Measurement of the pion form factor between 0.1 and 0.85 GeV^2 with the KLOE detector

Stefan E. Müller

Institut für Kernphysik, Universität Mainz

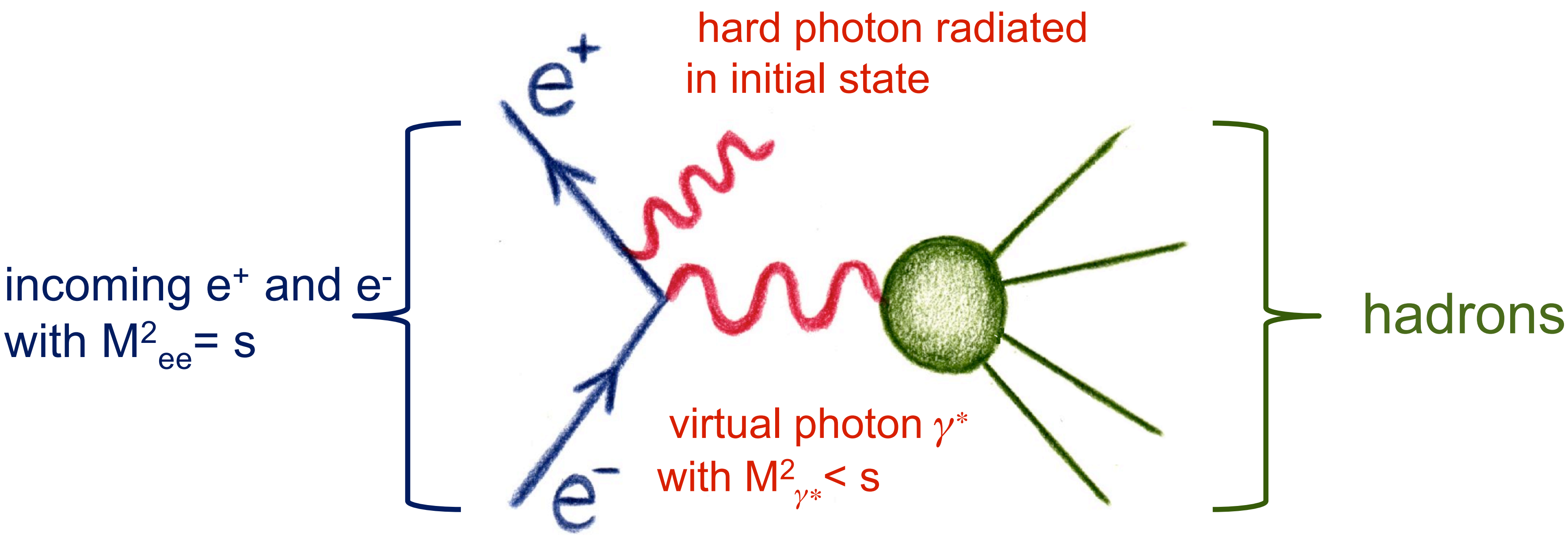
(for the KLOE collaboration)

PHIPSI09 Conference

Beijing, 14.10.2009

ISR: Initial state radiation

Particle factories (DAΦNE, PEP-II, KEK-B) can measure hadronic cross sections as a function of the hadronic c.m. energy using initial state radiation (**radiative return** to energies below the collider energy $\sqrt{s}$).

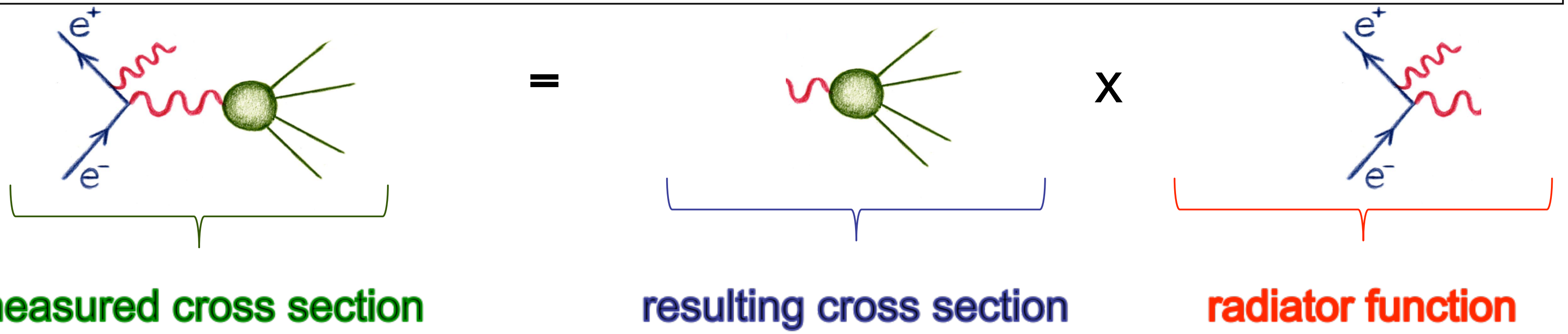


The emission of a hard γ in the bremsstrahlung process in the initial state reduces the energy available to produce the hadronic system in the e^+e^- collision.

ISR: Initial state radiation

Neglecting final state radiation (FSR) terms, one can relate the measured differential cross section $d\sigma_{hadr+\gamma}/dM^2_{hadr}$ to the hadronic cross section σ_{hadr} using the radiation function $H(s, M^2_{hadr})$:

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



Theoretical input:

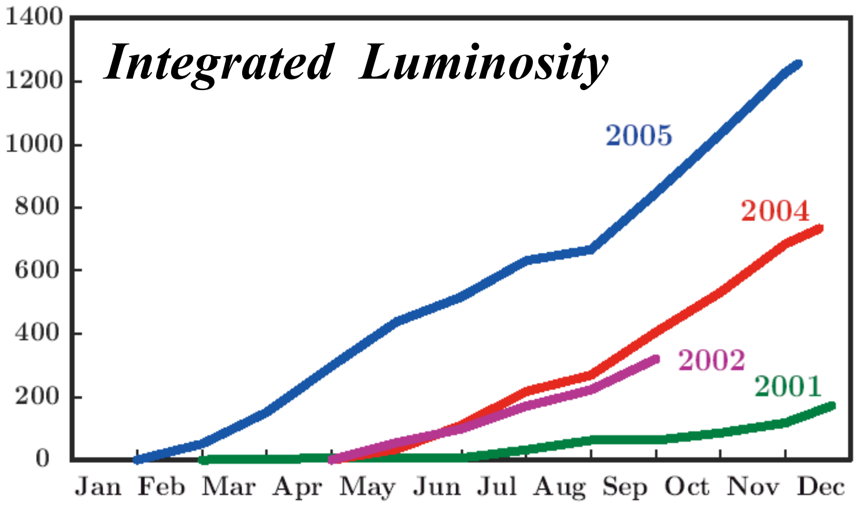
- precise calculation of the radiation function $H(s, M^2_{hadr})$

➔ EVA + PHOKHARA MC Generator

Binner, Kühn, Melnikov; Phys. Lett. B 459, 1999
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003
(exact next-to-leading order QED calculation of the radiator function)

DAΦNE: A Φ-Factory

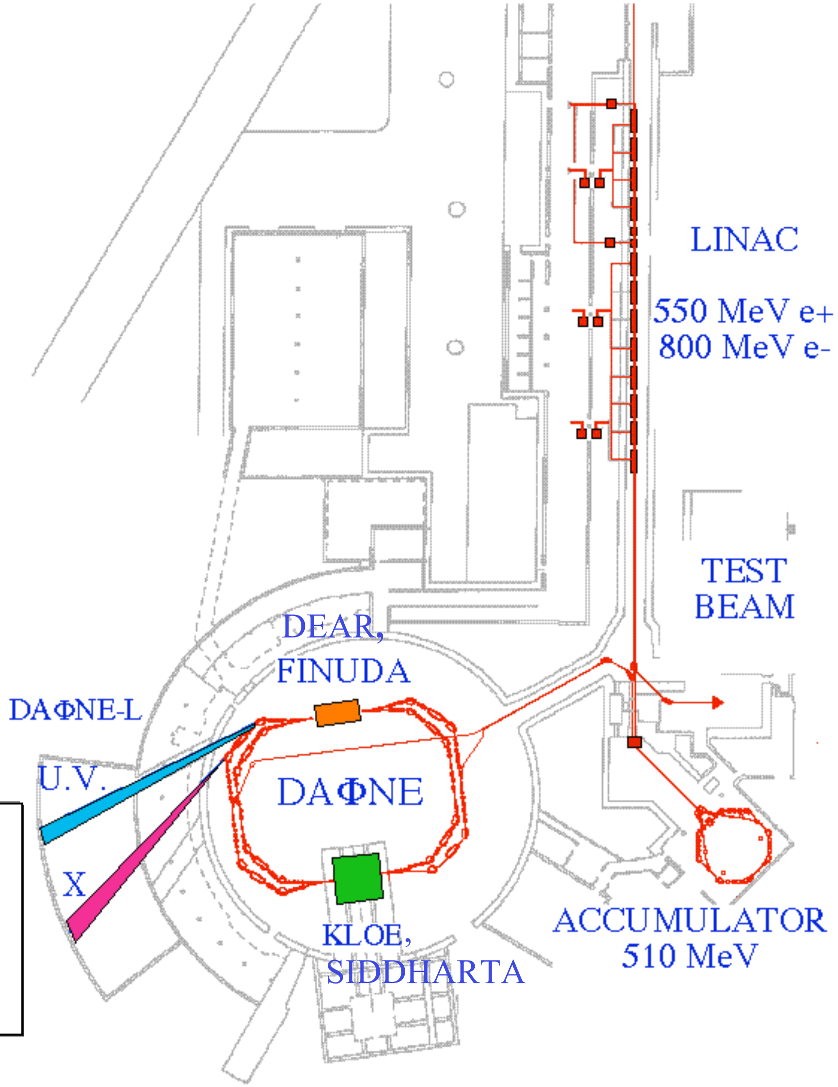
e^+e^- - collider with $\sqrt{s}=m_\phi\approx 1.0195$ GeV



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

Total KLOE int. Luminosity:

$\int \mathcal{L}\,dt \sim 2.1\ fb^{-1}$ (2001 - 05)

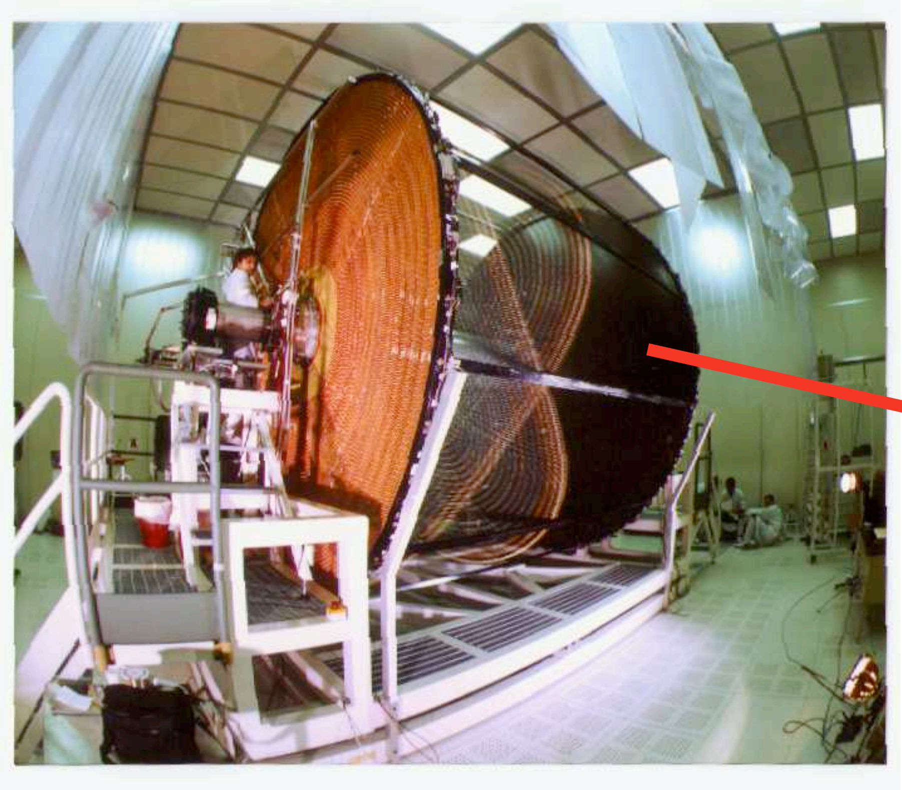


2006:

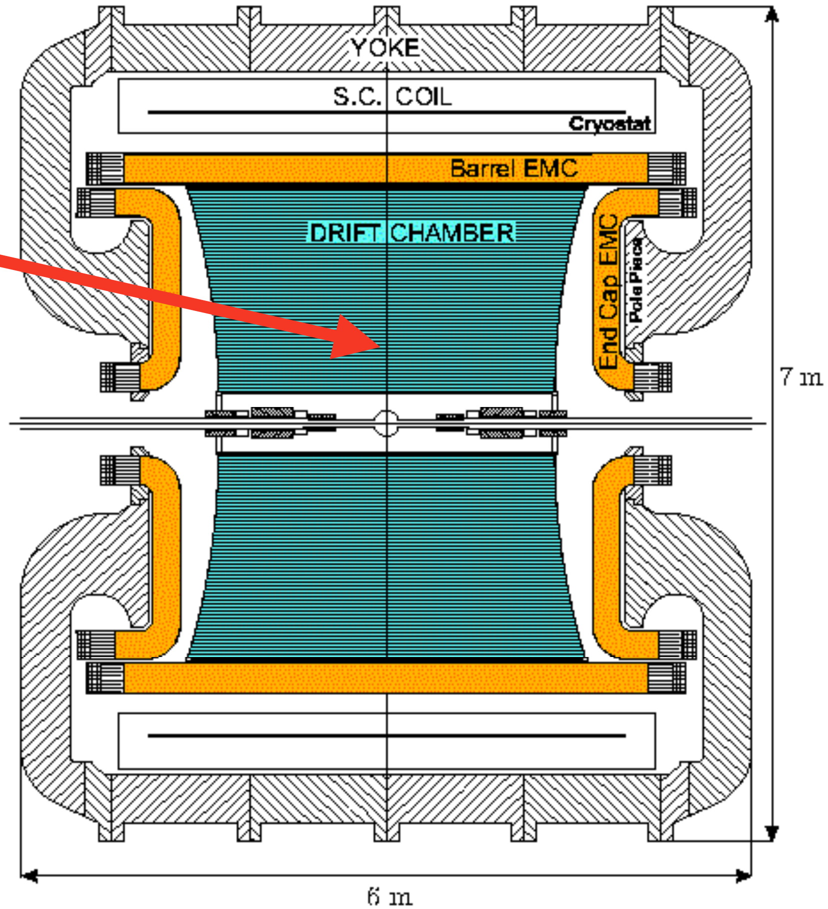
- **Energy scan with 4 points around m_ϕ-peak**
- **250 pb^{-1} at $\sqrt{s}$ = 1 GeV**

KLOE Detector

Drift Chamber



Full stereo geometry, 4m diameter, 52.140 wires 90% Helium, 10% iC_4H_{10}



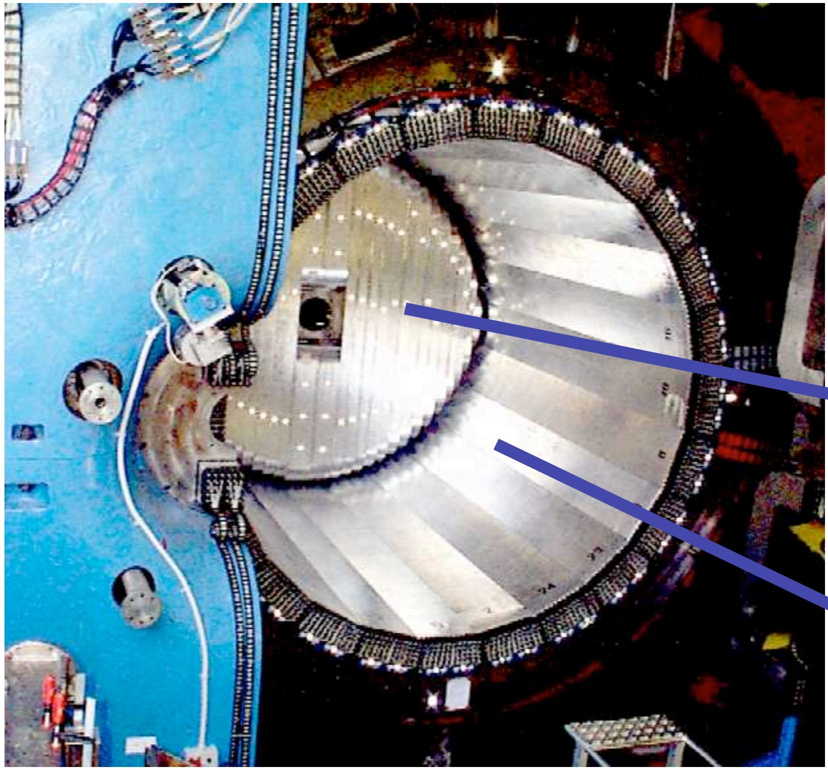
σ_p/p = 0.4% (for 90^0 tracks)

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

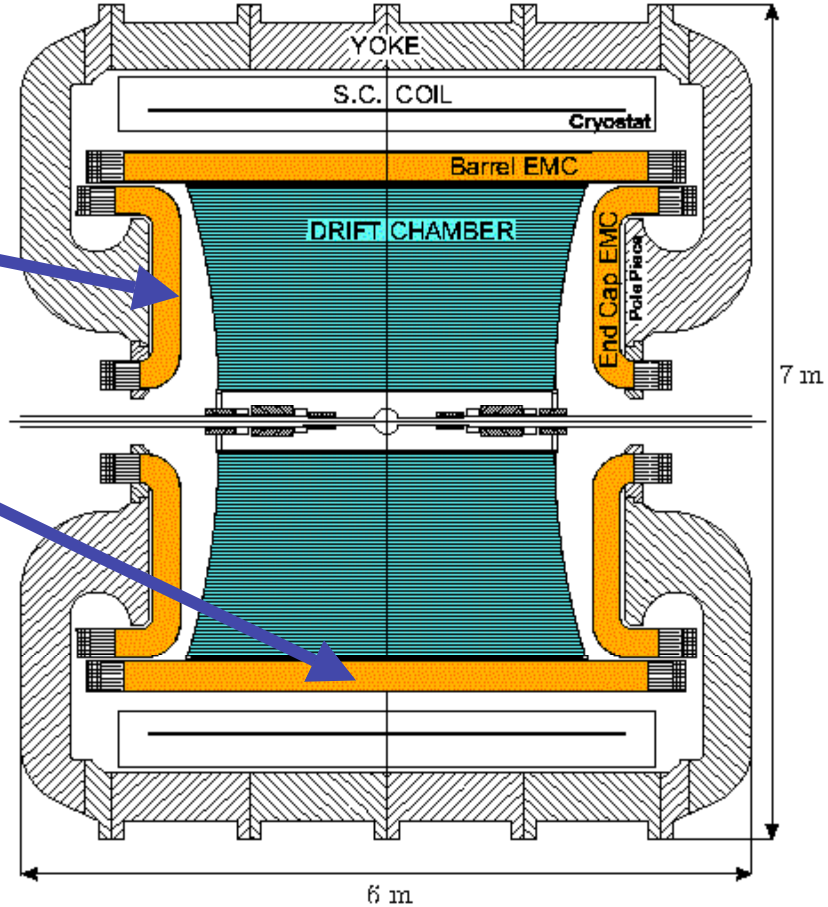
Excellent momentum resolution

KLOE Detector

Electromagnetic Calorimeter



Pb / scintillating fibres (*4880 PMT*)
Endcap - Barrel - Modules



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

$$\sigma_T = 54\ \text{ps} / \sqrt{E(\text{GeV})} \oplus 100\ \text{ps}$$

(Bunch length contribution subtracted from constant term)

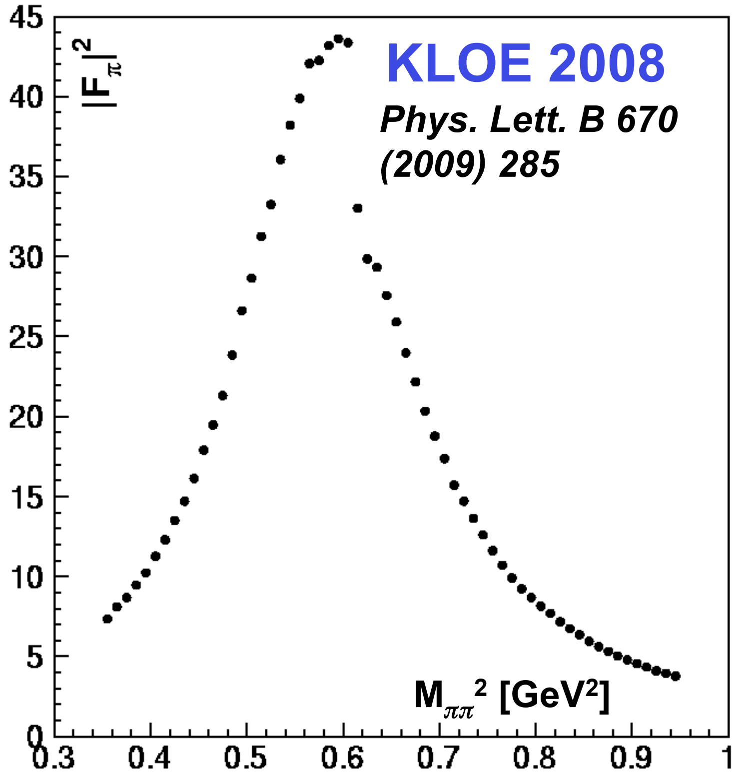
Excellent timing resolution

$|F_\pi|^2$ measurement: *small angle*

2 pion tracks at large angles
$50^o < \theta_\pi < 130^o$

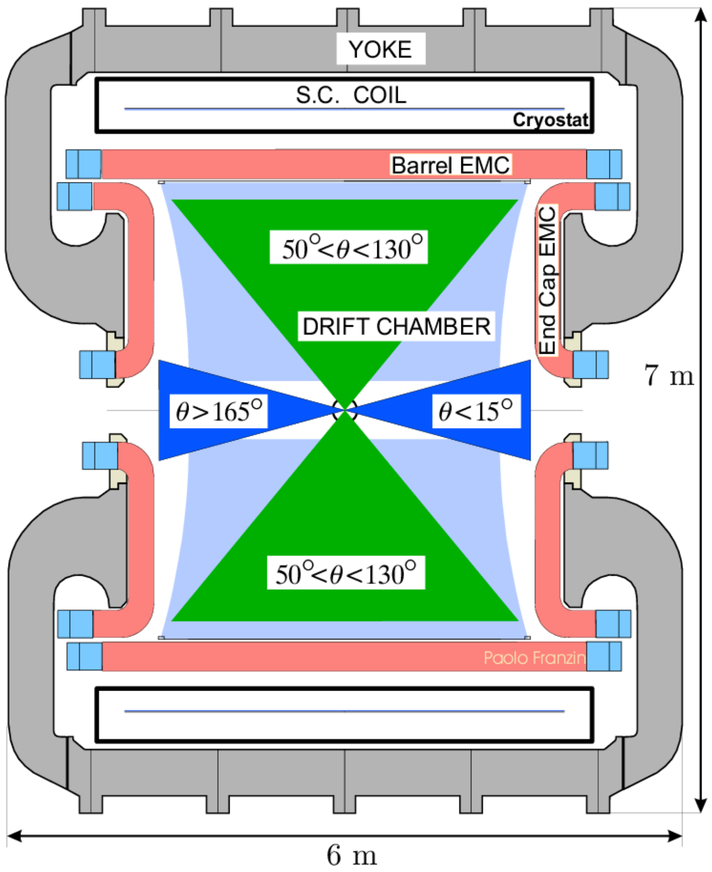
Photons at small angles
$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

- ✓ high statistics for ISR events
- ✓ low relative FSR contribution
- ✓ suppression of $\phi \to \pi^+\pi^-\pi^0$ background



➔ **photon momentum from kinematics:**

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



1st KLOE result using 2001 data: ***Phys. Lett. B 606, 12 (2005)***
Updated and superseded by new result based on 2002 data: ***Phys. Lett. B 670, 285 (2009)***

$|F_\pi|^2$ measurement: *large angle*

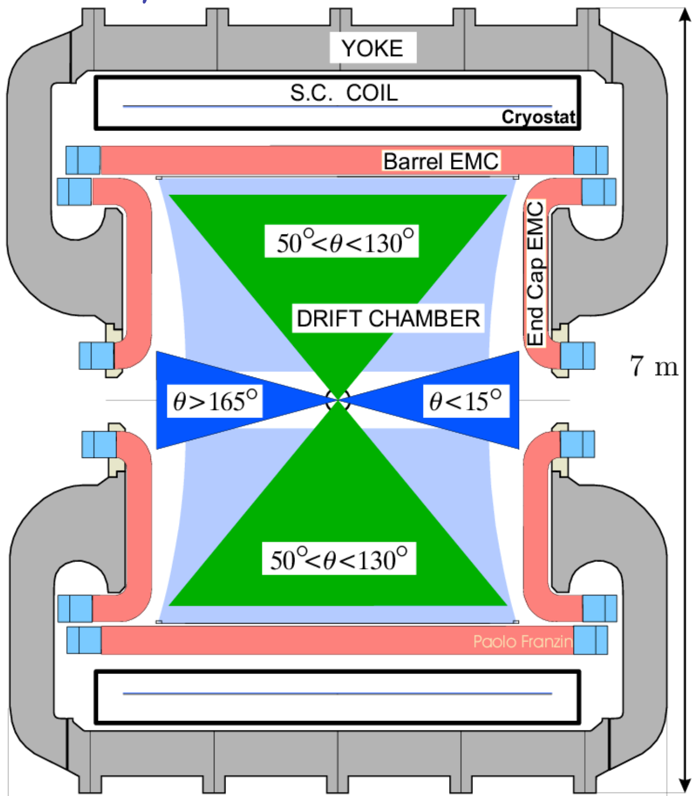
2 pion tracks at large angles
$50^o < \theta_\pi < 130^o$

Photons at large angles
$50^o < \theta_\gamma < 130^o$

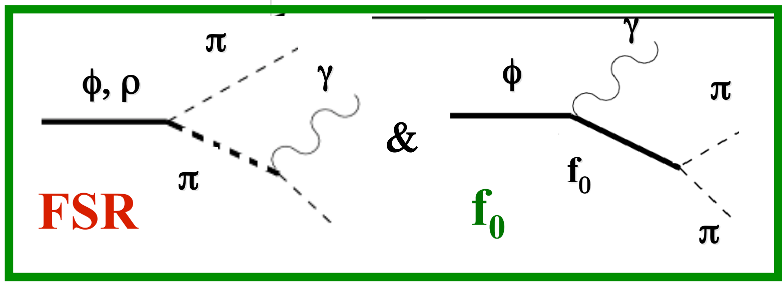
- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **γ_{ISR} photon detected (4-momentum constraints)**

- ✓ **lower signal statistics**
- ✓ **larger contribution from FSR events**
- ✓ **larger $\phi \to \pi^+\pi^-\pi^0$ background contamination**
- ✓ **irreducible background from ϕ decays ($\phi \to f_0\,\gamma \to \pi\pi\,\gamma$)**

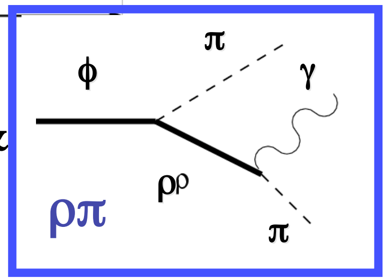
At least 1 photon with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 20$ MeV ➔ photon detected



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



&



$|F_\pi|^2$ measurement: *large angle*

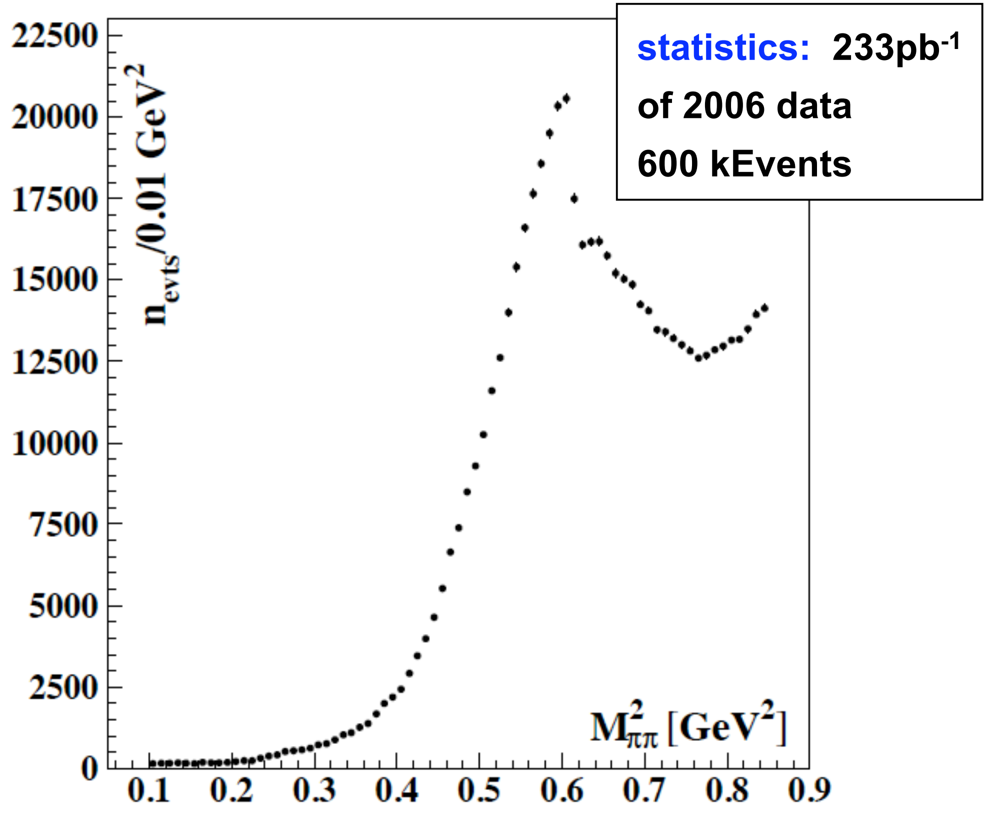
2 pion tracks at large angles
$50^o < \theta_\pi < 130^o$

Photons at large angles
$50^o < \theta_\gamma < 130^o$

- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **γ_{ISR} photon detected (4-momentum constraints)**

- ✓ **lower signal statistics**
- ✓ **larger contribution from FSR events**
- ✓ **larger $\phi \to \pi^+\pi^-\pi^0$ background contamination**
- ✓ **irreducible background from ϕ decays ($\phi \to f_0\,\gamma \to \pi\pi\,\gamma$)**

At least 1 photon with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 20$ MeV ➔ photon detected



Use data sample taken at **$\sqrt{s} \cong$ 1000 MeV**, 20 MeV below the ϕ − peak

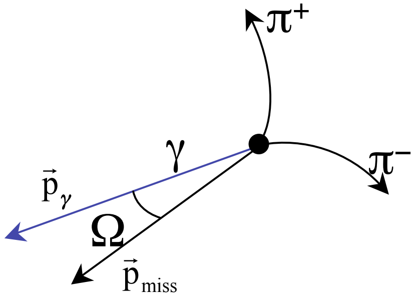
Event selection

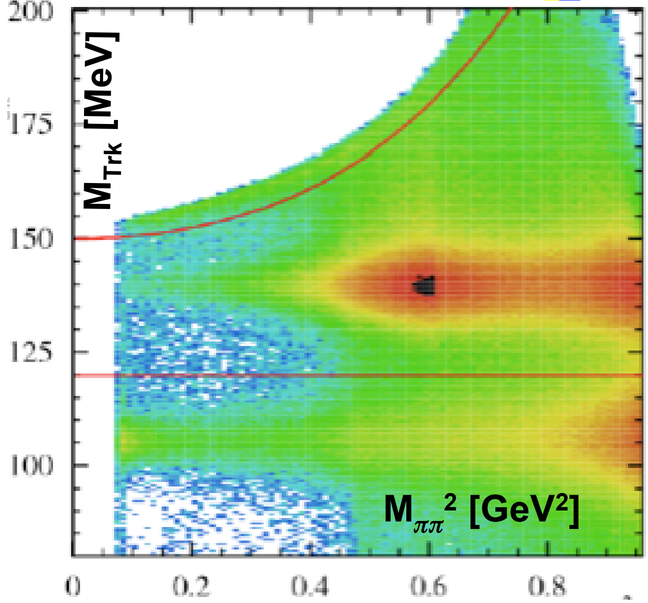
- Experimental challenge: Fight background from
  - $e^+e^- \rightarrow \mu^+\mu^- \gamma$,
  - $e^+e^- \rightarrow e^+e^- \gamma$
  - $\phi \rightarrow \pi^+\pi^-\pi^0$

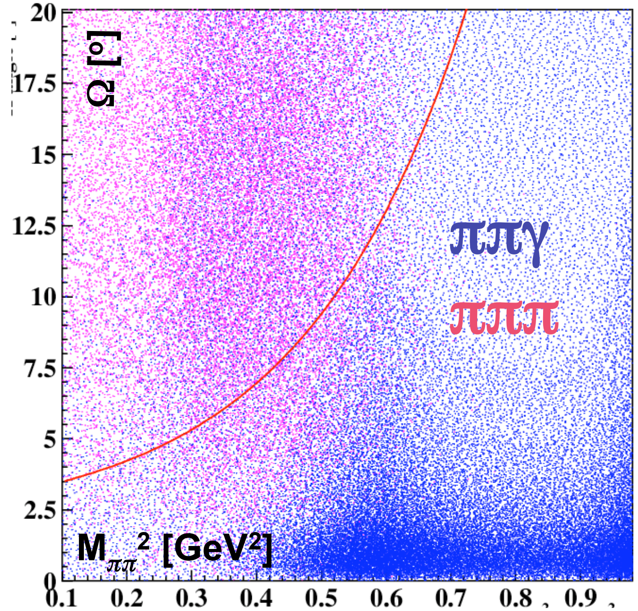
  separated by means of kinematical cuts in *trackmass* M_{Trk} (defined by 4-momentum conservation under the hypothesis of 2 tracks with equal mass and a γ)

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

and the angle Ω between the photon and the missing momentum $\vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$







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.

Luminosity:

KLOE measures *L* with Bhabha scattering

F. Ambrosino et al. (KLOE Coll.)
Eur.Phys.J.C47:589-596,2006

$55° < \theta < 125°$

acollinearity < 9°

p ≥ 400 MeV

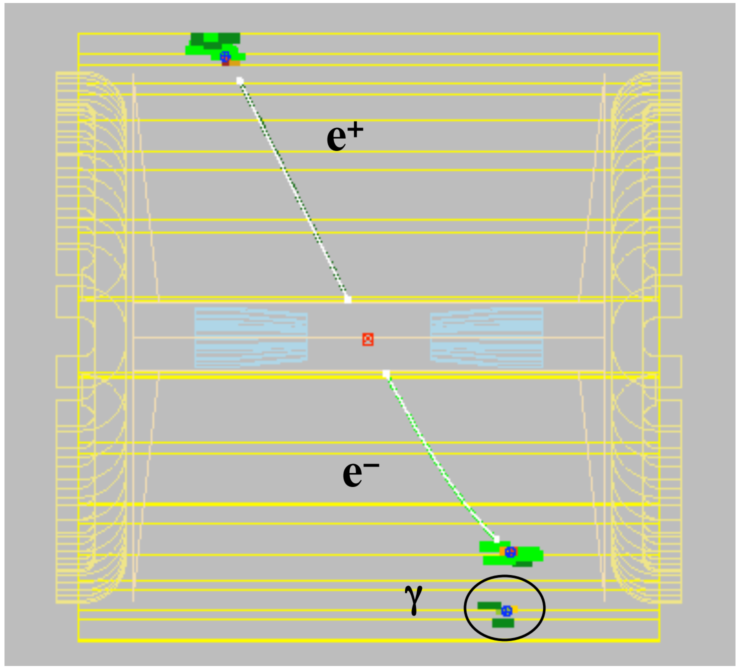
$$\int \mathcal{L}\,\mathrm{d}t = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

generator used for σ_{eff}

BABAYAGA (Pavia group):

C. M.C. Calame et al., NPB584 (2000) 459

Now: *C. M.C. Calame et al., NPB758 (2006) 22*



newer version (**BABAYAGA@NLO**) gives
0.7% decrease in cross section,
and better accuracy: 0.1%

Systematics on Luminosity	
Theory	0.1 %
Experiment	0.3 %
TOTAL 0.1 % th ⊕ 0.3% exp = 0.3%	

Radiative corrections

Radiator-Function $H(s,s_\pi)$ (ISR):

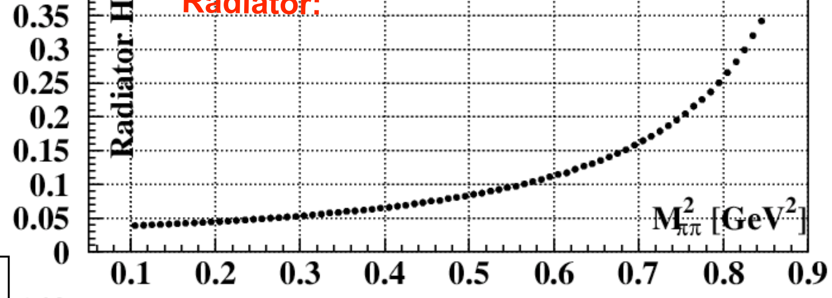
- ISR-Process calculated at NLO-level

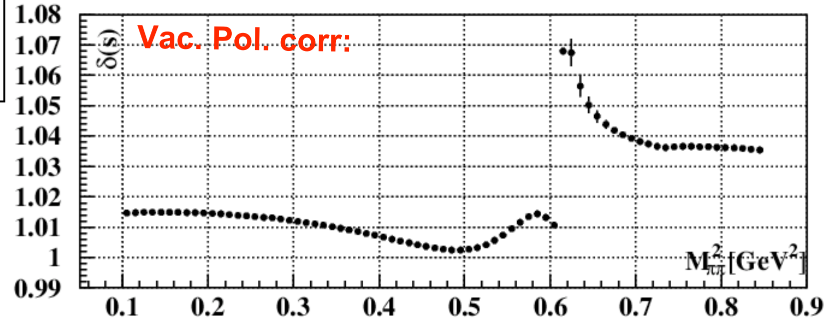
PHOKHARA generator

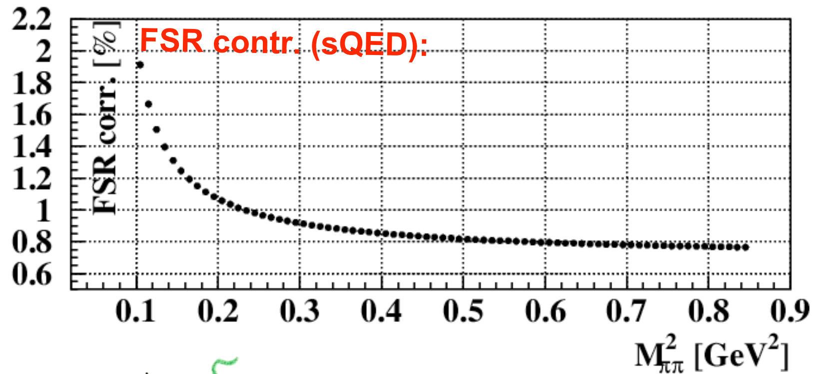
(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

Precision: *0.5%*

$$s \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi)$$







Radiative Corrections:

i) Bare Cross Section

divide by Vacuum Polarisation $\delta(s)=(\alpha(s)/\alpha(0))^2$

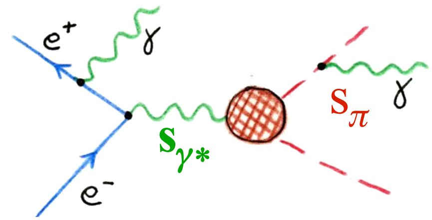
➔ from F. Jegerlehner

ii) FSR

Cross section $\sigma_{\pi\pi}$ must be incl. for FSR for use in the dispersion integral of a_μ

FSR corrections have to be taken into account in the efficiency eval. (Acceptance, M_{Trk}) and in the passage $s_\pi=M^2_{\pi\pi} \rightarrow (M^0_{\pi\pi})^2 = s_{\gamma*}$

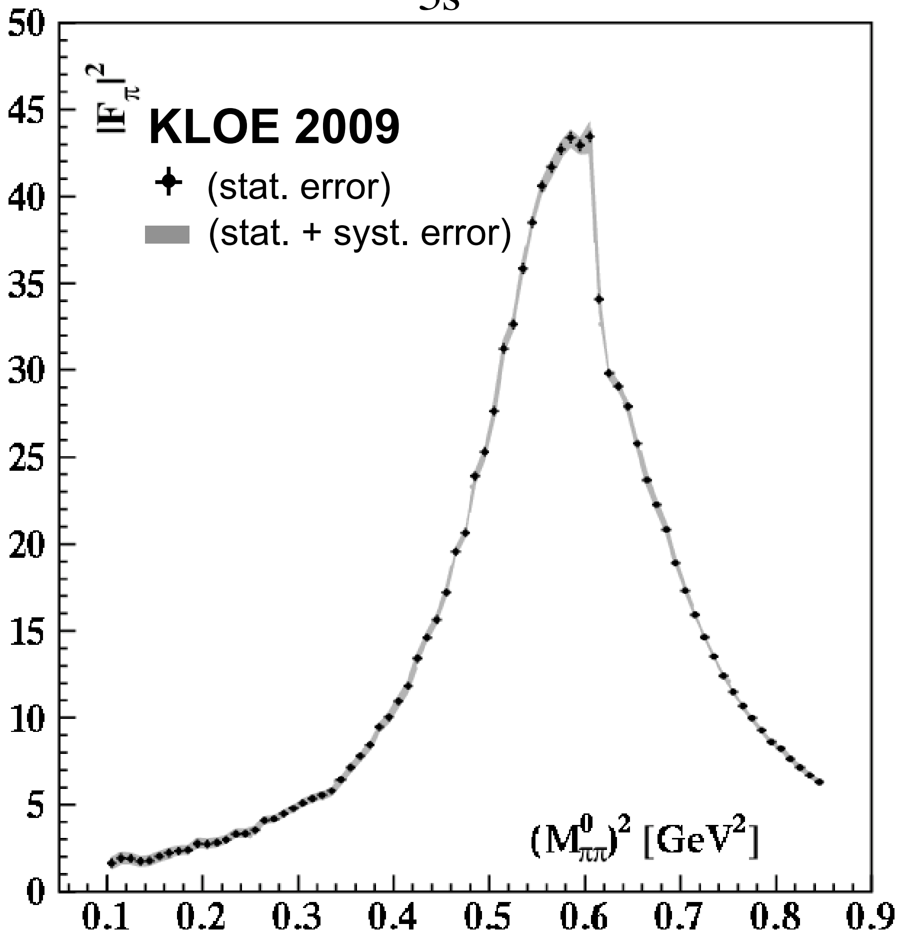
(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)



$s_{\gamma*} > s_\pi$

KLOE result on large angle 2006:

$$\sigma_{\pi\pi}(s_\pi) = \frac{\pi\alpha^2\beta_\pi^3}{3s}|F_\pi(s_\pi)|^2$$



Disp. Integral:

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{had}(s)K(s)\,ds$$

Table of systematic errors on $\Delta a_\mu^{\pi\pi}$(0.1-0.85 GeV^2):

Reconstruction Filter	< 0.1%
Background	0.5%
$f_0+\rho\pi$	0.4%
Omega	0.2%
Trackmass	0.5%
π/e-ID and TCA	< 0.1%
Tracking	0.3%
Trigger	0.2%
Acceptance	0.4%
Unfolding	negligible
Software Trigger	0.1%
Luminosity$(0.1_{th} \oplus 0.3_{exp})$%	0.3%

experimental fractional error on Δa_μ = 1.0 %

FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	< 0.1%

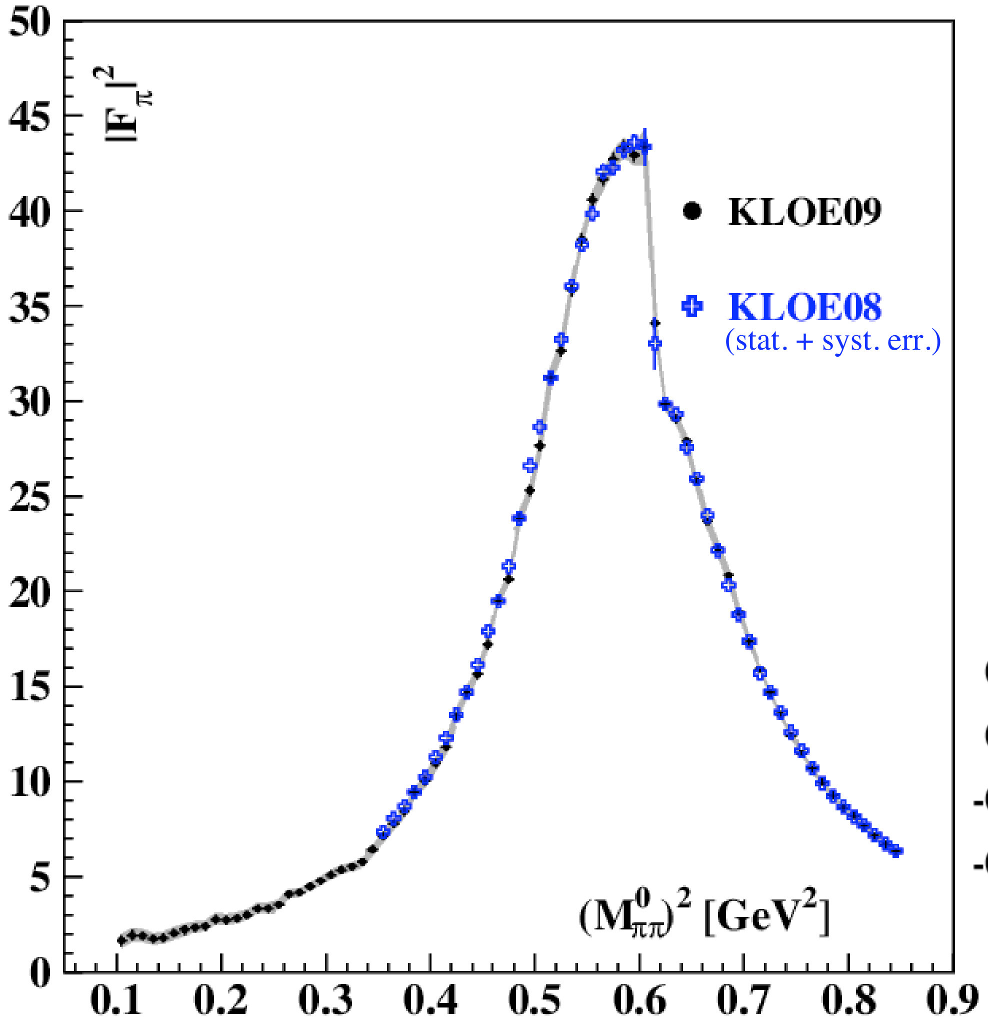
theoretical fractional error on Δa_μ = 0.6 %

$\Delta a_\mu^{\pi\pi}$(0.1-0.85 GeV^2) = (478.5 ± 2.0$_{stat}$±4.8$_{sys}$ ±2.9$_{theo}$) · 10^{-10}

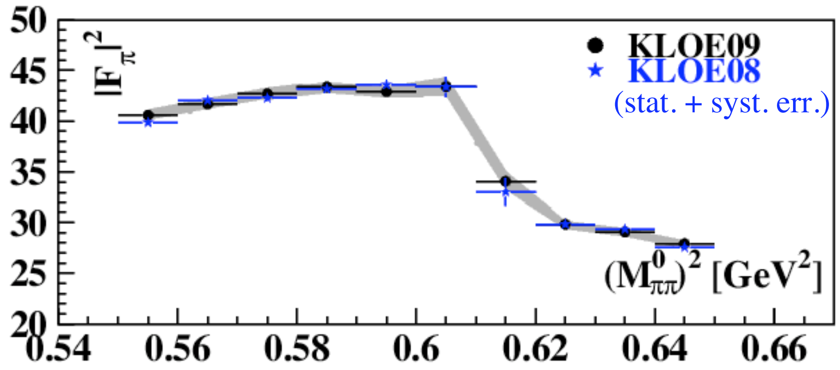
0.4% 1.0% 0.6%

Comparison of results:

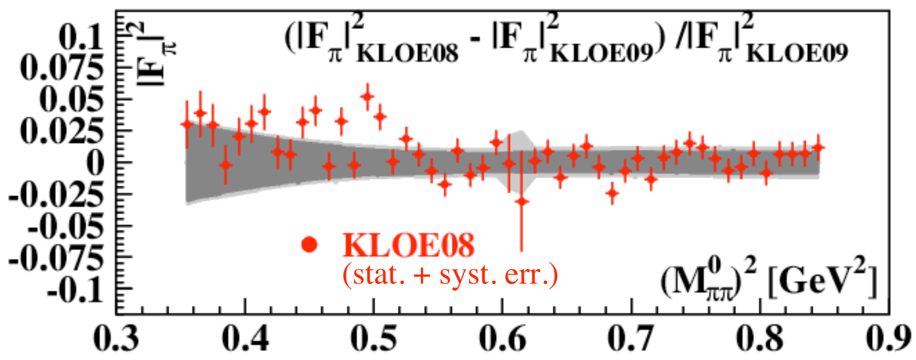
KLOE08 result compared to KLOE09:



Zoomed region around ρ-peak:



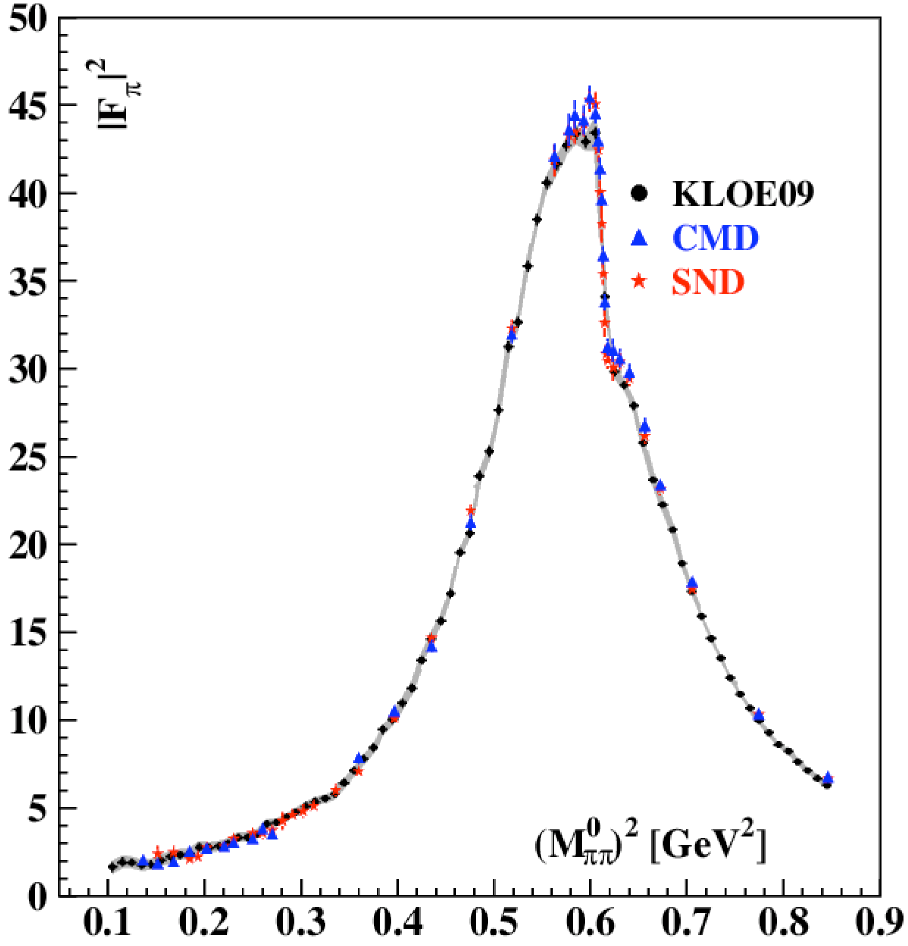
Fractional difference:



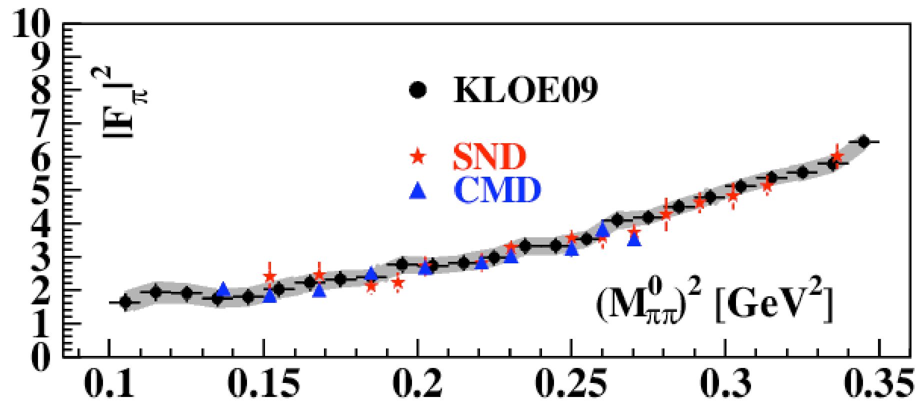
band: KLOE09 error

Comparison of results:

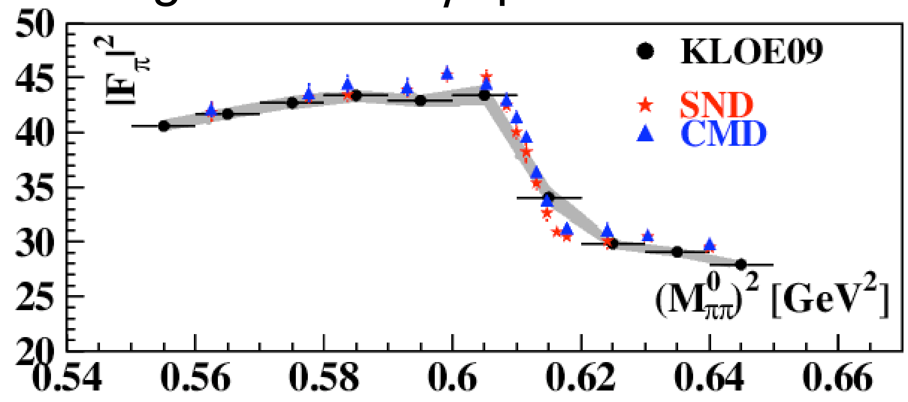
CMD and SND results compared to KLOE09:



Low $(\mathbf{M^0_{\pi\pi}})^2$: :



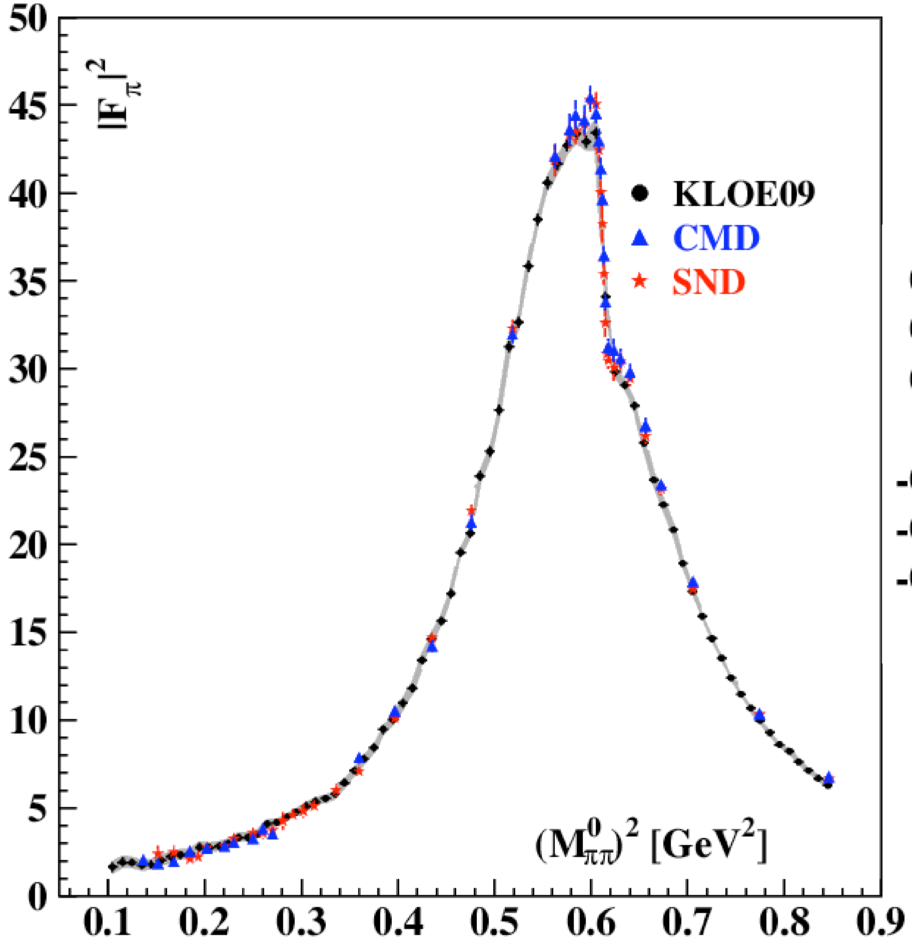
Region around ρ-peak:

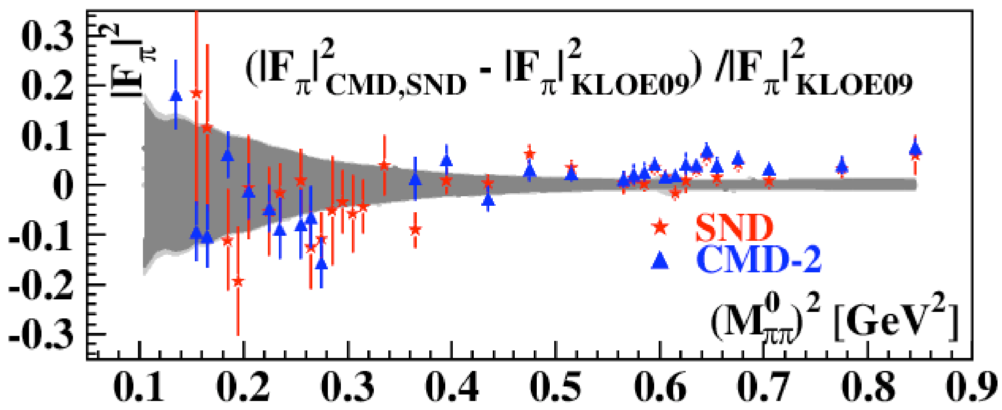


band: KLOE09 error

Comparison of results:

CMD and SND results compared to KLOE09: Fractional difference





band: KLOE09 error

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$\Delta a_\mu^{\pi\pi}$(0.35-0.85GeV²):

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{\text{had}}(s)\mathrm{K}(s)\,\mathrm{d}s$$

KLOE08 (small angle) — $a_\mu^{\pi\pi} = (379.6 \pm 0.4_{stat} \pm 2.4_{sys} \pm 2.2_{theo}) \cdot 10^{-10}$

KLOE09 (large angle) — $a_\mu^{\pi\pi} = (376.6 \pm 0.9_{stat} \pm 2.4_{sys} \pm 2.1_{theo}) \cdot 10^{-10}$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{had}(s) K(s) \, ds$$

$\Delta a_\mu^{\pi\pi}$(0.35-0.85GeV²):

KLOE08 (small angle) $a_\mu^{\pi\pi} = (379.6 \pm 0.4_{stat} \pm 2.4_{sys} \pm 2.2_{theo}) \cdot 10^{-10}$

KLOE09 (large angle) $a_\mu^{\pi\pi} = (376.6 \pm 0.9_{stat} \pm 2.4_{sys} \pm 2.1_{theo}) \cdot 10^{-10}$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$(0.152-0.270 GeV²):

KLOE09 (large angle) $a_\mu^{\pi\pi} = (48.1 \pm 1.2_{stat} \pm 1.2_{sys} \pm 0.4_{theo}) \cdot 10^{-10}$

CMD-2 $a_\mu^{\pi\pi} = (46.2 \pm 1.0_{stat} \pm 0.3_{sys}) \cdot 10^{-10}$

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$\Delta a_\mu^{\pi\pi}$(0.35-0.85GeV²):

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{had}(s) K(s) \, ds$$

KLOE08 (small angle) — $a_\mu^{\pi\pi} = (379.6 \pm 0.4_{stat} \pm 2.4_{sys} \pm 2.2_{theo}) \cdot 10^{-10}$

KLOE09 (large angle) — $a_\mu^{\pi\pi} = (376.6 \pm 0.9_{stat} \pm 2.4_{sys} \pm 2.1_{theo}) \cdot 10^{-10}$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$(0.152-0.270 GeV²):

KLOE09 (large angle) — $a_\mu^{\pi\pi} = (48.1 \pm 1.2_{stat} \pm 1.2_{sys} \pm 0.4_{theo}) \cdot 10^{-10}$

CMD-2 — $a_\mu^{\pi\pi} = (46.2 \pm 1.0_{stat} \pm 0.3_{sys}) \cdot 10^{-10}$

$\Delta a_\mu^{\pi\pi}$(0.397-0.918 GeV²):

KLOE08 (small angle) — $a_\mu^{\pi\pi} = (356.7 \pm 0.4_{stat} \pm 3.1_{sys}) \cdot 10^{-10}$

CMD-2 — $a_\mu^{\pi\pi} = (361.5 \pm 1.7_{stat} \pm 2.9_{sys}) \cdot 10^{-10}$

SND — $a_\mu^{\pi\pi} = (361.0 \pm 2.0_{stat} \pm 4.7_{sys}) \cdot 10^{-10}$

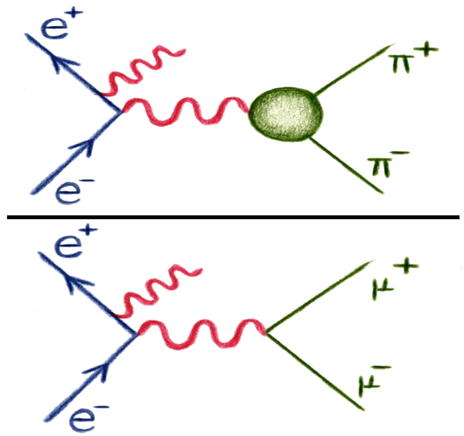
PLB670 (2009) 285

Good agreement in $\Delta a_\mu^{\pi\pi}$ for different experiments

Future $\sigma_{\pi\pi}$ measurement: π/μ

An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

$$|F_\pi(s')|^2 \approx \underbrace{\frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3}}_{\text{kinematical factor } (\sigma_{\mu\mu}^{\text{Born}}/\sigma_{\pi\pi}^{\text{Born}})} \underbrace{\frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}}_{\text{meas. quantities}}$$

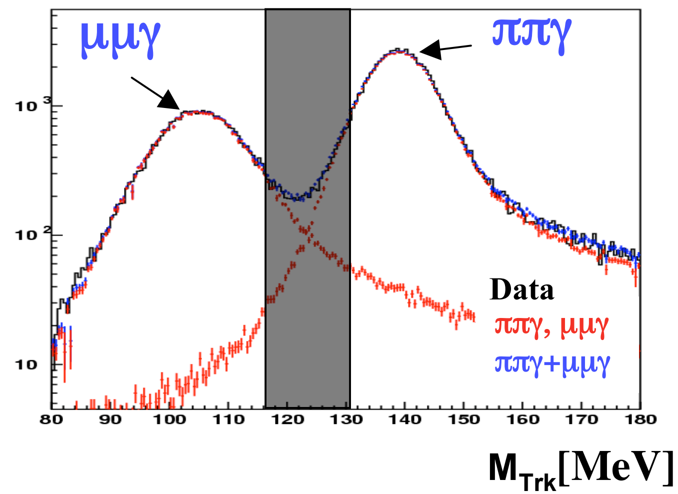


Many radiative corrections drop out:

- *radiator function*
- *int. luminosity from Bhabhas*
- *Vacuum polarization*

Separation between pions and muons done experimentally using kinematical cuts:

- *muons:* $M_{Trk} < 115$ *MeV*
- *pions :* $M_{Trk} > 130$ *MeV*



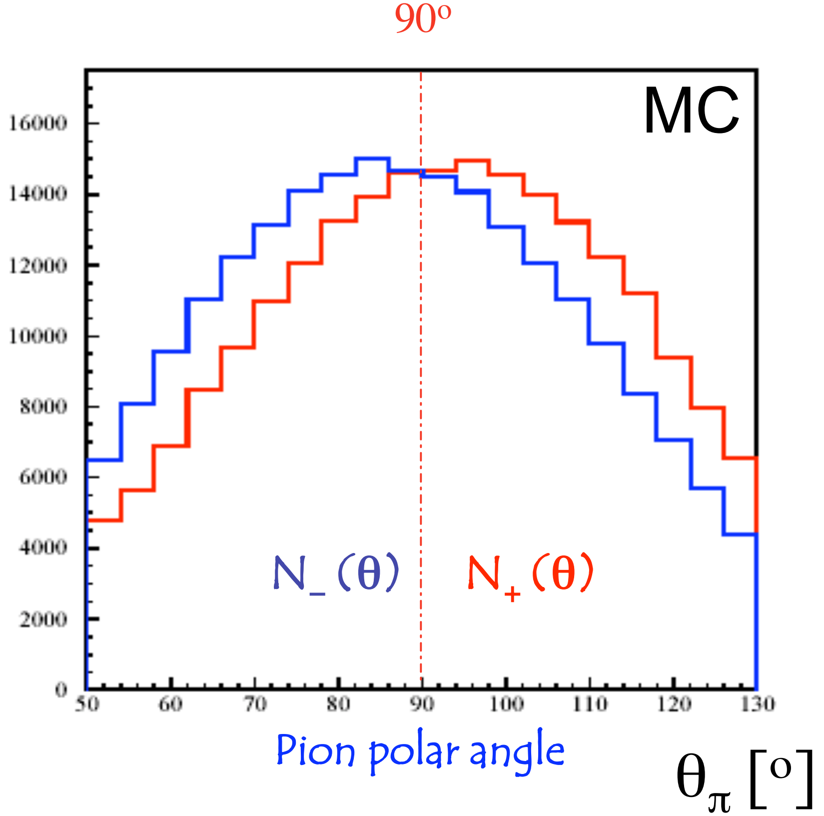
Forward-backward asymmetry:

In the case of a non-vanishing FSR contribution, the interference term between ISR and FSR is odd under exchange $\pi^+ \leftrightarrow \pi^-$ .This gives rise to a non-vanishing ***asymmetry***:

Binner, Kühn, Melnikov, Phys. Lett. B 459, 1999

Forward-backward asymmetry:

$$A = \frac{N(\theta^+ > 90^o) - N(\theta^+ < 90^o)}{N(\theta^+ > 90^o) + N(\theta^+ < 90^o)}$$



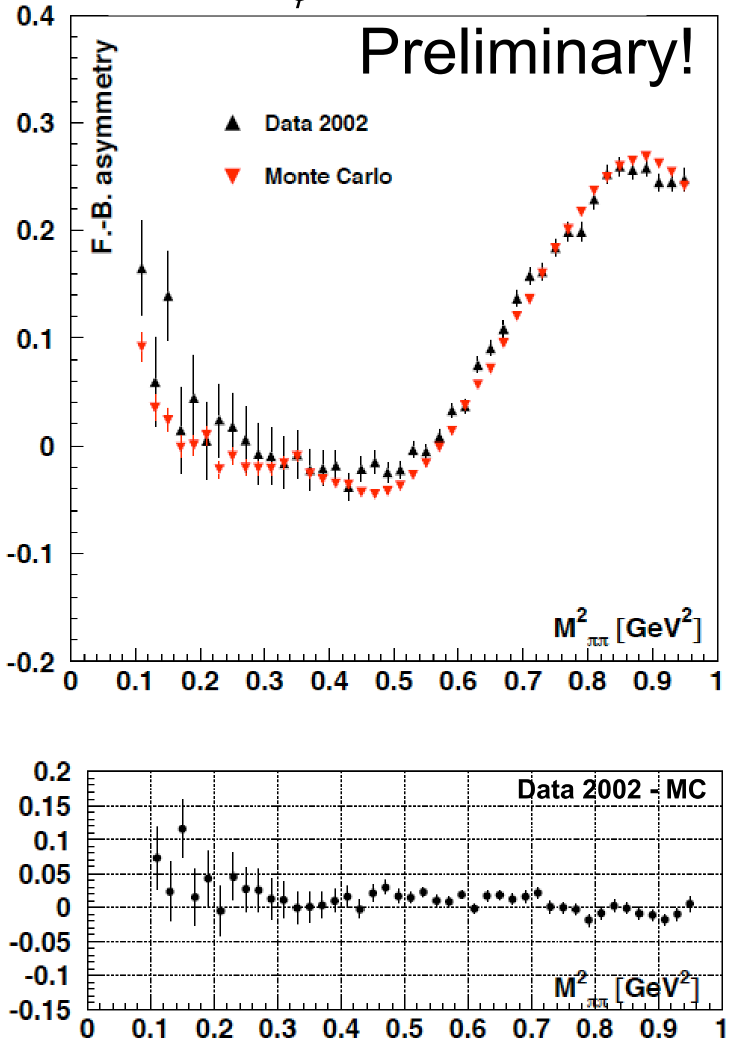
Ideal tool to test the validity of models used in Monte Carlo to describe the pionic final state radiation (point-like pion assumption, RχT, etc.)

In a similar way like FSR, radiative decays of the ϕ into scalar mesons decaying to $\pi^+\pi^-$ also contribute to the asymmetry.

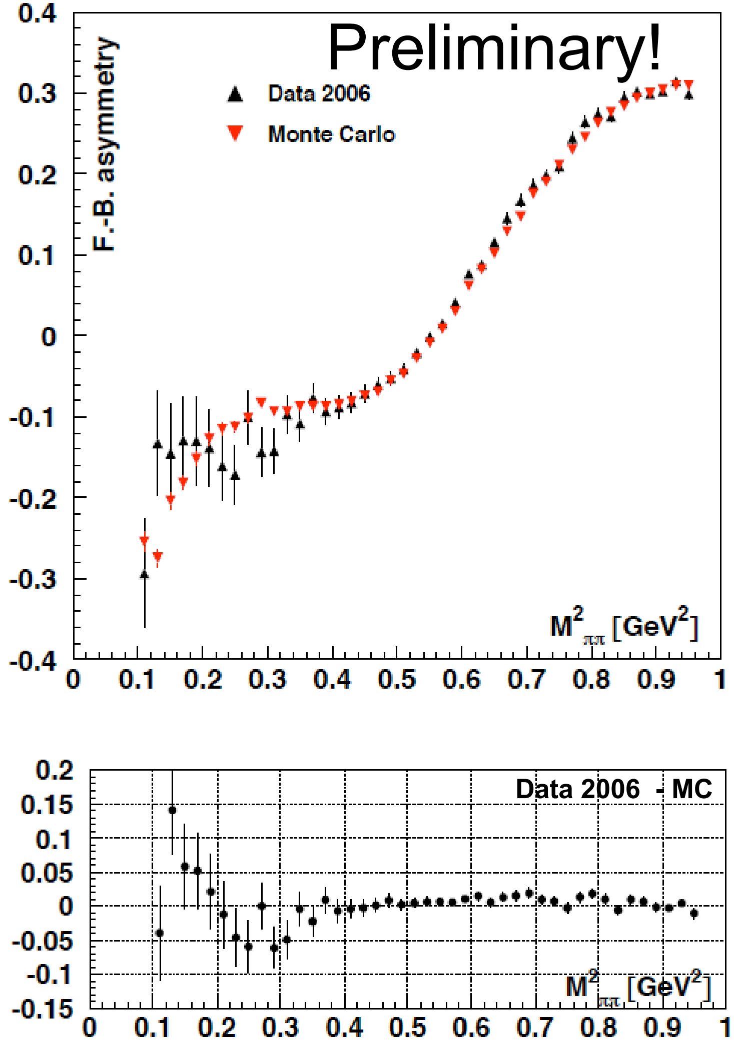
Czyz, Grzelinska, Kühn, hep-ph/0412239

Forward-backward asymmetry:

$\sqrt{s} = m_{\phi} \approx 1.0195$ GeV



$\sqrt{s} \approx 1.000$ GeV



PHOKHARA-MC modified by O. Shekhovtsova using Kaon-Loop-Model used in KLOE analysis of $\pi^0\pi^0\gamma$ final state (Talk of P. Gauzzi yesterday and **EPJC49(2007)473**)

Conclusions:

The KLOE experiment has used the radiative return to determine the pion form factor between 0.1 - 0.85 GeV^2:

- *In the overlap-region 0.35 -0.85 GeV^2, the result is in very good agreement with the previous KLOE result (KLOE08, PLB670 (2009) 285)*
- *Reasonable agreement with results from CMD-2 and SND data (especially at low $M_{\pi\pi}^2$)*
- *Good agreement in $\Delta a_\mu^{\pi\pi}$ with KLOE08 and CMD-2 results*

The new KLOE result for the large angle analysis using off-peak data is final, and will be published very soon.

Ongoing KLOE activities:

- *Measurement of the pion form factor with muon normalisation*
- *Study of charge asymmetry to determine model parameters of scalar mesons and FSR*