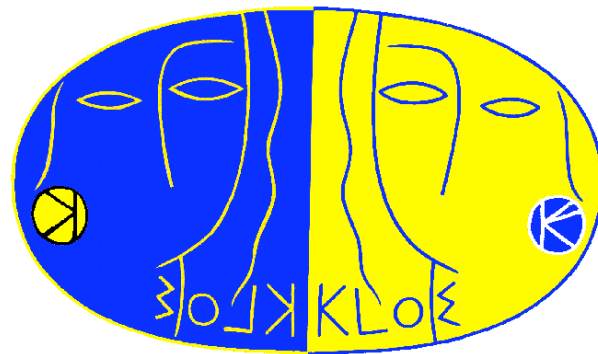


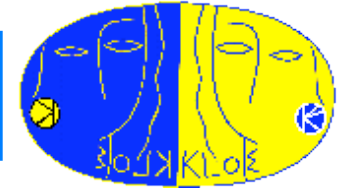
KLOE measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$ with Initial State Radiation and the $\pi\pi$ contribution to the muon anomaly

Graziano Venanzoni
(for the KLOE collaboration)
Laboratori Nazionali di Frascati



CERN, 23 March 2010

Outlook

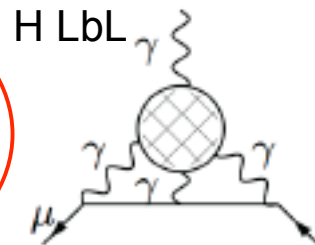
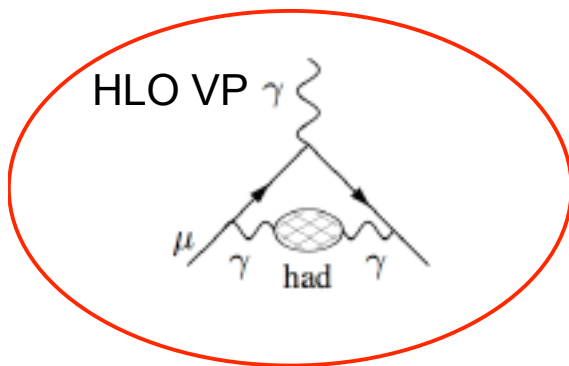


- Hadronic contribution to $(g-2)_\mu$ and ISR measurement (“Radiative Return”)
- KLOE measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$:
 - Small (photon) angle measurements (KLOE05, KLOE08)
 - Large (photon) angle measurement (KLOE09) **New!**
- Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar
- New measurement in progress:
 - Extraction of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$ by $\mu\mu\gamma$ normalization
- Test of Final State radiation (FSR) by Forward-Backward asymmetry in $e^+e^- \rightarrow \pi^+\pi^-\gamma$
- Conclusion & Outlook

Muon anomaly

$$a_\mu = \frac{(g_\mu - 2)}{2}$$

- Long established discrepancy ($>3\sigma$) between SM prediction and BNL E821 experiment
- Theoretical error δa_μ^{SM} ($\sim 6 \times 10^{-10}$) dominated by HLO VP ($4 \div 5 \times 10^{-10}$) and HLbL ($[2.5 \div 4] \times 10^{-10}$)
- Experimental error $\delta a_\mu^{\text{EXP}} \sim 6 \times 10^{-10}$ (E821). Plan to reduce it to 1.5×10^{-10} by the new g-2 experiment @FNAL (and J-PARC)



$$a_\mu^{\text{HLO}} = (690.9 \pm 4.4) \cdot 10^{-10}$$

[Eidelman, TAU08]

$$\delta a_\mu^{\text{HLO}} \sim 0.7\%$$

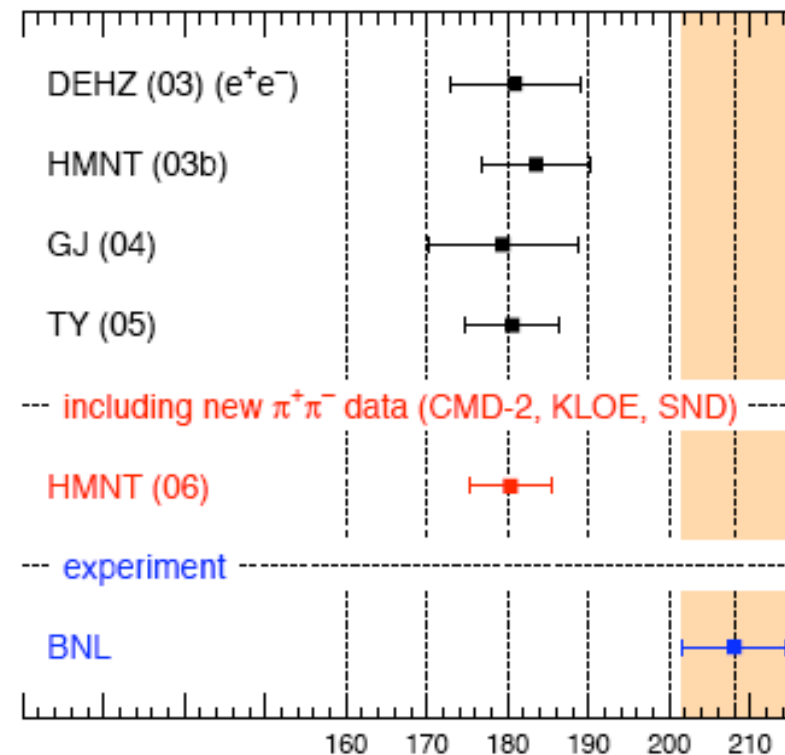
$$a_\mu^{\text{HLbL}} = (10.5 \pm 2.6) \cdot 10^{-10}$$

$$[Prades, de Rafael \& A. Vainshtein 08]$$

$$= (11 \pm 4) \cdot 10^{-10} \text{ (Jegerlehner, Nyffler)}$$

a_μ^{SM} compared to BNL world av.

T.Teubner, PHIPSI08

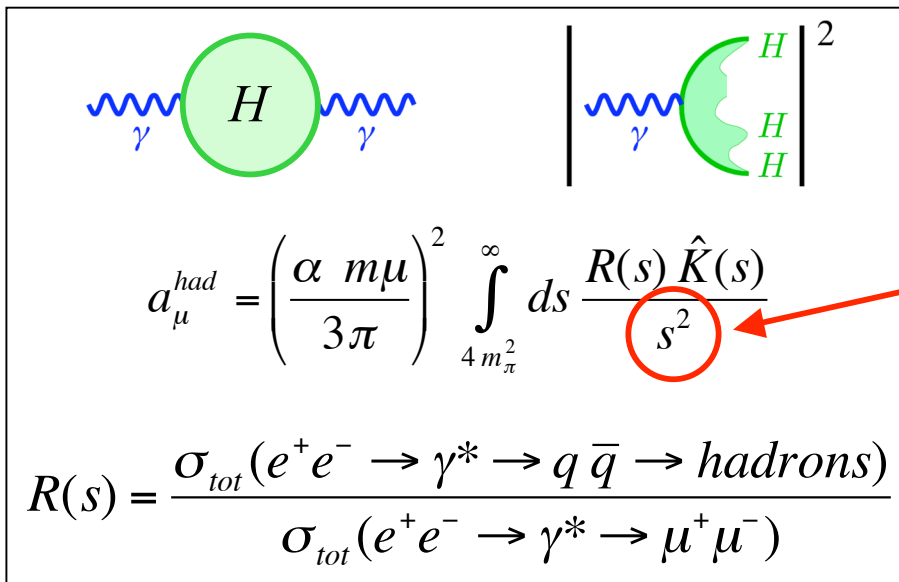


$$a_\mu^{\text{SM}} \times 10^{10} - 11659000$$

$$a_\mu^{\text{EXP}} - a_\mu^{\text{TH}} = (27.6 \pm 8.1) \cdot 10^{-10}, \sim 3.4\sigma$$

a_μ^{HLO} :

Hadronic contribution to a_μ can be estimated by means of a dispersion integral:



The diagram shows two Feynman diagrams. The left diagram is a self-energy loop where a photon (wavy line) emits a hadron (H, green circle) which then reabsorbs the photon. The right diagram is a vacuum polarization insertion where a photon (wavy line) splits into a hadron (H, green blob) which then splits back into a photon (wavy line). Below the diagrams is the dispersion integral for the hadronic contribution to the muon g-2 anomaly:

$$a_\mu^{\text{had}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s) \hat{K}(s)}{s^2}$$

The s^2 term in the denominator is circled in red. Below the integral is the definition of $R(s)$:

$$R(s) = \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q} \rightarrow \text{hadrons})}{\sigma_{\text{tot}}(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)}$$

$1/s^2$ makes **low energy contributions** especially important:

$$e^+e^- \rightarrow \pi^+\pi^-$$

in the range < 1 GeV contributes to 70% !

- $K(s)$ = analytic kernel-function

- above sufficiently high energy value, typically 2...5 GeV, use *pQCD*

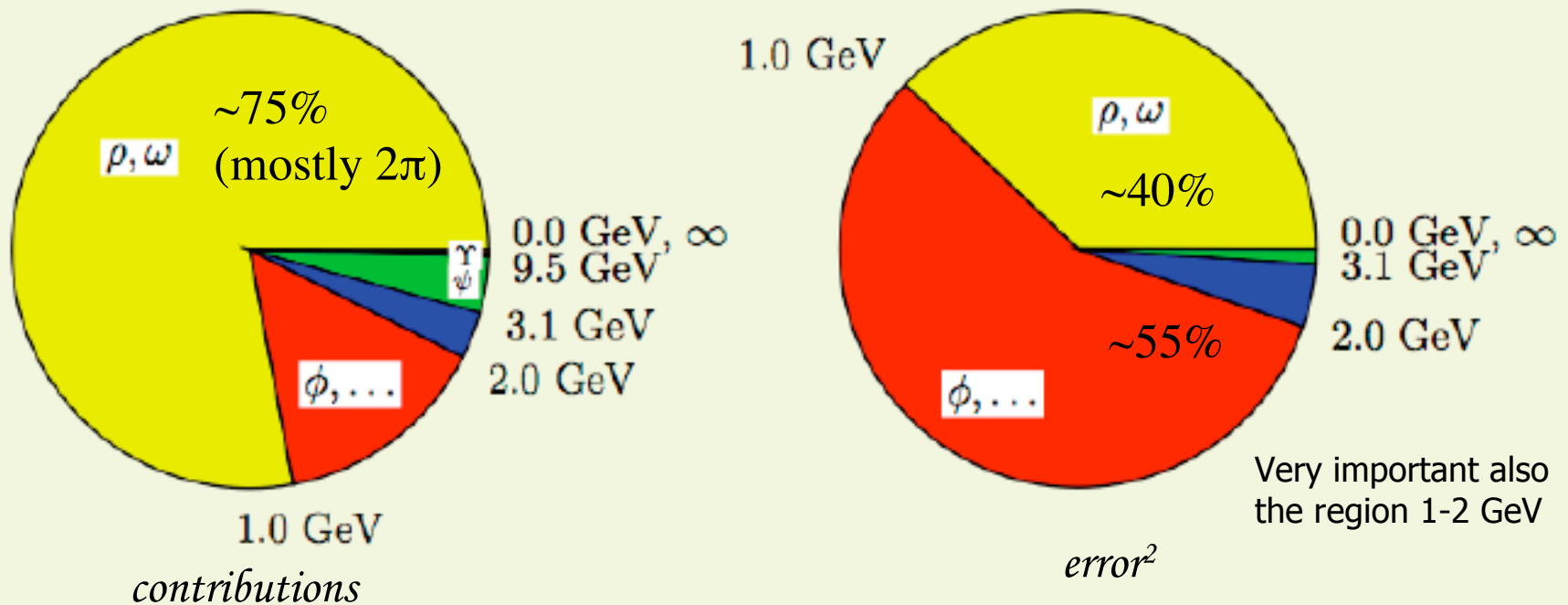
Input:

- hadronic electron-positron cross section data
- hadronic τ - decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

Dispersion Integral:

Contribution of different energy regions to the dispersion integral and the error to a_μ^{had}

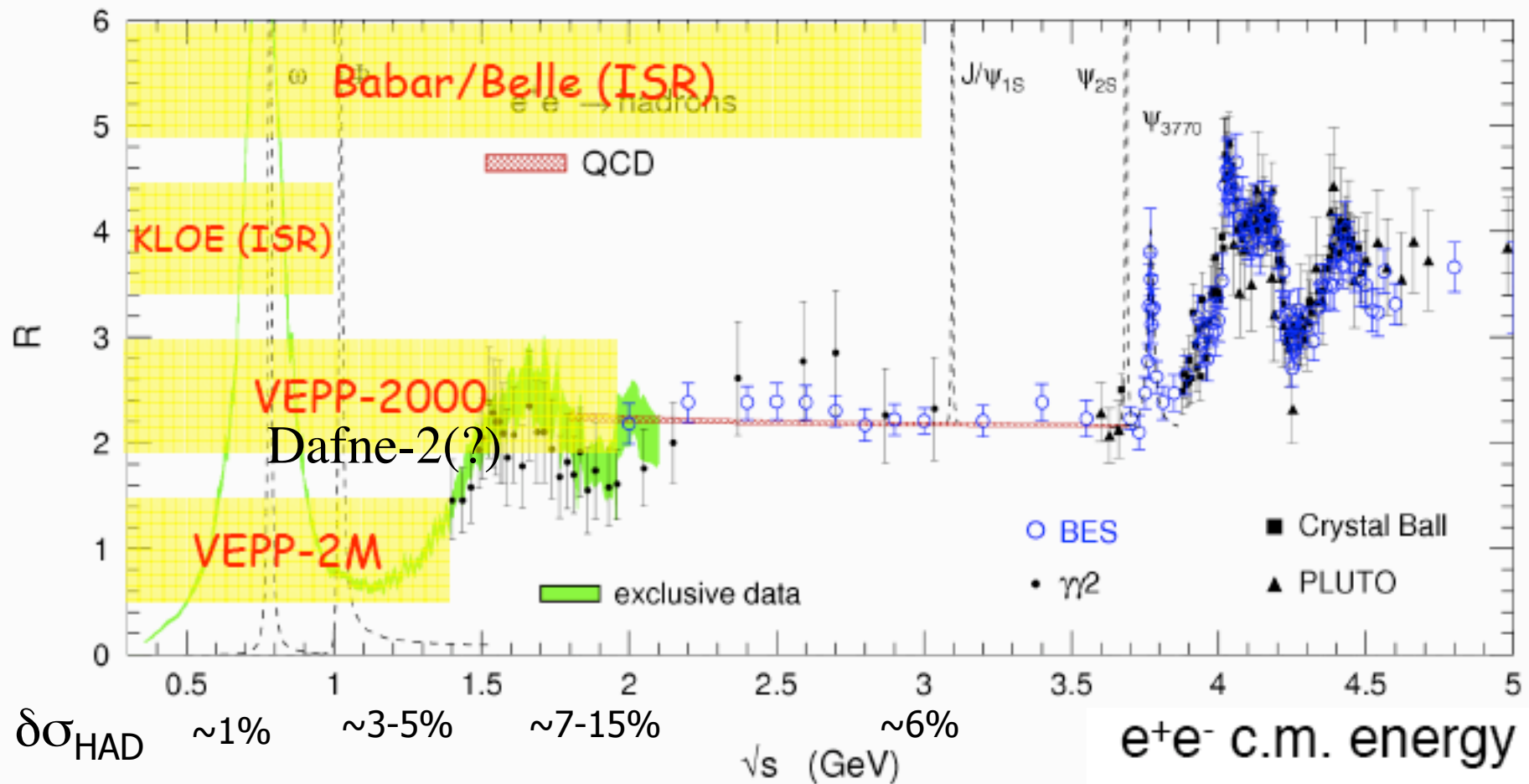
F. Jegerlehner, Talk at PHIPSI08



Experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{had} !
 → Needs precision measurements!

$$\delta a_\mu^{\text{exp}} \rightarrow 1.5 \cdot 10^{-10} = 0.2\% \text{ on } a_\mu^{\text{HLO}}$$

e^+e^- data: current and future/activities



Cross section data:

At low energies (< 2 GeV) only measurements of exclusive channels, two approaches:

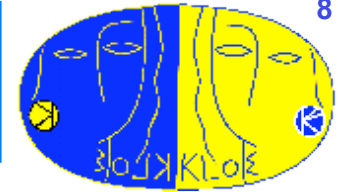
Energy scan (CMD2, SND):

- energy of colliding beams is changed to the desired value
- “direct” measurement of cross sections
- needs dedicated accelerator/physics program
- needs to measure luminosity and beam energy for every data point

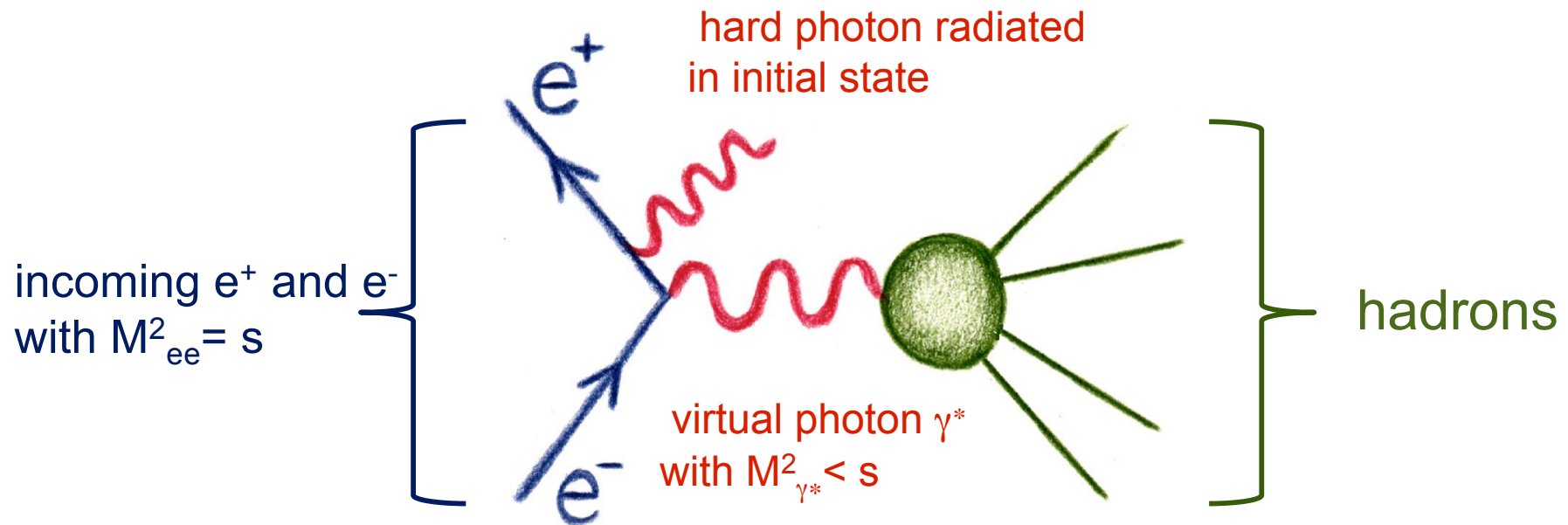
Radiative return (KLOE, BABAR, BELLE):

- runs at **fixed-energy machines** (meson factories)
- use **initial state radiation** process to access lower lying energies or resonances
- data come as by-product of standard physics program
- requires precise theoretical calculation of the **radiator function**
- luminosity and beam energy enter only once for all energy points
- needs larger integrated luminosity

ISR: Initial state radiation

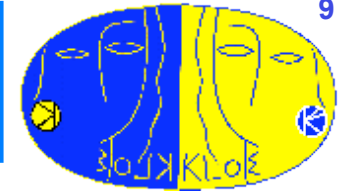


Particle factories (DAΦNE, PEP-II, KEK-B) can measure hadronic cross sections as a function of the hadronic c.m. energy using initial state radiation (**radiative return** to energies below the collider energy \sqrt{s}).



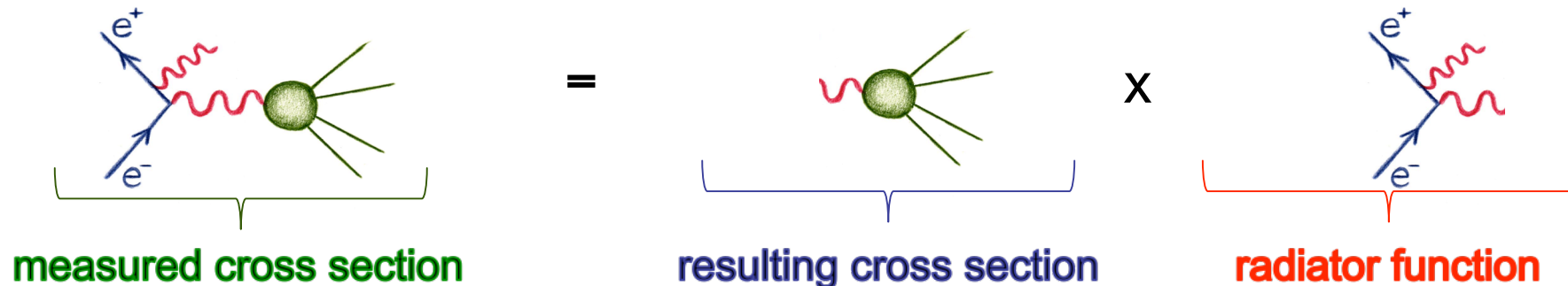
The emission of a hard γ in the bremsstrahlung process in the initial state reduces the energy available to produce the hadronic system in the e^+e^- collision.

ISR: Initial state radiation



Neglecting final state radiation (FSR):

$$\frac{d\sigma(e^+ e^- \rightarrow \text{hadrons} + \gamma)}{dM_{\text{hadr}}^2} = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons}, M_{\text{hadr}}^2)}{s} H(s, M_{\text{hadr}}^2)$$



Theoretical input: precise calculation of the radiation function $H(s, M_{\text{hadr}}^2)$

→ **EVA + PHOKHARA MC Generator**

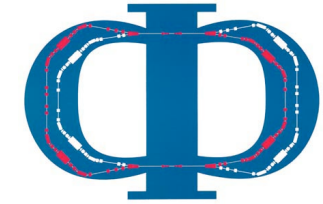
Binner, Kühn, Melnikov; Phys. Lett. B 459, 1999

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

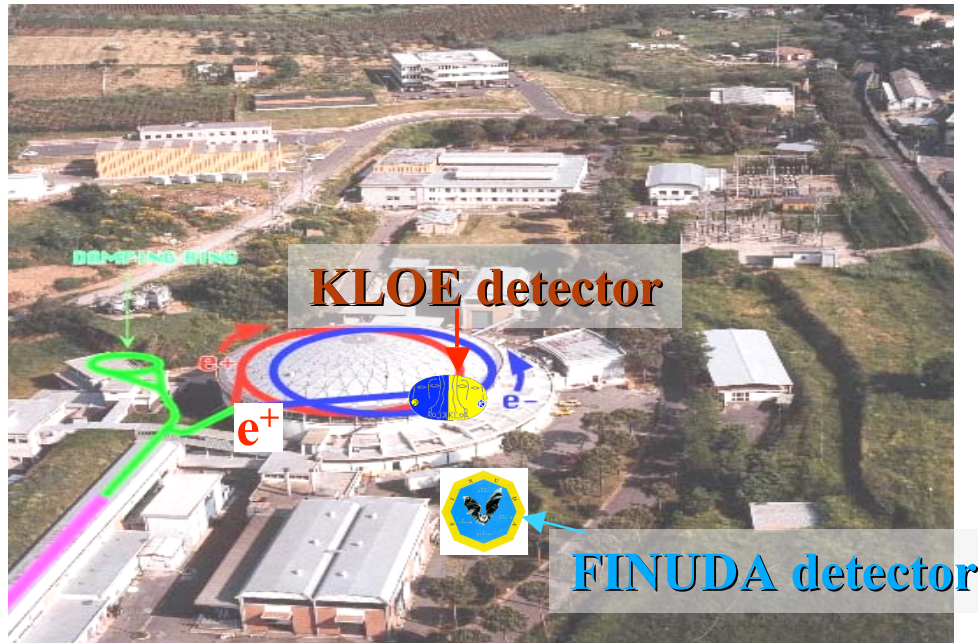
(exact next-to-leading order QED calculation of the radiator function)

IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR using 2001 data (140pb^{-1}) PLB606(2005)12 $\Rightarrow \sim 3\sigma$ discrepancy on a_μ btw a_μ^{SM} and a_μ^{exp}

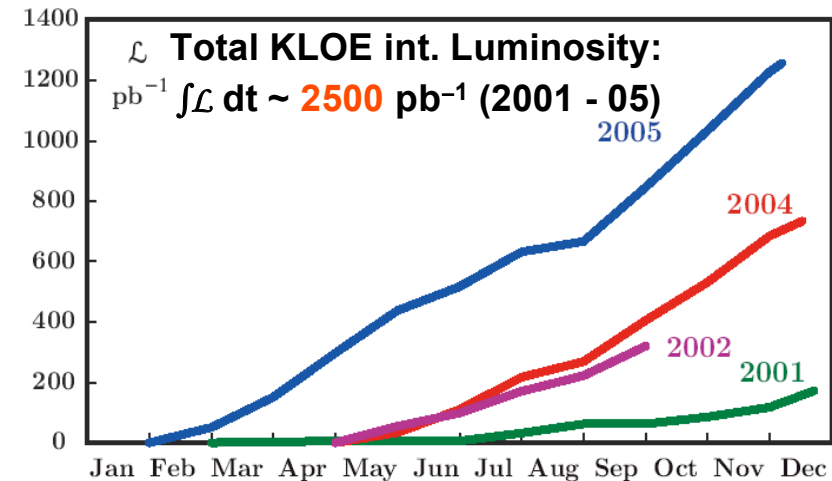
DAΦNE: A Φ-Factory



e^+e^- - collider with $\sqrt{s}=m_\Phi \approx 1.0195$ GeV



Integrated Luminosity



Peak Luminosity $L_{\text{peak}} = 1.5 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$

Our first measurement
(PLB606(2005)12) was based on
140 pb⁻¹ of 2001 data!

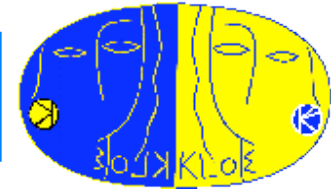
Our second measurement
(PLB670(2009)285) was based on
240 pb⁻¹ from 2002 data!

2006:

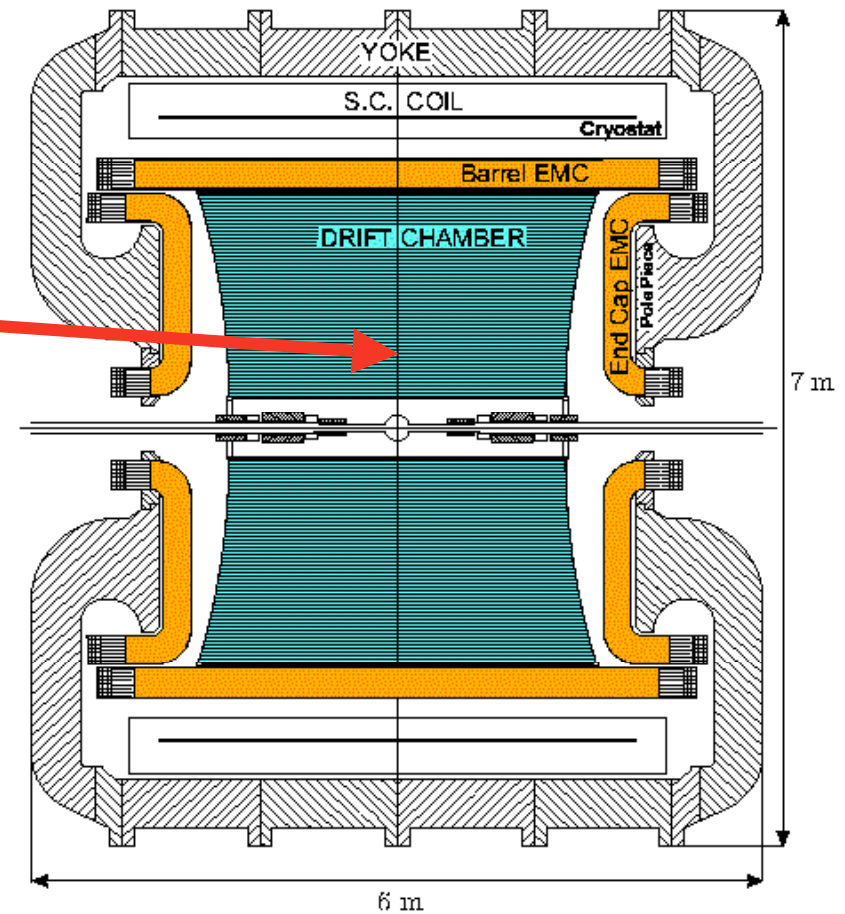
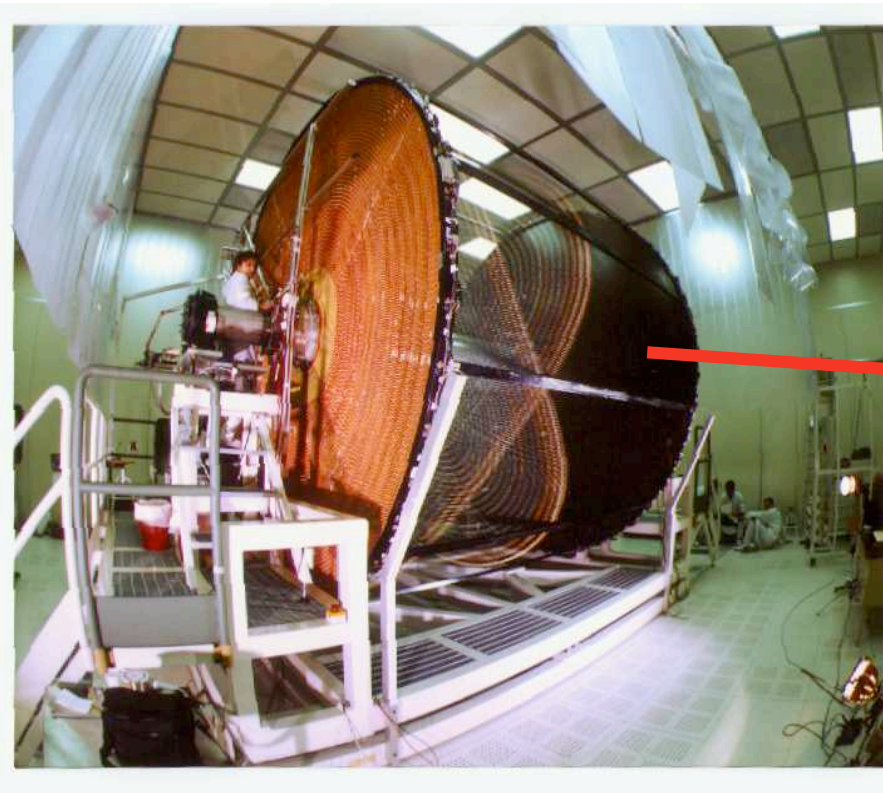
- Energy scan (4 points around m_Φ -peak)
- 220 pb⁻¹ at $\sqrt{s} = 1000$ MeV (off-peak data)

Our new measurement was based
on 220 pb⁻¹ at $\sqrt{s}=1$ GeV from 2006
data!

KLOE Detector



Drift chamber



$$\sigma_p/p = 0.4\% \text{ (for } 90^\circ \text{ tracks)}$$

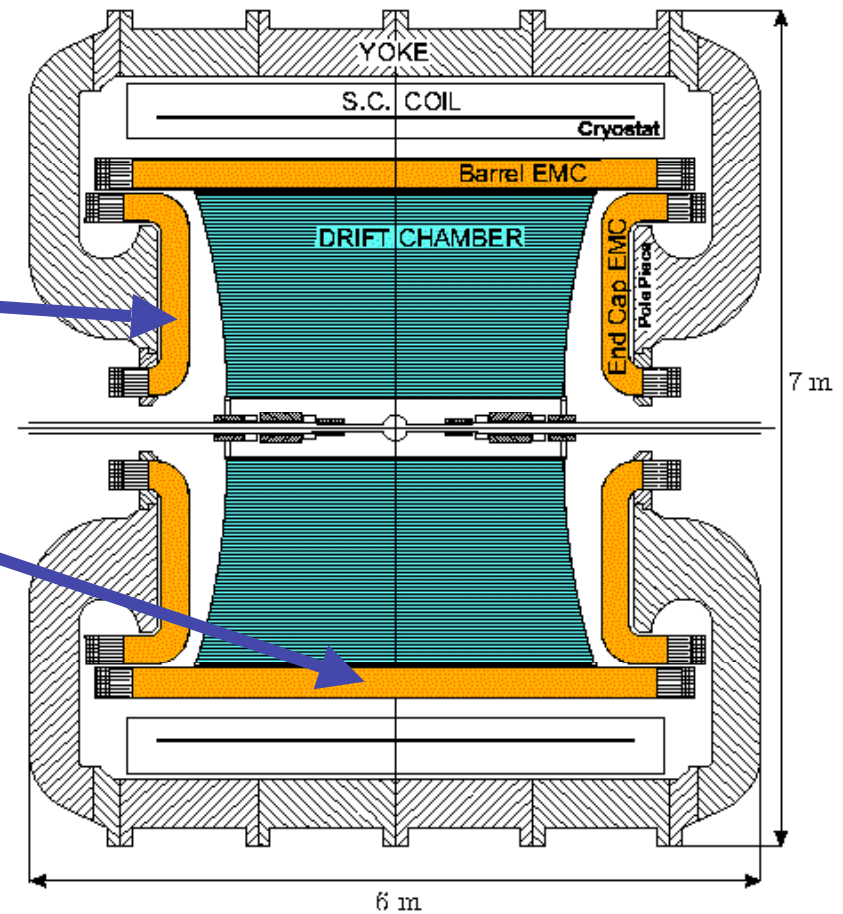
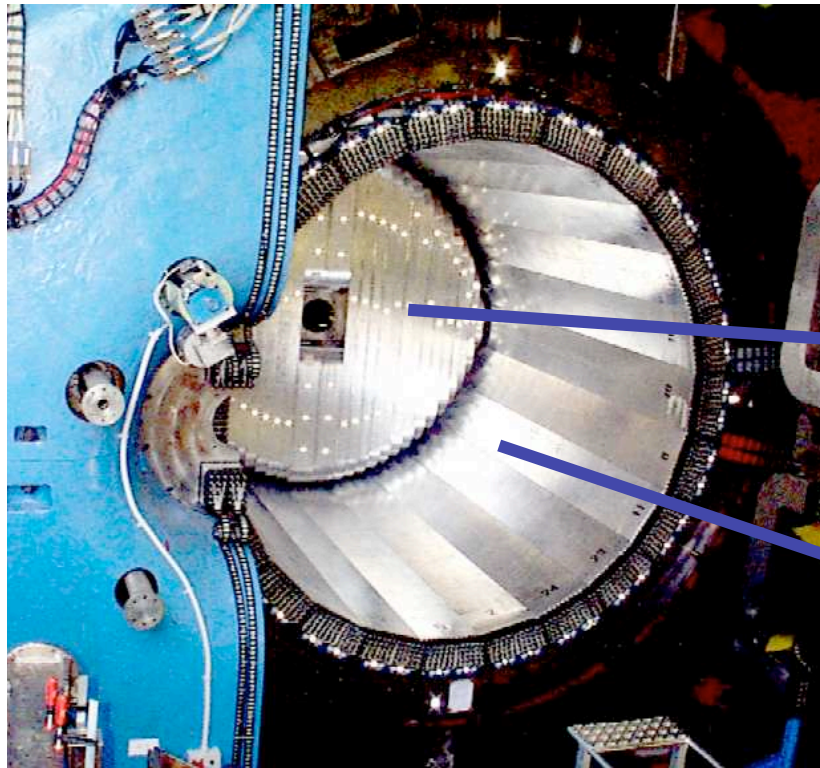
$$\sigma_{xy} \approx 150 \mu\text{m}, \sigma_z \approx 2 \text{ mm}$$

***Excellent momentum
resolution***

KLOE Detector



Electromagnetic Calorimeter



$$\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$$
$$\sigma_T = 54 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 100 \text{ ps}$$

(Bunch length contribution subtracted from constant term)

Excellent timing resolution

Extracting $|F_\pi|^2$ from $\pi\pi\gamma$ events



a) Via absolute Normalisation to VLAB Luminosity (as in 2005 analysis):

1)
$$\frac{d\sigma_{\pi\pi\gamma(\gamma)}^{obs}}{dM_{\pi\pi}^2} = \frac{\Delta N_{Obs} - \Delta N_{Bkg}}{\Delta M_{\pi\pi}^2} \cdot \frac{1}{\epsilon_{Sel}} \cdot \frac{1}{\int L dt}$$

$d\sigma_{\pi\pi\gamma(\gamma)}/dM^2$ is obtained by subtracting background from observed event spectrum, divide by selection efficiencies, and *int. luminosity*.

2)
$$\sigma_{\pi\pi}(s) \approx s \frac{d\sigma_{\pi\pi\gamma(\gamma)}^{obs}}{dM_{\pi\pi}^2} \cdot \frac{1}{H(s)}$$

Obtain $\sigma_{\pi\pi}$ from (ISR) - radiative cross section $d\sigma_{\pi\pi\gamma(\gamma)}/dM^2$ via theoretical radiator function $H(s)$:

3)
$$|F_\pi|^2 = \frac{3s}{\pi\alpha^2\beta_\pi^3} \sigma_{\pi\pi}(s)$$

Relation between $|F_\pi|^2$ and the cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

b) Via bin-by-bin Normalisation to rad. Muon events (*analysis is in well advanced phase, see later*)

Radiative Corrections



Radiator-Function $H(s, s_\pi)$ (ISR):

- ISR-Process calculated at NLO-level

PHOKHARA generator

(H.Czyż, A.Grzełińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

Precision: 0.5%

$$s \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s, s_\pi)$$

Radiative Corrections:

i) Bare Cross Section

divide by Vacuum Polarisation $\delta(s) = (\alpha(s)/\alpha(0))^2$

→ from F. Jegerlehner

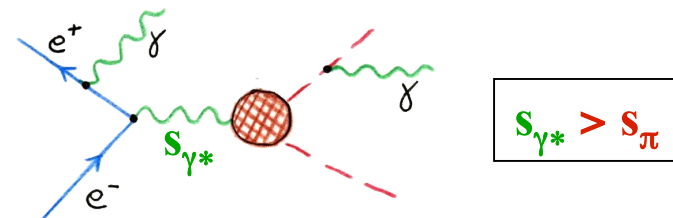
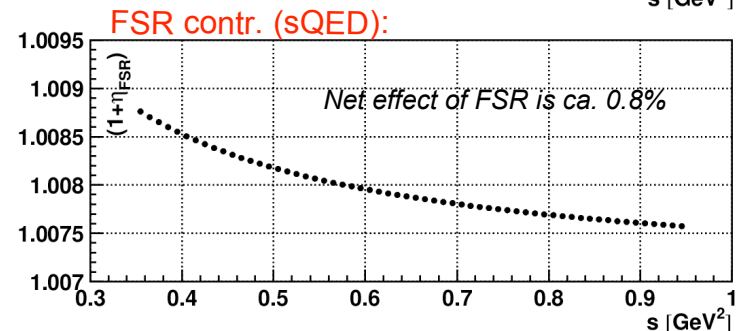
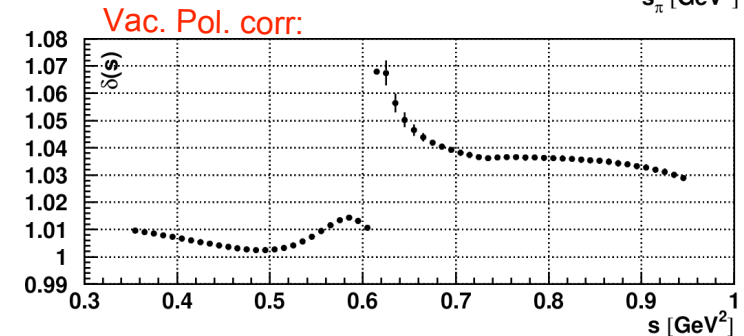
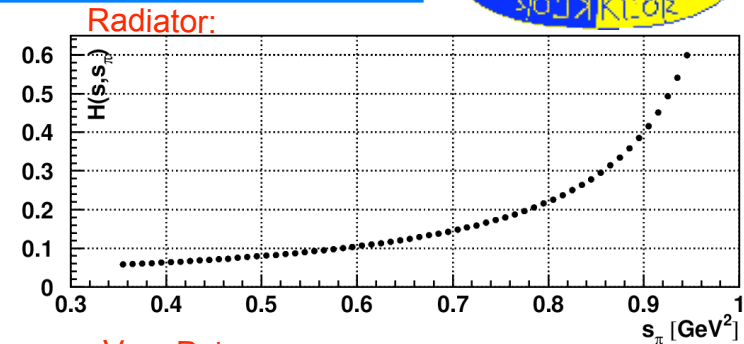
ii) FSR

Cross section $\sigma_{\pi\pi}$ must be incl. for FSR
for use in the dispersion integral of a_μ

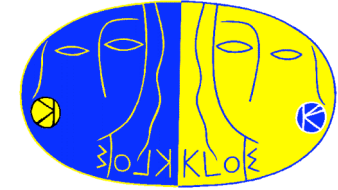


FSR corrections have to be taken into account
in the efficiency eval. (SA Acceptance, M_{Trk}) and
in the passage $s_\pi \rightarrow s_{\gamma^*}$

(H.Czyż, A.Grzełińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)



$$s_{\gamma^*} > s_\pi$$



Measurement of the $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$
with photon emitted at Small Angle
(“*SA Analysis*,,)

1st KLOE result using 2001 data: ***Phys. Lett. B 606, 12 (2005)***

Updated and superseded by new result

based on 2002 data: ***Phys. Lett. B 670, 285 (2009)***

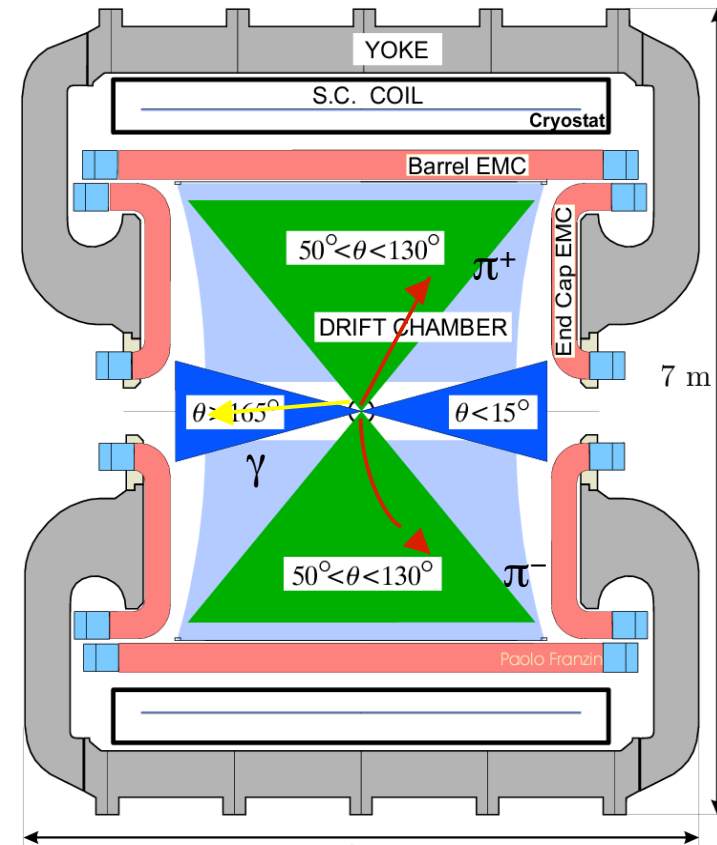
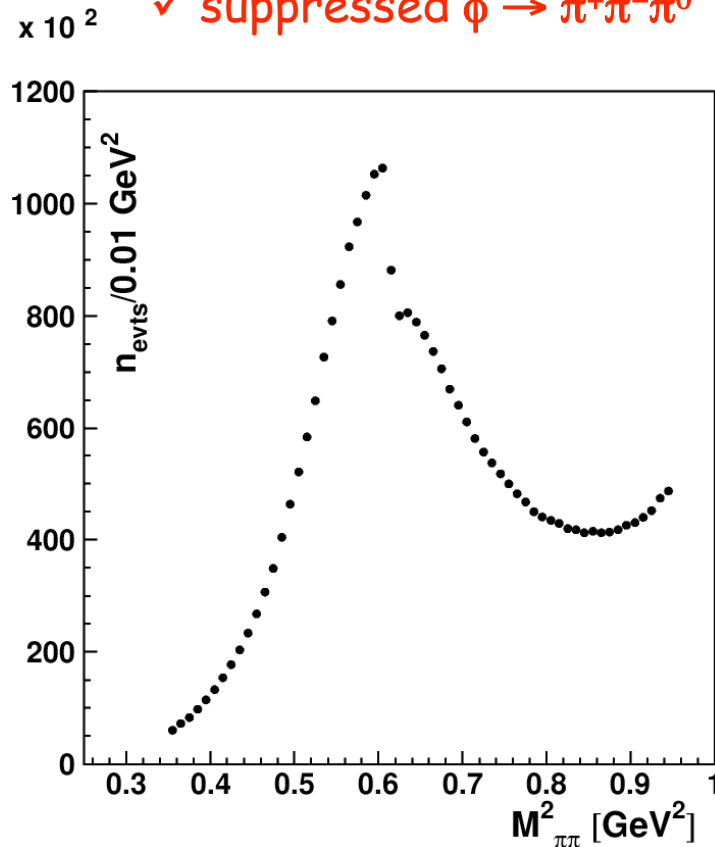
SA Event Selection (KLOE08)



- a) 2 tracks with $50^\circ < \theta_{\text{track}} < 130^\circ$
- b) small angle γ ($\theta_{\pi\pi} < 15^\circ$ or $> 165^\circ$)

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

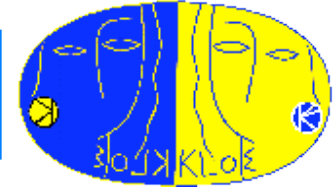
- ✓ high statistics for ISR
- ✓ low relative FSR contribution
- ✓ suppressed $\phi \rightarrow \pi^+\pi^-\pi^0$ wrt the signal



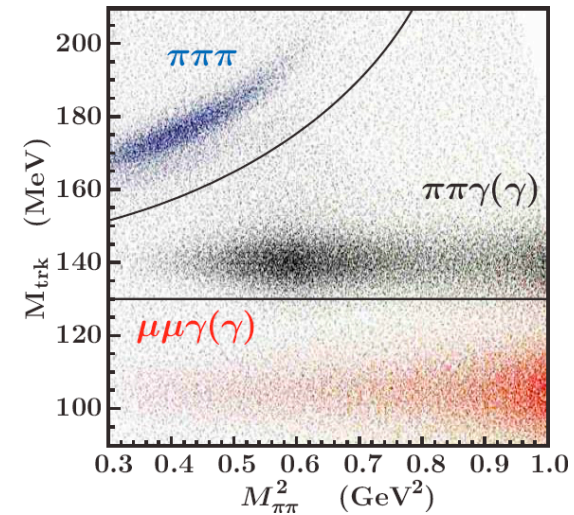
statistics: 242pb⁻¹ of 2002 data

3.1 Mill. Events between 0.35 and 0.95 GeV²

Event Selection



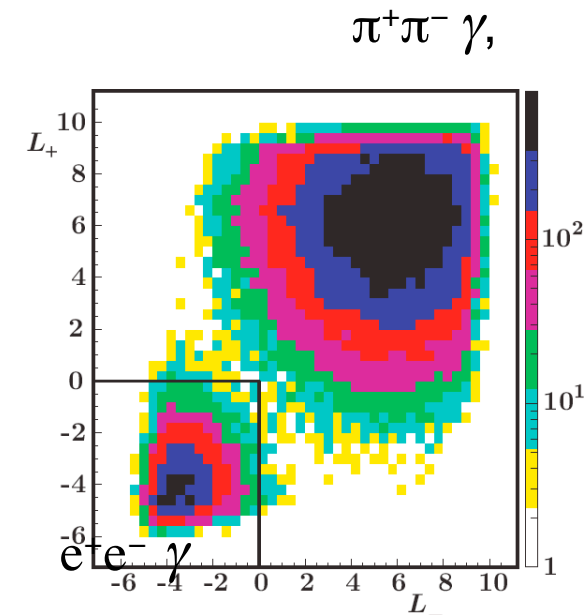
- Experimental challenge: control backgrounds from
 - $\phi \rightarrow \pi^+ \pi^- \pi^0$
 - $e^+ e^- \rightarrow e^+ e^- \gamma$
 - $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$,
 removed using kinematical cuts in *trackmass* $M_{Trk} - M_{\pi\pi}^2$ plane



M_{Trk} :
 defined by 4-momentum conservation
 under the hypothesis of 2 tracks with
 equal mass and one γ

$$\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2} \right)^2 - (p_1 + p_2)^2 = 0$$

To further clean the samples from radiative Bhabha events, we use a particle ID estimator for each charged track based on **Calorimeter** Information and Time-of-Flight.

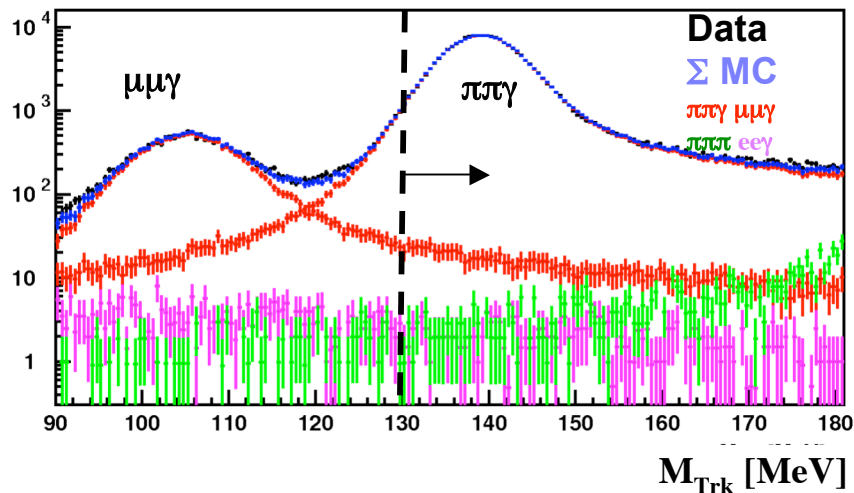


Background:

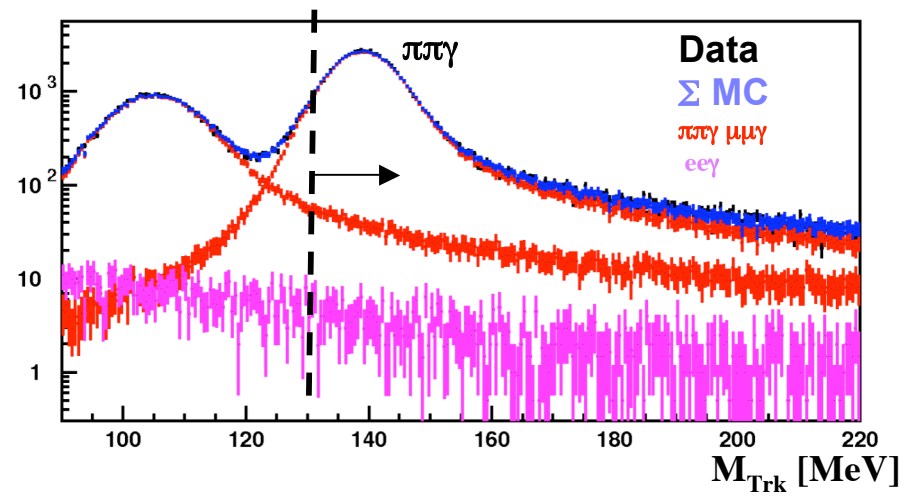


Main backgrounds estimated from MC shapes fitted to data distribution in M_{Trk}
 ($\pi\pi\gamma/\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)

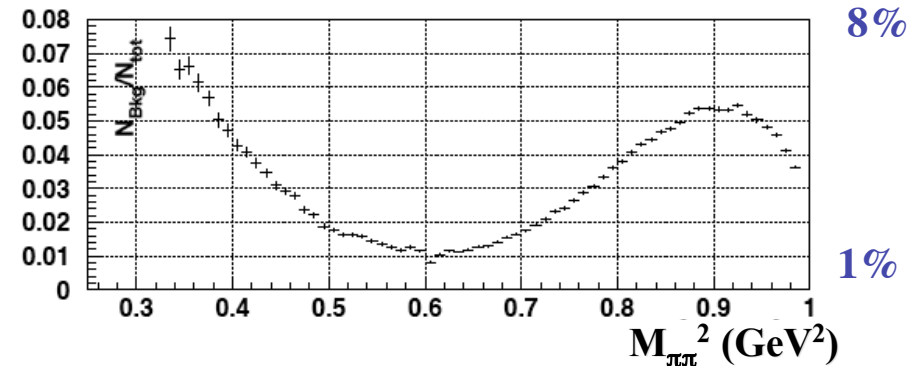
$0.60 < M_{\pi\pi}^2 < 0.62 \text{ GeV}^2, \chi^2/ndof = 158/180$



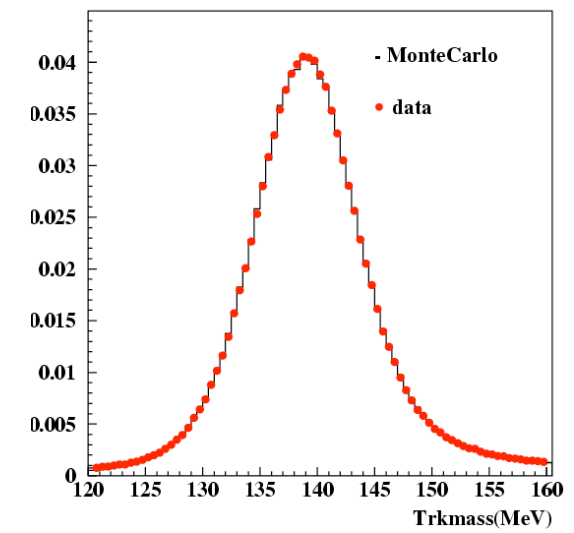
$0.84 < M_{\pi\pi}^2 < 0.86 \text{ GeV}^2, \chi^2/ndof = 179/258$



Tot bckg ($\mu\mu\gamma$, $\pi\pi\pi$ and $ee\gamma$) contribution



- Excellent agreement on M_{TRK} distribution between data and MC (2 different sets of „tuning“)



Tracking



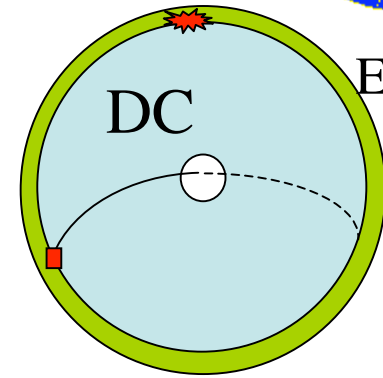
Two control samples

$\pi^+\pi^-\pi^0$

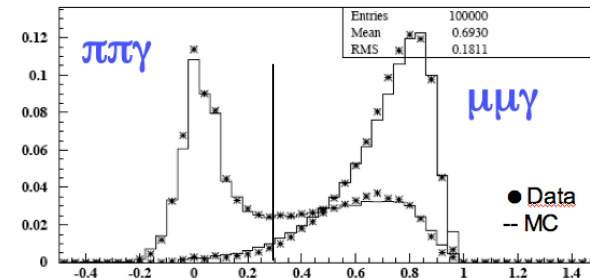
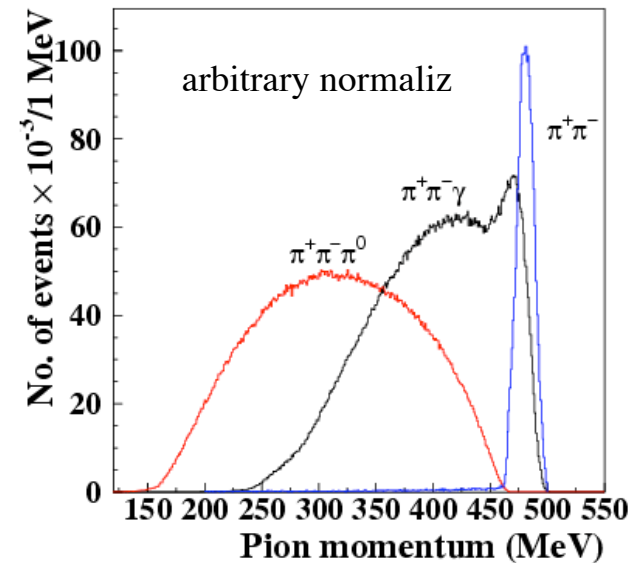
- 1) a tagging track recognized as a pion by PID, extrapolating back to the IP, which satisfies the trigger
- 2) 2 prompt clusters not associated to the tagging track with $E > 50$ MeV and distant each other 60 cm
- 3) A constraint on the photon energy and time to further clean the sample, and improve missing momentum and energy

$\pi^+\pi^-\gamma$

- 1) As for $\pi^+\pi^-\pi^0$ sample
- 2) 1 prompt clusters not associated to the tagging track with $E > 50$ MeV
- 3) The tagging track must have $p > 460$ MeV (to reject $\pi^+\pi^-\pi^0$ events), the *candidate* track must have mass (built from 4 momentum conservation) $M_{\text{miss}} > 120$ MeV and $NN < 0.3$, to suppress $\mu^+\mu^-\gamma$ events

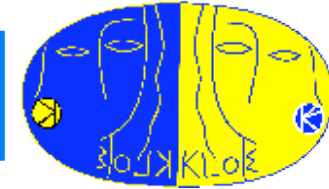


EMC



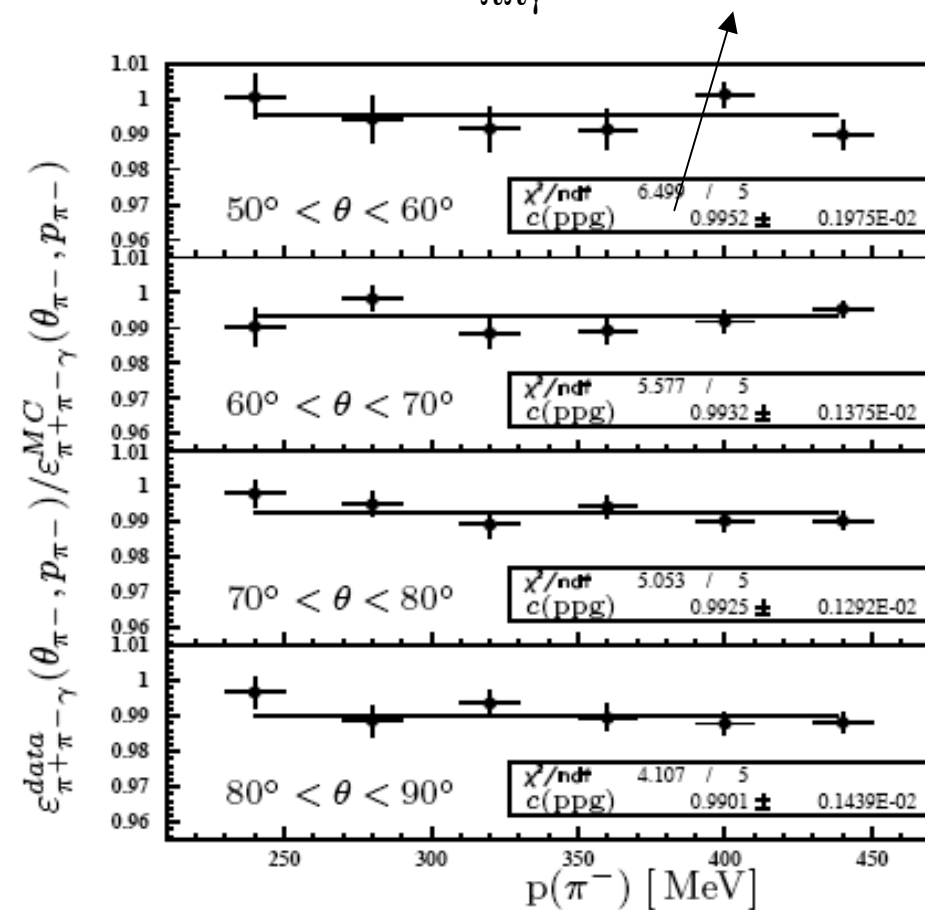
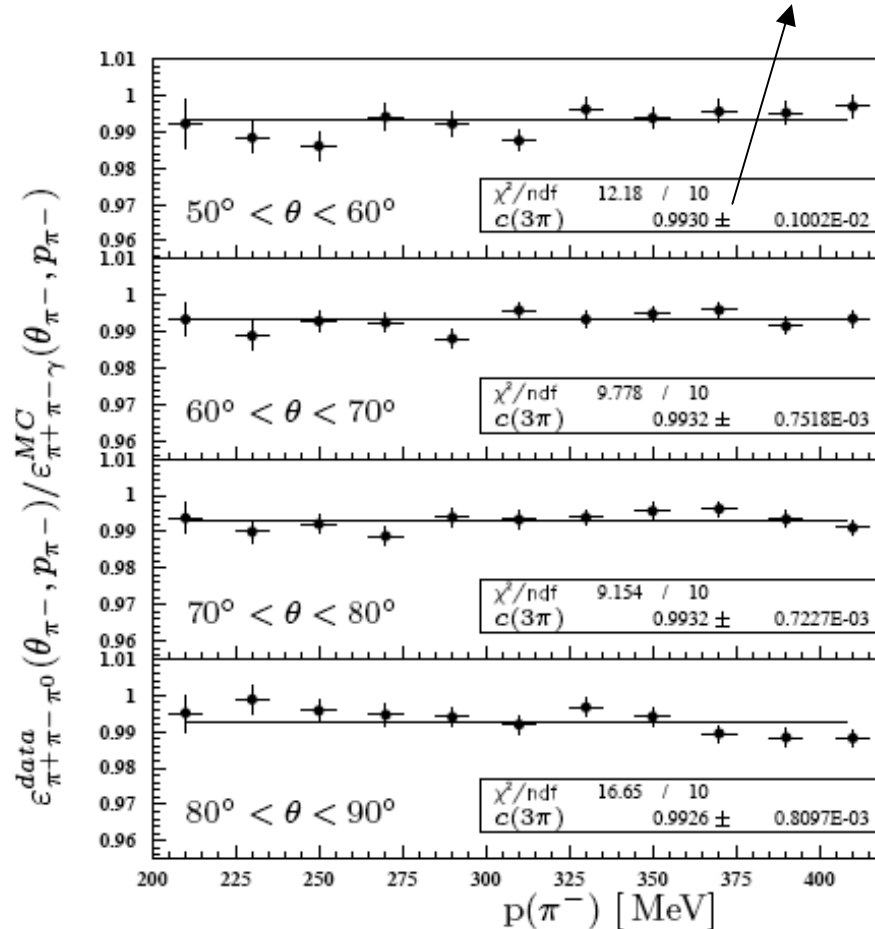
NN
output

Data/MC corrections from $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$



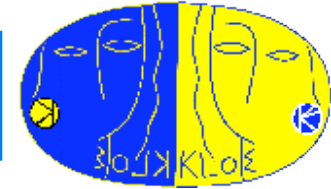
$$C_{3\pi} = 0.993 \pm 0.001$$

$$C_{\pi\pi\gamma} = 0.995 \pm 0.002$$



When “weighted” for the $\pi\pi\gamma$ event distribution the two methods gives 0.3% fractional difference in $M_{\pi\pi}^2$ which is the systematic error

π/e PID and TCA

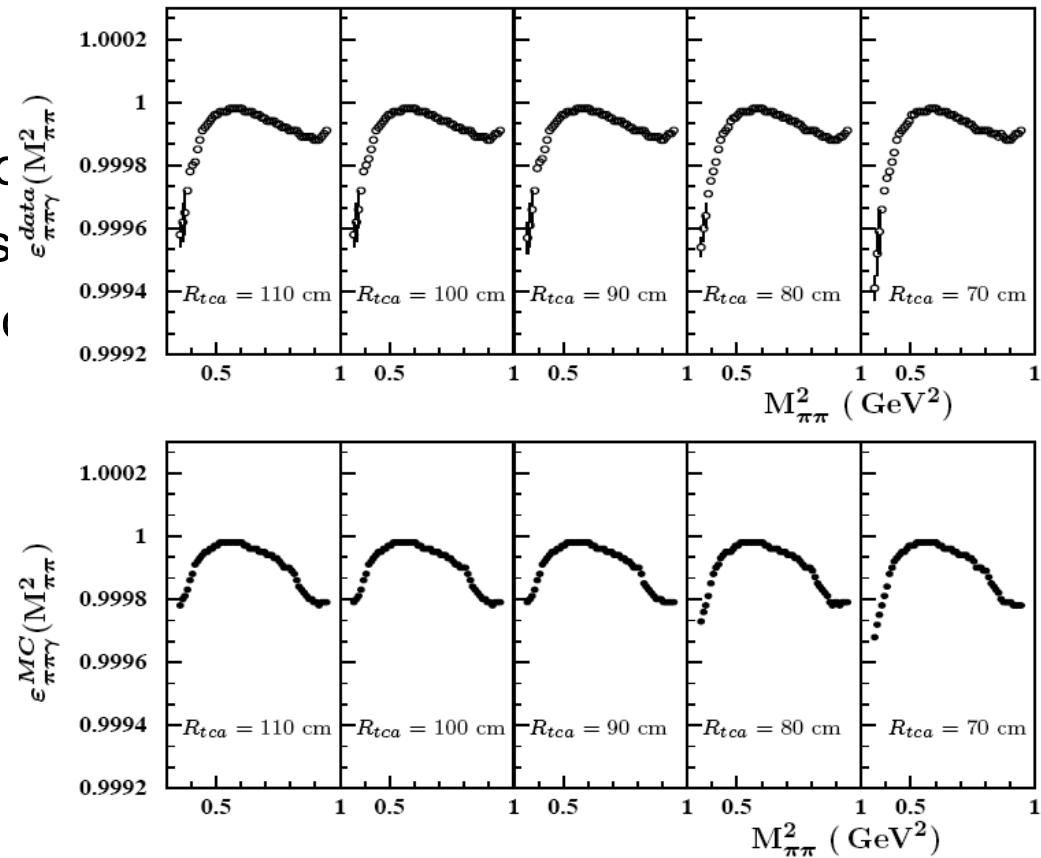


$\pi^+\pi^-\gamma$ sample

- 1) Two tracks satisfying $\pi\pi\gamma$ “tracking” acceptance selection
- 2) a tagging track recognized as pion by PID, extrapolating back to the IP, which satisfies the trigger
- 3) Look for a cluster with $PID > 0$ associated to the *candidate* track in slices of θ, p

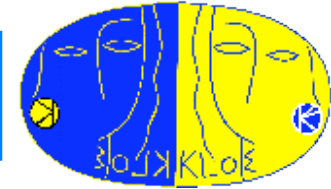
Efficiency ~ 1

data/MC correction = 1 at $R=90$ cm



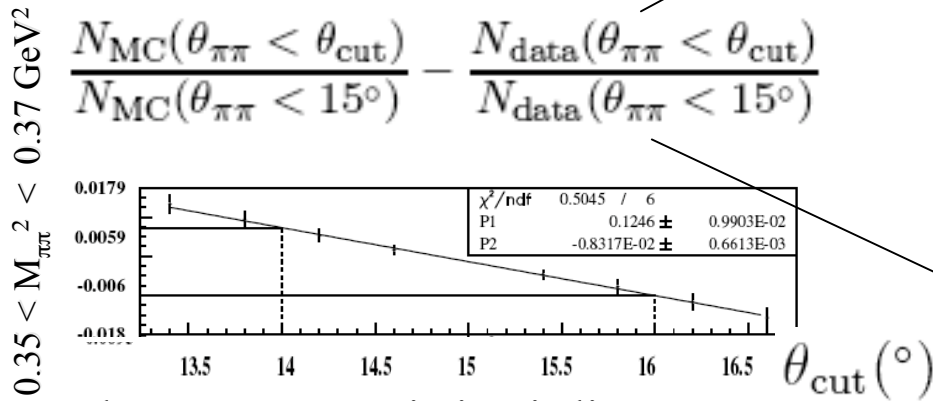
the systematic error is given by varying the association radius, the effect on the correction data/MC is negligible

Acceptance



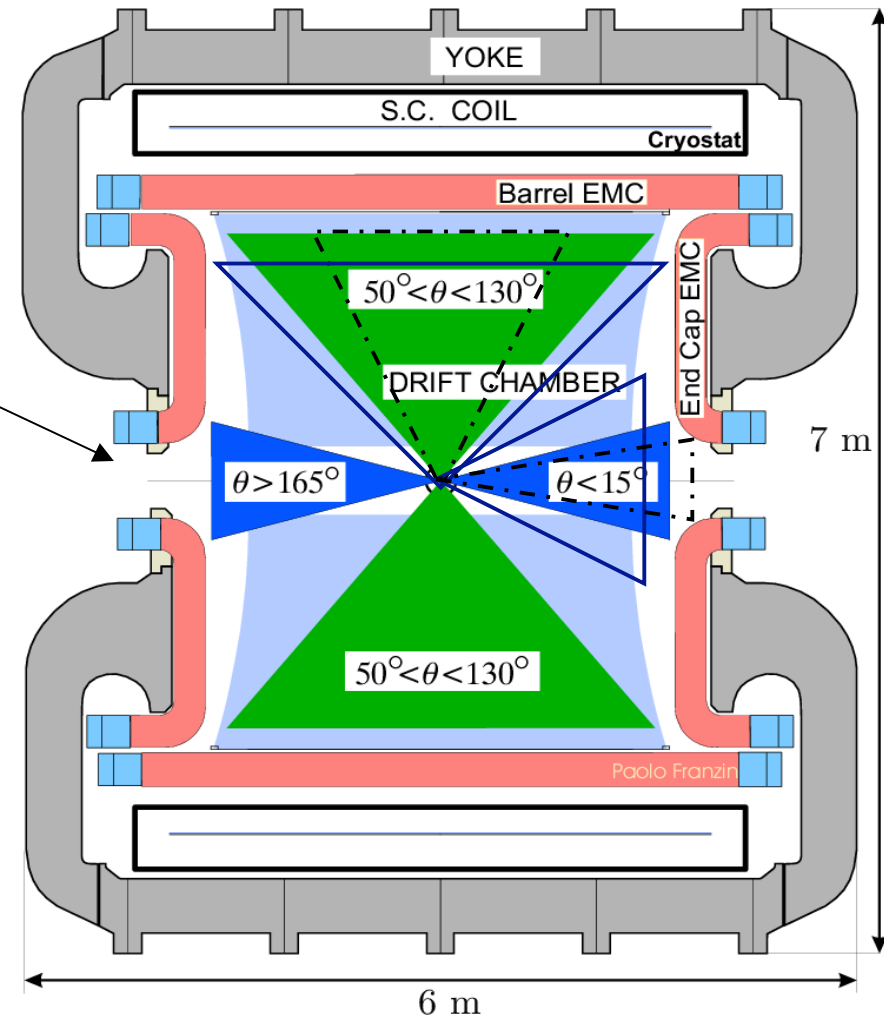
$\theta_{\pi\pi}$ is angle of the missing photon

We study the impact of enlarging/reducing the fiducial volume on the geometrical acceptance in slices of $M_{\pi\pi}^2$

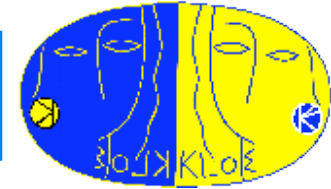


the spectrum variation is linear as a function of the cut, so the excursion at ± 1 degree is taken as systematic error

$M_{\pi\pi}^2$ range (GeV^2)	Systematic error (%)
$0.35 \leq M_{\pi\pi}^2 < 0.39$	0.6
$0.39 \leq M_{\pi\pi}^2 < 0.43$	0.5
$0.43 \leq M_{\pi\pi}^2 < 0.45$	0.4
$0.45 \leq M_{\pi\pi}^2 < 0.49$	0.3
$0.49 \leq M_{\pi\pi}^2 < 0.51$	0.2
$0.51 \leq M_{\pi\pi}^2 < 0.64$	0.1
$0.64 \leq M_{\pi\pi}^2 < 0.95$	-



Unfolding



Our bin width (0.01 GeV^2 is $\sim 5 \delta M_{\pi\pi}^2$) \Rightarrow Resolution
Matrix almost diagonal!

- We use Bayesian approach

G. D'Agostini, Nucl. Instrum. Meth. A 362 (1995) 487

- method based on Bayes' theorem
 - ◆ no matrix inversion needed
 - ◆ can be applied to multidimensional problems
 - ◆ **iterative** algorithm; can start with a uniform distribution

■ **Bayes formula:**
$$P(C_i|E_j) = \frac{P(E_j|C_i)P(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l)P(C_l)}$$
 "true", normalized distribution

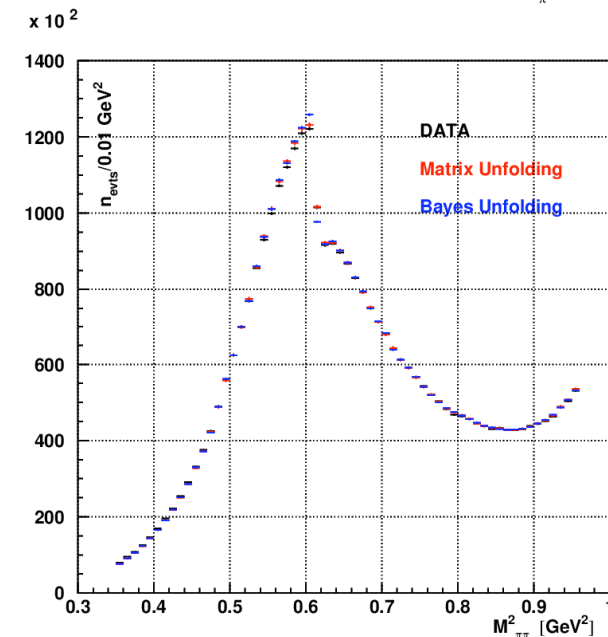
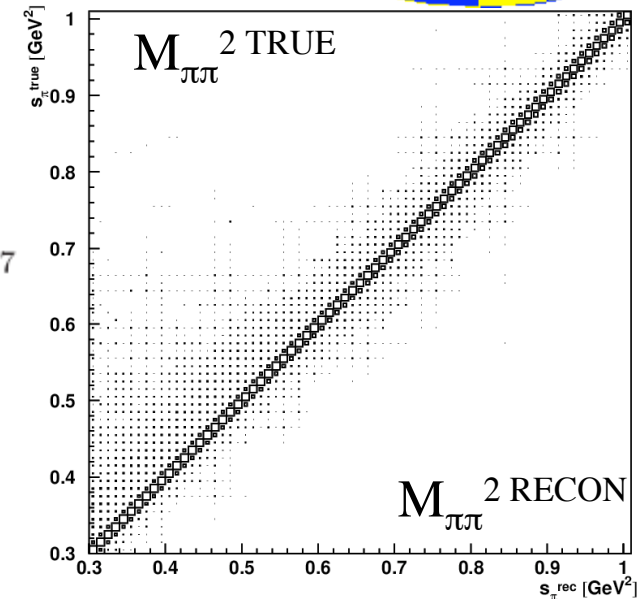
- ◆ "if we observe a single event "(effect E_j)", the probability that it has been due to the i -th cause "(C_i)," is proportional to the probability of the cause times probability of the cause to produce the effect"

D'Agostini

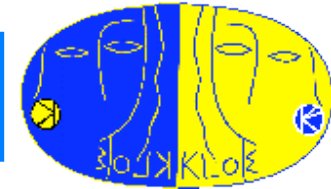
- We compare the result with the simple matrix procedure. They gives difference only around ρ - ω region

$M_{\pi\pi}^2 \text{ (GeV}^2\text{)}$	0.58	0.59	0.6	0.61	0.62
$\delta_{unf} \text{ (\%)}$	0.4	0.3	2.1	4.0	0.4

- Very small effect;
systematic error negligible on a_u !



Luminosity:



KLOE measures L with Bhabha scattering

F. Ambrosino et al. (KLOE Coll.)
Eur.Phys.J.C47:589-596,2006

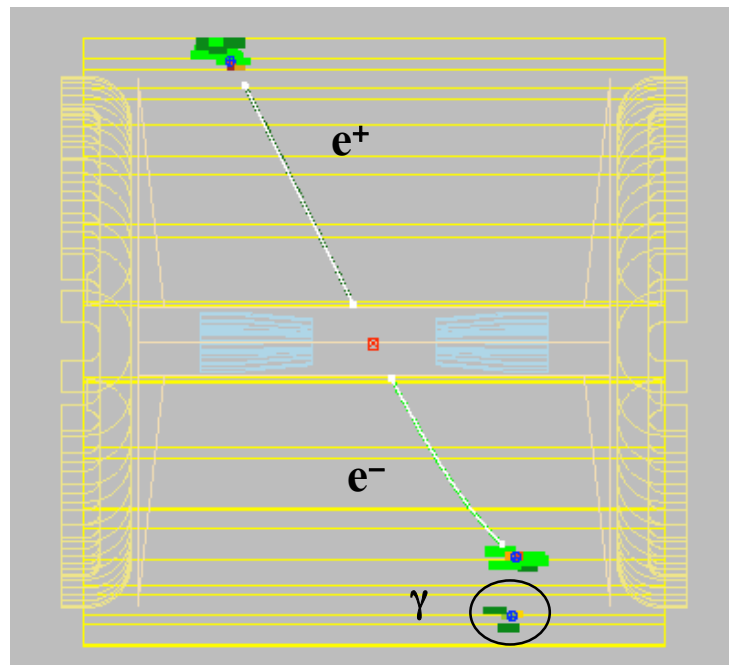
$55^\circ < \theta < 125^\circ$
 acollinearity $< 9^\circ$
 $p \geq 400$ MeV

$$\int \mathcal{L} dt = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

generator used for σ_{eff}

BABAYAGA (Pavia group):

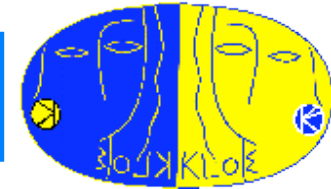
C. M.C. Calame et al., NPB758 (2006) 22



new version (**BABAYAGA@NLO**) gives
 0.7% decrease in cross section,
 and better accuracy: 0.1%

Systematics on Luminosity	
Theory	0.1 %
Experiment	0.3 %
TOTAL 0.1 % th \oplus 0.3% exp = 0.3%	

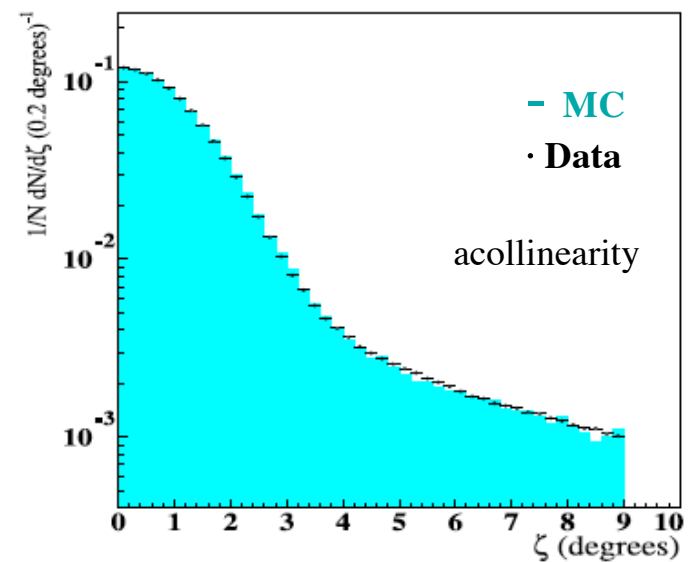
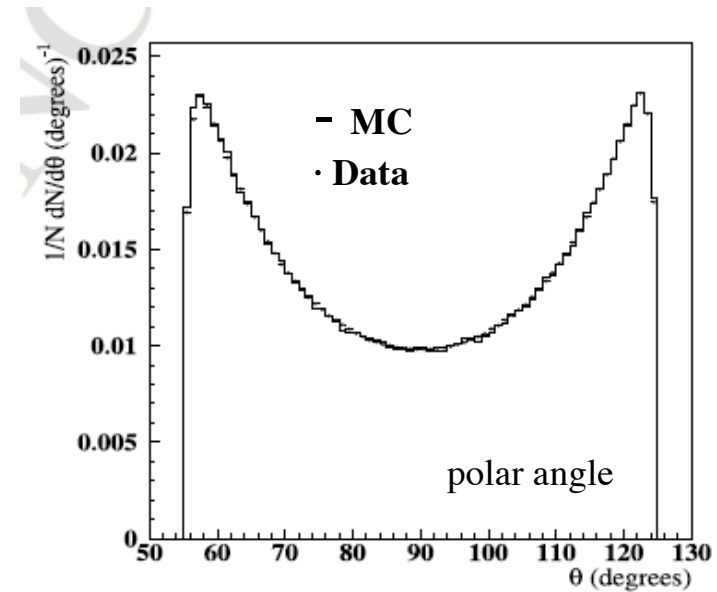
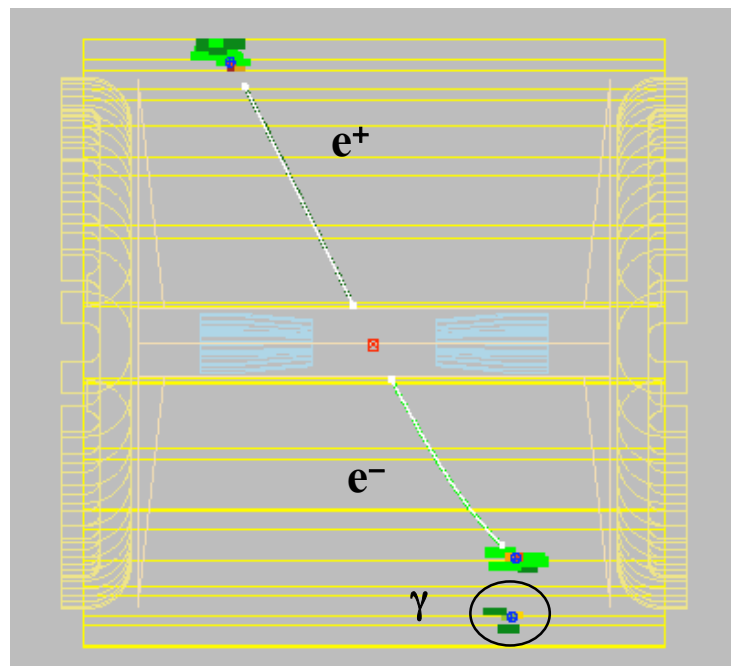
Luminosity:



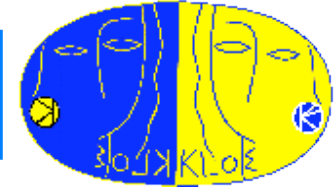
KLOE measures L with Bhabha scattering

$55^\circ < \theta < 125^\circ$
acollinearity $< 9^\circ$
 $p \geq 400$ MeV

$$\int \mathcal{L} dt = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$



KLOE result (KLOE08)



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

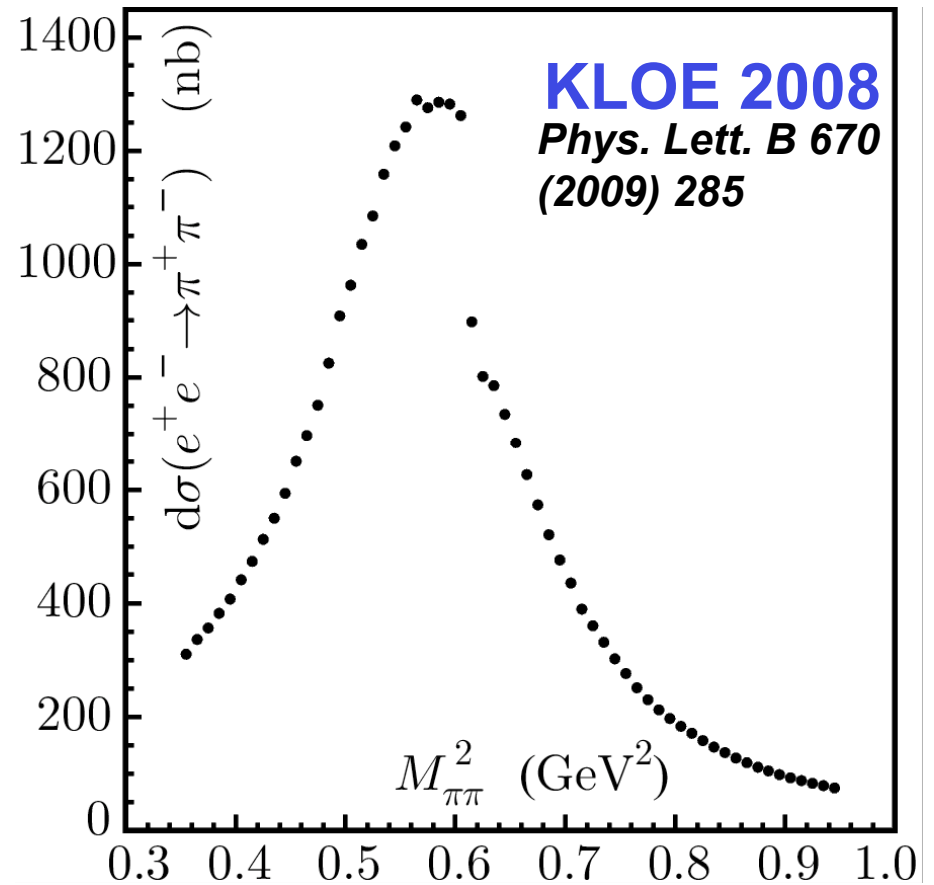
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
π/e -ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
\sqrt{s} dep. Of H	0.2%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

experimental fractional error on $a_\mu = 0.6\%$

FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	0.1%

theoretical fractional error on $a_\mu = 0.6\%$

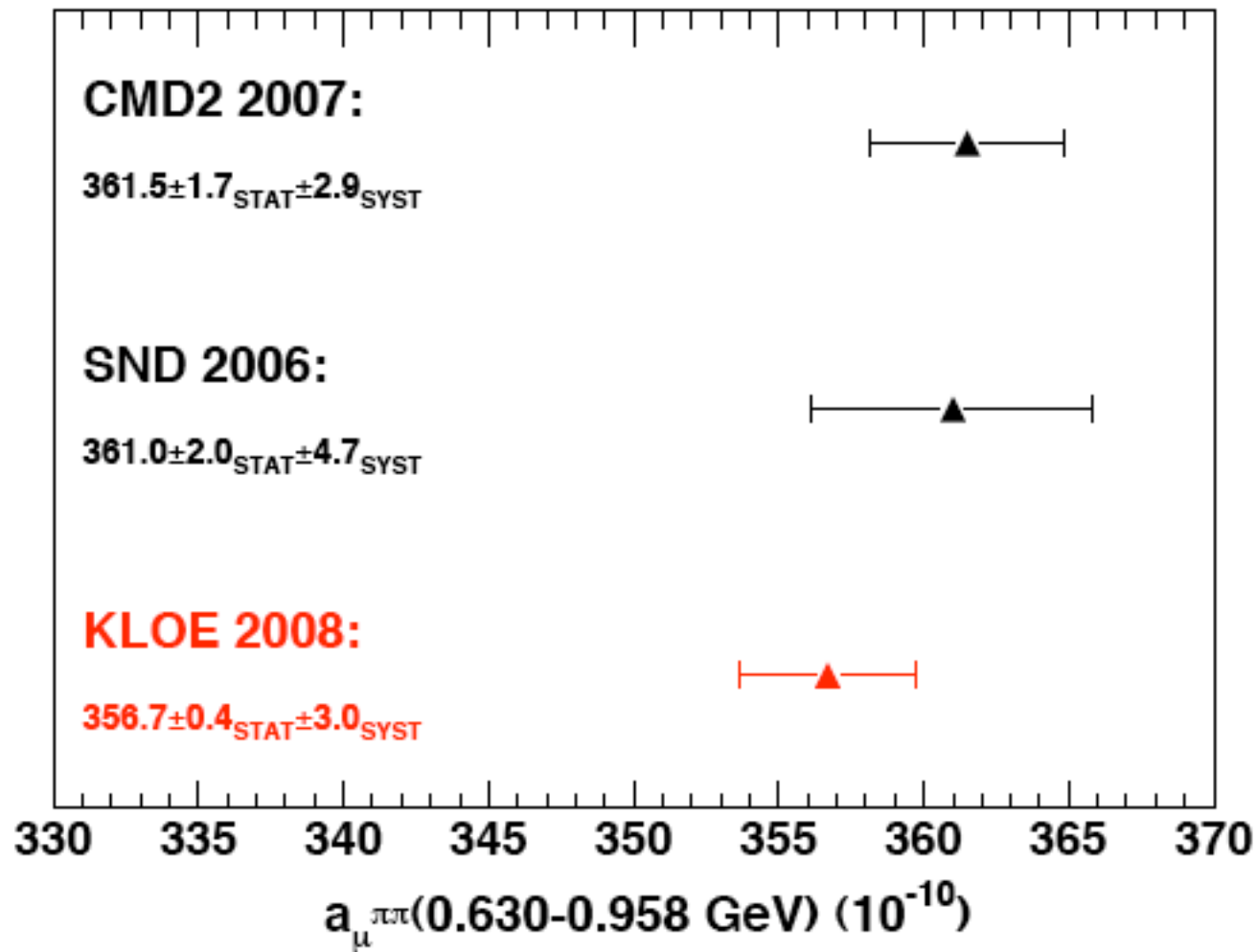
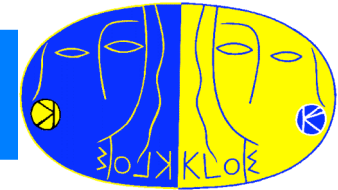
$\sigma_{\pi\pi}$, undressed from VP, inclusive for FSR as function of $(M_{\pi\pi}^0)^2$



stat. error only

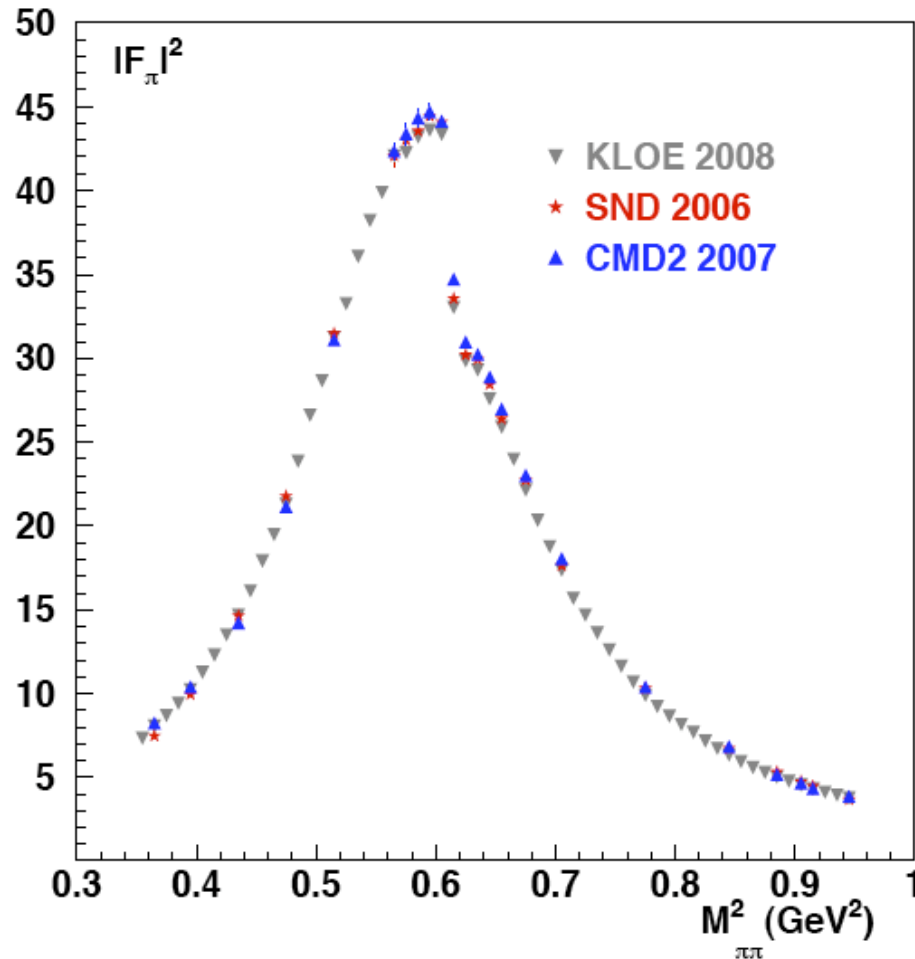
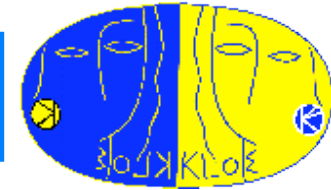
$$a_\mu^{\pi\pi}(0.35-0.95\text{GeV}^2) = (387.2 \pm 0.5_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.3_{\text{theo}}) \cdot 10^{-10}$$

$a_{\mu}^{\pi\pi}$: KLOE vs CMD-2/SND

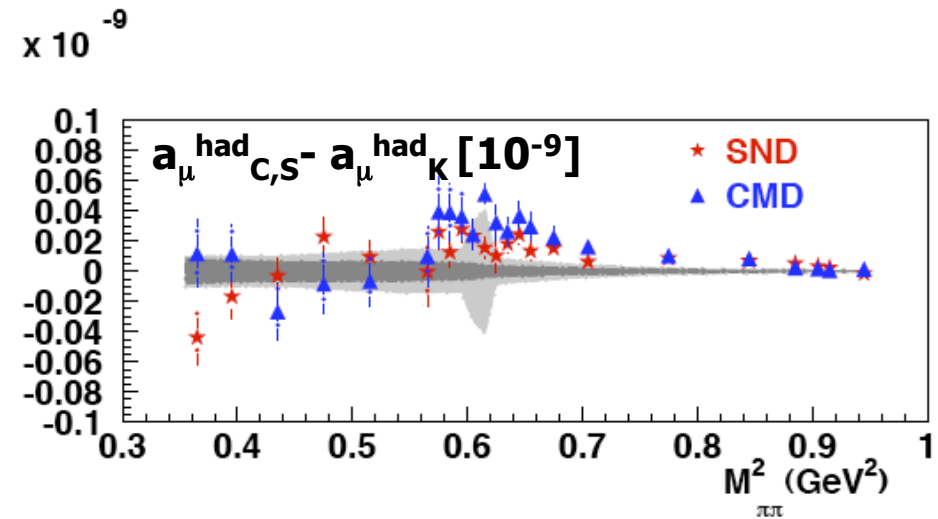
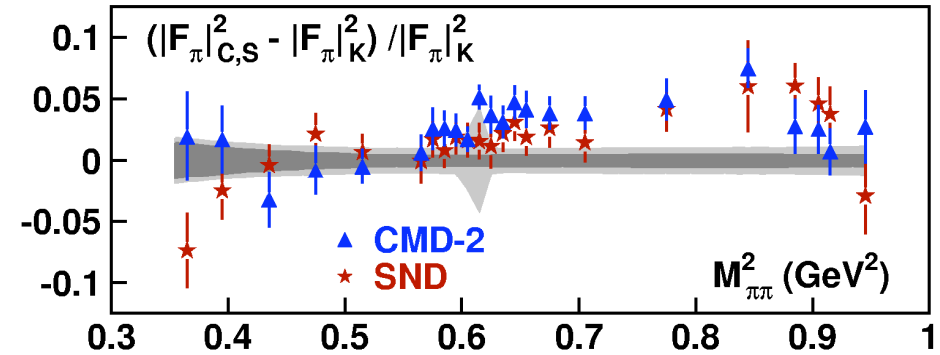


KLOE result in agreement with CMD2 and SND

Comparison with CMD2/SND



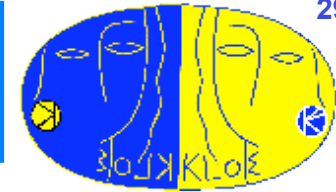
only statistical errors are shown



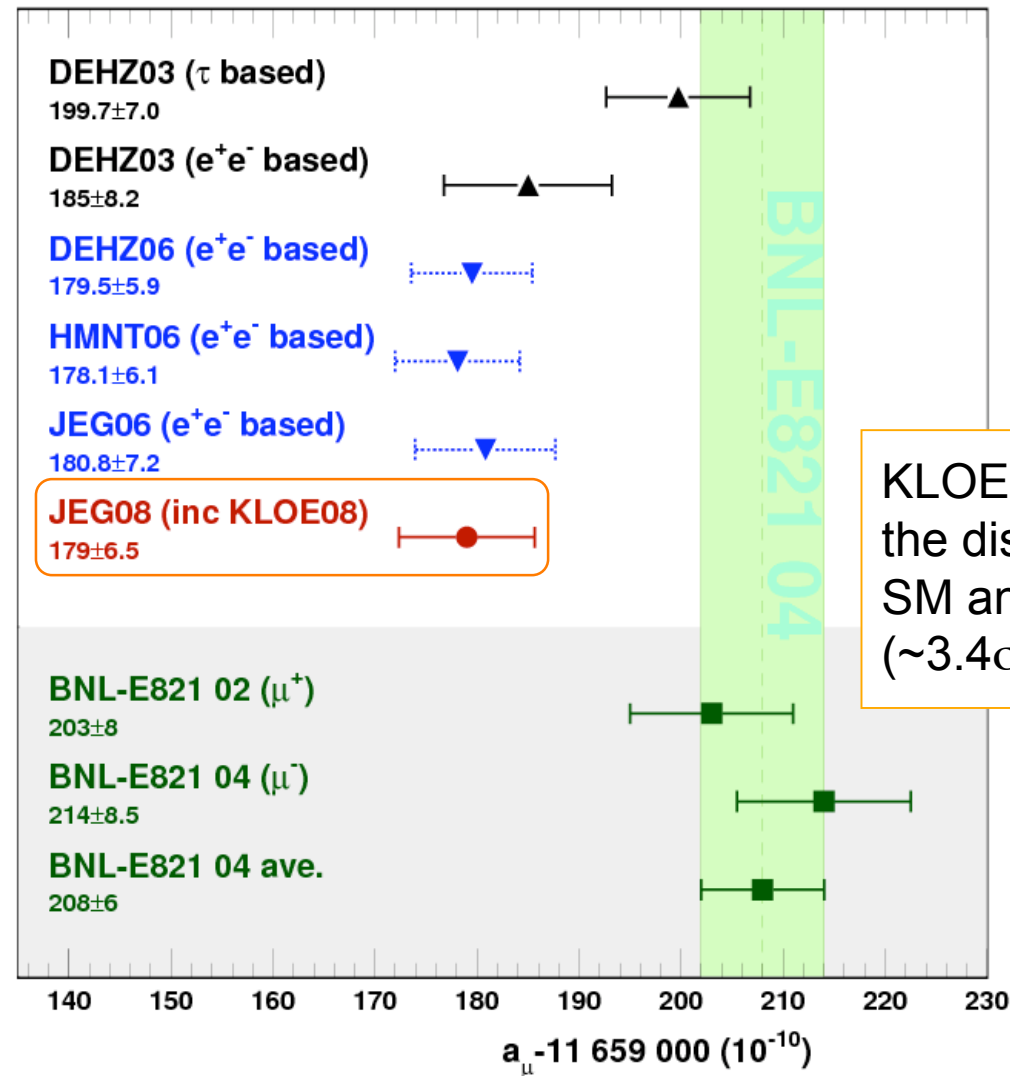
band: KLOE error
data points: CMD2/SND experiments

CMD-2 and SND data have been averaged over width of KLOE bin (0.01 GeV²)

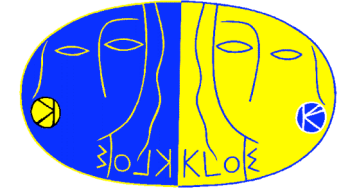
$$a_{\mu} = (g_{\mu} - 2)/2:$$



Theoretical predictions compared to the BNL result (in 2008):



KLOE08 strengthens the discrepancy between SM and BNL experiment ($\sim 3.4\sigma$)

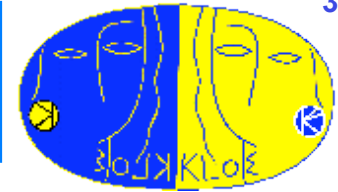


Measurement of the $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$
with photon emitted at Large Angle
(“*LA Analysis*,,)

***New measurement based on 220pb^{-1} at
 $\sqrt{s}=1000\text{ MeV}$ - 20 MeV below the ϕ -peak
(from 2006 data!)***

Results presented at PHIPSI09 Conference (Beijing, 13 Oct 2009);
paper in preparation

LA Event Selection



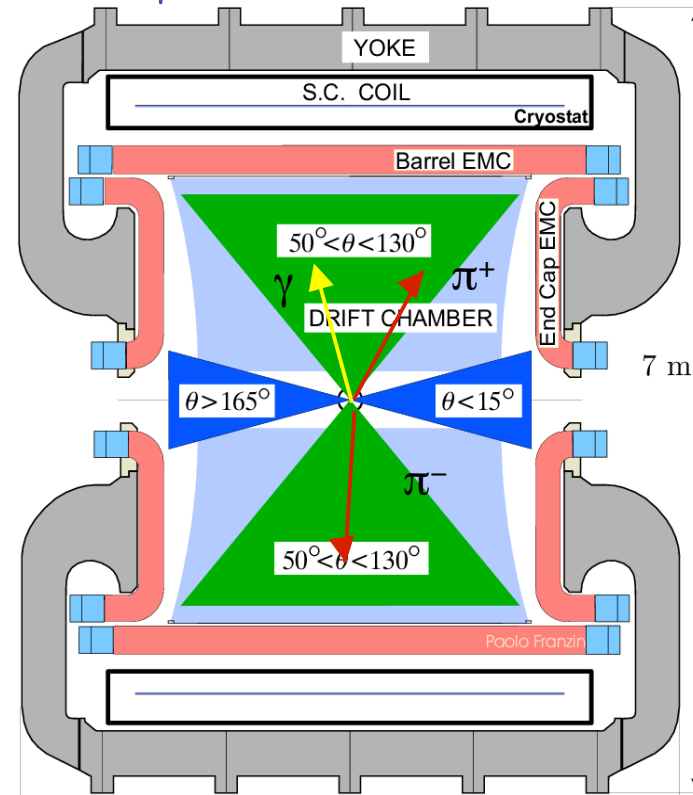
2 pion tracks at large angles

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

Photons at large angles

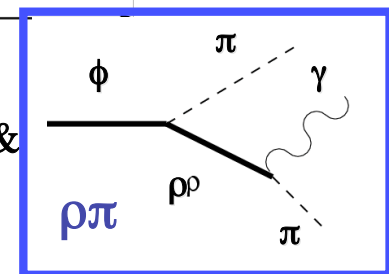
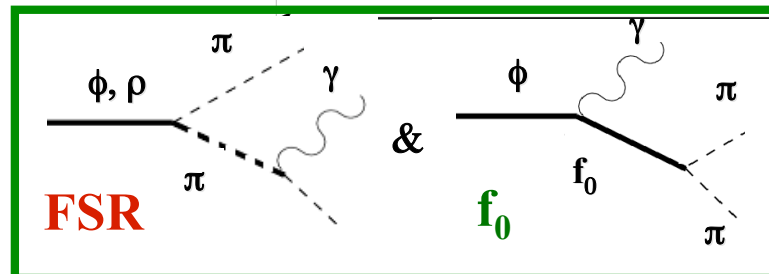
$$50^\circ < \theta_\gamma < 130^\circ$$

At least 1 photon with $50^\circ < \theta_\gamma < 130^\circ$
and $E_\gamma > 20 \text{ MeV} \rightarrow$ photon detected

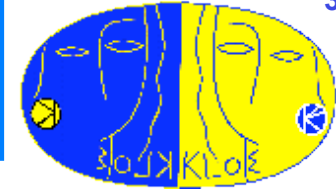


- ✓ independent complementary analysis
- ✓ threshold region $(2m_\pi)^2$ accessible
- ✓ γ_{ISR} photon detected (4-momentum constraints)
- ✓ lower signal statistics
- ✓ larger contribution from FSR events
- ✓ larger $\phi \rightarrow \pi^+\pi^-\pi^0$ background contamination
- ✓ irreducible background from ϕ decays ($\phi \rightarrow f_0 \gamma \rightarrow \pi\pi \gamma$)

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



LA Event Selection



2 pion tracks at large angles

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

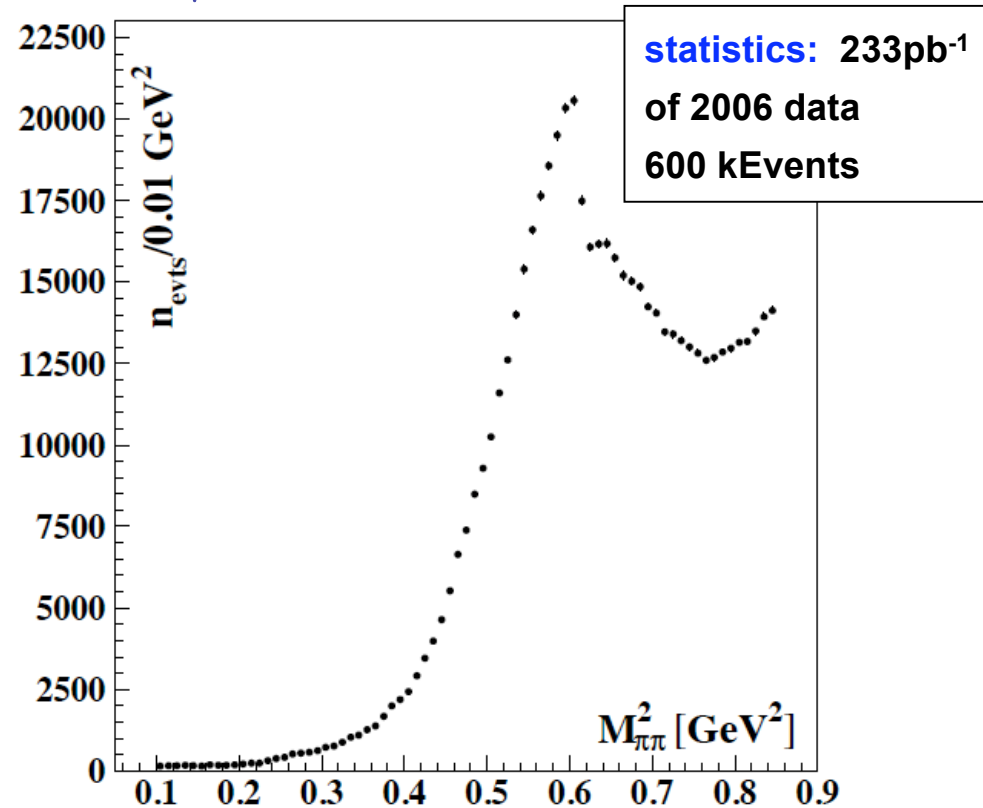
Photons at large angles

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

- ✓ independent complementary analysis
- ✓ threshold region $(2m_\pi)^2$ accessible
- ✓ γ_{ISR} photon detected
(4-momentum constraints)
- ✓ lower signal statistics
- ✓ larger contribution from FSR events
- ✓ larger $\phi \rightarrow \pi^+\pi^-\pi^0$ background contamination
- ✓ irreducible background from ϕ decays ($\phi \rightarrow f_0 \gamma \rightarrow \pi\pi \gamma$)



At least 1 photon with $50^\circ < \theta_\gamma < 130^\circ$
and $E_\gamma > 20 \text{ MeV} \rightarrow$ photon detected



Use data sample taken at $\sqrt{s} \approx 1000 \text{ MeV}$,
20 MeV below the ϕ -peak

Event selection



- **Experimental challenge: Fight background from**

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

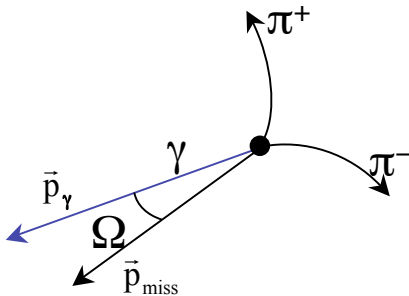
separated by means of kinematical

cuts in *trackmass* M_{Trk}

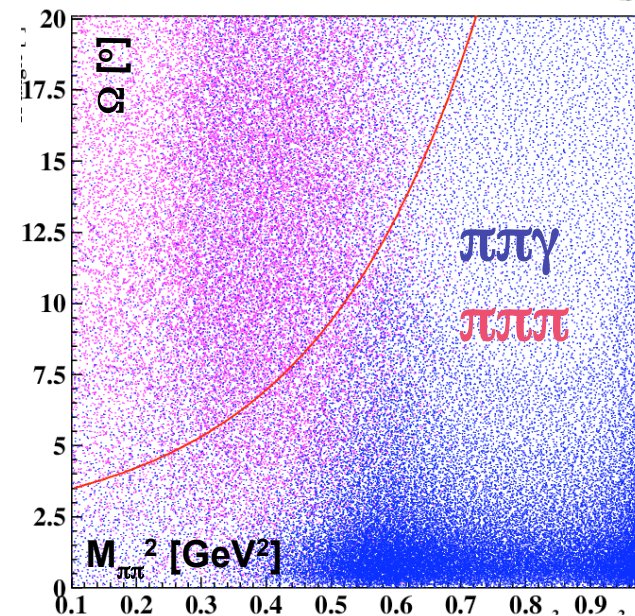
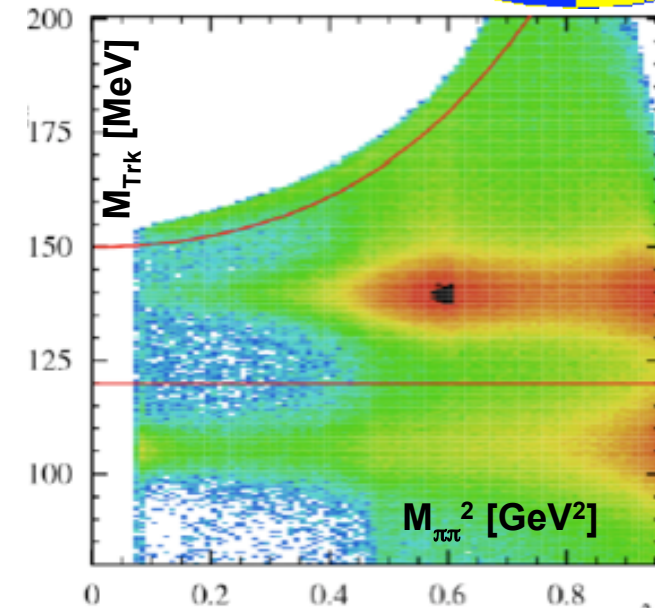
(defined by 4-momentum conservation under the hypothesis of 2 tracks with equal mass and a γ)

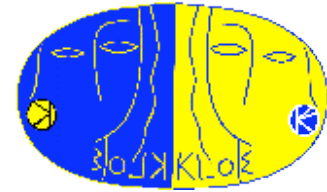
$$\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2} \right)^2 - (p_1 + p_2)^2 = 0$$

and the angle Ω between the photon and the missing momentum $\vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$



To further clean the samples from radiative Bhabha events, a particle ID estimator for each charged track based on **Calorimeter Information** and **Time-of-Flight** is used.





New KLOE result (KLOE09)

$$\sigma_{\pi\pi}(s_\pi) = \frac{\pi\alpha^2\beta_\pi^3}{3s} |F_\pi(s_\pi)|^2$$

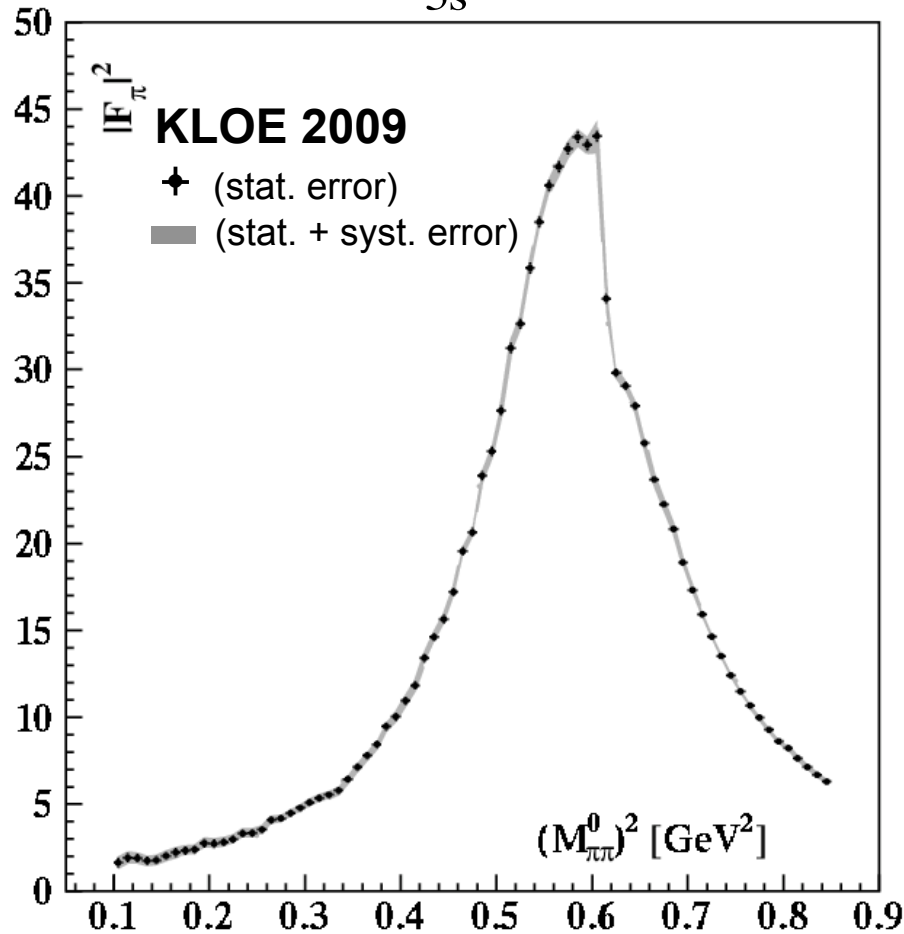


Table of systematic errors on $\Delta a_\mu^{\pi\pi}(0.1-0.85 \text{ GeV}^2)$:

Reconstruction Filter	< 0.1%
Background	0.5%
$f_0+\rho\pi$	0.4%
Omega	0.2%
Trackmass	0.5%
π/e -ID and TCA	< 0.1%
Tracking	0.3%
Trigger	0.2%
Acceptance	0.4%
Unfolding	negligible
Software Trigger	0.1%
Luminosity($0.1_{\text{th}} \oplus 0.3_{\text{exp}}$)%	0.3%

experimental fractional error on $\Delta a_\mu = 1.0 \%$

FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	< 0.1%

theoretical fractional error on $\Delta a_\mu = 0.6 \%$

Disp. Integral:

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{x_1}^{x_2} \sigma^{\text{had}}(s) K(s) ds$$

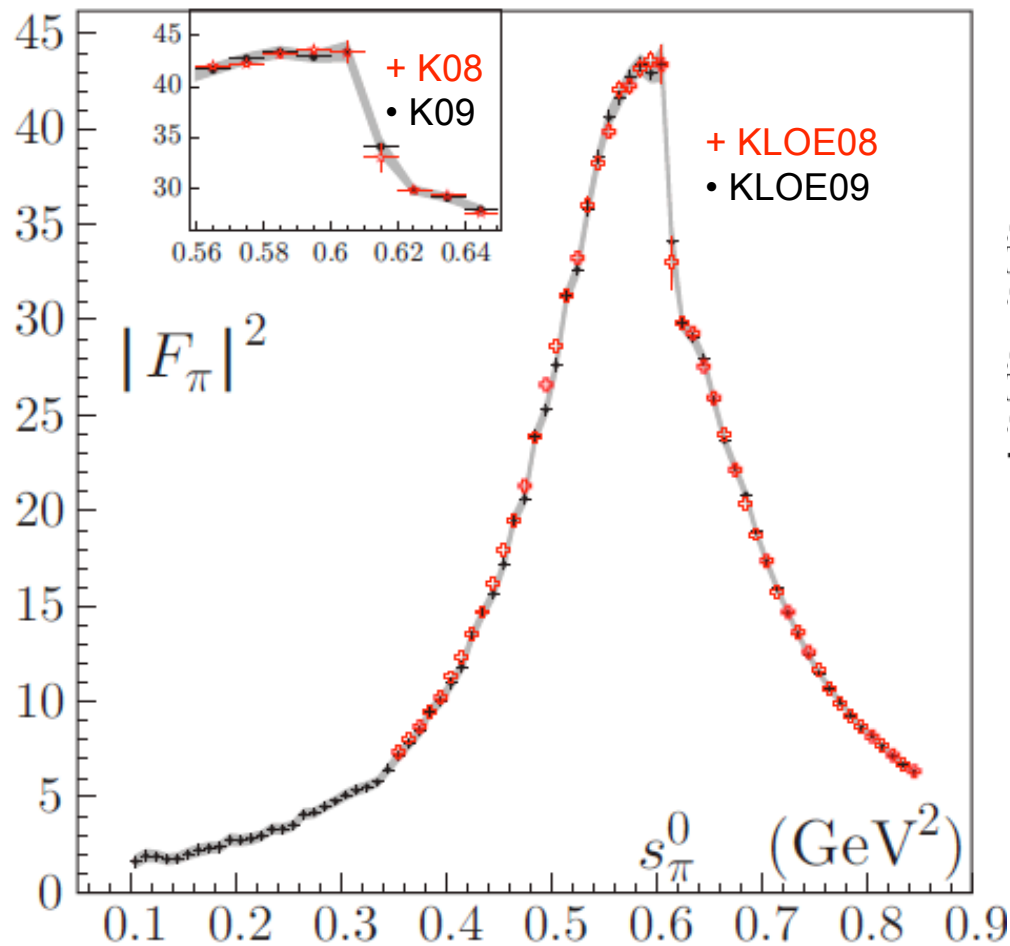
$$\Delta a_\mu^{\pi\pi}(0.1-0.85 \text{ GeV}^2) = (478.5 \pm 2.0_{\text{stat}} \pm 2.4_{\text{syst}} \pm 2.3_{\text{theo}}) \cdot 10^{-10}$$

0.4% 1.0% 0.6%

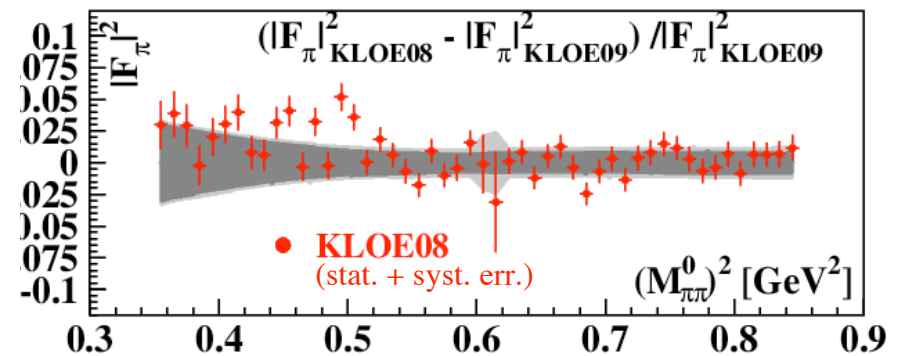
Comparison of results: KLOE09 vs KLOE08



KLOE08 result compared to KLOE09:



Fractional difference:



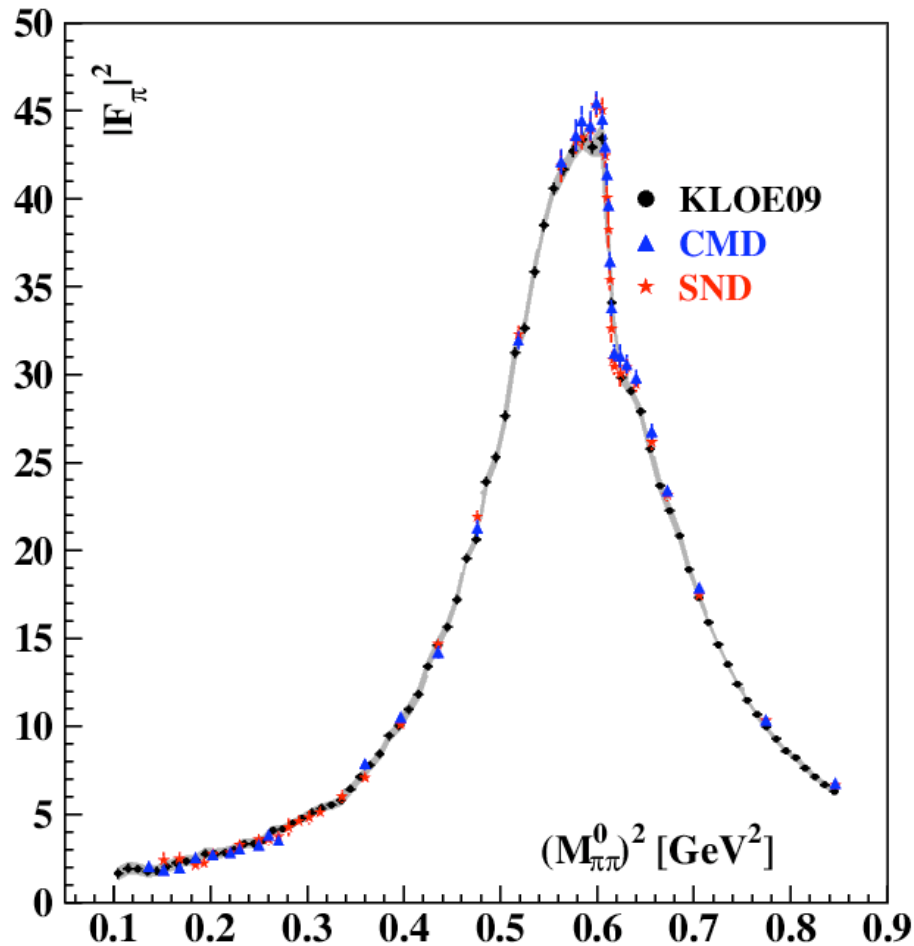
Excellent agreement with KLOE08, especially above 0.5 GeV^2

Combination of the two measurements in progress

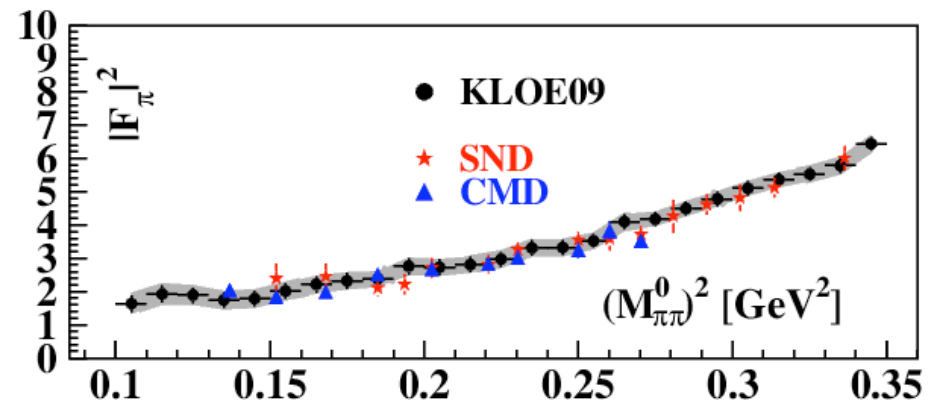
Comparison of results: KLOE09 vs CMD-2/SND



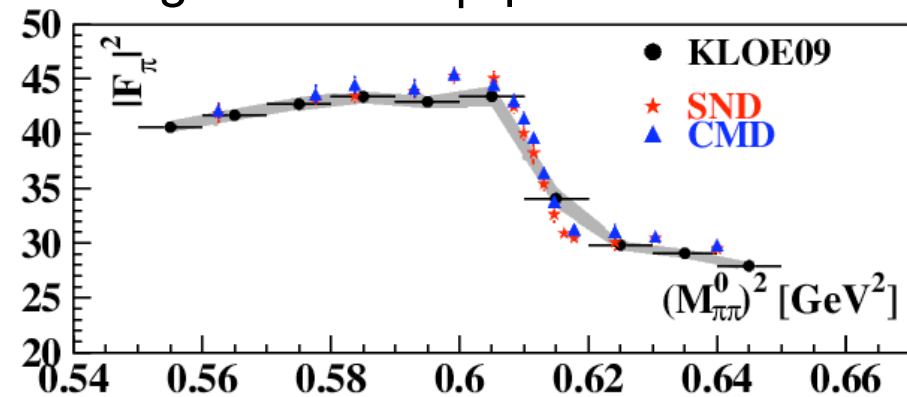
CMD and SND results compared to KLOE09:



Low $(M_{\pi\pi}^0)^2$:



Region around ρ -peak:

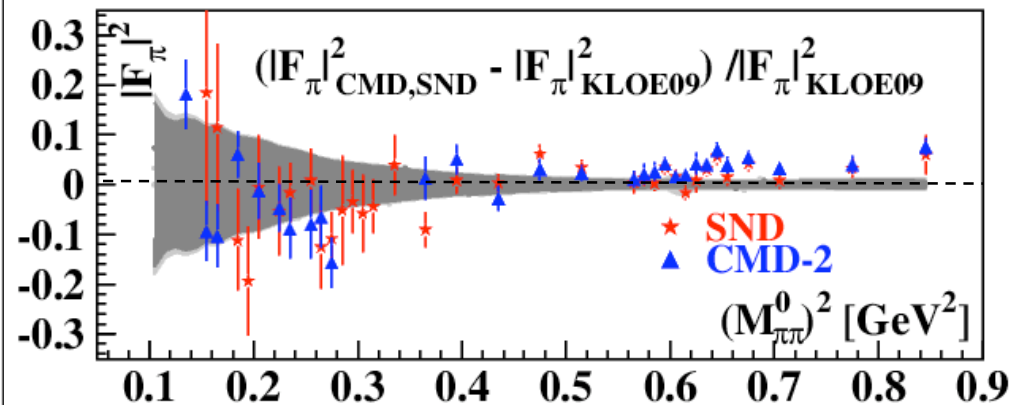
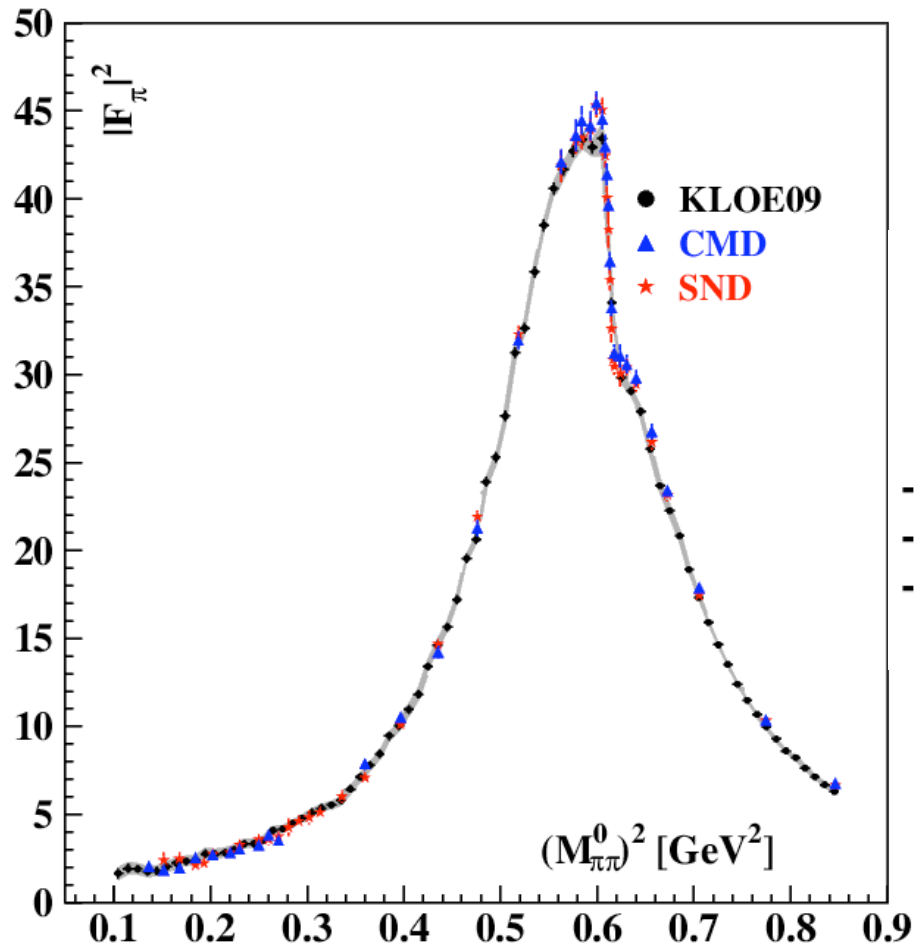


band: KLOE09 error

Comparison of results: KLOE09 vs CMD-2/SND



CMD and SND results compared to KLOE09: Fractional difference



band: KLOE09 error

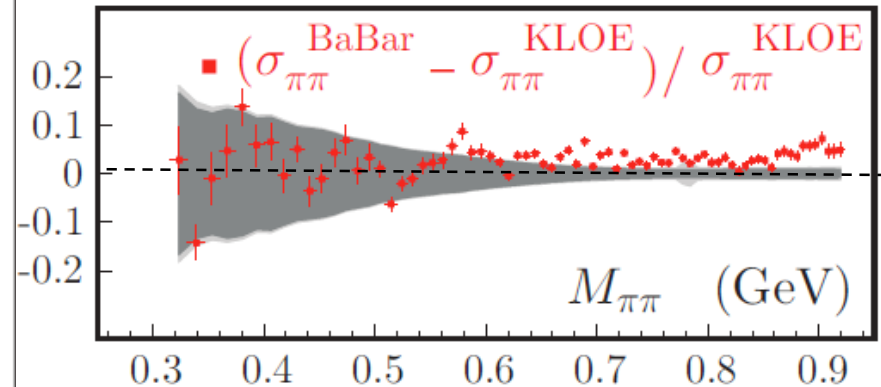
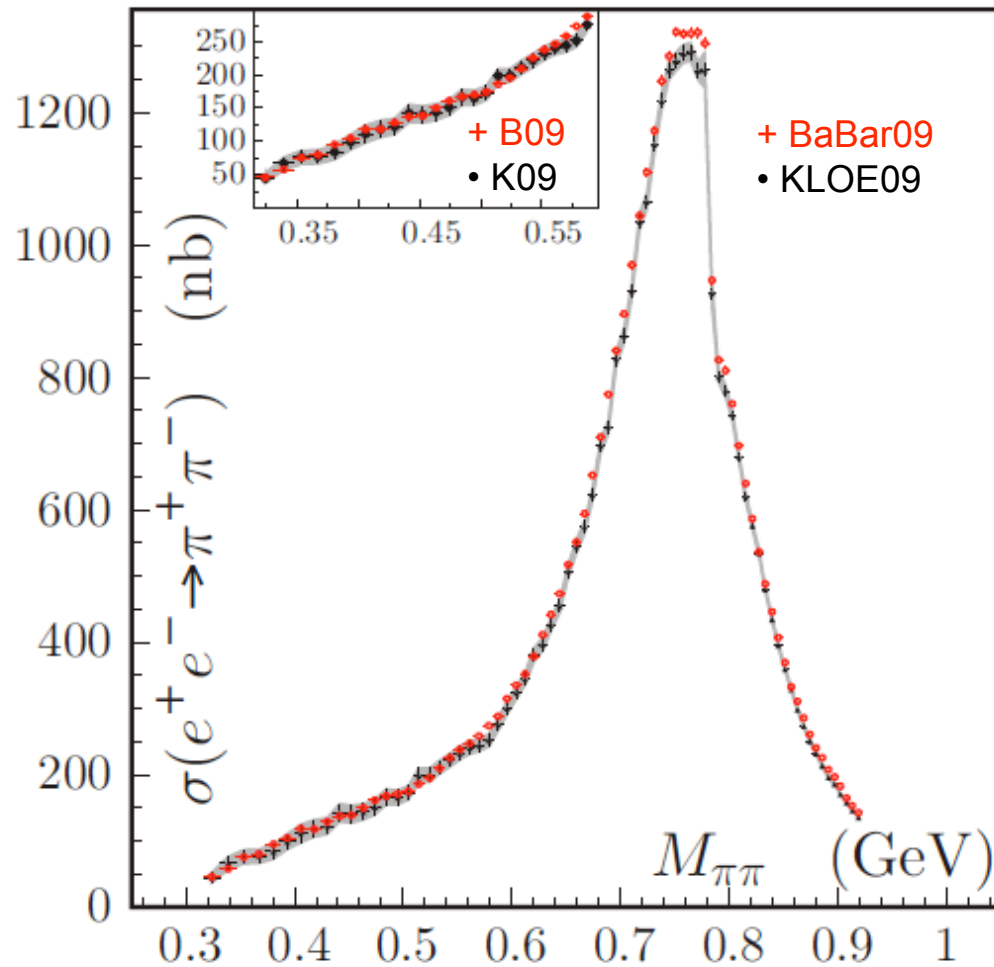
Below the ρ peak good agreement with CMD-2/SND.

Above the ρ peak CMD-2/SND slightly higher (as for KLOE08)

Comparison of results: KLOE09 vs BaBar



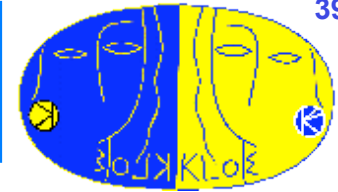
BaBar results compared to KLOE09: Fractional difference



band: KLOE09 error

*Agreement within the errors
up to 0.6 GeV;
BaBar higher by 2-3% above*

$\Delta a_\mu^{\pi\pi}$ for different exp.:



$\Delta a_\mu^{\pi\pi}(0.35-0.85\text{GeV}^2)$:

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{x_1}^{x_2} \sigma^{\text{had}}(s) K(s) ds$$

KLOE08 (small angle)

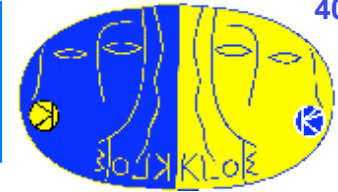
$$a_\mu^{\pi\pi} = (379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.2_{\text{theo}}) \cdot 10^{-10}$$

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.1_{\text{theo}}) \cdot 10^{-10}$$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$ for different exp.:



$\Delta a_\mu^{\pi\pi}(0.35-0.85\text{GeV}^2)$:

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{x_1}^{x_2} \sigma^{\text{had}}(s) K(s) ds$$

KLOE08 (small angle)

$$a_\mu^{\pi\pi} = (379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.2_{\text{theo}}) \cdot 10^{-10}$$

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.1_{\text{theo}}) \cdot 10^{-10}$$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}(0.152-0.270 \text{ GeV}^2)$:

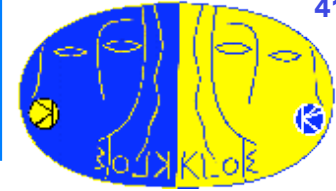
KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (48.1 \pm 1.2_{\text{stat}} \pm 1.2_{\text{sys}} \pm 0.4_{\text{theo}}) \cdot 10^{-10}$$

CMD-2

$$a_\mu^{\pi\pi} = (46.2 \pm 1.0_{\text{stat}} \pm 0.3_{\text{sys}}) \cdot 10^{-10}$$

$\Delta a_\mu^{\pi\pi}$ for different exp.:



$\Delta a_\mu^{\pi\pi}(0.35-0.85\text{GeV}^2)$:

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{x_1}^{x_2} \sigma^{\text{had}}(s) K(s) ds$$

KLOE08 (small angle)

$$a_\mu^{\pi\pi} = (379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.2_{\text{theo}}) \cdot 10^{-10}$$

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.1_{\text{theo}}) \cdot 10^{-10}$$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}(0.152-0.270 \text{ GeV}^2)$:

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (48.1 \pm 1.2_{\text{stat}} \pm 1.2_{\text{sys}} \pm 0.4_{\text{theo}}) \cdot 10^{-10}$$

CMD-2

$$a_\mu^{\pi\pi} = (46.2 \pm 1.0_{\text{stat}} \pm 0.3_{\text{sys}}) \cdot 10^{-10}$$

$\Delta a_\mu^{\pi\pi}(0.397-0.918 \text{ GeV}^2)$:

KLOE08 (small angle)

$$a_\mu^{\pi\pi} = (356.7 \pm 0.4_{\text{stat}} \pm 3.1_{\text{sys}}) \cdot 10^{-10}$$

CMD-2

$$a_\mu^{\pi\pi} = (361.5 \pm 1.7_{\text{stat}} \pm 2.9_{\text{sys}}) \cdot 10^{-10}$$

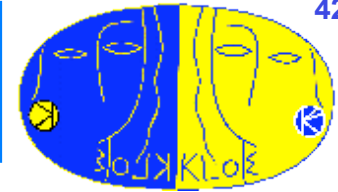
SND

$$a_\mu^{\pi\pi} = (361.0 \pm 2.0_{\text{stat}} \pm 4.7_{\text{sys}}) \cdot 10^{-10}$$

BaBar

$$a_\mu^{\pi\pi} = (365.2 \pm 1.9_{\text{stat}} \pm 1.9_{\text{sys}}) \cdot 10^{-10}$$

$a_\mu = (g_\mu - 2)/2:$

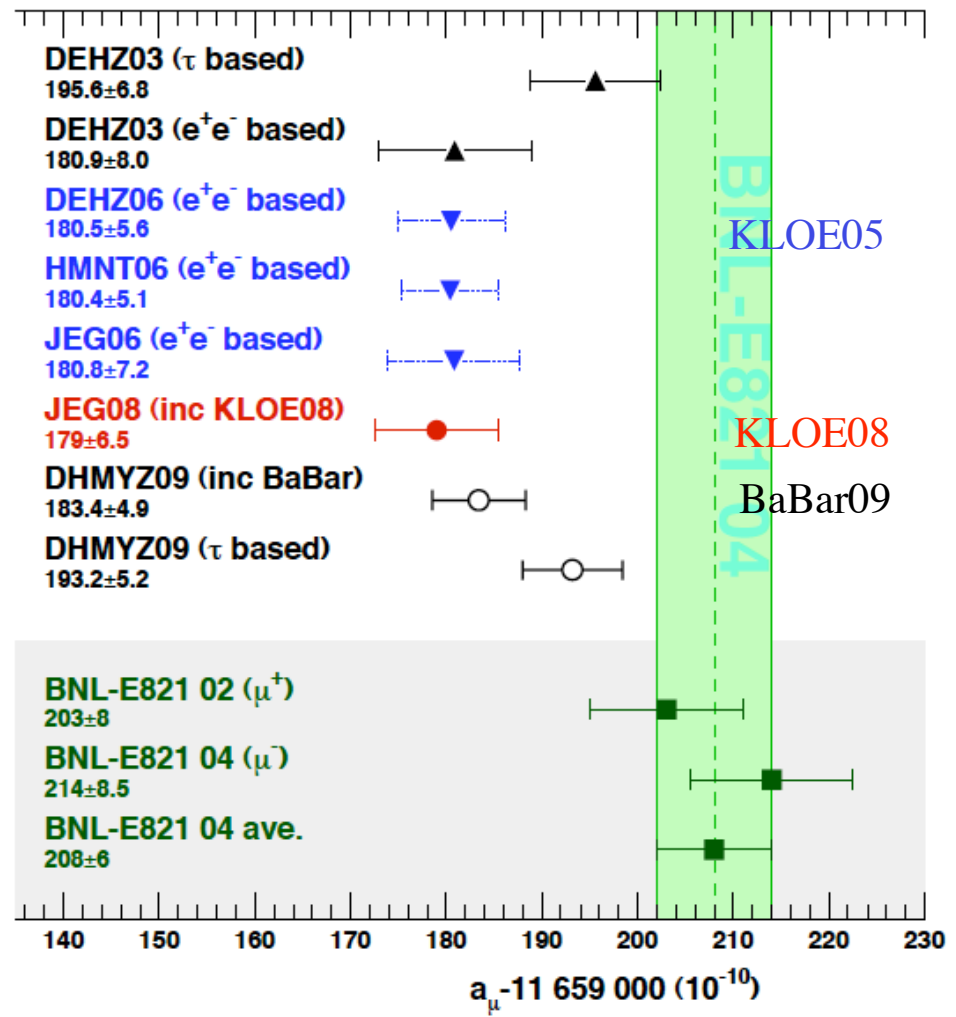


Theoretical predictions compared to the BNL result (2009)

■ The latest inclusion of all e^+e^- data (DHMYZ09) gives a discrepancy btw a_μ^{SM} and a_μ^{exp} of 3.2σ , as firstly confirmed by KLOE05

■ However remaining differences on $\sigma_{\pi\pi}$ btw the different experiments (mainly KLOE/BaBar) to be clarified.

→
KLOE09 is not yet in.



ISR: KLOE vs Babar 2π

KLOE:

- The photon is “soft” (detected or not)
- No Kinematic fit
- Bin of 0.01 GeV^2 ($\sim 8 \text{ MeV}$ at ρ peak) $\gg \delta M_{\pi\pi}^2 \sim 2 \cdot 10^{-3} \text{ GeV}^2$
 \Rightarrow Unfolding only relevant at low $M_{\pi\pi}^2$ (up to 4%) and at ρ - ω cusp,
- Negligible contribution of LO FSR, and $< 2\%$ contribution of NLO FSR ($1\gamma_{\text{ISR}} + 1\gamma_{\text{FSR}}$) only at low $M_{\pi\pi}^2$
- Normalize to **Luminosity** (=Bhabha)
- Use **Phokhara** for acceptance, radiator and additional-photon effects

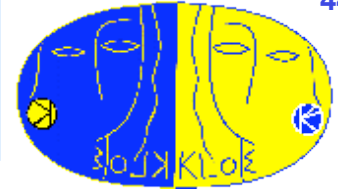
BaBar:

- The photon is “hard” and detected
- Kinematic fit to improve resolution
- Bin of 2 MeV in the region 0.5 - 1 GeV
 \Rightarrow Larger effects on the unfolding
- Negligible contribution of LO FSR, % contribution of NLO FSR ($1\gamma_{\text{ISR}} + 1\gamma_{\text{FSR}}$)
- Normalize to $\mu\mu\gamma$
- Interplay btw **Phokhara** and **AfkQED** to estimate additional-photon effects

KLOE, in very advanced phase:

- Normalization to $\mu\mu\gamma$ (very good π/μ separation by track mass)

$\sigma_{\pi\pi}$ measurement from π/μ

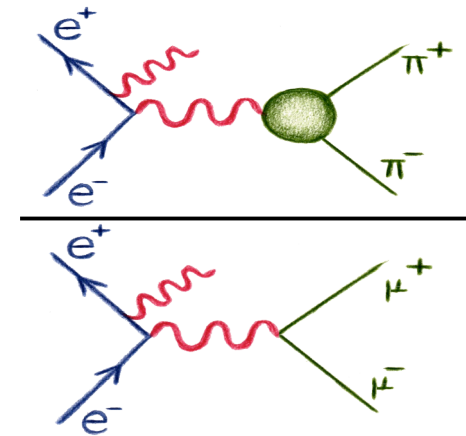


An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

$$|F_\pi(s')|^2 \approx \frac{4(1 + 2m_\mu^2/s')\beta_\mu}{\beta_\pi^3} \frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

kinematical factor
($\sigma_{\mu\mu}^{\text{Born}} / \sigma_{\pi\pi}^{\text{Born}}$)

meas. quantities



Many radiative corrections drop out:

- radiator function
- int. luminosity from Bhabhas
- Vacuum polarization

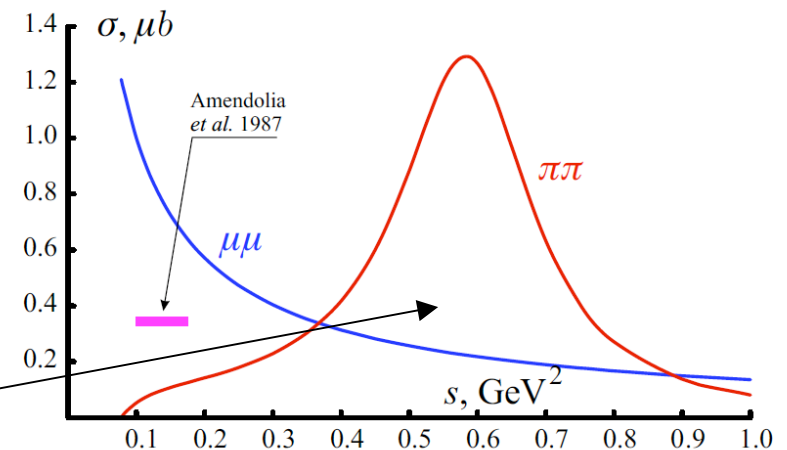
Separation btw $\pi\pi\gamma$ and $\mu\mu\gamma$ using M_{TRK}

- muons: $M_{\text{Trk}} < 120 \text{ MeV}$
- pions: $M_{\text{Trk}} > 130 \text{ MeV}$

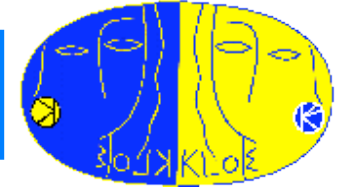
Very important control of pions in the ρ region

($\sigma_{\pi\pi} \gg \sigma_{\mu\mu}$)

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ and $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$



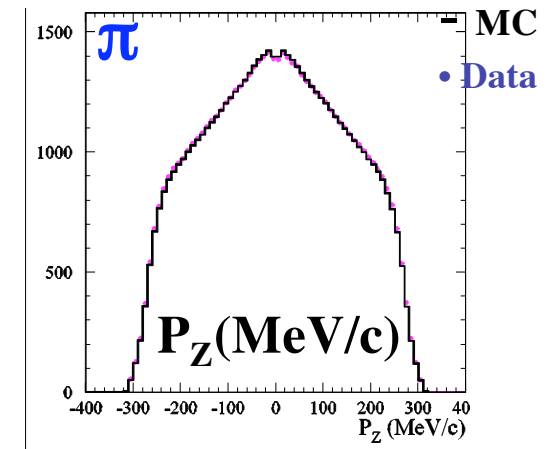
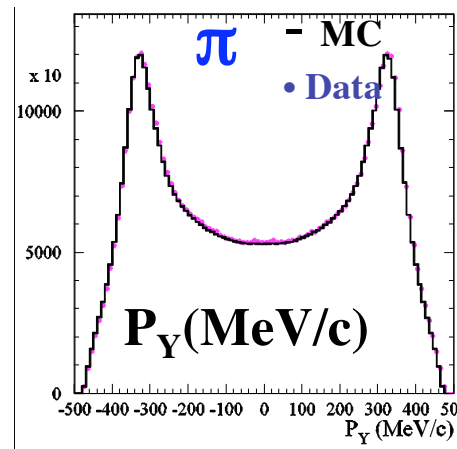
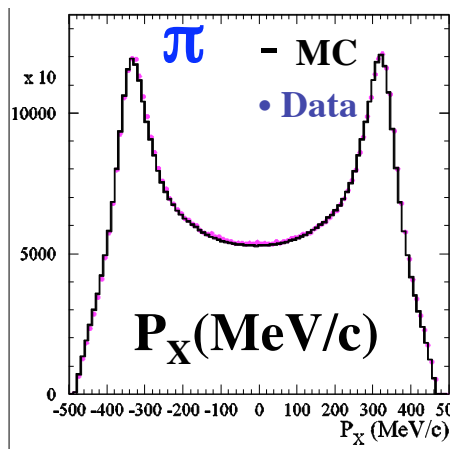
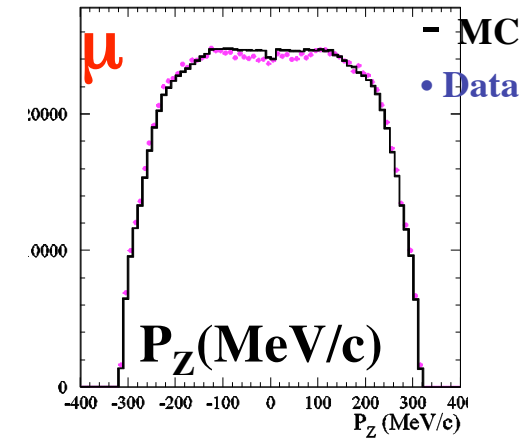
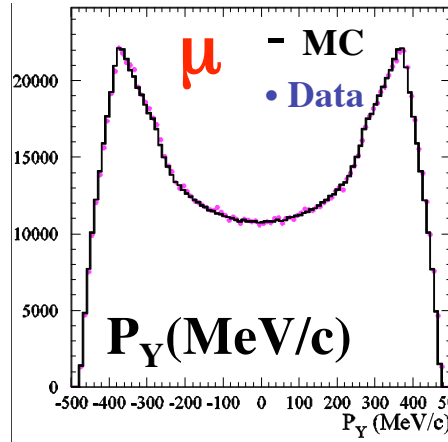
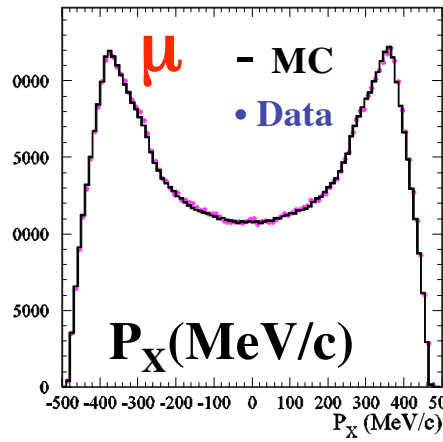
π/μ : Status of the Analysis



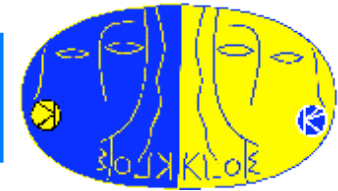
- ❑ 240 pb⁻¹ of 2002 data sample (the same used for the KLOE08 analysis): 0.87 Million $\mu\mu\gamma$ events expected (compared to 3.42 Million for $\pi\pi\gamma$)
- ❑ A lot of work has been done to achieve a control of $\sim 1\%$ in the μ selection, especially in the ρ region where $\pi/\mu \sim 10$ (see later)
- ❑ We have achieved an excellent Data/MC agreement for μ in many kinematic variables (as we did for pions)
- ❑ Most of efficiencies for μ have been done and are $\sim 100\%$
- ❑ We have not yet performed the absolute ratio $\mu\mu\gamma_{\text{DATA}}/\mu\mu\gamma_{\text{MC}}$ (test of QED) to check Radiator, Luminosity, FSR etc...

Results are expected for July conference (if everything goes smoothly)

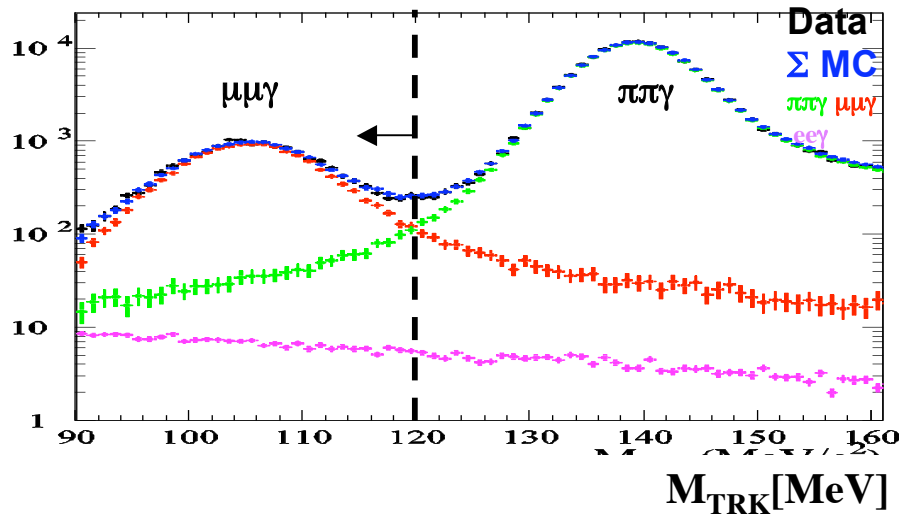
Example of data/MC for $\mu\mu\gamma$ and $\pi\pi\gamma$: momentum components of μ and π



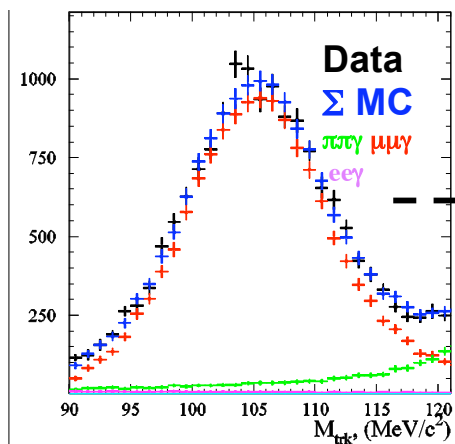
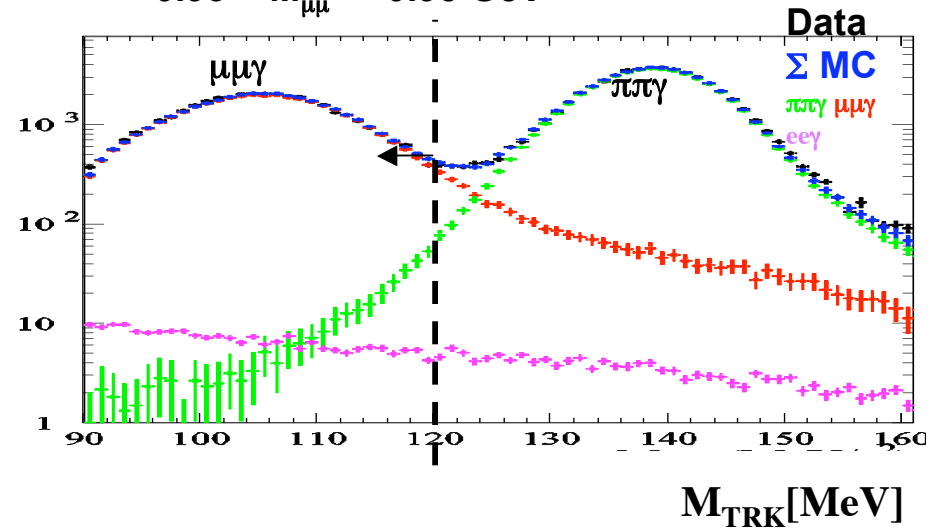
Example of $\mu\mu\gamma$ selection via M_{TRK}



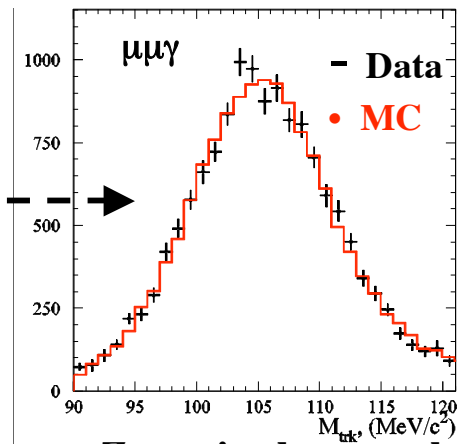
$0.59 < M_{\mu\mu}^2 < 0.61 \text{ GeV}^2$



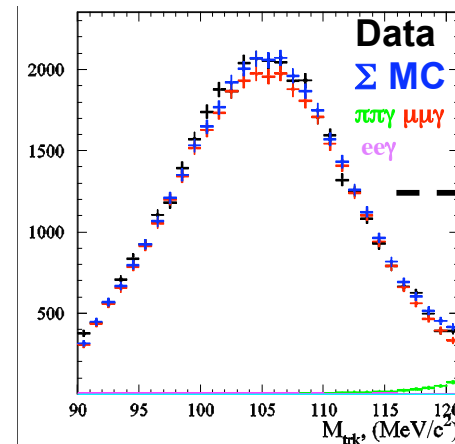
$0.93 < M_{\mu\mu}^2 < 0.95 \text{ GeV}^2$



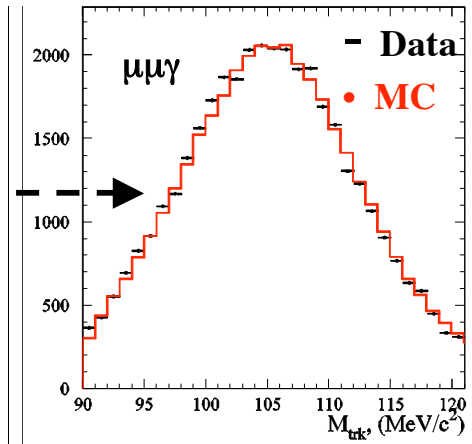
Zoom in the μ peak



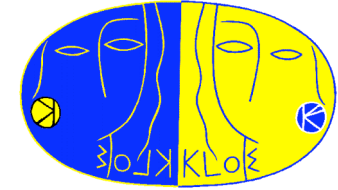
Zoom in the μ peak,
after background
subtraction



Zoom in the μ peak

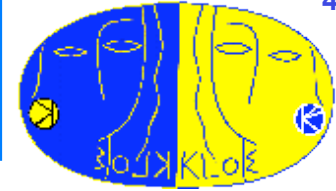


Zoom in the μ peak,
after background
subtraction



**Test of Final State Radiation model by
measurement of the Forward-Backward
asymmetry in $e^+e^- \rightarrow \pi^+\pi^-\gamma$ process**

Forward-backward asymmetry:



In the case of a non-vanishing FSR contribution, the interference term between ISR and FSR is odd under exchange $\pi^+ \leftrightarrow \pi^-$. This gives rise to a non-vanishing **asymmetry**:

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

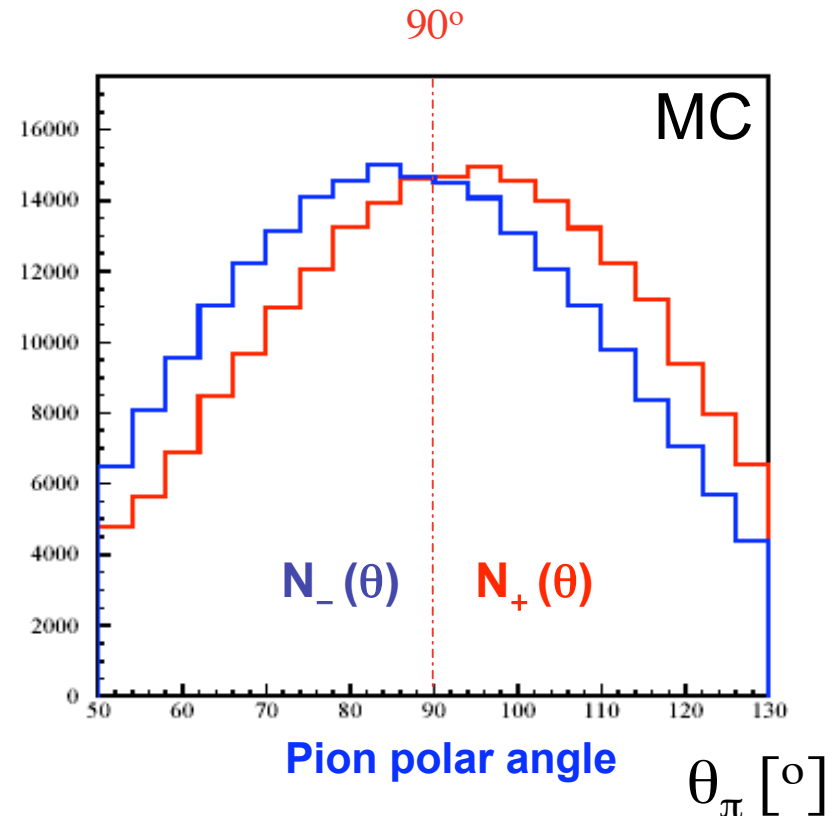
Forward-backward asymmetry:

$$A = \frac{N(\theta^+ > 90^\circ) - N(\theta^+ < 90^\circ)}{N(\theta^+ > 90^\circ) + N(\theta^+ < 90^\circ)}$$

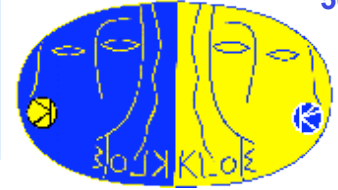
Ideal tool to test the validity of models used in Monte Carlo to describe the pionic final state radiation (point-like pion assumption, $R_{\chi T}$, etc.)

In a similar way like FSR, radiative decays of the ϕ into scalar mesons decaying to $\pi^+\pi^-$ also contribute to the asymmetry.

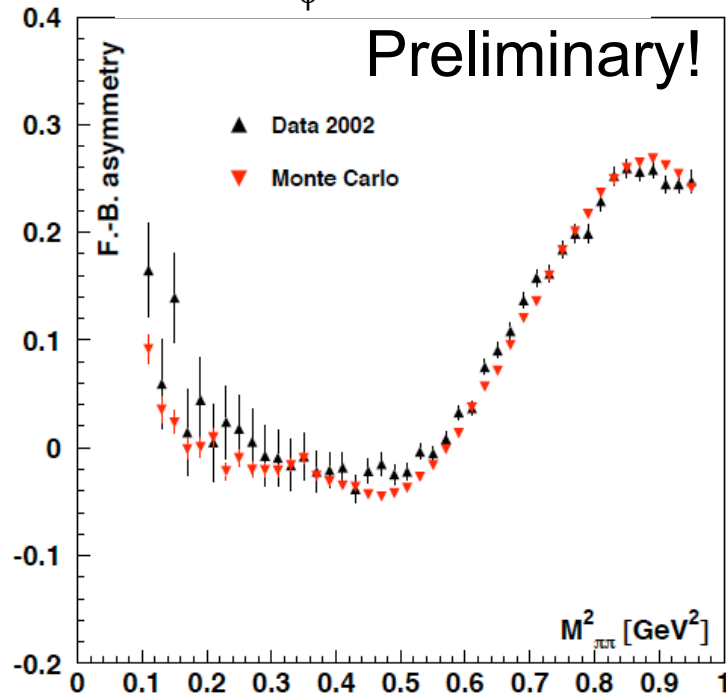
Czyz, Grzelinska, Kühn, hep-ph/0412239



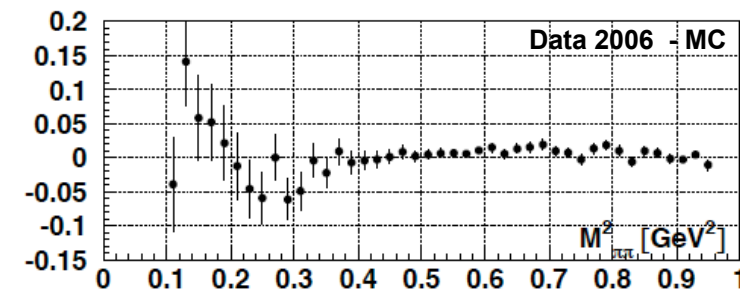
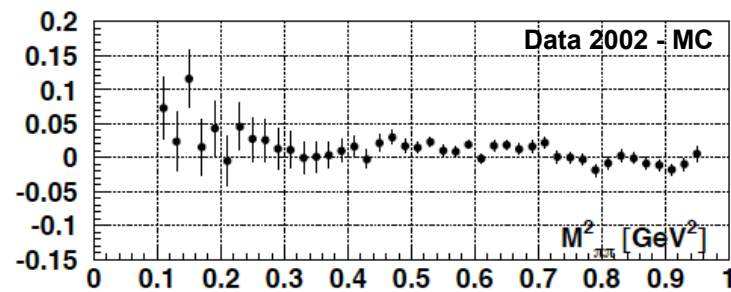
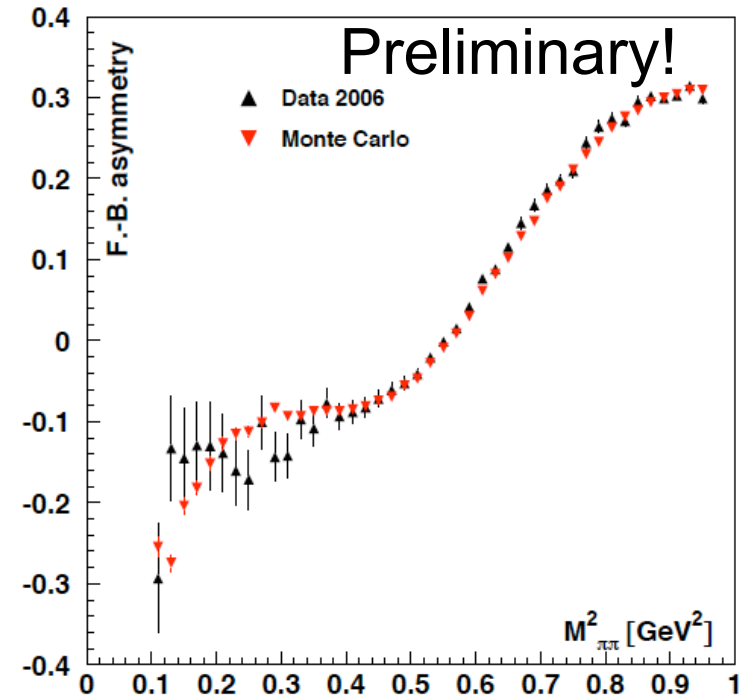
Forward-backward asymmetry:



$$\sqrt{s} = m_\phi \approx 1.0195 \text{ GeV}$$

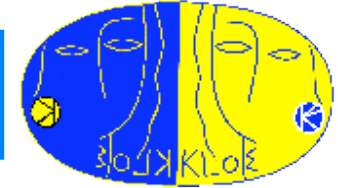


$$\sqrt{s} \approx 1.000 \text{ GeV}$$



PHOKHARA-MC modified by O. Shekhovtsova using Kaon-Loop-Model used in KLOE analysis of $\pi^0\pi^0\gamma$ final state (reference)

Conclusions



□ KLOE has performed the first precision measurement of $\sigma_{\pi\pi}$ in the region $0.35 - 0.95 \text{ GeV}^2$ with ISR (using 140 pb^{-1} of 2001 data) \rightarrow 1.3% systematic error (KLOE05, *Phys. Lett. B 606, 12 (2005)*)
- **discrepancy** between a_{μ}^{SM} and BNL experiment ($\sim 3\sigma$)

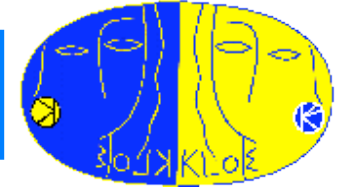
□ KLOE has presented a new measurement in 2008 (KLOE08, *Phys. Lett. B 670, 285 (2009)*) with a different data sample (242 pb^{-1} of 2002 data) using the same selection of KLOE05 (photon at small angle) \rightarrow 0.9% systematic error

- KLOE08 confirm the **discrepancy** of $\sim 3\sigma$ between a_{μ}^{SM} and a_{μ}^{EXP}
- KLOE08 $a_{\mu}^{\pi\pi}$ agrees with recent results from CMD2 and SND experiments. Reasonable agreement on the shapes

□ KLOE has presented a new measurement of $\sigma_{\pi\pi}$ (KLOE09) in the range $0.1 - 0.85 \text{ GeV}^2$ using data taken at 1.0 GeV (20 MeV below the ϕ -peak), and requiring a photon emitted at large angle \rightarrow 1.0% systematic error

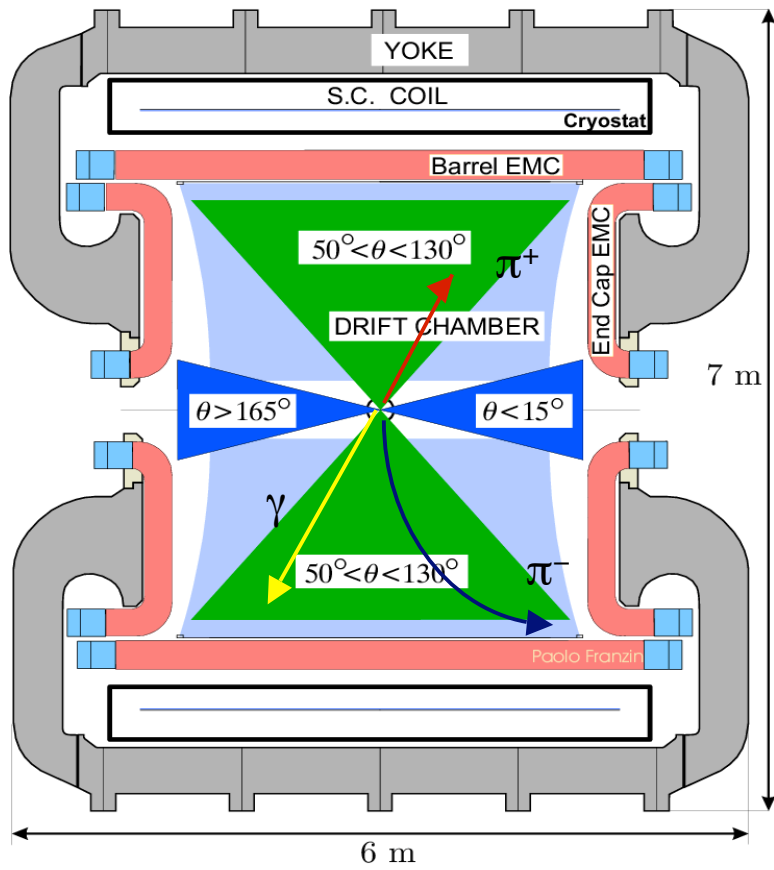
- Very good agreement with KLOE08 in the overlapping region ($0.35 - 0.85 \text{ GeV}^2$)
- Agreement within the errors with BaBar up to 0.6 GeV ; BaBar lies higher (2-3%) above

Outlook



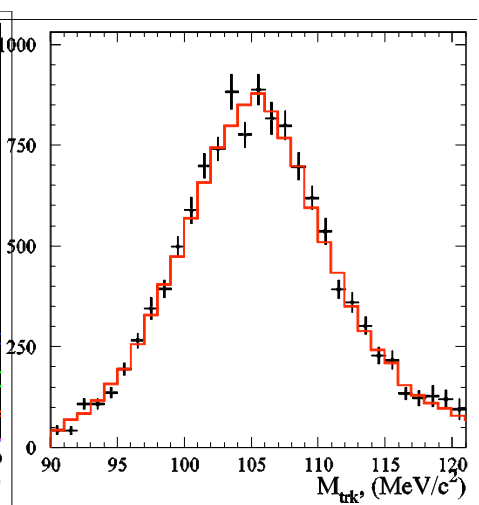
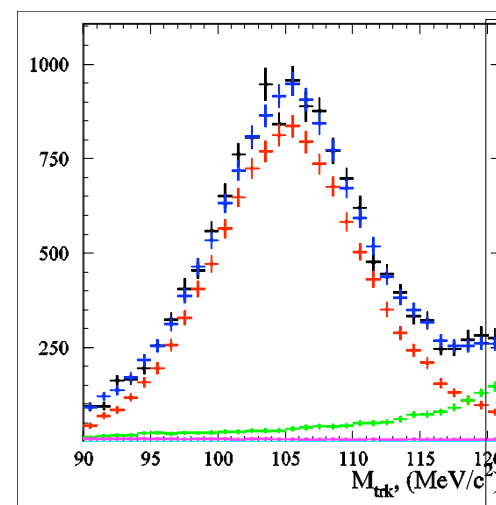
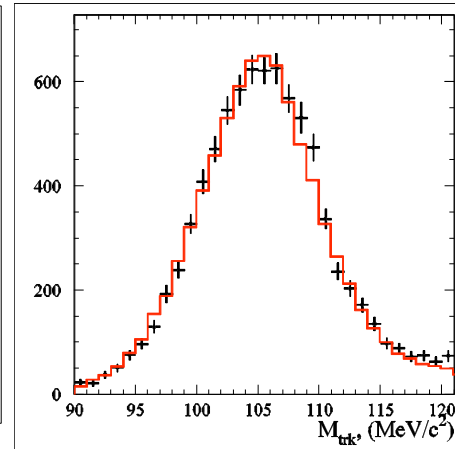
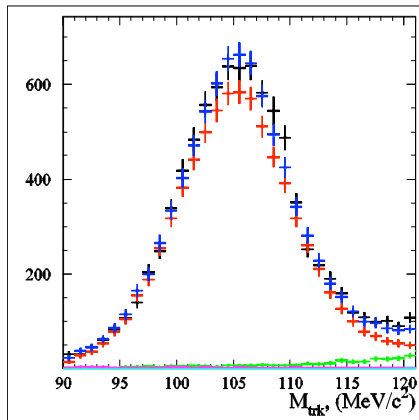
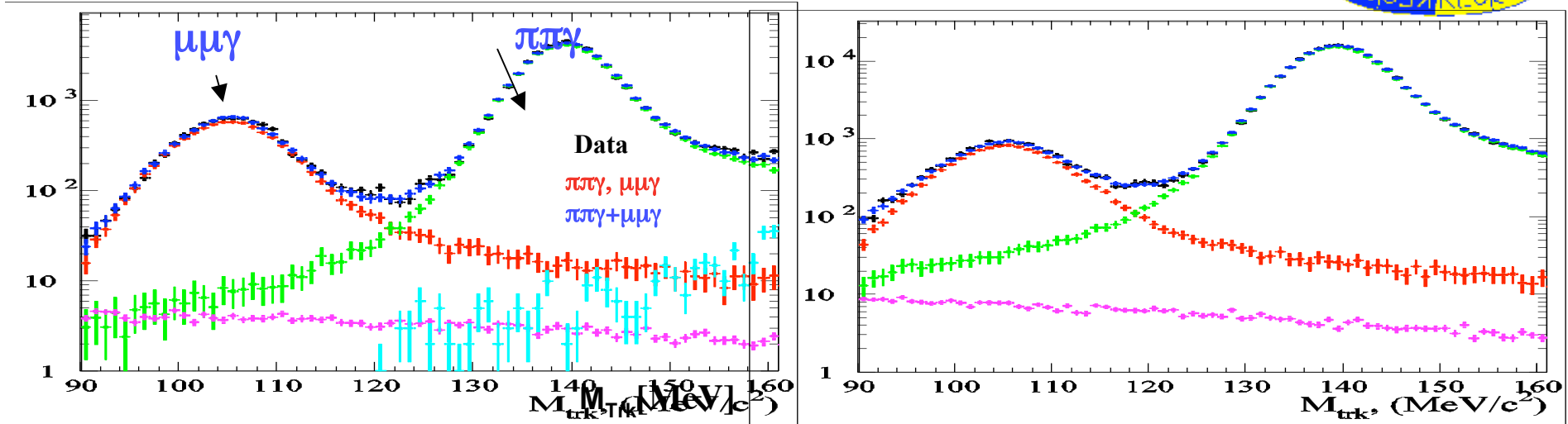
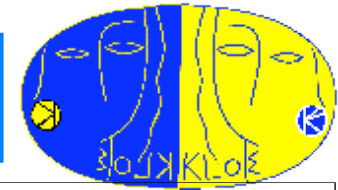
- Measurement of $\sigma_{\pi\pi}$ from $\pi\pi\gamma/\mu\mu\gamma$ ratio (as done by BaBar) in very advanced phase.
 - Comparison of $\mu\mu\gamma_{\text{DATA}}/\mu\mu\gamma_{\text{MC}}$ will provide an important consistency test for Radiator, Luminosity, FSR etc...
 - Results are expected soon.
- Check of FSR by Forward-Backward asymmetry
- Still about 1.5 fb^{-1} of KLOE from 2004/2005 data to be analyzed (3 times the statistics used up to now)
- Very important for a_{μ} also the region between **1 and 2 GeV**. Already a lot has been done from Babar and Belle with ISR, and more will come also from BES-III. To improve in statistics (and reach 1% accuracy) projects like VEPP2000 and DAFNE-2 (DAFNE upgraded in energy) will be essential.

Stay Tuned!



PARE SLIDES

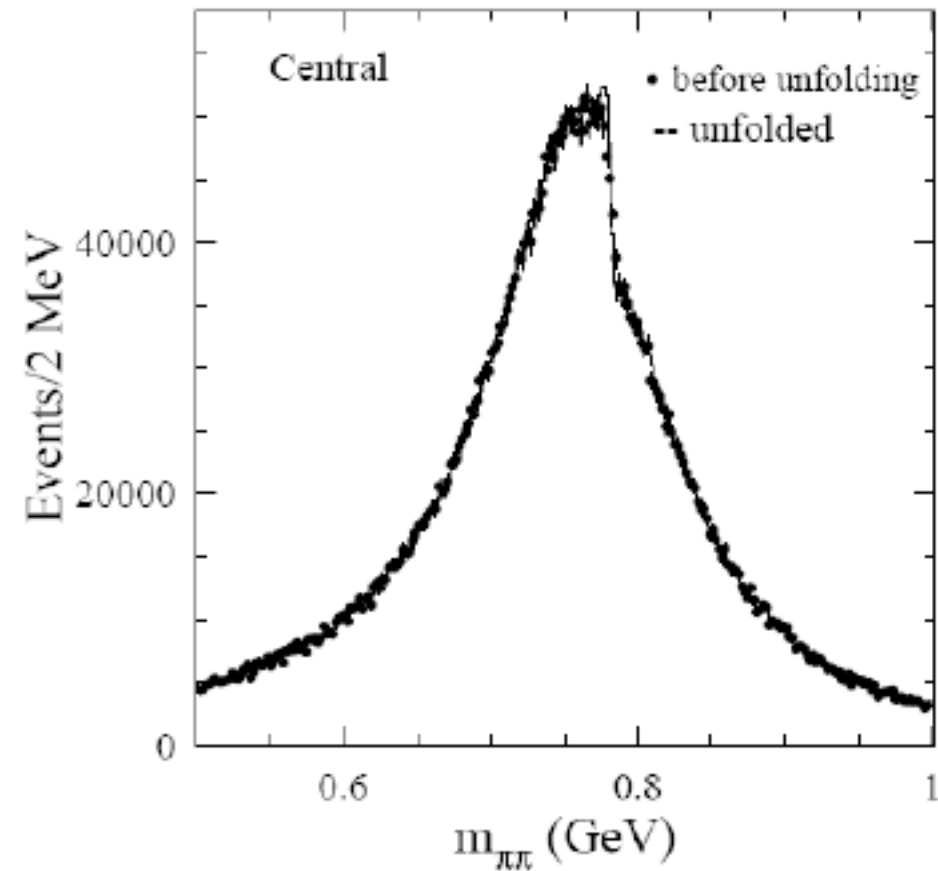
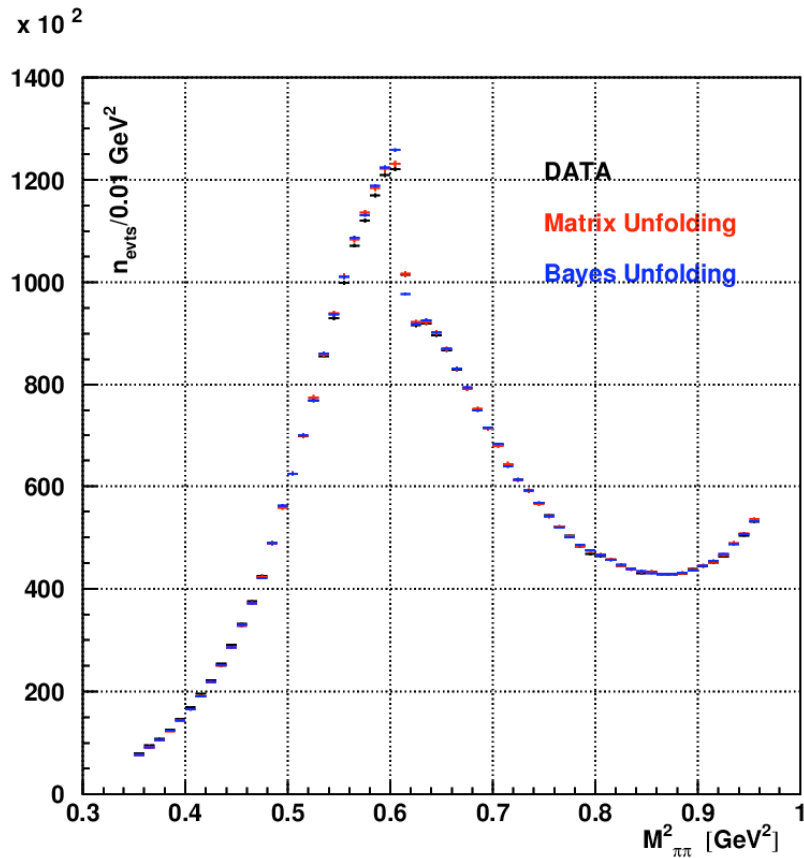
Control of M_{TRK} for muons



$$Q^2 = 0.41 \text{ GeV}^2$$

$$Q^2 = 0.55 \text{ GeV}^2$$

Unfolding: KLOE vs Babar 2π

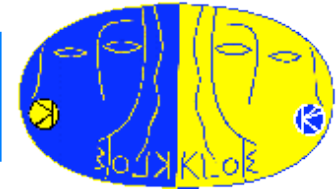


M. Davier Babar $\rho_1 \rho_1$

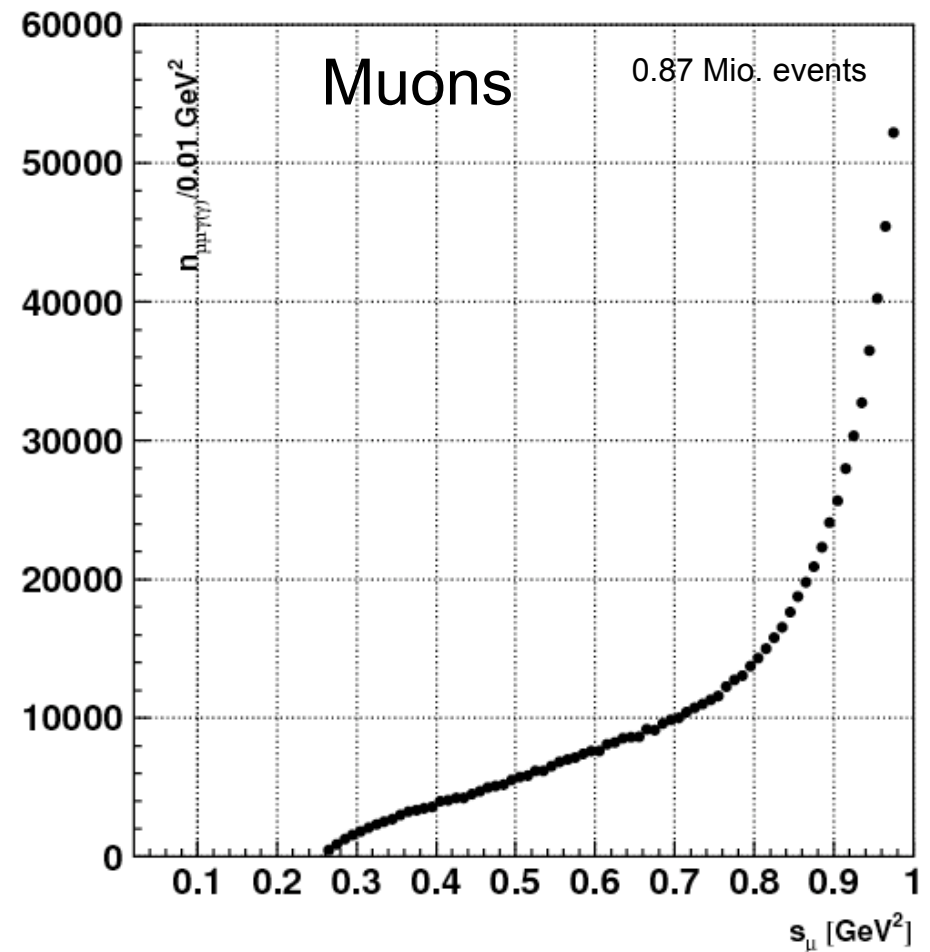
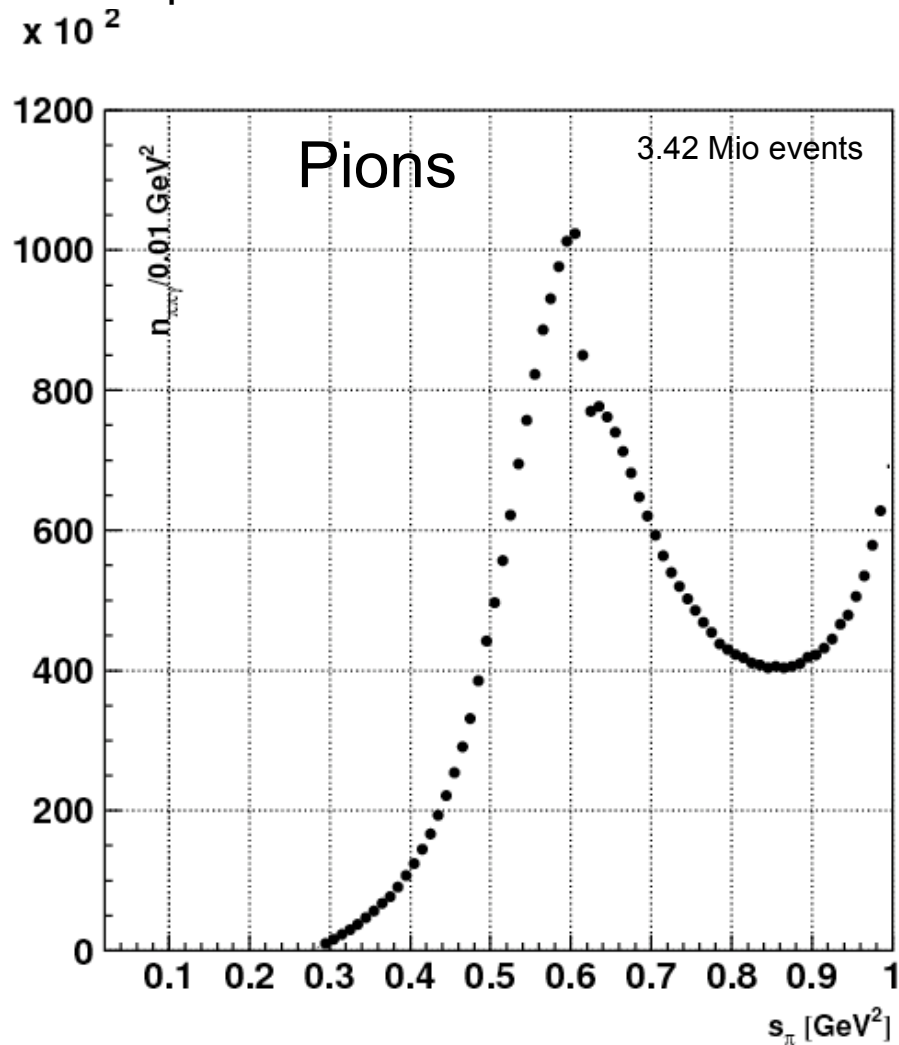
Tau08 2:

Large effect for Babar especially in the rho peak.
Essentially no effect for KLOE

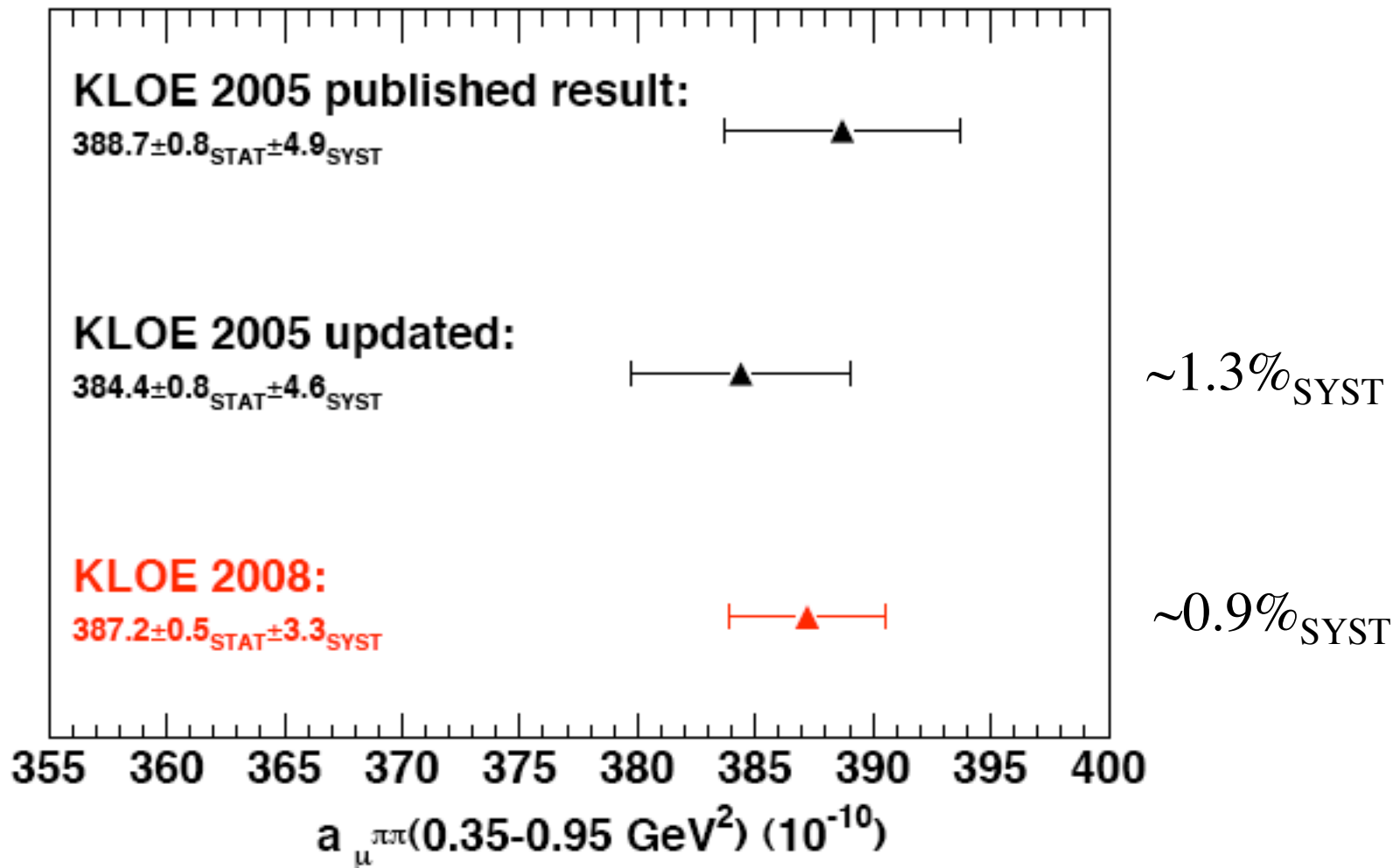
Spectra after SMA selection:



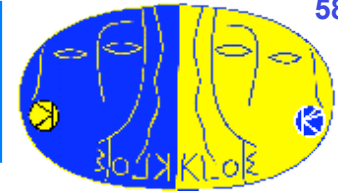
The spectra of selected events for the small angle analysis from 242.62 pb⁻¹ of data taken in 2002:



$a_{\mu}^{\pi\pi}$ from KLOE:

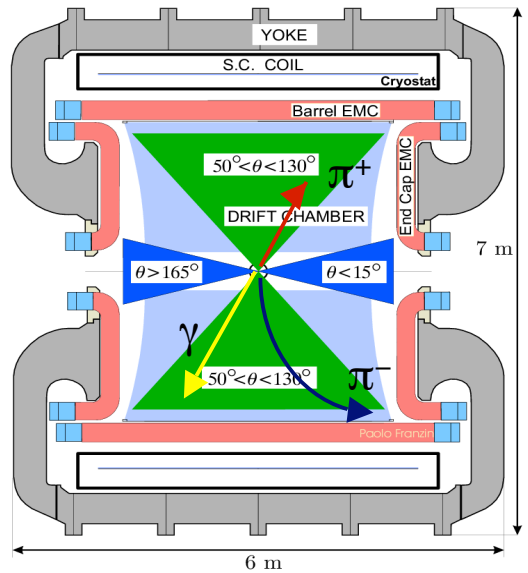


All results are in good agreement. New result has 30% better accuracy



New analysis in progress:

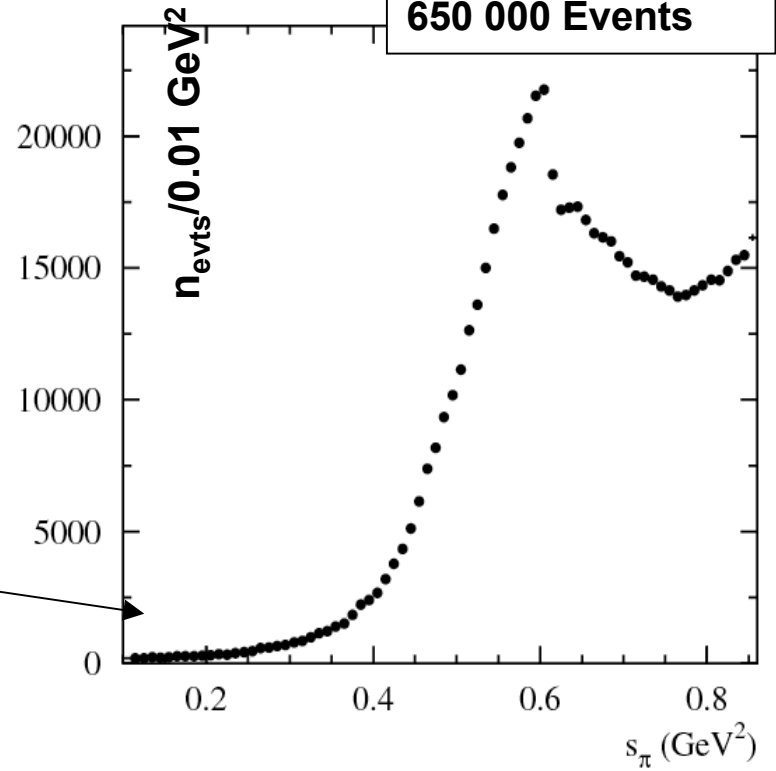
Use data sample taken at $\sqrt{s} \cong 1000$ MeV,
20 MeV below the ϕ -peak



2 pion tracks at large angles
 $50^\circ < \theta_p < 130^\circ$

Photons at large angles
 $50^\circ < \theta_\gamma < 130^\circ$

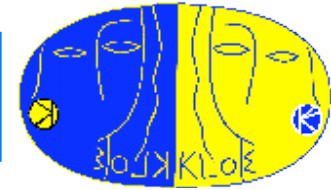
statistics: 233pb⁻¹
650 000 Events



- ✓ independent complementary analysis
- ✓ threshold region $(2m_\pi)^2$ accessible
- ✓ γ_{ISR} photon detected (4-momentum constraints)
- ✓ lower background from ϕ decays ($\phi \rightarrow f_0 \gamma \rightarrow \pi\pi \gamma, \phi \rightarrow \pi^+\pi^-\pi^0$) off-peak

Analysis very close to be finalized

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR:



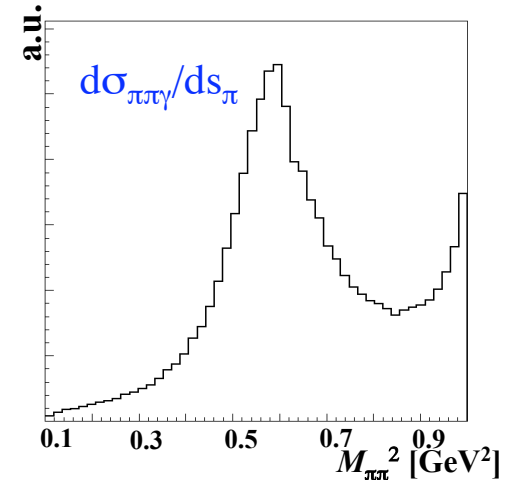
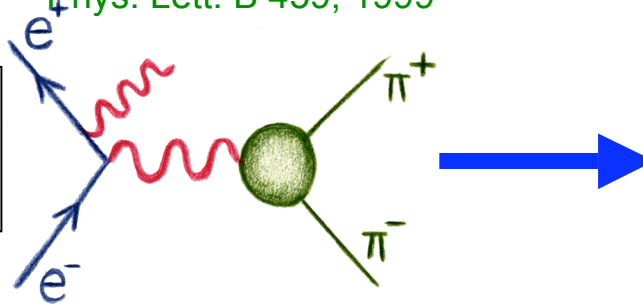
Since DAΦNE runs at fixed energy (1020 MeV), we measure the cross section $\sigma(e^+e^- \rightarrow \text{hadrons})$ as a function of the hadronic c.m. energy M_{hadr} by using

ISR ("radiative return"):

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

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

Neglecting FSR effects



$$4m_{\pi}^2 \leq s_{\pi} = M_{\pi\pi}^2 \leq m_{\phi}^2$$

This method is a complementary approach to the standard energy scan.

- Luminosity, acceptance (and other normalizations) enter only once !
- Requires precise calculations of the radiator **H**

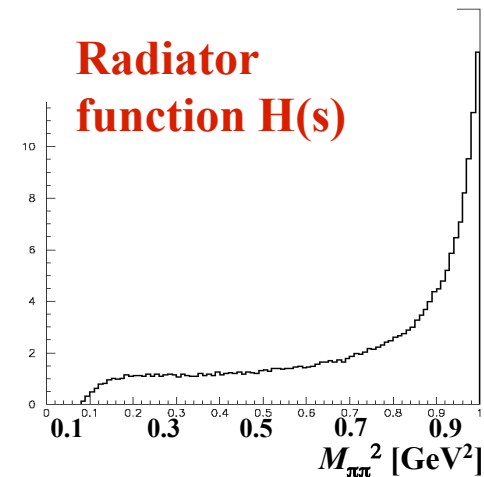
→ PHOKHARA MC NLO Generator

(H. Czyż, A. Grzebińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003)

KLOE has published the first precision measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR, using 2001 data (140pb⁻¹)

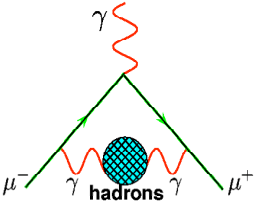
PLB606(2005)12

⇒ **~3σ discrepancy on a_{μ} between SM and BNL exp**



$a_{\mu}^{\text{had,LO}}$

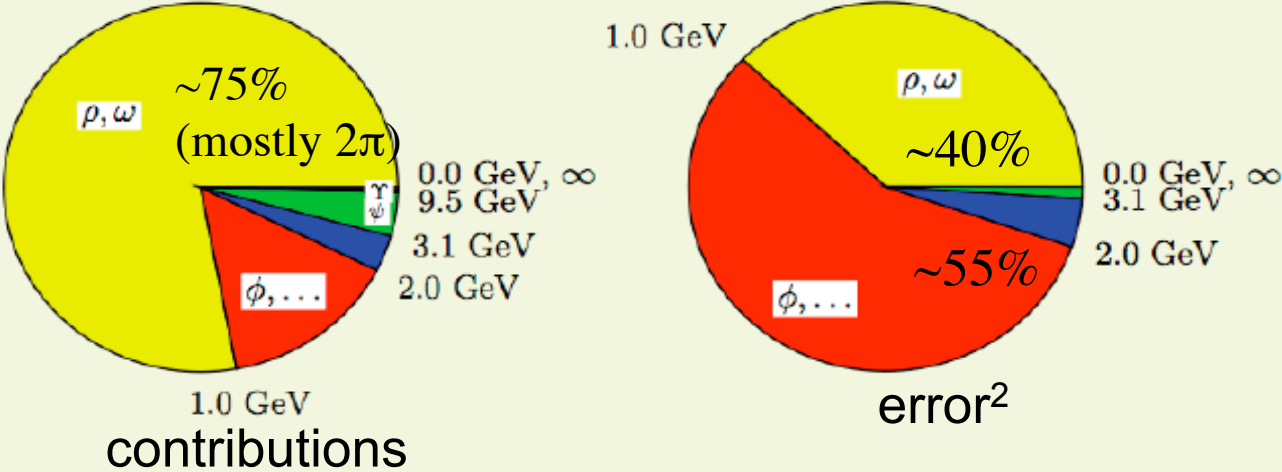
Hadronic contribution to a_{μ} can be estimated by means of a dispersion integral on e^+e^- data:



$$a_{\mu}^{\text{had,lo}} = \frac{1}{4\pi^3} \int_{4m_{\pi}^2}^{\infty} \sigma_{e^+e^- \rightarrow \text{hadr}}(s) K(s) ds$$

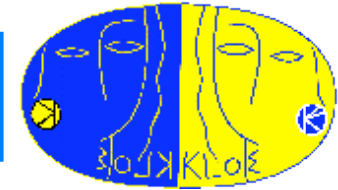
$K(S) \sim 1/s$; it emphasizes the role of low energies; particular important is the reaction $e^+e^- \rightarrow \pi^+\pi^-$ (below 1 GeV, contributes to $\sim 70\%$ to a_{μ}^{had})

F. Jegerlehner, Talk at PHIPSI08



σ_{HAD} traditionally measured by an energy scan (CMD-2/SND). At KLOE we use ISR to scan the energy below the ϕ peak

Correcting for γ_{FSR} energy:



Go from $M^2_{\pi\pi} \rightarrow S_{\gamma^*}$

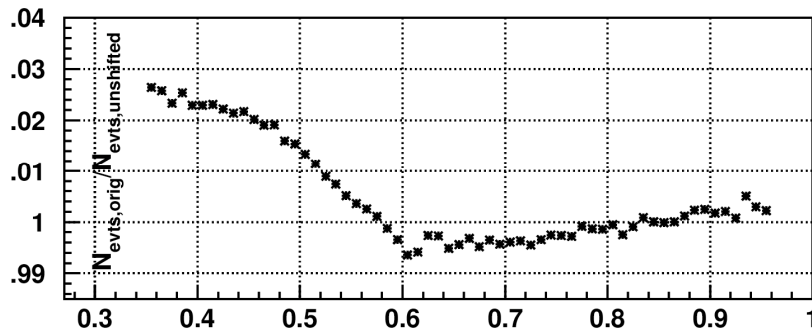
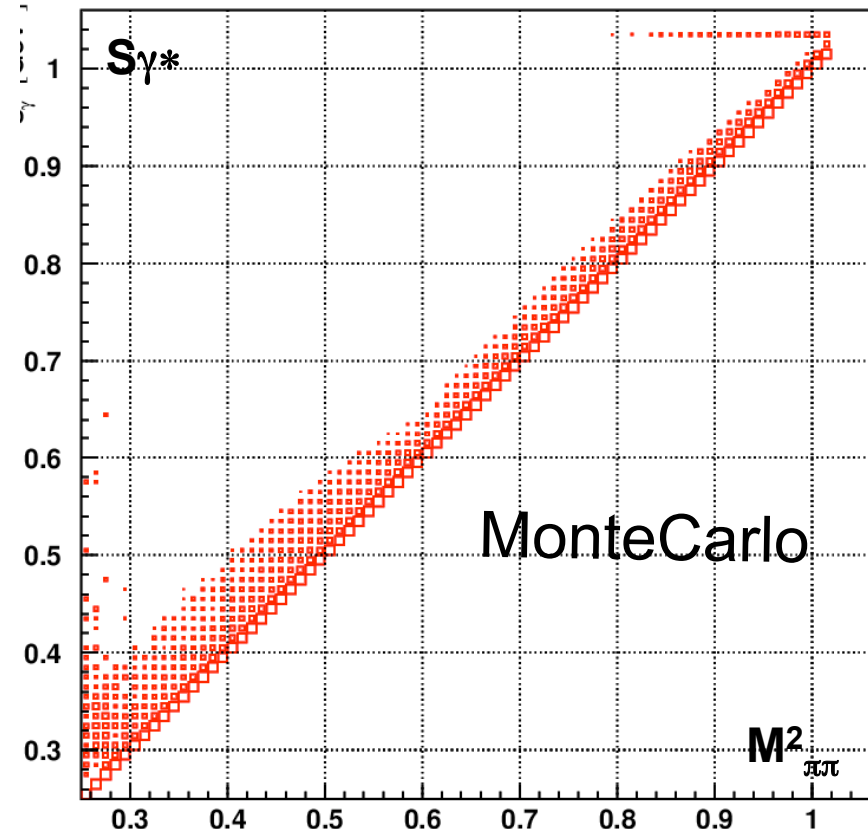
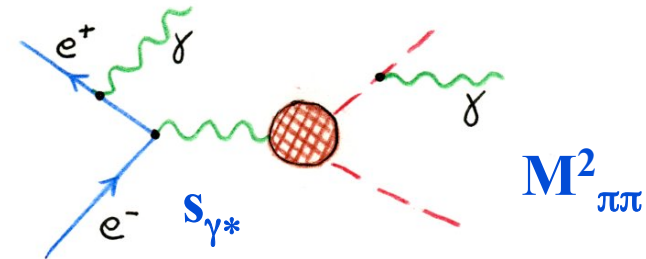
The presence of γ_{FSR} results in a shift of the measured quantity $M^2_{\pi\pi}$ towards lower values:

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

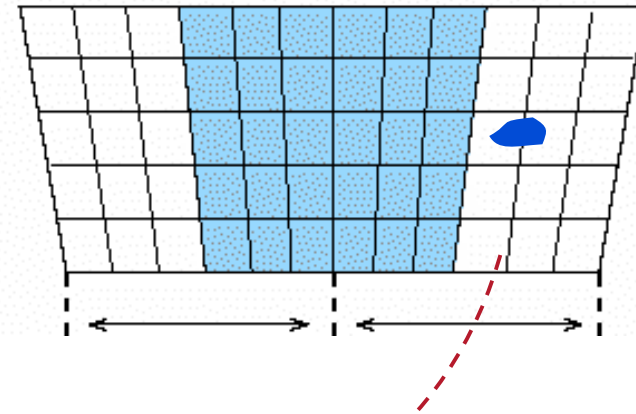
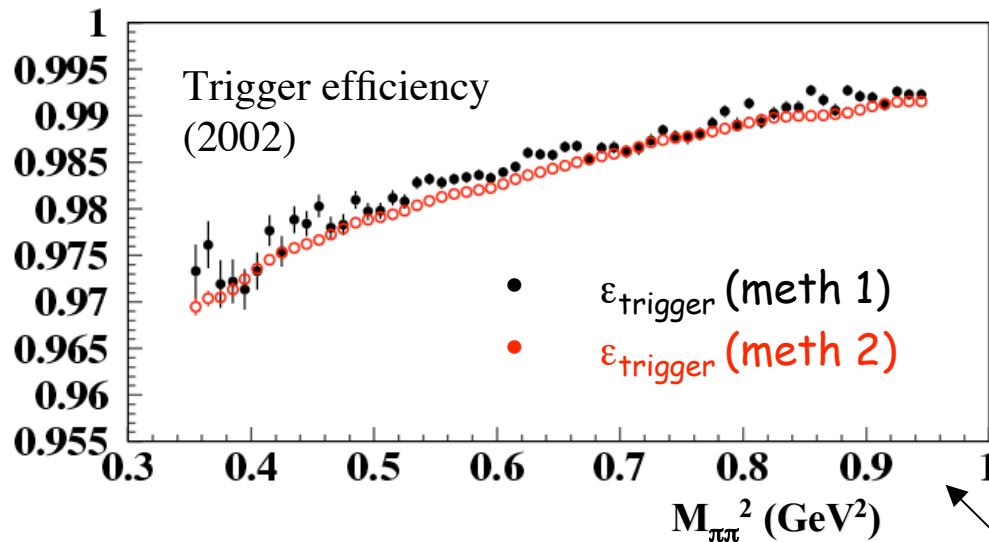
Use special version of PHOKHARA which allows to determine whether photon comes from initial or final state \rightarrow build matrix which relates $M^2_{\pi\pi}$ to $M^2_{\gamma^*}$.

ISR only: $S_{\gamma^*} = M^2_{\pi\pi}$

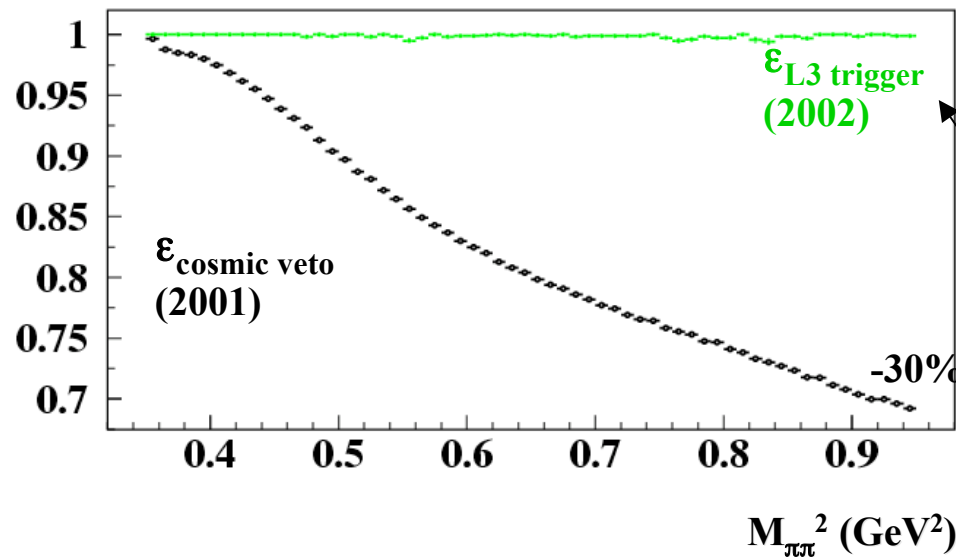
FSR photon present: $S_{\gamma^*} = M^2_{\pi\pi\gamma(\text{FSR})}$



Trigger



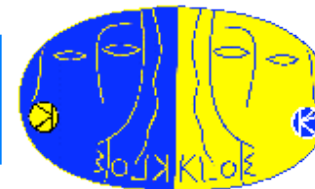
- The event is **triggered** by the (pion) tracks only which deposit $E > 50$ MeV in 2 sectors of the calorimeter



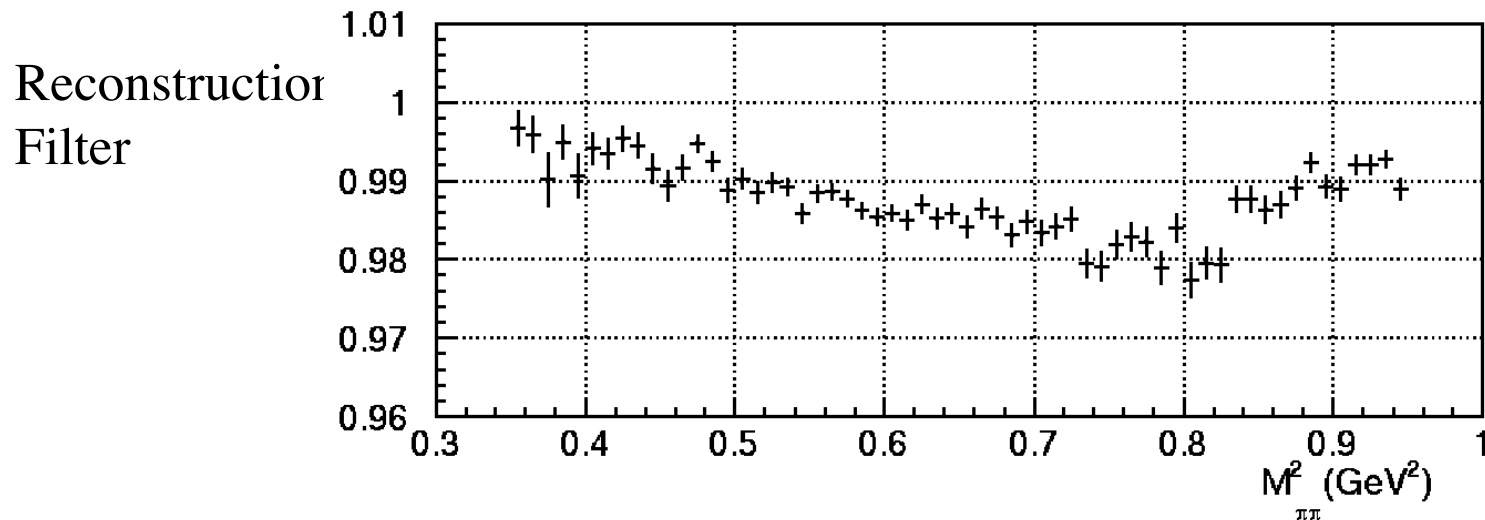
- trigger efficiency evaluated on data by 2 independent methods.
- Error is the fractional difference of the 2 methods: 0.1%

- The main source (**hardware veto of cosmic rays**) of inefficiency in the published result **has been replaced by an online filter (L3)**

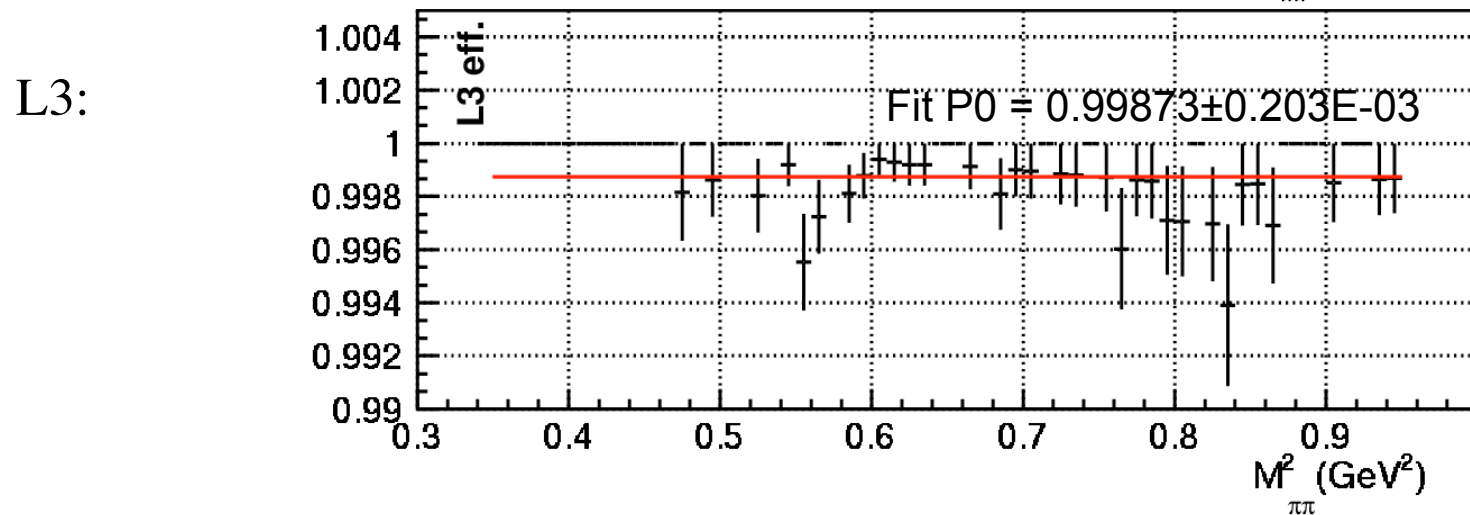
Reconstruction and L3 filters:



Both efficiencies estimated via downscaled control samples:

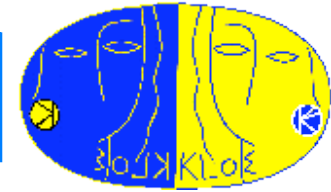


$\sim 2\%$

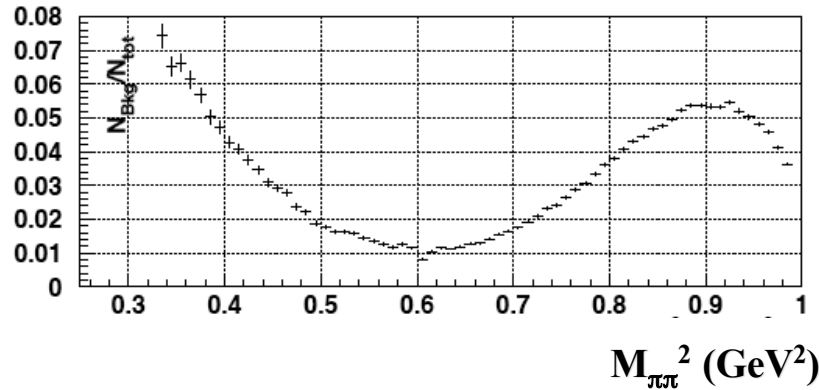


0.1% taken as uncertainty on the spectrum due to L3 trigger.

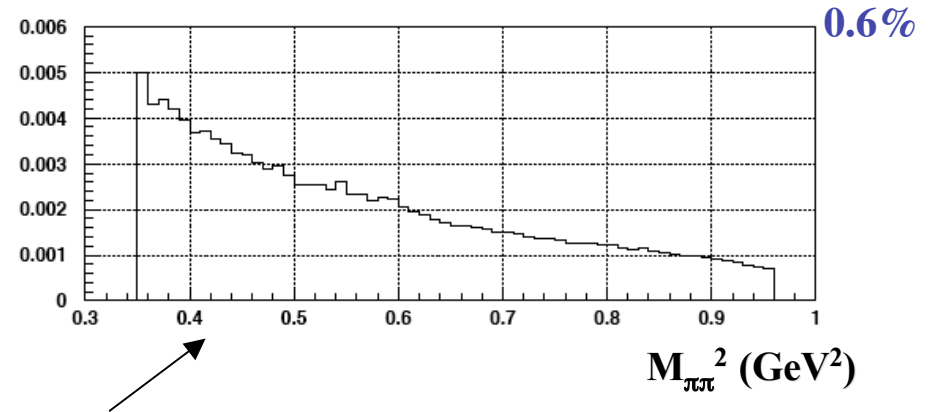
Background: total contribution and error



Tot bckg ($\mu\mu\gamma$, $\pi\pi\pi$ and $ee\gamma$) contribution **Error on bckg subtraction (in %)**



8%



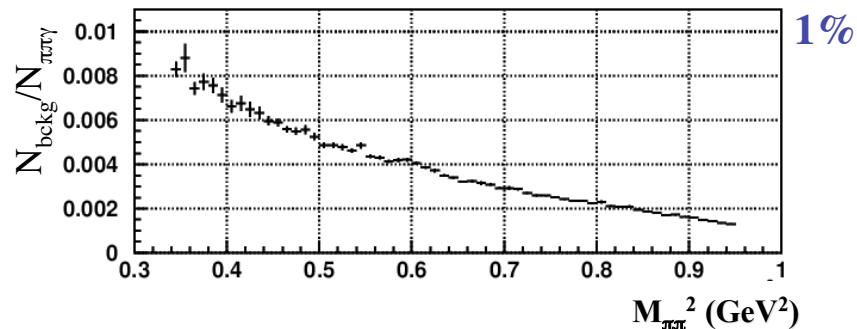
0.6%

Additional bckg channels:

- $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ (Ekhara) $\sim 0.8\%$ at low $M_{\pi\pi}^2$
- $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (Nextcalibur) negligible
- $\phi \rightarrow f_0\gamma \rightarrow \pi\pi\gamma$ (Phokhara, Fasterd) negligible
- $\phi \rightarrow \pi\rho \rightarrow \pi\pi\gamma$ (Phokhara, Fasterd) negligible
- $e^+e^- \rightarrow \omega\gamma_{ISR} \rightarrow \pi\pi\pi\gamma$ (Phokhara) negligible

Contribution to Bckg error :

- Uncertainty on $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ contribution
- Error from normalization parameters obtained from the fit



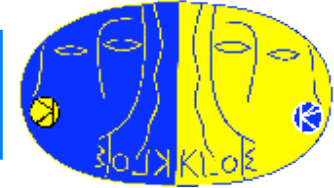
“Phokhara”: see talk of A. Grzielinska

“Ekhara”: C.zyz *et al*

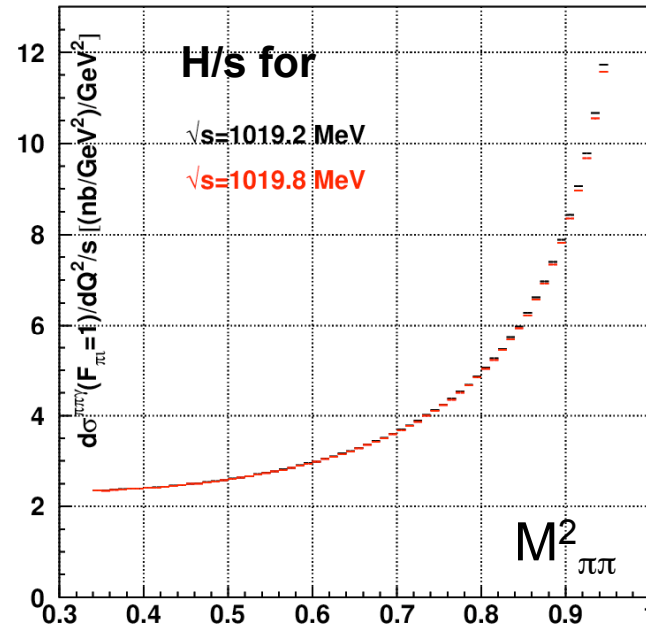
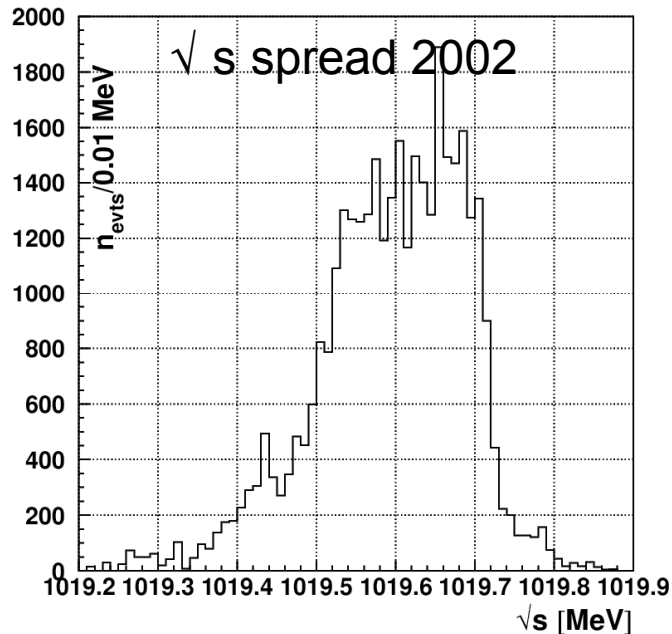
“Nextcalibur” : F.A. Berends *et al*

“Fasterd”: O. Shekhotvsova *et al*

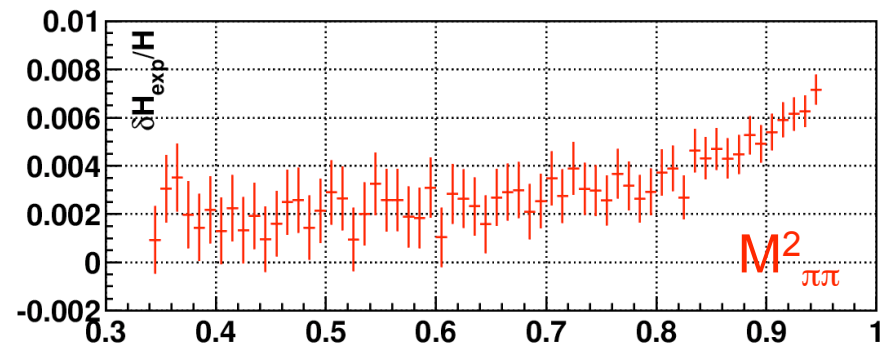
Radiator function (H)



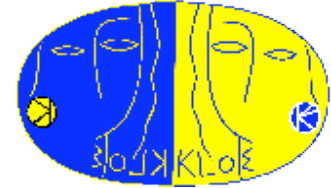
In addition to the 0.5% theoretical error we evaluate the experimental uncertainty due to the spread in \sqrt{s} during the data taking in 2002 (since we evaluated H at the fixed energy $\sqrt{s} = 1.019456$ GeV)



We take half the rel. difference between the radiator functions obtained at $\sqrt{s} = 1.0192$ GeV and $\sqrt{s} = 1.0198$ GeV as the experimental syst. uncertainty on the radiator function.

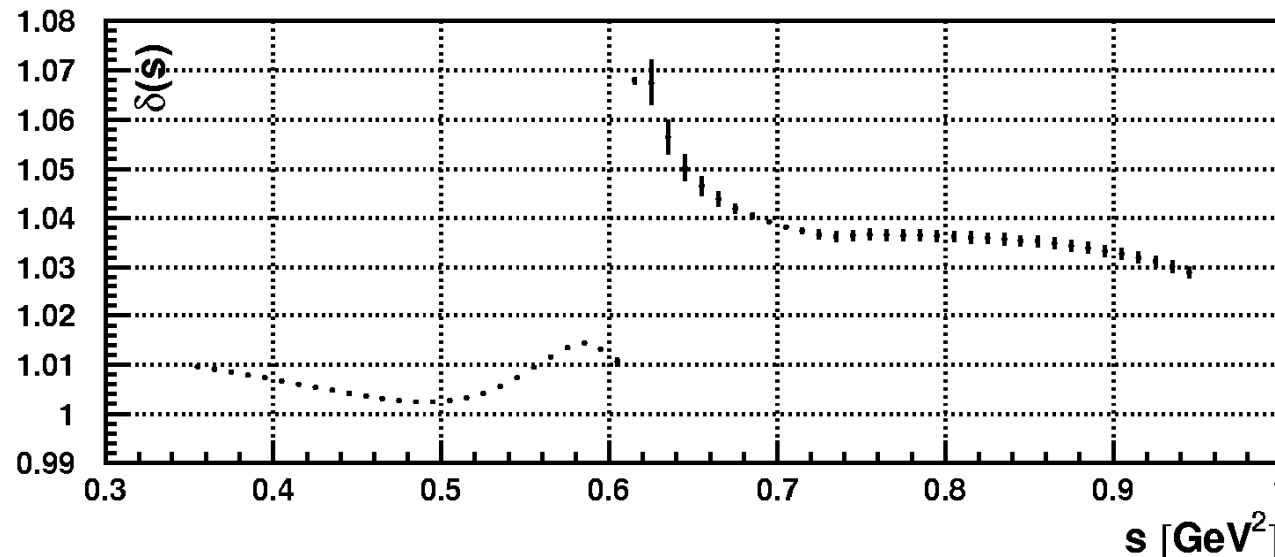


Vacuum Polarisation



For use in the dispersive integral for $\Delta^{\pi\pi}a_\mu$, one needs to subtract effects from vacuum polarization (VP) to obtain a *bare* cross section $\sigma_{\pi\pi}^0$:

$$\sigma_{\pi\pi}^0(s) = \sigma^{\text{dressed}}_{\pi\pi}(s) \left(\frac{\alpha(0)}{\alpha(s)} \right)^2 = \sigma_{\pi\pi}(s) / \delta(s)$$

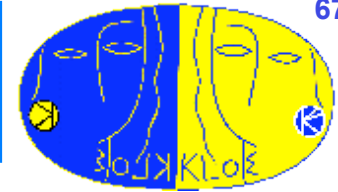


Points obtained from F. Jegerlehner's webpage
(the only points which are publicly available!)

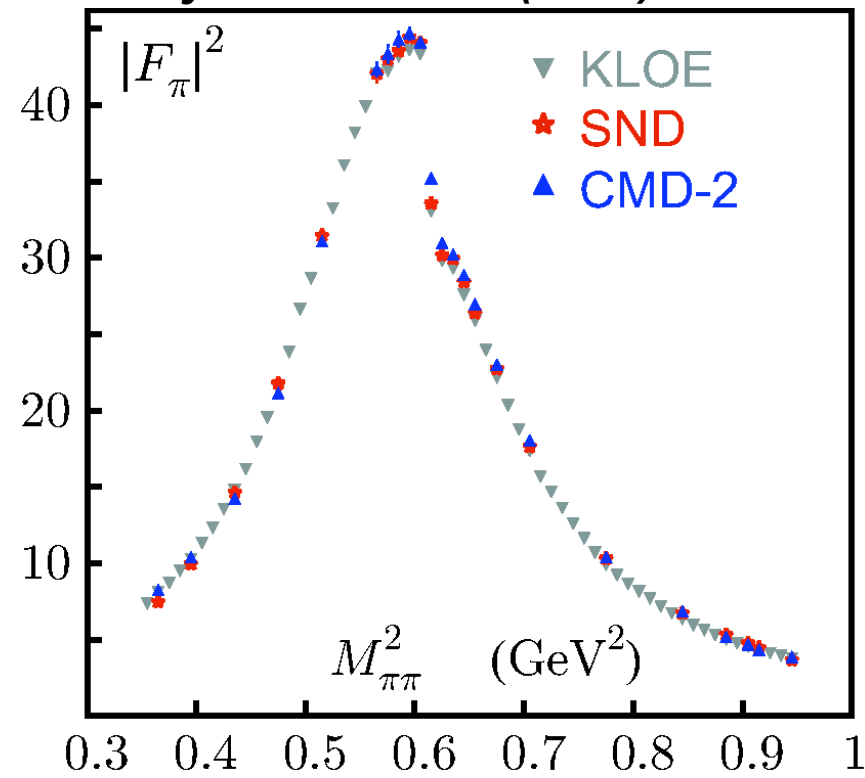
Correction is applied only to the cross section $\sigma_{\pi\pi}^0$ (not on $\sigma_{\pi\pi\gamma}$ and $|F_\pi|^2$).

Error on VP points introduces an relative error on the value of $\Delta^{\pi\pi}a_\mu$ of 0.1%.

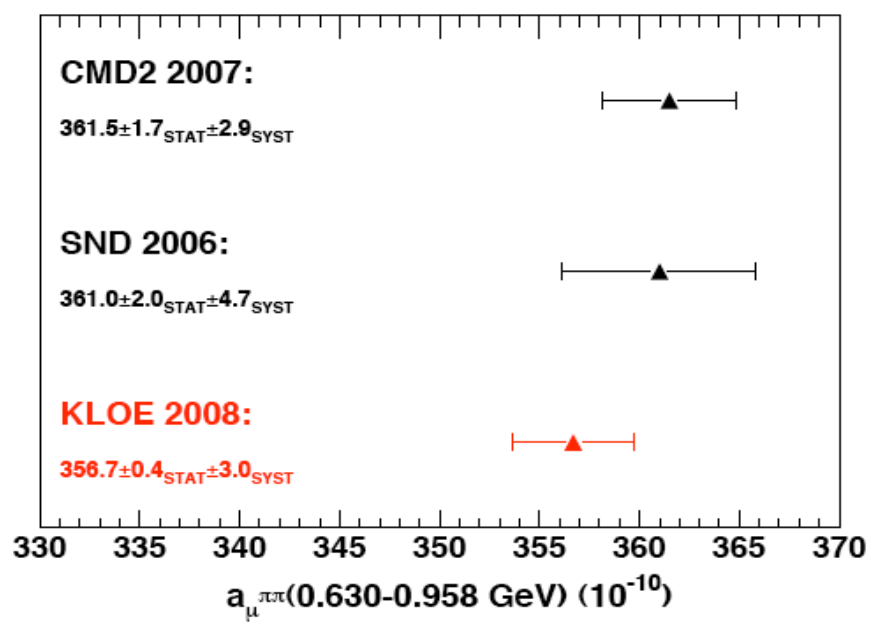
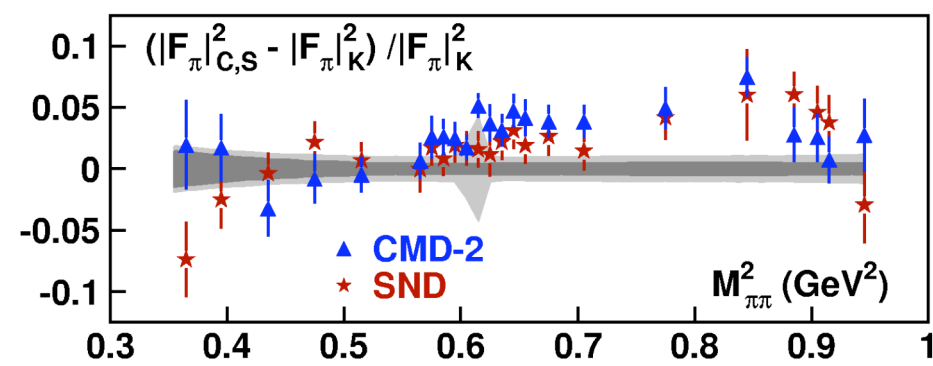
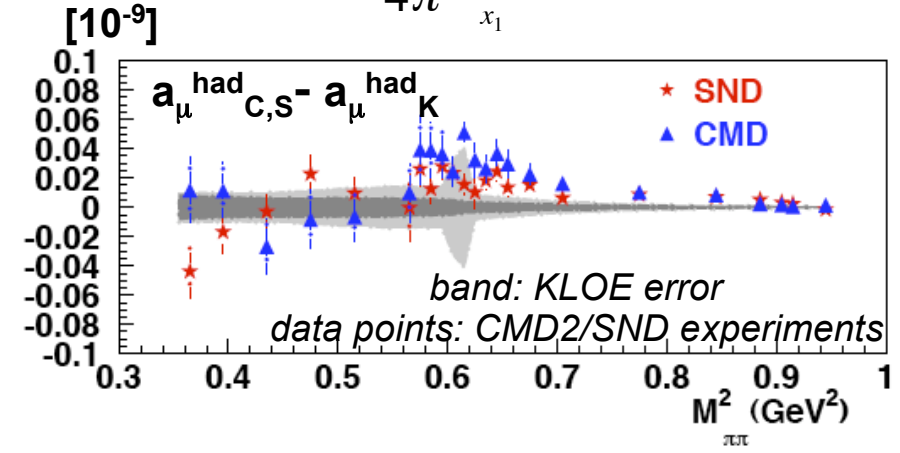
$|F_\pi|^2$ and $a_\mu^{2\pi}$ KLOE vs CMD2/SND



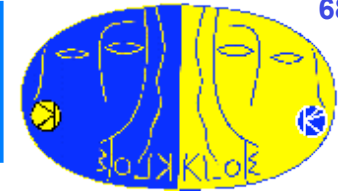
Phys. Lett. B 670 (2009) 285



abs. contr. to $a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{x_1}^{x_2} \sigma^{\text{had}}(s) K(s) ds$ per bin:

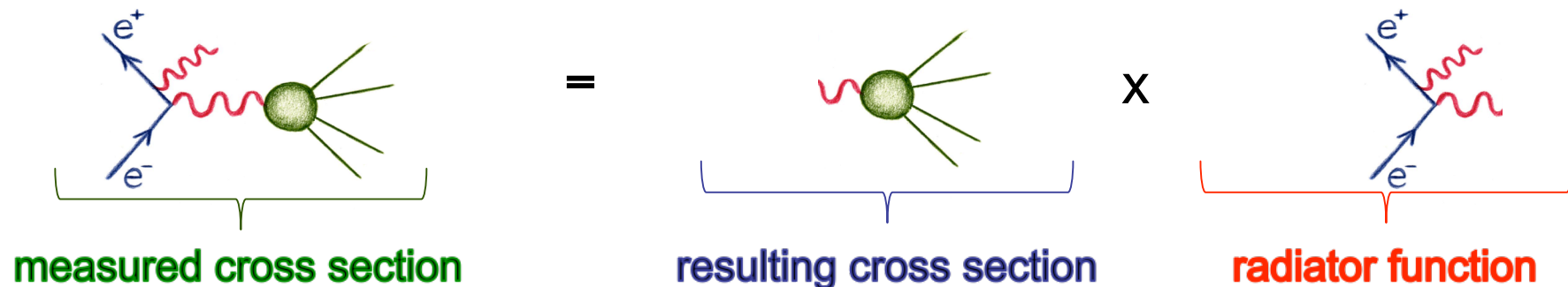


ISR: Initial state radiation



Neglecting final state radiation (FSR) terms, one can relate the measured differential cross section $d\sigma_{\text{hadr}+\gamma}/dM_{\text{hadr}}^2$ to the hadronic cross section σ_{hadr} using the radiation function $H(s, M_{\text{hadr}}^2)$:

$$\frac{d\sigma(e^+ e^- \rightarrow \text{hadrons} + \gamma)}{dM_{\text{hadr}}^2} = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons}, M_{\text{hadr}}^2)}{s} H(s, M_{\text{hadr}}^2)$$



Theoretical input: precise calculation of the radiation function $H(s, M_{\text{hadr}}^2)$

→ **EVA + PHOKHARA MC Generator**

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

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

(exact next-to-leading order QED calculation of the radiator function)

IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR, using 2001 data (140pb^{-1}) PLB606(2005)12

⇒ $\sim 3\sigma$ discrepancy on a_μ between SM and BNL exp