KOTO CsI calorimeter

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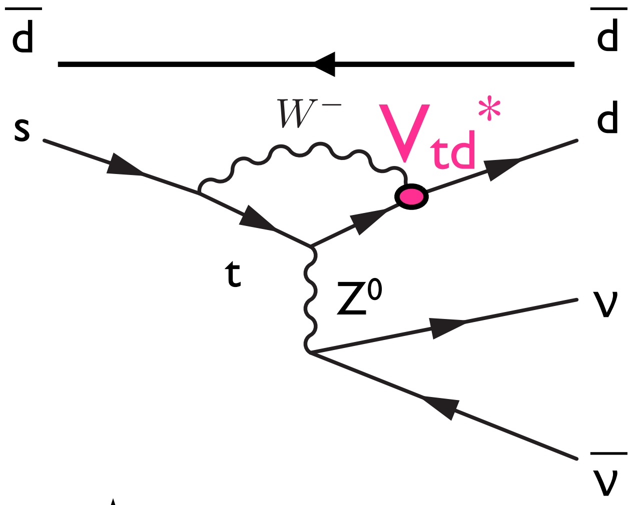
- shower shape on CsI

what's KOTO?

$K_L \to \pi^0 \nu\bar{\nu}$

KOTO : **Br($K_L \to \pi^0 \nu\bar{\nu}$) measurement in Japan**



in SM, CP violation is caused by imaginary part of CKM matrix elements

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \propto |\,\mathrm{Im}(V_{td})\,|^2$$

☆ theoretical uncertainty : **1~2% only**

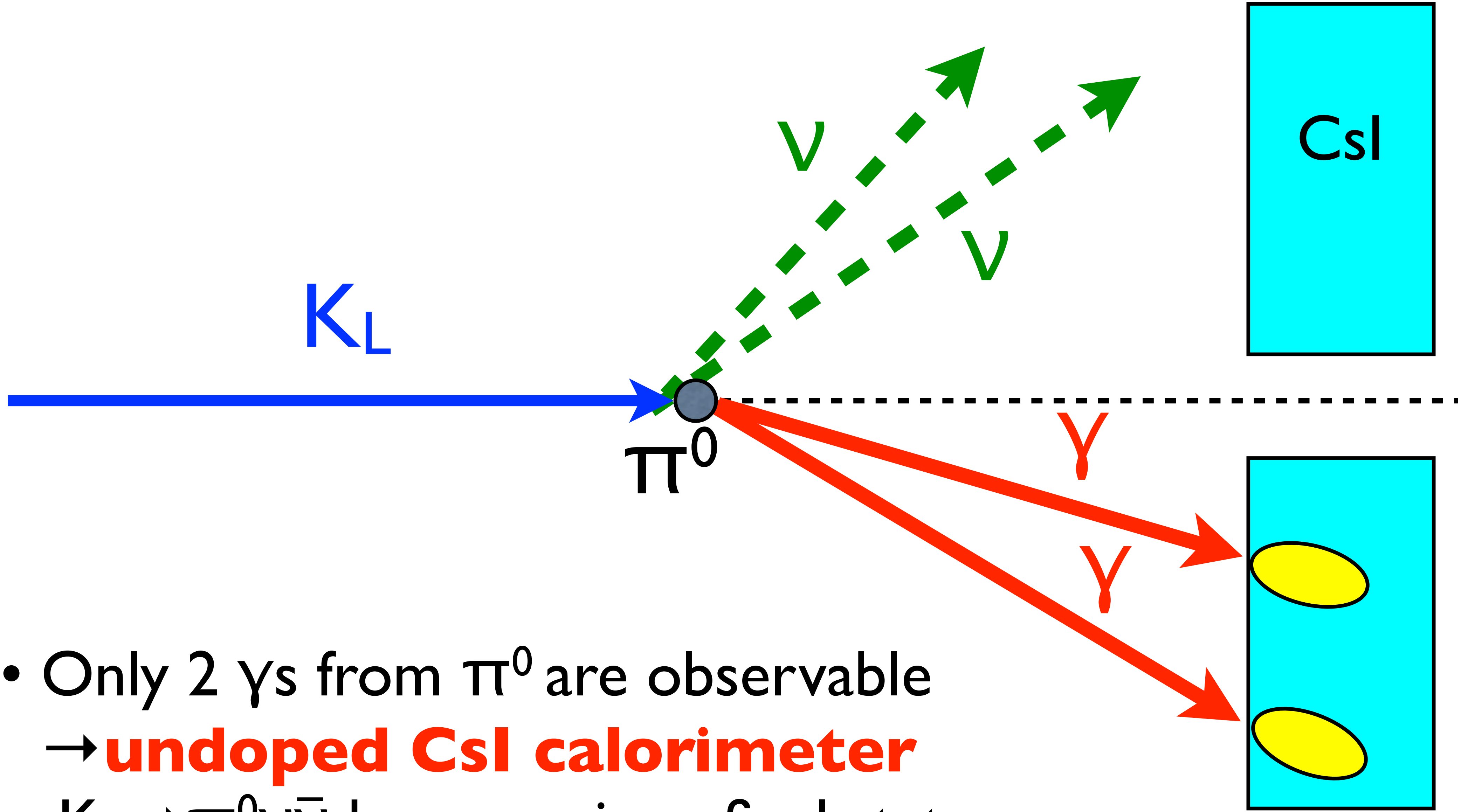
⇒sensitive to new physics beyond SM

☆ SM expectation : **Br($K_L \to \pi^0 \nu\bar{\nu}$)=3e-11**

upper limit = 2.6e-8 (90% CL) by KEK E391A

⇒ high intensity K_L beam @ J-PARC

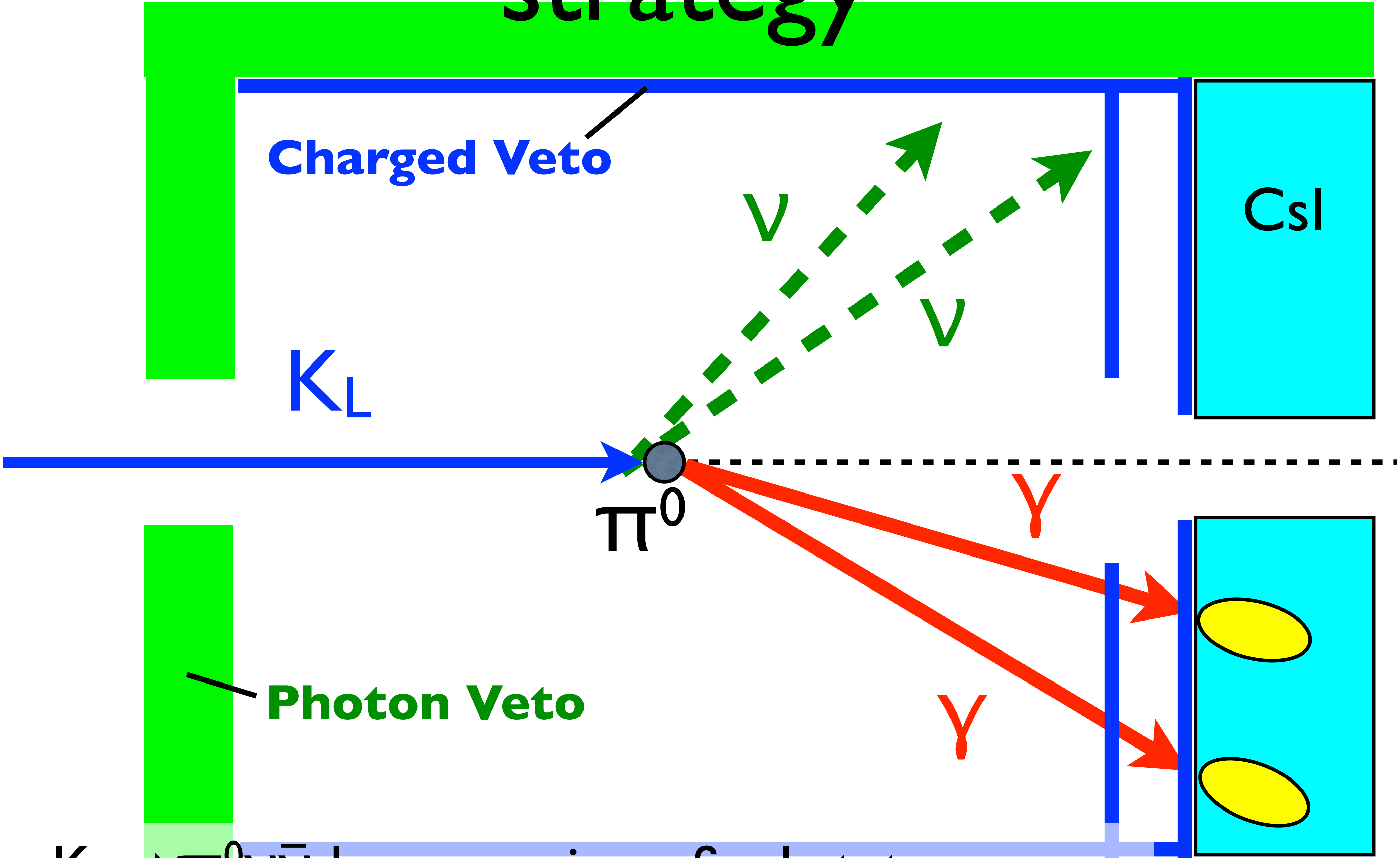
strategy



- Only 2 γs from π^0 are observable
  → **undoped CsI calorimeter**
- $K_L \rightarrow \pi^0 \nu\bar{\nu}$ has an unique final state

  2γ + $\not{P}t$

strategy

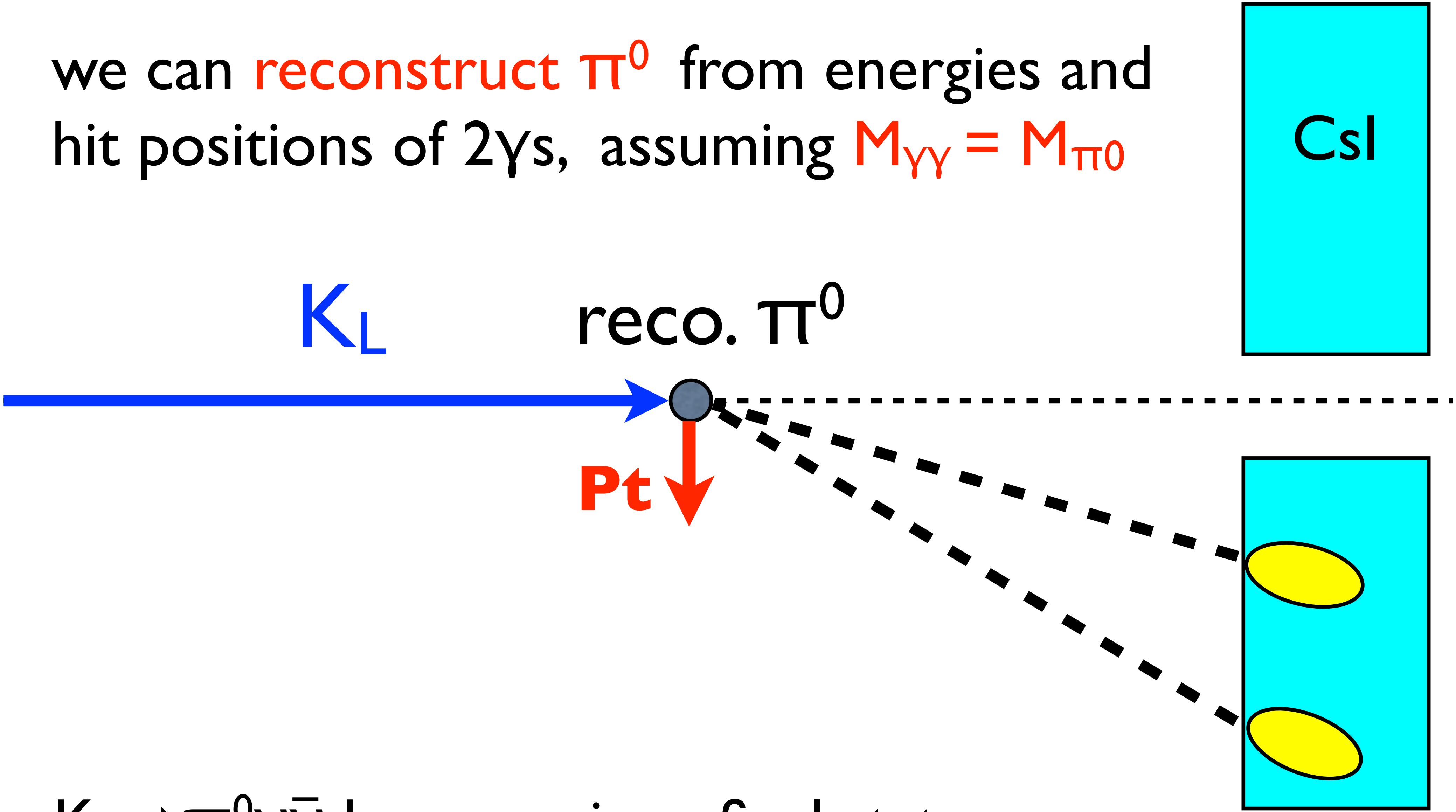


$K_L \to \pi^0 \nu \bar{\nu}$ has an unique final state

2γ + ~~Pt~~

strategy

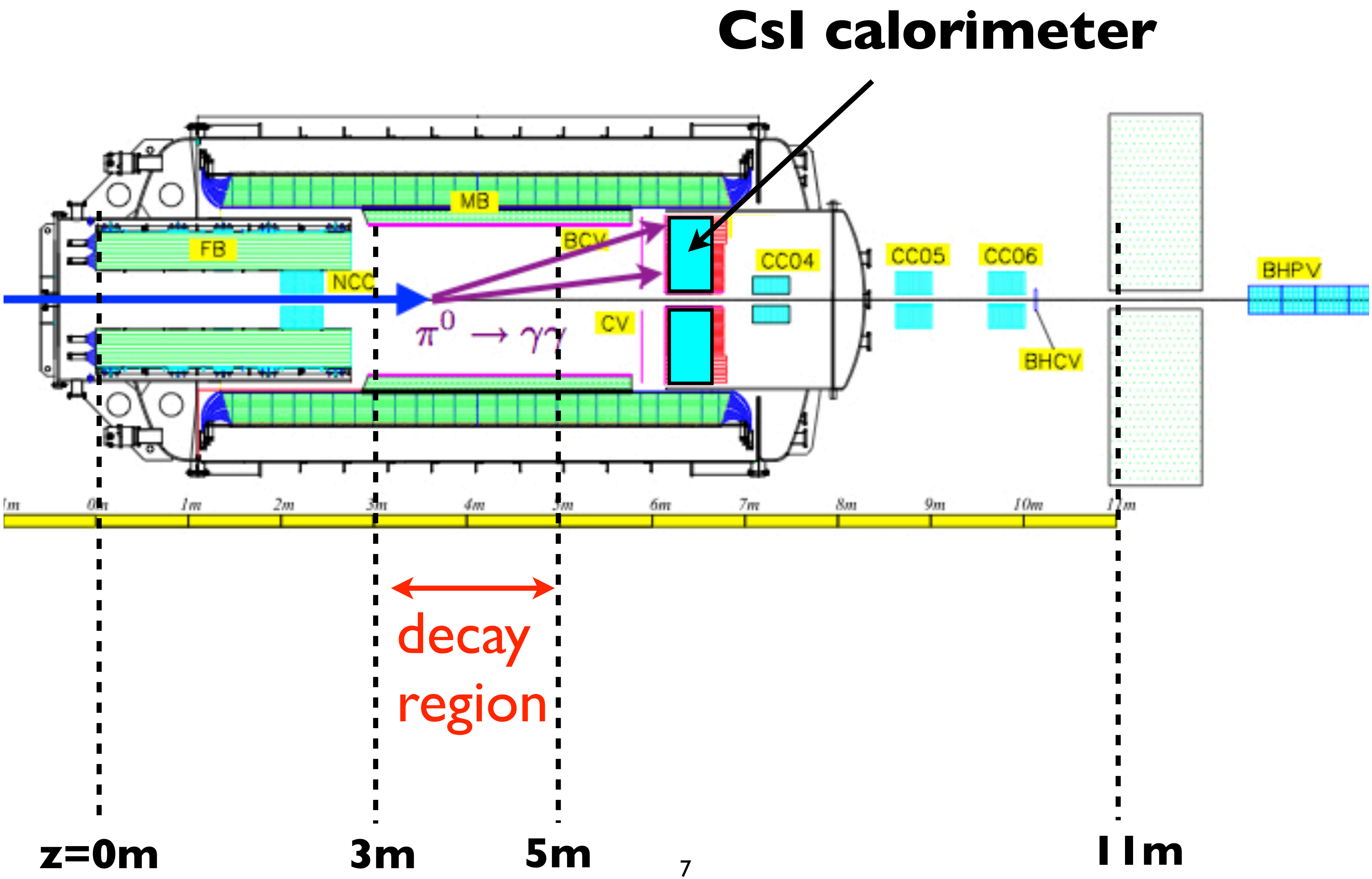
we can reconstruct π^0 from energies and hit positions of 2γs, assuming $M_{\gamma\gamma} = M_{\pi 0}$



$K_L \to \pi^0 \nu\bar{\nu}$ has an unique final state

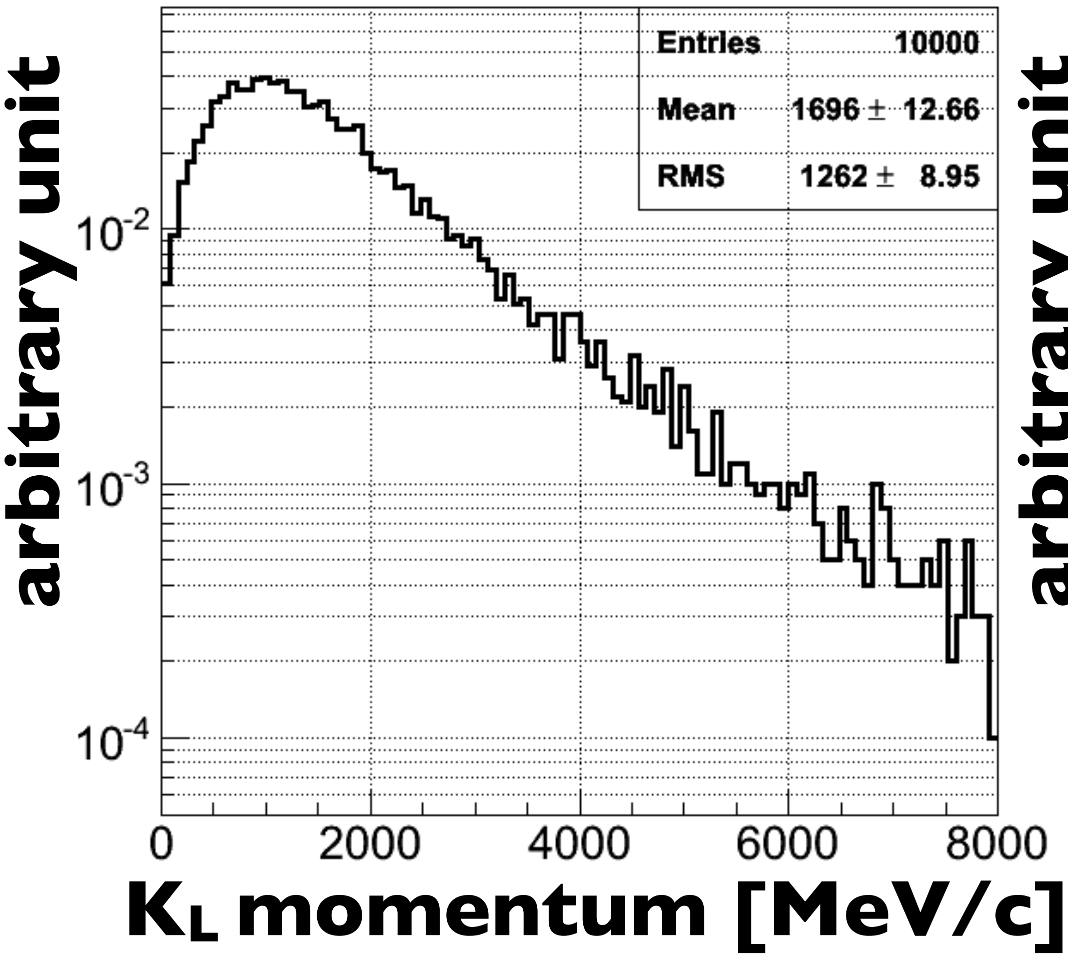
2γ + ~~Pt~~

KOTO detector

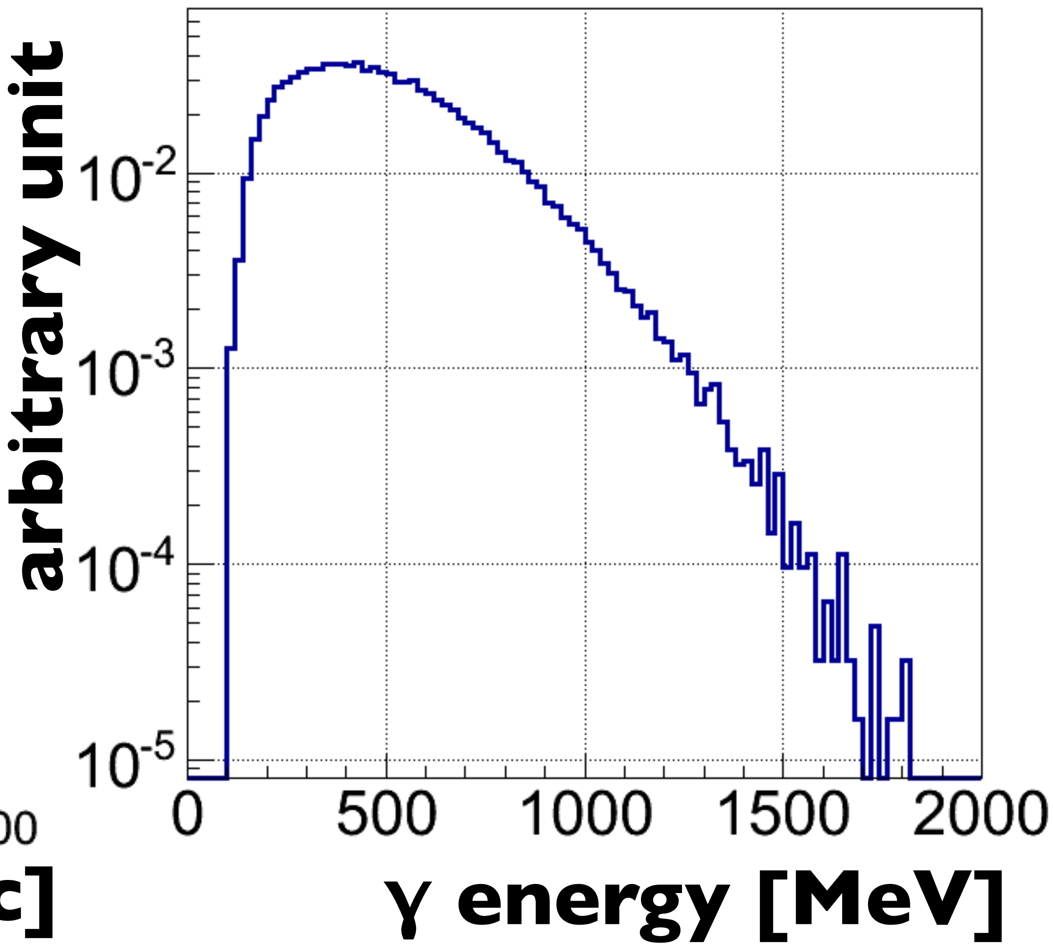


gamma energy

KL momentum

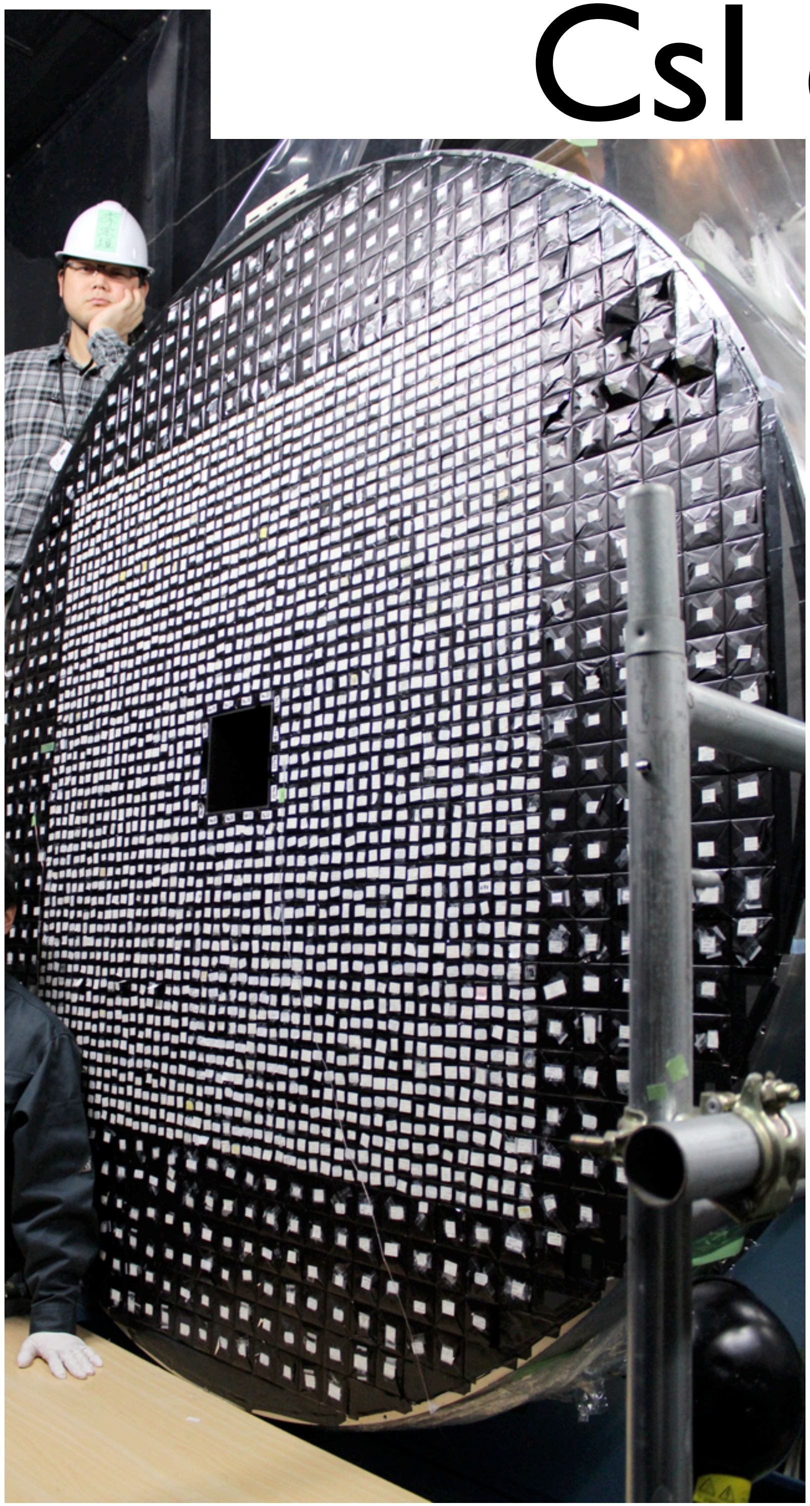


gamma energy



KOTO CsI calorimeter

CsI calorimeter



- diameter :1.9m
- consist of 2716 crystals
  - used in KTeV exp. at Fermilab
  - undoped CsI

•length:50cm(=27X_0)

→ensure good energy resolution

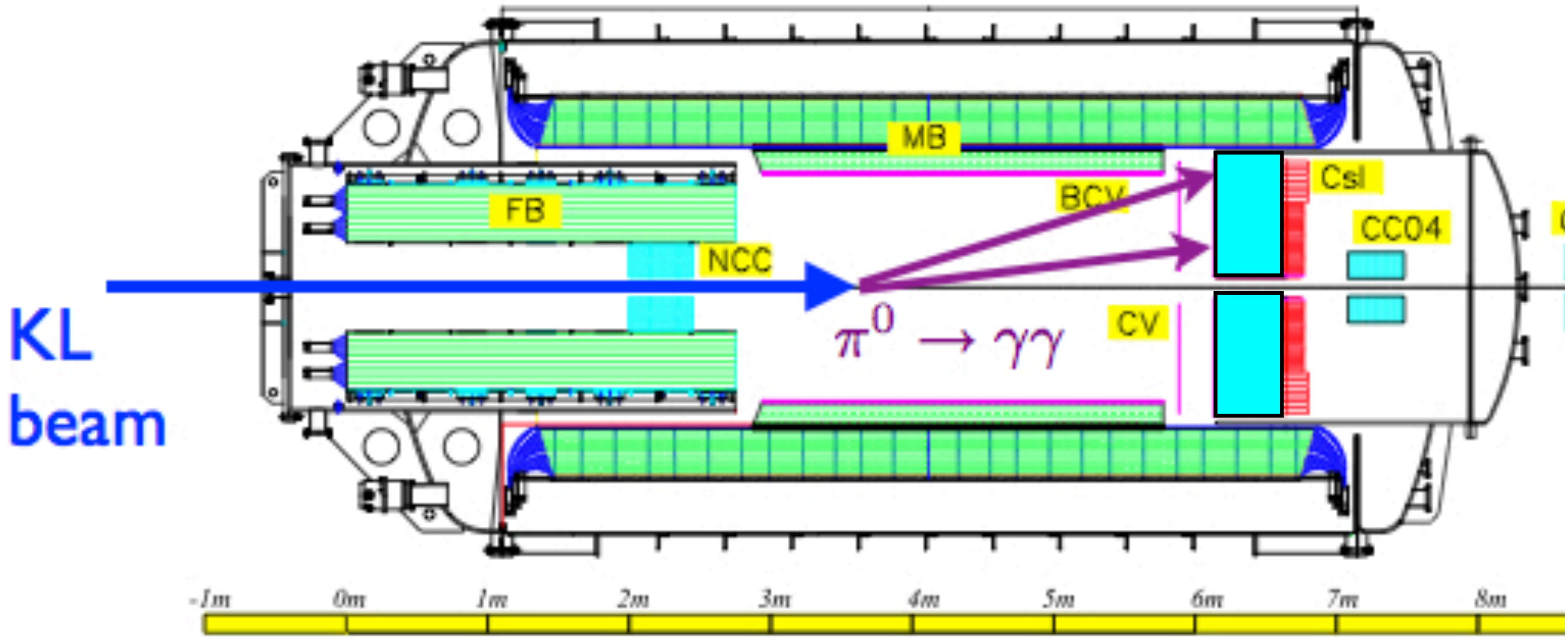
= good π^0 reconstruction

- cross section: 2.5x2.5cm, 5x5cm
  - smaller than R_M (=3.57cm)

→shower shape information

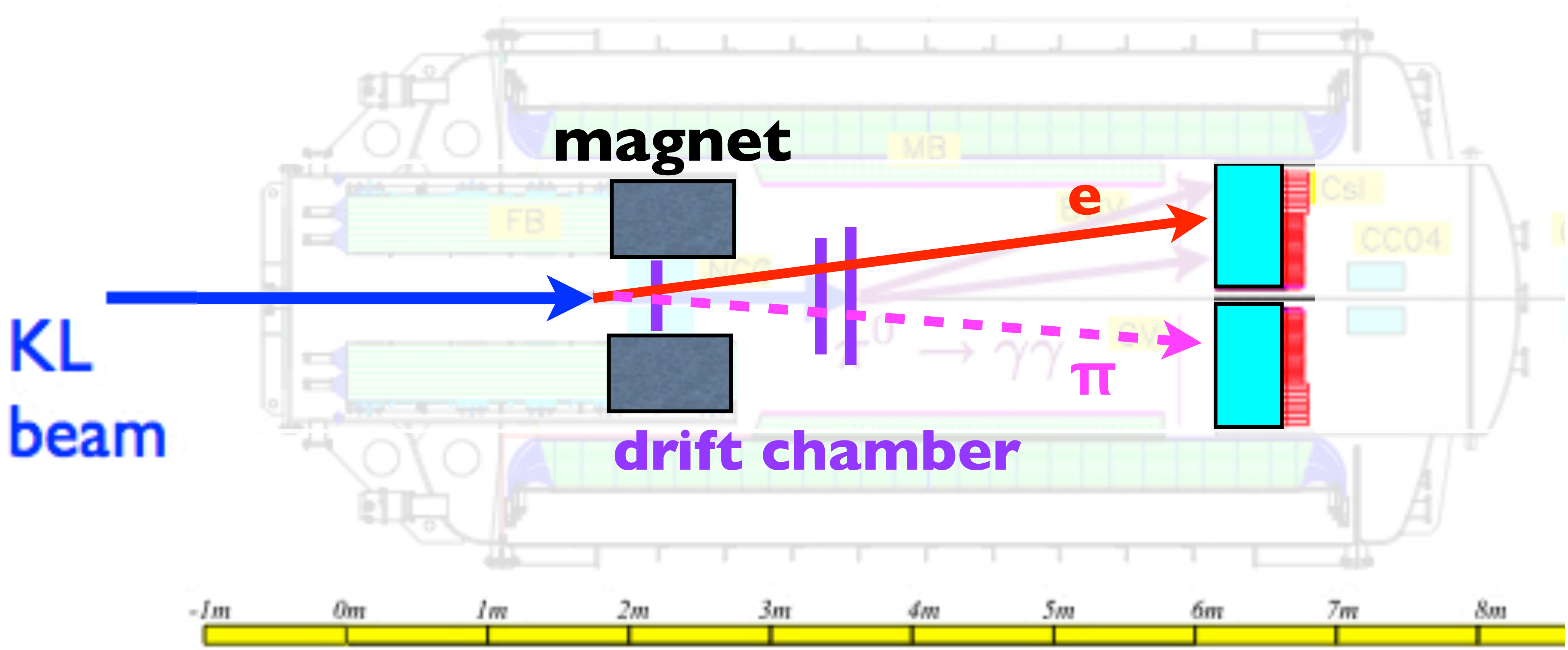
CsI calorimeter resolution

- measured using electrons from $K_L \to \pi e \nu$ decay in 2012, before installing veto detectors

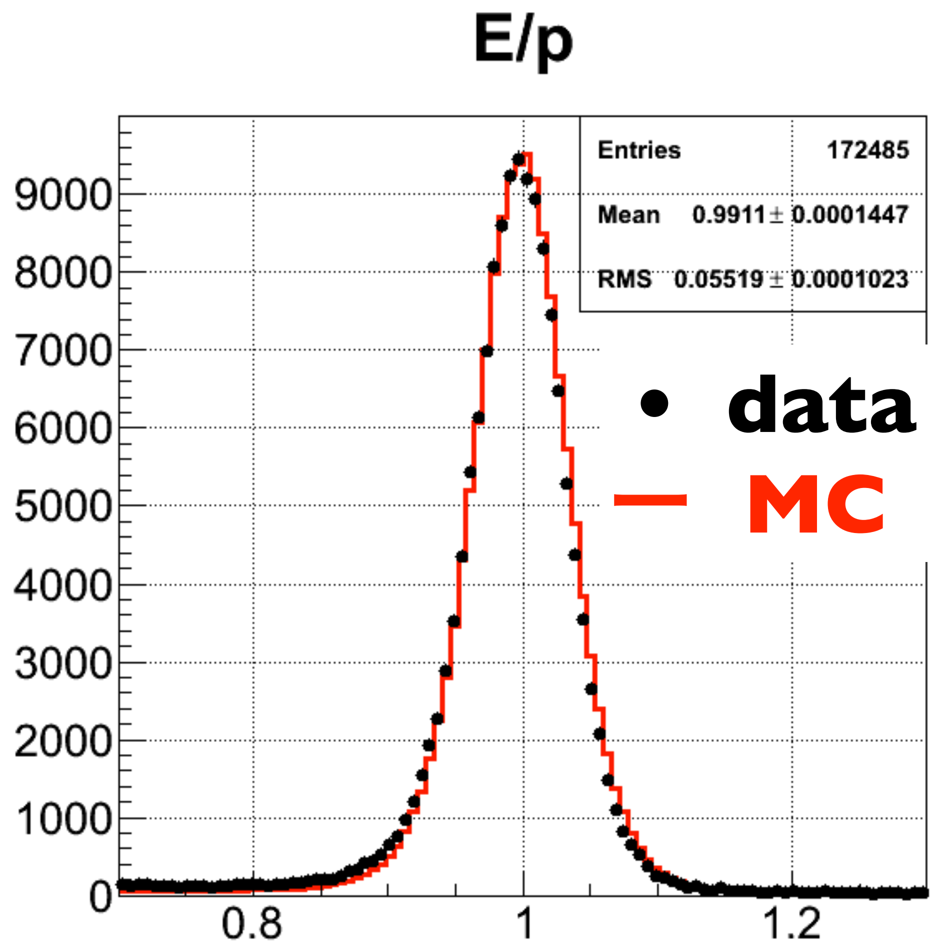


CsI calorimeter resolution

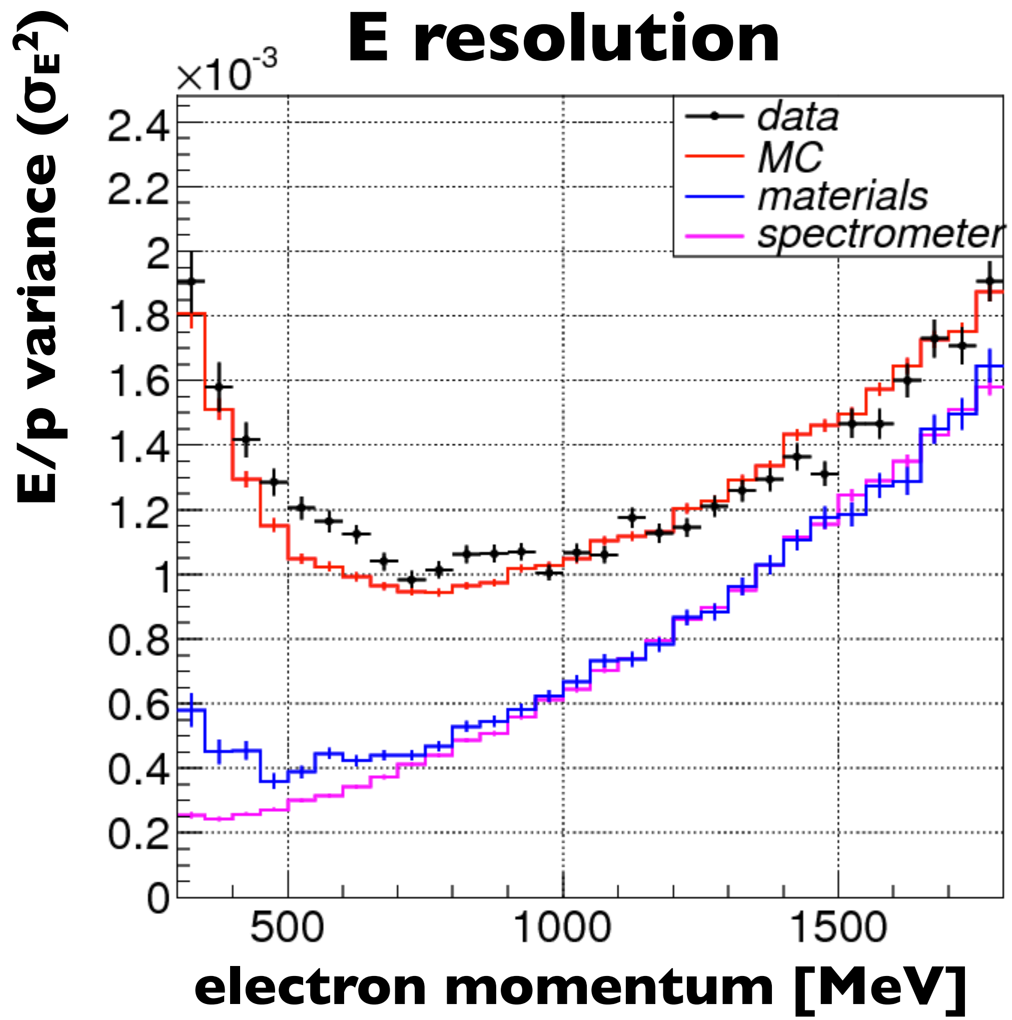
- tested using electrons from $K_L \to \pi e \nu$ decay in 2012, before installing veto detectors



E/p width

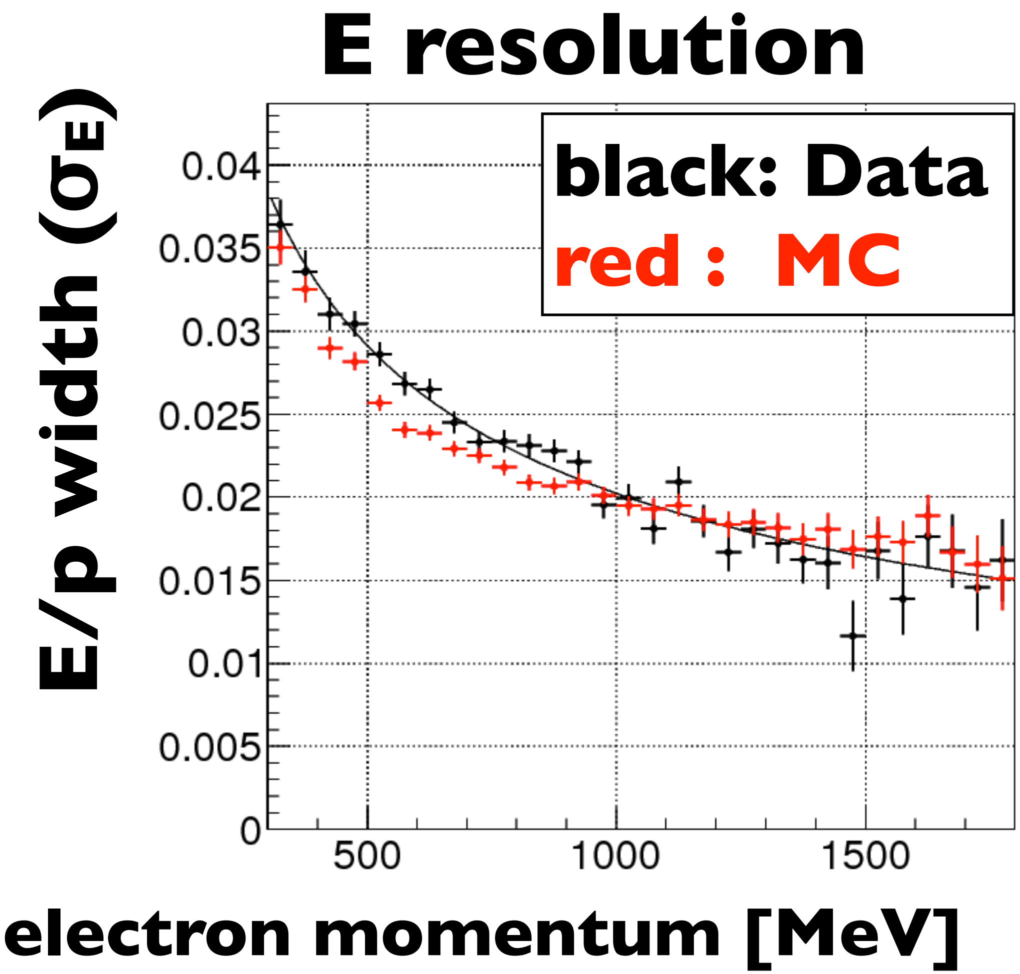


E/p
Entries 172485
Mean 0.9911 ± 0.0001447
RMS 0.05519 ± 0.0001023
• data
— MC



E resolution
×10⁻³
data
MC
materials
spectrometer
E/p variance (σ_E^2)
electron momentum [MeV]

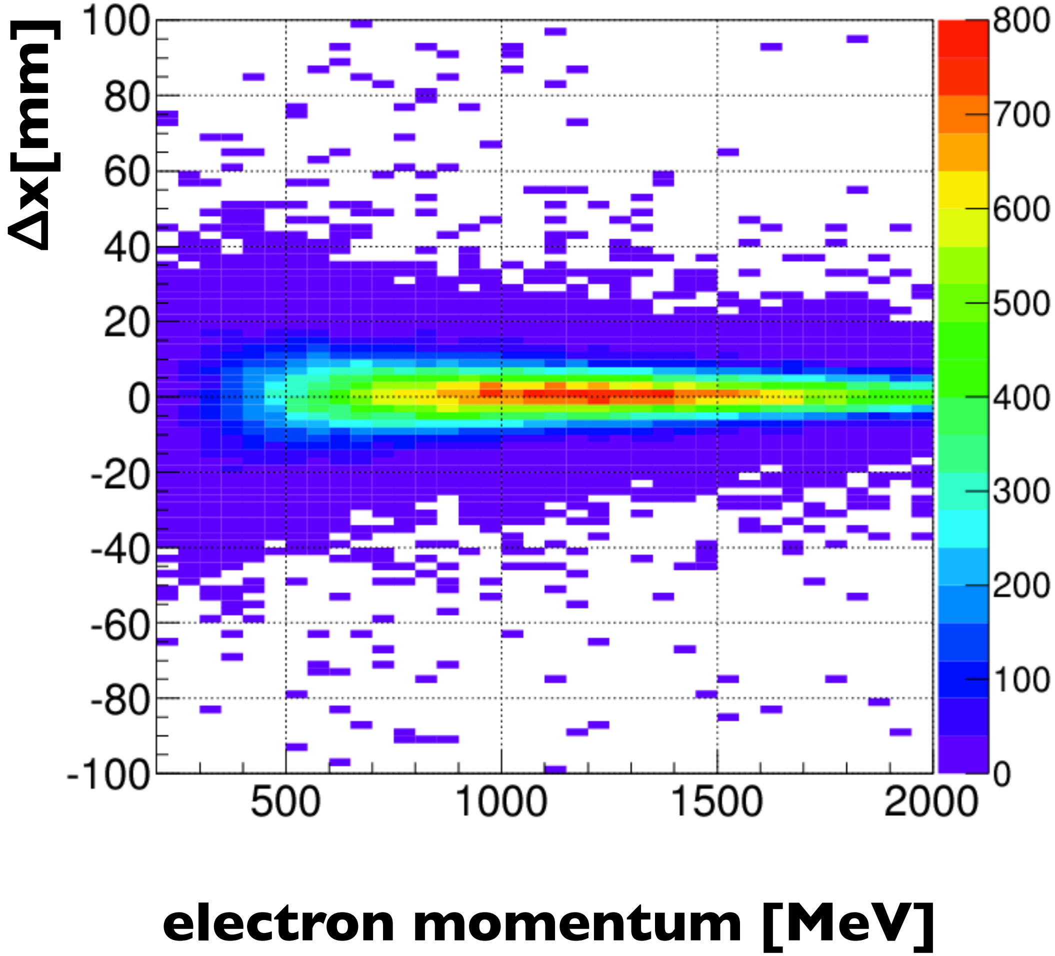
CsI calorimeter resolution

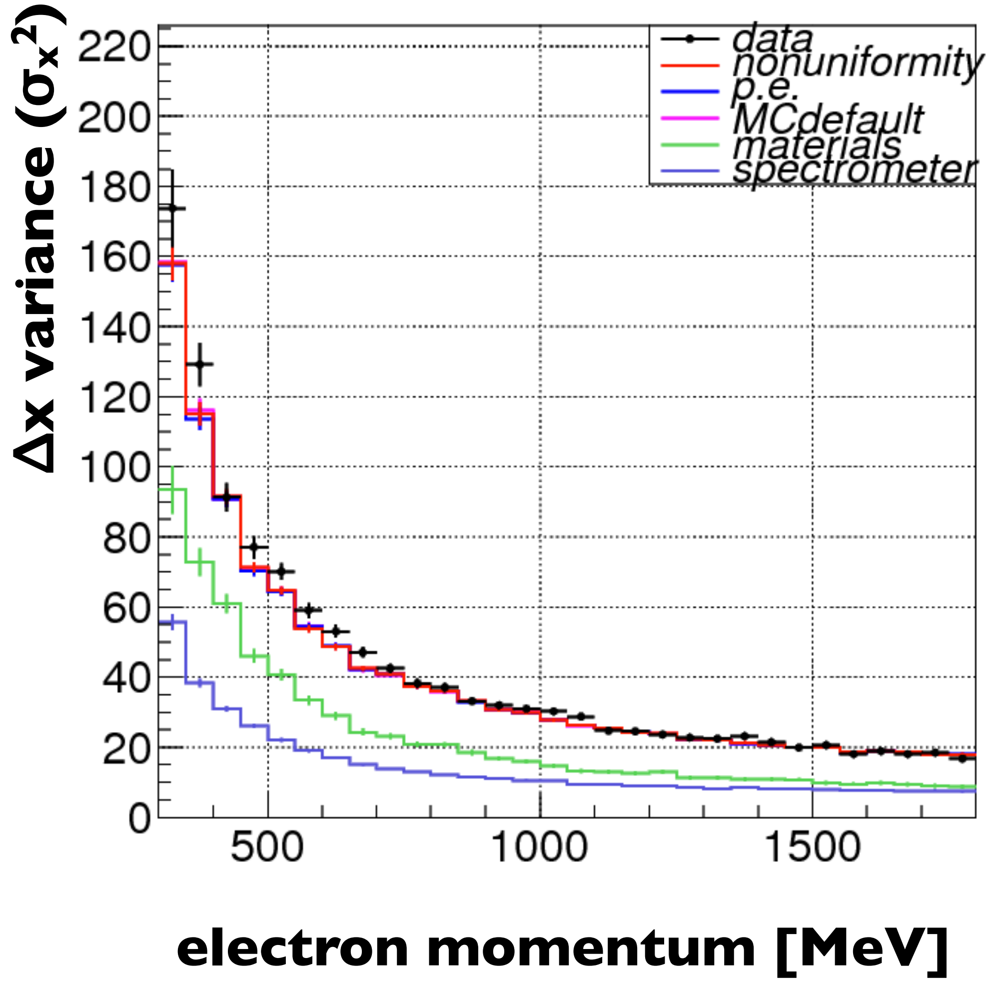


subtract the contribution of materials and spectrometer resolution

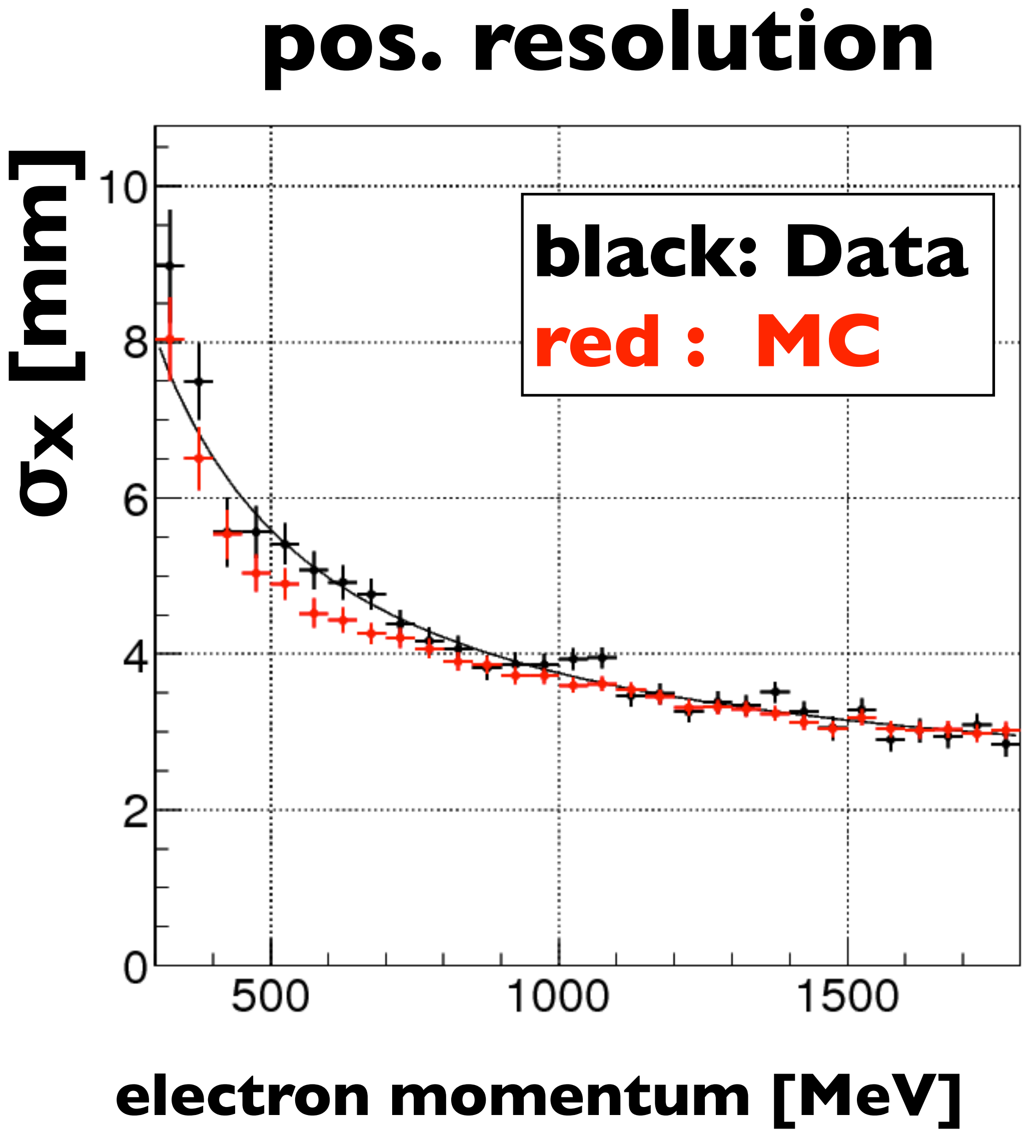
$$\sigma_E/E = 1.9\%/\sqrt{E[\mathrm{GeV}]}$$

pos. resolution





position resolution



subtract the contribution of materials and spectrometer resolution

σ_x [mm]= $1.8 \oplus 2.8/\sqrt{E_{[GeV]}} \oplus 1.73/E_{[GeV]}$

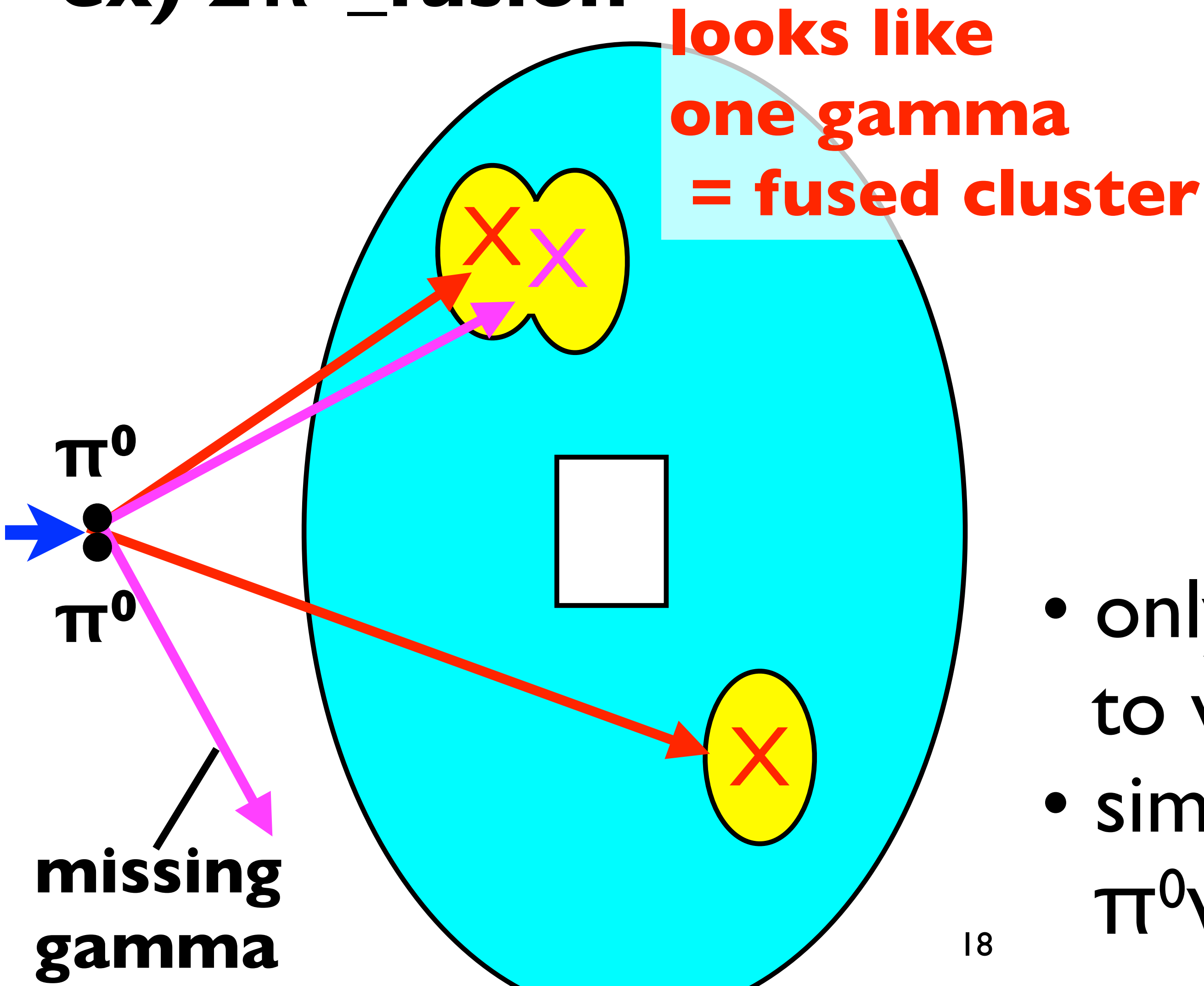
Shower Shape Information

- fusion BG discrimination
- γ angle discrimination

shower shape cut

shower shape information is useful to reject some types of backgrounds

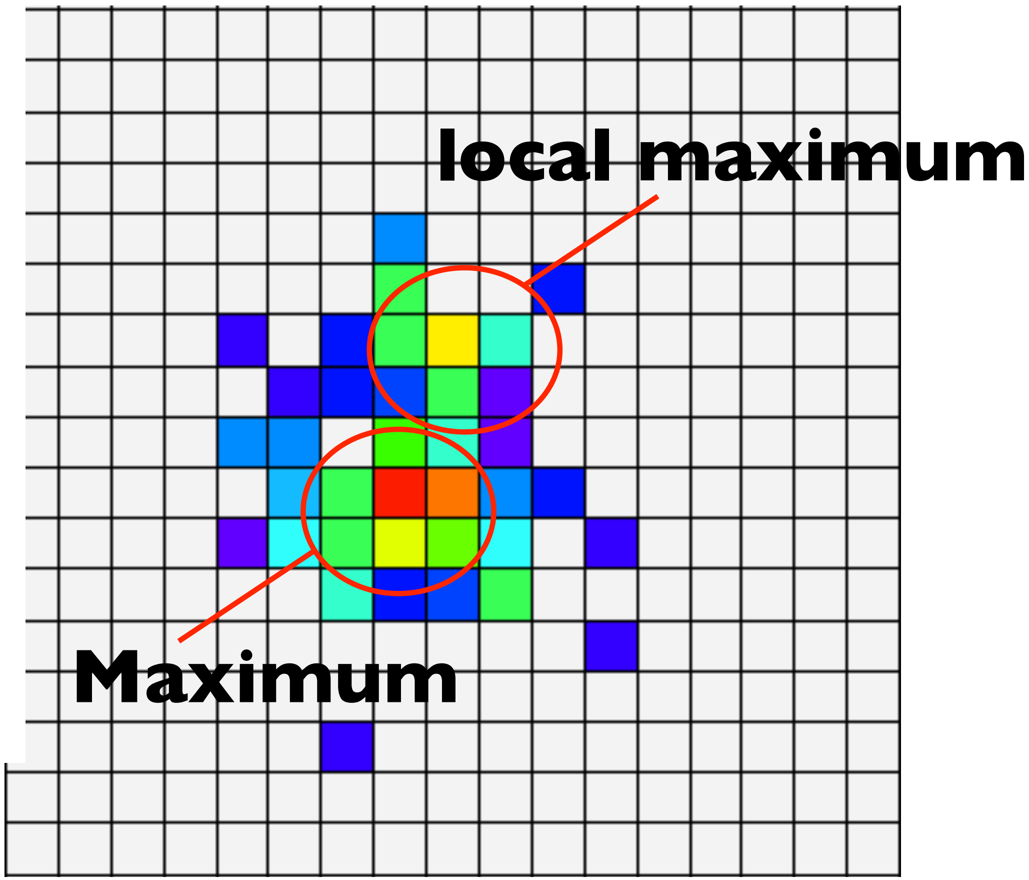
ex) $2\pi^0$_fusion



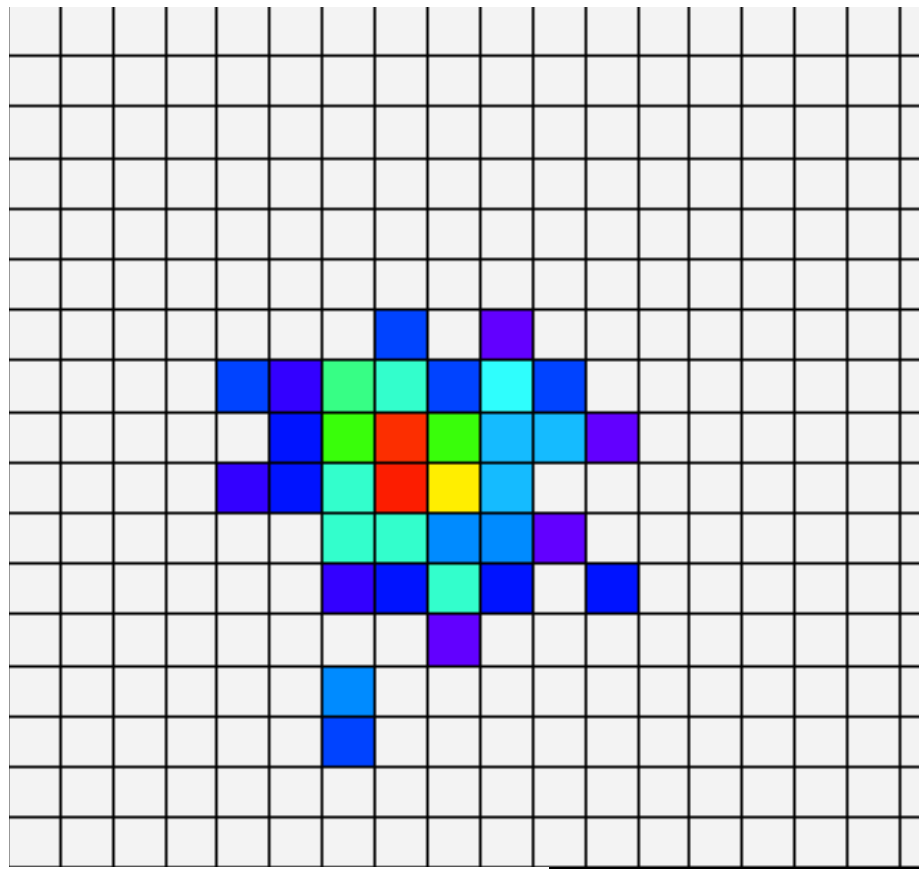
- only 1 extra gamma to veto
- similar kinematics as $\pi^0\nu\nu$

fused cluster

fused cluster



single photon cluster

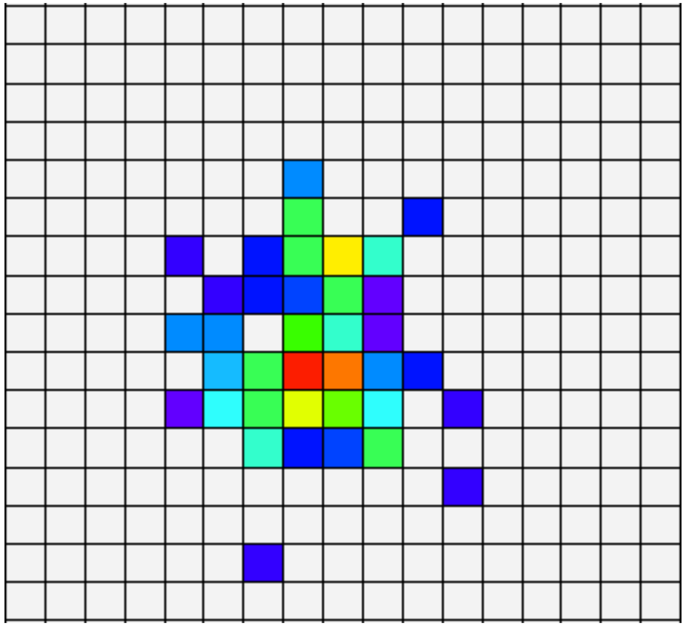


shape χ^2

Observed

observed shower (data)

=E_measured[MeV]

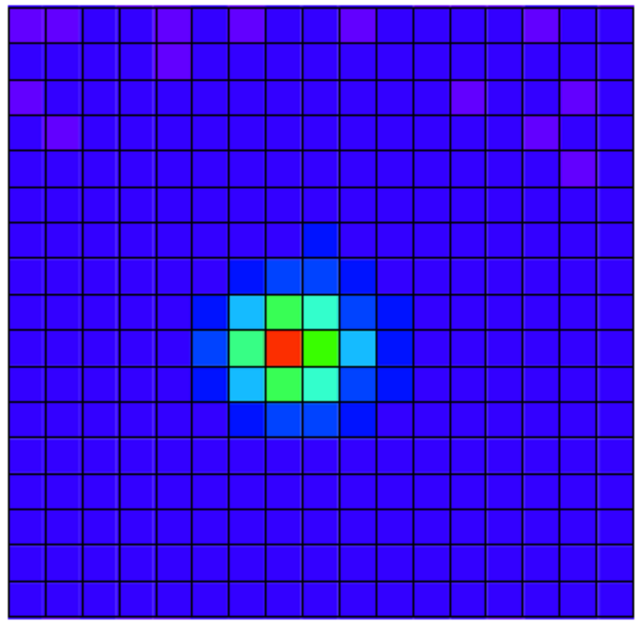


compare

simulation

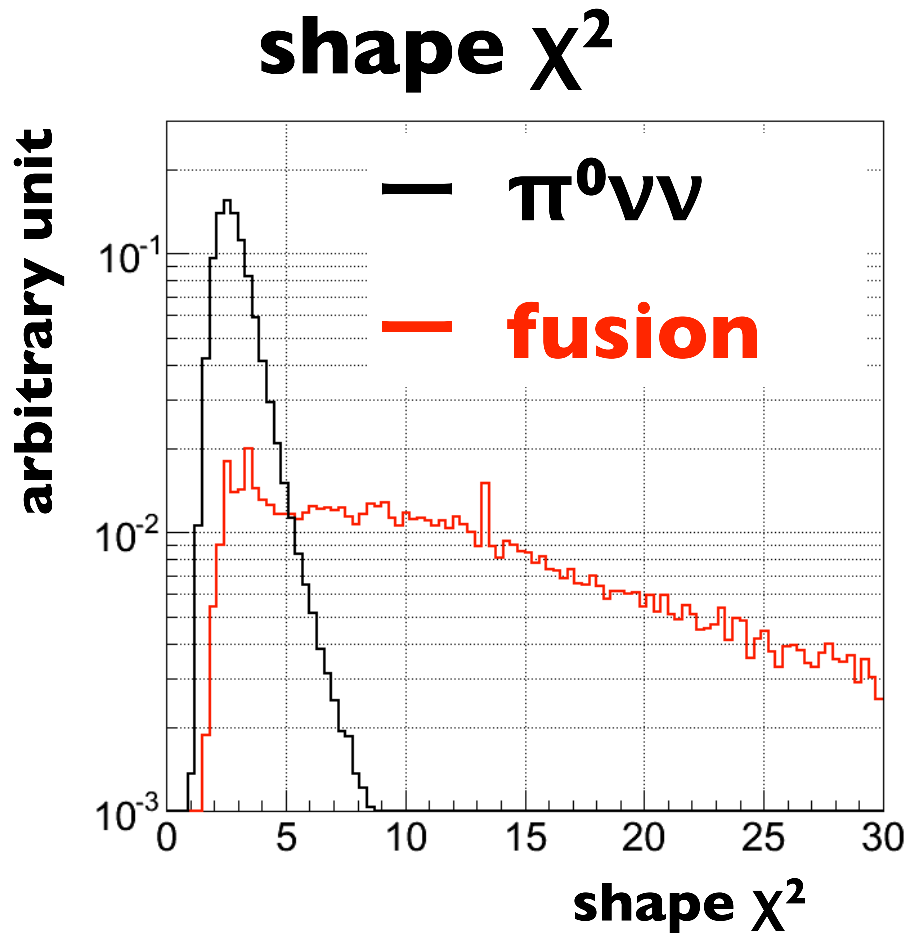
average shower (MC)

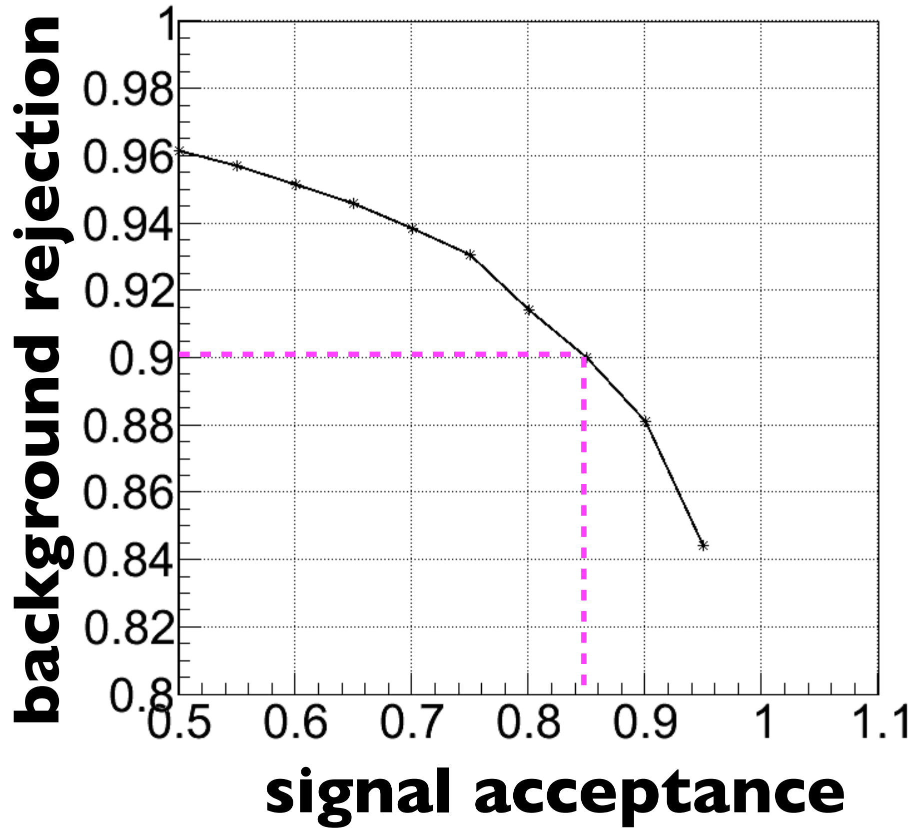
=E_simulated[MeV]



$$\chi^2 = \sum_{CsI} \left(\frac{E_{measured} - E_{simulated}}{RMS_{simulated}} \right)^2$$

fusion BG suppression



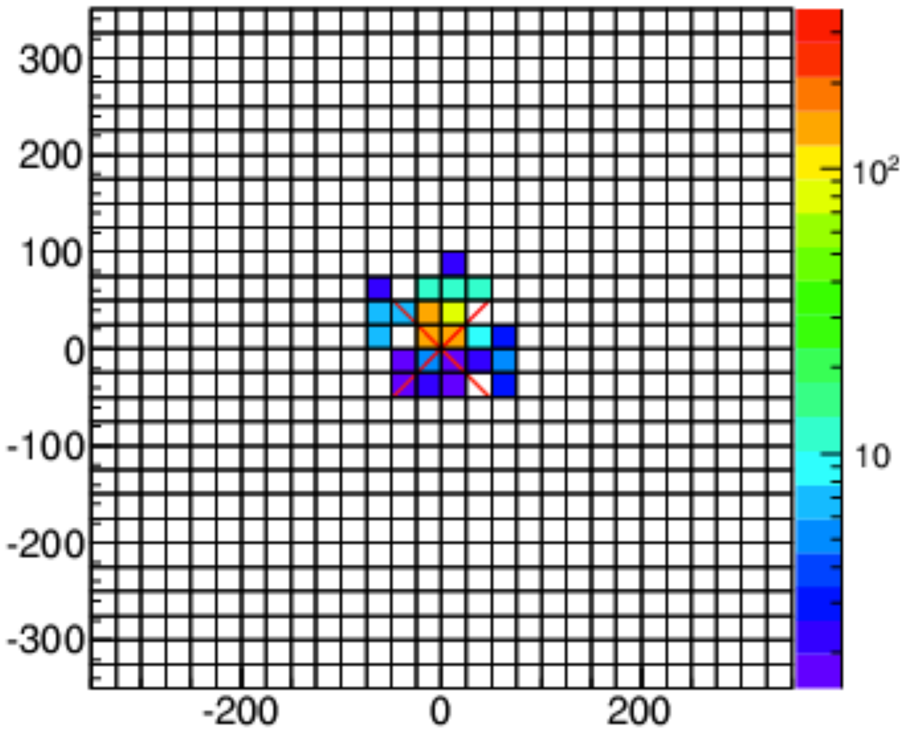


90% BGs are rejected with 85% signal acceptance

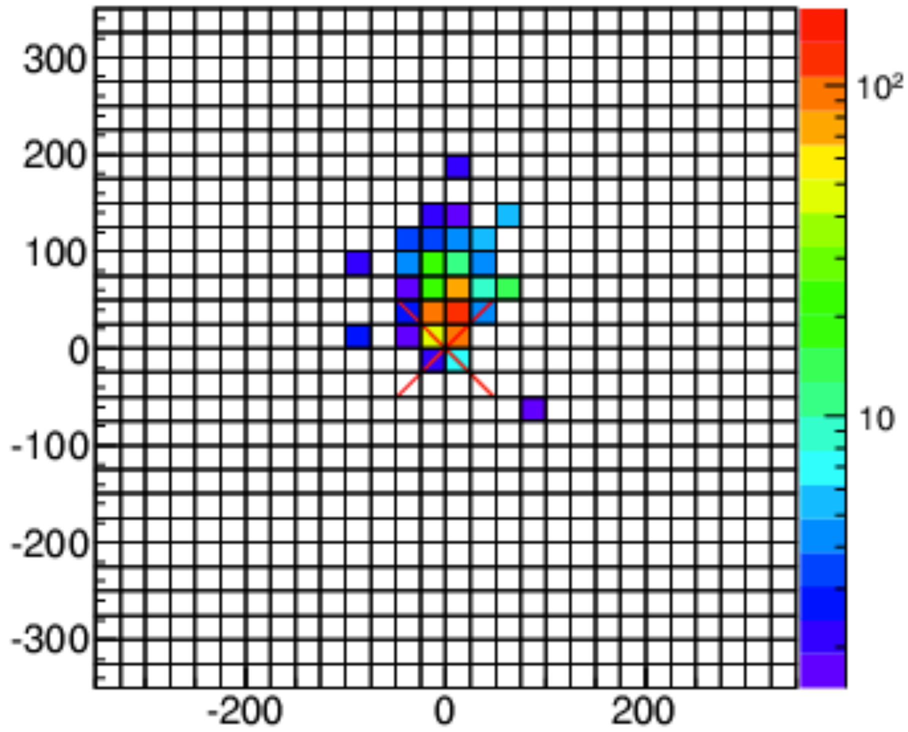
γ angle from shower shape

can derive γ incident angle from shower shape

θ = 10 deg



θ = 30 deg

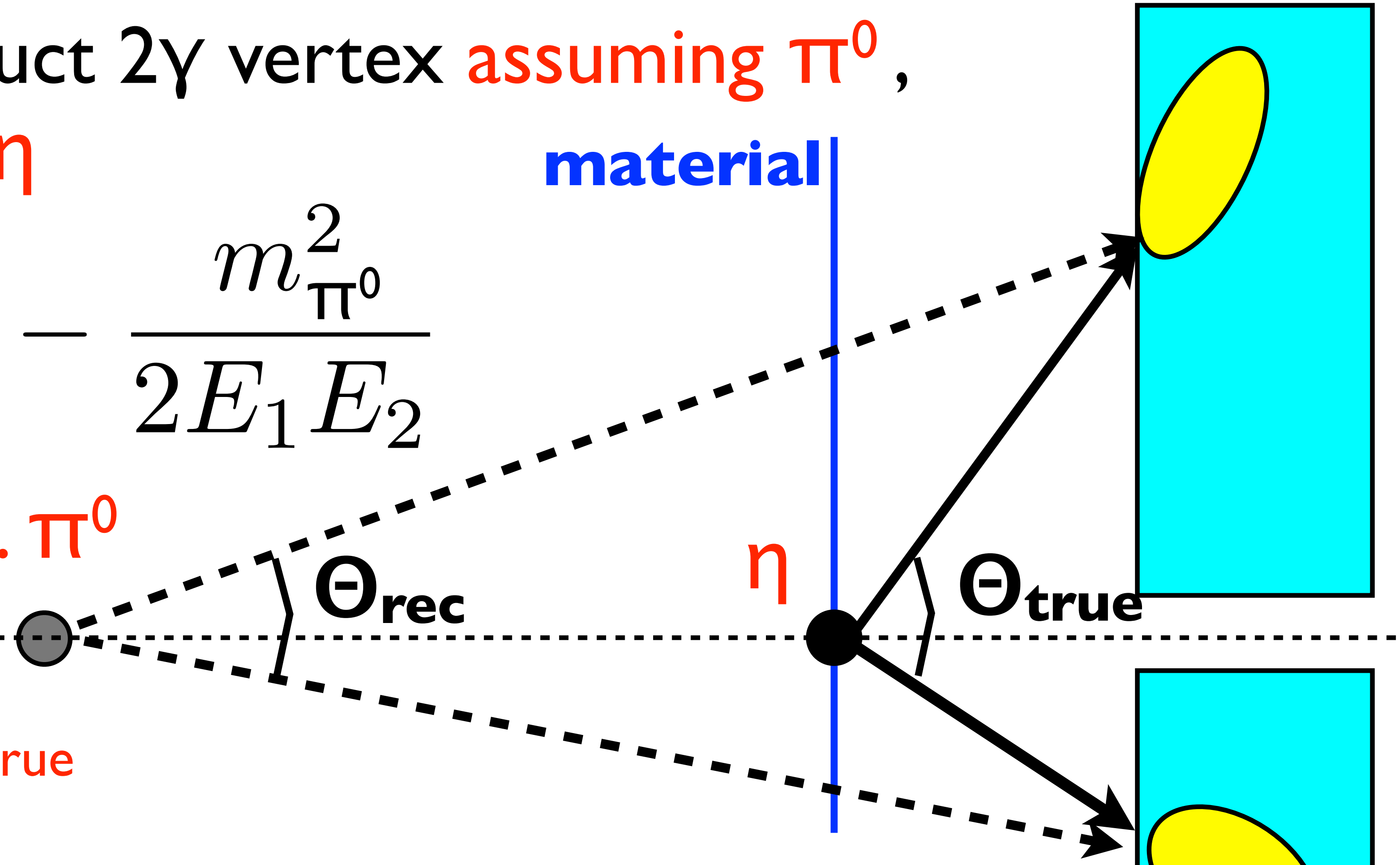


η background

ex) beam neutron interacts with material ⇒ $\eta \to 2\gamma$

we reconstruct 2γ vertex assuming π^0,
but actually η

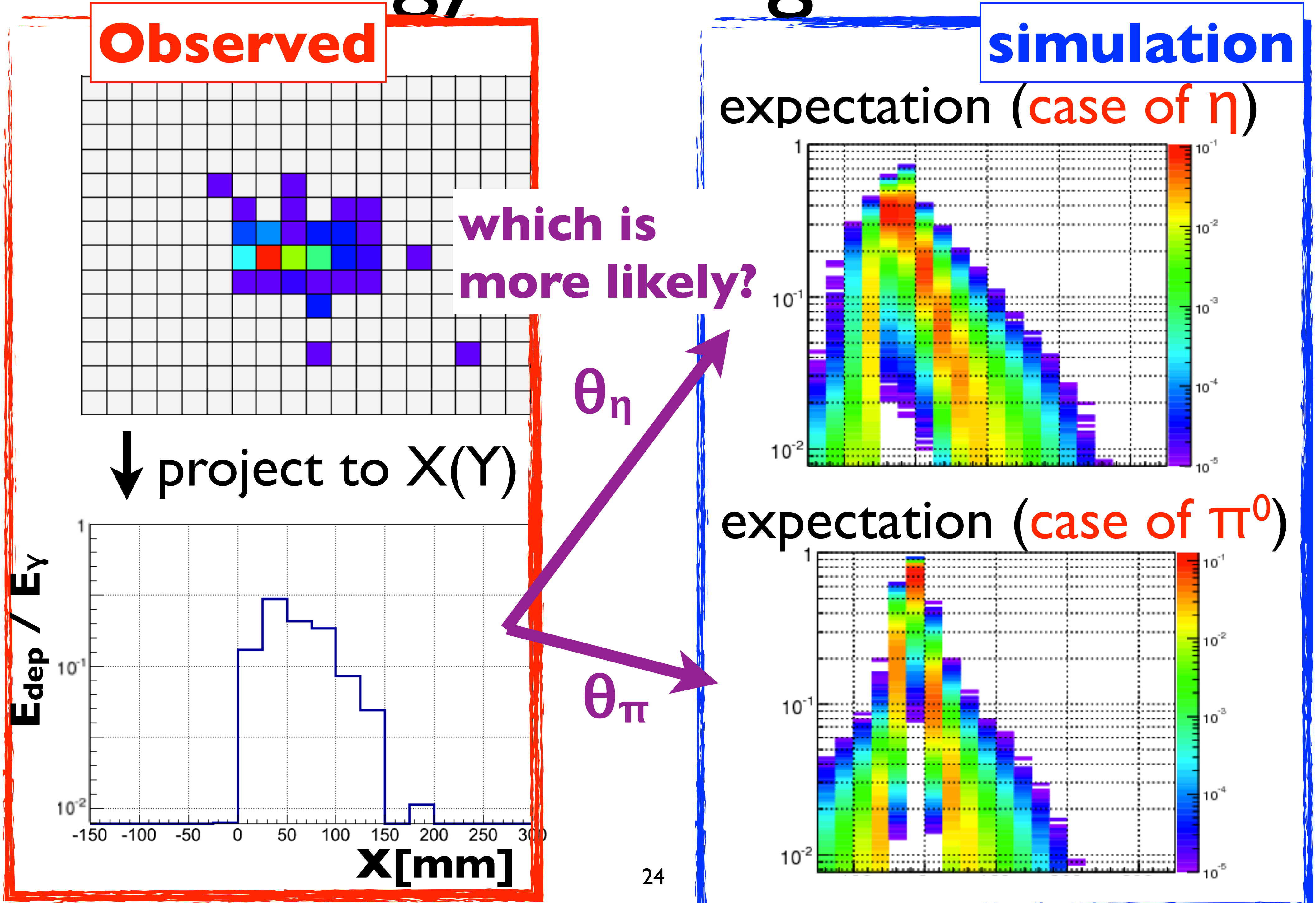
$$\cos\theta = 1 - \frac{m_{\pi^0}^2}{2E_1E_2}$$



$\Theta_{rec} < \Theta_{true}$

⇒**angle discrimination helps π^0 identification**

strategy for angle discri.



likelihood

calculate Likelihood
for each assumption (L_π, L_η)

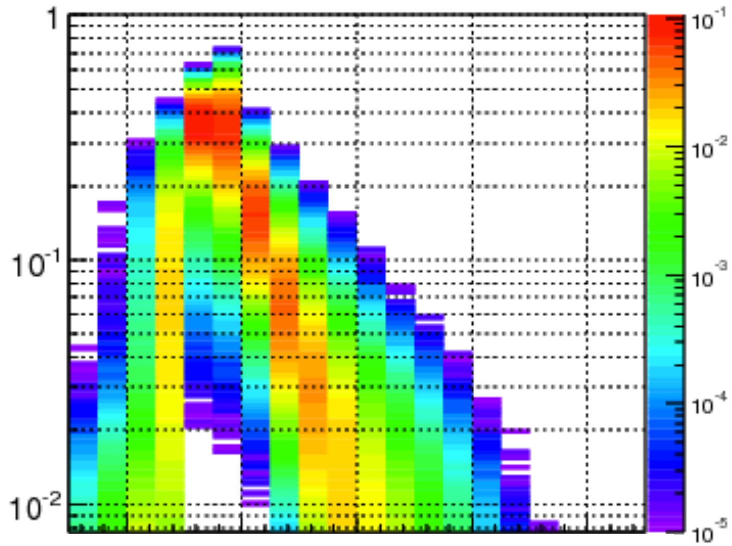
$$L_i = \prod_{j;\gamma} \prod_{x,y} \prod_{k;\text{row}} P(e_k | E_j, d_k, \theta_{ij}, \phi_j)$$

(i=π,η)

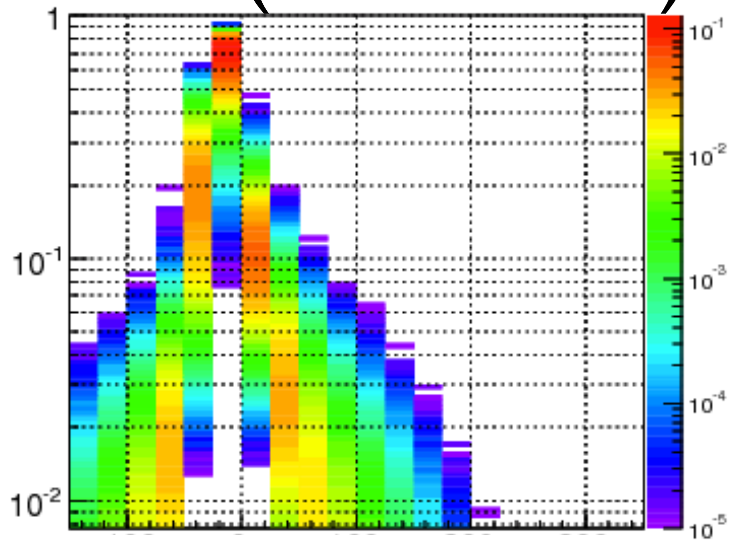
PDFs are prepared
for various E, Φ, θ

simulation

2D PDF (case of η)



2D PDF (case of π^0)

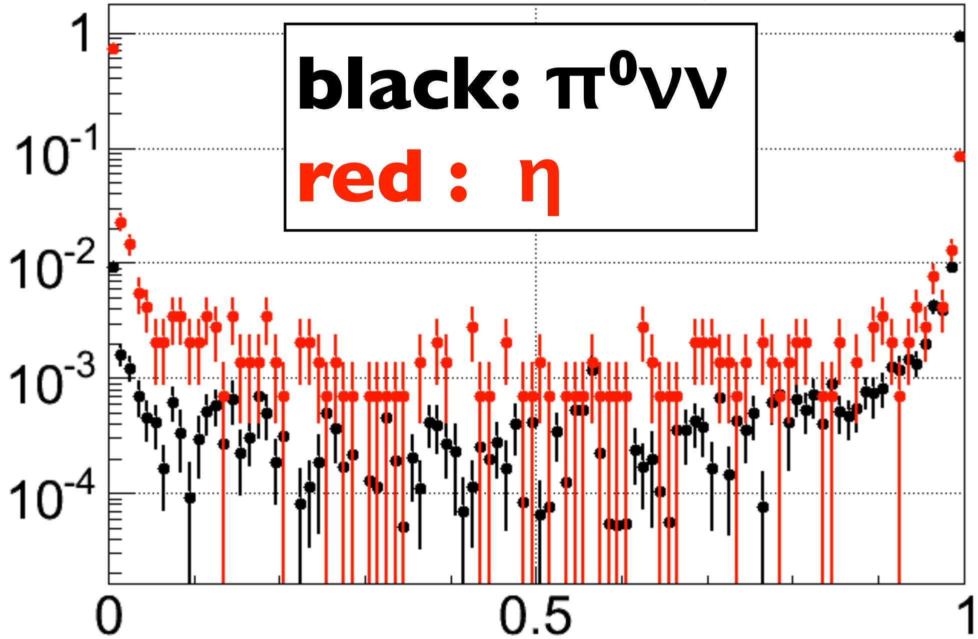


likelihood ratio

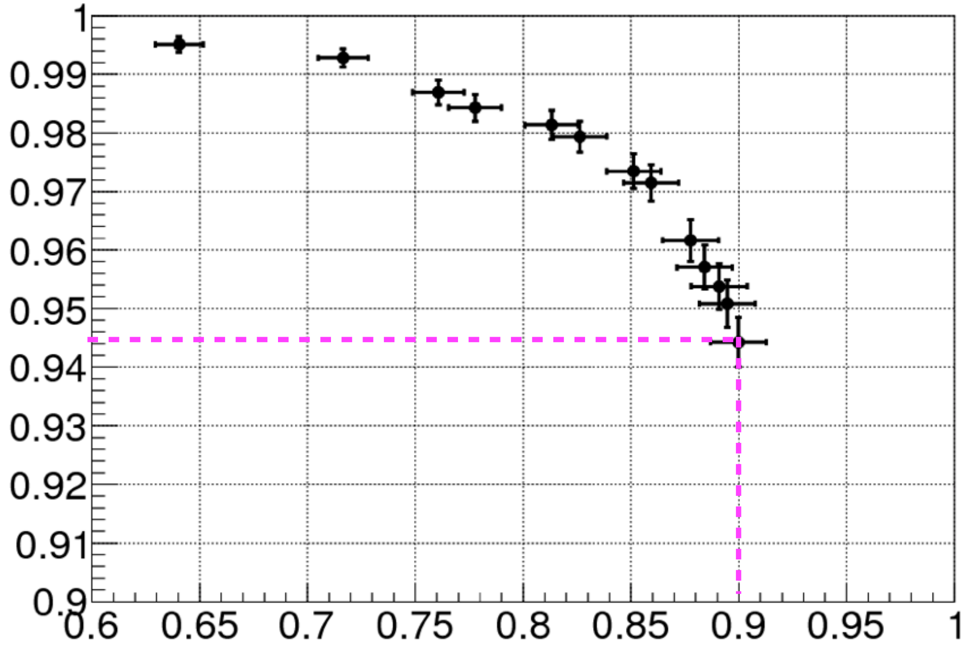
apply cut for likelihood ratio

$$\frac{L_{\pi^0}}{L_{\pi^0} + L_\eta}$$

η BG rejection



likelihood ratio



signal acceptance

94% of η BGs can be rejected with 90% efficiency

summary

- **KOTO** = **measurement for $K_L \to \pi^0 \nu\nu$**
  - observe **2γ** from π^0 with the **CsI calorimeter**
- beam test in 2012

$\sigma_E/E = 1.9\%/\sqrt{E[GeV]}$

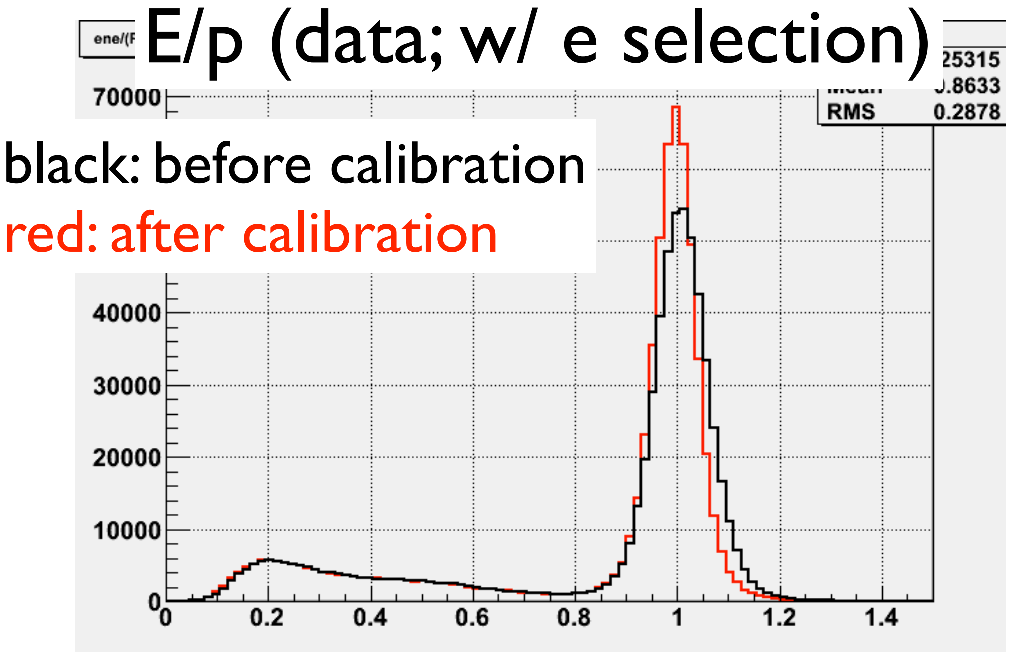
σ_x [mm] $= 1.8 \oplus 2.8/\sqrt{E[GeV]} \oplus 1.73/E[GeV]$

- **shower shape information** is useful
  - shape chi2
    - 2π0 fusion BG → x 1/10 (85% signal acc.)
  - angle discrimination
    - η BG → x 1/20 (90% signal acc.)

back up

ene. and pos. resolution

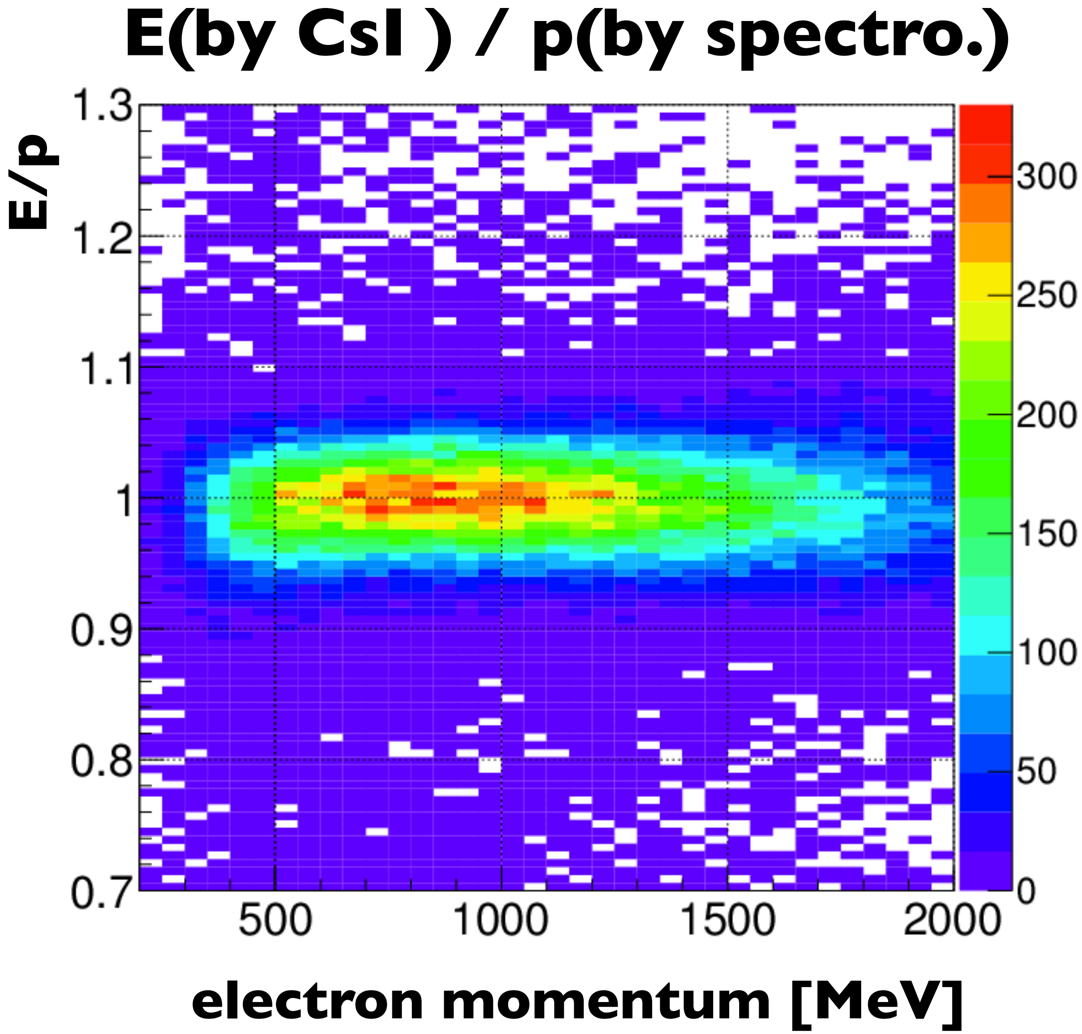
calibration constant

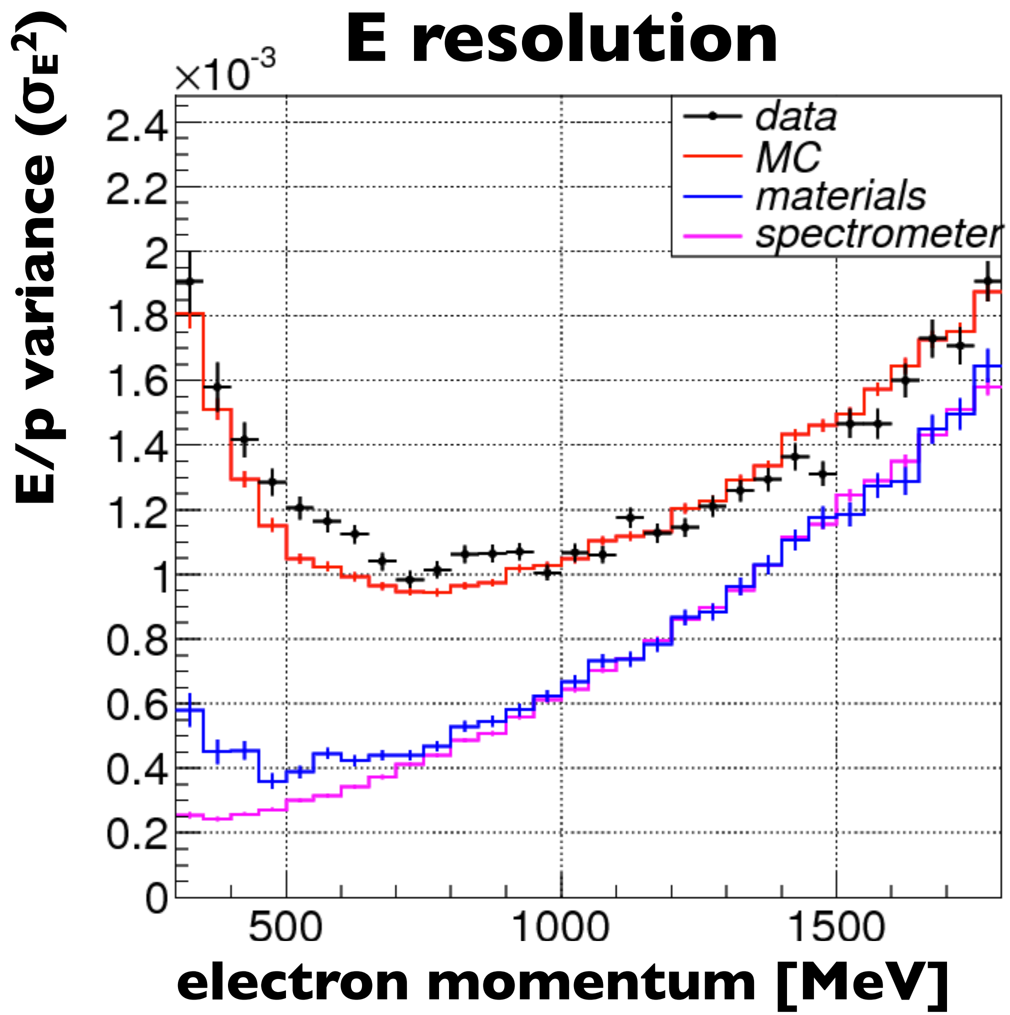


- in data analysis,
CsI calibration constants are decided using Ke3 calibration method.

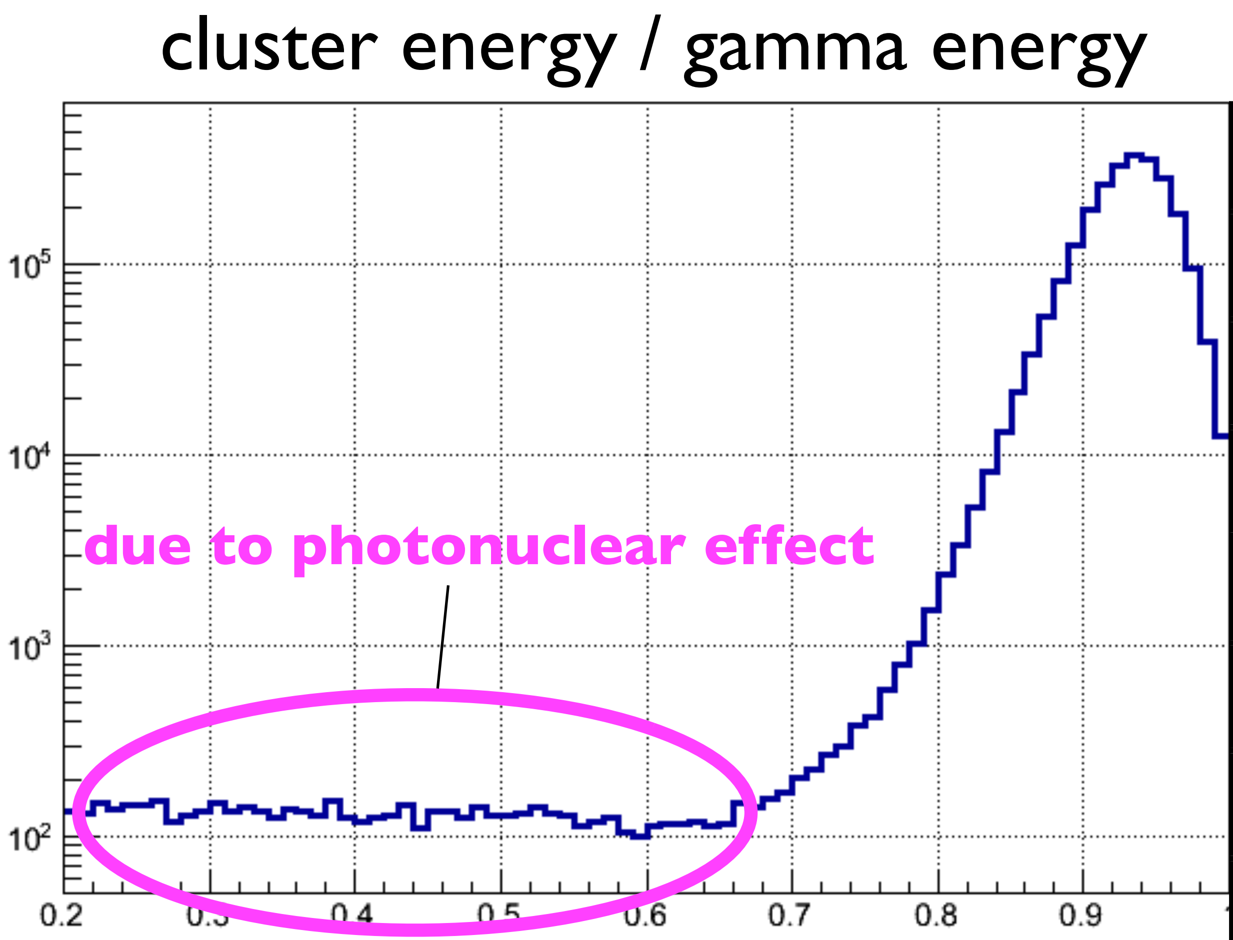
$$\chi^2 = \sum_{event} \left(\frac{E_{chamber} - E_{CsI}}{\sigma}\right)^2$$

E resolution





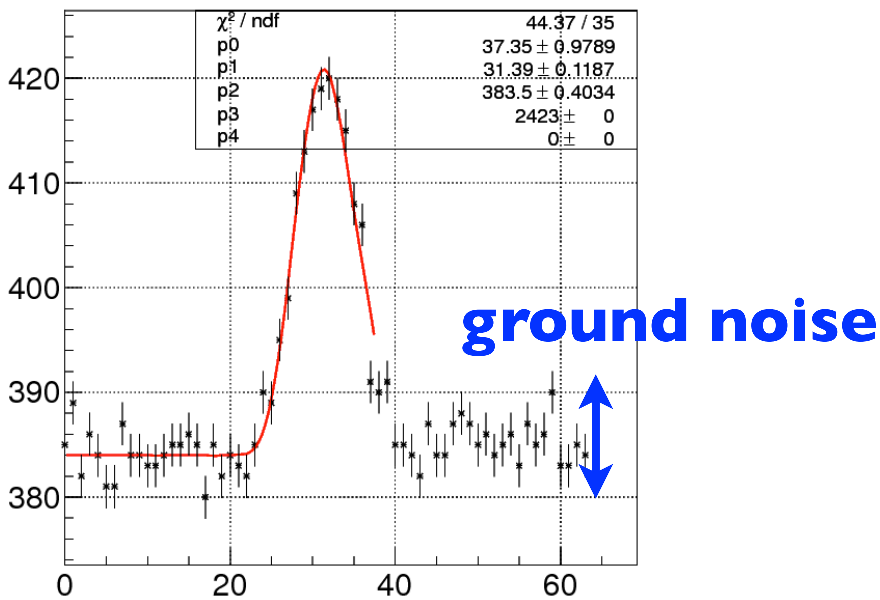
source of energy (MC study)



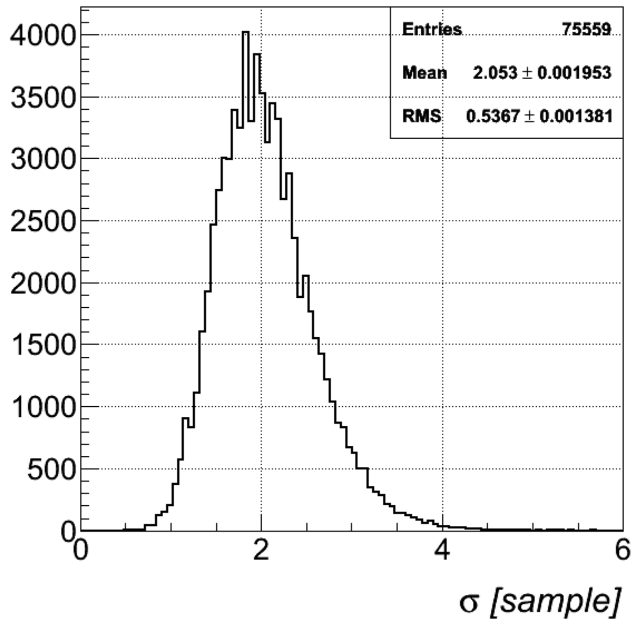
photonucl.	1.3%
backsplash	0.25%
shower leak	0.4%
threshold	1.6%
clustering	0.95%
p.e. fluctuation	1.3%
nonuniformity	0.85%
ground noise	0.2%

FADC ground noise

- FADC pedestal fluctuates due to ground noise (σ~2.05cnt) = ~ 0.2MeV

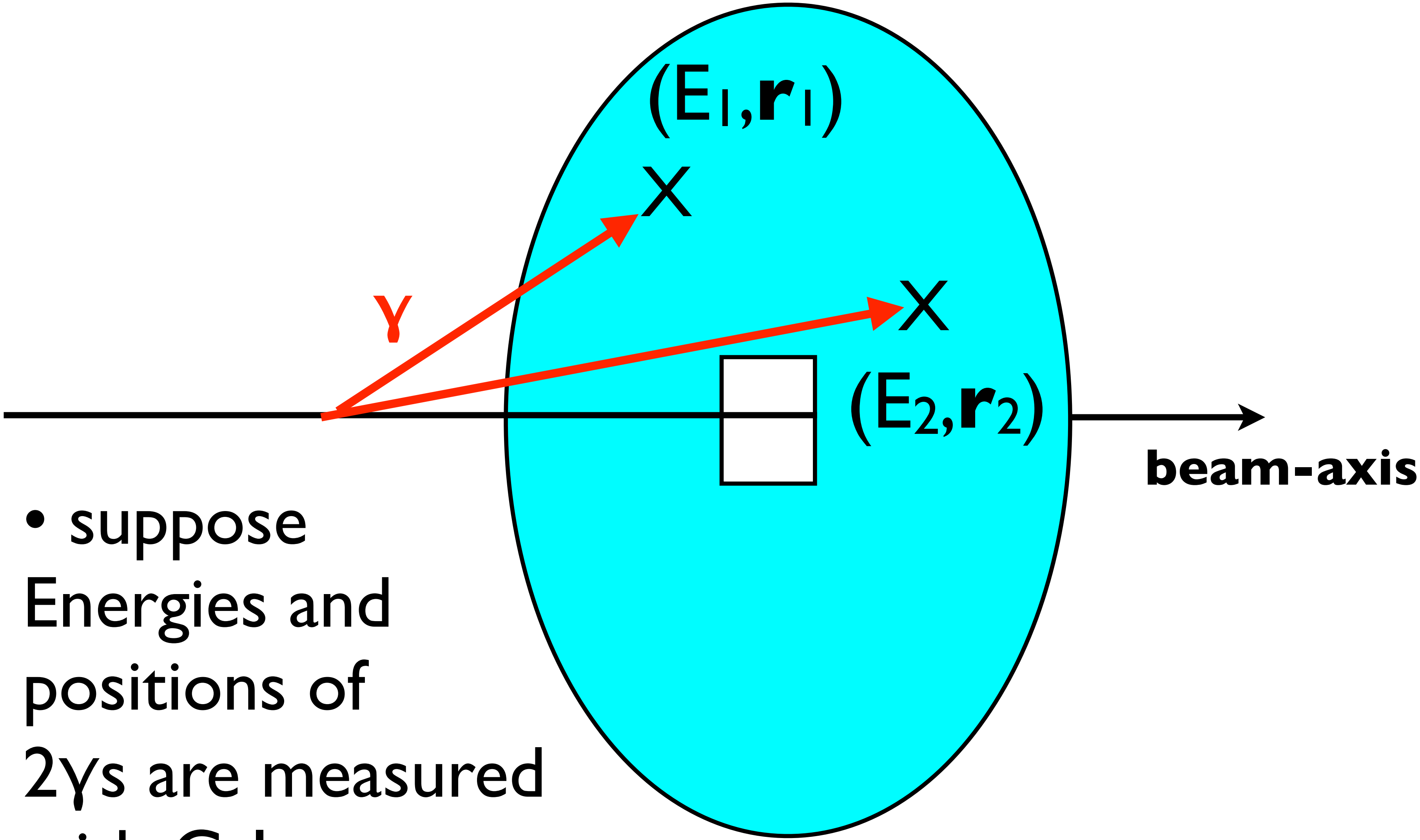


RMS of ground noise



pi0 reconstruciton

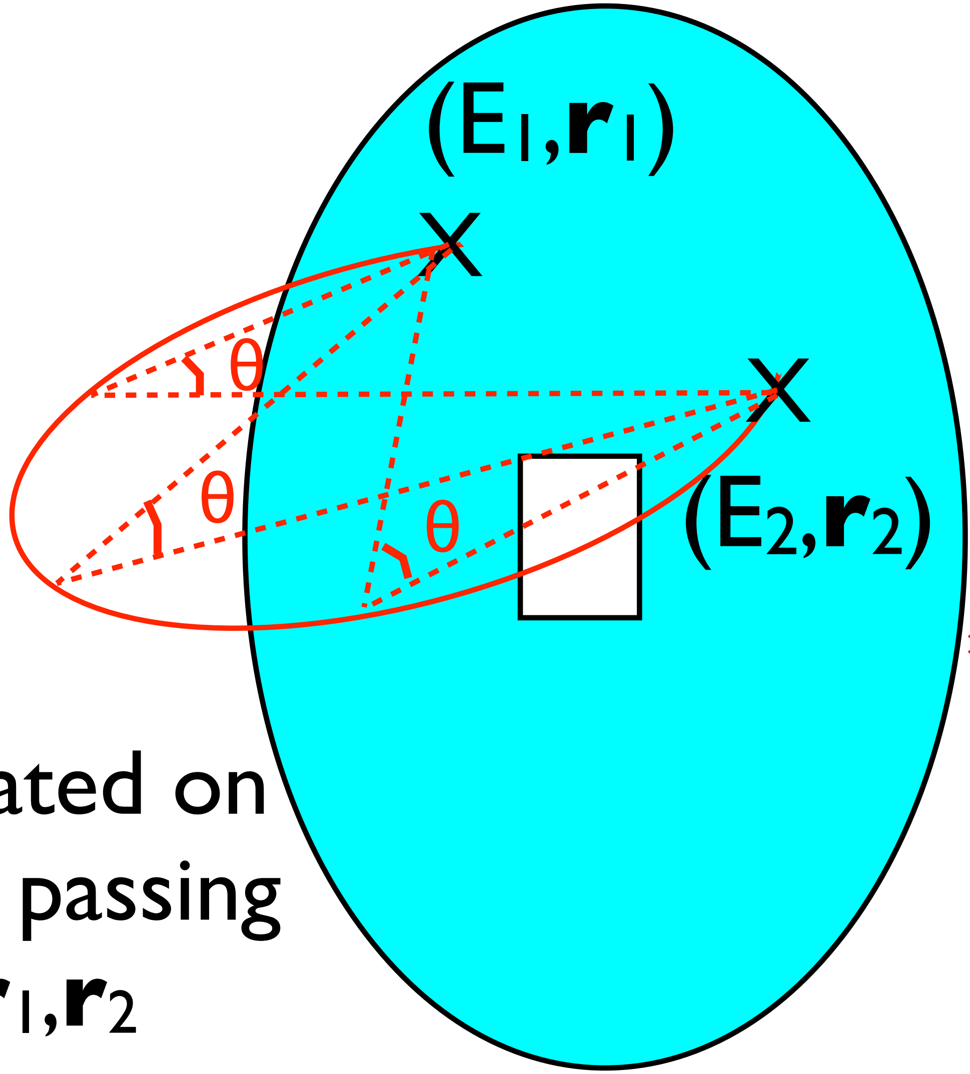
how to reconstruct π^0



- suppose Energies and positions of 2γs are measured with CsI

CsI calorimeter

how to reconstruct π^0



assuming...

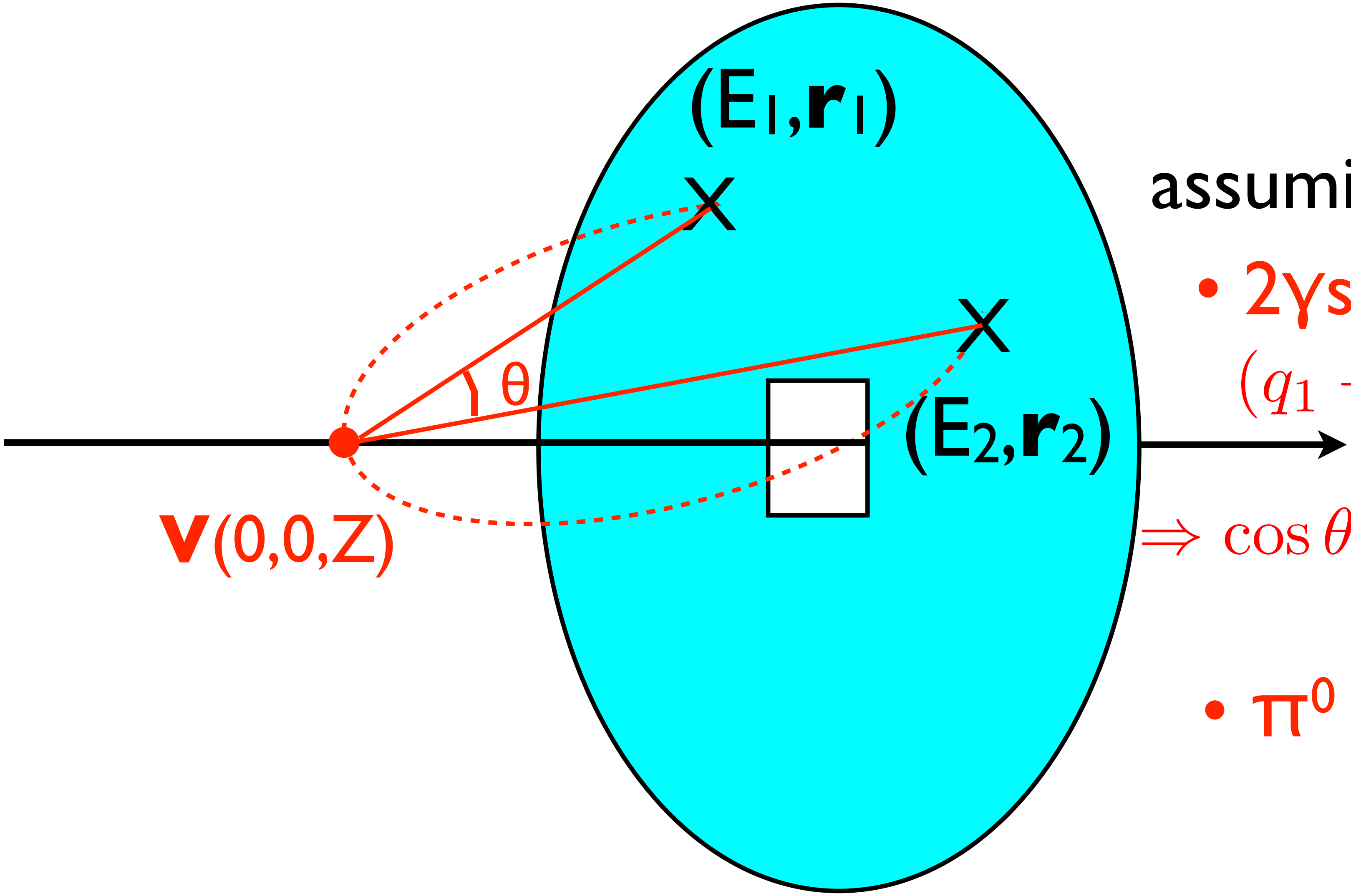
- 2γs from π^0

$$(q_1 + q_2)^2 = m_{\pi^0}$$

$$\Rightarrow \cos\theta = 1 - \frac{m_\pi^2}{2E_1E_2}$$

π^0 generated on the circle passing through $\mathbf{r}_1, \mathbf{r}_2$

how to reconstruct π^0



assuming...

- 2γs from π^0

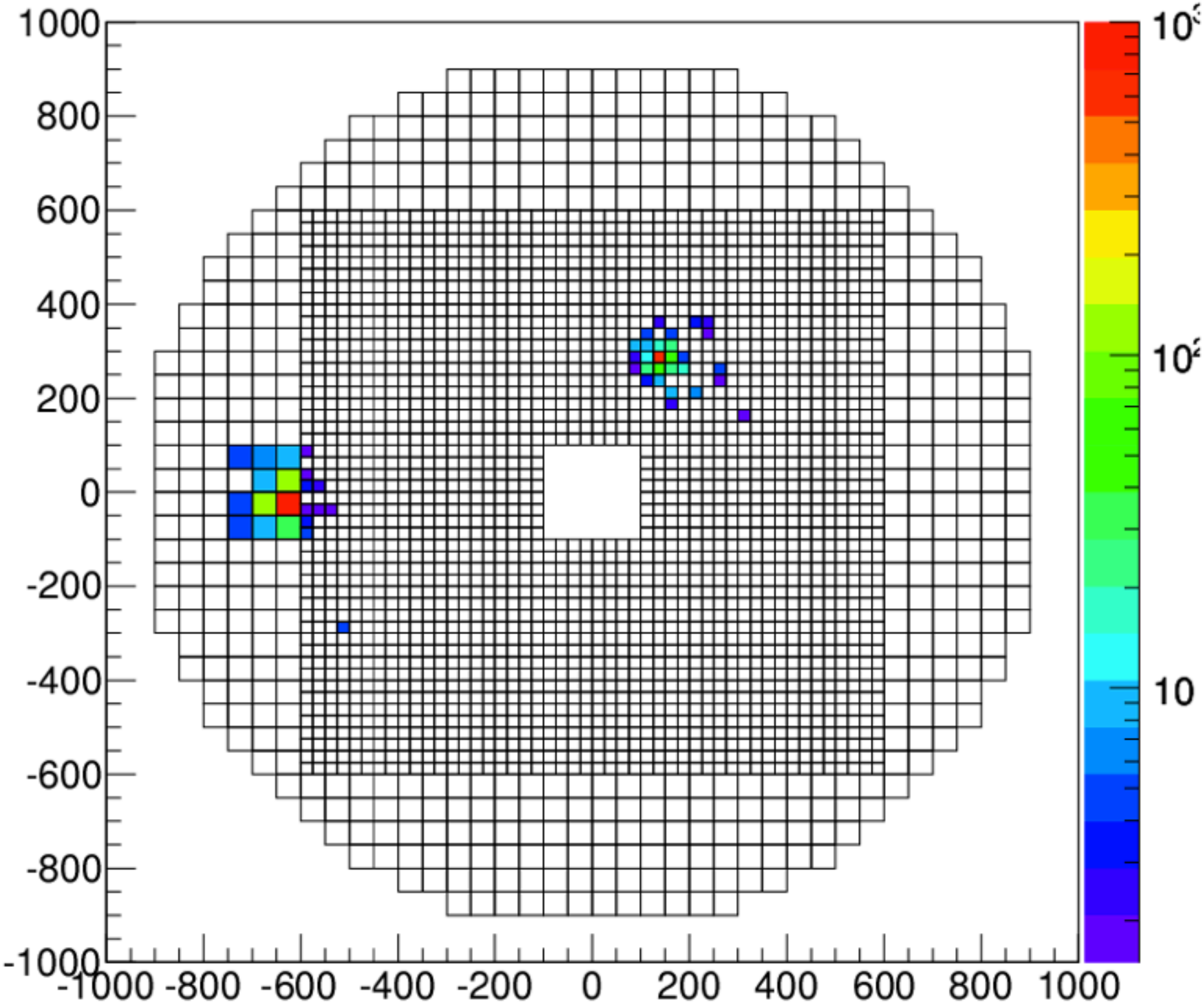
$$(q_1 + q_2)^2 = m_{\pi^0}$$

$$\Rightarrow \cos\theta = 1 - \frac{m_\pi^2}{2E_1E_2}$$

- π^0 on beam-axis

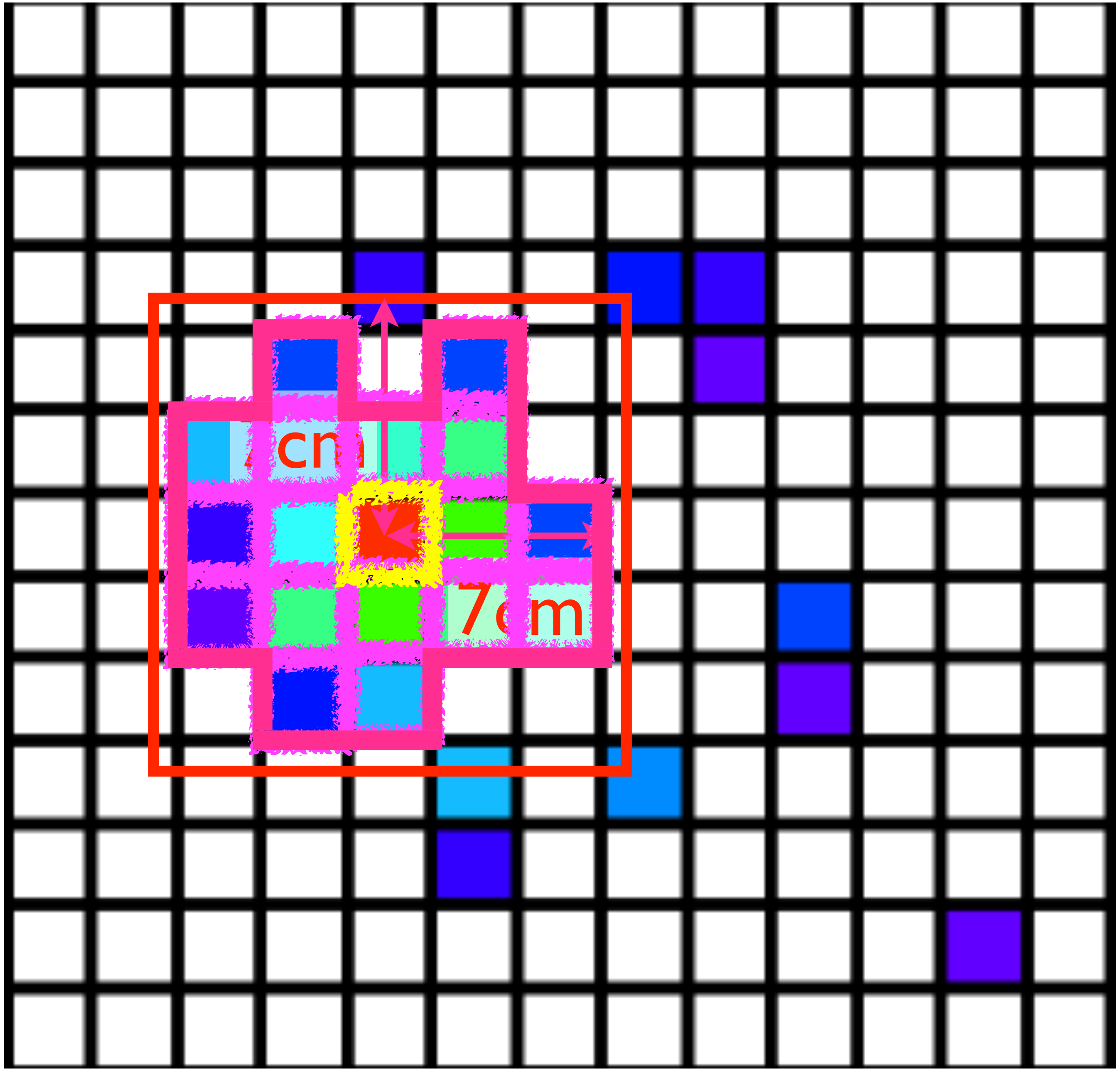
clustering procedure

clustering

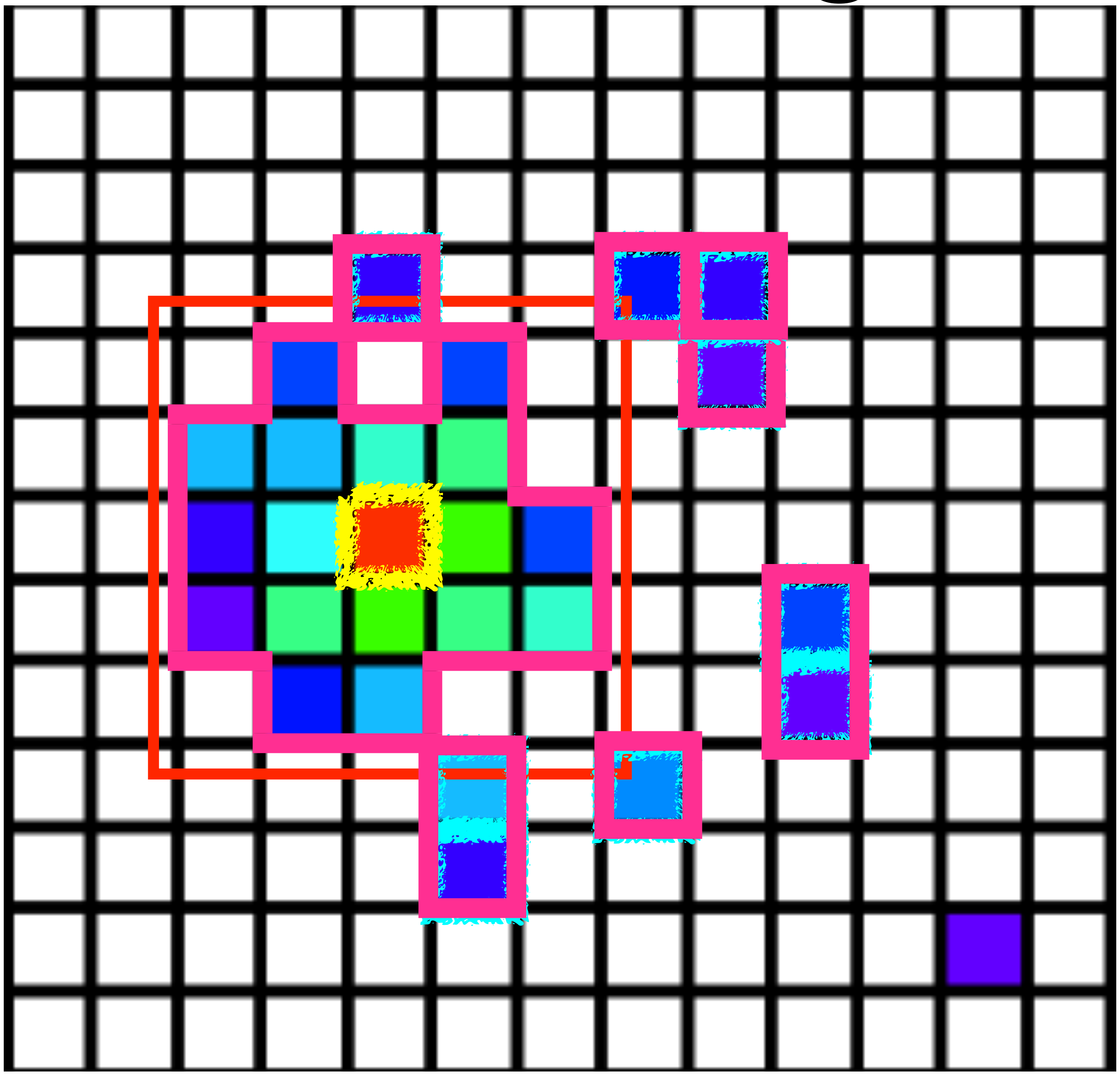


1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1000 -800 -600 -400 -200 0 200 400 600 800 1000
10^3
10^2
10

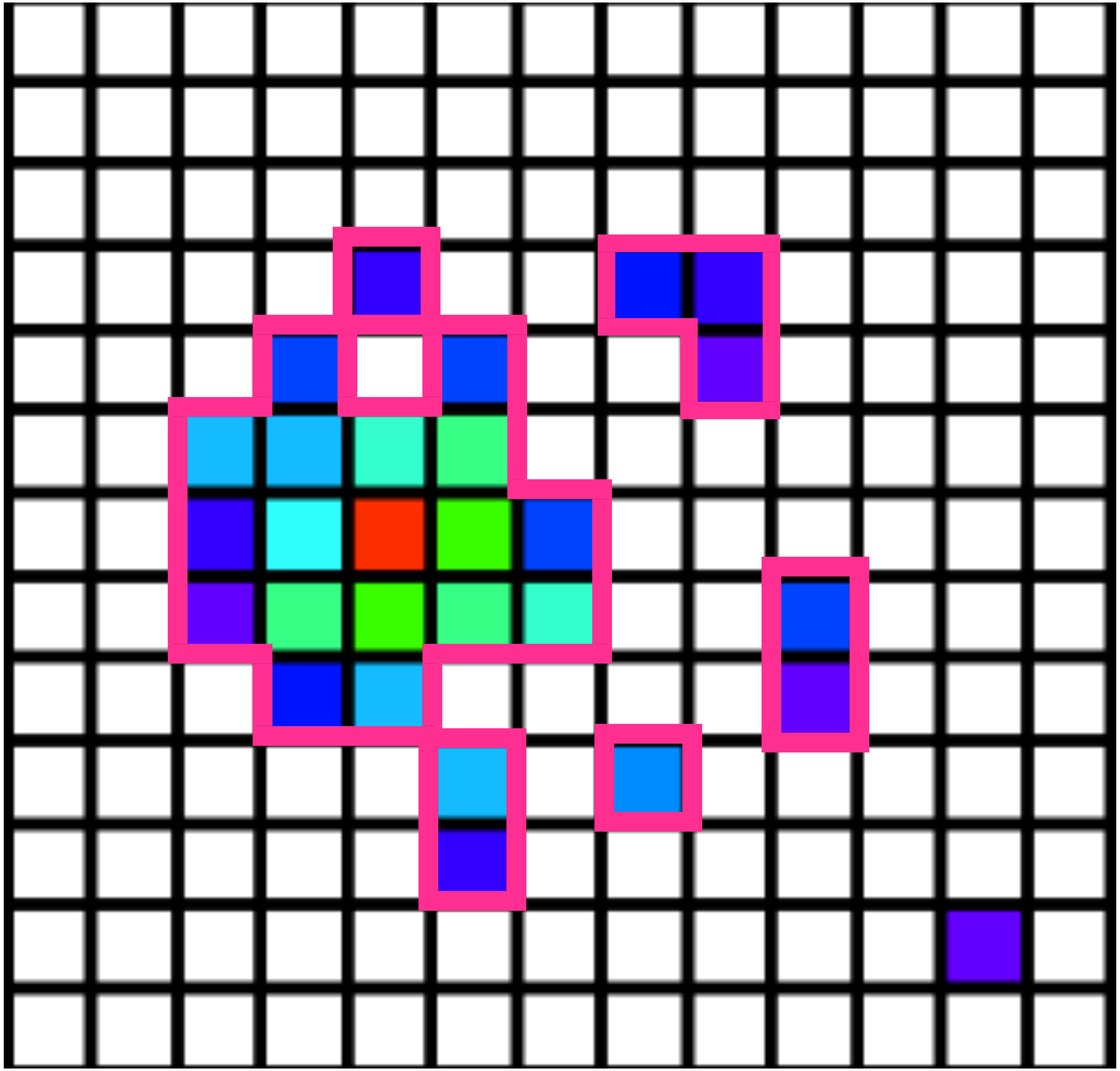
clustering



clustering

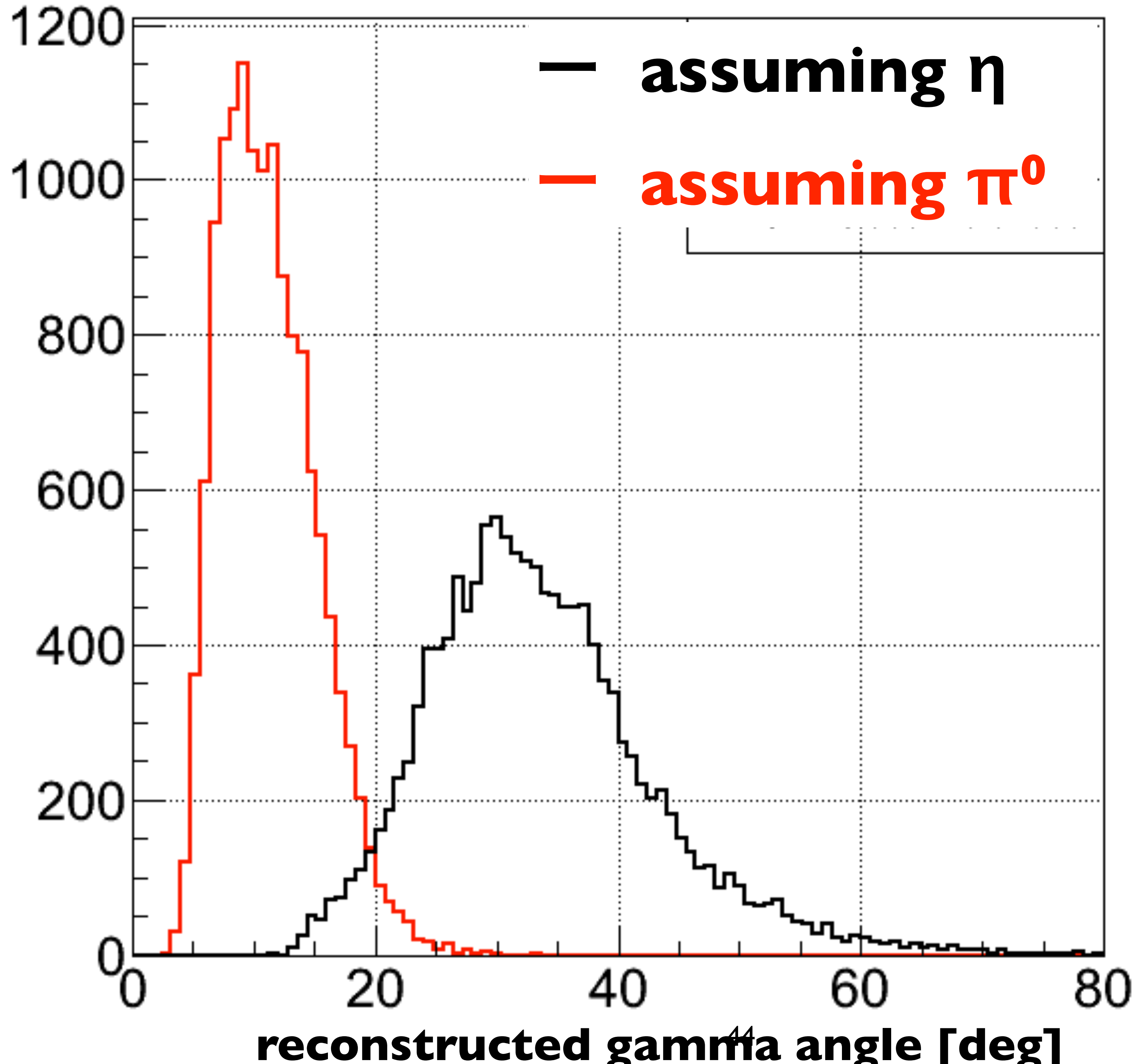


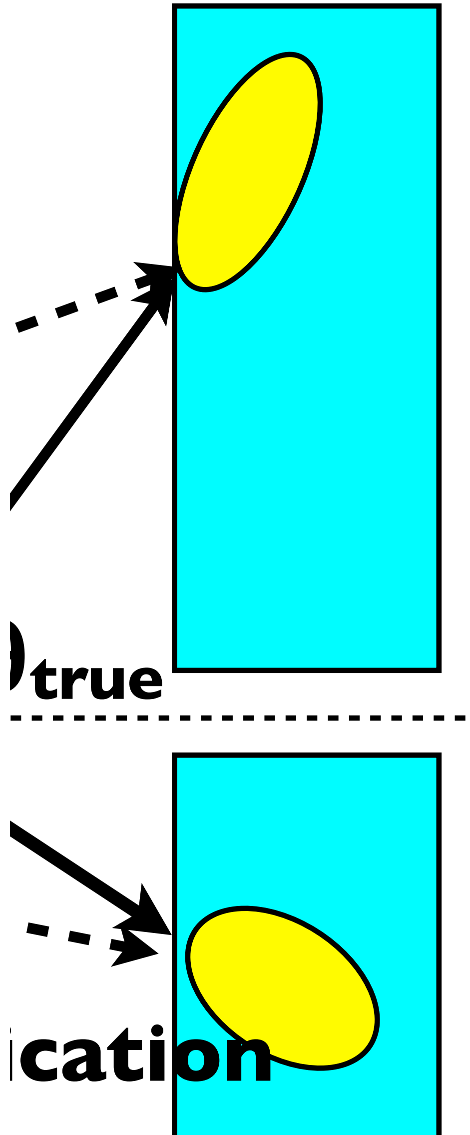
clustering



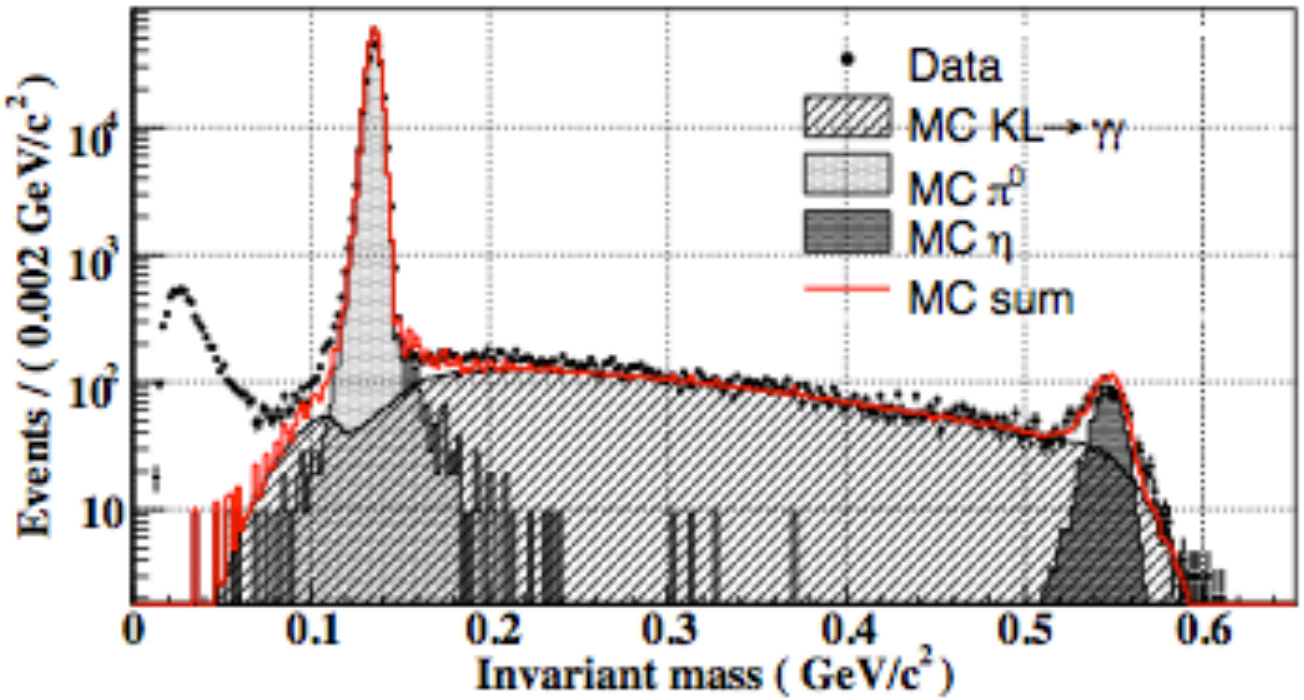
η backgrounds

impact of angle discrimination





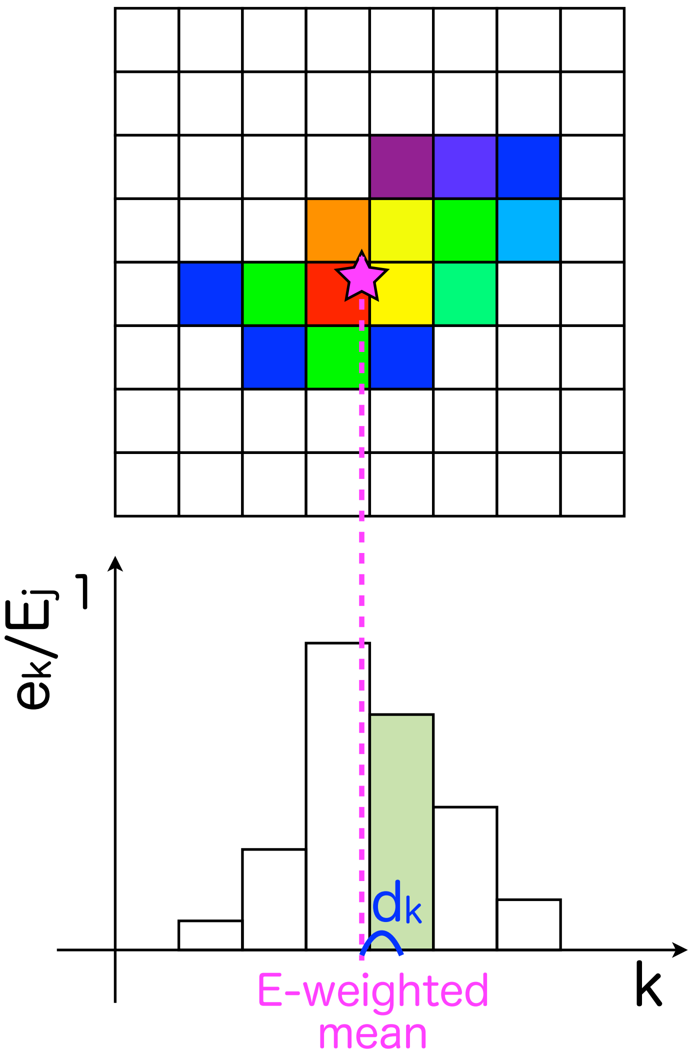
MC reproduction



Al target run in E391A

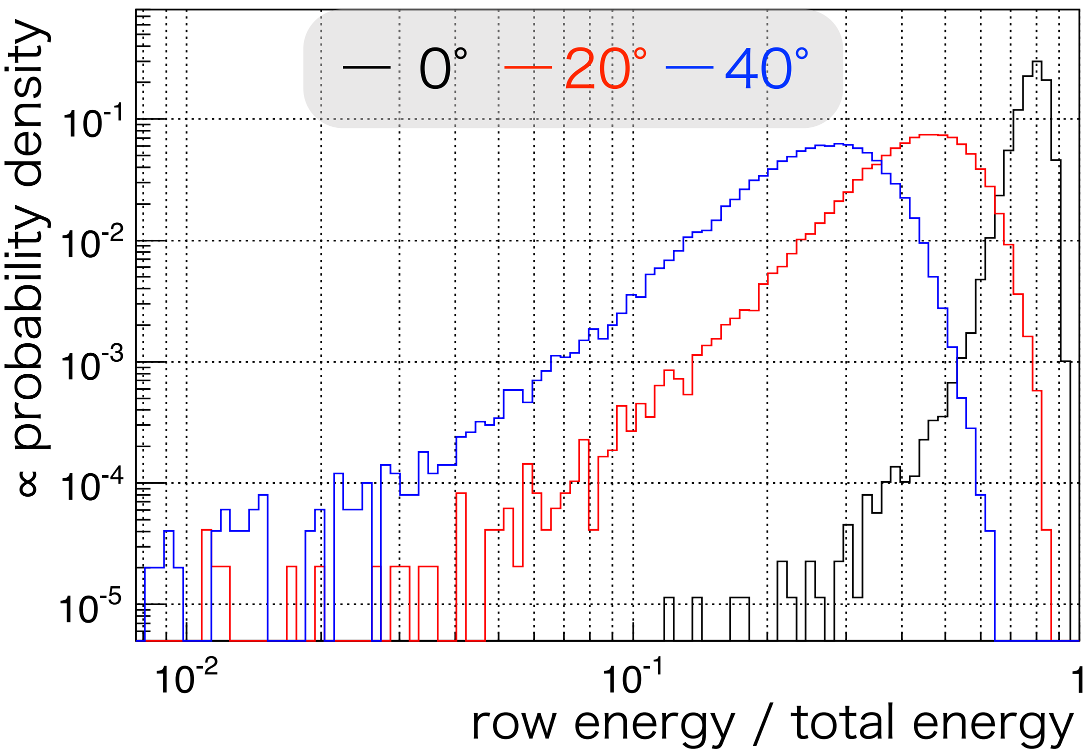
Probability Density Function

prepare PDF for each incident angle



$$L_i = \prod_{j;\gamma} \prod_{x,y} \prod_{k;\mathrm{row}} P(e_k | E_j, d_k, \theta_{ij}, \phi_j)$$

PDF in a certain condition for each incident angle

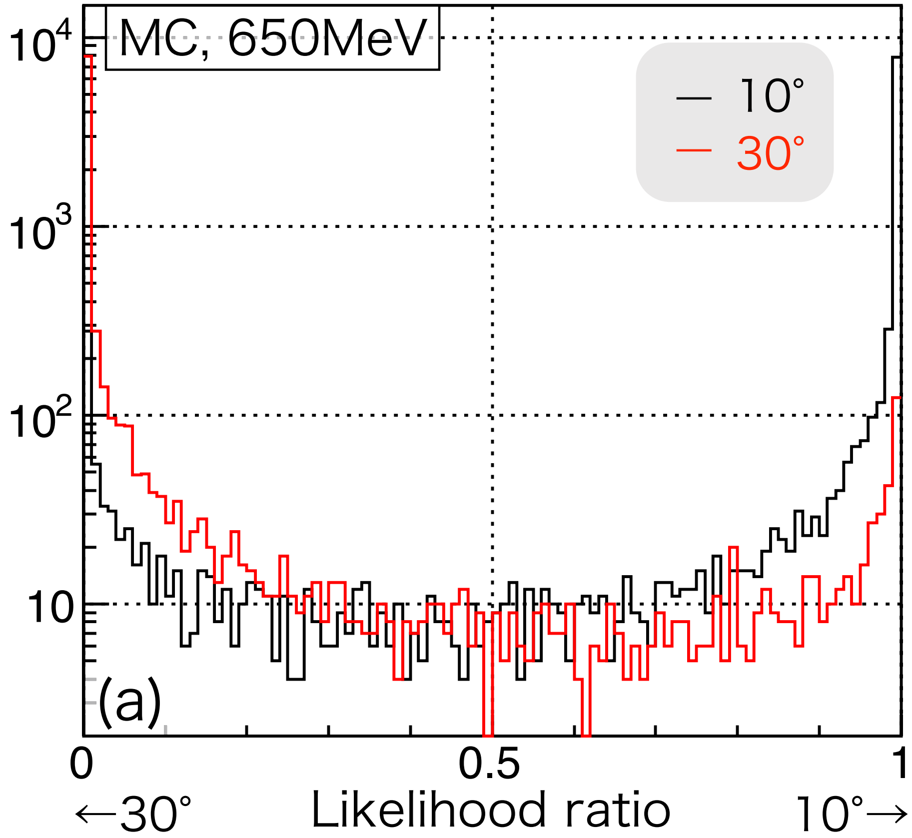


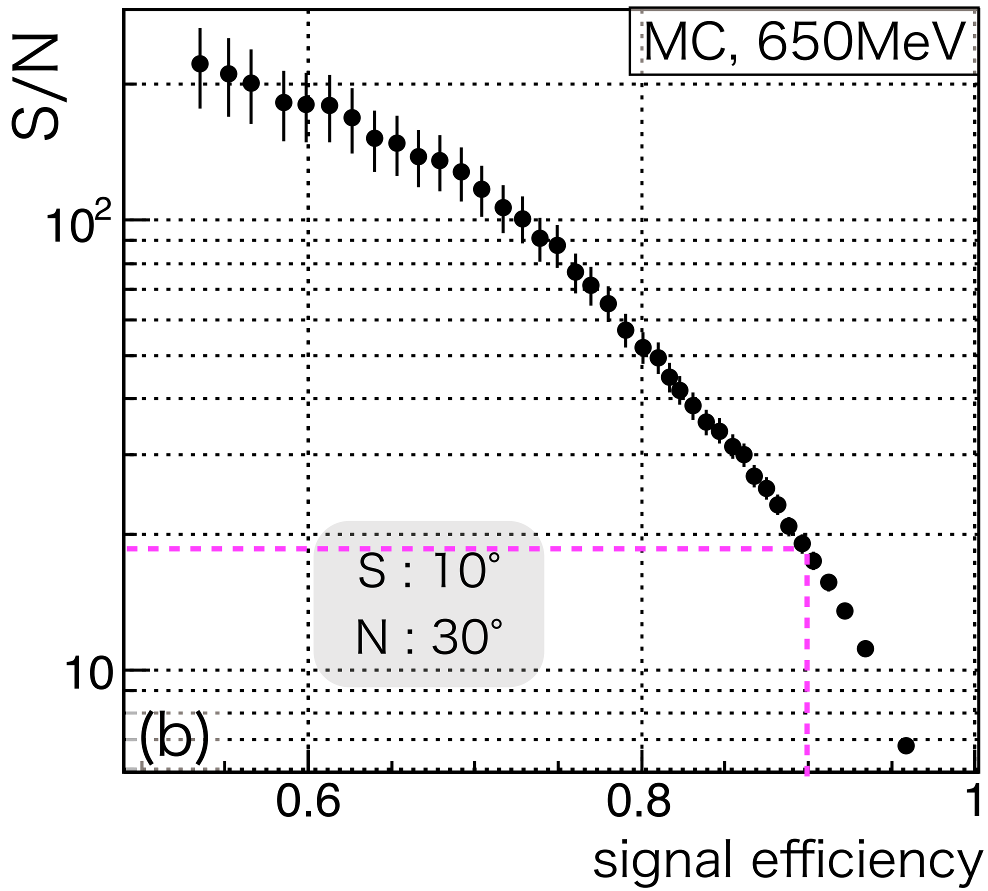
likelihood ratio

apply cut for likelihood ratio

$$\frac{L_{10\,\mathrm{deg}}}{L_{10\,\mathrm{deg}} + L_{30\,\mathrm{deg}}}$$

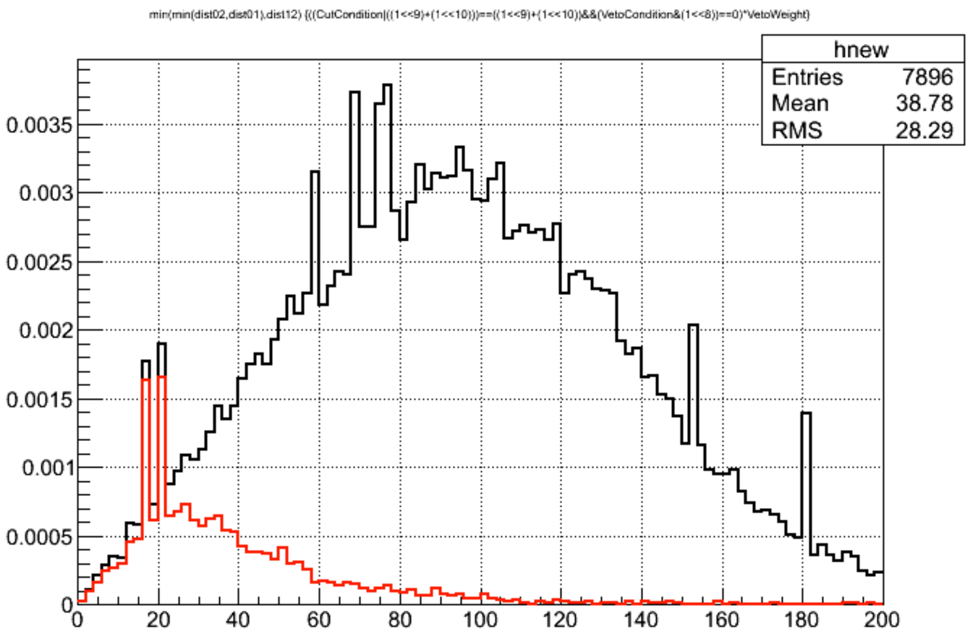
angle separation

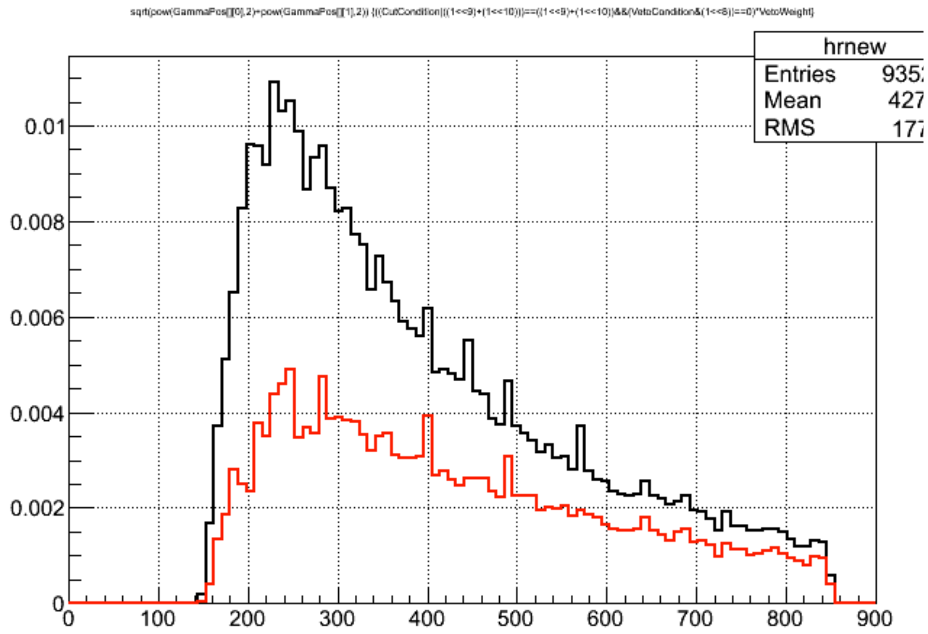


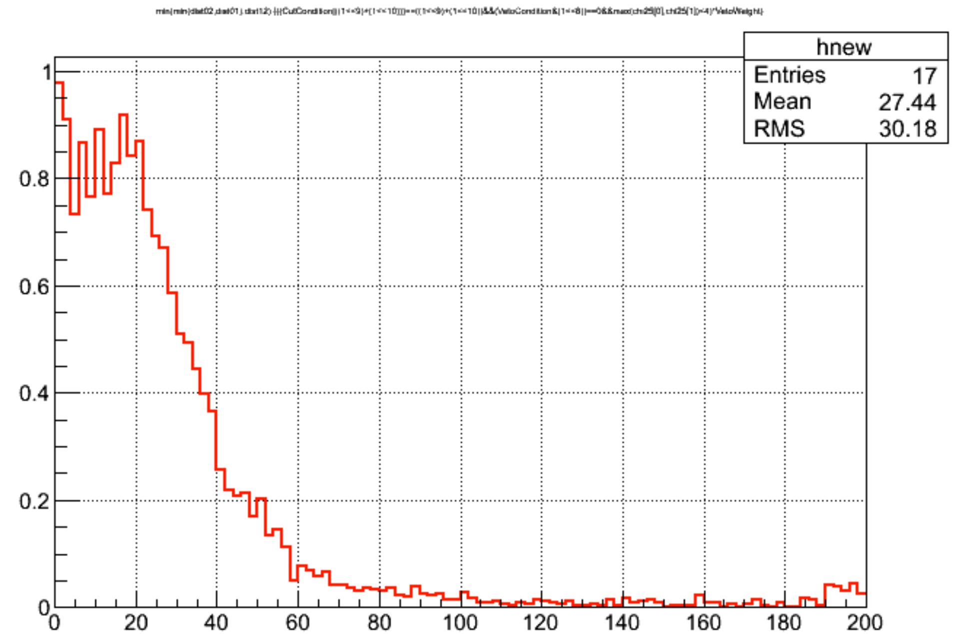


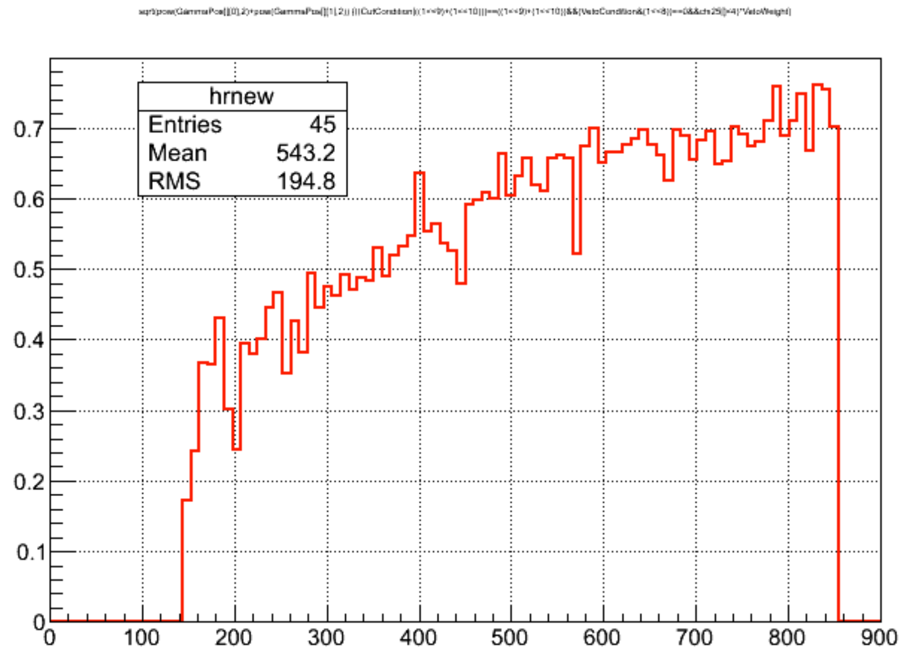
95% of 20° difference can be separated with 90% efficiency

shape chi2

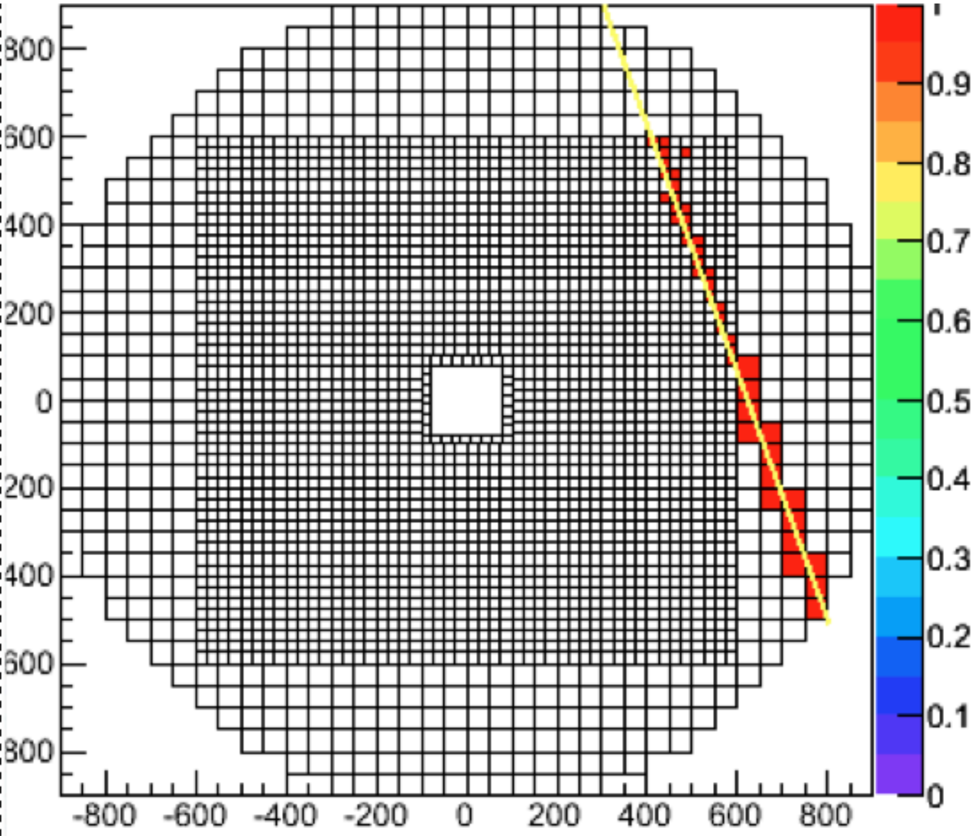

min(min(dist02,dist01),dist12) {((CutCondition|((1<<9)+(1<<10)))==((1<<9)+(1<<10))&&(VetoCondition&(1<<8))==0)*VetoWeight}
hnew
Entries 7896
Mean 38.78
RMS 28.29
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0 20 40 60 80 100 120 140 160 180 200

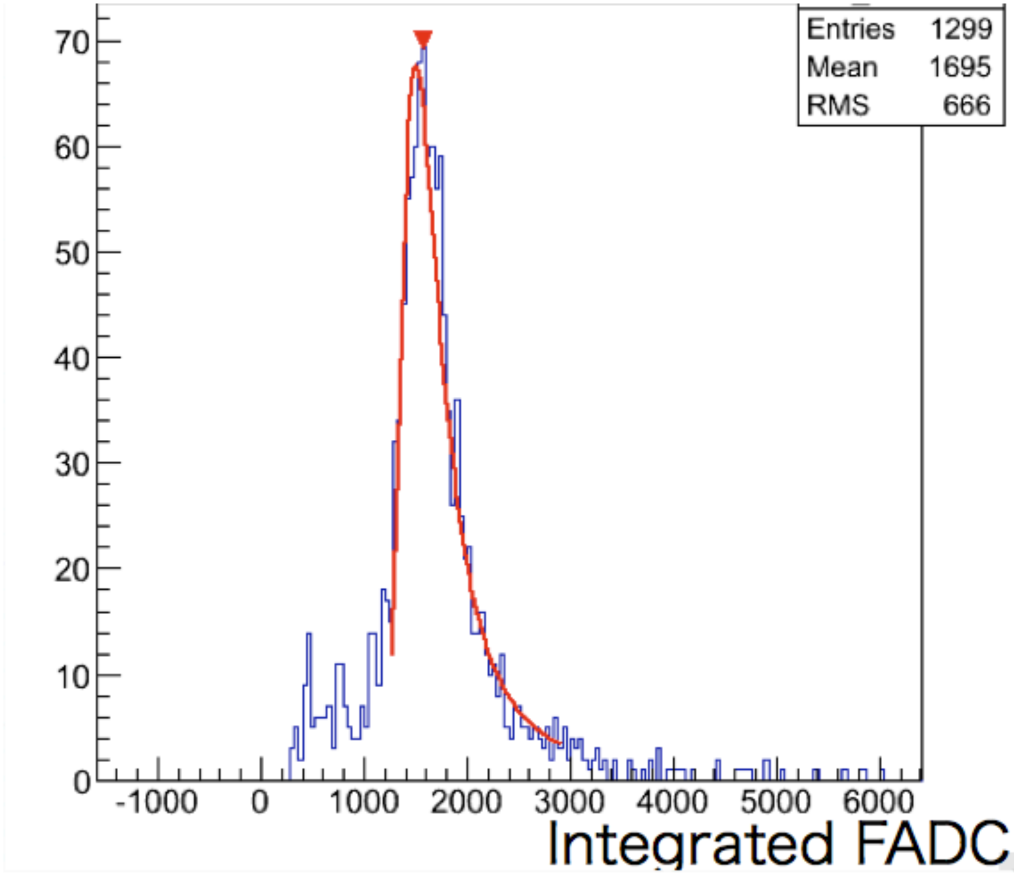

sqrt(pow(GammaPos[][0],2)+pow(GammaPos[][1],2)) {((CutCondition|((1<<9)+(1<<10)))==((1<<9)+(1<<10))&&(VetoCondition&(1<<8))==0)*VetoWeight}
hrnew
Entries 935
Mean 427
RMS 177
0.01
0.008
0.006
0.004
0.002
0
0 100 200 300 400 500 600 700 800 900


min(min(dist02,dist01),dist12) {((CutCondition|((1<<9)+(1<<10)))==((1<<9)+(1<<10))&&(VetoCondition&(1<<8))==0&&max(chi25[0],chi25[1])<4)*VetoWeight}
hnew
Entries 17
Mean 27.44
RMS 30.18
1
0.8
0.6
0.4
0.2
0
0 20 40 60 80 100 120 140 160 180 200


hrnew
Entries 45
Mean 543.2
RMS 194.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 100 200 300 400 500 600 700 800 900

calibration 1: cosmic





calibration 2: $K_L \rightarrow 3\pi^0$

π^0 mass constraint

$$(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2 = M^2_{\pi^0}$$

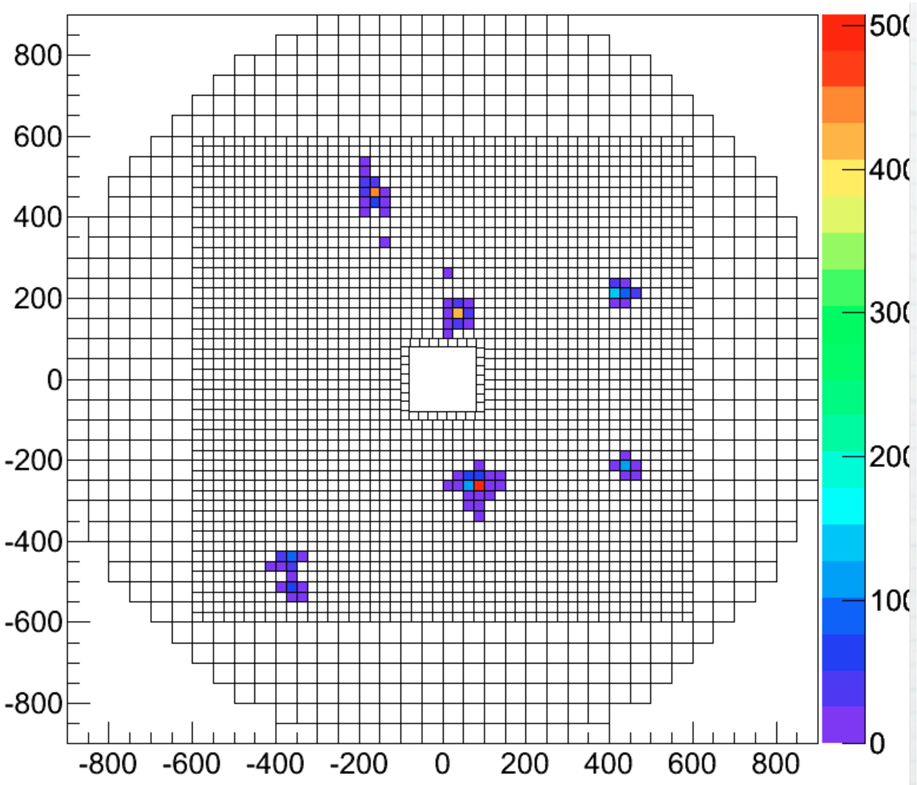
$$(E_3 + E_4)^2 - (\vec{P}_3 + \vec{P}_4)^2 = M^2_{\pi^0}$$

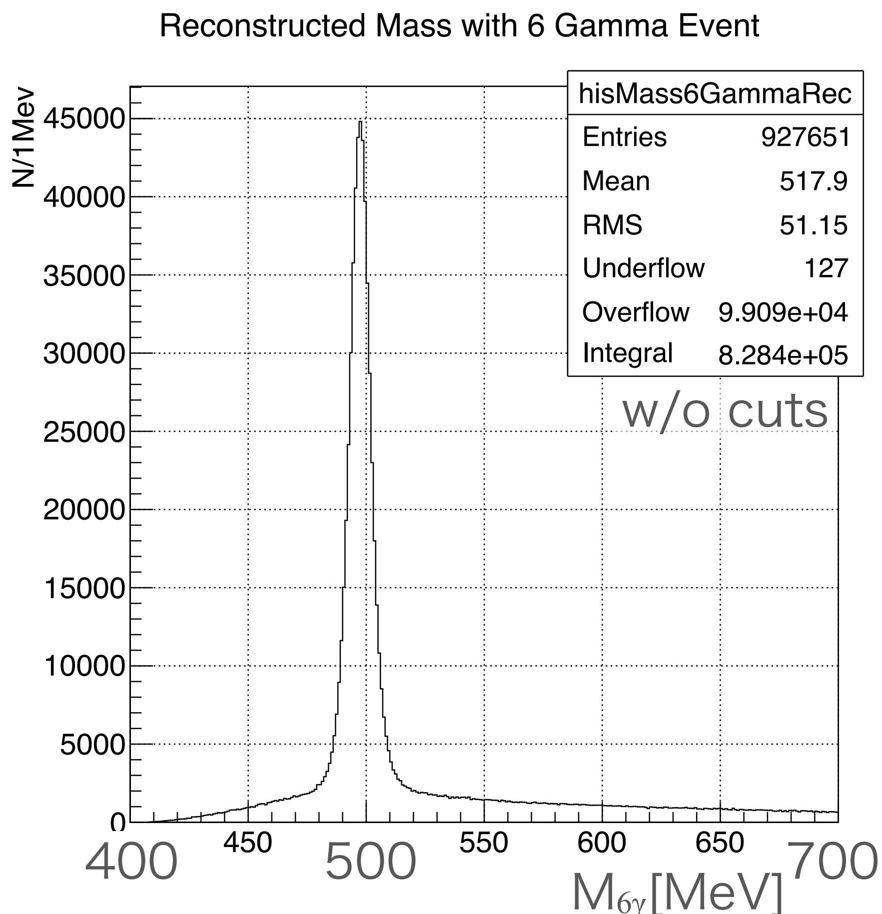
$$(E_5 + E_6)^2 - (\vec{P}_5 + \vec{P}_6)^2 = M^2_{\pi^0}$$

K_L mass constraint

$$\left(\sum E_i\right)^2 - \left(\sum P_i\right)^2 = M^2_{K^0_L}$$

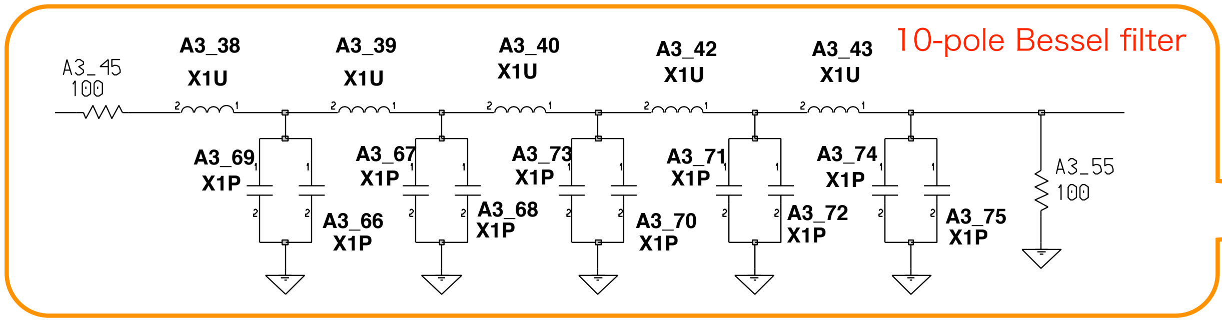
→ can calculate a given γ energy from other γs energy

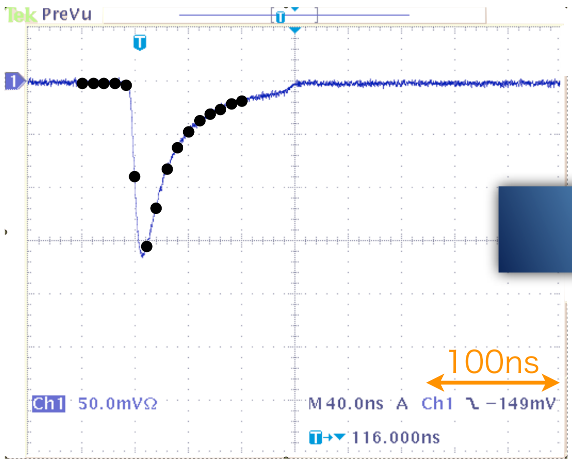


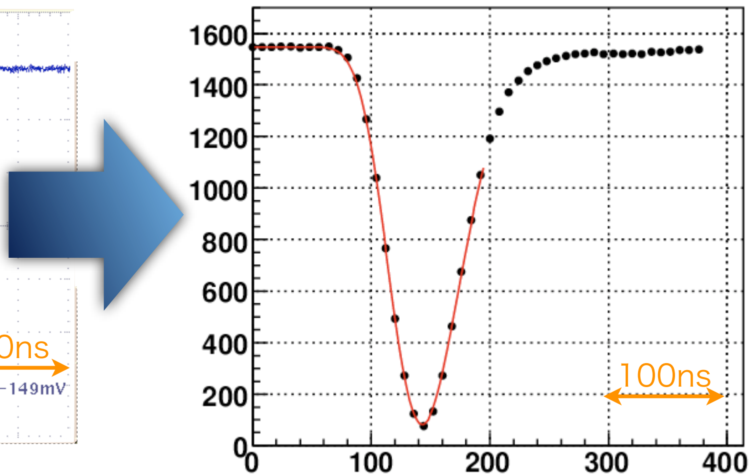


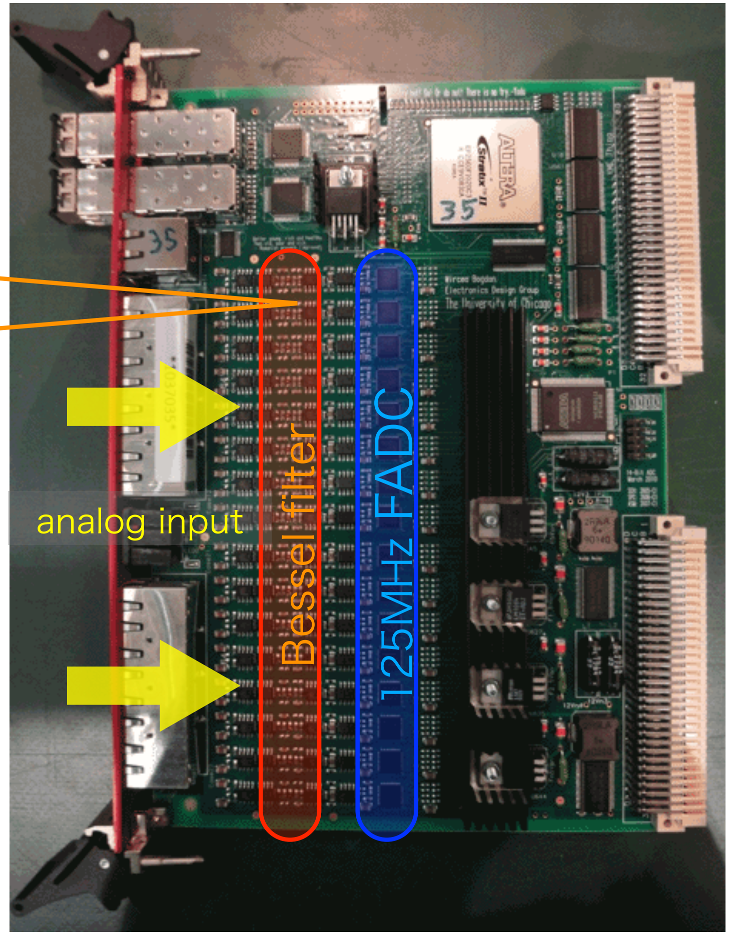
Waveform readout

- 14bit FADC
  - to record waveform
  - to form triggers digitally









Neutral beam line