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KLOE results on Hadronic Cross Section

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Motivations

&

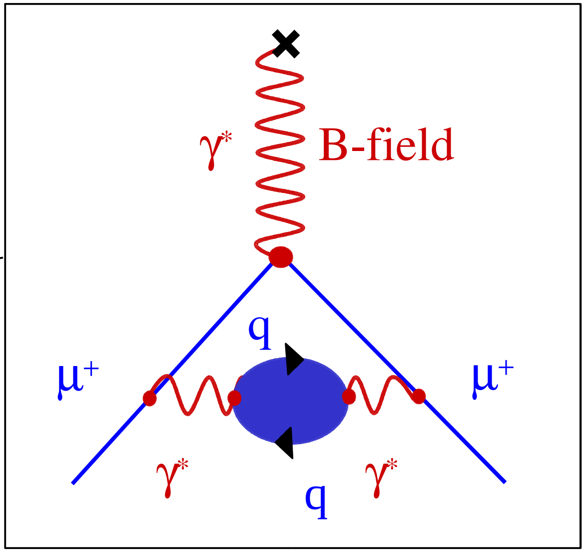
Radiative Return Method

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



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

2^{nd} largest contribution, *pQCD* not applicable

Error on hadronic contribution dominates total error on a_μ^{theo}

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

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

$\sigma_{\pi\pi} = (e^+e^- \rightarrow \pi^+\pi^-)$ gives >70% contribution to a_μ^{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 $\tau \rightarrow \nu_\tau$ hadrons

Radiative Return

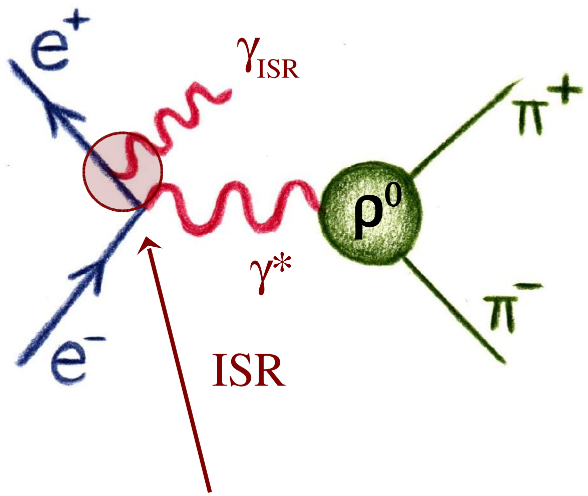
Particle factories, as **DAΦNE** (or PEP-II, KEK-B), **designed for a fixed center-of-mass energy**: $\sqrt{s} = m_\phi = 1.02$ GeV in the case of DAΦNE

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 $s_\pi = M_{\pi\pi}$

For ISR events

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

⇒ EVA + PHOKHARA **MC generator**

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

H. Czy , A. Grzeli ska, 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

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

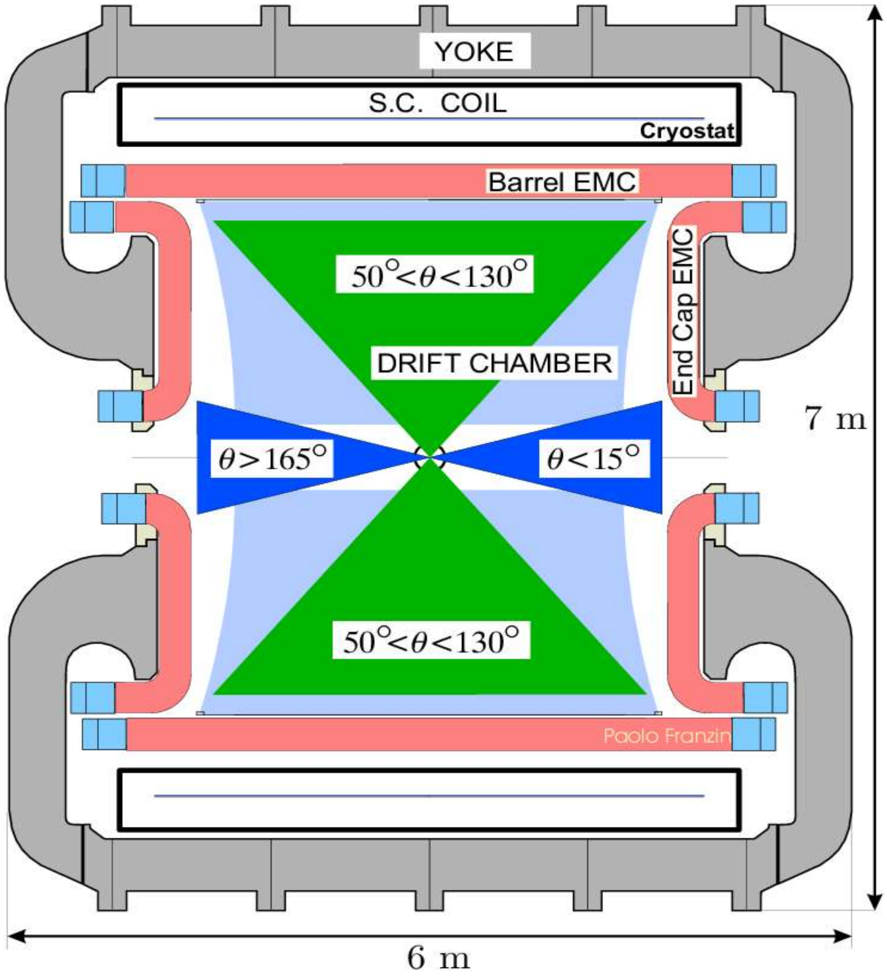
- High statistics for *ISR* photons
- Negligible contribution of *FSR*
- Reduced background

b) Photon at *large angle*

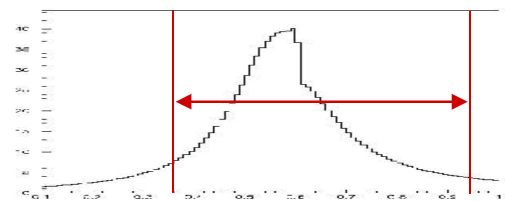
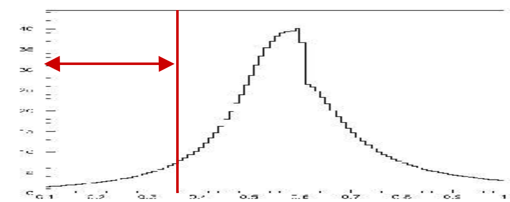
$50° < \theta_\gamma < 130°$

- Photon tagging possible

- Increased contribution of *FSR*
- Contribution from $\phi \rightarrow f_0(980)\gamma \rightarrow \pi^+\pi^-\gamma$



Overview Pion Form Factor at KLOE

Analysis	$\int L dt$	Syst. $0.6 < M_{\pi\pi} < 0.95$ GeV² 	Syst. $M_{\pi\pi} < 0.6$ GeV² 
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) 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

(γ_{ISR} untagged)

2001 $\rightarrow$ 2002 DATA

Event selection

Background:

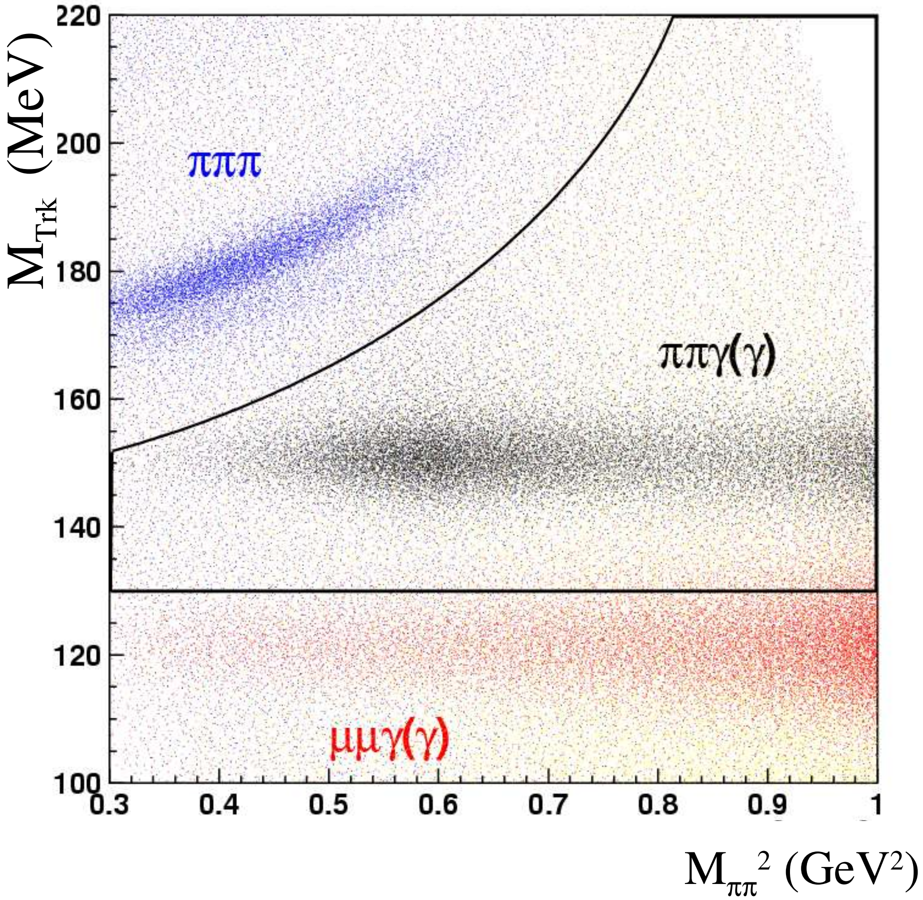
$\phi \rightarrow \pi^+\pi^-\pi^0$, $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^-\gamma$

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)

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



Efficiency:

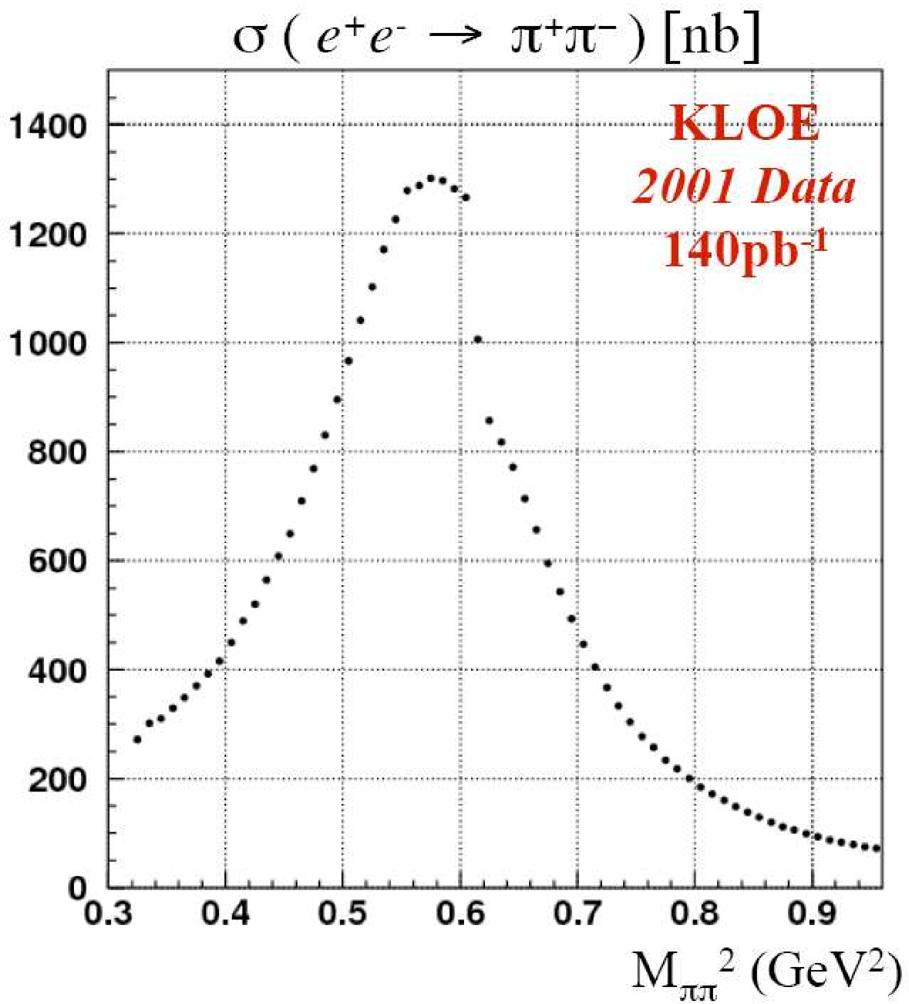
Whenever possible use DATA, rely on MC only for acceptance and M_{trk}

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 GeV^2) =**

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

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)

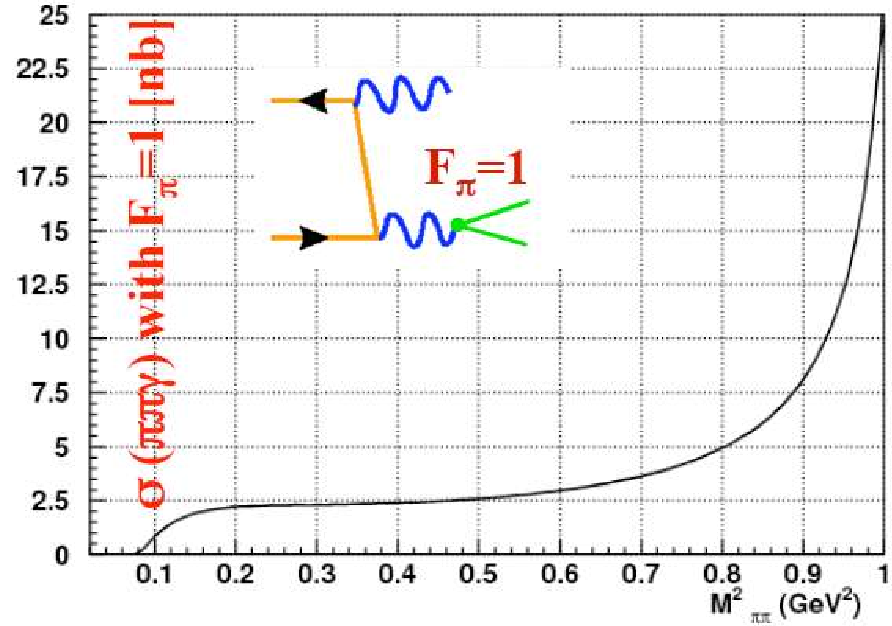
- Improved offline-event filter: systematic uncertainty to < 0.1% (0.6% in published analysis)

- 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 (Czy , Kühn et.al)
Precision: 0.5%

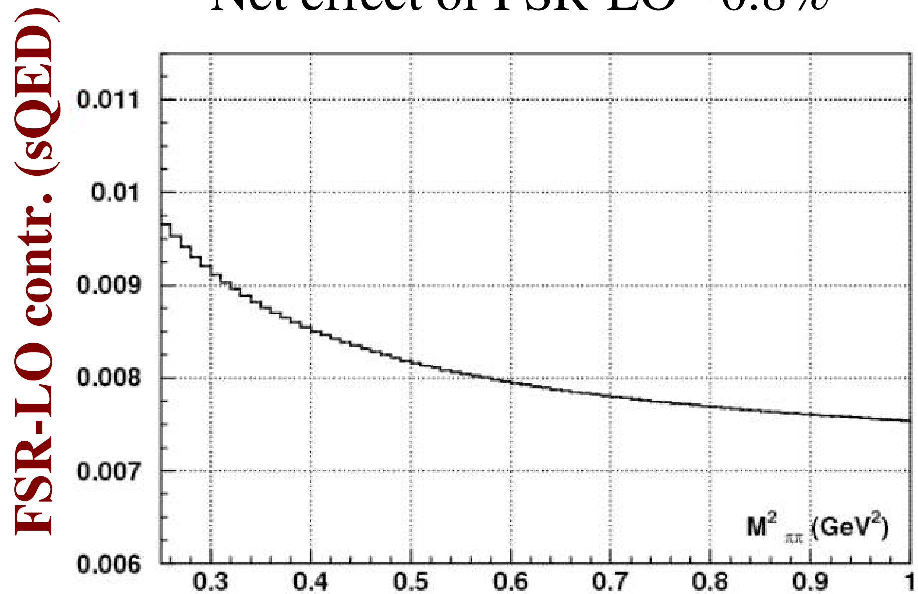


- Radiative Corrections:

i) Bare Cross Section
divide by Vacuum Polarization
from F. Jegerlehner:
http://www-com.physik.hu-berlin.de/~fjeger/

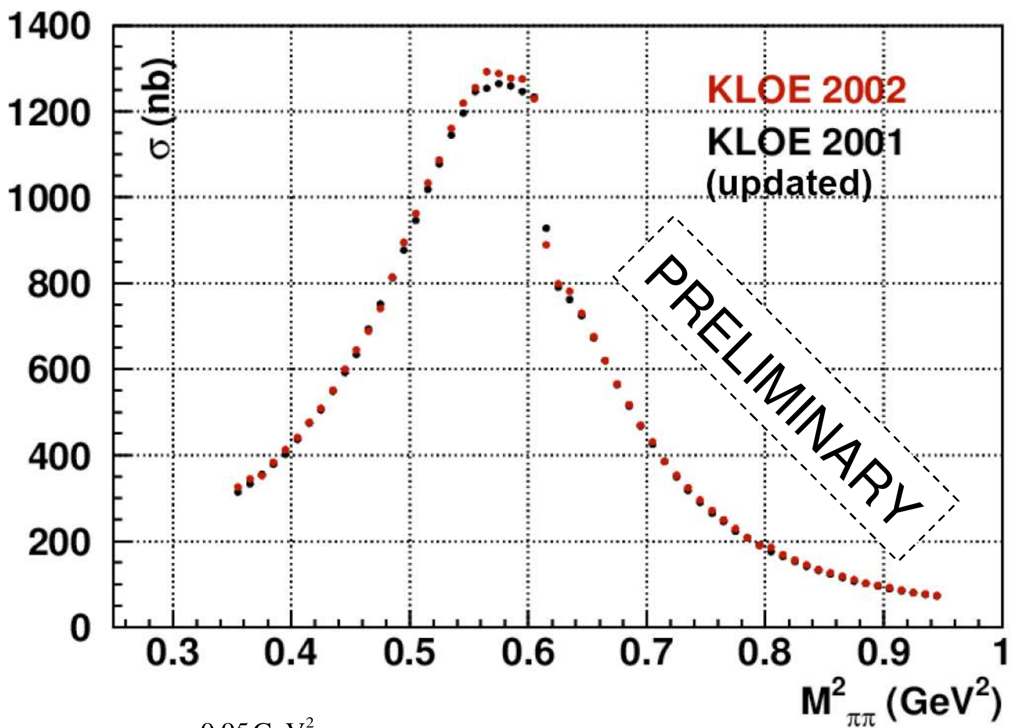
ii) FSR correction
Cross section $\sigma_{\pi\pi}$ must be inclusive for FSR

Net effect of FSR-LO ~0.8%



- FSR corrections have to be taken into account up to NLO
- sQED model

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

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

Systematic error contributions

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
$M_{\pi\pi} \to M_{\gamma*}$ (FSR contr)	0.3% (prelim)
Software Trigger	0.1%
Luminosity	0.3%
Acceptance (θ_{Miss})	0.1%
Radiator H	0.5%
Vacuum Polarization	negligible
SYSTEMATIC ERROR	1.1%

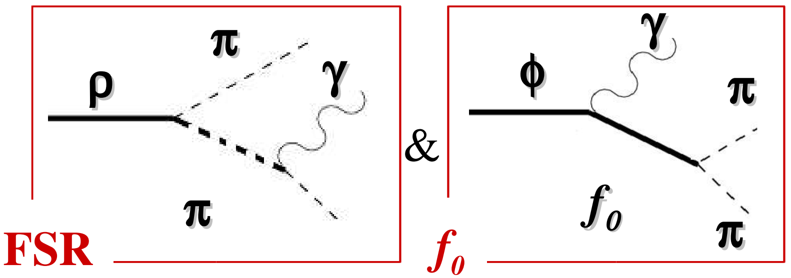
Large Angle Analysis

(γ_{ISR} tagged)

2002 DATA

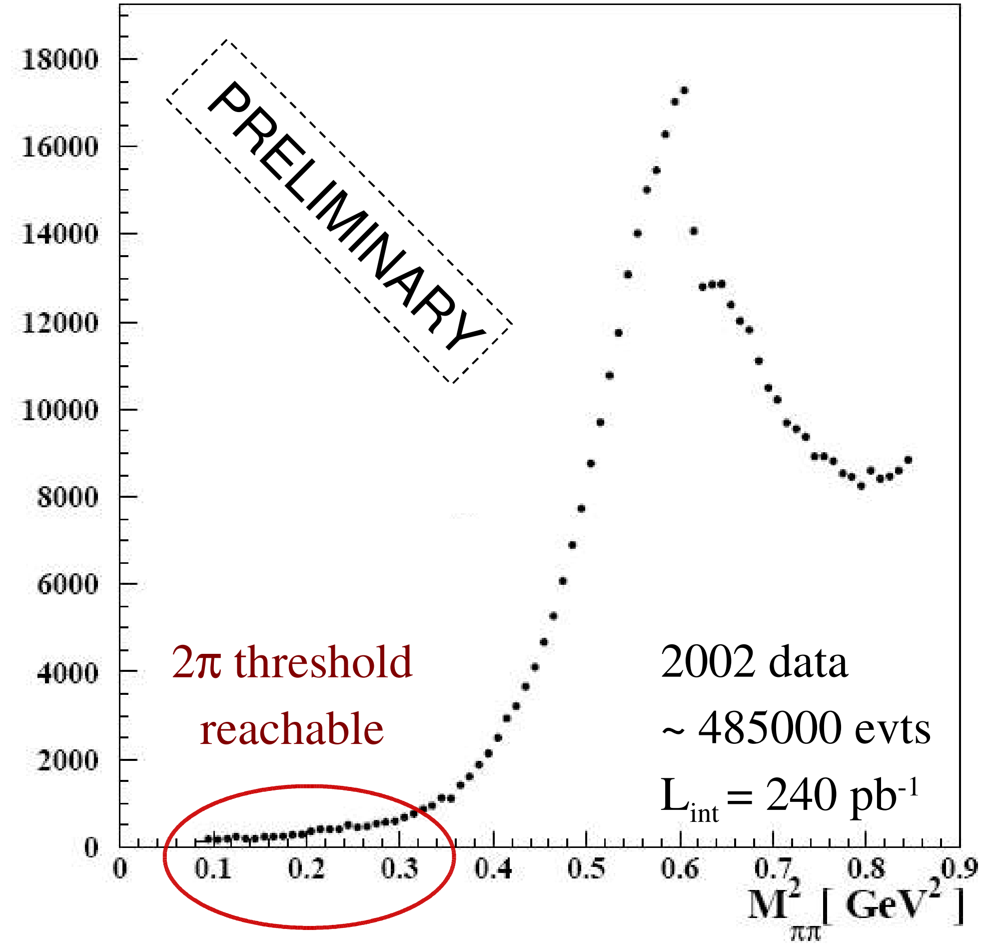
Pro & Contra

- ✓ 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 ϕ decay: $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$



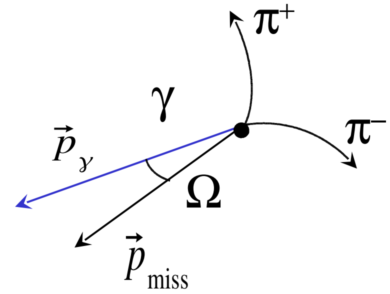
Estimated from MC using phenomenological models

- **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**



Exploiting the kinematic closure of the event:

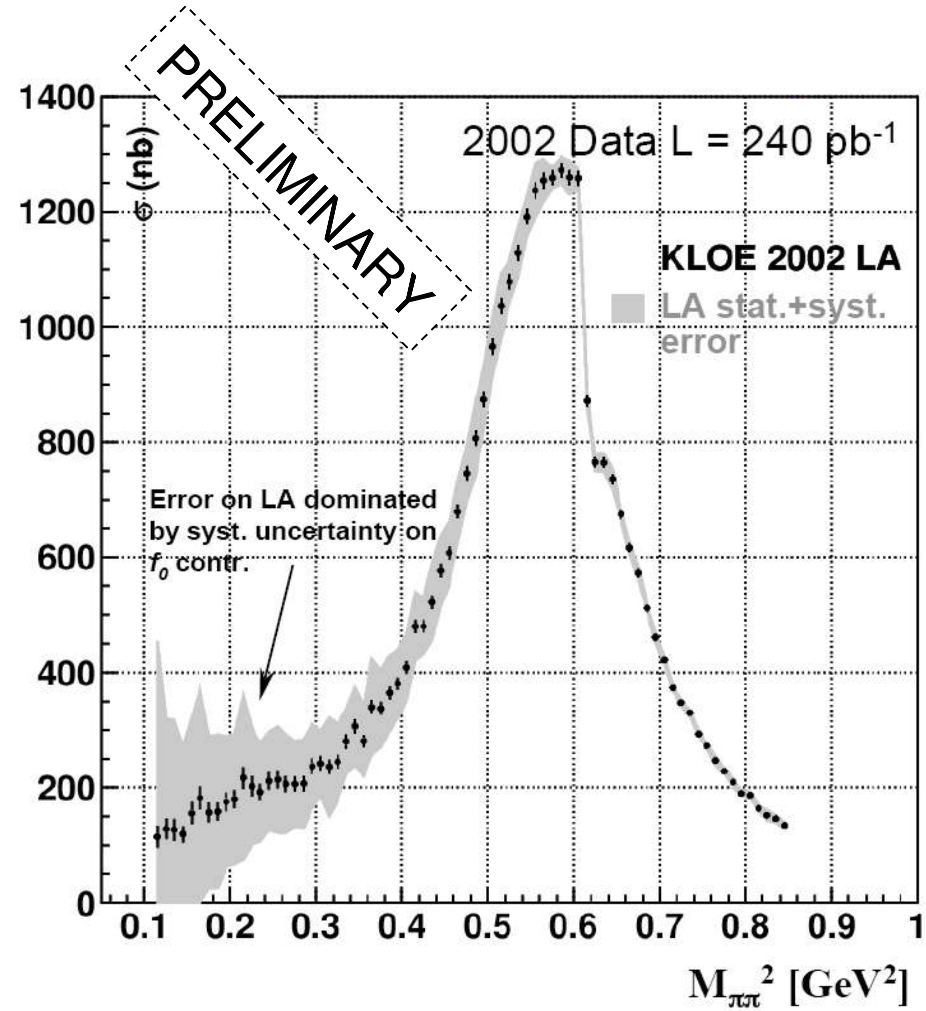
- Cut on angle Ω between ISR-photon and missing momentum



- Kinematic fit in $\pi^+\pi^-\pi^0$-bkg. hypothesis using 4-momentum and π^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

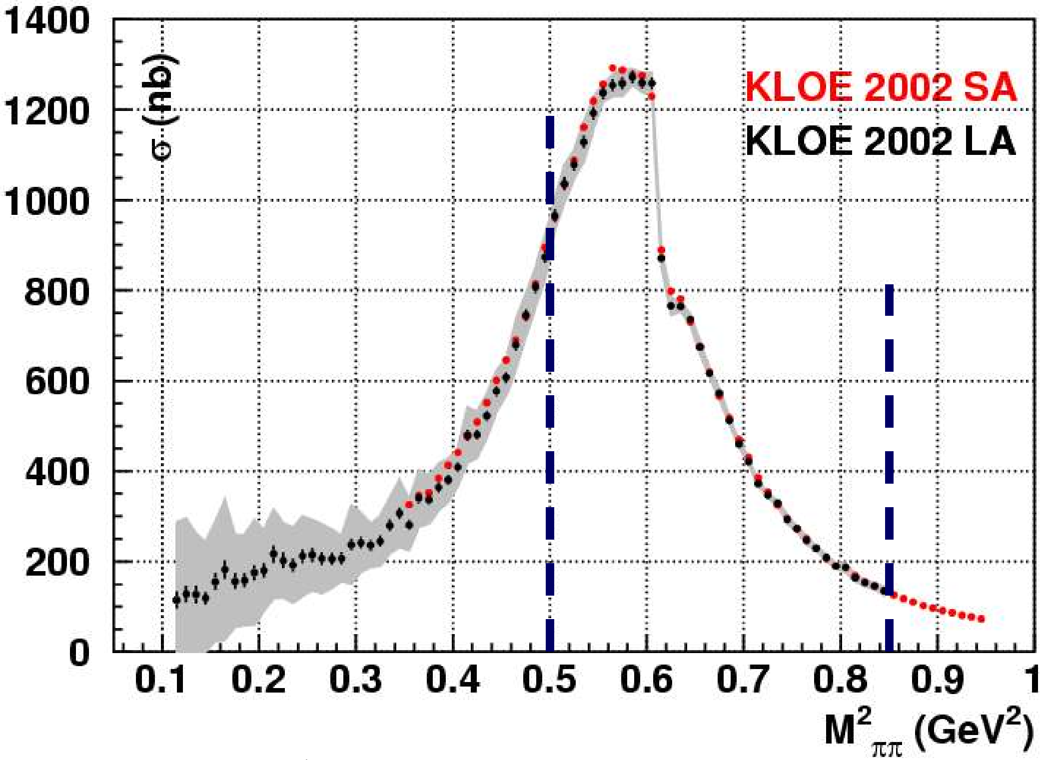


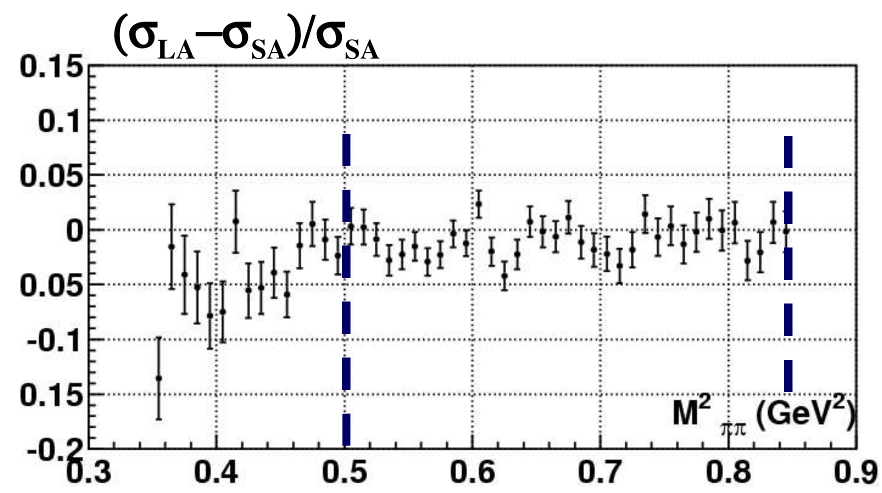
Dominating uncertainty from model dependence of irreducible background $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$. Using different models for f_0-decay and using input from dedicated KLOE $\phi \to f_0\gamma$ analyses (with $f_0 \to \pi^+\pi^-$ and $f_0 \to \pi^0\pi^0$).

$\Rightarrow$ Difference between the MC models as systematics

Comparisons, summary, conclusions and outlook

Small and Large Angle comparison





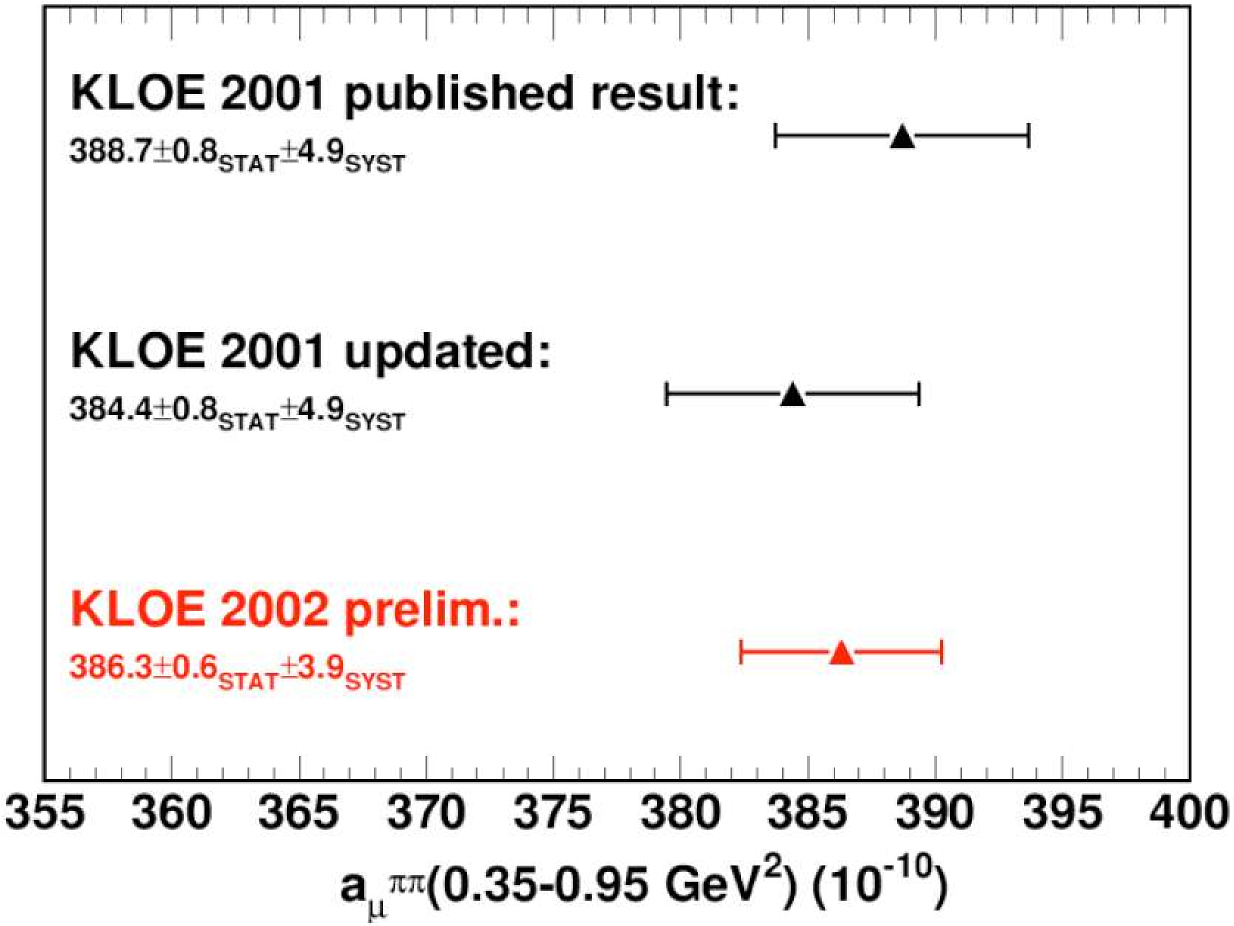
PRELIMINARY

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

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

60% of systematical error due to f_0-uncertainty

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



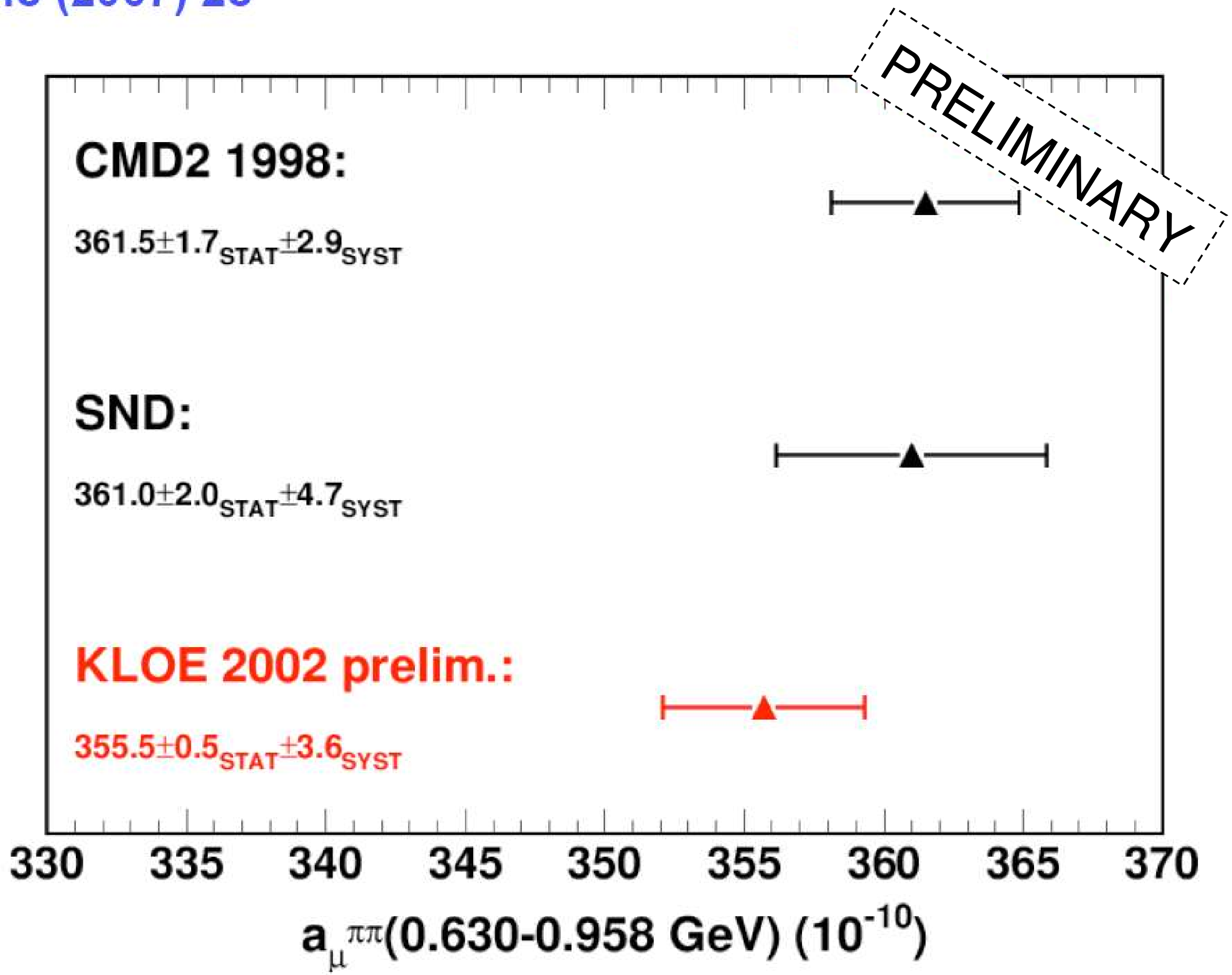
Jegerlehner (hep-ph/0703125): $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theo}} = (28.7 \pm 9.1) \cdot 10^{-10}$

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 for detector resolution 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

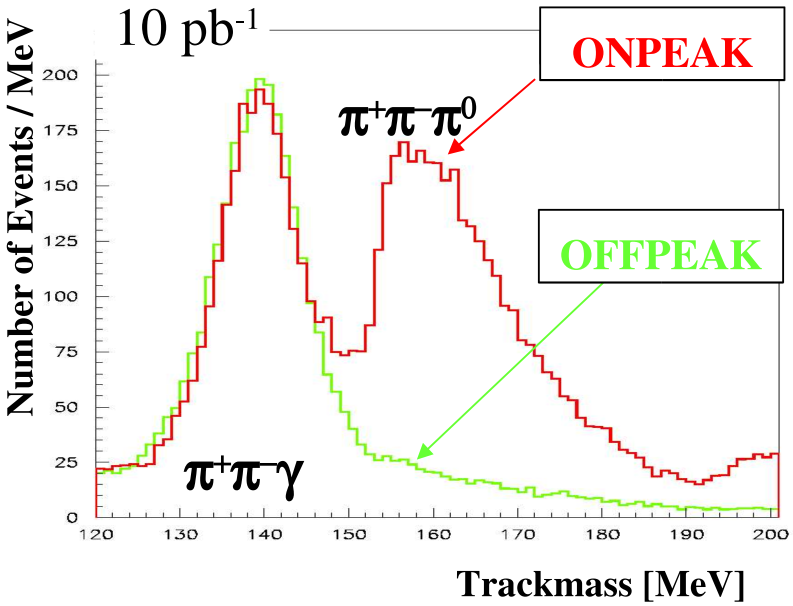
- Normalize $\pi^+\pi^-\gamma$ events to $\mu^+\mu^-\gamma$ events (many systematic effects cancel)

- Obtain Pion Form Factor from data taken in 2006 at $\sqrt{s}$ = 1000 MeV (**Off Peak**, outside the ϕ resonance)

  → suppression of background from ϕ-decays

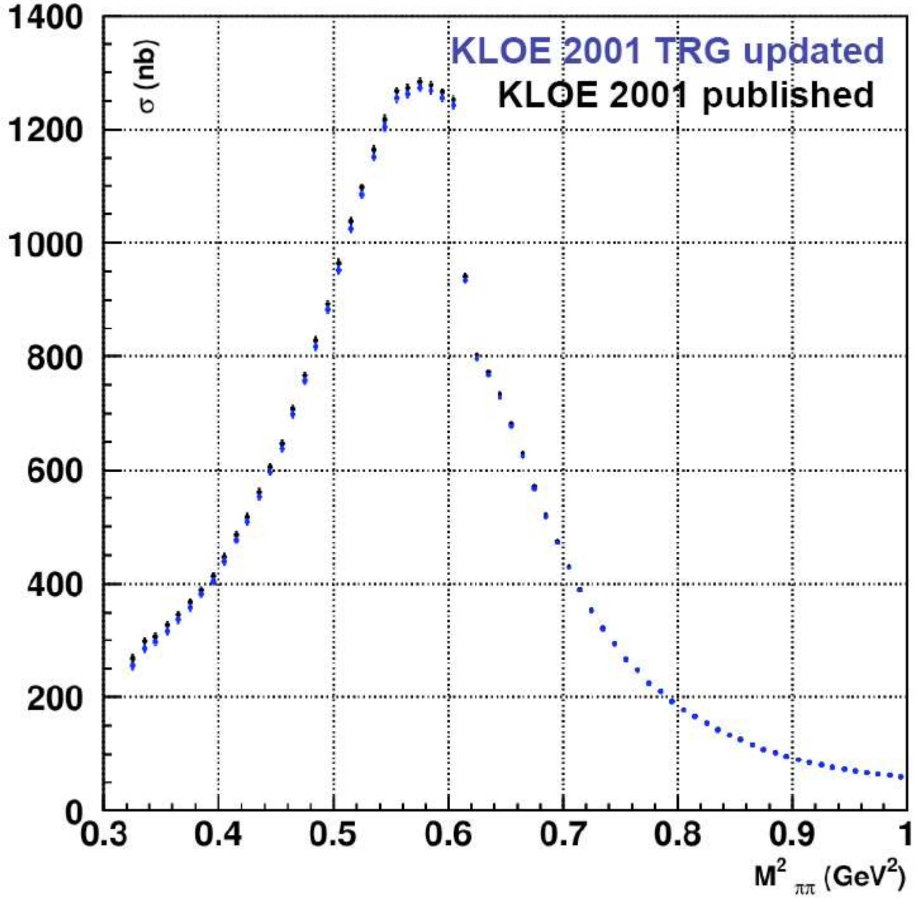
  → cover threshold region below 600 MeV

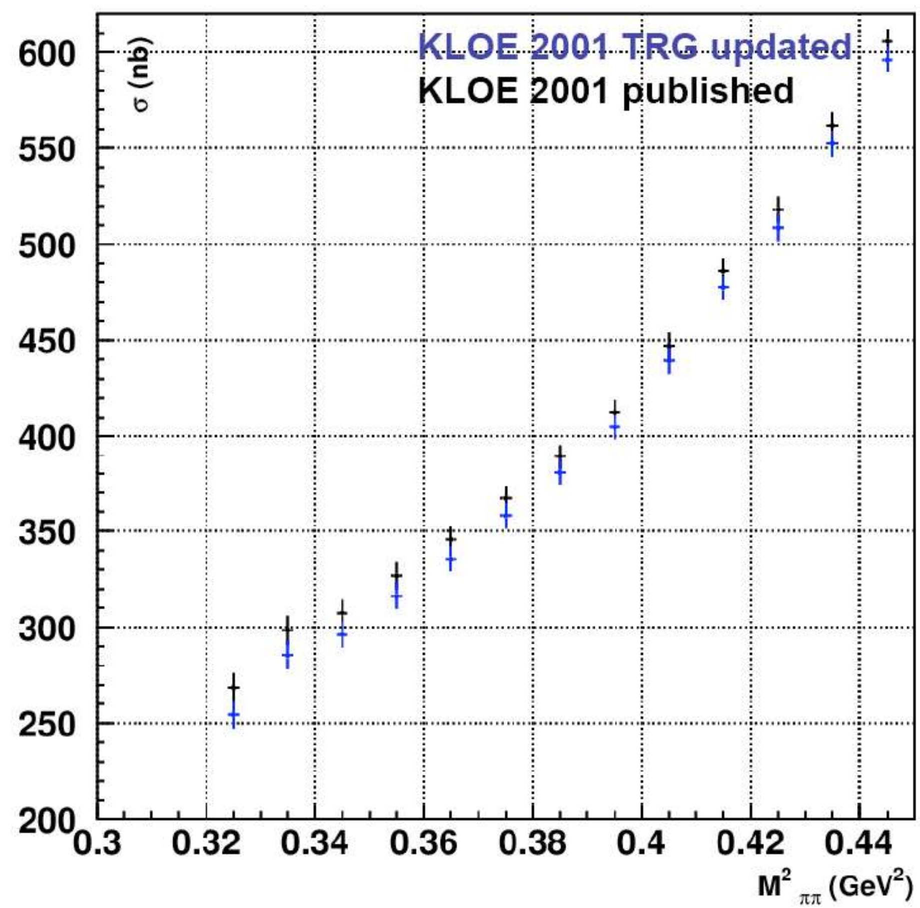
  → determination of f_0(980)-parameters



Spares slides

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





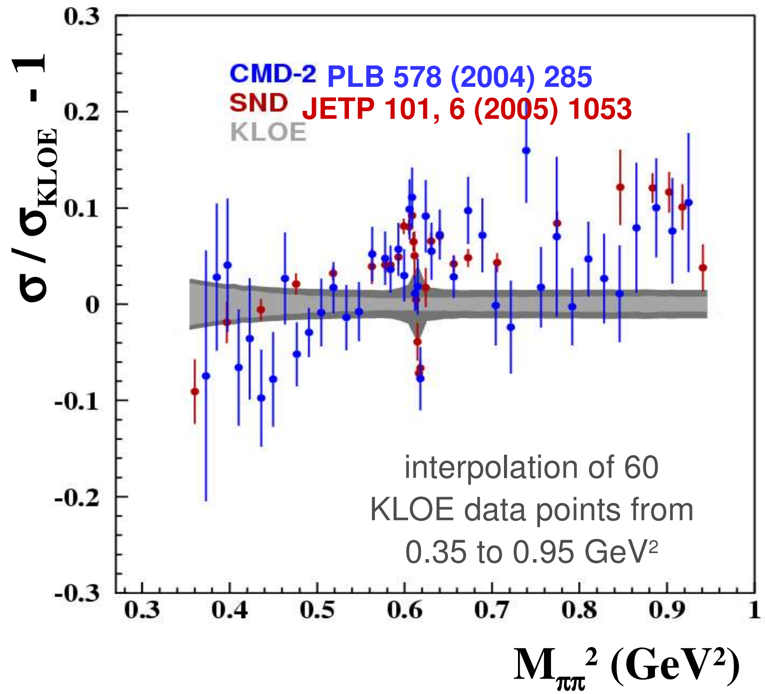
Impact of update on trigger correction on 2001 cross section:

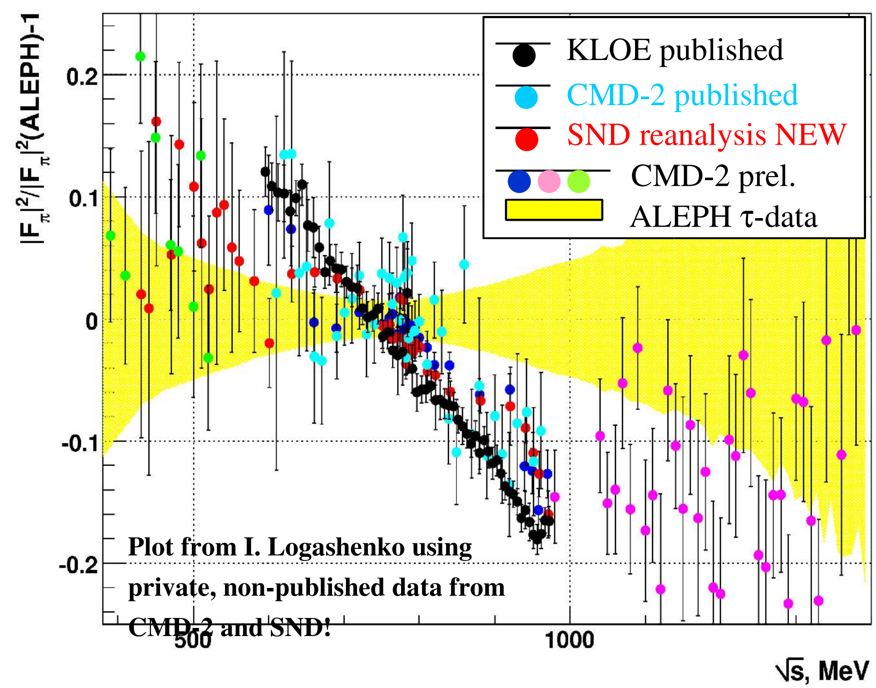
Changes (decreases) published value on $a_\mu^{\pi\pi}$ by 0.4%

A glance at the present status

1. Experimental inputs into the **theoretical computation**: **e^+e^-**– and **τ**– data (e.g. $\tau^+ \to \pi^+\pi^0\nu$)

Comparison among e^+e^- **and τ– data**





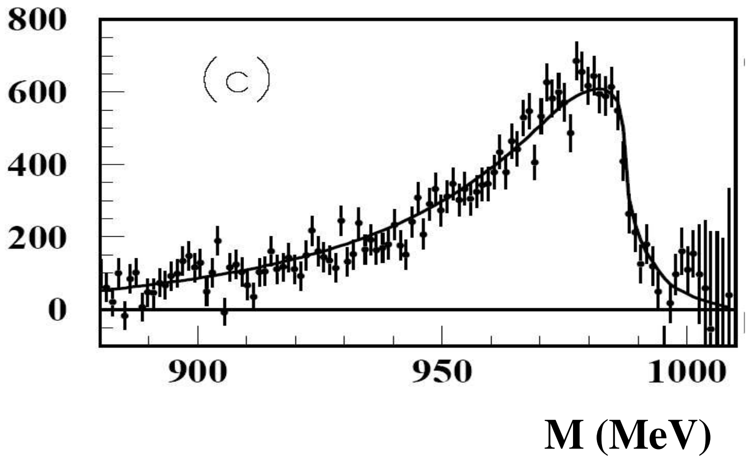
- All the recent e^+e^- experiments see large deviations with τ– data above ρ peak
- All recent e^+e^- experiments agree now within 0.5σ in the $\pi\pi$–contribution to a_μ^{had}
- Recent preliminary τ–analysis from BELLE in agreement with e^+e^- (hep-ex/0512071)

2. Direct measurement of a_μ

Experimental and **theoretical** value of a_μ differ of **~3.2σ**

f_0(980)

Mass spectrum fit



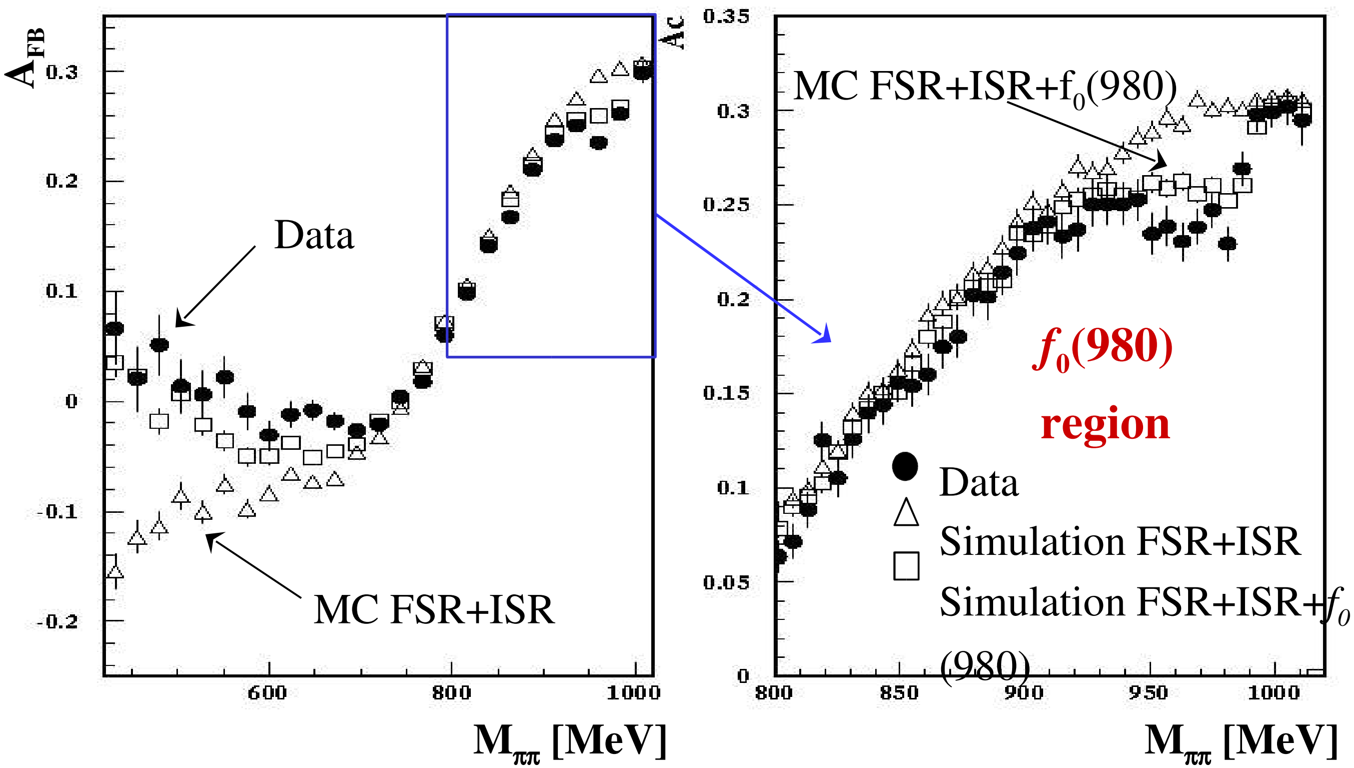
- Studied at KLOE in the decays

  $f_0(980)\to\pi^0\pi^0$, $f_0(980)\to\pi^+\pi^-$

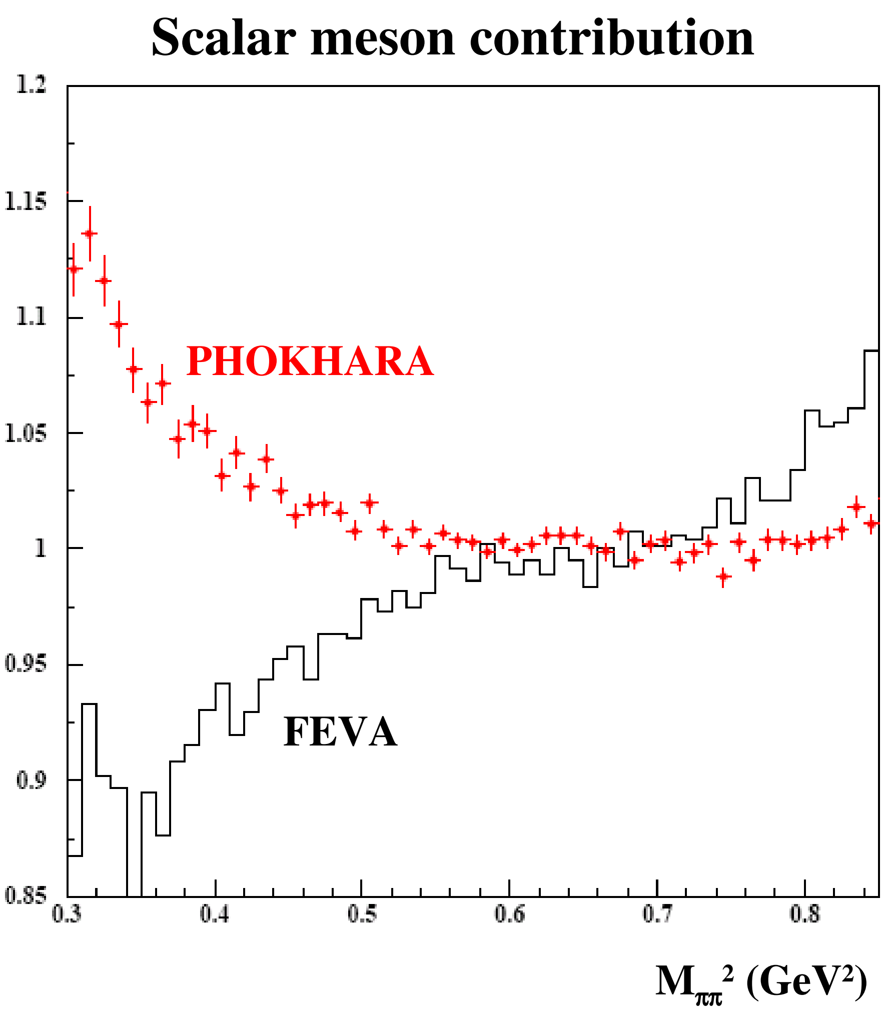
- Scalar background from f_0(980) large also at low masses due to non-Breit-Wigner shape of mass distribution in ϕ radiative decays

Forward-Backward asymmetry:
Consequence of different C-Parity of $\pi^+\pi^-$ for ISR- and either FSR- or f_0-amplitude

- **Clear f_0 signal at ~ 980 MeV**
- **Big threshold effect can be described by f_0(980) only**



Monte Carlo models for scalar meson contribution



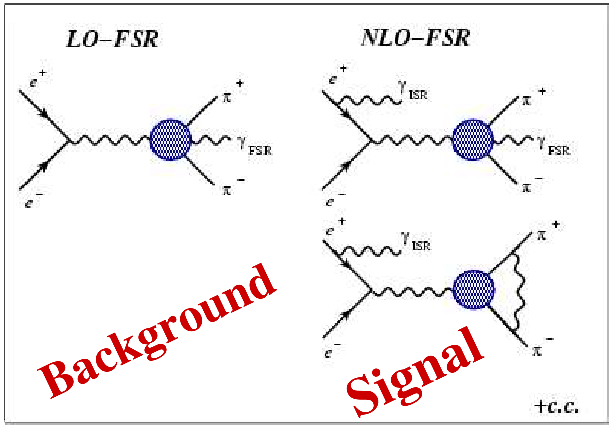
PHOKHARA: kaon loop model - f_0(980) couplings fixed by FB-asymmetry

FEVA: Achasov's model - couplings from the neutral channel $e^+e^- \to \pi^0\pi^0\gamma$
[KLOE Coll., Eur. Phys.J C49:473-488, 2006]
Huge differences between the two preditions

FSR (Final State Radiation)

Not only ISR radiative corrections have to be determined at high precision (NLO)

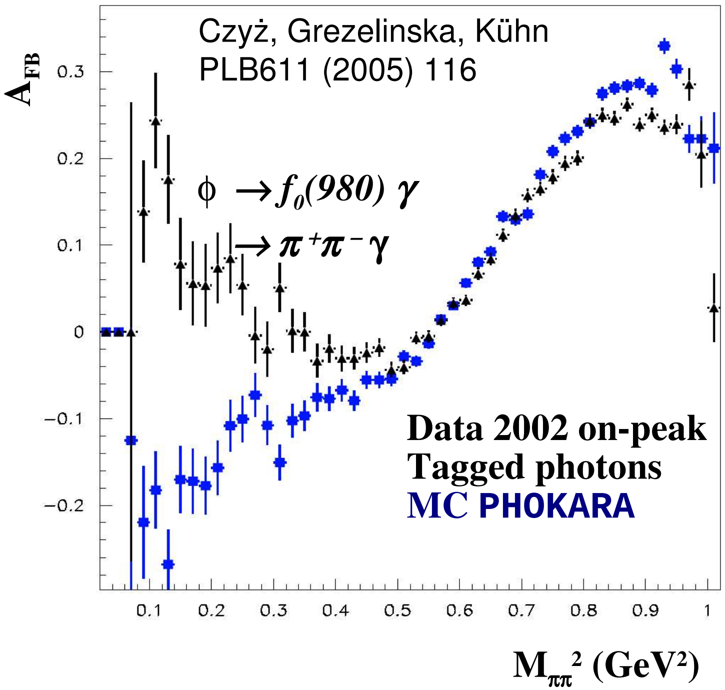
FSR - corrections are model dependent: use scalar QED, i.e. pointlike pions

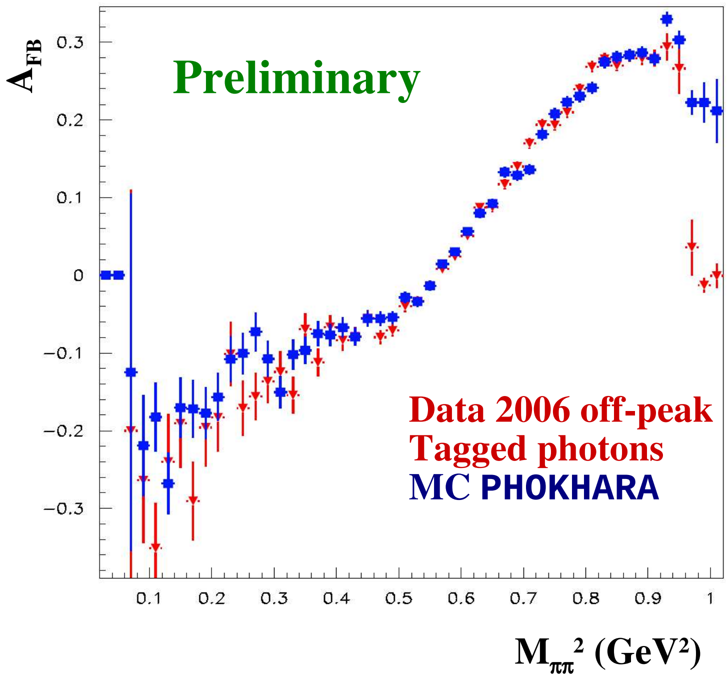


Forward-Backward-Asymmetry

is a consequence of ISR-FSR-interference

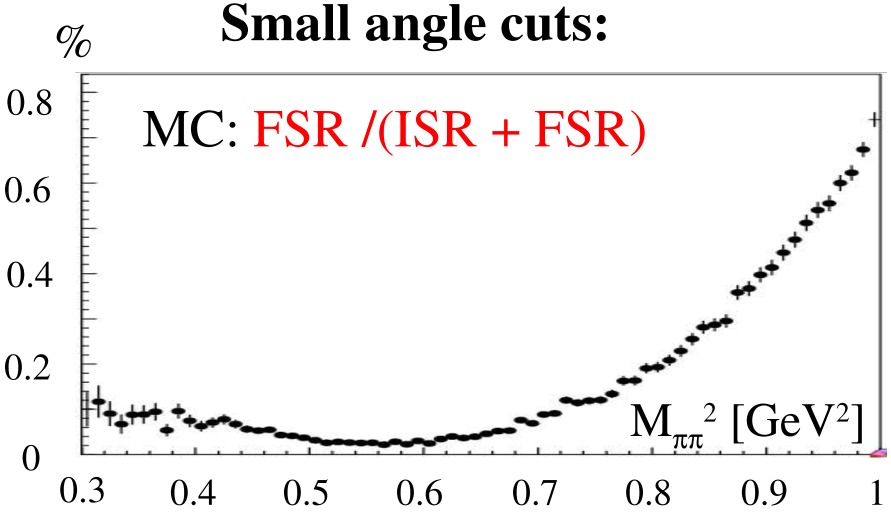
and is a **test of model of scalar QED for FSR**



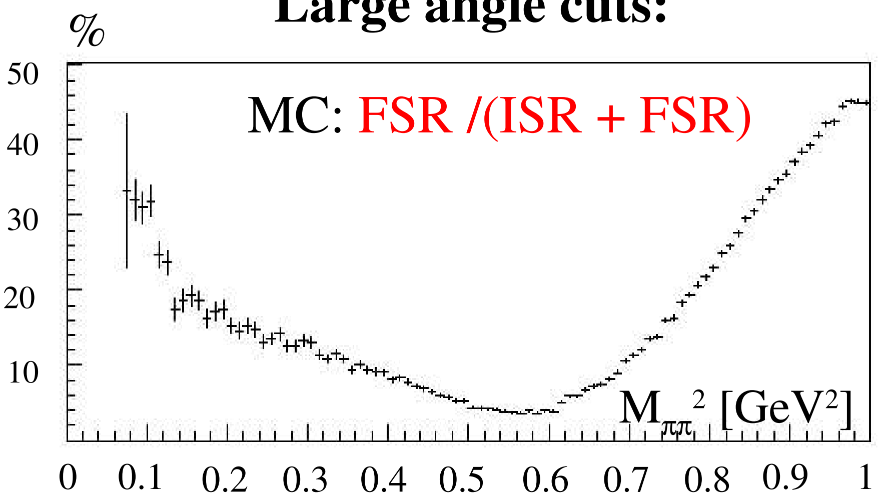


FSR (Final State Radiation) contribution

Small angle cuts:

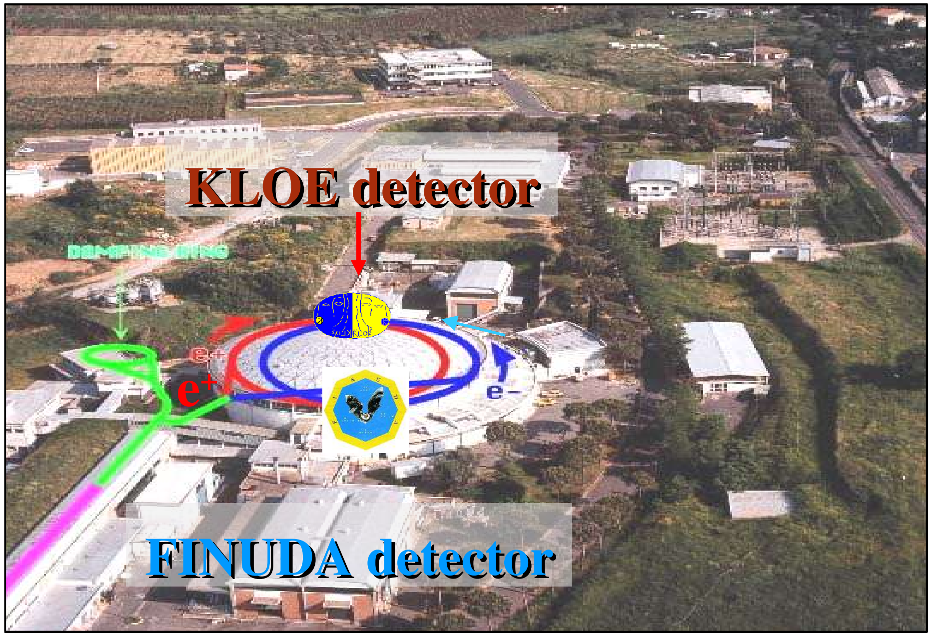


Large angle cuts:



DAΦNE

- $e^+e^- \to \phi$ $\sqrt{s} \sim m_\phi = 1019.4$ MeV
- beams cross at an angle of 12.5 mrad
- LAB momentum $p_\phi \sim 13$ MeV/c
- $L_{peak} = 1.5 \times 10^{32}$ cm^{-2}s^{-1}

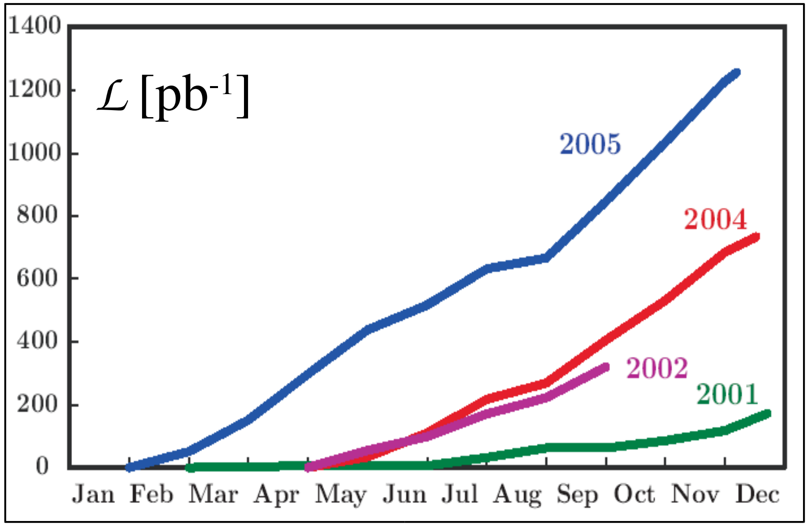


BR's for selected ϕ decays	
K^+K^-	49.1%
K_SK_L	34.1%
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%

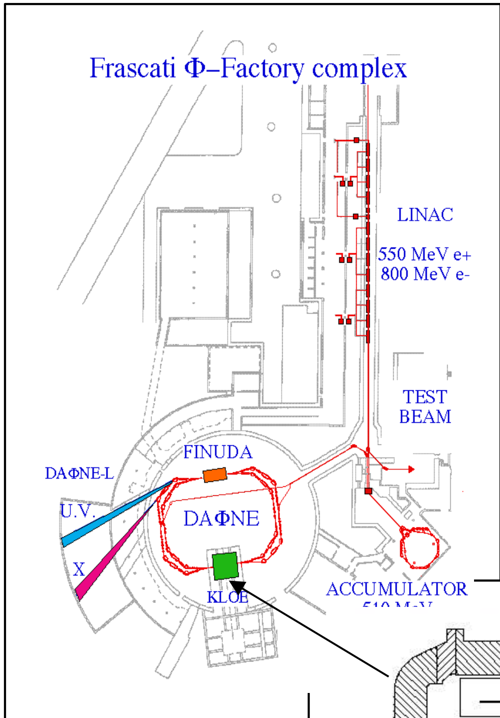
Day performance: 7-8 pb^{-1}

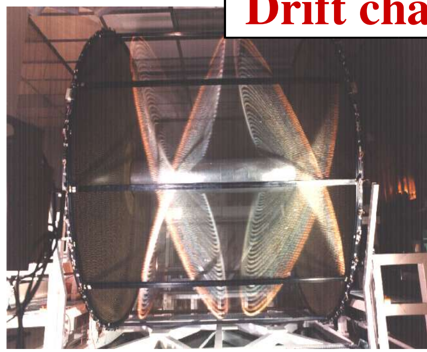
Best month $\int \mathcal{L}\, dt \sim 200$ pb^{-1}

Total KLOE $\int \mathcal{L}\, dt \sim 2400$ pb^{-1} (2001,02,04,05)



KLOE





Drift chamber

Track momentum resolution

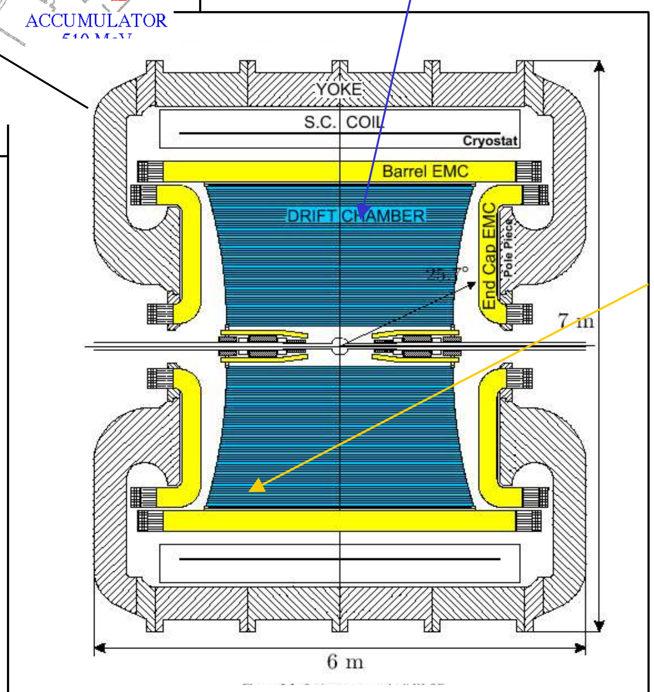
$\sigma_p/p \approx 0.4\%$ $(\theta > 45^\circ)$

Vertex resolution

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

12582 sense wires

52140 wires in total



Electromagnetic calorimeter

Pb/Scint fibers

4880 PM

Energy resolution

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

Time resolution

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

$\oplus$ 100 ps

Magnetic

Field of 0.52 T