# Measurement of the hadronic cross section at KLOE/KLOE-2


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(*for the KLOE/KLOE-2 collaborations*)

**Laboratori Nazionali di Frascati**


International workshop on $e^+e^-$ collisions from $\phi$ to $\psi$

Rome, Italy

09 September 2013

# Outline

- Hadronic contribution to $(g\text{-}2)_\mu$
- KLOE measurements of $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ : ← Normalized to luminosity $(e^+e^- \to e^+e^-(\gamma))$
  - Small (photon) angle measurements (KLOE05, KLOE08)
  - Large (photon) angle measurement (KLOE10)
  - Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar
- New measurement of $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ ← using $\pi\pi\gamma/\mu\mu\gamma$ ratio (KLOE12) PLB 720 (2013) 336–343
  - Comparison with KLOE08, KLOE10 and evaluation of $a_\mu^{\pi\pi}$
  - *Preliminary* combination of KLOE08, KLOE10, KLOE12 results

# Muon anomaly

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

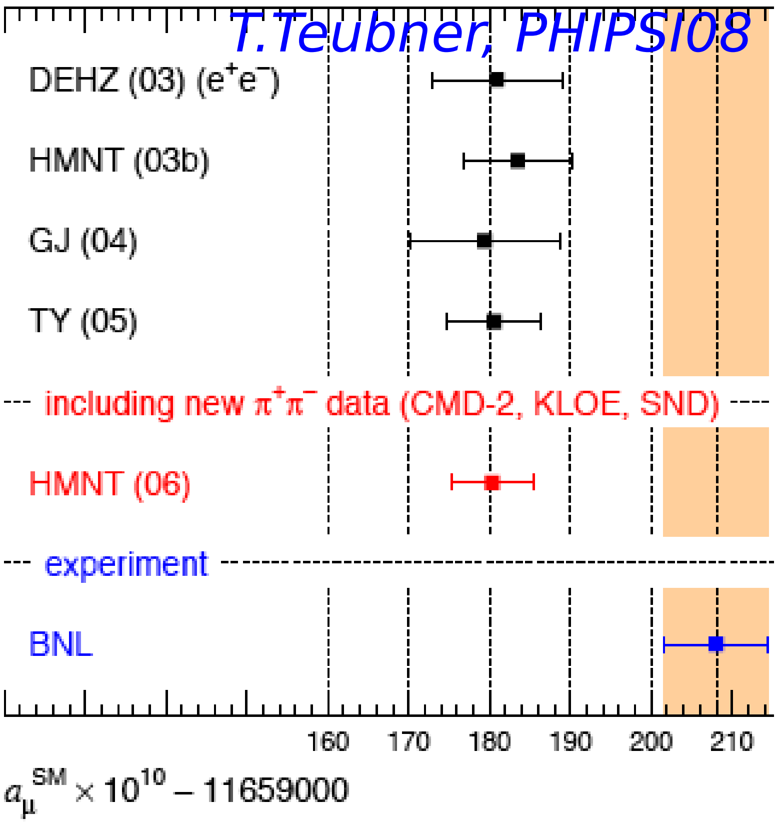
- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.

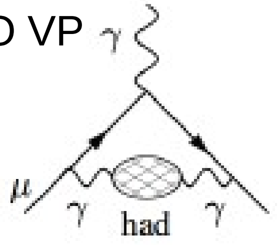
- Theoretical error $\delta a_\mu^{SM}$ (~6x10$^{-10}$) dominated by HLO VP ([4–5]x10$^{-10}$) and HLbL ([2.5–4]x10$^{-10}$).

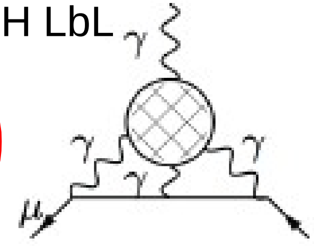
A **twofold** improvement on $\delta a_\mu^{SM}$ from 2001 (thanks to new $e^+e^-$ measurements)!

- Experimental error $\delta a_\mu^{EXP}$ ~6x10$^{-10}$(E821). Plan to reduce it to 1.6x10$^{-10}$ by the new g-2 experiments at FNAL and J-PARC.

$a_\mu^{SM}$ compared to BNL world av.




$a_\mu^{HLO}$ = (690.9±**4.4**)x10$^{-10}$
[Eidelman, TAU08]

$a_\mu^{HLbL}$ =(10.5±2.6)x10$^{-10}$
[Prades, dR&V. 08]
=(11 ±4)x10$^{-10}$ (Jegerlehner, Nyffler)

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

**$\delta a_\mu^{HLO}$ ~0.7%**

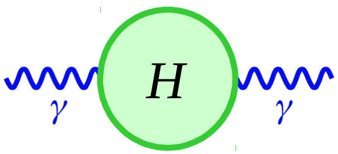
**$\delta a_\mu^{HLbL}$ ~25-40%**

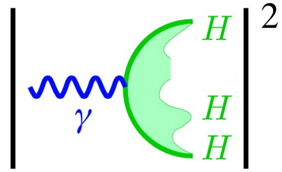
**In 2001 $a_\mu^{EXP}$-$a_\mu^{TH}$=(23±16)•10$^{-10}$**

# $a_\mu^{HLO}$:

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

L.O. Hadronic contribution to $a_\mu$ can be estimated by means of a dispersion integral:




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

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

$1/s^2$ makes low energy contributions especially important:
$e^+e^- \to \pi^+\pi^-$
in the region < 1 GeV contributes up to 70% !

- K(s) = analytic kernel-function
- above a sufficiently high energy value, typically 2…5 GeV, we can use *pQCD*

Input:

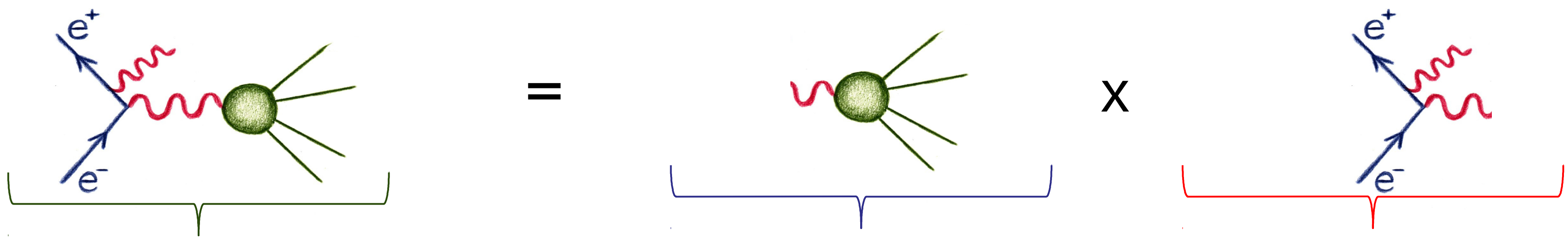
a) hadronic electron-positron cross section data (G.dR 69, E.J.95, A.D.H.'97,….)

b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)
(Alemany, Davier, Hoecker '97)

# ISR: Initial State Radiation

Neglecting final state radiation (FSR):

$$\frac{d\sigma(e^+e^- \to hadrons + \gamma)}{dM^2_{hadr}} = \frac{\sigma(e^+e^- \to hadrons, M^2_{hadr})}{s} H(s, M^2_{hadr})$$




measured cross section | resulting cross section | radiator function

**Theoretical input**: precise calculation of the radiation function $H(s, M^2_{hadr})$

→ **EVA + PHOKHARA MC Generator**

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

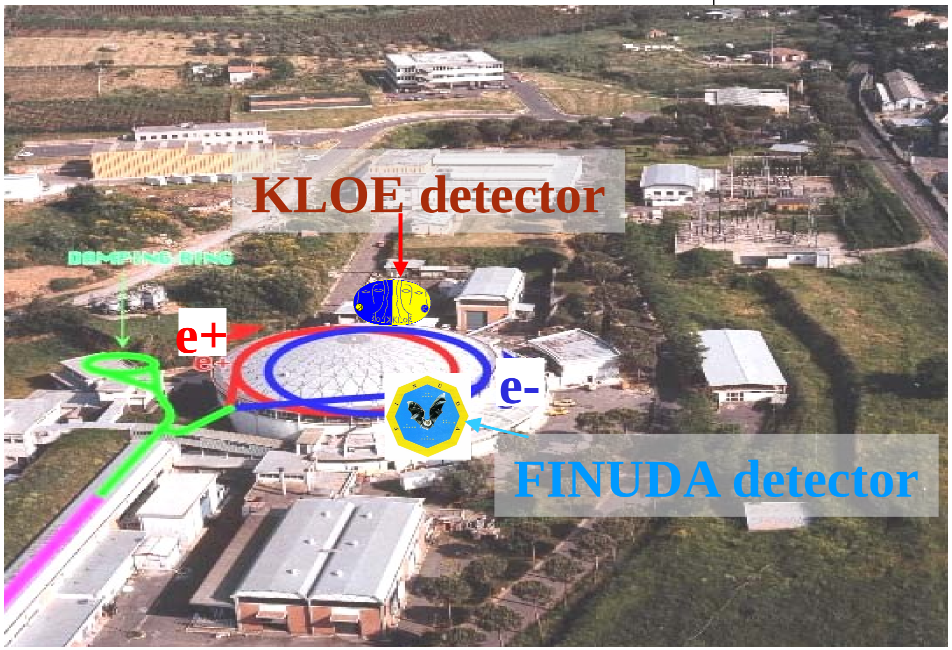
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003

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

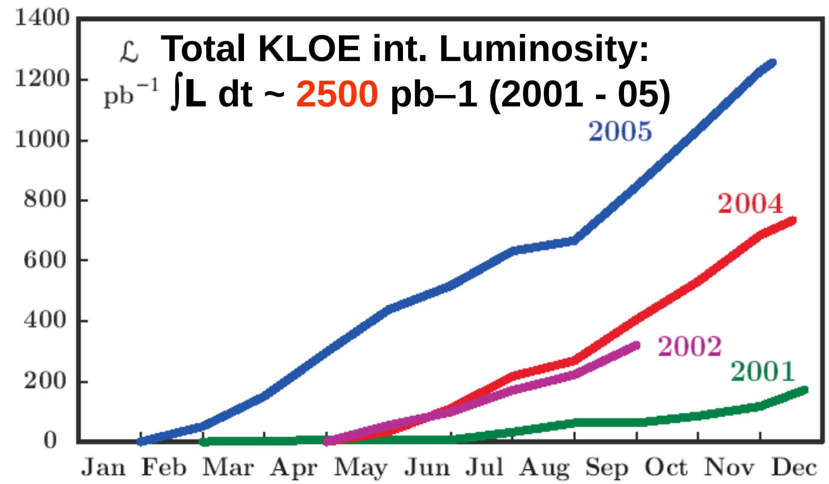
**IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ with ISR using 2001 data (140pb$^{-1}$) PLB606(2005)12 ⇒ ~3σ discrepancy btw $a_\mu^{SM}$ and $a_\mu^{exp}$**

# DAΦNE: A ϕ-Factory in Frascati (near Rome)

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




## *Integrated Luminosity*




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

***KLOE05 measurement*** (PLB606(2005)12)
***based on 140pb$^{-1}$ of 2001 data***

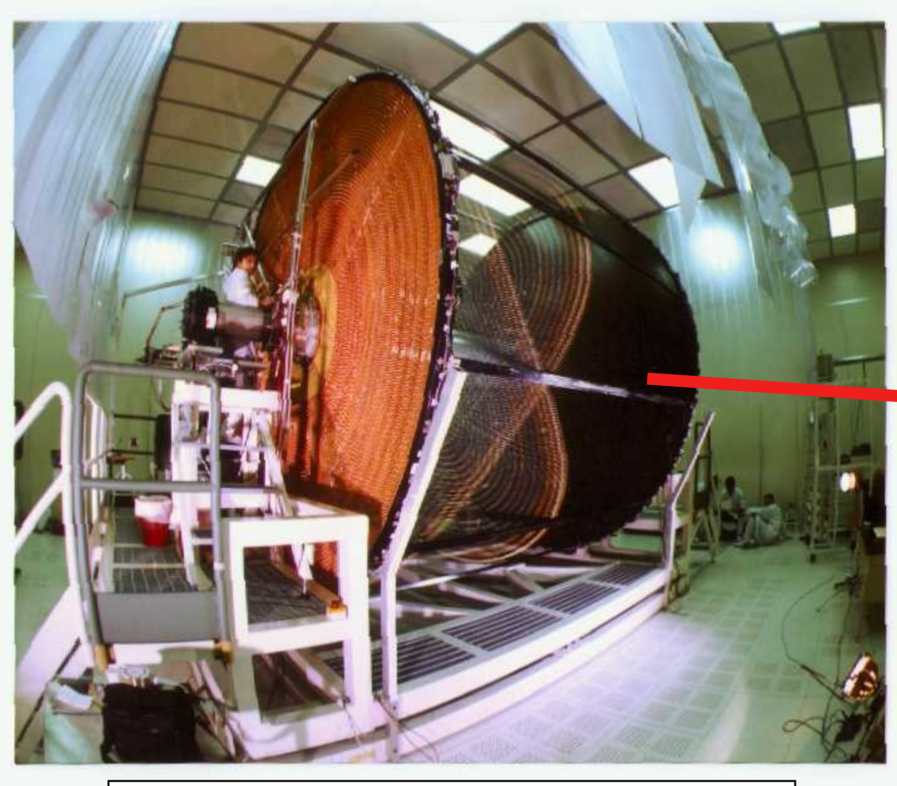
***KLOE10 measurement*** (PLB700 (2011)102)
***based on 233 pb$^{-1}$ of 2006 data***
***(at 1 GeV, different event selection)***

***KLOE08 measurement*** (PLB670(2009)285)
***was based on 240pb$^{-1}$ of 2002 data***

***KLOE12 measurement*** (PLB720(2013)336)
***based on 240 pb$^{-1}$ of 2002 data***
***(from ππγ/μμγ ratio)***

# KLOE Detector

Drift chamber

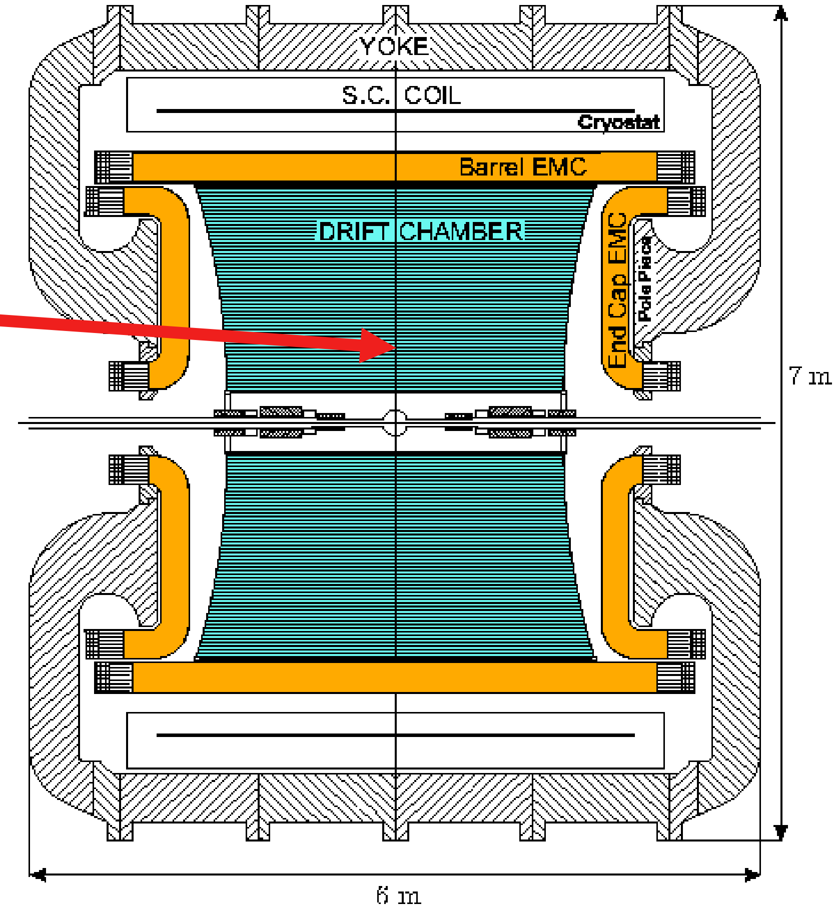


$\sigma_p/p$ = 0.4% (for 90$^0$ tracks)

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

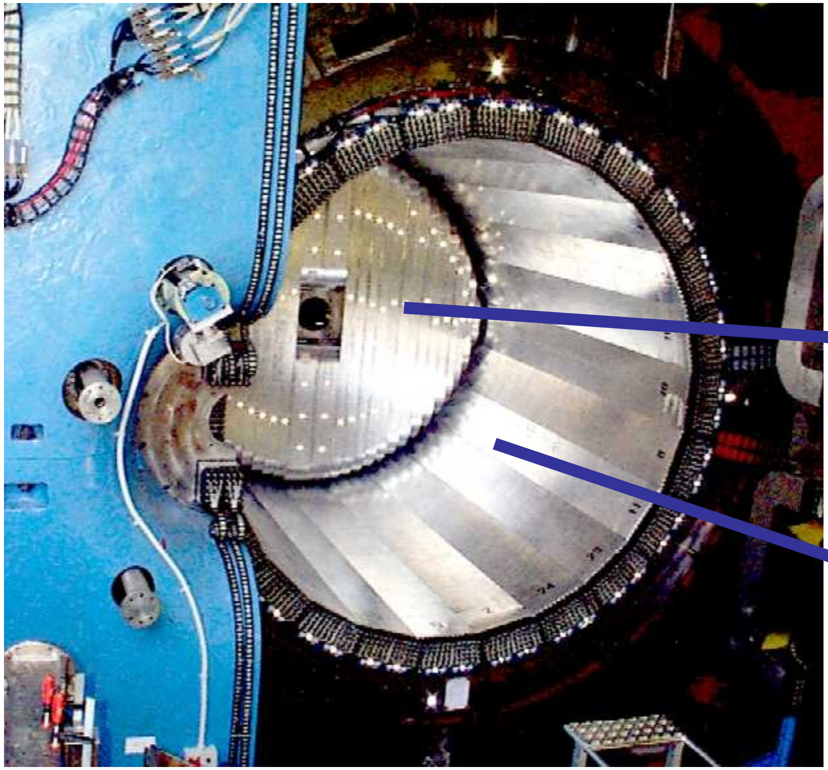
***Excellent momentum resolution***

**Full stereo geometry, 4m diameter, 52140 wires 90% Helium, 10% $iC_4H_{10}$**

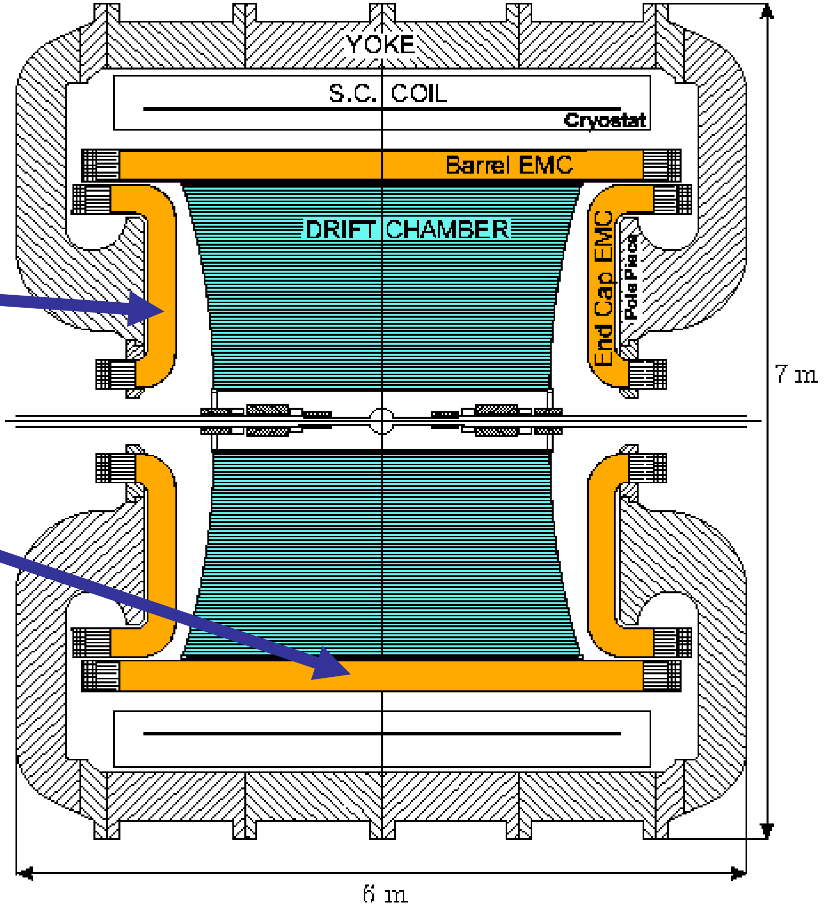


# KLOE Detector

## Electromagnetic Calorimeter



**Pb / scintillating fibers (4880 PMTs)**
**Endcap - Barrel - Modules**




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

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

(Bunch length contribution subtracted from constant term)

***Excellent timing resolution***

# Event Selection: Small Angle (SA)

**Pion tracks at large angles**

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

**a) Photons at small angles**

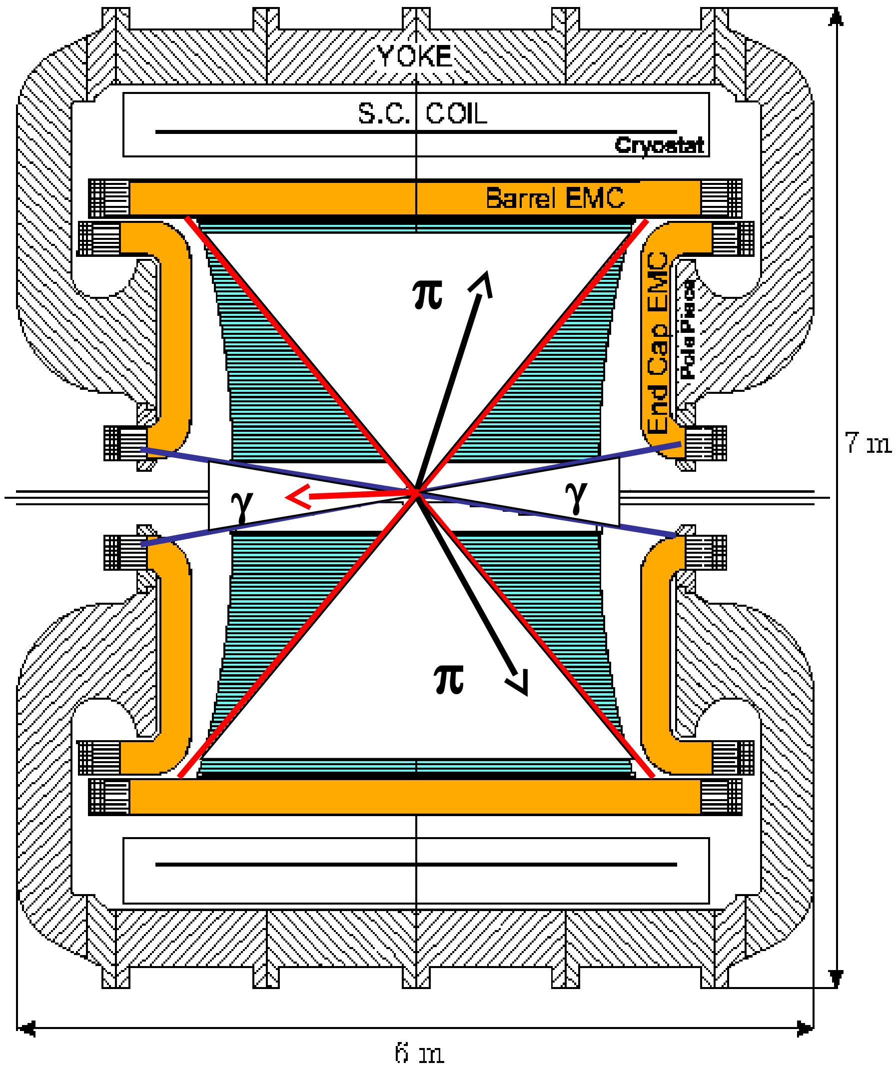
$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

**→ Photon momentum from kinematics:**

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

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination

KLOE



# Event Selection: Large Angle (LA)

**Pion tracks at large angles**

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

**a) Photons at small angles**

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

**→ Photon momentum from kinematics:**

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

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination

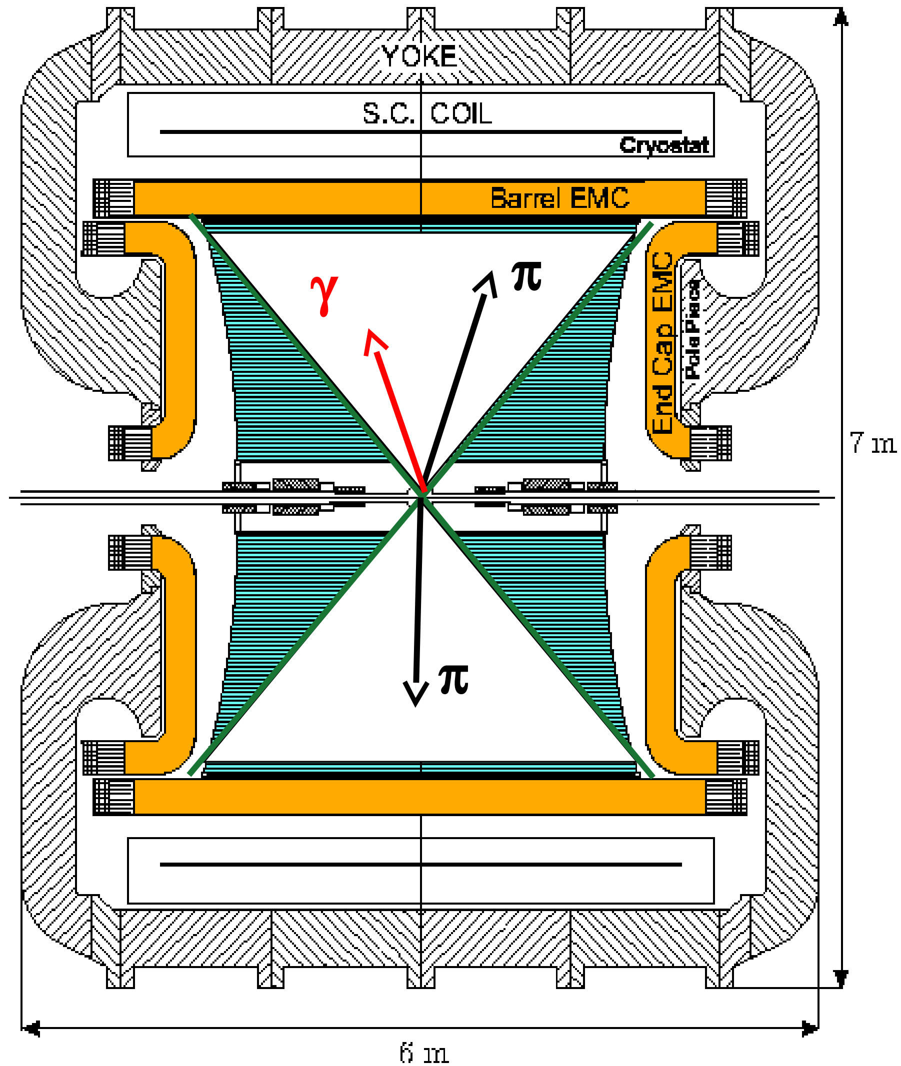
**b) Photons at large angles**

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

**→Photon is explicitly measured in the detector!**

- Threshold region accessible
- Lower signal statistics
- Increased contribution from FSR and $\phi \to \pi^+\pi^-\pi^0$ (use off-peak data)

KLOE



# Luminosity:

KLOE measures *L* with Bhabha scattering

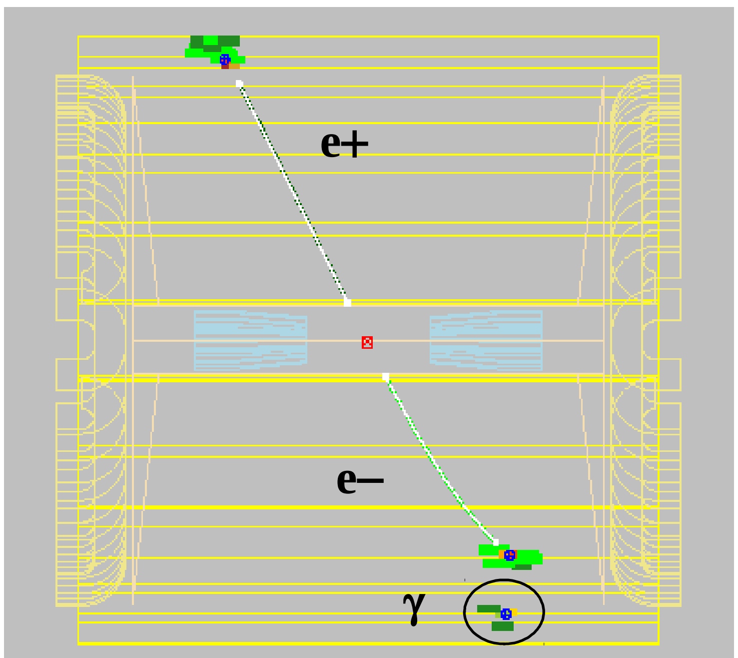
F. Ambrosino et al. (KLOE Coll.)
Eur.Phys.J.C47:589-596,2006

**$55° < \theta < 125°$**

**acollinearity < 9°**

**$p \geq 400$ MeV**

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




Generator used for $\sigma_{eff}$: **BABAYAGA** (Pavia):

*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% | |

# Luminosity:

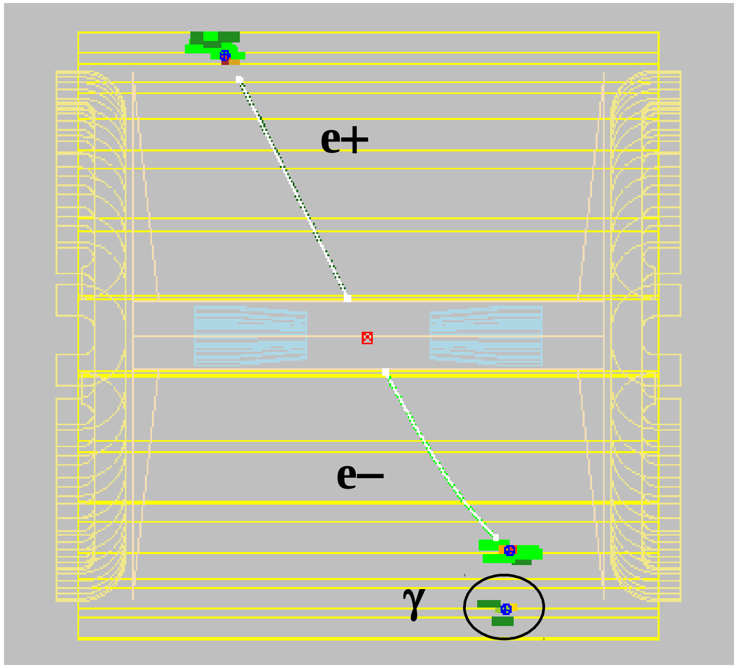
KLOE measures *L* with Bhabha scattering

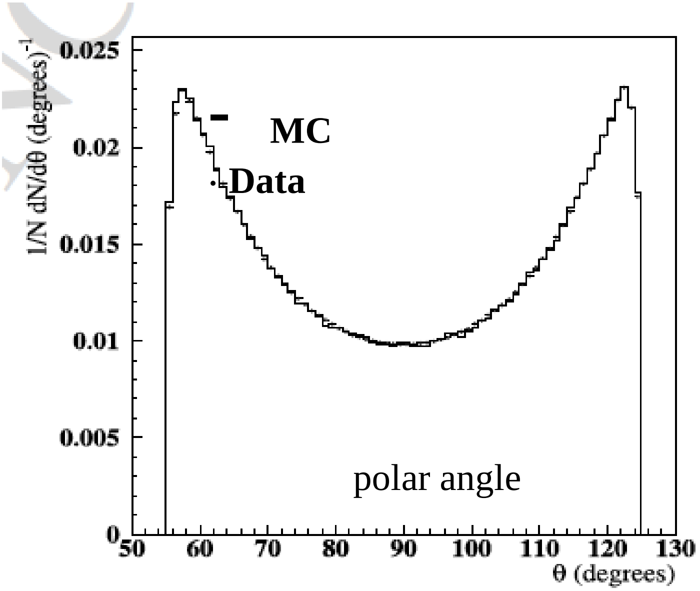
**55° < θ < 125°**

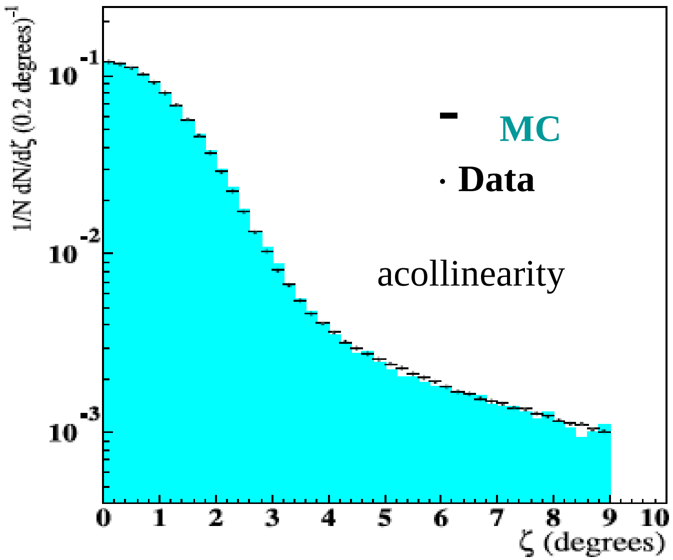
**acollinearity < 9°**

**p ≥ 400 MeV**

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



# KLOE08: Small Angle ($\sqrt{s}$= 1020 MeV)

*Phys. Lett. B 670 (2009) 285*

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

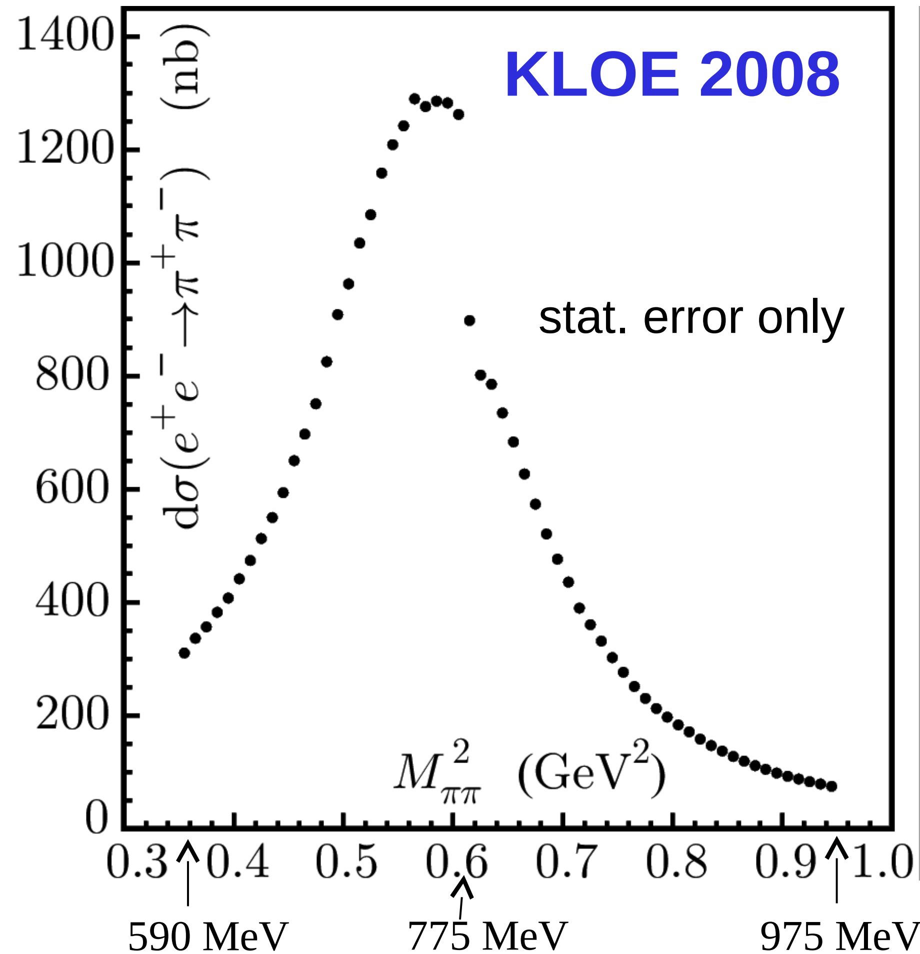
| | |
|---|---|
| Reconstruction Filter | negligible |
| Background | 0.3% |
| Trackmass/Miss. Mass | 0.2% |
| p/e-ID and TCA | negligible |
| Tracking | 0.3% |
| Trigger | 0.1% |
| Acceptance ($\theta_{\pi\pi}$) | 0.2% |
| Acceptance ($\theta_\pi$) | negligible |
| Unfolding | negligible |
| Software 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 treatment | 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 of FSR as function of $(M^0_{\pi\pi})^2$




$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

$a_\mu^{\pi\pi}$(0.35-0.95GeV$^2$) = (387.2 ± 0.5$_{stat}$ ±2.4$_{syst}$ ±2.3$_{theo}$) · $10^{-10}$

# KLOE10: Large Angle ($\sqrt{s}$= 1000 MeV)

*Phys. Lett. B 700 (2011) 102*

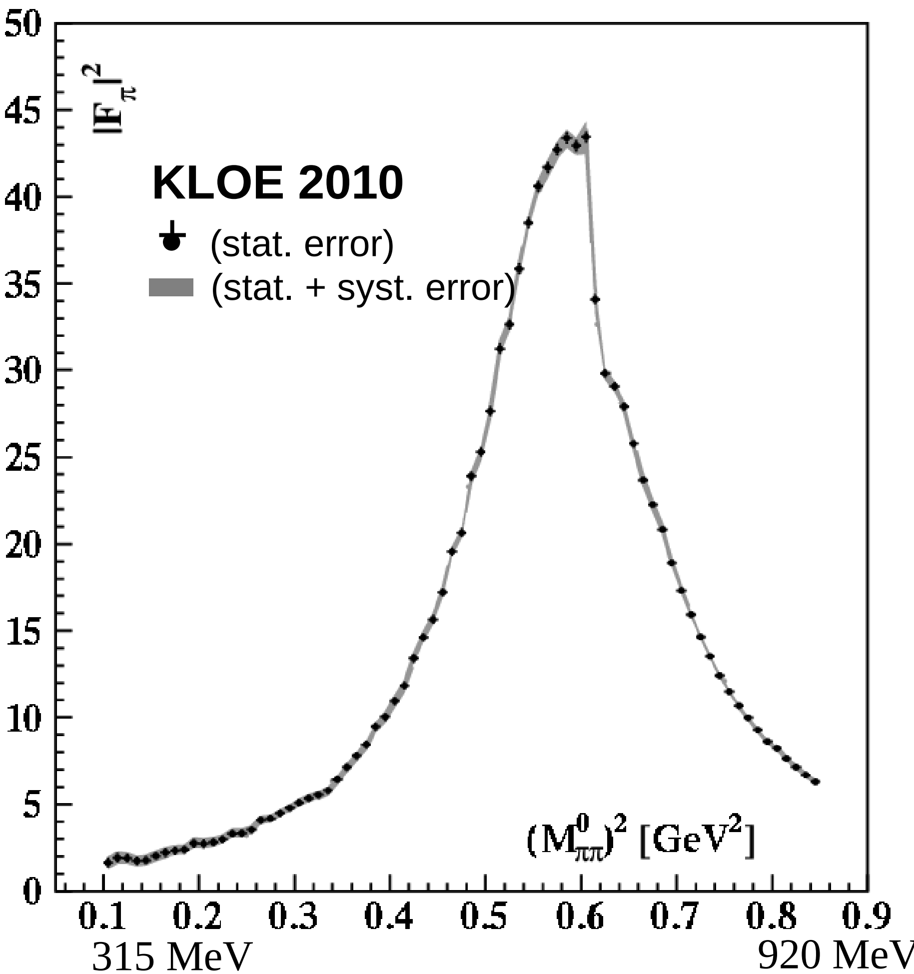



Table of systematic errors on $a_\mu^{\pi\pi}$(0.1-0.85 GeV$^2$):

| | |
|---|---|
| Reconstruction Filter | negligible |
| Background | 0.5% |
| f0+ρπ | 0.4% |
| Ω cut | 0.2% |
| Trackmass | 0.5% |
| p/e-ID and TCA | negligible |
| Tracking | 0.3% |
| Trigger | 0.2% |
| Acceptance | 0.5% |
| Unfolding | negligible |
| Software Trigger | 0.1% |
| Luminosity($0.1_{th} \oplus 0.3_{exp}$)% | 0.3% |

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

| | |
|---|---|
| FSR treatment | 0.8% |
| Radiator H | 0.5% |
| Vacuum polarization | 0.1% |

theoretical fractional error on $a_\mu$ = 0.9 %

Dispersion Integral:

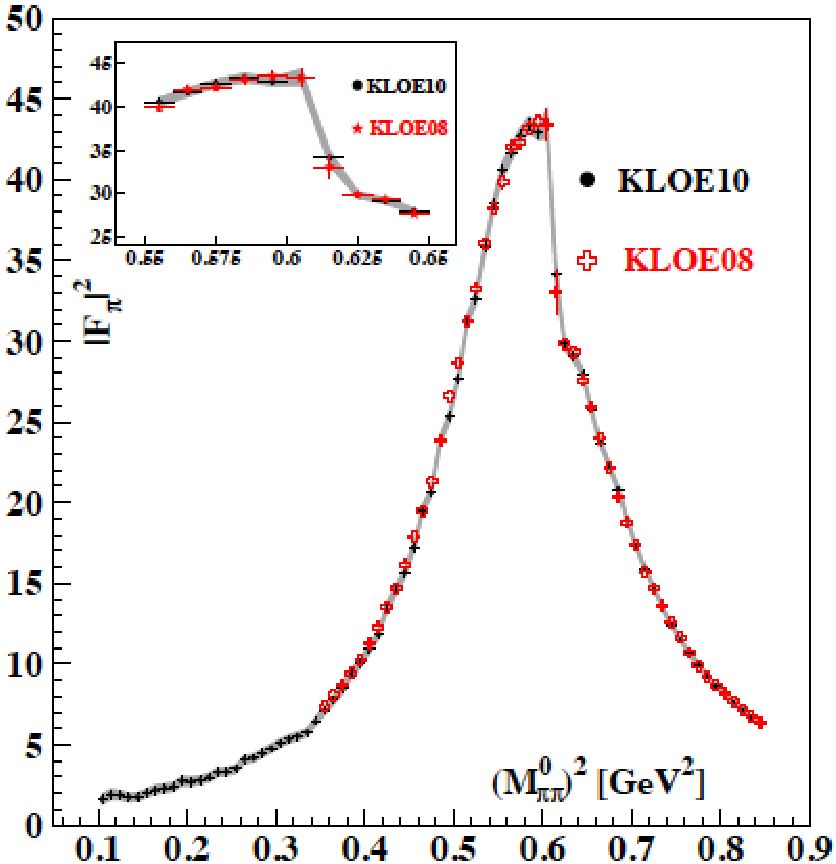
$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s)K(s)ds$$

**$a_\mu^{\pi\pi}$(0.1-0.85 GeV$^2$) = (478.5 ± 2.0$_{stat}$±5.0$_{syst}$ ±4.5$_{theo}$) · $10^{-10}$**

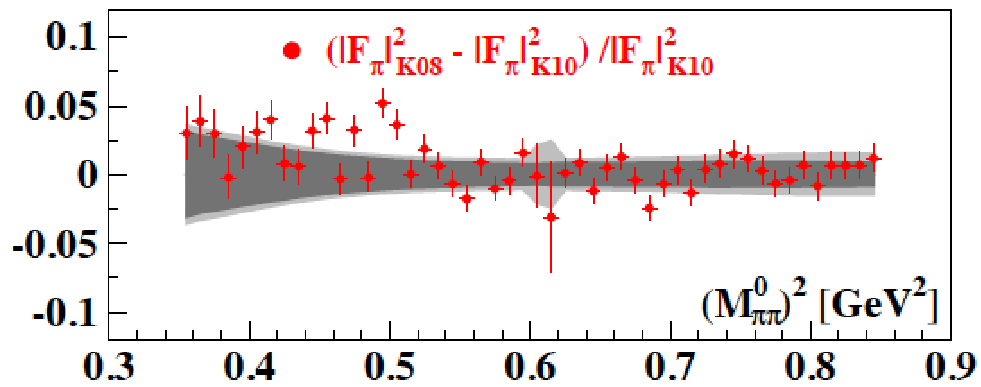
0.4% 1.0% 0.9%

# Comparison of results: KLOE10 vs KLOE08

KLOE08 result compared to KLOE10:




Fractional difference:




Good agreement with KLOE08, especially above 0.5 GeV²

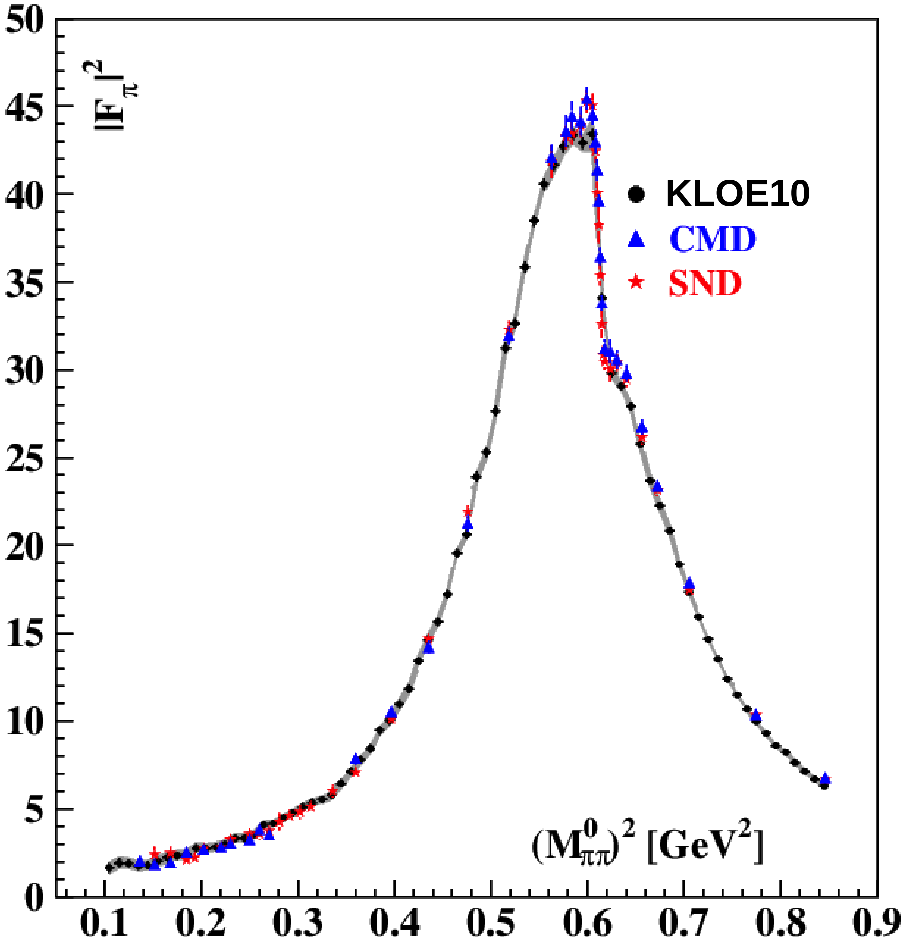
Combination of KLOE08 and KLOE10:

**$a_\mu^{\pi\pi}$(0.1-0.95 GeV²) = (488.6±6.0) · $10^{-10}$**

KLOE covers ~70% of total $a_\mu^{HLO}$ with a fractional total error of 1.2%

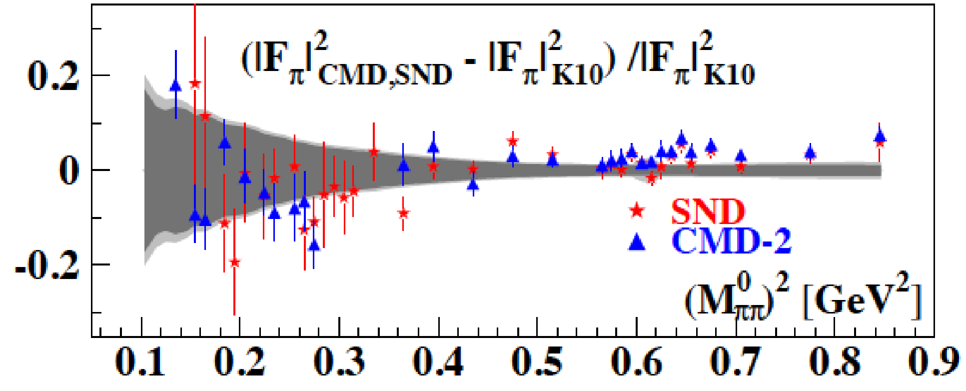
# Comparison of results: KLOE10 vs CMD-2/SND

CMD and SND results compared to KLOE10: Fractional difference




SND: M.N. Achasov et al., J. Exp. Theor. Phys. 103, 480 (2006)

CMD-2: R.R. Akhmetshin et al., PLB648, 28 (2007)

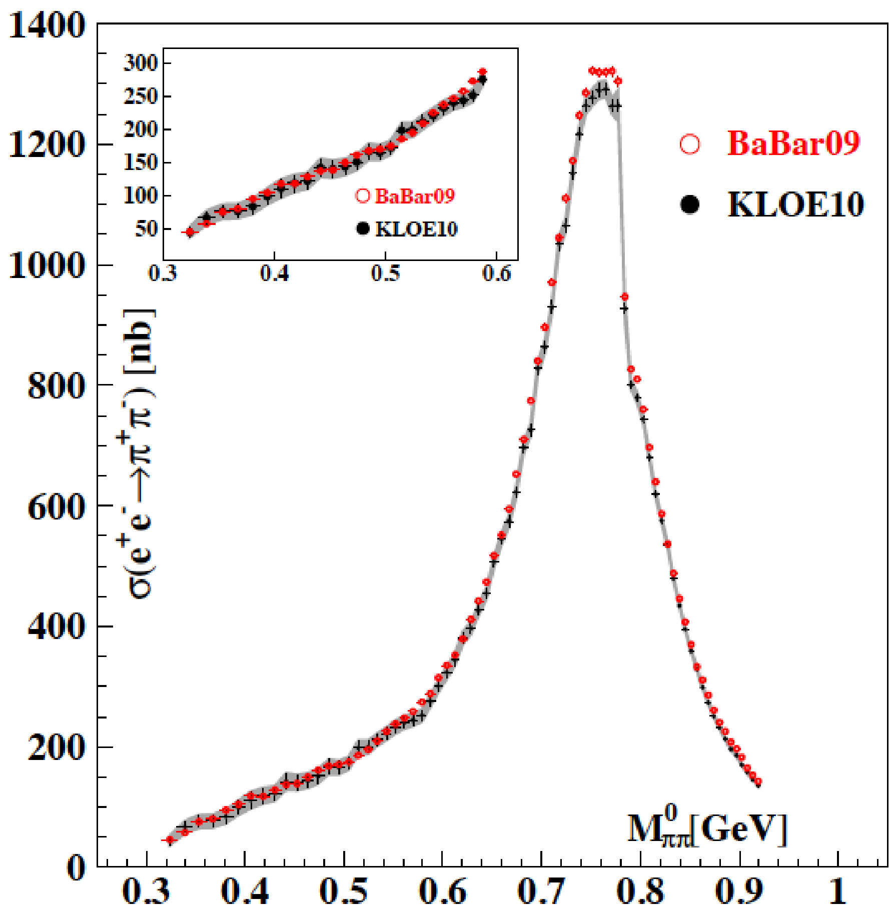



*band: KLOE10 error*

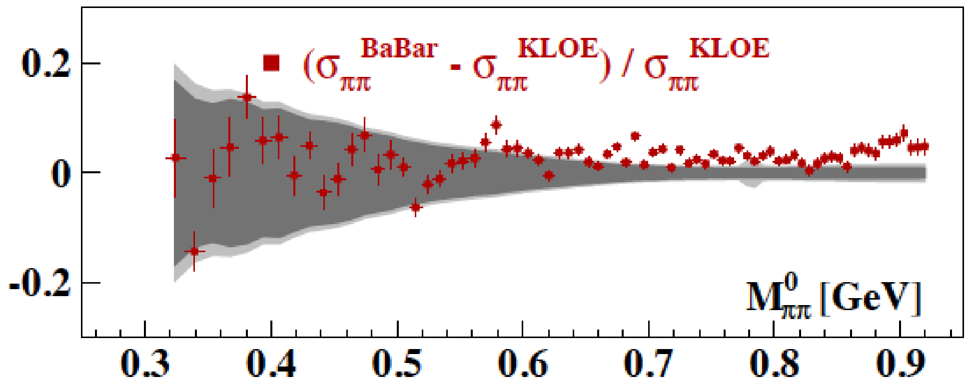
Below the ρ peak good agreement with CMD-2/SND.
Above the ρ peak KLOE10 slightly lower

# Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference




BaBar: B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009)




*band: KLOE10 error*

*Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above 0.6 GeV*

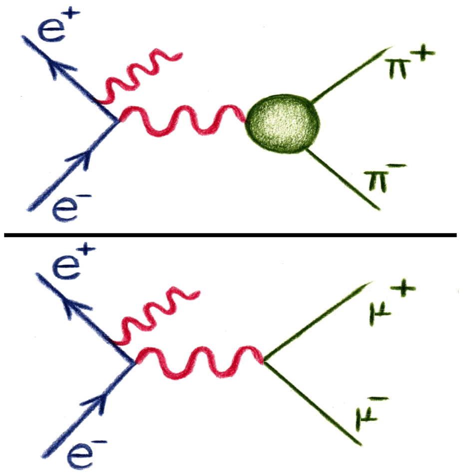
# KLOE12: New $\sigma_{\pi\pi}$ measurement from $\pi\pi\gamma/\mu\mu\gamma$

*Phys. Lett. B 720 (2013) 336–343*

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).

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

kinematical factor ($s_{\mu\mu}^{Born}$ / $s_{\pi\pi}^{Born}$) — meas. quantities




Many systematic effects drop out:

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

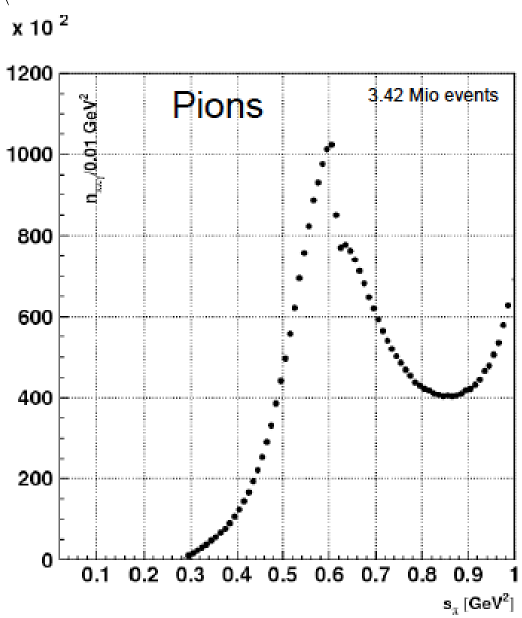
Data Sample:

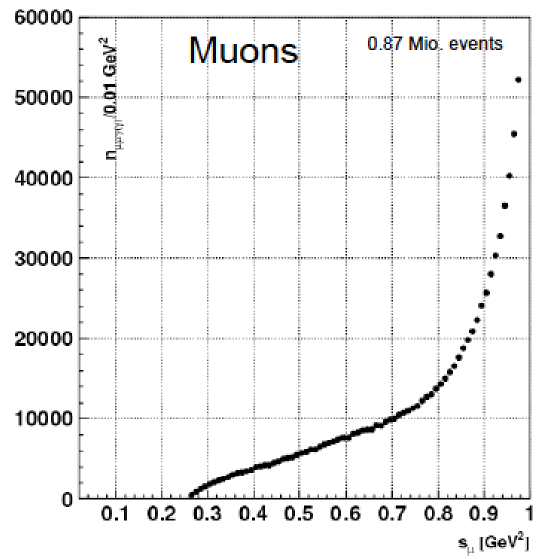
- 239.2 $pb^{-1}$ of 2002 data (the same used in KLOE08 analysis)
- photon at small angle
- 0.87 Million $\mu\mu\gamma$ events
- 3.4 Million $\pi\pi\gamma$ events

# KLOE12: New $\sigma_{\pi\pi}$ measurement from $\pi\pi\gamma/\mu\mu\gamma$

- *Important to get a good $\pi/\mu$ separation, especially in the $\rho$ region where $\sigma_{\pi\pi}/\sigma_{\mu\mu} \sim 10$*
  - Obtained ~1% uncertainty in the muon selection
  - $\pi/\mu$ separation cross-checked with three different methods ($M_{Track}$ fit, Kinematic fit, cut on $\sigma_{MTrack}$)
- $\mu\mu\gamma$ (and $\pi\pi\gamma$) efficiencies (Tracking,Triggering,PID) done on measurement data
- Excellent measurement/simulation agreement for many kinematic variables: $M_{Track}$, tracks, and $\gamma$ polar angle, etc...

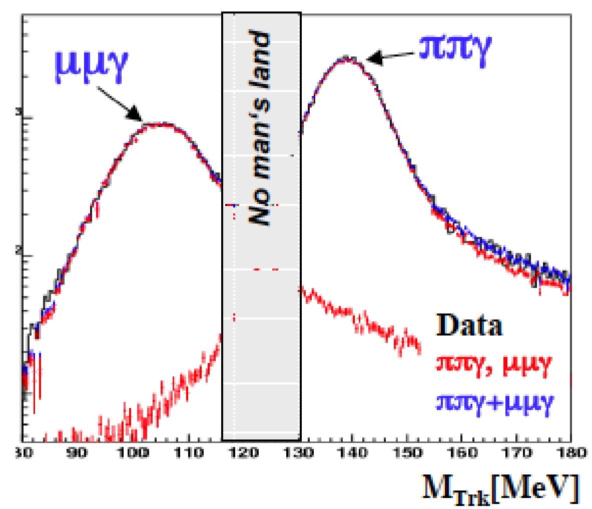
$$\left(\sqrt{s}-\sqrt{|\vec{p}_+|^2+M_{Track}^2}-\sqrt{|\vec{p}_-|^2+M_{Track}^2}\right)^2-\left(\vec{p}_++\vec{p}_-\right)^2=M_\gamma^2=0$$




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

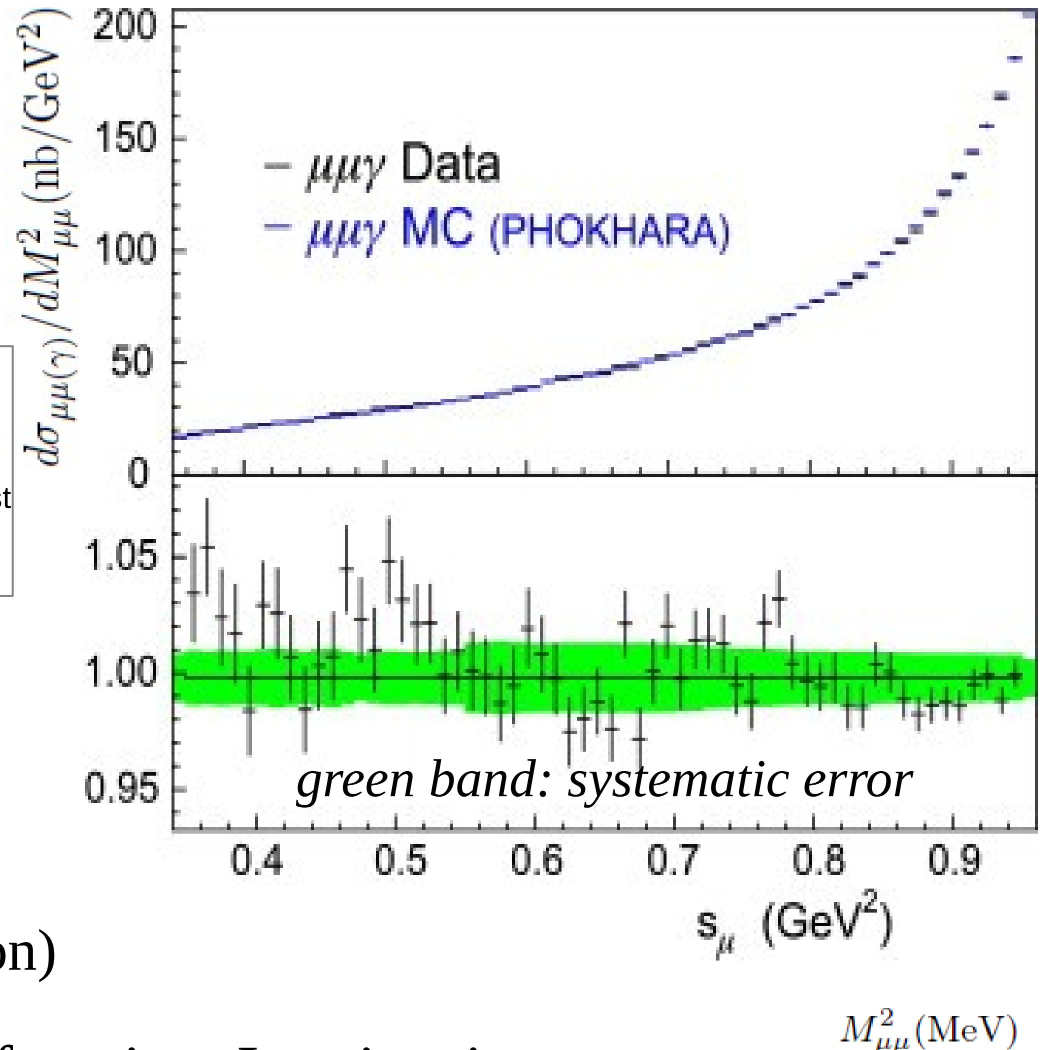
- *muons: $M_{Track}$ < 115 MeV*
- *pions : $M_{Track}$ > 130 MeV*



# μμγ cross section: meas/simu comparison

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

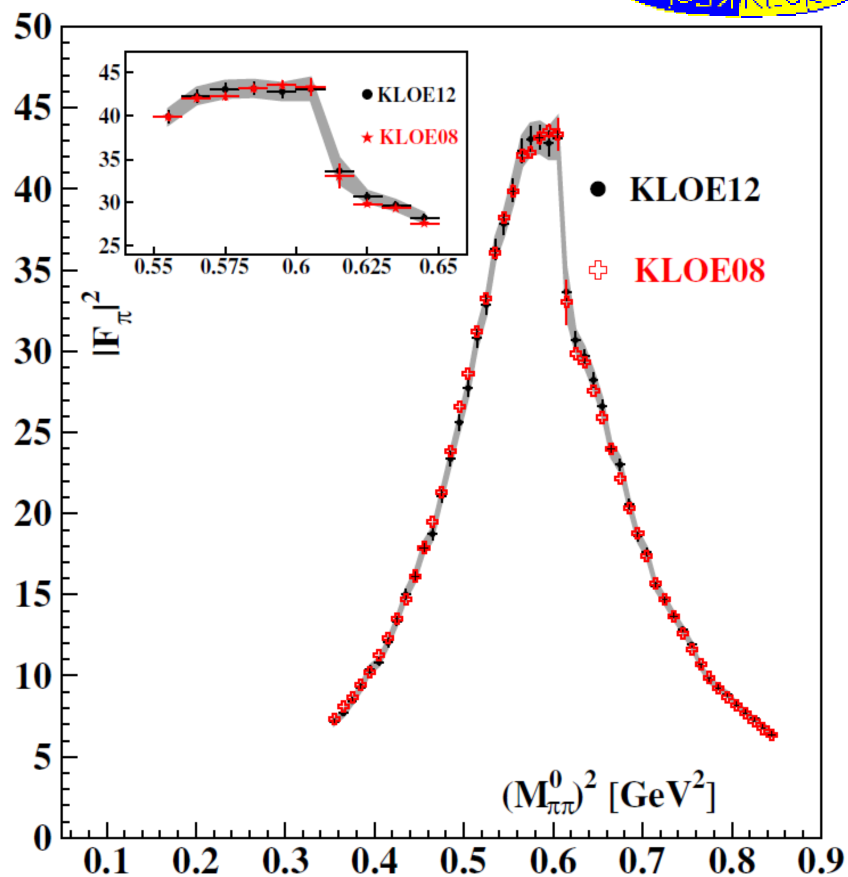
$$\frac{d\sigma^{DATA}_{\mu\mu\gamma(\gamma)}}{d\sigma^{MC}_{\mu\mu\gamma(\gamma)}} = 0.998 \pm 0.001_{stat} \pm 0.011_{syst}$$




- The systematic error has been averaged on $M^2_{\mu\mu}$
- Good agreement with PHOKHARA MC (NLO Calculation)
- Consistency check of Radiator function, Luminosity, etc…

# KLOE12 result: $|F_\pi|^2$ and comp. with KLOE08

| | KLOE08 | KLOE12 |
|---|---|---|
| Syst. errors (%) | $\Delta^{\pi\pi}a_\mu$ abs | $\Delta^{\pi\pi}a_\mu$ ratio |
| Reconstruction Filter | negligible | negligible |
| Background subtraction | 0.3 | 0.6 |
| Trackmass | 0.2 | 0.2 |
| Particle ID | negligible | negligible |
| Tracking | 0.3 | 0.1 |
| Trigger | 0.1 | 0.1 |
| Unfolding | negligible | negligible |
| Acceptance ($\theta_{\pi\pi}$) | 0.2 | negligible |
| Acceptance ($\theta_\pi$) | negligible | negligible |
| Software Trigger (L3) | 0.1 | 0.1 |
| Luminosity | 0.3 ($0.1_{th} \oplus 0.3_{exp}$) | - |
| $\sqrt{s}$ dep. of $H$ | 0.2 | - |
| Total exp systematics | 0.6 | 0.7 |
| Vacuum Polarization | 0.1 | - |
| FSR treatment | 0.3 | 0.2 |
| Rad. function $H$ | 0.5 | - |
| Total theory systematics | 0.6 | 0.2 |
| Total systematic error | 0.9 | 0.7 |

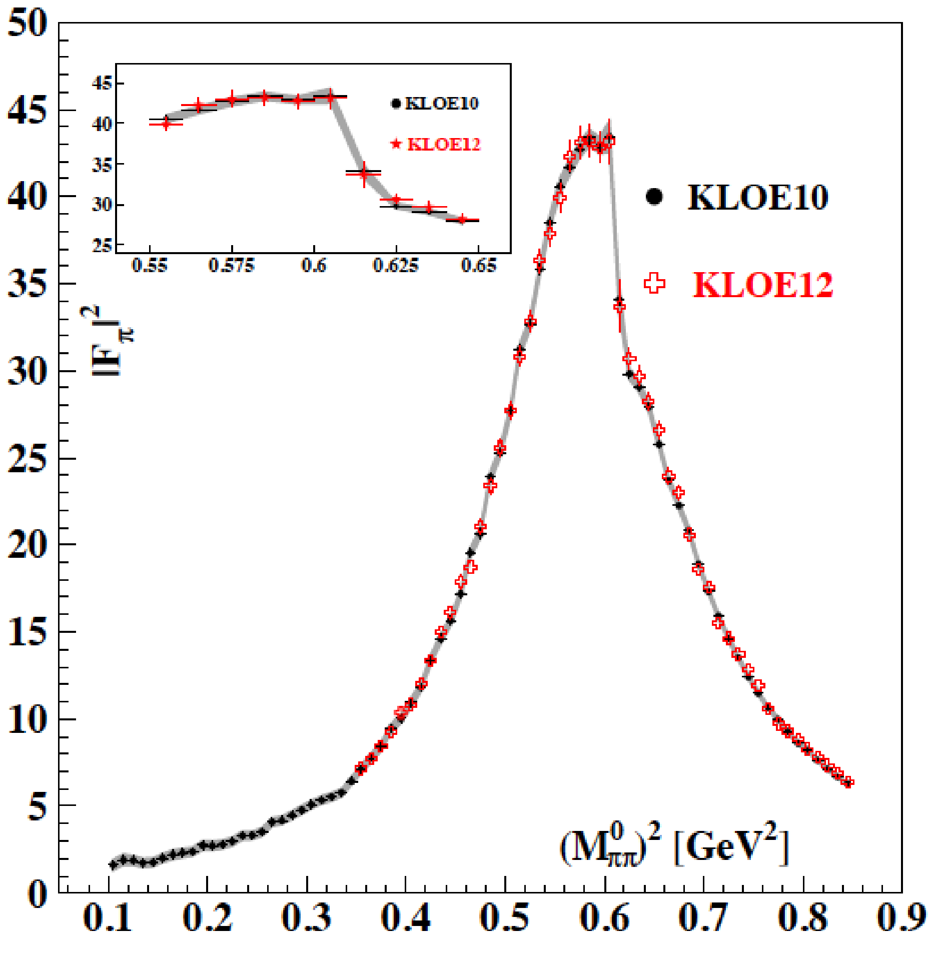



| | $a_\mu^{\pi\pi}(0.35 - 0.95\ \mathrm{GeV}^2) \times 10^{10}$ |
|---|---|
| KLOE12 | $385.1 \pm 1.1_{stat} \pm 2.7_{sys+theo}$ |
| KLOE08 | $387.2 \pm 0.5_{stat} \pm 3.3_{sys+theo}$ |

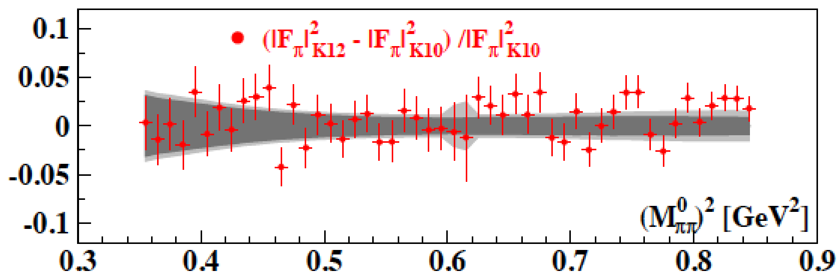
- Good agreement btw the two measurements, especially in the ρ region.
- Improved syst. error in KLOE12. Theoretical error strongly reduced
- These two measurements are not independent (ππγ sample is the same)...

# Comparison of results: KLOE12 vs KLOE10

KLOE12 result compared to KLOE10:




Fractional difference:



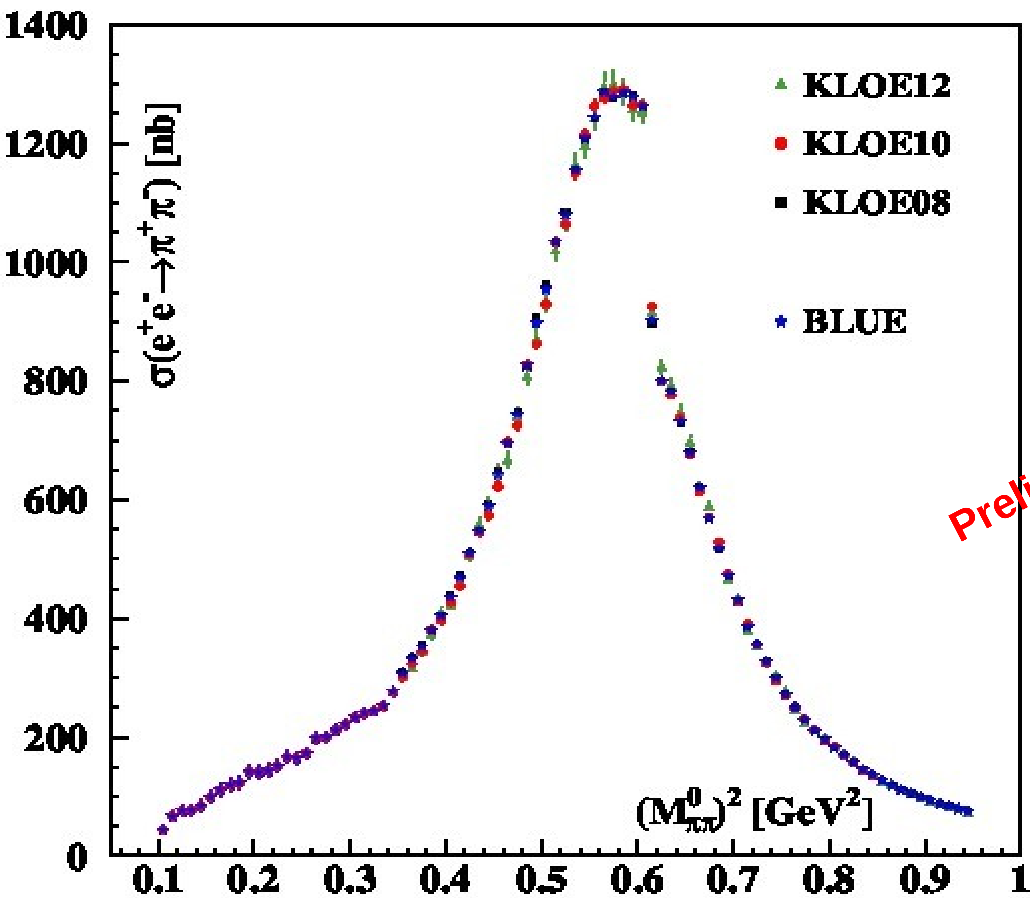

*band: KLOE10 error*

Excellent agreement between these two independent measurements!

| Analysis | $a_\mu^{\pi\pi}(0.35 - 0.85\ \text{GeV}^2) \times 10^{10}$ |
|---|---|
| KLOE12 | $377.4 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}$ |
| KLOE10 | $376.6 \pm 0.9_{\text{stat}} \pm 3.3_{\text{sys+theo}}$ |

# Preliminary combination of KLOE08,10,12

by Stefan E. Müller



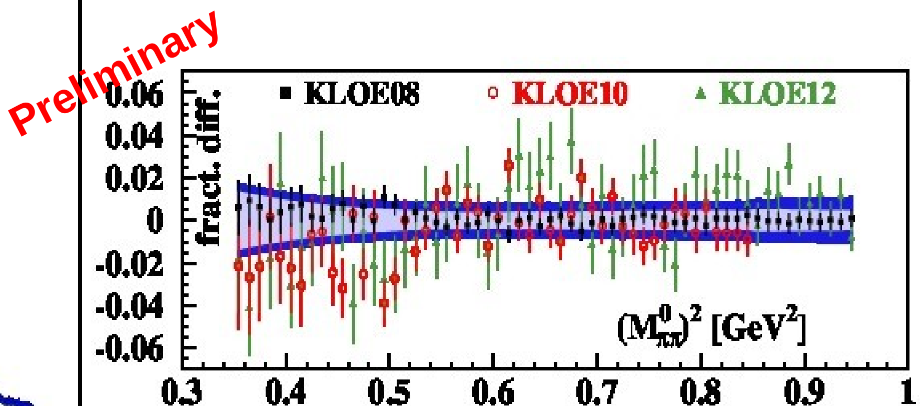

$a_\mu^{\pi\pi}(0.1\text{-}0.95\ \mathrm{GeV}^2) = (487.8 \pm 5.7) \cdot 10^{-10}$

$a_\mu^{\pi\pi}(0.1\text{-}0.85\ \mathrm{GeV}^2) = (378.1 \pm 2.8) \cdot 10^{-10}$

Combination of KLOE08,KLOE10, and KLOE12 using the Best Linear Unbiased Estimate (BLUE) based on:

A. Valassi, NIM A500 (2003) 391

G. D'Agostini, NIM A346 (1994) 306




$$\frac{|F_{\mathrm{KLOEXX}}|^2 - |F_{\mathrm{BLUE}}|^2}{|F_{\mathrm{BLUE}}|^2}$$

Grey band: Stat. errors

Blue band: Stat. + Syst. errors

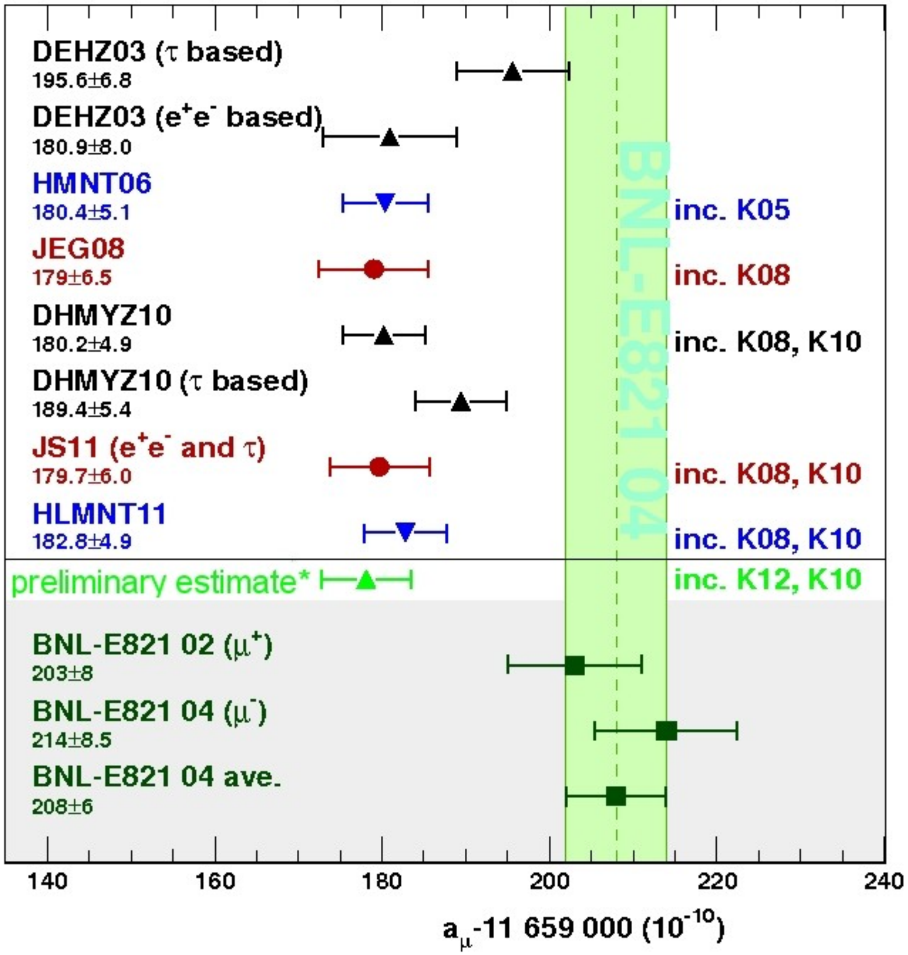
# $a_\mu=(g_\mu-2)/2$:

Theoretical predictions compared to the BNL result

- Discrepancy between $a_\mu^{SM}$ and $a_\mu^{EXP}$ at the 3.5σ level is confirmed by the KLOE measurement of the ratio of cross sections ππγ/μμγ

- KLOE12 is in agreement with previous KLOE measurements and confirms this discrepancy.

- Previous tension between $e^+e^-$ and τ data is reduced by 1σ [F. Jegerlehner et al., Eur.Phys.J. C71 (2011) 1632, ρ-γ treatment]




* Our extrapolation based on DHMYZ10

Results from new g-2 experiments (at FNAL and JPARC) will be very interesting!

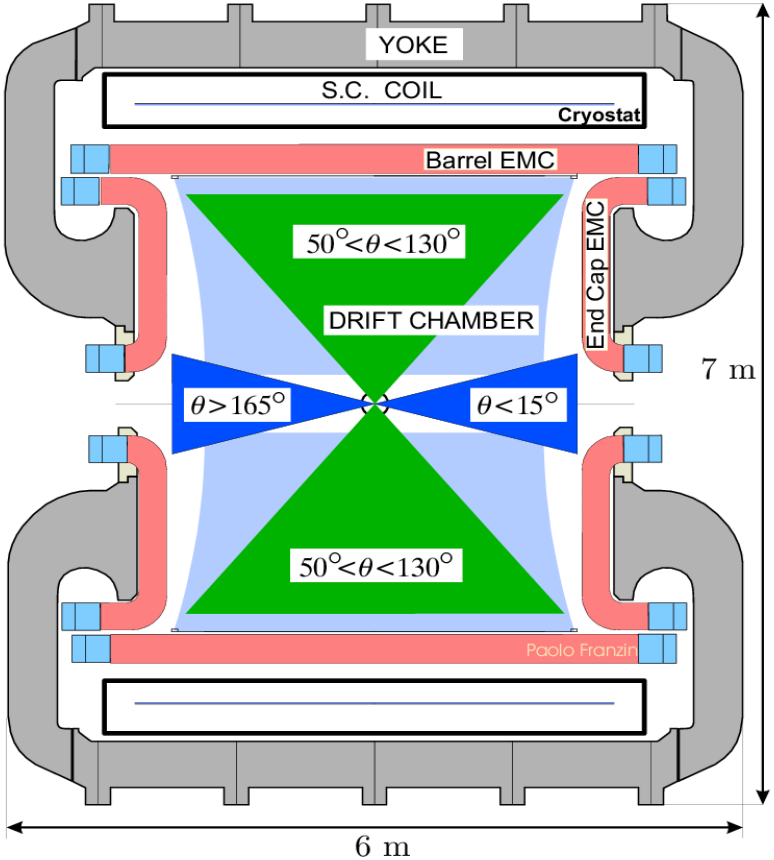
# Conclusion

- During the last 10 years KLOE has performed a series of precision measurements with ISR which confirmed a 3σ discrepancy between $a_\mu^{SM}$ and the value measured at BNL
- The published measurements (KLOE05, KLOE08, KLOE10), normalized to Bhabha events, have allowed us to measure $a_\mu^{\pi\pi}$ in the region below 1 GeV with **~1%** total error
- A new measurement (KLOE12) of $|F_\pi|^2$ from the $\pi\pi\gamma/\mu\mu\gamma$ ratio (based on 240 $pb^{-1}$) with **0.7%** systematic error has been published (**PLB720 (2013) 336–343**)
- It doesn't rely on specific theoretical input (like luminosity and radiator function) and allows a stringent cross check of the published measurements with comparable systematic error
- Good agreement for $\mu\mu\gamma$ cross section with NLO QED calculation (PHOKHARA MC) and for $|F_\pi|^2$ with previous KLOE measurements (confirming 3σ discrepancy on $a_\mu$)

# Outlook

- Still more than 1.5 $fb^{-1}$ of KLOE data on tape. This would represent a factor ~4 improvement in statistics.

- A new round of data taking with KLOE-2 upgraded detector is expected to begin Fall 2013.



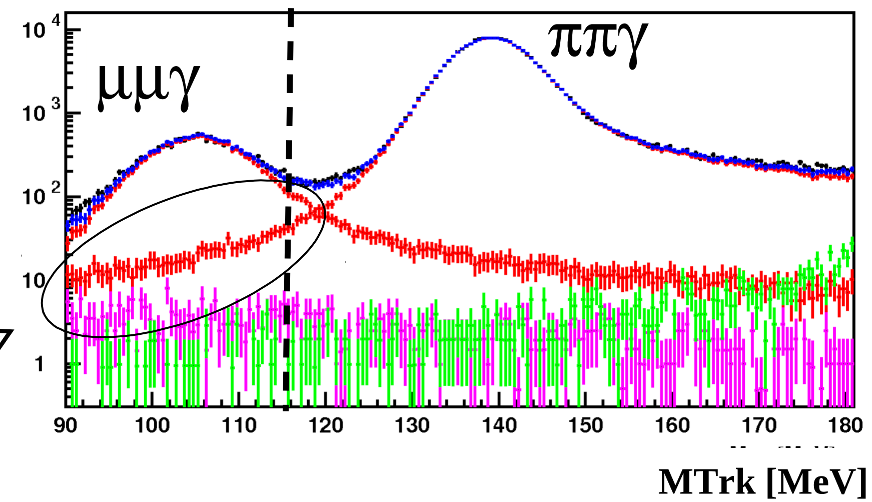

# SPARE SLIDES

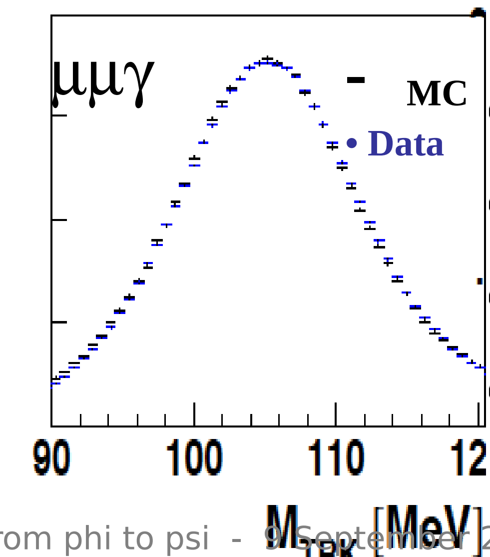
# $\pi/\mu$ separation: control of $\pi\pi\gamma$ $M_{TRK}$ tail

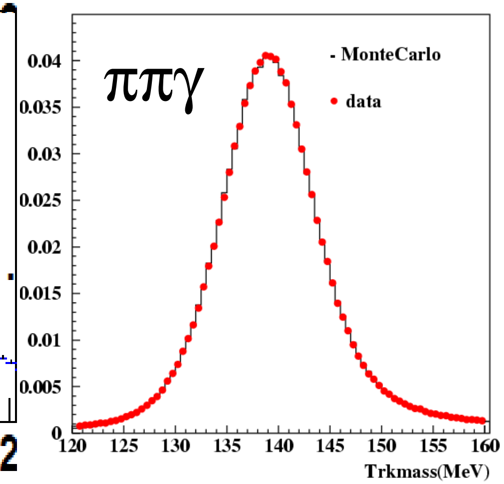
- A careful work has been done to achieve a control of ~1% in the muon selection, especially ~0.6 GeV2 ($\rho$ peak) where $\pi/\mu \sim 10$.
- $\pi\pi\gamma$ % background to $\mu\mu\gamma$ signal (MTRK<115 MeV) is ~15% at $\rho$ peak

$\Rightarrow$ $\pi\pi\gamma$ MTRK tail in the $\mu\mu\gamma$ region must be well under control.

- $\pi\pi\gamma$ MTRK tail tuned using $\phi \to \pi+\pi-\pi0$ control sample.
- Excellent agreement on MTRK ($\pi\pi\gamma$ and $\mu\mu\gamma$) distributions

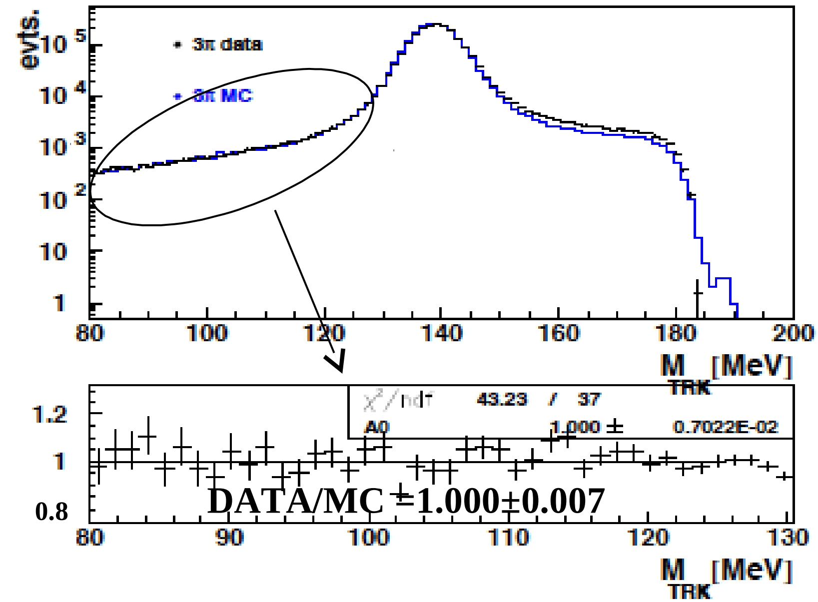


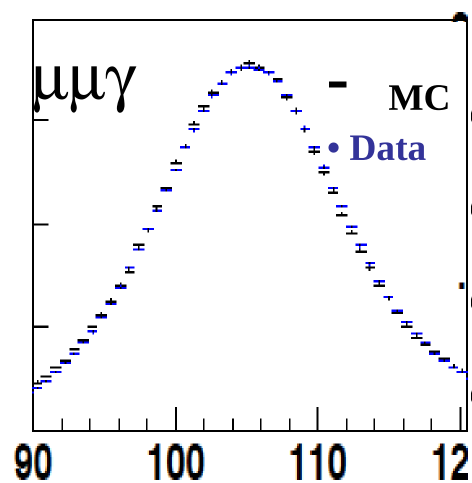



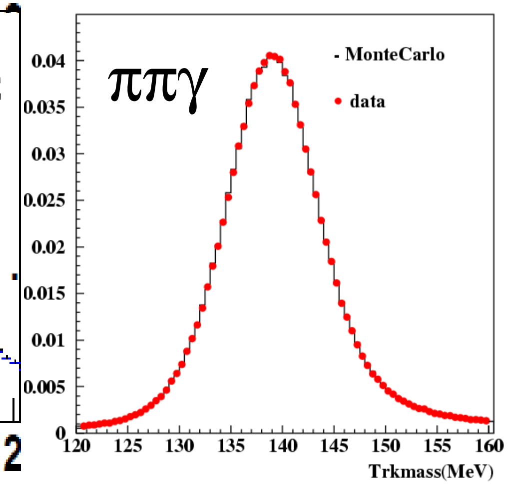



# π/μ separation: control of ππγ MTRK tail

- A careful work has been done to achieve a control of ~1% in the muon selection, especially ~0.6 GeV2 (ρ peak) where π/μ ~10.
- ππγ % background to μμγ signal (MTRK<115 MeV) is ~15% at ρ peak ⇒ ππγ MTRK tail in the μμγ region must be well under control.
- ππγ MTRK tail tuned using φ→π+π–π0 control sample.
- Excellent agreement on MTRK (ππγ and μμγ) distributions



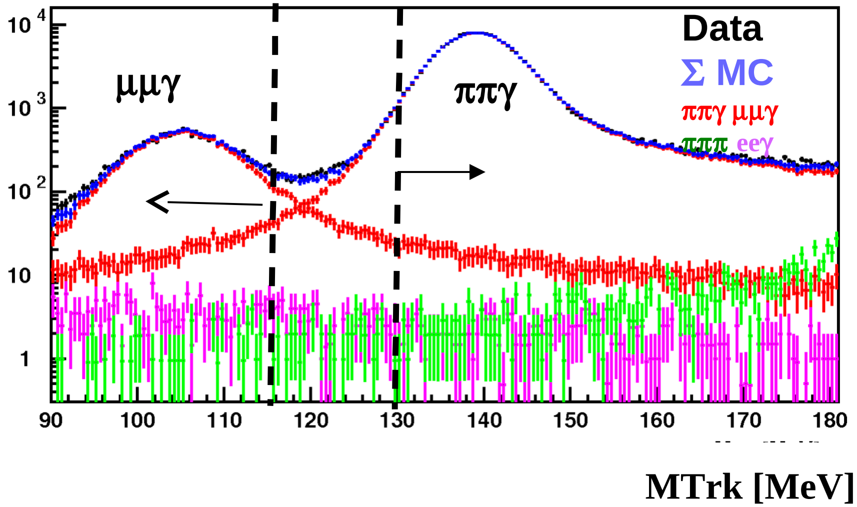



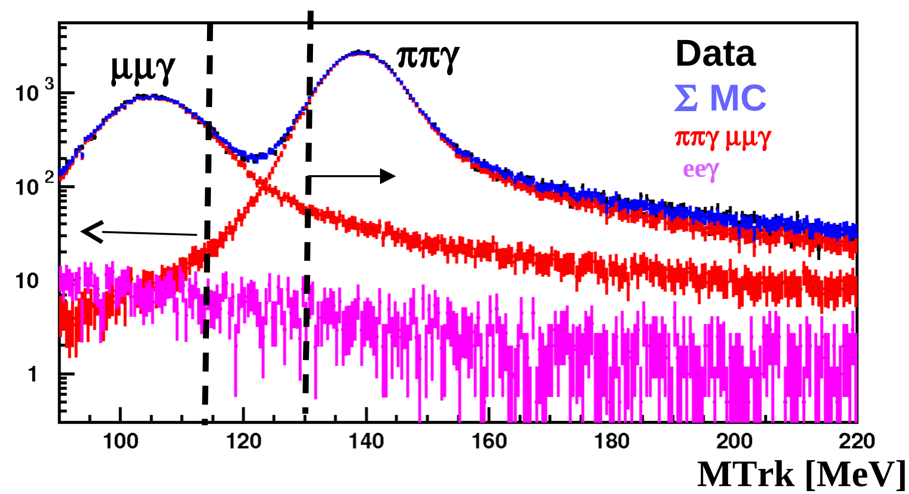
# Background:

**Main backgrounds estimated from MC shapes fitted to data distribution in MTrk ($\pi\pi\gamma/\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)**

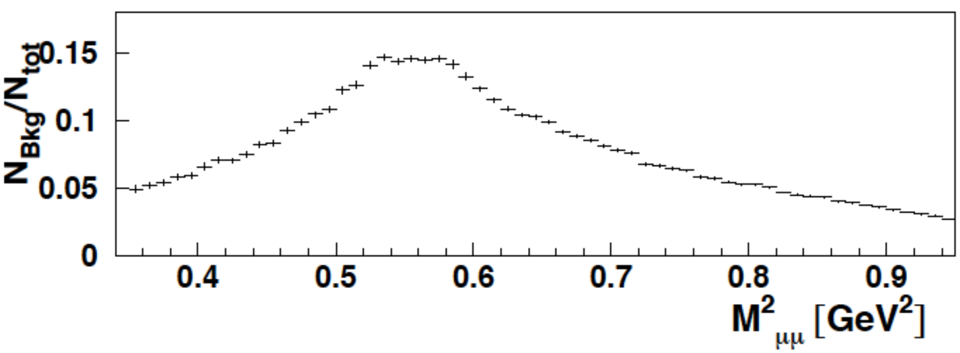
**$0.60 < M_{\pi\pi}^2 < 0.62$ GeV$^2$,** $\chi^2$/ndof = 158/180



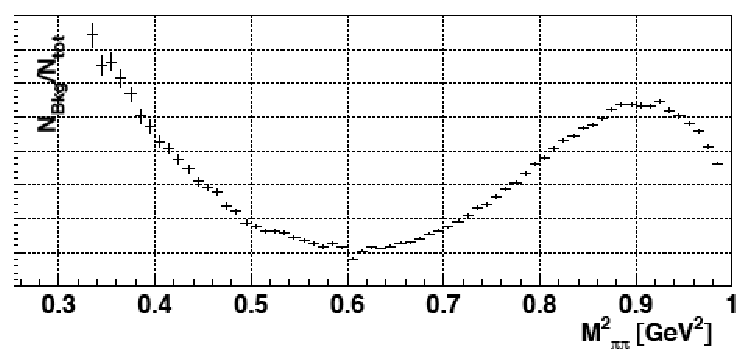

**$0.84 < M_{\pi\pi}^2 < 0.86$ GeV$^2$** $\chi^2$/ndof = 179/258




## Tot % bckg to μμγ




## Tot % bckg to ππγ

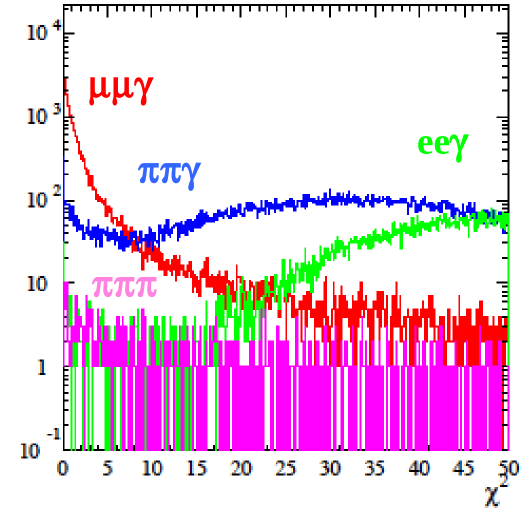



1%

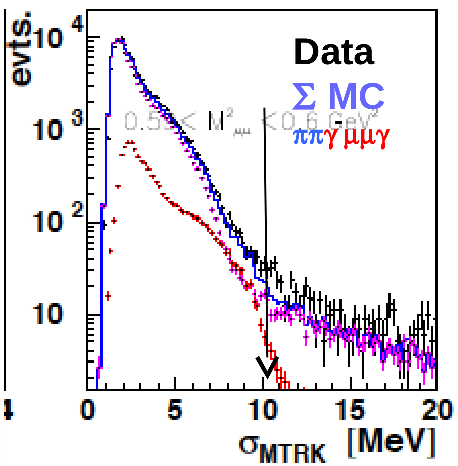
- Systematic error on μμγ due to background 1% in the ρ peak

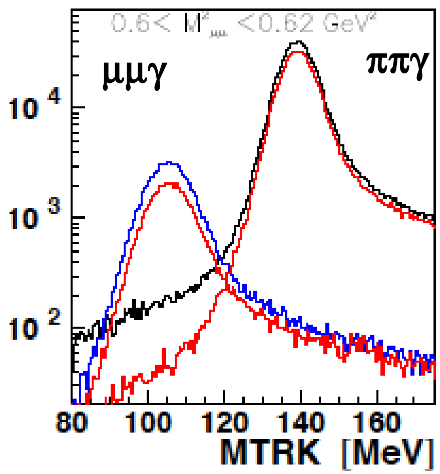
# Cross check of π/μ separation

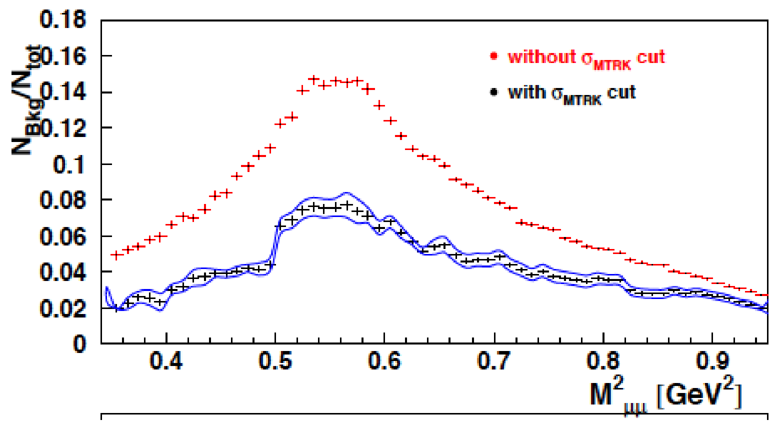
- The π/μ separation has been crosschecked with two different (and independent) methods:




- A kinematic fit, in the hypothesis of 2 body+1γ (ISR) events.
- A cut on the quality of the fitted tracks, parametrized by σMTRK

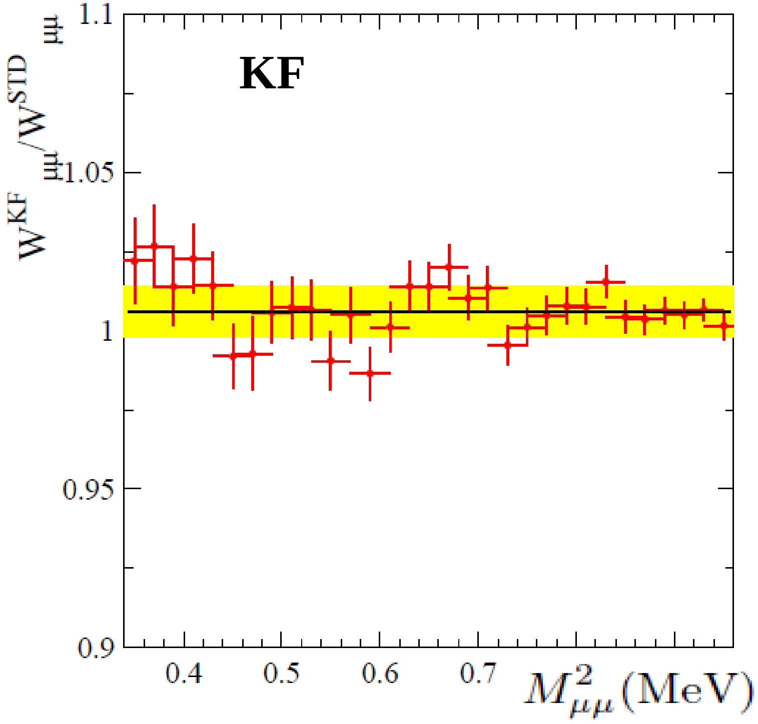


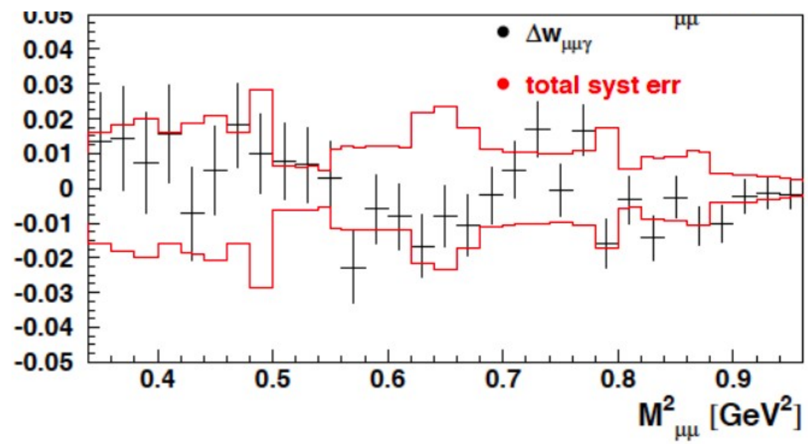



# Results of σMTRK and KF cross checks

π/μ separation obtained with these methods well in agreement with the standard one




σMTRK

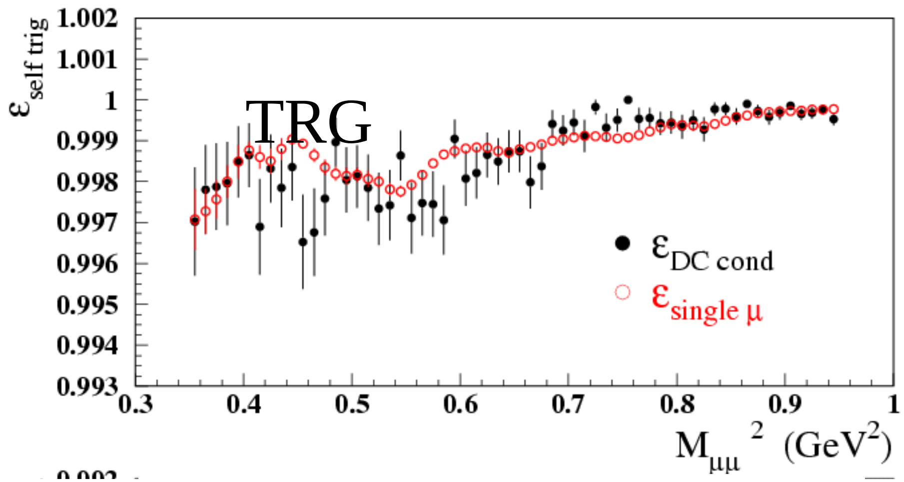



- The ratio of the muon yields from kinematic fit method with $\chi 2 \mu\mu < 10$ to the muon yields from standard method, fitted with the constant. Yellow bar is the systematic error of the kinematic fit method

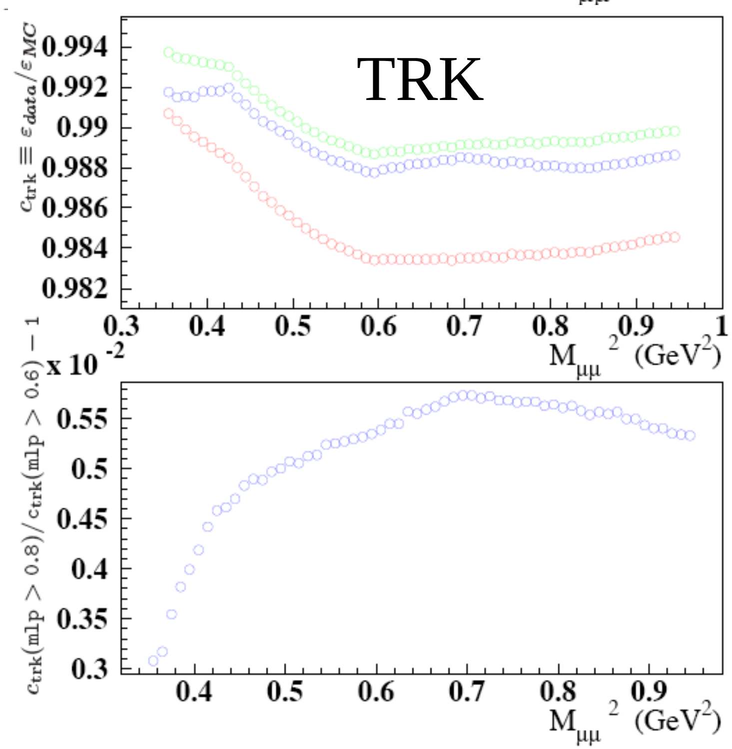
- Black dots are the differences of μμγ yields obtained with std and σMTRK methods; Red line is the total systematic error of the difference.

# Efficiencies for μμγ

- The efficiencies of μμγ (and ππγ) for trigger,tracking, and PID have been carefully studied with data, using the single particle method and taking into account the kinematics  by MC.
- Differently from ππγ, where the 3π sample was used to get the data/MC corrections, for μμγ there is no a direct control sample and we had used mmg itslef with lose selection criteria.




- All the efficiencies has been found to be above 96% with ~1% data/MC correction as maximum.



# Extracting σππ and |F⊥||2 from

**a) Via absolute Normalisation to Bhabha events (KLOE05,08,10):**

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

dσ□ □ γ(γ)/dM2 is obtained by subtracting background from observed event spectrum, divide by selection efficiencies, and ***int. luminosity***:

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

Obtain σ□ □ from (ISR) - radiative cross section ds□ □ γ(γ)/dM2 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 σ(e+e- → □ +□ -)

**b) Via bin-by-bin Normalization to rad. Muon events (New measurement!)**

# Radiative Corrections

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

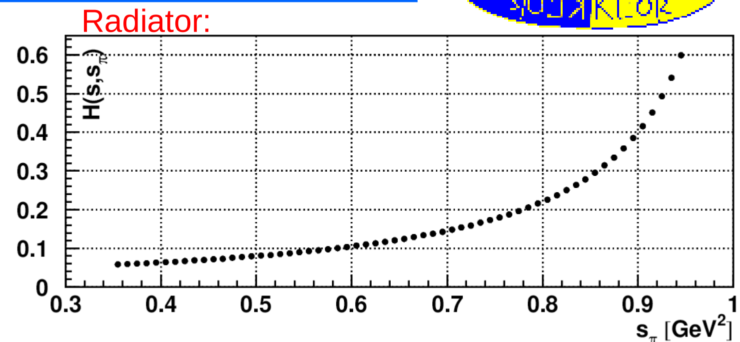
- **ISR-Process calculated at NLO-level**

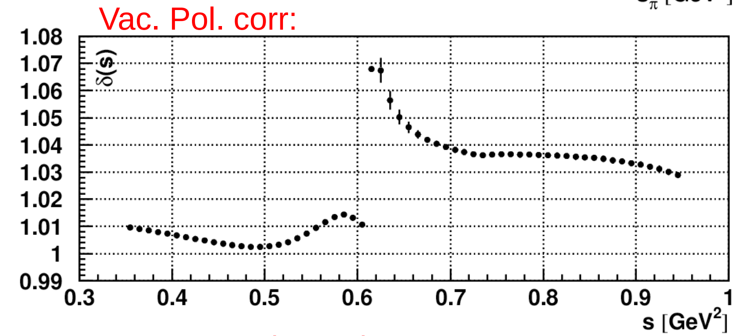
  **PHOKHARA** generator

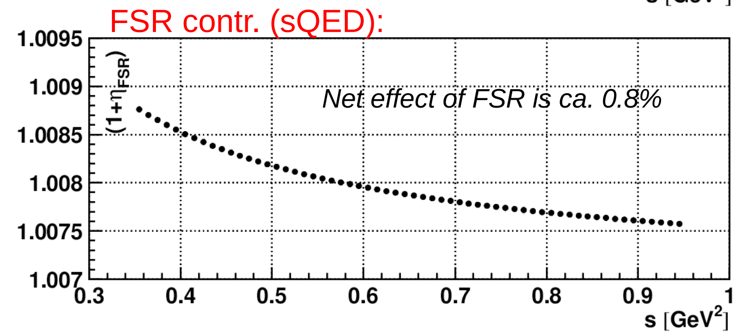
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

**Precision: 0.5%**

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




## Radiative Corrections:

**i) Bare Cross Section**

divide by Vacuum Polarization d(s)=(a(s)/a(0))2

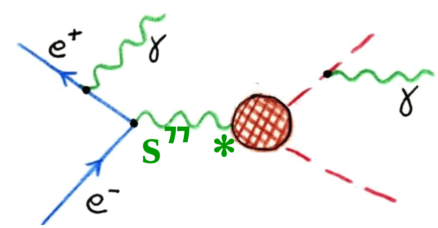
from F. Jegerlehner

**ii) FSR**

Cross section spp must be incl. for FSR for use in the dispersion integral of am


FSR corrections have to be taken into account in the efficiency eval. (Acceptance, MTrk) and in the mapping **sπ → sγ***

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




$s^{\gamma\gamma}$ * > sπ

# LA Event Selection (KLOE10)

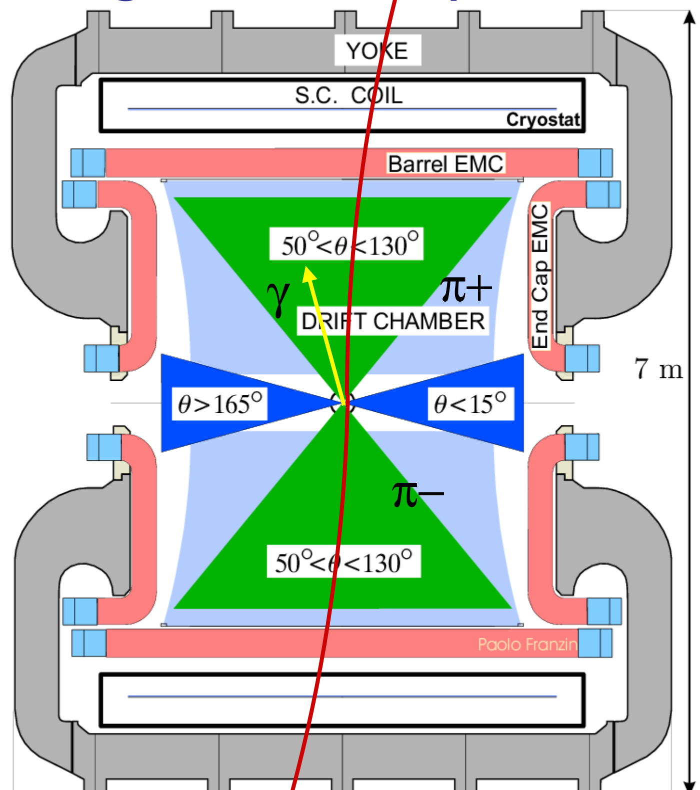
**2 pion tracks at large angles**
50o < θp <130o

**Photons at large angles**
50o < θγ < 130o

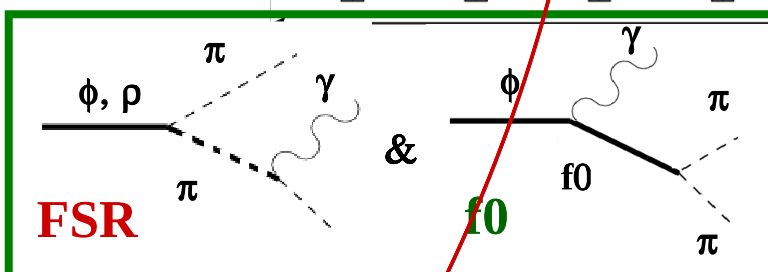
- ✓ **independent complementary analysis**
- ✓ **threshold region (2mπ)2 accessible**
- ✓ **γISR photon detected (4-momentum constraints)**

- ✓ **lower signal statistics**
- ✓ **larger contribution from FSR events**
- ✓ **larger φ → π+π−π0 background contamination**
- ✓ **irreducible background from φ decays (φ → f0 γ → ππ γ)**

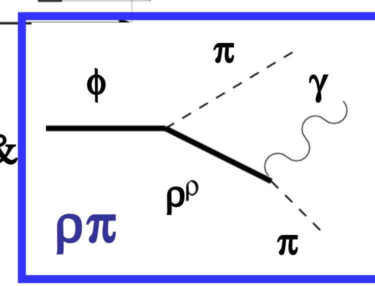
**At least 1 photon with** 50o< θg <130o
**and Eg > ⩧ 0 MeV ⩧ photon detected**




**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 (KLOE10)

**2 pion tracks at large angles**
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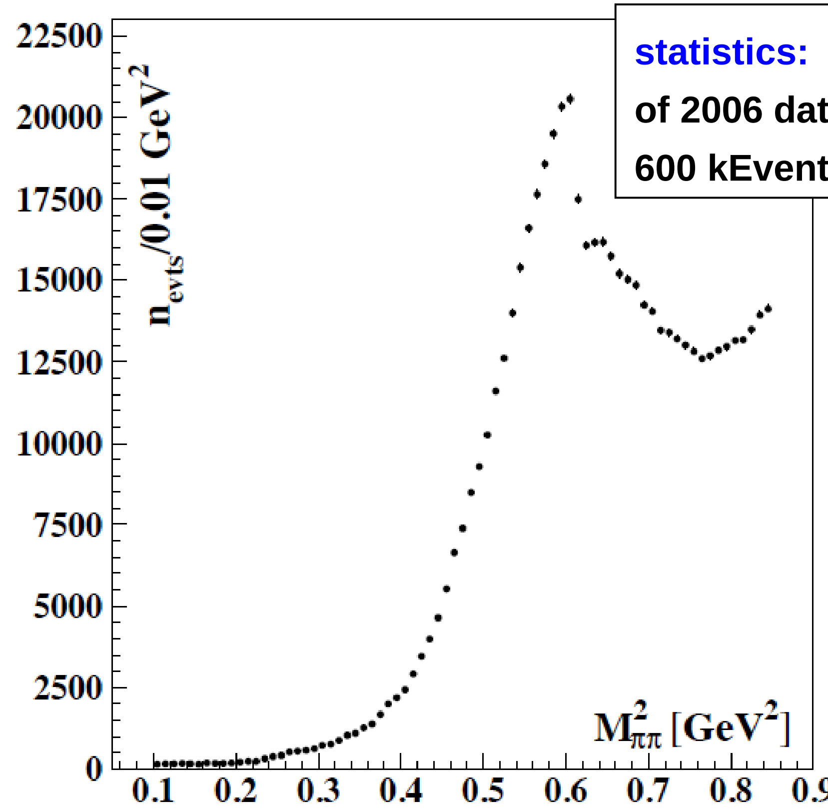
- ✓ **irreducible background from φ decays (φ → f0 γ → ππ γ)**

**At least 1 photon with** 50o< θg <130o
**and Eg > ≑ 0 MeV ≑ photon detected**




**statistics:** **233pb-1**
**of 2006 data**
**600 kEvents**

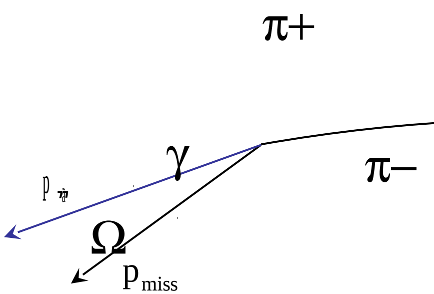
Use data sample taken at √s≅**1000 MeV**,
20 MeV below the f-peak

# Event selection

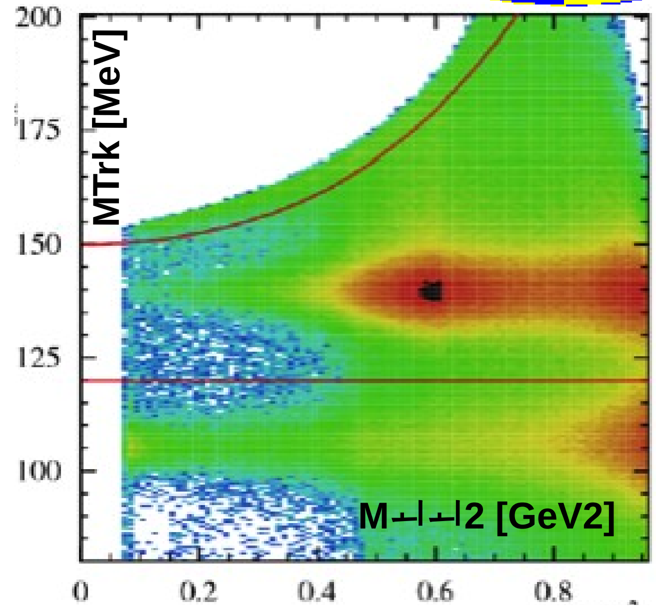
- Experimental challenge: Fight background from
  - e+e− → μ+μ− γ,
  - e+e− → e+e− γ
  - $\phi \to \pi^+\pi^-\pi^0$

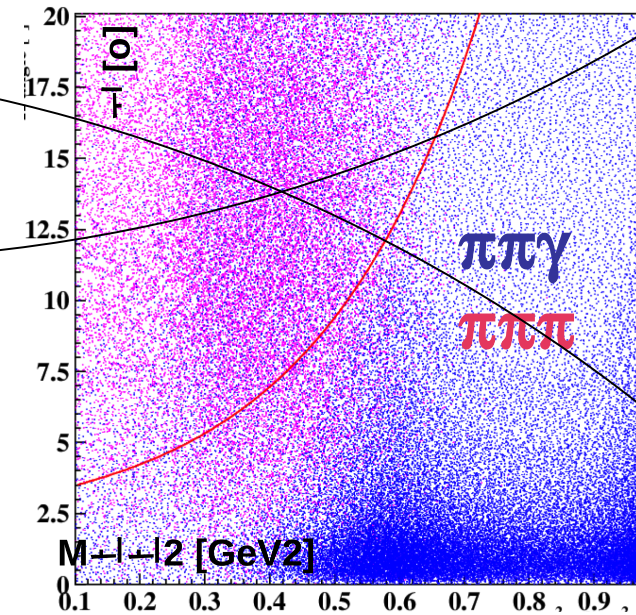
separated by means of kinematical cuts in *trackmass MTrk* and the angle Ω between the photon and the missing momentum

$$p_{miss} = -(p_+ + p_-)$$




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.

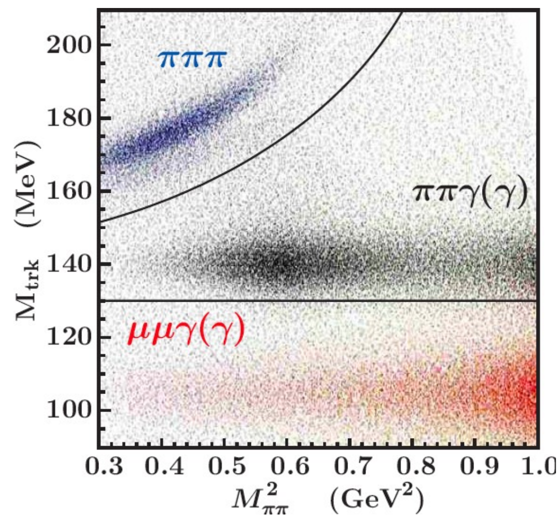


# Event Selection

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

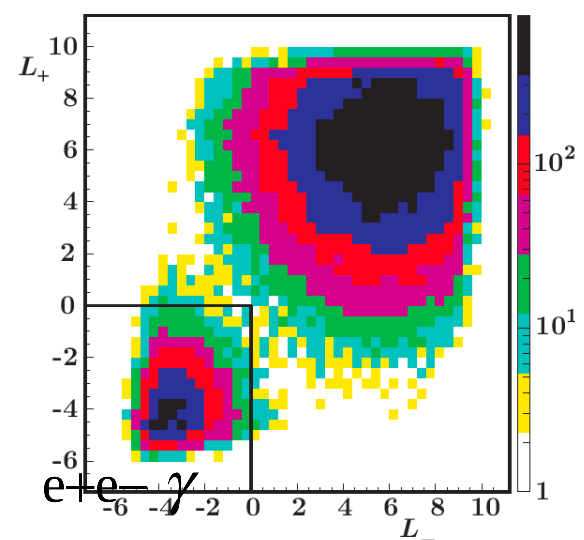
  removed using kinematical cuts in *trackmass MTrk* - $M_{\pi\pi}^2$ plane




*MTrk:* defined by 4-momentum conservation assuming 2 charged particle (of same mass) and one **γ** in the final state

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

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



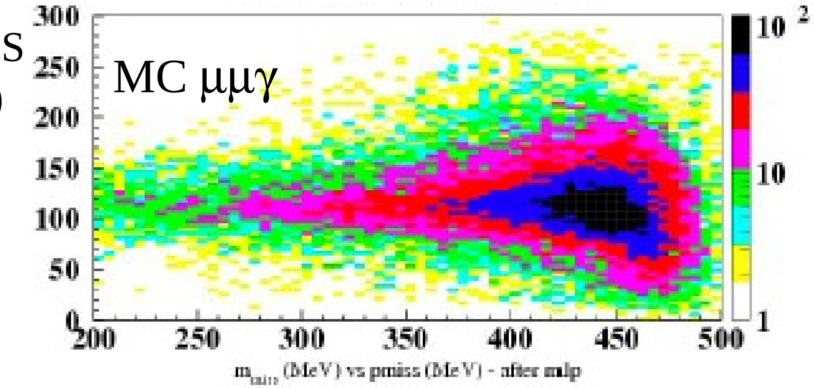

To further clean the samples from radiative Bhabha events, we use a particle ID estimator (PID) for each charged track based on Calorimeter Information and Time-of-Flight.

# μ Tracking efficiency

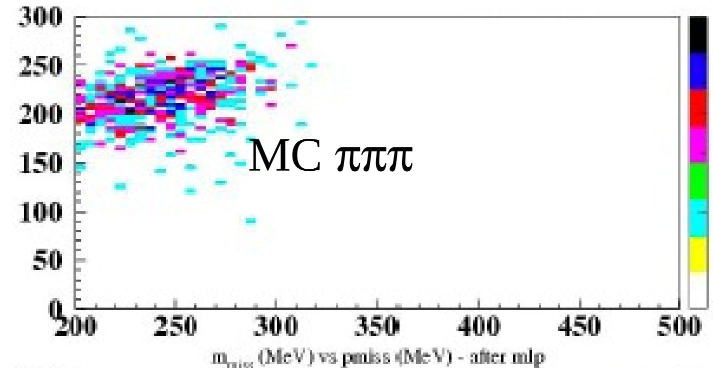
Since for muons we don't have an control sample (like 3π for pions), we have refiltered all 2002 data set (240 pb-1) according to:

1) a "good" tagging track extrapolating back to the IP, which satisfies the trigger associated to a cluster with LogrL>0, 1 and MLP>0.7
2) 1 neutral prompt clusters not associated to the tagging track with E>50 MeV. A constraint on the photon energy and time to further clean the sample, and improve missing momentum and energy
3) The tagging track must have p > 450 MeV (to reject π+π–π0 events), the *candidate* track must have mass (built from 4 momentum conservation) 50 <Mmiss < 130 MeV

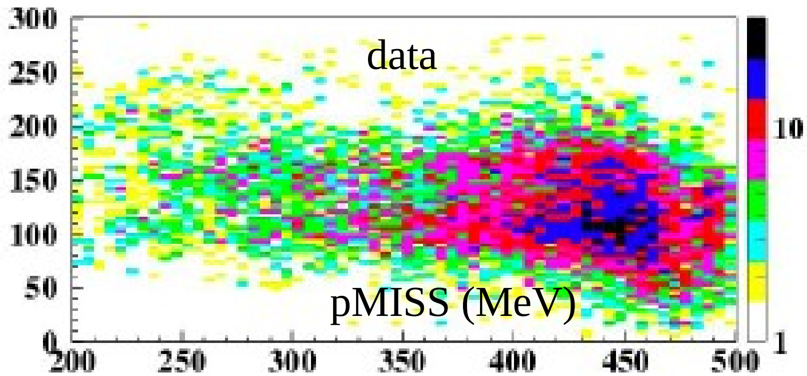
MMISS (MeV)

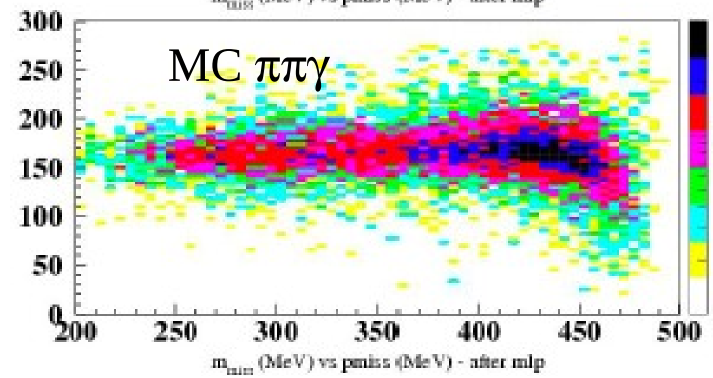



pMISS (MeV)

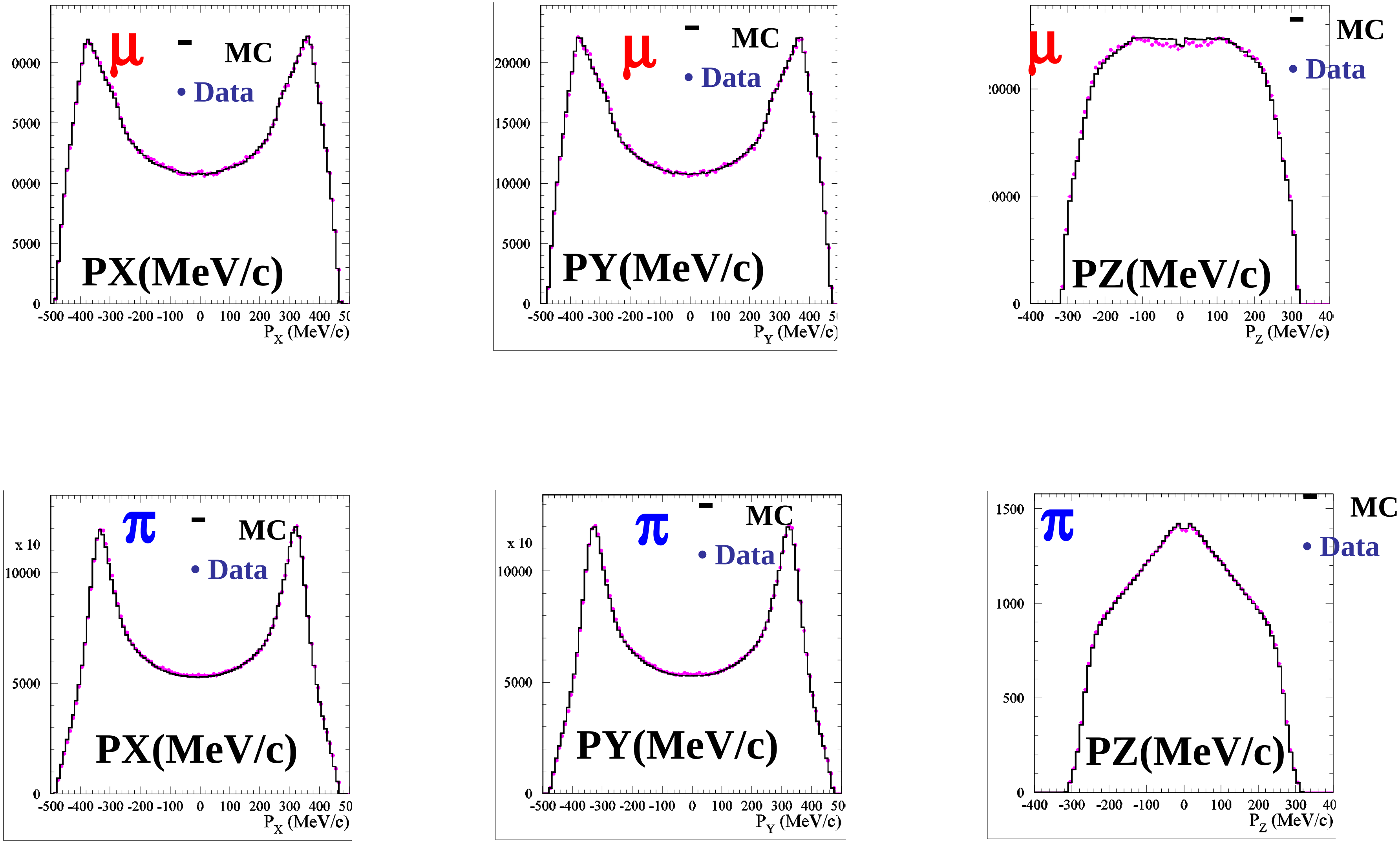



MMISS (MeV)



# Example of data/MC comparison for μμγ and ππγ: momentum components of μ and π



# ISR: KLOE vs BaBar 2π

KLOE:

- The photon is "soft" (detected or not)
- No Kinematic fit
- Bin of 0.01 GeV2 (~8 MeV at ρ peak)
  \>> δMππ2~2 10-3 GeV2

⇒ Unfolding only relevant at low Mππ2 (up to 4%) and at ρ–ω cusp,

- Negligible contribution of LO FSR, and <2% contribution of NLO FSR(1γISR+1γFSR) only at low Mππ2
- Normalize to **Luminosity** (=Bhabha), but also to **μμγ** (K12)
- 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

⇒ Larger effects on the unfolding

- Negligible contribution of LO FSR, % contribution of NLO FSR(1γISR+1γFSR)
- Normalize to **μμγ**
- Interplay btw **Phokhara** and **AfkQED** to estimate additional-photon effects

Different selections and use of theoretical ingredients (R.C., Luminosity, Radiator). Additional cross checks are possible (and needed)