HADRONIC τ DECAYS INTO 2 & 3 MESON MODES WITHIN RχT

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

See Phys.Rev.D69:073002,2004 ; **AIP Conf.Proc.964:40-46,2007 ; Work to appear soon**

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YOUNG RESEARCHERS WORKSHOP
Frascati May 11th 2009

SUMMARY:

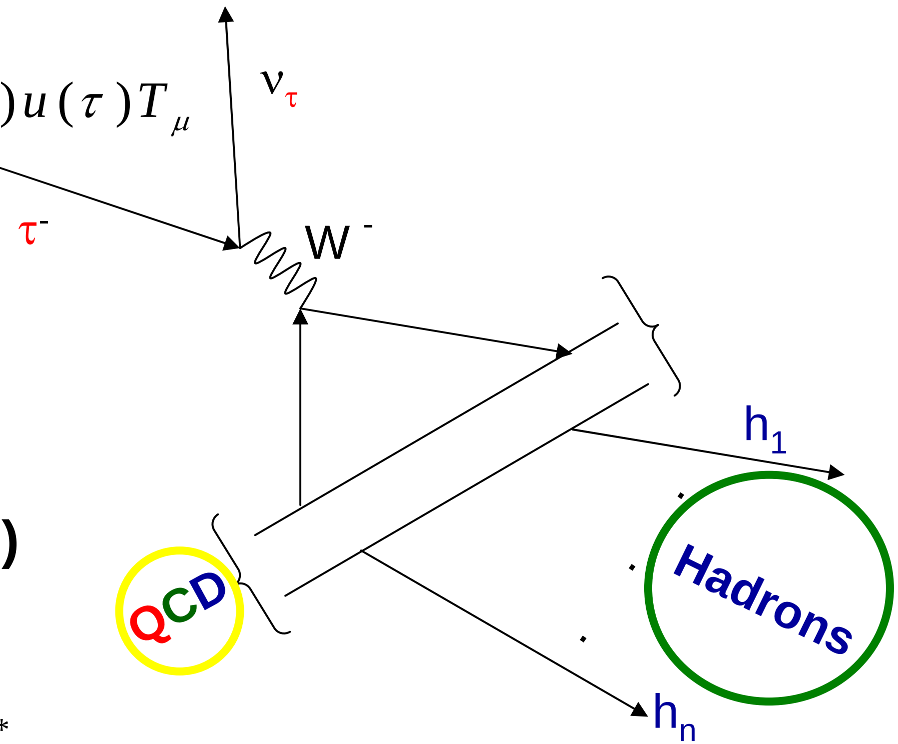
- Hadronic decays of the τ lepton
- ~~**K**ühn-**S**antamaría Model in TAUOLA~~
- **Our study:**

1. Tools : χPT, Large N_c , RχT
2. Two meson processes: $\tau^- \rightarrow (\pi\,\pi, \pi\,K)^- \,\nu_\tau$
3. Three meson processes: $\tau^- \rightarrow (3\pi, KK\pi)^- \,\nu_\tau$

- 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_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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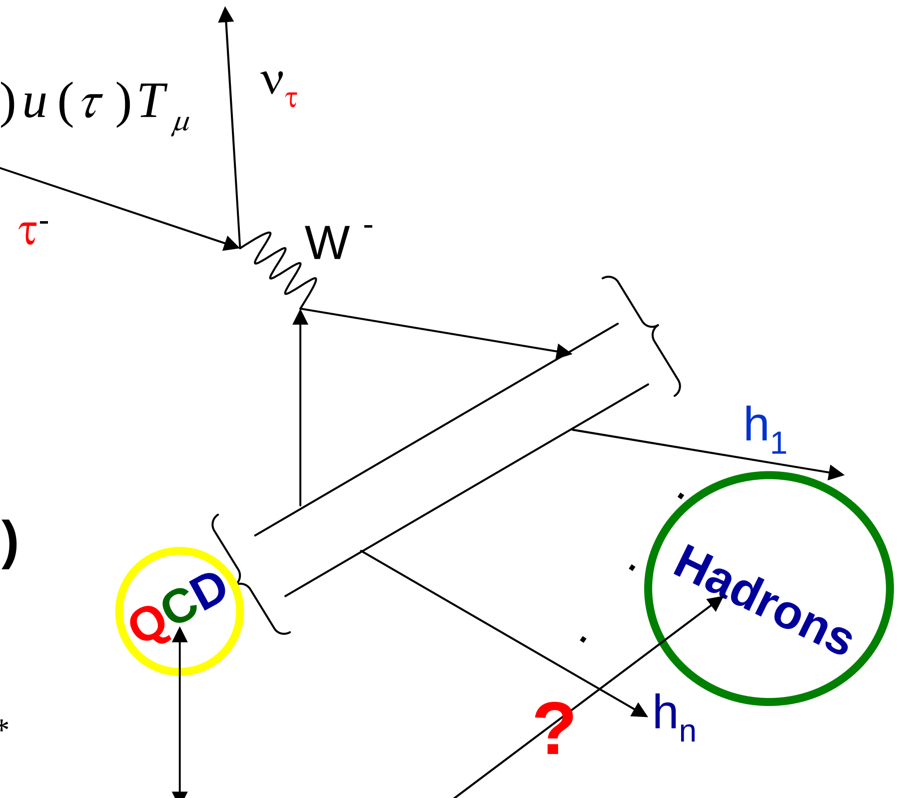

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$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}\,(q_i, G_\mu^{\;a}; g_s, m_i)$$

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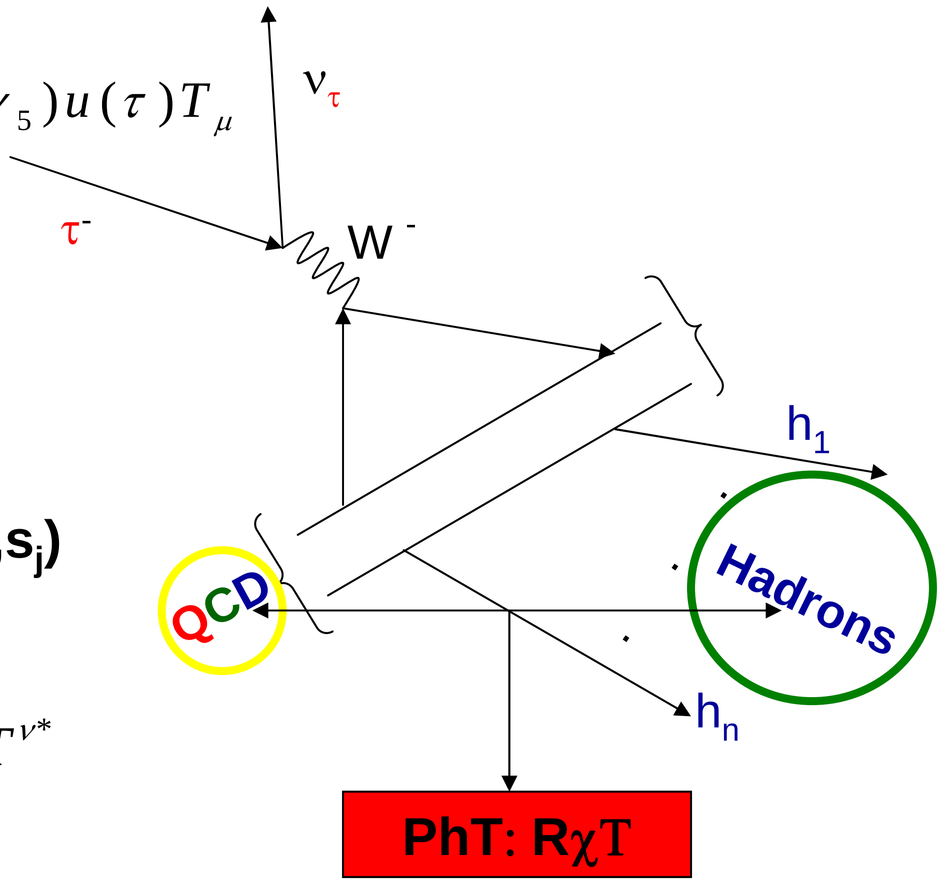

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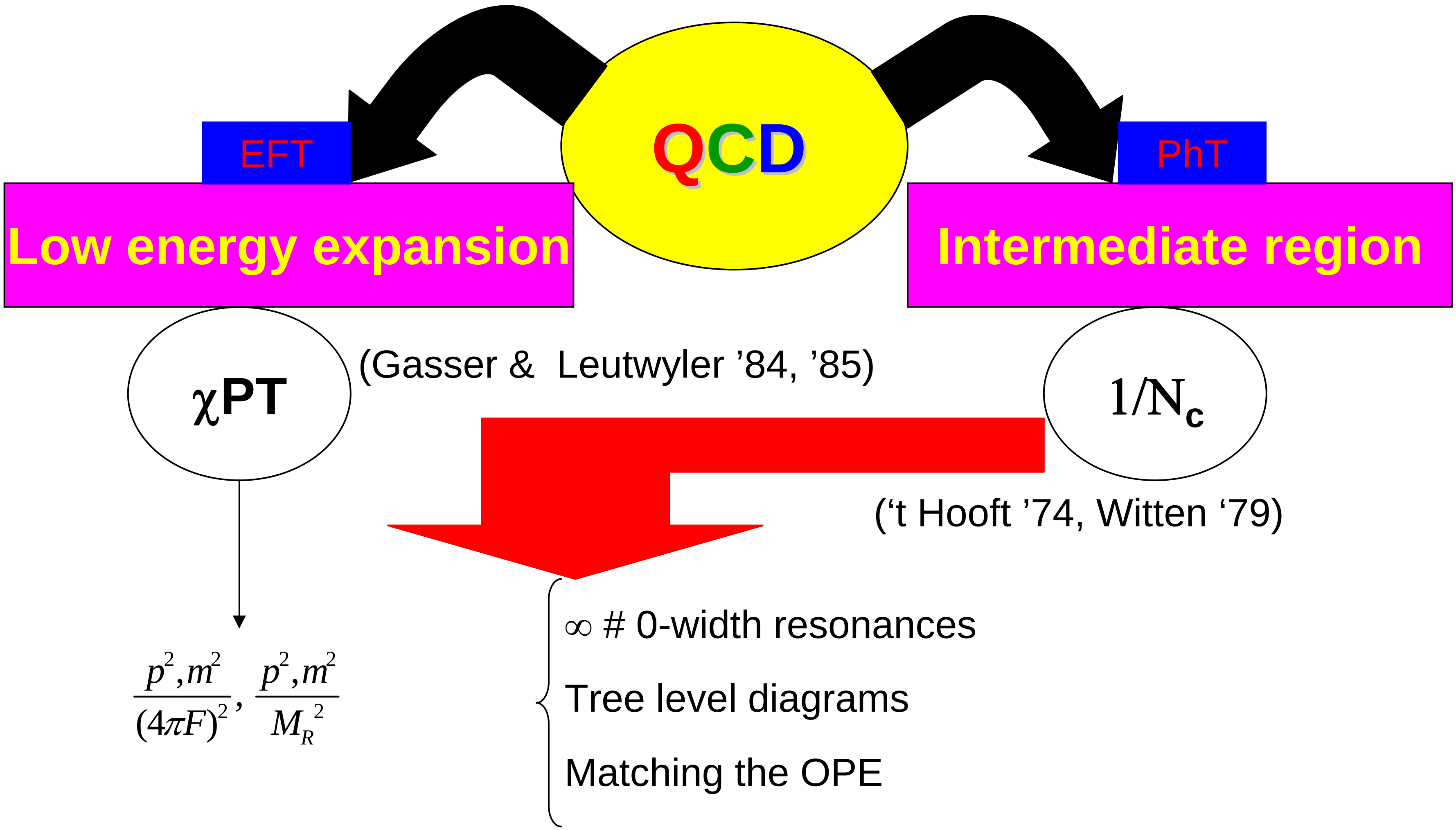
TOOLS: χPT, Large N_c , RχT



TOOLS: χPT, Large N_c, RχT

QCD

EFT

Low energy expansion

χPT (Gasser & Leutwyler '84, '85)

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

PhT

Intermediate region

$1/N_c$ ('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

Two meson processes: $\tau^- \to (\pi\,\pi)^- \nu_\tau$

A long story of successes in **VFF** of $\pi\ \pi$: See complete Bibliography in (Portolés, '05)

$$\left\langle \pi^-\pi^0 \left| \bar{d}\gamma^\mu u \right| \emptyset \right\rangle = \sqrt{2} F(s) (p_{\pi^-} - p_{\pi^0})^\mu$$

$\tau^- \to (\pi\,\pi)^- \,\nu_\tau$ (Ecker, Gasser, Pich, De Rafael '89)

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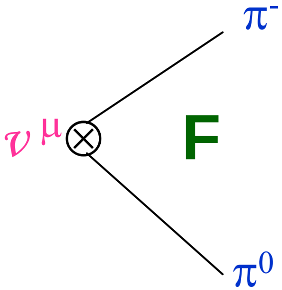
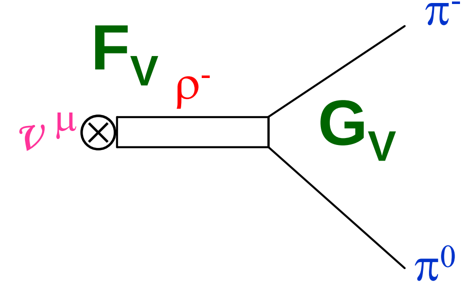


$$F(s) = 1 + \frac{F_V G_V}{F^2}\frac{s}{M_V^2 - s}$$



$$F(s) \xrightarrow[s\to\infty]{} \frac{const}{s} \Rightarrow F_V G_V = F^2$$

$$F(s)^{VMD} = \frac{M_\rho^2}{M_\rho^2 - s}$$

$\tau^- \rightarrow (\pi\,\pi)^- \nu_\tau$ (Ecker, Gasser, Pich, De Rafael '89)

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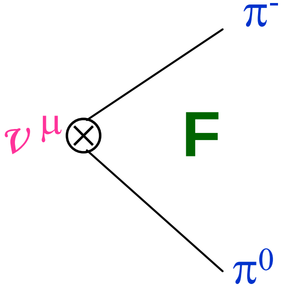

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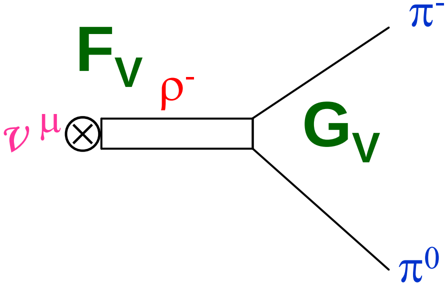

(Gasser & Leutwyler '84, '85)

$$F(s)^{\rm ChPT} = 1 + \frac{2L_9^r(\mu)}{f_\pi^2} s - \frac{s}{96\pi^2 f_\pi^2} \left[A(m_\pi^2/s, m_\pi^2/\mu^2) + \frac{1}{2} A(m_K^2/s, m_K^2/\mu^2) \right]$$

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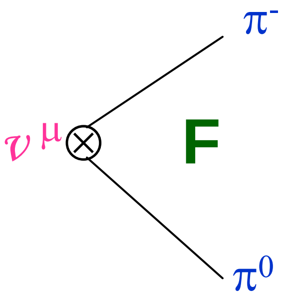

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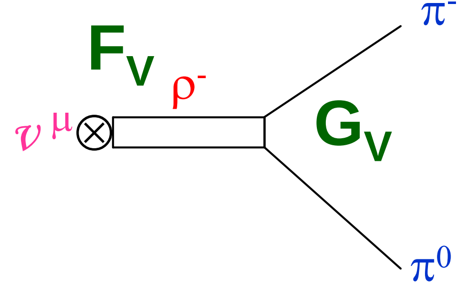

(Gasser & Leutwyler '84, '85)

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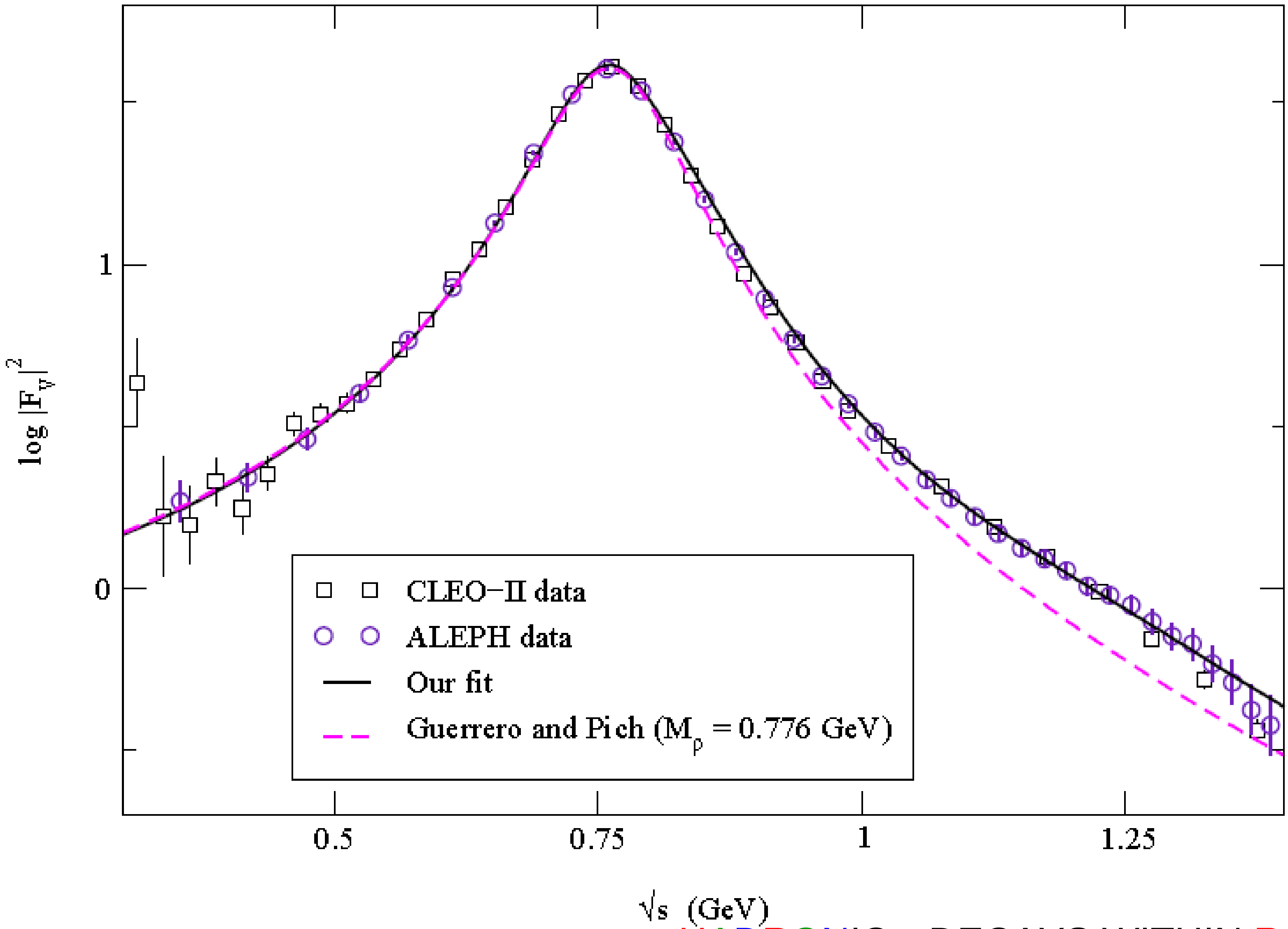
(Guerrero, Pich '97)

$\mathcal{O}(p^4)$ χPT Omnès resummed

$$F(s)^{R\chi T} = \frac{M_\rho^2}{M_\rho^2 - s - iM_\rho \Gamma_\rho(s)} \exp\left\{\frac{-s}{96\pi^2 F^2}\left[\Re e\, A\left(\frac{m_\pi^2}{s}, \frac{m_\pi^2}{M_\rho^2}\right) + \frac{1}{2}\Re e\, A\left(\frac{m_K^2}{s}, \frac{m_K^2}{M_\rho^2}\right)\right]\right\}$$

(Guerrero, Pich '97) $\tau^- \to (\pi\,\pi)^- \nu_\tau$ (Pich, Portolés '01, '03)



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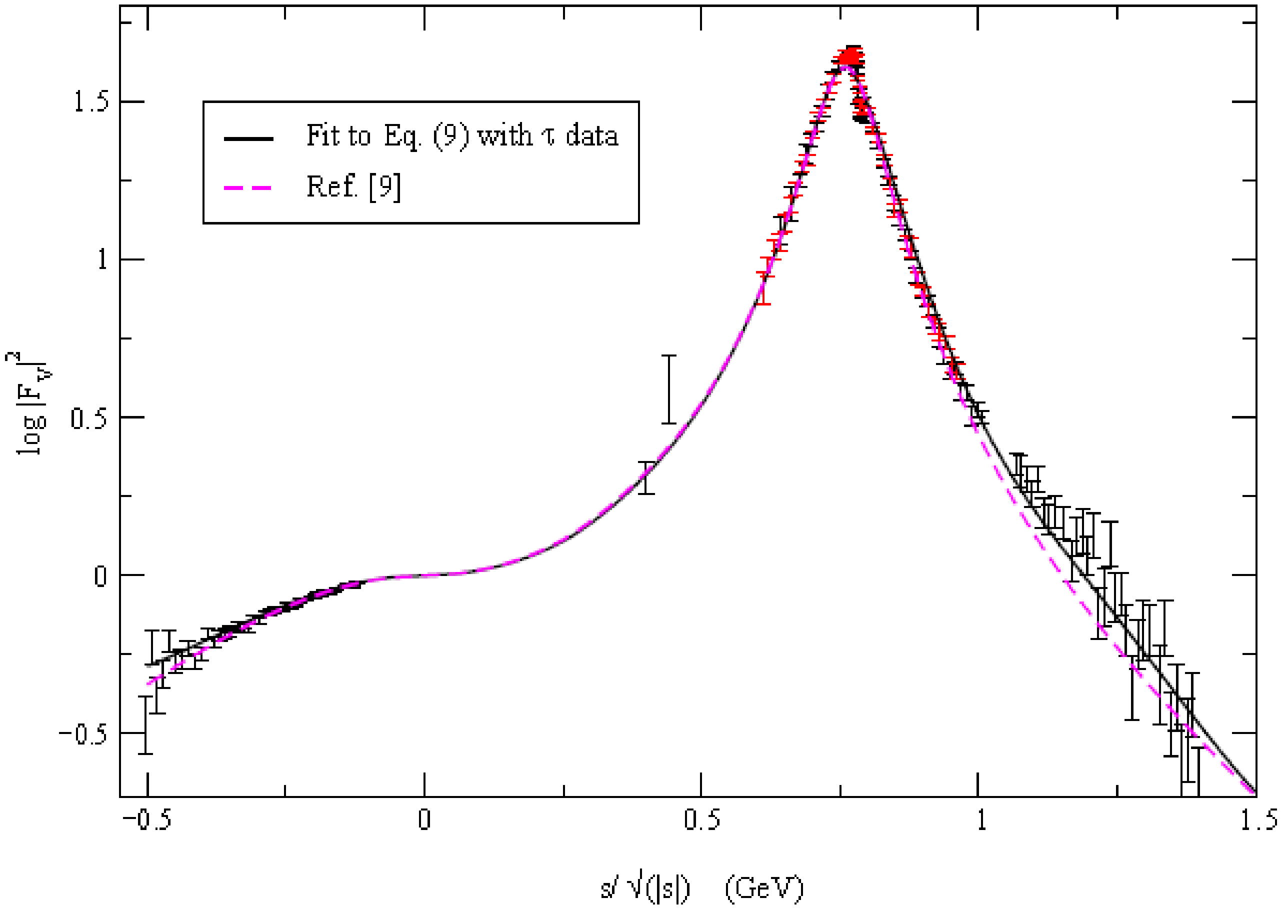


Figure 2: *Comparison of the result of our fit with the experimental data on $F_V(s)$ from $e^+e^- \to \pi^+\pi^-$ (time-like) [15] and $e^-\pi^\pm \to e^-\pi^\pm$ (space-like) [16]. The result of Ref. [9] ($M_\rho = 775$ MeV) is also shown. In the region $-0.4\ GeV \lesssim s/\sqrt{|s|} \lesssim 0.8\ GeV$ both curves are almost indistinguishable.*

(Jamin, Pich & Portolés, 08)

Two meson processes: $\tau^- \to (K\pi)^- \nu_\tau$

$$\left\langle \pi^-(p_2) K_S(p_1) \right| V_\mu \, e^{iL_{QCD}} \left| 0 \right\rangle = \frac{1}{\sqrt{2}} \left[\left(q_\mu - \frac{m_K^2 - m_\pi^2}{Q^2} Q_\mu \right) \underbrace{F_+^{K\pi}(q^2)}_{J^P=1^-} + Q_\mu \underbrace{F_0^{K\pi}(q^2)}_{J^P=0^+} \right]$$

$$q_\mu = (p_1 - p_2)_\mu \quad , \quad Q_\mu = (p_1 + p_2)_\mu$$

$J^P=1^-$ [M. Finkemeier, E. Mirkes, 1996] →

$$F_+^{K\pi}(s) = \frac{F_+^{K\pi}(0)}{1+\beta} \left[BW_{K^*(892)}(s) + \beta BW_{K^*(1410)}(s) \right]$$

$J^P=0^+$ [D. Aston et al, 1988] →

$$\begin{cases} F_0^{K\pi}(s) = \lambda \dfrac{\sqrt{s}}{q_{K\pi}(s)} \left[\sin \delta_B e^{i\delta_B} + e^{i2\delta_B} BW_{K^*(1430)}(s) \right] \\ \cot \delta_B = \dfrac{1}{a \, q_{K\pi}(s)} + \dfrac{b \, q_{K\pi}(s)}{2} \end{cases}$$

LASS parameterization

$\tau^- \to (K\pi)^- \nu_\tau$ (Jamin, Pich & Portolés, 08)

1) Vector form factor [M. Jamin, A. Pich, J.P., 2006]

K*(892) K*(1410)

$$F_+^{K\pi}(s) = \left[\frac{M_{K^*}^2 + \gamma s}{M_{K^*}^2 - s - iM_{K^*}\Gamma_{K^*}(s)} - \frac{\gamma s}{M_{K^{*\prime}}^2 - s - iM_{K^{*\prime}}\Gamma_{K^{*\prime}}(s)} \right] e^{\frac{3}{2}\mathrm{Re}\left[\overline{H}_{K\pi}(s) + \overline{H}_{K\eta}(s)\right]}$$

Resonance Chiral Theory (RχT)

chiral symmetry + Brodsky-Lepage asymptotic behaviour + Large-N_C + analyticity

1-loop χPT
Omnès resummed

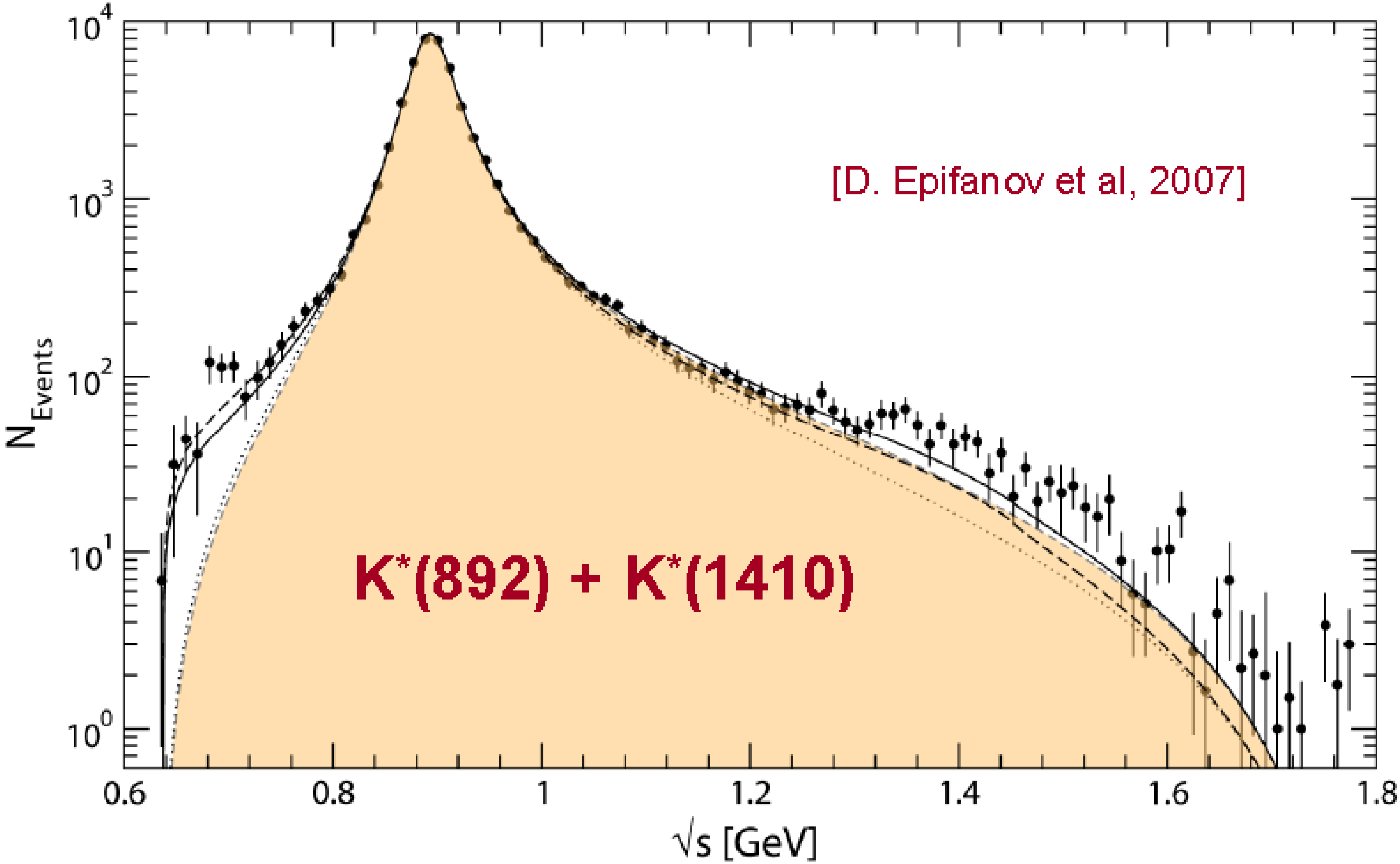
$\tau^- \to (K\,\pi)^- \,\nu_\tau$ (Jamin, Pich & Portolés, 08)

2) **Scalar form factor** [M. Jamin, J.A. Oller, A. Pich, 2002, 2006]

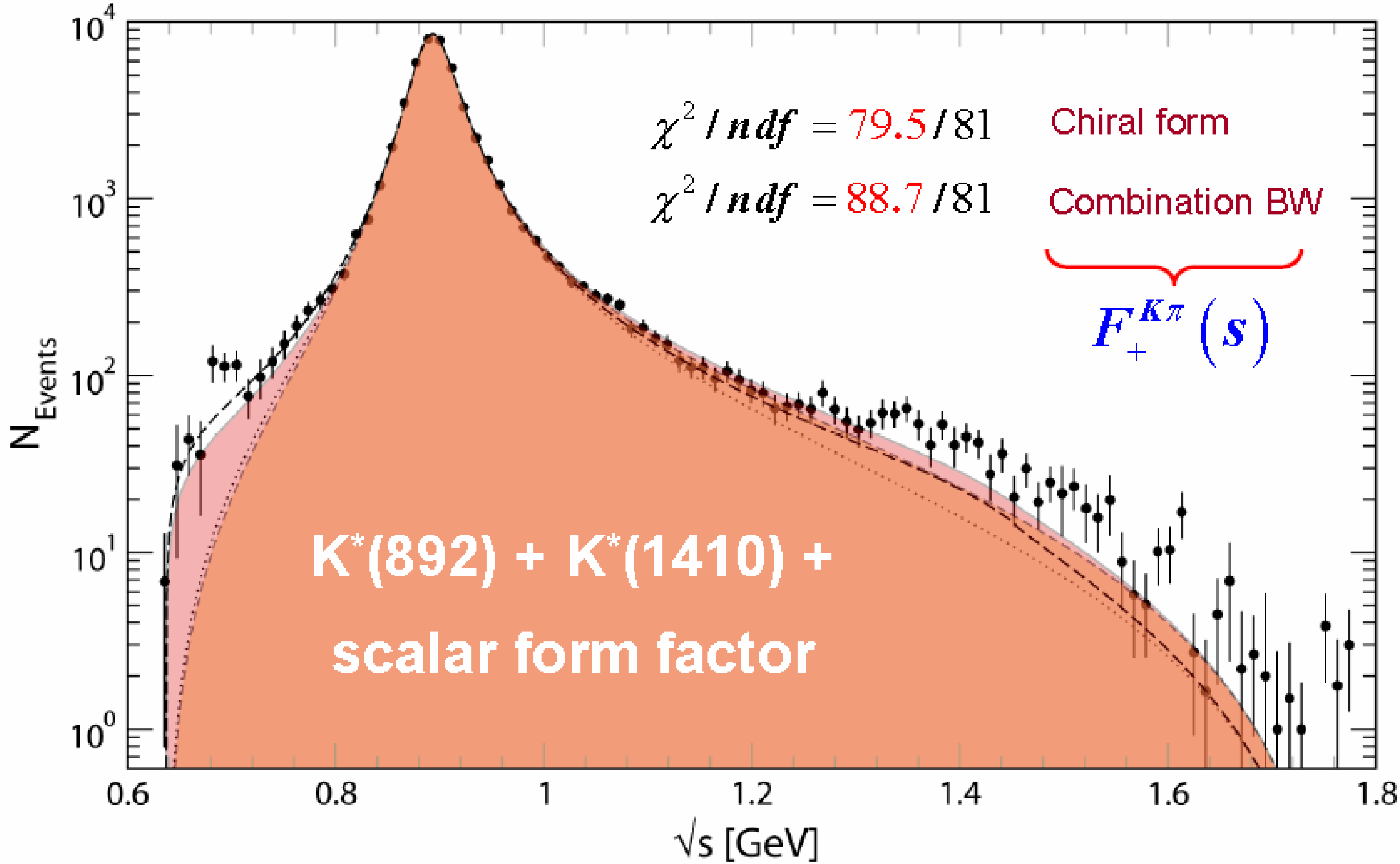
Coupled channel determination (**$K\pi$**, $K\eta$ and **$K\eta'$**)

- Chiral constraints
- Resonance Chiral Theory matching
- Analyticity and unitarity strictures

$\tau^- \to (K\,\pi)^- \,\nu_\tau$ (Jamin, Pich & Portolés, 08)



$\tau^- \to (K\pi)^- \nu_\tau$ (Jamin, Pich & Portolés, 08)



$\tau^- \to (K\pi)^- \nu_\tau$ (Jamin, Pich & Portolés, 08)

(MeV)	Our results	Our results BW combination	PDG
$M_{K^*(892)}$	895.28(20)	895.12(19)	891.66(26)
$\Gamma_{K^*(892)}$	47.50(41)	46.79(41)	50.8(9)
$M_{K^*(1410)}$	1307(17)	1598(25)	1414(15)
$\Gamma_{K^*(1410)}$	206(49)	224(47)	232(21)

Three meson processes: $\tau^- \to (3\pi)^- \nu_\tau$

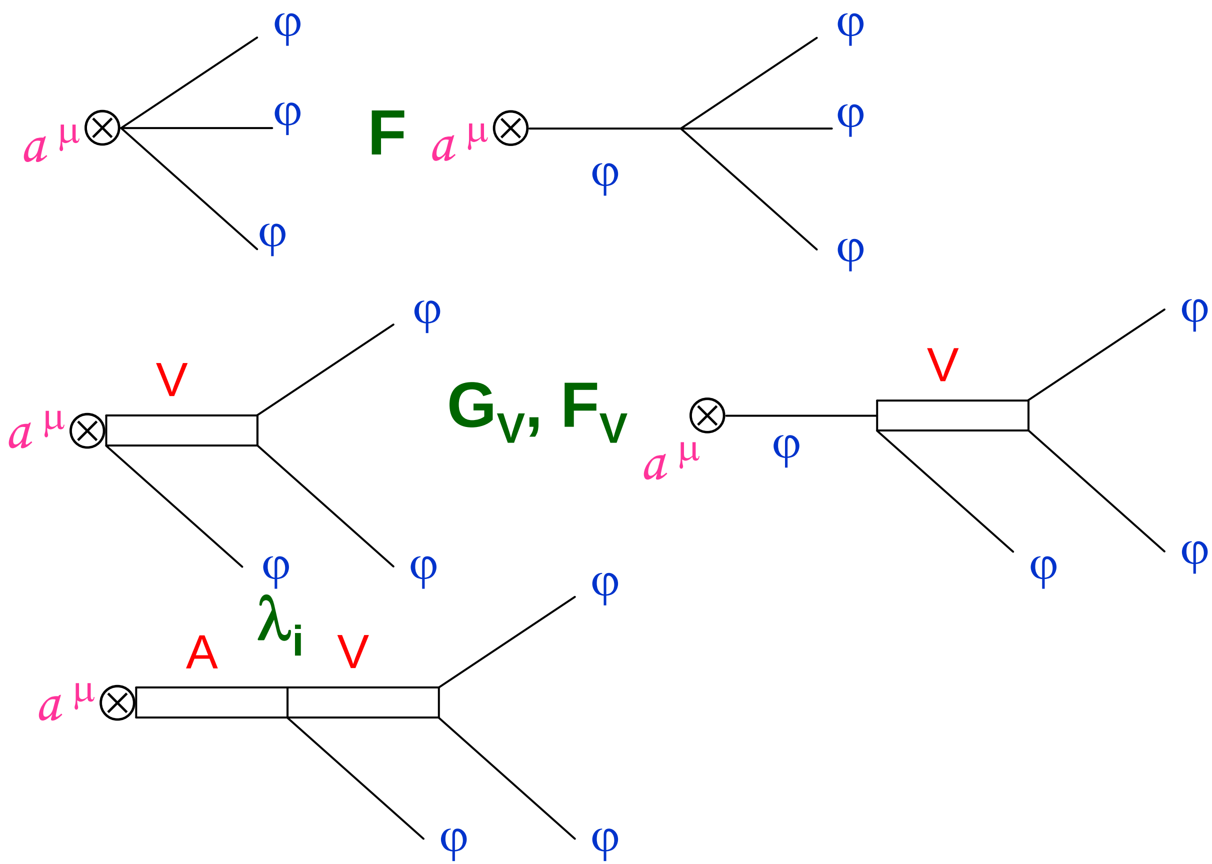
(Our work)

(Gómez-Dumm, Pich, Portolés ‘04)

χ**PT** $\mathcal{O}(p^2)$

RχT, 1R

RχT, 2R



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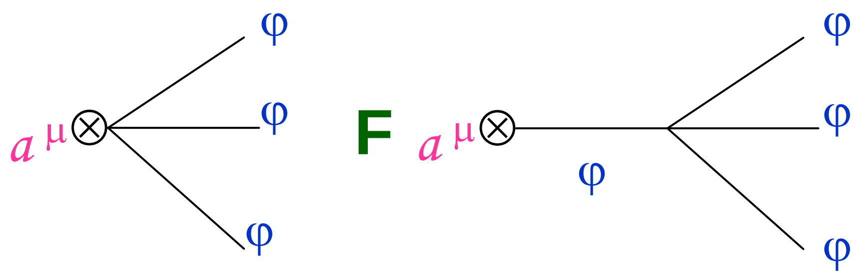
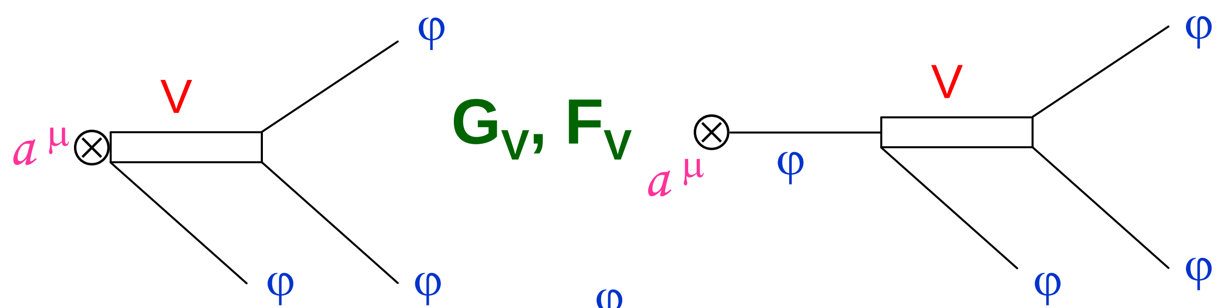
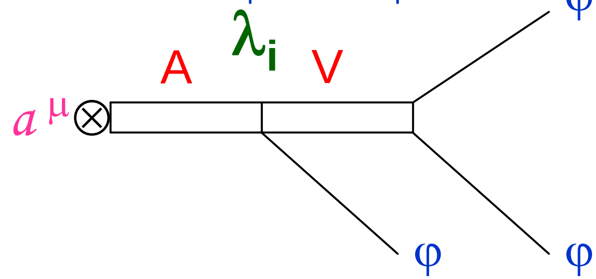


RχT, 1R



RχT, 2R

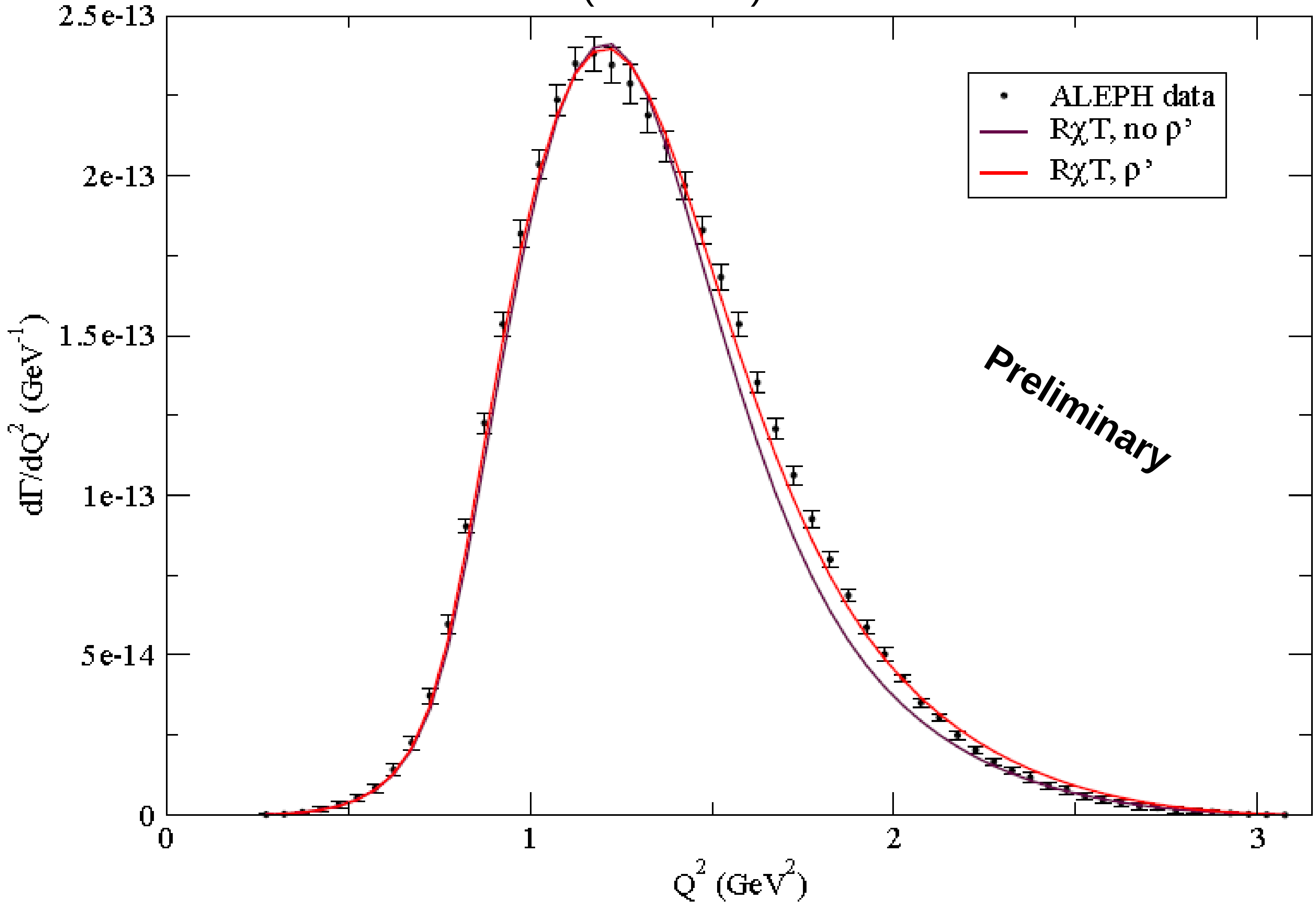


7 unknown couplings

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

Three meson processes: $\tau^- \to (3\pi)^- \nu_\tau$

(Our work)



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Three meson processes: $\tau^- \to (3\pi)^- \nu_\tau$

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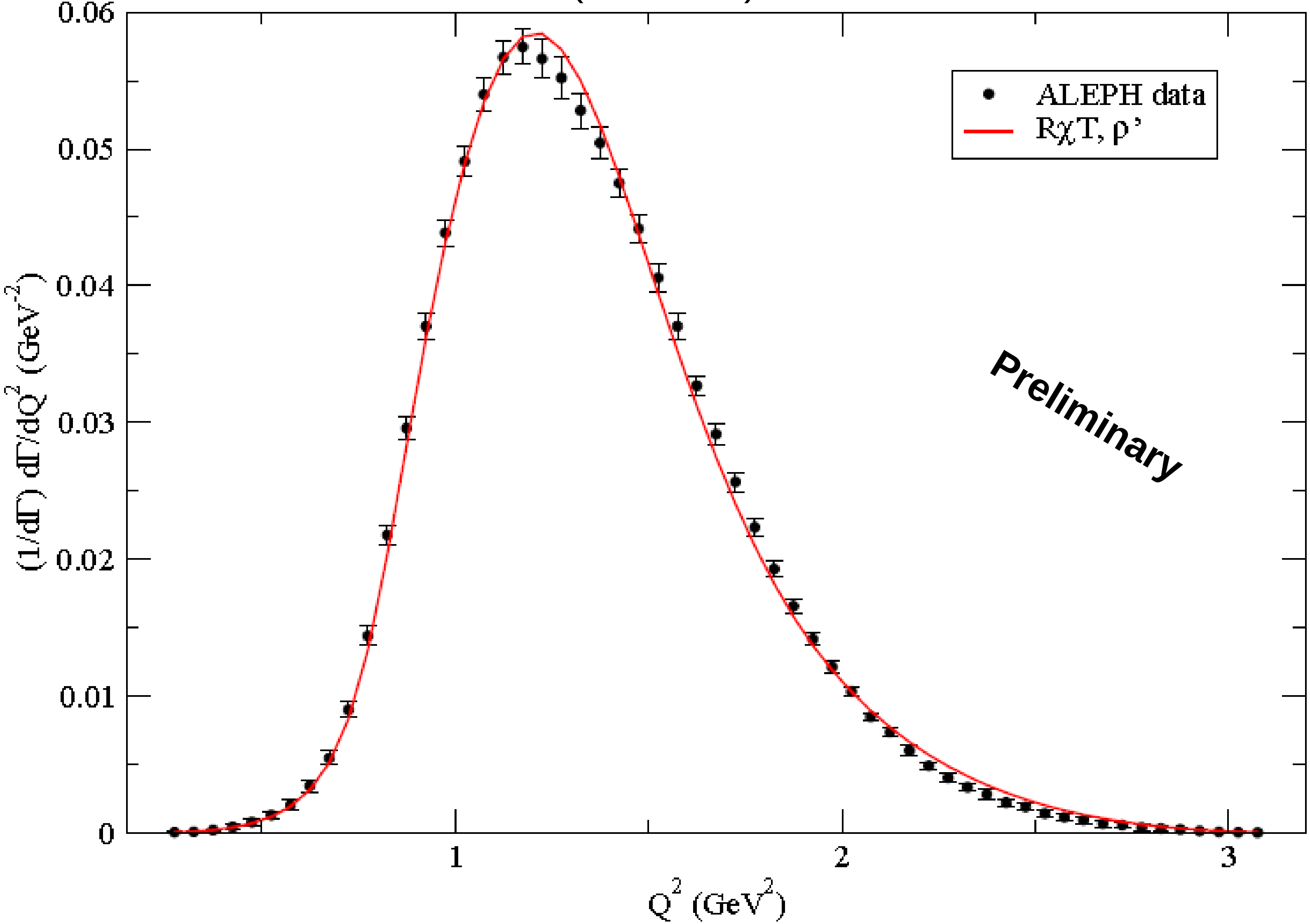

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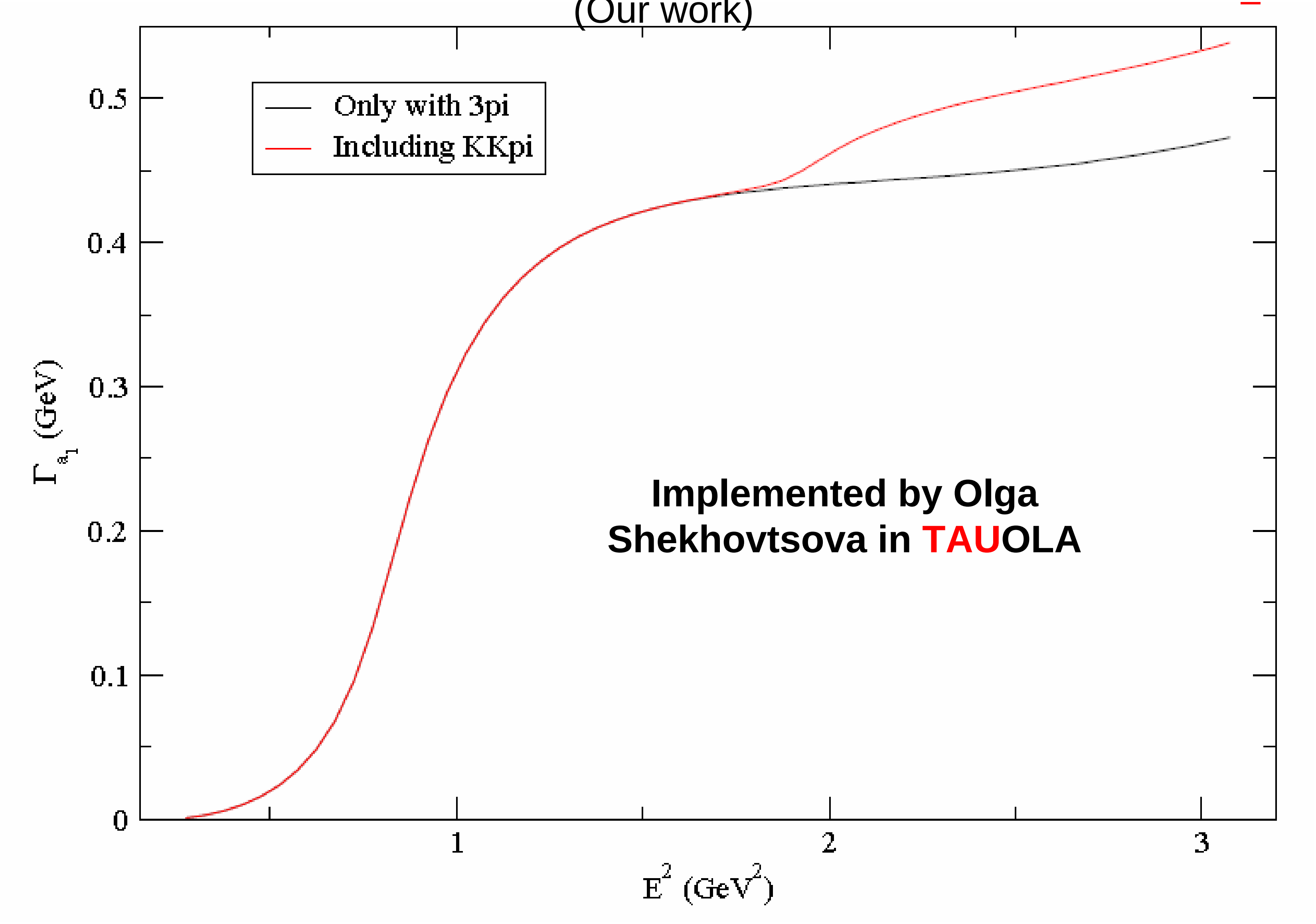

Three meson processes: $\tau^- \to (KK\pi)^- \nu_\tau$

(Our work)

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).

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λ_0 ~ **1/8**

Trying to do it with

$$\Gamma_{a_1}(Q^2) \leftarrow R\chi T$$

Three meson processes: $\tau^- \to (KK\pi)^- \nu_\tau$

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λ_0 ~ **1/8**

$$\Gamma_{a_1}(Q^2) \leftarrow R\chi T$$

Three meson processes: $\to (KK\pi)^- \nu_\tau$ & $e^+e^- \to KK\pi$

(Our work)

1. **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**).

2. **CVC** allows to relate **$e^+e^- \to KK\pi$ with $\tau^- \to (KK\pi)^-\nu_\tau$.**

BaBar has recently ('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, which let us check the couplings obtained in **1**.

Three meson processes: $\rightarrow(KK\pi)^{-}\nu_\tau$ & $e^+e^-\rightarrow KK\pi$

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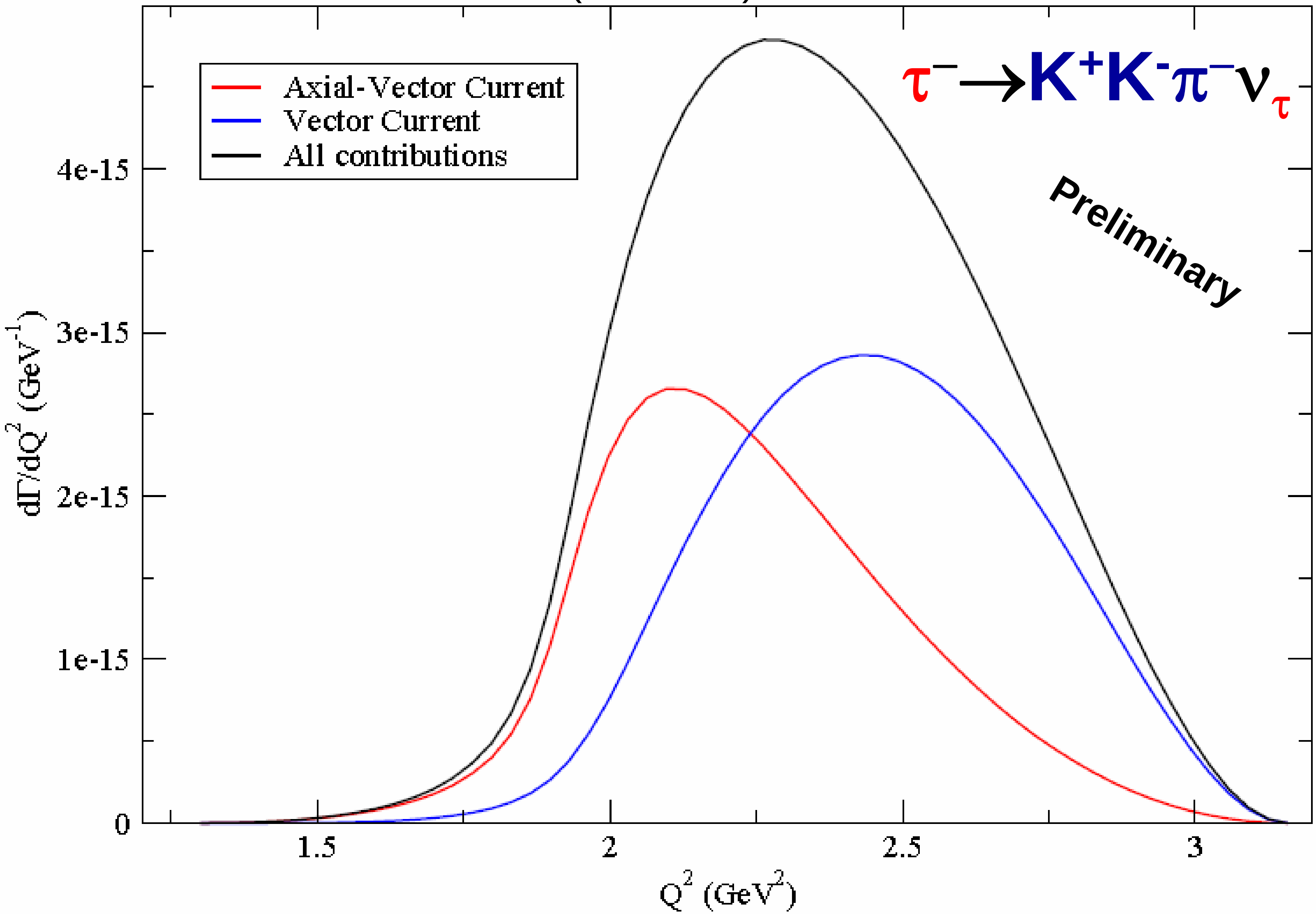
Hence, **we predict**: i) the **spectra** of the **$KK\pi$** modes

ii) $(\Gamma_V/\Gamma_T) \sim 0.55$

Three meson processes: $\rightarrow (KK\pi)^{-}\nu_{\tau}$ & $e^{+}e^{-}\rightarrow KK\pi$

(Our work)



HADRONIC τ DECAYS WITHIN RχT

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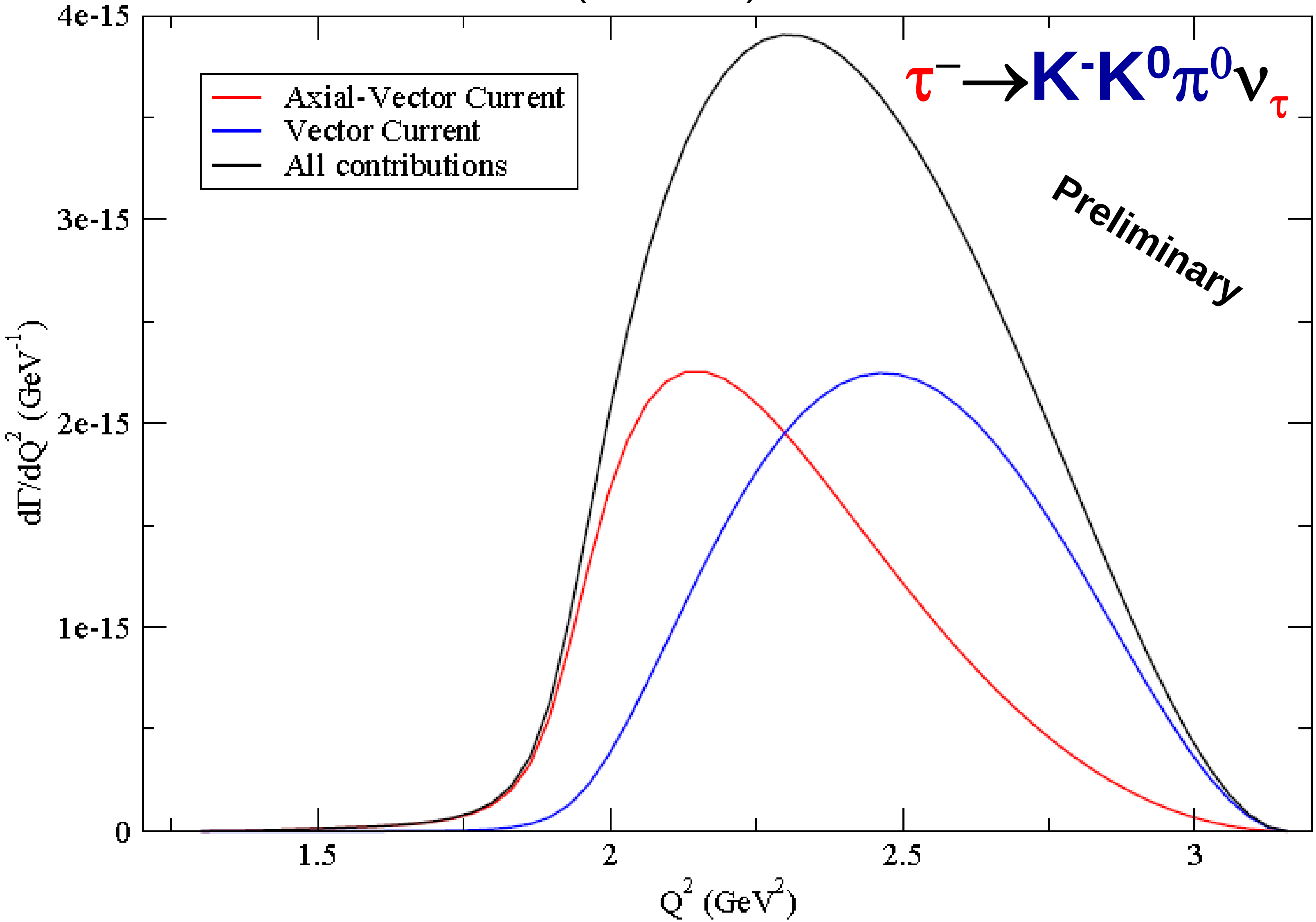
(Our work)



CONCLUSIONS

- Current analyses of $\tau^- \to (3\pi^-, K^+K^-\pi^-)\ \nu_\tau$ data using the **KS**(-like) model in **TAUOLA** have shown theoretical inconsistencies. We liked to improve the description of hadronization used**.**
- We have studied them within RχT with a **Large N$_C$**-inspired **QCD**-guided approach (as it was done for $\tau^- \to (\pi\pi, K\pi)\ \nu_\tau$). We have improved the off-shell **a_1** width and revisited $\tau^- \to 3\pi^-\ \nu_\tau$. Using the available experimental data, we are able to predict the spectra of all **K$K\pi$** charge channels.
- Our **resonance widths** (**V** and **A-V**) have been implemented in **TAUOLA** (matrix elements on the way) and all them may be used by the (super)**B-factories**.
- Our expressions are easy to extend to the **e^+e^-** scattering below 2 GeV and thus might be of use for **PHOKHARA**.
- **LHC**, **BABAR**, **BELLE**, **BES-III**… are & will be providing testing grounds for our predictions.
- Promising & exciting future: V_{us}, m_s and, of course, hadronization of **QCD**.

BACKUP SLIDES

HADRONIC DECAYS OF THE τ LEPTON

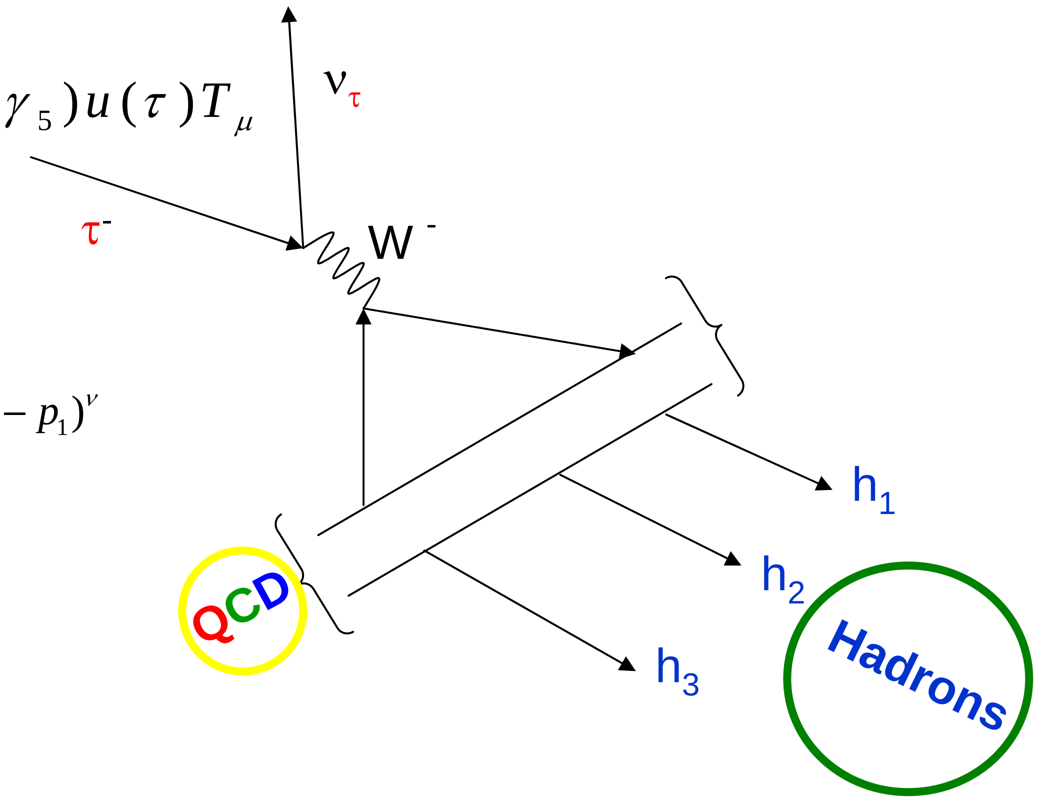
$$\mathfrak{M} = \frac{G_F}{\sqrt{2}} V_{CKM}\, \overline{u}(\nu_\tau)\gamma^\mu(1-\gamma_5)u(\tau)T_\mu$$

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

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

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

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



(**K**ühn, **S**antamaría ’90)(**KS**)

(**G**ómez-Cadenas, **G**onzález-García, **P**ich ’90) (**GGP**)

KÜHN-SANTAMARÍA MODEL in TAUOLA

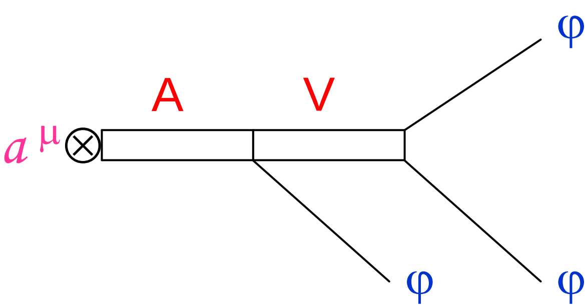
(Kühn-Santamaría '90) **$(2\pi,3\pi)$**

KS

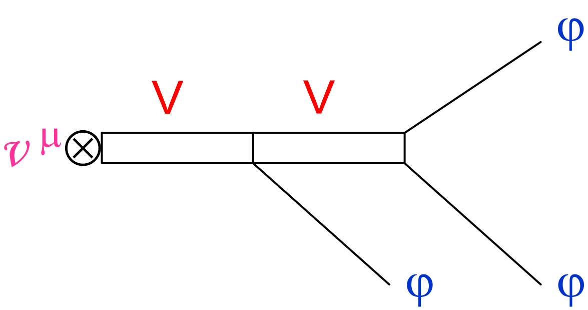
- χPT $\mathcal{O}(p^2)$ — (Gómez-Dumm, Pich, Portolés '04) χPT $\mathcal{O}(p^4)$
- Vector Meson Dominance (Sakurai '69, Kühn & Wagner '84, Pich '87)
- Asymptotic behaviour ruled by **QCD** (Brodsky-Farrar '73, B-Lepage '80)
- ? $$BW_R(x^2) = \frac{M_R^{\,2}}{M_R^{\,2} - x^2 - i\sqrt{x^2}\,\Gamma_R(x^2)}$$ (Gounaris-Sakurai '68)
- Ad-hoc off-shell widths

K-S-like MODEL IN TAUOLA

(Finkemeier, Mirkes ’95,’96)
(Finkemeier, Kühn, Mirkes ‘96)



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



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

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 MODEL IN TAUOLA

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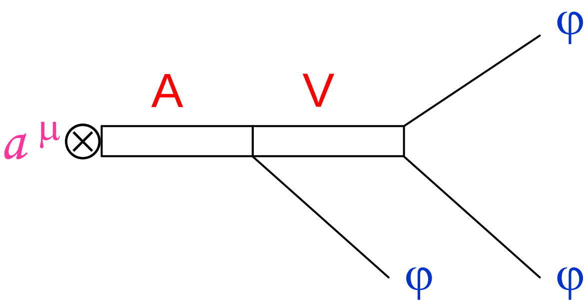

Some allowed contributions are lacking:

$\varphi\ \varphi\ \varphi$	**V-exchanged**	missing in
$K^+K^-\pi^-$	ρ^0	$V_{2\mu}$
	K^{*0}	$V_{1\mu}$
$K^-K^0\pi^0$	K^{*0}	$V_{1\mu}$
	ρ^-	$V_{1\mu}$
$K^-\pi^-\pi^+$	K^{*0}	$V_{1\mu}$
$\overline{K^0}\pi^0\pi^-$	ρ^-	$V_{1\mu}$

K-S-like MODEL IN TAUOLA

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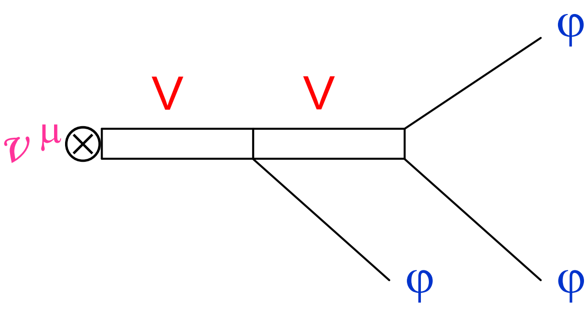
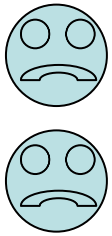


$$M_{\rho'}^{V_\mu} \neq M_{\rho'}^{A_\mu}$$

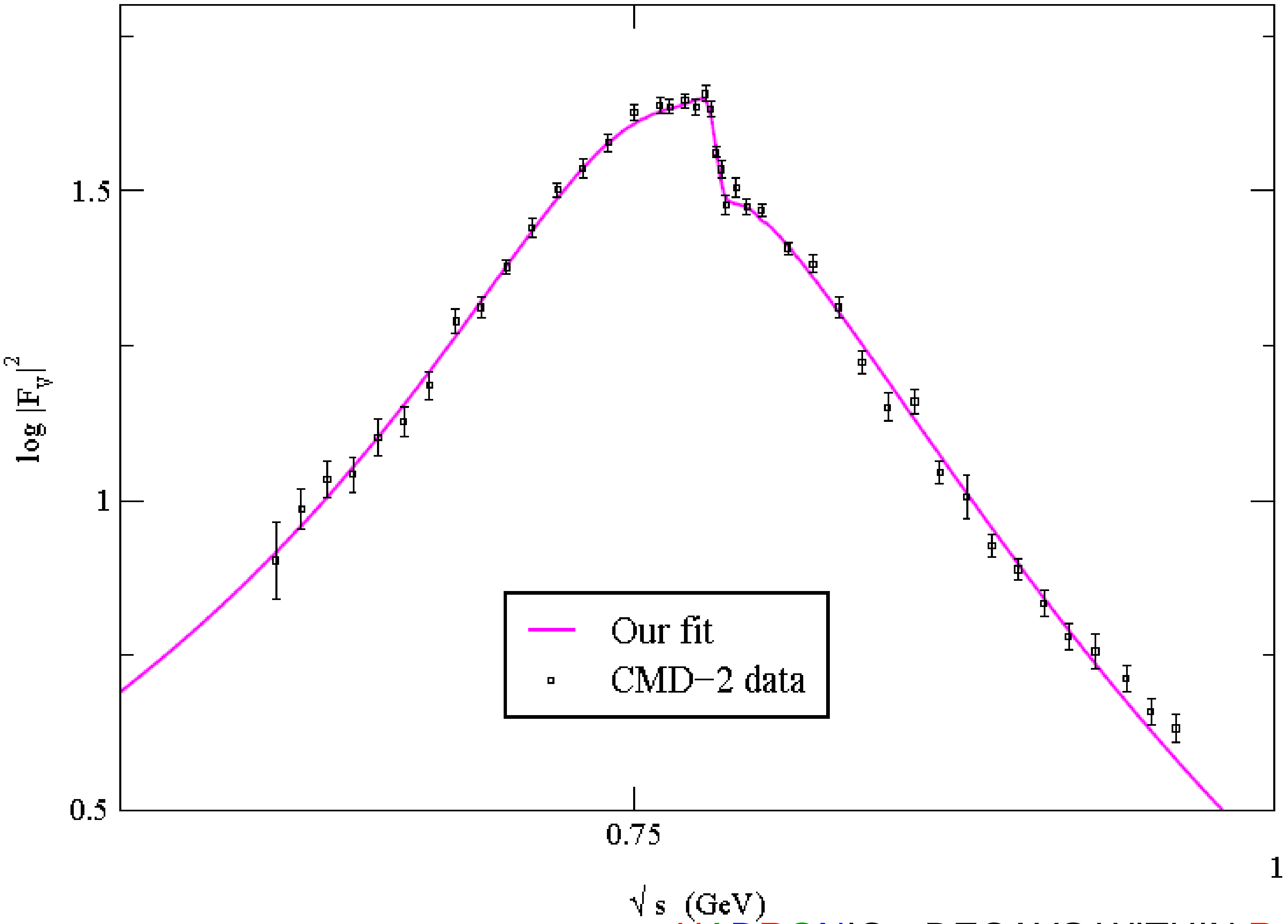
$$\Gamma_{\rho'}^{V_\mu} \neq \Gamma_{\rho'}^{A_\mu}$$

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



We are involved in an ambitious program for describing within a **theoretical framework** *as close as possible* to **QCD** the considered decays.

$\tau^- \to (\pi\,\pi)^- \, \nu_\tau$ (Pich, Portolés '01, '03)



$\tau^- \rightarrow (K\,\pi)^- \,\nu_\tau$

Many works on $K\,\pi$ FF: See complete Bibliography in (Jamin, Pich & Portolés, '06, '08)

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

(Our work)

(Gómez-Dumm, Pich, Portolés '04)

7 unknown couplings

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

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

(Our work)

7 unknown couplings

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

λ_0

~12

(Gómez-Dumm, Pich, Portolés '04)

Gives a pretty accurate description of ALEPH spectral function and structure functions

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

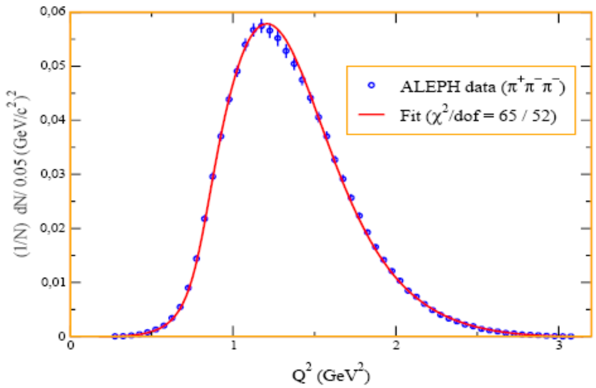
(Our work)

Procedure and results [Gómez Dumm, Pich, Portolés, 2004]

Fit to the spectrum and BR

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

input



output

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

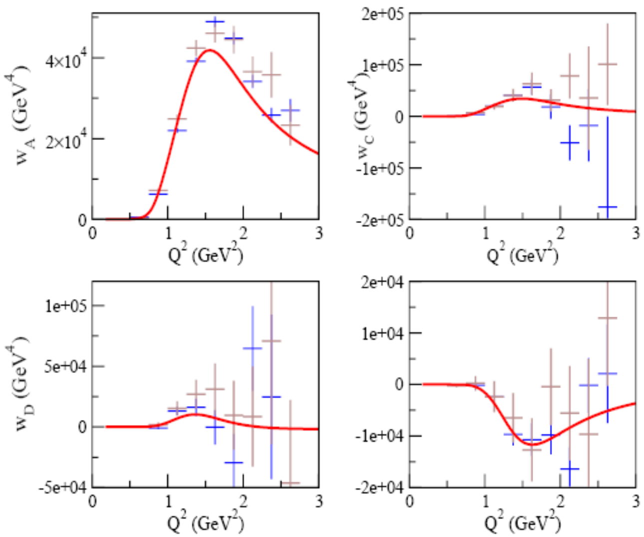
Structure Functions

PDG06

M_{a1} = (1.204 ± 0.007) GeV

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

λ_0=11.9$\underline{+}$0.4



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

Implemented in SHERPA ☑

IFIC - Instituto de Física Corpuscular

HADRONIC τ DECAYS WITHIN RχT

Pablo Roig (INFN)

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

(Our work)

Procedure and results [Gómez Dumm, Pich, Portolés, 2004]

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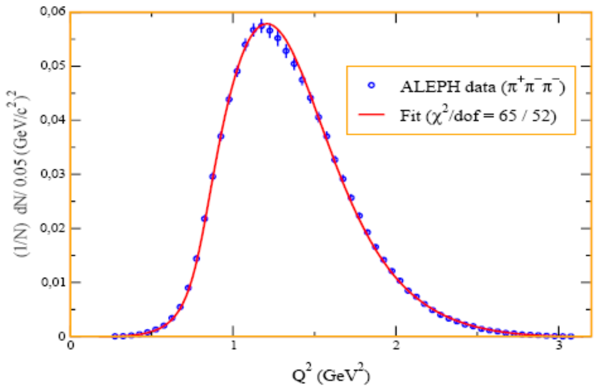

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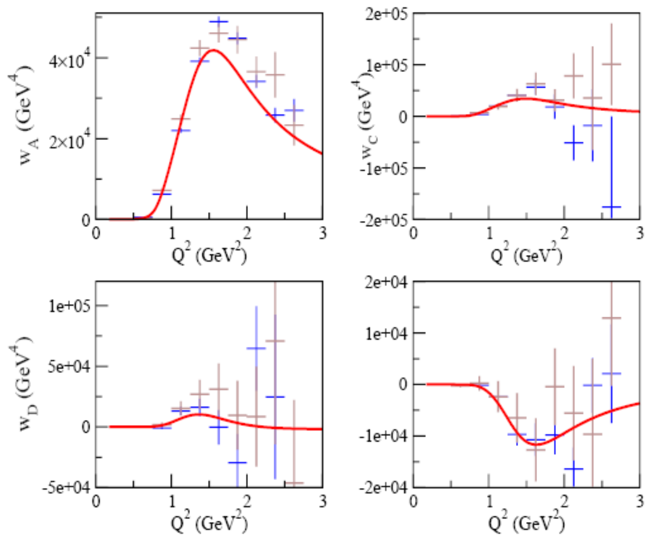
$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$

Structure Functions



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

Caveat:

PDG06

$$F_{1,2} \approx \lambda_0 \frac{m_\pi^2}{Q^2}$$

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

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

(Our work)

However, λ_0 ~ **1/8** (Cirigliano, Ecker, Eidemüller, Pich, Portolés '04) <VAP>

and the proposed a_1 width was just χ based

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$$\Gamma_{a_1}(Q^2) \leftarrow R\chi T$$

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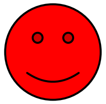

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- $\lambda_0 \sim$ **1/8**
- $\Gamma_{a_1}(Q^2) \leftarrow R\chi T$

Models and parameterizations

- [Gounaris, Sakurai,1968] — Pion form factor (resonance dynamics)
- [Tsai, 1971] — Current Algebra parameterization
- [Fischer, Wess, Wagner, 1980]
  [Berger, 1987]
  [Braaten, Oakes, Tse, 1990]
  [Colangelo, Finkemeier, Urech, 1996]
  — Chiral symmetry + Modelization VMD ($\pi\pi$, $\pi\pi\pi$)
- [Kühn, Wagner, 1984]
  [Pich et al, 1989,1990]
  [Kühn, Santamaría, 1990]
  [Decker, Finkemeier, Kühn, Mirkes, Was…,1990-2000]
  — Kühn & Santamaría model. Parameterization of 2P, 3P → TAUOLA
- [Bruch, Khodjamirian, Kühn, 2004] — (KS,GS) modified – dual QCD($N_C \to \infty$)

Models and parameterizations

- [Beldjoudi, Truong, 1995] — Current Algebra + Dispersion Relations ($\pi\pi$, $K\pi$, $K\eta$, 3π, $K\pi\pi$)

- [Guerrero, Pich, 1997] [Pich, Portolés, 2001] — χPT+ RχT + Dispersion Relations (Pion form factor)

- [Sanz-Cillero, Pich, 2003] [Rosell, Sanz-Cillero, Pich, 2004] — RχT + large-N_C expansion (Pion form factor)

- [Gómez Dumm, Pich, Portolés, 2004] — RχT (chiral symmetry); Large-N_C expansion; Asymptotic behaviour ruled by QCD; (3π) $\longrightarrow$ all 3P

About TAUOLA

- Kühn & Santamaría model

$$\text{F.F.} = \frac{M_R^2}{M_R^2 - q^2 - i\sqrt{q^2}\,\Gamma_R\left(q^2\right)}$$

- Low-energy expansion in $\tau \to \pi\pi\pi\nu_\tau$

$$F_1^A\left(Q^2, s_1, s_2\right)_{KS} = 1 + \frac{s_1}{M_V^2} + \frac{Q^2}{M_A^2} + \mathcal{O}\left(\frac{q^4}{M_R^4}\right)$$

$$F_1^A\left(Q^2, s_1, s_2\right)_{\chi PT} = \underbrace{1}_{O\left(p^2\right)\,\chi PT} + \underbrace{\frac{3}{2}\frac{s_1}{M_V^2} + \mathcal{O}\left(\frac{q^4}{M_R^4}\right)}_{O\left(p^4+\ldots\right)\,\chi PT}$$

$\tau^- \to (\pi\pi\pi)^- \nu_\tau$: Axial-vector form factors

$$\langle \pi^-_{p_1} \pi^-_{p_2} \pi^+_{p_3} \left| \left(V^-_\mu - A^-_\mu \right) e^{i L_{QCD}} \right| 0 \rangle = \left(g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2} \right) \left[F_1^A \left(Q^2, s_1, s_2 \right) \left(p_1 - p_3 \right)^\nu + F_1^A \left(Q^2, s_2, s_1 \right) \left(p_2 - p_3 \right)^\nu \right]$$

$$+ \underbrace{\cancel{F_2^A}}_{m_\pi = 0} Q_\mu + i \underbrace{\cancel{F_3^V}}_{SU(2)_I} \varepsilon_{\mu\alpha\beta\gamma} p_1^\alpha p_2^\beta p_3^\gamma$$

$$Q = p_1 + p_2 + p_3$$

$$s_i = (Q - p_i)^2$$

<u>Kühn & Santamaría Model</u>

$$F_1^A(Q^2, s_1, s_2) = N\Big|_{\chi O(p^2)} \; BW_{a_1}(Q^2) \frac{BW_\rho(s_1) + \alpha \; BW_{\rho'}(s_1) + \beta \; BW_{\rho''}(s_1)}{1 + \alpha + \beta}$$

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

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

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

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

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

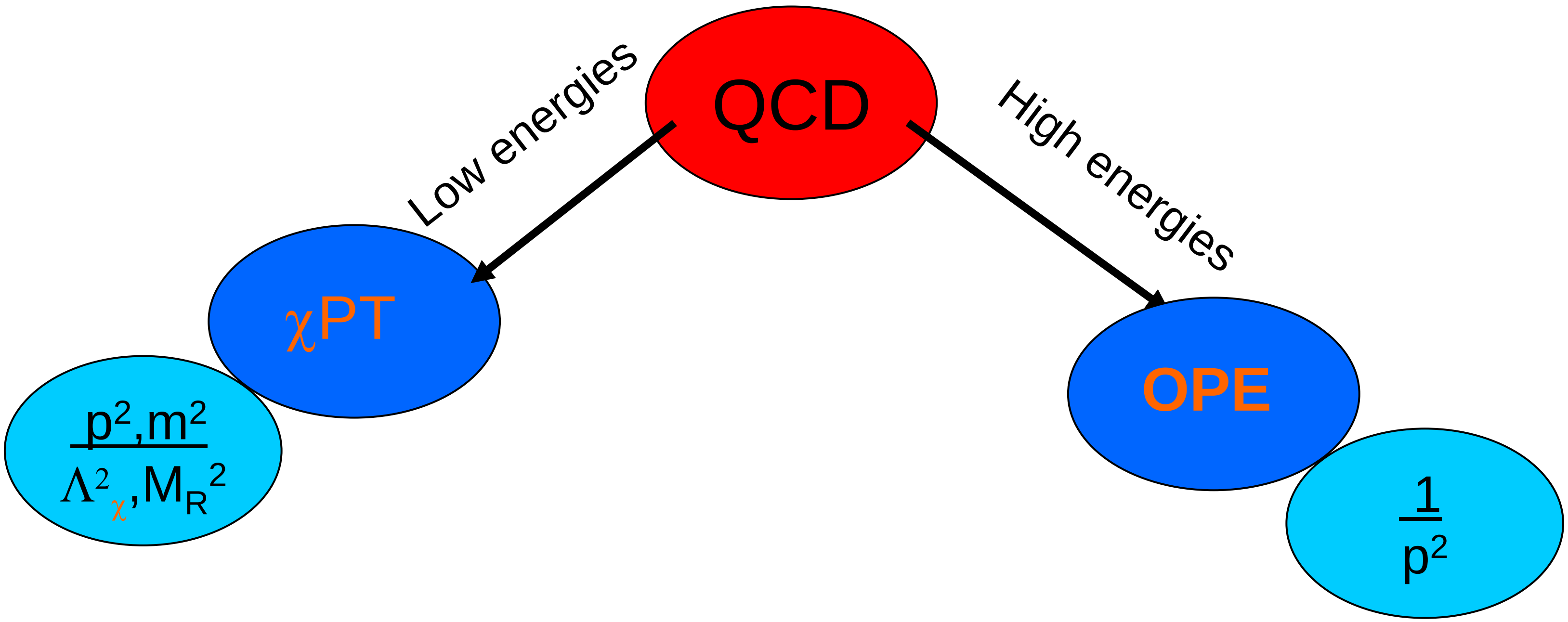
$$X \to h(g,\Phi)\, X\, h(g,\Phi)^\dagger$$

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

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

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

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



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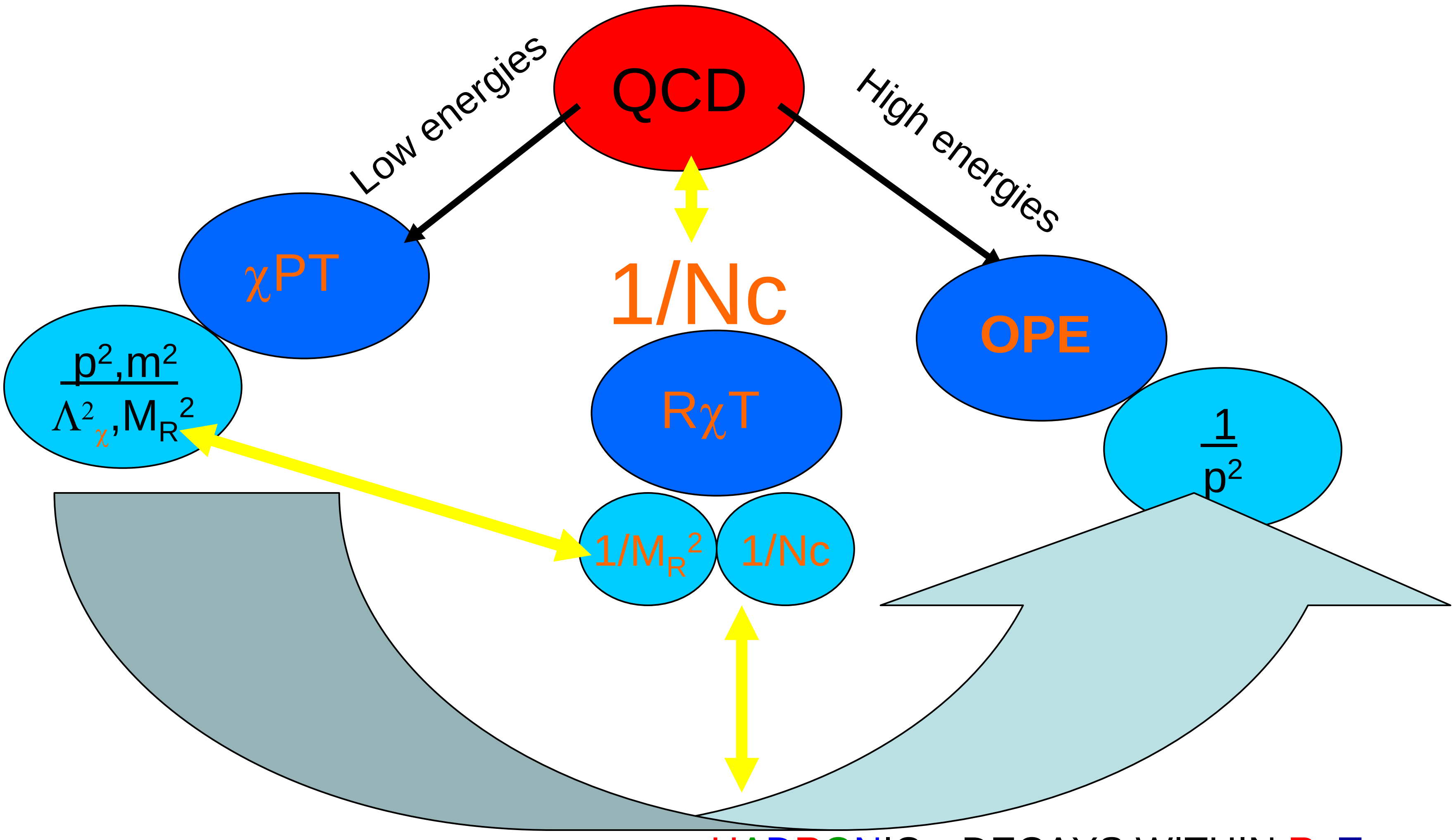

Resonances + Goldstone Bosons

TOOLS : RχT

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

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

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

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

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

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

Antisymmetric tensor formalism

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

(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

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

(Ruiz-Femenía, Pich, Portolés '03)

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

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

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

Resonances + Goldstone Bosons

TOOLS : RχT

(Ecker, Gasser, Pich, De Rafael ‘89)

(Ecker, Gasser, Leutwyler, Pich, De Rafael ‘89) ,…

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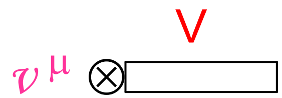
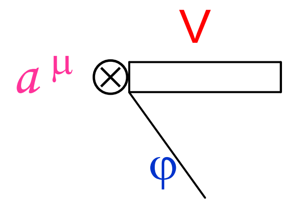
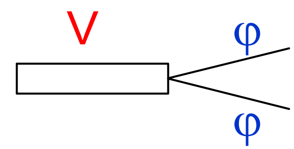
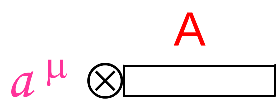


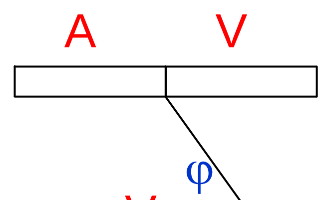




$$\mathcal{L}_A = \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle$$



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



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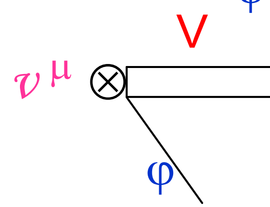

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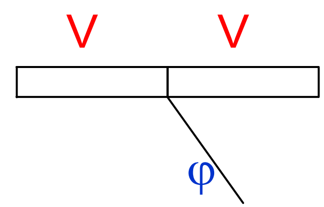

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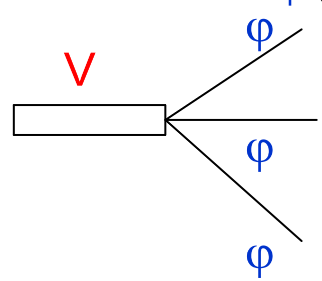
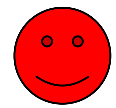


The axial-form factor and the a_1: $\tau^- \to (3\pi)^- \nu_\tau$

Our study attempts to provide a good phenomenological description of $\tau^- \to (3\pi)^- \nu_\tau$ with:

$$\lambda_0 \sim \mathbf{1/8}$$

$$\Gamma_{a_1}(Q^2) \leftarrow R\chi T$$ 

$$F_V G_V = F^2,$$

$$F_V^2 - F_A^2 = F^2,$$

$$M_V{}^2 F_V{}^2 = M_A{}^2 F_A{}^2,$$

$$\lambda' = \frac{F_V}{2\sqrt{2} F_A},$$

$$\lambda'' = \left(2 \frac{F^2}{F_V{}^2} - 1 \right) \lambda'.$$

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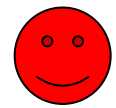
$$\Gamma_{a_1}(Q^2) \leftarrow R\chi T$$ 

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$$F_V G_V = F^2,$$

$F_A \sim$140 MeV, $F_V \sim$210 MeV

$$\lambda' = \frac{F_V}{2\sqrt{2}F_A},$$

$$\lambda'' = \left(2\frac{F^2}{F_V^2} - 1\right)\lambda'.$$

SHORT–DISTANCE CONSTRAINTS

Vector Form Factor $\langle \pi | v_\mu | \pi \rangle$:

$$F_V(t) \;=\; 1 \;+\; \sum_i \frac{F_{V_i}\, G_{V_i}}{f^2}\, \frac{t}{M_{V_i}^2 - t}$$

$$\lim_{t\to\infty} F_V(t) = 0 \quad \longrightarrow \quad \boxed{\sum_i F_{V_i}\, G_{V_i} \;=\; f^2}$$

Axial Form Factor $\langle \gamma | a_\mu | \pi \rangle$:

$$G_A(t) = \sum_i \left\{ \frac{2\, F_{V_i}\, G_{V_i} - F_{V_i}^2}{M_{V_i}^2} + \frac{F_{A_i}^2}{M_{A_i}^2 - t} \right\}$$

$$\lim_{t\to\infty} G_A(t) = 0 \quad \longrightarrow \quad \boxed{\sum_i \left(2\, F_{V_i}\, G_{V_i} - F_{V_i}^2\right) / M_{V_i}^2 \;=\; 0}$$

Weinberg Sum Rules:

$$\Pi_{LR}(t) \;=\; -\frac{f^2}{t} \;+\; \sum_i \frac{F_{V_i}^2}{M_{V_i}^2 + t} \;-\; \sum_i \frac{F_{A_i}^2}{M_{A_i}^2 + t}$$

$$\lim_{t\to\infty} t\; \Pi_{LR}(t) = 0$$

$$\lim_{t\to\infty} t^2\, \Pi_{LR}(t) = 0$$

$$\longrightarrow \quad \boxed{\begin{array}{c} \sum_i \left(F_{V_i}^2 - F_{A_i}^2\right) = f^2 \\ \sum_i \left(M_{V_i}^2\, F_{V_i}^2 - M_{A_i}^2\, F_{A_i}^2\right) = 0 \end{array}}$$

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

(Gómez-Dumm, Pich, Portolés '00)

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

(This work)

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

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

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

CLEO analyses & KS-like models

(Liu '03)

CLEO

$$\tau^- \to K \bar{K} \pi^- \nu_\tau$$

CLEO analyses & ~~KS~~-like models

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(Liu '03) (CLEO-III '04)

CLEO

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CLEO analyses & ~~KS~~-like models

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$$F_V = -\frac{1}{2\sqrt{2}\pi^2 F^3}\sqrt{R_B}\sum_i BW_i$$

CLEO analyses & ~~KS~~-like models

(Liu '03) (CLEO-III '04)

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$$BW_{V,A}(x=s_i,Q^2) = \frac{M_{V,A}{}^2}{M_{V,A}{}^2 - x - i\sqrt{x}\,\Gamma_{V,A}(x)}$$

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R_B: **1.80±0.53**

~~QCD~~

CLEO analyses & ~~KS~~-like models

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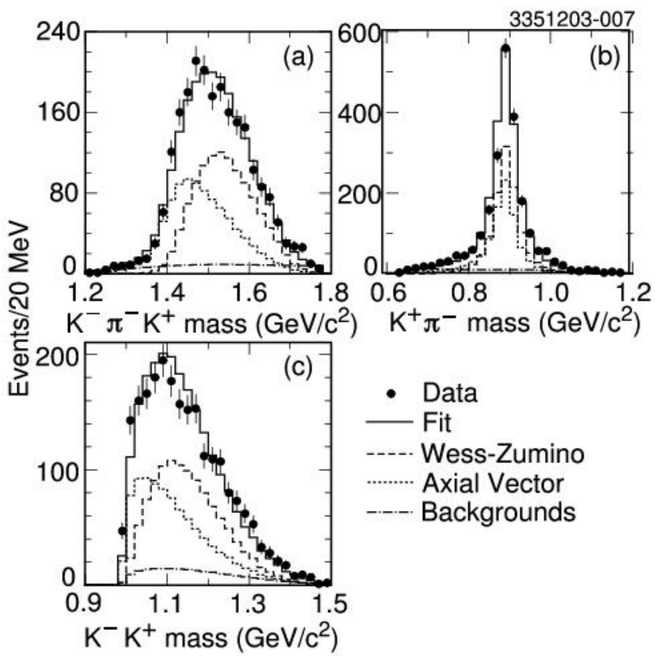
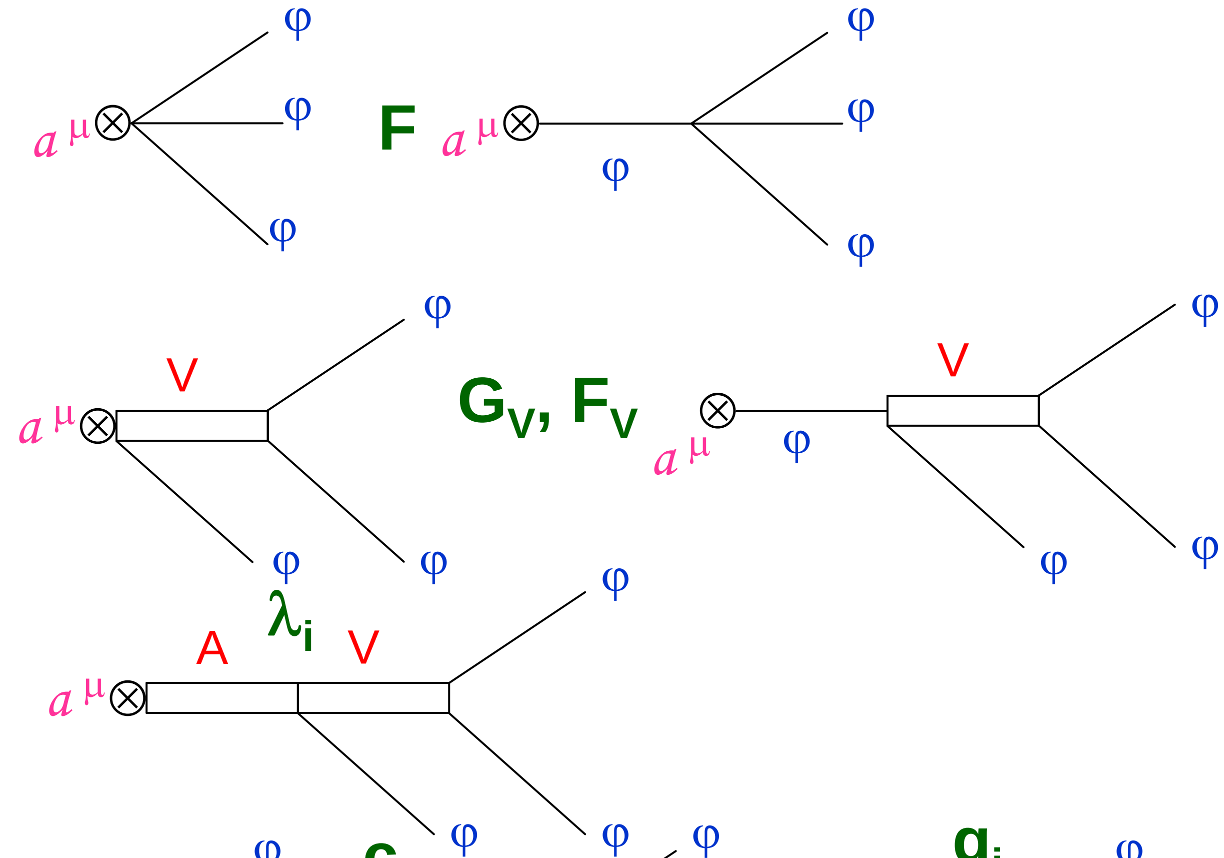
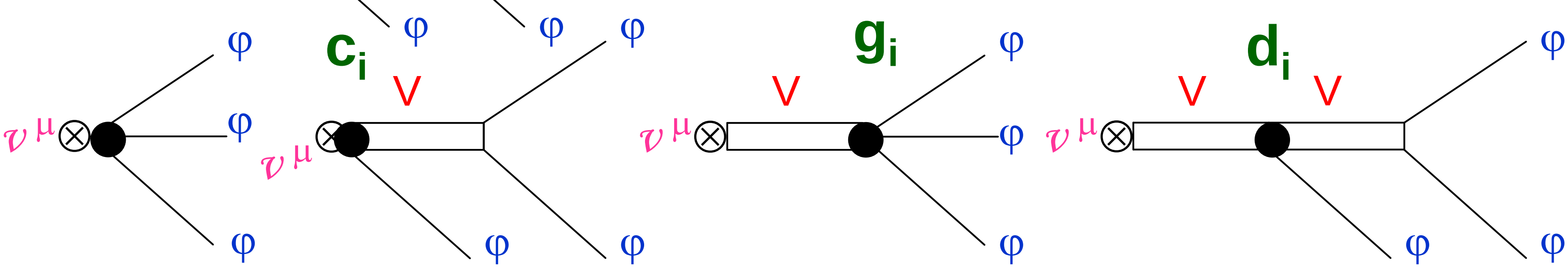


~~**QCD**~~

RχT APPLIED



23 unknown couplings

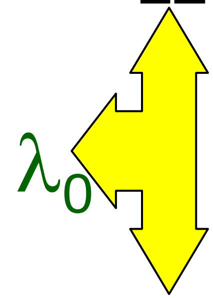


$K\,\bar{K}\,\pi^-$ channels within RχT

<u>Axial-vector Current</u>

$$F_V G_V = F^2,$$
$$F_V^2 - F_A^2 = F^2,$$
$$2G_V = F_V,$$
$$2\lambda' = 1,$$
$$\lambda'' = 0.$$

12 (Gómez-Dumm, Pich, Portolés '04)



1/8 (Cirigliano, Ecker, Eidemüller, Pich, Portolés '04)

<u>Vector Current</u>	Fixed	Free
vector$_1$: (This work)	c_{125}, c_{1256}, d_3, g_{123}, g_2	~~c_{1235}, d_{123}~~, c_4, g_4, g_5

0

(Ruiz-Femenía, Pich, Portolés '03)

$$c_{125} = c_1 - c_2 + c_5$$
$$c_{1256} = c_1 - c_2 - c_5 + 2c_6$$
$$g_{123} = g_1 + 2g_2 - g_3$$

$$c_{1235} = c_1 + c_2 + 8c_3 - c_5$$
$$d_{123} = g_1 + 8d_2 - d_3$$

$$\boxed{\omega \to \pi\,\pi\,\pi}$$

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

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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Assumptions of this procedure: SU(2) symmetry

K* >> ρ,ω,ϕ

Interferences are negligible

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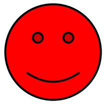
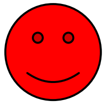
Assumptions of this procedure: SU(2) symmetry 

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

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$\downarrow$

Error of this simplification $\geq$ 30 % both in KS approach and in ours

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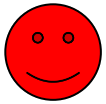
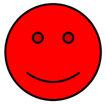
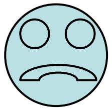
Assumptions of this procedure: SU(2) symmetry 

K* >> ρ,ω,ϕ 

Interferences are negligible 

Error of this simplification $\geq$ 30 % both in KS approach and in ours

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

SU(2) AND INTERFERENCES

Until recently, there was some confusion on this issue for the $K\overline{K}\pi$ modes:

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

1. In the ALEPH analysis of τ decay modes with kaons [12], an estimate of the vector contribution was obtained using the e^+e^- annihilation data from DM1 [13] and DM2 [14] in the $K\overline{K}\pi$ channel, extracted in the $I=1$ state. This contribution was found to be small, and, using the conserved vector current (CVC), a branching fraction of $\mathcal{B}_{CVC}(\tau \to \nu_\tau(K\overline{K}\pi)_V) = (0.26 \pm 0.39)\cdot 10^{-3}$, was found, corresponding to an axial fraction of $f_{A,CVC}(K\overline{K}\pi) = 0.94^{+0.06}_{-0.08}$.
2. The ALEPH CVC result was corroborated by a partial-wave and lineshape analysis of the a_1 resonance from τ decays in the $\nu_\tau\pi^-2\pi^0$ mode performed by CLEO [15]. The effect of the K^*K decay mode of the a_1 was seen through unitarity and a branching fraction of $\mathcal{B}(a_1 \to K^*K) = (3.3\pm 0.5)\%$ was derived. With the known $\tau^- \to \nu_\tau a_1^-$ branching fraction, this value more than saturates the total branching fraction available for the $K\overline{K}\pi$ channel, yielding an axial fraction of $f_{A,a_1}(K\overline{K}\pi) = 1.30 \pm 0.24$.
3. Another piece of information, also contributed by CLEO [16], but conflicting with the two previous results, is based on a partial-wave analysis in the $K^-K^+\pi^-$ channel using two-body resonance production and including many possible contributing channels. A much smaller axial fraction of $f_{A,K\overline{K}\pi}(K\overline{K}\pi) = 0.56 \pm 0.10$ was found here.

Since the three determinations are inconsistent, the value $f_A = 0.75 \pm 0.25$ has been used previously to account for the discrepancy [1]. This led to a systematic uncertainty in the V, A spectral functions that competed with the purely experimental uncertainties.

Precise cross section measurements for e^+e^- annihilation to $K^+K^-\pi^0$ and to $K^0K^\pm\pi^\mp$ have been recently published by the BABAR Collaboration [7], using the method of radiative return. In the mass range of interest for τ physics they show strong dominance of $K^*(890)K$ dynamics and a fit of the Dalitz plot yields a clean separation of the $I = 0,1$ contributions. Assuming CVC, the mass distribution of the vector final state in the decays $\tau \to \nu_\tau K\overline{K}\pi$ can be obtained. The result is shown in Fig. 1 and compared with the full τ spectrum from ALEPH [12] summing up the contributions from the $K^-K^+\pi^-$, $\overline{K}^0K^0\pi^-$, and $K^-K^0\pi^0$ modes. The BABAR results reveal a small vector component. After integration, one obtains

$$f_{A,CVC}(K\overline{K}\pi) = 0.833 \pm 0.024, \tag{7}$$

which is about 1.3σ lower than the ALEPH determination using the same method (but with much poorer e^+e^- input data) and 2.7σ higher than the CLEO partial-wave-analysis result. The new determination has a precision that exceeds the previously used value by an order of magnitude, thus effectively reducing the uncertainties in the vector and axial-vector spectral functions to the experimental errors only.

SU(2) AND INTERFERENCES

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

The final state $K^+K^-\pi^0$ can be produced through the intermediate states $K^{*\pm}(892)K^\mp$ or $K_2^{*\pm}(1430)K^\mp$, and we expect a Dalitz plot with a symmetric population density with respect to the exchange $K^+\pi^0(K^{*+}) \leftrightarrow K^-\pi^0(K^{*-})$, see Fig. 13.

The final state $K_S^0K^\pm\pi^\mp$ is obtained via the decays of $K^{*\pm}(892)K^\mp$ and $K^{*0}(892)K_S^0$, or $K_2^{*\pm}(1430)K^\mp$ and $K_2^{*0}(1430)K_S^0$, *i.e.*, both charged $K^{*\pm}(K_S^0\pi^\pm)$ and neutral $K^{*0}(K^\mp\pi^\pm)$ can be produced. The population density of the Dalitz plot is expected to be asymmetric in this case. This effect is clearly seen in Fig. 14.

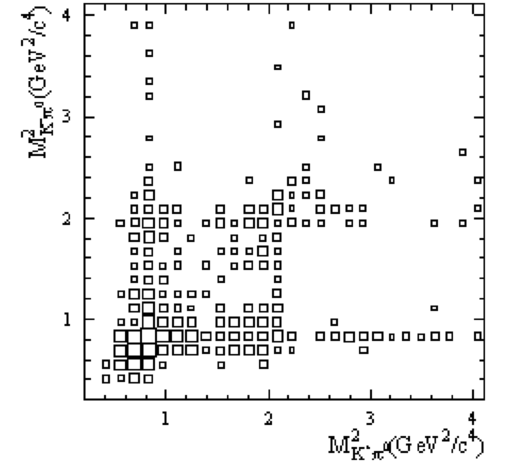


FIG. 13: The Dalitz plot distribution for the $K^+K^-\pi^0$ final state.

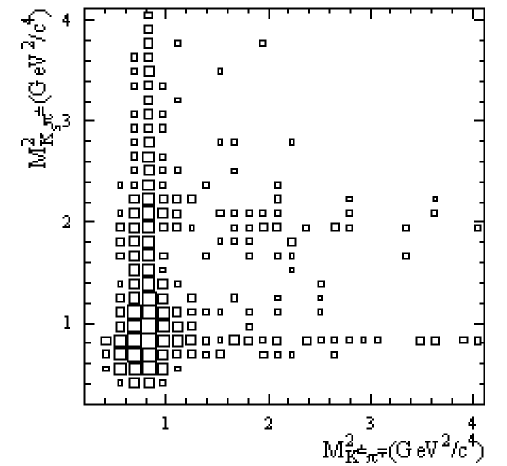


FIG. 14: The Dalitz plot distribution for the $K_S^0K^\pm\pi^\mp$ final state.

phase of the isospin components. The analysis described in the following applies only to the $K_S^0K^\pm\pi^\mp$ Dalitz plot, since only in this case, with both charged and neutral K^* contributing, we can separately extract the isoscalar and isovector components. Because the $KK^*(892)$ and

SU(2) AND INTERFERENCES

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

K* >> ρ,ω,ϕ

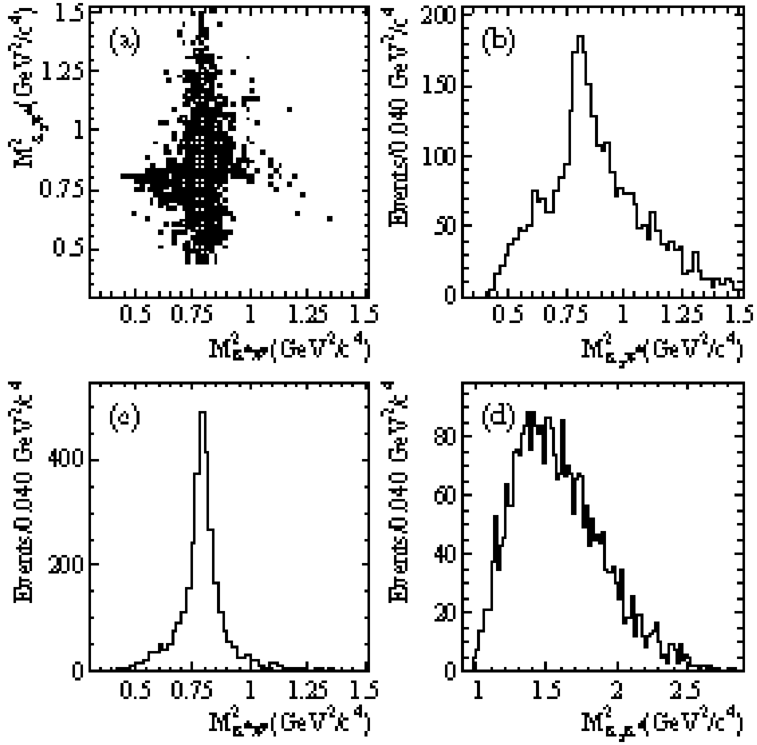
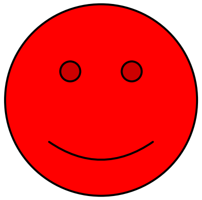


FIG. 15: (a) Dalitz plot distributions for $K^0_S K^\pm \pi^\mp$ events with an invariant mass $m_{K^0_S K \pi} < 2.0$ GeV/c^2. (b) $K^0_S \pi^\pm$ projection, with the broad charged $K^*(892)$ peak, (c) $K^\pm \pi^\mp$ projection, with the narrow neutral $K^*(892)$ peak. (d) K^0_S $K^\pm$ projection.

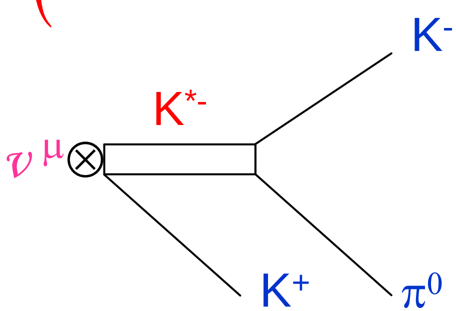


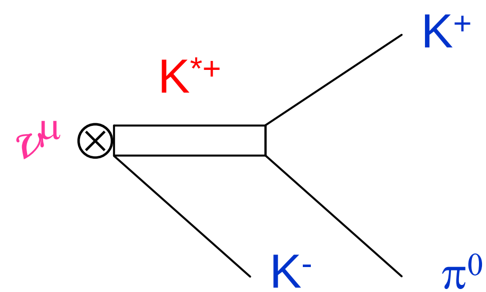
SU(2) AND INTERFERENCES

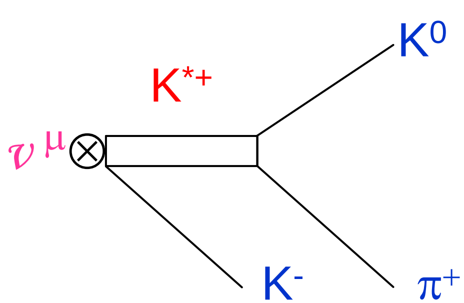
$$\sigma\left(e^+e^- \to KK\pi\right) \overset{?}{=} 3\cdot\sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right) = 6\cdot\sigma\left(e^+e^- \to K^0 K^- \pi^+\right)$$

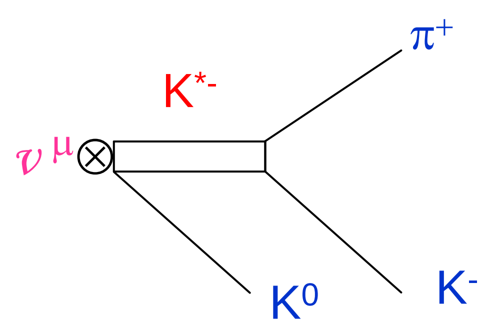
$$\sigma\left(e^+e^- \to K^+K^-\pi^0\right) \overset{?}{=} \sigma\left(e^+e^- \to K_S K^\pm \pi^\mp\right)$$

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









SU(2) AND INTERFERENCES

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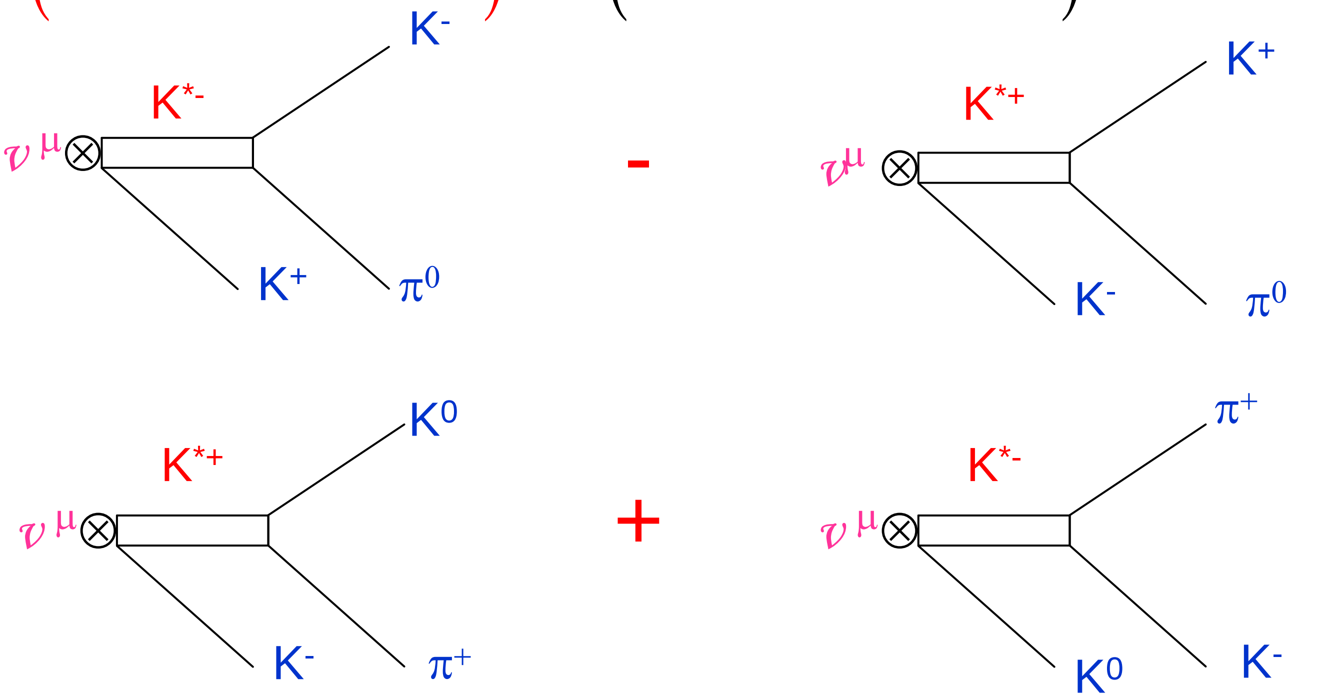

YRW 09 Frascati

HADRONIC τ DECAYS WITHIN RχT

Pablo Roig (INFN)