XXXI Intl. Conference “Matter to the Deepest”
Recent Developments in Physics
of Fundamental Interactions
Ustroń, September 7, 2007

KLOE Results on Hadronic Cross Section

Achim Denig
Institut für Experimentelle Kernphysik
University of Karlsruhe

for the KLOE collaboration

Motivation
&
Radiative Return Method

Hadronic Cross Section & Muon-Anomaly

Motivation:
High Precision Test of the Standard Model

→ Anomalous magnetic moment of the muon

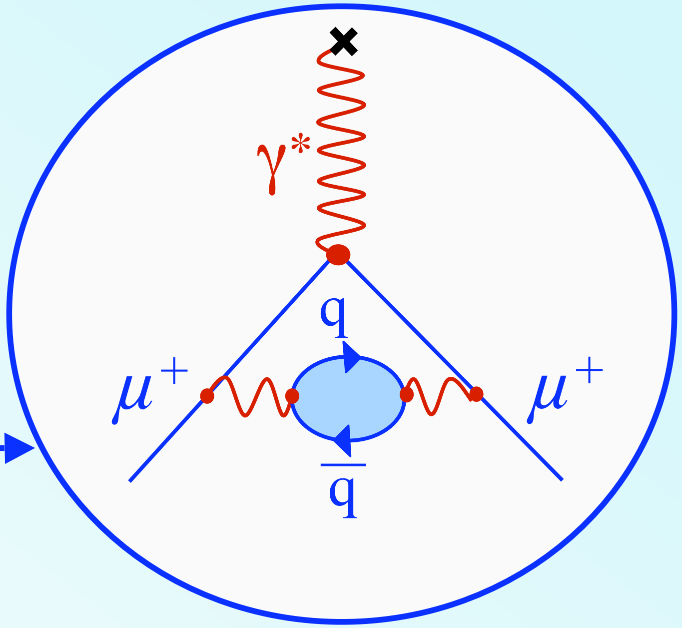
Muon-Anomaly $a_\mu = (g_\mu - 2)/2 = \alpha/2\pi + \ldots$

$$a_\mu^{theo} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak} + a_\mu^{New\ physics}$$

→ Fine structure constant at Z^0-mass $\alpha_{QED}(M_Z)$

2nd largest contribution, *pQCD* not applicable
Error of hadronic contribution dominates total error of a_μ!

Hadronic Vacuum Polarization



Dispersion-Relation

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

- $K(s)$ = analytic kernel-function,
- above typically 2…5 GeV, use *pQCD*

Channel $\sigma_{\pi\pi} = \sigma(e^+ e^- \to \pi^+\pi^-)$;
gives >70% contribution to a_μ^{had}!
Alternative: Spectral function from decay ($\tau \to \nu_\tau$ Hadrons) taking into account isospin breaking corrections

S. Eidelman

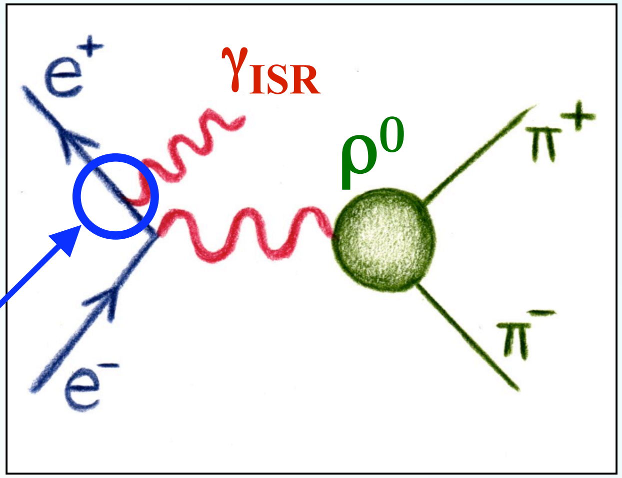
Radiative Return

Modern particle factories, 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

ISR



'Radiative Return' to ρ(ω)-resonance:

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

Measure cross section as a function of the 2π-invariant mass $s_\pi = M_{\pi\pi}^2$

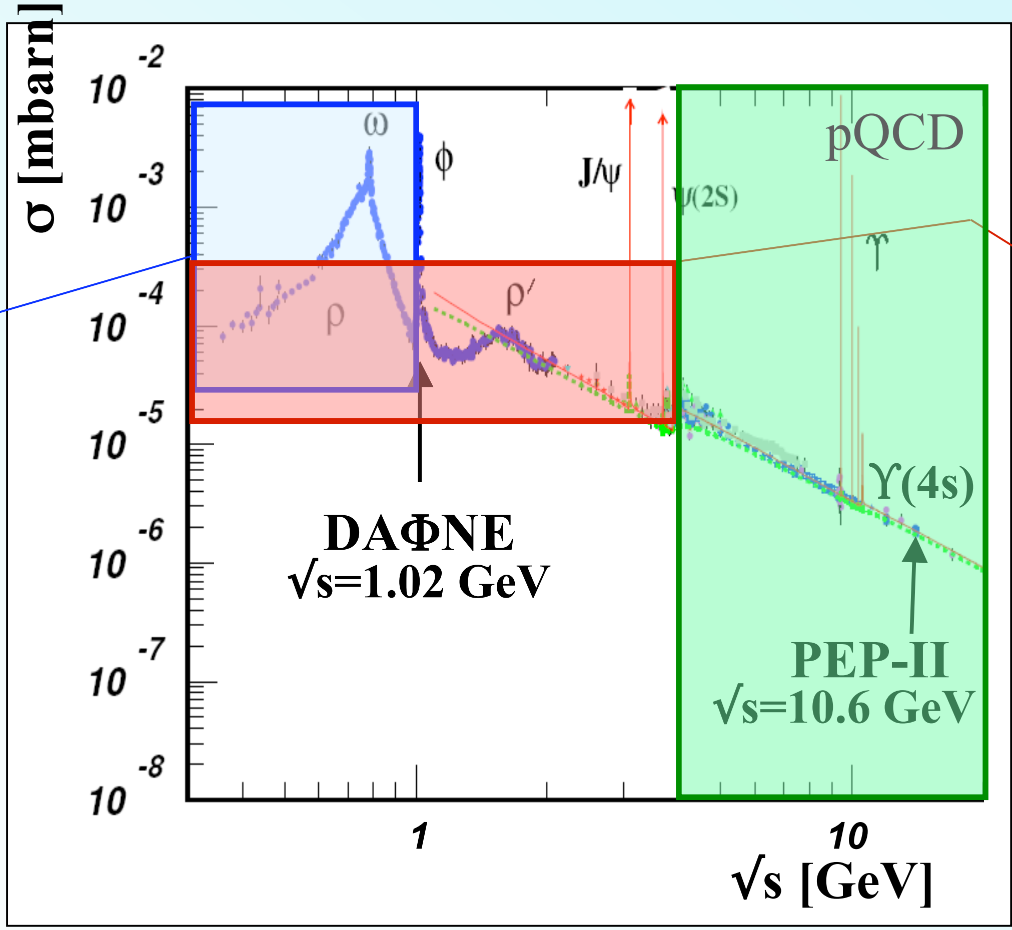
$$\frac{d\sigma(e^+ e^- \rightarrow \pi^+ \pi^- \gamma)}{dM_{\pi\pi}^2}$$

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

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

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 multi-plicities (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 GeV**!

Measurement of the Pion Form Factor at KLOE

Goal: O(1%) precision

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

Pion tracks at large angles

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

a) Photons at small angles (SA)

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

→ No photon tagging

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

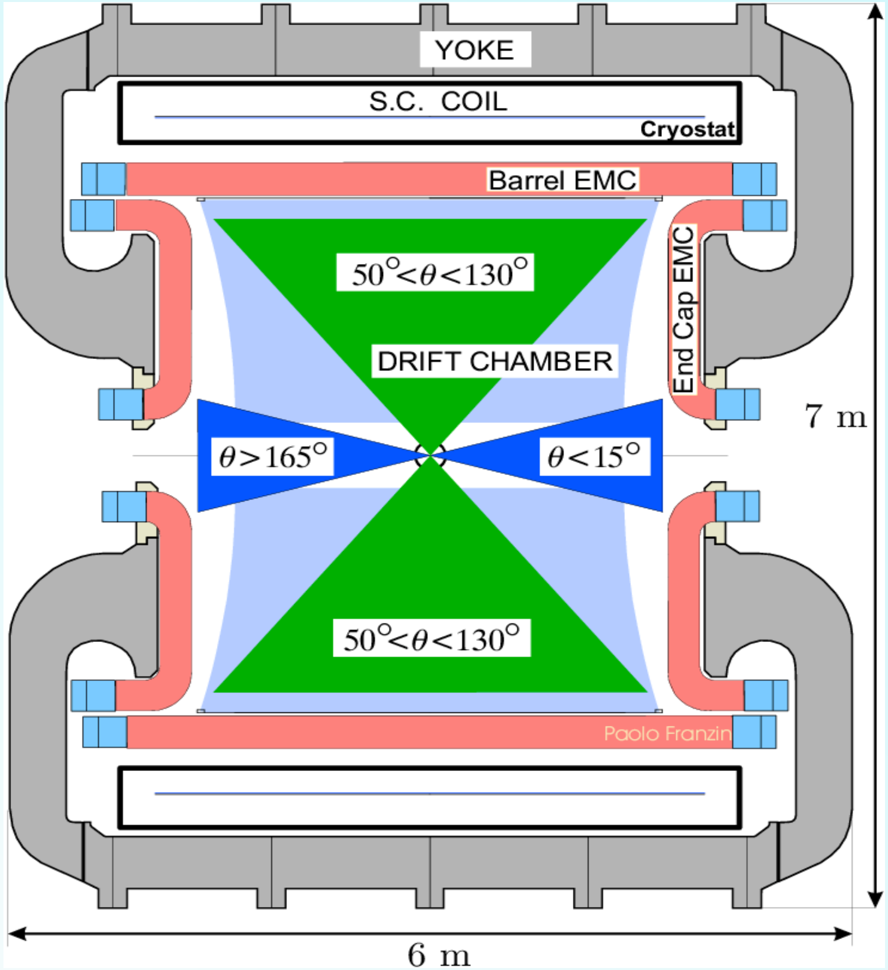
- High statistics for **ISR** photons
- Negligible contribution of **FSR**
- Reduced background

b) Photons at large angles (LA)

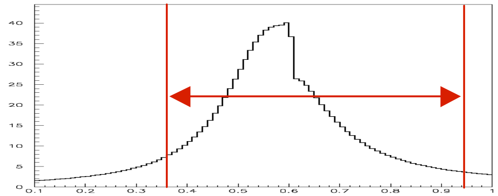
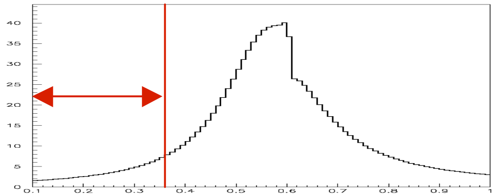
$50^o < \theta_\gamma < 130^o$

→ Photon tagging possible

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

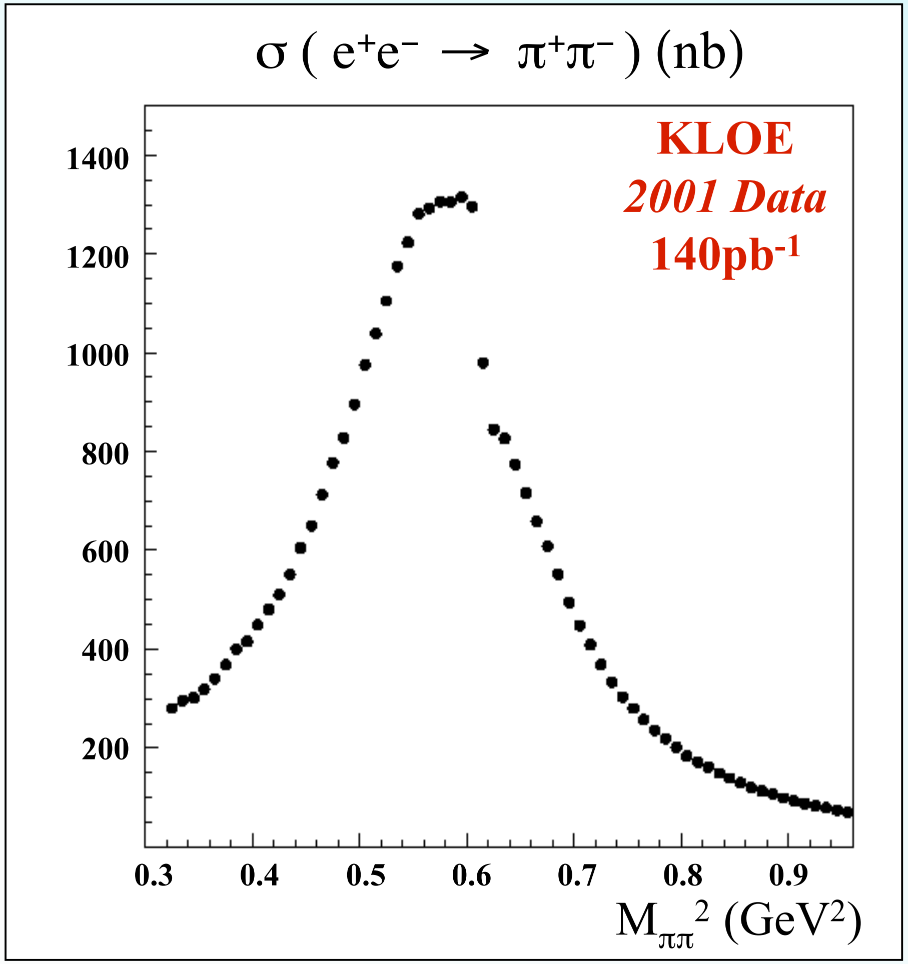


Overview pion form factor at KLOE

Analysis	$\int L dt$	Precis. $0.6<M_{\pi\pi}<0.95$ GeV 	Precision $M_{\pi\pi}<0.6$ GeV 
γ_{ISR} ***untagged*** 2001 data	140 pb^{-1}	1.3 % (published)	(kinematically forbidden)
γ_{ISR} ***untagged*** 2002 data	240 pb^{-1}	1.1 %	(kinematically forbidden)
γ_{ISR} ***tagged*** 2002 data	240 pb^{-1}	0.9 % $\oplus$ $f_0(980)$ contrib.	**limited by model dependence of irreducible background $\phi \rightarrow f_0(980)\,\gamma$**
Off-Peak 2006 **$\sqrt{s}$=1.00 GeV**	230 pb^{-1}	**<< 1 %**	**no limitation by $f_0(980)$ contribution**

Total KLOE data sample 2000-2005: 2.5 fb^{-1}

Reminder: published 2001 Result (SA)



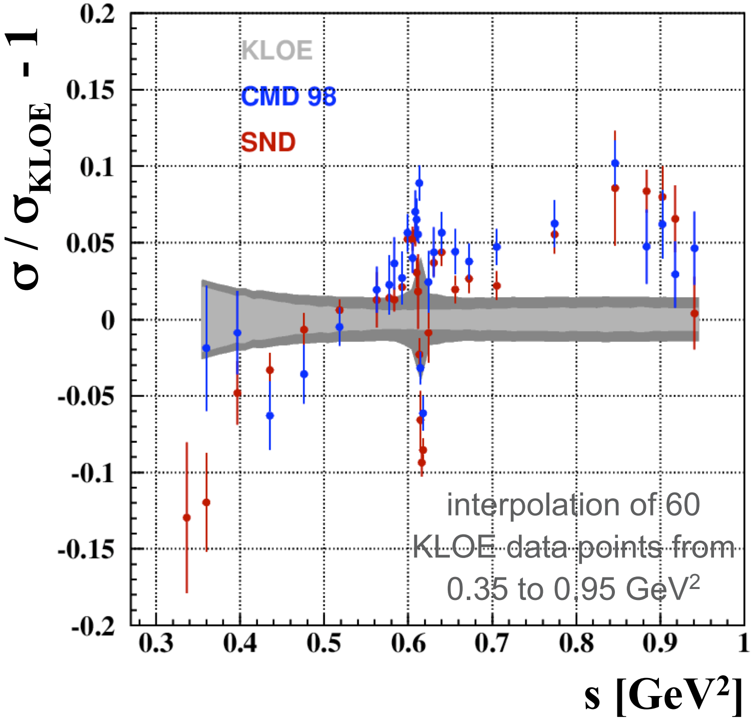
Statistical error negligible (1.5 Million events)

Acceptance	0.3%
Trigger	0.3%
Tracking	0.3%
Vertex	0.3%
Reconstruction filter	0.6%
Particle ID	0.1%
Trackmass cut	0.2%
Background	0.3%
Unfolding effects	0.2%
Total experimental Error	**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 1.3%	

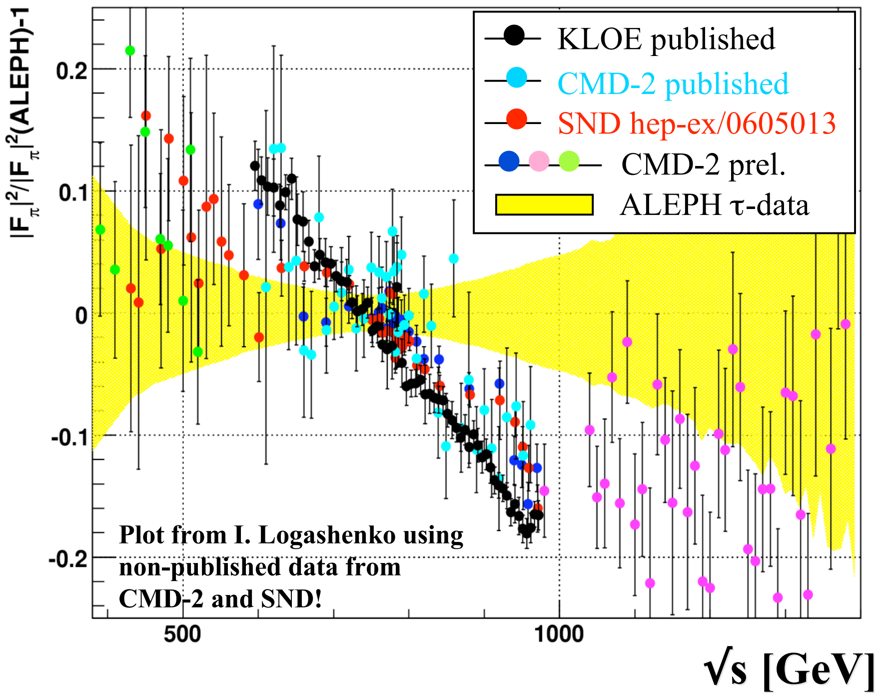
Phys. Lett. B606 (2005) 12

Reminder: Comparison with e^+e^- - and τ - Data

Relative difference btw.
KLOE (2001) and CMD-2, SND



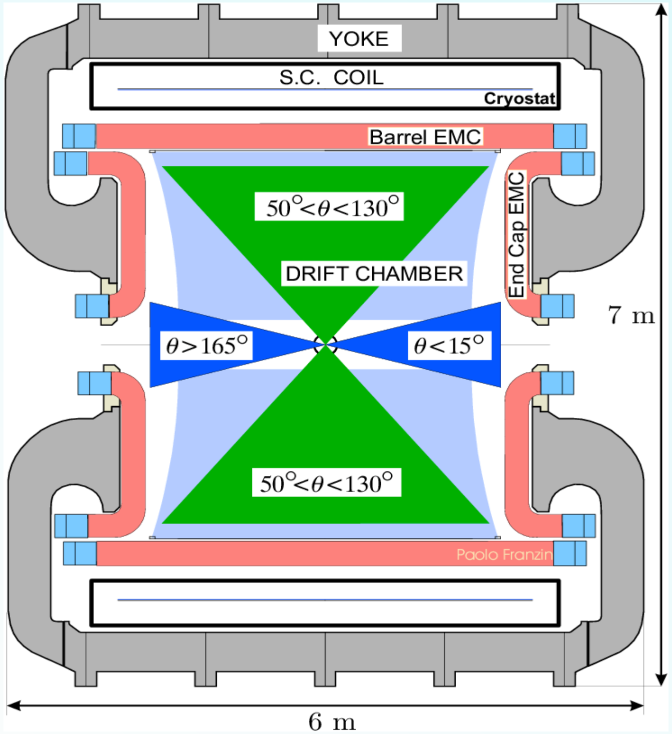
Relative difference btw. e^+e^- Data
and τ-spectral function from ALEPH



→ **Data sets of KLOE (2001) and SND/CMD-2 different at large and small s**

→ **In dispersion integral all 3 experiments are in agreement within 1σ**

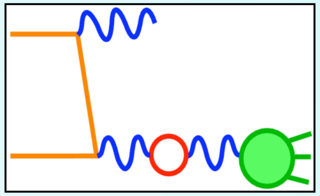
→ **Huge deviation btw. e^+e^- data sets and tau spectral functions (ALEPH, OPAL, CLEO), better agreement with prelimiary BELLE tau decay data?**



Small Angle Analysis 2002 Data

Extract $\sigma(\pi\pi)$ *from the* $\pi^+\pi^-\gamma$ *Yield*

$dN(\pi^+\pi^-\gamma) / dM_{\pi\pi}^2$
after acceptance cuts



Analysis:
Efficiency, Background
as function of $M_{\pi\pi}$

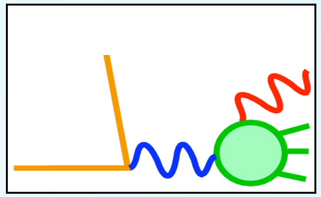
Normalize to **Luminosity**

Differential cross section
$d\sigma(\pi^+\pi^-\gamma)/dM_{\pi\pi}^2$

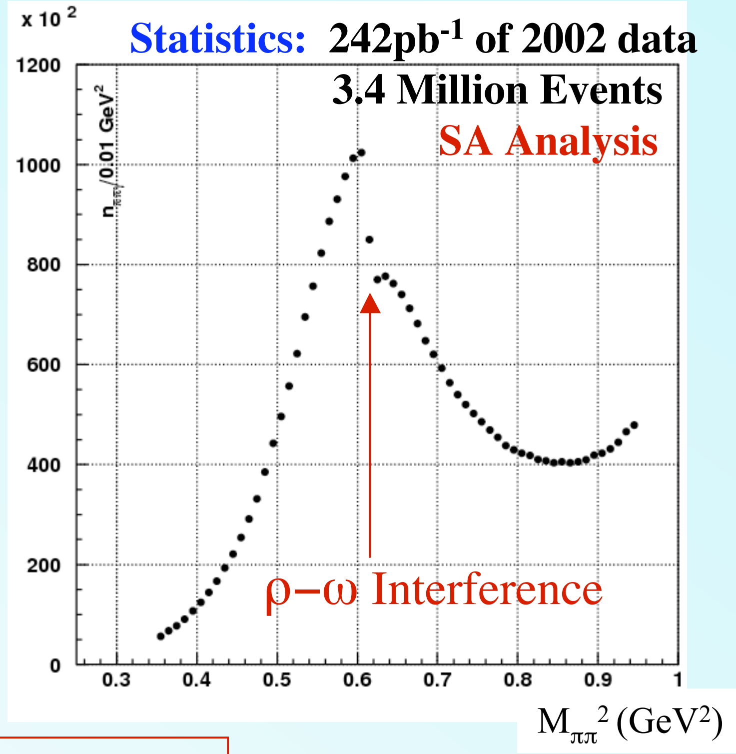
Divide by **radiator function**

Radiative corrections

Cross section
$\sigma(e^+e^- \to \pi^+\pi^-)$



Event Analysis



Experimental challenges

Background:

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)

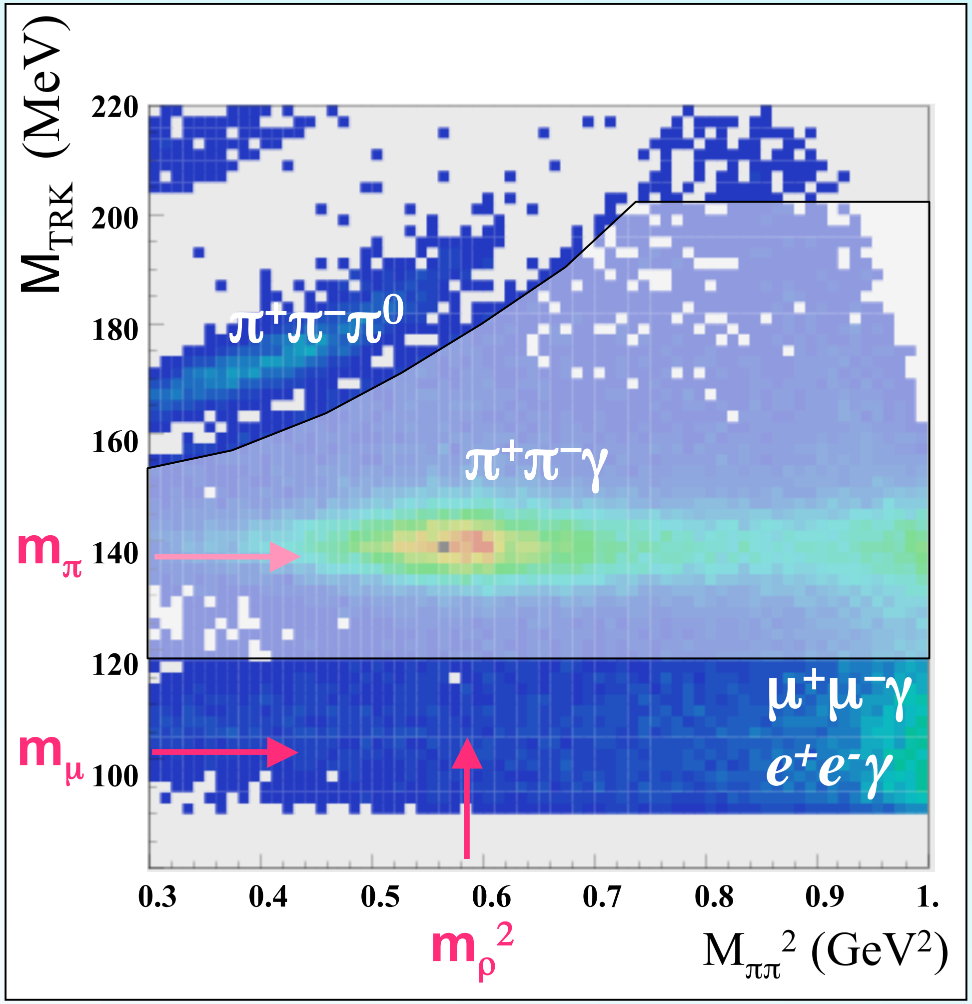
$$\left(M_\phi - \sqrt{\vec{p}_1^{\,2} + M_{trk}^2} - \sqrt{\vec{p}_2^{\,2} + M_{trk}^2}\right)^2 - (\vec{p}_1 + \vec{p}_2)^2 = q_\gamma^2 = 0$$

Efficicieny:

Whenever possible use data, rely on MC only for acceptance and Mtrk

Normalization:

Measure DAΦNE luminosity with **Bhabha events at large polar angles >50°** as normalization process

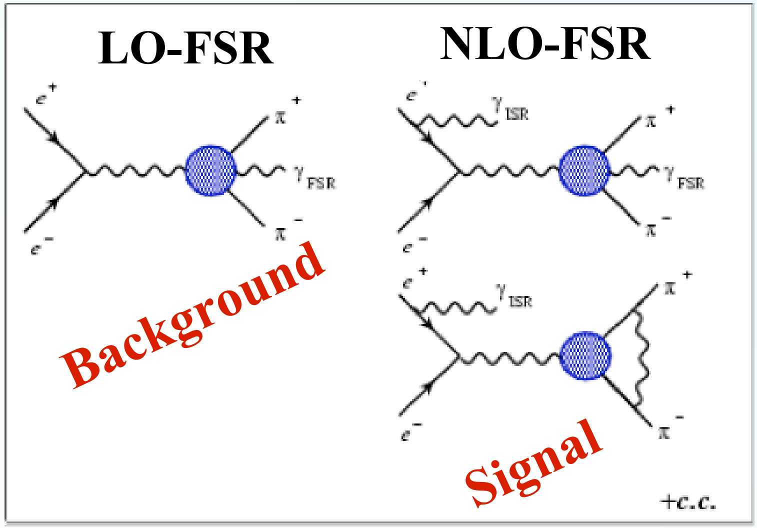


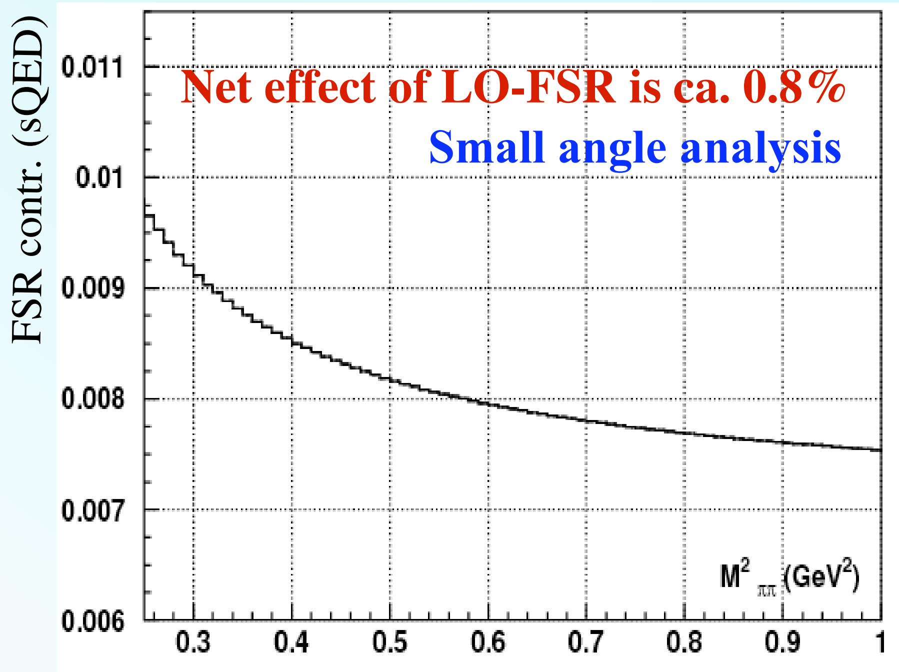
Theoretical challenges

H. Czyż

- **Not only ISR radiative corrections have to be determined at high precision (NLO)**
- **FSR - corrections are model dependent, typically model of scalar QED is used**

Final cross section $\sigma_{\pi\pi}$ must be inclusive in FSR → for radiative return consider also events with simultaneous presence of 1 ISR- and 1 FSR-photon (NLO-FSR)





2002 Data: Improvements wrt. 2001 Result

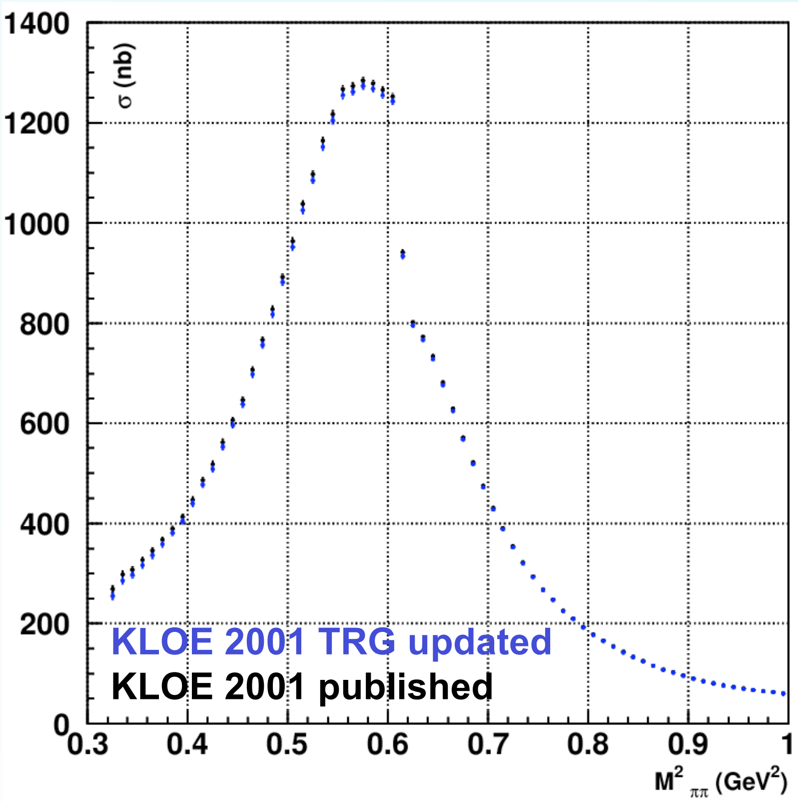
- Larger data set allows more refined evaluation of systematic errors associated with selection efficiencies; evaluate all contributions again
- 2002 data less effected by pile-up events from machine background
- additional online software trigger level introduced to recover cosmic veto inefficiency in 2002, which gave an inefficiency of up to 30% in 2001
- Improved offline-event filter reduces its systematic uncertainty to <0.1%, was the largest contribution (0.6%!) to the error in published result
- Trigger issue in 2001 data resolved (see above)
- New event generator BABAYAGA@NLO - theoretical error of Bhabha effective cross section goes from 0.5% to 0.1% - Bhabha cross section value is lowered by 0.7%; therefore also pion formfactor decreases by 0.7%

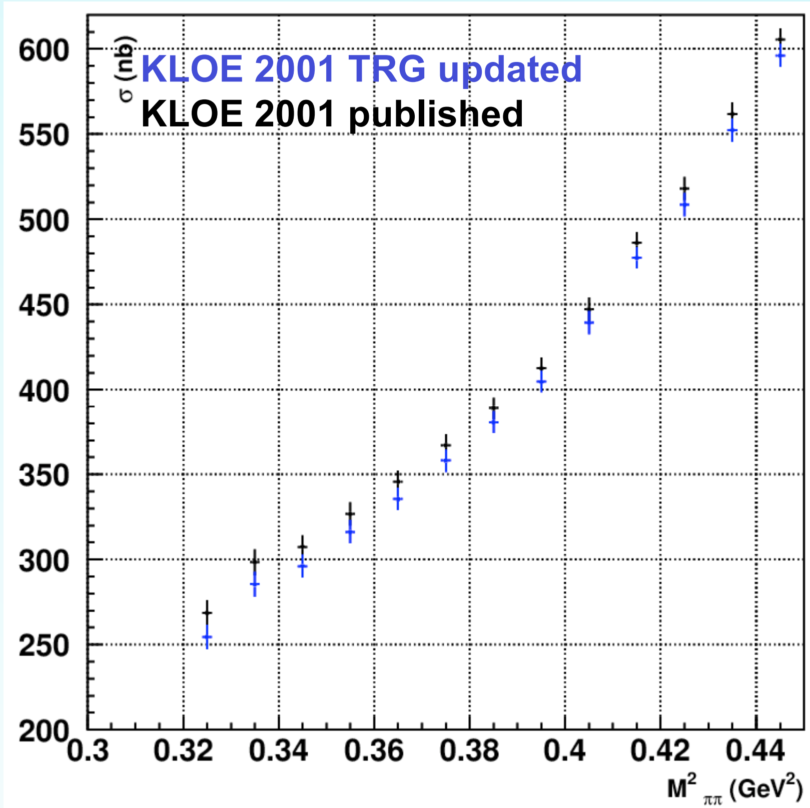
C. M. Calame et al., Nucl. Phys. B758 (2006) 227

G. Montagna

Trigger 2001 Update

- Trigger efficiency correction had to be updated due to a double counting of efficiencies; affects mainly low $M_{\pi\pi}$ region

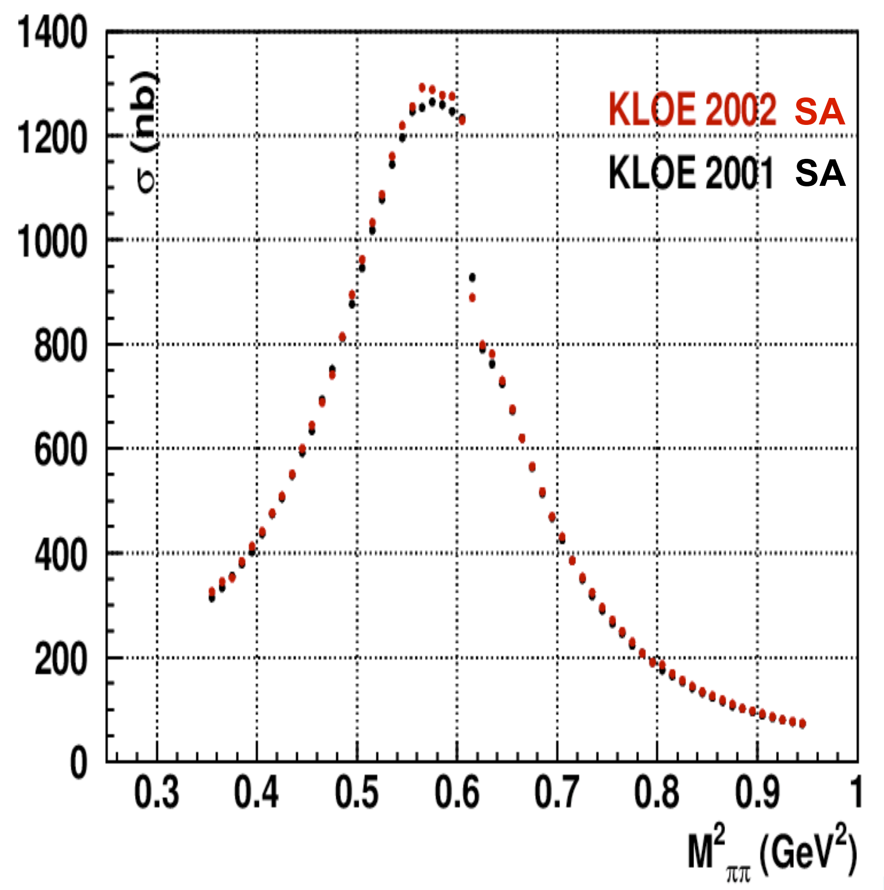




Impact of update on trigger correction on 2001 cross section:

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

Small Angle (SA) Result from 2002 Data



Important: sophisticated unfolding procedure to correct detector resolution effects not yet applied to 2002 data; not needed for integral a_μ

NEW

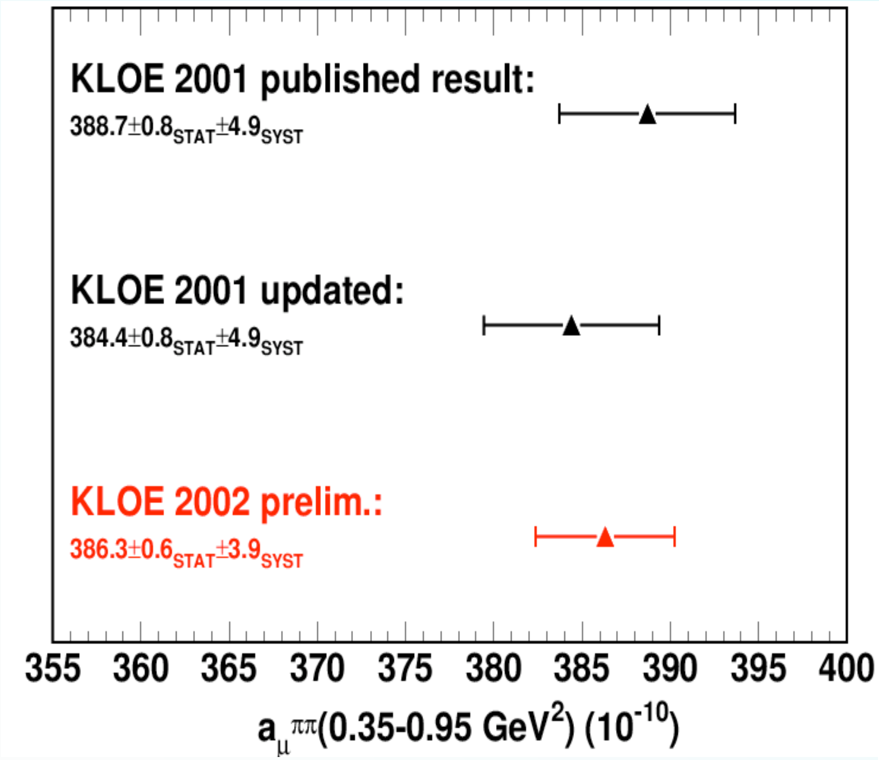
Systematic errors on $a_\mu^{\pi\pi}$:

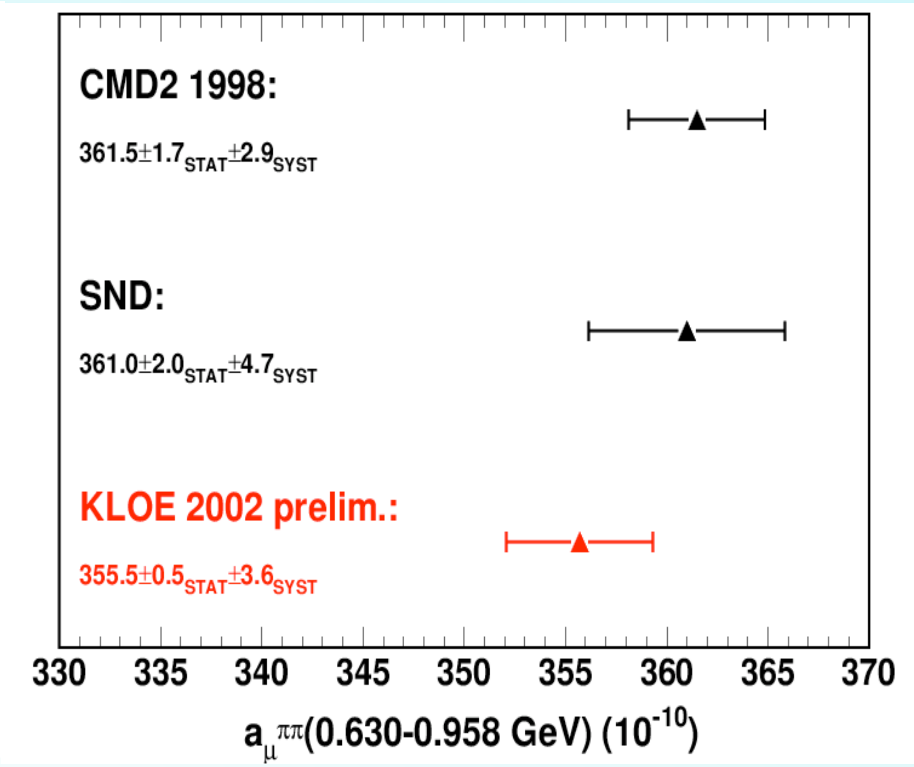
Offline Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2% (prelim)
π/e-ID	0.3%
Vertex	0.5%
Tracking	0.4%
Trigger	0.2%
Acceptance (θ_π)	negligible
$M_{\pi\pi}^2 \rightarrow M_{\gamma*}$ (FSR corr.)	0.3% (prelim)
Software Trigger	0.1 %
Luminosity	0.3%
Acceptance (θ_{Miss})	0.1%
Radiator H	0.5%
Vacuum polarization	negligible
TOTAL ERROR 1.1%	

Impact of new KLOE Data (SA) on a_μ^{hadr}

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

Comparison with $a_\mu^{\pi\pi}$ from CMD-2 and SND in the range 0.630-0.958 GeV



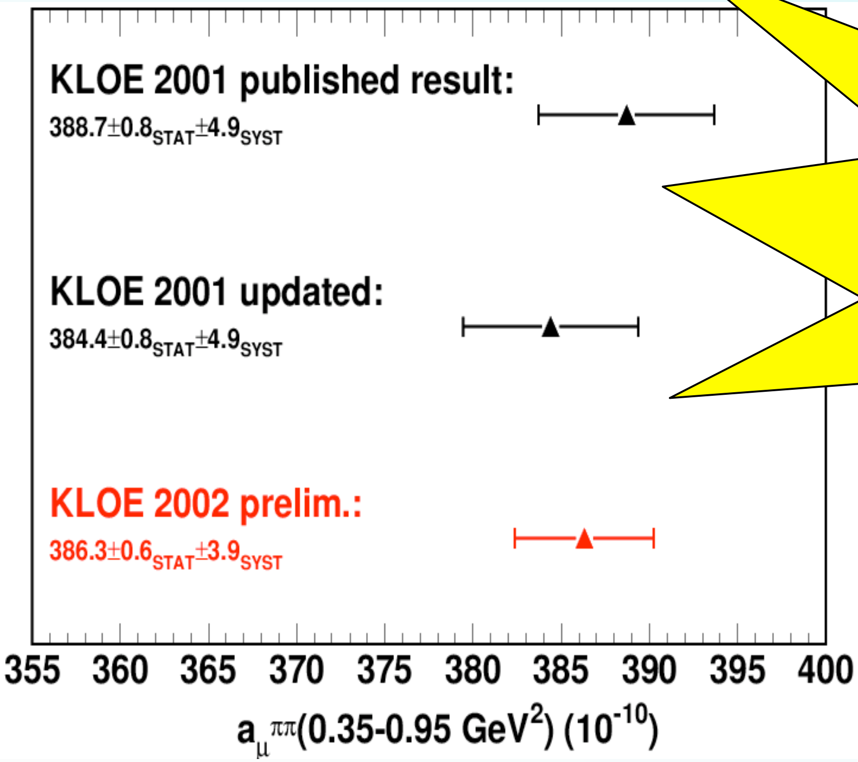


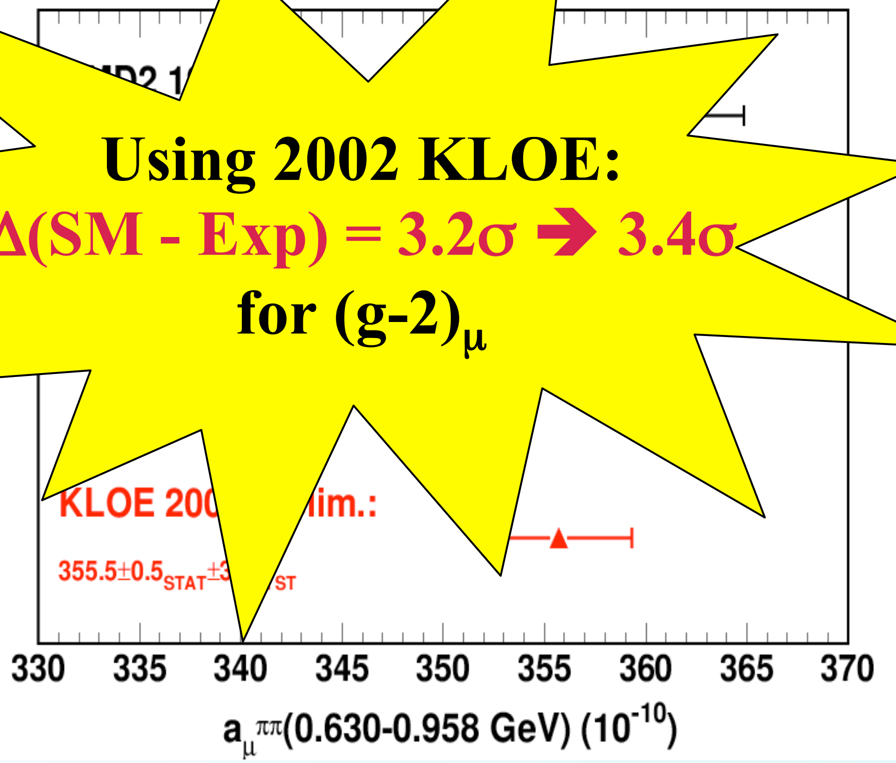
New KLOE data consistent with published 2001 SA result

Impact of new KLOE Data (SA) on a_μ^{hadr}

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

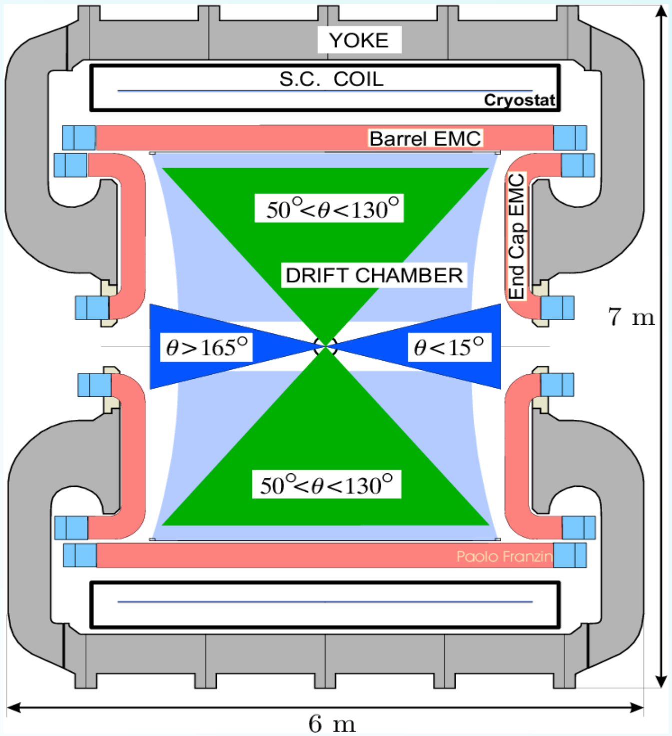
Comparison with $a_\mu^{\pi\pi}$ from CMD-2 and SND in the range 0.630-0.958 GeV





Using 2002 KLOE:
Δ(SM - Exp) = 3.2σ ➔ 3.4σ
for $(g-2)_\mu$

New KLOE data consistent with published 2001 SA result

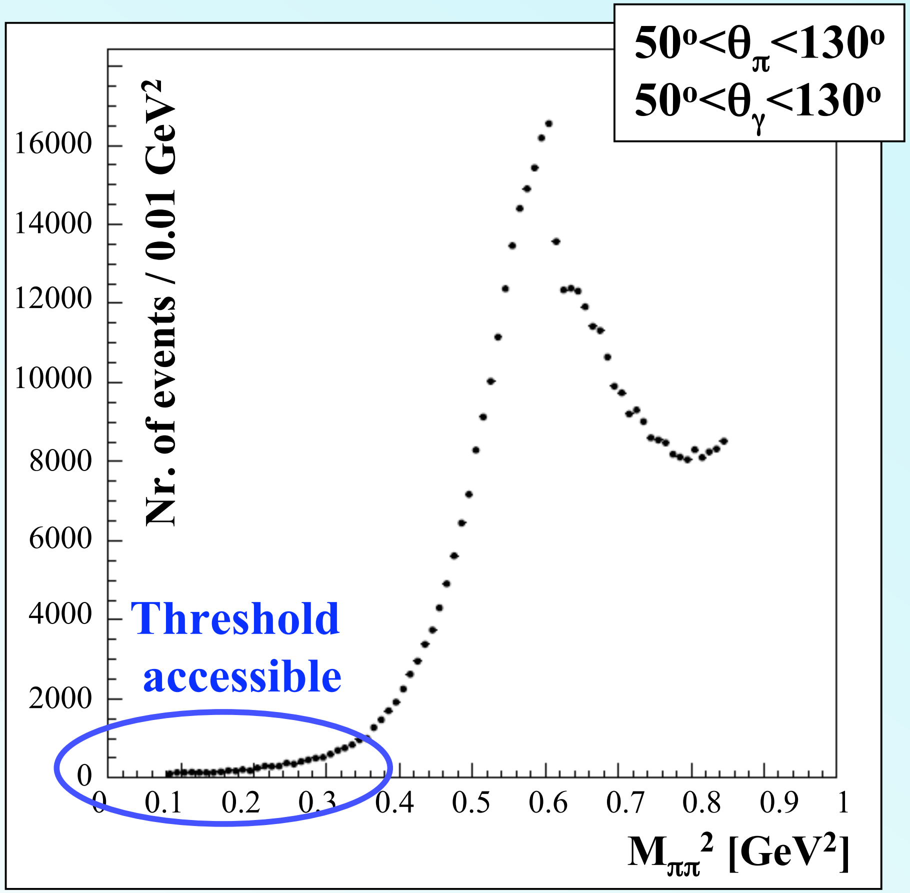


Large Angle Analysis 2002 Data

Analysis 2002 Data: Large Photon Angles (LA)

PRO & CONTRA

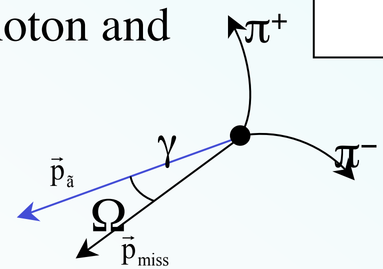
- ✓ important **cross-check**
- ✓ the **threshold region** is accessible
  ca. 20% contribution to a_μ^{hadr}
- ✓ **photon tagging** is possible
  (4-momentum constraints)
- ✓ lower signal statistics
- ✓ **large $\phi \rightarrow \pi^+\pi^-\pi^0$** background
- ✓ **large FSR** (charge asymmetry!)
- ✓ **irreducible bkg. from ϕ decays**



Exploit kinematic closure of the event:

→ Cut on angle btw. ISR-photon and missing momentum

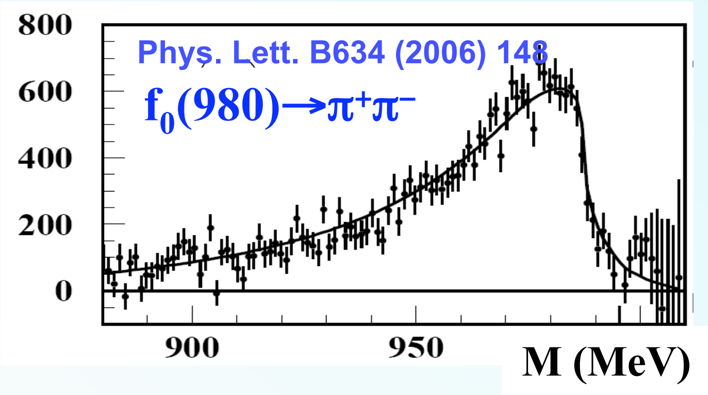
→ Kinematic fit in the bkg. hypothesis $\pi^+\pi^-\pi^0$



TOTAL ERROR 0.9%
⊕ error subtraction of irreducibel background

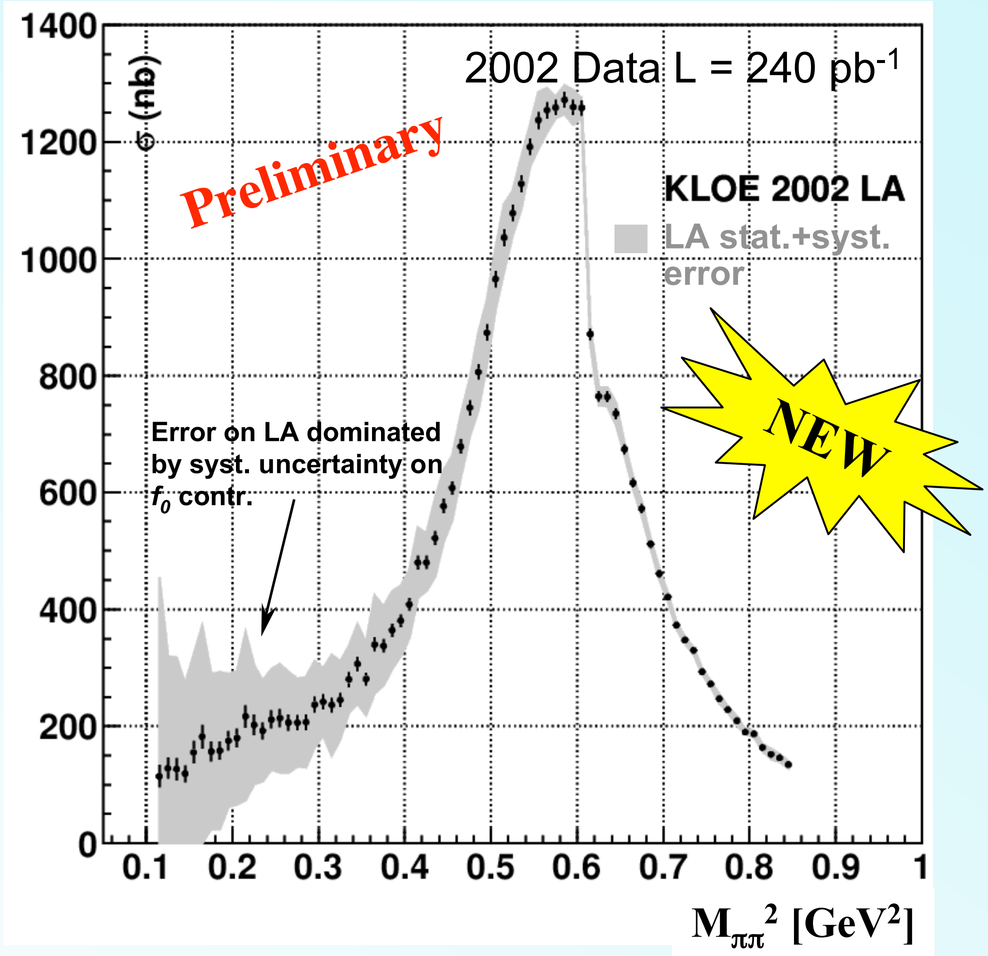
Large Background from $\phi \rightarrow f_0(980)\ \gamma$

Precision limited by irreducible bkg. from radiative ϕ-decay to $f_0(980)\gamma$



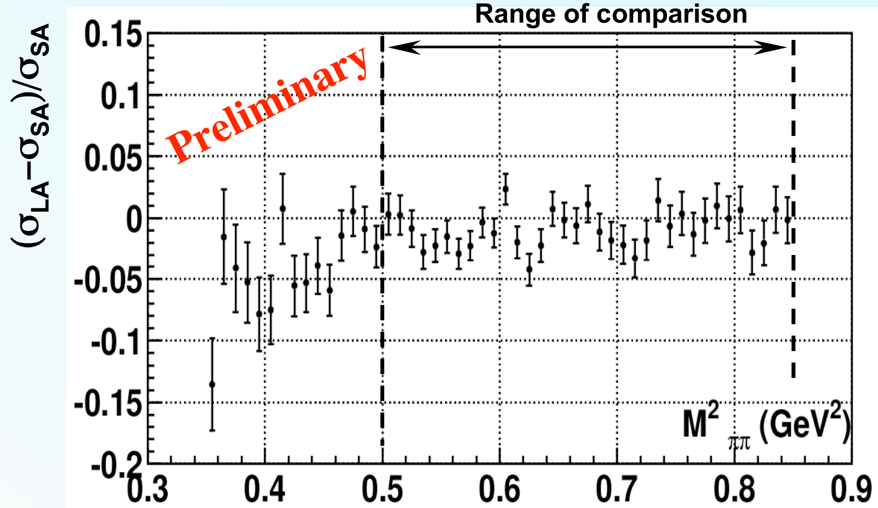
- Studied at KLOE in the decays $f_0(980)\rightarrow\pi^0\pi^0$, $f_0(980)\rightarrow\pi^+\pi^-$

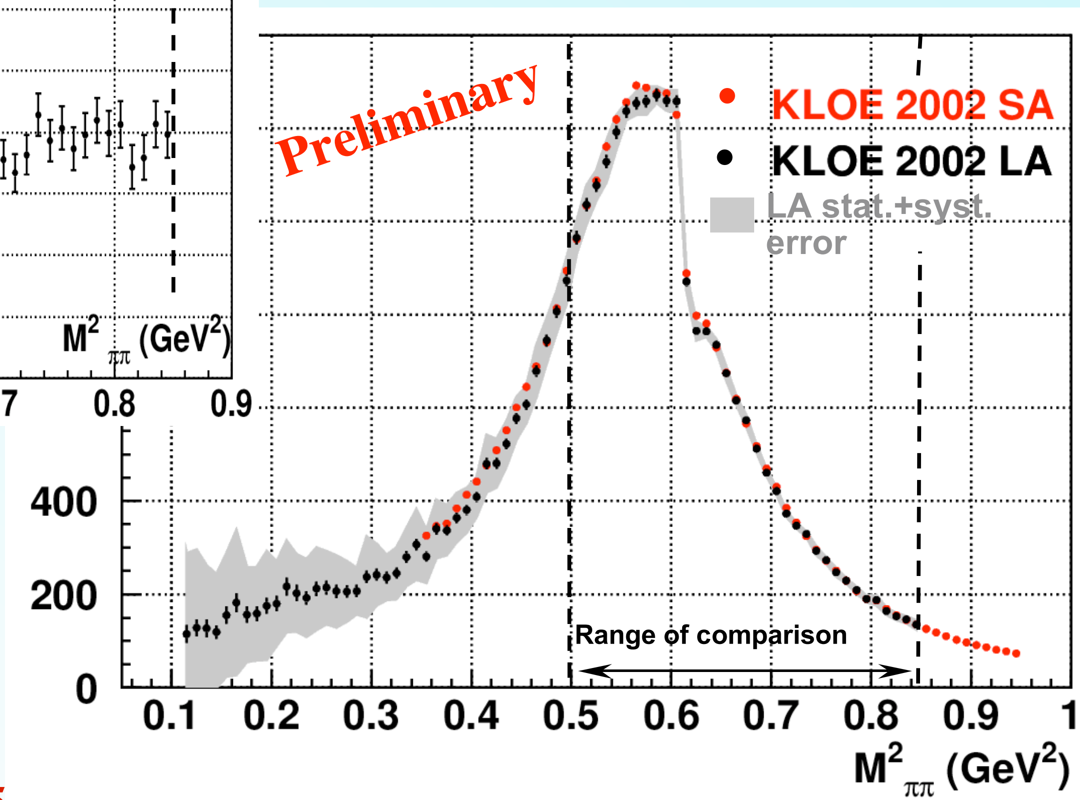
- Surprising result: scalar background from $f_0(980)$ large also at low masses due to non-Breit-Wigner shape of mass distribution in ϕ rad. decays



- Unfortunately large model dependence in description of scalar amplitude, take difference btw. 2 Monte-Carlos as conservative estimate of model dependence

Comparison 2002 Data: SA vs. LA Analyses

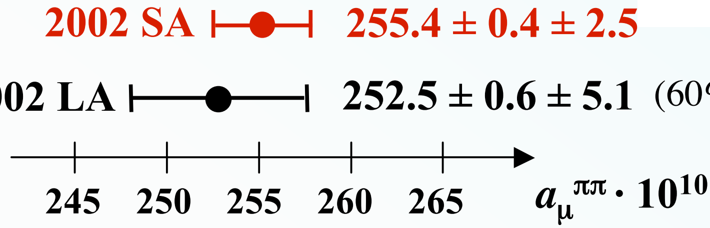




Comparison of SA and LA analysis (2002 data) in the mass range 0.50-0.85 GeV^2

2002 SA **255.4 ± 0.4 ± 2.5**

2002 LA **252.5 ± 0.6 ± 5.1** (60% of systematical error due to $f_0$uncertainty)



Forward-Backward-Asymmetry and $f_0(980)$

Define the forward-backward-asymmetry

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

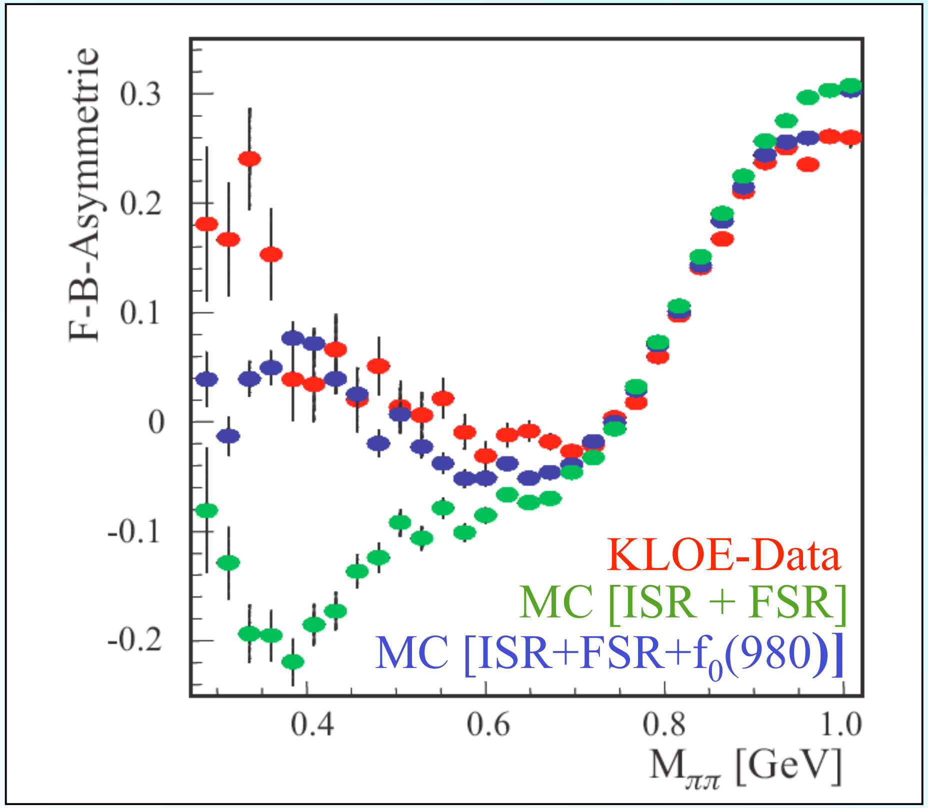
Asymmetry is a consequence of different C-Parity of $\pi^+\pi^-$ for ISR- and FSR-amplitude

Interesting for 2 aspects:

1) A_{FB} is sensitive on presence of a scalar amplitude from $f_0(980)$

2) Comparison data - MC for A_{FB} allows to test model of scalar QED (pointlike pions) for the description of FSR

New strategy:
Fit couplings for $f_0(980)$ (and probably $f_0(600)$?) using FB-Asymmetrie A_{FB}; constrain model dependence in LA analysis



Conclusions
&
Outlook

Conclusions

- KLOE has extracted $a_\mu^{\pi\pi}$ in the range between 0.35 - 0.95 GeV^2 using cross section data obtained via radiative return with photon emission at small angles (untagged analysis).

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

- Data from an independent KLOE measurement (*Large angle analysis*) of the 2π-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 CMD-2 and SND experiments at VEPP-2M in Novosibirsk

➔ *Differences in mass shape dependence to be understood?!*

Outlook

- Refine the small angle analysis by unfolding for detector resolution and release the $\pi\pi$ cross section table soon.

- Continue evaluation of scalar contributions in the large angle analysis to decrease model dependence from $f_0(980)$ contribution

- Measure the pion form factor via R-ratio, i.e. bin-by-bin ratios of pions over muons (normalization to radiative muon pairs)

- Obtain pion form factor from data taken at $\sqrt{s}$ = 1000 MeV (outside the phi resonance)
  - suppression of background from ϕ-decays
  - cover threshold region <600 MeV
  - determination of $f_0(980)$-parameters