# *Evaluation of $a_\mu^{\pi\pi}$ between 0.35 and 0.95 GeV$^2$ with data from the KLOE detector*

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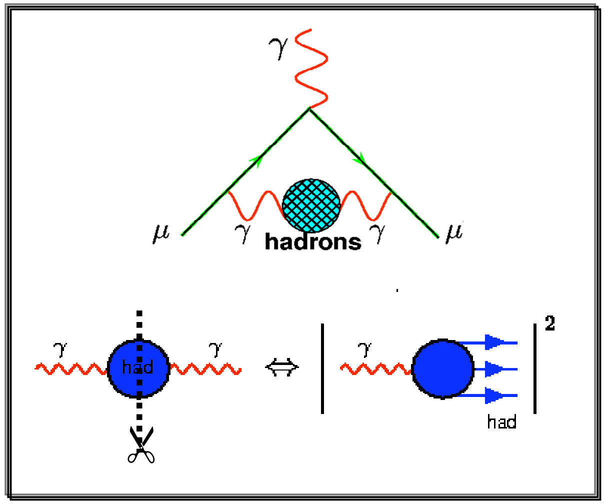
*(for the KLOE collaboration)*

***2007 Europhysics Conference on High Energy Physics***

***Manchester, 19-25 July 2007***

# Dispersion integral:

$a_\mu^{hadr}$ can be expressed in terms of $\sigma(e^+e^- \to$ hadrons) by the use of a dispersion integral:

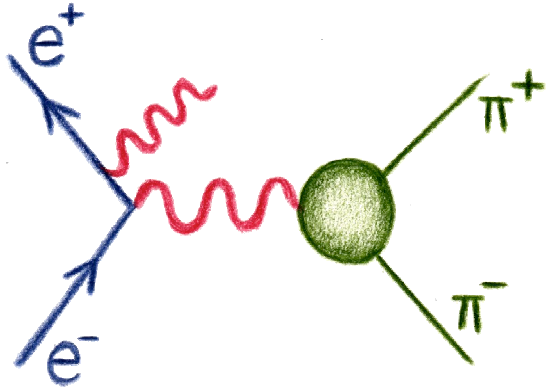



$$a_\mu^{hadr} = \frac{1}{4\pi^3}\left(\int_{4m_\pi^2}^{E_{Cut}^2} ds\,\sigma^{hadr,exp}(s)K(s) + \int_{E_{Cut}^2}^{\infty} ds\,\sigma^{hadr,pQCD}(s)K(s)\right)$$

- $E_{cut}$ is the threshold energy above which pQCD is applicable
- s is the c.m.-energy squared of the hadronic system
- K(s) is a monotonous function that goes with 1/s, ***enhancing low energy contributions of $\sigma^{hadr}(s)$***

# $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR:

Particle factories have the opportunity to measure the cross section $\sigma(e^+ e^- \rightarrow hadrons)$ as a function of the hadronic c.m. energy $M_{hadr}$ by using the ***radiative return***:




Neglecting FSR effects:

$$M^2_{hadr} \frac{d\sigma(e^+ e^- \rightarrow hadrons + \gamma)}{dM^2_{hadr}} = \sigma(e^+ e^- \rightarrow hadrons)\, H(M^2_{hadr})$$

This method is a **complementary approach** to the standard energy scan.

**Requires precise calculations of the radiator H**

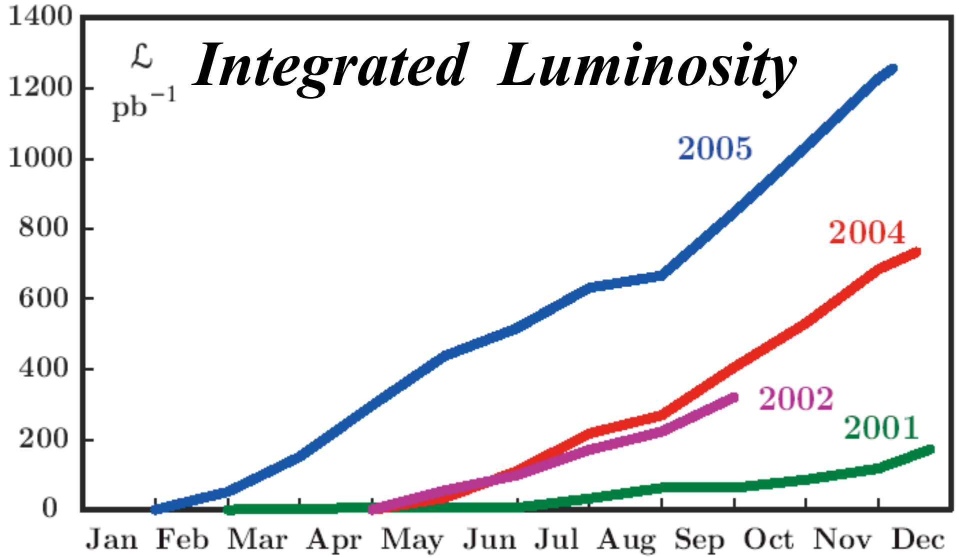
➔ **EVA + PHOKHARA MC Generator**

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

(H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003)

# DAΦNE: A Φ-Factory

$e^+e^-$ - collider with $\sqrt{s}=m_\Phi \approx 1.0195$ GeV




Peak Luminosity $L_{peak}$= 1.4 • $10^{32}$cm$^{-2}$s$^{-1}$

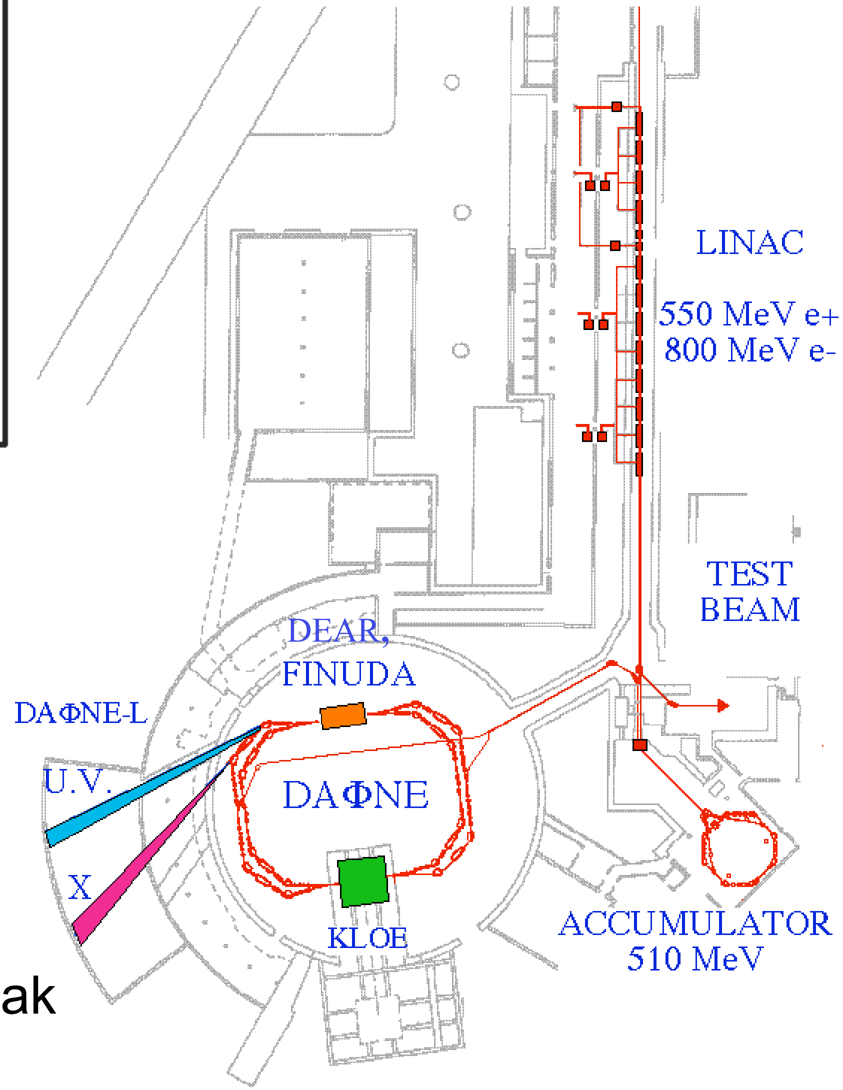
Total KLOE int. Luminosity:

$\int\mathcal{L}\,dt$ ~ 2500 pb$^{-1}$ (2001 - 05)

***This talk is based on 240pb$^{-1}$ from 2002 data!***

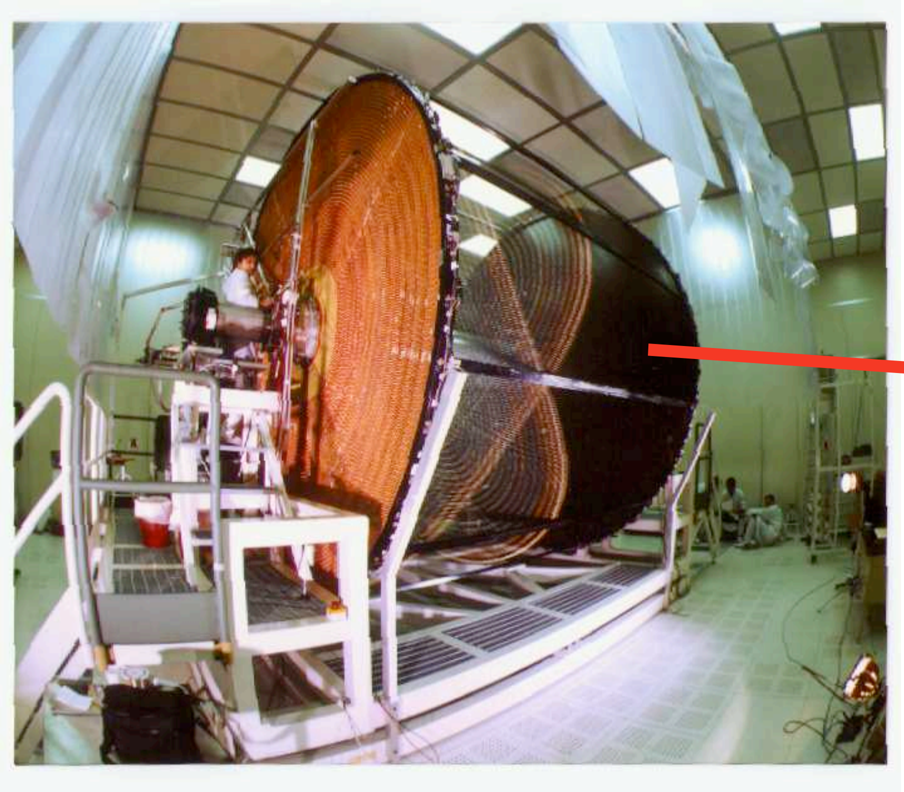
2006:

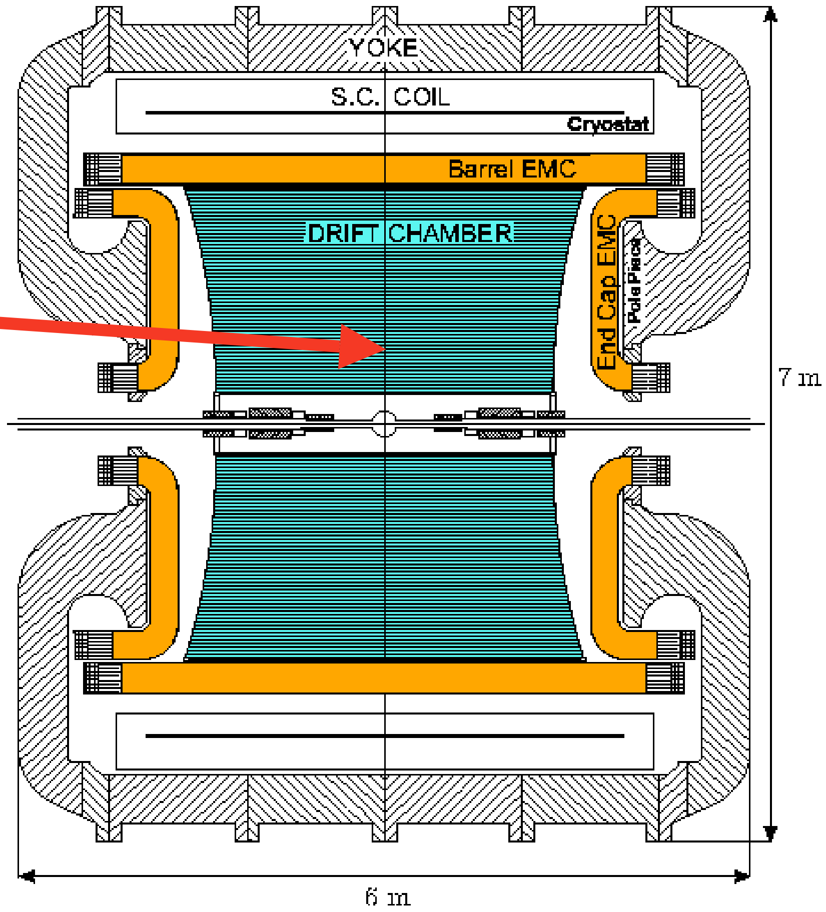
- Energy scan with 4 points around $m_\Phi$-peak
- 225pb$^{-1}$ at $\sqrt{s}$ = 1000 MeV



# KLOE Detector

Driftchamber





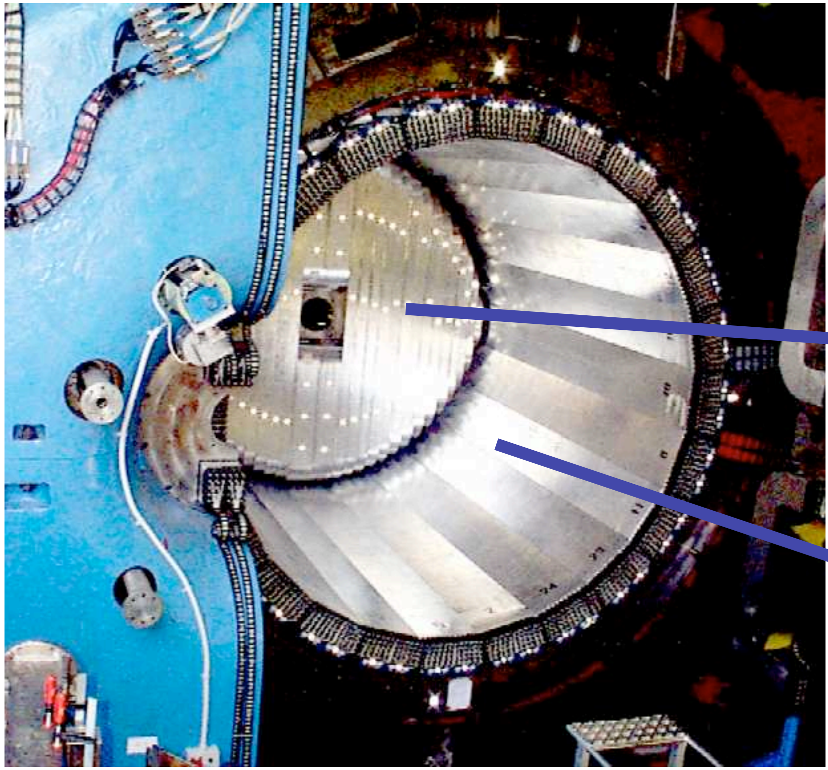

$\sigma_p/p = 0.4\%$ (for $90^0$ tracks)

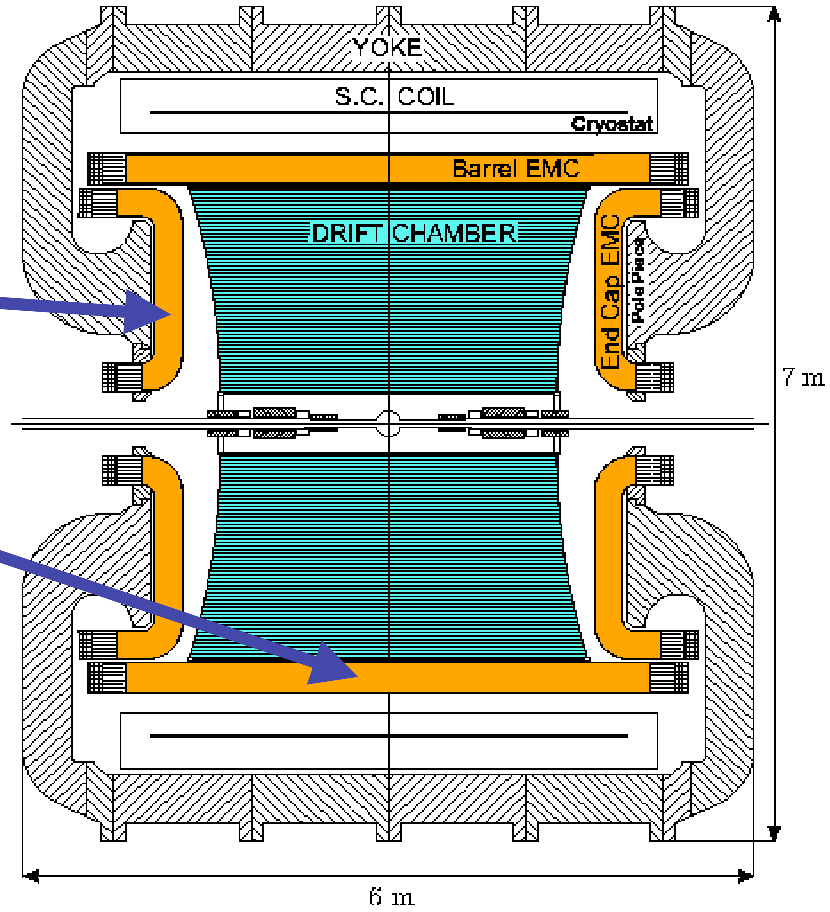
$\sigma_{xy} \approx 150\ \mu m$, $\sigma_z \approx 2$ mm

***Excellent momentum resolution***

# KLOE Detector

Electromagnetic Calorimeter






$$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$$

$$\sigma_T = 54 \text{ ps} / \sqrt{E(GeV)} \oplus 50 \text{ ps}$$

(Bunch length contribution subtracted from constant term)

***Excellent timing resolution***

# Event Selection

**Pion tracks at large angles**

$50^o < \theta_\pi < 130^o$

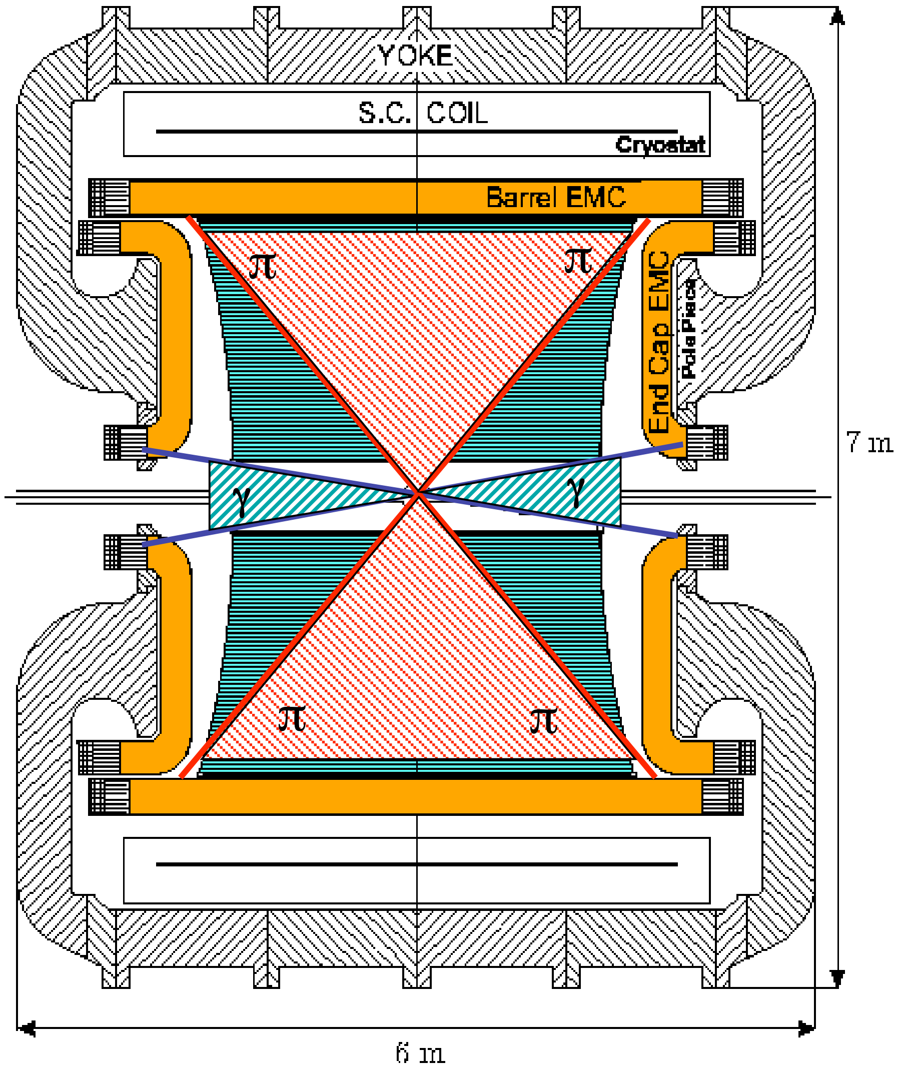
**a) Photons at small angles**

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

**➔ No photon detection!**

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

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination



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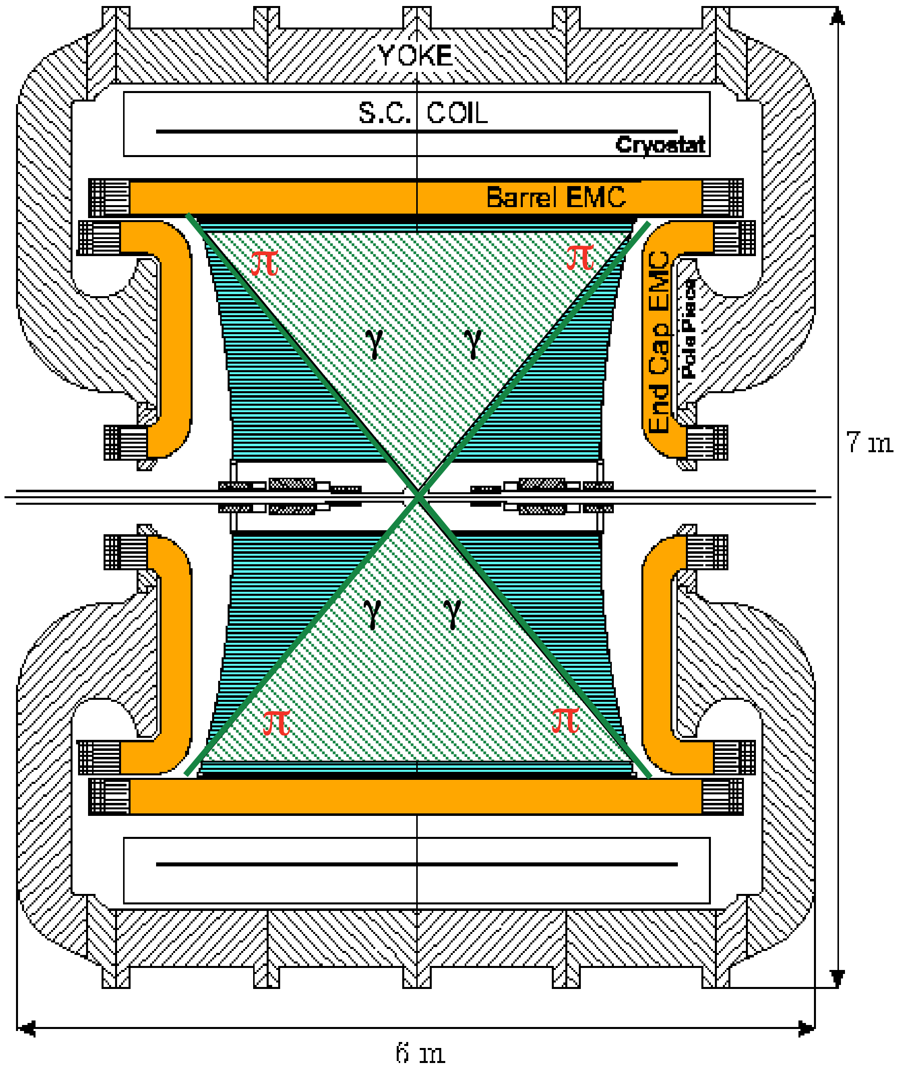



**b) Photons at large angles**

$50^o < \theta_\gamma < 130^o$

➔ **Photon is observed in the detector!**

- Threshold region accessible
- Increased contribution from FSR
- *Contribution from* $\phi \rightarrow f_0(980)\gamma \rightarrow \pi^+\pi^-\gamma$

# Event selection

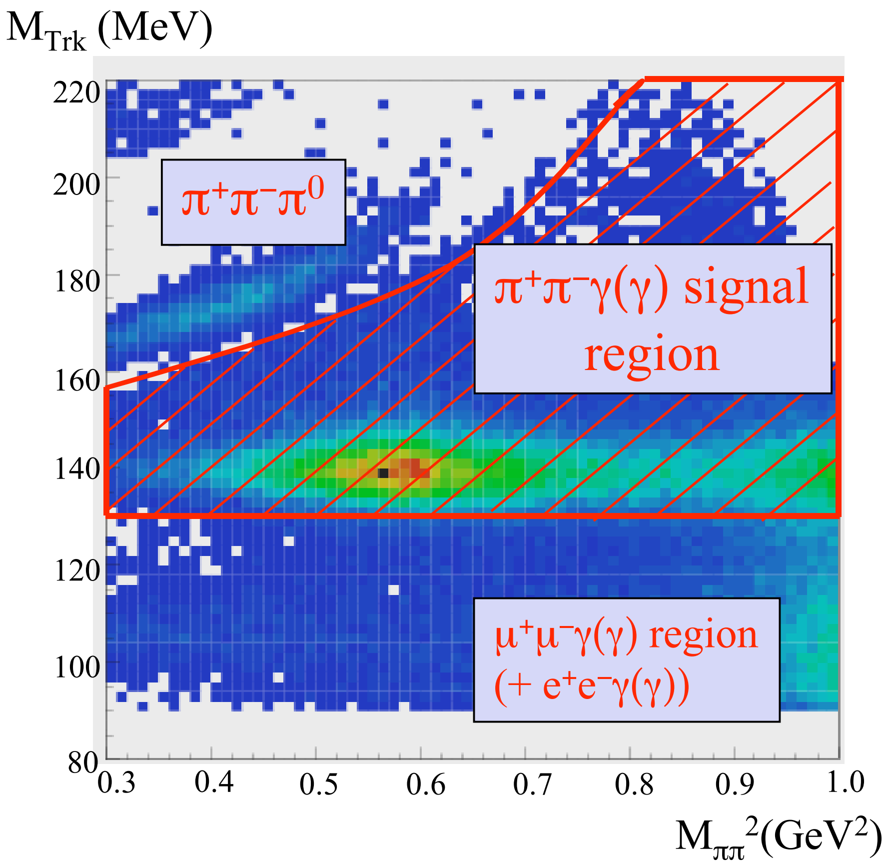
- Experimental challenge: Fight background from
  - $\phi \to \pi^+\pi^-\pi^0$
  - $e^+e^- \to e^+e^- \gamma(\gamma)$
  - $e^+e^- \to \mu^+\mu^- \gamma(\gamma)$,

  separated by means of kinematical cuts in *trackmass* $M_{Trk}$
  (defined by 4-momentum conservation under the hypothesis of 2 tracks with equal mass and one photon)

$$\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2}\right)^2 - (p_1 + p_2)^2 = 0$$

and *Missing Mass* $M_{miss}$
(defined by 4-momentum conservation under the hypothesis of $e^+e^- \to \pi^+\pi^- \mathbf{x}$

$$M_{miss} = \sqrt{E_X^2 - p_X^2}$$

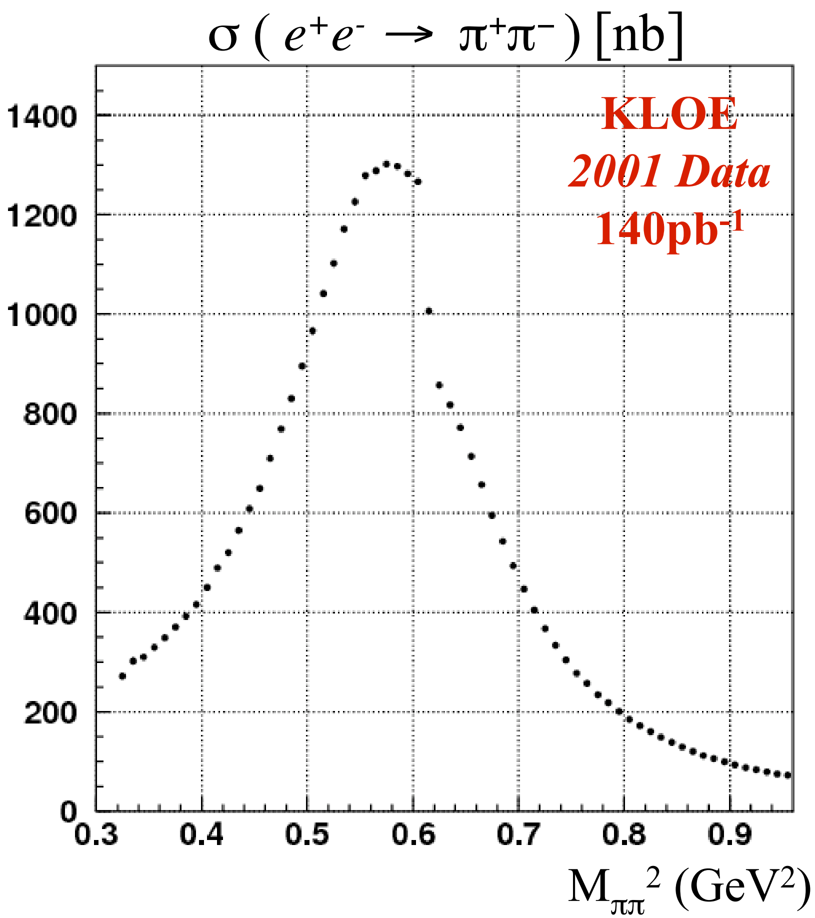



To further clean the samples from radiative Bhabha events, a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight is used.

# Published result with 2001 data

Published KLOE Result:

Phys. Lett. B606 (2005) 12




$a_{\mu}^{\pi\pi}$(0.35-0.95 GeV$^2$) =

(388.7 ± $0.8_{stat}$±$4.9_{syst}$) · $10^{-10}$

Improvements/updates with respect to 2001:

30% cosmic veto inefficiency recovered in 2002 by introducing additional software trigger level

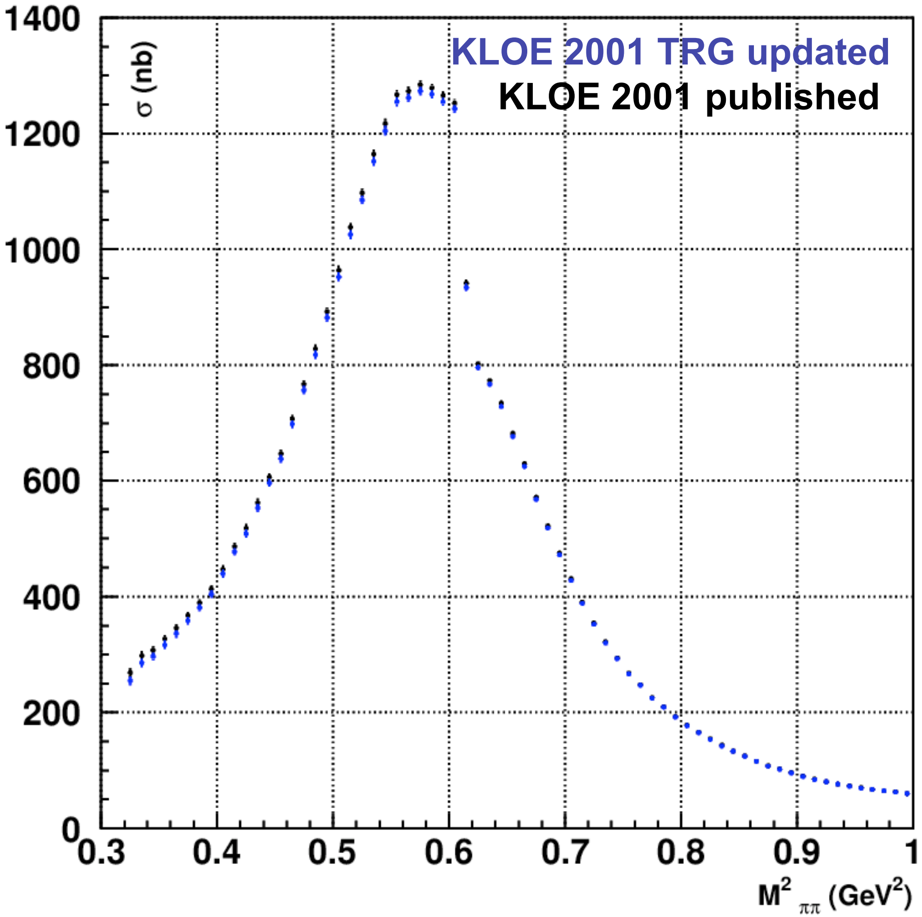
Improved offline-event filter reduces its systematic uncertainty to <0.1%

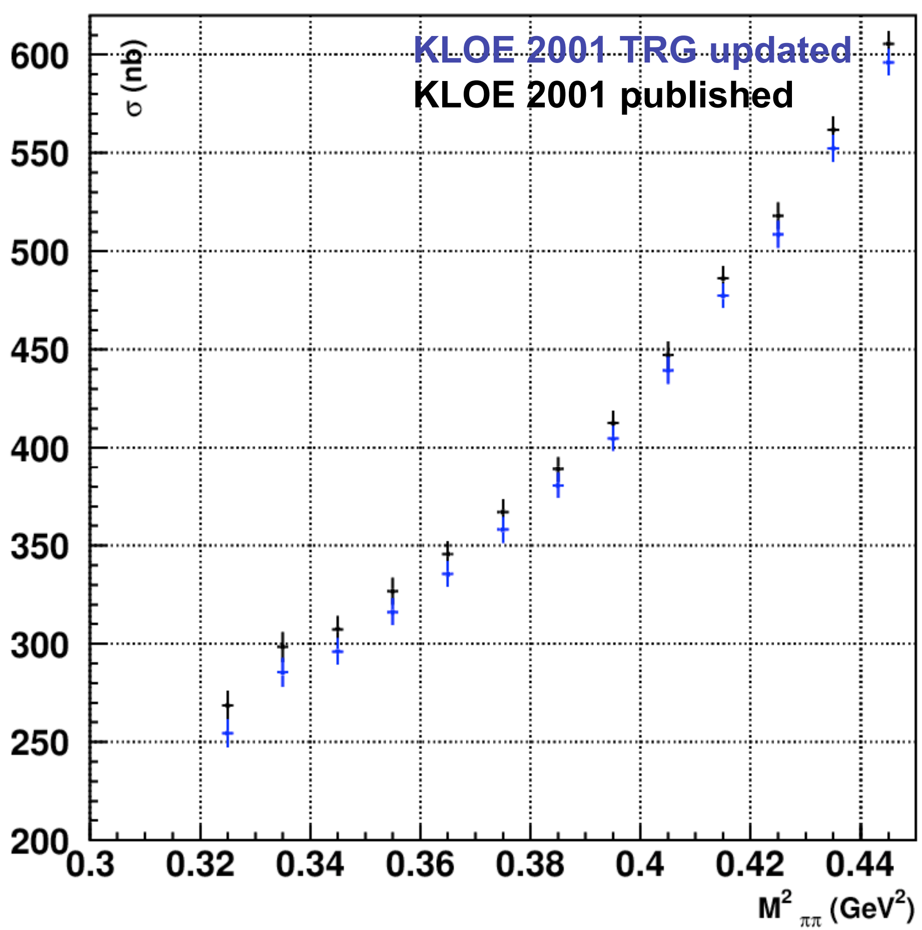
New generator BABAYAGA@NLO - theoretical error of Bhabha reference cross section goes from 0.5% to 0.1% - Bhabha cross section value is lowered by 0.7%

Trigger efficiency correction had to be updated due to a doublecounting of efficiencies.

# Trigger 2001 update

Impact of update on trigger correction on 2001 cross section:



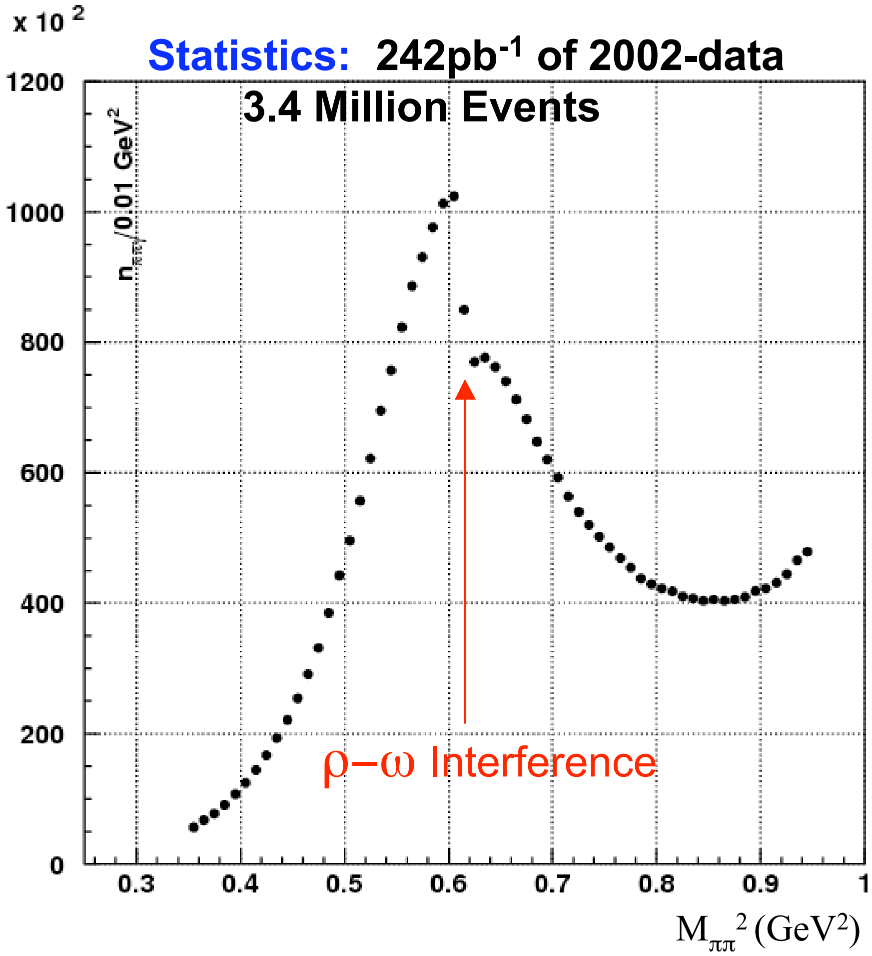



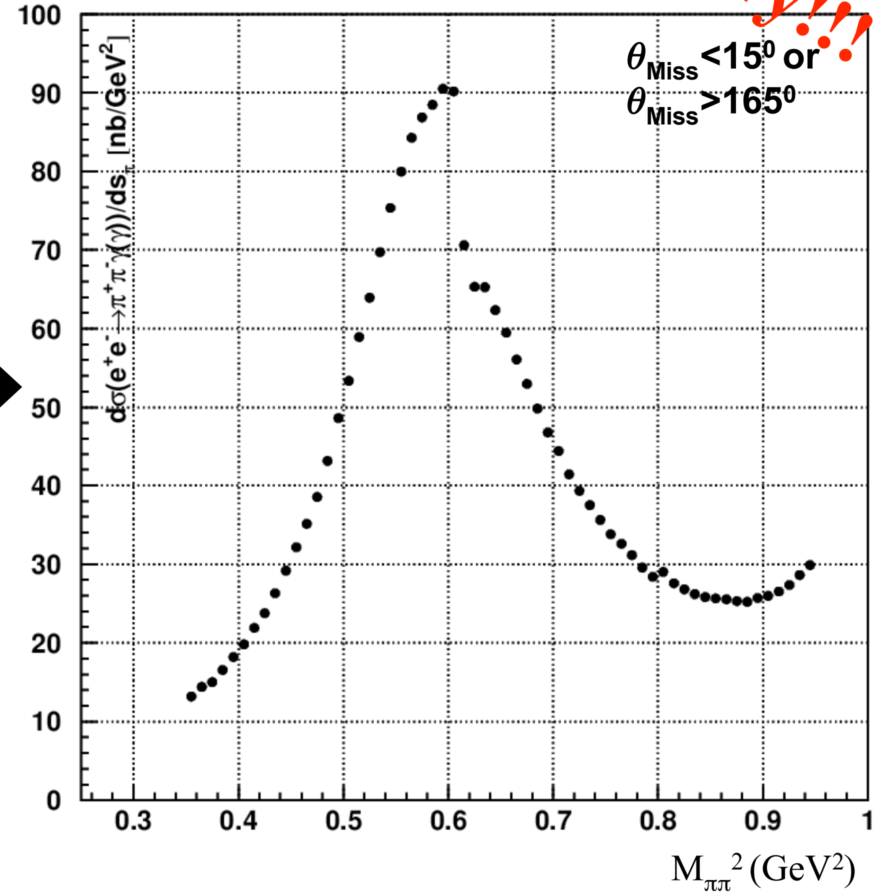

Changes published value on $a_\mu^{\pi\pi}$ by 0.4%

# Small angle analysis 2002

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

Preliminary!!!



# Luminosity:

At KLOE, Luminosity is measured using „Large angle Bhabha“ events ($55^o < \theta_e < 125^o$)

➔*KLOE is its own Luminosity Monitor!*

$$\int \mathcal{L}\,\mathrm{dt} = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

The luminosity is given by the number of Bhabha events divided for an effective cross section obtained by folding the theory with the detector simulation.

**Generator used for Bhabha cross section:**

**–BABAYAGA (Pavia group):**

**$\sigma_{eff}$ = (428.0±0.3$_{stat}$) nb**

*C. M. Calame et al., Nucl. Phys. B758 (2006) 227*

New version of generator gives 0.7% decrease in cross section compared to previous version

Quoted accuracy:
***0.1%***

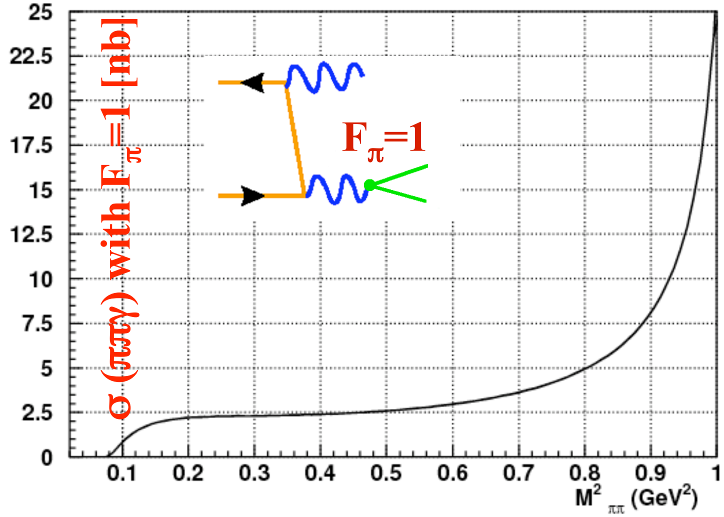
| Systematics on Luminosity | |
|---|---|
| Theory | 0.10 % |
| Acceptance | 0.25 % |
| Background ($\pi\pi\gamma$) | 0.08 % |
| Tracking+Clustering | 0.13 % |
| Energy Calibration | 0.10 % |
| Knowledge of √s run-by-run | 0.10 % |
| TOTAL 0.10 % theo ⊕ 0.32% exp = 0.34 % | |

# Radiative corrections

## Radiator-Function H(s) (ISR):

- **ISR-Process calculated at NLO-level**
  *PHOKHARA* generator (*Czyż, Kühn et.al*)
  **Precision:** ***0.5%***

$$M^2_{\pi\pi}\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s)\times \mathbf{H(s)}$$



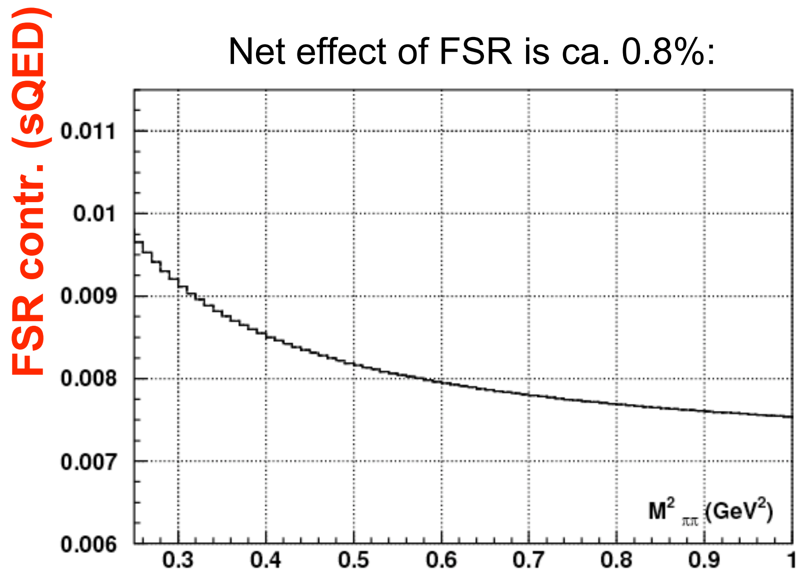

## Radiative Corrections:

**i) Bare Cross Section**
divide by Vacuum Polarisation

➔ from F. Jegerlehner:
http://www-com.physik.hu-berlin.de/~fjeger/

**ii) FSR - Corrections**
Cross section $\sigma_{\pi\pi}$ must be incl. for FSR


FSR corrections have to be taken into account in the efficiency eval. (small angle acceptance, $M_{Trk}$) and in the passage $\mathbf{M^2_{\pi\pi} \rightarrow M^2_{\gamma*}}$



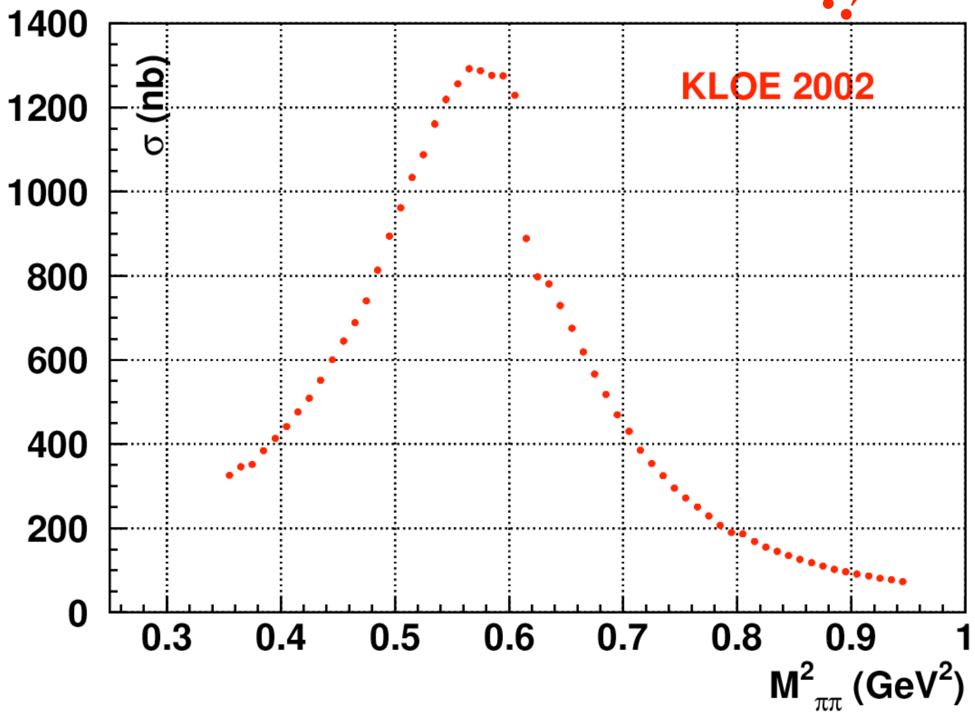
# Small angle result from 2002 data:

Preliminary!!!

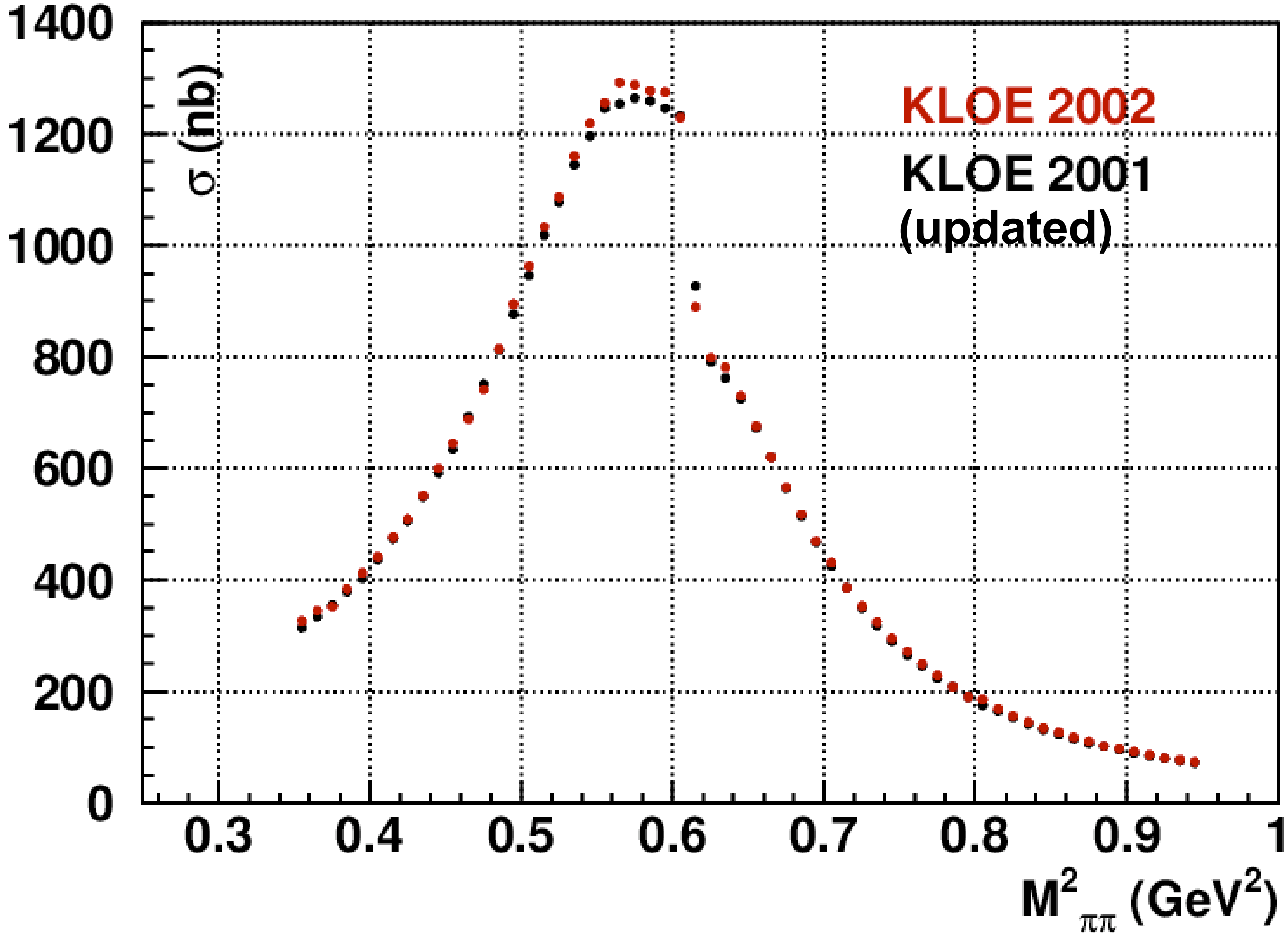
Systematic errors on $a_\mu^{\pi\pi}$:

| | |
|---|---|
| Offline Filter | negligible |
| Background | 0.3% |
| Trackmass/Miss. Mass | 0.2% (prelim) |
| $\pi$/e-ID | 0.3% |
| Vertex | 0.5% |
| Tracking | 0.4% |
| Trigger | 0.2% |
| Acceptance ($\theta_\pi$) | negligible |
| $M_{\pi\pi}^2 \rightarrow M_{\gamma*}$ (FSR corr.) | 0.3% (prelim) |
| Software Trigger | 0.1 % |
| Luminosity | 0.3% |
| Acceptance ($\theta_{Miss}$) | 0.1% |
| Radiator H | 0.5% |
| Vacuum polarization | negligible |

$\Sigma_{Total}$ = 1.1%



# Comparison 2001-2002:



# Evaluating $a_\mu^{\pi\pi}$ with small angle

Dispersion integral for 2π-channel in energy interval 0.35 <$M_{\pi\pi}^2$<0.95 GeV$^2$

$$a_\mu^{\pi\pi} = 1/4\pi^3 \int_{0.35\mathrm{GeV}^2}^{0.95\mathrm{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

2001 published result (Phys. Lett. B606 (2005) 12):

$a_\mu^{\pi\pi}(0.35\text{-}0.95\mathrm{GeV}^2) = (388.7 \pm 0.8_{stat} \pm 4.9_{syst}) \cdot 10^{-10}$

Applying update for trigger eff. and change in Bhabha-cross section used for luminosity evaluation:

$a_\mu^{\pi\pi}(0.35\text{-}0.95\mathrm{GeV}^2) = (384.4 \pm 0.8_{stat} \pm 4.9_{syst}) \cdot 10^{-10}$

**2002 preliminary:**

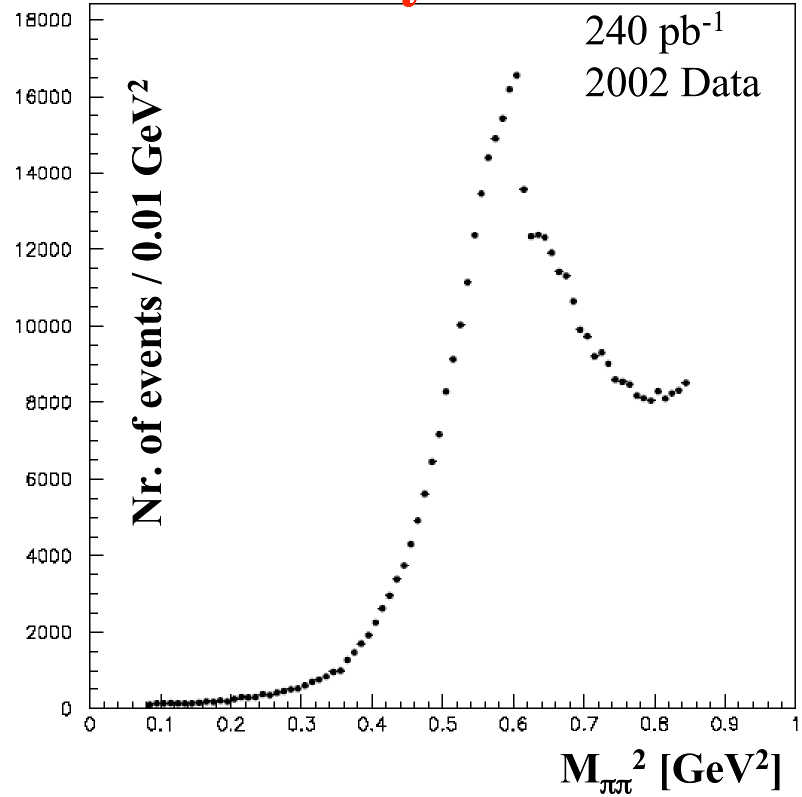
$a_\mu^{\pi\pi}(0.35\text{-}0.95\mathrm{GeV}^2) = (386.3 \pm 0.6_{stat} \pm 3.9_{syst}) \cdot 10^{-10}$

# Large angle analysis:

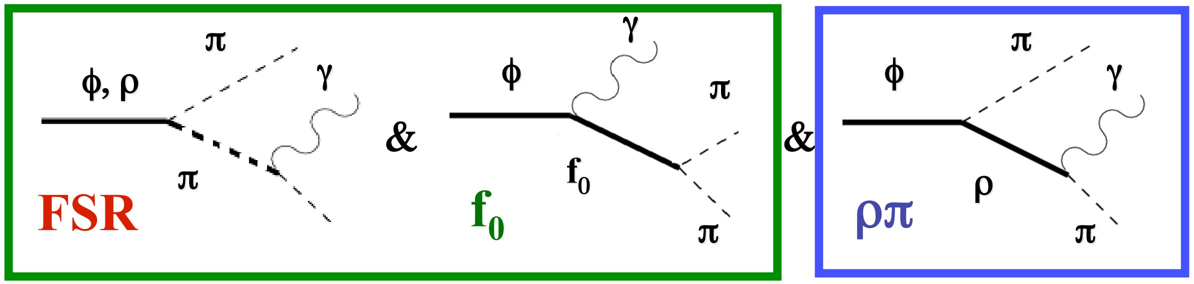
- ✓ important **cross check with small angle analysis**
- ✓**threshold region** is accessible
- ✓ **photon is detected**
  (4-momentum constraints)

- ✓lower signal statistics
- ✓ **FSR** not negligible anymore
- ✓ **large $\phi \rightarrow \pi^+\pi^-\pi^0$** background
- ✓ **irreducible bkg. from $\phi$ decays**

**Preliminary!!!**




Threshold region non-trivial
due to irreducible FSR-effects, to be estimated from MC using phenomenological models
(interference effects unknown)



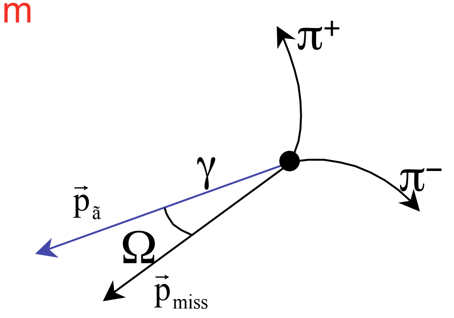

→ **important!**

→ **small!**

# Large angle analysis (cont'd):

*Apply dedicated selection cuts:*

- Exploit kinematic closure of the event
  → Cut on angle Ω btw. ISR-photon and missing momentum

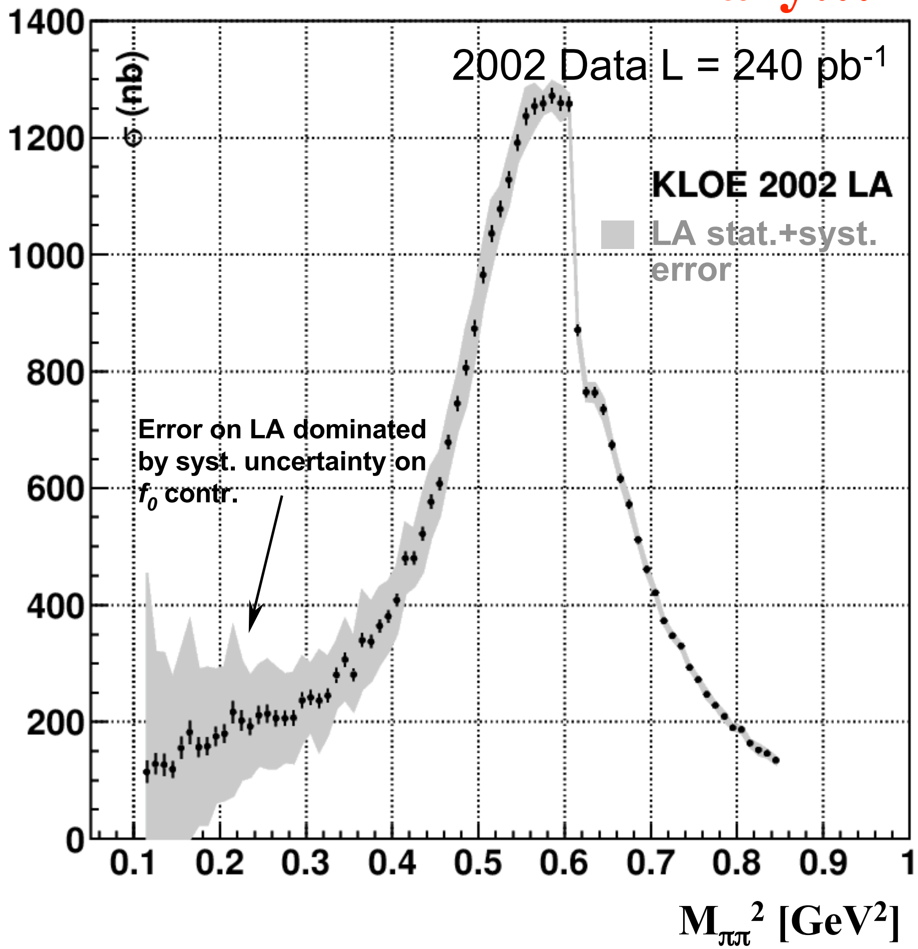



- Kinematic fit in $\pi^+\pi^-\pi^0$ hypothesis using 4-momentum and $\pi^0$-mass as constraints

- FSR contribution added back to cross section (estimated from PHOKHARA generator)

- Reducible background from $\pi^+\pi^-\pi^0$ and $\mu^+\mu^-\gamma$ well simulated by MC

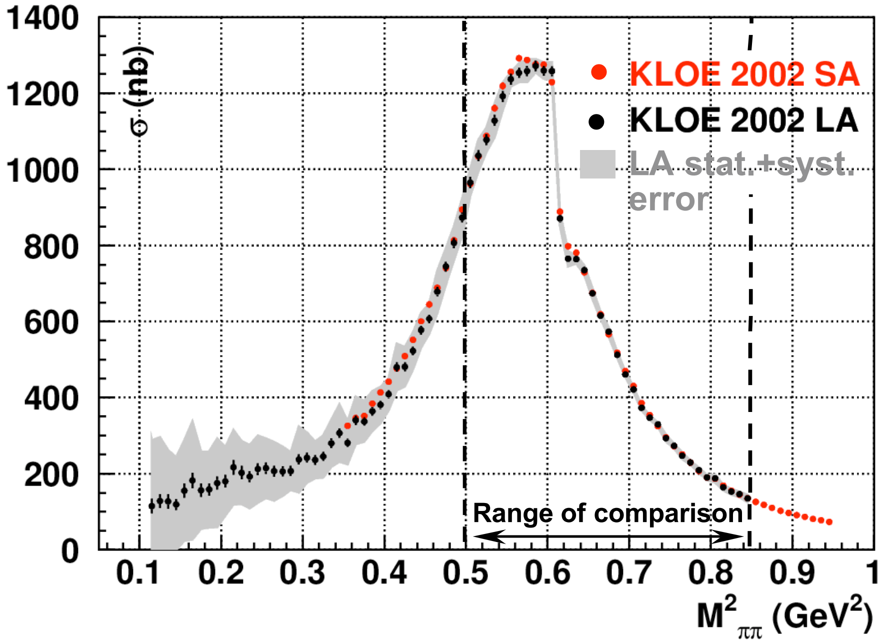
**Preliminary!!!**

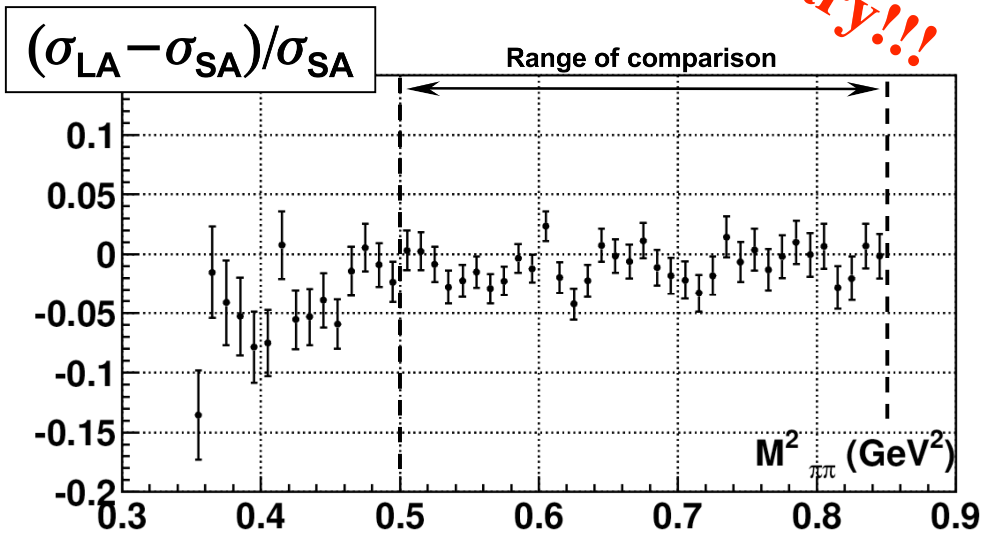



- Model dependence of irreducible background from $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$ is the dominating uncertainty. Estimated using different models for $f_0$-decay and input from dedicated KLOE $\phi \to f_0\gamma$ analyses (with $f_0$ decaying to charged and neutral pions).

# Comparison SA-LA 2002:

Preliminary!!!




$a_\mu^{\pi\pi}$ between 0.5 - 0.85 GeV$^2$:

**Small angle:**

$a_\mu^{\pi\pi}$(0.50-0.85GeV$^2$) =

**$(255.4 \pm 0.4_{stat} \pm 2.5_{syst}) \cdot 10^{-10}$**

**Large angle:**

$a_\mu^{\pi\pi}$(0.50-0.85GeV$^2$) =

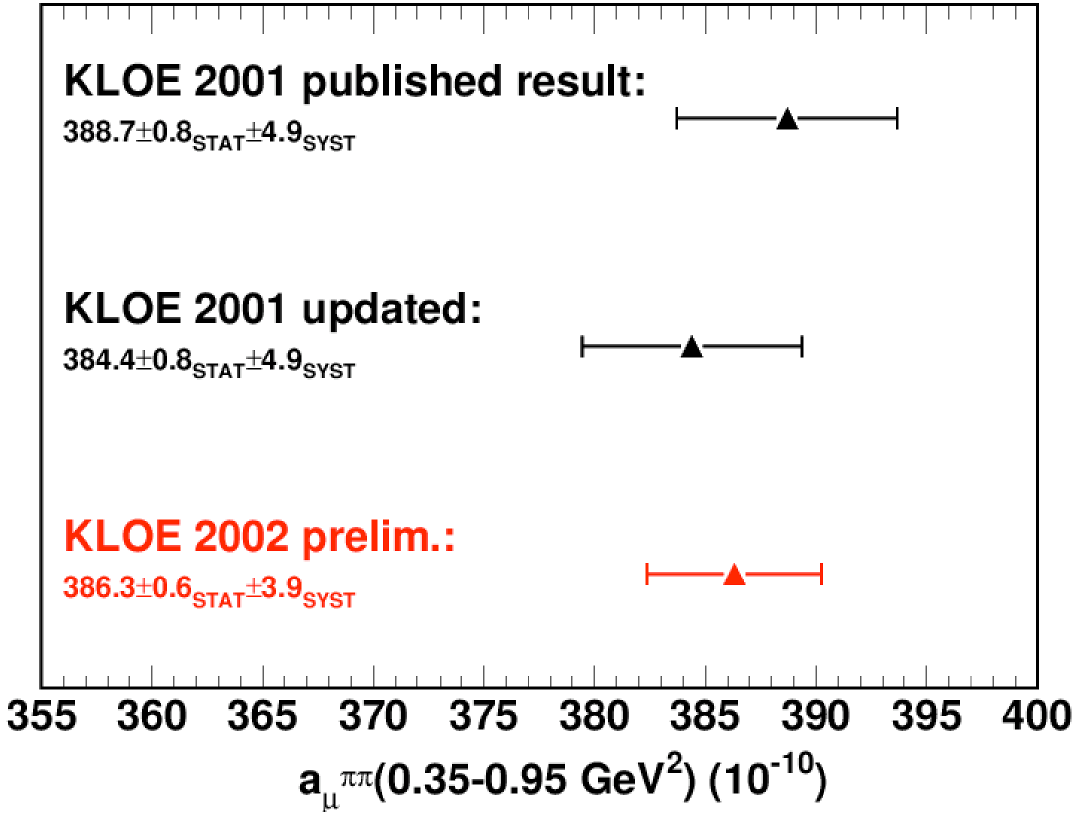
**$(252.5 \pm 0.6_{stat} \pm 5.1_{syst}) \cdot 10^{-10}$**

(60% of systematical error due to $f_0$-uncertainty)

# $a_\mu^{\pi\pi}$ Summary:

Preliminary!!!

Summary of the small angle results:



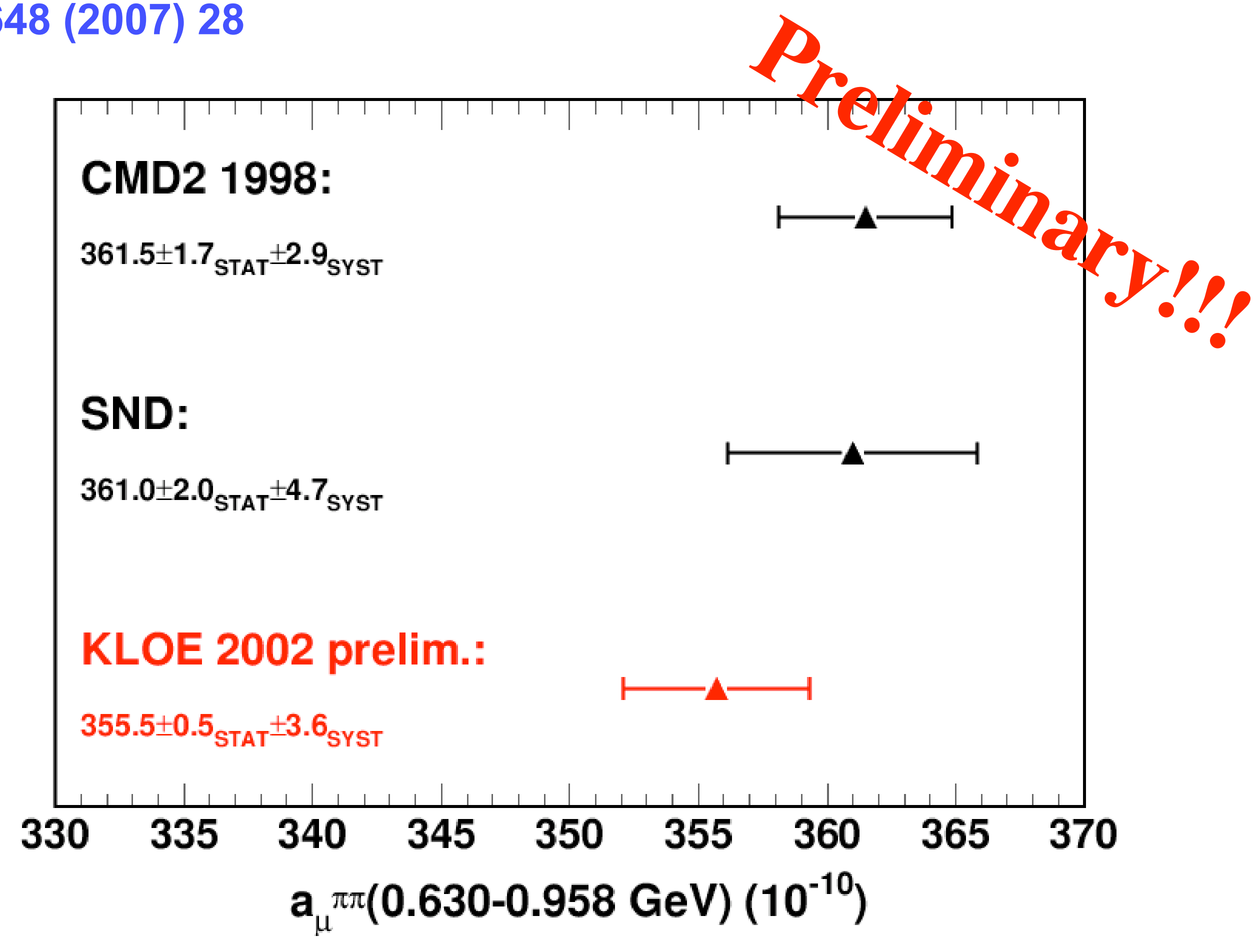

Jegerlehner (hep-ph/0703125): $\Delta a_\mu = a_\mu^{exp} - a_\mu^{the} = (28.7 \pm 9.1) \cdot 10^{-10}$

Using new KLOE result would increase difference from 3.2$\sigma$ to 3.4$\sigma$

# $a_\mu^{\pi\pi}$ Summary:

Comparison with $a_\mu^{\pi\pi}$ from CMD2 and SND in the range 0.630-0.958 GeV :

Phys. Lett. B648 (2007) 28



# Conclusions:

We have obtained $a_\mu^{\pi\pi}$ in the range between 0.35 - 0.95 $GeV^2$ using cross section data obtained via the radiative return with photon emission at small angles.

- *The preliminary result from 2002 data agrees with the updated result from the published KLOE analysis based on 2001 data*

Data from an independent and complementary KLOE measurement *(Large angle analysis)* of the $2\pi-$cross section has been used to obtain $a_\mu^{\pi\pi}$ in the range between 0.5 - 0.85 $GeV^2$

- *All three KLOE results are in good agreement*

KLOE results also agree with recent results on $a_\mu^{\pi\pi}$ from the CMD2 and SND experiments at VEPP-2M in Novosibirsk

# Outlook:

- Refine the small angle analysis by unfolding for detector resolution, evaluating further possible backgrounds, etc.

- Continue evaluation of resonance contributions in the large angle analysis

- Measure the pion form factor via bin-by-bin ratios of pions over muons (Normalization to muons instead of absolute normalization with Bhabhas)

- Obtain pion form factor from data taken at $\sqrt{s}$ = 1000 MeV (outside the $\phi$ resonance)
  - suppression of background from $\phi$-decays
  - determination of $f_0$-parameters