

# Photon and $\pi^0$ identification: recent GARLIC developments

- revisiting of algorithm
- performance in  $\pi^0$  events  
as function of  
 $\pi^0$  energy  
ILD size, ECAL design
- plans

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# GARLIC photon reconstruction algorithm

**G**amma **R**econstruction at a **L**inear **C**ollider experiment

(JINST 7 (2012) P06003)

Make use of characteristic shape of EM showers,  
revealed by dense, highly segmented ECAL

- narrow core of high energy deposit: radius  $\sim$  cell size
- lower energy “halo”: radius  $\sim$  Moliere radius  $\sim$  20 mm
- characteristic longitudinal profile

Algorithm outline:

Identify electrons seeded by tracks

Veto ECAL hits near track projections

Project hits in first part of ECAL onto front face

Search for peaks in projection --> “seeds”

Project seeds through ECAL, attach hits --> “cores”

Attach nearby hits to “cores” --> clusters

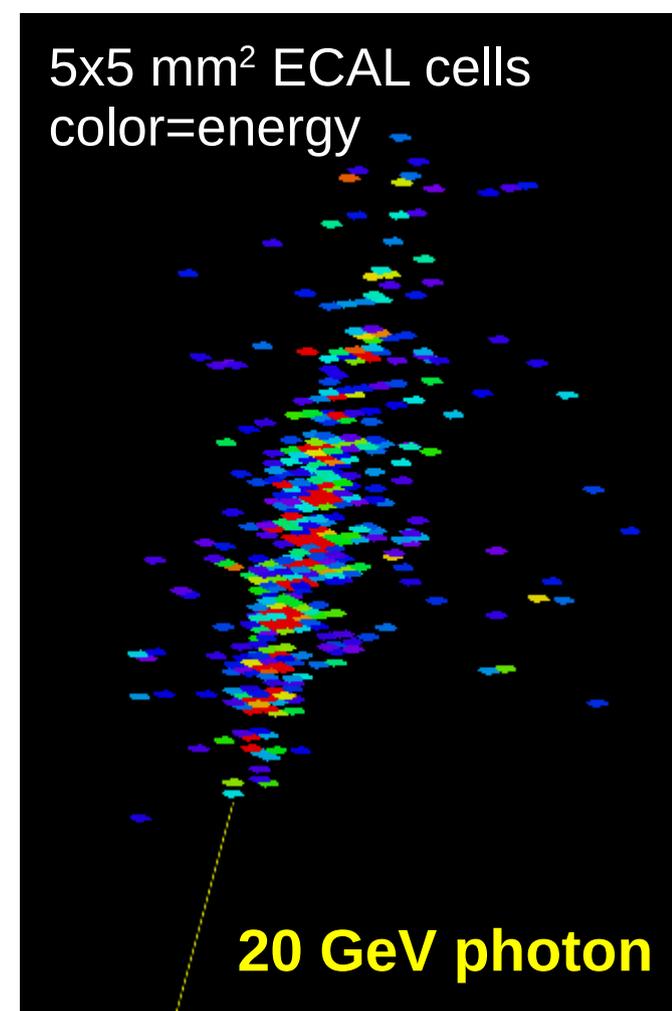
Decide if resulting cluster looks like photon

(old) Neural Network trained using jet events

(new) photon multi-var likelihood for  
combining nearby clusters  
selecting photon-like clusters

(now testing) simpler cut-based approach

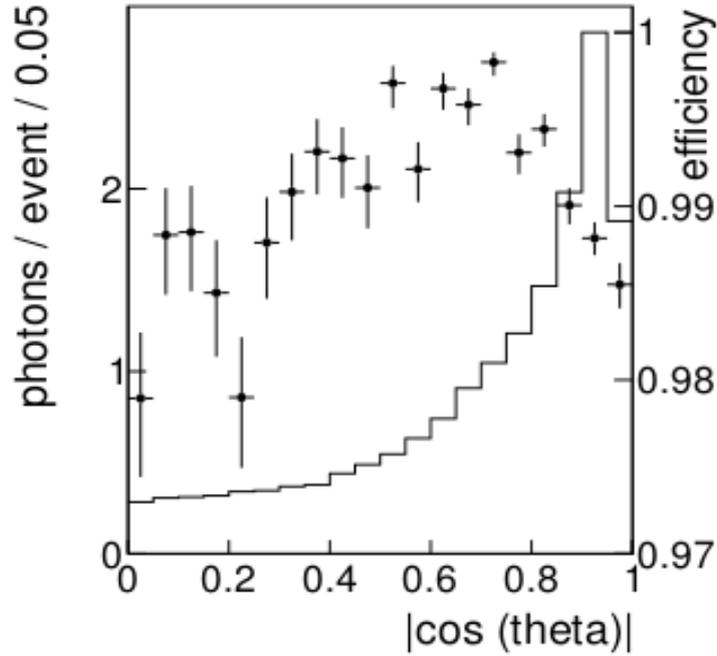
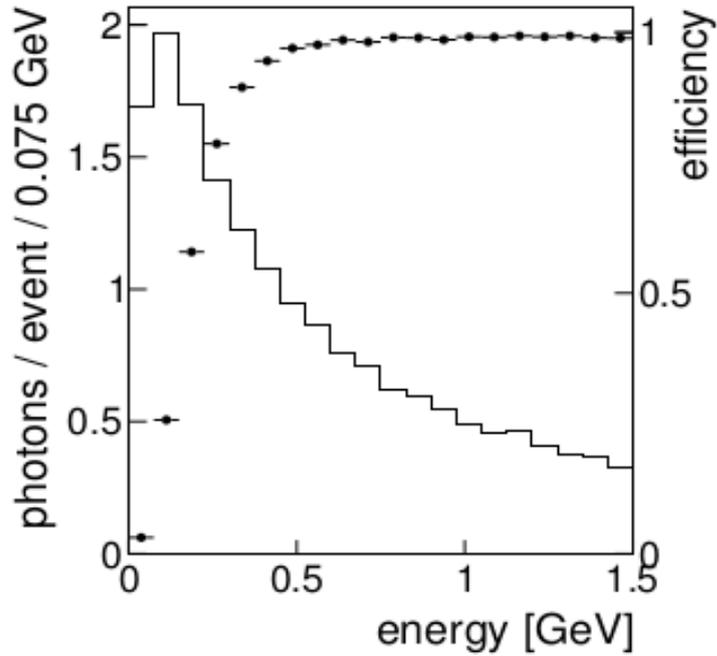
5x5 mm<sup>2</sup> ECAL cells  
color=energy



Example observables:

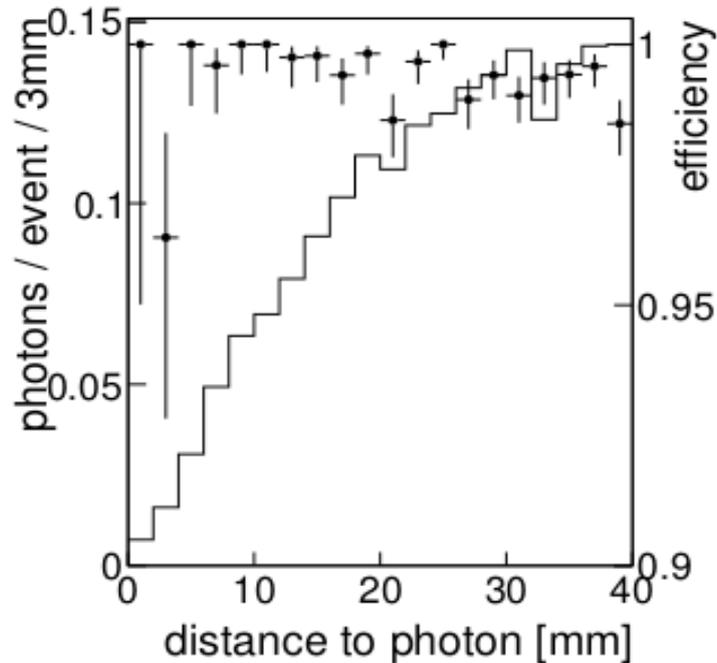
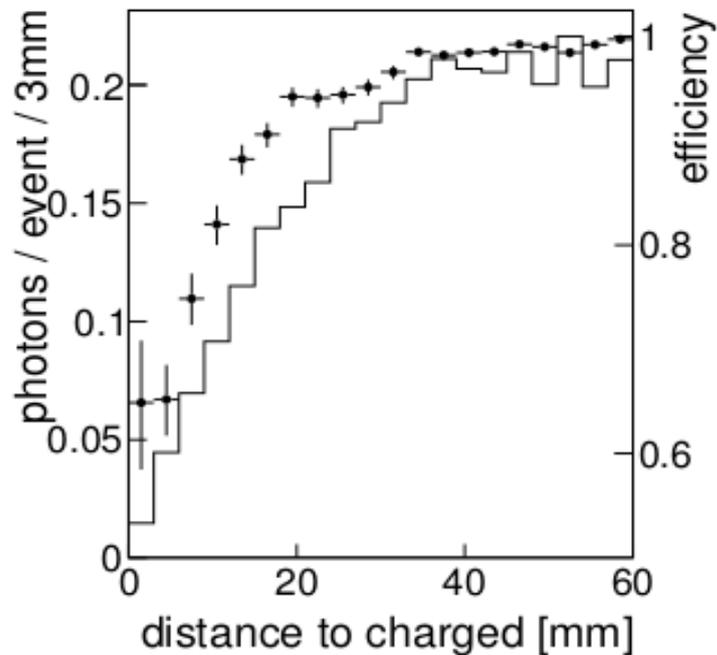
- Longitudinal shower shape
- Transverse shower shape & size
- Distribution of hit energies
- Pointing to IP

# “Original” GARLIC performance in jets

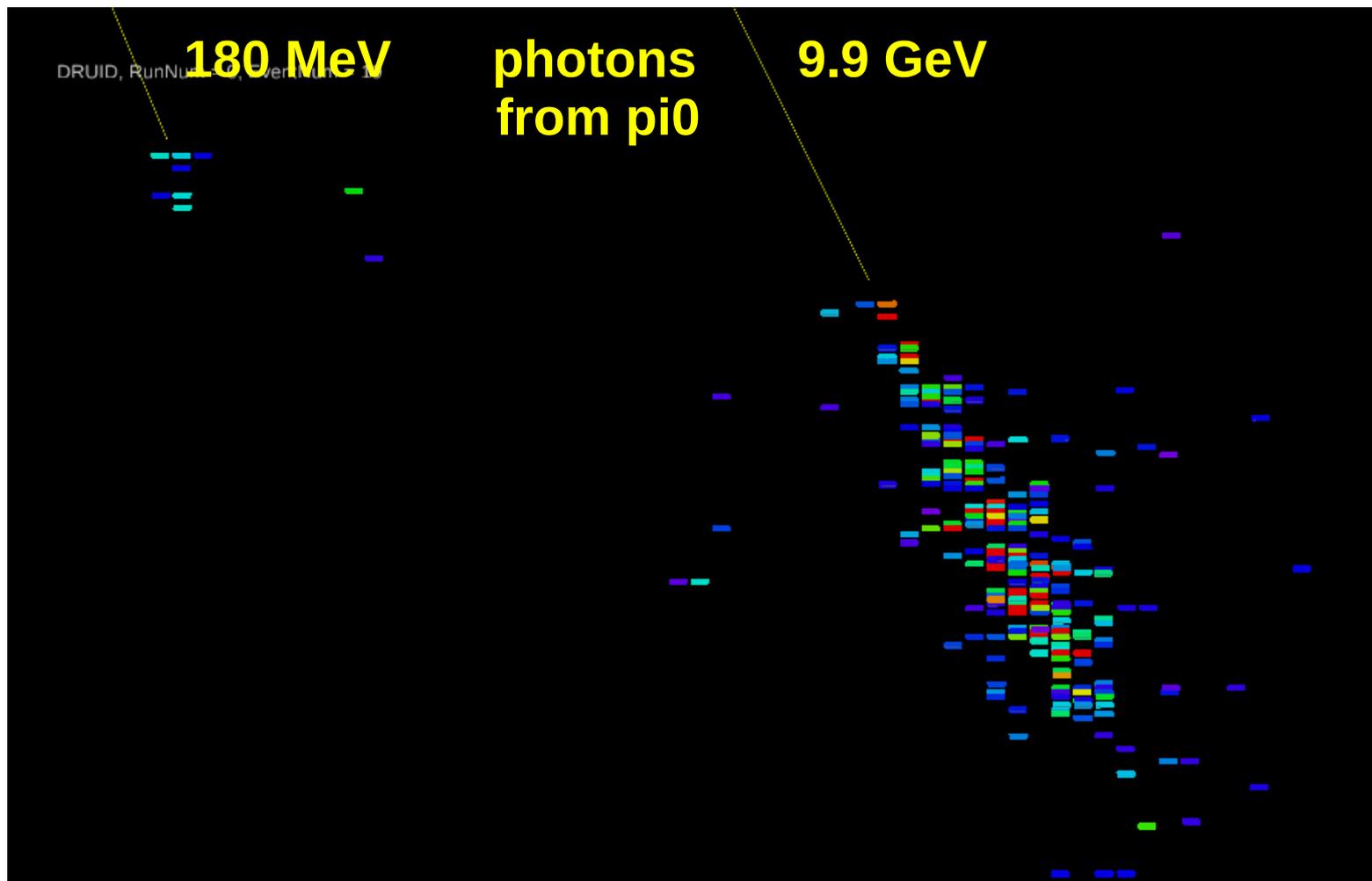


“Efficiency”  
=  
efficiency to collect  
photons into clusters

Merging nearby  
photons into a single  
cluster not penalised  
(~OK for Jet En Res)



Some inefficiency for  
energy  $< \sim 500$  MeV



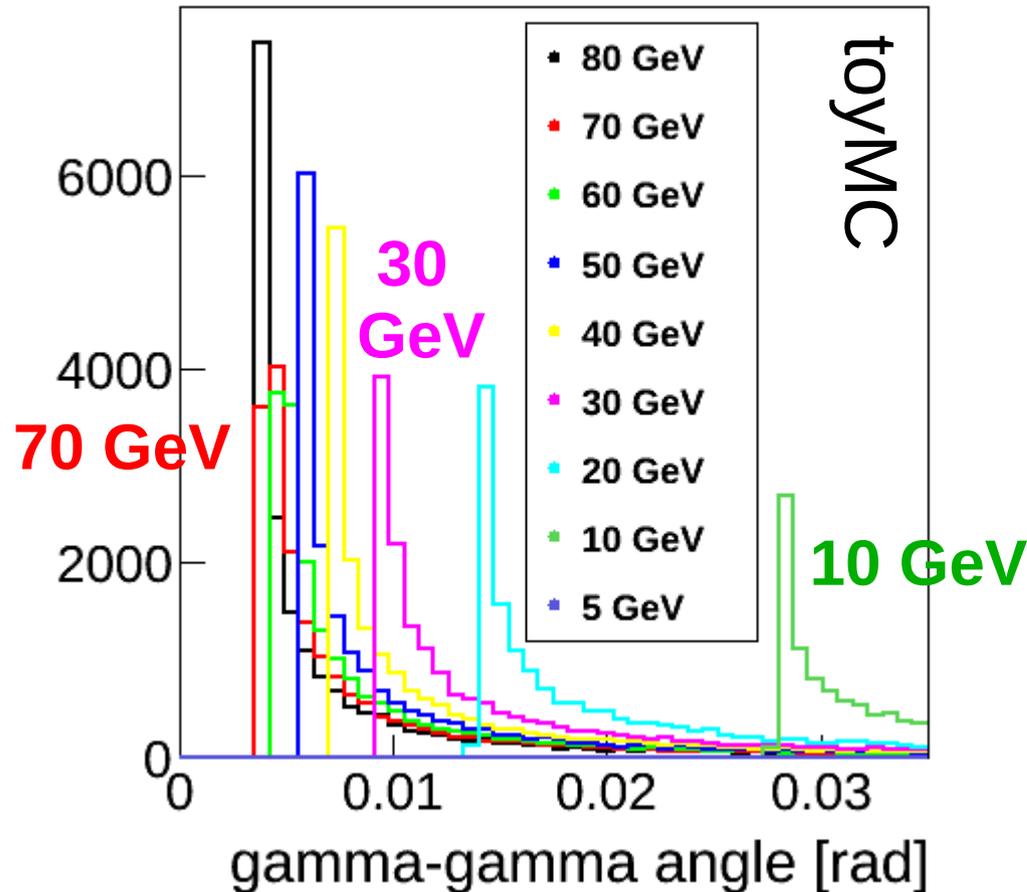
Recent work with view to:

- Better separate near-by photons: e.g. for high energy  $\pi^0$  decays
- Improve efficiency for low energy photons:  $\sim 100$  MeV
- “scalable algorithm”: parameterise in terms of  $X_0$ , Moliere radius, cell size  
easier to apply to different ECAL designs
- Try to simplify (no automatic MVAs if not required...)

**Still very much “in progress”**

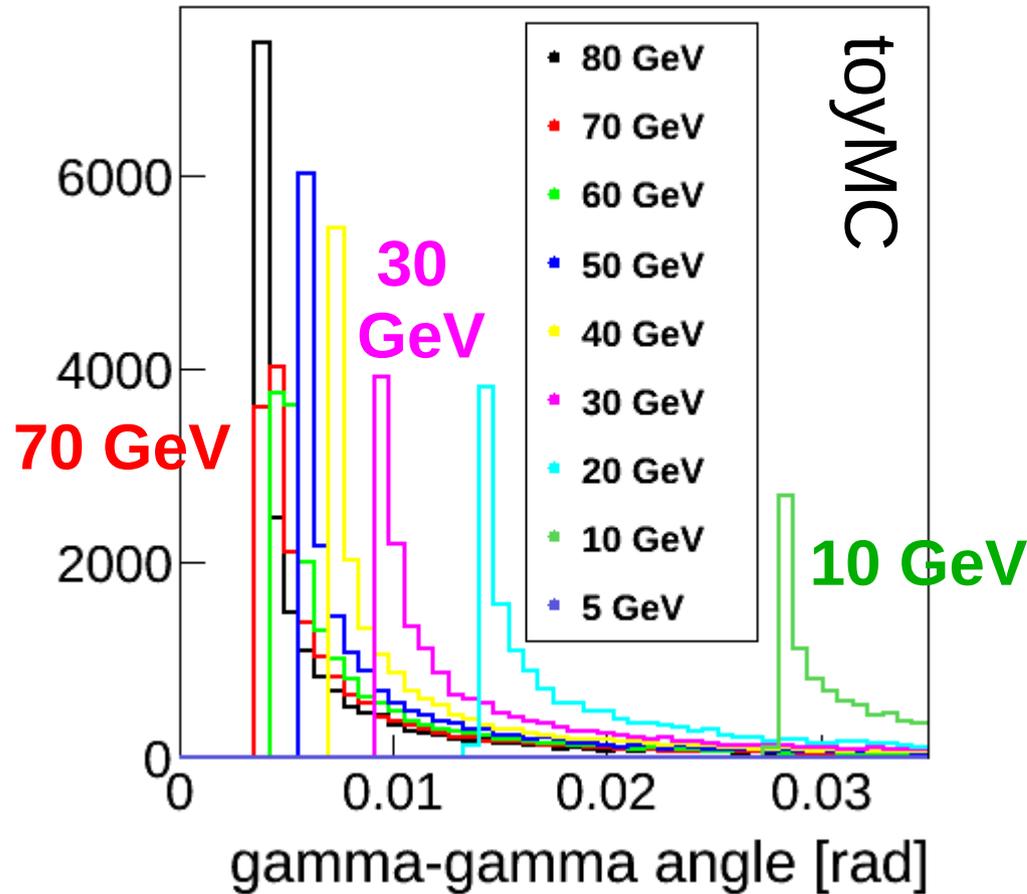
Introductory motivation:

angle between photons at different  $\pi^0$  energies



n.b. “usual” PFA doesn't care if 2 photons are combined into a single reconstructed cluster  
- Jet Energy Resolution is not degraded

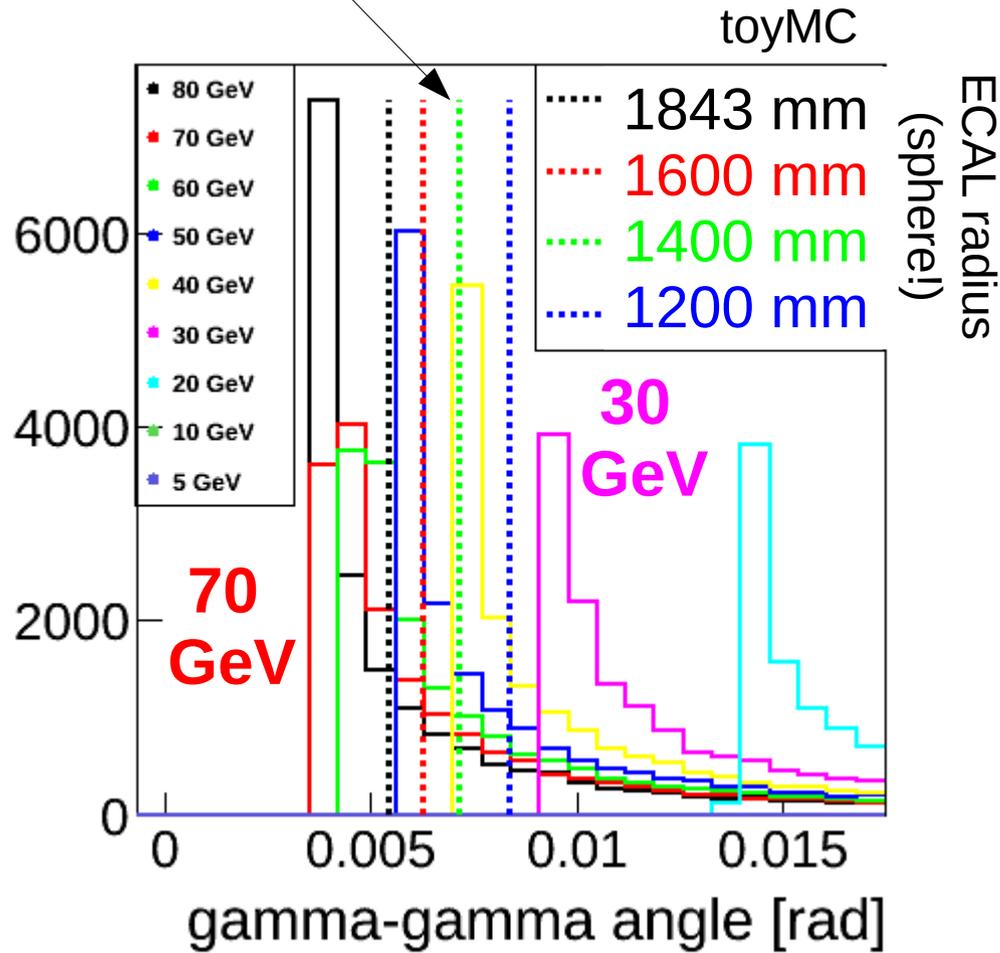
Introductory motivation:  
angle between photons at different  $\pi^0$  energies



Identification of  $\pi^0$  in tau decays from H is (probably) important for measurement of Higgs CP properties

# Angle subtended by 0.5\*Moliere radius at different ECAL radii

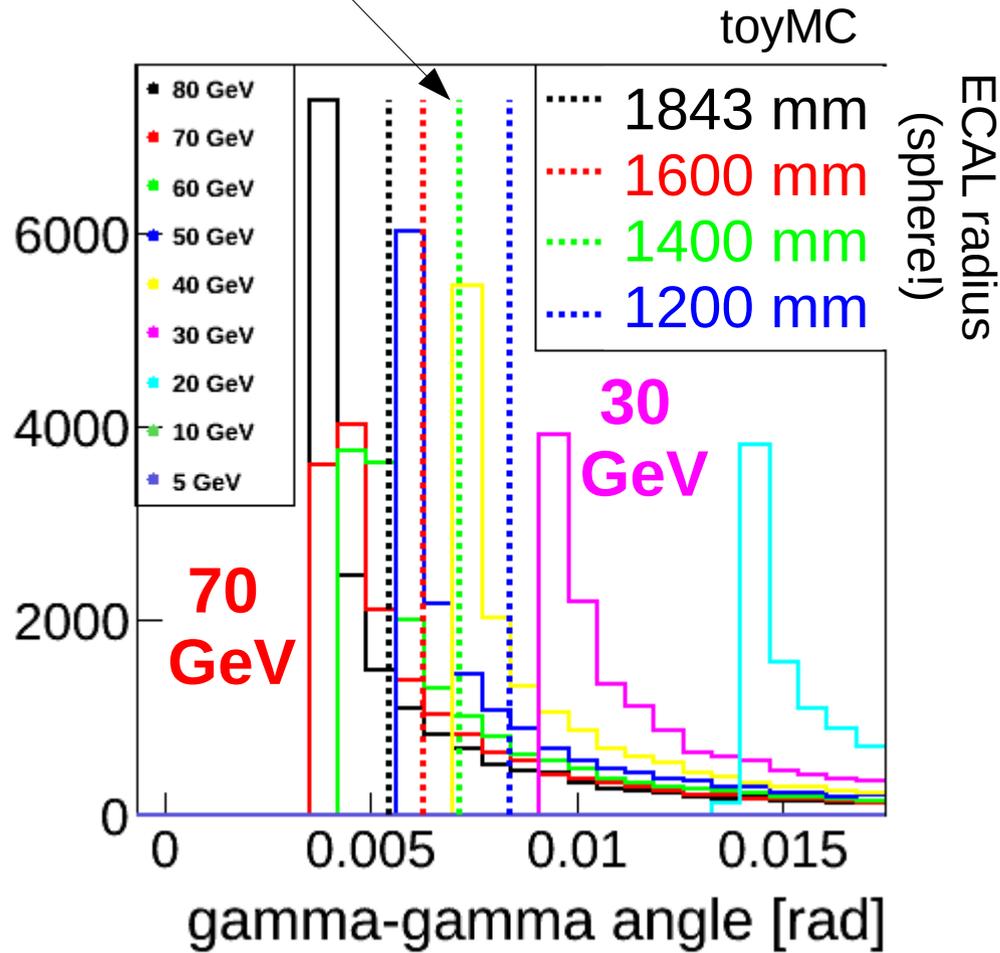
~1 cm



$\pi^0$  of 30 GeV and below should be identifiable  
in a typical ILC ECAL  
with a good photon separation algorithm  
 $\pi^0$  of 80 GeV look difficult

# Angle subtended by 0.5\*Moliere radius at different ECAL radii

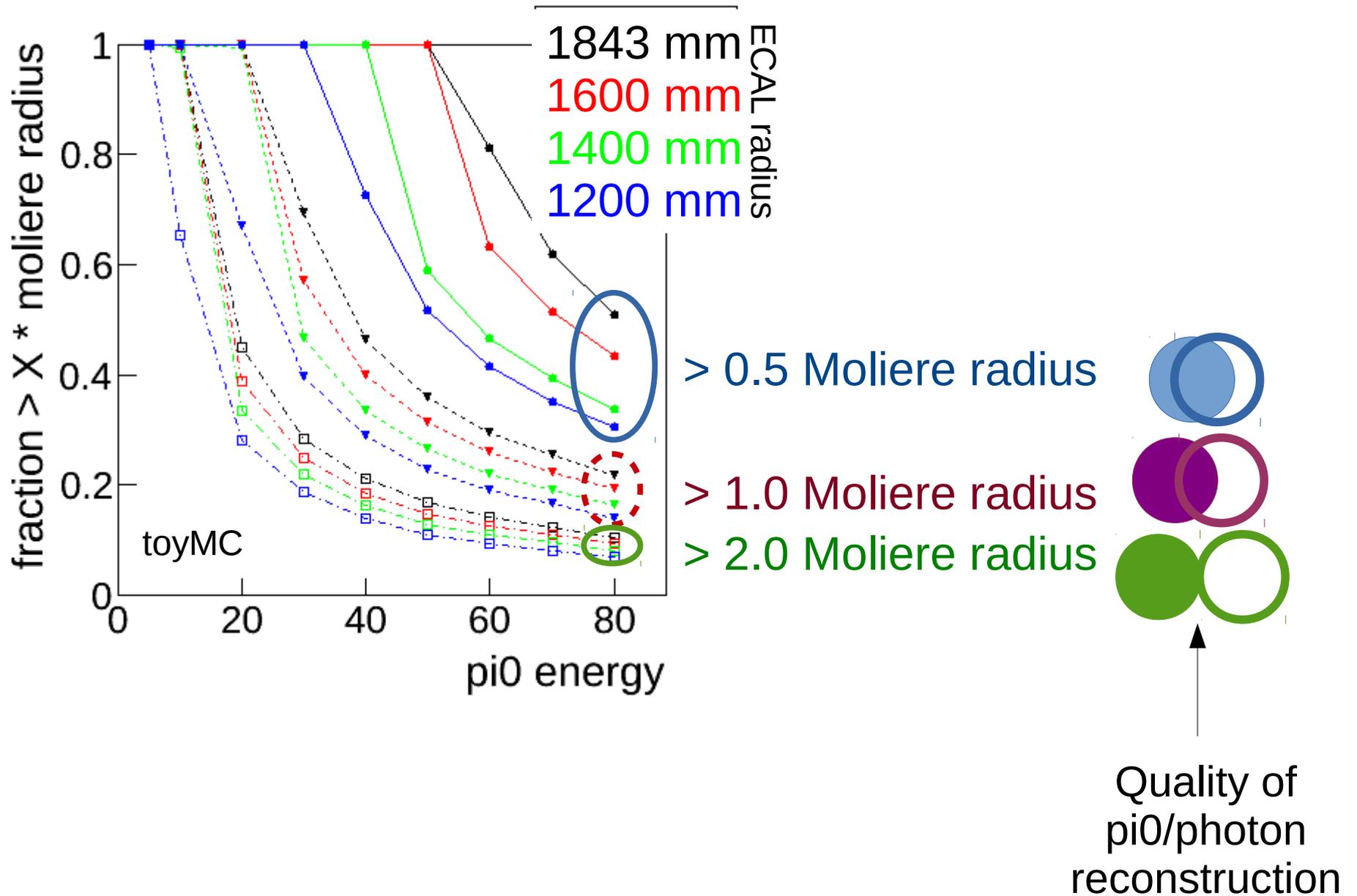
~1 cm



*n.b.*  
 pi0 produced in tau decays from ZH @ 250 GeV have energy up to ~60 GeV, average ~20 GeV

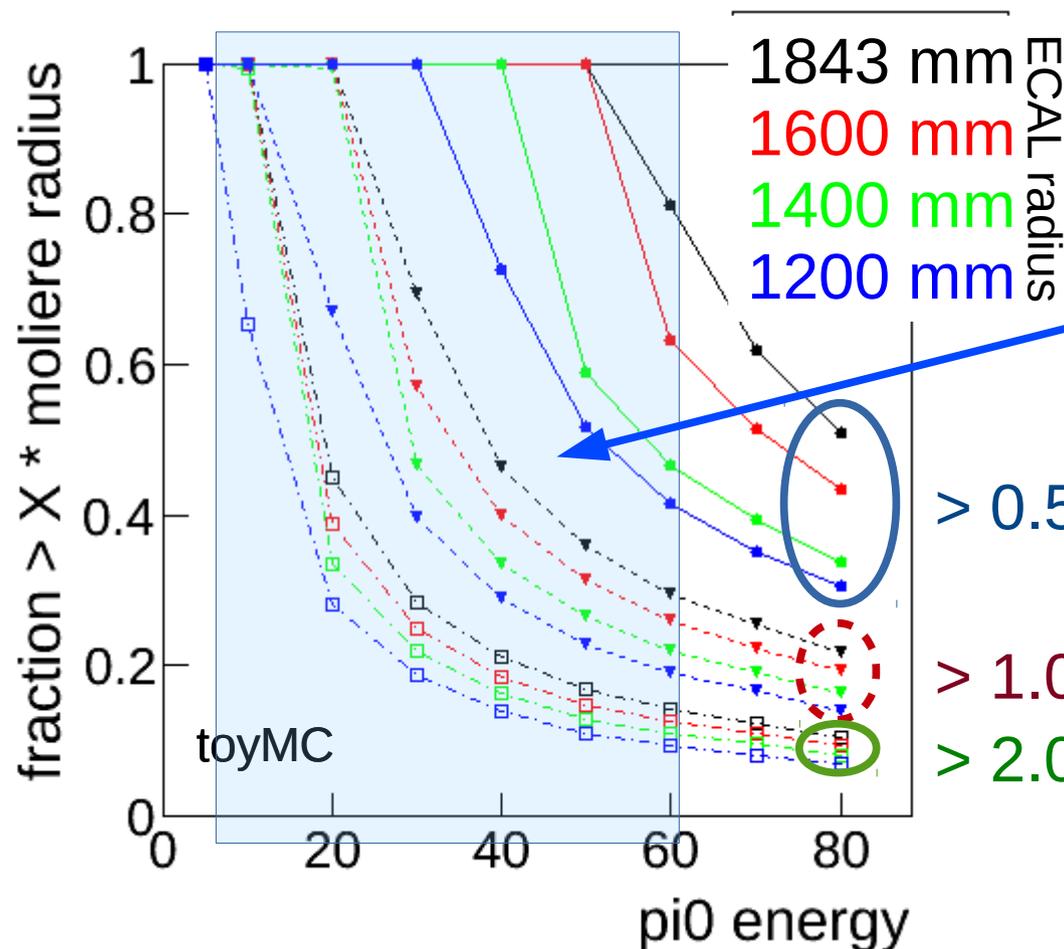
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Which fraction of  $\pi^0$  have photons separated by  $> 2, 1, 0.5$  Moliere radius in the ECAL?



Which fraction of  $\pi^0$  have photons separated by  $> 2, 1, 0.5$  Moliere radius in the ECAL?

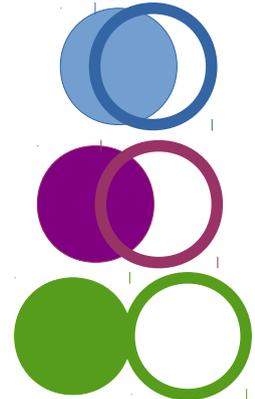
*n.b.*  
 $\pi^0$  produced in tau decays from ZH @ 250 GeV have energy up to  $\sim 60$  GeV, average  $\sim 20$  GeV



$> 0.5$  Moliere radius

$> 1.0$  Moliere radius

$> 2.0$  Moliere radius



Quality of  $\pi^0$ /photon reconstruction

We may expect reconstruction of  $\pi^0$  of a few 10s of GeV to depend strongly on:

- ECAL radius
- Quality of  $\pi^0$  reconstruction algorithm

# Full simulation

mono-energetic  $\pi^0$  in ILD detector  
from interaction point, in random direction

For now, exclude events in which:

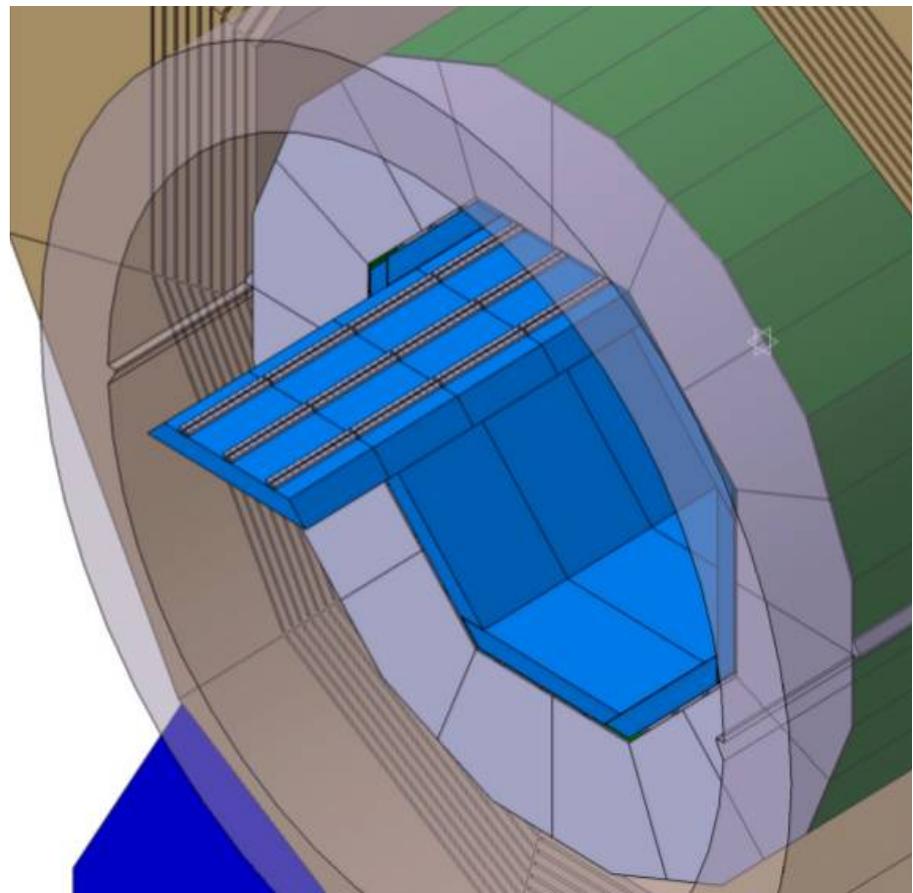
- $\pi^0$  does not decay to 2 photons
- one or more photons:
  - convert before ECAL
  - very forward ( $\cos(\theta) > 0.95$ )
  - in barrel-endcap overlap region
- hadron has interacted in tracker

Simulate in ILD detector

Silicon ECAL,  $5 \times 5 \text{ mm}^2$  readout cells

Analyse events using

- GARLIC photon reconstruction algorithm  
“yesterday's” unstable private version...
- PandoraPFA general reconstruction algorithm  
DBD version (in ilcsoft v01-16-02)

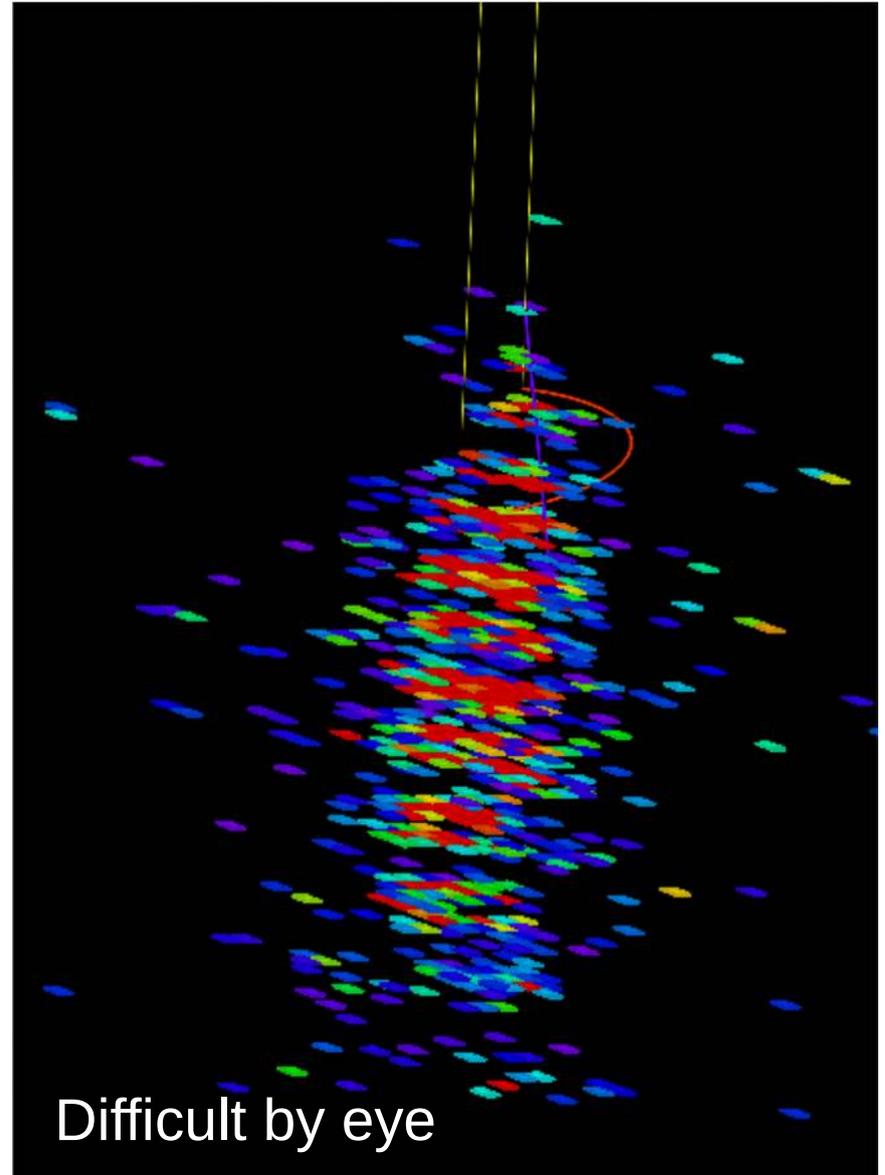
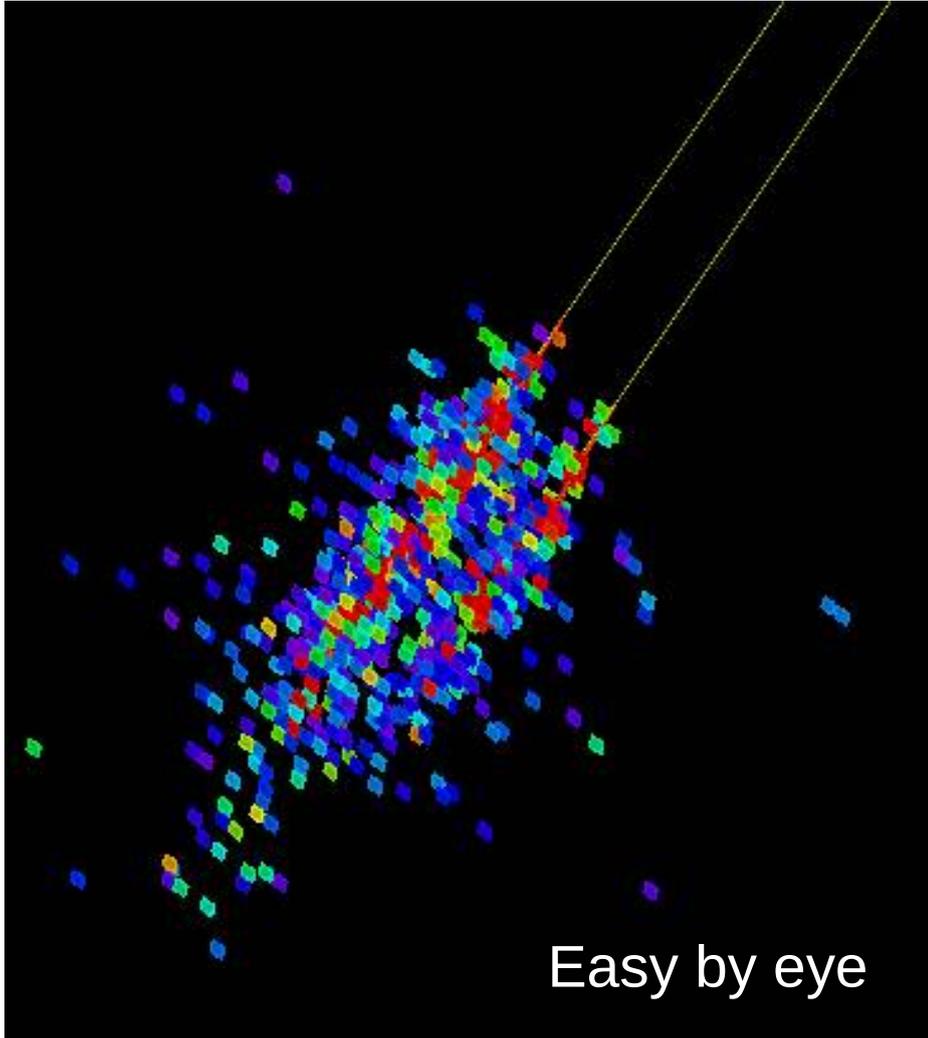


# ILD

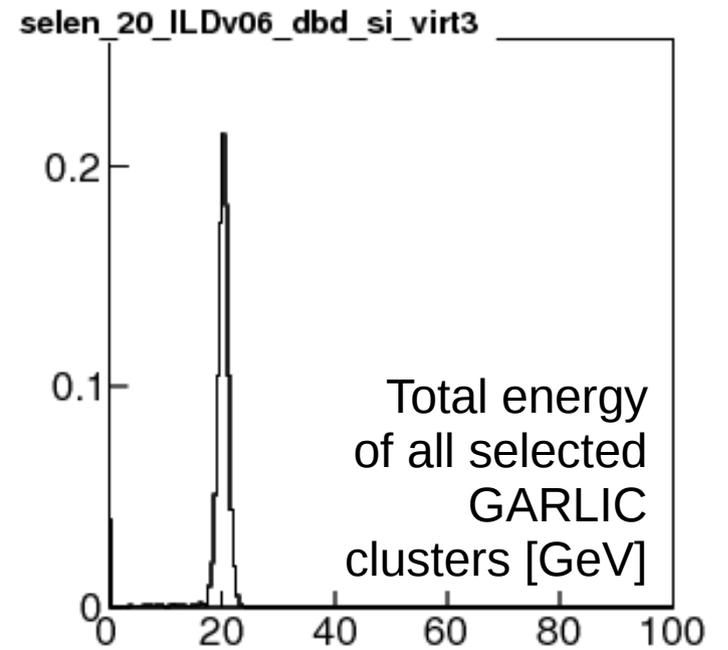
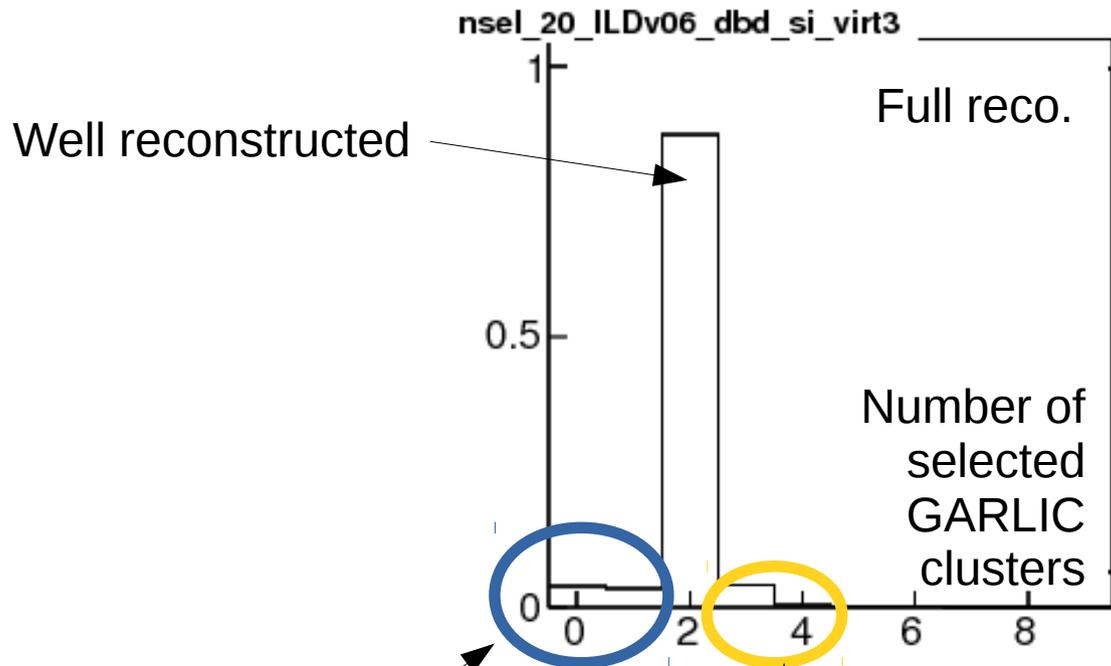
30 GeV

$\pi^0$

50 GeV



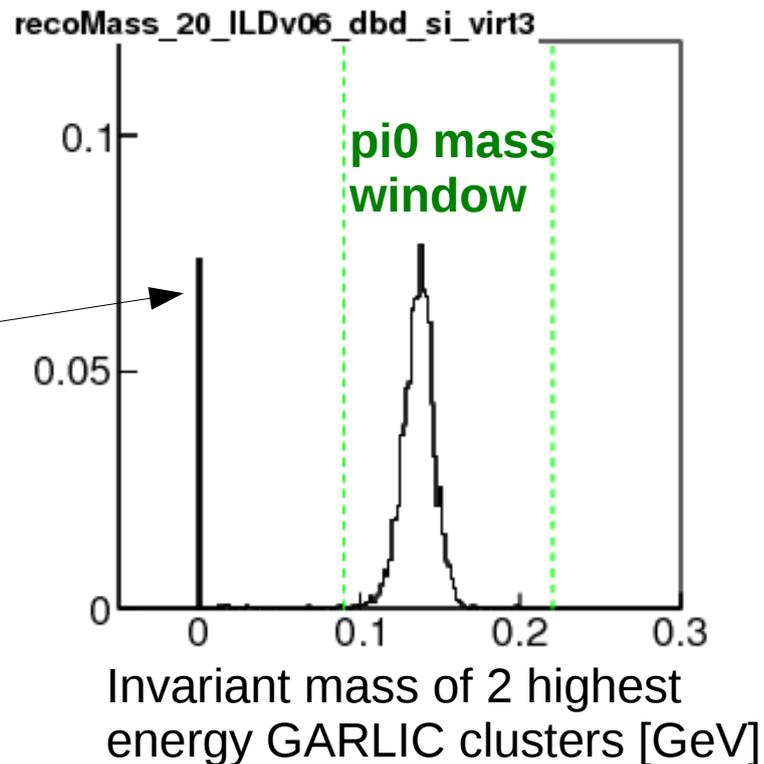
DBD-sized si-ECAL



Photon identification inefficiency & Cluster merging

Cluster splitting

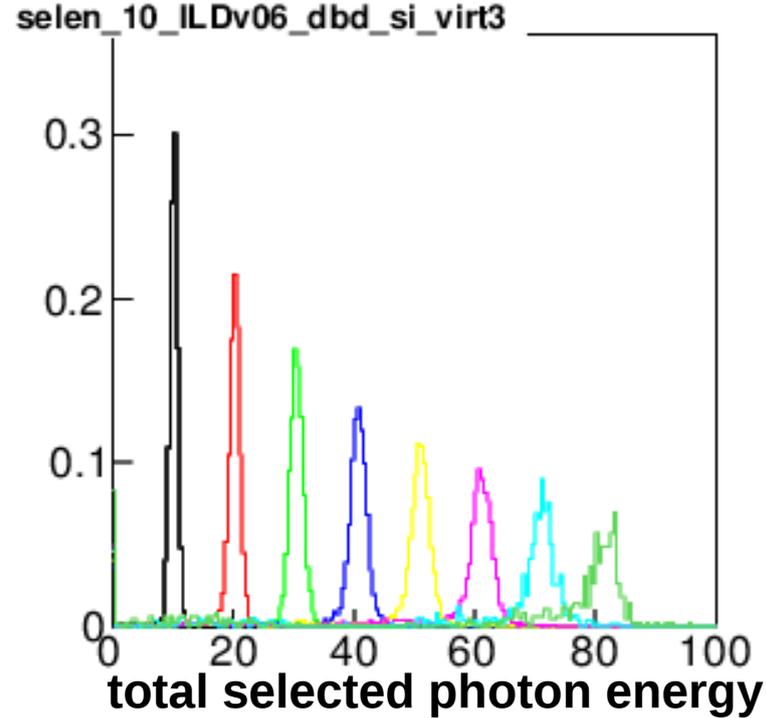
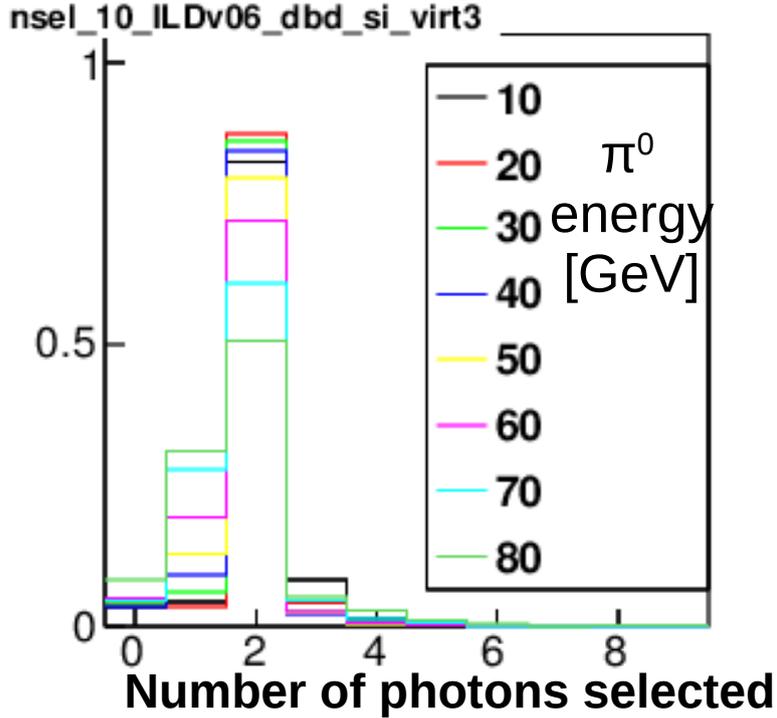
<2 selected GARLIC clusters



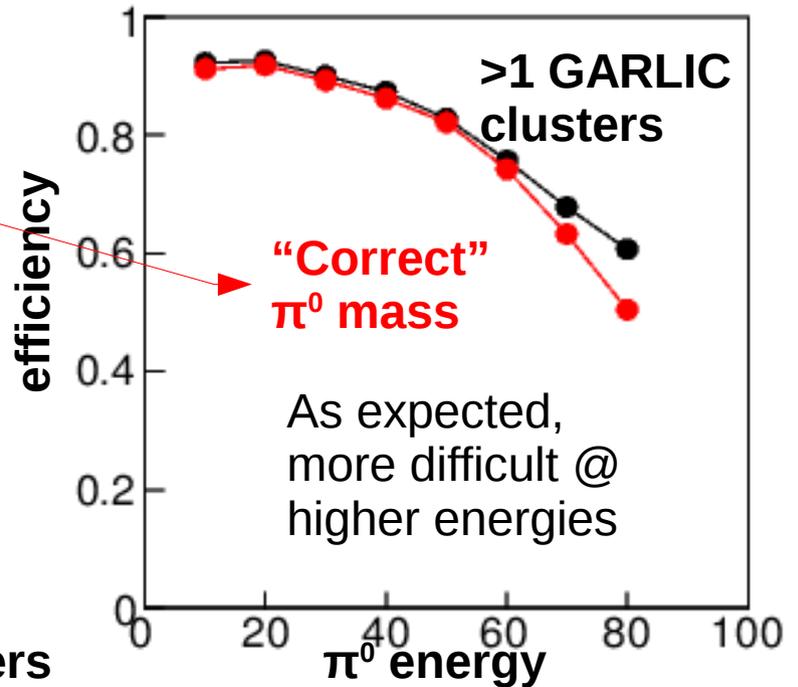
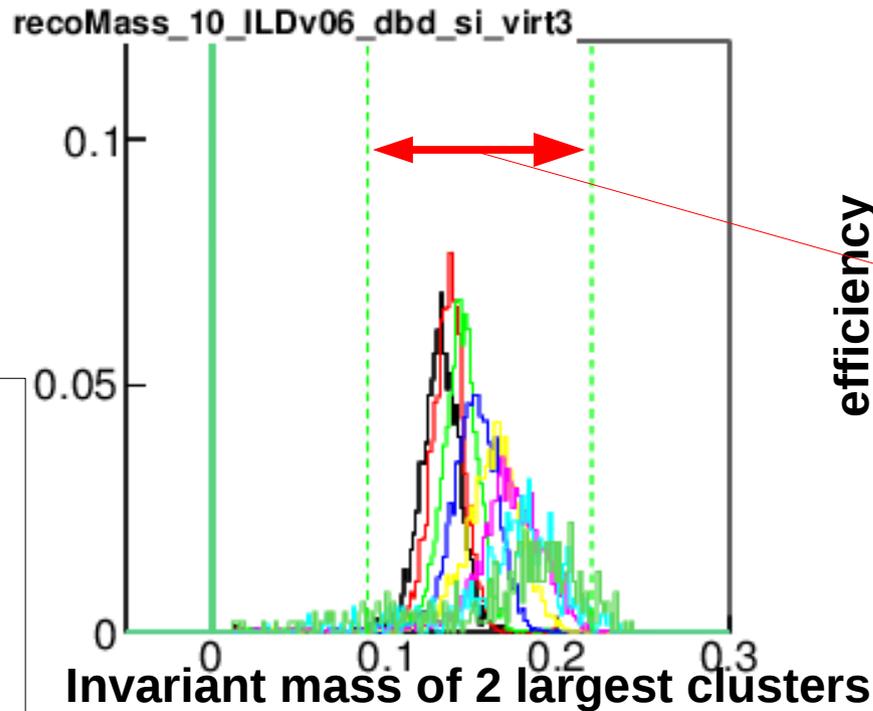
e.g.: 20 GeV pi0  
in DBD si-ECAL

# Compare different pi0 energies

Standard  
ILD size  
(1843 mm  
ECAL radius)



Single  $\pi^0$   
full simulation  
GARLIC reco.



- Exclude:
- Conversions
  - Barrel-endcap overlap
  - Very forward
  - Rare  $\pi^0$  decays

# Comparison of **GARLIC** and **PandoraPFA** algorithms for $\pi^0$ reconstruction

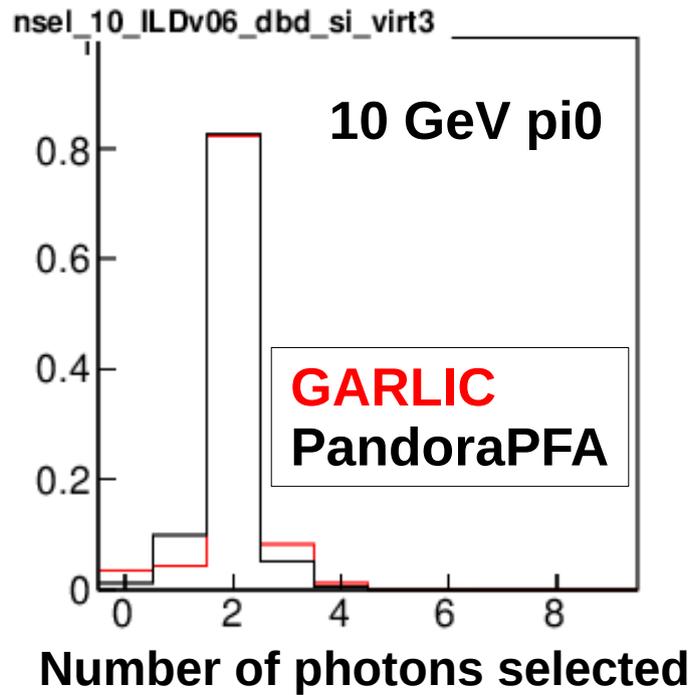
This GARLIC version tuned to separate nearby photons

2-photon separation (probably) not considered (at 1<sup>st</sup> order) in tuning/design of PandoraPFA

Still using “DBD” version of Pandora

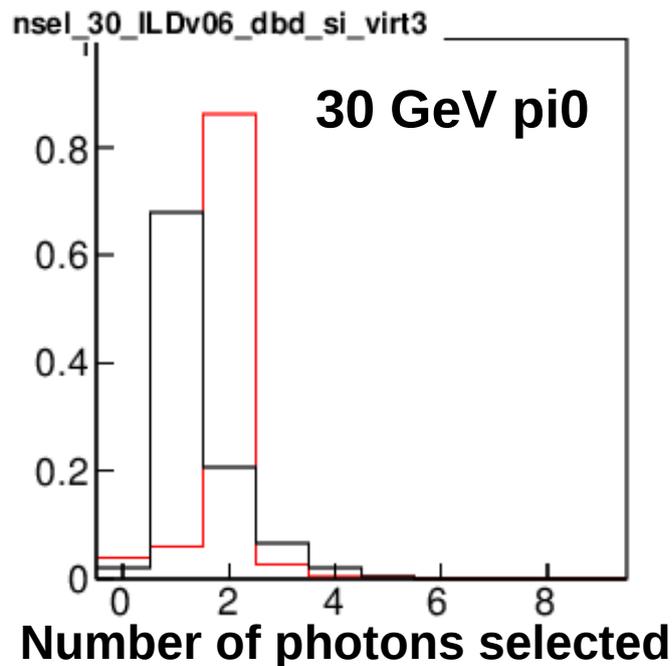
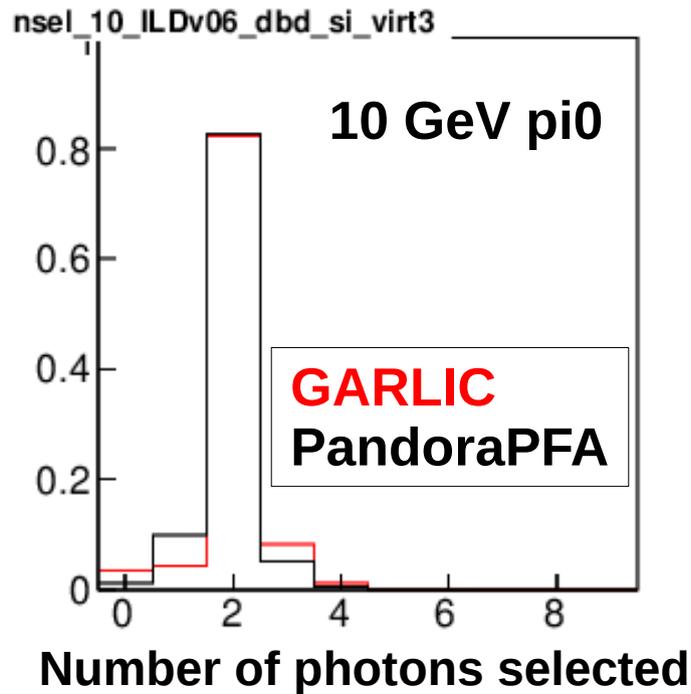
I know there are photon clustering improvements in the pipeline

# Comparison of **GARLIC** and **PandoraPFA** algorithms for $\pi^0$ reconstruction



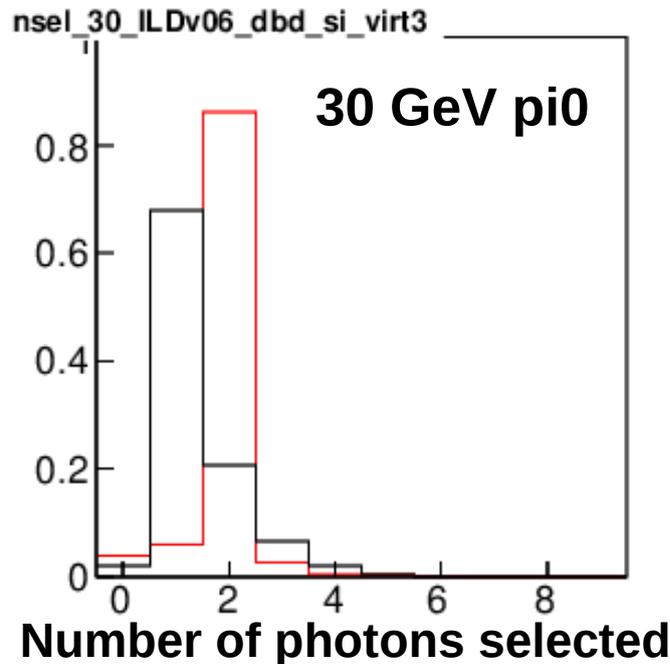
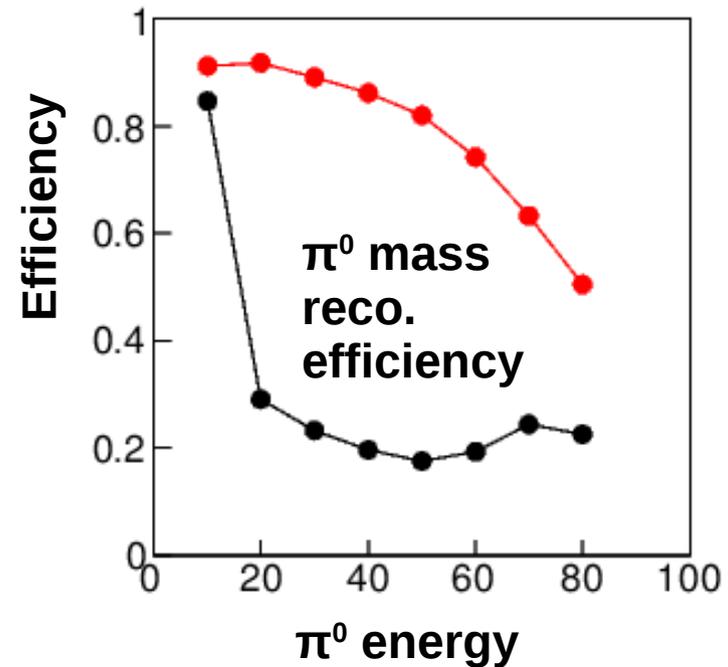
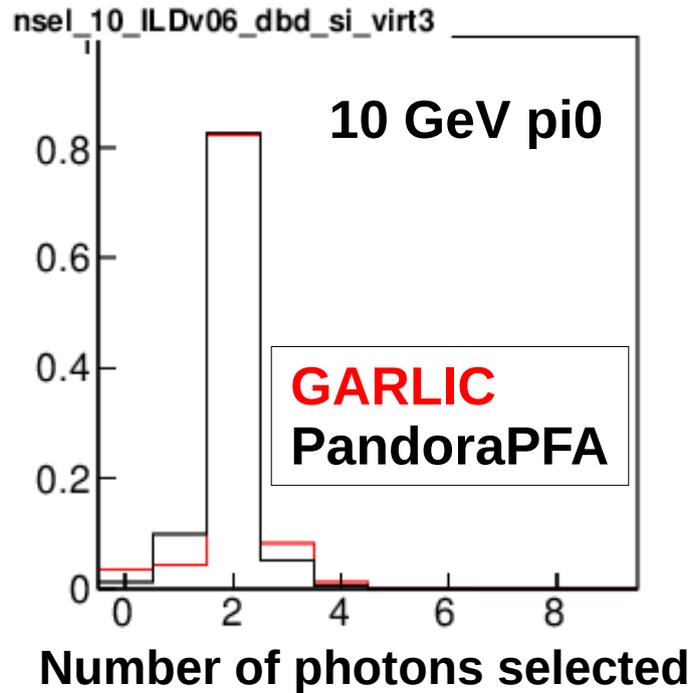
DBD detector,  
SiECAL

# Comparison of **GARLIC** and **PandoraPFA** algorithms for $\pi^0$ reconstruction



DBD detector,  
SiECAL

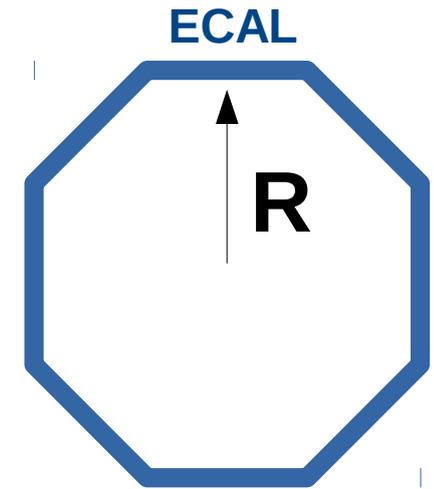
# Comparison of **GARLIC** and PandoraPFA algorithms for $\pi^0$ reconstruction



**GARLIC** reconstructs  $\pi^0$  significantly better than PandoraPFA for  $\pi^0$  energies > 10 GeV

DBD detector,  
SiECAL

Compare  $\pi^0$  reconstruction in detectors with different ECAL radius

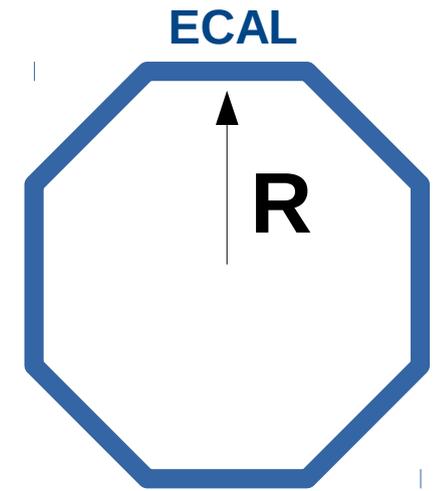
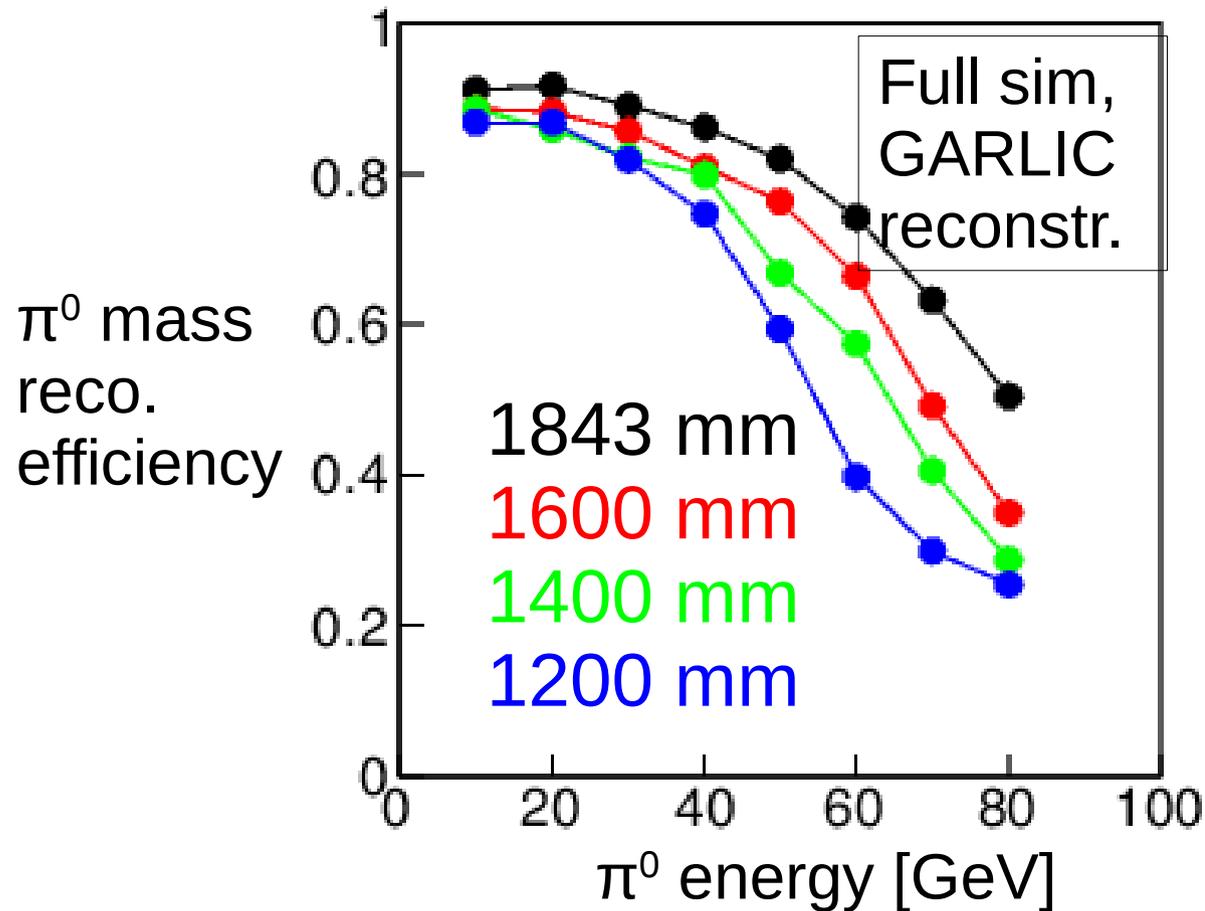


Attractive from a cost perspective,

however

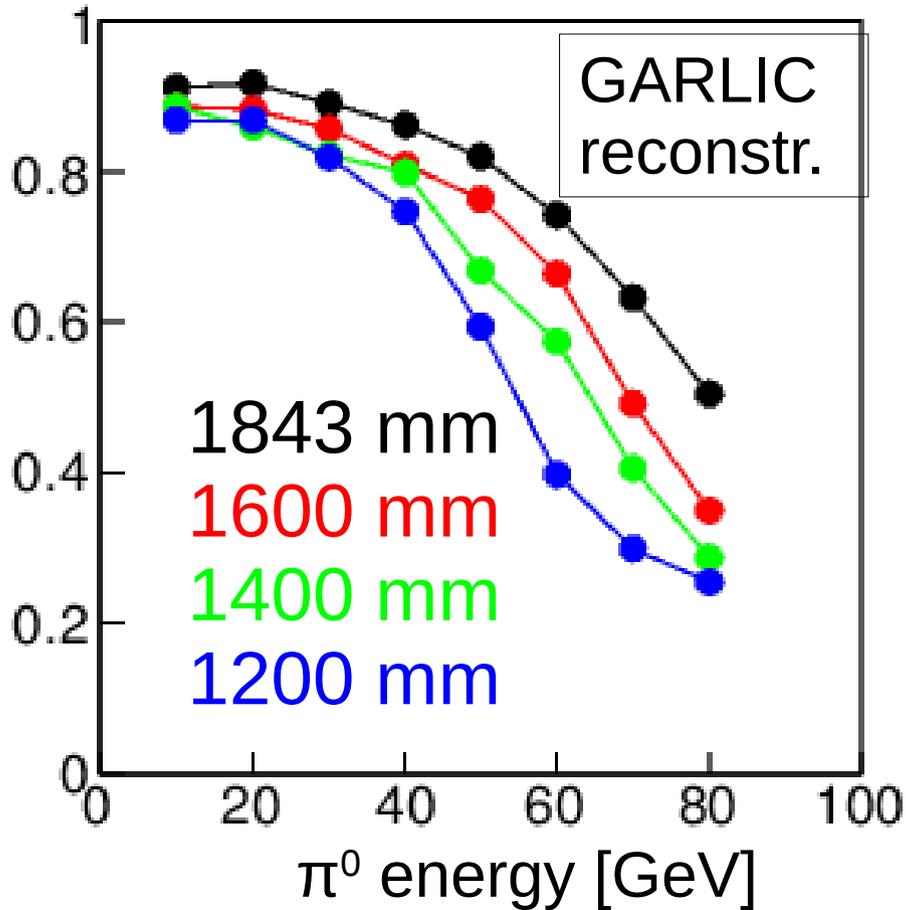
separation between photons at the ECAL  $\propto$  radius

# Compare $\pi^0$ reconstruction in detectors with different ECAL radius

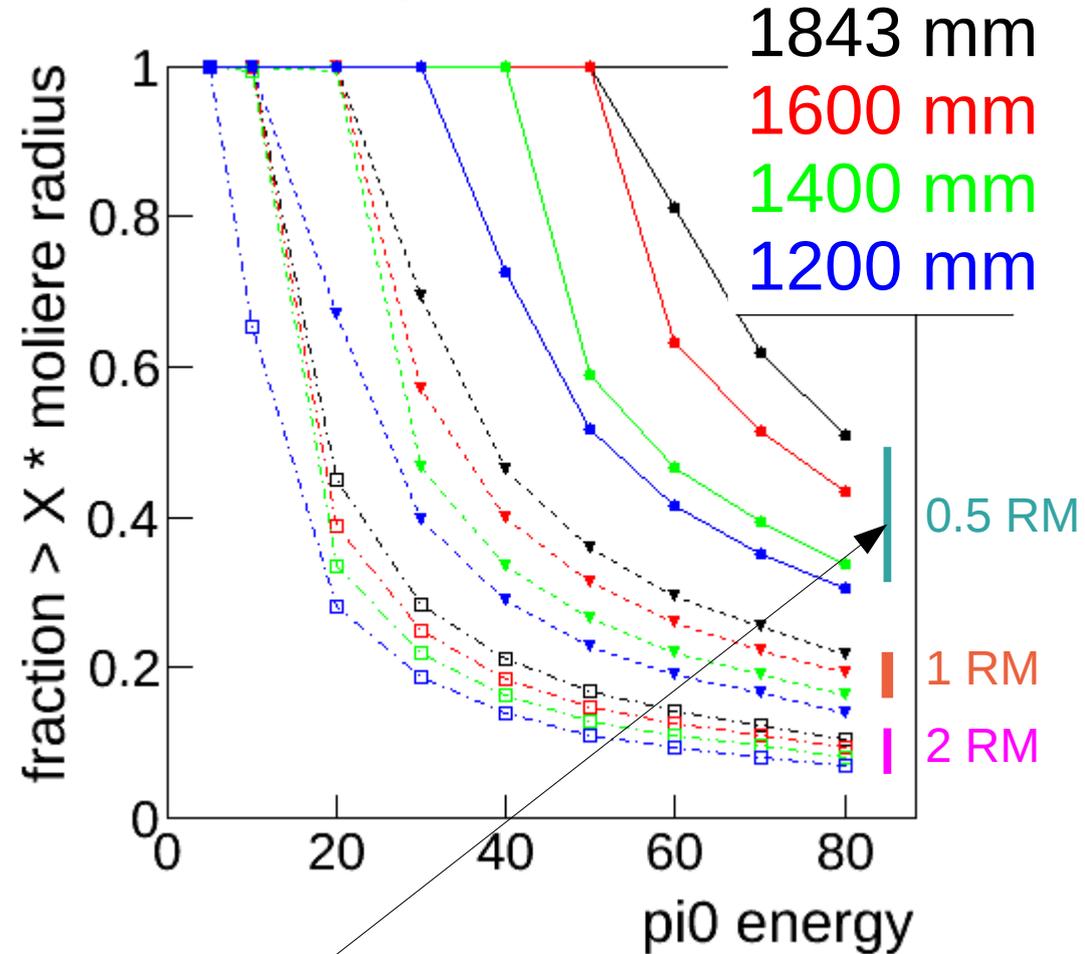


As expected, quite a strong dependence, particularly for  $\pi^0$  energies 40~80 GeV

## Full reconstruction



## Toy MC

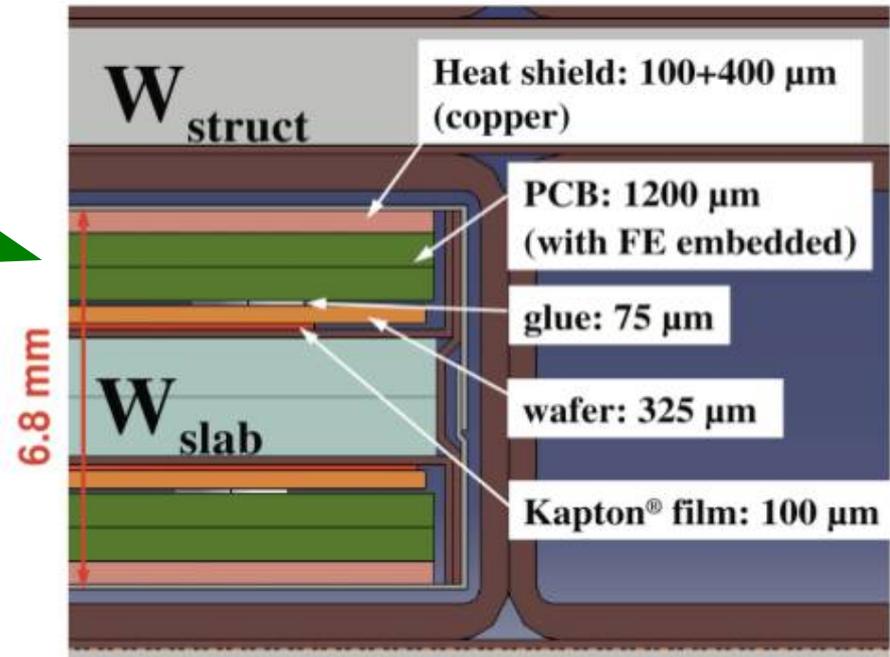


Rather similar dependency:  
GARLIC separation power  $\sim 0.5$  Moliere radii

# ECAL designs with different Moliere radius

Motivated by thickness of PCB in readout gaps

How thin must this PCB be?

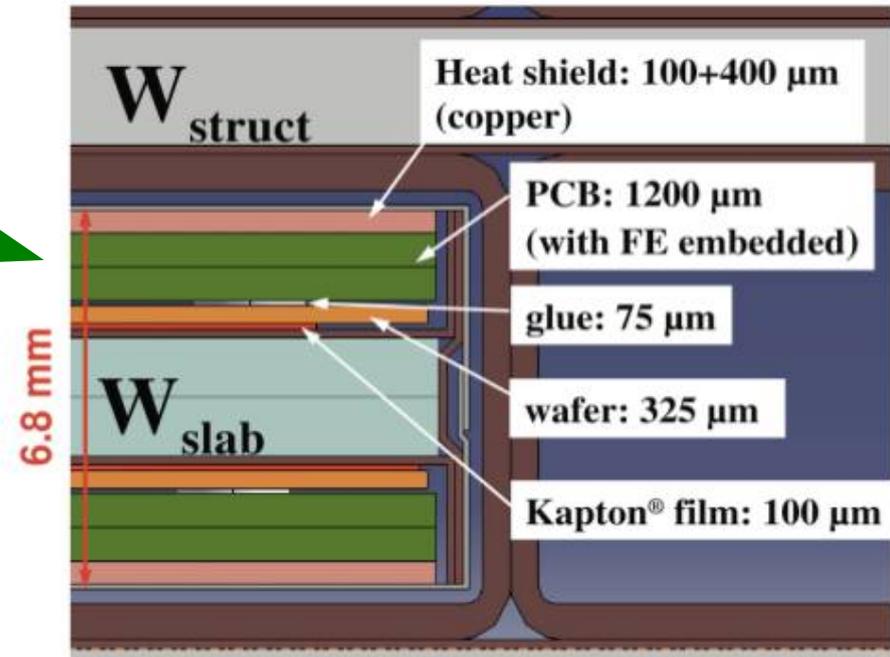
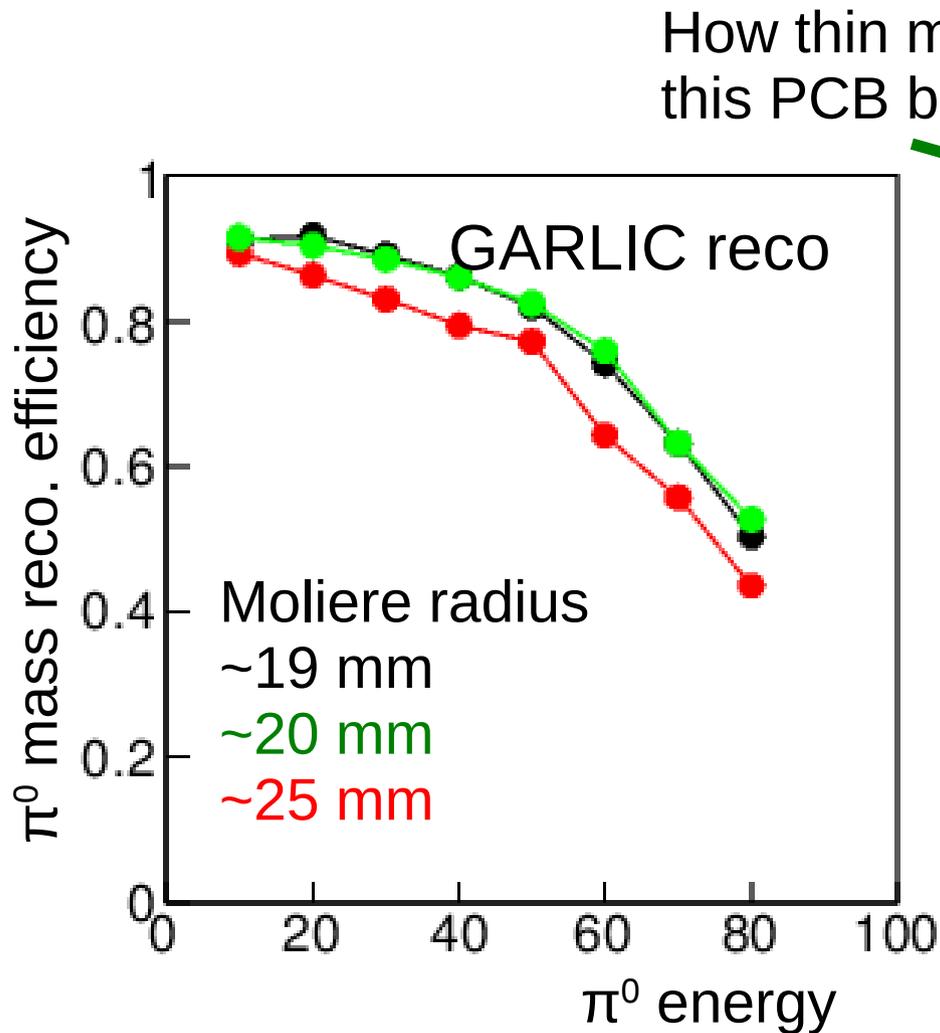


PCB thickness affects effective Moliere radius

<u>PCB thickness</u>	<u>R(Moliere)</u>
0.8 mm (DBD, difficult)	~19 mm
1.2 mm (possible)	~20 mm
2.8 mm (~easy)	~25 mm

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PCB thickness	R(Moliere)
0.8 mm (DBD, difficult)	~19 mm
1.2 mm (possible)	~20 mm
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Some modest degradation for thickest PCB design

# Plans

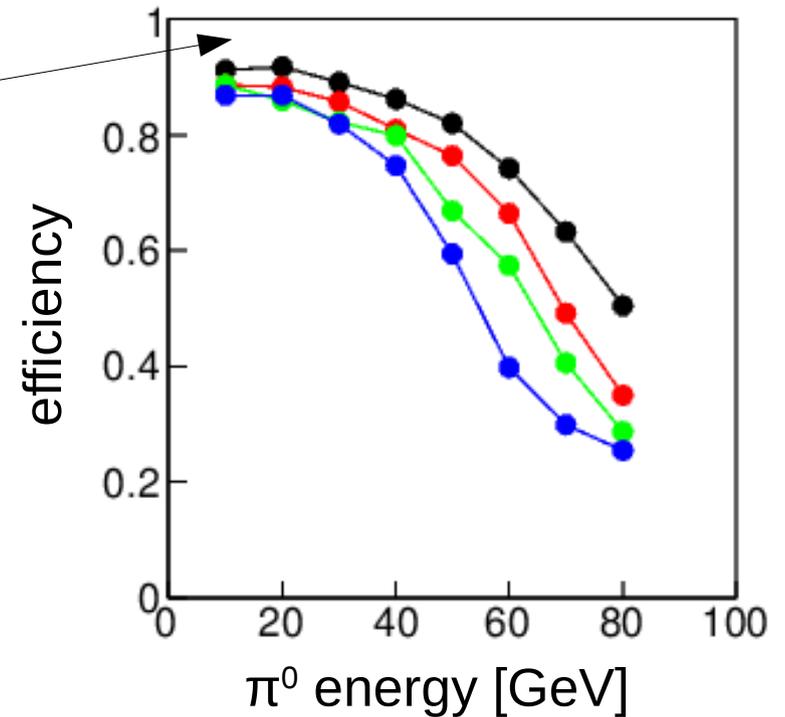
Further improvements in GARLIC:  
Photon and  $\pi^0$  reconstruction  
e.g. understand inefficiency  
Hadron rejection

Check performance in jets  
-> update code in SVN

$\pi^0$  reconstruction:  
dependence on ECAL cell size

Apply GARLIC to tau decays

Quantify impact of radius, cell size on  
tau decay mode reconstruction



# Summary

Snapshot of GARLIC performance  
further developments in the pipeline

$\pi^0$  reconstruction is important for some measurements at ILC

For example:

Higgs CP properties via  $\tau$  decays at ZH threshold

$\pi^0$  of a few 10s GeV

Ultimate jet energy reconstruction via  $\pi^0$  constrained fitting

Specialised GARLIC algorithm better than  
general purpose PandoraPFA  
at resolving photons from high energy  $\pi^0$   
...further improvements probably possible

Radius of ECAL has a strong impact on  $\pi^0$  reconstruction  
particularly in range 40-80 GeV  
demonstrated using realistic simulation and reconstruction

Moliere radius seems less critical  
(at least in technically reasonable range of variation)



BACKUP

# Role of ECAL in ILC experiments

Identify photons, and measure their  
Energy, Position, Angle

Main sources of photons:

Bhabha scattering

<---- very forward: “LumiCal”

$\pi^0$  decays in hadronic jets

I(F)SR, bremsstrahlung

Photons often not isolated:

require excellent pattern recognition  
to separate nearby particles

“prompt” photons are rarer: e.g.  $H \rightarrow \gamma\gamma$

such rare processes are not a top priority @ ILC

LHC usually does this better, thanks to high luminosity

Layer-based sampling EM calorimeter design  
natural segmentation of readout across layers

### Tungsten absorber layers

20-30 layers,  $0.5\sim 1.5 X_0$  thickness

**Highly segmented active layers**  $\sim 5\times 5 \text{ mm}^2$  granularity  
silicon PIN diodes  
or  
scintillator strips

Transverse size of EM shower governed by Moliere radius:

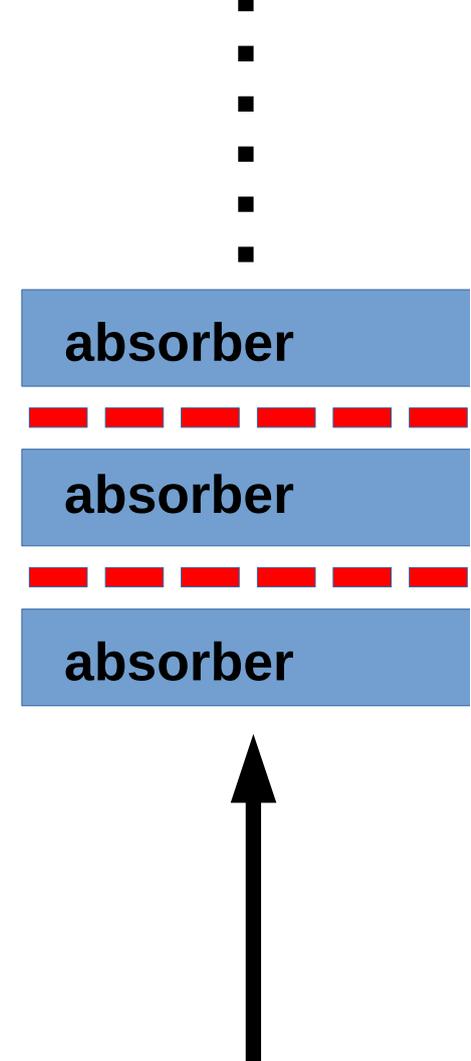
motivates:

use of tungsten

and

thin readout gap between absorber layers

Moliere radius  $\sim 20\text{mm}$  in ILD ECAL



ECAL is most expensive sub-detector  
large active area  
10-100M readout channels  
expensive readout technology (silicon detectors, SiPM)

Studies are underway to see if the ECAL cost can be reduced  
without severely affecting detector performance

Cost determined by total sensor area and number of readout channels

Most sensitive parameters:

Inner radius of ECAL

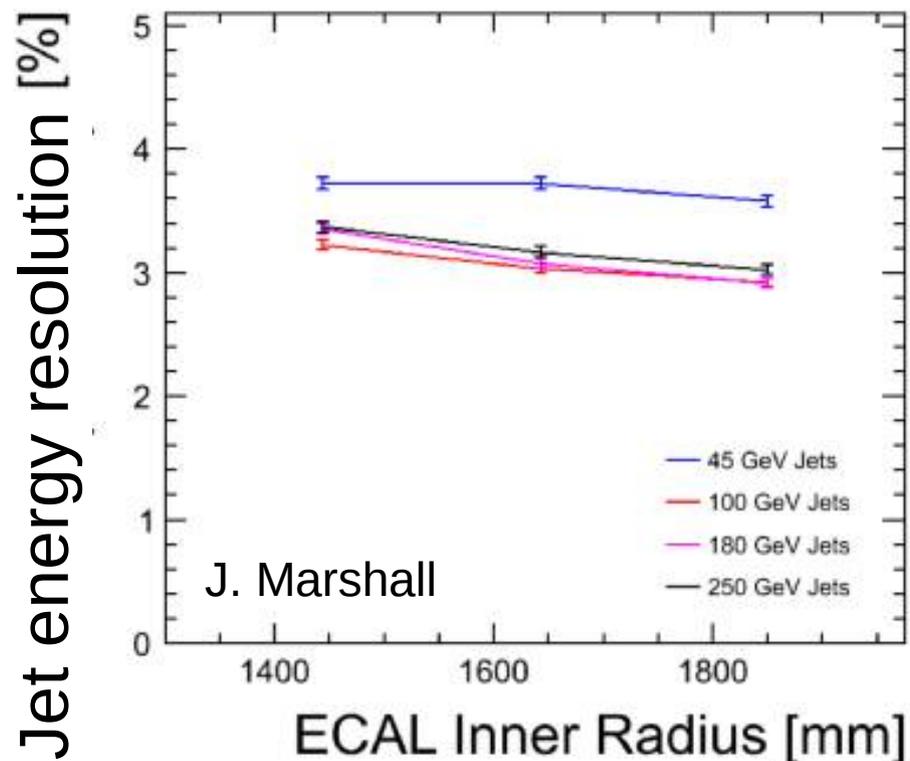
<--- affects particle separation in ECAL

Number of sensitive layers

<--- affects single particle energy resolution

★ **5 x 5 mm<sup>2</sup> ScW**

e.g. Reducing ECAL radius  
has rather little effect on  
Jet Energy Measurement



# $\pi^0$ reconstruction

Hadronic jets: interested in the total energy deposited by photons

$\pi^0$  reconstruction not particularly relevant

(although kinematic fits of  $\pi^0$  can somewhat improve jet energy resolution)

## Tau lepton

$\tau^-$ BRs	0 $\pi^0$	1 $\pi^0$	2 $\pi^0$	3 $\pi^0$
1 h $^-$	12%	26%	9%	1%
3 h $^-$	10%	4.5%	0.5%	0.1%

If the decay mode of  $\tau$  can be reconstructed, can be used as polarimeter

distribution of  $\tau$  decay products ---> orientation of  $\tau$  spin

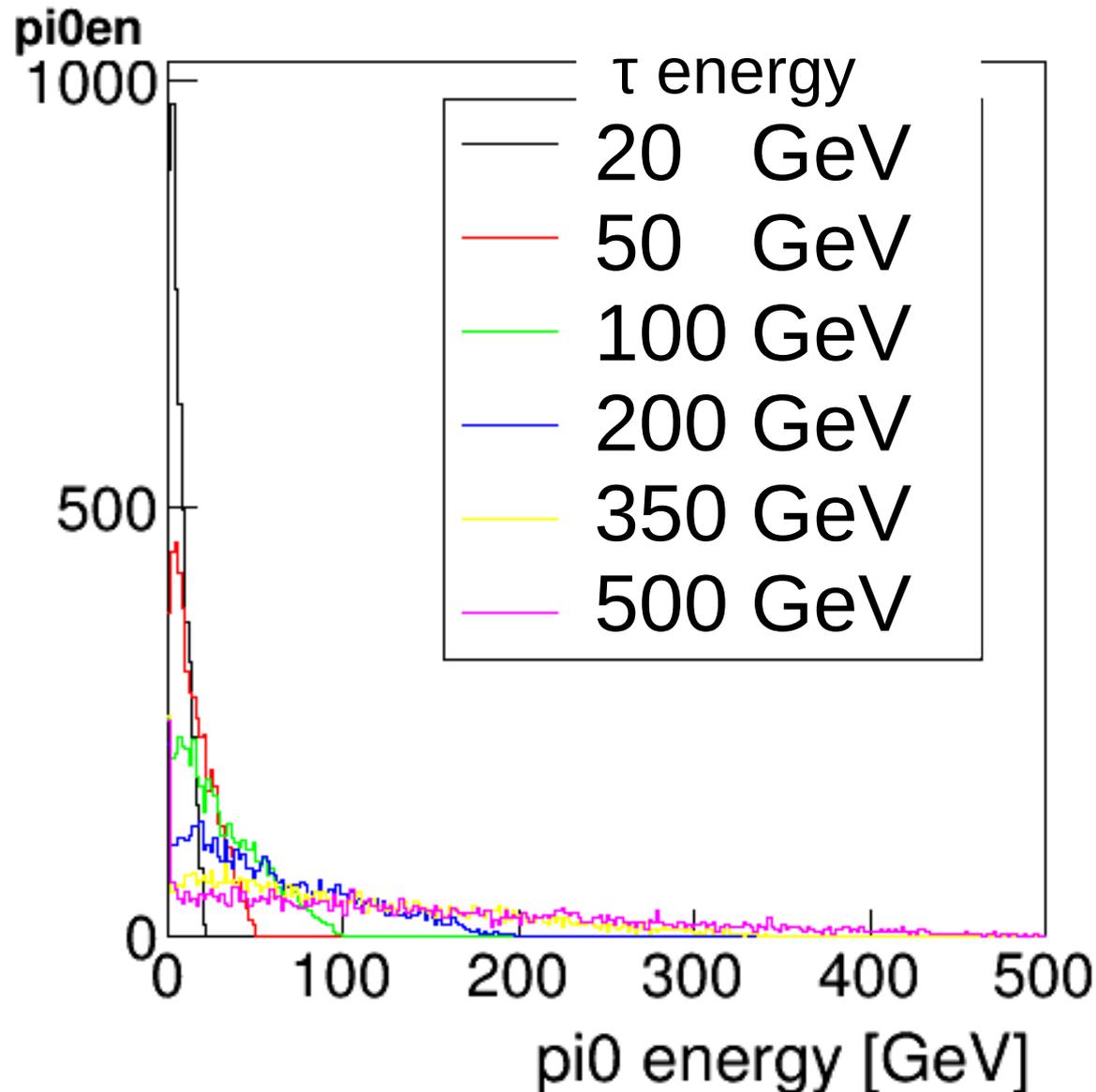
$\tau$  spin ---> spin properties of  $\tau$  parent

In particular,  $H \rightarrow \tau \tau$  allows direct measurement of **Higgs CP** properties

CP mixing angle measurable to a few % @ ILC (e.g. arXiv:1308.2674)

$\tau$  decay mode must be correctly identified

# Energy of $\pi^0$ produced in $\tau$ decays

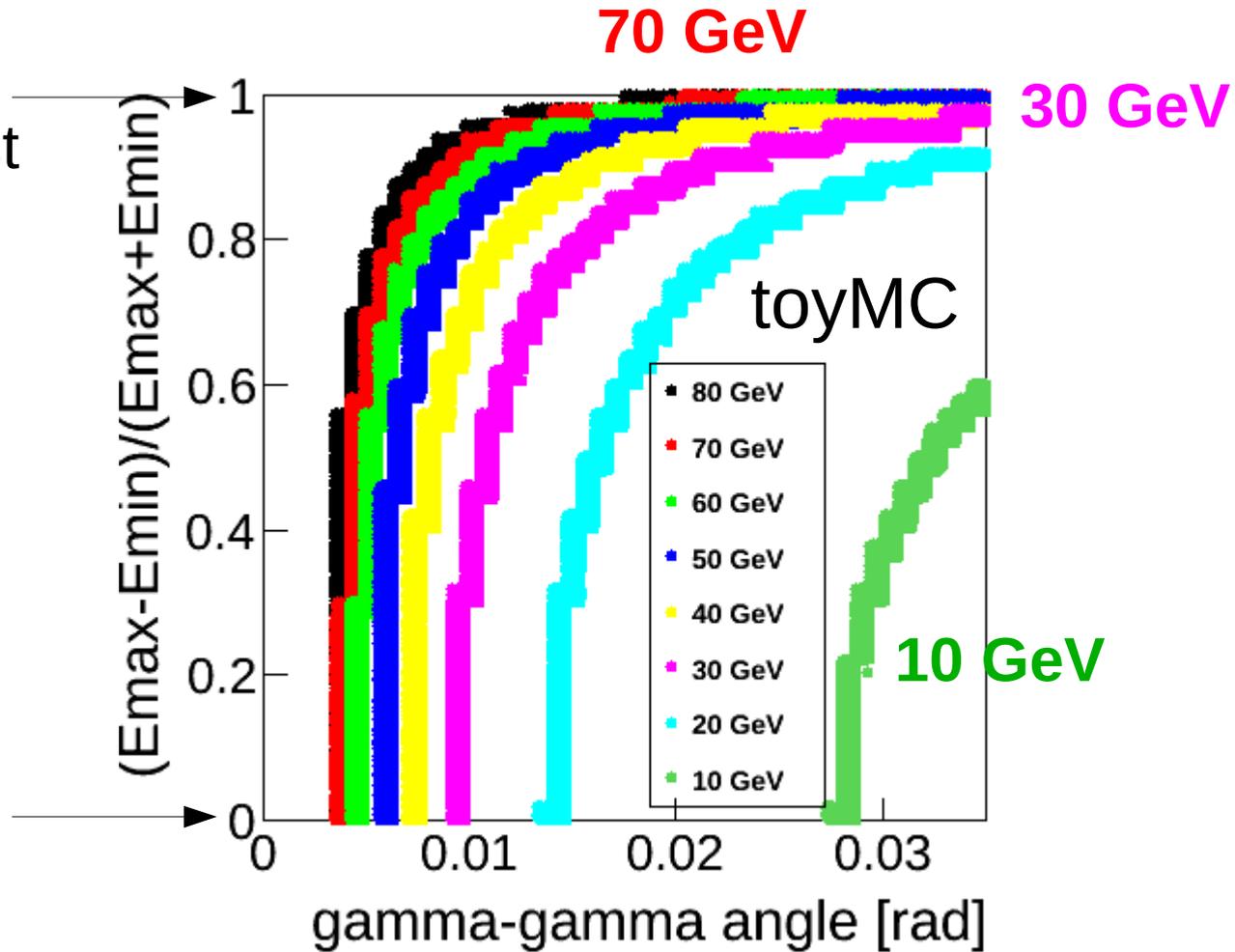


$\tau$  produced in Higgs decays near the  $e^+e^- \rightarrow ZH$  threshold  
are strongest motivation for reconstruction of  $\tau$  decay modes  
--->  $\tau$  energy  $\sim 60$  GeV,  $\pi^0$  energy typically few 10s of GeV

# $\pi^0$ decays mostly to 2 photons

One photon carries almost all  $\pi^0$  energy

Two photons have same energy



$\pi^0$  of different energies

- angle between photons
- asymmetry between photon energies

Angle subtended by  $0.5 \times$  Moliere radius for different ECAL radii

