Status of PHOKHARA

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in collaboration with

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The radiative return

4π revisited

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

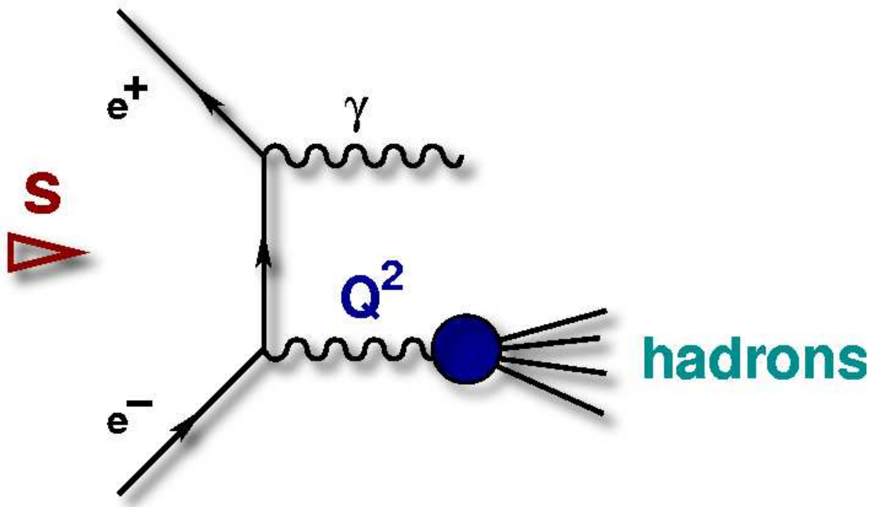
Narrow Resonances J/ψ and $\psi(2S)$

Conclusions

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.]

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

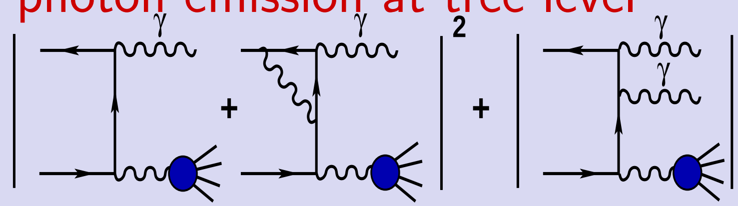
- ISR at LO + Structure Function

[Czyż, Kühn,2000]

Henryk Czyż, A.G.,
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/

4π channels

There are altogether four different channels accessible in e^+e^- annihilation and τ decays into four pions

$$e^+e^- \to 2\pi^+2\pi^-$$

$$e^+e^- \to 2\pi^0\pi^+\pi^-$$

$$\tau^- \to \nu 2\pi^-\pi^+\pi^0$$

$$\tau^- \to \nu 3\pi^0\pi^-$$

sufficient to determine all four amplitudes

Isospin relations: 4π

$$\langle \pi^+\pi^-\pi_1^0\pi_2^0|J_\mu^3|0\rangle = J_\mu(p_1,p_2,p^+,p^-)$$

$$\langle \pi_1^+\pi_2^+\pi_1^-\pi_2^-|J_\mu^3|0\rangle =$$
$$J_\mu(p_2^+,p_2^-,p_1^+,p_1^-) \quad +J_\mu(p_1^+,p_2^-,p_2^+,p_1^-)$$
$$+J_\mu(p_2^+,p_1^-,p_1^+,p_2^-) \quad +J_\mu(p_1^+,p_1^-,p_2^+,p_2^-)$$

$$\langle \pi^-\pi_1^0\pi_2^0\pi_3^0|J_\mu^-|0\rangle =$$
$$J_\mu(p_2,p_3,p^-,p_1) + J_\mu(p_1,p_3,p^-,p_2) + J_\mu(p_1,p_2,p^-,p_3)$$

$$\langle \pi_1^-\pi_2^-\pi^+\pi^0|J_\mu^-|0\rangle =$$
$$J_\mu(p^+,p_2,p_1,p^0) \quad +J_\mu(p^+,p_1,p_2,p^0)$$

J. H. Kühn (1999)

Isospin relations: 4π

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

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

$$\int J_\mu^- J_\nu^{-*} d\bar{\Phi}_n(Q; q_1, \ldots, q_n) = \frac{(Q_\mu Q_\nu - g_{\mu\nu} Q^2)}{3\pi} R^\tau(Q^2)$$

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

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

Isospin relations: 4π

The relations between τ decay rates and e^+e^- annihilation cross sections are:

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

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

Isospin relations: 4π; exp. situation

from the experimental side e^+e^- cross section has been measured by:

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

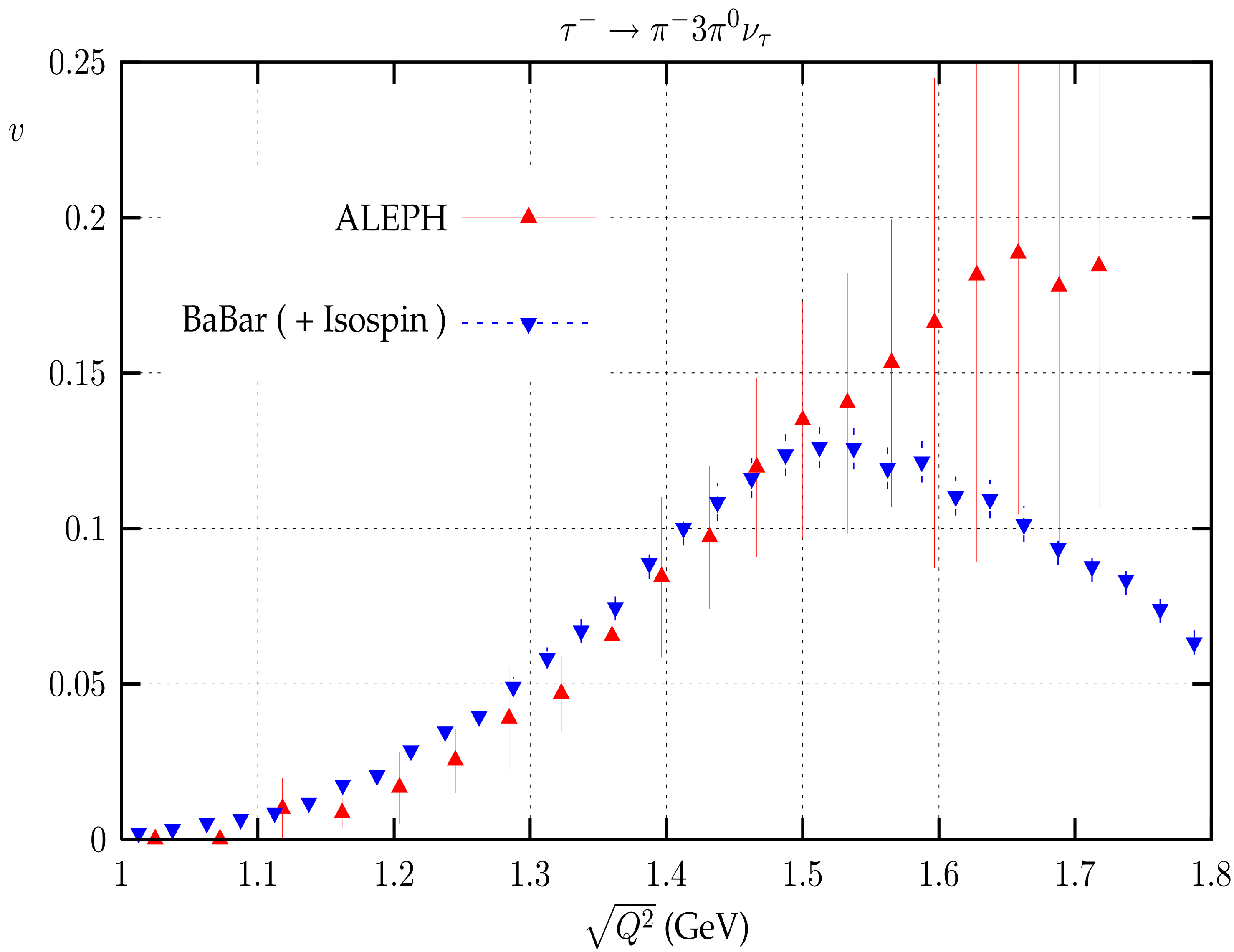
$e^+e^- \to 2\pi^0\pi^+\pi^-$: BaBar(preliminary), CMD2, SND

the τ data are from:

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

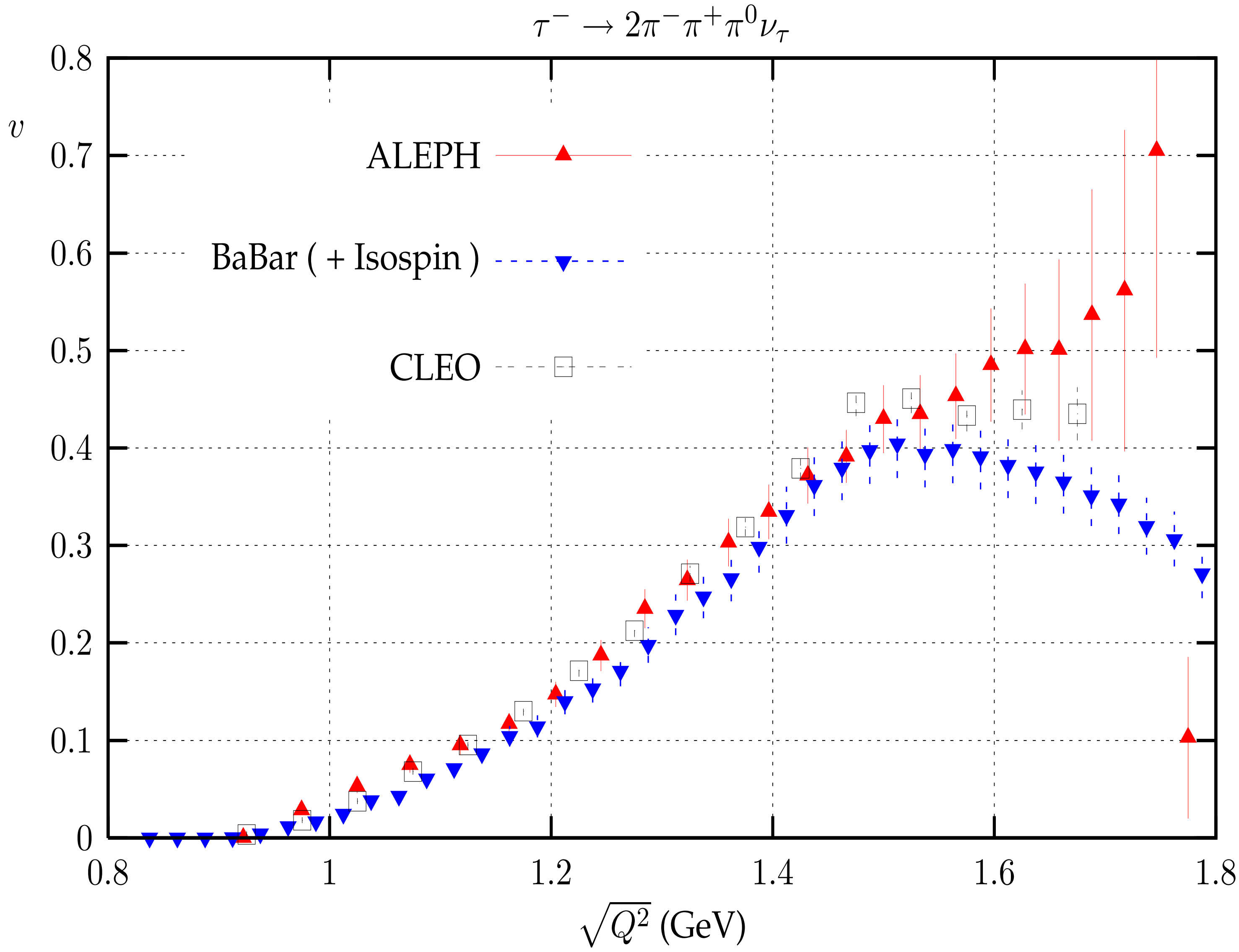
$\tau^- \to \nu 2\pi^-\pi^+\pi^0$: ALEPH, CLEO

Isospin relations: 4π; exp. situation



v - the τ spectral function (normalization chosen by ALEPH)

Isospin relations: 4π; exp. situation



we included effects from the pion mass difference in the phase space

The model

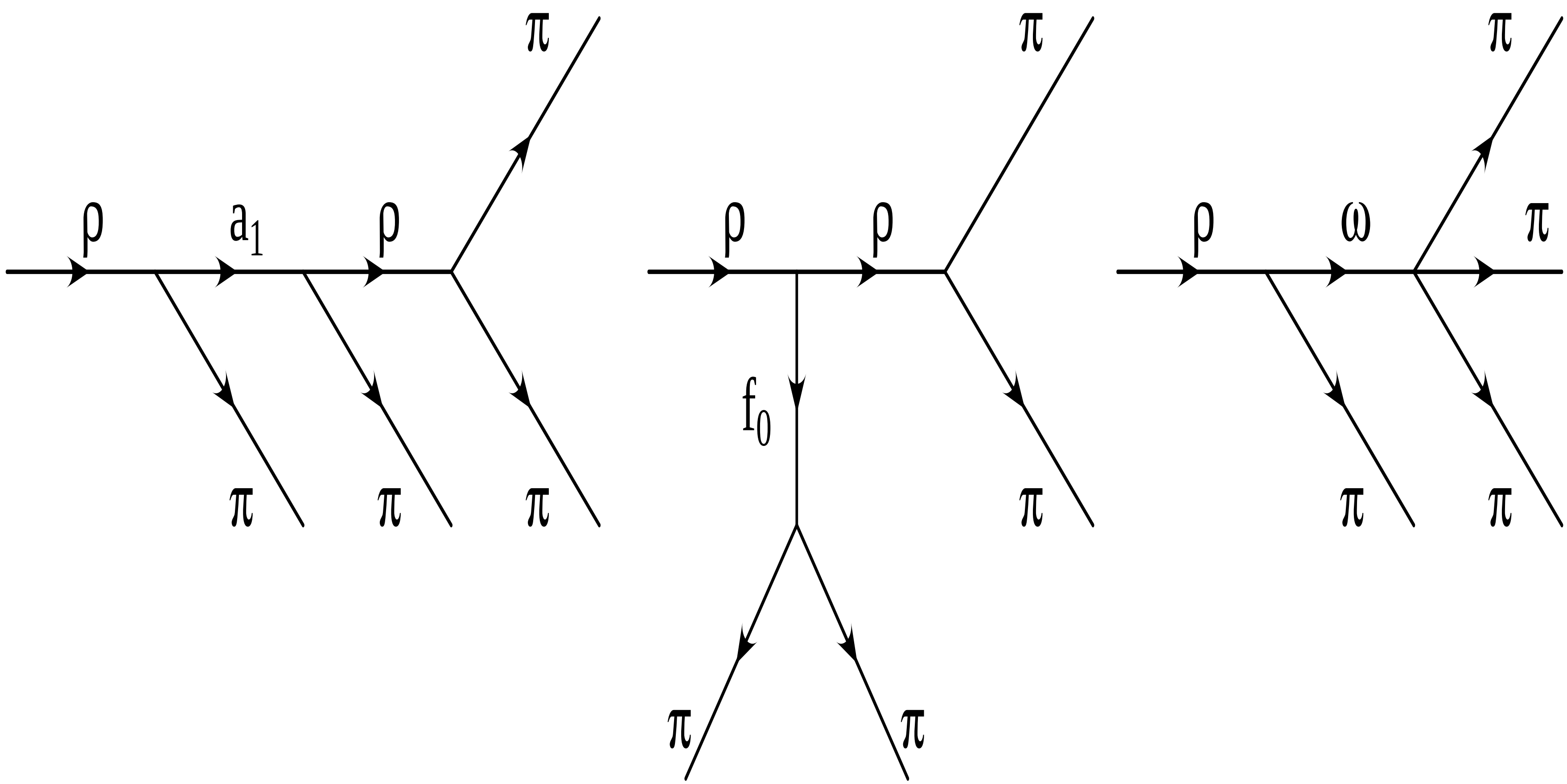
We updated the old 4π model from H. Czyż and J.H. Kühn Eur. Phys. J. C 18, 497 (2001) which was implemented to program PHOKHARA

- new and more accurate data

- new $\rho - \rho$ contributions
- properly modeled ω contributions
- new ρ resonance $\rho(2040)$

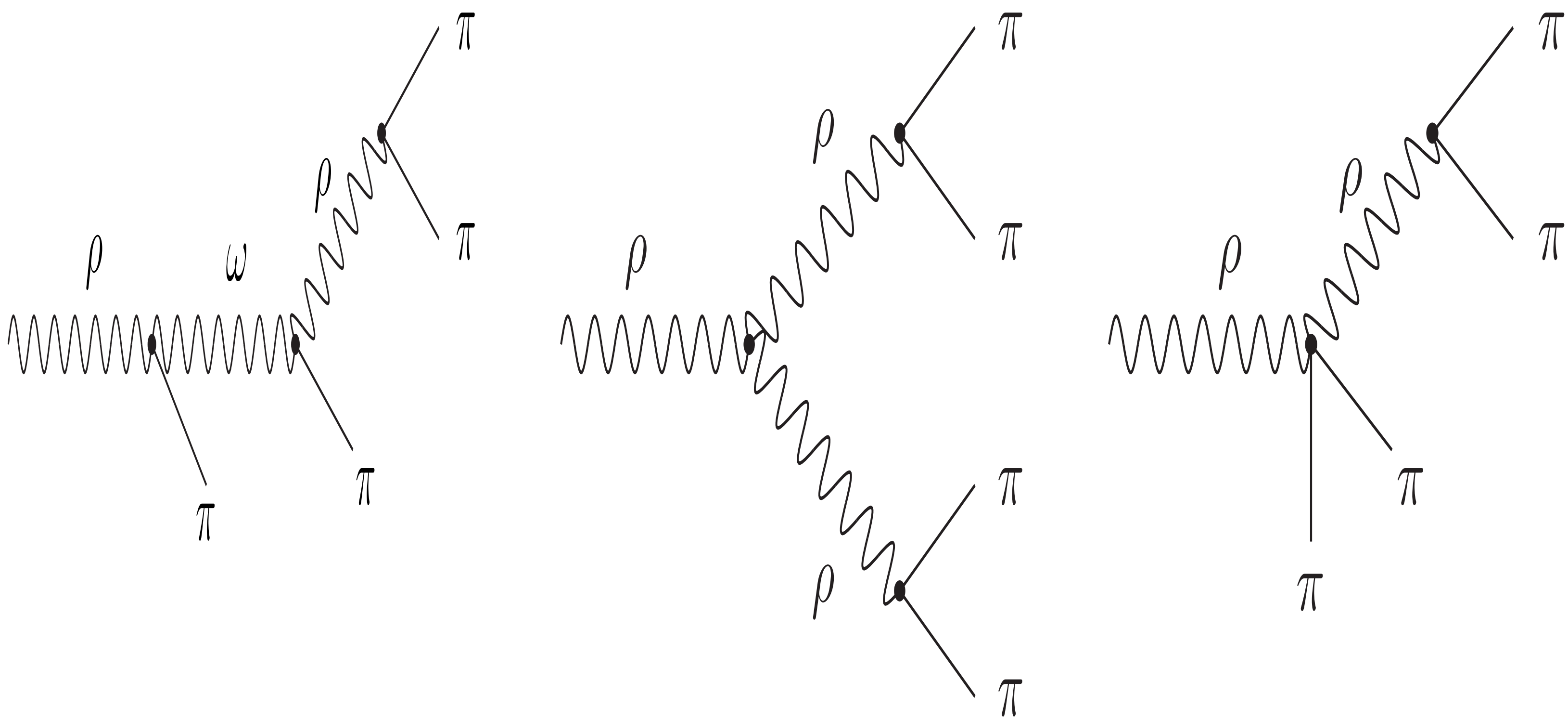
The model

The amplitude used by **H. Czyż, J.H. Kühn (2001)** is schematically depicted:



The model

The new contributions from the omega part and $\boldsymbol{\rho}$ mesons:



H. Czyż, J.H. Kühn, A. Wapienik (2008)

H. Czyż, A.G., J.H. Kühn, G. Rodrigo(2006)

The model

The SU(2) symmetric Lagrangian describing rho-pair production

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

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

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

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

The fit

When we built our model we fitted its parameters to the existing data.

We fitted external masses $m_{\rho'}, m_{\rho''}, m_{\rho'''}$

and widths $\Gamma_{\rho'}, \Gamma_{\rho''}, \Gamma_{\rho'''}$

together with the couplings:

4 couplings in a_1- part

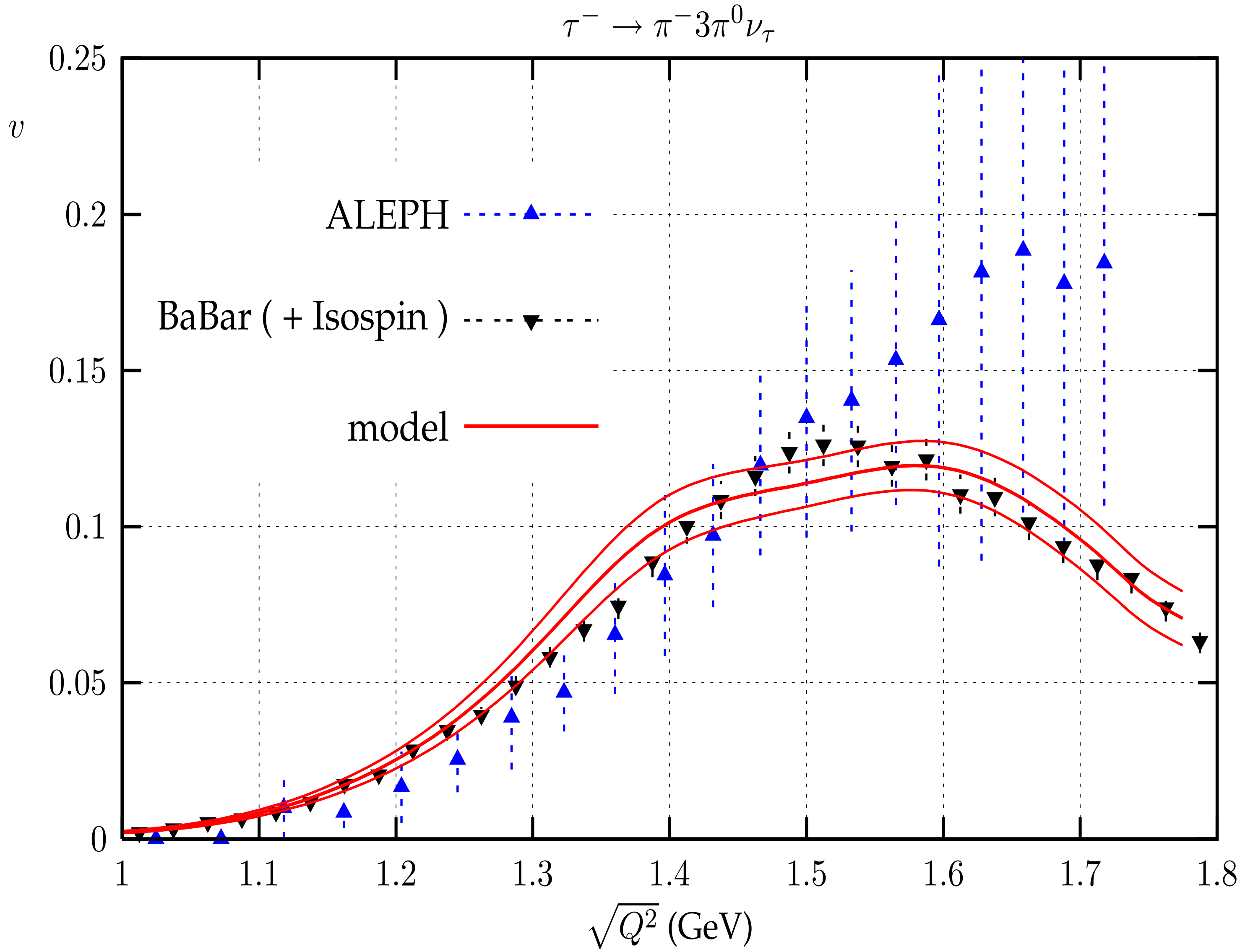
4 couplings in f_0- part

4 couplings in ω- part

1 coupling in ρ- part

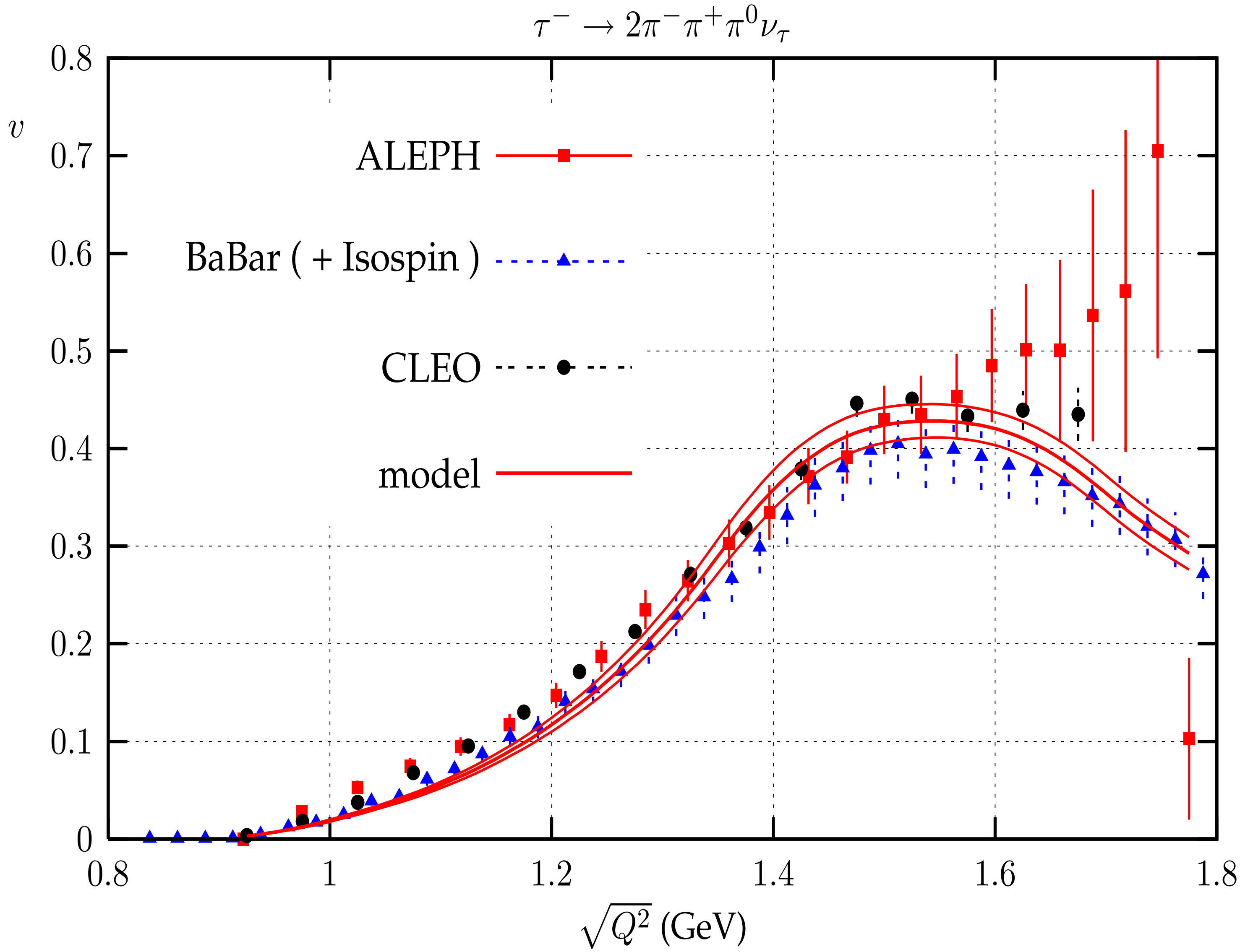
$\chi^2 = 275$, $n_{d.o.f} = 287$

Comparing with τ data



the upper and lower curves represents error bars

Comparing with τ data



Comparing with τ data

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

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

Comparing with τ data

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

Narrow Resonances

Up to now we have two narrow resonances

$$J/\psi \text{ and } \psi(2S)$$

in the event generator PHOKHARA

They have the following masses and widths:

$$J/\psi \quad \rightarrow \quad M_{J/\psi} = 3096.916 \text{ MeV}, \quad \Gamma_{J/\psi} = 93.4 \text{ keV}$$

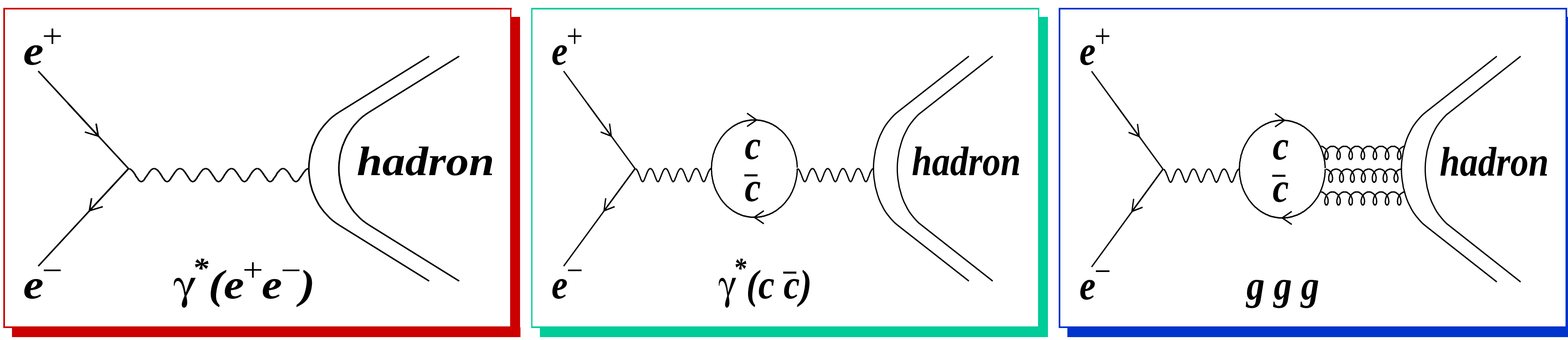
$$\psi(2S) \rightarrow \quad M_{\psi(2S)} = 3686.093 \text{ MeV}, \; \Gamma_{\psi(2S)} = 337 \text{ keV}$$

Narrow Resonances

We put narrow resonances to the fallowing final states:

$$\pi^+\pi^-, \mu^+\mu^-, KK$$

Depends on the final states one has to take into account amplitudes:



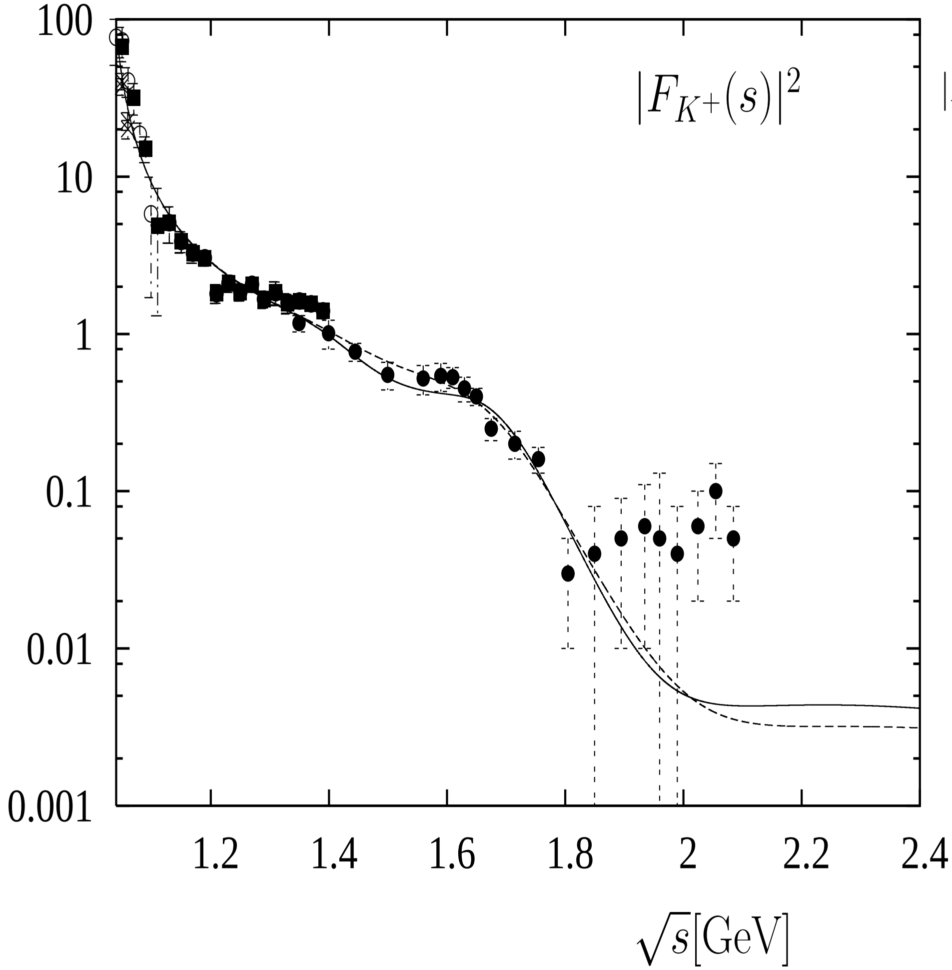
one-photon continuum one-photon annihilation three-gluon annihilation

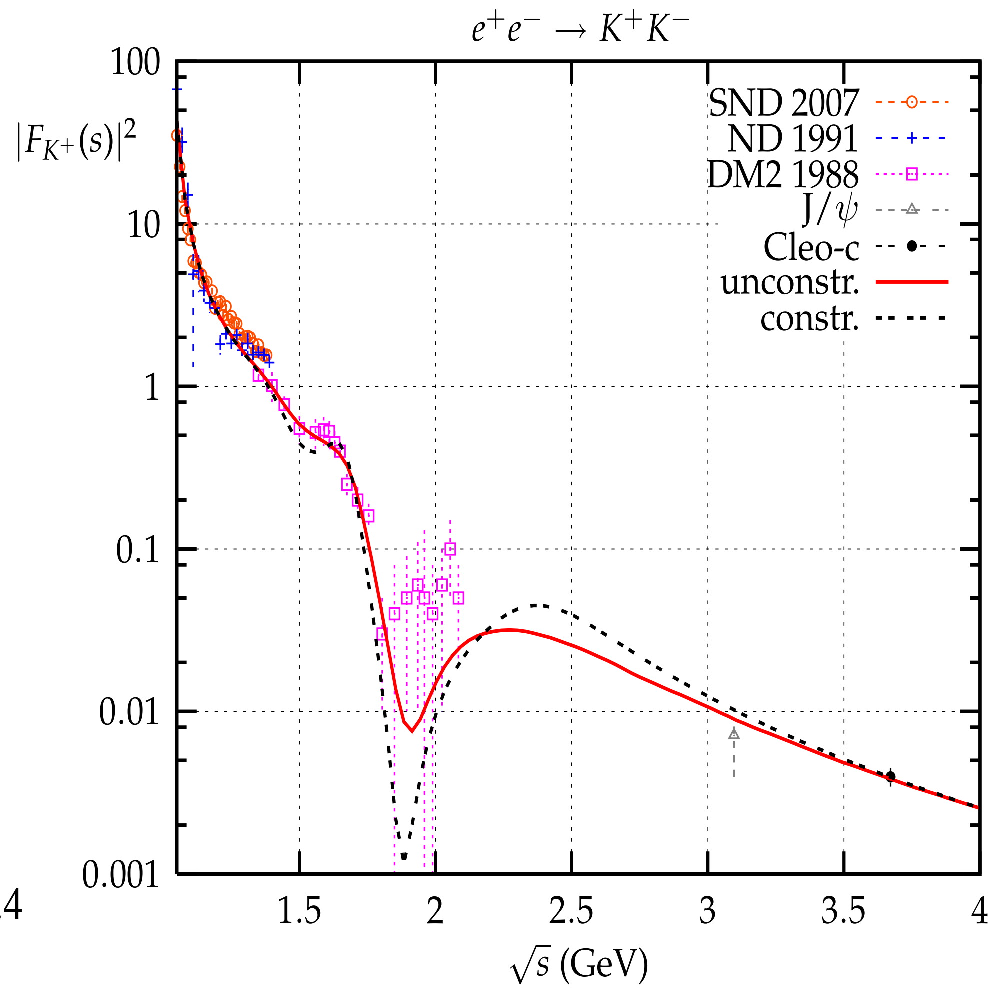
only for kaons

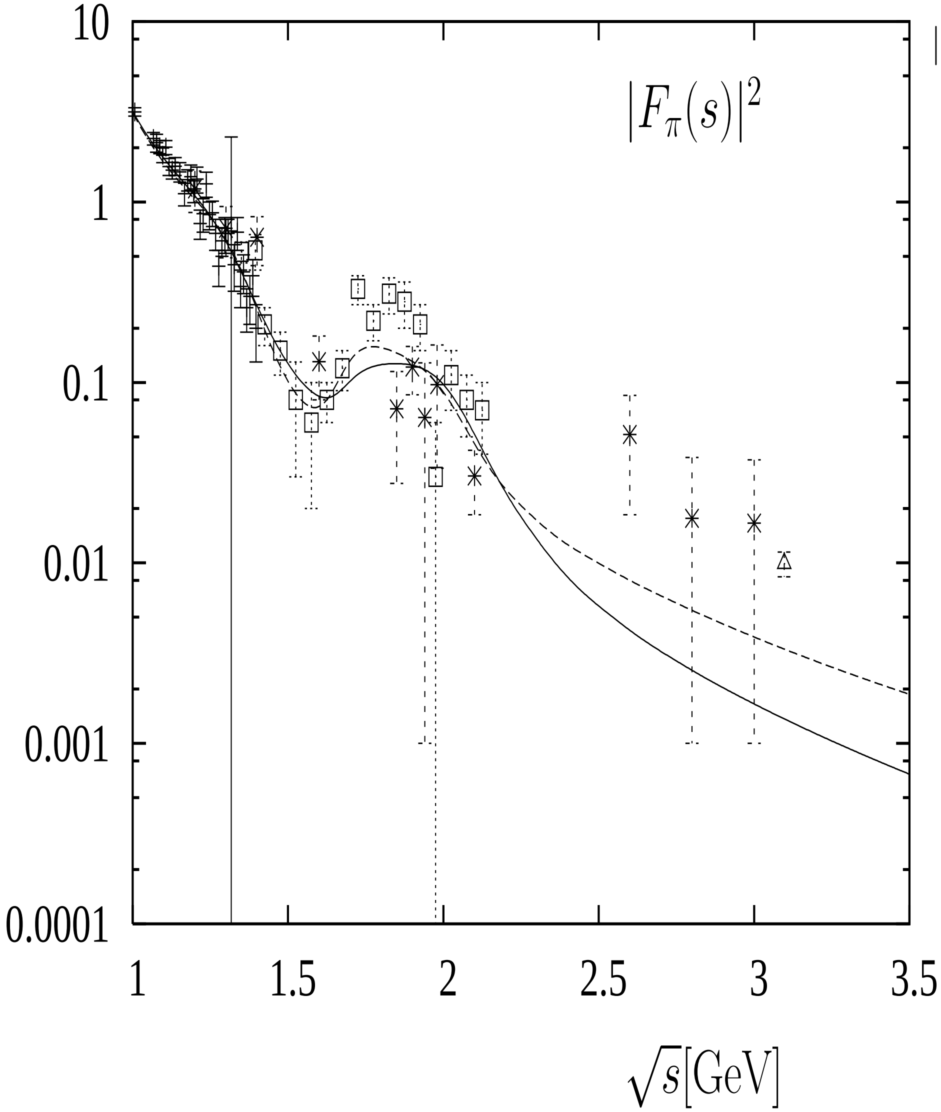
Form Factors

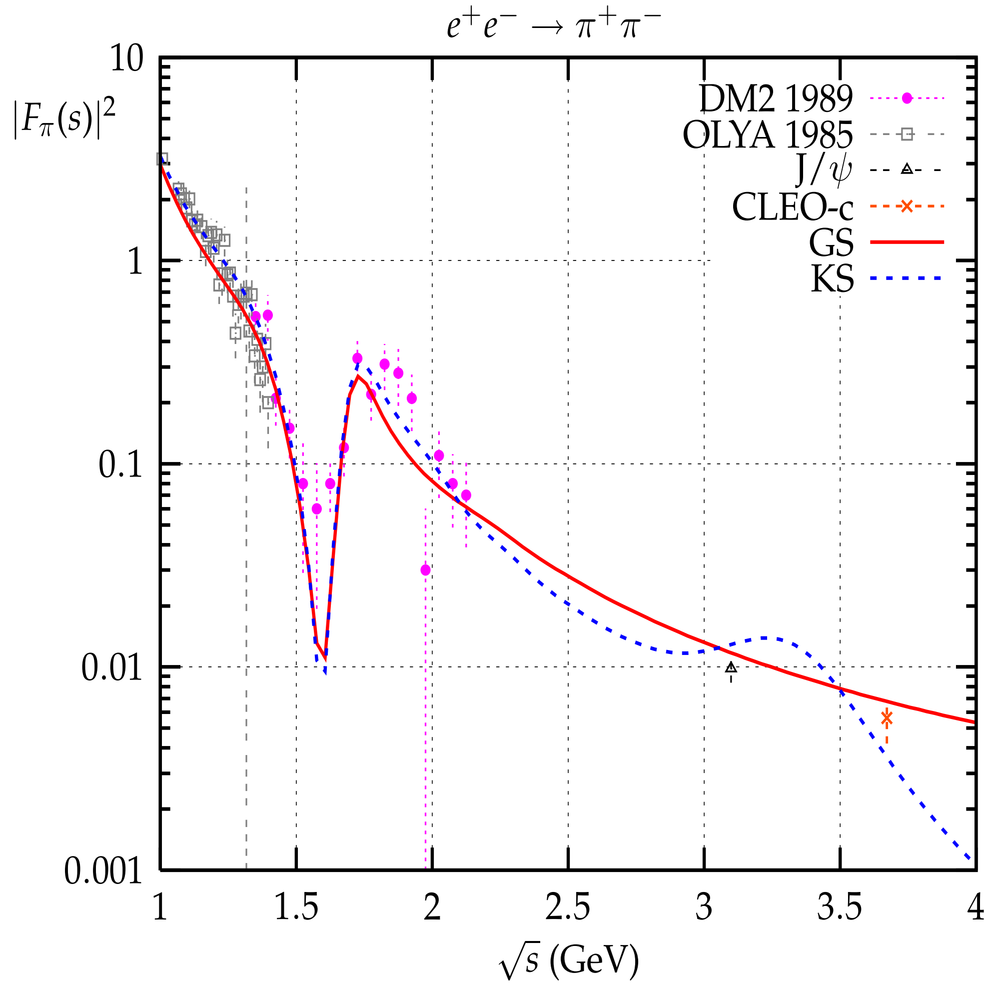
C. Bruch, A. Khodjamirian and J.H. Kühn, Eur. Phys. J. C39(2005)41

H. Czyż, A.G. and J.H. Kühn in preparation



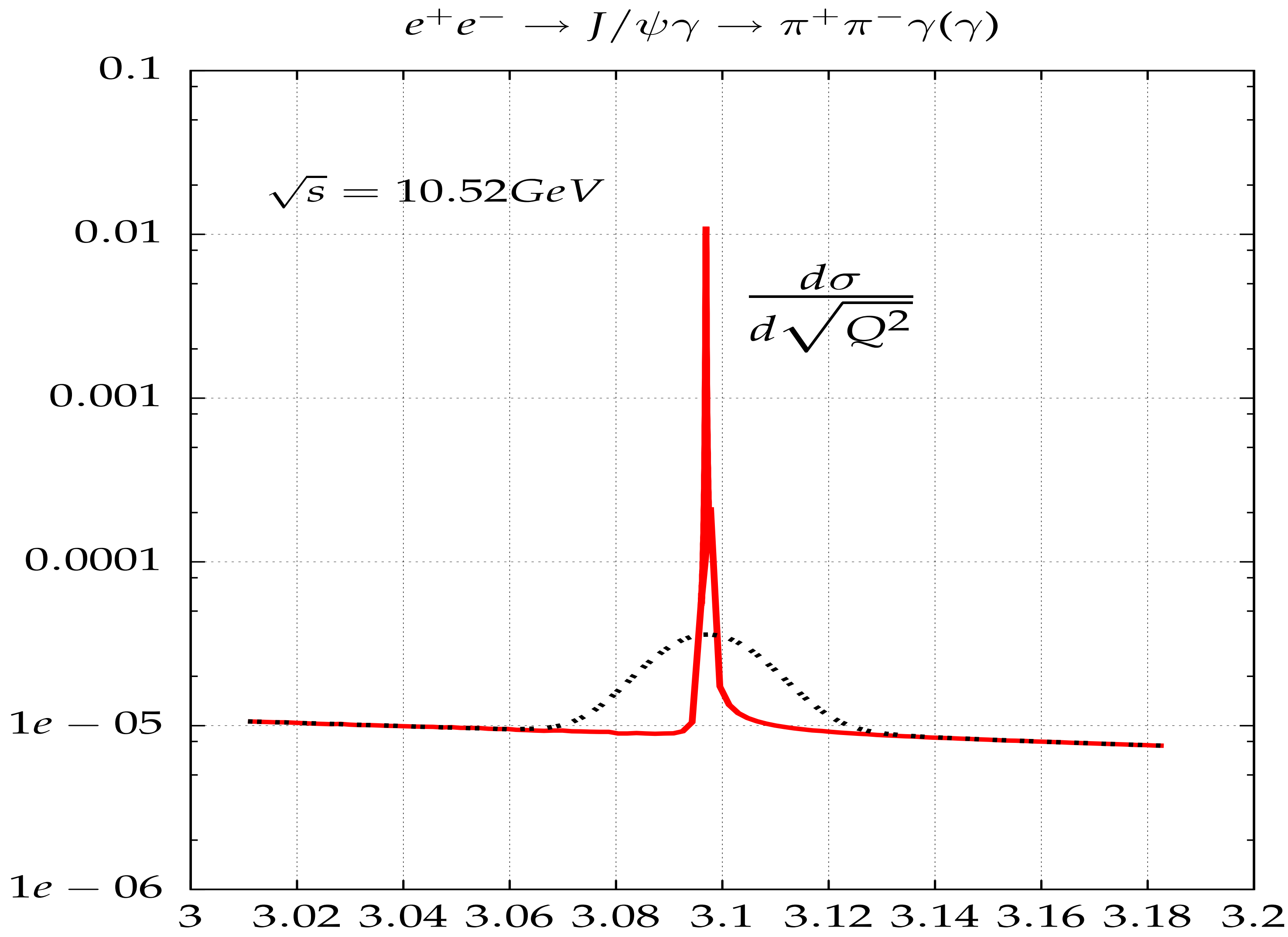



$|F_\pi(s)|^2$
10
1
0.1
0.01
0.001
0.0001
1
1.5
2
2.5
3
3.5
$\sqrt{s}$[GeV]

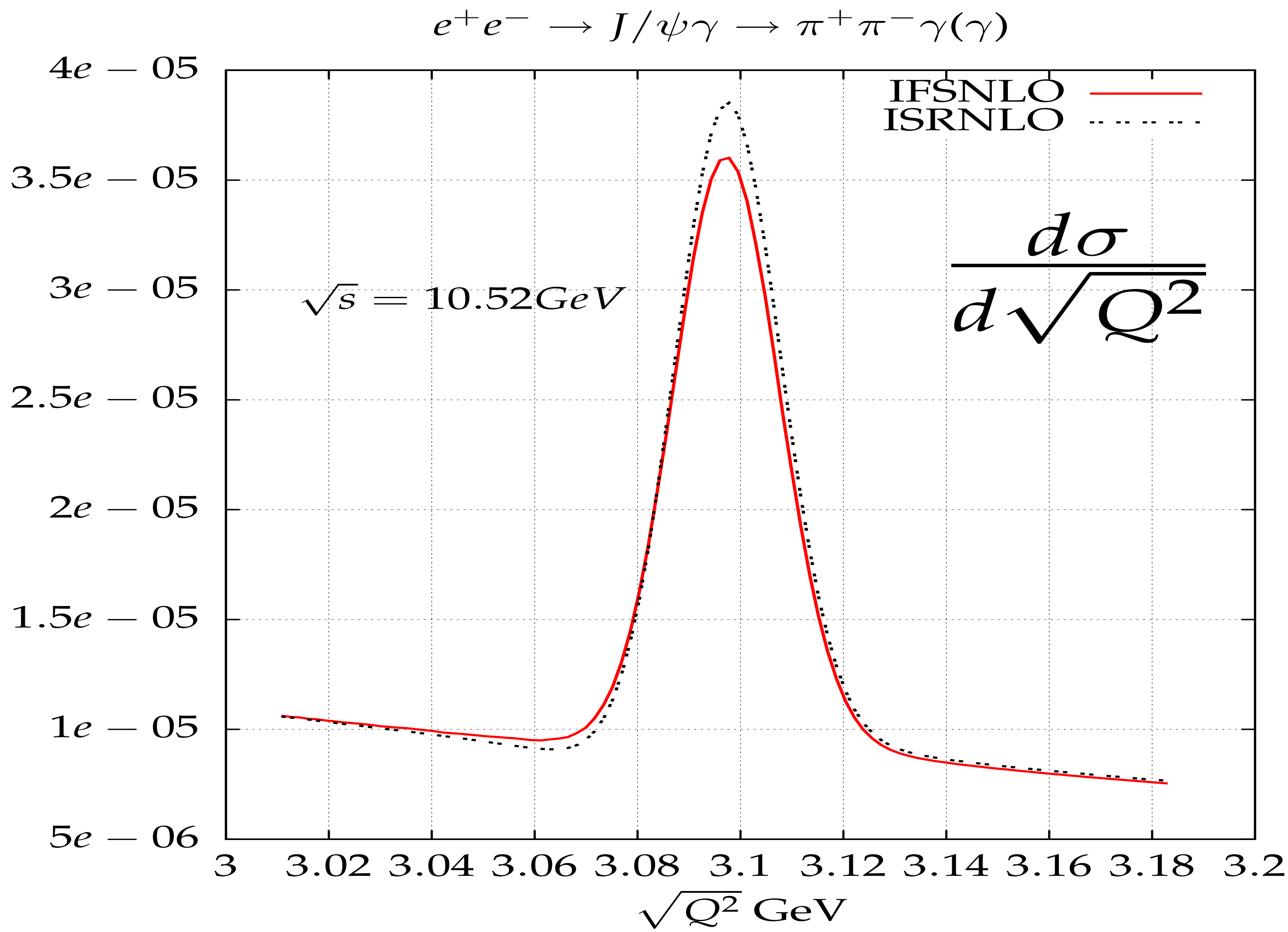

$e^+e^- \to \pi^+\pi^-$
$|F_\pi(s)|^2$
DM2 1989
OLYA 1985
J/ψ
CLEO-c
GS
KS
10
1
0.1
0.01
0.001
1
1.5
2
2.5
3
3.5
4
$\sqrt{s}$ (GeV)

Narrow Resonances

$\boldsymbol{\Delta q}$ = 14.5 MeV the detector spread



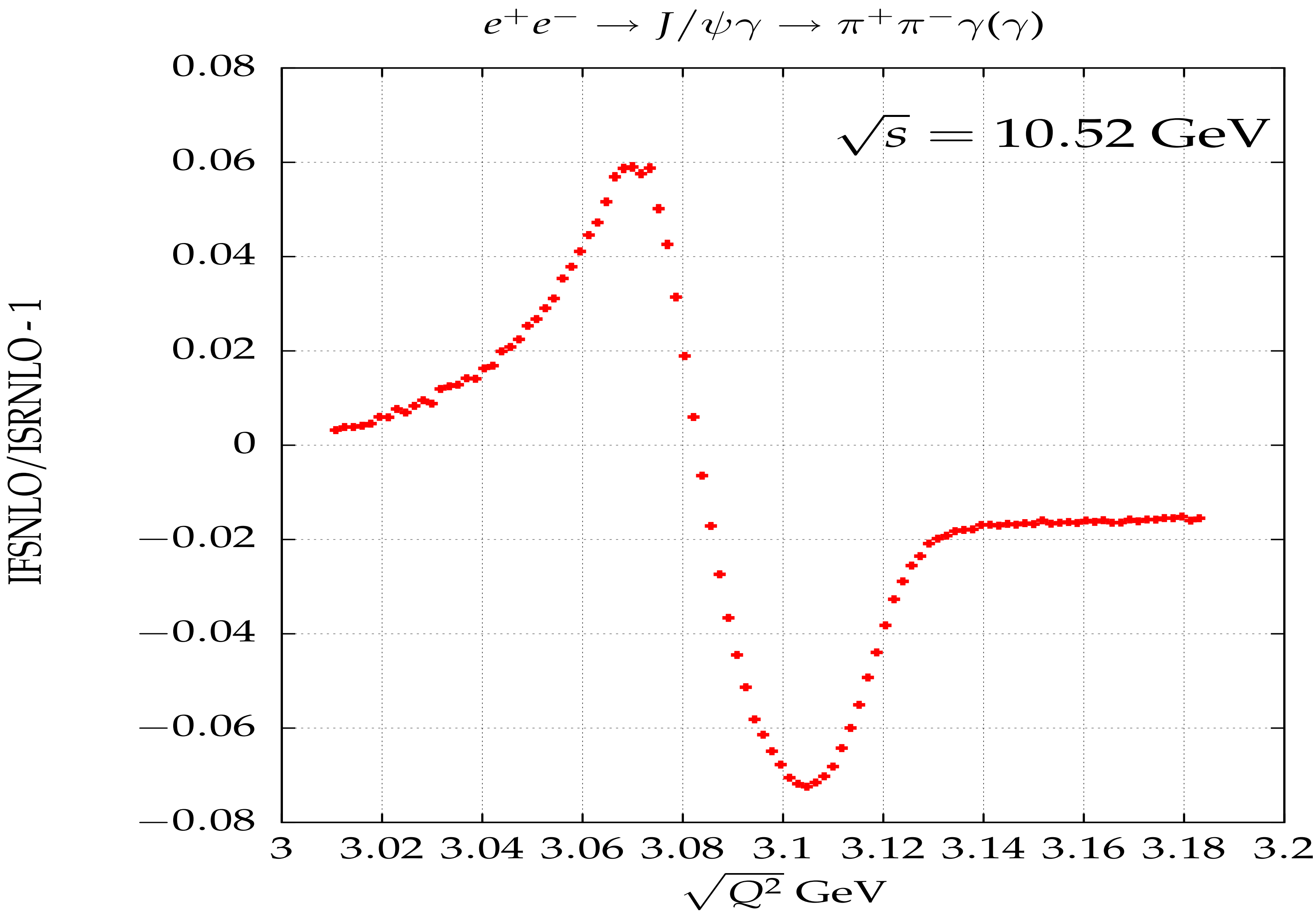
FSR



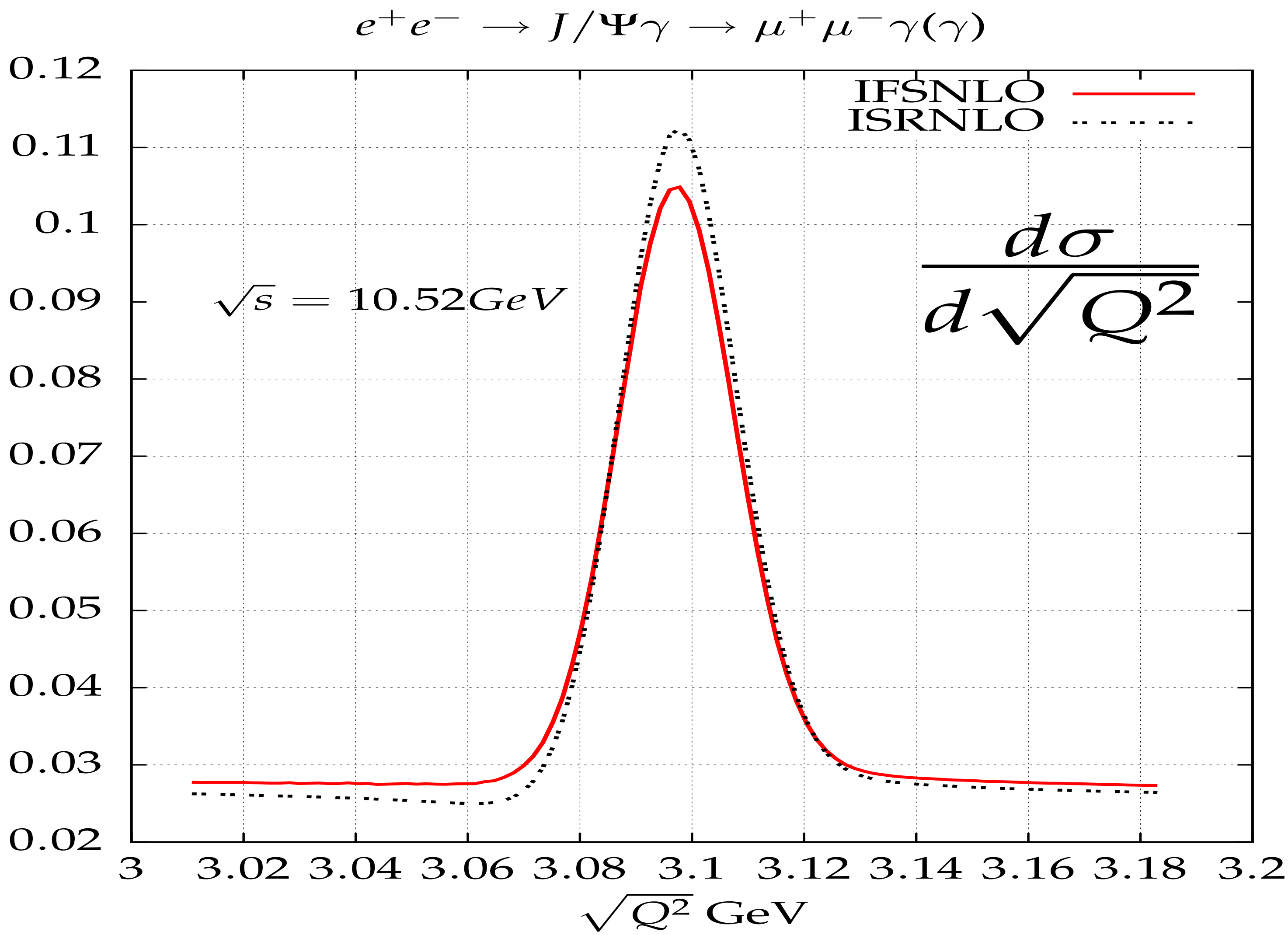
$\boldsymbol{\sigma(IFSNLO)}$ = (2.27808 ± 0.00013) fb

$\boldsymbol{\sigma(ISRNLO)}$ = (2.32720 ± 0.00006) fb

Relative difference of the cross sections



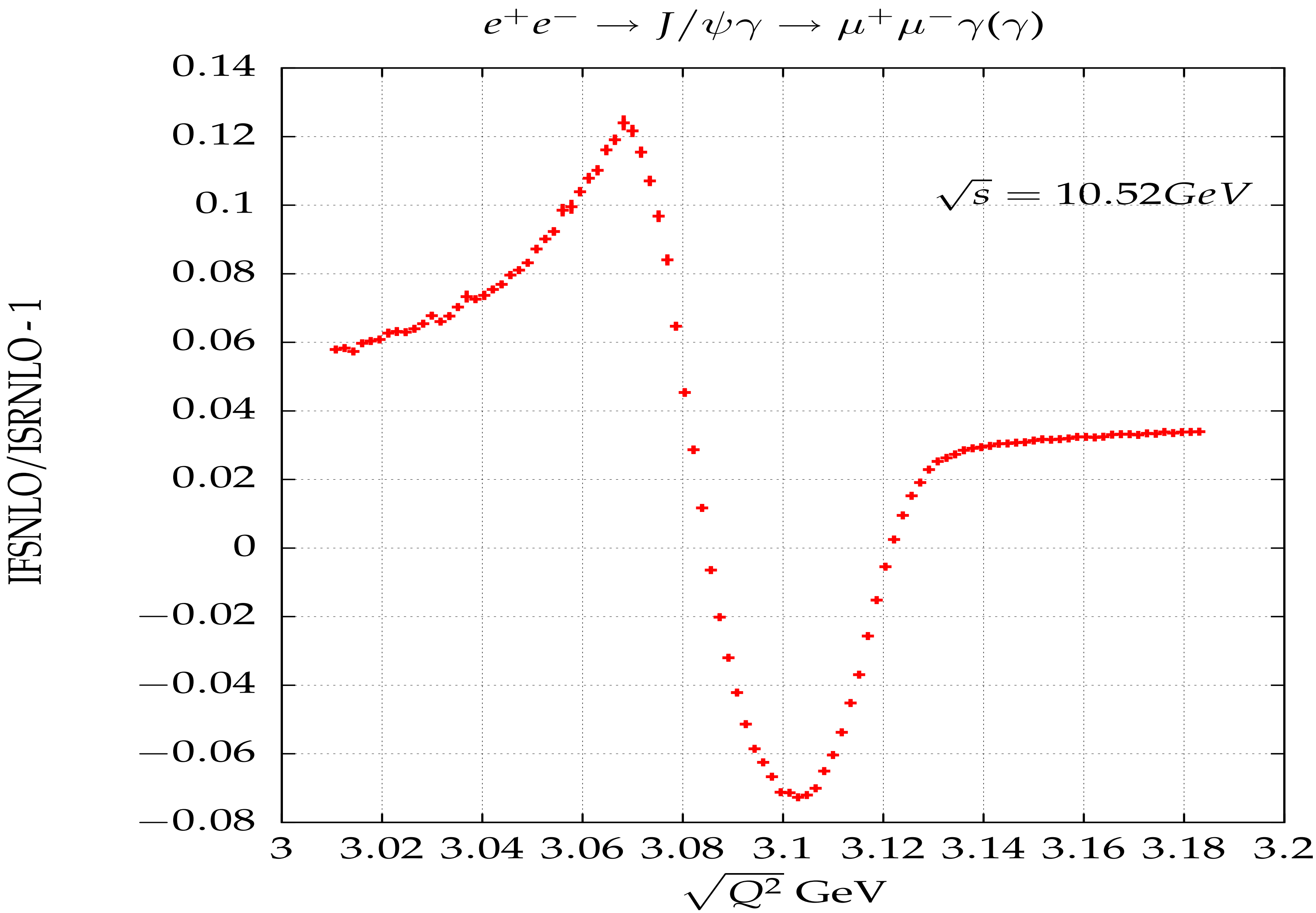
FSR



$\boldsymbol{\sigma(IFSNLO)}$ = (6.8527 $\pm$ 0.0006) pb

$\boldsymbol{\sigma(ISRNLO)}$ = (6.79862 $\pm$ 0.00008) pb

Relative difference of the cross sections



Summary

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

Summary

- implementation J/ψ and $\psi(2S)$ in PHOKHARA
  - with FSR corrections included
  - required more tests