The Radiative Return at Φ- and B-Meson Factories

KARLSRUHE–KATOWICE–VALENCIA

J. H. Kühn

I Basic Idea

II Monte Carlo Generators: Status & Perspectives

III Charge Asymmetry and Radiative Φ-Decays ($\Rightarrow$ H. Czyż)

IV Nucleon Form Factor at B-Factories

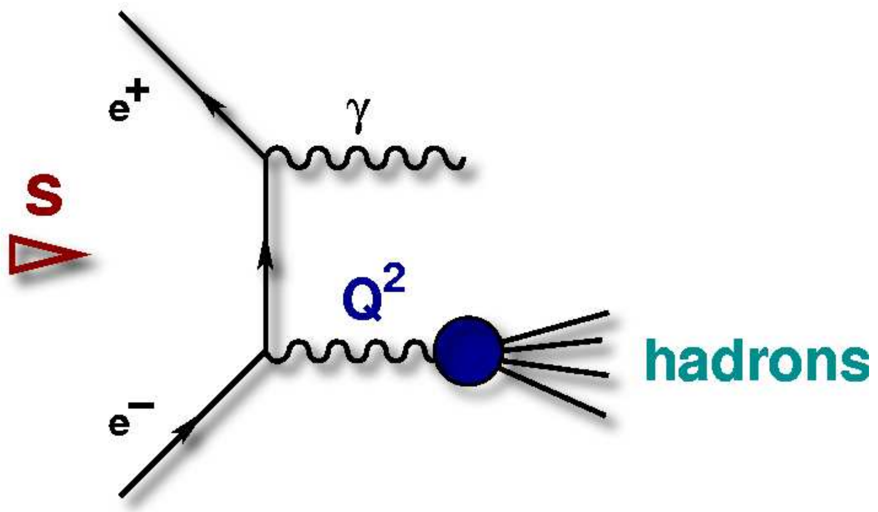
V Conclusions

(with H. Czyż, A. Grzelinska, E. Nowak, G. Rodrigo)

I BASIC IDEA

photon radiated off the initial e^+e^- (ISR) reduces the effective energy of the collision

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



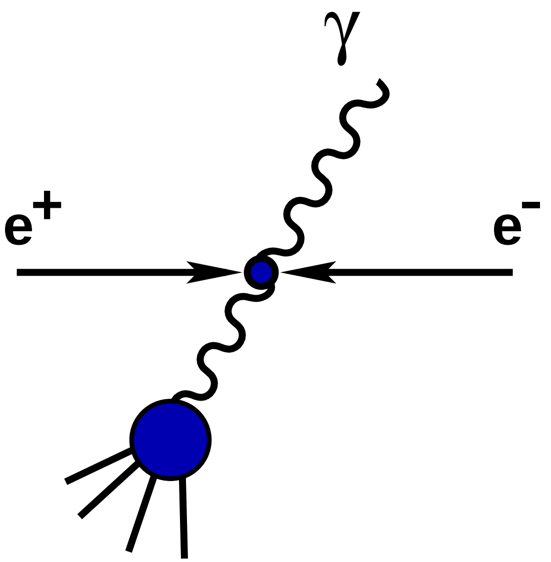
- measurement of $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$
- large luminosities of factories compensate α/π from photon radiation
- radiative corrections essential (NLO)
- advantage over energy scan (BES, CMD2, SND): systematics (e.g. normalization) only once

High precision measurement of the hadronic cross-section at DAΦNE, CLEO-C, B-factories

DAΦNE versus B-factories:

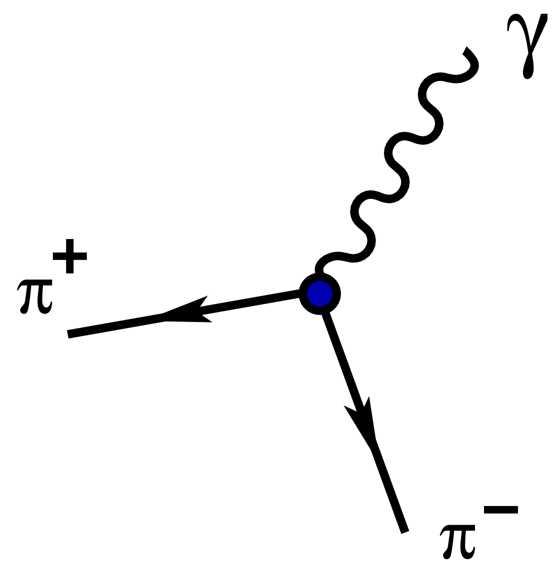
configurations in the cms - frame

10 GeV



very hard photon: clear kinematic separation between photon and hadrons

1 GeV



no natural kinematic separation

➪ cuts to control FSR versus ISR

(two step process: $e^+e^- \to \gamma\ \rho(\to \gamma\pi\pi) \Rightarrow$ see below)

Rough estimates for rates:

$\pi^+ \pi^- \gamma$: $E_\gamma > 100 MeV$

$\sqrt{s}$ $[GeV]$	$\int \mathcal{L}$ $[fb^{-1}]$	#events, $\theta_{min} = 7^\circ$
1.02	1.35	16 $\cdot 10^6$
10.6	100	3.5 $\cdot 10^6$

multi-hadron-events (R $\equiv 2$) $\sqrt{s} = 10.6\, GeV$

Q^2-interval $[GeV]$	#events, $\theta_{min} = 7^\circ$
$[\,1.5\,,\ 2.0\,]$	9.9 $\cdot 10^5$
$[\,2.0\,,\ 2.5\,]$	7.9 $\cdot 10^5$
$[\,2.5\,,\ 3.0\,]$	6.6 $\cdot 10^5$
$[\,3.0\,,\ 3.5\,]$	5.8 $\cdot 10^5$

Lowest order

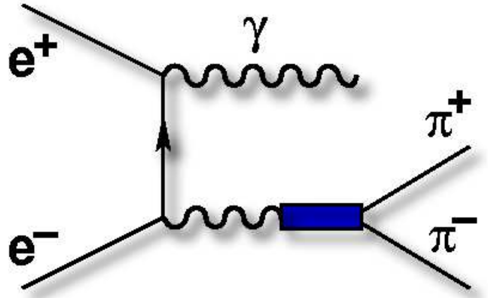
$$\frac{d\sigma}{dQ^2}\left(e^+e^- \to \gamma \; + \; \mathrm{had}(Q^2)\right) = \sigma\left(e^+e^- \to \mathrm{had}(Q^2)\right)$$

$$\times \frac{\alpha}{\pi s} \left\{ \begin{array}{l} \frac{s^2+Q^4}{s(s-Q^2)}\left(\log(s/m_e^2) - 1\right), \text{ no angular cut} \\ \frac{s^2+Q^4}{s(s-Q^2)} \log\left(\frac{1+\cos\theta_{min}}{1-\cos\theta_{min}}\right) - \frac{s-Q^2}{s}\cos\theta_{min} \end{array} \right\}$$

$\Rightarrow$ differential luminosity: $\frac{dL}{dQ^2}\left(Q^2, s\right) = \frac{\alpha}{\pi s}\left\{\cdots\right\} L(\text{at } s)$

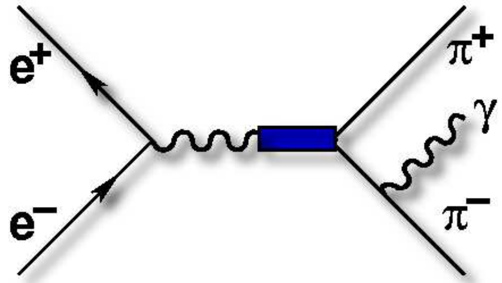
Basic Ingredients for Pion Formfactor

▶ ISR



pion form factor
➪ to be tested

▶ FSR



radiation from point-like pions (probably overestimated)

▶ **additional radiation:** collinear (EVA MC) (Binner, JK, Melnikov)
or NLO calculation (PHOKHARA MC)

II MONTE CARLO GENERATORS

P
H
OTONS FROM
KARLSRUHE
H
ADRONICALLY
R
ADIATED

References etc. ⟶ http://cern.ch/german.rodrigo/phokhara

http://cern.ch/german.rodrigo/phokhara

PHOKHARA

radiative return at meson factories

Physics	Electron--positron annihilation into hadrons plus an energetic photon from initial state radiation (ISR) allows the hadronic cross-section to be measured over a wide range of energies at high luminosity meson factories [DAPHNE, CESR, PEP-II, KEK-B].
Content	PHOKHARA is a Monte Carlo event generator which simulates this process at the next-to-leading order (NLO) accuracy. This includes virtual and soft photon corrections to one photon emission events and the emission of two real hard photons.
Downloads	VERSION 4.0 (April 2004): Incorporates nucleon pair production (proton-antiproton and neutron-antineutron) as new channels. FSR at NLO for muon pair production added, with some improvements in the pion pair channel. Effect of vacuum polarization implemented. • manual [Postscript, PDF], source [uuencoded]

PHOKHARA

radiative return at meson factories

Forthcoming features	• Simulation of other exclusive hadronic channels (see also hep-ph/0312217)
Previous versions	VERSION 3.0 (August 2003): simulates ISR at NLO for two charged pions or muons, and four-pion channels, and FSR at leading order for two charged pions or muons. FSR at NLO for two charged pions added.
	• manual [Postscript, PDF], source [uuencoded]
	VERSION 2.0 (December 2002): includes small angle photon generation, four-pion channels and FSR at leading order for two charged pions or muons.
	• manual [Postscript, PDF], source [uuencoded]
	VERSION 1.0 (December 2001): includes ISR only and is limited to two charged pions or muons together with one or two hard photons as final states.
	• manual [Postscript, PDF], source [uuencoded]
	EVA: simulates two pion events and includes ISR, FSR, and their interference at the leading order (LO), and the dominant radiative corrections from additional collinear radiation through structure function techniques.
	• manual [Postscript, PDF], source [uuencoded]

PHOKHARA

radiative return at meson factories

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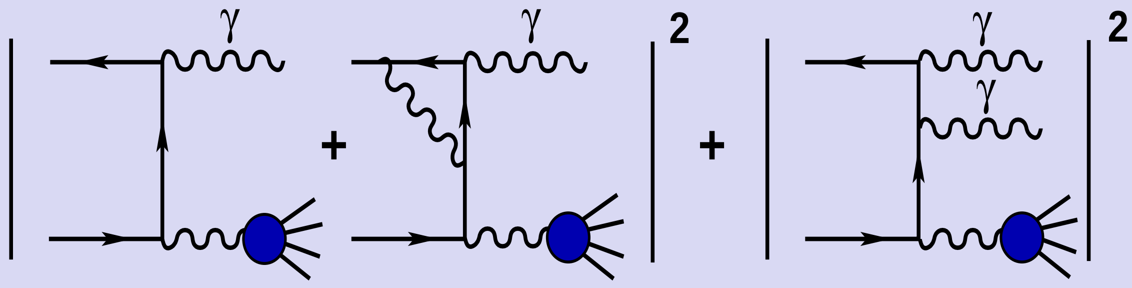
PHOKHARA 2.0:
$\pi^+\pi^-$, $\mu^+\mu^-$, 4π

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



- FSR at LO: $\pi^+\pi^-$, $\mu^+\mu^-$
- tagged or untagged photons
- modular structure

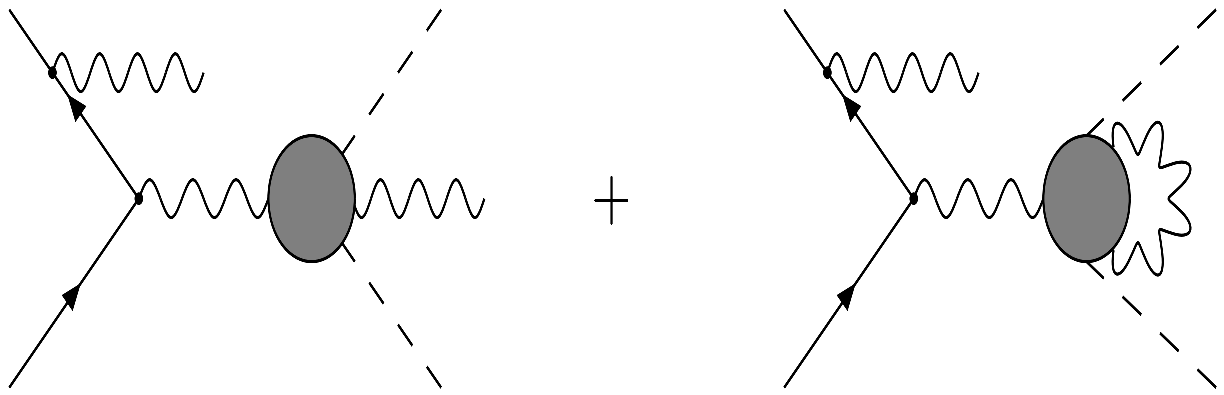
QED CORRECTIONS AT LEPTONIC SIDE

$\Longrightarrow$ BASIC BUILDING BLOCK

FOR ALL HADRONIC FINAL STATES

PHOKHARA 3.0

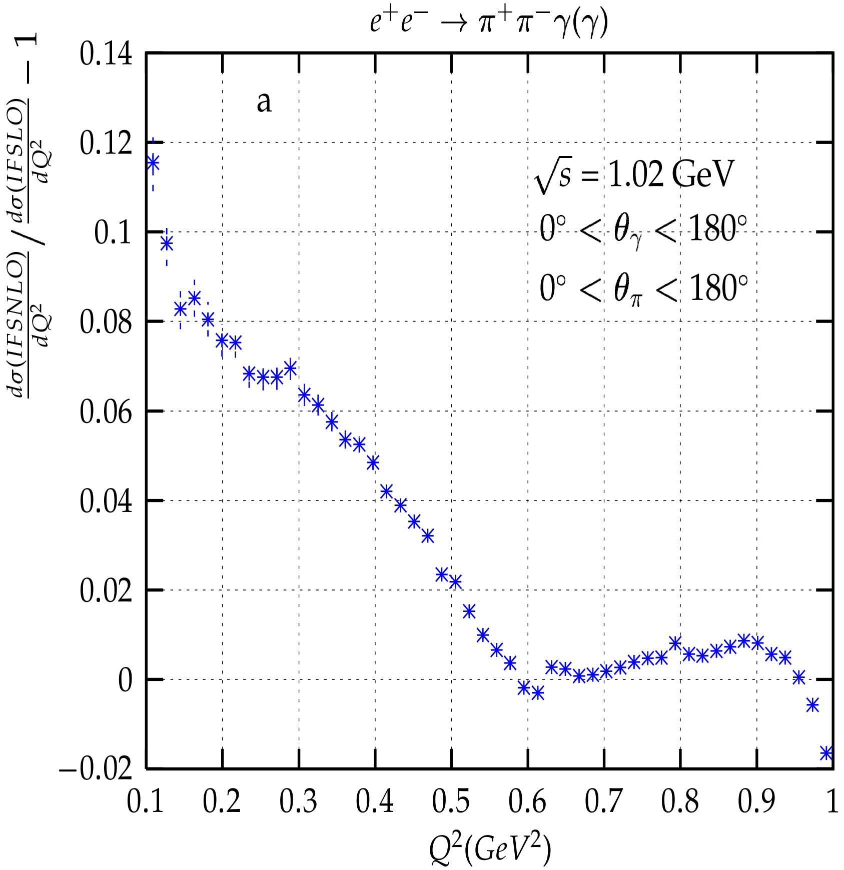
- specifically developed for $\pi^+\pi^-$ (plus photons)
- allows for simultaneous emission of photons
  from initial and final state,
  including virtual corrections (interference neglected).

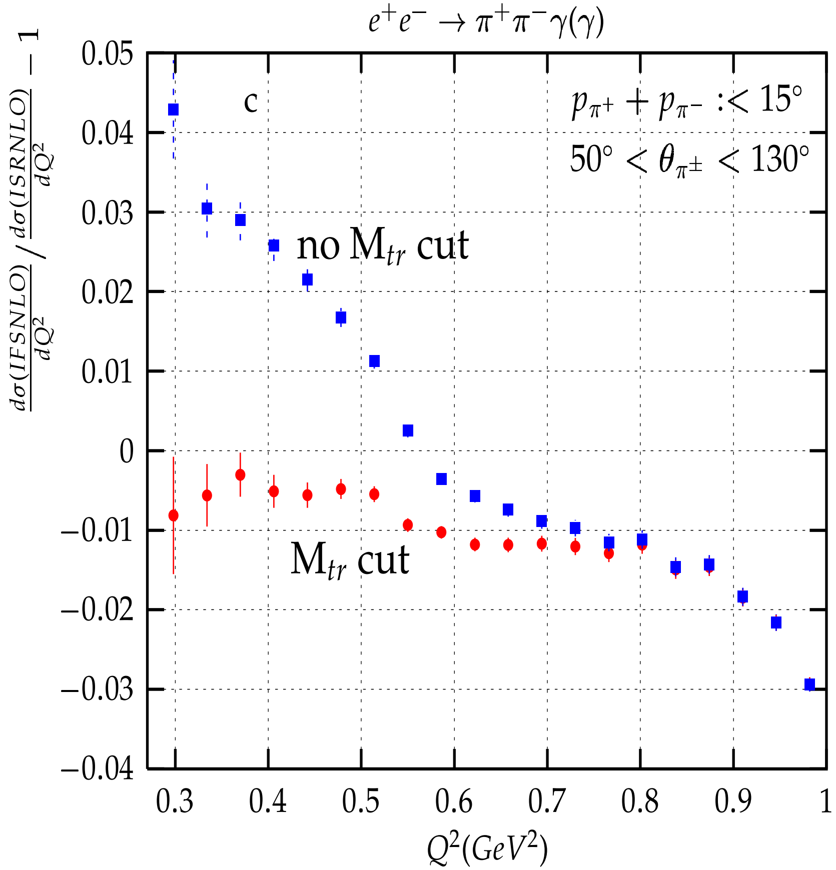


$\Rightarrow$ dominated by "two step process": $e^+e^- \to \gamma\ \rho\ (\to \gamma\ \pi\pi)$

$\Rightarrow$ importance of $\pi\pi\gamma$ as input for a_μ

Large effect for $Q^2 < m_\rho^2$ eliminated by suitable cuts on $\pi^+\pi^-$ configuration (suppress 2γ events)





or measure photon

Experimental Perspectives

KLOE $\Longrightarrow$ TALK BY STEFAN MÜLLER

- $\pi\pi$

pion form factor

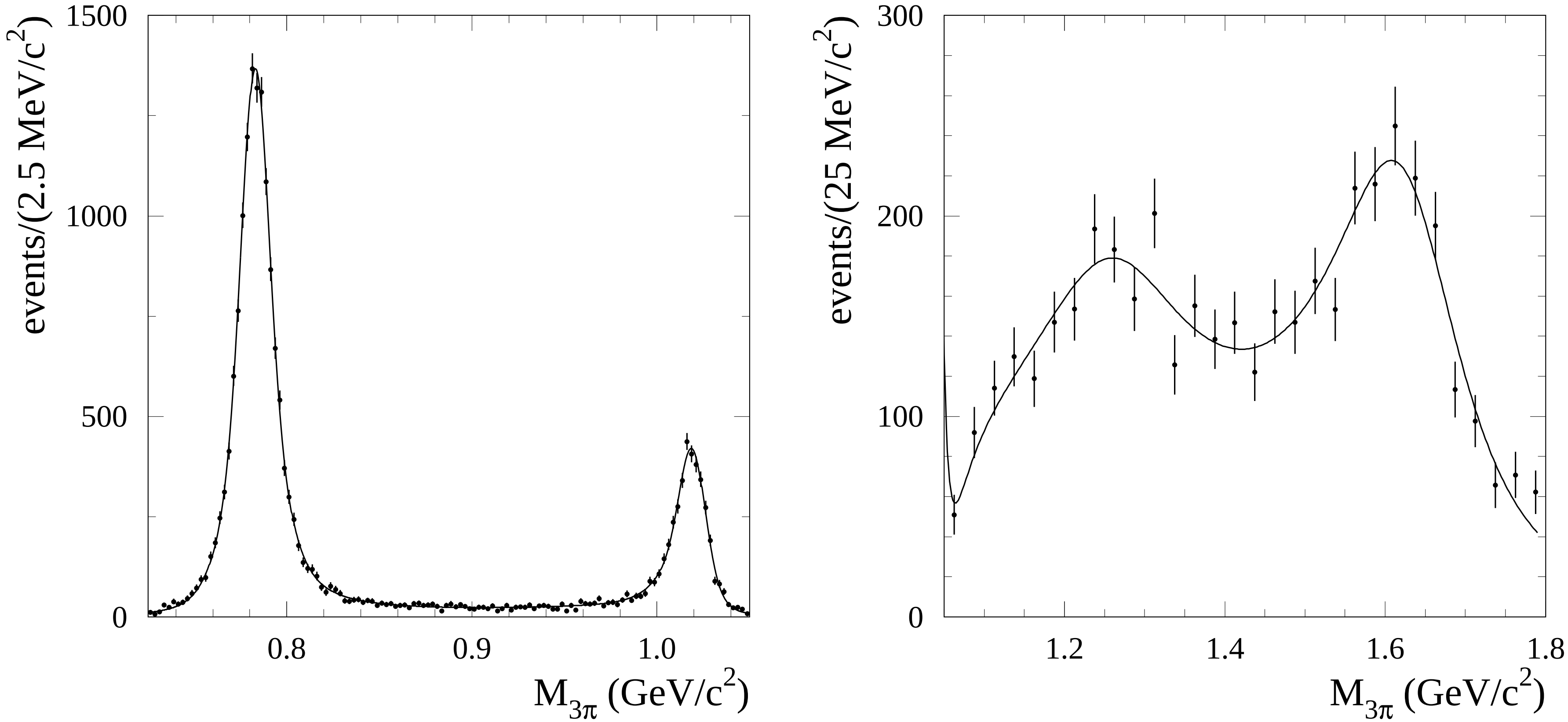
BABAR, BELLE

higher Q^2 available

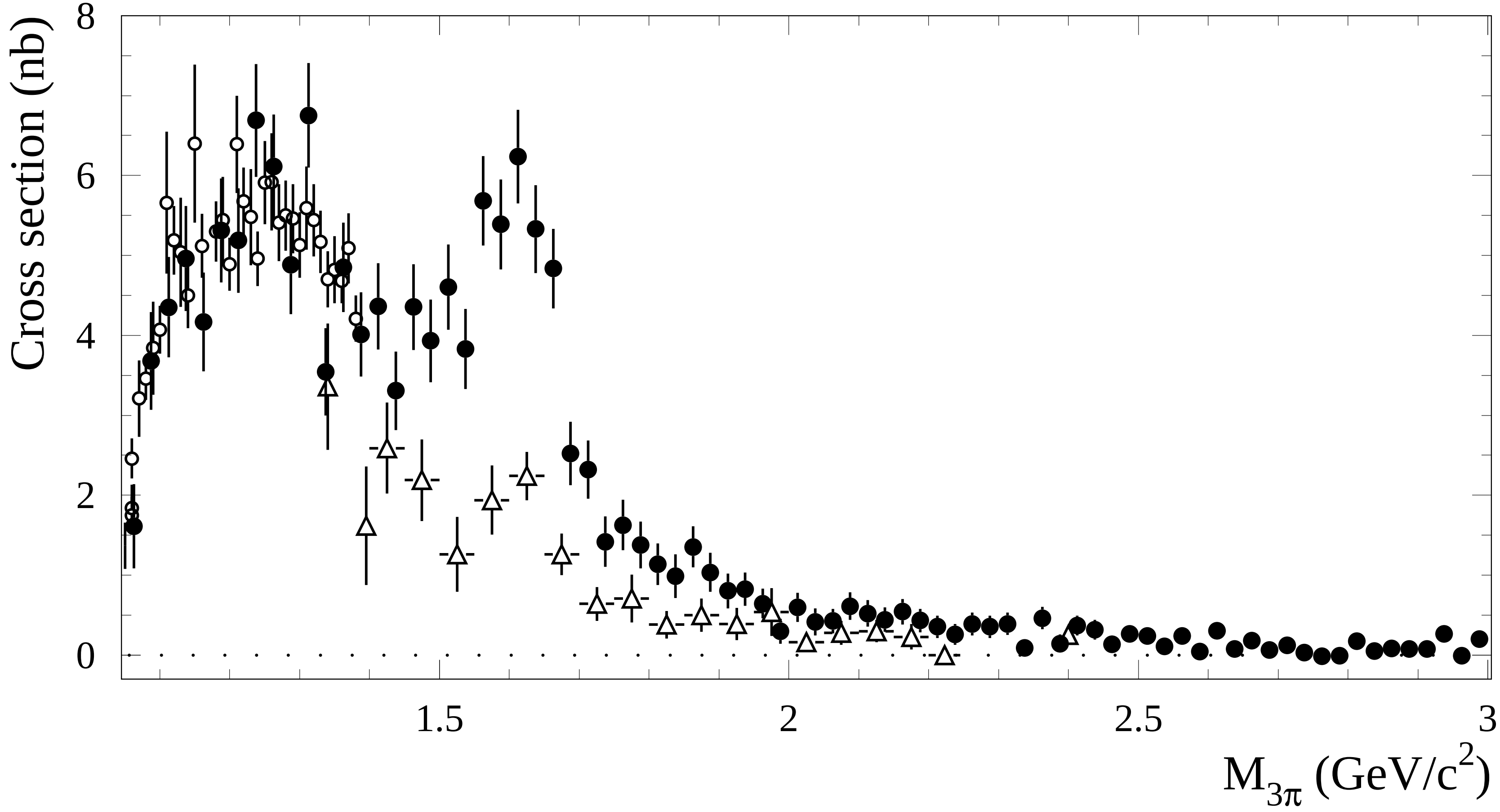
$\Rightarrow$ measurement of R(Q^2) from threshold up to at least 5 GeV.

Examples:

- 3π
- $4\pi^{\pm}$
- K K $\pi\pi$
- K K K K
- J/Ψ



The background-subtracted 3π mass spectrum for masses between 0.70 and 1.05 MeV/c^2 (plot on the left) and for masses from 1.05 to 1.80 MeV/c^2 (plot on the right). BaBar



The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section measured by BaBar (filled circles), by SND (open circles), and DM2 (open triangles). BaBar

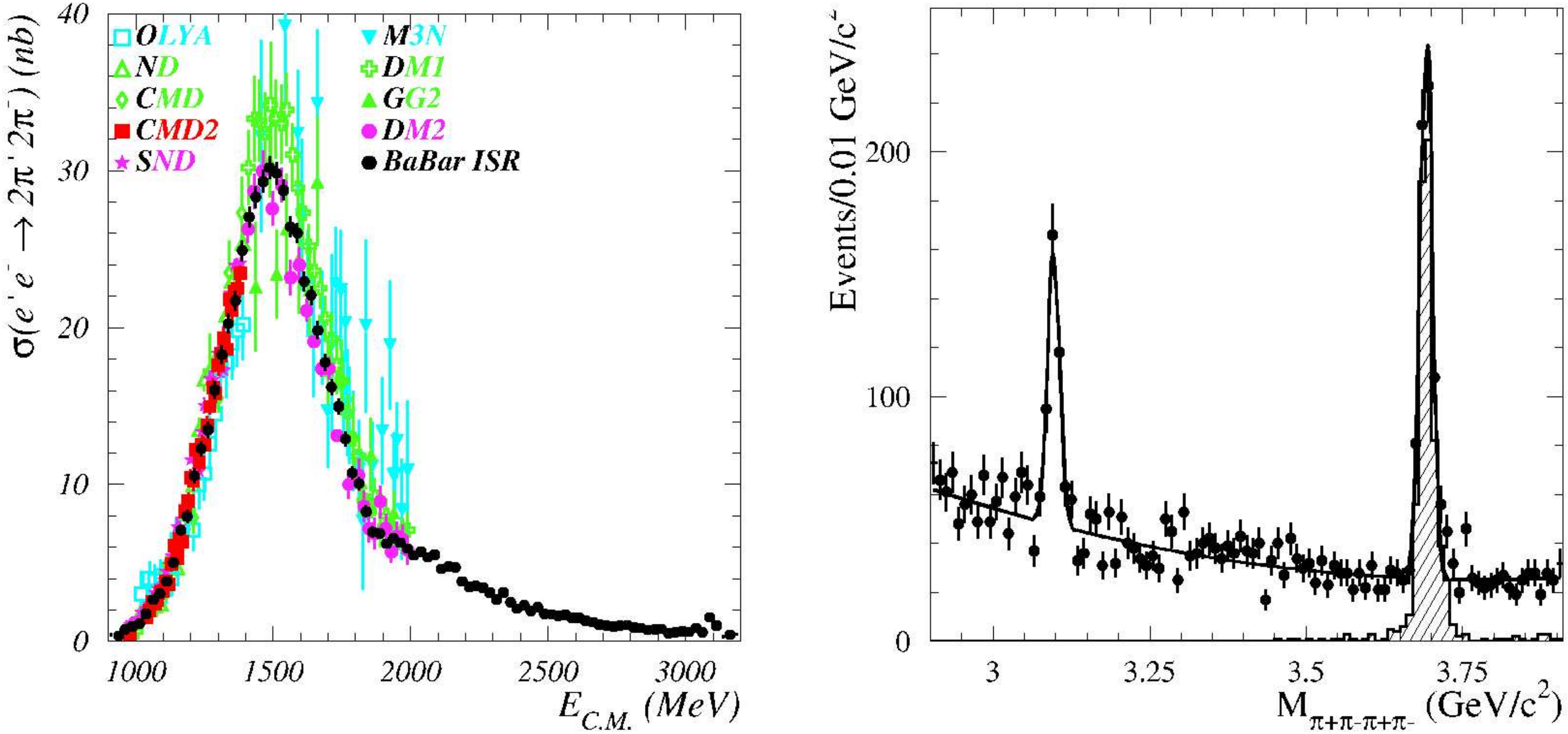
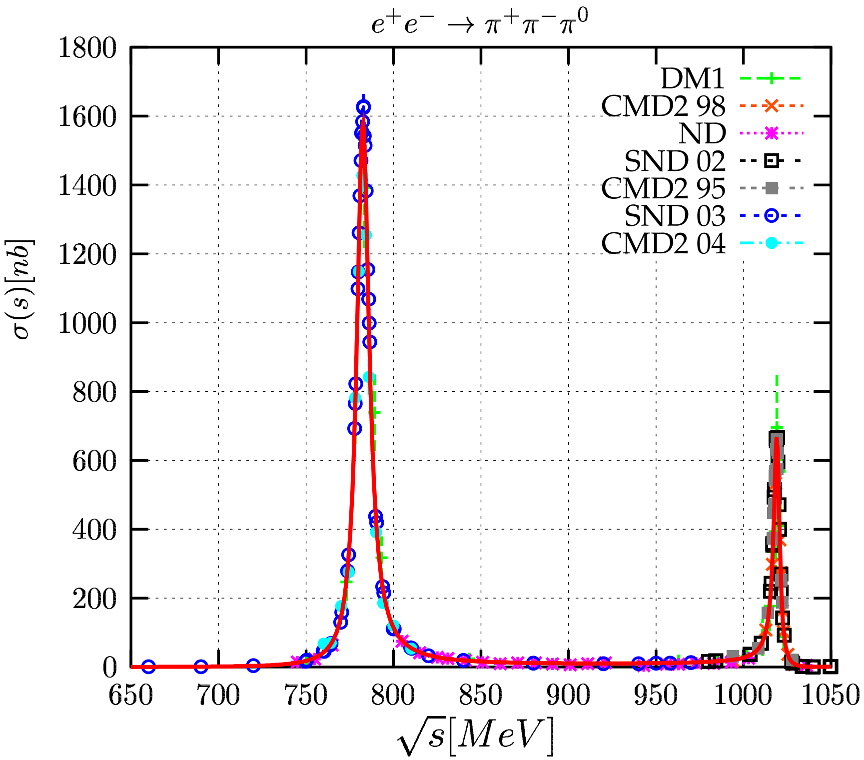
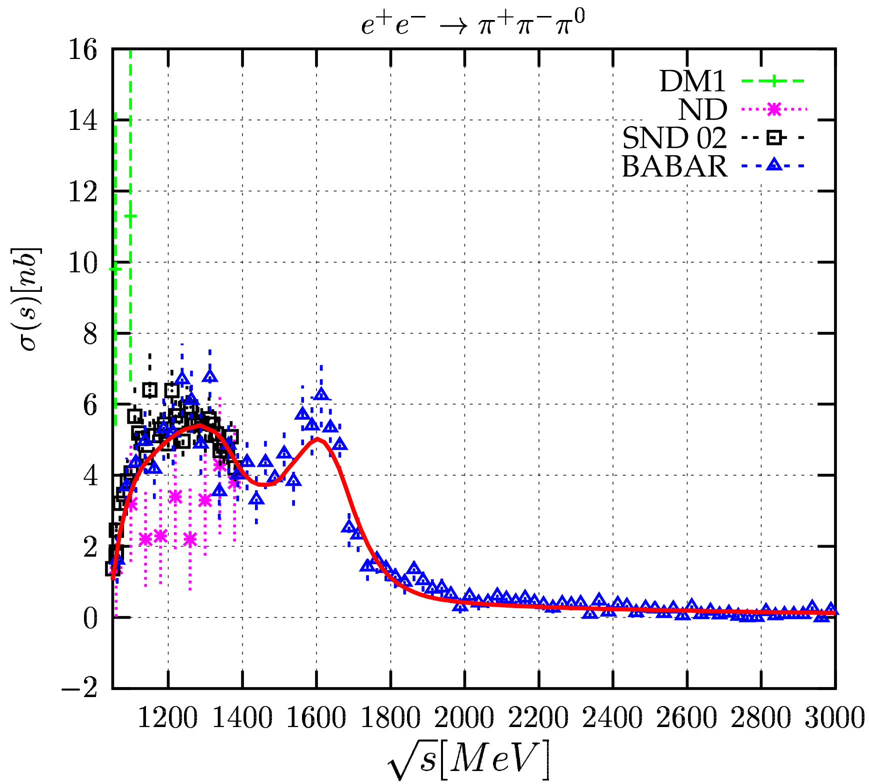


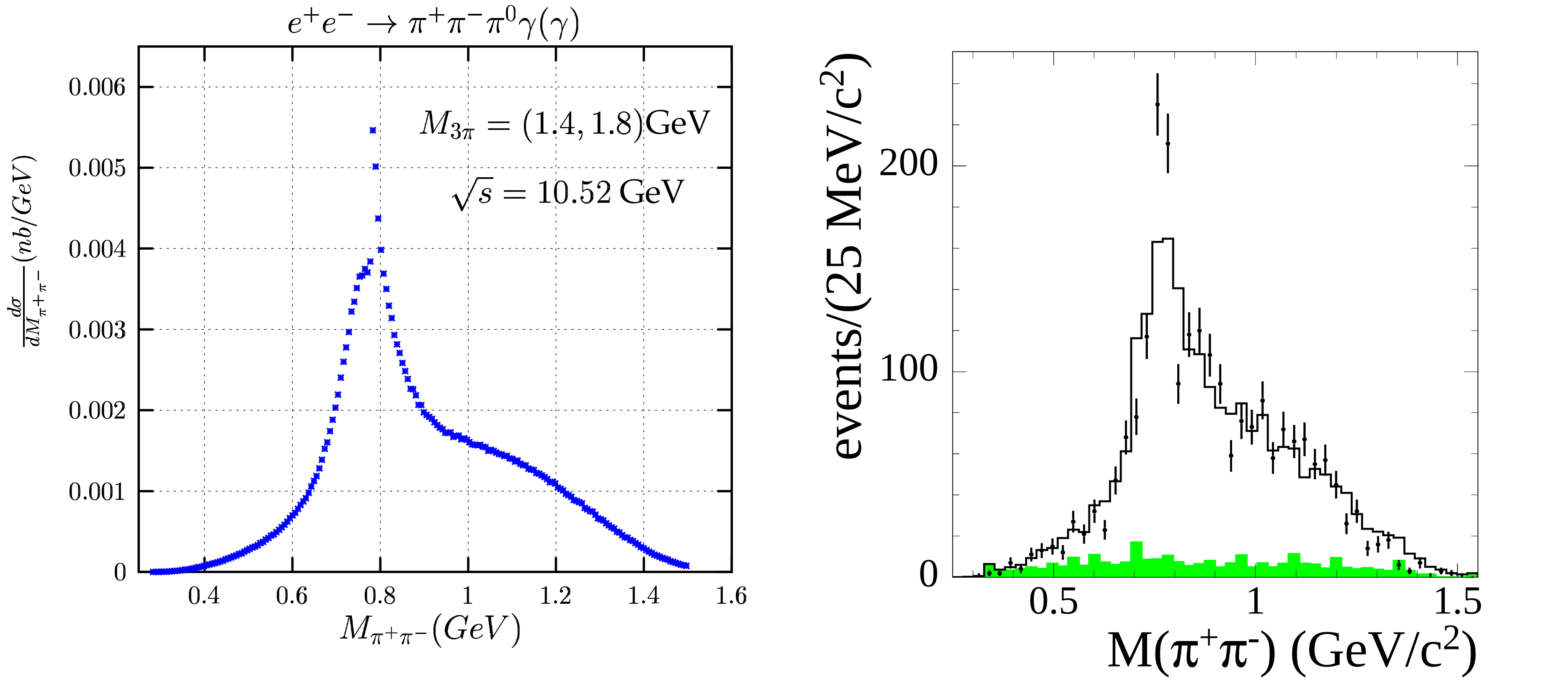
FIGURE 2. On the left: The $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section obtaind from ISR at *BABAR* in comparison with all e^+e^- data. On the right: The signals from J/ψ and $\psi(2S)$ in 4π invariant mass. The shaded region at the latter corresponds to $\psi(2S) \to J/\psi\pi^+\pi^-$, with $J/\psi \to \mu^+\mu^-$.

BaBar


$e^+e^- \to \pi^+\pi^-\pi^0$
DM1
CMD2 98
ND
SND 02
CMD2 95
SND 03
CMD2 04
$\sigma(s)[nb]$
$\sqrt{s}[MeV]$


$e^+e^- \to \pi^+\pi^-\pi^0$
DM1
ND
SND 02
BABAR
$\sigma(s)[nb]$
$\sqrt{s}[MeV]$

BaBar


$e^+e^- \to \pi^+\pi^-\pi^0\gamma(\gamma)$
$M_{3\pi} = (1.4, 1.8)$GeV
$\sqrt{s} = 10.52$ GeV
$\frac{d\sigma}{dM_{\pi^+\pi^-}}(nb/GeV)$
$M_{\pi^+\pi^-}(GeV)$
events/(25 MeV/c^2)
M($\pi^+\pi^-$) (GeV/c^2)

BaBar

PHOKHARA 4.0

- $\mu^+\mu^-\gamma$ **with FSR at NLO**
- **vacuum polarisation can be switched on**
- **nucleon pair production included**

III Charge Asymmetries and Radiative Φ-Decays

(H. Czyż, A. Grzelinska, JK, hep-ph/0412239)

$\Longrightarrow$ talk by Henryk Czyż

IV NUCLEON FORM FACTORS

(with Czyż, Nowak, Rodrigo, hep-ph/0403062)

$Q^2 \gtrsim 4m_N^2$ accessible at B-factories

$\Rightarrow$ study $e^+e^- \to \gamma N\bar{N}$ (with $N = p$ or n)

hadronic current:

$$J_\mu = -ie \cdot \bar{u}(q_2) \left(F_1^N(Q^2)\, \gamma_\mu - \frac{F_2^N(Q^2)}{4m_N} [\gamma_\mu, \not{Q}] \right) v(q_1)\,,$$

$$Q = q_1 + q_2\,, \quad q = (q_1 - q_2)/2$$

or

$$G_M = F_1 + F_2\,, \quad G_E = F_1 + \frac{Q^2}{4m^2} F_2$$

Separation of $|G_M|^2$ and $|G_E|^2$ through angular distribution:

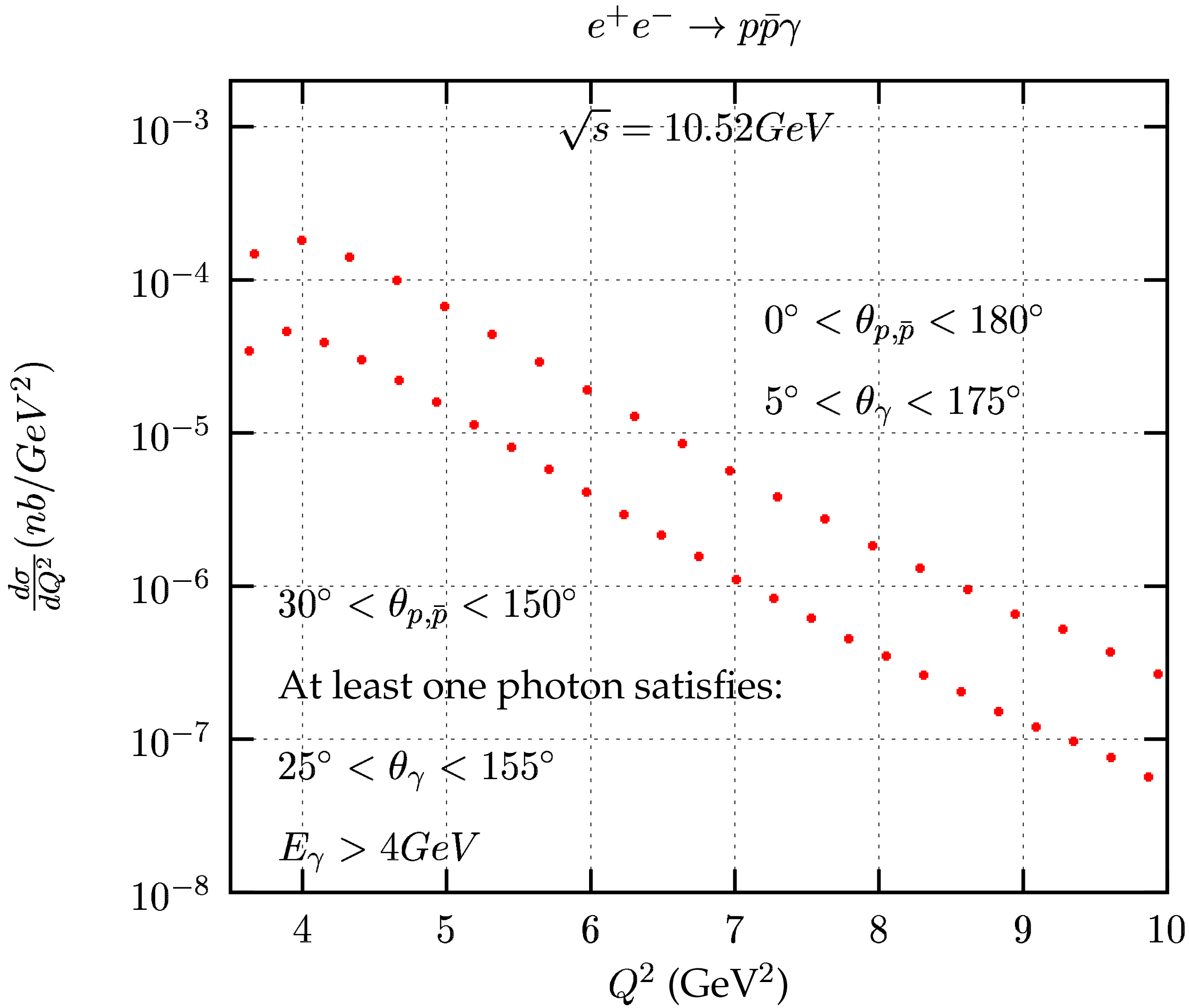
$$L_{\mu\nu}H^{\mu\nu} = \frac{(4\pi\alpha)^3}{Q^2}\frac{(1+\cos^2\theta_\gamma)}{(1-\cos^2\theta_\gamma)} \times 4\left(|G_M^N|^2\,(1+\cos^2\hat\theta) + \frac{1}{\tau}|G_E^N|^2\,\sin^2\hat\theta\right)$$

$\hat\theta$ = angle of nucleon with respect to γ-direction in hadronic rest frame

(valid for $s/Q^2 \ll 1$, corrections and "optimal frame" $\longrightarrow$ hep-ph/0403062)

Similarity to $e^+e^- \longrightarrow N\bar{N}$:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta_N}{4Q^2}\left(|G_M^N|^2\,(1+\cos^2\theta) + \frac{1}{\tau}|G_E^N|^2\,\sin^2\theta\right)$$

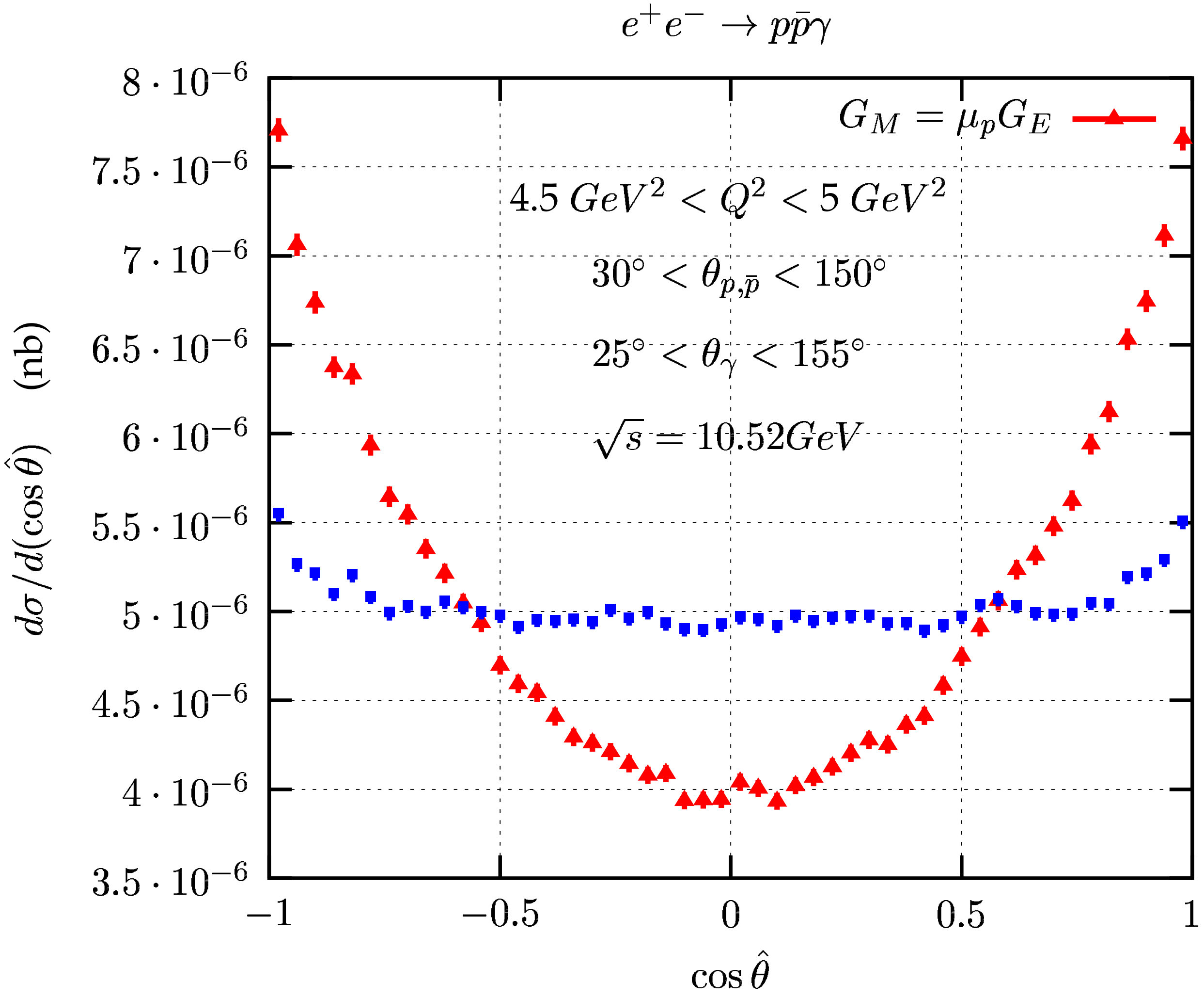


$$e^+e^- \to p\bar{p}\gamma$$

implementation in PHOKHARA

(large rates $\sim$ 400 evt/10MeV around 4GeV^2)

Angular distributions of nucleon



hadronic rest frame

(two choices for G_M/G_E)

- **similar results for neutron pair production**
- **NLO corrections from ISR included** (corrections $\sim$ 1–2%)
- **no FSR**

thousands of events around 4–5 GeV^2
several events up to 7–8 GeV^2

V Conclusions

- **continuous development of PHOKHARA**

  ⇒ radiative corrections (completed for ISR)

  ⇒ more channels

  ⇒ cooperation between theory and experiment crucial

- **charge asymmetry as analysis tool**

- **nucleon form factors:**

  G_E and G_M can be measured for a wide range of Q^2

central issue: hadronic form factors !