PHOKHARA 7.0 Monte Carlo generator: the narrow resonances implementation and new pion and kaon form factors.

H. CZYŻ, IF, UŚ, Katowice

TAU 2010, Manchester

Based on:

H. Czyż, J. H. Kühn and A. Wapienik,

"Four-pion production in tau decays and e+e- annihilation:

an update,"

Phys. Rev. D **77** (2008) 114005

H. Czyż, J. H. Kühn

"Strong and Electromagnetic J/psi and psi(2S) Decays

into Pion and Kaon Pairs,"

Phys. Rev. D **80** (2009) 034035

H. Czyż, A. Grzelińska and J. H. Kühn

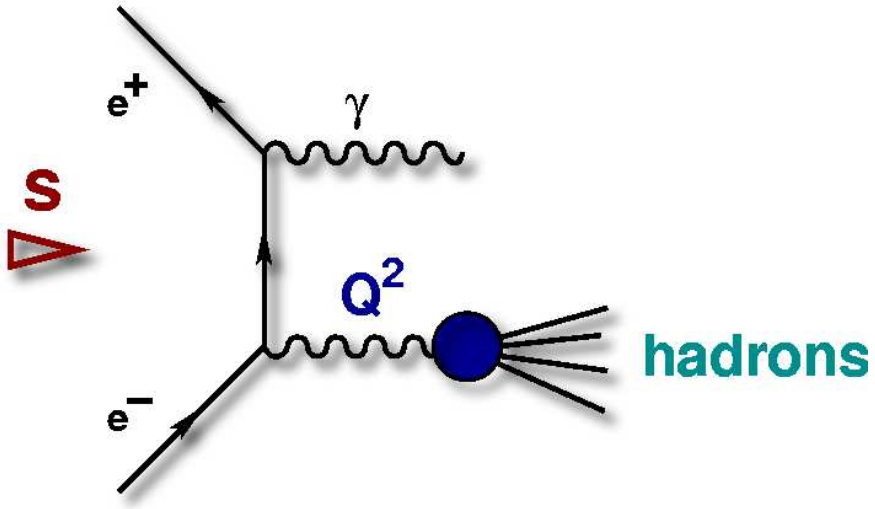
'Narrow resonances studies with the radiative return method,"

Phys. Rev. D **81** (2010) 094014

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

MC generators needed

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.]

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

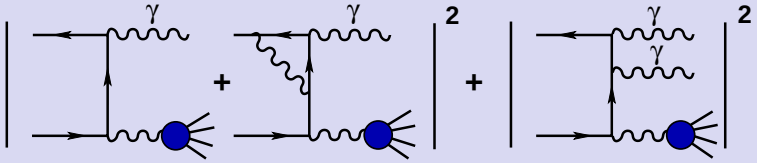
- ISR at LO + Structure Function

[Czyż, Kühn,2000]

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

PHOKHARA 7.0: $\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda(\to\cdots)\bar{\Lambda}(\to\cdots)$, $J/\psi, \psi(2S)$

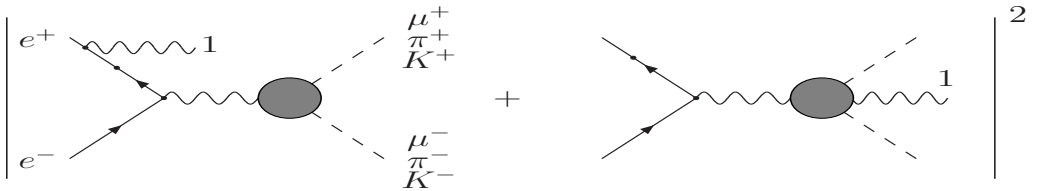
- **ISR at NLO:** virtual corrections to one photon events and two photon emission at tree level



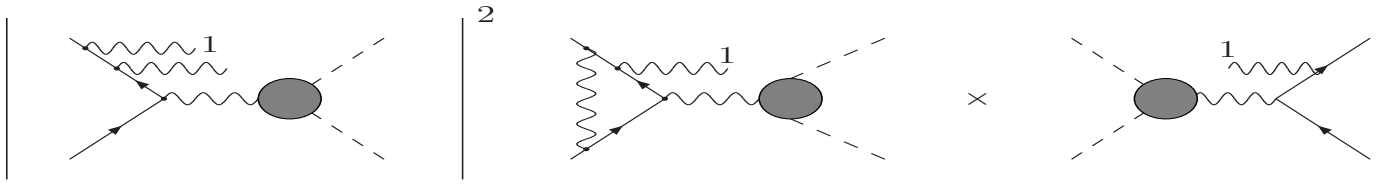
- FSR at NLO:$\pi^+\pi^-$, $\mu^+\mu^-$,K^+K^-
- tagged or untagged photons
- Modular structure

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

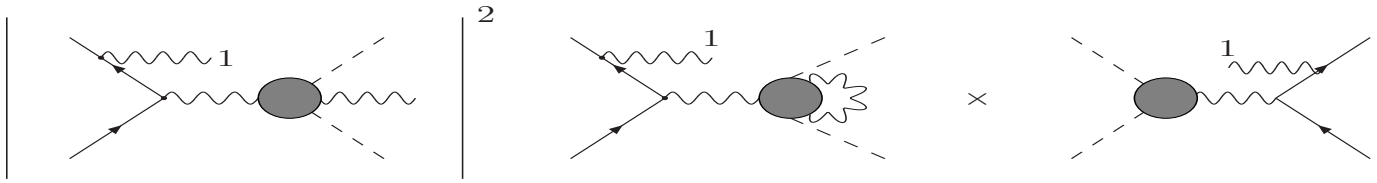
Contributing amplitudes



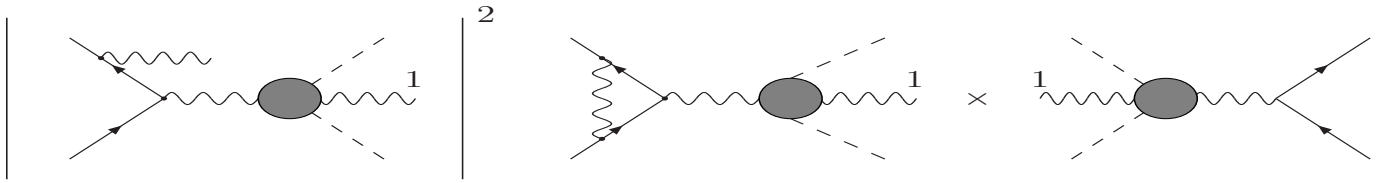
$|M_{\gamma_1,LOISR} + M_{\gamma_1,LOFSR}|^2$



$|M_{2\gamma,ISR}|^2$ $\quad 2\ \mathrm{Re}(M_{\gamma_1,NLOISR} \times M^{\dagger}_{\gamma_1,LOISR})$



$|M_{\gamma_1,ISR\ ;\ \gamma,FSR}|^2$ $\quad 2\ \mathrm{Re}(M^{NLOFSR}_{\gamma_1,LOISR} \times M^{\dagger}_{\gamma_1,LOISR})$



$|M_{\gamma,ISR\ ;\ \gamma_1,FSR}|^2$ $\quad 2\ \mathrm{Re}(M^{NLOISR}_{\gamma_1,LOFSR} \times M^{\dagger}_{\gamma_1,LOFSR})$

%

The cross section

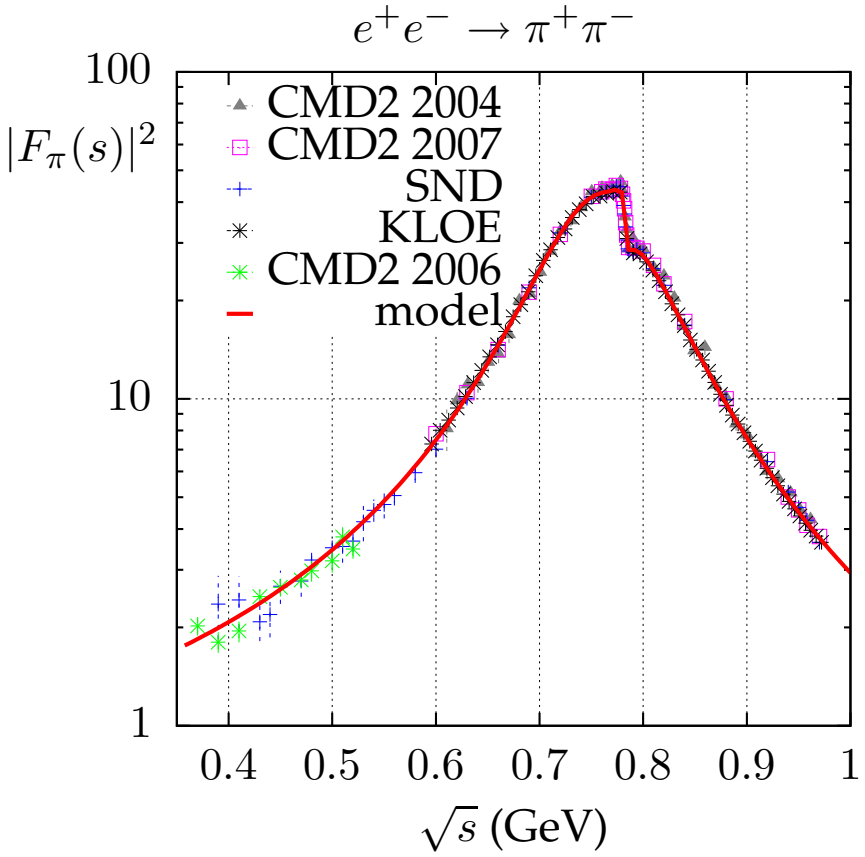
$$
\begin{aligned}
&d\sigma = \\
&|M_{\gamma_1,LOISR} \cdot C^{VP}_{R,P}(Q^2) + M_{\gamma_1,LOFSR} \cdot C^{VP}_{R,P}(s)|^2 d\Phi_1 \\
&+|M_{2\gamma,ISR} \cdot C^{VP}_{R,P}(Q^2)|^2 d\Phi_2 \\
&+2\,\mathrm{Re}(M_{\gamma_1,NLOISR} \times M^{\dagger}_{\gamma_1,LOISR}) \cdot |C^{VP}_{R,P}(Q^2)|^2 d\Phi_1 \\
&+|M_{\gamma_1,ISR\,;\,\gamma,FSR} \cdot C^{VP}_{R,P}((Q+k_\gamma)^2)|^2 d\Phi_2 \\
&+2\,\mathrm{Re}(M^{NLOFSR}_{\gamma_1,LOISR} \times M^{\dagger}_{\gamma_1,LOISR}) \cdot |C^{VP}_{R,P}(Q^2)|^2 d\Phi_1 \\
&+|M_{\gamma,ISR\,;\,\gamma_1,FSR} \cdot C^{VP}_{R,P}((Q+k_{\gamma_1})^2)|^2 d\Phi_2 \\
&+2\,\mathrm{Re}(M^{NLOISR}_{\gamma_1,LOFSR} \times M^{\dagger}_{\gamma_1,LOFSR}) \cdot |C^{VP}_{R,P}(s)|^2 d\Phi_1\,,
\end{aligned}
$$

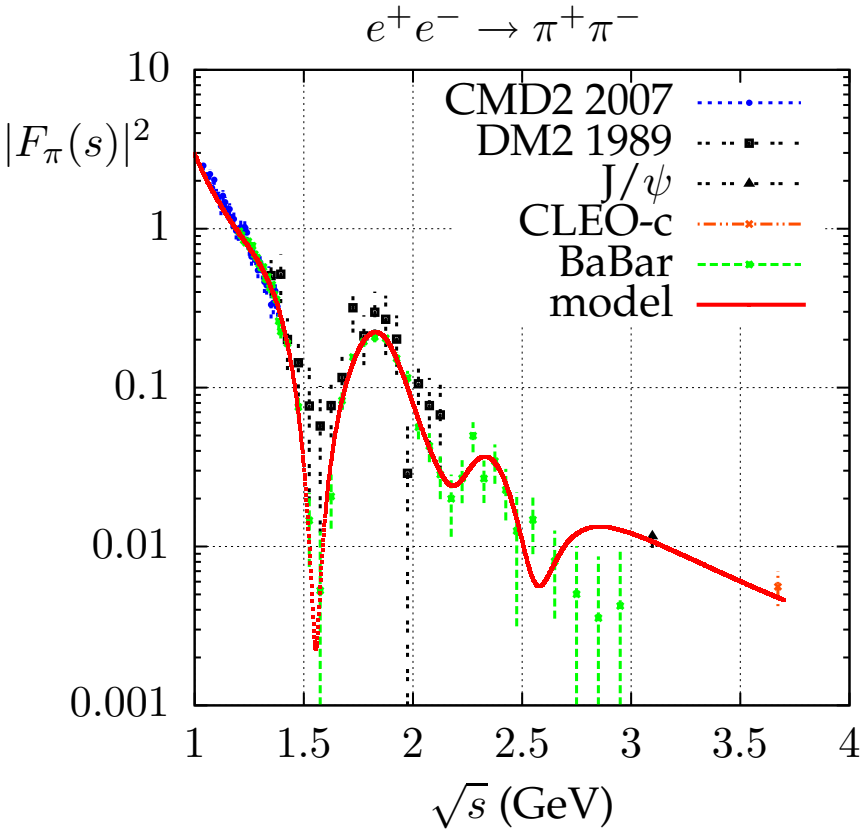
The cross section ...

$$C^{VP}_{R,P}(s) = \frac{1}{1-\Delta\alpha(s)} - \frac{3\Gamma^{\phi}_{e}}{\alpha m_{\phi}} BW_{\phi}(s)\delta_{P} + C_{J/\psi,P}(s) + C_{\psi(2S),P}(s) \ ,$$

$$C_{R,P}(s) = \frac{3\sqrt{s}}{\alpha} \frac{\Gamma^{R}_{e}(1+c^{R}_{P})}{s - M^{2}_{R} + i\Gamma_{R}M_{R}} \ .$$

The 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

The pion form factor

$$F_\pi(s) = \left[\sum_{n=0}^{N} c^\pi_{\rho_n} BW_{\rho_n}(s)\right]_{fit} + \left[\sum_{n=(N+1)}^{\infty} c^\pi_{\rho_n} BW_{\rho_n}(s)\right]_{dQCD}$$

$$BW_{\rho_n}(s) = \frac{m^2_{\rho_n} + H(0)}{m^2_{\rho_n} - s + H(s) - i\sqrt{s}\,\Gamma_{\rho_n}(s)}$$

The pion form factor

ω contribution

$$c^{\pi}_{\rho_0} BW_{\rho_0}(s) \to \frac{c^{\pi}_{\rho_0} BW_{\rho_0}(s)}{1 + c^{\pi}_{\omega}} (1 + c^{\pi}_{\omega} BW_{\omega})$$

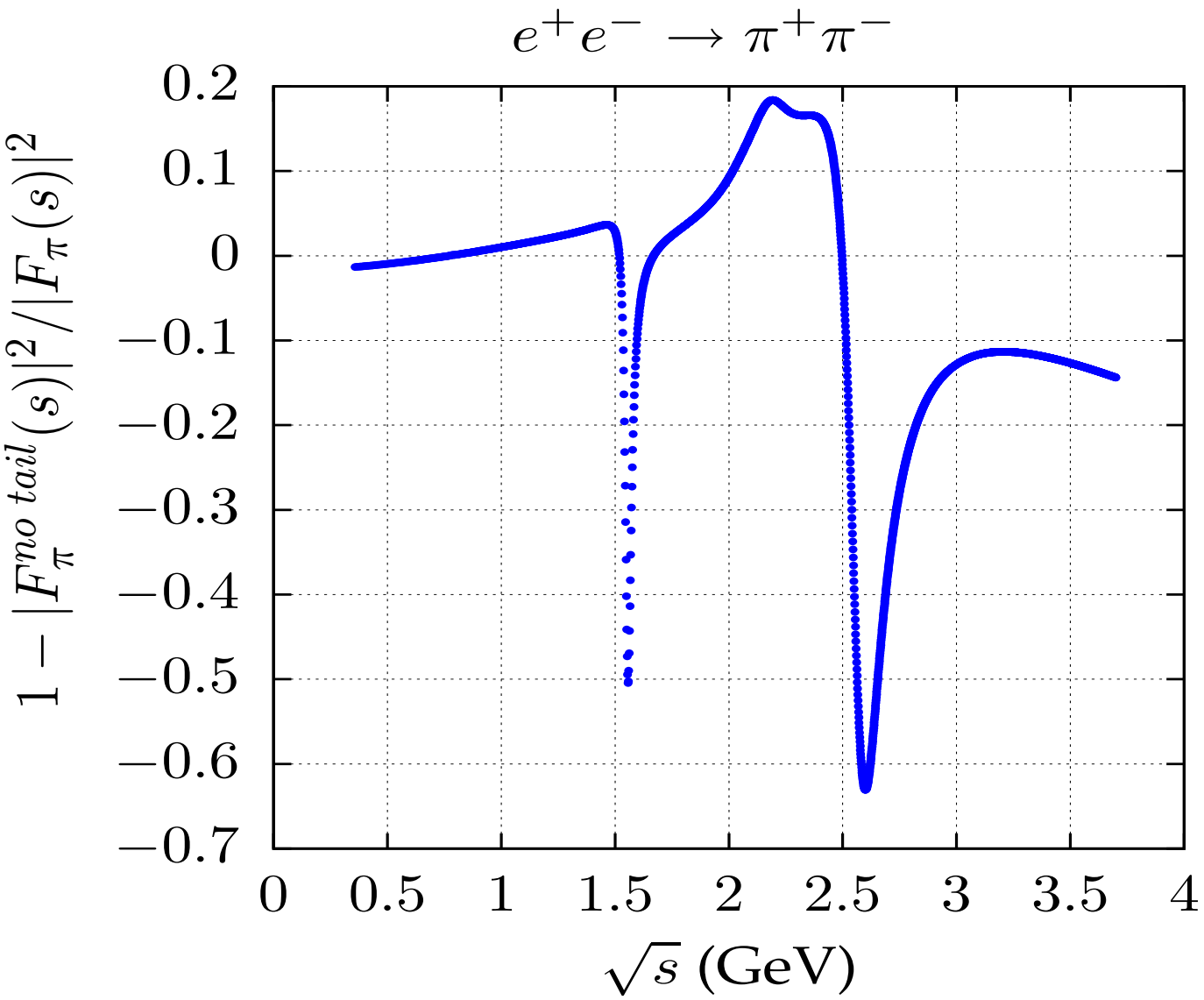
expansion parameters

$$c^{\pi}_{\rho_n} = \frac{(-1)^n \Gamma(\beta - 1/2)}{\alpha' m^2_{\rho_n} \sqrt{\pi} \Gamma(n+1) \Gamma(\beta - 1 - n)} \,,$$

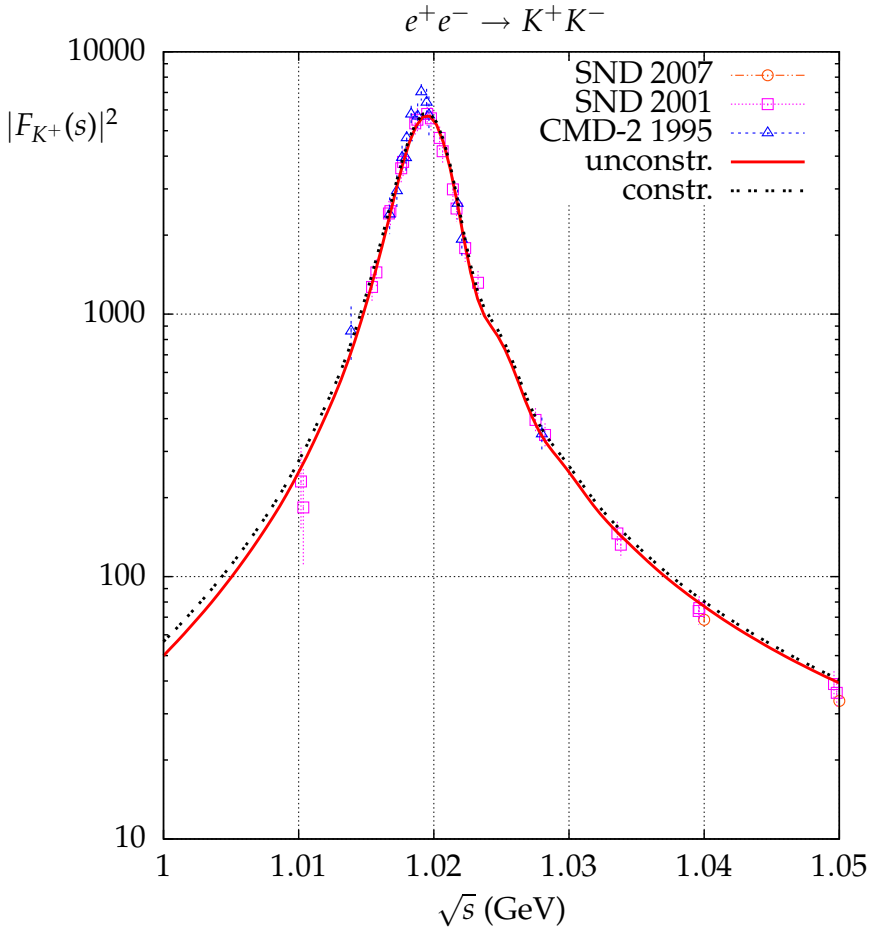
$$\alpha' = 1/(2m^2_{\rho_0}), \quad m^2_{\rho_n} = m^2_{\rho_0} (1 + 2n)$$

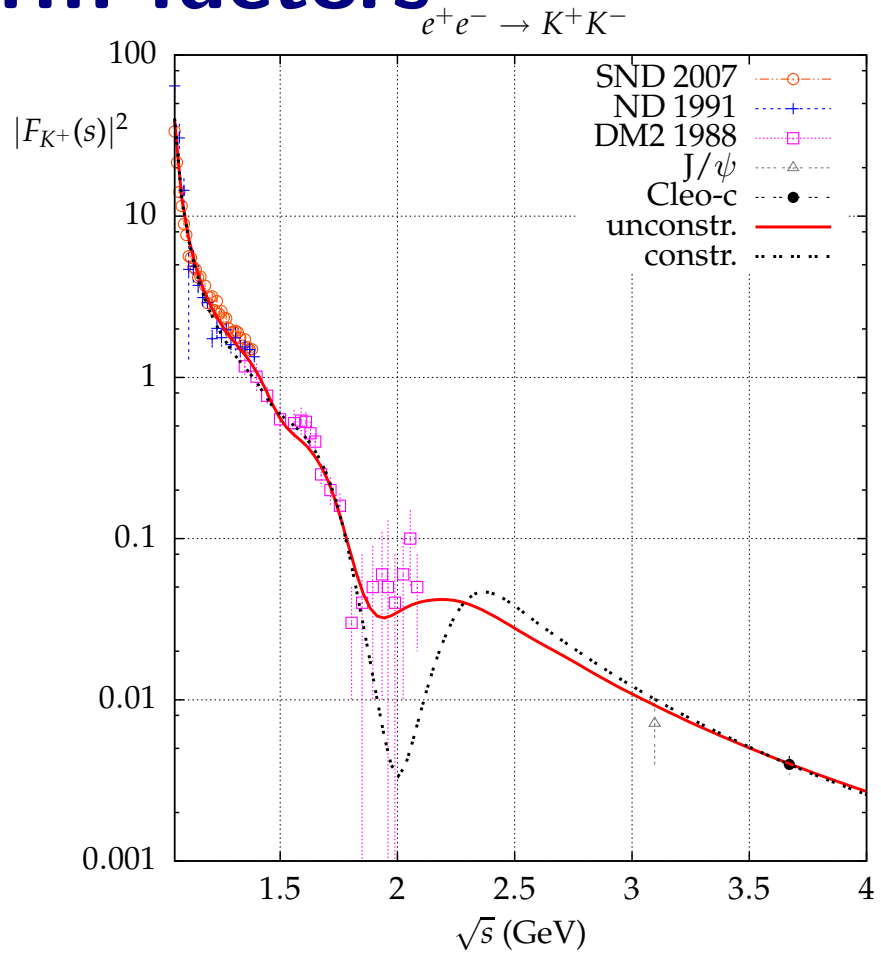
$$f_n = F_n \left(\sum_{i=1}^{5} c^{\pi}_{\rho_i} \right) / \left(\sum_{i=1}^{5} F_i \right) \quad n = 1, 2, 3, 4, 5$$

The pion form factor



The kaon form factors



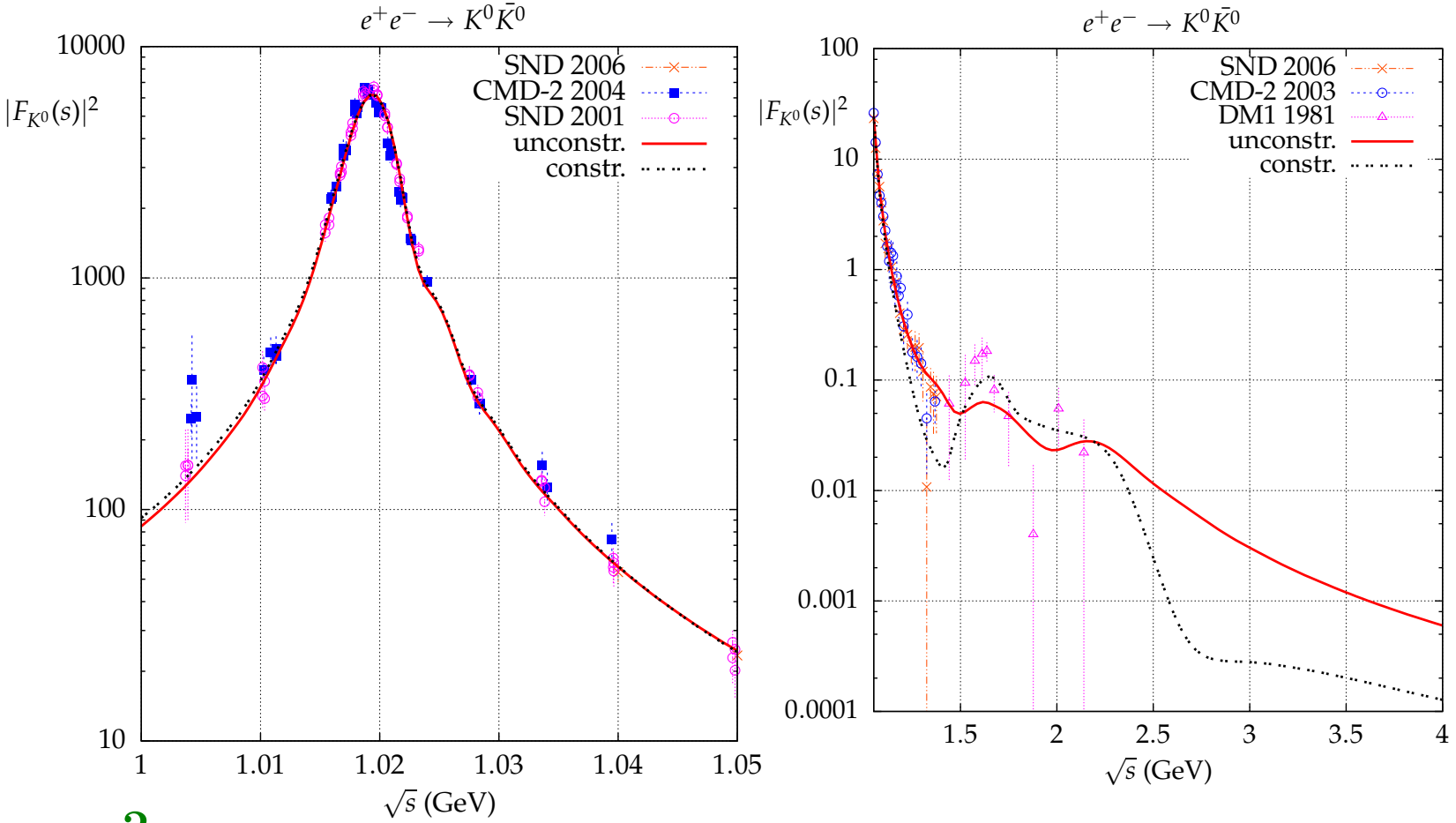


$$\chi^2/d.o.f. = 277/256(con)221/260(uncon)$$

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

The kaon form factors



$$\chi^2/d.o.f. = 277/256(con)221/260(uncon)$$

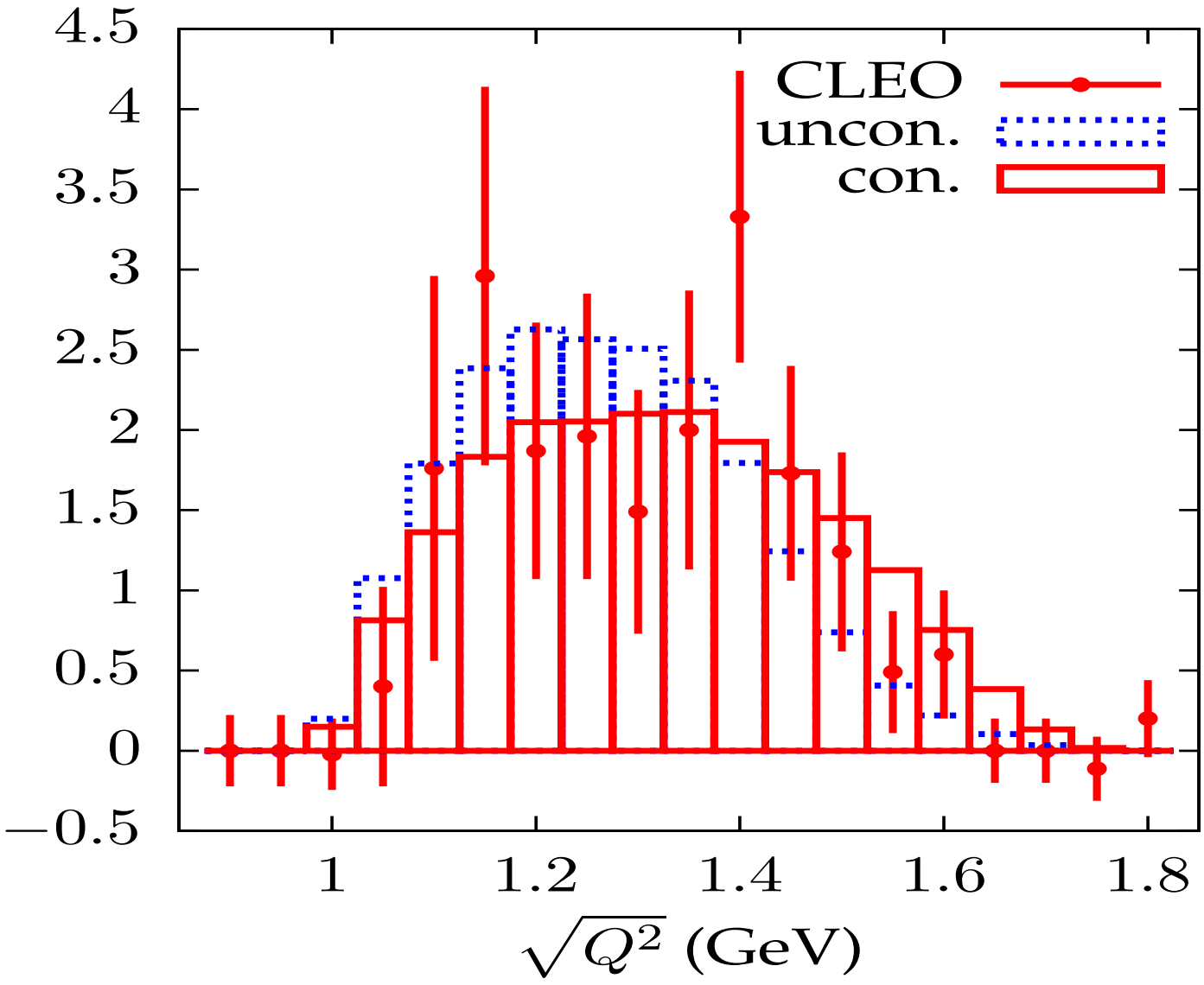
C. Bruch, A. Khodjamirian and J.H. Kühn, Eur. Phys. J. C39(2005)41

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

The kaon form factors

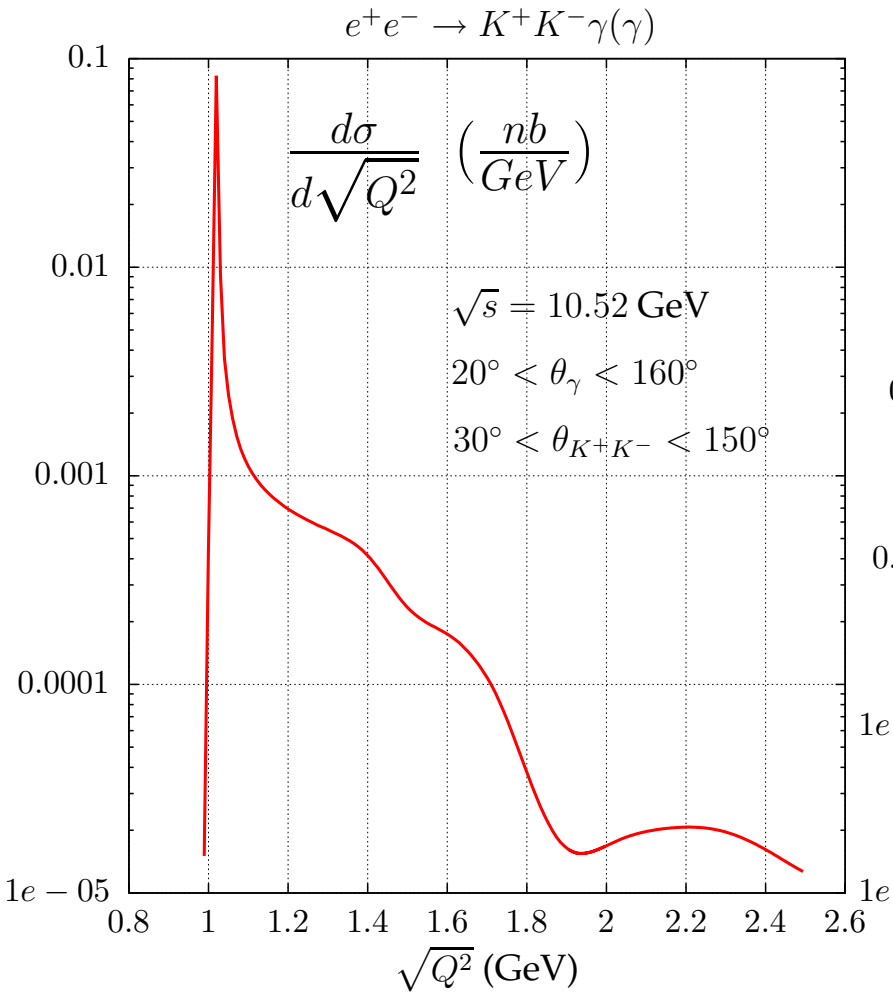
$$F_{K^+}(s) = \frac{1}{2}\left(\left[\sum_{n=0}^{N_\rho} c^K_{\rho_n} BW_{\rho_n}(s) \right]_{fit} + \left[\sum_{n=N_\rho+1}^{\infty} c^K_{\rho_n} BW_{\rho_n}(s) \right]_{dQCD} \right)$$
$$+\frac{1}{6}\left(\left[\sum_{n=0}^{N_\omega} c^K_{\omega_n} BW^c_{\omega_n}(s) \right]_{fit} + \left[\sum_{n=N_\omega+1}^{\infty} c^K_{\omega_n} BW^c_{\omega_n}(s) \right]_{dQCD} \right)$$
$$+\frac{1}{3}\left(\left[\sum_{n=0}^{N_\phi} c^K_{\phi_n} BW^K_{\phi_n}(s) \right]_{fit} + \left[\sum_{n=N_\phi+1}^{\infty} c^K_{\phi_n} BW^K_{\phi_n}(s) \right]_{dQCD} \right)$$

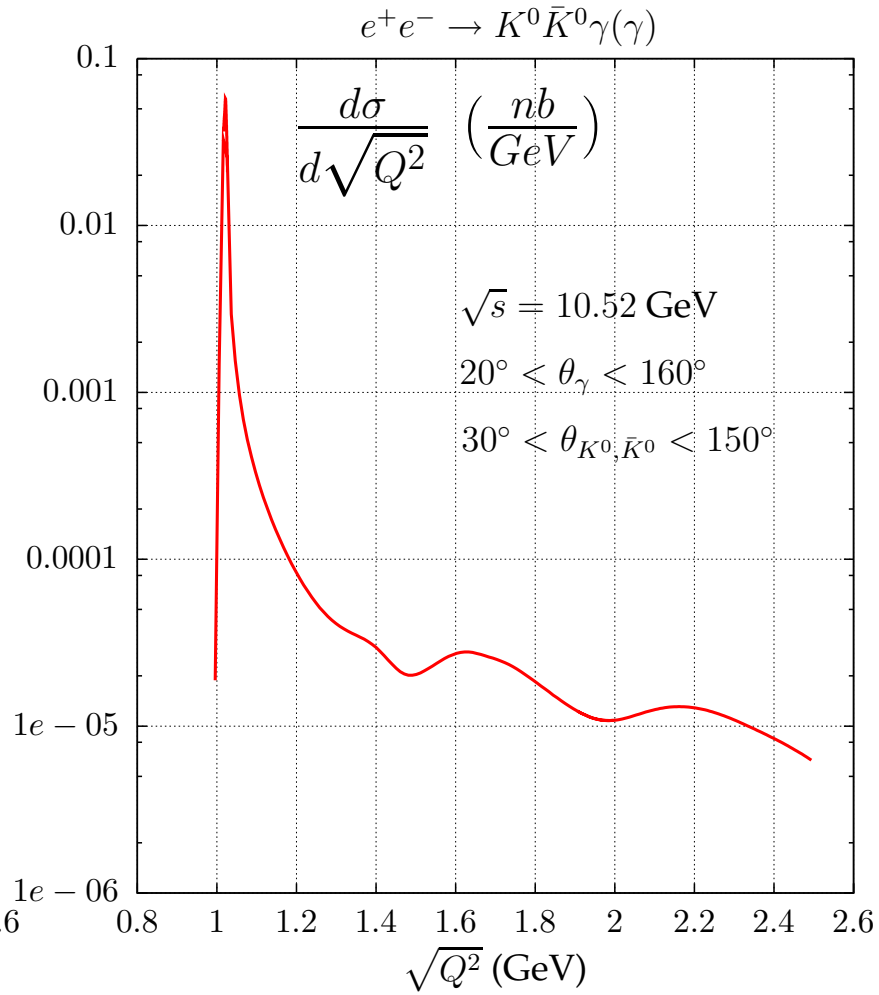
$\tau \to KK\nu$



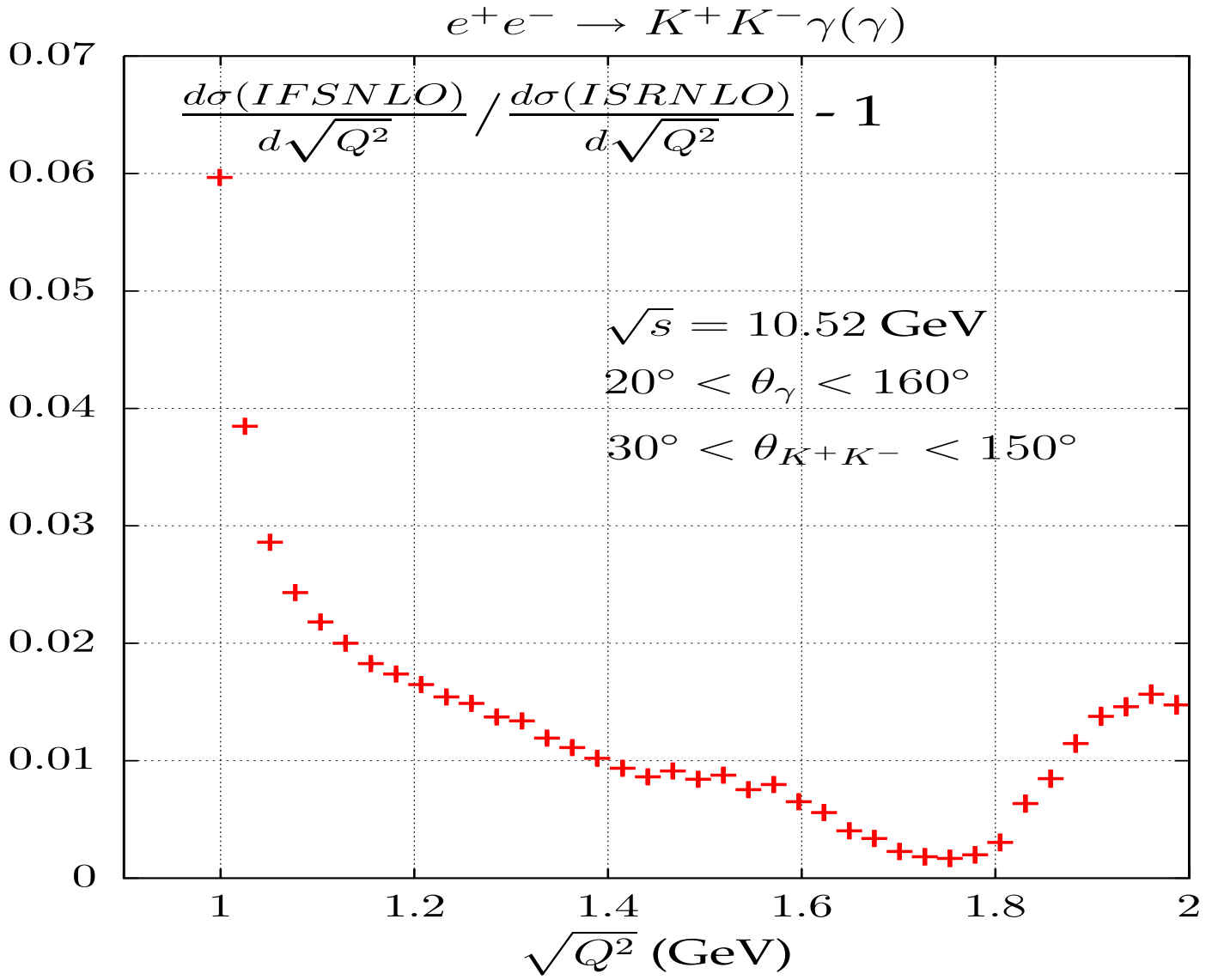
CLEO Phys. Rev. D **53**, 6037 (1996)

PHOKHARA 7.0


$e^+e^- \to K^+K^-\gamma(\gamma)$
$\frac{d\sigma}{d\sqrt{Q^2}}$ $\left(\frac{nb}{GeV}\right)$
$\sqrt{s} = 10.52$ GeV
$20^\circ < \theta_\gamma < 160^\circ$
$30^\circ < \theta_{K^+K^-} < 150^\circ$
0.1
0.01
0.001
0.0001
$1e-05$
0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6
$\sqrt{Q^2}$ (GeV)

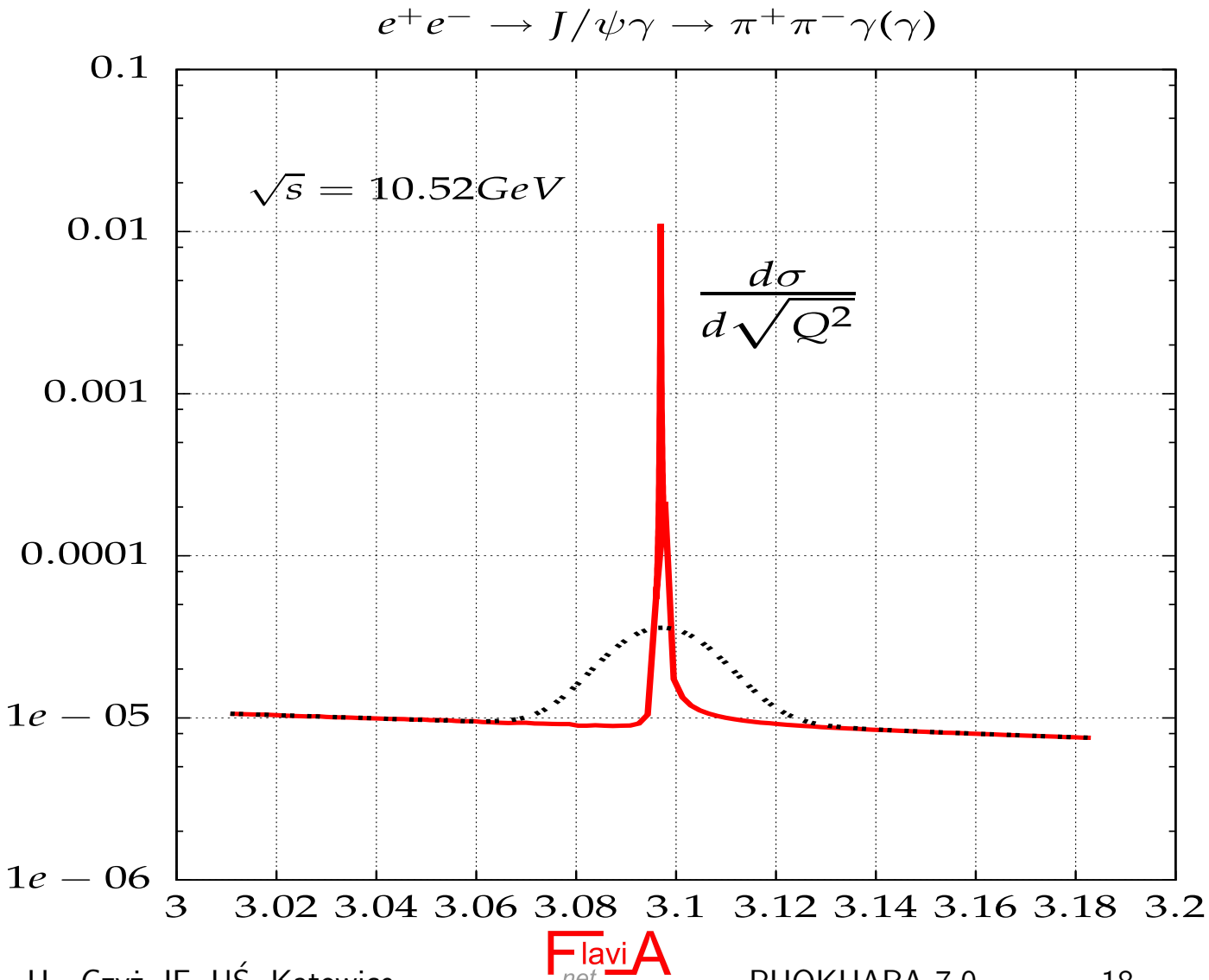

$e^+e^- \to K^0\bar{K}^0\gamma(\gamma)$
$\frac{d\sigma}{d\sqrt{Q^2}}$ $\left(\frac{nb}{GeV}\right)$
$\sqrt{s} = 10.52$ GeV
$20^\circ < \theta_\gamma < 160^\circ$
$30^\circ < \theta_{K^0,\bar{K}^0} < 150^\circ$
0.1
0.01
0.001
0.0001
$1e-05$
$1e-06$
0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6
$\sqrt{Q^2}$ (GeV)

PHOKHARA 7.0 - FSR

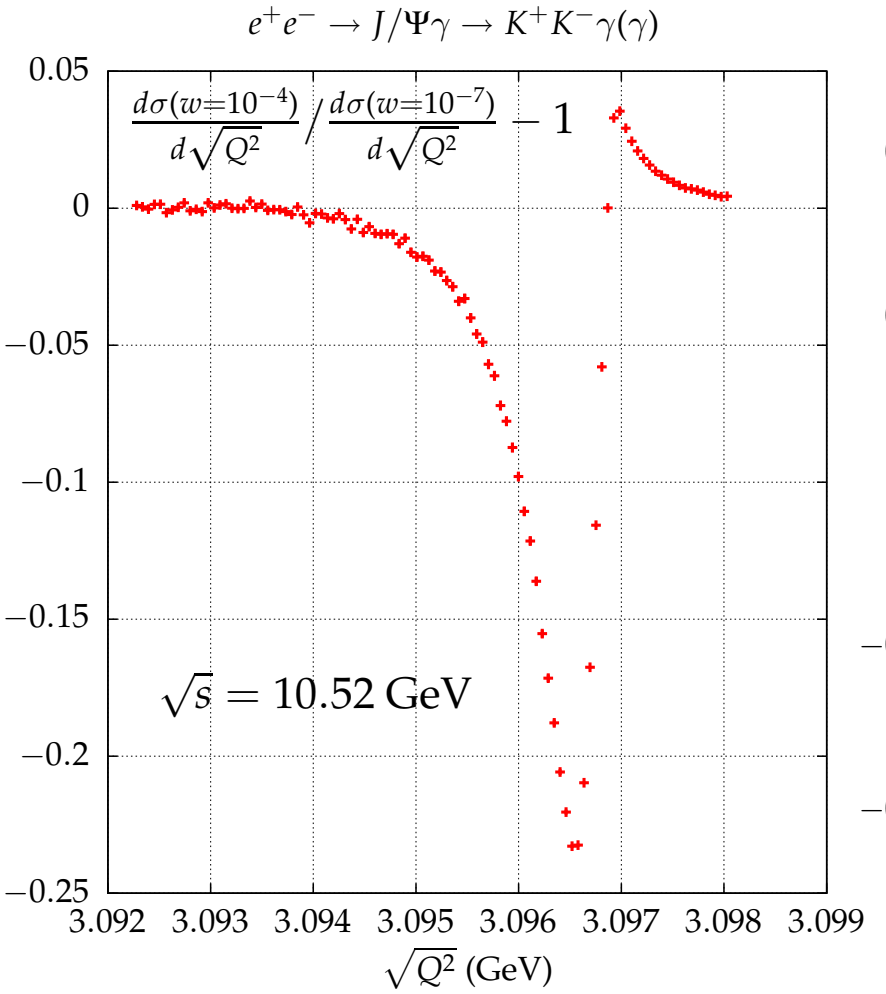


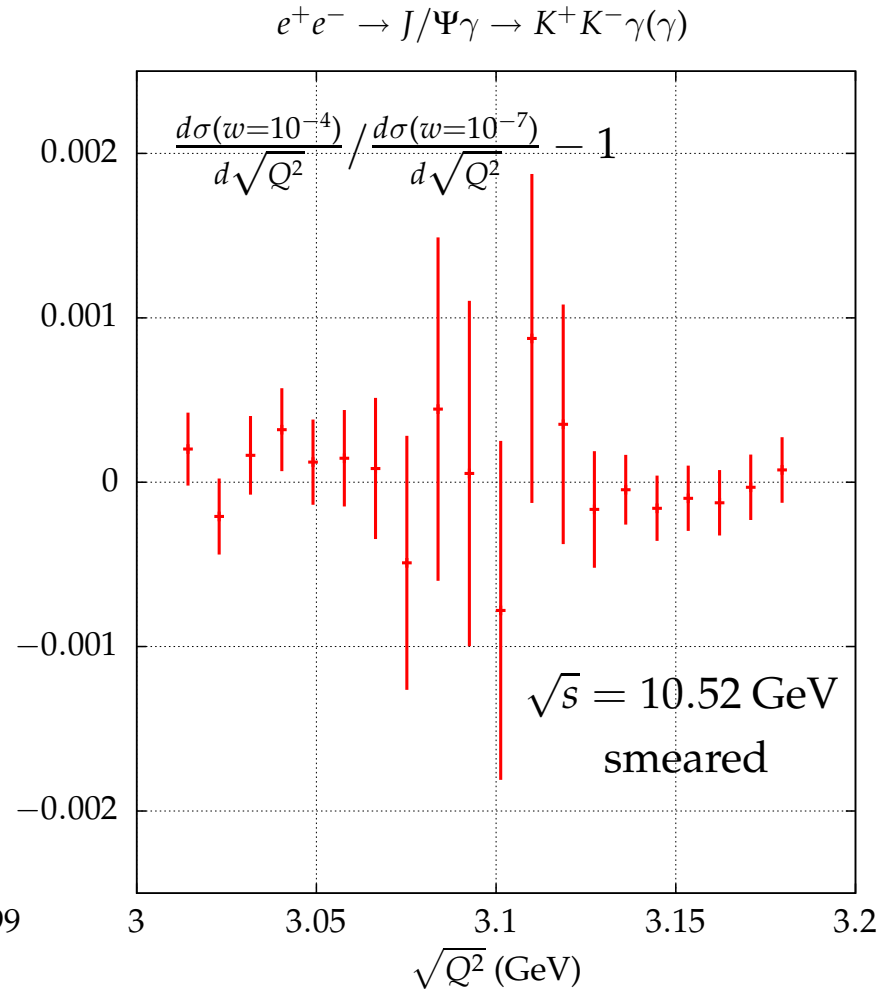
Energy resolution

$\Delta q = 14.5$ MeV

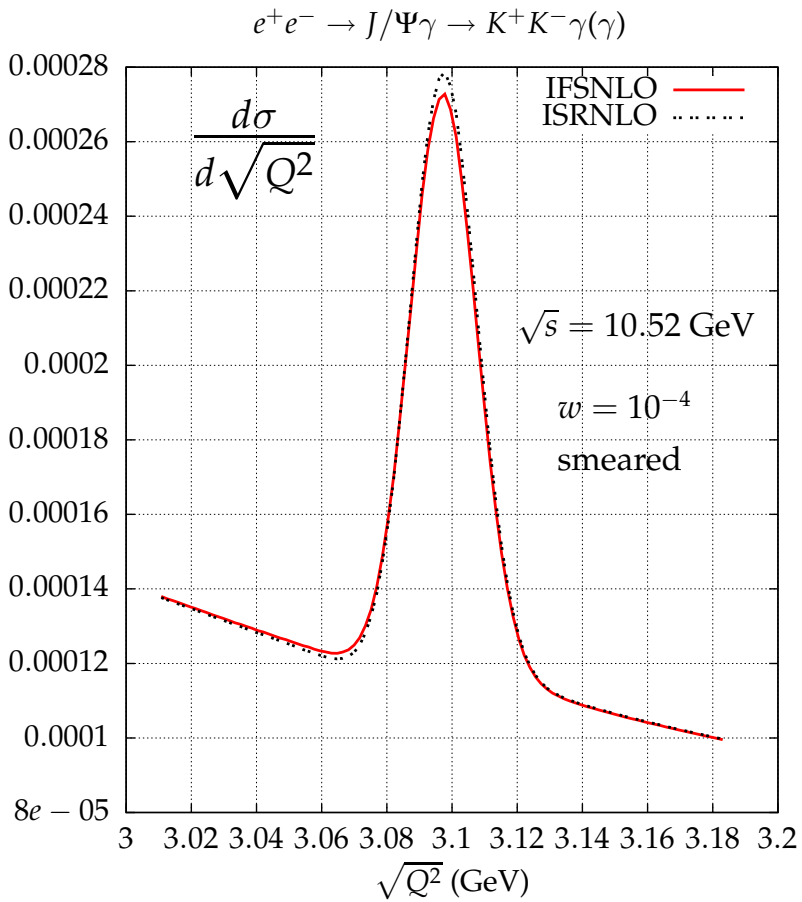


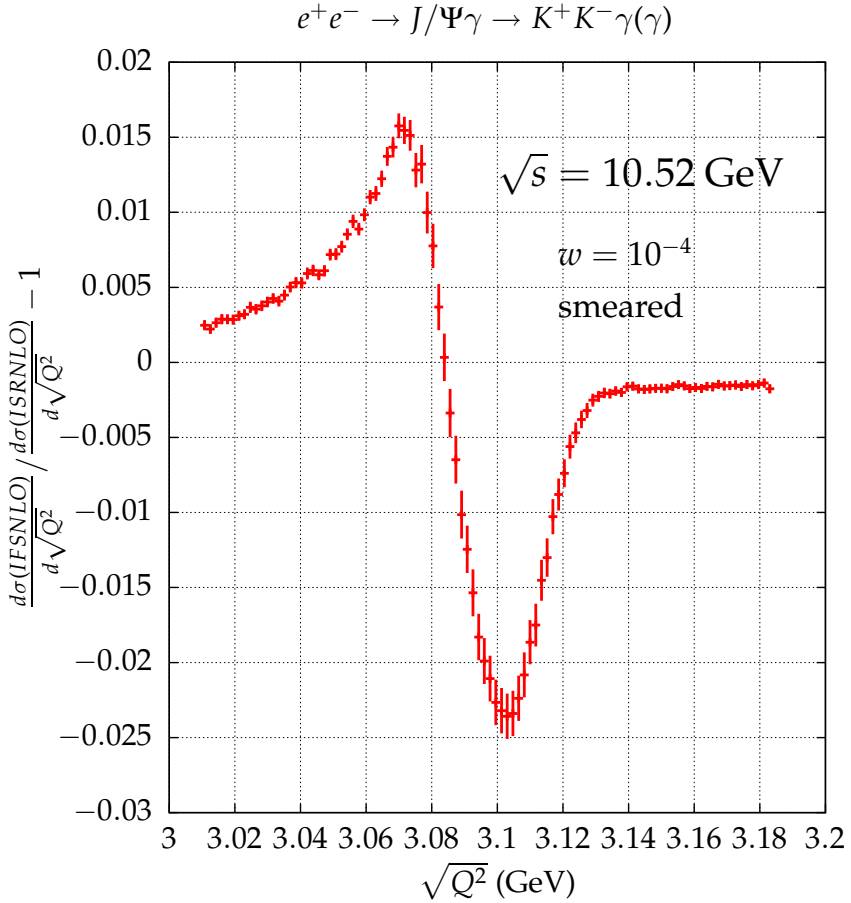
PHOKHARA 7.0 - FSR





PHOKHARA 7.0 - FSR





Summary and outlook

PHOKHARA 7.0 - fully tested

- new 4 π hadronic current
- new pion and kaon form factors
- J/ψ and $\psi(2S)$ contributions included

NLO FSR corrections important at a few percent level

Left over 1-loop corrections to $e^+e^- \to \mu^+\mu^-\gamma$ to be included soon