4. 2. $\sigma(e^+e^- \to \pi^+\pi^-)$ by using Initial State Radiation ($e^+e^- \to \pi^+\pi^-\gamma$), ('radiative return' to ρ, ω)

Conventionally $\sigma(e^+e^- \to hadrons, Q^2_{hadr})$ is determined by an energy scan

at *DAΦNE* not foreseen for the near future, *DAΦNE* has been designed for high luminosity at the ϕ resonance

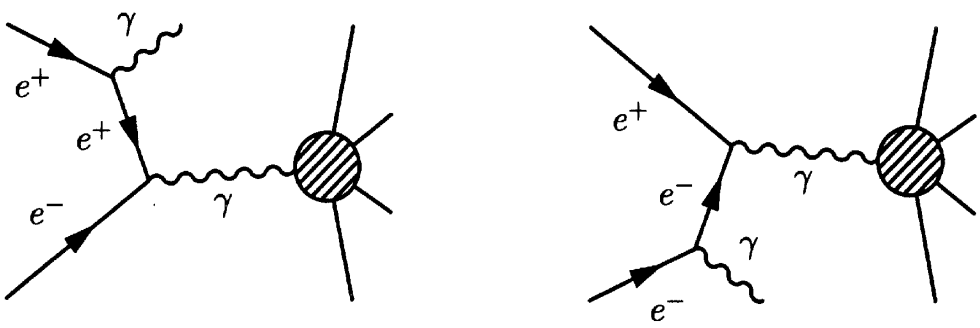
with permanent field focusing quadrupoles closest to the interaction point optimised for ϕ resonance

But, alternative approach ('radiative return')

Run at fixed energy $\sqrt{s} = m_\phi$ and exploit the process $e^+e^- \to hadrons + \gamma$ with the γ emitted in the initial state (*ISR*) to reduce c.m. energies of the colliding e^+ e^-

$$\frac{d\sigma(e^+e^- \to hadrons + \gamma)}{dQ^2} = \sigma(e^+e^- \to hadrons, Q^2\ )\ H(Q^2, cos\,\theta_o)$$

$Q^2 = m_\phi^2 - 2m_\phi E_\gamma$ and varies between $4m_\pi^2 < Q^2 < m_\phi^2$



$$e^+e^- \to \gamma + hadrons$$

$$2m_\pi^2 < s_{e^+e^-} < m_\phi^2$$

also NLO calculations under way *(MC generator Kühn et al.)*

ISR and energy scan

The method using *ISR* is not a surrogate for an energy scan, but has its value in itself

It does not make, however, an independent energy scan unnecessary

ISR has the merits that

- the error of the luminosity enters the Q^2 spectrum only once, is the same for the full c. m. energy range of electron positron annihilations

- the error of the electron (positron) energies enters the Q^2 spectrum only once

- the data are taken as a by-product within the standard research program of *KLOE* without changing any part of the experimental set-up

ISR has the constraints

- to be restricted to $Q^2 < m_\phi^2$ (ρ resonance)

- to depend on the precise knowledge of the photon emission in the inital state including radiative corrections (*EVA MC* generator, Kühn et al. 1999, 2001)

- to need an efficient suppression of the radiation from the particles in the final state (*FSR*) ($< 1\%$)

- to require a higher luminosity than an energy scan (due to the suppression by α_{em})

- *MC* studies mit the EVA Generator have been performed to demonstrate the feasibility to determine

$\sigma(e^+e^- \to \pi^+\pi^-)$

in the process $e^+e^- \to \pi^+\pi^-\gamma$ (exploiting *ISR*)
with a required precision of ~ *1%*

Rejection of *FSR* and other backgrounds below *1%*
Statistical and systematic errors below *1%*

G. Cataldi et al., *KLOE* memo 195/99

Also the possibility to measure the luminosity with *1%* has been studied with *MC* calculations

G. Cabibbo and G. Venanzoni,
Measuring the *DAΦNE* luminosity with large angle Bhabha scattering', *KLOE* memo 168/98

BABAYAGA (C. M. Carloni Calame, C. Lunardini, G. Montagna, O. Nicrosini, F. Piccinini), hep-ph/0003268

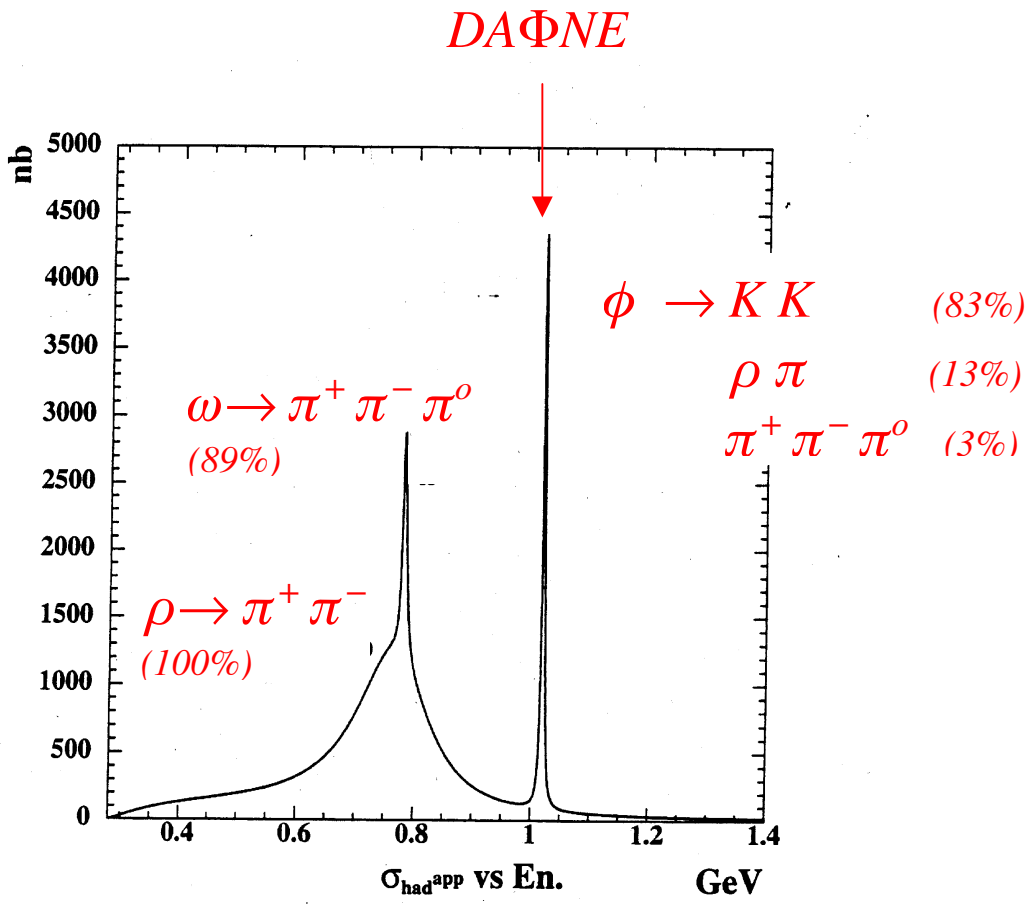
F. A. Behrends et al., Nucl. Phys**. B 202** (1981) 63

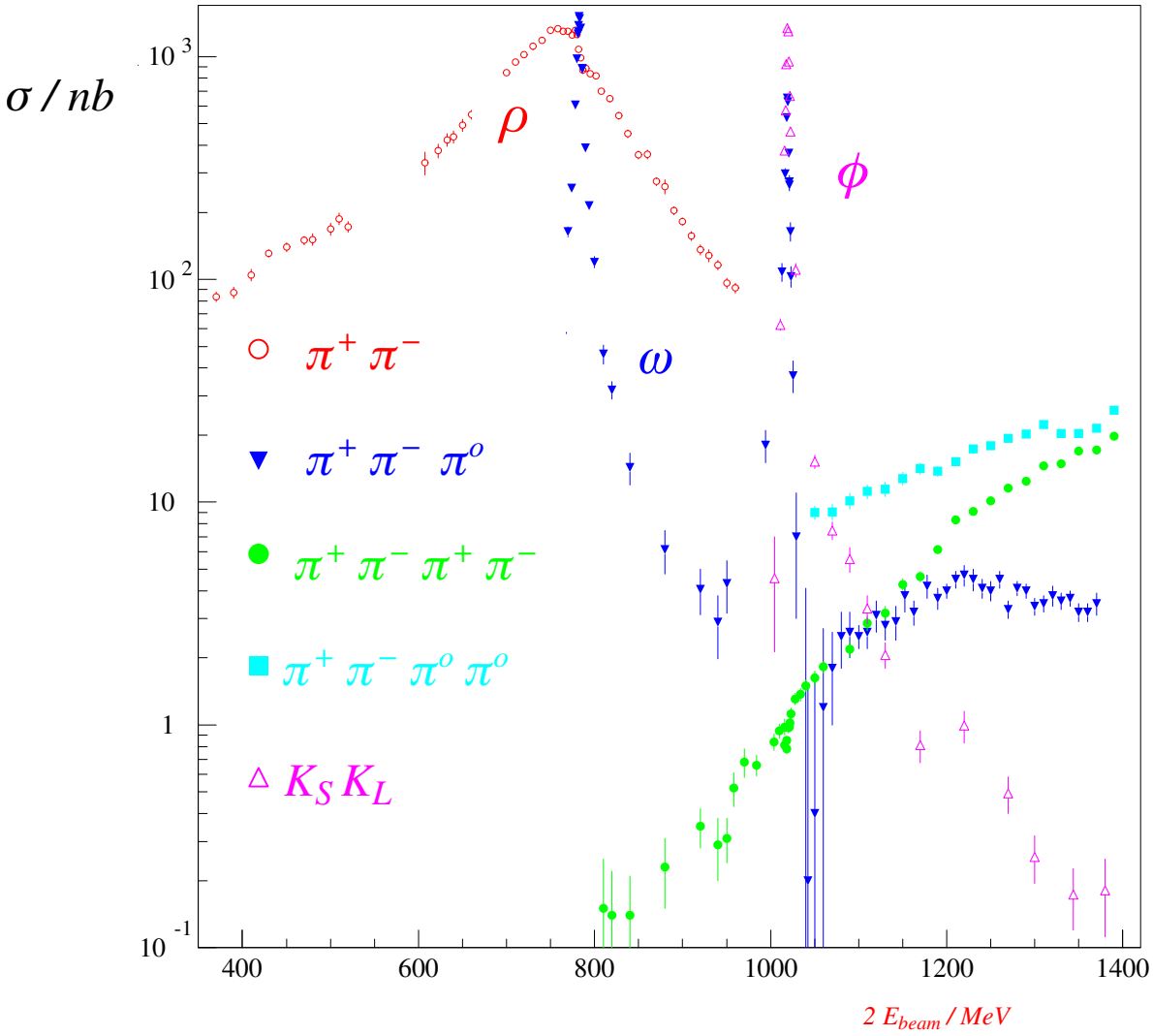
and with real data

A. Denig

- It turned out that the required accuracy can be achieved by selecting appropriate kinematical regions

Hadronic cross sections (Monte Carlo simulation)



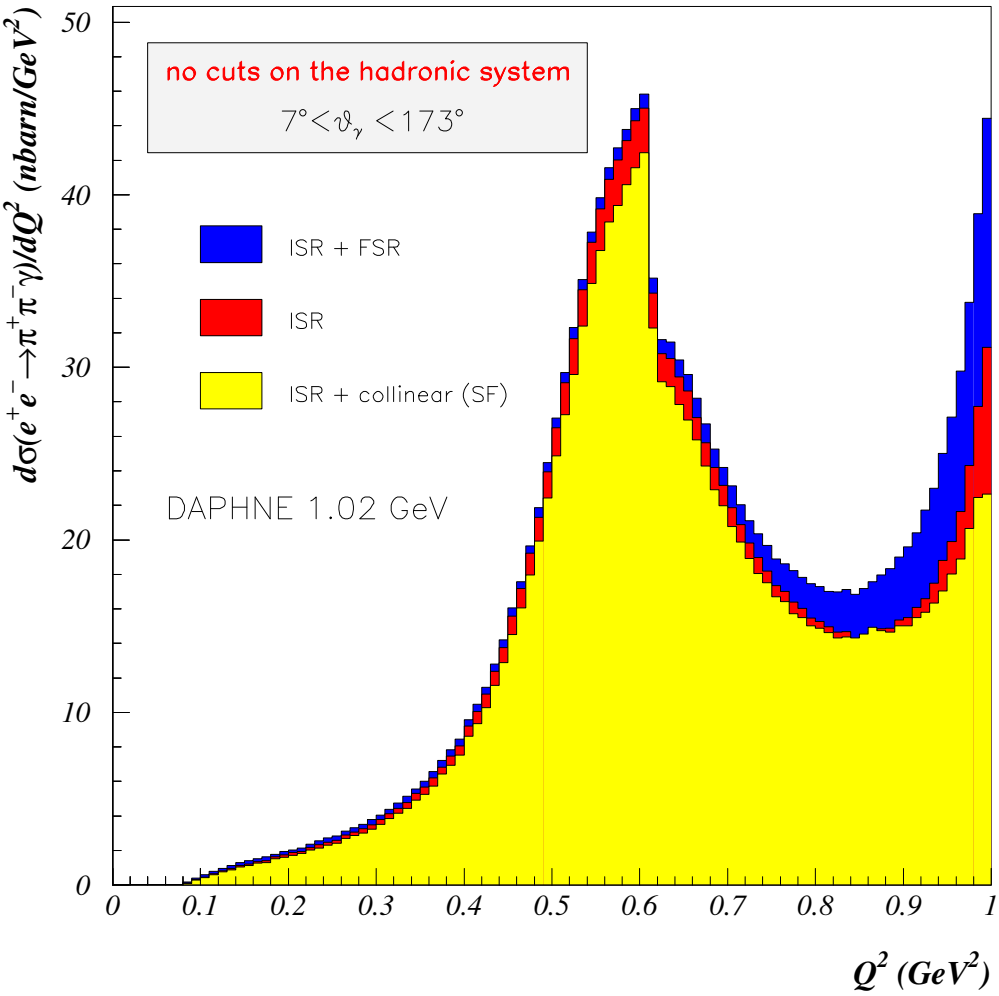


Hadronic cross sections

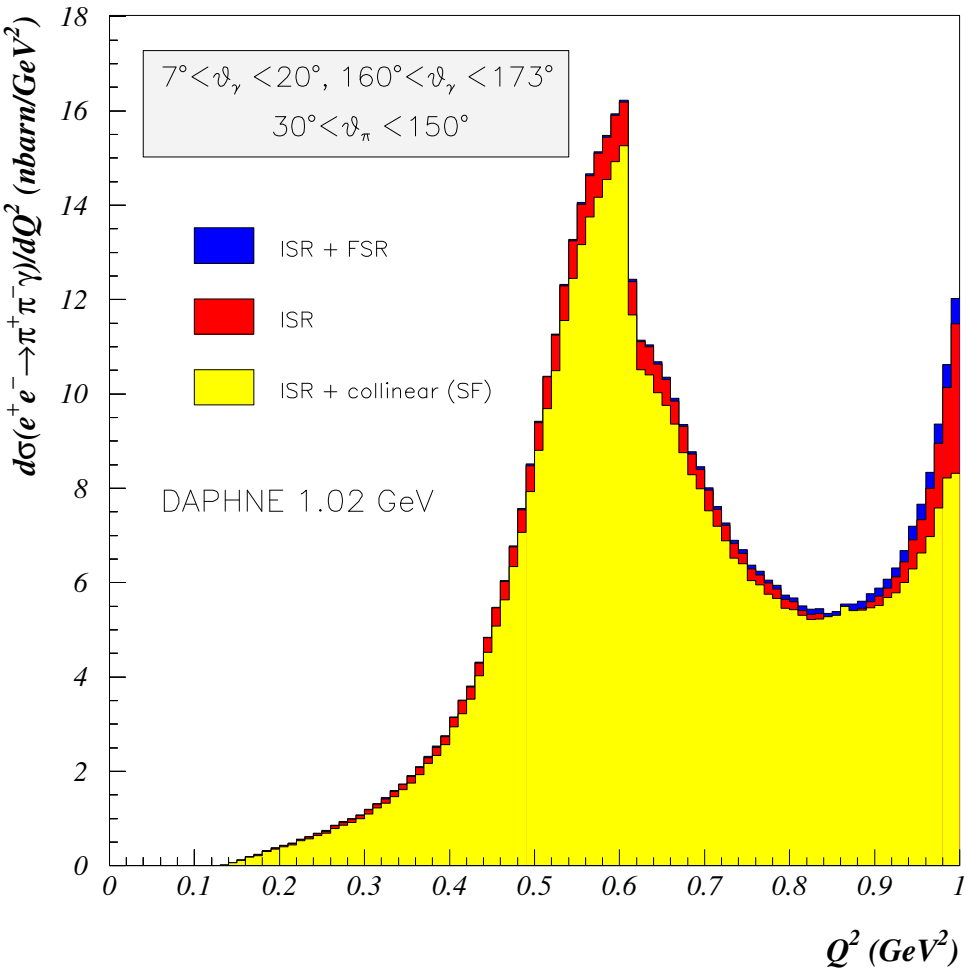
as function of c.m. energy (*VEPP-2M*)

Results from EVA MC

$e^+e^- \to \pi^+\pi^-\gamma$ dominant at DAΦNE

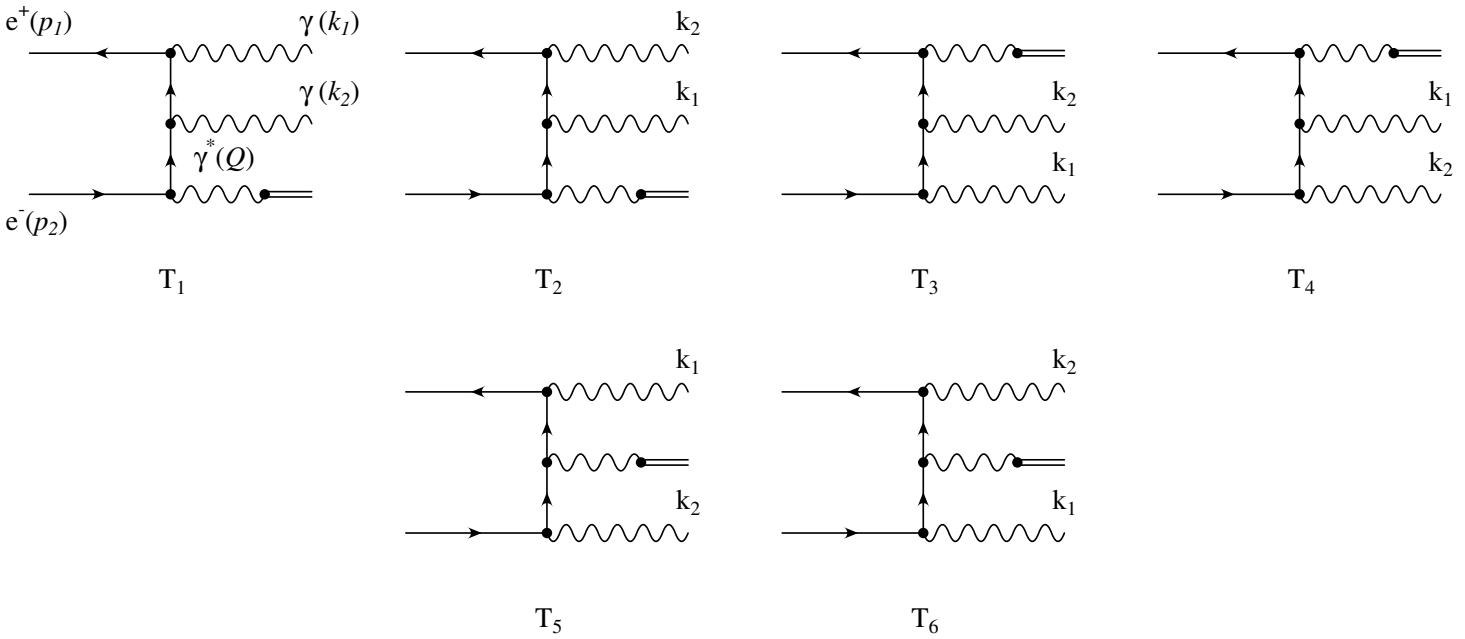


with kinematical cuts



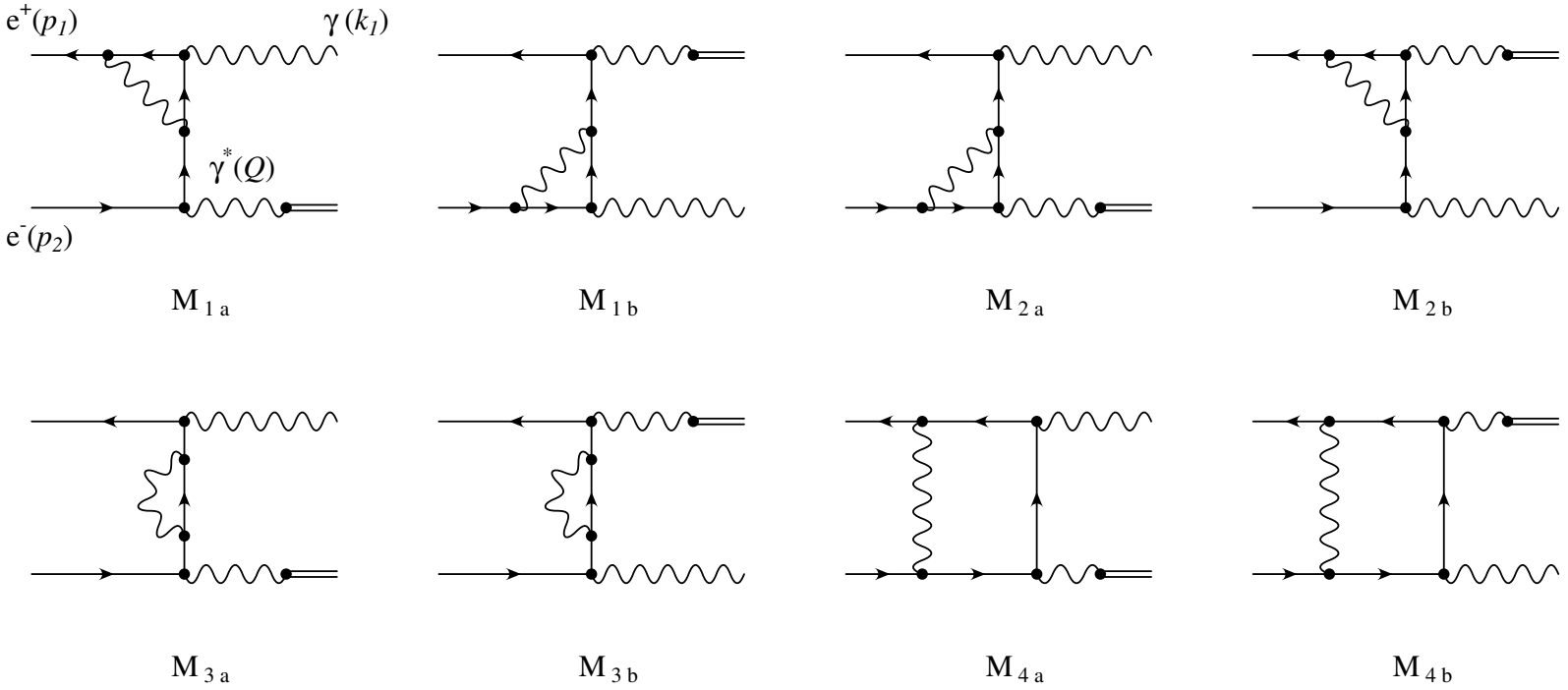
- collinear radiation (LL radiative QED corrections) important ➪ full NLO

Real corrections: two hard photons



$$L^{\mu\nu} = \alpha^3 \left[b_{00}\, g^{\mu\nu} + b_{11}\, \frac{p_1^\mu p_1^\nu}{s} + b_{22}\, \frac{p_2^\mu p_2^\nu}{s} \right.$$
$$\left. + b_{12}\, \frac{p_1^\mu p_2^\nu + p_2^\mu p_1^\nu}{s} + b_{33}\, \frac{k_1^\mu k_1^\nu}{s} + b_{13}\, \frac{p_1^\mu k_1^\nu + k_1^\mu p_1^\nu}{s} + b_{23}\, \frac{p_2^\mu k_1^\nu + k_1^\mu p_2^\nu}{s} \right]$$

Virtual corrections



- UV: on-shell renormalization
- IR: soft photon $E_\gamma < w\sqrt{s}$

4.3. Preliminary experimental results

total integrated luminosity in 1999: $\mathcal{L} \sim 2.4\ pb^{-1}$

total integrated luminosity in 2000: $\mathcal{L} \sim 25\ pb^{-1}$

- first $\pi^+ \pi^- \gamma$ analysis has been performed with $16.1\ pb^{-1}$ of reconstructed data (Nov.- Dec. 2000) and
- with γ's detected in *EmC* (large photon angles) and without (small photon angles)

Particle separation (electrons and pions)

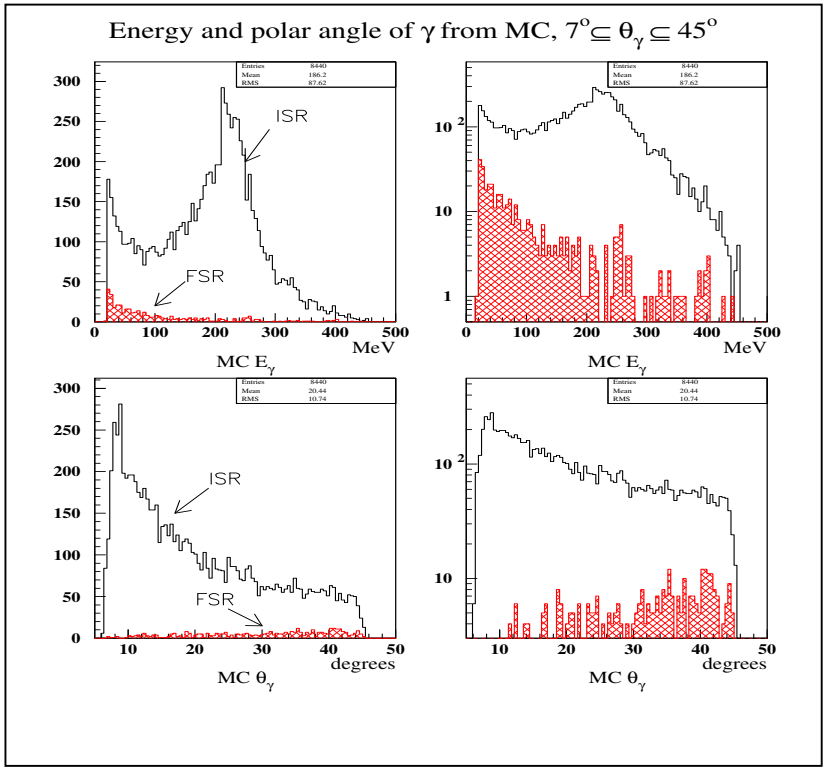
- likelihood method
- neural net
- kinematical fit

4.3.1. *ISR* versus *FSR* (*EVA - MC**)

FSR is background for $e^+ e^- \rightarrow \pi^+ \pi^- \gamma$

ISR is peaked at small photon angles
and is enhanced by the ρ-resonance

FSR follows pion angular distribution,
enhanced at small E_γ and larger photon angles



* S. Binner, J. H. Kühn, K. Melnikov
Phys. Lett. **B 459** (1999)

Cut in E_γ - θ_γ plane:

- $E_\gamma > 20$ *MeV*
- $5° < \theta_\gamma < 21°$
- $55° < \theta_\pi < 125°$
- more kinematical cuts

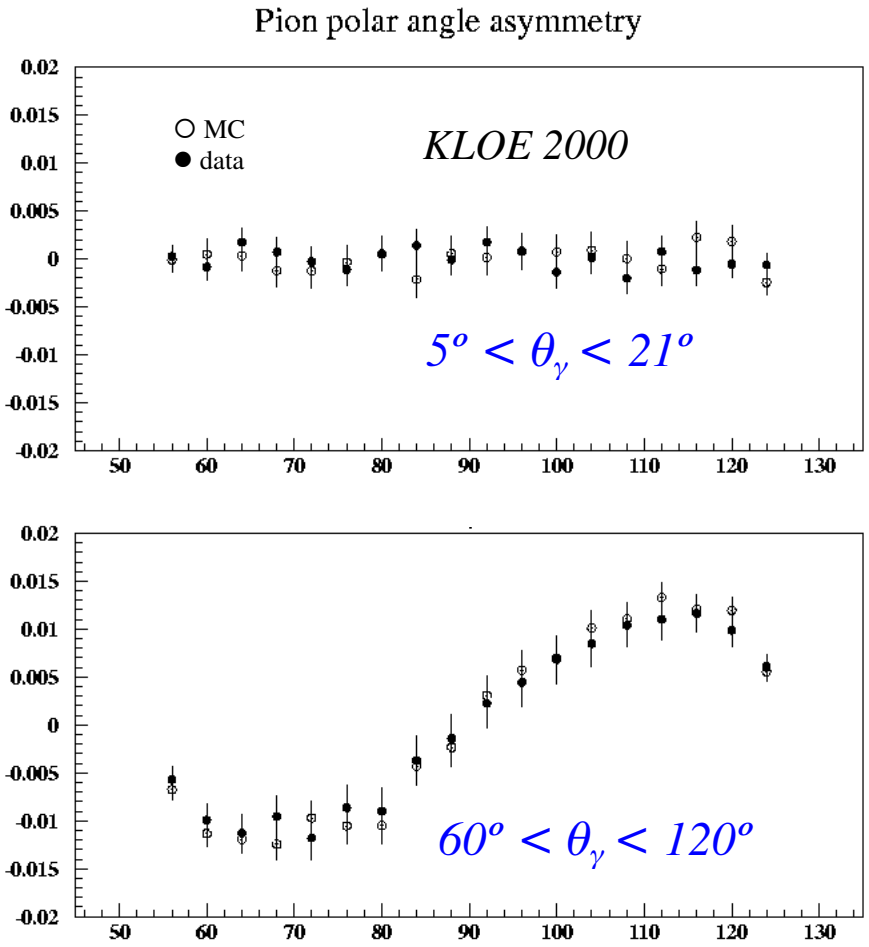
ISR / (ISR+FSR) > 99%

Select events with θ_γ as low as possible
$\sigma_{ISR} \approx$ *3.5 nb*

ISR / FSR

$$A(\theta_i) = \frac{N_{\pi^+}(\theta_i) - N_{\pi^-}(\theta_i)}{N_{\pi^+}(\theta_i) + N_{\pi^-}(\theta_i)}$$

The model of *FSR* in *MC* is tested by looking at the charge asymmetry of the pion pairs



Good agreement between data and *MC*

EVA -MC seems to describe *FSR* at the % level

Background $\phi \to f_o(980)\gamma \to \pi^+\pi^-\gamma$

The direct decay $\phi \to \pi^+\pi^-\gamma$ gives an additional background which has to be subtracted down to the *1%* level

Problem: Parameters of the f_o meson through which the decay proceeds are poorly known:

$$\phi \to f_o\,\gamma \to \pi^+\pi^-\gamma$$

constructive / destructive interference with *FSR* ?
get information from $\phi \to f_o\,\gamma \to \pi^o\pi^o\,\gamma$

Study decay experimentally at large photon angle $60^o < \theta_\gamma < 120^o$

complementary analysis to hadronic cross section (*ISR*)

Experimental values:

$BR\,(\phi \to \pi^+\pi^-\gamma)_{exp} = (0.41 \pm 0.13) \cdot 10^{-4}$
$BR\,(\phi \to f_o\gamma)_{exp} = (1.93 \pm 0.68) \cdot 10^{-4}$ (destructive interference ?)

} *CMD2*

$BR(\phi \to f_0\gamma)_{exp} < 1.6 \cdot 10^{-4}$ @ 95% CL

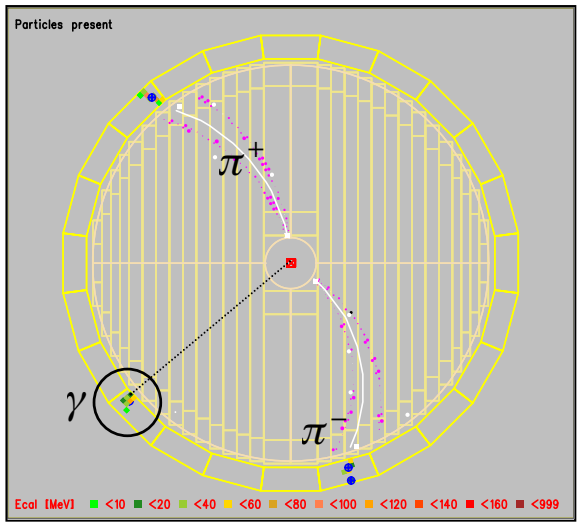
} *KLOE* 1999 data

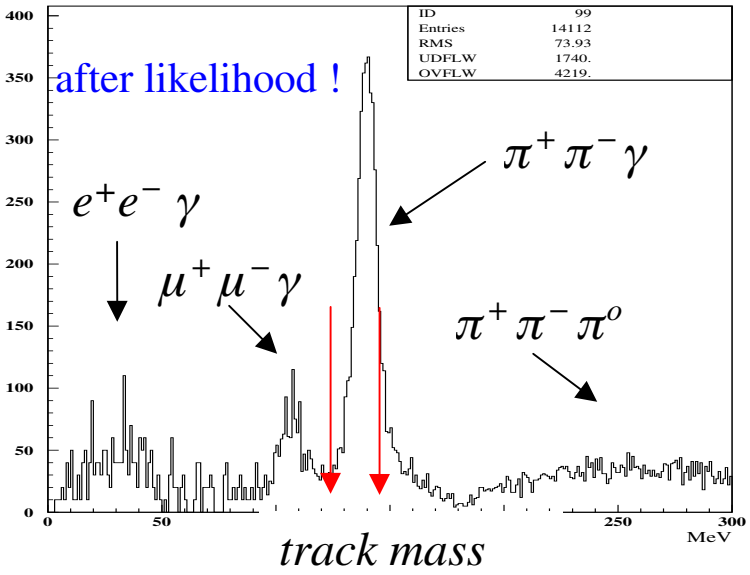
4.3.2. Selection of $e^+ e^- \to \pi^+ \pi^- \gamma$

Events with photon polar angle θ_γ as small as possible:

$\theta_\gamma > 21^o$: electromagnetic calorimeter *EmC*
$\theta_\gamma > 5^o$: quadrupole instrumentation

efficient photon detection not possible at very small angles where *ISR* is enhanced





Select $\pi\,\pi\,\gamma$ by using only information from the high resolution drift chamber, calculate θ_γ from missing momentum, no explicit photon detection

- *1* charged vertex close to *I.R.* with *2* tracks
- likelihood method for Bhabha suppression
- cut on kinematical variables (track mass)

4.3.3. Separation of Bhabha events

To reduce Bhabha contamination, a likelihood method has been developed based on:

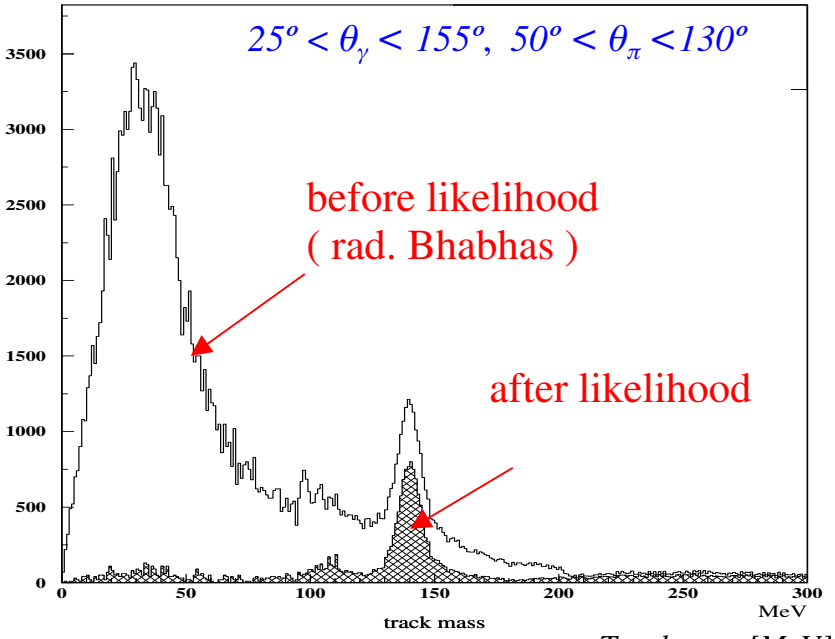
- *TOF* of charged clusters in *EmC*
- shape and energy deposition of the "charged" cluster

Two control samples have been taken from data in order to find suitable variables to separate electrons and pions:

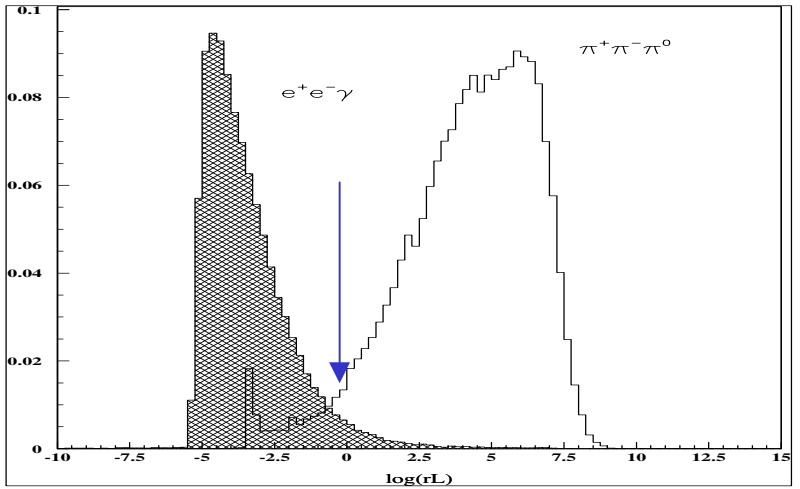
$\pi^+\pi^-\pi^o$ are used for pion information
$e^+e^-\gamma$ are used for electron

$aL^{e,\pi} = \Pi f_i^{e,\pi}(x_i)$ abs. likelihood

$rL = aL^{\pi} / aL^{e}$ rel. likelihood



Trackmass [MeV]



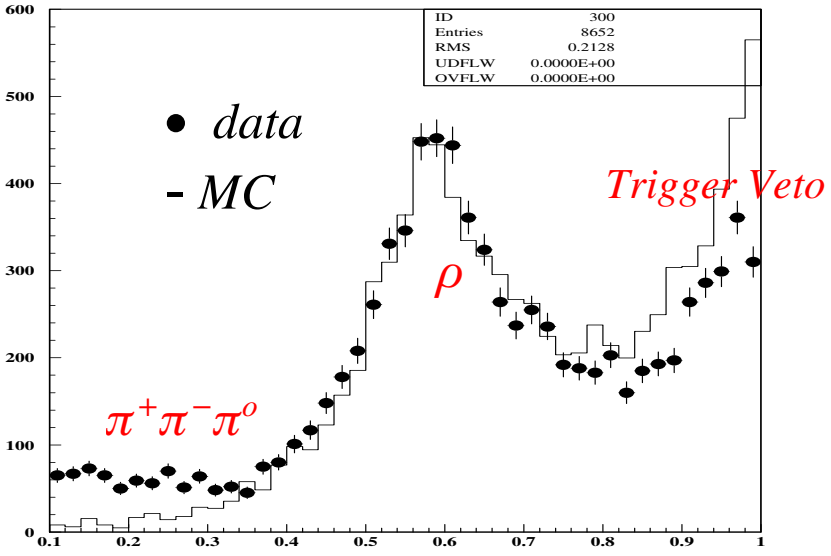
Log(rL)

4.3.4. First results and differential cross sections

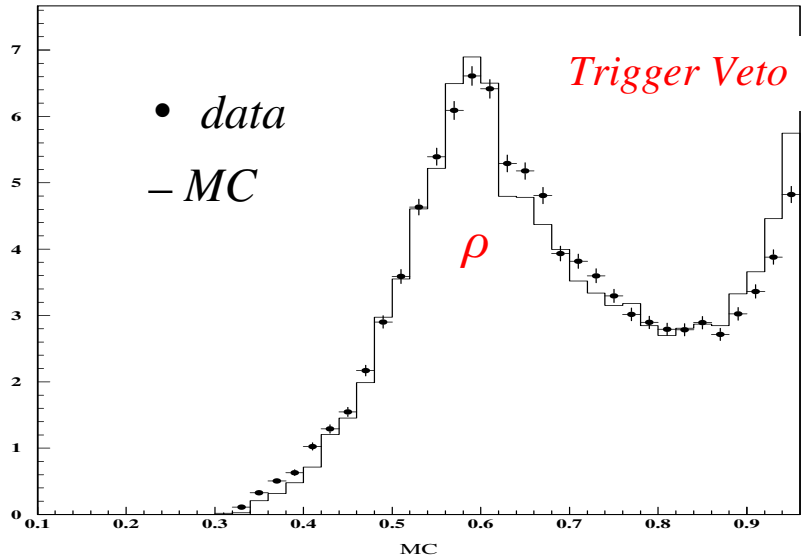
After the application of the Likelihood method, the cut $|\text{mass}_{trk} - 139.5| < 10\ MeV$ is applied

We compare the distributions with *MC* for large photon angle and small photon angle ("online") and normalize both distributions to the same number of events around the ρ peak

$60^o < \theta_\gamma < 120^o$ photons detected in *EmC*



$2^o < \theta_\gamma < 21^o$

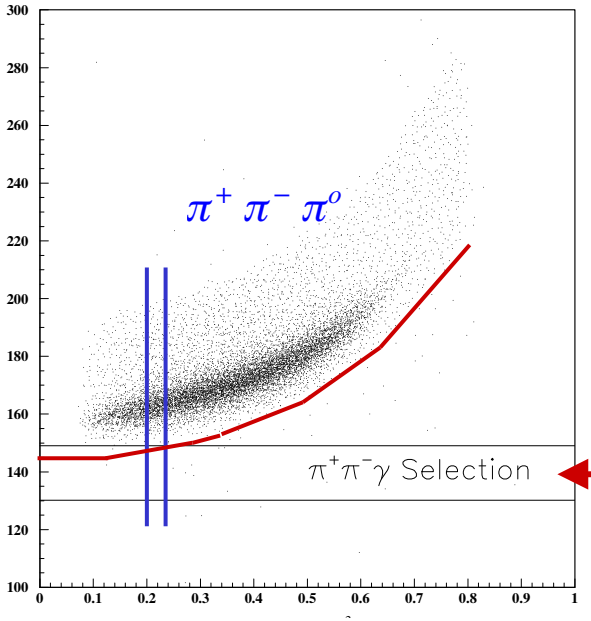


background contributions have to be taken into account,
various efficiencies have to be checked and calculated using data as function of Q^2

Background from $\phi \rightarrow \pi^+ \pi^- \pi^o$

BR ($\phi \rightarrow \pi^+ \pi^- \pi^o$) $\approx 15.5\%$, is separated during the selection phase by applying a cut in the 2-dim. plane $\text{mass}_{\text{track}}$ vs. Q^2

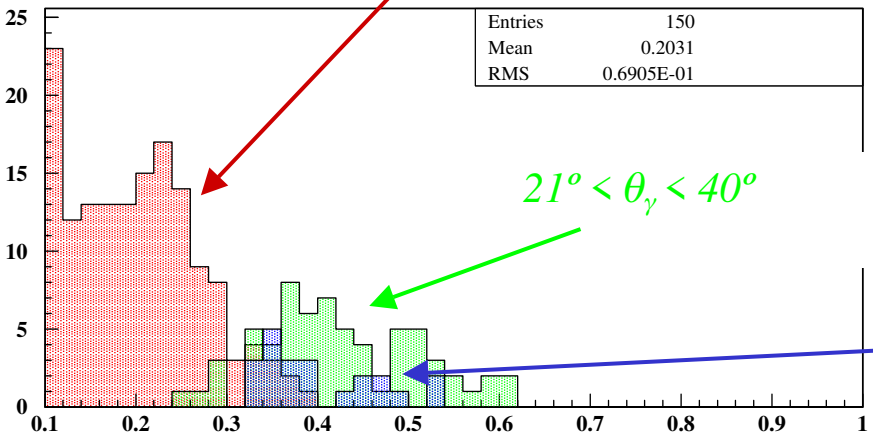
Look at the events which fall into the $\pi^+ \pi^- \gamma$ interval (as function of Q^2)



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

$Mass_{track}$ vs. Q^2

$60^o < \theta_\gamma < 120^o$ $\pi^+ \pi^- \pi^o$ dominates at very low Q^2



$21^o < \theta_\gamma < 40^o$

$5^o < \theta_\gamma < 21^o$

$\pi^+ \pi^- \pi^o$ background almost negligible

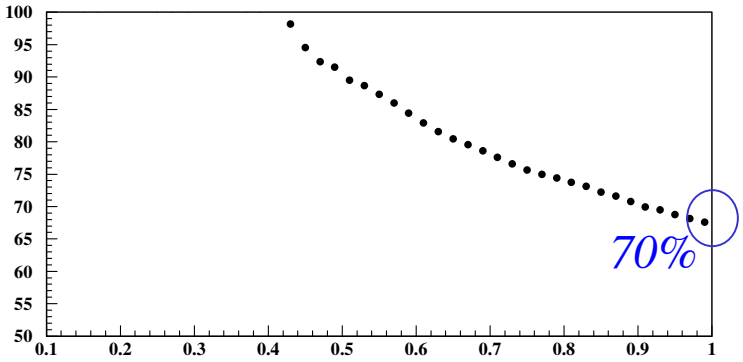
$\pi^+ \pi^- \pi^o$ background in $6.5\ pb^{-1}$

Selection efficiencies

Numbers in Blue: data
Numbers in Green: *MC*

Trigger

- 'hardware cosmic veto'* at high Q^2 causes efficiency losses for data with $Q^2 > 0.7\ GeV^2$
  - downscaled anti veto events
  - parametrize probability for single pions as function of p_π and θ_π
- standard trigger efficiency



70% @ 1 GeV² ; 100% @ 0.45

≈ *95% ... 99%*, some Q^2 dependance

Reconstruction

- Filter for machine background + cosmics
  downscaled anti filter events → ≈ 98 %, flat in Q^2

Event Selection

- vertex efficiency
- likelihood method
- other kinematic

- Bhabha events (*EmC*, independent from *DC*) ≈ 98 %, loss at small Q^2
- using data → ≈ 98 %, flat in Q^2
- taken from *MC*

Acceptance

taken from *MC*, losses at small Q^2 due to kinematics (phase space cuts, p_t)

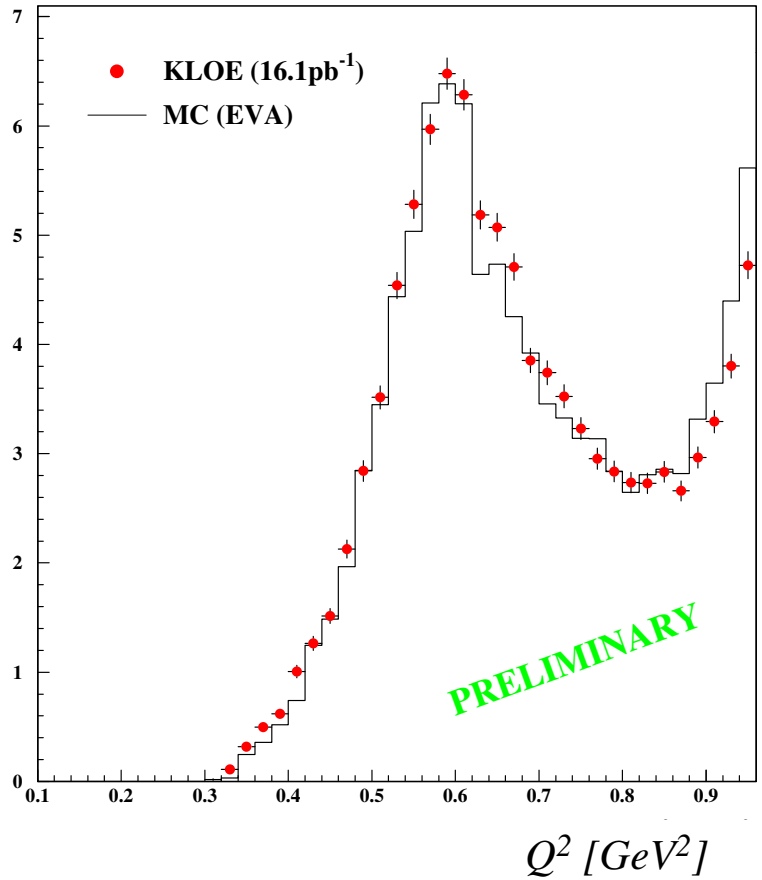
* *2* energy deposits > *40 MeV* on outer plane of *EmC*

Differential cross sections

16.1 pb^{-1} of Nov. / Dec. 2000 data have been analysed
(*1/2* of full data set 1999 + 2000)

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

$d\sigma / dQ^2$
$[\ nb / GeV^2\ ]$



data are not corrected for
tracking resolution effects

Acceptance cuts:

$5° < \theta_\gamma < 21°$ and $159° < \theta_\gamma < 175°$
$E_\gamma > 10$ MeV
$55° < \theta_\pi < 125°$
$p_t > 200$ MeV

4.3.5. Luminosity measurement

DAΦNE does not have luminosity monitors at small angles due to *QUAD's*

KLOE itself is used for measurement :
Large angle Bhabhas ($\sigma_{eff} = 425\ nb$)

- $55° < \theta_{+-} < 125°$
- acollinearity $< 9°$
- $E_{+-} \geq 400\ MeV$

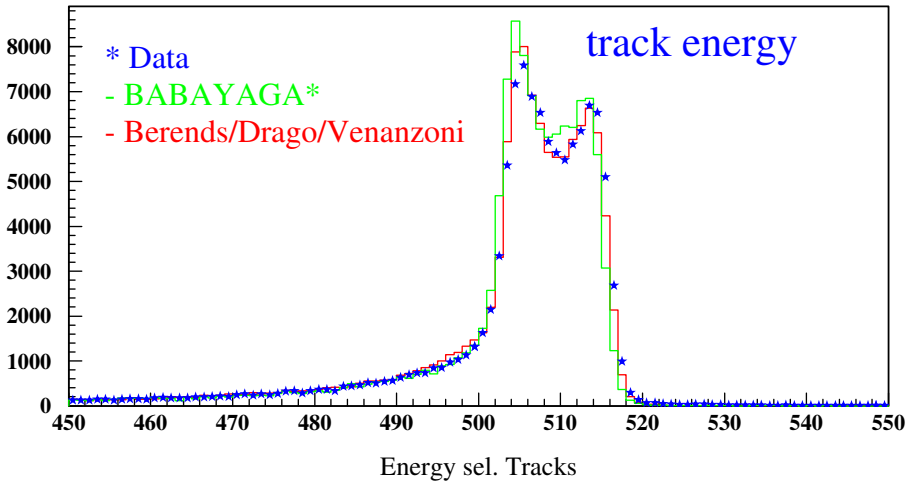
$$\int \mathcal{L}\, dt = \frac{N_{lab}\,(1-\delta_{bkg})}{\sigma^{MC}_{lab}(E)}$$

lab. candidates
(Systematics, acceptance)

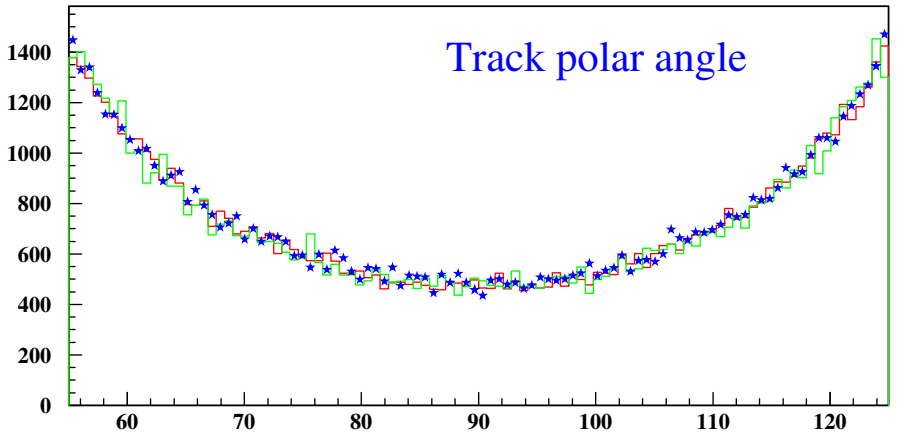
background
($\gamma\,\gamma$, $\pi\,\pi\,\gamma$, ...)

theoretical generators
with radiative corrections

Berends / Drago / Venanzoni
*BABAYAGA**

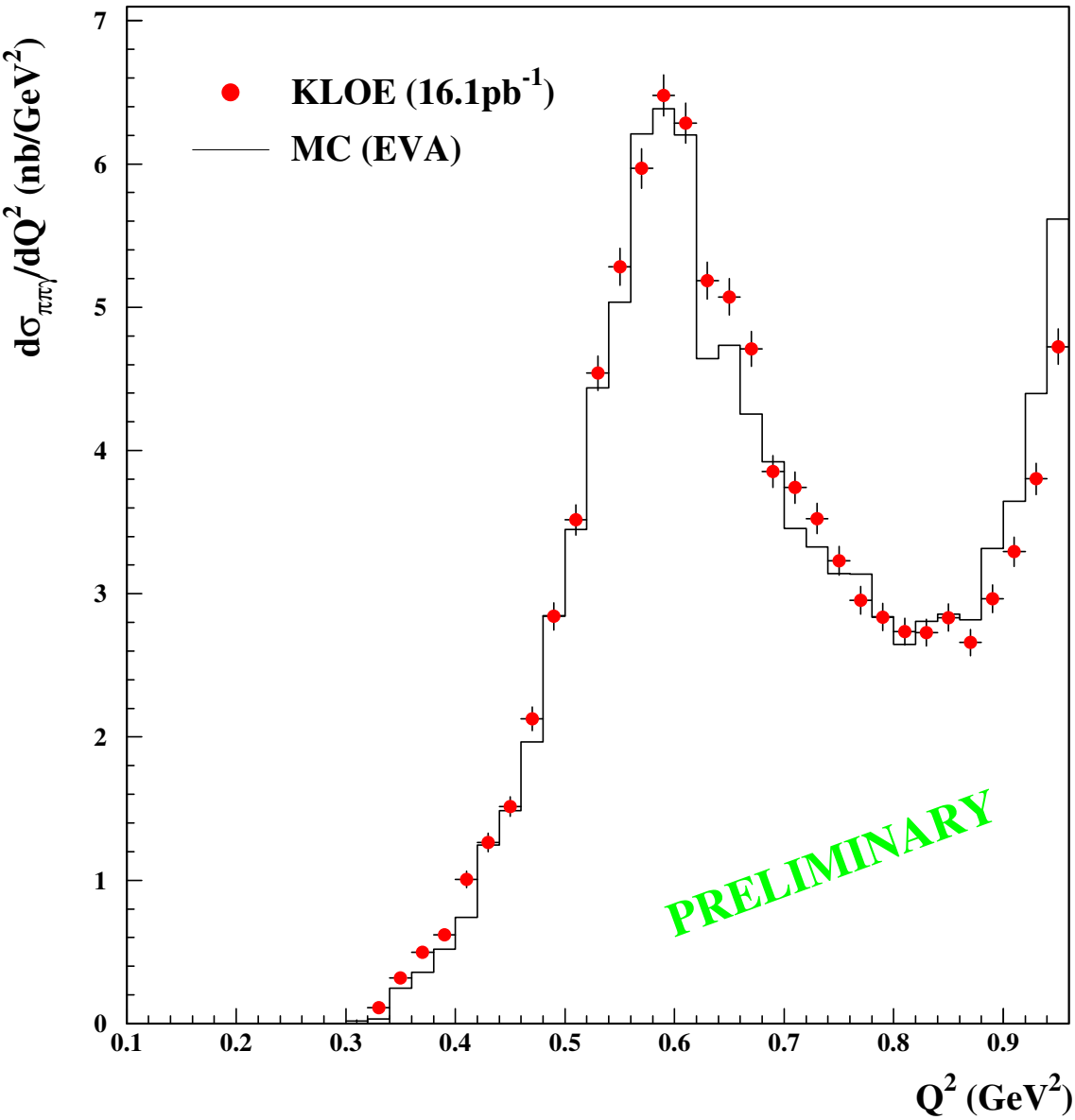


Energy sel. Tracks



Polar Angle sel. Tracks

Luminosity measurement at % level
agreement with independent $\gamma\gamma$ counter $< 1\%$


KLOE (16.1pb^{-1})
MC (EVA)
PRELIMINARY
$d\sigma_{\pi\pi\gamma}/dQ^2$ (nb/GeV^2)
Q^2 (GeV^2)
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Pion form factor $|F_\pi(Q^2)|^2$

$$|F_\pi(Q^2)|^2 = \frac{d\sigma(\pi^+\pi^-\gamma, Q^2)}{dQ^2\, H(Q^2, \cos\theta_\gamma^{min}, \cos\theta_\gamma^{max})} = \frac{c_i^{ISR}}{\varepsilon_i \cdot L \cdot A_i(\theta_\pi)} \cdot \frac{\Delta N_i}{\Delta Q^2 \cdot H_i}$$

$$H(Q^2, \cos\theta_\gamma^{min}, \cos\theta_\gamma^{max}) = \frac{\alpha^3}{3s^2} \cdot \left(1 - \frac{4m_\pi^2}{Q^2}\right)^{1.5} *$$

$$* \int_{\cos\theta_\gamma^{max}}^{\cos\theta_\gamma^{min}} \left(\frac{(s^2 + Q^4)}{Q^2(s - Q^2)} \cdot \frac{1}{1 - \cos^2\theta_\gamma} - \frac{s - Q^2}{2Q^2} \right) d\cos\theta_\gamma$$

$H_i = H(Q_i^2)$ in Born approximation (no radiative corrections)

$c_i^{ISR} = \Delta\sigma_{ISR}(Q_i^2) \;/\; \Delta\sigma_{ISR+FSR}(Q_i^2)$, $< c^{ISR} > = 0.95$

$A_i(\theta_\pi) = \Delta\sigma_{ISR}(Q_i^2,\ 50° < \theta_\pi < 130°) \,/\, \Delta\sigma_{ISR}(Q_i^2,\ 0° < \theta_\pi < 180°)$

Pion form factor $|F_\pi(Q^2)|^2$ has been compared with

$$F_\pi(Q^2) = \frac{BW_\rho \dfrac{(1+\alpha\ BW_\omega)}{1+\alpha} + \beta\ BW_{\rho'}}{1+\beta}$$

$m_\rho = 0.773\ GeV$ $\quad \Gamma_\rho = 0.145\ GeV$

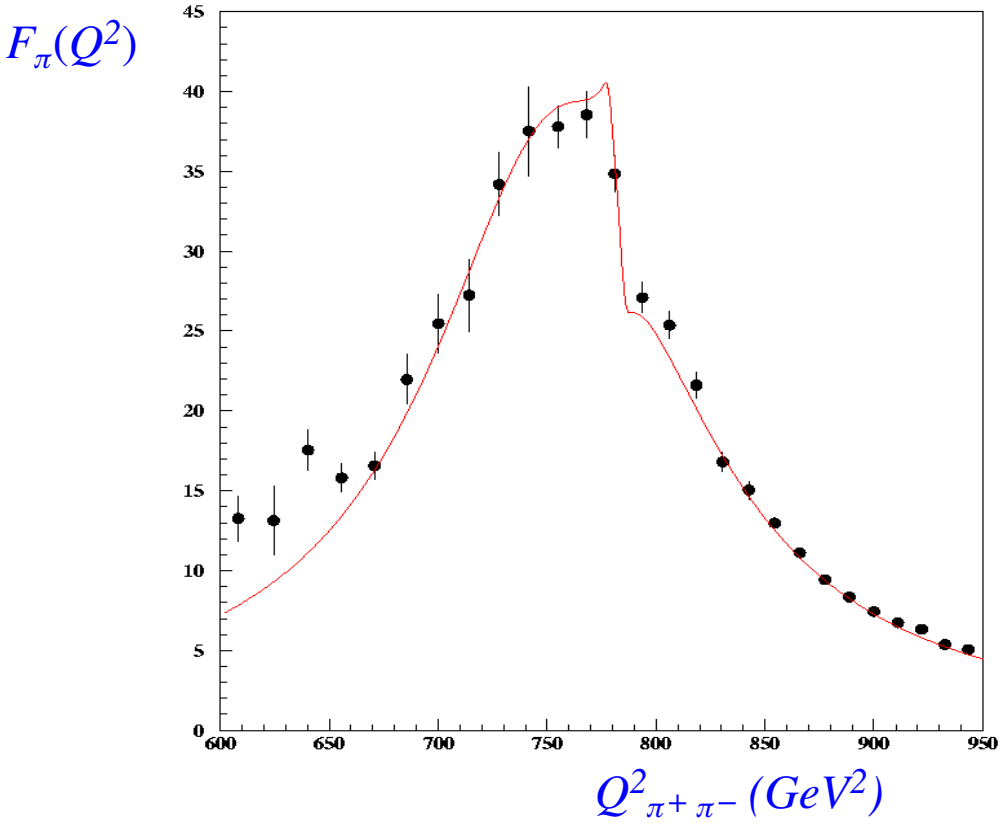
$m_\omega = 0.782\ GeV$ $\quad \Gamma_\omega = 8.5 \cdot 10^{-3}\ GeV$

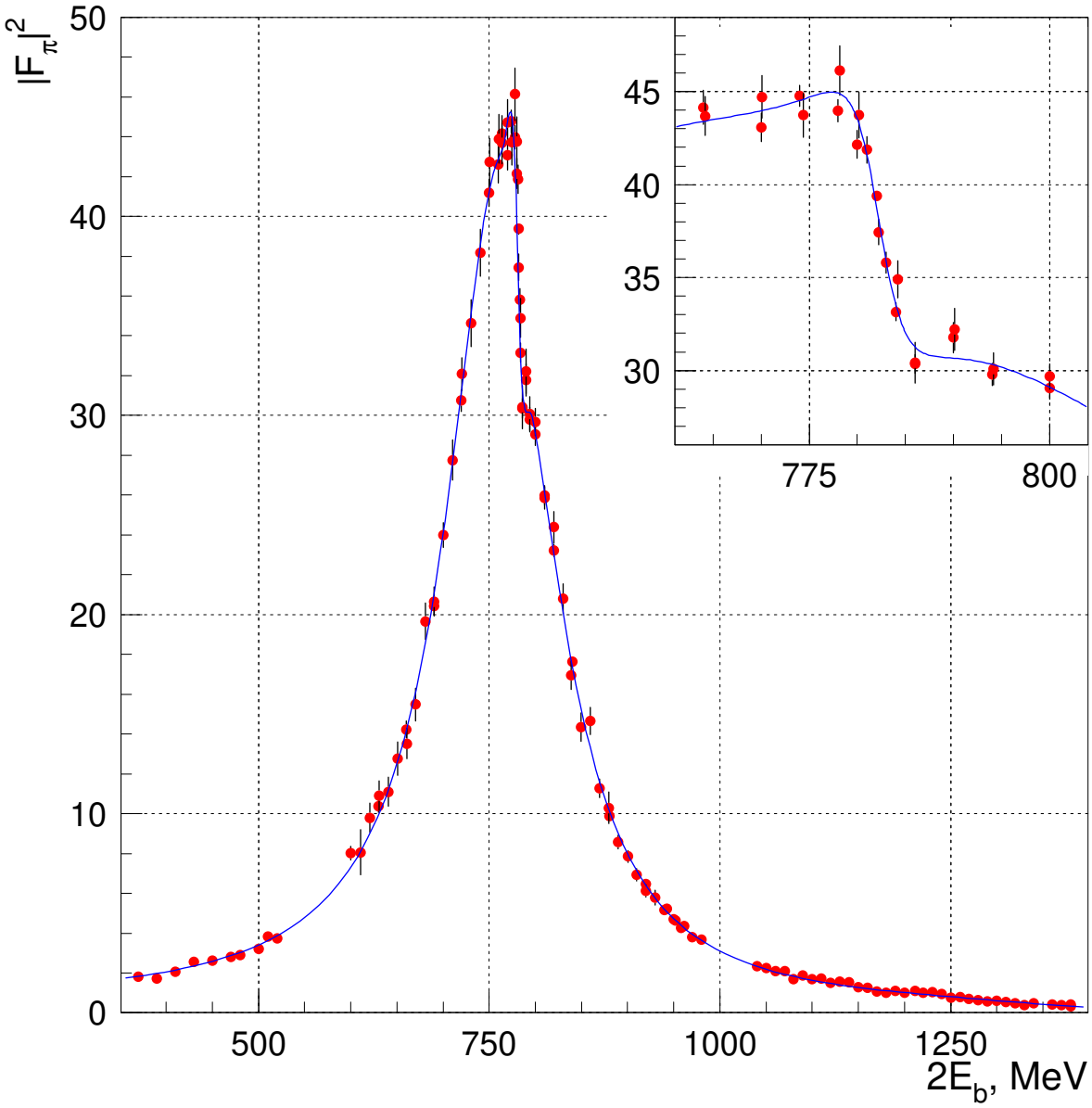
$m_{\rho'} = 1.37\ GeV$ $\quad \Gamma_{\rho'} = 0.51\ GeV$

$\alpha = 1.85 \cdot 10^{-3}$ $\quad \beta = -0.145$ $\quad BW_i = Breit\text{-}Wigner\ formulae$

J. H. Kühn and A. Santamaria, Z. Phys. C48 (1990) 445

reasonable agreement
at low Q^2 still background due to $\pi^+\pi^-\pi^o$

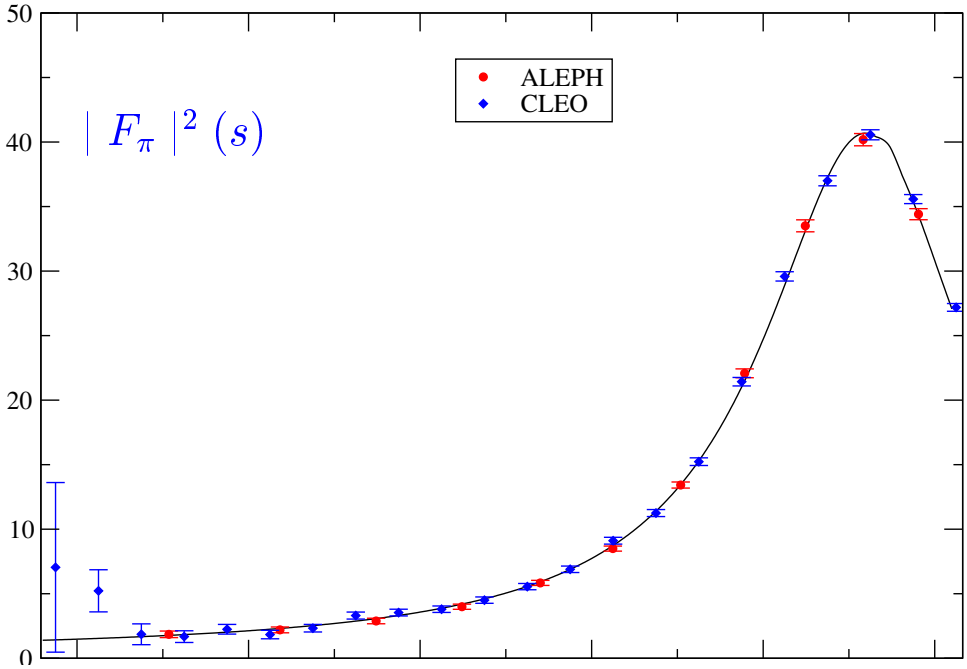


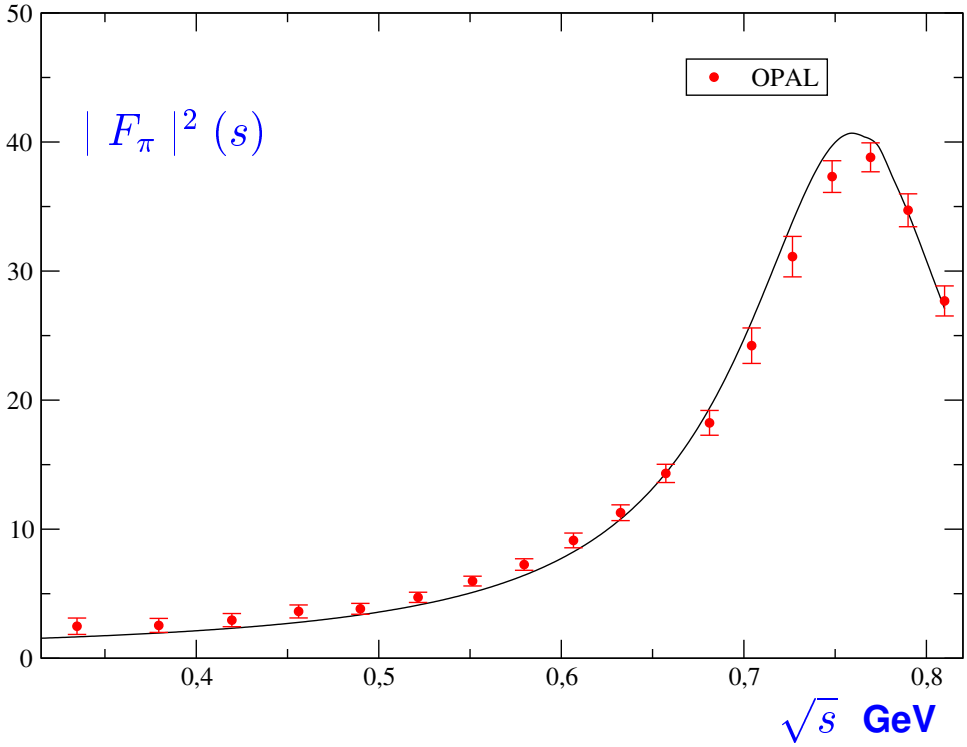


Pion form factor

as function of c.m. energy (*VEPP-2M, CMD2*)

NA7+CMD-2 e^+e^-–data analytized+unitarized+chiral limit: solid line vs. τ –data





4.4. Summary and conclusions

- σ_{hadr} is important for *2* problems of high energy precision physics

  - to determine the hadronic contribution of $(g_\mu - 2)$:

    $\delta a_\mu^{hadr} = 1.5 \cdot 10^{-10}$

    error of Brookhaven exp. *E821* $\delta a_\mu = 4 \cdot 10^{-10}$
    in order to establish the electroweak contribution

  - to determine the hadronic contribution of $\alpha_{em}(m_Z^2)$ limiting precision tests and predictions of the *SM*

    constraining the *Higgs mass, Weinberg angle* etc.

- At *DAΦNE-KLOE* measurements of hadronic cross sections $\sigma(e^+e^- \rightarrow hadrons)$ have started

  Phase I : σ_{hadr} for $E < 1\ GeV$ via *Initial State Radiation*

  data taking with *KLOE* since 1999

  Phase II : systematic energy scan ($2\ m_\pi < E < 1.4\ GeV$)

  data taking not before 2004

- *Initial State Radiation* $e^+e^- \rightarrow$ *hadrons+* γ *allows* to scan the region $Q^2 < 1\ GeV$ while running at fixed energy $\sqrt{s} = m_\phi$

  complementary to beam energy scan

- *MC* studies (*EVA*, Kühn et al.) and first data taken of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ using the process $e^+e^- \rightarrow \pi^+\pi^-\gamma$ indicate that *KLOE* is able to do this measurement with the required accuracy

  total integrated luminosity in 1999: $\mathcal{L} \sim 2.4\ pb^{-1}$

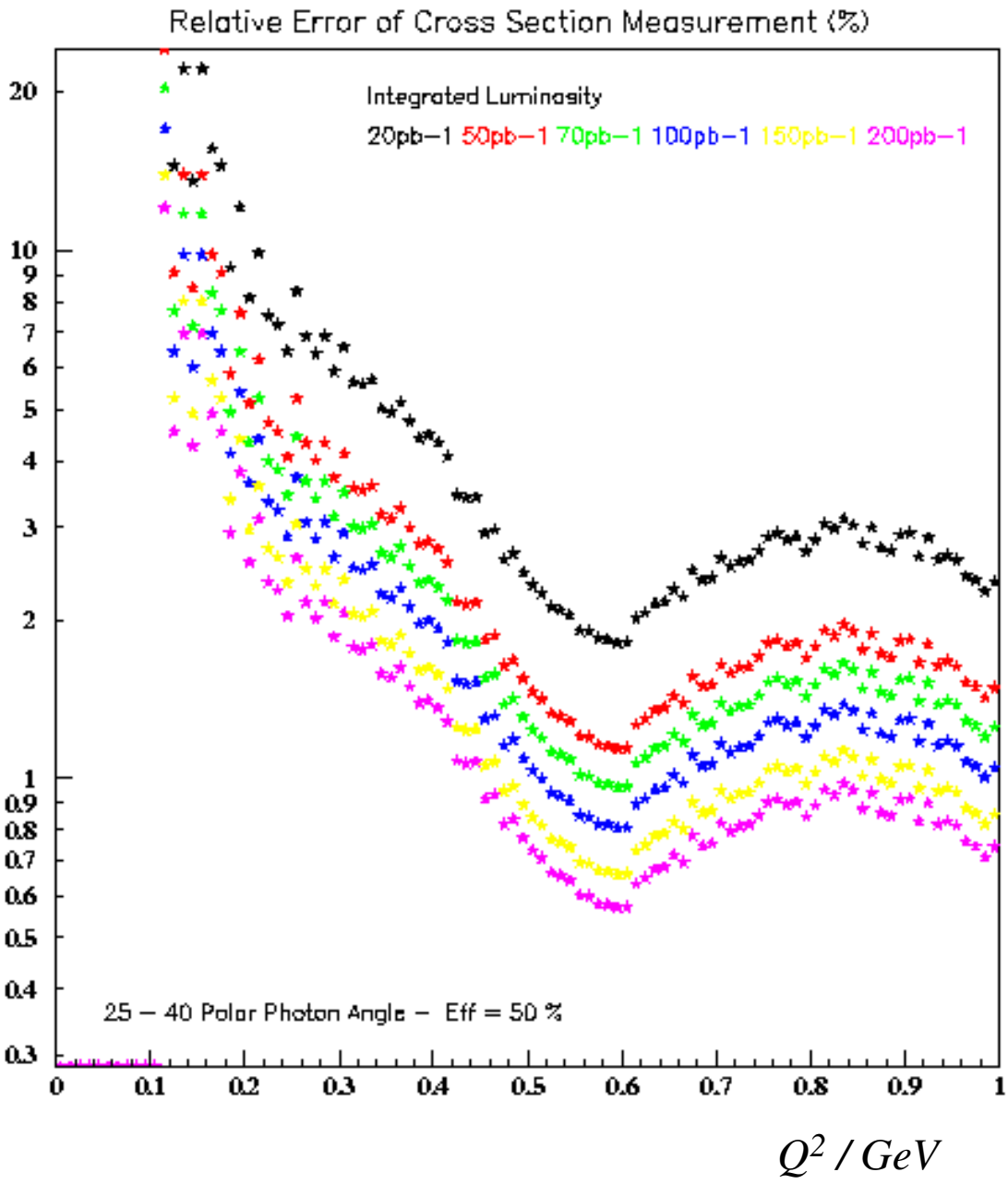
  total integrated luminosity in 2000: $\mathcal{L} \sim 25\ pb^{-1}$

  good for 2 % error of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

  total integrated luminosity in 2001: $\mathcal{L} \sim 200\ pb^{-1}$ *?*

- first $\pi^+\pi^-\gamma$ analysis has been performed with $16.1\ pb^{-1}$ of reconstructed data

- efficiencies, systematics, background evaluated from data under control


Relative Error of Cross Section Measurement (%)
Integrated Luminosity
20pb−1 50pb−1 70pb−1 100pb−1 150pb−1 200pb−1
25 − 40 Polar Photon Angle − Eff = 50 %
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Q^2 / GeV

A. Denig

How to proceed further?

$$\frac{d\sigma}{dQ^2} = \frac{(dN_{obs} - dN_{bkg})}{dQ^2} \cdot \frac{1}{\varepsilon_{eff}\ \varepsilon_{syst}\ \mathcal{L}}$$

Efficiencies ε_{eff}: already at a few % , independent

Luminosity $\mathcal{L}$: precision already at the % level (< *2 %*)
more tests are going on

Background dN_{bkg}: small background from Bhabhas, $\mu\ \mu\ \gamma$

Systematics ε_{syst}: errors from $\delta\sqrt{s}$, δQ^2, $\delta\theta_\pi$, $\delta\theta_\gamma$
have been studied with *MC*,
still more emphasis on data, esp. $\delta\theta_\gamma$

Statistics dN_{obs}: < *1 %* level for integrated luminosity of *200* pb^{-1}

Theory: *NLO* generator from Kühn et.al. ($\theta_\gamma = 0$)

Extract the hadronic cross section $e^+ e^- \to \rho \to \pi^+ \pi^-$

(compare with Novosibirsk results)

Final goal

- to measure $\sigma\ (e^+\ e^-\ \rightarrow\ \pi^+\ \pi^-)$ at the level of *1 %*

  1 % accuracy for $\sigma\ (e^+e^-\rightarrow hadrons)$ up to *1.4 GeV* will result in $\delta\alpha_{\mu}^{had} = \pm\, 7 \cdot 10^{-10}$

  1 % accuracy of $\sigma(e^+e^-\rightarrow hadrons)$ for *[1.40...3.10] GeV* will result in $\delta\alpha_{\mu}^{had} = \pm\, 1.5 \cdot 10^{-10}$

- to reduce $\delta\alpha_{em}^{had}$