Review of Tau physics

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Searching for Physics Beyond the Standard Model Using Charged Leptons

COFI Workshop, Puerto Rico, May 21, 2018

Outline :

1. Tau lepton as a laboratory to explore the Standard Model and possible extensions

2. Lepton Flavour Violation

3. CP violation in tau decays

4. Other interesting topics in tau physics:
   1. Lepton Universality
   2. Extraction of V_{us} from hadronic Tau decays and test of the CKM unitarity

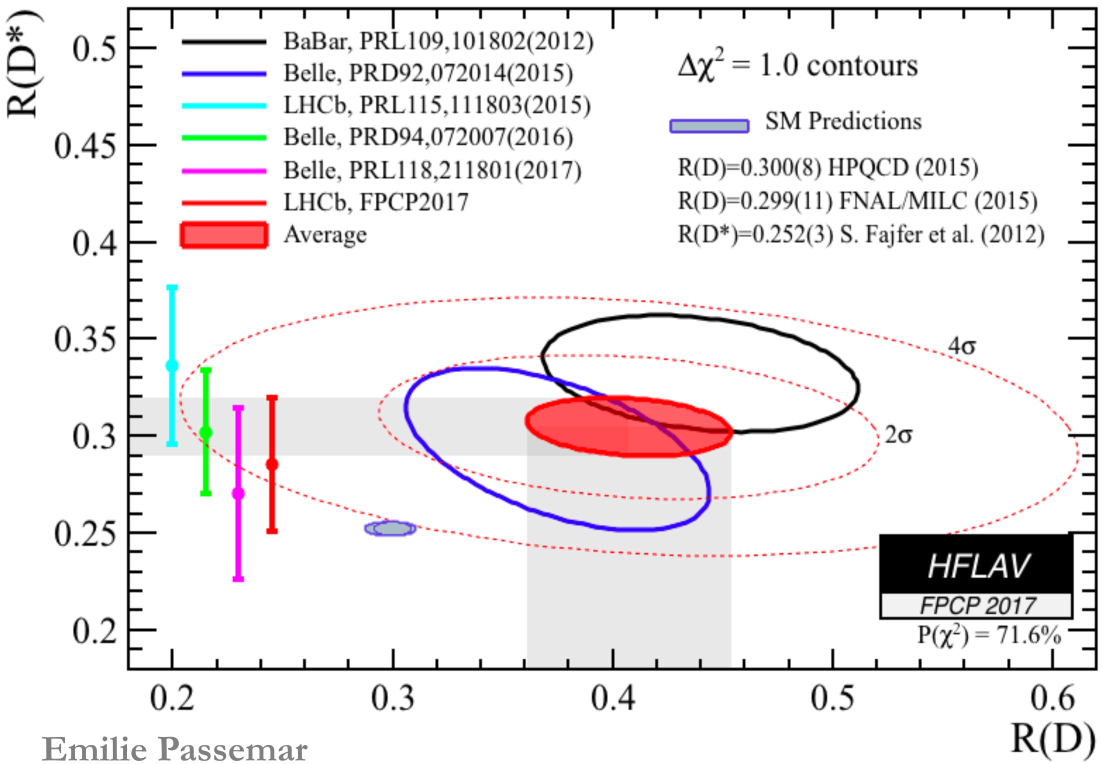
5. Conclusion and outlook

1. Introduction and Motivation

1.1 Quest for New Physics

- New era in particle physics :
  ⇒ (unexpected) *success of the Standard Model*: a successful theory of microscopic phenomena with *no intrinsic energy limitation*

- *Where do we look?* Everywhere! ⇒ search for New Physics with *broad search strategy* given lack of clear indications on the SM-EFT boundaries (*both in energies and effective couplings*)



- Hint from B physics anomalies?

$b \to c$ charged currents:

τ vs. light leptons (μ, e) [R(D), R(D*)]

$$\boxed{R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}}$$

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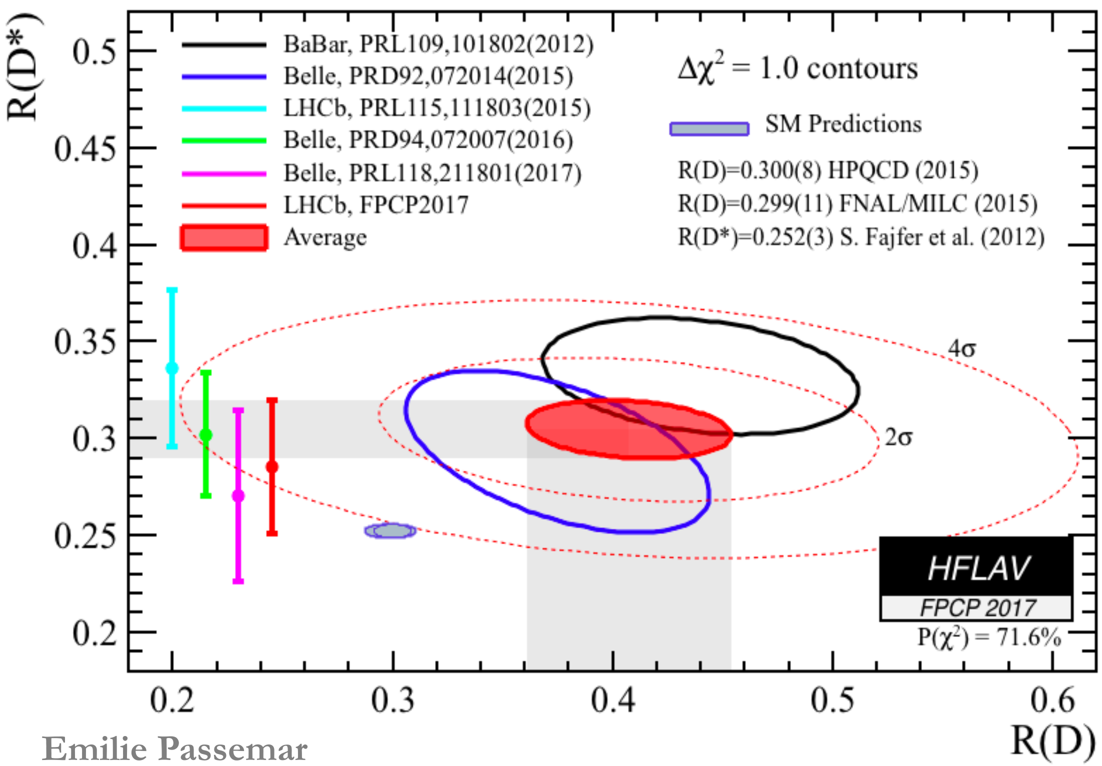

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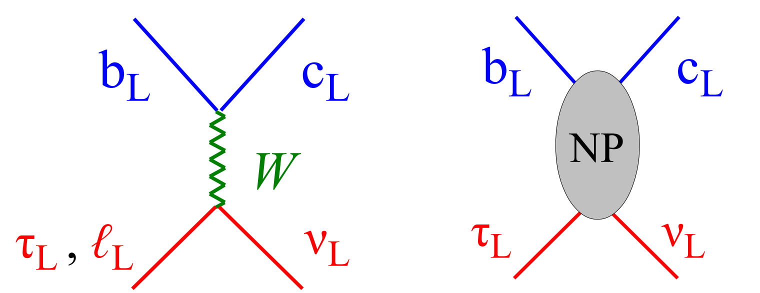
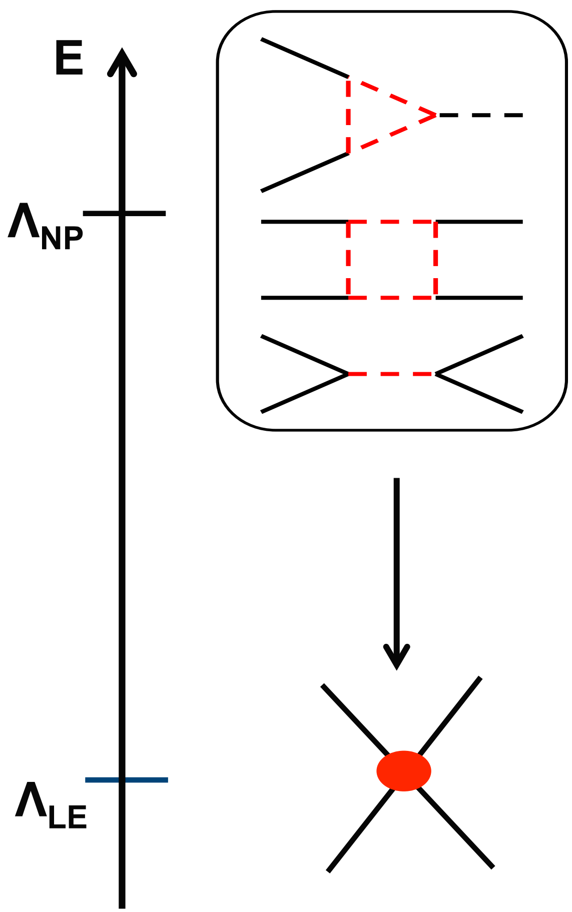


⇨ Key unique role of *Tau physics*

1.2 τ lepton as a unique probe of new physics



- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: *$[\varepsilon_K]$* $\boxed{\dfrac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^5 \text{ TeV}}$
  - Tau Leptons: *$[\tau \to \mu\gamma]$* $\boxed{\dfrac{\boldsymbol{\tau\bar{\mu}}\, f\bar{f}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^2 \text{ TeV}}$
- At low energy: lots of experiments e.g., *BaBar*, *Belle*, *BESIII, LHCb* ⇨ important improvements on measurements and bounds obtained and more expected (*Belle II*, *LHCb, ATLAS, CMS*)
- In many cases no SM background: e.g., LFV, EDMs
- For some modes accurate calculations of hadronic uncertainties essential, e.g. CPV in hadronic Tau decays, V_{us}, α_S extraction, etc

⇨ Tau leptons very important to look for *New Physics*!

1.2 τ lepton as a unique probe of new physics

- Unique probe of *Lepton Universaity* and *Charged Lepton Flavour Violation*
  No SM background
  Indirect probe of flavor-violating NP occurring at energies not directly accessible at accelerators

- Tool to search for *New Physics* at *colliders*:
  Ex: $h \to \tau\tau$, LFV in $h \to \tau\mu$

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- Studying its hadronic decays: *inclusive* & *exclusive*
  - Unique probe of some of the *fundamental SM parameters*

    ⇨ α_S, $|V_{us}|$, m_s

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  - Ideal set-up for the "R&D" of theory tools about *non perturbative* & *perturbative dynamics*: OPE, Chiral Perturbation Theory, Resonances, large N_c, dispersion relations lattice QCD, etc…

    ⇨ improve our understanding of the SM and QCD at low energy

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  - Inputs for the *muon g-2*

1.2 τ lepton as a unique probe of new physics

- A lot of progress in tau physics since its discovery on all the items described before ⇒ important experimental efforts from *LEP*, *CLEO, B factories: Babar, Belle, BES, VEPP-2M, LHCb, neutrino experiments*,…

  ⇒ More to come from *LHCb, BES, VEPP-2M, Belle II, CMS, ATLAS*

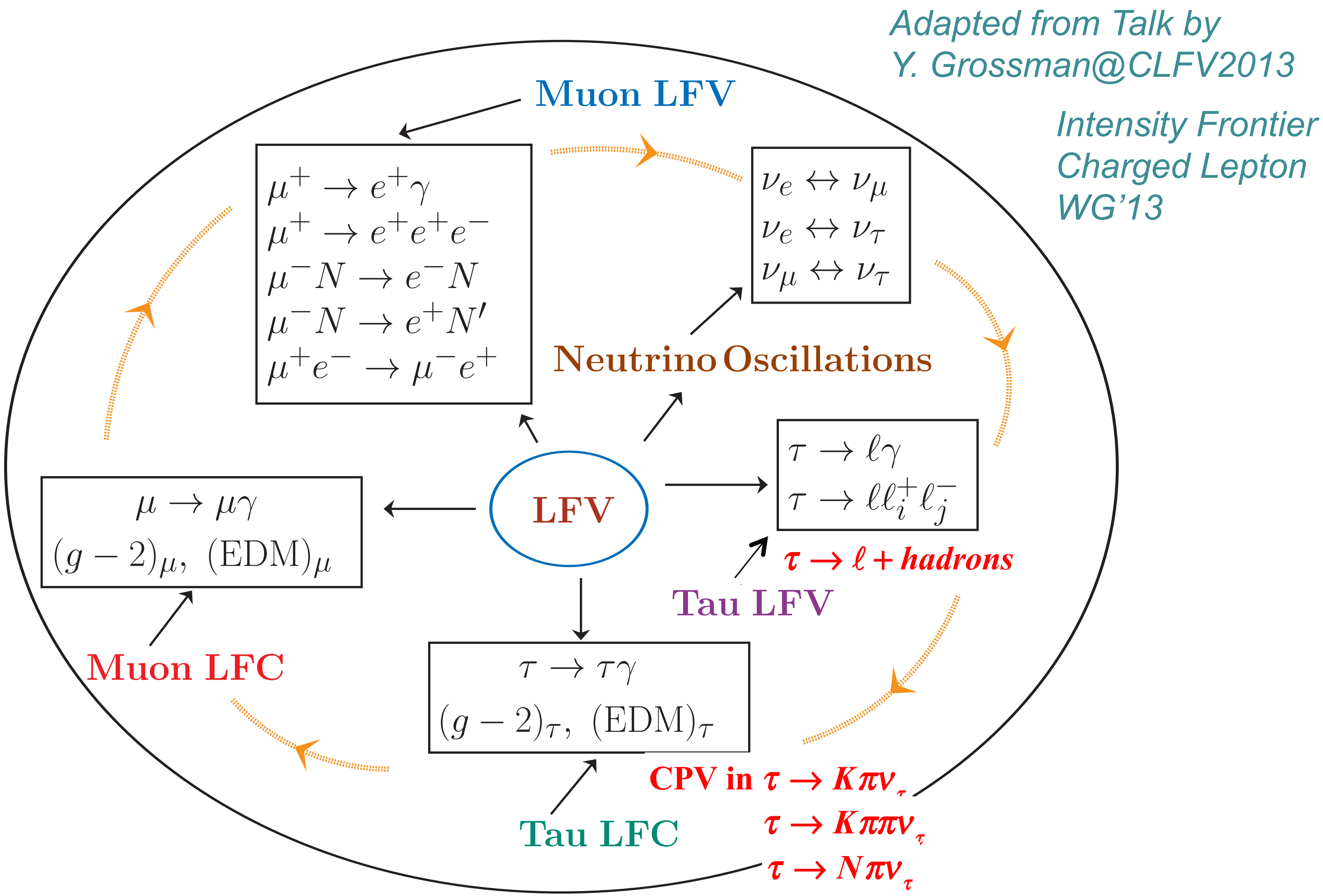
Experiment	Number of τ pairs
LEP	~3×10^5
CLEO	~1×10^7
BaBar	~5×10^8
Belle	~9×10^8
Belle II	~10^{12}

- But τ physics has still potential "*unexplored frontiers*"

  ⇒ deserve future exp. & th. efforts

- In the following, some selected examples and *J. Berryman* will give more

1.3 The Program

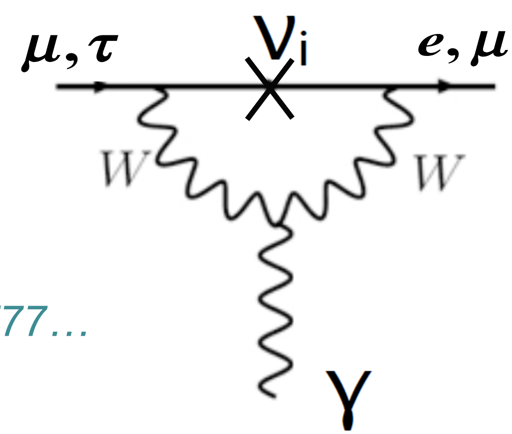


2. Charged Lepton-Flavour Violation

2.1 Introduction and Motivation

- Lepton Flavour Number is an « accidental » symmetry of the SM (m_ν=0)
- In the *SM* with massive neutrinos effective CLFV vertices are tiny due to GIM suppression ⇨ *unobservably small rates!*

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



$$\boxed{Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 5\mathrm{x}10^{-53}}$$

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

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

- Extremely *clean probe of beyond SM physics*
- In New Physics models: seazible effects
  Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic

2.1 Introduction and Motivation

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

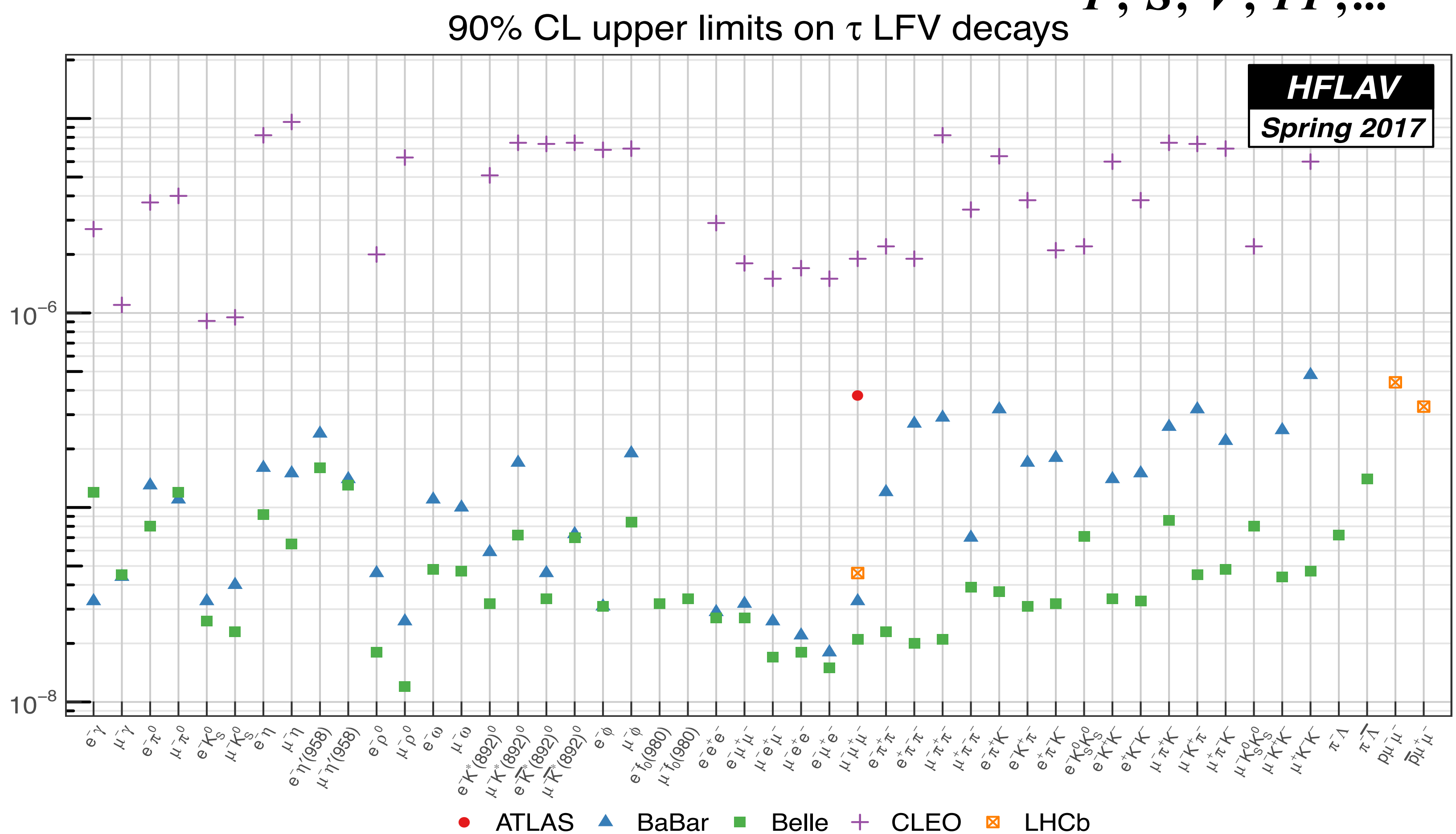
Talk by D. Hitlin @ CLFV2013

		$\tau \to \mu\gamma$	$\tau \to \ell\ell\ell$
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 Tau LFV

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



- 48 LFV modes studied at Belle and BaBar

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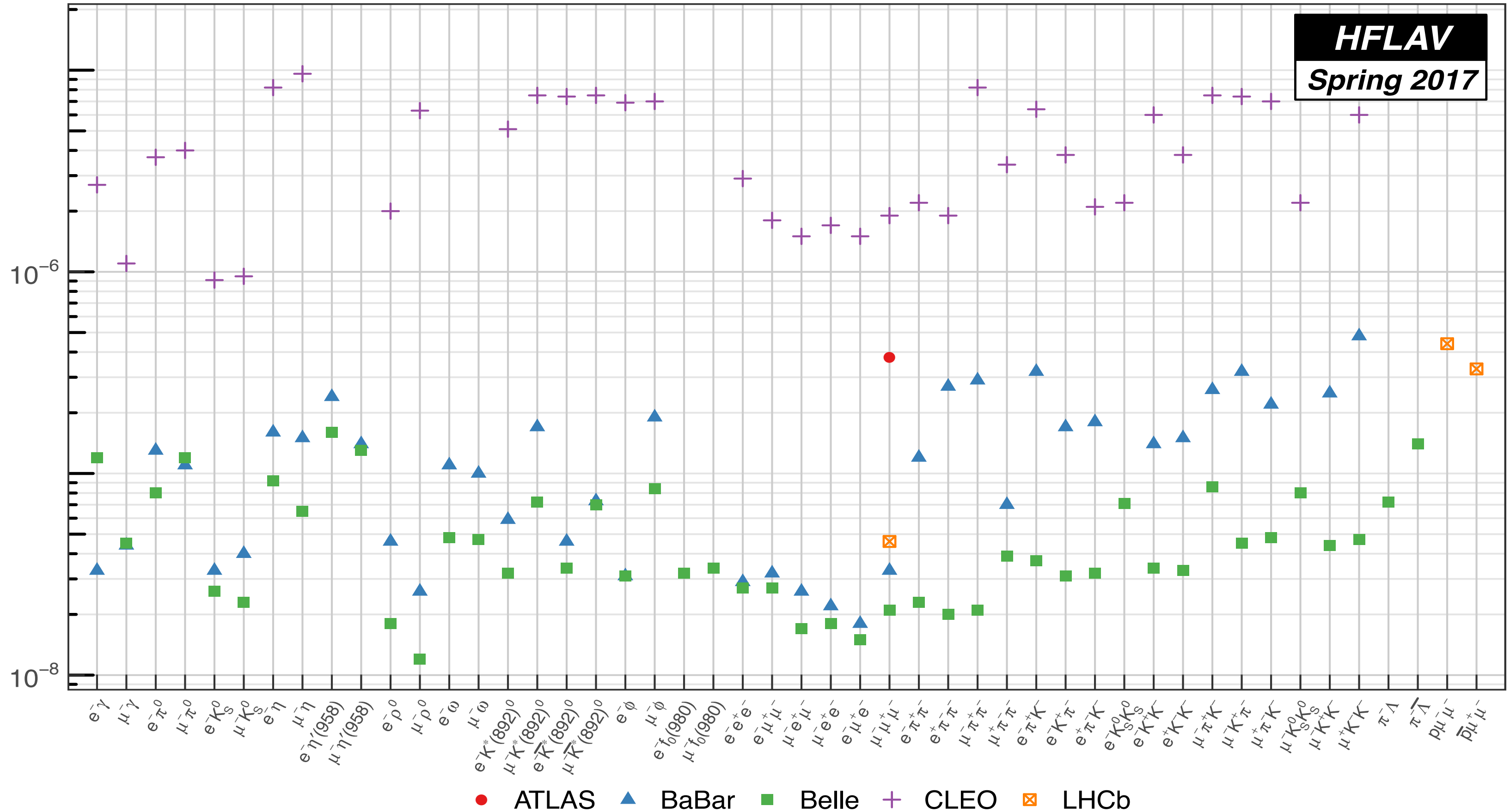
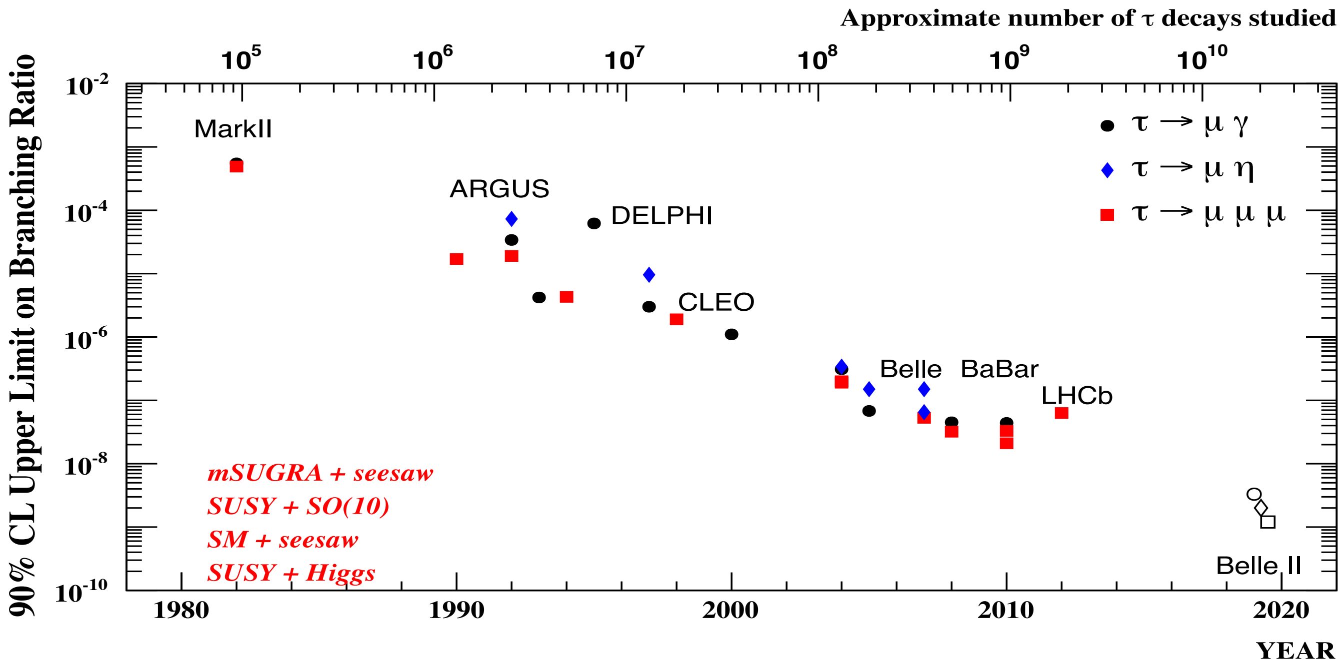
$P,\ S,\ V,\ P\bar{P}, \ldots$

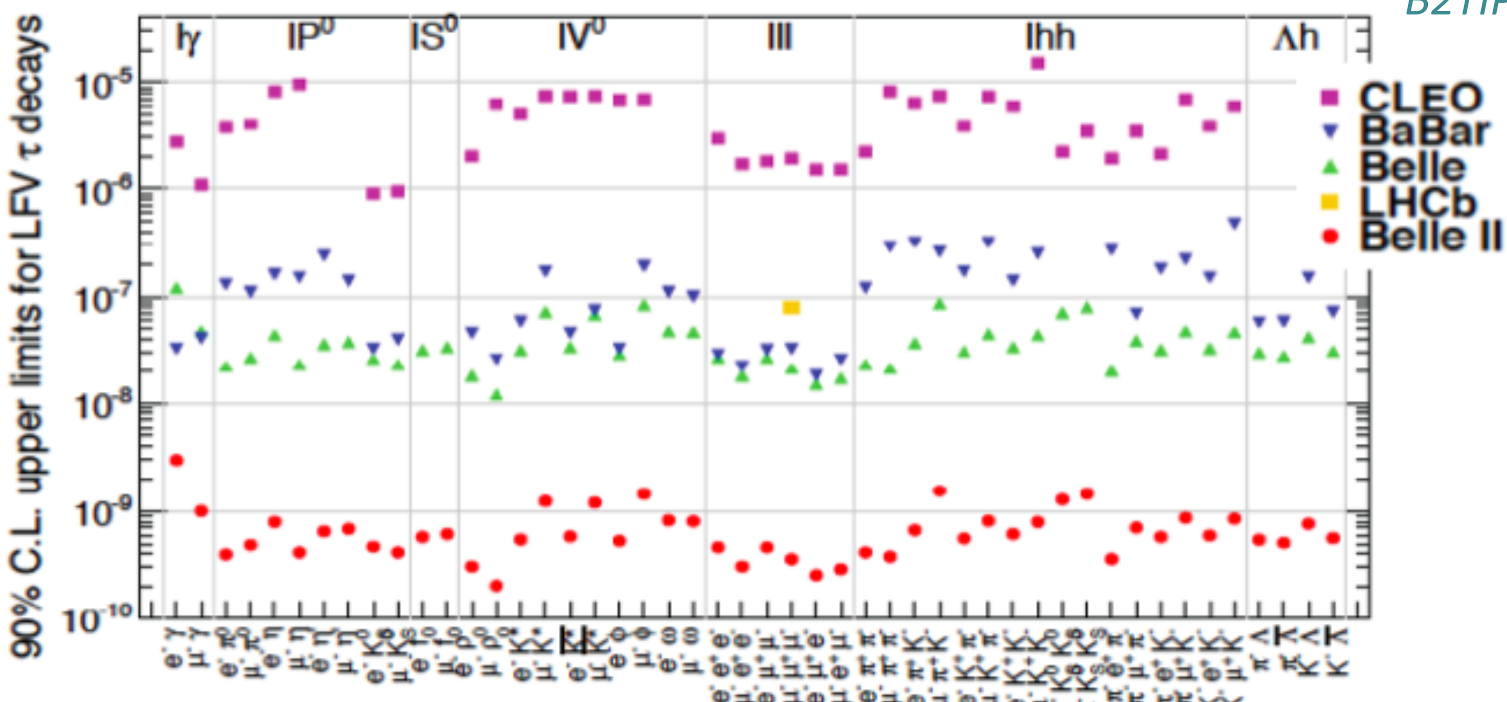
90% CL upper limits on τ LFV decays



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



S. Banerjee'17



B2TIP'18

2.3 Effective Field Theory approach

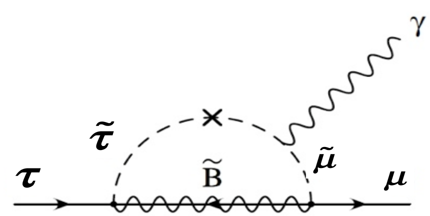
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

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:

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

e.g.



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

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

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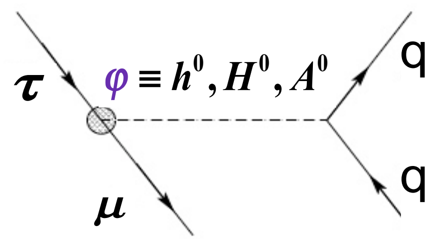
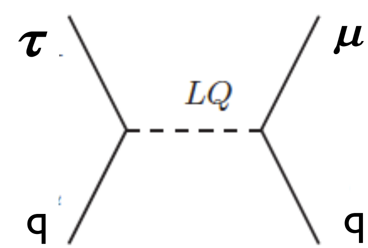


$\boxed{\Gamma \equiv 1}$



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

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  - Integrating out heavy quarks generates *gluonic operator*

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

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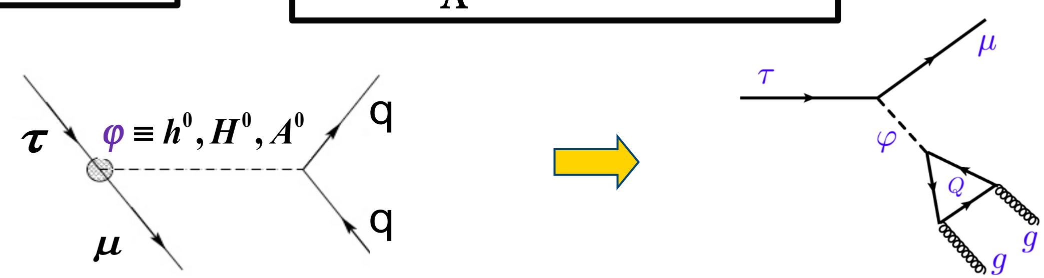

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  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\boxed{\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu}\,\Gamma P_{L,R}\tau\ \bar{\mu}\,\Gamma P_{L,R}\mu}$

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

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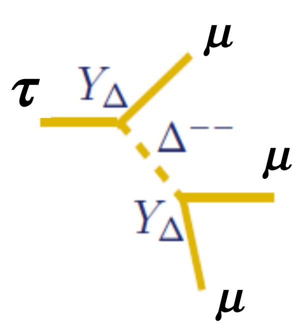

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  - Lepton-gluon (Scalar, Pseudo-scalar): $\boxed{\mathcal{L}_{eff}^{G} \supset -\frac{C_G}{\Lambda^2} m_\tau G_F \bar{\mu} P_{L,R} \tau\, G_{\mu\nu}^a G_a^{\mu\nu}}$
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$\boxed{\Gamma \equiv 1, \gamma^\mu}$

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

2.4 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, $f_{\eta'}$)

2.4 Model discriminating power of Tau processes

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Celis, Cirigliano, E.P.'14

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

- 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

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

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

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

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

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Celis, Cirigliano, E.P.'14

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

- 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 Handles

- 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: $\boxed{\dfrac{dBR(\tau \to \mu\mu\mu)}{d\sqrt{s}}}$
- 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

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

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

⇨ Disentangle the *underlying dynamics* of NP

Dassinger, Feldman, Mannel, Turczyk' 07
Celis, Cirigliano, E.P.'14

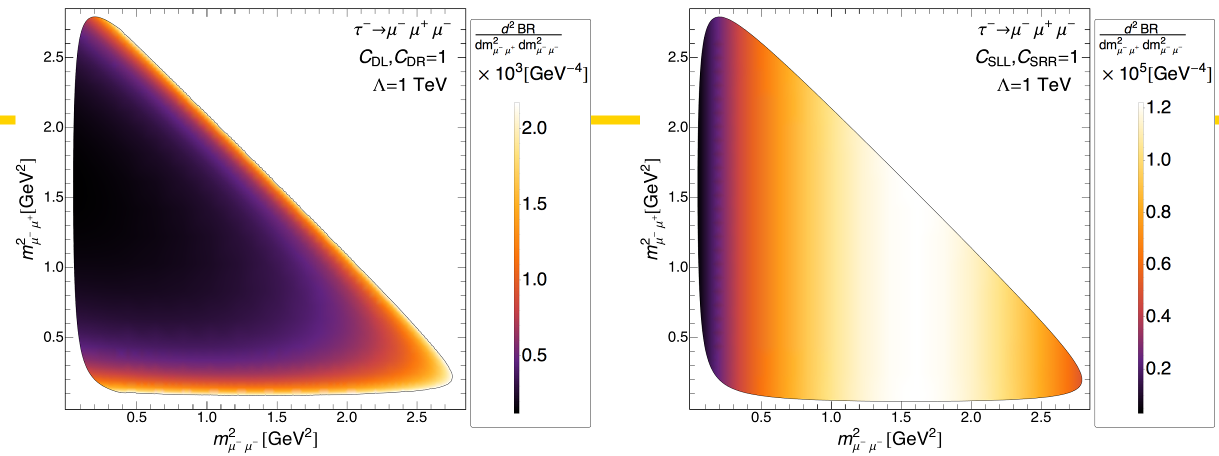


Figure 3: *Dalitz plot for $\tau^- \to \mu^-\mu^+\mu^-$ decays when all operators are assumed to vanish with the exception of* $C_{DL,DR} = 1$ *(left) and* $C_{SLL,SRR} = 1$ *(right), taking* $\Lambda = 1$ *TeV in both cases. Colors denote the density for* $d^2BR/(dm^2_{\mu^-\mu^+} dm^2_{\mu^-\mu^-})$*, small values being represented by darker colors and large values in lighter ones. Here* $m^2_{\mu^-\mu^+}$ *represents* m^2_{12} *or* m^2_{23}*, defined in Sec. 3.1.*

Angular analysis with polarized taus

Dassinger, Feldman, Mannel, Turczyk' 07

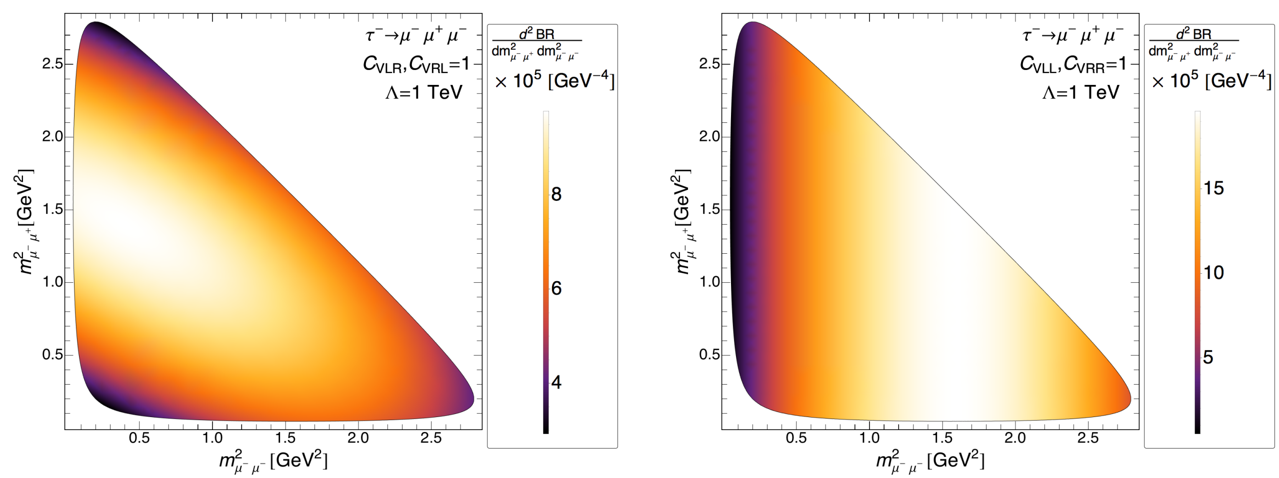
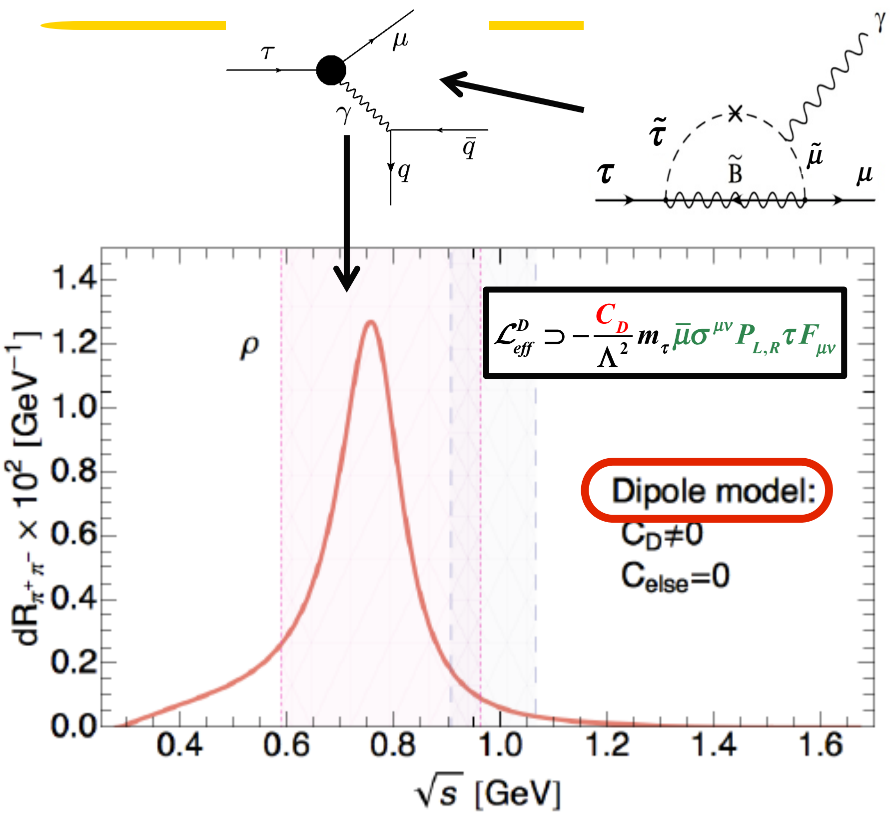


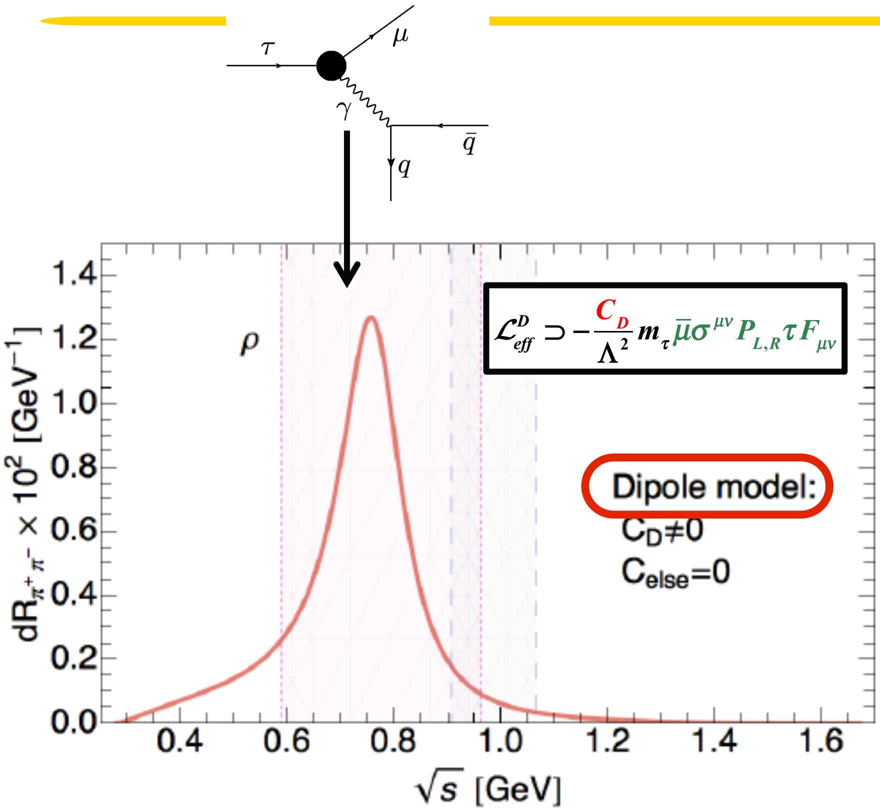
Figure 4: *Dalitz plot for $\tau^- \to \mu^-\mu^+\mu^-$ decays when all operators are assumed to vanish with the exception of* $C_{VRL,VLR} = 1$ *(left) and* $C_{VLL,VRR} = 1$ *(right), taking* $\Lambda = 1$ *TeV in both cases. Colors are defined as in Fig. 3.*

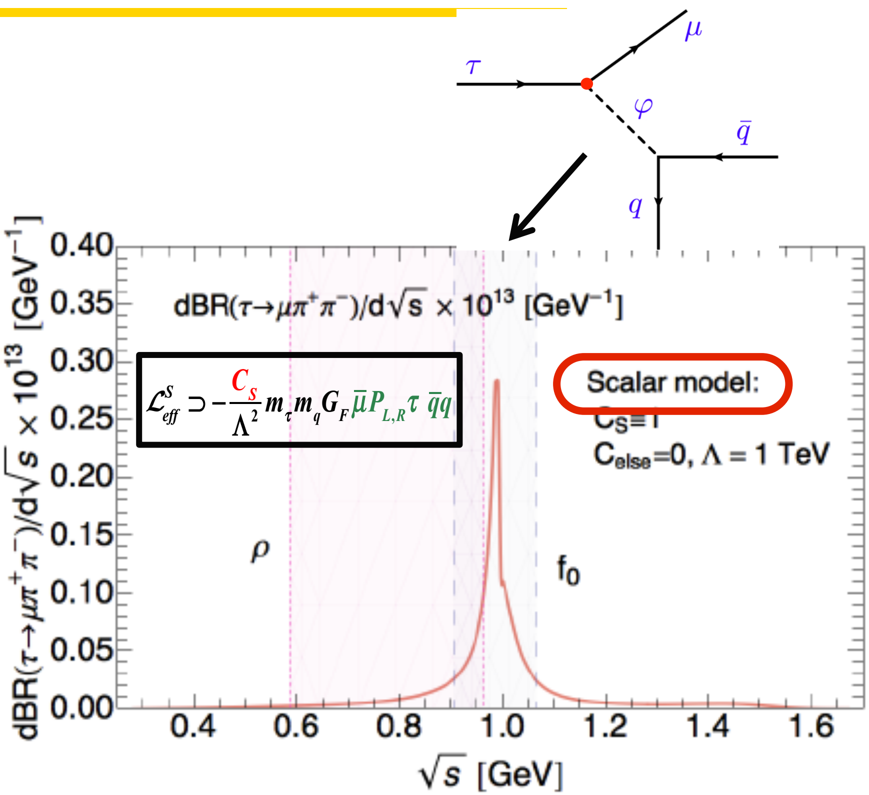
2.7 Discriminating power of $\tau \to \mu(e)\pi\pi$ decays

Celis, Cirigliano, E.P.'14

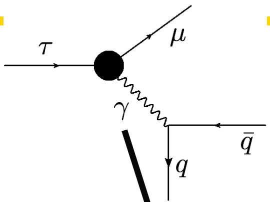


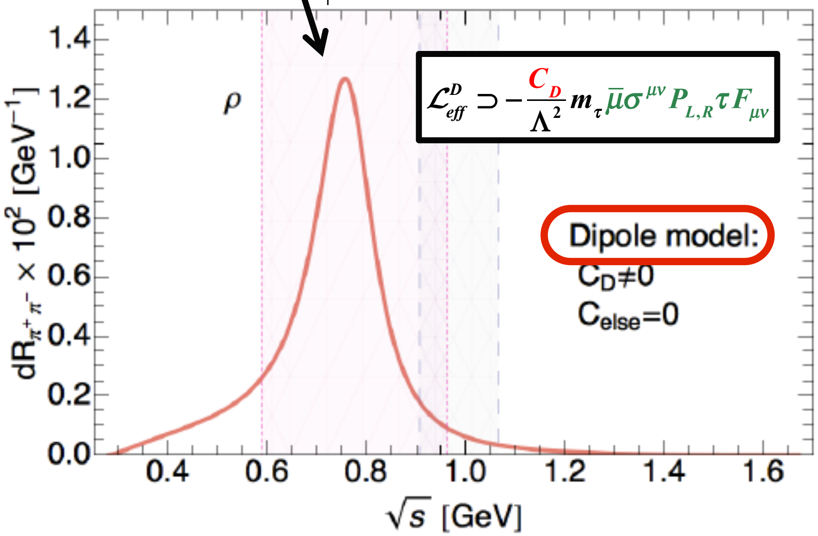
2.7 Discriminating power of τ→μ(e)ππ decays

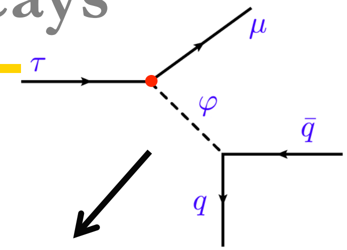


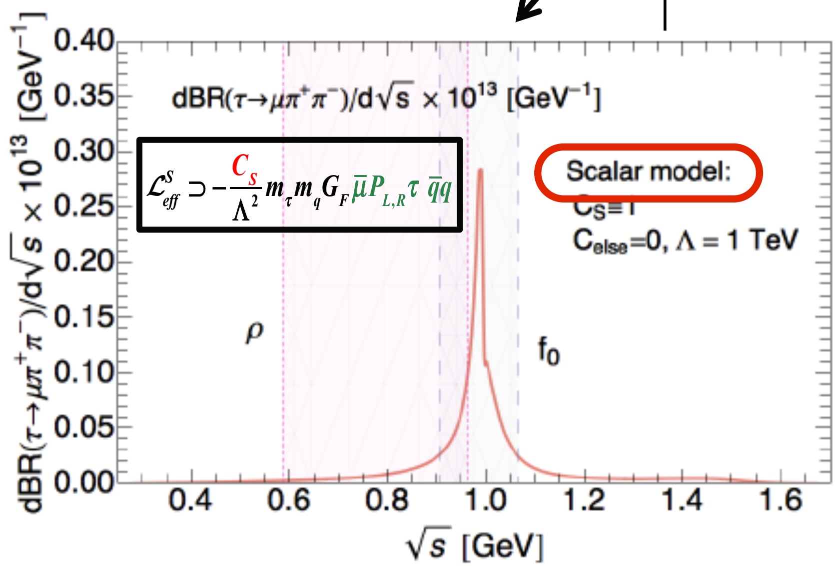


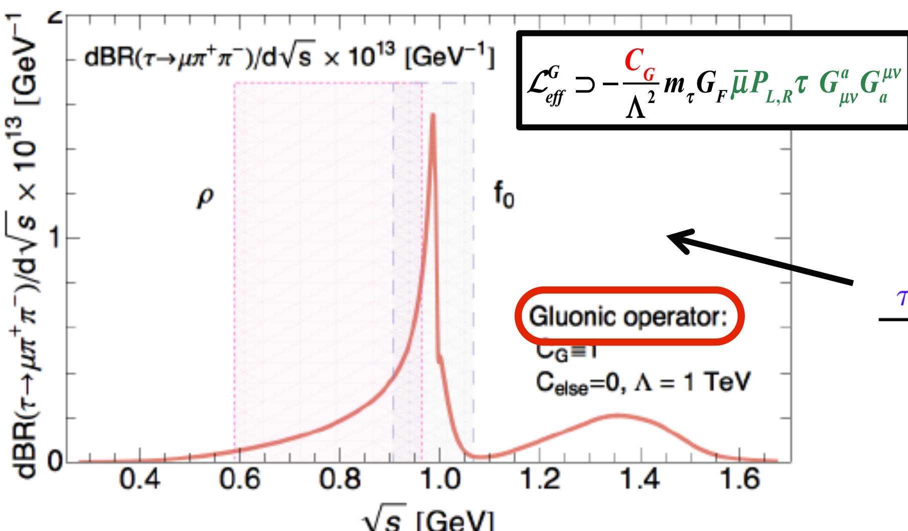
2.7 Discriminating power of τ→μ(e)ππ decays



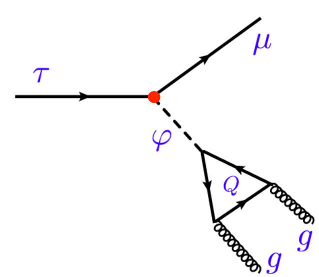








Different distributions according to the *operator!*



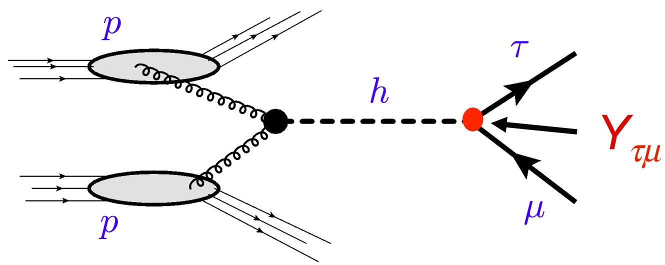
2.8 Non standard LFV Higgs coupling

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

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

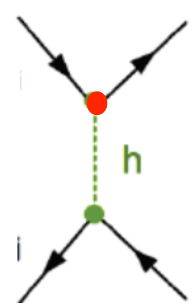
Goudelis, Lebedev, Park'11
Davidson, Grenier'10
Harnik, Kopp, Zupan'12
Blankenburg, Ellis, Isidori'12
McKeen, Pospelov, Ritz'12
Arhrib, Cheng, Kong'12

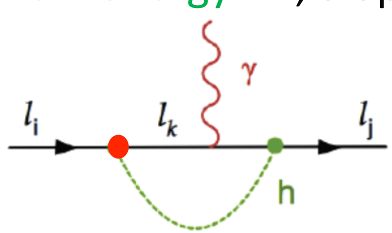
- High energy : LHC

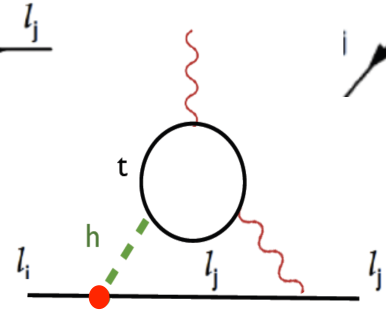


Hadronic part treated with perturbative QCD

- Low energy : D, S operators







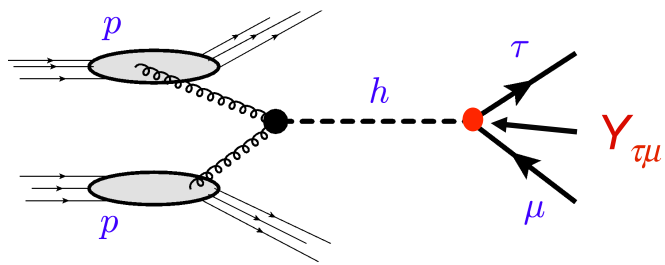
2.8 Non standard LFV Higgs coupling

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

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

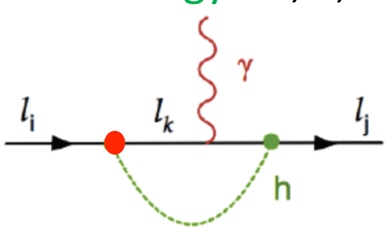
- High energy : LHC

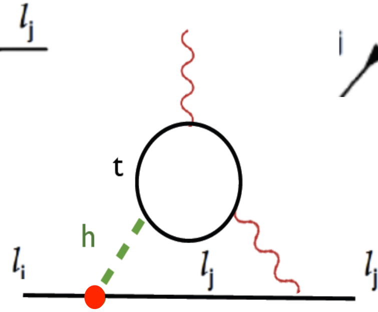


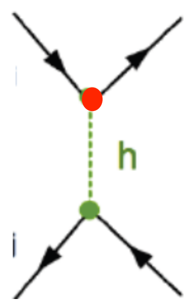
Hadronic part treated with perturbative QCD

Reverse the process

- Low energy : D, S, G operators







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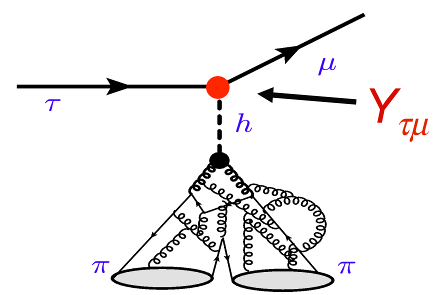
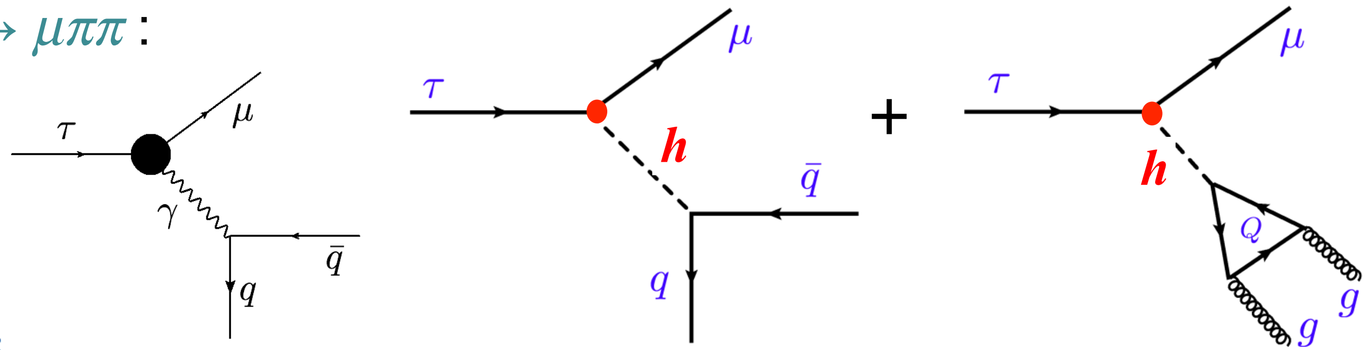


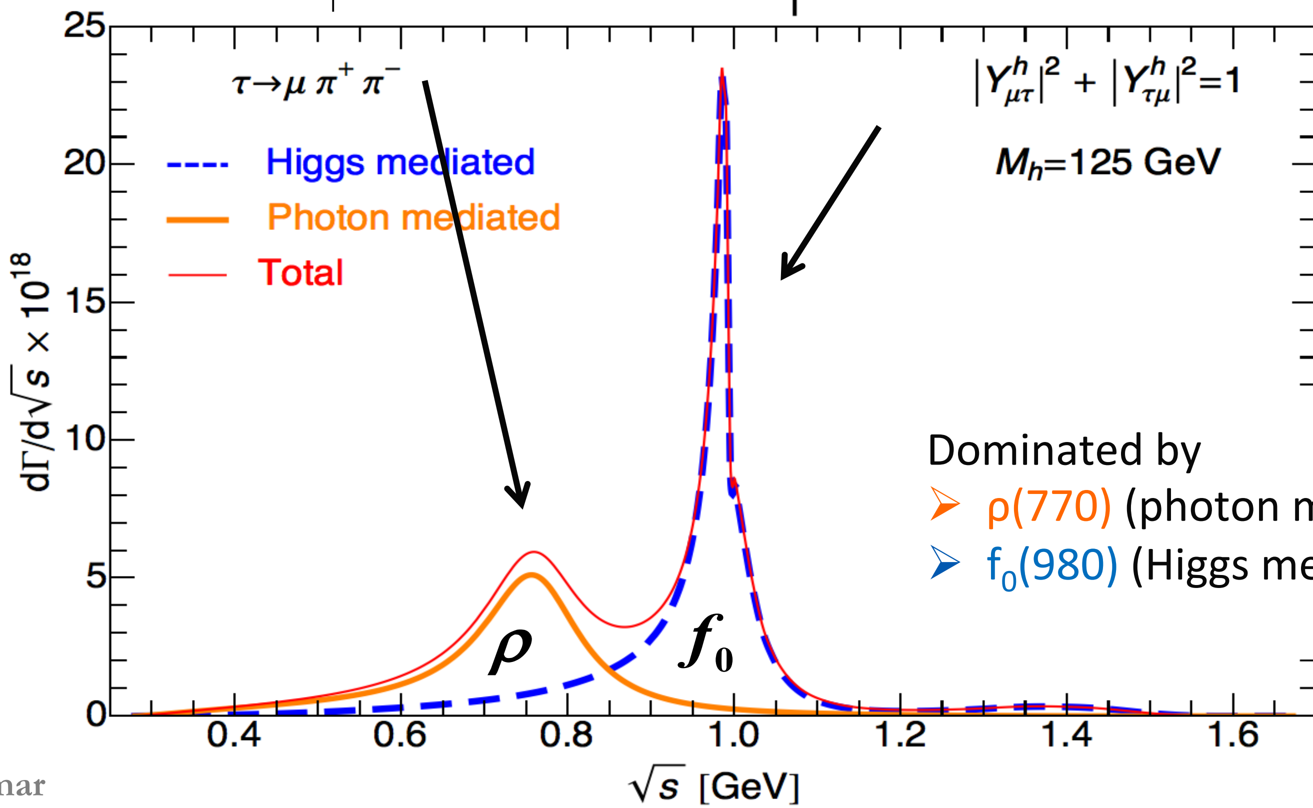
Hadronic part treated with non-perturbative QCD

Constraints in the τμ sector

Cirigliano, Celis, E.P.'14

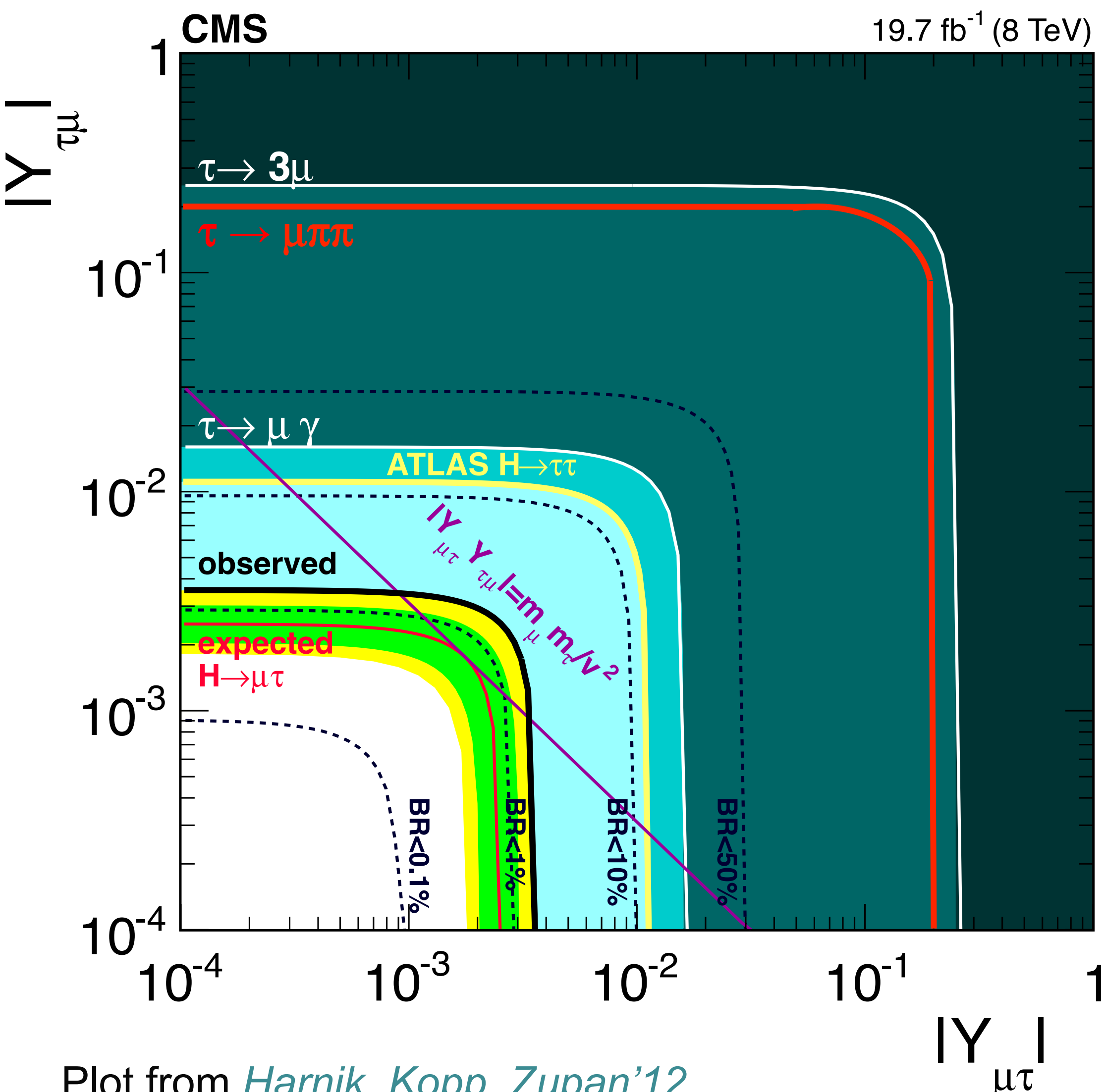
- At low energy
  - $\tau \to \mu\pi\pi$:





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

Constraints in the τμ sector



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

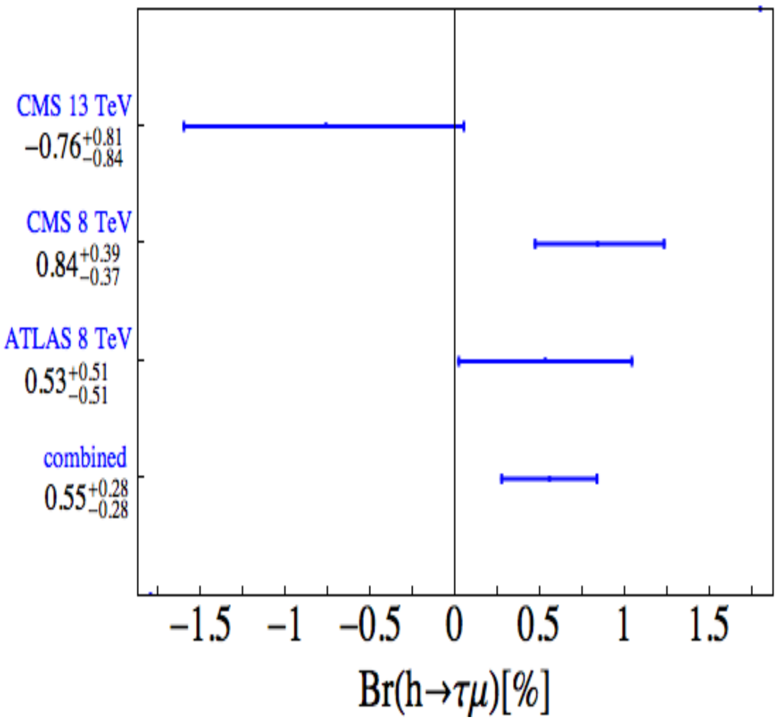
- Constraints from LE:
  - $\tau \to \mu\gamma$: best constraints but loop level
    ⇨ sensitive to UV completion of the theory
  - $\tau \to \mu\pi\pi$: tree level diagrams
    ⇨ robust handle on LFV
- Constraints from HE:
  LHC wins for τμ!
- Opposite situation for μe!
- For LFV Higgs and nothing else: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

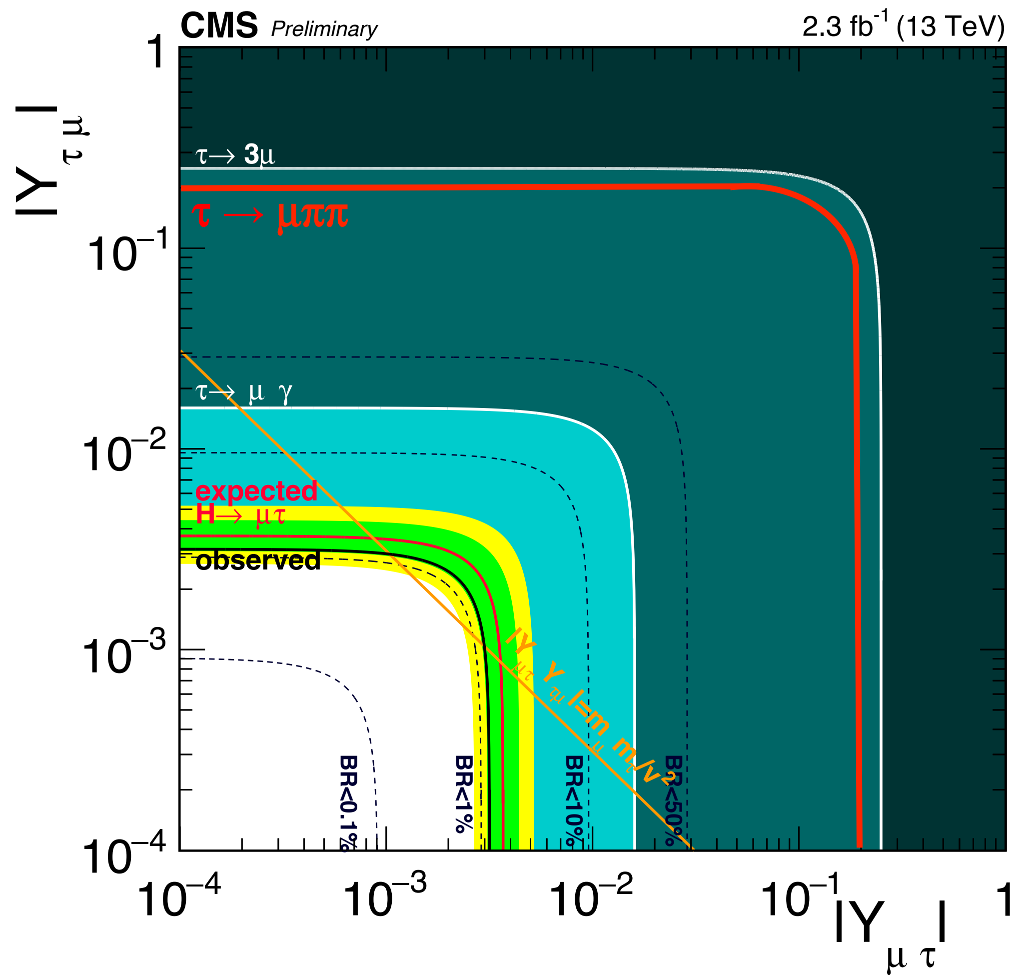
⇨ $\boxed{BR(\tau \to \mu\gamma) < 2.2\times 10^{-9}}$

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

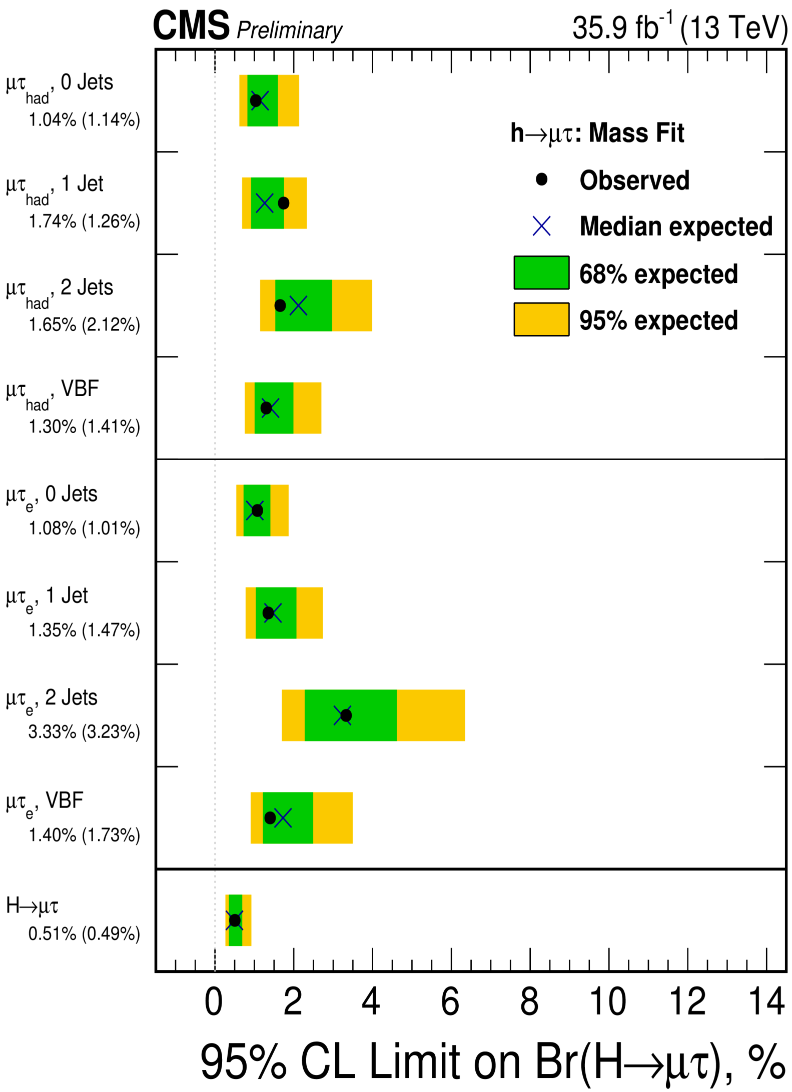
Hint of New Physics in h → τμ?

CMS'16

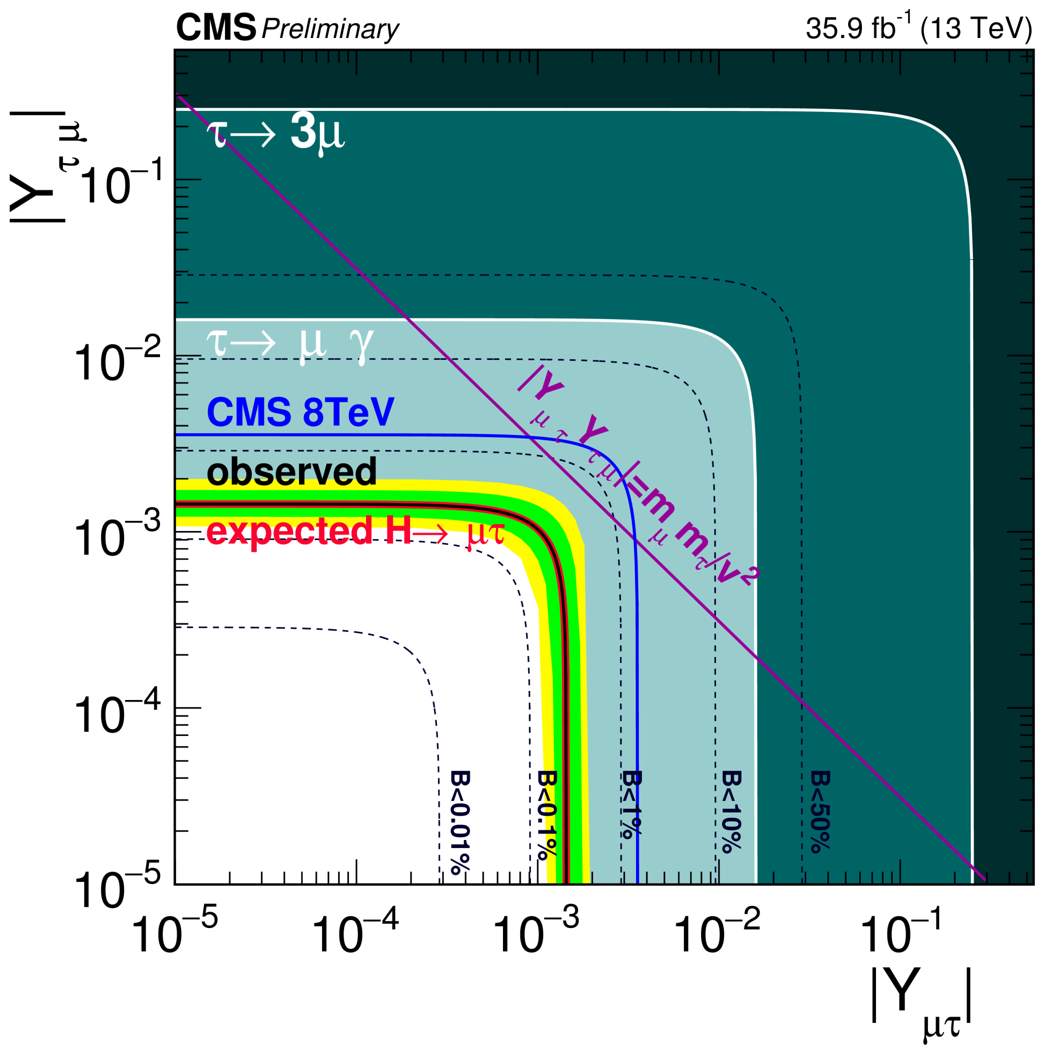




Hint of New Physics in h → τμ?



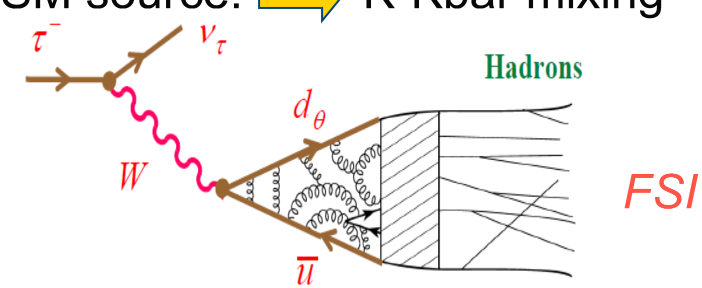
CMS'17

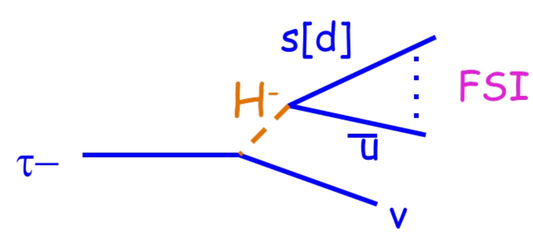


3. LFC processes: CPV in tau decays

3.1 Introduction

- CP violation measured in K and B decays ⇨ in agreement with SM
- Not enough CP violation to explain asymmetry matter/anti-matter
- Look elsewhere:
  - Neutrinos
  - Charged leptons
  - Electric dipole moments
- Aim: pin down new sources of CPV in the lepton sector and discriminating between NP scenarios
- Study of tau decays:
  - CPV in tau pair production ($e^+e^- \rightarrow \tau^+\tau^-$) ⇨ EDM
  - CPV in hadronic tau decays
    - SM source: ⇨ K-Kbar mixing   NP source: In the vertex

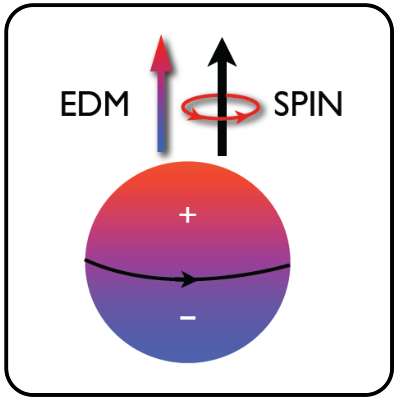




3.2 EDM of the Tau

- Probe to test new sources of CP violation

No SM background



P and T violation:

$$\vec{d} \propto \vec{J}$$

$$\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$$

- CPV in tau pair production ($e^+e^- \rightarrow \tau^+\tau^-$) ⇒ EDM
- Very challenging measurement for τ
- Measured using spin correlations of decay product of the taus
- Help of polarized beams?

EDMs in $e \cdot cm$ *From V. Cirigliano*

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

3.2 EDM of the Tau

- The squared spin density matrix for $e^+(\mathbf{p})\, e^-(-\mathbf{p}) \rightarrow \gamma^* \rightarrow \tau^+(\mathbf{k},\mathbf{S}_+)\, \tau^-(-\mathbf{k},\mathbf{S}_-)$

$$\mathcal{M}^2 = \mathcal{M}^2_{SM} + \mathrm{Re}(\mathrm{d}_\tau)\mathcal{M}^2_{\mathrm{Re}} + \mathrm{Im}(\mathrm{d}_\tau)\mathcal{M}^2_{\mathrm{Im}} + |\mathrm{d}_\tau|^2\mathcal{M}^2_{\mathrm{d}^2}$$

- Study of spin momentum correlations:

$$\boxed{\begin{array}{lll} \mathcal{M}^2_{\mathrm{Re}} & \propto & (S_+ \times S_-)\cdot\hat{k}, \quad (S_+ \times S_-)\cdot\hat{p}, \\ \mathcal{M}^2_{\mathrm{Im}} & \propto & (S_+ - S_-)\cdot\hat{k}, \quad (S_+ - S_-)\cdot\hat{p}, \end{array}}$$

τ spin vector

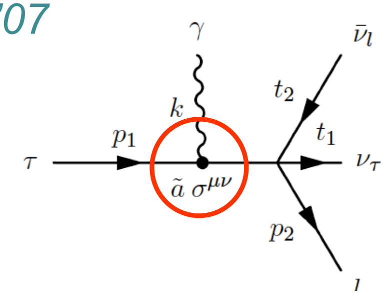
unit vectors of momenta of τ and e^- in CMS

Belle'02

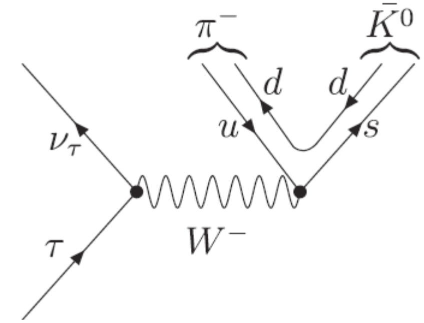
$$\boxed{-0.22 < \mathrm{Re}\,(d_\tau) < 0.45 \quad (10^{-16} e\cdot\mathrm{cm})} \quad \text{and} \quad \boxed{-\,0.25 < \mathrm{Im}\,(d_\tau) < 0.08 \quad (10^{-16} e\cdot\mathrm{cm})}$$

- Polarized beams will help since the decay products of only one tau could be studied *Bernabeu, Gonzalez-Sprinberg, Vidal'04,'07*

- Radiative decay possibility
  Eidelmana, Epifanov, Fael, Mercolli, Passera'16



3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry



- $$A_Q = \frac{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}$$

  $$= |p|^2 - |q|^2 \quad \boxed{\approx (0.36 \pm 0.01)\%}$$ in the SM

  Bigi & Sanda'05
  Grossman & Nir'11

$$|K_S^0\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$

$$|K_L^0\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$

$$\boxed{\langle K_L | K_S \rangle = |p|^2 - |q|^2 \simeq 2\,\mathrm{Re}(\varepsilon_K)}$$

- Experimental measurement : *BaBar'11*

  $$\boxed{A_{Q\,\mathrm{exp}} = \left(-0.36 \pm 0.23_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}\right)\%} \Rightarrow \boxed{2.8\sigma}$$ from the SM!

- CP violation in the tau decays should be of opposite sign compared to the one in D decays in the SM

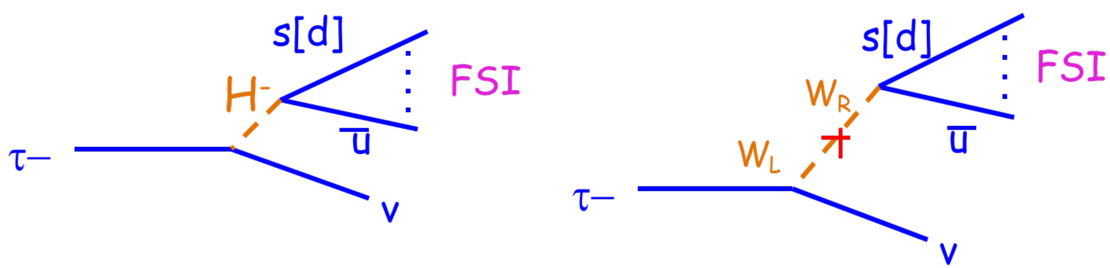
  Grossman & Nir'11

  $$\boxed{A_D = \frac{\Gamma\left(D^+ \to \pi^+ K_S^0\right) - \Gamma\left(D^- \to \pi^- K_S^0\right)}{\Gamma\left(D^+ \to \pi^+ K_S^0\right) + \Gamma\left(D^- \to \pi^- K_S^0\right)}} = (-0.54 \pm 0.14)\%$$

  Belle, Babar, CLEO, FOCUS

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- New physics? Charged Higgs, W_L-W_R mixings, leptoquarks, tensor interactions (*Devi, Dhargyal, Sinha'14, Cirigliano, Crivellin, Hoferichter'17*)?



Bigi'Tau12

Very difficult to explain!

- Need to investigate how large can be the prediction in realistic new physics models: it looks like *a tensor interaction* can explain the effect but in conflict with bounds from neutron EDM and $D\bar{D}$ mixing

Cirigliano, Crivellin, Hoferichter'17

⇨ light BSM physics?

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- In this measurement, need to know hadronic part ⇨ form factors

$$\boxed{\langle \mathbf{K}\pi | \ \bar{\mathbf{s}}\gamma_\mu \mathbf{u} \ |0\rangle = \left[\left(p_K - p_\pi\right)_\mu + \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu \right] f_+(s) - \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu f_0(s)}$$

vector　　scalar

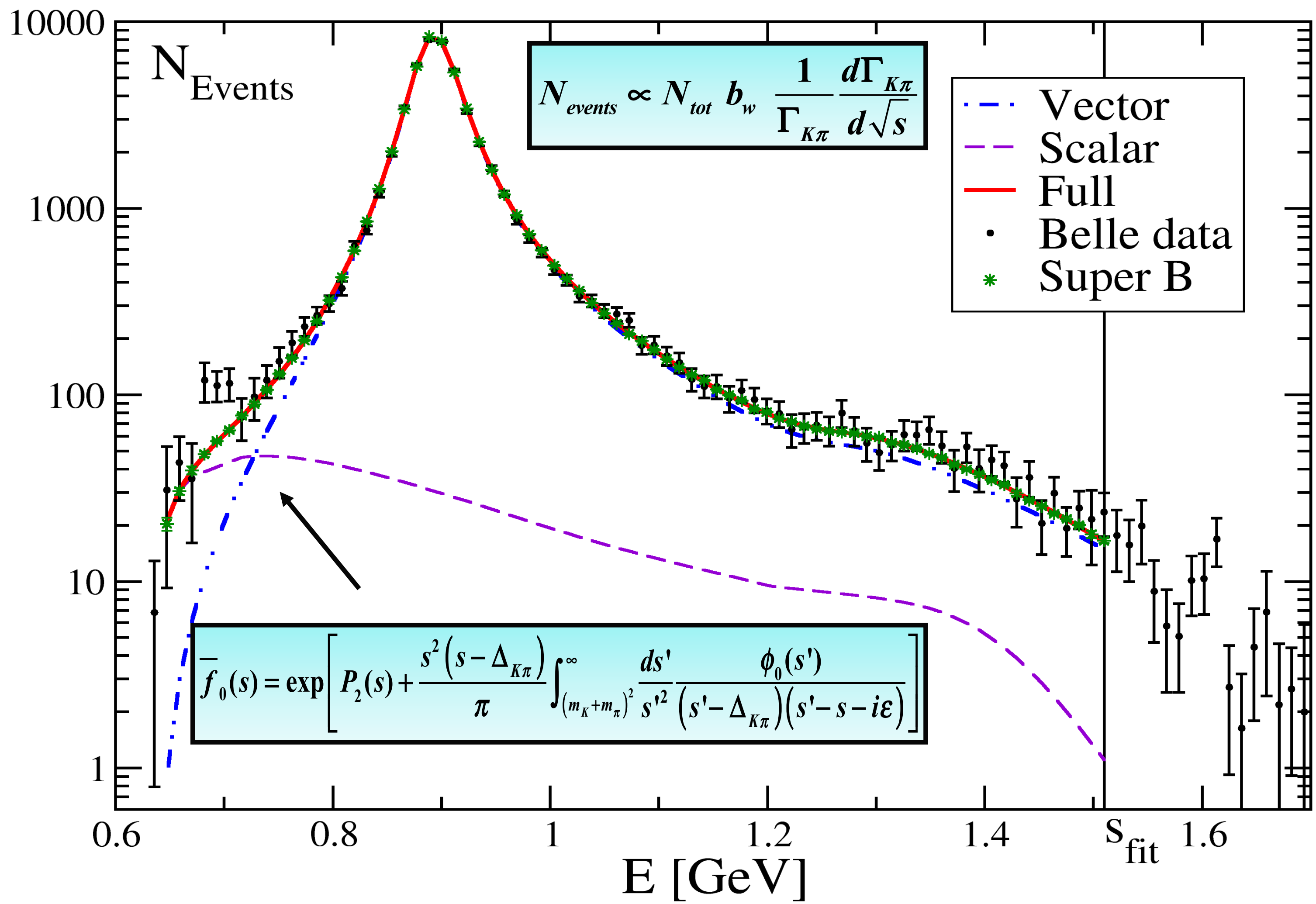
with $s = Q^2 = (p_K + p_\pi)^2$

$$\Delta_{K\pi} = \left(M_K^2 - M_\pi^2\right)$$

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

Bernard, Boito, E.P.'11

Antonelli, Cirigliano, Lusiani, E.P.'13



3.3 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

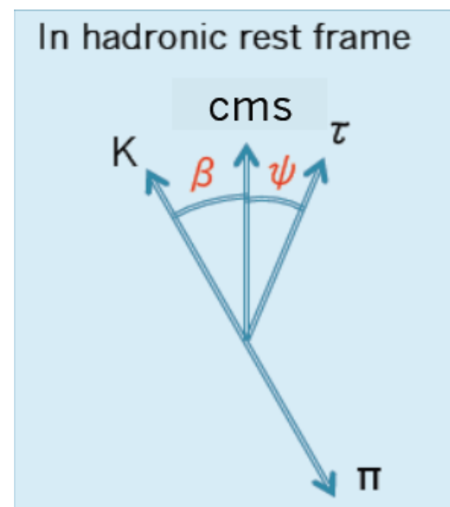
$$\frac{d\Gamma\left(\tau^- \to K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\,d\cos\theta\;d\cos\beta} = \left[A(Q^2) - B(Q^2)\;\left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

CP violating term
S-P interference

– $A(Q^2)$, $B(Q^2)$, $C(Q^2)$: kinematic factors

– Angles:
in $K\pi$ rest frame
  - β: angle between kaon and e^+e^- CMS frame
  - Ψ: angle between τ and CMS frame

in τ rest frame
  - θ: angle between τ direction in CMS and direction of $K\pi$ system (dependence with Ψ)



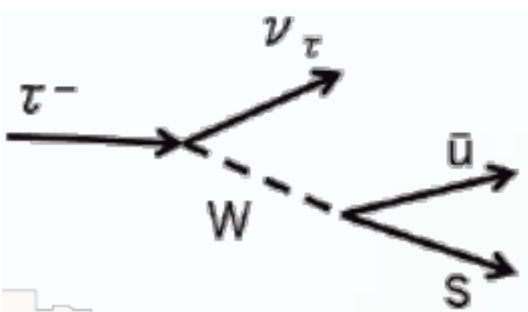
3.3 $\tau \rightarrow K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

$$\frac{d\Gamma\left(\tau^- \rightarrow K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\, d\cos\theta\; d\cos\beta} = \left[A(Q^2) - B(Q^2)\;\left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

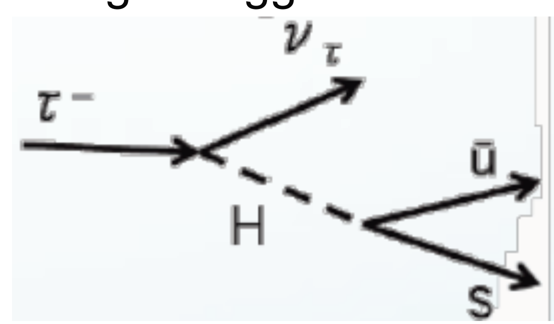
CP violating term
S-P interference

– $A(Q^2)$, $B(Q^2)$, $C(Q^2)$: kinematic factors



+

Charged Higgs contribution



Khün & Mirkes'05

$$\tilde{f}_0(s) = f_0(s) + \frac{\eta^2}{m_\tau^2} f_H(s)$$

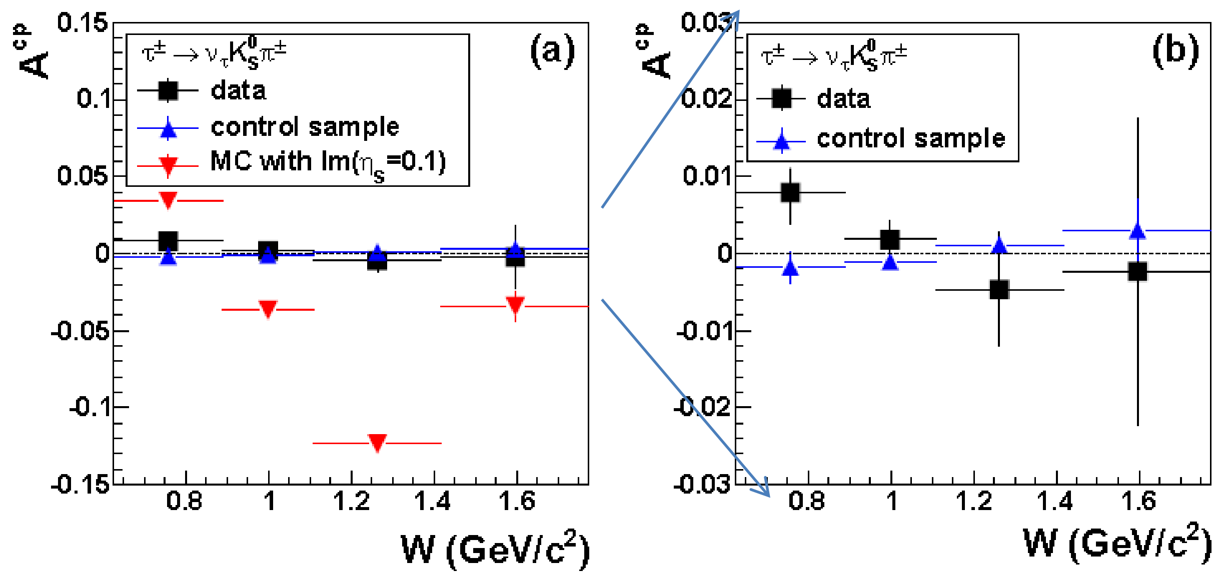
with $$f_H(s) = \frac{s}{m_u - m_s} f_0(s)$$

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- Measurement of the direct contribution of NP in the angular CP violating asymmetry done by *CLEO* and *Belle*

  ⇒ Belle does not see any asymmetry at the *0.2 - 0.3% level*

Belle'11



- Problem with this measurement? ⇒ It would be great to have other experimental measurements from *Belle II*

3.3 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

- The angular CP asymmetry from Belle:

$$\frac{d\Gamma\left(\tau^- \rightarrow K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\,d\cos\theta\;d\cos\beta} = \left[A(Q^2) - B(Q^2)\;\left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

CP violating term
S-P interference

- When integrating on the angle the interference term between scalar and vector vanishes

$$\frac{d\Gamma}{d\sqrt{Q^2}} = \frac{G_F^2\sin^2\theta_c m_\tau^3}{3\times 2^5\times\pi^3 Q^2}\left(1-\frac{Q^2}{m_\tau^2}\right)^2\left(1+\frac{2Q^2}{m_\tau^2}\right)$$

$$\times q_1(Q^2)\left\{q_1(Q^2)^2\,|F_V|^2 + \frac{3}{4}\frac{Q^2}{\left(1+2Q^2/m_\tau^2\right)}|F_S|^2\right\}$$

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

Devi, Dhargyal, Sinha'14
Cirigliano, Crivellin, Hoferichter'17

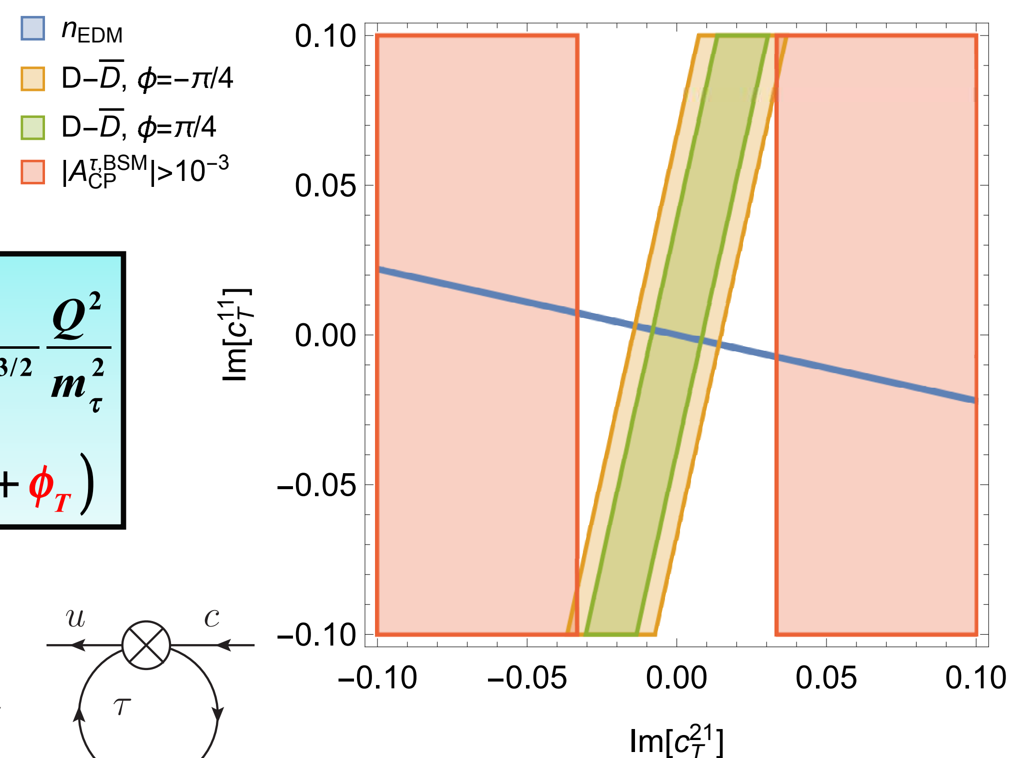
- We need a tensor interaction to get some interference:

$$\boxed{\mathcal{H}_T^{eff} \equiv G'(\bar{s}\sigma_{\mu\nu}u)(\bar{\nu}_\tau(1+\gamma_5)\sigma^{\mu\nu}\tau)} \quad \text{with} \quad G' = \frac{G_F}{\sqrt{2}}C_T, \quad C_T = |C_T|e^{i\phi_T}$$

- When integrating the interference term between vector and tenson does not vanish:

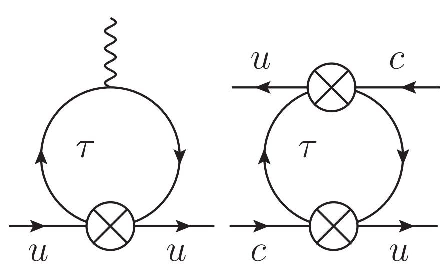
$$\frac{d\Gamma}{dQ^2} = \frac{d\Gamma_{SM}}{dQ^2} + \frac{d\Gamma_T}{dQ^2} + \frac{d\Gamma_{V-T}}{dQ^2}$$

$$\frac{d\Gamma_{V-T}}{dQ^2} = G_F^2 \sin^2\theta_C \frac{m_\tau^3}{32\pi^3}\left(\frac{m_\tau^2 - Q^2}{m_\tau^2}\right)^2 \frac{q_1^3}{(Q^2)^{3/2}} \frac{Q^2}{m_\tau^2} \times |C_T||F_V(s)||F_T(s)|\cos(\delta_T(s) - \delta_V(s) + \phi_T)$$



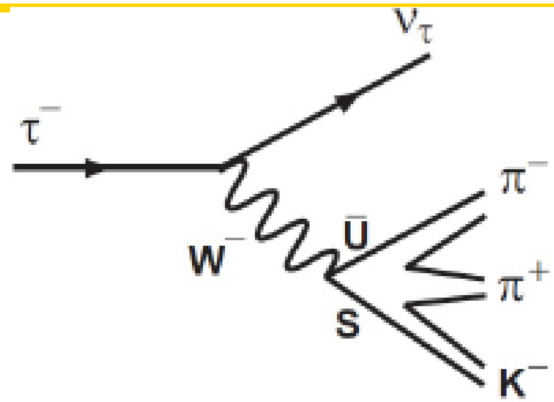
In conflict with bounds from neutron EDM and DD mixing

Cirigliano, Crivellin, Hoferichter'17



3.4 Three body CP asymmetries

- Ex: $\tau \to K\pi\pi\nu_\tau$



- A variety of CPV observables can be studied : $\tau \to K\pi\pi\nu_\tau$, $\tau \to \pi\pi\pi\nu_\tau$ rate, angular asymmetries, triple products,….

  e.g., Choi, Hagiwara and Tanabashi'98
  Kiers, Little, Datta, London et al.,'08
  Mileo, Kiers and Szynkman'14

  Same principle as in charm, *see Bevan'15*

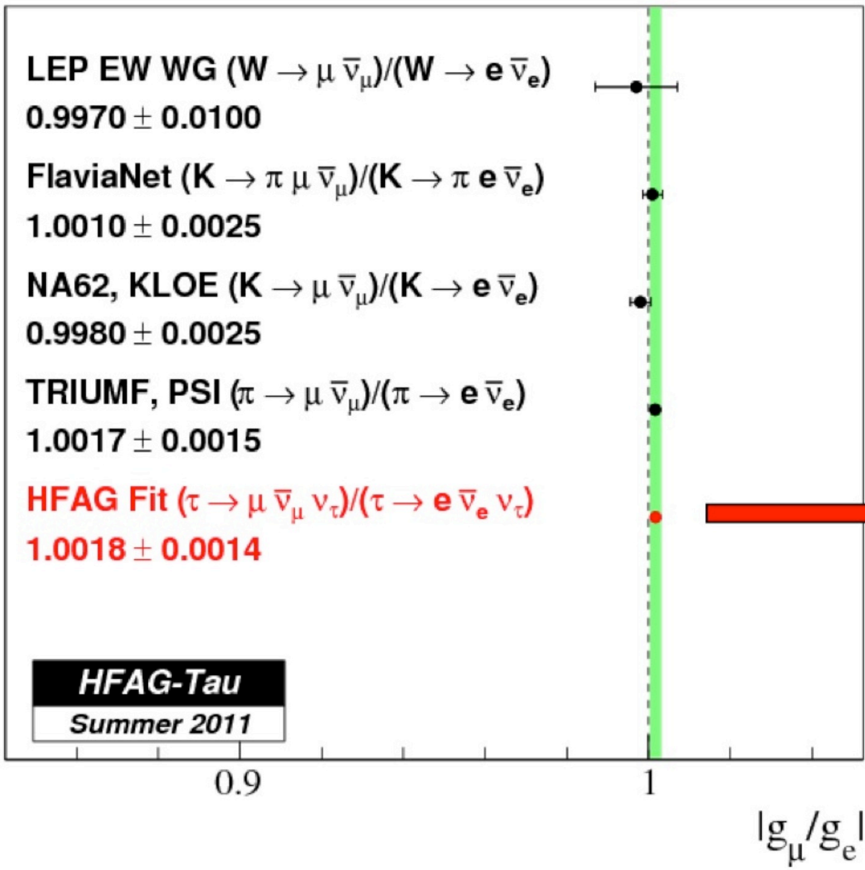
  Difficulty : Treatement of the hadronic part
  Hadronic final state interactions have to be taken into account!
  ⇨ Disentangle weak and strong phases

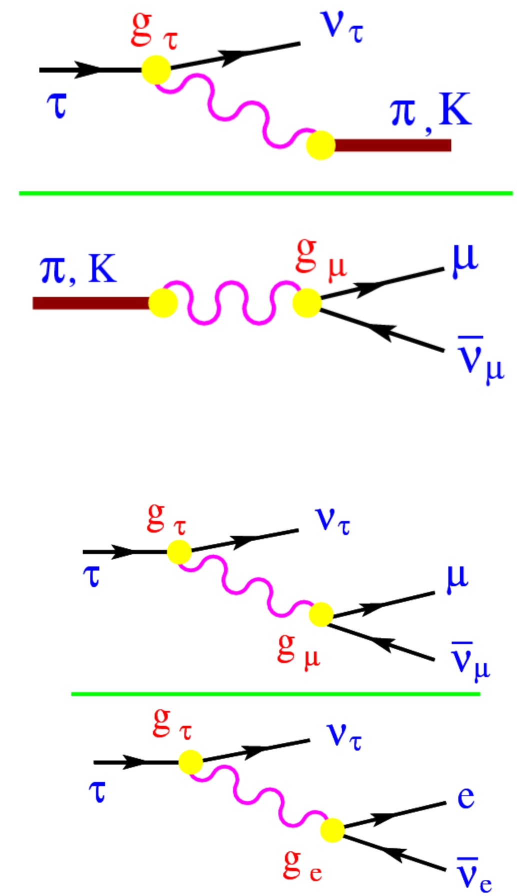
- More form factors, more asymmetries to build but same principles as for 2 bodies

4. Other interesting topics with tau decays

4.1 Lepton Universality

- Test of μ/e universality:

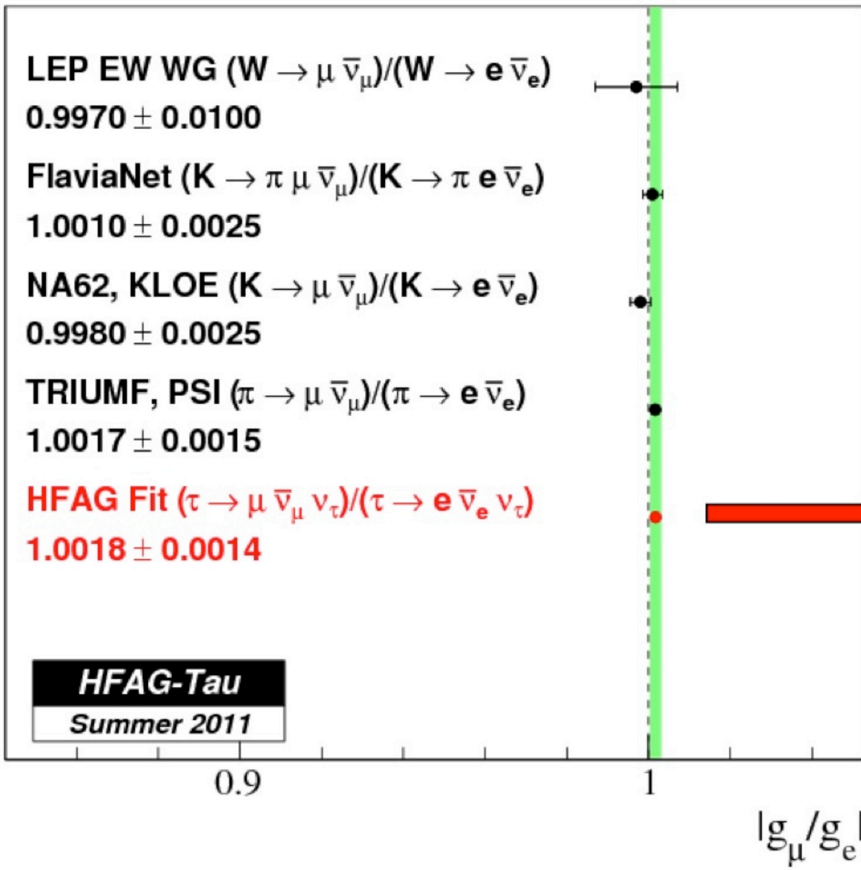


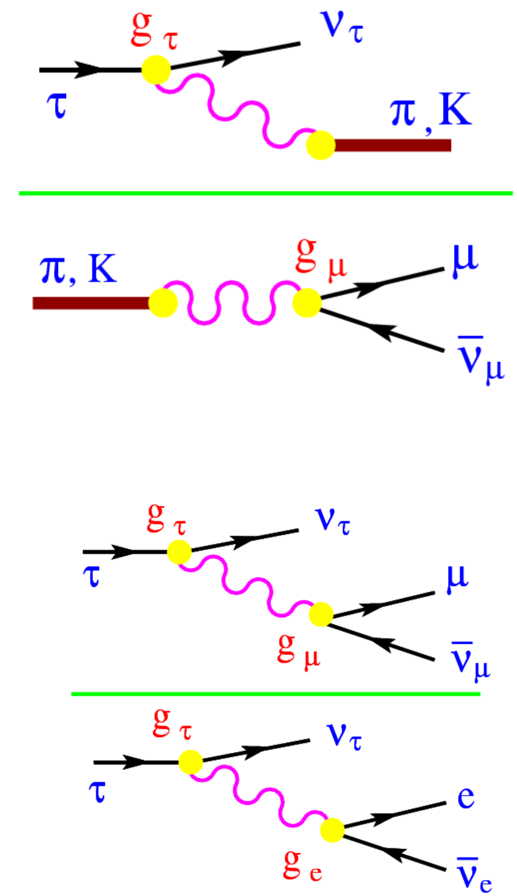


- Tested at *0.14%* from Tau leptonic Brs! (0.28% in Z decays)

4.1 Lepton Universality

- Test of μ/e universality:

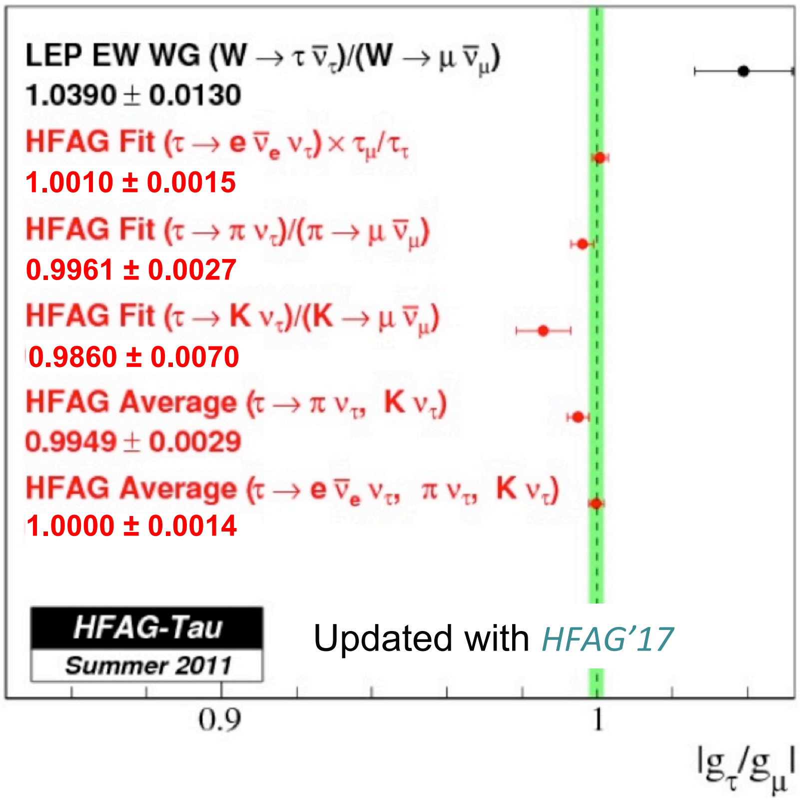


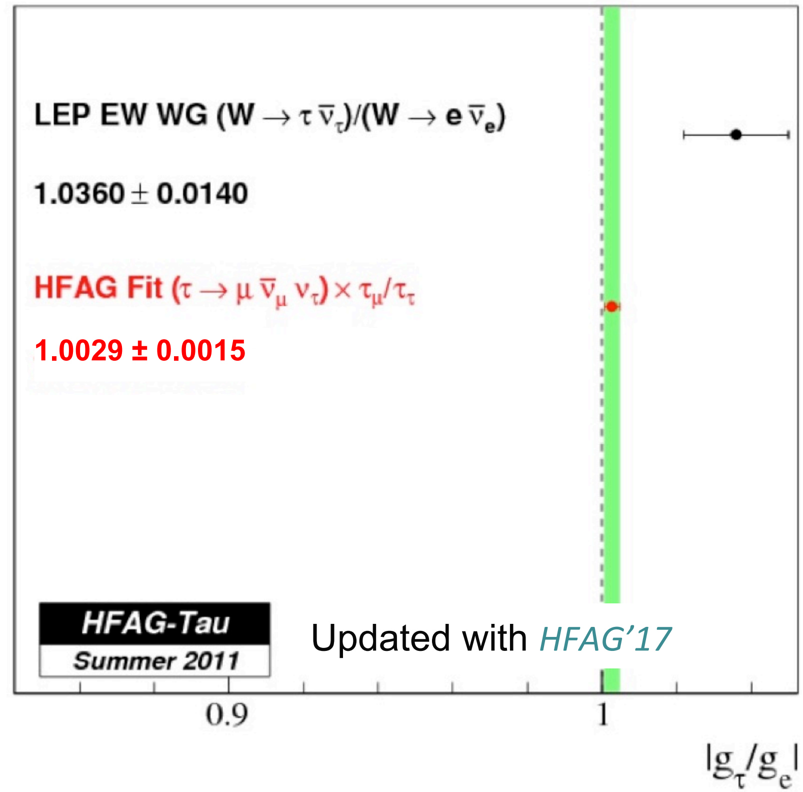


- Tested at *0.14%* from Tau leptonic Brs! (0.28% in Z decays)
- What about the *third family*?

4.1 Lepton Universality

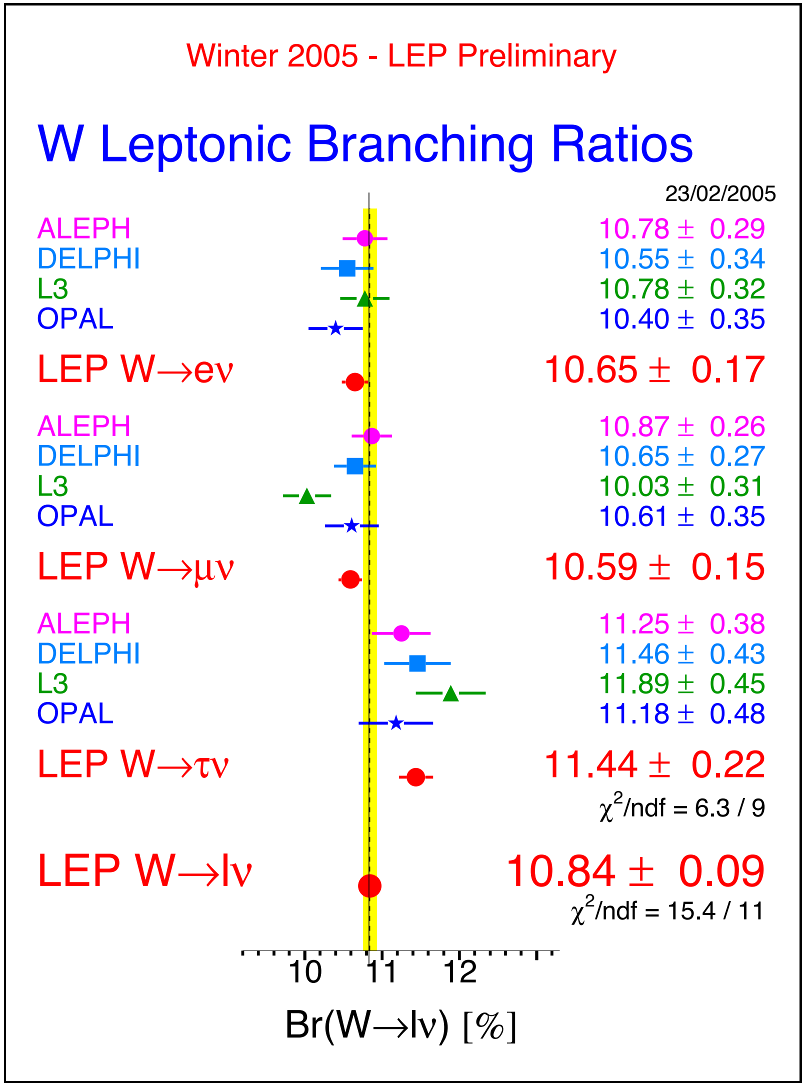
- What about the *third family*?





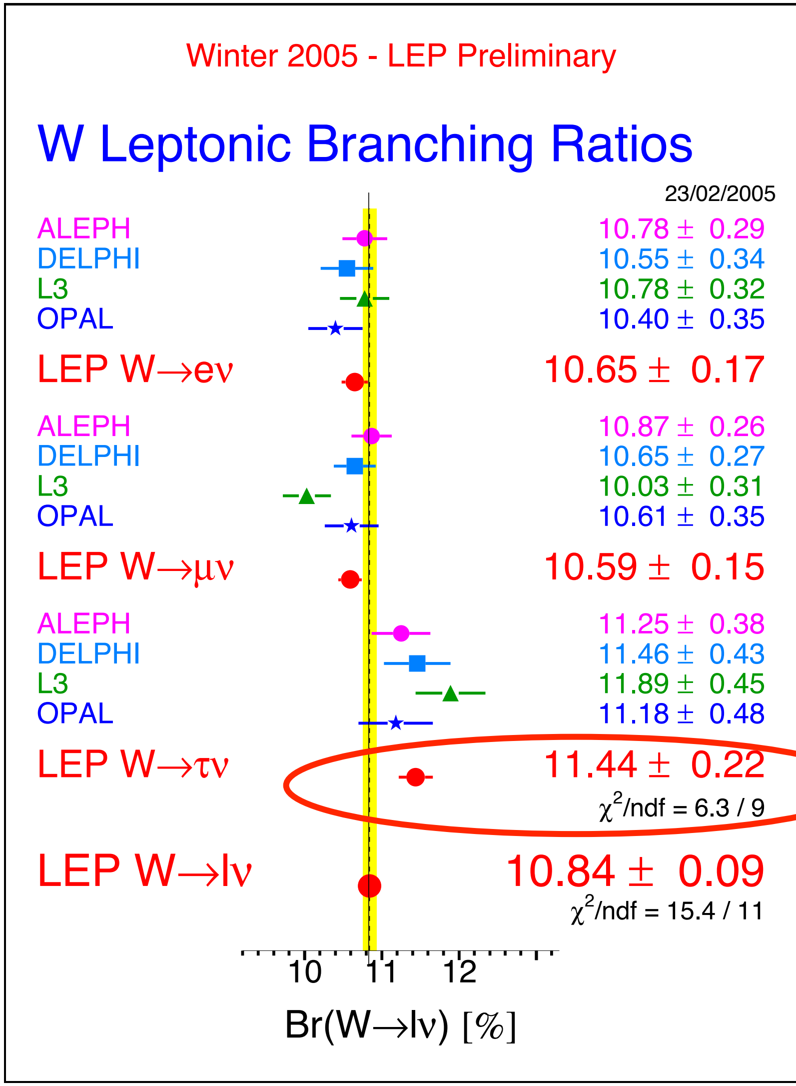
- Universality tested at 0.15% level and good agreement except for
  - W decay old anomaly
  - B decays ⇒ *See talks on Thursday*

4.1 Lepton Flavour Universality anomaly $W \to \tau\nu_\tau$



- Old LEP anomaly

4.1 Lepton Flavour Universality anomaly $W \to \tau\nu_\tau$



- Old LEP anomaly

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W \to \tau\,\bar{\nu}_\tau)}{\mathrm{BR}\,(W \to e\,\bar{\nu}_e) + \mathrm{BR}\,(W \to \mu\,\bar{\nu}_\mu)} = 1.077(26)$$

2.8σ away from SM!

- New physics?

Some models:
Li & Ma'05, Park'06, Dermisek'08

Try to explain with SM EFT approach with $[U(2)\mathrm{x}U(1)]^5$ flavour symmetry

⇨ Very difficult to explain without modifying any other observables
Filipuzzi, Portoles, Gonzalez-Alonso'12

- Would be great to have another measurement by LHC

4.2 Probing the CKM mechanism: extraction of Vus

- The CKM Mechanism source of *Charge Parity Violation* in SM

- Unitary 3x3 Matrix, parametrizes rotation between mass and weak interaction eigenstates in Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

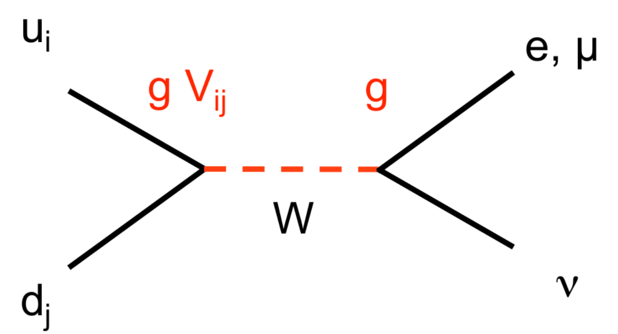
Weak Eigenstates CKM Matrix Mass Eigenstates

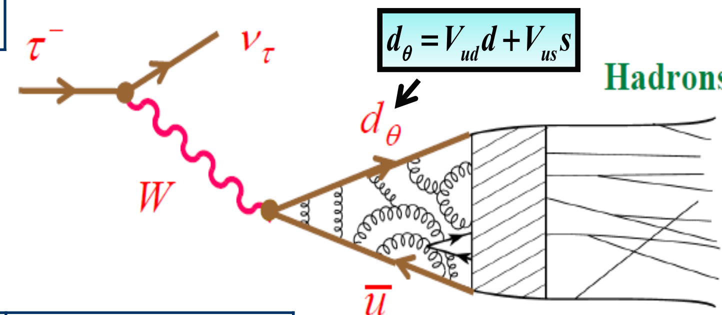
$$\sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

4.2 Paths to V_{ud} and V_{us}

- From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi^\pm \to \pi^0 e \nu_e$	$n \to p e \nu_e$	$\pi \to l \nu_l$
V_{us}	$K \to \pi l \nu_l$	$\Lambda \to p e \nu_e$	$K \to l \nu_l$





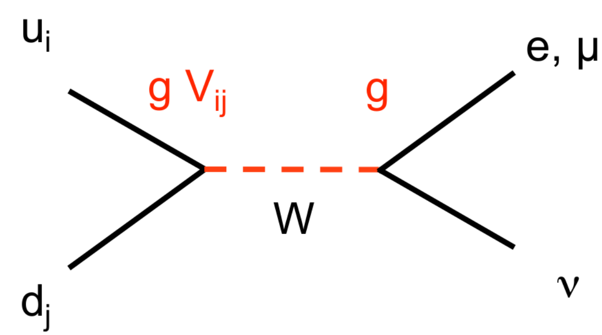
- From τ decays (crossed channel)

V_{ud}	$\tau \to \pi\pi\nu_\tau$		$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$		$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$ (inclusive)

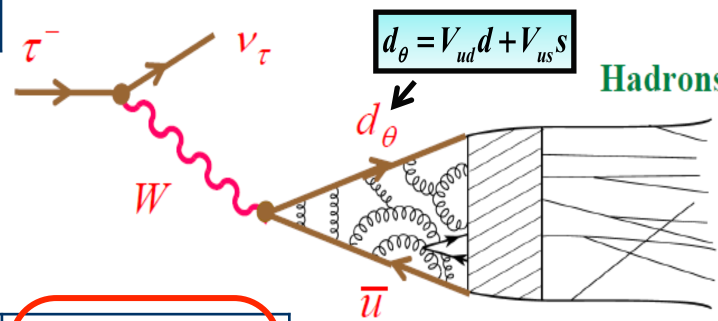
4.2 Paths to V_{ud} and V_{us}

- From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi^\pm \to \pi^0 e \nu_e$	$n \to p e \nu_e$	$\pi \to l \nu_l$
V_{us}	$K \to \pi l \nu_l$	$\Lambda \to p e \nu_e$	$K \to l \nu_l$

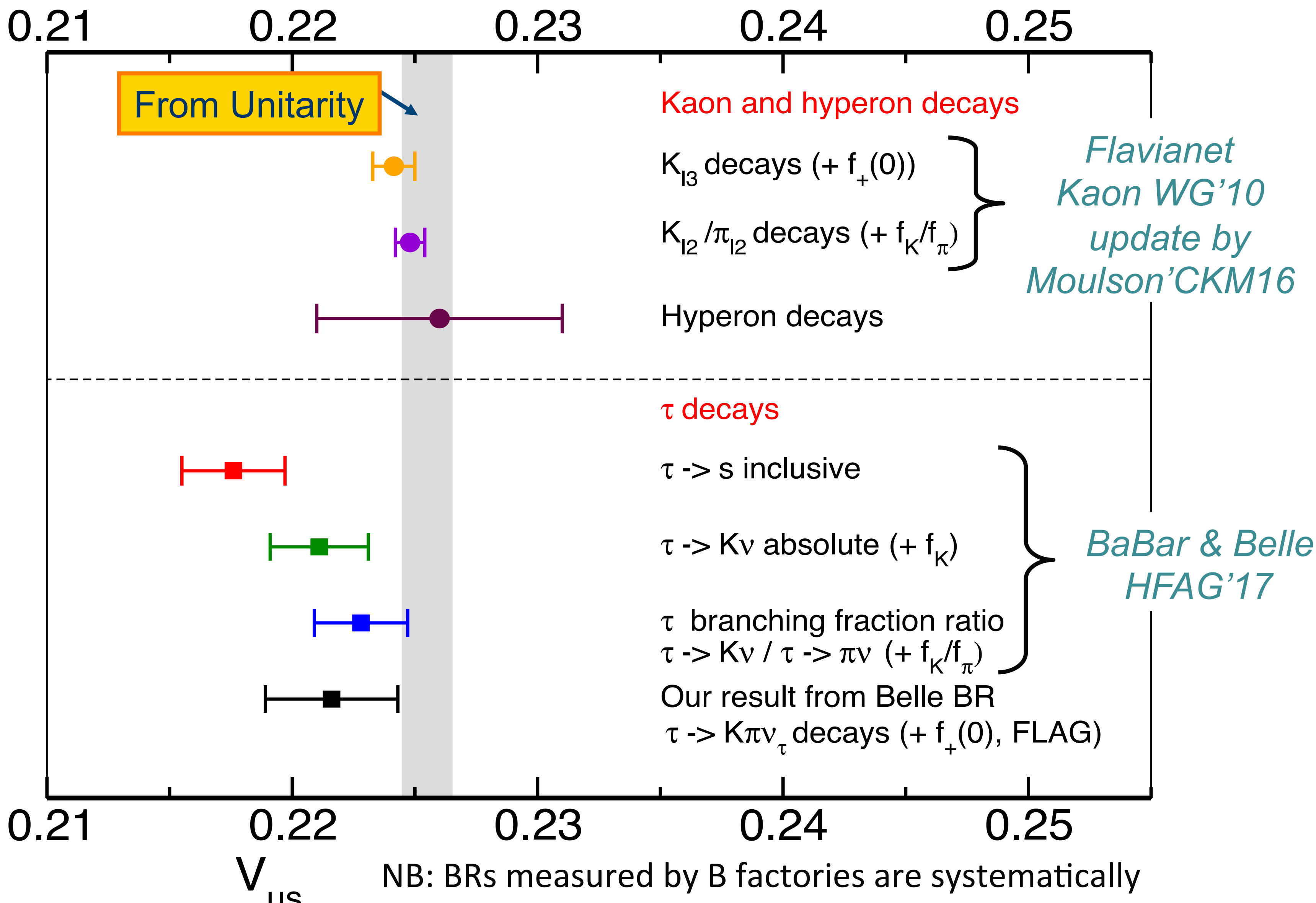


- From τ decays (crossed channel)



V_{ud}	$\tau \to \pi\pi\nu_\tau$		$\tau \to \pi \nu_\tau$	$\tau \to h_{NS} \nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$		$\tau \to K \nu_\tau$	$\tau \to h_S \nu_\tau$ (inclusive)

4.2 V_{us} determination

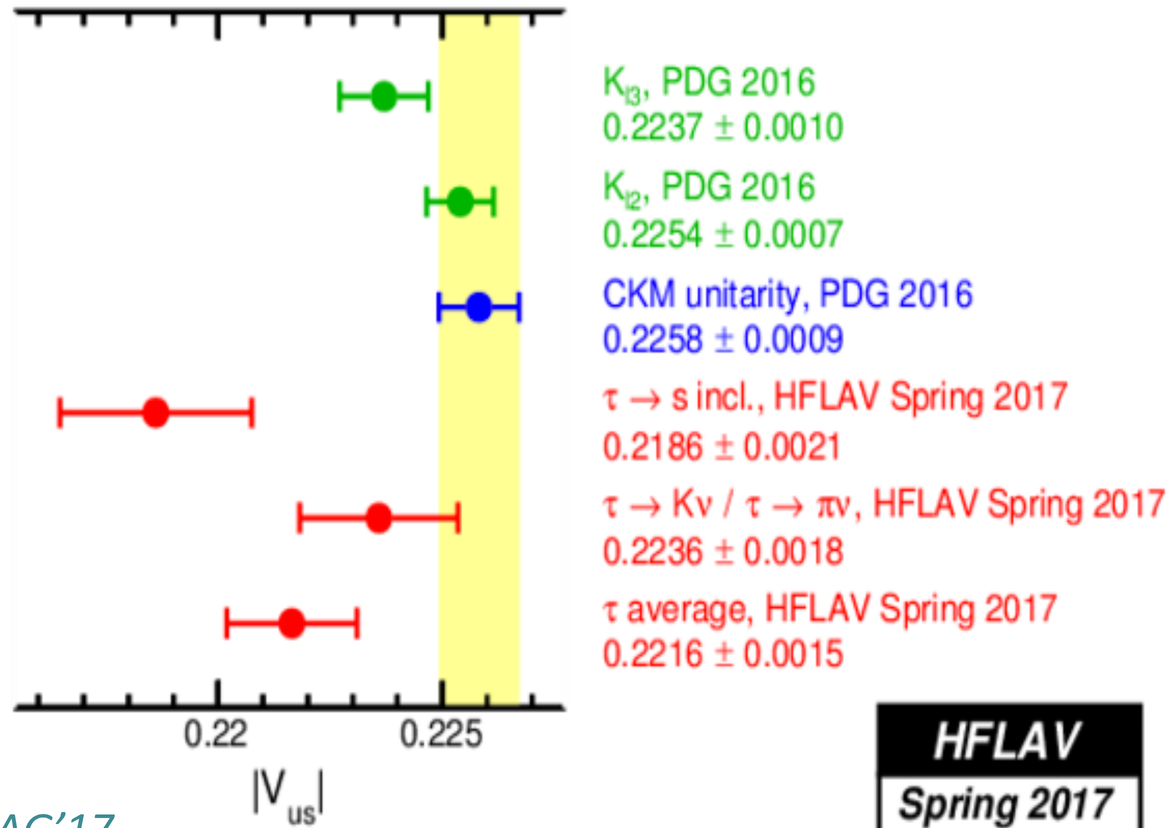


NB: BRs measured by B factories are systematically smaller than previous measurements

4.2 V_{us} determination

- Longstanding inconsistencies between inclusive τ and kaon decays in extraction of V_{us}
- Inclusive τ decays:

$$\boxed{\delta R_\tau \equiv \frac{R_{\tau,NS}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}}$$



SU(3) breaking quantity, strong dependence in m_s computed from OPE (L+T) + phenomenology

$$\delta R_{\tau,th} = 0.0242(32)$$

Gamiz et al'07, Maltman'11

$$\boxed{|V_{us}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,NS}}{|V_{ud}|^2} - \delta R_{\tau,th}}}$$

HFAG'17

$$R_{\tau,S} = 0.1633(28)$$

$$R_{\tau,NS} = 3.4718(84)$$

$$|V_{ud}| = 0.97417(21)$$

$$\Rightarrow \quad \boxed{|V_{us}| = 0.2186 \pm 0.0019_{exp} \pm 0.0010_{th}}$$

3.1σ away from unitarity!

5. Conclusion and outlook

Conclusion and outlook

- 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 and in particular *tau physics* offer an important spectrum of possibilities:
  - LFV measurement has SM-free signal
  - Current experiments and mature proposals promise orders of magnitude sensitivity improvements (*Belle II*, *Tau-Charm factory*, etc.)
  - There is a hint of new dynamics in CPV asymmetries in the tau sector
  - Progress towards a better knowledge of hadronic uncertainties
  - New physics models usually strongly correlate the flavours sectors

Conclusion and outlook

- We show how CLFV decays offer 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

- We discussed the possibilities to look for CP violation in the tau sector: BaBar result does not agree with SM expectation but needs to be confirmed ⇒ A lot of new measurements possible (A_{CP}, A_{FB}, etc.) to shed light on CP violation in the tau sector: combine strong and weak phase determination

- EDM of the tau also very interesting to study but difficult

- Several topics extremely interesting to study that I just mentioned or had no time to talk about:
  - α_S, $|V_{us}|$ and m_s from hadronic tau decays
  - Lepton universality tests, Michel parameters, g-2 of the tau…

- A lot of very interesting physics remains to be done in the tau sector!

6. Back-up

3.3 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

- Belle uses sum of BWs to fit the invariant mass distribution *Belle'08*

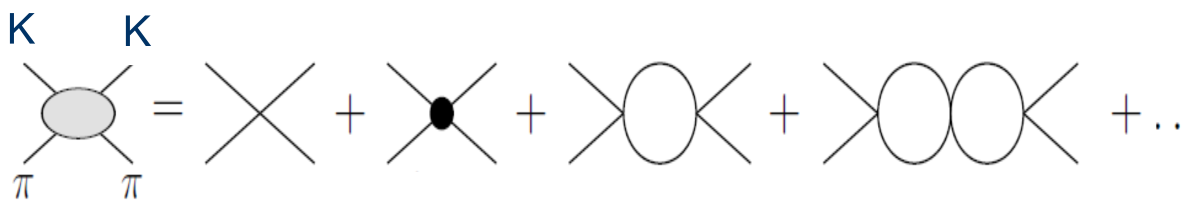
$$F_V = \frac{1}{1+\beta+\chi}\left[BW_{K^*(892)}(s) + \beta BW_{K^*(1410)}(s) + \chi BW_{K^*(1680)}(s)\right]$$

$$F_S = \varkappa \frac{s}{M^2_{K_0^*(800)}} BW_{K_0^*(800)}(s) + \gamma \frac{s}{M^2_{K_0^*(1430)}} BW_{K_0^*(1430)}(s)$$

- Can be justified for the vector but not for the scalar!

  ⇨ Use a parametrization relying on dispersion relations instead:

  – Resum all final state $K\pi$ rescattering

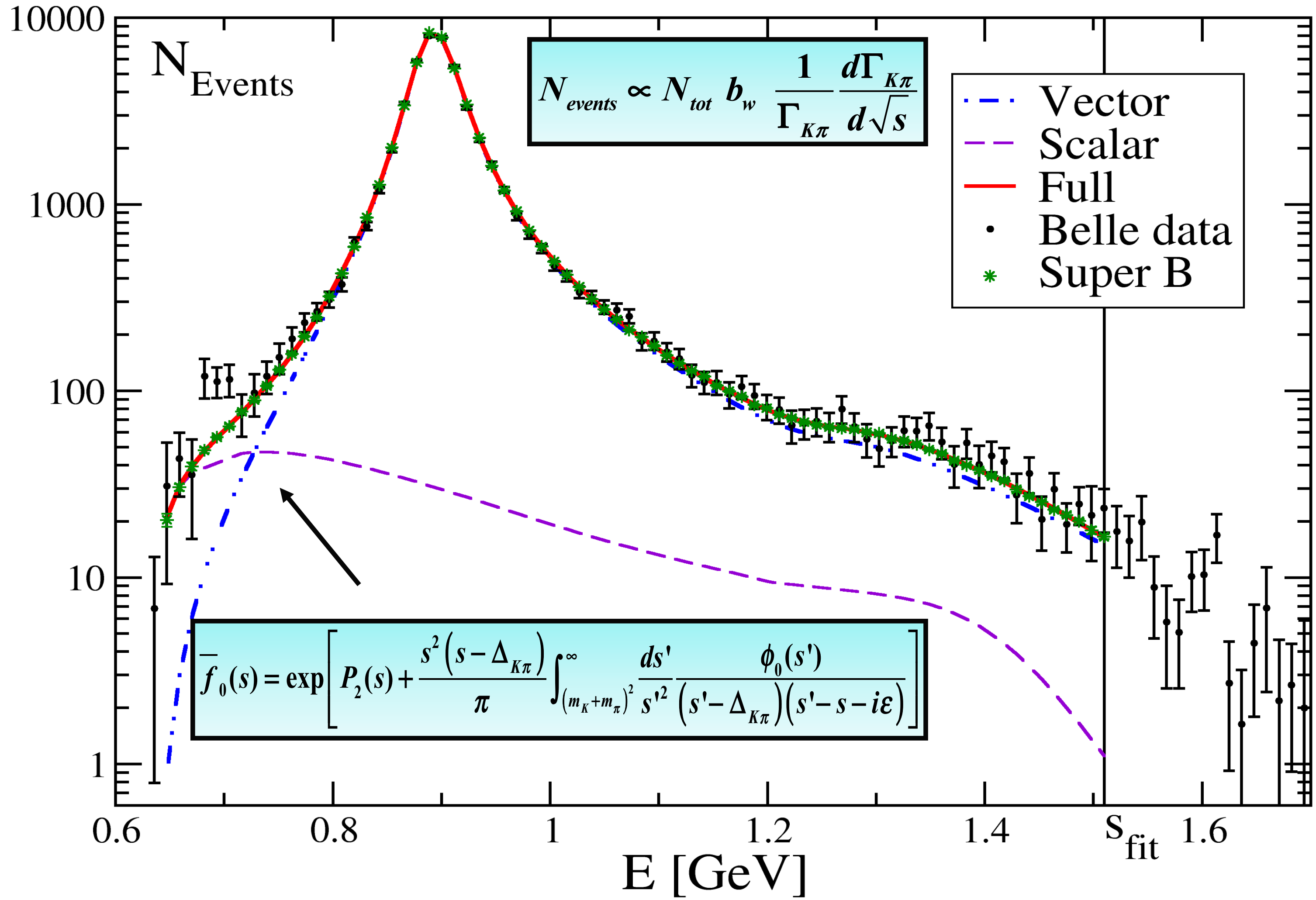


  – Allow to combine with $K \to \pi l \nu_l$ precise measurements

- Several theoretical parametrizations proposed: All rely on analyticity and unitarity and crossing symmetry *Jamin, Pich, Portolés'06,'08, Moussallam'08, Boito, Escribano, Jamin'09,'10, Bernard, Boito, E.P.'11, Bernard'14*

3.3 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

Bernard, Boito, E.P.'11
Antonelli, Cirigliano, Lusiani, E.P.'13



3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- In this measurement, need to know hadronic part ⇨ form factors

$$\boxed{\langle \mathbf{K}\pi |\ \bar{\mathbf{s}}\gamma_\mu \mathbf{u}\ |0\rangle = \left[\left(p_K - p_\pi\right)_\mu + \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu\right] f_+(s) - \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu f_0(s)}$$

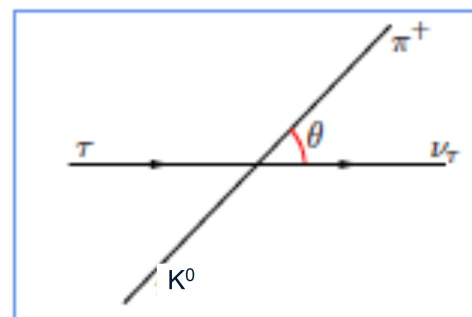
with $s = Q^2 = (p_K + p_\pi)^2$

vector (for $f_+(s)$) — scalar (for $f_0(s)$)

- Up to now know from decay spectrum but difficult to disentangle scalar and vector form factor ⇨ consider the FB asymmetry instead

$$\boxed{A_{\mathrm{FB}} = \frac{d\Gamma(\cos\theta) - d\Gamma(-\cos\theta)}{d\Gamma(\cos\theta) + d\Gamma(-\cos\theta)}}$$

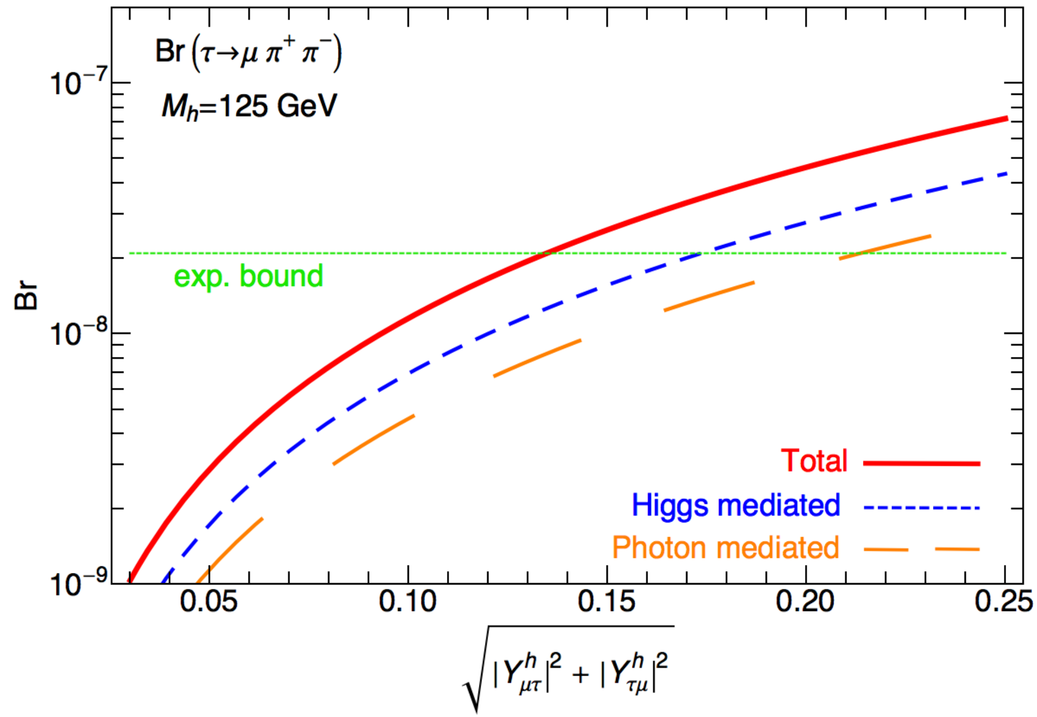
Beldjoudi & Truong'94
Moussallam, B2TIP



- Formula: can disentangle scalar and vector FF easily

$$A_{FB}(s) = \frac{3\Delta_{\pi^+K^0}\sqrt{\lambda_{\pi^+K^0}(s)}\,|f_V^{K\pi}(s)||f_0^{K\pi}(s)|\,\cos\left(\delta_1^{1/2} - \delta_0^{1/2}\right)}{\underbrace{|f_V^{K\pi}(s)|^2\lambda_{\pi^+K^0}(s)}_{\text{vanishes at threshold}}(1 + 2s/m_\tau^2) + 3|f_0^{K\pi}(s)|^2\Delta^2_{\pi^+K^0}}.$$

3.5 Results



Bound:

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

Process	(BR × 10^8) 90% CL	$\sqrt{\lvert Y^h_{\mu\tau}\rvert^2+\lvert Y^h_{\tau\mu}\rvert^2}$	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

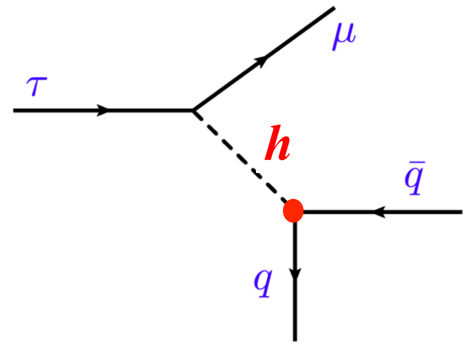
?

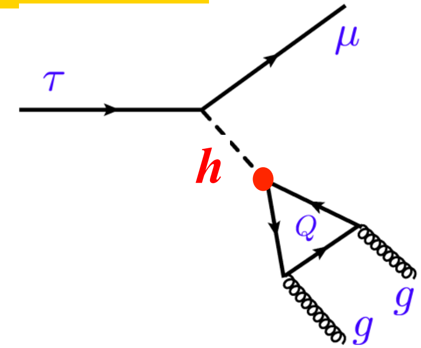
Belle'08'11'12 except last from *CLEO'97*

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 $Y_{u,d,s}$!
- $Y_{u,d,s}$ 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:

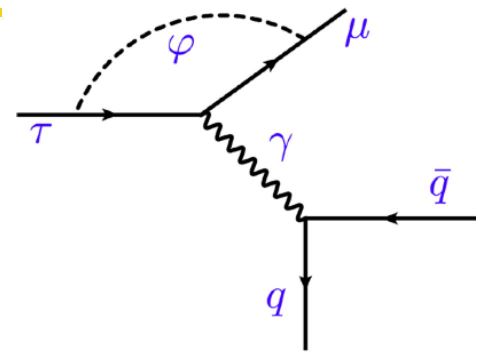
$$\boxed{\begin{array}{l} Br(\tau \to \mu\pi^+\pi^-) < 3.0 \times 10^{-8}, Br(\tau \to \mu\pi^0\pi^0) < 1.5 \times 10^{-8} \\ Br(\tau \to e\pi^+\pi^-) < 4.3 \times 10^{-7}, Br(\tau \to e\pi^0\pi^0) < 2.1 \times 10^{-7} \end{array}}$$

below present experimental limits!

- If discovered ⇒ among other things *upper limit* on $Y_{u,d,s}$*!*

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

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



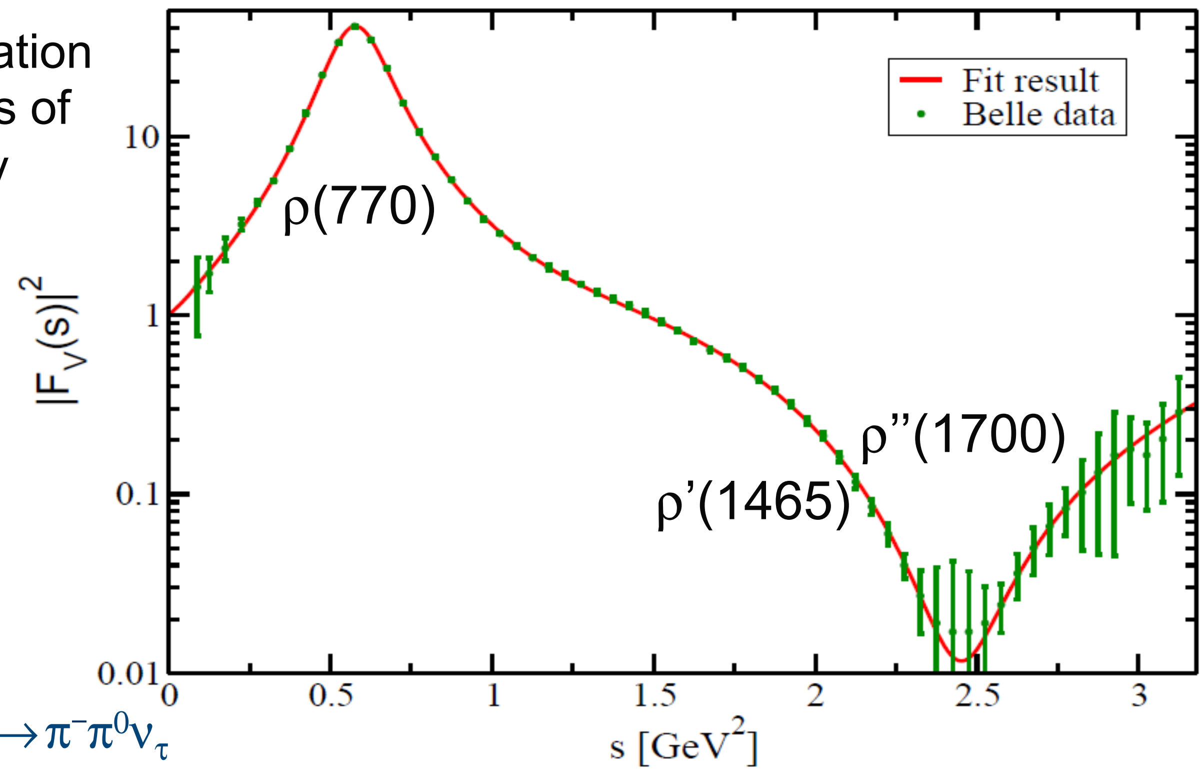
- Photon mediated contribution requires the pion vector form factor:

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

- Dispersive parametrization following the properties of analyticity and unitarity of the Form Factor

Gasser, Meißner´91
Guerrero, Pich'97
Oller, Oset, Palomar´01
Pich, Portolés ´08
Gómez Dumm&Roig'13
...

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



Celis, Cirigliano, E.P.'14

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 $F_V(s)$

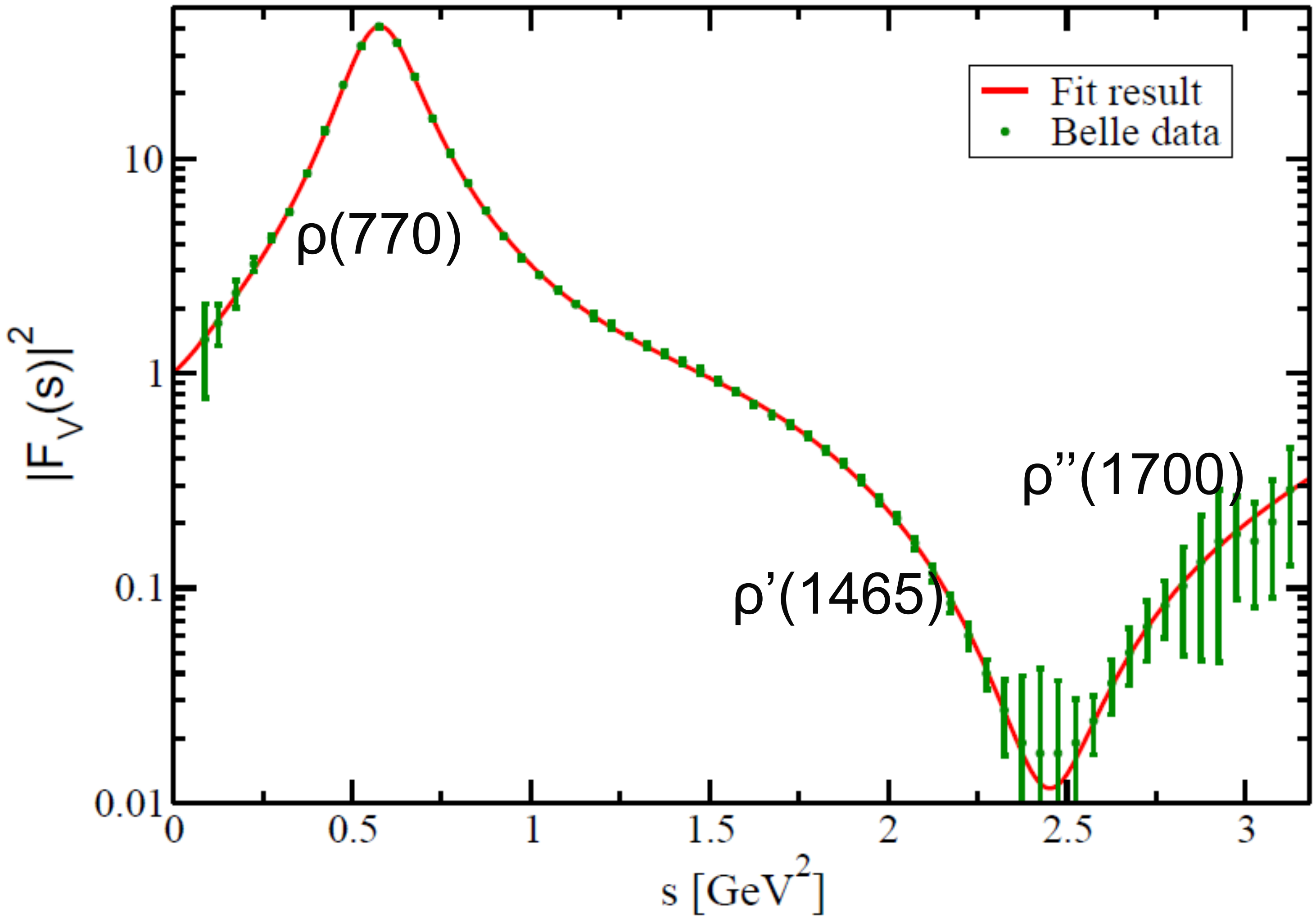
Guerrero, Pich'98, Pich, Portolés'08
Gomez, Roig'13

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

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

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

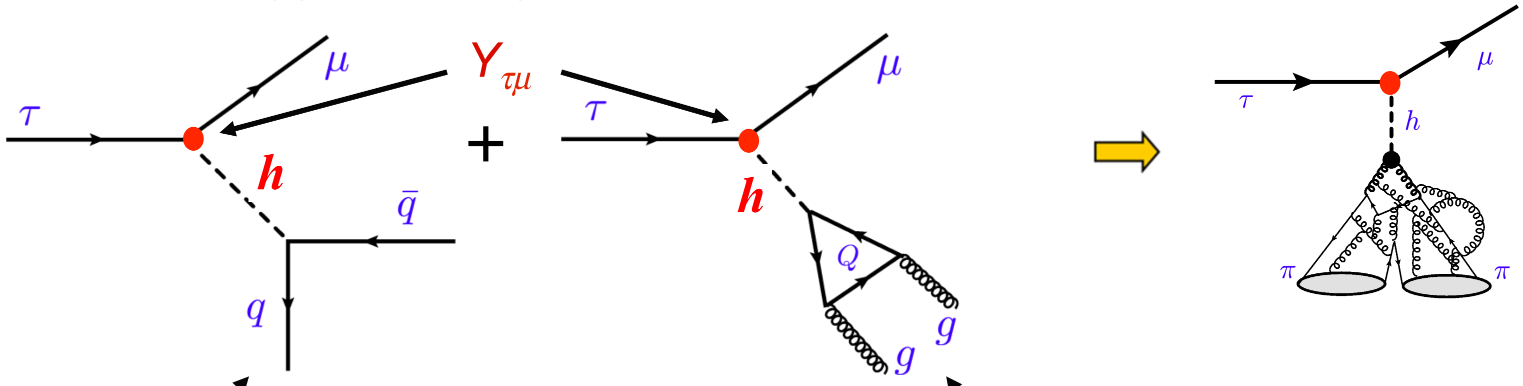
Determination of $F_V(s)$



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

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

- Tree level Higgs exchange



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

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

Voloshin'85

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

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

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

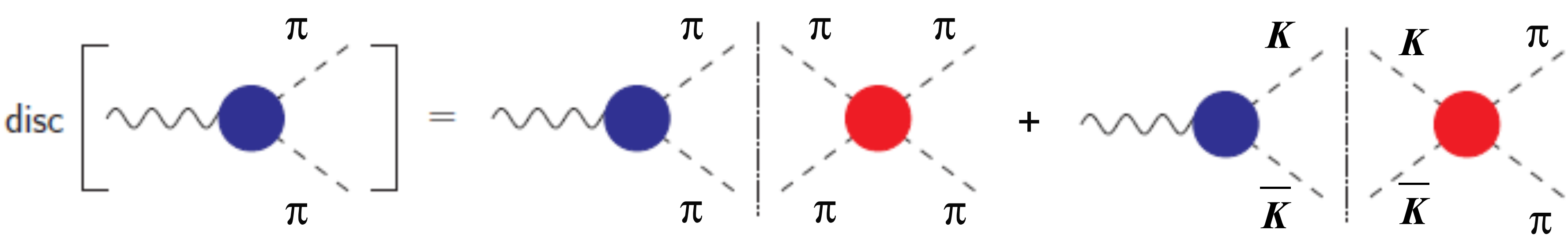
$$f\left(y_q^h\right)$$

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

- No experimental data for the other FFs ⇨ *Coupled channel analysis*
  up to √s ~1.4 GeV
  Inputs: I=0, S-wave ππ and KK data

Donoghue, Gasser, Leutwyler'90
Moussallam'99
Daub et al'13

- Unitarity:

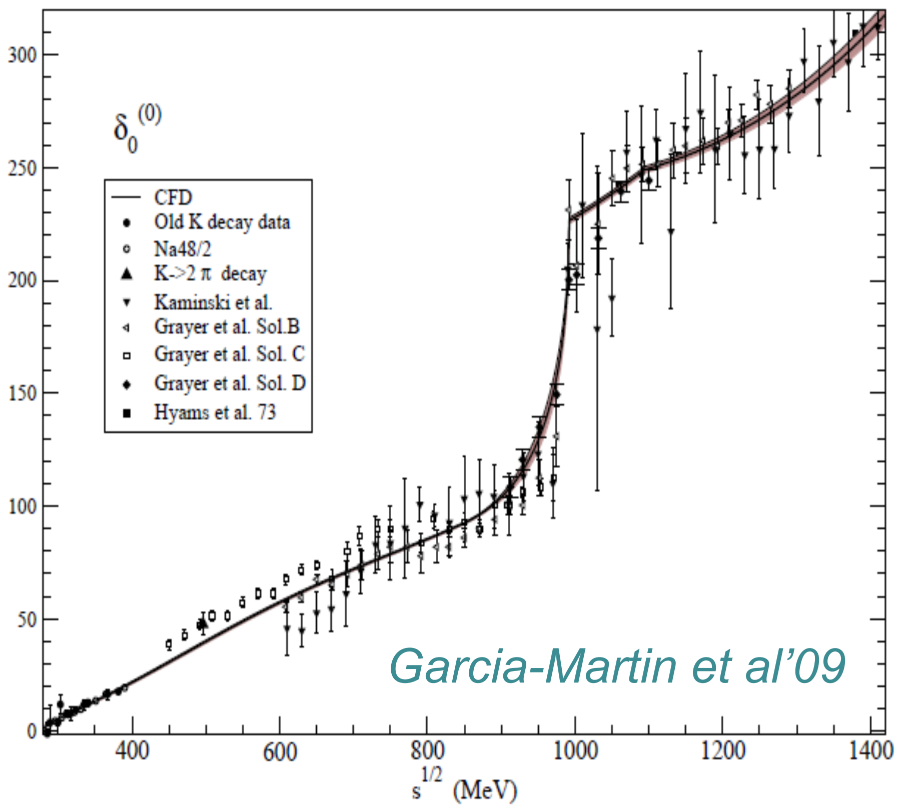


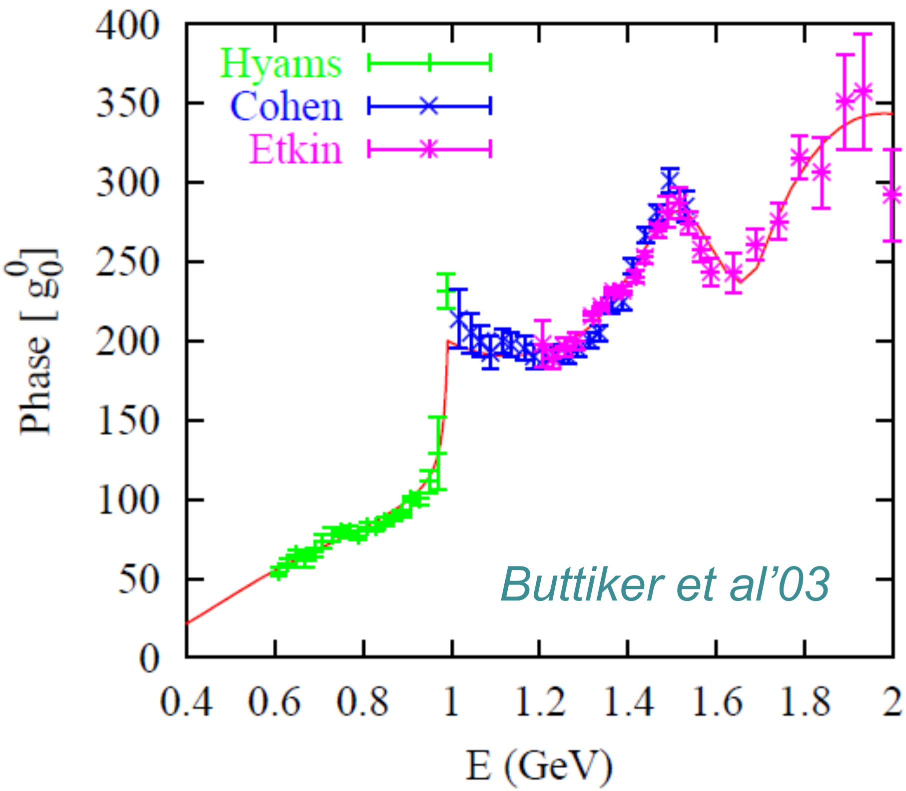
⇨ $$\boxed{\mathrm{Im}F_n(s) = \sum_{m=1}^{2} T^*_{nm}(s)\sigma_m(s)F_m(s)}$$ $\quad n = \pi\pi, K\bar{K}$

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

Celis, Cirigliano, E.P.'14

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





- 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:

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

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

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

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

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

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

Determination of the polynomial

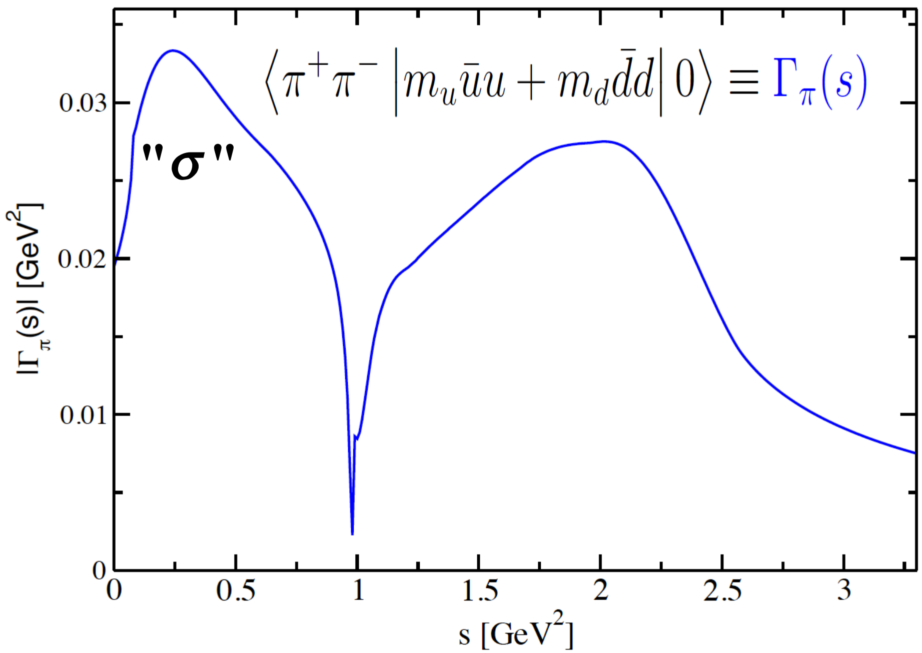
- General solution

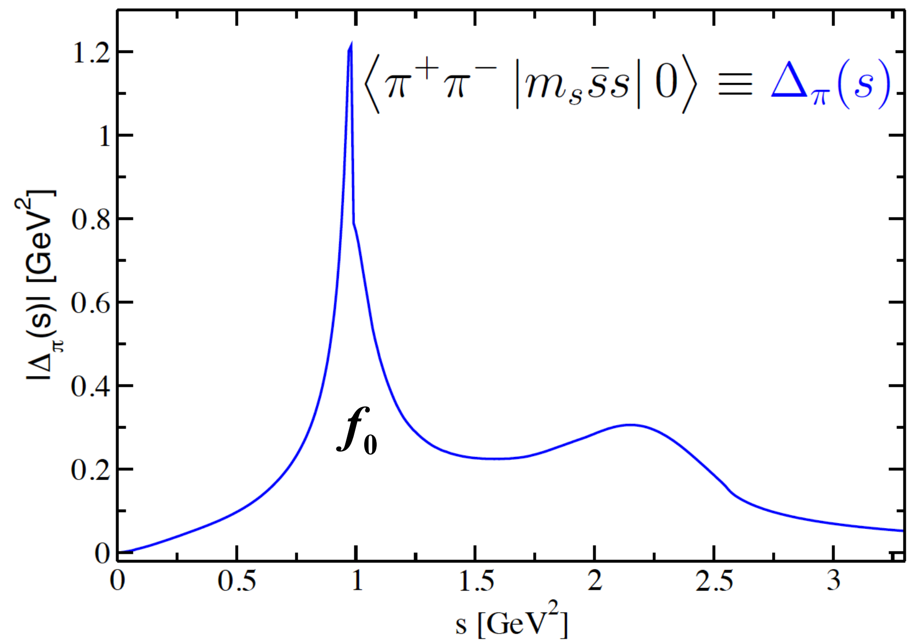
$$\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}$$

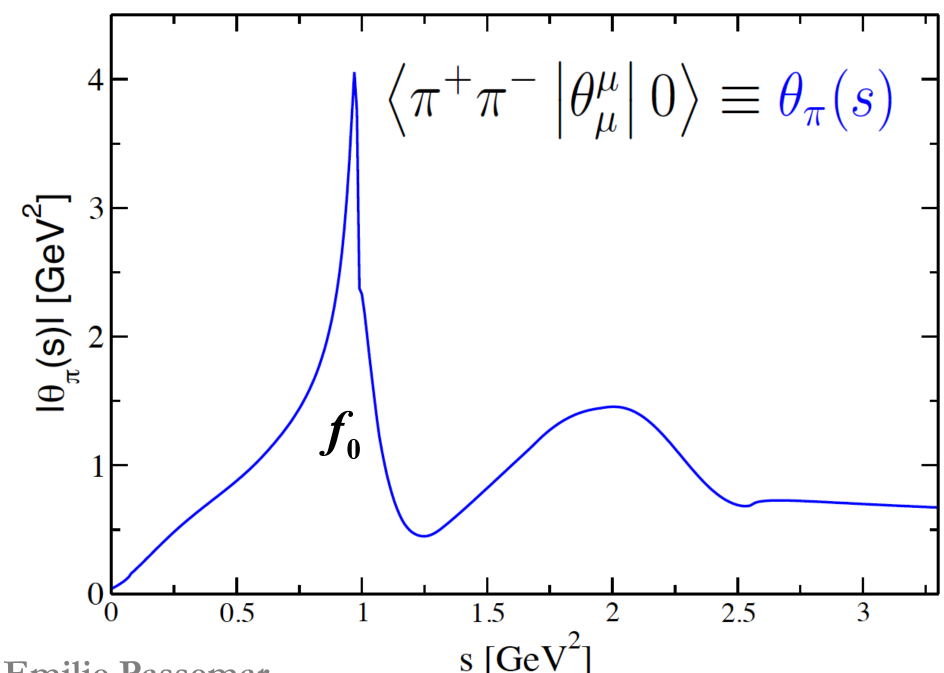
- For θ_P enforcing the asymptotic constraint is not consistent with ChPT
  The unsubtracted DR is not saturated by the 2 states

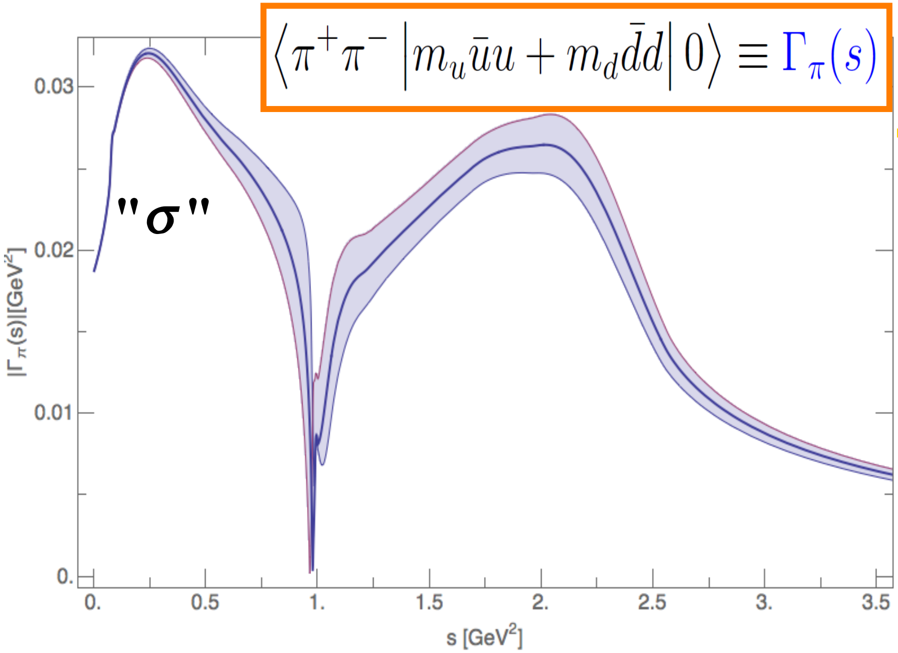
⇨ Relax the constraints and match to ChPT

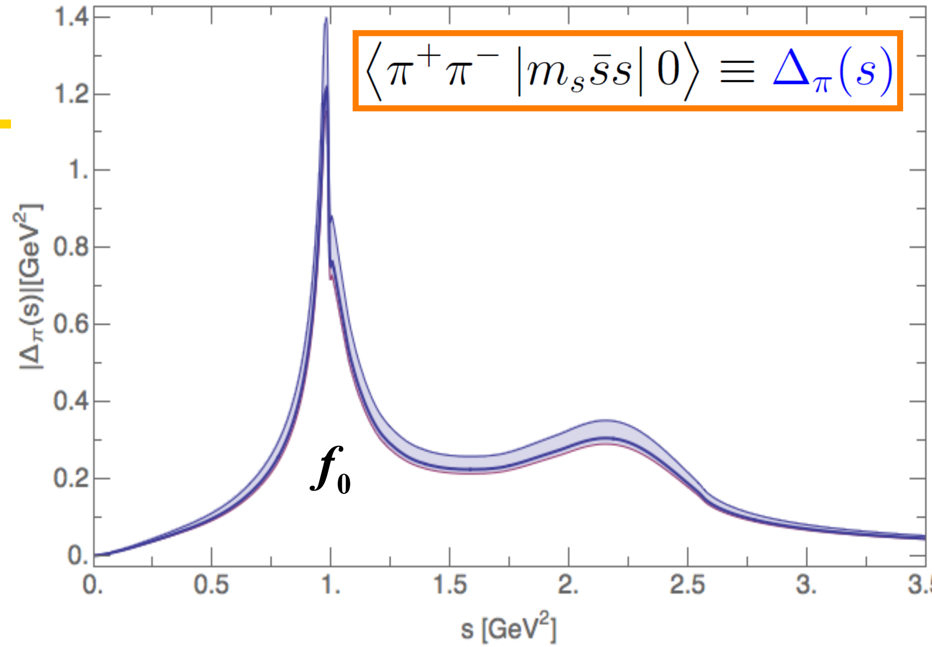
$$\begin{aligned} P_\theta(s) &= 2M_\pi^2 + \left(\dot{\theta}_\pi - 2M_\pi^2 \dot{C}_1 - \frac{4M_K^2}{\sqrt{3}} \dot{D}_1\right) s \\ Q_\theta(s) &= \frac{4}{\sqrt{3}} M_K^2 + \frac{2}{\sqrt{3}} \left(\dot{\theta}_K - \sqrt{3} M_\pi^2 \dot{C}_2 - 2M_K^2 \dot{D}_2\right) s \end{aligned}$$

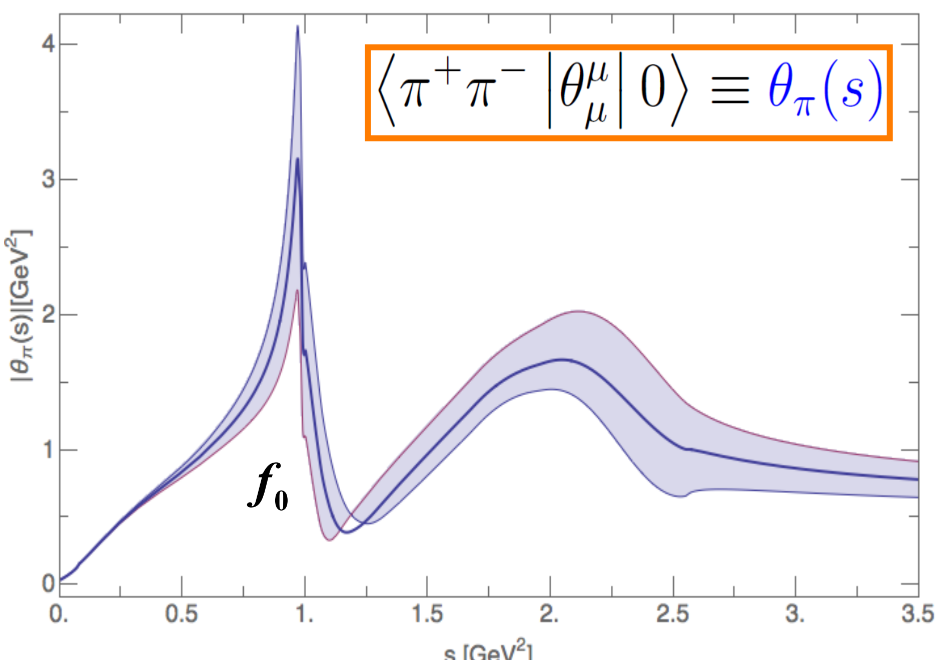

$\langle \pi^+\pi^- | m_u \bar{u}u + m_d \bar{d}d | 0 \rangle \equiv \Gamma_\pi(s)$
"σ"
$|\Gamma_\pi(s)|$ [GeV^2]
s [GeV^2]
0
0.01
0.02
0.03
0.5
1
1.5
2
2.5
3


$\langle \pi^+\pi^- | m_s \bar{s}s | 0 \rangle \equiv \Delta_\pi(s)$
f_0
$|\Delta_\pi(s)|$ [GeV^2]
s [GeV^2]
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2
2.5
3

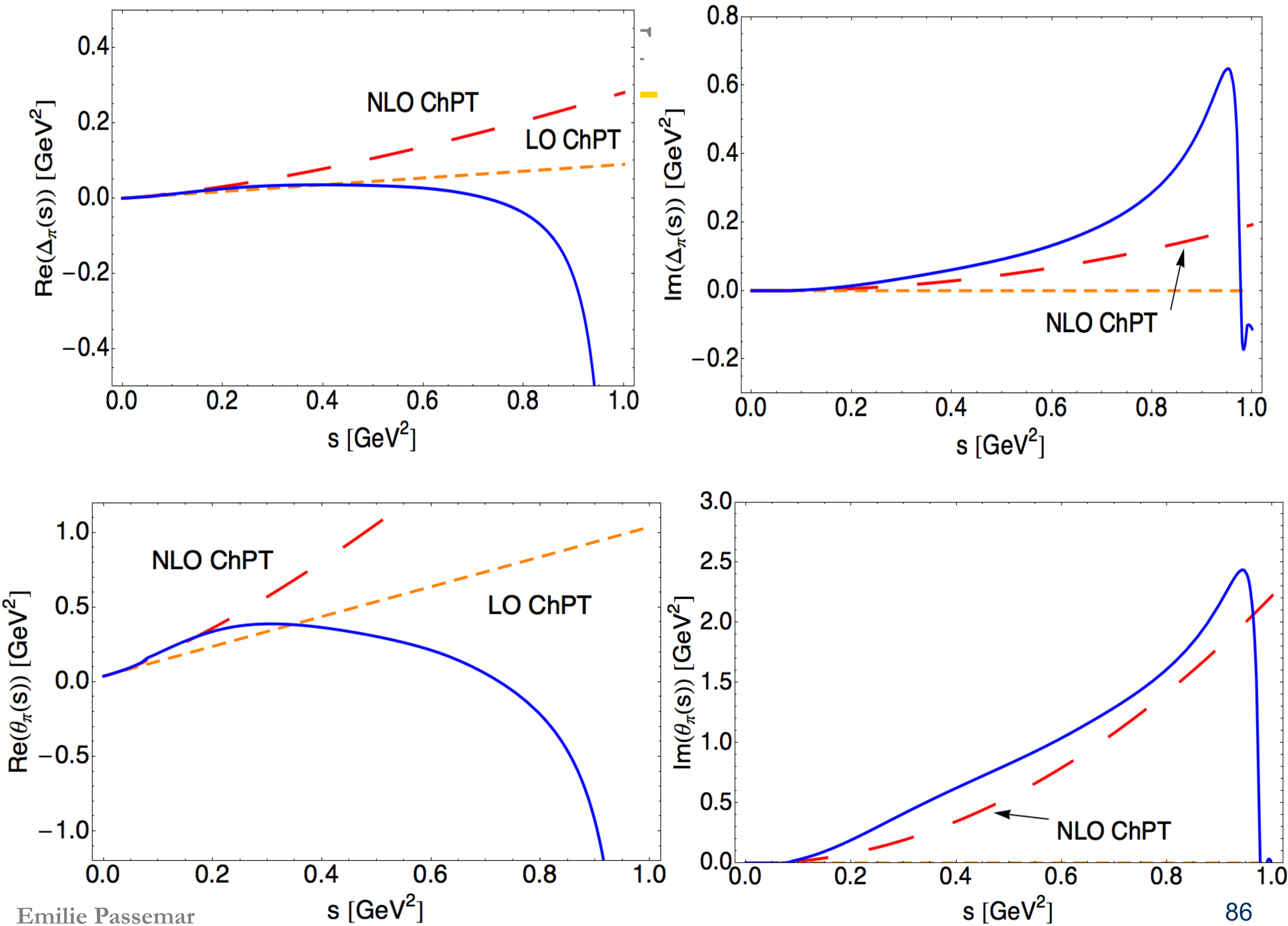

$\langle \pi^+\pi^- | \theta^\mu_\mu | 0 \rangle \equiv \theta_\pi(s)$
f_0
$|\theta_\pi(s)|$ [GeV^2]
s [GeV^2]
0
1
2
3
4
0.5
1.5
2.5







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



NLO ChPT
LO ChPT
Re(Δ_π(s)) [GeV^2]
s [GeV^2]
Im(Δ_π(s)) [GeV^2]
NLO ChPT
s [GeV^2]
NLO ChPT
LO ChPT
Re(θ_π(s)) [GeV^2]
s [GeV^2]
Im(θ_π(s)) [GeV^2]
NLO ChPT
s [GeV^2]