3rd International Symposium on Lepton Moments
June 19-22, 2006
Cape Cod

The Measurement of the Hadronic Cross Section using Radiative Return at KLOE

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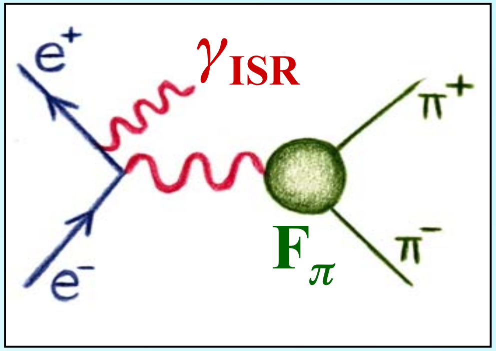
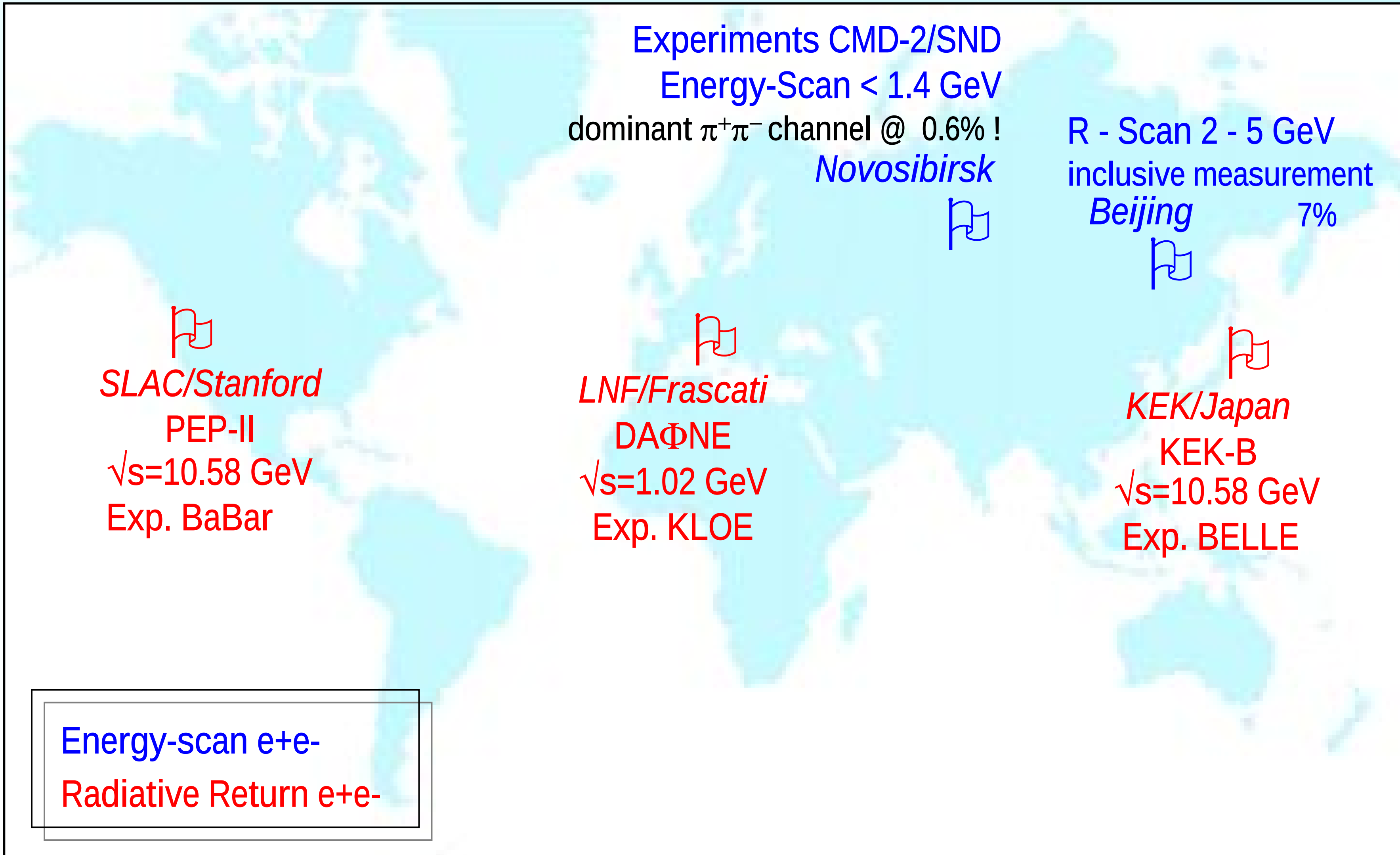


The
Radiative Return

Cross Section Measurements Worldwide

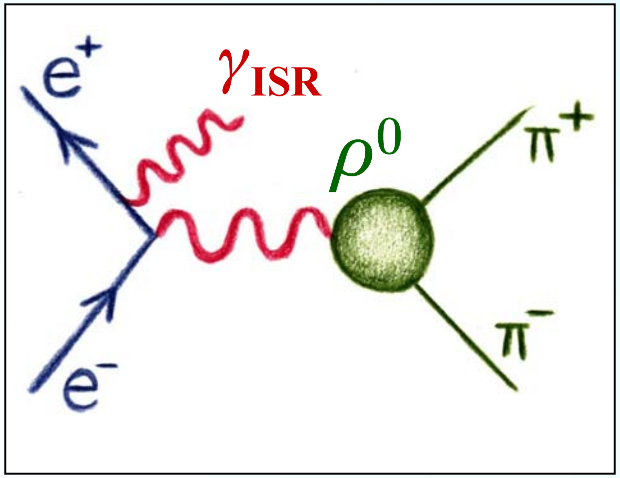


Radiative Return - How?

Modern particle factories, such as **DAΦNE or PEP-II/KEK-B are designed for a fixed center-of-mass energy**: $\sqrt{s} = m_\phi = 1.02$ GeV in the case of DAΦNE, $\Upsilon(4s)$ in case of B-factories: **Energy-scan not possible!**

New and completely complementary ansatz:
Consider events with **Initial State Radiation (*ISR*)**

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



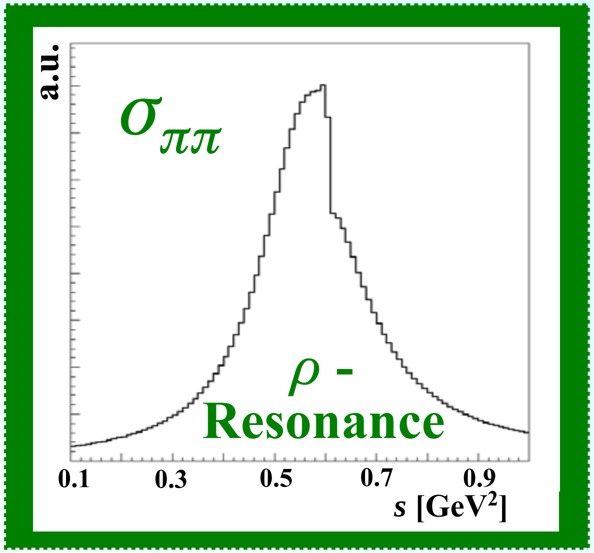
'Radiative Return' to $\rho(\omega)$-resonance:

$$e^+ e^- \to \rho(\omega) + \gamma \to \pi^+ \pi^- + \gamma$$

$$\frac{d\sigma_{hadr+\gamma}}{dM_{hadr}^2} = \frac{d\sigma(e^+ e^- \to \text{hadr} + \gamma_{ISR})}{dM_{hadr}^2}$$

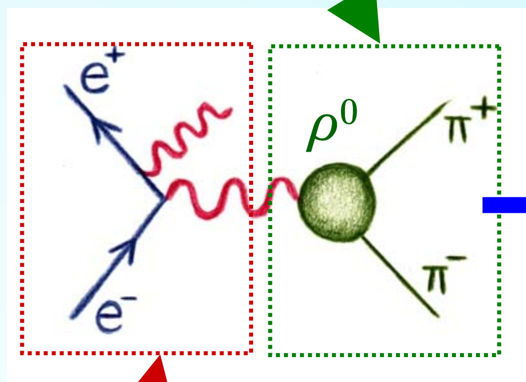
for $(2m_\pi)^2 < M_{hadr}^2 < s$

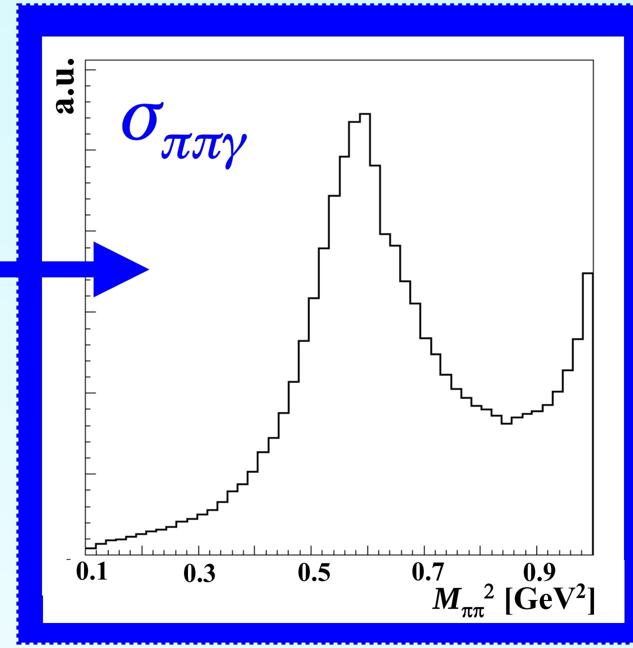
Extract the Non-Radiative Cross Section



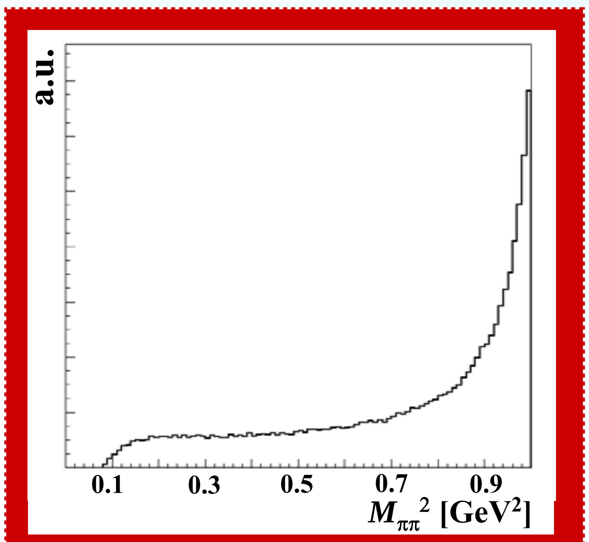
Non-radiative cross section

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





Radiative cross section



Correct for ISR-process
Radiator function H(s)
MC- Generator *PHOKHARA*
H.Czyż, H.Kühn, G.Rodrigo

Pros & Contras

Energy Scan seems the natural way to measure hadronic cross sections, experience at DAΦNE/PEP-II has shown that the Radiative Return has to be considered as a complementary approach

Advantages:

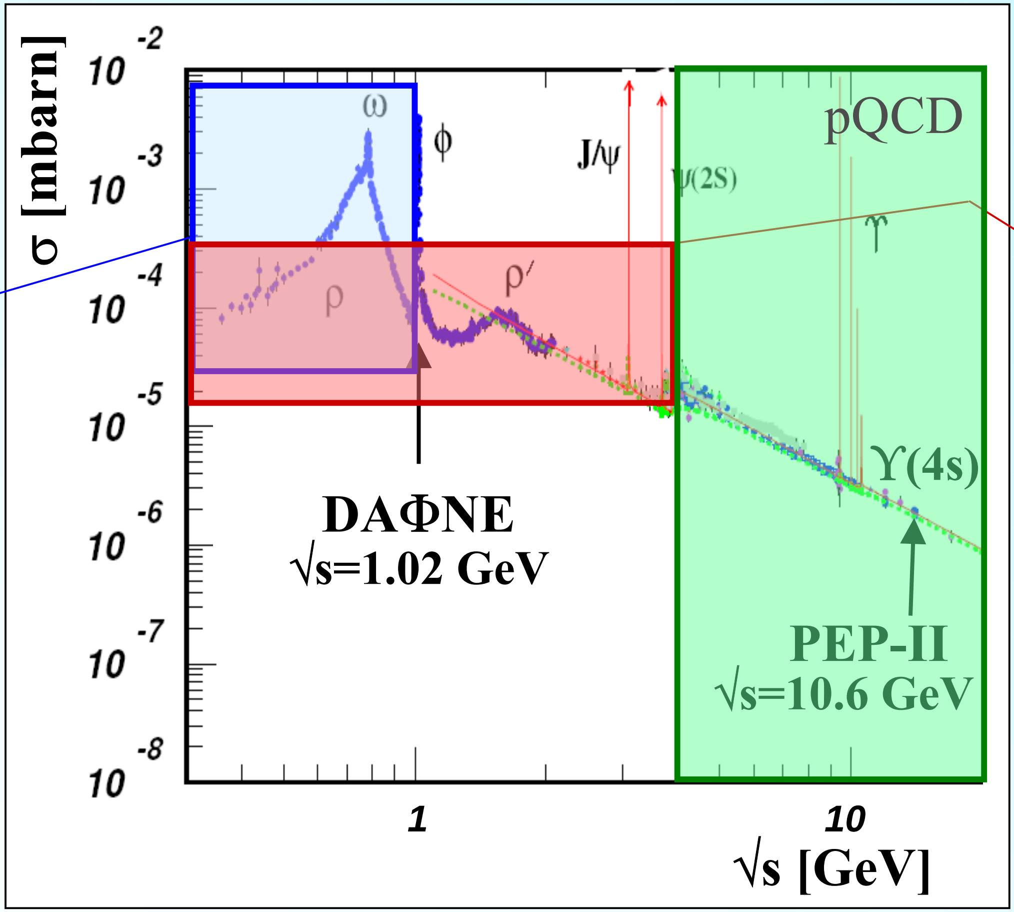
- Data comes as a by-product of the standard program of the machine, no dedicated runs necessary
- Overall energy scale $\sqrt{s}=m_\phi$ is well known and applies to all values of $M_{\pi\pi}$
- Systematic errors from luminosity, $\sqrt{s}$, rad. corrections... enter only once and do not have to be studied for each point of s

Issues:

- Requires a precise theoretical calculation of the radiator function
- Requires good suppression (or under= standing) of Final State Radiation (FSR);
  - appropriate selection cuts very effective
  - test model of scalar QED in data (charge asymmetry)
- Needs high integrated luminosity; for 2-Pion-channel at DAΦNE no problem, but more critical for channels with higher multiplicities with much lower cross sections, which are under study at PEP-II

Radiative Return at Particle Factories

Experiment KLOE:
Energy region < 1 GeV, dominated by 2π-channel (ρ-resonance)



Experiment BaBar:
Energy region 1 ... 3 GeV, dominated by higher multiplicities (esp. 4π), up to recently data with 20 ... 50% systematic errors!

Using the method of the **Radiative Return** one can study the entire **energy region below ca. 4...5 GeV** → **this is the relevant region for $(g\text{-}2)_\mu$!**

Connection to the Muon Anomaly

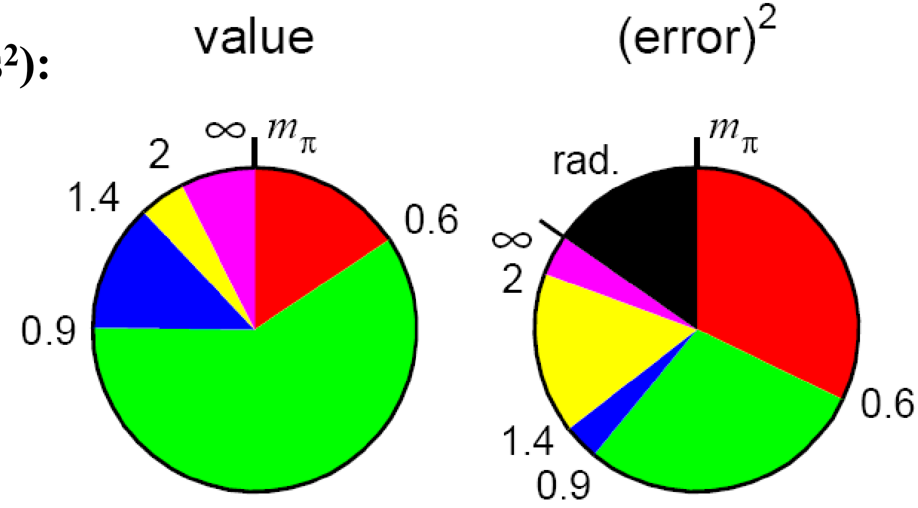
- **Hadronic contribution a_μ^{hadr} is limiting the standard model prediction for $(g-2)_\mu$!**

a_μ^{hadr} estimated by means of a dispersion relation (intrinsically ~1/s²):

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

Experimental input into dispersion integral

$\sigma(e^+e^- \to \pi^+\pi^-)$ needed with $\leq$ 1% precision (70% contr.)!



K. Hagiwara, A.D. Martin, D. Nomura and T. Teubner, Phys. Rev. **D69** (2004) 093003

- Threshold region $\sigma_{\pi\pi}$ < 600 MeV now equally important as ρ-peak region in the error for a_μ^{hadr} even so absolute contribution much smaller
  → needs to be measured with better accuracy (this talk!)
- Also region between 1.4 – 2.0 GeV contributes significantly to error
  → radiative return at PEP-II with BaBar

KLOE Measurement of the Pion Formfacor

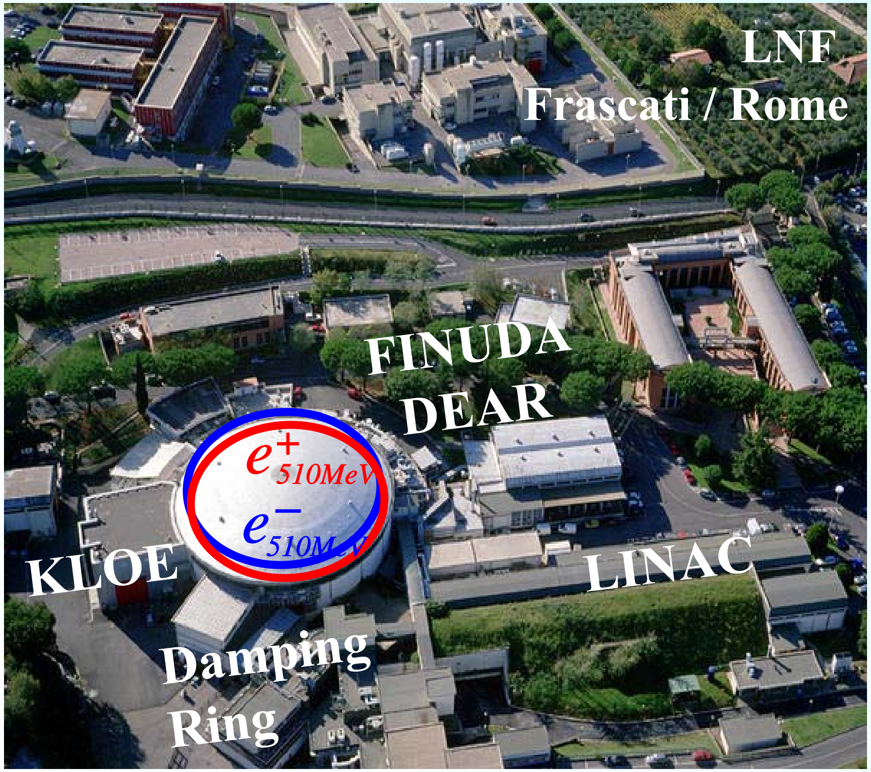
(i) Untagged analysis with 2001 data — Phys. Lett. B606 (2005) 12

(ii) Untagged analysis with 2002 data — New

(iii) Tagged analysis with 2002 data

KLOE @ DAΦNE

Electron-Positron-Collider with
$\sqrt{s} = m_\phi = 1.0194$ GeV
Detectors KLOE and FINUDA/DEAR

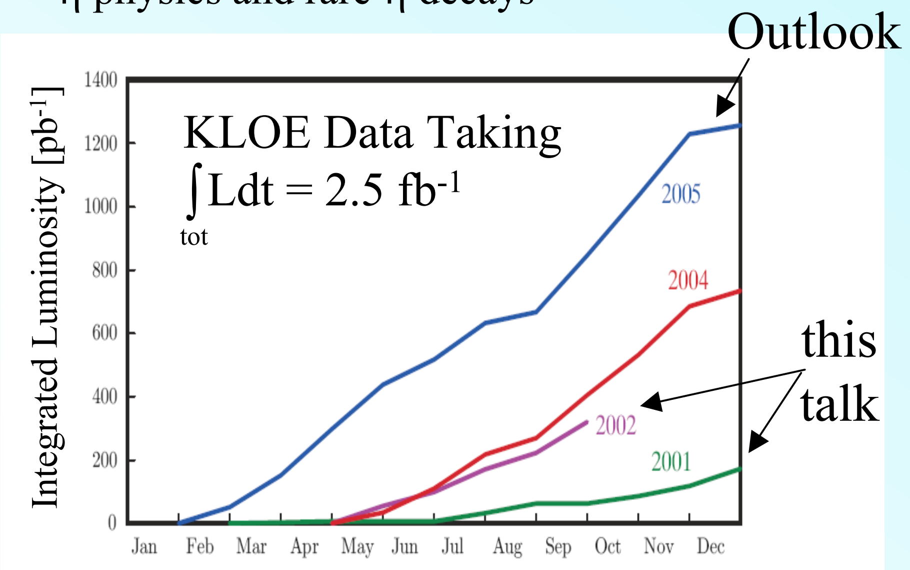


Main focus on KAON physics

- CPT test: **semileptonic K_s** - K_L charge asymm.
- **V_{us}**, kaon form factors from semileptonic $K_{S,L}$, $K^\pm$ decays, K_L and $K^\pm$ lifetimes
- Rare $K_{S,L}$ decays (**$K_S \to 3\pi^0$**, $\pi^+\pi^-\pi^0$, $K_L \to \pi^+\pi^-$, $K_L \to \gamma\gamma$...)

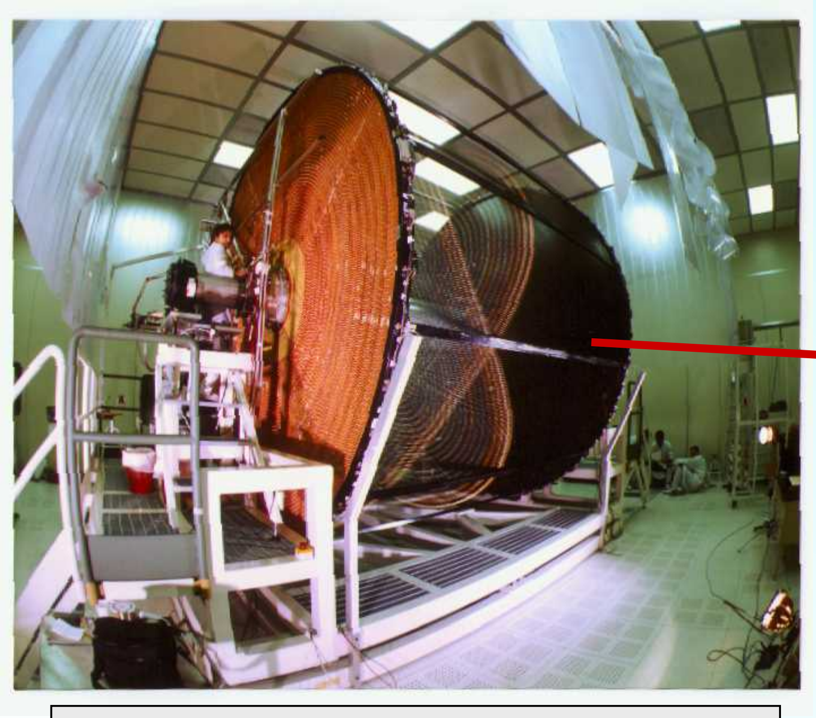
Non Kaon Physics

- **radiative ϕ decays** (scalars, pseudoscalars)
- **hadronic cross section**
- η physics and rare η decays

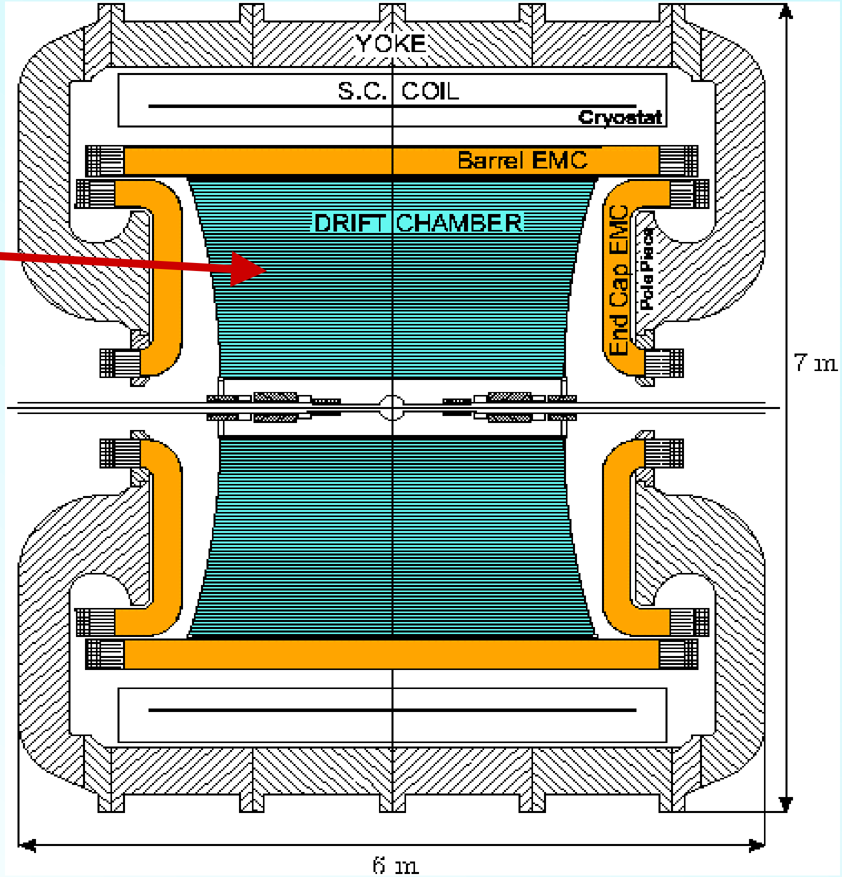


Selection $\pi^+\pi^-\gamma_{ISR}$

Drift chamber



The KLOE Detector

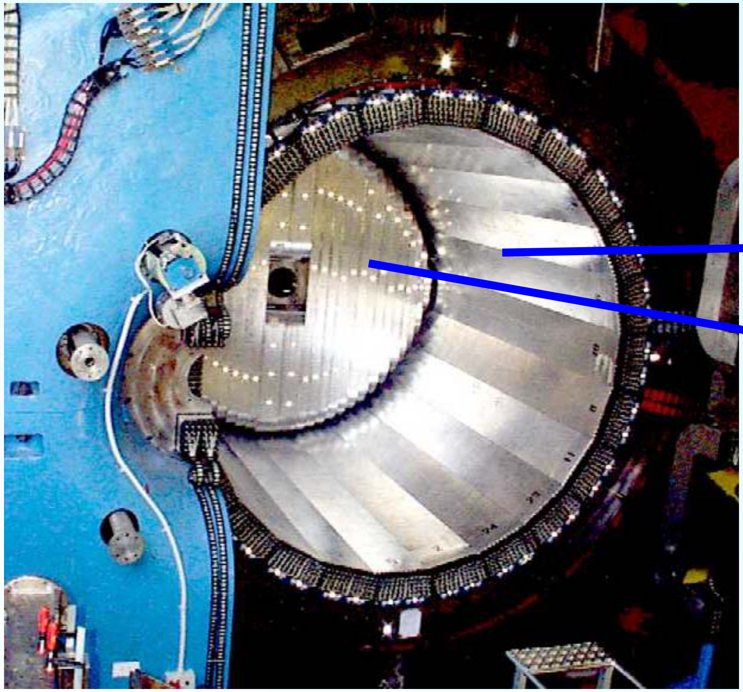


$\sigma_{r\phi} = 150\ mm$, $\sigma_z = 2\ mm$
$\sigma_p / p = 0.4\%$ (for 90^o Tracks)
Excellent momentum resolution

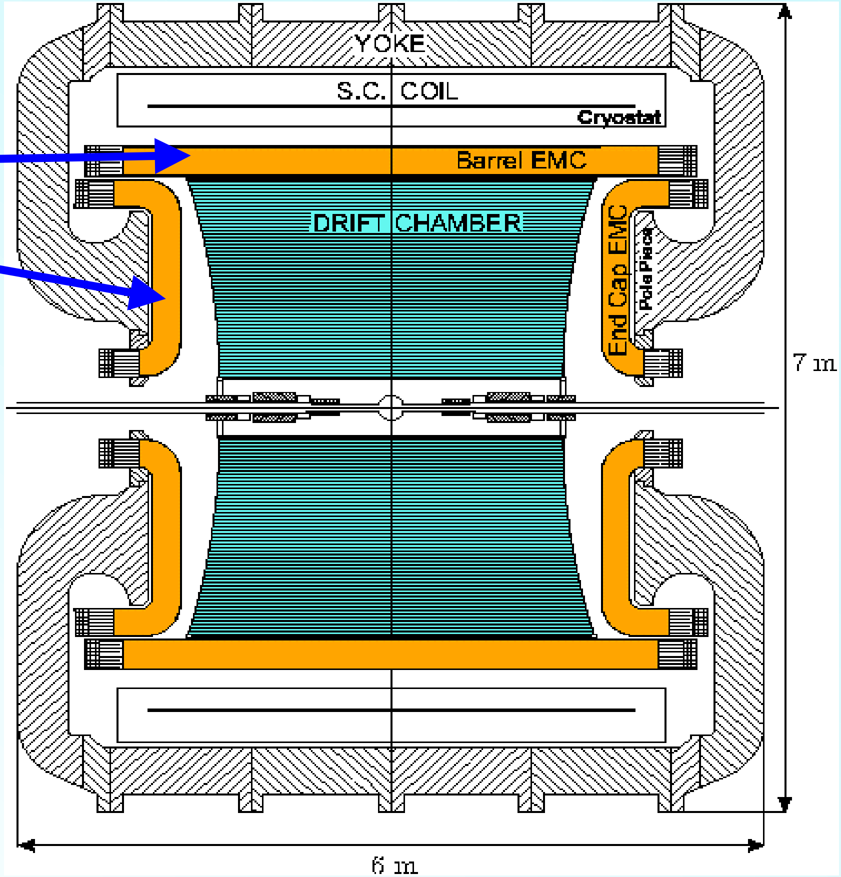
Full stereo geometry, 4m diameter,
52.140 wires *90%* **Helium**, *10%* **iC_4H_{10}**

Selection $\pi^+\pi^-\gamma_{ISR}$

Electromagnetic Calorimeter



The KLOE Detector



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

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

Excellent time resolution

***Pb* / scintillating fibres (*4880 PMT*)**

Endcap - Barrel - Modules

Selection $\pi^+\pi^-\gamma_{ISR}$

Pion tracks at large angles

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

a) Photons at small angles

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

→ No photon tagging

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

- High statistics for *ISR* photons
- Negligible contribution of *FSR*
- Reduced background

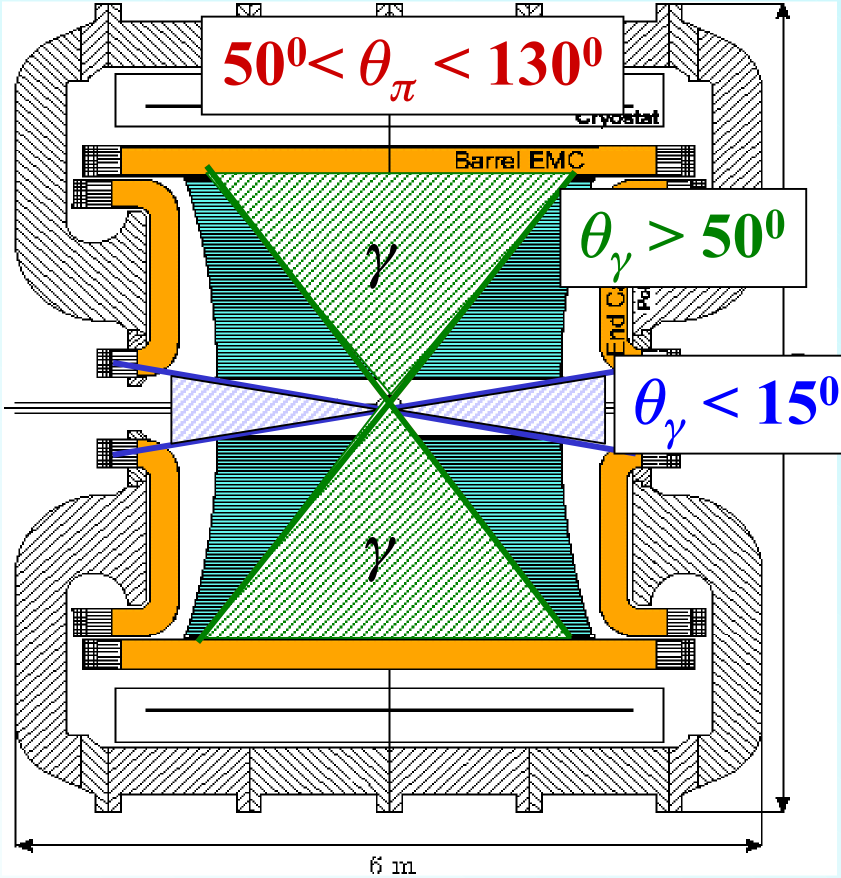
b) Photons at large angles

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

→ Photon tagging possible

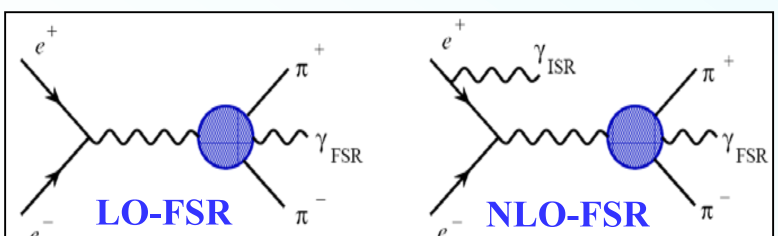
- Measurement of threshold region
- Increased contribution of *FSR*
- Contribution $\phi \to f_0(980)\,\gamma \to \pi^+\pi^-\gamma$

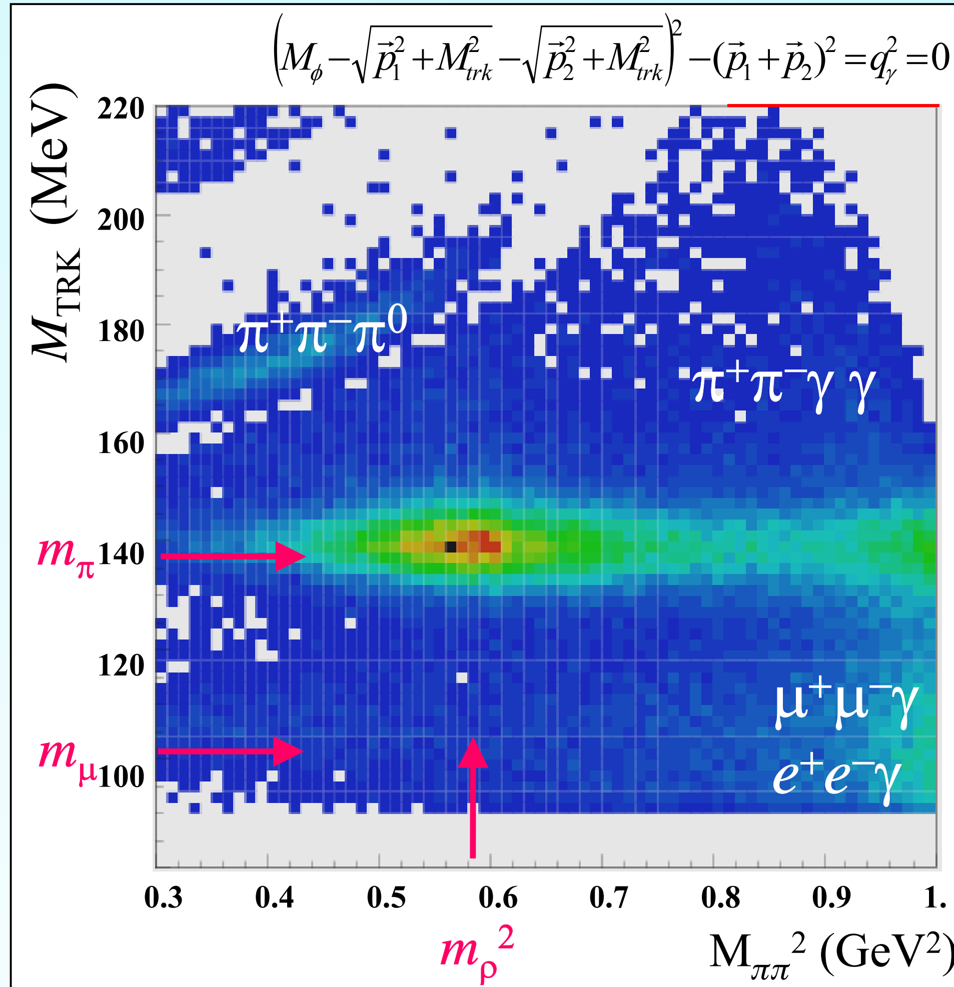
The KLOE Detector



Small Angle Analysis

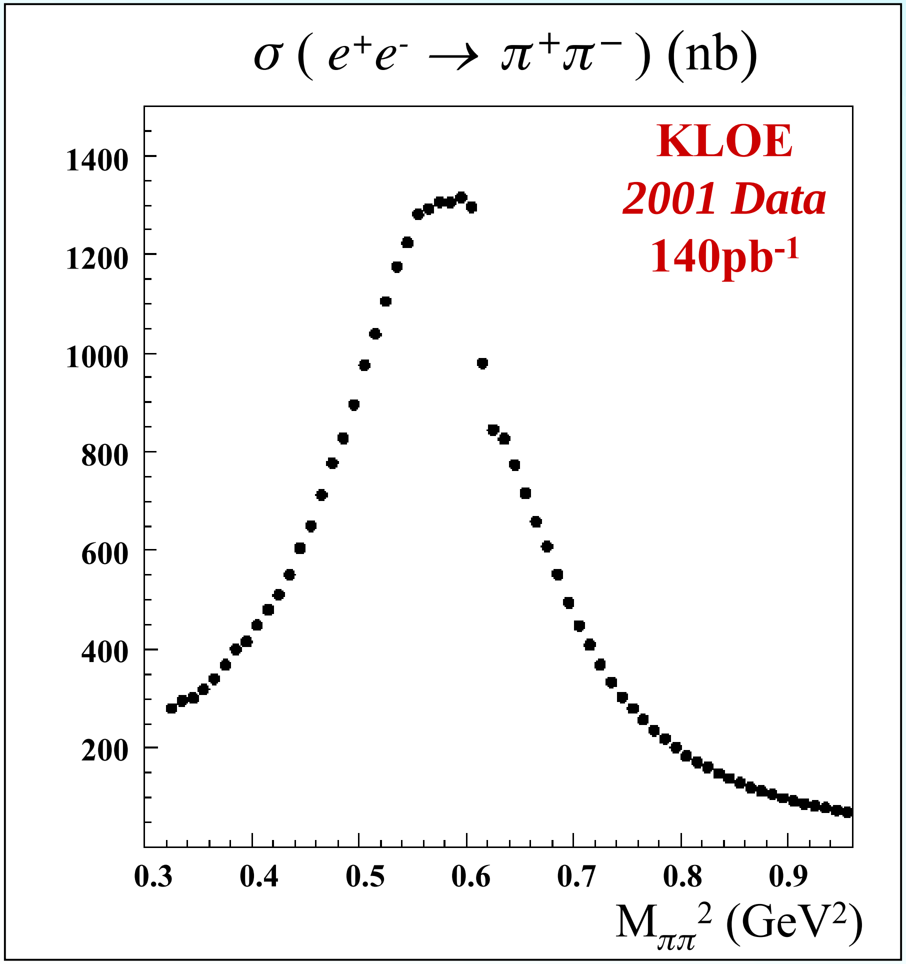
- Experimental challenge: fight background from $\phi \rightarrow \pi^+\pi^-\pi^0$, $\mu^+\mu^-\gamma$ and $e^+e^-\gamma$, reduced by means of kinematic cuts (trackmass), and likelihood function (e-π-separation)
- Normalization to integrated luminosity, which is obtained from large-angle-Bhabha events (clean exp. selection)
- Background from LO-FSR negligible (reduced by acceptance cuts: small Θ_γ), NLO-FSR not reduced and not a background, efficiency has to be known





Result Small Angles

Phys. Lett. B606 (2005) 12

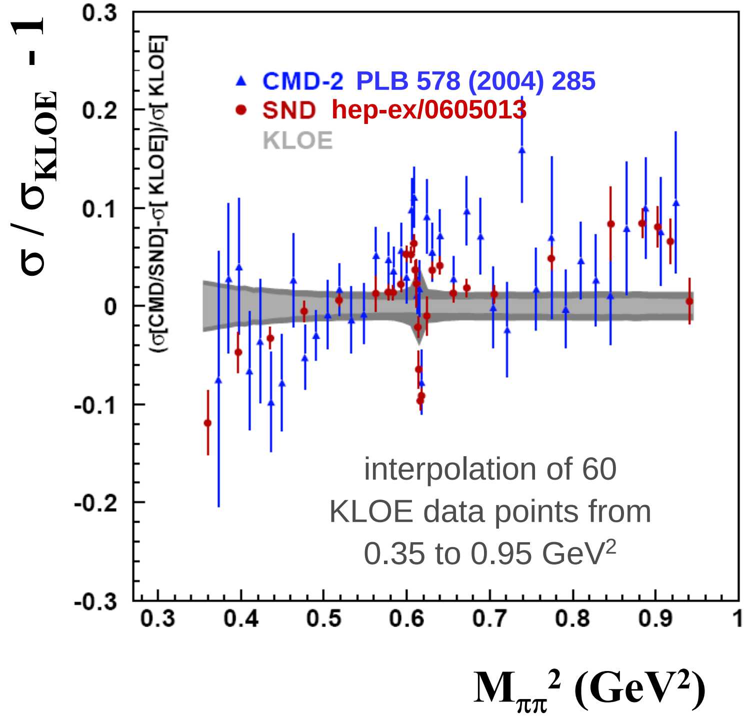


Statistical error negligible (1.5 Million events)

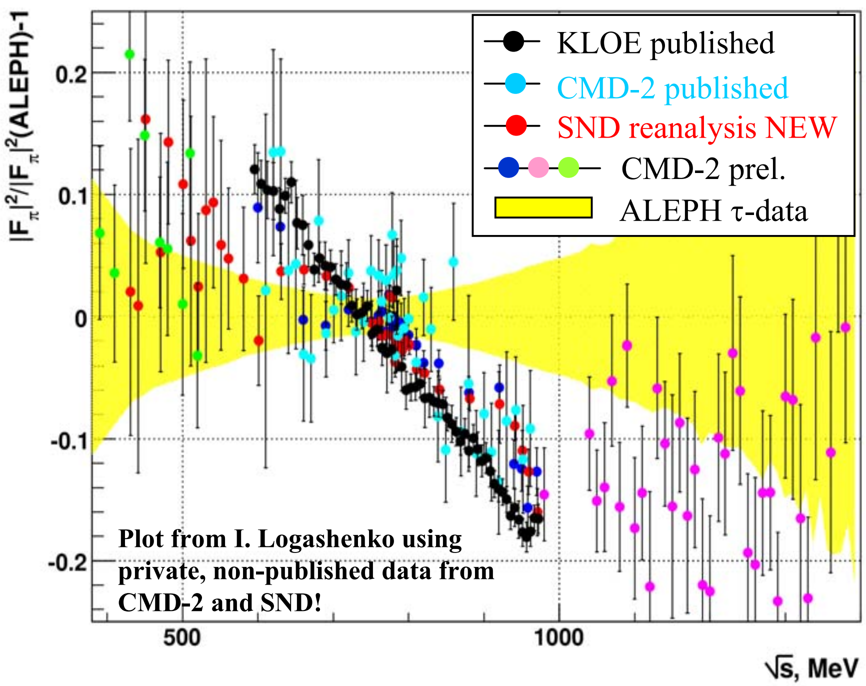
Acceptance	0.3%
Trigger	0.3%
Tracking	0.3%
Vertex	0.3%
Offline reconstruction filter	0.6%
Particle ID	0.1%
Trackmass cut	0.2%
Background	0.3%
Unfolding effects	0.2%
Total experim. systematics	**0.9%**
Luminosity (LA Bhabhas)	0.6%
Vacuum polarization	0.2%
FSR corrections	0.3%
Radiator function	0.5%
Total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

Comparison with recent e^+e^- - and τ - Data

Relative difference of CMD-2 and SND‘06 wrt KLOE interpolated data



Relative difference of e+e- data (published and preliminary) wrt τ-data from ALEPH



→ All recent e+e- experiments see large deviations with τ-data above ρ peak

→ Some disagreement btw. KLOE and SND (and CMD-2?) seen at low and high masses

→ **All recent e+e- experiments agree now within 0.5σ in the 2π-contribution to a_μ^{had}**

(ii)

Untagged analysis with 2002 data

Small Angle Analysis with 2002 Data

A new analysis is carried out at small photon angles using 2002 data (240pb^{-1}) with improved machine background conditions and calibration conditions

Goals: - **reduction of the total systematic error <1%** (was 1.3% for exp.+theory)

- **measure the R-Ratio=$\sigma_{\pi\pi}/\sigma_{\mu\mu}$**

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

Error was limited by cosmic veto filter, which caused up to 30% inefficiency **CURED** by introducing L3-Filter, no cosmic veto inefficiency anymore

Main syst. experimental error due machine background dependence of an offline-event filter **CURED** by changing reconstruction filter, error reduces to <0.1%

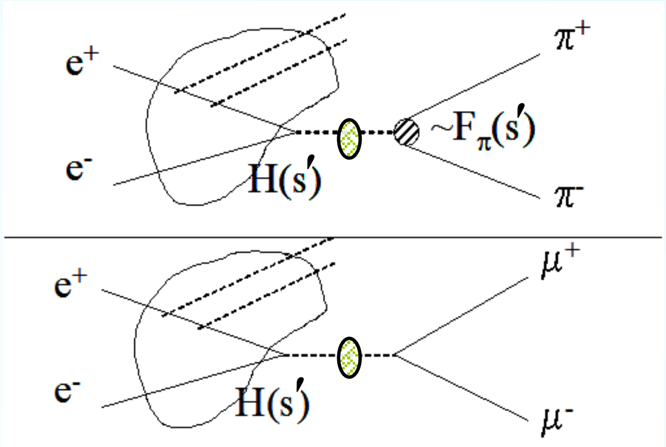
*** Reduction of error, larger data set allows more precise determination**

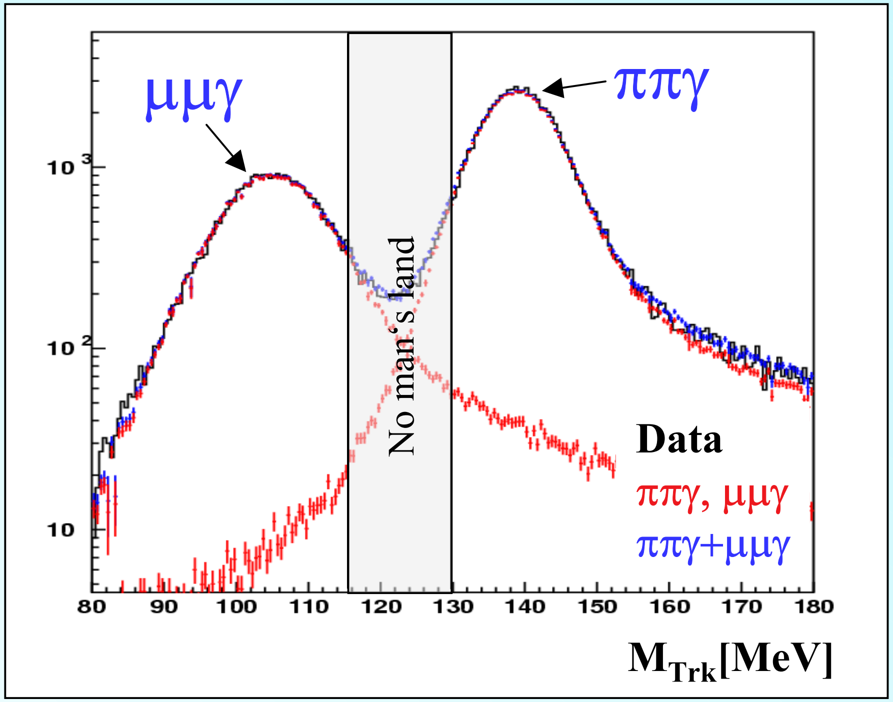
→ see later large angle analysis!

Normalization to Muon - Pairs

Normalization to muon pairs allows to determine directly R-Ratio=$\sigma_{\pi\pi}/\sigma_{\mu\mu}$

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



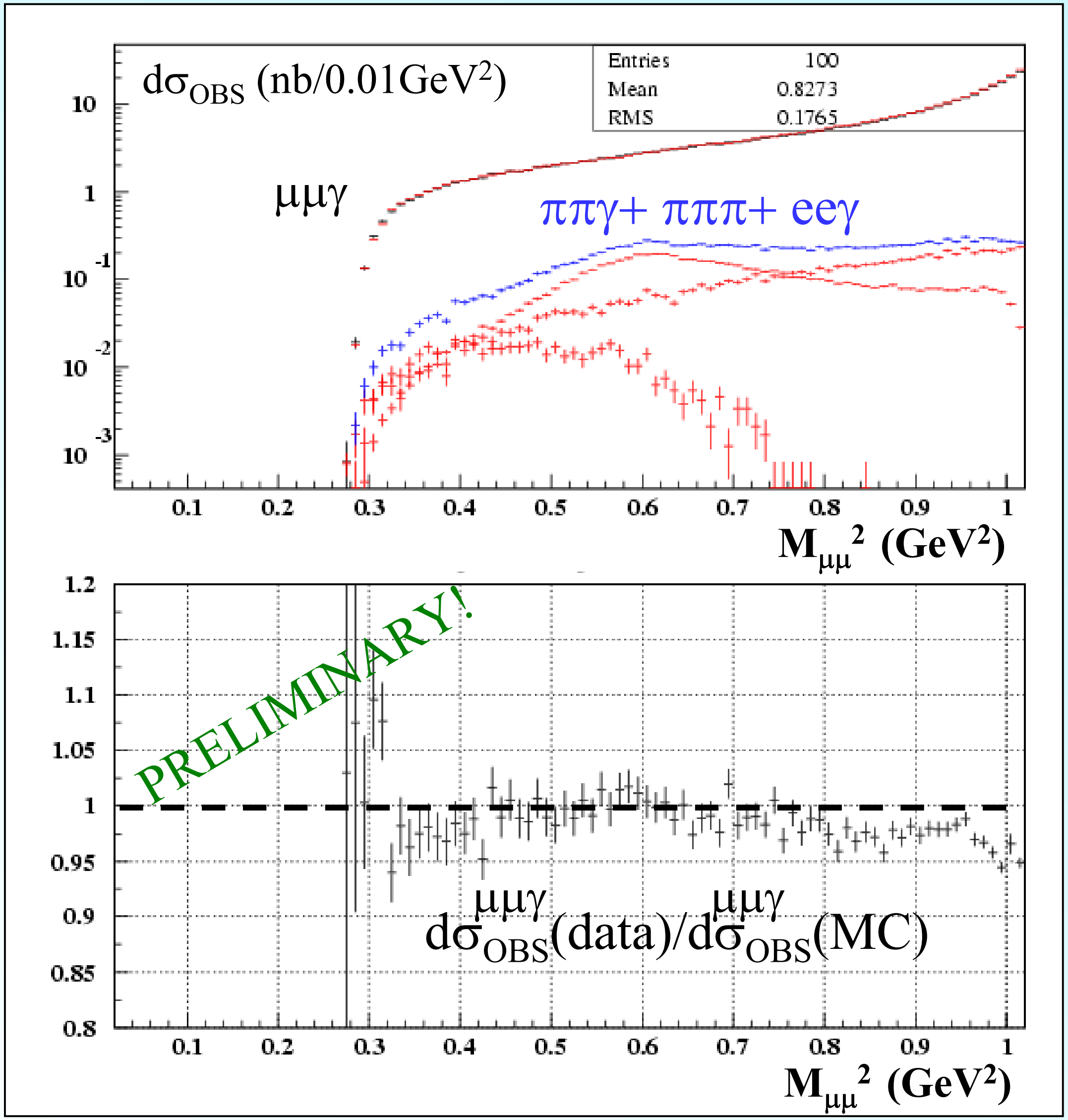


~~Luminosity (LA Bhabhas)~~	~~0.6%~~
~~Vacuum polarization~~	~~0.2%~~
FSR corrections	0.3%
~~Radiator function~~	~~0.5%~~
Theory Error 2001 data:	**0.9%**

These contributions to the theoretical error drop in case the R-ratio is measured
BUT: requires to select μμγ events with similar precision as ππγ !

Test of the Radiator-Function

- **Compare μμγ–yield in data with Monte-Carlo simulation (PHOKHARA generator),** which is using identical radiative ISR-corrections as for the F_π analysis (radiator function)



Important cross check of radiator function; preliminary comparison gives agreement with an accuracy <2%;

Previous comparison with KKMC event generator gave <0.5% agreement

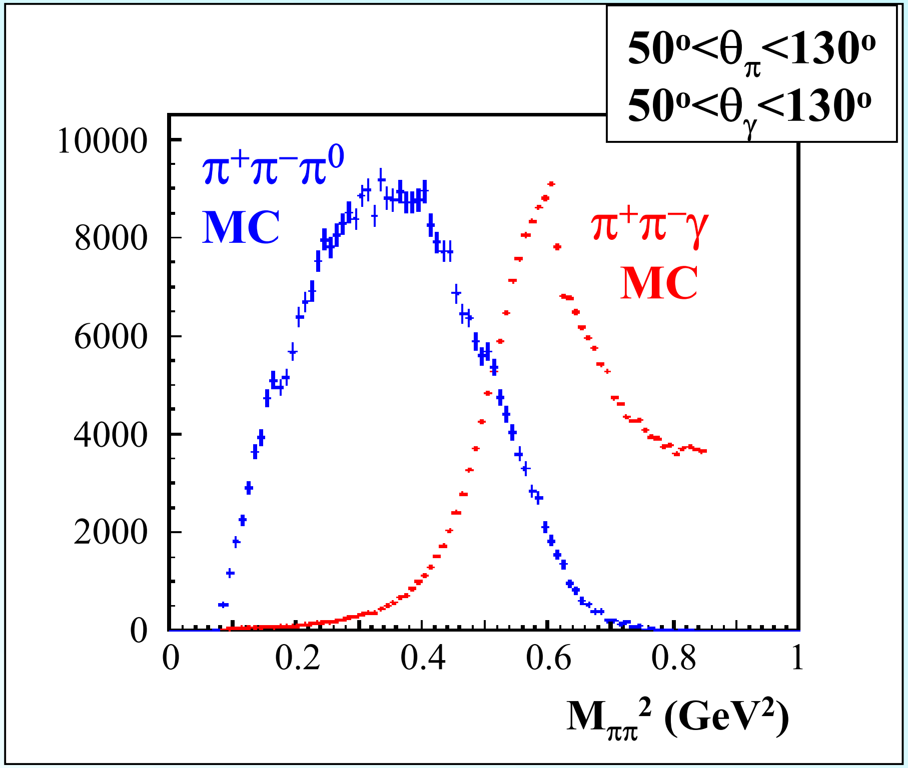
(iii)

Tagged analysis with 2002 data

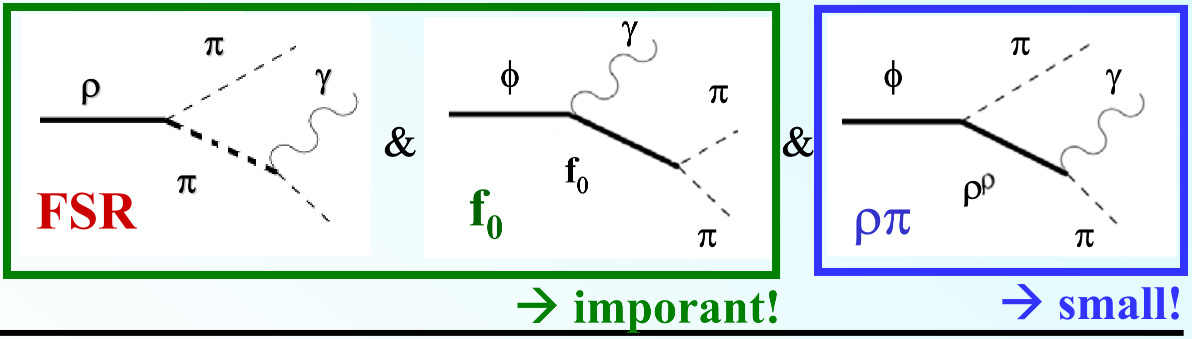
Analysis 2002 Data: Large Photon Angles

PRO & CONTRA

- ✓ important **cross-check**
- ✓ the **threshold region** is accessible
  ca. 20% contribution to a_μ^{hadr}
- ✓ **photon tagging** is possible
  (4-momentum constraints)
- ✓ lower signal statistics
- ✓ **large $\phi \to \pi^+\pi^-\pi^0$** background
- ✓ **LO-FSR** not negligible anymore
- ✓ **irreducible bkg. from ϕ decays**



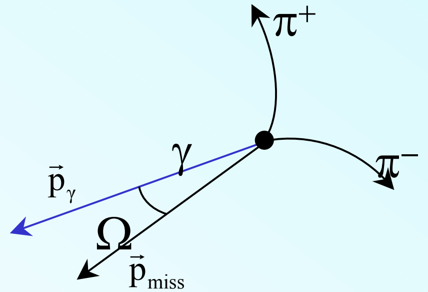
Threshold region non-trivial
due to irreducible FSR-effects,
which have to be cut from MC
using phenomenological models
(interference effects unknown)

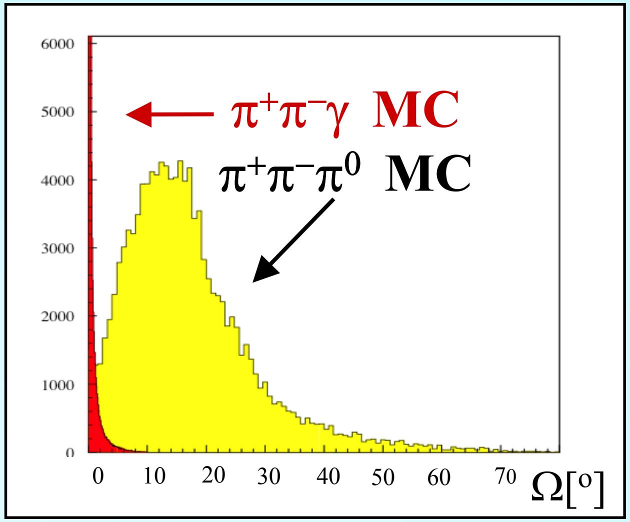


Background $\phi \to \pi^+\pi^-\pi^0$

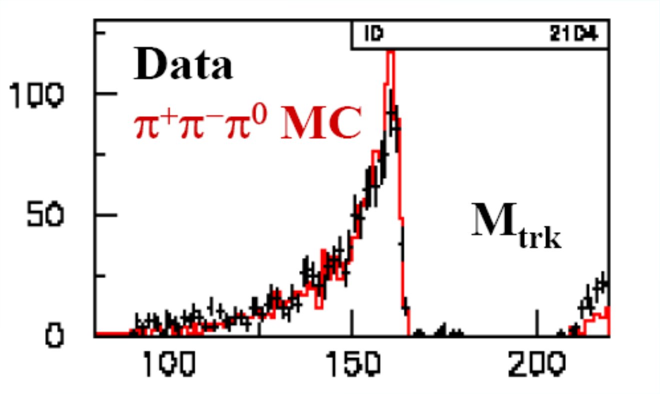
Dedicated selection cuts :

- Exploit tagging, i.e. kinematic closure of the event
  → Angle Ω btw. ISR-photon and missing momentum





- Kinematic fit in $\pi^+\pi^-\pi^0$ hypothesis using 4-momentum and π^0-mass as contstraints → cut on $\chi^2_{\pi\pi\pi}$ reduces background while having high efficiency (>98%) for signal events; allows also to test MC reliability for bkg. events

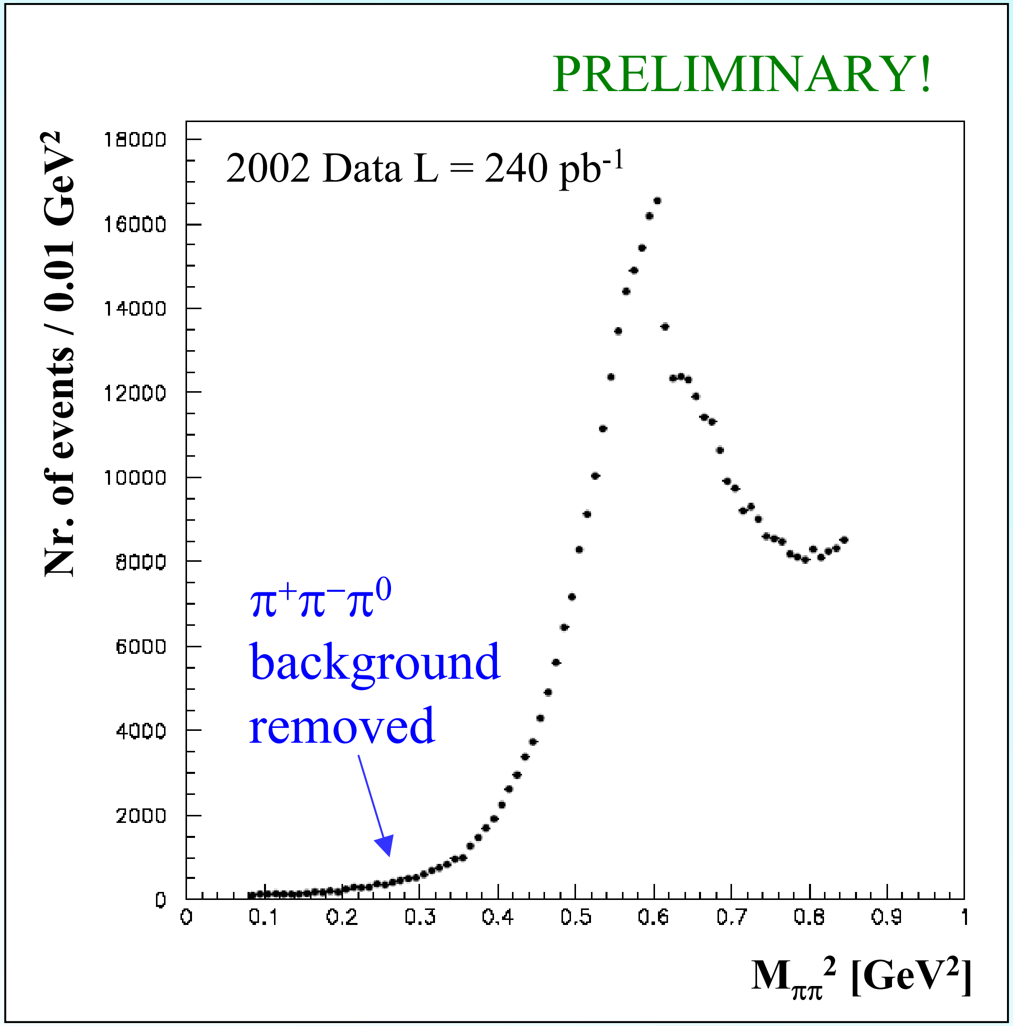


Reducible background $\pi^+\pi^-\pi^0$ (and also $\mu^+\mu^-\gamma$) very well simulated by Monte-Carlo!

Spectrum $\pi^+\pi^-\gamma$ @ Large Photon Angles

- **Background** $\pi\pi\pi$, $\mu\mu\gamma$ subtracted according to MC-simulation
- **(N)LO-FSR** from PHOKHARA
- **Efficiencies** taken from (red=MC, blue=data):
  - Acceptance
  - Trackmass-Cut
  - Ω-Cut
  - $\chi^2_{\pi\pi\pi}$-Cut
  - FILFO (offline rec. filter)
  - Cosmic Veto
  - Trigger
  - Tracking
  - Vertex
- **Correction for f_0(980) bkg. !**

Missing for final result → this talk



Trigger Efficiency

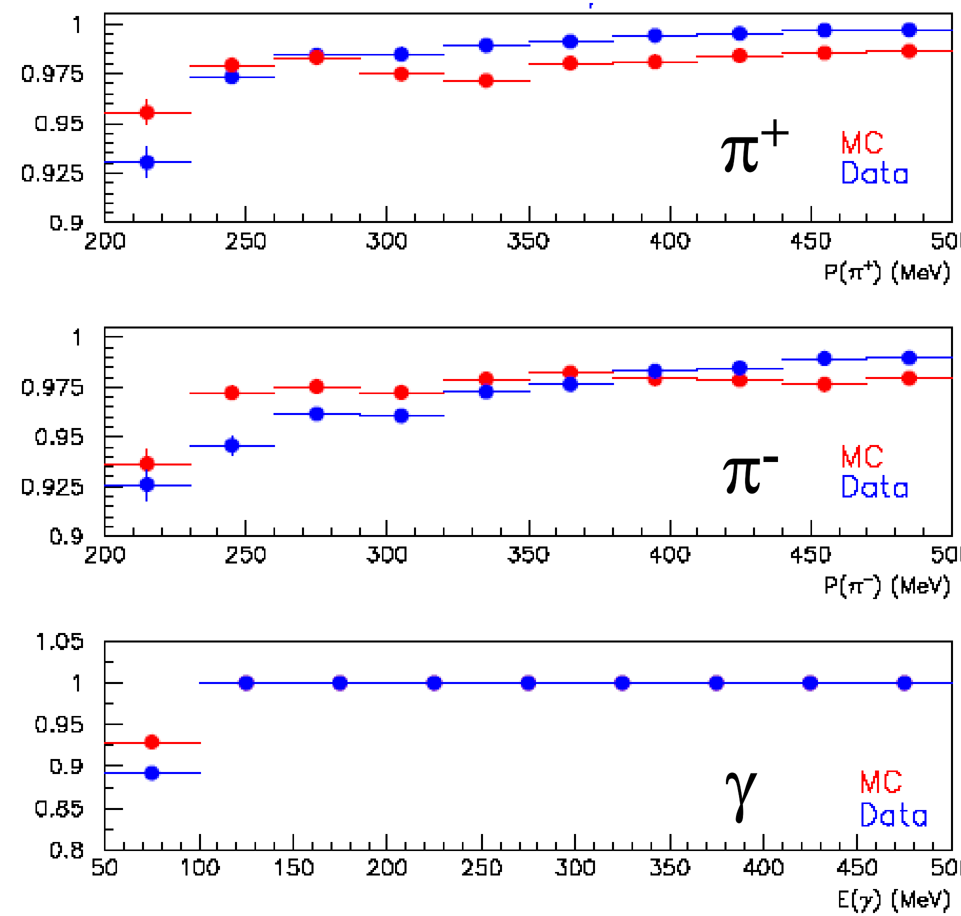
- **Trigger-requirement**: ≥ 2 energy releases (2 trigger sectors) above threshold in EmC

- **Strategy**: tagged $\pi^+\pi^-\gamma$ - analysis has 3 particles in final state
  → use 2 out of 3 particles to trigger the event and obtain trigger sector efficiency of third particle
  → measure efficiencies as a function of p and Θ

- **Results**:
  - good agreement btw. data and simulation
  - efficiencies very high, above 95% for most bins

➡ **Trigger inefficiency < 10^{-3} in agreement with MC prediction (was 0.3%!)**

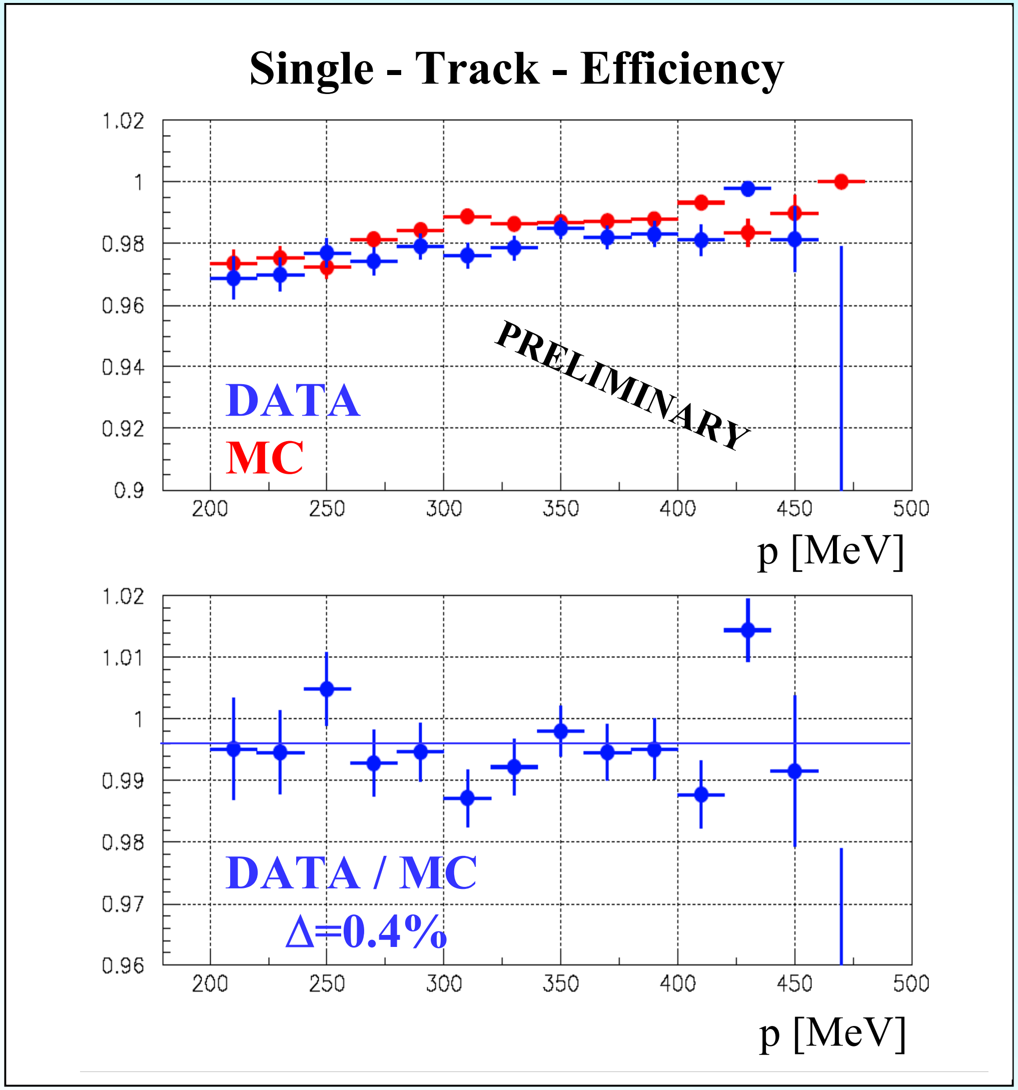
Trigger-Sector-Efficiencies



Tracking Efficiency

- **Strategy**: use $\pi^+\pi^-\pi^0$ - control sample, which is selected via kinematic fit
  - → Use 1st measured track, 2 γ's and missing moment as input for fit
  - → additional PID-cuts and others to suppress machine background
  - → look for presence of 2nd track with $\rho_{PCA}<8$cm, $|z|_{PCA}<12$cm, $\rho_{FirstHit}<50$cm

Tracking efficiency (97...99)%
0.4% disagreement with MC
Systematic error: ~0.2% prel.
(was 0.3%!)



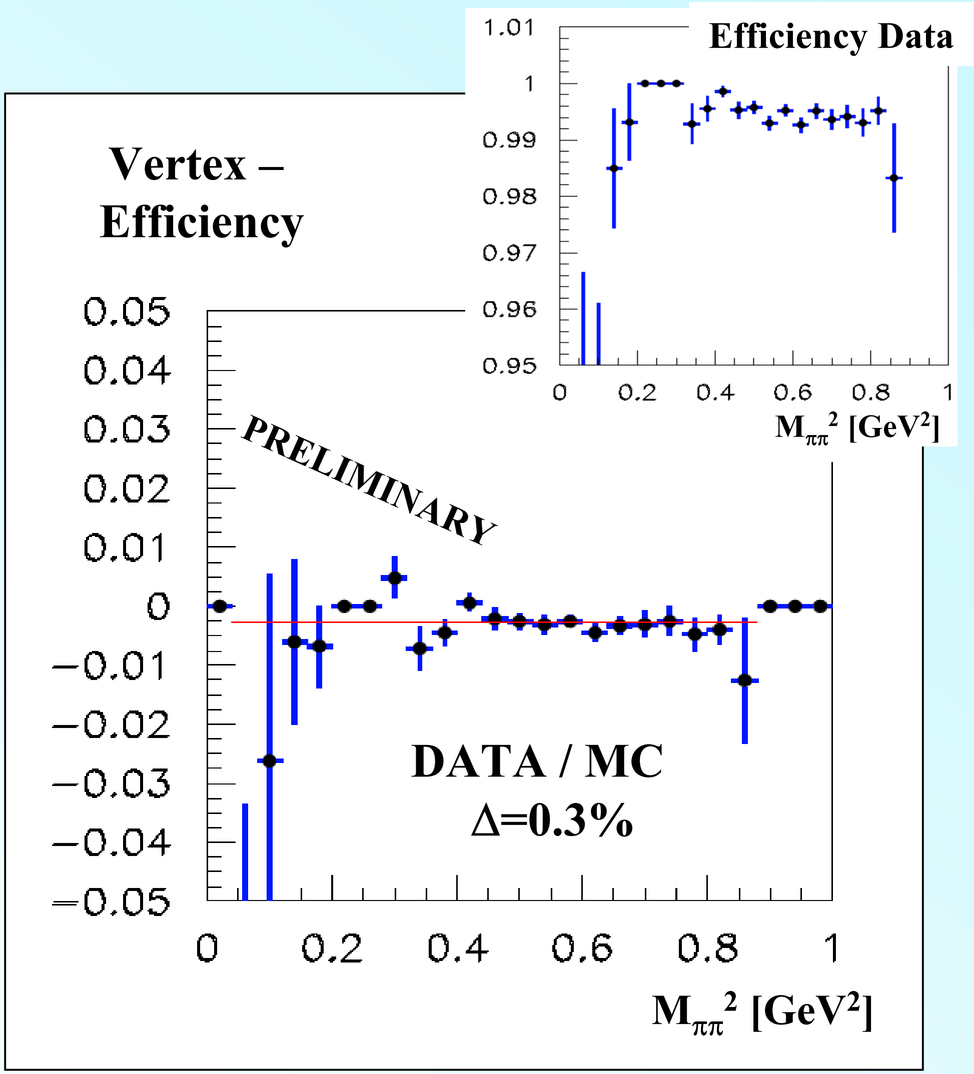
- **Comments**:
  - inefficiency contains π-decay and nuclear interaction effects
  - difference data - MC due to limited description of track splitting in MC

Vertex Efficiency

- **Strategy**: use $\pi^+\pi^-\gamma$ – events; measure $M_{\pi\pi}$-dependence directly
  → in the offline event selection the requirement of a charged vertex has been removed since 2002
  → repeat entire analysis (except $\chi^2_{\pi\pi\pi}$ cut) without vertex requirement
  → look for presence of a vertex at I.P.

Vertex efficiency ~99.2%
0.3% disagreement with MC;
Systematic error ~0.2% prel.
(was 0.3%!)

- **Comments**:
  - still limited by statistics at low $M_{\pi\pi}^2$
  - difference data - MC due to limited description of track splitting im MC



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

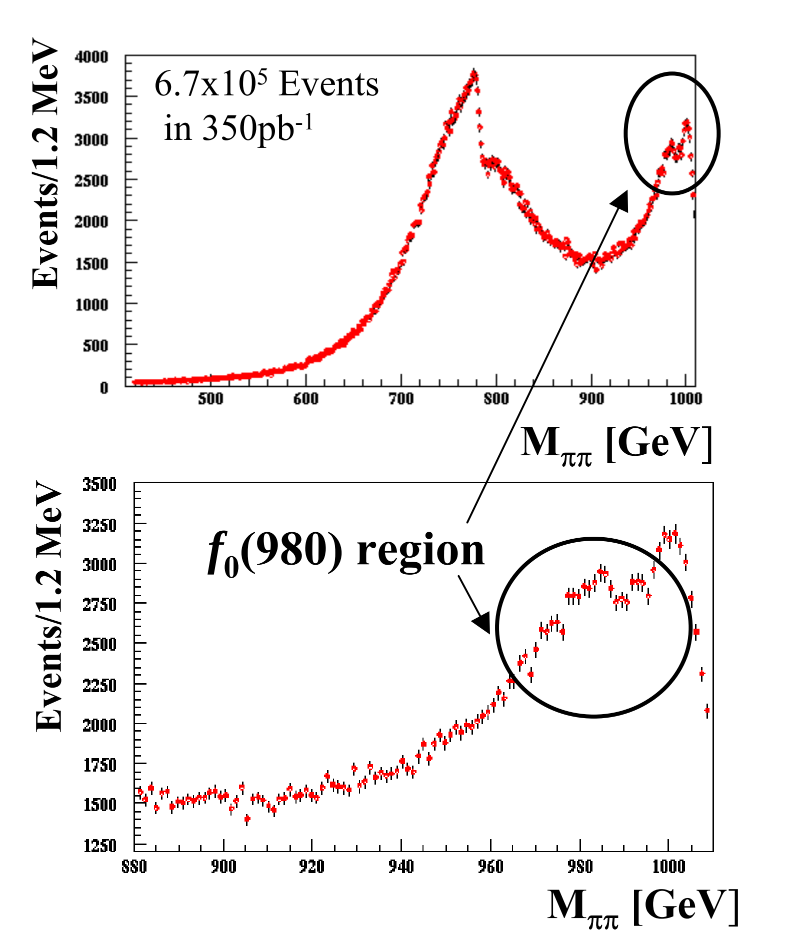
Phys. Lett. B634 (2006) 148

Scalar meson f_0(980) produced in radiative ϕ-decays
→ Very interesting physics in itself with a dedicated publication: !

- In radiative ϕ-decays there is a high sensitivity to distinguish btw. different models for the nature of the scalars:
  not easily interpreted as conventional $q\bar{q}$
  probably $q\bar{q}q\bar{q}$ (Jaffe '77)
  $K\bar{K}$ (Weinstein-Isgur '90)
- Can broad f_0(600) "σ" be seen in spectrum?

- **Large Angle Analysis** with very similar cuts as described before → extension to high mass region: **f_0(980) signal seen**
- **Fit : ISR + FSR + scalar f_0(980)**
  ± interference (scalar+ FSR)
  + background ($\rho\pi\to\pi\pi\gamma$)

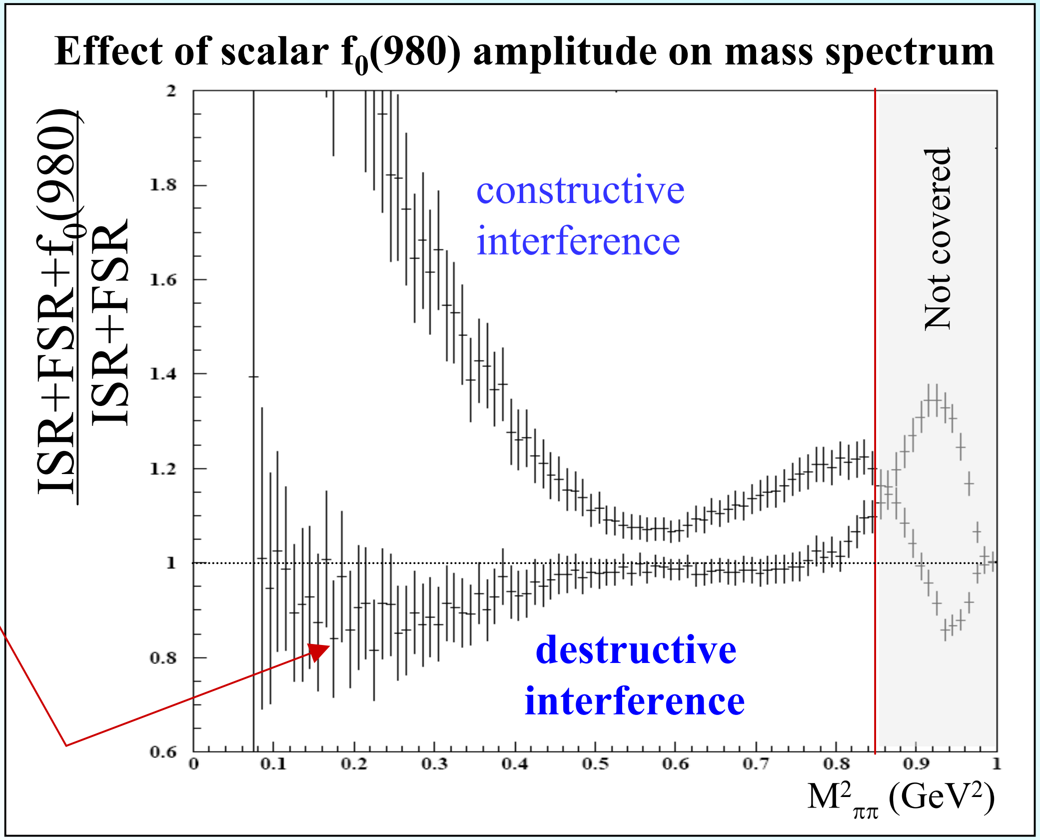
fit with 3 models for scalar amplitude



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

Results from the f_0(980) fit studies have been used to compute the relative background of scalar events in the large-angle-analysis, destructive interference with FSR is clearly preferred in the fit.

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



At maximum 15% effect in threshold region due to f_0(980) scalar amplitude

systematic effect under study by varying fit parameters of 3 models:

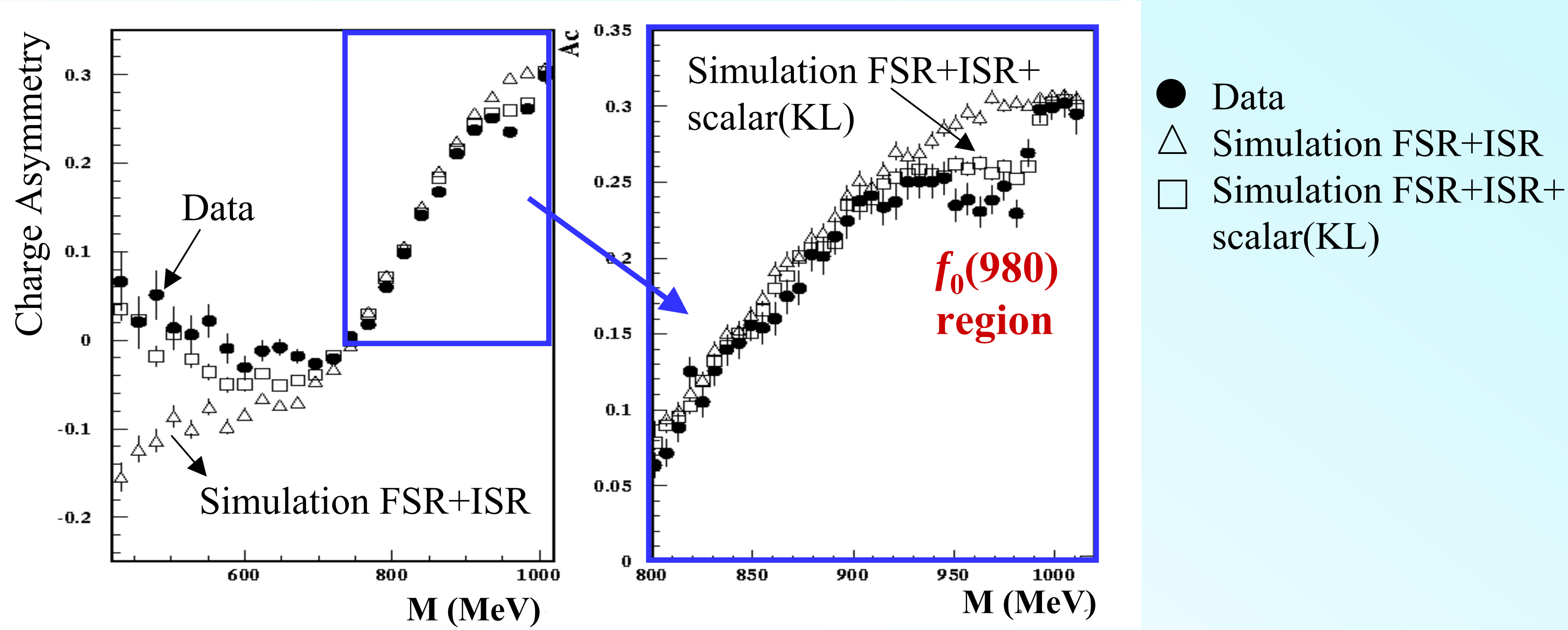
- Kaon-Loop-Model (*Achasov*)
- No-Structure-Model (*Isidori-Maiani*)
- Scattering-Ampl.-Model (*Pennington*)

→ **main limitation at threshold due to model dependence in f_0(980) amplitude**

Forward - Backward - Asymmetry

Forward-backward-asymmetry $A_{FB}(M_{\pi\pi}) = \frac{N(\theta^{+} > 90^{o}) - N(\theta^{+} < 90^{o})}{N(\theta^{+} > 90^{o}) + N(\theta^{+} < 90^{o})}(M_{\pi\pi})$

Asymmetry is a consequence of different C-Parity of $\pi^{+}\pi^{-}$ for ISR- and FSR-amplitude



→ Clear signal ~ 980MeV but also huge threshold effect, no f_0(600) needed

→ On ρ-peak (where scalar amplitude is small) very good agreement btw. data and simulation → **precision test of the model of scalar QED for FSR**

Conclusions and Outlook

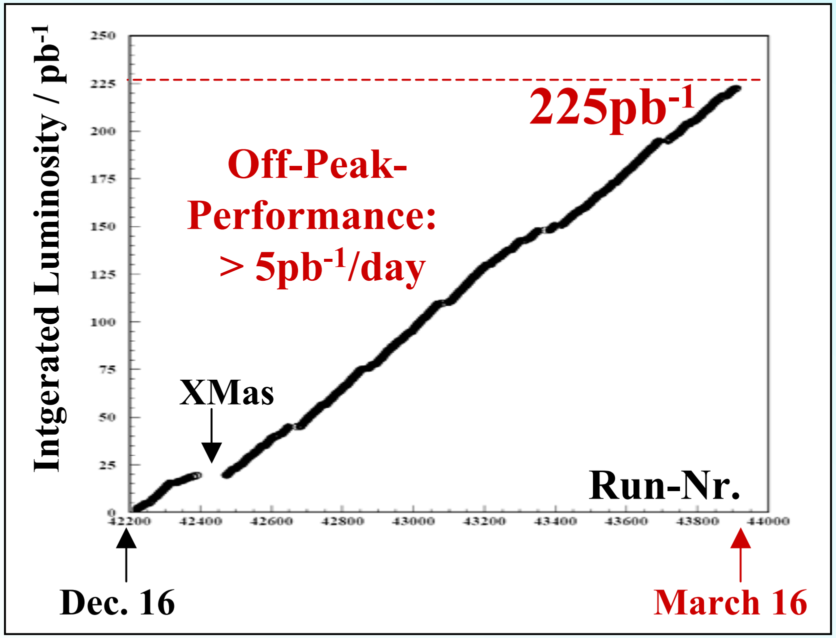
Conclusions

- Feasibility of the Radiative Return for high-precision measurements proven at KLOE
- Published analysis without photon tagging (1.3% precision) will be updated with 2002 data; Normalization to muon pairs
- Analysis with photon tagging (large polar angle of ISR-photon) allows to access threshold region; expect result for summer 2006; ρ-peak region with improved precision wrt. published result!

➡ **Improve further measurement of Pion Formfactor < 1GeV; together with BaBar program this leads to a substantial im-provement of the theoretical knowledge of the muon anomaly**

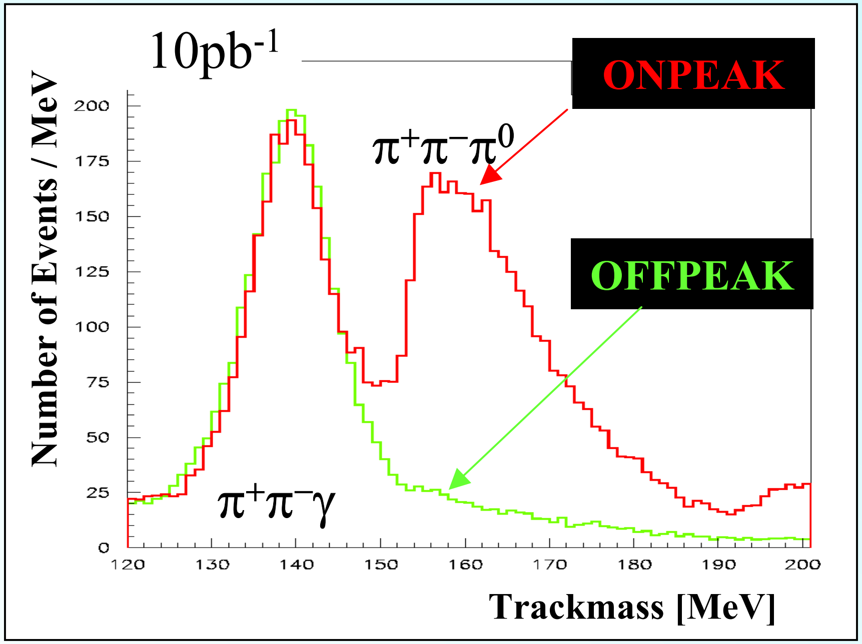
- Main limitations due to $\phi \to \pi^+\pi^-\pi^0$ and $\phi \to f_0(980)\gamma$
  → dedicated DAΦNE-run off-resonance ($\sqrt{s}$=1.00 GeV) will allow ultimate precision for pion formfactor @ DAΦNE

DAΦNE - Run Off - Resonance



Physics Case:

- **background-free Radiative Return** 200pb^{-1} allow to be statistically competitive with VEPP-2M at threshold
- a ϕ-scan allows to **study the model-dependence in desciption of $f_0(980)$**
- background-free **γγ - program**



- Run at **$\sqrt{s}$ = 1.00 GeV** between Dec. 2005 and March 2006

  → Good machine performance off-peak:
  ~ 225pb^{-1} written on tape!

- In addition **energy scan around ϕ peak** with 4 scan points, 10 pb^{-1} per point each