Status and Prospects

of MC Tools for the Radiative Return

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In collaboration with

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I Basic Idea
II Monte Carlo Generators
III Experimental Results
IV Perspectives
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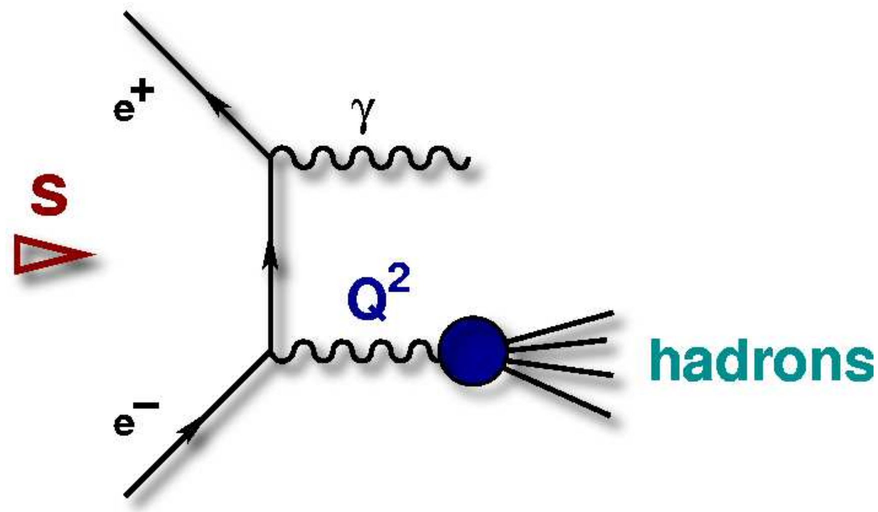
I BASIC IDEA

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

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



- 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

Original estimates for rates :

(Binner,JK,Melnikov 1999)

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

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

[actual values: KLOE = 0.5 fb^{-1}, BABAR = 131 fb^{-1} i BELLE = 159 fb^{-1}]

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

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

$$\times \frac{\alpha}{\pi s}\left\{ \begin{array}{c} \frac{s^2+Q^4}{s(s-Q^2)}\left(\log(s/m_e^2)-1\right) \\ \frac{s^2+Q^4}{s(s-Q^2)}\log\left(\frac{1+\cos\theta_{min}}{1-\cos\theta_{min}}\right) - \frac{s-Q^2}{s}\cos\theta_{min} \end{array} \right\}$$

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

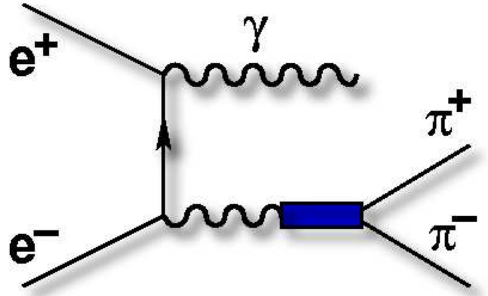
e.g. $\theta_{min} = 30^\circ$; $\sqrt{s} = 10.58$ GeV ; $Q = 1$ GeV ; $\Delta Q = 0.1$ GeV

$$\frac{dL}{dQ^2}(Q^2, s)\,\Delta Q^2 = 7.6 \cdot 10^{-6}\ L(at\ s)$$

100 fb^{-1} at 10.58 GeV $\Rightarrow$ 0.76 pb^{-1} per scan point at 1 GeV

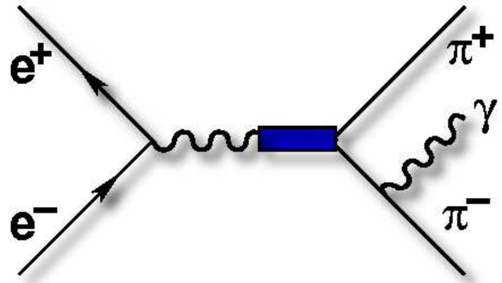
Basic Ingredients for Pion Formfactor

- ISR



pion form factor
⇨ to be tested

- FSR

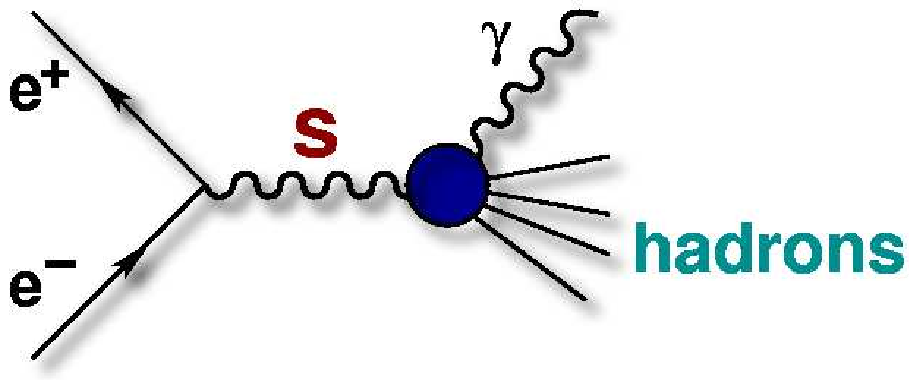


radiation from point-like pions (probably overestimated)

- **additional radiation:** collinear (EVA MC)
  or NLO calculation (PHOKHARA MC)

FSR versus ISR

background for our process and Model dependent



Solutions:

❶ select configurations with dominantly ISR

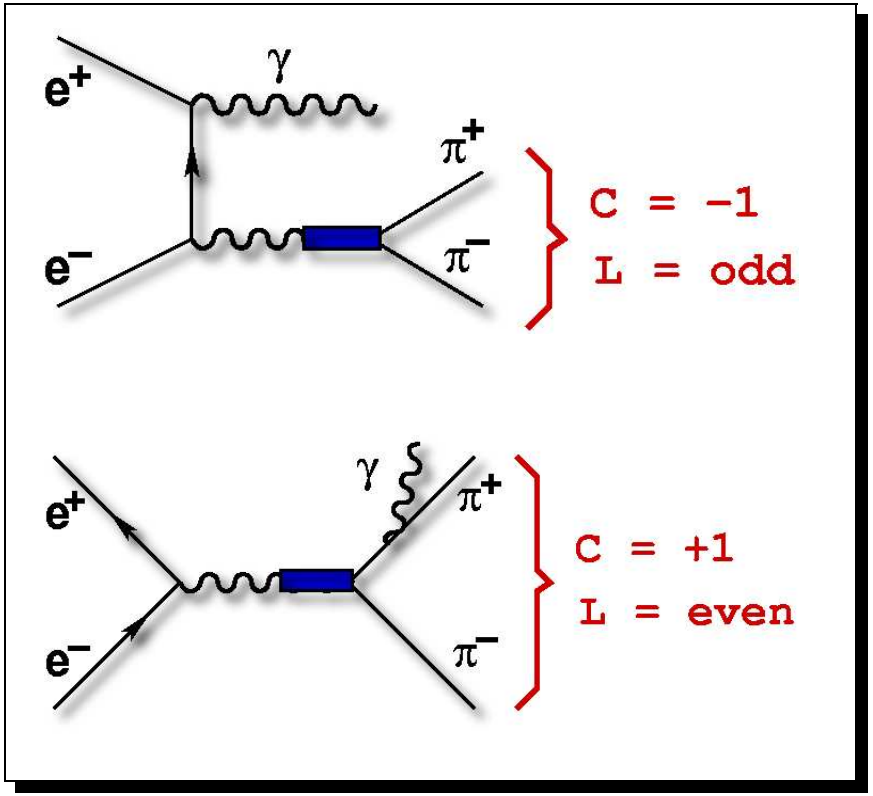
❷ allow only configurations where FSR is well predicted: γ soft, collinear

❸ identify distributions which test FSR model: angular distributions, charge asymmetry

✚ ISR-FSR interference is C-odd: cancels under C-symmetric cuts

Test of FSR model

interference:



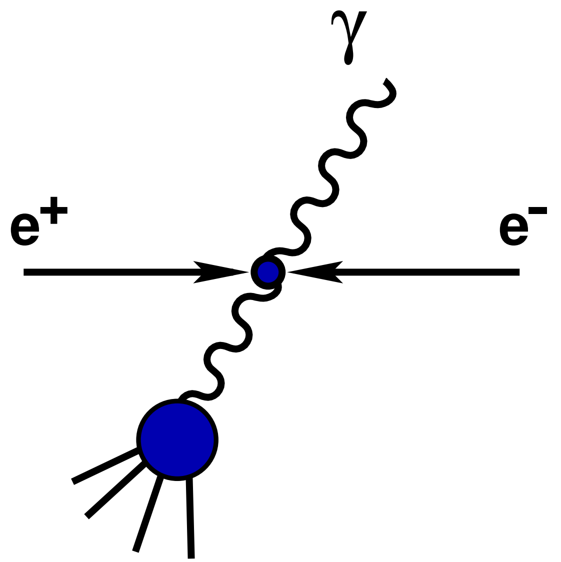
- interference odd under $\pi^+ \leftrightarrow \pi^-$
- asymmetric differential distribution: $\int$ interf. $= 0$

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

DAΦNE versus B-factories:

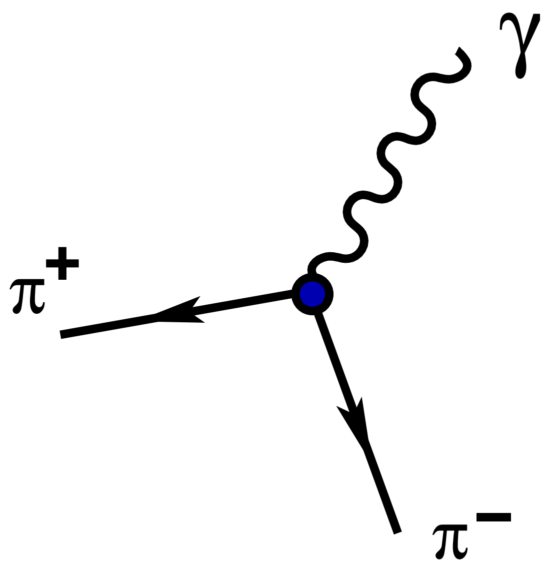
configurations in the cms - frame

10 GeV



very hard photon: clear kinematic separation between photon and hadrons

1 GeV

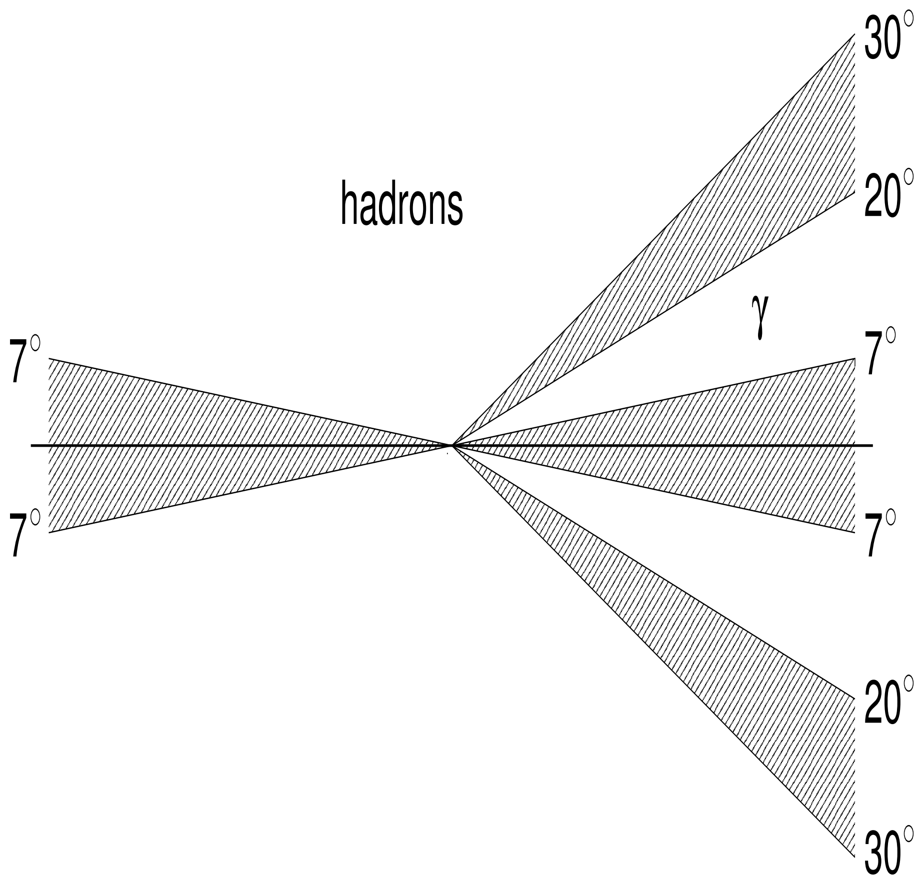


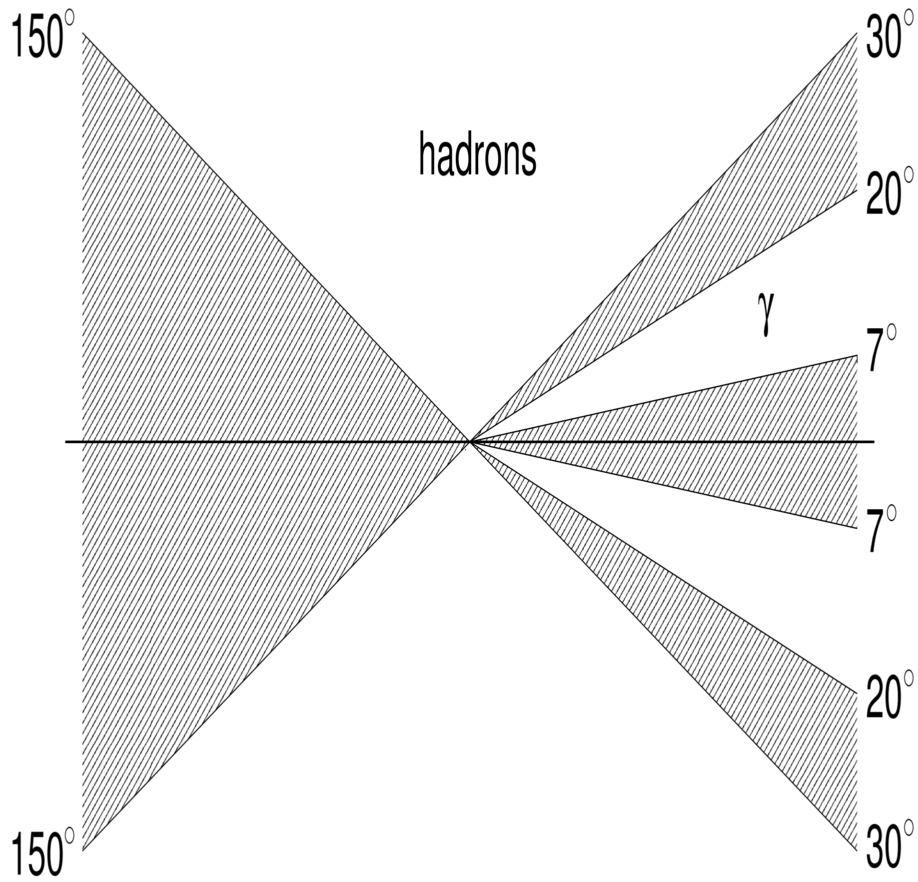
no natural kinematic separation

➯ cuts to control FSR versus ISR

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

reject FSR





High energy (10.52GeV)

Low energy (1.02 GeV)

II MONTE CARLO generators

Quantitative Analysis :

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.]

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

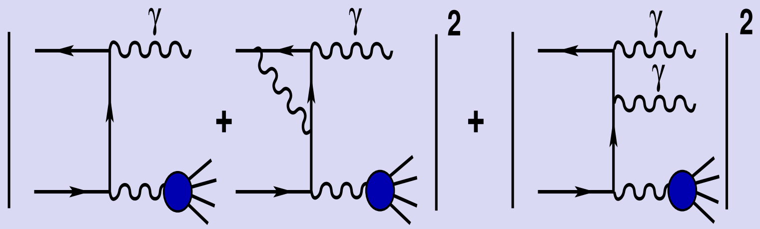
- ISR at LO + Structure Function

[Czyż, Kühn]

other exclusive channels: 3π, KK

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

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

P
H
OTONS FROM
KARLSRUHE
H
ADRONICALLY
R
ADIATED

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

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LL versus NLO

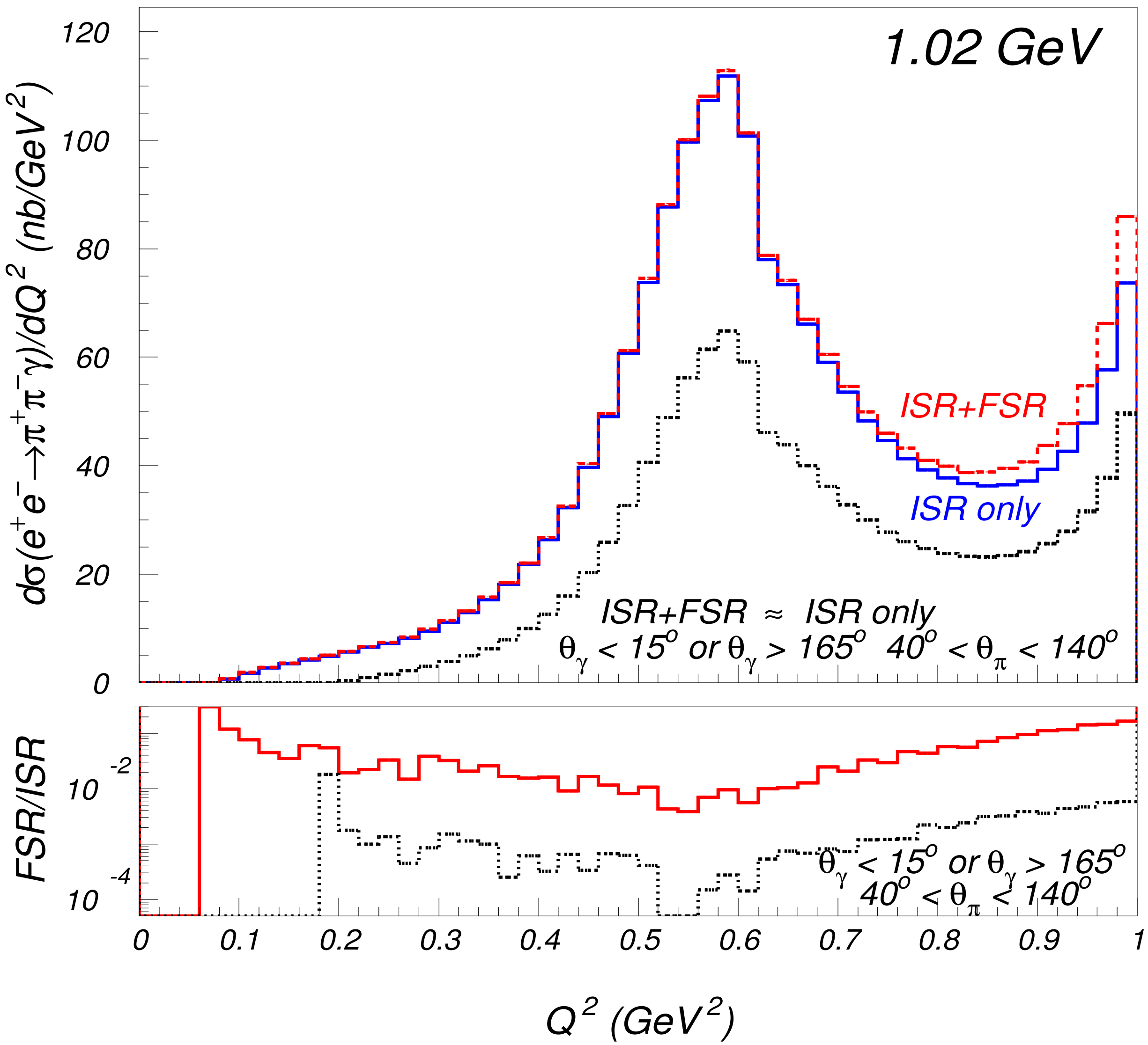
LL (EVA)

1. Resums big logs $L = \log(s/m_e^2)$ to all orders
2. Valid only in the collinear limit
3. Extra collinear emission integrated out ➪ no momentum conservation
4. Untagged photon: double counting

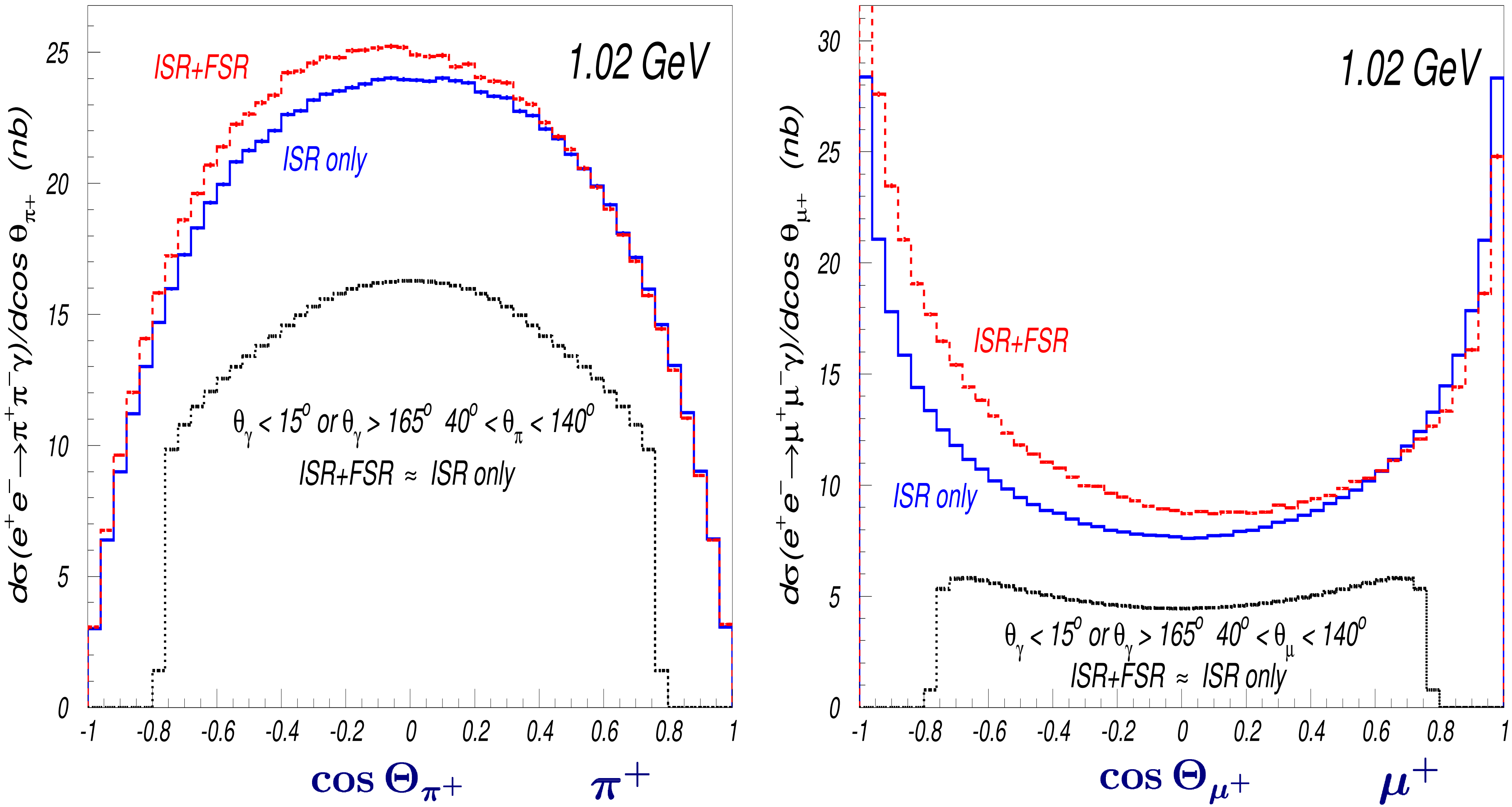
NLO (PHOKHARA)

1. LL at a fixed order + subleading terms **(1 %)**
2. Full angular dependence
3. Momentum conservation
4. Tagged or untagged photon: ✔

IMPACT OF ANGULAR CUTS



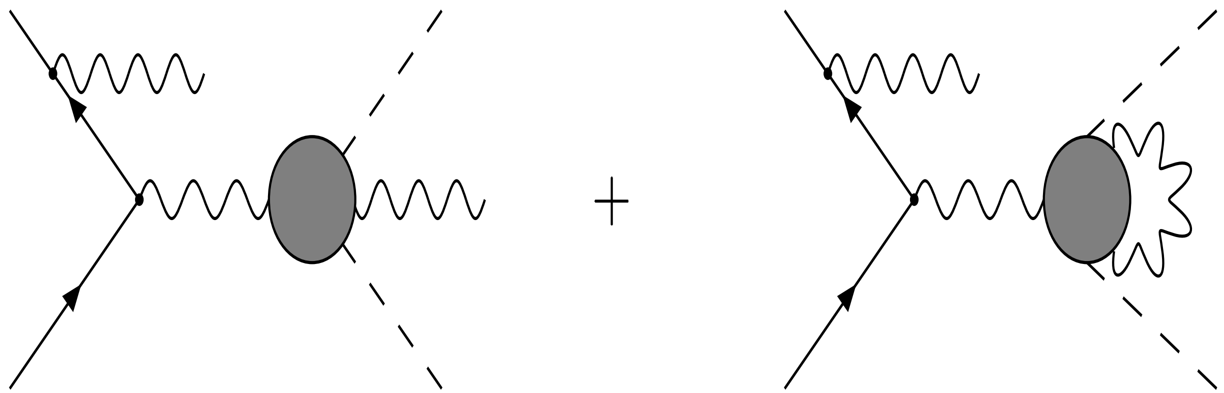
ASYMMETRY



Importance of simulation with cuts: nontrivial cut-dependence of $\pi^+\pi^-/\mu^+\mu^-$

new developments: PHOKHARA 3.0

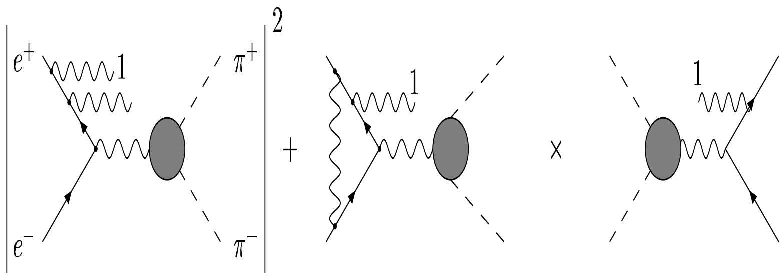
- specifically developed for $\pi^+\pi^-$ (plus photons)
- allows for simultaneous emission of photons from initial and final state, including virtual corrections (interference neglected).



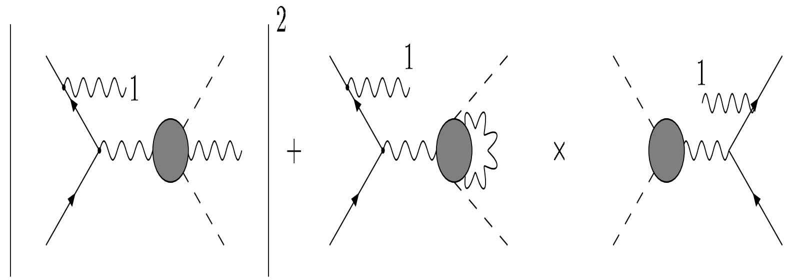
$\Rightarrow$ dominated by "two step process": $\mathrm{e}^+\mathrm{e}^- \to \gamma\ \rho(\to \gamma\pi\pi)$

$\Rightarrow$ importance of $\pi\pi\gamma$ as input for $a_\mu \Rightarrow$ Rodrigo

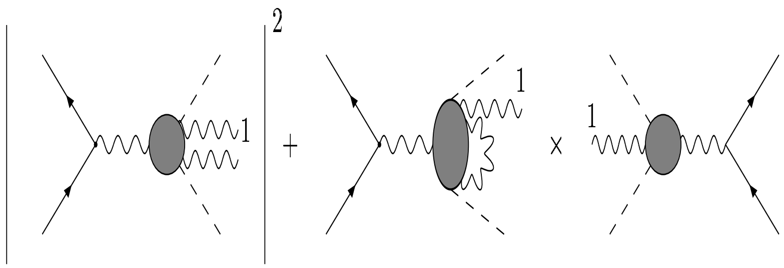
complete set of NLO contributions:



PHOKHARA 2.0



PHOKHARA 3.0



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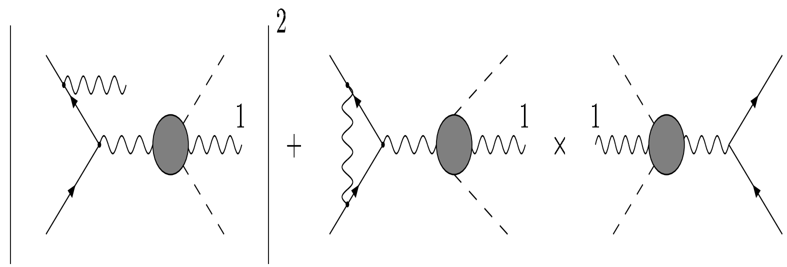

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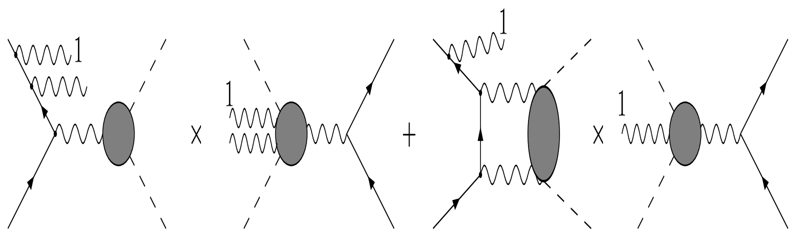
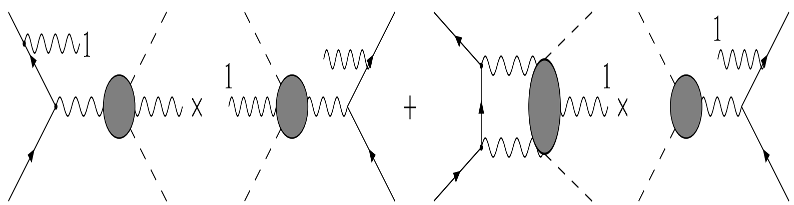
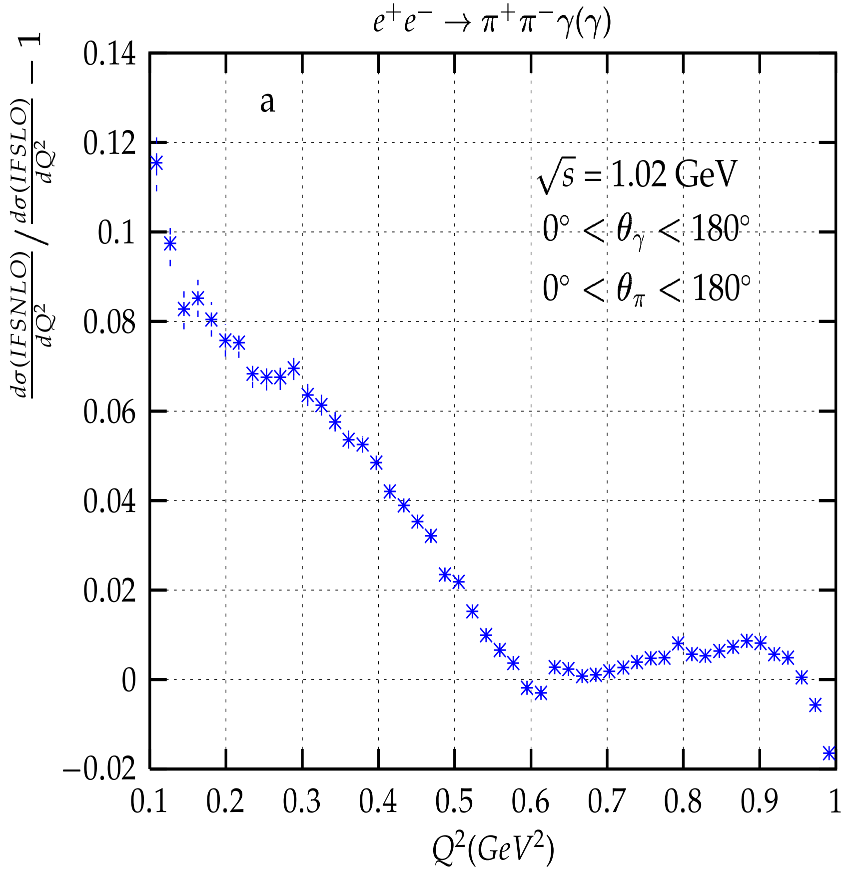


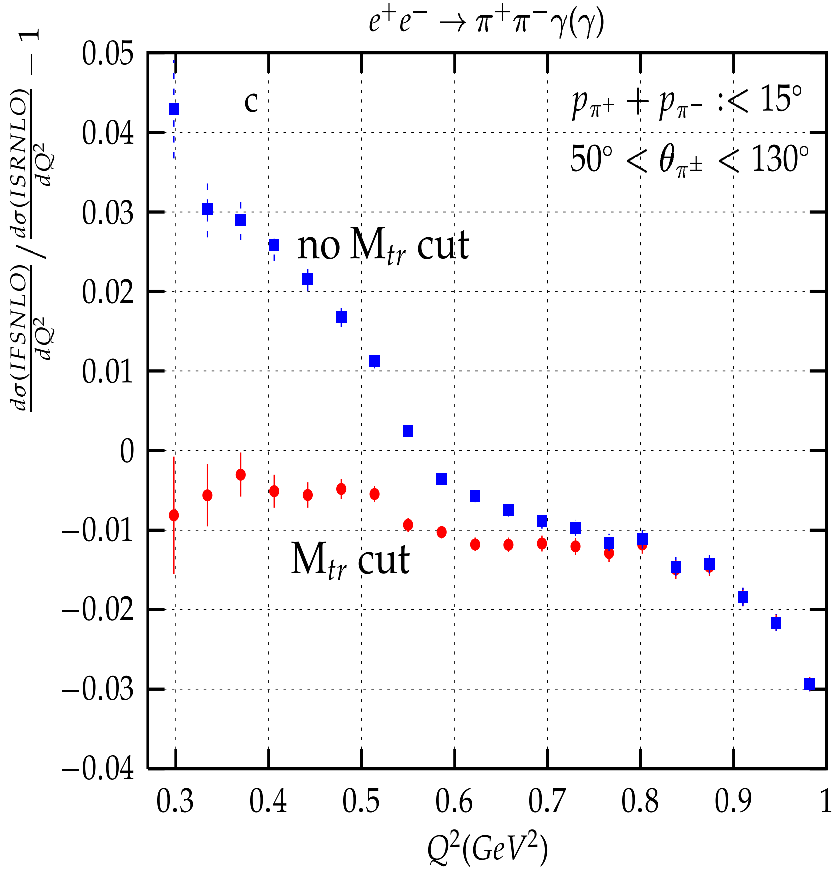
E



F

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

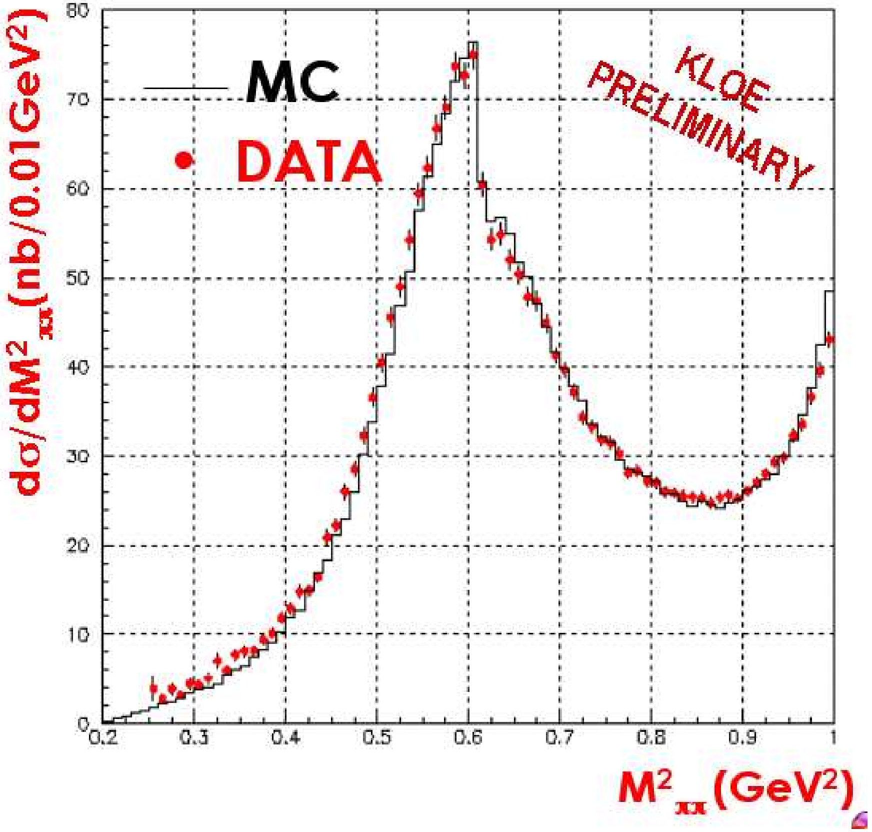


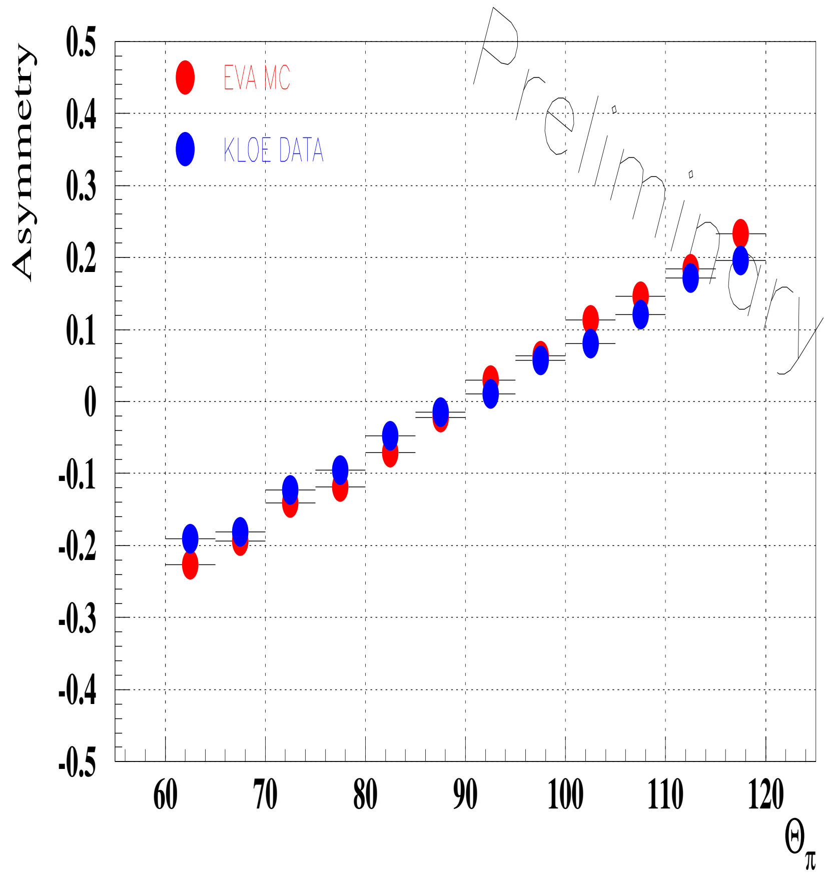


or measure photon

III Experimental Results

KLOE:





BABAR

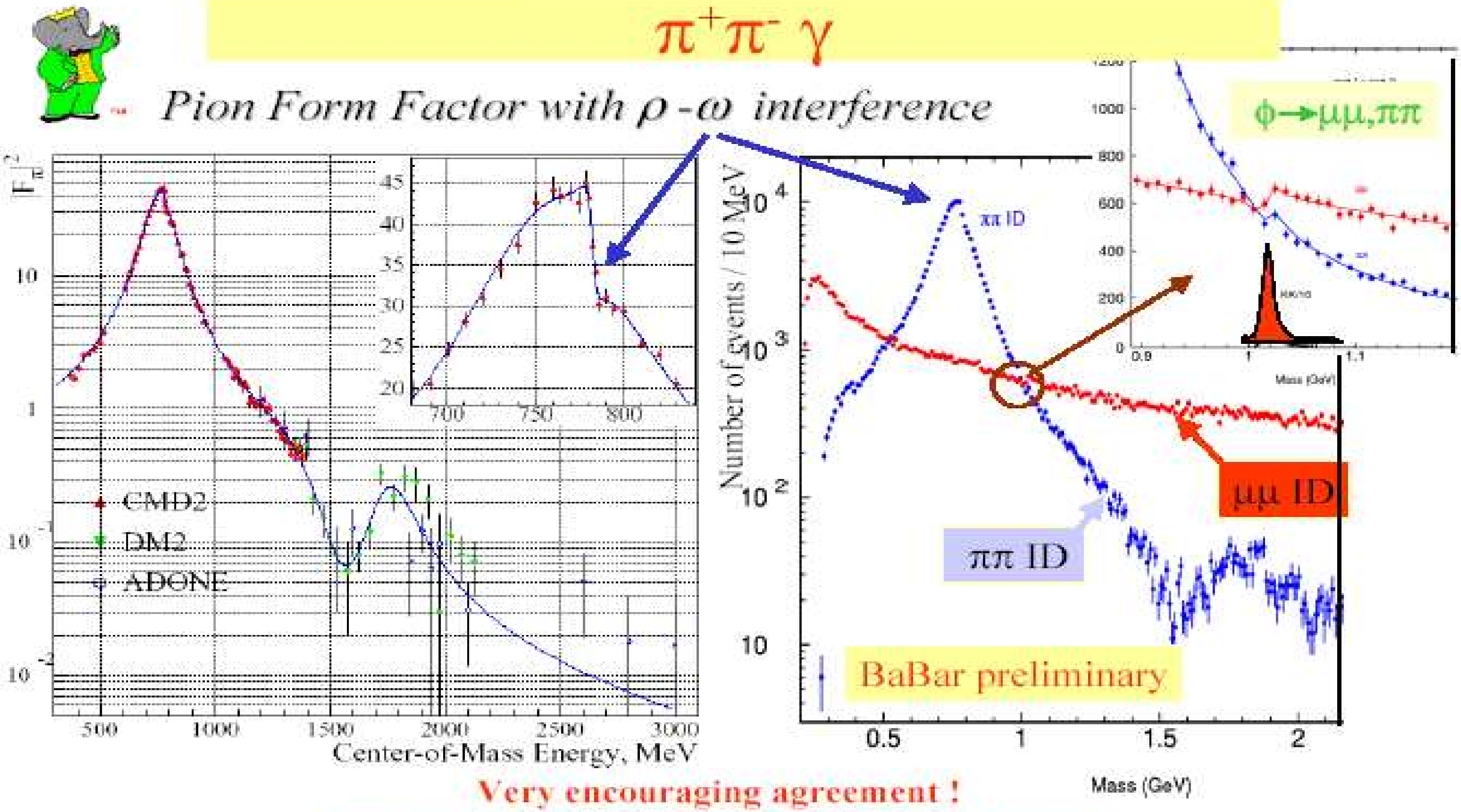
higher Q^2 available

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

Examples:

- $\pi\pi$
- $4\pi^{\pm}$
- K K $\pi\pi$
- K K K K

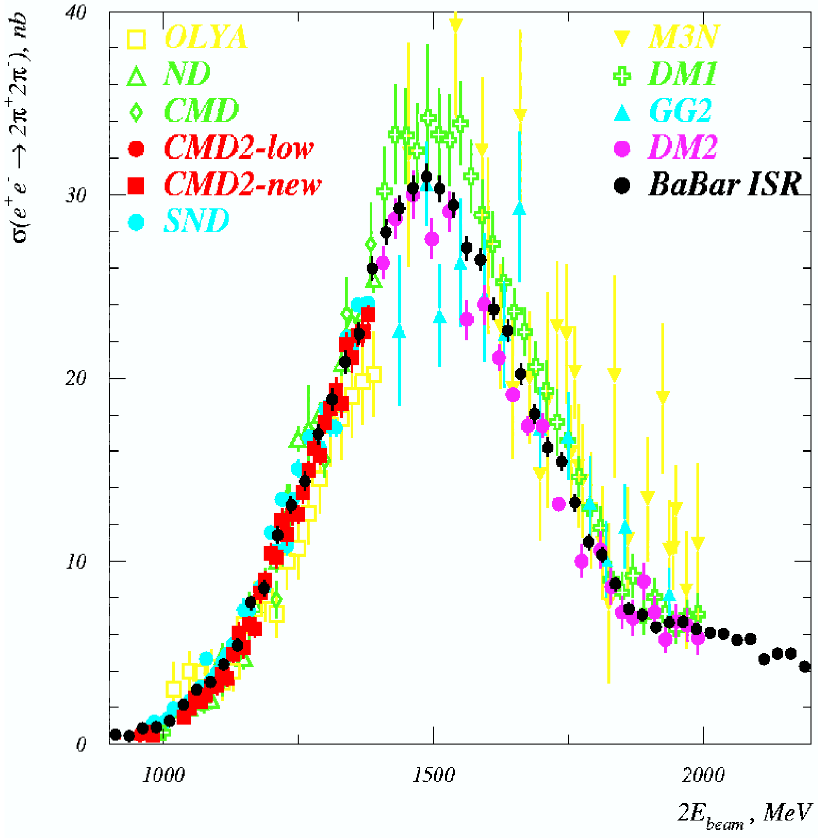
$\pi^+\pi^-\gamma$

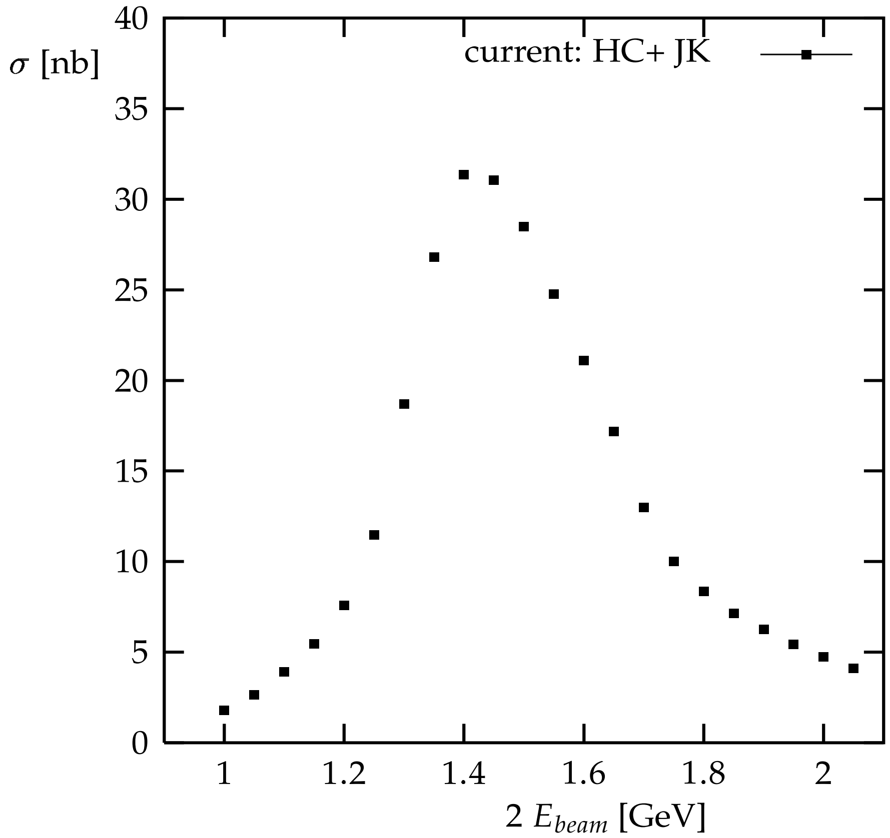


Very encouraging agreement !

hard work! <1% systematic error is needed for g-2

4 $\pi^{\pm}\gamma$





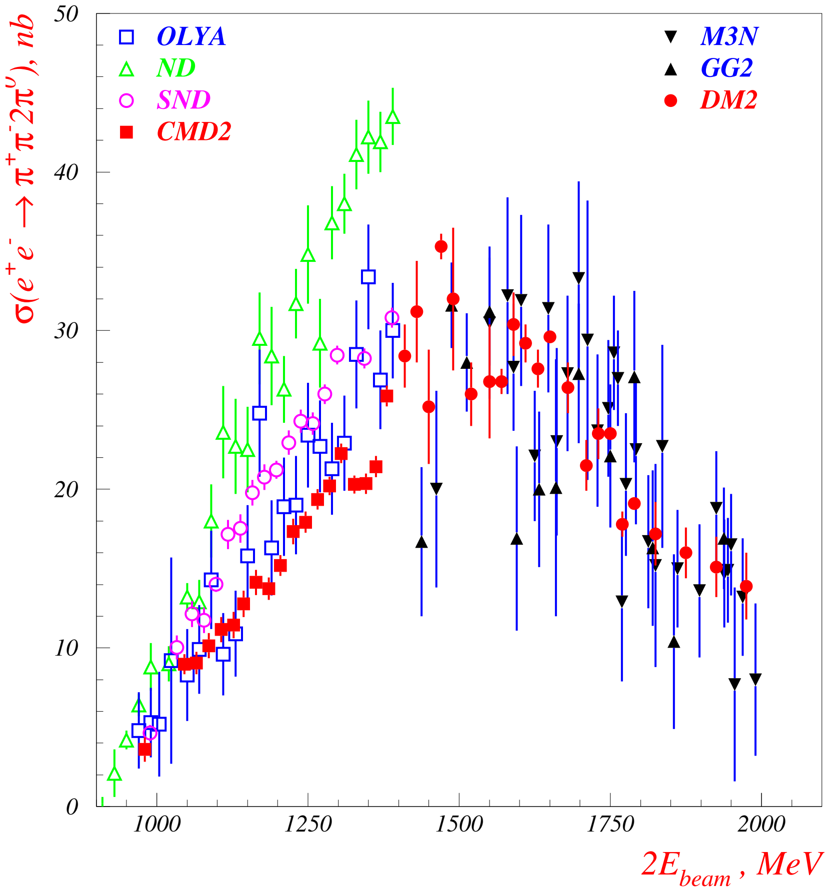
remarkable agreement with predictions: Czyż + Kühn

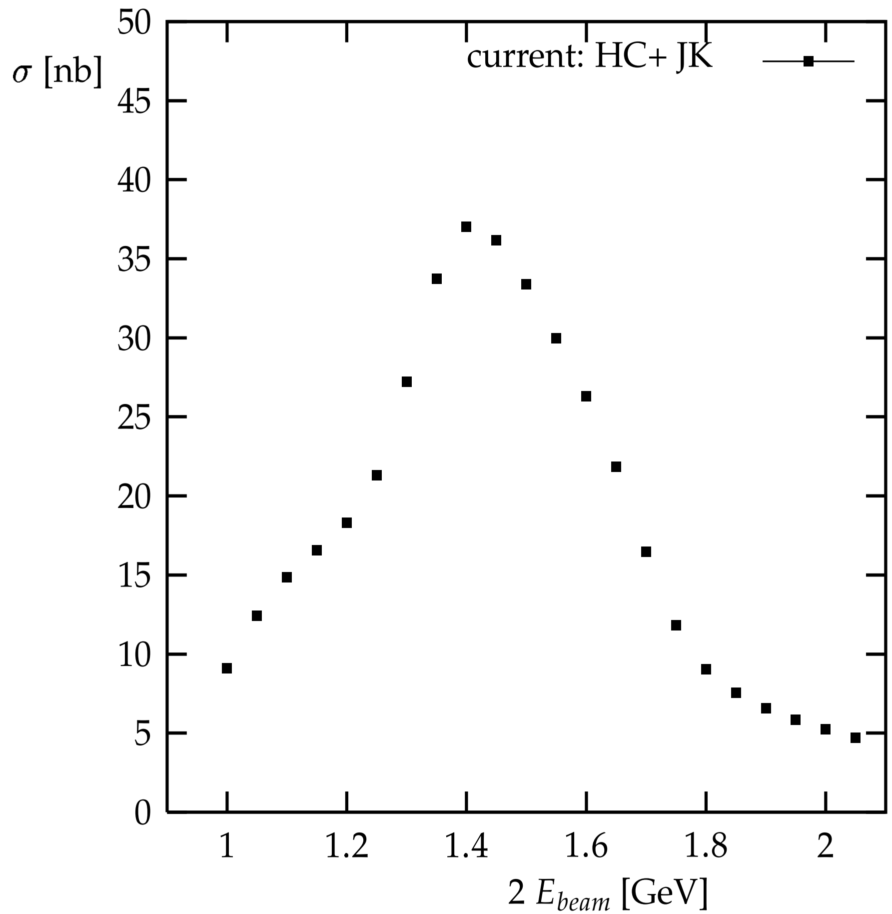
based on model by Decker et al.,

internal dynamics predicted: ρf_0, $a_1\pi$, $\omega\pi$ (for $\pi^+\pi^-\pi^0\pi^0$)

chiral limit !

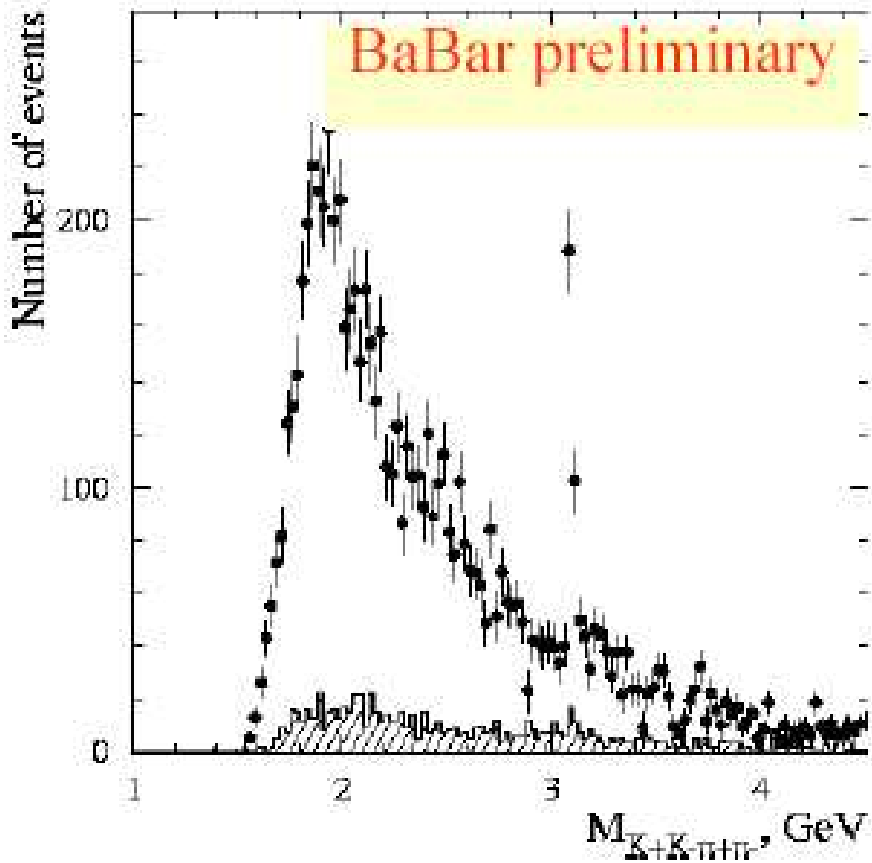
isospin prediction for $\pi^+\pi^-\pi^0\pi^0$

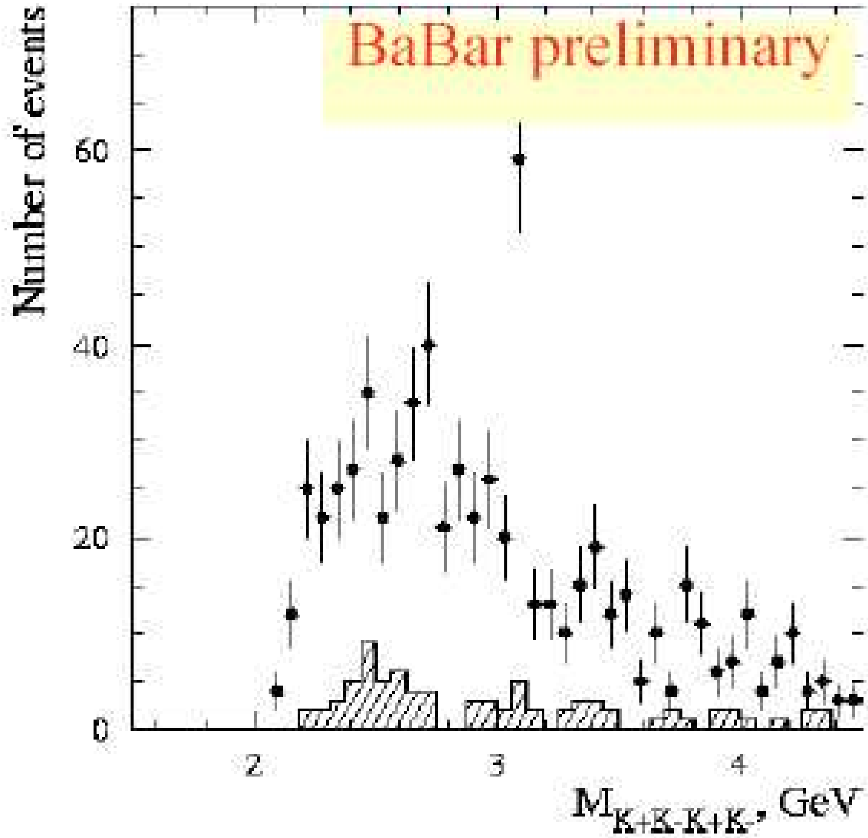




Czyż + Kühn based on model by Decker et al.

$K^+K^-\pi^+\pi^-$ and $4K^{\pm}$ production





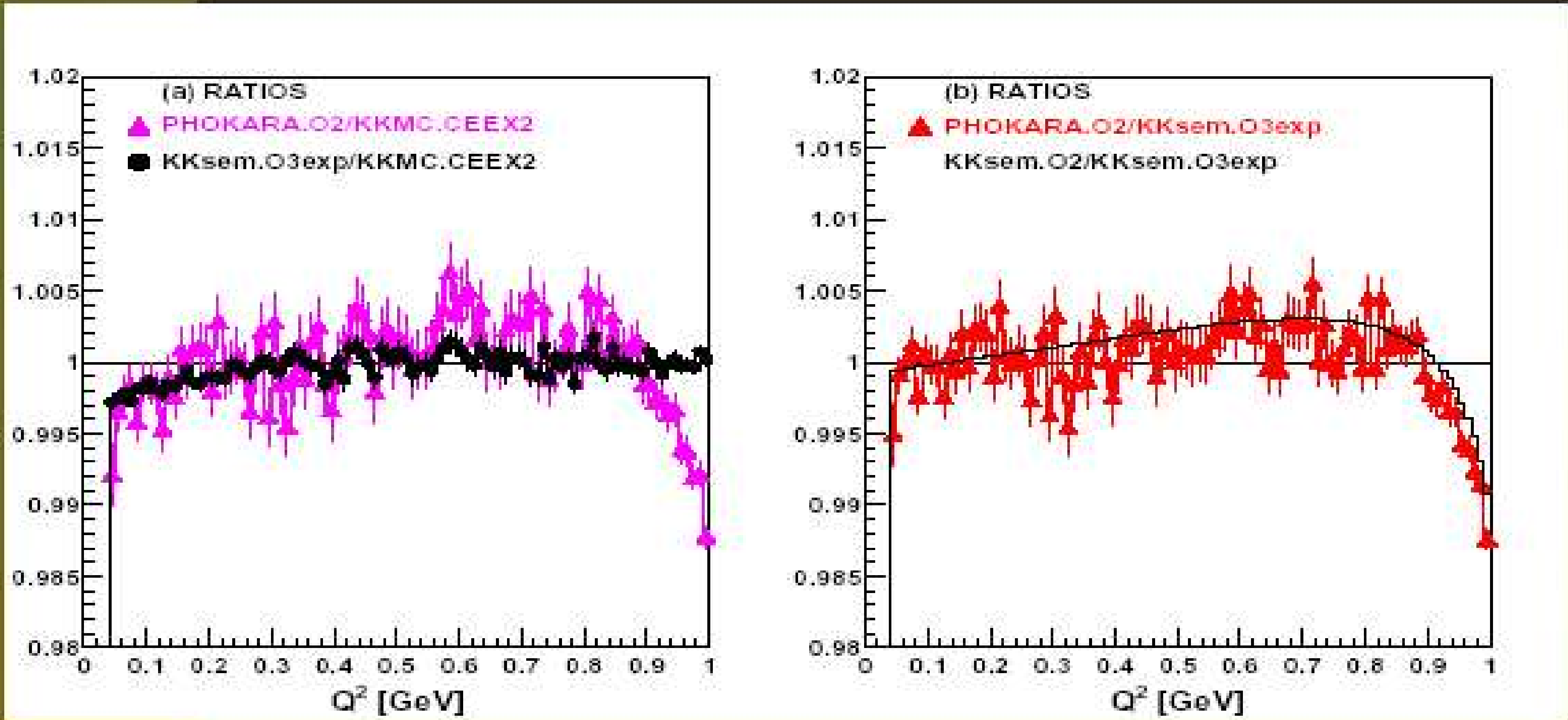
IV PERSPECTIVES

Monte Carlo:

- **PHOKHARA 3.0 for $\mu^+\mu^-\gamma$ (with FSR at NLO)**
- **include narrow resonances (J/ψ, $\cdots$)**
- **collinear radiation of e^+e^- from initial state**
- **benchmarks with other programs:**
  ($\mu^+\mu^-$: KKMC ; hadrons: ???)

S.Jadach: KKMC

PHOKHARA included in the game, μ-pairs again



PHOKHARA agrees to within 0.3% with KKMC and KKsem.

Discrepancy at high Q^2 reflects lack of exponentiation in PHOKHARA

S.Jadach: KKMC

Summary

- We found very good agreement of KKMC and PHOKHARA to within 0.2% for μ-pair final states for pure ISR
- Discrepancy of order 1-2% between KKMC and PHOKHARA or even larger at low mass, was found for π-pair final state.
- This is due to use of the inferior EEX matrix element in KKMC instead of CEEX.
- NB. We know how to upgrade ISR in KKMC to CEEX level for any hadronic final state...

Hadronic Final States

- **two mesons: K^+K^-, $K^0\bar{K}^0$, $\pi\pi$ at large Q^2**
  technically trivial !
  choice of formfactor ? isospin , SU(3), ...
- **three mesons: 3π ($\to \rho\pi$)**
  $KK\pi$ (compare τ decays)
- **$p\bar{p}$ (Dirac vs. Pauli formfactors)**
- **multiparticle continuum**
  $e^+e^- \to \gamma q\bar{q}$
  hadronisation of $q\bar{q}$ e.g. via Lund
  importance of FSR !

new topics

- **parameters of J/ψ , ψ' :**

observable: $\Gamma_e \frac{\Gamma_f}{\Gamma_{tot}}$; $f = \mu^+\mu^-$, $\pi^+\pi^-$, 3π , 4π , $4K$, ...

compare : $\frac{\sigma_f}{\sigma_{\mu^+\mu^-}}(off\ resonance)$?=? $\frac{\sigma_f}{\sigma_{\mu^+\mu^-}}(on\ resonance)$

$f = \mu^+\mu^-$, $\pi^+\pi^-$, 4π ...

virtual photon only (I=1)

$f = 3\pi$, $K\bar{K}$, $K\bar{K}\pi$ ...

3 gluon intermediate state (I=0)

- R_c

  separate charm and non-charm above $D\bar{D}$ threshold

  $R_c \quad \Rightarrow \quad m_c$ (Steinhauser, Hoang)

$$e^+e^- \to u\bar{u},\ \ d\bar{d}\ ,\ \ s\bar{s} \qquad R = 6/3$$

$$e^+e^- \to c\bar{c} \qquad R = 4/3$$

large boost for D , vertices

- radiative production of ψ'' ($\to D\bar{D}$)

$$100\ \text{fb}^{-1} \quad \Rightarrow \quad 40\,000\ \psi''$$

- energy dependence of $D^+D^-/D^0\bar{D}^0$
- CP- tests :

$$\text{example, } \text{Br}(D^0 \to \pi^+\pi^-) = 1.43 \times 10^{-3}$$

$$\text{Br}(D^0 \to K^+K^-) = 4.12 \times 10^{-3} \quad \text{CP=+}$$

$$\text{Br}(D^0 \to K_S\pi^0) = 1.14 \times 10^{-2}$$

$$\ldots$$

$$\psi'' \to D^0(\to \pi^+\pi^-)\bar{D}^0(\to \pi^+\pi^-) \quad \textbf{forbidden !}$$

amplification of small mixing effects ?

(JK, Mannel, Selz)

V CONCLUSIONS

Radiative Return at $\Phi-$ and $B-$ Factories

- gives huge event rates for R(Q^2) measurements
  in a large range of Q^2.

- Monte Carlo for precise measurements
  are important and available or under construction.

- numerous new measurements:
  multi-meson states; charm, J/ψ ; $\psi'' \to D\bar{D}$