Hadronization effects in $\tau \to \pi \gamma \nu_\tau$ decays

Pablo Roig LPT (CNRS), Orsay (France)

Work done in collaboration with Z. H. Guo

FlaviA net

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Manchester, 14/09/10

SUMMARY:

- Hadron decays of the τ lepton
- Theoretical setting: χPT, Large N_c , RχT
- $\tau^- \to \pi^- \gamma \nu_\tau$
- Conclusions and Outlook

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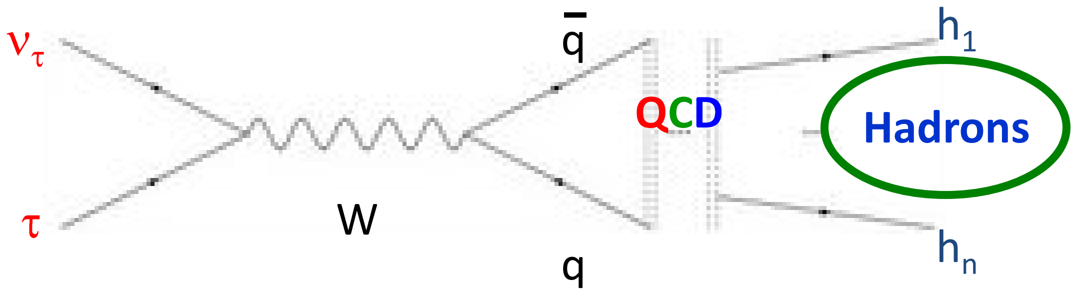
Hadron decays of the τ lepton :



Talks by
M. Jamin
and
A.Pich

Pablo Roig

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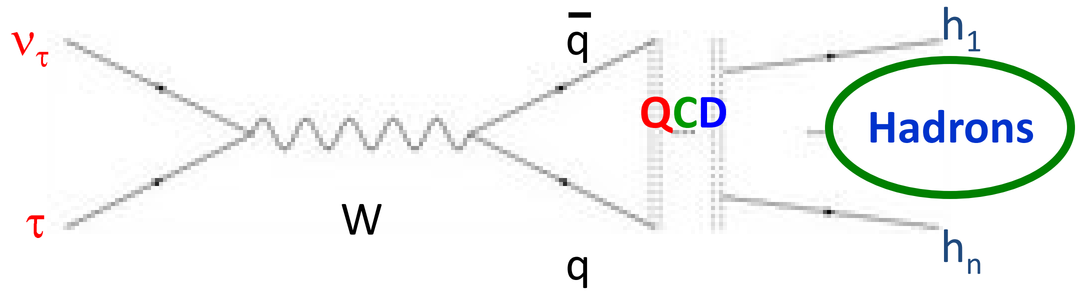

Talks by M. Jamin and A.Pich

$$M = \frac{G_F}{\sqrt{2}} V_{CKM} \bar{u}(\nu_\tau)\gamma^\mu(1-\gamma_5)u(\tau)T_\mu$$

T_μ=<Hadrons|(V-A)$_\mu$ $e^{iS_{QCD}}$|0>=Σ_i(Lorentz Structure)^i $F_i(Q^2,s_j)$

$$d\Gamma = \frac{G_F{}^2}{4M_\tau{}^2} |V_{CKM}|^2 \, d\Phi^{(n+1)} \, L_{\mu\nu} T^\mu T^{\nu *}$$

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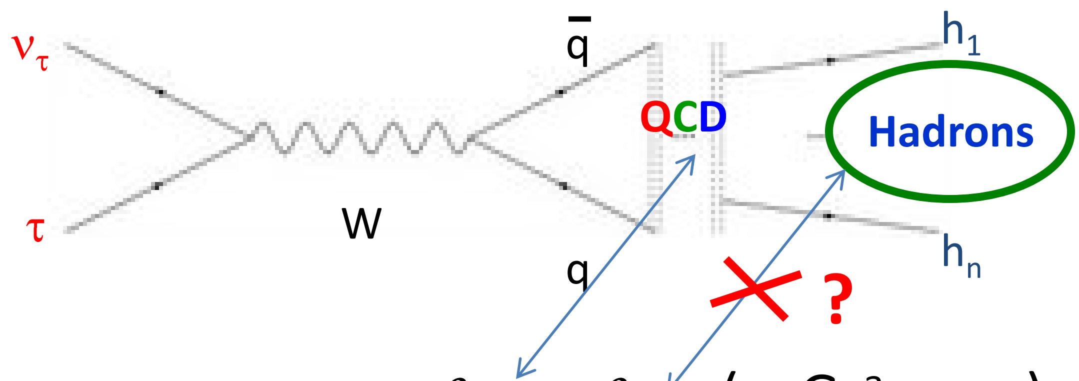

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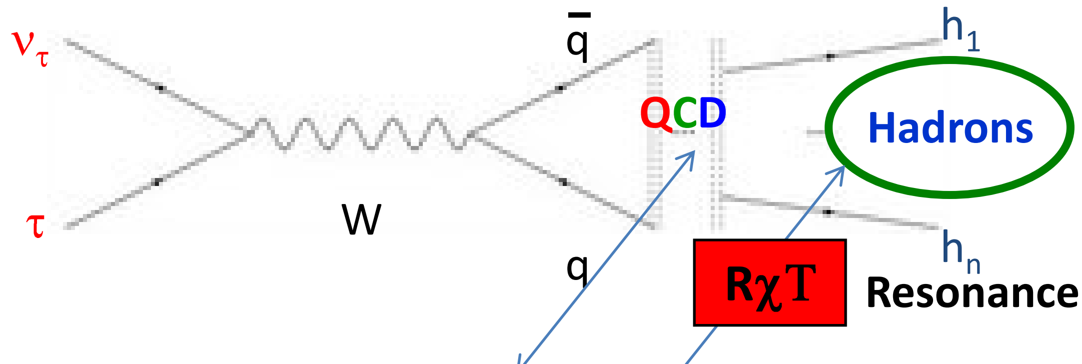

Resonance Chiral Theory

Talks by M. Jamin and A.Pich

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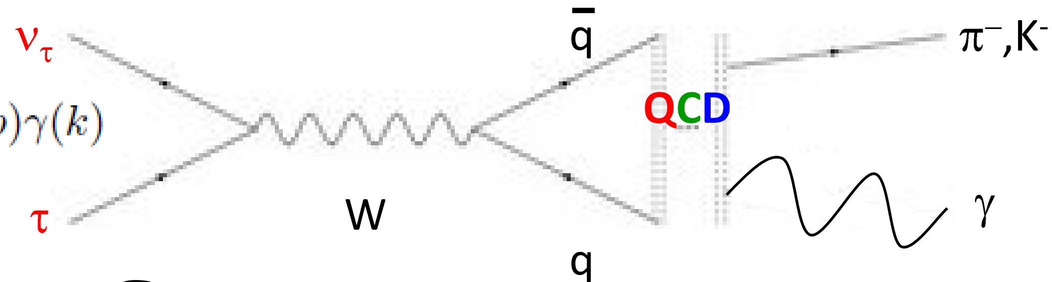

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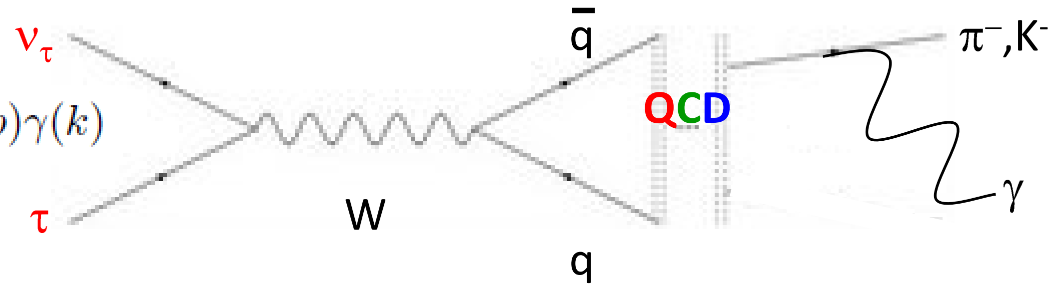

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Structure independent

$$i\mathcal{M}_{\mathrm{IB}_{\tau+\pi}} = G_F\, V_{ud}\, e\, F_\pi\, m_\tau\, \epsilon^\nu(k)\overline{u}_{\nu_\tau}(q)\,(1+\gamma_5)\left(\frac{s_\nu}{s\cdot k} - \frac{p_\nu}{p\cdot k} - \frac{\not{k}\gamma_\nu}{2s\cdot k}\right) u_\tau(s)$$

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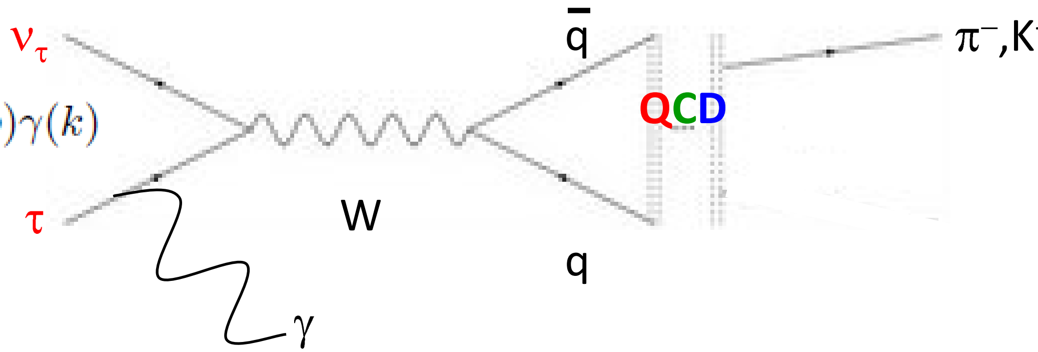

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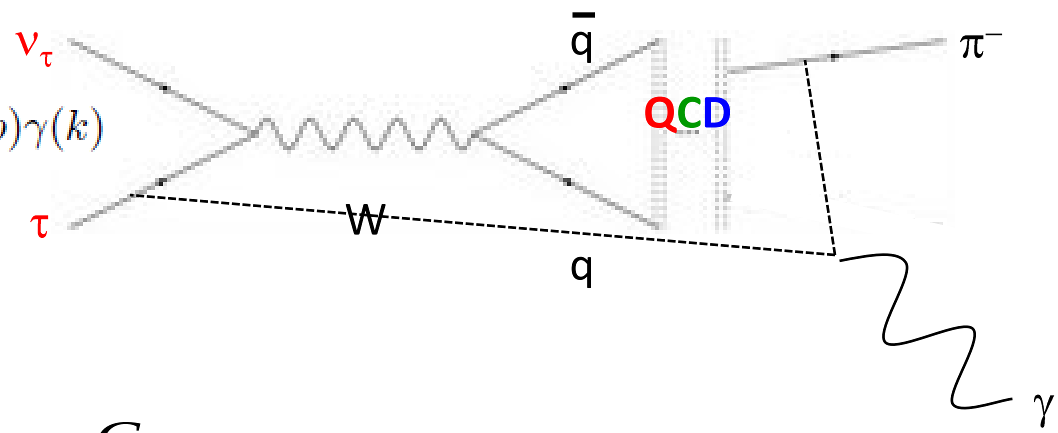

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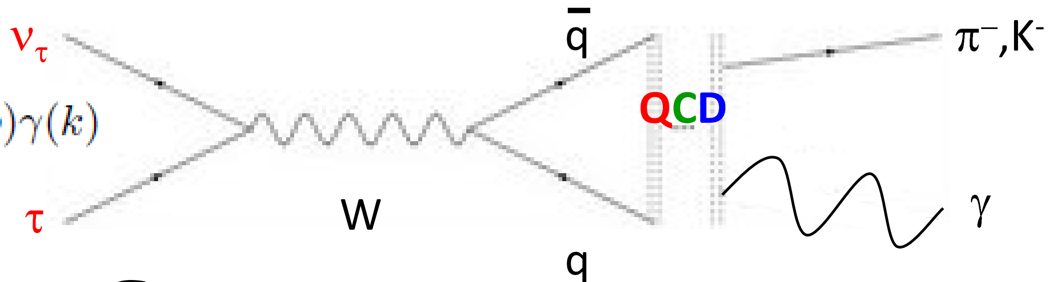

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Structure dependent

$$i\mathcal{M}_{\mathrm{IB_V}} = iG_F\, V_{ud}\, e\, \overline{u}_{\nu_\tau}(q)\,\gamma^\mu(1-\gamma_5)\, u_\tau(s)\varepsilon_{\mu\nu\alpha\beta}\, \epsilon^\nu(k)\, k^\alpha p^\beta\, F_V^\pi(t)$$

$$i\mathcal{M}_{\mathrm{IB_A}} = G_F\, V_{ud}\, e\, \overline{u}_{\nu_\tau}(q)\,\gamma^\mu(1-\gamma_5)\, u_\tau(s)\, \epsilon^\nu(k)\, \left[(t-m_\pi^2)g_{\mu\nu} - 2k_\mu p_\nu\right] F_A^\pi(t)$$

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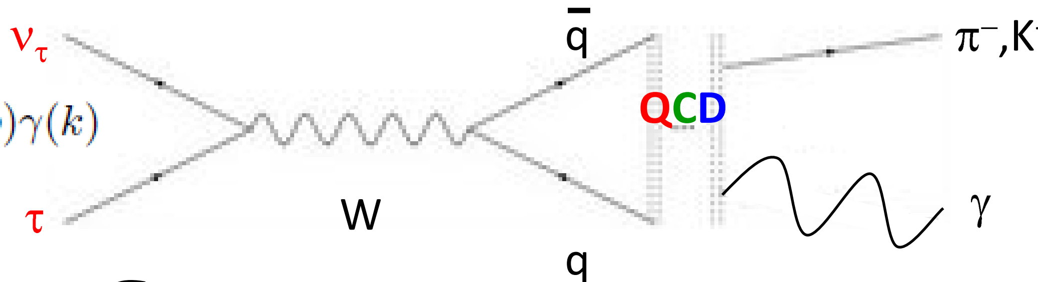

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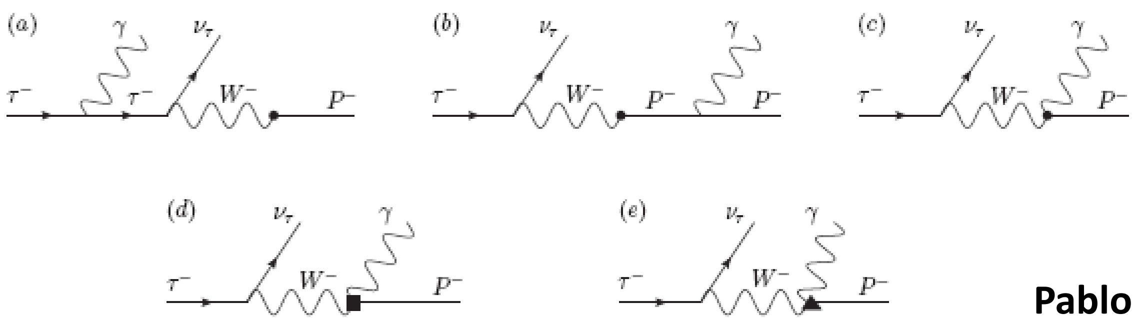

Hadronization in $\tau \to \pi\, \gamma\, \nu_\tau$ decays

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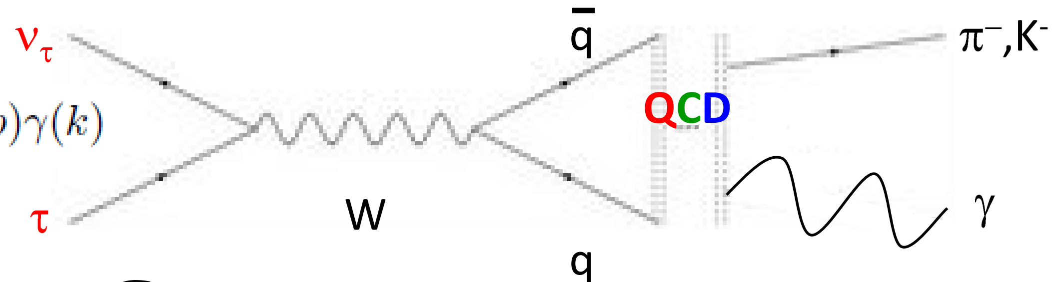

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$$i\mathcal{M}_{\mathrm{IB}_{\tau+\pi}} = G_F\, V_{ud}\, e\, F_\pi\, m_\tau\, \epsilon^\nu(k)\overline{u}_{\nu_\tau}(q)\,(1+\gamma_5)\left(\frac{s_\nu}{s\cdot k} - \frac{p_\nu}{p\cdot k} - \frac{k\!\!\!/\gamma_\nu}{2s\cdot k}\right) u_\tau(s)$$

Structure dependent

$$i\mathcal{M}_{\mathrm{IB_V}} = iG_F\, V_{ud}\, e\, \overline{u}_{\nu_\tau}(q)\,\gamma^\mu(1-\gamma_5)\, u_\tau(s)\varepsilon_{\mu\nu\alpha\beta}\,\epsilon^\nu(k)\, k^\alpha p^\beta F_V^\pi(t)$$

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$$\frac{d^2\Gamma}{dx\,dy} = \frac{m_\tau}{256\pi^3}\overline{|\mathcal{M}|^2}$$

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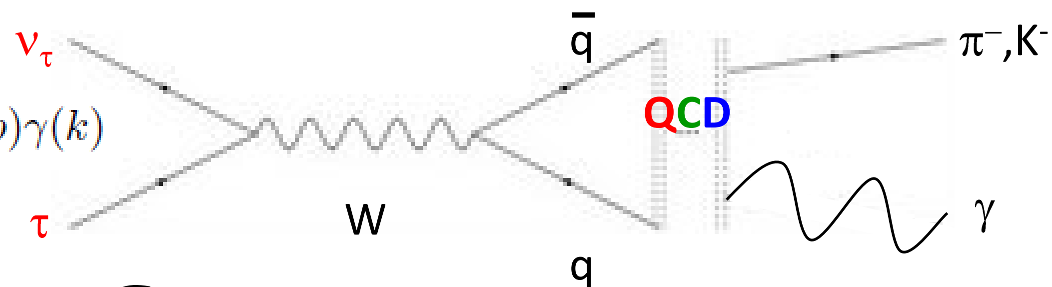

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Structure independent

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Structure dependent

$$i\mathcal{M}_{\text{IB}_\text{V}} = iG_F\, V_{ud}\, e\, \overline{u}_{\nu_\tau}(q)\,\gamma^\mu(1-\gamma_5)\,u_\tau(s)\varepsilon_{\mu\nu\alpha\beta}\,\epsilon^\nu(k)\,k^\alpha p^\beta F_V^\pi(t)$$

$$i\mathcal{M}_{\text{IB}_\text{A}} = G_F\, V_{ud}\, e\, \overline{u}_{\nu_\tau}(q)\,\gamma^\mu(1-\gamma_5)\,u_\tau(s)\,\epsilon^\nu(k)\,\left[(t-m_\pi^2)g_{\mu\nu} - 2k_\mu p_\nu\right] F_A^\pi(t)$$

$$\frac{d^2\Gamma}{dx\,dy} = \frac{m_\tau}{256\pi^3}\overline{|\mathcal{M}|^2}$$

$$x := \frac{2s\cdot k}{m_\tau^2} \qquad y := \frac{2s\cdot p}{m_\tau^2} \qquad E_\gamma = \frac{m_\tau}{2}x \qquad E_\pi = \frac{m_\tau}{2}y$$

Hadronization in $\tau \to \pi\,\gamma\,\nu_\tau$ decays

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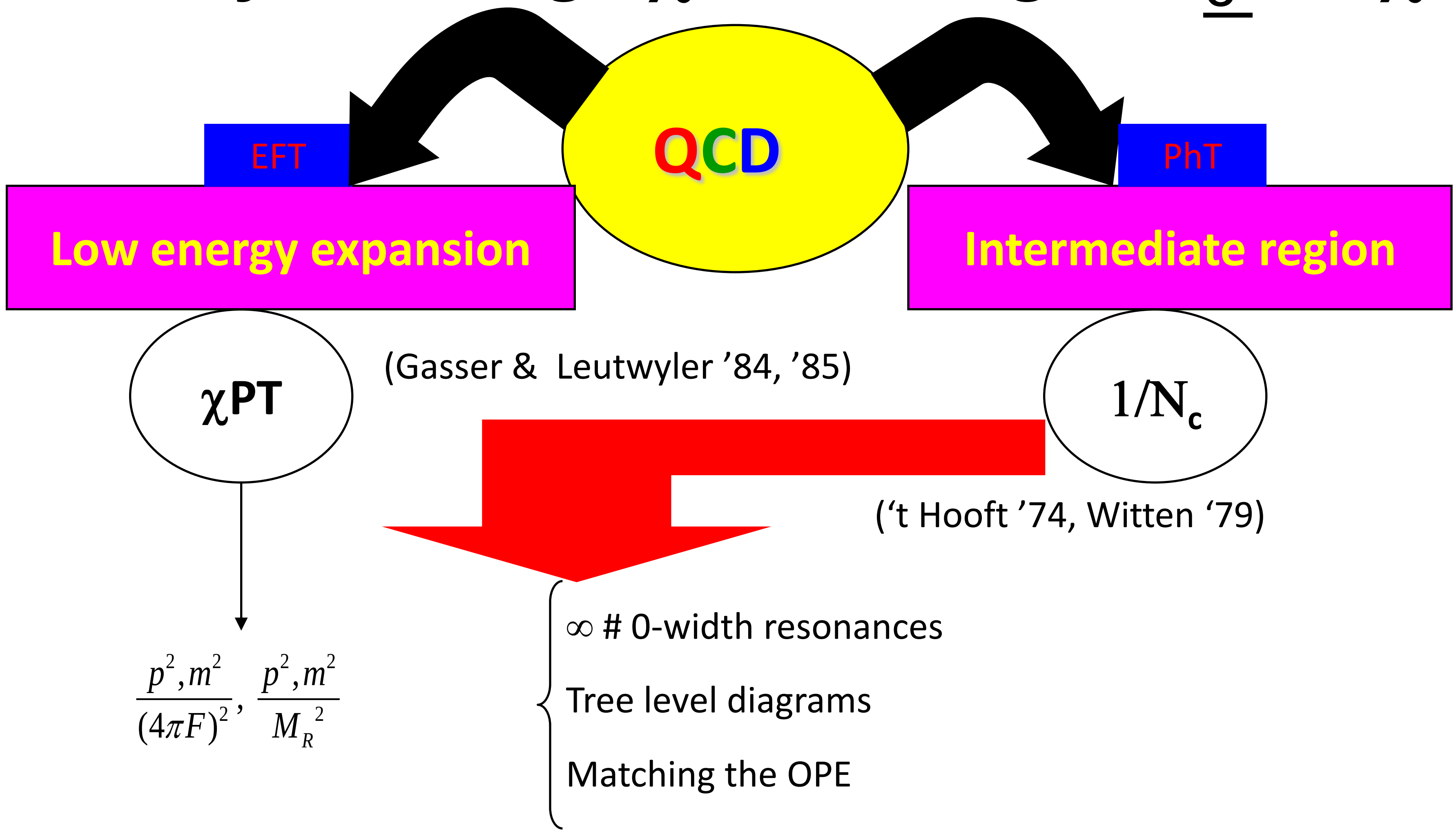
Theory setting: χPT, Large N_c , RχT



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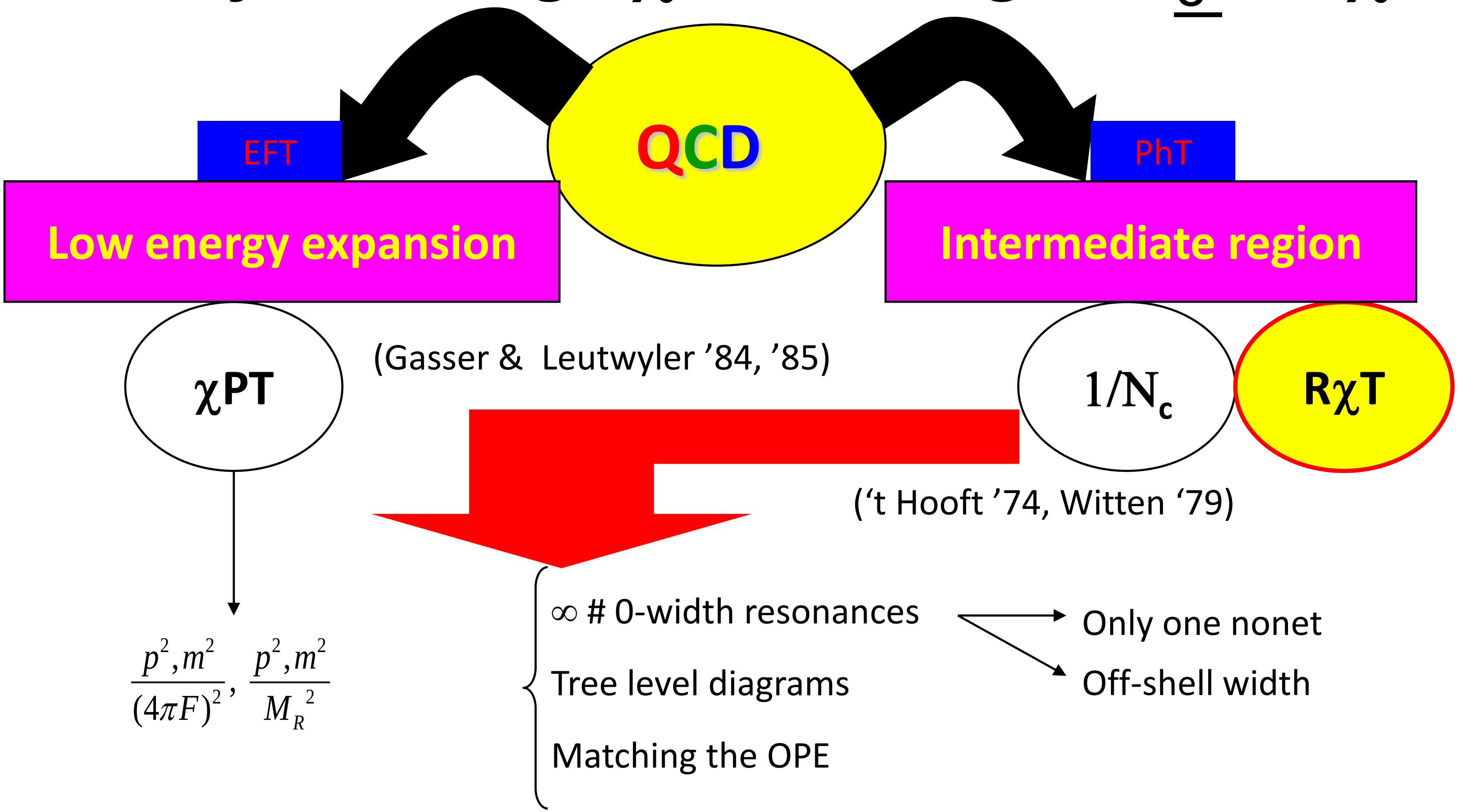

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$\tau^- \to \pi^- \gamma \nu_\tau$

Hadronic contributions

Axial form factor

Vector form factor

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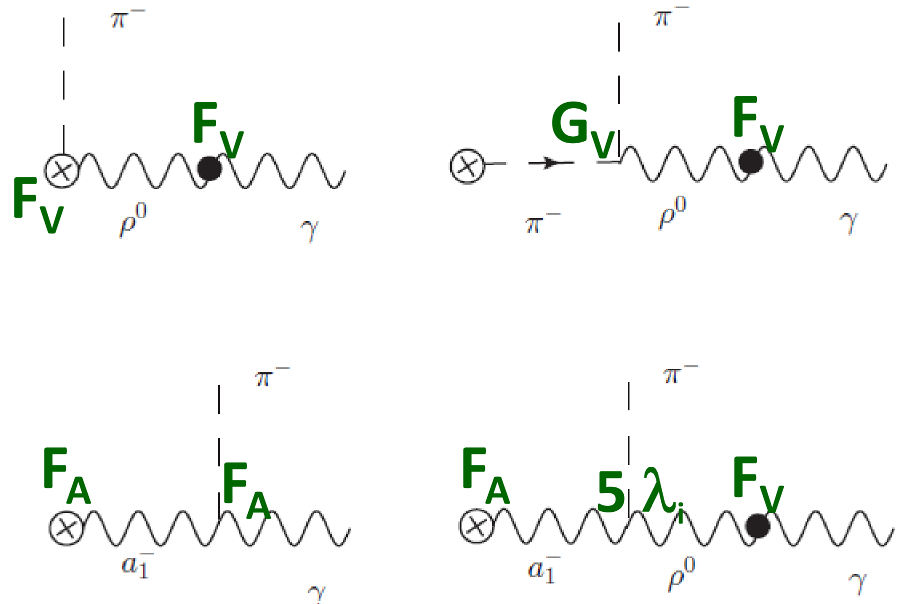
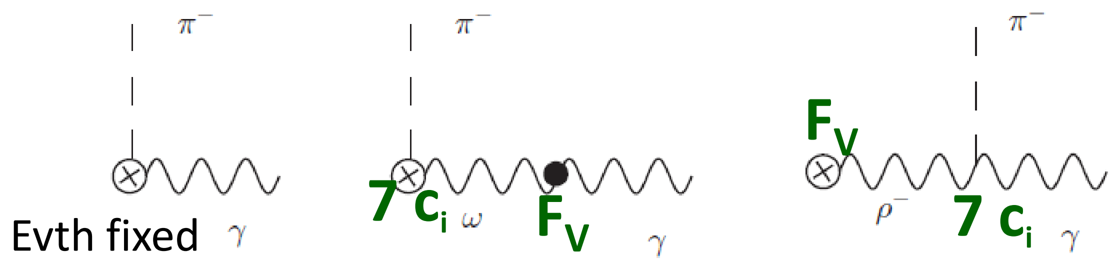
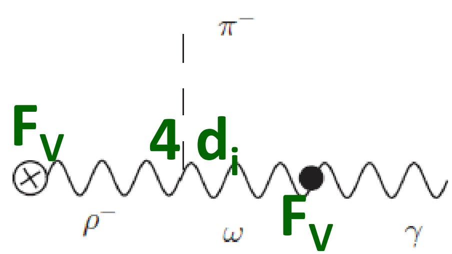
Hadronic contributions $\tau^- \to \pi^- \gamma \nu_\tau$

Axial form factor



Vector form factor





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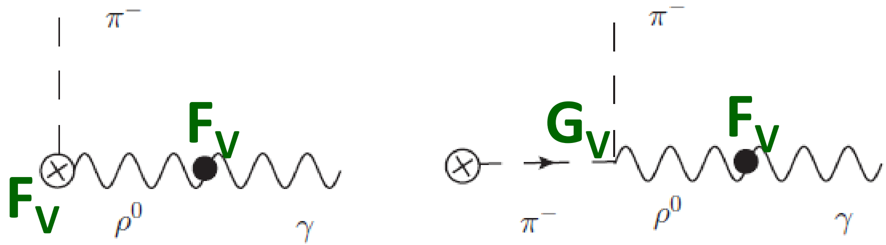
Hadronic contributions $\tau^- \to \pi^- \gamma \nu_\tau$



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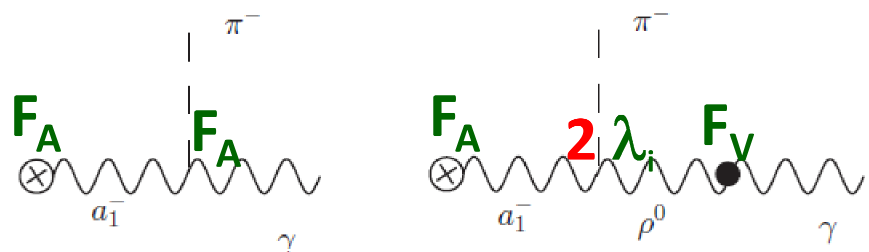
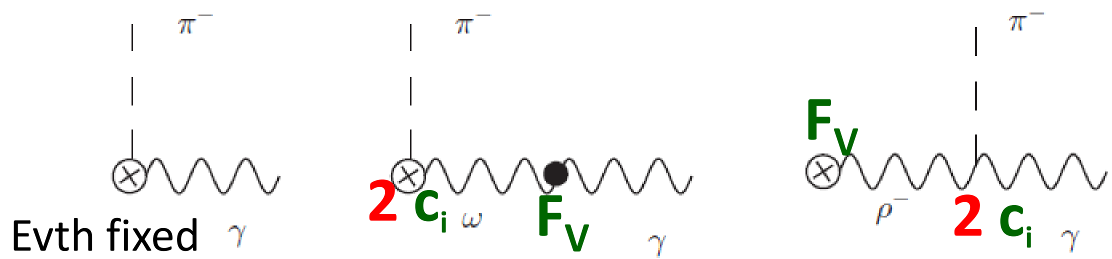
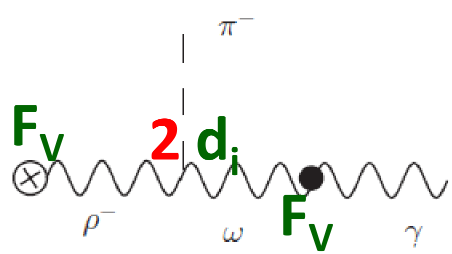


Vector form factor



(One c_i contributes to both diags)

19 → 10



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The program (for hadronic τ decays)

- After evaluating the matrix elements, we require the short-distance QCD constraints. This reduces the number of independent couplings and renders RχT predictive.
- Then we perform a phenomenological analysis using all the available information at hand.
- For the previous step a faithful description of the off-shell width of the broadest resonances is mandatory. **(Phys.Rev.D62:054014,2000; Phys.Lett.B685:158-164,2010)**

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High-energy QCD constraints on $\tau^- \to \pi^- \gamma \nu_\tau$

(more details in backup slides)

- If one subtraction is assumed, no conditions on **axial** form factor.

(Decker, Finkemeier '93)

- If no subtraction is assumed in the **axial** form factor, the results are **consistent** with those in $\tau^- \to (PPP)^- \nu_\tau$

(Phys.Rev.D81:034031,2010; Phys.Lett.B685:158-164,2010)

$$F_V^P(t \to -\infty) = \frac{F}{t}$$ (B rodsky, Lepage ' 7 9, ' 81)

- In the **VFF** the results are **consistent** with those in $\tau^- \to (PPP)^- \nu_\tau$

(Phys.Rev.D81:034031,2010)

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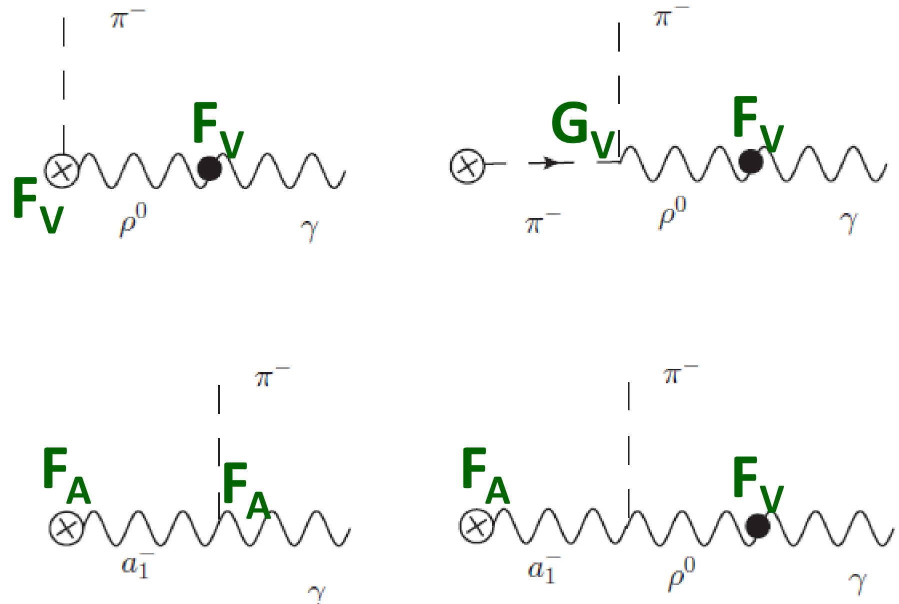
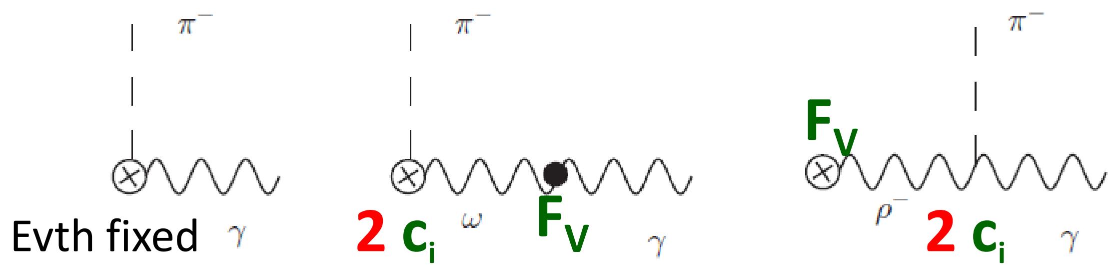
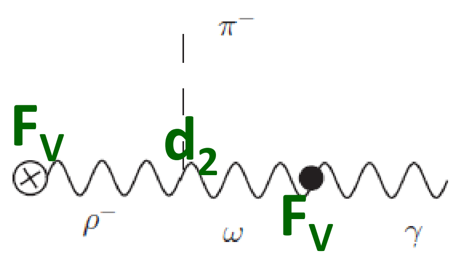
$\tau^- \to \pi^- \gamma \nu_\tau$

Axial form factor



Vector form factor





19 → 10 → 2

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The program (for $\tau^- \to \pi^- \gamma \nu_\tau$)

- Short-distance **QCD** constraints required to the participating axial-vector and vector form-factors: 10 unknowns $\to$ 2 free couplings (isospin breaking).
- These 2 unknowns can be predicted using **QCD** high-energy conditions for the VVP Green Function (**JHEP 0307:003,2003**)
- Since this mode has not been measured yet there are no experimental constraints but we can give a parameter-free prediction to be tested with the discovery data.

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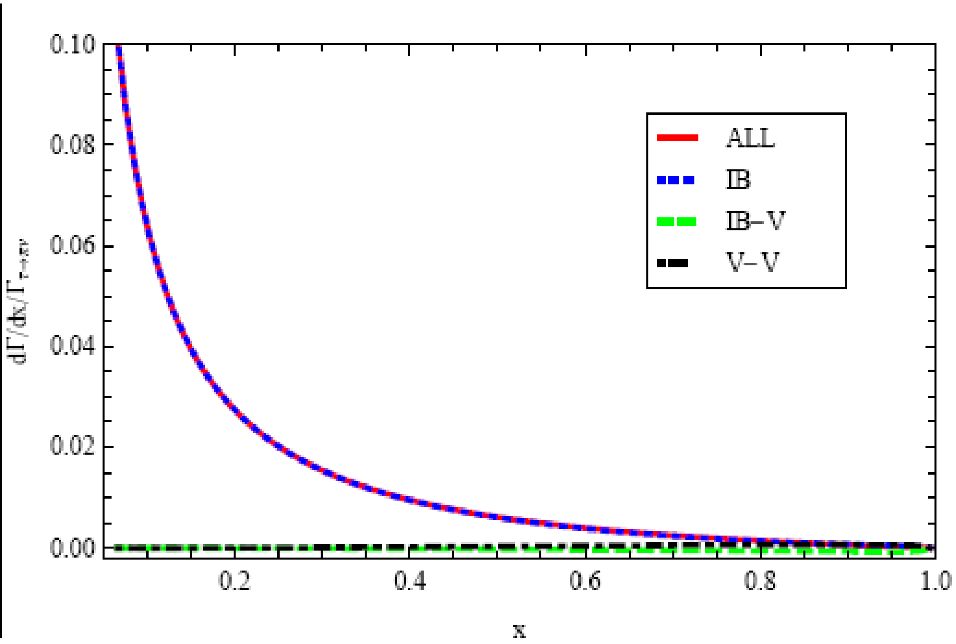
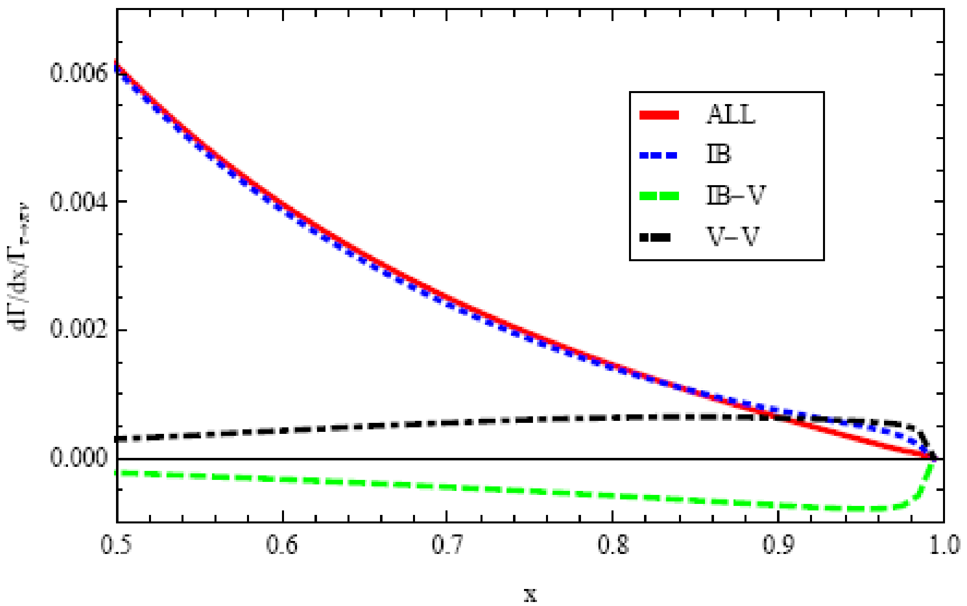
$\tau^- \to \pi^- \gamma \nu_\tau$

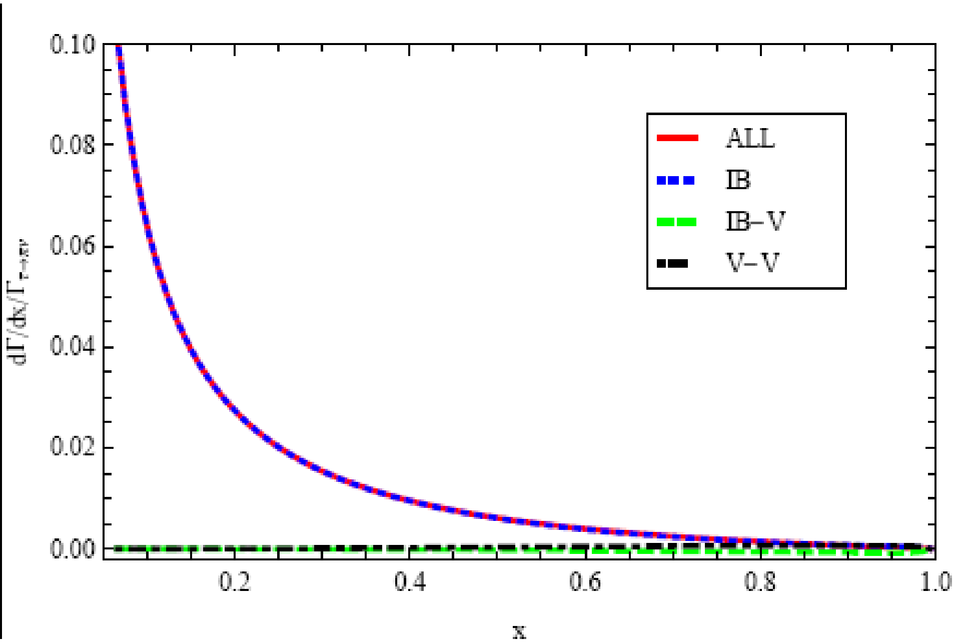
Model independent prediction: Only WZW for the VFF



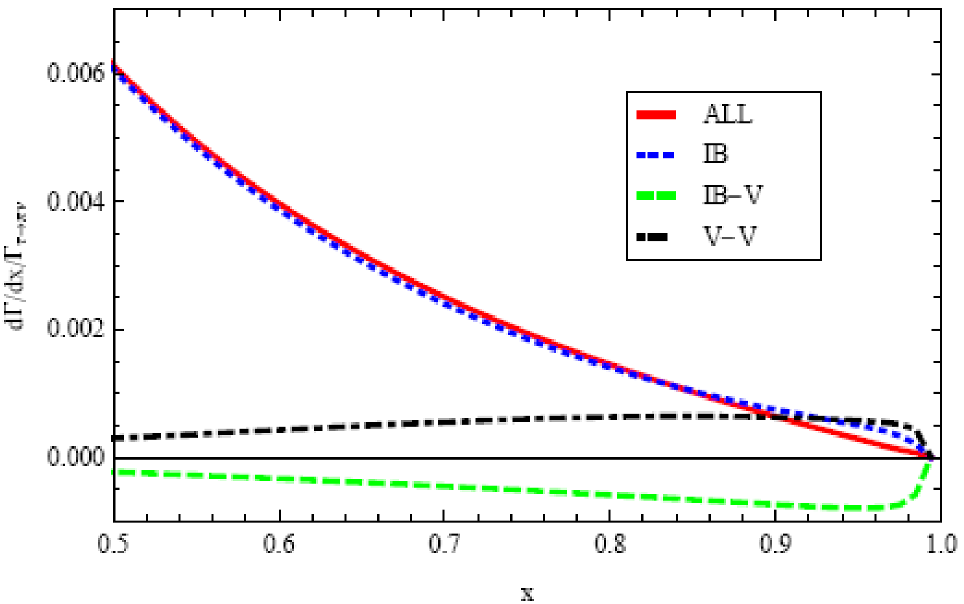


$\tau^- \to \pi^- \gamma \nu_\tau$

Model independent prediction: Only WZW for the VFF



$\Gamma(\tau^- \to \pi^- \gamma \nu_\tau) = 3.182 \cdot 10^{-15}$ GeV



$\Gamma(\tau^- \to \pi^- \gamma \nu_\tau) = 3.615 \cdot 10^{-16}$ GeV

For any reasonable cut on E_γ, this decay should have already been discovered by the heavy-flavour factories

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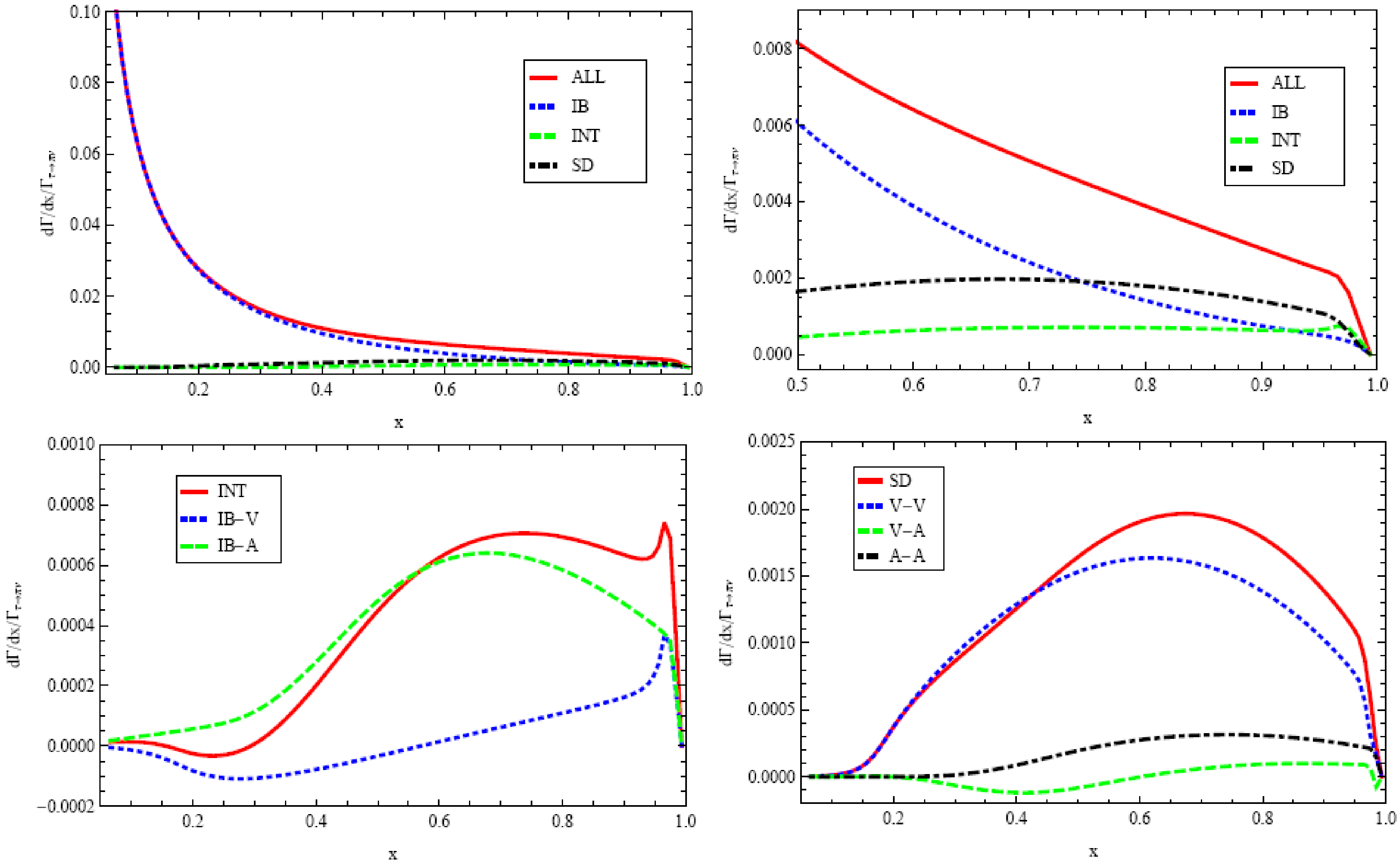
$\tau^- \rightarrow \pi^- \gamma \nu_\tau$

All contributions



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Hadronization in $\tau \rightarrow \pi \gamma \nu_\tau$ decays

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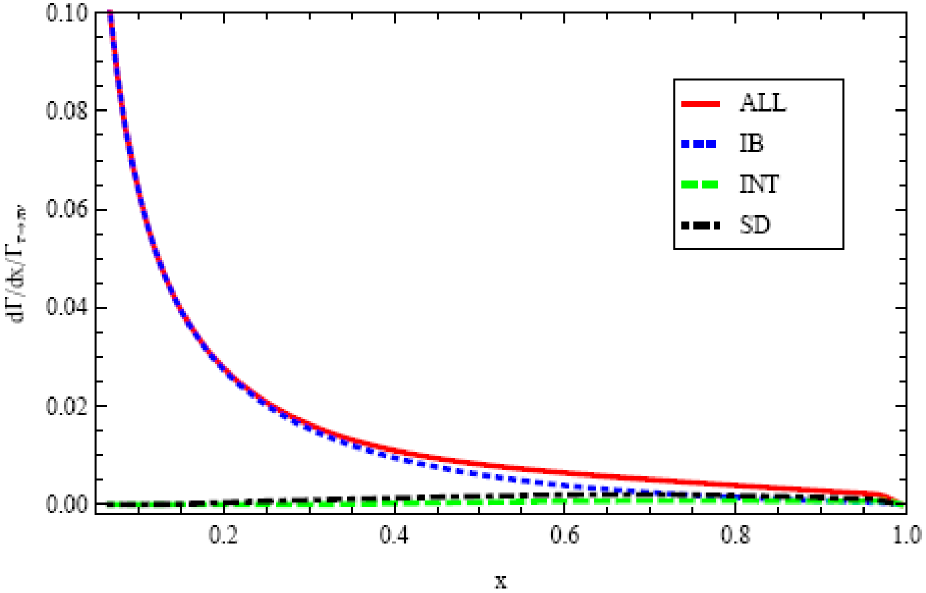
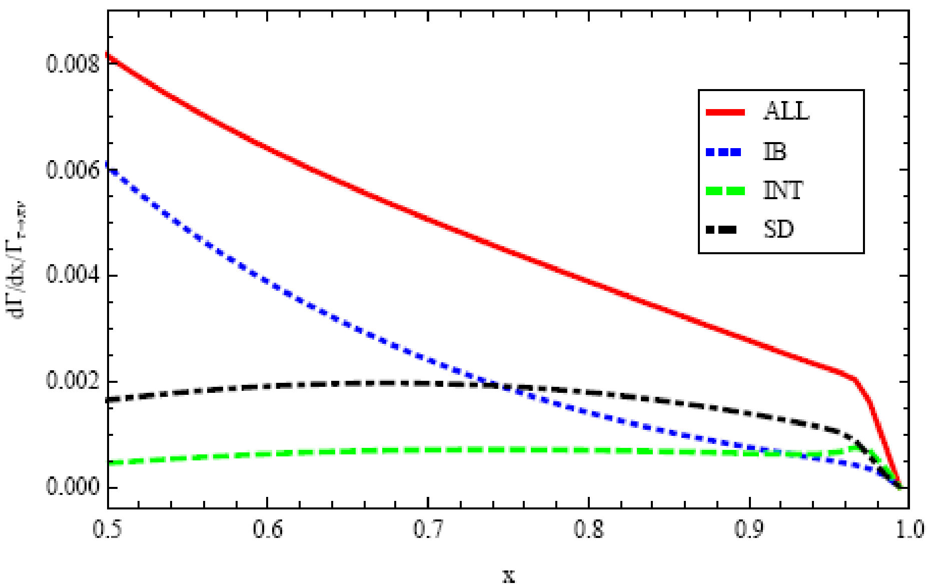
$\tau^- \to \pi^- \gamma \nu_\tau$

All contributions





$\Gamma(\tau^- \to \pi^- \gamma \nu_\tau) = 3.304 \cdot 10^{-14}$ GeV

$\Gamma(\tau^- \to \pi^- \gamma \nu_\tau) = 6.116 \cdot 10^{-15}$ GeV

$\Gamma(\tau^- \to \pi^- \nu_\tau) = 2.471 \cdot 10^{-13}$ GeV

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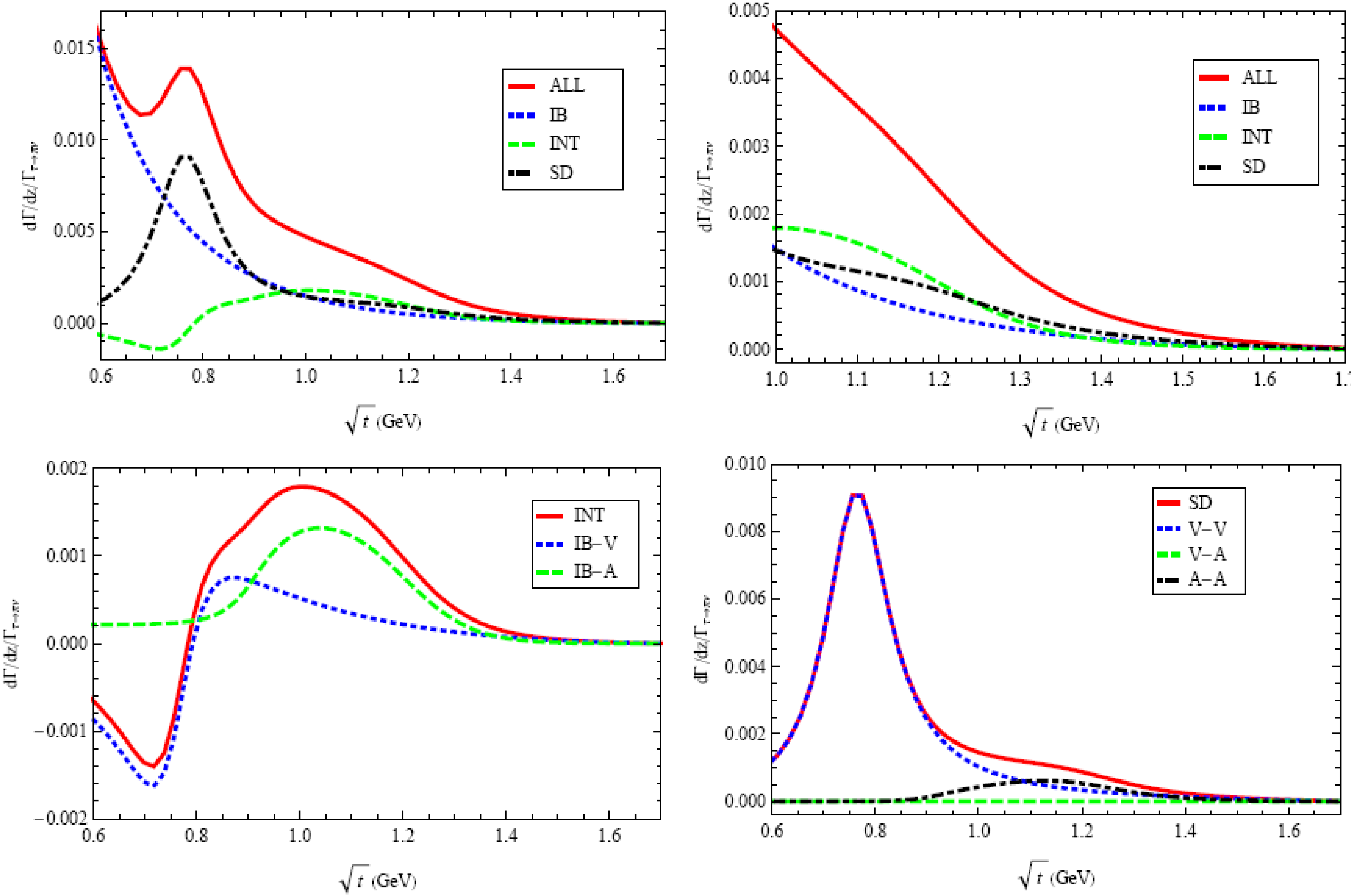
$\tau^- \to \pi^- \gamma \nu_\tau$

$t := (p_\tau - q)^2 = (k+p)^2 = M_\tau^2(x+y-1)$

All contributions



Hadronization in $\tau \to \pi \gamma \nu_\tau$ decays

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Use in data analysis

- τ decay dynamics is interesting in low-energy experiments (Eur. Phys. J.C66:585,2010).
- In order to obtain full benefit of precise data collected at τ-c factories, one should exploit the synergies of theory, and MCGen for bkg estimation and data analysis. For this purpose, TAUOLA (Z. Was talk, arXiv:1001.0070 hep/ph) is an essential tool at disposal of the experimental community that can be interfaced to their software (arXiv:0812.3215 hep/ph).
- There are as well interesting applications in high-energy Physics. In particular, in the Higgs discovery program at ATLAS (arXiv:0901.0512 hep/ex, arXiv:0903.4198 hep/ex)
- Close communication between experts in the theory and MC side and experimental Collaborations should be fostered (TAU10 conference and the satellite WG meeting are ideal arenas for that).

Pablo Roig

LPT (CNRS), Orsay (France)

CONCLUSIONS

- Resonance Chiral Theory is a convenient framework to study hadron decays of the tau based on some properties of QCD: its chiral limit, its large-N_C limit and its known asymptotic behaviour.
- We have applied to the study of the $\tau^- \to \pi^- \gamma \nu_\tau$, decays and checked the consistency of the whole procedure with previous results in other $\tau^- \to (PPP)^- \nu_\tau$ processes.
- This rare decay is of great interest for the B- and τ-c-factories and should be discovered soon allowing for stringent tests of the SM through suitable ratios (Z.H. Guo and P. Roig, in progress).
- Our results are being implemented in **TAUOLA** (more details in the satellite meeting at Liverpool, 18th-19th of September) providing the experimental community a theory based tool to analyze these decays.

Pablo Roig

LPT (CNRS), Orsay (France)

BACKUP SLIDES

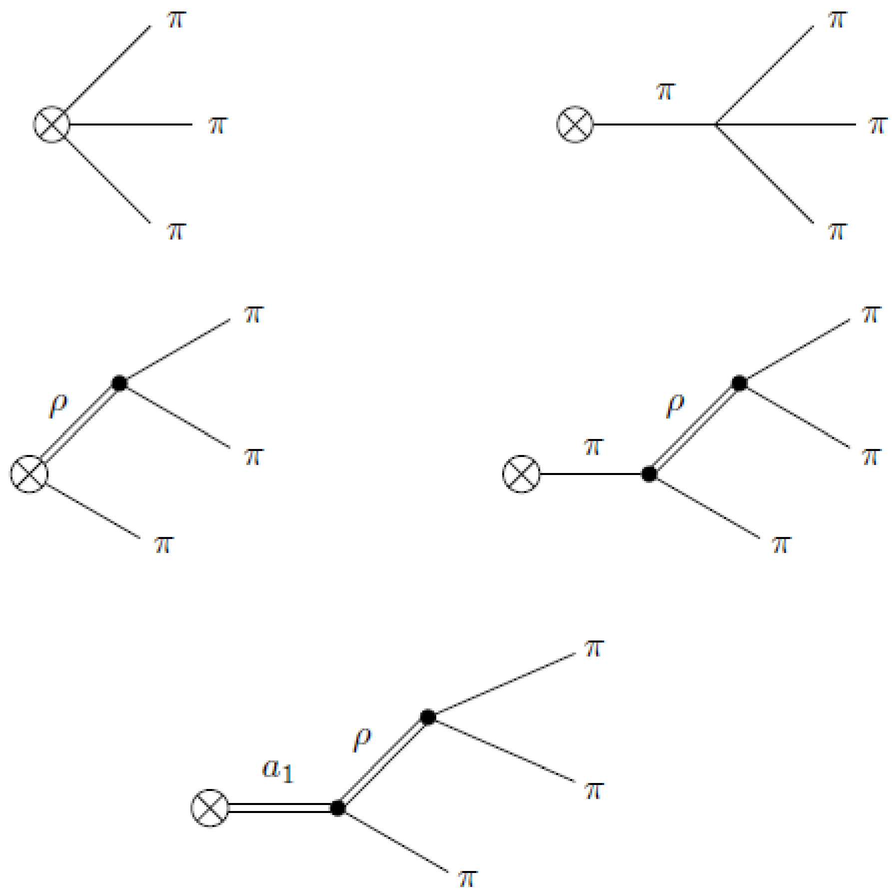
Axial form factor and a_1: $\tau^- \to (3\pi)^- \nu_\tau$

(Gómez-Dumm, Pich, Portolés '04) (Gómez-Dumm, Pich, Portolés, R. **arXiv:0911.4436**)

χPT $\mathcal{O}(p^2)$

RχT, 1R

RχT, 2R



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LPT (CNRS), Orsay (France)

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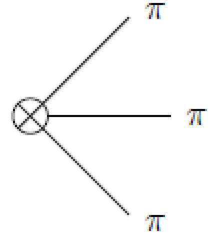
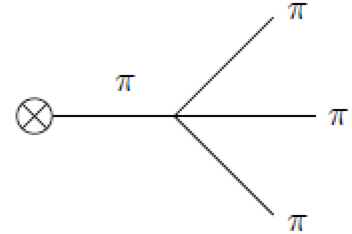
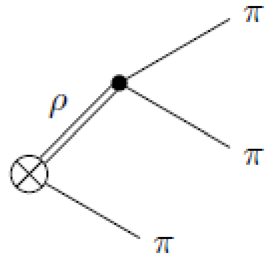


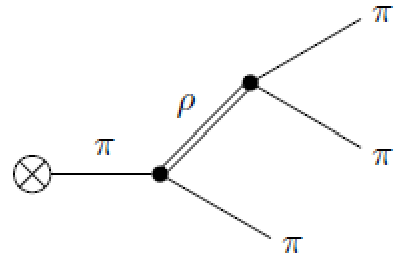
F



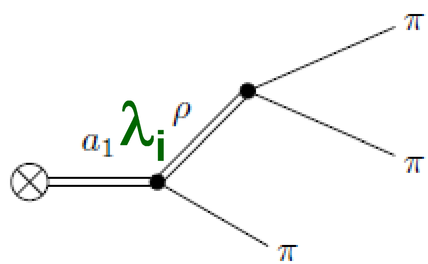
RχT, 1R



$\mathbf{G_V, F_V}$



RχT, 2R



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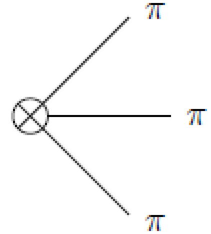

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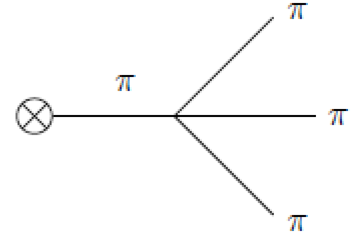
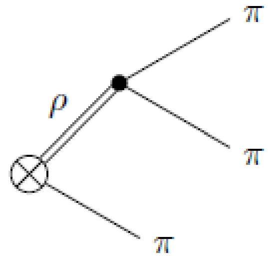
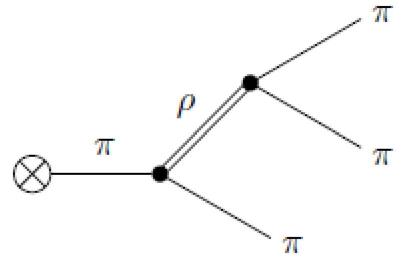


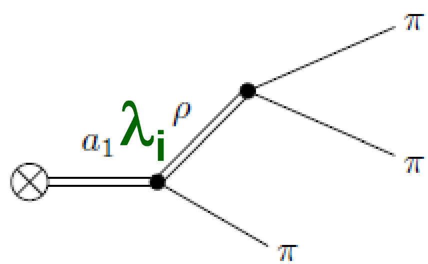
RχT, 1R



G_V, F_V



RχT, 2R



7 unknown couplings

Axial form factor and a_1: $\tau^- \to (3\pi)^- \nu_\tau$

(Gómez-Dumm, Pich, Portolés ‘04) (Gómez-Dumm, Pich, Portolés, R. **arXiv:0911.4436**)

7 unknown couplings

↓

Brodsky-Lepage behaviour demanded to the Form Factors (**7-6 = 1** coupling).

Pablo Roig

LPT (CNRS), Orsay (France)

Axial form factor and a_1: $\tau^- \rightarrow (3\pi)^- \nu_\tau$

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7 unknown couplings

↓

Brodsky-Lepage behaviour demanded to the Form Factors (**7-6 = 1** coupling).

We have **improved** the off-shell description of the **a_1 width** by including all cuts corresponding to 3π and $KK\pi$ intermediate states in the A-A correlator.

The value of this coupling that provides a pretty **accurate description of ALEPH data** is **consistent with** the prediction from **<VAP>** (Cirigliano, Ecker, Eidemüller, Pich, Portolés '04).

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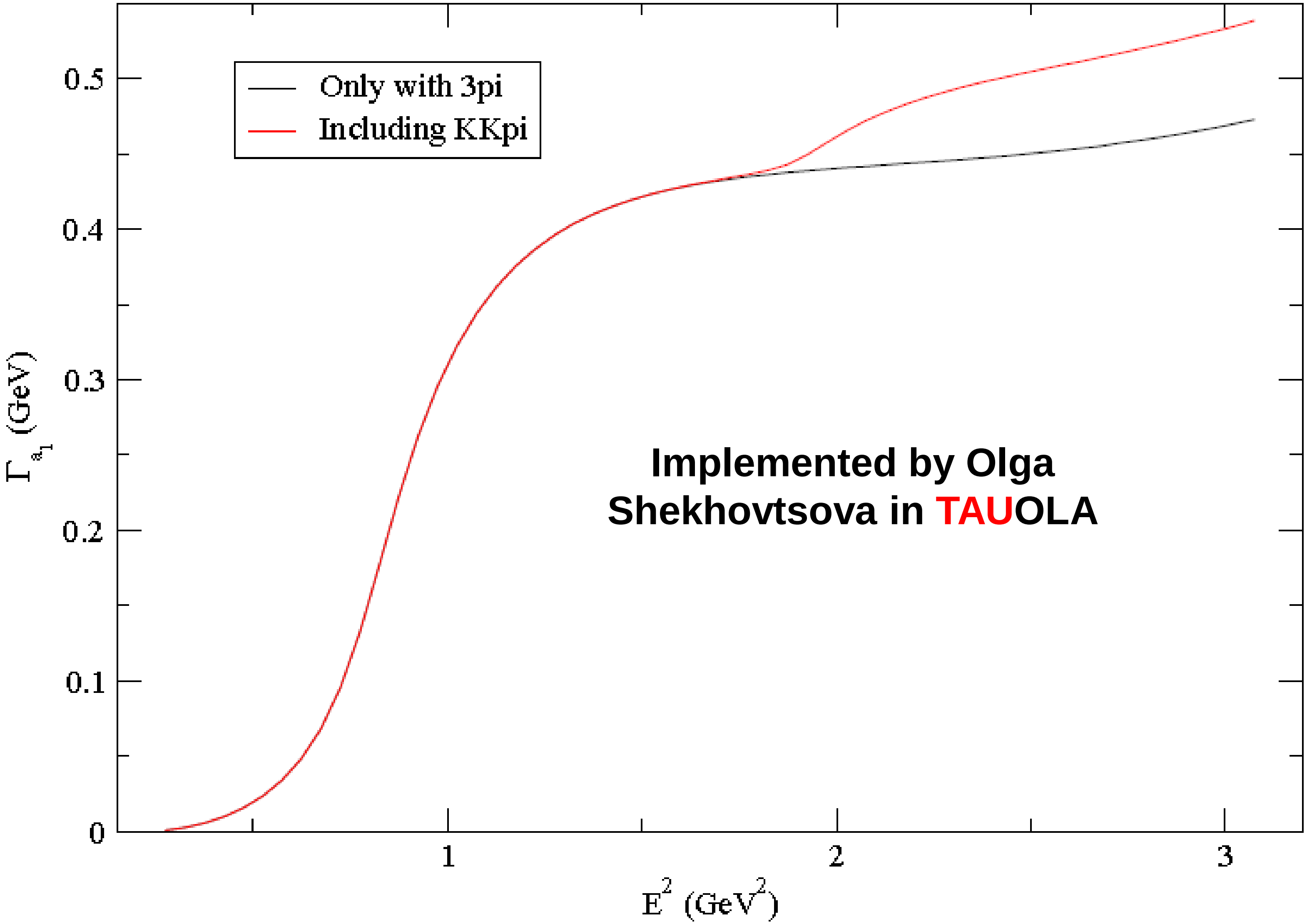
Axial-FF and the a_1: Γ_{a_1} (in TAUOLA)

(R. , Shekhovtsova, Was in progress)



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Axial-FF and the a_1 a_1: $\tau^- \to (3\pi)^- \nu_\tau$

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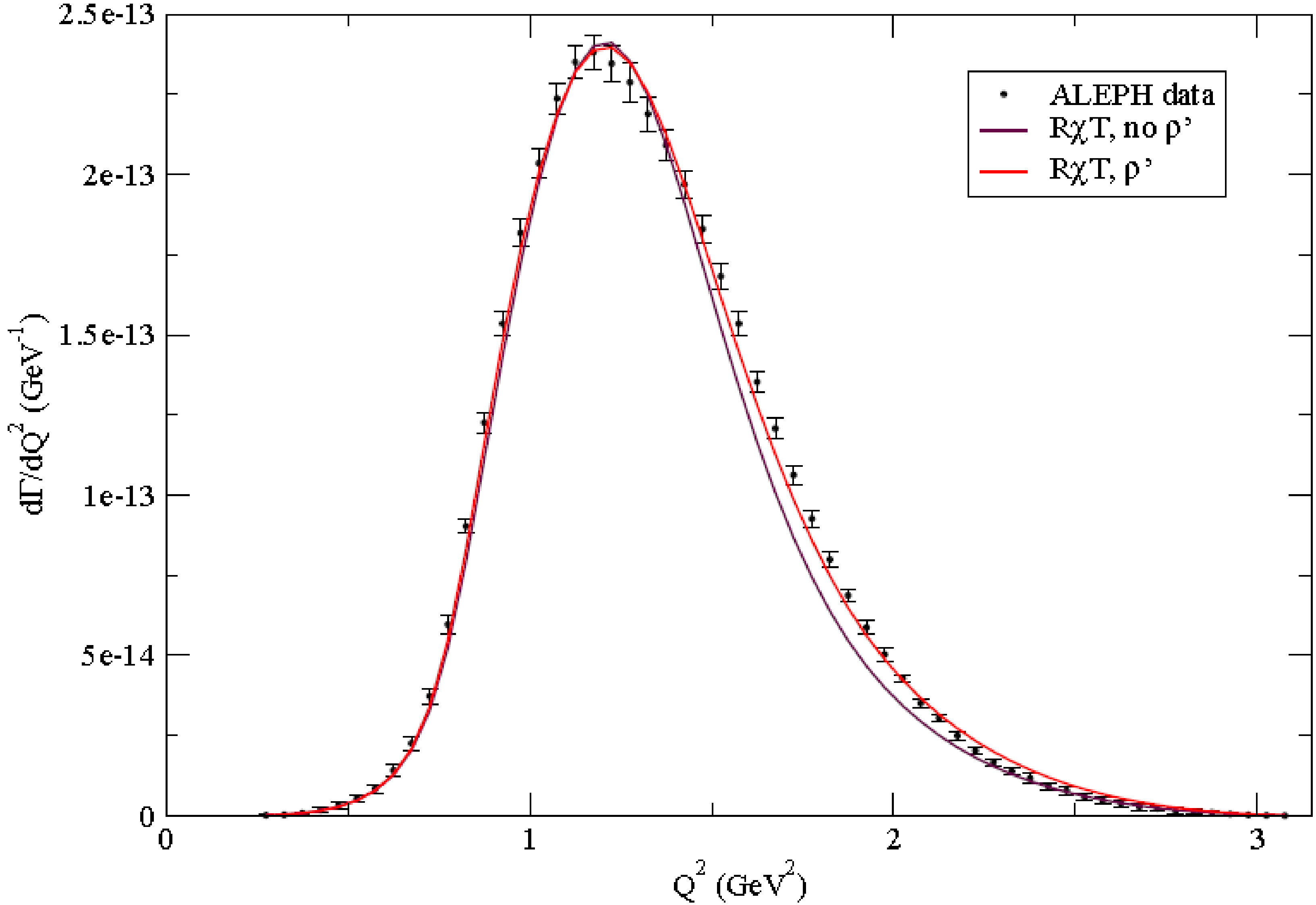

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χPT: The low-energy EFT of QCD

(Gasser & Leutwyler '84, '85)

$$\phi(x)=\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}$$

Goldstone Bosons

$$SU(3)_L \otimes SU(3)_R \to SU(3)_V$$

$$u(x)=\exp\left(\frac{i\phi(x)}{\sqrt{2}F}\right),\quad u_\mu = i\left[u^\dagger(\partial_\mu - ir_\mu)u - u(\partial_\mu - il_\mu)u^\dagger\right]$$

$$\chi = 2B_0(s+ip),\quad \chi_\pm = u^\dagger \chi u^\dagger \pm u\chi u$$

$$f_\pm^{\mu\nu} = uF_L^{\mu\nu}u^\dagger \pm u^\dagger F_R^{\mu\nu}u$$

$$X \to h(g,\Phi)\, X\, h(g,\Phi)^\dagger$$

$$\mathcal{L}^{(2)}_\chi = \frac{F^2}{4}\langle u_\mu u^\mu + \chi_+\rangle$$

$$\mathcal{L}^{(4)}_\chi = L_1\langle u_\mu u^\mu\rangle^2 + \ldots + L_4\langle u_\mu u^\mu\rangle\,\langle\chi_+\rangle + \ldots + L_7\langle\chi_-\rangle^2 + \ldots - iL_9\langle f_+^{\mu\nu}u_\mu u_\nu\rangle + \ldots$$

$\mathcal{L}^{(4)}_{\chi,\,WZW}$ in the odd-intrinsic parity sector

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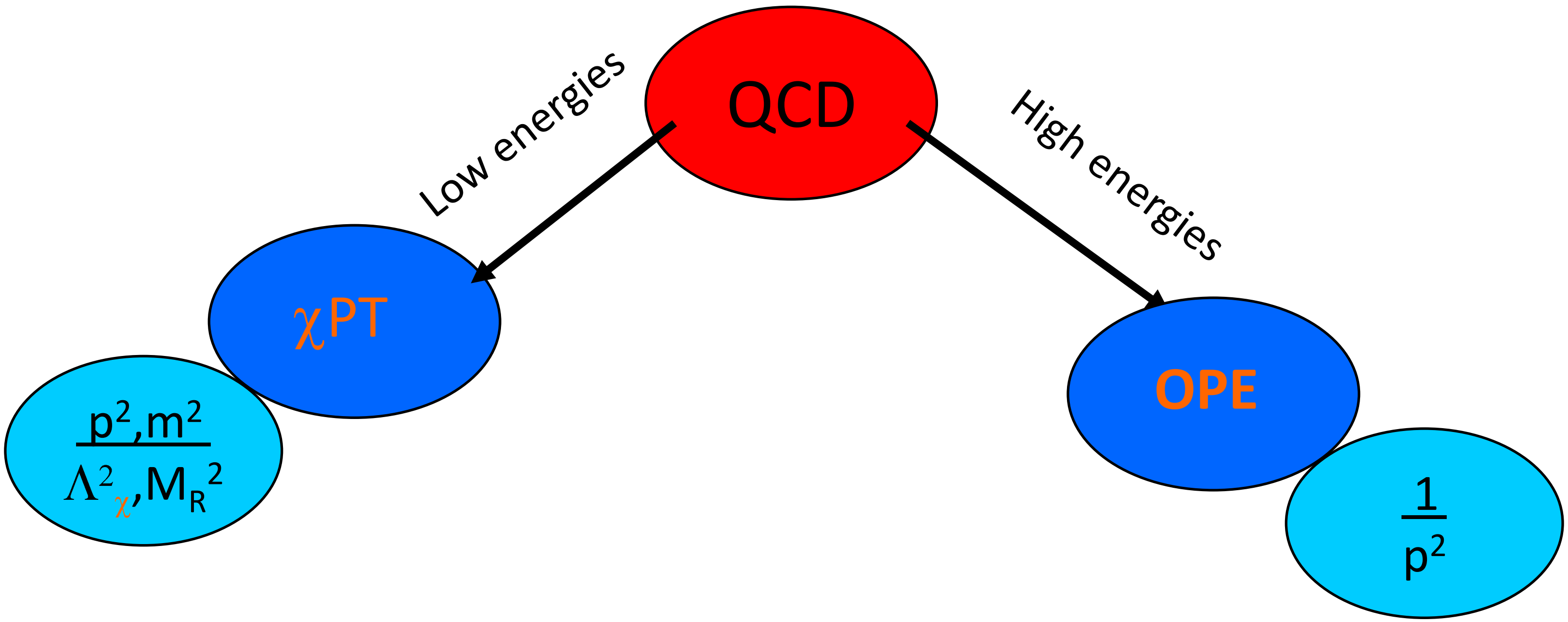
LPT (CNRS), Orsay (France)

RχT matching to the OPE allows it to reproduce QCD high-energy behaviour:



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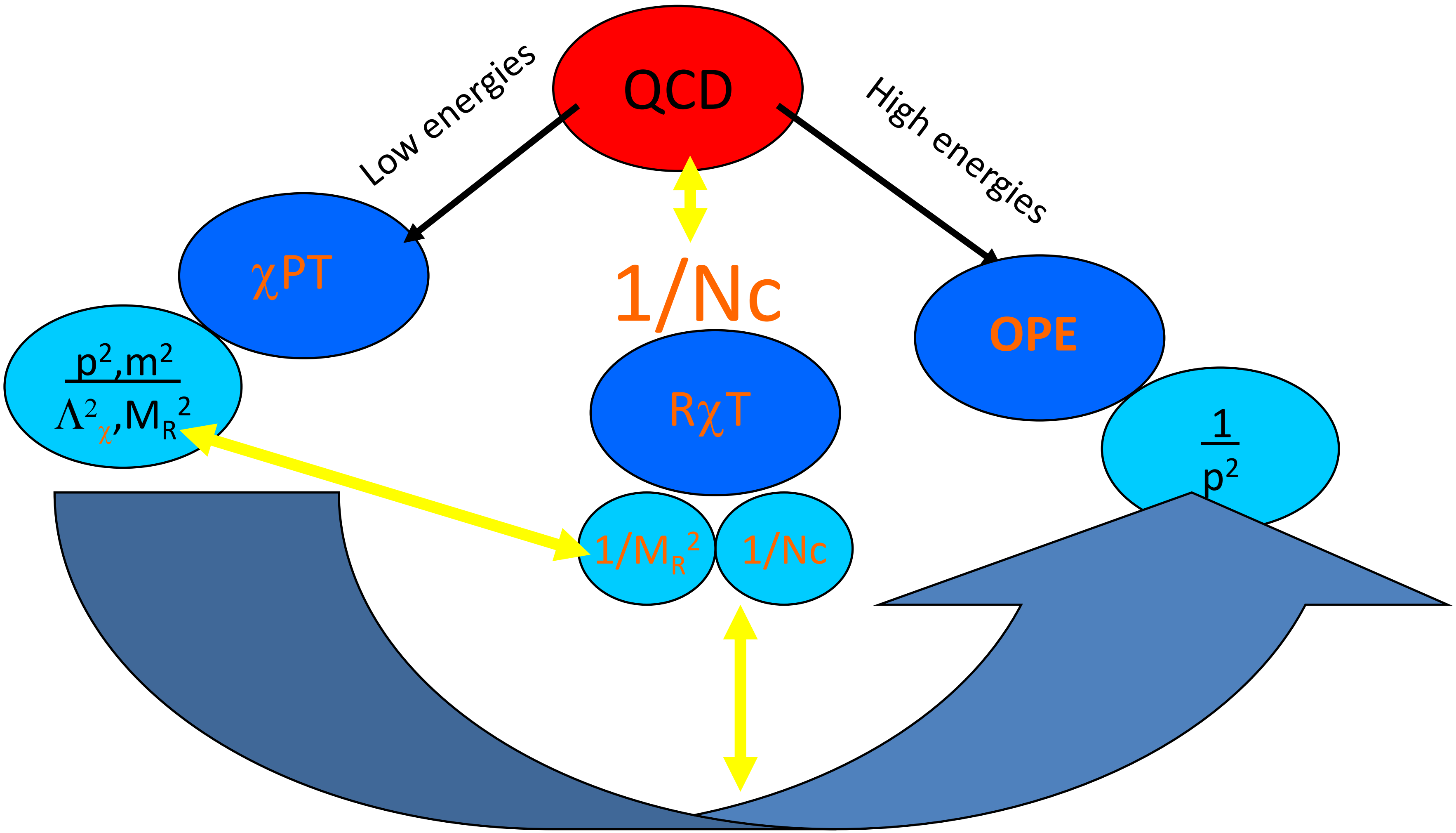

Hadronization in $\tau \to \pi \gamma \nu_\tau$ decays

Pablo Roig

LPT (CNRS), Orsay (France)

Resonances+
Goldstone
Bosons

TOOLS : RχT

(Ecker, Gasser, Pich, De Rafael '89)

(Ecker, Gasser, Leutwyler, Pich, De Rafael '89)

$$\mathcal{L}^{(P_I=+)}_{R\chi T} = \mathcal{L}^{(2)}_{\chi} + \mathcal{L}^{kin}_{V,A} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VAP};$$

$$\mathcal{L}_V = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{\sqrt{2}}\langle V_{\mu\nu} u^\mu u^\nu\rangle$$

$$\mathcal{L}_A = \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle$$

Antisymmetric tensor formalism

$$V_{\mu\nu}(x) = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega_8}{\sqrt{6}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega_8}{\sqrt{6}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & -\frac{2\omega_8}{\sqrt{6}} \end{pmatrix}_{\mu\nu}$$

$$\mathcal{L}_{VAP} = \sum_{i=1}^{5} \lambda_i O^i(V_{\mu\nu}, A^{\mu\nu}, \phi) = \lambda_1 \langle [V_{\mu\nu}, A^{\mu\nu}] \chi_- \rangle + \ldots$$

(Gómez Dumm, Pich, Portolés '04)

$$\mathcal{L}^{(P_I=-)}_{R\chi T} = \mathcal{L}^{(4)}_{\chi(WZW)} + \mathcal{L}_{VJP} + \mathcal{L}_{VVP} + \mathcal{L}_{VPPP};$$

VMD

$$\mathcal{L}_{VJP} = \sum_{i=1}^{7} \frac{c_i}{M_V} O^i(V_{\mu\nu}, j^\nu, \partial^\mu \phi) = \frac{c_5}{M_V}\varepsilon_{\mu\nu\rho\sigma}\langle \{\nabla_\alpha V^{\mu\nu}, f_+^{\rho\alpha}\} u^\sigma \rangle + \ldots$$

(Ruiz-Femenía, Pich, Portolés '03)

$$\mathcal{L}_{VVP} = \sum_{i=1}^{5} d_i O^i(V_{\mu\nu}, V_{\rho\sigma}, \phi) = d_1 \varepsilon_{\mu\nu\rho\sigma}\langle \{V^{\mu\nu}, V^{\rho\alpha}\} \nabla_\alpha u^\sigma \rangle + \ldots$$

$$\mathcal{L}_{VPPP} = \sum_{i=1}^{5} \frac{g_i}{M_V} O^i(V_{\mu\nu}, \phi) = \frac{g_4}{M_V}\varepsilon_{\mu\nu\alpha\beta}\langle \{V^{\mu\nu}, u^\alpha u^\beta\} \chi_- \rangle + \ldots$$

(Gómez-Dumm, Pich, Portolés, R. **arXiv:0911.2640**)

Resonances+ Goldstone Bosons

TOOLS : RχT

(Ecker, Gasser, Pich, De Rafael '89)

(Ecker, Gasser, Leutwyler, Pich, De Rafael '89) ,...

$$\mathcal{L}^{(P_I=+)}{}_{R\chi T} = \mathcal{L}^{(2)}{}_{\chi} + \mathcal{L}^{kin}{}_{V,A} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VAP};$$

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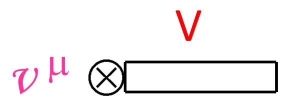

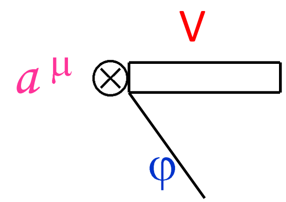

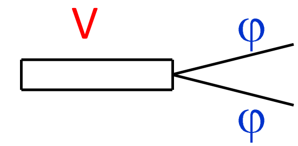

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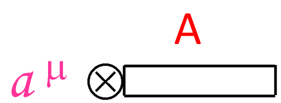
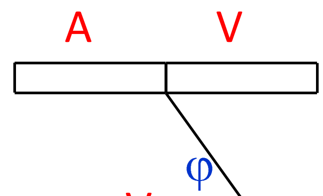
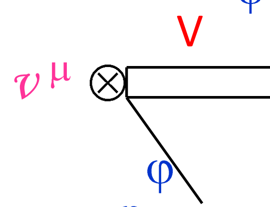


$$\mathcal{L}_{VAP} = \sum_{i=1}^{5} \lambda_i O^i(V_{\mu\nu}, A^{\mu\nu}, \phi) = \lambda_1 \langle [V_{\mu\nu}, A^{\mu\nu}]\chi_-\rangle + \ldots$$

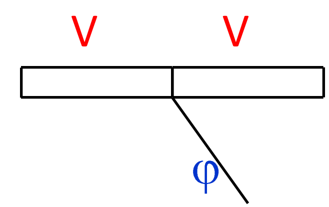


$$\mathcal{L}^{(P_I=-)}{}_{R\chi T} = \mathcal{L}^{(4)}{}_{\chi(WZW)} + \mathcal{L}_{VJP} + \mathcal{L}_{VVP} + \mathcal{L}_{VPPP};$$

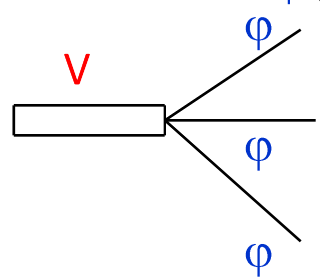
$$\mathcal{L}_{VJP} = \sum_{i=1}^{7} \frac{c_i}{M_V} O^i(V_{\mu\nu}, j^\nu, \partial^\mu\phi) = \frac{c_5}{M_V}\varepsilon_{\mu\nu\rho\sigma}\langle \{\nabla_\alpha V^{\mu\nu}, f_+^{\rho\alpha}\} u^\sigma\rangle + \ldots$$



$$\mathcal{L}_{VVP} = \sum_{i=1}^{5} d_i O^i(V_{\mu\nu}, V_{\rho\sigma}, \phi) = d_1 \varepsilon_{\mu\nu\rho\sigma}\langle \{V^{\mu\nu}, V^{\rho\alpha}\}\nabla_\alpha u^\sigma\rangle + \ldots$$



$$\mathcal{L}_{VPPP} = \sum_{i=1}^{5} \frac{g_i}{M_V} O^i(V_{\mu\nu}, \phi) = \frac{g_4}{M_V}\varepsilon_{\mu\nu\alpha\beta}\langle \{V^{\mu\nu}, u^\alpha u^\beta\}\chi_-\rangle + \ldots$$

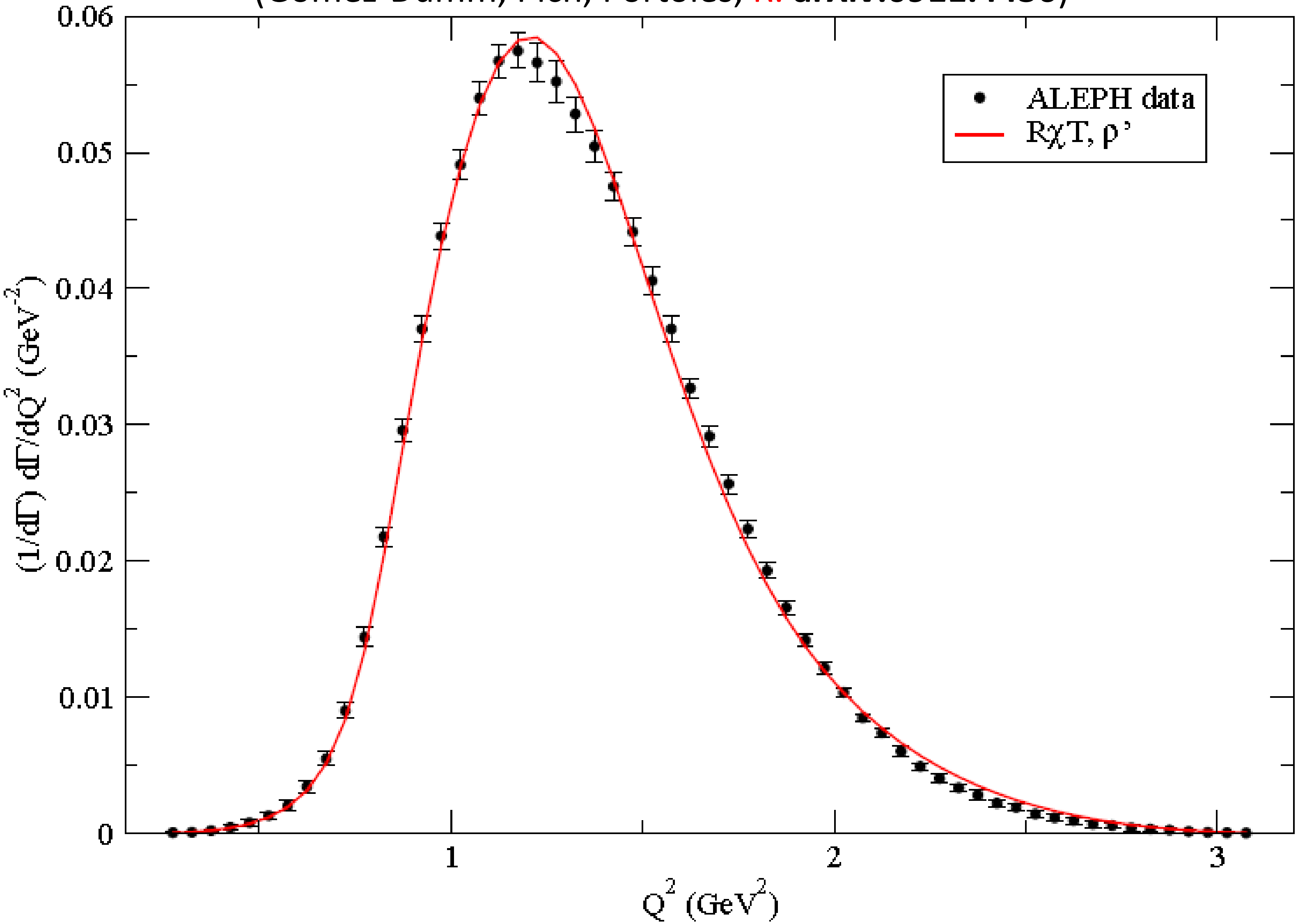


Pablo Roig

LPT (CNRS), Orsay (France)

The axial-form factor and the a_1: $\tau^- \to (3\pi)^- \nu_\tau$

(Gómez-Dumm, Pich, Portolés, R. **arXiv:0911.4436**)



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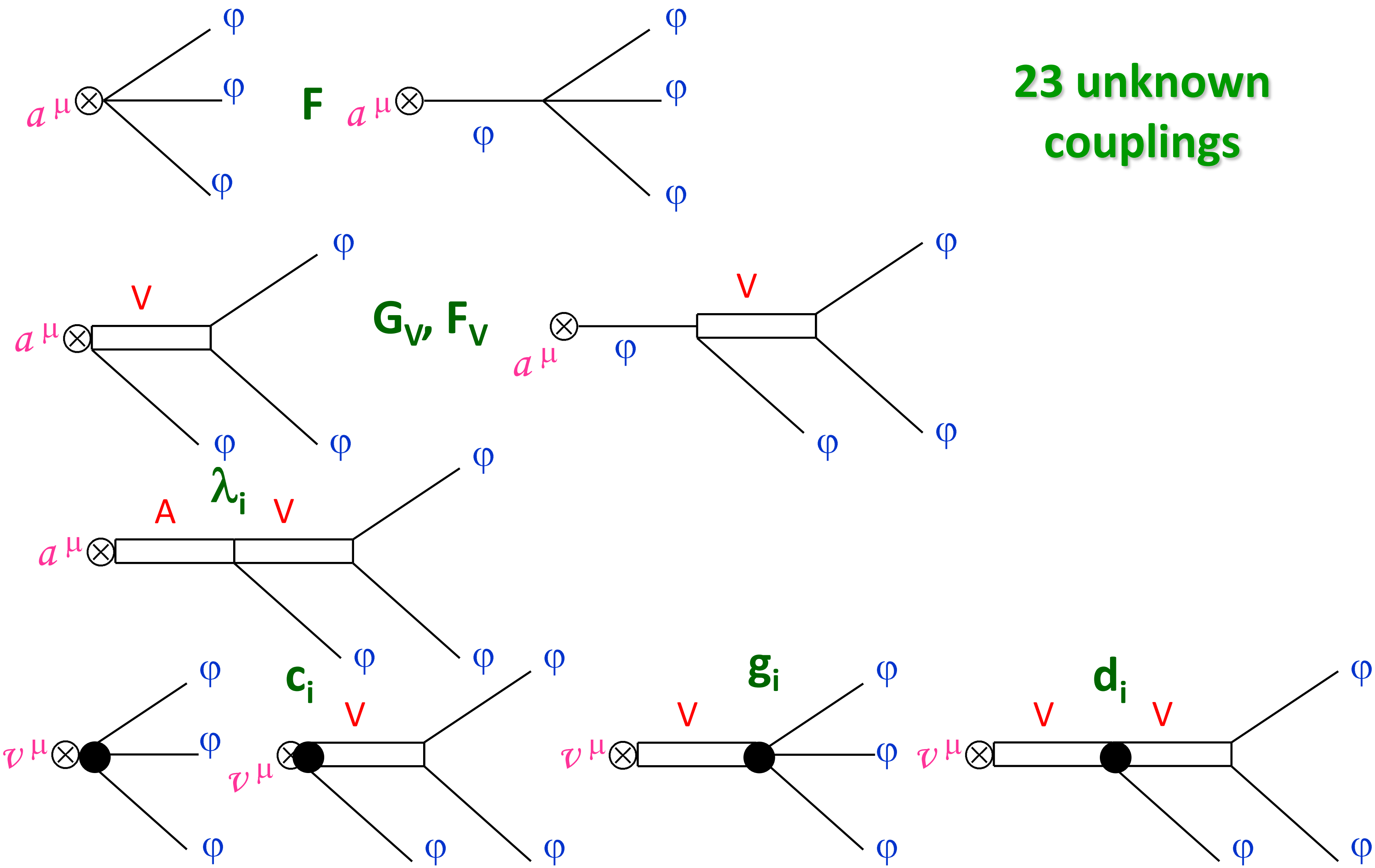
RχT APPLIED



23 unknown couplings

Pablo Roig

LPT (CNRS), Orsay (France)

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(Gómez-Dumm, Pich, Portolés '00) (Gómez-Dumm, Pich, Portolés, R. **arXiv:0911.4436**)

$$\Gamma_\rho(s) = \frac{M_\rho s}{96\pi F^2}\left[\sigma^3_\pi \Theta(s-4m_\pi^2) + \frac{1}{2}\sigma^3_K \Theta(s-4m_K^2)\right]$$

$$\Gamma_{a_1}(Q^2) = \Gamma_{a_1}^{3\pi}(Q^2) + \Gamma_{a_1}^{K\bar{K}\pi}(Q^2) + \Gamma_{a_1}^{(K\pi)^0 K^0}(Q^2),$$

$$\Gamma_{a_1}^{3\pi}(Q^2) = \frac{1}{48(2\pi)^3 M_{a_1}}\left(\frac{Q^2}{M_{a_1}^2}\right)\iint ds\,dt\ \ F_1' V_{1\mu} + F_2' V_{2\mu}\ \cdot$$

$$F_1'^{\dagger} V_{1\mu} + F_2'^{\dagger} V_{2\mu}\ , \quad F_i' = F_i \frac{M_{a_1}^2 - Q^2}{\sqrt{2} F_A Q^2}$$

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