e^+e^- – Hadronic Cross Section measurement at DAΦNE with the KLOE detector

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Motivation

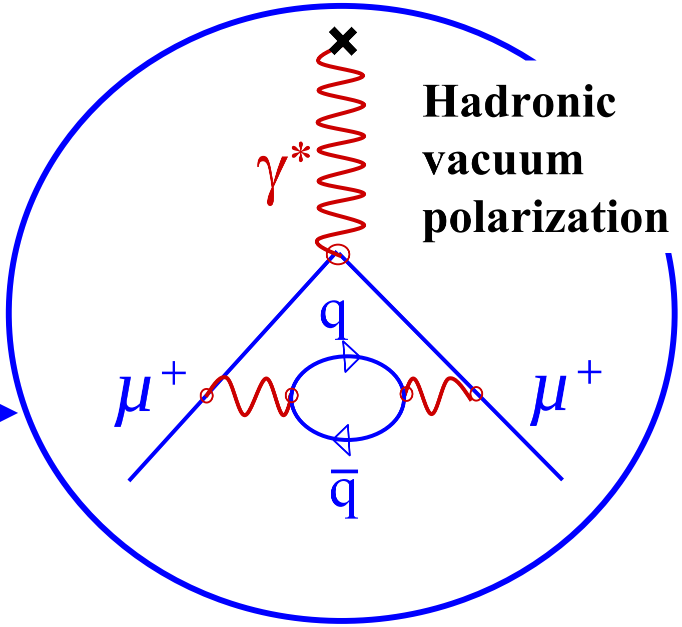
High precision test of the Standard Model

- Anomalous magnetic moment of the muon
- Fine structure constant at Z^0 mass $\alpha_{QED}(M_Z)$

Anomalous magnetic moment of the muon

Muon anomaly $a_\mu = (g_\mu - 2)/2 = \alpha/2\pi + \ldots$

$$a_\mu^{theor} = a_\mu^{QED} + \boxed{a_\mu^{had}} + a_\mu^{weak} + a_\mu^{new}$$



Hadronic vacuum polarization

Second largest contribution, pQCD not applicable

Error of hadronic contribution dominates the total error of a_μ

Dispersion relation

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma_{had}(s)ds$$

Pion Form Factor $\sigma(e^+e^- \to \pi^+\pi^-)$ below 1 GeV contributes to ~ 70%

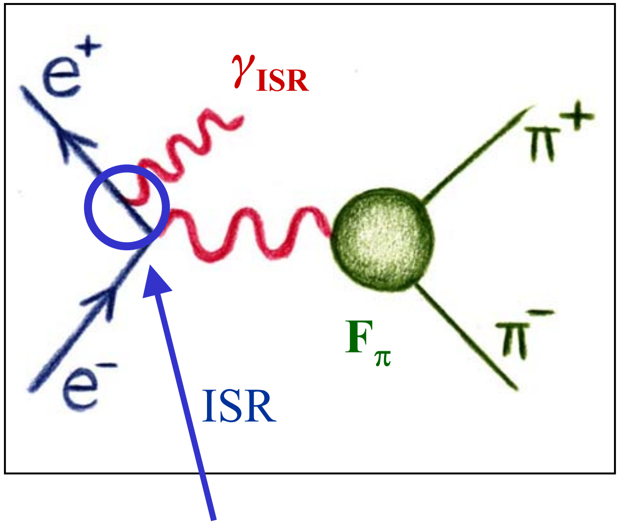
- ✓ *K(s)* analytic kernel function
- ✓ above tipically 2…5 GeV pQCD is applied

Alternative: Spectral function from decay ($\tau \to \nu_\tau$ Hadrons) taking into account isospin breaking corrections

Radiative return at DAΦNE

DAΦNE is designed for a fixed center-of-mass energy: $\sqrt{s} = M_\phi = 1.02$ GeV

"Radiative Return" to ρ(ω)-resonance: $e^+e^- \to \rho(\omega) + \gamma \to \pi^+\pi^- + \gamma$



MC Generator *PHOKHARA*
J. Kühn, H. Czyż, G. Rodrigo
Radiator-Function *H(s)*

1. Experimentally what one gets is:

$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{d\sigma\left(e^+e^- \to \pi^+\pi^-\gamma_{ISR}\right)}{dM^2_{\pi\pi}}$$

$(2m_\pi)^2 < M_{\pi\pi}{}^2 < M^2_\phi$

... Actually:

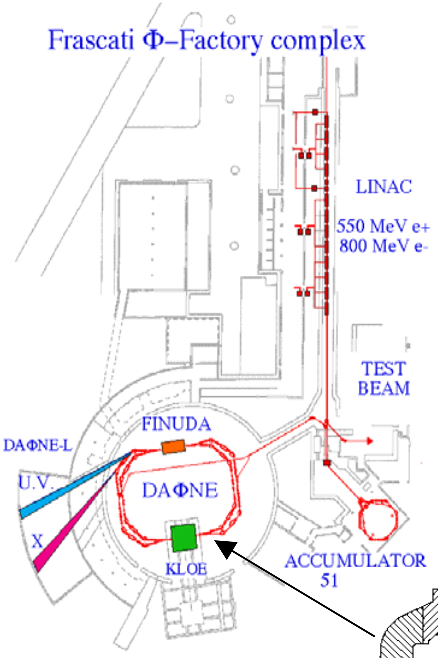
$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{\Delta N_{Obs} - \Delta N_{Bkg}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon_{Sel}} \cdot \frac{1}{\int L dt}$$

2. With MC generator:

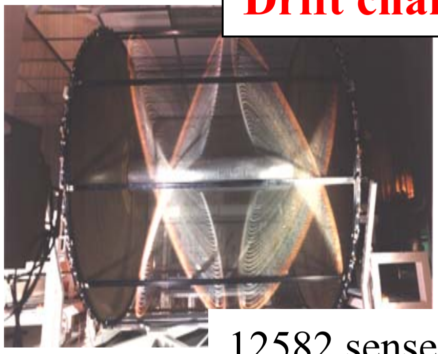
$$M^2_{\pi\pi} \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi} \times H(s) \Rightarrow \boxed{\sigma_{\pi\pi} = M^2_{\pi\pi} \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} \cdot \frac{1}{H(s)}}$$

S. Binner, J.H. Kühn, K. Melnikov, Phys.Lett. B459 (1999) 279

The KLOE detector at the DAΦNE Φ-factory



Drift chamber



12582 sense wires

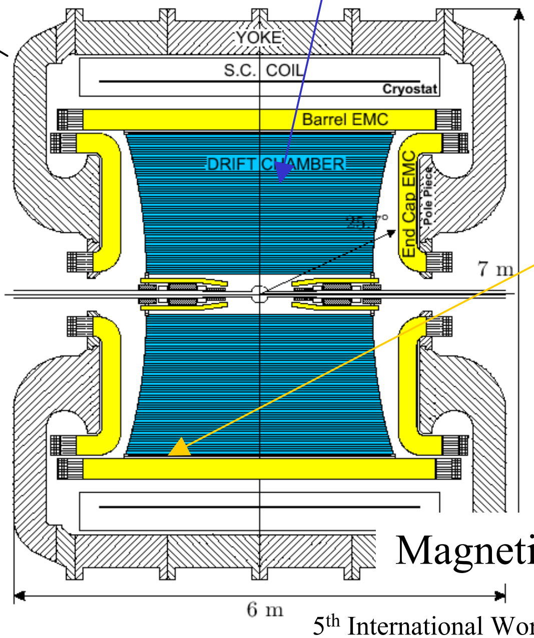
52140 wires in total

Track momentum resolution

$\sigma_p/p \approx 0.4\% \ (\theta > 45^\circ)$

Vertex resolution

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



Electromagnetic calorimeter

Pb/Scint fibres

4880 PM

Energy resolution

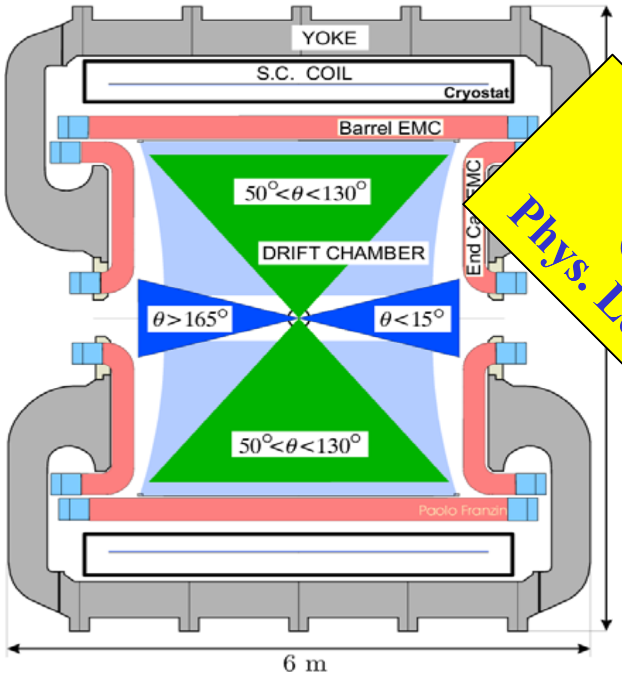
$\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$

Time resolution

$\sigma_T = 57\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$

Magnetic Field of 0.52 T

KLOE: Small Photon Angle analysis



KLOE result
(140 pb^{-1} of 2001)
Phys. Lett. B606 (2005) 12

SELECTION

- ✓ **Pion tracks:** $50^o < \theta_\pi < 130^o$
- ✓ **Photons:** $\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

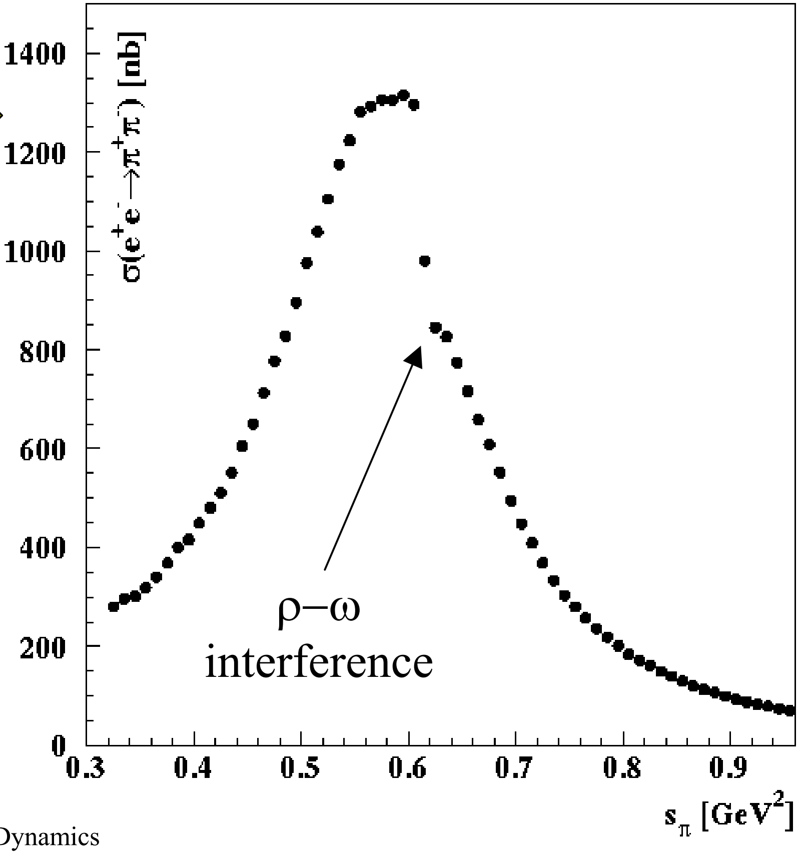
No photon tagging:

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

PRO & CONTRA

- ✓ high statistics for ISR
- ✓ low relative FSR contribution
- ✓ suppressed $\phi \to \pi^+\pi^-\pi^0$ background
- ✓ threshold region not covered
- ✓ no kinematic closure of event

Total
Fractional
Error
KLOE: 1.3%
CMD-2: 0.9%
SND: 1.3%

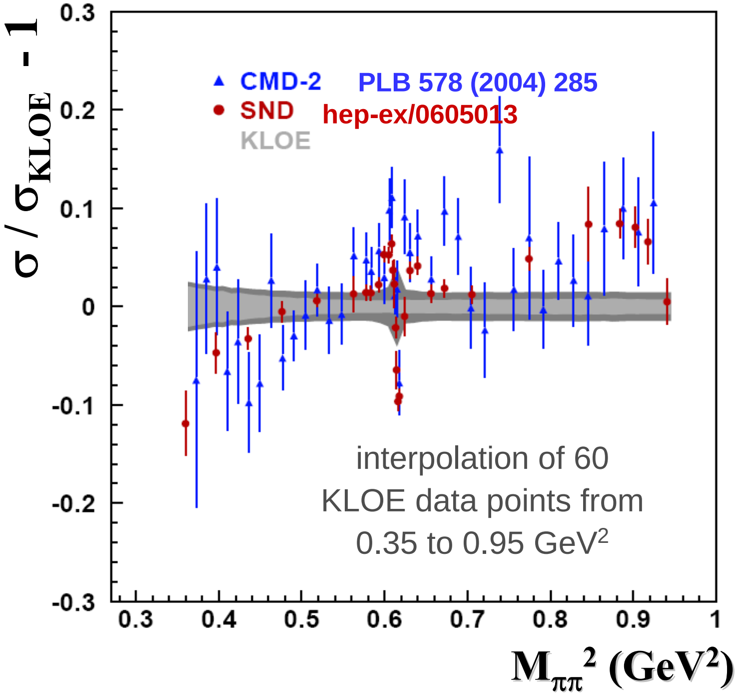


ρ−ω
interference

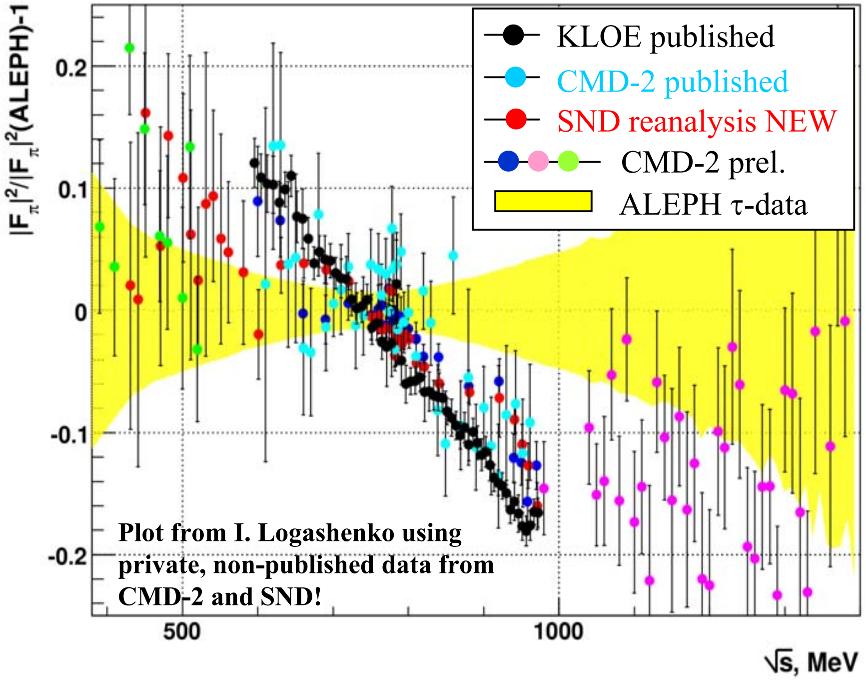
A glance at the present status

Experimental input into the theoretical computation: e^+e^-– and τ– data

Comparison among e^+e^- and τ– data



interpolation of 60 KLOE data points from 0.35 to 0.95 GeV^2



Plot from I. Logashenko using private, non-published data from CMD-2 and SND!

- ✓ All the recent e^+e^- experiments see large deviations with τ– data above ρ peak
- ✓ Some disagreement between KLOE and CMD-2/SND
- ✓ All recent e^+e^- experiments agree now within 0.5σ in the ππ–contribution to a_μ^{had}
- ✓ Recent preliminary $\tau^\pm \to \pi^\pm\pi^0\nu$ from BELLE in agreement with e^+e^- (hep-ex/0512071)?!

Update on small angle

A new analysis is carried out at small photon angles using 2002 data (240 pb^{-1})
with improved machine background and calibration conditions.
Two goals:
1. Reduction of total systematical error, 2. Perform the normalization with $\mu\mu\gamma$ events

1. Reduction of total systematical error < 1%

Acceptance	0.3%
Trigger	0.3%
Tracking *	0.3%
Vertex *	0.3%
Offline reconstruction filter	0.6%
Particle ID	0.1%
Trackmass cut	0.2%
Background *	0.3%
Unfolding effects	0.2%
Exp. Syst. with 2001 data: 0.9%	

Precision was limited by cosmic veto filter which caused up to 30% of inefficiency
Cured by introducing L3-Filter,
no cosmic veto inefficiency anymore

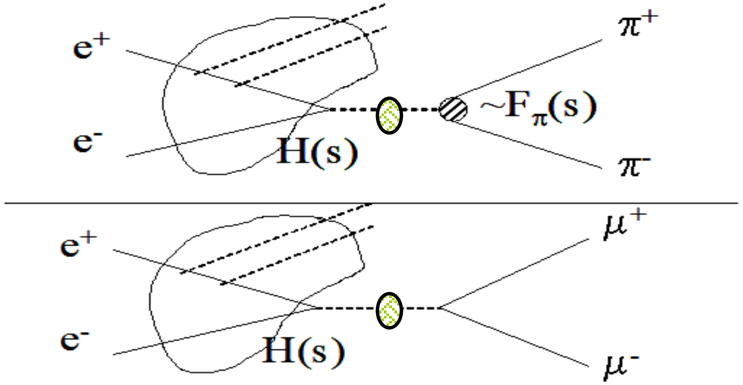
Main systematic experimental error due to machine background dependence of an offline-event filter
Cured by changing reconstruction filter, error reduces to < 0.1%

*** Reduction of error, larger data set allows more precise determination**

Update on small angle

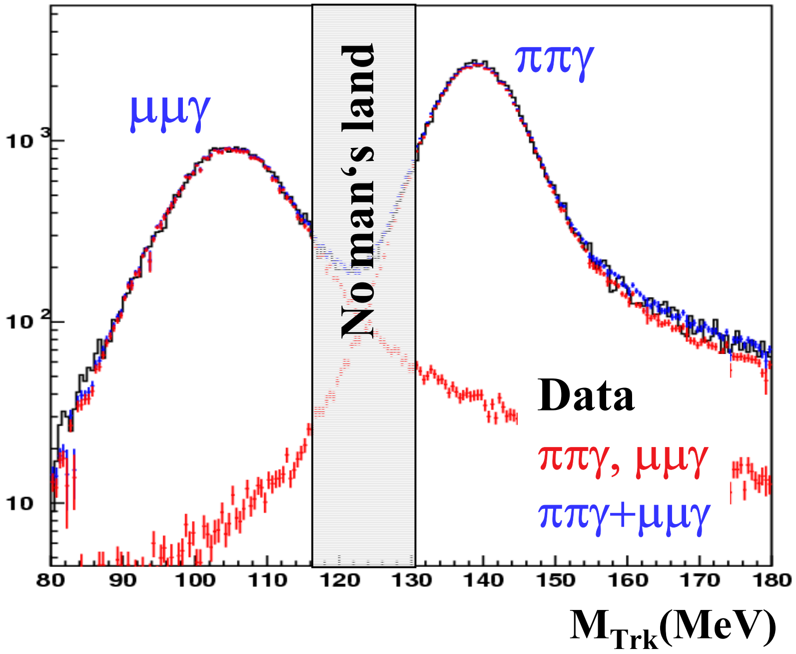
2. Normalization with μμγ events

$$\sigma_{\pi\pi}^{Born}(s') \approx \frac{d\sigma_{\pi\pi\gamma}^{obs}/ds'}{d\sigma_{\mu\mu\gamma}^{obs}/ds'}\,\sigma_{\mu\mu}^{Born}(s')$$



Pions and muons are separated using a cut in trackmass:

$$\left(\sqrt{s}-\sqrt{\vec{p}_{x+}^{\,2}+M_{trk}^2}-\sqrt{\vec{p}_{x-}^{\,2}+M_{trk}^2}\right)^2-(\vec{p}_{x+}+\vec{p}_{x-})^2=q_\gamma^2=0$$



Some effects cancel out in the ratio

~~Luminosity (LA Bhabhas)~~	~~0.6%~~
~~Vacuum polarization~~	~~0.2%~~
FSR corrections	0.3%
~~Radiator function~~	~~0.5%~~
Total theoretical Error	~~0.9%~~

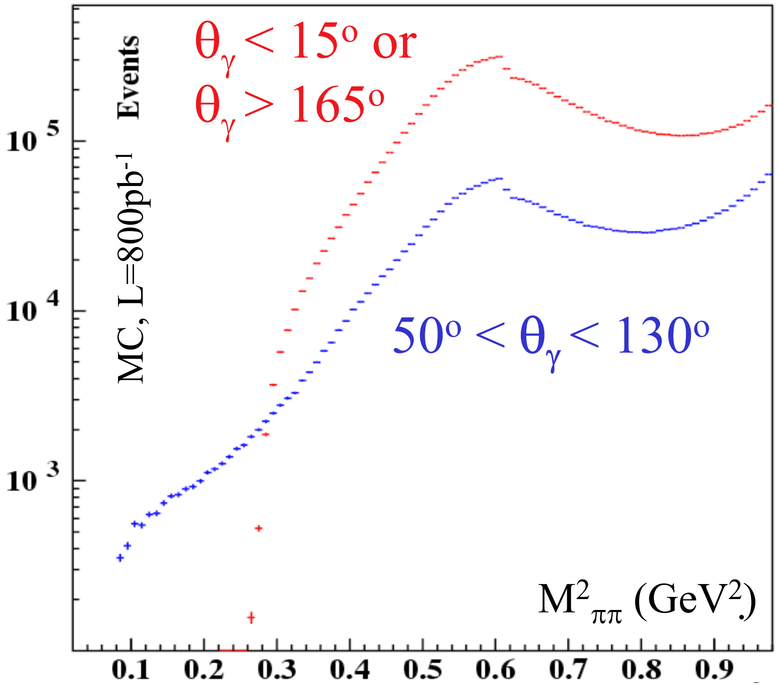
→ **0.3%**

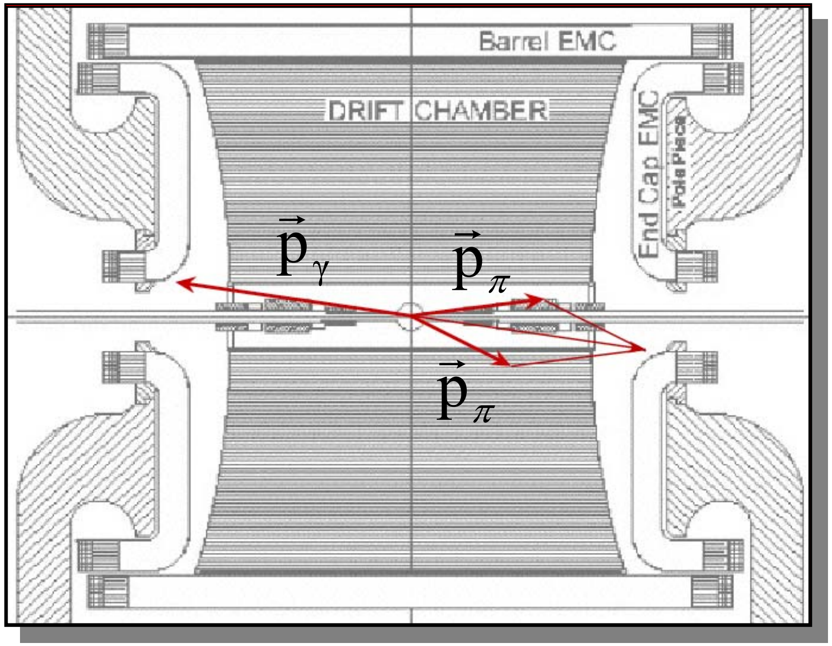
requires to select μμγ events with similar precision as ππγ

The threshold region

Kinematics do not allow to cover events with $M^2_{\pi\pi} < 0.35\ \text{GeV}^2$ in the **small angle** selection cuts:
a high energy ISR photon ($\approx$ small $M^2_{\pi\pi}$) emitted at a small angle
forces the pions to be at low angles too.

PHOKHARA MC generator



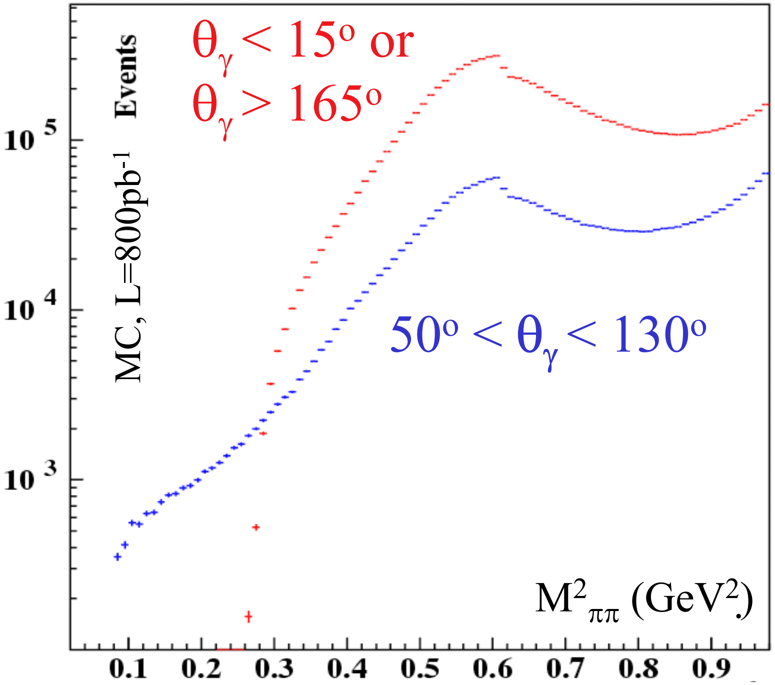


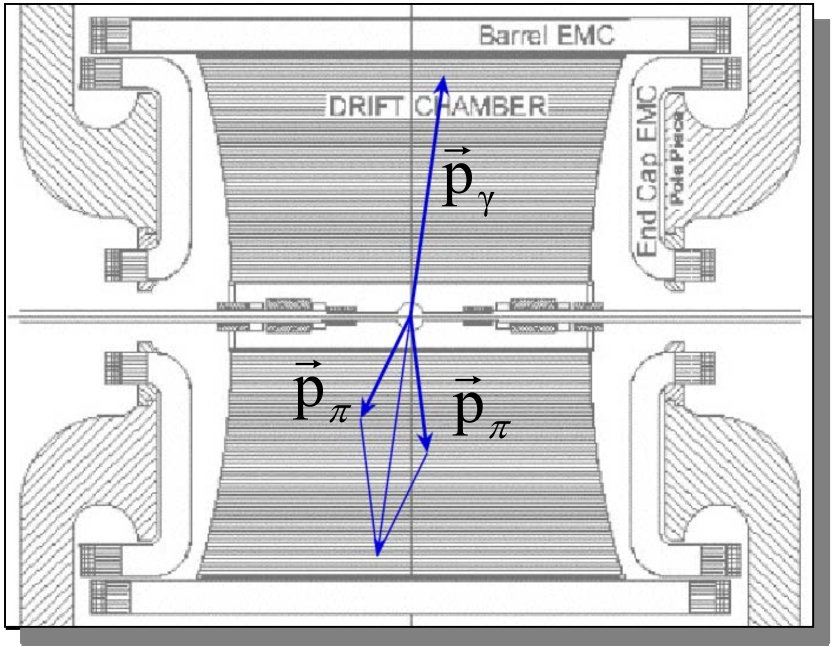
$$\boxed{\Delta a_\mu^{had}(s < 0.35\ \text{GeV}^2) \approx 100\cdot 10^{-10} \text{ from } e^+e^- \to \pi^+\pi^-}$$

The threshold region

Kinematics do not allow to cover events with $M^2_{\pi\pi} < 0.35$ GeV^2 in the **small angle** selection cuts: a high energy ISR photon (≈ small $M^2_{\pi\pi}$) emitted at a small angle forces the pions to be at low angles too.

PHOKHARA MC generator





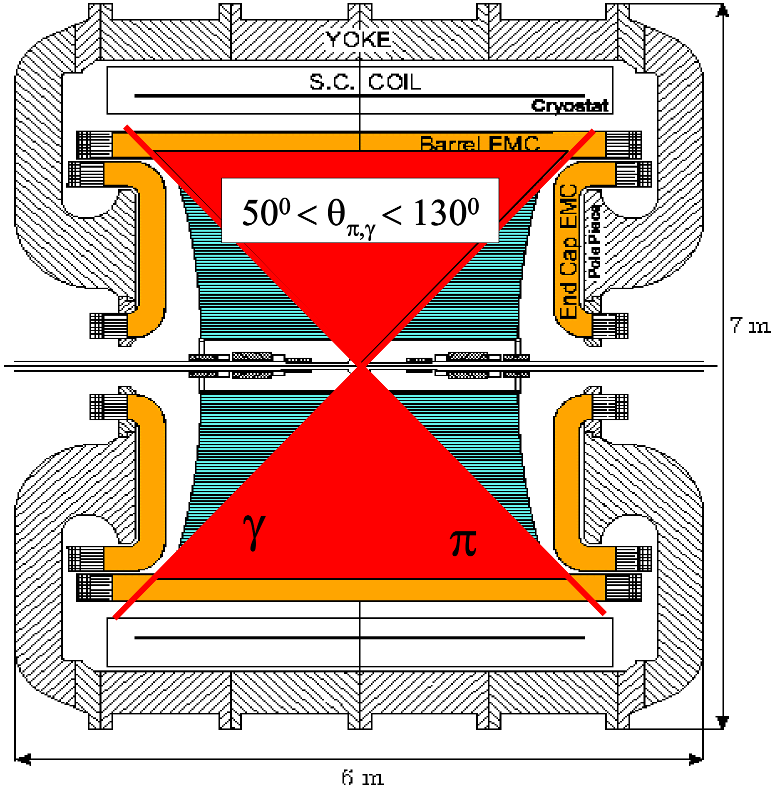
If the high-energy photon is emitted at a **large angles**, also the pions will be emitted at large angles. Thus the event will be selected.

$$\Delta a_\mu^{had}(s < 0.35\ \mathrm{GeV}^2) \approx 100 \cdot 10^{-10} \text{ from } e^+e^- \rightarrow \pi^+\pi^-$$

KLOE: Large Photon Angle analysis

SELECTION

- ✓ **Pion tracks:** $50^o < \theta_\pi < 130^o$
- ✓ **Photons:** at least one with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 50$ MeV

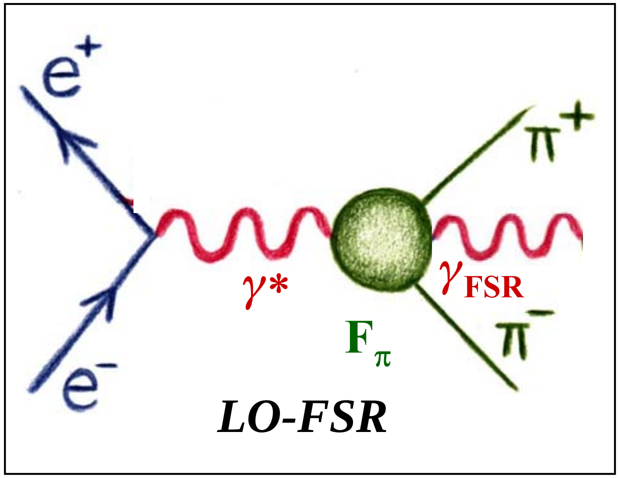


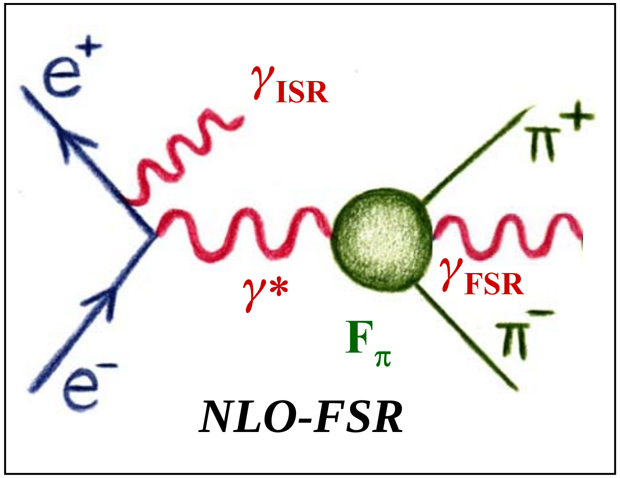
PRO & CONTRA

- ✓ the threshold region is accessible
- ✓ the ISR photon is detected (4-momentum constraints)
- ✓ large $\phi \to \pi^+\pi^-\pi^0$ background contamination
- ✓ lower signal statistics
- ✓ large FSR contributions
- ✓ irreducible background from ϕ decays

Final State Radiation photon

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. There are two kinds of FSR contributions:





LO-FSR: No initial state radiation, e^+ and e^- collide at $M^2_{\gamma*} = M^2_\phi$

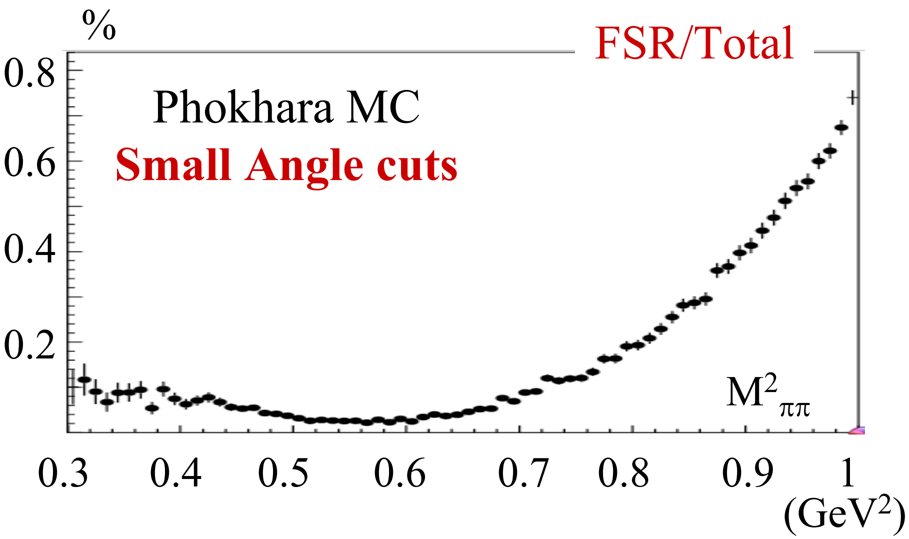
NLO-FSR: Simultaneous presence of one photon from initial state radiation and from final state radiation

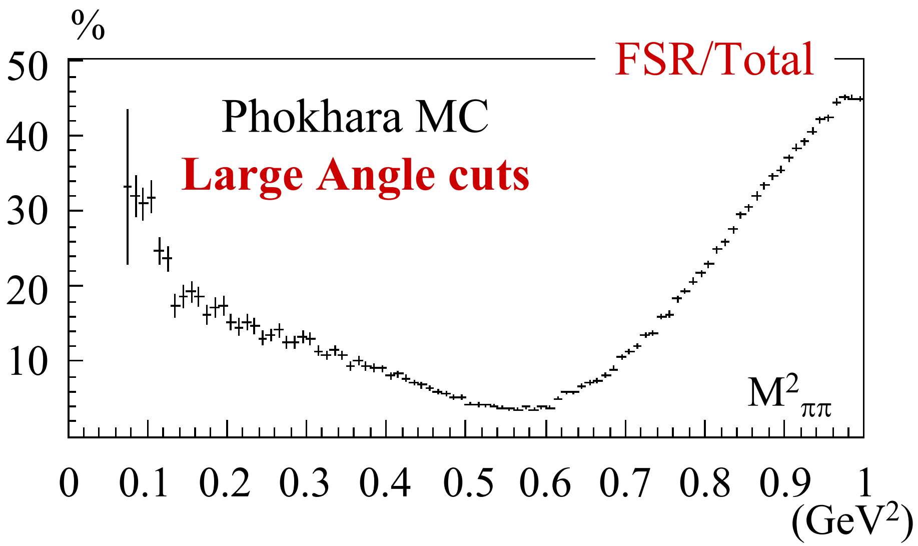
In both cases the presence of γ_{FSR} results in a shift of the measured quantity $M^2_{\pi\pi}$ towards lower value:

$$\boxed{M^2_{\pi\pi} < M^2_{\gamma*}}$$

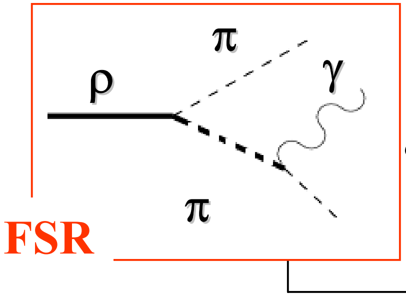
FSR for large angle and irreducible background

The presence of **FSR EVENTS** is an issue especially for the large angle selection





Under large angle cuts FSR events as $\rho \to \pi\pi(+\gamma)$, $\phi \to f_0\gamma \to \pi\pi\gamma$ and $\phi \to \rho\pi \to \pi\gamma\pi$, all of them with $\pi\pi\gamma$ final state, are **IRREDUCIBLE BACKGROUND**



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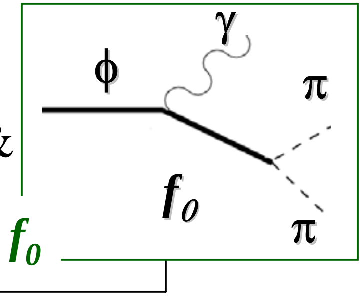

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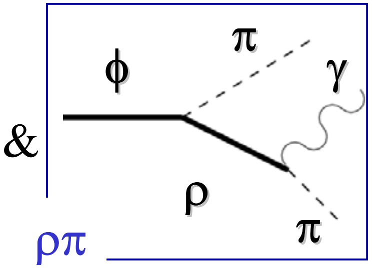


important

small

They make the threshold region non-trivial

These must be subtracted using in MC phenomenological models (interference effects unknown)

Event selection

Acceptance

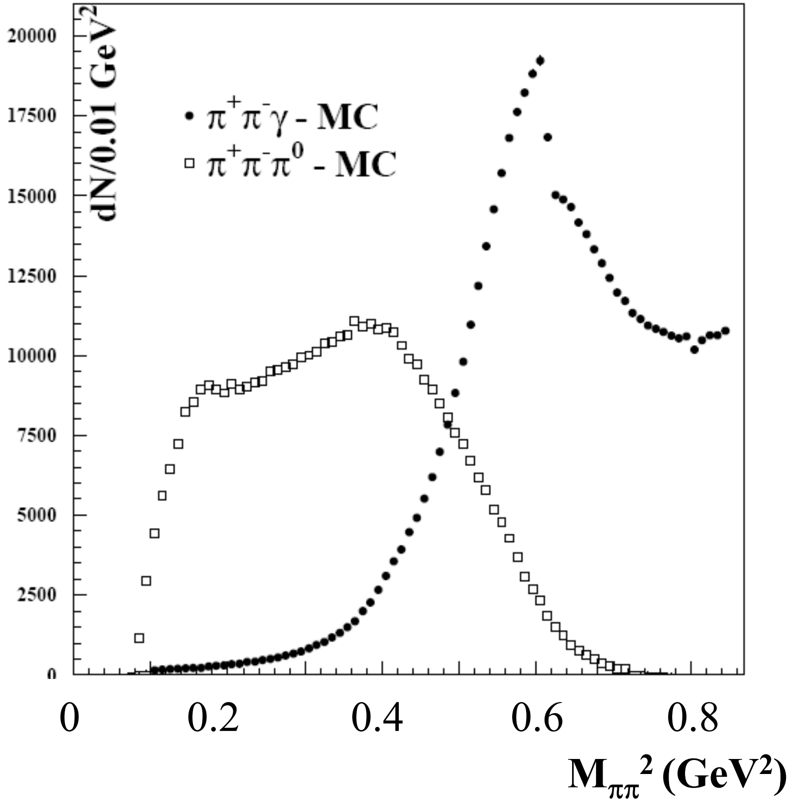
LARGE ANGLE

✓ **Pion tracks:** $50^o < \theta_\pi < 130^o$

✓ **Photons:** at least one with $50^o < \theta_\gamma < 130^o$
and $E_\gamma > 50$ MeV

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

With large angle acceptance cuts and application of a first level filter (ppgtag): huge amount of $\phi \rightarrow \pi^+\pi^-\pi^0$

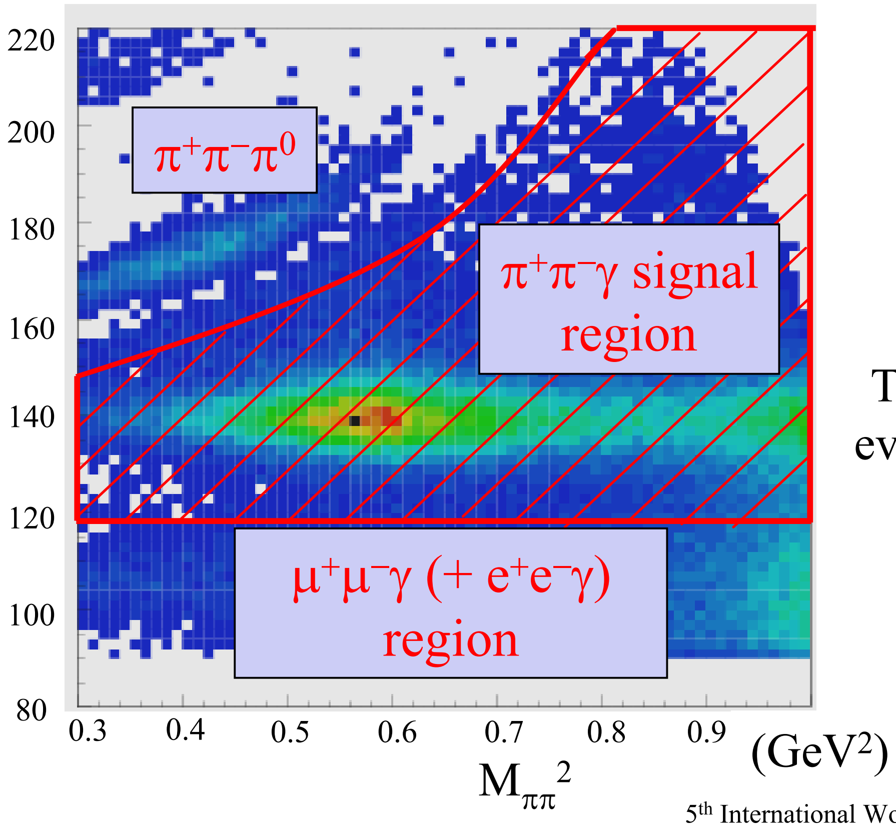


… still event selection…

Trackmass

Four momentum conservation under the hypothesis of two tracks with the same mass and a photon: M_{trk} is the charged particle ($x^{\pm}$) of **$e^+e^- \to x^+x^-\gamma$**

$$\left(\sqrt{s}-\sqrt{\vec{p}_{x+}^{\,2}+M_{trk}^2}-\sqrt{\vec{p}_{x-}^{\,2}+M_{trk}^2}\right)^2-(\vec{p}_{x+}+\vec{p}_{x-})^2=q_\gamma^2=0$$



Likelihood

To further clean the sample from radiative Bhabha events a particle ID estimator for each charged track based on **calorimeter information** and **time of flight** is used

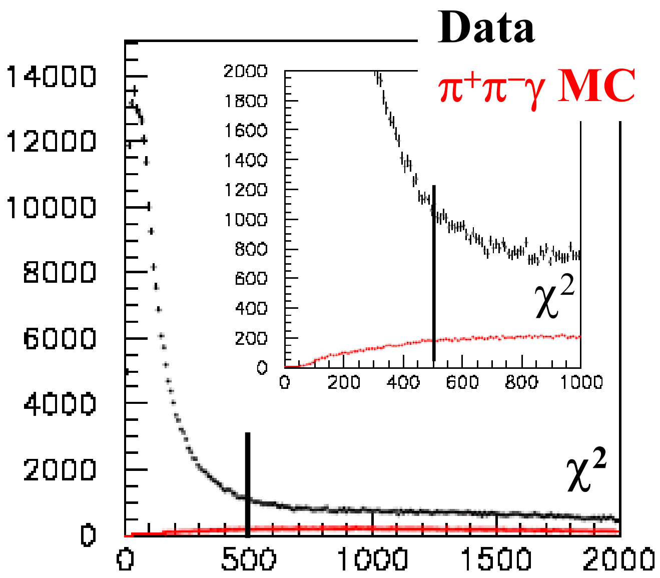
… and other cuts, dedicated for the large angle…

Kinematic fit

Kinematic fit with **$\pi^+\pi^-\pi^0$ background hypothesis**

✓ **Two tracks** in $40° < \theta_\pi < 140°$ and
at least two photons one of them
with $E_\gamma > 40$ MeV and $40° < \theta_\gamma < 140°$

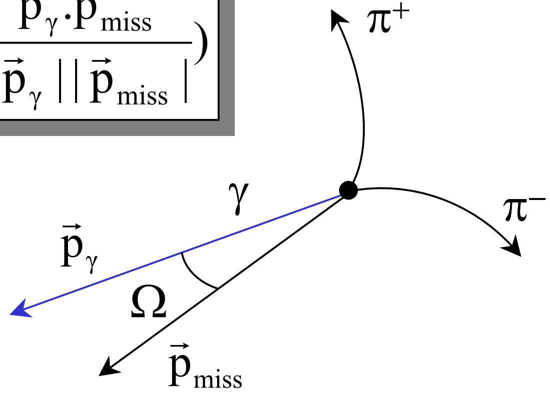
➢ **4-momenta conservation** and $\mathbf{M_{inv}(\gamma\gamma) = m_{\pi 0}}$

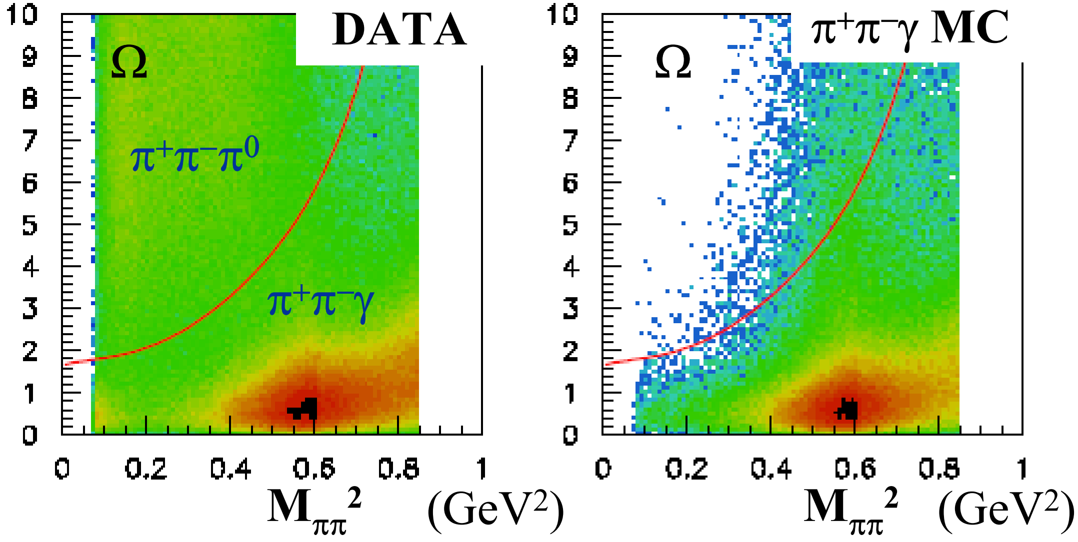


Ω angle

Angle between **the missing momentum and the detected photon momentum**

$$\Omega = \mathrm{acos}\left(\frac{\vec{p}_\gamma . \vec{p}_{miss}}{|\vec{p}_\gamma|\,|\vec{p}_{miss}|}\right)$$





Preliminary $dN/dM_{\pi\pi}^2$ large angle spectrum

After all the dedicated cuts

✓ $50^o < \theta_{\pi,\gamma} < 130^o$, $E_\gamma > 50$MeV

✓ Both the particles not identified as electrons

✓ Cut on $\chi^2_{\pi\pi\pi}$

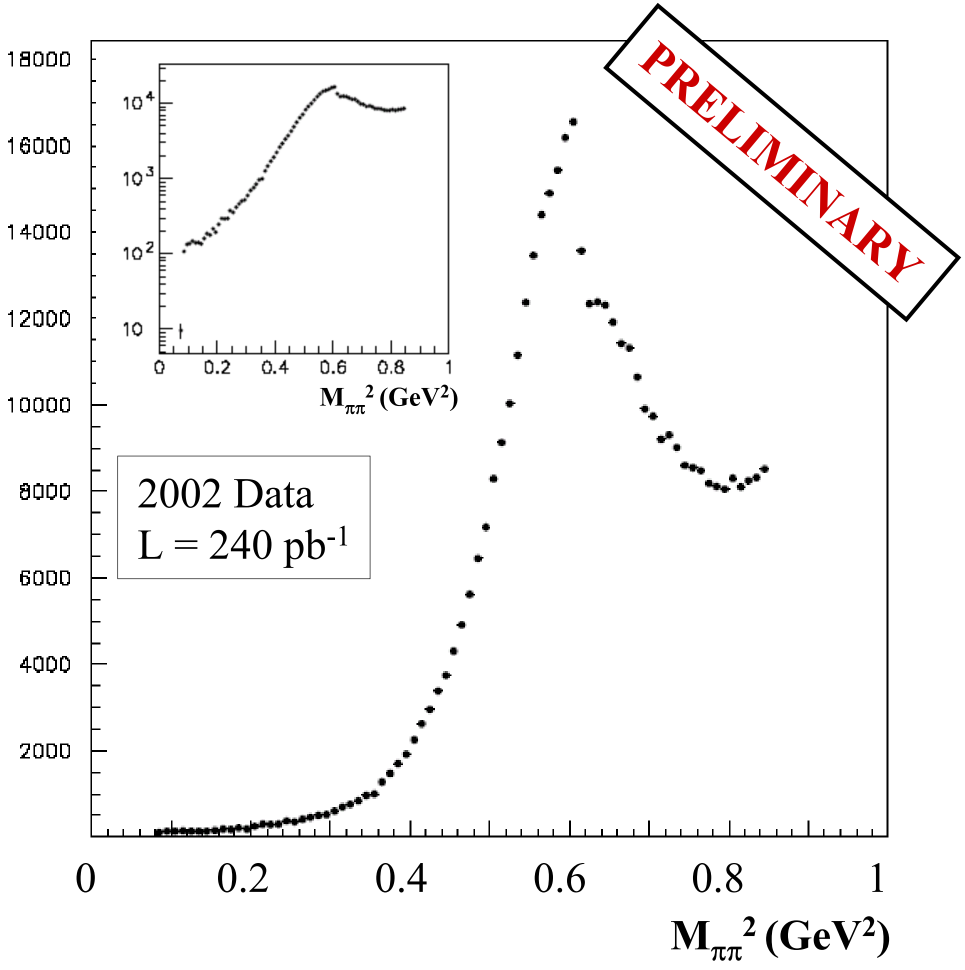
✓ Cut on TrackMass vs. $M_{\pi\pi}^2$

✓ Cut on Ω angle

The signal selection efficiency is **never below 80%**
The **reducible background contribution** is **negligible**.

Still under construction
(... close to be complete)

- Efficiencies:
  - trigger, tracking, vertex ⇒ complete
  - acceptance, selection cuts ⇒ final checks
- FSR corrections (Phokhara 5.0 Ω)
- f_0 contribution (Phokhara 5.1)
- Systematics



Charge asymmetry

In the case of a non vanishing FSR contribution the interference term between ISR and FSR is odd under the exchange of $\pi^+ \leftrightarrow \pi^-$.

This gives rise to a non vanishing forward-backward asymmetry

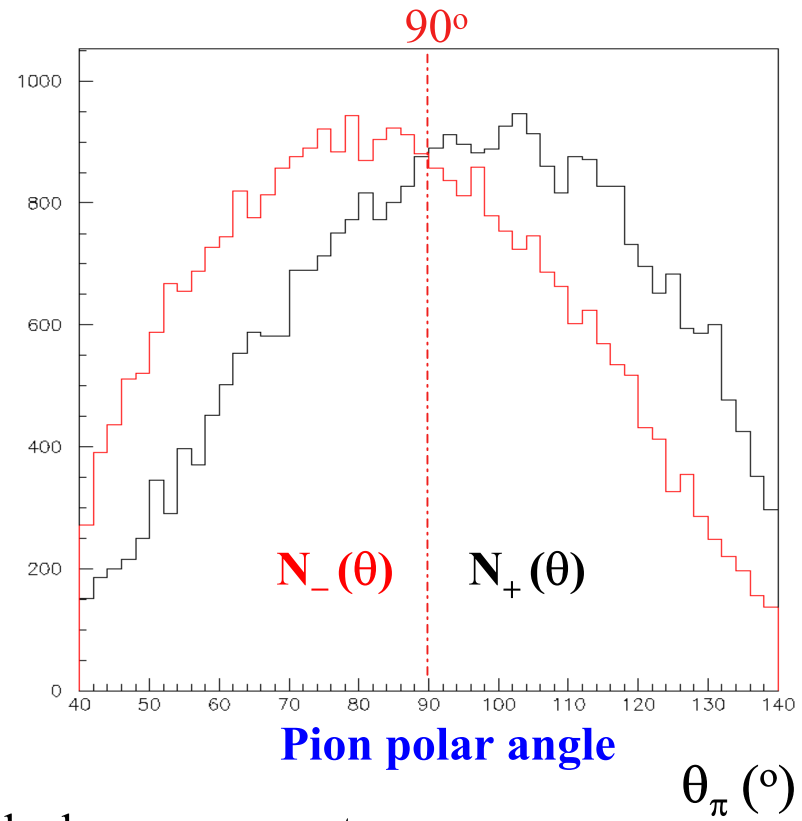
Binner, Kühn, Melnikov, Phys. Lett. B 459, 1999

$$\boxed{A_{FB}(M_{\pi\pi}^{\;2}) = \frac{N(\theta_{\pi+} > 90^\circ) - N(\theta_{\pi+} < 90^\circ)}{N(\theta_{\pi+} > 90^\circ) + N(\theta_{\pi+} < 90^\circ)}}$$

➢ Check the validity of the FSR model used in the Monte Carlo comparing the charge asymmetry between data and Monte Carlo in the presence of FSR

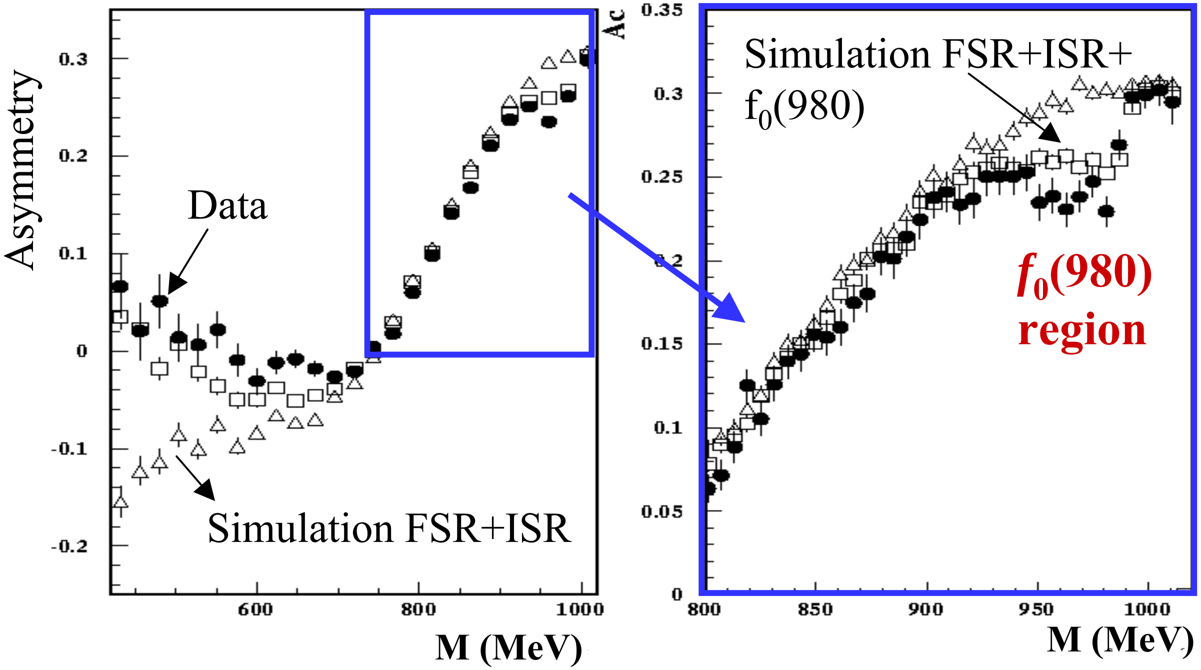
➢ In a similar way, the radiative decay of the $\phi \to f_0(980)\,\gamma$ with $f_0 \to \pi^+\pi^-$ contributes to the charge asymmetry

Czyż, Grzelinska, Kühn, hep-ph/0412239



Possible to study the properties of scalar mesons with charge asymmetry

Charge asymmetry



● Data
△ Simulation FSR+ISR
□ Simulation FSR+ISR+f_0(980)

Monte-Carlo used:
hep-ph/0605244
G. Pancheri, O. Shekhovtsova,
G. Venanzoni

- Clear signal at ~ 980 MeV
- Large threshold effect, even without f_0(600), can be described by f_0(980) only
- On ρ-peak (where scalar amplitude is small) very good agreement between data and simulation: precision test of the model of scalar QED for FSR

Model dependence in f_0(980) amplitude represents the main limitation at threshold

Off peak data

Radiative Return measurements at large ISR-photon angles are limited by reducible and irreducible background from ϕ-decays

Off peak program:

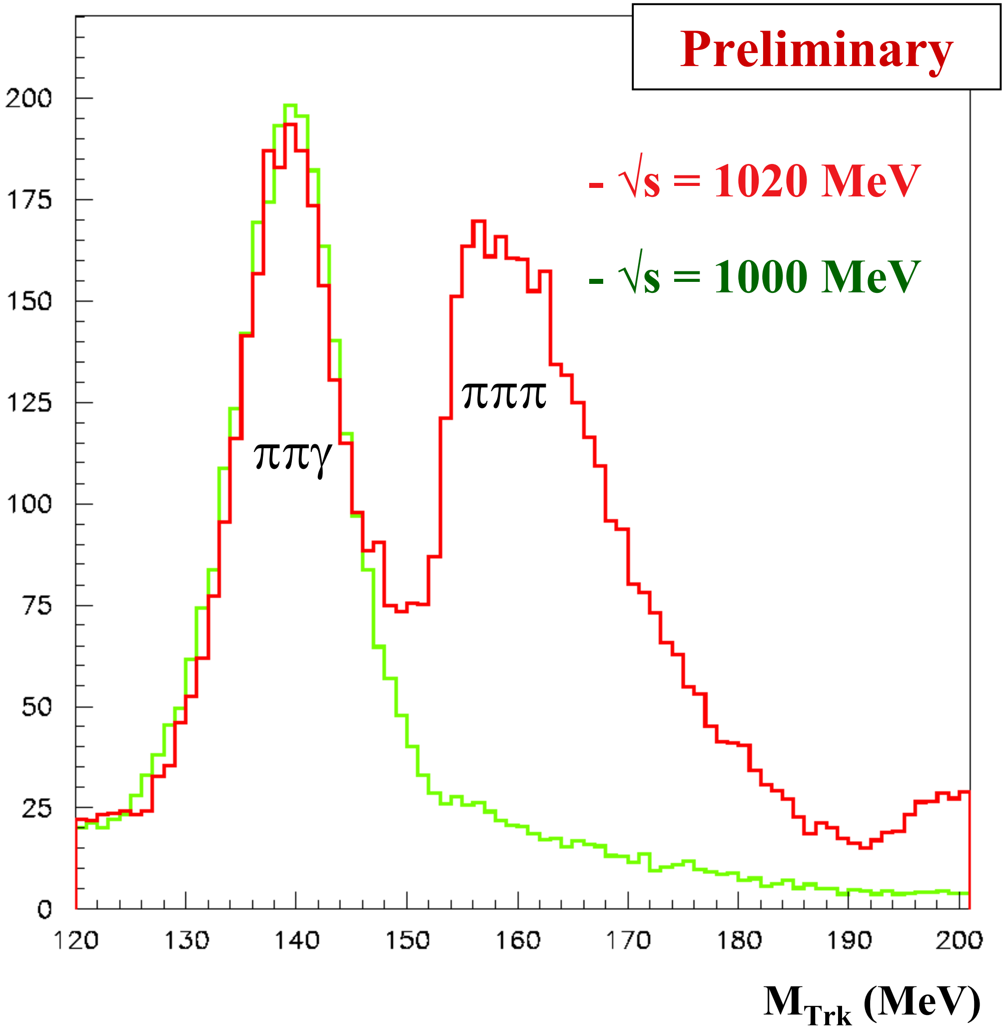
1) Run for 3 months at √s = 1.00 GeV
225 pb^{-1} off-peak collected
(ended on March 16, 2006):

⇒ the ultimate background-free data sample for Radiative Return

⇒ background-free γγ – physics program

2) ϕ - scan with 4 scanning points at
√s = 1.030, 1.023, 1.018, 1.010 GeV
integrated luminosity 10 pb^{-1} each

⇒ study the model-dependence in description of $f_0(980)$



Conclusions

1. KLOE experiment has proven that the radiative return analysis is feasible and has its own merits!

2. Pion form factor measured with 1.3% total precision, some disagreement with CMD-2 and SND

3. Update of small photon angle analysis with 2002 data in progress

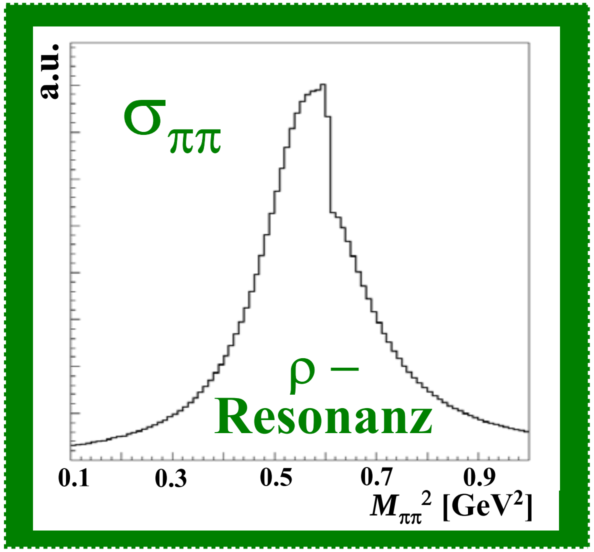
4. Large angle analysis with tagged photon allows to access threshold region, results expected soon with improved precision of region around ρ – peak

❑ Main limitations due to contributions from $\phi \to \pi^+\pi^-\pi^0$ and $\phi \to f_0(980)\gamma$

⇒ dedicated DAΦNE Off-Peak data at $\sqrt{s}=1000$ MeV will allow ultimate precision for $\sigma^{\pi\pi}$ at DAΦNE

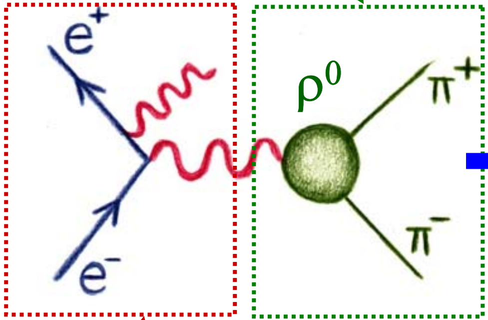
Backup slides

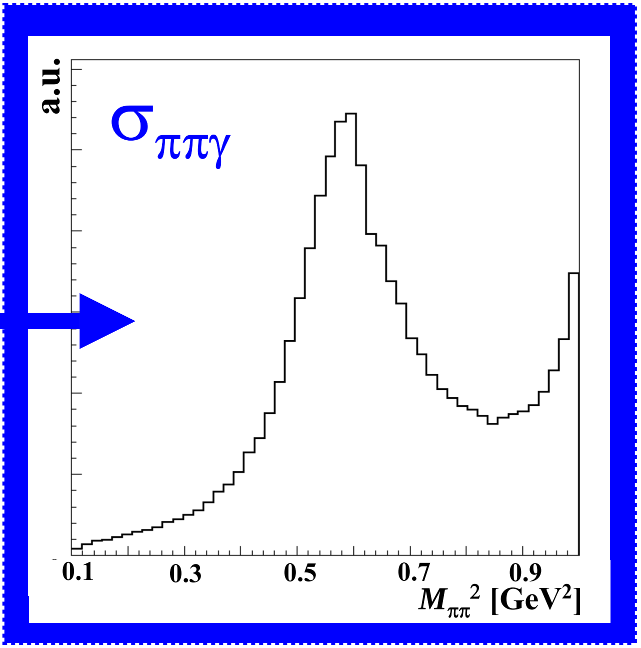
The radiative return



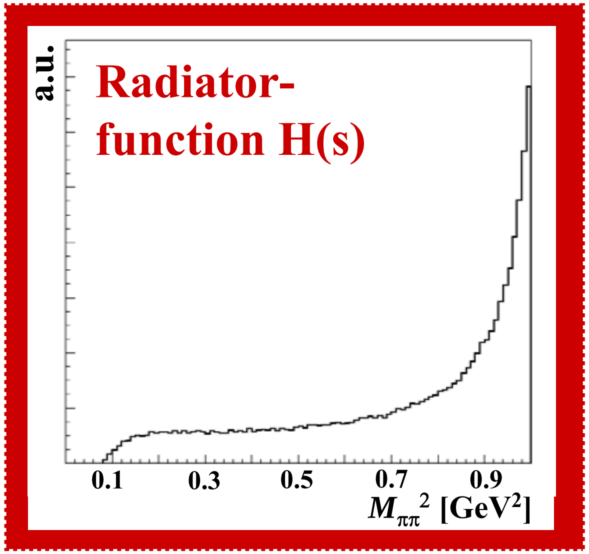
Non-radiative cross section

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





Radiative cross section



J. Kühn, H. Czyż, G. Rodrigo

Theoretical radiator-function

MC- generator *PHOKHARA*

σ^{had} via ISR: a complementary way

While the Energy Scan seems the natural way to measure the σ^{had}, the experience at DAΦNE and PEP-II has shown that the **Radiative Return via Initial State Radiation (ISR)** has to be considered as a complementary approach

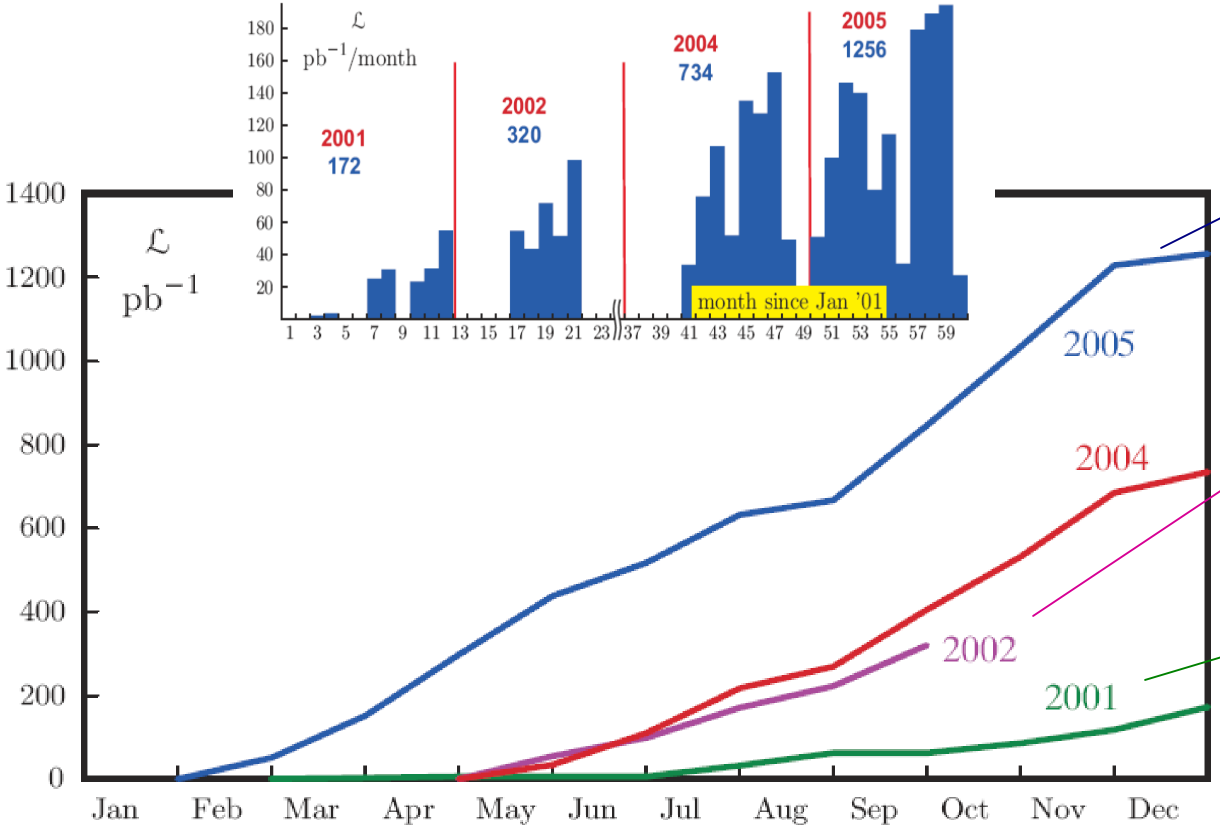
Advantages

- Data comes as by-product of the standard program of the machine, dedicated runs are not needed
- Overall energy scale $\sqrt{s} = M$ well known and applies to all values of M_{had}
- Systematic errors from L, radiative corrections, etc. enter only once and studies for every point in $\sqrt{s}$ are not needed

Issues

- Precise theoretical calculations of the radiator function *H* are required
- Good suppression (or good understanding) of Final State Radiation (FSR) is needed
  - find effective selection cuts
  - test model of scalar QED with data (charge asymmetry)
- High luminosity is needed

DAΦNE statistics



225pb-1 off peak

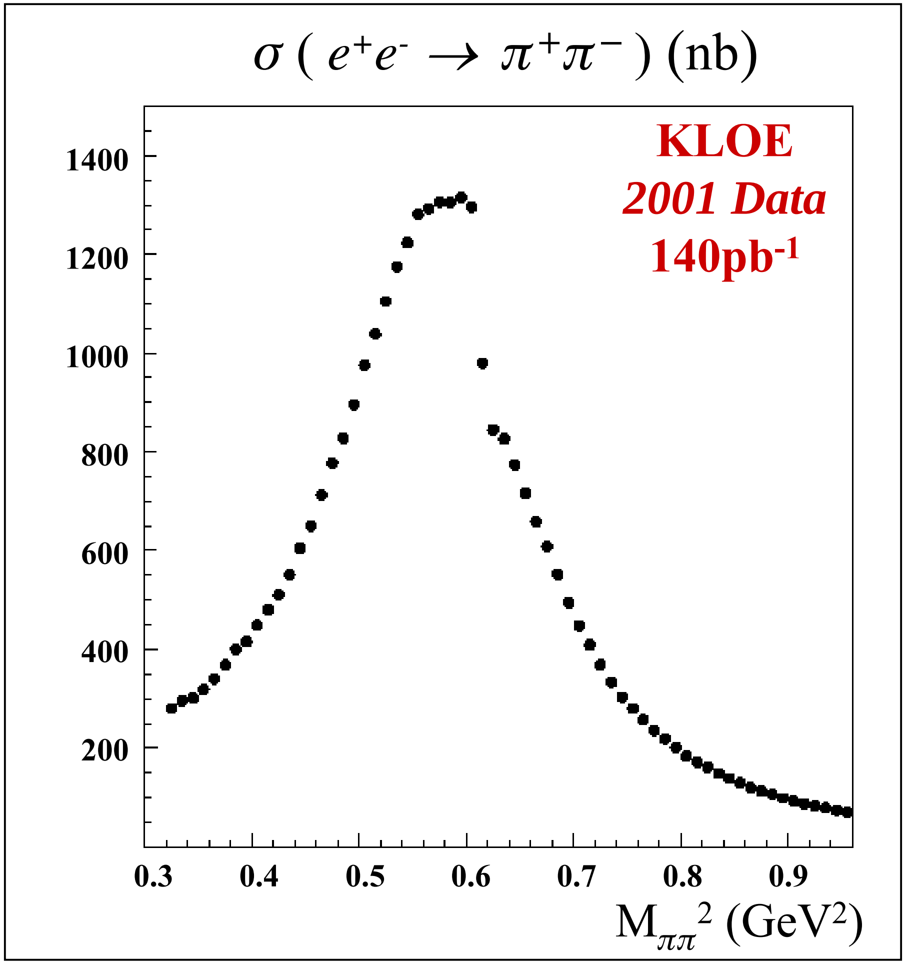
Data for the analysis in preparation

Statistics used for the published analysis (Small angle analysis)

2001 170 pb^{-1}
2002 280 pb^{-1}
analyses nearly completed

2004 734 pb^{-1}
2005 1256 pb^{-1}
ongoing analyses

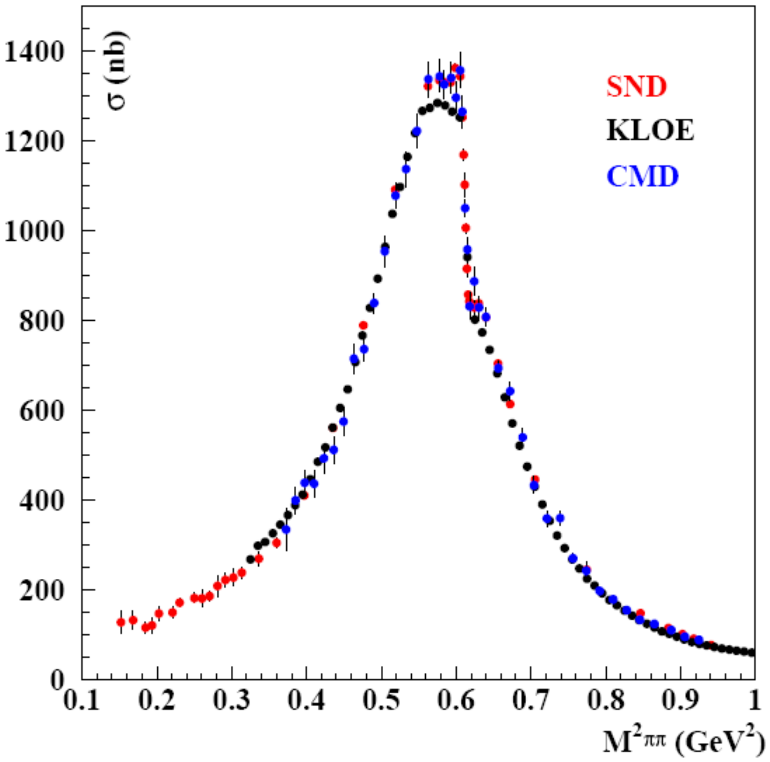
KLOE published result, errors

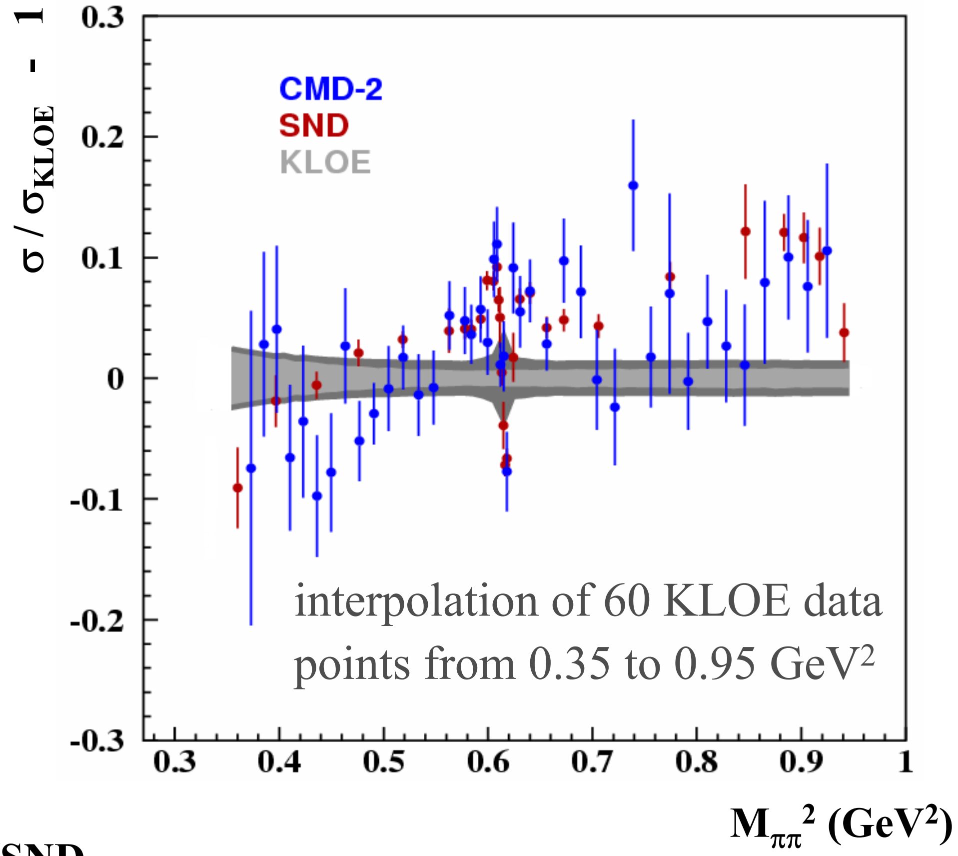


Statistical error negligible (1.5 Million events)

Acceptance	0.3%
Trigger	0.3%
Tracking	0.3%
Vertex	0.3%
Offline reconstruction filter	0.6%
Particle ID	0.1%
Trackmass cut	0.2%
Background	0.3%
Unfolding effects	0.2%
Total experim. systematics	**0.9%**
Luminosity (LA Bhabhas)	0.6%
Vacuum polarization	0.2%
FSR corrections	0.3%
Radiator function	0.5%
Total theoretical Error	**0.9%**
TOTAL ERROR KLOE 1.3% **(CMD-2: 0.9%, SND 1.3%)**	

Comparison among e^+e^- experiments



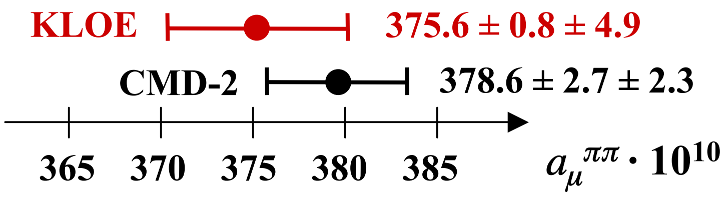


interpolation of 60 KLOE data points from 0.35 to 0.95 GeV²

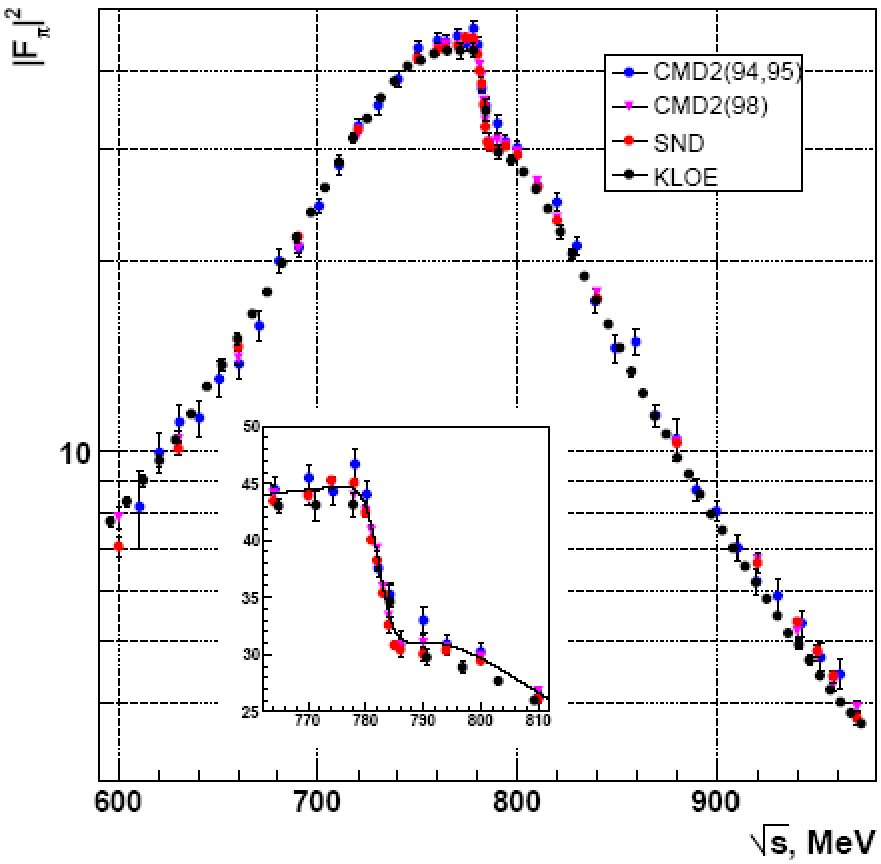
- ✓ CMD-2 and KLOE agree at high $M^2_{\pi\pi}$
- ✓ disagreement between KLOE and CMD-2/SND around the ρ peak

$a_\mu^{\pi\pi}$ contribution (0.37 – 0.93 GeV²)

KLOE:
$(375.6 \pm 0.8_{stat} \pm 4.9_{syst+theo})\ 10^{-10}$
CMD-2:
$(378.6 \pm 2.7_{stat} \pm 2.3_{syst+theo})\ 10^{-10}$

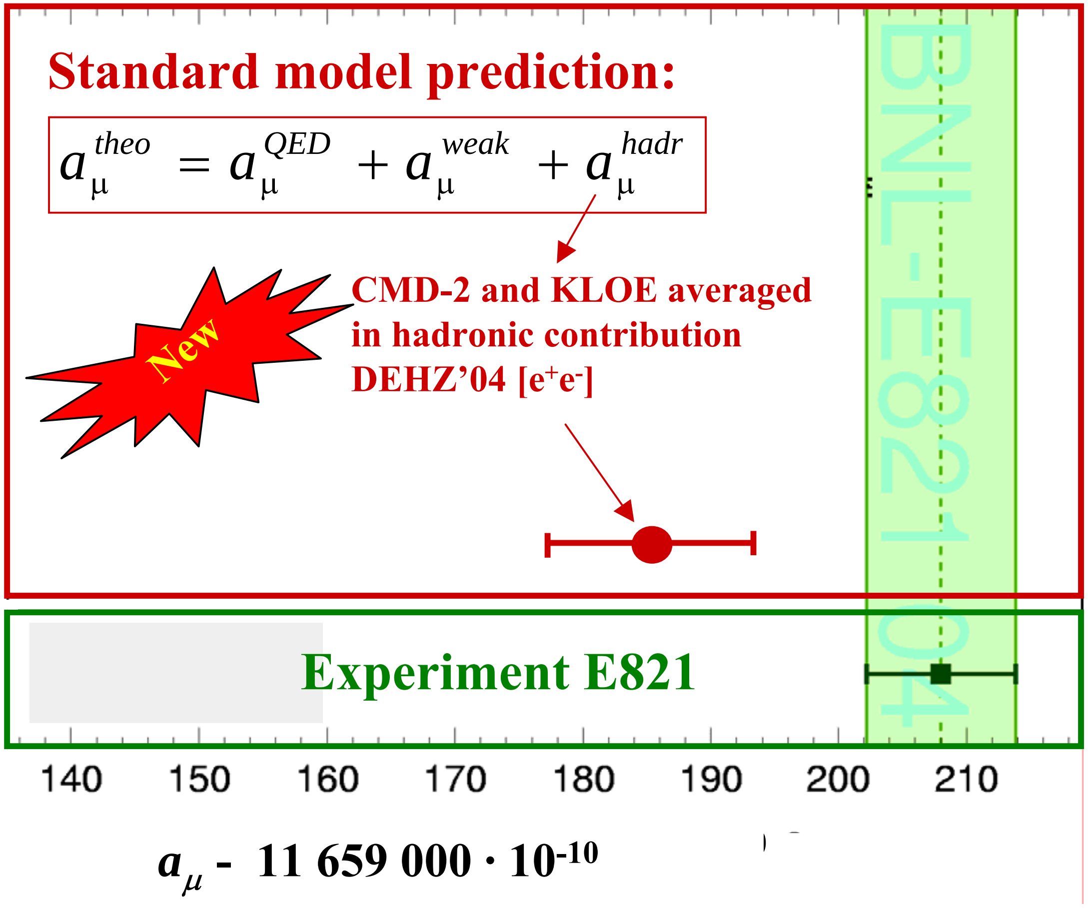


Backup slides



Muon anomaly comparison Theory - Experiment

KLOE and CMD-2 results used to evaluate the hadronic contribution and therefore the muon anomaly



Standard model prediction:

$$a_\mu^{theo} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadr}$$

New

CMD-2 and KLOE averaged in hadronic contribution DEHZ'04 [e^+e^-]

Experiment E821

New KLOE measurement Phys. Lett. B606 (2005) 12

- New 4th order QED calculation (Kinoshita, Nio) Phys. Rev. D70 (2004) 113001
- New 'Light-by-light' calculation (Melnikov, Vainshtein) Phys. Rev. D70 (2004) 113006

Theory (SM) - Experiment

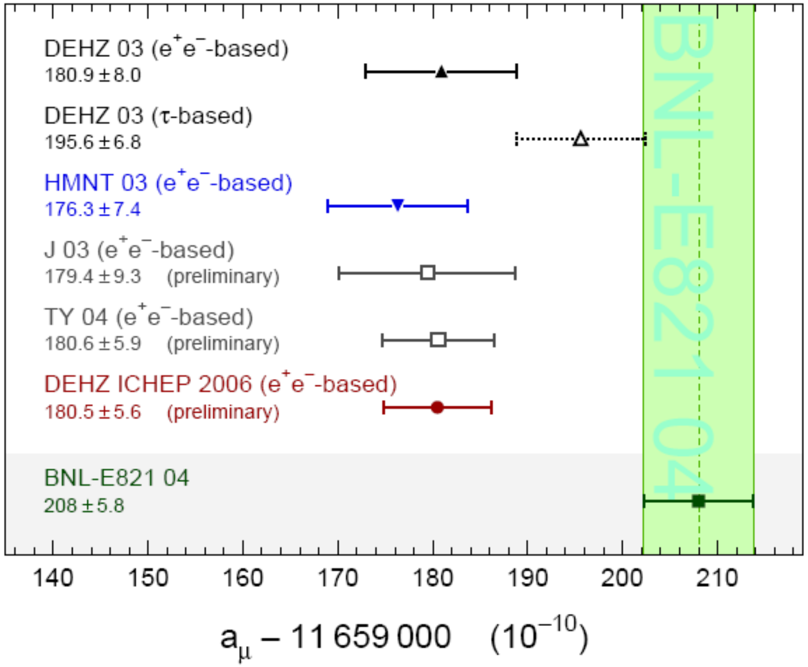
$$a_\mu^{exp} - a_\mu^{theo} = (25.2 \pm 9.2) \cdot 10^{-10}$$

2.7 standard deviations difference !

Muon anomaly comparison Theory - Experiment

Theory vs Experiment

Contribution	$a_\mu, 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.8 ± 0.016
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.3 ± 5.6
Exp.–Theory	$27.7 \pm 8.4\ (3.3\sigma)$



The difference between experiment and theory is 3.3σ!

Final State Radiation photon

Events end up in the wrong $M^2_{\pi\pi}$ bin in the measured spectrum

LO-FSR: events with $M_{\gamma *} = \sqrt{s} = 1020$ MeV contaminate signal region with $M^2_{\pi\pi} < 0.95$ GeV^2

- subtract by means of Monte Carlo (scalar QED)
- small angle selection cuts highly suppress these events
- interference between FSR- and f_0- amplitude in large angle analysis

NLO-FSR: spectrum has to be “reweighted” in order to move events to the correct $M^2_{\pi\pi}$ bin

- reweighting function obtained by Monte Carlo (scalar QED)