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# KLOE results on Hadronic Cross Section


**Paolo Beltrame**

Institut für Experimentelle Kernphysik

University of Karlsruhe

for the KLOE Collaboration

# Motivations

# &

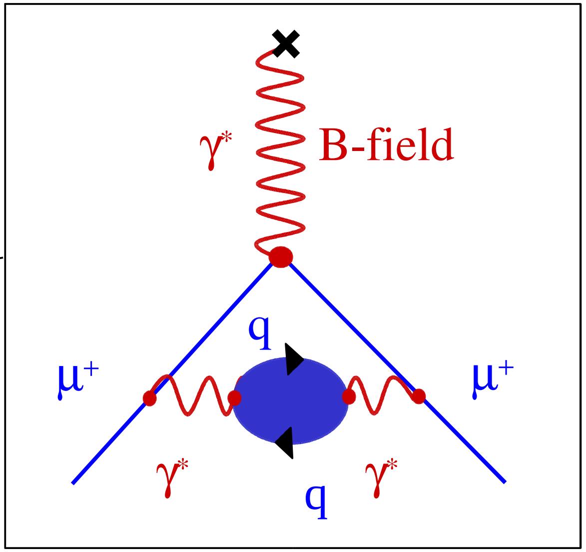
# Radiative Return Method

**High Precision Test of the Standard Model**

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

⇒ Anomalous magnetic moment of the muon

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




$$a_\mu^{theo} = a_\mu^{QED} + a_\mu^{hadr} + a_\mu^{EW} + a_\mu^{New\ Phys}$$

**2nd largest contribution, *pQCD* not applicable**

**Error on hadronic contribution dominates total error on $a_\mu^{theo}$**

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

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

**$\sigma_{\pi\pi} = (e^+e^- \to \pi^+\pi^-)$ gives >70% contribution to $a^{had}$**

- $E_{cut}$ is the threshold energy above which pQCD is applicable
- s is the c.m.-energy squared of the hadronic system
- K(s) is a monotonous function that goes with 1/s, ***enhancing low energy contributions of $\sigma^{Hadr}(s)$***

Alternative: spectral function from decay $\tau \to \nu_\tau$ hadrons

# Radiative Return

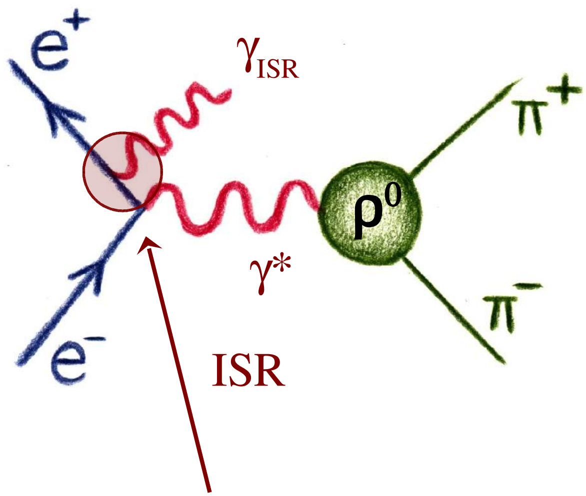
Particle factories, as **DAΦNE** (or PEP-II, KEK-B), **designed for a fixed center-of-mass energy**: $\sqrt{s} = m_\phi = 1.02$ GeV in the case of DAΦNE

**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**




**Radiator-Function H(s)**

**"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 $\mathbf{s_\pi = M_{\pi\pi}^2}$

For ISR events

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

⇒ `EVA + PHOKHARA` **MC generator**

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

**H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003**

# Measurements of the Pion Form Factor at KLOE

# KLOE selection of $\pi^+\pi^-\gamma_{ISR}$

**Pion tracks at *large angle***

**$50° < \theta_\pi < 130°$**

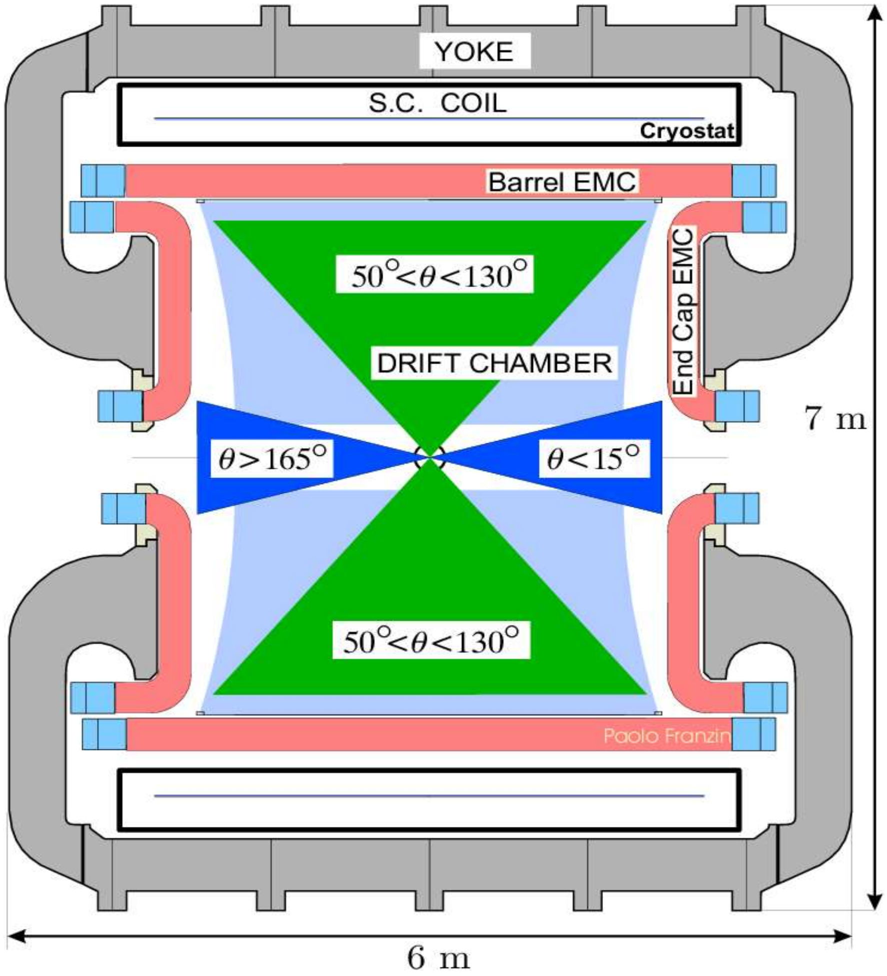
**a) Photon at *small angle***

**$\theta_\pi < 15°, 165° < \theta_\pi$**

- **No photon tagging**

$$\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_1 + \vec{p}_2)$$

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

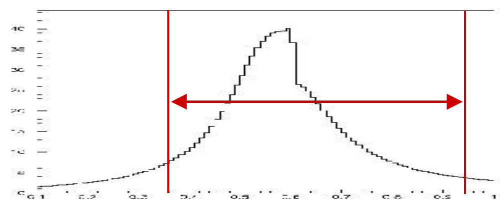
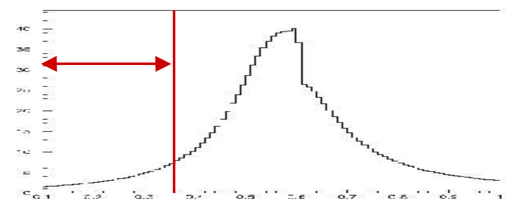



**b) Photon at *large angle***

**$50° < \theta_\gamma < 130°$**

- **Photon tagging possible**
- Increased contribution of *FSR*
- Contribution from $\phi \to f_0(980)\gamma \to \pi^+\pi^-\gamma$

# Overview Pion Form Factor at KLOE

| Analysis | $\int L dt$ | Syst. $0.6<M_{\pi\pi}<0.95$ GeV$^2$  | Syst. $M_{\pi\pi}<0.6$ GeV$^2$  |
|---|---|---|---|
| $\gamma_{ISR}$ ***untagged*** 2001 data | 140 pb$^{-1}$ | 1.3 % (published) | (kinematically forbidden) |
| $\gamma_{ISR}$ ***untagged*** 2002 data | 240 pb$^{-1}$ | 1.1 % | (kinematically forbidden) |
| $\gamma_{ISR}$ ***tagged*** 2002 data | 240 pb$^{-1}$ | 0.9 % $\oplus$ $f_0$(980) contribution | limited by model dependence of irreducible background $\phi \to f_0(980)\,\gamma$ |
| ***Off-Peak*** 2006 **$\sqrt{s}$ = 1.00 GeV** | 230 pb$^{-1}$ | << 1 % | suppressed $f_0$(980) contribution |

# Small Angle Analysis

# 2001 $\rightarrow$ 2002 DATA

# Event selection

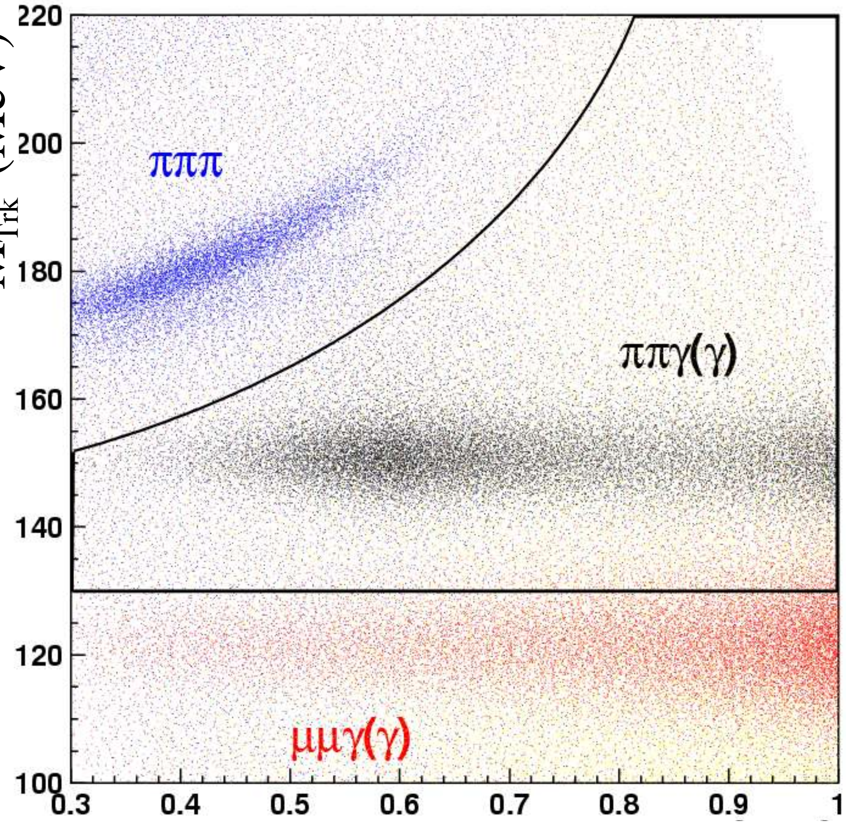
**Background**:

$\phi \to \pi^+\pi^-\pi^0$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^-\gamma$

reduced by means of

- likelihood function (e-π-separation)
- kinematic cuts: missing mass and trackmass (4-momenta conservation under the hypothesis of two tracks with the same mass)

$$\left(\sqrt{s}-\sqrt{\vec{p}_{x_1}^{\,2}+M_{\mathrm{trk}}^2}-\sqrt{\vec{p}_{x_2}^{\,2}+M_{\mathrm{trk}}^2}\right)^2-(\vec{p}_{x_1}+\vec{p}_{x_2})^2=q_\gamma^2=0$$




$M_{\mathrm{Trk}}$ (MeV)

$M_{\pi\pi}^2$ (GeV$^2$)

**Efficiency**:

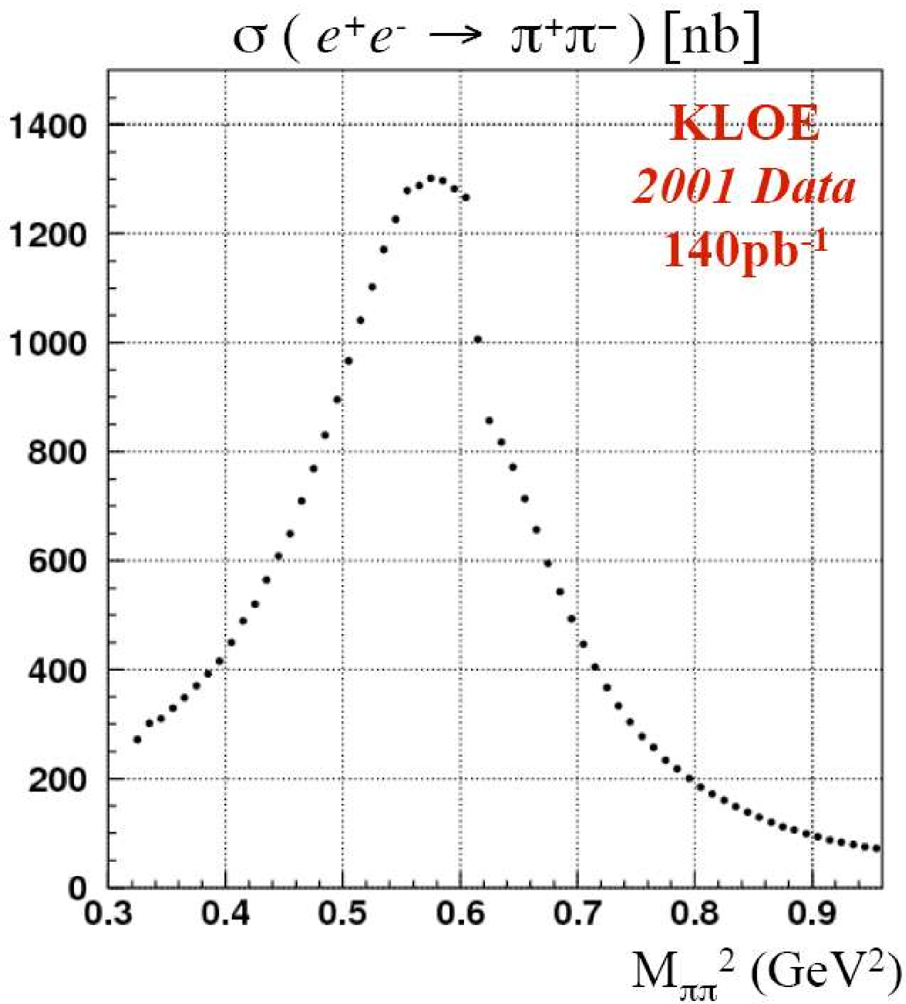
Whenever possible use DATA, rely on MC only for acceptance and $M_{\mathrm{trk}}$

**Luminosity normalization**:

Measure DAΦNE luminosity with **Bhabha events at large polar angles > 55°** as normalization process

# Published result with 2001 DATA

**Phys. Lett. B606 (2005) 12**




$a_\mu^{\pi\pi}$**(0.35-0.95 GeV²) =**

**$(388.7 \pm 0.8_{stat} \pm 4.9_{syst}) \cdot 10^{-10}$**

## 2001 → 2002

- Larger DATA set: more refined evaluation of systematic errors associated with selection efficiencies

- DATA less affected by machine background

- Additional online software trigger level: recover cosmic veto inefficiency (30% in 2001)

- Improved offline-event filter: systematic uncertainty to < 0.1% (0.6% in published analysis)

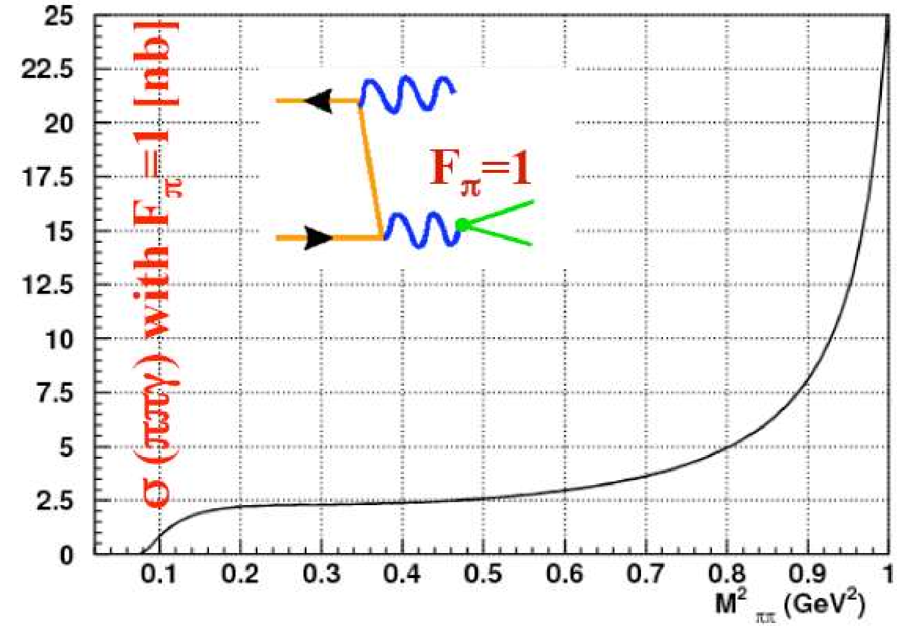
- Trigger efficiency estimate in 2001 data corrected. Mainly low $M_{\pi\pi}$ region, published $a_\mu^{\pi\pi}$ decreased by 0.4%

- New event generator BABAYAGA@NLO (theoretical error of Bhabha effective cross section from 0.5% to 0.1%) Bhabha cross section value lowered by 0.7%, Pion Form Factor decreases by 0.7%

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

## - Radiator-Function H(s) (ISR):

**ISR-Process calculated at NLO-level**
**PHOKHARA** generator (Czyż, Kühn et.al)
Precision: 0.5%




## - Radiative Corrections:

**i) Bare Cross Section**

divide by Vacuum Polarization

from F. Jegerlehner:

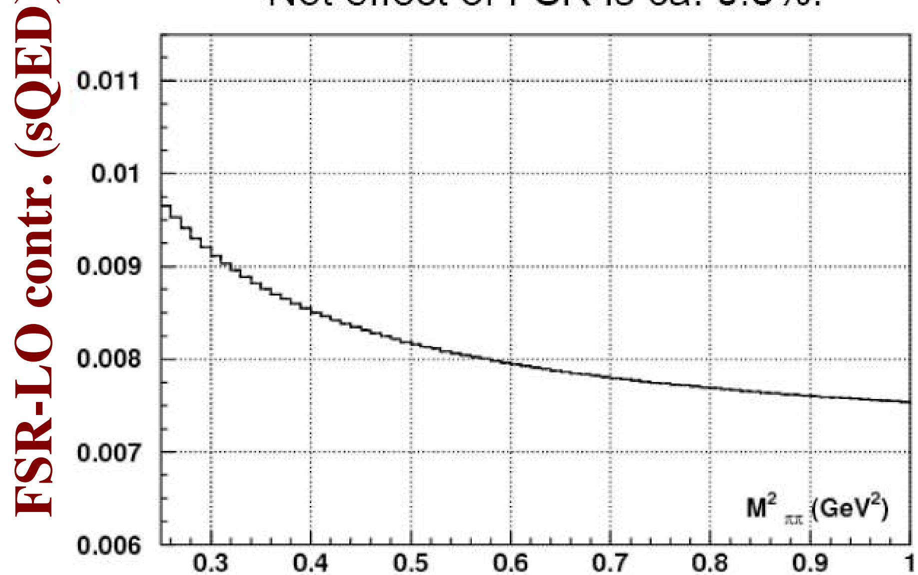
http://www-com.physik.hu-berlin.de/~fjeger/

**ii) FSR correction**

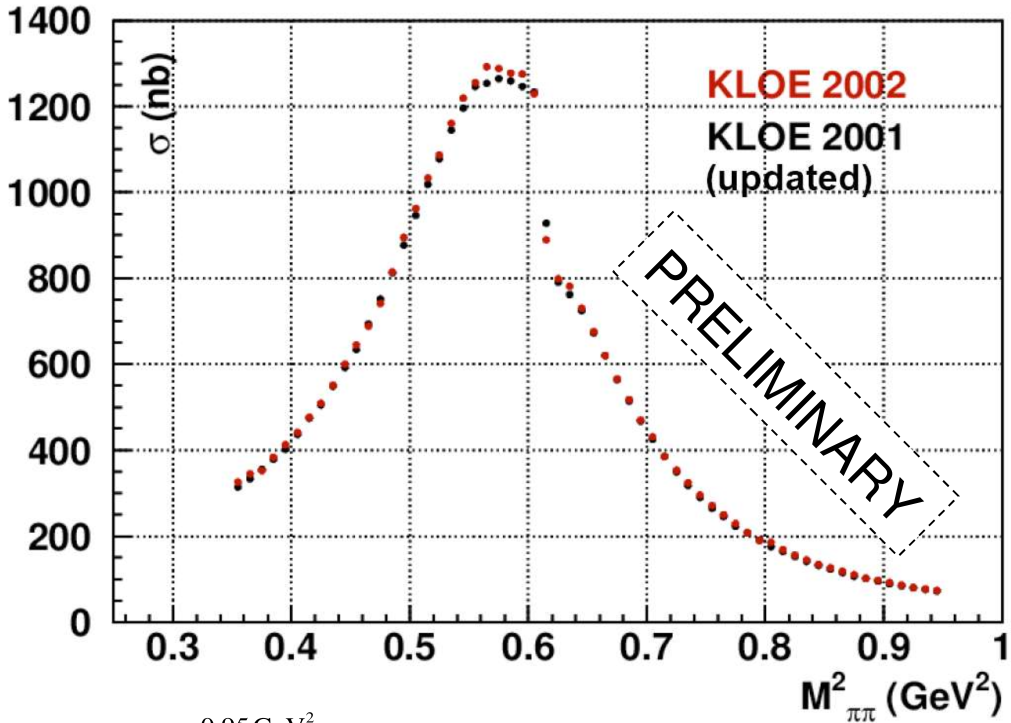
Cross section $\sigma_{\pi\pi}$ must be inclusive for FSR


FSR corrections have to be taken into account up to NLO

Net effect of FSR is ca. 0.8%:



# Small Angle Result from 2002 DATA $\sigma_{\pi\pi}$ and $a_\mu^{\pi\pi}$




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

**2001** updated for trigger efficiency and change in Bhabha-cross section

$$\boldsymbol{a_\mu^{\pi\pi}(0.35\text{-}0.95\,\mathrm{GeV}^2) = (384.4 \pm 0.8_{stat} \pm 4.9_{syst}) \cdot 10^{-10}}$$

**2002** preliminary

$$\boldsymbol{a_\mu^{\pi\pi}(0.35\text{-}0.95\,\mathrm{GeV}^2) = (386.3 \pm 0.6_{stat} \pm 3.9_{syst}) \cdot 10^{-10}}$$

| | |
|---|---|
| Offline filter | negligible |
| Background | 0.3% |
| Trackmass/Miss. mass | 0.2% (prelim) |
| $\pi$/e – ID | 0.3% |
| Vertex | 0.5% |
| Tracking | 0.4% |
| Trigger | 0.2% |
| Acceptance ($\theta_\pi$) | negligible |
| $M_{\pi\pi} \to M_{\gamma*}$ (FSR contr) | 0.3% (prelim) |
| Software Trigger | 0.1% |
| Luminosity | 0.3% |
| Acceptance ($\theta_{Miss}$) | 0.1% |
| Radiator H | 0.5% |
| Vacuum Polarization | negligible |
| SYSTEMATIC ERROR | 1.1% |

# Large Angle Analysis

# 2002 DATA

# Pro & Contra

✓ independent analysis and cross check

✓ the threshold region is accessible

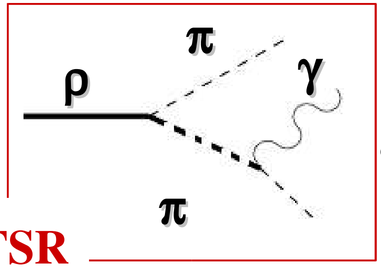
✓ the ISR photon is detected (4-momentum constraints)

✓ lower signal statistics

✓ large $\phi \to \pi^+\pi^-\pi^0$ background contamination (strong analysis cuts needed)

✓ large FSR contributions

✓ irreducible background from radiative $\phi$ decay: $\phi \to f_0\gamma \to \pi\pi\gamma$

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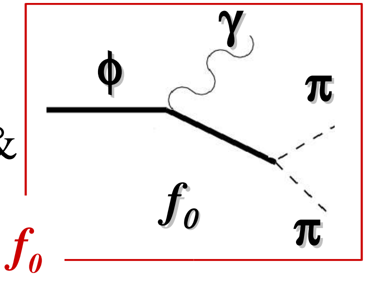
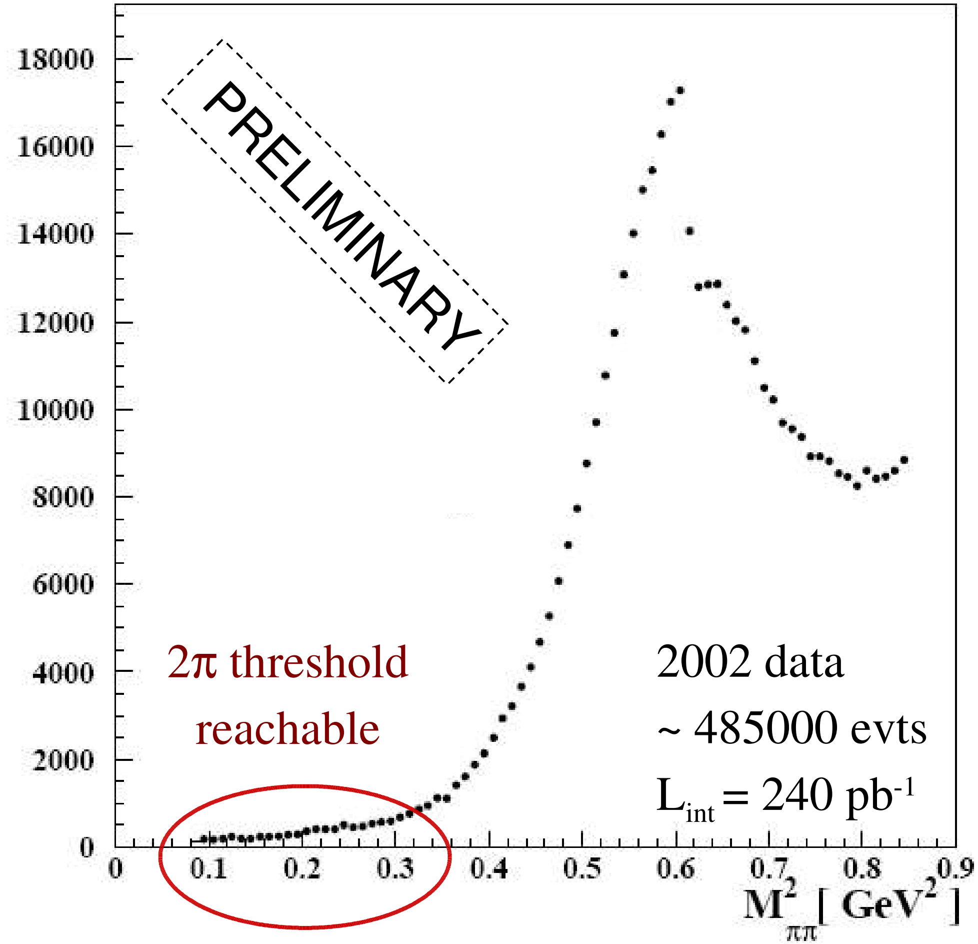



Estimated from MC using phenomenological models

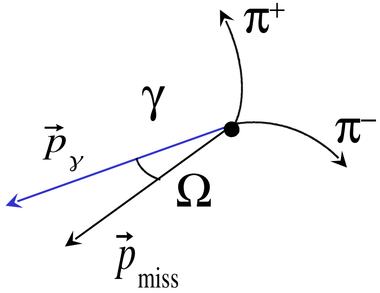
- **Pion tracks:** $50^o < \theta_\pi < 130^o$
- **Photons:** at least one with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 50$ MeV. **Photon tagging**



# Event selection & backgrounds

Exploiting the kinematic closure of the event:

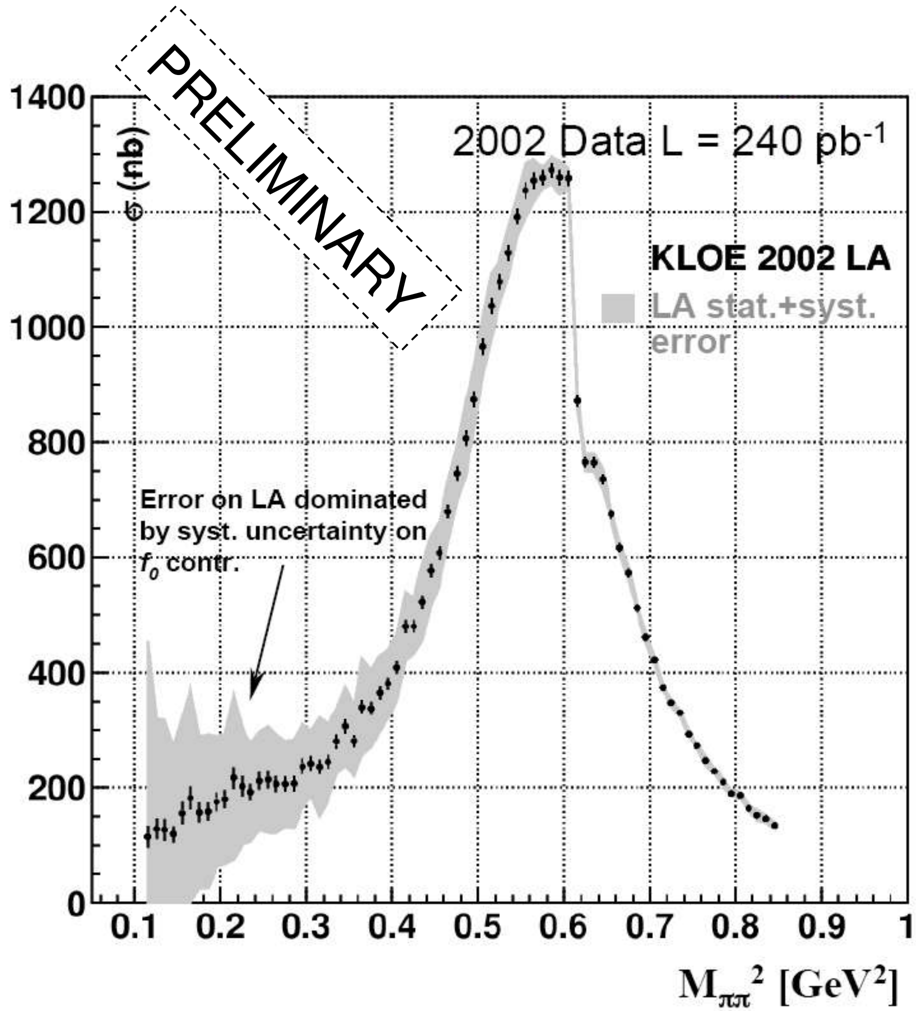
- Cut on angle $\Omega$ between ISR-photon and missing momentum




- Kinematic fit in $\pi^+\pi^-\pi^0$ hypothesis using 4-momentum and $\pi^0$-mass as constraints

FSR contribution added back to cross section (estimated from PHOKHARA generator)

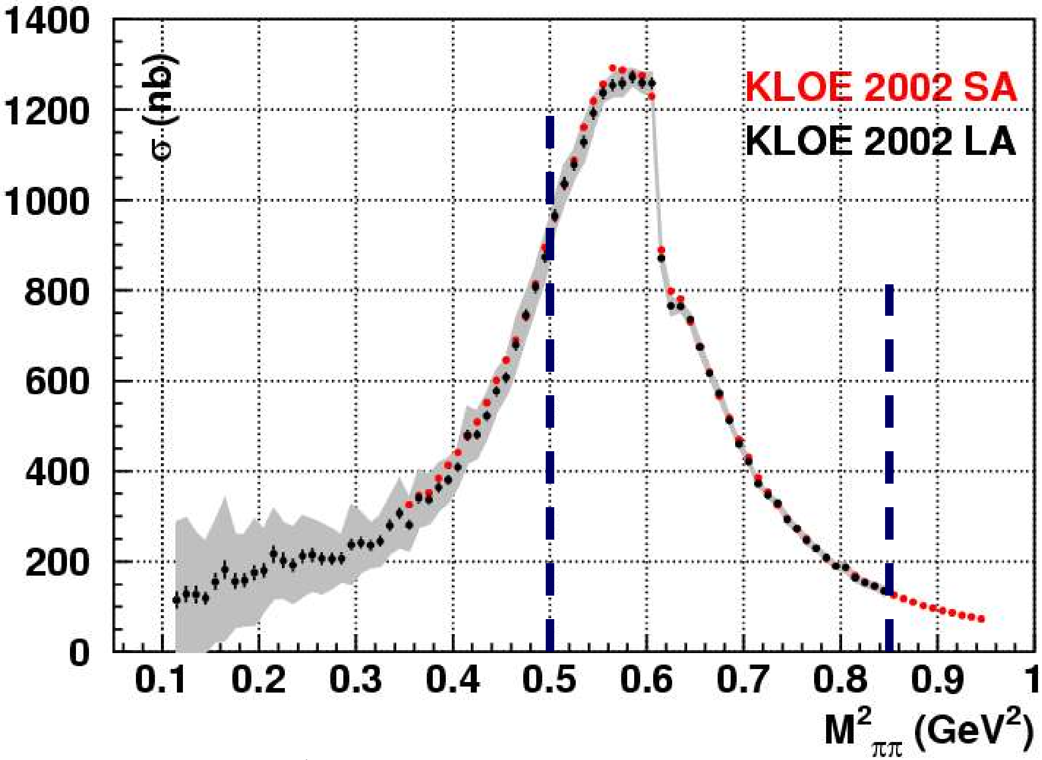
Reducible background from $\pi^+\pi^-\pi^0$ and $\mu^+\mu^-\gamma$ well simulated by MC

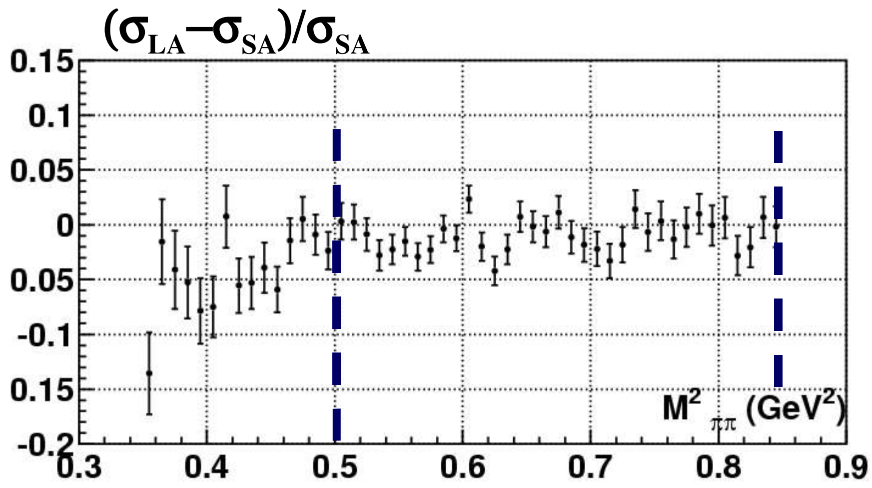



Dominating uncertainty from model dependence of irreducible background $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$. Using different models for $f_0$-decay and using input from dedicated KLOE $\phi \to f_0\gamma$ analyses (with $f_0 \to \pi^+\pi^-$ and $f_0 \to \pi^0\pi^0$).

**$\Rightarrow$ Difference between the MC models as systematics**

## Comparisons, summary, conclusions and outlook



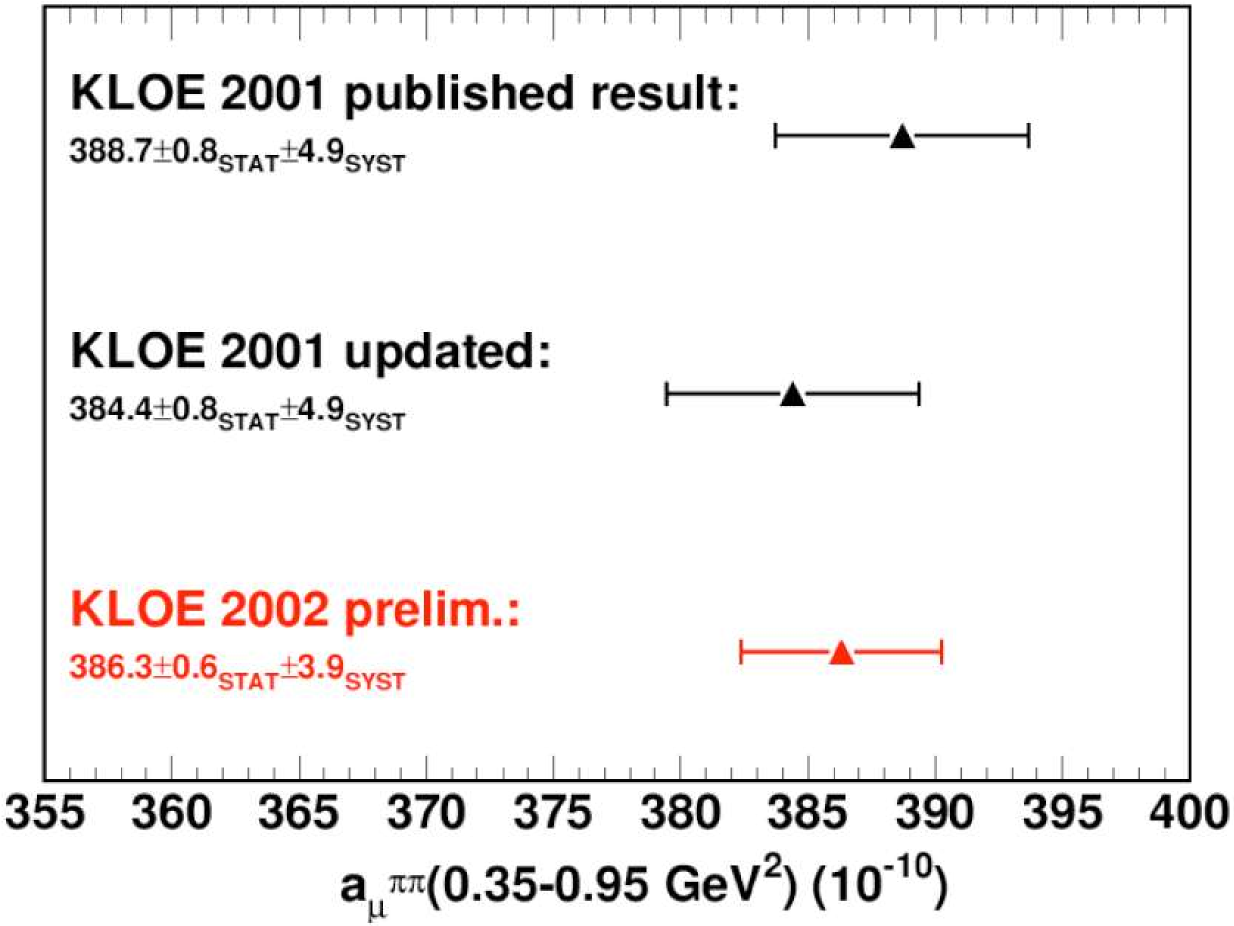

PRELIMINARY

Small Angle $a_\mu^{\pi\pi}(0.50\text{-}0.85\mathrm{GeV}^2) = \mathbf{(255.4 \pm 0.4_{stat} \pm 2.5_{syst}) \cdot 10^{-10}}$

Large Angle $a_\mu^{\pi\pi}(0.50\text{-}0.85\mathrm{GeV}^2) = \mathbf{(252.5 \pm 0.6_{stat} \pm 5.1_{syst}) \cdot 10^{-10}}$

60% of systematical error due to $f_0$-uncertainty

# $a_\mu^{\pi\pi}$ Summary: KLOE Small Angle analyses



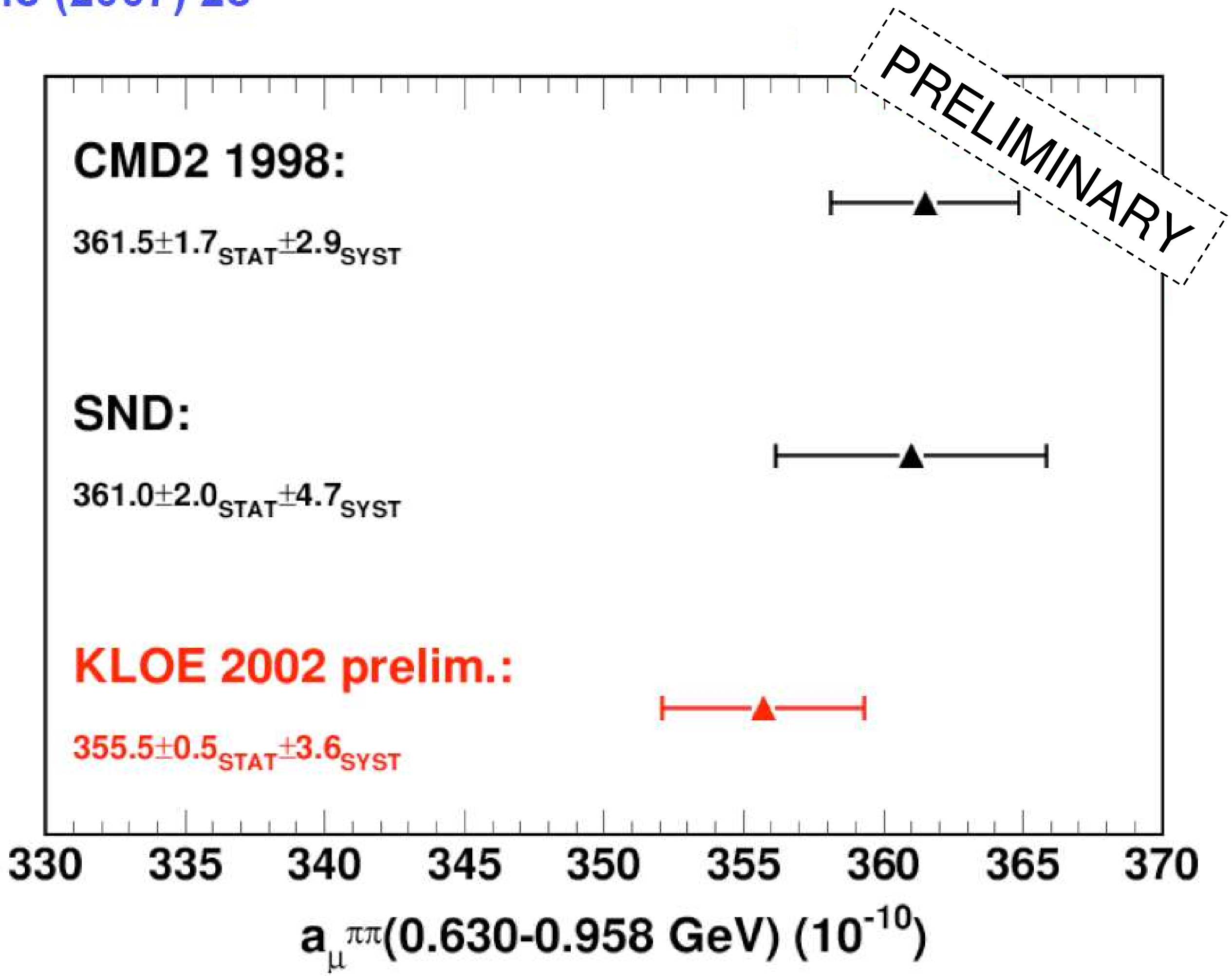

Jegerlehner (hep-ph/0703125): $\Delta a_m = a_m^{\exp} - a_m^{\text{theo}} = (28.7 \pm 9.1) \cdot 10^{-10}$

**Using new KLOE result would increase difference from 3.2σ to 3.4σ**

# $a_\mu^{\pi\pi}$ Summary: $e^+e^-$ experiments

$a_\mu^{\pi\pi}$ from KLOE, CMD2 and SND in the range 0.630-0.958 GeV

Phys. Lett. B648 (2007) 28




No comparison between spectra since sophisticated unfolding procedure yet to be done. (Negligible effect on $a_\mu^{\pi\pi}$)

# Conclusion

**Using cross section data obtained via the radiative return, $\sigma(\pi^+\pi^-\gamma)$,**

**$a_\mu^{\pi\pi}$ determinations have been performed**

Two complementary analyses:

**1. Small photon polar angle**

- the published result from 2001 data (140 $pb^{-1}$) has been updated with new Babayaga version (-0.7%) and trigger effect (-0.4%)
- the updated 2001 result agrees with the preliminary result from 2002 data (240 $pb^{-1}$)

**2. Large photon polar angle**

- results in the range 0.5-0.85 $GeV^2$ (less sensitive to resonances background) agree with above ones

**KLOE results are lower but consistent within one sigma**

**with those from CMD-2 and SND**

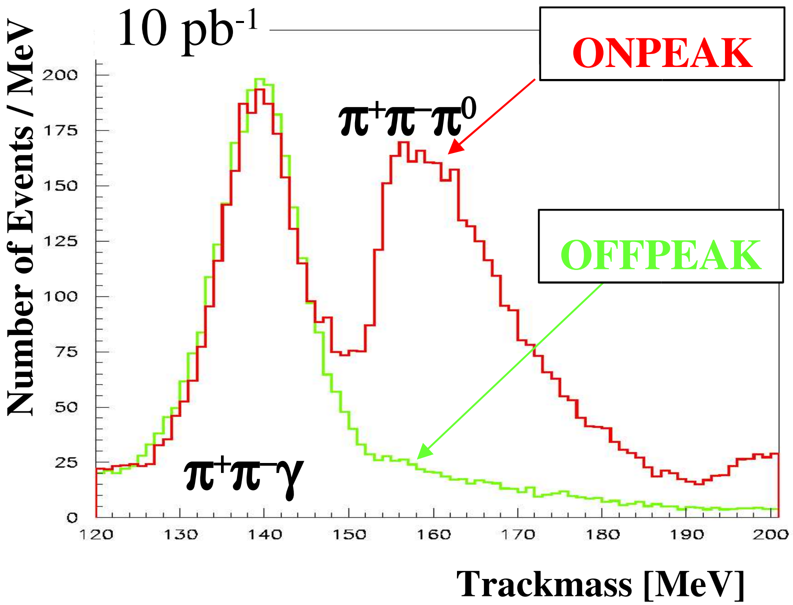
# Outlook

- Refine the **Small Angle** analysis by unfolding for detector resolution and release the $e^+e^- \to \pi^+\pi^-$ cross section soon

- Improve evaluation of contribution from resonances in the **Large Angle** analysis

- Normalize $\pi^+\pi^-\gamma$ events to $\mu^+\mu^-\gamma$ events (many systematic effects cancel)

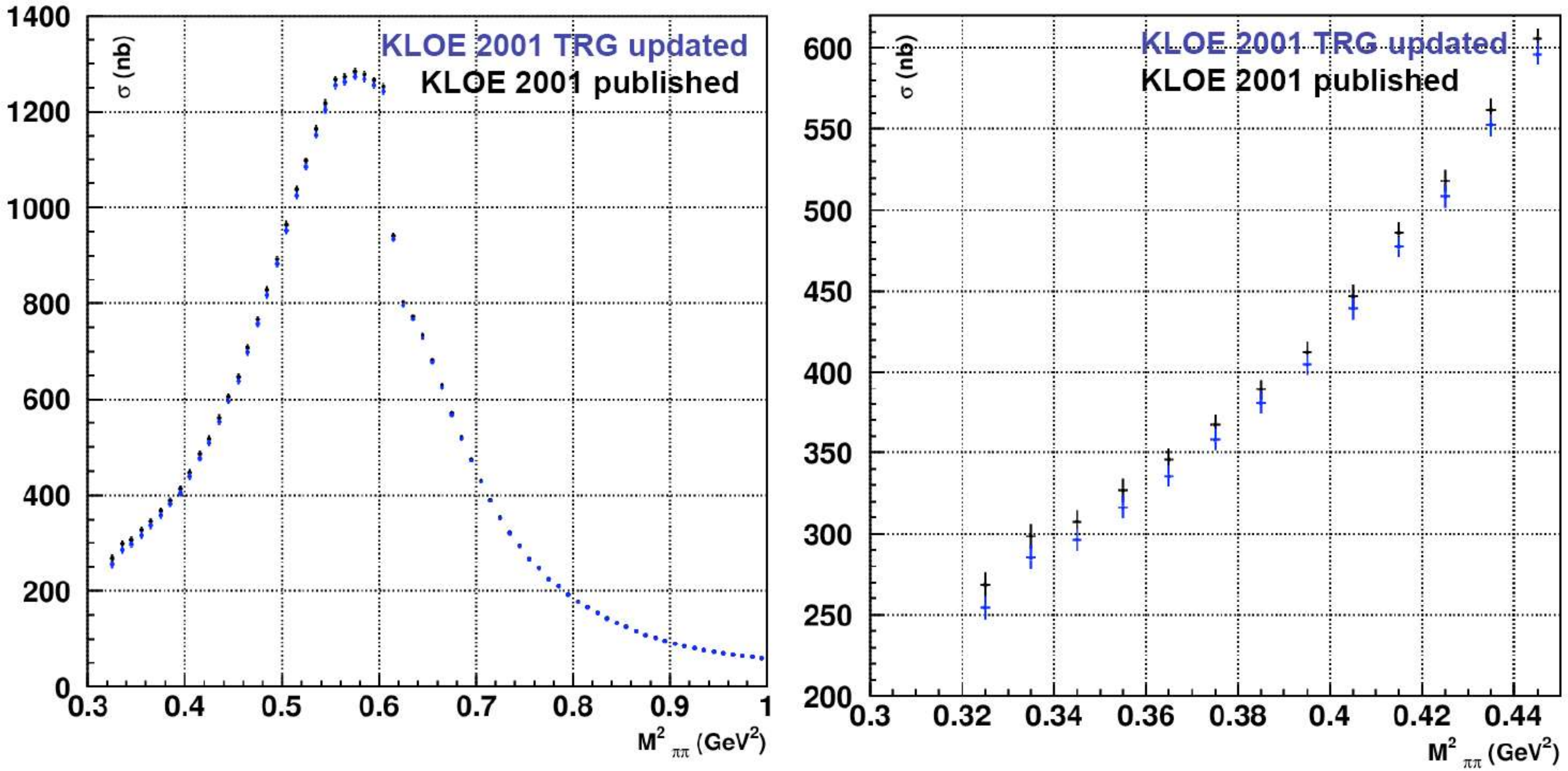
- Obtain Pion Form Factor from data taken in 2006 at $\sqrt{s}$ = 1000 MeV (**Off Peak**, outside the $\phi$ resonance)
  - $\to$ suppression of background from $\phi$-decays
  - $\to$ cover threshold region below 600 MeV
  - $\to$ determination of $f_0(980)$-parameters



# Spares slides

# 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%**