η mass measurement
blessing of the final result

Biagio Di Micco

Motivation

The most precise measurements differ by 8σ

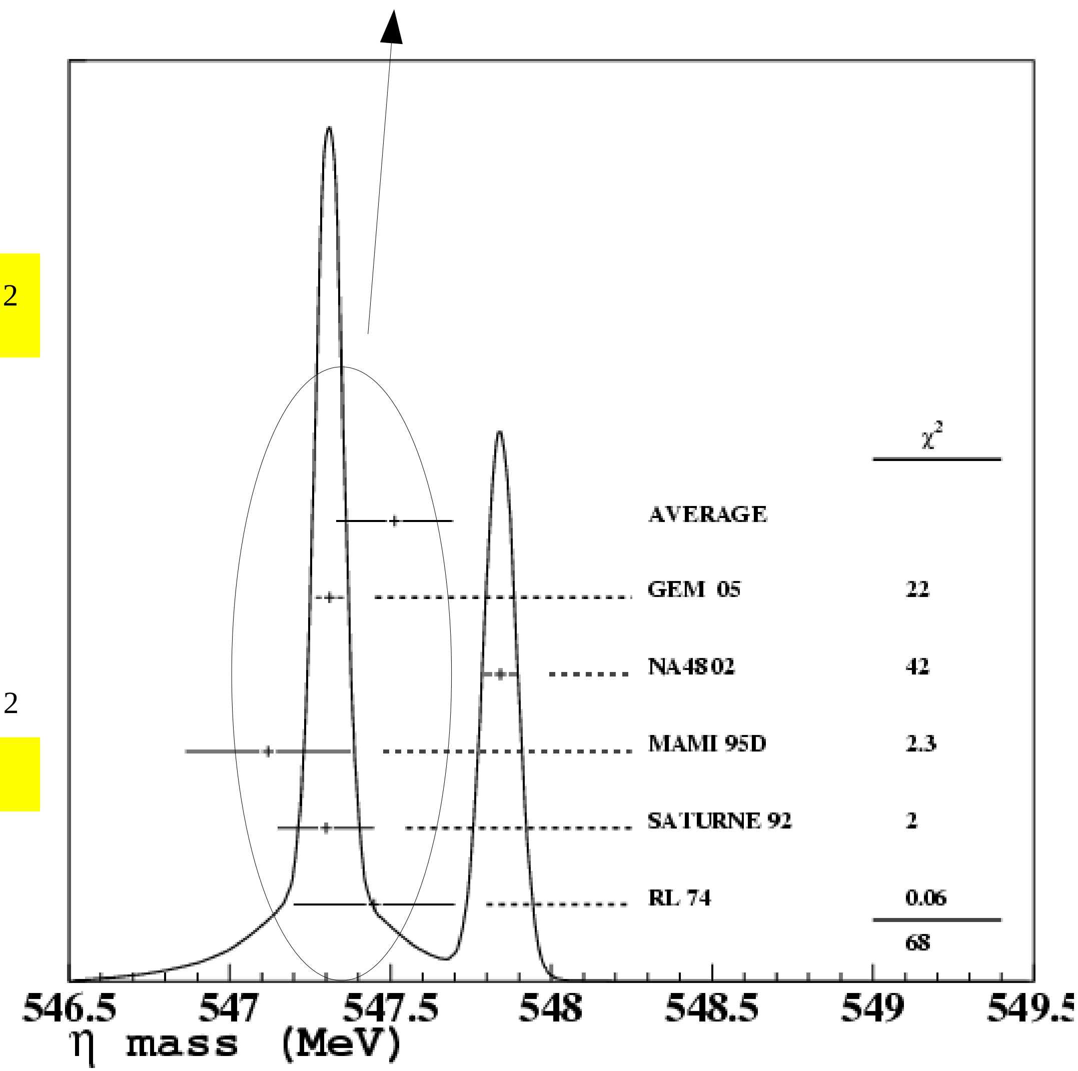
GEM is in good agreement with old measurements

GEM result:

$M_\eta = (547.311 \pm 0.028 \pm 0.032)$ MeV/c^2
Reaction used: $p + d \rightarrow {}^3He + \eta$

High discrepancy with NA48!

Using $\eta \rightarrow 3\pi^0$ from $\pi^- + p \rightarrow \eta + n$:
$M_\eta = (547.843 \pm 0.030 \pm 0.041)$ MeV/c^2
[A, Lai et al., Phys. Lett. B 533 (2002) 196]



Method and selection.

$\phi \to \eta\gamma \; (\eta \to \gamma\gamma)$ ⟶ η mass

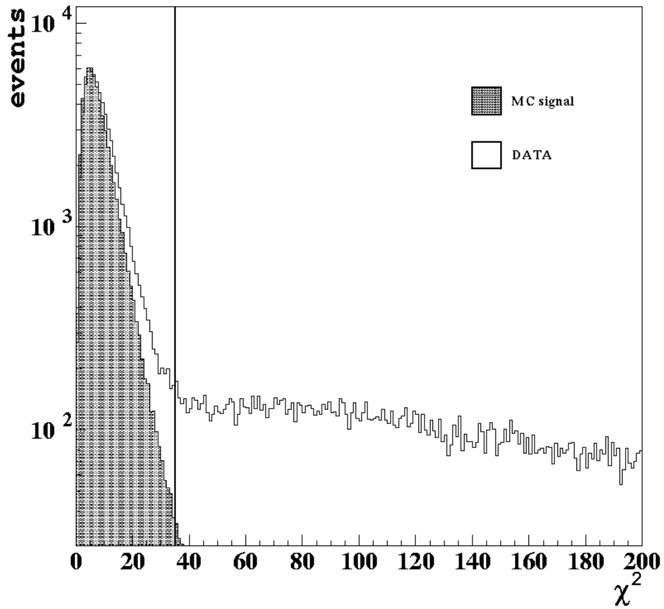
$\phi \to \pi^0\gamma \; (\pi^0 \to \gamma\gamma)$ ⟶ π^0 mass

3γ final state

A kinemati fit is performed imposing energy-momentum conservation and time of flight of photons
the energy momentum conservation imposes 4 constraints

the energies of the three photons are over constrained and determined by the angles through the kinematic fit.

$\chi^2 < 35$



Selection

At least 3 photons with the requirements:

$|t - r/c| < \min(5\sigma_t, 2\text{ns})$

$50° < \theta_\gamma < 130°$

the kinematic fit is performed on all combinations and that with the smallest χ^2 is retained.

Measurement method

constraints equation

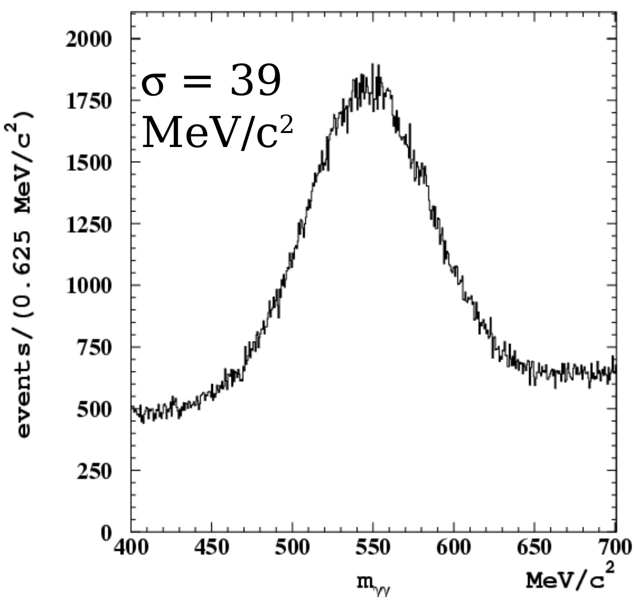
- energy-momentum conservation
- t-r/c of clusters

measured quantities

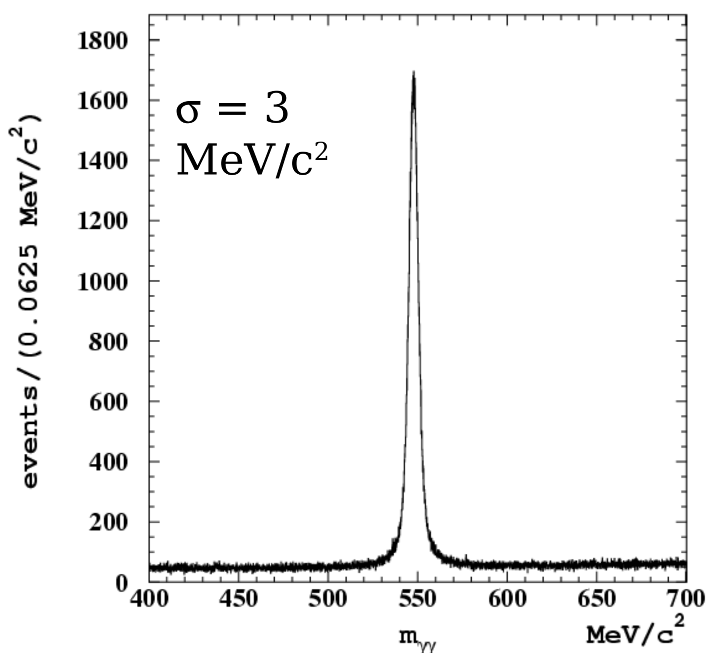
- cluster position x,y,z
- cluster energies
- cluster times
- $\sqrt{s}$
- momentum
- vertex position

} from $e^+e^- \to e^+e^-$
86000 ev./run

before kin. fit



after kin. fit



the kinematic fit squeeze the distribution because of the very good angular resolution.

Biagio Di Micco

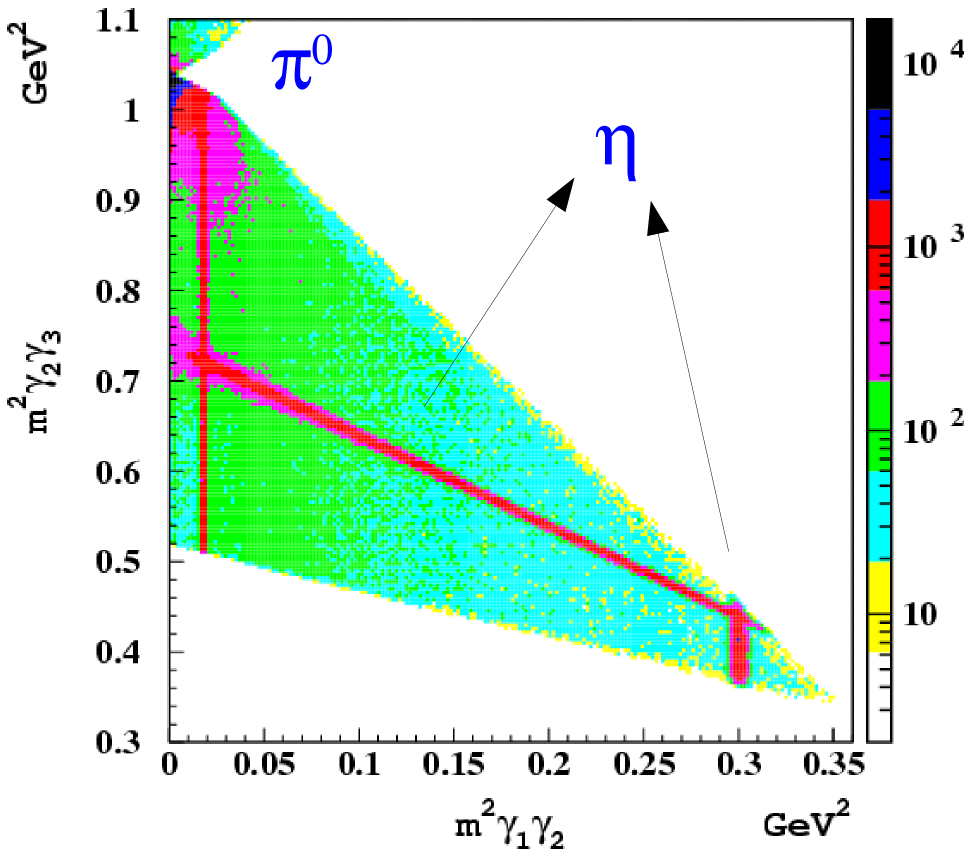
Dalitz plot

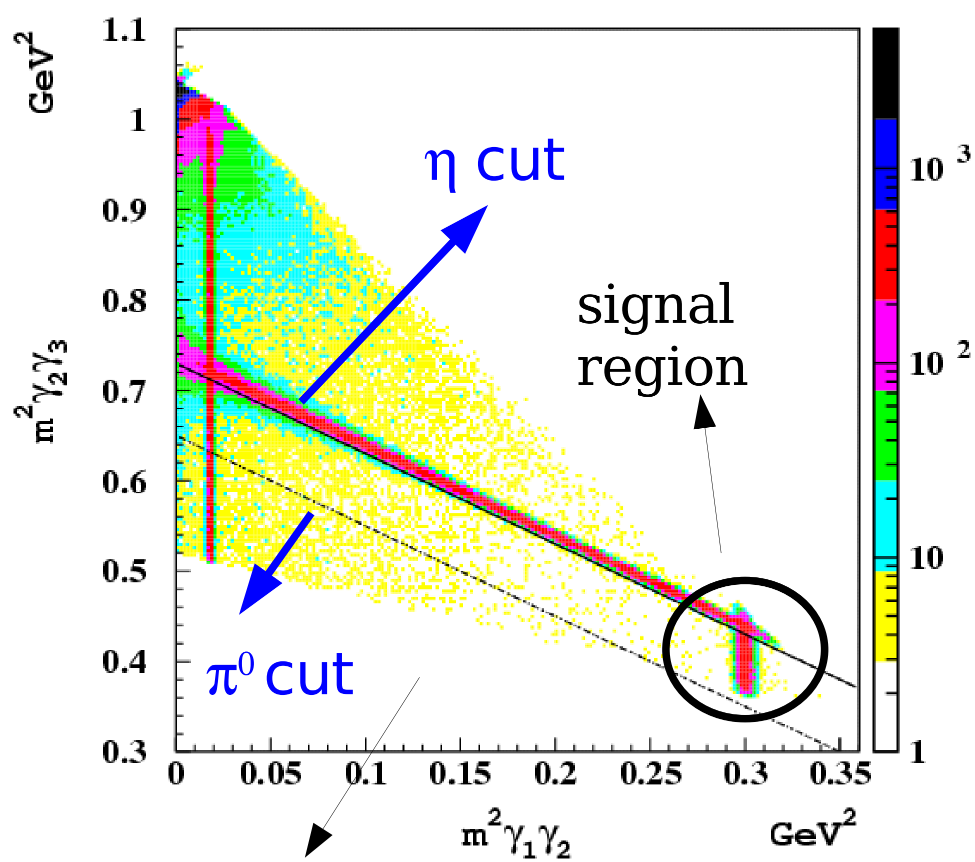
The photons are ordered according their energies

$E_1 < E_2 < E_3$

DATA

$\chi^2 < 35$





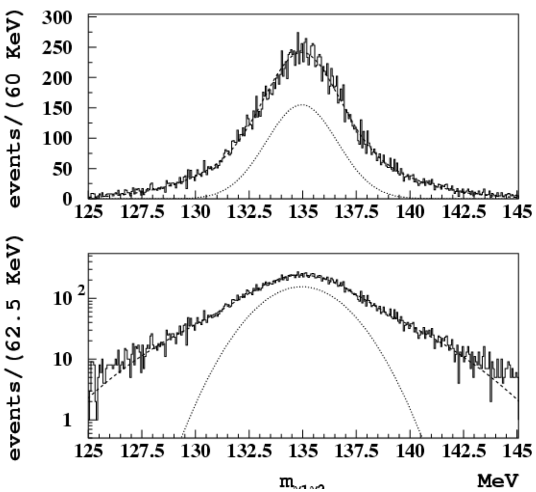
Accepted region

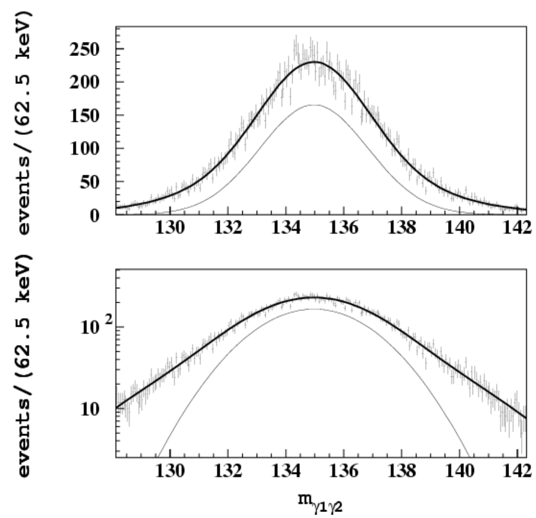
Fit of the $\gamma\gamma$ invariant mass

Fit to the invariant mass distribution

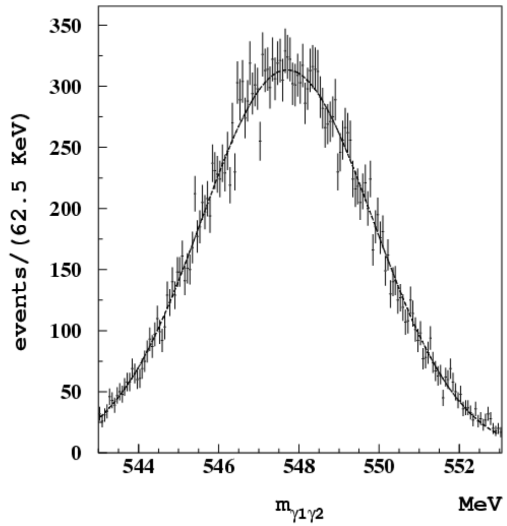
DATA **MC**

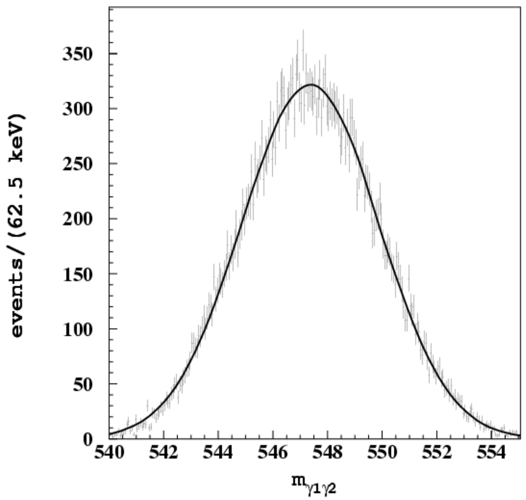
double gaussian for π^0





single gaussian for η





systematic checks

Cuts

Dalitz plot cut

χ^2

photon angle dependence

azimuthal and polar angle;

vertex position

vertex position determination;

DC – EMC global misalignment

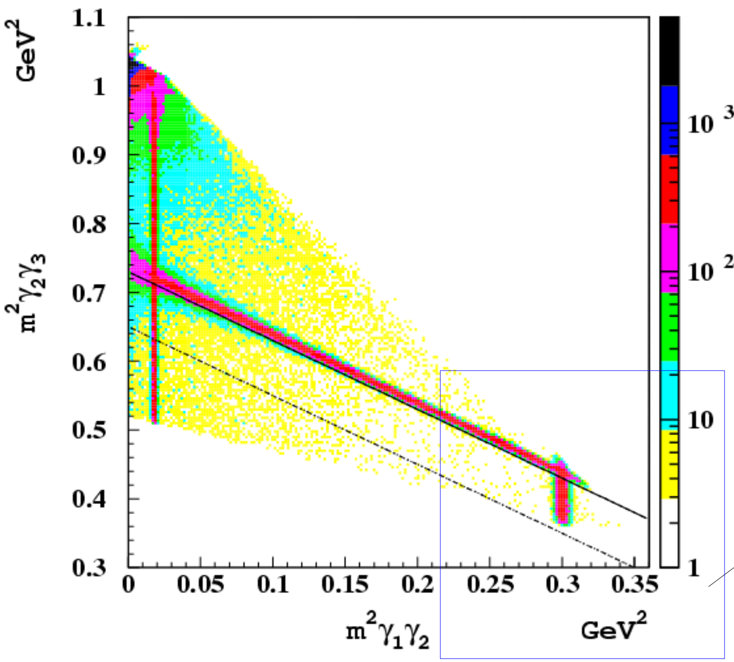
calorimeter energy response

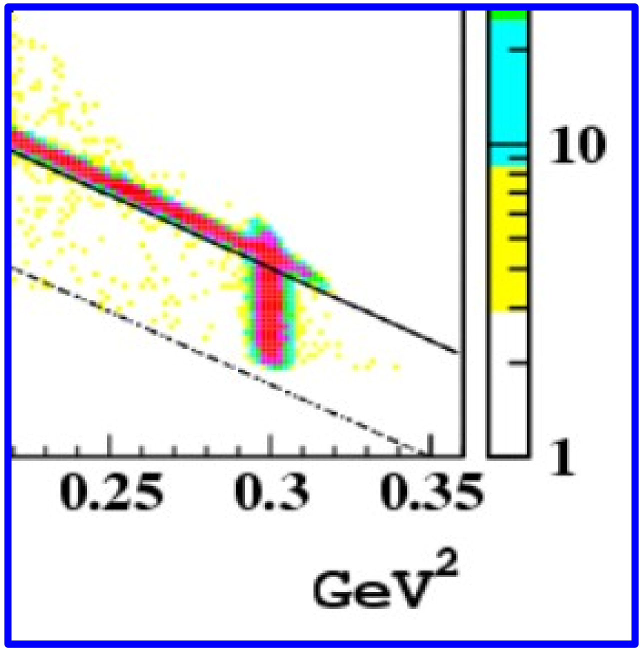
energy scale knowledge

deviation from linearity

ISR effect on sqrt(s)

Dalitz cut systematic



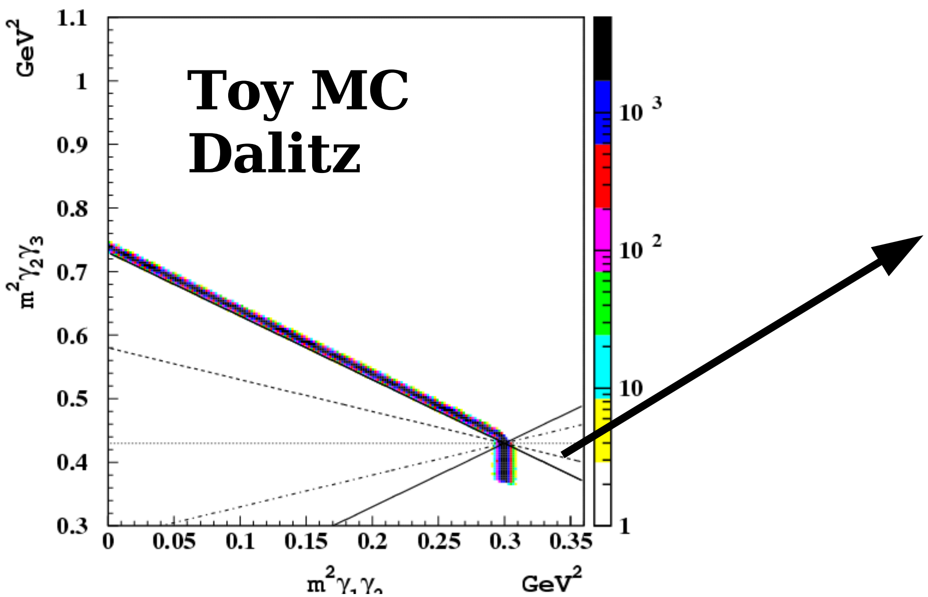


The cut on the Dalitz produces a small distortion on the invariant mass distribution that shifts the measured mass.

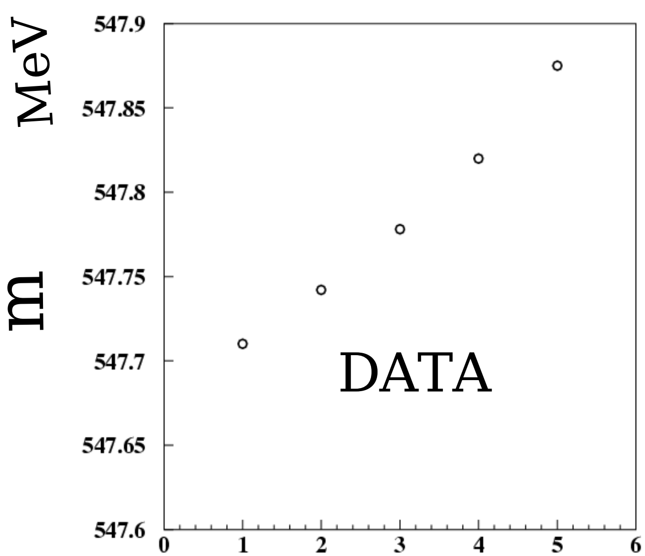
The distortion is null in the limit of infinite resolution and can be easily corrected using MC.

The effect is evaluated using a toy MC that just generate η decays with a gaussian mass spectrum with σ(DATA)

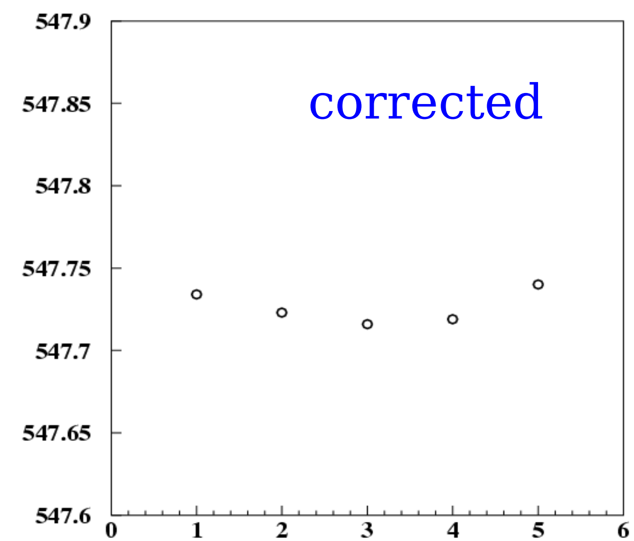
Dalitz cut correction - slope



cut	MC(547.78)	DATA	DATA corr
0.73-x	547,756	547,710	547,734
0.58-0.5x	547,799	547,742	547,723
0.43	547,842	547,778	547,716
0.28+0.5x	547,881	547,820	547,719
0.13+x	547,915	547,875	547,740

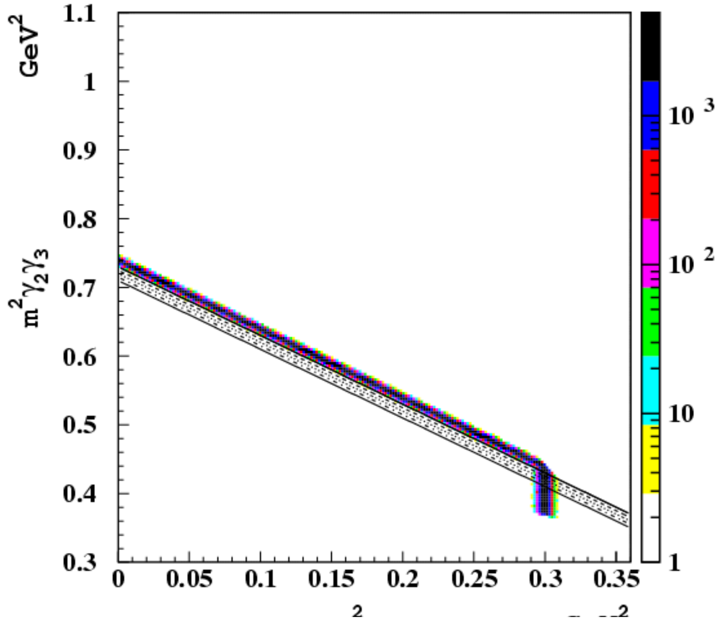


200 keV variation

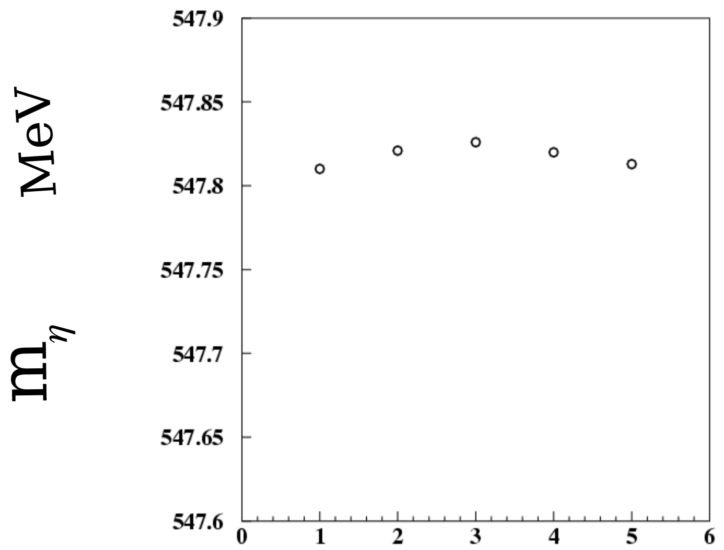


12 keV residual systematic

Dalitz cut correction - constant



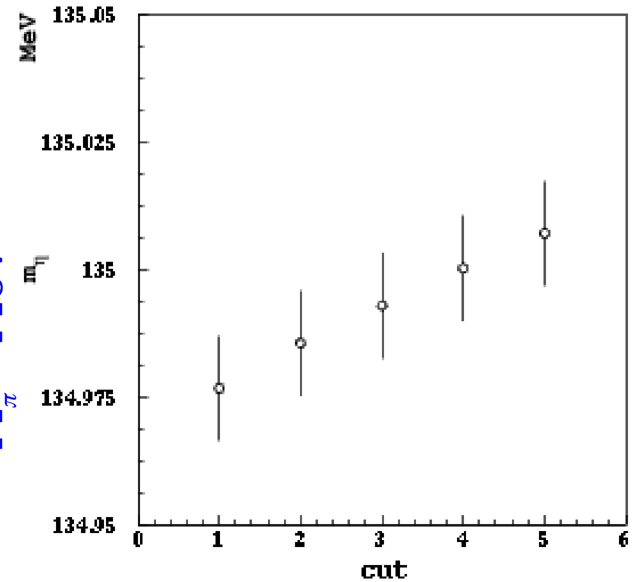
cut	MC(547.78)	DATA
0.73-x	547,756	547,810
0.72-x	547,753	547,821
0.71-x	547,748	547,826
0.70-x	547,744	547,820
0.69-x	547,736	547,813



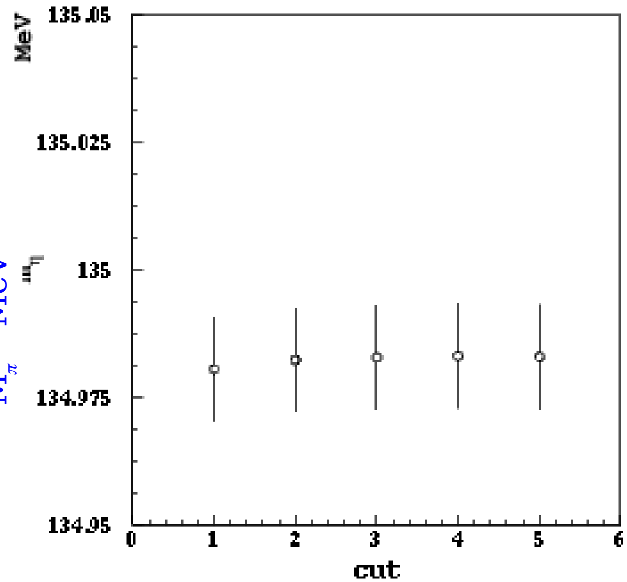
12 keV systematic
rms of the points
without correction.

π^0 case

M_π MeV

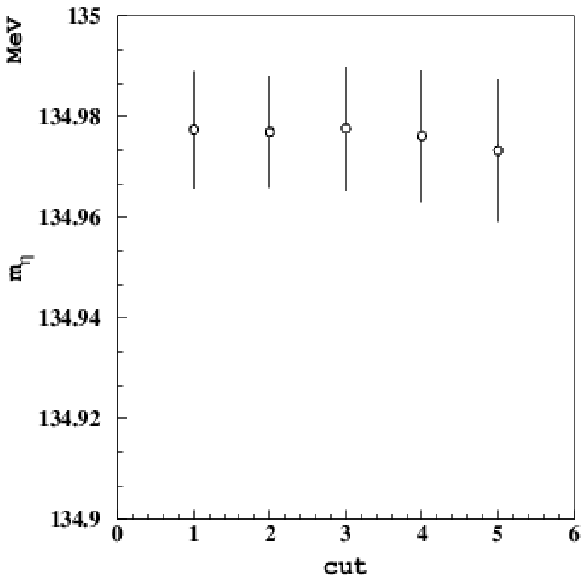


M_π MeV



Slope cut

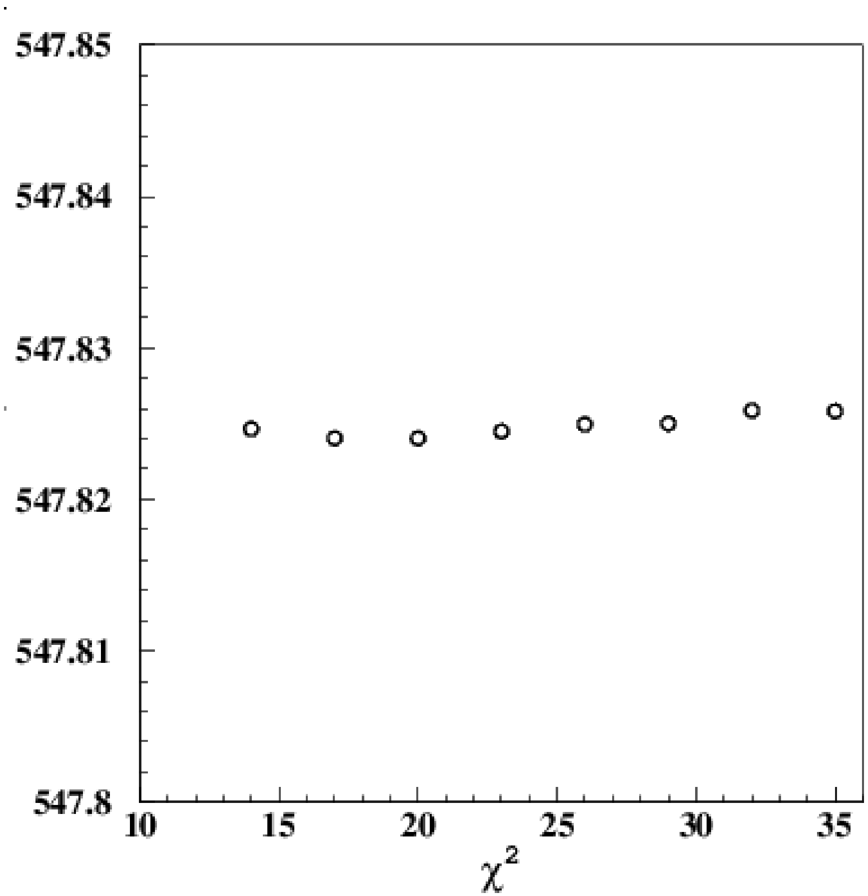
4 keV



Constant cut

1.9 keV

χ^2 cut

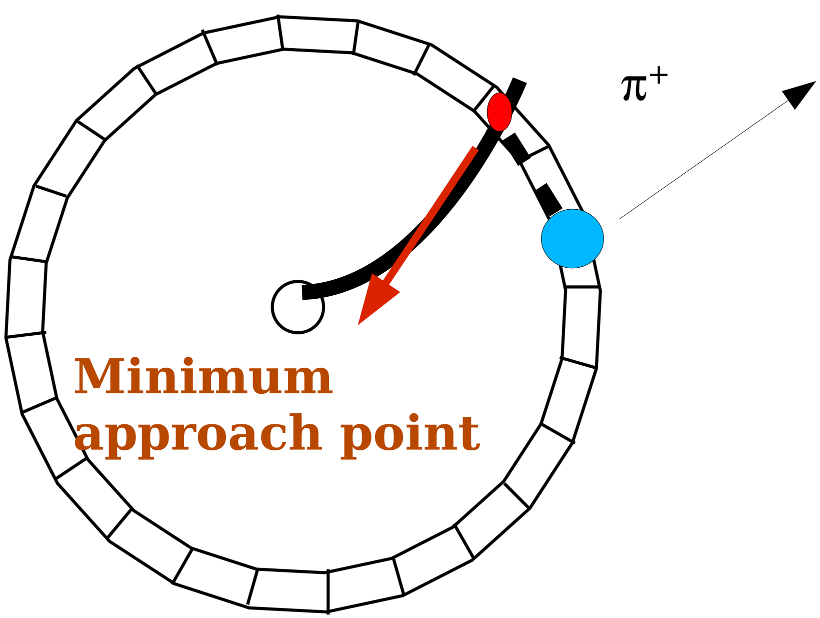


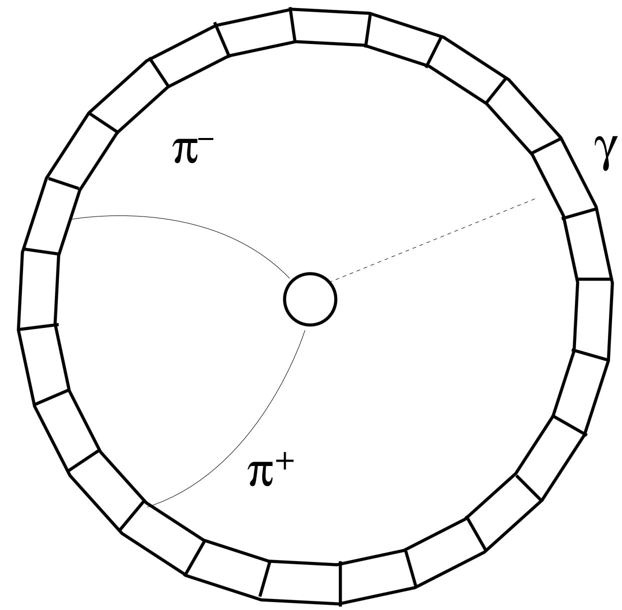
	m_η (keV)	m_π (keV)	m_η/m_π
χ^2 cut	0.7	4	1.3×10^{-4}

A sample of $\pi^+ \pi^- \gamma$ has been used to determine shifts in the vertex position and displacement between DC and EMC.

The $\pi^+ \pi^-$ vertex is compared with that coming form $e^+ e^- \rightarrow e^+ e^-$.

The tracks are extrapolated from the vertex to the calorimeter, and compared with the cluster position.





$\pi^+ \pi^- \gamma$ selection criteria

$50° < \theta_\pi, \theta_\gamma < 130°$

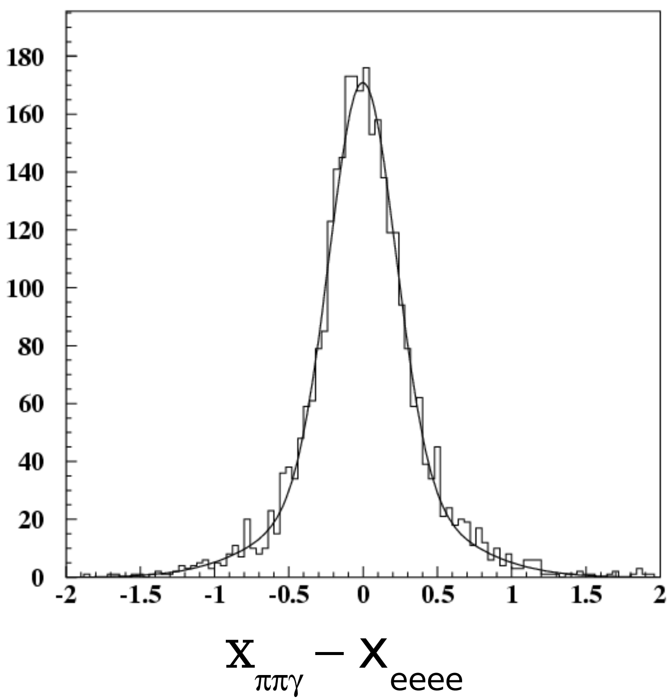
Trackmass, and of the likelihood

$\pi^+ \pi^- \pi^0$ rejection through kinematic fit

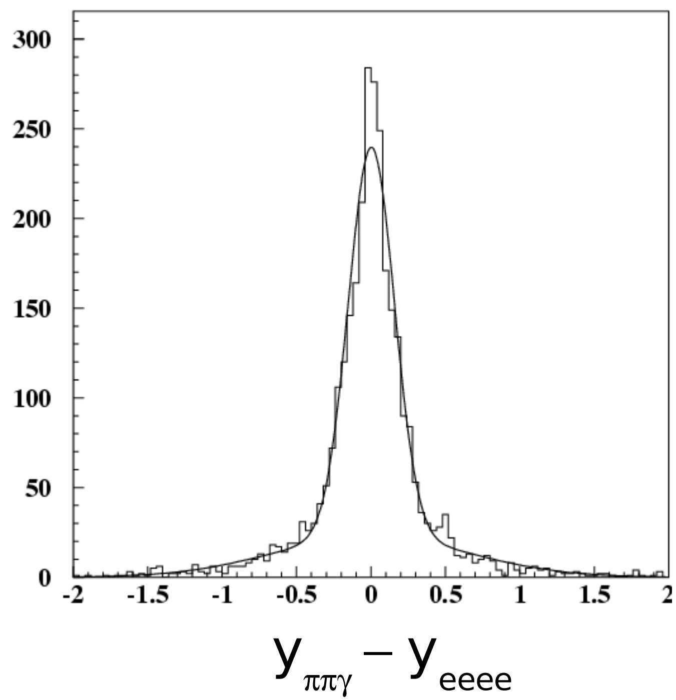
Mis-determination of the I.P

We keep the vertex from the tracking algorithm and compare it with the BPOS values event by event

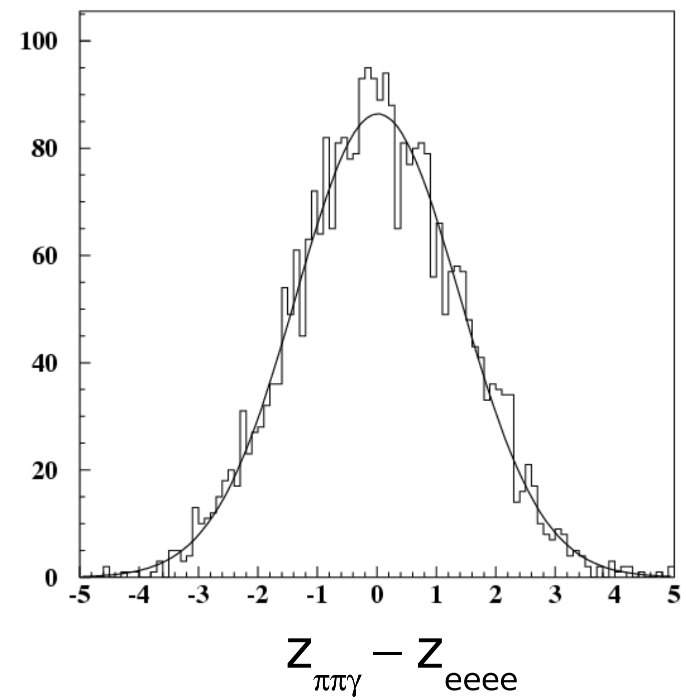
2 normal dist.



2 normal dist.



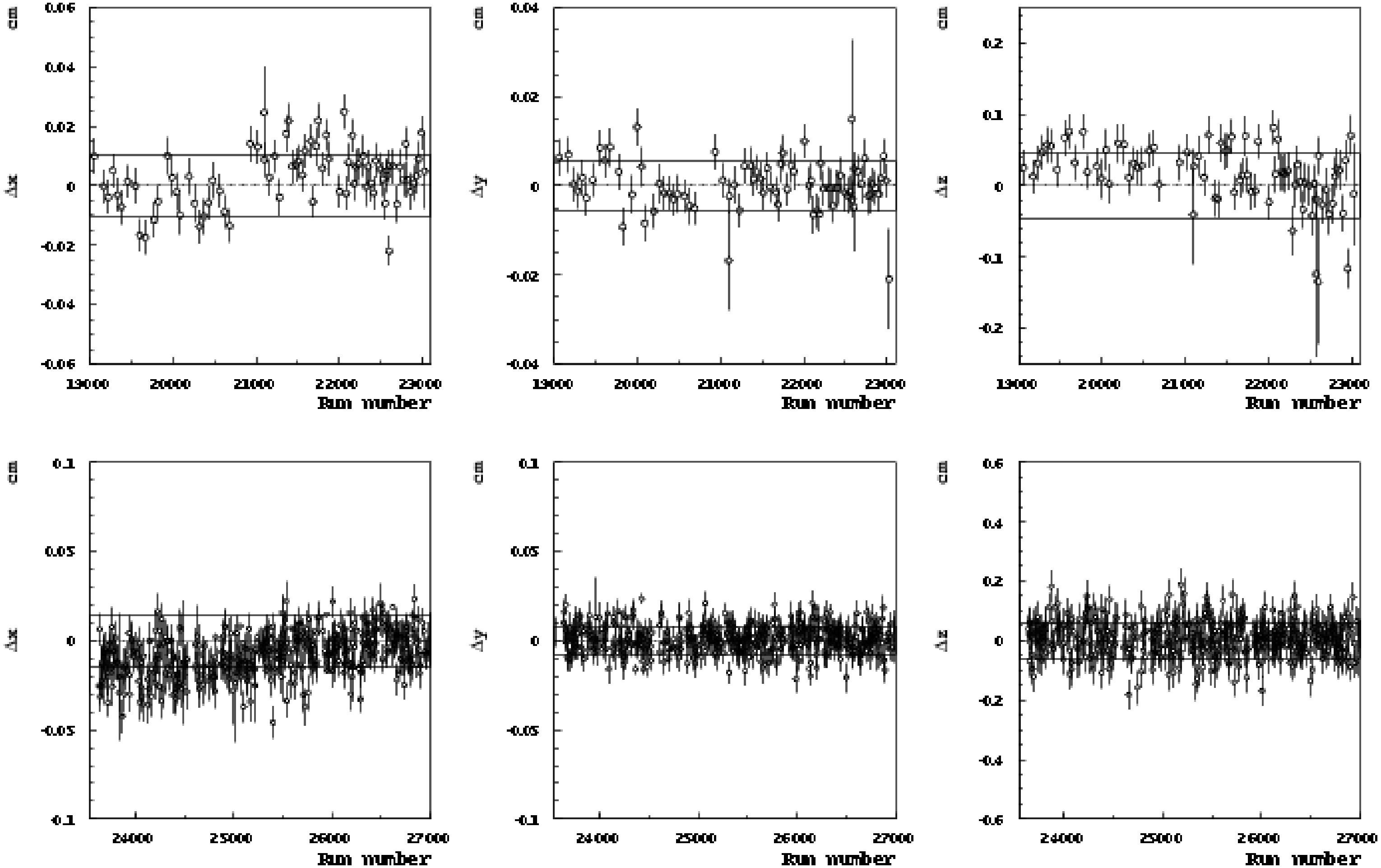
1 normal distr.



displacement as a function of run n.

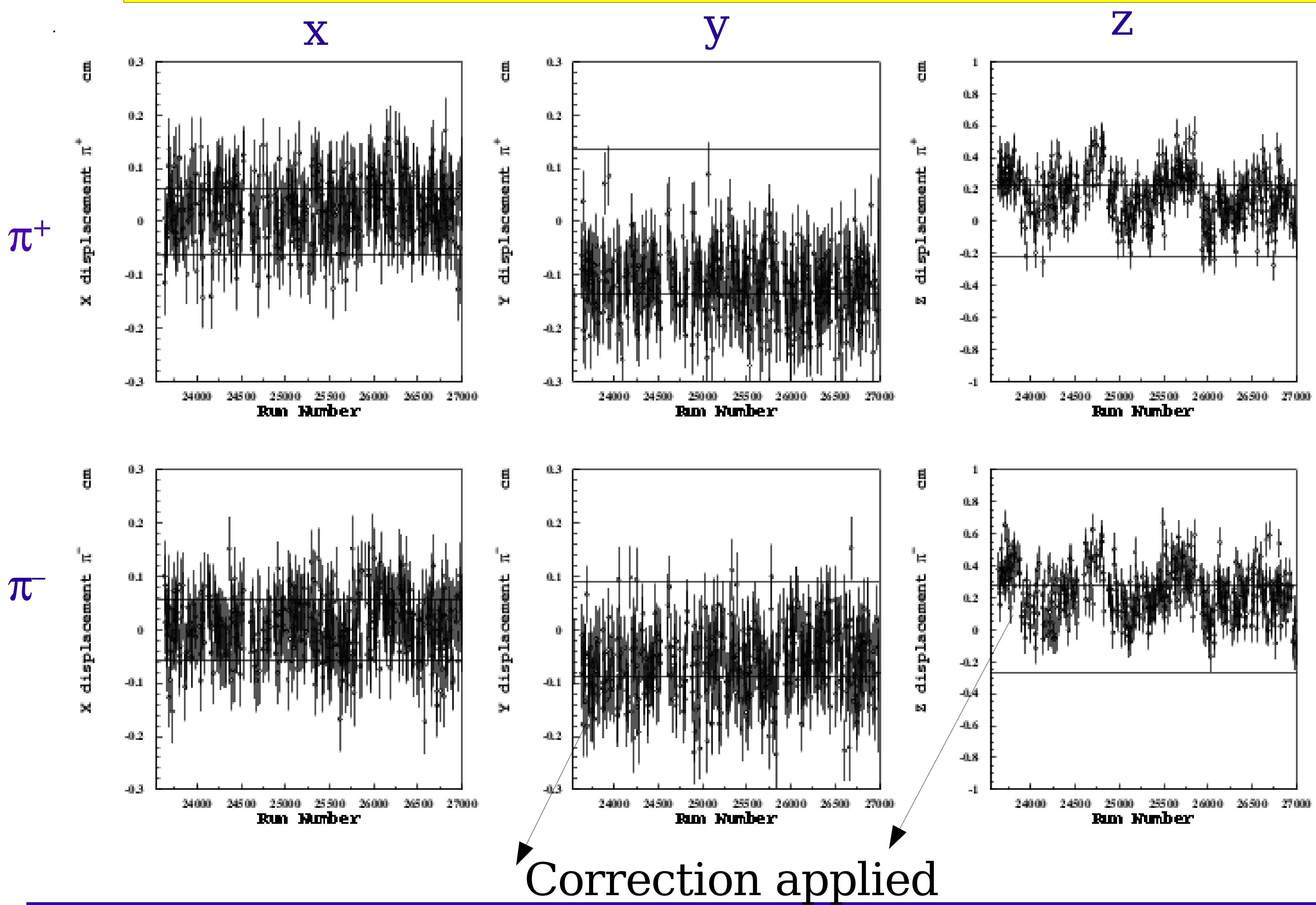
2001

2002



The standard deviation respect to the zero value is taken as systematic

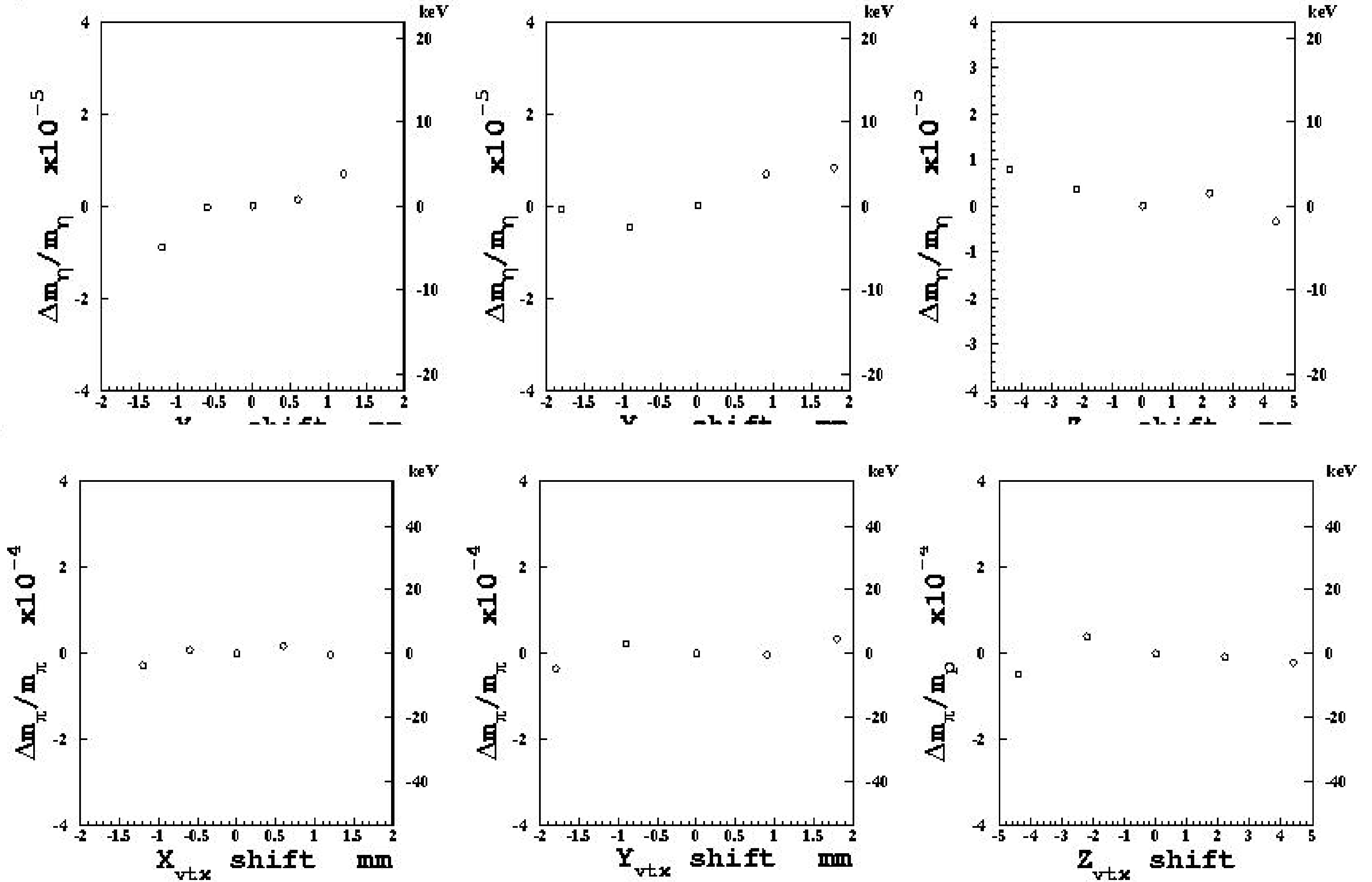
2002 EMC-DC displacement



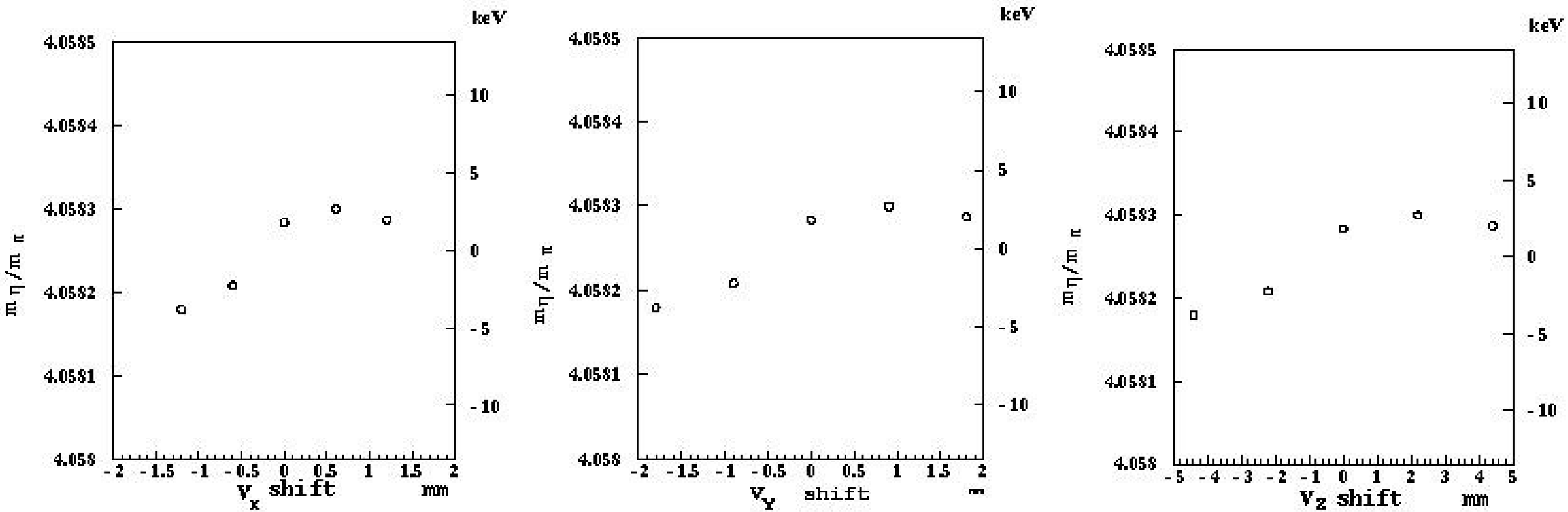
Vertex+alignment systematic

Systematic due to the vertex position (cm).							
	2001			2002			
coord.	rms I.P	DC-calo al. π^+	DC-calo al. π^-	rms I.P	DC-calo al. π^+	DC-calo al. π^-	tot. syst.
x	0.010	0.04	0.034	0.014	0.062	0.056	0.056
y	0.006	0.12	0.08	0.008	0.13	0.088	0.088
z	0.046	0.16	0.17	0.061	0.22	0.28	0.22

Mass versus vertex position



Mass ratio versus vertex position

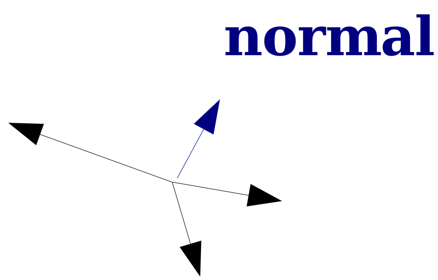


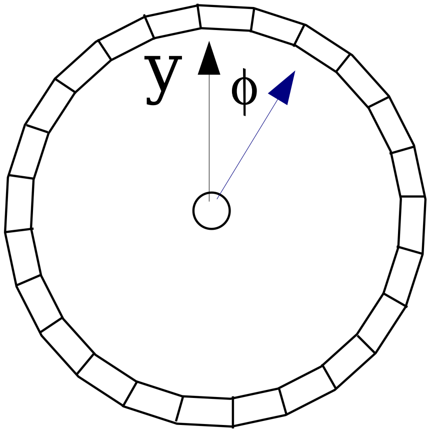
Uncertainty on the mass values (fractional error)

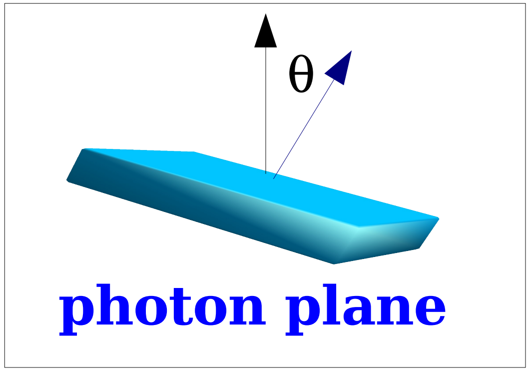
	m_η $(\times 10^{-6})$	m_π $(\times 10^{-6})$	m_η/m_π $(\times 10^{-6})$
V_X	1.8	15	15
V_Y	7	22	27
V_Z	4	37	35
overall	8	45	47

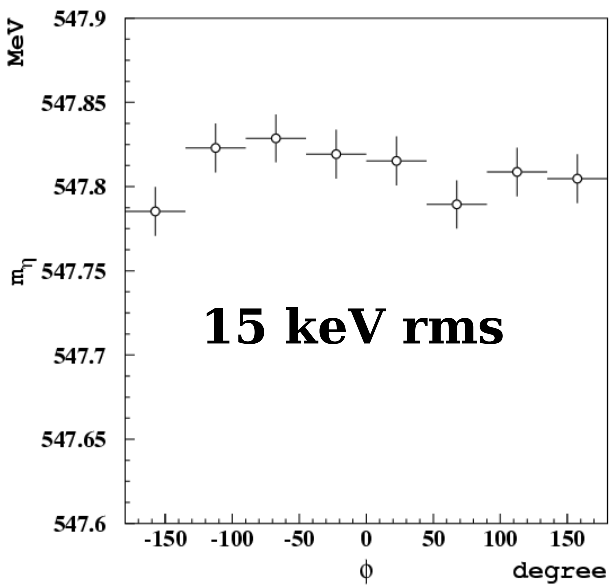
Angular dependence

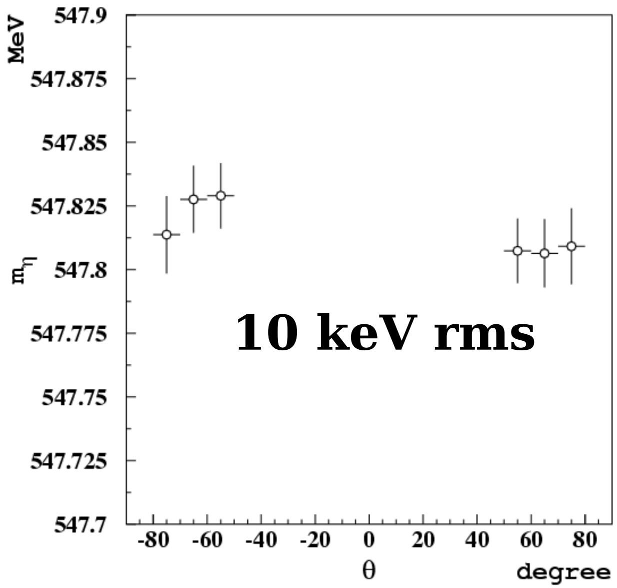
The 3 photons are boosted back in the ϕ rest frame.
The normal to the plane of the 3 photons is evaluated.











Energy response

The same $\pi\pi\gamma$ sample can be used to check the energy response of the calorimeter, comparing the g energy evaluated from the $\pi\pi$ tracks with the cluster energy.

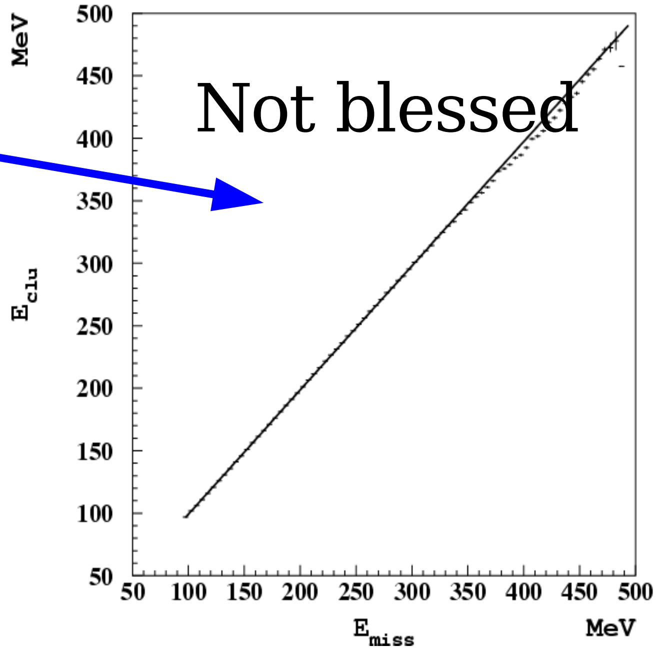
$E_{clu} = 0.994 \times E_{true} - 0.2$ MeV

linearity deviation are 2% at most.

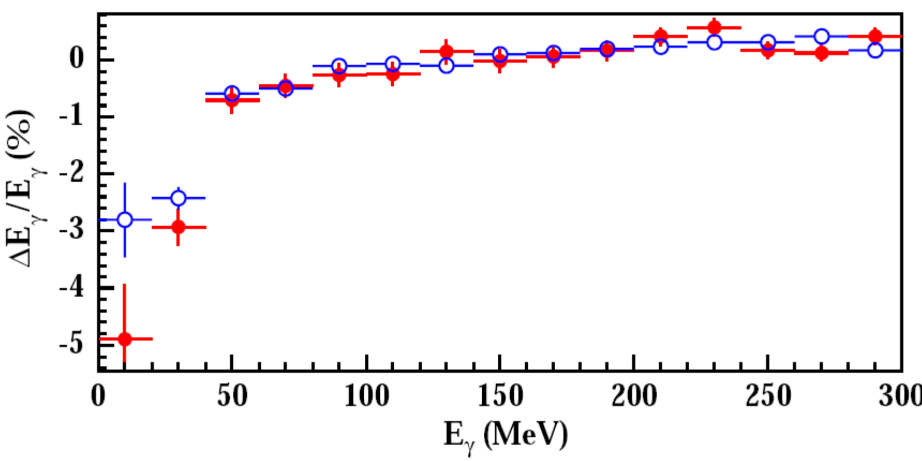
Applying these correction we find:

energy scale $\delta m/m = 8\times10^{-6}$ (4 keV)

lin. dev. $\delta m/m = 7\times10^{-6}$ (4 keV)



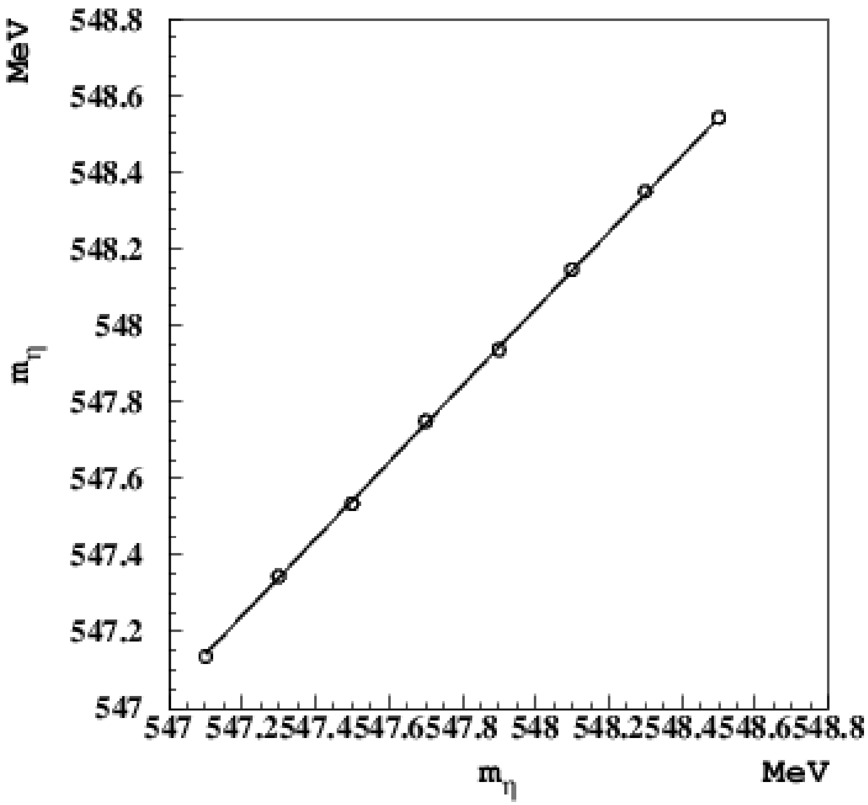
Different approach using $\phi \to \pi^+ \pi^- \pi^0 (\pi^0 \to \gamma\gamma)$



The same result in the overlapping region

(different γ energy allowed by the kinematics)

Global check of the method



To check possible distortions due to the algorithm itself.

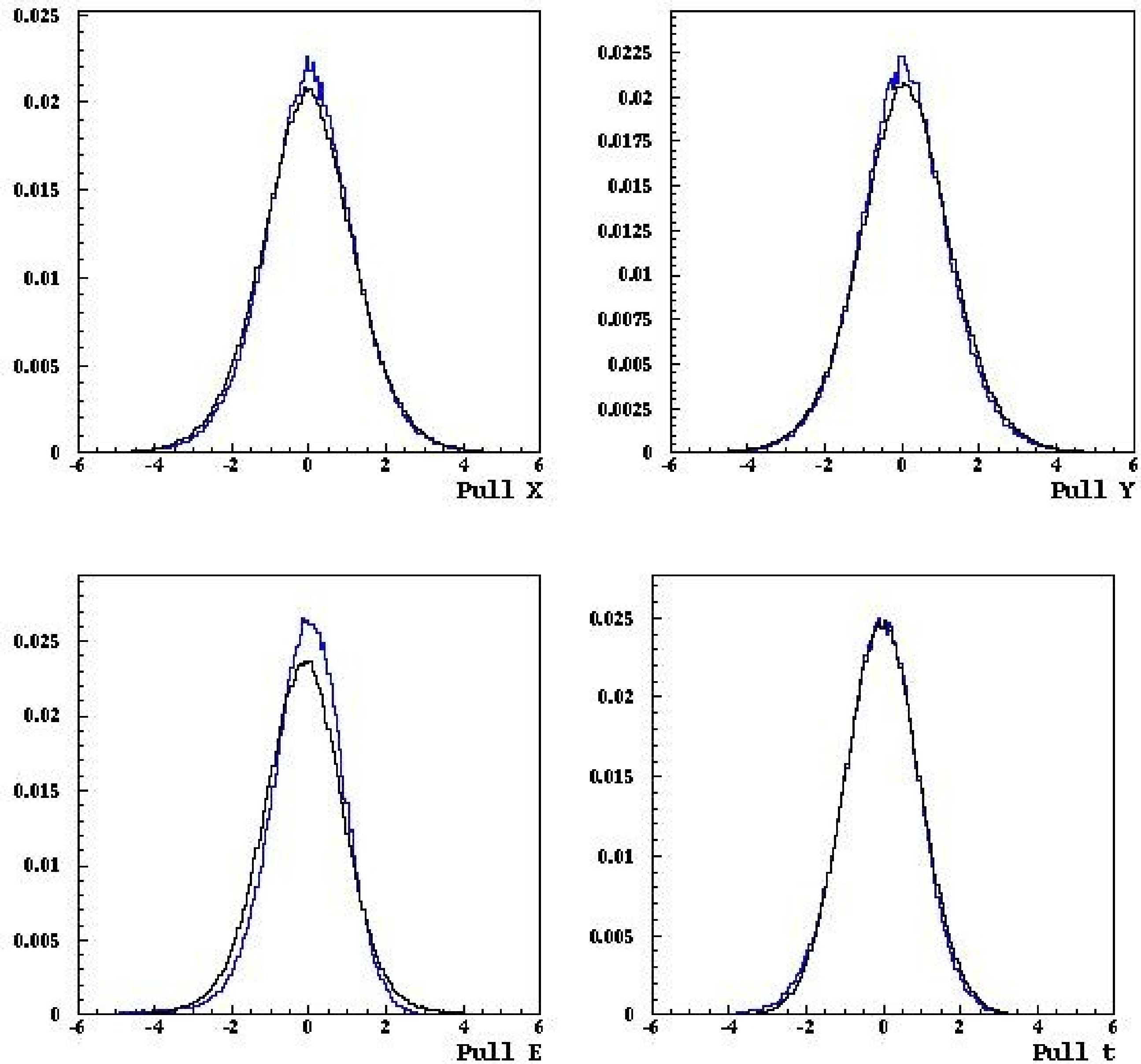
$M_{fit} = M_{input} + (41 \pm 3)$ keV/c^2

χ^2/n.d.f $= 0.32$

50pb^{-1} for each point

linearity is perfect.
A correction for the constant term is needed.

Fit pulls checking



x,y,t ok

z,E difficult to correct.

DATA
MC

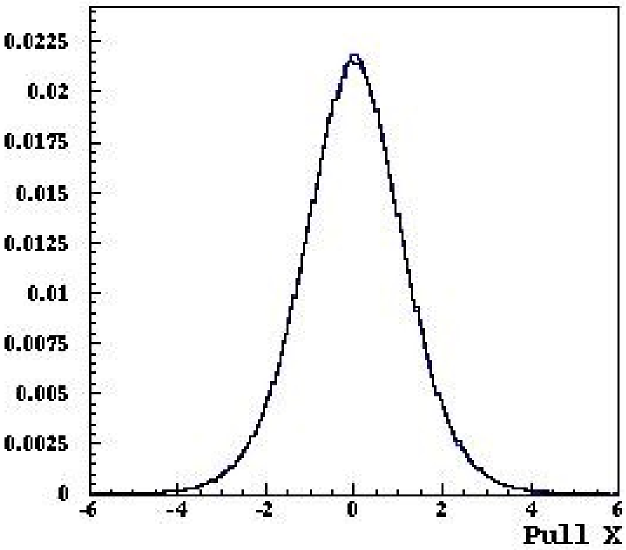
Dummy simulation

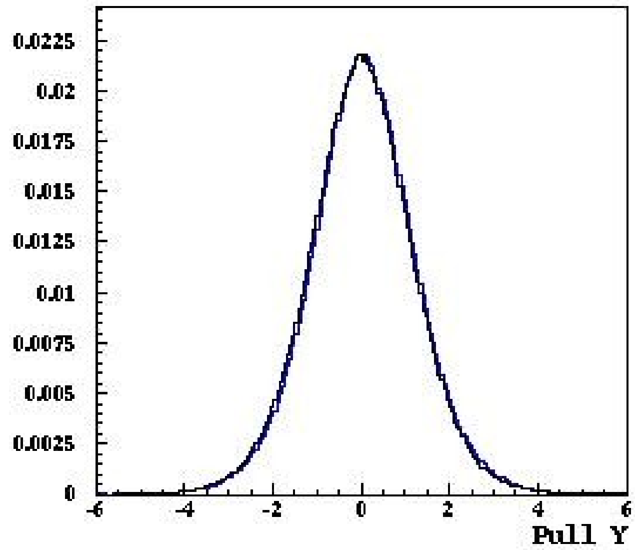
A dummy simulation has been performed that uses GEANFI for vertex simulation and photon transport up to calorimeter: we take the photo conversion point coordinate and then apply a smearing using the following resolution values:

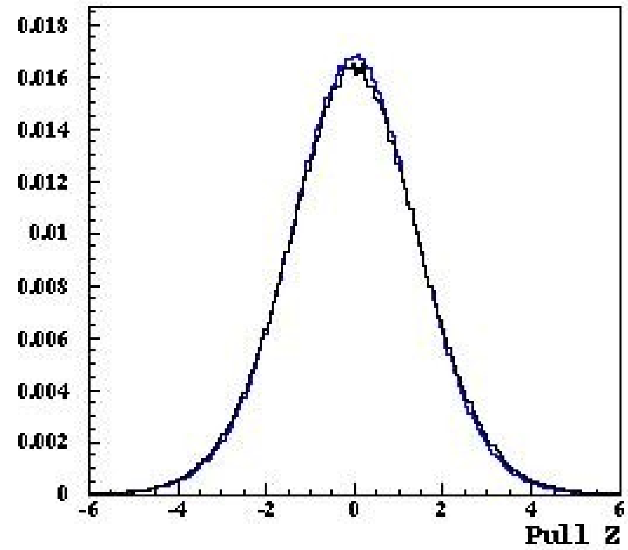
$$\frac{\sigma E}{E} = \frac{0.057}{\sqrt{E GeV}} \qquad \sigma_t = \sqrt{\frac{(54\,ps)^2}{E(GeV)} + (140\,ps)^2} \qquad \sigma_z = \frac{0.9\,cm}{\sqrt{E(GeV)}}$$

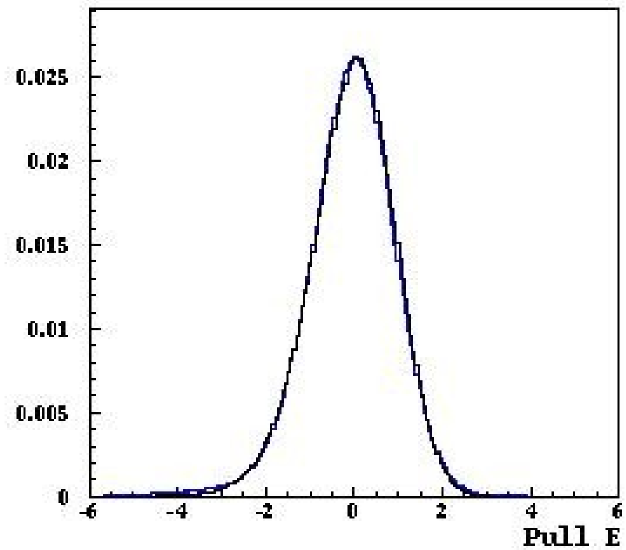
$$\sigma_x = \frac{3.4}{\sqrt{12}}\,cm \quad \sigma_y = \frac{2.81}{\sqrt{12}}\,cm$$

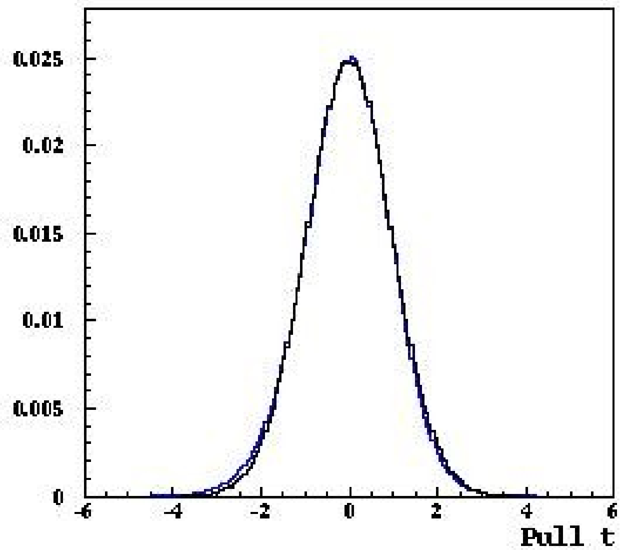
Fit pulls dummy simulation

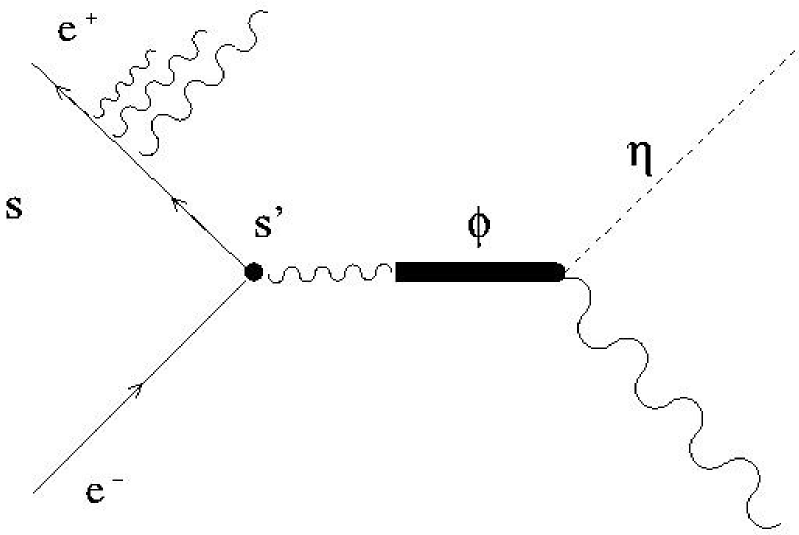












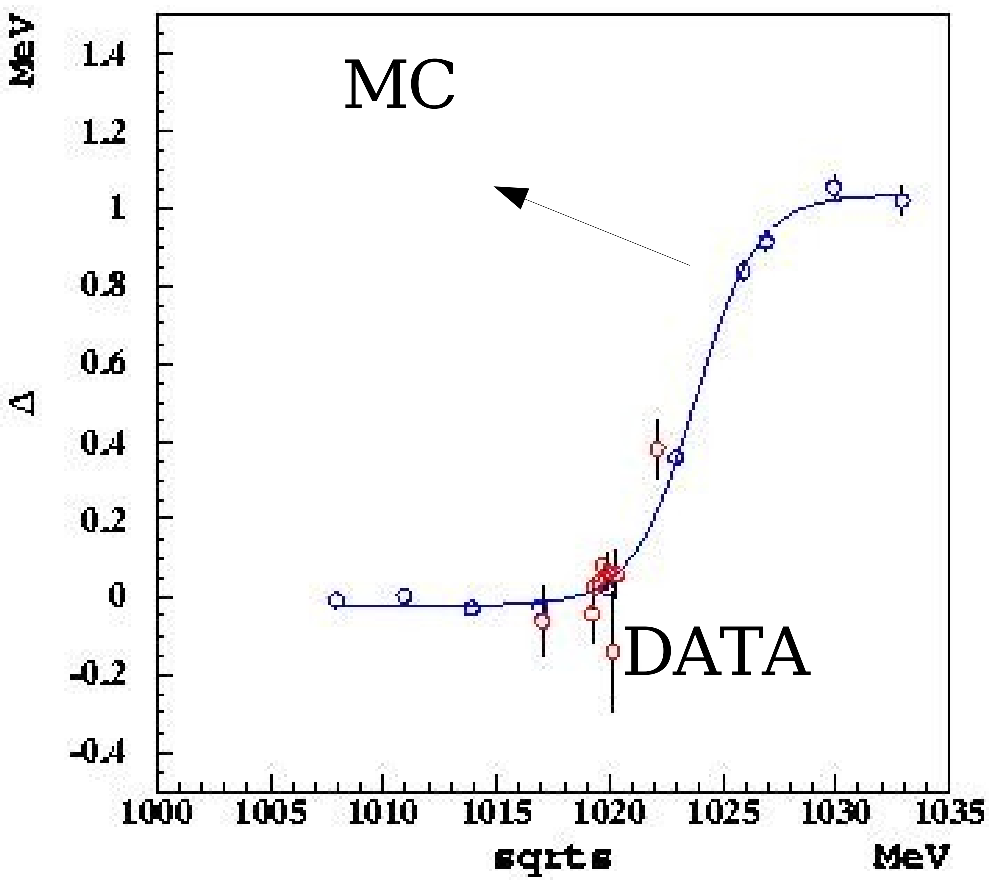
Due to the ISR the average $\sqrt{s}$ of the $\eta\gamma$ system is lower than the $\sqrt{s}$ of the beams.
The difference between the two can induce a correction of 100 keV on the value of the η mass.

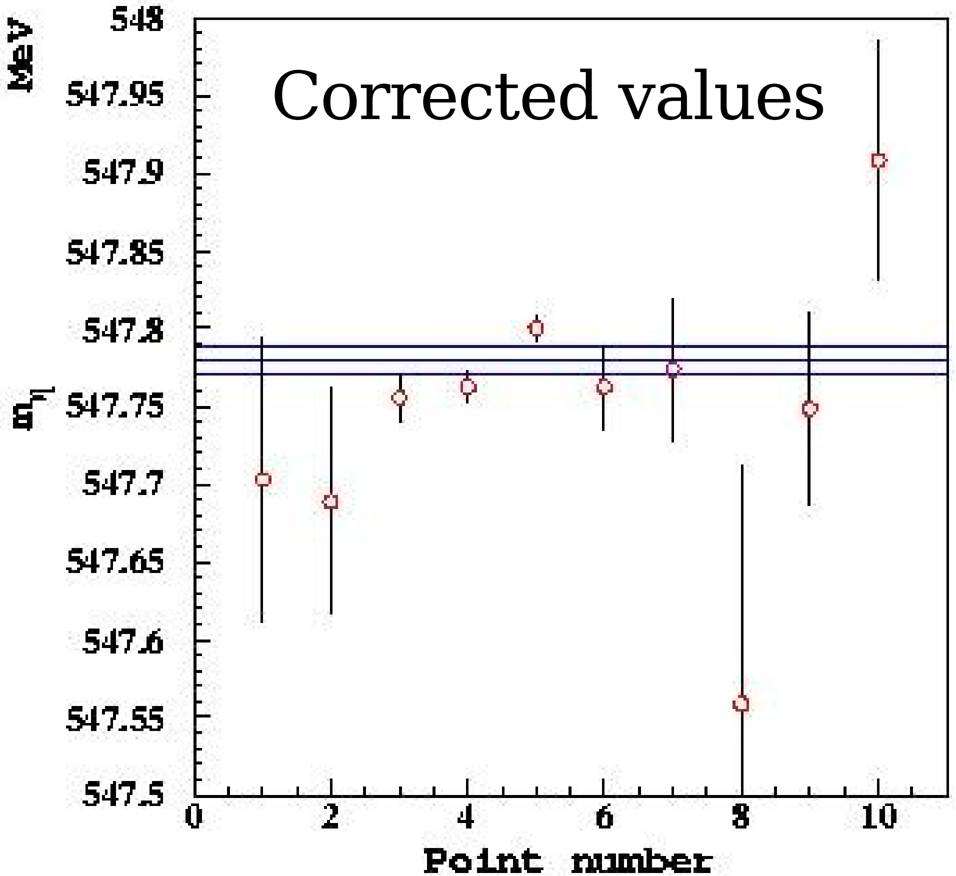
To determine the correction and the systematic:

1) we evaluate the correction using the dummy MC as a function of $\sqrt{s}$;

2) we divide the DATA in $\sqrt{s}$ bins and correct for the MC curve, the spread in the corrected value is taken as systematic.

ISR correction and systematics η





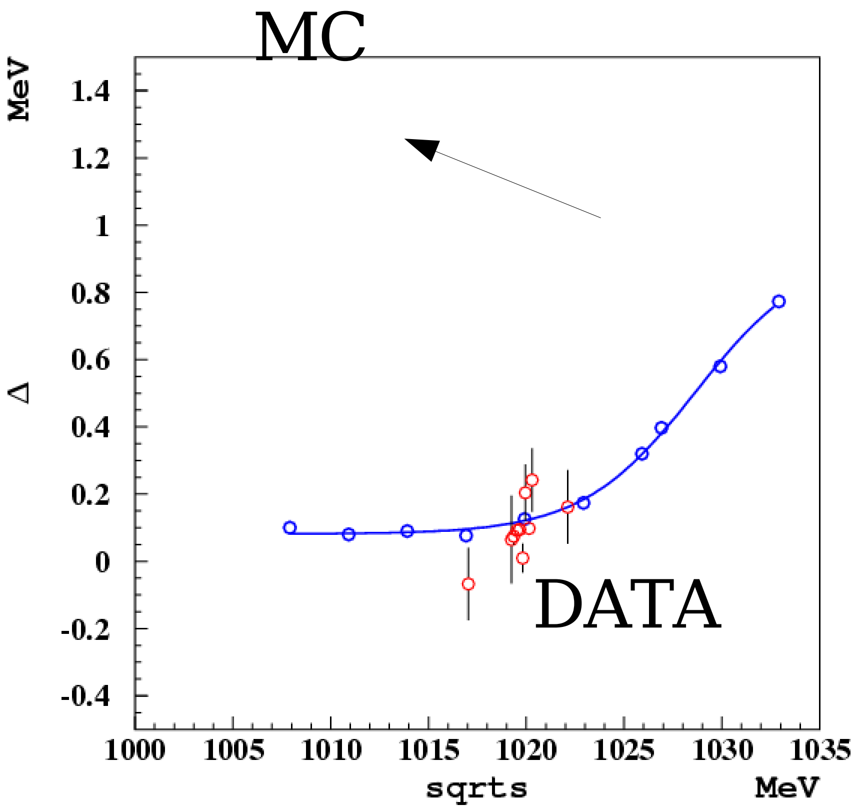
The $\chi^2/9 = 2.2$

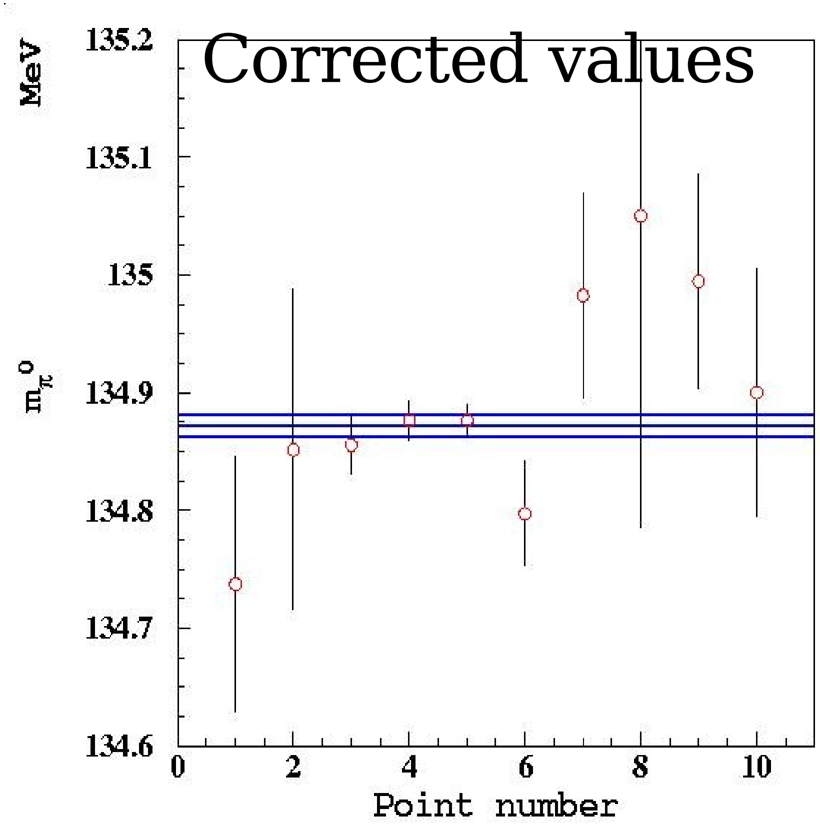
$\sigma_{ISR} = 0.008$ MeV

$m_{mean} = 547.779 \pm 0.005$ MeV

Scale factor $S = \sqrt{\chi^2} = 1.5$

ISR correction and systematics π^0





The $\chi^2/9 = 1.07$

$m_{mean} = 134.874 \pm 0.004$ MeV

Scale factor $S = \sqrt{\chi^2} = 1$

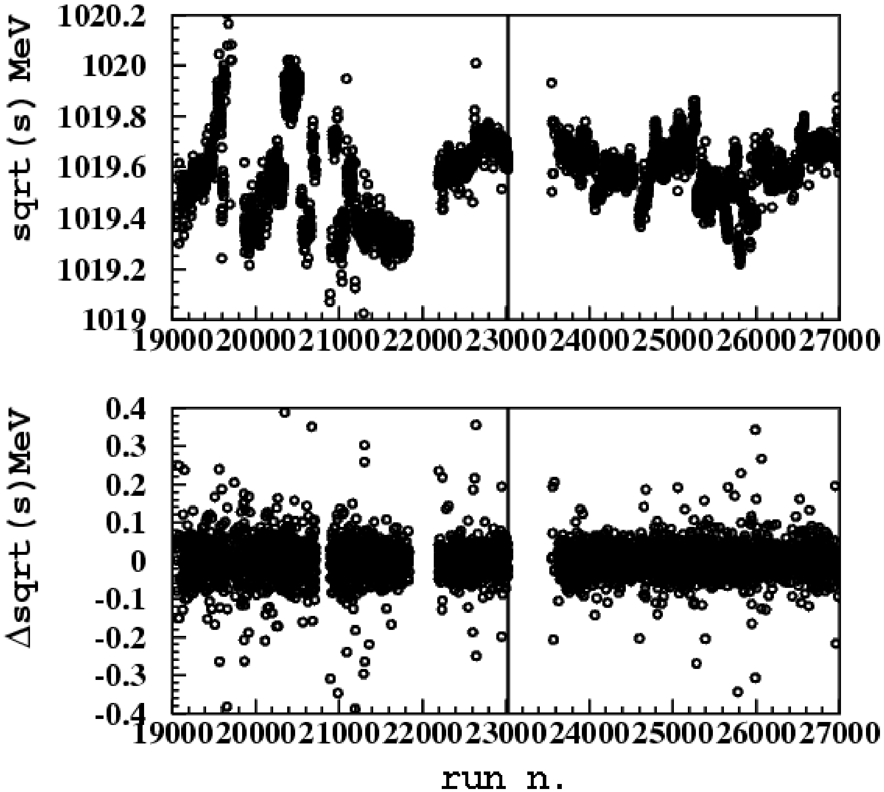
$\sigma_{ISR} = 0.004$ MeV

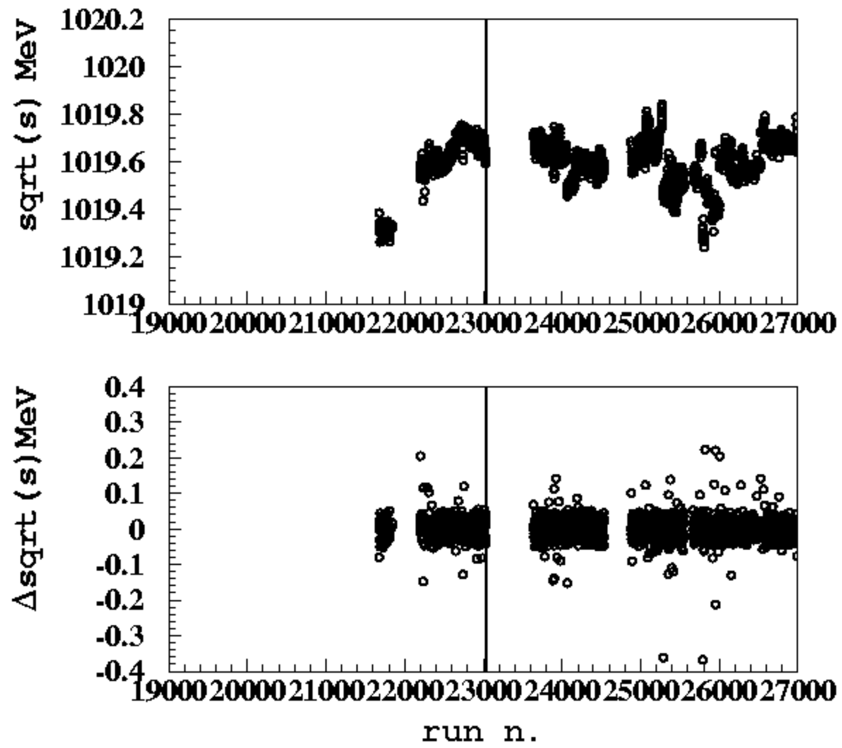
Systematic summary

systematic effect	m_η (keV)	m_{π^0} (keV)	$m_\eta / m_{\pi^0} \times 10^{-5}$
Calorimeter energy constants	4	1	5.6
Calorimeter not linearity	4	11	31
Vertex position	4	6	19
Angular uniformity ϕ	15	12	37
Angular uniformity θ	10	44	120
ISR effect	8	9	28
Dalitz plot slope	12	4	15
Dalitz plot cut (constant)	12	1.9	10
χ^2 cut	0.7	4	13
overall	27	49	136

DATA quality filtering

2001-2002
separation
line



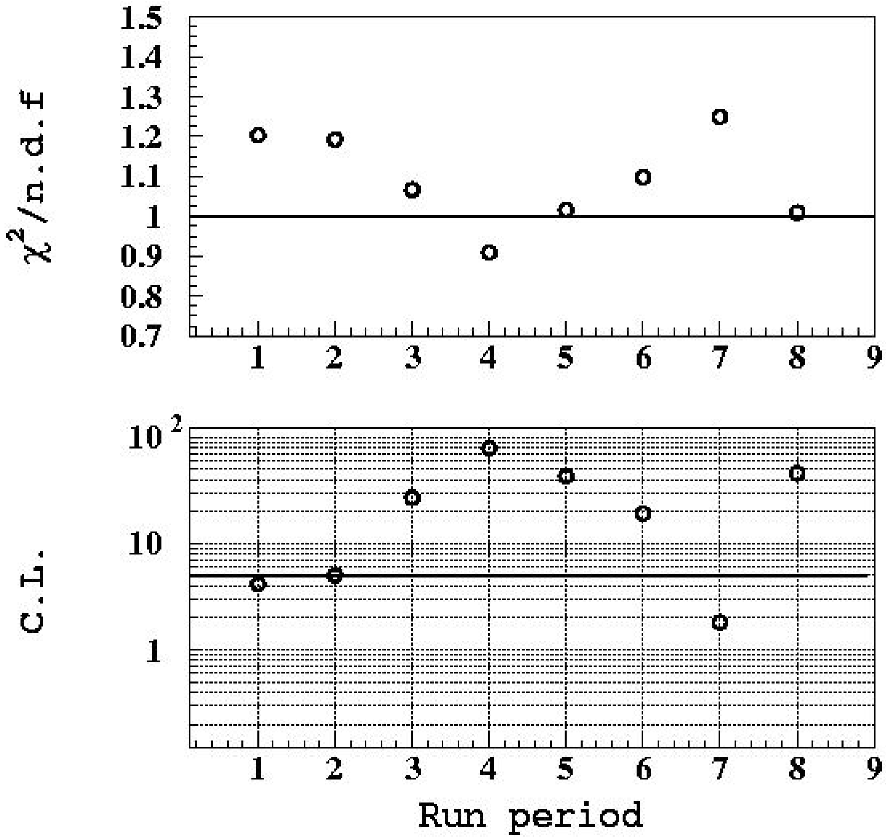


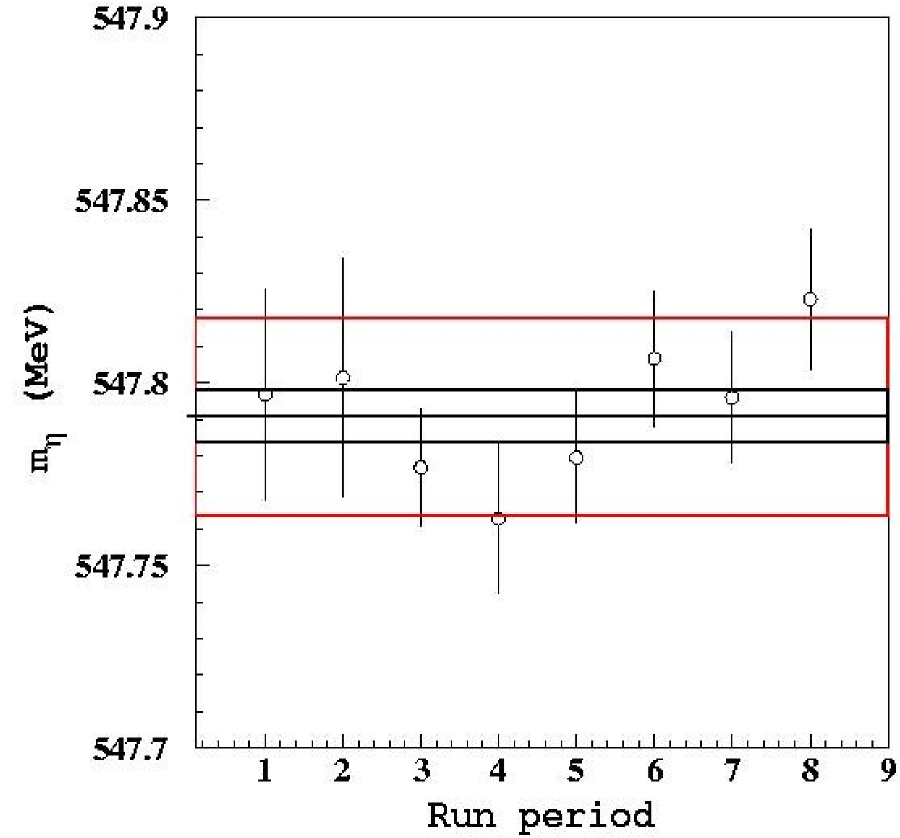
Period with large √s instability have been discarded from the analysis.

η mass fit

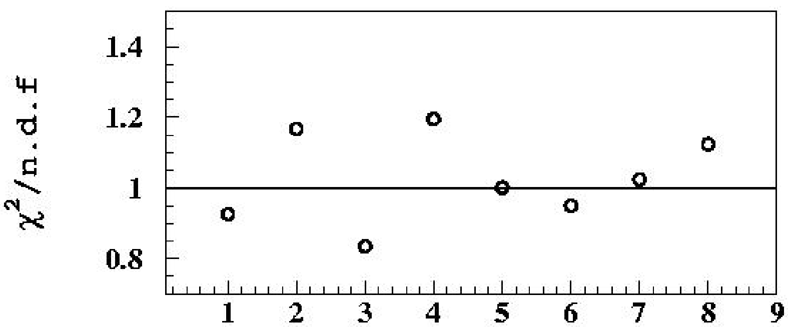
Each selected value of the mass, is corrected event by event for the evaluated MC ISR correction and put in the histogram. Then the histogram is fitted.

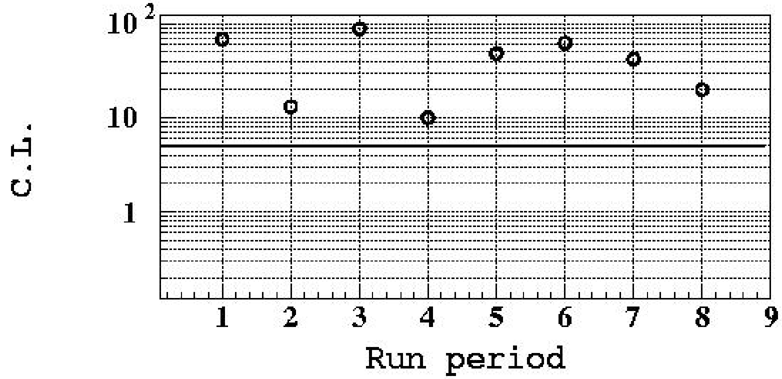
The DATA have been divided in 8 periods.

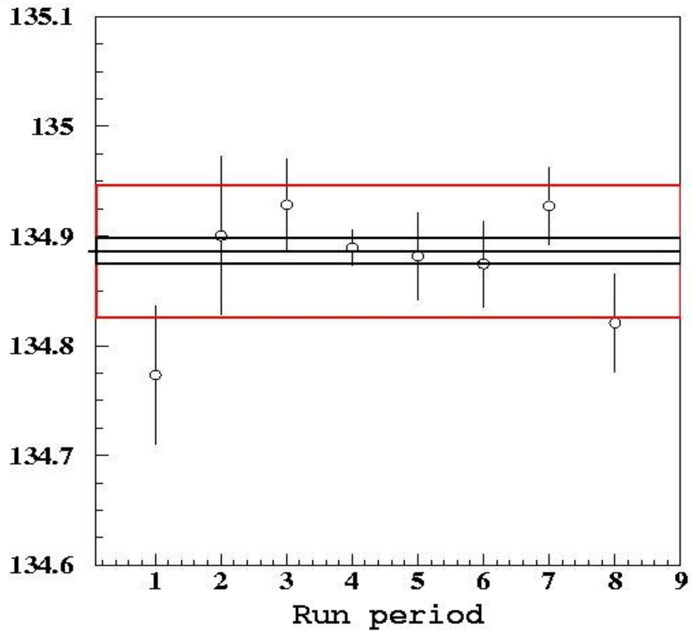


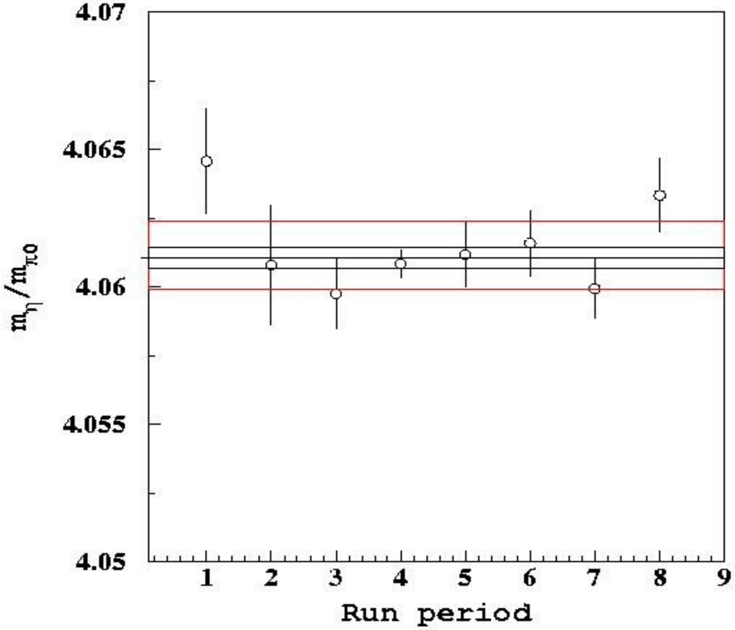


π^0 mass and mass ratio fit









Fit results

Fit results				
	Value	Error	$\chi^2/n.d.f$	C.L
m_η	547791 keV	7 keV	6.9/7	45%
m_{π^0}	134886 keV	12 keV	7.7/7	34%
m_η/m_π	4.0610	0.0004	8.9/7	26%

$$\frac{m_\eta}{m_{\pi^0}} = 4.0610 \pm 0.0004(\text{stat.}) \pm 0.0014(\text{syst.})$$

Using $m_{\pi 0} = 134976.6 \pm 0.6$ keV (PDG06)

we obtain

$m_\eta = 548140 \pm 50_{\text{stat.}} \pm 190_{\text{syst.}}$ keV

Final value

From the ϕ line shape fit we obtain:

$$m_\phi = 1019.329 \pm 0.011 \text{ MeV}$$

The ratio with the CMD-2 $(1019.483 \pm 0.011_{stat} \pm 0.025_{syst}$ value sets the absolute scale of our √s measurement.

We obtain:

$$\frac{m_\eta}{m_\phi} = 0.537403 \pm 0.000007(\text{stat.}) \pm 0.000026(\text{syst.}) \pm 0.000006(m_\phi \quad \text{stat.})$$

and

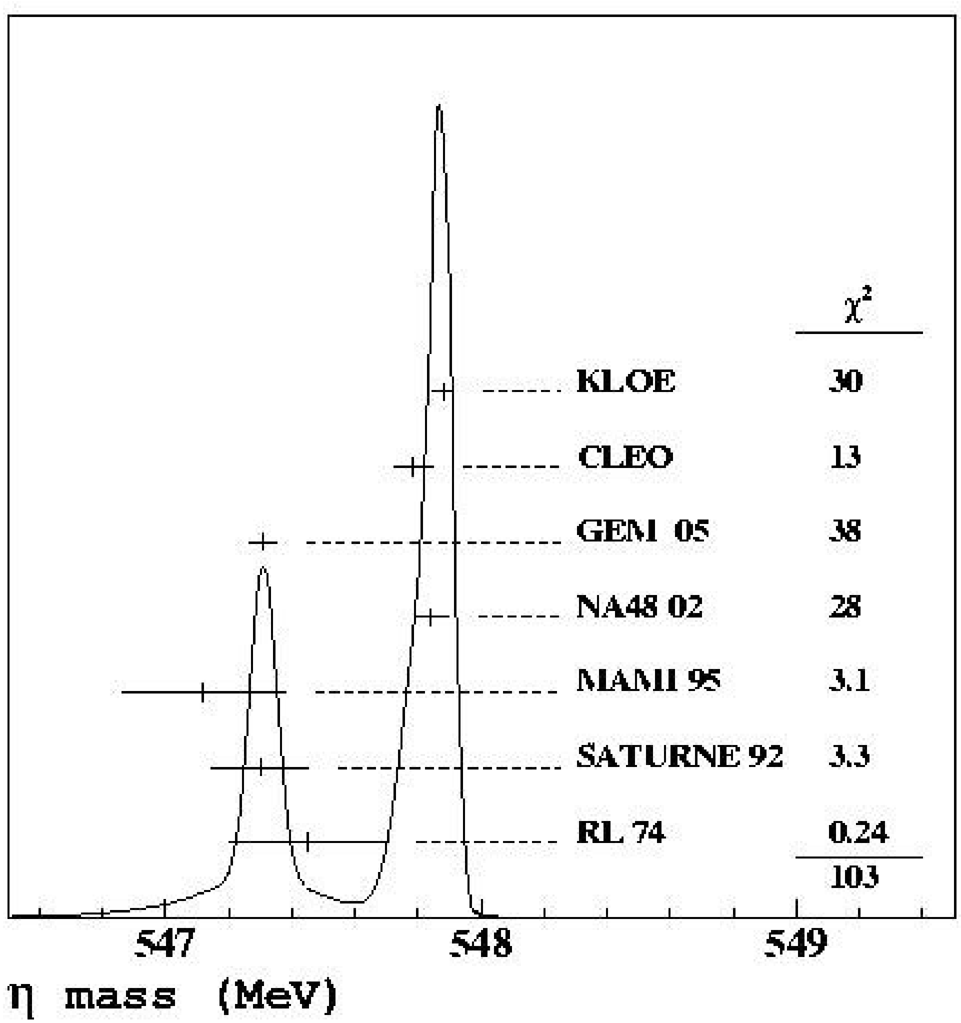
$$\frac{m_{\pi^0}}{m_\phi} = 0.132328 \pm 0.000012(\text{stat.}) \pm 0.000048(\text{syst.}) \pm 0.000001(m_\phi \quad \text{stat.})$$

$$m_{\pi_0} = 134.906 \pm 0.012(\text{stat.}) \pm 0.048(\text{syst.}) \quad \text{MeV}$$

1.4 σ from PDG

$$m_\eta = 547.873 \pm 0.007(\text{stat.}) \pm 0.031(\text{syst.}) \quad \text{MeV}$$

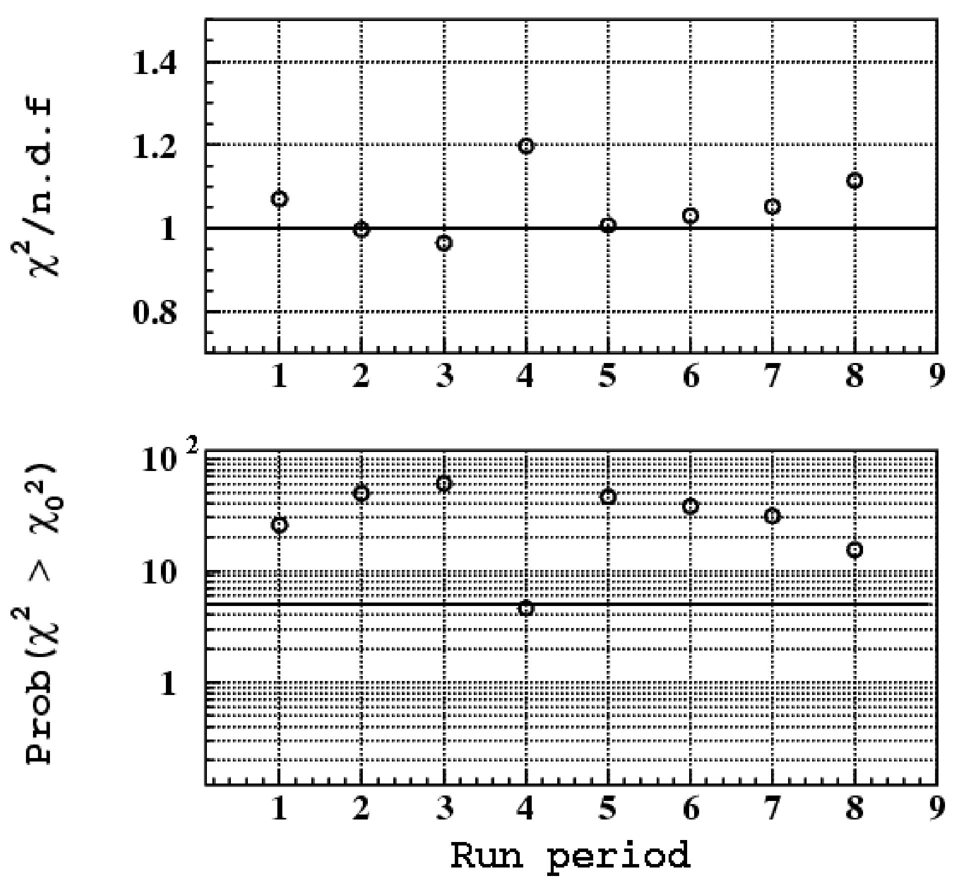
Conclusions



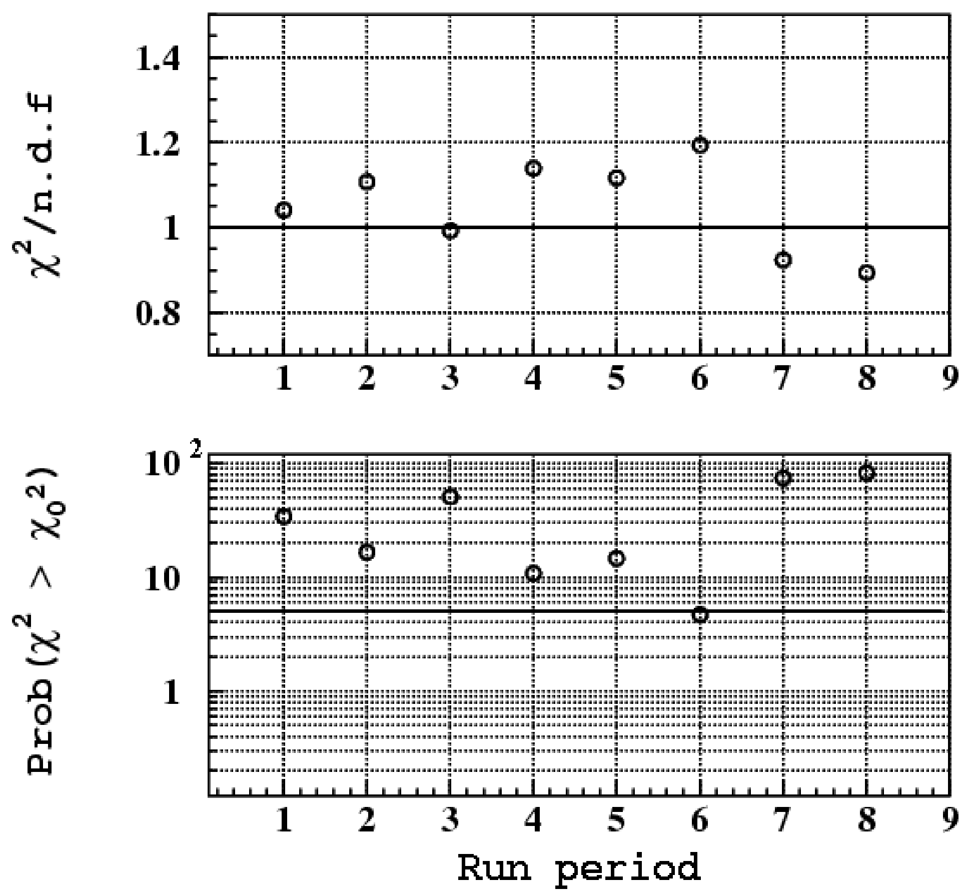
0.6 σ from NA48
1.4 σ from CLEO
11 σ from GEM

Fit quality (data sample divided in 8 periods)

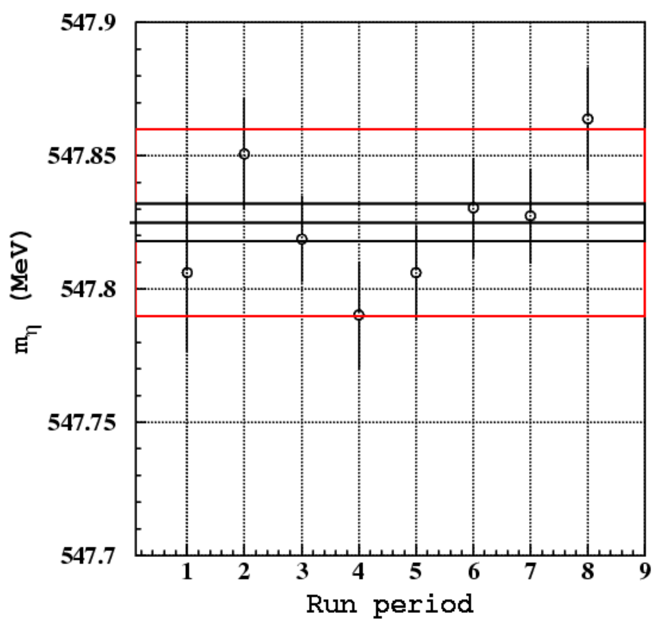
η

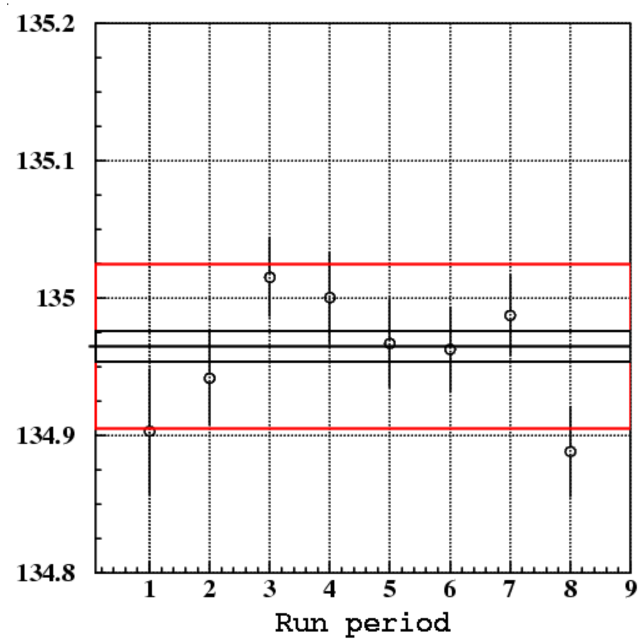


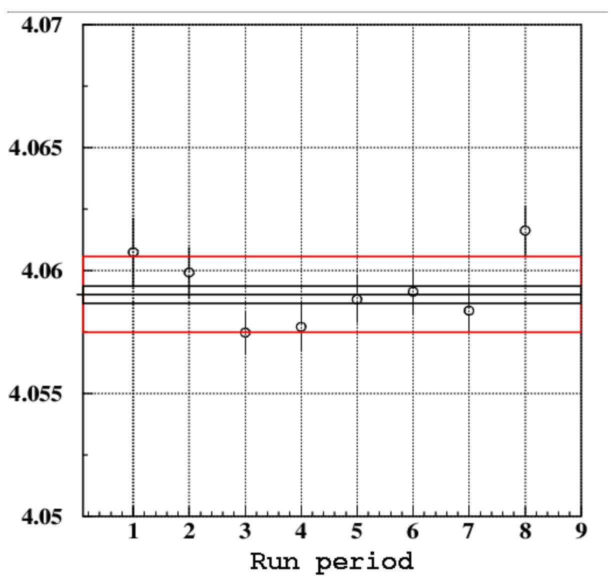
π^0



Fit results



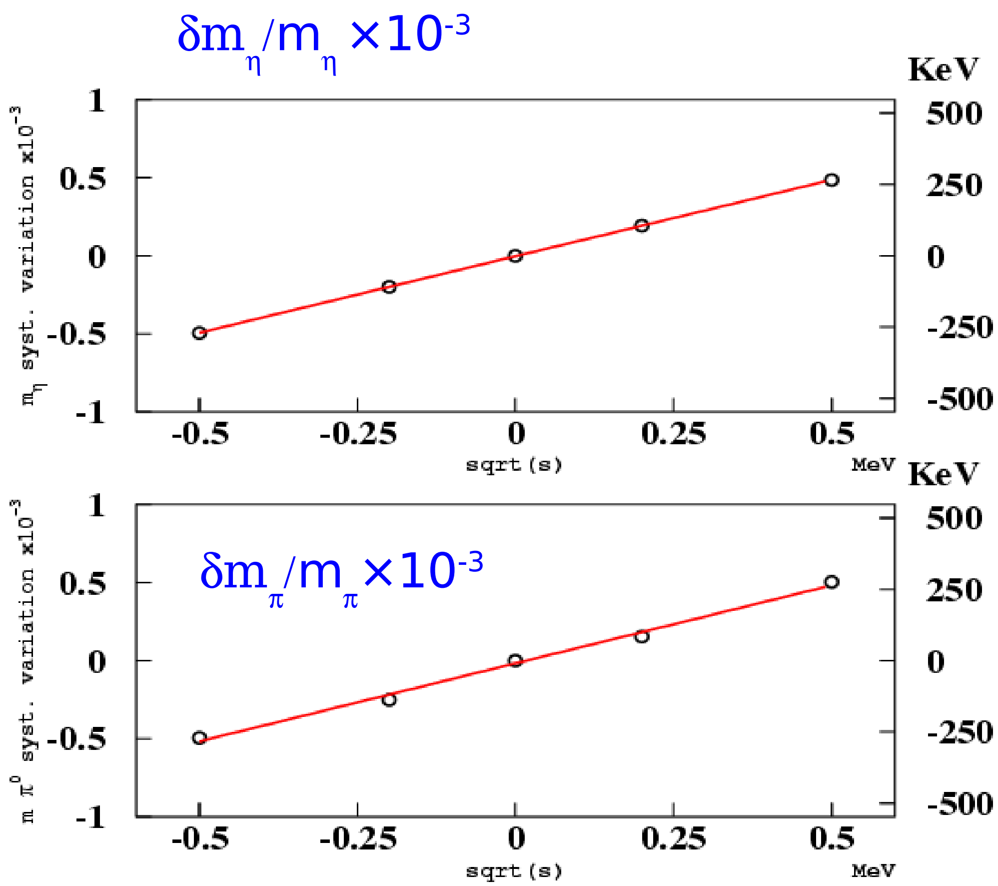




Fit results				
	Value	Error	$\chi_0^2/n.d.f$ (7 n.d.f)	Prob($\chi^2 > \chi_0^2$)
m_η	547825 keV	7 keV	1.5	17%
m_{π^0}	134965 keV	11 keV	1.8	9%
m_η/m_π	4.05901	0.00034	2.1	4.4%

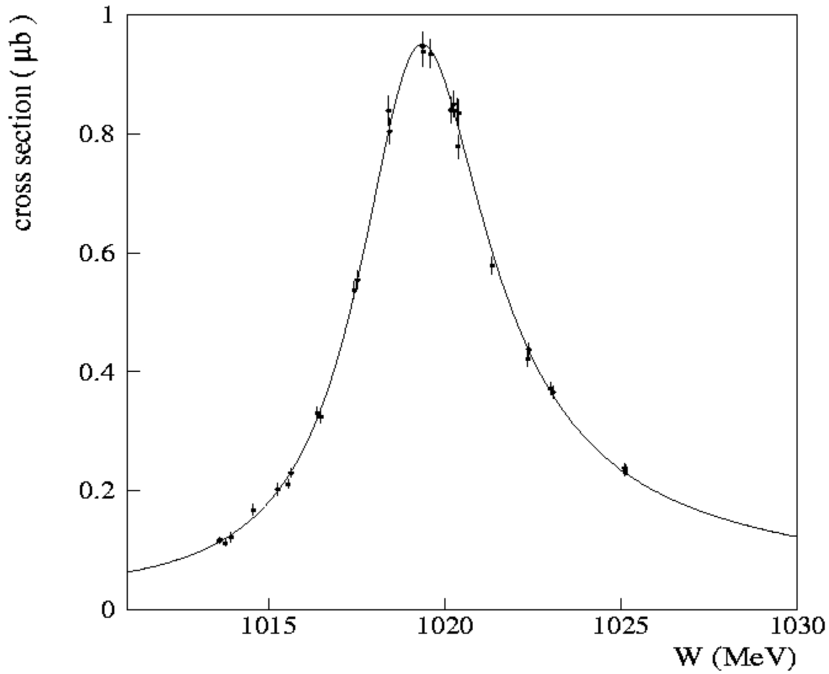
sqrt(s) correction

The mass shows an high sensitivity to the sqrt(s) value.



sqrt(s) determination

The absolute scale of the √s is obtained fitting the cross section $e^+e^- \to K_S K_L$ (ϕ line shape).



The fit takes into account the ISR effect and the phase space factor of the KK couple.

$$m_\phi = 1019.329 \pm 0.011 \text{ MeV}$$

m_ϕ (CMD-2) = 1019.483±0.011±0.025 MeV

The ratio m_ϕ (CMD-2)/m_ϕ (KLOE) is used to set the absolute √s scale.

	value	correction	final value
m_η	547825	-52	547773
m_{π^0}	134965	-67	134898
m_η/m_{π^0}	4.05901	+0.00164	4.06065

sqrt(s) not affected estimate:

$$\frac{m_\eta}{m_{\pi^0}} = 4.06065 \pm 0.00034(\text{stat.}) \pm 0.00154(\text{syst.})$$

$$(m_{\pi^0} = 1349766 \pm 0.6 \text{ keV})$$

$$m_\eta = 548093 \pm 46 \pm 207 \text{ keV}$$

$$\frac{m_\eta}{m_\phi} = 0.537386 \pm 0.000007(\text{stat.}) \pm 0.000034(\text{syst.}) \pm 0.000006(m_\phi \quad \text{stat.})$$

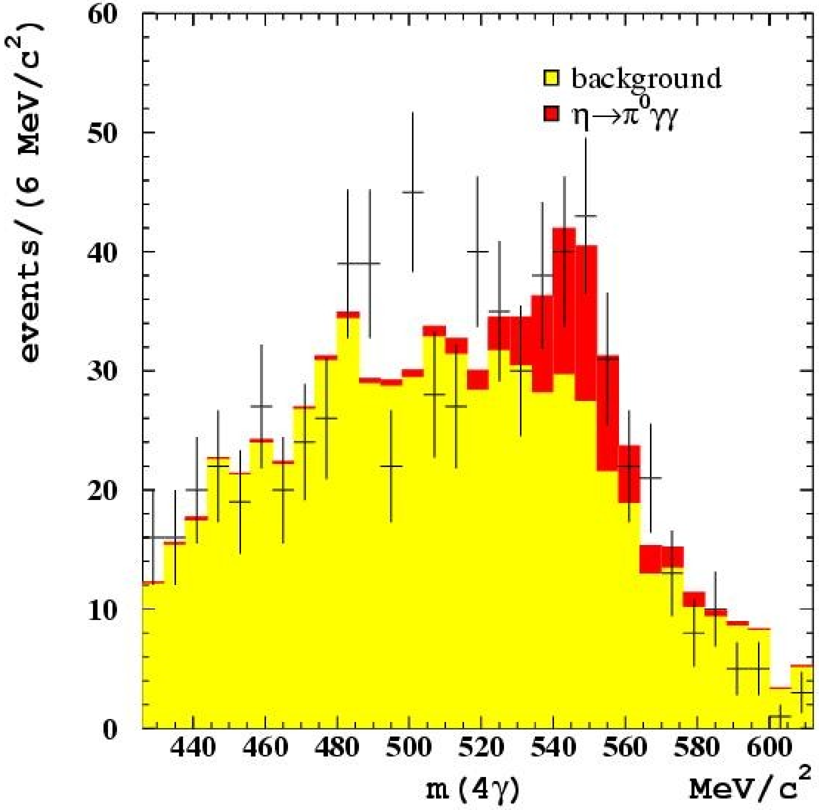
$$\frac{m_{\pi^0}}{m_\phi} = 0.132340 \pm 0.000011(\text{stat.}) \pm 0.000057(\text{syst.}) \pm 0.000001(m_\phi \quad \text{stat.})$$

$$m_{\pi^0} = 134918 \pm 11 \pm 58 \pm 1 \pm 1.4(\text{CMD2} \quad \text{stat.}) \pm 3(\text{CMD2} \quad \text{syst.}) \quad \text{keV}$$

$\Delta_{PDG} = 1\sigma$

$$m_\eta = 547856 \pm 7 \pm 35 \pm 6 \pm 6(\text{CMD2} \quad \text{stat.}) \pm 14(\text{CMD2} \quad \text{syst.})$$

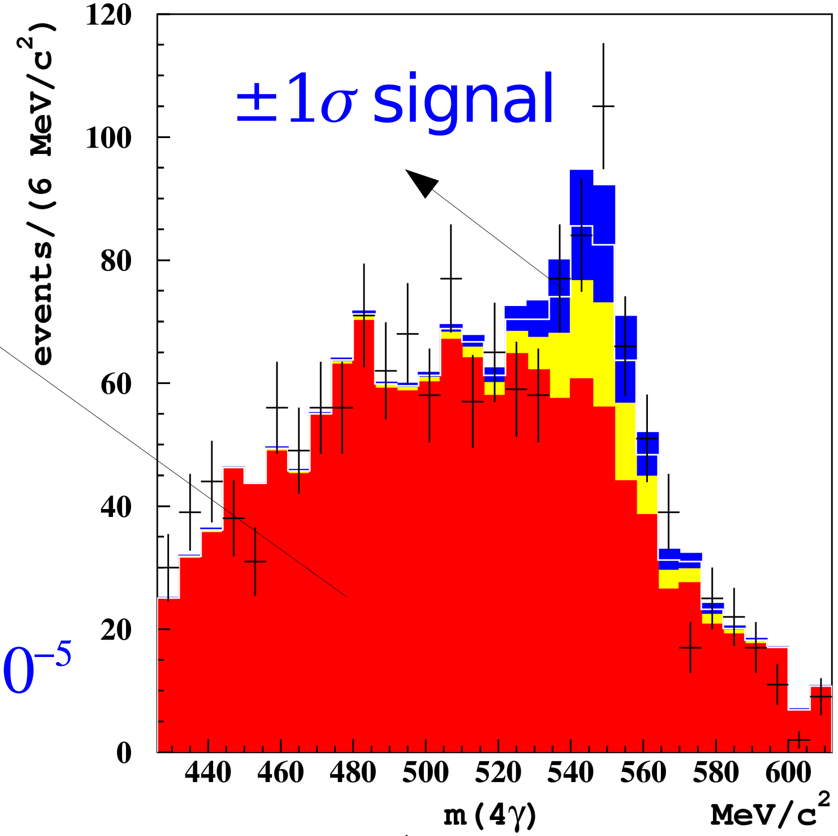
434 pb^{-1}



Using the Br evaluated on 2002 data.

½ 2005 statistics 600 pb^{-1}

bkg



$$Br(\eta\to\pi^0\gamma\gamma) = (8.4 \pm 2.7_{stat} \pm 1.4_{syst}) \times 10^{-5}$$

$m(\eta\to\pi^0\gamma\gamma)$
MC shape from rad04

Results and systematics

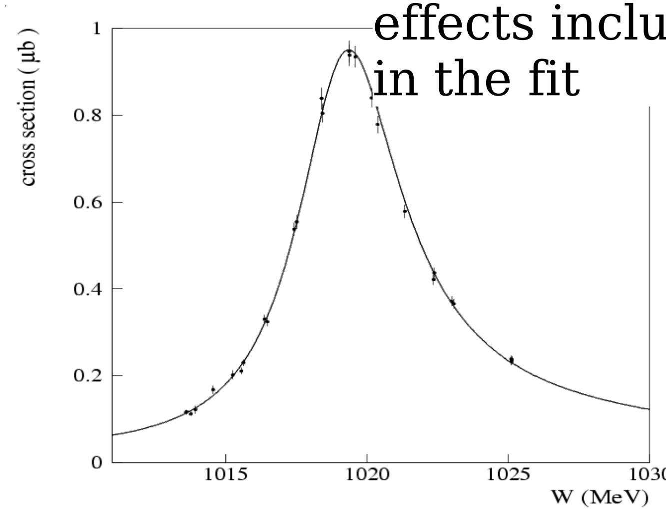
KLOE PRELIMINARY

the energy calibration has been determined using $\pi^+\pi^-\gamma$ and $e^+e^-\gamma$ events,
the calorimeter calibration is know at better than 2%
$\delta m/m = 11\times10^{-6}$ (6 keV) on the η mass.

Systematic due to the vertex position determination have been also evaluated, the sqrt(s) is calibrated by fitting the ϕ line shape.

$m(\phi) = 1019.483 \pm 0.011 \pm 0.025$
CMD-2 Phys. Lett. B578, 285

radiative return and threshold effects included in the fit



$M(\pi^0) = (134990 \pm 6_{stat} \pm 30_{syst})$ keV

$M(\pi^0)_{PDG} = (134976.6 \pm 0.6)$ keV

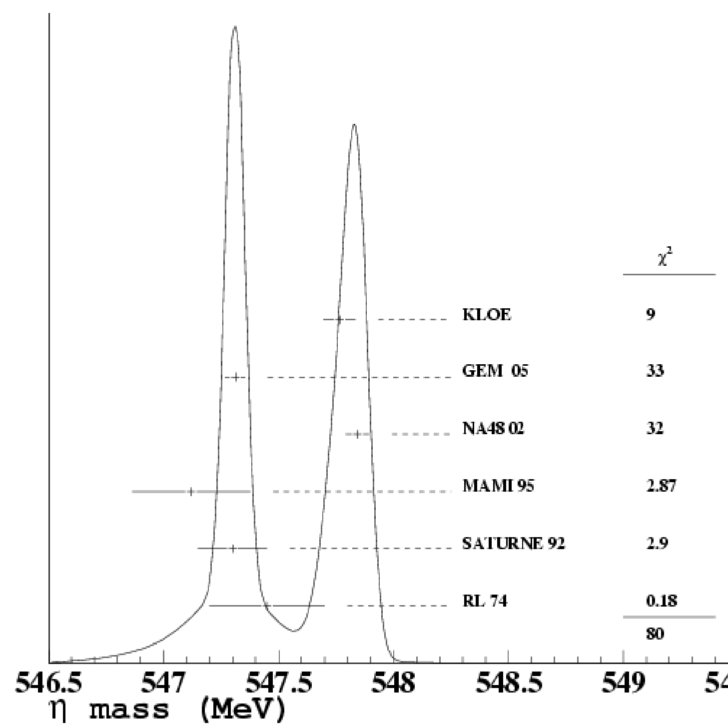
$M(\eta) = (547822 \pm 5_{stat} \pm 69_{syst})$ keV

NA48 compatibility: 0.24 σ

Independent measurement with the $\eta\to\pi^+\pi^-\pi^0$ decay mode in progrees:

$$m_\eta = 547.95 \pm 0.15\ \mathrm{MeV}/c^2$$

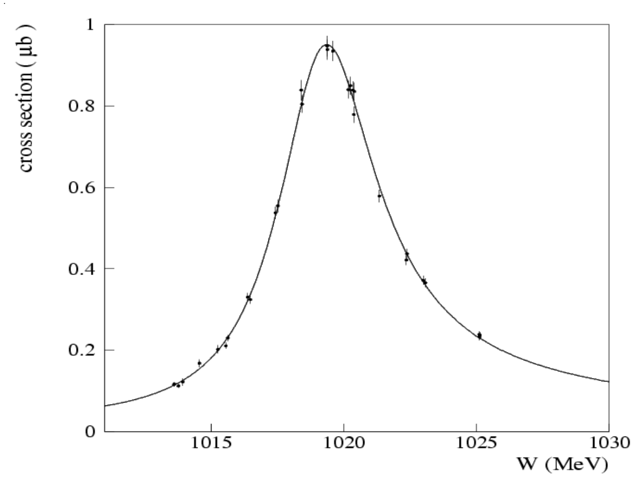
(very preliminary fully in agreement with the $\gamma\gamma$ channel)



Results and systematics

KLOE PRELIMINARY

Systematic due to the vertex position determination have been also evaluated, the sqrt(s) is calibrated by fitting the ϕ line shape.

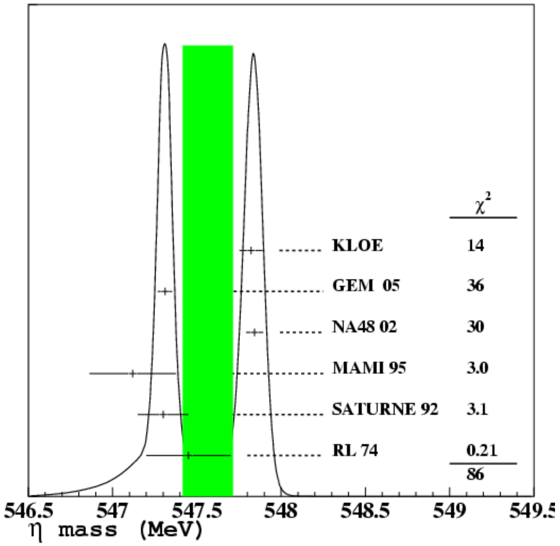


$m(\phi) = 1019.483 \pm 0.011 \pm 0.025$
CMD-2 Phys. Lett. B578, 285

$M(\pi^0) = (134990 \pm 6_{stat} \pm 30_{syst})$ keV

$M(\pi^0)_{PDG} = (134976.6 \pm 0.6)$ keV

$M(\eta) = (547822 \pm 5_{stat} \pm 69_{syst})$ keV



Systematics dominated by $\sqrt{s}$ knowledge

NA48 compatibility: 0.24 σ

Cross check with $\eta \to \pi^+\pi^-\pi^0$ decay mode:

$m_\eta = 547.95 \pm 0.15\ \mathrm{MeV}/c^2$