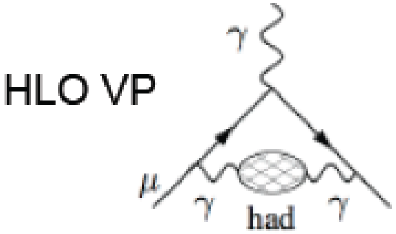
Measurement of the hadronic cross sections at KLOE with ISR and their impact to the muon anomaly and U-boson search

A. Passeri, on behalf of the KLOE and KLOE-2 collaborations

Reminder: test of the SM with a_μ

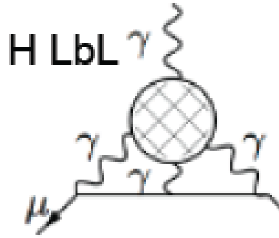
Theoretical calculation of the muon anomaly $a_\mu = (g_\mu - 2)/2$ are currently ~3.5 σ away from its direct measument.

Calculations and their error depend on hadron vacuum polarization (HLO) and light by light scattering (LBL).



$a_\mu^{HLO} = (692.4 \pm \mathbf{5.6}) 10^{-10}$

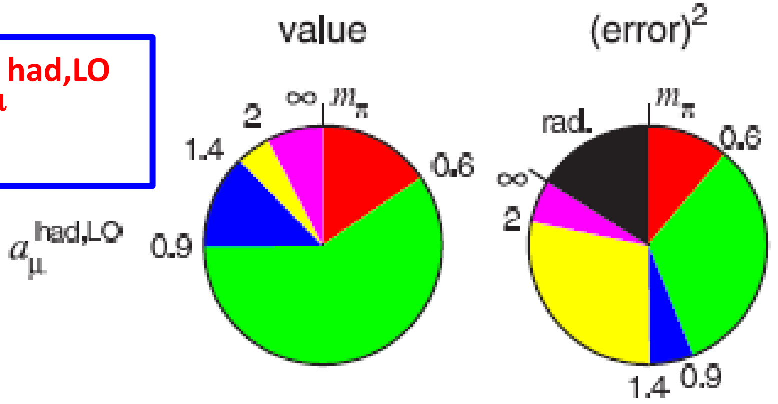
[Jegerlehner, Phys.Rept. 477 (2009) 1]



$a_\mu^{HLbL} = (11.6 \pm 3.9) 10^{-10}$

At low q^2, HLO evaluation relies on the hadronic cross section measurements

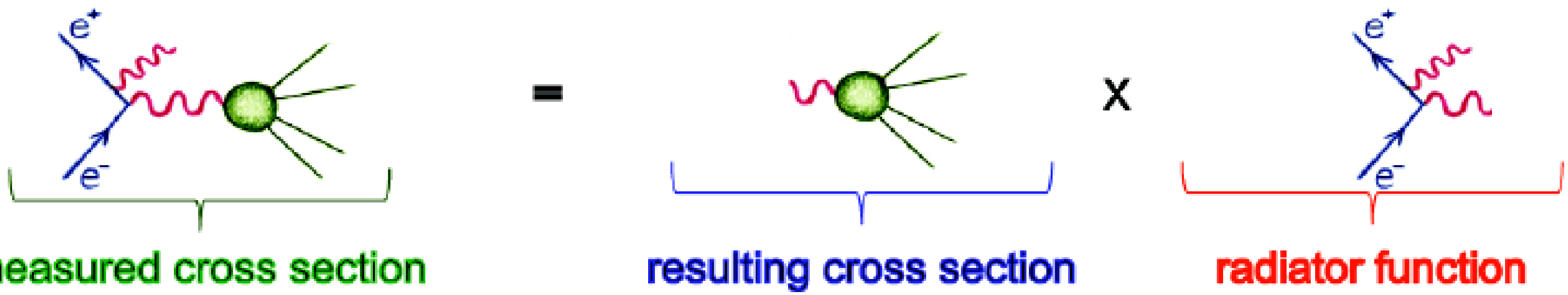
75% of the value and 40% of the error of $a_\mu^{had,LO}$ comes from the region of $q^2 < 1$ GeV^2



Reminder/2: the ISR technique

Neglecting final state radiation (FSR):

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



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

➔ **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

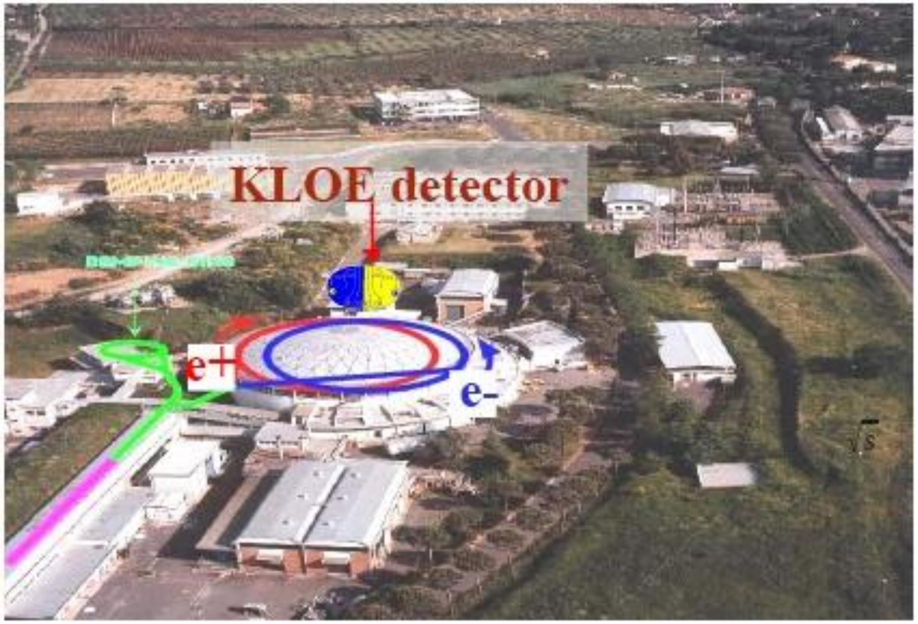
(exact next-to-leading order QED calculation of the radiator function)

KLOE first used the ISR technique to precisely measure $\sigma(e^+e^- \to \pi^+\pi^-)$ using 140 pb^{-1} collected in 2001 observing a 3σ discrepancy between a_μ^{SM} and a_μ^{exp} : PLB606 (2005)12

KLOE @ DAΦNE

DAFNE is an e^+e^- collider
in Frascati INFN lab
operated at $\sqrt{s}=M_\phi$~1020 MeV

With the ISR technique the KLOE detector can measure $\sigma_{\pi\pi}$ from threshold up to 1 GeV



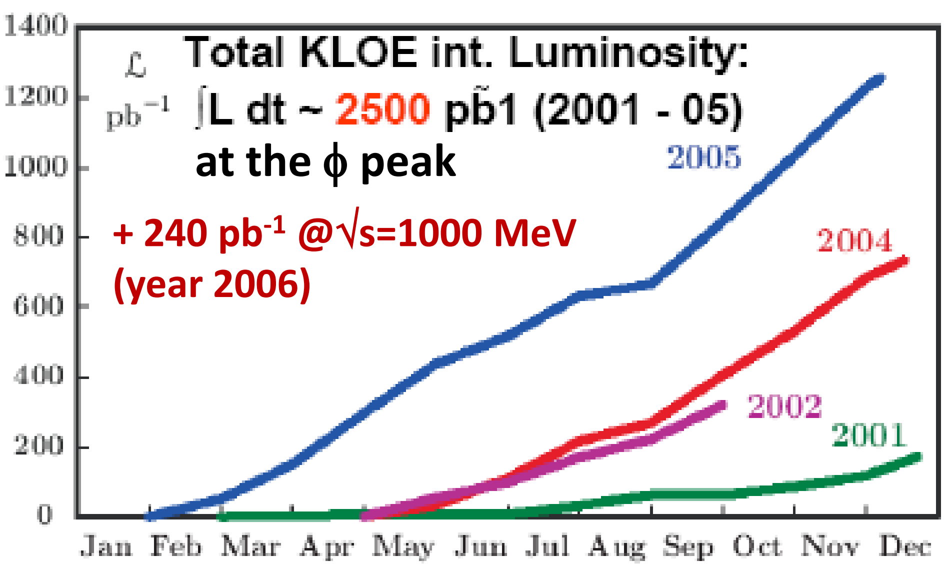
KLOE has published 4 such measurements:

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

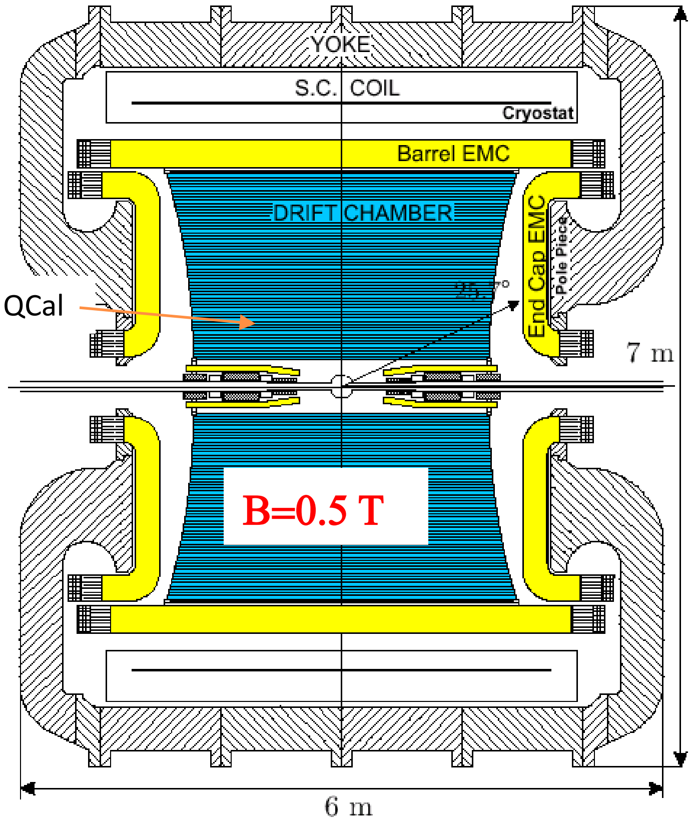
KLOE08 measurement (PLB670(2009)285) was based on $240 pb^{-1}$ from 2002 data!

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

KLOE12 measurement (PLB720(2013) 336) using $\pi\pi\gamma/\mu\mu\gamma$ ratio in 240 pb^{-1} 2002 data



The KLOE detector



Large volume Drift Chamber (13K cells, He gas mixt.) :

4m-∅, 3.75m-length, all-stereo

σ_p/p = 0.4 % (tracks with θ > 45)

σ_x^{hit} = 150 μm (xy), 2 mm (z)

σ_x^{vertex} ~1 mm $\sigma_{M\pi\pi}$ ~ 1 MeV

Pb-SciFi Calorimeter (barrel + endcap, 15 X_0 depth, 98% solid angle coverage) :

σ_E/E = 5.7% / √E(GeV)

σ_T = 54 ps / √E(GeV) ⊕ 50 ps

- **PID capabilities mostly from TOF**

Interaction region:
Instrument quadrupoles,
Al-Be spherical beam pipe

Selection with ISR photon at Small Angle (SA): KLOE08

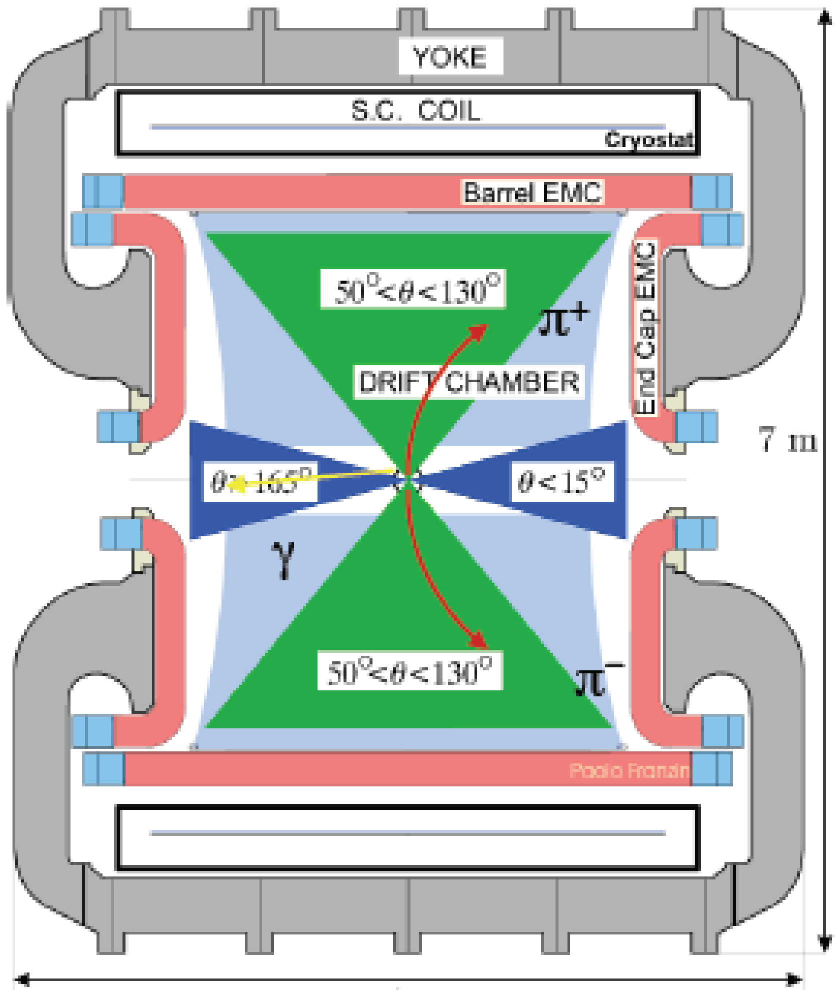
a) 2 tracks with $50^o < \theta_{track} < 130^o$
b) small angle (not detected) γ
($\theta_{\pi\pi} < 15^o$ or $> 165^o$)

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

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

Measurement based on 240 pb^{-1} collected in 2002 at the ϕ peak:

3.1×10^6 evts between 0.35 and 0.95 GeV^2



Selection with ISR photon at Large Angle (LA): KLOE10

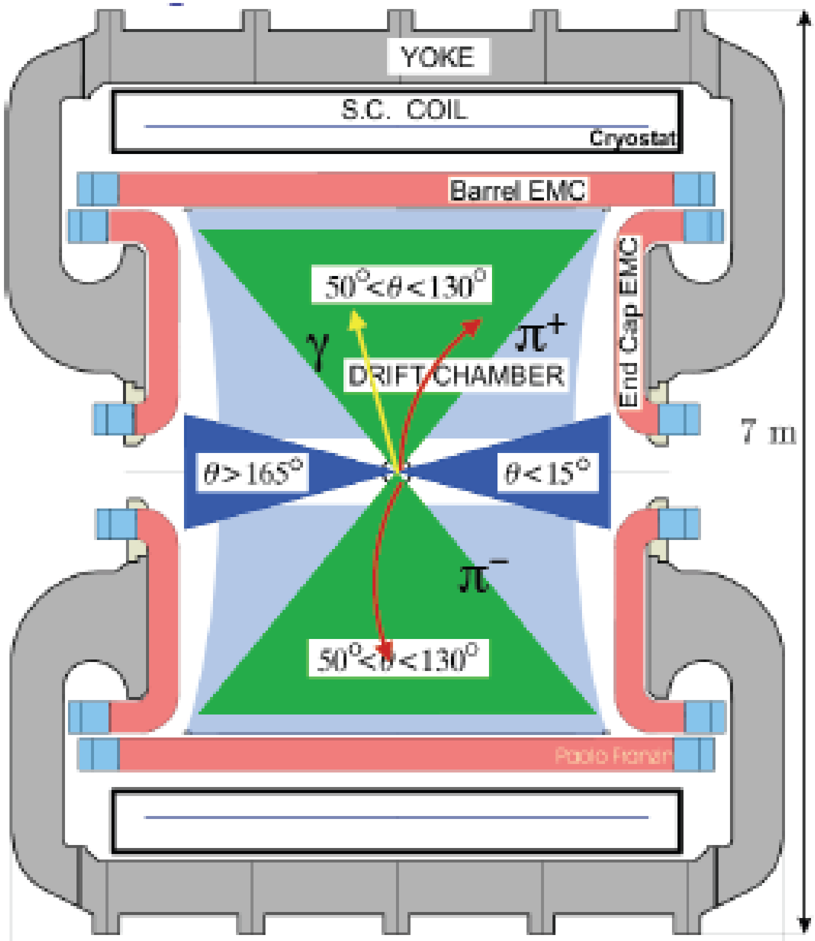
2 pion tracks at large angles

$50° < \theta_\pi < 130°$

Photons at large angles (i.e. detected !)

$50° < \theta_\gamma < 130°$

- ✓ independent complementary analysis
- ✓ threshold region $(2m_\pi)^2$ accessible



However:

- ✓ lower signal statistics
- ✓ larger contribution from FSR events
- ✓ larger $\phi \to \pi^+\pi^-\pi^0$ background contamination
- ✓ irreducible background from ϕ decays ($\phi \to f_0\,\gamma \to \pi\pi\,\gamma$)

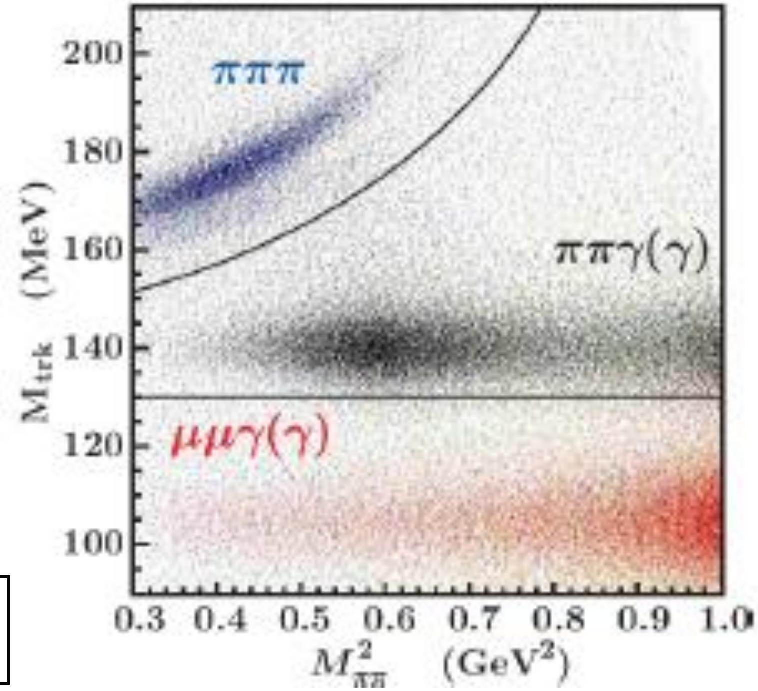
Event selection

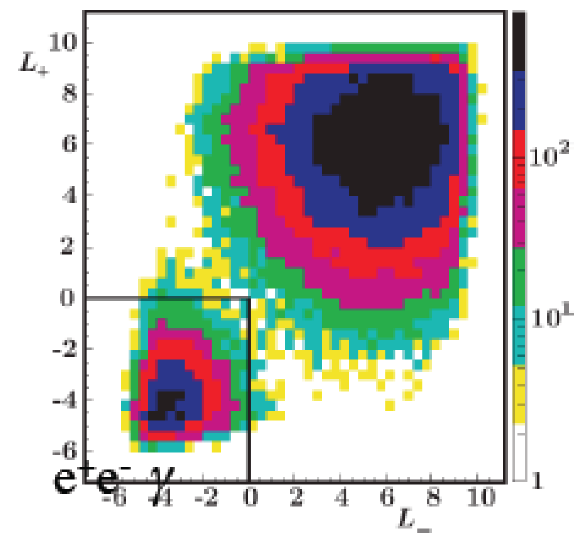
Main backgrounds come from:

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

We define the "trackmass" variable assuming there are only 1 photon + 2 charged particles of same mass M_{trk} and requiring 4-momentum conservation:

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





- **Different final states are nicely separated in the M_{trk}-$M_{\pi\pi}$ plane**
- **Calorimeter time of flight is also used to improve radiative bhabha rejection**

Luminosity

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

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

$55° < \theta < 125°$

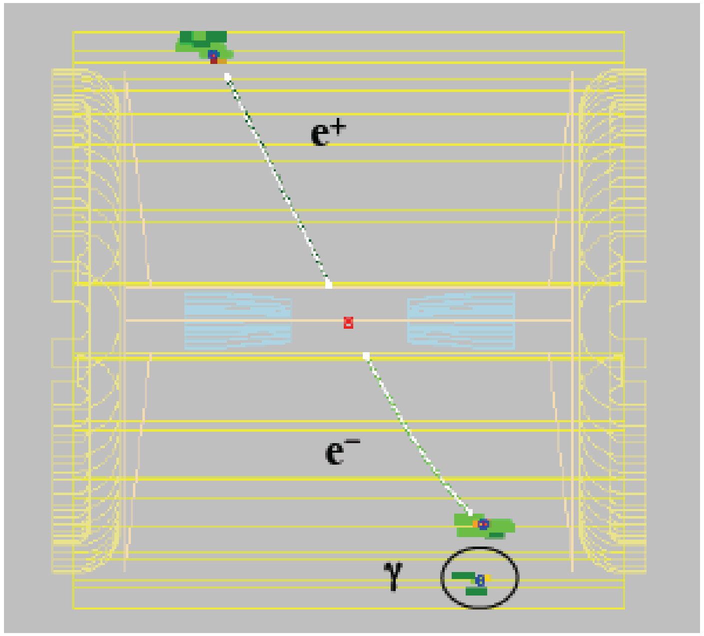
acollinearity $< 9°$

$p \geq 400$ 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 ⊕ 0.3% exp = 0.3%	

KLOE08 : Small Angle technique, $\sqrt{s}$=1020 MeV

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 (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%

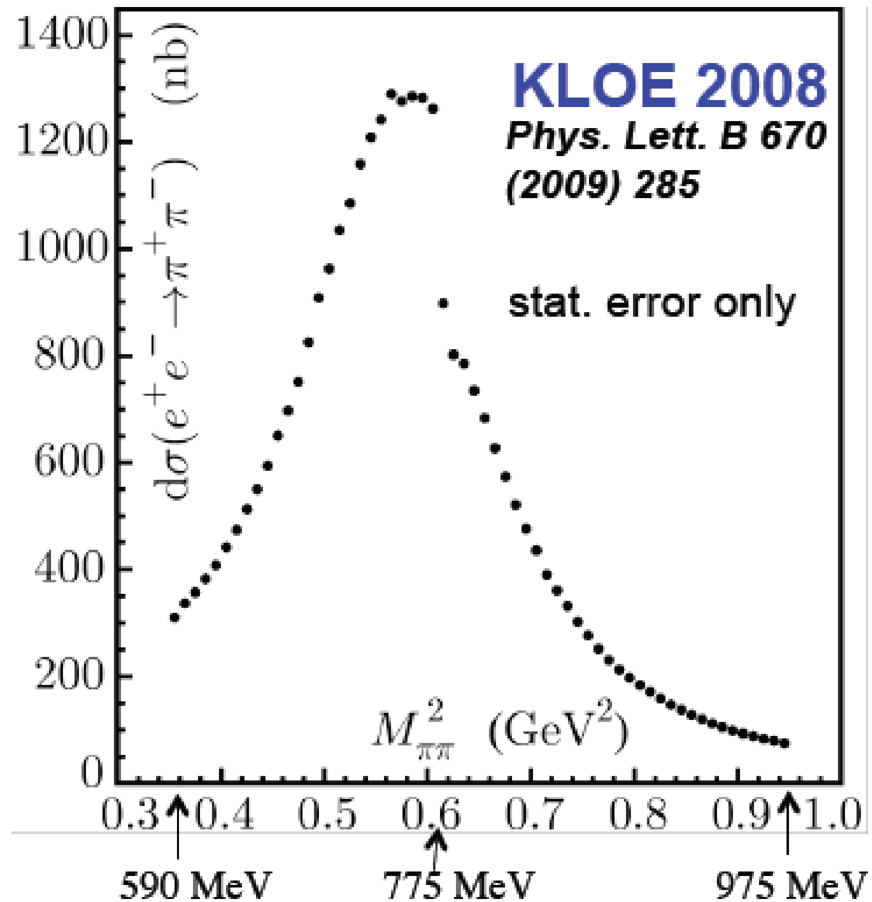
experimental fractional error on a_μ = 0.6 %

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

theoretical fractional error on a_μ = 0.6 %

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

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



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

KLOE10 : Large Angle technique, $\sqrt{s}$=1000 MeV

KLOE10: Phys. Lett. B 700 (2011) 102

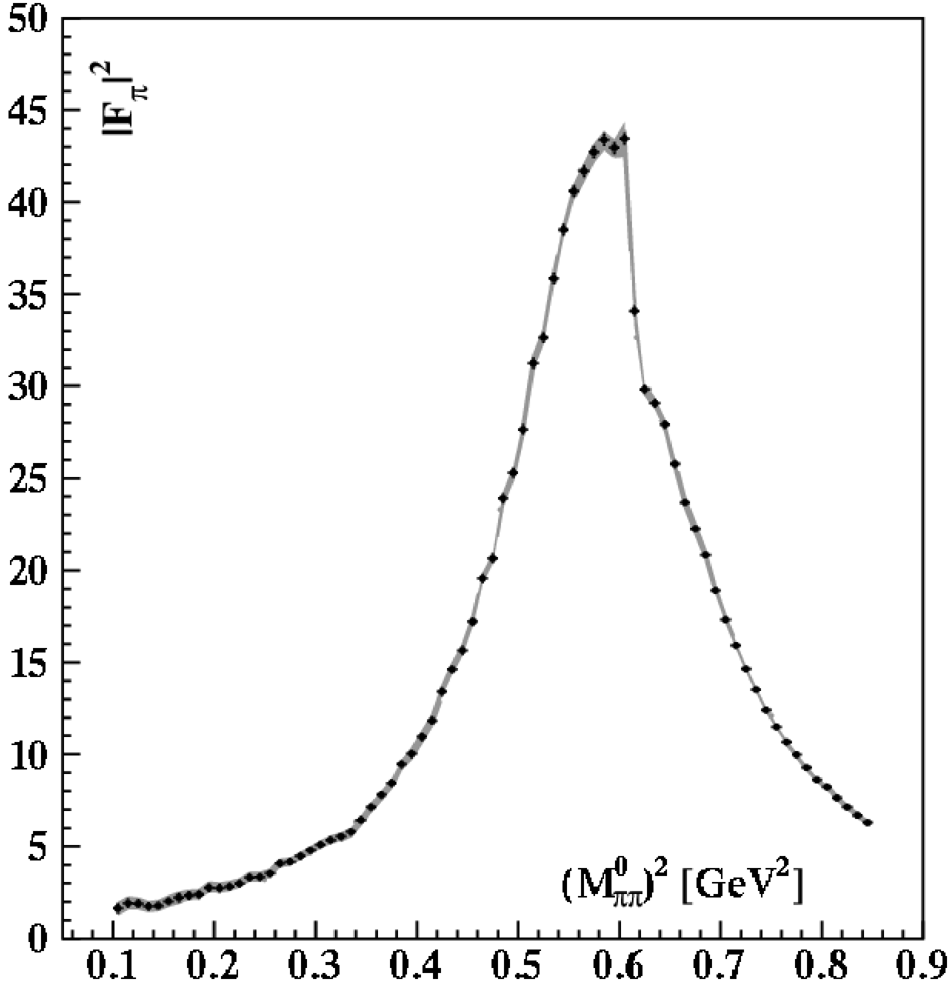


Table of systematic errors on $a_\mu^{\pi\pi}$(0.1-0.85 GeV^2):

Reconstruction Filter	negligible
Background	0.5%
f_0+rp	0.4%
Omega	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_μ = 1.0 %

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

theoretical fractional error on a_μ = 0.9 %

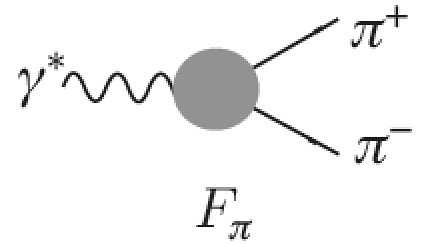
$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

$a_\mu^{\pi\pi}$(0.1-0.85 GeV^2) = $(478.5 \pm 2.0_{stat} \pm 5.0_{sys} \pm 4.5_{theo}) \cdot 10^{-10}$

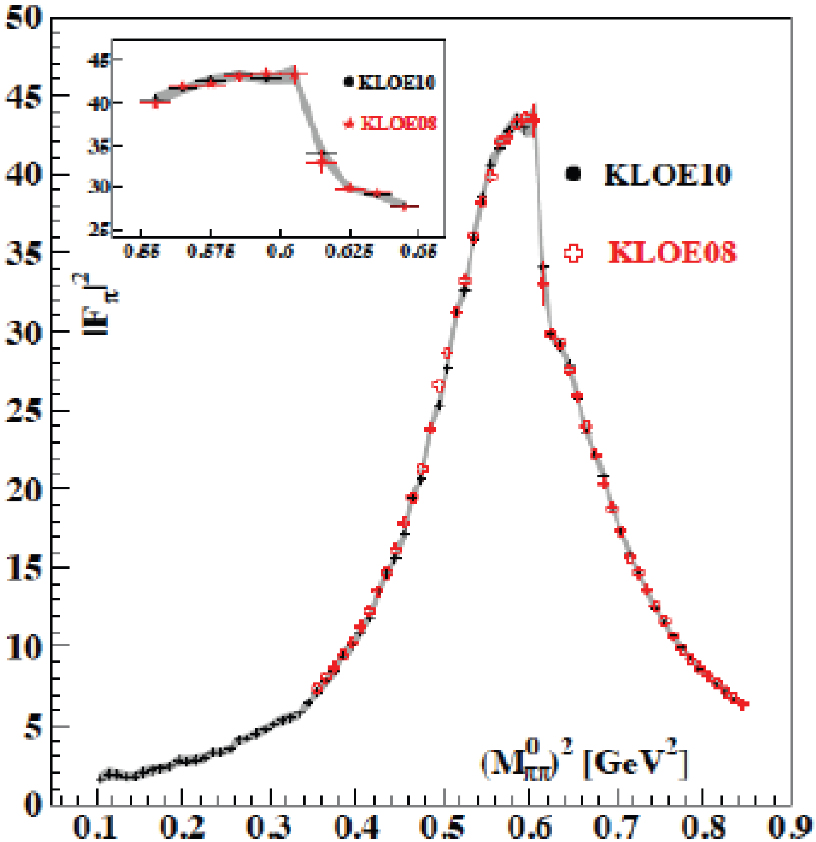
0.4% 1.0% 0.9%

Pion Form Factor :

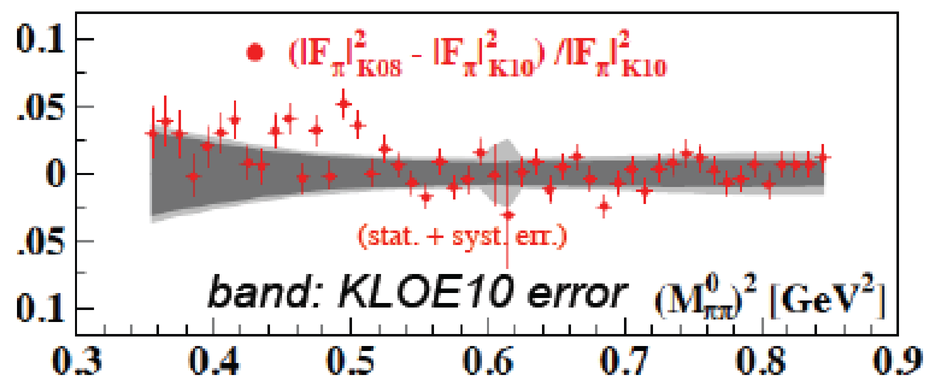
$$|F_\pi(s)|^2 = \frac{3}{\pi}\frac{s}{\alpha^2\beta_\pi^3}\sigma^0_{\pi\pi(\gamma)}(s)(1+\delta_{VP})(1-\eta_\pi)$$



KLOE08 vs KLOE10



Fractional difference:



Excellent agreement with KLOE08, expecially above 0.5 GeV^2

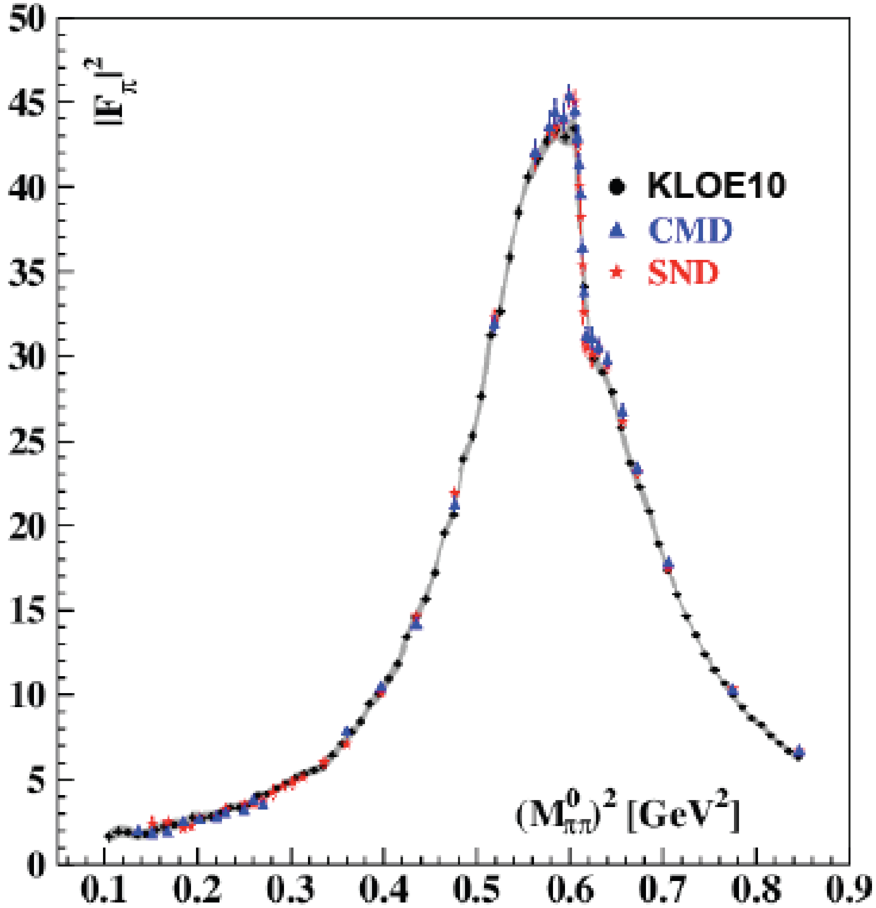
Combination of KLOE08 and KLOE10:

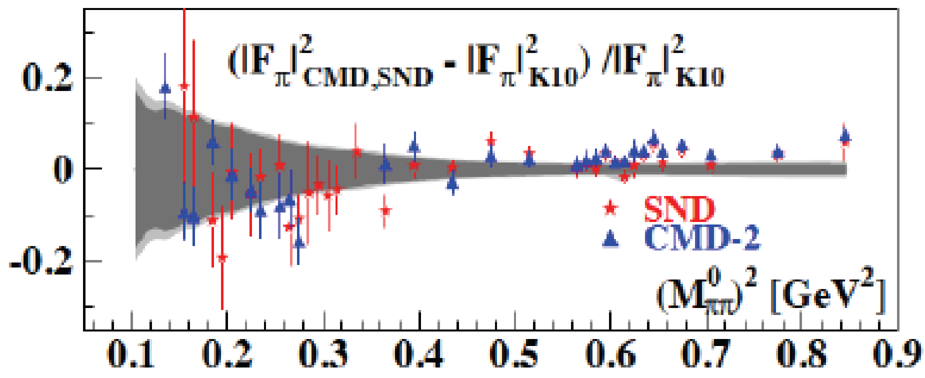
$a_\mu^{\pi\pi}(0.1\text{-}0.95\ \text{GeV}^2) = (488.6 \pm 6.0) \cdot 10^{-10}$

KLOE covers ~70% of total a_μ^{HLO} with a fractional total error of 1.2%

KLOE10 vs CMD-2 / SND

CMD and SND results compared to KLOE10: Fractional difference





band: KLOE10 error

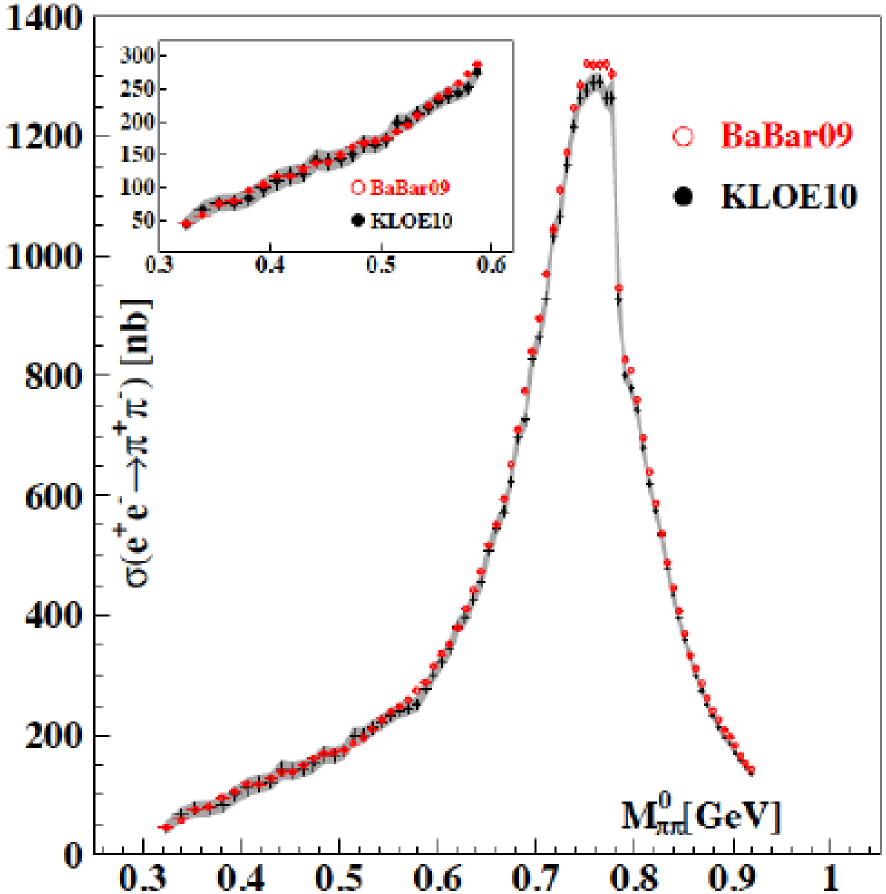
Below the ρ peak good agreement with CMD-2/SND.

Above the ρ peak KLOE10 slightly lower (as KLOE08)

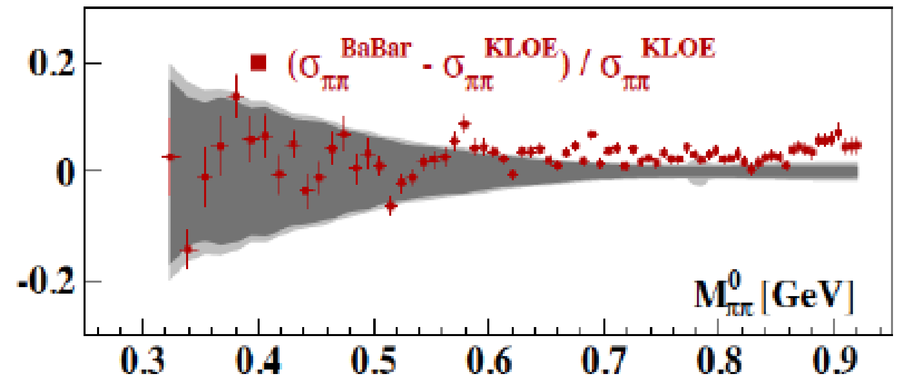
CMD-2: Phys. Lett. B 648 (2007) 28.
CMD-2: JETP Lett. 84 (2006) 413.
SND : J. Exp. Theor. Phys. 103 (2006) 380.

KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference



BaBar derives the pion form factor from the ππγ/μμγ ratio



band: KLOE10 error

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

BaBar09: Phys. Rev. Lett. 103 (2009) 231801.

New measurement based on the ratio $\pi\pi\gamma/\mu\mu\gamma$

PLB720(2013) 336

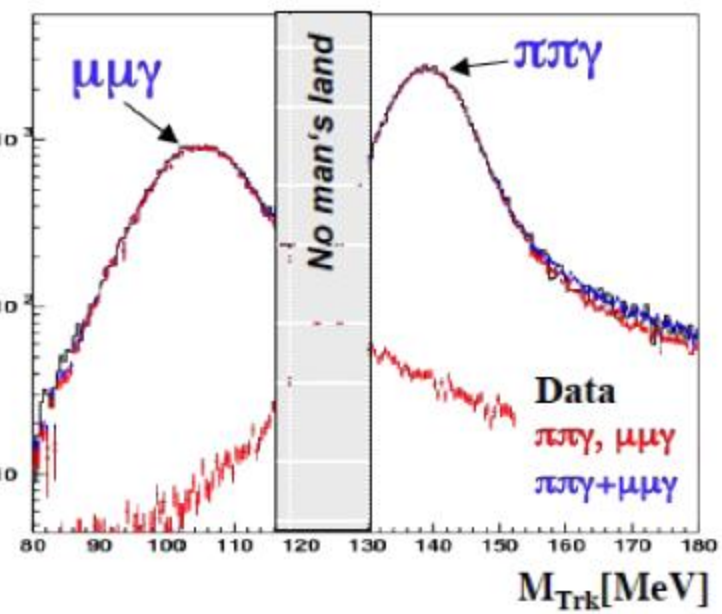
The pion form factor can be obtained from the ratio of the $\pi\pi\gamma$ to $\mu\mu\gamma$ yields, without any absolute normalization to Bhabha events:

$$|F_\pi(s')|^2 \approx \underbrace{\frac{4(1+2m_\mu^2/s')\beta_\mu}{\beta_\pi^3}}_{\text{kinematic factor } (\sigma_{\mu\mu}^{Born}/\sigma_{\pi\pi}^{Born})} \underbrace{\frac{d\sigma_{\pi\pi\gamma}ds'}{d\sigma_{\mu\mu\gamma}ds'}}_{\text{meas. quantities}}$$

Most radiative corrections drop out !

- **Radiator Function**
- **Integrated Luminosity**
- **Vacuum polarization**

MC $\pi\pi\gamma$ and $\mu\mu\gamma$ M_{TRK}, distributions (Red)
MC sum (Blue), Data (black)



Same data sample as the KLOE08 measurement with SA (undetected photon) selection

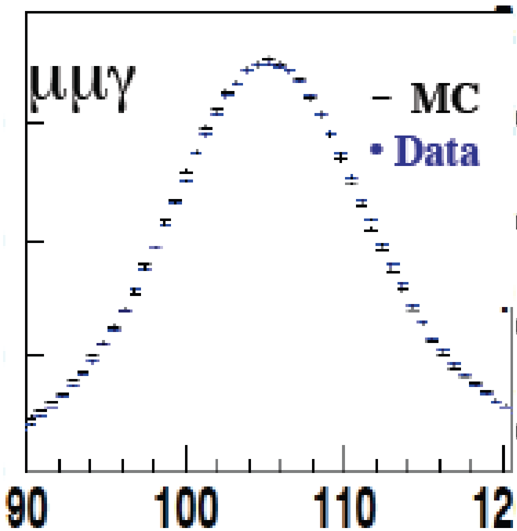
π/μ efficiently separated using M_{TRK} :

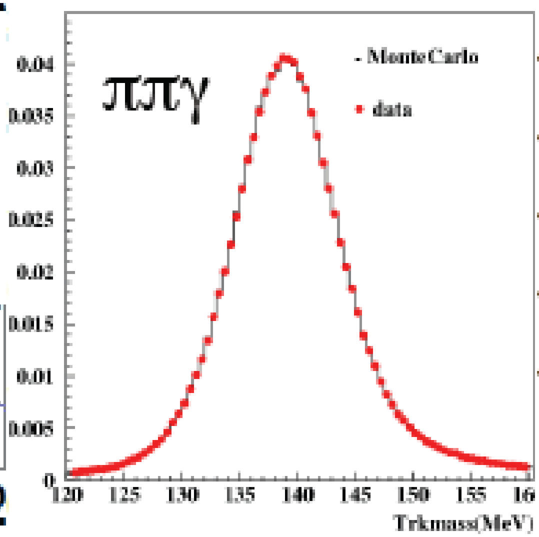
- **$M_{TRK} < 115$ MeV → 0.87×10^6 $\mu\mu\gamma$ events**
- **$M_{TRK} > 130$ MeV → 3.4×10^6 $\pi\pi\gamma$ events**

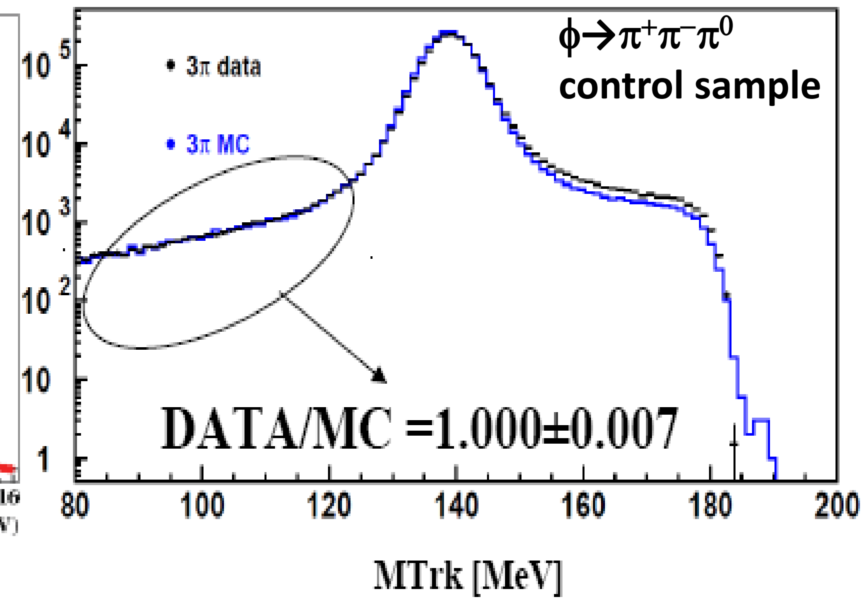
ρ region is critical ($\sigma_{\pi\pi} >> \sigma_{\mu\mu}$)

$\pi\pi\gamma$ / $\mu\mu\gamma$ analysis

- selection efficiencies (TRG, TRK, PID) evaluated on data
- 1% control of $\mu\mu\gamma$ selection, even in the ρ region
- π/μ separation checked with 3 independent methods (M_{TRK}, Kin fit, σ_{MTRK})
- excellent data/MC agreement on M_{TRK} and several other distributions





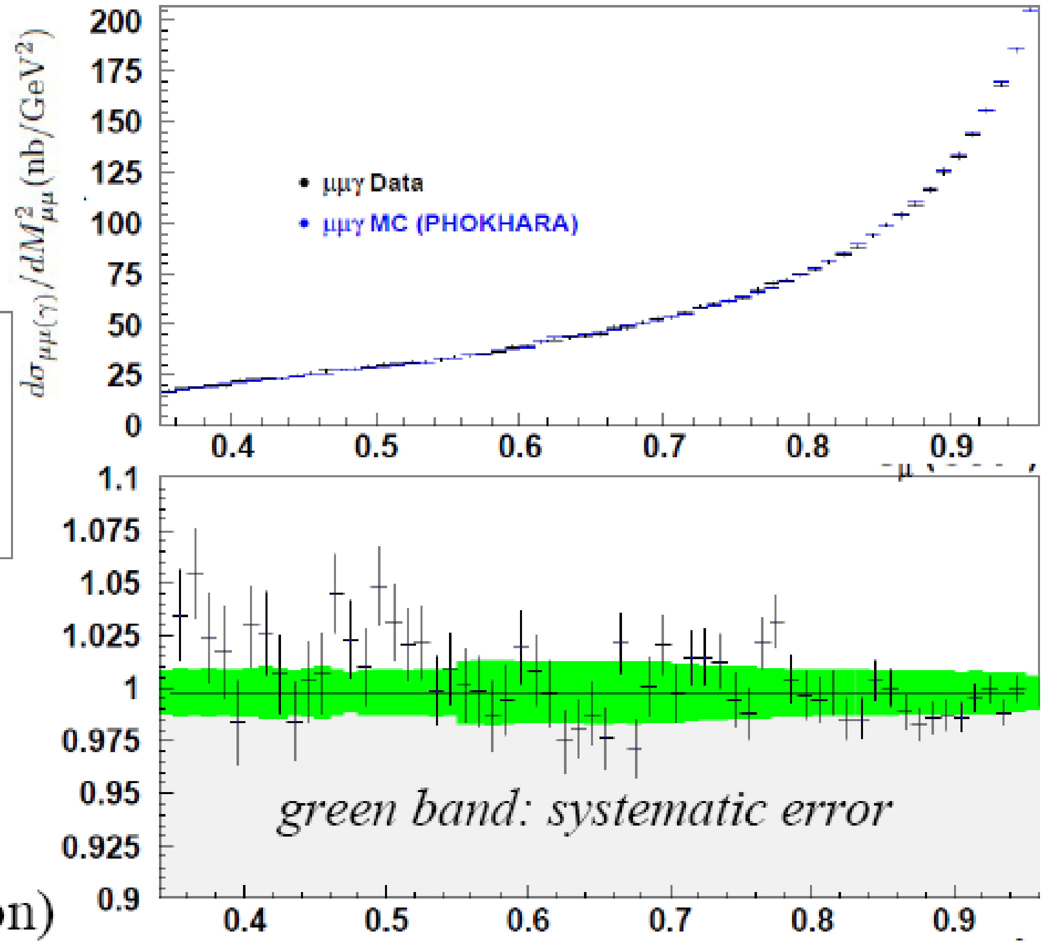


- $\phi \rightarrow \pi^+\pi^-\pi^0$ used as control sample to precisely estimate $\pi\pi\gamma$ efficiency and contamination in the $\mu\mu\gamma$ sample
- backgrounds estimated from MC shapes fitted to M_{TRK} data distribution
- All efficiencies above 96%, with data/MC corrections ~ 1%

μμγ spectrum

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

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



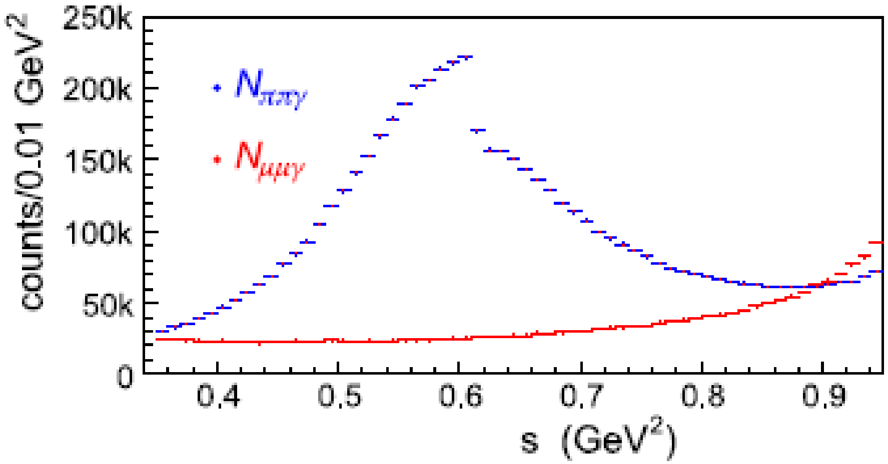
The systematic error has been averaged on $M^2_{\mu\mu}$

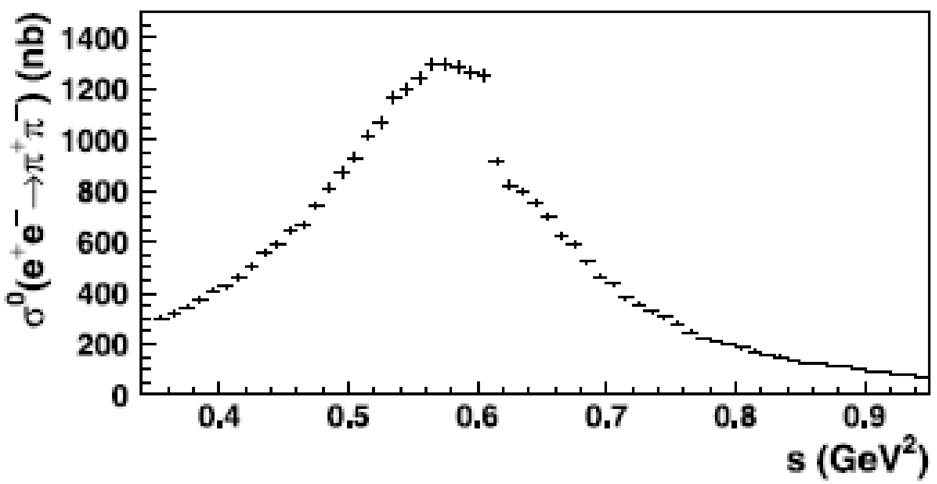
Good agreement with PHOKHARA MC (NLO Calculation)

Consistency check of Radiator function, Luminosity, etc…

Results

Cross section is directly obtained from the bin-by-bin ratio of the measured distribution (independently from radiator functions, VP and luminosity!) :





$$\Delta a_\mu^{\pi\pi} = \int^{s_{max}} \sigma^0_{\pi\pi(\gamma)}(s) \cdot K(s) ds$$

$\Delta^{\pi\pi} a_\mu \times 10^{10}$

$0.35 < M^2_{\pi\pi} < 0.95$ Gev²

this measurement:	**$385.1 \pm 1.1_{stat} \pm 2.7_{sys\&theo}$**
KLOE08:	**$387.2 \pm 0.5_{stat} \pm 3.3_{sys\&theo}$**

$0.35 < M^2_{\pi\pi} < 0.85$ Gev²

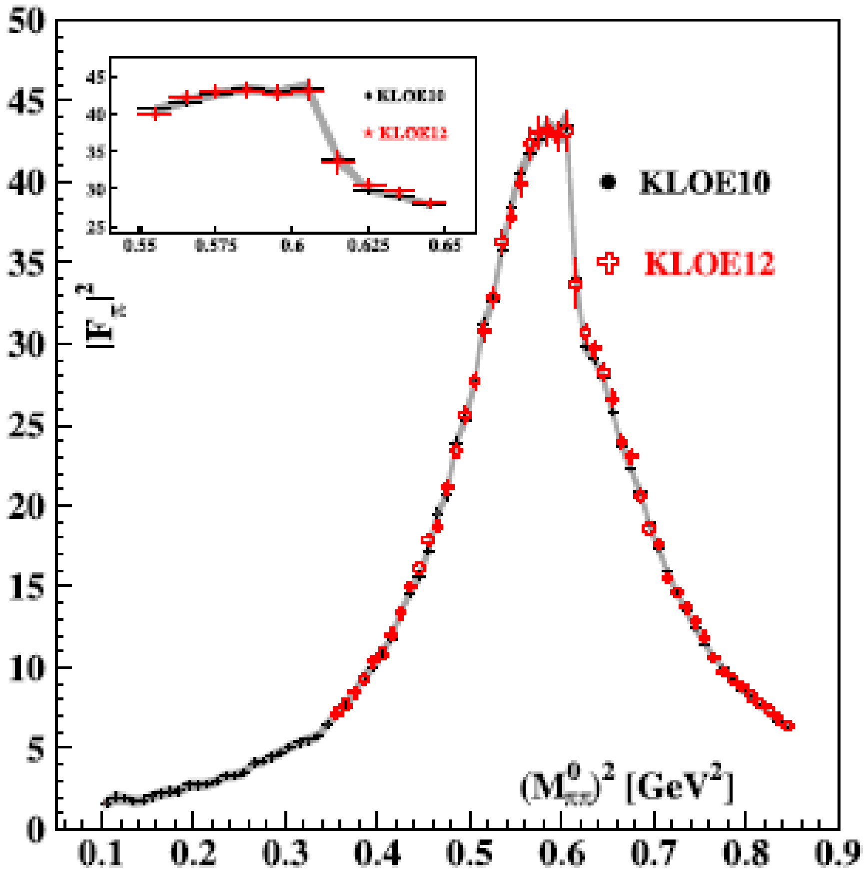
this measurement:	**$377.4 \pm 1.1_{stat} \pm 2.7_{sys\&theo}$**
KLOE10:	**$376.6 \pm 0.9_{stat} \pm 3.3_{sys\&theo}$**

Systematic errors

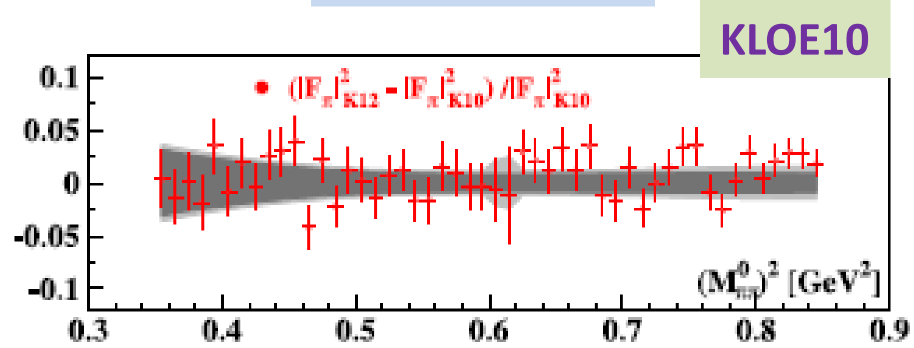
- **New measurement has different systematic error sources with respect to past ones**
- **Very little dependence on acceptance and on theory corrections !**

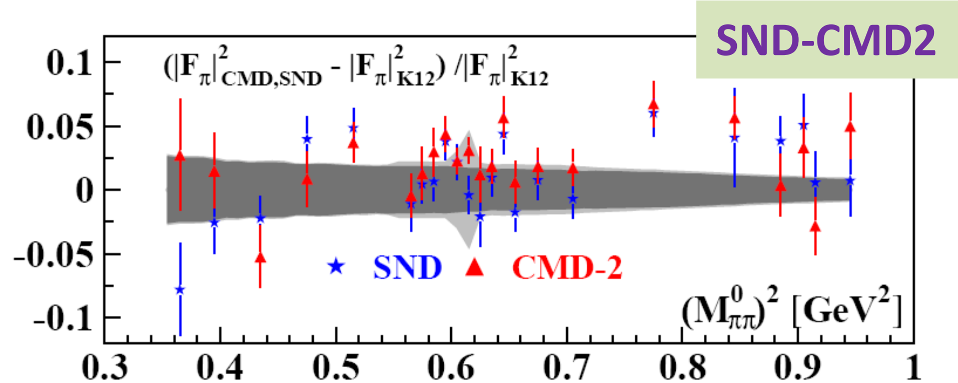
	KLOE12	KLOE08	KLOE10
Contribution to systematics %	$\Delta^{\pi\pi} a_\mu$ ratio, SA-γ	$\Delta^{\pi\pi} a_\mu$ abs, SA-γ	$\Delta^{\pi\pi} a_\mu$ abs, LA-γ
Background subtraction	0.6	0.3	0.5
$f_0+\rho\pi$	negligible	negligible	0.4
Ω cut	-	-	0.2
Particle mass/PID	0.2	0.2	0.5
Tracking	0.1	0.3	0.3
Trigger	0.1	0.1	0.2
Acceptance	negligible	0.2	0.5
L3 Trigger	0.1	0.1	0.1
Luminosity	-	0.3	0.3
Total experimental	**0.7**	**0.6**	**1.0**
FSR treatment	0.2	0.3	0.8
Radiator H	-	0.5	0.5
Vacuum polarization	-	0.1	0.1
Total theoretical	**0.2**	**0.6**	**0.9**
Total systematics	**0.7 %**	**0.9 %**	**1.1 %**

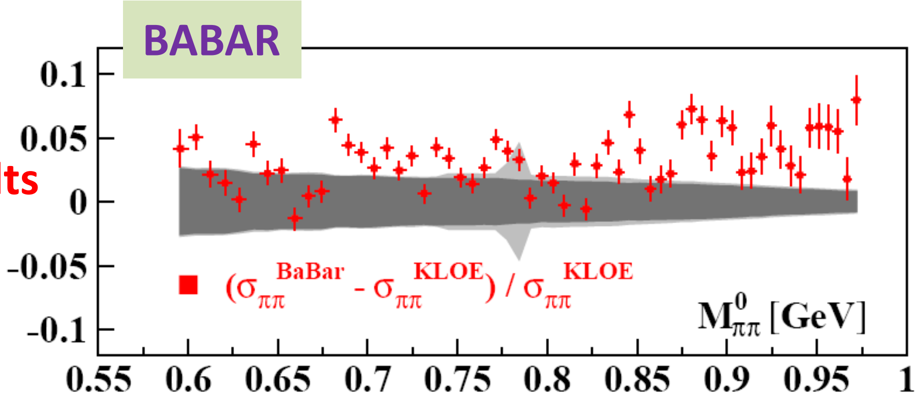
Pion FF: comparison of results



KLOE12 vs :



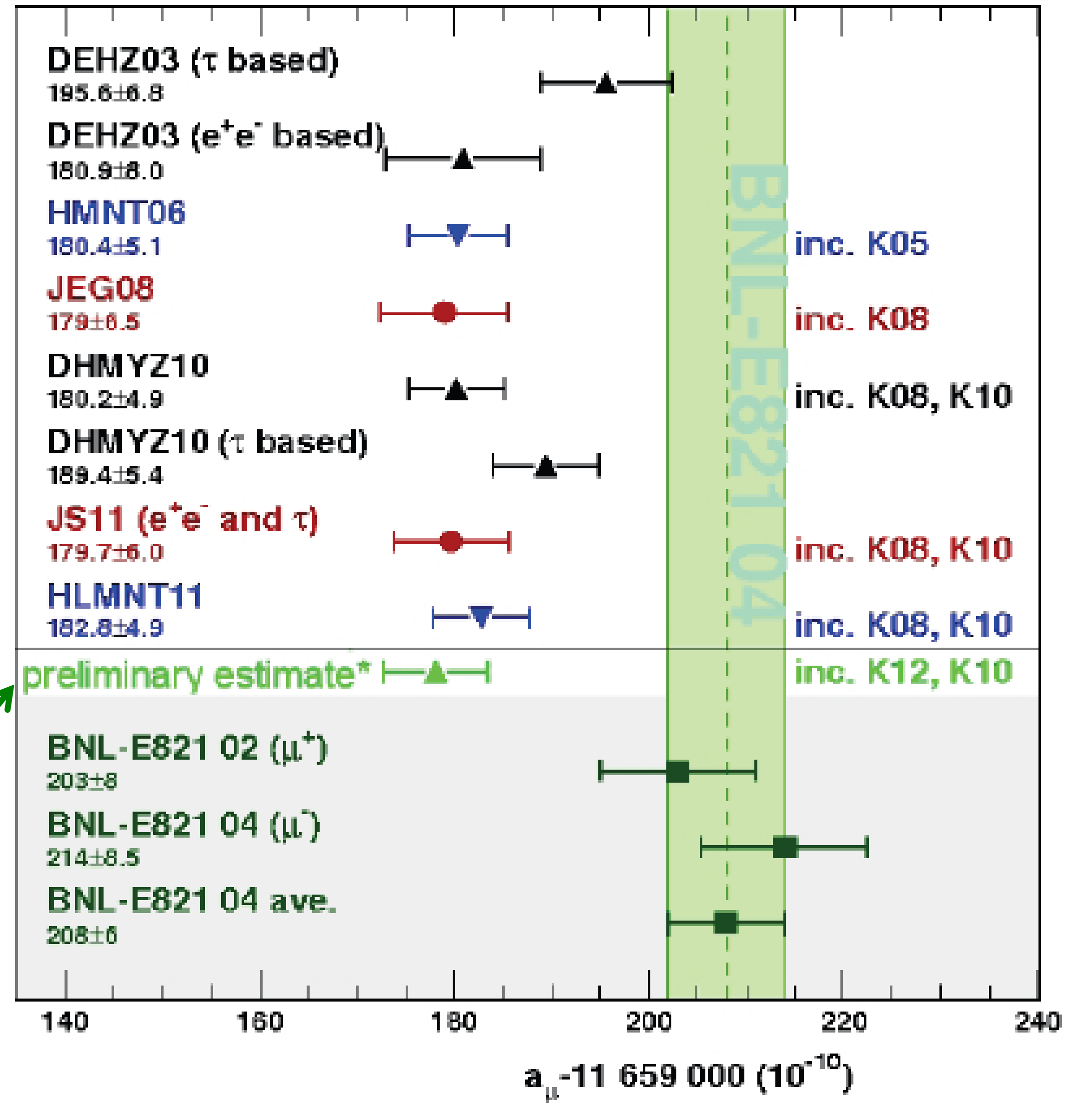




- excellent agreement with previous KLOE results
- reasonable agreement with SND CMD-2
- fair agreement with BaBar

Muon anomaly grand comparison

New result confirms 3.5 σ discrepancy with direct measurement



Our extrapolation based on DHMYZ10

Dark photon searches

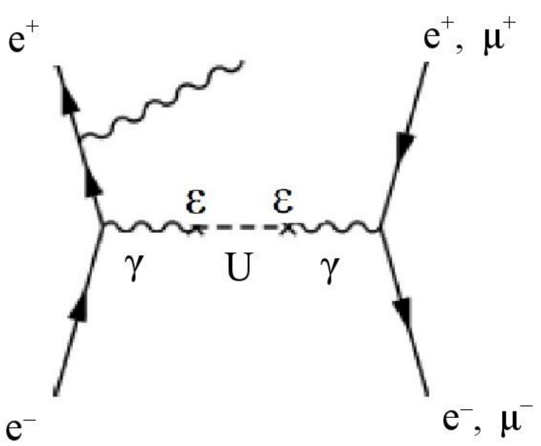
After recent astrophysical observations (PAMELA, ATIC, Hess, FERMI, AMS…) many theoretical models postulate the existence of a secluded gauge sector: a DARK FORCE !

The dark sector should be mediated by a low mass gauge boson, the U boson (with $m_U < 2\ m_{proton}$), and should be kinetically coupled to the SM photon.

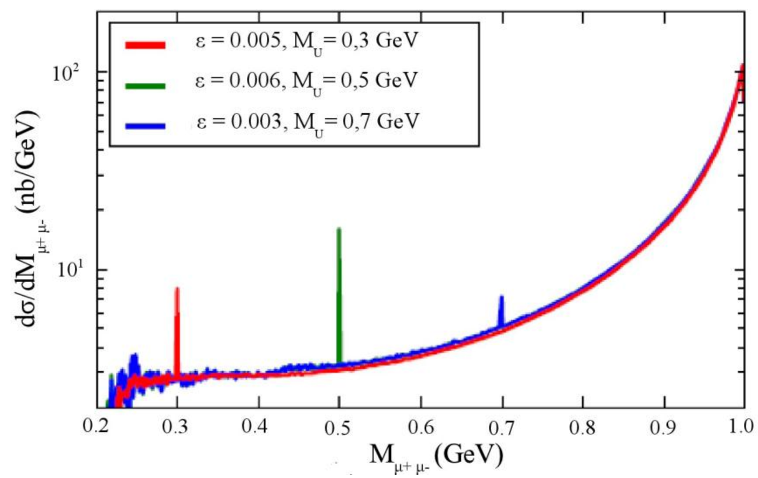
The kinetic mixing parameter ε expected to be $\leq 10^{-3}$

At DAFNE the processes $\phi \rightarrow \eta U$ and $e^+e^- \rightarrow U\gamma$ can be studied.

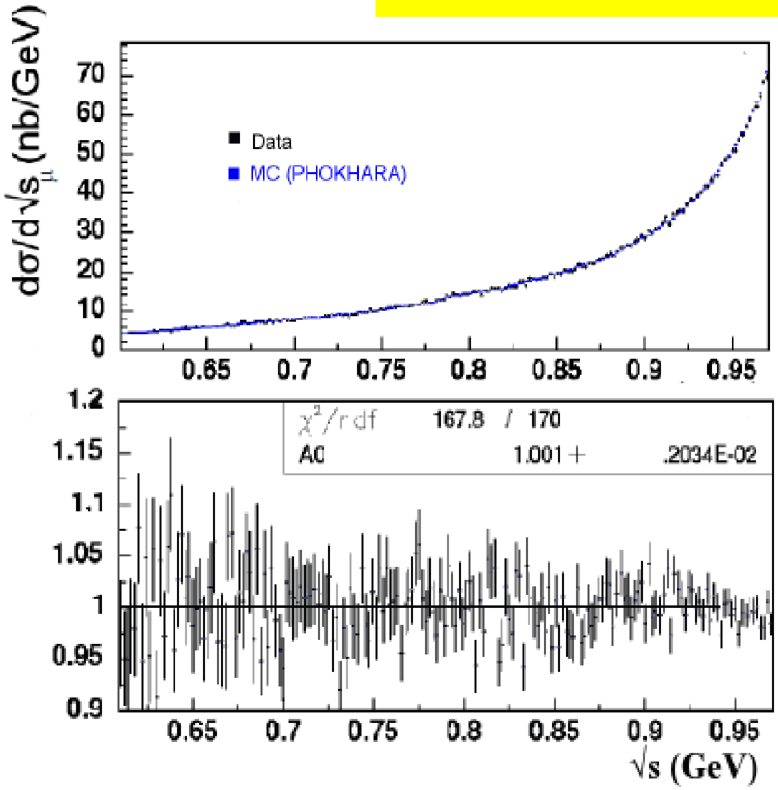
$$e^+ e^- \rightarrow U\gamma \rightarrow l^+ l^- \gamma,\ l = e, \mu$$



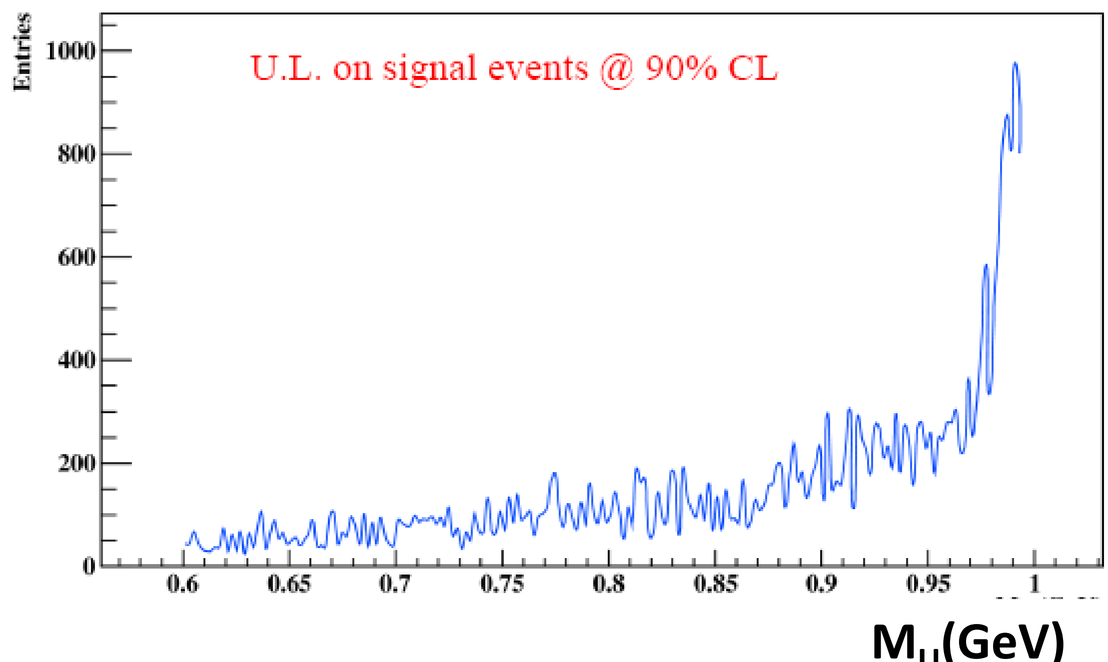
U boson can show up as a peak in the $\mu\mu\gamma$ spectrum



Upper limits from μμγ spectrum



High precision in the μμγ spectrum and excellent agreement with PHOKARA montecarlo in the region 0.6< √s<1.0 GeV allow to extract an upper limit in terms of number of evts per bin.



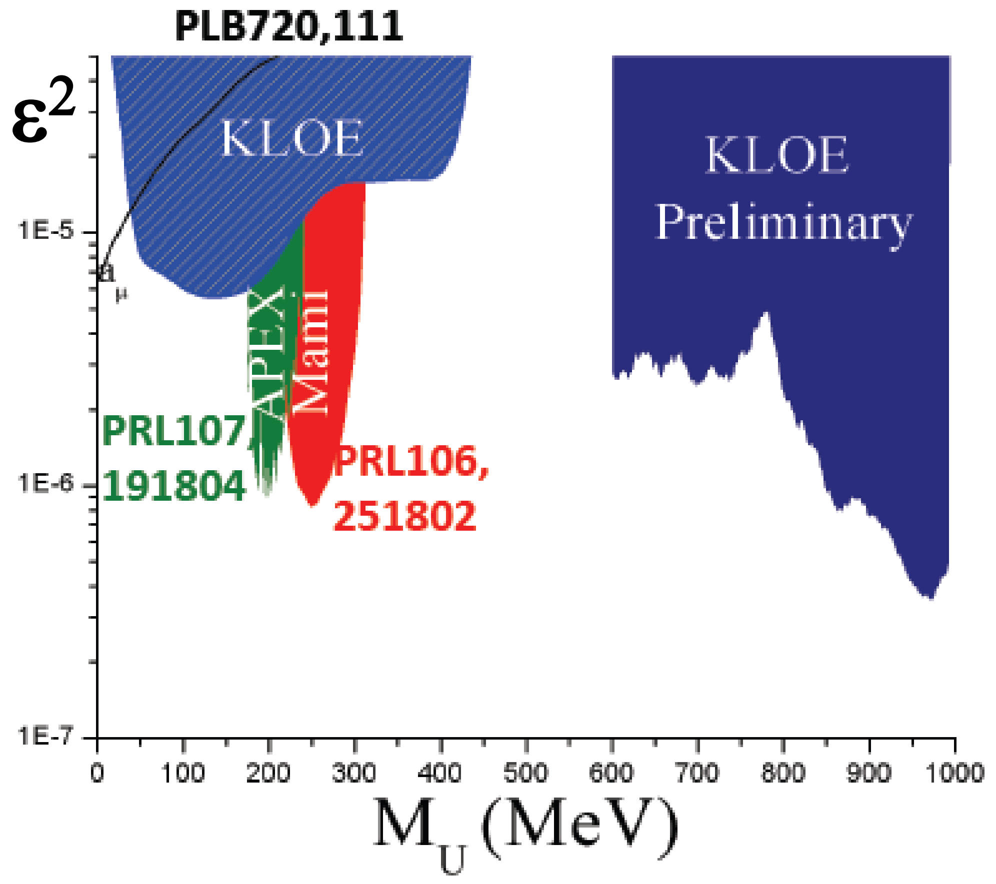
This correspond to a sensitivity to $\varepsilon \sim 10^{-3}$

U boson exclusion plot

Analysis of $\phi \rightarrow \eta ee$ allowed KLOE to set limits in the region 50<MU<400 MeV (PLB 720,111)

In the region 60<MU<200 our limit rules out the hypotesis that a dark photon could originate the a_μ discrepancy

The $\mu\mu\gamma$ spectrum allows KLOE to explore higher M_U masses. Work is in progress to improve and extend this method.



Conclusions

- KLOE has performed a new measurement of σ_{had} below 1 GeV from the $\pi\pi\gamma/\mu\mu\gamma$ spectra ratio

- Systematic uncertainties of this measurement are smaller and from different sources with respect to the past

- The result confirms the previous measurements and the a_μ discrepancy

- The $\mu\mu\gamma$ spectrum can be used also to put interesting limits on the existence of the so called “U boson”

SPARES

Radiative Corrections

Radiator-Function $H(s,s_p)$ (ISR):

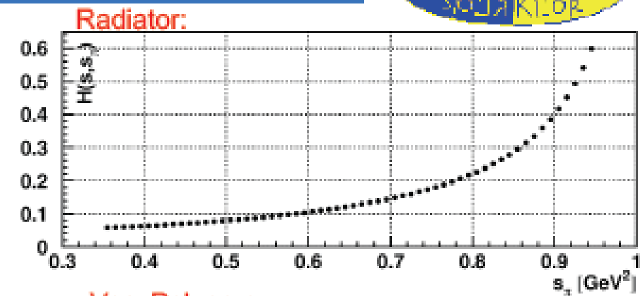
- **ISR-Process calculated at NLO-level**

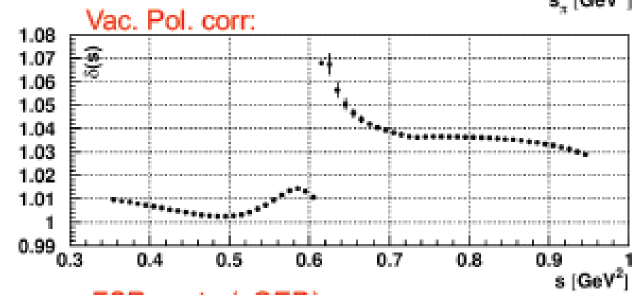
  PHOKHARA generator

  (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:

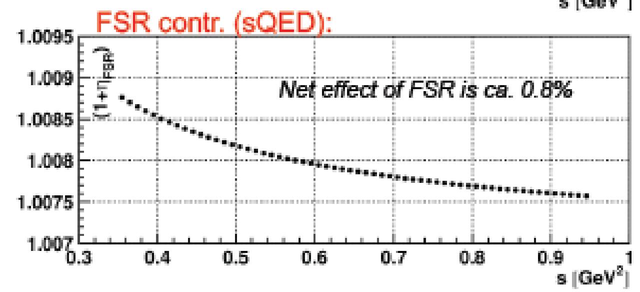
i) Bare Cross Section

divide by Vacuum Polarisation $d(s)=(a(s)/a(0))^2$

➔ from F. Jegerlehner

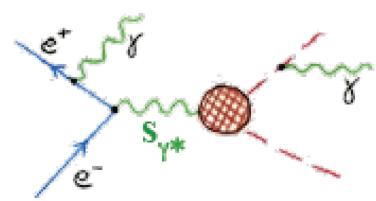
ii) FSR

Cross section s_{pp} must be incl. for FSR for use in the dispersion integral of a_m

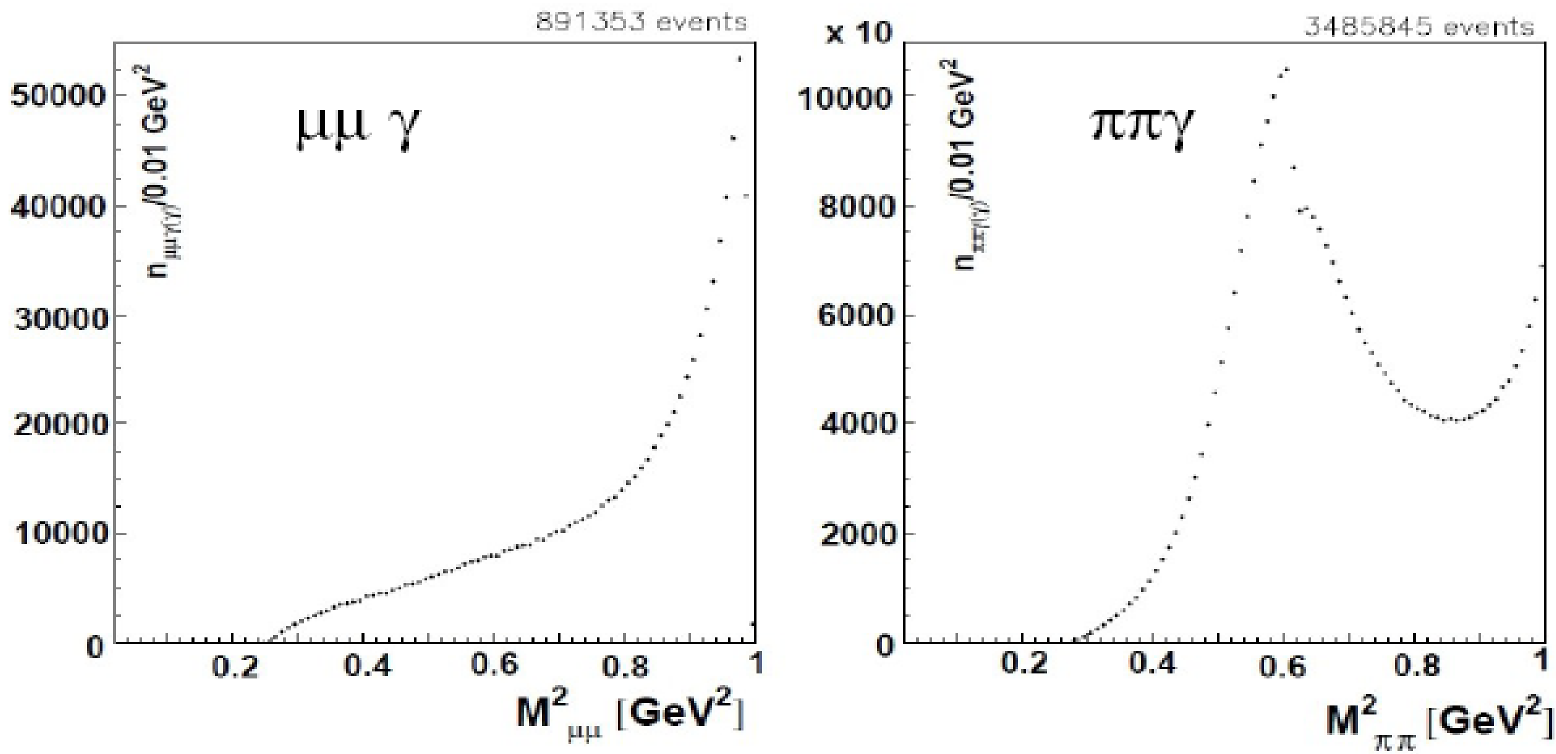


FSR corrections have to be taken into account in the efficiency eval. (Acceptance, M_{Trk}) and in the mapping $s_\pi \rightarrow s_{\gamma*}$

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



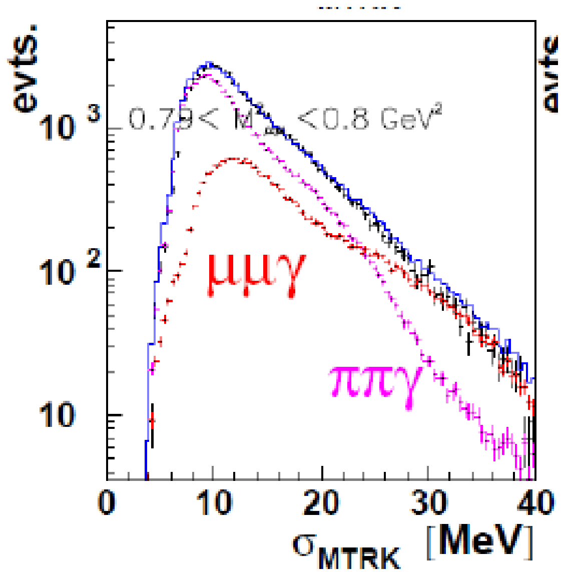
$s_{\gamma*} > s_\pi$



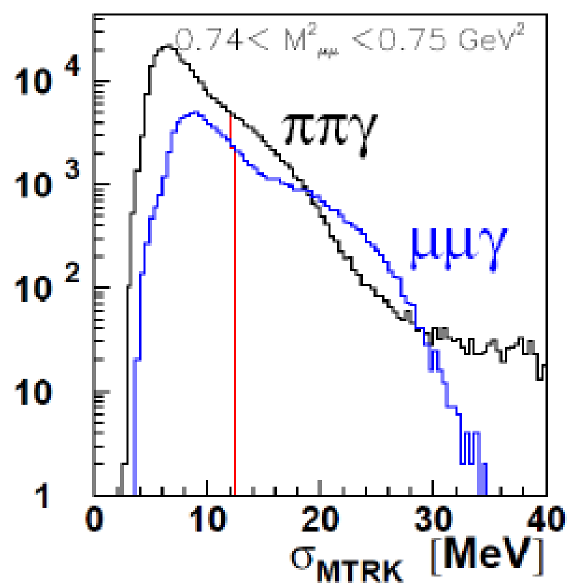
$$\sigma^0_{\pi\pi(\gamma)}(M^2) = \frac{\left.\dfrac{d\sigma(e^+e^- \to \pi\pi\gamma)}{dM^2}\right|_{ISR}}{\left.\dfrac{d\sigma(e^+e^- \to \mu\mu\gamma)}{dM^2}\right|_{ISR}} \sigma^0_{\mu\mu}(M^2)$$

Cross check of $\pi\pi\gamma/\mu\mu\gamma$ separation

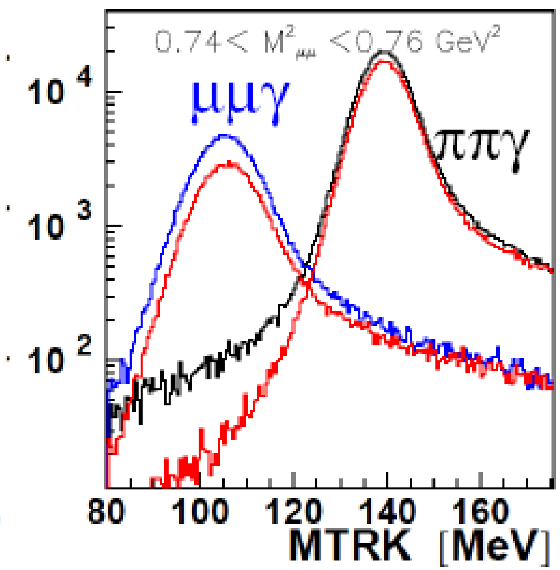
- The π/μ separation has been crosschecked with two different (and independent) methods:
- A kinematic fit (KF), in the hypothesis of 2 body+1γ (ISR) events.
- A cut on the quality of the fitted tracks, parametrized by σ_{MTRK}



σ_{MTRK} Data / MC comp. MC $\mu\mu\gamma+\pi\pi\gamma$ (blue) and data (black).



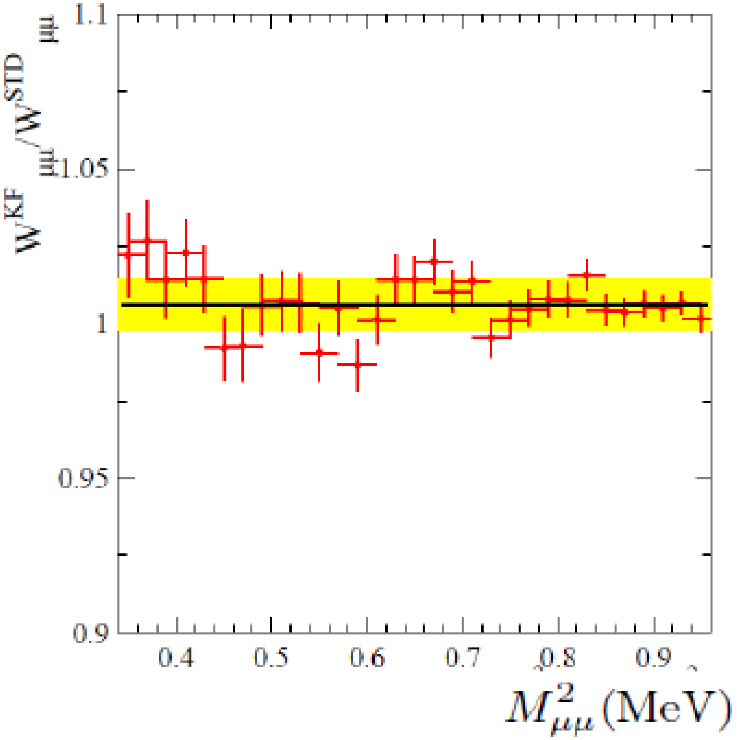
σ_{MTRK} cut (red) on MC $\mu\mu\gamma$ and $\pi\pi\gamma$ distr.



MC MTRK distributions with σ_{MTRK} cut (red).

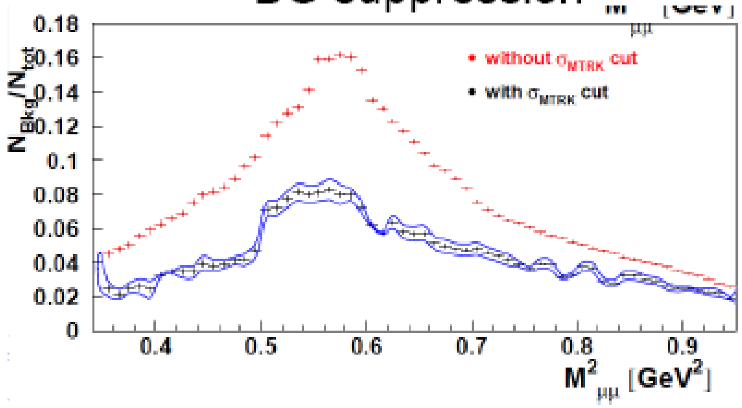
Results of σ_{MTRK} and KF cross checks

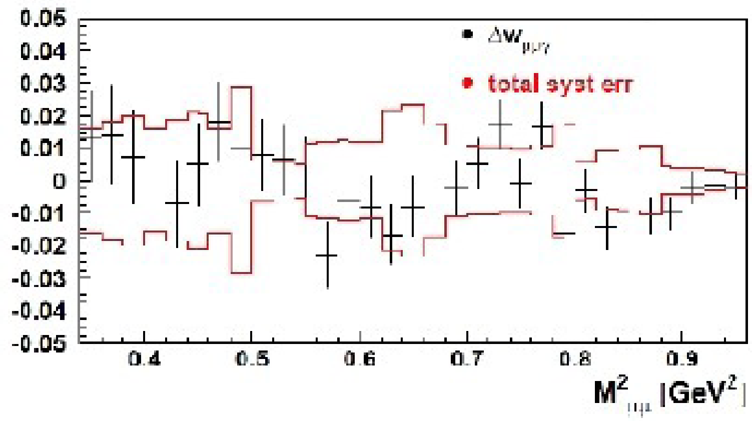
π/μ separation obtained with these methods well in agreement with the standard one.



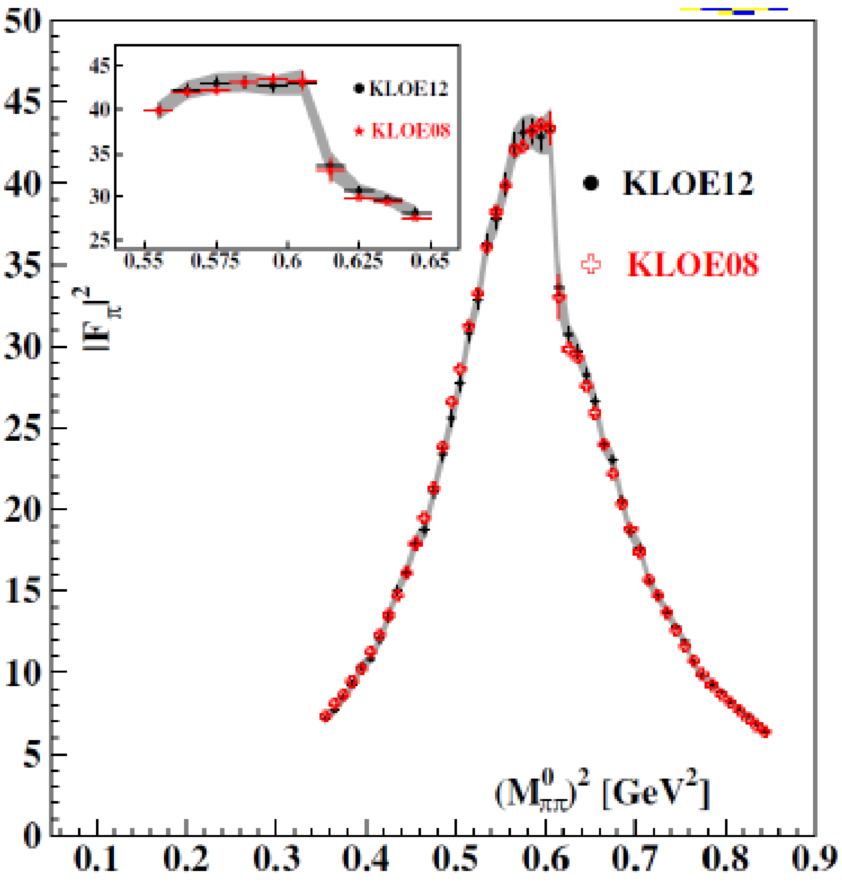
The ratio of the muon yields from kinematic fit method with $\chi2_{\mu\mu}$ < 10 to the muon yields from standard method, fitted with the constant. Yellow bar the systematic error of the kinematic fit method

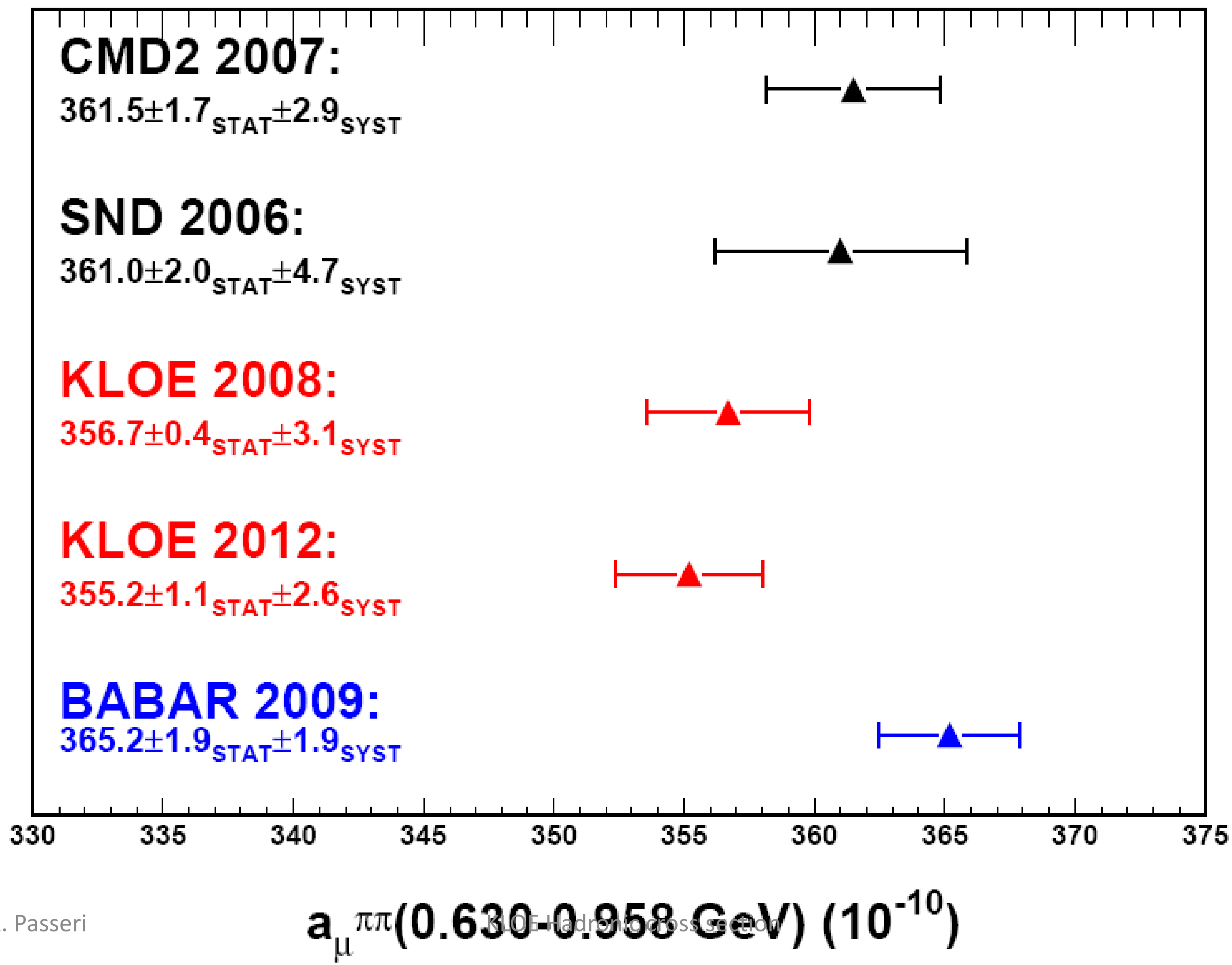
BG suppression

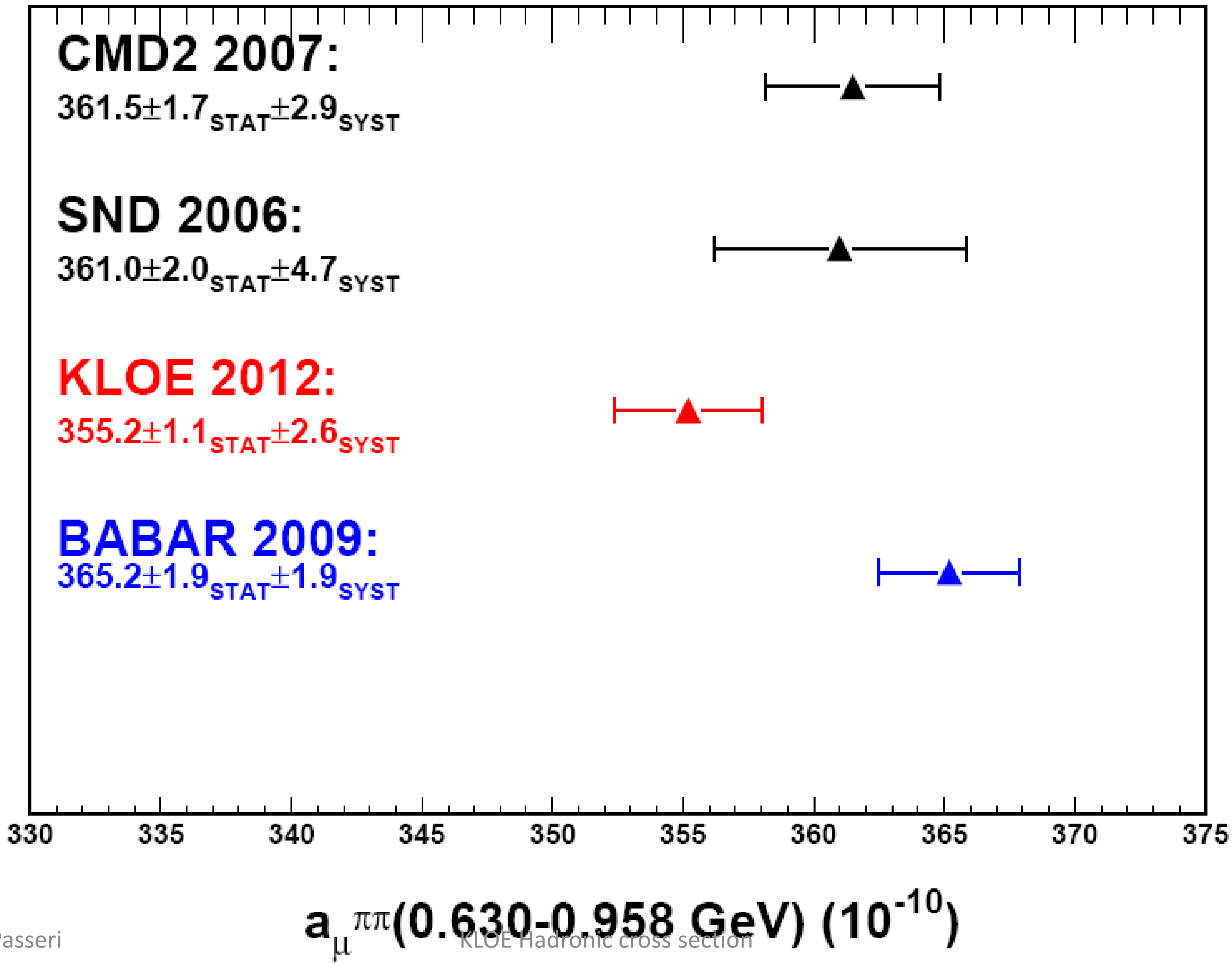




Black dots are the difference of $\mu^+\mu^-\gamma$ yields obtained with std and σ_{MTRK} methods; Red line is the total systematic error of the difference.


KLOE12
KLOE08
$|F_\pi|^2$
$(M^0_{\pi\pi})^2$ [GeV^2]


CMD2 2007:
361.5±1.7 STAT ±2.9 SYST
SND 2006:
361.0±2.0 STAT ±4.7 SYST
KLOE 2008:
356.7±0.4 STAT ±3.1 SYST
KLOE 2012:
355.2±1.1 STAT ±2.6 SYST
BABAR 2009:
365.2±1.9 STAT ±1.9 SYST
330 335 340 345 350 355 360 365 370 375
a_μ^ππ(0.630-0.958 GeV) (10^-10)


CMD2 2007:
361.5±1.7STAT±2.9SYST
SND 2006:
361.0±2.0STAT±4.7SYST
KLOE 2012:
355.2±1.1STAT±2.6SYST
BABAR 2009:
365.2±1.9STAT±1.9SYST
330
335
340
345
350
355
360
365
370
375
aμππ(0.630-0.958 GeV) (10-10)