KLOE Dalitz plot analysis of $\eta \to 3\pi$ decays

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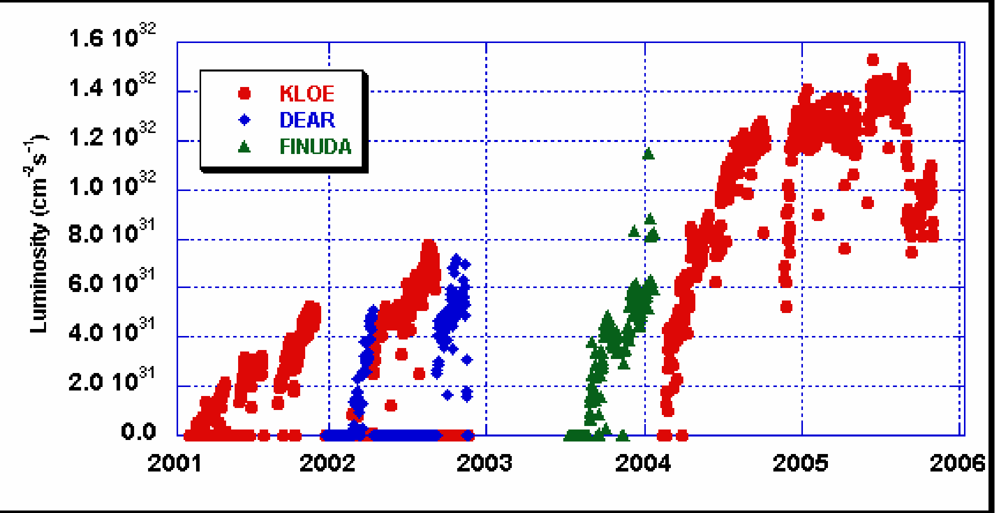
DAΦNE at LNF

- e^+e^- collider @ $\sqrt{s} = M_\phi$ **= 1019.4 MeV**
- Separate e^+, e^- rings
- Crossing angle: 12.5 mrad ($p_x(\phi) \approx 13$ MeV)
- Injection during data-taking
- $L_{peak} = 1.5 * 10^{32}\ cm^{-2}s^{-1}$
- L_{int} (KLOE) = 2.7 fb^{-1}



STATUS:

March 2006: *end of KLOE data taking*

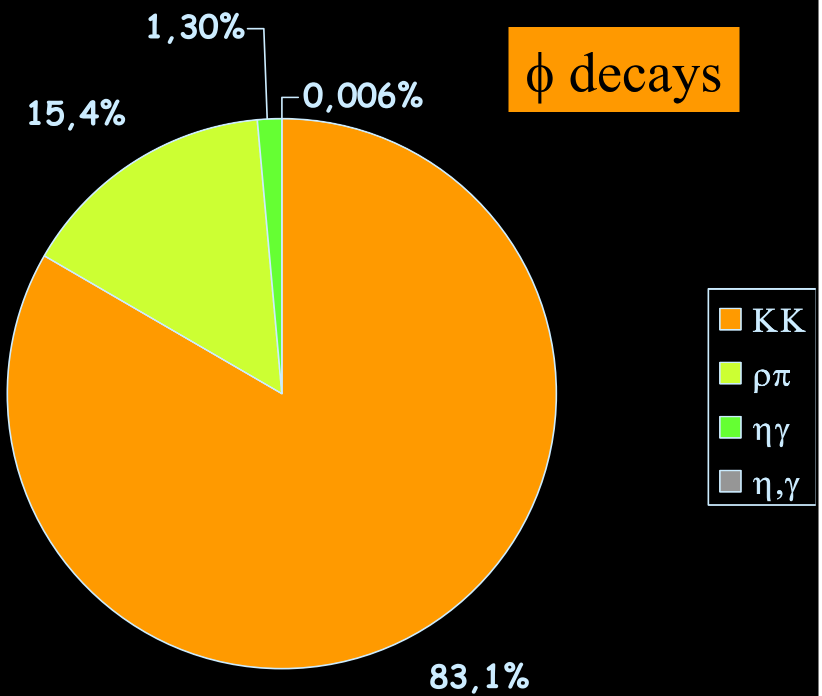
2500 pb^{-1} on-peak ➔ **8 × 10^9** ϕ decays

200 pb^{-1} off-peak (energy scan + 1 GeV run)

η / η' production rate at DAFNE

Process	Cross section (μb)
$e^+e^- \to \phi$	≈ 3
$e^+e^- \to e^+e^-(\gamma)$	6.2 $(\theta > 20°)$
$e^+e^- \to \mu^+\mu^-(\gamma)$	0.1
$e^+e^- \to \pi^+\pi^-(\gamma)$	0.05

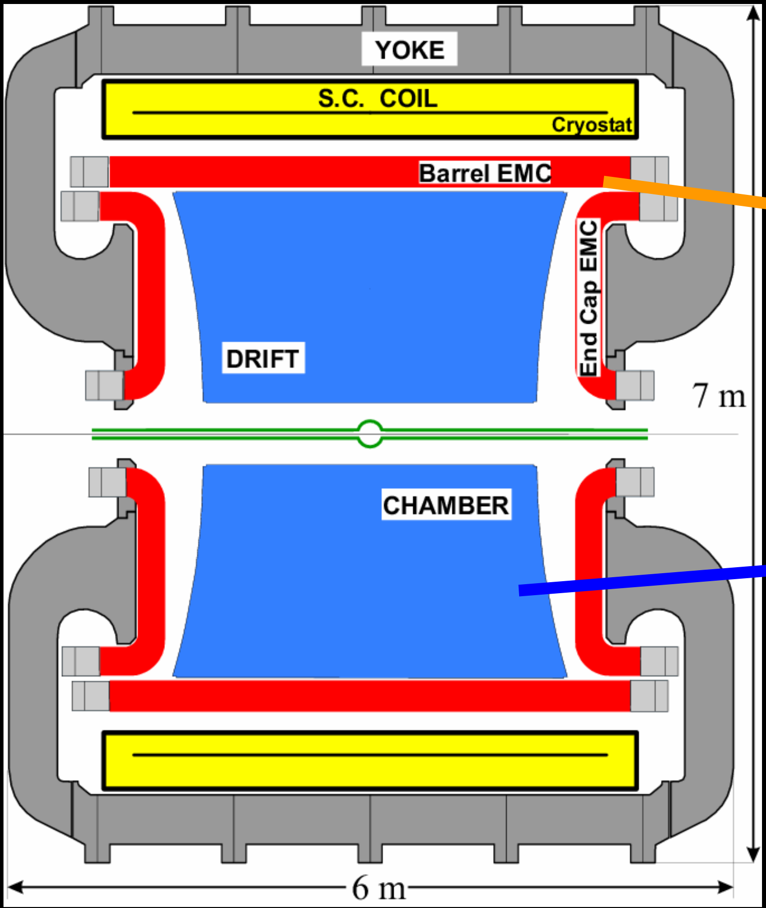
ϕ decays



Collected:

- **100 millions η decays**
- **500 thousands η' decays**

The KLOE detector



- $\sigma_E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
- $\sigma_t = 54\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$
- $\sigma_{vtx}(K_L \to \pi^0\pi^0) \sim 1.5\ \mathrm{cm}$

- $\sigma_p/p = 0.4\%$ (tracks with $\theta > 45°$)
- $\sigma_{x/y} = 150\ \mu\mathrm{m}$, $\sigma_z = 2\ \mathrm{mm}$
- $\sigma_{vtx} \sim 3\ \mathrm{mm}$
- $\sigma\ (M_{Ks \to \pi^+\pi^-}) \sim 1\ \mathrm{MeV}$

$\eta \to 3\pi$ in chiral theory

The decay $\eta \to 3\pi$ occours primarily on account of the d-u quark mass differences and the result arising from lowest order chiral pertubation theory is well known:

$$A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$$

With: $$\boxed{Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}}$$ And, at l.o. $$M(s,t,u) = \frac{3s - 4m_\pi^2}{m_\eta^2 - m_\pi^2}$$

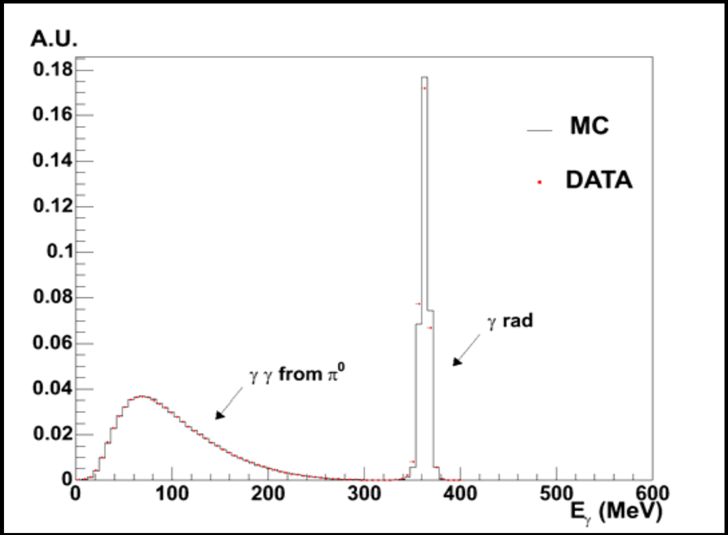
A good understanding of M(s,t,u) can *in principle* lead to a very accurate determination of Q:

$$\boxed{\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}}$$

Need to check the description of the dynamics for both $\pi^+\pi^-\pi^0$ and $3\pi^0$ final states !

$\eta \to 3\pi$ at KLOE

At KLOE η is produced in the process $\phi \to \eta\gamma$.
The final state for $\eta \to \pi^+\pi^-\pi^0$ is thus $\pi^+\pi^-\gamma\gamma\gamma$, and the final state for $\eta \to \pi^0\pi^0\pi^0$ is 7γ, both with almost no physical background.



$\pi^+\pi^-\pi^0$ selection:

- 2 track vertex+3 γ candidates
- Kinematic fit

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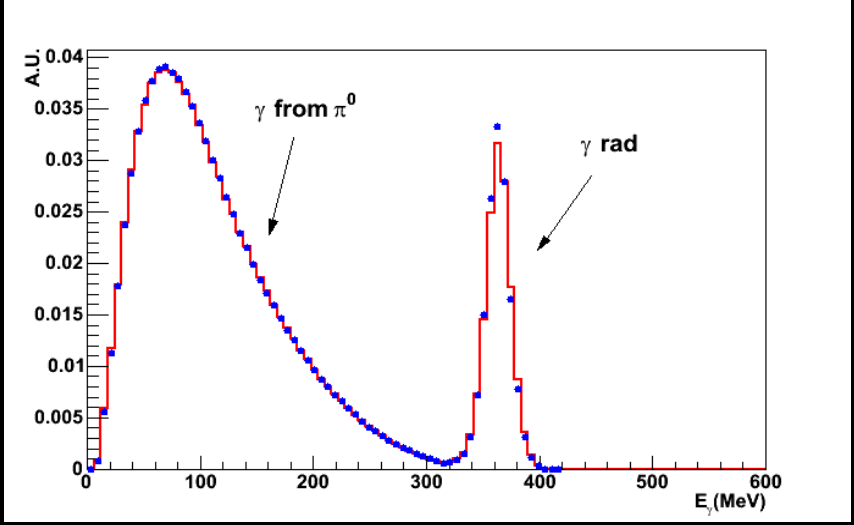


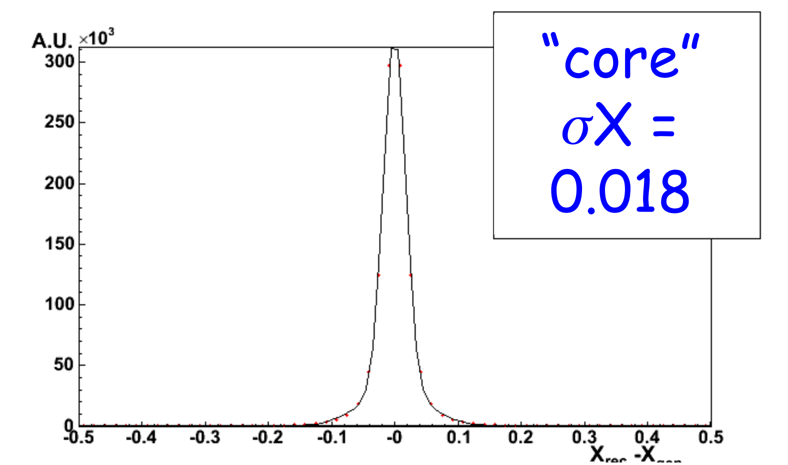
$\pi^+\pi^-\pi^0$ selection:

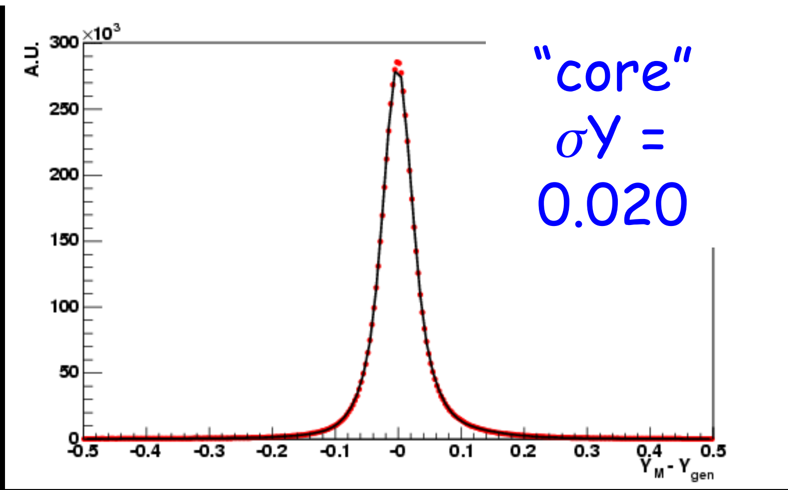
- 2 track vertex+3 γ candidates
- Kinematic fit

$\pi^0\pi^0\pi^0$ selection:

- 7 γ candidates
- Kinematic fit

$\pi^+\pi^-\pi^0$: resolution and efficiency

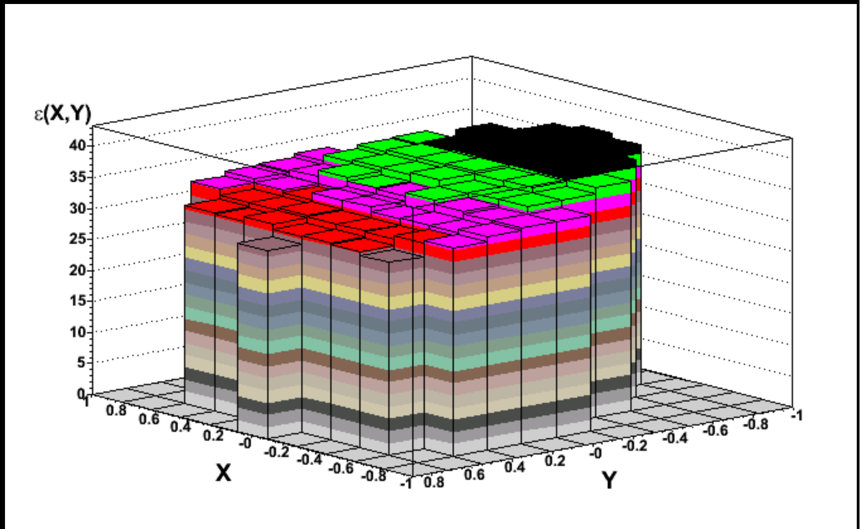




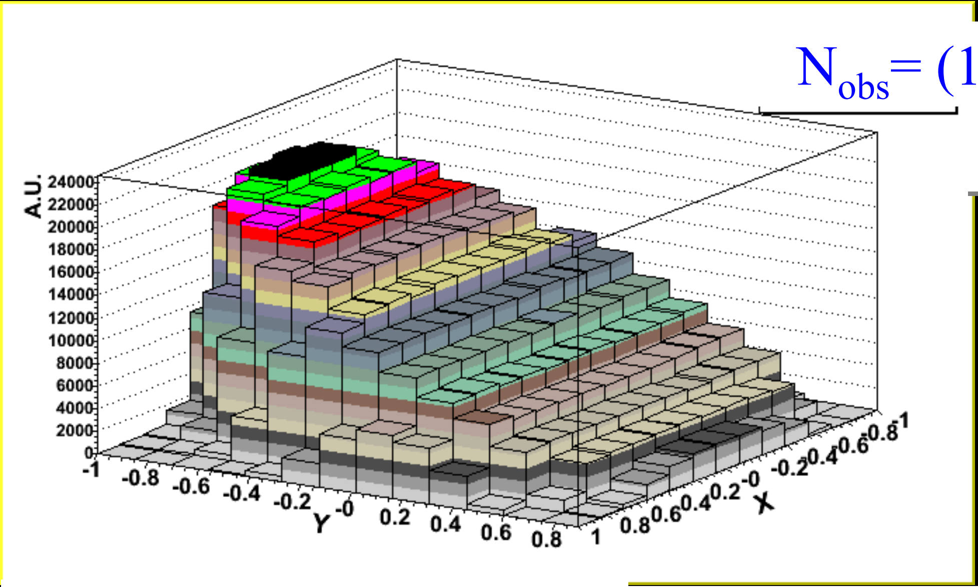
$$X = \sqrt{3}\,\frac{T_+ - T_-}{Q_\eta} = \frac{\sqrt{3}}{2M_\eta Q_\eta}(u-t)$$

$$Y = \frac{3T_0}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}\left\{(m_\eta - m_{\pi^0})^2 - s\right\} - 1$$

Efficiency almost flat, and ≈ 35%

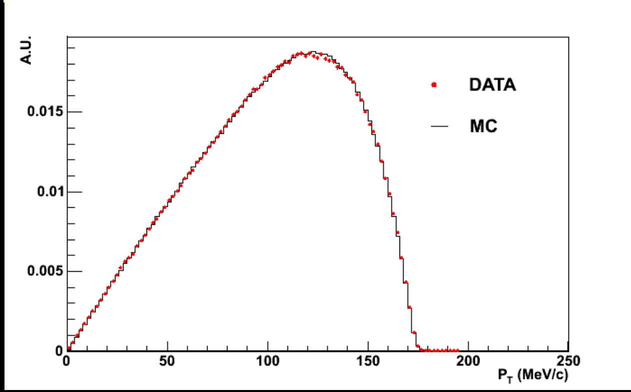


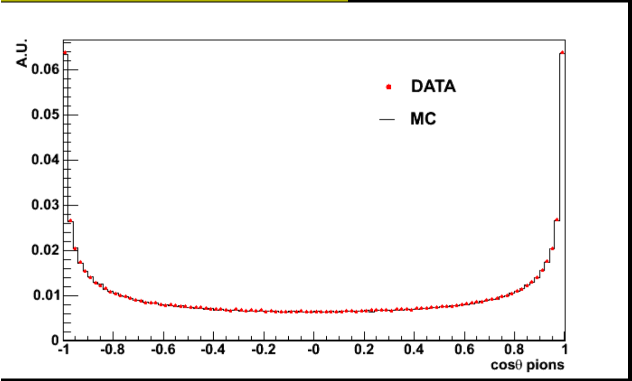
Signal



$N_{obs} = (1.377 \pm 0.001) \times 10^6$

$B/S \approx 0.3\%$





Results

$|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3$

$$a = -1.090 \pm 0.005\left(stat\right)^{+0.008}_{-0.019}\left(syst\right)$$

$$b = 0.124 \pm 0.006\left(stat\right) \pm 0.010\left(syst\right)$$

$$d = 0.057 \pm 0.006\left(stat\right)^{+0.007}_{-0.016}\left(syst\right)$$

$$f = 0.14 \pm 0.01\left(stat\right) \pm 0.02\left(syst\right)$$

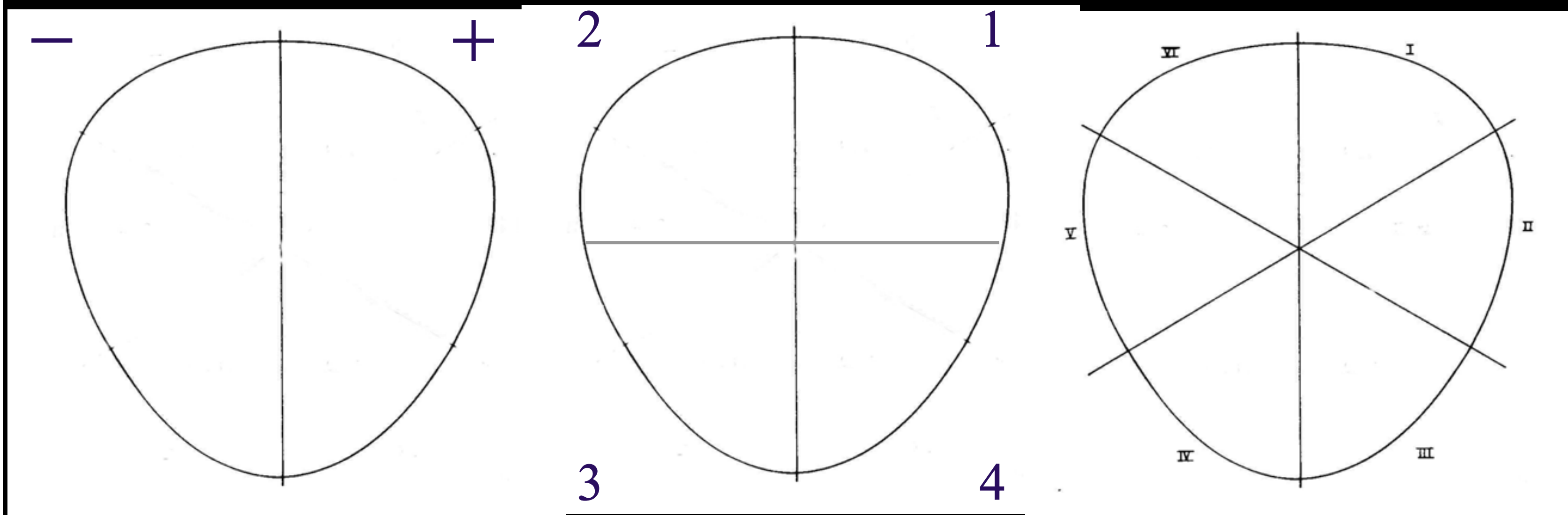
$\cancel{C}$

$$c = 0.002 \pm 0.003(stat) \pm 0.001(syst)$$

$$e = -0.006 \pm 0.007(stat)^{+0.005}_{-0.003}(syst)$$

The fit has $P(\chi^2) = 75\%$ for 149 dof

Asymmetries



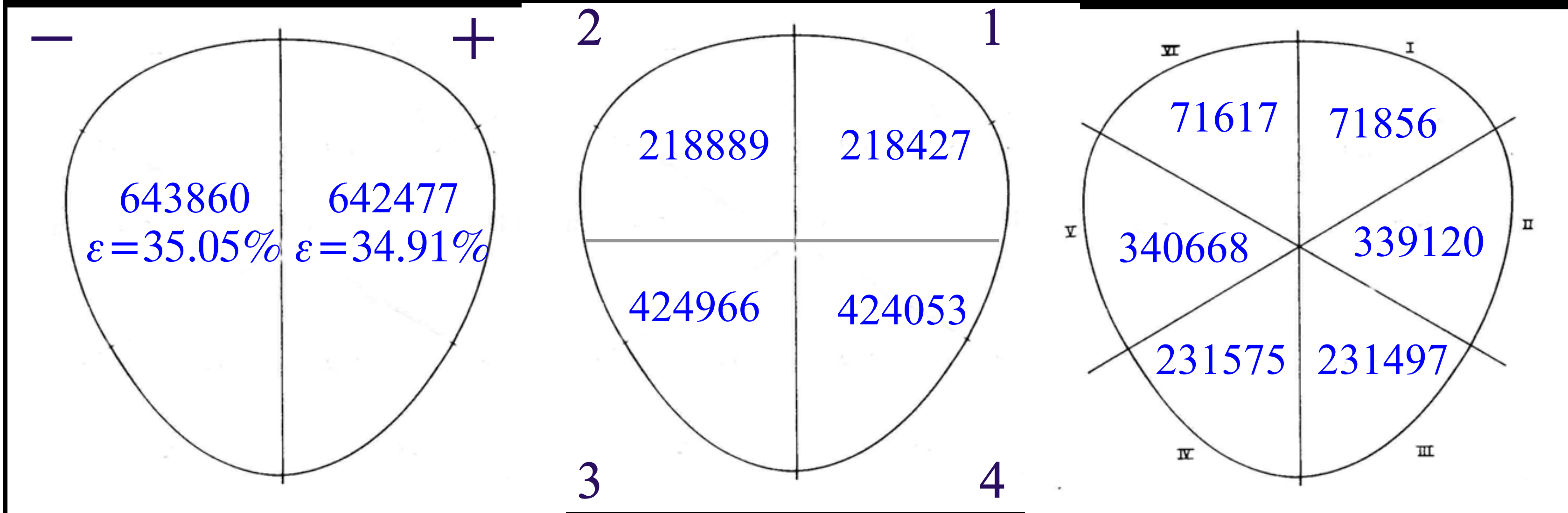
$$A_{L,R} = \frac{N_+ - N_-}{N_+ + N_-}$$

$$A_Q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4}$$

$$A_S = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N}{N_1 + N_2 + N_3 + N_4 + N_5 - N}$$

$A_{PDG} = (0.09 \pm 0.17) \cdot 10^{-2}$ $A_{PDG} = (-0.17 \pm 0.17) \cdot 10^{-2}$ $A_{PDG} = (0.18 \pm 0.16) \cdot 10^{-2}$

Asymmetries



$A_{LR} = (0.09 \pm 0.10^{+0.09}_{-0.14}) \cdot 10^{-2}$

$A_Q = (-0.5 \pm 0.10^{+0.03}_{-0.05}) \cdot 10^{-2}$

$A_S = (0.09 \pm 0.10^{+0.08}_{-0.13}) \cdot 10^{-2}$

In agreement with the null value of the c and e parameters in our fit, we find no evidence for C violation in the $\eta \to \pi^+\pi^-\pi^0$ decay.

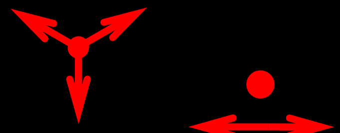
$\eta \to 3\pi^0$: Dalitz plot expansion

The Dalitz plot density for $\eta \to \pi^0\,\pi^0\,\pi^0$ ($|A|^2$) is specified by a single quadratic slope α:

$$|A|^2 \propto 1 + 2\alpha z$$

with:

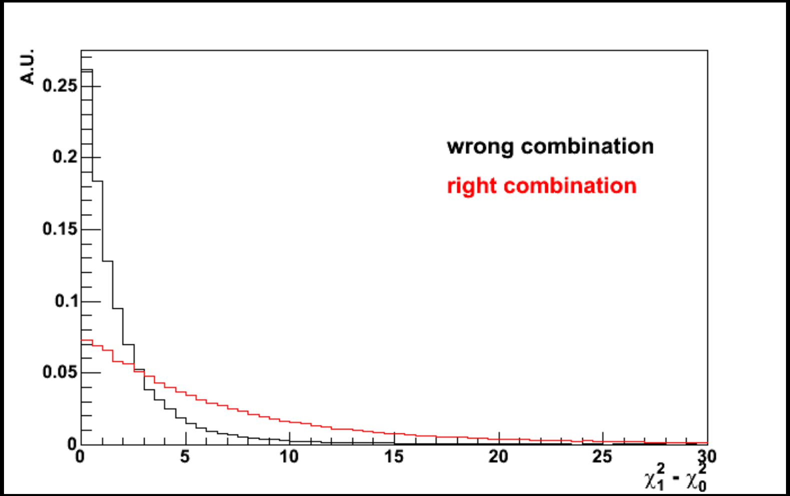
$$z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - m_\eta}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho^2_{\max}}$$



$Z \in [\,0 \quad , \quad 1\,]$

E_i = Energy of the *i*-th pion in the η rest frame.
ρ = Distance to the center of Dalitz plot.
ρ_{max} = Maximun value of ρ.

Matching γ to π^0 's



A χ^2 like variable is built for each of the 15 combinations in order to find the correct matching of photons to π^0 's

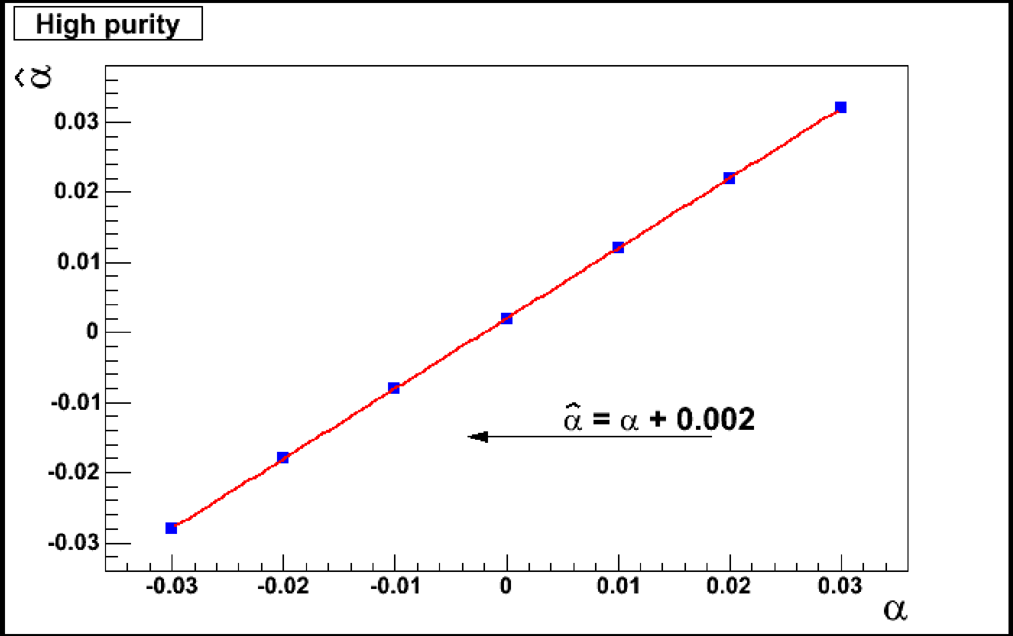
Using this disriminant variable one can obtain samples with different purity- efficiency

Purity= Fraction of events with all photons correctly matched to π^0 's

To check systematics we used samples with purity ranging from 75% to 97% corresponding to datasets going from 1.4 Mevts down to 0.2 Mevts

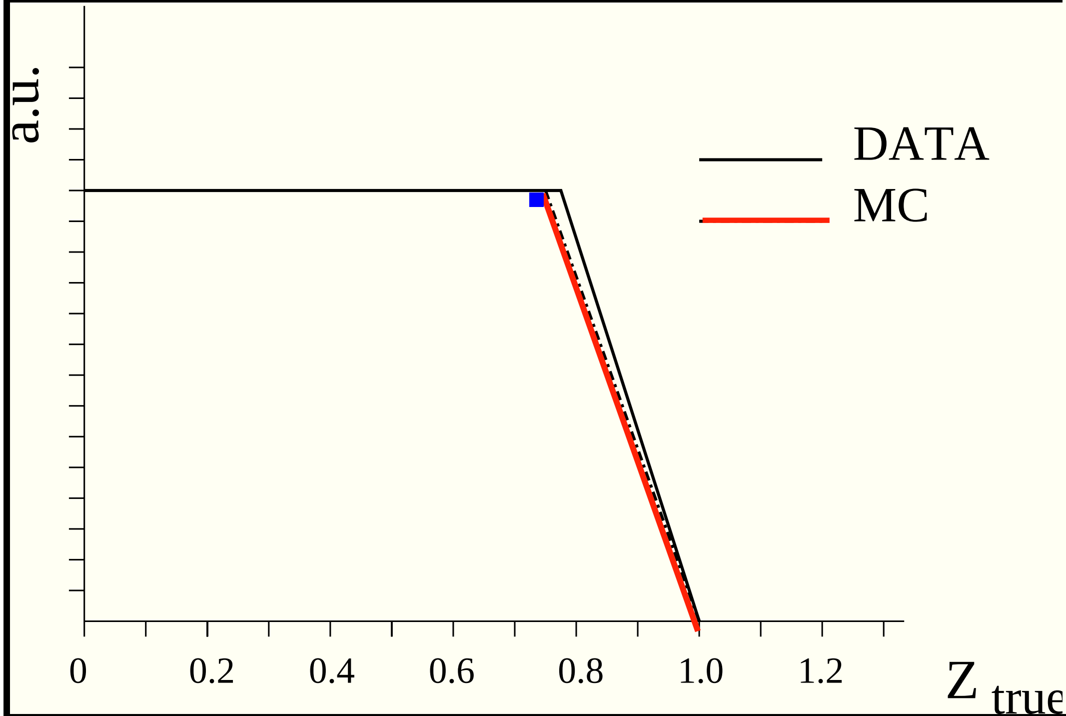
Results of fit on MC

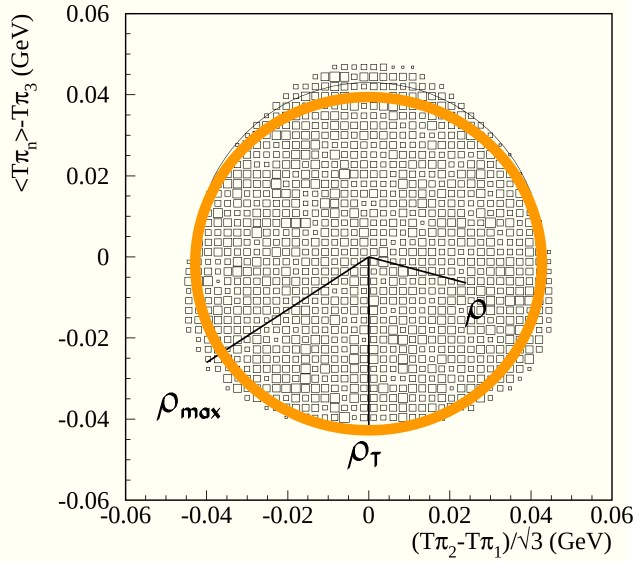
The fit procedure is quite complex: it is unbinned and includes a correction for the fraction of mis-id pions and the full convolution with the resolution function. We have tested it on MC by generating samples with different values of the parameter and looking at the result of our fit for these samples:



Importance of M_η

The edge of the flat part of the phase space depends on the value of the eta mass. What if its value on data is larger (e.g. by 0.5 MeV) than the nominal one ?





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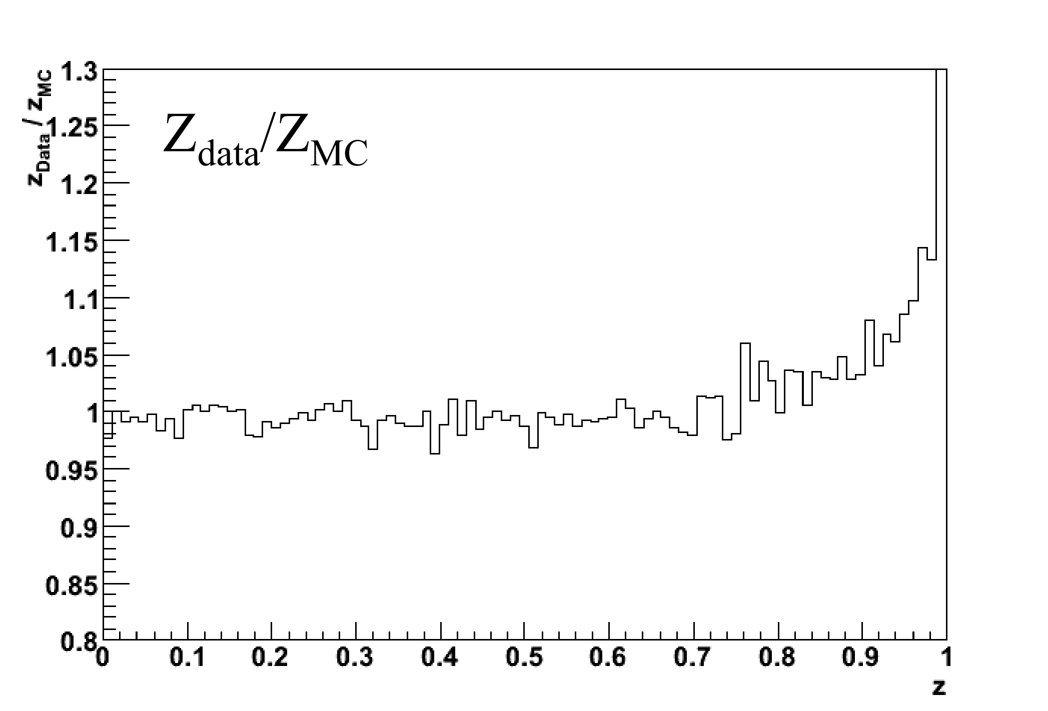
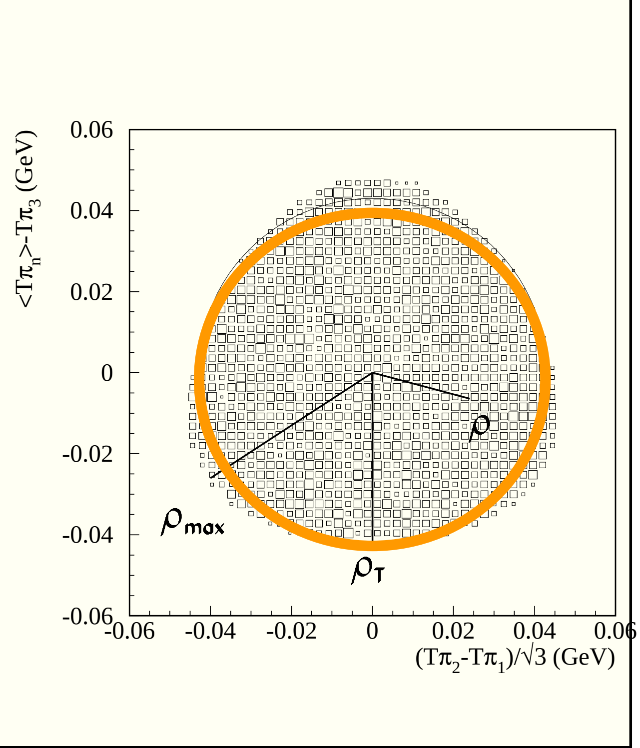


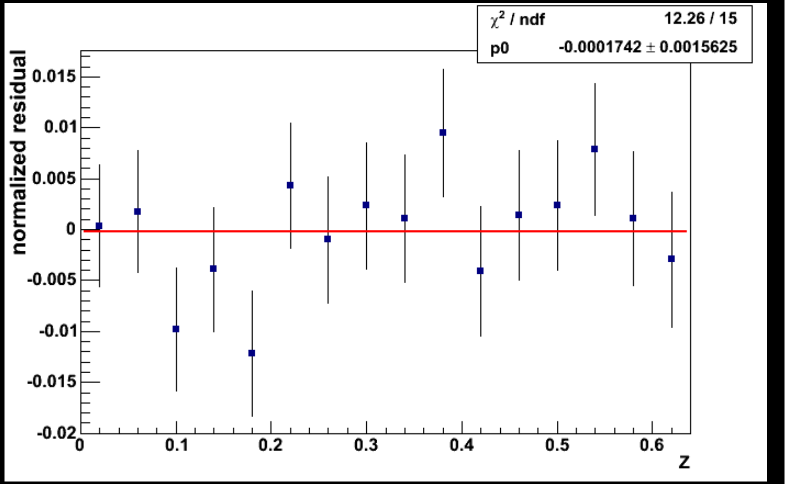


New preliminary result

We give the preliminary result for the slope parameter α in corrispondence of a sample of about 650 Kevts with 92% purity. Fitting in the range [0,0.7] we get:

$$\alpha = -\,0.027 \pm 0.004_{stat} \pm 0.006_{syst}$$

This results superseeds our previous preliminary result (presented at Hadron '05) which used M_η = 547.3 in the simulation and was thus systematically biased by the kinematic effect shown before.



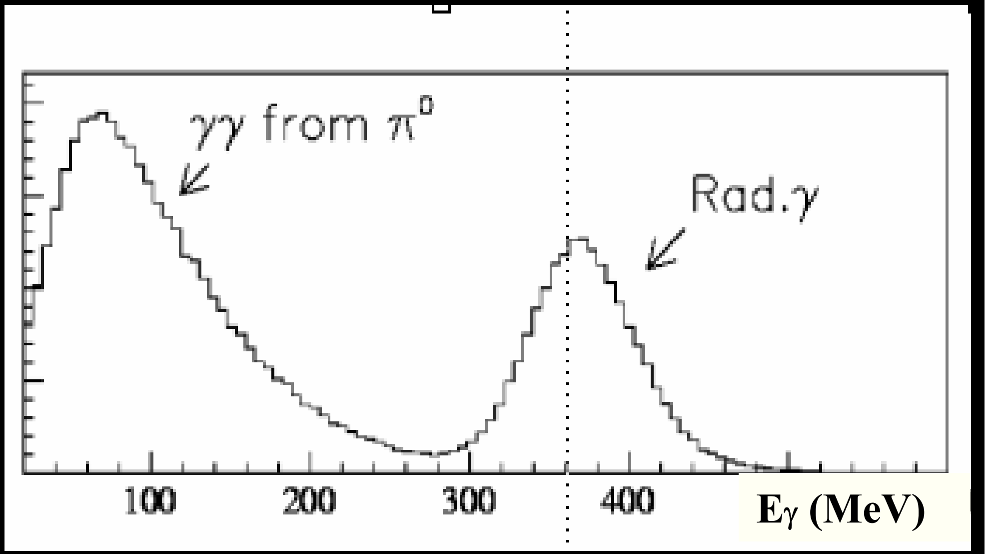
Conclusions

- New accurate results have been produced for both Dalitz plot slopes and asymmetries in $\eta \to \pi^+\pi^-\pi^0$
- An unexpectedly large effect of the discrepancy between the PDG η mass used in our MC simulation and the "true" η mass caused a systematic bias in our preliminary result for the $\eta \to 3\pi^0$ slope. A new result is presented here. It is compatible with Crystal Ball result and with chiral unitary calculations.
- The experimental scenario for $\eta \to 3\pi$ dynamics is now clear and solid.

SPARE SLIDES

Kinematic fit

As a general tool we employ a kinematic fit imposing energy momentum conservation: this allows dramatic improvement on photon energy resolution.



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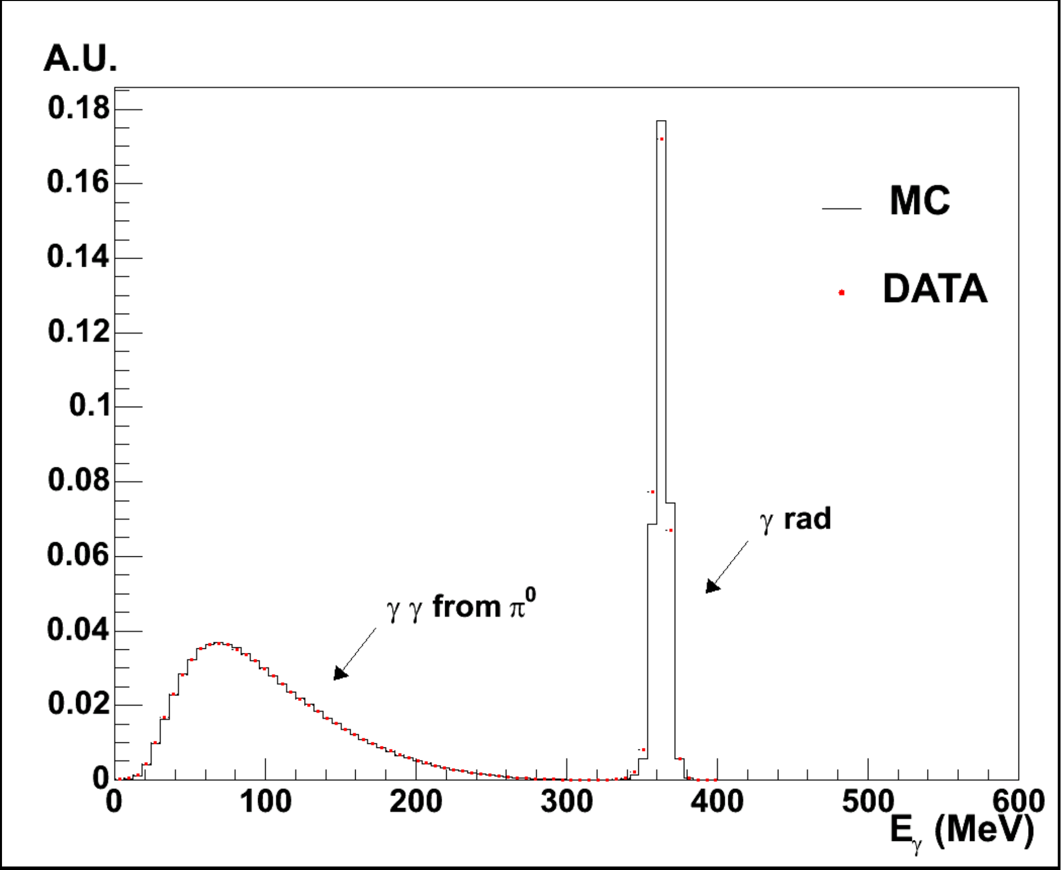
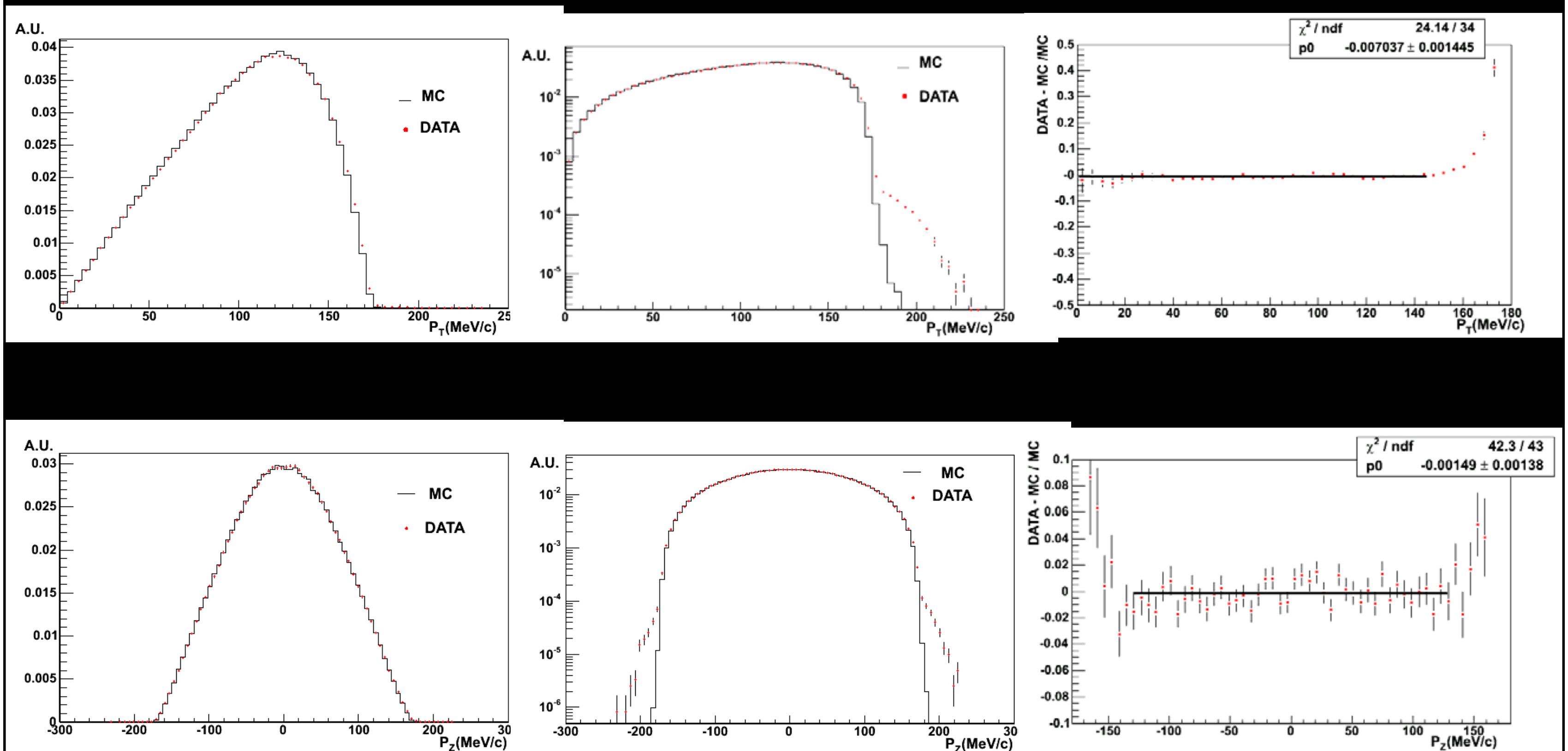
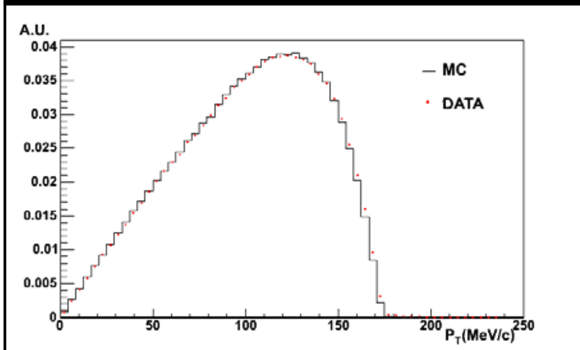
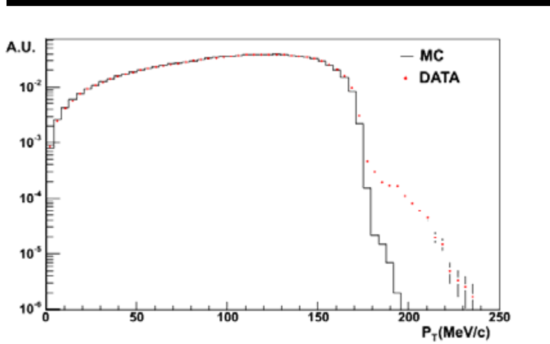


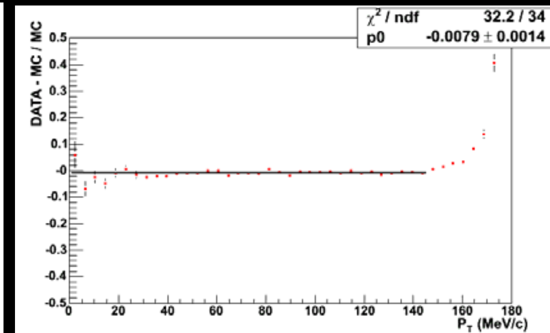
Comparison Data-MC: π^+

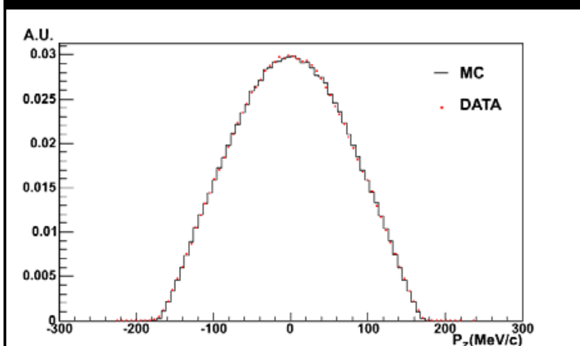


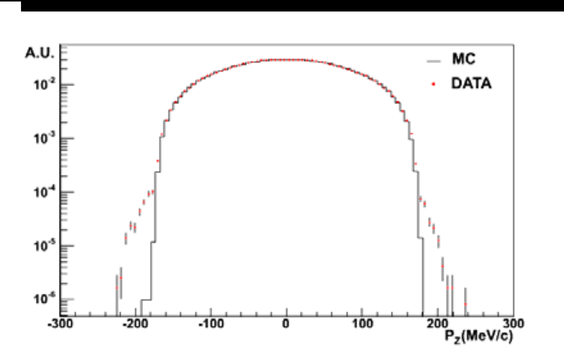
Comparison Data-MC: π^-

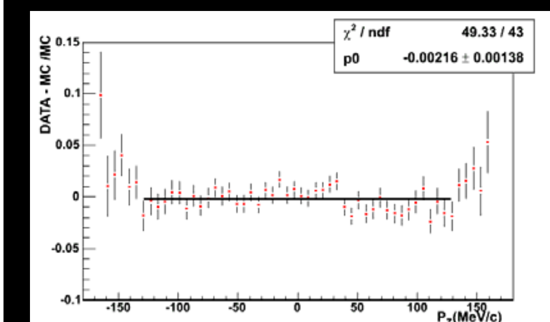






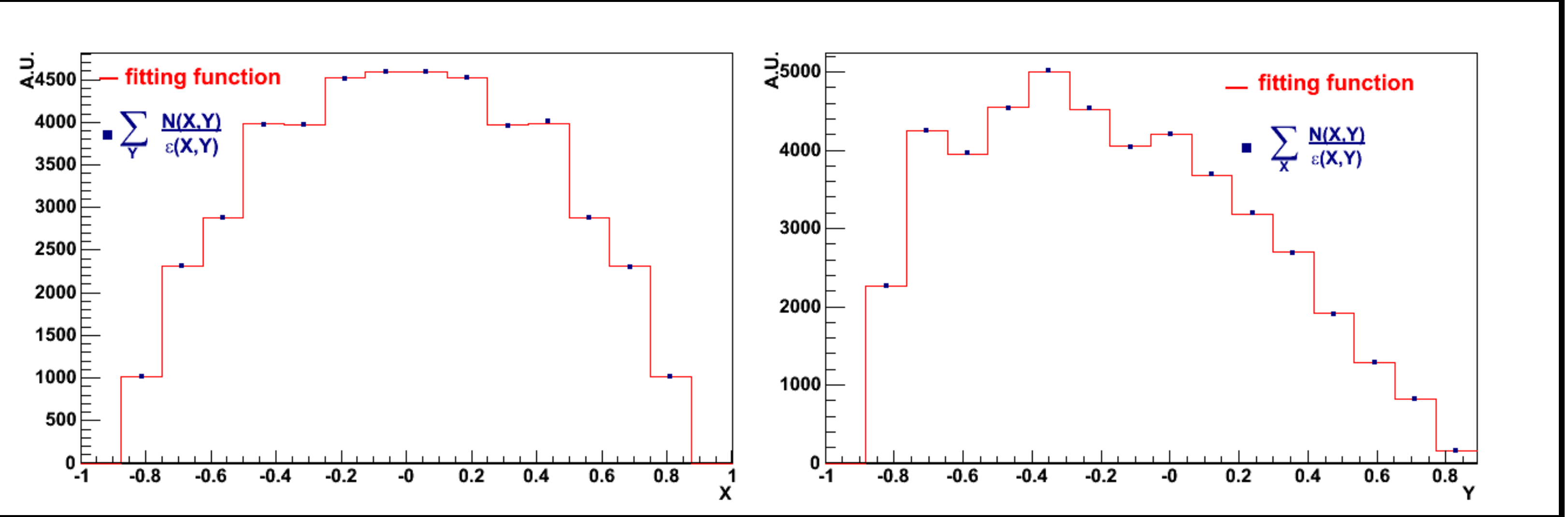






Fit quality

$$|A(X,Y)|^2 = 1+aY+bY^2+cX+dX^2+eXY+fY^3$$



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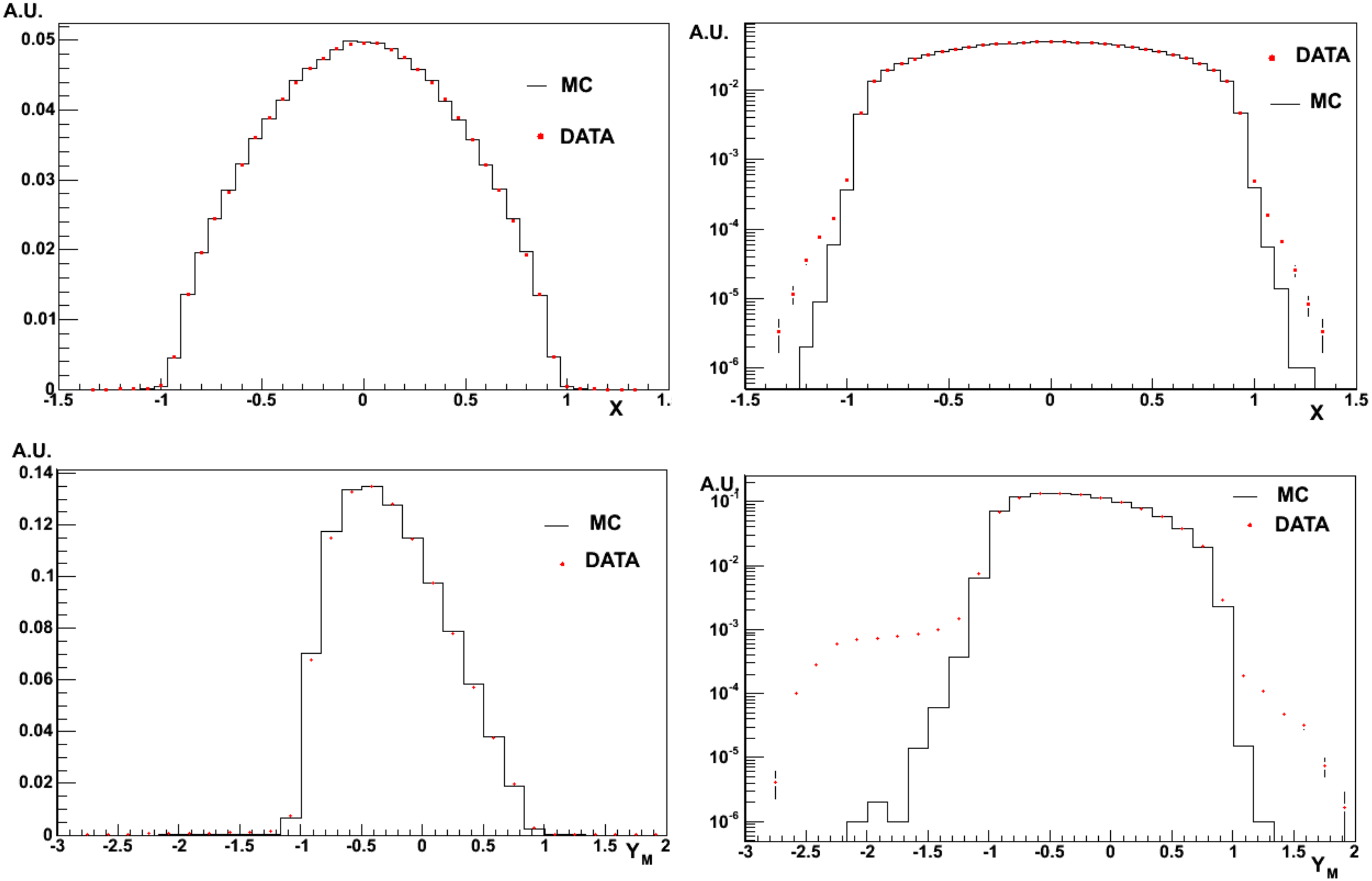
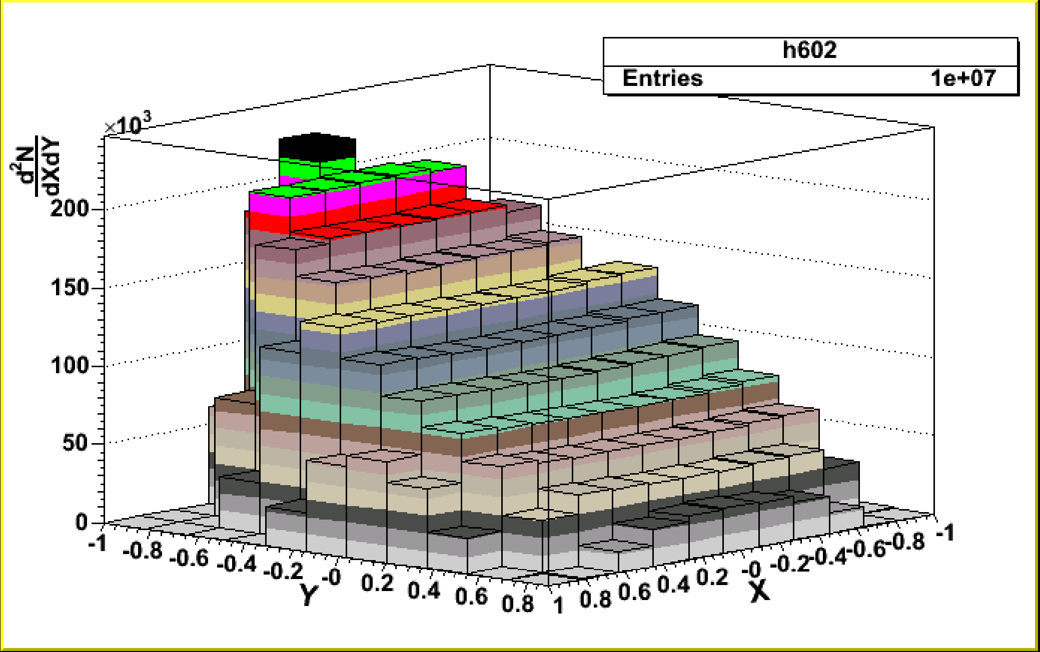
Comparison Data-MC: X & Y



$\eta \rightarrow \pi^+\pi^-\pi^0(\gamma)$

We have tested the effect of radiative corrections to the Dalitz plot density.



The ratio of the two plots has been fitted with the usual expansion: corrections to parameters are compatible with zero

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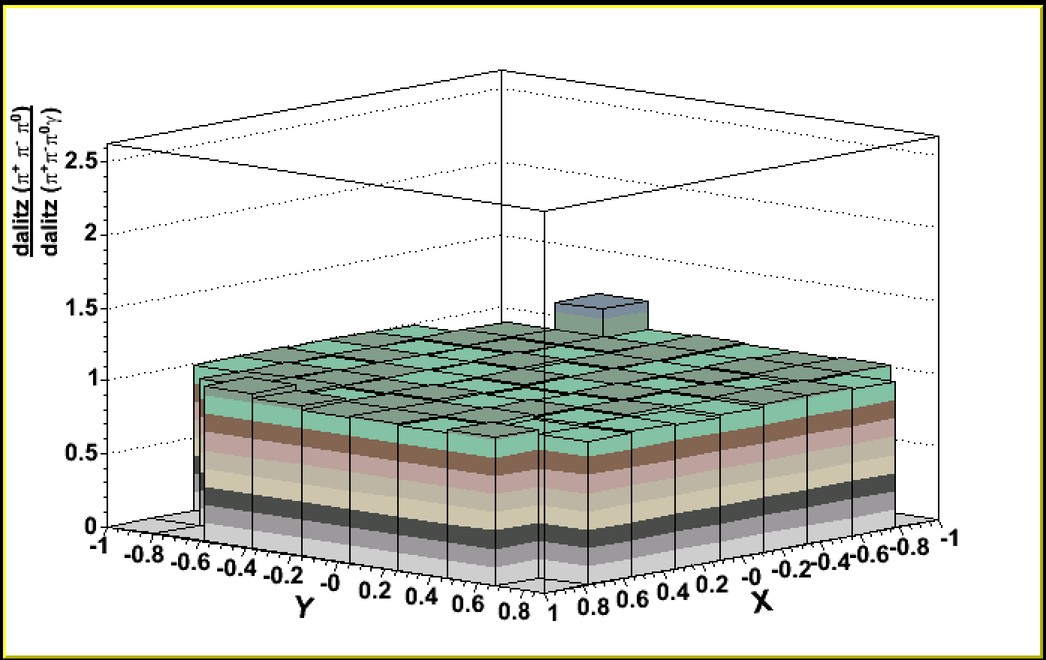

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Dashen theorem violation ?

Using preliminary KLOE results

B.V. Martemyanov and V.S. Sopov (hep-ph\0502023) have extracted:

$|A(X,Y)|^2 = 1-1.072\,Y+0.117\,Y^2+0.047\,X^2+0.13Y^3$

$Q = 22.8 \pm 0.4$ against $Q_{Dashen} = 24.2$

Remember
$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

$$Q^2{}_{Dashen} = \frac{m_K^2}{m_\pi^2}\frac{m_K^2 - m_\pi^2}{m_{K^0}^2 - m_{K^+}^2 + m_{\pi^+}^2 - m_{\pi^0}^2}$$

Check on cubic term

Fitted function is actually :

$$\frac{\varepsilon^{Real}(X,Y)}{\varepsilon^{MC}(X,Y)} \cdot |A(X,Y)|^2$$

Assume:

$$\frac{\varepsilon^{Real}(X,Y)}{\varepsilon^{MC}(X,Y)} \approx 1+\alpha Y+\beta X^2$$

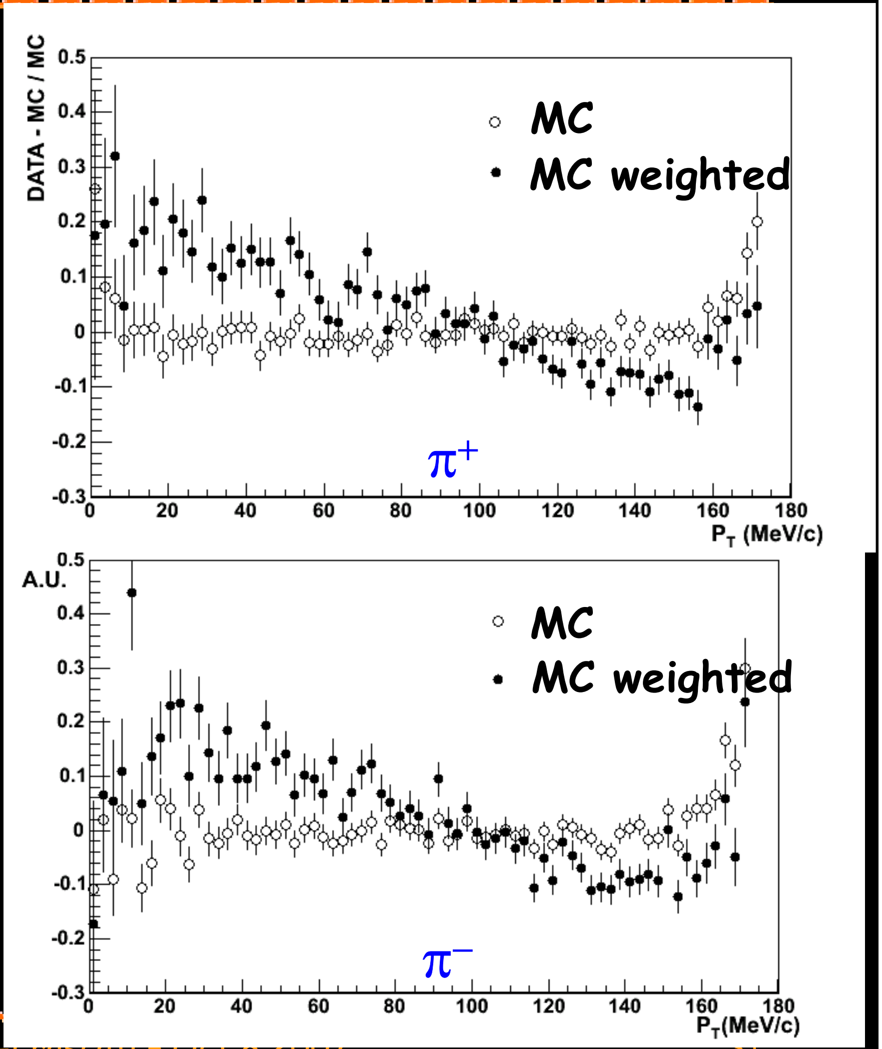
No cubic dependence in $|A(X,Y)|^2$

$$|A(X,Y)|^2 = 1 + aY + bY^2 + dX^2 \quad \text{with } a \approx -1.$$

Can evaluate α such as to mimic the cubic term.

Check on cubic term (2)

Cubic term is not an artifact …



Dalitz expansion: theory vs experiment

Calculation	a	b	d
Tree	-1.00	0.25	0.00
One-loop[1]	-1.33	0.42	0.08
Dispersive[2]	-1.16	0.26	0.10
Tree dispersive	-1.10	0.31	0.001
Absolute dispersive	-1.21	0.33	0.04

[1] Gasser,J. and Leutwyler, H., Nucl. Phys. B **250**, 539 (1985)
[2] Kambor, J., Wiesendanger, C. and Wyler, D., Nucl. Phys. B **465**, 215 (1996)

Measurement	N_η	a	b	d
Layter	80884	-1.08 ± 0.14	0.034 ± 0.027	0.046 ± 0.031
Gormley	30000	-1.17 ± 0.02	0.21 ± 0.03	0.06 ± 0.04
Crystal Barrel	1077	-0.94 ± 0.15	0.11 ± 0.27	
Crystal Barrel	3230	-1.22 ± 0.07	0.22 ± 0.11	0.06 fixed

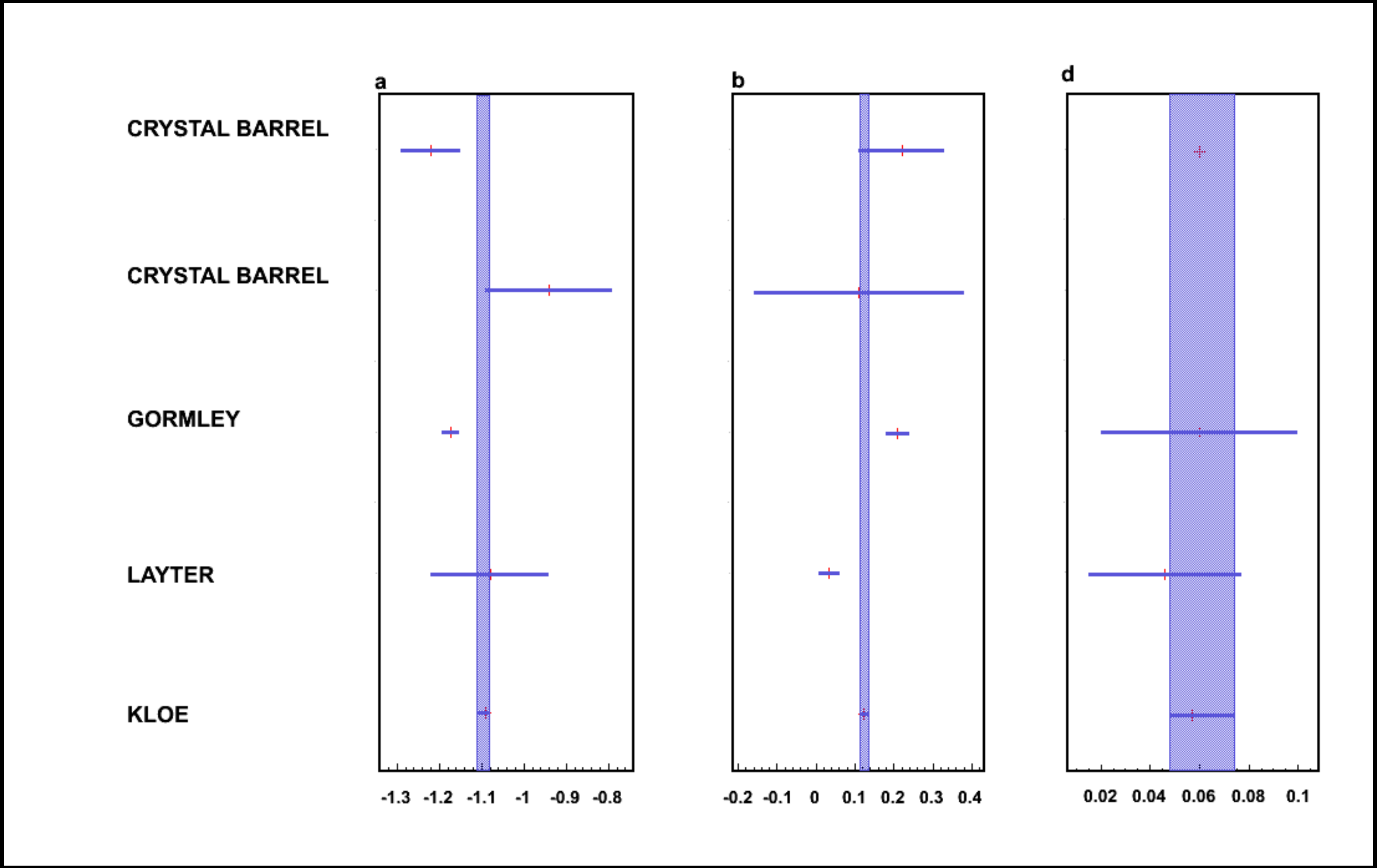
Dalitz expansion: theory vs experiment

Calculation	α
Tree	0.00
One-loop[1]	0.0015
Dispersive[2]	-0.007 - -0.014
Tree dispersive	-0.006
Absolute dispersive	-0.007

[1] Gasser,J. and Leutwyler, H., Nucl. Phys. B **250**, 539 (1985)
[2] Kambor, J., Wiesendanger, C. and Wyler, D., Nucl. Phys. B **465**, 215 (1996)

Alde (1984)	-0.022 ± 0.023
Crystal Barrel (1998)	-0.052 ± 0.020
Crystal Ball (2001)	-0.031 ± 0.004

Results (II)



a
b
d
CRYSTAL BARREL
CRYSTAL BARREL
GORMLEY
LAYTER
KLOE
-1.3 -1.2 -1.1 -1 -0.9 -0.8
-0.2 -0.1 0 0.1 0.2 0.3 0.4
0.02 0.04 0.06 0.08 0.1

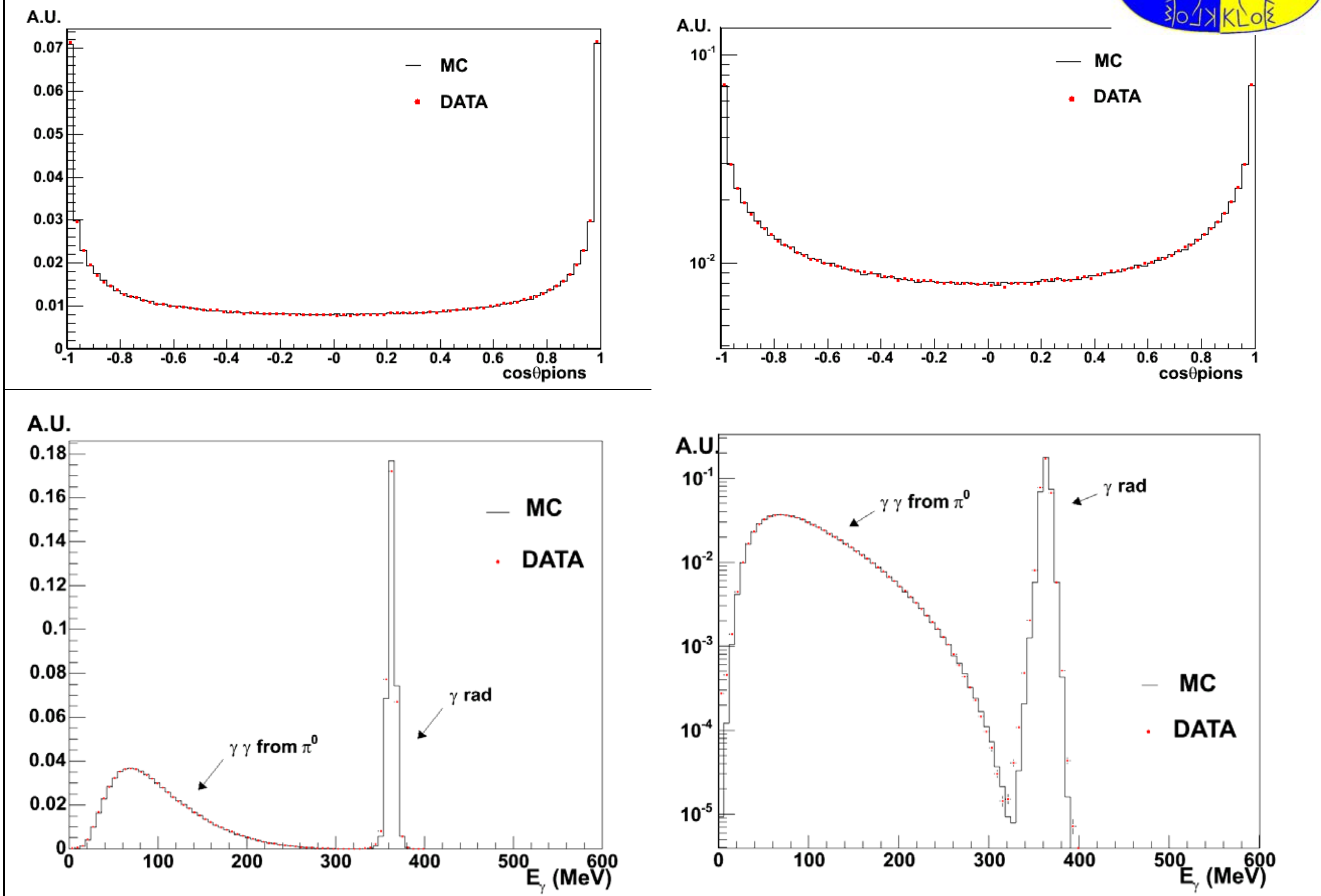
Sample selection

The cuts used to select: $\eta \to \pi^0 \pi^0 \pi^0$ are :

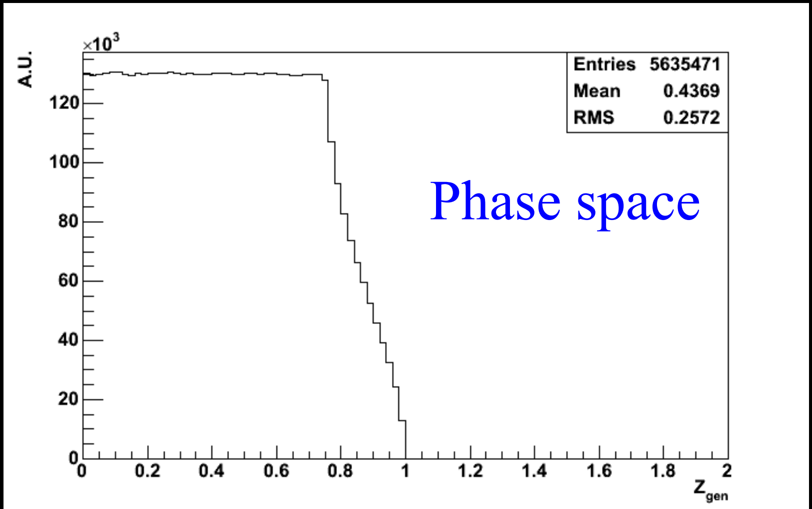
- 7 and only 7 prompt neutral clusters with $21^\circ < \theta_\gamma < 159^\circ$ and $E_\gamma > 10$ MeV
- opening angle between each couple of photons > 18°
- Kinematic Fit with no mass constraint
- $P(\chi 2) > 0.01$
- 320 MeV < $E_{\gamma rad}$ < 400 MeV (after kin fit)

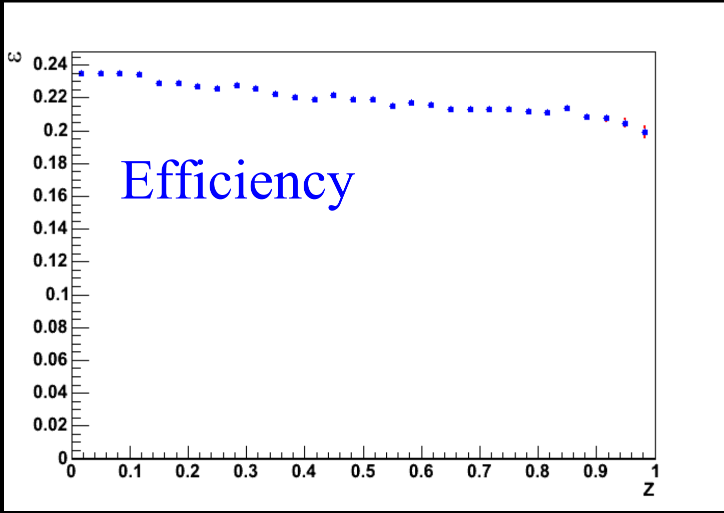
With these cuts the expected contribution from events other than the signal is <0.5%

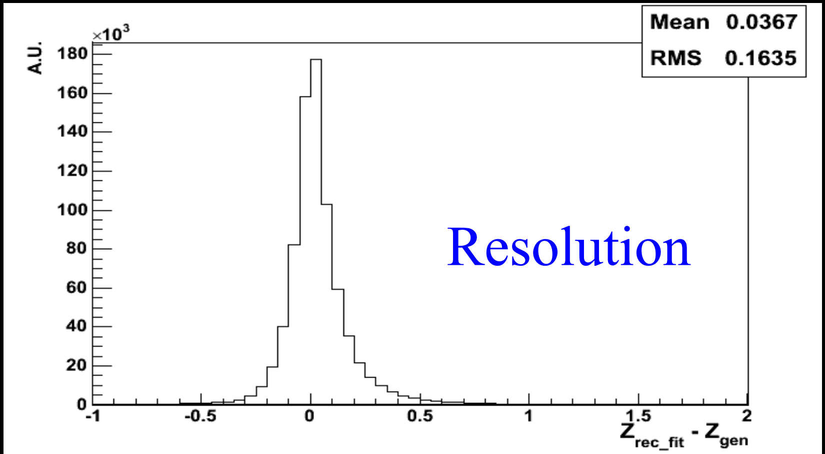
Comparison Data-MC



Resolution and efficiency







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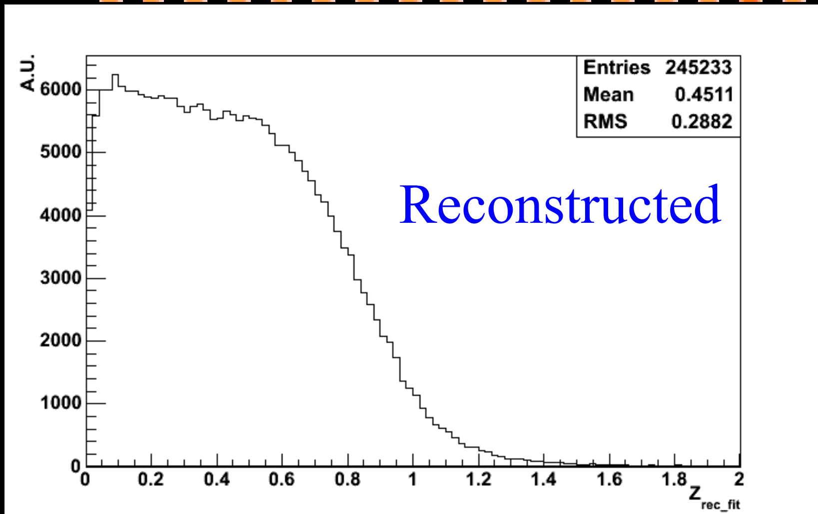

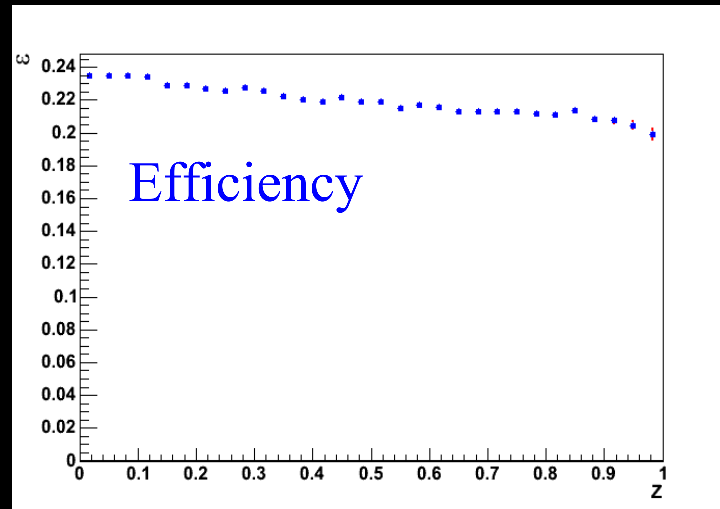

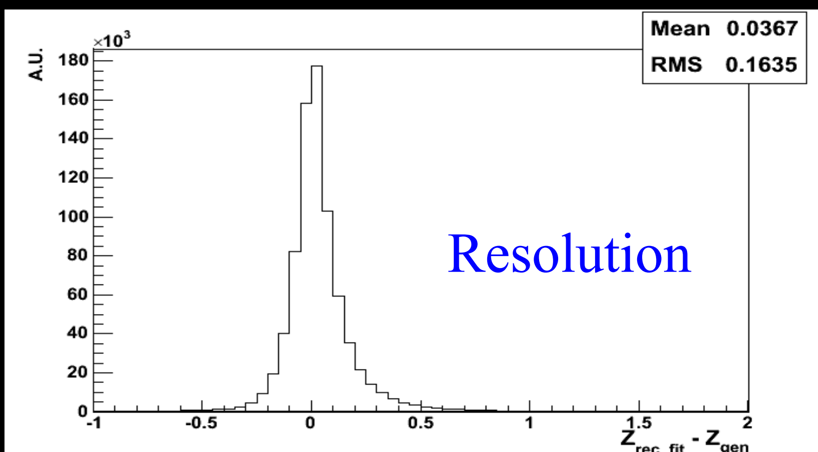

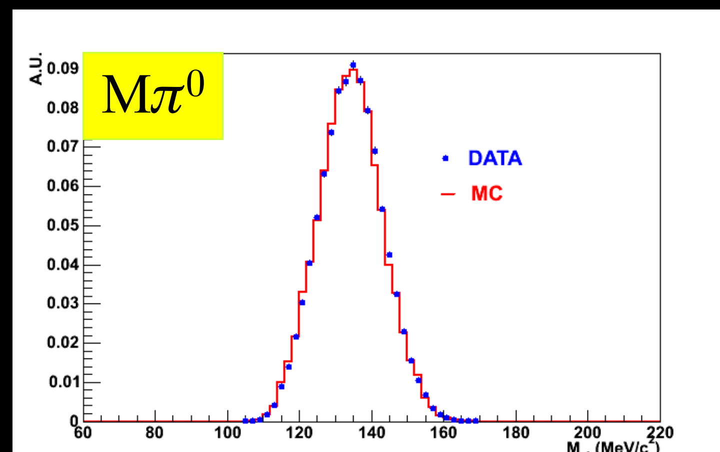

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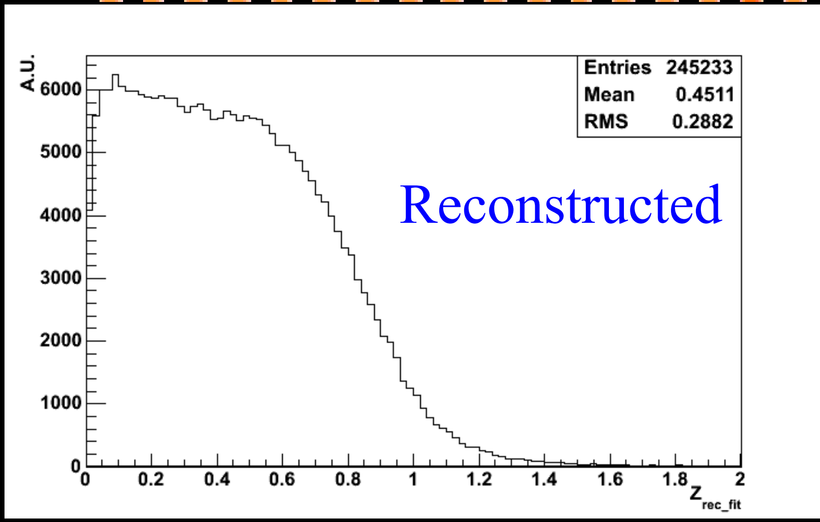

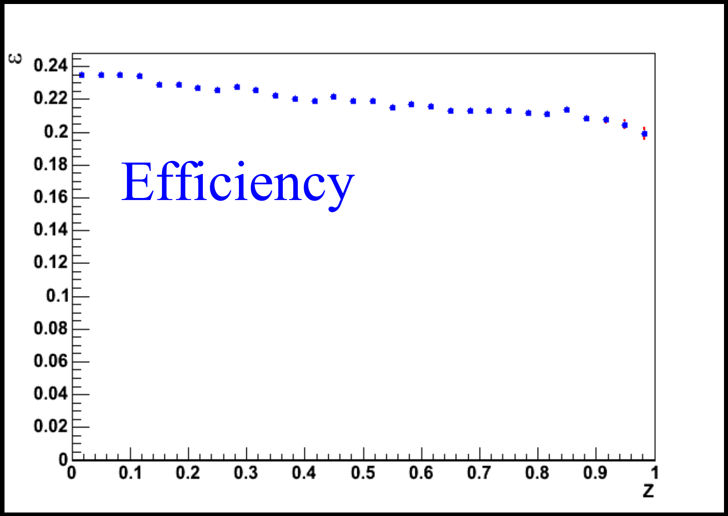

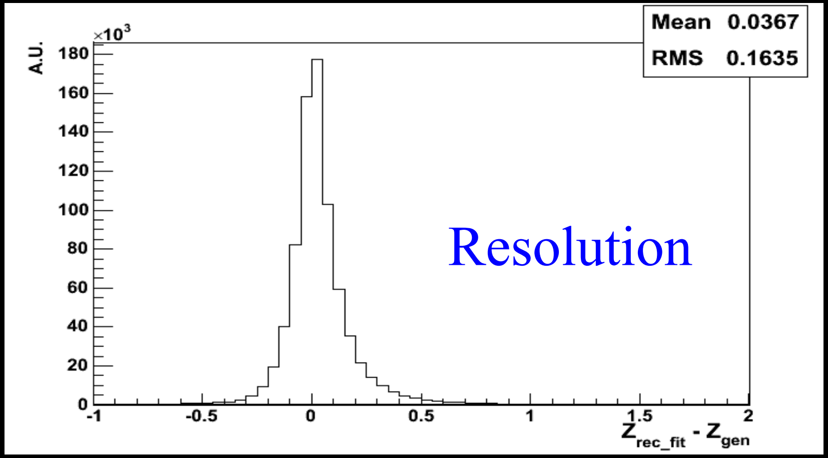

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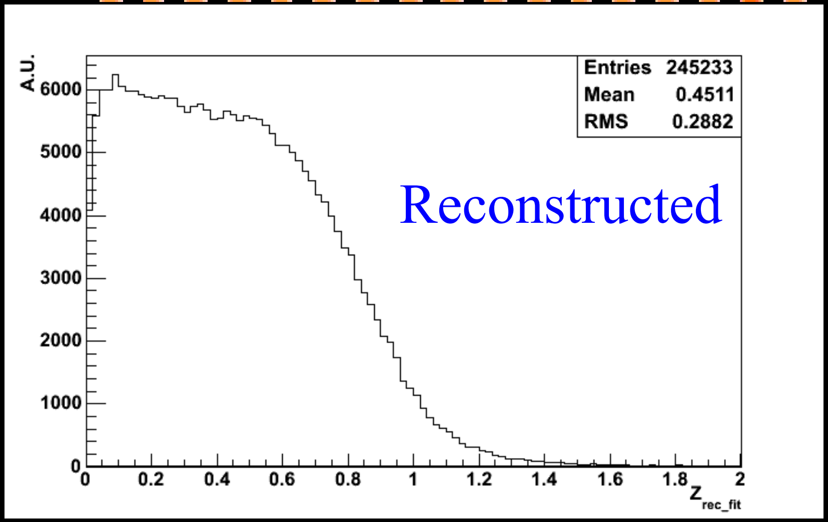
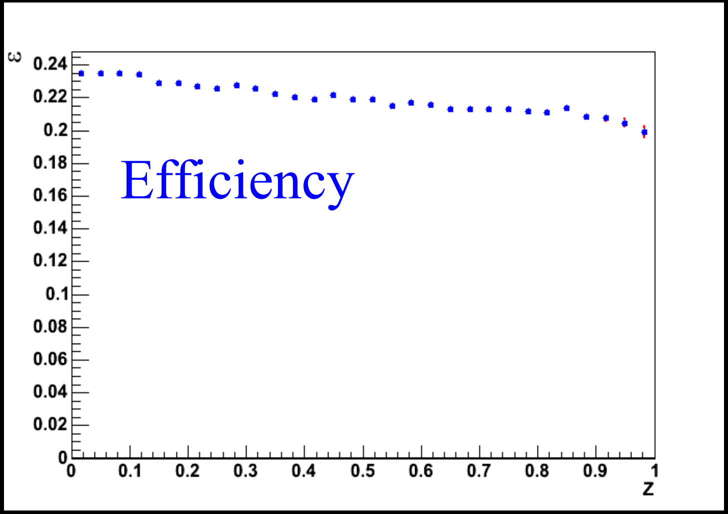
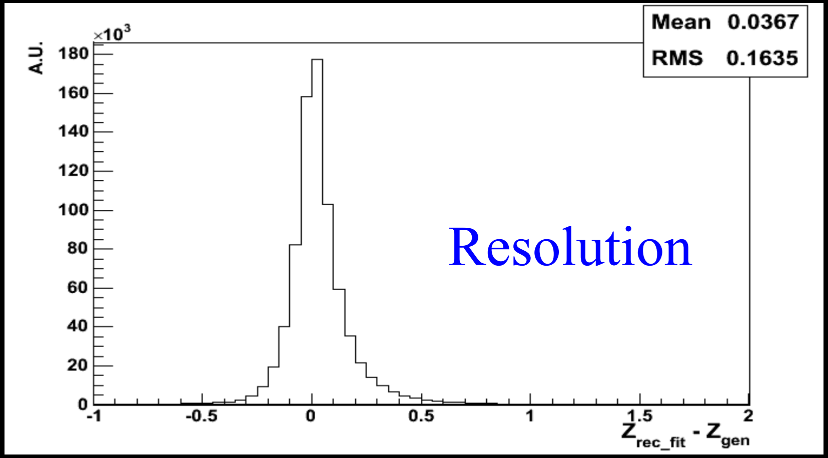
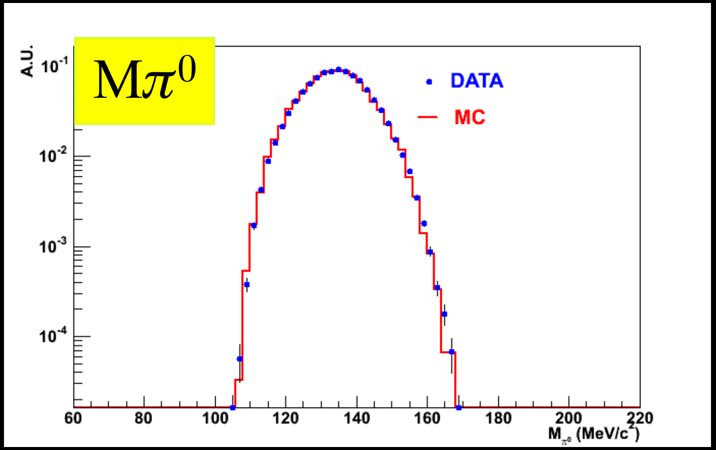


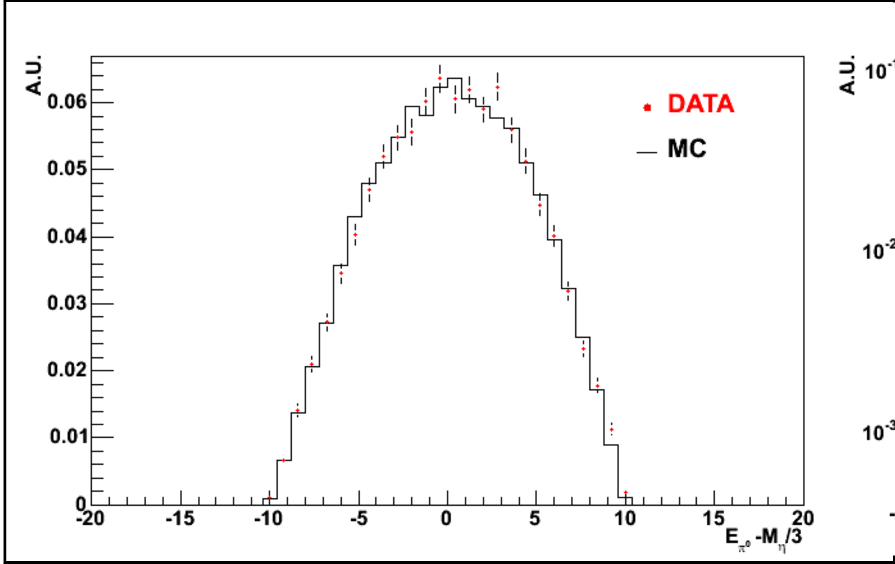


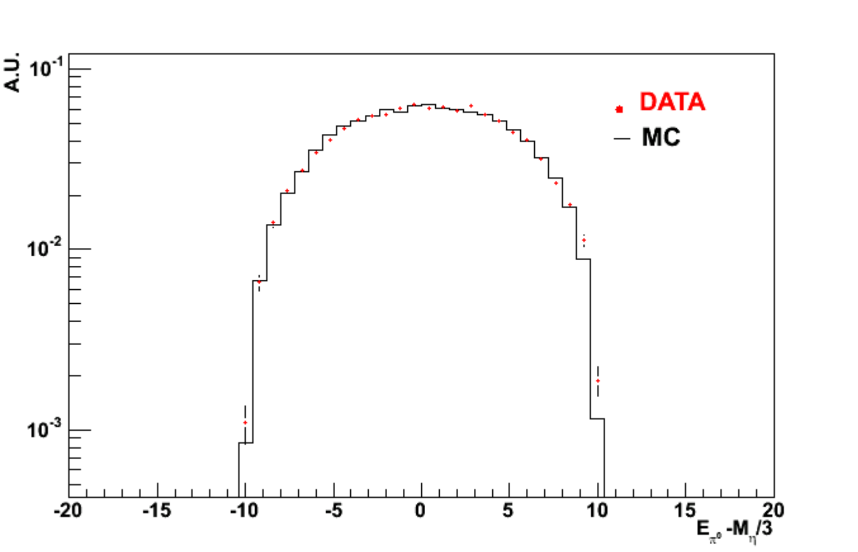




Resolution (II)

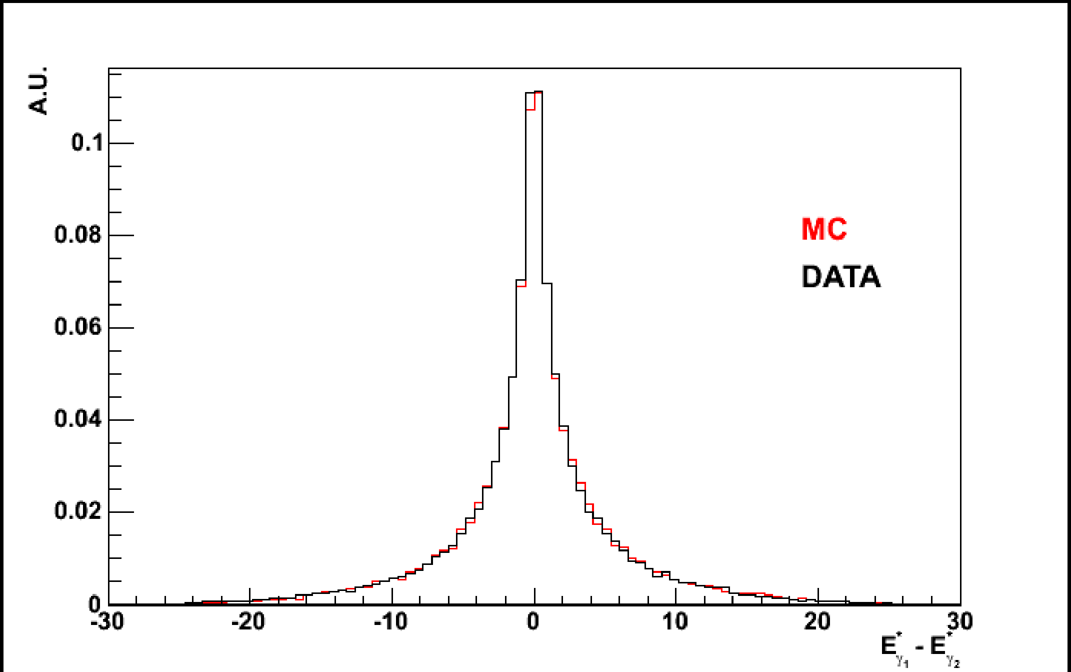
The center of Dalitz plot correspond to 3 pions with the same energy (E_i = $M_\eta/3$ = 182.4 MeV). A good check of the MC performance in evaluating the energy resolution of π^0 comes from the distribution of $E_{\pi0}$ - E_i for z = 0





Resolution (III)

A further check can be done comparing the energies of the two photons in the pion rest frame as function of pion energy



$E^*_{\gamma 1} - E^*_{\gamma 2}$

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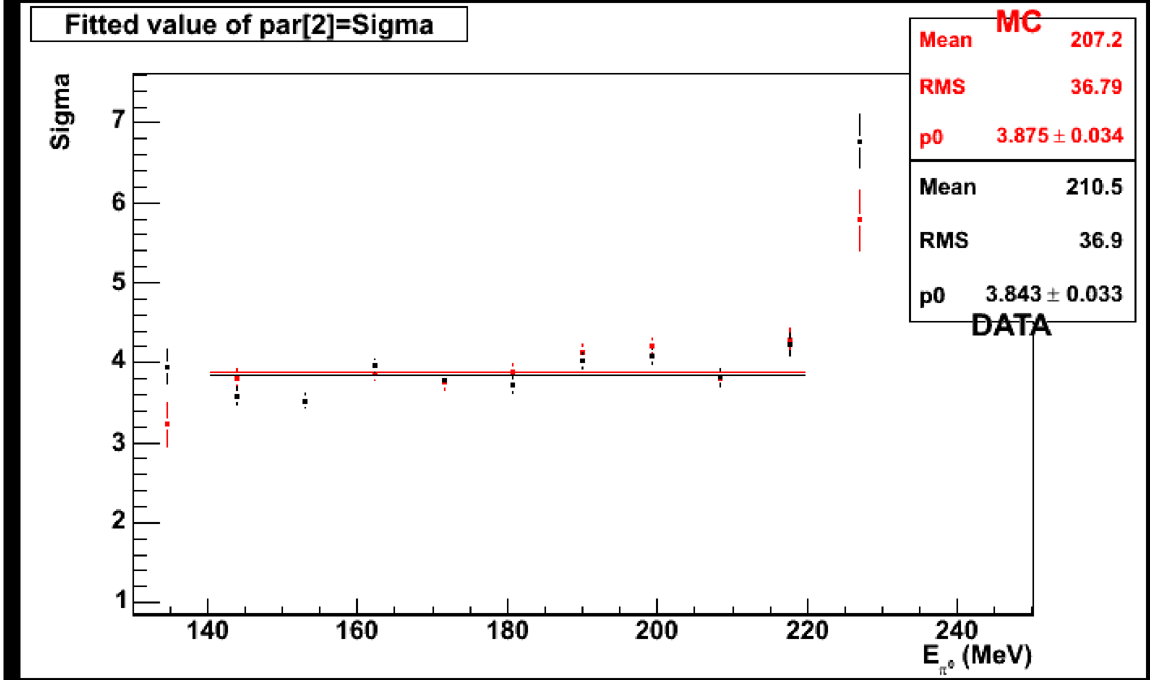
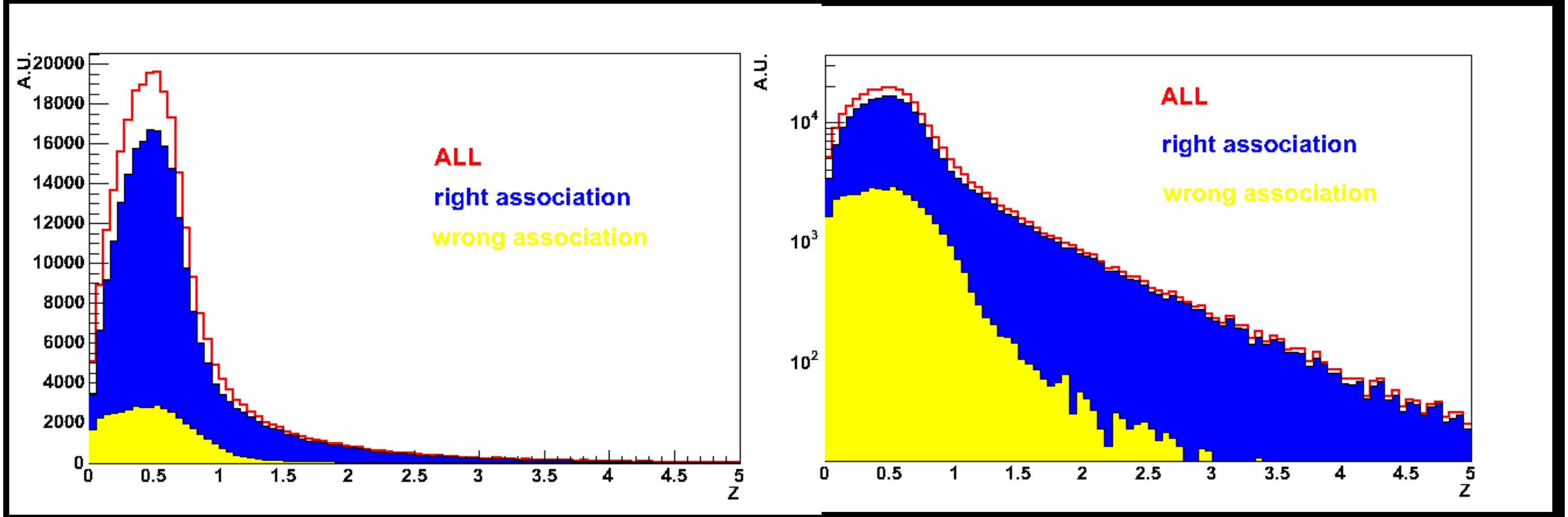


$E^*_{\gamma 1} - E^*_{\gamma 2}$

Vs.

$E\pi$

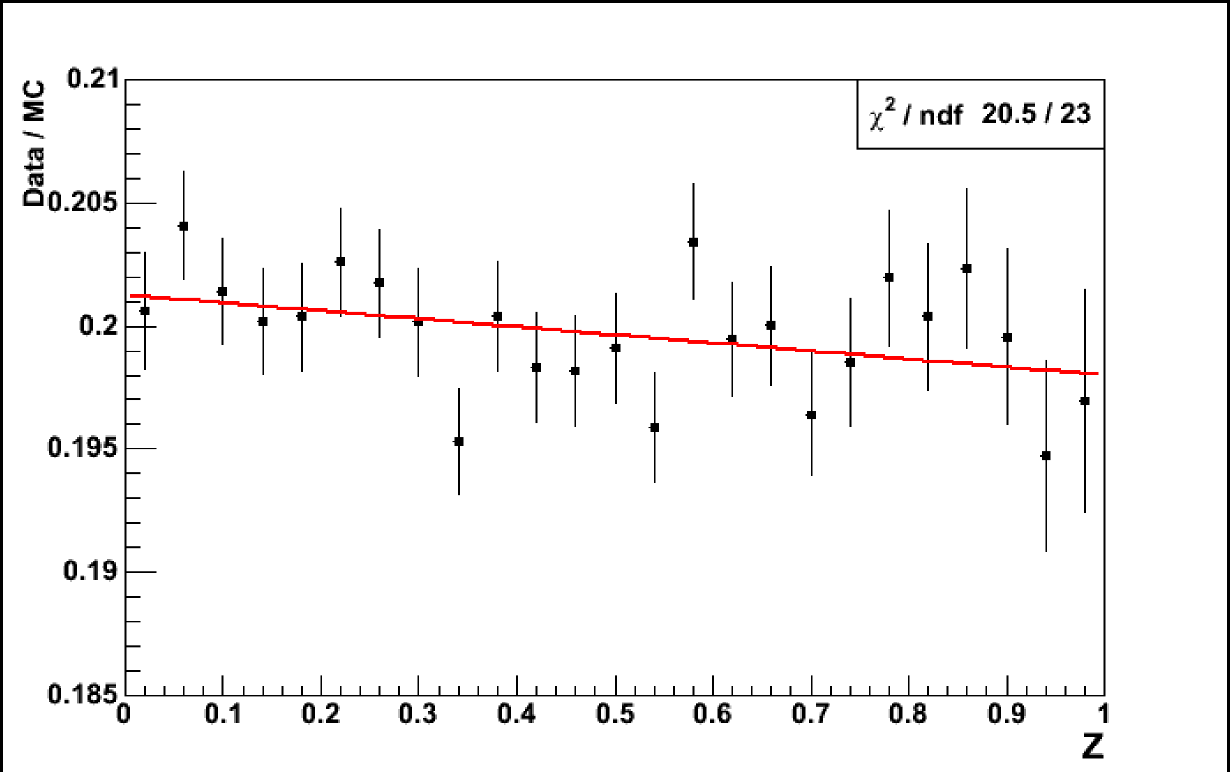
Checks of purity on data



Purity on data compatible with the one expected from MC for all different samples analyzed

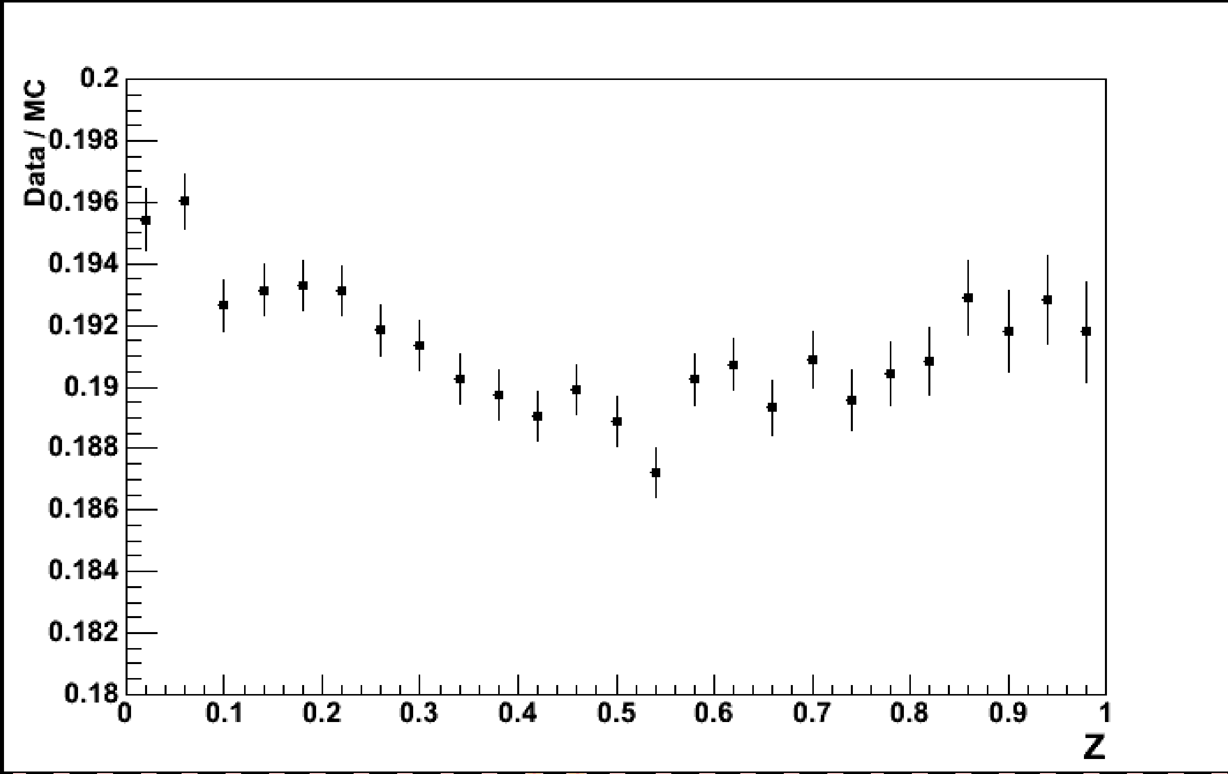
Linearity of DATA/MC ratio

High purity sample (used for the old preliminary result) -> no evident effect is visible



Linearity of DATA/MC ratio (2)

We observed a relevant dependence of α on the fitting range for low purity (=high statistics) sample…

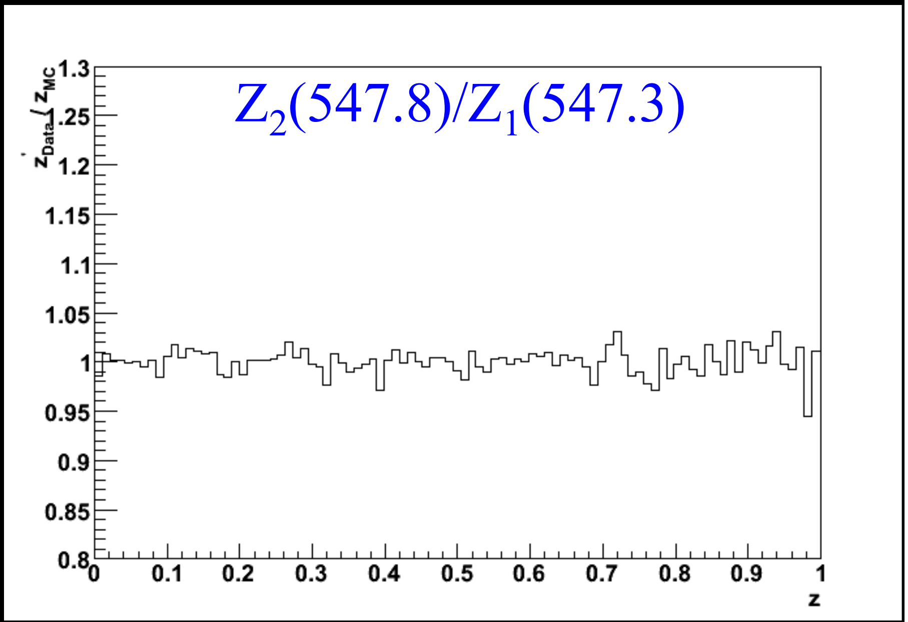


A toy MC

To understand the effect we used a toy MC to generate 1200000 events with different eta masses:

$$z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - m_\eta}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho^2_{\max}}$$

Sample 1 : M = 547.30 MeV
Sample 2 : M = 547.822 MeV



We observe that when the input mass value is used to build the z variable the phase space shape does not change. But if one uses M = 547.30 MeV to build the z variable for sample 2 big deviations are observed…

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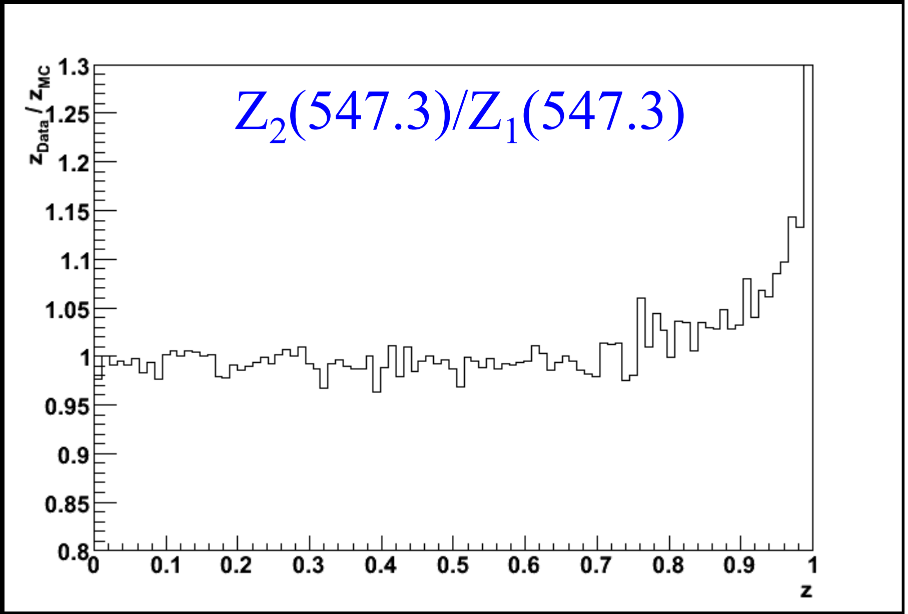
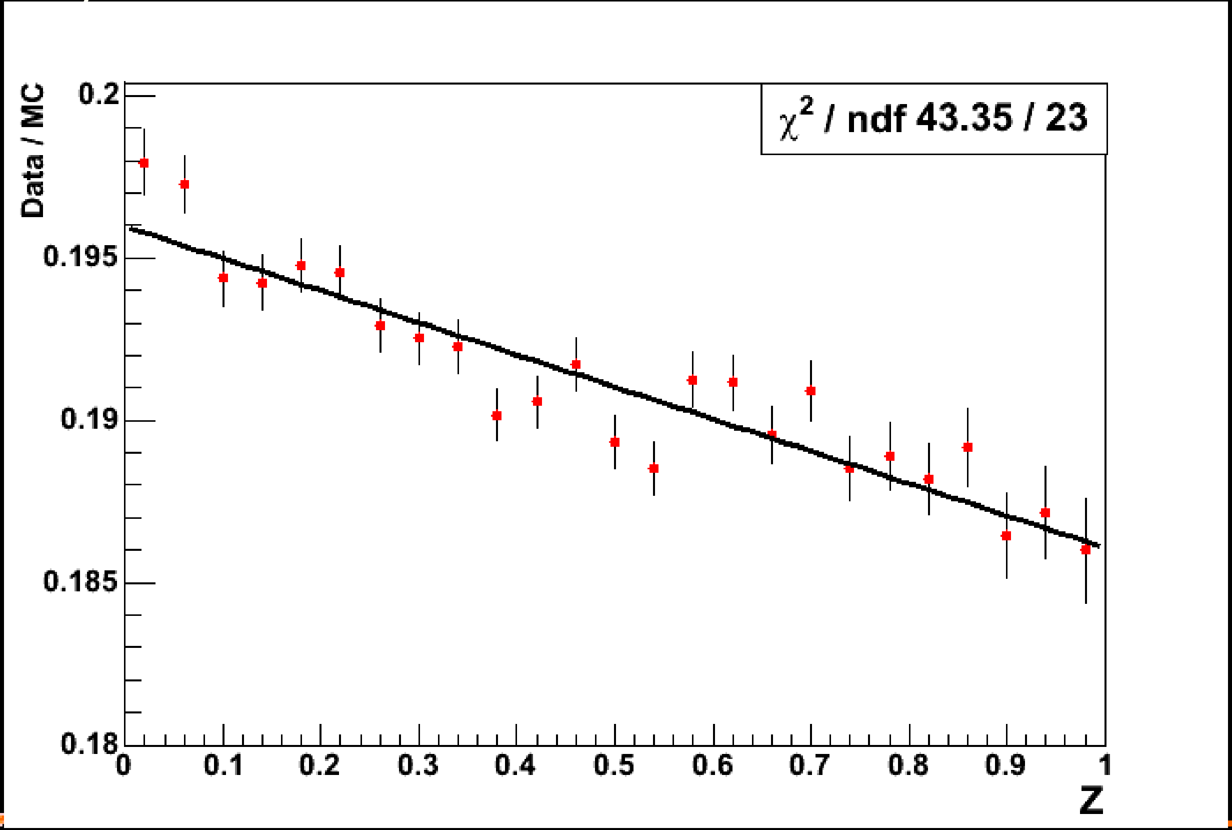


Linearity

If the effect is given by the eta mass, correcting for it now all samples should exhibit good linearity for the ratio DATA/MC_{rec} (phase space)



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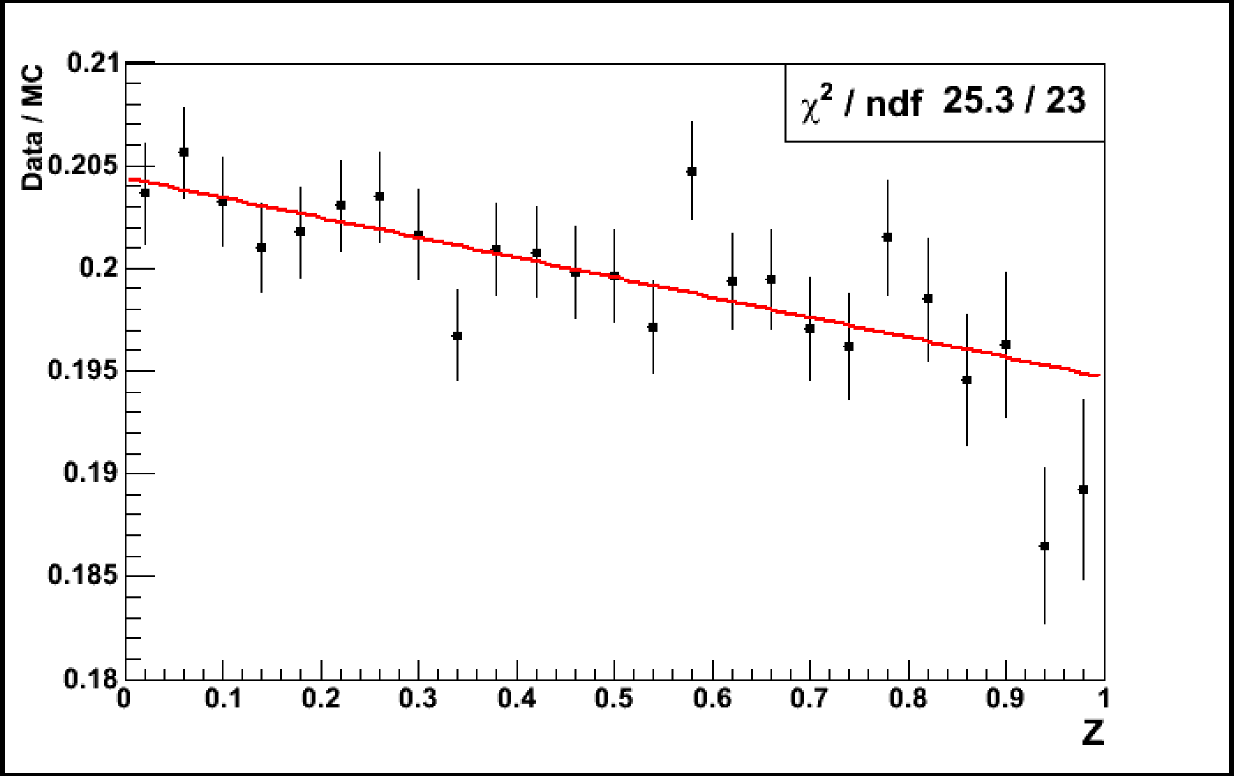

Effect of mass constraint in fit

Why did this effect not pop up in other experiments analyses ? The reason is the effect is much less evident if you constrain in a kinematic fit the η mass and then use the value you have constrained to build z…