Measurement of the hadronic cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with KLOE detector at DAΦNE

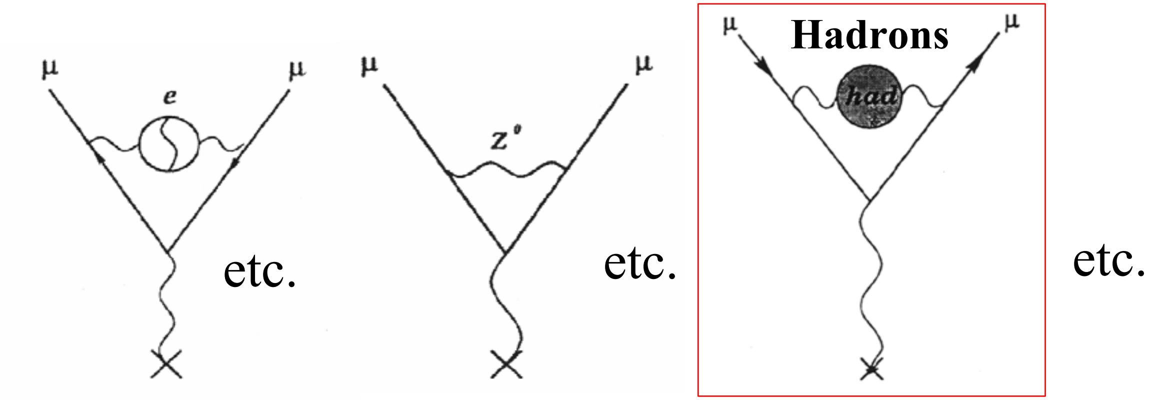
Paolo Beltrame
Institut für Exp. Kernphysik,
Universität Karlsruhe

(for the KLOE collaboration)

Spring School

Frascati, 16 - 20 May 2005

$(g\text{-}2)_\mu$ & dispersion integral



a_μ^{QED} + a_μ^{weak} + a_μ^{had}

a_μ^{had} can be expressed in terms of $\sigma(e^+e^- \rightarrow \text{hadrons})$ by the use of a **dispersion integral**:

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

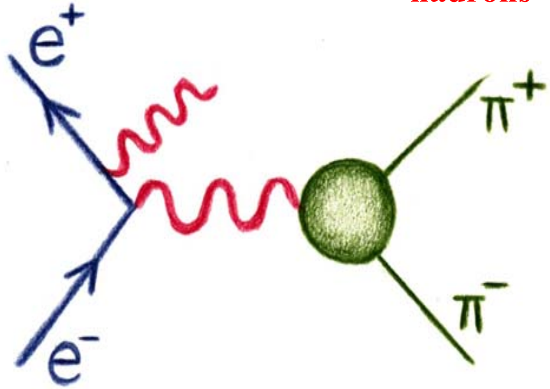
The region around the energy of the ρ-meson adds with ca. 67% to the total value of a_μ^{hadr}.
[Jegerlehner; hep-ph/0312372]

The ρ-meson decays to 100% in $\pi^+\pi^-$,
so in this energy region the analysis efforts concentrate on the determination of $\sigma(e^+e^- \longrightarrow \pi^+\pi^-)$

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

Particle factories have the opportunity to measure the cross section **$\sigma(e^+ e^- \longrightarrow$ hadrons)** as a function of the hadronic center of mass energy **$M^2_{hadrons}$** by using the

RADIATIVE RETURN



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

This method is a complementary approach to the standard energy scan

It requires precise calculations of the radiator ***H***.

➔ ***EVA + PHOKHARA* MC Generator**

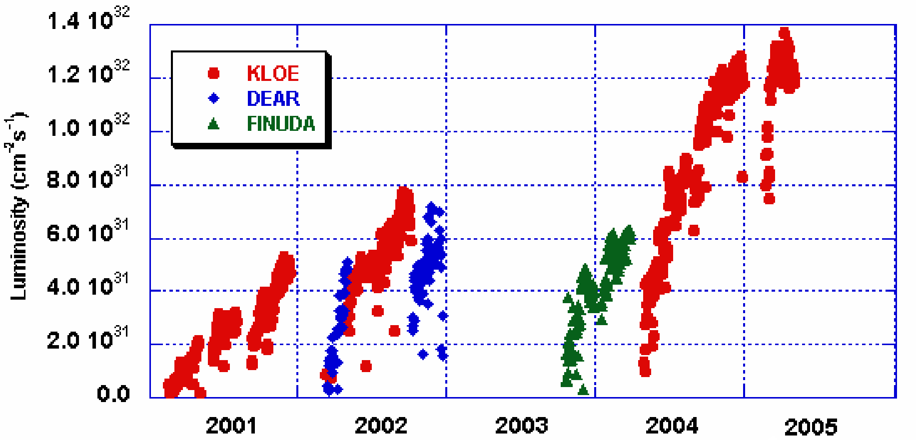
(S. Binner, J.H. Kühn, K. Melnikov, Phys. Lett. B 459, 1999)

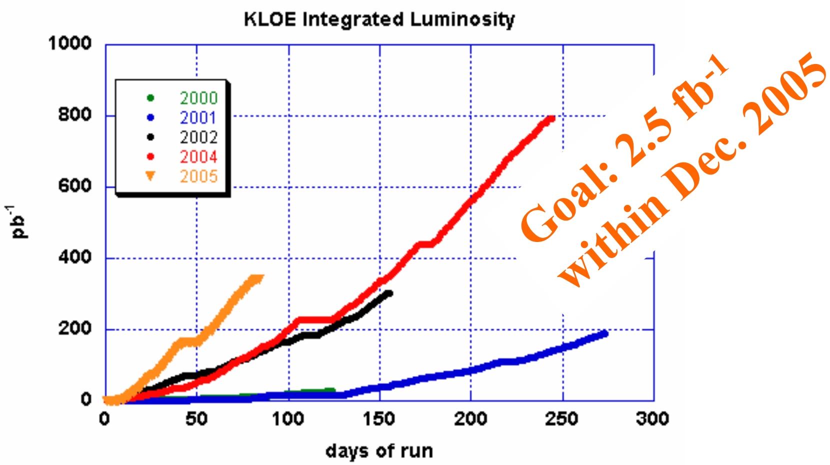
(H. Czyz, A. Grzelinska, J.H. Kühn, G. Rodrigo, hep-ph/0308312)

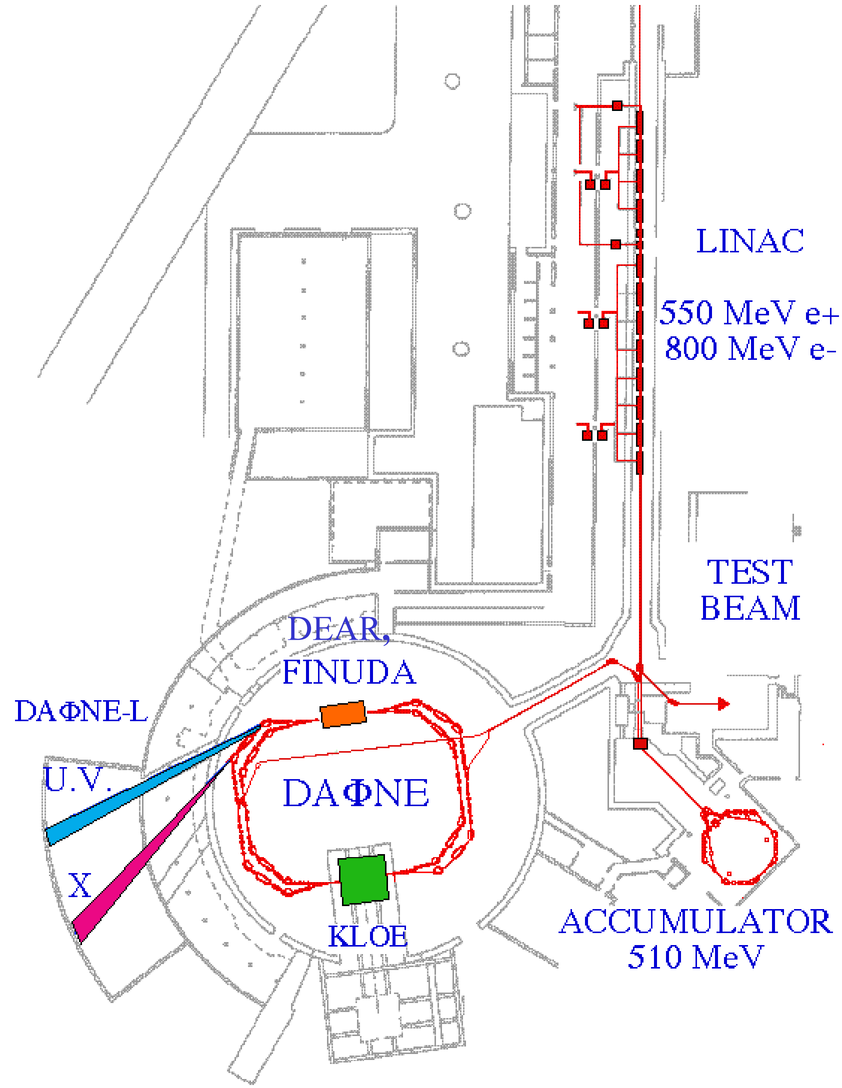
DAΦNE: A Φ-Factory

(**D**ouble **A**nnular **Φ**-Factory for **N**ice **E**xperiments)

e^+e^- - collider with $\sqrt{s} = m_\phi \approx 1.0194$ GeV

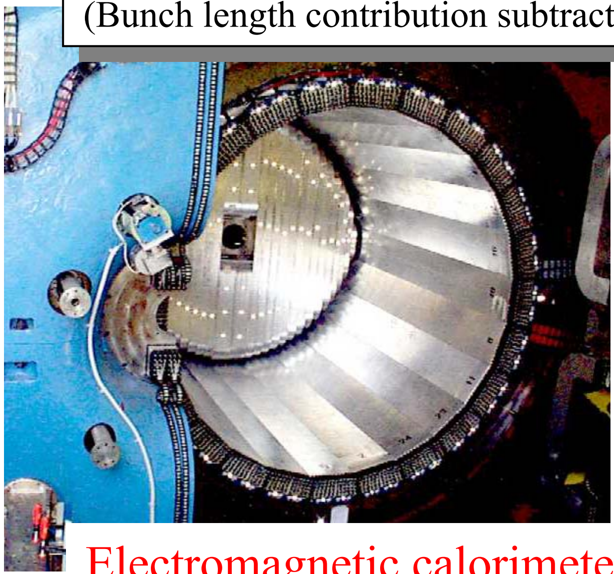






KLOE

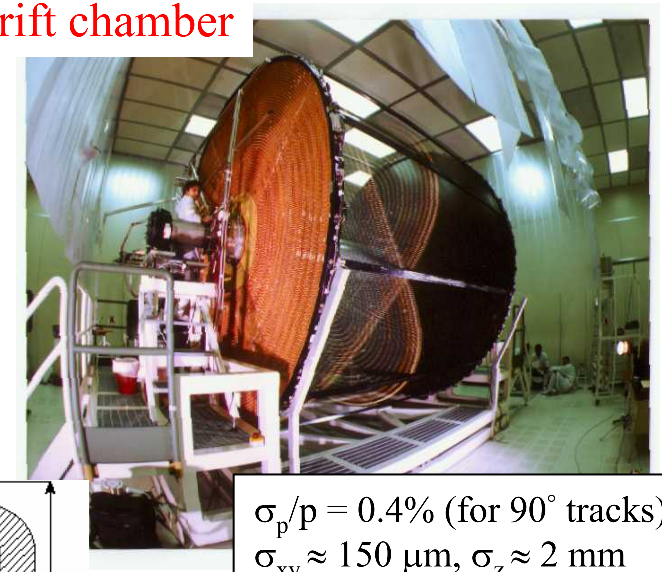
$\sigma_E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
$\sigma_T = 54\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 50\ \mathrm{ps}$
(Bunch length contribution subtracted from constant term)



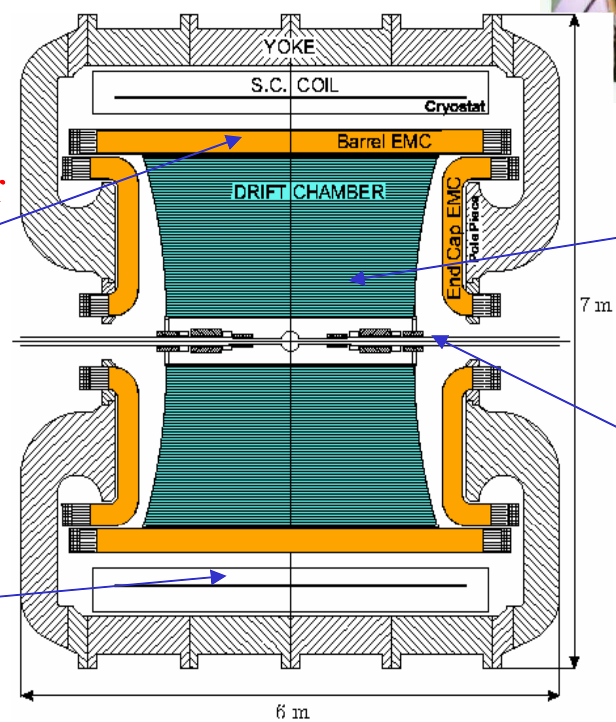
Electromagnetic calorimeter

(**KLO**ng **E**xperiment)

Drift chamber



$\sigma_p/p = 0.4\%$ (for 90° tracks)
$\sigma_{xy} \approx 150\ \mu\mathrm{m}$, $\sigma_z \approx 2$ mm



EM Calorimeter:
Lead/Scintillating fibres
4880 PM

Drift chamber:
12582 Sense Wires
52140 wires in total

Beryllium Beampipe:
R=10 cm, 0.5 mm thick

Magnet:
Superconducting coil (B=0.52 T)

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

I. Small photon angle analysis

II. Large photon angle analysis

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ @ KLOE (I)

I. Small photon angle analysis

II. Large photon angle analysis

Small angle analysis

Pion tracks are measured at angles
$50^o < \theta_\pi < 130^o$

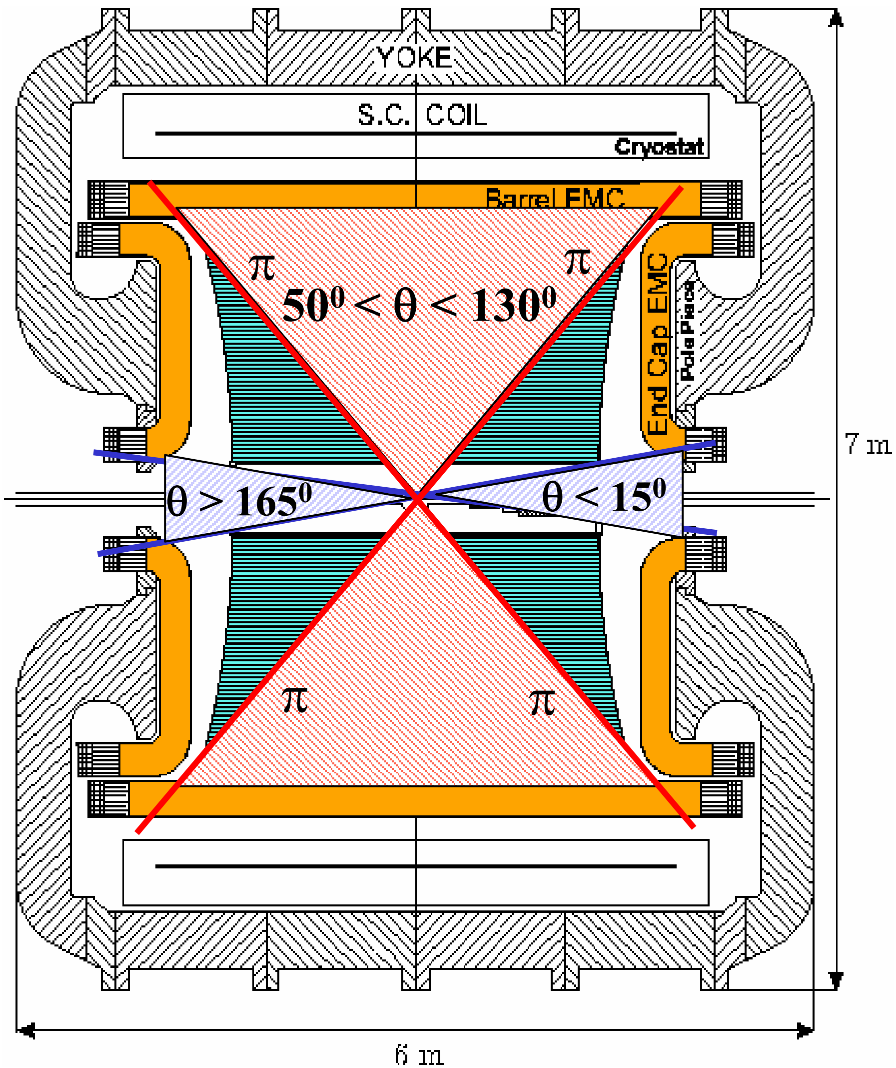
Photons are required to be within
$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

Untagged **measurement in which we cut on the direction of the missing momentum**

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

The choice of this kinematical region was motivated by:

- **small relative contribution of FSR**
- **reduced background contamination:**
  - $e^+e^- \to e^+e^-\gamma$
  - $e^+e^- \to \mu^+\mu^-\gamma$
  - $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$



Background subtraction I

Pion-Electron-Separation

Radiative Bhabhas $\mathbf{e^+e^- \rightarrow e^+e^-}\,\gamma$ are separated by means of a **Likelihood-Method** (Signature of EMC-Cluster and TOF of particle tracks)

Kinematic Separation

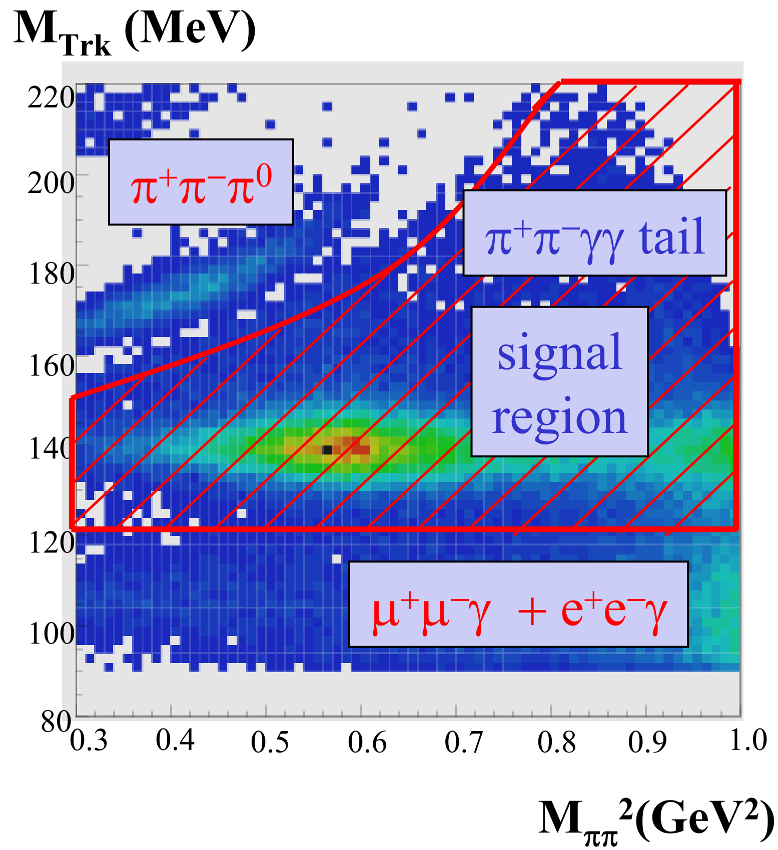
$\phi \rightarrow \pi^+\pi^-\pi^0$

$e^+e^- \rightarrow \mu^+\mu^-\gamma$

using **„Trackmass“**-variable

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

$M_{\pi\pi}$ – dependent M_{TRK}-Cut



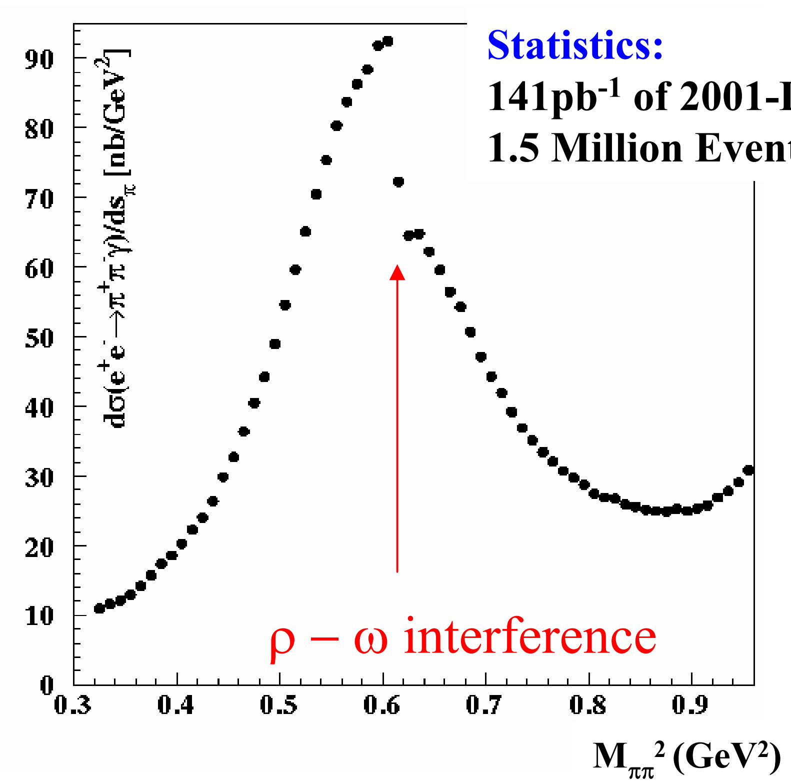
Residual Background

Fit Trackmass-Spectra for signal and background with free normalization parameters (shape from MC)

$\sigma(e^+e^- \to \pi^+\pi^-\gamma) \Rightarrow \sigma(e^+e^- \to \pi^+\pi^-)$ I

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

- Luminosity from Bhabha events ($55° < \theta_{+,-} < 125°$) 0.6% of systematic error
- All the efficiencies from DATA but Trackmass and geometrical acceptance



Radiator-Function H(s) (ISR):

ISR-Process calculated at NLO-level

Generator ***PHOKHARA*** *(Kühn et.al)*

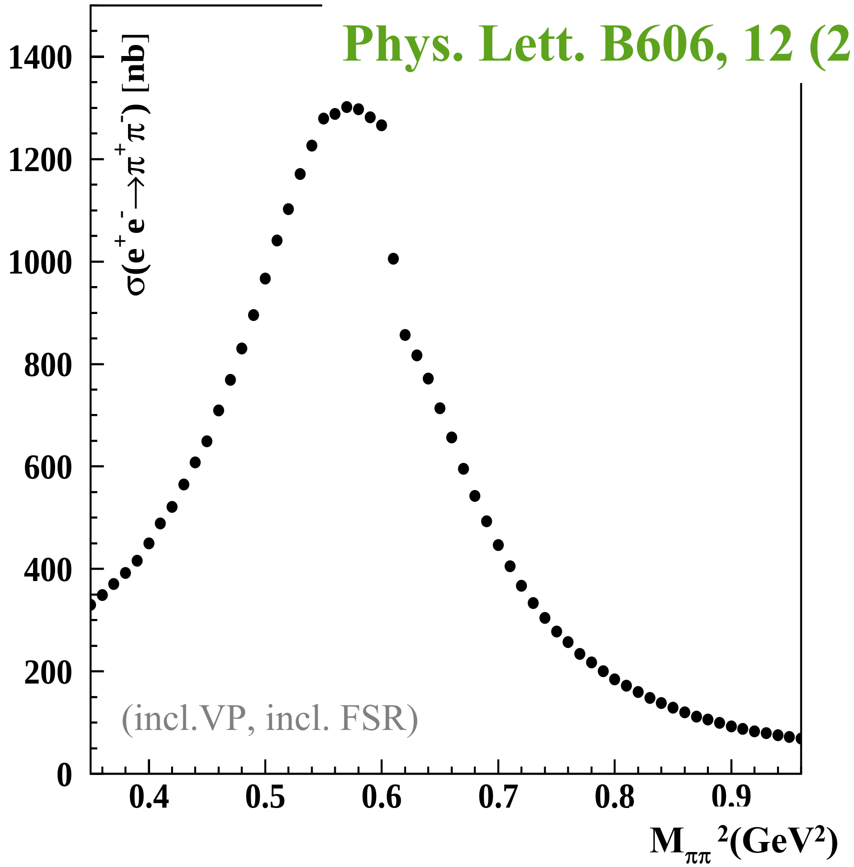
$$M^2_{\pi\pi} \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s) \times \mathbf{H(s)}$$

→ **Cross Section $e^+e^- \to \pi^+\pi^-$**

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

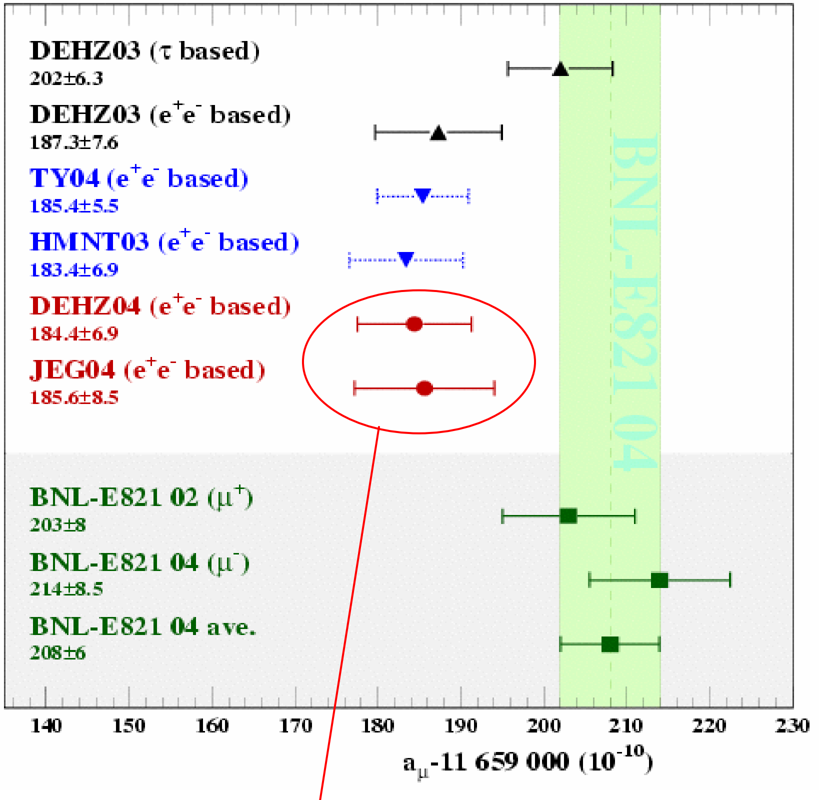
Result: Cross Section $\sigma(e^+e^- \to \pi^+\pi^-)$

Phys. Lett. B606, 12 (2005)



TOTAL syst. ERROR 1.3%

Muon anomaly@ICHEP04:



Including KLOE

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ @ KLOE (II)

I. Small photon angle analysis

II. Large photon angle analysis

$\sigma(e^+e^- \to \pi^+\pi^-)$ @ KLOE (II)

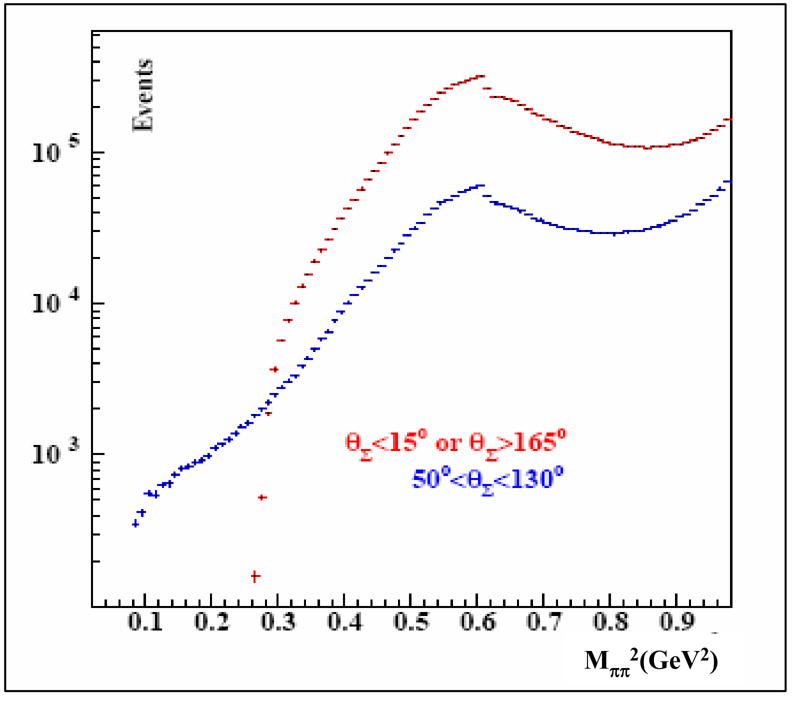
II. Large photon angle analysis

Motivation:

- Only at large photon angles can the threshold mass region be reached

But...

- **STATISTICS** become an issue (different from small angle analysis)
- Relative amount of **FSR** is very large, also $\pi^+\pi^-\pi^0$**-BACKGROUND.**



Large angle analysis

Pion tracks are measured at angles
$50^o < \theta_\pi < 130^o$

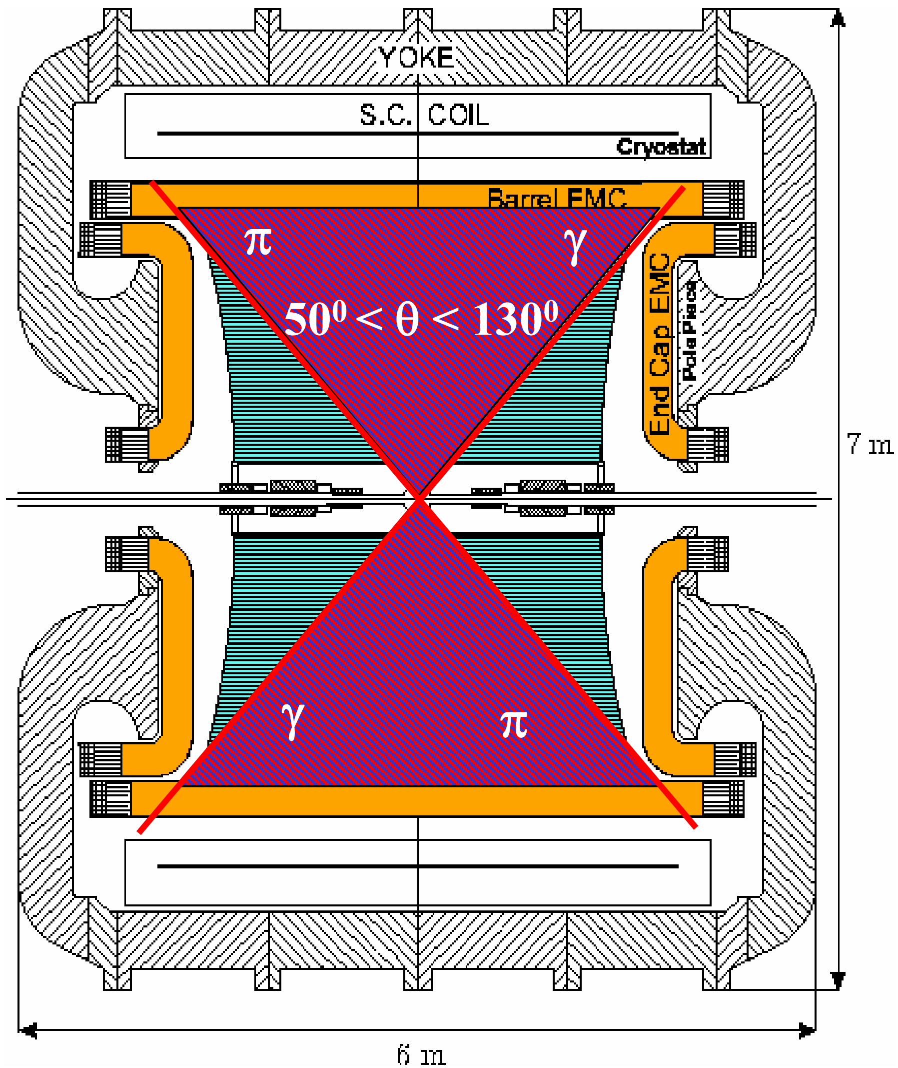
Photon direction is required to be within
$50^o < \theta_\gamma < 130^o$

In this region, the photons can be detected ⇒ *tagged* measurement!

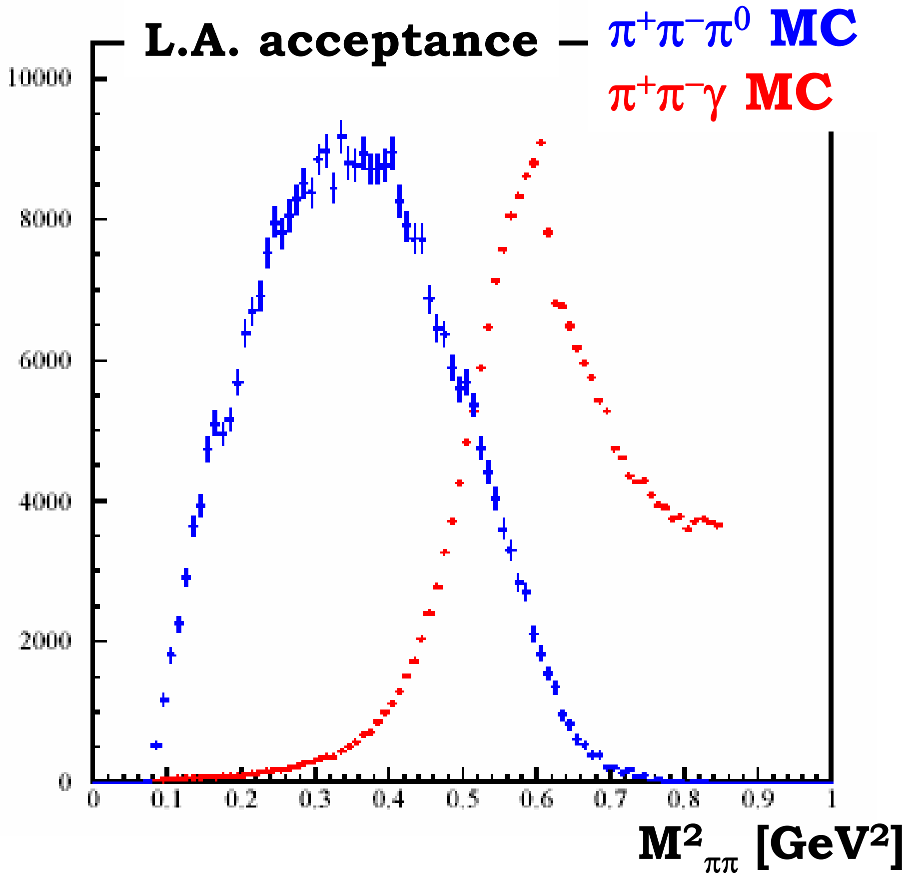
Event gets selected if at least one photon is detected with

$E_\gamma > 50$ MeV
$50^o < \theta_\gamma < 130^o$

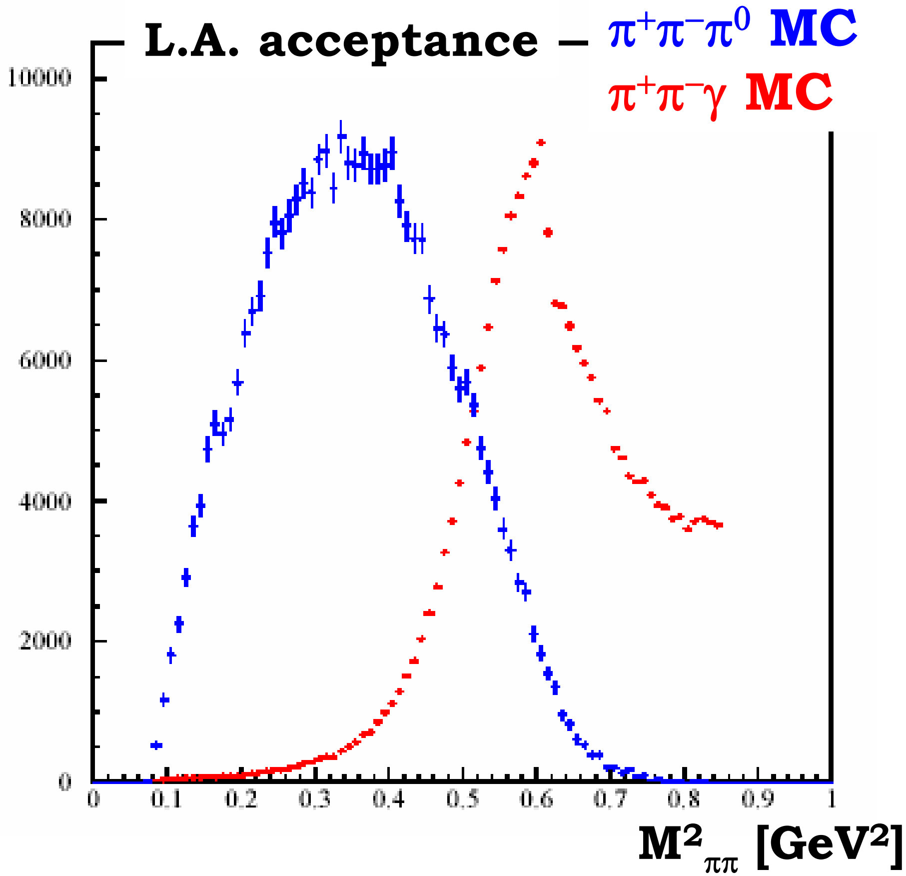
In case of more than 1 photon, choose the one with smallest angle Ω between the directions of θ_{miss} and θ_γ



$\pi^+\pi^-\pi^0$ background II



$\pi^+\pi^-\pi^0$ background II



Kinematic fit
(in $\pi^+\pi^-\pi^0$ hypothesis)

Trackmass cut

Ω cut

$$\Omega = a\cos\left(\frac{\vec{p}_\gamma \cdot \vec{p}_{miss}}{|\vec{p}_\gamma||\vec{p}_{miss}|}\right)$$

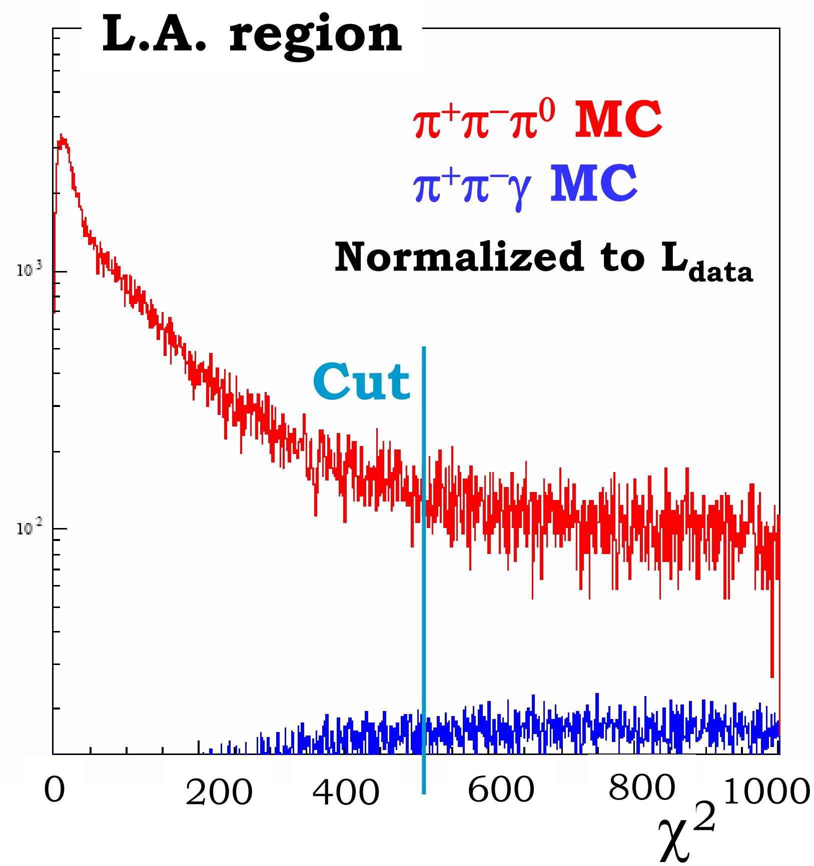
$\pi^+\pi^-\pi^0$ background II

Kinematic fit
(in $\pi^+\pi^-\pi^0$ hypothesis)

Kinematic fit in the hypothesis of background channel $\pi^+\pi^-\pi^0$
Idea: **reject events with low values of χ^2**

Selection:
- 2 tracks in $40° < \theta_\pi < 140°$
- ≥ 2 „prompt” photons
- at least one photon with
  $E_\gamma > 40$ MeV and $40° < \theta_\gamma < 140°$

Constraints:
4-momenta conservation +
$M_{inv}(\gamma\gamma) = m_{\pi 0}$

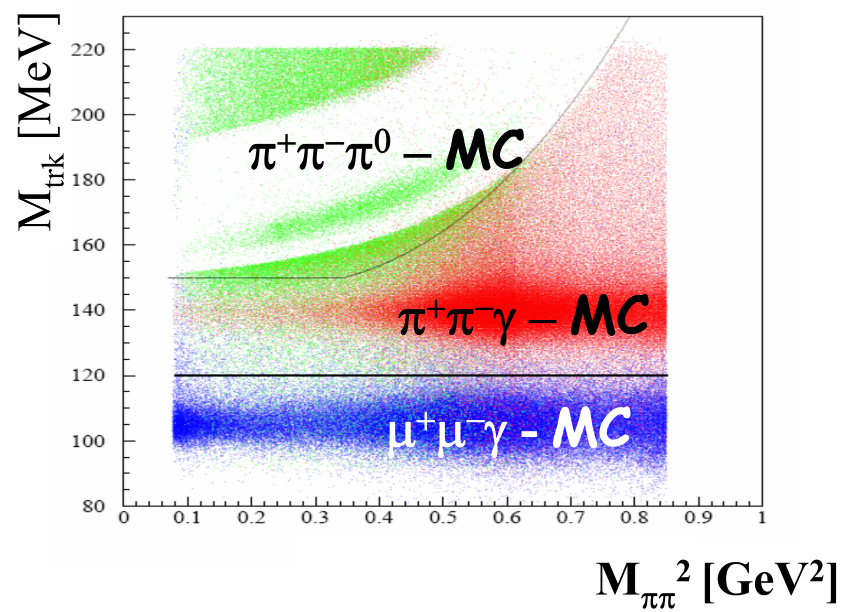


Cut has a negligible inefficiency for the $\pi\pi\gamma$ signal and rejects ca. 40% of $\pi^+\pi^-\pi^0$ events

$\pi^+\pi^-\pi^0$ background II

Trackmass cut

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



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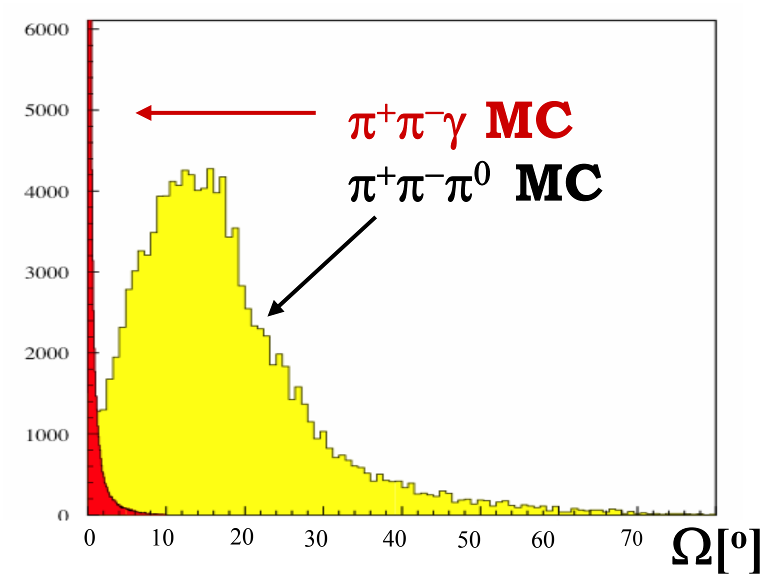
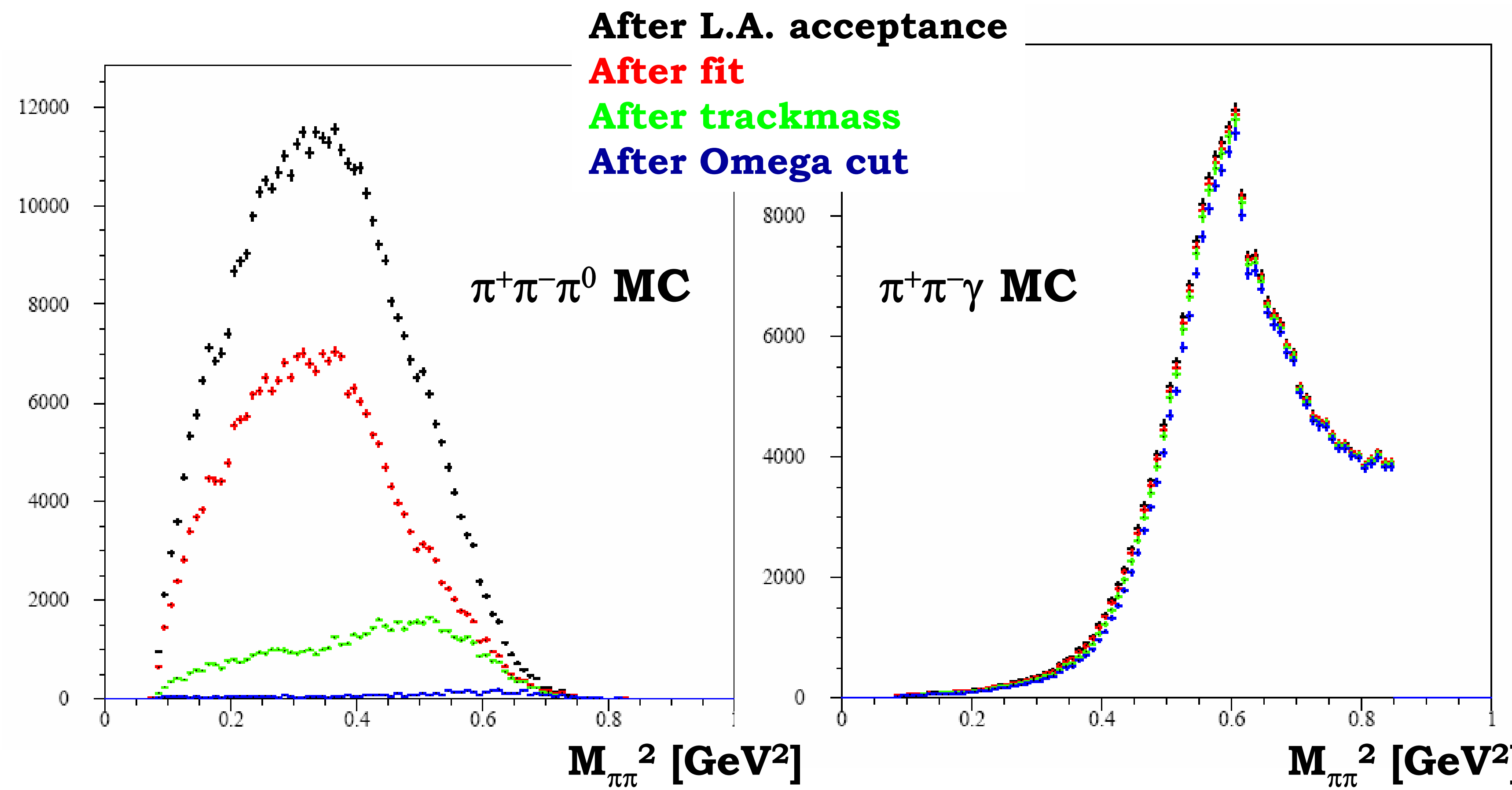


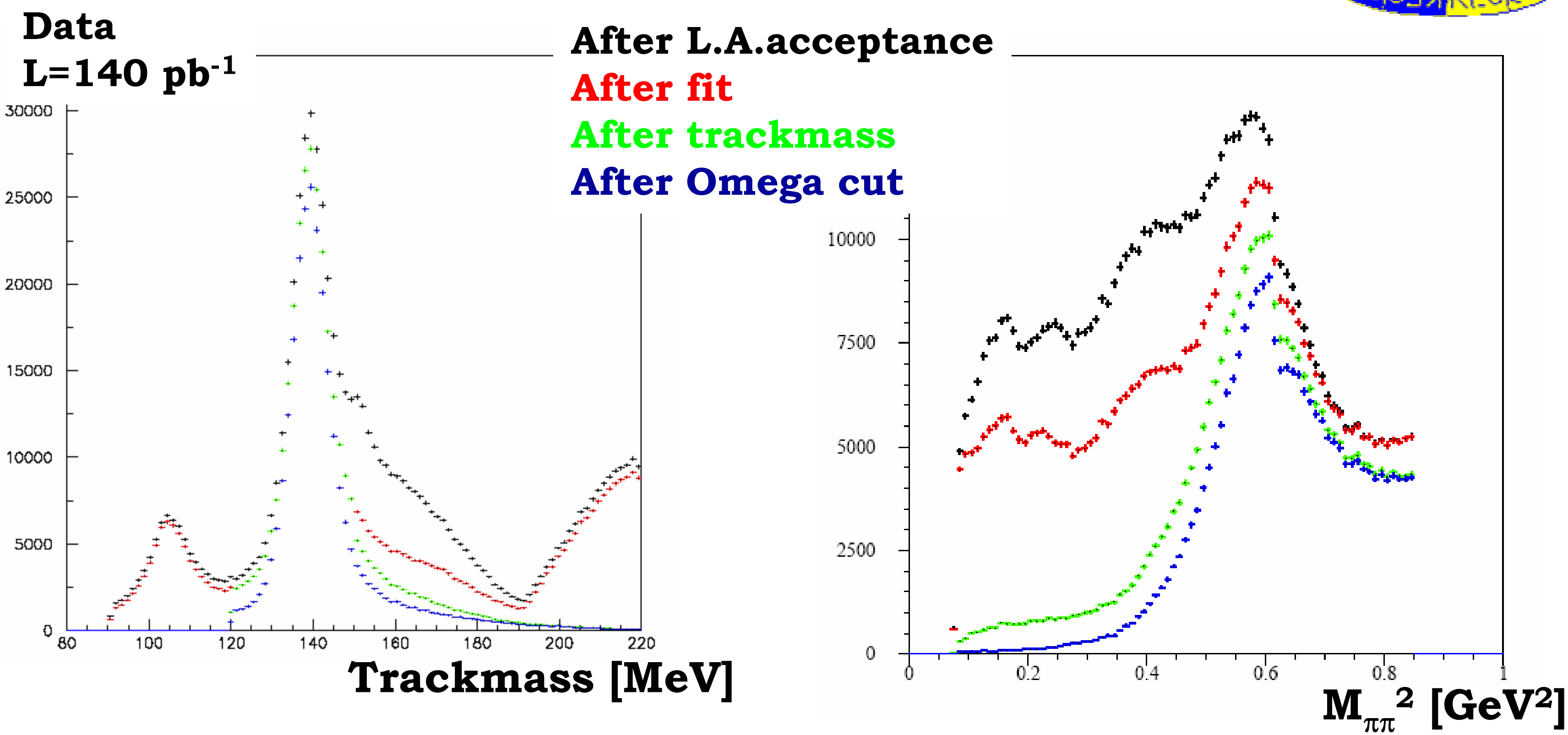
Inclusive in $M_{\pi\pi}^2$:
The cut applied is $M_{\pi\pi}^2$-dependent
below 0.5 GeV^2: $\Omega < \approx 1°$

Effect of cuts on MC

II



Effect of cuts on DATA II



We have studied:

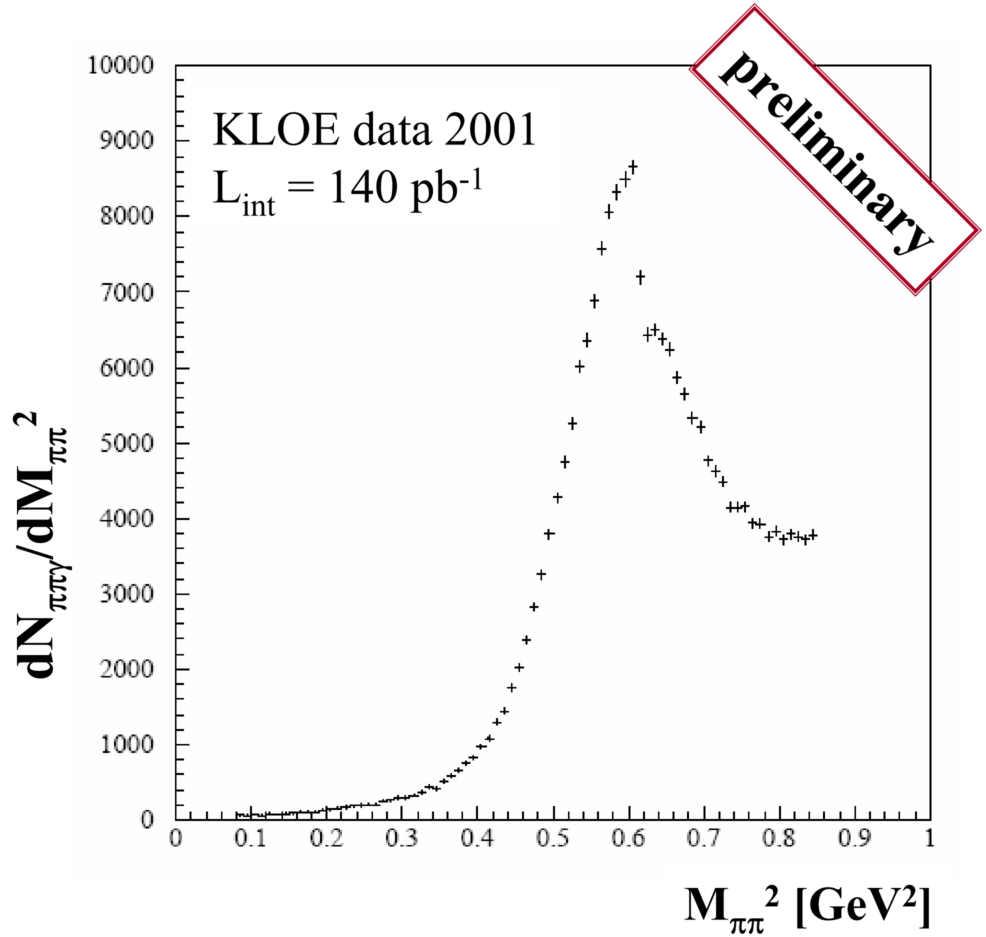
- ✓ Selection Cuts
- ✓ Background

Missing:

- ➢ FSR corrections
- ➢ Measurement of absolute background contamination
- ➢ Efficiency evaluation from Data

Just a preliminary spectrum ➡

Spectrum (preliminary) II



Conclusions

- KLOE has published the first measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section between 0.35 GeV^2 and 0.95 GeV^2 using the radiative return with a negligible statistical error and 1.3% total systematic uncertainty

- Complementary analysis requiring the photon to be emitted at large angles has been started, which allows to enter the region for $M_{\pi\pi}^2 < 0.3$ GeV^2
  - ✓ The selection of the signal is finished and well stable
  - ✓ Next step: efficiency and background content from DATA

A glance at the future

- An upgrade of the small photon angle analysis is being done using 2002 data
- Measurement of $\sigma(e^+ e^- \rightarrow \pi^+\pi^-)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ (normalization to muons) $\Rightarrow$ direct measurement of R
- … and **PoP** **(Physics – or peck(!?) – at off-Peak)**:

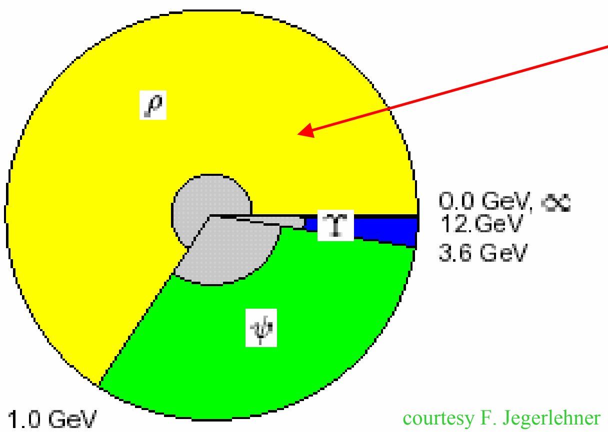
move the center of mass energy of DAΦNE below the ϕ resonance to reduce $\pi^+\pi^-\pi^0$ background

Backup Slides

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

- E_{cut} is the threshold energy above which pQCD is applicable
- s is the c.o.m.-energy squared of the hadronic system
- K(s) is a steady function that goes with 1/s,

enhancing low energy contributions of $\sigma^{hadr}(s)$



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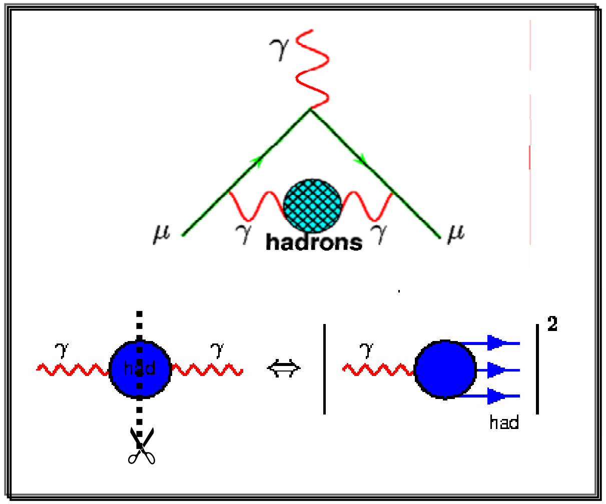
[Jegerlehner; hep-ph/0312372]

The ρ-meson decays to 100% in $\pi^+\pi^-$, so in this energy region the analysis efforts concentrate on the determination of $\boldsymbol{\sigma(e^+e^- \longrightarrow \pi^+\pi^-)}$

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



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  enhancing low energy contributions of $\sigma^{hadr}(s)$

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

Efficiencies:
- Trigger & Cosmic veto
- Tracking, Vertex
- π–e separation
- Reconstruction filter
- Trackmass-cut
- Unfolding resolution
- Acceptance

Background:
- $e^+e^- \rightarrow e^+e^-\gamma$
- $e^+e^- \rightarrow \mu^+\mu^-\gamma$
- $e^+e^- \rightarrow f \rightarrow \pi^+\pi^-\pi^0$

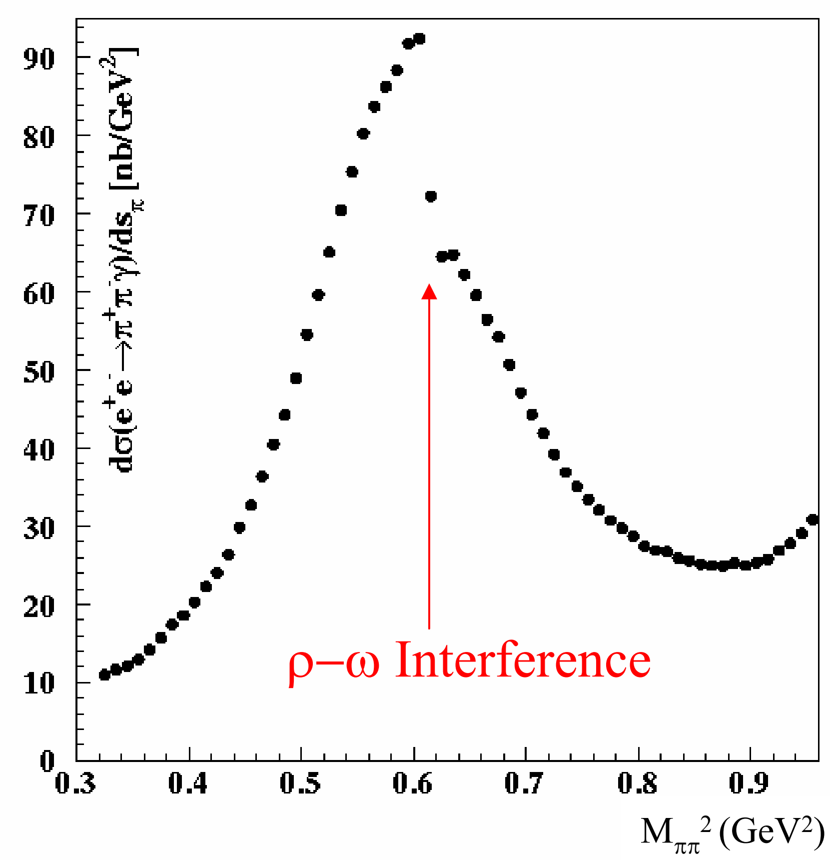
Luminosity:
Bhabhas at large angles
> 55°, σ_{eff} = 430 nb

Errors:

0.9%

$0.3\%_{exp}$
$0.5\%_{theo}$

Statistics: 141pb^{-1} of 2001-Data
1.5 Million Events

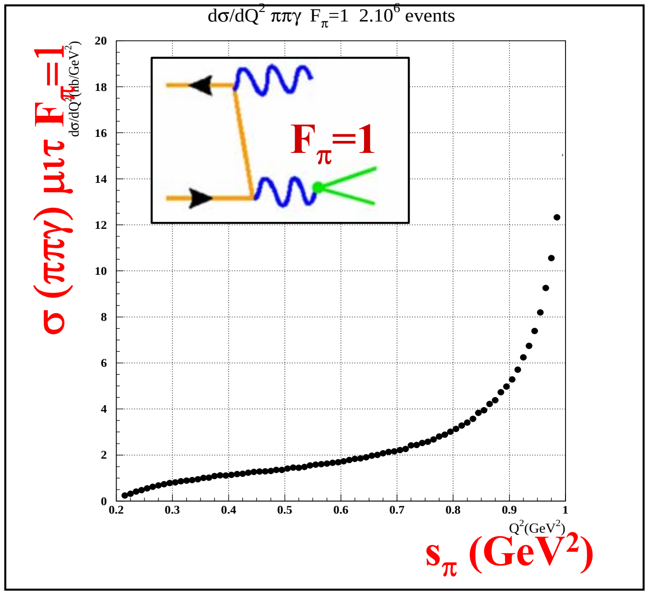


Radiator-Function H(s) (ISR):

$$M_{\pi\pi}^2 \frac{d\sigma_{\pi\pi\gamma}}{dM_{\pi\pi}^2} = \sigma_{\pi\pi}(s) \times \mathbf{H(s)}$$

- **ISR-Process calculated at NLO-level**
  Generator ***PHOKHARA*** *(Kühn et.al)*
- Comparison with *KKMC (Jadach et.al.)*

Precision: 0.5%



Radiative Corrections:

i) Bare Cross Section
divide by Vacuum Polarisation

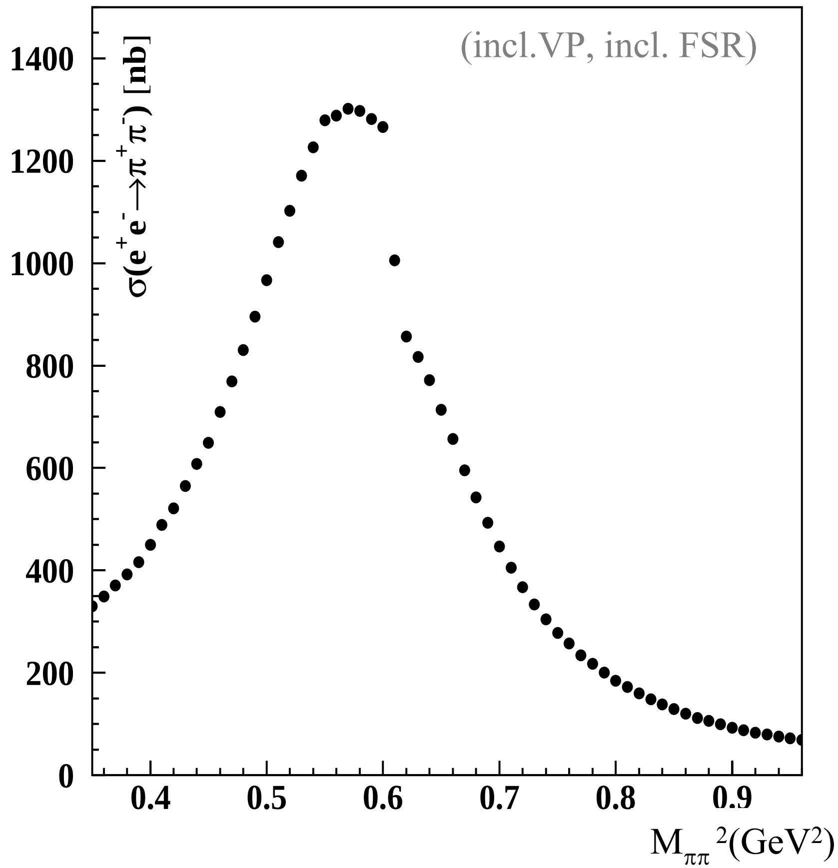
ii) FSR - Corrections
Cross section $\sigma_{\pi\pi}$ must be incl. for FSR

Radiative Return requires ISR photon ➔ be inclusive for ISR-FSR-events

$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}(\gamma_{FSR})$

Error of 0.3% assigned to FSR-corrections

Result: Cross Section $e^+e^- \rightarrow \pi^+\pi^-$



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Exp. syst. uncertainties:

- Efficiencies
- Background Subtraction

TOTAL 0.9%

Theory syst. uncertainties:

– Radiator Function H	0.5%
– Vacuum Polarization	0.2%
– Luminosity	0.6%
– FSR resummation	0.3%
TOTAL	**0.9%**

TOTAL syst. ERROR 1.3%

Comparison with results from CMD-2 experiment (pion form factor)

$$\sigma_{\pi\pi}(M^2_{\pi\pi}) = \frac{\pi\alpha^2}{3M^2_{\pi\pi}} \beta^3_\pi \left|F_\pi\left(M^2_{\pi\pi}\right)\right|^2$$

Evaluating the dispersion integral

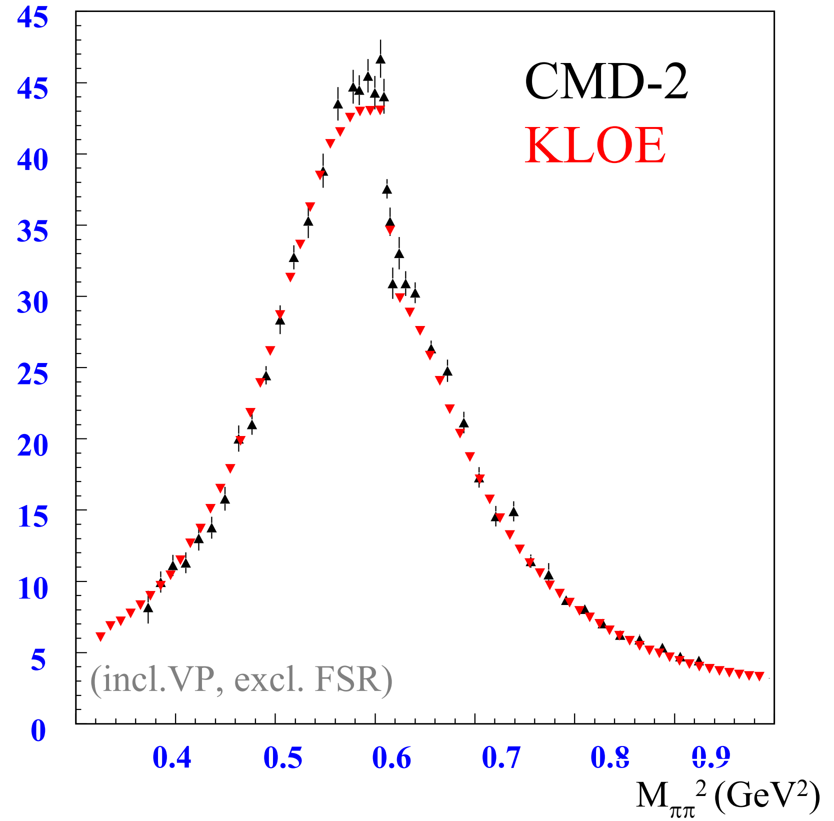
$$\frac{1}{4\pi^3}\int \sigma^{\pi\pi}(s)K(s)ds$$

between $0.37 < M_{\pi\pi}^2 < 0.93$ GeV^2:

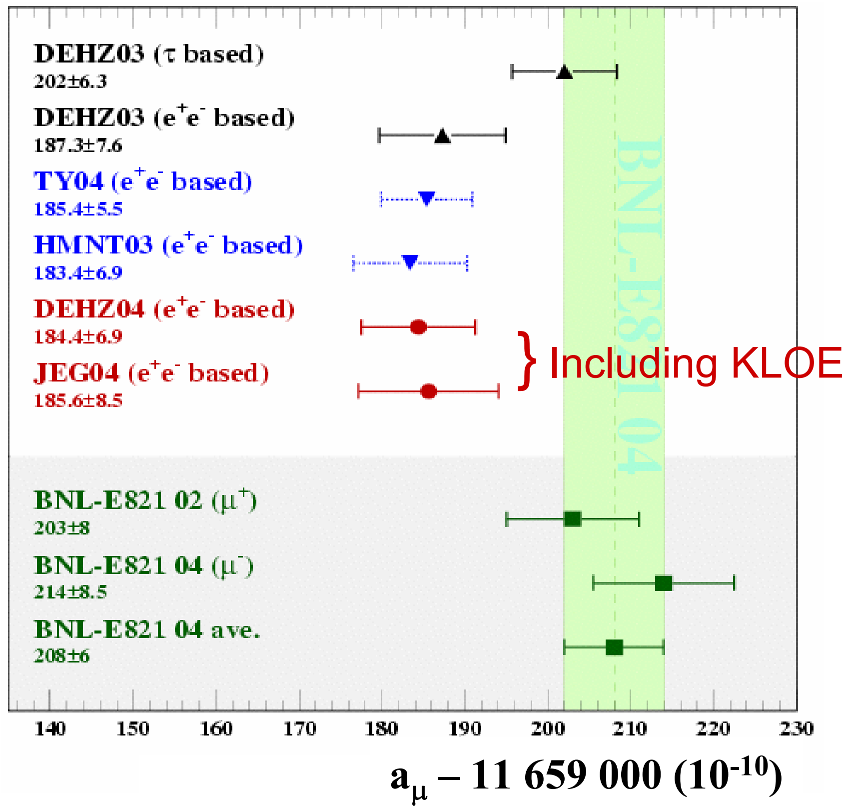
KLOE: $(375.6 \pm 0.8_{stat} \pm 4.9_{syst+theo})\ 10^{-10}$

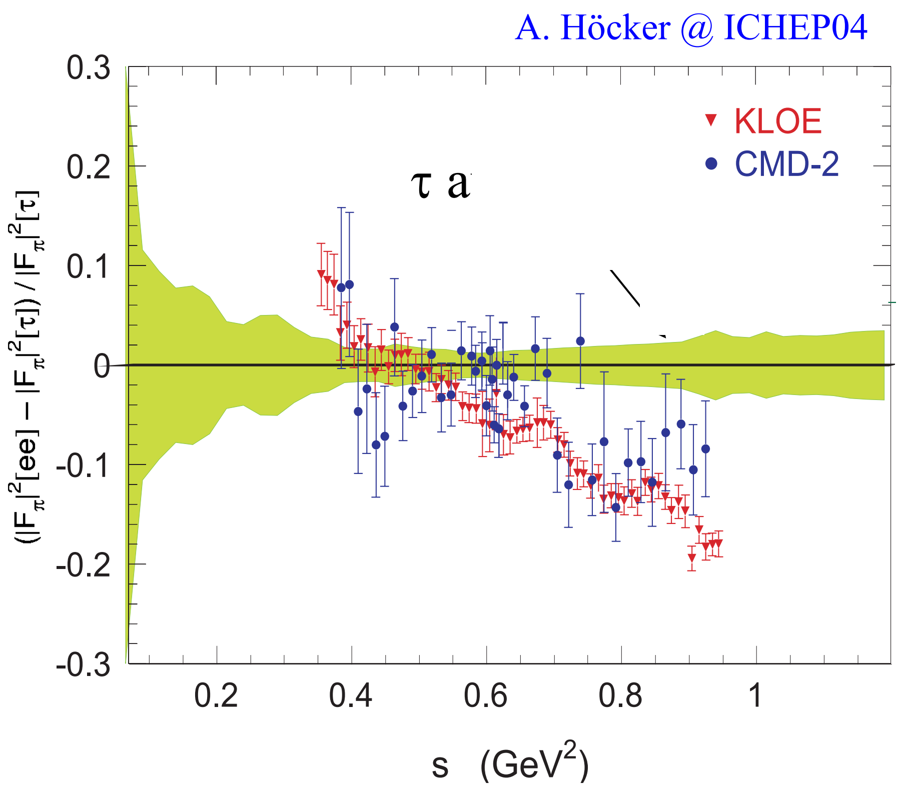
CMD2: $(378.6 \pm 2.7_{stat} \pm 2.3_{syst+theo})\ 10^{-10}$

Pion Formfactor



- KLOE data points are not in excellent but in a fair agreement with CMD-2
- Significant discrepancies in the diff. spectrum: KLOE higher at low s_π and lower at large s_π
- Apparently effects compensate in the evaluation of the dispersion integral





KLOE Data included!

- New 4th order QED contribution
- New Light-by-light contribution

τ – data excluded!

$a_\mu^{exp} - a_\mu^{theo} = (23.6 \pm 9.1) \cdot 10^{-10}$

2.6 "standard deviations"

The current status of a_μ from experiment and (SM-) theory:

a_μ^{exp}

$$(g_\mu-2)/2 = (11\,659\,208.0 \pm 6.0) \times 10^{-10}$$

E821, hep-ex/0401008

$a_\mu^{theor,SM}$

$$(g_\mu-2)/2 = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

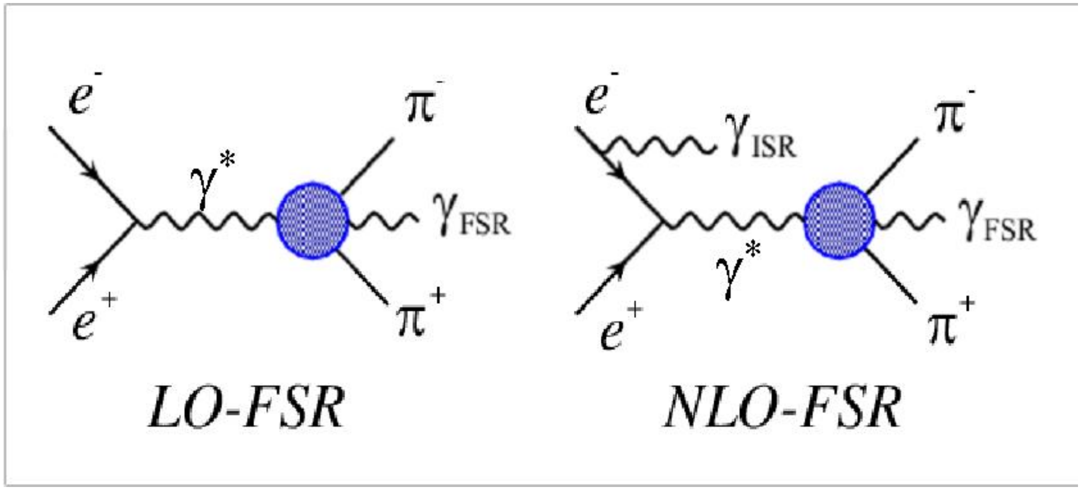
a_μ^{QED}	$= (11\,658\,471.8 \pm 0.1) \times 10^{-10}$	Kinoshita (TAU04)	
a_μ^{weak}	$= (15.4 \pm 0.2) \times 10^{-10}$	CzMaVa hep-ph/0212229v2	
a_μ^{had}	$= (714.8 \pm 6.4) \times 10^{-10}$	based on τ decays	DEHZ hep-ph/0308213
	$= (697.2 \pm 7.0) \times 10^{-10}$	based on e+e- data	H hep-ph/0410081

$$a_\mu^{exp} - a_\mu^{theor,SM} = 0.7 - 2.6\ \sigma \text{ difference}$$

- The nature of the difference in the two evaluations of a_μ^{had} is currently not understood
- The reduction of the error on the hadronic contribution to the SM calculation of a_μ could (together with a further reduction of the experimental error) give this discrepancy between theory and experiment a higher significance

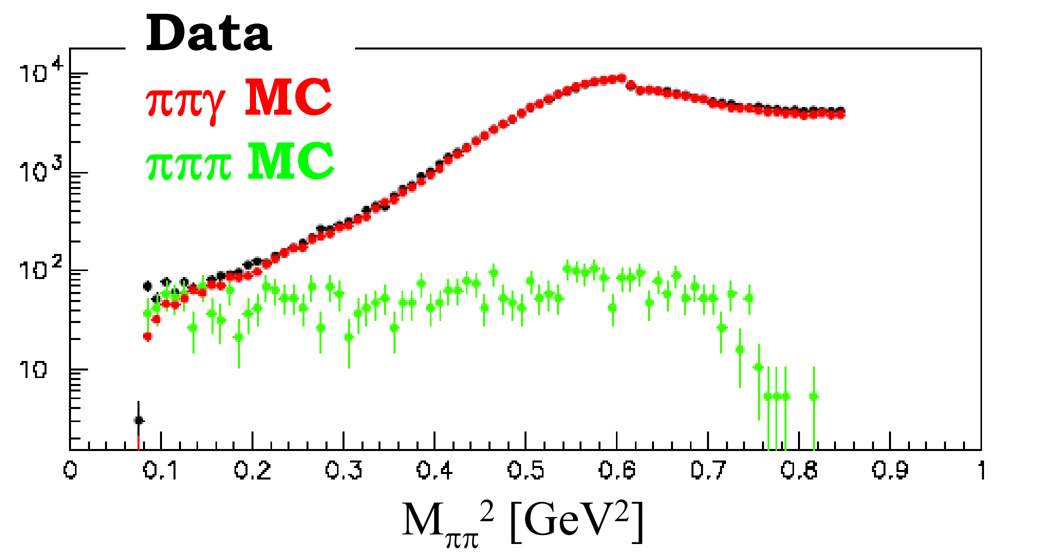
The cross section for $e^+e^- \rightarrow \pi^+\pi^-$ has to be inclusive with respect to final state radiation events in order to evaluate a_μ

We distinguish between two kinds of FSR contributions:



LO-FSR: No initial state radiation, e^+ and e^- collide at the energy M_ϕ=1.02 GeV

NLO-FSR: Simultaneous presence of one photon from initial state radiaition and one photon from final state radiation



Are we overestimating one (or more) efficiency in the MC?

Or are we overestimating the 3π contribution?