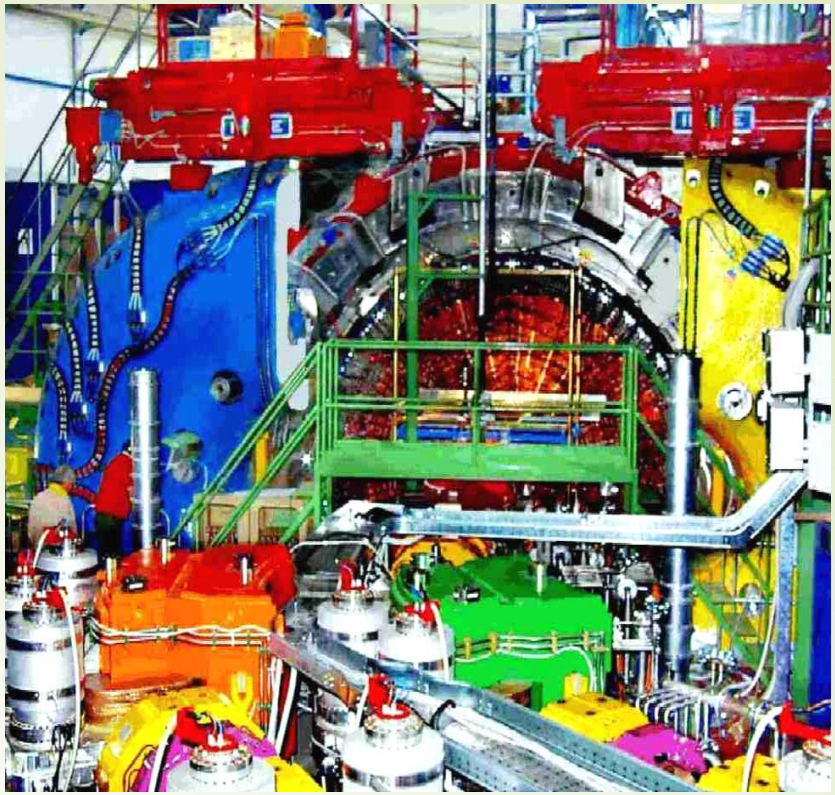
Achim Denig (Universität Karlsruhe)
for the KLOE collaboration

KLOE Results on Hadronic Physics

30 May 2003
26th Meeting Scientific Committee
Laboratori Nazionali di Frascati

KLOE in DAΦNE Hall



Outline:

- Updates on rad. ϕ decays into $f_0(980)$, $a_0(980)$ and η
- Radiative Return
- Preliminary Results σ_{hadr}
- Outlook

ϕ– radiative decays

$\phi \to \eta\pi^0\gamma$ *$a_0(980)$ - Analysis*

$\hookrightarrow \gamma\gamma, \quad \pi^+\pi^-\pi^0$

$\phi \to \pi^0\pi^0\gamma$

$\phi \to \pi^+\pi^-\gamma$ *$f_0(980)$ - Analysis*

$\phi \to \eta\gamma$

$\hookrightarrow 3\gamma$ *C-Violation*

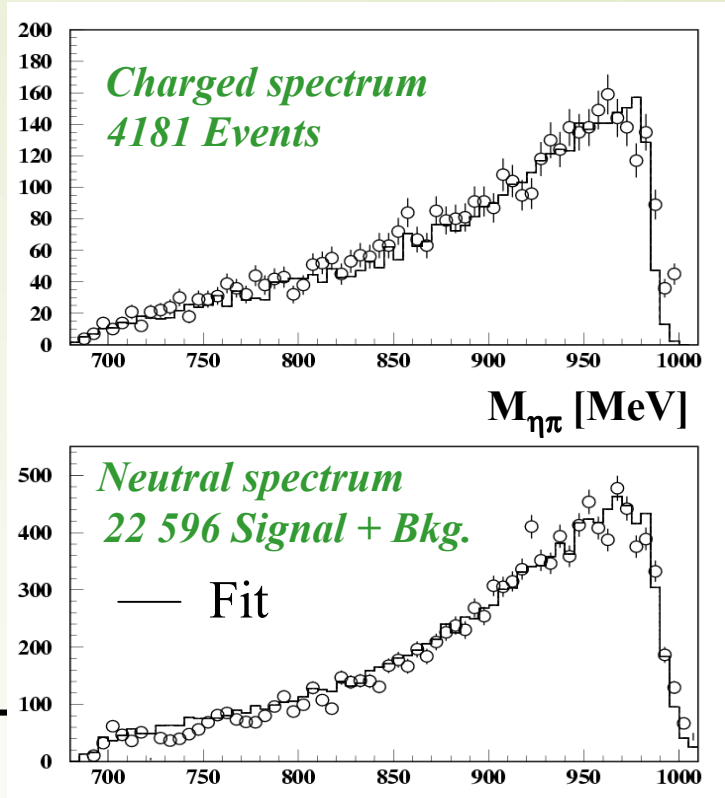
$\phi \to \eta\pi^0\gamma$ $a_0(980)$

- Reanalysis with much higher 2001+2002 Statistics (= 20 x publ. Statistics 2000)
- Off-peak data analyzed in order to verify resonant behaviour

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

- New MC for important Background-process $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$
  → Better agreement DATA-MC
- $M_{\eta\pi}$ - Shape in good agreement with published 2000 - data
  → ongoing work: common fit to charged and neutral spectrum

- Analysis revised → Agreement with 2000



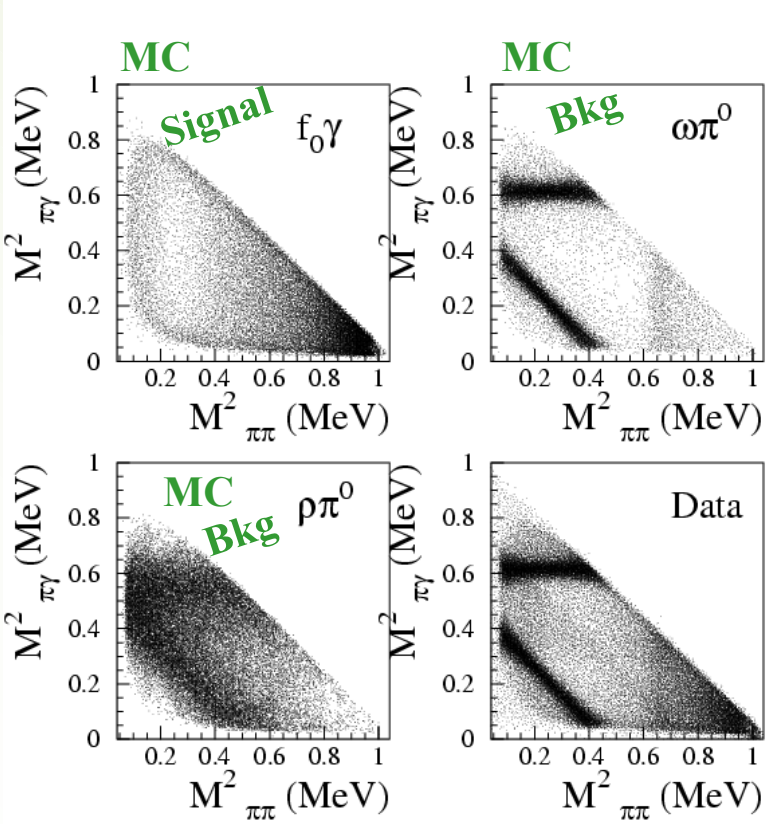
$$Br(\phi \to \eta\pi^0\gamma) = (7.25 \pm 0.15_{stat+bkg}) \times 10^{-5} \quad (\eta \to \gamma\gamma)$$

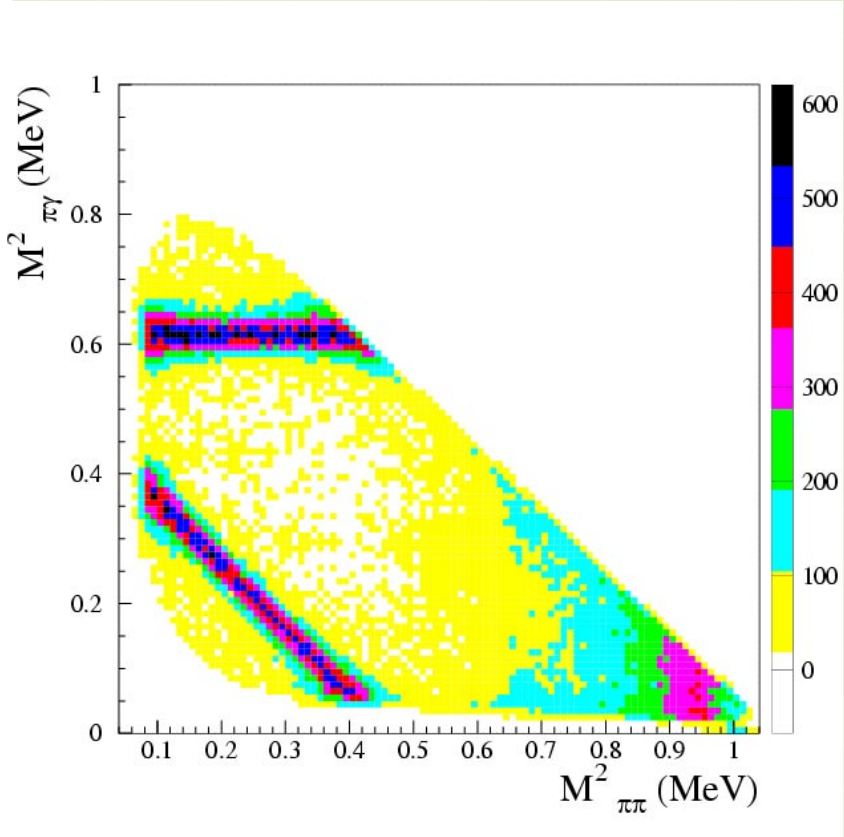
PRE-LIMINARY

$$= (7.45 \pm 0.11_{stat} \pm 0.19_{syst}) \times 10^{-5} \quad (\eta \to \pi^+\pi^-\pi^0)$$

$\phi \rightarrow \pi^0\pi^0\gamma$ $f_0(980)$

- Reanalysis of 2001+2002 data ➔ agreement with published data
- The large statistics allows to perform a Dalitz plot fit

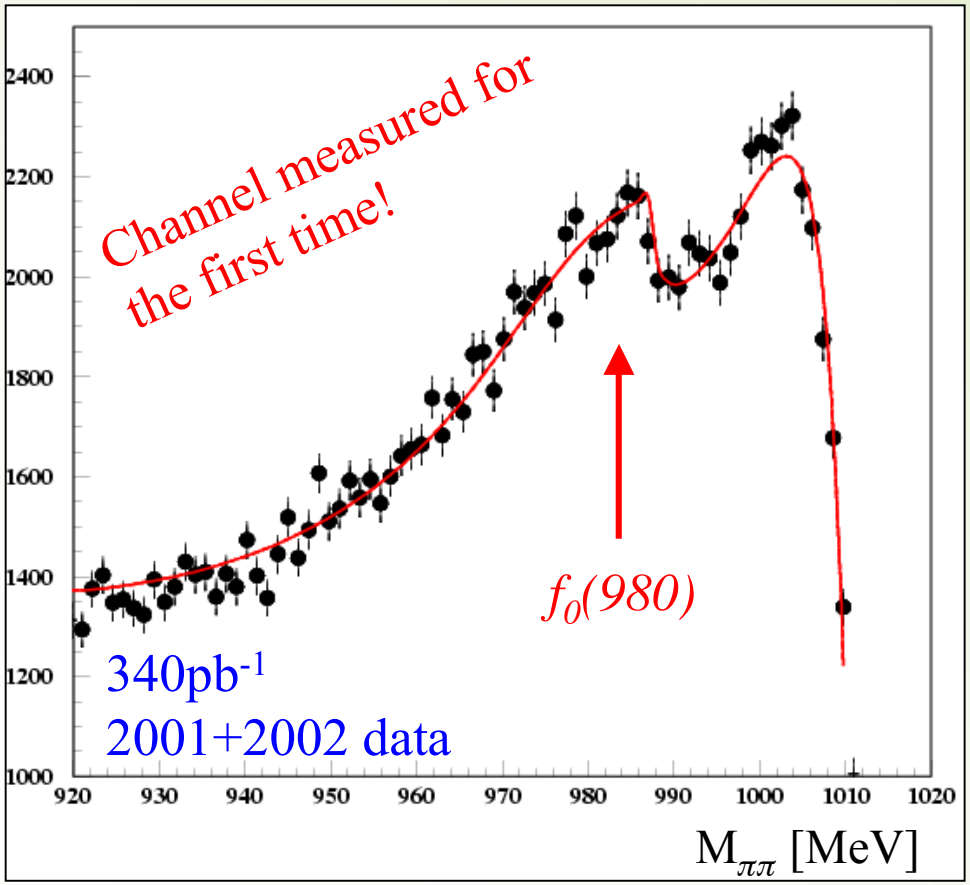




- Goal: extract the scalar contributions and a possible interference scheme

$\phi \rightarrow \pi^+\pi^-\gamma$ $f_0(980)$

- We also looked for the charged decay $f_0(980) \rightarrow \pi^+\pi^-$
- Huge background due to ISR $e^+e^- \rightarrow \pi^+\pi^-\gamma$ and interference with FSR
- Large photon angles ($45° < \Theta_\gamma < 135°$) and explicit tagging of photon



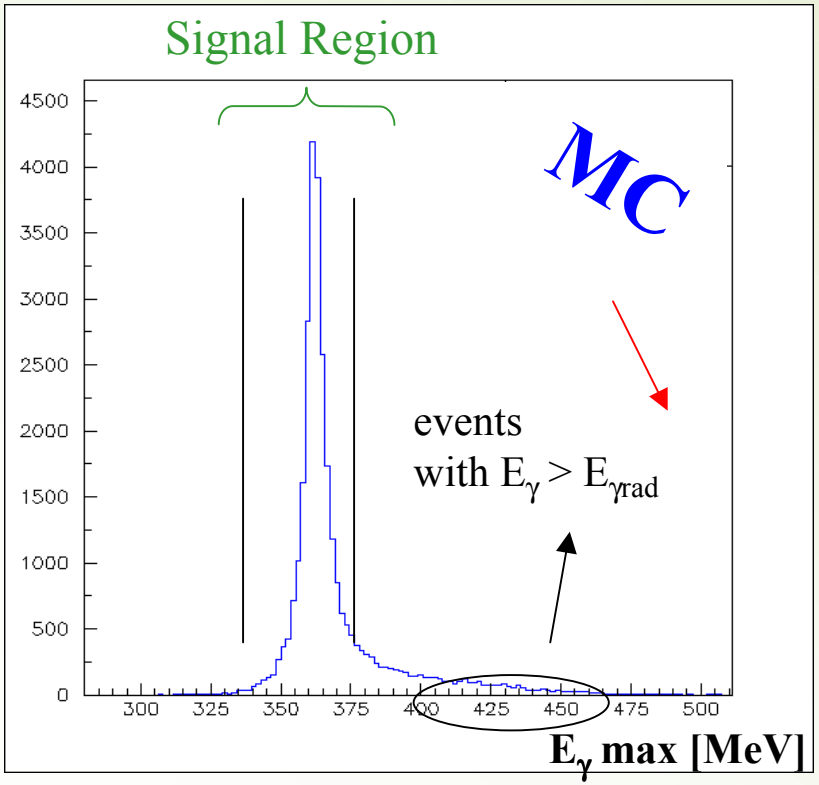
Fitting the spectrum with:
- Signal f_0 (980)
- Background (ISR, FSR)
- Interference with FSR

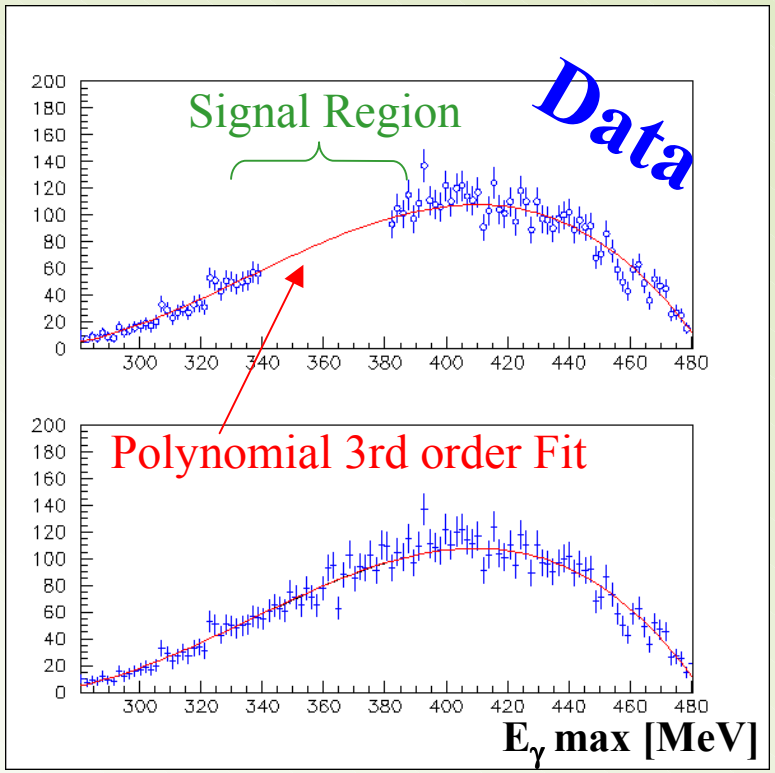
⇒ Best results for destructive interference

⇒ Fit improves if a possible σ-contribution is added

BR ($\eta \rightarrow \gamma\gamma\gamma$) *C-Violation*

- Selection: 4 prompt neutral photons ($\phi \rightarrow \eta\gamma$) , $E_\gamma^{min} > 50$ MeV , $\cos(\theta)| < 0.91$
- Look at maximum energy distribution of prompt neutral clusters E_γ^{max}





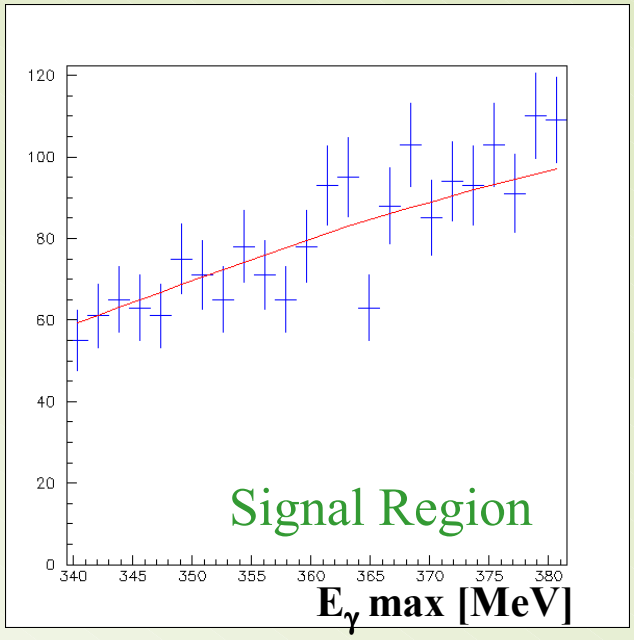
BR ($\eta \to \gamma\gamma\gamma$)

- Background channel for 4γ final state:
  $e^+e^- \to \omega\gamma \to \pi^0\gamma\gamma$ (Radiative Return to ω)
  subtracted by cut on π^0 mass

- Result: $N_{signal}=1.8\pm30$
  Normalisation to $\eta\to\pi^0\pi^0\pi^0$

$$\frac{Br(\eta \to \gamma\gamma\gamma)}{Br(\eta \to \pi^0\pi^0\pi^0)} \le \frac{N_{Up-sig} \cdot \varepsilon_{\eta\to\pi^0\pi^0\pi^0}}{N_{\eta\to\pi^0\pi^0\pi^0} \cdot \varepsilon_{\eta\to\gamma\gamma\gamma}} = 4.3 \cdot 10^{-5}$$

$$\Rightarrow \boxed{Br(\eta \to 3\gamma) \le 1.4 \cdot 10^{-5} \ @\ 95\%\ \mathrm{CL}}$$



- Present Limits: $<5 \cdot 10^{-4}$ @ 95% CL (PDG2002 from Serpukhov 140)
  $<4.5 \cdot 10^{-5}$ @ 95% CL (2000)
  $<1.8 \cdot 10^{-5}$ @ 90% CL (2002)
  } Crystal Ball [preliminary]

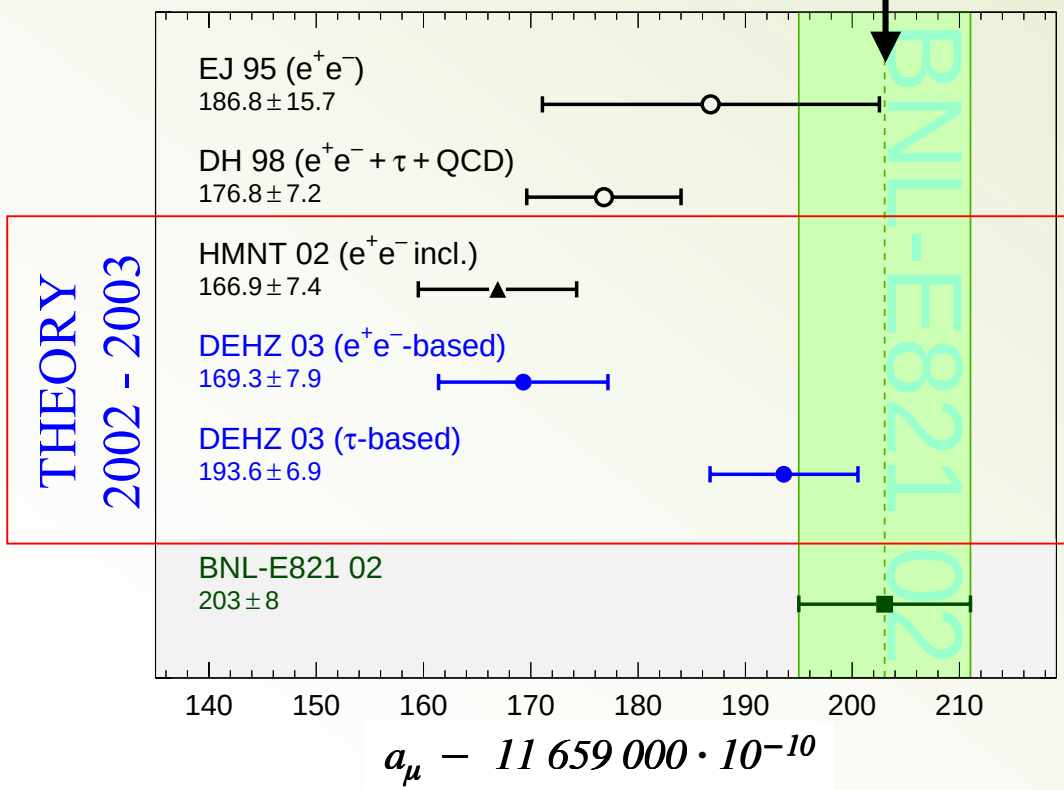
Measurement of the Hadronic Cross Section

Muon - Anomaly $a_\mu=(g-2)_\mu$

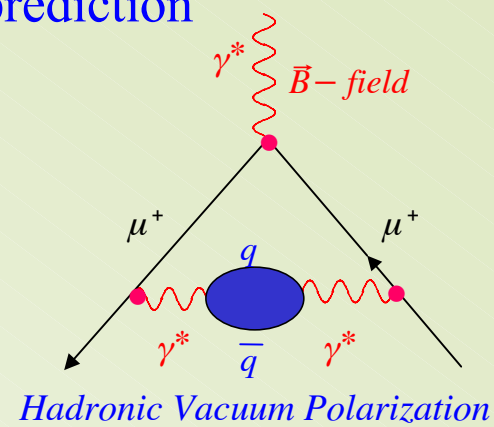
Comparison experimental value with theoretical prediction

Experiment E821 (BNL '02)

δa_μ(exp.) = ± 0.7 ppm



THEORY 2002 - 2003



Theory evaluation using e^+e^- - data: 3 σ - Deviation

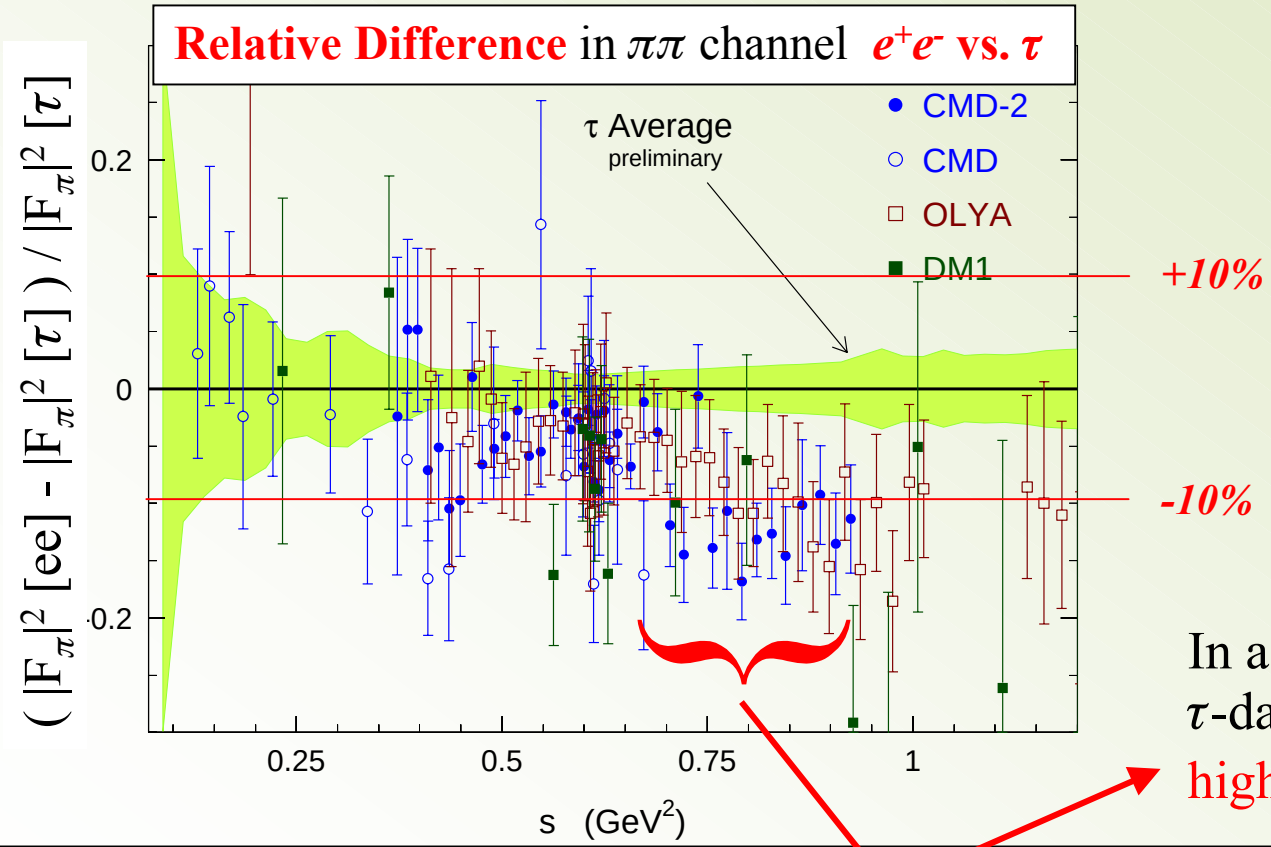
Theory with τ - data in agreement with experiment

σ_{hadr} @ DAΦNE

The two-fold rôle of KLOE:

1) Cross check difference between e^+e^- - and τ - data in the dominating $\pi\pi$ channel

$$\Delta a_\mu^{hadr}(\tau - e^+e^-) = (-24.9 \pm 6.9_{exp} \pm 2.7_{rad} \pm 2.8_{SU(2)}) \times 10^{-10}$$



In a large energy range τ-data is systematically higher ≈ 10% … 15% !

σ_{hadr} @ DAΦNE

e^+e^- - data with CMD-2 results

2) Cross check the central value of $a_\mu^{hadr} = (\,684.7 \pm 6.0_{exp} \pm 3.6_{rad}\,) \times 10^{-10}$

➡ At which precision can we be significant /competitive?

Benchmark measurement

CMD-2 '01 : systematic error = 0.6%

$a_\mu^{2\pi} = (\,368.1 \pm 2.6_{stat} \pm 2.2_{syst}\,) \times 10^{-10}$

to be compared

KLOE statistics :

2001: factor 20 more data

⇒ will be dominated by systematics!

KLOE systematics:

$$\delta a_\mu \approx \delta a_\mu^{hadr} = \sqrt{\underbrace{(\delta a_\mu^{2\pi})^2}_{\text{KLOE systematics???}} + \underbrace{(\delta a_\mu^{Rest})^2}_{\pm\, 5.1 \times 10^{-10}}} = \begin{cases} \pm 6.3_{exp} \times 10^{-10} & @\ 1\% \text{ precision} \\ \pm 9.0_{exp} & 2\% \text{ precision} \\ \pm 12.2_{exp} & 3\% \text{ precision} \end{cases}$$

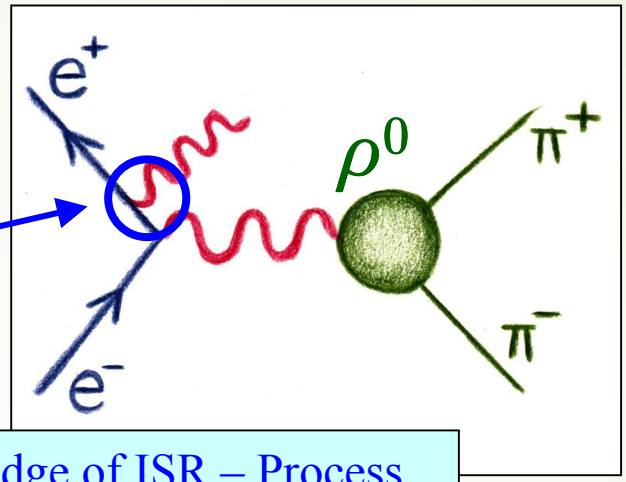
KLOE

Radiative Return

- Standard method for cross section measurement is the Energy-Scan, i.e. the systemat. variation of the center-of-mass energy of the accelerator

- DAΦNE = ϕ - factory and therefore designed for fixed energy

Alternative:
Look at events with Initial State Radiation (*ISR*)



"Radiative Return" to ρ-Resonance:

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

Cross Section as a function of the Invariant Mass $M_{\pi\pi}$

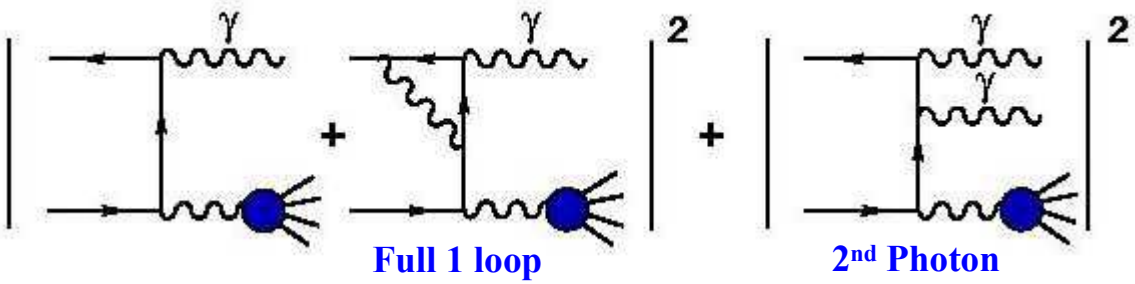
$$\frac{d\sigma(e^+ e^- \rightarrow \pi^+ \pi^- \gamma)}{dM_{\pi\pi}}$$

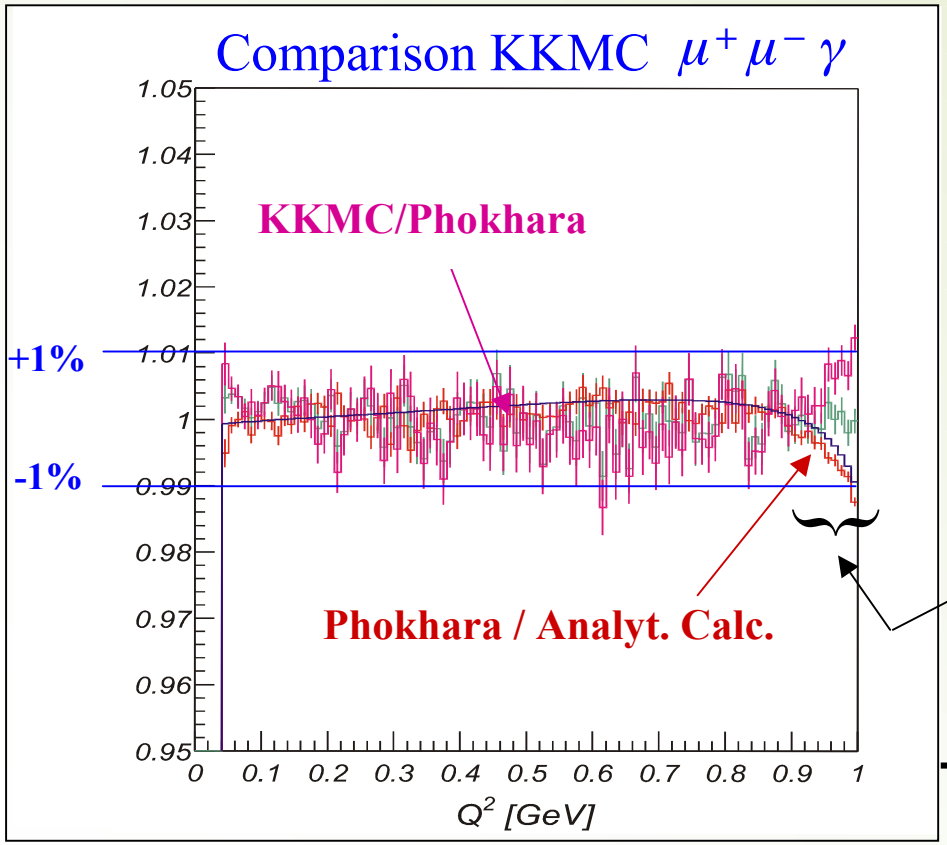
Precise Knowledge of ISR – Process
→ Radiation Function H

Radiative Corrections

PHOKHARA = full NLO - calculation to $\pi\pi\gamma$ initial state radiation

H. Kühn, H. Czyz, G. Rodrigo





We have performed together with S. Jadach a comparison between Phokhara and KKMC for radiative muon pair production

⇒ Agreement on few permil level in entire energy range

⇒ Effect of higher order corr. (3rd photon, …) only visible > ca. 0.9GeV^2 and small

Radiative corrections on the level of few permil

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

- Final state $e^+e^- \rightarrow \pi^+\pi^-\gamma$ relatively easy signature, however cross section measurement on percent level is a challenging task (Normalization, Efficiencies, Background)
- KLOE Detector designed for CP – Violation, we are having a high resolution tracking chamber ideal for the measurement of $M_{\pi\pi}$!

Analysis-Items:

$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{N^{obs} - N^{bkg}}{\Delta M^2_{\pi\pi}} \times \frac{1}{\varepsilon_{Select.} \cdot \varepsilon_{Accept.}} \times \frac{1}{L}$$

Signal

Background

Luminosity

Selections-Efficiency

Acceptance

- Measure all quantities as a function of $M_{\pi\pi}$!

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

Pion Track at large Angles

$40^o < \theta_\pi < 140^o$

Photons under small Angles

$\theta_\gamma < 15^o$ and $\theta_\gamma > 165^o$

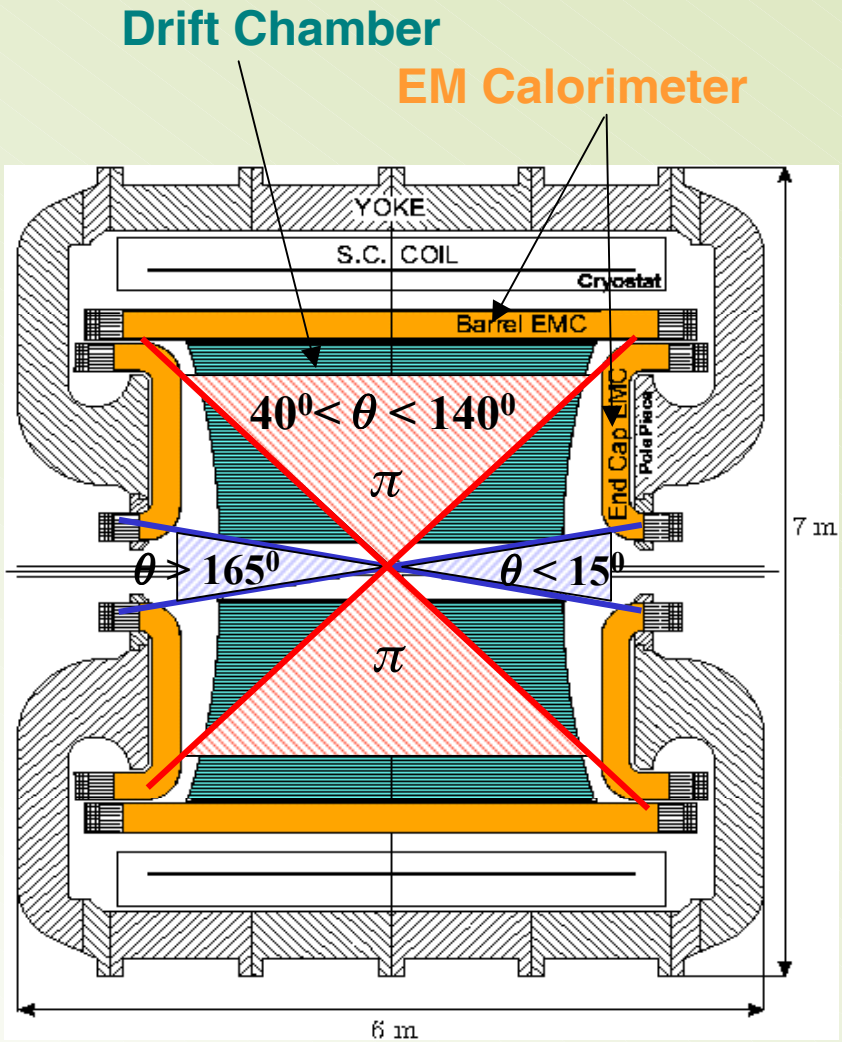
are NOT DETECTED due

to missing acceptance in EmC

$$\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$$

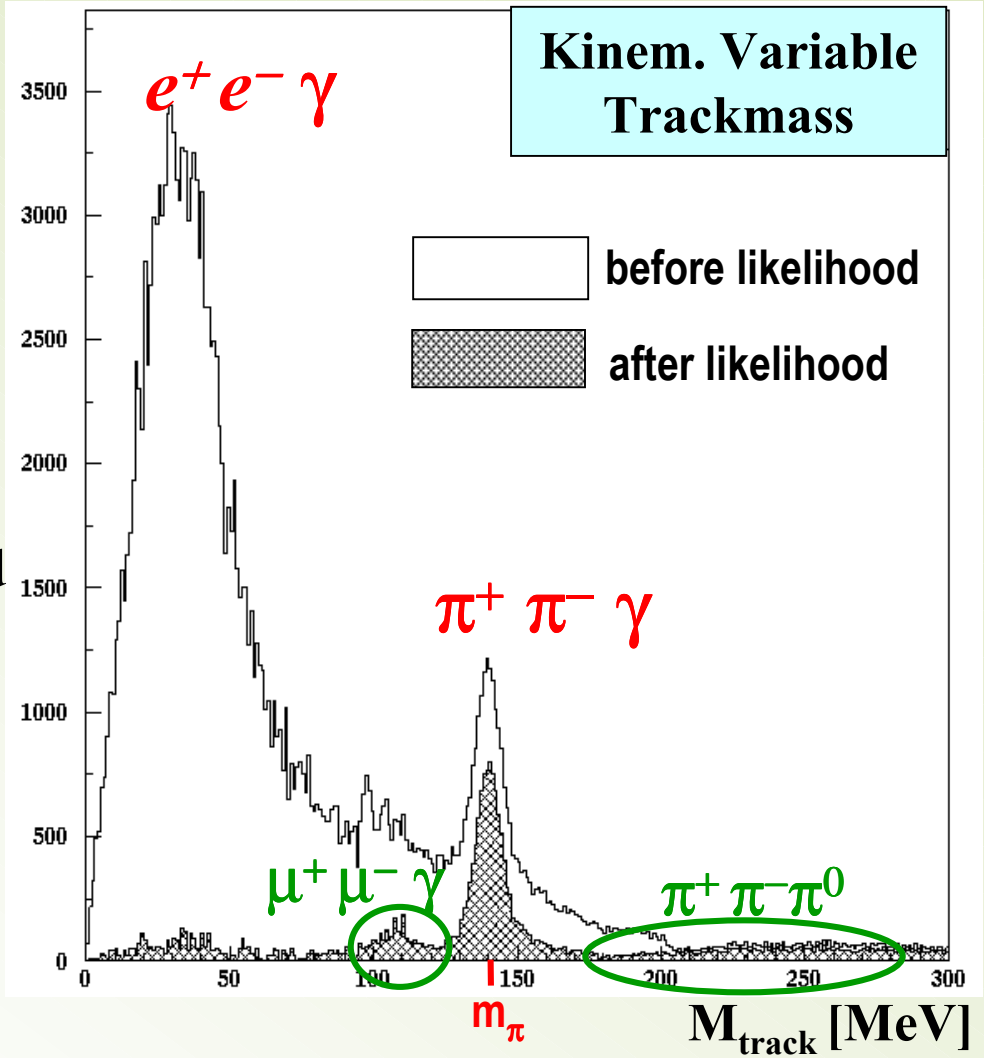
Untagged Photon!

- High Statistics for ***ISR*** Photons
- Small relative contribution of ***FSR***
- Reduced Background Contamination



Background

- Main source = Radiative Bhabhas
- π-e Separation by means of a Likelihood - Method
- Method is using EmC information:
  - Time of Flight of Tracks
  - Signature of the energy deposit of Tracks in EmC
- Standard- Analysis: 1 Track required to be identified as Pion (OR)



Effect of the Method becomes visible in the **Trackmass distribution** which is a kinematical variable obtained by solving 4-momentum-conservation:

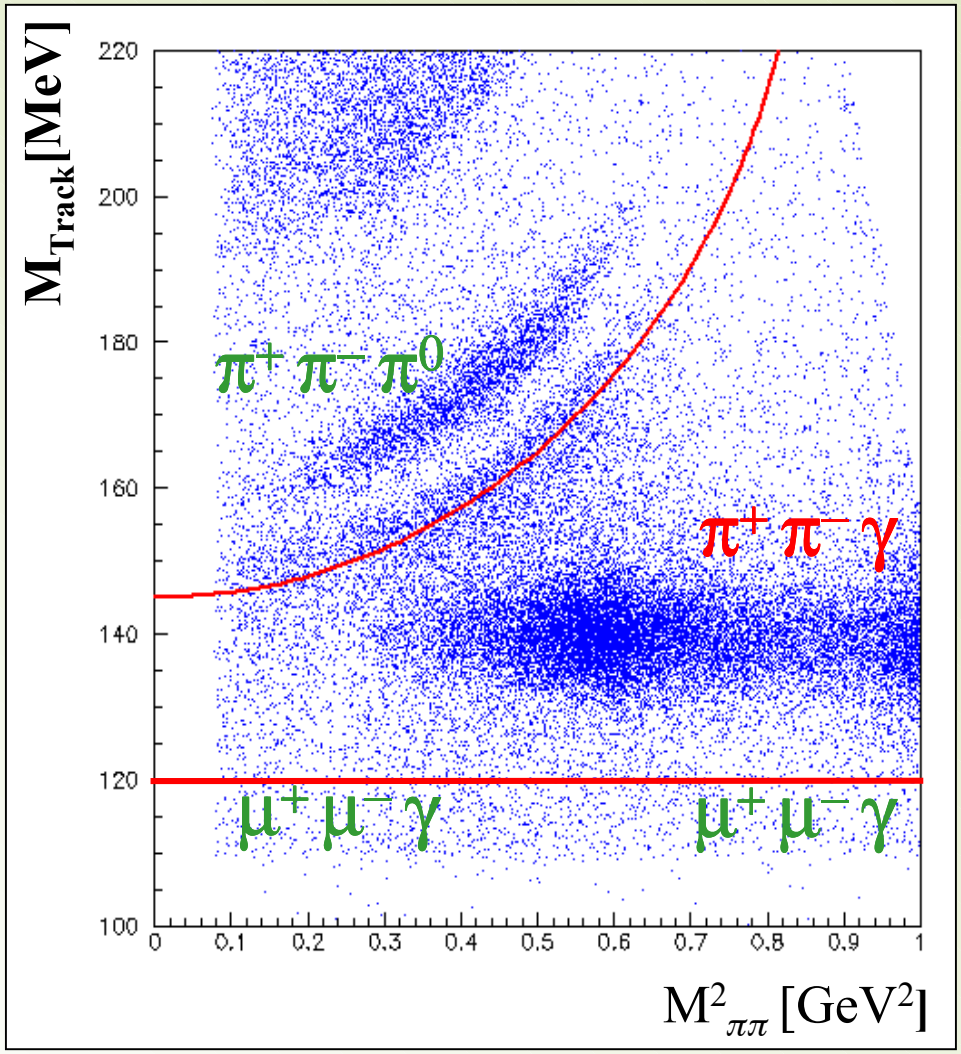
$$\left(M_\phi - \sqrt{\vec{p}_1^{\,2} + M_{trk}^2} - \sqrt{\vec{p}_2^{\,2} + M_{trk}^2}\right)^2 - (\vec{p}_1 + \vec{p}_2)^2 = q_\gamma^2 = 0$$

Background

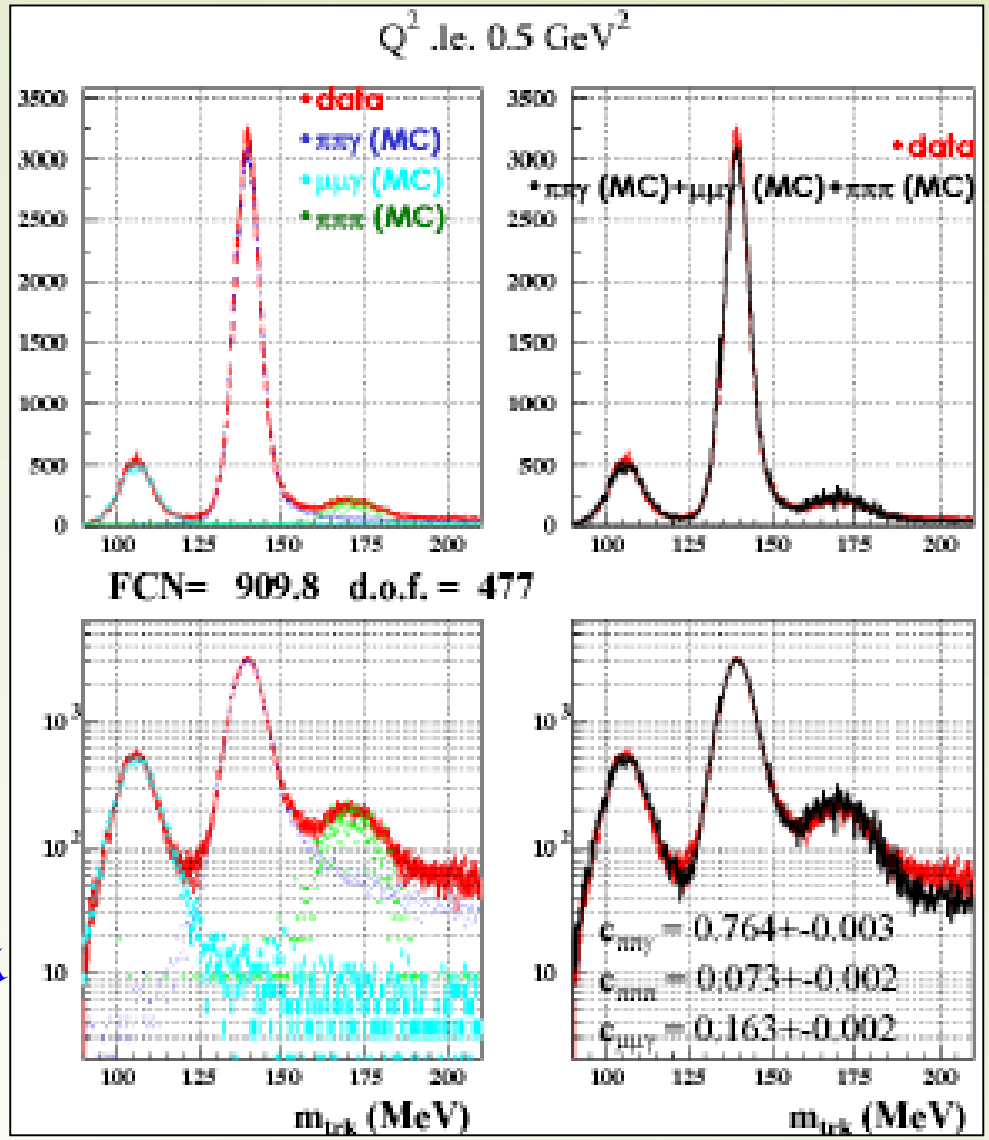
Additional Background:

- $\phi \rightarrow \pi^+ \pi^- \pi^0$ at low values of $M_{\pi\pi}$ (ϕ-decay with 16% B.R.!)
- $e^+e^- \rightarrow \mu^+ \mu^- \gamma$ at high and low values of $M_{\pi\pi}$

➡ Cut in the plane M_{track} vs. $M^2_{\pi\pi}$



➡ Remaining contamination are measured by fitting the shape of signal and background in the trackmass distribution in Bins of $M_{\pi\pi}$



PRELIMINARY

Efficiencies

Trigger

including Cosmic Veto Eff.

Reconstr. Filter

Event Classification

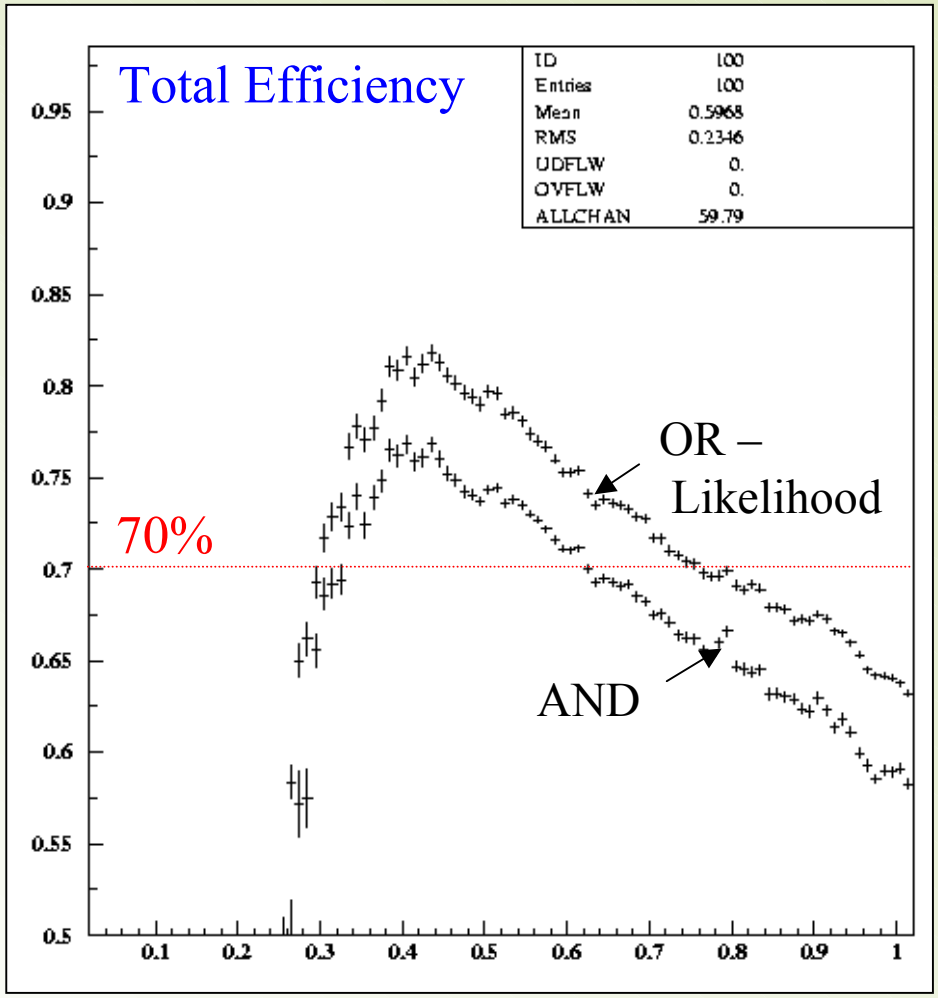
Tracking - Eff., Vertex - Eff.

Likelihood

OR = 1π,1e
AND= 2π

Trackmass

blue = estimated from data and/or indep. control samples $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$
Kinematics simulated by MC
red = estimated from MC and compared with data (s.before)

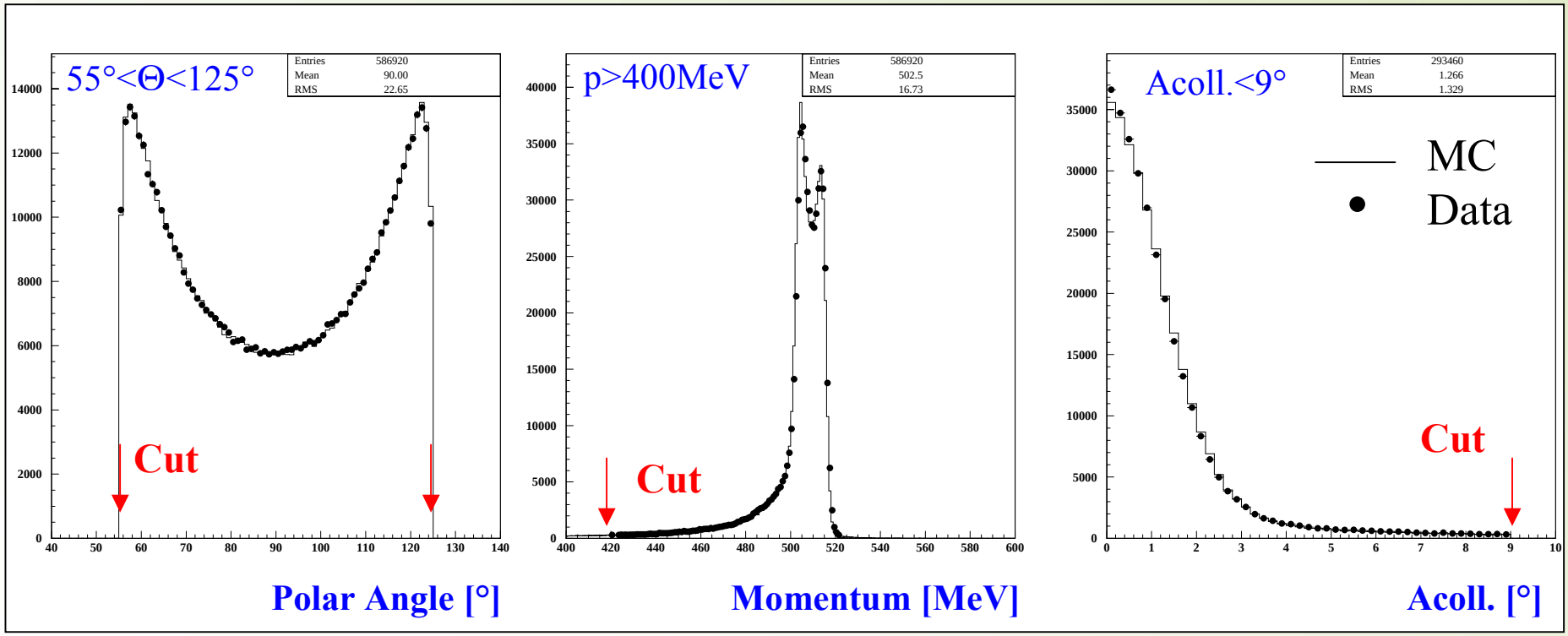


$M_{\pi\pi}^2$ [GeV^2]

Luminosity

- KLOE uses Large Angle Bhabha Events for the Luminosity determination
- 2 independent generators used for radiative corrections:

BABAYAGA [Pavia, Carloni et al.]: $\sigma_{VLAB} = (428.8 \pm 0.3_{stat})$ nb
BHAGENF [modified Berends]: $\sigma_{VLAB} = (428.5 \pm 0.3_{stat})$ nb
} $0.1\% \pm 0.1\%_{stat}$



Luminosity

$$L = N_{Bhabhas} / \sigma_{eff}$$

Method requires a precise MC simulation of (radiative) Bhabha events, the systematics have been studied by comparing data and MC

PRELIMINARY

SYSTEMATICS Luminosity		
Theory	0.5%	
Acceptance	0.3%	**correct by 0.28%**
Background ($\pi\pi$)	0.1%	**correct by 0.53%**
Tracking	0.1%	
Clustering	0.1%	**correct by 0.23%**
Trigger	<0.1%	**correct by 0.51%**
Knowledge $\sqrt{s}$	0.1%	**run-by-run correct.**
TOTAL	0.5% Theory $\oplus$ 0.4% Exper.	

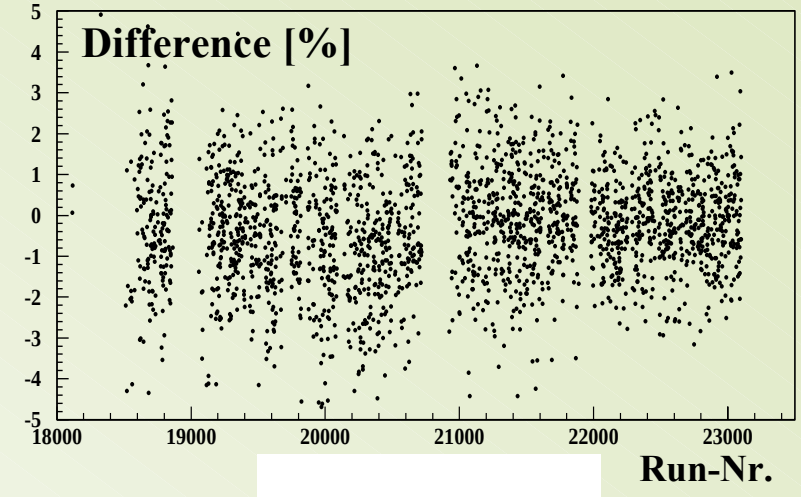
Variations due to running conditions small, final effect is still under evaluation

Luminosity

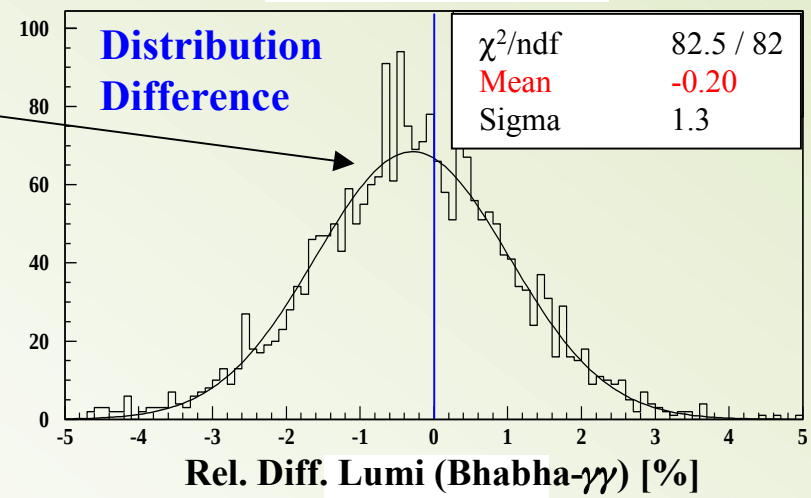
We cross check our results by comparing Luminosity with an independent

$e^+e^- \rightarrow \gamma\gamma$ counter ($45° < \Theta < 135°$)

$\sigma_{\gamma\gamma}$ = 120nb



Agreement with Bhabhas: ± 0.2%



But more work to be done both on experimental und theoretical side:

- theor. Uncertainty $\gamma\gamma$ = 1%
- Background estimated from MC (2%)

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

Analysis Flow

Obs. Spectrum $dN/dM_{\pi\pi}^2$
140.7pb^{-1} of 2001 data

Background Subtraction

Event - Filter

Trackmass

Unfolding Procedure

TCLO

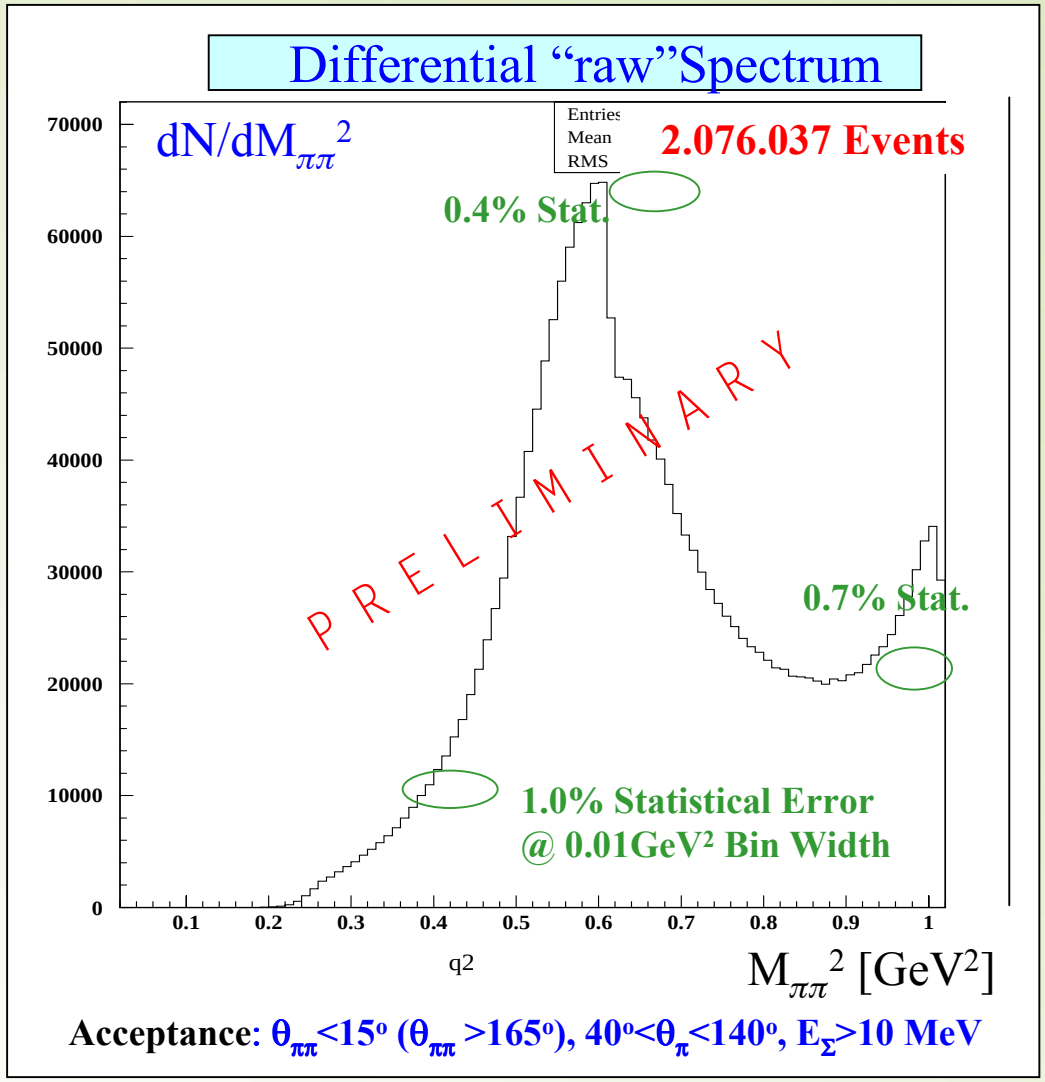
Vertex

Tracking

Trigger & Tr.-Veto

Divide by Luminosity

Diff. Cross Section $d\sigma/dM_{\pi\pi}^2$



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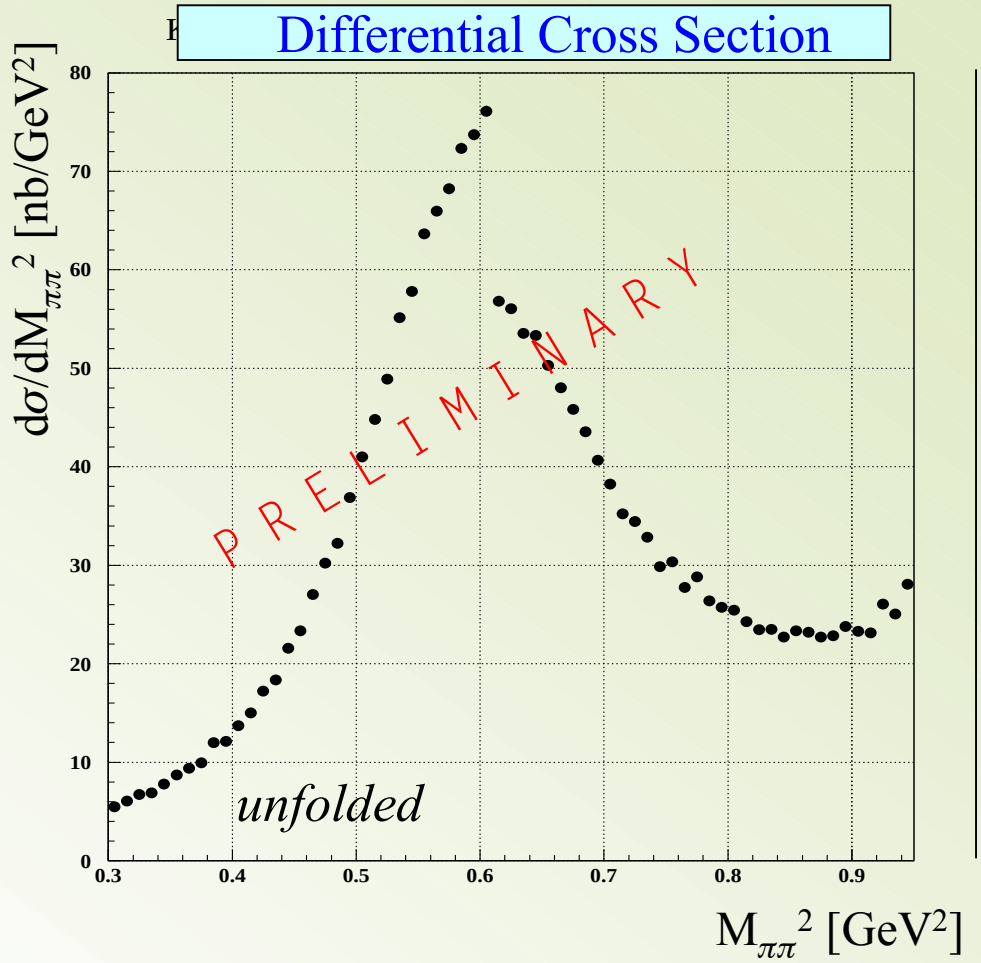


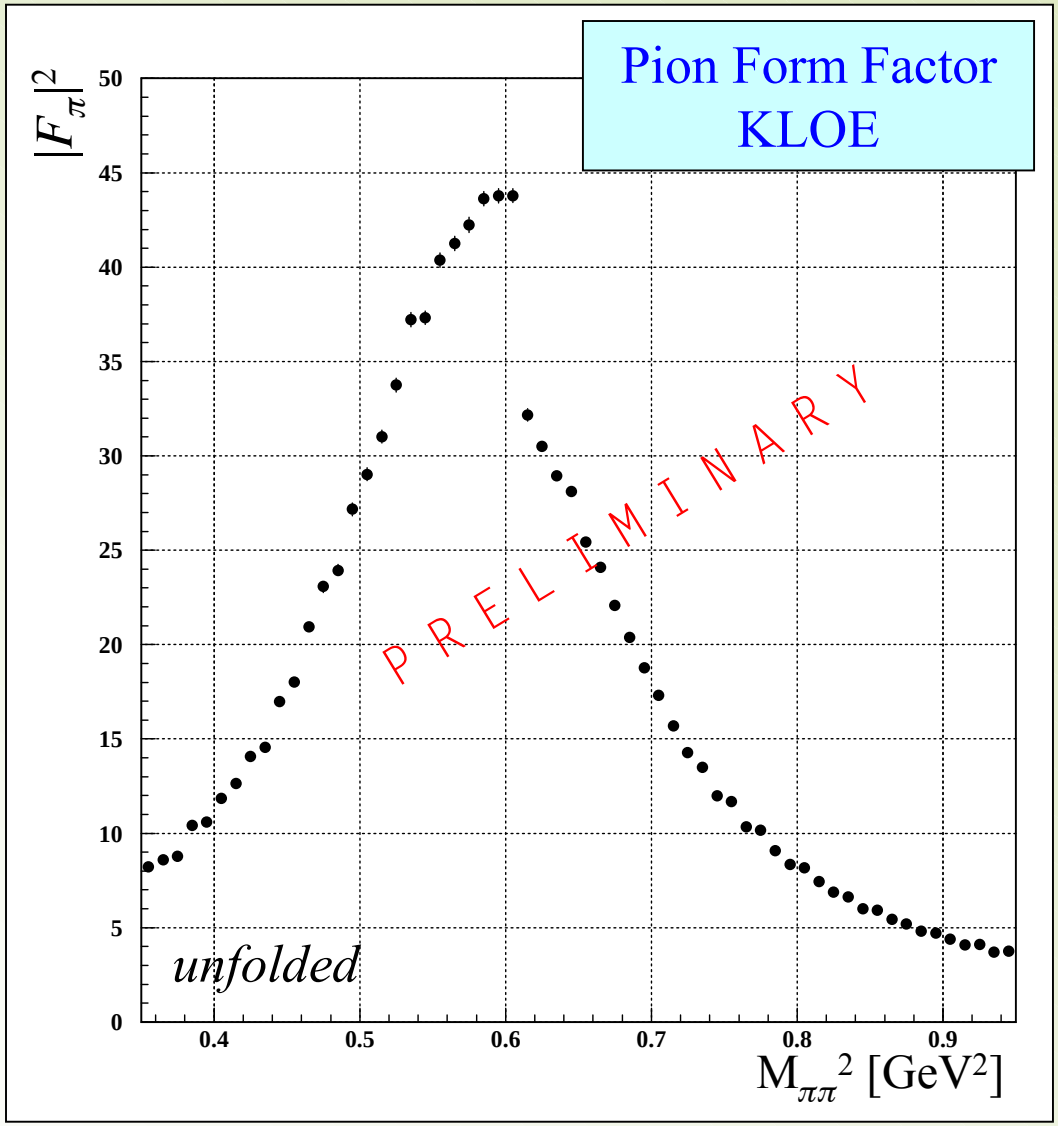
Acceptance: $\theta_{\pi\pi}<15^o$ ($\theta_{\pi\pi}>165^o$), $40^o<\theta_\pi<140^o$, $E_\Sigma>10$ MeV

Pion Form Factor

Dividing $d\sigma_{\pi\pi\gamma}/dM_{\pi\pi}^2$ by the theoretical Radiation Function $H(M_{\pi\pi}^2)$ we get the Pion Form Factor F_π:

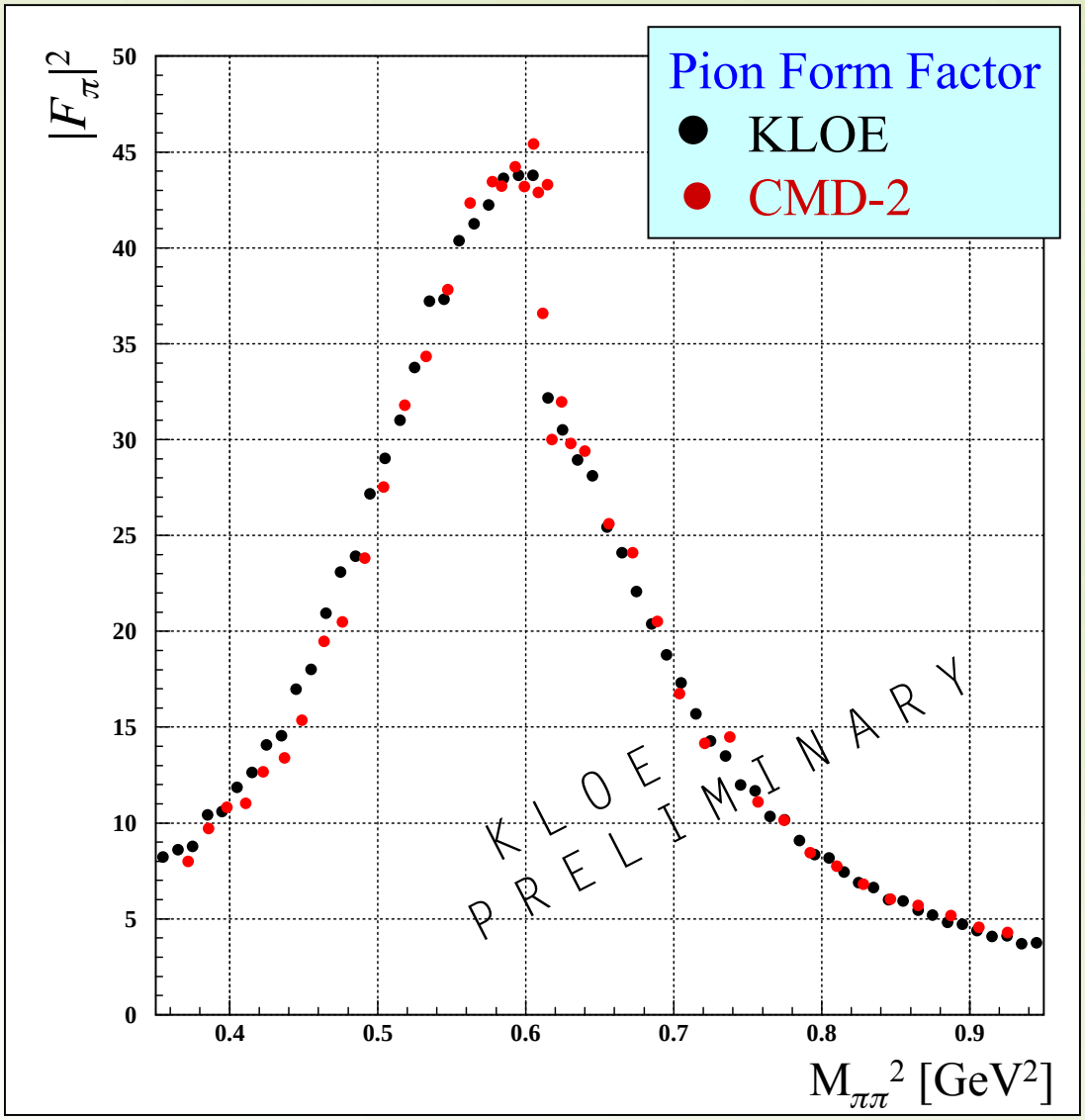
$$M_{\pi\pi}^2 \cdot \frac{d\sigma(e^+e^- \to \pi^+\pi^-\gamma)}{dM_{\pi\pi}^2} = H(M_{\pi\pi}^2) \cdot \underbrace{\sigma(e^+e^- \to \pi^+\pi^-)}_{\propto |F_\pi(s)|^2}$$

Technically we get $H(M_{\pi\pi}^2)$ by setting $F_\pi = 1$ in the MC – Program PHOKHARA



Comparison

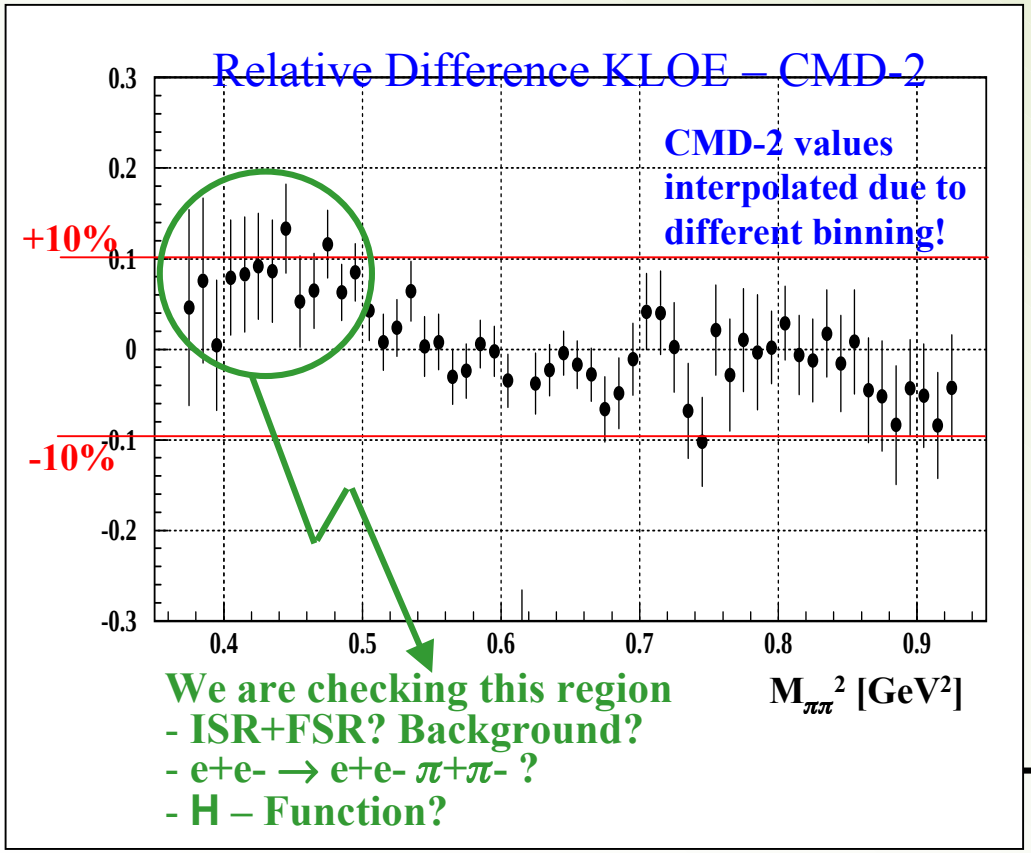
Our Pion Form Factor - measurement can be compared with the CMD-2 experiment



CMD-2 &KLOE data F_π:

- no FSR corrections
- not divided by vacuum polarization

To be done for the final cross section table $\sigma_{\pi\pi}$!


Relative Difference KLOE – CMD-2
CMD-2 values interpolated due to different binning!
+10%
-10%
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.4
0.5
0.6
0.7
0.8
0.9
$M_{\pi\pi}^2$ [GeV^2]
We are checking this region
- ISR+FSR? Background?
- e+e- → e+e- π+π- ?
- H – Function?

$a_\mu^{\pi\pi} \times 10^{10}$

calculate: $a_\mu^{\pi\pi} \propto \int_{Q^2\,\min}^{Q^2\,\max} ds\ \sigma_{\pi\pi}(s)\ K(s)$

* our own calculation values w/o FSR and V.P. corrections (like us)

KLOE: PRELIMINARY

$a_\mu^{\pi\pi} = 424.7$ $0.30 < Q^2 < 0.95\ \mathrm{GeV}^2$

$a_\mu^{\pi\pi} = 381.4$ $0.37 < Q^2 < 0.93\ \mathrm{GeV}^2$

$a_\mu^{\pi\pi} = 240.1$ $0.50 < Q^2 < 0.93\ \mathrm{GeV}^2$

CMD-2:

$a_\mu^{\pi\pi} = 376.7^*$ $0.37 < Q^2 < 0.93\ \mathrm{GeV}^2$

$a_\mu^{\pi\pi} = 241.4^*$ $0.50 < Q^2 < 0.93\ \mathrm{GeV}^2$

Ca. 0.5% Agreement with CMD-2 > 0.5GeV² !

BUT

Corrections for V.P. and FSR are not included!

Systematic Error

Radiative Corr. H ($M_{\pi\pi}^2$) (Phokhara)

The systematic error is under final evaluation!

Contributions from:

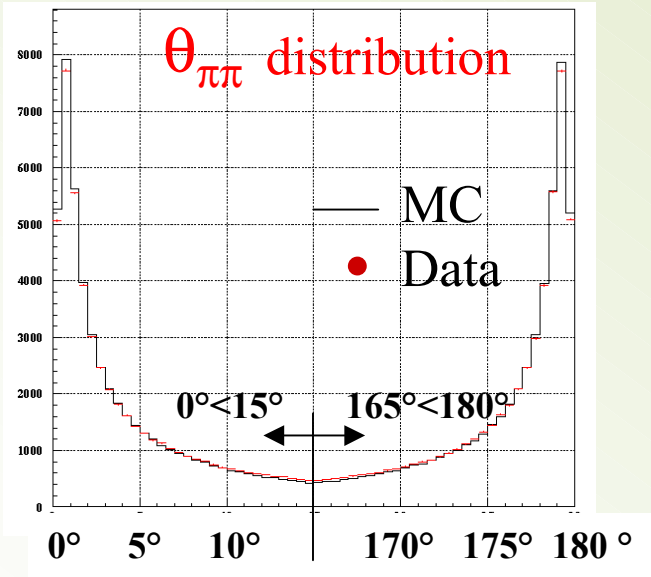
Luminosity

almost

0.5% Theory ⊕ 0.4% Exper.

PRELIMINARY

Acceptance Cuts



Good agreement Data - MC

Efficiencies

Individual contributions from the various items; Effects are expected to be on some permil-level for each items

Trigger	**0.2%**
Tracking	**0.3%**
Vertex	**< 2%**
Ev.-Filter	**< 0.5%**
Trackmass	**0.2%**

PRELIMINARY

Conclusion

- KLOE has performed a measurement of the Pion Form Factor with 140.7pb^{-1} of 2001 data using the Radiative Return

- Statistical Error is negligible

- In the energy range $M_{\pi\pi}^2 > 0.5$ GeV^2 we do not reproduce the large deviation seen by τ-data with respect to CMD-2

- Final checks on Background at low $M_{\pi\pi}^2$
  Final cross checks with different acceptance cuts
  Final systematic error under evaluation

Future … ?

Outlook (1)

Large Angle Analysis

- The analysis performed so far is an untagged "small angle analysis" (small photon angles $\Theta_{\pi\pi}<15°$, large pion angles $40°<\Theta_{\pi}<140°$)
  → Kinematically limited to $M_{\pi\pi}^2>0.3\text{GeV}^2$

- In a second step we plan to perform a complementary analysis at Large photon angles which allows to cover the whole energy range needed for the evaluation of $(g\text{-}2)_\mu$ and for which no new measurement is available:
  → $(2m_\pi)^2 < M_{\pi\pi}^2 < (m_\phi)^2$

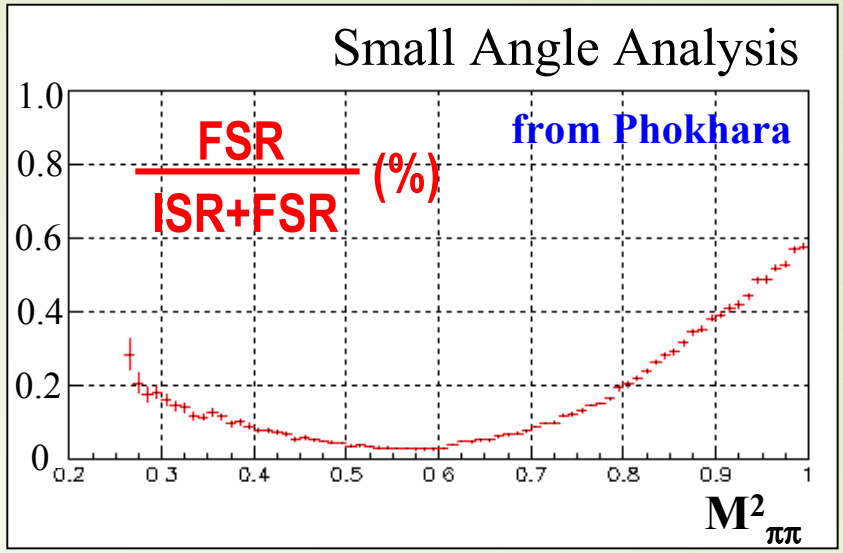
Features:

- considerably less statistics but this can be compensated with new data taking
- Different background contamination (especially $\phi \rightarrow \pi^+\pi^-\pi^0$)
- Different systematics: photon tagging possible!
- normalization to muons with exp. and theoretical advantages (cross check L)
- FSR becomes an issue

Outlook (2)

Final State Radiation

In small angle analysis we checked from MC that the relative contrib. of FSR is <<1% in the entire $M_{\pi\pi}^2$-Range



→ Possible Model dependence relevant for Large Angle Analysis

→ Check Model (=“point-like Pions”) by looking at Charge Asymmetry at large photon angles (where FSR is actually large!)

- Important information for any Experiment (especially also CMD-2) since FSR – contribution has to be added for evaluation of $(g\text{-}2)_\mu$