HADRONIZATION OF QCD CURRENTS: $\tau \to KK\pi\nu_\tau$

Work done in collaboration with D. Gómez-Dumm, A. Pich, J. Portolés

TAU'08

BINP, Novosibirsk

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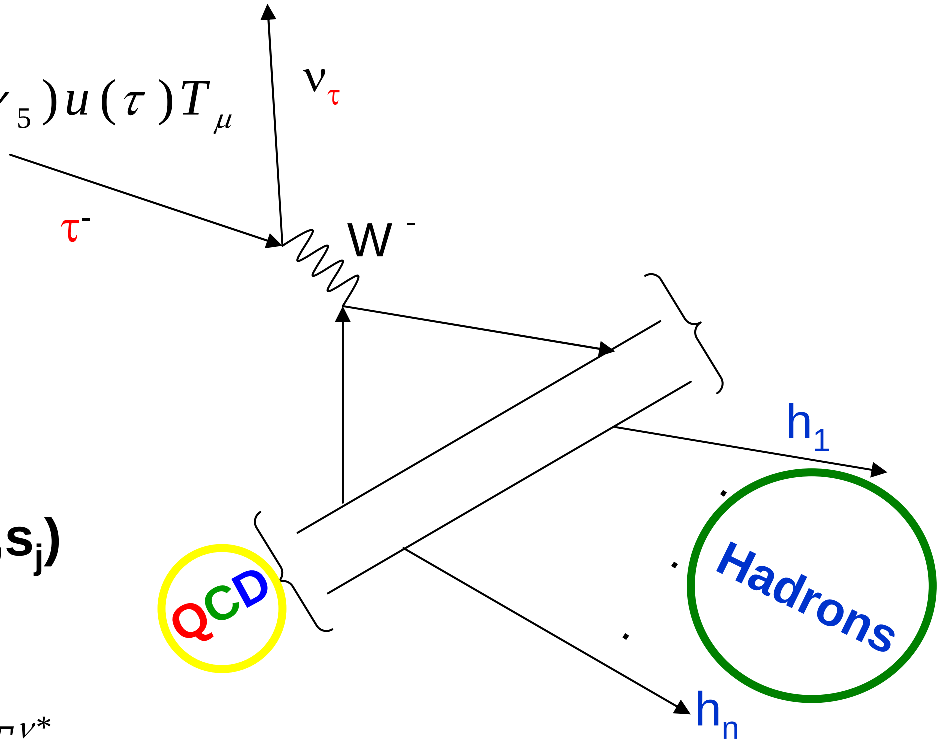
SUMMARY:

- Hadronic decays of the τ lepton
- **K**ühn-**S**antamaría Model in TAUOLA
- Tools : χPT, Large N_c , RχT
- $\tau^- \to (2K\,\pi)^- \nu_\tau$ (Gómez Dumm, Pich, Portolés, R. to appear)
- Conclusions

HADRONIC DECAYS OF THE τ LEPTON

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



$$T_\mu = \langle \text{Hadrons} | (V-A)_\mu \, e^{iS_{QCD}} | 0 \rangle =$$

$$= \Sigma_i (\text{Lorentz Structure})^i \, F_i(Q^2, s_j)$$

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

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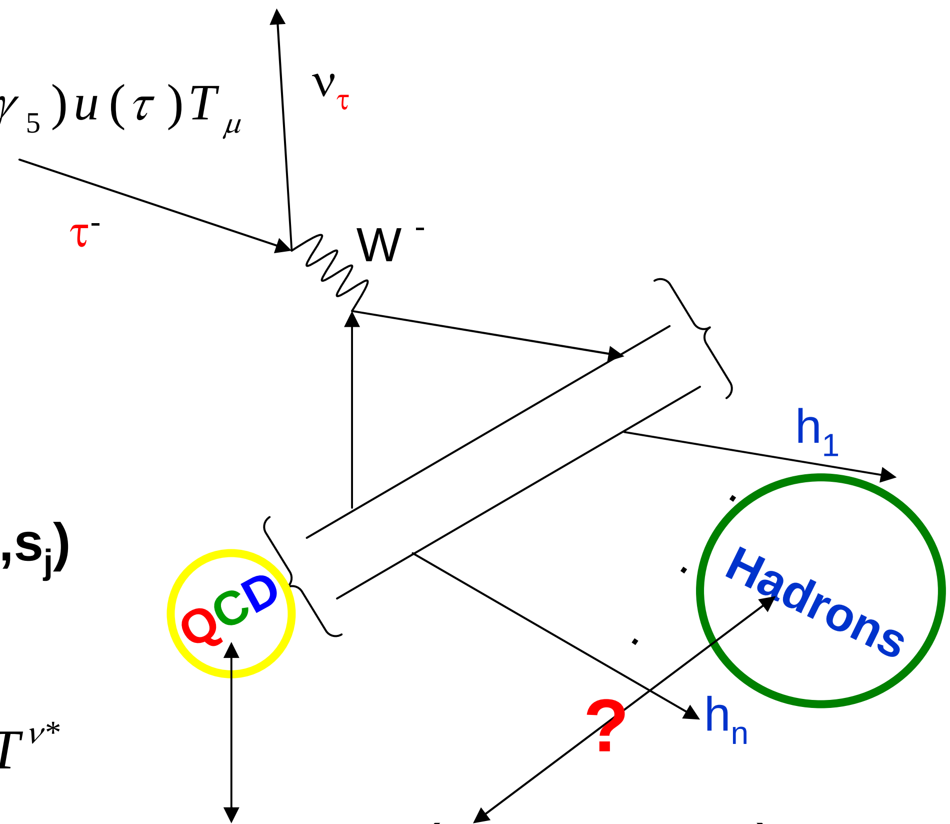

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$$d\Gamma = \frac{G_F^{\,2}}{4M_\tau^{\,2}} |V_{CKM}|^2\, d\Phi^{(n+1)}\, L_{\mu\nu} T^\mu T^{\nu *}$$

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}\,(q_i, G_\mu^a; g_s, m_i)$$

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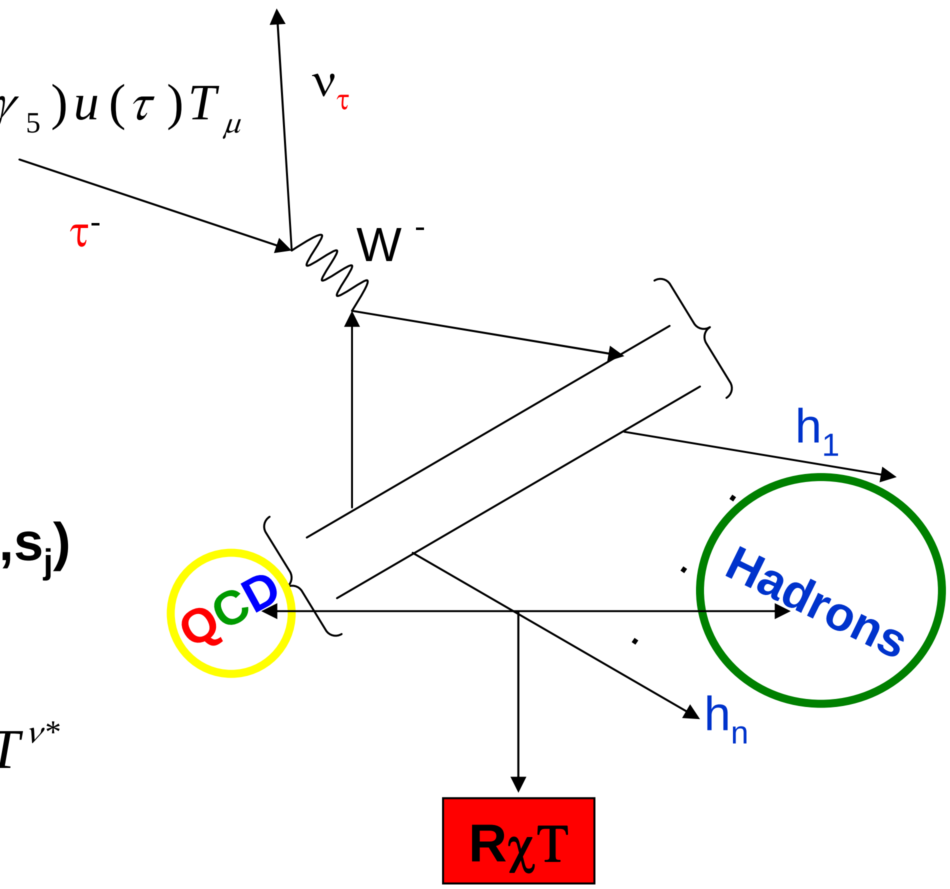

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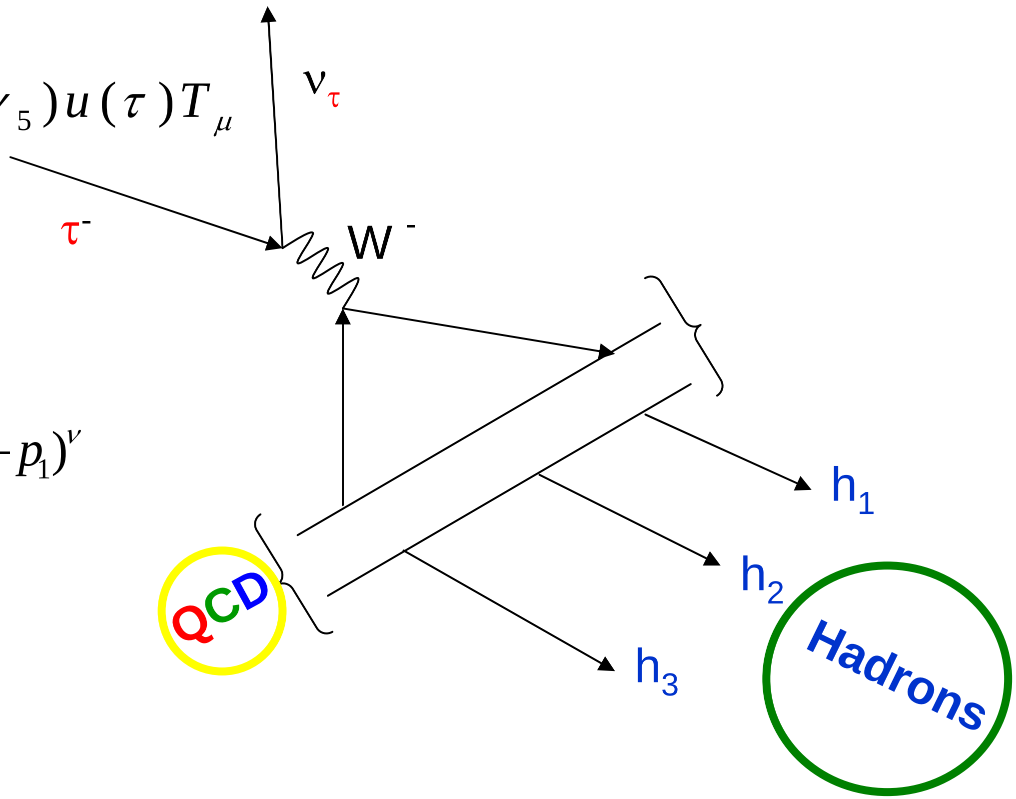
$$\tau^- \to h_1(p_1)h_2(p_2)h_3(p_3)\nu_\tau$$

$$(p_1+p_2+p_3)^\mu = Q^\mu,\ V_{\substack{1\mu\\2\mu}} = \left(g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2}\right)(p_{\substack{2\\3}} - p_1)^\nu$$

$$T_\mu = V_{1\mu}F_1 + V_{2\mu}F_2 + Q_\mu F_P + i\varepsilon_{\mu\nu\rho\sigma}p_1^\nu p_2^\rho p_3^\sigma F_V$$

$$\frac{d\Gamma}{dQ^2} = \frac{G_F^{\,2}|V_{CKM}|^2}{128(2\pi)^5 M_\tau^{\,3}}\int ds\,dt\, f\left(I_{0^-}, I_{1^+}, I_{1^-}\right)$$



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KÜHN-SANTAMARÍA MODEL

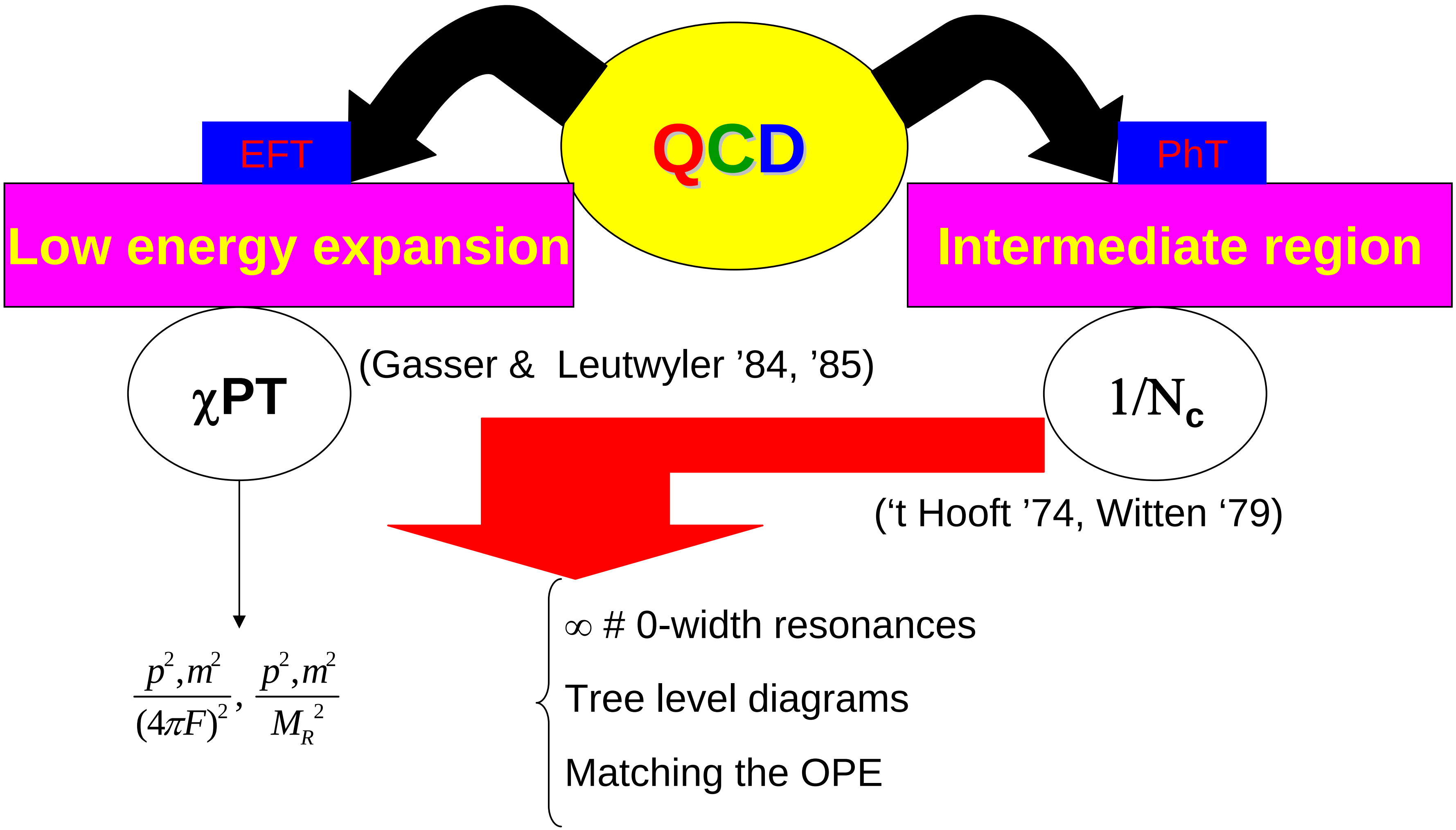
(Kühn-Santamaría ‘90)

KS

- χPT $\mathcal{O}(p^2)$ — χPT $\mathcal{O}(p^4)$
- Vector Meson Dominance (Sakurai ’69, Kühn & Wagner ’84, Pich ’87)
- Asymptotic behaviour ruled by QCD (Brodsky-Farrar ’73, B-Lepage ‘80)

? $$BW_R(x^2) = \frac{M_R^{\,2}}{M_R^{\,2} - x^2 - i\sqrt{x^2}\,\Gamma_R(x^2)}$$ (Gounaris-Sakurai ‘68)

TOOLS: EFFECTIVE FIELD THEORIES



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TOOLS: EFFECTIVE FIELD THEORIES

QCD

EFT — Low energy expansion

PhT — Intermediate region

χPT (Gasser & Leutwyler '84, '85)

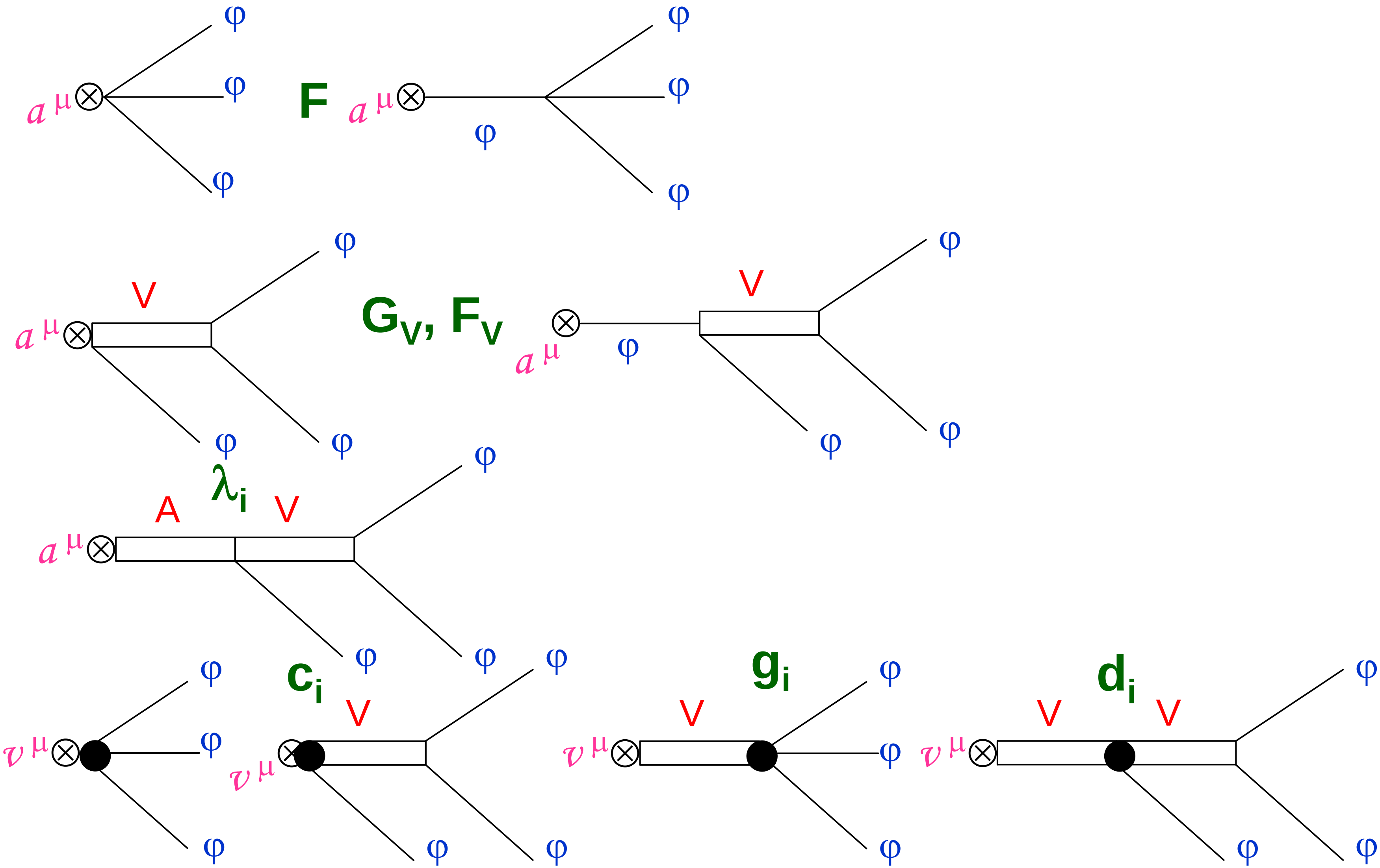
$$\frac{p^2, m^2}{(4\pi F)^2}, \quad \frac{p^2, m^2}{M_R^2}$$

$1/N_c$ ('t Hooft '74, Witten '79)

RχT

- ∞ # 0-width resonances → Only one nonet (Peris, Perrottet, de Rafael '98); → Off-shell width (Gómez-Dumm, Pich, Portolés '00)
- Tree level diagrams
- Matching the OPE

RχT APPLIED



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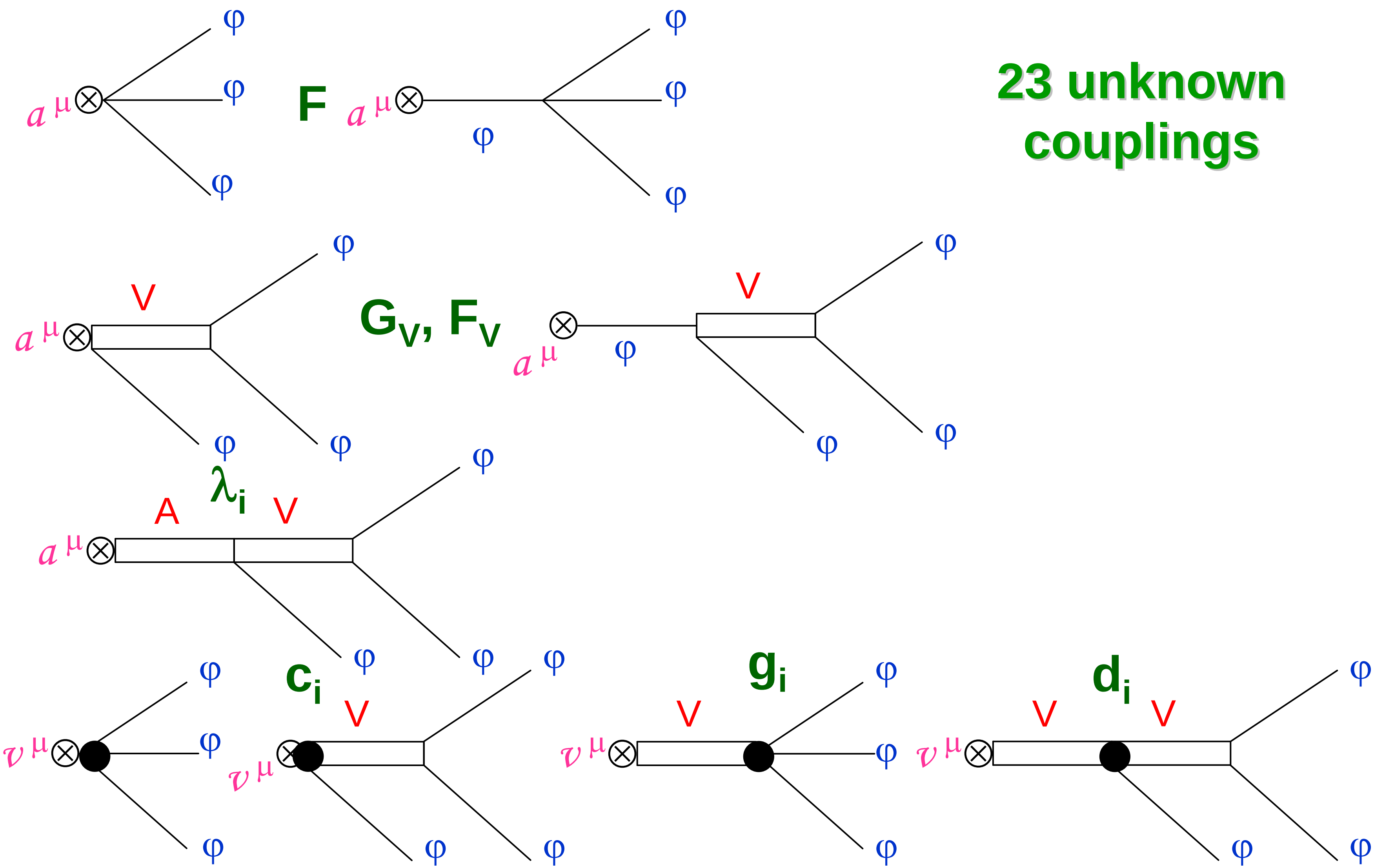

23 unknown couplings

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$\tau^- \to (2K\pi)^- \nu_\tau$

The phenomenological approach of KS-like works (Finkemeier and Mirkes '95, '96) does not include all possible contributions for the exchanged resonances and depends noticeably on the excited *resonance parameters*.

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CLEO (Liu ’03, CLEO ‘04) could not fit their data using KS expressions and reshaped the model violating the normalization of the WZ term (i.e. low-energy **QCD**).

$\tau^- \to (2K\pi)^- \nu_\tau$

BaBar has recently (BaBar '07) published very precise data on $e^+e^- \to KK\,\pi/\eta$ using **ISR** events. Furthermore, their Dalitz-plot fit has allowed to separate cleanly the I=0,1 contributions.

Assuming **CVC** and comparing to ALEPH '99 allows to derive $(\Gamma_V/\Gamma_T) = 0.167 \pm 0.024$ in $\tau^- \to (KK\,\pi)^- \nu_\tau$. Under **CVC** one can relate e^+e^- data to the τ decay.

(Davier, Descotes-Genon, Höcker, Malaescu, Zhang '08)

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$K^* >> \rho,\omega,\phi$

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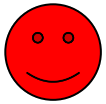
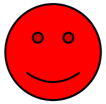
Assumptions of this procedure: SU(2) symmetry 

$K^* >> \rho,\omega,\phi$ 

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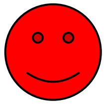
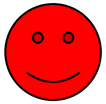
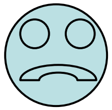
Assumptions of this procedure: SU(2) symmetry 

$K^* >> \rho,\omega,\phi$ 

Interferences are negligible 

↓

Error of this simplification ~ 30 % both in KS approach and in ours

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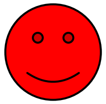
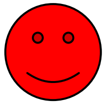
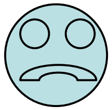
Assumptions of this procedure: SU(2) symmetry 

$K^* \gg \rho,\omega,\phi$ 

Interferences are negligible 

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Error of this simplification ~ 30 % both in KS approach and in ours

(Apart from the error intrinsic to using Breit-Wigner function for resonance exchange)

$\tau^- \to (2K\pi)^- \nu_\tau$

Our work:

(Gómez Dumm, Pich, Portolés, R. to appear)

1. Computation of the involved process within **RχT**(**23-8 =15** couplings).
2. Brodsky-Lepage behaviour demanded to the Form Factors (**15-9= 6** couplings).
3. Computation and fit to Br($\omega \to 3\pi$) completing (Pich, Portolés, Ruiz-Femenía '03). Use of some constraints from this work for **<VVP>** (**6-3= 3** couplings).
4. **Axial-form factor fixed** by $\tau \to 3\pi\, \nu_\tau$ (**3-1= 2** couplings)**.** (Gómez-Dumm, Pich, Portolés '04) (Cirigliano, Ecker, Eidemüller, Pich, Portolés '04).
5. **Vector-form factor fixed** thanks to br ($\tau \to K^+ K^- \pi^- \nu_\tau$) and br($\tau \to K^- K^0 \pi^0 \nu_\tau$) (**2-2= 0** couplings)**.**

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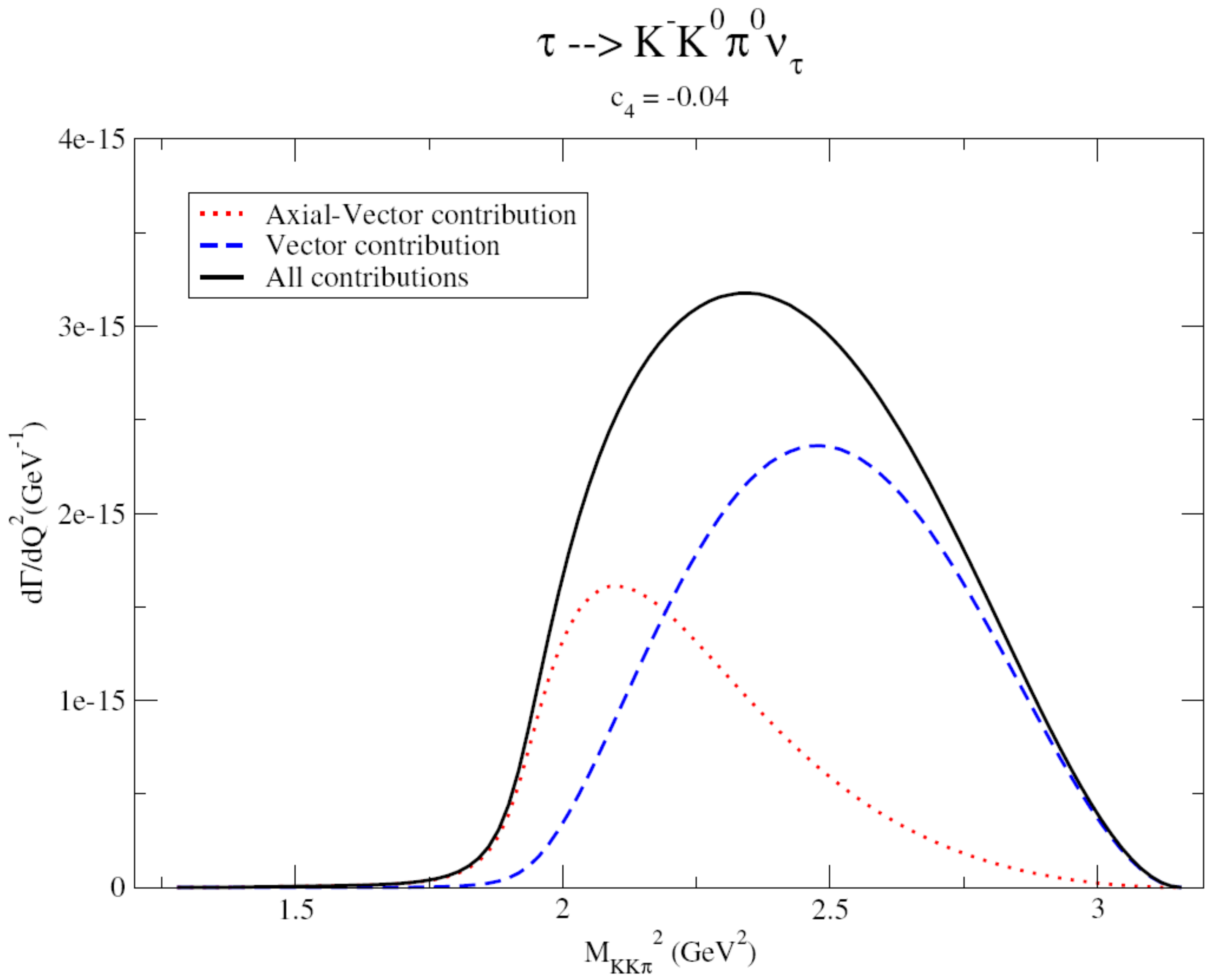
Hence, **we predict**: i) the spectra of the $KK\pi$ modes

ii)$(\Gamma_V/\Gamma_T) \sim 0.66$

(Gómez Dumm, Pich, Portolés, R. to appear)



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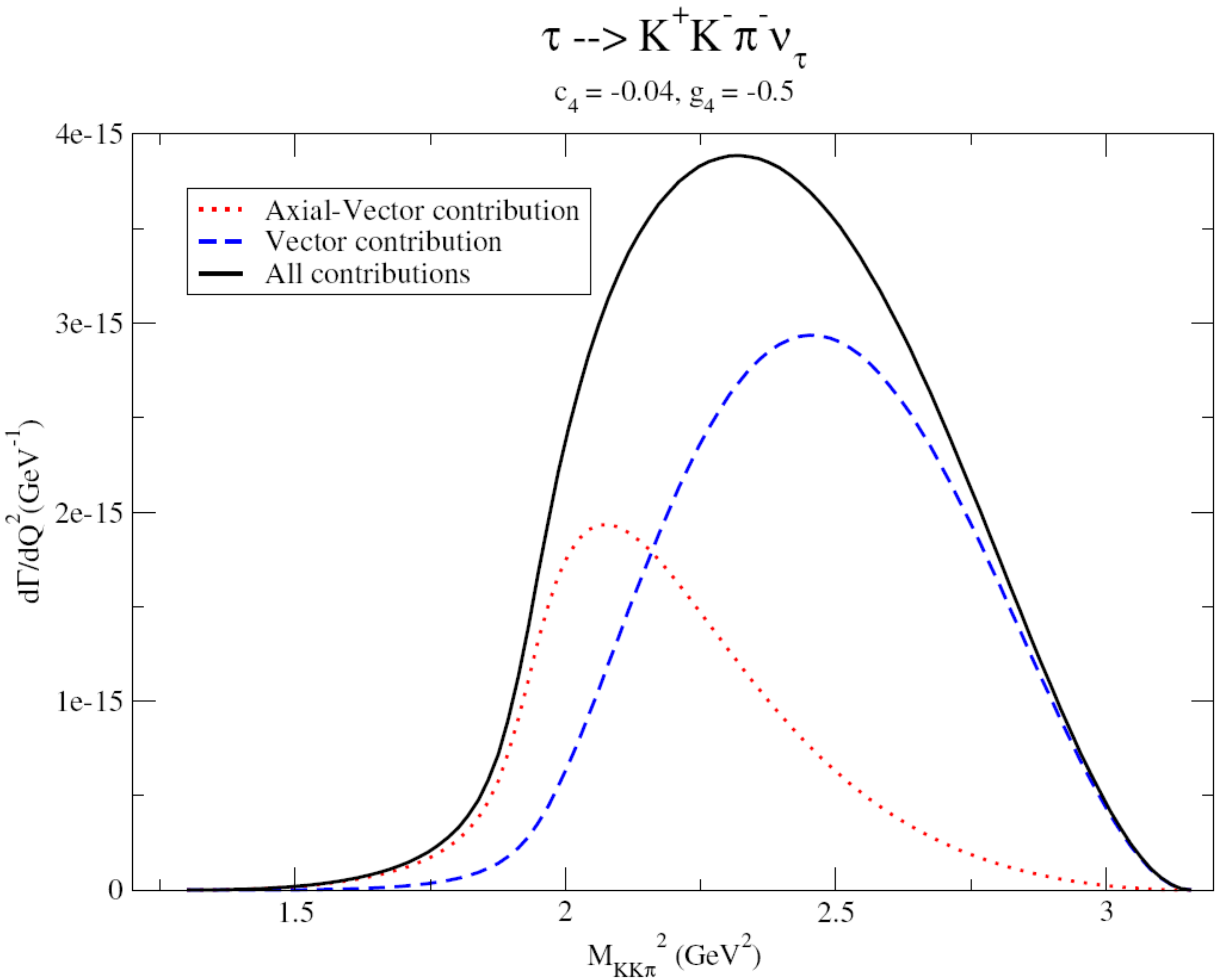

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CONCLUSIONS

- Current analyses of $\tau^- \to (3\pi^-, K^+K^-\pi^-)\,\nu_\tau$ data using **TAUOLA** have shown theoretical inconsistencies. We would like to improve the hadronic matrix elements in **TAUOLA.**
- We have studied these decays within RχT with a **Large N_C**-inspired model guided by **QCD**.
- We have improved our off-shell a_1 width and revisited $\tau^- \to 3\pi^-\,\nu_\tau$.
- Using the available experimental data, we have been able to predict the spectra of all **KKπ** charge channels.
- Our expressions are easy to extend to the e^+e^- scattering below 2 GeV and thus may be of use for **PHOKHARA**.
- Our results have been implemented in **SHERPA** (**LHC** and **TEVATRON**) and may be used by the **B-factories**.
- **LHC**, **BABAR**, **BELLE**, **BES-III**…are promising facilities to test our predictions.
- The future looks even more promising and exciting: V_{us}, m_s and, of course, hadronization of **QCD** currents.

BACKUP SLIDES

K-S-like works & HADRONIZATION IN TAUOLA

(Finkemeier, Mirkes ’95,’96)
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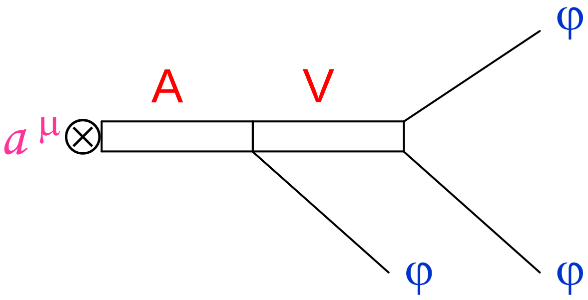
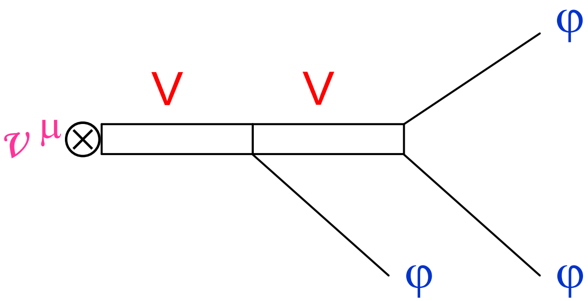


$$\to V_{\substack{1\mu\\2\mu}} = \left(g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2} \right) (p_{\substack{2\\3}} - p_1)^\nu$$



$$\to i\varepsilon_{\mu\nu\rho\sigma} p_1^{\nu} p_2^{\rho} p_3^{\sigma}$$

χ,1R & 2R obtained from:

$$\frac{M_{R1}^2}{M_{R1}^2 - x^2 - i\sqrt{x^2}\,\Gamma_{R1}(x^2)} \; \frac{M_{R2}^2}{M_{R2}^2 - y^2 - i\sqrt{y^2}\,\Gamma_{R2}(y^2)}$$

K-**S**-like works & HADRONIZATION IN TAUOLA

(Finkemeier, Mirkes ’95,’96)
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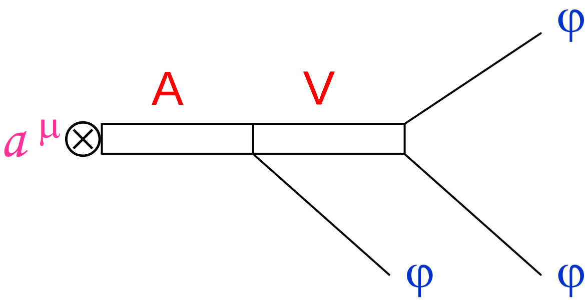
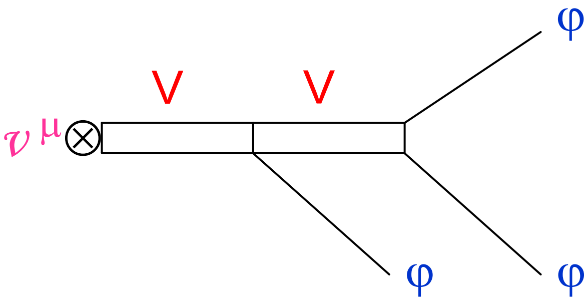


Some allowed $\rho^{0,-}$, K^{*0} contributions are lacking in the modes: $K^+K^-\pi^-$, $K^-K^0\pi^0$, $K^-\pi^-\pi^+$, $K^0\pi^0\pi^-$



$$M_{\rho'}^{V_\mu} \neq M_{\rho'}^{A_\mu}$$

$$\Gamma_{\rho'}^{V_\mu} \neq \Gamma_{\rho'}^{A_\mu}$$

$$3\,Multiplets^{V_\mu} \neq 2\,Multiplets^{A_\mu}$$

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

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

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

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

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

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

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

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

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

Resonances + Goldstone Bosons

TOOLS : RχT

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

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

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

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

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

Antisymmetric tensor formalism

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

(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

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

(Ruiz-Femenía, Pich, Portolés '03)

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

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

(Gómez Dumm, Pich, Portolés, R. to appear)

Resonances + Goldstone Bosons

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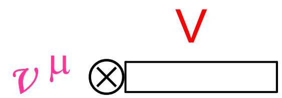
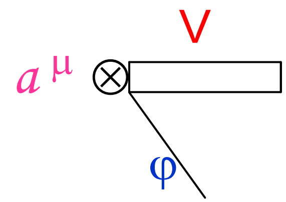
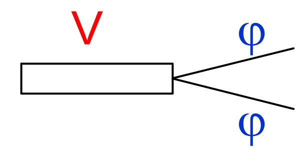
$$\mathcal{L}^{(P_I=+)}{}_{R\chi T} = \mathcal{L}^{(2)}{}_{\chi} + \mathcal{L}^{kin}{}_{V,A} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VAP};$$

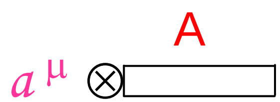
$$\mathcal{L}_V = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{\sqrt{2}}\langle V_{\mu\nu} u^\mu u^\nu\rangle$$



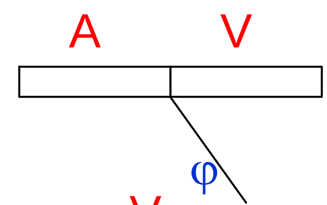




$$\mathcal{L}_A = \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle$$

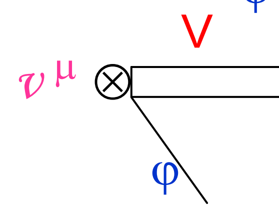


$$\mathcal{L}_{VAP} = \sum_{i=1}^{5}\lambda_i O^i(V_{\mu\nu}, A^{\mu\nu}, \phi) = \lambda_1\langle[V_{\mu\nu}, A^{\mu\nu}]\chi_-\rangle + \ldots$$

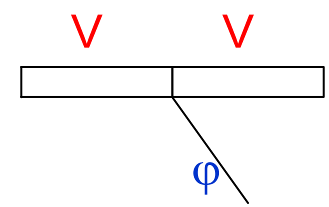


$$\mathcal{L}^{(P_I=-)}{}_{R\chi T} = \mathcal{L}^{(4)}{}_{\chi(WZW)} + \mathcal{L}_{VJP} + \mathcal{L}_{VVP} + \mathcal{L}_{VPPP};$$

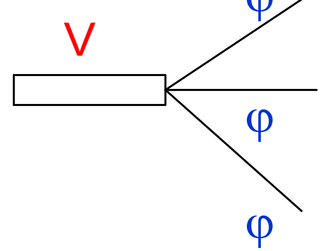
$$\mathcal{L}_{VJP} = \sum_{i=1}^{7}\frac{c_i}{M_V} O^i(V_{\mu\nu}, j^\nu, \partial^\mu\phi) = \frac{c_5}{M_V}\varepsilon_{\mu\nu\rho\sigma}\langle\left\{\nabla_\alpha V^{\mu\nu}, f_+^{\rho\alpha}\right\}u^\sigma\rangle + \ldots$$



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



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



PREVIOUS WORK : $\tau^- \rightarrow (\pi\,\pi\,\pi)^-\,\nu_\tau$

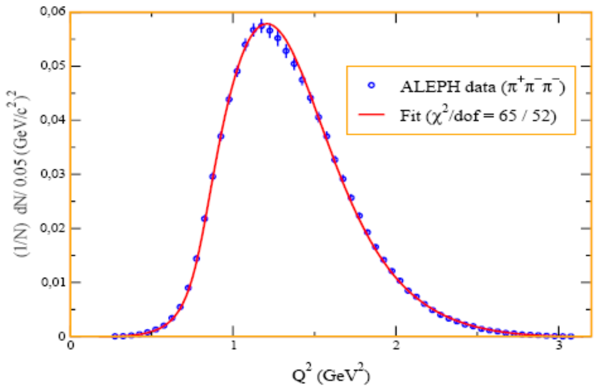
Procedure and results

[Gómez Dumm, Pich, Portolés, 2004]

Fit to the spectrum and BR

[ALEPH, 1998] $\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau$

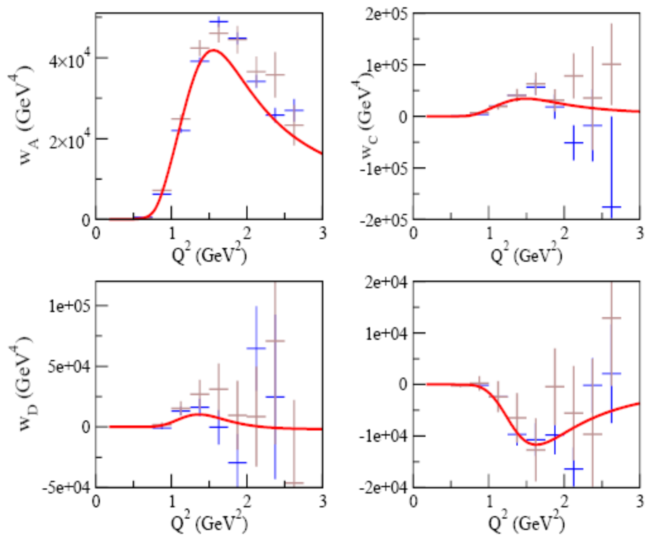
input



output

$\tau^- \rightarrow \pi^-\pi^0\pi^0\nu_\tau$

Structure Functions



[CLEO-II,2000,(blue)] [OPAL,1997,(grey)]

PDG06

M_{a1} = (1.204 ± 0.007) GeV

$\Gamma_{a1}(M_{a1})$ = (0.48 ± 0.02) GeV

λ_0=11.9±0.4

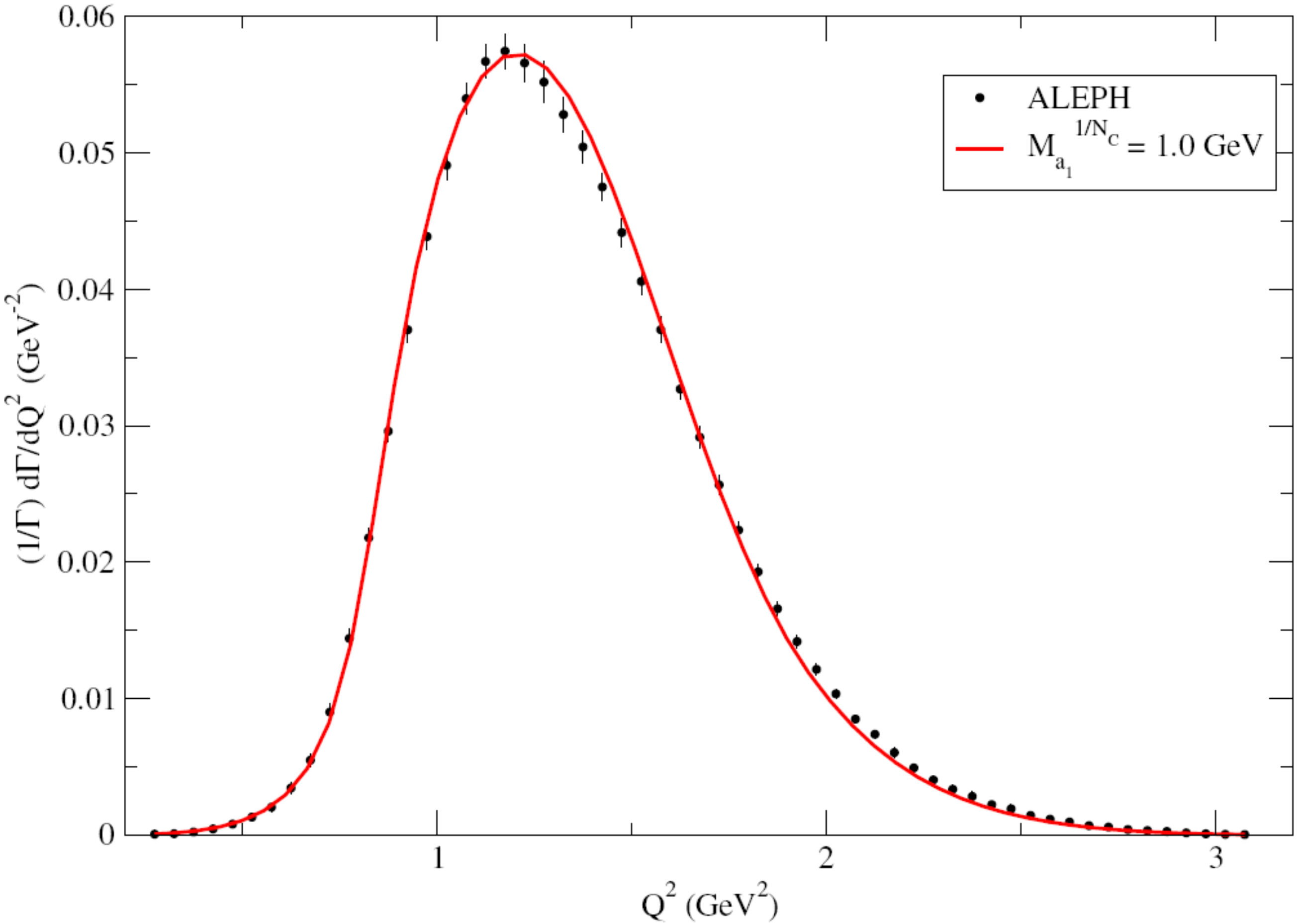
Implemented in SHERPA ☑

IFIC - Instituto de Física Corpuscular

OUR WORK : $\tau^- \to (\pi\,\pi\,\pi)^- \nu_\tau$

(Gómez Dumm, Pich, Portolés, R. to appear)

$M_{a_1} = 1.17$ GeV



λ_0=0.10±0.03

Fixed: **QCD** prediction for <**VAP**>

M_{a1} = (1.17 ± 0.01) GeV

The only parameter of the fit!!

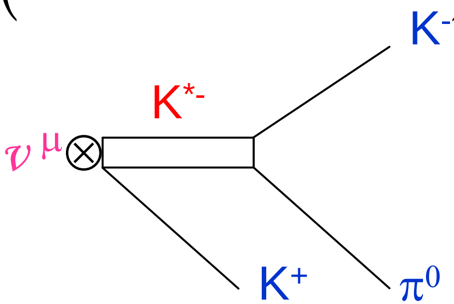
Γ_{a1} = (0.50 ± 0.02) GeV

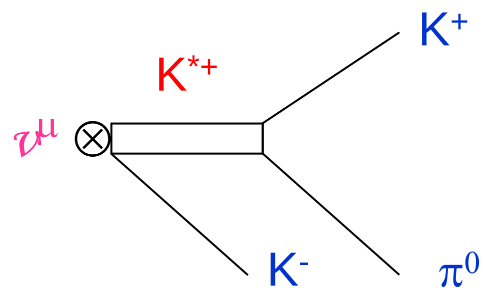
SU(2) AND INTERFERENCES

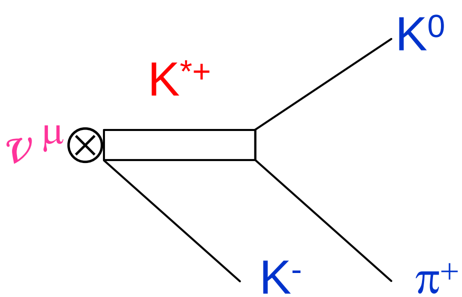
$$\sigma\left(e^+e^- \to KK\pi\right) \stackrel{?}{=} 3\cdot\sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right) = 6\cdot\sigma\left(e^+e^- \to K^+K^-\pi^-\right)$$

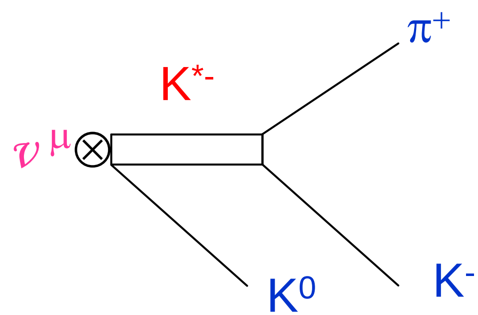
$$\sigma\left(e^+e^- \to K^+K^-\pi^-\right) \stackrel{?}{=} \sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right)$$

$$\sigma\left(e^+e^- \to K^0K^-\pi^+\right) \stackrel{?}{=} 2\sigma\left(e^+e^- \to K^+K^-\pi^-\right)$$









TAU 08

BINP, Novosibirsk

HADRONIZATION OF QCD CURRENTS

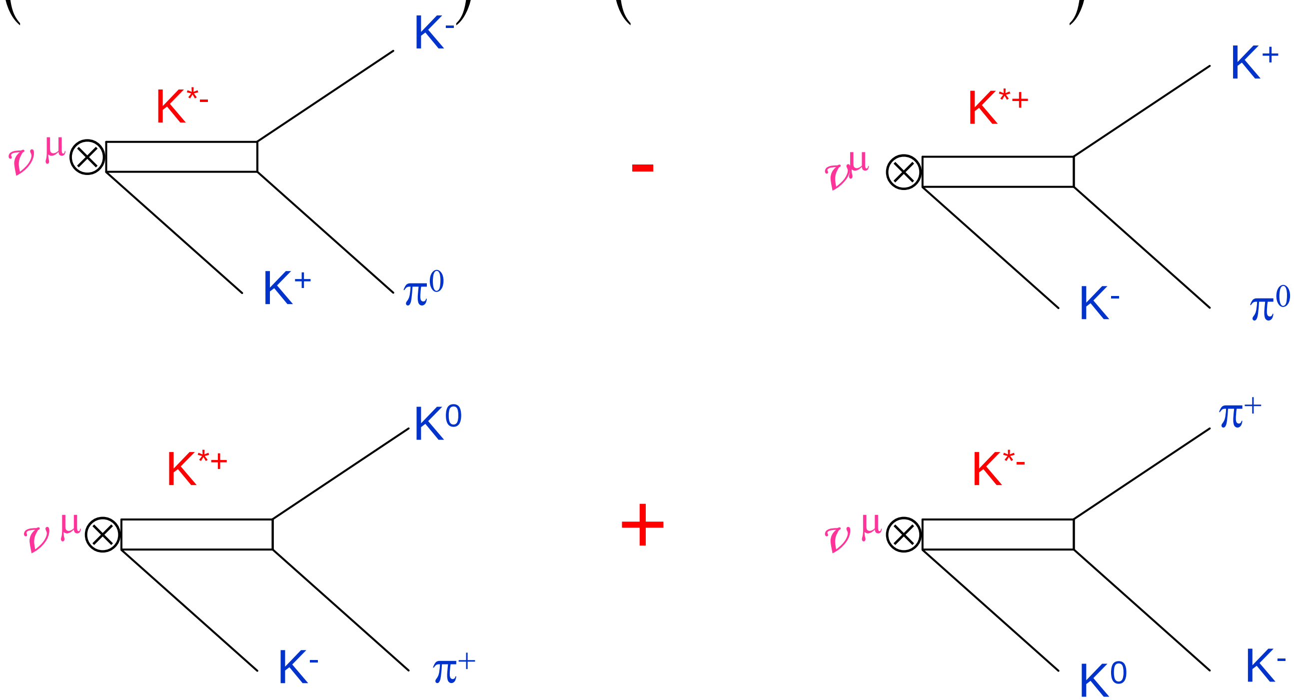
Pablo Roig (IFIC)

SU(2) AND INTERFERENCES

$$\sigma\left(e^+e^- \to KK\pi\right) \overset{?}{=} 3\cdot\sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right) = 6\cdot\sigma\left(e^+e^- \to K^+K^-\pi^-\right)$$

$$\sigma\left(e^+e^- \to K^+K^-\pi^-\right) \overset{?}{=} \sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right)$$

$$\sigma\left(e^+e^- \to K^0K^-\pi^+\right) \overset{?}{=} 2\sigma\left(e^+e^- \to K^+K^-\pi^-\right)$$



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OFF-SHELL WIDTH OF MESON RESONANCES

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

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

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

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

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OUTLOOK: $\tau^- \to (h_1\, h_2\, h_3)^- \nu_\tau$

$h_1\, h_2\, h_3$	F_A	F_V		
3π	√			
$2K\,\pi$	√	√		
$K\,2\pi$	√	√	→	V_{us}, m_s
$2\pi\,\eta$		√		
$\pi\,K\,\eta$	√	√	→	V_{us}, m_s
$3K$	√	√	→	V_{us}, m_s