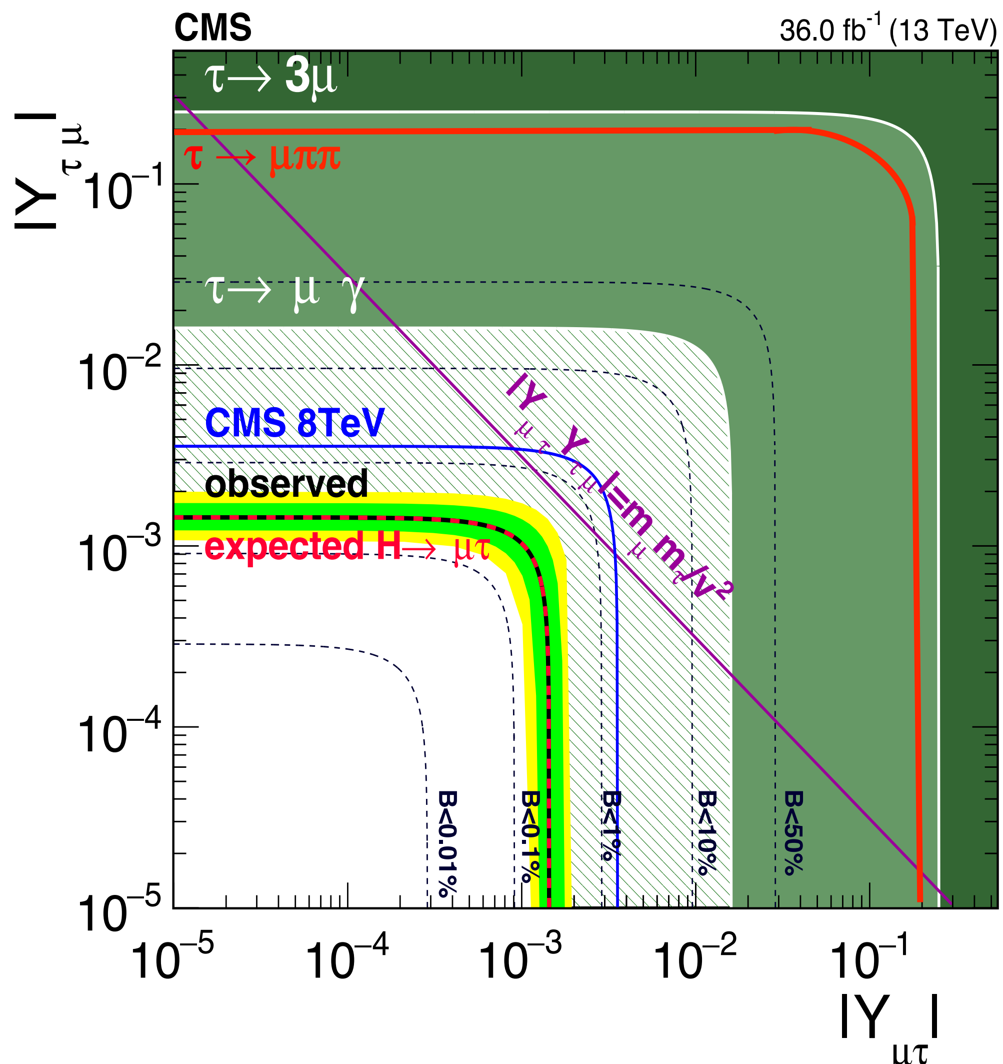
ATLAS'15



3.4 Hint of New Physics in h → τμ?

CMS'17

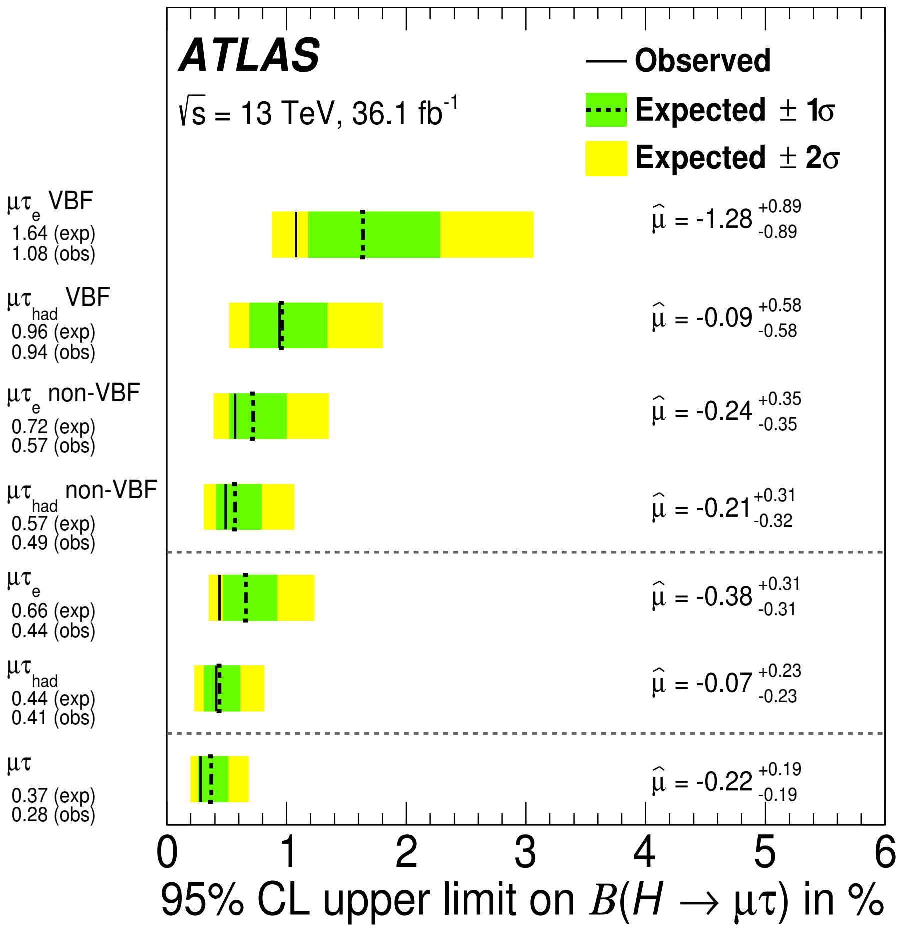


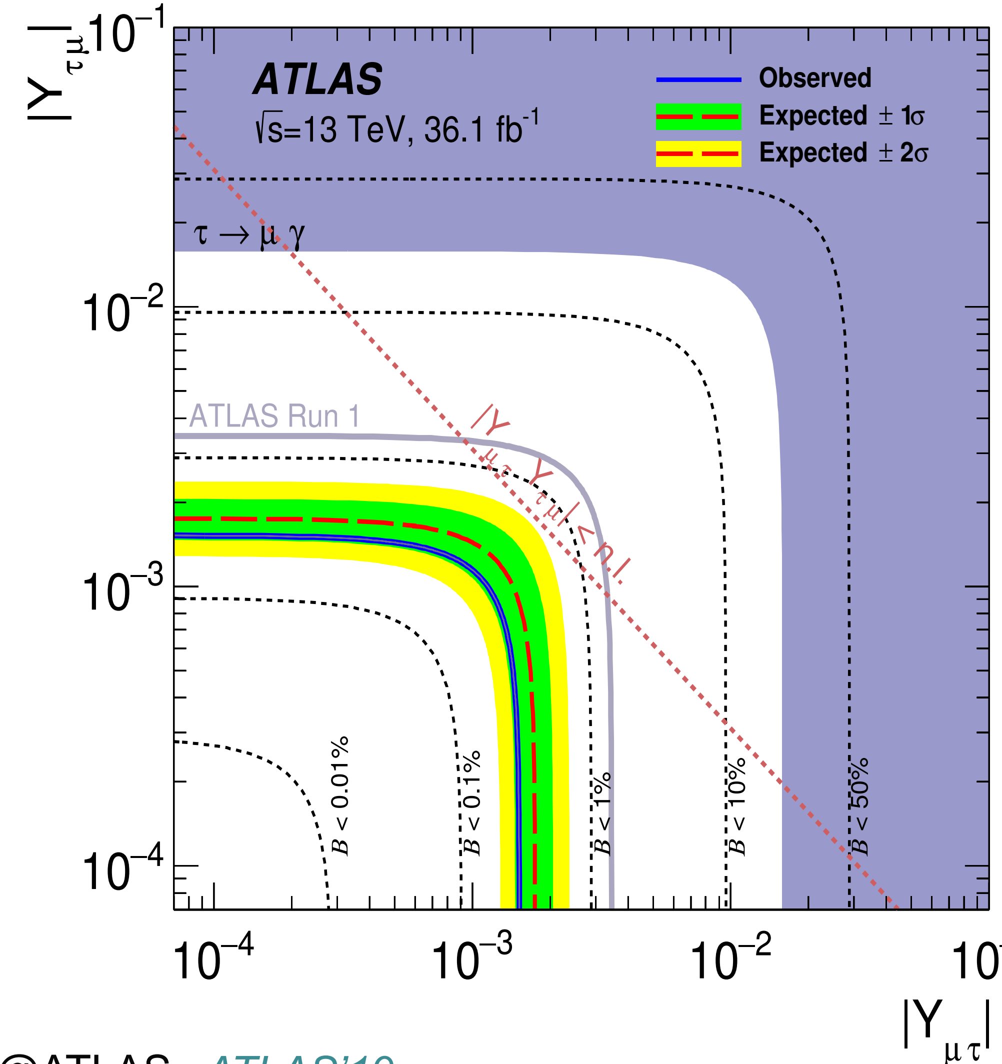


$BR(h \to \tau\mu) = (0.25 \pm 0.25)\%$ 13 TeV@CMS CMS'17

3.4 Hint of New Physics in h → τμ?

ATLAS'19





$BR(h \to \tau\mu) \leq 0.28\%$ 13 TeV@ATLAS ATLAS'19