Dipion Spectrum : Isospin Breaking in e^+e^- annihilations and τ decays

M. Benayoun

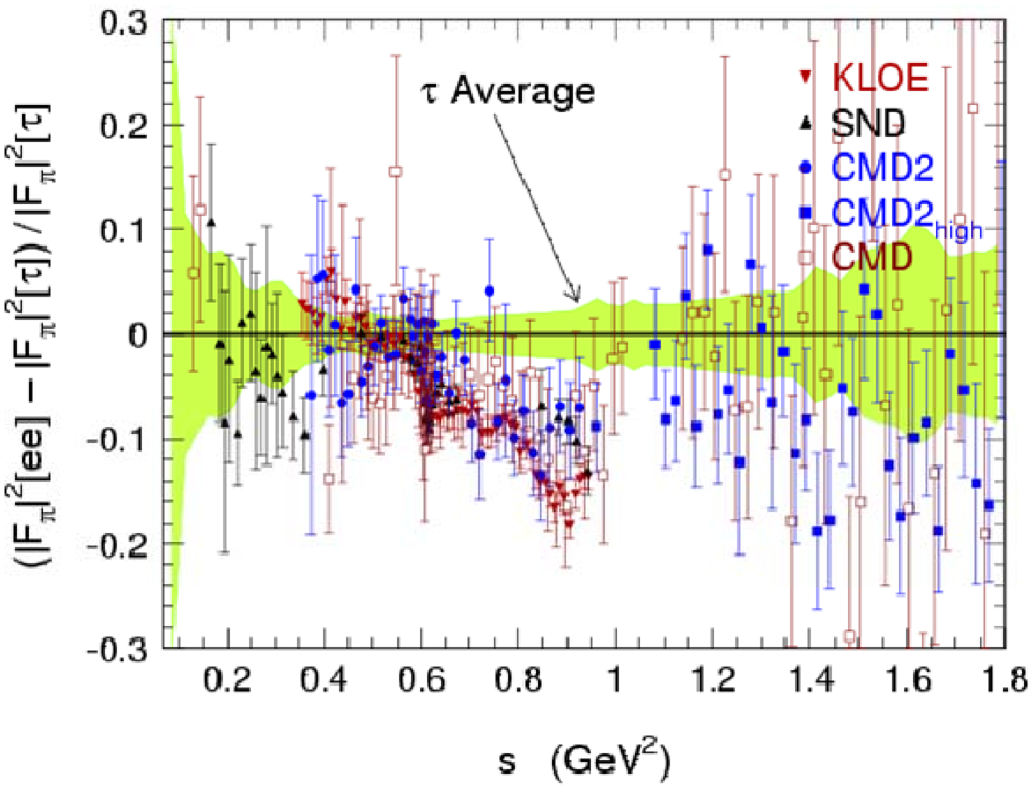
LPNHE Paris 6/7

The Pion Form factor in e^+e^- and τ Data

- Since the advent of τ data, disagreement with e^+e^- data
- Large activity in identifying isospin symmetry breaking in both e^+e^- annihilation and τ decay
- Disagreement survived accounting for identified isospin breaking corrections!
- Is there a missing piece, a systematic effect (in e^+e^- or τ data) or new physics?

Dipion Mass Spectrum : The Latest Account

- M. Davier NP Proc. Supp. 169 (2007) 288
- Inv. Mass dependent missing effect



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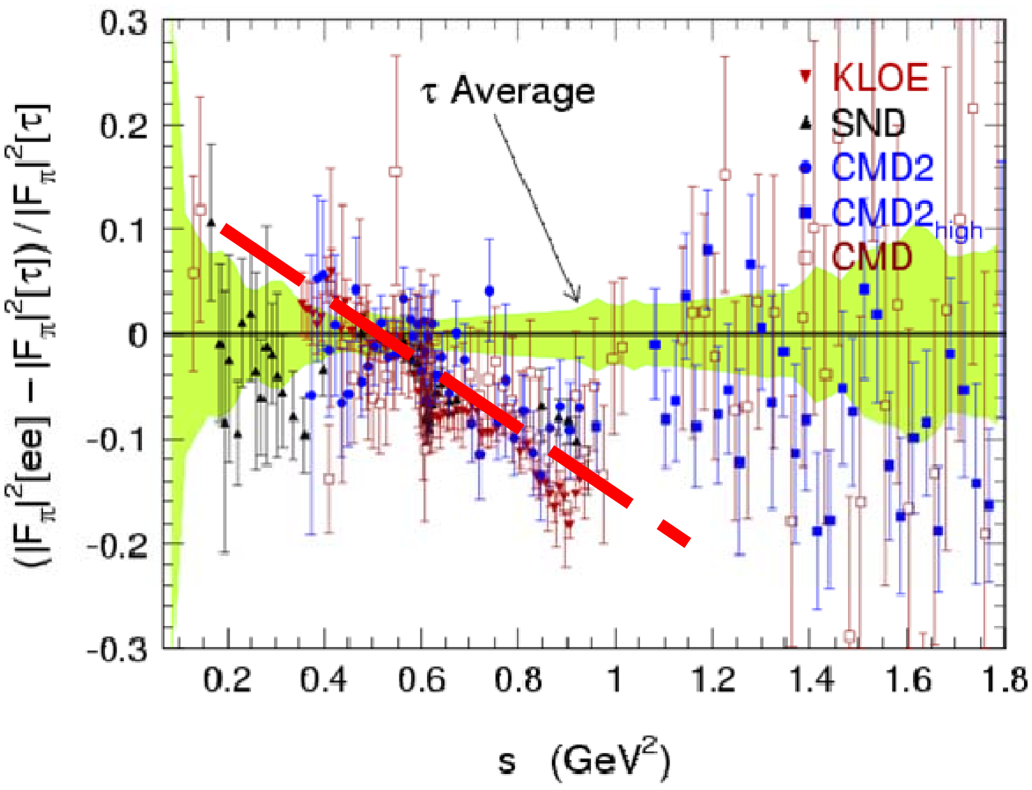
- **Inv. Mass dependent missing effect !**



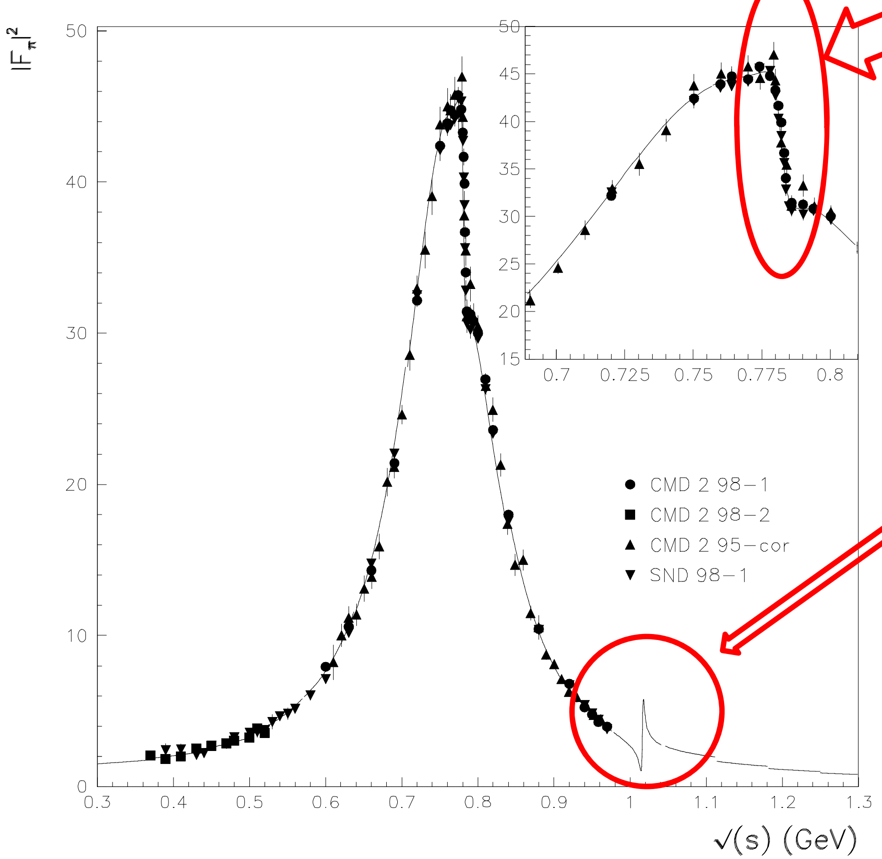
Is it isospin breaking?

Possible Missing Effect : (ρ-ω-φ) Mixing

FF's New Data

Isospin 1 part of ω

Isospin 1 part of φ



Possible Missing Effect : (ρ-ω-ϕ) Mixing

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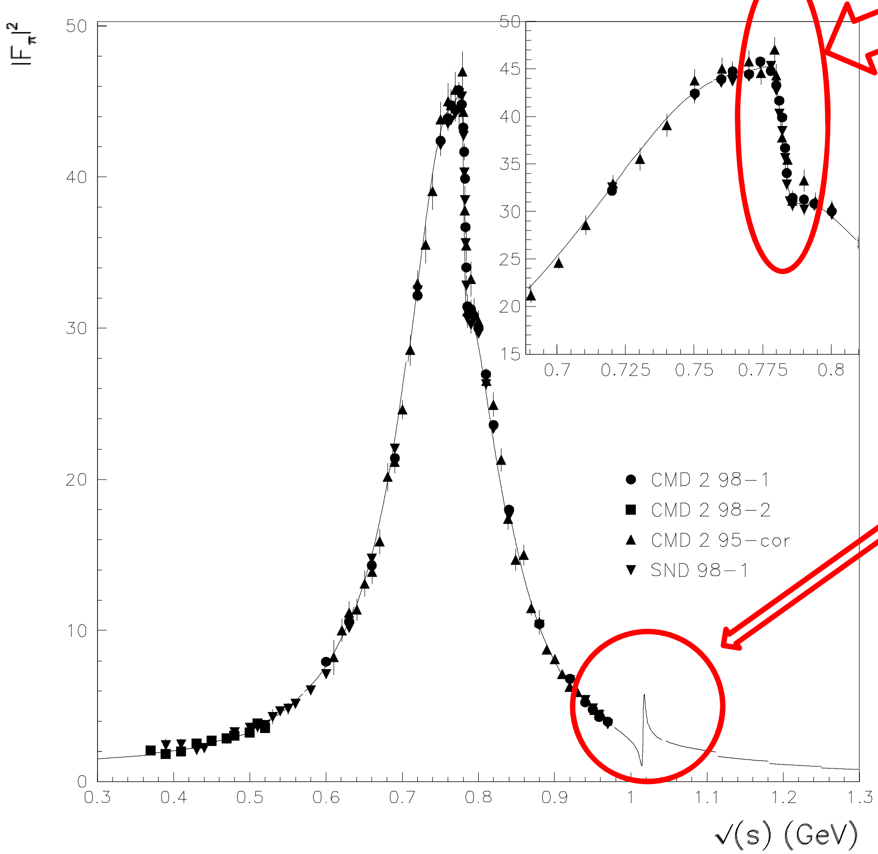

Isospin 1 part of ω

Isospin 1 part of ϕ

Missing Piece :

Isospin 0 part of ρ^0 ?

OUTLINE

- A VMD-like Framework : The HLS Model
  (Breaking of U(3)/SU(3) Symmetries)
- The Pion Form Factor in e^+e^- Annihilation and τ Decay (& Isospin Breaking)
- Loop Transition Effects in e^+e^- : Physical ρ^0, ω, ϕ
- Extended Data Sample submitted to fit, Why?
- Fit results & Plots
- Conclusions

The Framework

- Hidden Local Symmetry Model (HLS)

M.Bando, T. Kugo & K. Yamawaki Phys. Rep. 164 (1988) 217
M. Harada & K. Yamawaki Phys. Rep. 381 (2003) 1

M.Benayoun & H.O'Connell PR D 58 (1998) 074006

⇒ L_A, L_V, L_{YM} , $L_{anomalous}$

(pion form factor, VPγ & Pγγ couplings)

- BKY-like flavor U(3)/SU(3) breaking mechanisms

M. Benayoun et al. PR D 59 (1999) 114027

A. Bramon, A. Grau & G. Pancheri PL B 345 (1995) 263

G. Morpurgo PR D 42 (1990) 1497

M.Benayoun, L. DelBuono & H.O'Connell EPJ C 17 (2000) 593

⇒ M. Benayoun et al. hep-ph 0711.4482→EPJC

The Pion form Factor in e^+e^- and τ Physics

- Without Symmetry Breaking :

$$F_\pi^{e/\tau}(s) = \left[\left(1 - \frac{a}{2}\right) - \frac{F_\rho^{\gamma/W}(s) g_{\rho\pi\pi}}{D_\rho(s)} \right]$$

- Isospin symmetry breaking: mass splittings +

$$\tau \Rightarrow \times S_{EW} G_{EM}(s) \quad , e^+e^- \Rightarrow - \left[\frac{F_\omega^{\gamma/W}(s) g_{\omega\pi\pi}}{D_\omega(s)} + \frac{F_\varphi^{\gamma/W}(s) g_{\varphi\pi\pi}}{D_\varphi(s)} \right]$$

W. Marciano & A. Sirlin PRL 71 (1993) 3629

V. Cirigliano G. Ecker & H. Neufeld PL B 513 (2001) 361

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The Pion form Factor in e^+e^- and τ Physics

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a $\approx$[2.3,2.4]

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The Pion form Factor in e$^+$e$^-$ and τ Physics

- **With Symmetry Breaking :**

$$F_\pi^{e/\tau}(s) = \left[\left(1-\frac{a}{2}\right) - \frac{F_\rho^{\gamma/W}(s)\, g_{\rho\pi\pi}}{D_\rho(s)} \right]$$

(γ/W)V ?

ρππ?

δm²

- Isospin symmetry breaking : mass splittings **+**

$$\tau \Rightarrow \times S_{EW} G_{EM}(s) \qquad e^+e^- \Rightarrow -\left[\frac{F_\omega^\gamma(s) g_{\omega\pi\pi}}{D_\omega(s)} + \frac{F_\varphi^\gamma(s) g_{\varphi\pi\pi}}{D_\varphi(s)} \right]$$

W. Marciano & A. Sirlin PRL 71 (1993) 3629

V. Cirigliano G. Ecker & H. Neufeld PL B 513 (2001) 361

γ/W- ρ Transitions

- No isospin breaking :

$$F_\rho^{\gamma/W}(s) = agf_\pi^2 - \Pi_{(\gamma/W)\rho}(s)$$

- Isospin symmetry breaking :

ρ$^\pm$ component

$$F_\rho^{W}(s) = agf_\pi^2 - \Pi_{W\rho}(s)$$

$$F_\rho^{\gamma}(s) = agf_\pi^2 + \ldots - \Pi_{\gamma\rho}(s)$$

ρ_I component

ϕ_I and ω_I components

Transitions among vector fields at one loop

- At tree level **ideal fields ≡ mass *eigenstates***
- At one loop, the HLS Lagrangian piece

$$\left(\rho_I + \omega_I - \sqrt{2}\, z_V\, \varphi_I\right) K^- \overleftrightarrow{\partial} K^+ + \left(\rho_I - \omega_I + \sqrt{2}\, z_V\, \varphi_I\right) K^0 \overleftrightarrow{\partial} \overline{K}^0$$

induces transitions among ideal fields

ideal fields ≢ mass *eigenstates*

isospin symmetry breaking :

$$m_{K^\pm} \neq m_{K^0}$$

Transitions among vector fields at one loop

- Define the loops :

$= K^+ K^-$, $= K^0 \, \overline{K^0}$

VVP Lagrangian ⇒ K*K loops // Yang-Mills ⇒ $K^* \overline{K^*}$ loops

Then, beside self-masses :

$\Pi_{\omega\varphi}(s)$ = + ~ $\varepsilon_2(s) \neq 0$ always

$\Pi_{\rho\omega}(s)$ = -

$\neq 0$ by isospin brk

$\Pi_{\rho\varphi}(s)$ = -

~ $\varepsilon_1(s)$

f(s)

The Modified Vector Mass Matrix

$$
\begin{array}{cccc}
 & \rho_I & \omega_I & \phi_I \\
M^2(s) = & \left(\begin{array}{c} m^2 + \Pi_{\pi\pi}(s) + \varepsilon_2(s) \\ \varepsilon_1(s) \\ -\mu\varepsilon_1(s) \end{array} \right. & \begin{array}{c} \varepsilon_1(s) \\ m^2 + \varepsilon_2(s) \\ -\mu\varepsilon_2(s) \end{array} & \left. \begin{array}{c} -\mu\varepsilon_1(s) \\ -\mu\varepsilon_2(s) \\ z_V m^2 + \mu^2\varepsilon_2(s) \end{array} \right)
\end{array}
$$

With $m^2 = a\, g^2 f_\pi^{\,2}$ and $\mu = z_V \sqrt{2}$

No SU(3) Brk :: $z_V = 1$ *, No SU(2) Brk ::* $\varepsilon_1(s) = 0$

[Blue : Loop effects magenta : SU(3) breaking
red : isospin breaking]

Loop Corrections : (ω , ϕ) Mixing

$$M^2(s) = \begin{array}{c} \begin{array}{ccc} \rho_I & \omega_I & \phi_I \end{array} \\ \begin{pmatrix} m^2 + \Pi_{\pi\pi}(s) + \varepsilon_2(s) & \varepsilon_1(s) & -\mu\varepsilon_1(s) \\ \varepsilon_1(s) & m^2 + \varepsilon_2(s) & \boxed{-\mu\varepsilon_2(s)} \\ -\mu\varepsilon_1(s) & \boxed{-\mu\varepsilon_2(s)} & z_V m^2 + \mu^2\varepsilon_2(s) \end{pmatrix} \end{array}$$

[Blue : Loop effects magenta : SU(3) breaking
red : isospin breaking]

Isospin Breaking : (ρ, ω , φ) Mixing

$$\begin{array}{cccc} & \rho_I & \omega_I & \phi_I \\ M^2(s) = & \multicolumn{3}{c}{\left(\begin{array}{ccc} m^2 + \Pi_{\pi\pi}(s) + \varepsilon_2(s) & \varepsilon_1(s) & -\mu\varepsilon_1(s) \\ \varepsilon_1(s) & m^2 + \varepsilon_2(s) & -\mu\varepsilon_2(s) \\ -\mu\varepsilon_1(s) & -\mu\varepsilon_2(s) & z_V m^2 + \mu^2\varepsilon_2(s) \end{array} \right)} \end{array}$$

[Blue : Loop effects magenta : SU(3) breaking
red : isospin breaking]

The Mass Matrix Eigen System

- **Expect :** $\boxed{\left(m^2, \Pi_{\pi\pi}(s)\right) \gg \varepsilon_2(s) \gg \varepsilon_1(s)}$
- Then solve for the eigensystem **perturbatively** :

$$M_0^2(s) = \begin{pmatrix} m^2 + \Pi_{\pi\pi}(s) & 0 & 0 \\ 0 & m^2 + \varepsilon_2(s) & 0 \\ 0 & 0 & z_V m^2 + \mu^2 \varepsilon_2(s) \end{pmatrix}$$

and :

$$\delta M^2(s) = \begin{pmatrix} \varepsilon_2(s) & \varepsilon_1(s) & -\mu\varepsilon_1(s) \\ \varepsilon_1(s) & 0 & -\mu\varepsilon_2(s) \\ -\mu\varepsilon_1(s) & -\mu\varepsilon_2(s) & 0 \end{pmatrix}$$

From Ideal To Physical Fields I

$$\begin{pmatrix} \rho^0 \\ \omega \\ \varphi \end{pmatrix} = R(s) \begin{pmatrix} \rho_I^0 \\ \omega_I \\ \varphi_I \end{pmatrix}$$

$R(s)$: Real analytic matrix function

$$R(s+i\varepsilon)\tilde{R}(s+i\varepsilon) = 1$$

$$R(s) = \begin{pmatrix} 1 & \dfrac{\varepsilon_1}{\Pi_{\pi\pi} - \varepsilon_2} & \dfrac{-\mu\varepsilon_1}{(1-z_V)m^2 + \Pi_{\pi\pi} - \mu^2\varepsilon_2} \\ \dfrac{-\varepsilon_1}{\Pi_{\pi\pi} - \varepsilon_2} & 1 & \dfrac{-\mu\varepsilon_2}{(1-z_V)m^2 + (1-\mu^2)\varepsilon_2} \\ \dfrac{\mu\varepsilon_1}{(1-z_V)m^2 + \Pi_{\pi\pi} - \mu^2\varepsilon_2} & \dfrac{\mu\varepsilon_2}{(1-z_V)m^2 + (1-\mu^2)\varepsilon_2} & 1 \end{pmatrix}$$

Solution valid for all $s : \Pi_{\pi\pi}(s) - \varepsilon_2(s) \neq 0$ $\qquad + O(\varepsilon_i^2)$

From Ideal To Physical Fields II

Mass term derived from the eigenvalues of $M^2(s)$

:

$$\frac{m^2}{2}\left[\rho_I^2+\omega_I^2+z_V\varphi_I^2\right]\Rightarrow \frac{1}{2}\left[m^2+\Pi_{\pi\pi}(s)+\varepsilon_2(s)\right]\rho^2$$

$$+\frac{1}{2}\left[m^2+\varepsilon_2(s)\right]\omega^2+\frac{1}{2}\left[z_V m^2+\mu^2\varepsilon_2(s)\right]\varphi^2$$

(Self masses include subtraction polynomials)

Leading order propagators become $\sim\left[s-\lambda_V(s)\right]^{-1}$

V π π Couplings

$$\frac{iag}{2}\rho_I \bullet \pi^- \overleftrightarrow{\partial} \pi^+ \Rightarrow$$

$$\frac{iag}{2}\left[\rho^0 - \frac{\varepsilon_1}{\Pi_{\pi\pi} - \varepsilon_2}\omega + \frac{\mu\varepsilon_1}{(1-z_V)m^2 + \Pi_{\pi\pi} - \mu^2\varepsilon_2}\varphi\right] \bullet \pi^- \overleftrightarrow{\partial} \pi^+$$

*At leading order : **ρ term unchanged**

***s-dependent ω and ϕ couplings** generated

V π π Couplings

$$\frac{iag}{2}\rho_I^0 \bullet \pi^- \overleftrightarrow{\partial} \pi^+ \Rightarrow$$

Orsay Phase ≈90° at peak

$$\frac{iag}{2}\left[\rho^0 - \frac{\varepsilon_1}{\Pi_{\pi\pi} - \varepsilon_2}\omega + \frac{\mu\varepsilon_1}{(1-z_V)m^2 + \Pi_{\pi\pi} - \mu^2\varepsilon_2}\varphi\right] \bullet \pi^- \overleftrightarrow{\partial} \pi^+$$

*At leading order : **ρ term unchanged** $+O(\varepsilon_i^2)$

$$\boxed{g_{\rho\pi\pi} \Rightarrow g_{\rho\pi\pi} + O(\varepsilon_i^2)}$$

***s-dependent ω and ϕ couplings** generated

γ – V Couplings

- In terms of Ideal Fields

$$-e\, agf_\pi^2 \left[\rho_I^0 + \frac{1}{3}\omega_I - \frac{\sqrt{2}}{3} z_V \phi_I \right]_\mu \bullet A^\mu \Rightarrow$$

- Becomes

$$\Rightarrow -e \left[f_\rho^\gamma \rho^0 + f_\omega^\gamma \frac{1}{3}\omega - f_\phi^\gamma \frac{\sqrt{2}}{3} z_V \phi \right]_\mu \bullet A^\mu$$

With $\boxed{agf_\pi^2 \Rightarrow f_V^\gamma \equiv f_V^\gamma(s) = agf_\pi^2 \left[1 + O(\varepsilon_1(s))\right] \quad !!!}$

Vector Meson Couplings to γ/W

- (γ/W) V transitions : constant + (PP,VP…) loops

- loop term : disp. relation (subtractions) $\Pi^{\gamma/W}(s)$
- tree terms :

$$f_\rho^\gamma = a\, g\, f_\pi^2 \left[1 + \frac{1}{3}\frac{\varepsilon_1}{\Pi_{\pi\pi} - \varepsilon_2} + \frac{1}{3}\frac{\mu^2 \varepsilon_1}{(1 - z_V)\, m^2 + \Pi_{\pi\pi} - \mu^2 \varepsilon_2} \right]$$

$$f_\rho^W = a g f_\pi^2$$

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$$f_\rho^W = a g f_\pi^2$$

Parameter Freedom

- If only using the pion form factor (e^+e^-,τ) the **parameter freedom is far too large**:
- a (HLS), g , z_A , δm^2 (4)
- Subtraction polynomials in :

$$\Pi^{\rho}_{\pi\pi}(s), \Pi^{\gamma/W}_{\pi\pi}(s), \varepsilon_1(s), \varepsilon_2(s) \qquad (\sim 8)$$

Too many parameters, too few structures

- Solution : **extend the fitted data sample**:

more information, less correlations

The Extended Data Sample

- Add anomalous decay modes VPγ, Pγγ :

$$\rho^0/\omega/\varphi \to \pi^0\gamma/\eta\gamma \;\|\; \varphi \to \eta'\gamma \;\|\; \eta' \to (\rho^0/\omega)\gamma$$

$$K^* \to K\gamma \;\|\; \eta/\eta' \to \gamma\gamma \;\|\; \rho^\pm \to \pi^\pm\gamma$$

- Price Brk params.: x, z_T, z_V, z_A for 14 modes

$(\rho^0)\,\boxed{\omega/\varphi \to e^+e^-}$ for free

$\boxed{\mathit{Modulus\ and\ phase}\,(\varphi \to \pi^+\pi^-)}$ for free + 4

measured data :: **Total 18 add. data**

M.B.,L.D. ,S.E, V.I. & H.OC, PR D 59 (1999) 114027

M.B, H.OC EPJ C22 (2001) 503

The Main Guess

- Main Guess ≈ Proof of Principle

18 Decay Modes + Pion FF in e^+e^- annihilation

- Fully reconstruct

The Pion FF in τ decay

(improvement of parameter fit values)

The X^2 contributions to fits

Data Set (#data points)	Full Data Fit	No τ data	No Spacelike Data
Decays (18+1)	11.13	11.52	11.48
New Timelike (127+1)	128.1	122.0	125.8
Old Timelike (82+1)	59.1	54.7	55.2
Spacelike (59+2)	65.7	55.2	**89.8/(59)**
τ ALEPH (33)	23.9	**42.3/(33)**	20.8
τ CLEO (25+1)	26.1	**26.2/(25)**	29.7
X^2/dof Probability	313.8/331 74%	257.7/274 75%	238.8/272 93%

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The X^2 contributions to fits

τ DATA **OUTSIDE FIT** : X^2 distance to ***prediction***

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The X^2 contributions to fits

Spacelike data **OUTSIDE FIT**

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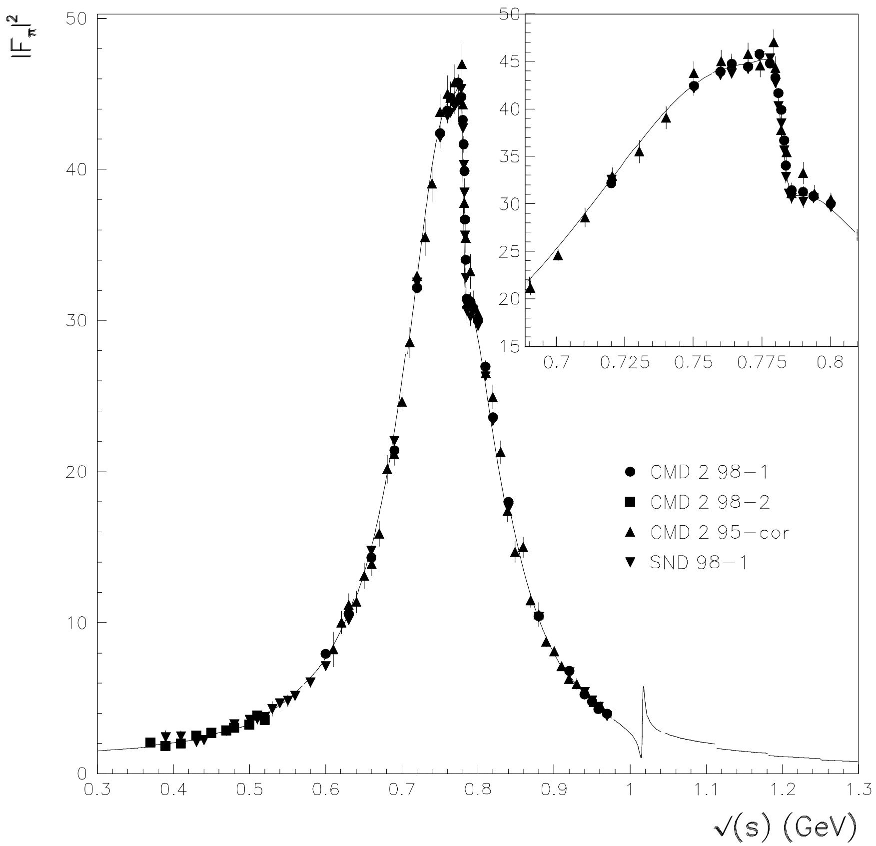
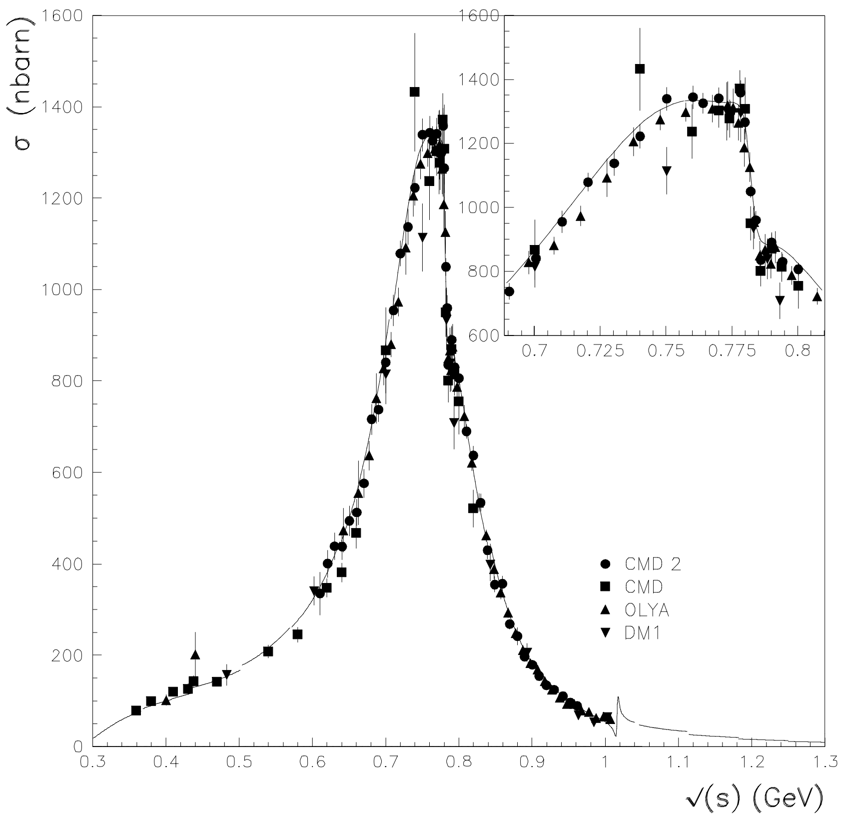
Global Fit to e^+e^- Data

FF's New Data

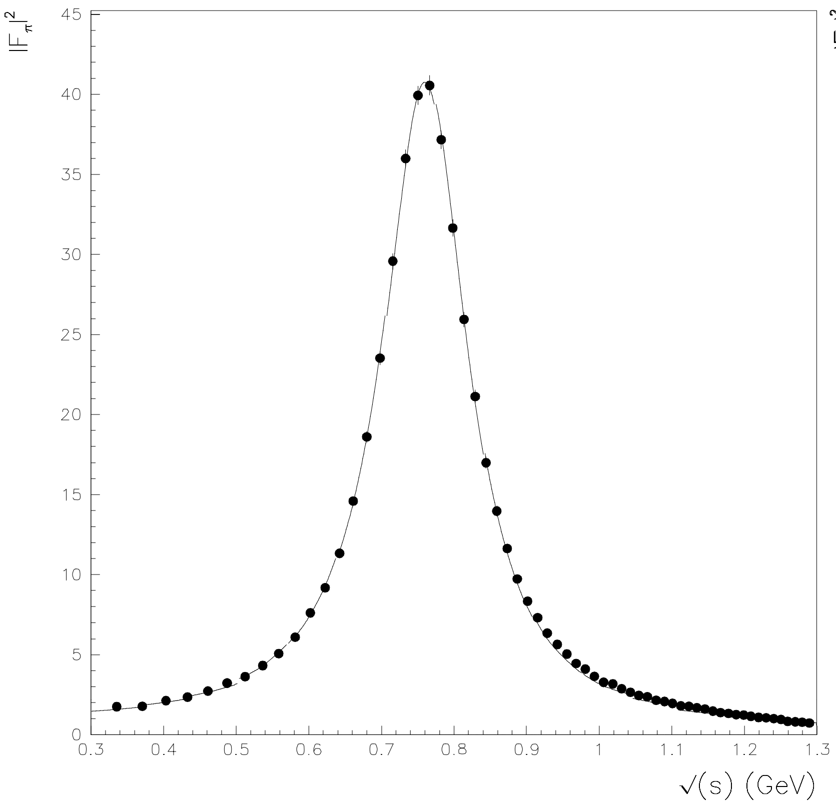


Cross Sections Old Data

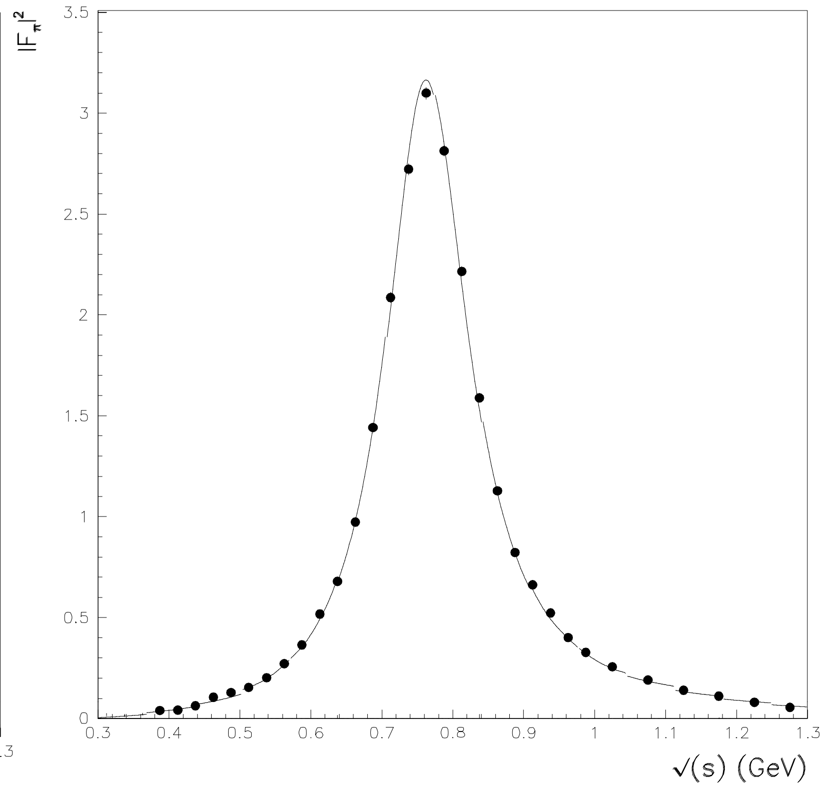


Fits to τ Data

ALEPH Data

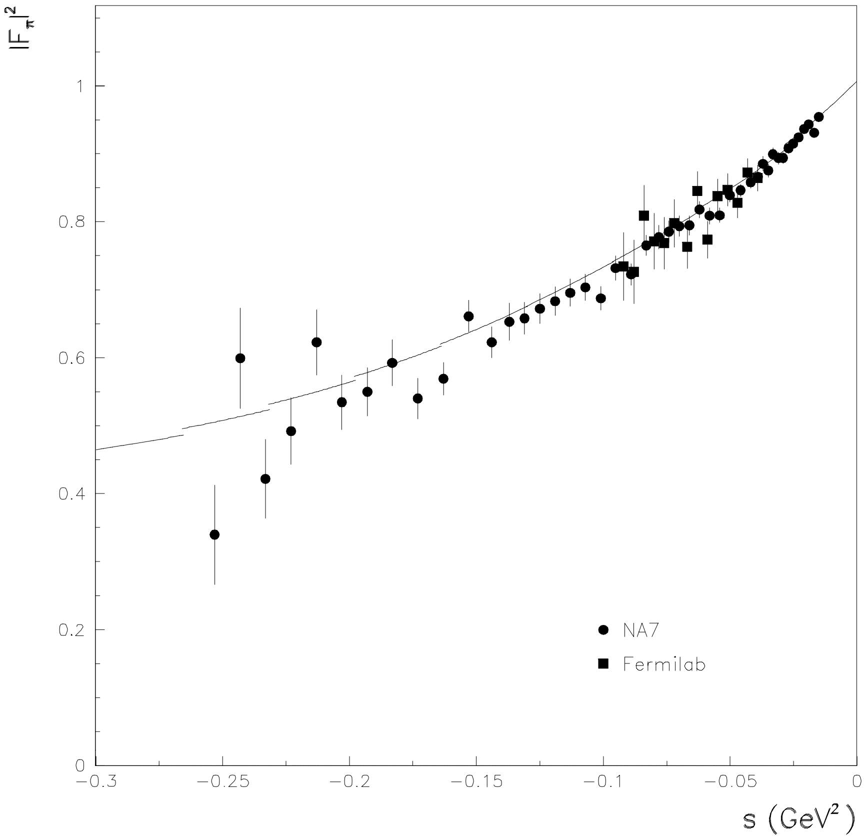


CLEO Data



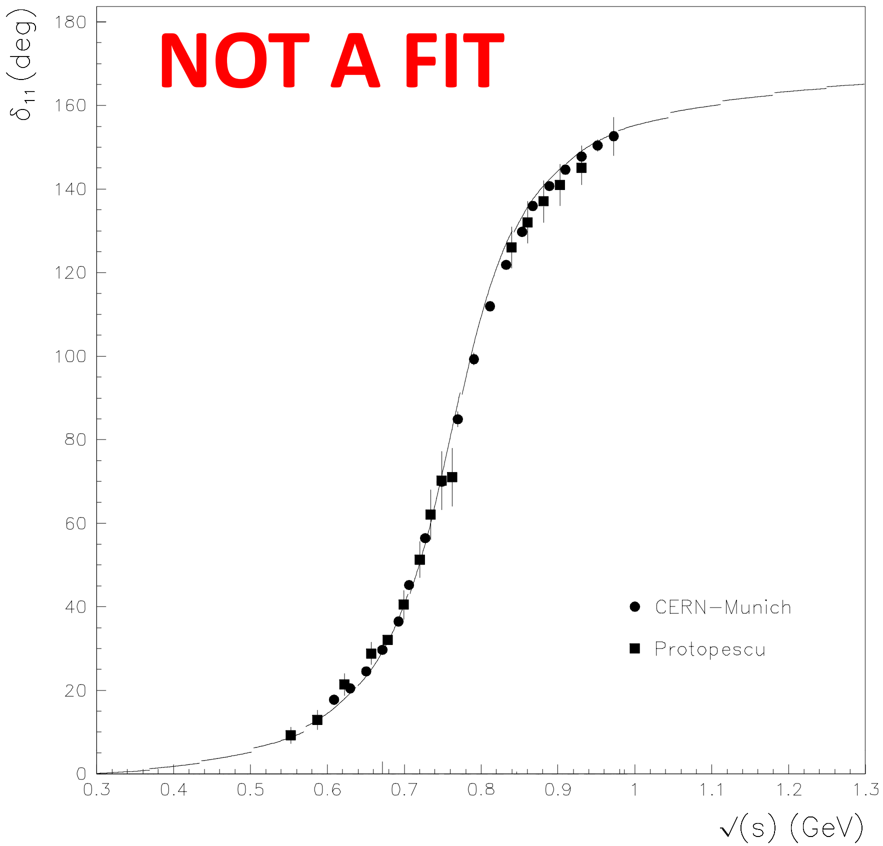
Spacelike Data & ππ Phase Shift

SpaceLike Data

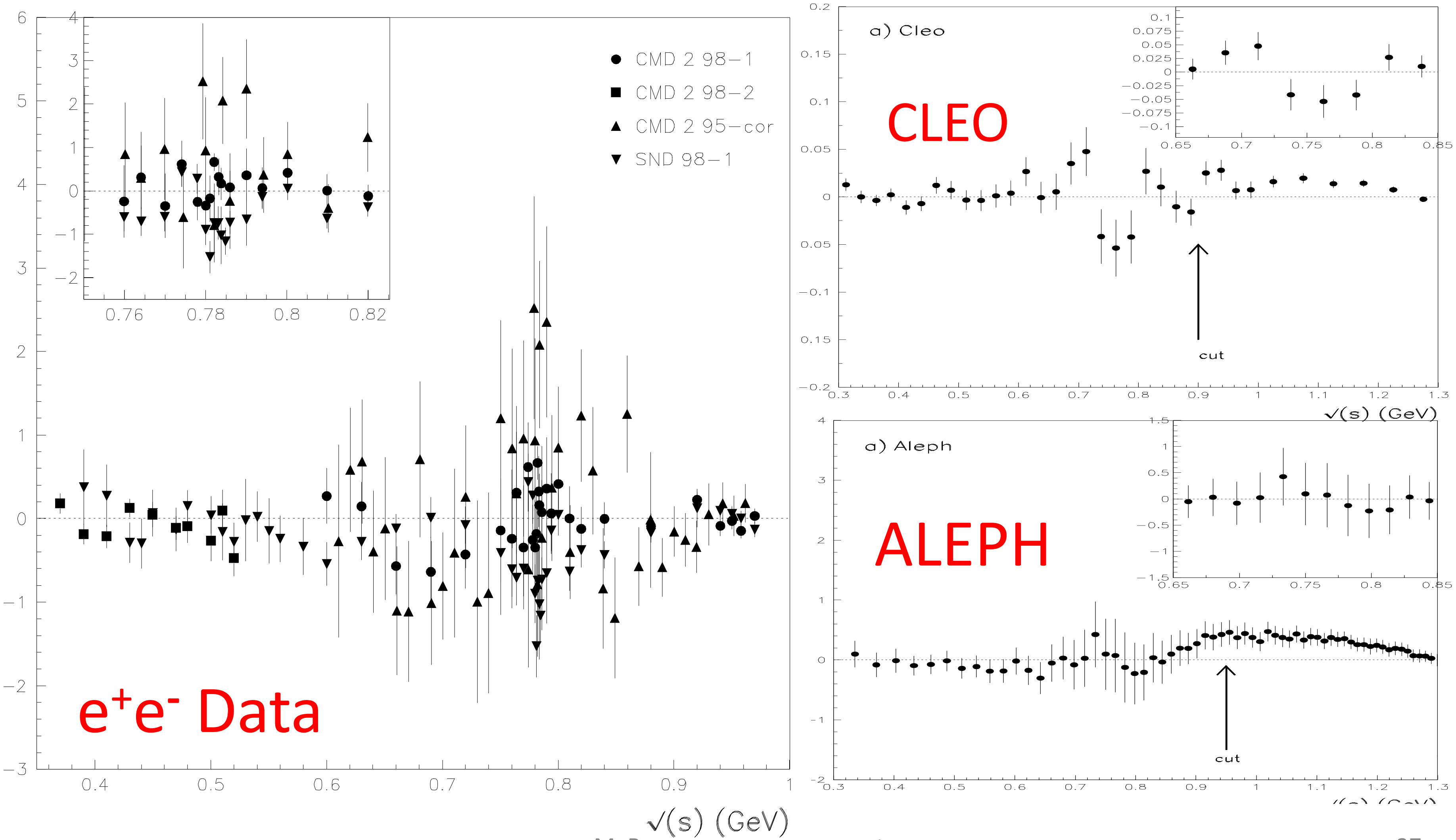


I=1 ππ Phase shift

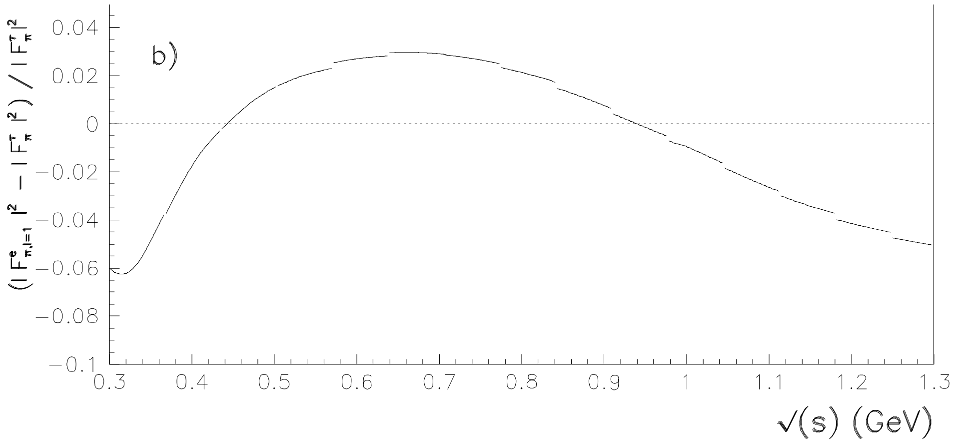
NOT A FIT



Fit Residuals : No Structure



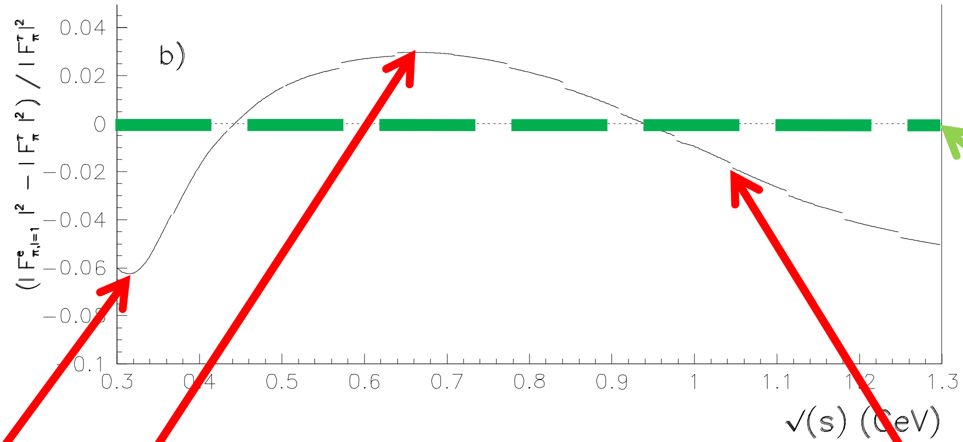
Isospin Symmetry Breaking : ρ^0 VS $\rho^\pm$



$$\frac{\left(|F^{e}_{\pi\ "I=1"}(s)|^2 - |F^{\tau}_{\pi}(s)|^2\right)}{|F^{\tau}_{\pi}(s)|^2}$$

$$I = 1 \equiv \rho^0 \ \ part$$

Isospin Symmetry Breaking : ρ^0 VS $\rho^{\pm}$



0 :: NO IS Brk

Threshold : -6%

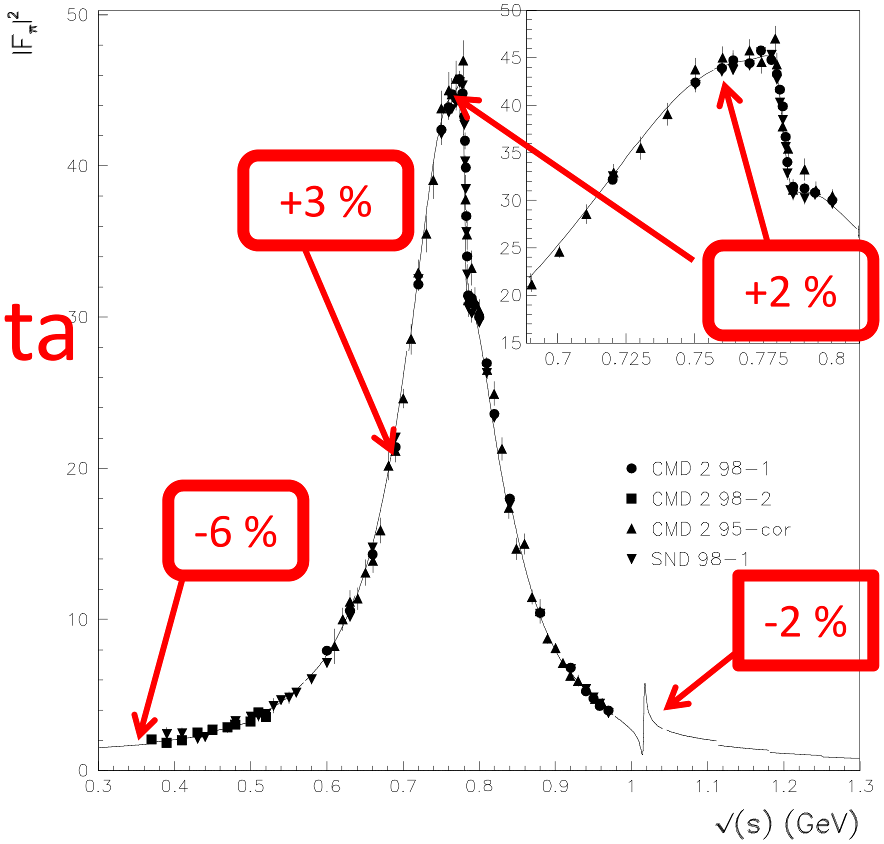
ρ Peak : + 3%

Φ Mass : -2%

$$\frac{\left(|F^{e}_{\pi\,"I=1"}(s)|^2 - |F^{\tau}_{\pi}(s)|^2\right)}{|F^{\tau}_{\pi}(s)|^2}$$

Magnitude of Isospin Breaking

FF's New Data

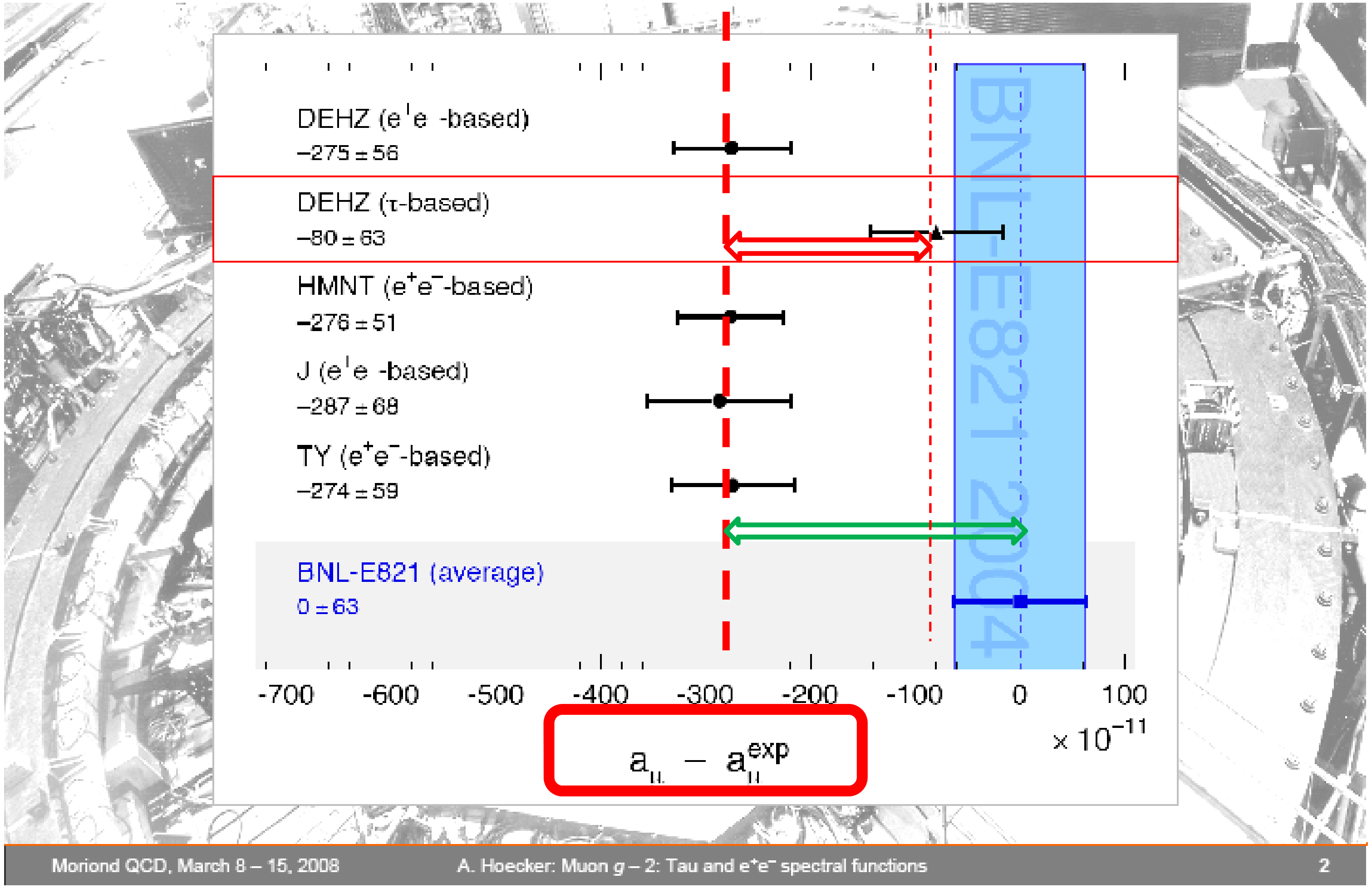


Conclusions

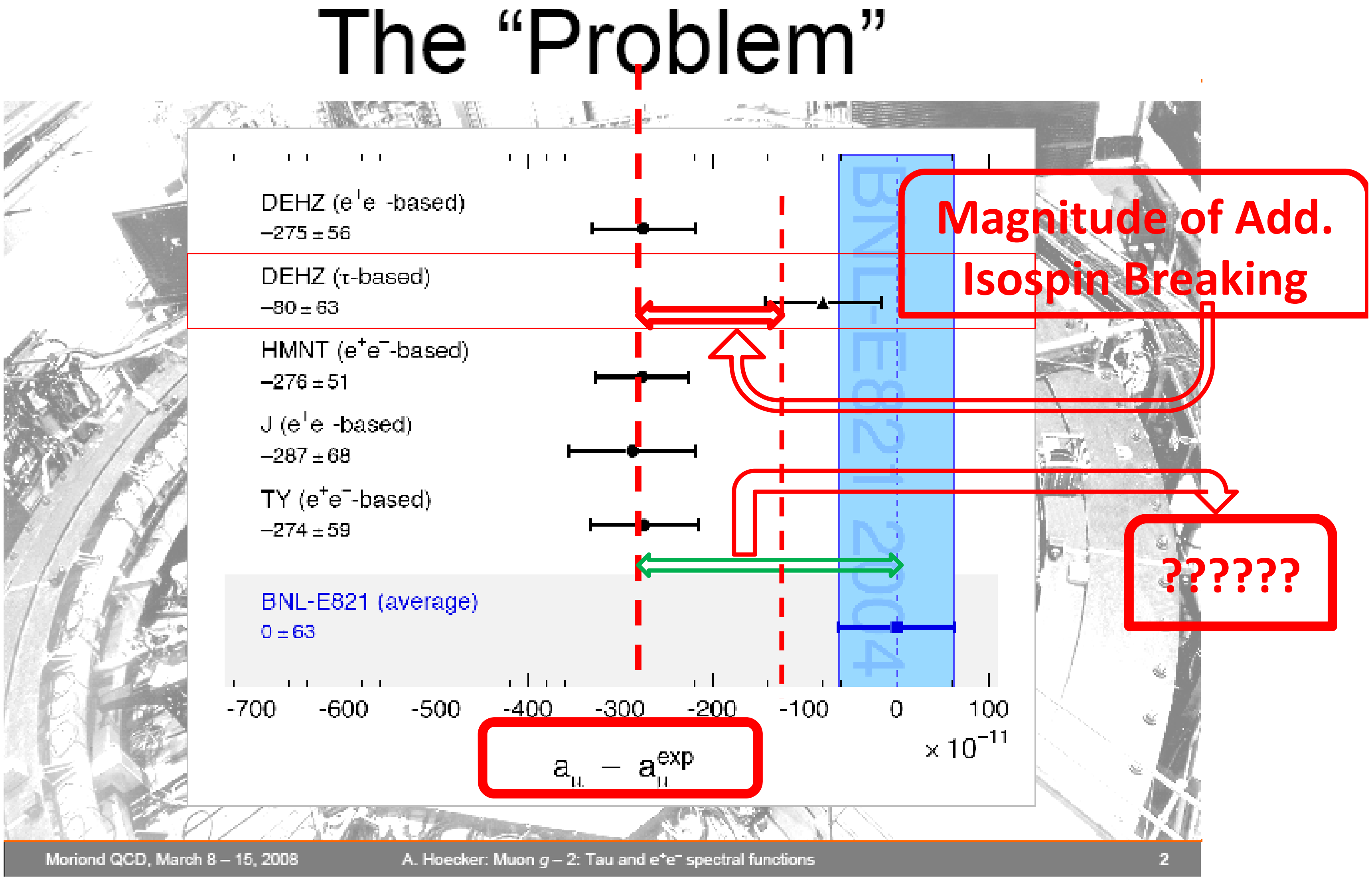
- **No mismatch between e^+e^- and τ data**
- Radiative decays & pion form factor in e^+e^- annihilation ⟹ **predict the observed pion form factor in τ decay**
- Previously unaccounted for effects : I=0 (ω_I, ϕ_I) components inside the ρ^0 meson.
- The 3.3 σ discrepancy between prediction (using e^+e^- data) and the BNL measurement for the muon anomalous moment is confirmed

A. Hoecker Moriond QCD 2008

The "Problem"



A. Hoecker Moriond QCD 2008



Fit Decay Modes Vs PDG

Decay Mode	FIT/PDG	Remark
$\rho^0 \to \pi^0\gamma$	0.86 ±0.15	
$\rho^\pm \to \pi^\pm\gamma$	1.12±0.11	
$\rho^0 \to \eta\gamma$	1.04±0.11	
$K^{*\pm} \to K^\pm\gamma$	1.00±0.14	
$K^{*0} \to K^0\gamma$	0.98±0.09	
$\omega \to \pi^0\gamma$	0.93±0.03	***
$\omega \to \eta\gamma$	1.35±0.11	***
$\phi \to \pi^0\gamma$	0.99±0.08	
$\phi \to \eta\gamma$	0.99±0.03	

Decay Mode	FIT/PDG	Remark
$\eta' \to \rho^0\gamma$	1.13±0.04	
$\eta' \to \omega\gamma$	1.04±0.11	
$\phi \to \eta'\gamma$	0.97±0.12	
$\eta \to \gamma\gamma$	0.90±0.02	!!! !
$\eta' \to \gamma\gamma$	0.99±0.07	
$\omega \to e^+e^-$	1.00±0.02	
$\phi \to e^+e^-$	1.00±0.02	
$\phi \to \pi^+\pi^-$	0.98±0.29	
Phase [$\phi \to \pi^+\pi^-$]	0.79±0.15	

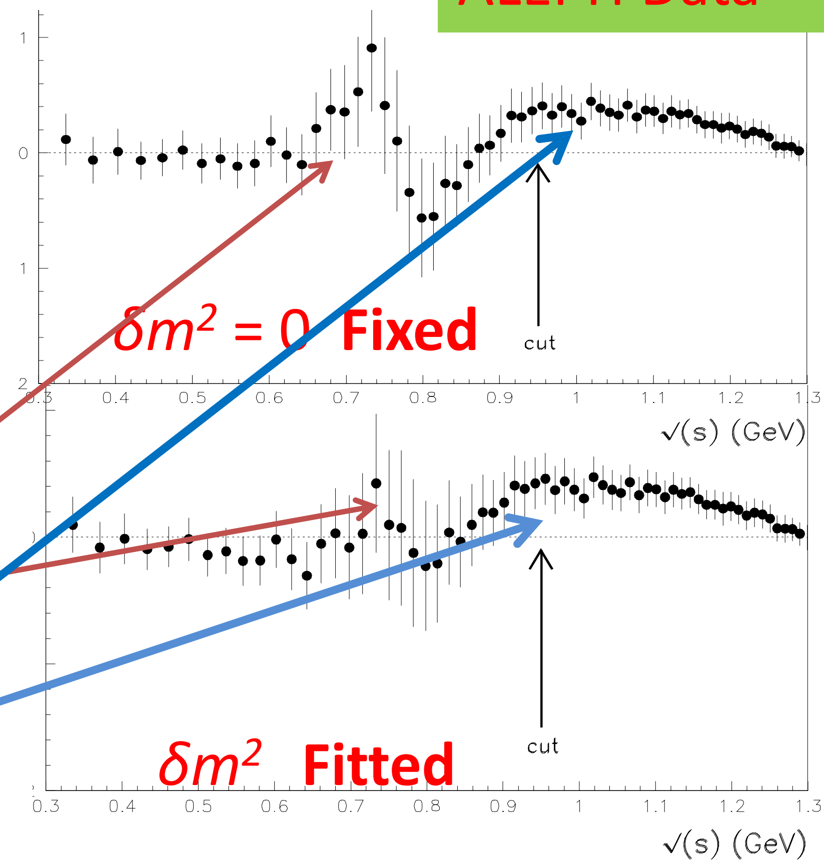
The ρ^0 - ρ$^\pm$ Mass Difference

$$M_{\rho^0} - M_{\rho^\pm} \simeq 1.35 \pm 0.15_{def.} \pm 0.53_{stat./syst.} MeV$$

ALEPH Data

The ρ^0-ρ$^\pm$ Mass Difference :
1/ Only visible in ALEPH data
2/ ~1 .2 σ from ChPT

J. Bijnens & P. Gosdzinsky PL B 388 (1996) 203



ρ Peak Region

High mass Vector mesons

Two New Results

Process	FIT	PDG
$\rho^0 \rightarrow e^+e^-$ [x10^5]	5.56±0.06	4.70±0.08
$\omega \rightarrow \pi^+\pi^-$ (%)	1.13±0.08	1.70±0.27
$\rho^0 \rightarrow \pi^+\pi^-$ [MeV]	144.5±0.6	149.4±1.0

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~ 15 σ apart starting from the same data!

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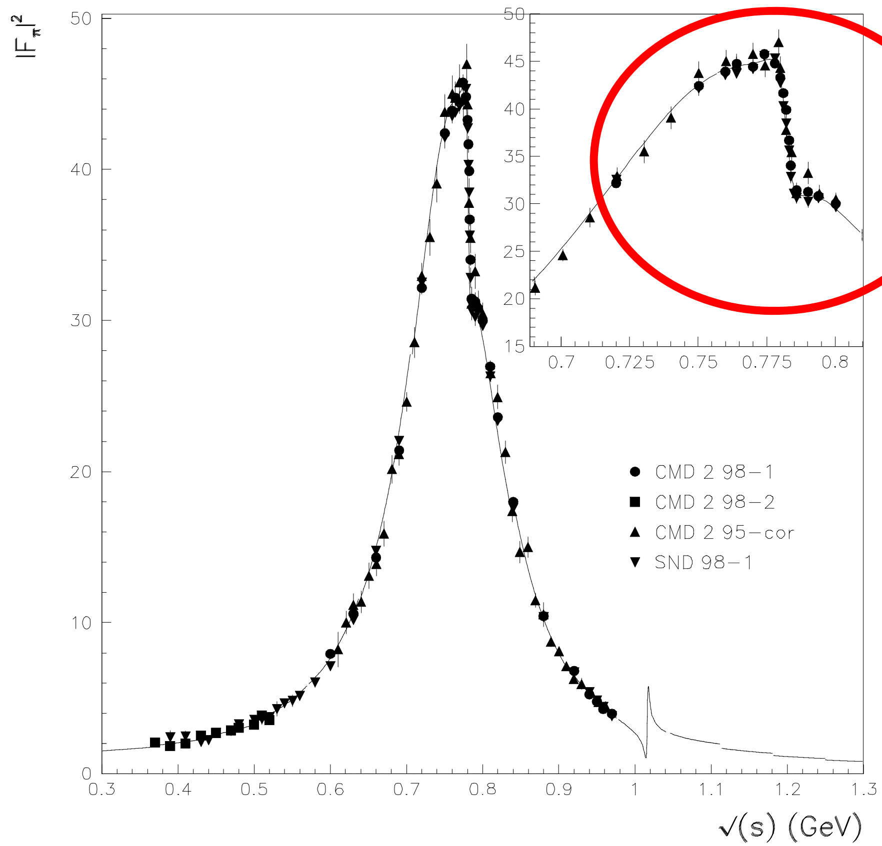
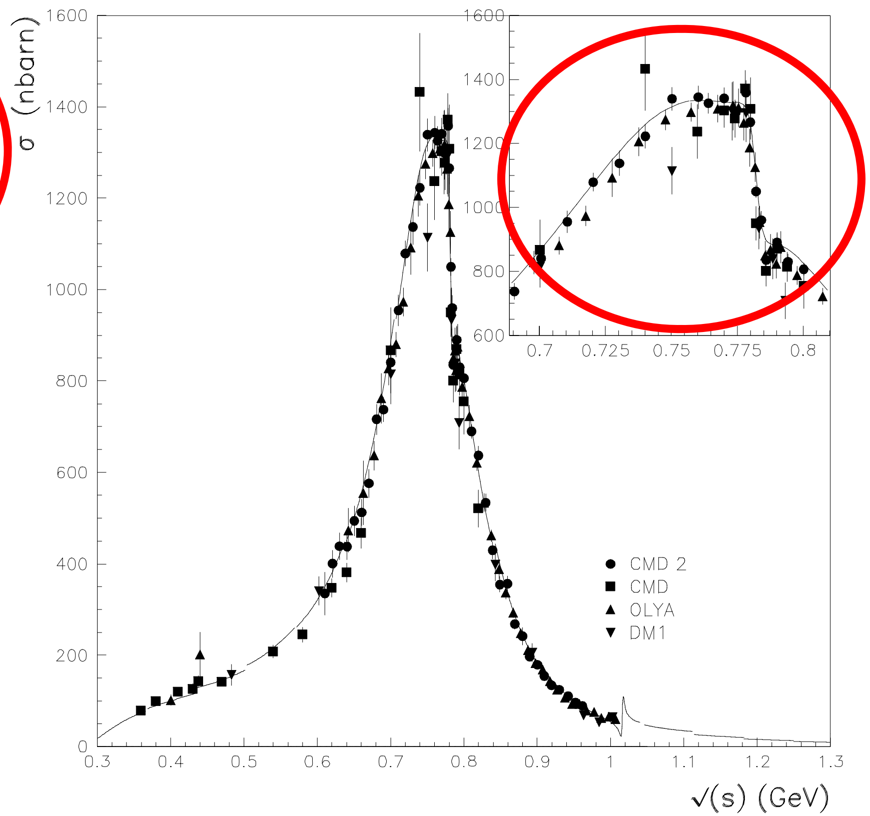
May change the global fit to ω branching ratios

Fit Of The ω Mass Region : Perfect

FF's New Data | Cross Sections Old Data

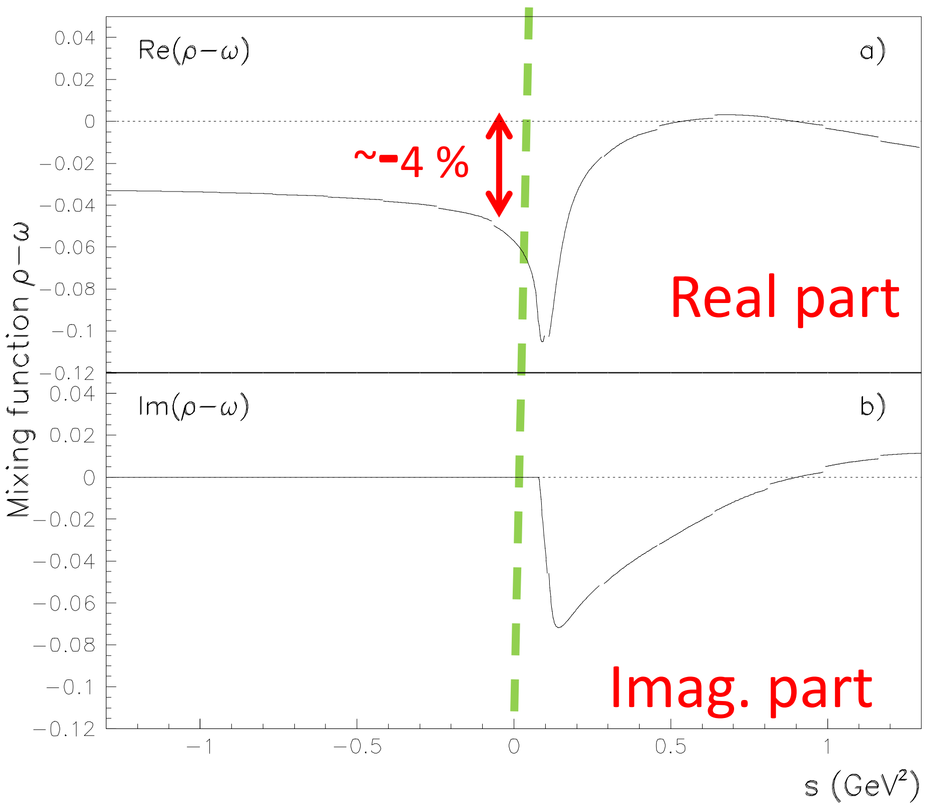




Additional Information

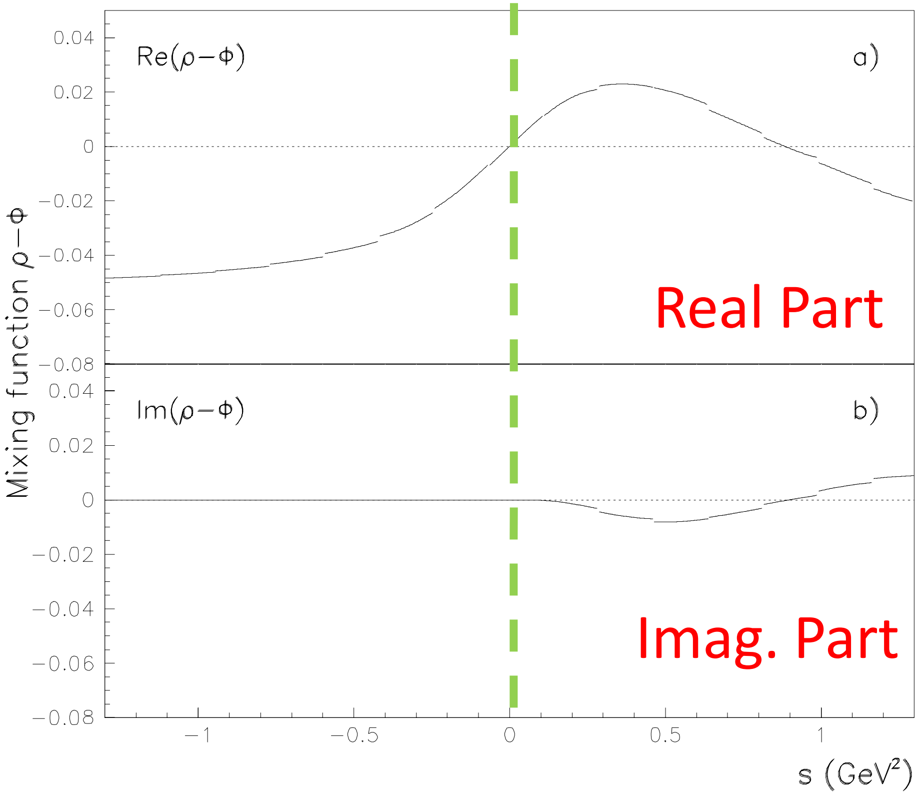
- THE MIXING « ANGLES »
- The (ρ,ω) and (ρ, ϕ) mixing «angles» are small (wrt 1) complex numbers
- The (ω, ϕ) mixing «angle» is real and small (wrt 1)

The (ρ, ω) Mixing «Angle»



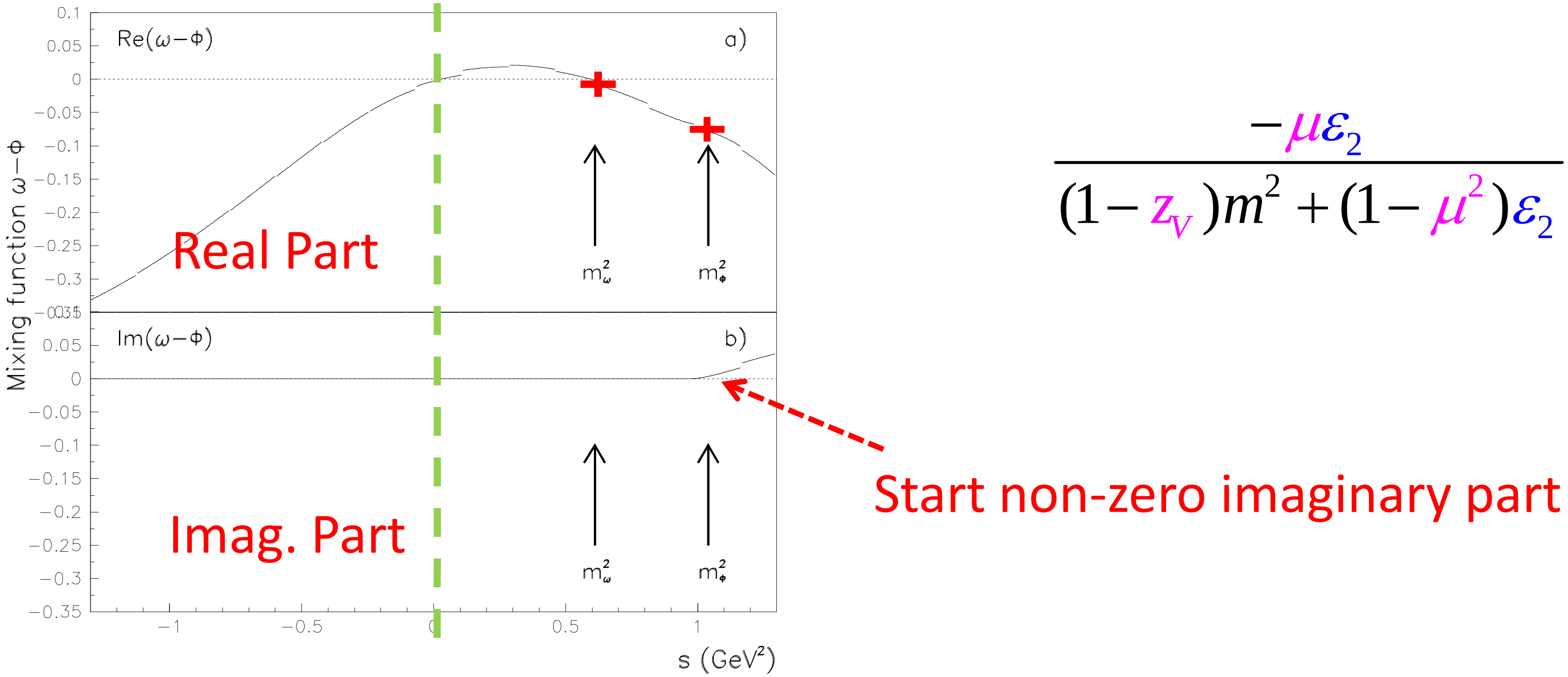
$$\frac{\varepsilon_1(s)}{\Pi_{\pi\pi}(s)-\varepsilon_2(s)}$$

The (ρ, ϕ) Mixing «Angle»



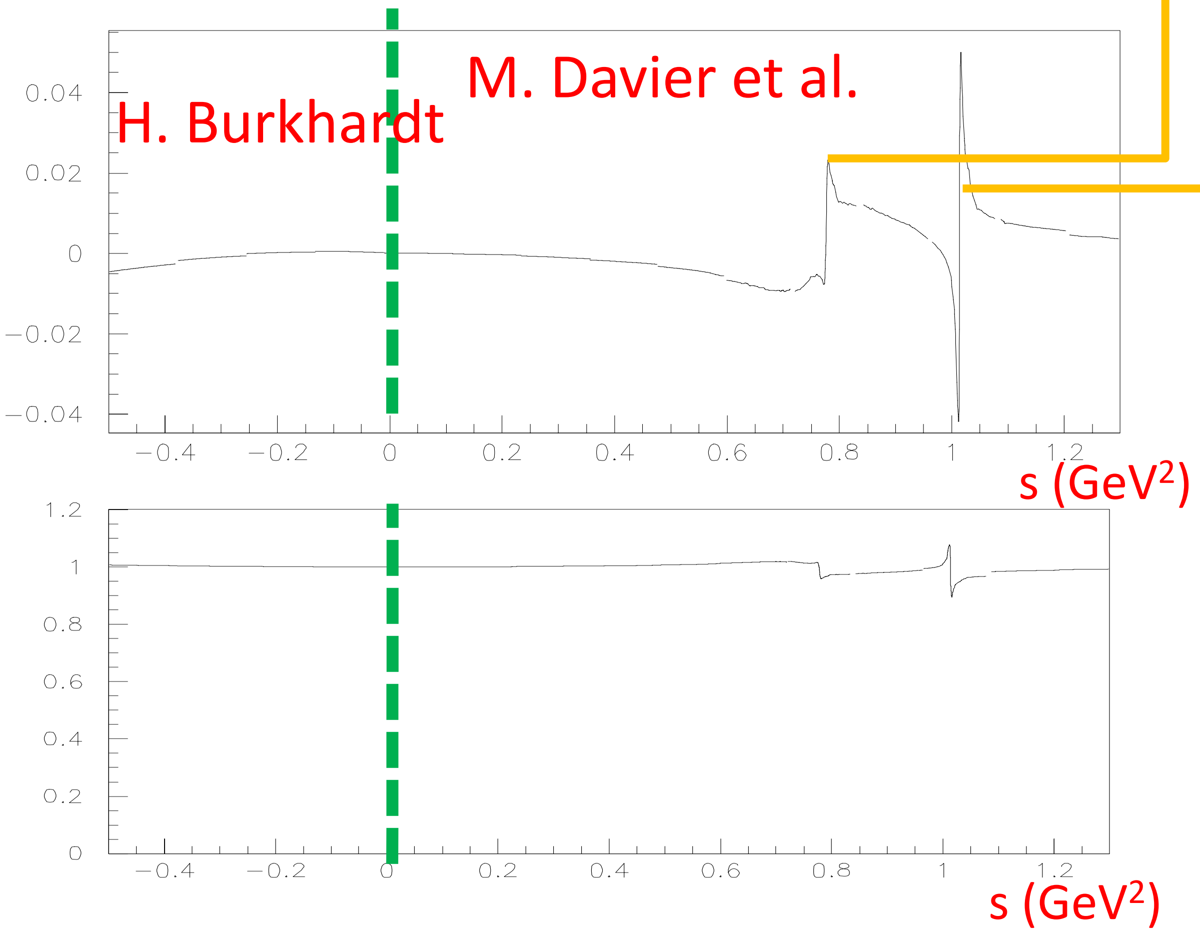
$$\frac{-\mu\varepsilon_1}{(1-z_V)m^2+\Pi_{\pi\pi}-\mu^2\varepsilon_2}$$

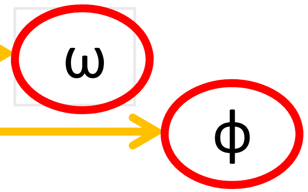
The (ω, ϕ) mixing «angle»



$$\frac{-\mu\varepsilon_2}{(1-z_V)m^2+(1-\mu^2)\varepsilon_2}$$

Hadronic Photon Vacuum Polarization

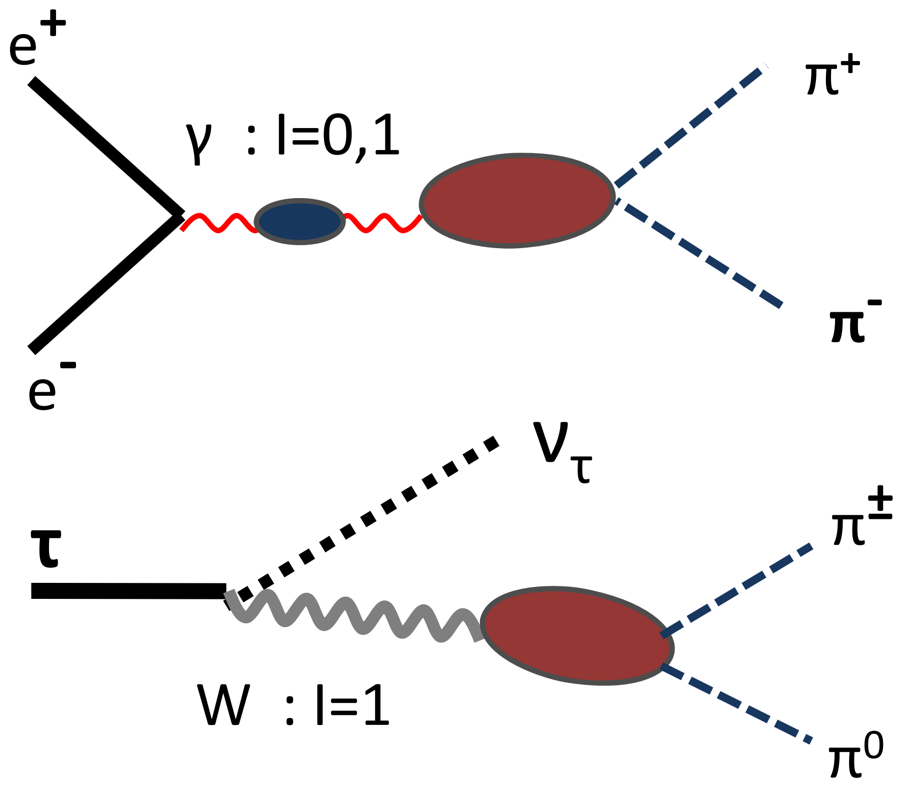




Photon Hadronic VP

Full Correction Factor
(Hadr. & Lept.)

The Pion Form Factor



The Hidden Local Symmetry Model

- Vector Mesons ≡ gauge bosons of a HL symmetry
-

M.Bando, T. Kugo & K. Yamawaki Phys. Rep. 164 (1988) 217
M. Harada & K. Yamawaki Phys. Rep. 381 (2003) 1

- Define $\xi_{L/R} = e^{[\mp i P / f_\pi]}$
- Define covariant derivatives $D_\mu \xi_L \, , \, D_\mu \xi_R$
- Then $L / R = D_\mu \xi_{L/R} \xi^\dagger_{L/R}$ and $\mathcal{L}_{A/V} = -\frac{f_\pi^2}{4} Tr\left[L \mp R\right]^2$
- The HLS Lagrangian $\mathcal{L}_{HLS} = \mathcal{L}_A + a\, \mathcal{L}_V$

Expanded form: M.Benayoun & H.O'Connell PR D 58 (1998) 074006

- VMD : a=2 , Phenomenology a ~ 2.4

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- The HLS Lagrangian $\boxed{L_{HLS} = L_A + a\, L_V}$

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- $\boxed{\text{VMD : a=2 , Phenomenology a ~ 2.4}}$

The Covariant Derivatives

- Covariant derivatives ≠ for left- right-ξ fields :

$$D_\mu \xi_{L/R} = \partial_\mu \xi_{L/R} - igV_\mu \xi_{L/R} + i\xi_{L/R} G_{L/R}$$

- With :

$$G_R = eQA_\mu \quad , \quad G_L = eQA_\mu + \frac{g_2}{\sqrt{2}}\left(W_\mu^+ T_+ + W_\mu^- T_-\right)$$

$T_\pm$ is CKM matrix reduced to V_{us} and V_{ud} terms

Breaking of SU(3) Flavor Symmetry

Several possible schemes

$$L_{A/V} = -\frac{f_\pi^2}{4} Tr\left[L \mp R\right]^2 \Rightarrow$$

Benayoun & O'Connell op. cit.

$$L_{A/V} = -\frac{f_\pi^2}{4} Tr\left[(L \mp R) X_{A/V}\right]^2$$

With Breaking matrices $X_{A/V} = Diag(1, 1, z_{A/V})$

z_V related to vector meson masses, $z_A = \left[\frac{f_K}{f_\pi}\right]^2$

Bando Kugo Yamawaki op. cit.

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z_V related to vector meson masses, $z_A = \left[\frac{f_K}{f_\pi}\right]^2 \approx 1.5$

Bando Kugo Yamawaki op. cit.

Nonet Symmetry Breaking in HLS Model

Nonet Symmetry Breaking accounted for by adding determinant terms to HLS Lagrangian

M. Benayoun L. DelBuono H. O'Connell EPJ C 17 (2000) 593

Effective way : $\boxed{P_8^{'} + xP_0^{'} = X_A^{1/2}\left(P_8 + P_0\right)X_A^{1/2}}$

P.J. O'Donnell RMP 53 (1981) 673

Radiative decays of light mesons vs glue :

$\boxed{\textit{no glue} \Rightarrow x \sim 0.9 \quad \text{but} \quad x = 1 \Rightarrow \textit{glue in } (\eta, \eta')}$

M. Benayoun et al. PR D 59 (1999) 114027

Anomalous Sector of the HLS Model

- HLS Model has an anomalous sector for VPγ and Pγγ couplings ; can be derived from :

$$L = C\varepsilon^{\mu\nu\rho\sigma} Tr\left[X_T \partial_\mu \left(eQA_\nu + gV_\nu \right) X_T^{-2} \partial_\rho \left(eQA_\sigma + gV_\sigma \right) X_T P \right]$$

M. Benayoun et al. PR D 59 (1999) 114027

A. Bramon, A. Grau & G. Pancheri PL B 345 (1995) 263

- X_T allows for correct account of K* rad. decays

  [C = - 3 /(4 π² f_π)] G. Morpurgo PR D 42 (1990) 1497

- (η, η') mixing angle related with (x, z_A) vanishes when no SU(3) breaking

MB, LD & HO EPJ C 17 (2000) 593