New Hadronic Form Factors in Tauola

arXiv:1203.3955 [hep-ph]

Pablo Roig (IFAE, Barcelona)

Based on Collaborations with Tomasz Przedzinski, Olga Shekhovtsova, Z. Was **Tauola**
Daniel Gómez-Dumm, Antonio Pich, Jorge Portolés **RχT**

XL International Meeting on Fundamental Physics & Flavour Mini-Workshop
Centro de Ciencias Pedro Pascual. Benasque, 24 Mayo-3 Junio 2012

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- Theoretical setting
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- Comparisons
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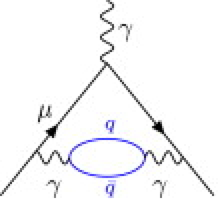
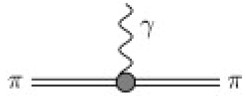
See Matthias' talk



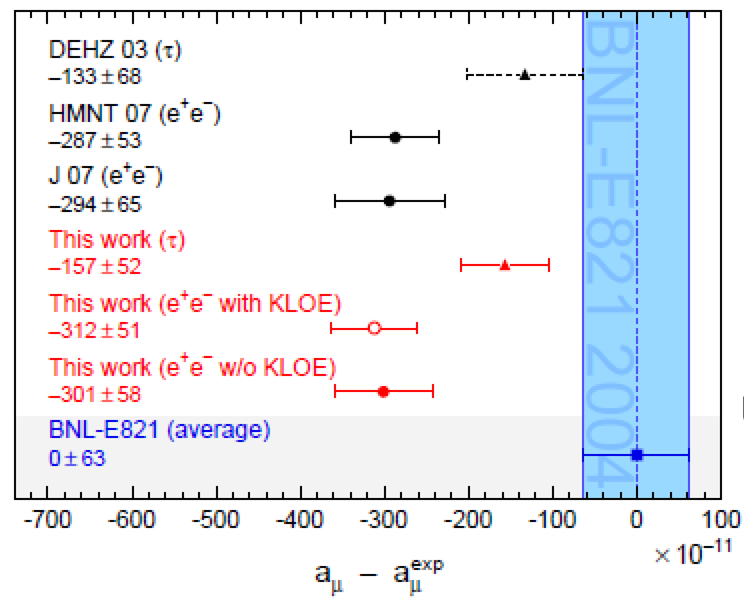


$$a_\mu^{\mathrm{exp}} = 11\,659\,208.9 \pm 5.4_{\mathrm{stat}} \pm 3.3_{\mathrm{syst}}$$

Units: 10^{-10}

MOTIVATION

Precise low-energy measurements



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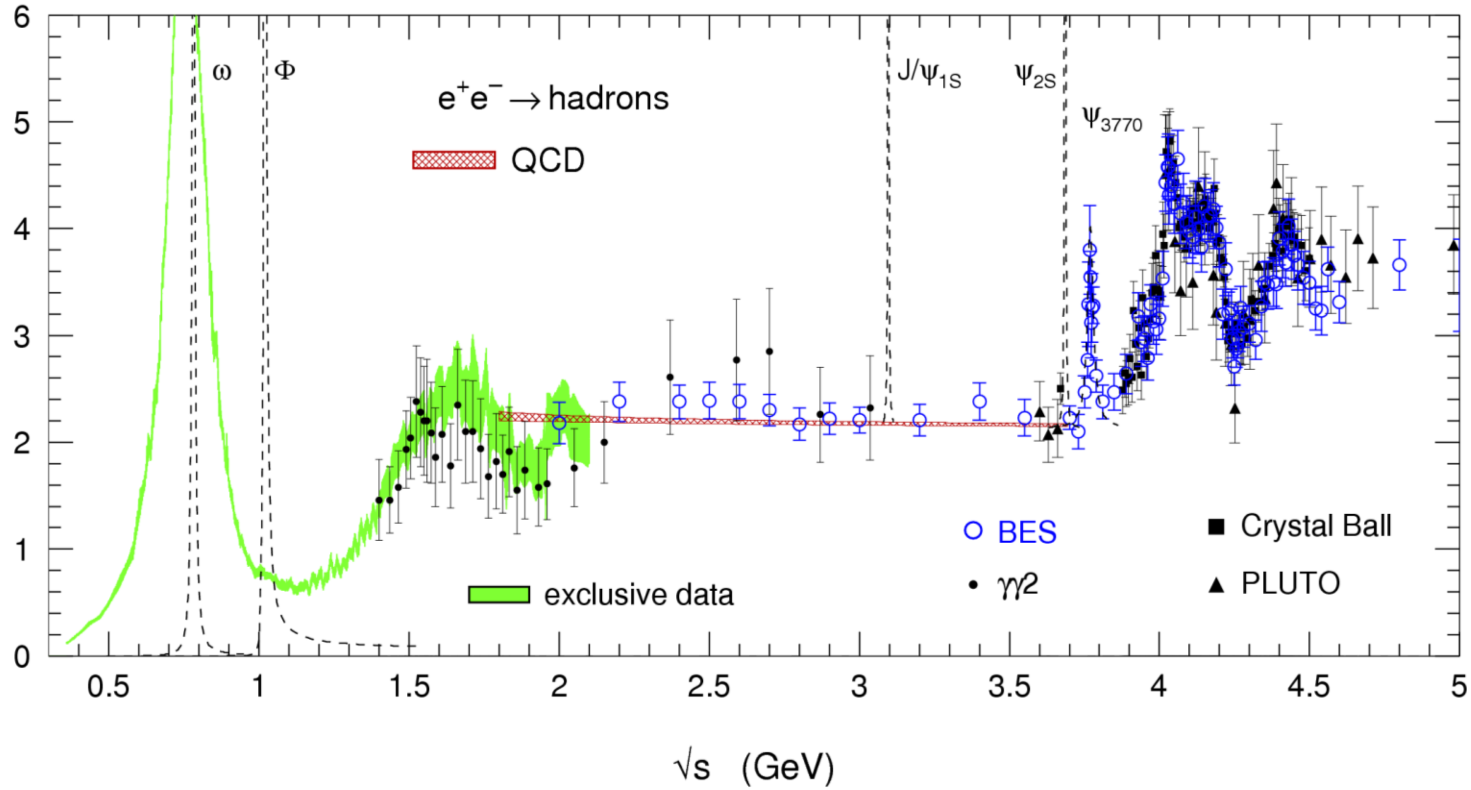
MOTIVATION

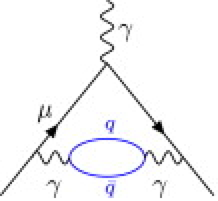
$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma^{(0)}(e^+e^- \to \mu^+\mu^-)}$$

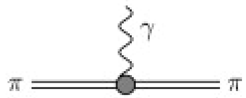
- Low energies (flavour factories):
  Hadronic tau decays

$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \mathrm{d}s K(s)\sigma^0(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s}{s}K(s)R(s)$$

$$a_\mu^{had,\pi\pi} = \left(\frac{\alpha m_\mu}{6\pi}\right)^2\int_{4m_\pi^2}^{\Lambda}\frac{\mathrm{d}s}{s}\sigma_\pi^3|F_V^{\pi\pi}(s)|^2K(s)$$







$$a_\mu^{\exp} = 11\,659\,208.9 \pm 5.4_{\rm stat} \pm 3.3_{\rm syst}$$

MOTIVATION

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73% from $\pi\pi(\gamma)$

Davier et. al. '09

82% from $\pi\pi(\gamma)$

Including contributions from other exclusive channels at energy below 1.8 GeV as well as the inclusive perturbative QCD calculation at higher energy, one obtains $a_\mu^{\rm had,LO}[\tau] = 705.3 \pm 3.9_{\rm exp} \pm 0.7_{\rm rad} \pm 0.7_{\rm QCD} \pm 2.1_{\rm IB}$ and $a_\mu^{\rm had,LO}[e^+e^-] = 689.8 \pm 4.3_{\rm exp+rad} \pm 0.7_{\rm QCD} (690.9 \pm 5.2_{\rm exp+rad} \pm 0.7_{\rm QCD})$ Including further $a_\mu^{\rm QED}$, $a_\mu^{\rm weak}$, $a_\mu^{\rm had,HO} = -9.79 \pm 0.08_{\rm exp} \pm 0.03_{\rm rad}$ [19] and $a_\mu^{\rm LBL} = 10.5 \pm 2.6$ [20], one gets the total SM predictions $a_\mu^{\rm SM}[\tau] = 11\,659\,193.2 \pm 4.5_{\rm LO} \pm 2.6_{\rm HO+LBL} \pm 0.2_{\rm QED+weak}$ and $a_\mu^{\rm SM}[e^+e^-] = 11\,659\,177.7 \pm 4.4_{\rm LO} \pm 2.6_{\rm HO+LBL} \pm 0.2_{\rm QED+weak} (11\,659\,178.8 \pm 5.2_{\rm LO} \pm 2.6_{\rm HO+LBL} \pm 0.2_{\rm QED+weak})$, which are compared with the direct measurement [1, 2] and other SM predictions [5,

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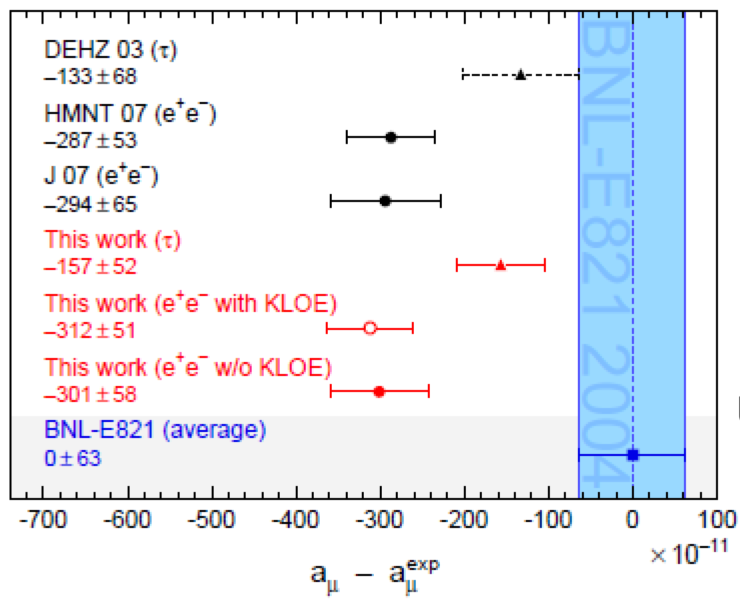
- a_μ [th,exp] – a_μ [th,exp´]



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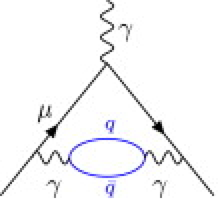

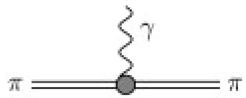

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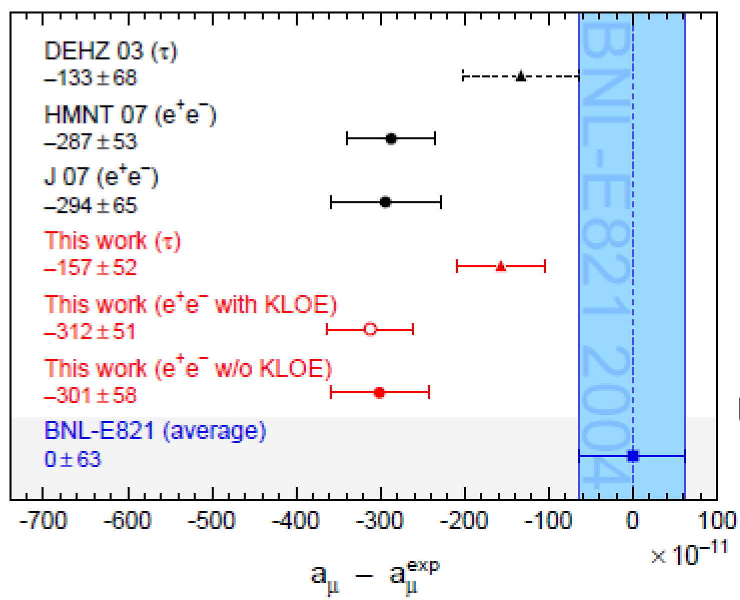

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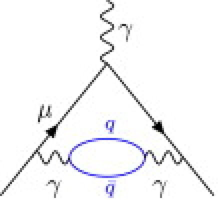

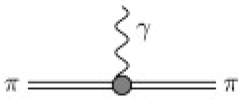

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UP TO TWO WEEKS AGO

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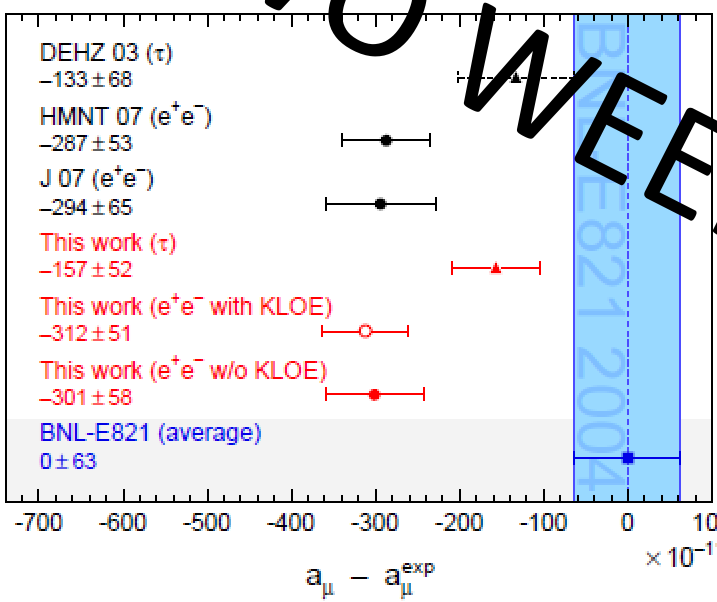

BaBar 1205.2228 hep-ex

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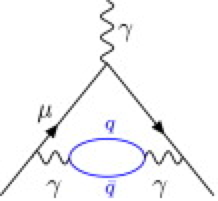

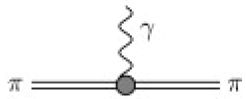

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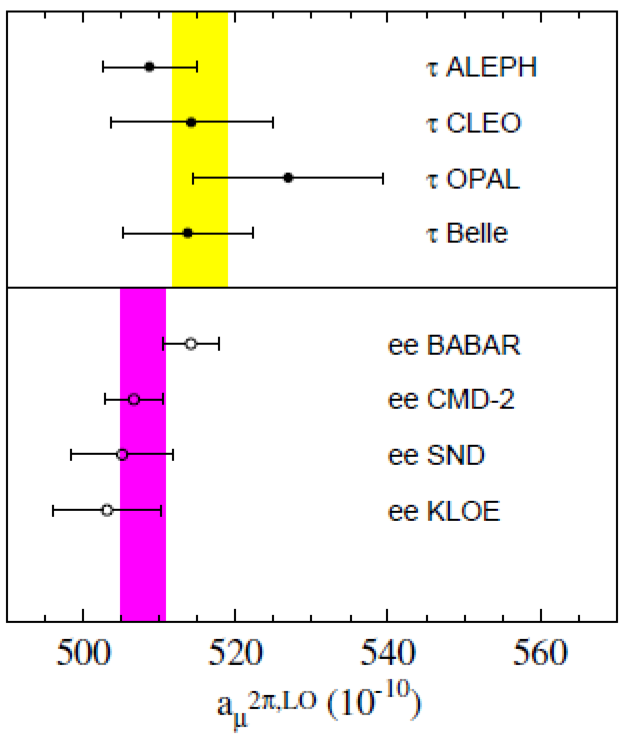

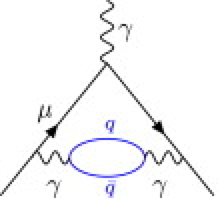

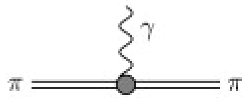

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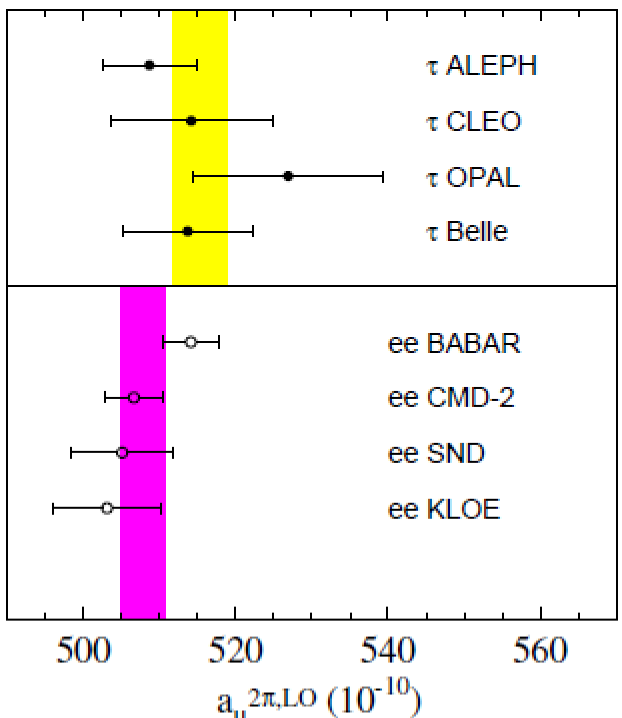
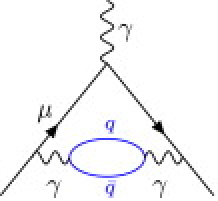
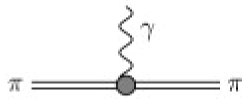
This contribution amounts to $(514.1 \pm 2.2_{stat} \pm 3.1_{syst}) \times 10^{-10}$, the most precise result yet from a single experiment. This result brings the contribution estimated from all $e^+e^- \to \pi^+\pi^-(\gamma)$ data combined in better agreement with the τ estimate. When adding all other Standard Model contributions to the present 2π result, in particular using all available *BABAR* data on multihadronic processes, the predicted muon magnetic anomaly is found to be $(\underline{11\,659}\,186.5 \pm 5.4) \times 10^{-10}$, which is smaller than the direct measurement at BNL by $\underline{2.7\sigma}$. Adding all previous 2π data increases the deviation to 3.6σ.







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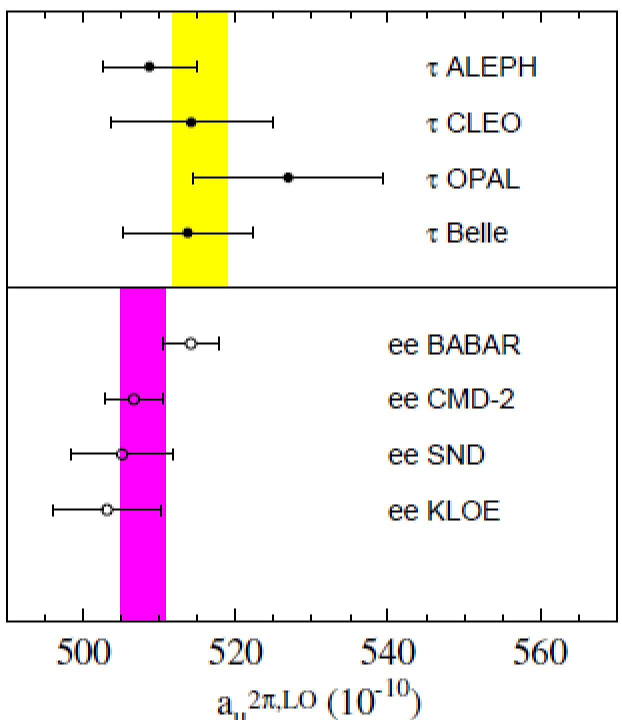

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MOTIVATION

- Low energies (**Flavour factories**):
  Hadronic tau decays

See Matthias' talk

a_μ, $\Delta\alpha(M_z^2)$ $\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = -\left(\frac{\alpha M_Z^2}{3\pi}\right) {\rm Re} \int_{m_\pi^2}^{\infty} {\rm d}s \frac{R(s)}{s(s-M_Z^2-i\epsilon)}$

CC & NC Universality

~~CP~~ BaBar '11

Resonance Dynamics (NP QCD)

τ hadronic width $\Rightarrow \alpha_s(m_\tau^2) \rightarrow \alpha_s(M_z^2)$ Rodrigo, Pich, Santamaría '98

Baikov, Chetyrkin, Kuhn '08; Davier, Descotes-Genon, Malaescu, Zhang '08; Boito et. al. '11, '12

$m_s(m_\tau^2)$ & V_{us} Gámiz, Jamin, Pich, Prades, Schwab '02,'04

MOTIVATION

• High energies (**LHC**):
Hadronic tau decays

Search of the scalar sector of the SM, origin of EWSB

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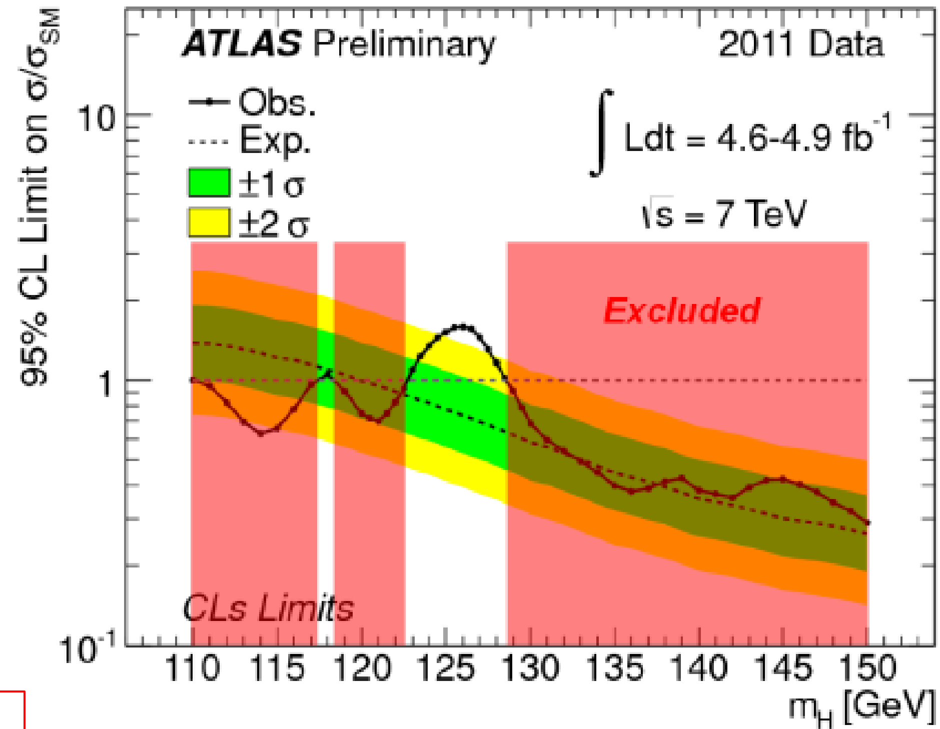

CMS(preliminary)

Allowed Scalar Boson mass has been squeezed into a tiny region:
~~117.5-118.5 GeV~~ or 122.5-129 GeV

MOTIVATION

See last TAUOLA Workshop (Krakow, May 2012) devoted talks
http://indico.cern.ch/conferenceDisplay.py?confId=188018

- High energies (**LHC**):
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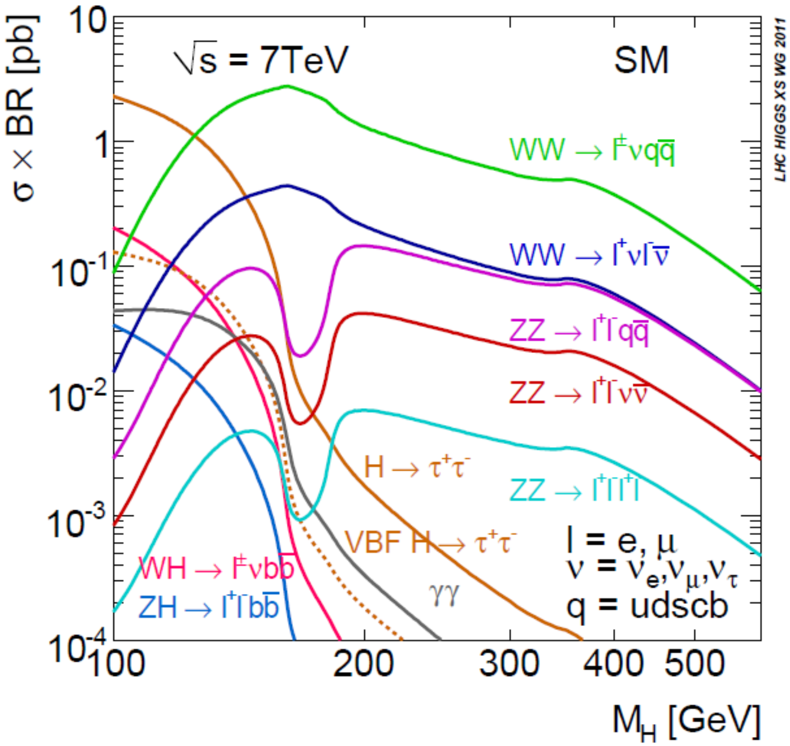
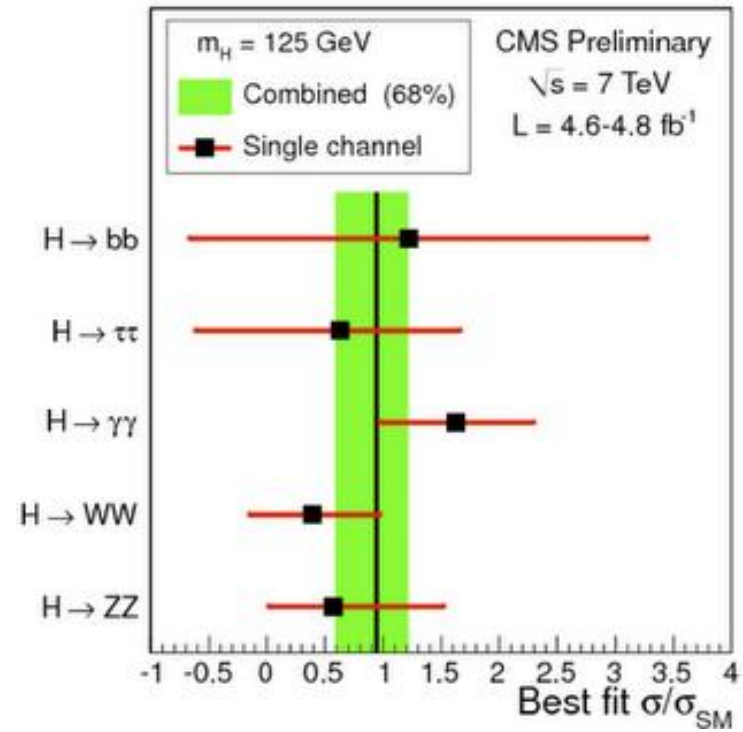
Search of the scalar sector of the SM, origin of EWSB

→ In the interesting low-E region the di-τ decay channel can give valuable information





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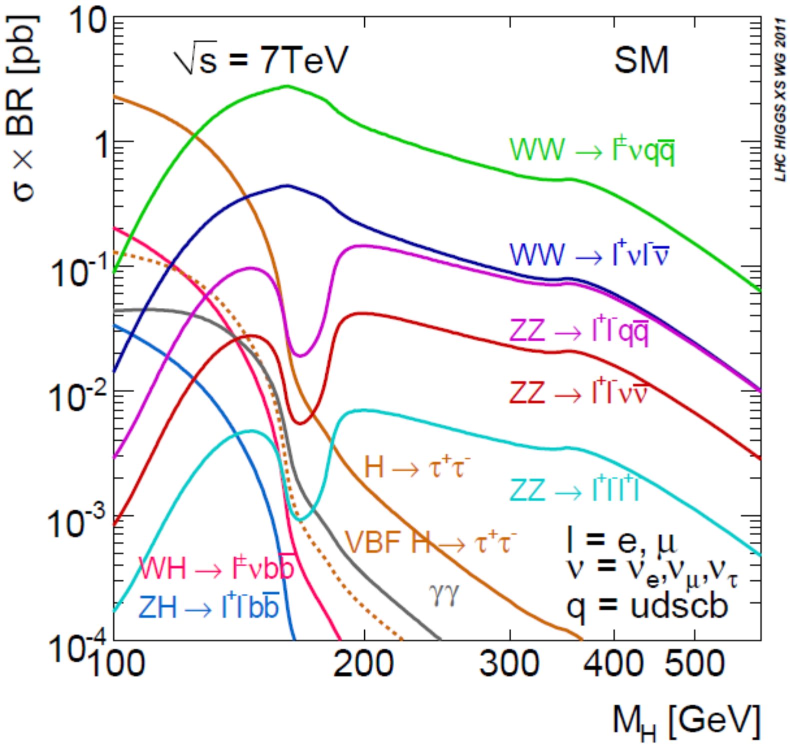
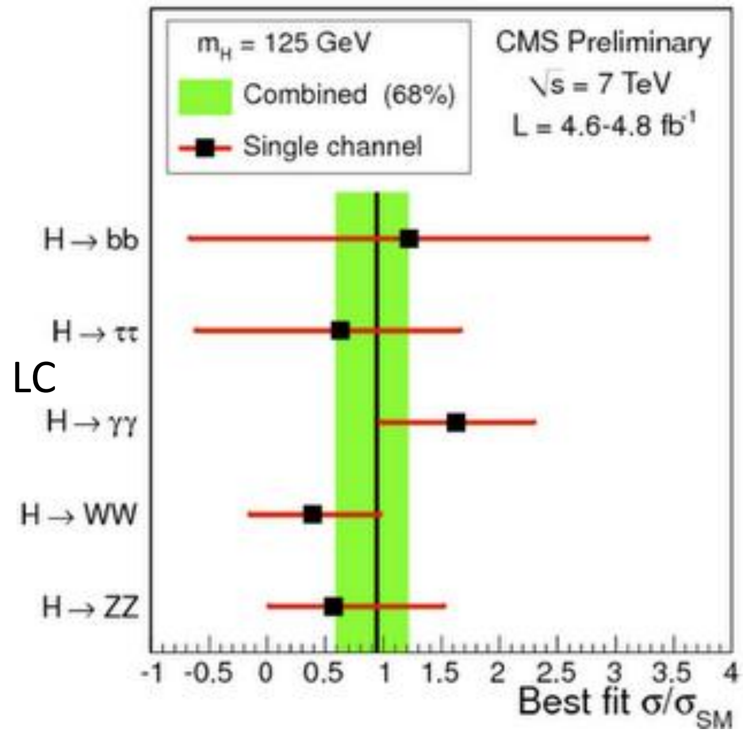
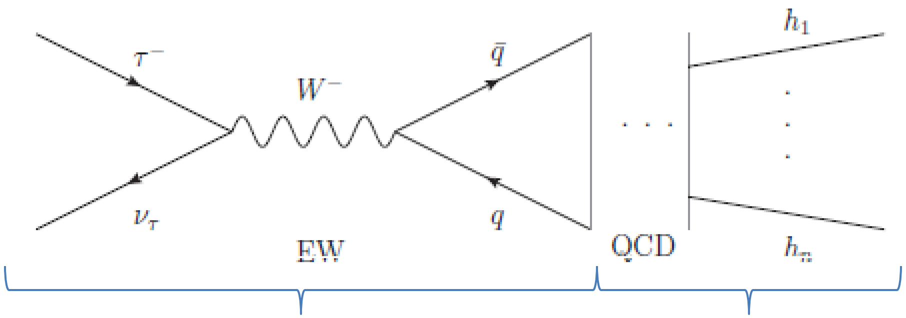


Polarization, CP
Although better at LC



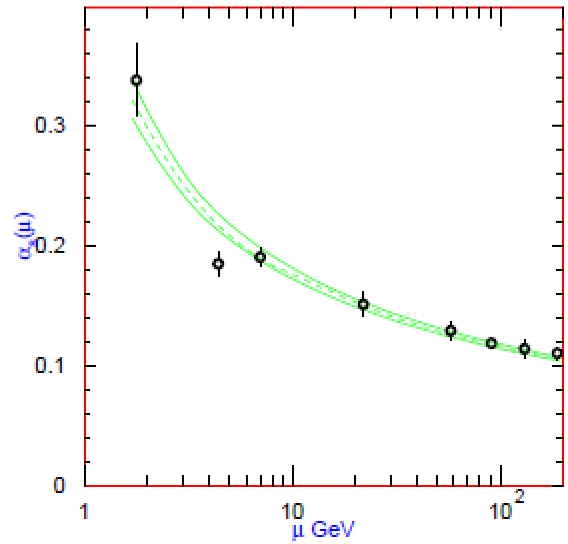
THEORETICAL SETTING



Controlled

Problem

Hadronization in $2m_\pi \leq E \leq M_\tau$



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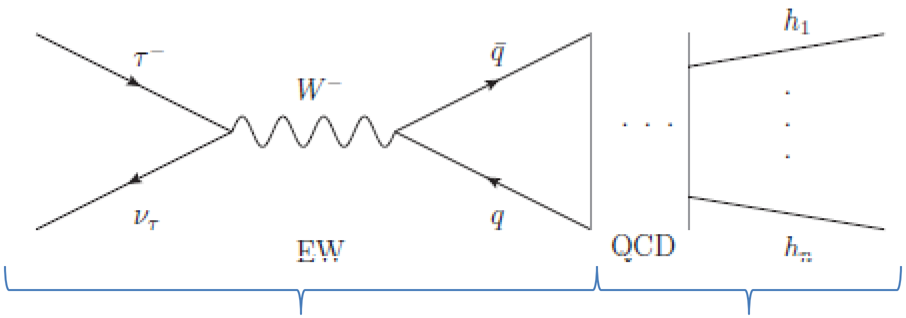

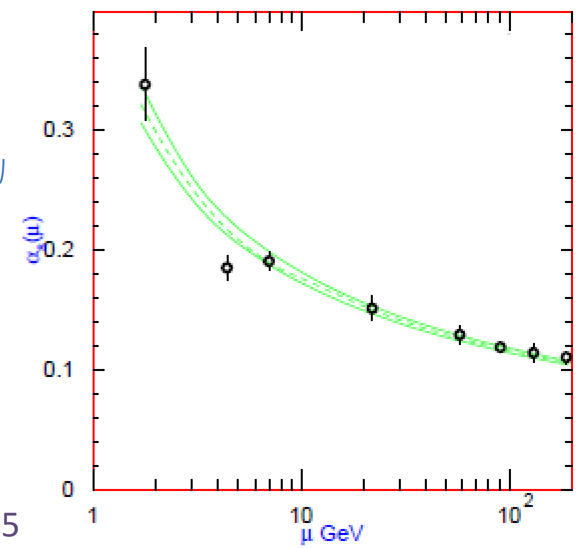

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Hadronization in $2m_\pi \leq E \leq M_\tau$

→ At very low energies, **χPT** is the **EFT** of QCD Gasser, Leutwyler '85

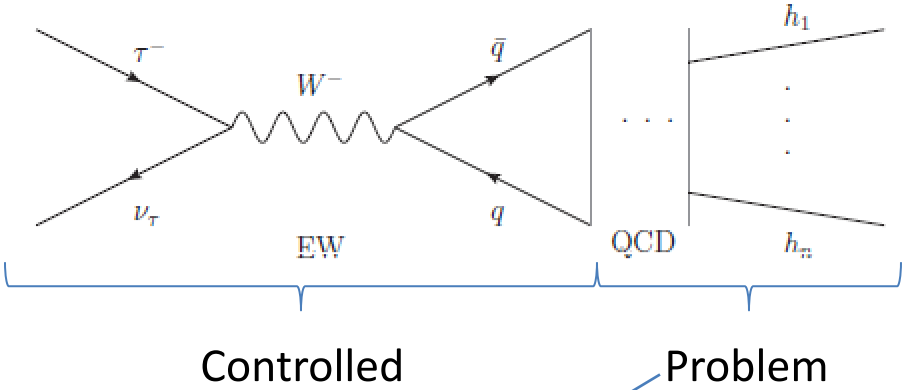
Only light quarks (u, d, s). In the massless limit $G \equiv SU(n_f)_L \otimes SU(n_f)_R$

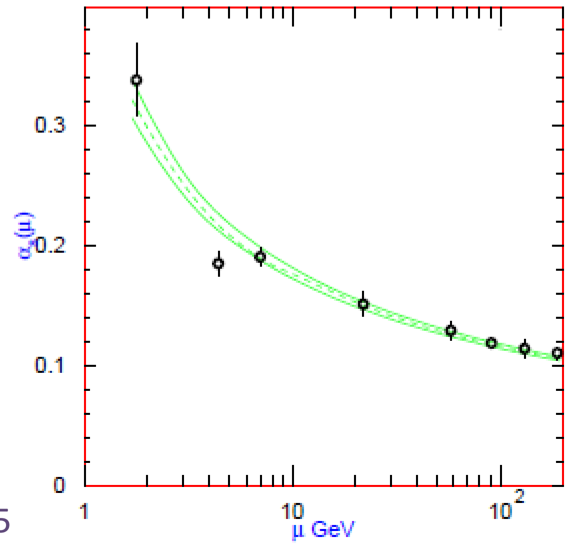
Spontaneous Symmetry Breaking $SU(3)_L \otimes SU(3)_R \to SU(3)_V$

Approximately massless pGbs $\pi^\pm, \pi^0, \eta, K^\pm, K^0, \bar{K}^0$

Small masses ($m<M_\rho,M_{a_1}$) by explicit Symmetry Breaking

THEORETICAL SETTING





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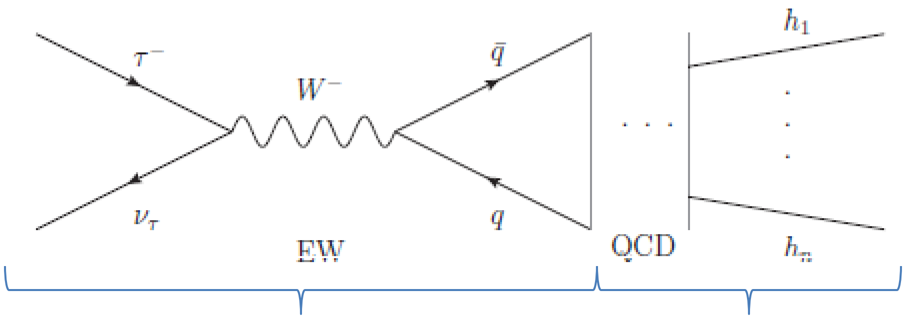

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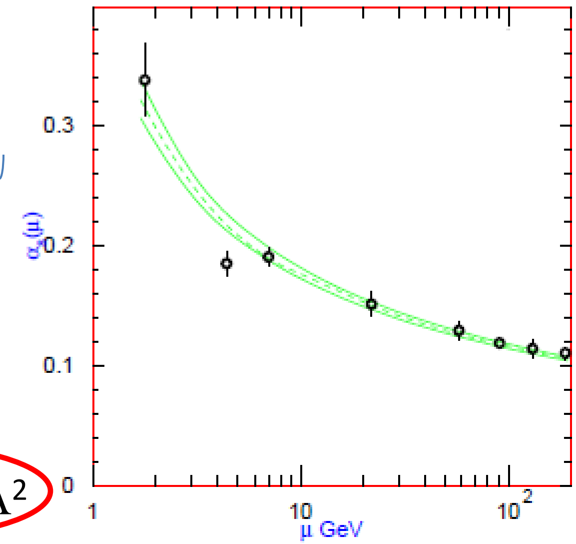


→ At very low energies, **χPT** is the **EFT** of QCD EFT: $(p^2,m^2)/\Lambda^2$

→ At larger energies the expansion breaks down and new dofs are needed

1/Nc 't Hooft '74

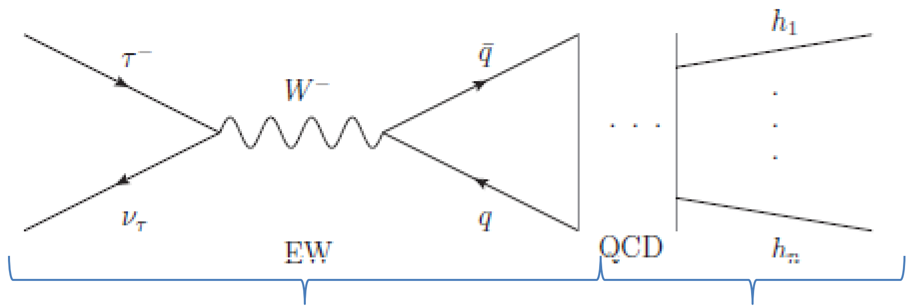
ρ, K^*, a_1, a_0,…

RχT Ecker et. al. '89

Simple description at LO

Preserves χPT results at low energies

THEORY AT WORK



Controlled Problem

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

$$T_\mu = \langle \mathrm{Hadrons} | (V-A)_\mu \, e^{iS_{QCD}} | 0 \rangle = \Sigma_i (\text{Lorentz Structure})^i F_i(Q^2, s_j)$$

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

THEORY AT WORK

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Different approaches to deal with the diverse energy regimes

- For E<M_ρ $\rightarrow$ χPT up to O(p^6) Gasser, Leutwyler'85, Bijnens, Colangelo, Talavera '98, Bijnens, Talavera'02

THEORY AT WORK

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Different approaches to deal with the diverse energy regimes

• For $E<M_\rho \rightarrow \chi PT$ up to $O(p^6)$ Gasser, Leutwyler'85, Bijnens, Colangelo, Talavera '98, Bijnens, Talavera'02

Guerrero, Pich '97

• For $M_\rho \leq E \leq 1$ GeV$\rightarrow$ Match χPT results to VMD using an Omnés solution for dispersion relation.

Omnés solution for dispersion relation Pich, Portolés '01

Unitarization approach Trocóniz, Yndruáin '01, Oller, Oser, Palomar '01

THEORY AT WORK

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

Different approaches to deal with the diverse energy regimes

- For E<M_ρ $\rightarrow$ χPT up to O(p^6) Gasser, Leutwyler'85, Bijnens, Colangelo, Talavera '98, Bijnens, Talavera'02

Guerrero, Pich '97

- For $M_\rho \leq$ E$\leq$ 1 GeV$\rightarrow$ Match χPT results to VMD using an Omnés solution for dispersion relation.

Omnés solution for dispersion relation Pich, Portolés '01

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- 1 GeV $\leq$ E$\leq$ 2 GeV $\rightarrow$ Include ρ' through Schwinger-Dyson-like resummation.

Sanz-Cillero, Pich '03

Tower of resonances based on dual QCD

Domínguez '01, Bruch, Khodjamiriam, Kuhn '05

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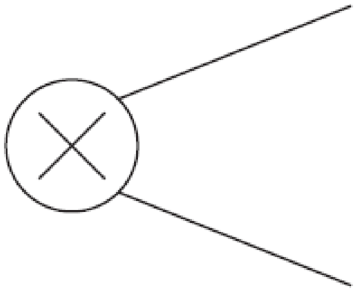
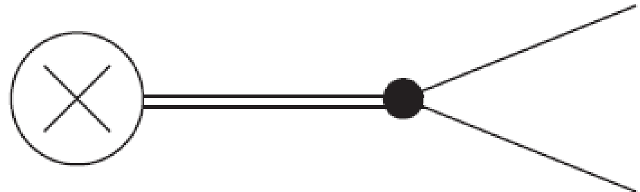


$$\mathcal{L}_\chi^{(2)} = \frac{F^2}{4}\langle u_\mu u^\mu + \chi_+\rangle$$



$$\mathcal{L}_2[V(1^{--})] = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{i\,G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle$$

$$u_\mu = i\,\{u^\dagger(\partial_\mu - ir_\mu)\,u - u\,(\partial_\mu - il_\mu)\,u^\dagger\}$$

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

$$u(\varphi) = \exp\left\{i\frac{\Phi}{\sqrt{2}\,F}\right\} \quad \Phi(x) \equiv \frac{1}{\sqrt{2}}\sum_{a=1}^{8}\lambda_a\,\varphi_a = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}$$

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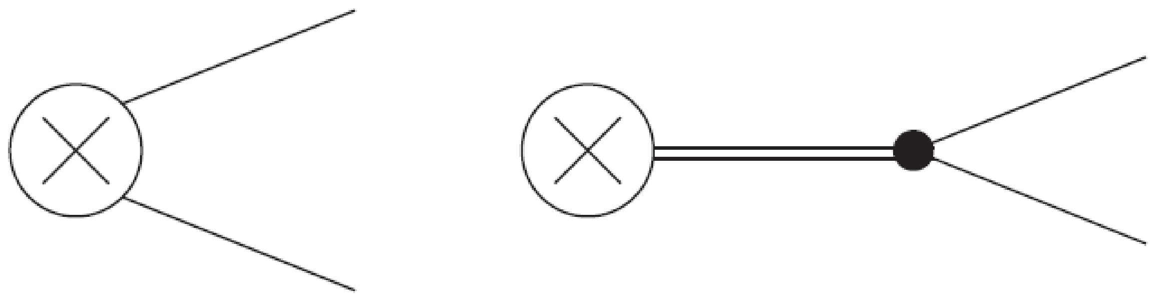
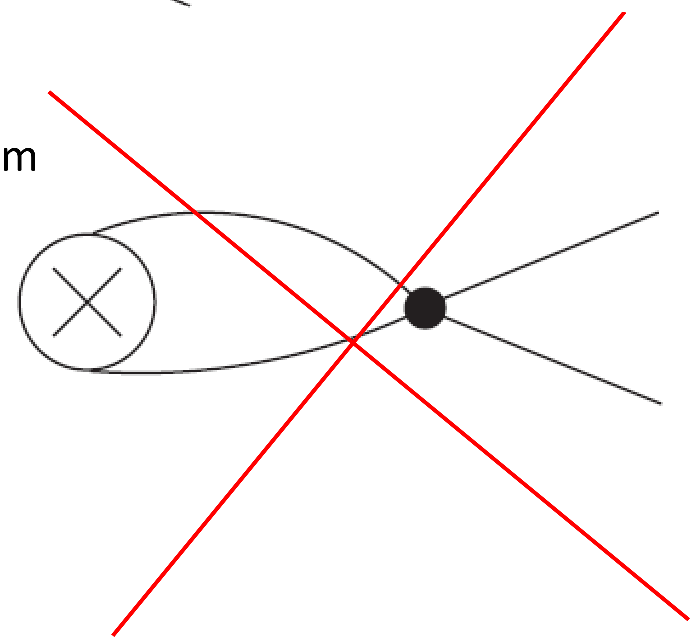


Antisymmetric tensor formalism for spin-one resonances

Ecker *et al.*

Phys.Lett.B223:425,1989

Nucl.Phys.B321:311,1989



To avoid double counting

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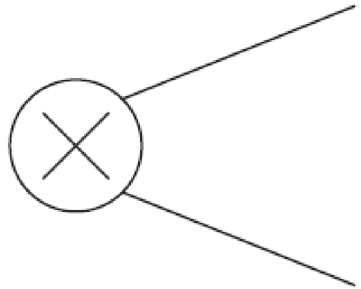

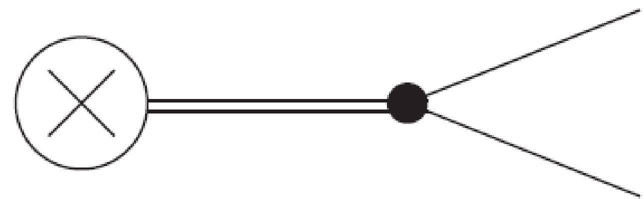

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$$F(s)^V = 1 + \frac{F_V G_V}{f_\pi^2}\frac{s}{M_\rho^2 - s}$$

Short-distance constraints

F(s) →0, for s→∞ $\Rightarrow F_V G_V / f_\pi^2 = 1$

$$\Downarrow$$

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

THEORETICAL SETTING: χPT, Large N_c , RχT

Portolés '10

Gasser, Leutwyler, '84, '85

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

• Finally, QCD **high-energy** behaviour imposed to the **Green functions** or **form factors**.

Ruiz-Femenía, Pich, Portolés '03 Cirigliano, Ecker,Eidemüller, Pich, Portolés '04

Cirigliano, Ecker, Eidemüller, Kaiser, Pich, Portolés '05, '06

THE PROJECT

Shekhovtsova, Przedzinski, Roig, Was

- Tauola is the standard library for MC generation of tau lepton decays. Jadach, Kuhn, Was ’90

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The parametrizations used by experimental collaborations (based on 1997-1998 data):

1. Alain Weinstein : http://www.cithep.caltech.edu/~ajw/korb_doc.html#files *(cleo version)*
2. B. Bloch, private communication *(aleph version)* **MOST USED NOWADAYS**

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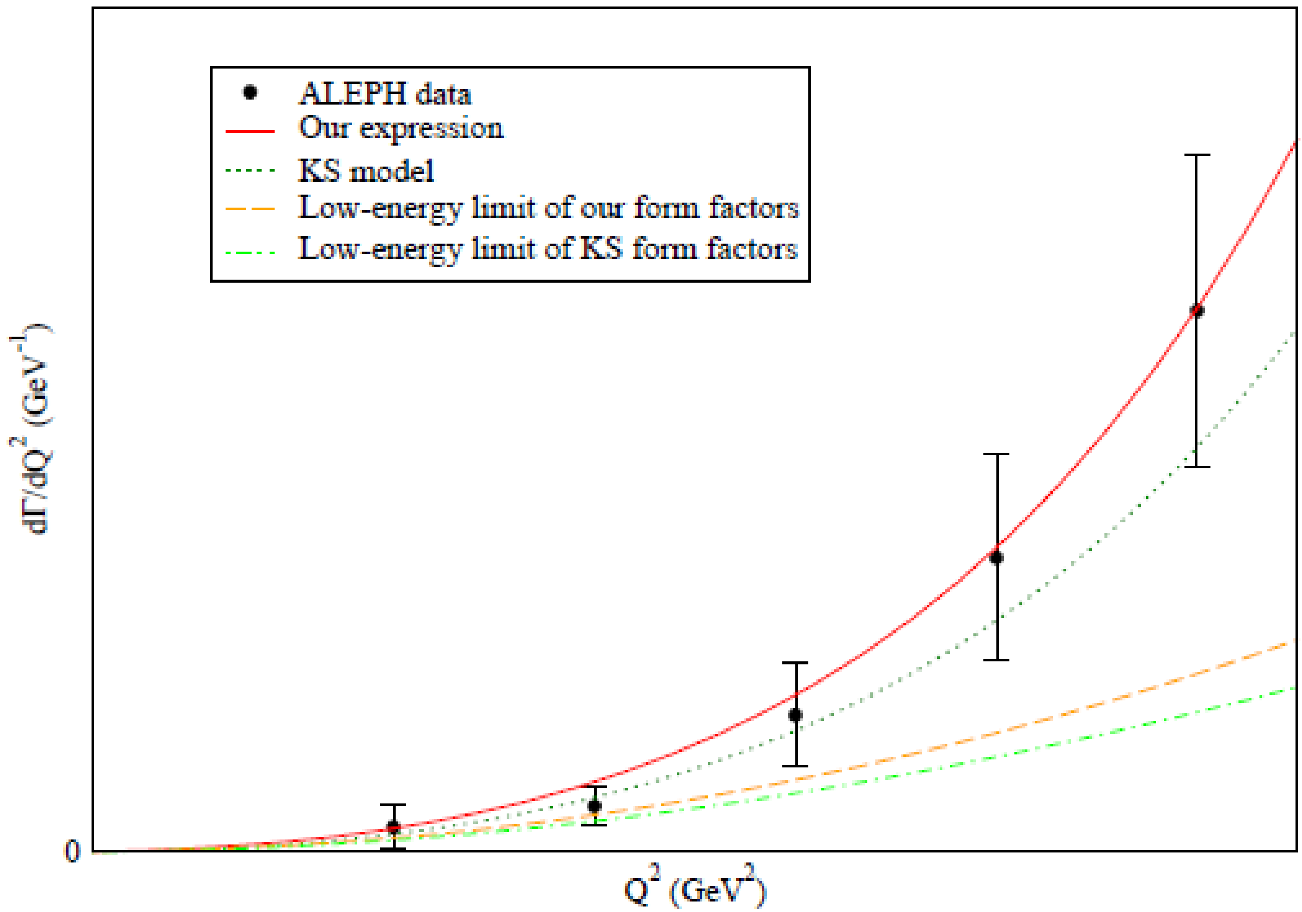
$\tau \longrightarrow \pi\pi\pi\nu_\tau$



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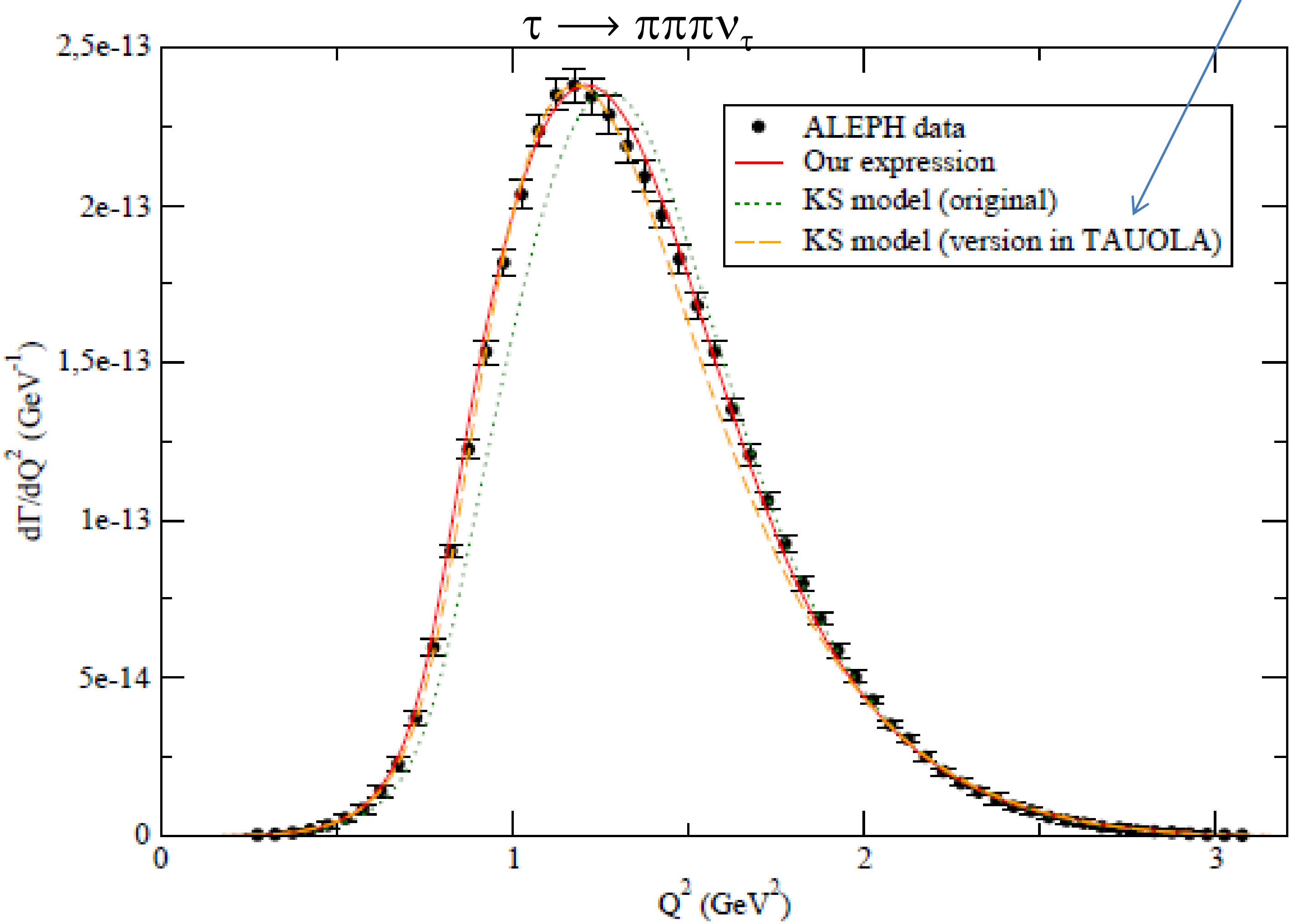
Private old version



THE PROJECT

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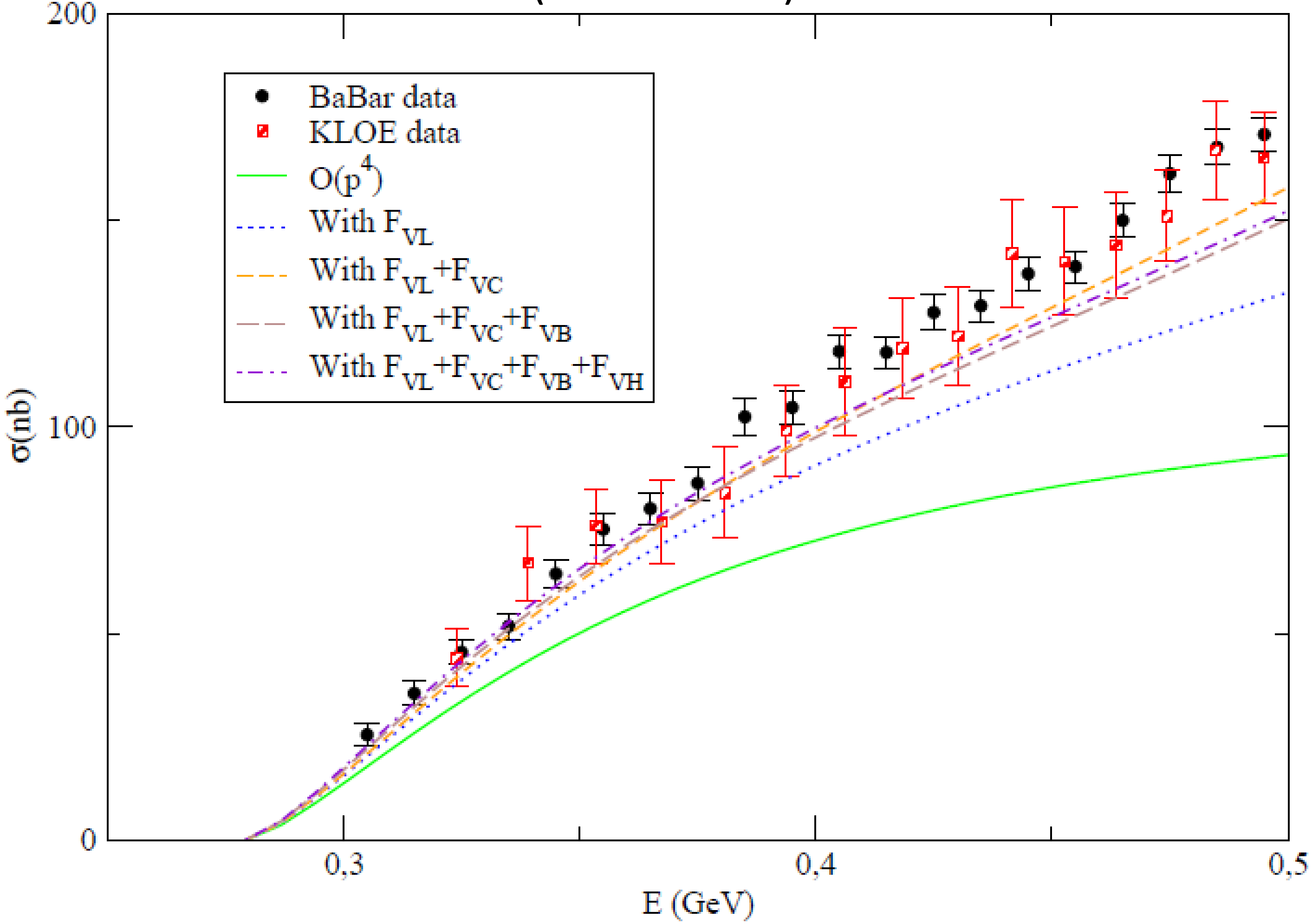
$\sigma(e^+e^- \longrightarrow \pi^+\pi^-)$



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Chiral dynamics is important

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Released version: http://annapurna.ifj.edu.pl/~wasm/RChL/RChL.htm

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NEW HADRONIC FORM FACTORS

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

Two mesons $h_1(p_1)$, $h_2(p_2)$: $J^\mu = N\left[(p_1-p_2)^\mu F^V(s) + (p_1+p_2)^\mu F^S(s)\right]$ $\quad s = (p_1+p_2)^2$

($T_\mu \sim J_\mu$)

Three mesons $h_1(p_1)$, $h_2(p_2)$, $h_3(p_3)$:

$$J^\mu = N \left\{T^\mu_\nu\left[c_1(p_2-p_3)^\nu F_1 + c_2(p_3-p_1)^\nu F_2 + c_3(p_1-p_2)^\nu F_3\right] + c_4 q^\mu F_4 - \frac{i}{4\pi^2F^2} c_5 \epsilon^\mu{}_{\nu\rho\sigma} p_1^\nu p_2^\rho p_3^\sigma F_5\right\}.$$

$$T_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu/q^2 \qquad q^\mu = (p_1+p_2+p_3)^\mu$$

$$q^2 = (p_1+p_2+p_3)^2 \qquad s_1 = (p_2+p_3)^2 \qquad s_2 = (p_1+p_3)^2 \qquad s_3 = (p_1+p_2)^2$$

More mesons ~ 4π (Fischer, Wess and Wagner '80; Bondar et. al. '02)

Form factors

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Guerrero, Pich '97

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$$A(m_P^2/s, m_P^2/\mu^2) = \ln\left(m_P^2/\mu^2\right) + \frac{8m_P^2}{s} - \frac{5}{3} + \sigma_P^3 \ln\left(\frac{\sigma_P + 1}{\sigma_P - 1}\right) \qquad \sigma_P \equiv \sqrt{1 - 4m_P^2/s}$$

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Unitarity+Analiticity Omnés, '58

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Gómez-Dumm, Pich, Portolés '00

$$\begin{aligned}\Gamma_\rho(s) &= \frac{M_\rho\, s}{96\pi f_\pi^2}\left\{\theta(s-4m_\pi^2)\,\sigma_\pi^3 + \frac{1}{2}\theta(s-4m_K^2)\,\sigma_K^3\right\} \\ &= -\frac{M_\rho\, s}{96\pi^2 f_\pi^2}\,\mathrm{Im}\left[A(m_\pi^2/s, m_\pi^2/M_\rho^2) + \frac{1}{2}A(m_K^2/s, m_K^2/M_\rho^2)\right]\end{aligned}$$

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Guerrero, Pich '97

Gómez-Dumm, Pich, Portolés '00

$$\begin{aligned}\Gamma_\rho(s) &= \frac{M_\rho\, s}{96\pi f_\pi^2}\left\{\theta(s-4m_\pi^2)\,\sigma_\pi^3 + \frac{1}{2}\theta(s-4m_K^2)\,\sigma_K^3\right\}\\ &= -\frac{M_\rho\, s}{96\pi^2 f_\pi^2}\,\mathrm{Im}\left[A(m_\pi^2/s, m_\pi^2/M_\rho^2) + \frac{1}{2}A(m_K^2/s, m_K^2/M_\rho^2)\right]\end{aligned}$$

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

NEW HADRONIC FORM FACTORS

Starting point

Guerrero, Pich '97

Match χPT results to VMD using an Omnés solution for dispersion relation

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

NEW HADRONIC FORM FACTORS

Starting point

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Match χPT results to VMD using an Omnés solution for dispersion relation

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

- χPT up to O(p^4) and leading O(p^6) contributions Guerrero '98
- Right fall-off at high energies
- SU(2)
- Analiticity and unitarity constraints (NNLO)

Idea: Follow the approach of Jamin, Pich, Portolés '06 including excited resonances while retaining (some of) these nice properties

NEW HADRONIC FORM FACTORS

Starting point

Guerrero, Pich '97

Match χPT results to VMD using an Omnés solution for dispersion relation

$$\boxed{F(s)} = \frac{M_\rho^2}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)} \exp\left\{\frac{-s}{96\pi^2 f_\pi^2}\left[\mathrm{Re}A(m_\pi^2/s, m_\pi^2/M_\rho^2) + \frac{1}{2}\mathrm{Re}A(m_K^2/s, m_K^2/M_\rho^2)\right]\right\}$$

- χPT up to O(p^4) and leading O(p^6) contributions Guerrero '98
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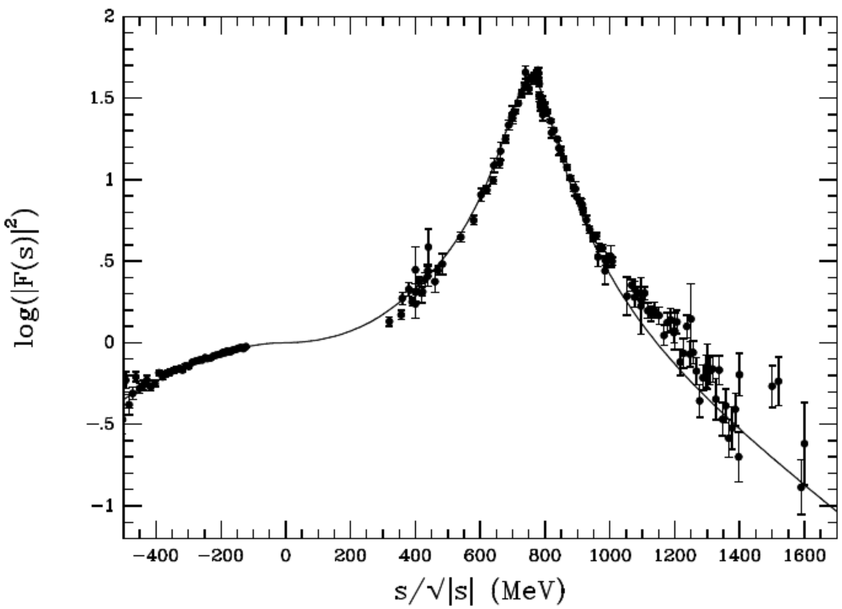

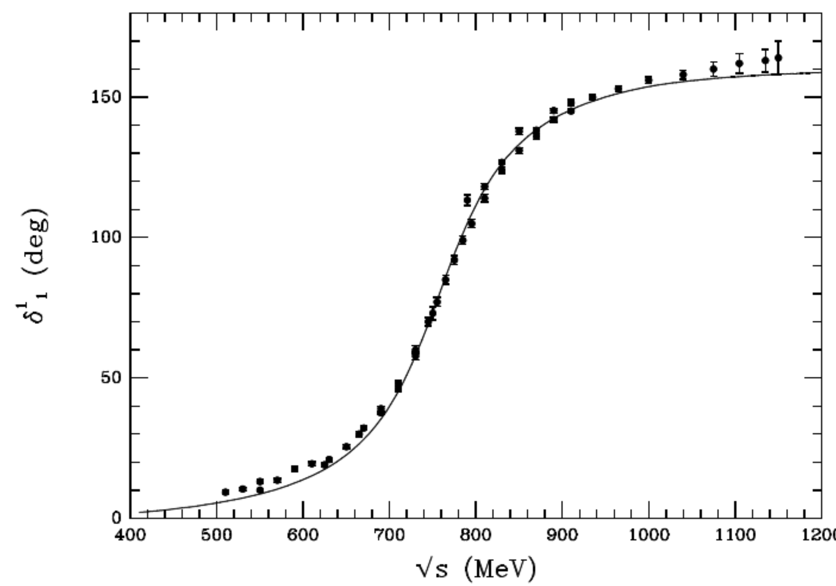

NEW HADRONIC FORM FACTORS

Starting point

Guerrero, Pich '97

Match χPT results to VMD using an Omnés solution for dispersion relation

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

Our formula

$$F_V^-(s) = \frac{M_\rho^2 + s(\gamma e^{i\phi_1} + \delta e^{i\phi_2})}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)} \exp\left[\frac{-s}{96\pi^2 F_\pi^2}\left(\Re e A_\pi(s) + \Re e A_K(s)/2\right)\right]$$
$$- \frac{\gamma s e^{i\phi_1}}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)} \exp\left[\frac{-s\Gamma_{\rho'}(M_{\rho'}^2)}{\pi M_{\rho'}^3 \sigma_\pi^3(M_{\rho'}^2)} \Re e A_\pi(s)\right]$$
$$- \frac{\delta s e^{i\phi_2}}{M_{\rho''}^2 - s - iM_{\rho''}\Gamma_{\rho''}(s)} \exp\left[\frac{-s\Gamma_{\rho''}(M_{\rho''}^2)}{\pi M_{\rho''}^3 \sigma_\pi^3(M_{\rho''}^2)} \Re e A_\pi(s)\right].$$

Roig '11

- χPT up to $O(p^4)$ and leading $O(p^6)$ contributions Guerrero '98
- Right fall-off at high energies
- SU(2)

- Analiticity and unitarity constraints (NNLO)
- (Phenomenological) contribution of ρ' + ρ''

NEW HADRONIC FORM FACTORS

Starting point

Guerrero, Pich '97

Match χPT results to VMD using an Omnés solution for dispersion relation

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

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$$- \frac{\gamma s e^{i\phi_1}}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)} \exp\left[\frac{-s\Gamma_{\rho'}(M_{\rho'}^2)}{\pi M_{\rho'}^3 \sigma_\pi^3(M_{\rho'}^2)} \Re e A_\pi(s)\right]$$
$$- \frac{\delta s e^{i\phi_2}}{M_{\rho''}^2 - s - iM_{\rho''}\Gamma_{\rho''}(s)} \exp\left[\frac{-s\Gamma_{\rho''}(M_{\rho''}^2)}{\pi M_{\rho''}^3 \sigma_\pi^3(M_{\rho''}^2)} \Re e A_\pi(s)\right].$$

Roig '11

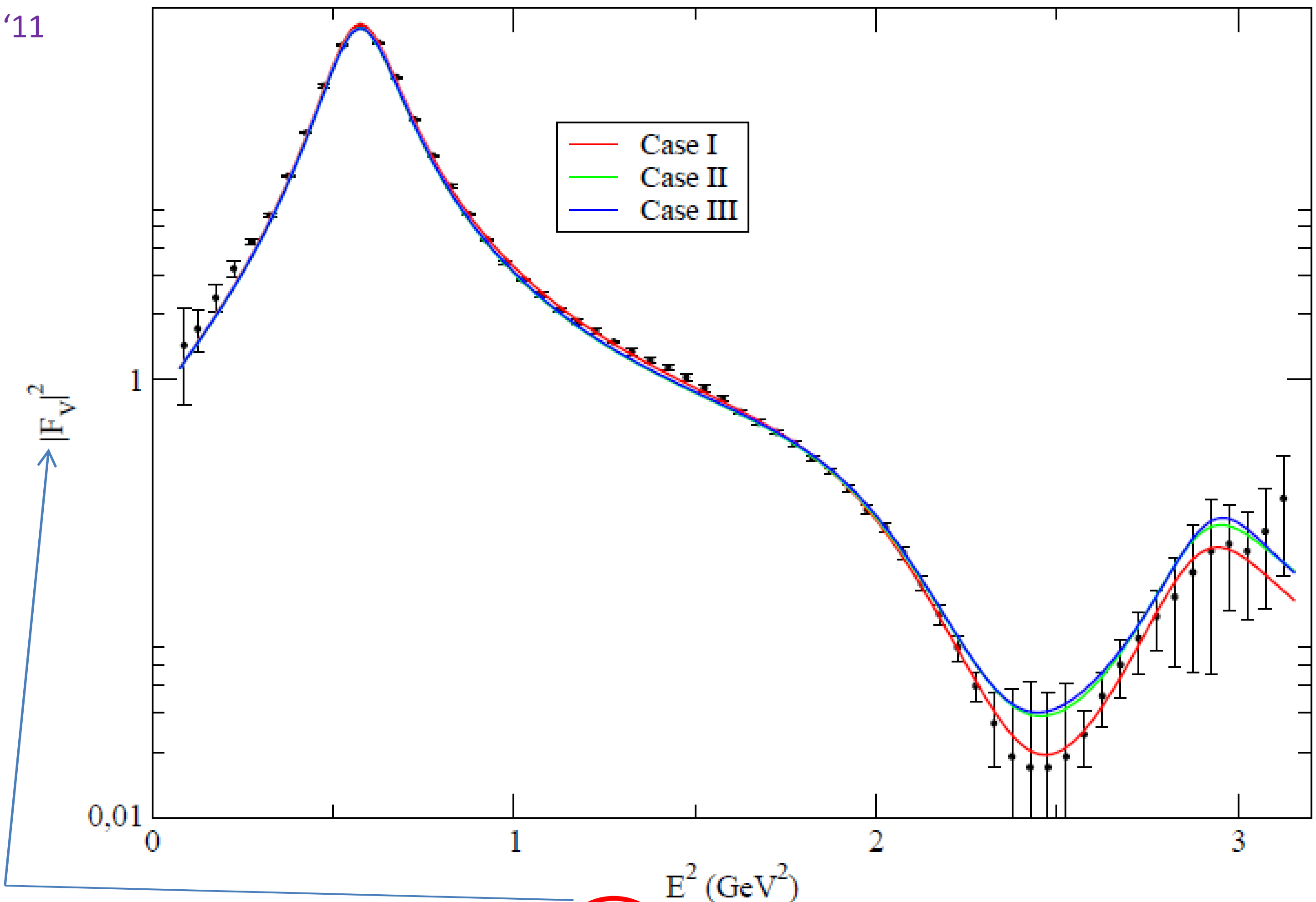
- χPT up to O(p^4) and leading O(p^6) contributions Guerrero '98
- Right fall-off at high energies
- SU(2)

- Analiticity and unitarity constraints (NNLO)
- (Phenomenological) contribution of $\rho' + \rho''$

This is what is included in TAUOLA right now

NEW HADRONIC FORM FACTORS

Roig '11



$$\langle \pi^-(p_{\pi^-})\pi^0(p_{\pi^0})|\overline{d}\gamma^\mu u|0\rangle = \sqrt{2}(p_{\pi^-} - p_{\pi^0})^\mu F_V^\pi(s)$$

NEW HADRONIC FORM FACTORS

On the inclusion of excited resonances

Our formula

Roig '11

$$F_V^-(s) = \frac{M_\rho^2 + s(\gamma e^{i\phi_1} + \delta e^{i\phi_2})}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)} \exp\left[\frac{-s}{96\pi^2 F_\pi^2}\left(\Re e A_\pi(s) + \Re e A_K(s)/2\right)\right]$$
$$- \frac{\gamma s e^{i\phi_1}}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)} \exp\left[\frac{-s\Gamma_{\rho'}(M_{\rho'}^2)}{\pi M_{\rho'}^3 \sigma_\pi^3(M_{\rho'}^2)} \Re e A_\pi(s)\right]$$
$$- \frac{\delta s e^{i\phi_2}}{M_{\rho''}^2 - s - iM_{\rho''}\Gamma_{\rho''}(s)} \exp\left[\frac{-s\Gamma_{\rho''}(M_{\rho''}^2)}{\pi M_{\rho''}^3 \sigma_\pi^3(M_{\rho''}^2)} \Re e A_\pi(s)\right].$$

$$\gamma \equiv -F_V' G_V'/F^2 \qquad \delta \equiv -F_V'' G_V''/F^2 \qquad F_V G_V + F_V' G_V' + F_V'' G_V'' + \ldots = F^2$$

$$\mathcal{L}_2[V(1^{--})] = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle$$

NEW HADRONIC FORM FACTORS

On the inclusion of excited resonances

Our formula

Roig '11

$$F_V^-(s) = \frac{M_\rho^2 + s(\gamma e^{i\phi_1} + \delta e^{i\phi_2})}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)} \exp\left[\frac{-s}{96\pi^2 F_\pi^2}\left(\Re e A_\pi(s) + \Re e A_K(s)/2\right)\right]$$
$$- \frac{\gamma s e^{i\phi_1}}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)} \exp\left[\frac{-s\Gamma_{\rho'}(M_{\rho'}^2)}{\pi M_{\rho'}^3 \sigma_\pi^3(M_{\rho'}^2)} \Re e A_\pi(s)\right]$$
$$- \frac{\delta s e^{i\phi_2}}{M_{\rho''}^2 - s - iM_{\rho''}\Gamma_{\rho''}(s)} \exp\left[\frac{-s\Gamma_{\rho''}(M_{\rho''}^2)}{\pi M_{\rho''}^3 \sigma_\pi^3(M_{\rho''}^2)} \Re e A_\pi(s)\right].$$

$$\gamma \equiv -F_V' G_V' / F^2 \qquad \delta \equiv -F_V'' G_V'' / F^2 \qquad F_V G_V + F_V' G_V' + F_V'' G_V'' + \ldots = F^2$$

$$\mathcal{L}_2[V(1^{--})] = \frac{F_V}{2\sqrt{2}} \langle V_{\mu\nu} f_+^{\mu\nu} \rangle + \frac{iG_V}{2\sqrt{2}} \langle V_{\mu\nu} [u^\mu, u^\nu] \rangle$$

→ Easy to implement for two meson modes. For three meson modes a number of new couplings (involving new operator structures) appear. At which stage shall we include them?

NEW HADRONIC FORM FACTORS

Similar philosophy for other two meson tau decay modes

$$F^V_{PQ}(s) = F^{VMD}(s)\ \exp\left[\sum_{P,Q} N^{PQ}_{loop}\frac{-s}{96\pi^2F^2}ReA_{PQ}(s)\right]$$

$$F^V_{KK}(s) = \frac{M^2_\rho}{M^2_\rho - s - iM_\rho\Gamma_\rho(s)}\exp\left\{\frac{-s}{96\pi^2F^2}\left[ReA_\pi(s)+\frac{1}{2}ReA_K(s)\right]\right\}$$

Guerrero, Pich ‘97, Arganda, Herrero, Portolés ‘08

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

Jamin, Pich, Portolés ‘06

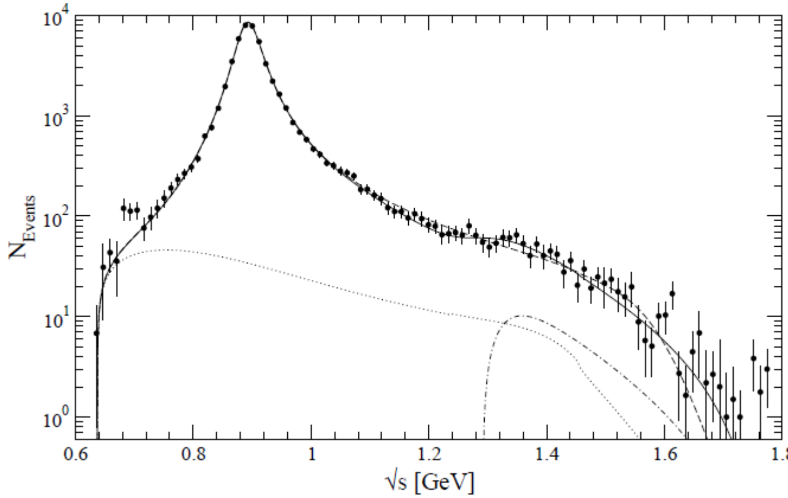
$$\Gamma_{K^*}(q^2) = \frac{M_{K^*}q^2}{128\pi F^2}\left[\lambda^{3/2}\left(1,\frac{m_K^2}{q^2},\frac{m_\pi^2}{q^2}\right)\theta(q^2-thr_{K\pi})+\lambda^{3/2}\left(1,\frac{m_K^2}{q^2},\frac{m_\eta^2}{q^2}\right)\theta(q^2-thr_{K\eta})\right]$$

$$\langle\pi^-(p)|\bar{s}\,\gamma^\mu\,u|K^0(k)\rangle = \left[(k+p)^\mu - \frac{m_K^2-m_\pi^2}{q^2}(k-p)^\mu\right]F_+(q^2)+\frac{m_K^2-m_\pi^2}{q^2}(k-p)^\mu F_0(q^2)$$

Jamin, Oller, Pich ’01, ‘06

NEW HADRONIC FORM FACTORS

Similar philosophy for other two meson tau decay modes



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

Jamin, Pich, Portolés ‘06

$$\Gamma_{K^*}(q^2) = \frac{M_{K^*}q^2}{128\pi F^2}\left[\lambda^{3/2}\left(1, \frac{m_K^2}{q^2}, \frac{m_\pi^2}{q^2}\right)\theta(q^2 - thr_{K\pi}) + \lambda^{3/2}\left(1, \frac{m_K^2}{q^2}, \frac{m_\eta^2}{q^2}\right)\theta(q^2 - thr_{K\eta})\right]$$

$$\langle \pi^-(p)|\bar{s}\,\gamma^\mu\, u|K^0(k)\rangle = \left[(k+p)^\mu - \frac{m_K^2 - m_\pi^2}{q^2}(k-p)^\mu\right] F_+(q^2) + \frac{m_K^2 - m_\pi^2}{q^2}(k-p)^\mu F_0(q^2)$$

Jamin, Oller, Pich ’01, ‘06

NEW HADRONIC FORM FACTORS

$$\tilde{F}_{+,0}(q^2) \equiv \frac{F_{+,0}(q^2)}{F_+(0)}$$

With new improvements also
Exact analiticity and unitarity

Boito, Escribano, Jamin '08

$$\bar{F}_+^{K\pi}(s) = \frac{m_{K^*}^2 - \kappa_{K^*}\bar{A}_{K\pi}(0) + \gamma s}{D(m_{K^*},\gamma_{K^*})} - \frac{\gamma s}{D(m_{K^{*\prime}},\gamma_{K^{*\prime}})}$$

$$D(m_n,\gamma_n) = m_n^2 - s - \kappa_n \mathrm{Re}\bar{A}_{K\pi}(s) - i m_n \gamma_n(s)\,,$$

$$\gamma_{K^*}(s) = \gamma_{K^*}\frac{s}{m_{K^*}^2}\frac{\sigma_{K\pi}^3(s)}{\sigma_{K\pi}^3(m_{K^*}^2)}, \qquad \kappa_{K^*} = \frac{192\pi F F_K}{\sigma_{K\pi}(m_{K^*}^2)^3}\frac{\gamma_{K^*}}{m_{K^*}},$$

$$F_+^{K\pi}(0) = \frac{m_{K^*}^2}{m_{K^*}^2 - \kappa\bar{A}_{K\pi}(0)}$$

$$\sigma_{K\pi}(s) = \sqrt{\left(1 - \frac{(m_K+m_\pi)^2}{s}\right)\left(1 - \frac{(m_K-m_\pi)^2}{s}\right)}\theta(s-(m_K+m_\pi)^2)$$

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right]$$

$$F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} \mathrm{d}s' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

Other approaches: Jamin, Pich, Portolés '06, '08

Boito, Escribano, Jamin '06

Moussallam '07

Bernard, Boito, Passemar '11

NEW HADRONIC FORM FACTORS

$$\tilde{F}_{+,0}(q^2) \equiv \frac{F_{+,0}(q^2)}{F_+(0)}$$

With new improvements also
Exact analiticity and unitarity

Boito, Escribano, Jamin '08

$$\begin{aligned} \tilde{F}_+^{K\pi}(s) &= \frac{m_{K^*}^2 - \kappa_{K^*}\bar{A}_{K\pi}(0) + \gamma s}{D(m_{K^*},\gamma_{K^*})} - \frac{\gamma s}{D(m_{K^{*\prime}},\gamma_{K^{*\prime}})} \\ D(m_n,\gamma_n) &= m_n^2 - s - \kappa_n \mathrm{Re}\bar{A}_{K\pi}(s) - i m_n \gamma_n(s)\,, \end{aligned}$$

$$\gamma_{K^*}(s) = \gamma_{K^*}\frac{s}{m_{K^*}^2}\frac{\sigma_{K\pi}^3(s)}{\sigma_{K\pi}^3(m_{K^*}^2)}, \qquad \kappa_{K^*} = \frac{192\pi F F_K}{\sigma_{K\pi}(m_{K^*}^2)^3}\frac{\gamma_{K^*}}{m_{K^*}},$$

$$F_+^{K\pi}(0) = \frac{m_{K^*}^2}{m_{K^*}^2 - \kappa \bar{A}_{K\pi}(0)}$$

$$\sigma_{K\pi}(s) = \sqrt{\left(1-\frac{(m_K+m_\pi)^2}{s}\right)\left(1-\frac{(m_K-m_\pi)^2}{s}\right)}\,\theta(s-(m_K+m_\pi)^2)$$

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right]$$

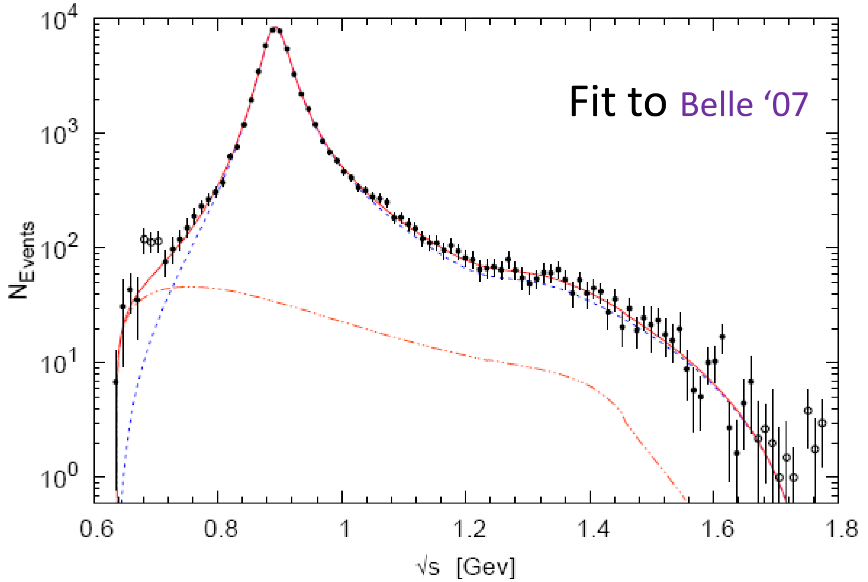
$$F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} ds' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

Other approaches: Jamin, Pich, Portolés '06, '08

Boito, Escribano, Jamin '06

Moussallam '07

Bernard, Boito, Passemar '11



NEW HADRONIC FORM FACTORS

$$\tilde{F}_{+,0}(q^2) \equiv \frac{F_{+,0}(q^2)}{F_+(0)}$$

With new improvements also
Exact analiticity and unitarity

Boito, Escribano, Jamin '08

$$\begin{aligned}\tilde{F}_+^{K\pi}(s) &= \frac{m_{K^*}^2 - \kappa_{K^*}\bar{A}_{K\pi}(0) + \gamma s}{D(m_{K^*},\gamma_{K^*})} - \frac{\gamma s}{D(m_{K^{*\prime}},\gamma_{K^{*\prime}})} \\ D(m_n,\gamma_n) &= m_n^2 - s - \kappa_n \mathrm{Re}\bar{A}_{K\pi}(s) - i m_n \gamma_n(s)\,,\end{aligned}$$

$$\gamma_{K^*}(s) = \gamma_{K^*}\frac{s}{m_{K^*}^2}\frac{\sigma_{K\pi}^3(s)}{\sigma_{K\pi}^3(m_{K^*}^2)}, \qquad \kappa_{K^*} = \frac{192\pi F F_K}{\sigma_{K\pi}(m_{K^*}^2)^3}\frac{\gamma_{K^*}}{m_{K^*}},$$

$$F_+^{K\pi}(0) = \frac{m_{K^*}^2}{m_{K^*}^2 - \kappa\bar{A}_{K\pi}(0)}$$

$$\sigma_{K\pi}(s) = \sqrt{\left(1-\frac{(m_K+m_\pi)^2}{s}\right)\left(1-\frac{(m_K-m_\pi)^2}{s}\right)}\theta(s-(m_K+m_\pi)^2)$$

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right]$$

$$F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} ds' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

We will include also the dispersive approach for other two-meson decay channels

Other approaches: Jamin, Pich, Portolés '06, '08

Boito, Escribano, Jamin '06

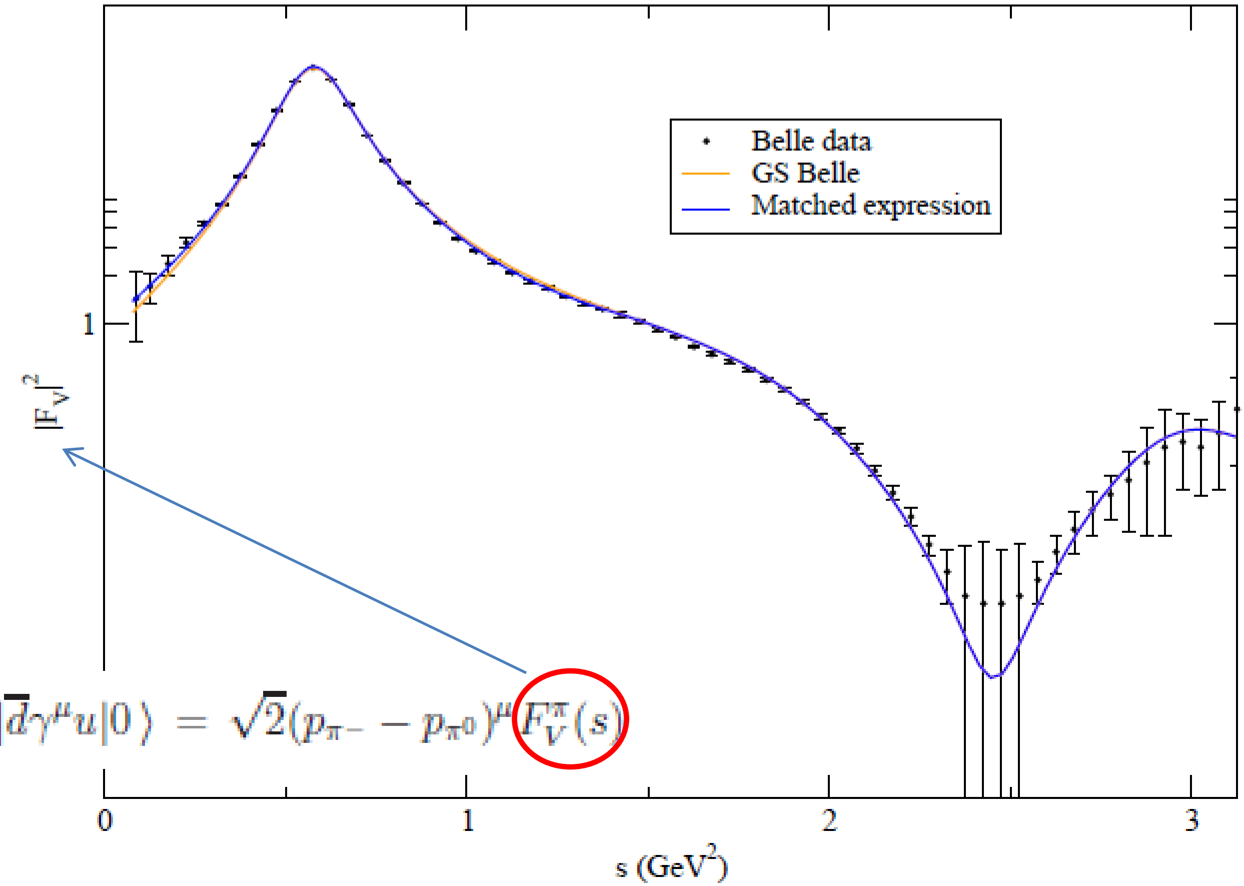
Moussallam '07

Bernard, Boito, Passemar '11

NEW HADRONIC FORM FACTORS

With new improvements also
Exact analiticity and unitarity

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right] / Re\left[F_V^{PQ}(s)\right] \longrightarrow F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} \mathrm{d}s' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

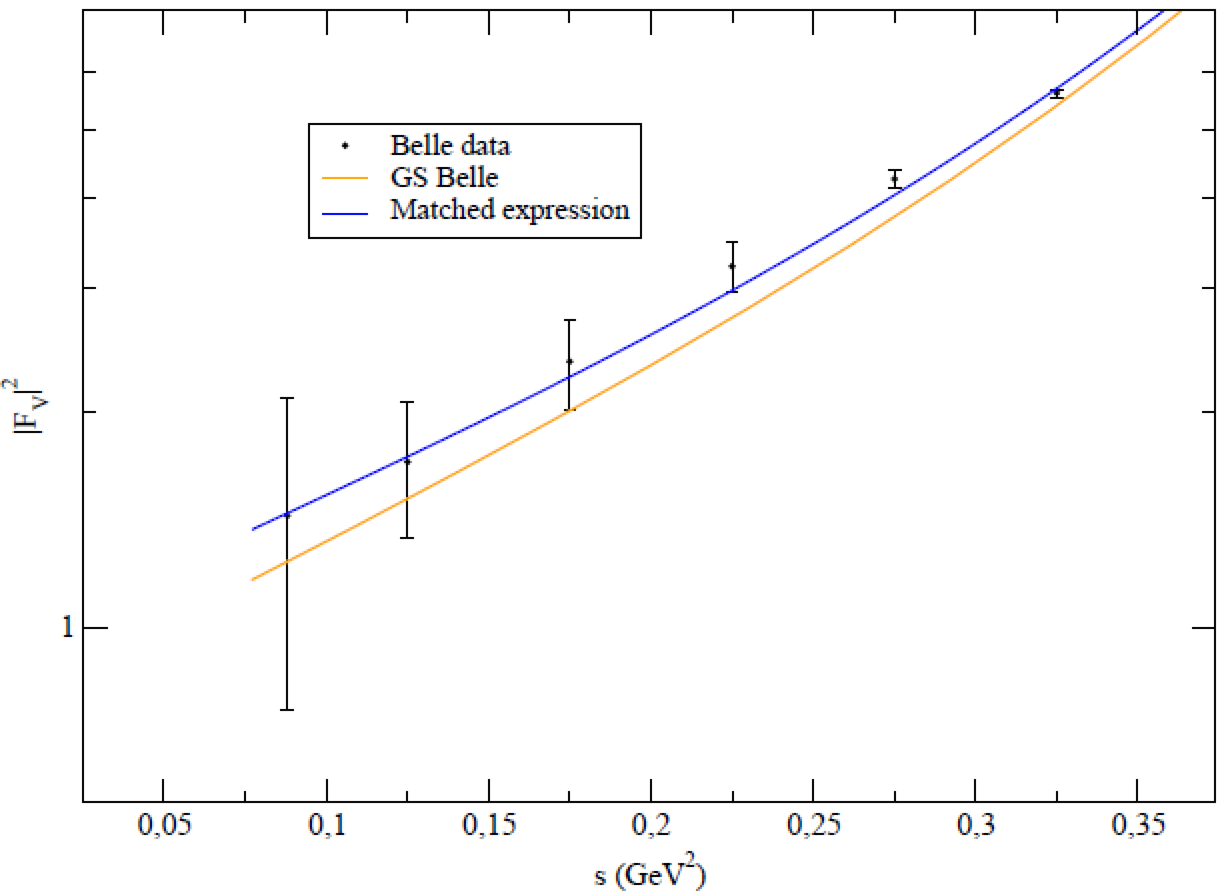


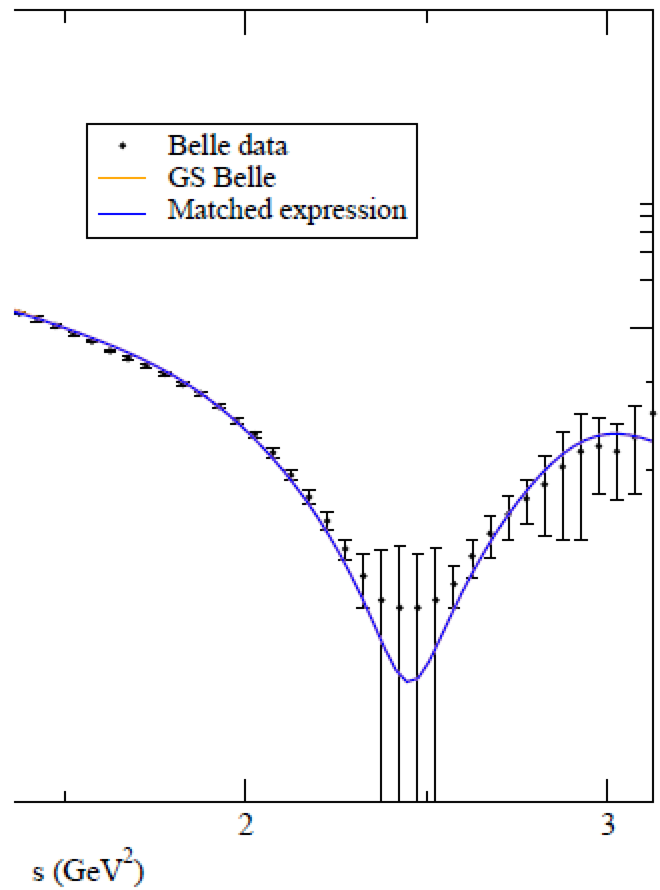
$$\langle \pi^-(p_{\pi^-})\pi^0(p_{\pi^0})|\bar{d}\gamma^\mu u|0\rangle = \sqrt{2}(p_{\pi^-} - p_{\pi^0})^\mu F_V^\pi(s)$$

NEW HADRONIC FORM FACTORS

With new improvements also
Exact analiticity and unitarity

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right] \longrightarrow F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} ds' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

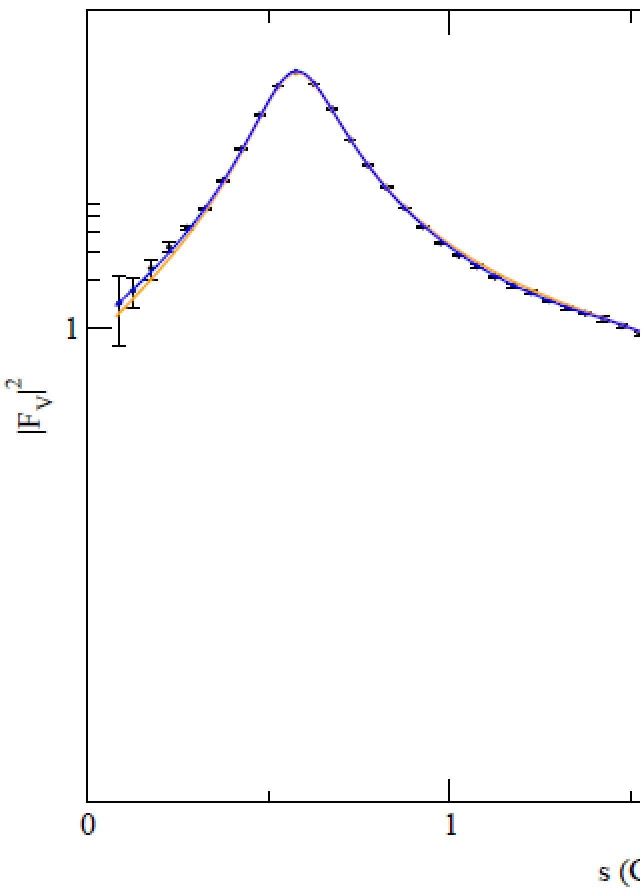


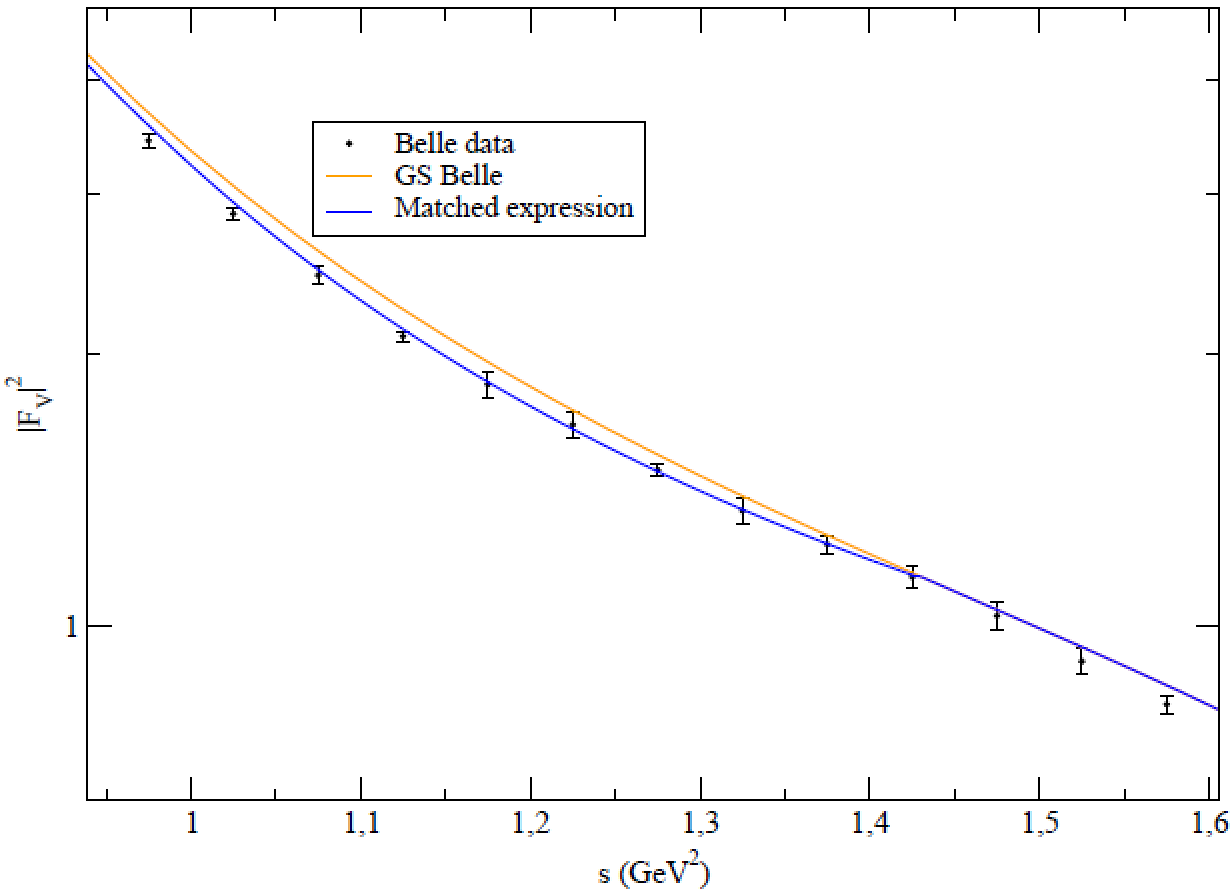


NEW HADRONIC FORM FACTORS

With new improvements also
Exact analiticity and unitarity

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right] \longrightarrow F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} ds' \frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$



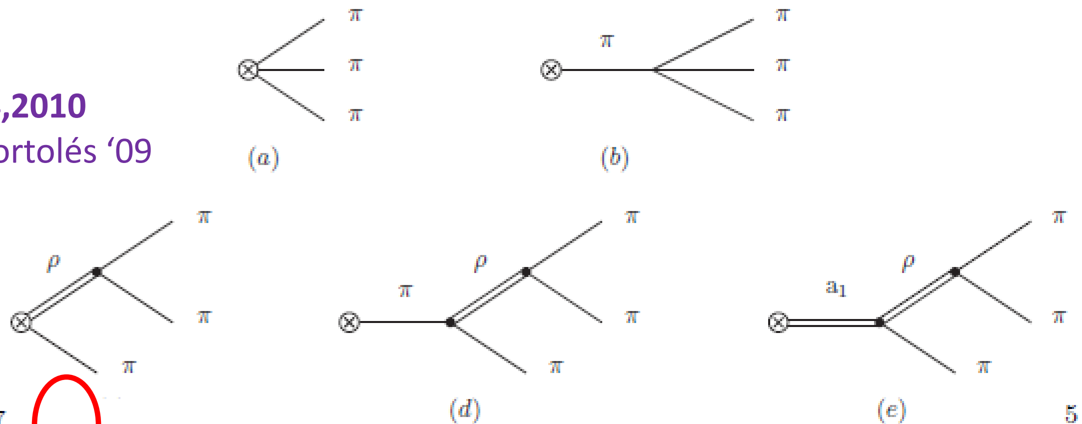


NEW HADRONIC FORM FACTORS

$$\tau \longrightarrow \pi\pi\pi\nu_\tau$$

Phys.Lett.B685:158-164,2010

Gómez-Dumm, Roig, Pich, Portolés '09



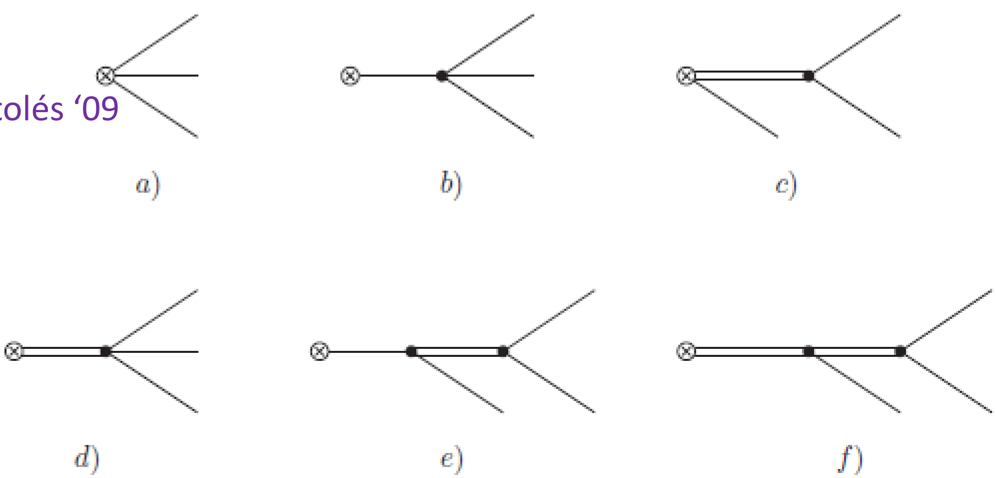
$$\mathcal{L}_4^{\mathrm{V}} = \sum_{i=1}^{5} \frac{g_i}{M_V} \mathcal{O}^i_{\mathrm{VPPP}} + \sum_{i=1}^{7} \frac{c_i}{M_V} \mathcal{O}^i_{\mathrm{VJP}}$$

$$\mathcal{L}_2^{\mathrm{RR}} = \sum_{i=1}^{5} \lambda_i \mathcal{O}^i_{\mathrm{VAP}} + \sum_{i=1}^{4} d_i \mathcal{O}^i_{\mathrm{VVP}}$$

$$\tau \longrightarrow KK\pi\nu_\tau$$

Gómez-Dumm, Roig, Pich, Portolés '09

Phys.Rev.D81:034031,2010



NEW HADRONIC FORM FACTORS

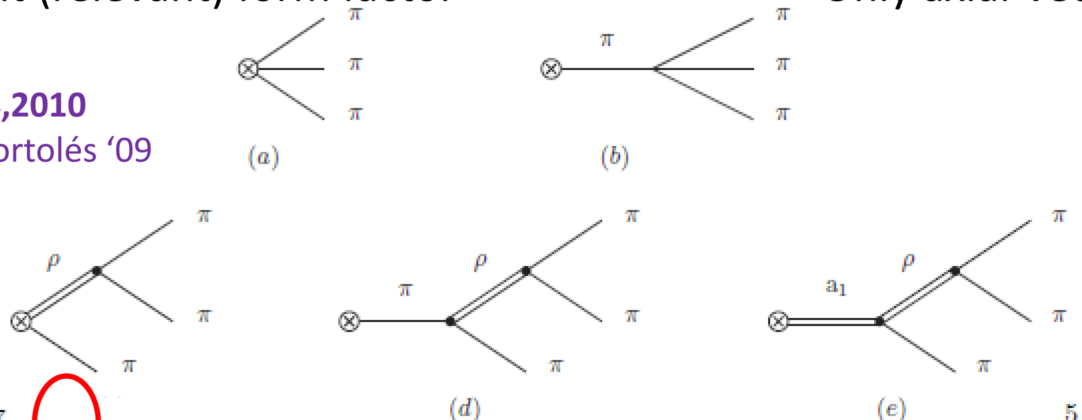
$$\tau \longrightarrow \pi\pi\pi\nu_\tau$$

Only one independent (relevant) form factor

Only axial-vector current

Phys.Lett.B685:158-164,2010

Gómez-Dumm, Roig, Pich, Portolés ‘09



$$\mathcal{L}_4^{V} = \sum_{i=1}^{5} \frac{g_i}{M_V}\mathcal{O}^i_{VPPP} + \sum_{i=1}^{7}\frac{c_i}{M_V}\mathcal{O}^i_{VJP}$$

$$\mathcal{L}_2^{RR} = \sum_{i=1}^{5} \lambda_i \mathcal{O}^i_{VAP} + \sum_{i=1}^{4} d_i \mathcal{O}^i_{VVP}$$

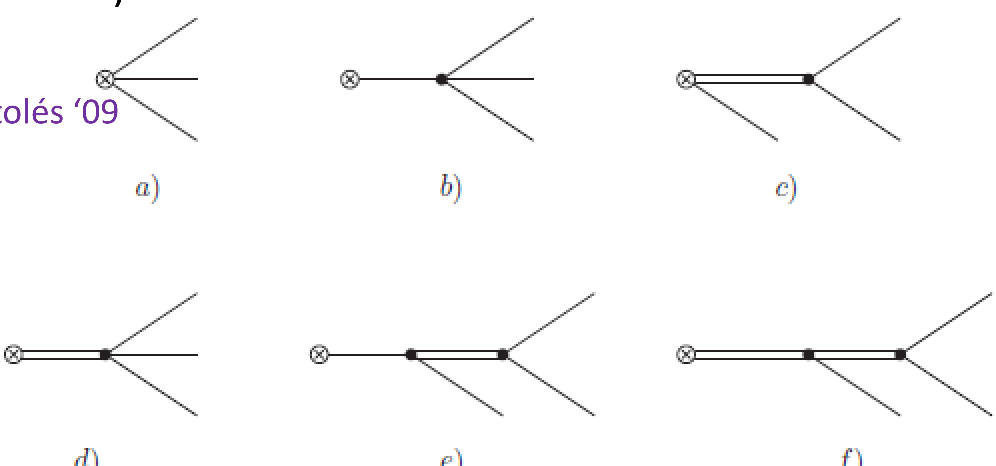
$$\tau \longrightarrow KK\pi\nu_\tau$$

Three independent (relevant) FFs

Both axial-vector and vector current

Gómez-Dumm, Roig, Pich, Portolés ‘09

Phys.Rev.D81:034031,2010



NEW HADRONIC FORM FACTORS

Phys.Rev.D69:073002,2004
Gómez-Dumm, Pich, Portolés '03

Phys.Lett.B685:158-164,2010
Gómez-Dumm, Roig, Pich, Portolés '09

$$F_{\pm i} = \pm (F_i^{\chi} + F_i^{R} + F_i^{RR}) , \qquad i = 1,2 \qquad\qquad F_2(Q^2,s,t) = F_1(Q^2,t,s)$$

$$F_1^{\chi}(Q^2,s,t) = -\frac{2\sqrt{2}}{3F}$$

$$F_1^{R}(Q^2,s,t) = \frac{\sqrt{2}\,F_V\,G_V}{3\,F^3}\left[\frac{3\,s}{s-M_V^2} - \left(\frac{2G_V}{F_V}-1\right)\left(\frac{2Q^2-2s-u}{s-M_V^2}+\frac{u-s}{t-M_V^2}\right)\right]$$

$$F_1^{RR}(Q^2,s,t) = \frac{4\,F_A\,G_V}{3\,F^3}\,\frac{Q^2}{Q^2-M_A^2}\left[-\,(\lambda'+\lambda'')\,\frac{3\,s}{s-M_V^2} + H(Q^2,s)\,\frac{2Q^2+s-u}{s-M_V^2} + H(Q^2,t)\,\frac{u-s}{t-M_V^2}\right]$$

$$H(Q^2,x) = -\,\lambda_0\,\frac{m_\pi^2}{Q^2} + \lambda'\,\frac{x}{Q^2} + \lambda''$$

Relations from short-distance QCD:

$$\begin{cases} F_V\,G_V = F^2 \\ F_V^2 - F_A^2 = F^2 \\ F_V^2\,M_V^2 = F_A^2\,M_A^2 \end{cases}$$

$$\lambda' = \frac{F^2}{2\sqrt{2}\,F_A\,G_V} = \frac{M_A}{2\sqrt{2}\,M_V} ,$$

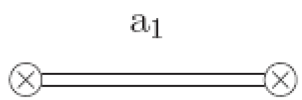
$$\lambda'' = \frac{2\,G_V - F_V}{2\sqrt{2}\,F_A} = \frac{M_A^2 - 2M_V^2}{2\sqrt{2}\,M_V\,M_A} ,$$

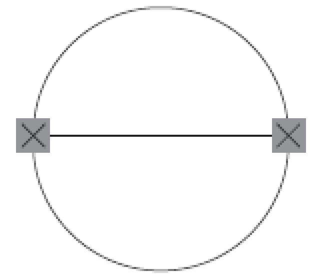
$$4\,\lambda_0 = \lambda' + \lambda'' = \frac{M_A^2 - M_V^2}{\sqrt{2}\,M_V\,M_A} ,$$

NEW HADRONIC FORM FACTORS

Gómez-Dumm, Roig, Pich, Portolés '09

$\Gamma a_1(Q^2)$:





$$\Gamma_{a_1}(Q^2) \;=\; \Gamma^{\pi}_{a_1}(Q^2)\,\theta(Q^2-9m_\pi^2) \;+\; \Gamma^{K}_{a_1}(Q^2)\,\theta(Q^2-(2m_K+m_\pi)^2)\ ,$$

$$\Gamma^{\pi,K}_{a_1}(Q^2) \;=\; \frac{-S}{192(2\pi)^3 F_A^2 M_{a_1}}\left(\frac{M_{a_1}^2}{Q^2}-1\right)^2 \int \mathrm{d}s\,\mathrm{d}t\; T^{\pi,K\mu}_{1^+}\, T^{\pi,K*}_{1^+\mu}\ .$$

NEW HADRONIC FORM FACTORS

Gómez-Dumm, Roig, Pich, Portolés '09

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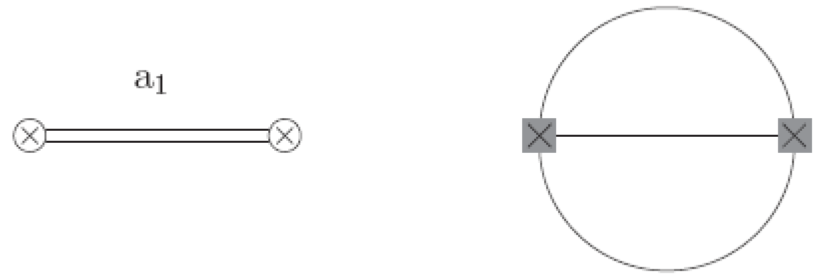

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$$\frac{1}{M_\rho^2 - q^2 - iM_\rho\Gamma_\rho(q^2)} \longrightarrow \frac{1}{1+\beta_{\rho'}} \left[\frac{1}{M_\rho^2 - q^2 - iM_\rho\Gamma_\rho(q^2)} + \frac{\beta_{\rho'}}{M_{\rho'}^2 - q^2 - iM_{\rho'}\Gamma_{\rho'}(q^2)} \right]$$

NEW HADRONIC FORM FACTORS

Gómez-Dumm, Roig, Pich, Portolés '09

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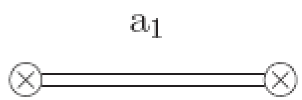

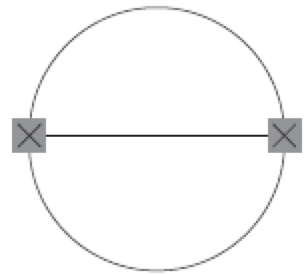

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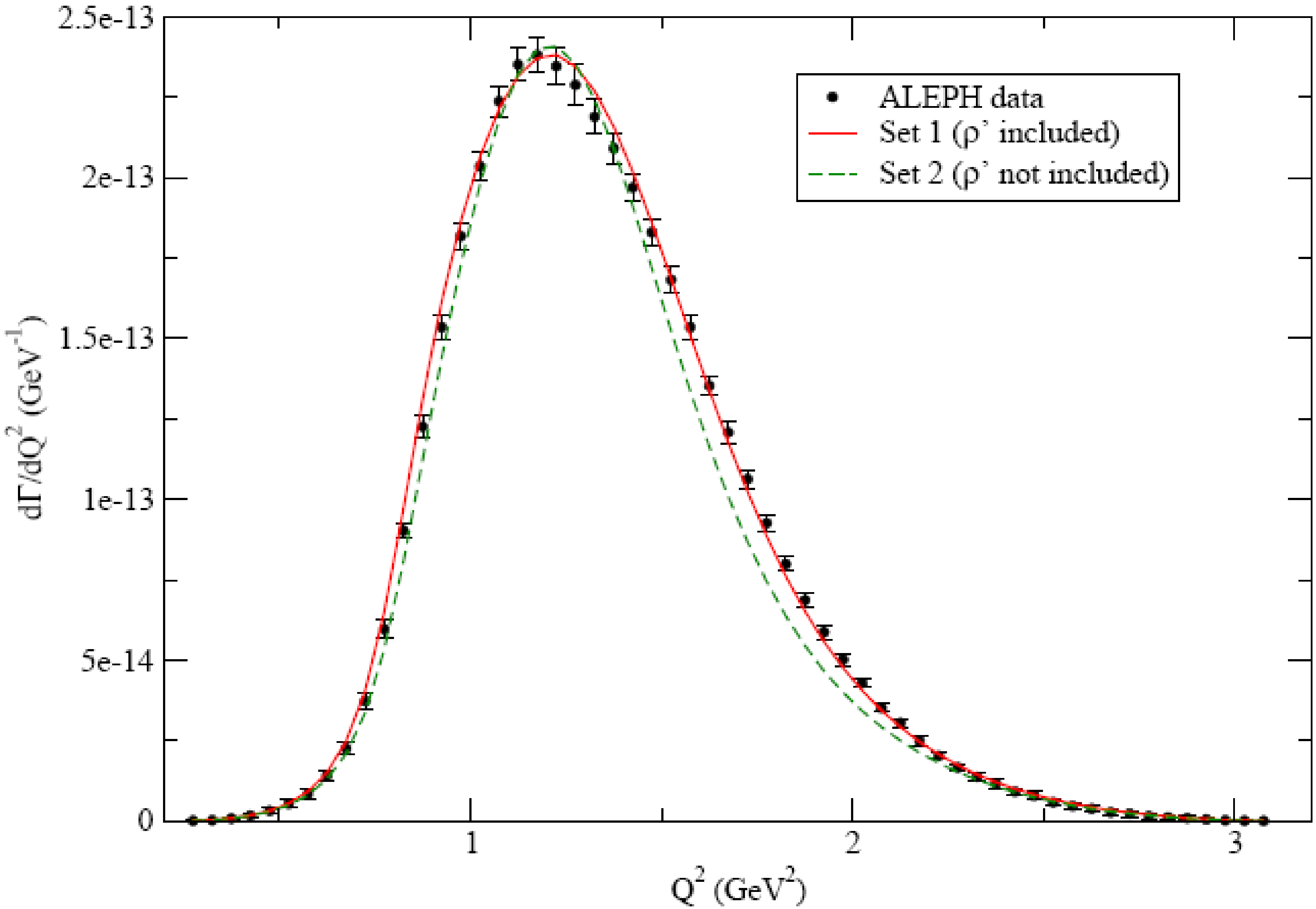
→ Inclusion from a Lagrangian would imply 3 coups. instead of $\beta_{\rho'}$

F_V', G_V', F_A'

NEW HADRONIC FORM FACTORS

Gómez-Dumm, Roig, Pich, Portolés '09



NEW HADRONIC FORM FACTORS

Additional high-energy constraints are found on the **KKπ** channels:

$$
\begin{aligned}
c_1 - c_2 + c_5 &= 0\,, \\
c_1 - c_2 - c_5 + 2c_6 &= -\frac{N_C}{96\,\pi^2}\frac{F_V\,M_V}{\sqrt{2}\,F^2}\,, \\
d_3 &= -\frac{N_C}{192\,\pi^2}\frac{M_V^2}{F^2}\,, \\
g_1 + 2g_2 - g_3 &= 0\,, \\
g_2 &= \frac{N_C}{192\,\sqrt{2}\,\pi^2}\frac{M_V}{F_V}\,.
\end{aligned}
$$

•We do not have any hint on the value of two of the odd-intrinsic parity couplings.

• Up to now, excited resonances have not been implemented.

• Through the framework provided by TAUOLA, with the new currents from RχT installed, it will be much easier to learn about the unknown couplings and to estimate properly the size of the excited resonances contribution.

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•Essential to study the most relevant channels in unified framework for signal/background splitting and data analysis: New TAUOLA currents.

COMPARISONS

MC-Tester Davidson, Golonka, Przedzinski, Was '08

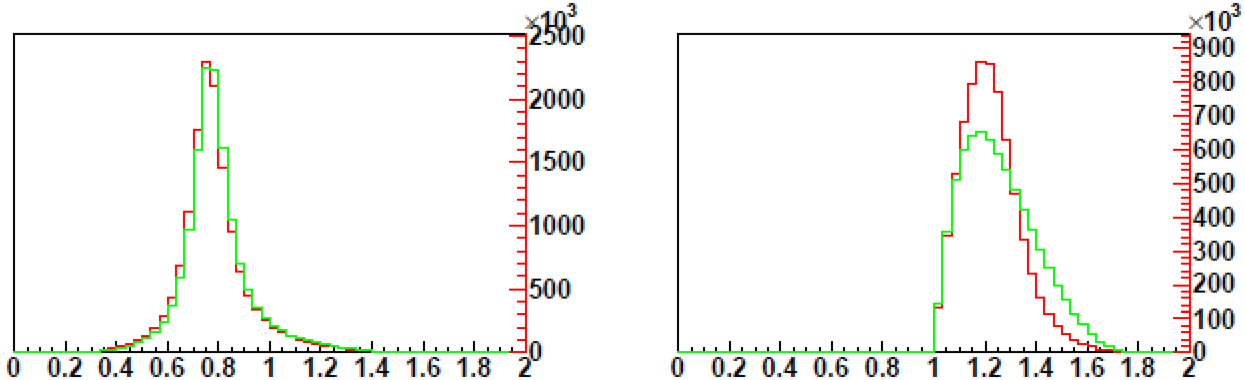

Figure 6: $\tau \to \pi^-\pi^0\nu_\tau$ and $\tau \to K^-K^0\nu_\tau$ decays: Comparison of distributions for `TAUOLA cleo` current [21] and for our new current. On the left-hand side, plot of $\pi^-\pi^0$ invariant mass is shown and on the right-hand side $K^-K^0_S$ are for new current, red (darker grey) are for `TAUOLA cleo`.

Shekhovtsova, Przedzinski, Roig, Was '12

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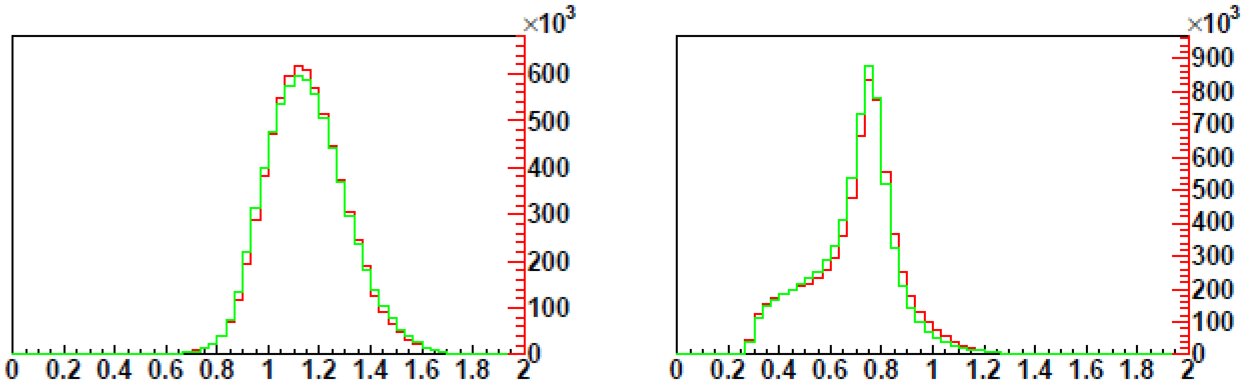

Figure 2: The $\tau \to \pi^+\pi^-\pi^-\nu_\tau$ decay: comparison of distributions for `TAUOLA cleo` current [21] and for our new current. On the left-hand side, the plot of $\pi^+\pi^-\pi^-$ invariant mass is shown and on the right-hand side $\pi^+\pi^-$ invariant mass is given. Green histograms (light grey) are for the new current, red (darker grey) are for `TAUOLA cleo`. Distributions for the $\tau \to \pi^-\pi^0\pi^0\nu_\tau$ decay coincide with the ones for $\tau \to \pi^+\pi^-\pi^-\nu_\tau$.

Shekhovtsova, Przedzinski, Roig, Was '12

http://annapurna.ifj.edu.pl/~wasm/RChL/RChL.htm

BABAR data: *Ian M. Nugent, (Victoria U.)*

SLAC-R-936, Dec16, 2009. Ph.D. Thesis

COMPARISONS

MC-Tester Davidson, Golonka, Przedzinski, Was ’08

Shekhovtsova, Przedzinski, Roig, Was ’12

σ

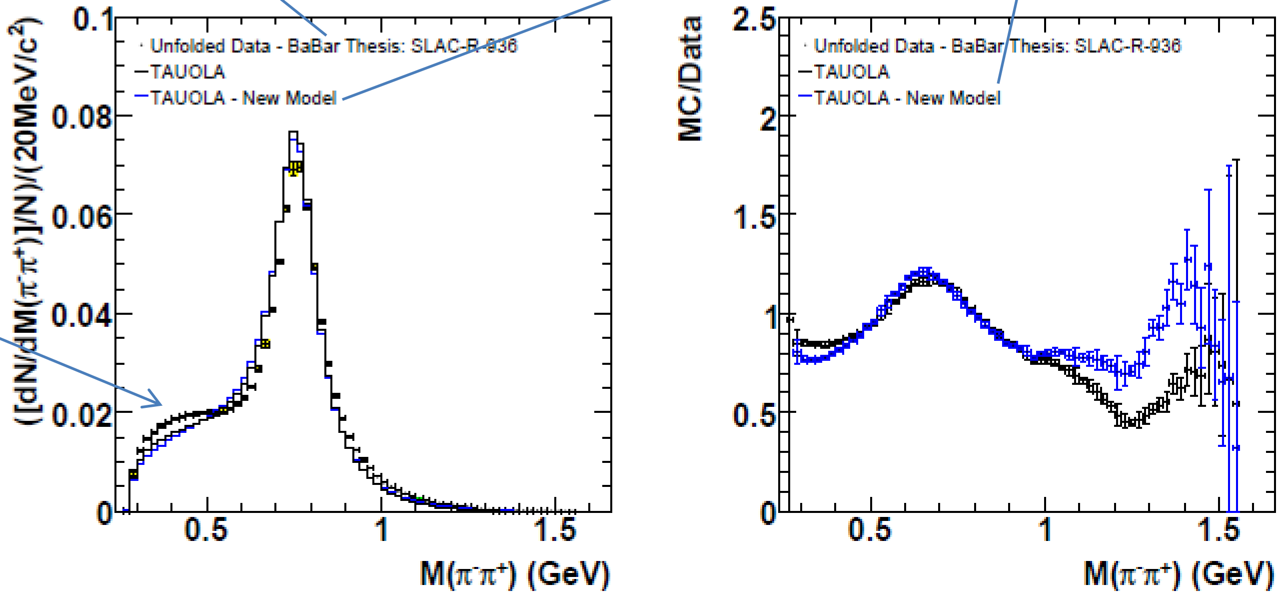

Figure 8: Invariant mass distribution of the $\pi^+\pi^-$ pair in $\tau \to \pi^+\pi^-\pi^-\nu_\tau$ decay. Lighter grey histogram is from our model, darker grey is from default parametrization of `TAUOLA cleo`. The unfolded BaBar data are taken from Ref. [57] . The plot on the left-hand side corresponds to the differential decay distribution, and the one on the right-hand side to plot ratios between Monte Carlo results and data. Courtesy of Ian Nugent.

http://annapurna.ifj.edu.pl/~wasm/RChL/RChL.htm

COMPARISONS

MC-Tester Davidson, Golonka, Przedzinski, Was '08

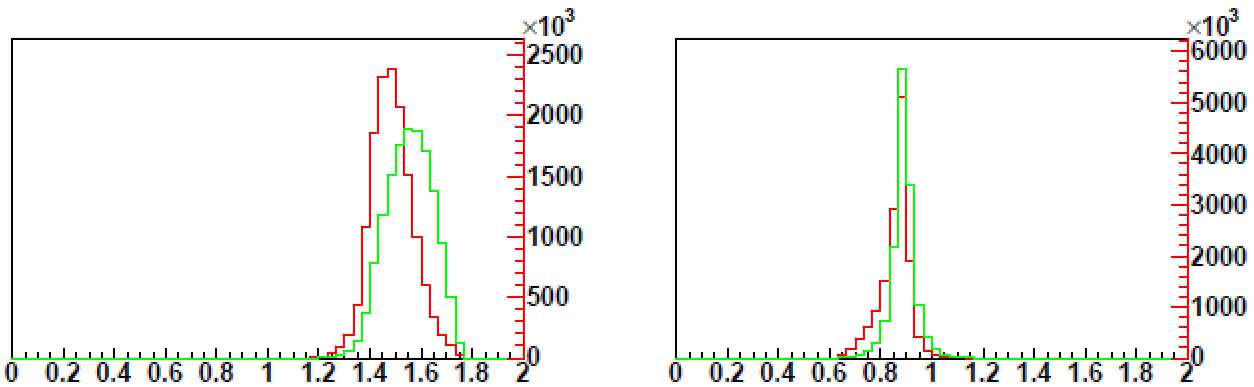

Figure 3: The $\tau \to K^+K^-\pi^-\nu_\tau$ decay: comparison of distributions for `TAUOLA cleo` current [21] and for our new current. On the left-hand side, plot of $K^+K^-\pi^-$ invariant mass is shown and on the right-hand side $K^+\pi^-$ invariant mass is given. Green histograms (light grey) are for the new current, red (darker grey) are for `TAUOLA cleo`.

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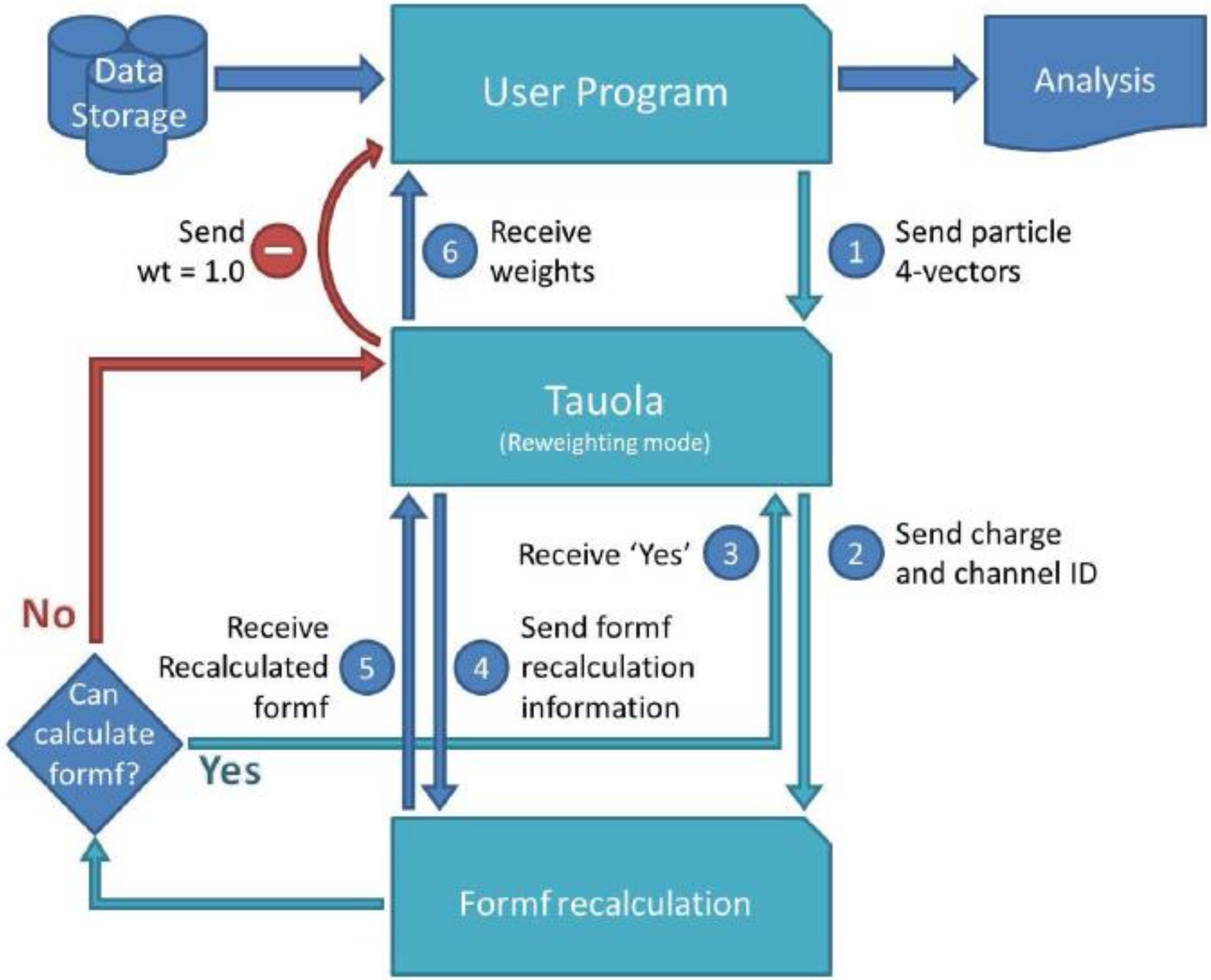

CONCLUSIONS

Shekhovtsova, Przedzinski, Roig, Was '12

Hadronic currents for the modes: $\pi^-\pi^0$, $(K\pi)^-$, K^-K^0, $(\pi\pi\pi)^-$, $(KK)\pi^-$, $K^-K^0\pi^0$ - from $R\chi T$ have been implemented in TAUOLA (88% of hadronic decays of the tau lepton). They are ready for precise confrontation with data amassed at Belle and BaBar (and future Belle II & Frascati superB data). Collaboration with experimentalists is essential for the success of the project.

In order to obtain the maximum possible information from experiments, the theory input to the MC has to be as accurate as possible with known properties respected (χPT results at low energies, smooth behaviour of FF at short distances, unitarity, analiticity,…). That is why our effort is and will be worth.

There are improvements to be done in all modes…

Ongoing/Future improvements

• Resummation in the two meson modes. ε below 3%.

•FSI in three meson modes. Relevant in $d\Gamma/ds$ ($\sim$ 10%).

•SU(3) breaking terms in the Lagrangian. (KKπ, $\sim$ 30%)

•Spin zero resonance contributions. ($\pi\pi\pi$)

Moussallam
Eur.Phys.J.C53:401-412,2008

•Excited resonance contribution in KKπ channels.

• Complete O(p^6) χPT, i.e. NNLO, in $\pi\pi$ channels.

Bijnens, Colangelo, Talavera
JHEP 9805:014,1998

López Castro et. al. **Phys.Rev.D74:071301,2006**

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Cirigliano, Ecker, Neufeld
Phys.Lett.B513:361-370,2001 **JHEP 0208:002,2002**

•Some important remaining modes: $\pi\pi\pi\pi$, K$\pi\pi$, SFF in Kπ ...

•Remaining two meson modes: $\pi\eta^{(\prime)}, K\eta^{(\prime)}$

Jamin, Oller, Pich '01,'06

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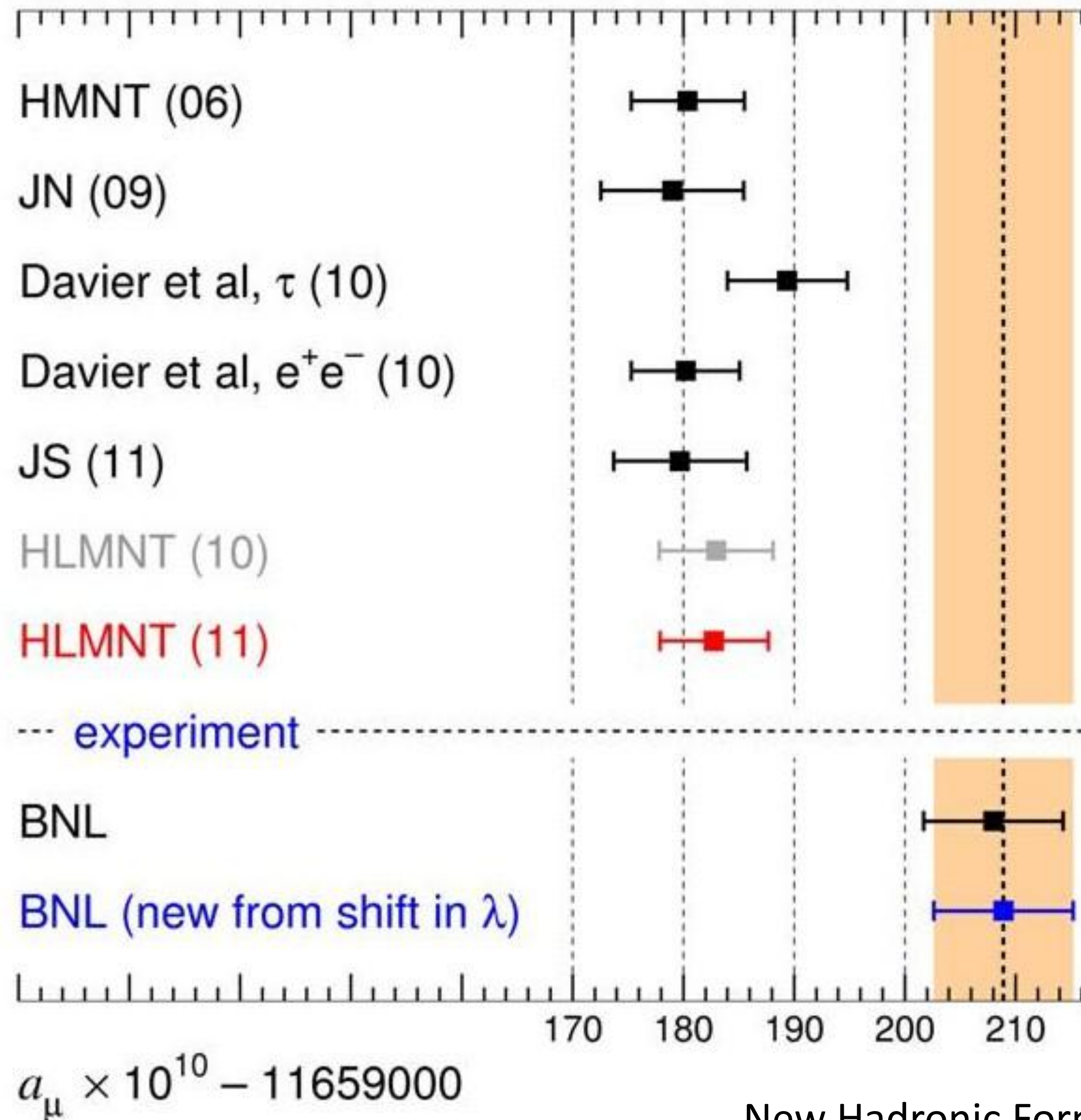
Jamin, Oller, Pich '01,'06

THANK YOU!

SKIPPED SLIDES

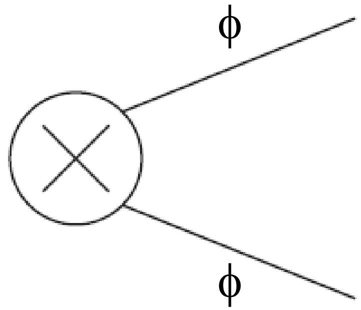
AMMM

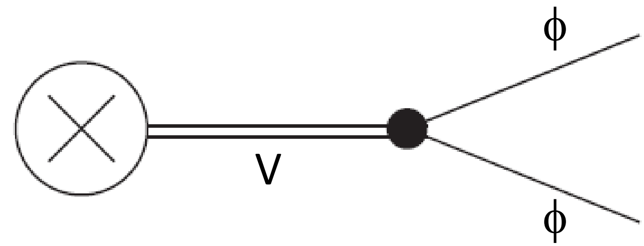

HMNT (06)
JN (09)
Davier et al, τ (10)
Davier et al, e⁺e⁻ (10)
JS (11)
HLMNT (10)
HLMNT (11)
experiment
BNL
BNL (new from shift in λ)
170
180
190
200
210
$a_\mu \times 10^{10} - 11659000$

Form factors in two meson τ decays

$\phi = \pi, K$

$V = \rho, K^*$





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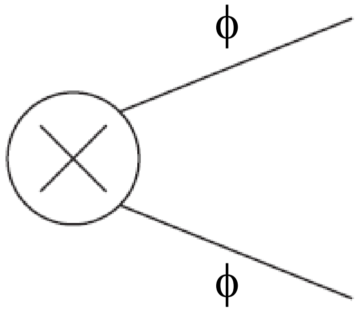
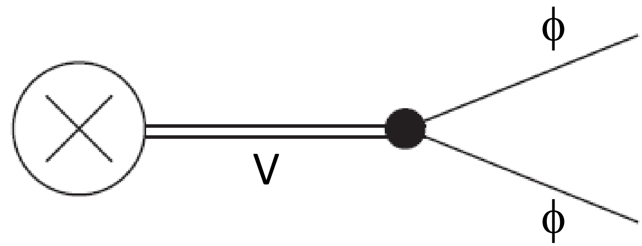


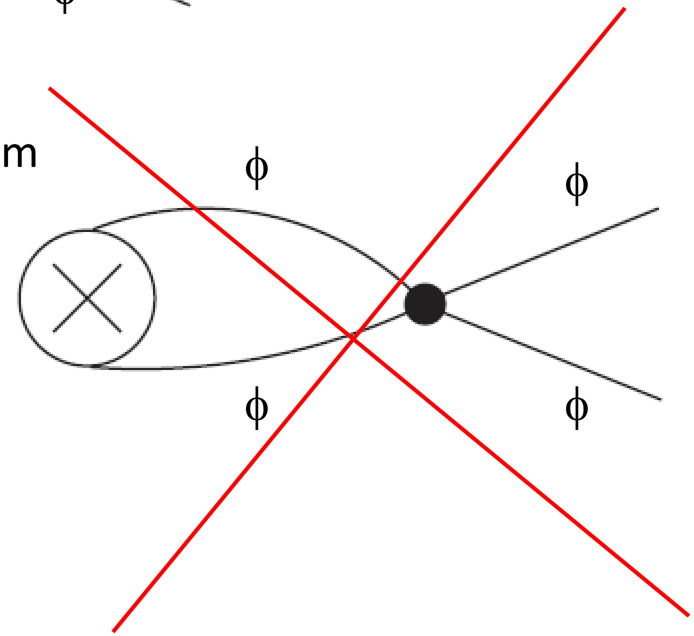


Antisymmetric tensor formalism for spin-one resonances

Ecker *et al.*

Phys.Lett.B223:425,1989

Nucl.Phys.B321:311,1989



To avoid double counting

Discussion on the errors

- $\varepsilon(1/N_c) \sim 1/3$?

't Hooft '74, Witten '79

Nucl.Phys.B72:461,1974 **Nucl.Phys.B160:57,1979**

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Ecker *et al.* '88, '89

QED: $\alpha \equiv e^2/(4\pi)^2$; χPT: $(p,m)^2/(4\pi F, M_V)^2$; RχT: ($\sim 1/N_c$)

Gasser, Leutwyler '83,'84

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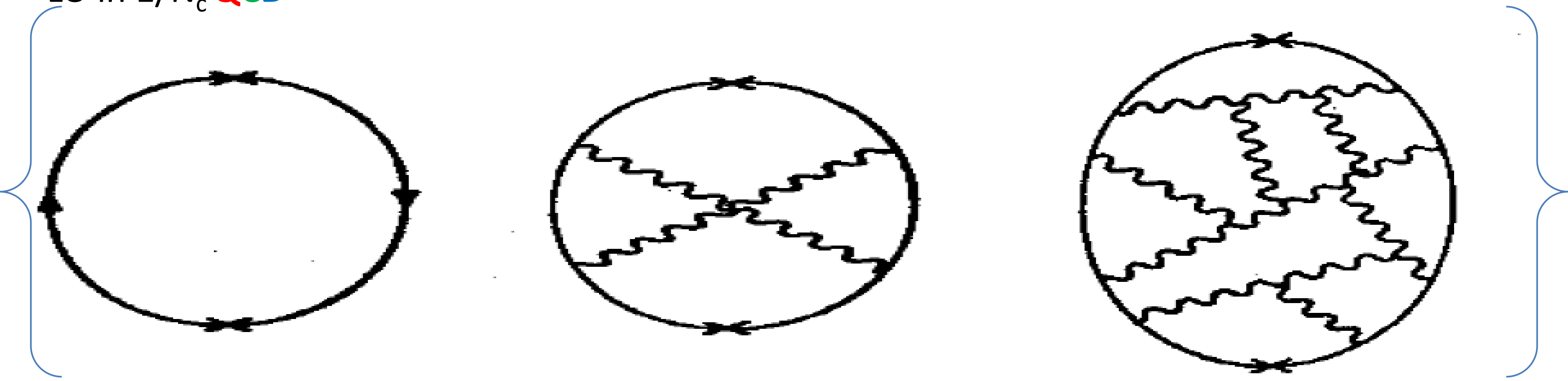
LO in $1/N_c$ **QCD**



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Pich, Rosell, Sanz Cillero '04,'06,'08,'10 Portolés, Rosell, Ruiz-Femenía '06

JHEP 0408:042,2004 **JHEP 0701:039,2007** **JHEP 0807:014,2008** **JHEP 1102:109,2011** **Phys.Rev.D75:114011,2007**

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Jamin, Pich, Portolés '06, '08 Boito, Escribano, Jamin '07 Gómez-Dumm, Roig, Pich, Portolés '09

Phys.Lett.B664:78-83,2008 **Eur.Phys.J.C59:821-829,2009** **Phys.Lett.B685:158-164,2010**

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Alternatively:

Exact Unitarity

$$F_V(s) = \frac{M_V^2}{M_V^2\left[1+\sum_{P,Q}N^{PQ}_{loop}\frac{s}{96\pi^2F^2}A_{PQ}(s)\right]-s}$$

$$\delta^{PQ}(s) = Im\left[F_V^{PQ}(s)\right]/Re\left[F_V^{PQ}(s)\right]$$

$$F_V^{PQ}(s) = \exp\left\{\alpha_1 s + \alpha_2 s^2 + \frac{s^3}{\pi}\int_{s_{thr}}^{s_{cut}} ds'\frac{\delta^{PQ}(s')}{s'^3(s'-s-i\epsilon)}\right\}$$

Tiny differences in observables between both approaches

Jamin, Pich, Portolés ’06, ’08 Boito, Escribano, Jamin ’07

Discussion on the errors

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$$F_I^{\rm scal}(x) = F_I^{\rm resonant}(x) + R_I^{\rm scal}(x)$$

$$\begin{aligned} F_+ &= F_+^{\chi} + F_+^{R} + F_+^{RR} + \sqrt{2}\left[R_0^{\rm scal}(s) + R_0^{\rm scal}(t)\right] + R_2^{\rm scal}(s) + R_2^{\rm scal}(t)\,, \\ F_- &= -(F_+^{\chi} + F_+^{R} + F_+^{RR}) - \left[R_0^{\rm scal}(s) + R_0^{\rm scal}(t)\right] + \sqrt{2}\left[R_2^{\rm scal}(s) + R_2^{\rm scal}(t)\right] \end{aligned}$$

Isidori, Maiani, Nicolacci, Pacetti

JHEP 0605 (2006) 049

$$R_0(x) = \left\{\frac{\alpha_0}{Q^2} + \frac{\alpha_1}{Q^4}(x - M_{f_0}^2) + \mathcal{O}\left[(x - M_{f_0}^2)^2\right]\right\} e^{i\delta_0(x)}$$

Schenk **Nucl.Phys. B363 (1991) 97-116**

Colangelo, Gasser, Leutywler

Nucl.Phys. B603 (2001) 125-179

$$\tan\delta_I(x) = \sigma_\pi(x)\left(A_0^I + B_0^I q^2 + C_0^I q^4 + D_0^I q^6\right)\frac{4m_\pi^2 - x_0^I}{x - x_0^I}$$

We have to check if this approach is enough to confront the data successfully.

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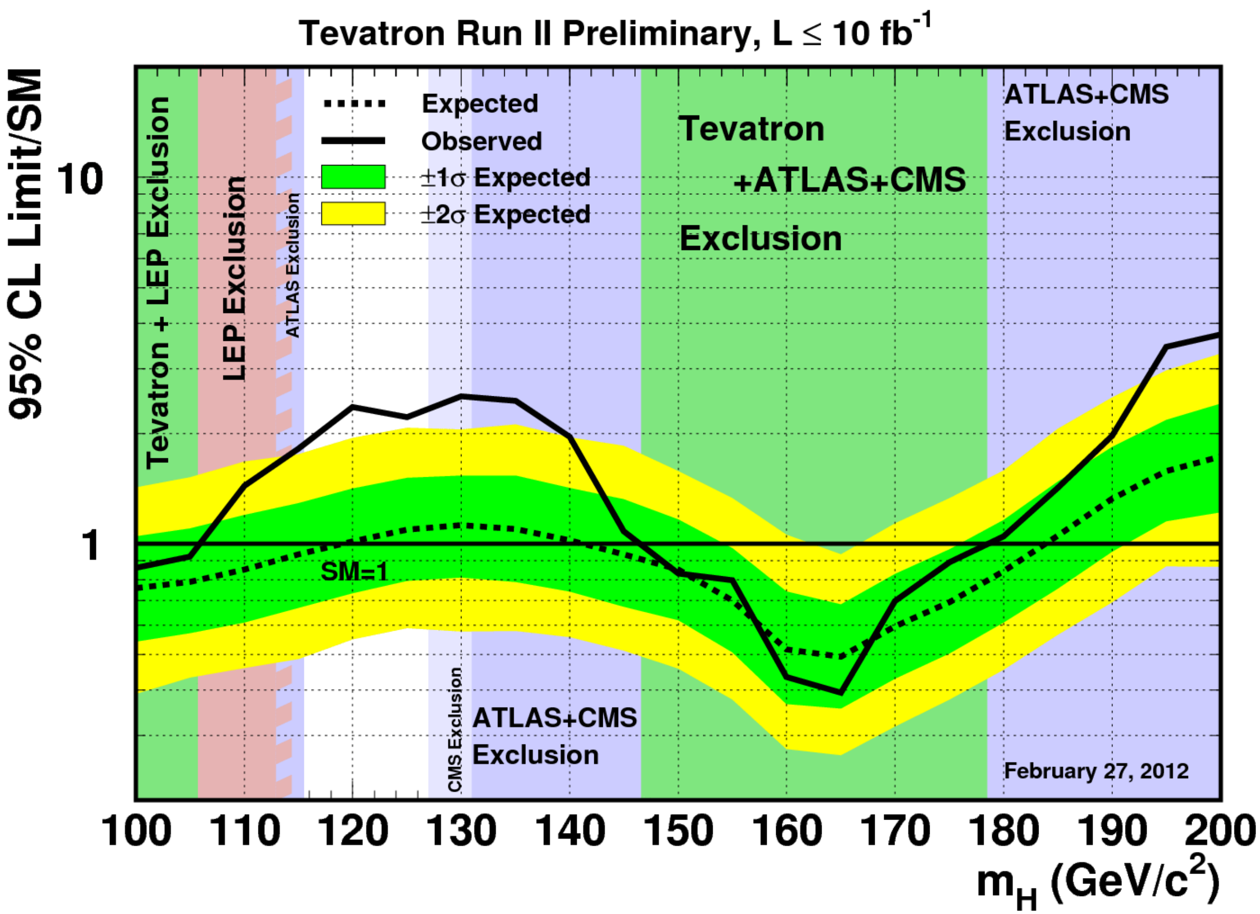
Jamin, Oller, Pich '01,'06

Nucl.Phys.B622:279-308,2002 Phys.Rev.D74:074009,2006

MOTIVATION

• High energies (**LHC**):
Hadronic tau decays

Search of the scalar sector of the SM, origin of EWSB



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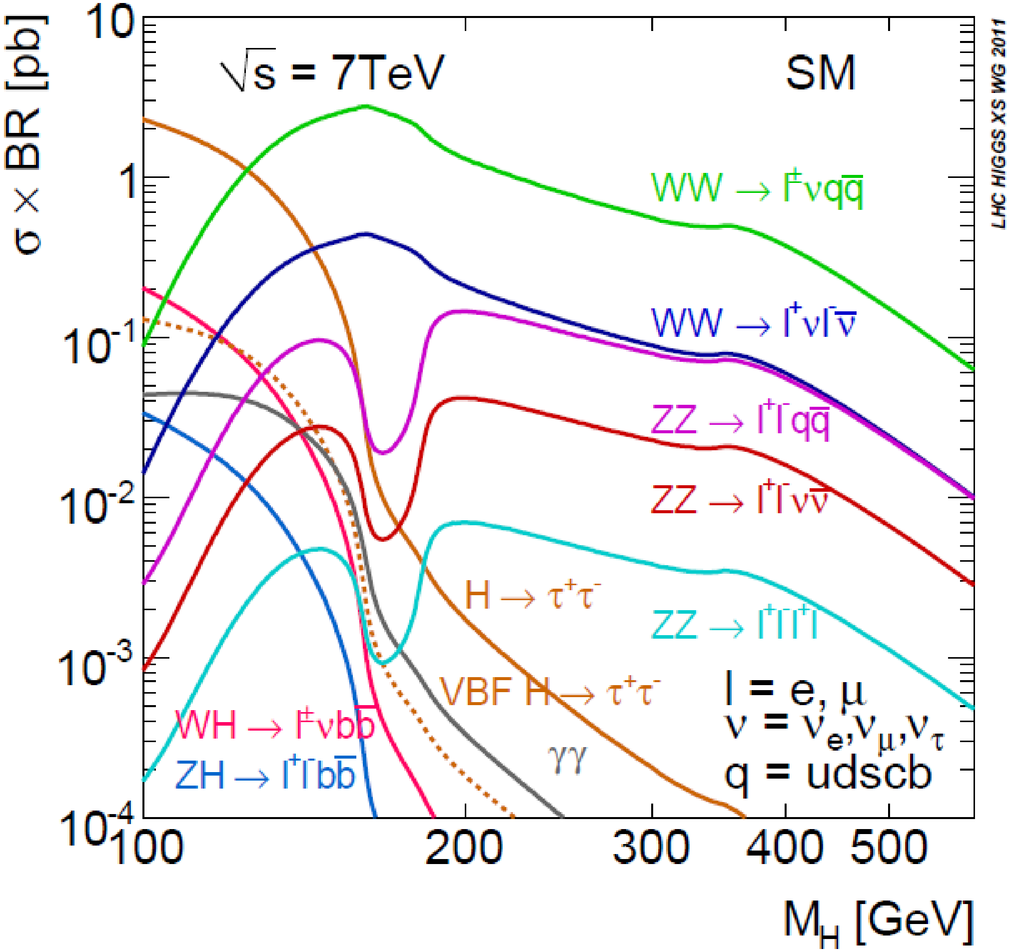

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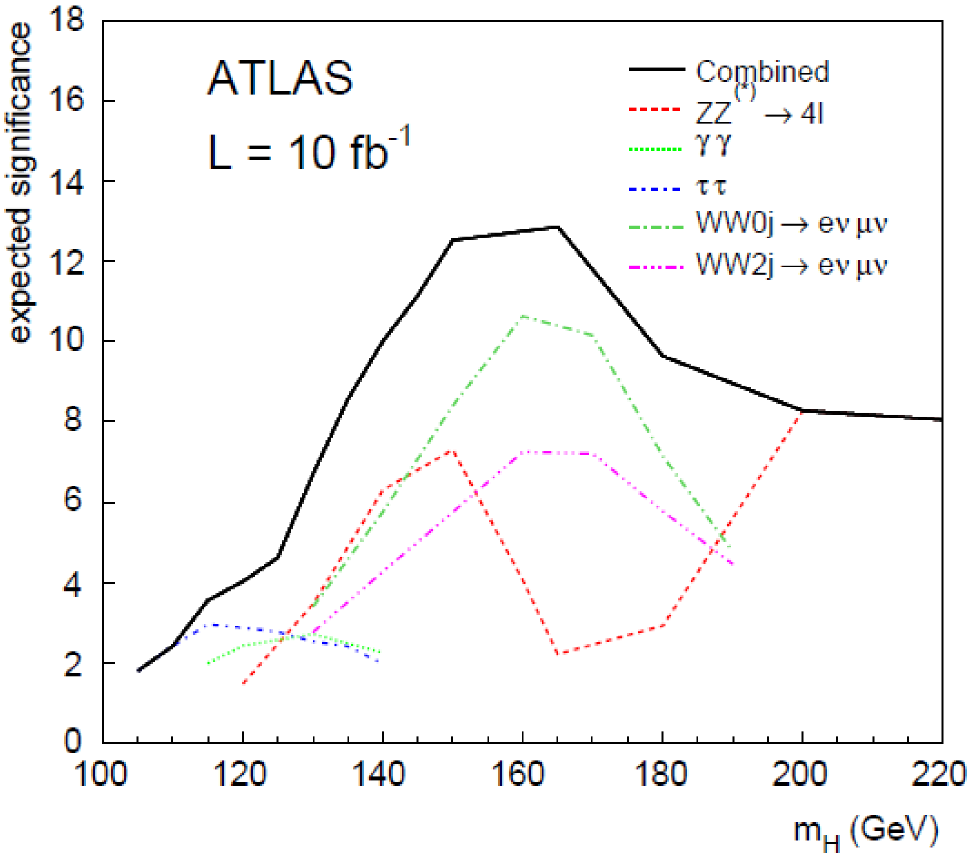
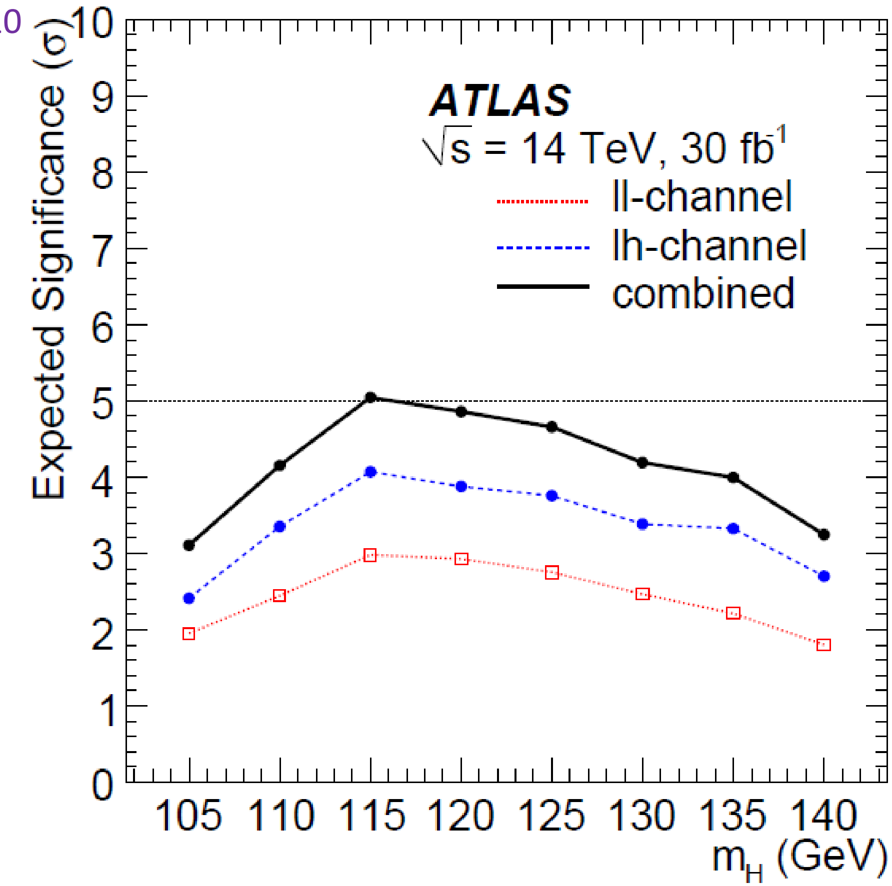


ATLAS '10



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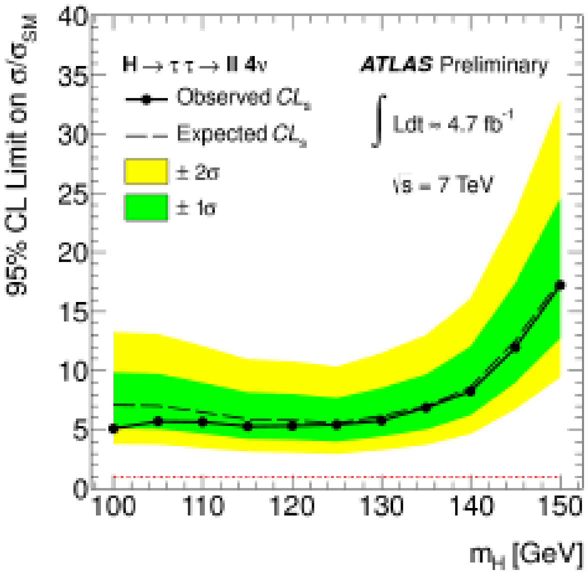

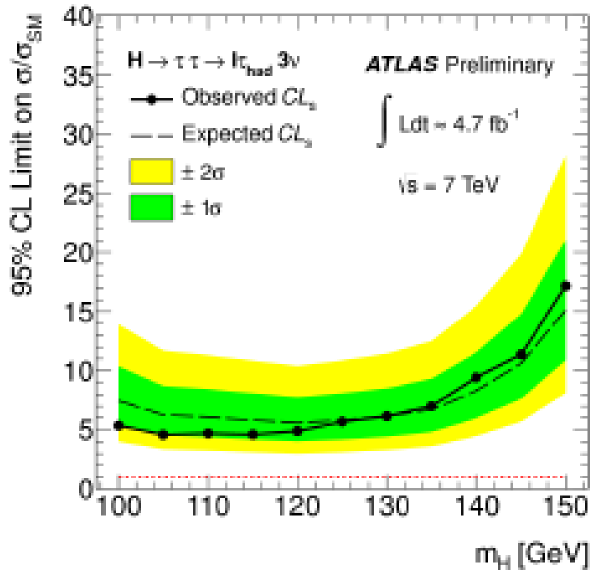

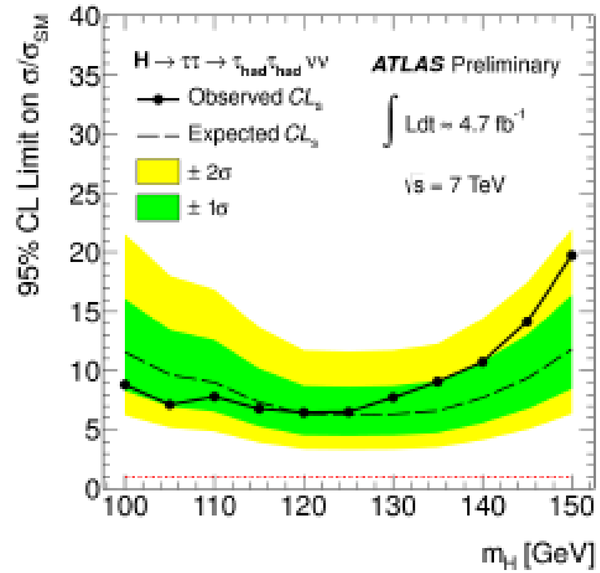

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