Blessing of the $\eta \to \pi^+ \pi^- e^+ e^-$ analysis: measurement of the BR and of the decay plane asymmetry

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Outline

Motivations

Data sample

Event and track selection

Background rejection part-1

Particle ID

Background rejection part-2

Efficiencies

Fit results

Data - MC comparison

Asymmetry

Motivations

η structure, using virtual photon

Model comparison (VMD, χPT)

Test of CP violation: Gao model

Mod.PhysLett.A17
1583-1588.2002

Angular asymmetry between ee and $\pi\pi$ planes, A_{CP},

can be due to unconventional CPV mechanism

described by a T×V 4 quarks operator with Ds=0.

Within SM constrained by BR($\eta \to \pi\pi$),

using the experimental upper limit: $A_{CP} < 10^{-4}$

using theoretical prediction: $A_{CP} \sim 10^{-15}$

CPV model predicts an upper bound of 10^{-2}

BR: theory & experiment

Jarlskog, Pilkuhn 1967 Using PDG08	$0.0065 \times BR(\eta \to \pi^+\pi^-\gamma)$ Using CLEO '07
$(29.9 \pm 1.0) \times 10^{-5}$	$(25.7 \pm 1.3) \times 10^{-5}$
Picciotto, Richardson 1993	$(32 \pm 3) \times 10^{-5}$
Faessler et al. 2000	36×10^{-5}
Borasoy, Nissler 2007	$(29.9^{+0.6}_{-0.9}) \times 10^{-5}$

CMD-2 (4 events)	$(37\ ^{+25}_{-18\ stat} \pm 3_{syst}) \times 10^{-5}$
CELSIUS-WASA-2006 (16 events)	$(43 \pm 13_{stat} \pm 4_{syst}) \times 10^{-5}$
CELSIUS-WASA-2007 (16 events)	$(43\ ^{+20}_{-16\ stat} \pm 4_{syst}) \times 10^{-5}$

Data sample

Using drc/mrc streams
with ETA4C tag

1734 pb^{-1} data 2004/05

50517 pb^{-1} MC signal only → Run by run background simulation

3479 pb^{-1} MC `all_phys`(2/3) 2004/05

250 pb^{-1} data off-peak ($\sqrt{s}$ = 1000 MeV)

Event selection

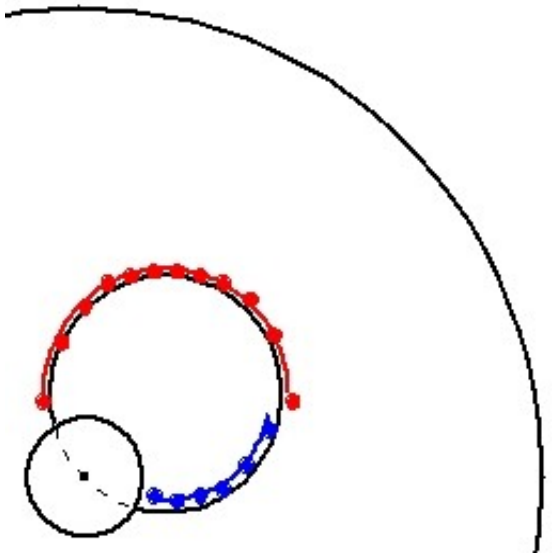
EVCL algorithm ETA4CTAG:

- ≥ 4 tracks from the Interaction Point
- 1 high energy neutral cluster ($E_{cl} \geq 250$ MeV)
- 0 medium energy neutral cluster ($50 \leq E_{cl} \leq 250$ MeV)

Track selection

Tracks are required to came from a cylinder around the IP:

$R \leq 4$ cm $h/2 = 10$ cm



Check on broken tracks is applied:

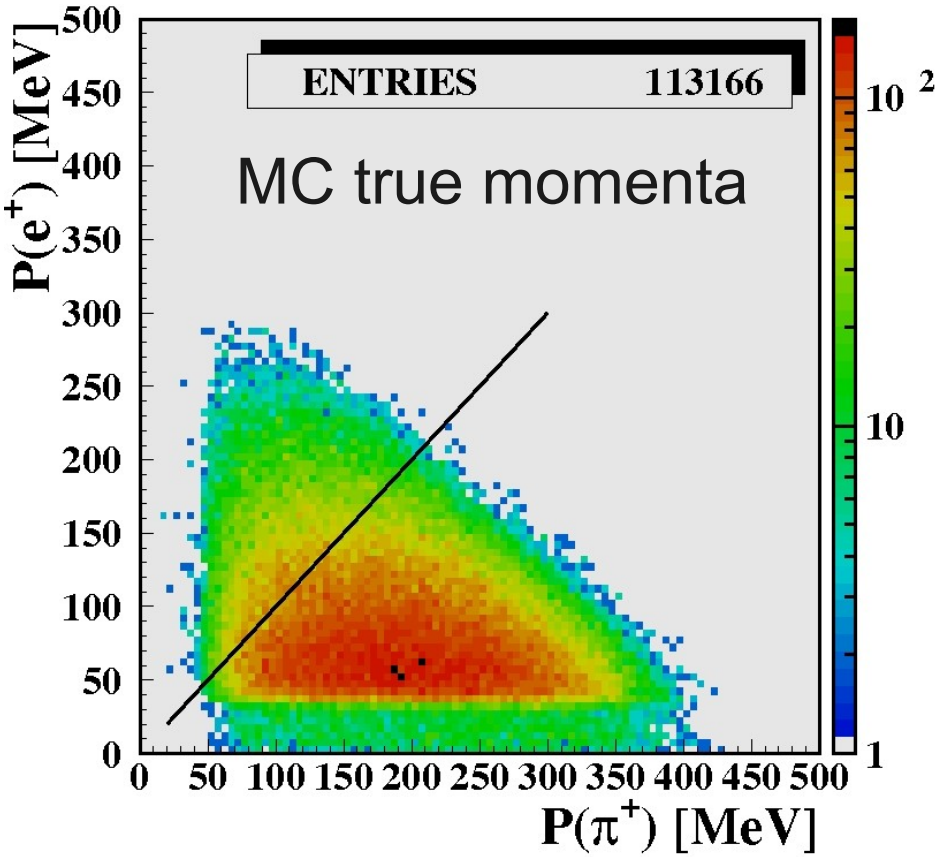
$\Delta P_T < 4.5$ MeV $\Delta P_Z < 3$ MeV

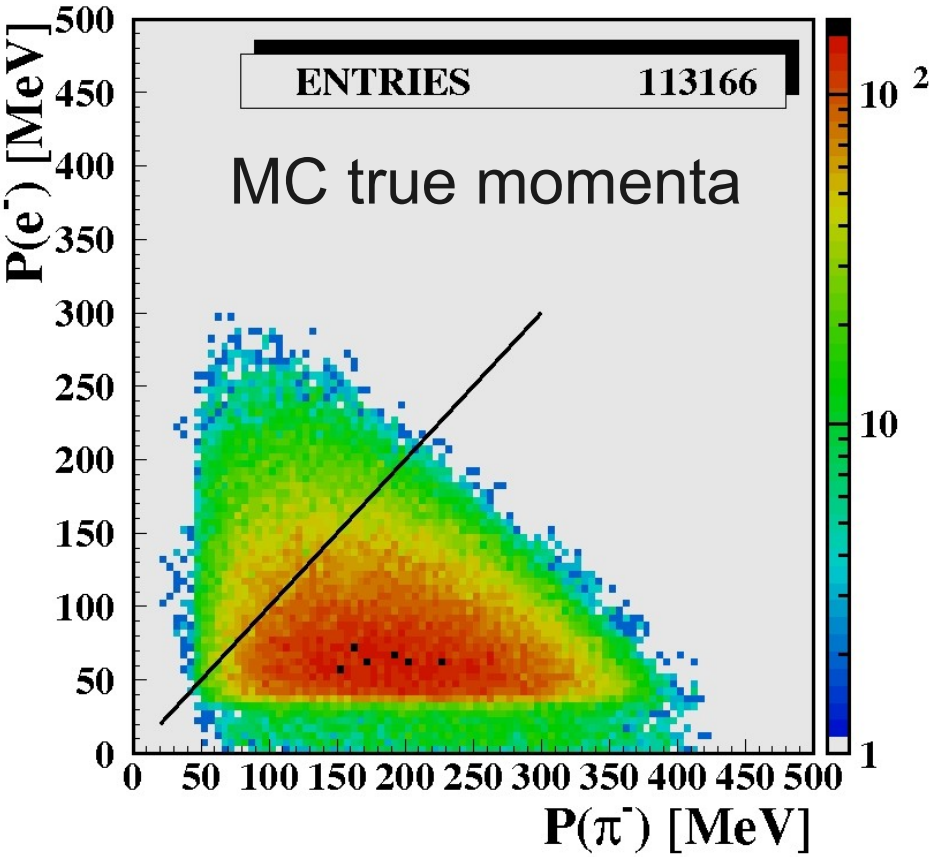
≥ 2 positive and ≥ 2 negative tracks are requested

Tracks are ordered by momentum

Track identification

Higher momentum tracks assigned to pion





Kinematic fit

A kinematic fit to the ϕ meson is performed for all the events having # good tracks ≥ 4

The 22 inputs are:

- 4 tracks x 3 momenta
- x,y,z,E,t of the neutral cluster
- x,y,z of the IP
- $\sqrt{s}$ and f momentum

The 5 constraints are:

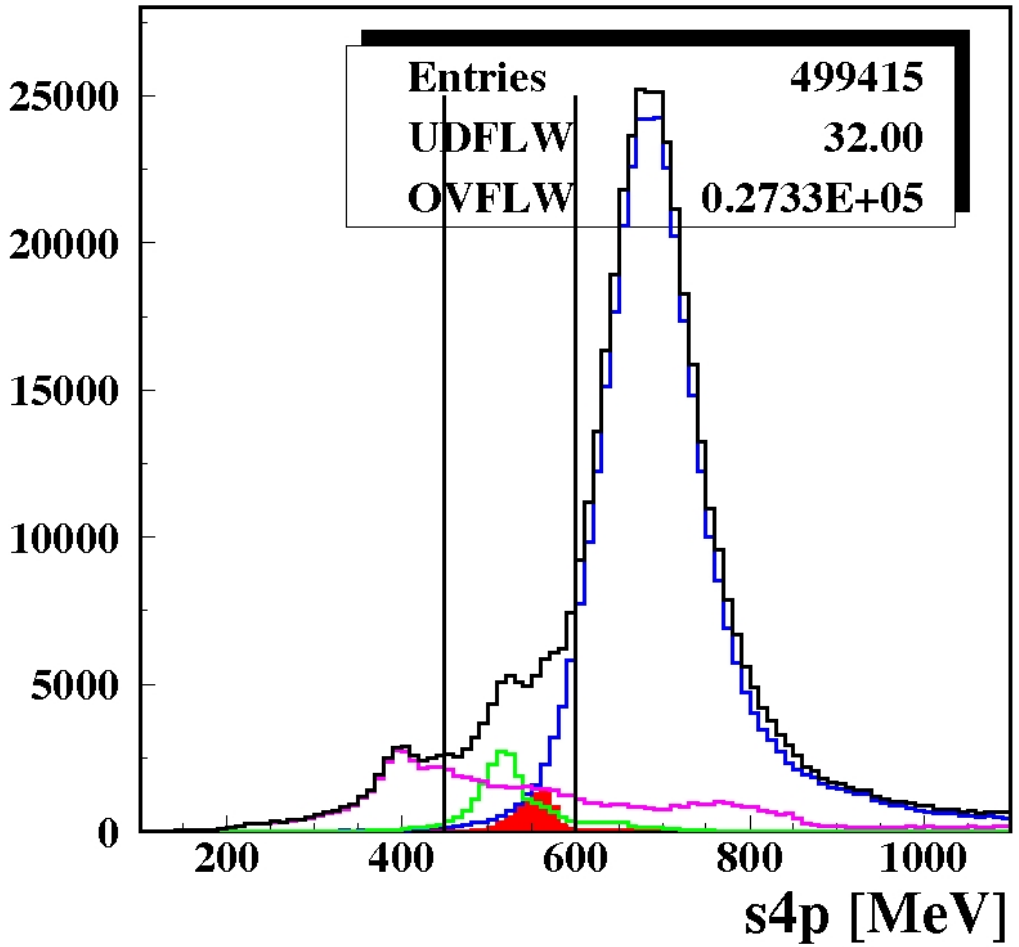
- Four momentum conservation
- Photon time of flight ($cT_\gamma = R_\gamma$)

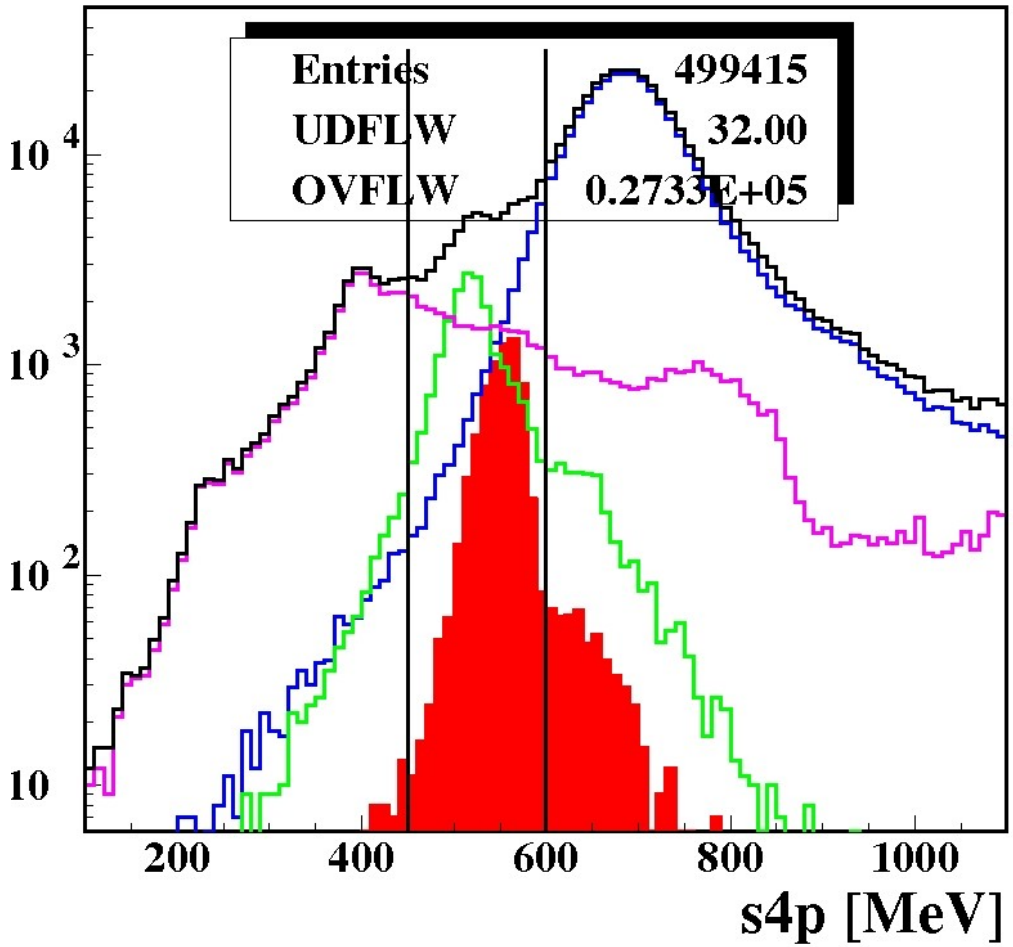
Background rejection - step 1

$$450\ \text{MeV} < \sum_{i=1}^{4} |\vec{p}_i| = s4p < 600\ \text{MeV}$$

Total MC $\phi \to \eta\gamma$ $\phi \to \rho\pi + \pi^+\pi^-\pi^0$

Signal $\eta \to \pi^+\pi^-e^+e^-$ Other backgrounds



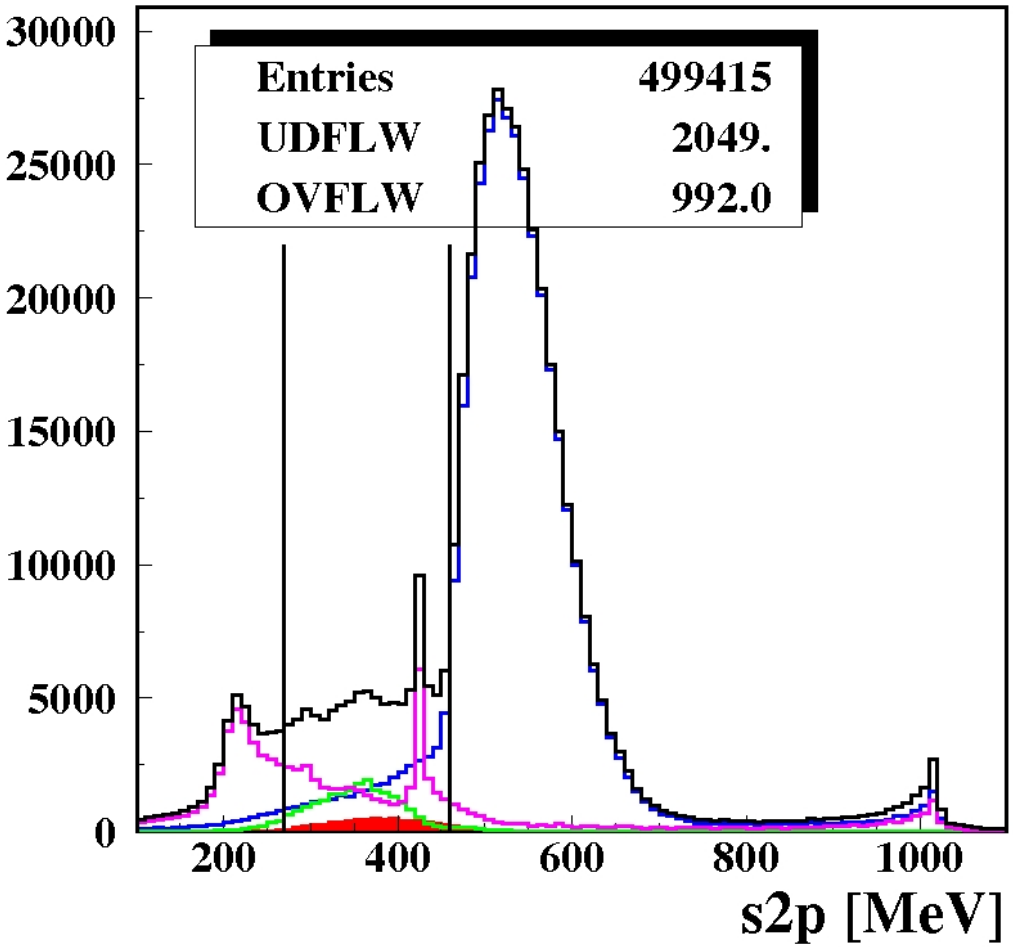


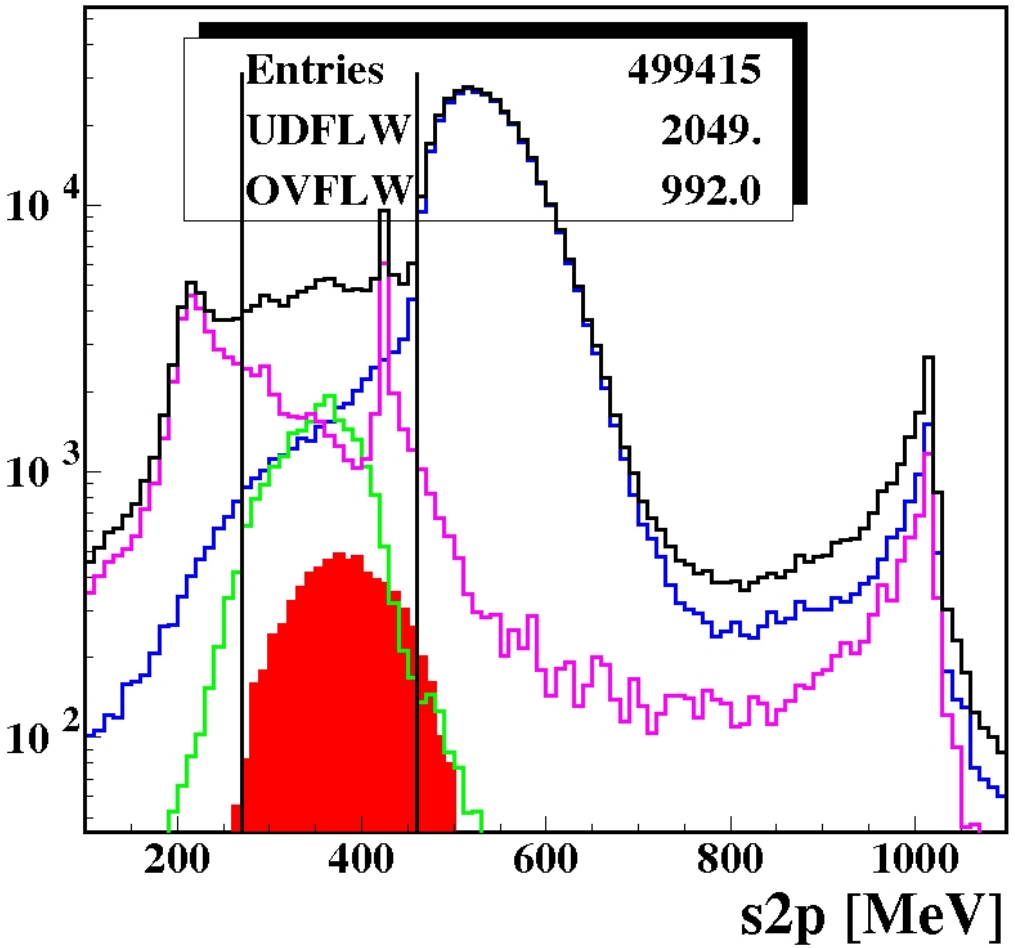
Background rejection - step 2

$270 < |P(p^+1)| + |P(p^-1)| = s2p < 460$ MeV

Total MC $\phi \to \eta\gamma$ $\phi \to \rho\pi + \pi^+\pi^-\pi^0$

Signal $\eta \to \pi^+\pi^-e^+e^-$ Other backgrounds





Background rejection - step 3

$\chi^2_{KF} < 4000$

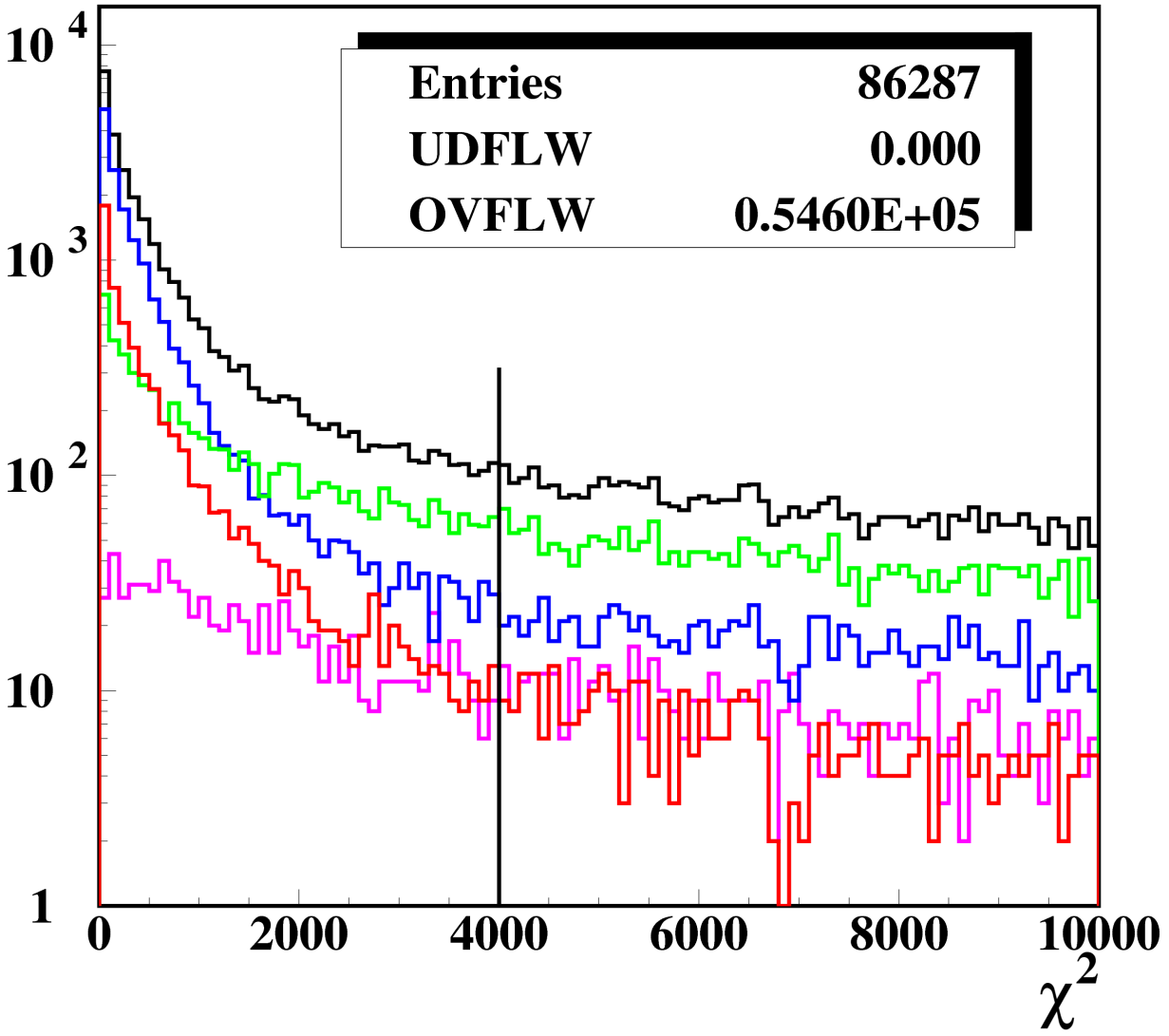
Total MC

$\phi \to \eta\gamma$

$\phi \to \rho\pi + \pi^+\pi^-\pi^0$

Signal $\eta \to \pi^+\pi^-e^+e^-$

Other backgrounds



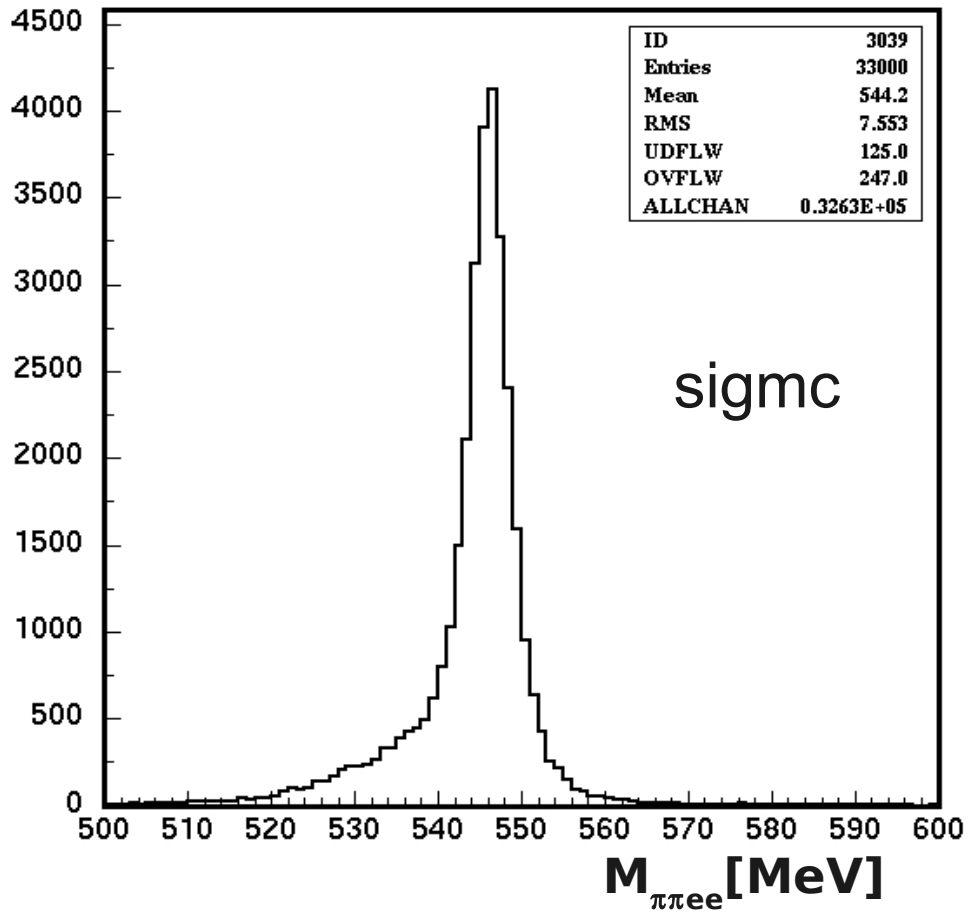
PID using TOF

Asymmetry in Mππee spectrum due to *wrong mass assignment*

Can be improved using TOF

We evaluate $\Delta t = t_{track} - t_{cluster}$ in both electron (Δt_e) and pion (Δt_p) hypothesis

#tracks associated to cluster and fraction of events	4	0.04
	≥3	0.29
	≥2	0.74
	≥1	0.99

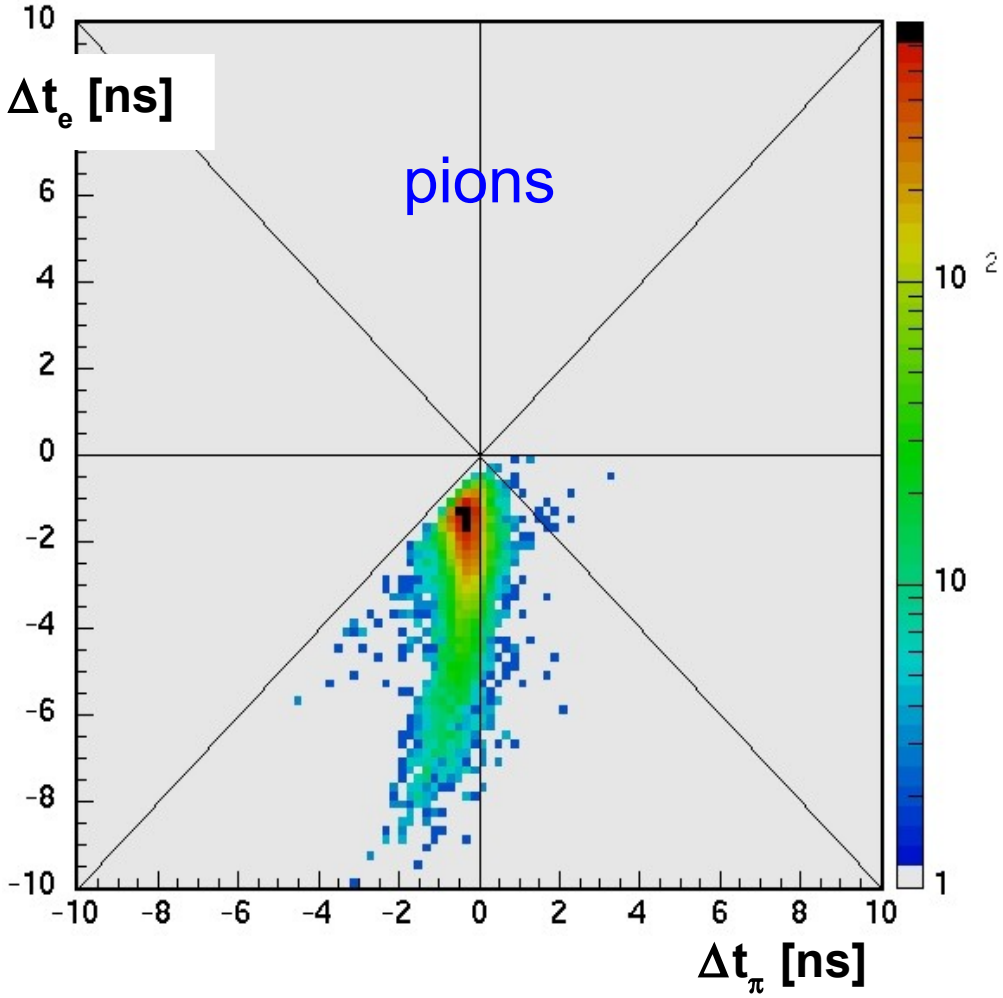


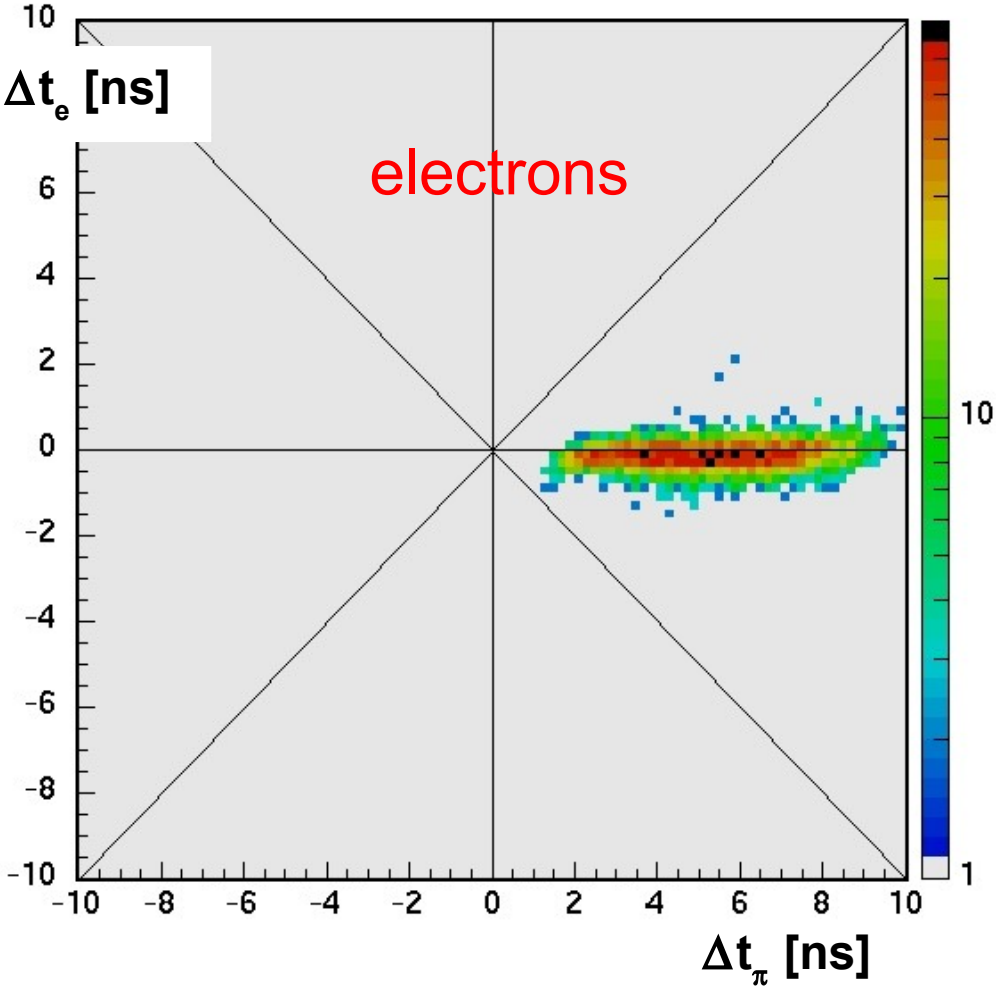
Also look for kink (i.e. decay)

Extrapolation to EMC using Spadaro's libraries

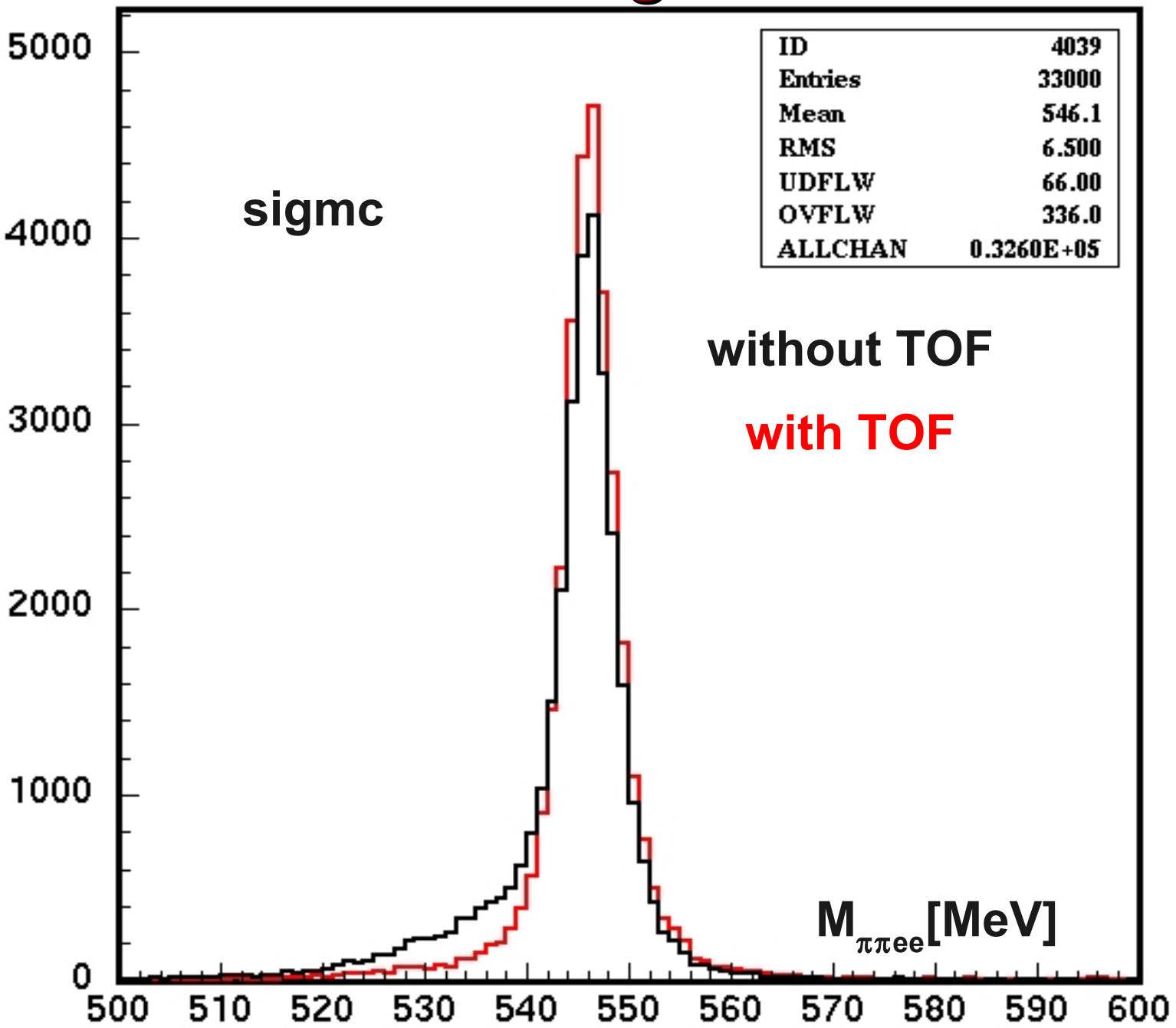
PID using TOF

Can be very powerful

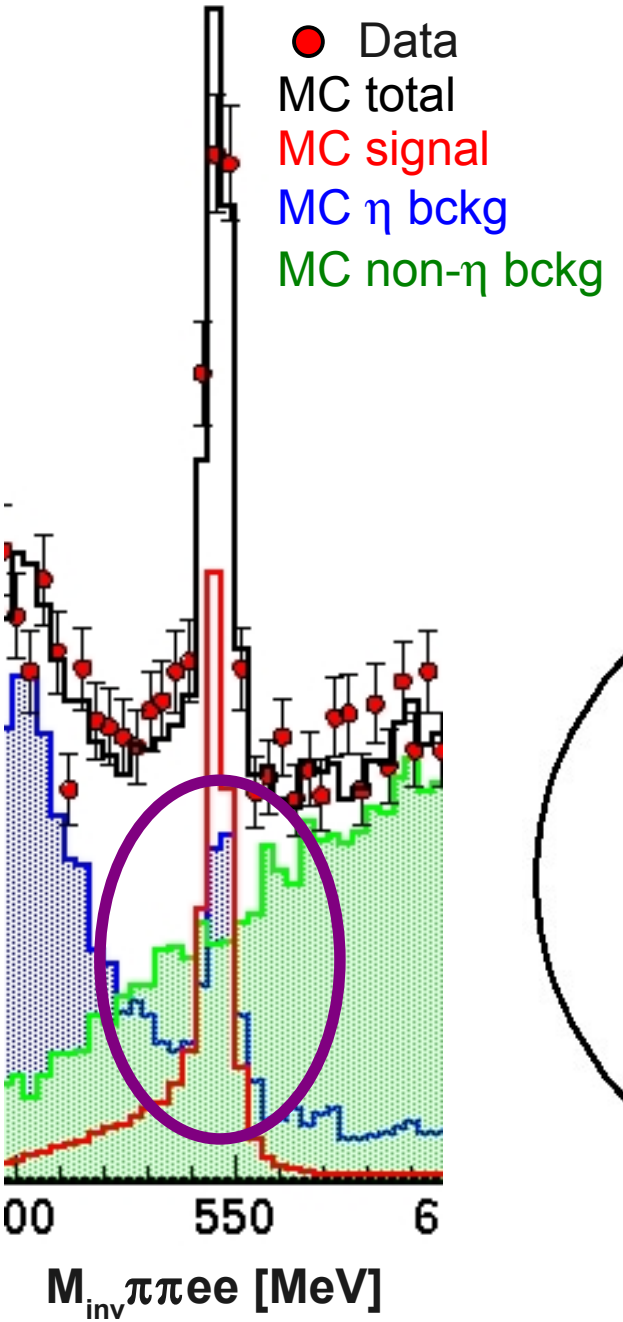




PID using TOF

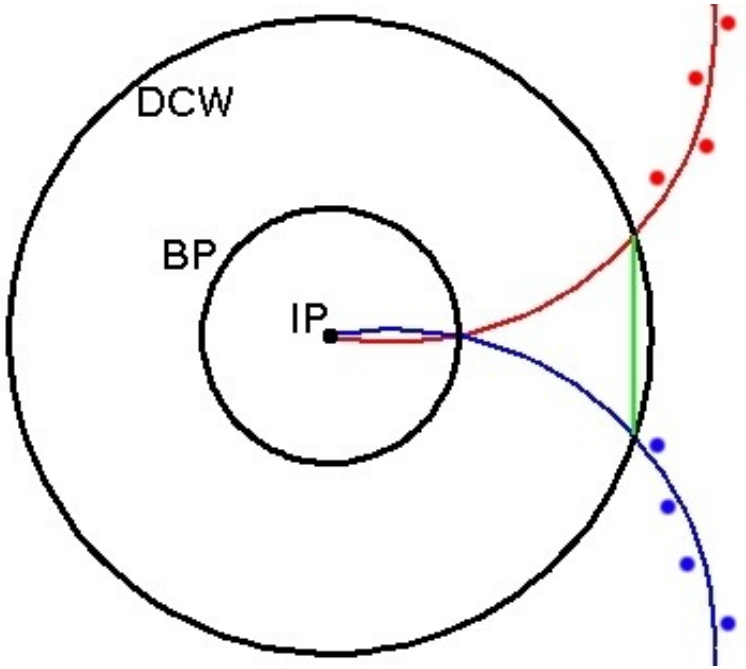


Background rejection - step 4



There is a background having the same signature of $\eta \to \pi\pi ee$

It is mainly due to photon conversion on the BP in $\eta \to \pi\pi\gamma$ events

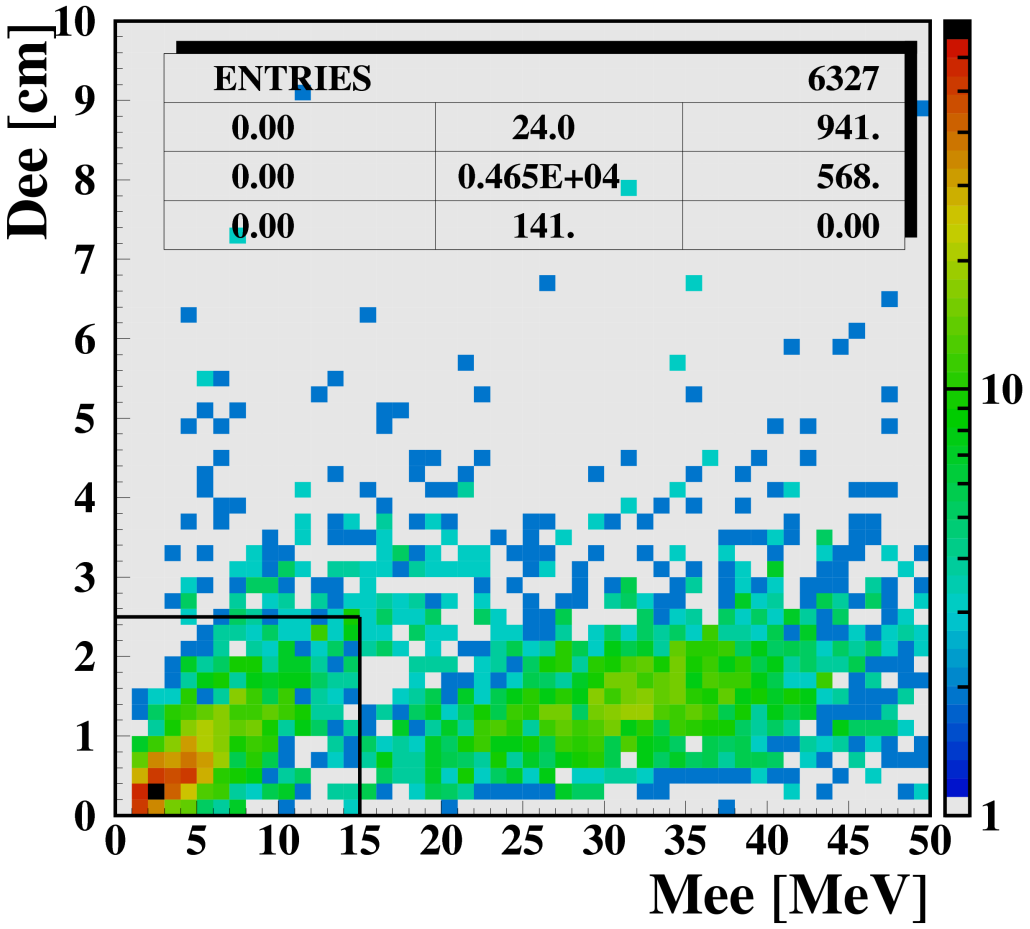


Disentangle using $M_{inv}(e^+e^-)$ and $Dist(e^+e^-)$ Should be zero at the conversion

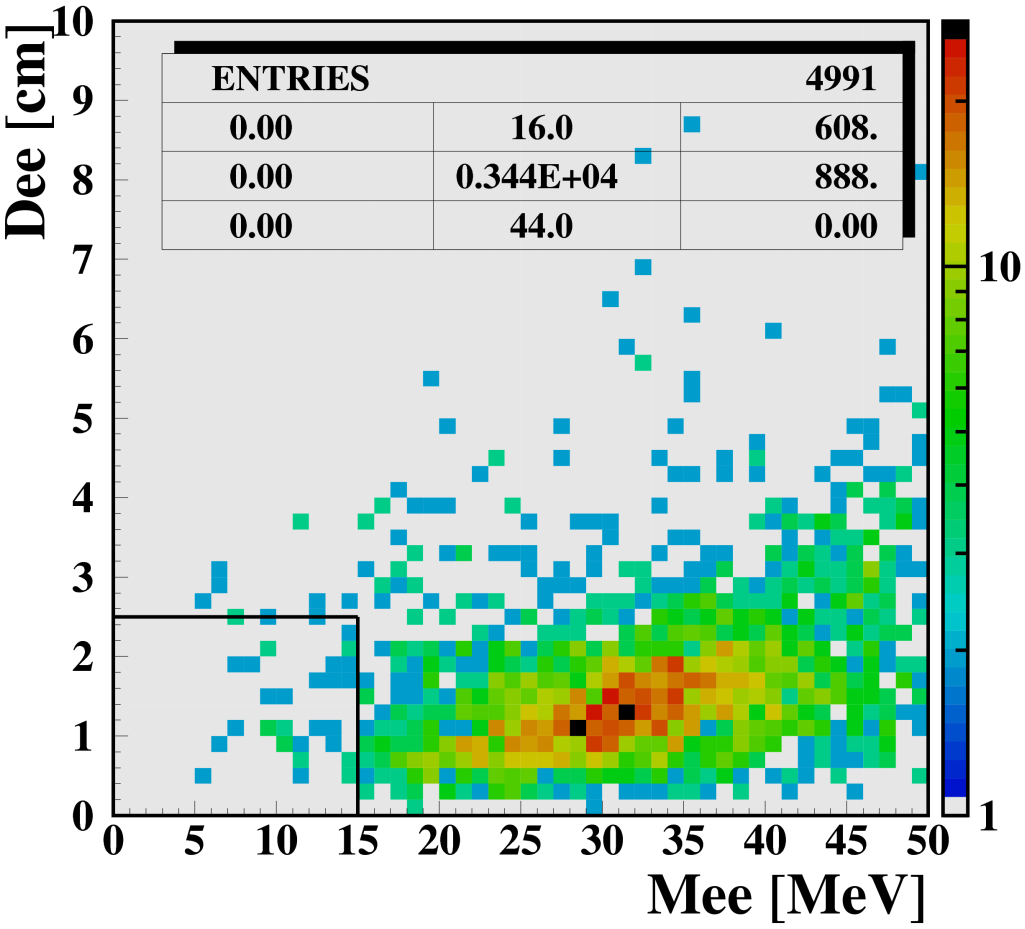
Background rejection - step 4

Mee@BP > 15 MeV .or. Dee@BP > 2.5 cm

Backgrounds

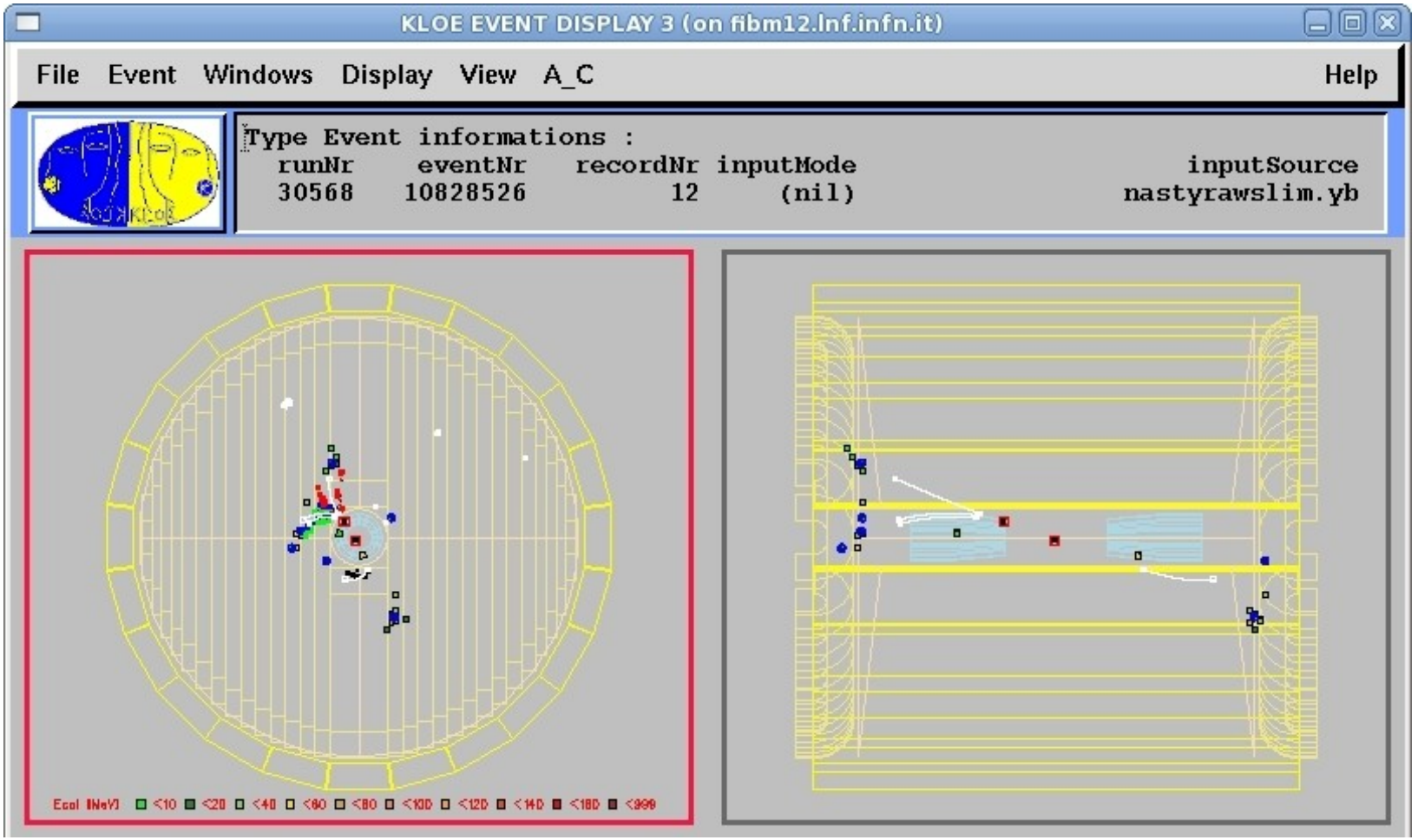


Signal



Background rejection - step 5

$$\langle \cos\theta_f \rangle < 0.85 \ .\text{and.} \ \langle \cos\theta_b \rangle > -0.85$$



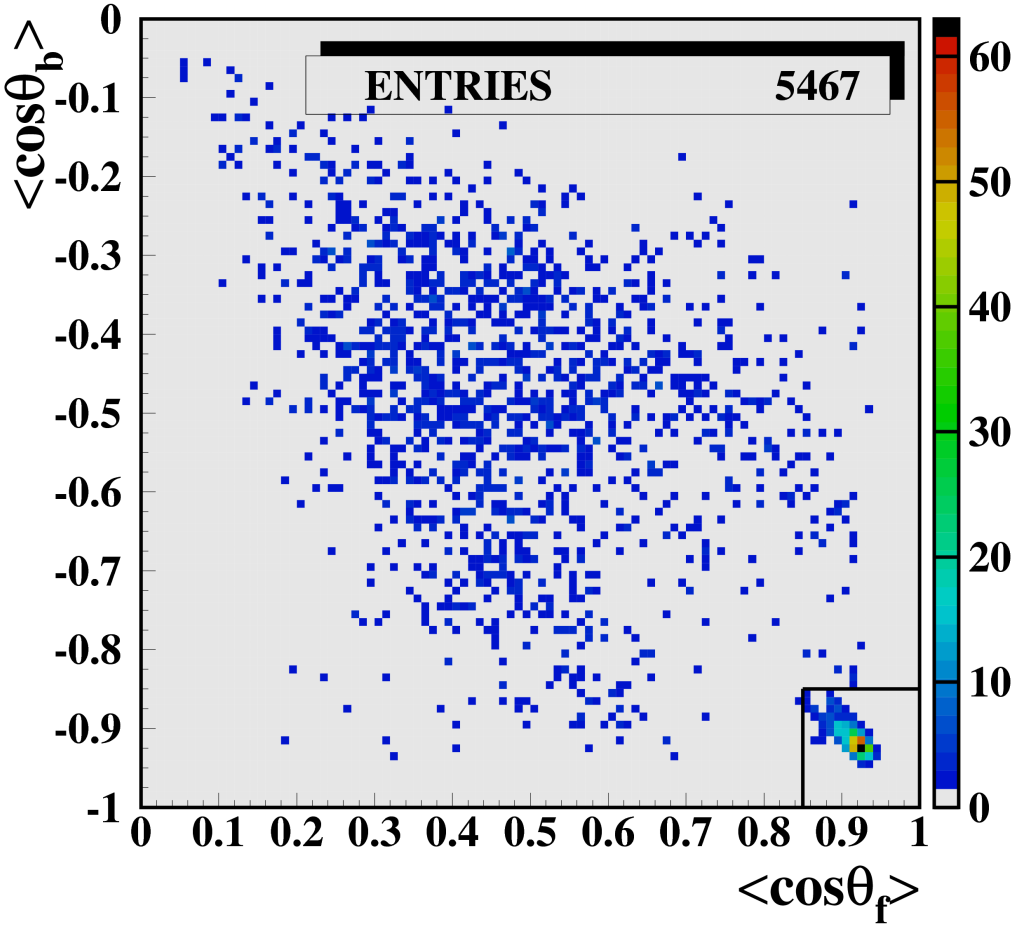
Small angle tracks

A particle hits something in the BP producing two more particles

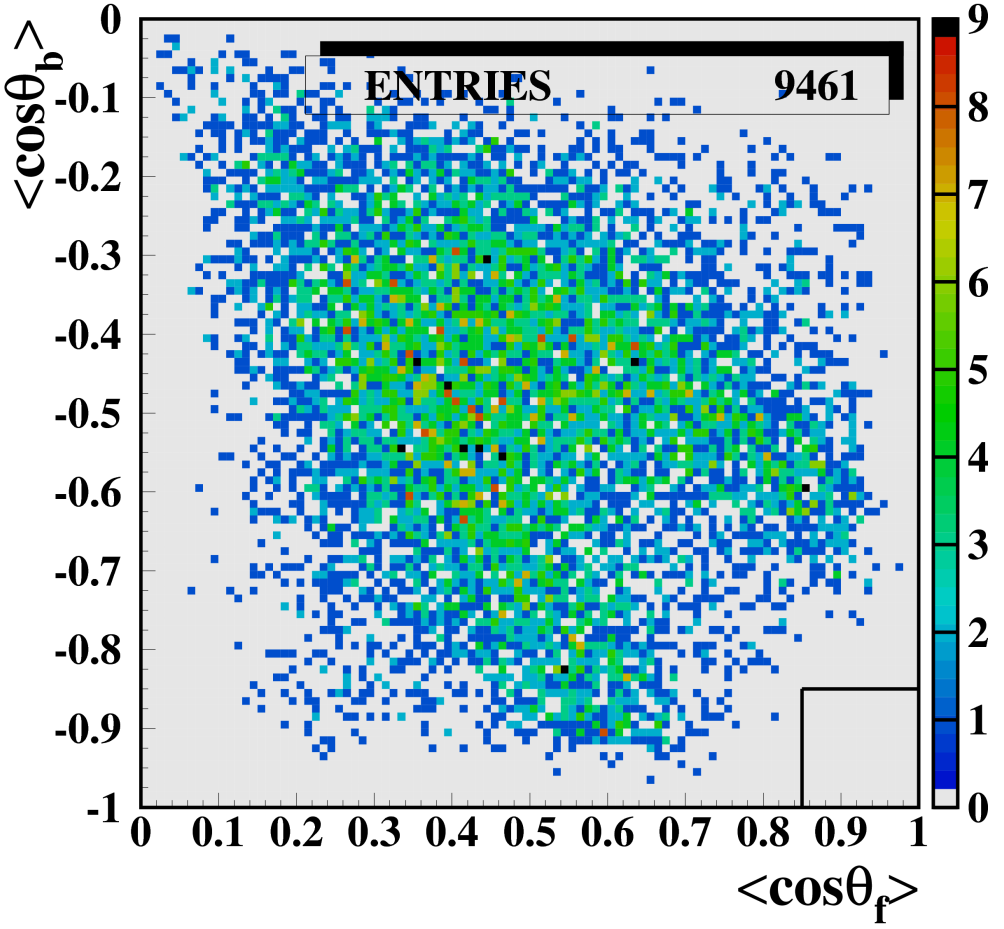
Background rejection - step 5

$\langle\cos\theta_f\rangle < 0.85$ .and. $\langle\cos\theta_b\rangle > -0.85$

Data



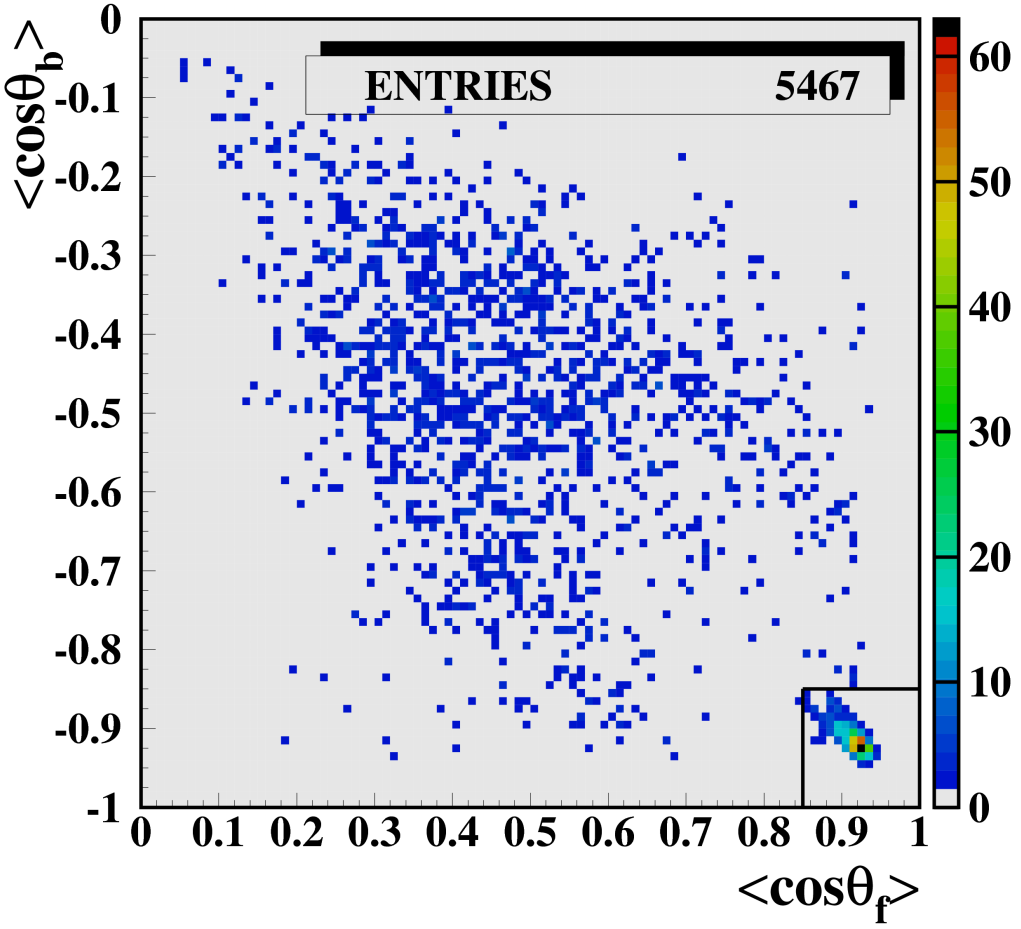
MC all_phys



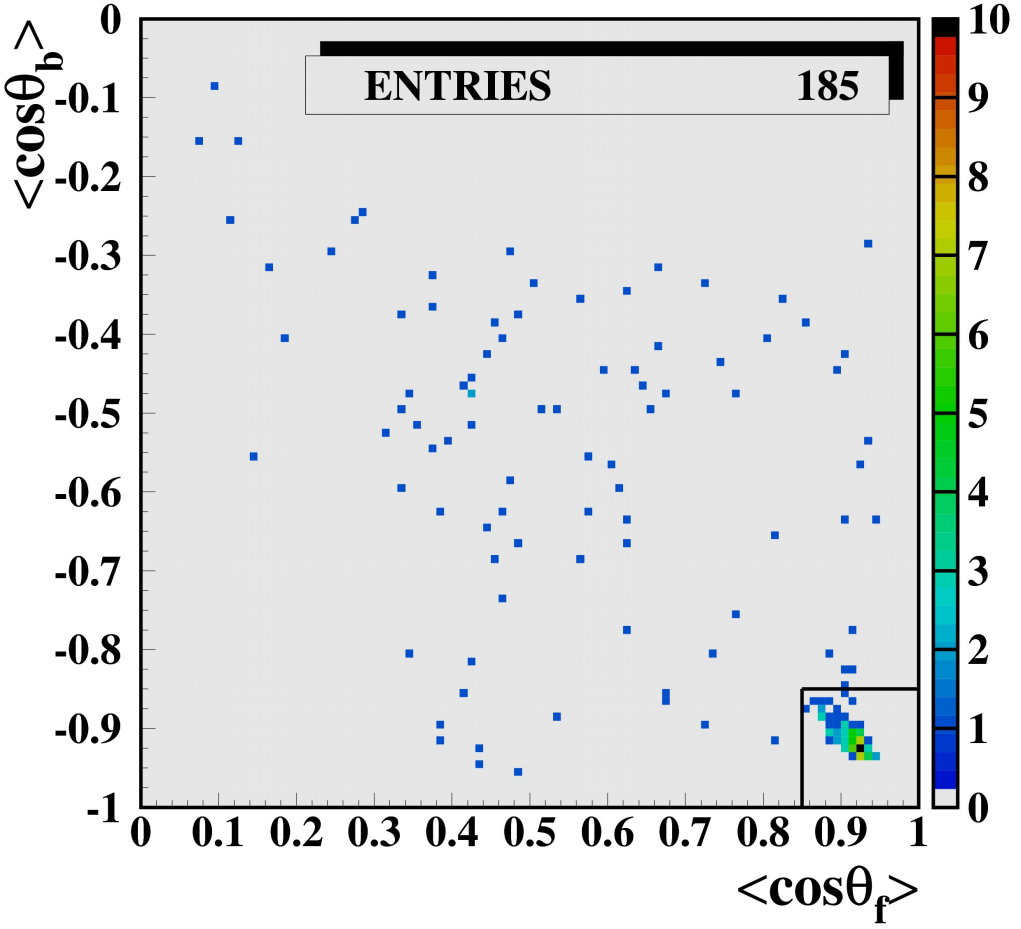
Background rejection - step 5

$\langle\cos\theta_f\rangle < 0.85$ .and. $\langle\cos\theta_b\rangle > -0.85$

Data



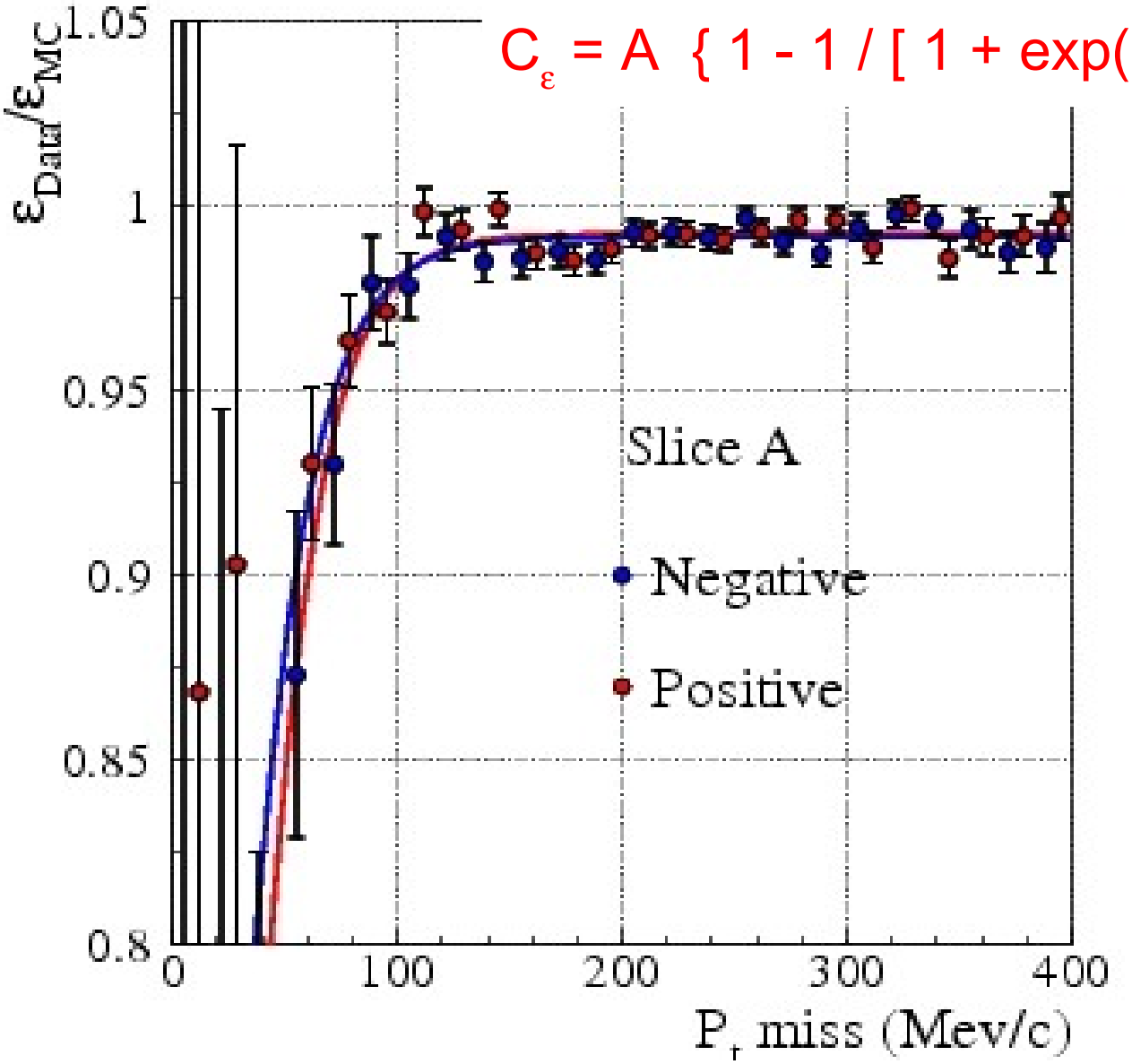
Off-peak data



Tracking efficiency

using ρπ sample work done together with A. De Santis

$C_\varepsilon = A \{ 1 - 1 / [1 + \exp((X-X_0)/\delta)] \}$



KLOE Memo 343

The correction 0(1%) is applied to any track before track selection as (P_t-P_z) function

Procedure review

1. **EVCL** ETA4CTAG
2. **Momenta** 450 < s4p < 600 MeV `.and.` 270 < s2p < 460 MeV
3. **χ^2** $\chi^2 < 4000$

At this level we perform the fit to get the scale factors

4. **Conversions** Mee > 15 MeV `.or.` Dee > 2.5 cm (@BP)
5. **Low θ** $\langle\cos\theta_f\rangle < 0.85$ `.and.` $\langle\cos\theta_b\rangle > -0.85$
6. **$M_{\pi\pi ee}$** $535 < M_{\pi\pi ee} < 555$ MeV

At this level we count

Fit description

- Stand alone program using HBOOK and MINUIT
- Fit performed on sidebands:

  [420.,530.] MeV U [560.,680.] MeV
- Components used:

  MC `all_phys` and off-peak data
- Off-peak data scale factor fixed using luminosity

  because of its small statistics

  $SF_{offpeak} = L_{data} / L_{offpeak} = 7.14$

  $\sqrt{s}$ has been accounted for

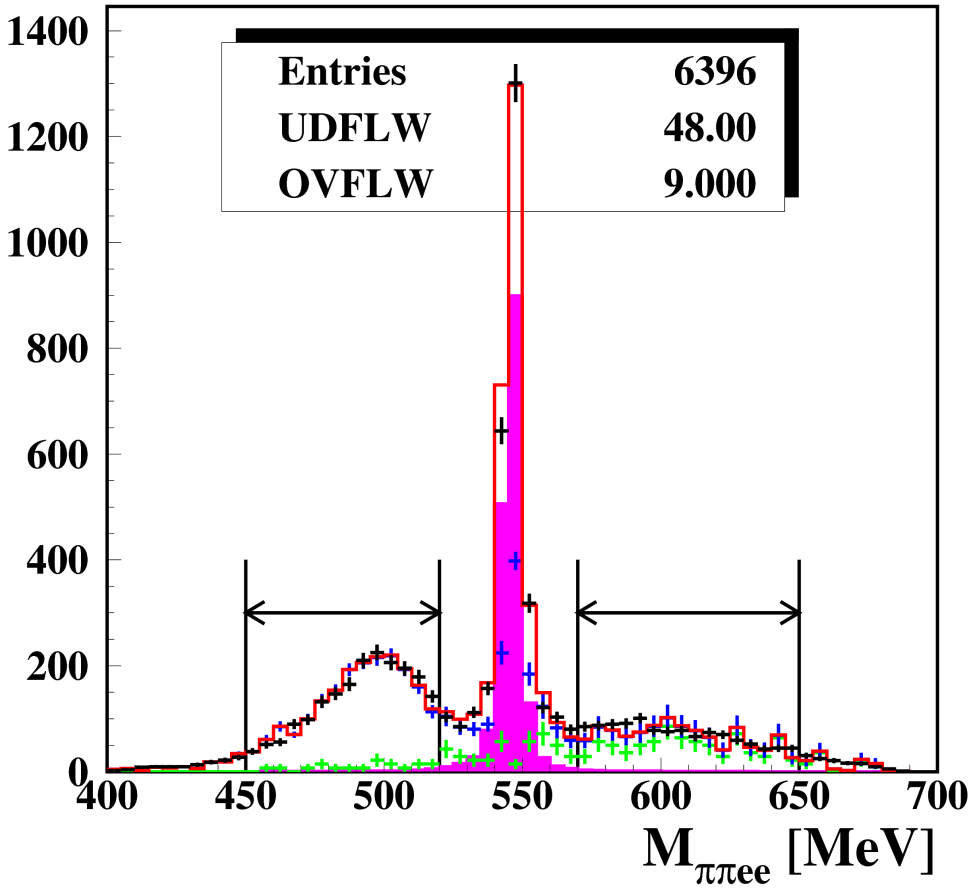
Fit result

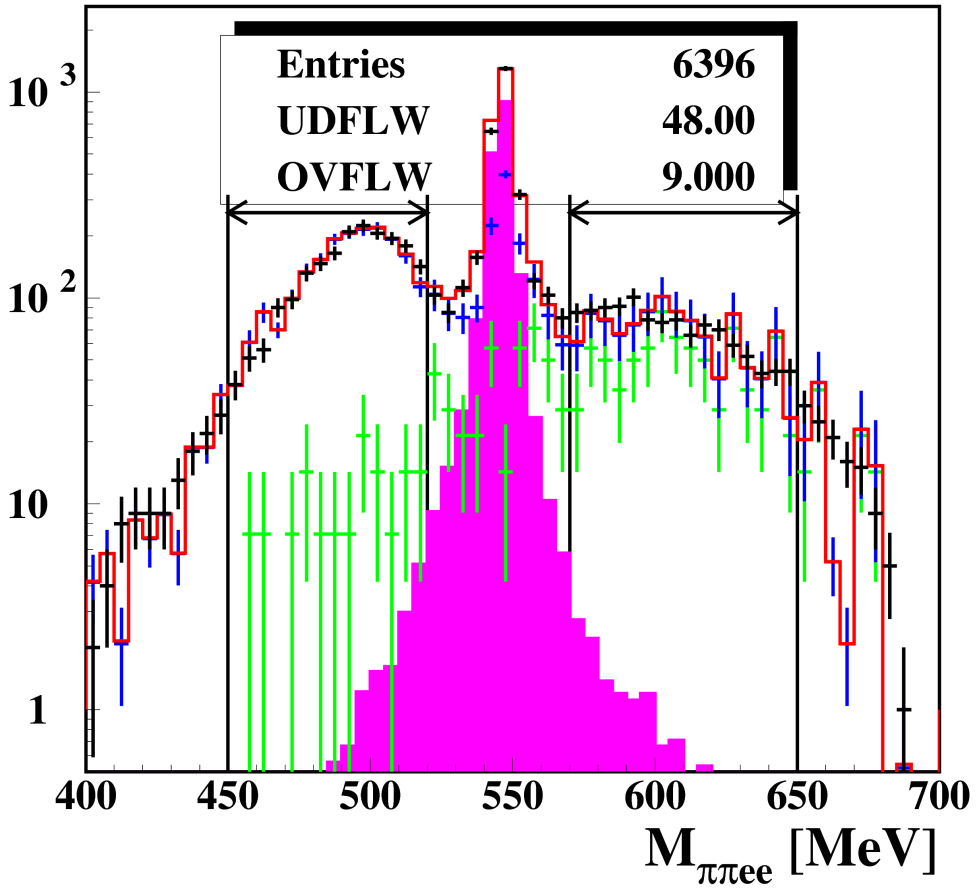
Data
Total
MC `all_phys`
Off-peak data
Signal MC

χ^2/dof = 32.1/30 $P(\chi^2)$ = 0.36

SF_{ap} = 0.522 ± 0.018

SF_{op} = 7.14 ± 0.03





Signal SF = N_{ev} (data-bck) / N_{ev} (signal MC)

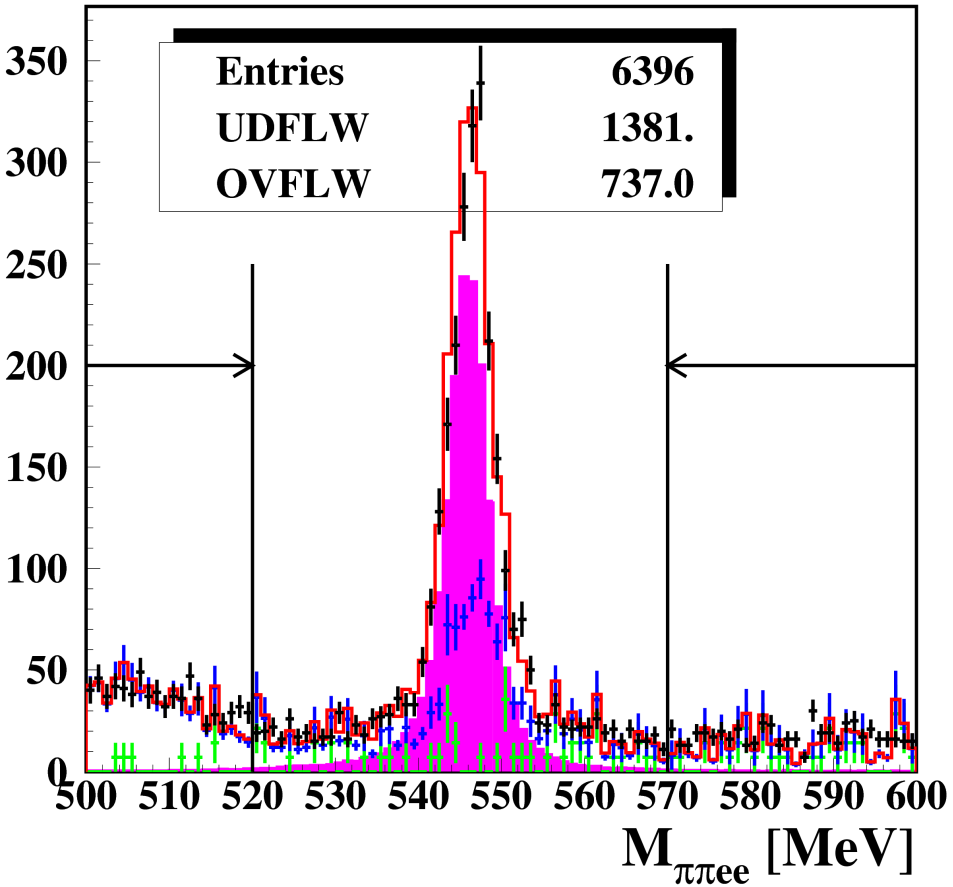
Fit result

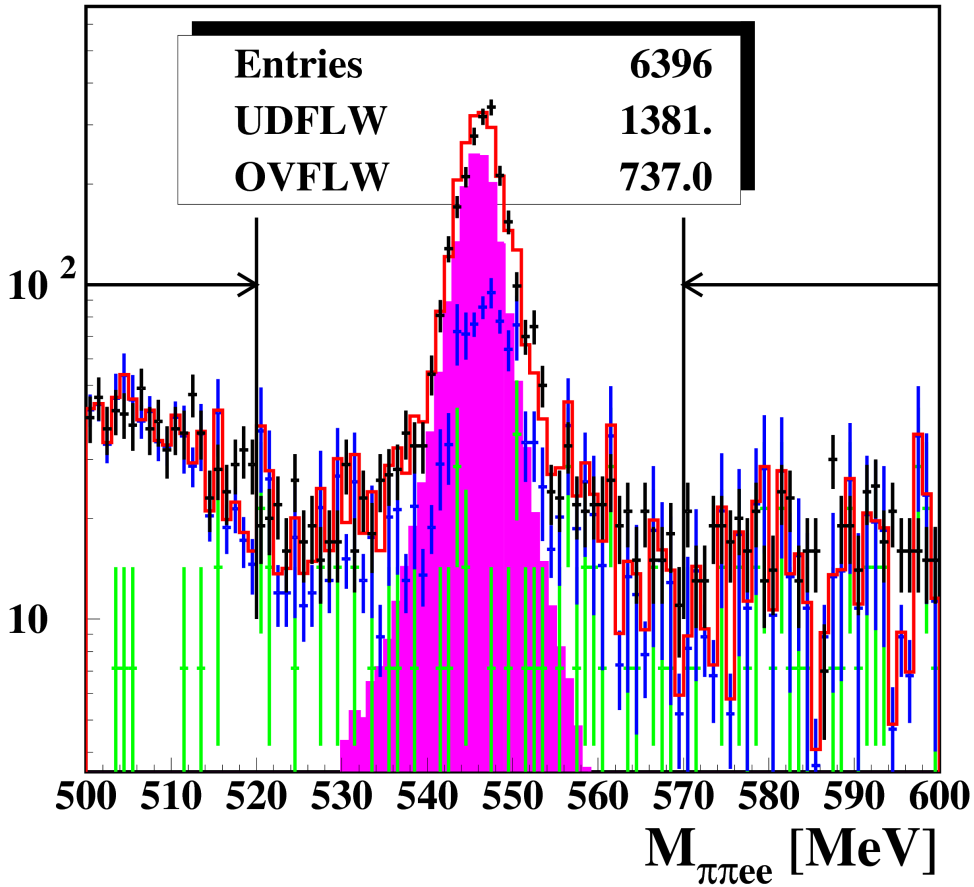
Data
Total
MC `all_phys`
Off-peak data
Signal MC

χ^2/dof = 32.1/30 P(χ^2) = 0.36

SF_{ap} = 0.522 ± 0.018

SF_{op} = 7.14 ± 0.03

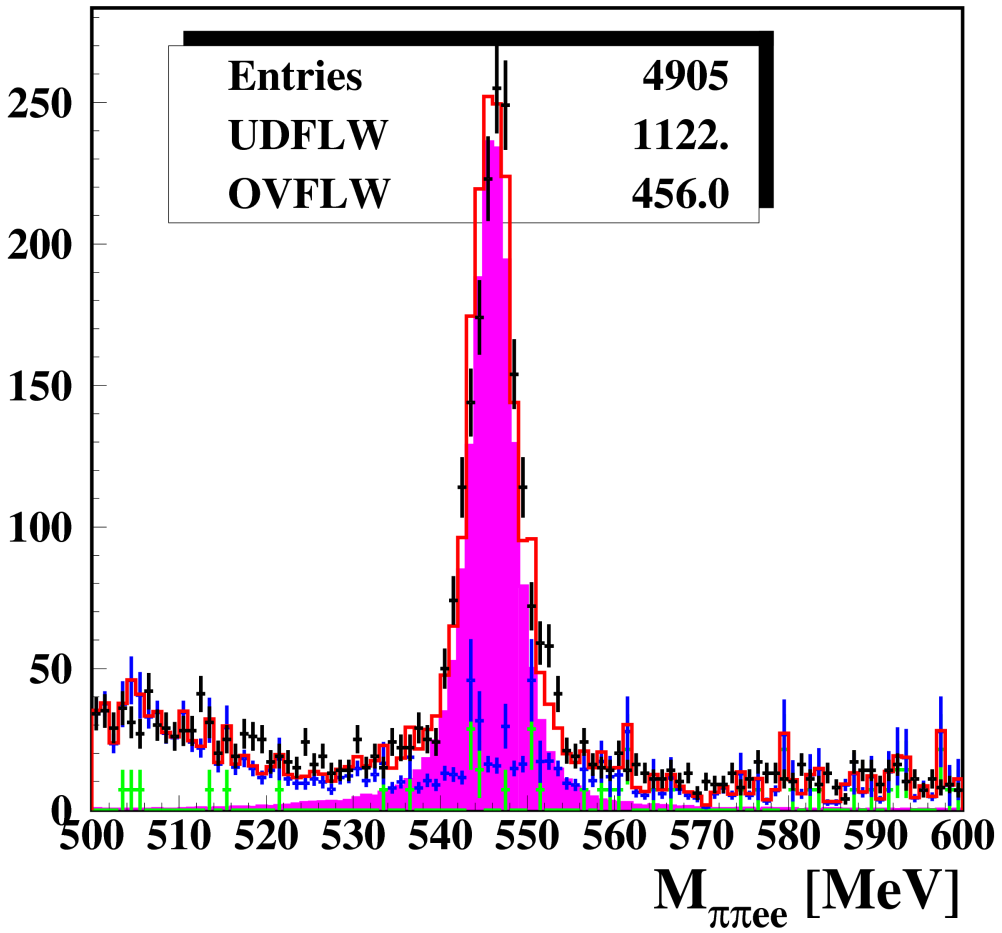


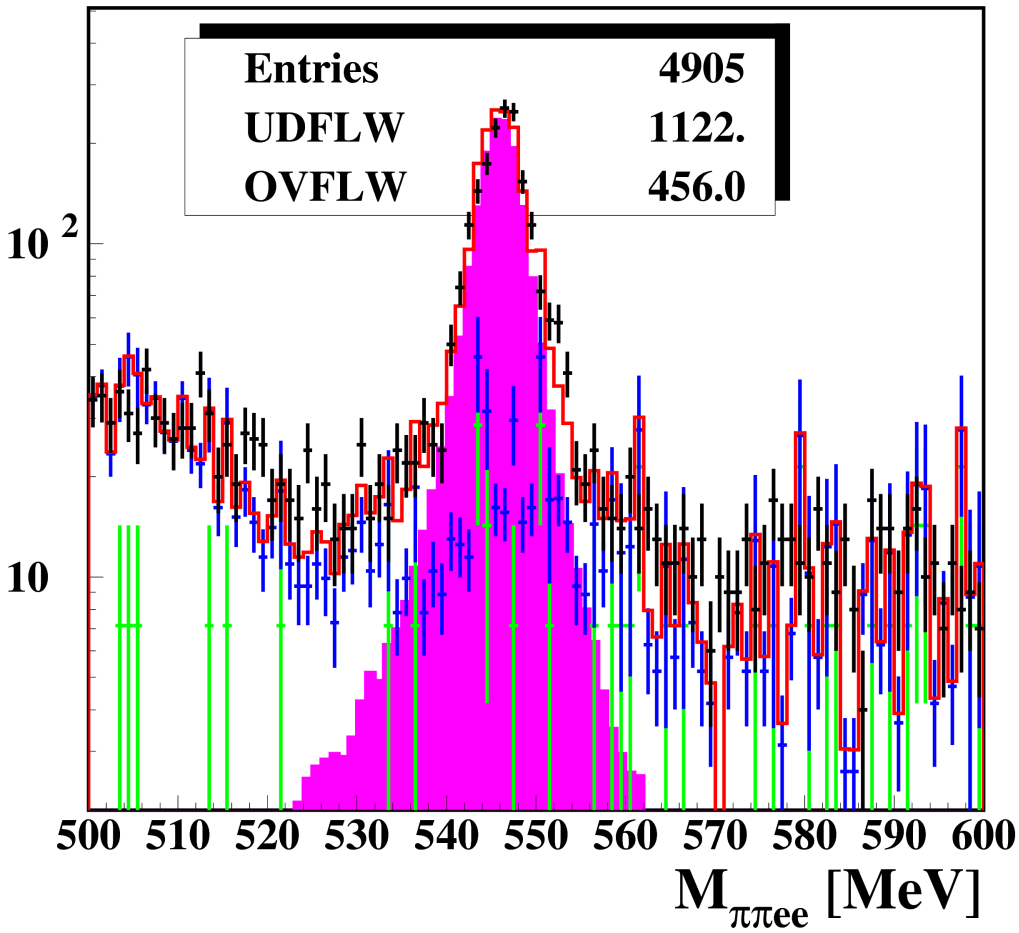


Signal SF = N_{ev} (data-bck) / N_{ev} (signal MC)

Data-MC comparison

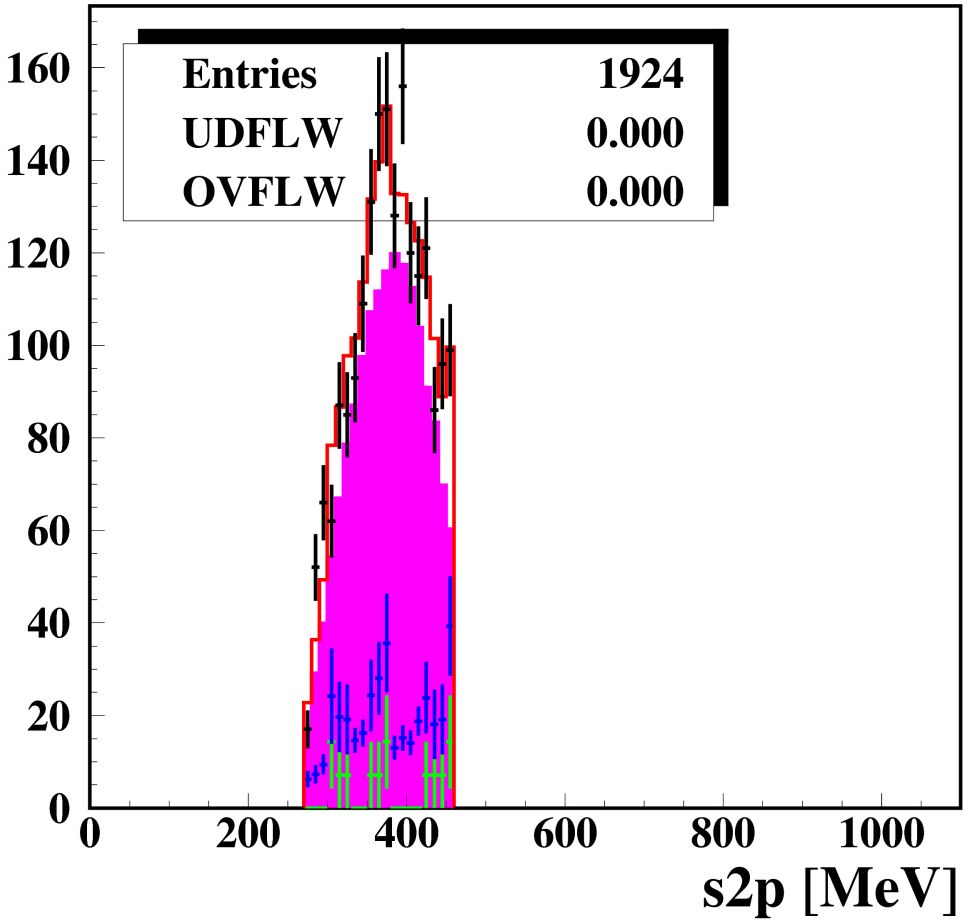
Data
Total
MC `all_phys`
Off-peak data
Signal MC

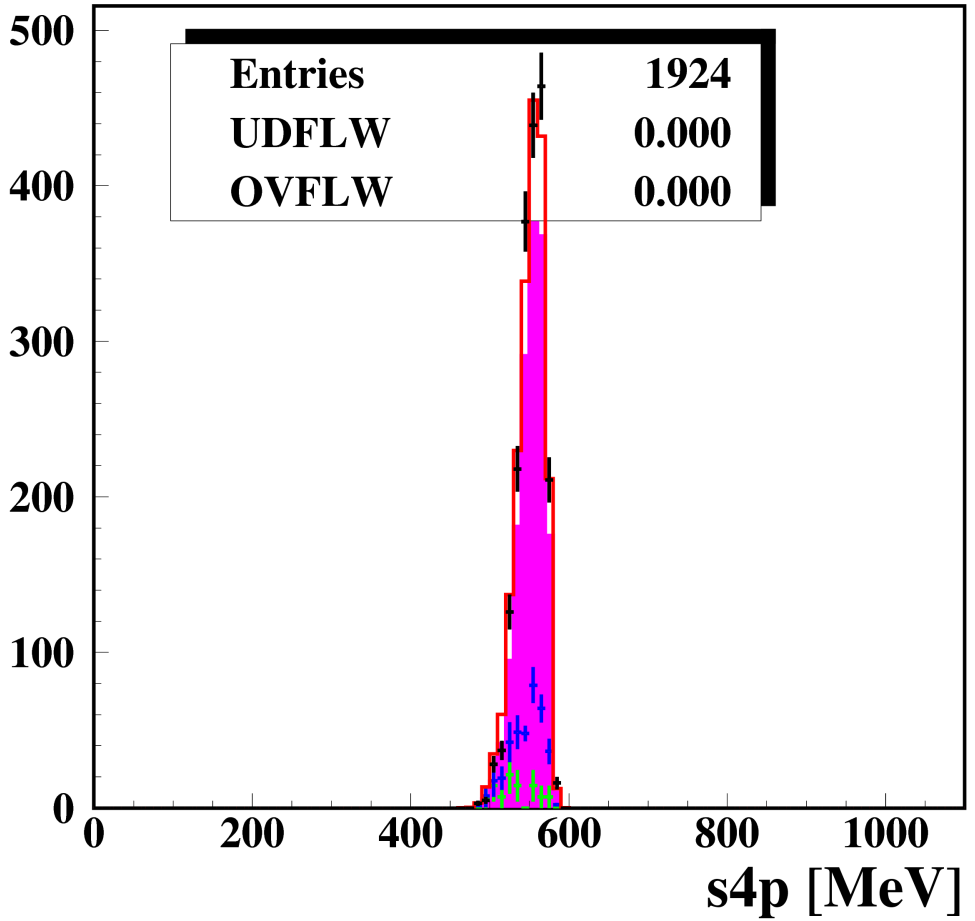




Data-MC comparison

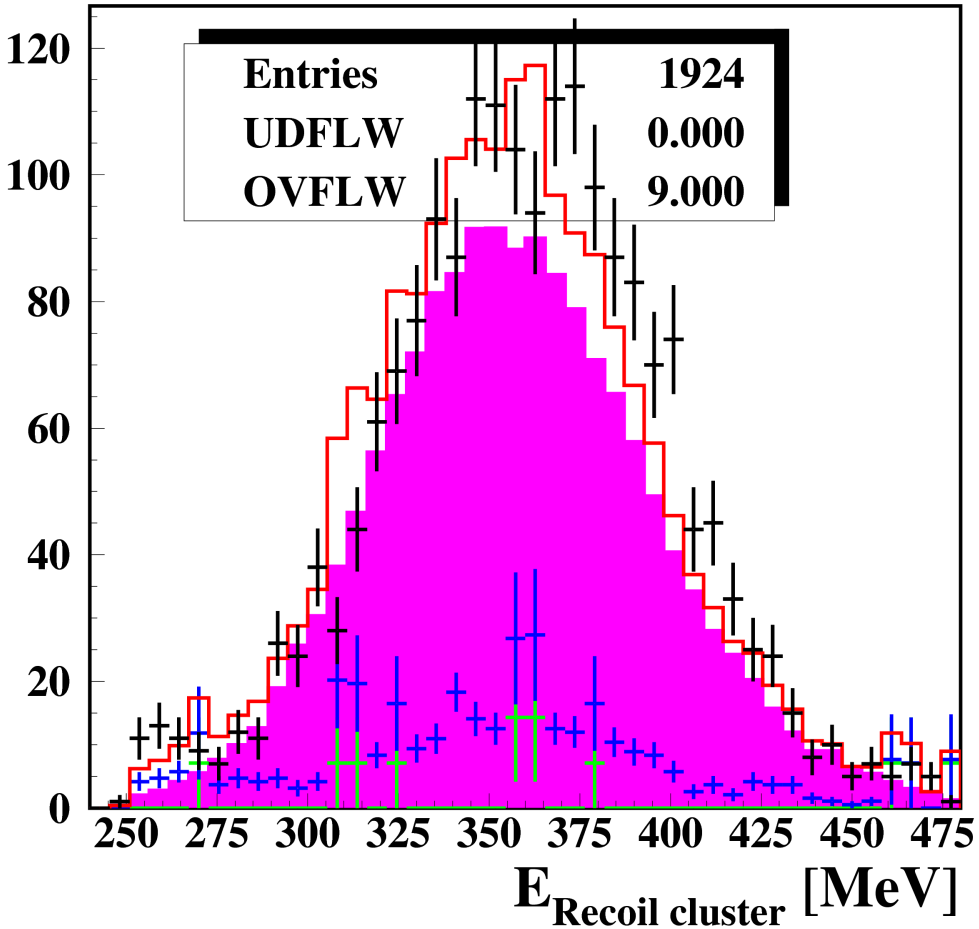
Data
Total
MC `all_phys`
Off-peak data
Signal MC

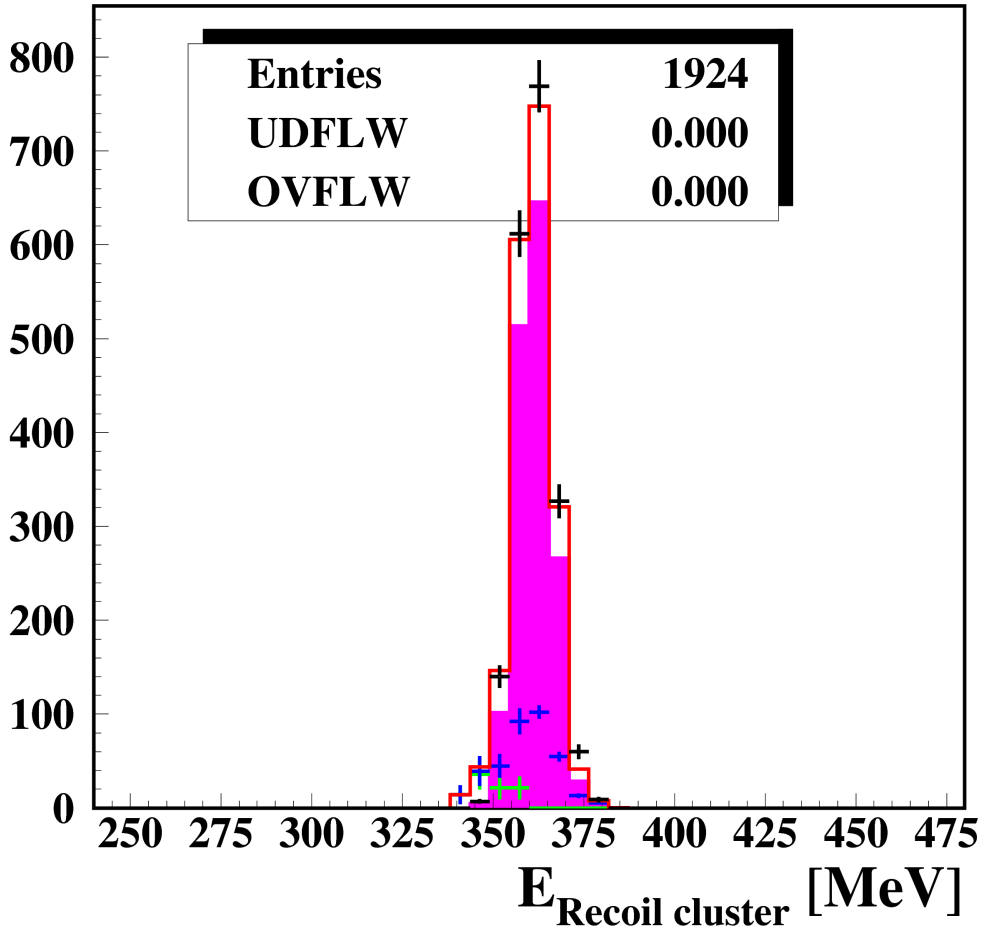




Data-MC comparison

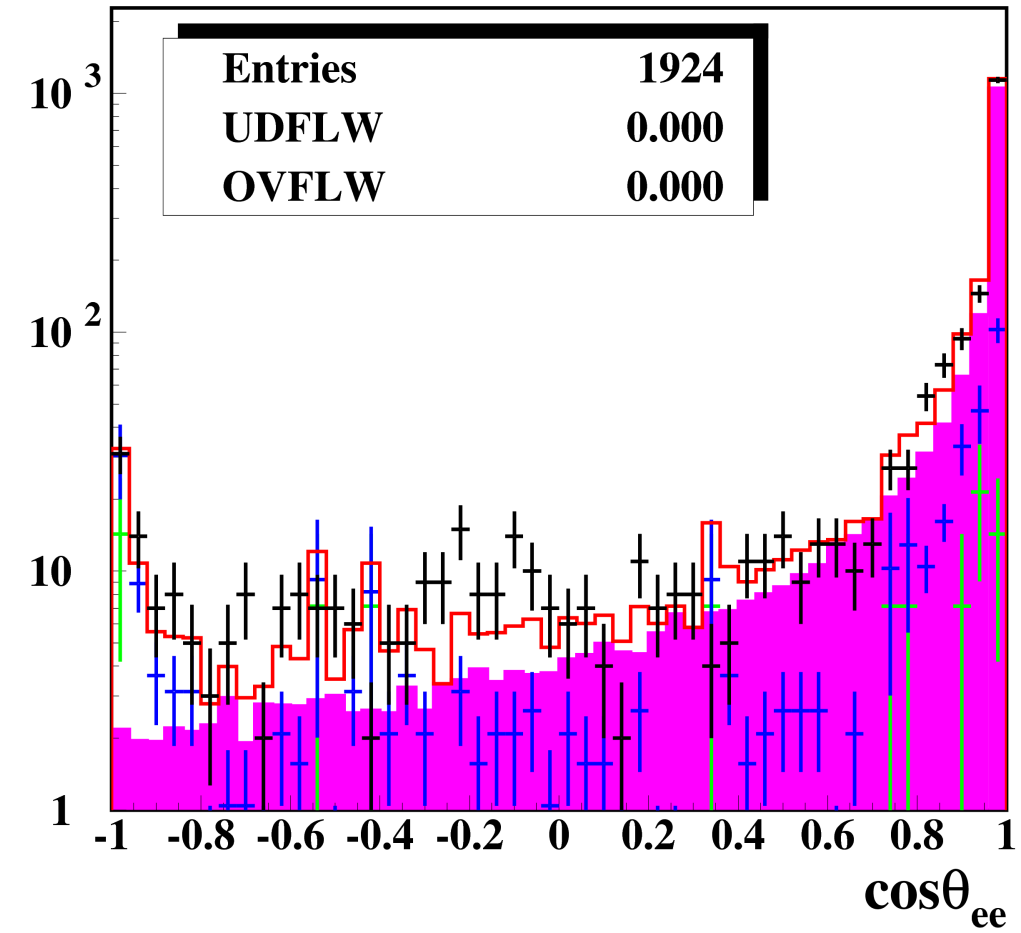
Data
Total
MC `all_phys`
Off-peak data
Signal MC

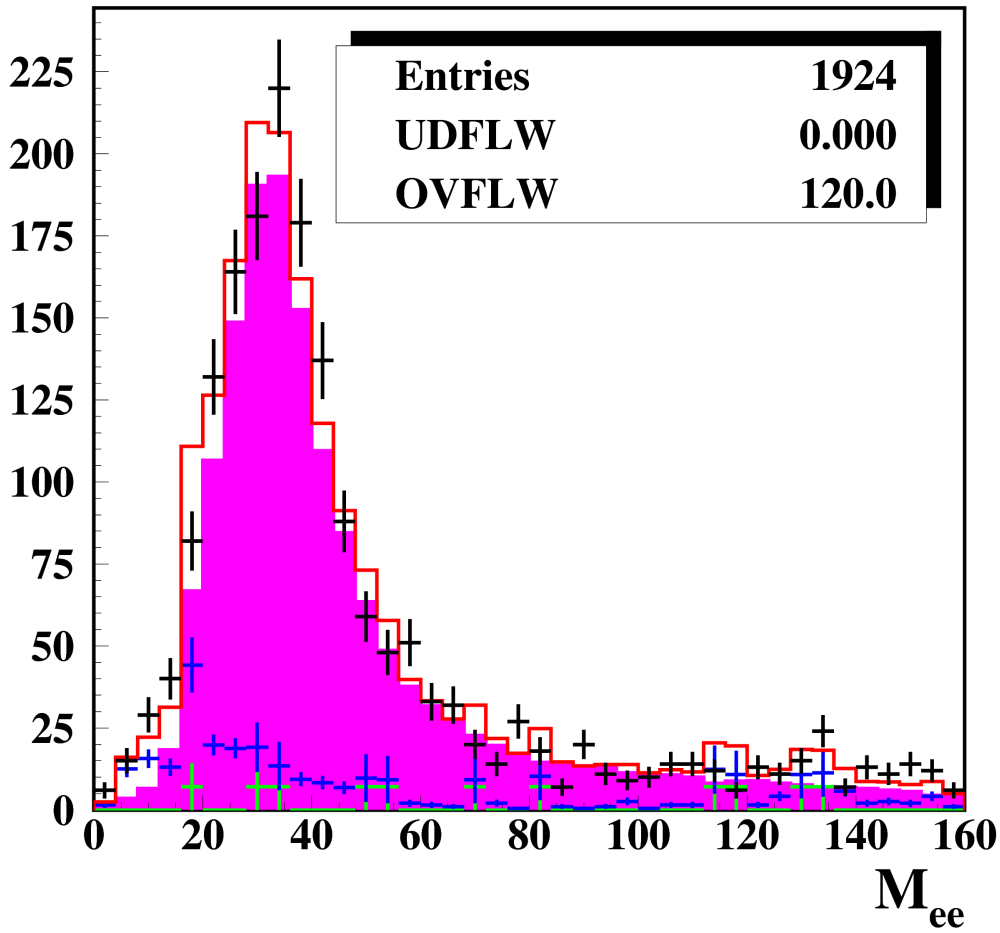




Data-MC comparison

Data
Total
MC `all_phys`
Off-peak data
Signal MC



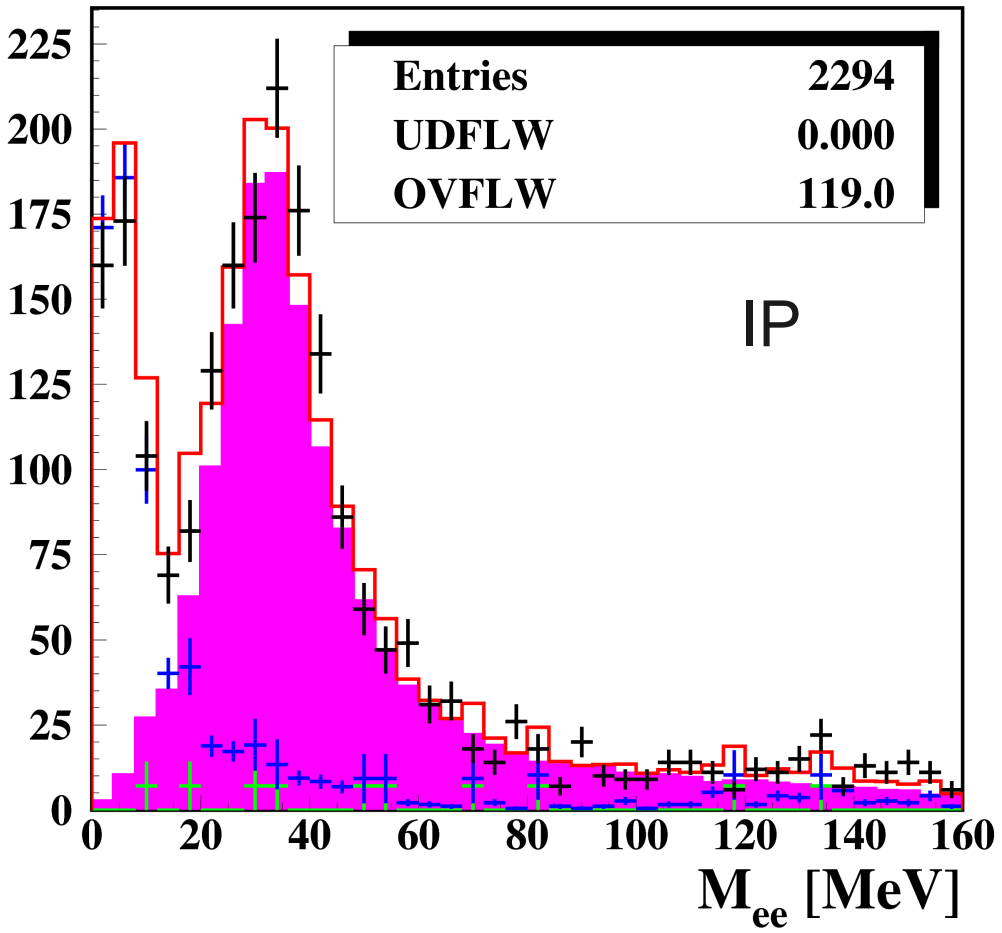


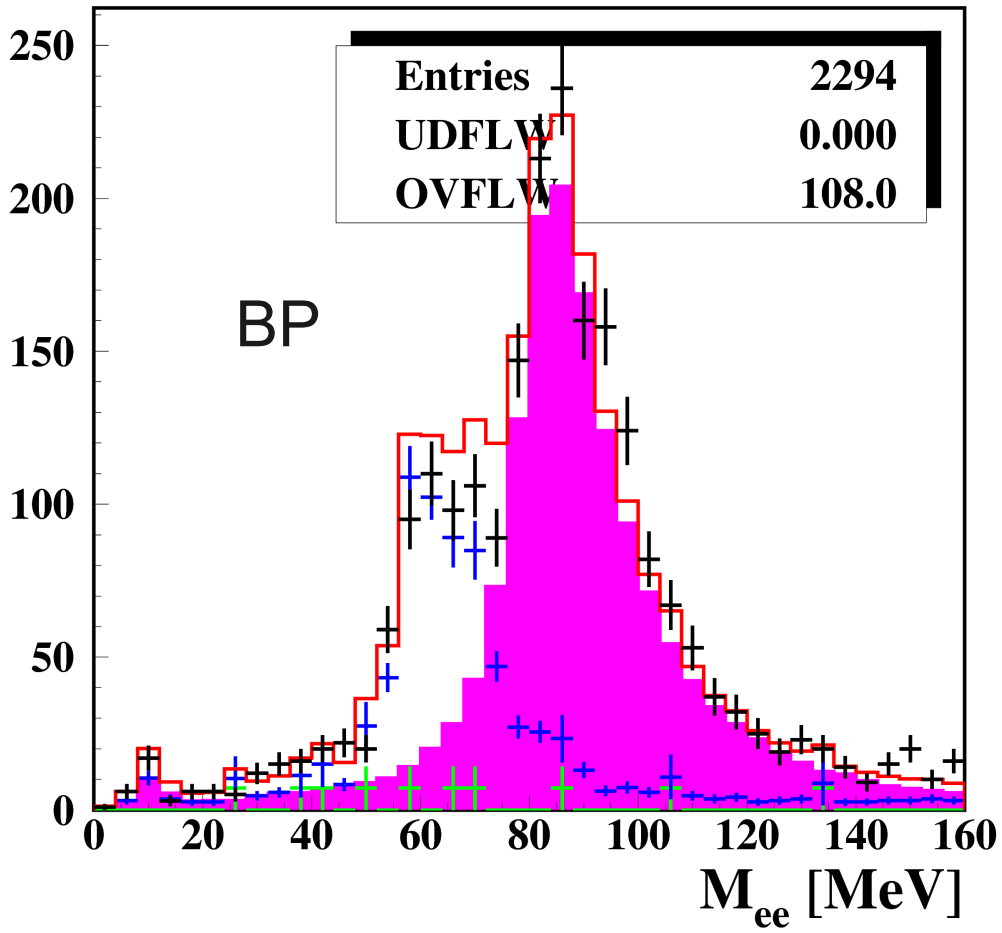
Data-MC comparison

Data
Total
MC `all_phys`
Off-peak data
Signal MC

Removing the cut on Mee

Under the η peak [535,555] MeV





BR calculation

$$BR = N_{ev} \; / \; \varepsilon \, L \, \sigma_{\phi \to \eta\gamma}$$

Number of events	Luminosity
1558 ± 56	(1734 ± 10) pb^{-1}
Efficiency	Cross section
0.0835 ± 0.0003	(41.7 ± 0.6) nb

$$BR(\eta \to \pi^+ \pi^- e^+ e^-) = (25.8 \pm 0.9_{Stat.} \pm 0.4_{Norm.}) \cdot 10^{-5}$$

Systematics

Evaluated varying:

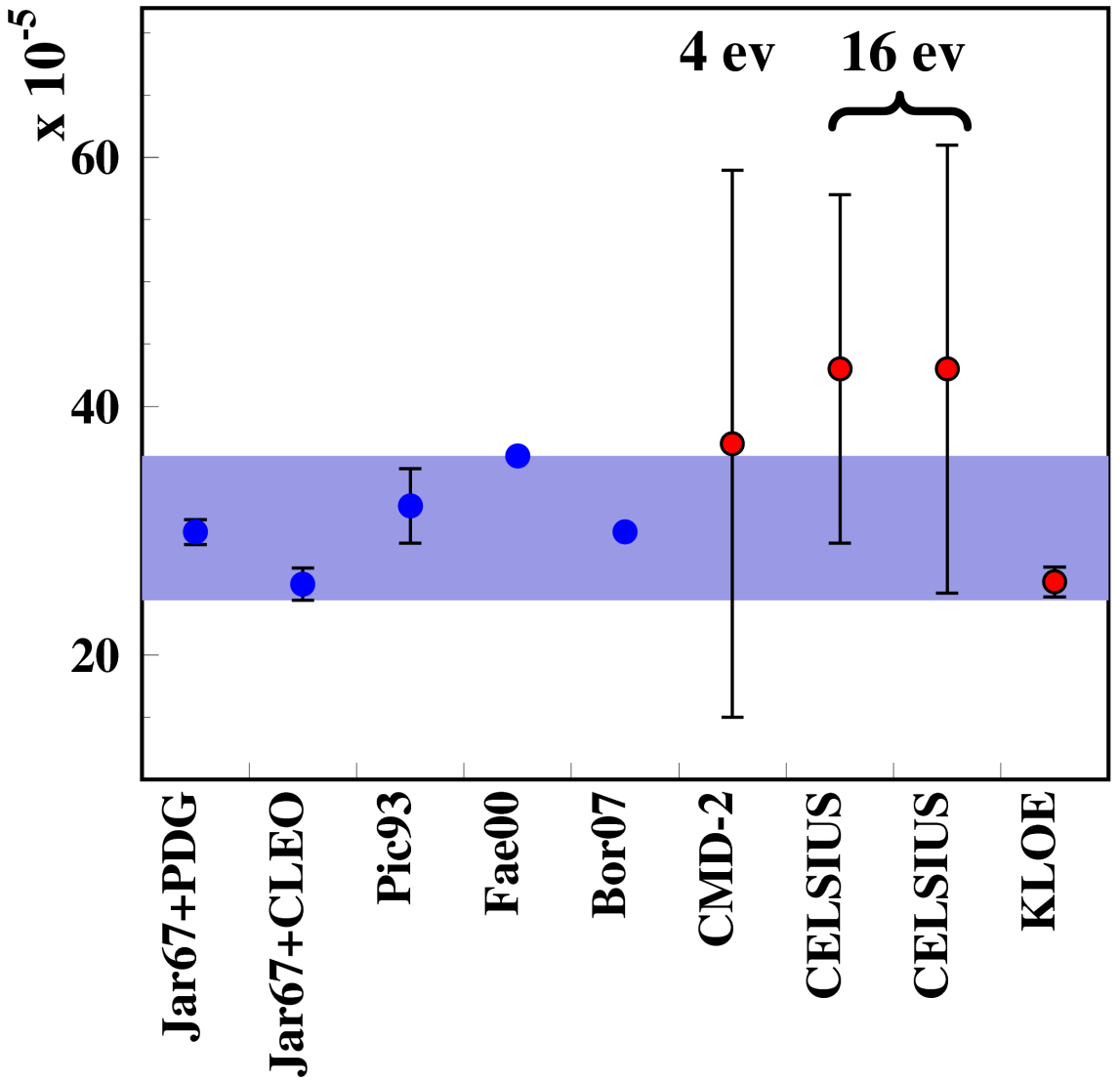
• sidebands range	$0.04 \cdot 10^{-5}$	
• histogram binning	$0.02 \cdot 10^{-5}$	
• analysis cuts $\pm 3\sigma$	$0.55 \cdot 10^{-5}$	
• SF free/fix with luminosity	$0.29 \cdot 10^{-5}$	**$0.62 \cdot 10^{-5}$**

Analysis cuts:

• χ^2	$0.14 \cdot 10^{-5}$	
• Dee	$0.03 \cdot 10^{-5}$	
• Mee	$0.45 \cdot 10^{-5}$	
• s2p	$0.22 \cdot 10^{-5}$	
• s4p	$0.01 \cdot 10^{-5}$	
• $M\pi\pi ee$	$0.18 \cdot 10^{-5}$	
• low θ	$0.02 \cdot 10^{-5}$	**$0.55 \cdot 10^{-5}$**

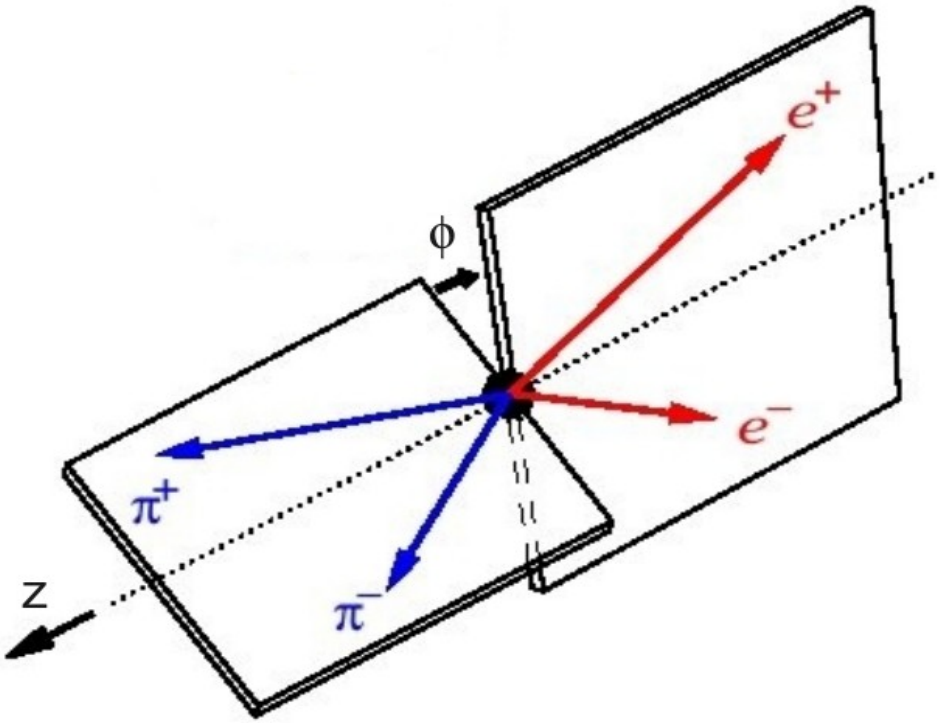
BR calculation

$$BR(\eta \to \pi^+ \pi^- e^+ e^-) = (25.8 \pm 0.9_{Stat.} \pm 0.4_{Norm.} \pm 0.6_{Syst.}) \cdot 10^{-5}$$



Asymmetry

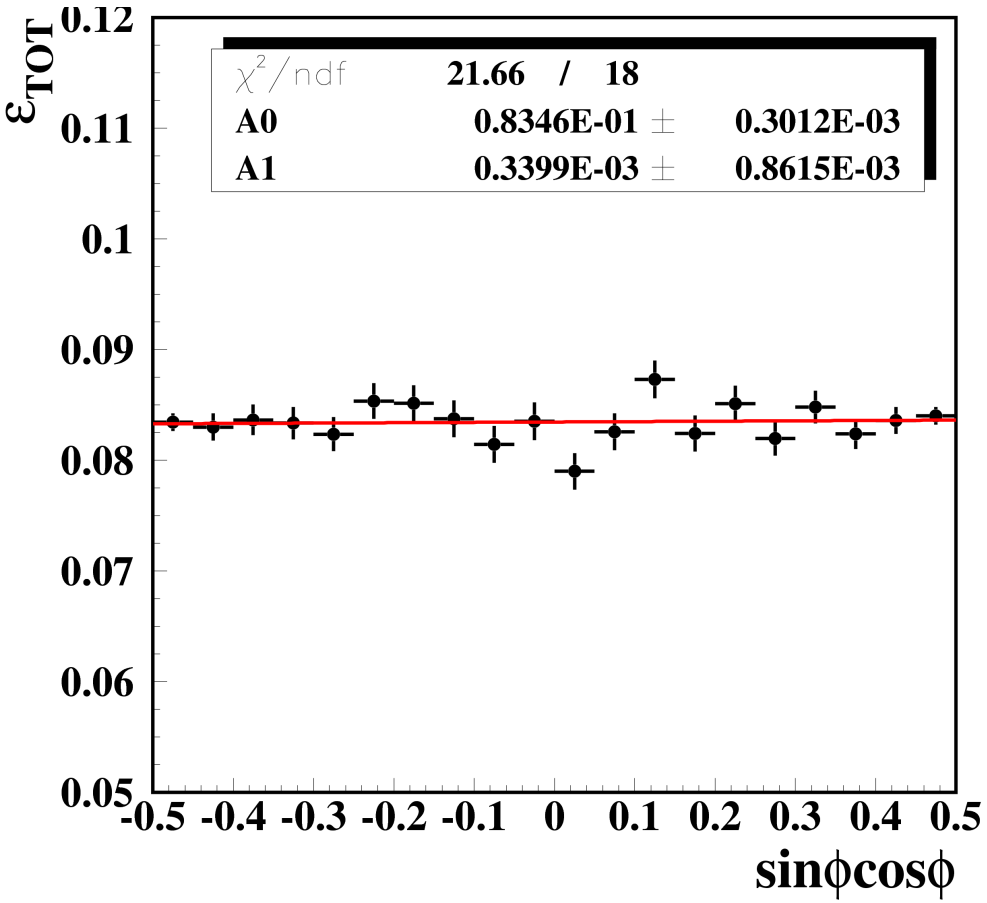
$$A_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$$



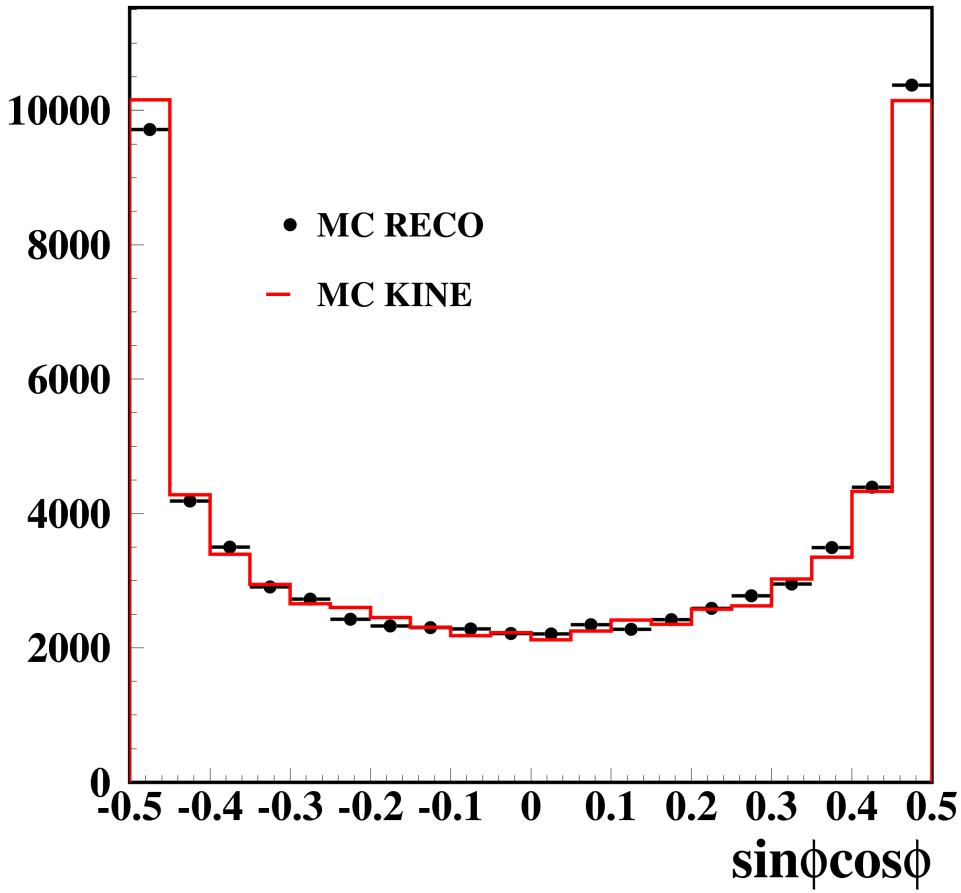
$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi})\hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

Asymmetry

Analysis does not distort the generated asymmetry

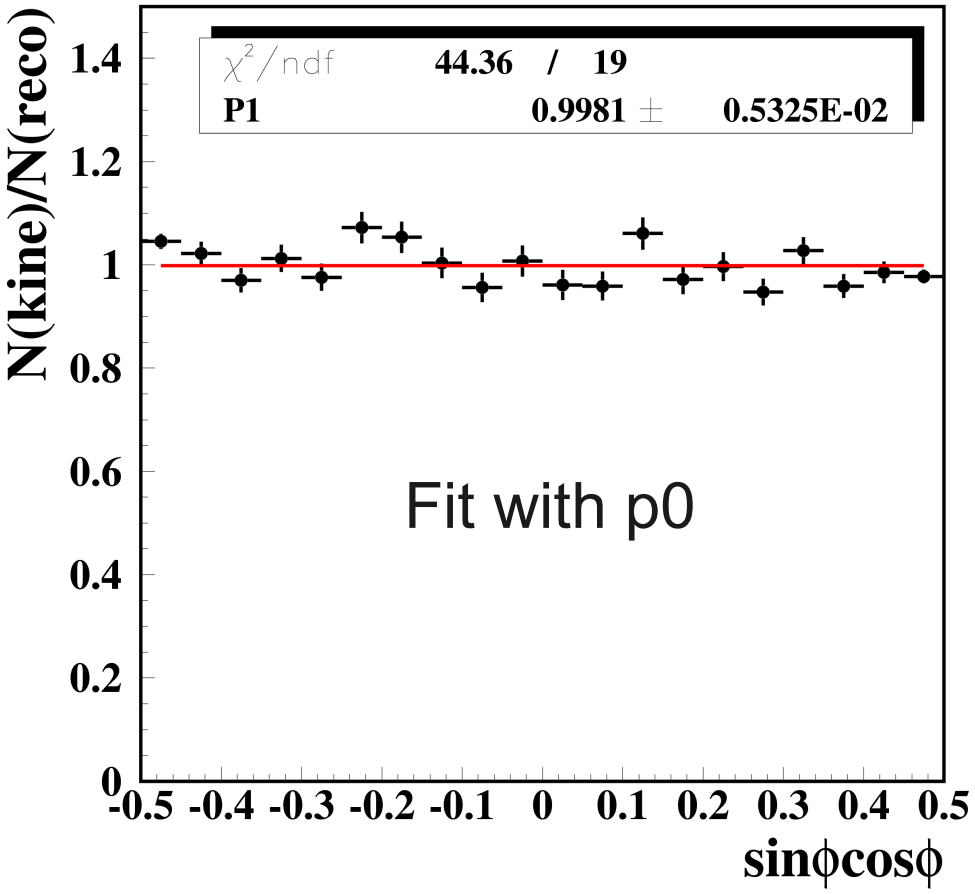


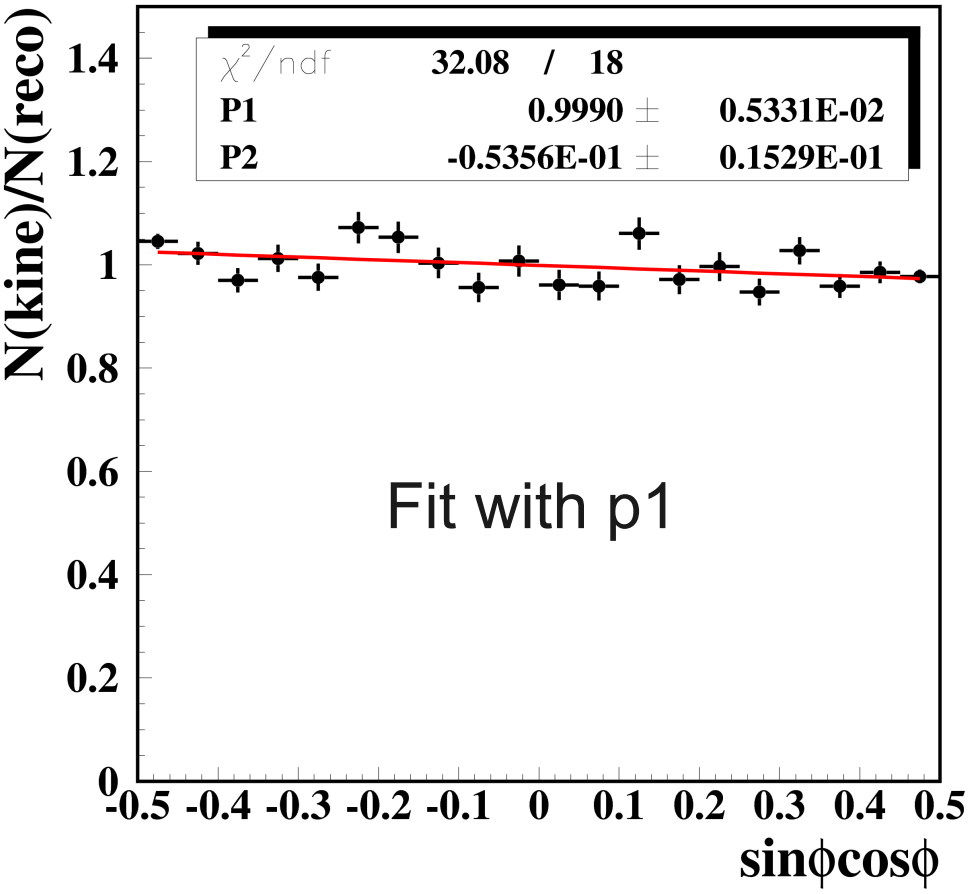
Reconstruction distorts the asymmetry



Asymmetry

Reconstruction distorts the asymmetry

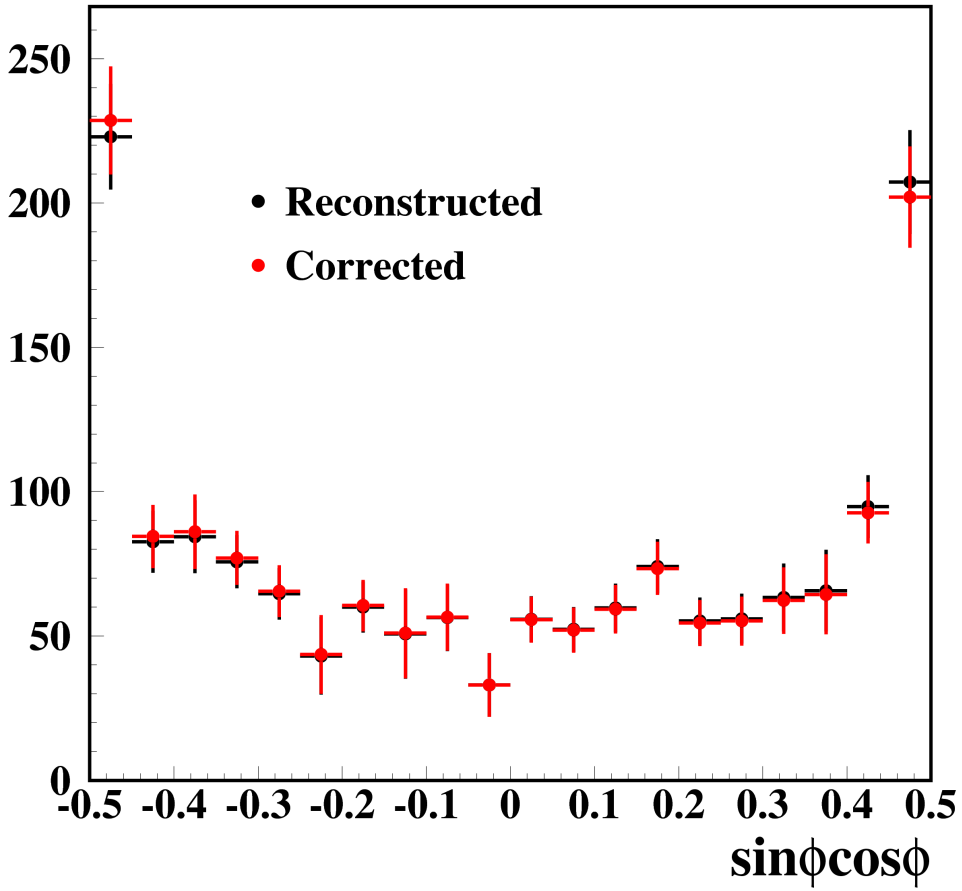




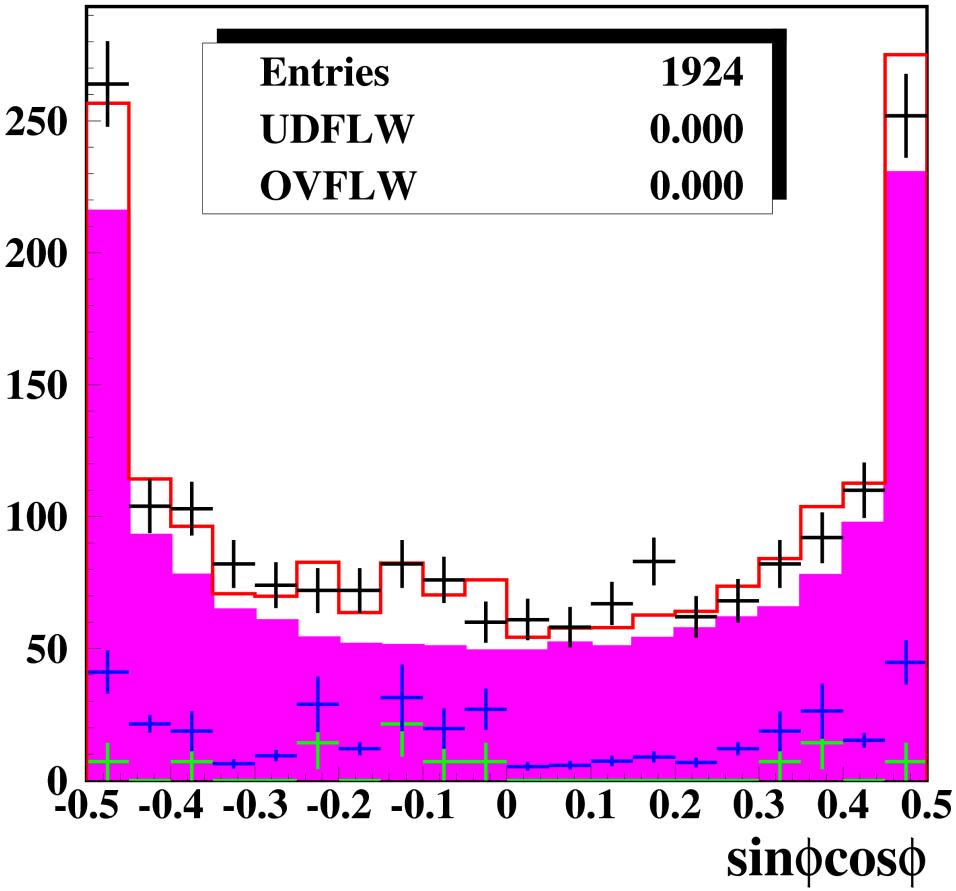
Higher polynomial does not improve the fit

Asymmetry

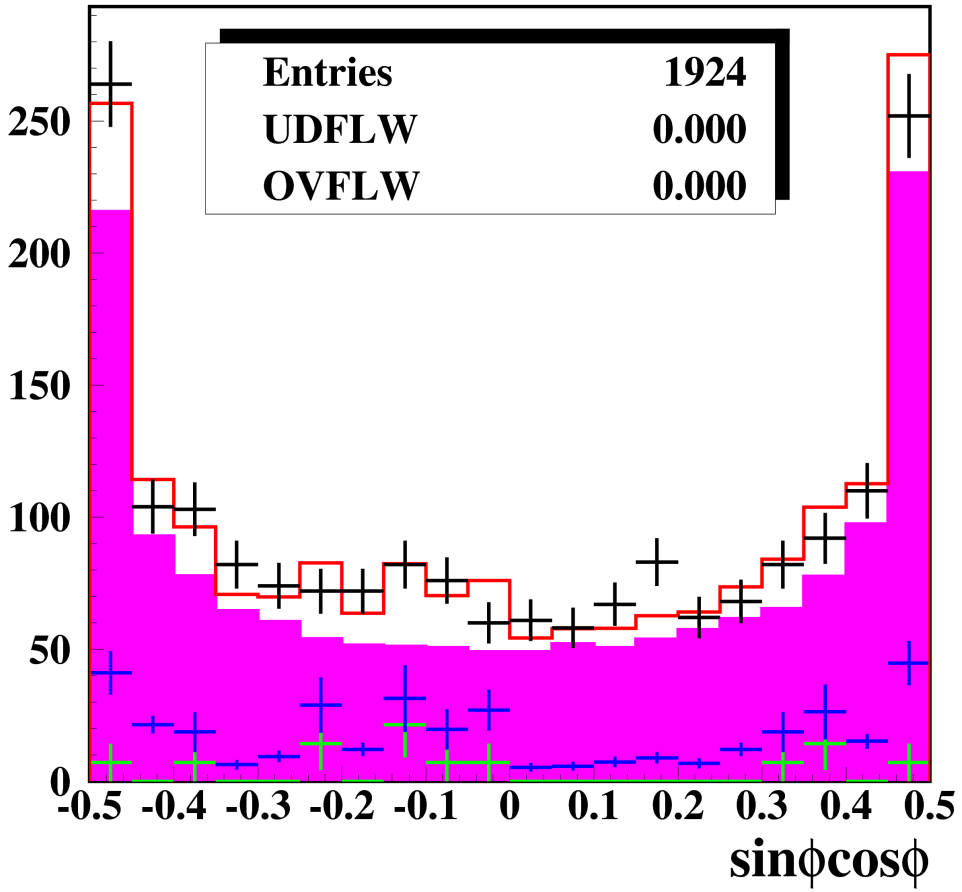
Linear correction
has been applied
Systematics evaluation
with a ±1σ slope variation



Data
Total
MC all_phys
Off-peak data
Signal MC



Asymmetry



Data
Total
MC `all_phys`
Off-peak data
Signal MC

$A_\phi = (0.7 \pm 2.5_{Stat.} \pm 1.9_{Syst.}) \cdot 10^{-2}$ without correction

$A_\phi = (-1.0 \pm 2.5_{Stat.} \pm 1.7_{Syst.} \pm 0.5_{Corr.}) \cdot 10^{-2}$ with correction

Open points

1. How to quote the final result on the asymmetry
2. Signal MC does not take into account FSR
3. ...

Backup slides

Motivations

Consider $\eta \to \pi\pi\gamma$: most general decay amplitude
using Lorentz and gauge invariance

$$A \propto \bar{u}(k_-)\gamma_\mu v(K_+)(M\,\epsilon^{\mu\nu\alpha\beta}\,p_{+\nu}\,p_{-\alpha}\,q_\beta + E_+\,p_+^\mu + E_-\,p_-^\mu)$$

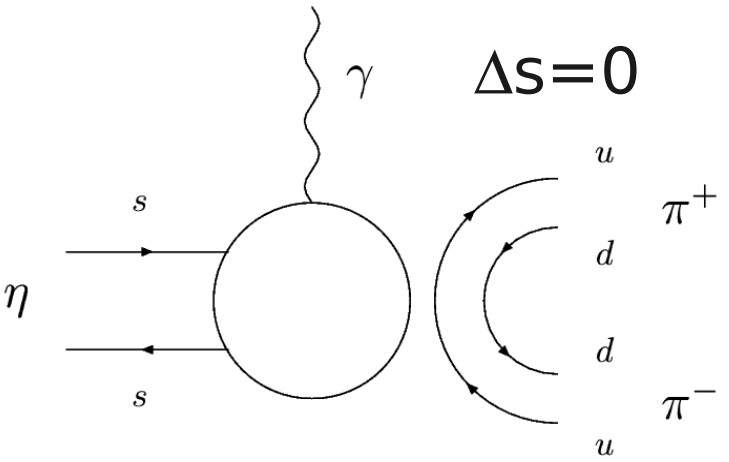
M parity conserving E+- parity violating
CP arises from E-M interference visible in the photon polarization

Summing over photon polarization CP not visible anymore
but still visible in decay plane asymmetry ee-$\pi\pi$

Non negligible CPV $\Leftrightarrow$ operator not contributing to ε,ε' and d_n

$$O = \frac{1}{m_\eta^3} G\,\bar{s}\,i\,\sigma_{\mu\nu}\gamma_5 (p-q)^\nu\, s\,\bar{\psi}\,\gamma^\mu\,\psi$$

$$\frac{G}{m_\eta^3}\langle\eta|\bar{s}\,i\,\sigma_{\mu\nu}\gamma_5(p-k)^\nu s|\gamma\rangle\langle 0|\bar{u}\,\gamma^\mu\,u|\pi^+\pi^-\rangle$$



PID using TOF

Algorithm for mass assignment

T#1 = Track #1 T#2 = Track #2

1-Look for track pair having the same charge and extrapolation to the calorimeter (both tracks)

T#1 with kink
T#2 without kink
$\Rightarrow$
T#1=π
T#2=e

2-For all other tracks use Δt_e vs Δt_π to assign mass

3-Use pair's charge to solve ambiguities

PID using TOF

Algorithm for mass assignment

3-Use pair's charge to solve ambiguities

T#1	T#2	
e	e	min(Δt_e) $\Rightarrow$ e
e	π	ok
e	?	T#2 = p
π	e	ok
π	π	min(Δt_e) $\Rightarrow$ e
π	?	T#2 = e
?	e	T#1 = π
?	π	T#1 = e
?	?	if T#1 w/ kink and T#2 w/o kink $\Rightarrow$ T#1=π & T#2=e (and vice versa)

Ordered momenta are used for remaining assignment ambiguities

Tracking efficiency

using $\rho\pi$ sample work done together with A. De Santis

Sample selection

#tracks from IP = 1 or 2

tagging tracks checked for flips

One and only one cluster pair such that:

$t_{cl} - r_{cl}/c < \min(2\text{ ns}, 3s_t)$

$0.65 < \cos(\gamma\gamma) < 0.85$

$300 < E_{\gamma\gamma} < 600$ MeV

w/o associated tracks (Official TCLO)

self-triggering (on the barrel and $E_{cl} > 70$ MeV)

$|m_{\pi 0} - m_{\gamma\gamma}| < 40$ MeV

Efficiency on $\rho\pi$ stream ~ 0.09

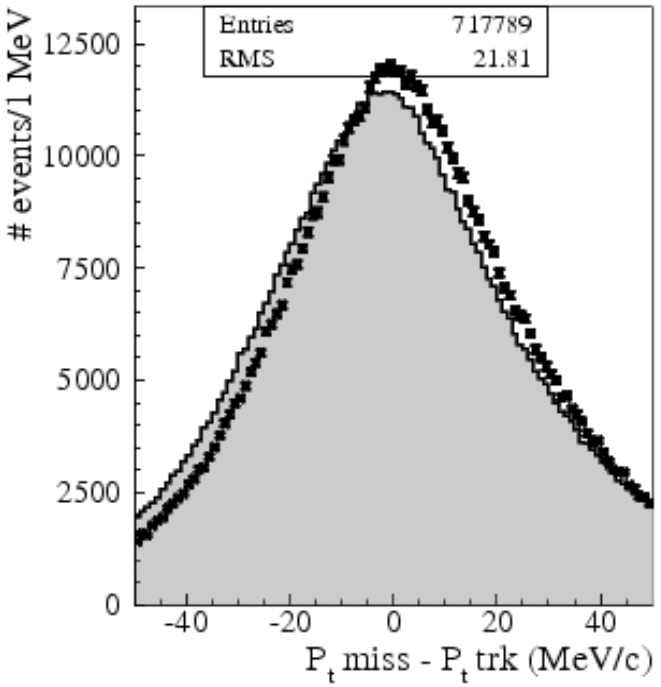
Sample purity ~ 0.994

Tracking efficiency

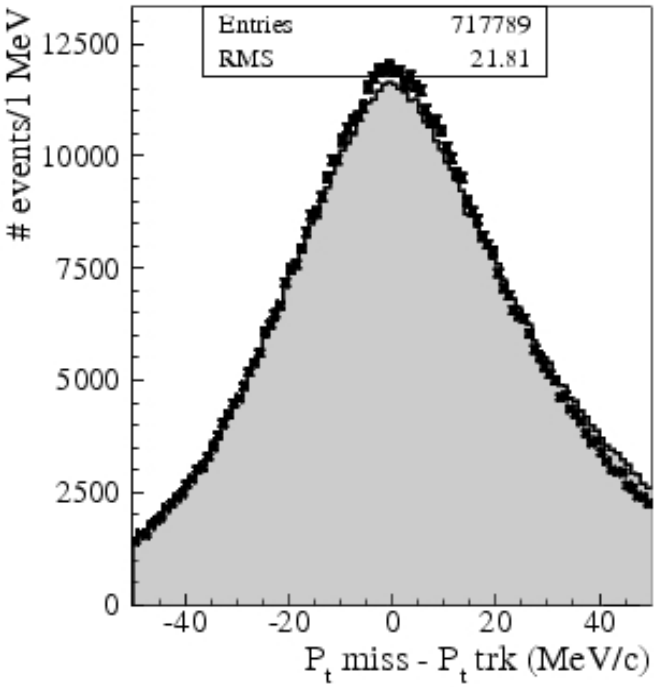
After $\gamma\gamma$ selection, kinematic fit to π^0 mass is applied

It improves the knowledge of the missing momentum

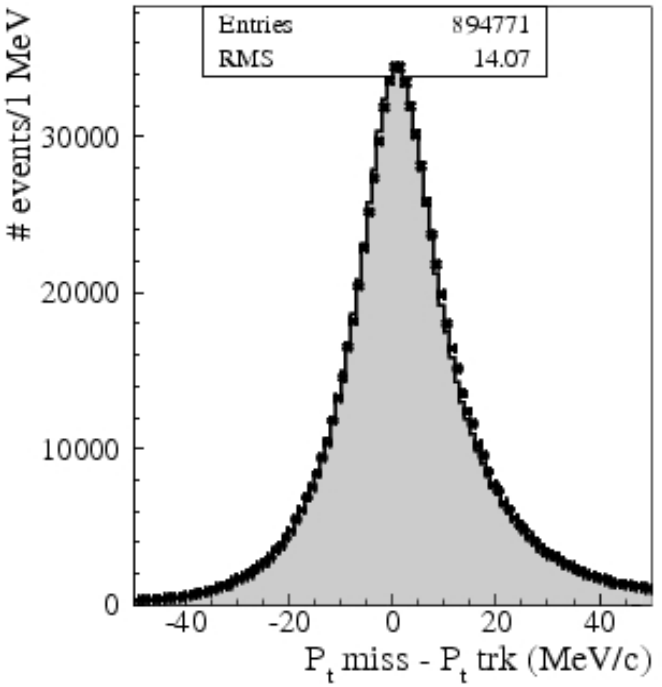
Cluster energy correction applied $E_{eff}=1.014\times E_{rec}$ (KM342)



Raw



Linearization



Linear. & Fit

Dots: data

Filled: MC

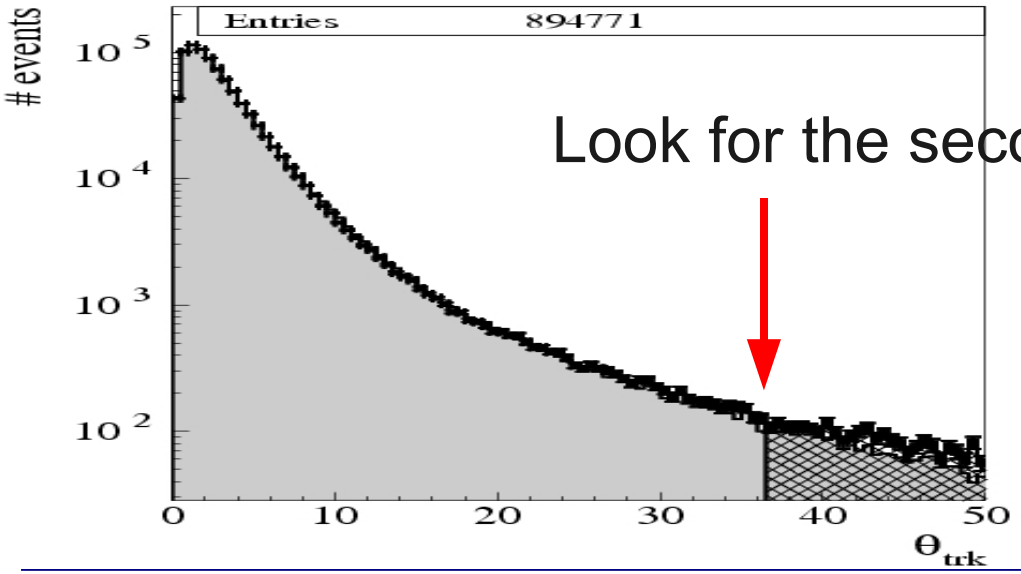
Tracking efficiency

Multiplicity has to be considered in efficiency evaluation

$$\varepsilon_{obs} = \frac{2N_2P(C_2)}{2N_2P(C_2) + N_1P(C_1)} = \frac{2\varepsilon_1^2}{2\varepsilon_1^2 + 2\varepsilon_1(1-\varepsilon_1)} = \varepsilon_1$$

Efficiency can be evaluated separately per charge

$$\varepsilon^{\pm}_{obs} = \frac{n(\pm\, track | \mp\ tag)}{n(\mp\, tag)} = \frac{P(C_2)}{P(C_2) + P(C_1^{\mp})} = \frac{\varepsilon^2_{1\pm}}{\varepsilon^2_{1\pm} + \varepsilon_{1\pm}(1-\varepsilon_{1\pm})} = \varepsilon_{1\pm}$$

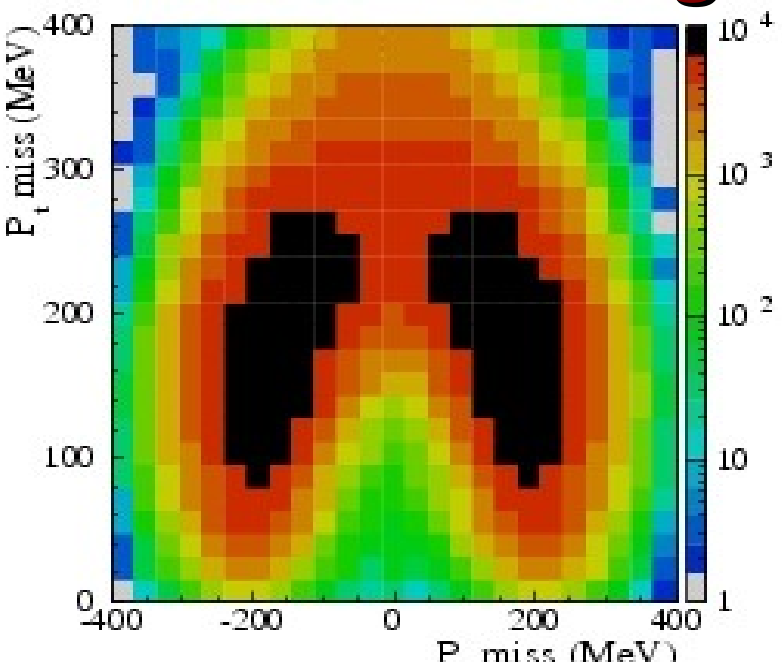


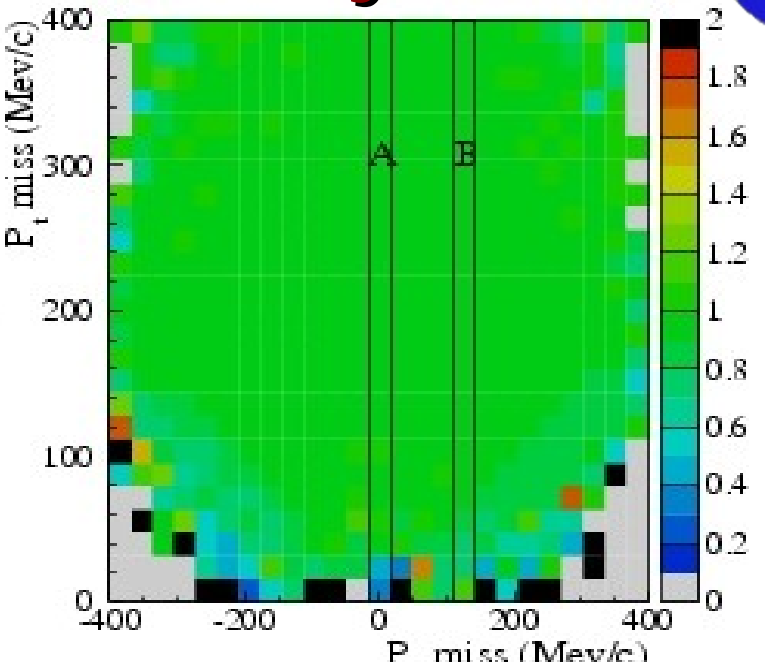
Look for the second track around the pointer

$\cos\theta_{trk} < 0.8$

Tracking efficiency

Data pointer

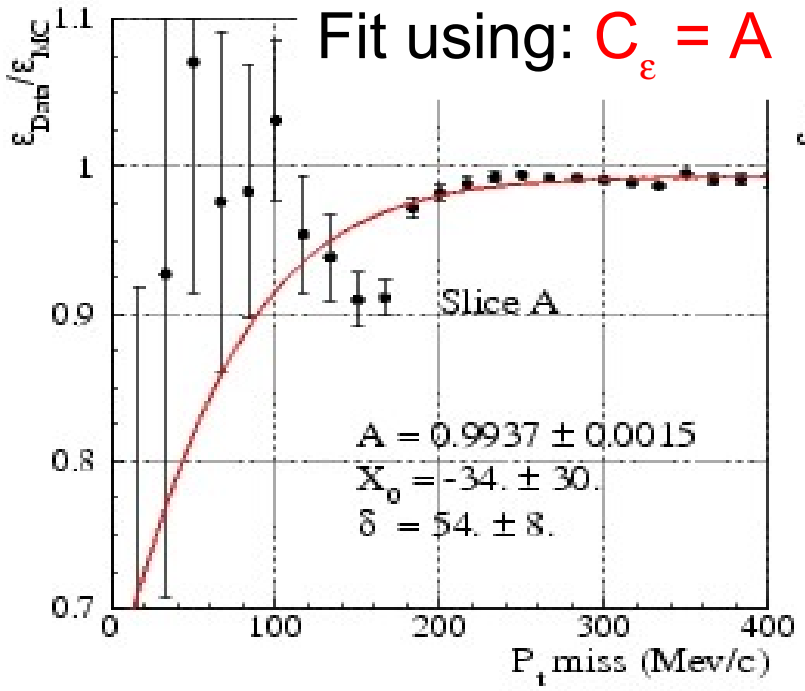


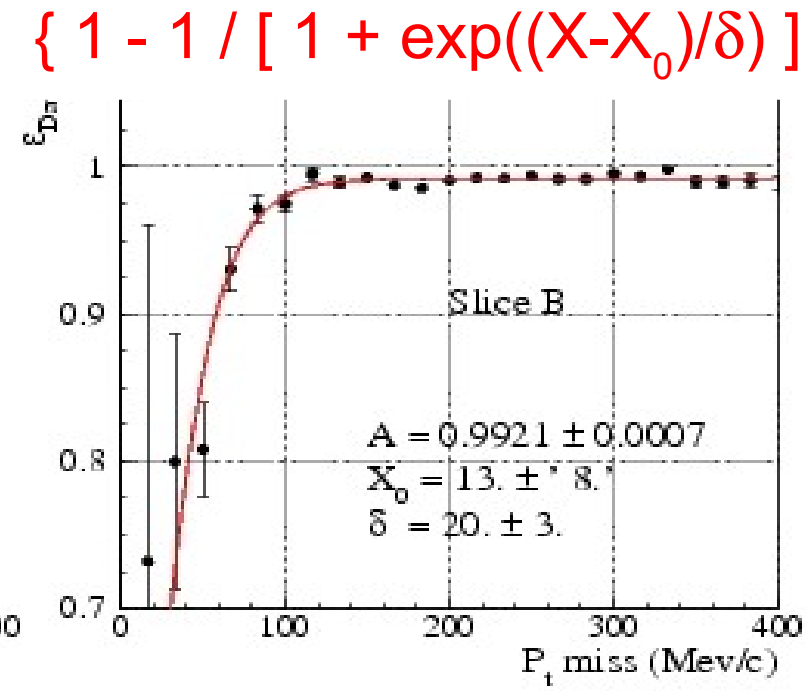


$\frac{\varepsilon_{Data}}{\varepsilon_{MC}}$

Fit using: $C_\varepsilon = A \{ 1 - 1 / [1 + \exp((X-X_0)/\delta)] \}$

$\frac{\varepsilon_{Data}}{\varepsilon_{MC}}$





$\frac{\varepsilon_{Data}}{\varepsilon_{MC}}$

Cluster veto correction

Effect of the veto in ETA4CTAG has been evaluated

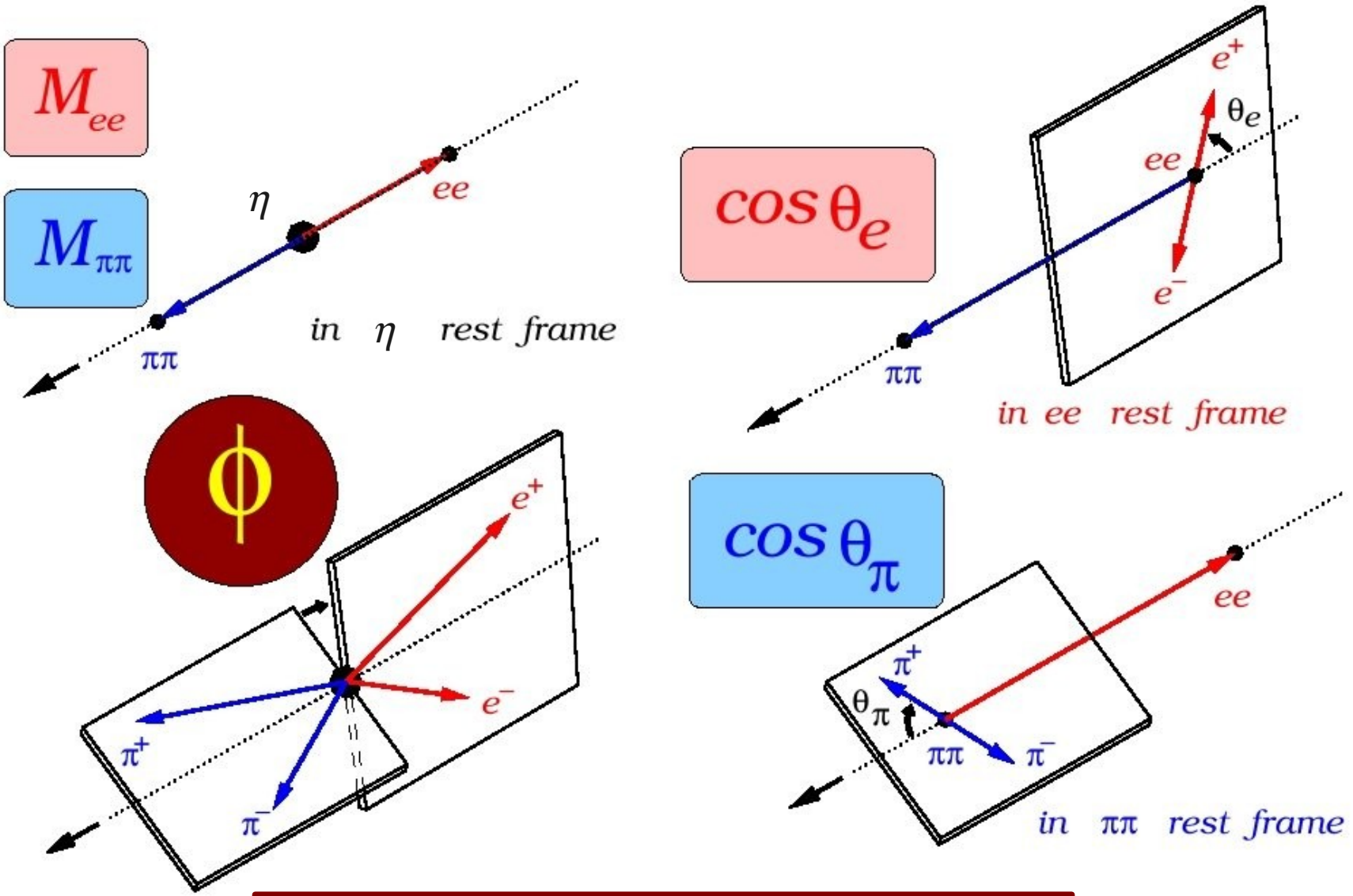
Reminder: ETA4CTAG rejects events having neutral clusters in the range $50 < E_{cl} < 250$ MeV

	#events w/ accidental clusters in vetoed range	#events w/o accidental clusters in vetoed range	Ratio
2004	125937	26483346	0.00475(1)
2005	327349	61225992	0.00535(1)
2004⊕2005	453286	87709338	0.00517(1)

Correction to be applied to the branching ratio

Remind

Asymmetry

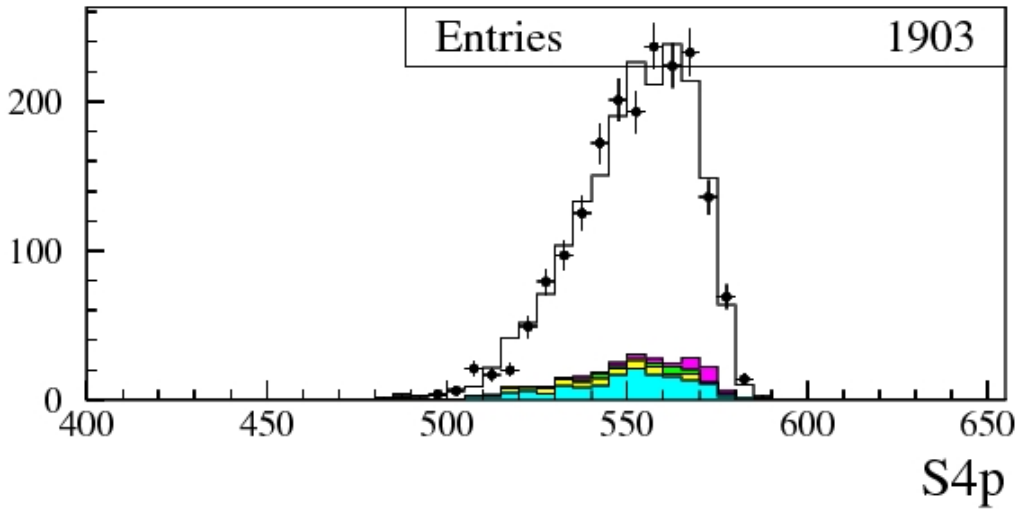


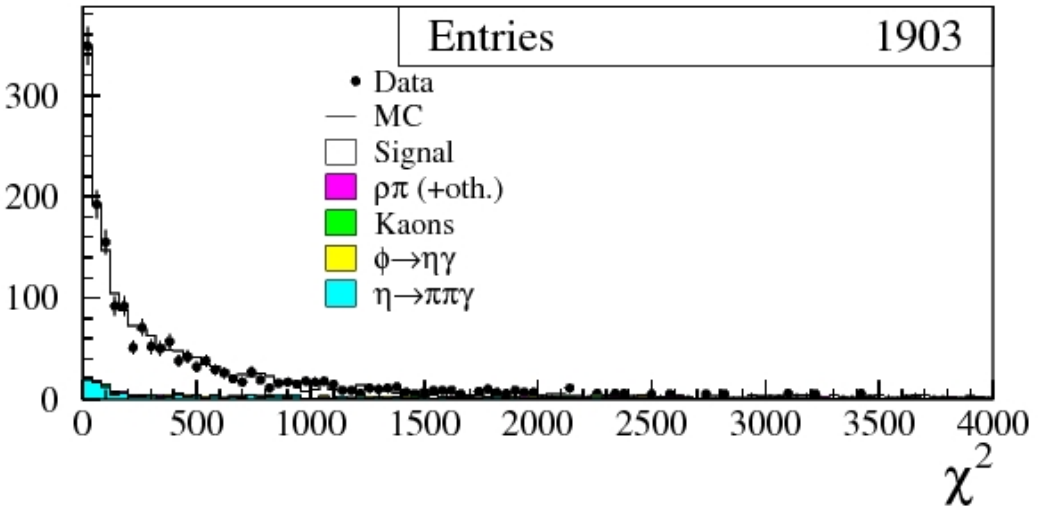
$$\sin\phi\cos\phi = (\hat{n}_{ee}\times\hat{n}_{\pi\pi})\hat{z}(\hat{n}_{ee}\cdot\hat{n}_{\pi\pi})$$

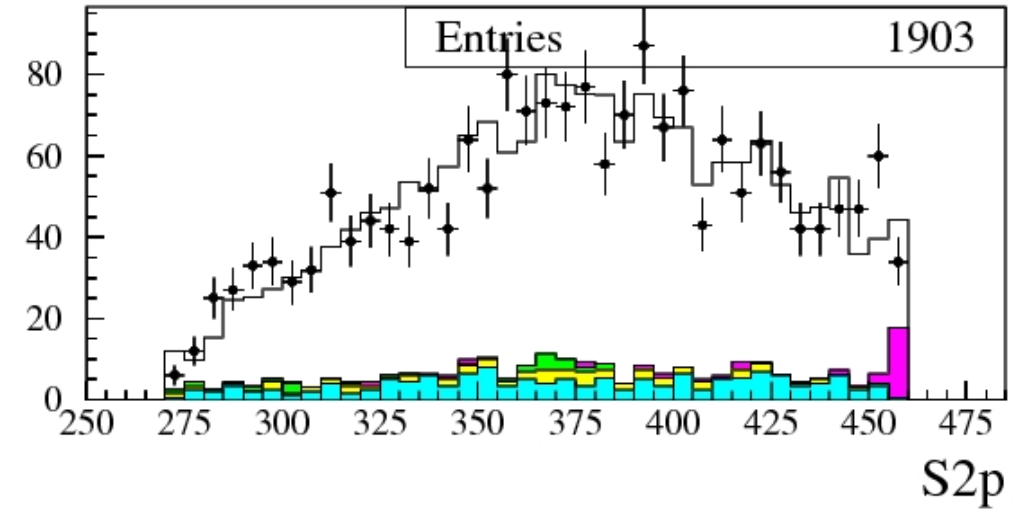
Data-MC comparison

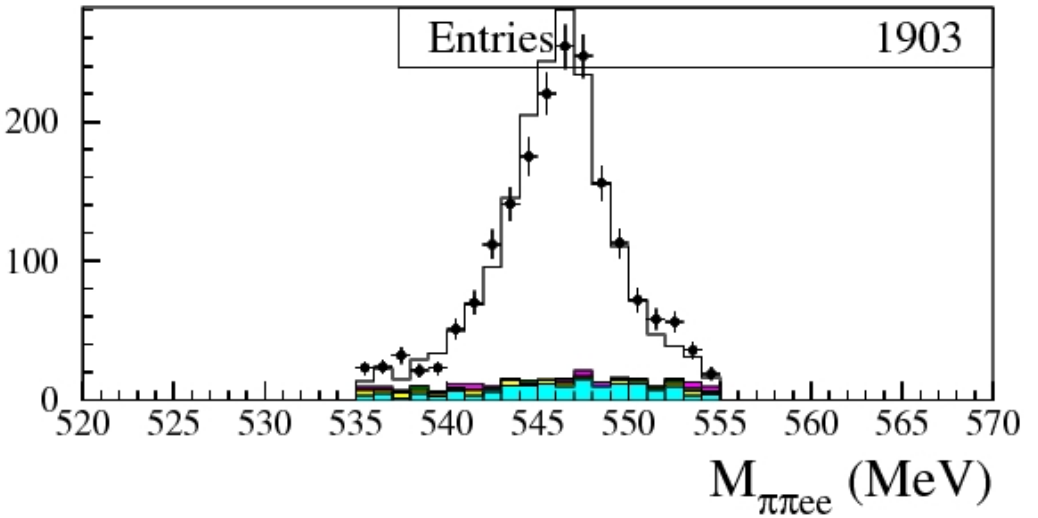
Data
MC total
signal
$\rho\pi$ + others
kaons
$\phi \to \eta\gamma$
$\eta \to \pi\pi\gamma$

Very good agreement





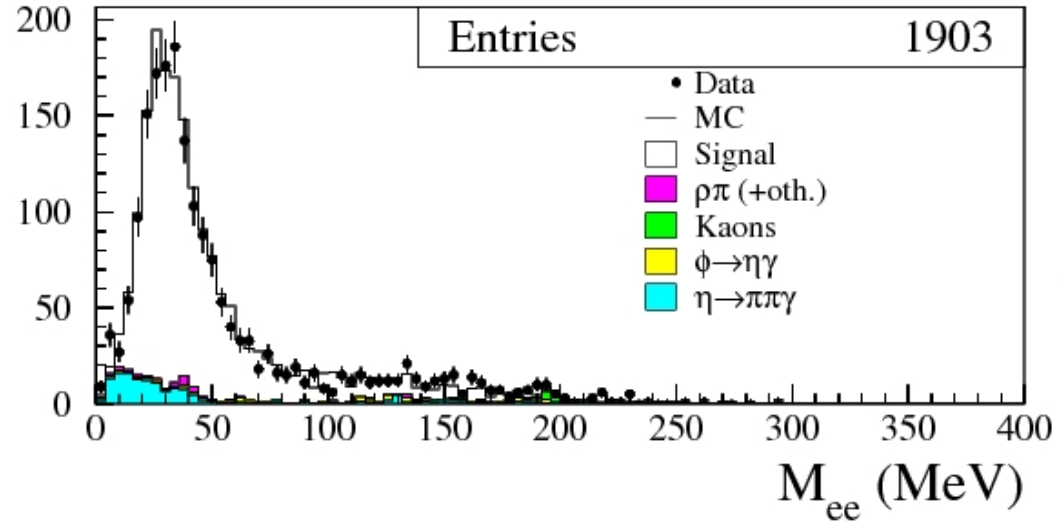


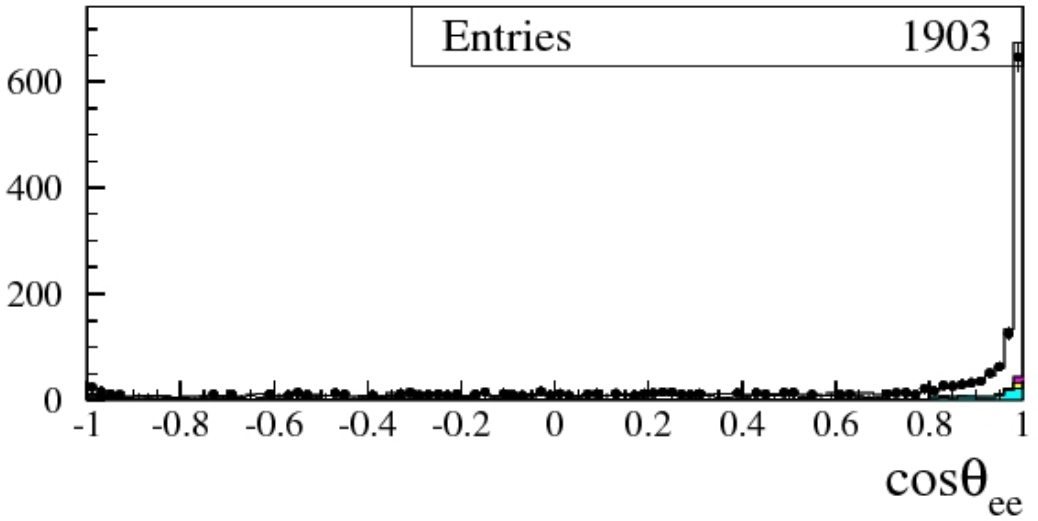


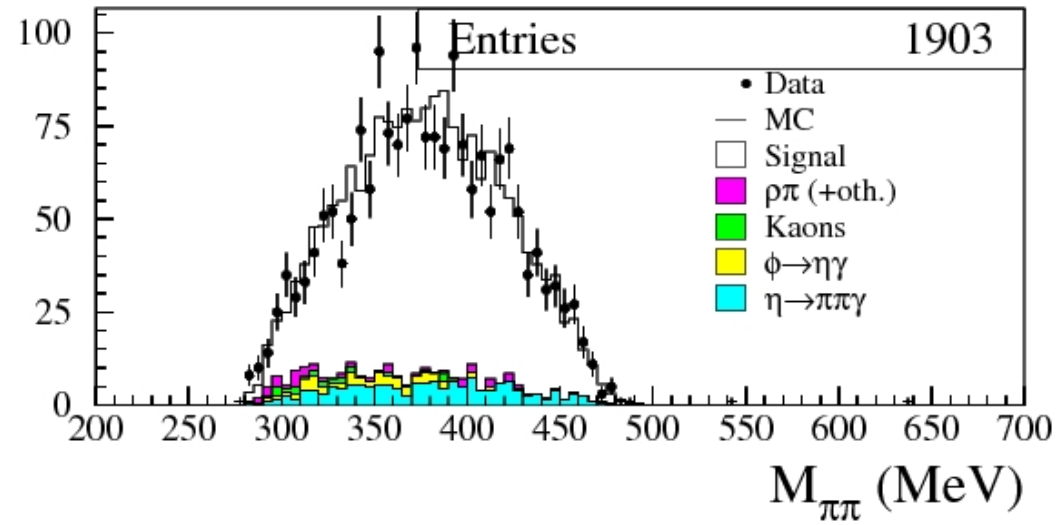
Data-MC comparison

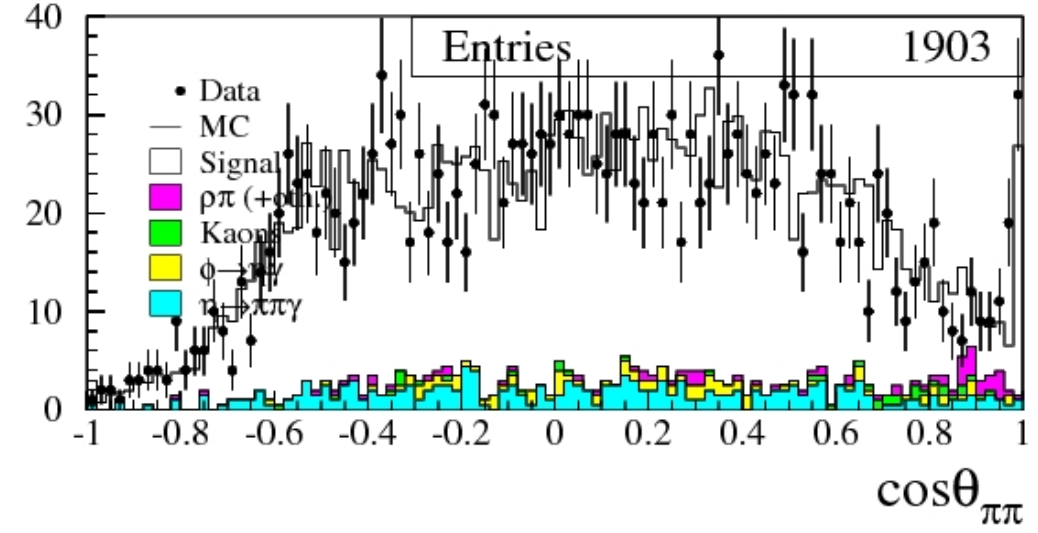
Data
MC total
signal
$\rho\pi$ + others
kaons
$\phi \to \eta\gamma$
$\eta \to \pi\pi\gamma$

Very good agreement





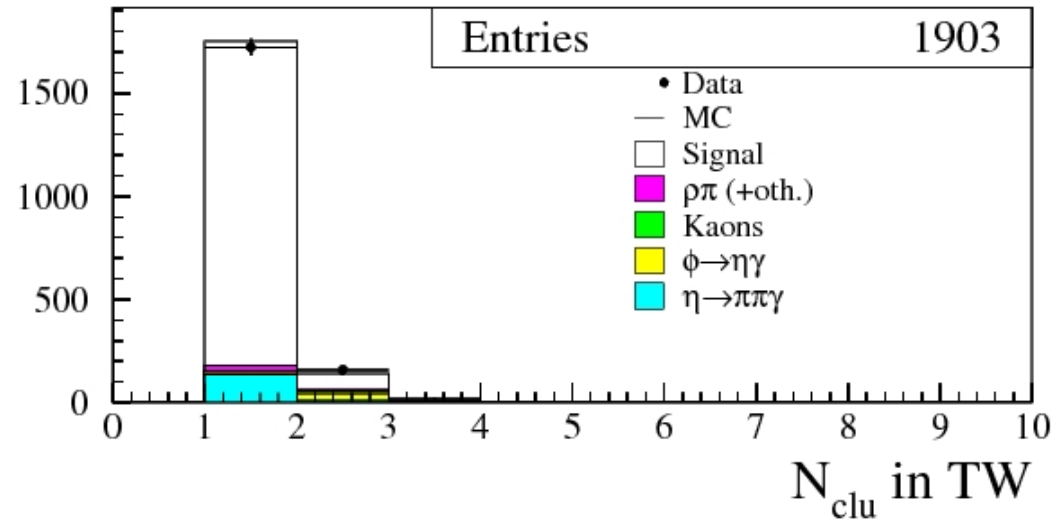


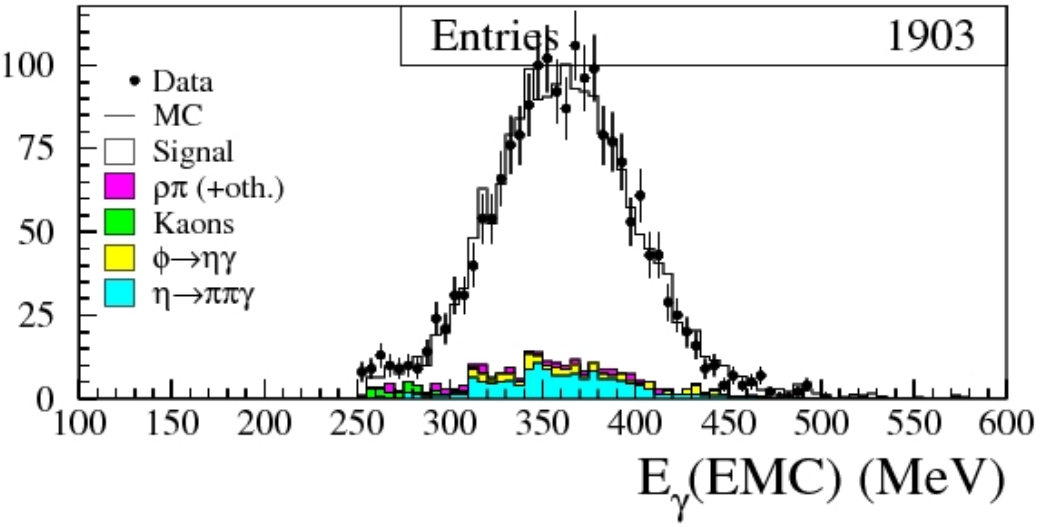


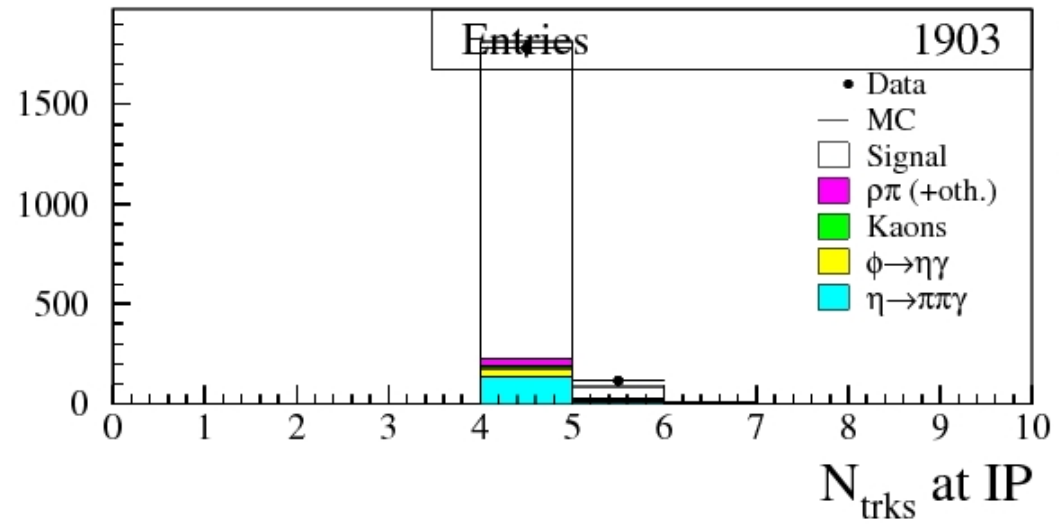
Data-MC comparison

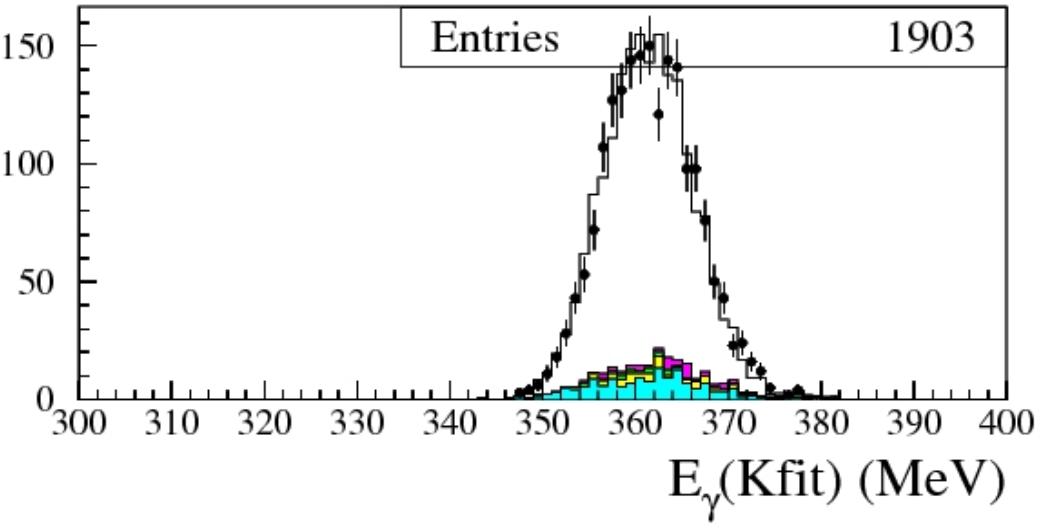
Data
MC total
signal
$\rho\pi$ + others
kaons
$\phi \to \eta\gamma$
$\eta \to \pi\pi\gamma$

Very good agreement





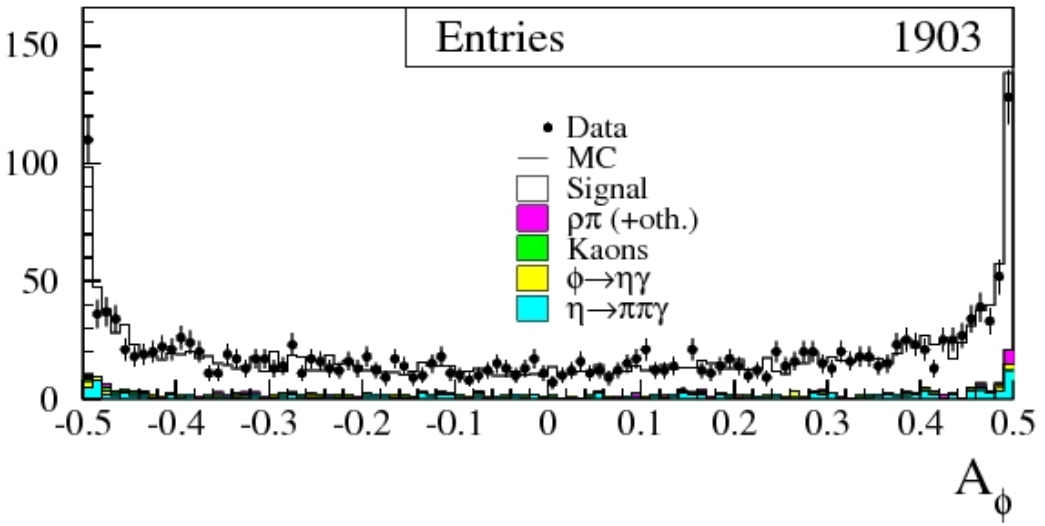


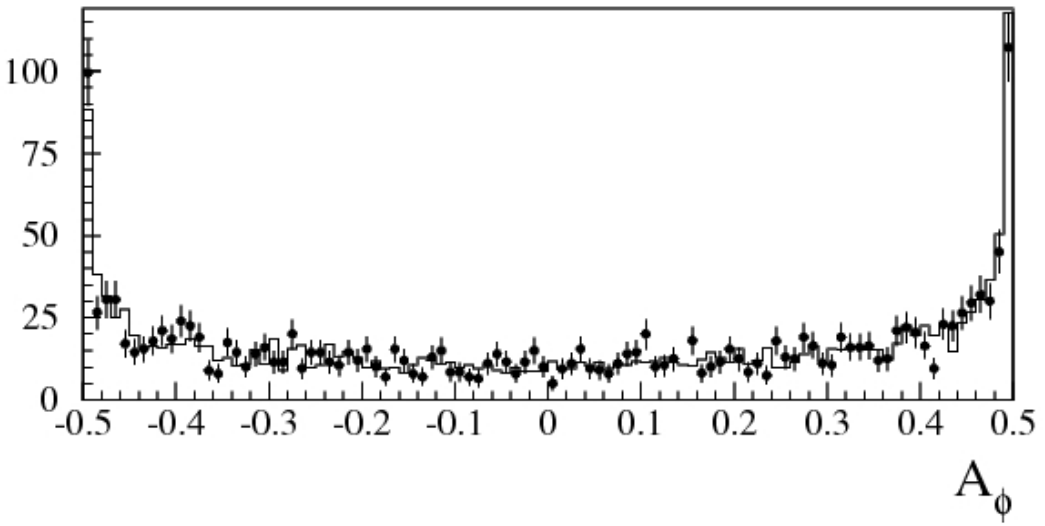


Data-MC comparison

Very good agreement (even in the asymmetry!)

- Data
- MC total
- signal
- $\rho\pi$ + others
- kaons
- $\phi \to \eta\gamma$
- $\eta \to \pi\pi\gamma$





← After background subtraction

Data-MC comparison

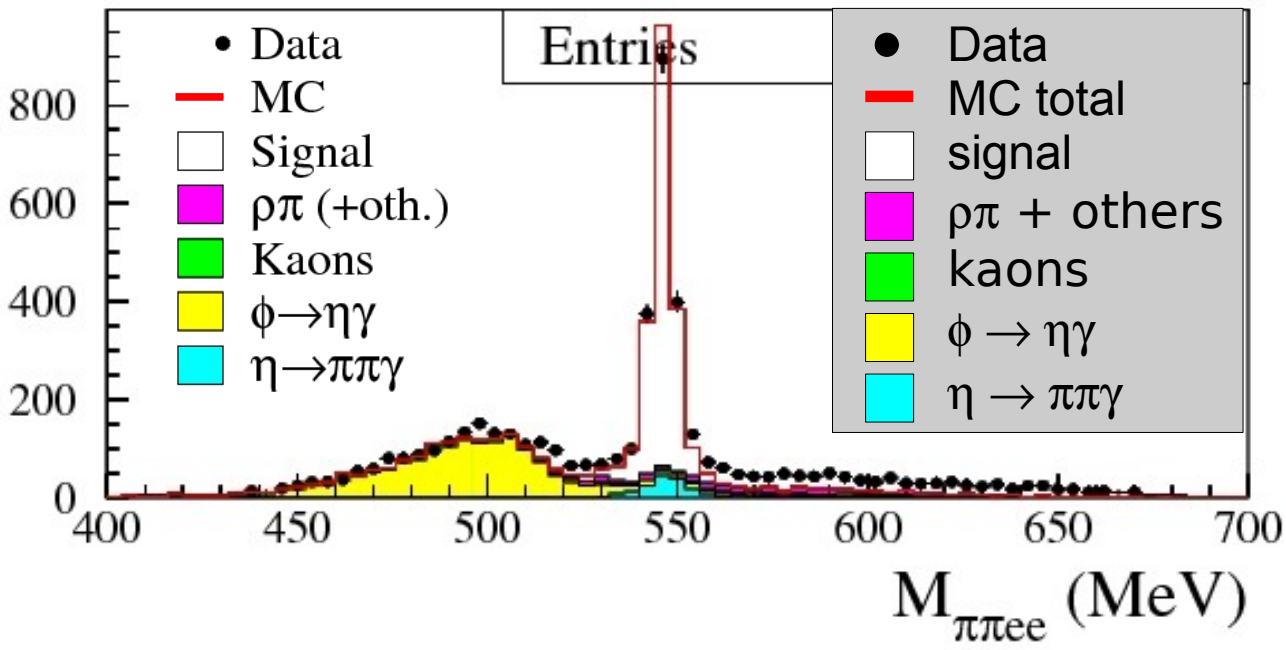
Not applying the cut

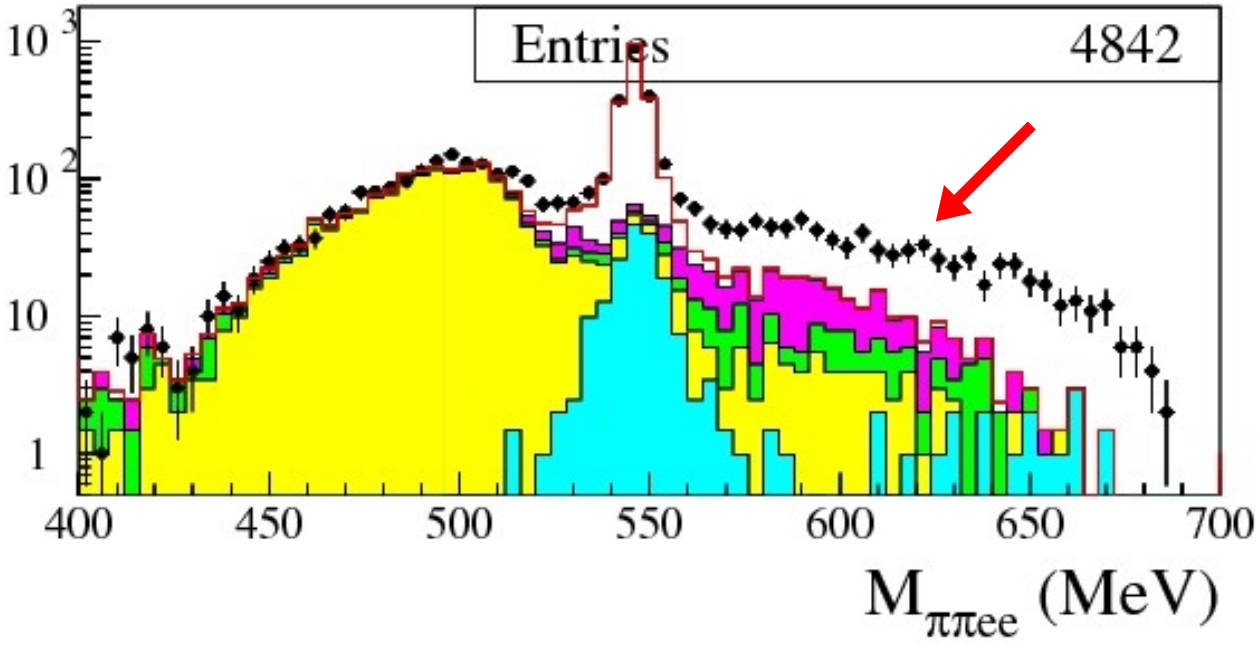
$535 < M_{\pi\pi ee} < 555$ MeV

Something is rotten in the state of ~~Denmark~~ etappee

Data-MC disagreement for $M_{\pi\pi ee} > M_{\eta}$

Could come from continuum processes, not in `all_phys` MC





Data-MC comparison

Q: Why we didn't see this before?

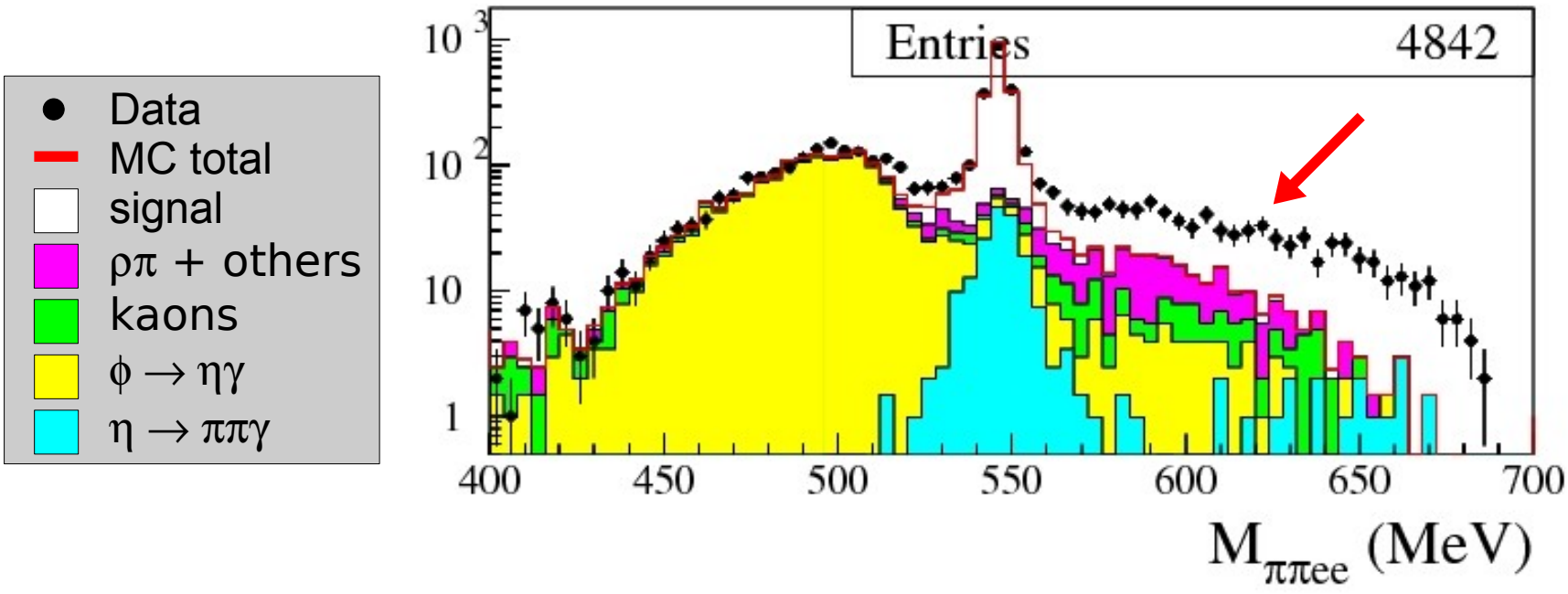
A: Today we take MC all_phys spectrum as it is,

just scaling for luminosity

Before we used to fit the data spectrum using

the different components separately

Mysterious background was hidden by non-η decays



Non-ϕ backgrounds

After EVCL $\pi\pi\gamma$ and $ee\gamma$ still present, $\omega\pi^0$ disappeared

Reduced by momenta and χ^2 cuts $\Rightarrow$ Too few events left