Status of PHOKHARA

and its theoretical accuracy

H. CZYŻ, IF, UŚ, Katowice, **PHIPSI08**

in collaboration with

J. H. KÜHN, and A. WAPIENIK

The radiative return

4π revisited

- experimental situation: τ vs. e^+e^- data
- improved model
- model predictions

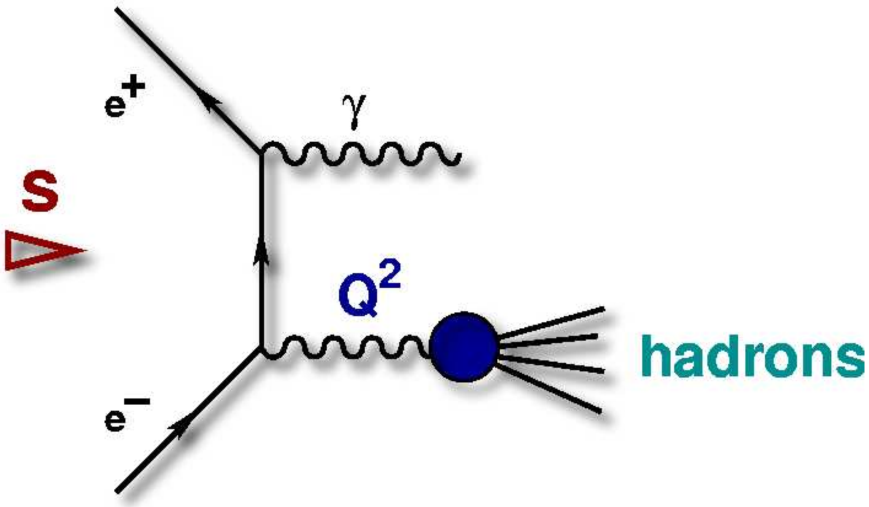
Theoretical accuracy

Plans

THE RADIATIVE RETURN METHOD

$$d\sigma(e^+e^- \to \text{hadrons} + \gamma(ISR)) =$$

$$H(Q^2, \theta_\gamma)\ d\sigma(e^+e^- \to \text{hadrons})(s = Q^2)$$



- measurement of $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$
- large luminosities of factories compensate α/π from photon radiation
- radiative corrections essential (NLO,...)

High precision measurement of the hadronic cross-section at meson-factories

From EVA to PHOKHARA

EVA: $e^+e^- \to \pi^+\pi^-\gamma$

- tagged photon ($\theta_\gamma > \theta_{cut}$)
- ISR at LO + Structure Function
- FSR: point-like pions

[Binner et al.]

$e^+e^- \to 4\pi + \gamma$

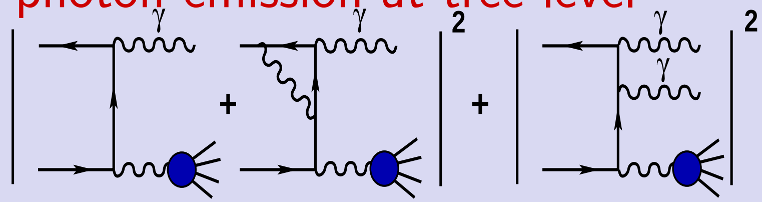
- ISR at LO + Structure Function

[Czyż, Kühn,2000]

H.C., A. Grzelińska, J. H. Kühn, E. Nowak-Kubat, G. Rodrigo, A. Wapienik

PHOKHARA 6.0: $\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda(\to\cdots)\bar{\Lambda}(\to\cdots)$

- **ISR at NLO:** virtual corrections to one photon events and two photon emission at tree level



- FSR at NLO: $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-
- tagged or untagged photons
- Modular structure

http://ific.uv.es/~rodrigo/phokhara/

Isospin relations: 4π

$$\langle \pi^+\pi^-\pi^0_1\pi^0_2|J^3_\mu|0\rangle = J_\mu(p_1,p_2,p^+,p^-)$$

$$\langle \pi^+_1\pi^+_2\pi^-_1\pi^-_2|J^3_\mu|0\rangle =$$
$$J_\mu(p^+_2,p^-_2,p^+_1,p^-_1) \quad +J_\mu(p^+_1,p^-_2,p^+_2,p^-_1)$$
$$+J_\mu(p^+_2,p^-_1,p^+_1,p^-_2) \quad +J_\mu(p^+_1,p^-_1,p^+_2,p^-_2)$$

$$\langle \pi^-\pi^0_1\pi^0_2\pi^0_3|J^-_\mu|0\rangle =$$
$$J_\mu(p_2,p_3,p^-,p_1) + J_\mu(p_1,p_3,p^-,p_2) + J_\mu(p_1,p_2,p^-,p_3)$$

$$\langle \pi^-_1\pi^-_2\pi^+\pi^0|J^-_\mu|0\rangle =$$
$$J_\mu(p^+,p_2,p_1,p^0) \quad +J_\mu(p^+,p_1,p_2,p^0)$$

J. H. Kühn (1999)

Isospin relations: 4π

$$\int J_\mu^{em}(J_\nu^{em})^* \; d\bar{\Phi}_n(Q;q_1,\dots,q_n)$$
$$= \frac{1}{6\pi}\left(Q_\mu Q_\nu - g_{\mu\nu}Q^2\right) \; R(Q^2)$$

$$R(Q^2) = \sigma(e^+e^- \to hadrons)(Q^2)/\sigma_{point}$$

Isospin relations: 4π

$$\frac{d\Gamma_{\tau\to\nu+hadrons}}{dQ^2}$$

$$= 2\ \Gamma_e \frac{|V_{ud}|^2 S_{EW}}{m_\tau^2}\left(1-\frac{Q^2}{m_\tau^2}\right)^2\left(1+2\frac{Q^2}{m_\tau^2}\right) R^\tau\left(Q^2\right)$$

$$\int J_\mu^- J_\nu^{-*}\ d\bar{\Phi}_n(Q;q_1,\ldots,q_n) =$$

$$\frac{1}{3\pi}\left(Q_\mu Q_\nu - g_{\mu\nu}Q^2\right)\ R^\tau(Q^2)$$

Isospin relations: 4π

$$R^\tau(-\ 0\ 0\ 0) = \frac{1}{2} R(+\ +\ -\ -)$$

$$R^\tau(-\ -\ +\ 0) = \frac{1}{2} R(+\ +\ -\ -) + R(+\ -\ 0\ 0)$$

Isospin relations: 4π; exp. situation

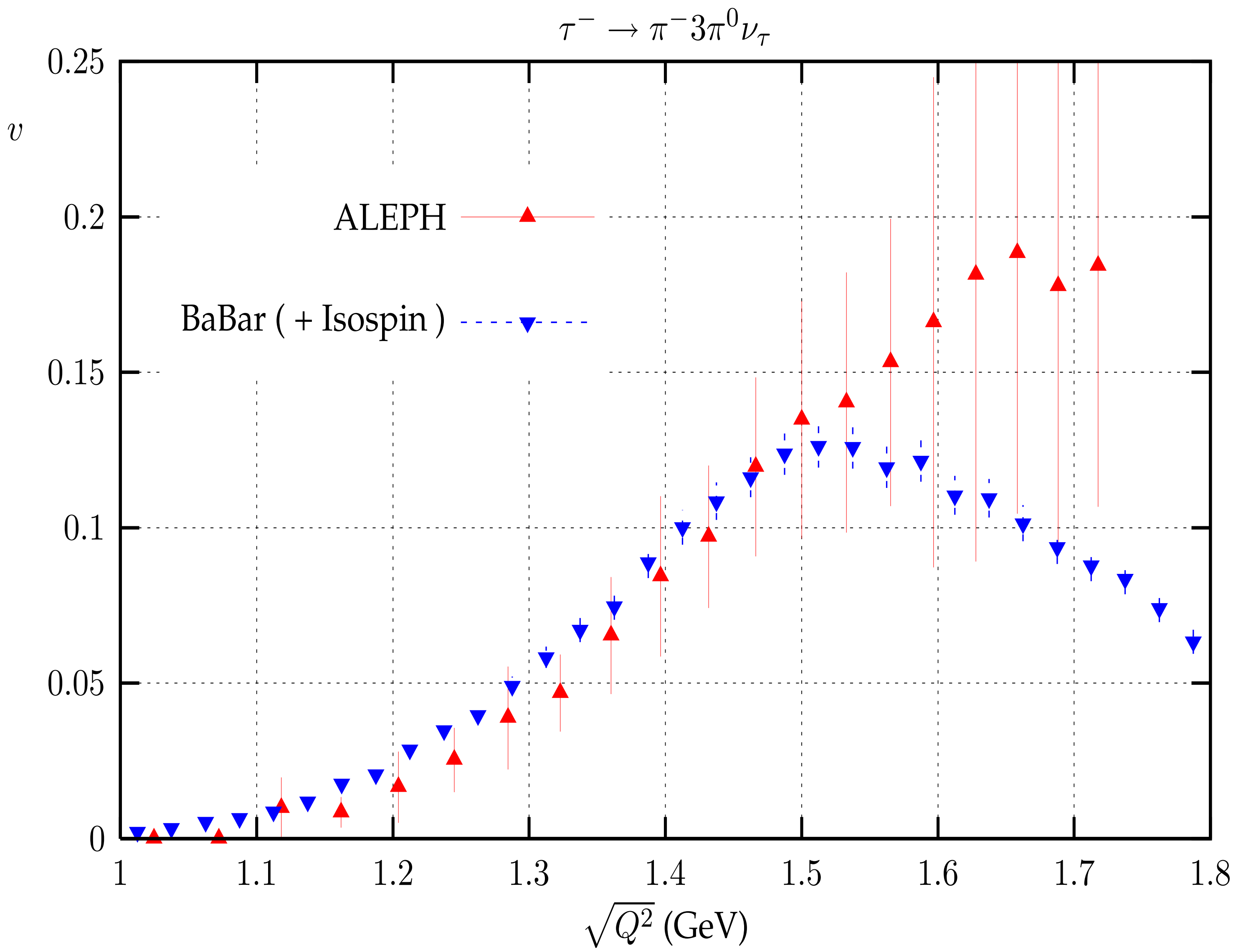
$e^+e^- \rightarrow 2\pi^+2\pi^-$: BaBar, CMD2, SND

$e^+e^- \rightarrow 2\pi^0\pi^+\pi^-$: BaBar(preliminary), CMD2, SND

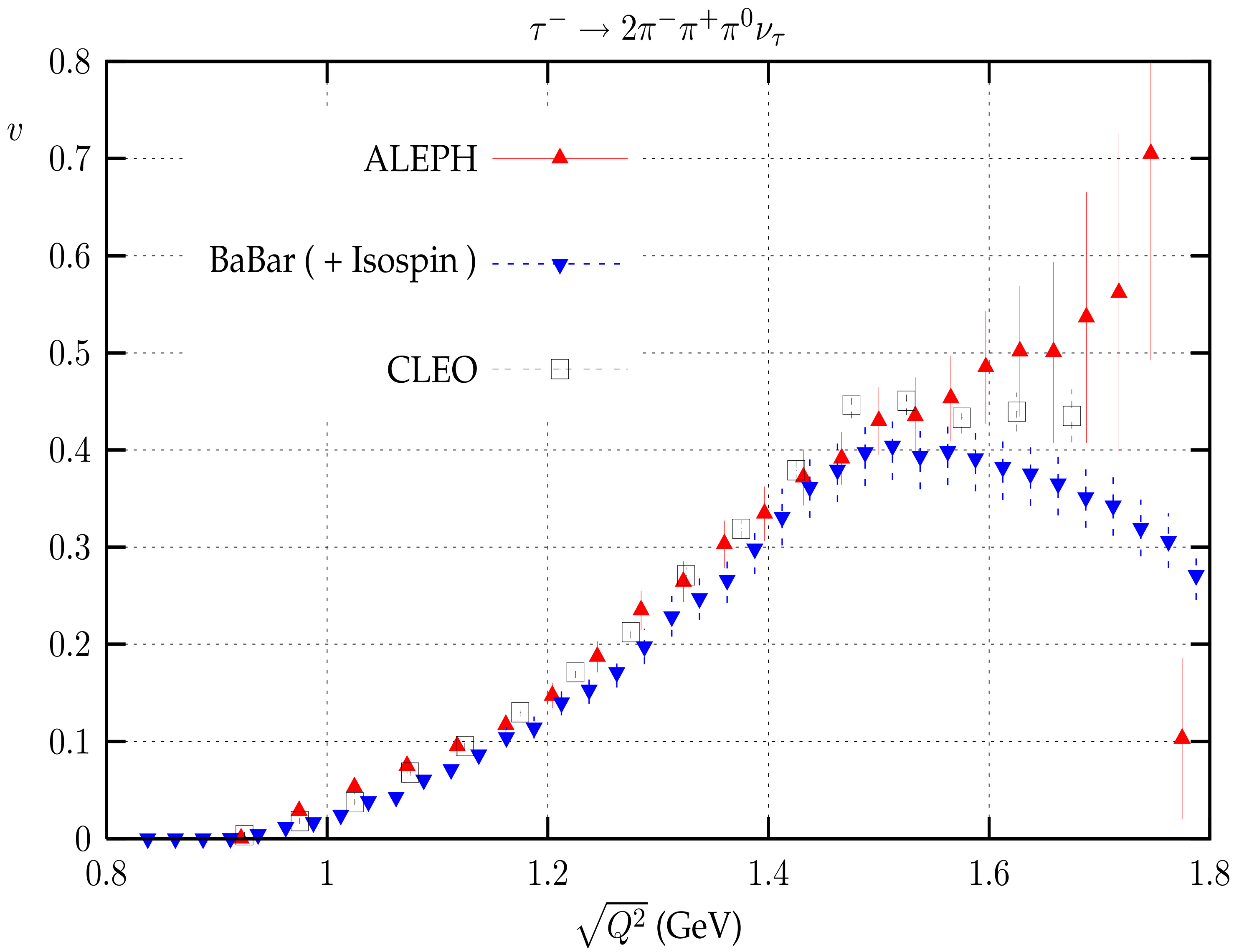
$\tau^- \rightarrow \nu 3\pi^0\pi^-$: ALEPH

$\tau^- \rightarrow \nu 2\pi^-\pi^+\pi^0$: ALEPH, CLEO

Isospin relations: 4π; exp. situation



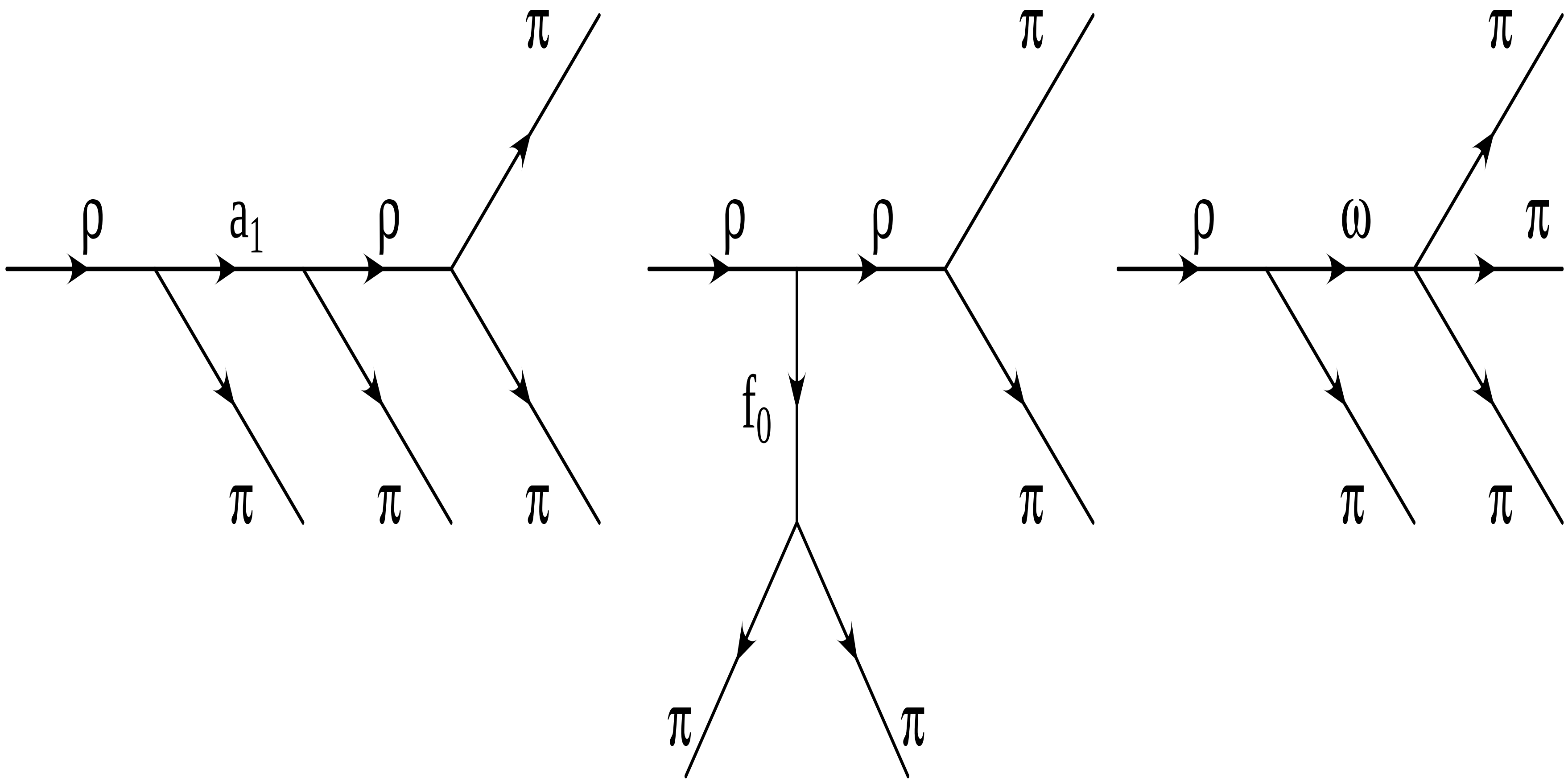
Isospin relations: 4π; exp. situation



4π: exp. situation

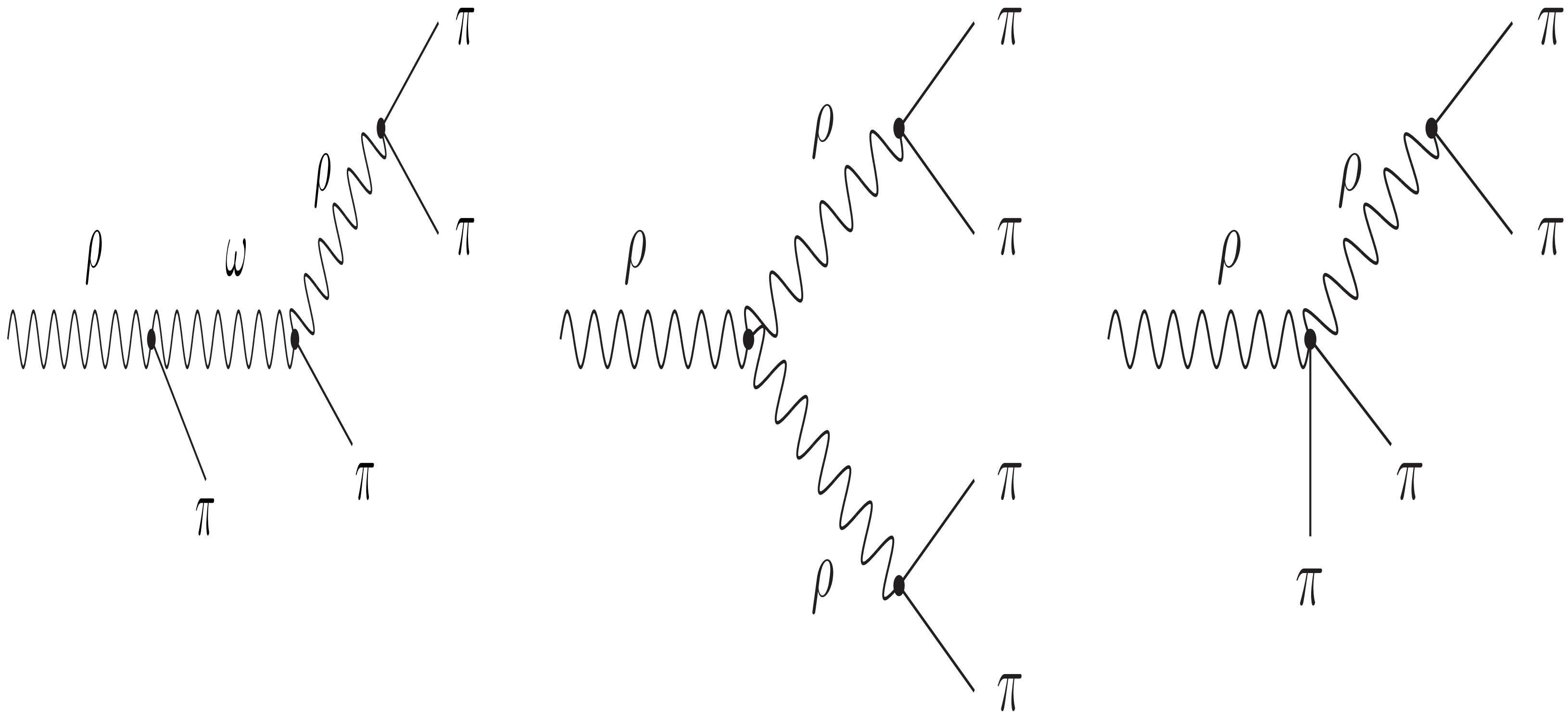
- $\pi\omega(\rightarrow \pi^+\pi^-\pi^0)$: CLEO, BaBar(prel.)
- $\rho \rightarrow \rho(\rightarrow \pi\pi)\rho(\rightarrow \pi\pi)$: BaBar(prel.)

The model



H.C., J.H. Kühn (2000)

The model



H.C., J.H. Kühn, A. Wapienik (2008)

H.C., A. Grzelińska, J.H. Kühn, G. Rodrigo(2006)

The model

$$\mathcal{L}_\rho = \frac{1}{4}\vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu} + \frac{1}{2}(\overrightarrow{D^\mu\phi}) \cdot (\overrightarrow{D_\mu\phi})$$

$$+ \frac{1}{2}m_\pi^2\vec{\phi} \cdot \vec{\phi} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu \cdot \vec{\rho}^\mu$$

$$\overrightarrow{D_\mu\phi} = \partial_\mu\vec{\phi} + g\left(\vec{\rho}_\mu \times \vec{\phi}\right)$$

$$\vec{F}_{\mu\nu} = \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu - g\vec{\rho}_\mu \times \vec{\rho}_\nu$$

The fit

$m_{\rho'}, m_{\rho''}, m_{\rho'''}, \Gamma_{\rho'}, \Gamma_{\rho''}, \Gamma_{\rho'''}$

4 couplings in a_1- part

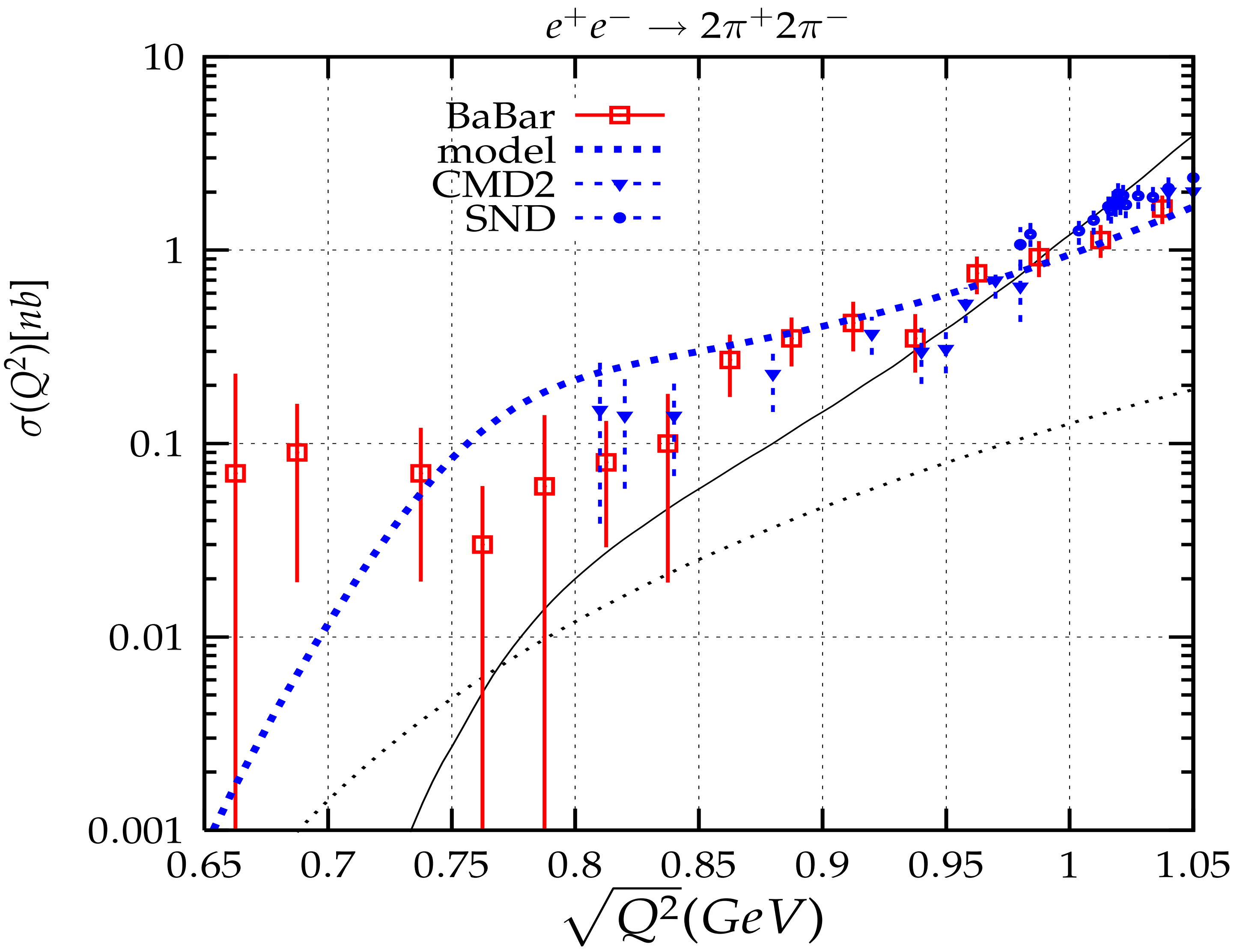
4 couplings in f_0- part

4 couplings in ω- part

1 coupling in ρ- part

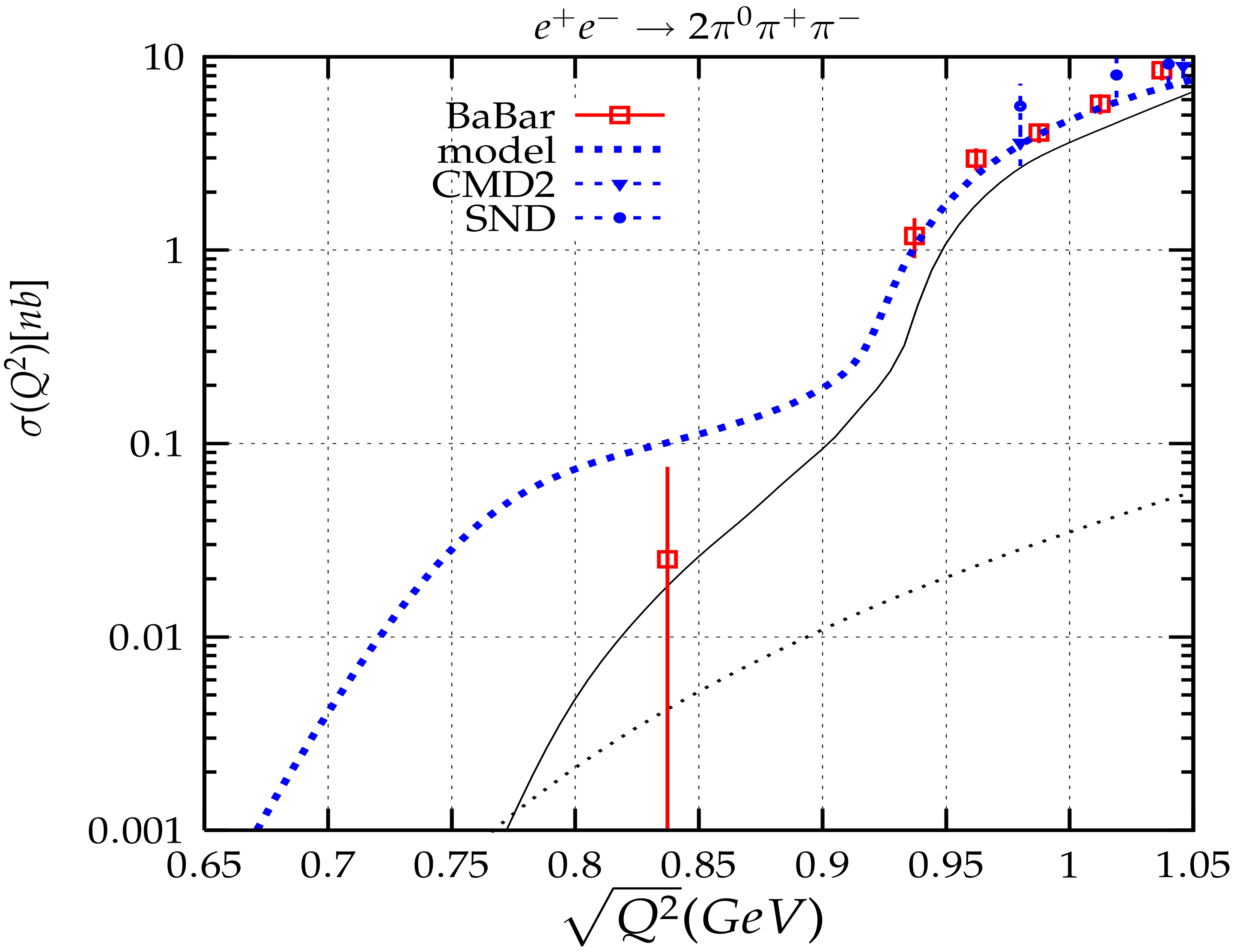
$\chi^2 = 275$, $\quad n_{d.o.f} = 287$

The model at low Q^2



compared with: G. Ecker and R. Unterdorfer (2002)

The model at low Q^2



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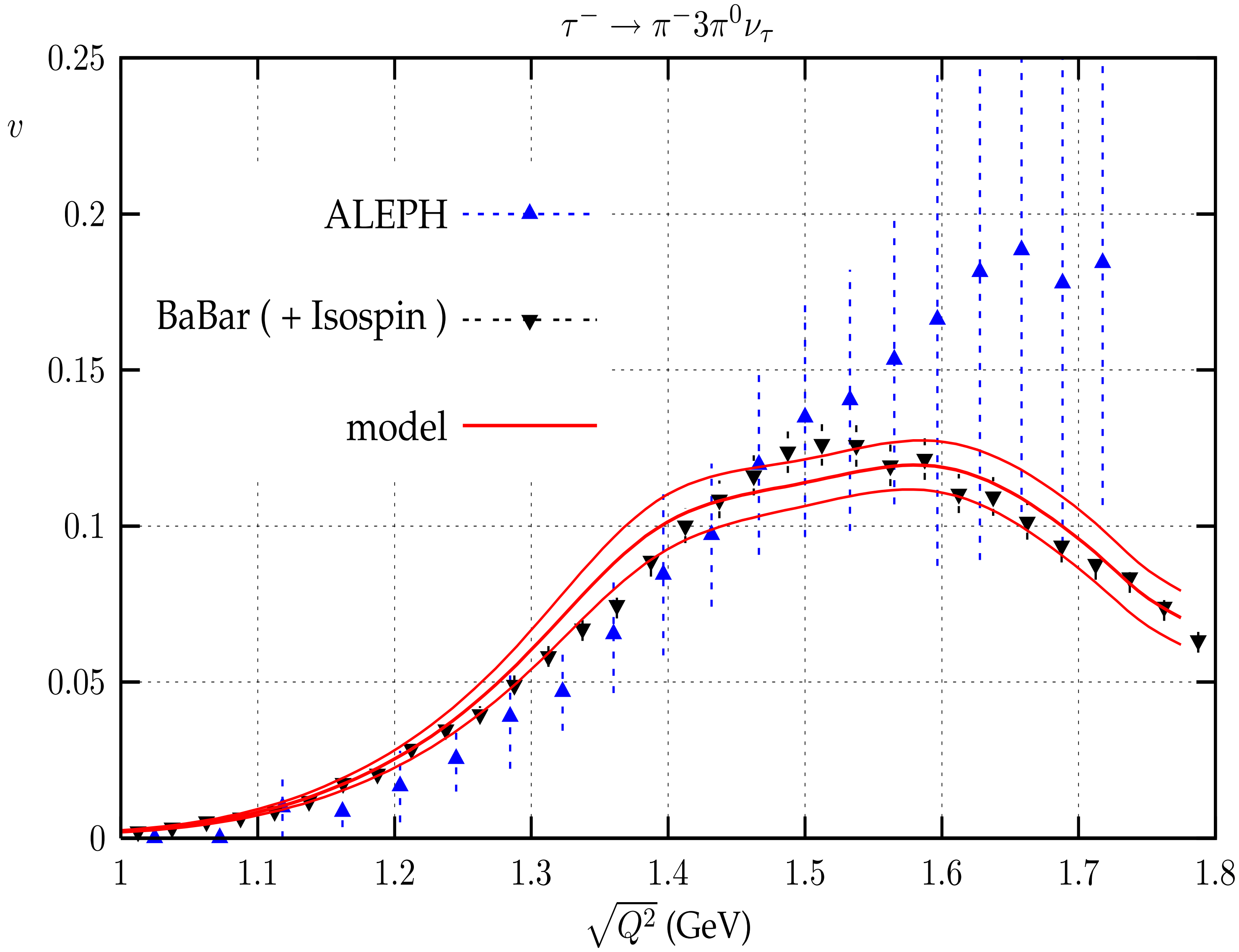
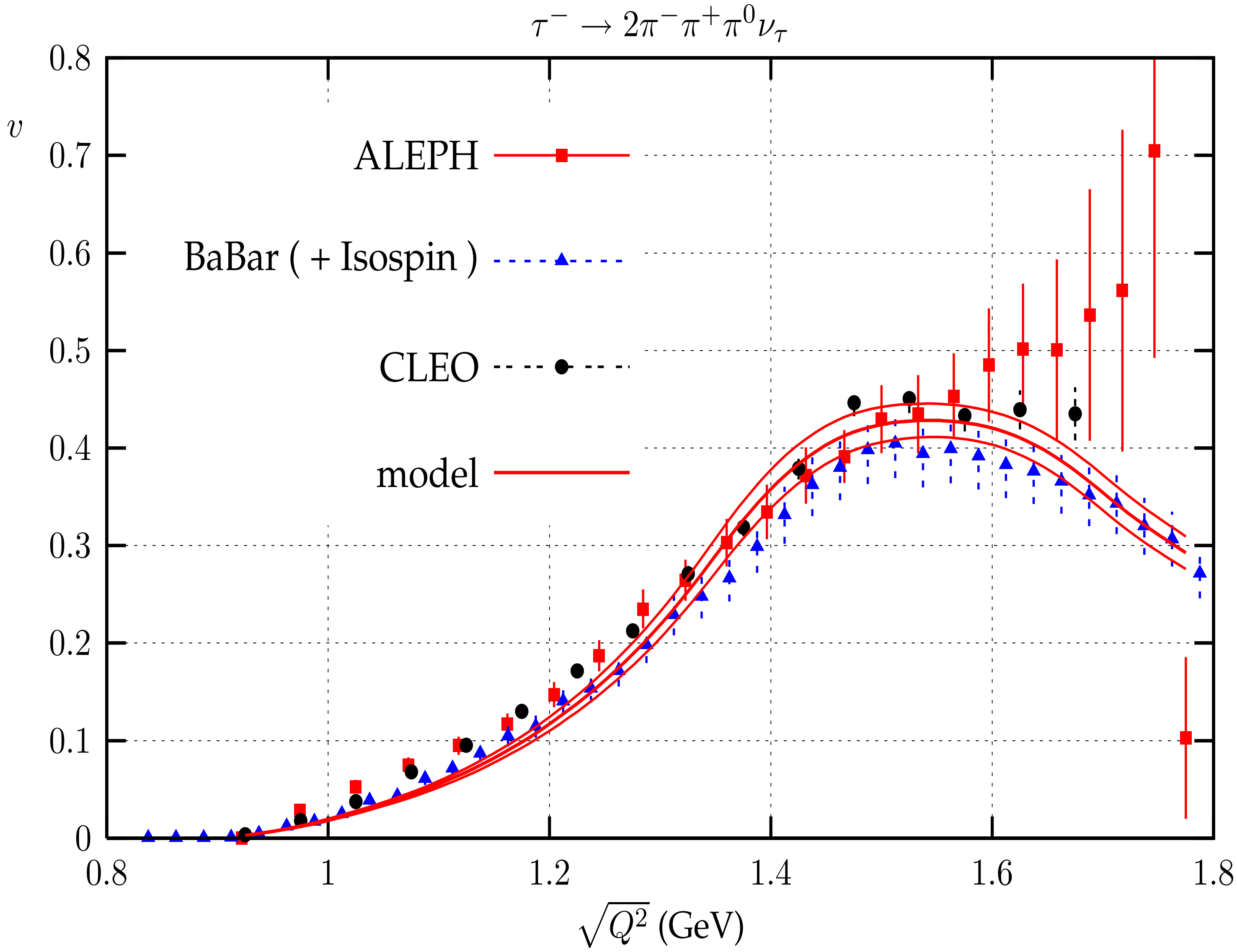
Comparing with τ data



Comparing with τ data



Comparing with τ data

	$\mathrm{Br}(\tau- \to \nu_\tau 2\pi^-\pi^+\pi^0)$
PDG06	$(4.46 \pm 0.06)\%$
model	$(4.12 \pm 0.21)\%$
BaBar (CVC)	$(3.98 \pm 0.30)\%$

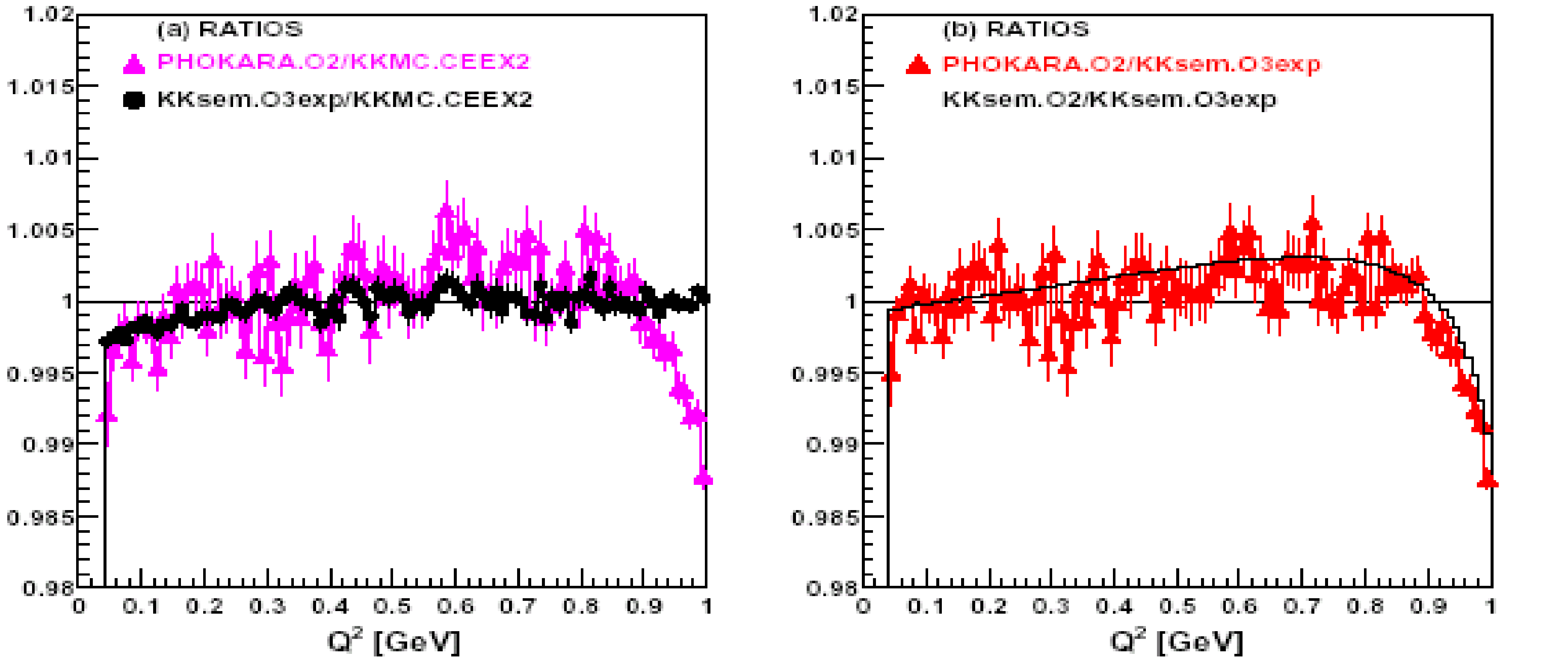
	$\mathrm{Br}(\tau- \to \nu_\tau \pi^-\omega(\pi^-\pi^+\pi^0))$
PDG06	$(1.77 \pm 0.1)\%$
model	$(1.60 \pm 0.13)\%$
BaBar (CVC)	$(1.57 \pm 0.31)\%$

Comparing with τ data

	$\mathrm{Br}(\tau- \to \nu_\tau \pi^- 3\pi^0)$
PDG06	$(1.04 \pm 0.08)\%$
model	$(1.06 \pm 0.09)\%$
BaBar (CVC)	$(1.02 \pm 0.05)\%$

S.Jadach: KKMC

PHOKHARA included in the game, μ-pairs again



PHOKHARA agrees to within 0.3% with KKMC and KKsem.

Discrepancy at high Q^2 reflects lack of exponentiation in PHOKHARA

FSR

- **carefull study of FSR necessary**
  - **tools for these studies were proposed**
  - **and are used**

Summary and plans

- **4π channels reanalysis was performed**
  - **isospin symmetry violation not seen**
  - **new model proposed and implemented in PHOKHARA**

Summary and plans

- **PHOKHARA: ISR accuracy 0.5%**
  - **need for ISR accuracy ∼0.2%**

- **soon J/ψ and $\psi(2S)$ in PHOKHARA**
  - **with FSR corrections included**