Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and the dipion contribution to the muon anomaly with the KLOE detector

Phys. Lett. B 670, 285 (2009)

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Outlook

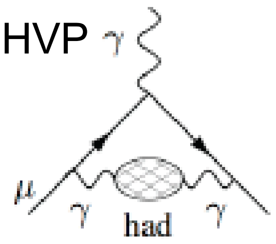
- Hadronic contribution to a_μ and ISR measurement ("Radiative Return")
- New KLOE measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ via ISR (KLOE08)
- Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND
- Conclusion & Outlook

Muon anomaly

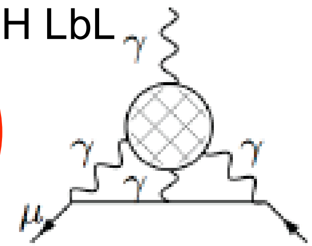
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

• Long established discrepancy (>3σ) between SM prediction and BNL E821 experiment
•Theoretical error δa_μ^{SM} (~6x10^{-10}) dominated by LO HVP (4÷5^{-10}) and HLbL(2.5÷4)
•Experimental error δa_μ^{EXP} ~6 x10^{-10} (E821). Plan to reduce it to 1.5 10^{-10} (new g-2 experiment @FNAL)

LO HVP



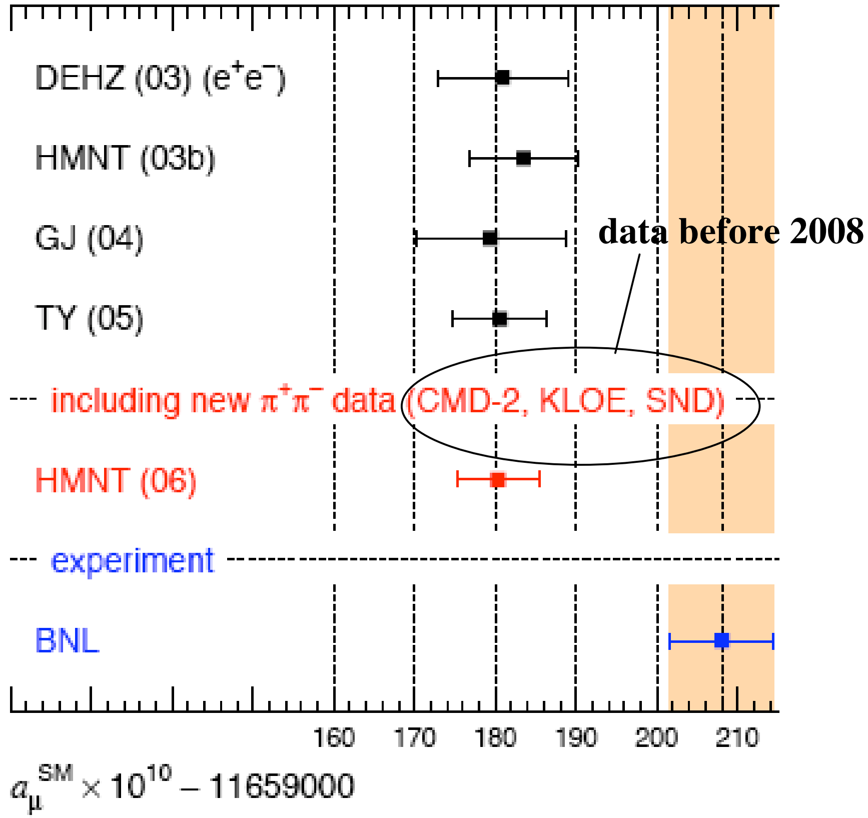
H LbL



$a_\mu^{had,LO}$ = (690.9±**4.4**)10^{-10}
[Eidelman, TAU08]

$a_\mu^{had,LbL}$ ~ (11 ±4)10^{-10}
=10.5±2.6
[Prades, de Rafael & A. Vainshstein 08]

a_μ^{SM} compared to BNL world av.

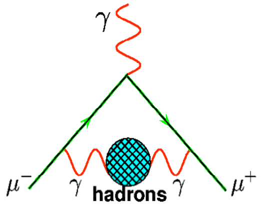


$$a_\mu^{EXP} - a_\mu^{TH} = (27.6 \pm 8.1) \cdot 10^{-10}, \quad \sim 3.4\sigma$$

T.Teubner, PHIPSI08

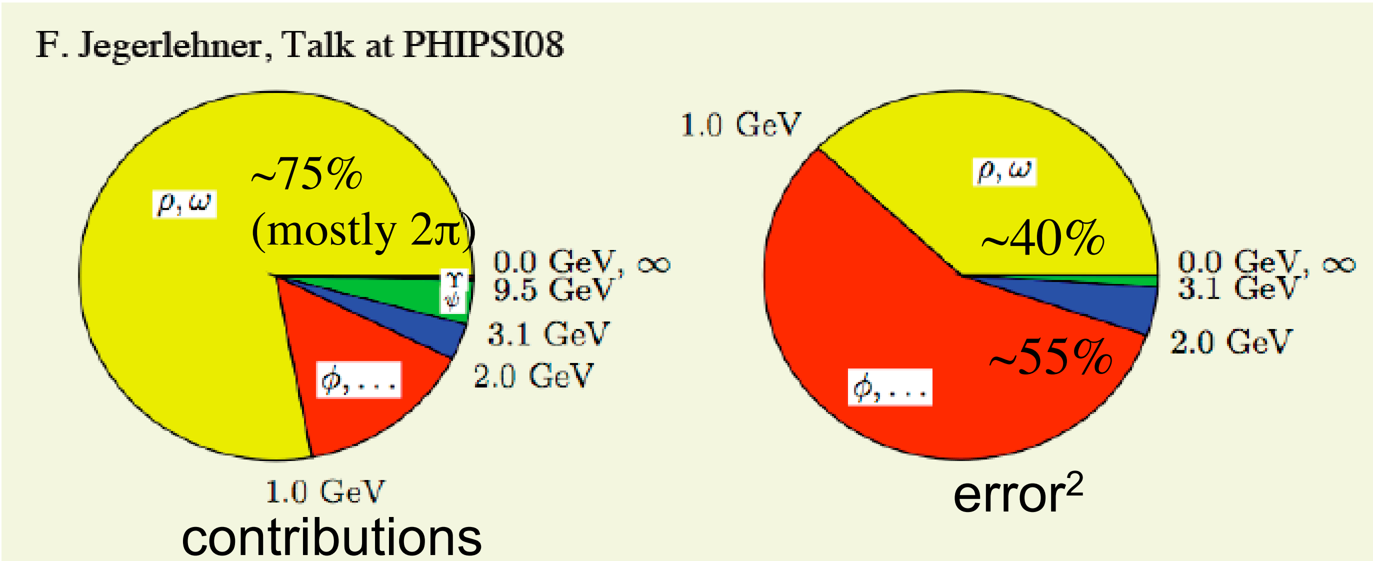
$a_\mu^{had,LO}$:

Hadronic contribution to a_μ can be estimated by means of a dispersion integral on e^+e^- data:



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

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



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

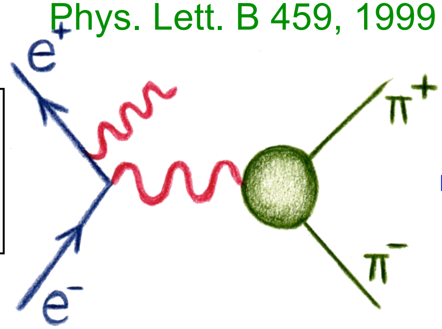
$\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ with ISR:

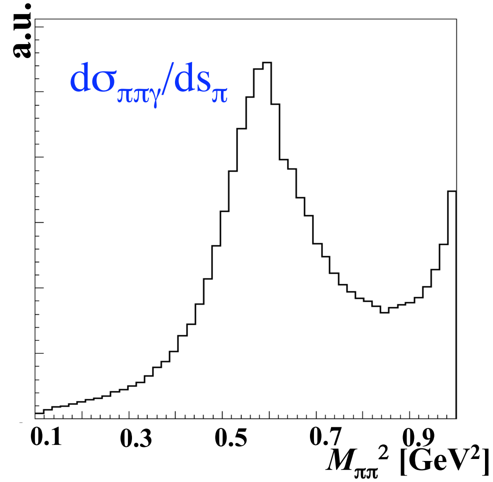
Since DAΦNE runs at fixed energy (1020 MeV), we measure the cross section $\sigma(e^+ e^- \rightarrow hadrons)$ as a function of the hadronic c.m. energy M_{hadr} by using ISR ***("radiative return")***:

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

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

Neglecting FSR effects





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

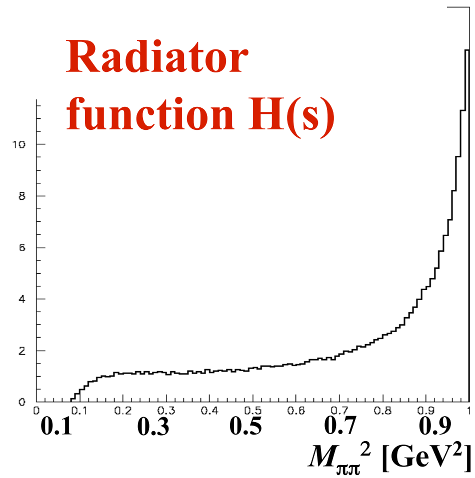
This method is a **complementary approach** to the standard energy scan.

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

➔ **PHOKHARA MC NLO Generator**

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

Radiator function H(s)

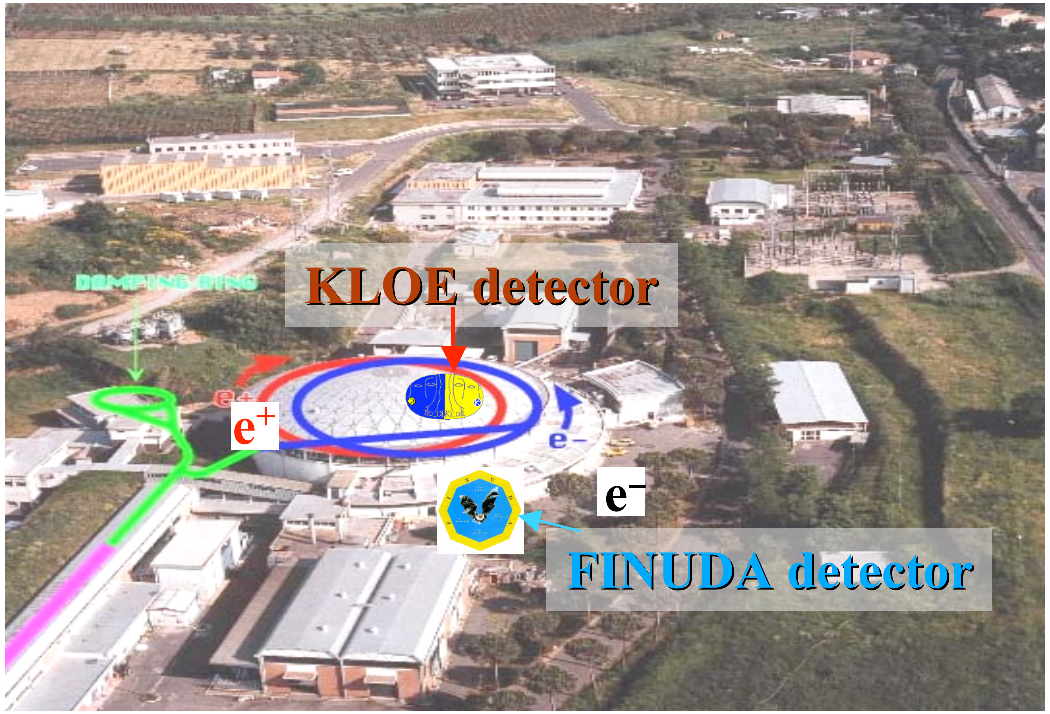


KLOE has published a first measurement of $\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ with ISR, using 2001 data (140pb^{-1}) PLB606(2005)12

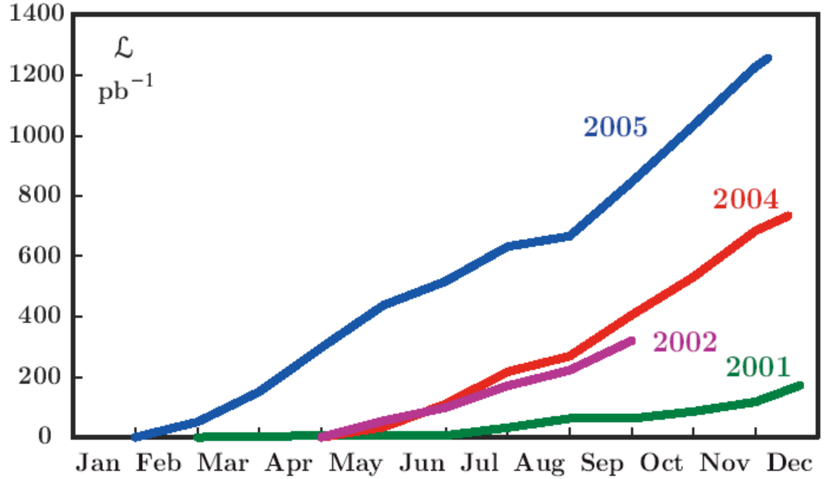
⇒ ~3σ discrepancy on a_μ between SM and BNL exp

DAΦNE: A Φ-Factory

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



Integrated Luminosity



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

Our published results (PLB606(2005)12) were based on $140pb^{-1}$ of 2001 data!

Total KLOE int. Luminosity:

$\int \mathcal{L}\, dt \sim 2500\ pb^{-1}$ (2001 - 05)

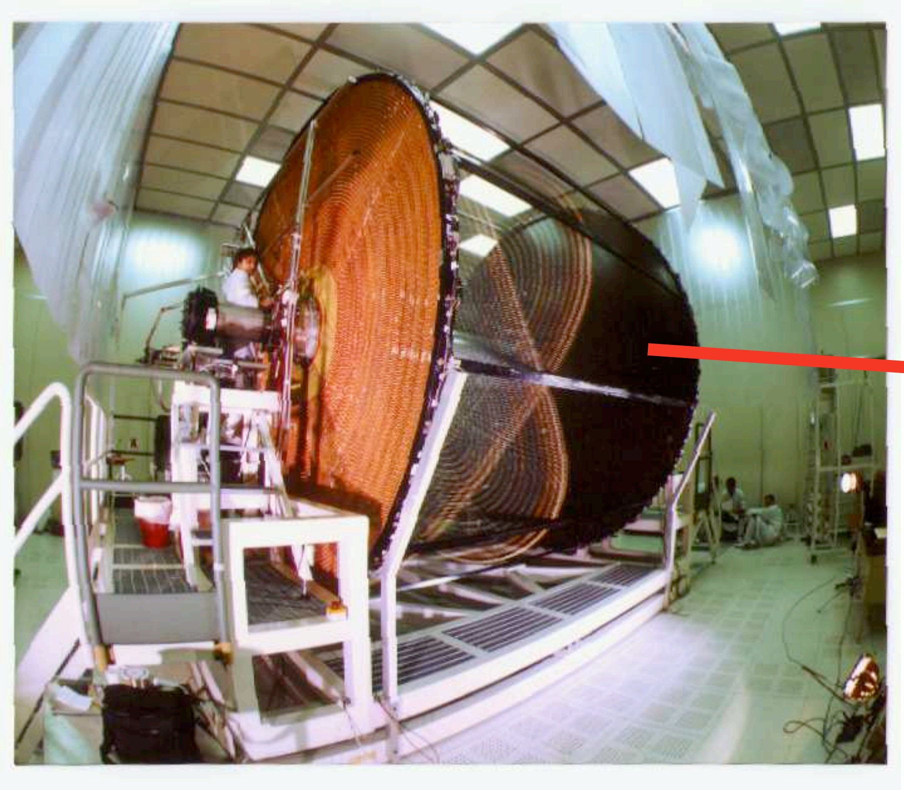
Our new results (2008) are based on $240pb^{-1}$ from 2002 data!

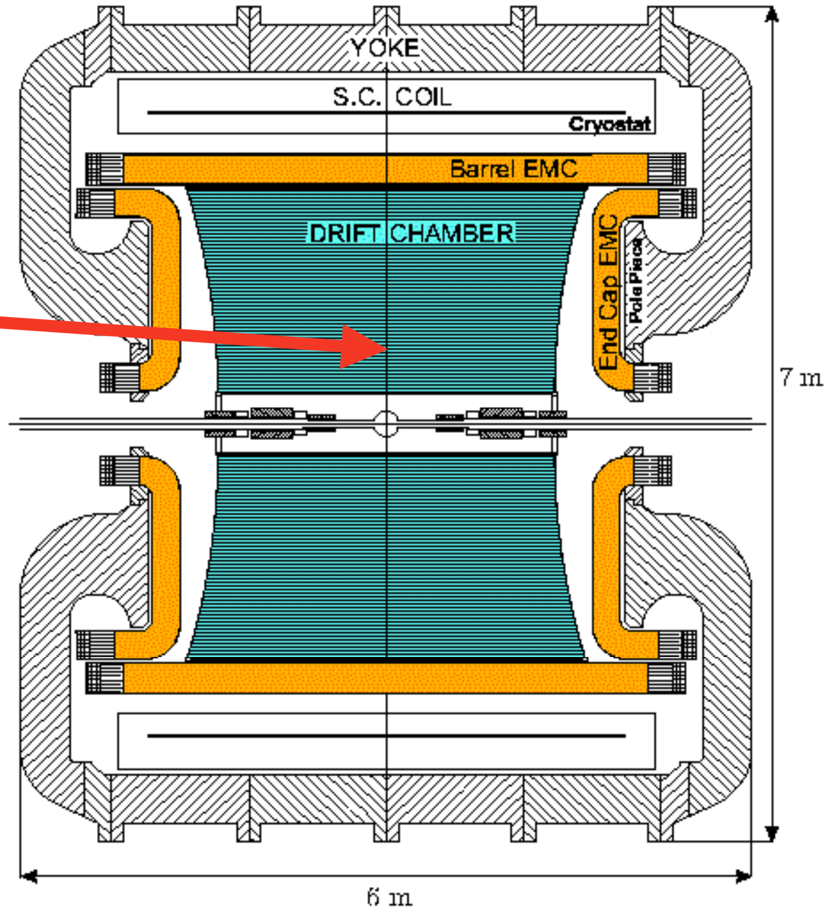
2006:

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

KLOE Detector

Drift chamber





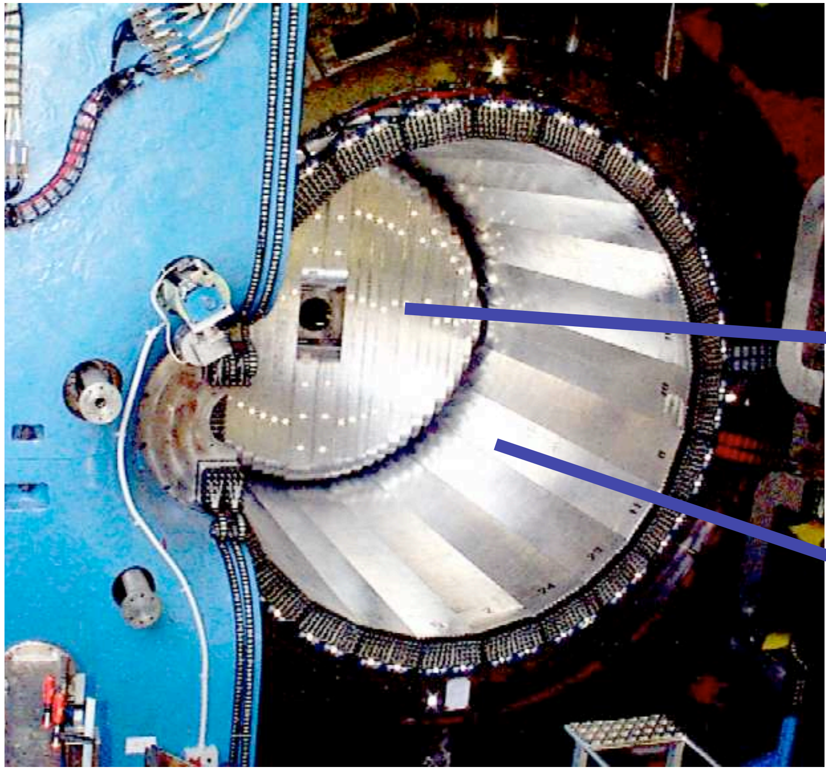
σ_p/p = 0.4% (for 90^0 tracks)

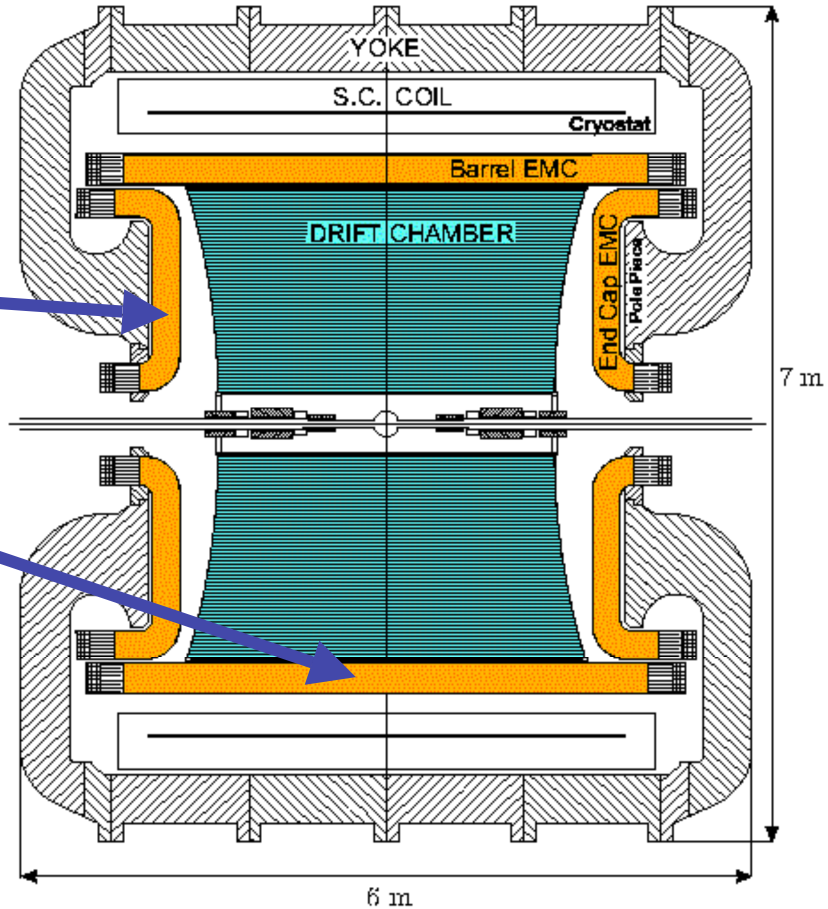
$\sigma_{xy} \approx 150\ \mu m$, $\sigma_z \approx 2$ mm

Excellent momentum resolution

KLOE Detector

Electromagnetic Calorimeter





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

$\sigma_T = 54\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$

(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)

$$\frac{d\sigma^{obs}_{\pi\pi\gamma(\gamma)}}{dM^2_{\pi\pi}} = \frac{\Delta N_{\text{Obs}} - \Delta N_{\text{Bkg}}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon_{\text{Sel}}} \cdot \frac{1}{\int L dt}$$

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

2)

$$\sigma_{\pi\pi}(\mathrm{s}) \approx s \frac{d\sigma^{obs}_{\pi\pi\gamma(\gamma)}}{dM^2_{\pi\pi}} \cdot \frac{1}{H(\mathrm{s})}$$

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

3)

$$|\mathrm{F}_\pi|^2 = \frac{3s}{\pi\alpha^2\beta^3_\pi}\sigma_{\pi\pi}(\mathrm{s})$$

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 progress)*

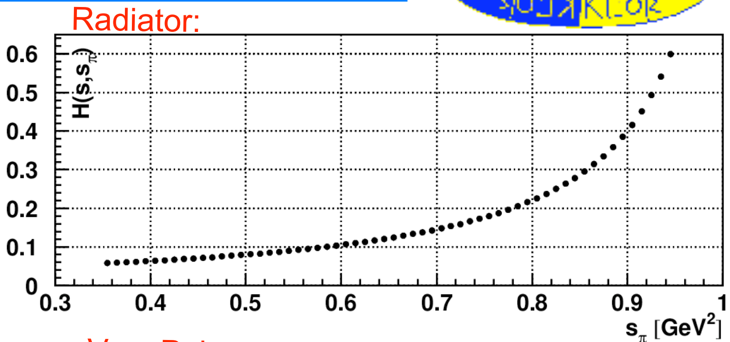
Radiative Corrections

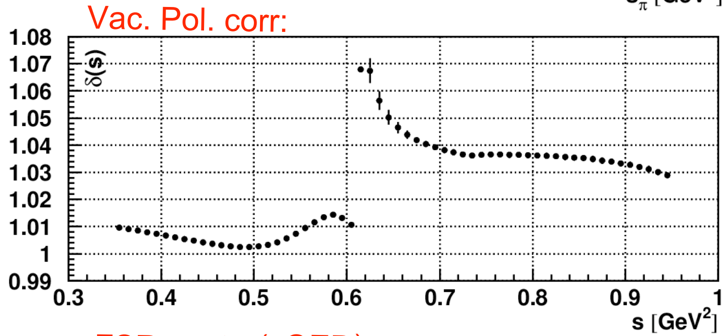
Radiator-Function $H(s,s_\pi)$ (ISR):

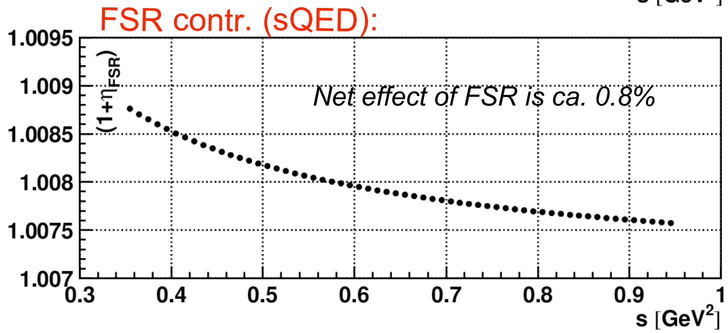
- ISR-Process calculated at NLO-level
  PHOKHARA generator
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

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 $\delta(s)=(\alpha(s)/\alpha(0))^2$

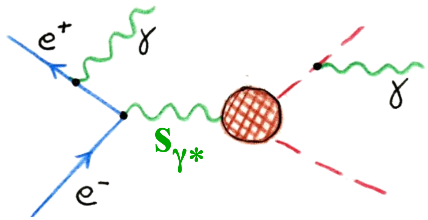
➔ from F. Jegerlehner

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.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)



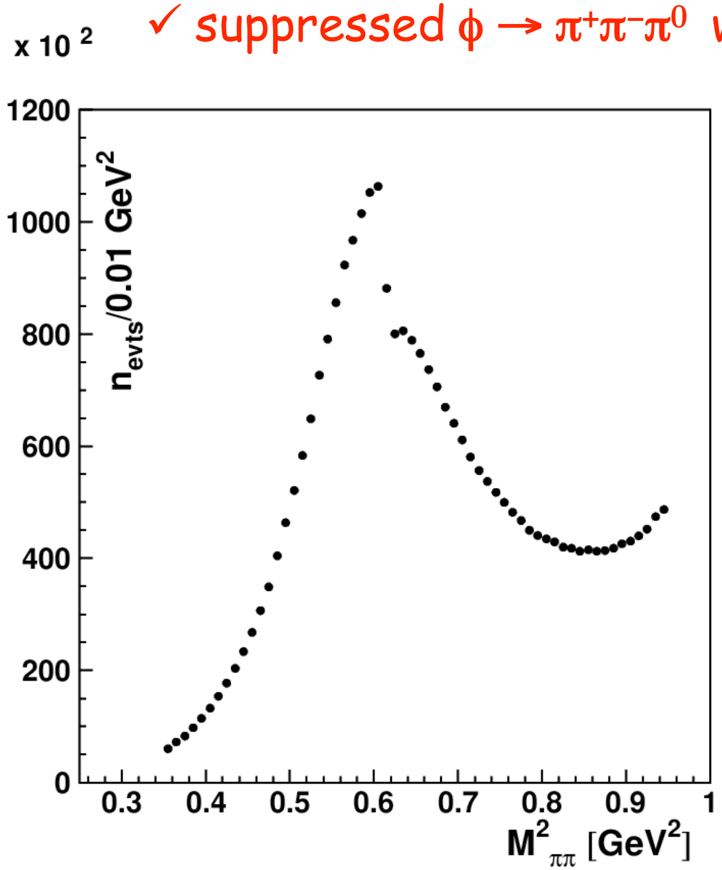
$s_{\gamma*} > s_\pi$

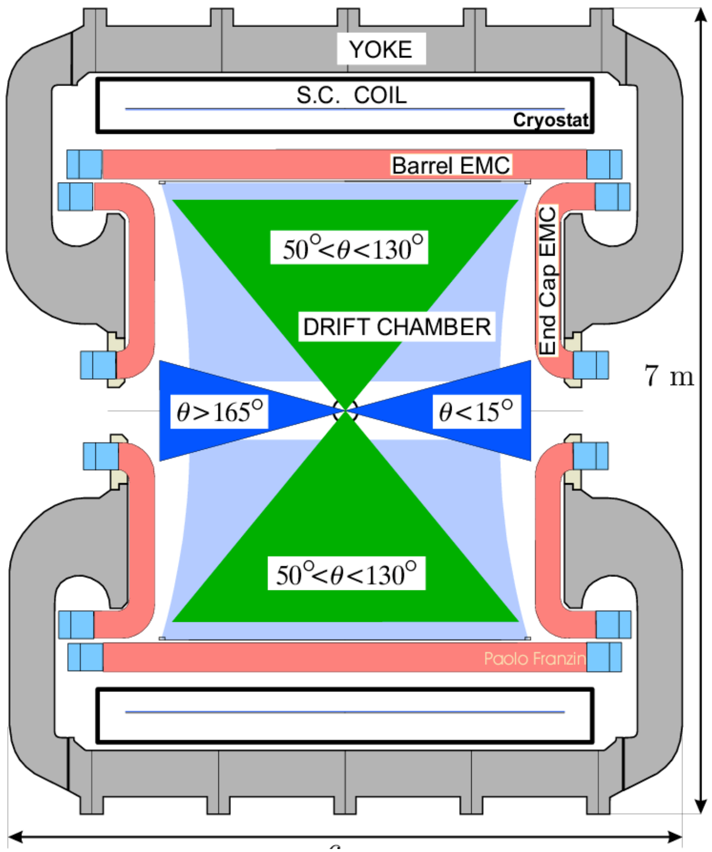
Event Selection

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

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

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





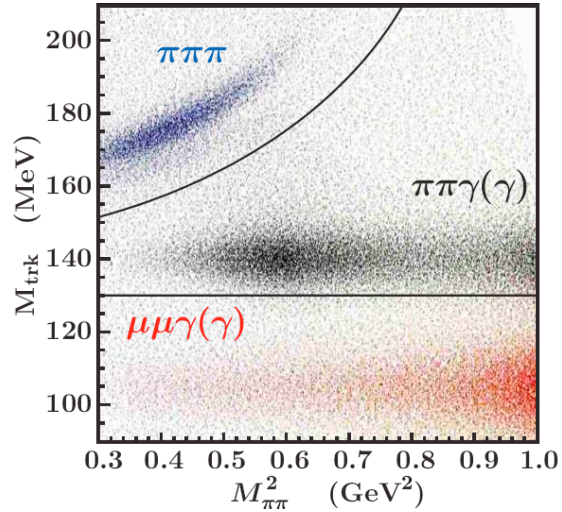
statistics: 242pb^{-1} of 2002 data

3.1 Mill. Events between 0.35 and 0.95 GeV^2

Event Selection

- Experimental challenge: control backgrounds from
  - $\phi \rightarrow \pi^{+}\pi^{-}\pi^{0}$
  - $e^{+}e^{-} \rightarrow e^{+}e^{-}\gamma$
  - $e^{+}e^{-} \rightarrow \mu^{+}\mu^{-}\gamma$,

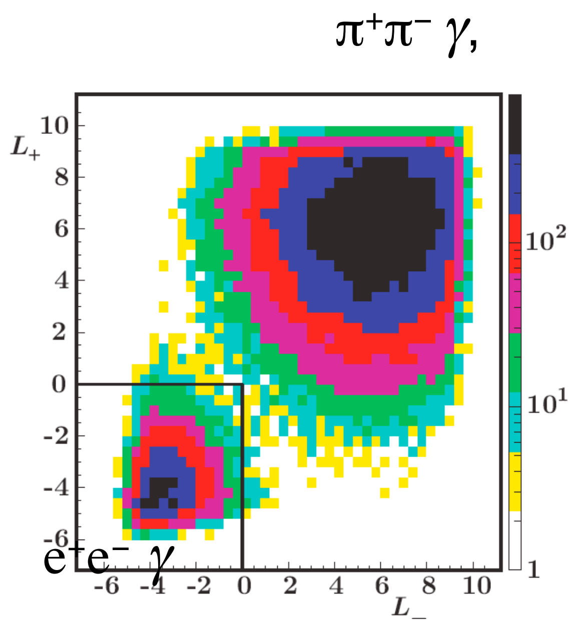
  removed using kinematical cuts in *trackmass* M_{Trk} - $M_{\pi\pi}^{2}$ plane



M_{Trk}:

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

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

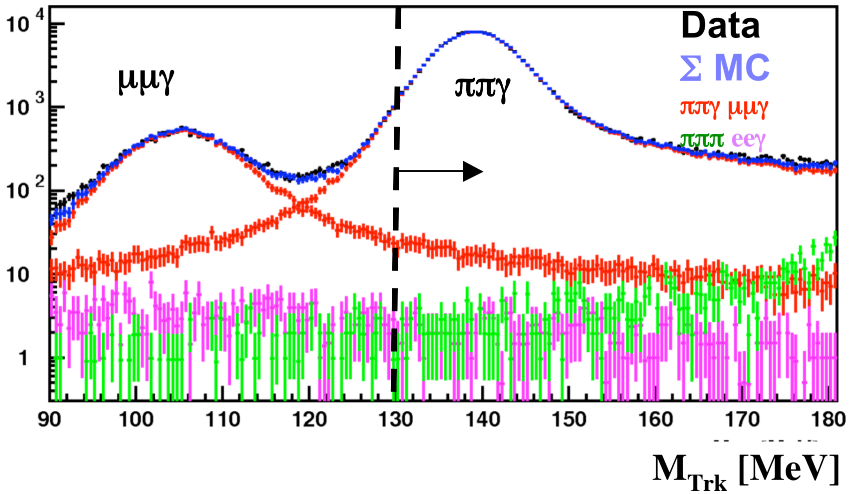


To further clean the samples from radiative Bhabha events, we use a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight.

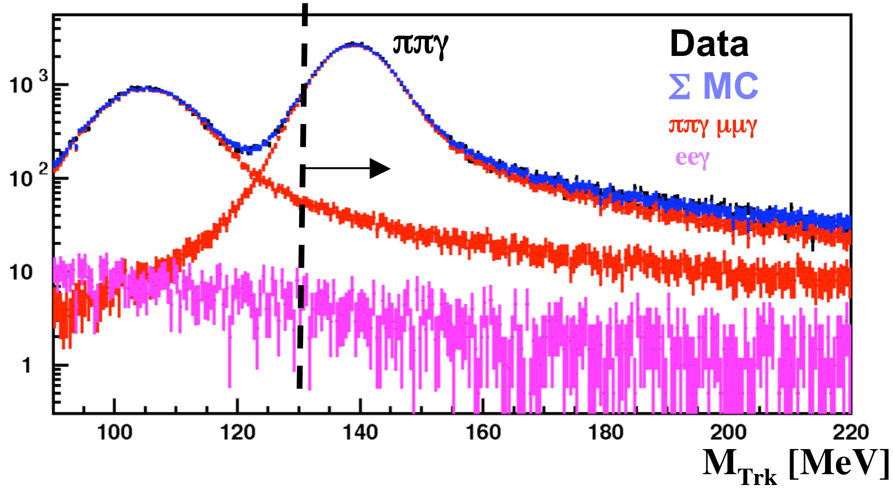
Background:

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

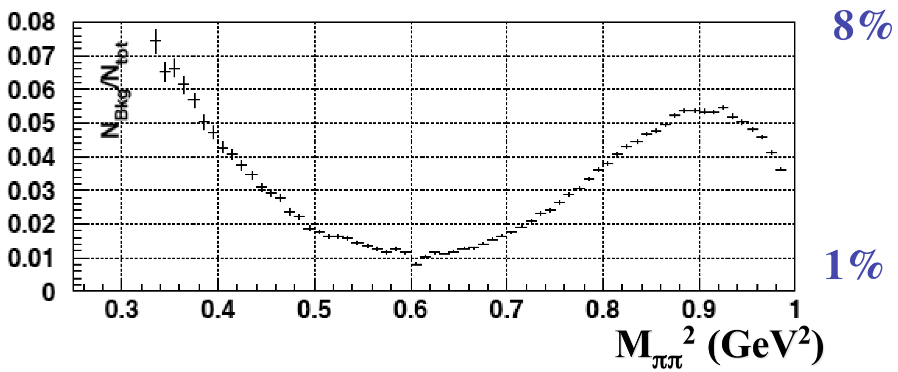
$0.60 < M_{\pi\pi}^2 < 0.62$ GeV^2, χ^2/ndof = 158/180



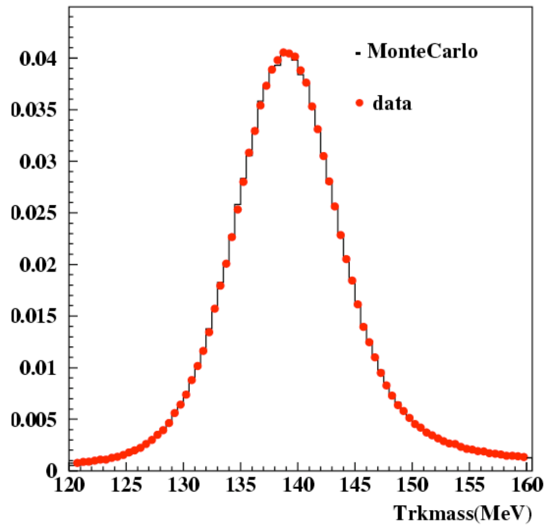
$0.84 < M_{\pi\pi}^2 < 0.86$ GeV^2 χ^2/ndof = 179/258



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

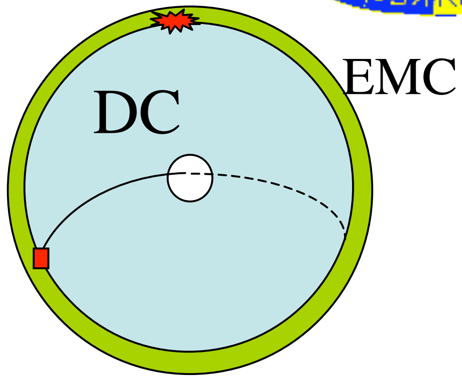
Two control samples

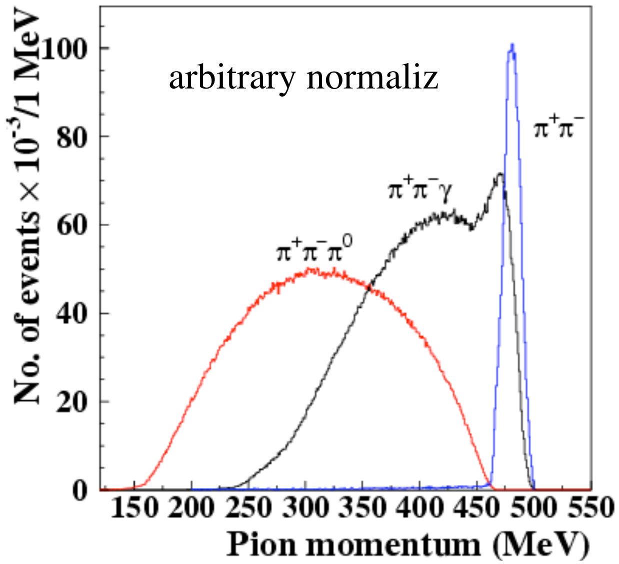
$\pi^+\pi^-\pi^0$

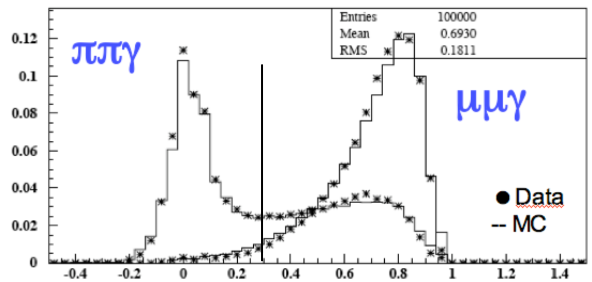
1) a tagging track recognized as a pion by PID, extrapolating back to the IP, which satisfies the trigger
2) 2 prompt clusters not associated to the tagging track with E>50 MeV and distant each other 60 cm
3) A constraint on the photon energy and time to further clean the sample, and improve missing 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_{miss} > 120 MeV and NN < 0.3, to suppress $\mu^+\mu^-\gamma$ events





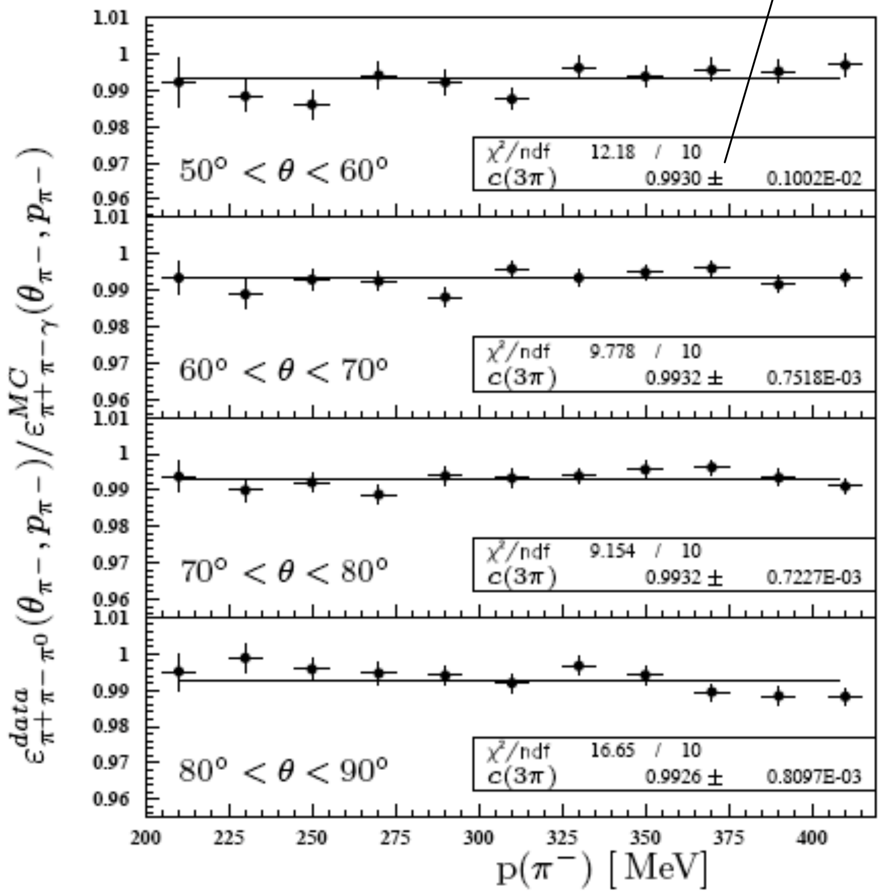


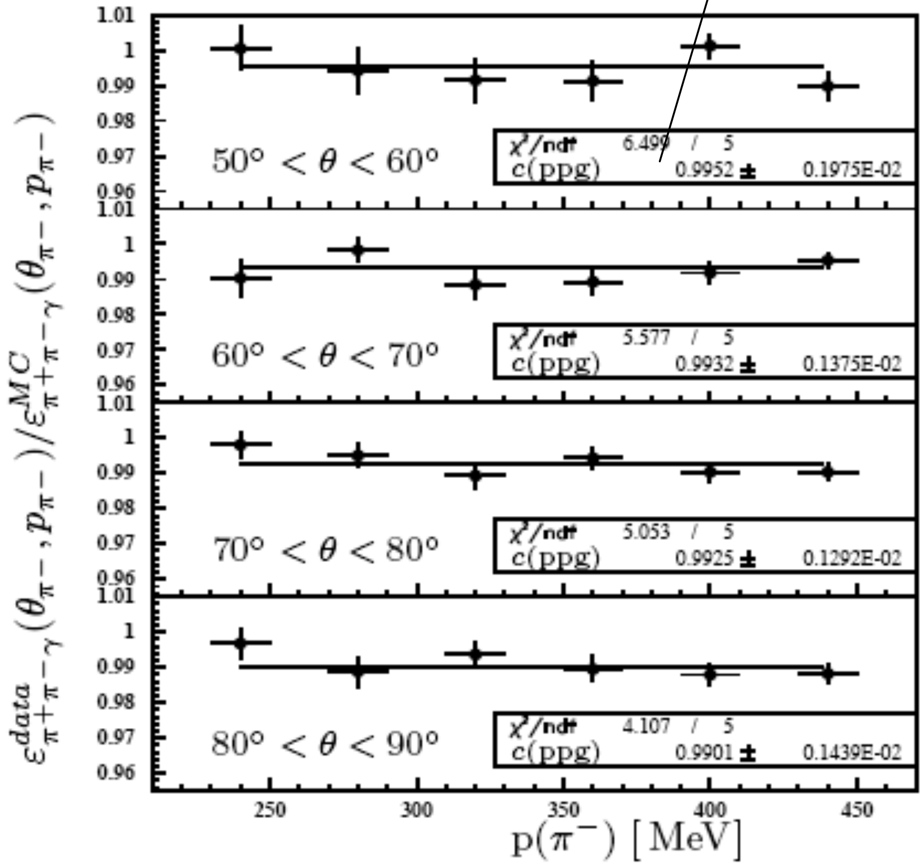
NN output

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 $M^2_{\pi\pi}$ which is the systematic error

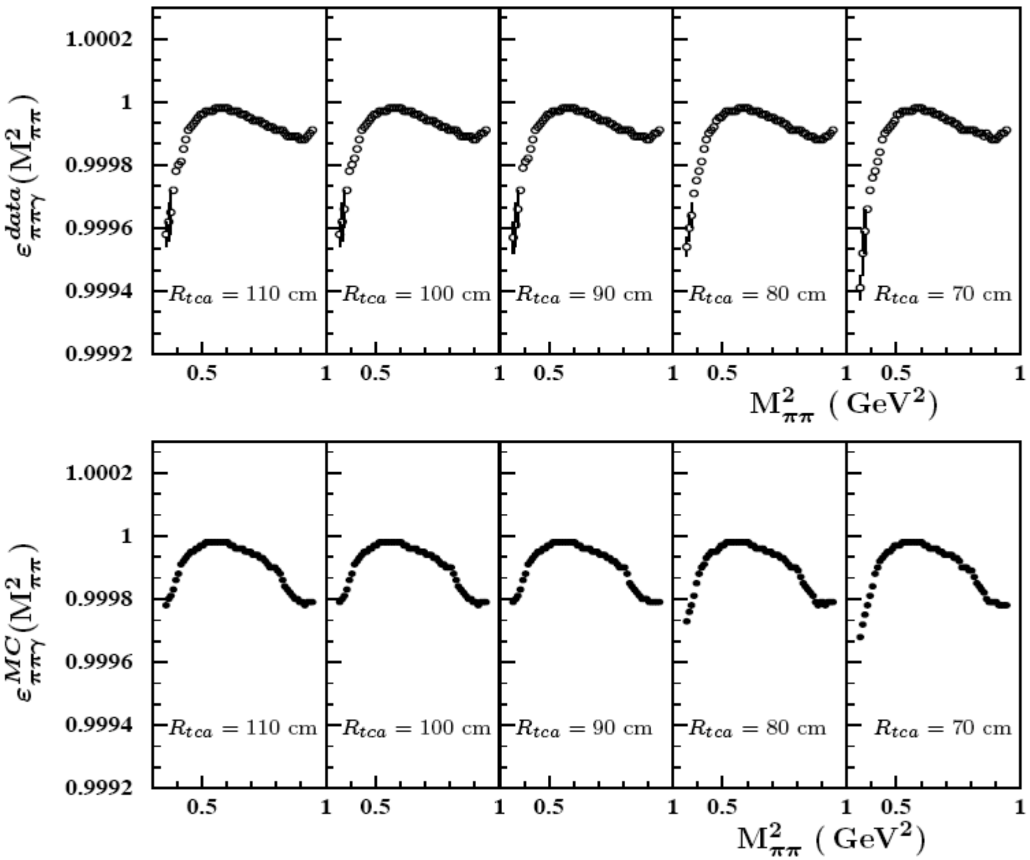
π/e PID and TCA

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

1) Two tracks satisting $\pi\pi\gamma$ "tracking" acceptance selectic
2) a tagging track recognized as pion by PID, extrapolating ba 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



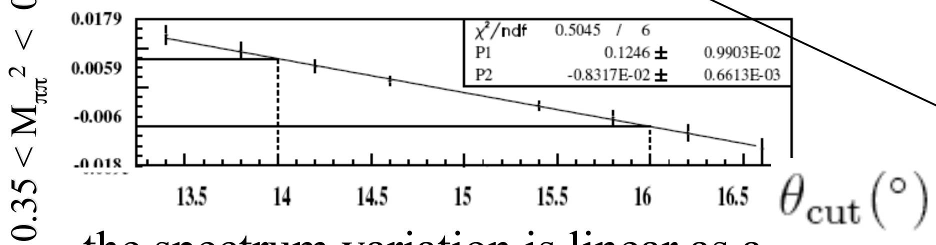
the systematic error is given varying the association radius, the effect on the correction data/MC is negligible

Acceptance

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

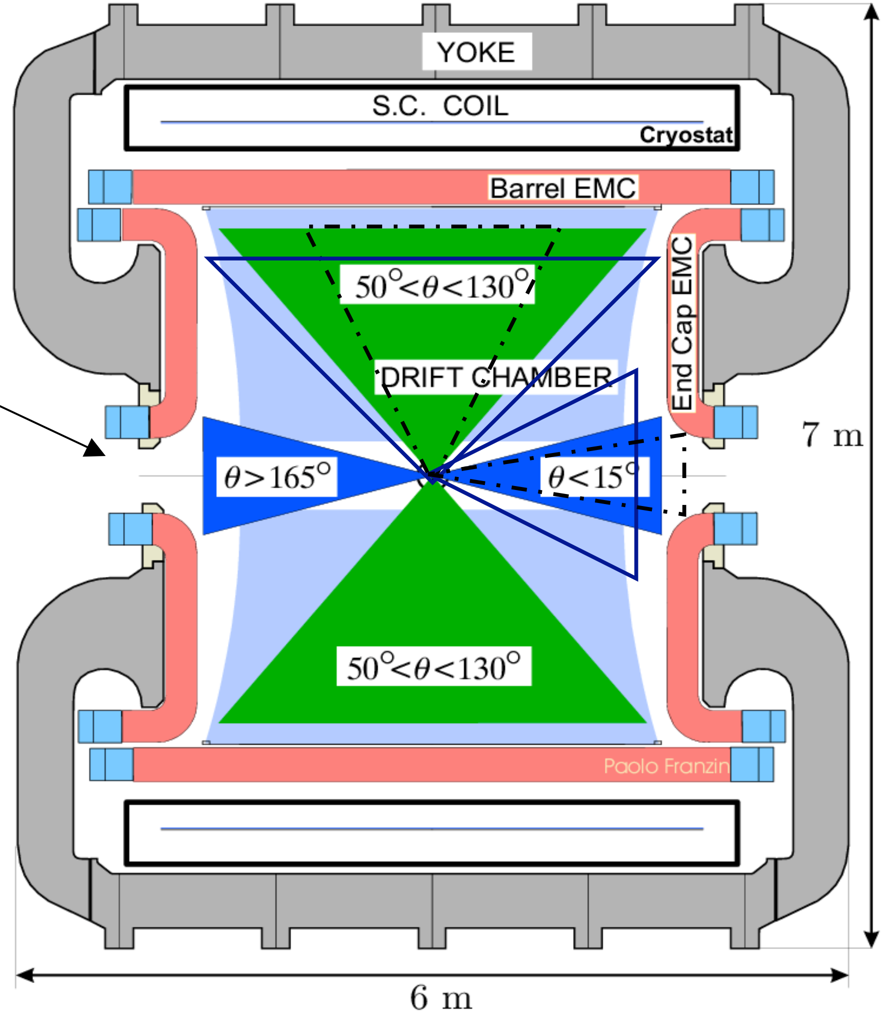
We study the impact of enlarging/reducing the fiducial volume on the geometrical acceptance in slices of $M^2_{\pi\pi}$

$$\frac{N_{\rm MC}(\theta_{\pi\pi} < \theta_{\rm cut})}{N_{\rm MC}(\theta_{\pi\pi} < 15^\circ)} - \frac{N_{\rm data}(\theta_{\pi\pi} < \theta_{\rm cut})}{N_{\rm data}(\theta_{\pi\pi} < 15^\circ)}$$



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

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



Unfolding

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

- We use Bayesan 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

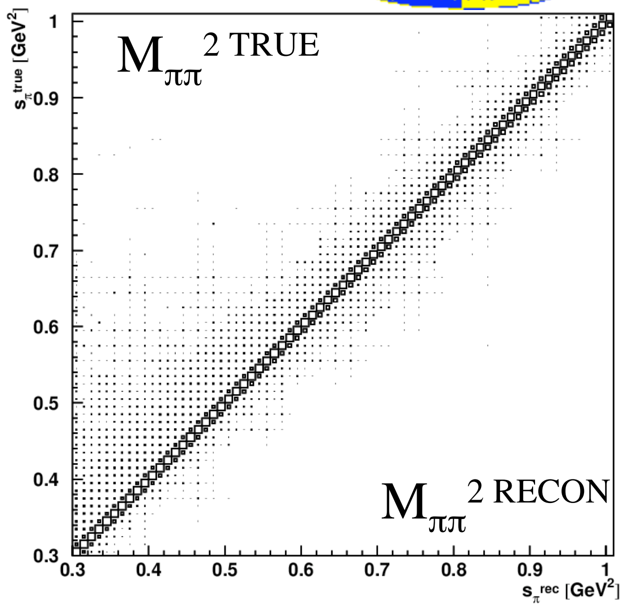
  - "if we observe a single event "(effect E_j)", the probability that it has been due to the i-th cause "(C_i)," is proportional to the probability of the cause times probability of the cause to produce the effect"

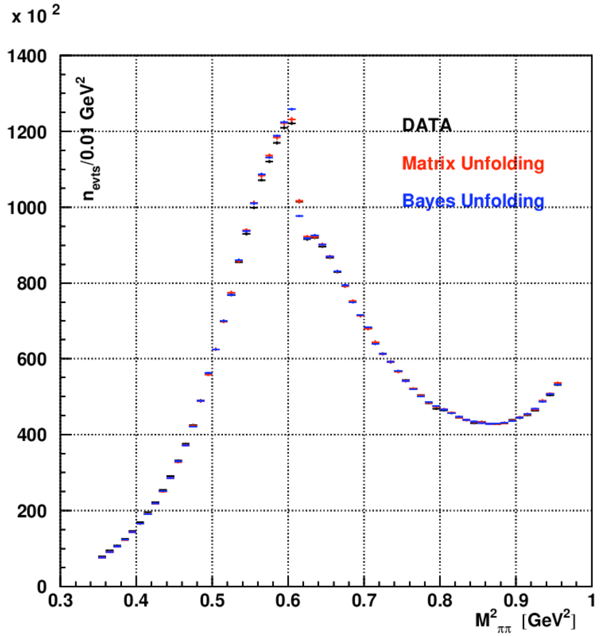
D'Agostini

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

$M^2_{\pi\pi}$ (GeV^2)	0.58	0.59	0.6	0.61	0.62
δ_{unf}(%)	0.4	0.3	2.1	4.0	0.4

- Very small effect;
systematic error negligible on a_μ !





Luminosity:

KLOE measures $\mathcal{L}$ with Bhabha scattering

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

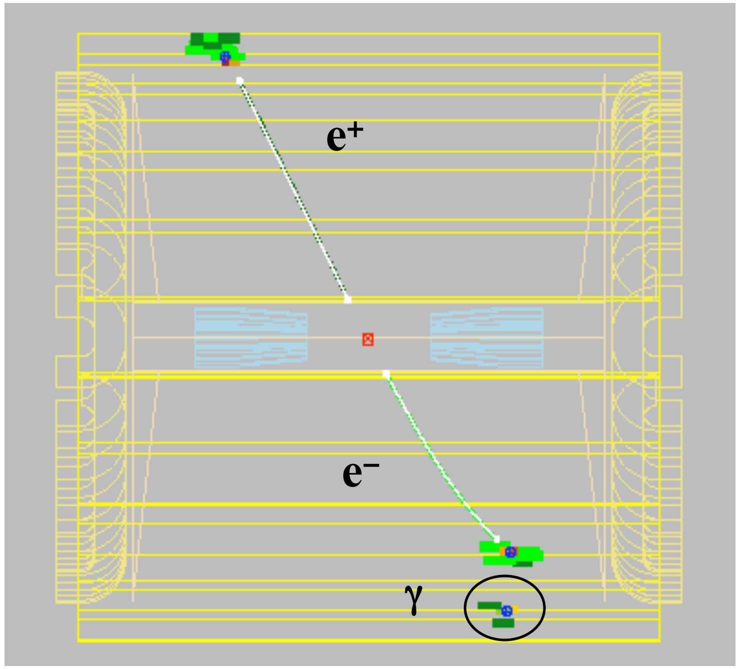
$55° < \theta < 125°$

acollinearity < 9°

p ≥ 400 MeV

$$\int \mathcal{L}\,\mathrm{d}t = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

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 ⊕ 0.3% exp = 0.3%	

New KLOE result (KLOE08)

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

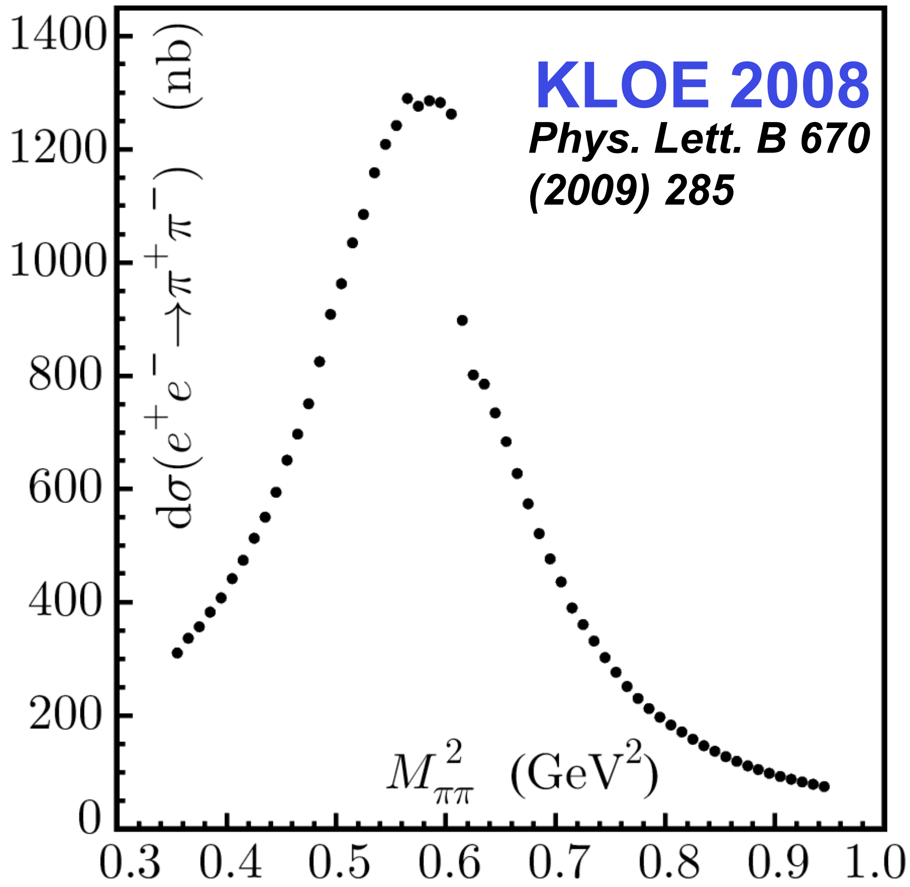
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
π/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
√ s dep. Of H	0.2%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

experimental fractional error on a_μ = 0.6 %

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

theoretical fractional error on a_μ = 0.6 %

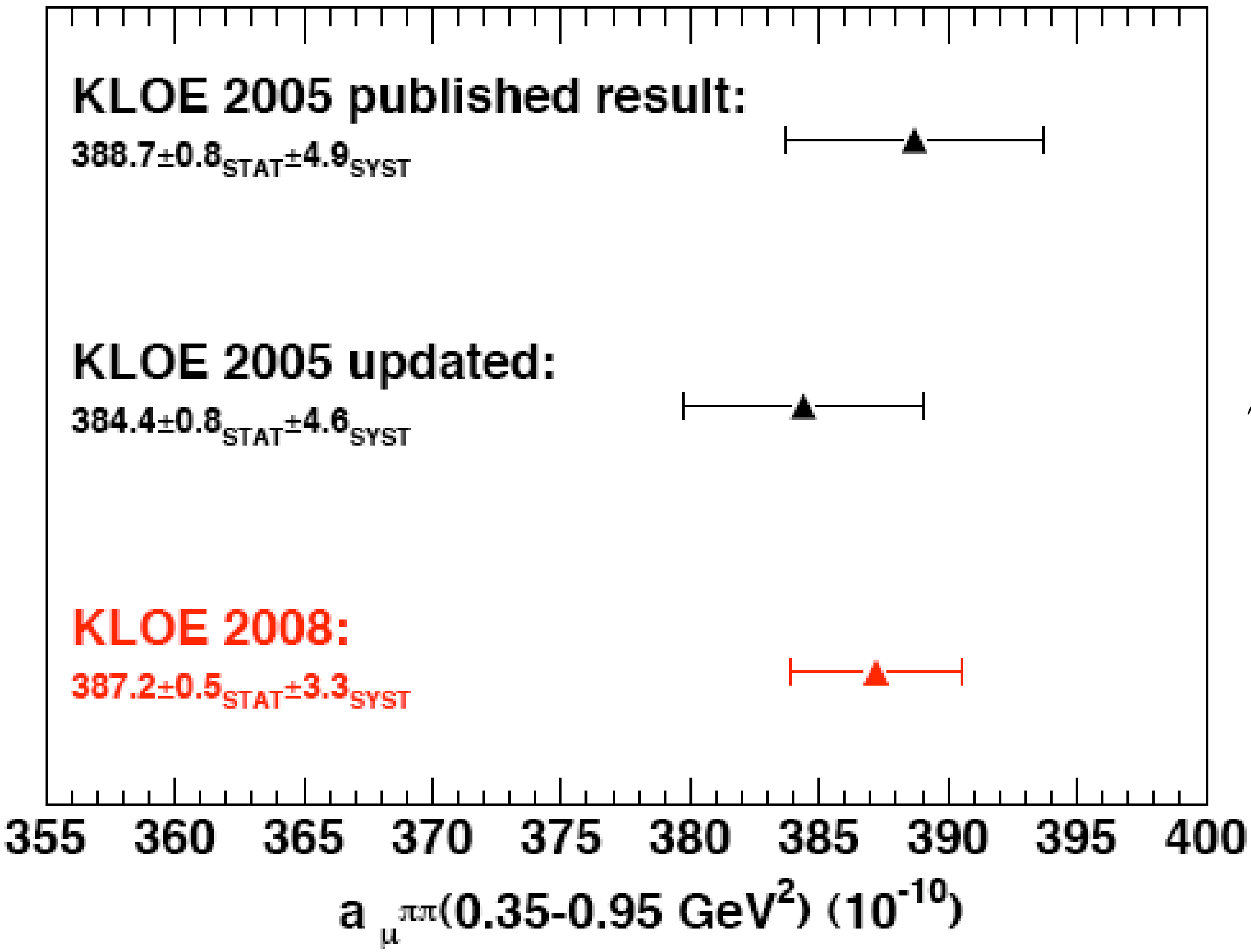
$\sigma_{\pi\pi}$, undressed from VP, inclusive for FSR as function of $(M^0_{\pi\pi})^2$



stat. error only

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

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



~1.3% SYST

~0.9% SYST

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

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

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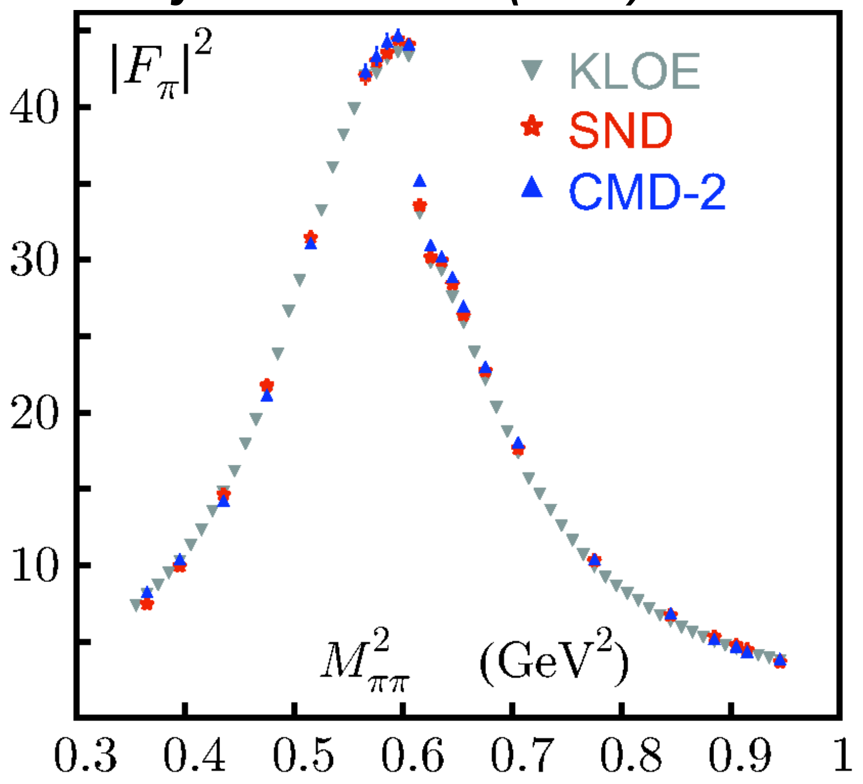
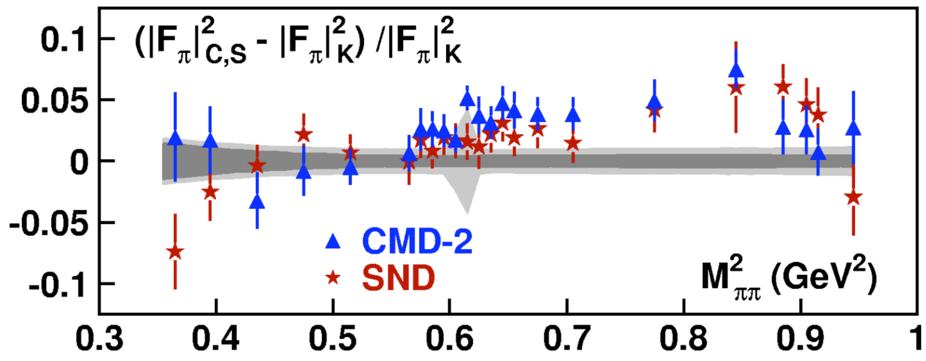
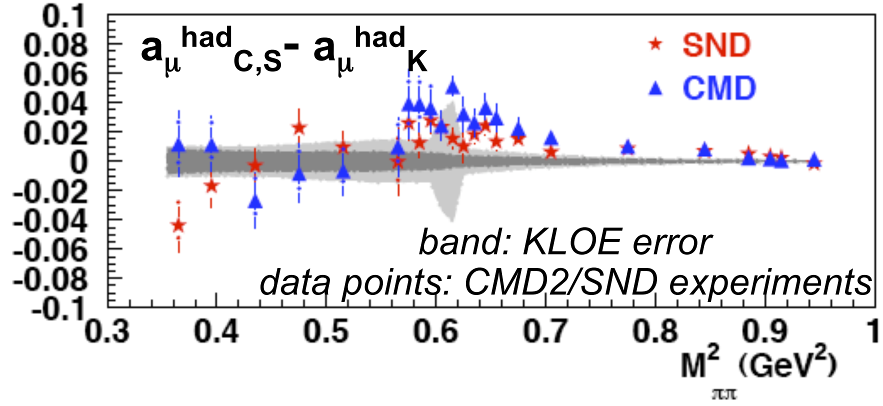
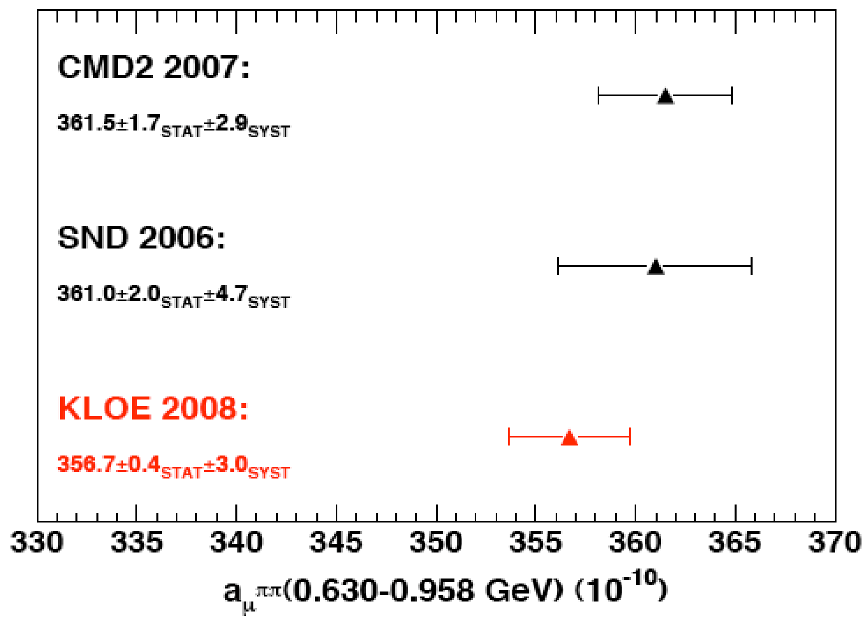




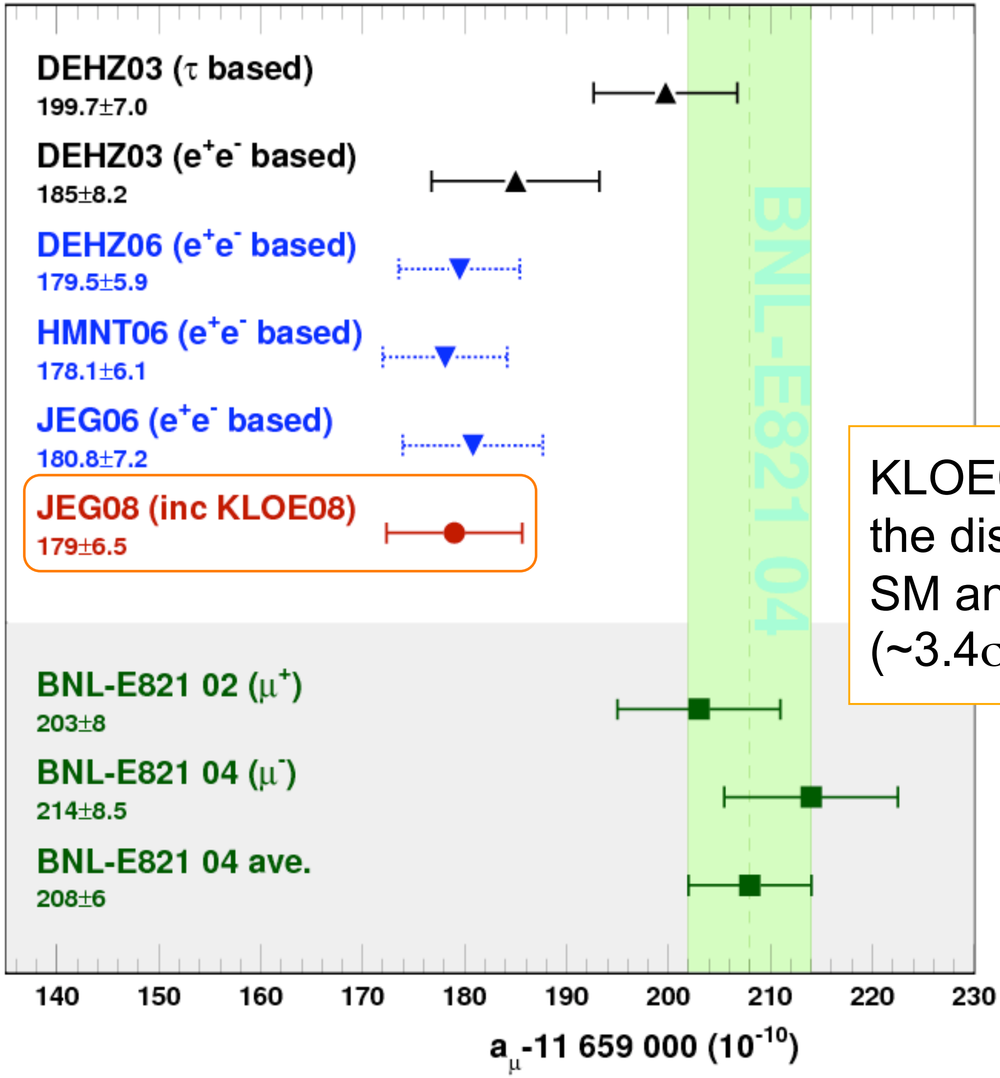
abs. contr. to $a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{\mathrm{had}}(s)\mathrm{K}(s)\,\mathrm{d}s$ per bin:





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

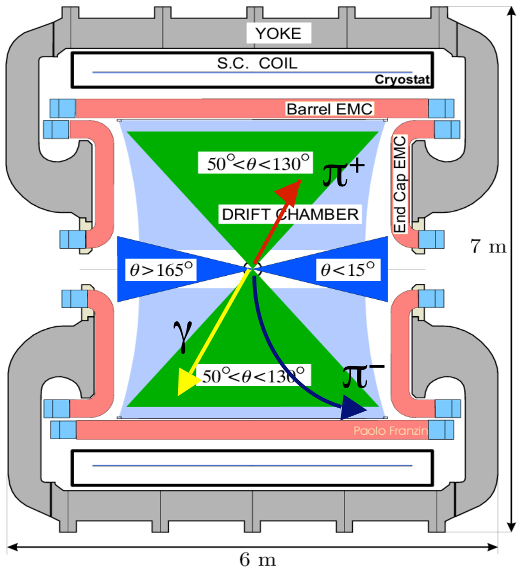
Theoretical predictions compared to the BNL result:



KLOE08 strengthens the discrepancy between SM and BNL experiment (~3.4σ)

New analysis in progress:

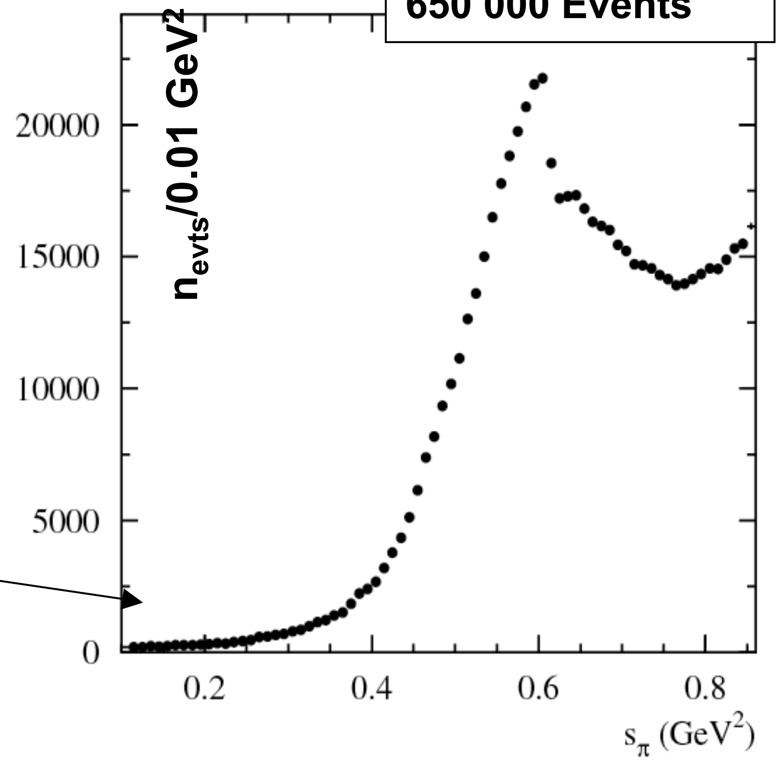
Use data sample taken at $\sqrt{s} \cong 1000$ MeV,
20 MeV below the ϕ-peak



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

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

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**

($\phi \to f_0 \gamma \to \pi\pi\gamma$, $\phi \to \pi^+\pi^-\pi^0$) off-peak

Analysis very close to be finalized

Conclusions

❑ KLOE has performed the first precision measurement of 2π cross section using ISR (KLOE05, ***Phys. Lett. B 606, 12 (2005)***)

❑We have presented a new measurement of $\sigma_{\pi\pi}$ and to $a_\mu^{\pi\pi}$ in the range between 0.35 - 0.95 GeV^2 with 0.9% systematic error (KLOE08, ***Phys. Lett. B 670, 285 (2009)***)

- *KLOE08 result on* $a_\mu^{\pi\pi}$ *agrees with KLOE05 and strengthens*
- *the discrepancy between SM and BNL experiment (~3.4σ)*
- *KLOE08* $a_\mu^{\pi\pi}$ *agrees with recent results from CMD2 and SND experiments at VEPP-2M in Novosibirsk*

❑ Results are also expected in near future from other KLOE analyses:

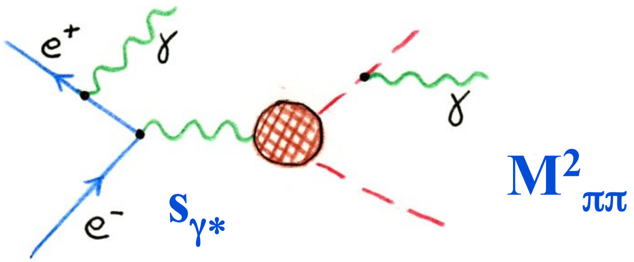
- ➢F_π by photon detected at large angle off-resonance data (1 GeV)
- ➢F_π by the π/μ ratio

Stay Tuned!

SPARE SLIDES

Correcting for γ_{FSR} energy:

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



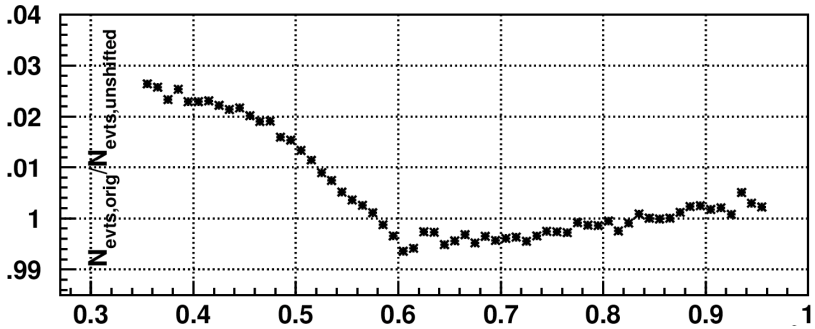
The presence of γ_{FSR} results in a shift of the measured quantity $M^2_{\pi\pi}$ towards lower values:

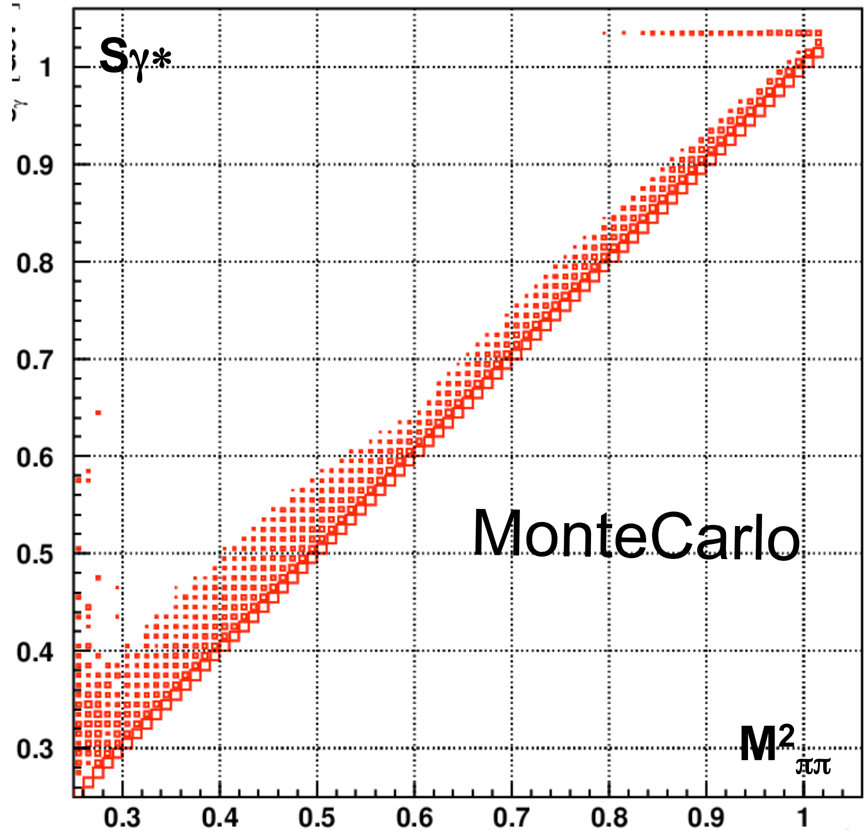
$$M^2_{\pi\pi} < S_{\gamma*}$$

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

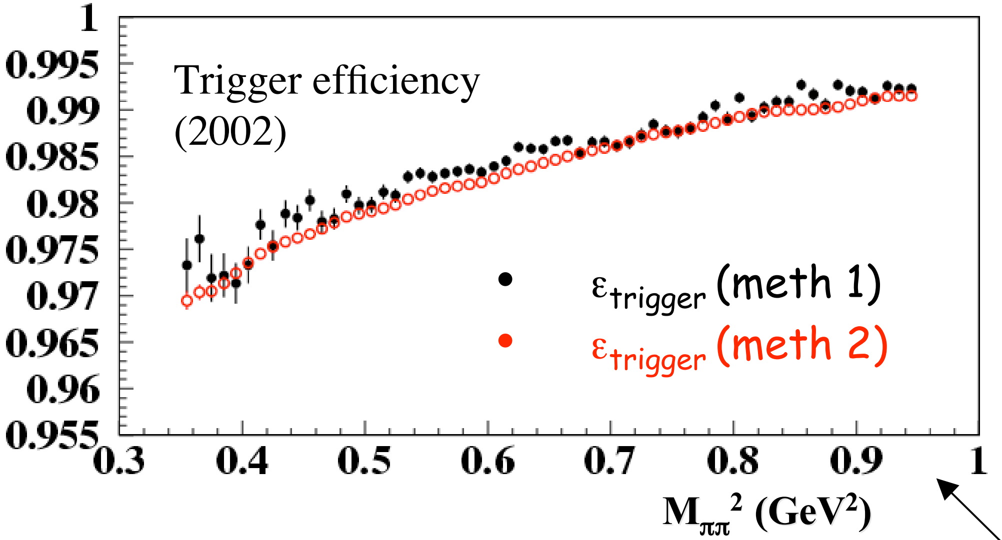
ISR only: $s_{\gamma*} = M^2_{\pi\pi}$

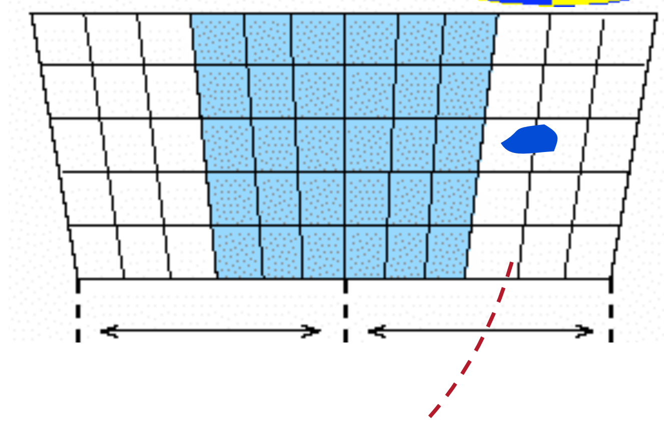
FSR photon present: $s_{\gamma*} = M^2_{\pi\pi\gamma(FSR)}$





Trigger

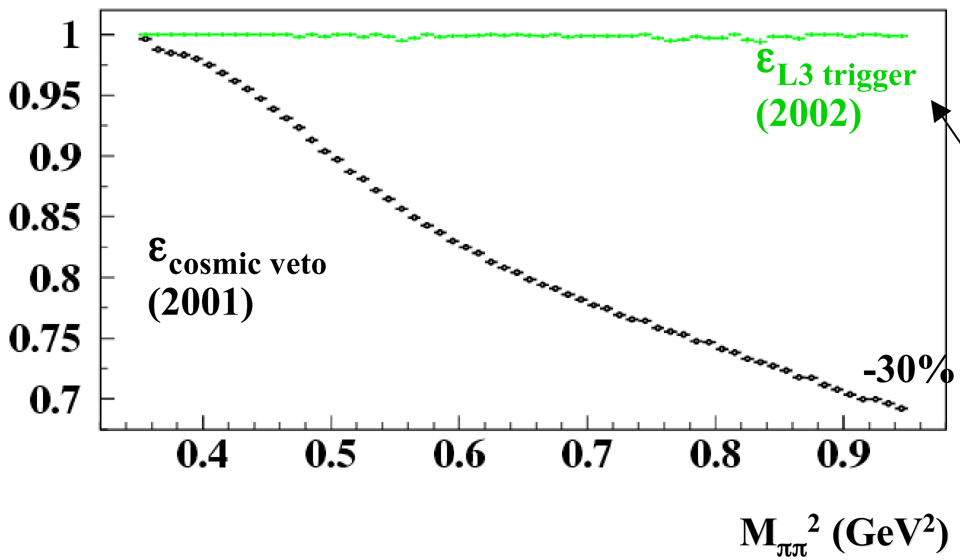




- The event is **triggered** by the (pion) tracks only which deposit E>50 MeV in 2 sectors of the calorimeter

~99.9%

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



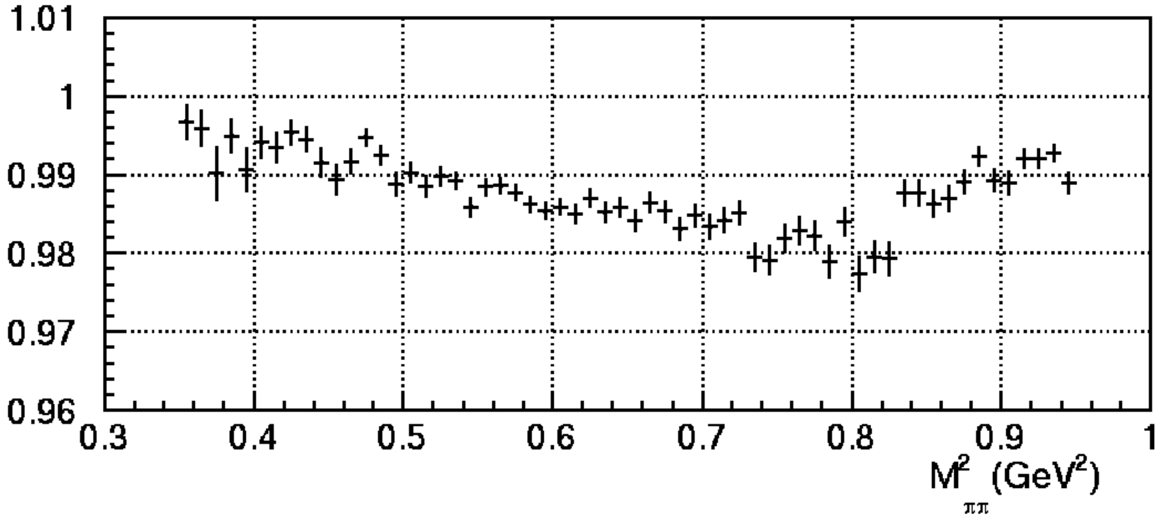
~70.%

- 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:

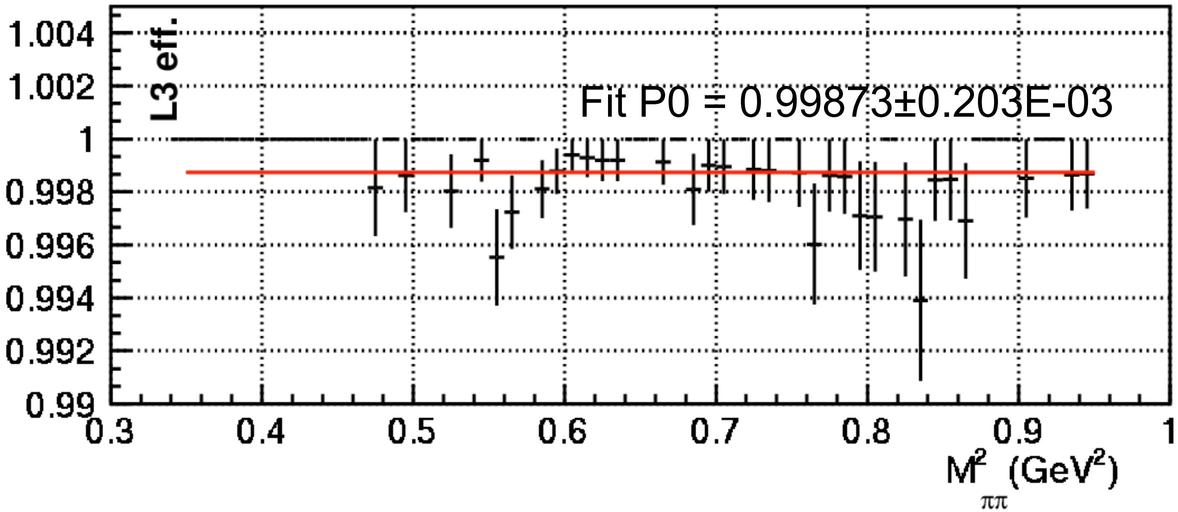
Both efficiencies estimated via downscaled control samples:

Reconstruction Filter



~2%

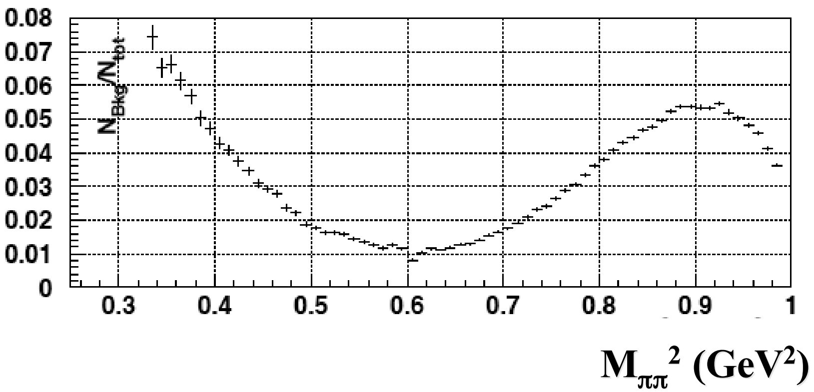
L3:



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

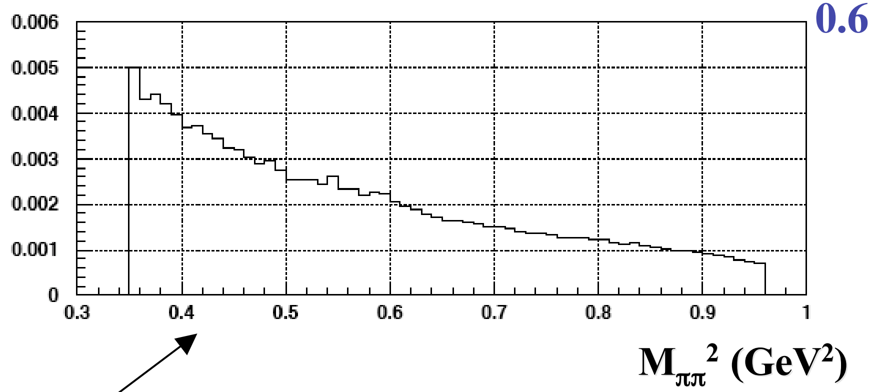
Background: total contribution and error

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



8%

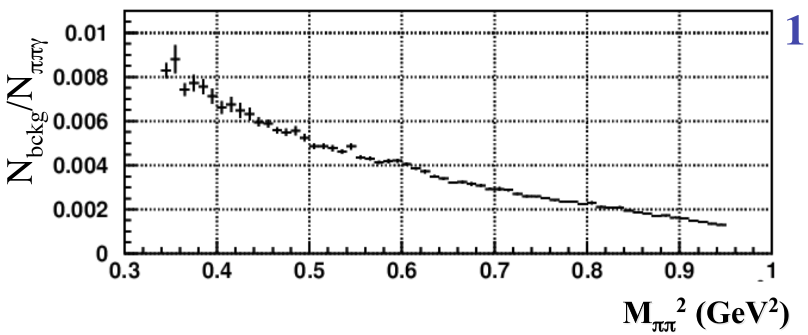
Error on bckg subtraction (in %)



0.6%

Additional bckg channels:

- $e^+e^- \to e^+e^-\pi^+\pi^-$ (Ekhara) ~ *0.8% at low $M^2_{\pi\pi}$*
- $e^+e^- \to e^+e^-\mu^+\mu^-$ (Nextcalibur) *negligible*
- $\phi \to f_0\gamma \to \pi\pi\gamma$ (Phokhara,Fasterd) *negligible*
- $\phi \to \pi\rho \to \pi\pi\gamma$ (Phokhara,Fasterd) *negligible*
- $e^+e^- \to \omega\gamma_{ISR} \to \pi\pi\pi\gamma$(Phokhara) *negligible*



1%

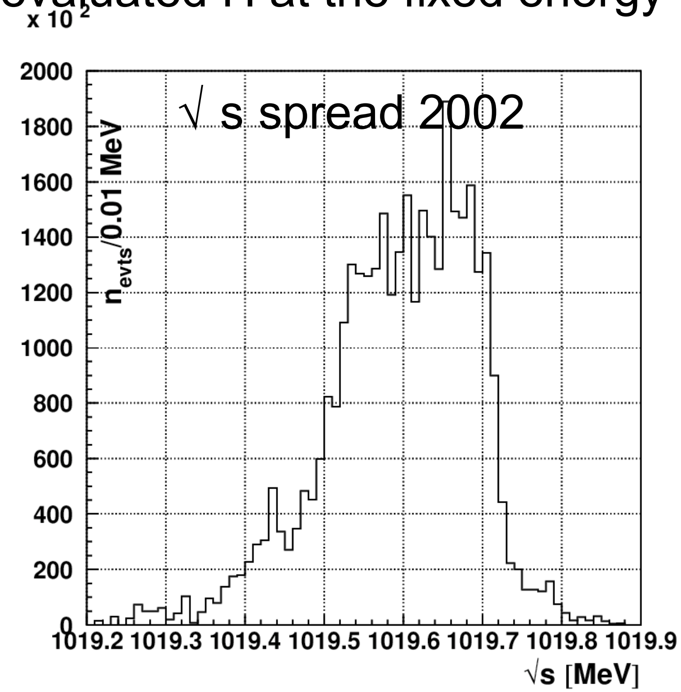
Contribution to Bckg error :

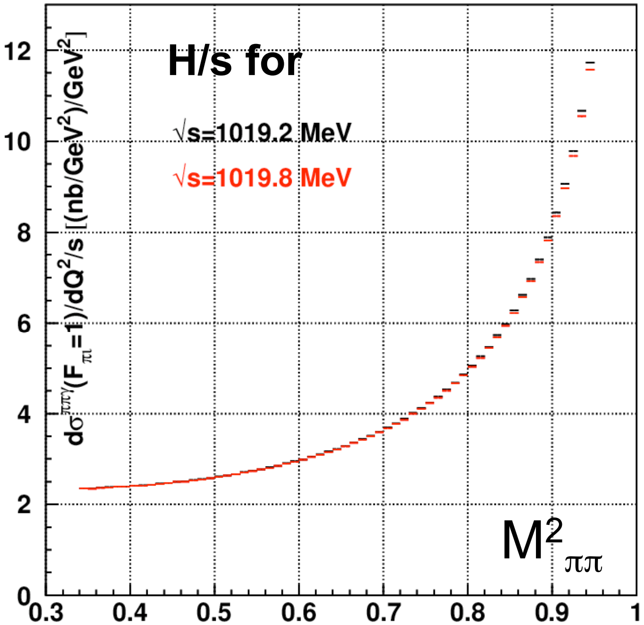
- Uncertainty on e+e- → e+e-$\pi^+\pi^-$ contribution
- Error from normalization parameters obtained from the fit

"Phokhara": see talk of A. Grzielinska
"Ekhara": C.zyz *et al*
"Nextcalibur" : *F.A. Berends et al*
"Fasterd": *O. Shekhotvsova et al*

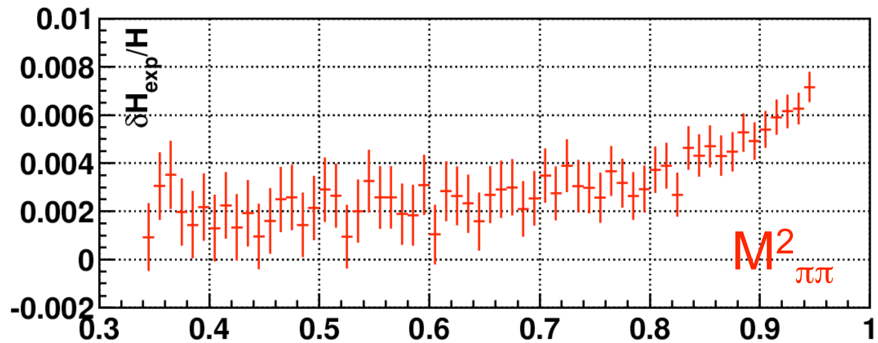
Radiator function (H)

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





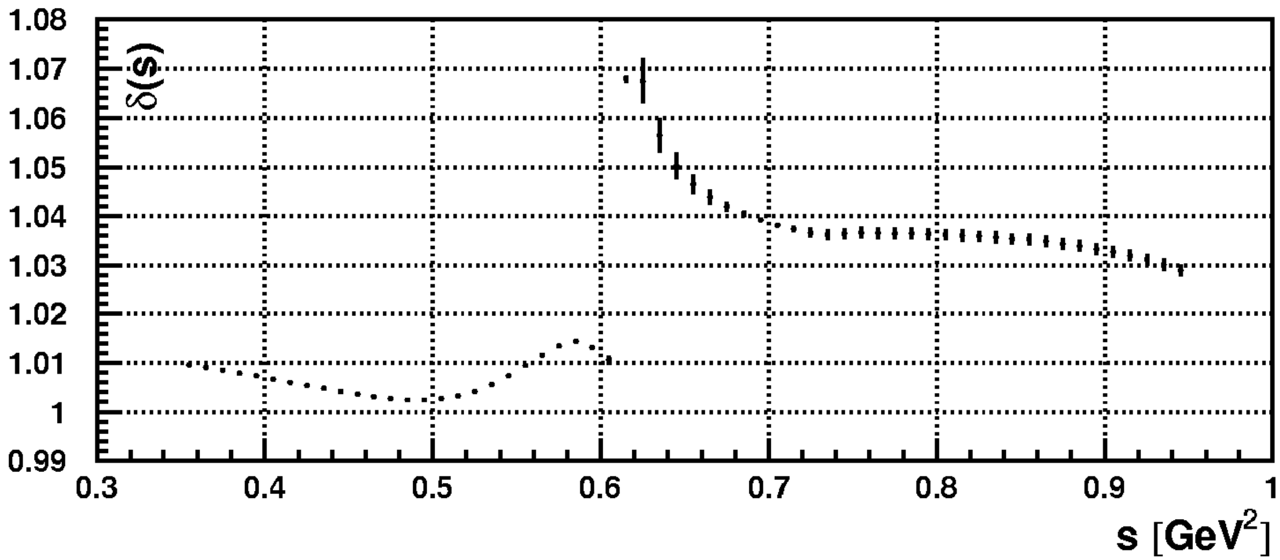
We take half the rel. difference between the radiator functions obtained at
√ s = 1.0192 GeV and √ s = 1.0198 GeV as the experimental syst. uncertainty on the radiator function.



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 $\sigma^0_{\pi\pi}$:

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



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

Correction is applied only to the cross section $\sigma^0_{\pi\pi}$ (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%.