INDIANA UNIVERSITY
BLOOMINGTON

Jefferson Lab

Tau theory review

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Mainz, Germany
June 27, 2017

Outline :

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

2. Extraction of V_{us} from hadronic Tau decays and test of the CKM unitarity

3. Lepton Flavour Violation

4. Conclusion and outlook

NB: several very interesting topics not covered:
lepton universality, CP violation, g-2, EDMs, neutrinos, etc…

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 a *broad search strategy* given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

Y. Grossman@KEKFF'14

Where is the tail?

⇨ Key unique role of *Tau 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:
  - Kaon physics: $\frac{s\bar{d}s\bar{d}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^5$ TeV
    [ε_K]
  - Tau physics: $\frac{\tau\bar{\mu} f\bar{f}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2$ TeV
    [$\tau \to \mu\gamma$]

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  Ex: h → $\tau\tau$, LFV in h → $\tau\mu$

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  - 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*

1.3 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	~3x10^{5}
CLEO	~1x10^{7}
BaBar	~5x10^{8}
Belle	~9x10^{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 *D. Epifanov, A. Luisiani* and *O. Shekhovtsova* will give more

2. V_{us} and CKM unitarity test

2.1 Probing the CKM mechanism

- 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

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

2.2 Extraction of V_{us}

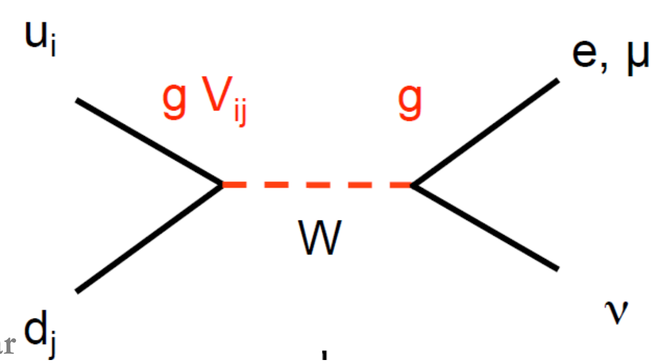
- Extraction of the Cabibbo-Kobayashi-Maskawa matrix element V_{us}
  - Fundamental parameter of the Standard Model
    Check unitarity of the first row of the CKM matrix:
    ⇨ *Cabibbo Universality*

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$$

Negligible (B decays)

  - Input in UT analysis

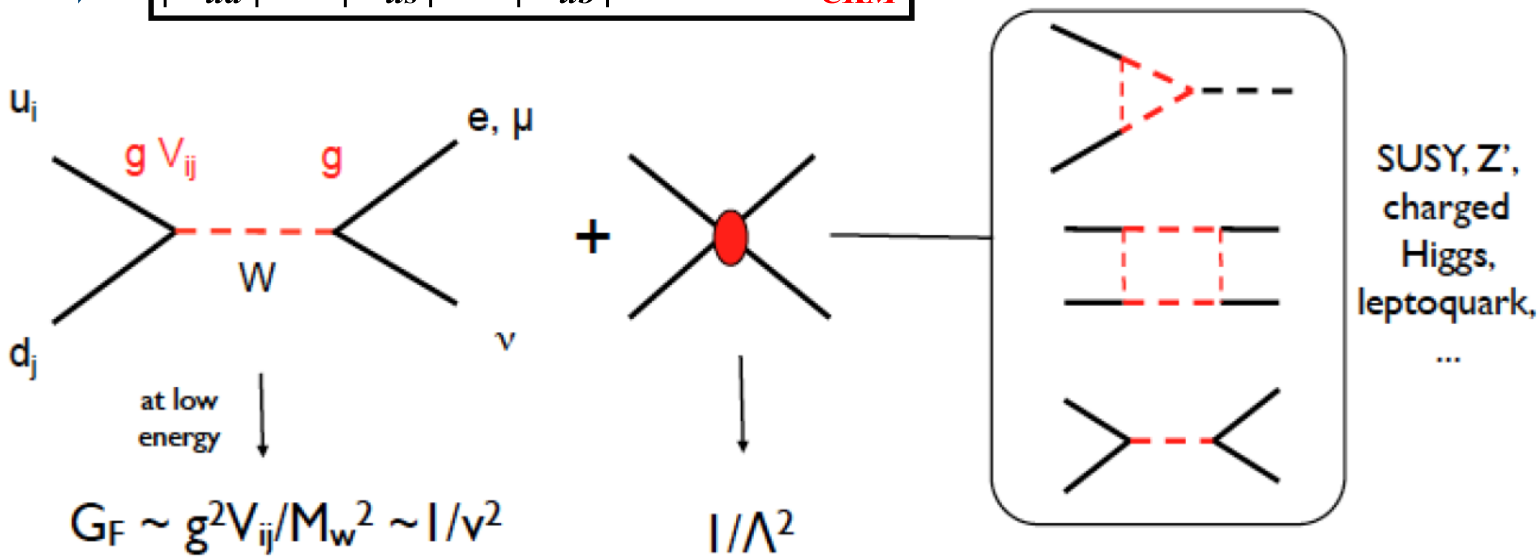
- Look for *new physics*
  - In the Standard Model : W exchange ⇨ only V-A structure



2.2 Extraction of V_{us}

- BSM: sensitive to tree-level and loop effects of a large class of models

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1+\Delta_{CKM}$$

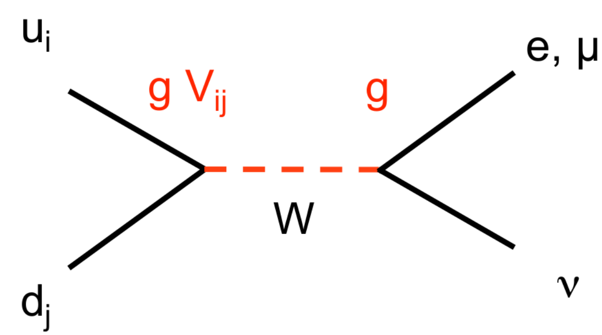


BSM effects : $\Delta_{CKM} \sim (v/\Lambda)^2$

- Look for new physics by comparing the extraction of V_{us} from different processes: helicity suppressed $K_{\mu 2}$, helicity allowed K_{l3}, hadronic τ decays

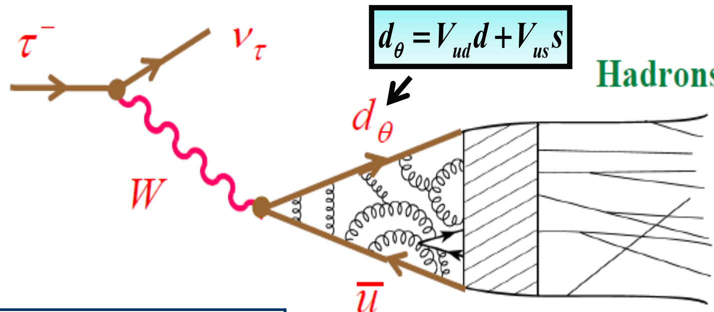
2.2 Paths to V_{ud} and V_{us}

- 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)

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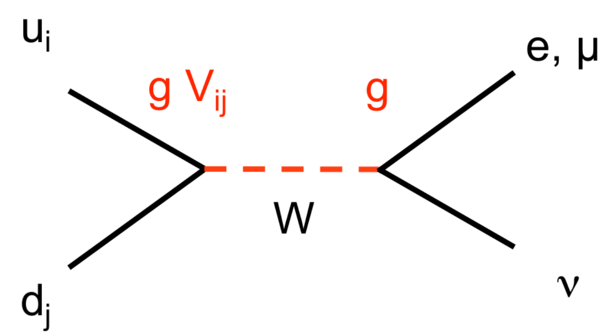

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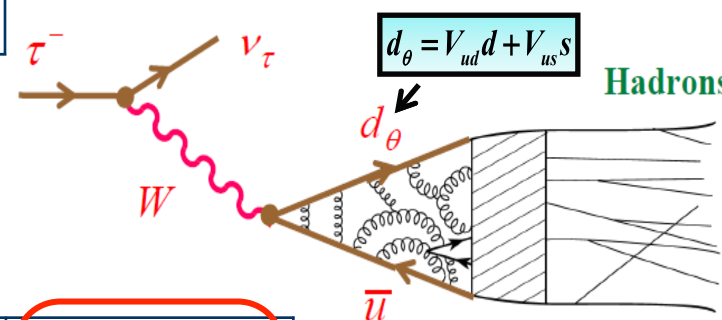

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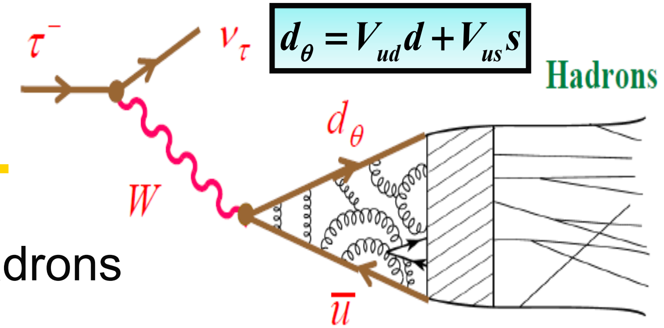
2.3 V_{us} from inclusive measurement

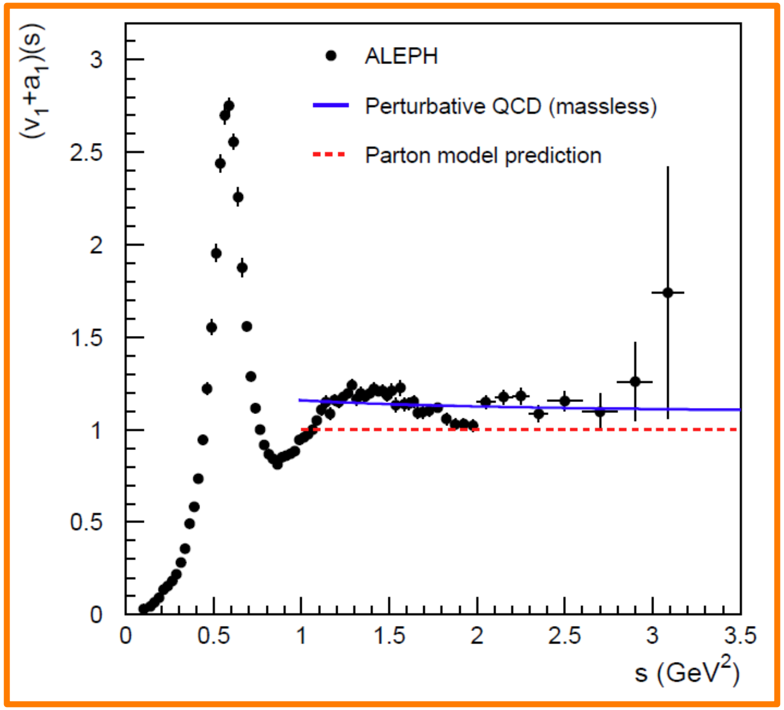


- Tau, the only lepton heavy enough to decay into hadrons
- $m_\tau \sim 1.77\text{GeV} > \Lambda_{QCD}$ ⇒ use *perturbative tools: OPE…*
- Inclusive τ decays : $\tau \to (\bar{u}d, \bar{u}s)\nu_\tau$ ⇒ fund. SM parameters $(\alpha_S(m_\tau), |V_{us}|, m_s)$
- We consider $\Gamma(\tau^- \to \nu_\tau + \text{hadrons}_{S=0})$

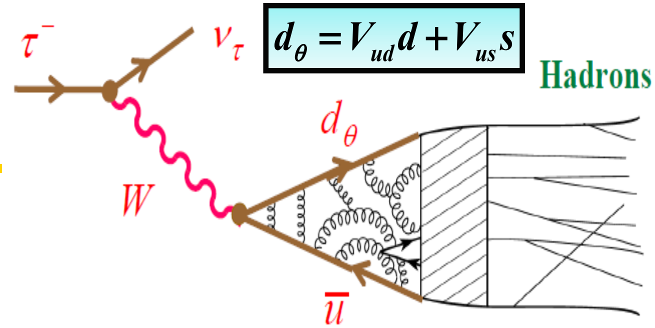
  $\Gamma(\tau^- \to \nu_\tau + \text{hadrons}_{S\neq0})$

- ALEPH and OPAL at LEP measured with precision not only the total BRs but also the energy distribution of the hadronic system ⇒ huge *QCD activity*!
- Observable studied: $R_\tau \equiv \dfrac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$

Davier et al'13



2.4 Theory



- $$R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau e^- \bar{\nu}_e\right)} \approx N_C$$ parton model prediction

- $$R_\tau = R_\tau^{NS} + R_\tau^{S} \approx \left|V_{ud}\right|^2 N_C + \left|V_{us}\right|^2 N_C$$

- $$\frac{\left|V_{us}\right|^2}{\left|V_{ud}\right|^2} = \frac{R_\tau^S}{R_\tau^{NS}}$$ ⇒ $\left|V_{us}\right|$

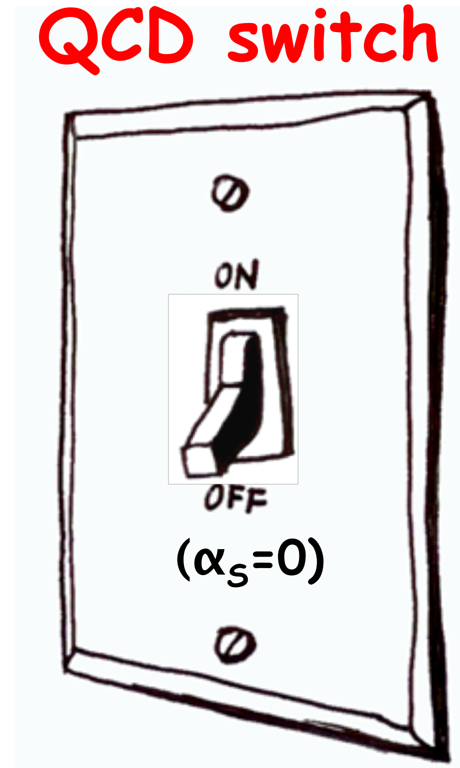
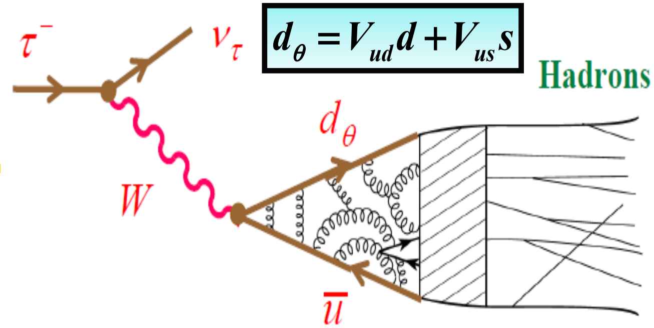


Figure from
M. González Alonso'13

2.4 Theory



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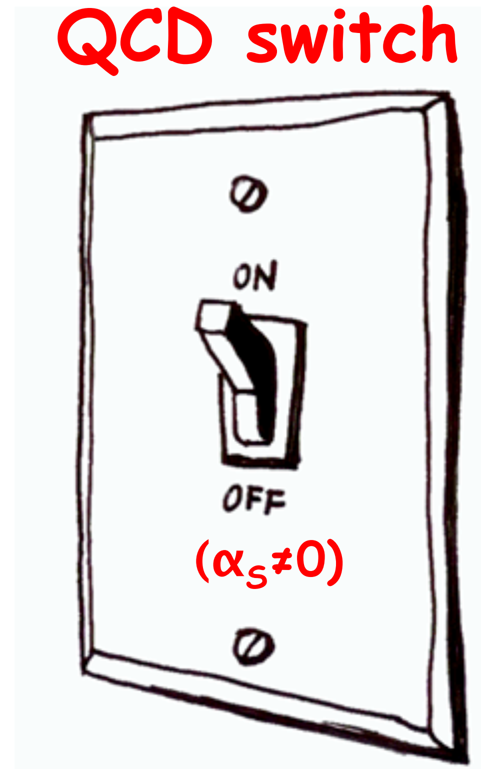

- $$R_\tau = R_\tau^{NS} + R_\tau^{S} \approx |V_{ud}|^2 N_C + |V_{us}|^2 N_C$$

- Experimentally: $$R_\tau = \frac{1 - B_e - B_\mu}{B_e} = 3.6291 \pm 0.0086$$

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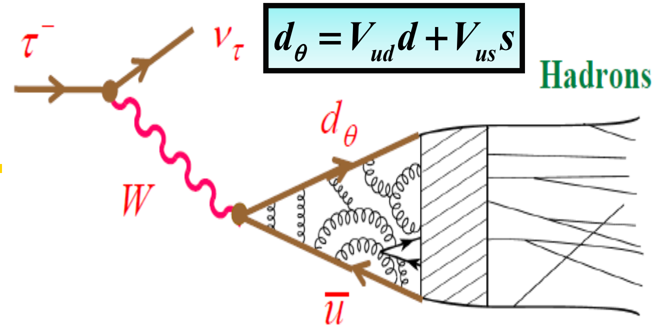

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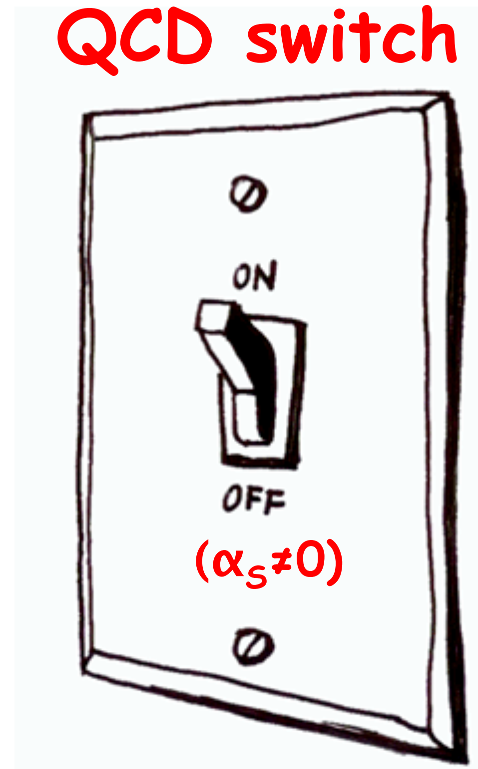
- Experimentally: $$R_\tau = \frac{1 - B_e - B_\mu}{B_e} = 3.6291 \pm 0.0086$$

- Due to *QCD corrections*: $R_\tau = \left|V_{ud}\right|^2 N_C + \left|V_{us}\right|^2 N_C + O(\alpha_s)$



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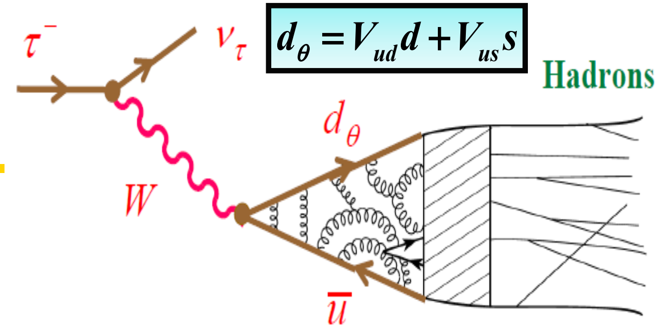
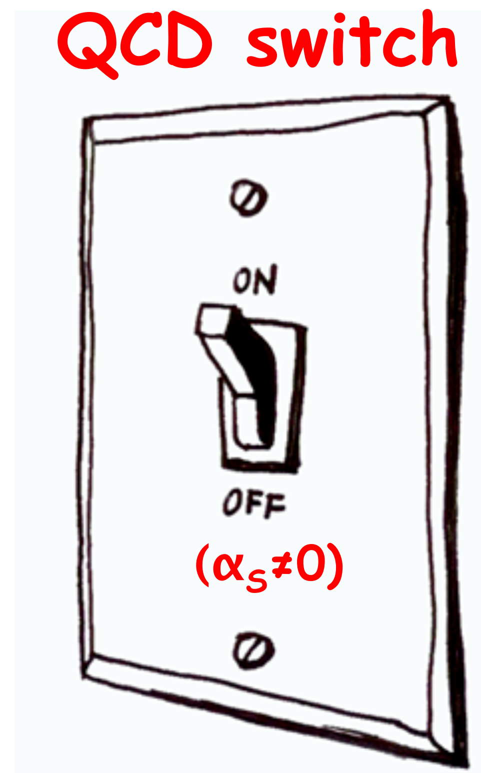


- From the measurement of the spectral functions, extraction of α_S, $|V_{us}|$

- $$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} \approx N_C$$ naïve QCD prediction



- Extraction of the strong coupling constant :

$$R_\tau^{NS} = |V_{ud}|^2 N_C + O(\alpha_S) \Rightarrow \alpha_S$$

measured (R_τ^{NS}), calculated ($O(\alpha_S)$)

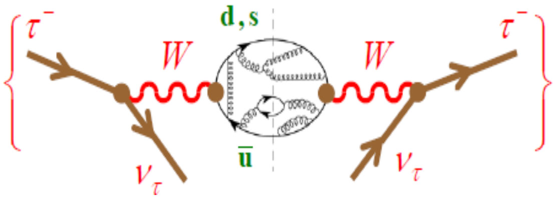
- Determination of V_{us} : $$\frac{|V_{us}|^2}{|V_{ud}|^2} = \frac{R_\tau^S}{R_\tau^{NS}} + O(\alpha_S)$$

- Main difficulty: compute the QCD corrections with the best accuracy

2.5 Calculation of the QCD corrections

- Calculation of R_τ:

$$\Gamma_{\tau\to\nu_\tau+\mathrm{had}} \sim \mathrm{Im}\left\{ \right\}$$



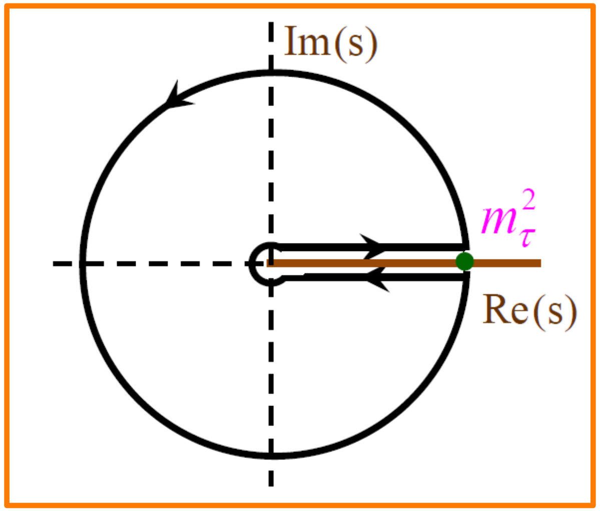
$$R_\tau(m_\tau^2) = 12\pi S_{EW} \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right)\mathrm{Im}\,\Pi^{(1)}(s+i\varepsilon) + \mathrm{Im}\,\Pi^{(0)}(s+i\varepsilon)\right]$$

Braaten, Narison, Pich'92

- Analyticity: Π is analytic in the entire complex plane except for s real positive

⇨ Cauchy Theorem

$$R_\tau(m_\tau^2) = 6i\pi S_{EW} \oint_{|s|=m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right)\Pi^{(1)}(s) + \Pi^{(0)}(s)\right]$$



- We are now at sufficient energy to use OPE:

$$\Pi^{(J)}(s) = \sum_{D=0,2,4\ldots} \frac{1}{(-s)^{D/2}} \sum_{\dim O=D} C^{(J)}(s,\mu)\, \langle O_D(\mu)\rangle$$

Wilson coefficients — Operators

μ: separation scale between short and long distances

2.5 Calculation of the QCD corrections

Braaten, Narison, Pich'92

- Calculation of R_τ:

$$R_\tau\left(m_\tau^2\right) = N_C \; S_{EW} \left(1 + \delta_P + \delta_{NP}\right)$$

- Electroweak corrections: $S_{EW} = 1.0201(3)$ *Marciano &Sirlin'88, Braaten & Li'90, Erler'04*

- Perturbative part (D=0): $\delta_P = a_\tau + 5.20\; a_\tau^2 + 26\; a_\tau^3 + 127\; a_\tau^4 + ... \approx 20\%$ $\qquad a_\tau = \frac{\alpha_s(m_\tau)}{\pi}$

Baikov, Chetyrkin, Kühn'08

- D=2: quark mass corrections, *neglected* for R_τ^{NS} $(\propto m_u, m_d)$ but not for R_τ^{S} $(\propto m_s)$

- D ≥ 4: Non perturbative part, not known, *fitted from the data*
  ⇨ Use of weighted distributions

2.5 Calculation of the QCD corrections

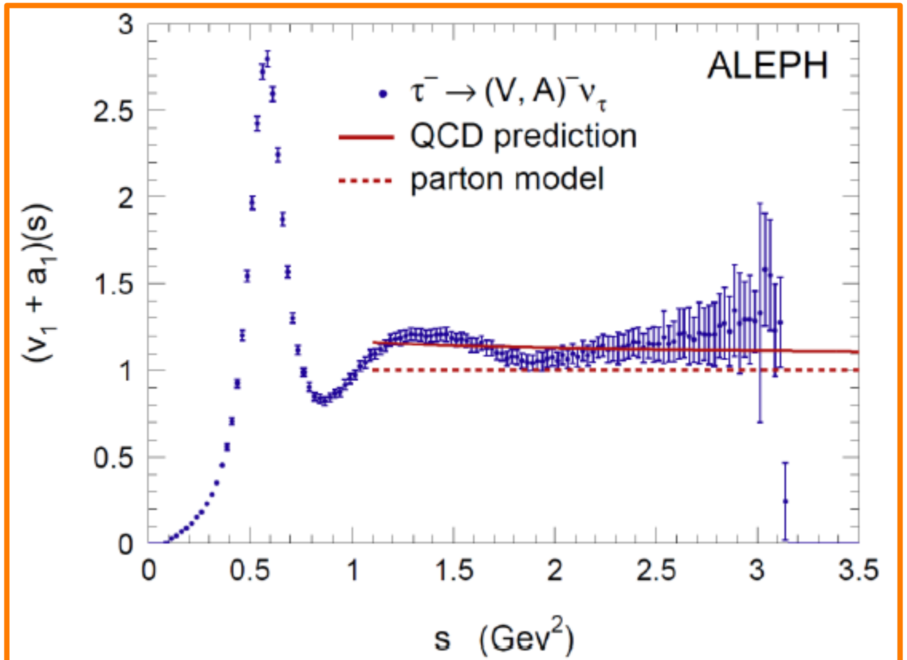
Le Diberder&Pich'92

- D ≥ 4: Non perturbative part, not known, *fitted from the data*

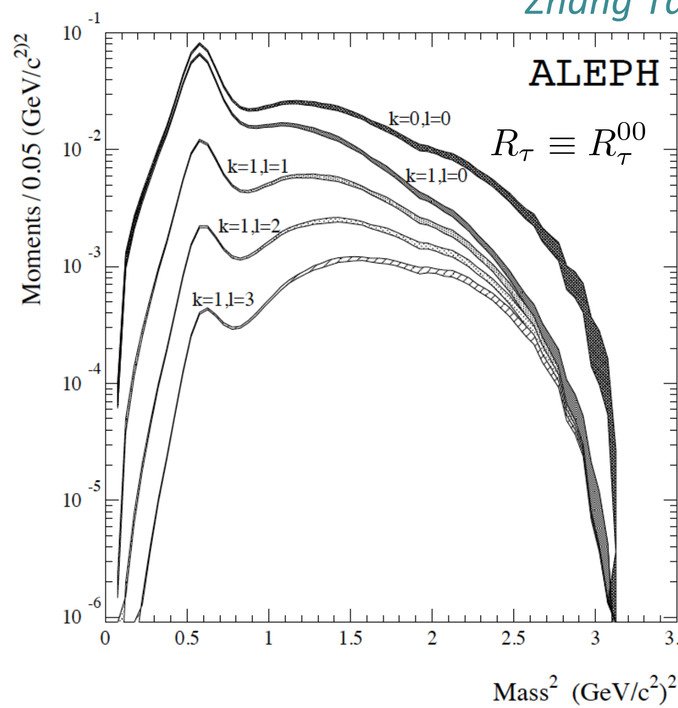
  ⇒ Use of weighted distributions

Exploit shape of the spectral functions to obtain additional experimental information

$$R^{k\ell}_{\tau,U}(s_0) = \int_0^{s_0} ds \left(1 - \frac{s}{s_0}\right)^k \left(\frac{s}{s_0}\right)^\ell \frac{dR_{\tau,U}(s_0)}{ds}$$



Zhang'Tau14



2.5 Inclusive determination of V_{us}

- With QCD on: $$\frac{|V_{us}|^2}{|V_{ud}|^2} = \frac{R_\tau^S}{R_\tau^{NS}} + O(\alpha_s)$$

- Use OPE: $$R_\tau^{NS}(m_\tau^2) = N_C\, S_{EW} |V_{ud}|^2 \left(1 + \delta_P + \delta_{NP}^{ud}\right)$$

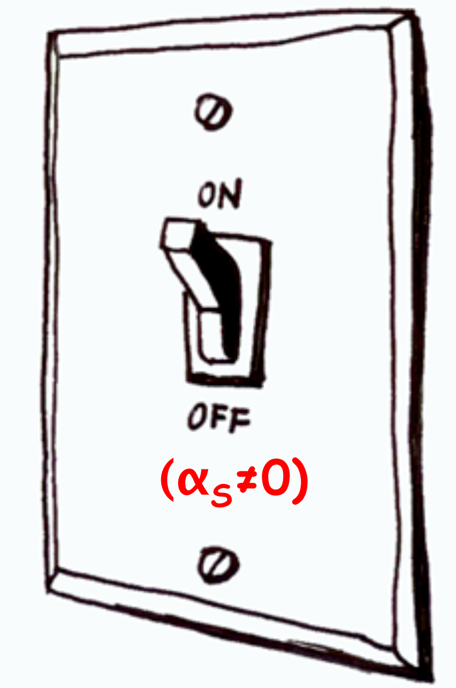
$$R_\tau^{S}(m_\tau^2) = N_C\, S_{EW} |V_{us}|^2 \left(1 + \delta_P + \delta_{NP}^{us}\right)$$

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

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*

QCD switch



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

HFAG'17

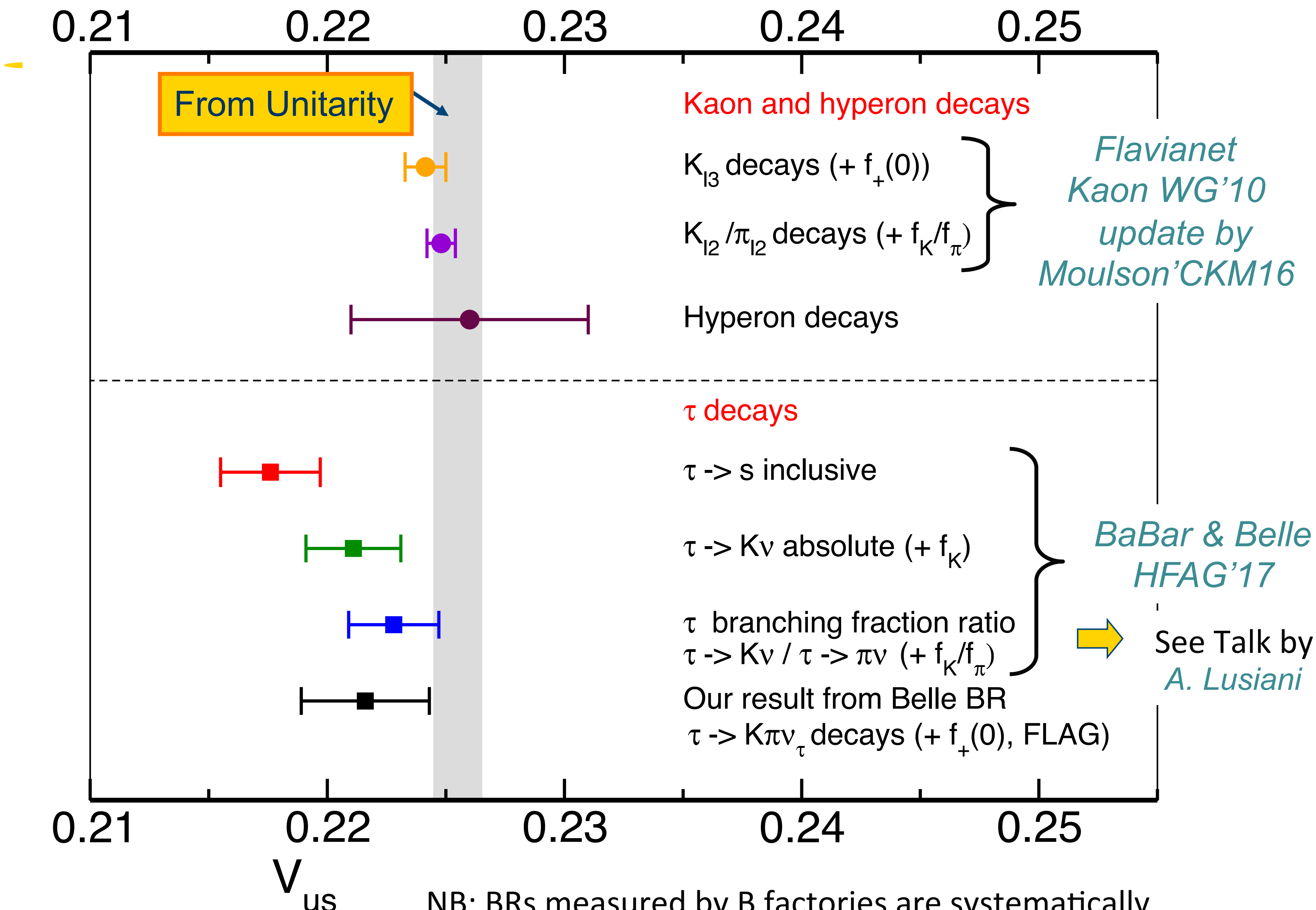
$$R_{\tau,S} = 0.1633(28)$$

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

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

⇒ $$|V_{us}| = 0.2186 \pm 0.0019_{\text{exp}} \pm 0.0010_{\text{th}}$$

3.1σ away from unitarity!



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

2.6 V_{us} using info on Kaon decays and $\tau \to K\pi\nu_\tau$

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

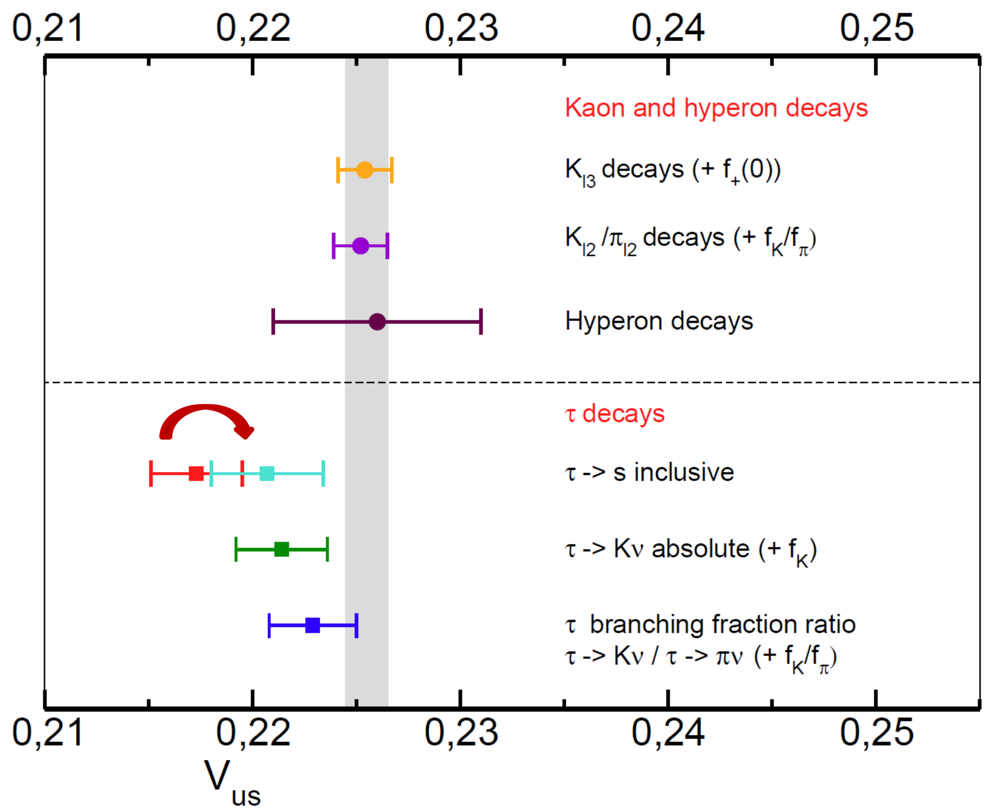
Branching fraction	HFAG Winter 2012 fit	
$\Gamma_{10} = K^-\nu_\tau$	$(0.6955 \pm 0.0096) \cdot 10^{-2}$	→ **(0.713 ± 0.003)%**
$\Gamma_{16} = K^-\pi^0\nu_\tau$	$(0.4322 \pm 0.0149) \cdot 10^{-2}$	→ **(0.471 ± 0.018)%**
$\Gamma_{23} = K^-2\pi^0\nu_\tau$ (ex. K^0)	$(0.0630 \pm 0.0222) \cdot 10^{-2}$	
$\Gamma_{28} = K^-3\pi^0\nu_\tau$ (ex. K^0, η)	$(0.0419 \pm 0.0218) \cdot 10^{-2}$	
$\Gamma_{35} = \pi^-\bar{K}^0\nu_\tau$	$(0.8206 \pm 0.0182) \cdot 10^{-2}$	→ **(0.857 ± 0.030)%**
$\Gamma_{110} = X_s^-\nu_\tau$	$(2.8746 \pm 0.0498) \cdot 10^{-2}$	→ **(2.967 ± 0.060)%**

- Longstanding inconsistencies between τ and kaon decays in extraction of V_{us} seem to have been resolved !
  R. Hudspith, R. Lewis, K. Maltman, J. Zanotti'17

- Crucial input:
  $\tau \to K\pi\nu_\tau$ Br + spectrum

$$|V_{us}| = 0.2229 \pm 0.0022_{exp} \pm 0.0004_{theo}$$

⇒ need new data



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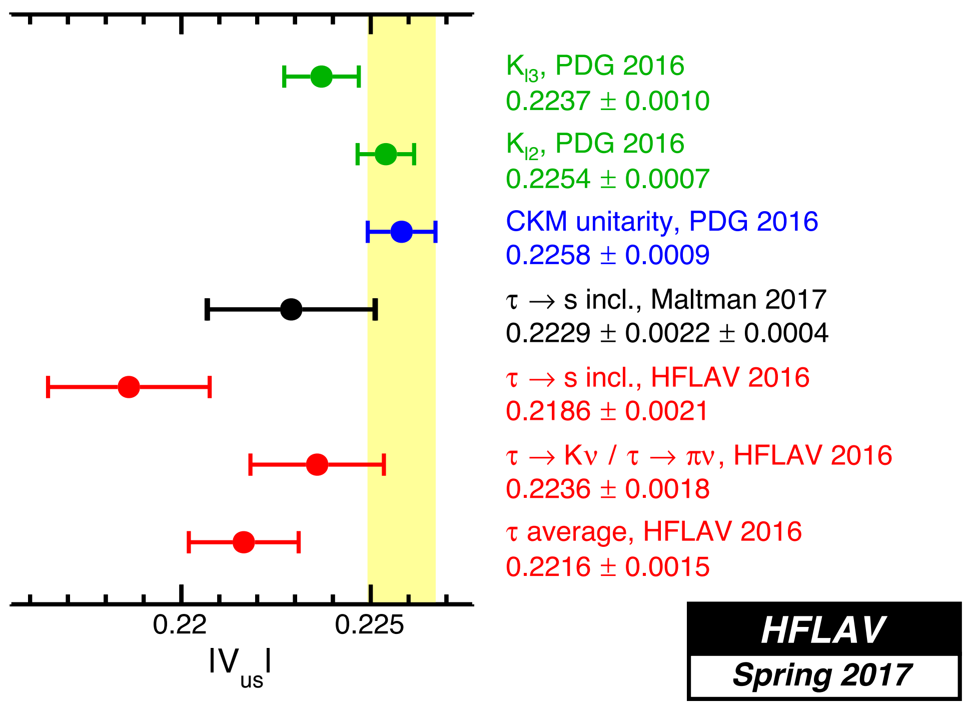


➡ need new data

Very good prospect from Belle II, BES?

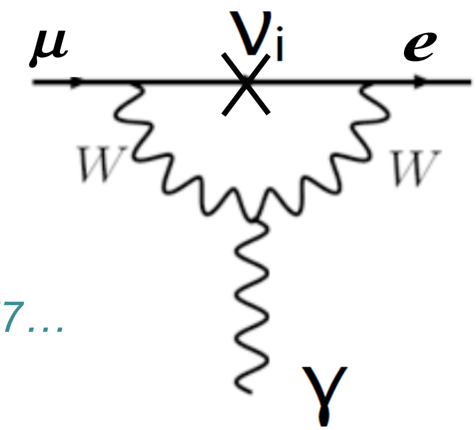
3. Charged Lepton-Flavour Violation

3.1 Tau LFV

- 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.: $\mu \to e\gamma$

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



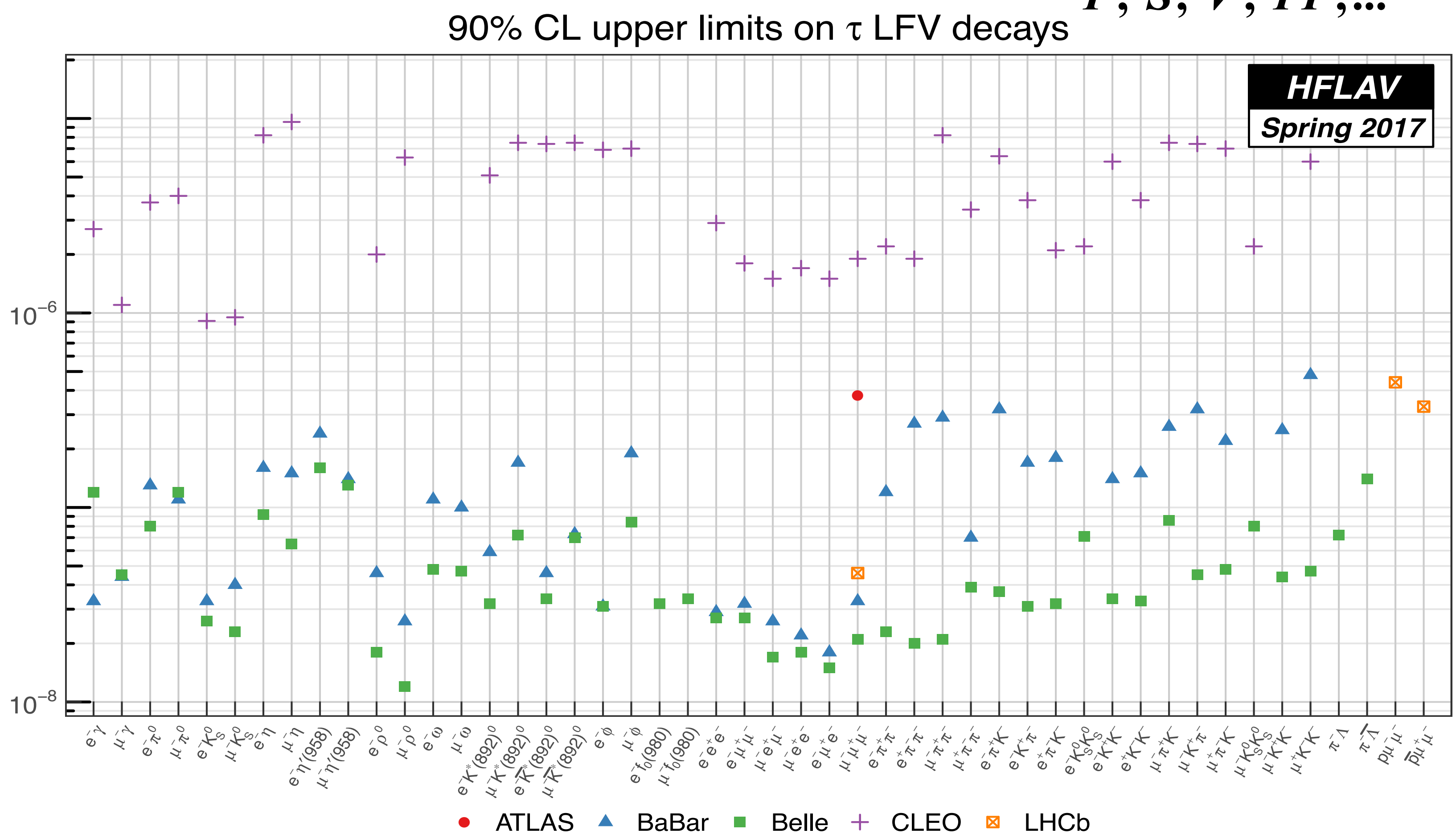
Petcov'77, Marciano & Sanda'77, Lee & Shrock'77…

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

- Extremely *clean probe of beyond SM physics* ⇒ See Talk by *A. De Gouvea*
- In New Physics models: seazible effects
  Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic

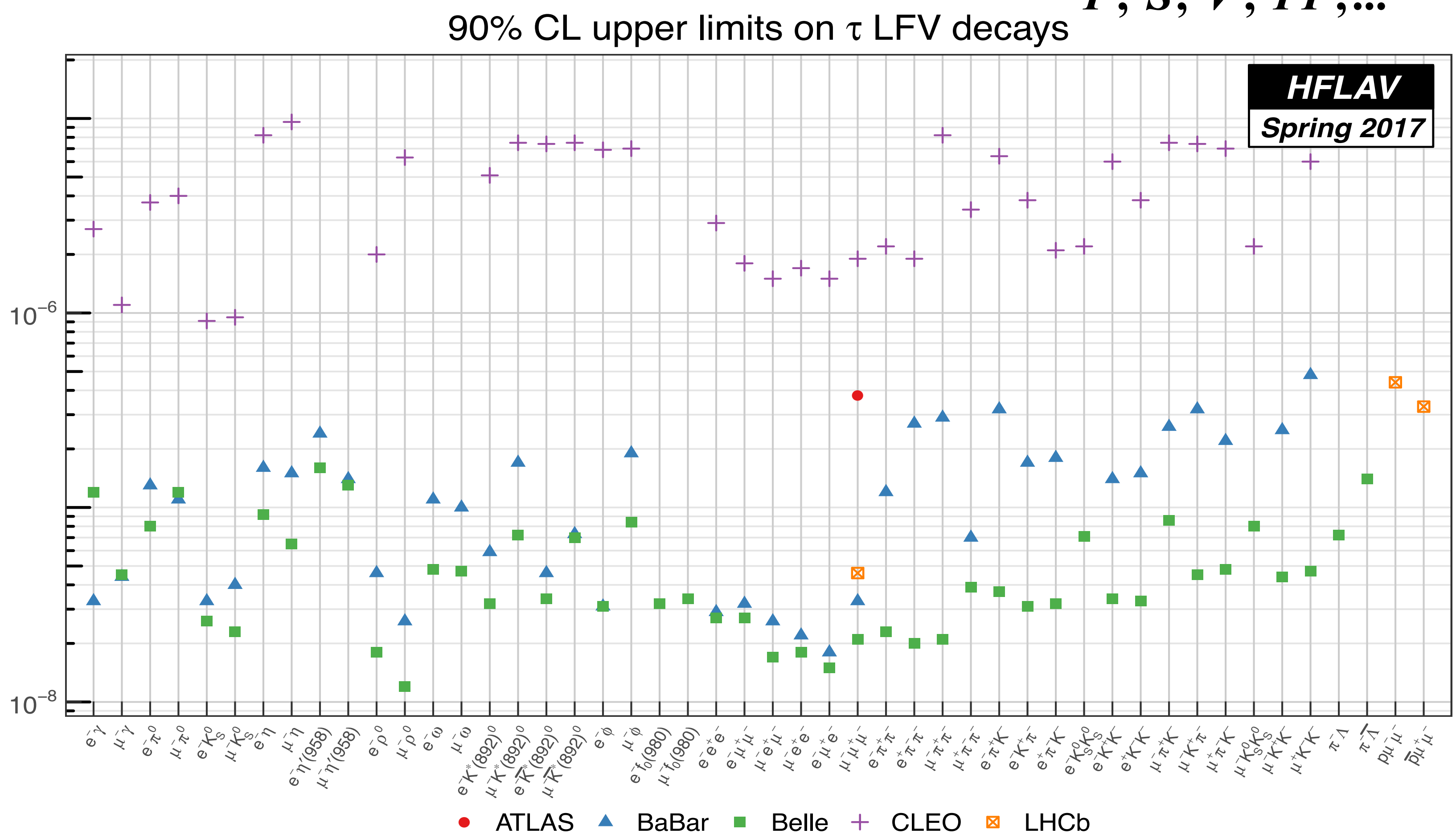
3.2 Tau LFV

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

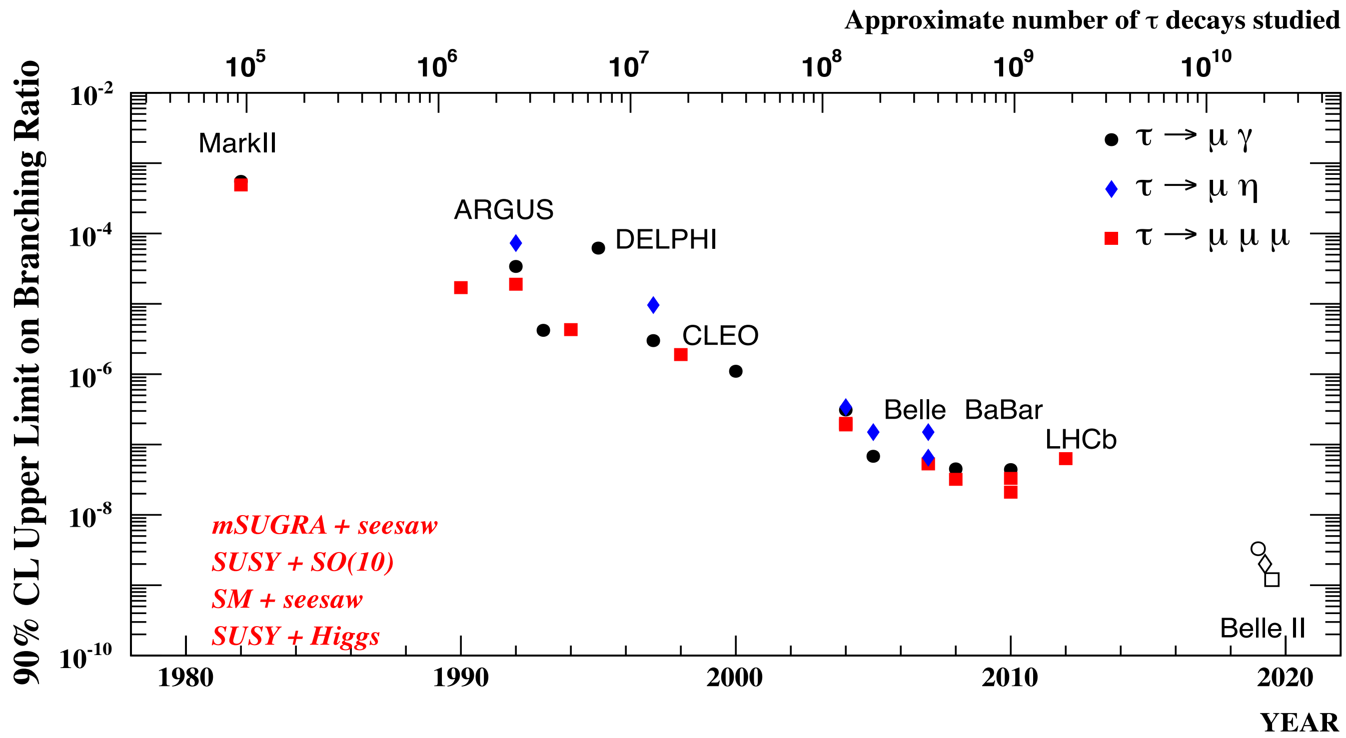


- 48 LFV modes studied at Belle and BaBar

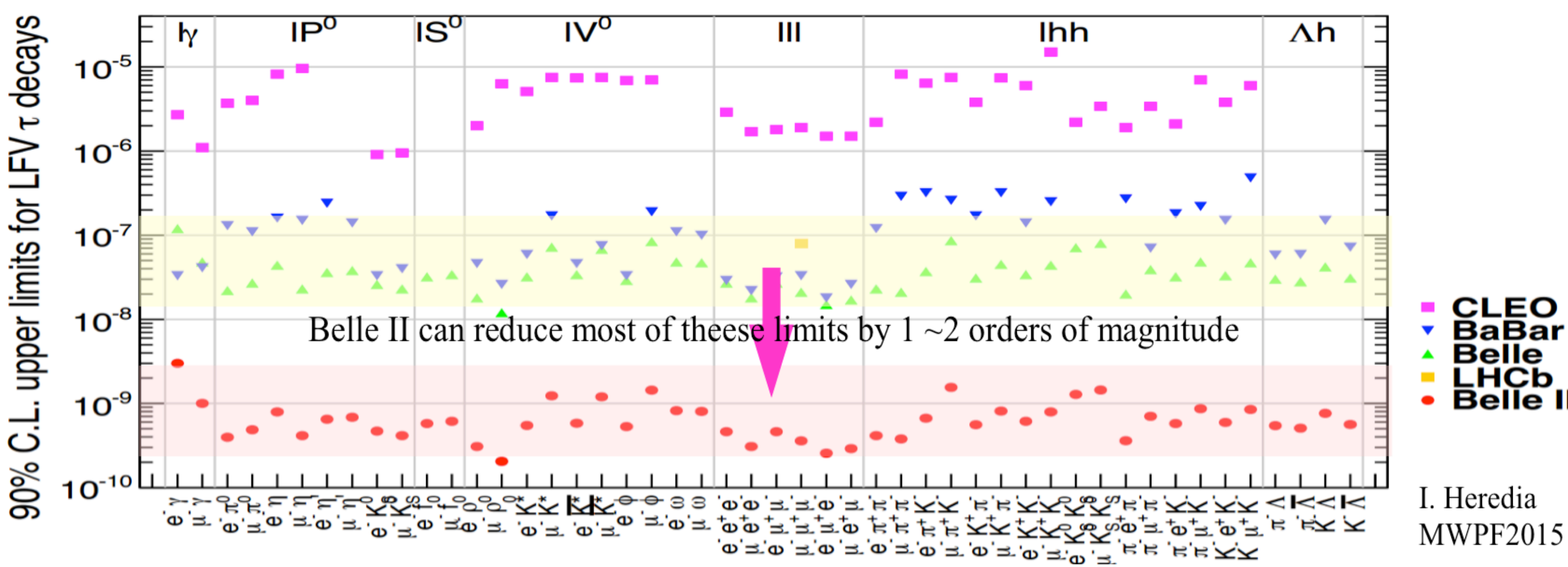
- Several processes: $\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y$ ↖ $P,\ S,\ V,\ P\bar{P}, \ldots$



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



S. Banerjee'17



I. Heredia
MWPF2015

3.3 Effective Field Theory approach

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

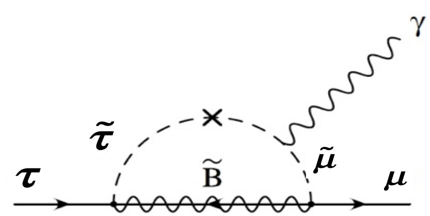
See e.g.
Black, Han, He, Sher'02
Brignole & Rossi'04
Dassinger et al.'07
Matsuzaki & Sanda'08
Giffels et al.'08
Crivellin, Najjari, Rosiek'13
Petrov & Zhuridov'14
Cirigliano, Celis, E.P.'14

- Build all D>5 LFV operators:

  - Dipole:

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

e.g.



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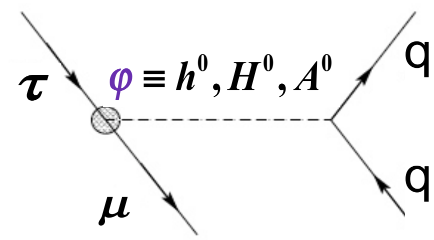
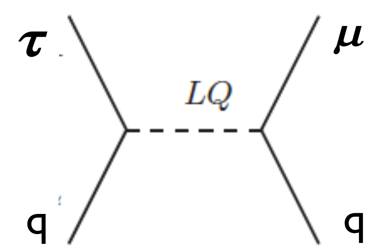
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):

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

e.g.



$\Gamma \equiv 1$



$\Gamma \equiv \gamma^\mu$

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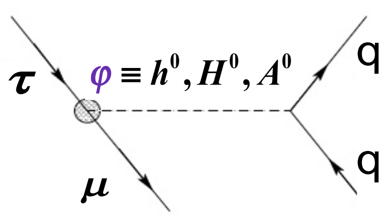
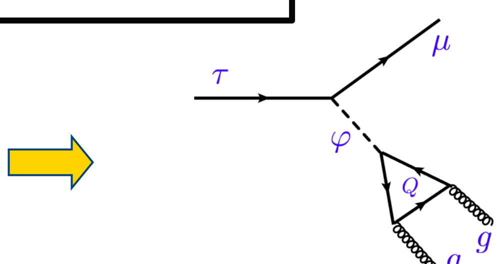
  - Integrating out heavy quarks generates *gluonic operator*

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

.





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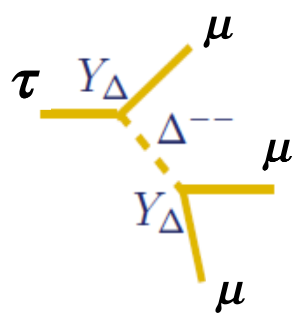
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu}\, \Gamma P_{L,R} \tau\, \bar{\mu}\, \Gamma P_{L,R} \mu$

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

e.g.



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

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

3.4 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)
$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

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

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

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Celis, Cirigliano, E.P.'14

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$O_{S,V}^{4\ell}$	✓	–	–	–	–	–
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, $f_{\eta'}$)

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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

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

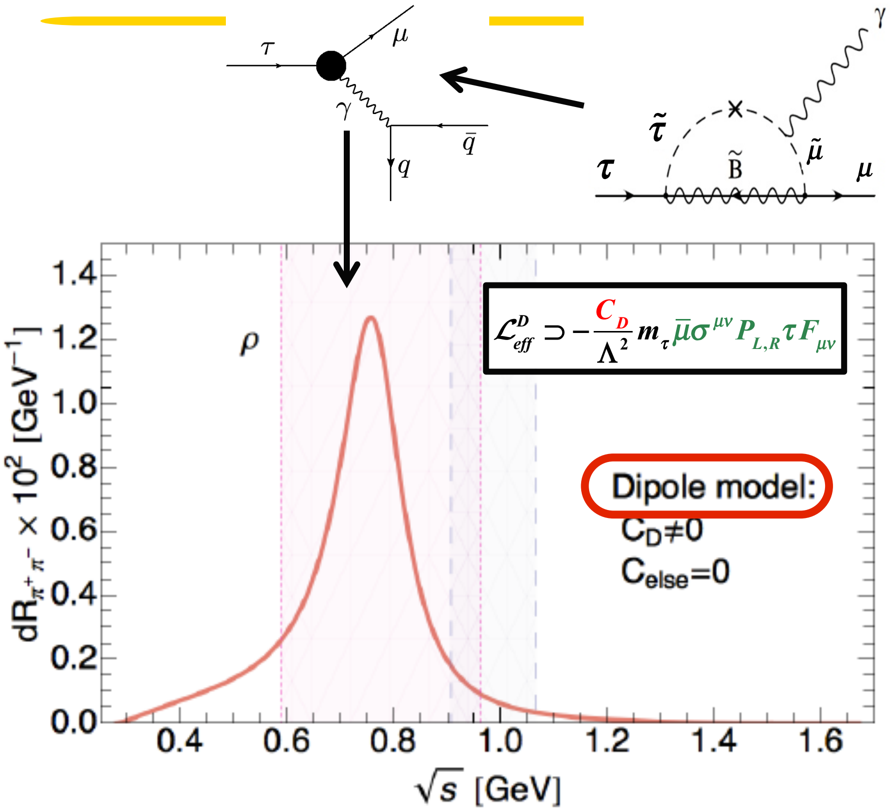
- 2-channel unitarity condition is solved with I=0 S-wave ππ and KK scattering data as input

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

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

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

Celis, Cirigliano, E.P.'14



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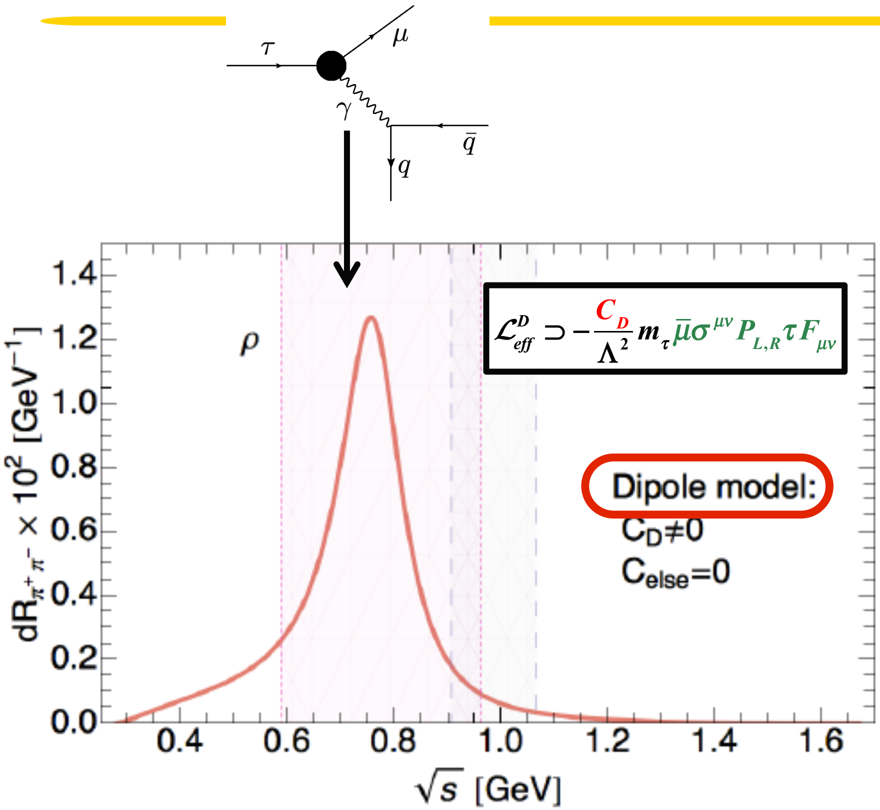
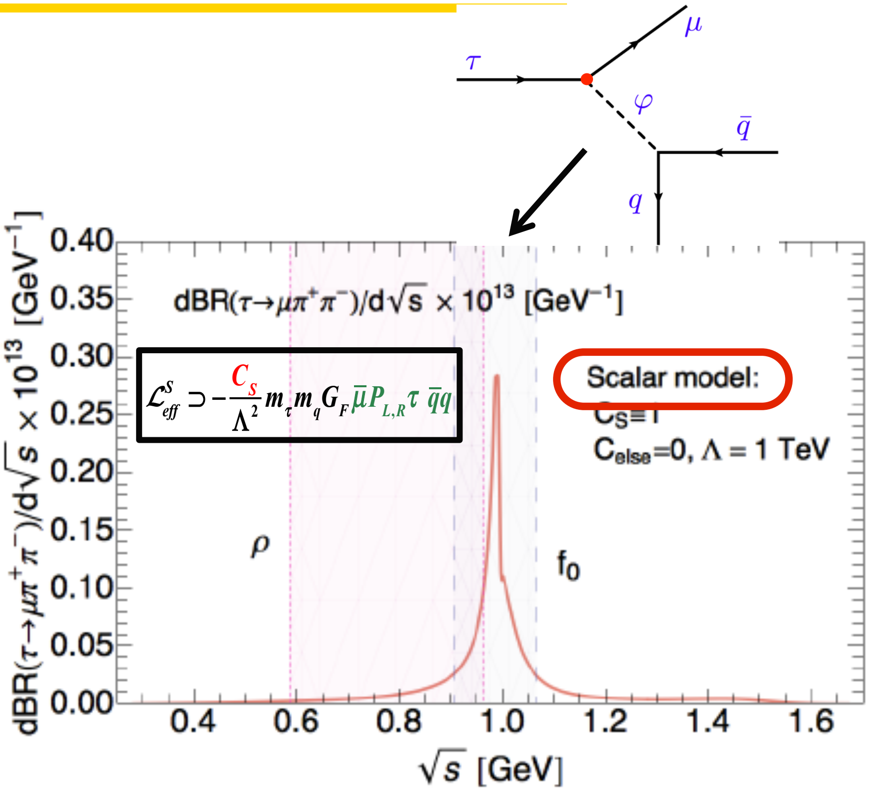
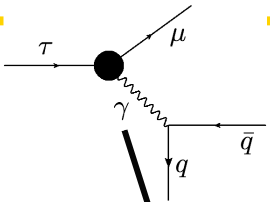
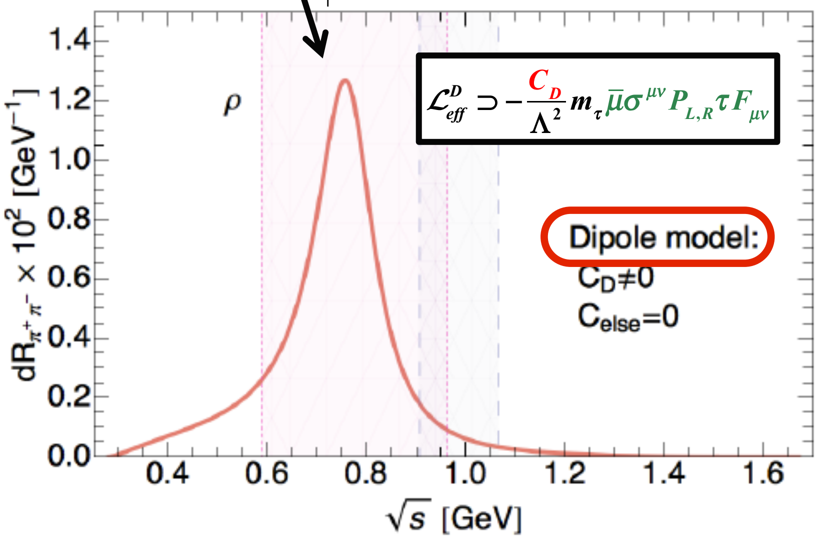
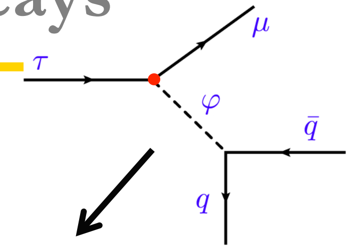


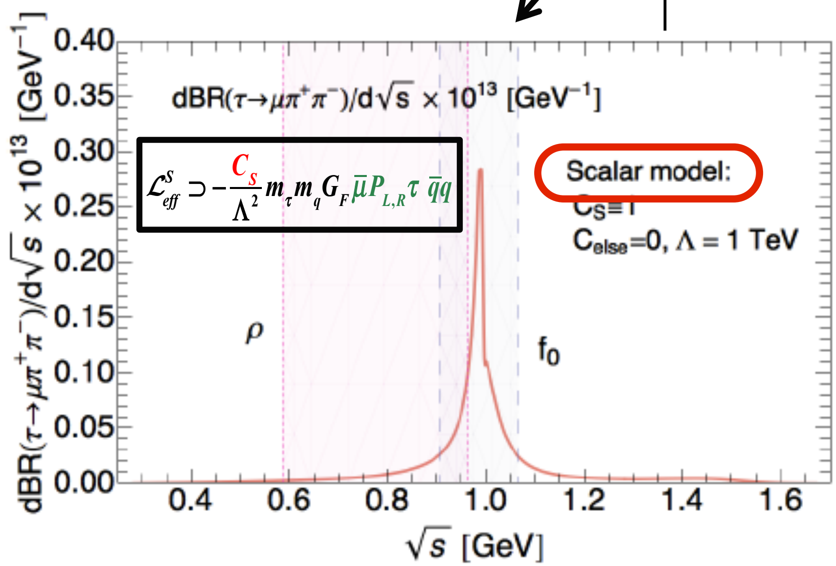


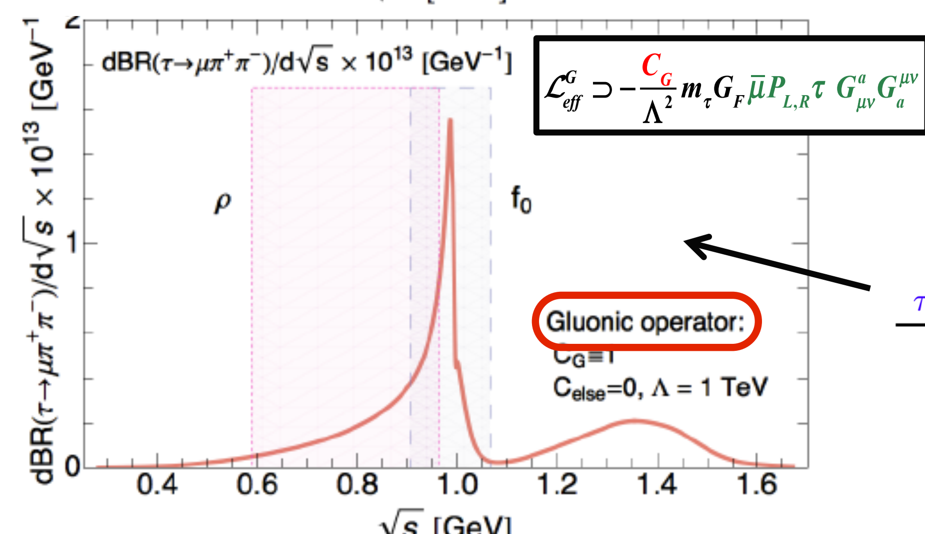
3.5 Discriminating power of $\tau \to \mu(e)\pi\pi$ decays



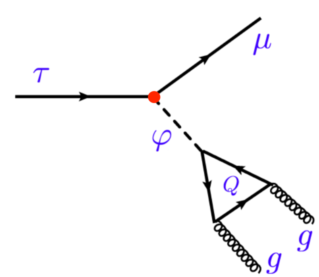








Different distributions according to the *operator!*



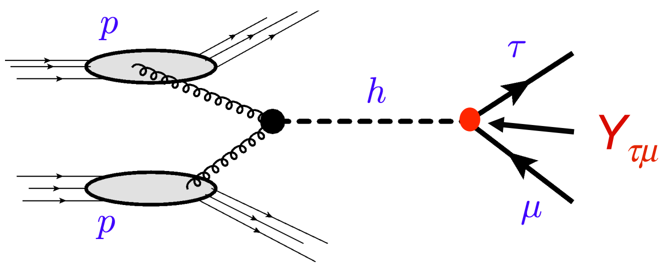
3.6 Non standard LFV Higgs coupling

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

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

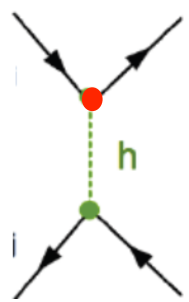
In the SM: $Y_{ij}^{h_{SM}} = \frac{m_i}{v}\delta_{ij}$

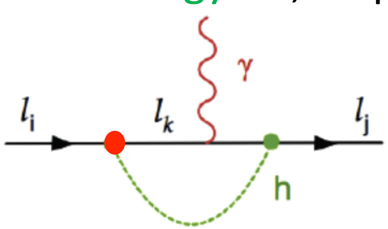
- High energy : LHC

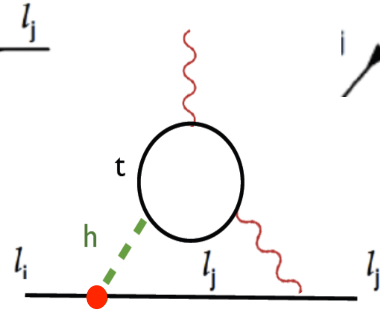


Hadronic part treated with perturbative QCD

- Low energy : D, S operators







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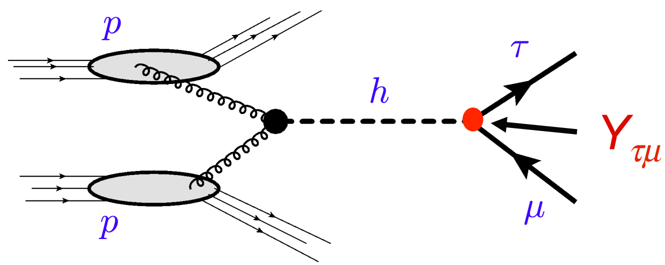
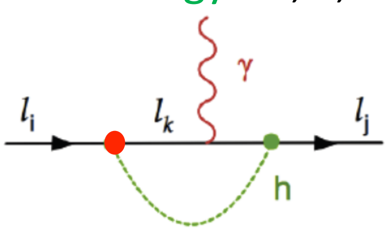
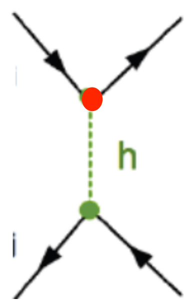


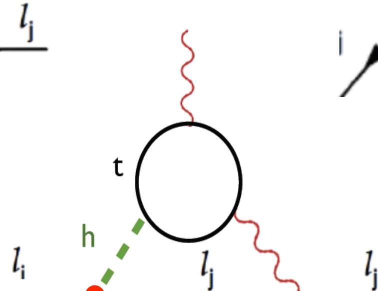
Hadronic part treated with perturbative QCD

Reverse the process

- Low energy : D, S, G operators







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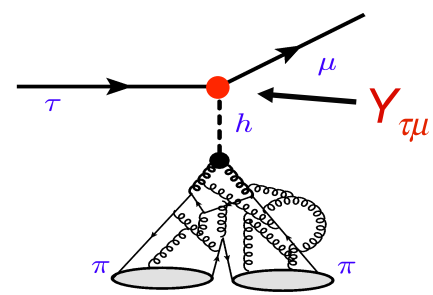


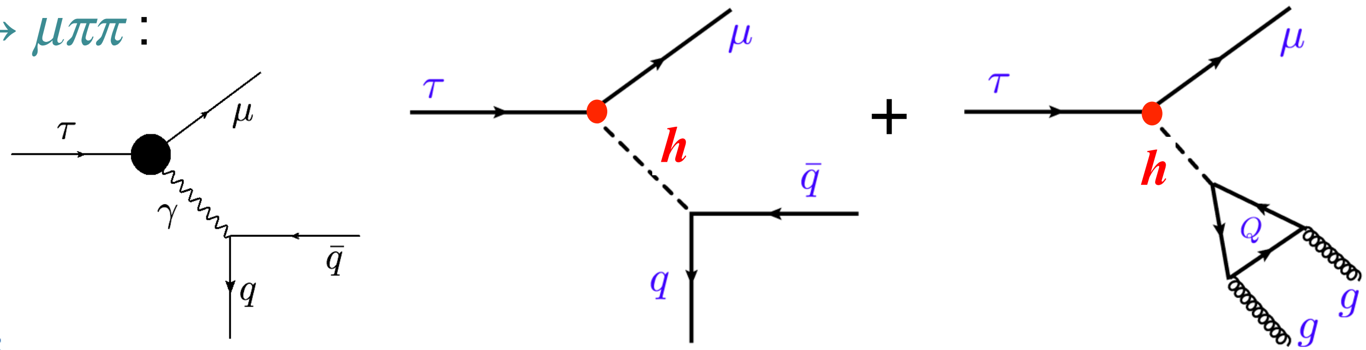
Hadronic part treated with non-perturbative QCD

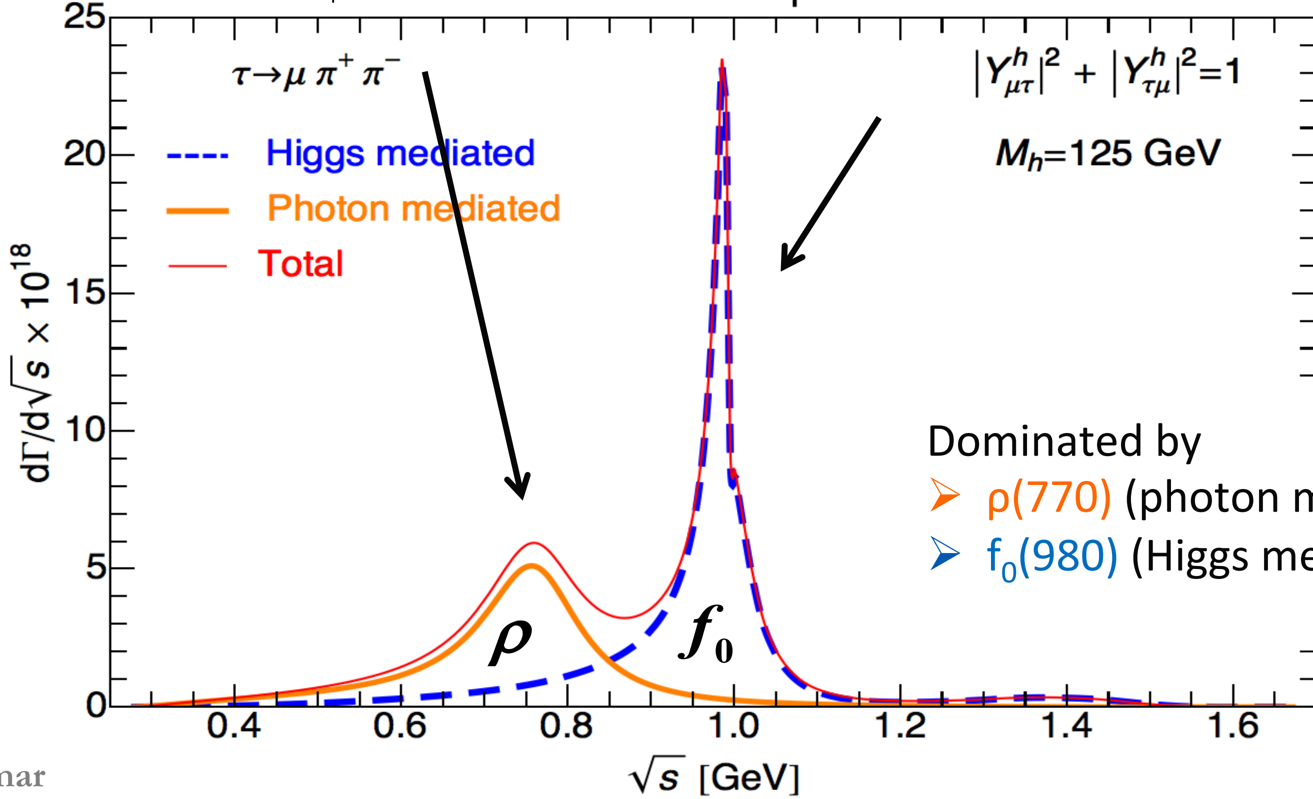
Constraints in the τμ sector

- At low energy

Cirigliano, Celis, E.P.'14

  - $\tau \to \mu\pi\pi$:

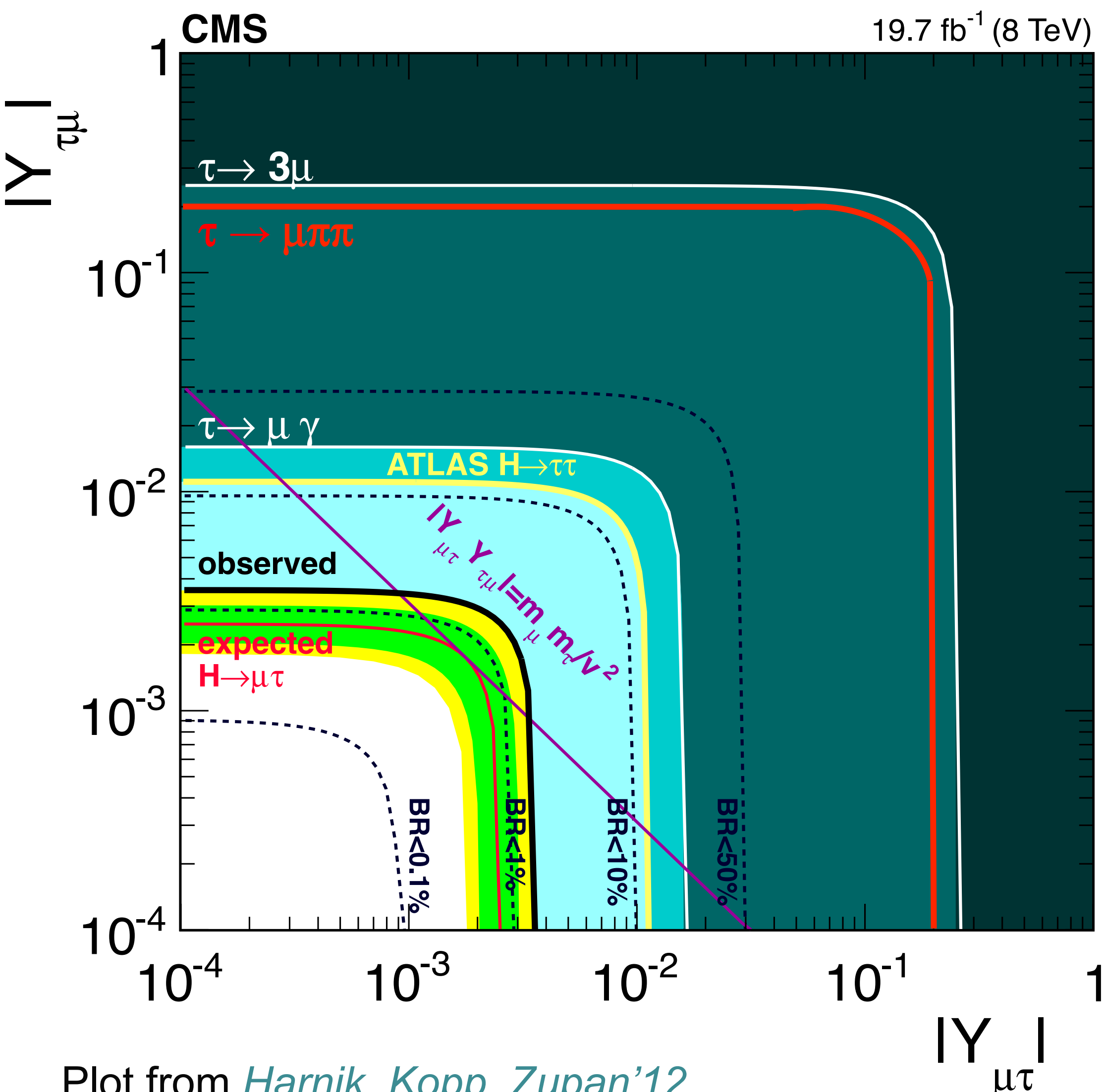




Dominated by

- 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

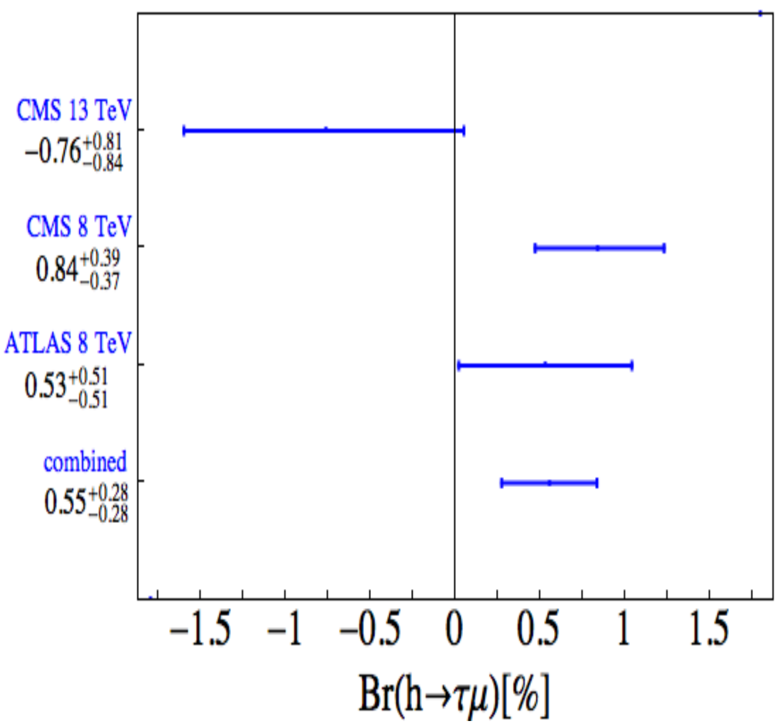
⇨

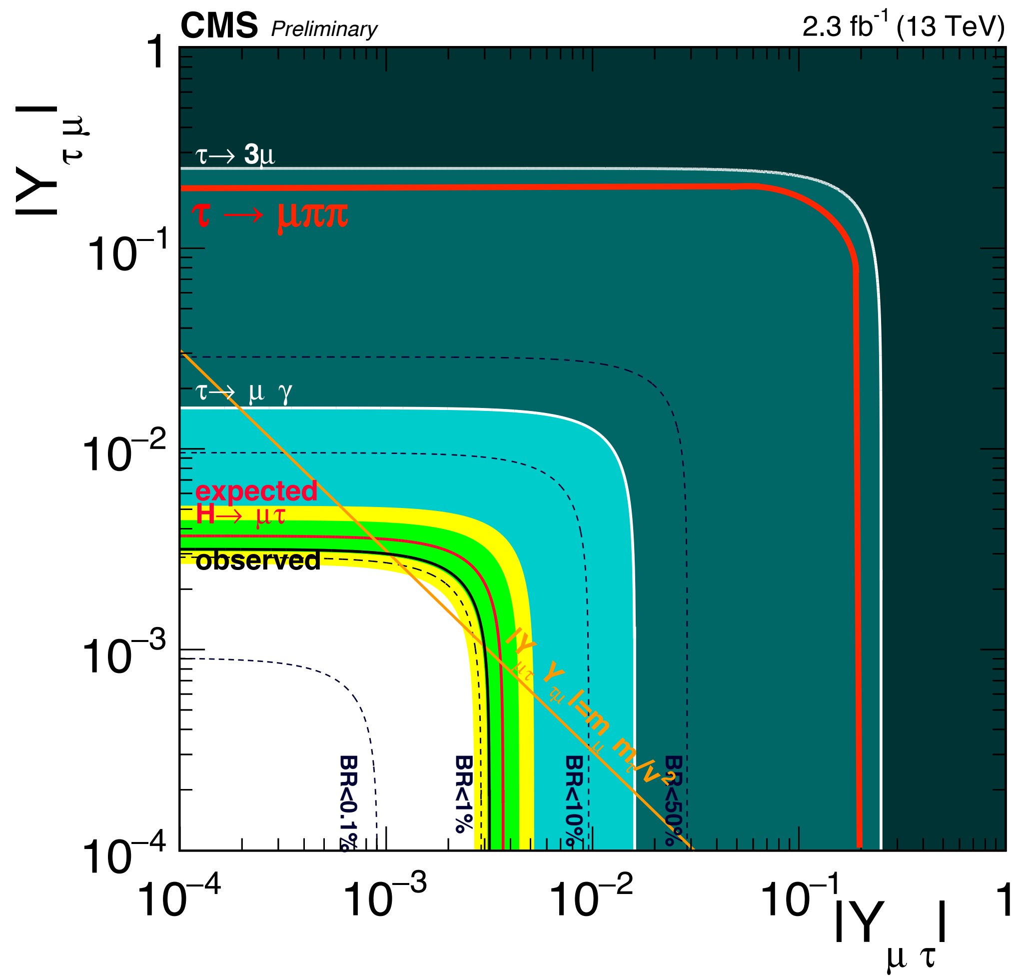
$$BR(\tau \to \mu\gamma) < 2.2\times10^{-9}$$

$$BR(\tau \to \mu\pi\pi) < 1.5\times10^{-11}$$

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

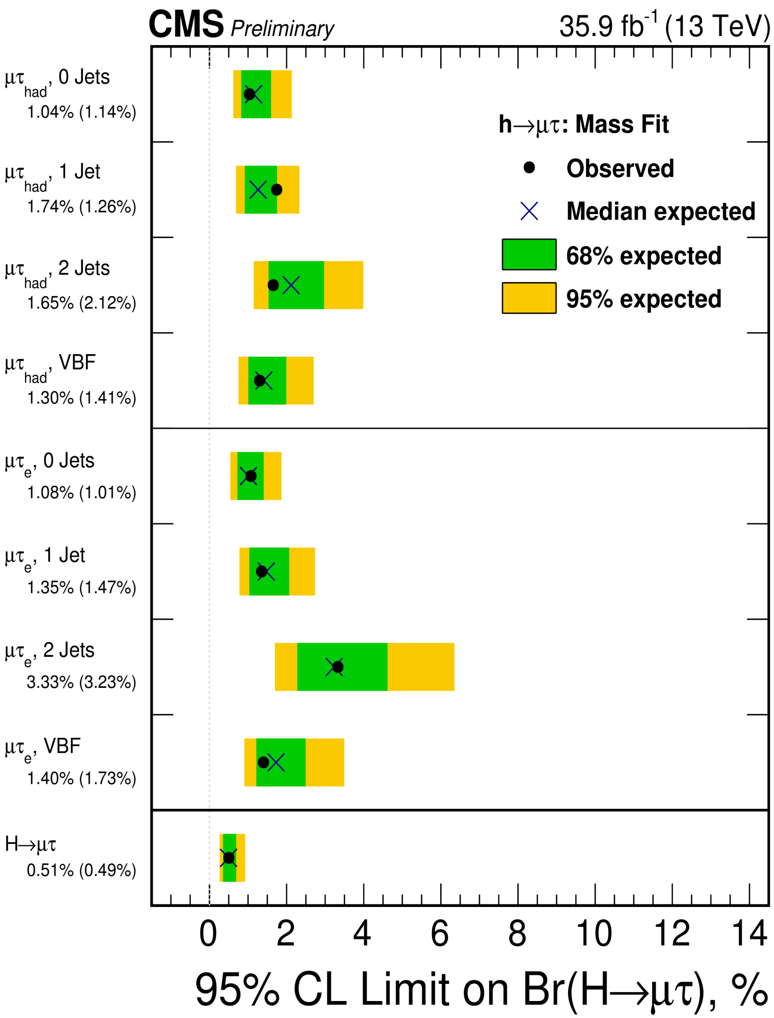
CMS'16

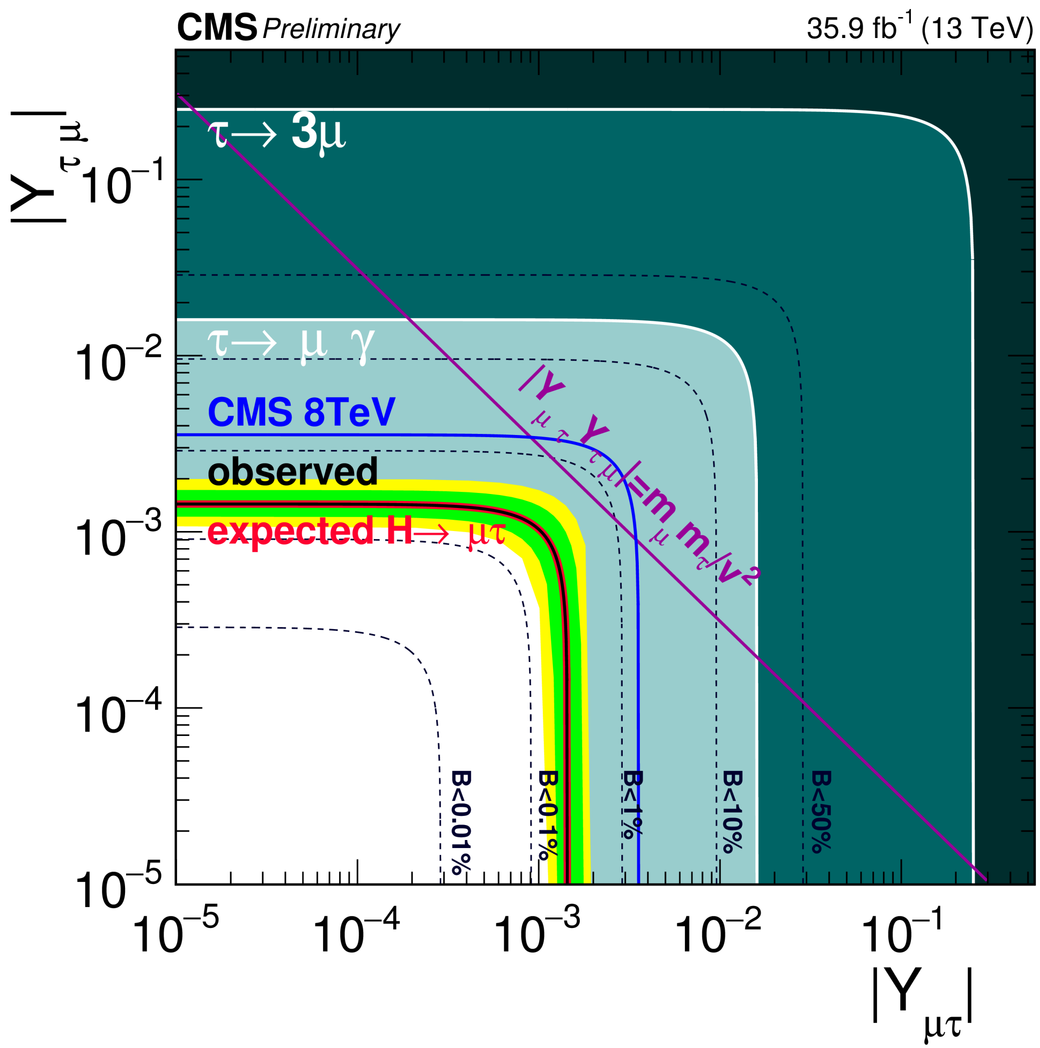




Hint of New Physics in h → τμ?

CMS'17





4. Conclusion and outlook

4.1 Conclusion

- Tau physics is a very rich field: test QCD and EW, neutrino physics, etc..
- Several interesting anomalies: LFU, V_{us}, Higgs LFV, CPV in $\tau \to K\pi\nu_\tau$, g-2
- Important experimental activities: Belle, BaBar, LHCb, BESIII, VEPP
- Intense theoretical activities : QCD, new physics
- A lot of *very interesting physics* remains to be done in the tau sector!

4.2 Outlook

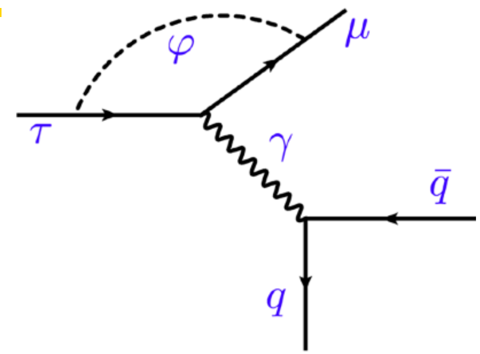
- 45 billion $\tau^+\tau^-$ pairs in full dataset from $\sigma(\tau^+\tau^-)_{E=\Upsilon(4S)}$= 0.9 nb *@Belle II*
- B2TiP initiative: define the first set of measurements to be performed at *Belle II*
  https://confluence.desy.de/display/BI/B2TiP+WebHome
- *Golden/Silver modes* for the Tau, Low Multiplicity and EW working group

	Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb/BESIII	vs Belle	Anomaly	NP
● (gold)	$\tau \to \mu\gamma$	$Br.$	⋆⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
● (gold)	$\tau \to lll$	$Br.$	⋆⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
● (gold)	$\tau \to K\pi\nu$	$A_{\rm CP}$	⋆⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆
● (gold)	$e^+e^- \to \gamma A'(\to\text{invisible})$	σ	⋆⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
● (gold)	$e^+e^- \to \gamma A'(\to \ell^+\ell^-)$	σ	⋆⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
● (silver)	π form factor	$g-2$	⋆⋆	-	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆⋆
● (silver)	ISR $e^+e^- \to \pi\pi$ g-2	$g-2$	⋆⋆	-	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆

5. Back-up

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

- Photon mediated contribution requires the pion vector form factor:

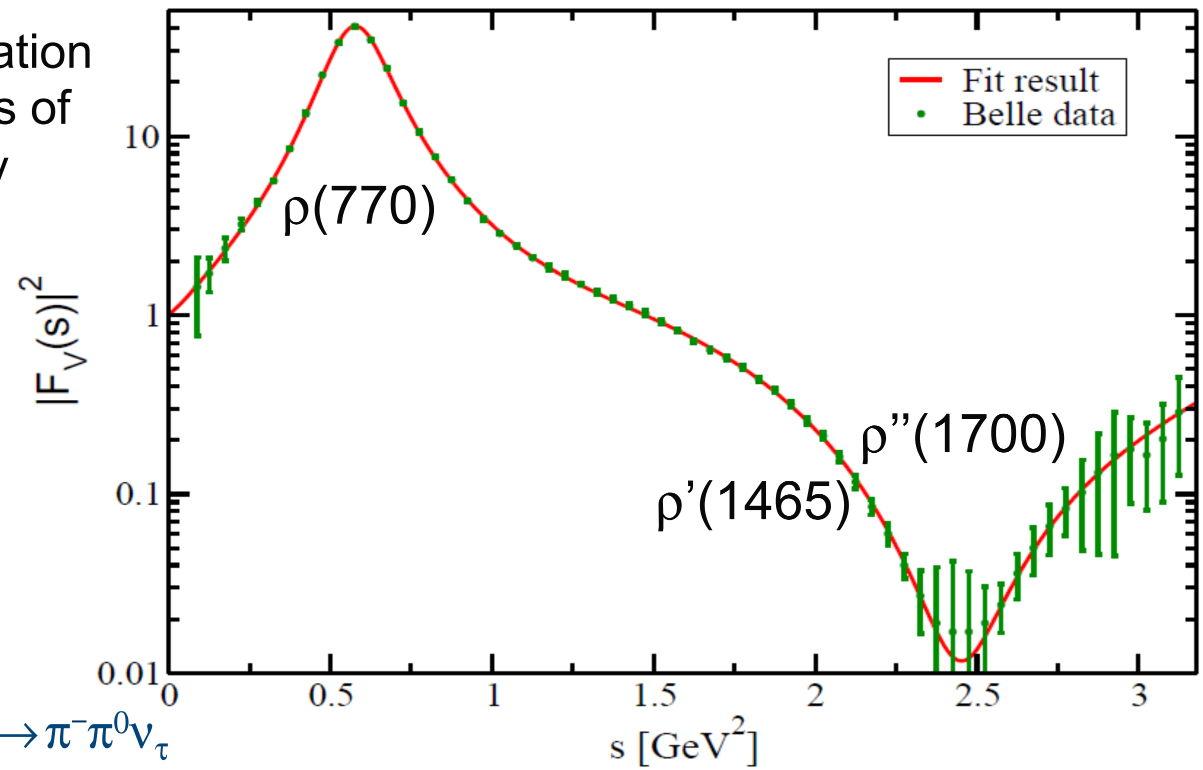


$$\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-}) | \tfrac{1}{2}(\bar{u}\gamma^\alpha u - \bar{d}\gamma^\alpha d) | 0 \rangle \equiv F_V(s)(p_{\pi^+} - p_{\pi^-})^\alpha$$

- 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 $F_V(s)$

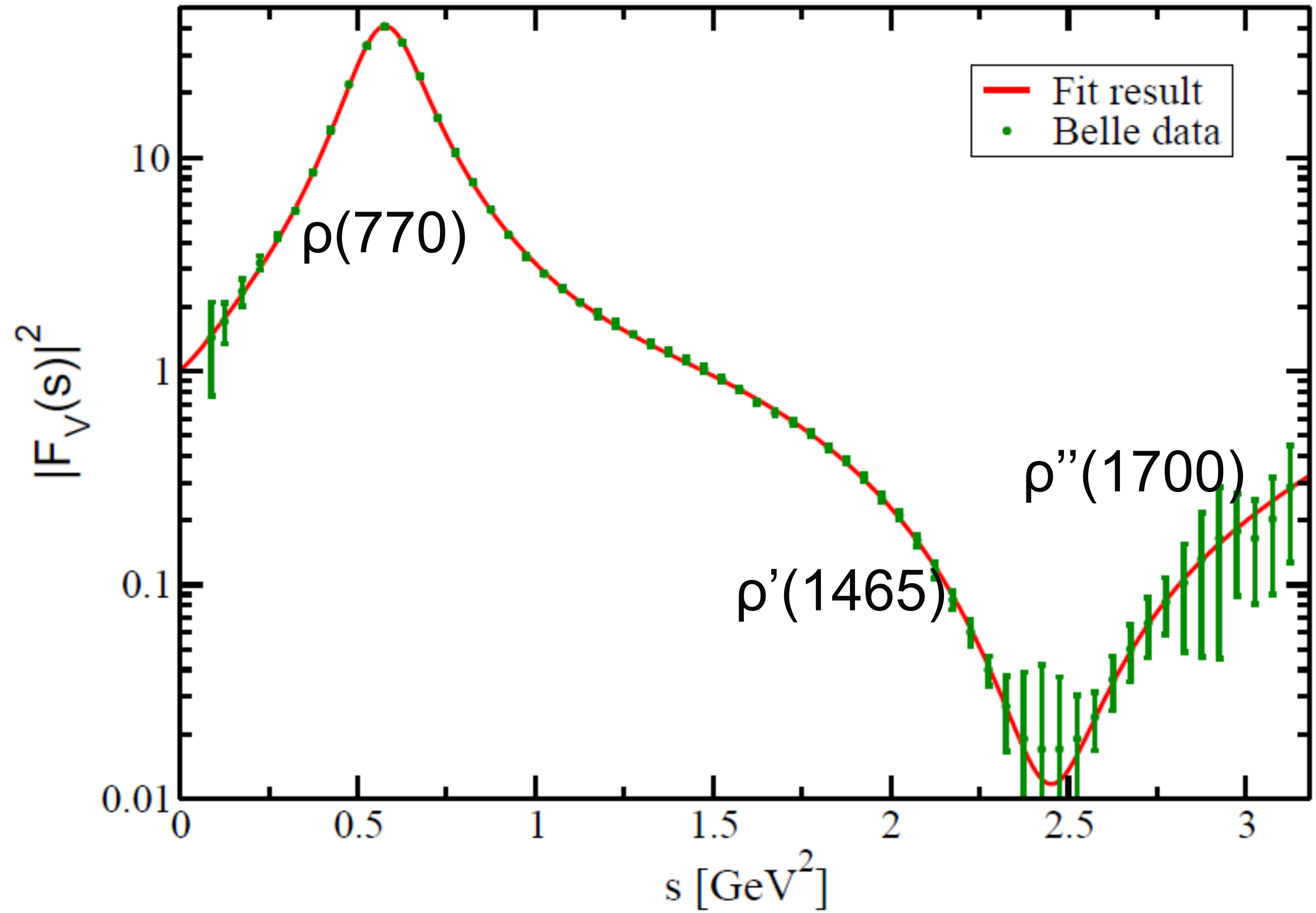
Guerrero, Pich'98, Pich, Portolés'08
Gomez, Roig'13

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

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

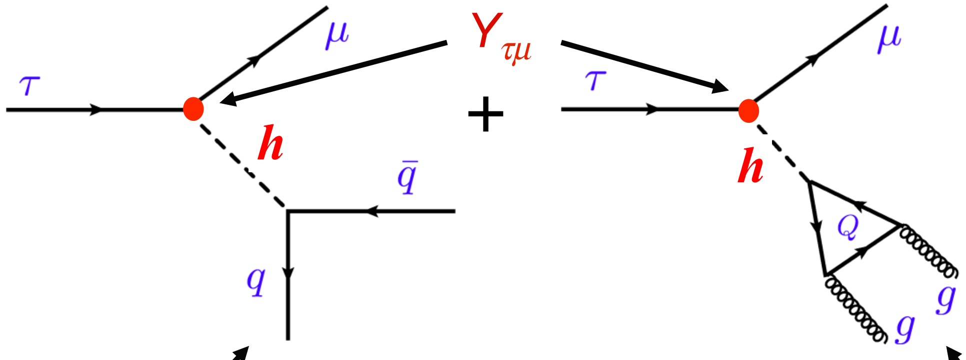
Determination of $F_V(s)$

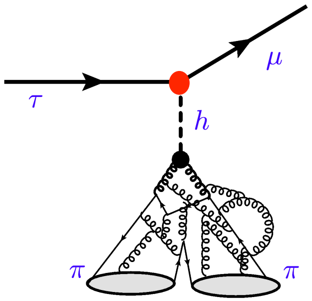


Determination of $F_V(s)$ thanks to precise measurements from Belle!

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

- Tree level Higgs exchange





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

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

Voloshin'85

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

$$\theta_\mu^\mu = -9\frac{\alpha_s}{8\pi} G_{\mu\nu}^a G_a^{\mu\nu} + \sum_{q=u,d,s} m_q \bar{q}q$$

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

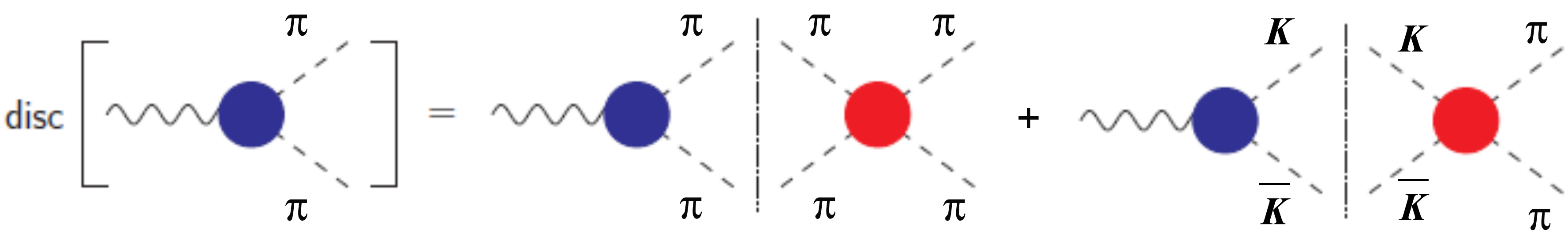
$$f\left(y_q^h\right)$$

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 $\sqrt{s}\sim 1.4$ GeV
  Inputs: I=0, S-wave $\pi\pi$ and KK data

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

- Unitarity:



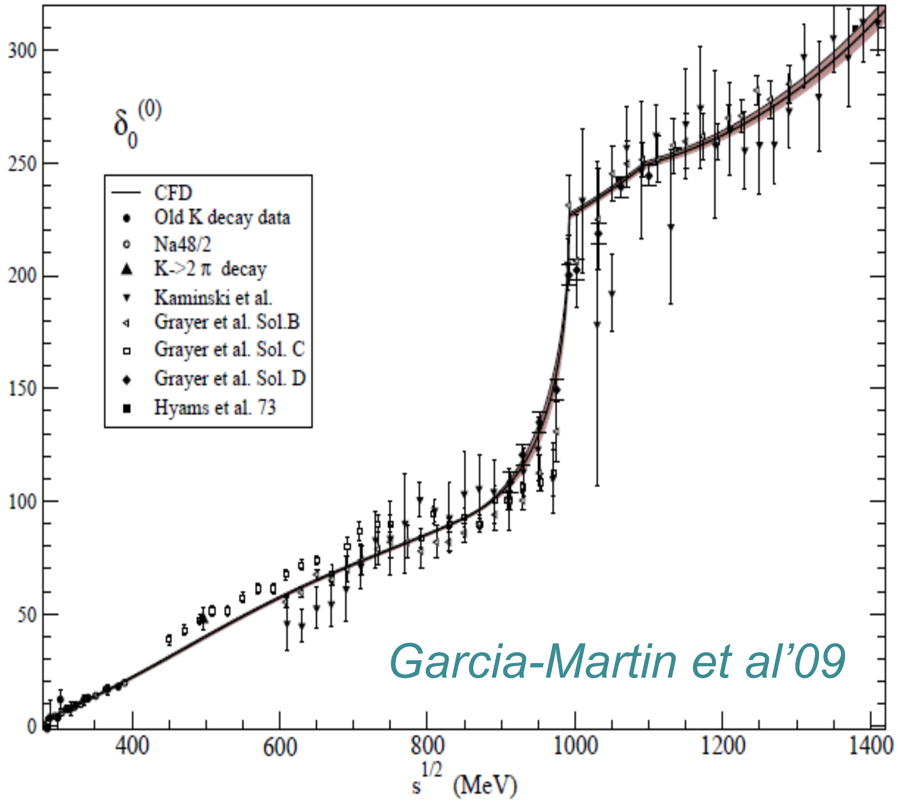
⇨
$$\mathrm{Im}F_n(s) = \sum_{m=1}^{2} T^*_{nm}(s)\sigma_m(s)F_m(s)$$

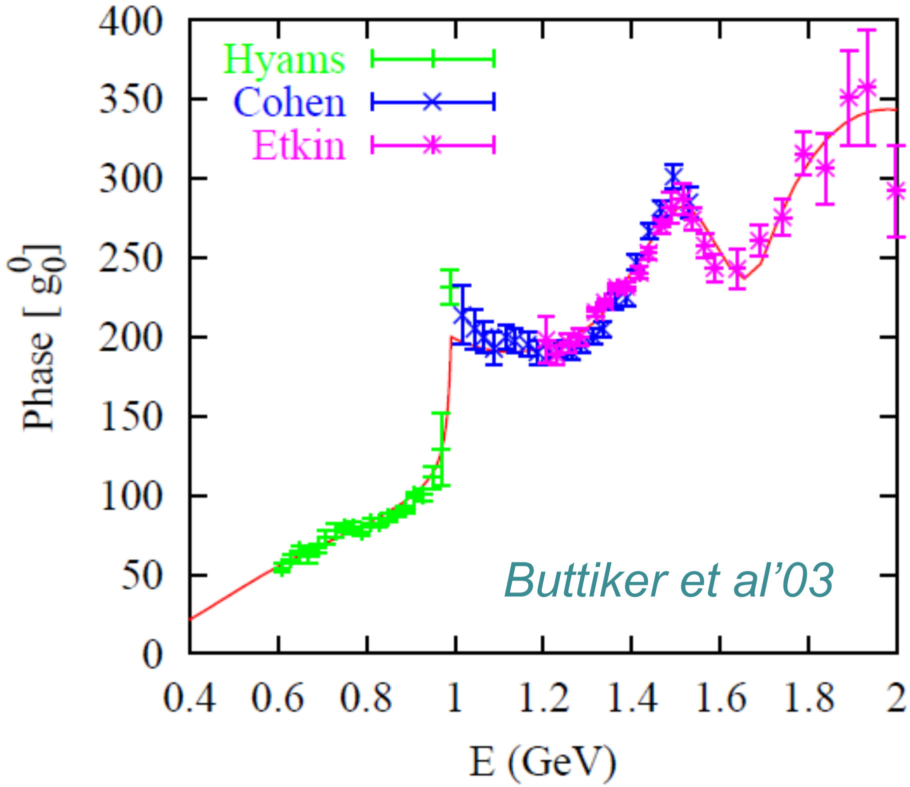
$$n = \pi\pi, K\bar{K}$$

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:

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

Canonical solution

Polynomial determined from a matching to ChPT + lattice

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

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

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

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:

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

$\Rightarrow$

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

- Problem: large corrections in the case of the kaons!

  $\Rightarrow$ Use lattice QCD to determine the SU(3) LECs

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

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

Dreiner, Hanart, Kubis, Meissner'13

Bernard, Descotes-Genon, Toucas'12

Determination of the polynomial

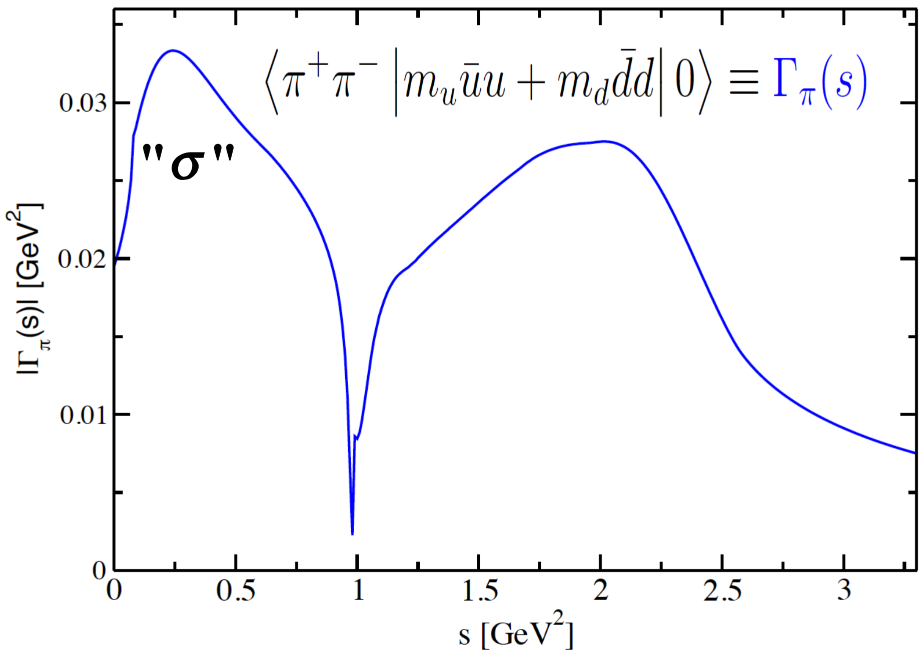
- General solution

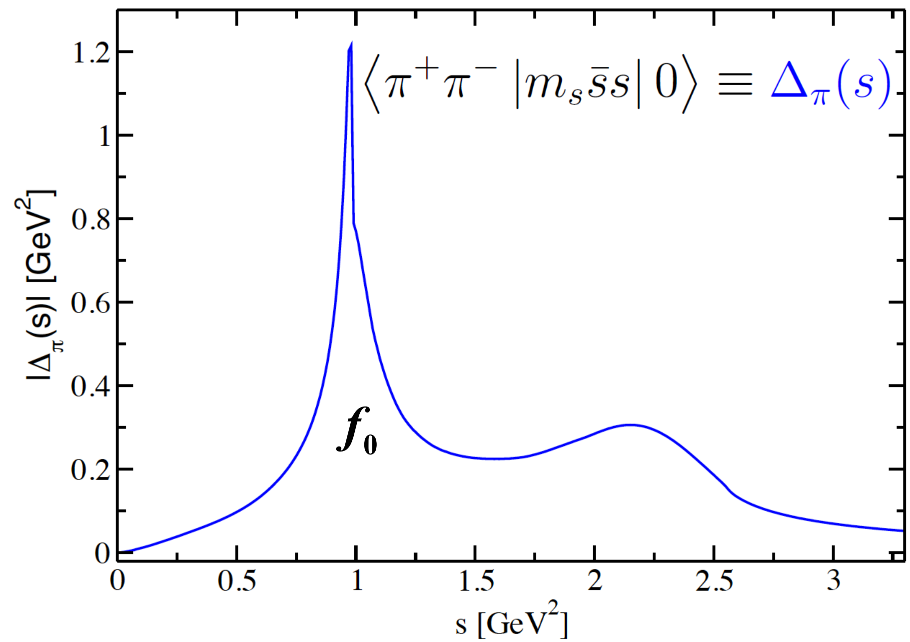
$$\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}$$

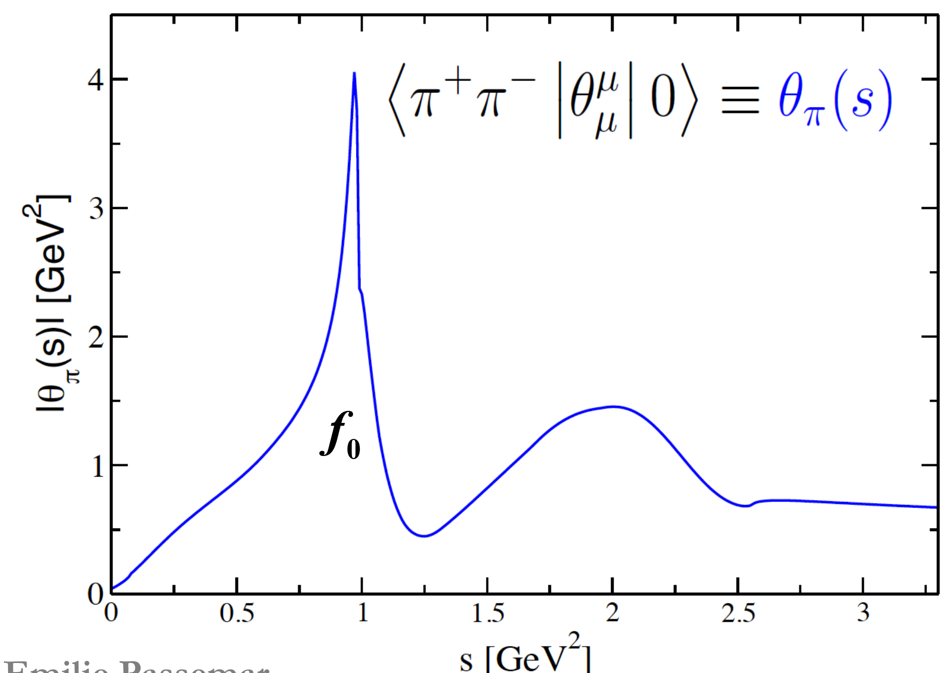
- For θ_P enforcing the asymptotic constraint is not consistent with ChPT
  The unsubtracted DR is not saturated by the 2 states

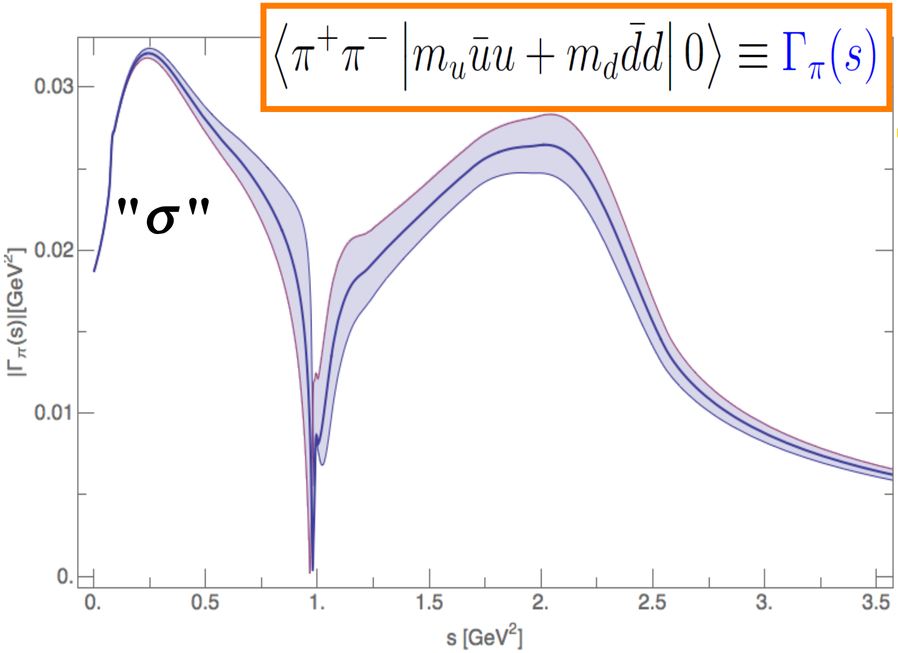
⇨ Relax the constraints and match to ChPT

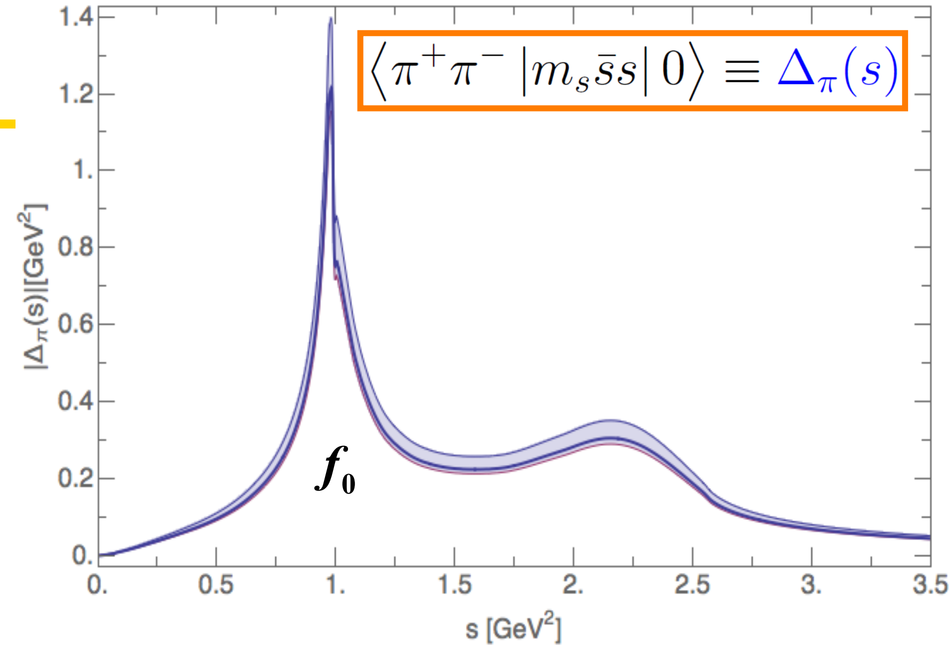
$$\begin{aligned} P_\theta(s) &= 2M_\pi^2 + \left(\dot{\theta}_\pi - 2M_\pi^2 \dot{C}_1 - \frac{4M_K^2}{\sqrt{3}} \dot{D}_1 \right) s \\ Q_\theta(s) &= \frac{4}{\sqrt{3}} M_K^2 + \frac{2}{\sqrt{3}} \left(\dot{\theta}_K - \sqrt{3} M_\pi^2 \dot{C}_2 - 2M_K^2 \dot{D}_2 \right) s \end{aligned}$$

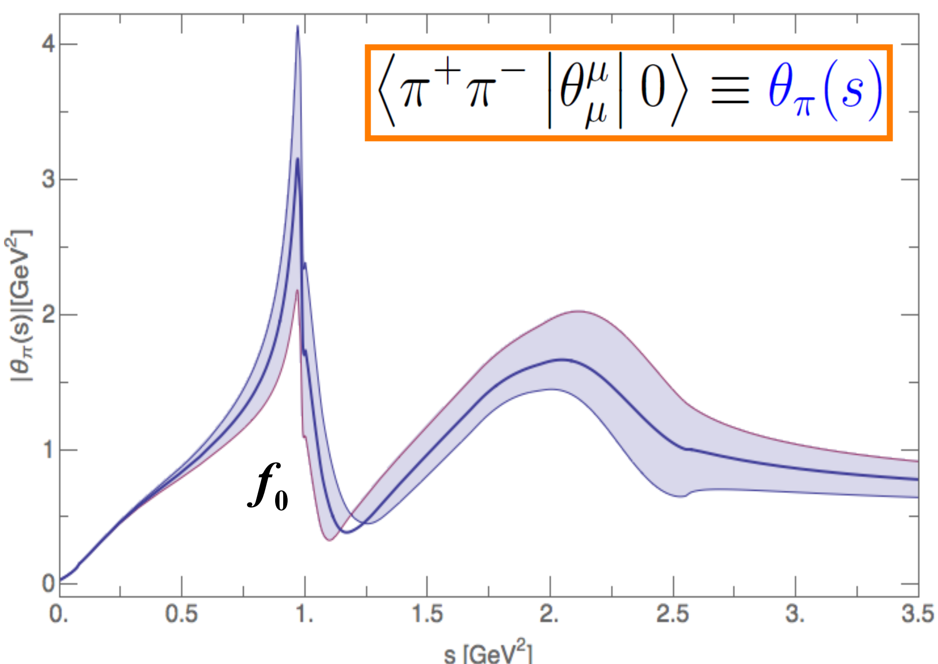

$\langle \pi^+\pi^- | m_u\bar{u}u + m_d\bar{d}d | 0 \rangle \equiv \Gamma_\pi(s)$
"σ"
$|\Gamma_\pi(s)|$ [GeV^2]
s [GeV^2]
0
0.01
0.02
0.03
0
0.5
1
1.5
2
2.5
3


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

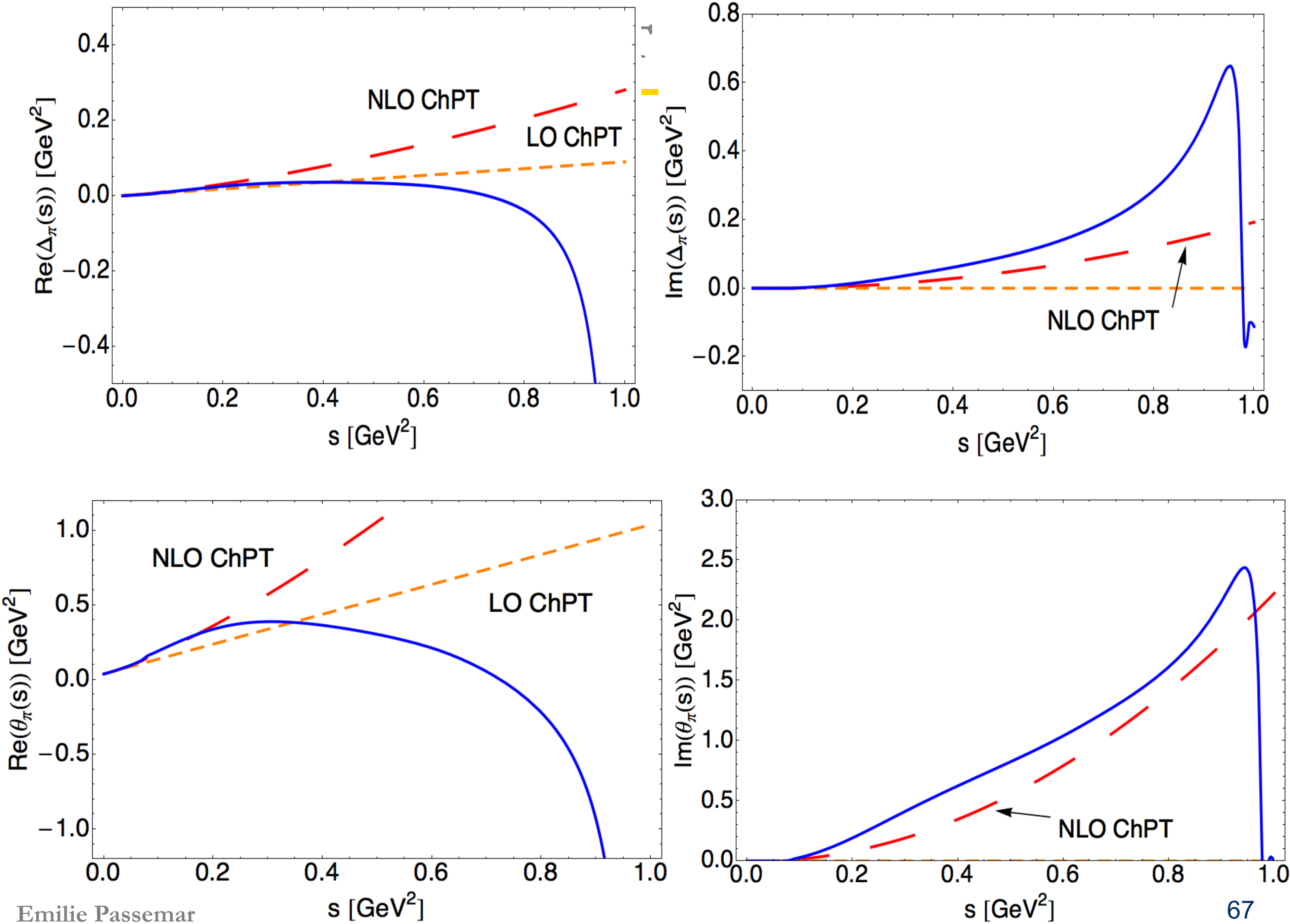

$\langle \pi^+\pi^- | \theta^\mu_\mu | 0 \rangle \equiv \theta_\pi(s)$
f_0
$|\theta_\pi(s)|$ [GeV^2]
s [GeV^2]
0
1
2
3
4
0
0.5
1
1.5
2
2.5
3





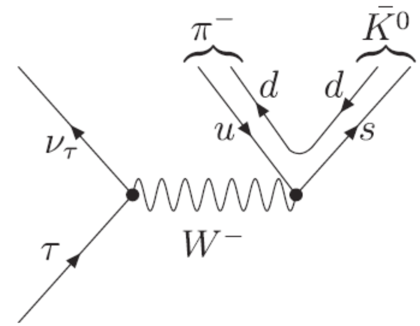


- Uncertainties:
  - Varying s_{cut} (1.4 GeV^2 - 1.8 GeV^2)
  - Varying the matching conditions
  - T matrix inputs


NLO ChPT
LO ChPT
Re(Δπ(s)) [GeV²]
s [GeV²]
Im(Δπ(s)) [GeV²]
NLO ChPT
s [GeV²]
NLO ChPT
LO ChPT
Re(θπ(s)) [GeV²]
s [GeV²]
Im(θπ(s)) [GeV²]
NLO ChPT
s [GeV²]

5. CPV in tau decays

5.1 $\tau \to K\pi\nu_\tau$ CP violating asymmetry



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

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

  Bigi & Sanda'05

  Grossman & Nir'11

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

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

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

- Experimental measurement : *BaBar'11*

  $$A_{Q\,\exp} = \left(-0.36 \pm 0.23_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}\right)\%$$ ⇨ 2.8σ 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

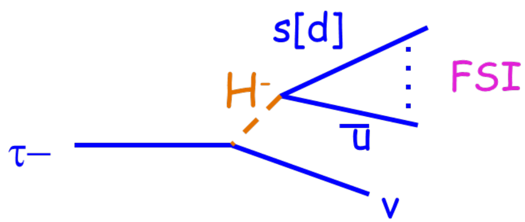
  $$A_D = \frac{\Gamma\left(D^+ \to \pi^+ K_S^0\right) - \Gamma\left(D^- \to \pi^- K_S^0\right)}{\Gamma\left(D^+ \to \pi^+ K_S^0\right) + \Gamma\left(D^- \to \pi^- K_S^0\right)} = (-0.54 \pm 0.14)\%$$

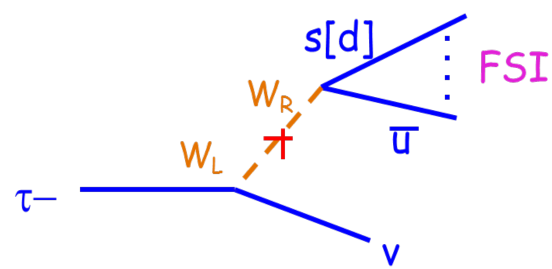
  Belle, Babar, CLOE, FOCUS

5.1 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

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

Bigi'Tau12





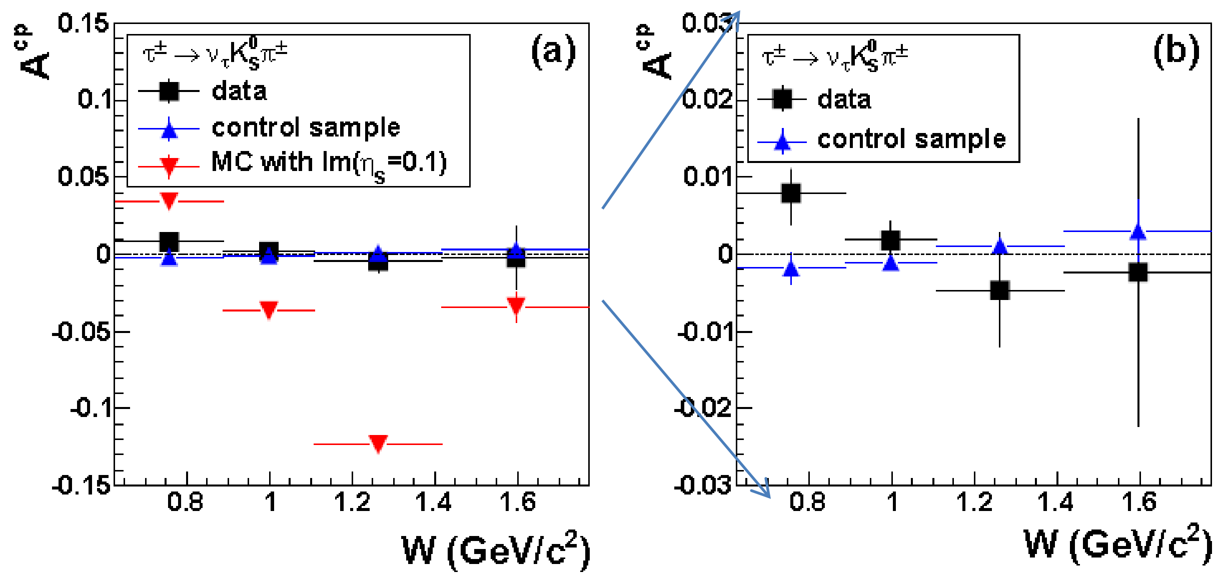
Very difficult to explain!

- Problem with this measurement? ⇨ It would be great to have other experimental measurements from *Belle, BES III or Tau-Charm factory*

Belle'11

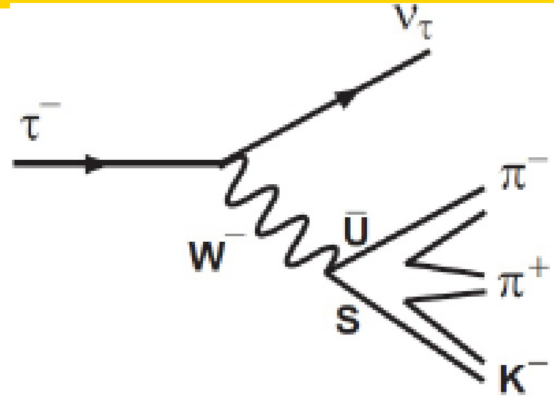
- Measurement of the direct contribution of NP in the angular CP violating asymmetry done by *CLEO* and *Belle*

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



5.2 Three body CP asymmetries

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



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

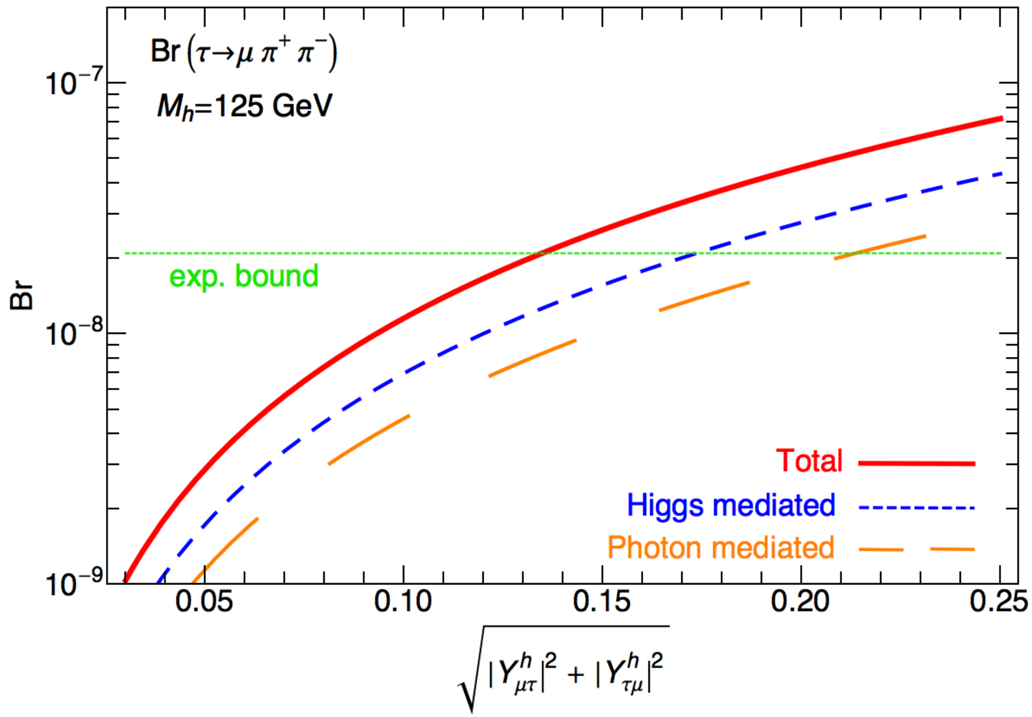
e.g., Choi, Hagiwara and Tanabashi'98
Kiers, Little, Datta, London et al.,'08
Mileo, Kiers and, Szynkman'14

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

3.5 Results



Bound:

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

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

Less stringent but more robust handle on LFV Higgs couplings

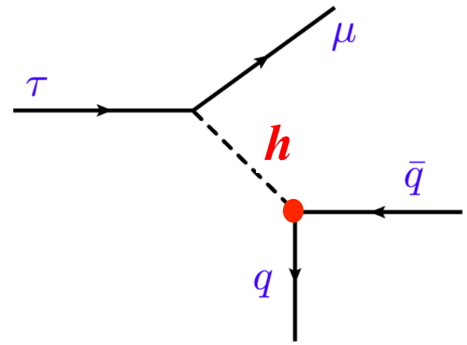
?

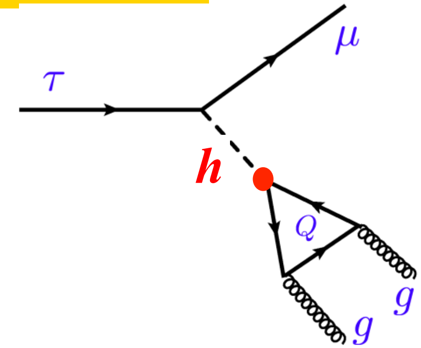
Belle'08'11'12 except last from *CLEO'97*

3.5 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:

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

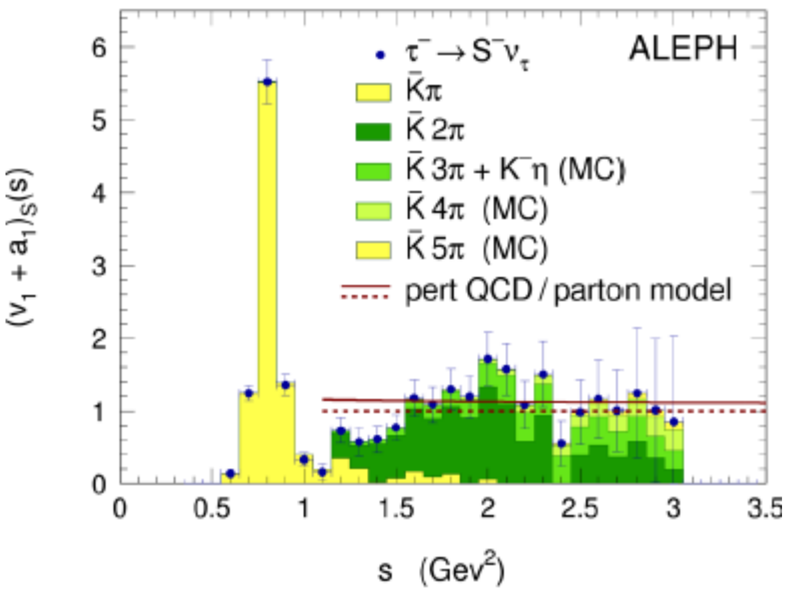
below present experimental limits!

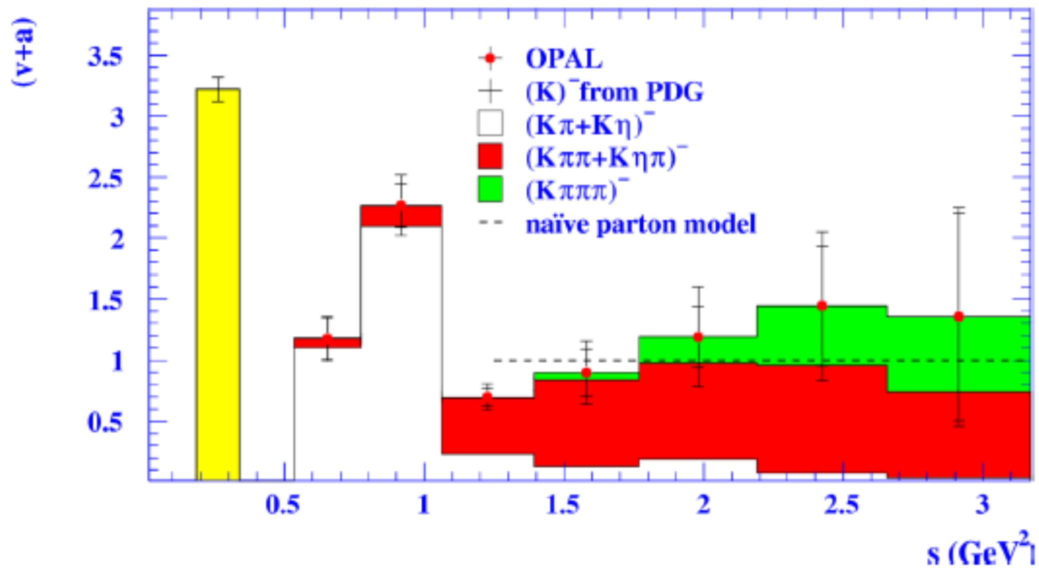
- If discovered ⇒ among other things *upper limit* on $Y_{u,d,s}$*!*

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

3.6 Prospects : τ strange Brs

- Experimental measurements of the strange spectral functions not very precise





➡ New measurements are needed !

- Before B-factories
- With B-factories new measurements :

Smaller $\tau \to$ K branching ratios ➡ smaller $R_{\tau,S}$ ➡ smaller V_{us}

$$\left.R_\tau^S\right|_{\text{old}} = 0.1686(47) \;\Rightarrow\; \left.R_\tau^S\right|_{\text{new}} = 0.1615(28)$$

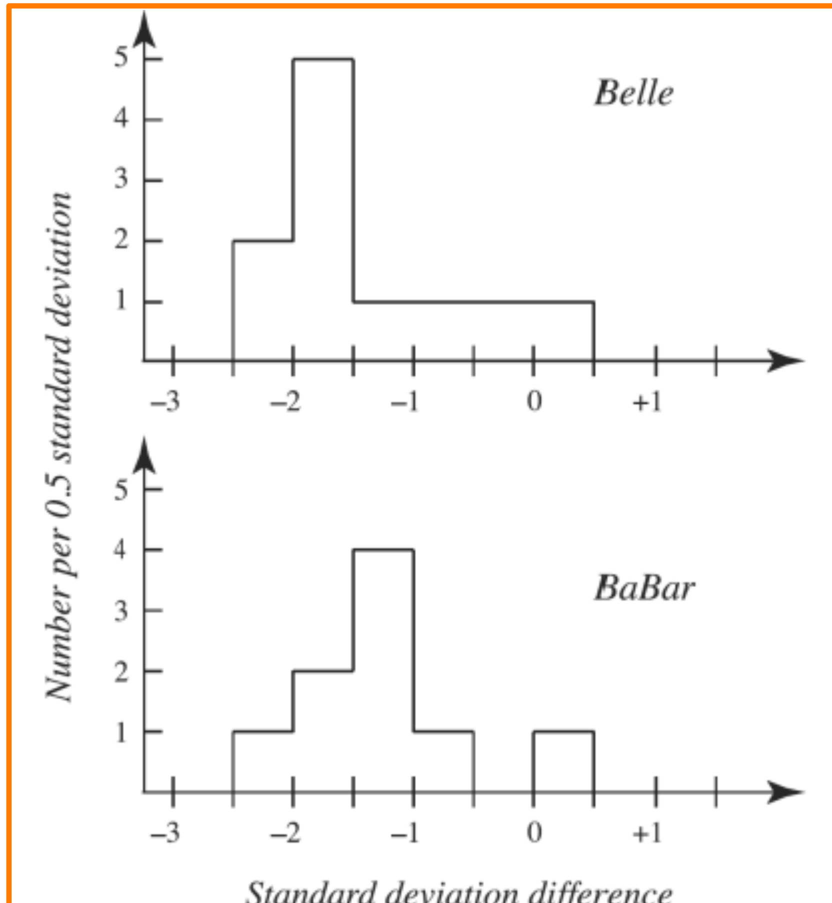
$$\left|V_{us}\right|_{\text{old}} = 0.2214 \pm 0.0031_{\text{exp}} \pm 0.0010_{\text{th}} \;\Rightarrow\; \left|V_{us}\right|_{\text{new}} = 0.2176 \pm 0.0019_{\text{exp}} \pm 0.0010_{\text{th}}$$

3.6 Prospects : τ strange Brs

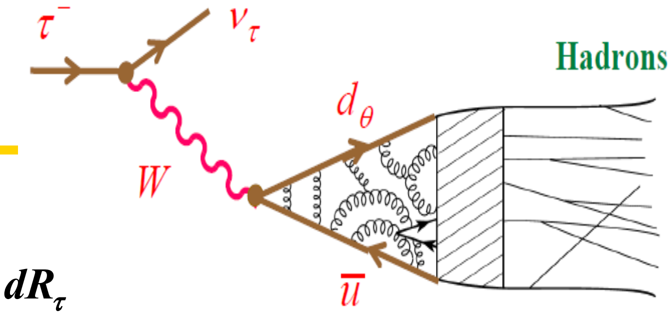
- *PDG 2014*: « Eigtheen of the 20 *B*-factory branching fraction measurements are smaller than the non-*B*-factory values. The average normalized difference between the two sets of measurements is -1.30 » (-1.41 for the 11 Belle measurements and -1.24 for the 9 BaBar measurements)

- Measured modes by the 2 B factories:

Mode	BaBar – Belle Normalized Difference (#σ)
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0)	+1.4
$K^-\pi^+\pi^-\nu_\tau$ (ex. K^0)	−2.9
$K^-K^+\pi^-\nu_\tau$	−2.9
$K^-K^+K^-\nu_\tau$	−5.4
$\eta\ K^-\nu_\tau$	−1.0
$\phi\ K^-\nu_\tau$	−1.3



2.2 Experimental situation



- Observable studied $R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau e^- \bar{\nu}_e\right)}$ and $\frac{dR_\tau}{ds}$

- Decomposition as a function of observed and separated final states

$$R_\tau = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$$

Zhang'Tau14

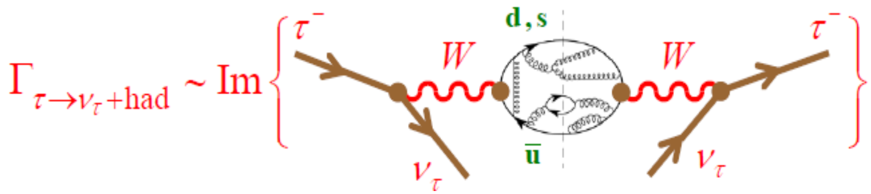
$$\upsilon_1 / a_1\left[\tau^- \to V^- / A^- \nu_\tau\right] \propto \frac{\text{BR}\left[\tau^- \to V^- / A^- \nu_\tau\right]}{\text{BR}\left[\tau^- \to e^- \bar{\nu}_e \nu_\tau\right]} \frac{1}{N_{V/A}} \frac{dN_{V/A}}{ds} \frac{m_\tau^2}{\left(1 - s/m_\tau^2\right)^2 \left(1 + 2s/m_\tau^2\right)}$$

Vector/Axial-vector spectral functions — branching fractions — mass spectrum — kinematic factor

2.4 Calculation of the QCD corrections

Braaten, Narison, Pich'92

- Calculation of R_τ:



$$\text{Im}\Pi^{(1)}_{\bar{u}d,V/A}(s) = \frac{1}{2\pi} v_1/a_1(s)$$

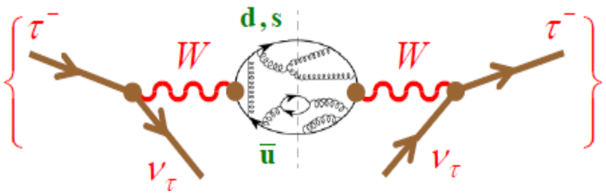
$$\Rightarrow \quad R_\tau(m_\tau^2) = 12\pi S_{EW} \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right)\text{Im}\,\Pi^{(1)}(s+i\varepsilon)+\text{Im}\,\Pi^{(0)}(s+i\varepsilon)\right]$$

2.4 Calculation of the QCD corrections

Braaten, Narison, Pich'92

- Calculation of R_τ:

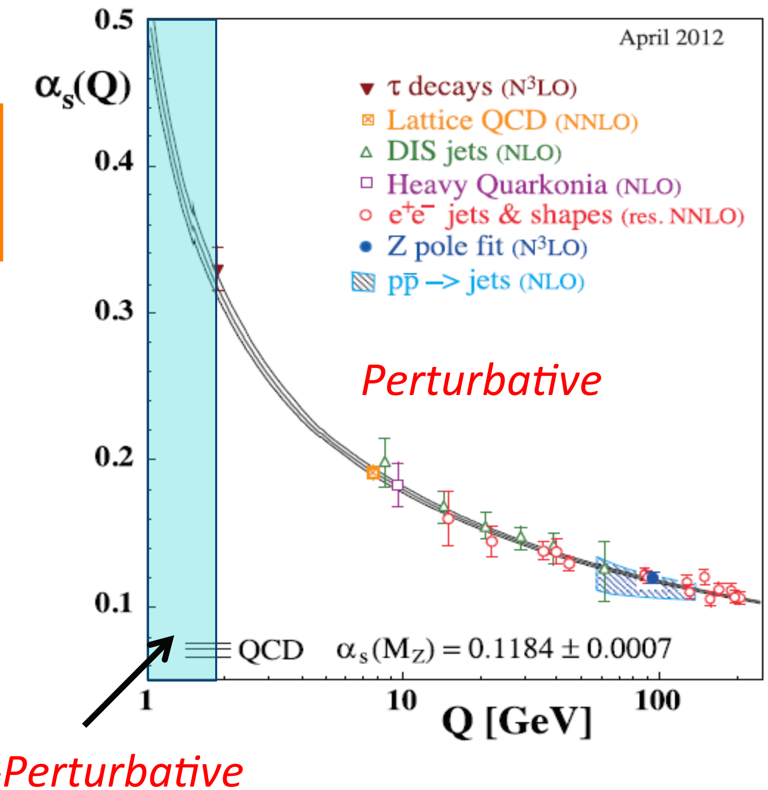
$$\Gamma_{\tau\to\nu_\tau+\text{had}} \sim \text{Im}\left\{ \right.$$



$$R_\tau(m_\tau^2) = 12\pi S_{EW}\int_0^{m_\tau^2}\frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2\left[\left(1+2\frac{s}{m_\tau^2}\right)\text{Im}\,\Pi^{(1)}(s+i\varepsilon)+\text{Im}\,\Pi^{(0)}(s+i\varepsilon)\right]$$

- We are in the *non-perturbative* region: we do not know how to compute!

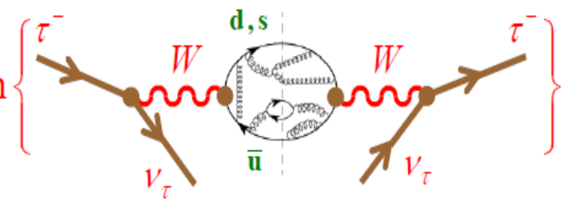
- Trick: use the analytical properties of Π!



2.4 Calculation of the QCD corrections

- Calculation of R_τ:

$\Gamma_{\tau \to \nu_\tau + \mathrm{had}} \sim \mathrm{Im}\{\ \}$



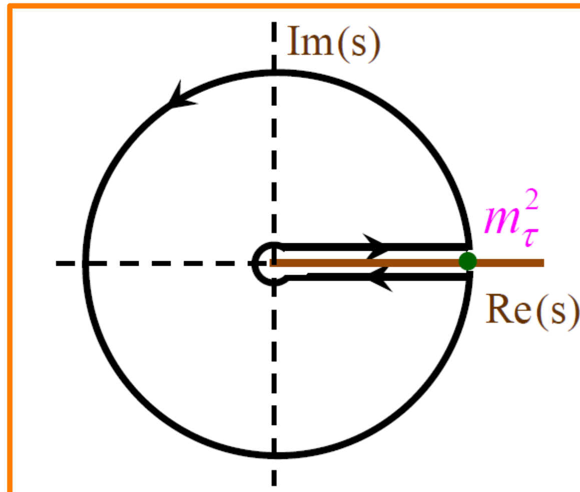
$$R_\tau(m_\tau^2) = 12\pi S_{EW} \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right)\mathrm{Im}\,\Pi^{(1)}(s+i\varepsilon) + \mathrm{Im}\,\Pi^{(0)}(s+i\varepsilon)\right]$$

Braaten, Narison, Pich'92

- Analyticity: Π is analytic in the entire complex plane except for s real positive

  ⇨ Cauchy Theorem

$$R_\tau(m_\tau^2) = 6i\pi S_{EW} \oint_{|s|=m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right)\Pi^{(1)}(s) + \Pi^{(0)}(s)\right]$$



- We are now at sufficient energy to use OPE:

$$\Pi^{(J)}(s) = \sum_{D=0,2,4\ldots} \frac{1}{(-s)^{D/2}} \sum_{\dim O = D} C^{(J)}(s,\mu)\, \langle O_D(\mu) \rangle$$

Wilson coefficients — Operators

μ: separation scale between short and long distances

2.4 Calculation of the QCD corrections

Braaten, Narison, Pich'92

- Calculation of R_τ:

$$R_\tau\left(m_\tau^2\right) = N_C \; S_{EW} \left(1 + \delta_P + \delta_{NP}\right)$$

- Electroweak corrections: $S_{EW} = 1.0201(3)$ *Marciano &Sirlin'88, Braaten & Li'90, Erler'04*

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- Perturbative part (D=0): $\delta_P = a_\tau + 5.20\ a_\tau^2 + 26\ a_\tau^3 + 127\ a_\tau^4 + \ldots \approx 20\%$ $\qquad a_\tau = \frac{\alpha_s(m_\tau)}{\pi}$

Baikov, Chetyrkin, Kühn'08

2.4 Calculation of the QCD corrections

Braaten, Narison, Pich'92

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- D=2: quark mass corrections, *neglected* for $R_\tau^{NS}\ \left(\propto m_u, m_d\right)$ but not for $R_\tau^{S}\ \left(\propto m_s\right)$

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- D ≥ 4: Non perturbative part, not known, *fitted from the data*
  ⇒ Use of weighted distributions

2.4 Calculation of the QCD corrections

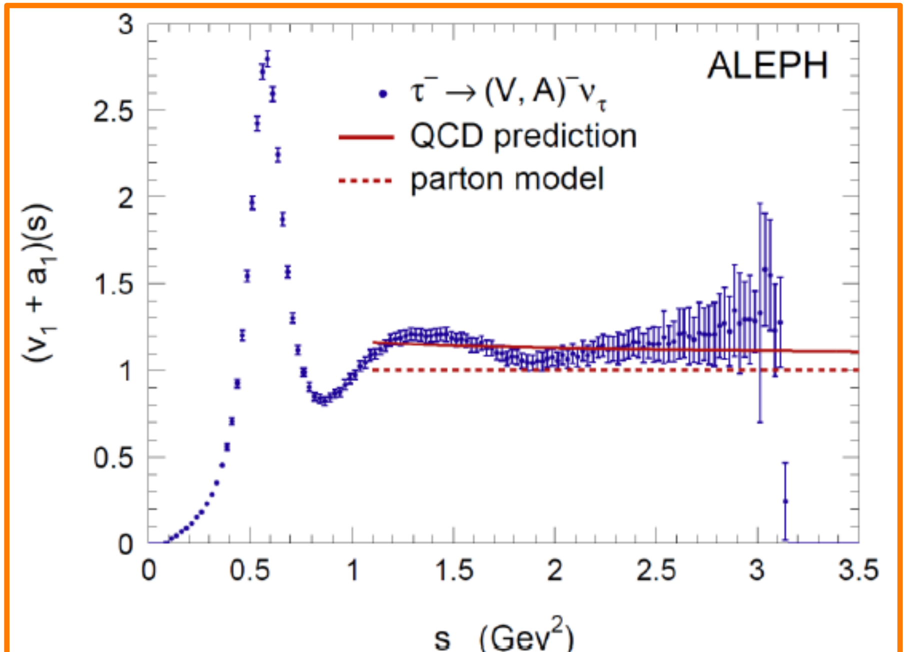
Le Diberder&Pich'92

- D ≥ 4: Non perturbative part, not known, *fitted from the data*

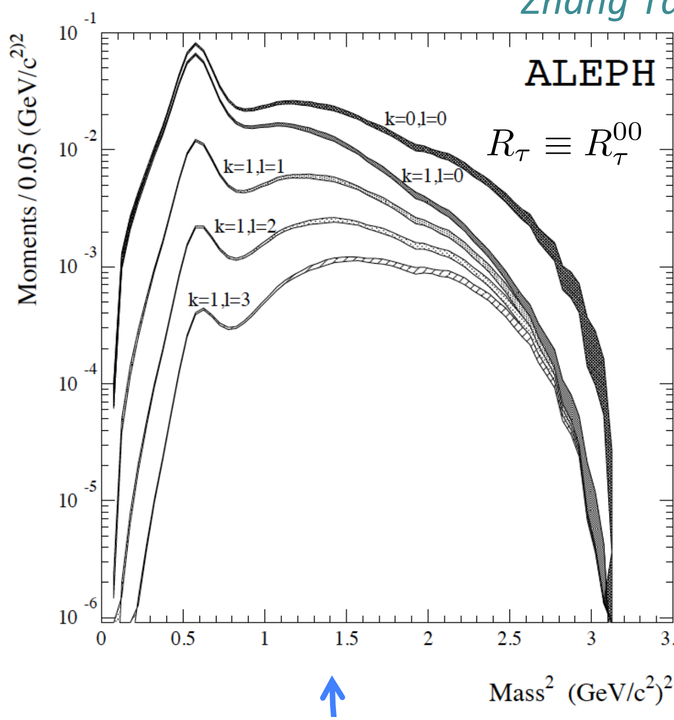
  ⇨ Use of weighted distributions

Exploit shape of the spectral functions to obtain additional experimental information

$$R^{k\ell}_{\tau,U}(s_0) = \int_0^{s_0} ds \left(1-\frac{s}{s_0}\right)^k \left(\frac{s}{s_0}\right)^\ell \frac{dR_{\tau,U}(s_0)}{ds}$$



Zhang'Tau14



Braaten, Narison, Pich'92

- Calculation of R_τ:

$$R_\tau\left(m_\tau^2\right) = N_C\ S_{EW}\left(1+\delta_P+\delta_{NP}\right)$$

- Electroweak corrections: $S_{EW} = 1.0201(3)$

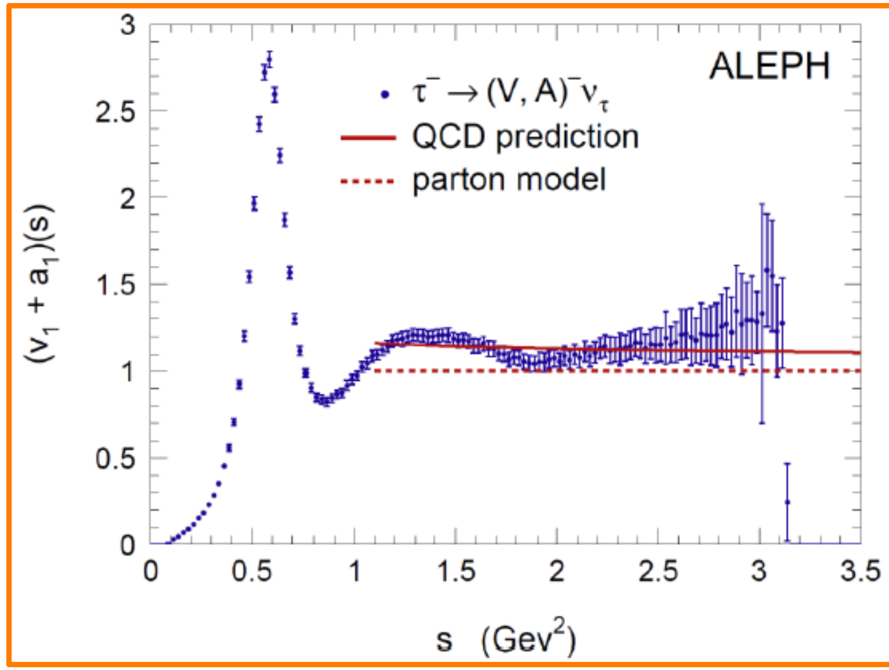
- Perturbative part (D=0): $\delta_P \approx 20\%$

- D=2: quark mass corrections, *neglected*

- D ≥ 4: Non perturbative part, not known, *fitted from the data*
  Use of weighted distributions

$$\Rightarrow \quad \delta_{NP} = -0.0064 \pm 0.0013$$

Davier et al'14



- Small unknown NP part $\left(\delta_{NP} \sim 3\%\ \delta_P\right)$ very precise extraction of α_S !

2.5 Results and determination of α_s

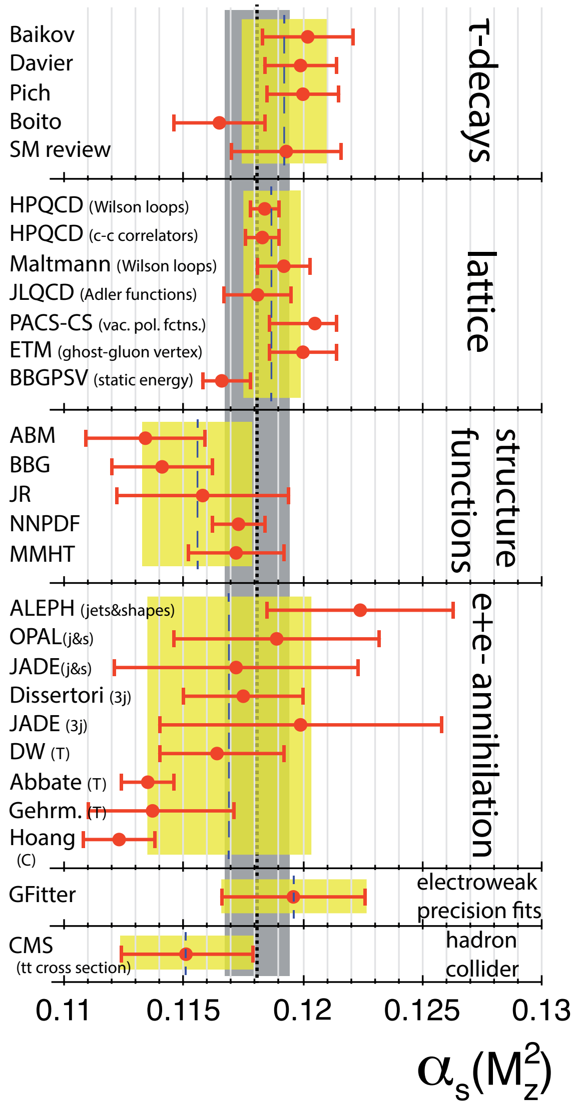
Pich'Tau14

Reference	Method	δ_{NP}	δ_P	$\alpha_s(m_\tau)$	$\alpha_s(m_Z)$
Baikov et al	CIPT, FOPT		0.1998 (43)	**0.332 (16)**	**0.1202 (19)**
Davier et al'14	**CIPT, FOPT**	**– 0.0064 (13)**	**–**	**0.332 (12)**	**0.1199 (15)**
Beneke-Jamin	BSR + FOPT	– 0.007 (3)	0.2042 (50)	**0.316 (06)**	**0.1180 (08)**
Maltman-Yavin	PWM + CIPT	+ 0.012 (18)	–	**0.321 (13)**	**0.1187 (16)**
Menke	CIPT, FOPT		0.2042 (50)	**0.342 (11)**	**0.1213 (12)**
Narison	CIPT, FOPT		–	**0.324 (08)**	**0.1192 (10)**
Caprini-Fischer	BSR + CIPT		0.2037 (54)	**0.322 (16)**	–
Abbas et al	IFOPT		0.2037 (54)	**0.338 (10)**	
Cvetič et al	β_{exp} + CIPT		0.2040 (40)	**0.341 (08)**	**0.1211 (10)**
Boito et al	CIPT, DV	– 0.002 (12)	–	**0.347 (25)**	**0.1216 (27)**
	FOPT, DV	– 0.004 (12)		**0.325 (18)**	**0.1191 (22)**
Pich'14	CIPT	– 0.0064 (13)	0.2014 (31)	**0.342 (13)**	**0.1213 (14)**
	FOPT			**0.320 (14)**	**0.1187 (17)**
Pich'14	**CIPT, FOPT**	**– 0.0064 (13)**	**0.2014 (31)**	**0.332 (13)**	**0.1202 (15)**

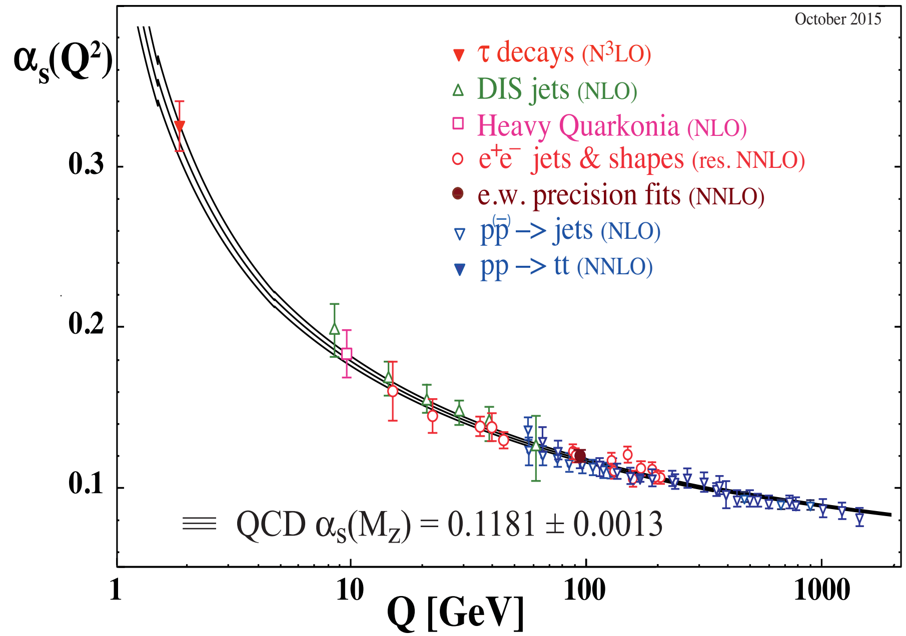
CIPT: Contour-improved perturbation theory
FOPT: Fixed-order perturbation theory
BSR: Borel summation of renormalon series
IFOPT Improved FOPT

β_{exp}: Expansion in derivatives of α_s (β function)
PWM: Pinched-weight moments
CIPTm: Modified CIPT (conformal mapping)
DV: Duality violation (OPAL only)

3.4 Extraction of α_s



Bethke, Dissertori, Salam, PDG'15



- *Extraction of α_s* from hadronic τ very interesting : Moderate precision at the τ mass ⇨ very good precision at the Z mass

- Beautiful test of the QCD running

3.4 Extraction of α_s

- Several delicate points:
  - How to compute the perturbative part: CIPT vs. FOPT?
  - How to estimate the non perturbative contribution? Where do we truncate the expansion, what is the role of higher order condensates?
  - Which weights should we use?
  - What about duality violations?

⇨ A MITP topical workshop in Mainz: March 7-12, 2016

Determination of the fundamental parameters of QCD

- New data on spectral functions needed to help to answer some of these questions

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

3.6 Model discriminating of BRs

- Studies in specific models

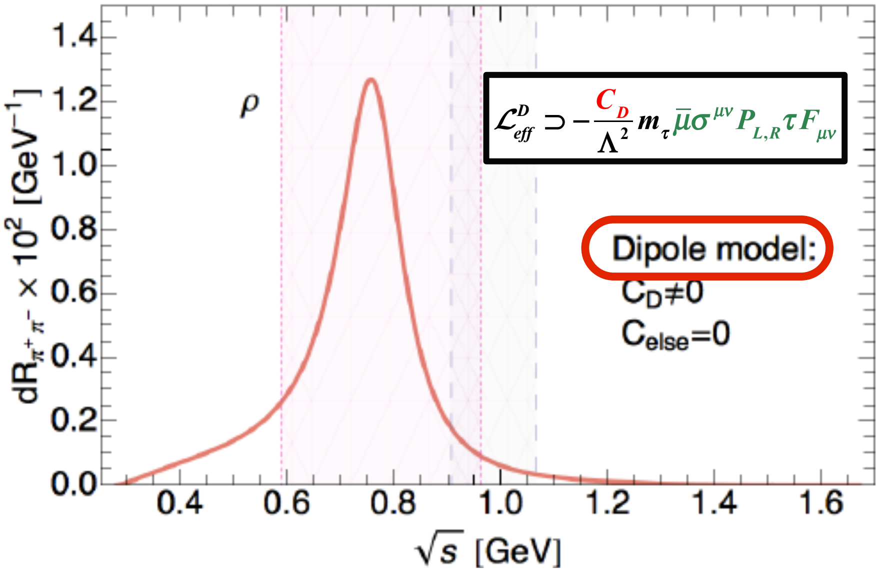
Buras et al.'10

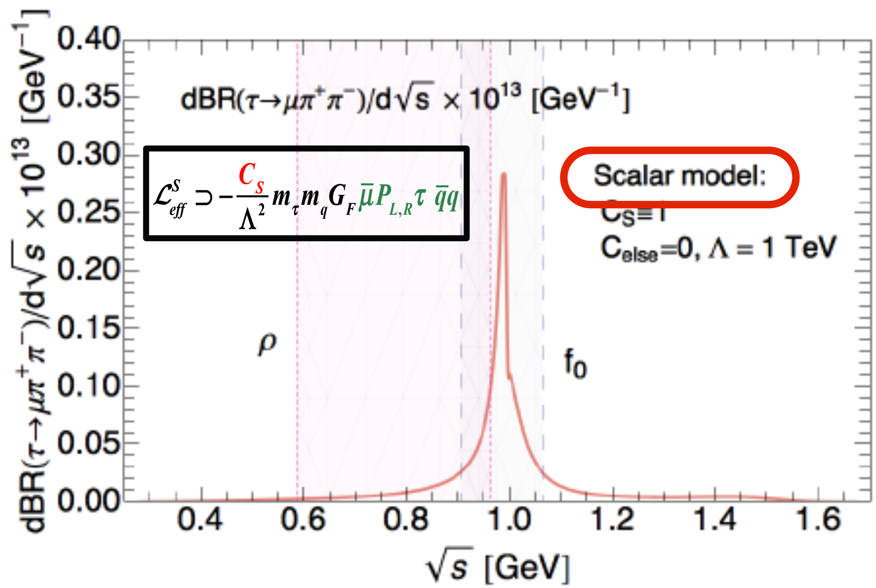
ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\mathrm{Br}(\mu^- \to e^- e^+ e^-)}{\mathrm{Br}(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	$0.06 \ldots 2.2$
$\frac{\mathrm{Br}(\tau^- \to e^- e^+ e^-)}{\mathrm{Br}(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot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

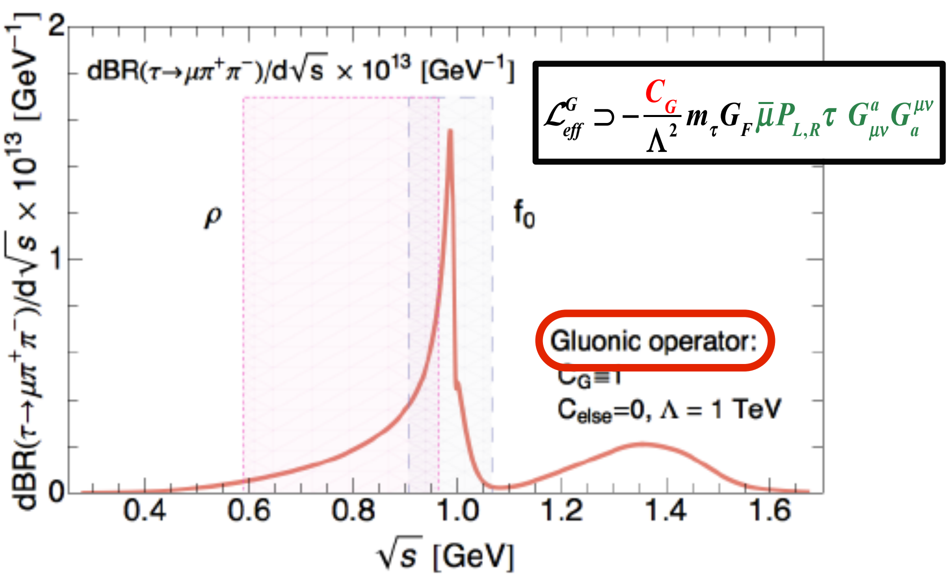
⇨ Disentangle the *underlying dynamics* of NP

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

Celis, Cirigliano, E.P.'14







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

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

Dassinger et al.'07

1.1 The triumph of the Standard Model

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

- Key results at LHC after run I + beginning of run II
  - *The Higgs boson* (last missing piece of the SM) has been found:
    ⇨ it looks very standard
  - The Higgs boson is "*light*" (m_h ~ 125 GeV → not the heaviest SM particle)
  - *No* "*mass-gap*" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

- *Was this unexpected*?
  Not really! ⇨ *Consistent* with (pre-LHC) indications coming from indirect NP searches (*EWPO* + *flavour physcs*)

1.2 Quest for New Physics

- *Shall we continue to test the Standard Model and search for New Physics?*

  Yes! ⇨ Despite its phenomenological successes, the SM has some *deep unsolved* problems:

  - hierarchy problem
  - flavour pattern
  - dark-matter, etc….

  - Strong interaction not so well understood: confinement, etc

1.2 Quest for New Physics

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  Yes! ⇨ Despite its phenomenological successes, the SM has some *deep unsolved* problems:
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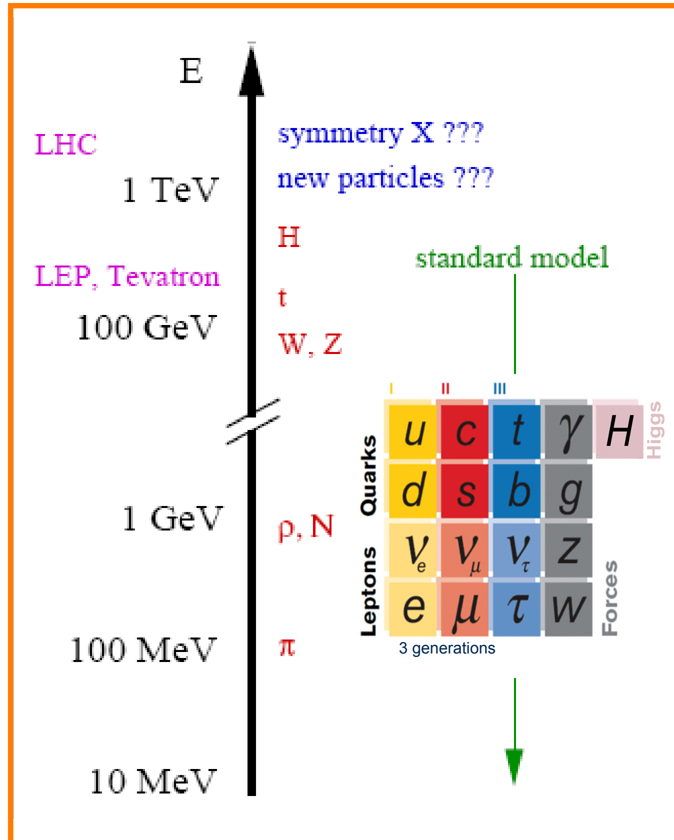
  - flavour pattern
  - dark-matter, etc.…
  - Strong interaction not so well understood: confinement, etc



- Consider the SM as as an *effective theory*, i.e. the limit *–in the accessible range of energies and effective couplings–* of a more fundamental theory, with
  - new degrees of freedom
  - new symmetries