Forthcoming PHOKHARA upgrades
and
few reminiscences

H. CZYŻ, IF, UŚ, Katowice, FlaviA net, BEIJING 2008

in collaboration with

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

The outline of the talk

The radiative return

4π revisited

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

Narrow resonances - FSR

NLO vs. structure functions, or

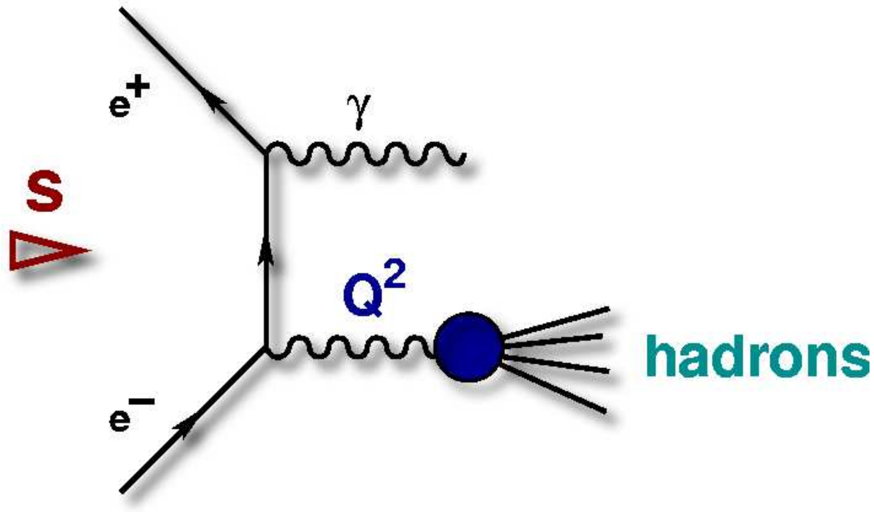
how a theorist can know what the experimentalists do

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]

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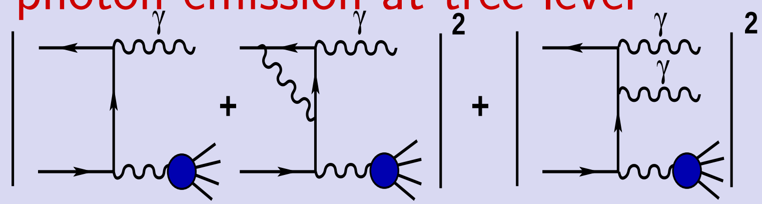
PHOKHARA 6.0: $\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda(\to \cdots)\bar{\Lambda}(\to \cdots)$

- **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

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

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

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

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

J. H. Kühn (1999)

Isospin relations: 4π

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

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

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

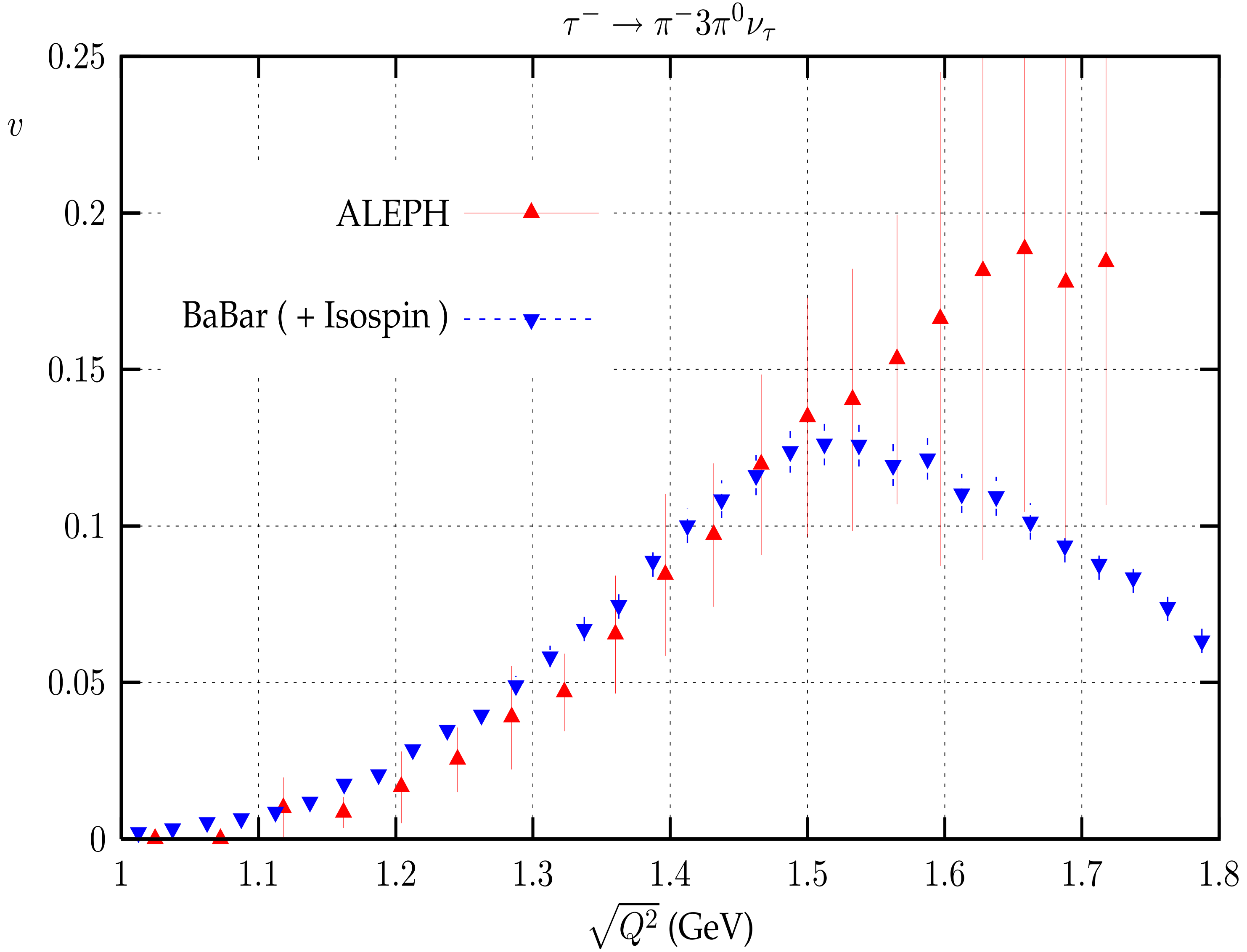
$e^+e^- \to 2\pi^+2\pi^-$: BaBar, CMD2, SND

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

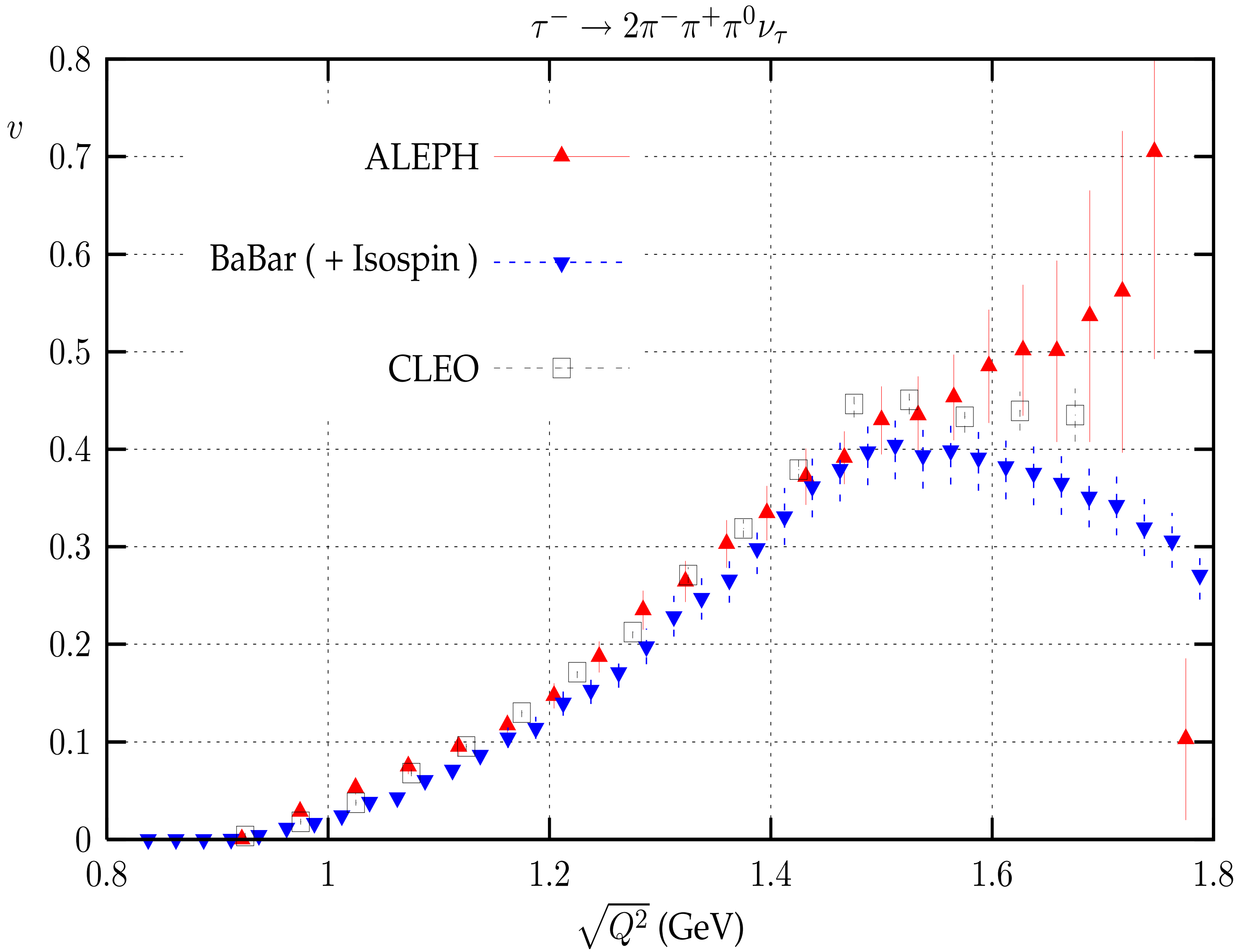
$\tau^- \to \nu 3\pi^0\pi^-$: ALEPH

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

Isospin relations: 4π; exp. situation



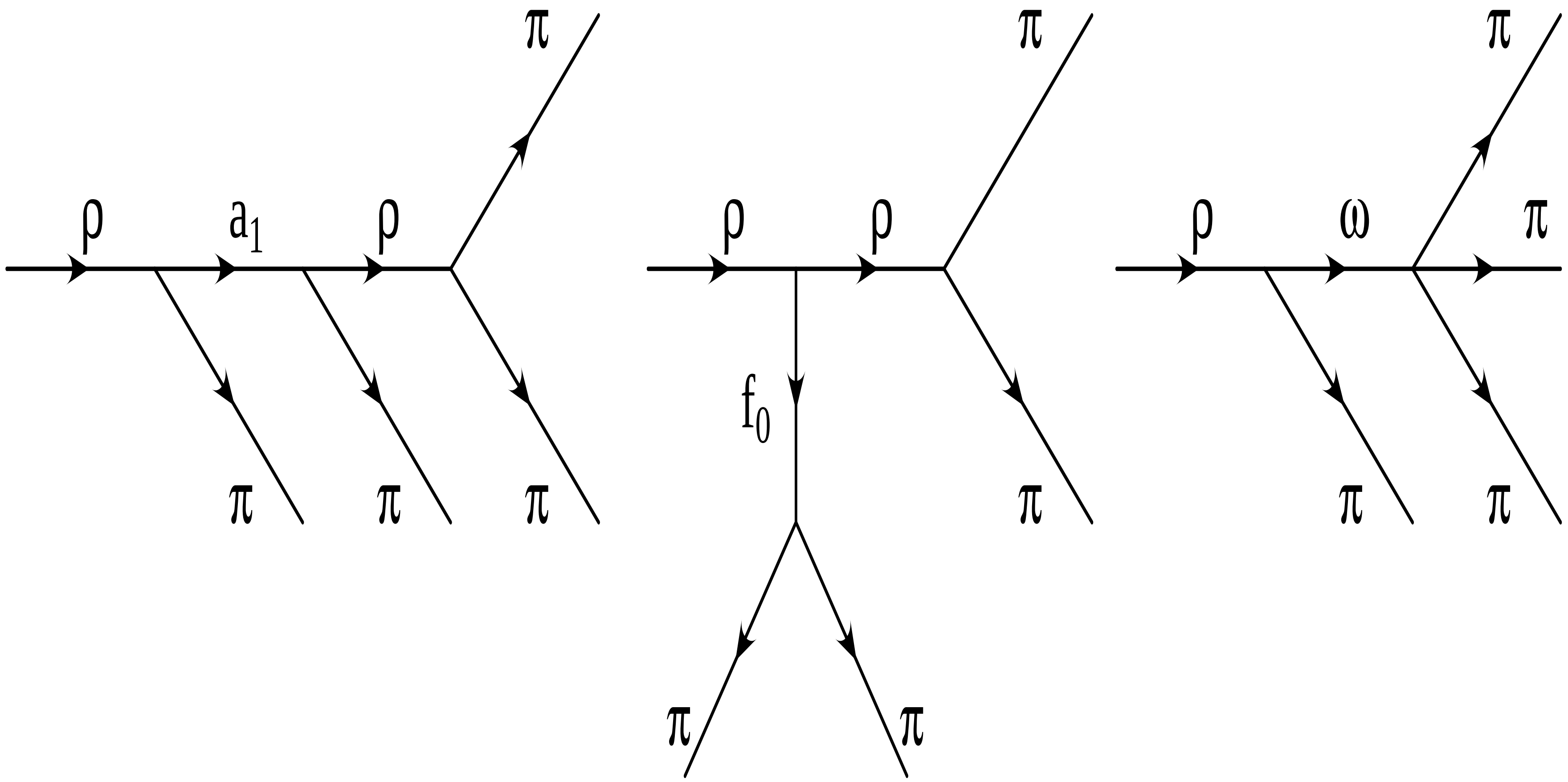
Isospin relations: 4π; exp. situation



4π: exp. situation

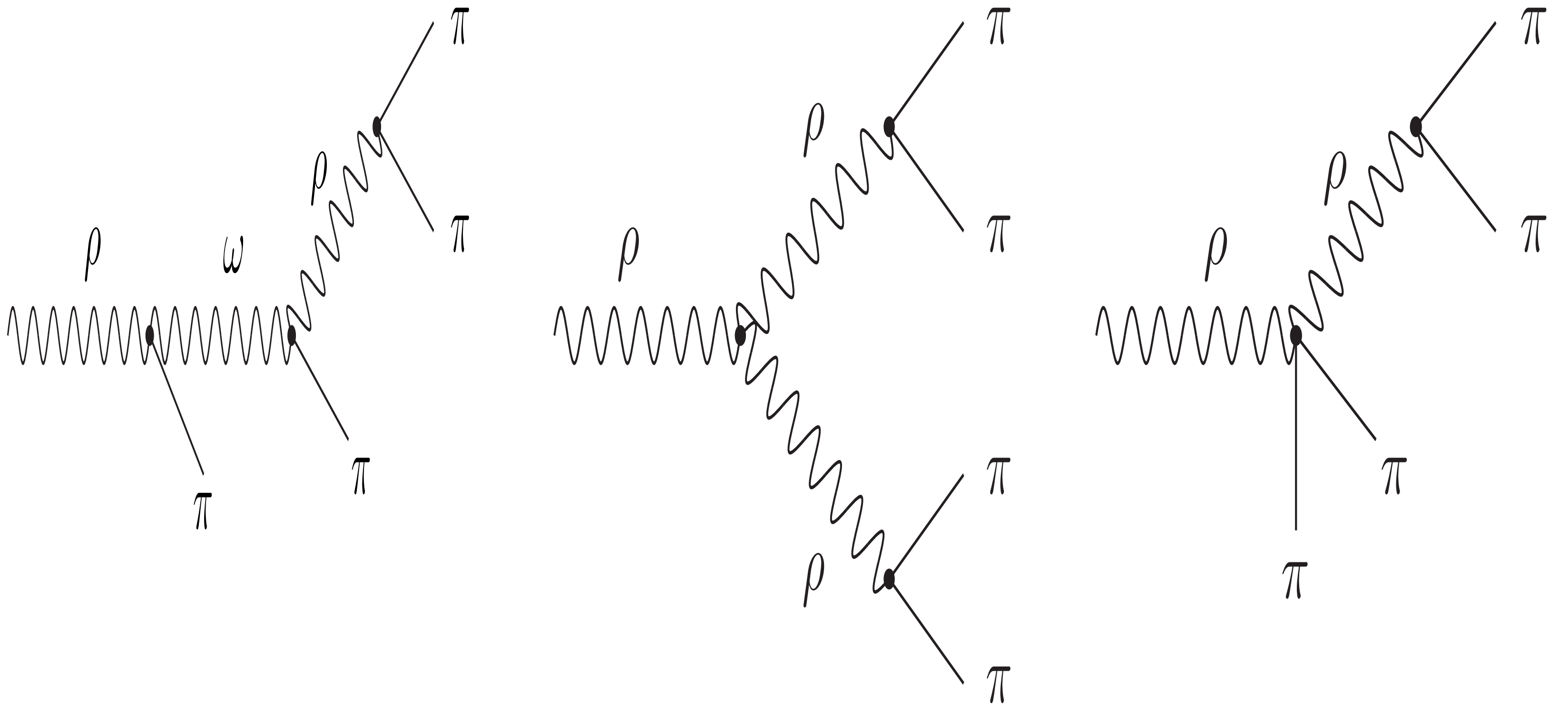
- $\pi\omega(\to \pi^+\pi^-\pi^0)$: CLEO, BaBar(prel.)
- $\rho \to \rho(\to \pi\pi)\rho(\to \pi\pi)$: BaBar(prel.)

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)

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

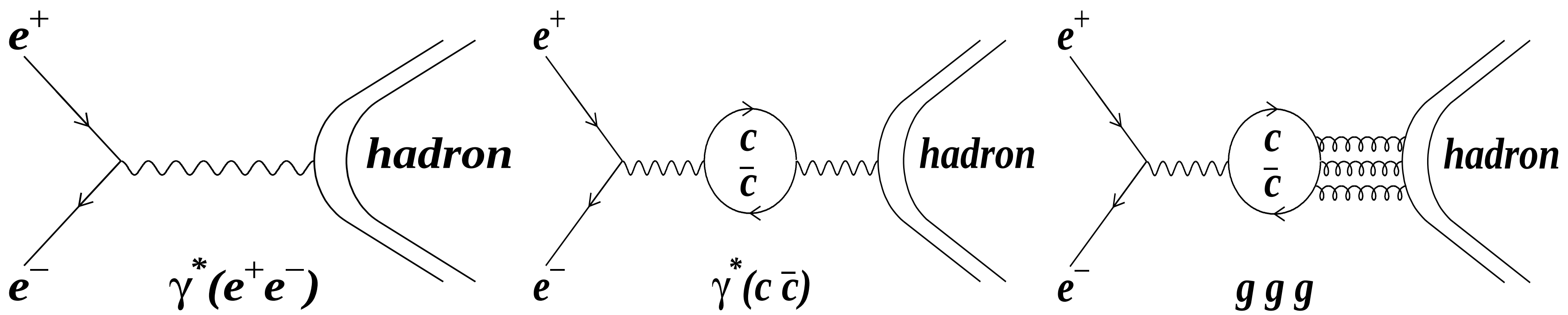
	$\mathrm{Br}(\tau- \to \nu_\tau \pi^- 3\pi^0)$
PDG06	$(1.04 \pm 0.08)\%$
model	$(1.06 \pm 0.09)\%$
BaBar (CVC)	$(1.02 \pm 0.05)\%$

Narrow Resonances

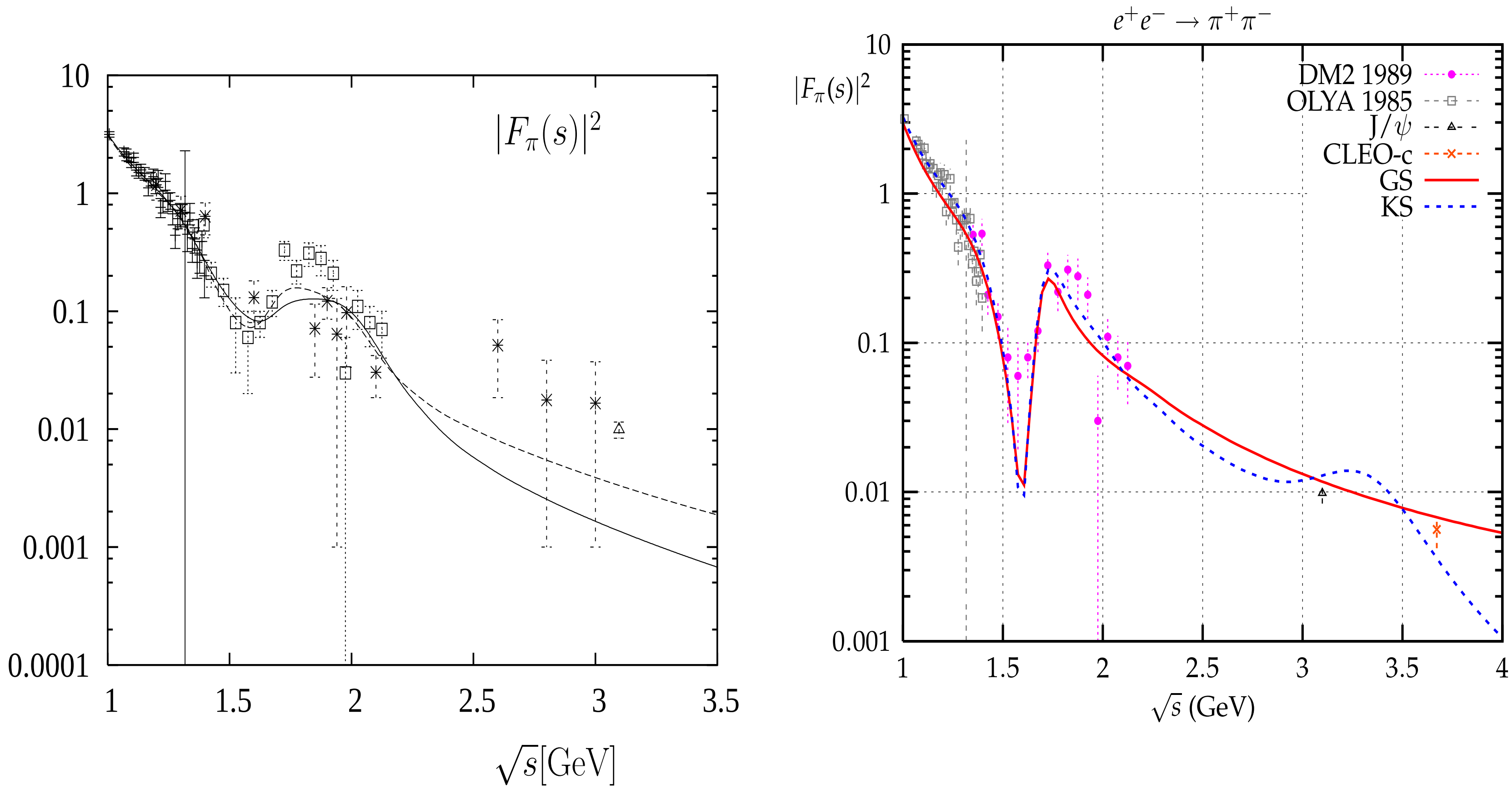
$$e^+e^- \to J/\psi\ (\psi(2S))\gamma \to \pi^+\pi^-, \mu^+\mu^-, KK + \gamma(\gamma)$$

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

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



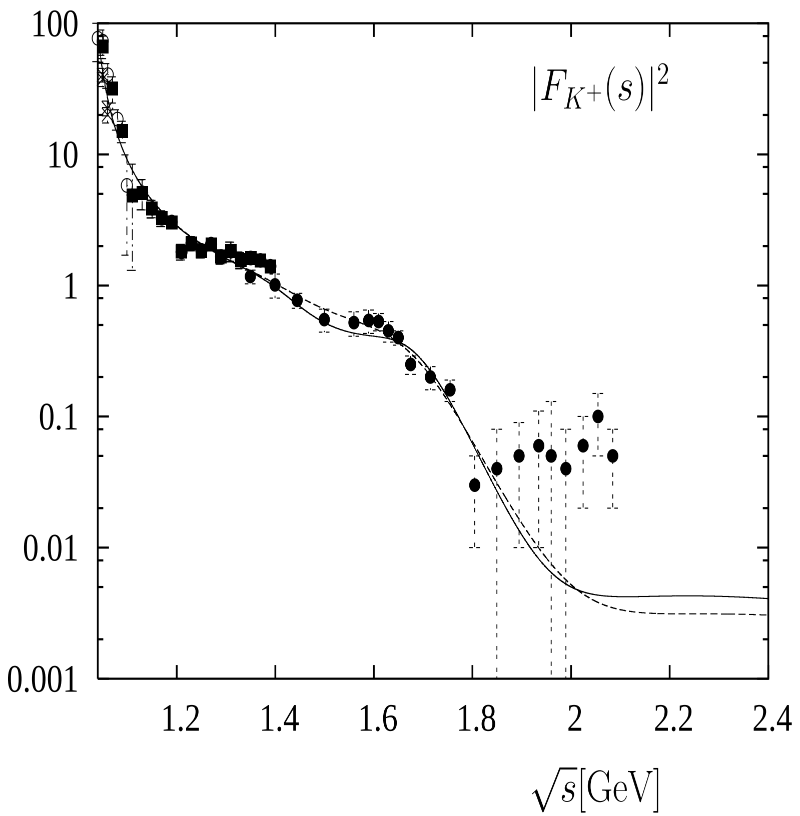
Pion form factor

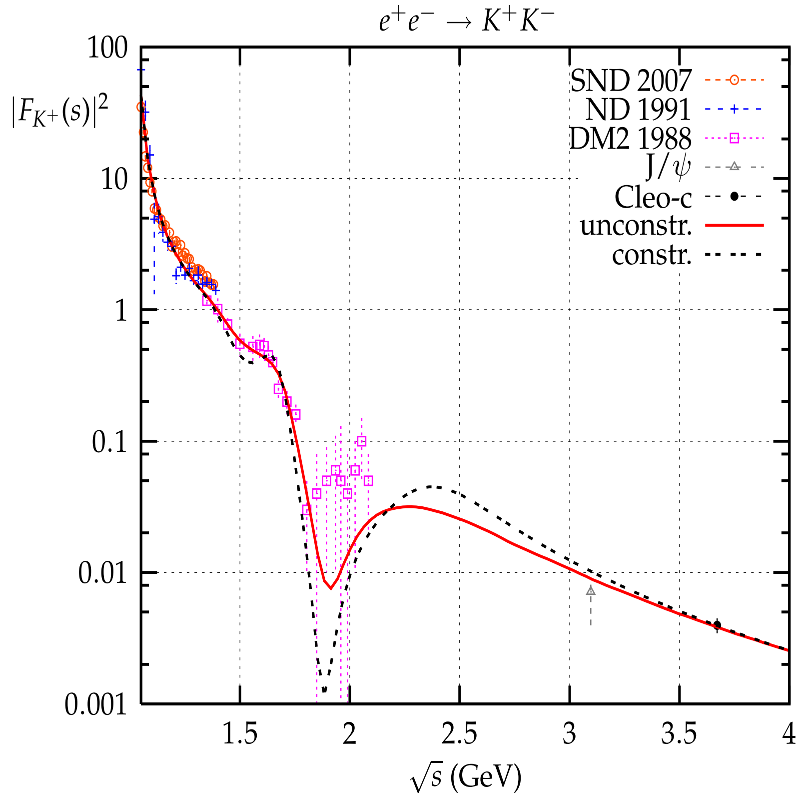


C. Bruch, A. Khodjamirian and J.H. Kühn, Eur. Phys. J. C39(2005)41

H. C., A. Grzelińska, E. Nowak-Kubat and J.H. Kühn, in preparation

Kaon form factor



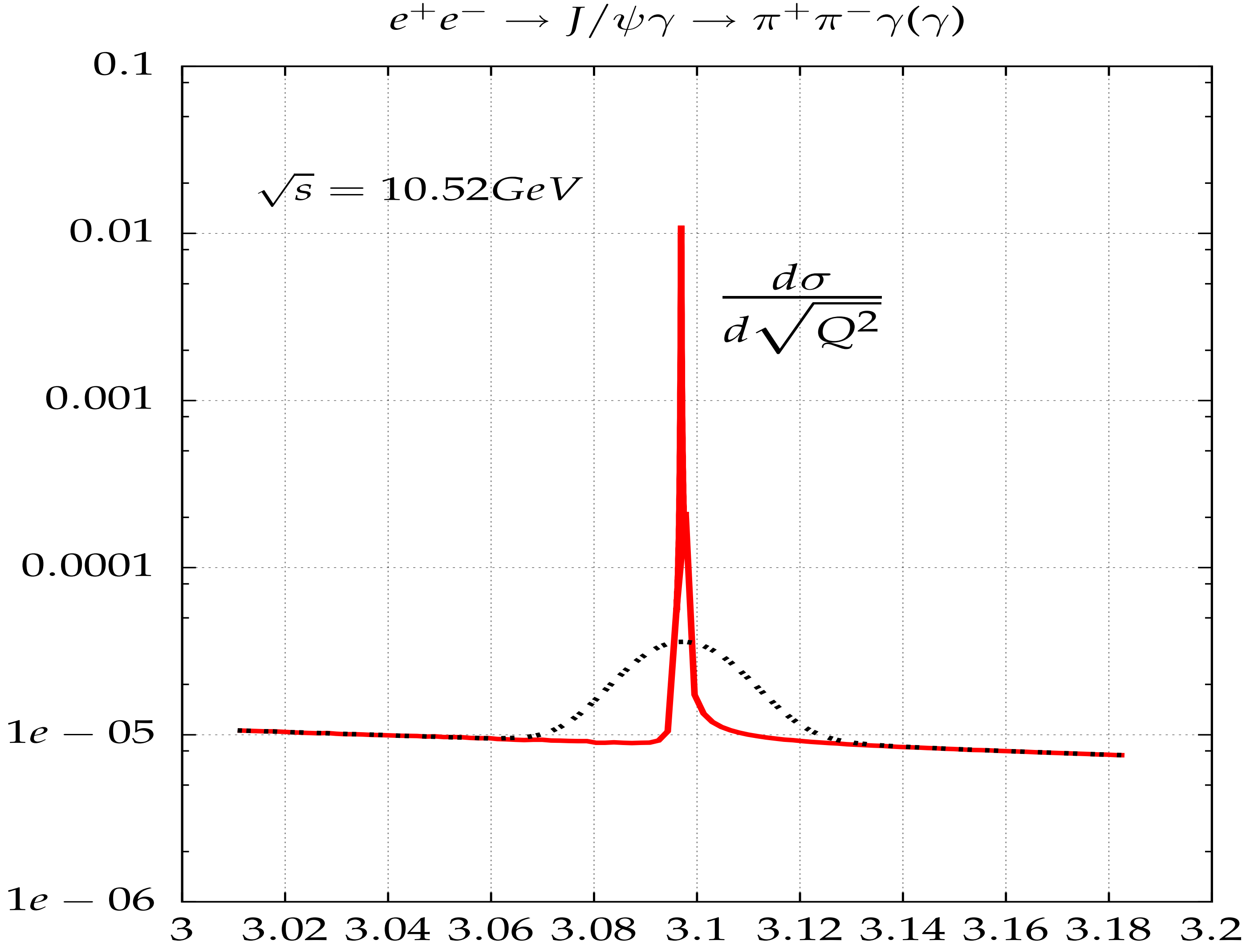


C. Bruch, A. Khodjamirian and J.H. Kühn, Eur. Phys. J. C39(2005)41

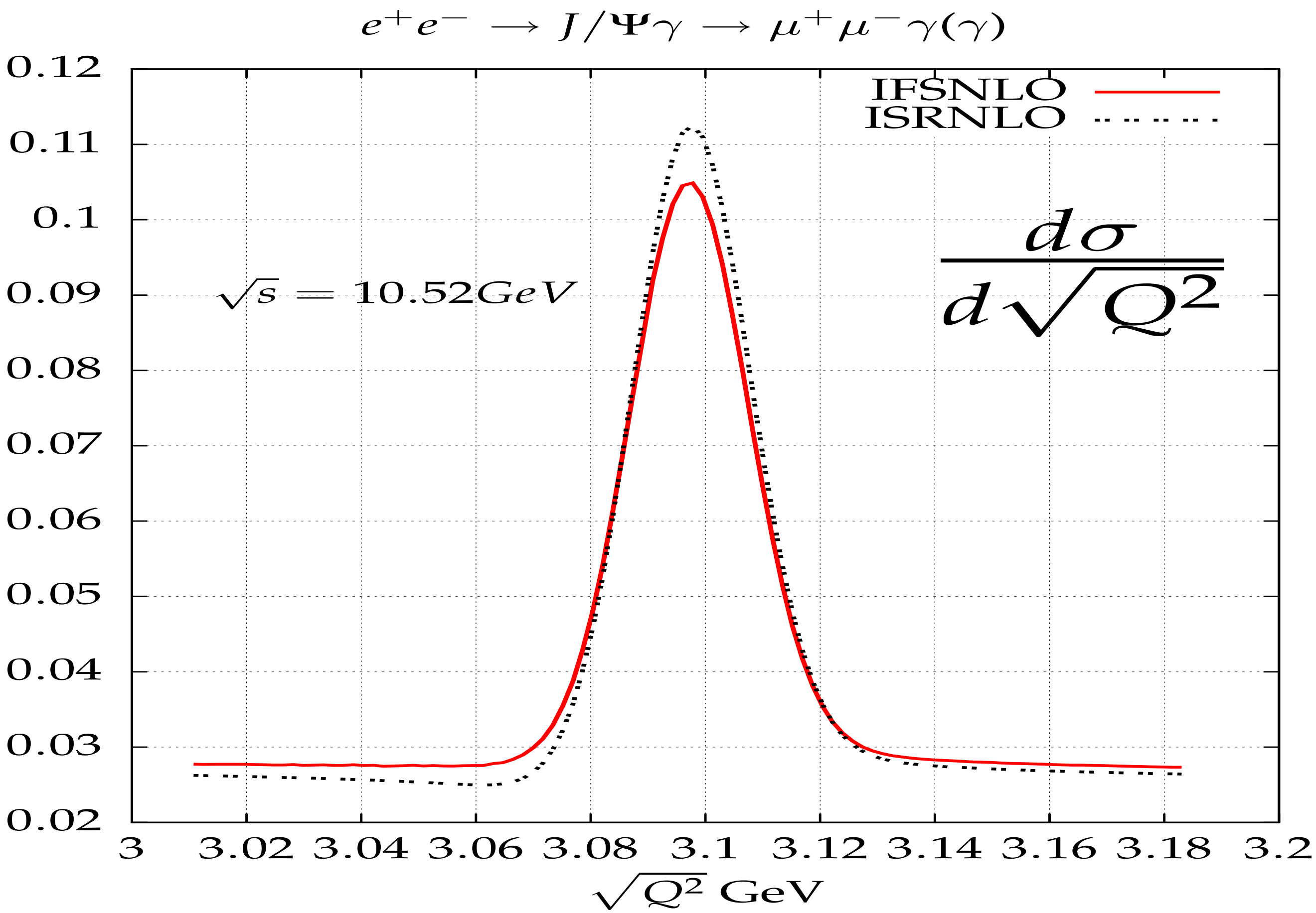
H. C., A. Grzelińska, E. Nowak-Kubat and J.H. Kühn, in preparation

Energy resolution

$\Delta q = 14.5$ MeV



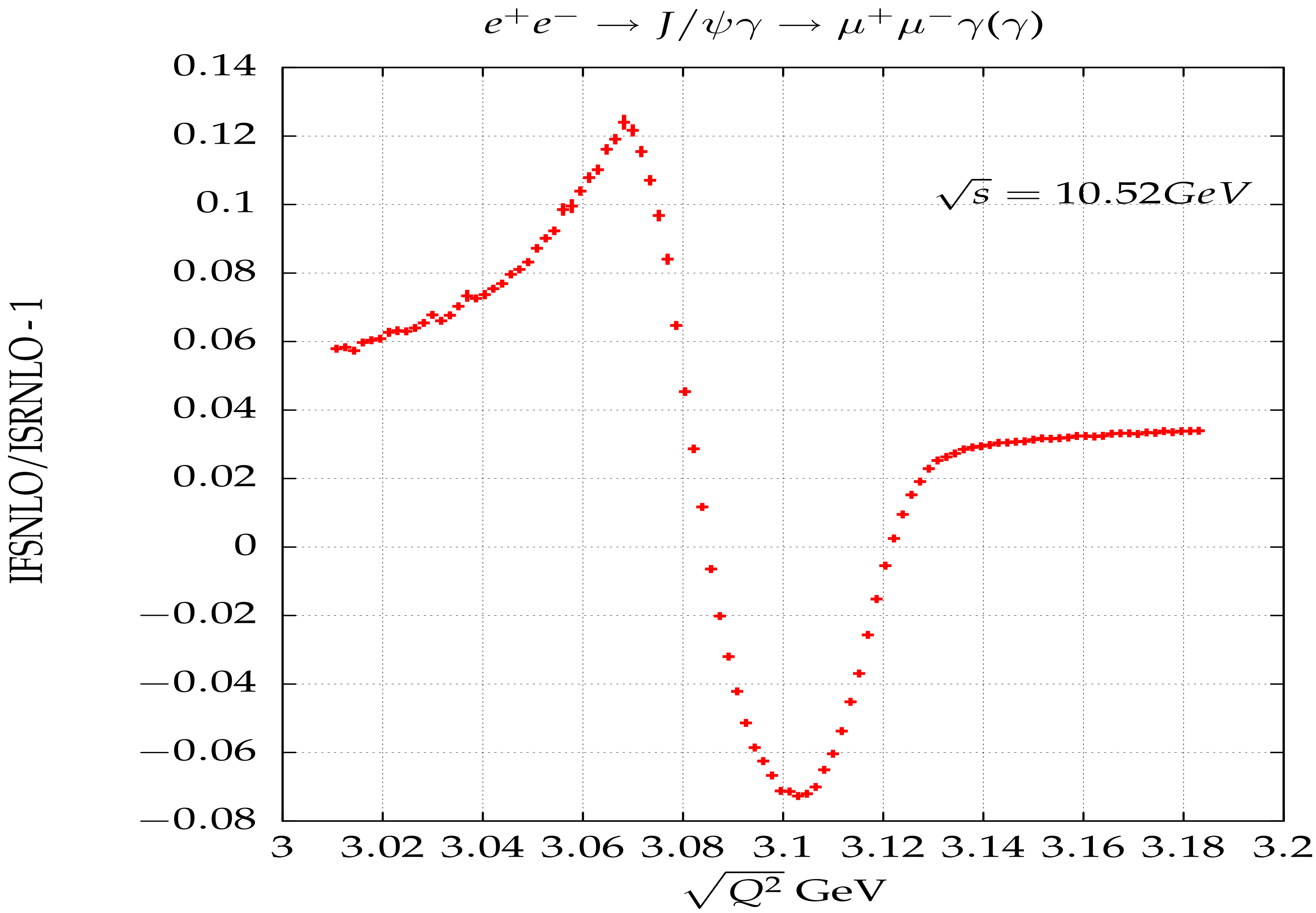
FSR - muons



$\sigma(IFSNLO) = (\ 6.8527 \pm 0.0006\ )$ pb

$\sigma(ISRNLO) = (\ 6.79862 \pm 0.00008\ )$ pb

FSR - muons



$e^+e^- \longrightarrow J/\psi\gamma \longrightarrow \mu^+\mu^-\gamma(\gamma)$
IFSNLO/ISRNLO - 1
$\sqrt{s} = 10.52 GeV$
$\sqrt{Q^2}$ GeV
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
3
3.02
3.04
3.06
3.08
3.1
3.12
3.14
3.16
3.18
3.2

a_μ, BaBar preliminary

Conclusions

- BaBar analysis of $\pi\pi$ and $\mu\mu$ ISR processes completed
- Precision goal has been achieved: 0.6% in ρ region (0.6-0.9 GeV)
- Absolute $\mu\mu$ cross section agrees with NLO QED within 1.2%
- Preliminary results available for $\pi\pi$ in the range 0.5-3 GeV
- Structures observed in pion form factor at large masses

- Comparison with results from earlier experiments
  - discrepancy with CMD-2 and SND mostly below ρ
  - large disagreement with KLOE
  - better agreement with τ results, especially Belle
- Contribution to a_μ from BaBar agrees better with τ results
- Deviation between BNL measurement and theory prediction significantly reduced using BaBar $\pi\pi$ data

$$a_\mu[\mathrm{exp}] - a_\mu[\mathrm{SM}] = (27.5 \pm 8.4) \times 10^{-10} \Rightarrow (14.0 \pm 8.4) \times 10^{-10}$$

- Wait for final results and contributions of multi-hadronic modes

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a_μ, BaBar preliminary

The Measurement

- ISR photon at large angle in EMC
- 1 (for efficiency) or 2 (for physics) tracks of good quality
- identification of the charged particles
- separate ππ/KK/μμ event samples
- kinematic fit (not using ISR photon energy) including 1 additional photon
- obtain all efficiencies (trigger, filter, tracking, ID, fit) from same data
- measure ratio of ππγ(γ) to μμγ(γ) cross sections to cancel
  - ee luminosity
  - additional ISR
  - vacuum polarization
  - ISR photon efficiency

  } otherwise 3-4% syst error
- still need to correct for $|FSR|^2$ contribution in μμγ(γ) and additional FSR, both calculated in QED, but also checked in data (ISR-FSR interference, additional detected photons)

$$R_{exp}(s) = \frac{\sigma[\pi\pi\gamma(\gamma)](s)}{\sigma[\mu\mu\gamma(\gamma)](s)} = \frac{\sigma^0[\pi\pi(\gamma)](s)}{(1+\delta_{FSR}^{\mu\mu})\sigma^0[\mu\mu(\gamma)](s)} = \frac{R(s)}{(1+\delta_{FSR}^{\mu\mu})(1+\delta_{addFSR}^{\mu\mu})}$$

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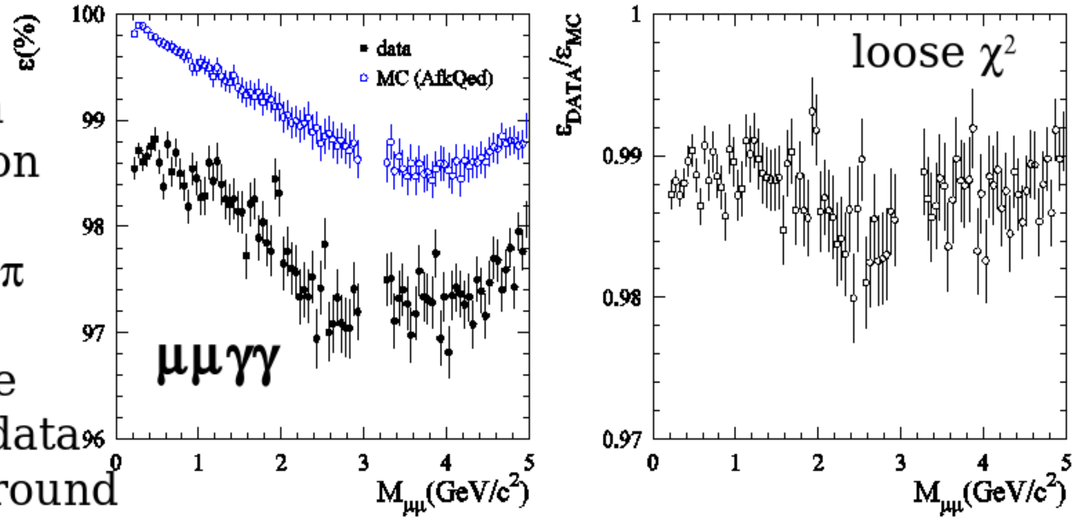
a_μ, BaBar preliminary

χ^2 cut Efficiency Correction

- depends on simulation of ISR (FSR), resolution effects (mostly ISR γ direction) for $\mu\mu$ and $\pi\pi$
- χ^2 cut efficiency can be well measured in $\mu\mu$ data because of low background



- main correction from lack of angular distribution for additional ISR in AfkQed
- common correction: 1% for loose χ^2, 7% for tight χ^2
- additional loss for $\pi\pi$ because of interactions studied with sample of interacting events agreement data/MC

1.00 ± 0.16 loose χ^2

1.07 ± 0.11 tight χ^2

syst error $0.5\text{-}1.5 \times 10^{-3}$

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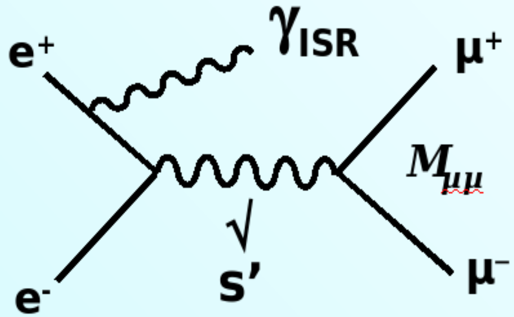
AfkQED

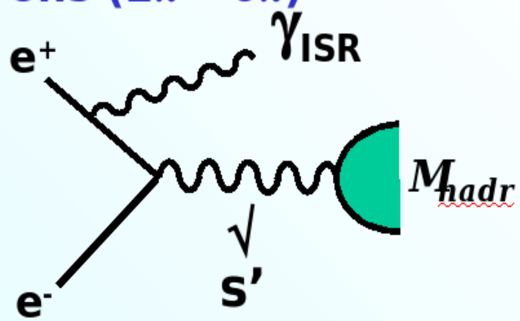
Working Horse: Generator AfkQED

Muons



- Theory: Born section formula according to Arbusov et.al. (hep-ph/9702262)
- ISR, FSR and ISR-FSR-interference
- Extra photon radiation with structure function technique à la Caffo, Czyż, Remiddi (Nuo. Cim. 110A (1997) 515, PLB327, 369)
- Leptonic and hadronic vacuum polarization

Hadrons (2π – 6π)



- Theory: Born ISR description according to Czyż, Kühn (EPJC18 (2001), 497), Basis = EVA-Generator developed for 2π, 4π channel
- No LO-FSR, considered negligible at PEP-II
- NLO-FSR ($1\gamma_{ISR} + 1\gamma_{FSR}$) by means of PHOTOS
- Extra ISR photon radiation with structure function technique à la Caffo, Czyż, Remiddi (Nuo. Cim. 110A (1997) 515, PLB327, 369)
- Modular structure of EVA-gen. allows easily to incorporate new exclusive hadronic channels

Achim Denig
Physics at BABAR

Generator Issues for ISR-

Some remarks on using of the SF

G. Rodrigo, H. C., J. H. Kuhn and M. Szopa,
Eur.Phys.J.C24:71-82,2002.

	$\sqrt{s}$ =1.02 GeV	4 GeV	10.6 GeV
E_γ^{min} (GeV)	**0.01**	**0.1**	**1**
θ_γ (degrees)	$[5, 21]$	$[10, 170]$	$[25, 155]$
θ_π (degrees)	$[55, 125]$	$[20, 160]$	$[30, 150]$
$M^2_{\pi^+\pi^-\gamma}$ (GeV^2)	**0.9**	**12**	**90**

Some remarks on using of the SF

G. Rodrigo, H. C., J. H. Kuhn and M. Szopa, Eur.Phys.J.C24:71-82,2002.

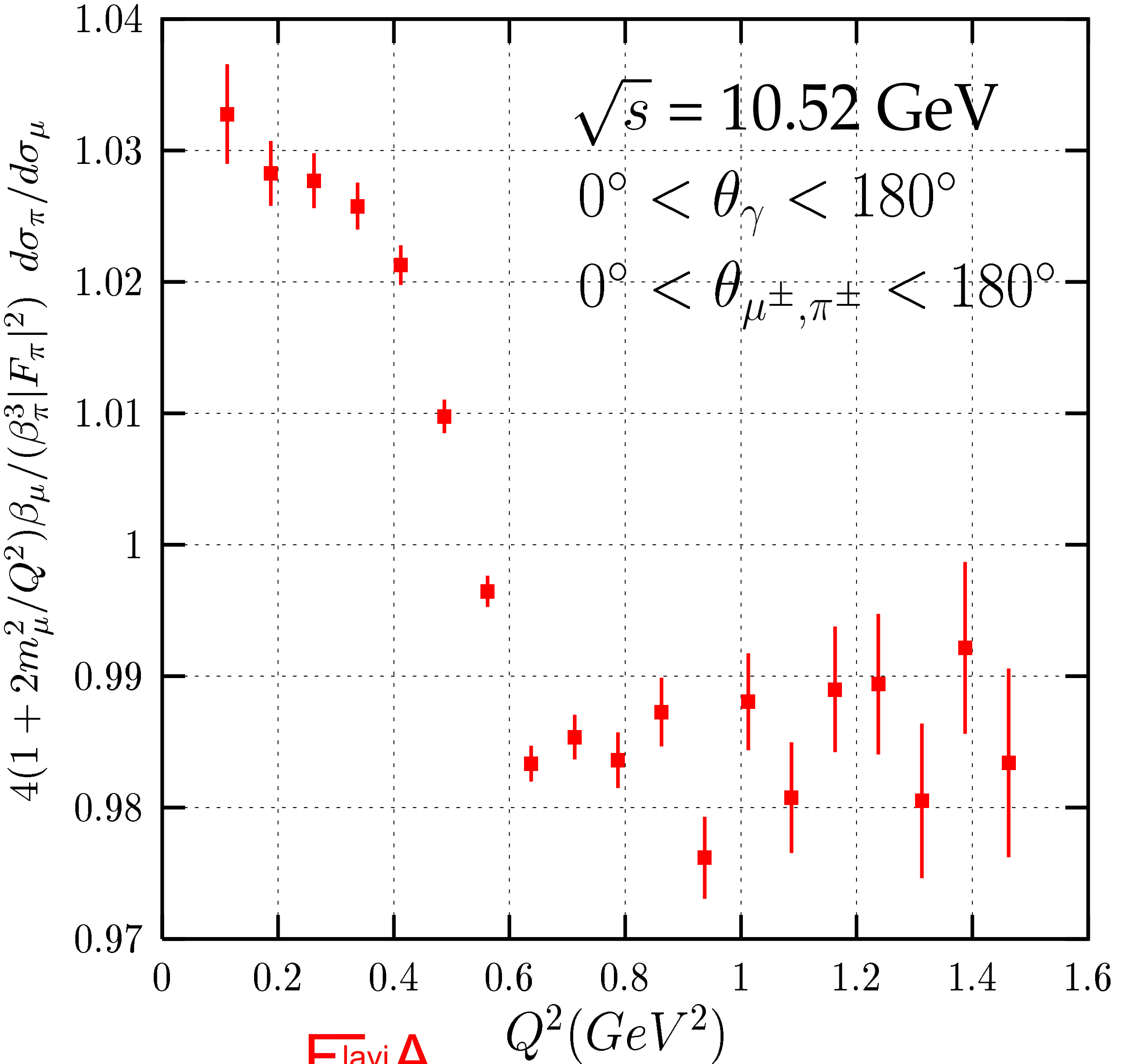
$\sqrt{s}$	=1.02 GeV	4 GeV	10.6 GeV
Born	2.1361 (4)	0.12979 (3)	0.011350 (3)
SF	2.0192 (4)	0.12439 (5)	0.010526 (3)
NLO (1)	2.0332 (5)	0.12526 (5)	0.010565 (4)
NLO (2)	2.4126 (7)	0.14891 (9)	0.012158 (9)

$\pi\pi$ / $\mu\mu$ ratio

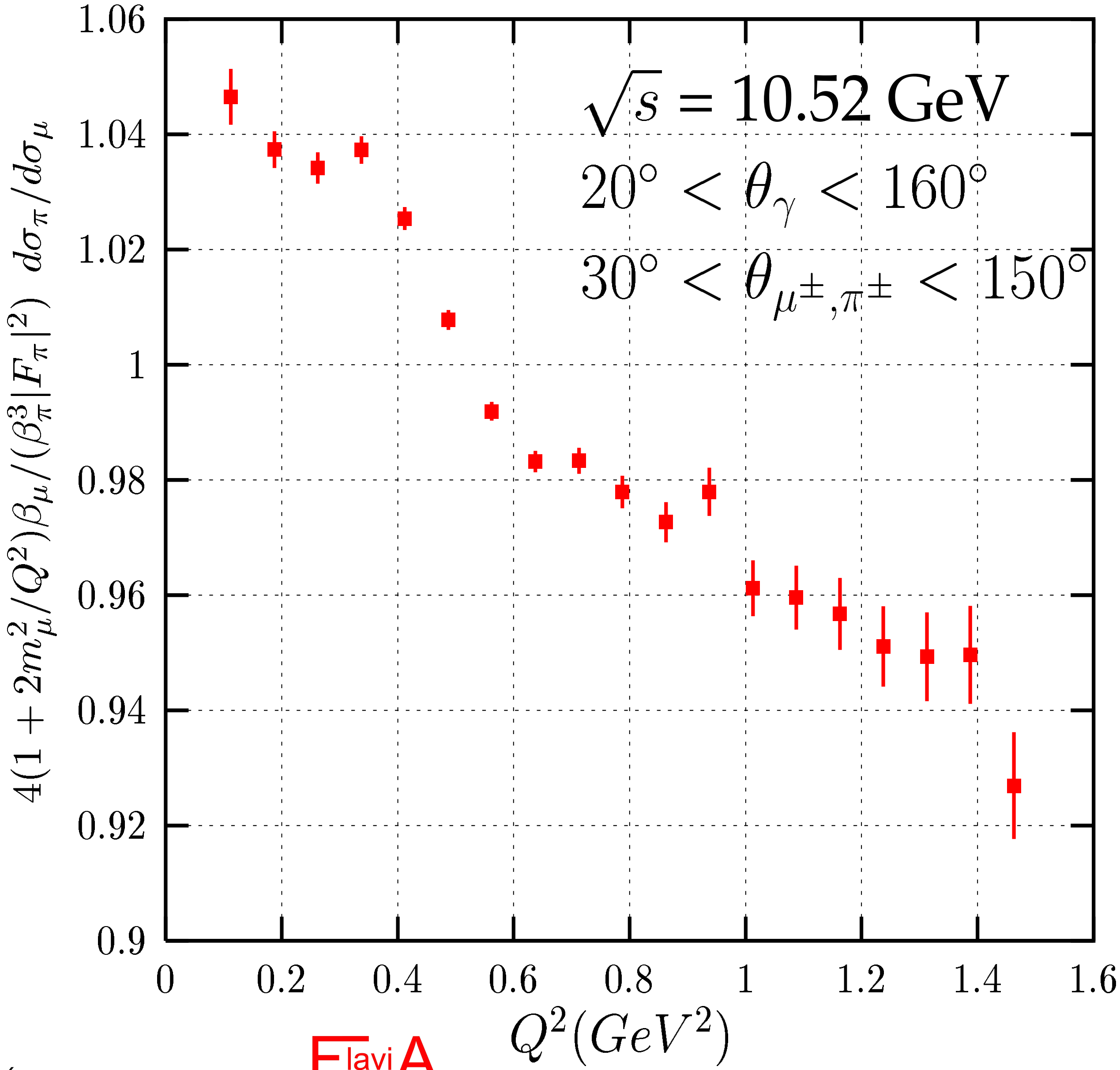
H. C., A. Grzelinska, J. H. Kuhn and G. Rodrigo
Eur.Phys.J.C39:411-420,2005.

$$\mathcal{R}(Q^2) = \frac{4(1+\frac{2m_\mu^2}{Q^2})\beta_\mu \frac{d\sigma_\pi}{dQ^2}}{\beta_\pi^3 |F_\pi(Q^2)|^2 \frac{d\sigma_\mu}{dQ^2}} ,$$

$\pi\pi$ / $\mu\mu$ ratio: FSRNLO



$\pi\pi$ / $\mu\mu$ ratio: FSRNLO



Summary and plans

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

Summary and plans

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

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