Hadrons in Phokhara

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5th Workstop / Thinkstart:
Radiative corrections and Monte Carlo tools for Strong 2020
5th June 2023

PHOKHARA MC generator

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]

F. Campanario, H.C., J. Gluza,

A. Grzelińska, M. Gunia, P. Kisza,

J. H. Kühn, E. Nowak-Kubat, T. Riemann,

G. Rodrigo, Sz. Tracz, A. Wapienik,

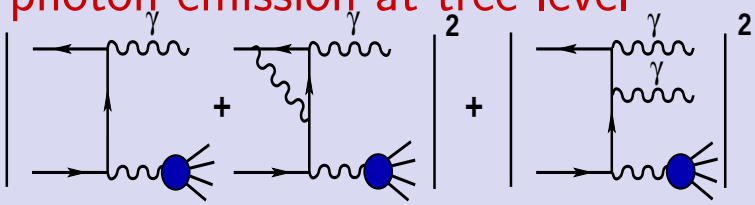
V. Yundin, D. Zhuridov

PHOKHARA 10.0: $\pi^+\pi^-$,$\mu^+\mu^-$,

4π, $\bar{N}N$, 3π, KK,$\Lambda\bar{\Lambda}$, $P\gamma$

$J/\psi, \psi(2S), \chi_{c_1}, \chi_{c_2}$

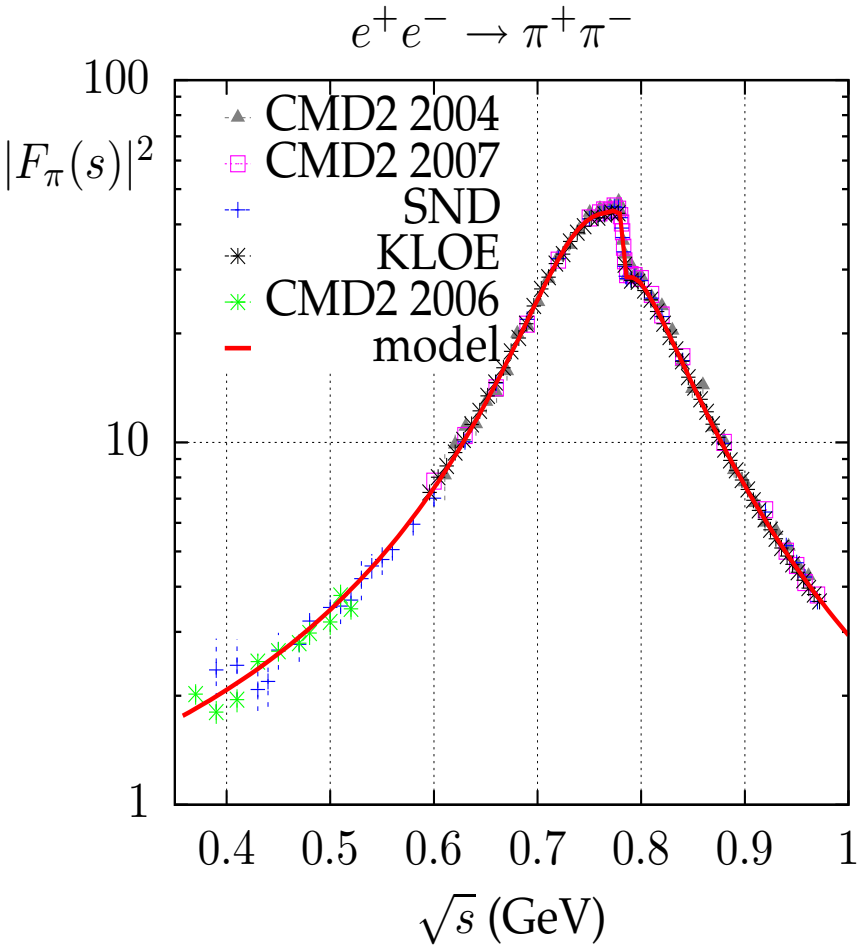
- **ISR at NLO:** virtual corrections to one photon events and two photon emission at tree level

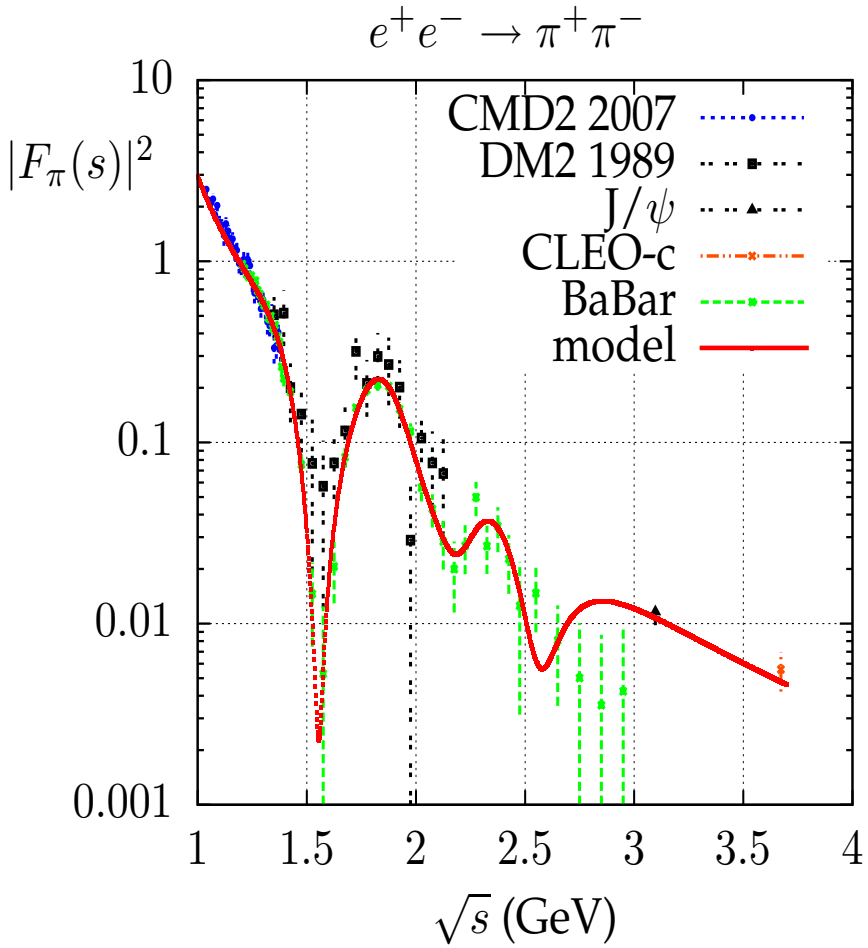


- FSR at NLO:$\pi^+\pi^-$, $\mu^+\mu^-$,K^+K^-, $\bar{p}p$
- tagged or untagged photons
- $e^+e^- \to hadrons$ ($muons$) ISR at NNLO
- Modular structure

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

Pion form factor



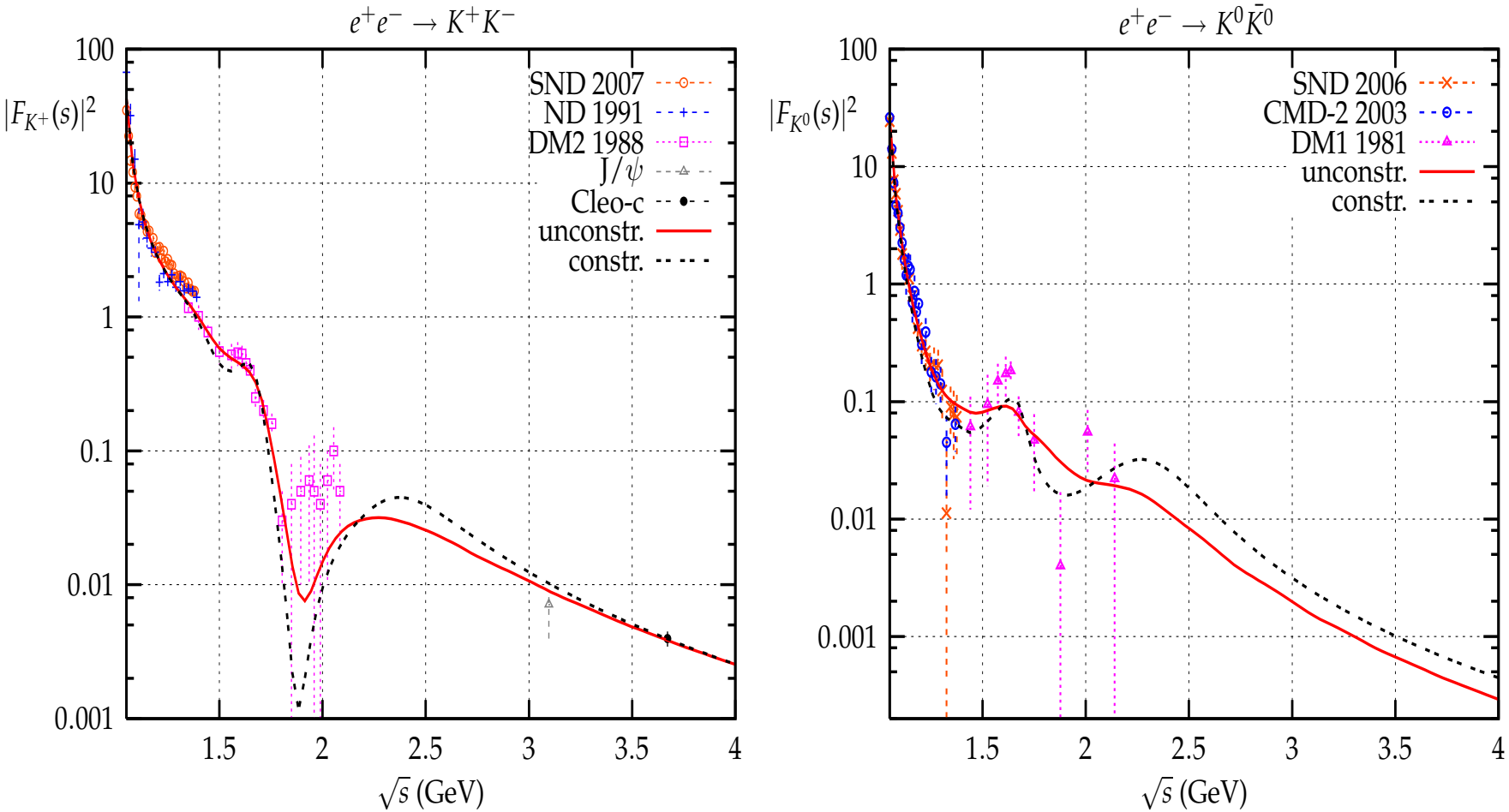


$\chi^2/d.o.f. = 271/270$

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

H. C., A. Grzelińska and J.H. Kühn, Phys.Rev.D81:094014,2010

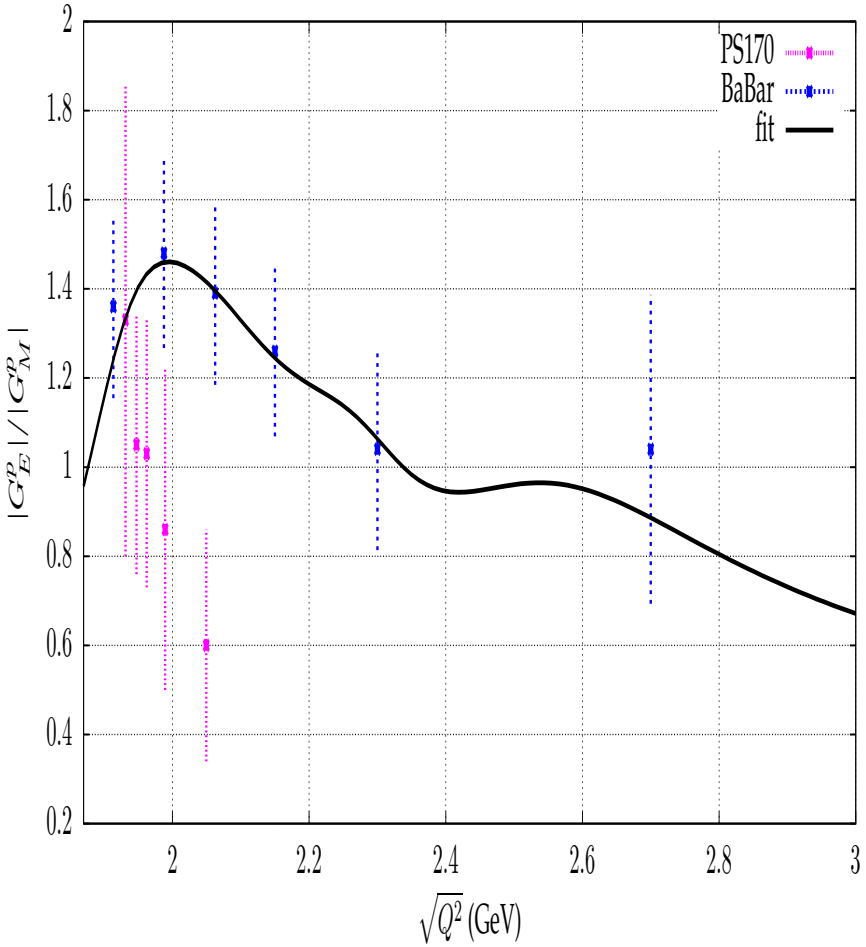
Kaon form factors

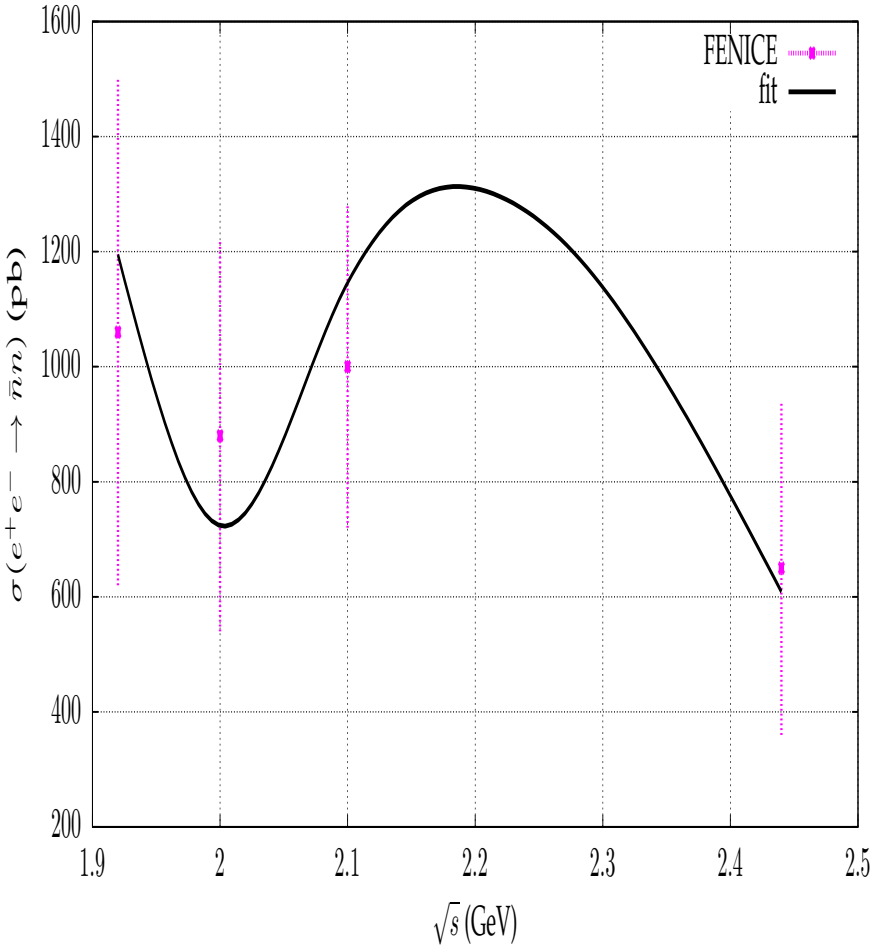


$$\chi^2/d.o.f. = 277/256; 221/260$$

H. C., A. Grzelińska and J.H. Kühn, Phys.Rev.D81:094014,2010

Nucleon form factors

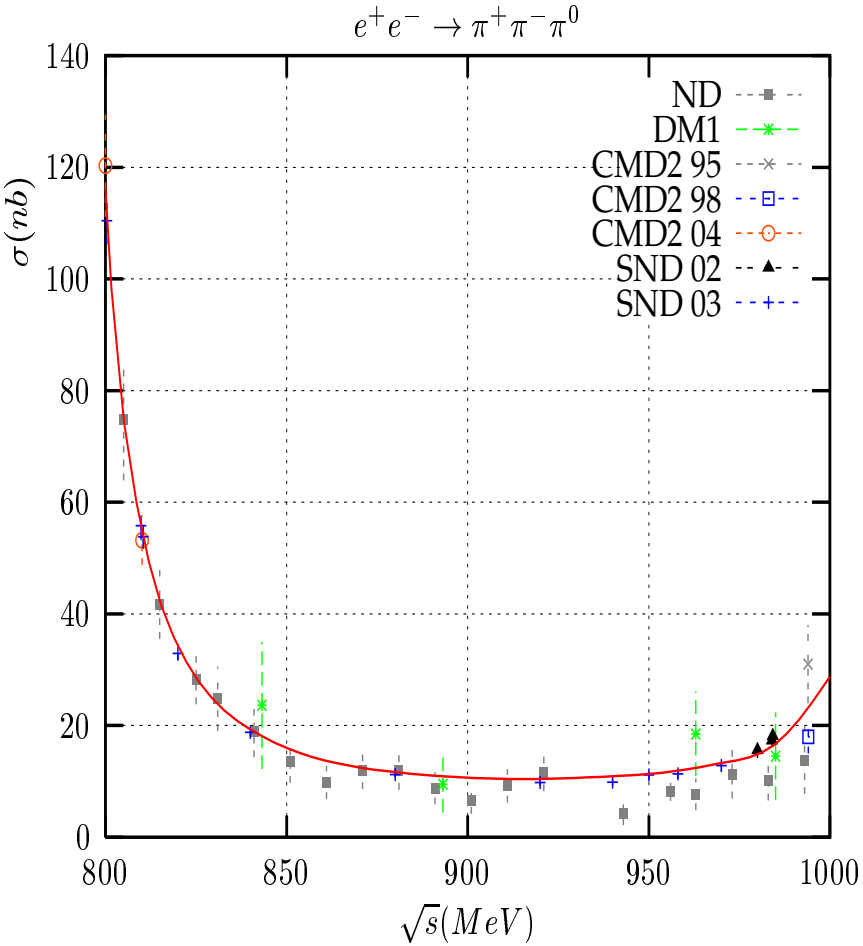


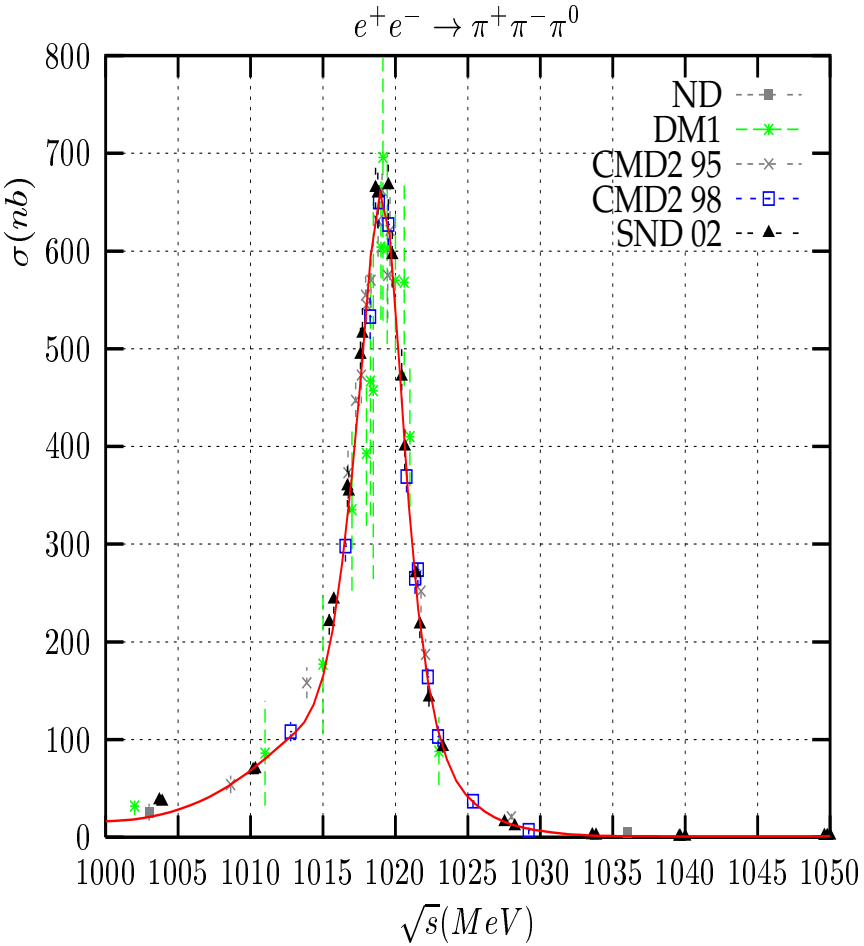


$\chi^2/d.o.f. = 124/130$

H. C., J.H. Kühn and Sz. Tracz, Phys.Rev. D90 (2014) 11, 114021

$\pi^+\pi^-\pi^0$

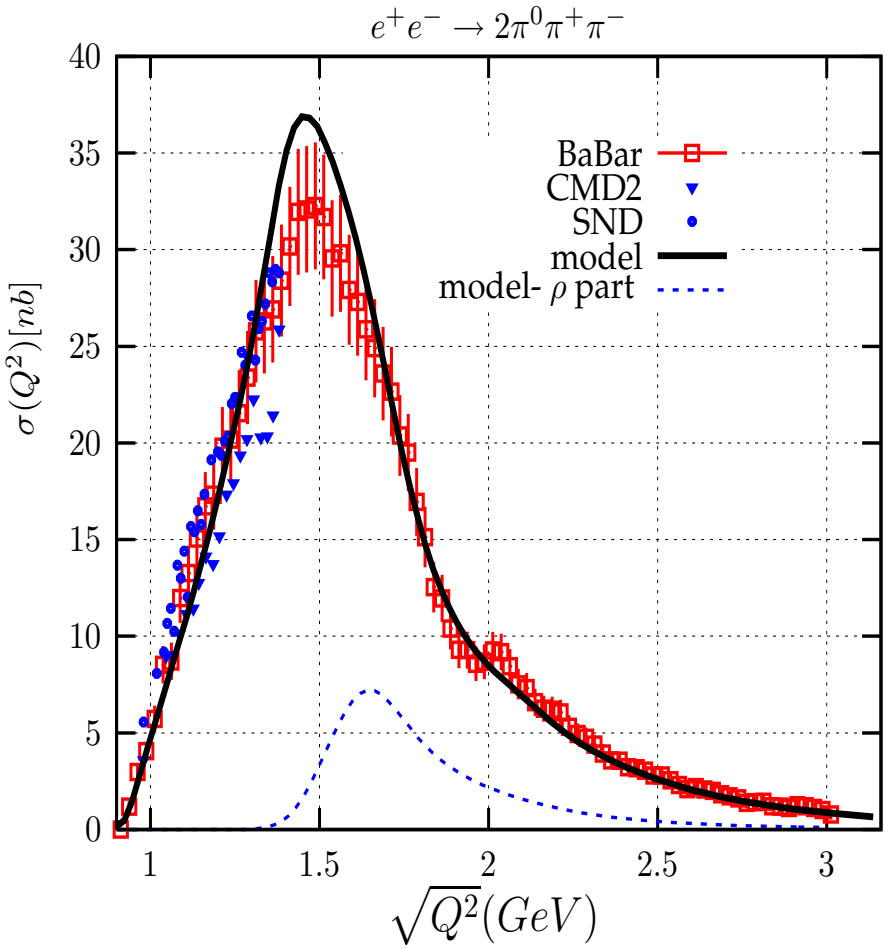


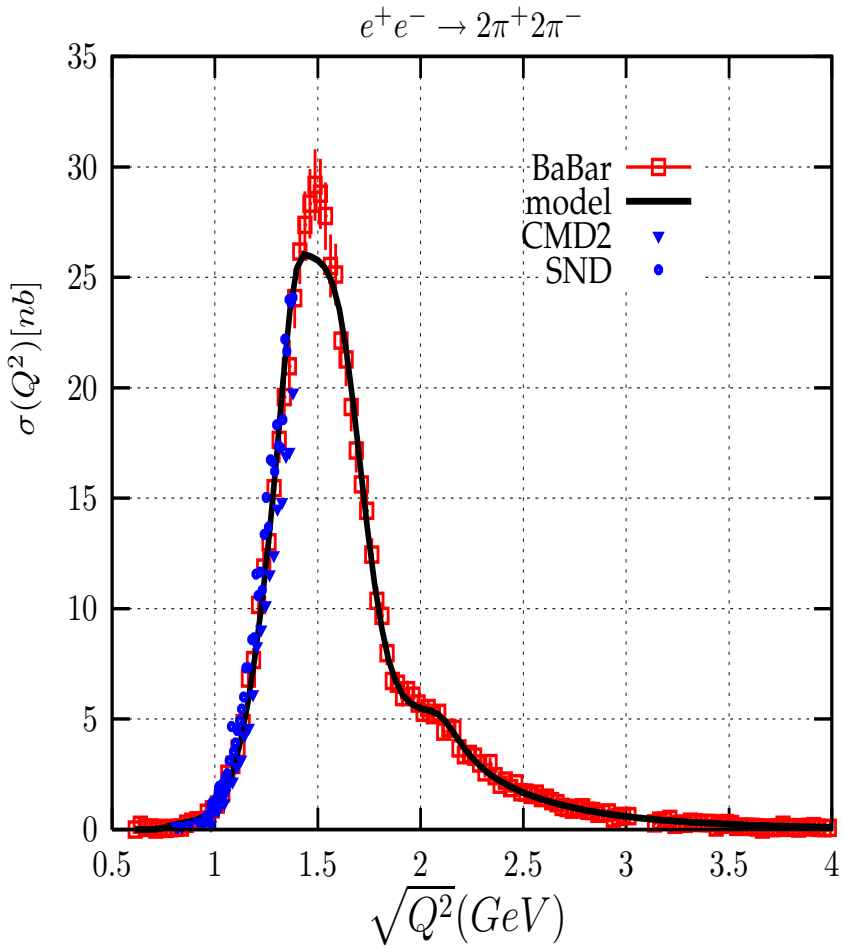


$\chi^2/d.o.f. = 320/281$

H. C., A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur.Phys.J.C 47 (2006) 617

4π





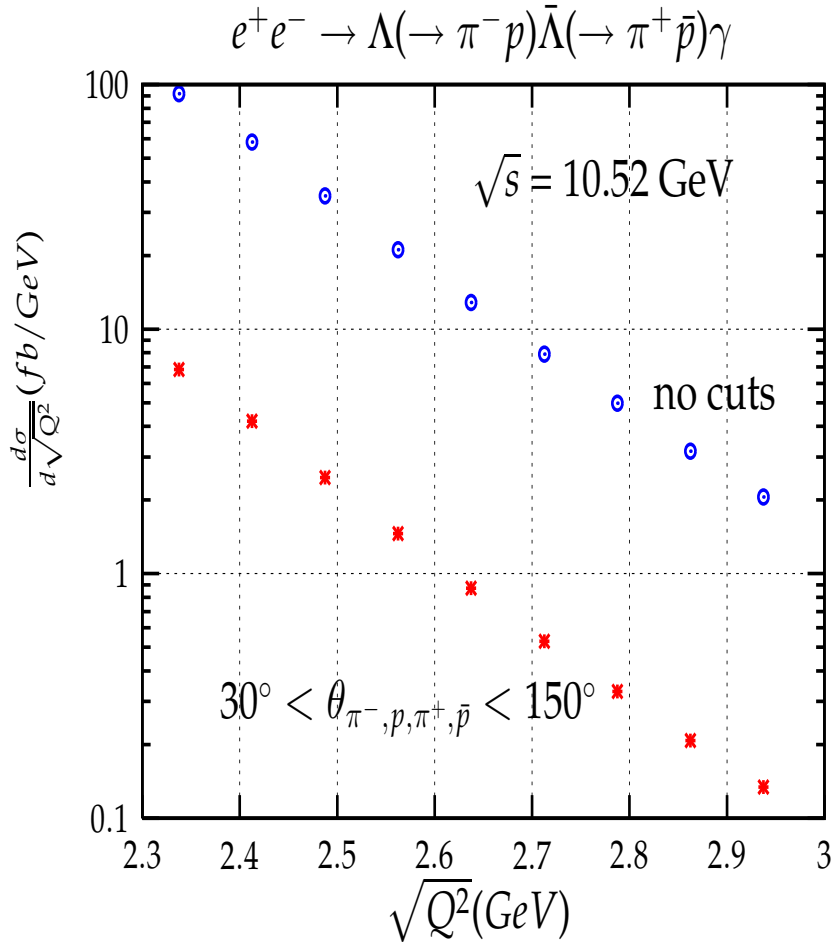
$\chi^2/d.o.f. = 275/287$

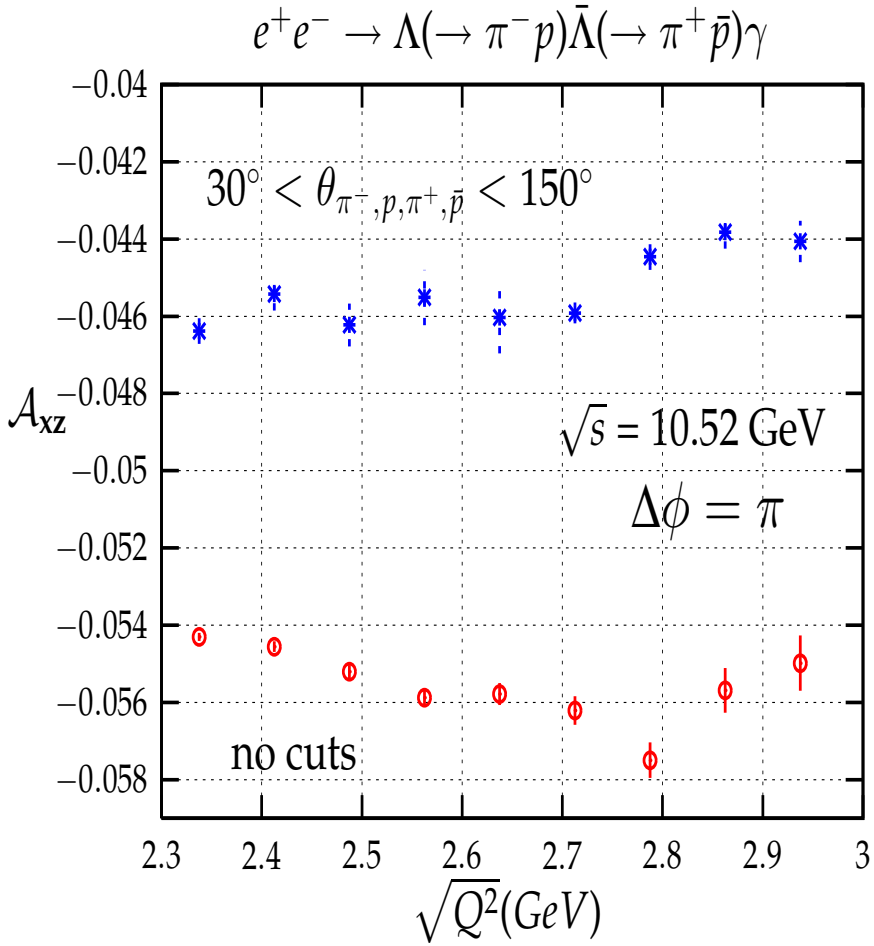
H. C., J.H. Kühn, A. Wapienik, Phys.Rev.D 77 (2008) 114005

H. C., J.H. Kühn, Eur.Phys.J.C 18 (2001) 497

$e^+e^- \to \bar{\Lambda}(\to \pi^+\bar{p})\Lambda(\to \pi^- p)\gamma$

FF from Körner et al. Phys. Rev. D 16 (1977) 2165



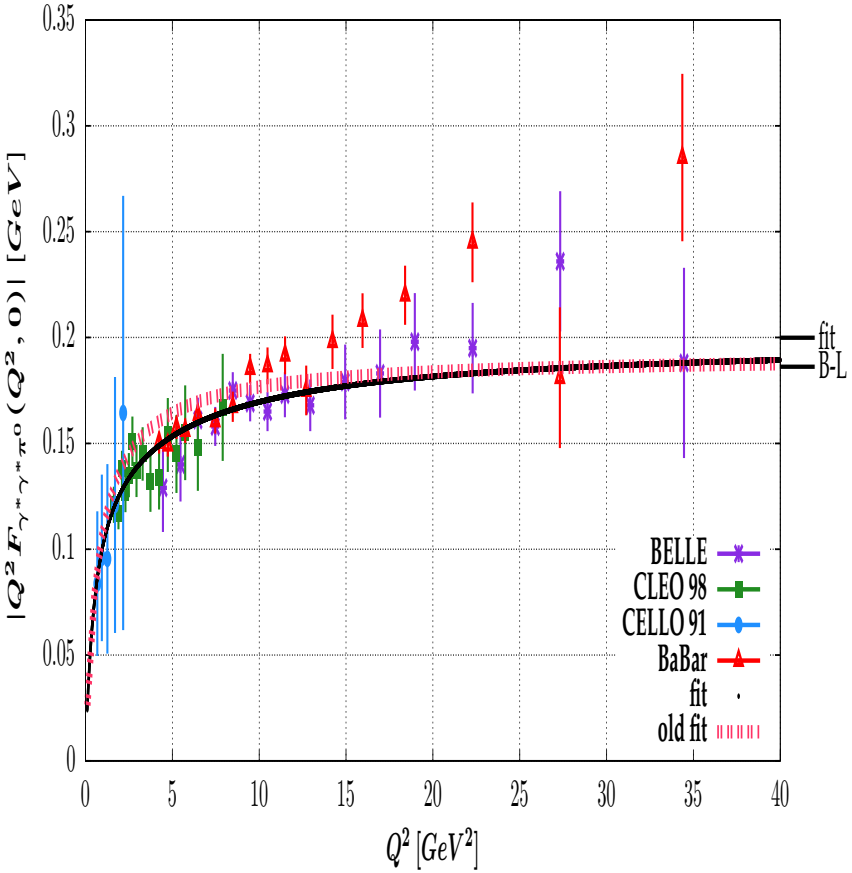


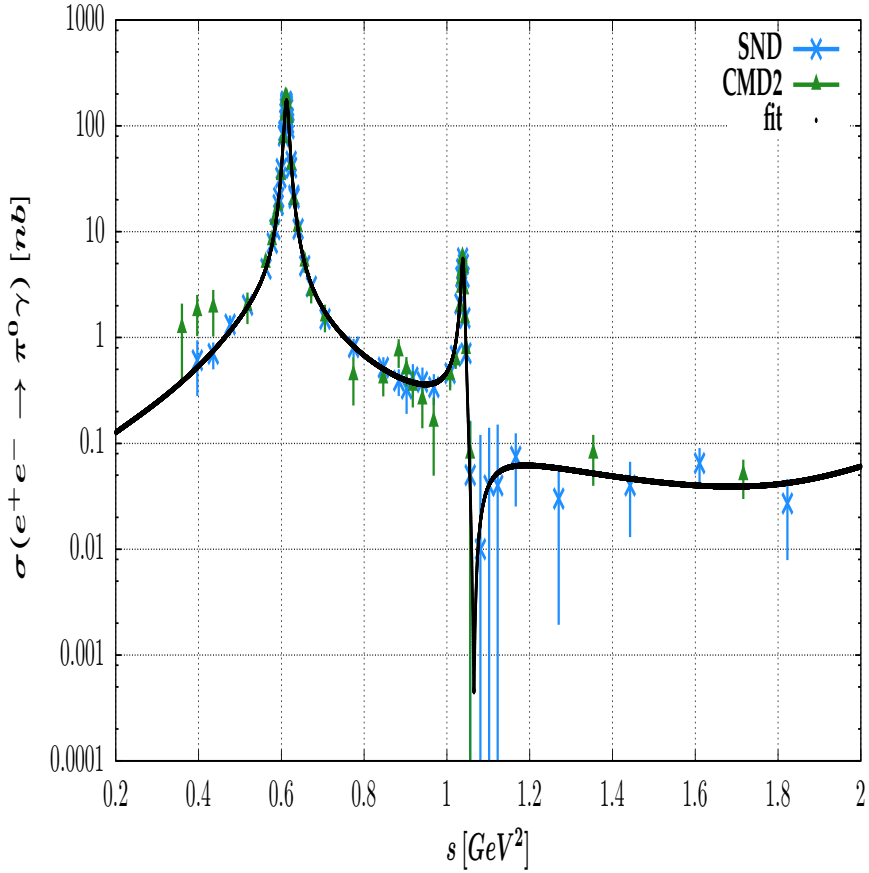
At B-factories we expect about 130 events per 100 fb^{-1}.

H. C., A. Grzelińska and J.H. Kühn, Phys.Rev.D 75 (2007) 074026

$e^+e^- \to P\gamma(\gamma)$

Transition form factors needed





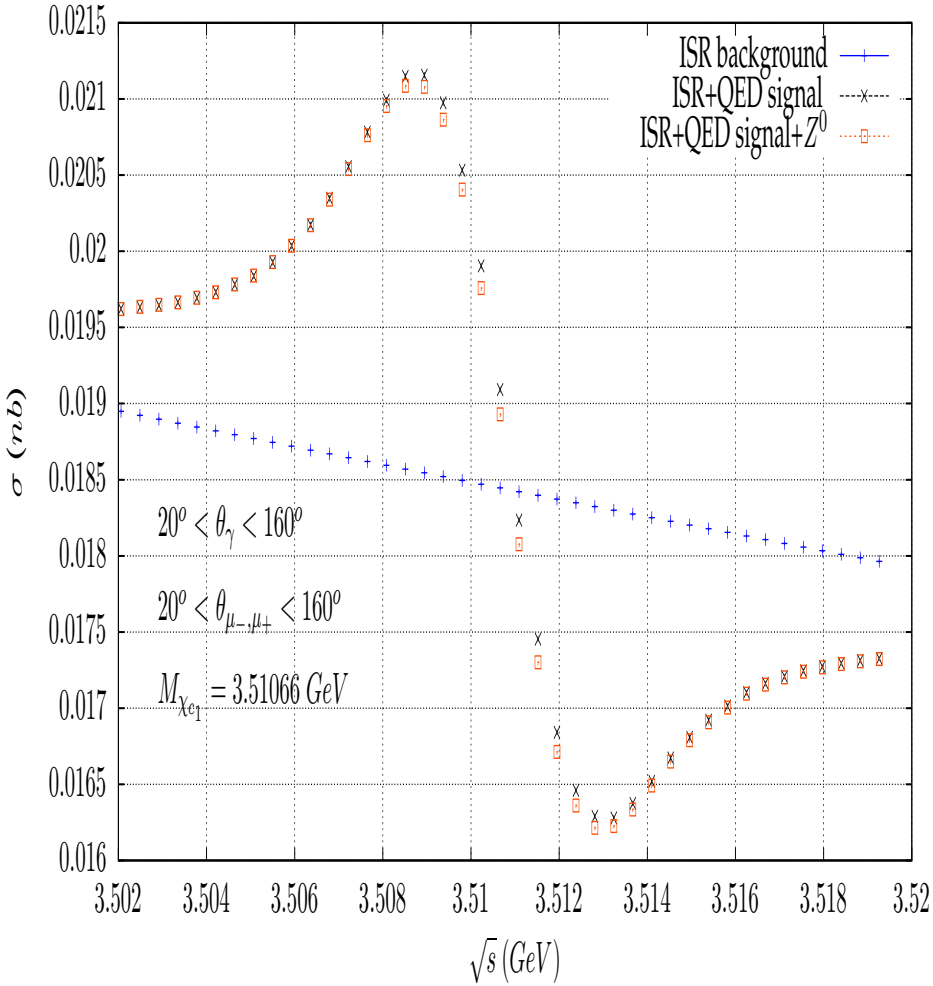
$\chi^2/d.o.f. = 454/519; 415/514$

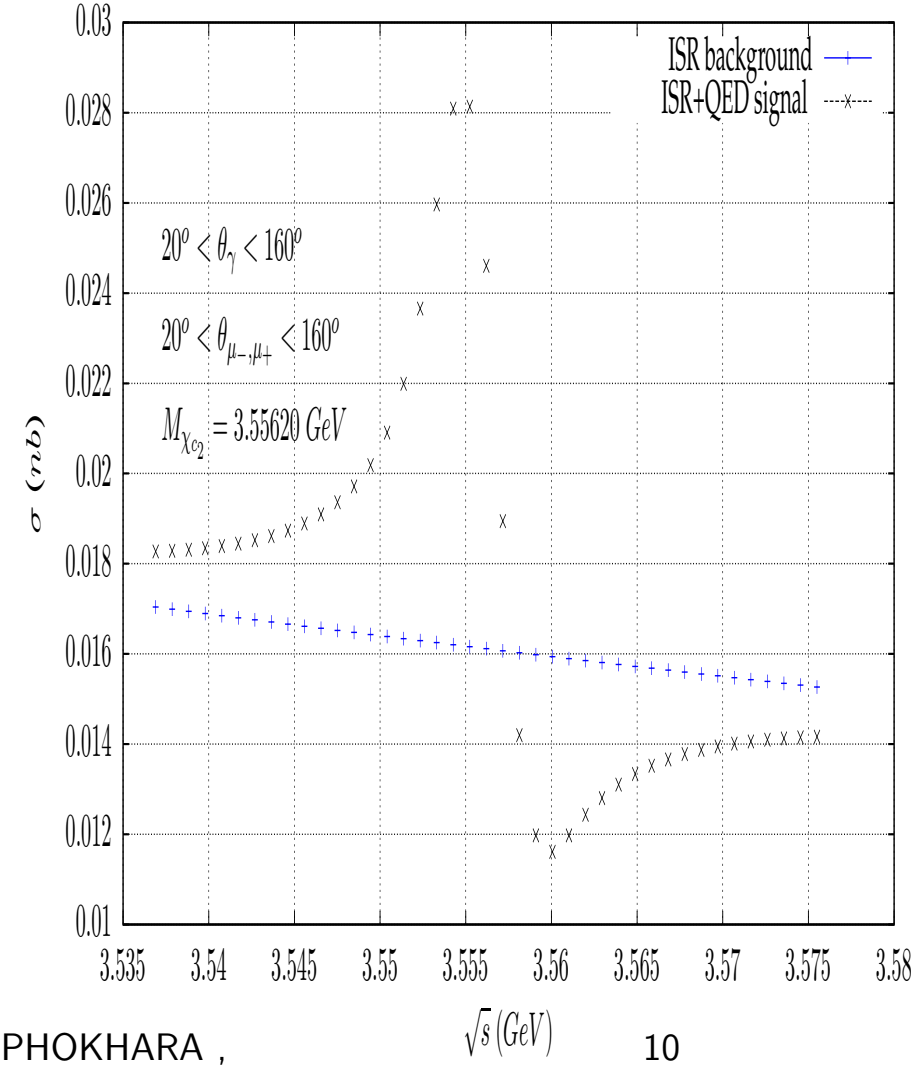
H. Czyż, P.Kisza, Sz. Tracz, Phys.Rev. D97 (2018), 016006

$J/\psi, \psi(2S), \chi_{c1}, \chi_{c2}$

H. Czyż, J. H. Kühn, Sz. Tracz, Phys. Rev. D94 (2016), 034033

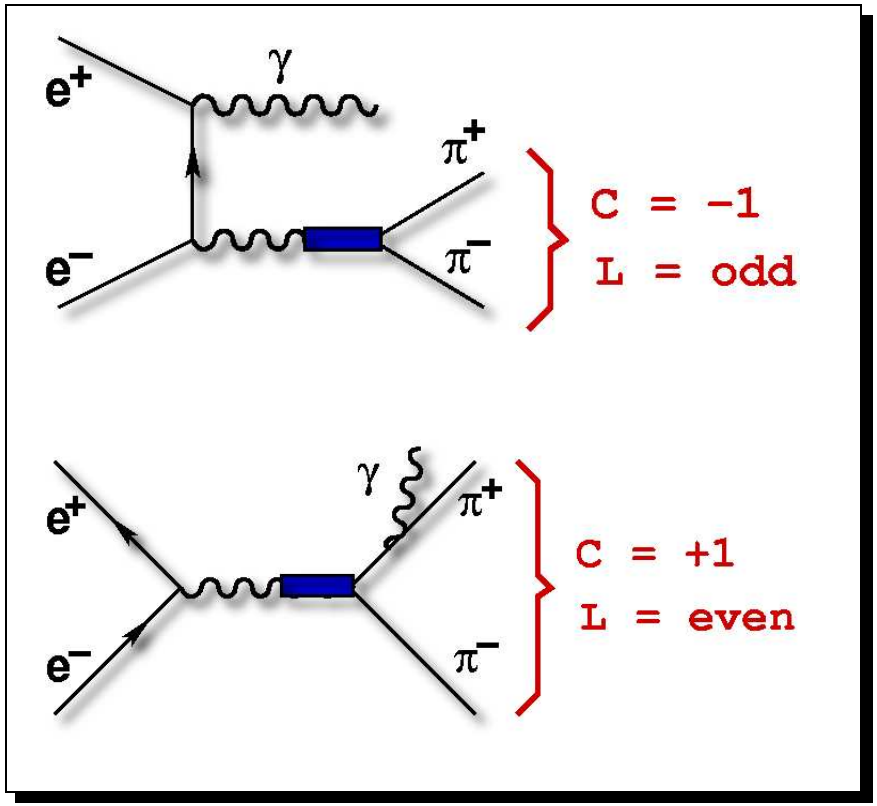
$$e^+e^- \to \mu^+\mu^-\gamma,\ e^+e^- \to \chi_{c_i}(\to J/\psi(\to \mu^+\mu^-)\gamma)$$





Tests of a FSR model

interference:

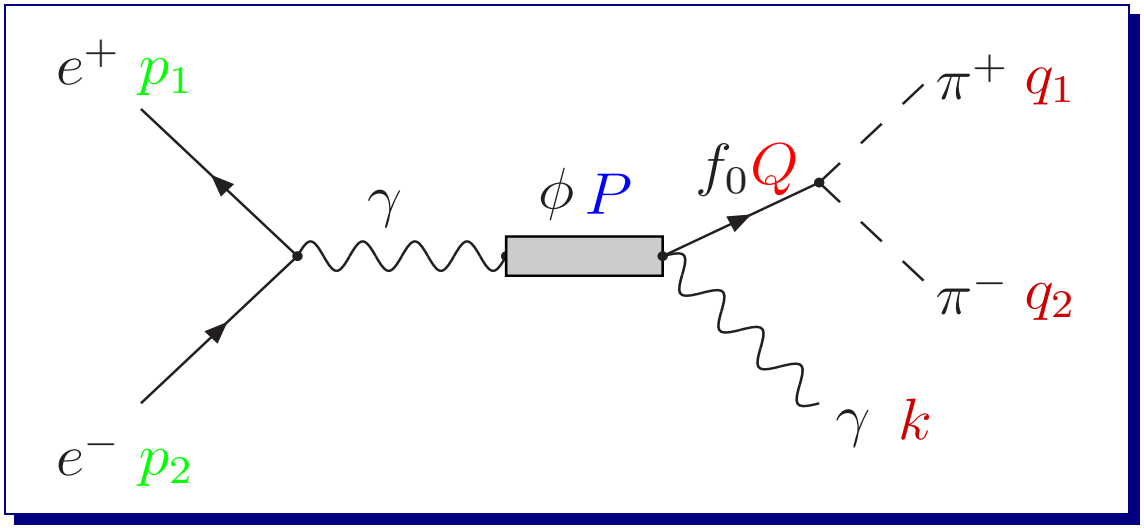


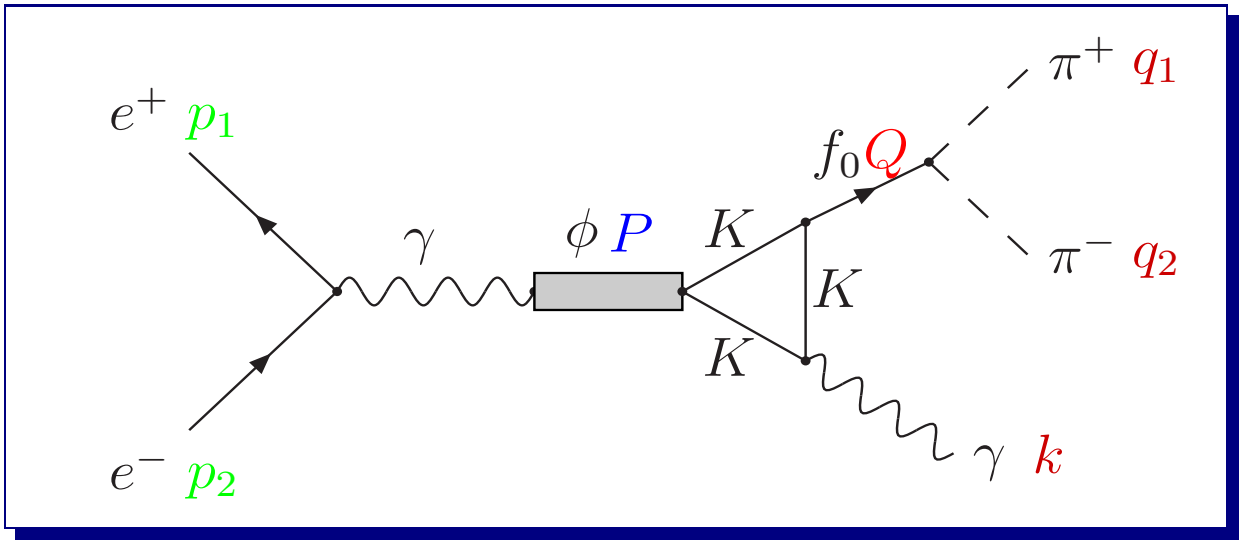
- interference odd under $\pi^+ \leftrightarrow \pi^-$
- asymmetric differential distribution: $\int$ interf. $= 0$

$$A(\theta) = \frac{N^{\pi^+}(\theta) - N^{\pi^-}(\theta)}{N^{\pi^+}(\theta) + N^{\pi^-}(\theta)}$$

FSR at KLOE, additional contributions:

$$e^+e^- \to \phi^* \to (f_0(980)_{f_0} + f_0(600)_\sigma)\gamma \to \pi\pi\gamma$$





Charge asymmetries

⇒ forward-backward asymmetry defined for π^+

$$\mathcal{A}_{FB}(Q^2) = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)}(Q^2)$$

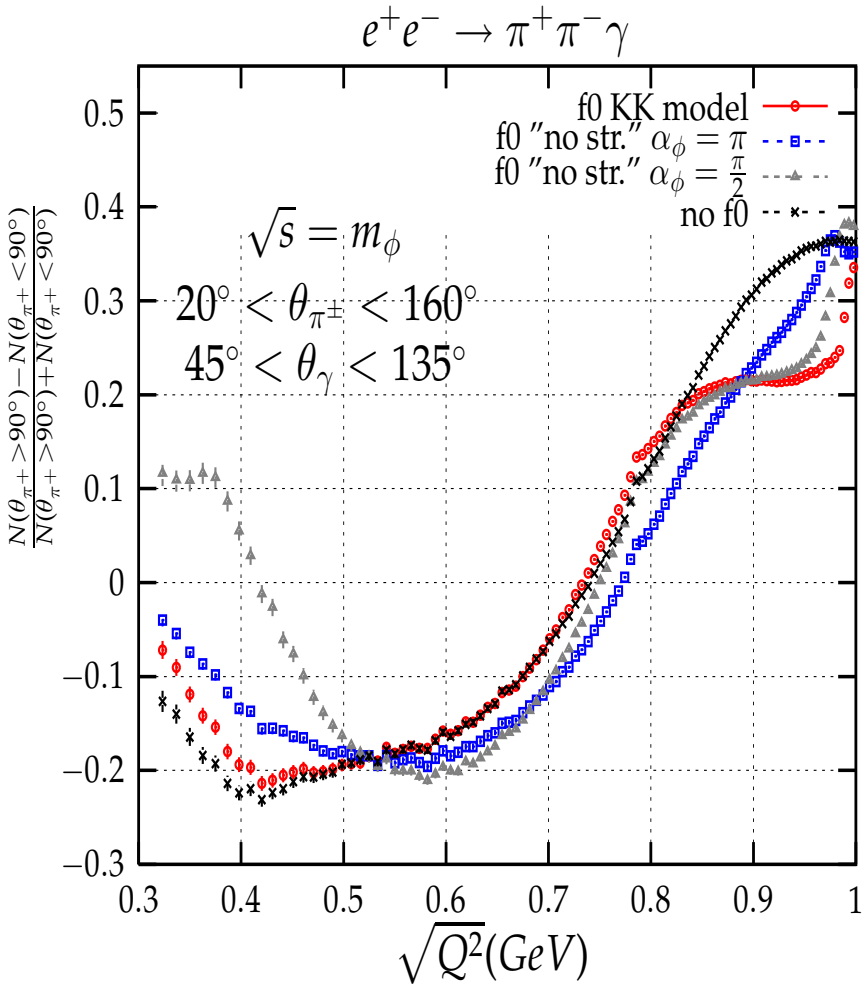
⇒ charge asymmetry

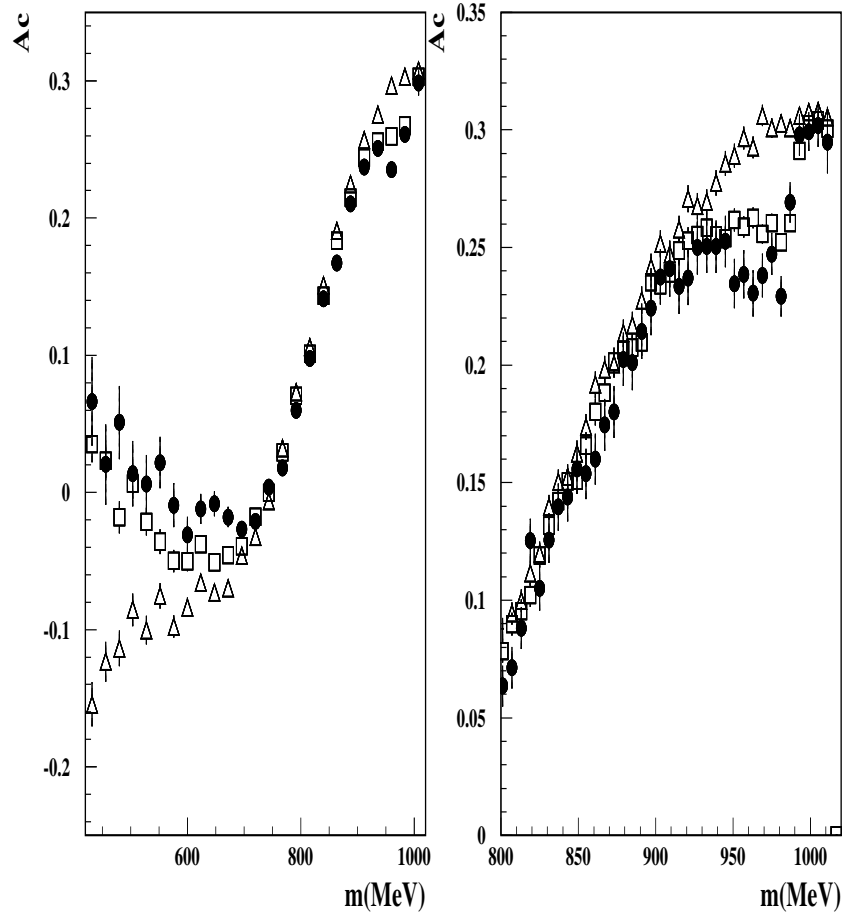
$$\mathcal{A}_C(\theta_\pi) = \frac{N(\pi^+) - N(\pi^-)}{N(\pi^+) + N(\pi^-)}(\theta_\pi)$$

Test of a FSR model

H. Czyż, A. Grzelińska and J. H. Kühn, Phys.Lett.B611:116,2005

KLOE Collaboration: Phys.Lett.B634:148,2006





'Backlook'

It was a pleasure to work in that field
for about 20 years.