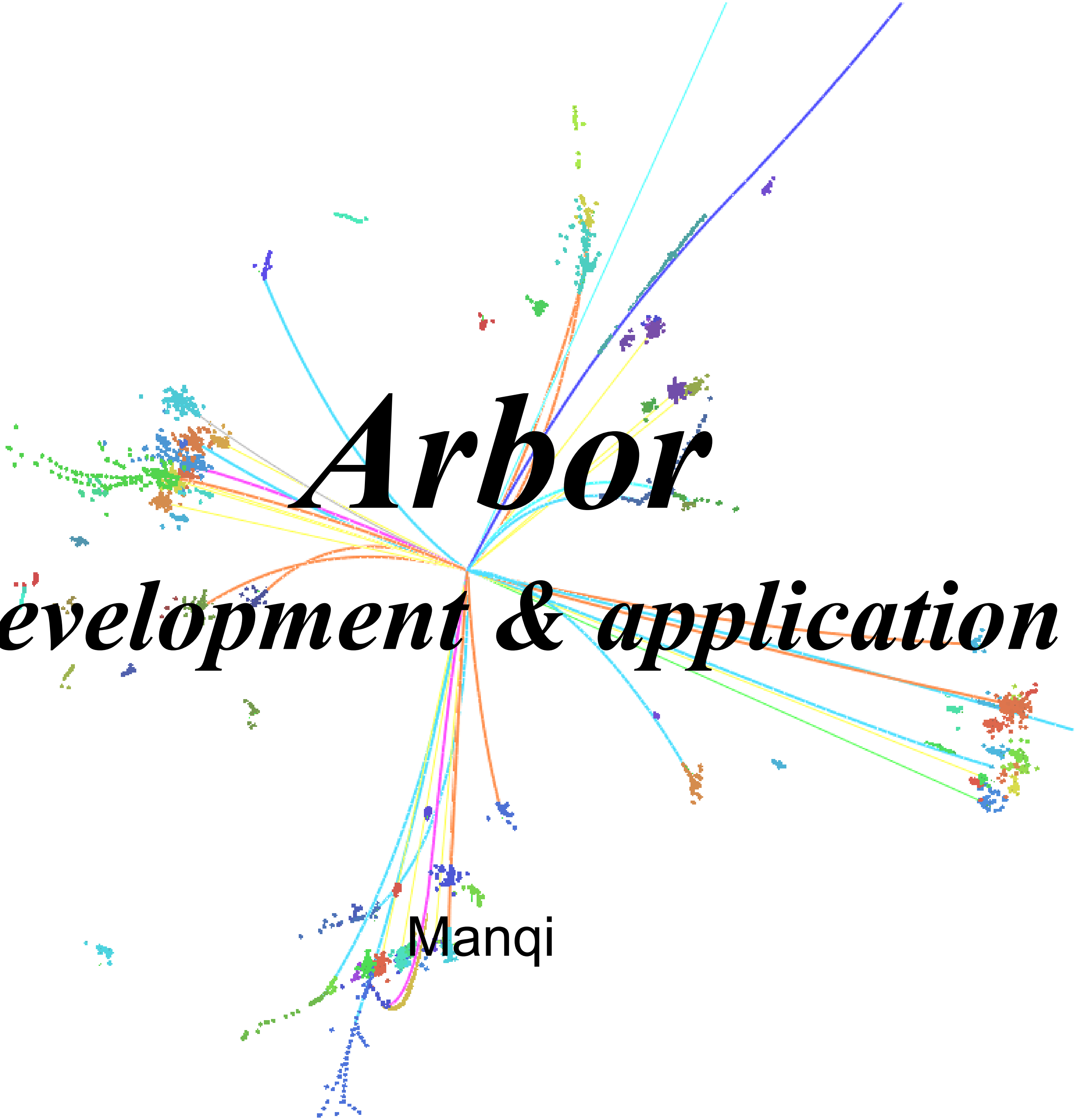
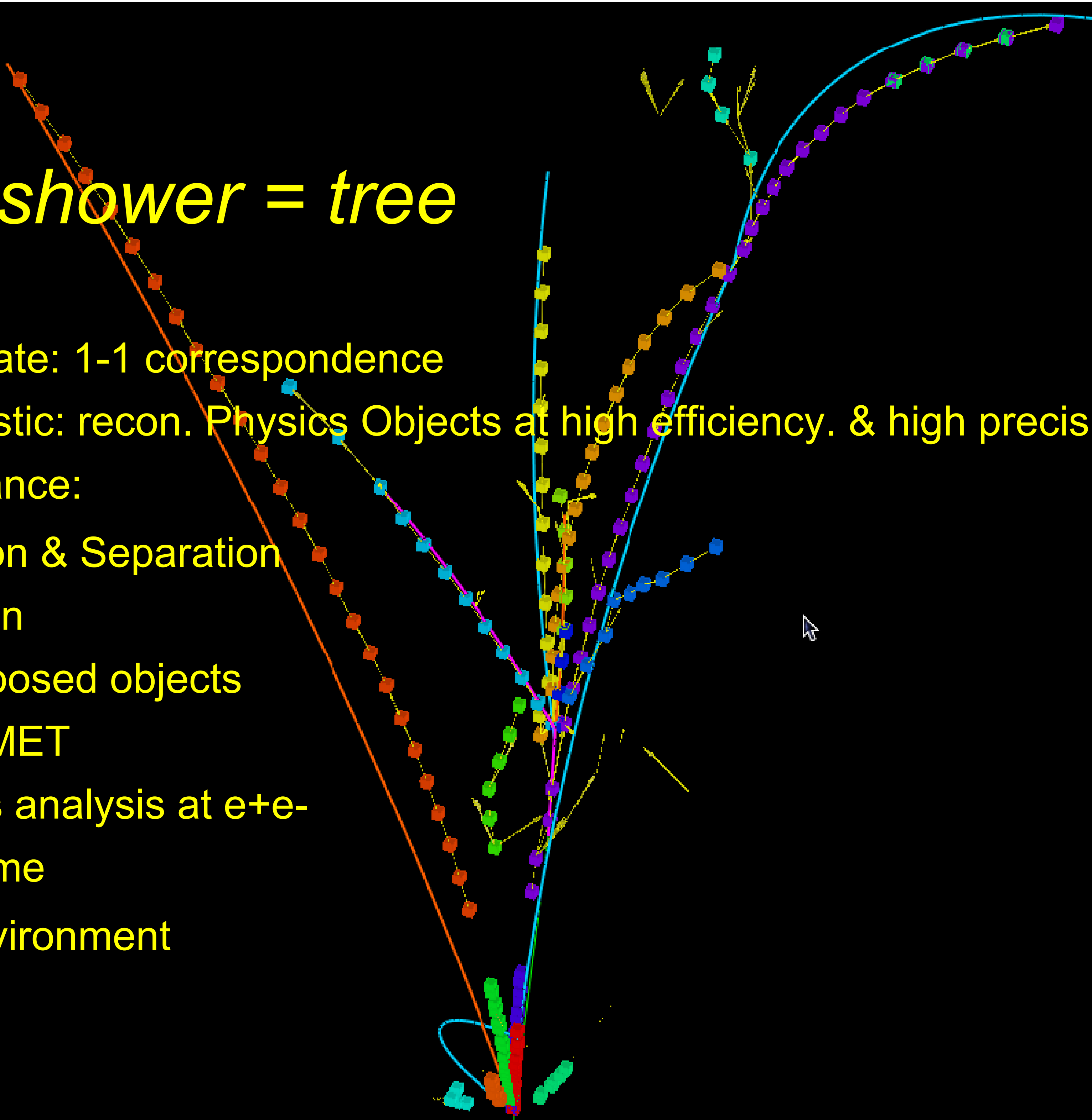


Arbor

development & application

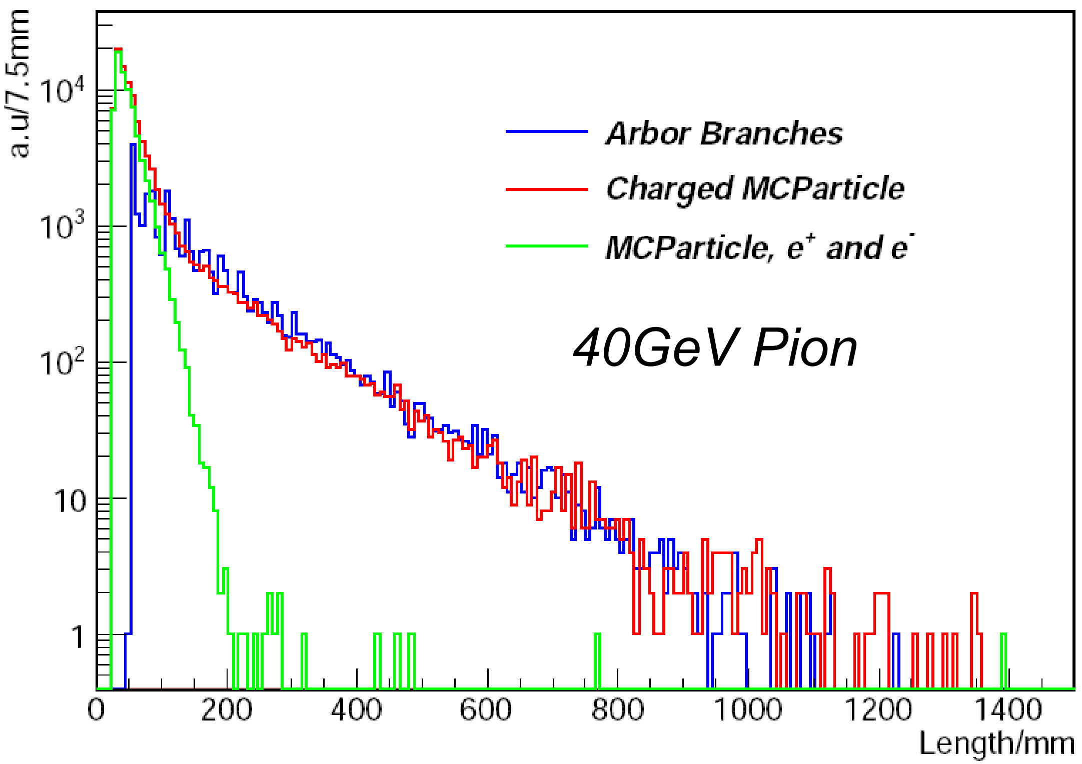
Manqi

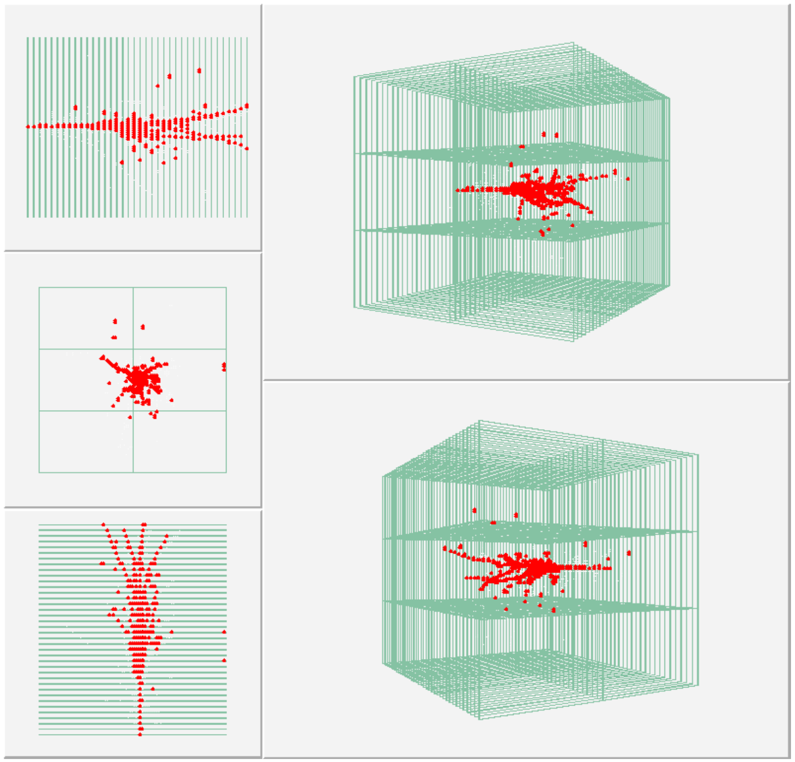
Arbor: shower = tree



- Goal:
  - Ultimate: 1-1 correspondence
  - Realistic: recon. Physics Objects at high efficiency. & high precision
- Performance:
  - Photon & Separation
  - Lepton
  - Composed objects
  - JET/MET
  - Higgs analysis at e+e-
- About Time
- At pp environment

Validation: Arbor Branch Length

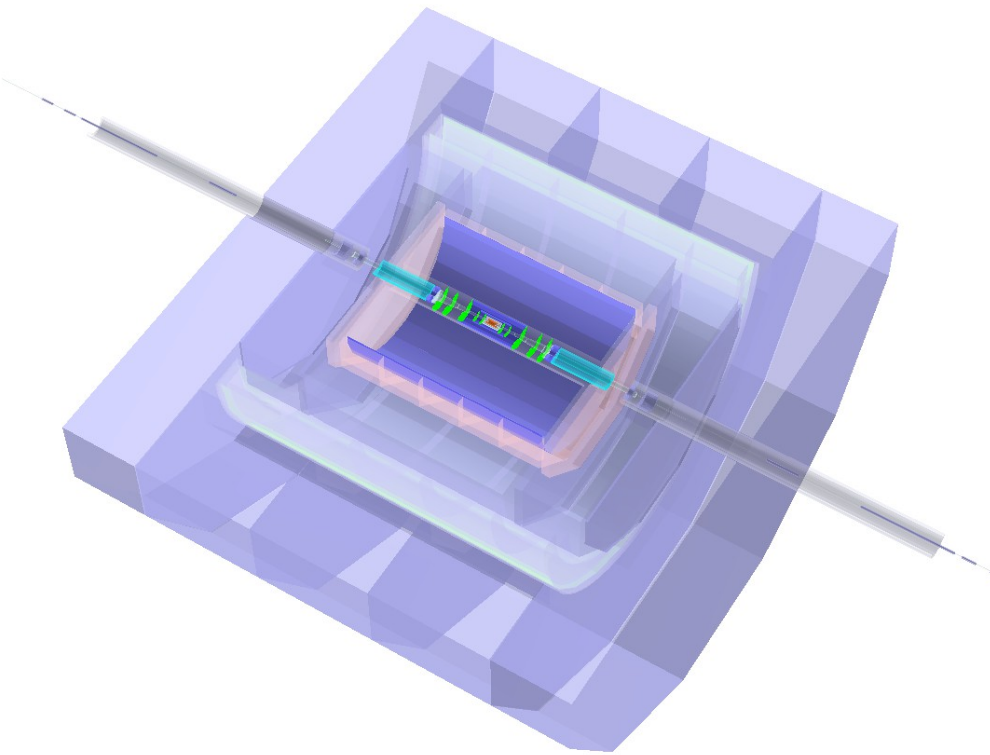




Arbor: successfully tag sub-shower structure

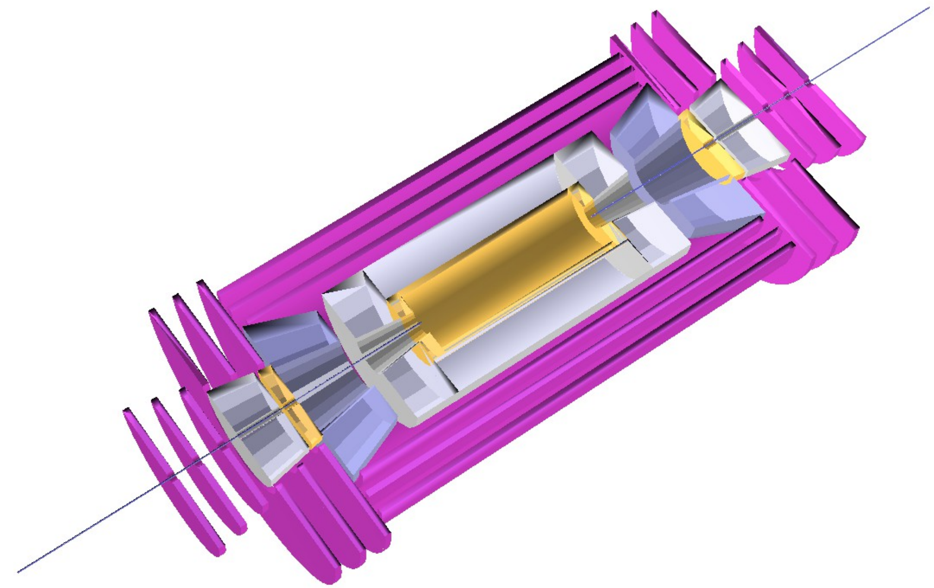
Samples: Particle gun event at ILD HCAL (readout granularity 1cm^2 & layer thickness 2.65cm)
Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighbor hits

Geometries



CEPC_v1
Forward Region & Yoke Thickness
Modified w.r.t ild_o2_v05

Used for CEPC Higgs analysis



Simplified, Defect free geometry...
Cylinder like calorimeter layers,
& Silicon tracker (Optional)

Used for Arbor tuning, Calorimeter optimization & Conceptual SPPC Detector study...

Photons @ ECAL with 90mm W & 30 layers

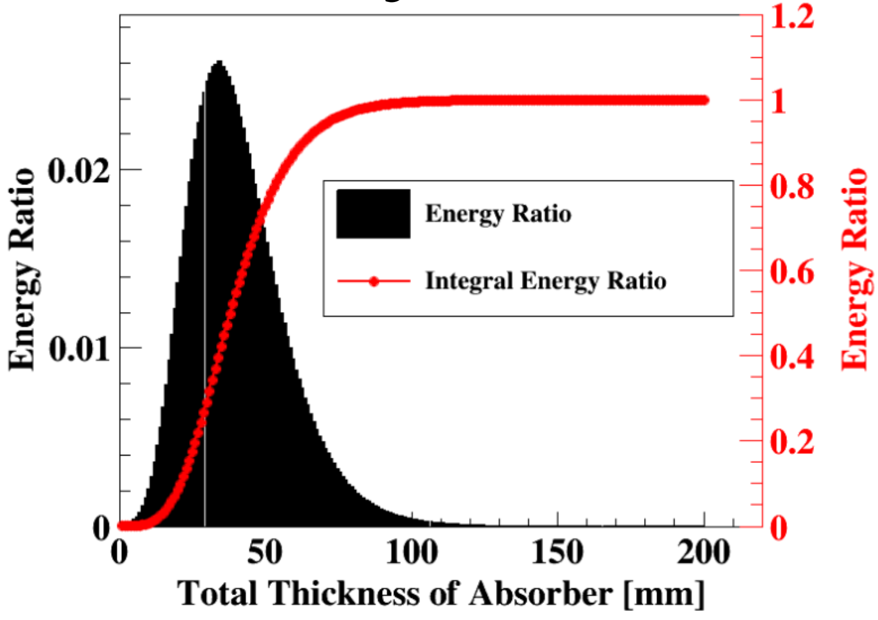


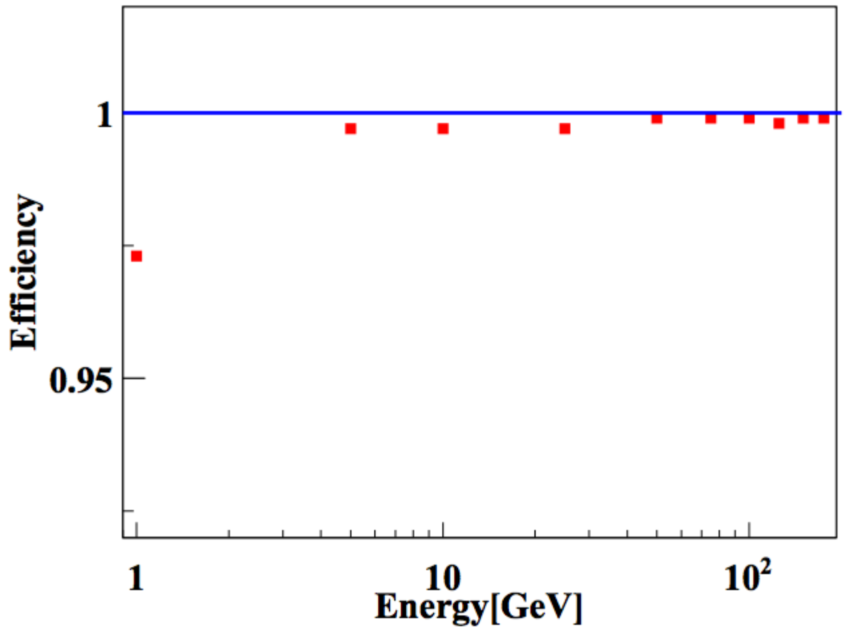
Figure 3. Deposit energy ratio of 120GeV photon shower by the depth in tungsten, and the integrated result.

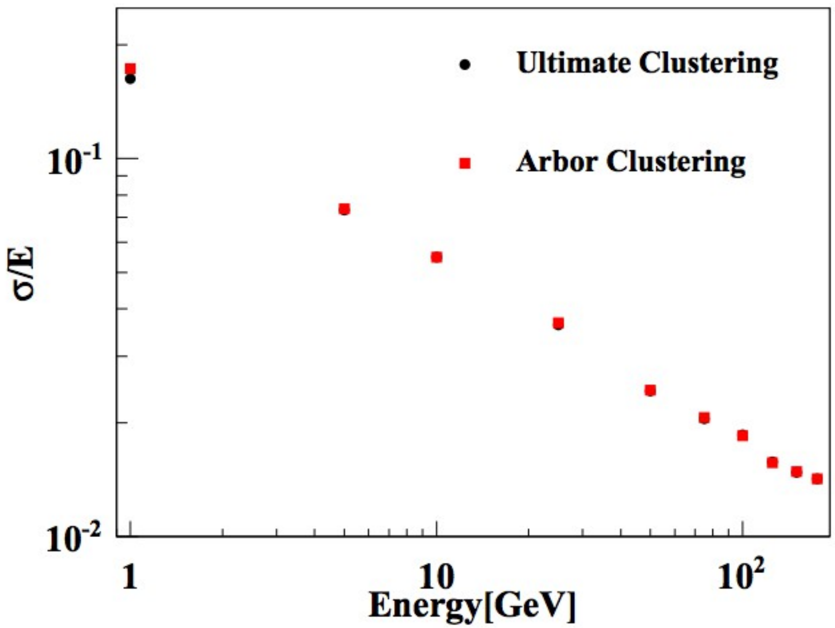
Table 1. Percentage of EM showers energy deposit in 80mm-95mm tungsten

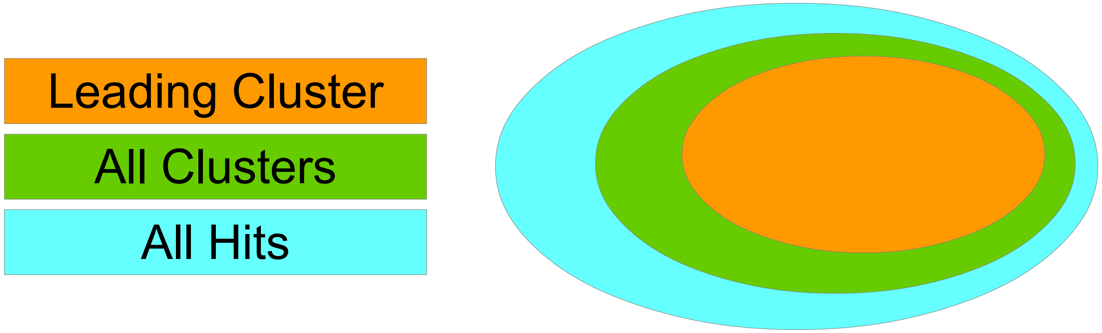
Photon Energy	95mm W	90mm W	85mm W	80mm W
175GeV	99.0%	98.6%	97.9%	96.9%
120GeV	99.2%	98.8%	98.2%	97.3%
75GeV	99.4%	99.1%	98.7%	98.1%

30 * (3 mm W + 0.5 mm Silicon + 2 mm PCB)

Clustering: Ideal Vs Realistic

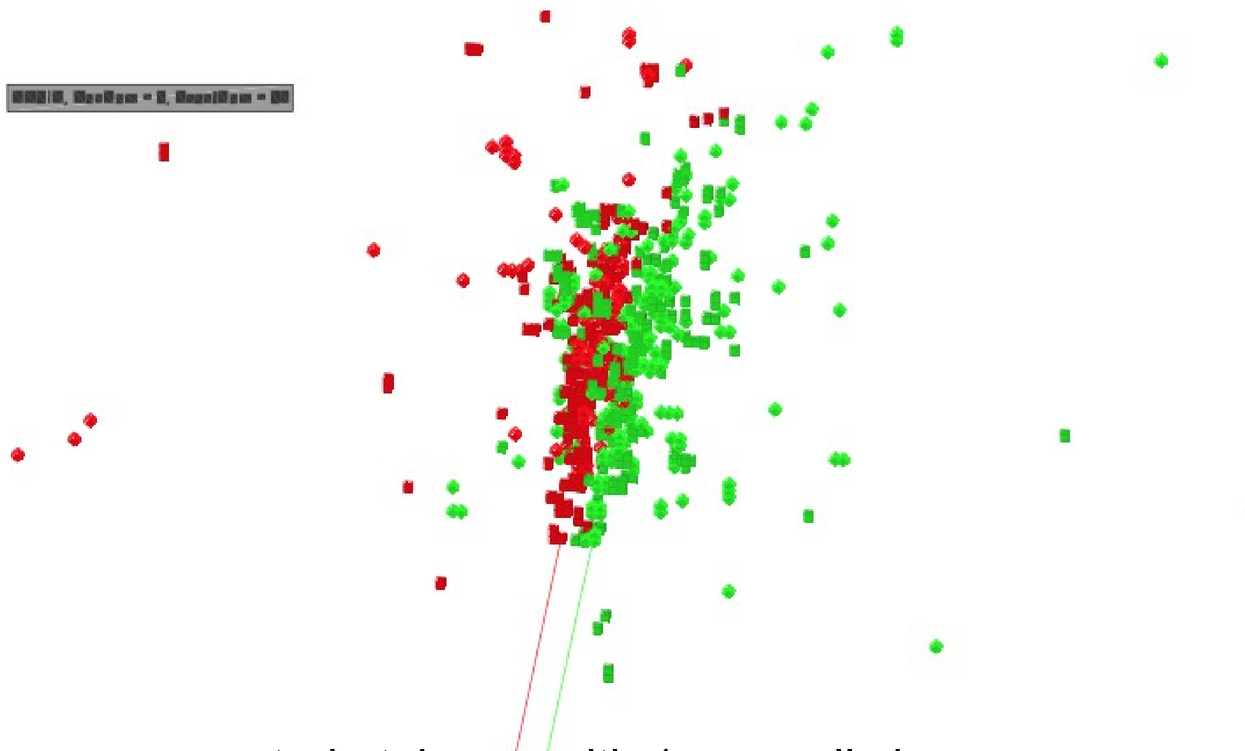






Efficiency
= LC Energy/total hit energy

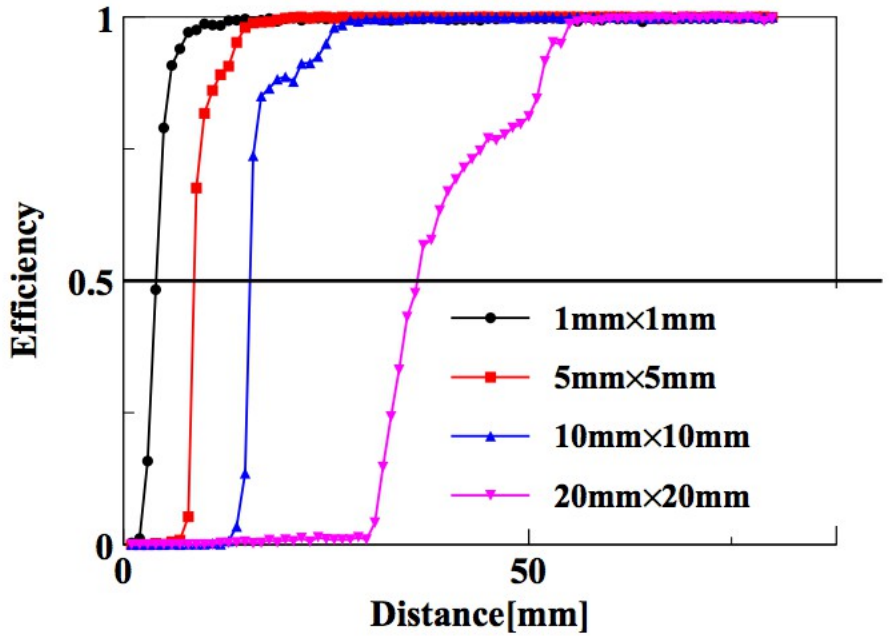
Separation

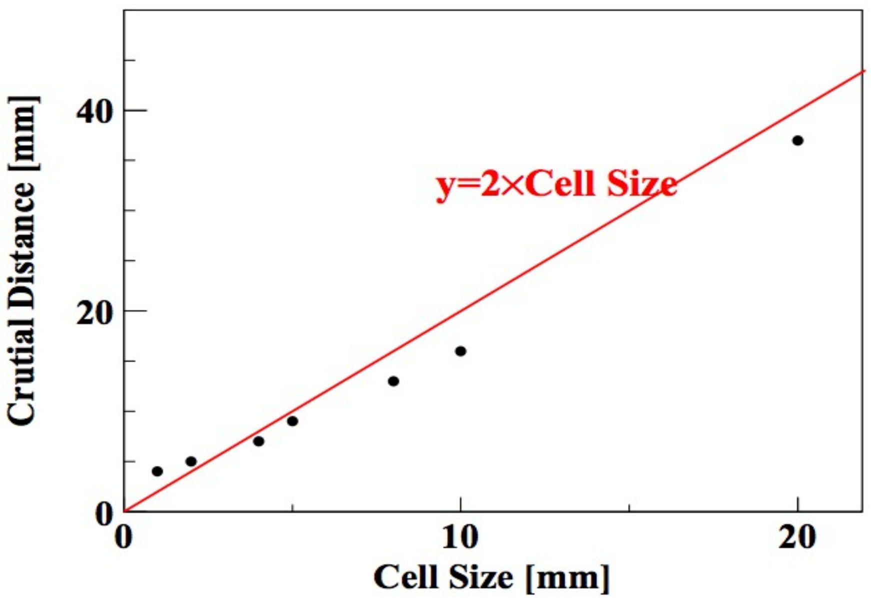


Two 5 GeV photons – separated at 4 mm, with 1 mm cell size

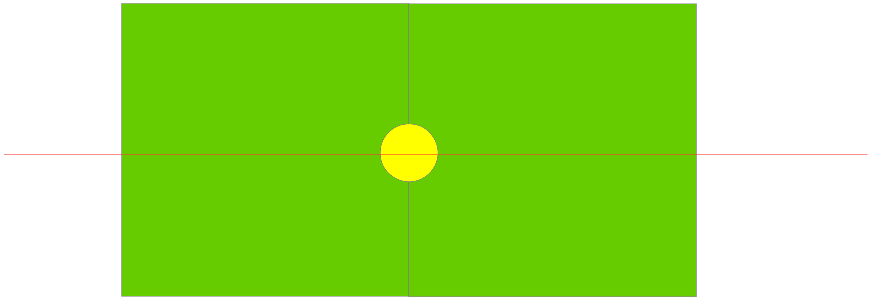
Figure 11. Event display of reconstructed di-photon.

Separation

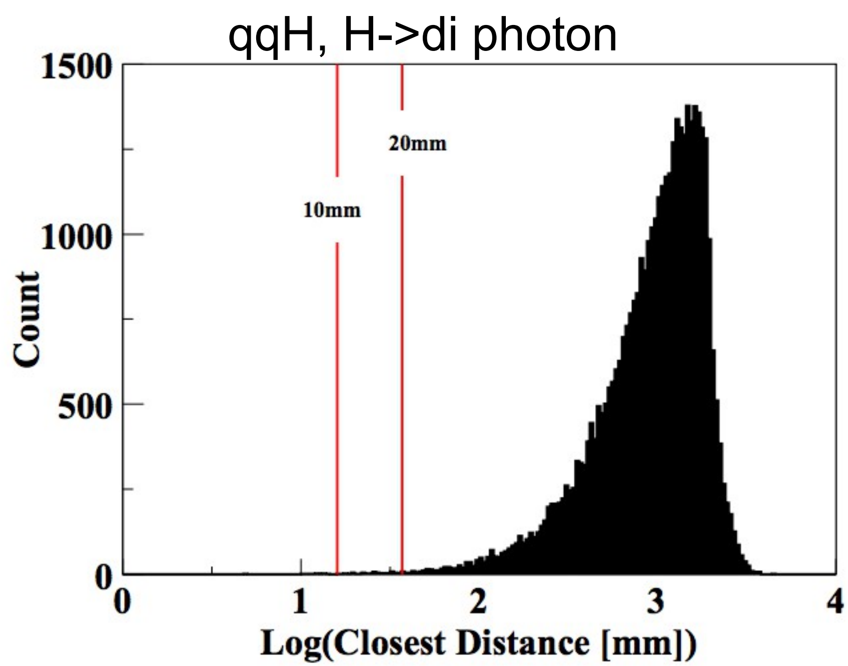




Separation ~ 2 times Cell Size
Phase transition ~ Moliere radius



Impact of Separation



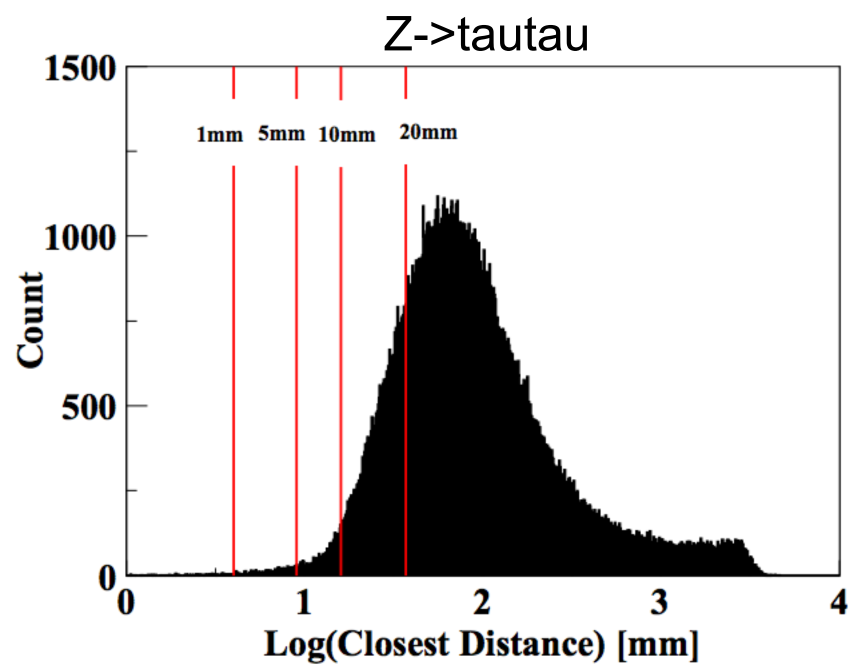


Table 2. Percentage of photons that would be polluted by neighbor particle

Cell Size	Crucial Separation Distance with Arbor	Percentage of H->di photon	Percentage of Z->tautau
1mm	4mm	0	0.827%
5mm	9mm	0	0.486%
10mm	16mm	0.03%	1.96%
20mm	37mm	0.17%	18.4%

@ H->di photon

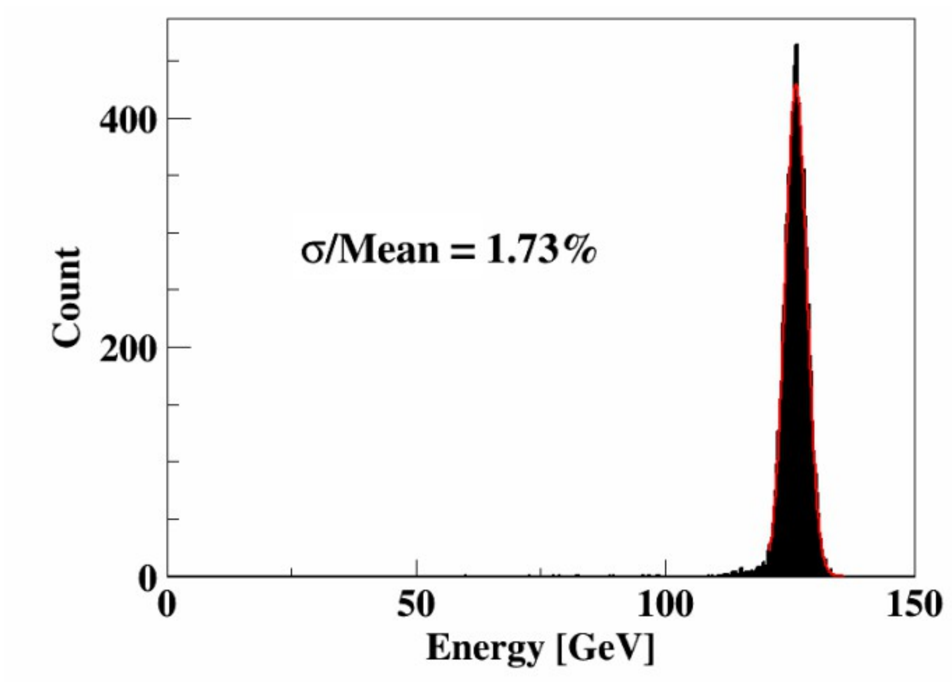
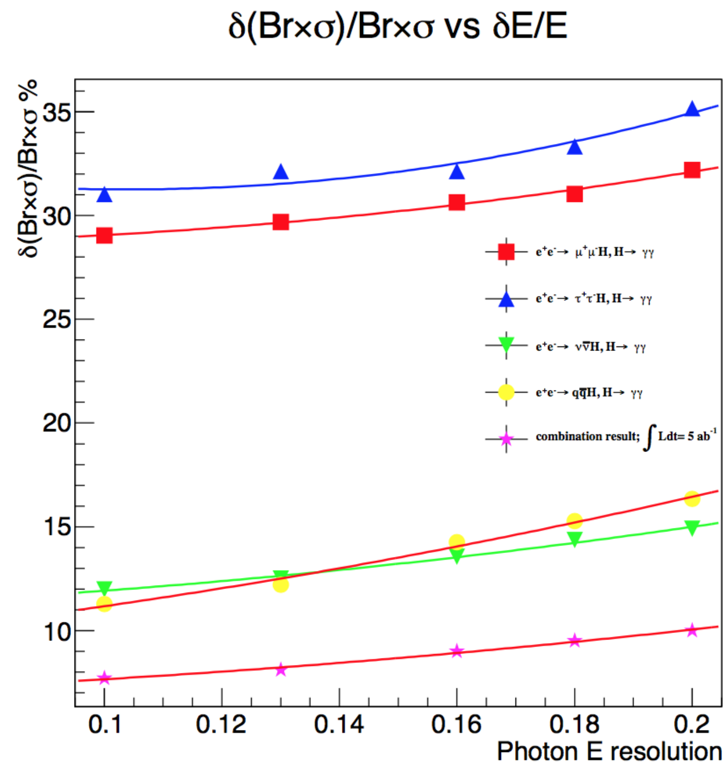
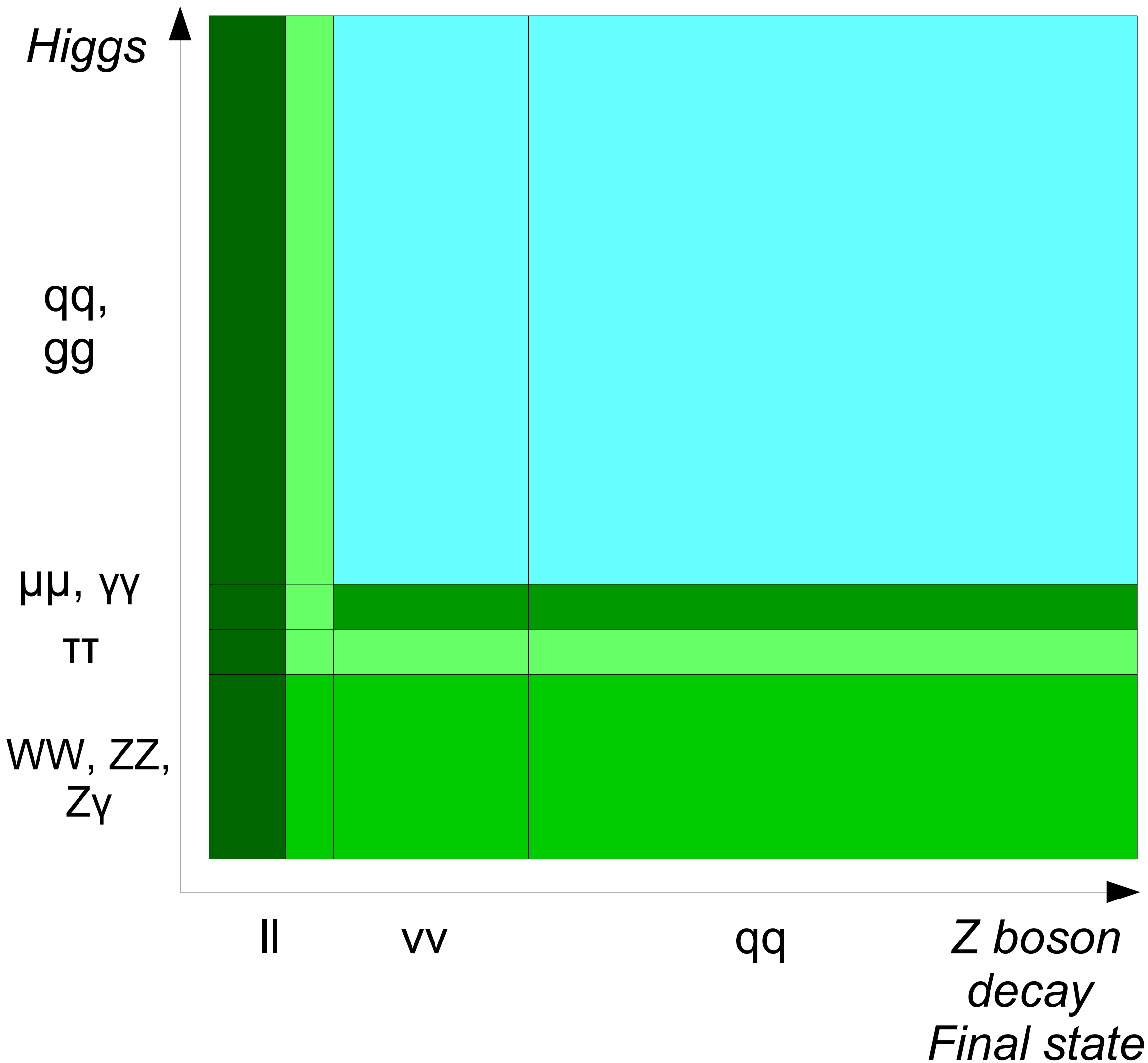


Figure 15. The invariant mass distribution of reconstructed Higgs.



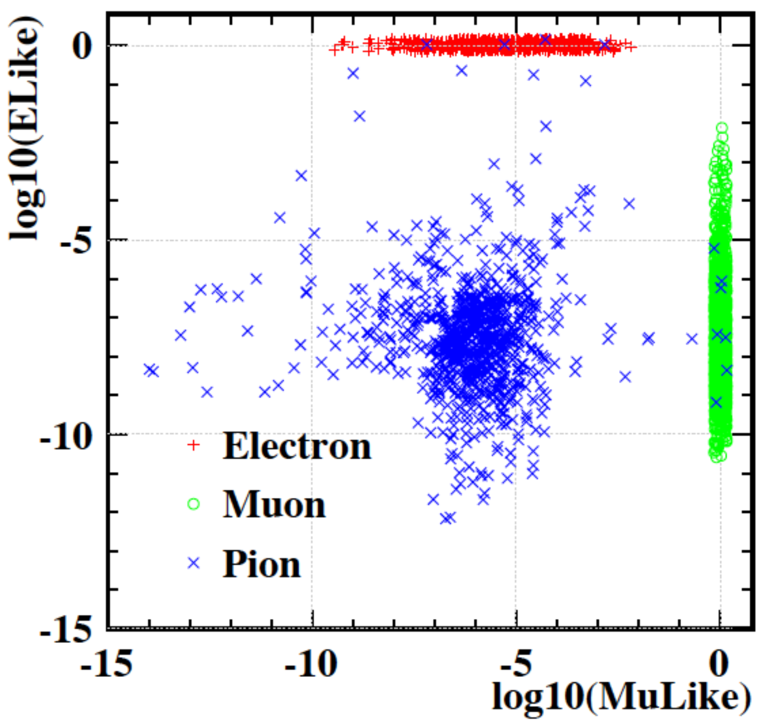
Relative Accuracy: ~ 8.5%

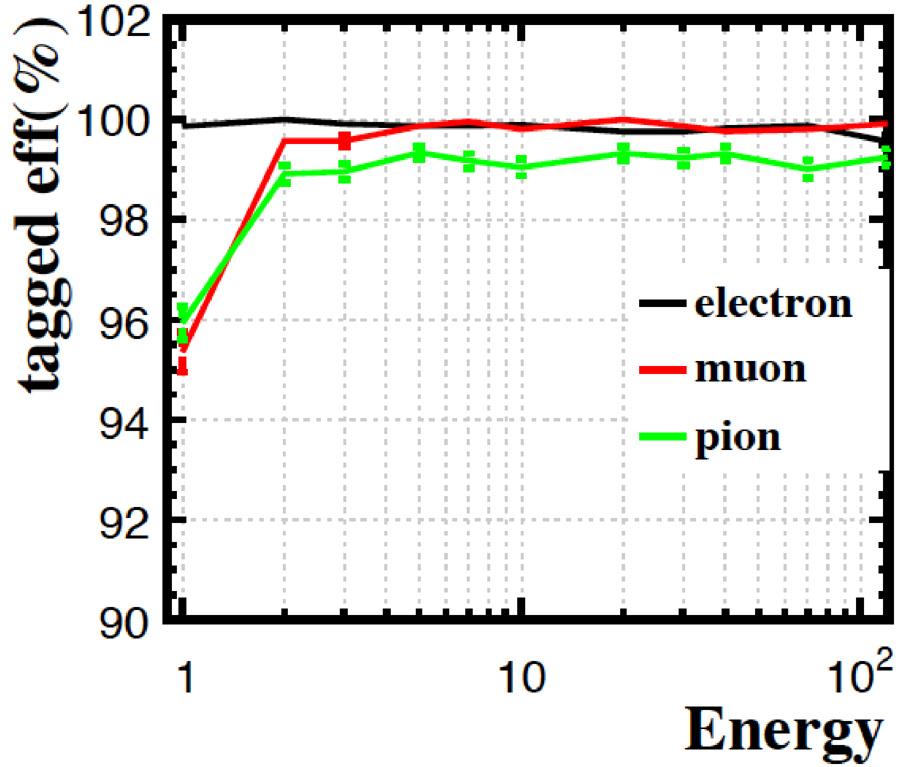
Leptons: essential for Higgs program



- Key objective: Identify the initial leptons
  - Leptons generated in Z decays in ZH events
  - Electrons in Z fusions
- Secondary: leptons generated in Higgs decay
  - H->WW/ZZ/tautau/μμ
  - H->bb, cc->leptonic decay
  - Hadron decays

Dan Yu: general Lepton ID for Calorimeter with High granularity (LICH)





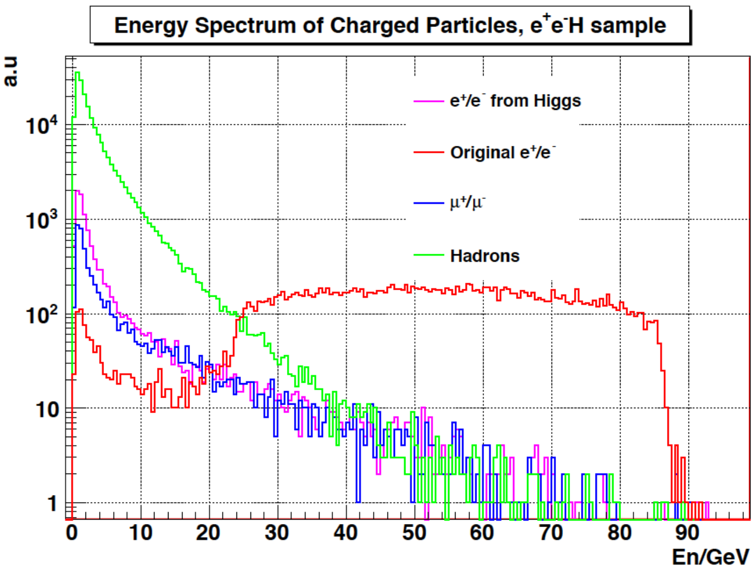
BDT method using 4 classes of 24 input discrimination variables.

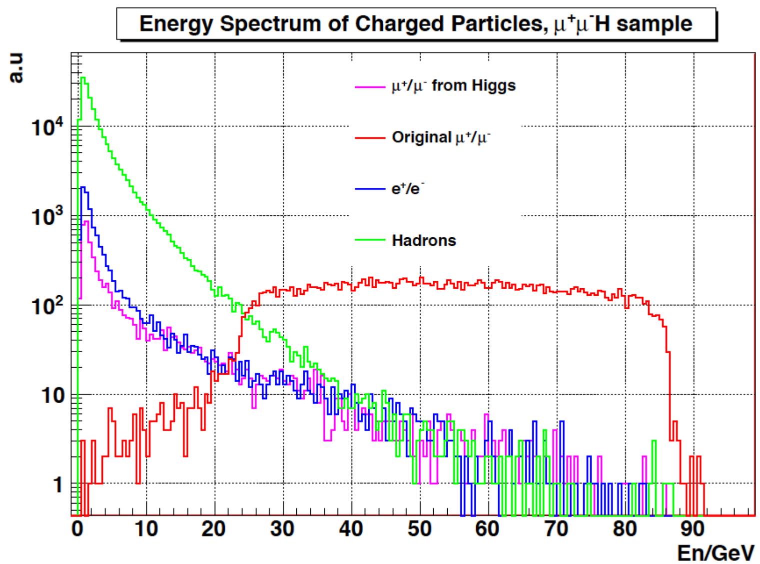
Test performance by requesting

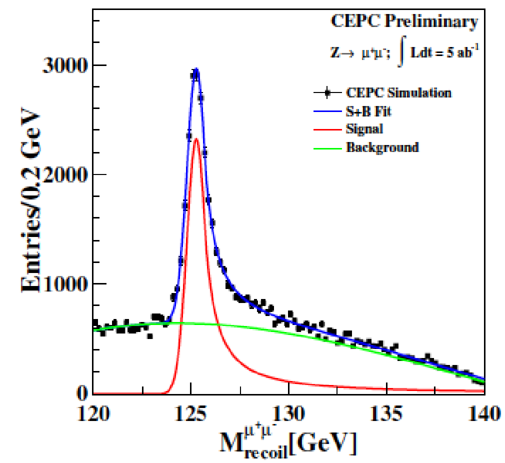
Electron = E_likeness > 0.5 ; Muon = Mu_likeness > 0.5

Single charged reconstructed particle, for E > 2 GeV: lepton efficiency > 99.5% && Pion mis id rate ~ 1%

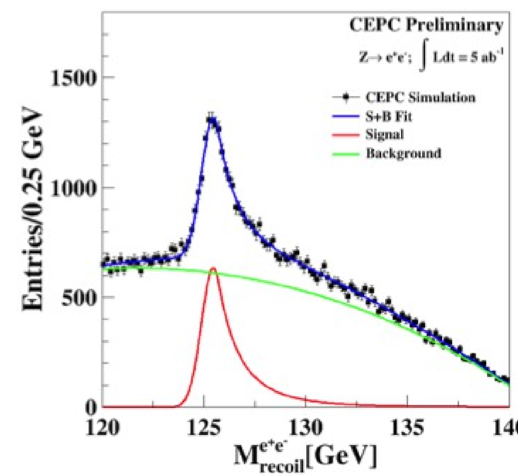
LICH @ llH events







	Geom 1		Geom 2	
	$\mu\mu$H	eeH	$\mu\mu$H	eeH
Cut$_\mu$	0.1	0.1	0.1	0.1
Cut$_e$	0.01	0.001	0.01	0.001
ε_E	93.41 ± 0.92	$\mathbf{98.64 \pm 0.08}$	91.60 ± 1.02	$\mathbf{97.89 \pm 0.11}$
η_E	92.02 ± 1.00	$\mathbf{99.74 \pm 0.04}$	89.89 ± 1.10	$\mathbf{99.67 \pm 0.04}$
ε_μ	$\mathbf{99.54 \pm 0.05}$	95.53 ± 0.76	$\mathbf{99.19 \pm 0.06}$	86.48 ± 1.26
η_μ	$\mathbf{99.60 \pm 0.04}$	96.31 ± 0.70	$\mathbf{99.83 \pm 0.03}$	95.38 ± 0.81
ε_{event}	98.53 ± 0.13	97.06 ± 0.19	97.24 ± 0.18	95.40 ± 0.24



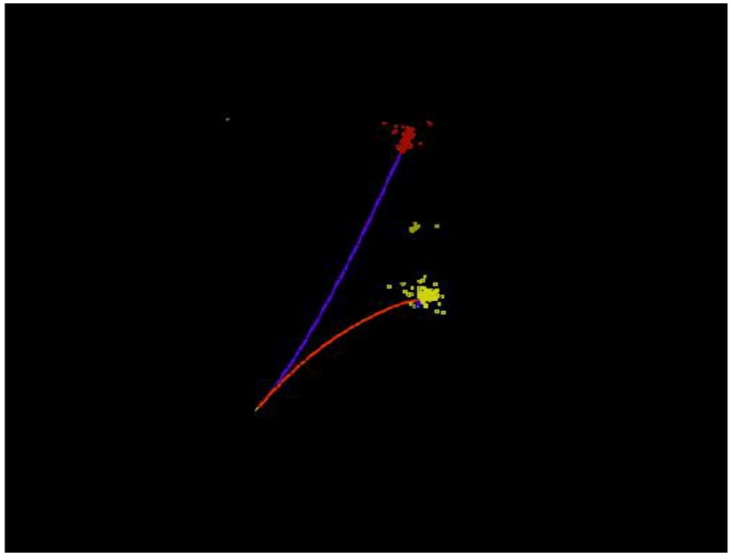
Geom 1/2: 10 (20) mm ECAL/HCAL Cell

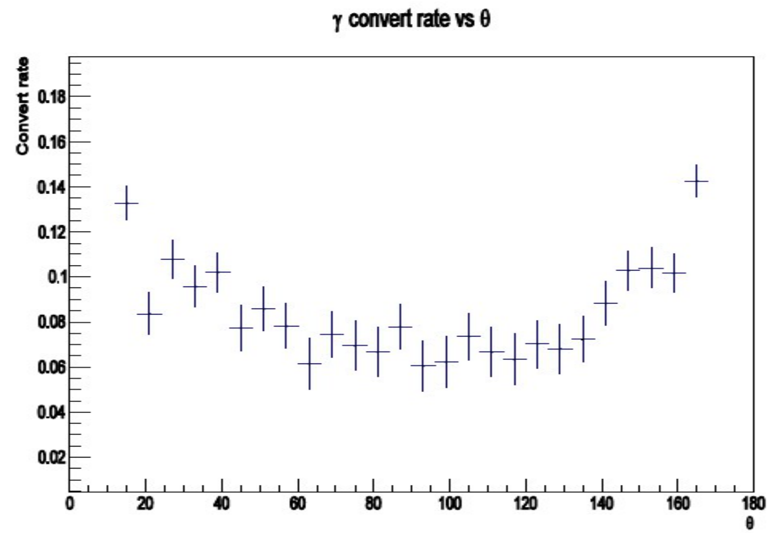
Initial Leptons identified at satisfactory efficiency & purity (limited by separation power)

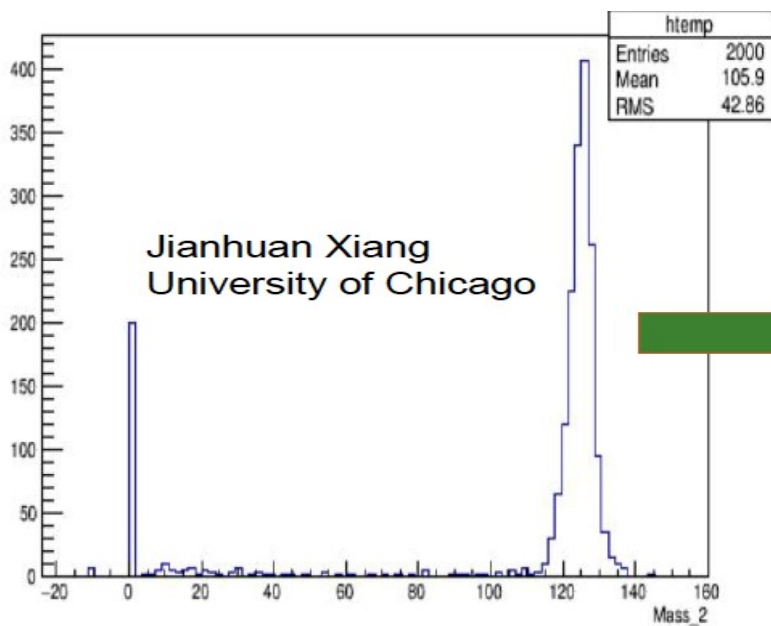
More stringent requirement arrises from jet leptons...

https://arxiv.org/abs/1701.07542

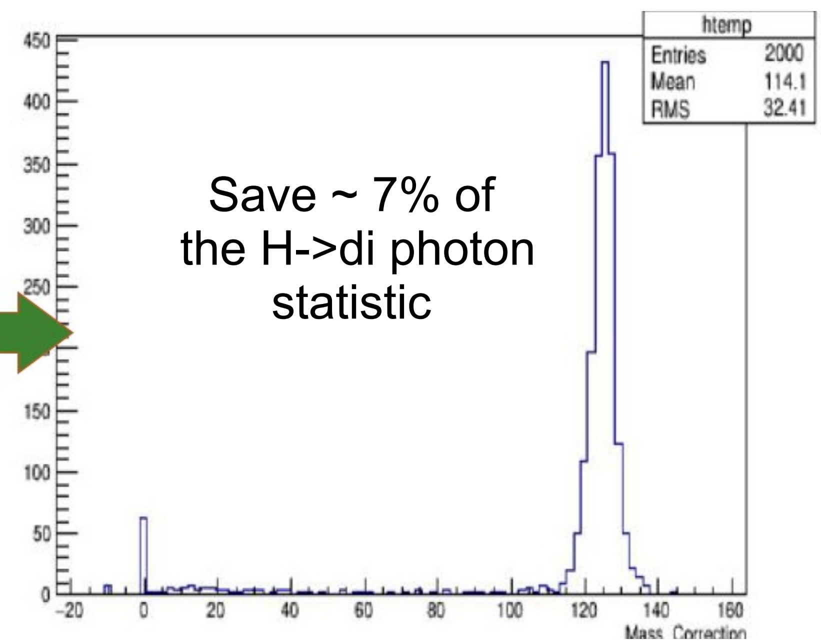
Composed object: converted photon





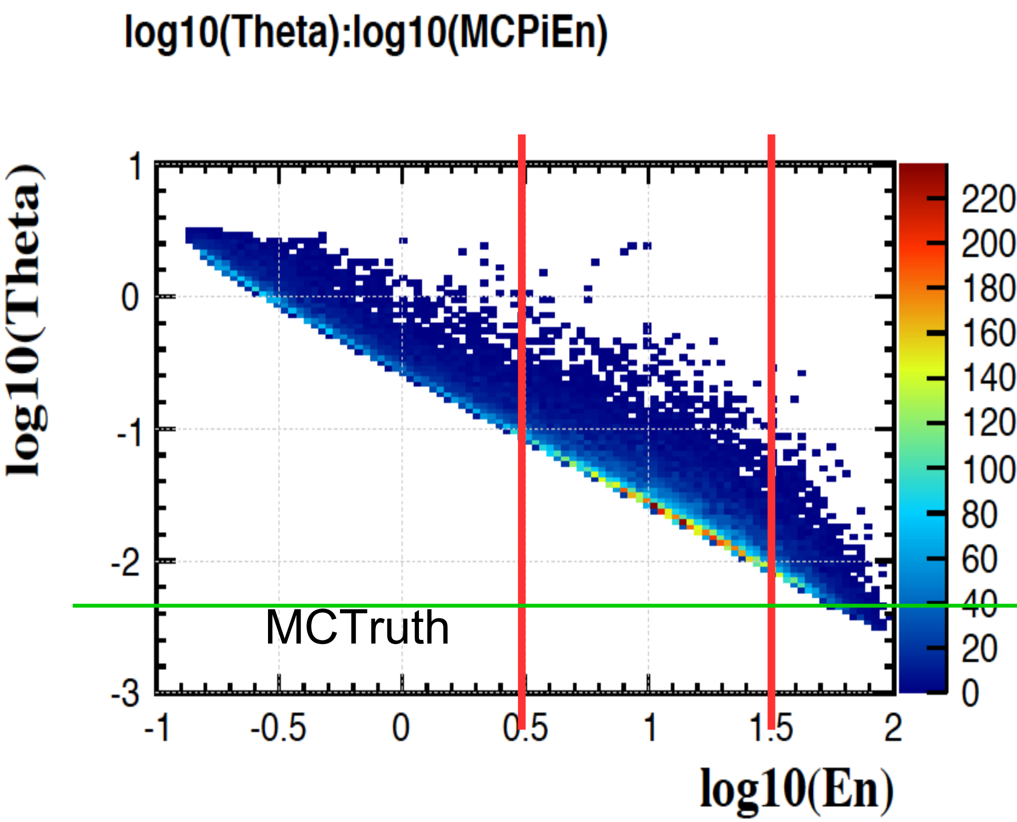


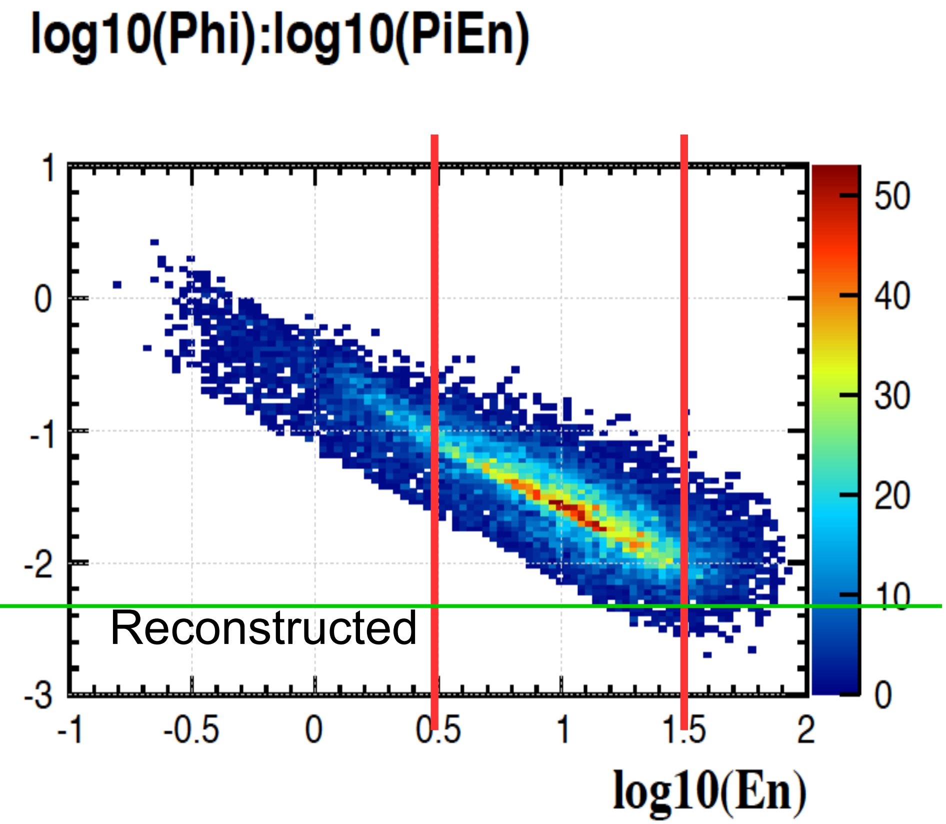
Jianhuan Xiang
University of Chicago



Save ~ 7% of
the H->di photon
statistic

Composed object: π_0 (Preliminary)

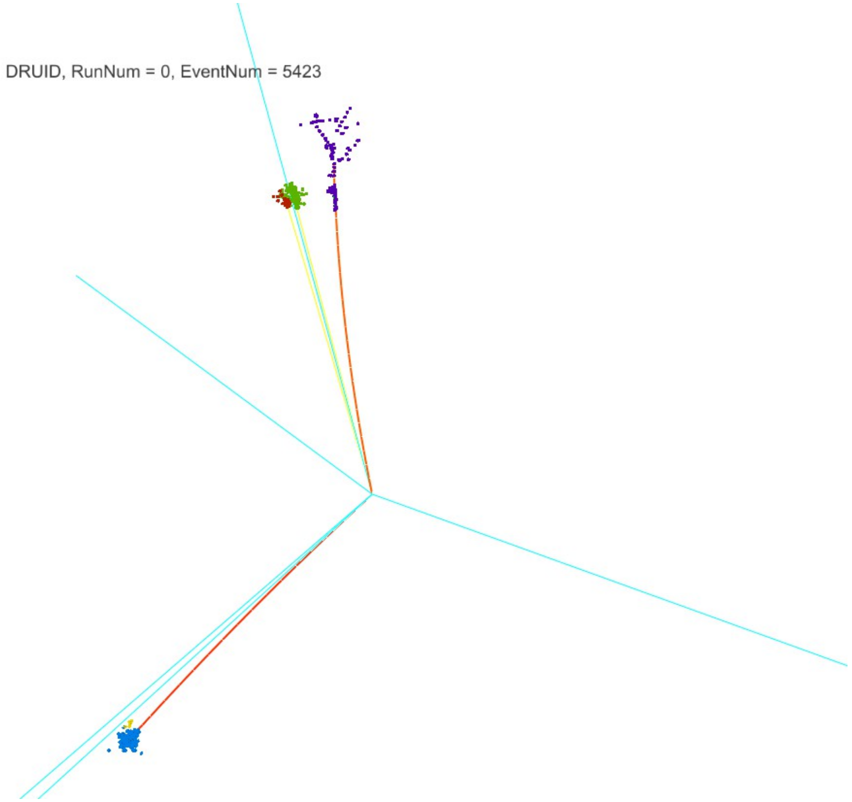


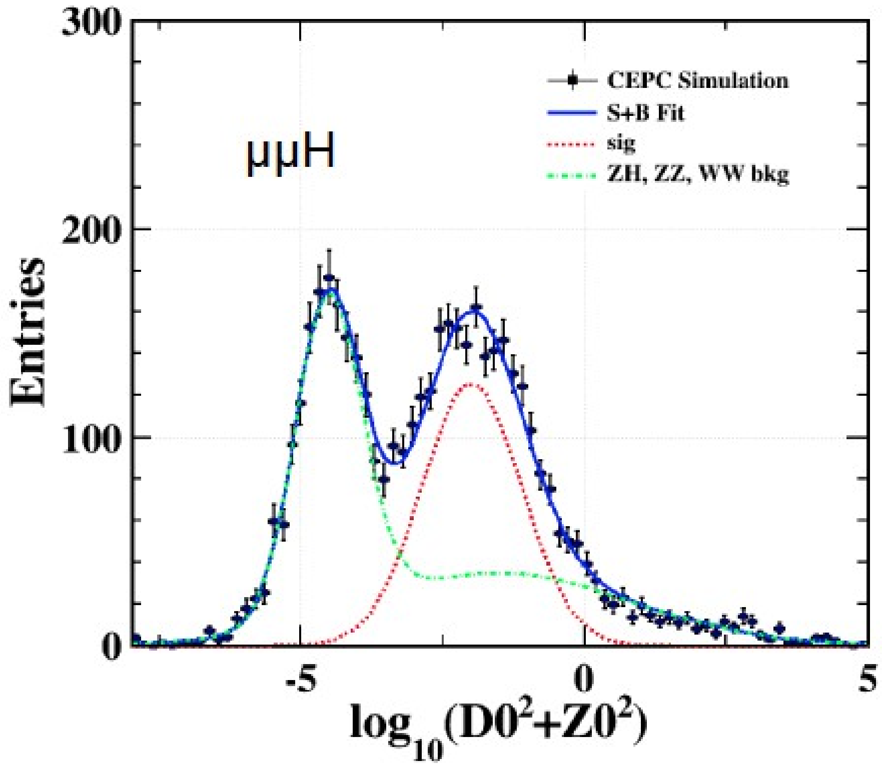


Testing on Higgs to di tau events. Tau inclusive decay
(X axis, Energy of Pi0, Y axis, Angle between two photons decayed from pi0)

For pi0 with En > 3 GeV && En < 30 GeV, Reconstruction efficiency ~ 65%..
Horizontal line corresponding to 9 mm separation at ECAL.

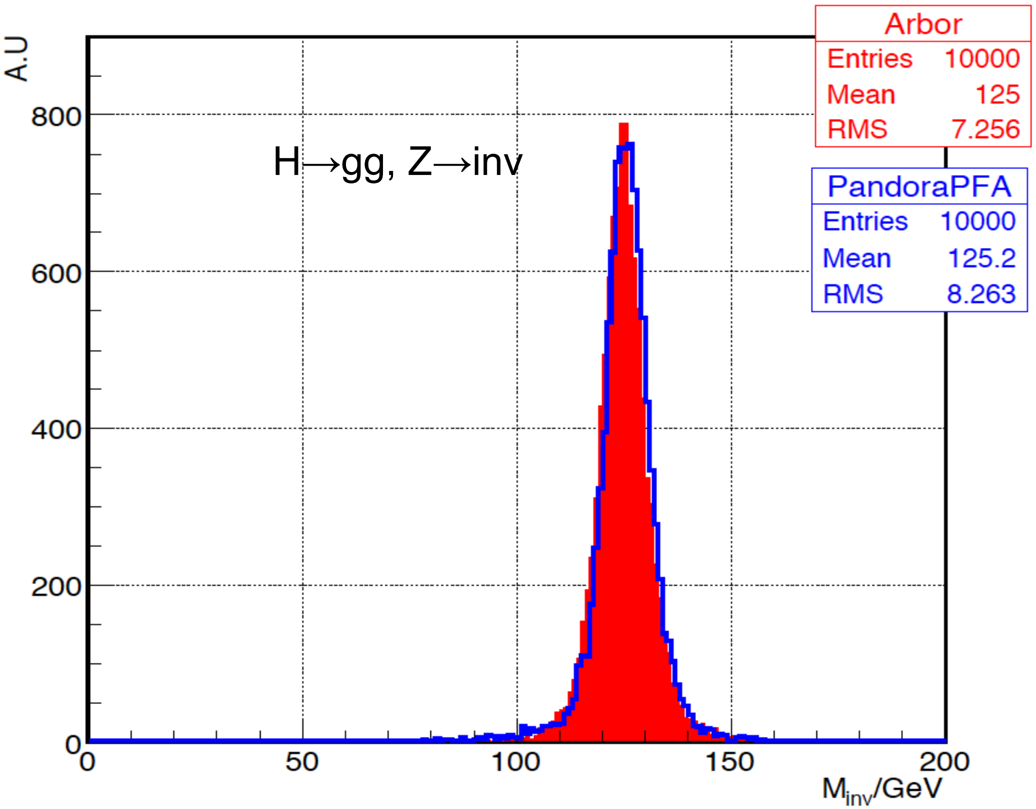
Tau reconstruction

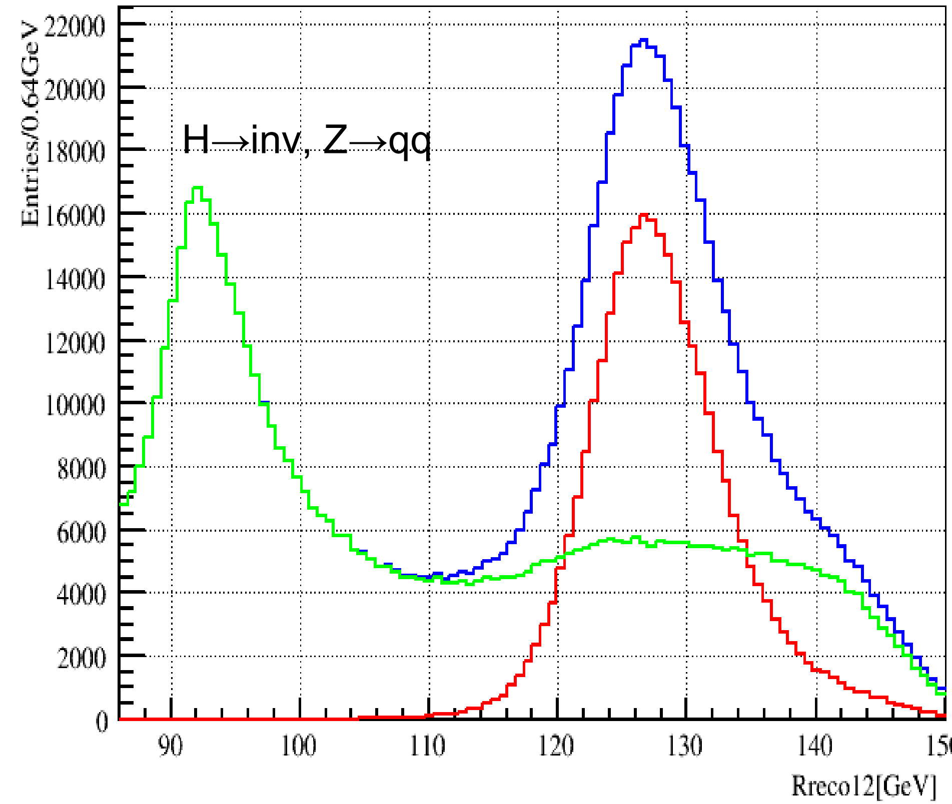




- In no-jet environment: counting number of charged particle – (pions & leptons), photons (pi0s) + restrict impact parameters leads to very high efficiency in Tau finding:
  - At inclusive Higgs decay sample: Efficiency ~ 98% for of H→ττ event finding, with llH and ννH final state. The remaining bkgrds are irreducible: H→WW/ZZ→leptonic/tau final state
  - In μμH channel: δN/N = 3%

JER/MET



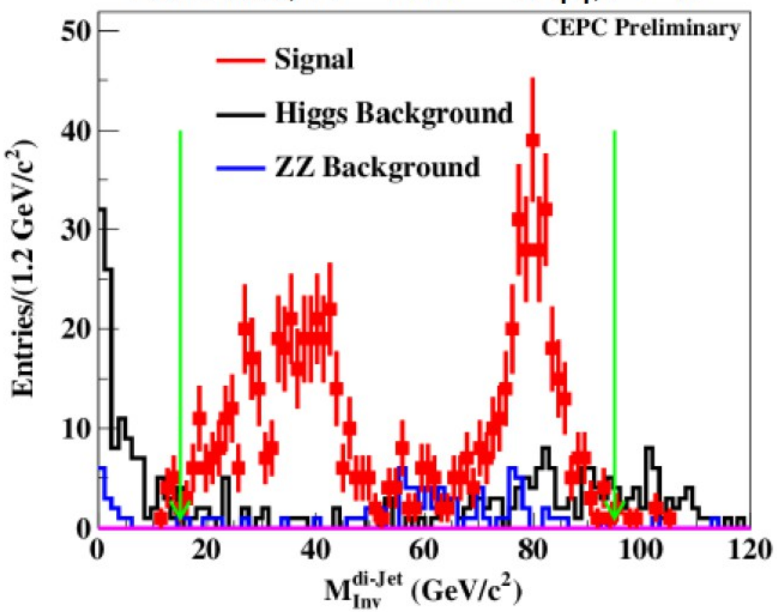


- Digital ECAL mode: Energy Estimated as k*NHit for HCAL Cluster, Calibration Constant (k) optimized for both Pandora & Arbor via Scan
- MET: usually no ambiguity;
- Jet: Highly depending on Jet clustering if #Jet > 2...

Br(H→WW)

H→WW/ZZ: Portal to Higgs width & perfect test bed for detector/reconstruction performance...

Liao libo, H→WW*→lνqq, Z→ll



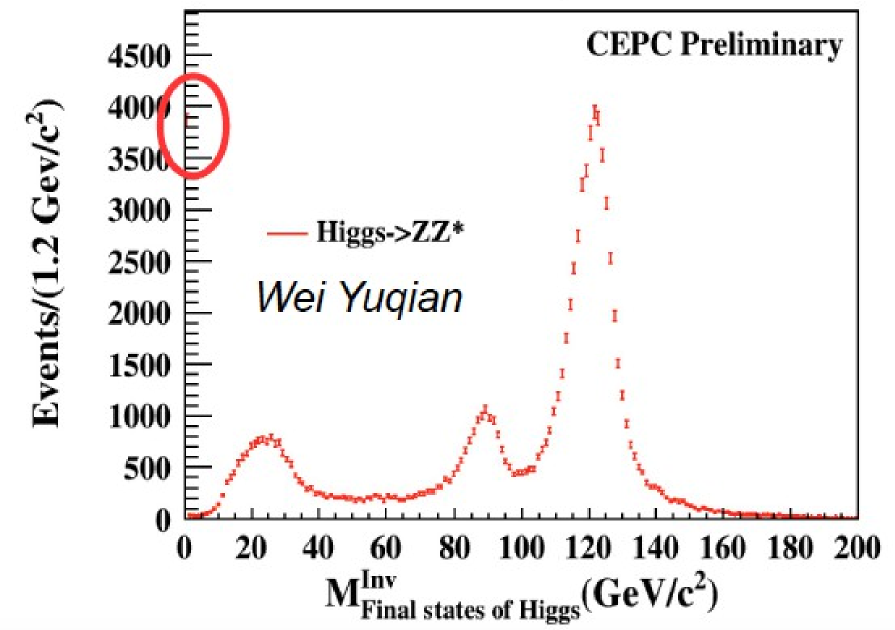
Expected Number of events with different objects

	Z→ll	tautau	νν	qq
H→WW*→4q	6.91k	3.45k	19.74k	69.1k
μνqq	2.27k	1.14k	6.47k	22.7k
eνqq	2.27k	1.14k	6.47k	22.7k
eeνν	186	93	527	1.9k
μμνν	186	93	527	1.9k
eμνν	372	186	1154	3.7k
X + tau	3.2k	1.6k	9.14k	32.0k

- Extrapolated from ILC results
- Await for tau finder
- Await for the SM Background simulation
- Full Simulation
- Preliminary result acquired
- Unexplored

- Br(H→WW), Combined accuracy ~ 1.0% from 13 independent full simulation analyses
  - 1.45% at llH, H→WW*→ inc channels, 12 independent channels.
  - *~ 1.7% at ννH, H→WW*→ 4q channel (Preliminary. ILC extrapolation = 2.3%)*
  - 2.3% at qqH, H→WW*→ 2qlν channel (extrapolated from ILC full simulation)
  - Combined: 1.0%
- High efficiency in event reconstruction

Br(H→ZZ)



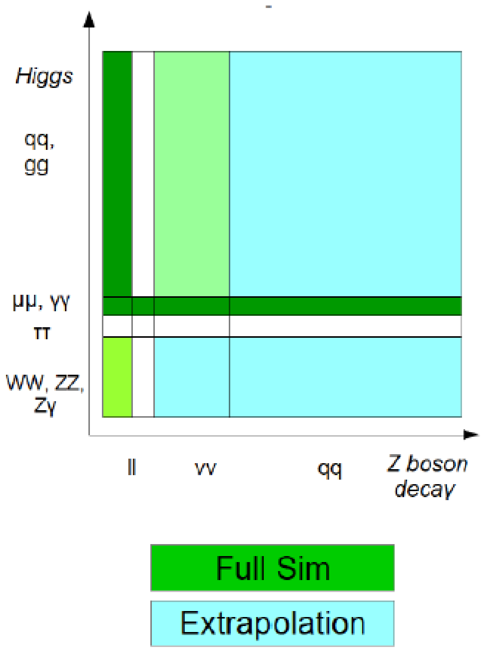
Expected Number of events with different objects

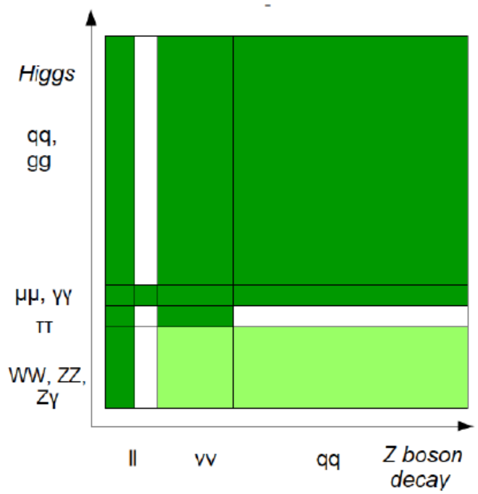
	Z→ll	tautau	vv	qq
H→ZZ*→4q	888	444	3.10k	9.24k
2v + 2q	508	254	1.77k	5.29k
2l + 2q	170	85	596	1.8k
4v	73	36	254	756
2l + 2v	49	24	170	508
4l	8	4	28	86
X + tau	120	60	418	1246

- More than 2 jets, Await for sophisticated Jet Clustering
- Await for tau finder
- limited accuracy ~ > 50%
- Explored by H->invisible analysis -> Accuracy ~ 40%
- Promising channels
- Unexplored

- Br(H→ZZ), explored at 18 different channels with full simulation (llvvqq, 4lqq, ll4q, 2l4v)
  - 8 Channels has individual accuracy better than 25%: Combined accuracy **~ 5.4%**
  - 8 with accuracy worse than 25 - 50%
  - 2 with accuracy worse than 50% (llH, H→ZZ→4q and vvH, H→ZZ→llvv)
  - *If electron id efficiency ~ muon id:* ***4.8%***
  - ***If tau finder (used for veto) is mature: ??***
  - TLEP extrapolation: **4.3%**

Applied to CEPC Higgs analysis

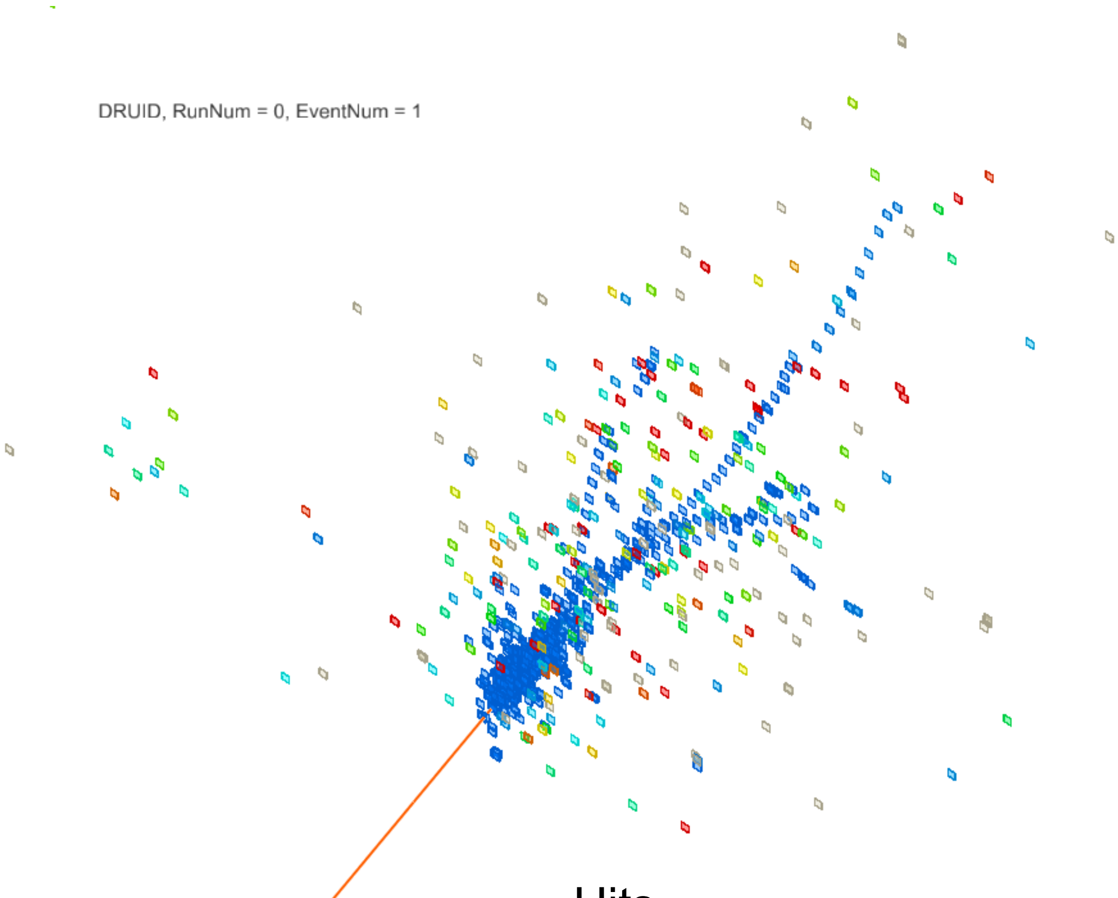




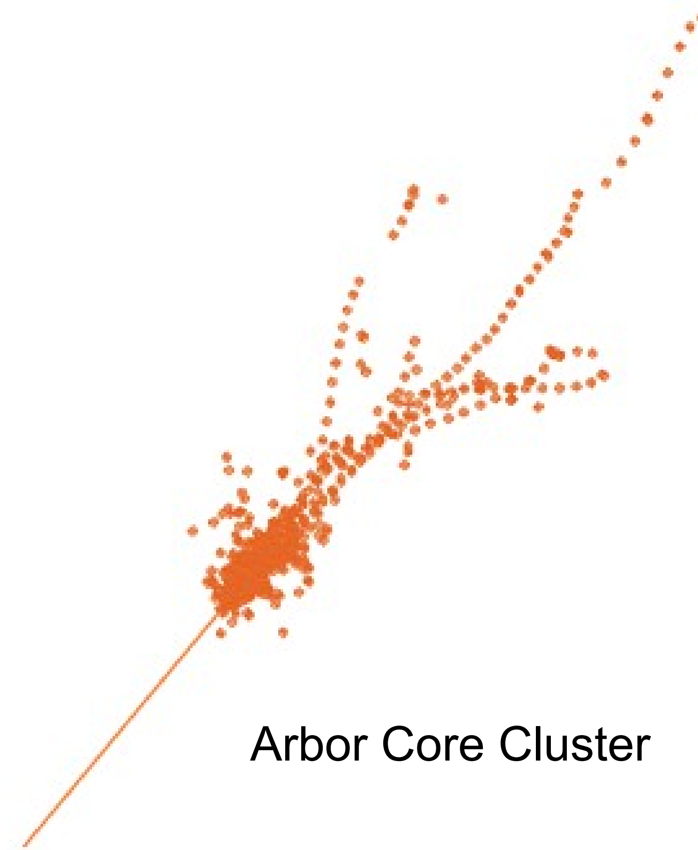
	PreCDR (Jan 2015)	Now (Aug 2016)
σ(ZH)	0.51%	0.50%
σ(ZH)*Br(H→bb)	0.28%	0.21%
σ(ZH)*Br(H→cc)	2.1%	2.5%
σ(ZH)*Br(H→gg)	1.6%	1.2%
σ(ZH)*Br(H→WW)	1.5%	1.0%
σ(ZH)*Br(H→ZZ)	4.3%	4.3%
σ(ZH)*Br(H→ττ)	1.2%	1.0%
σ(ZH)*Br(H→γγ)	9.0%	9.0%
σ(ZH)*Br(H→Zγ)	-	~4 σ
σ(ZH)*Br(H→μμ)	17%	12%
σ(ννH)*Br(H→bb)	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
σ(ZH)*Br(H→inv)	95%. CL = 1.4e-3	1.4e-3
Br(H→ee/emu)	-	1.7e-4/1.2e-4
Br(H→bbχχ)	$<10^{-3}$	3.0e-4

Now: ~50 independent analyses at Full Simulation level

About time...

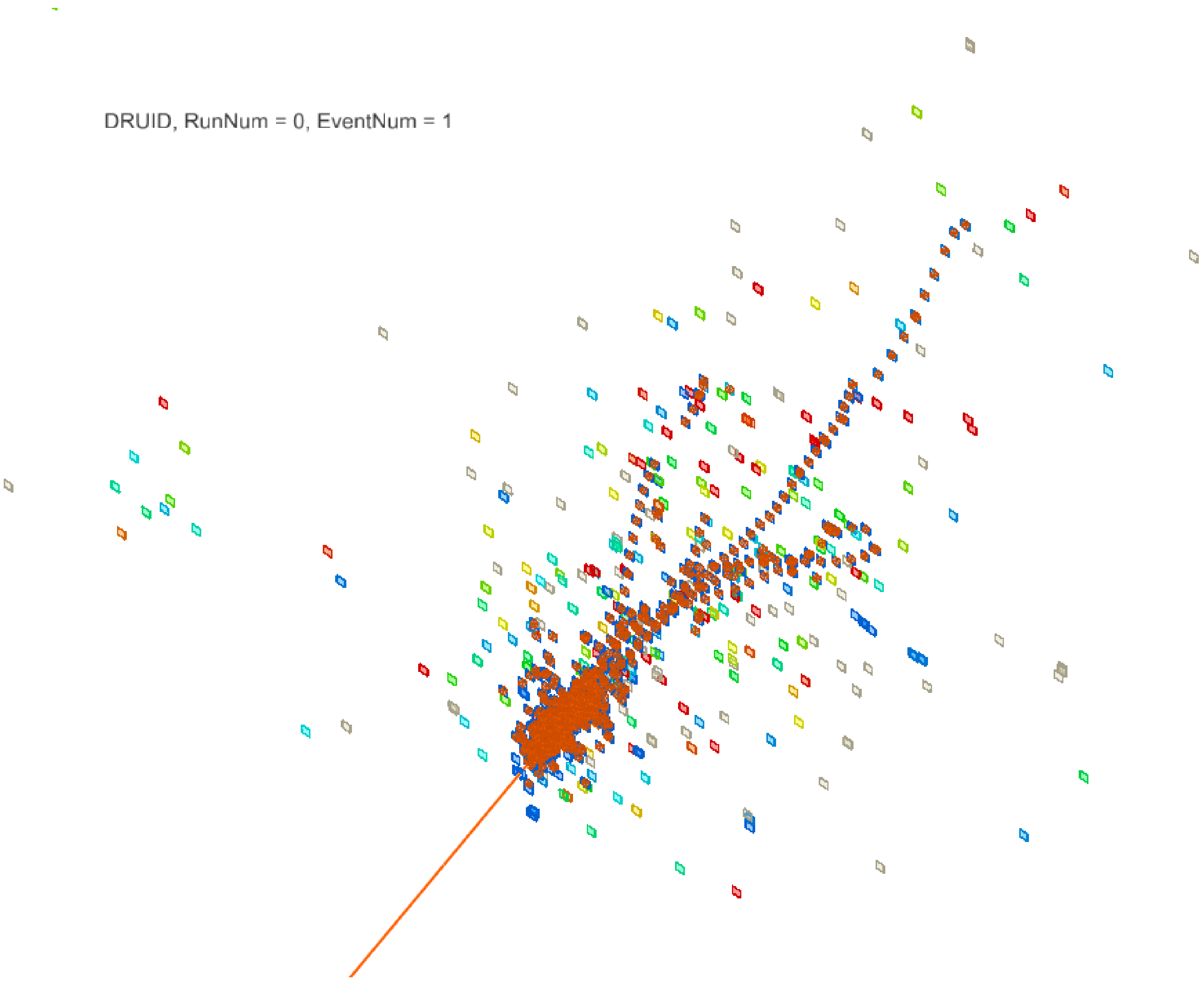


Hits

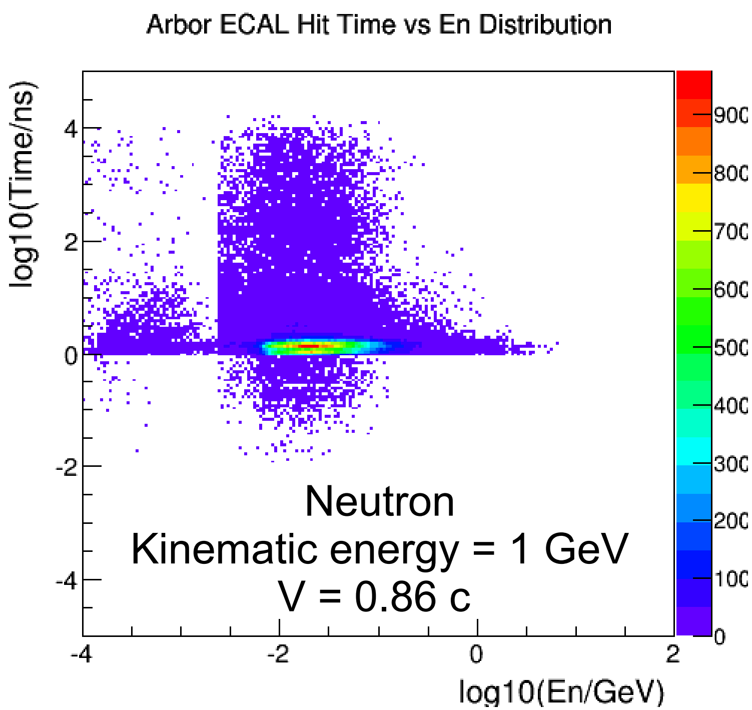


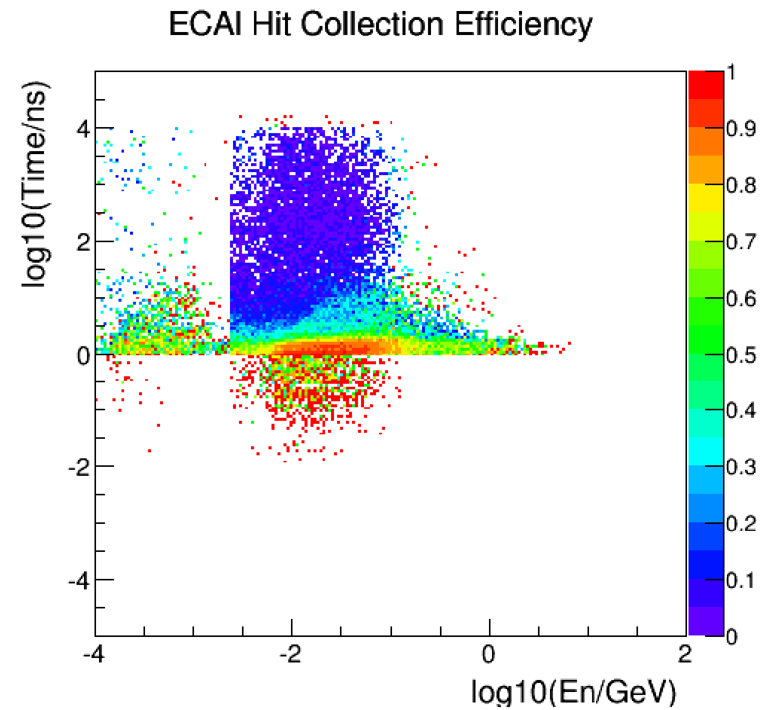
Arbor Core Cluster

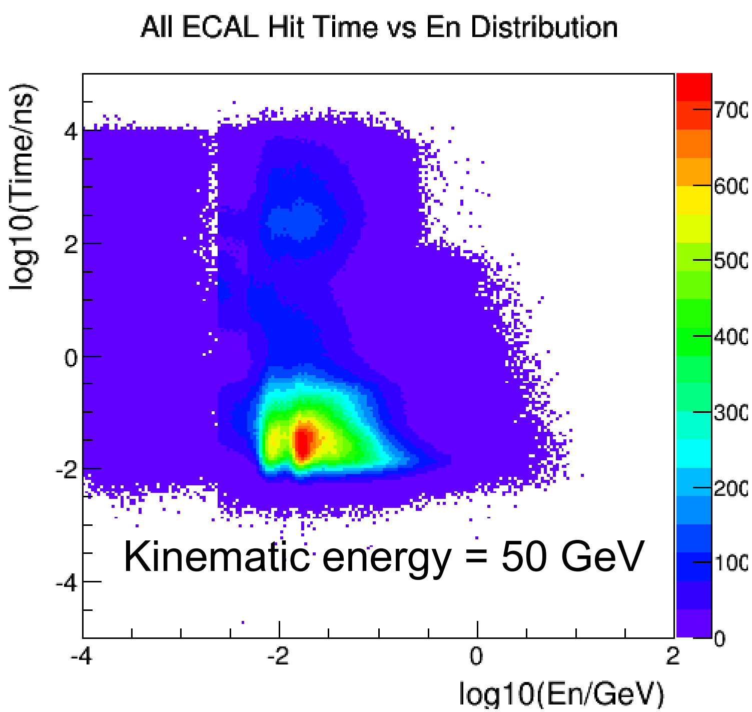
50GeV Pion at defect-free geometry...

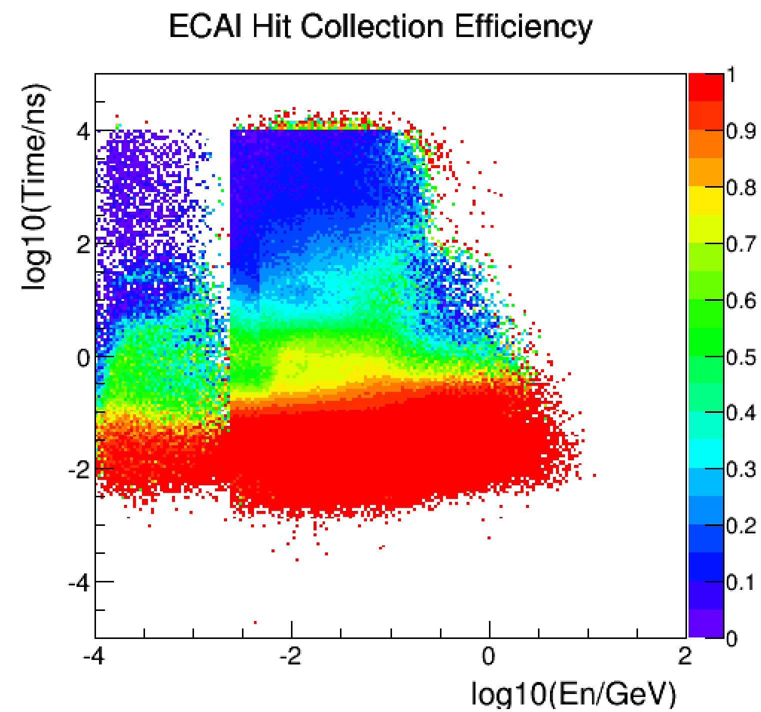

DRUID, RunNum = 0, EventNum = 1

High Efficiency in collecting fast hit



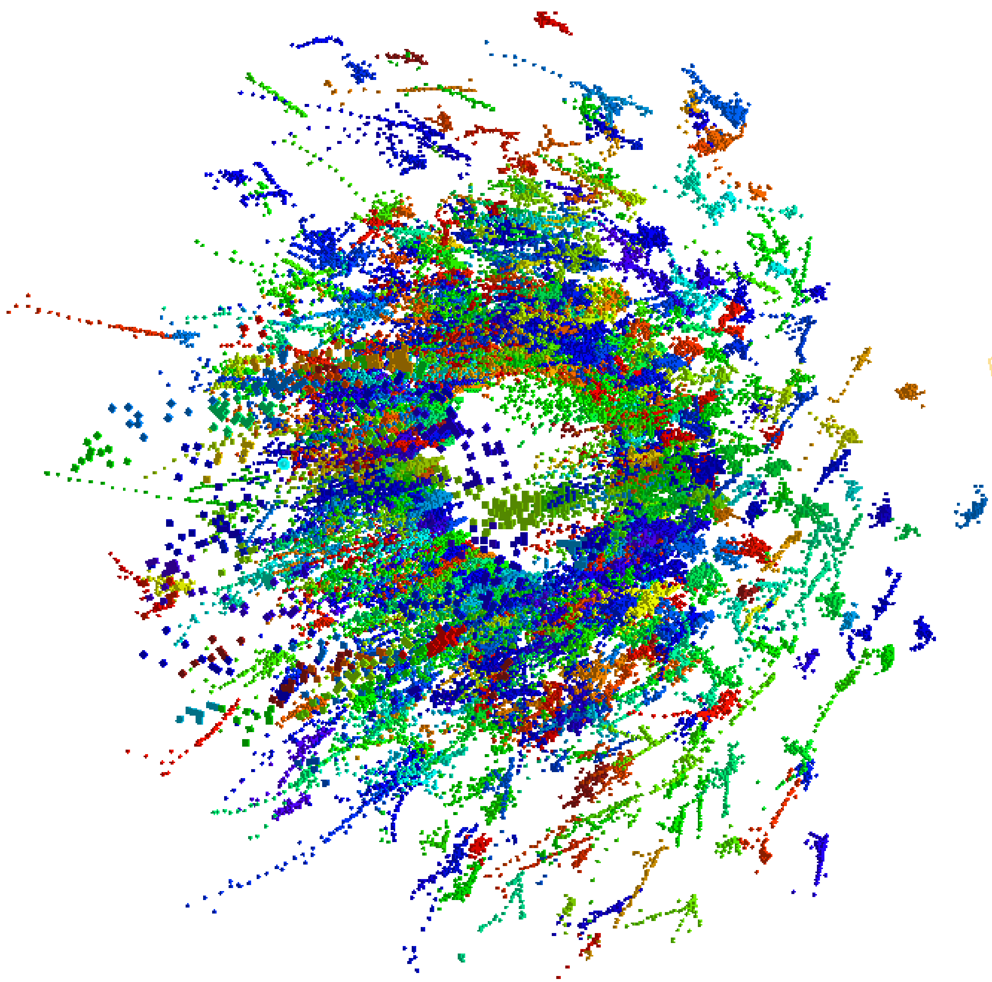


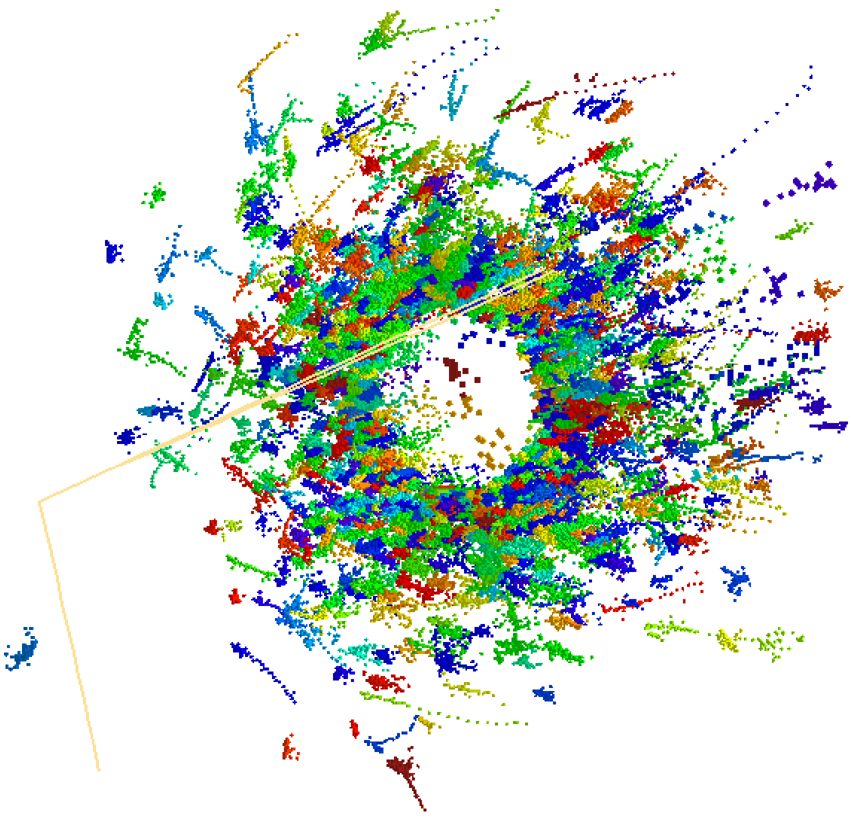




CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 1201
Lumi section: 13

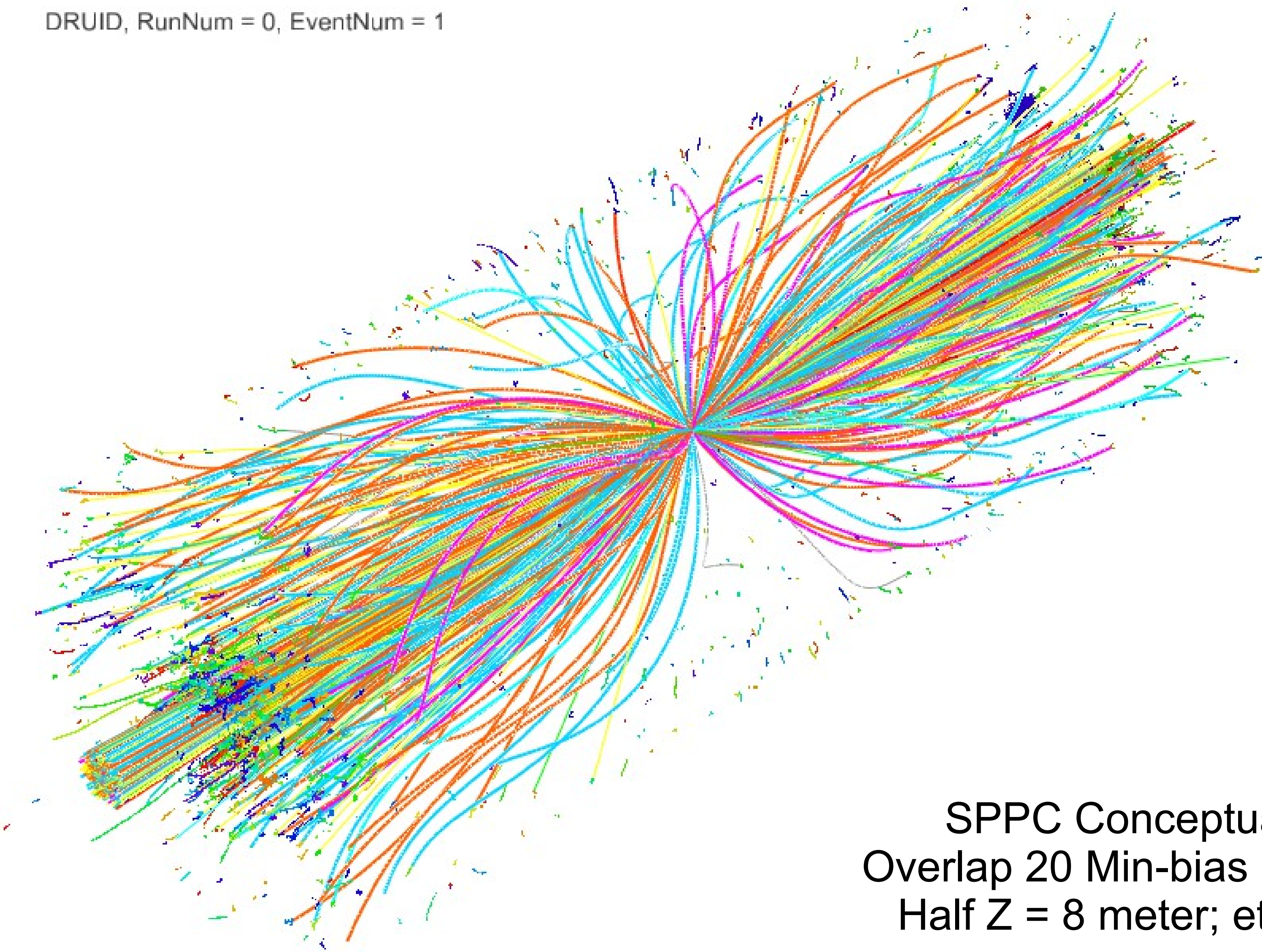
Separation & Speed @ pp



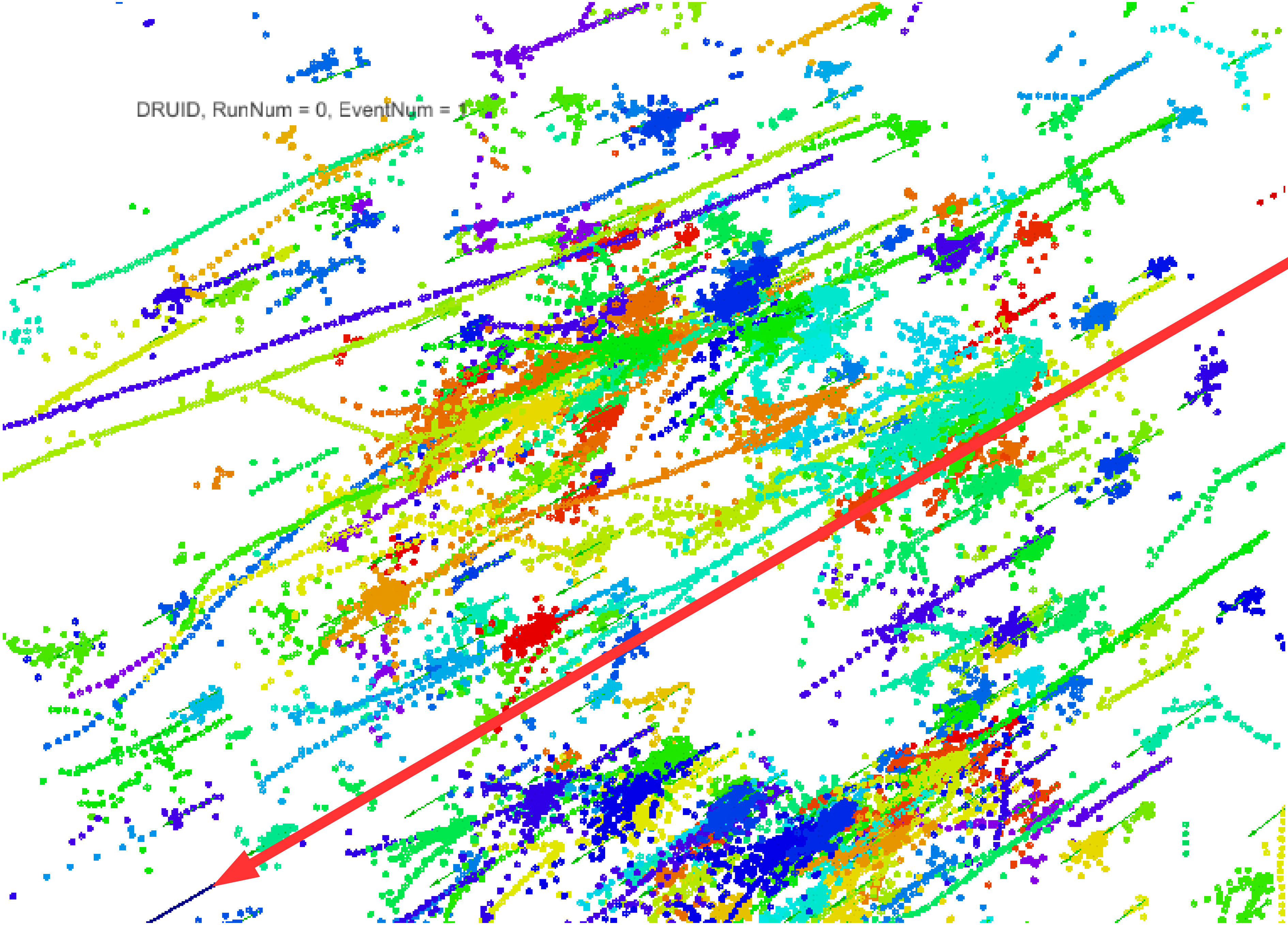


Arbor @ pp collisions

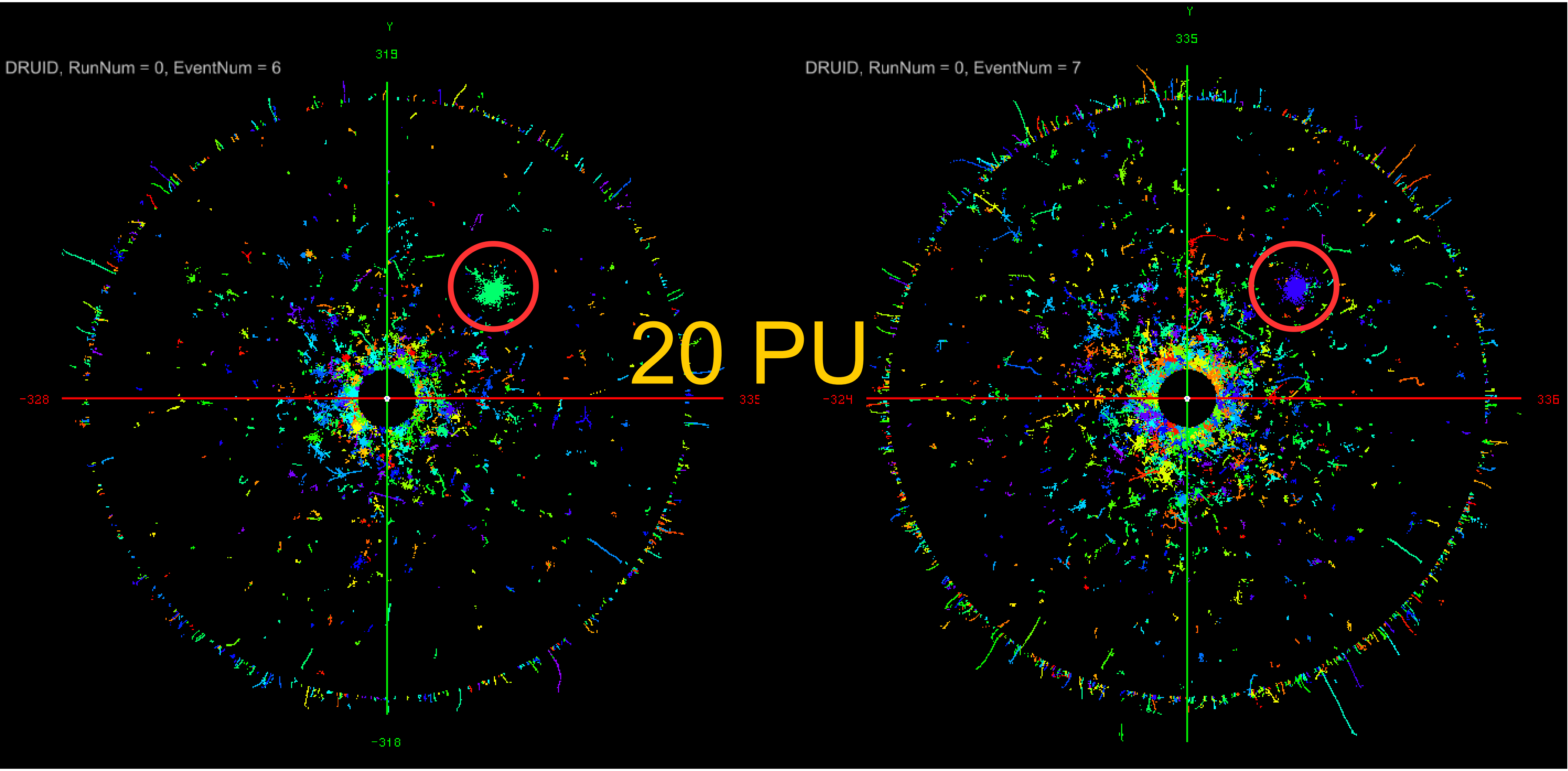
140 PU event reconstructed at ~1 min/evt
With KD-tree algorithm, complexity reduced
From N^2 to $N\log(N)$



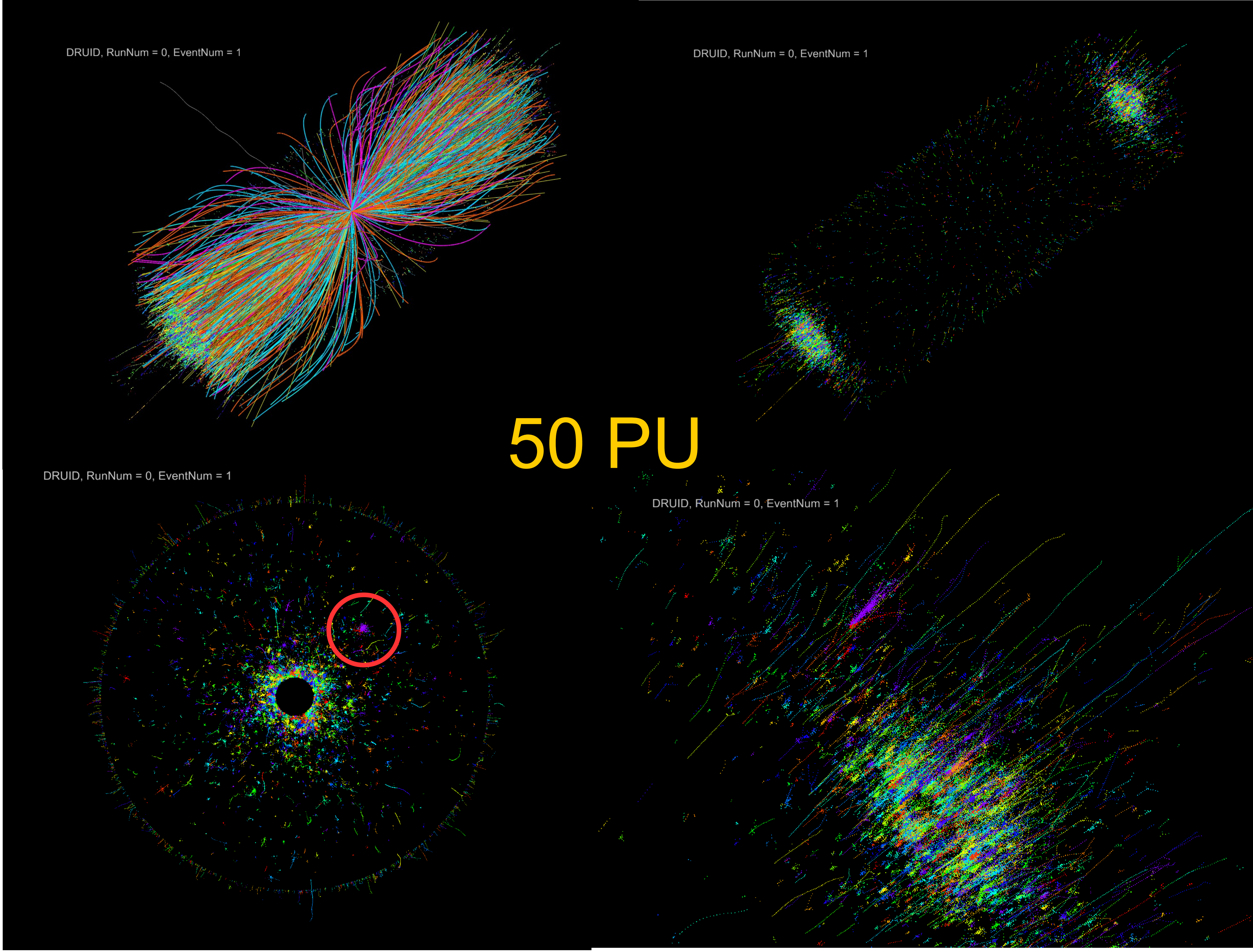
SPPC Conceptual
Overlap 20 Min-bias events
Half Z = 8 meter; eta: 4


DRUID, RunNum = 0, EventNum = 1

Reconstructed with Arbor



1 TeV hadronic shower at 20 PU, at eta ~ 2:
Perturbation from PU ~ 0.1% level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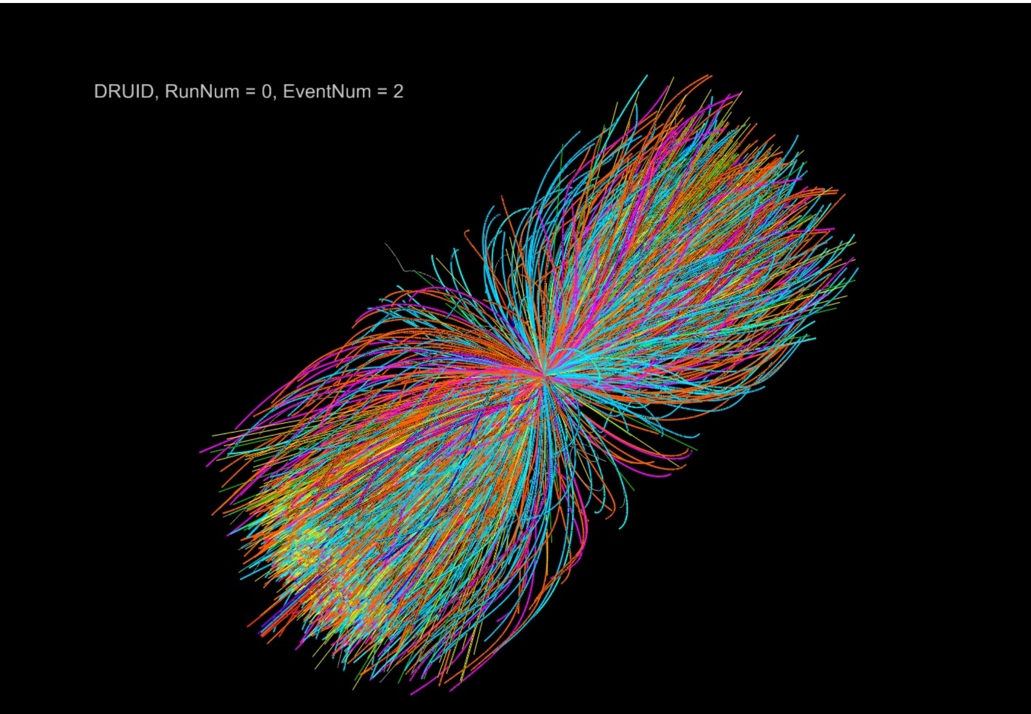
DRUID, RunNum = 0, EventNum = 1
50 PU
DRUID, RunNum = 0, EventNum = 1
DRUID, RunNum = 0, EventNum = 1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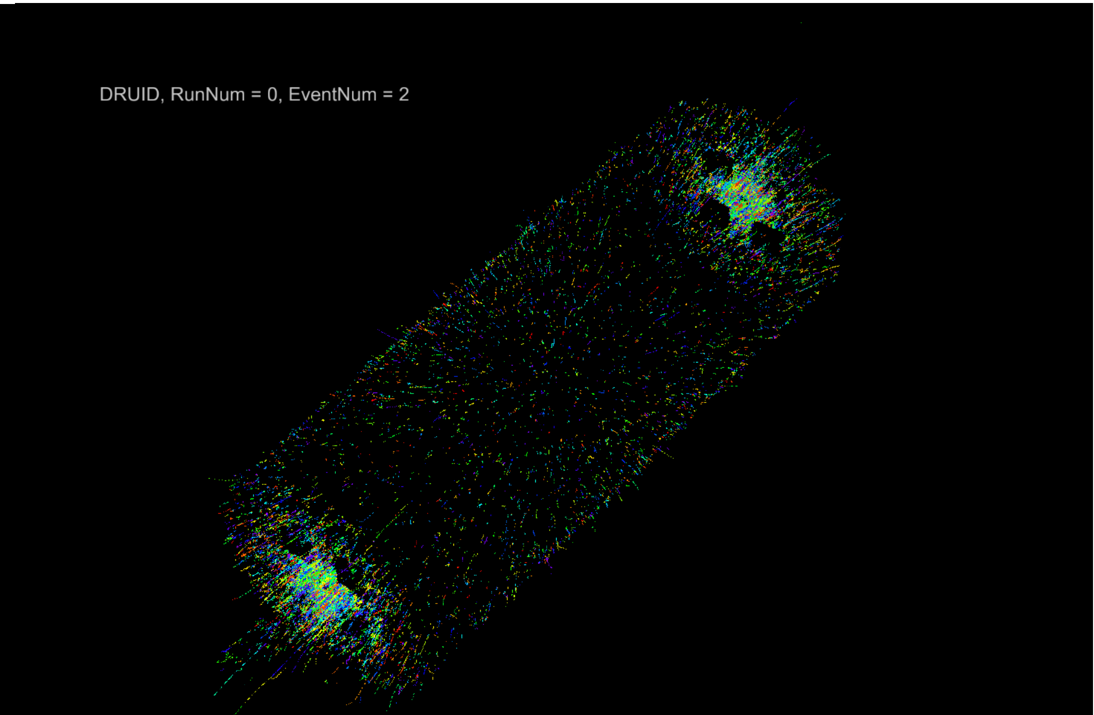
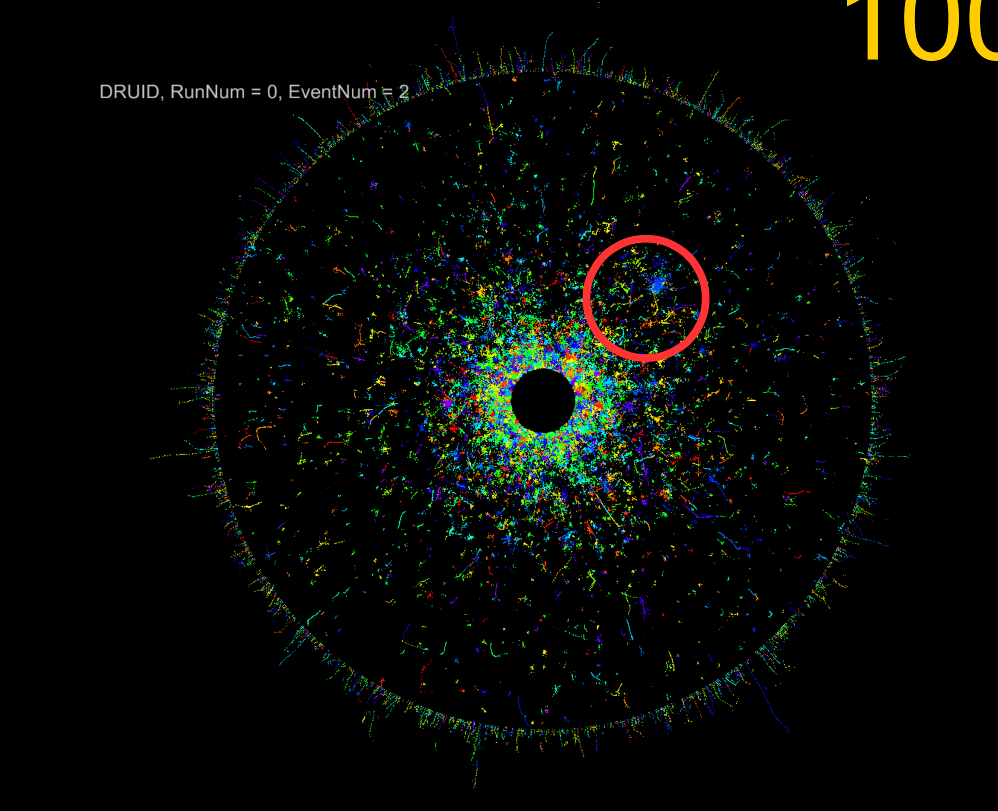
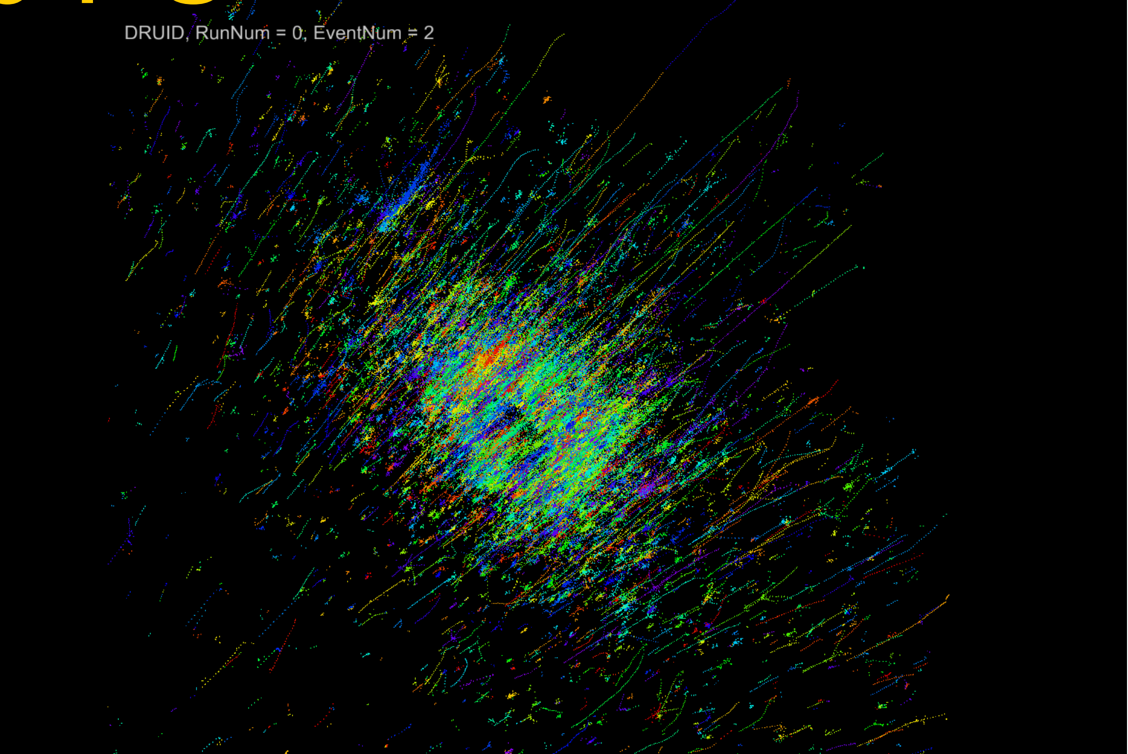
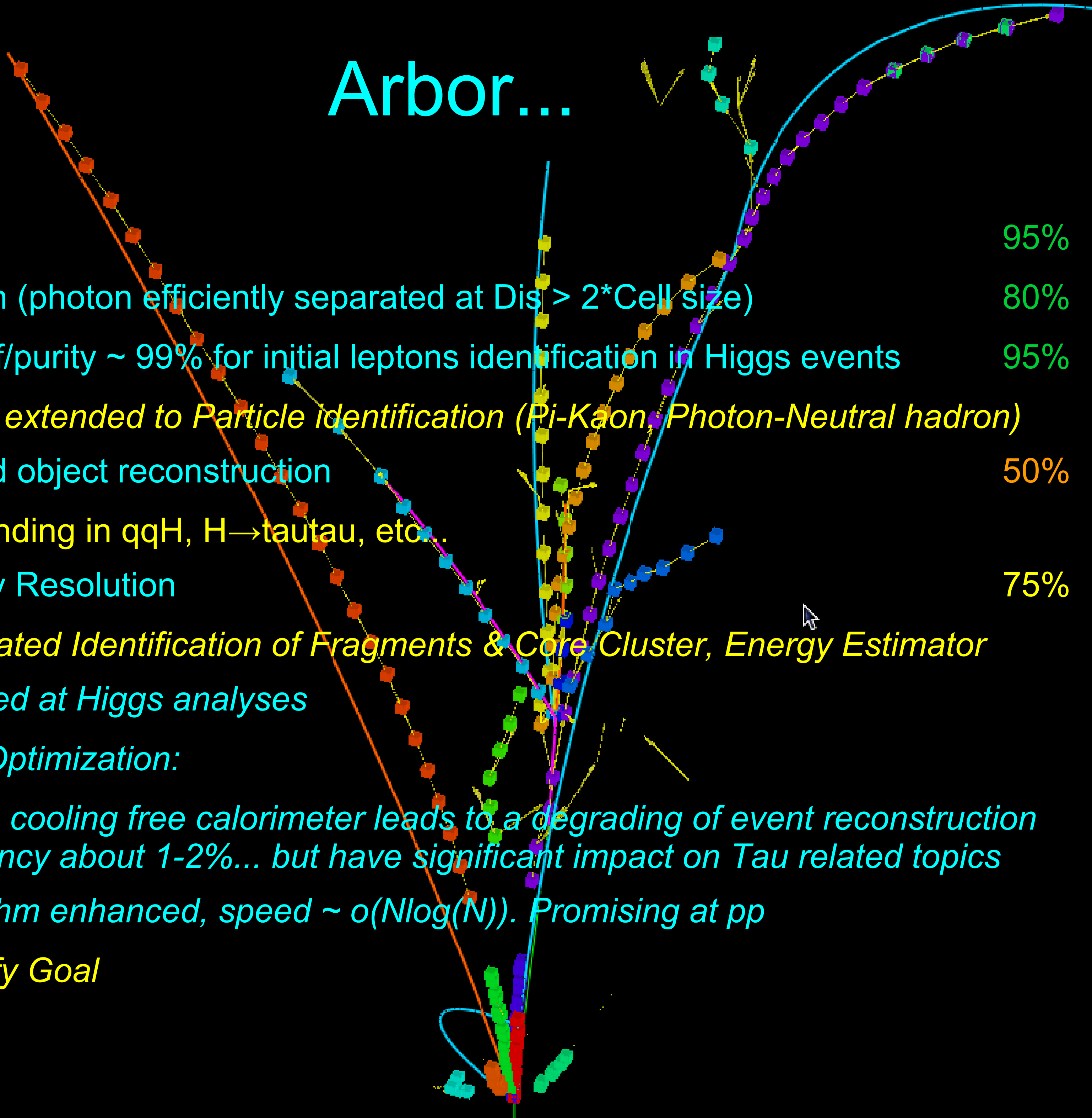

DRUID, RunNum = 0, EventNum = 2

100 PU


DRUID, RunNum = 0, EventNum = 2


DRUID, RunNum = 0, EventNum = 2

Arbor...



Photon 95%

Separation (photon efficiently separated at Dis > 2*Cell size) 80%

Lepton: eff/purity ~ 99% for initial leptons identification in Higgs events 95%

To be extended to Particle identification (Pi-Kaon, Photon-Neutral hadron)

Composed object reconstruction 50%

Tau finding in qqH, H→tautau, etc...

Jet Energy Resolution 75%

Dedicated Identification of Fragments & Core Cluster, Energy Estimator

Fully Tested at Higgs analyses

Detector Optimization:

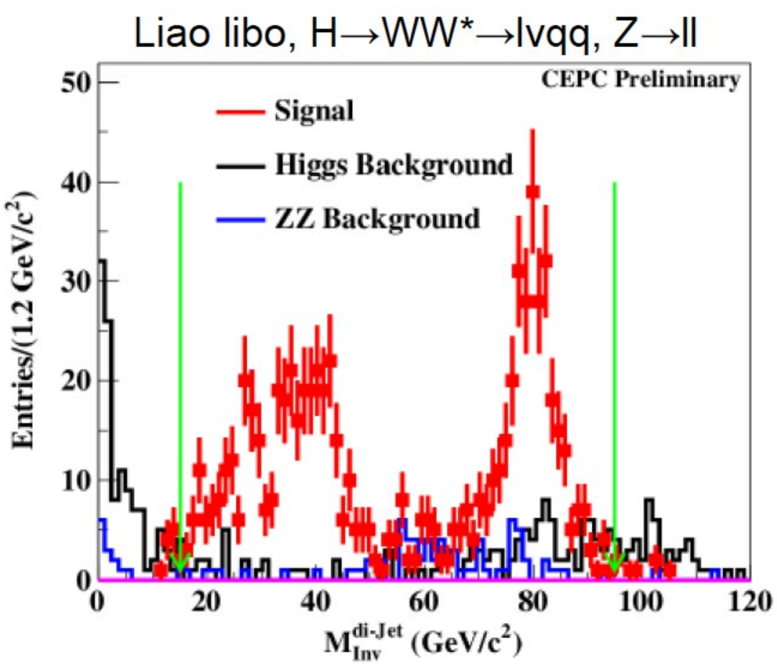
Active cooling free calorimeter leads to a degrading of event reconstruction efficiency about 1-2%... but have significant impact on Tau related topics

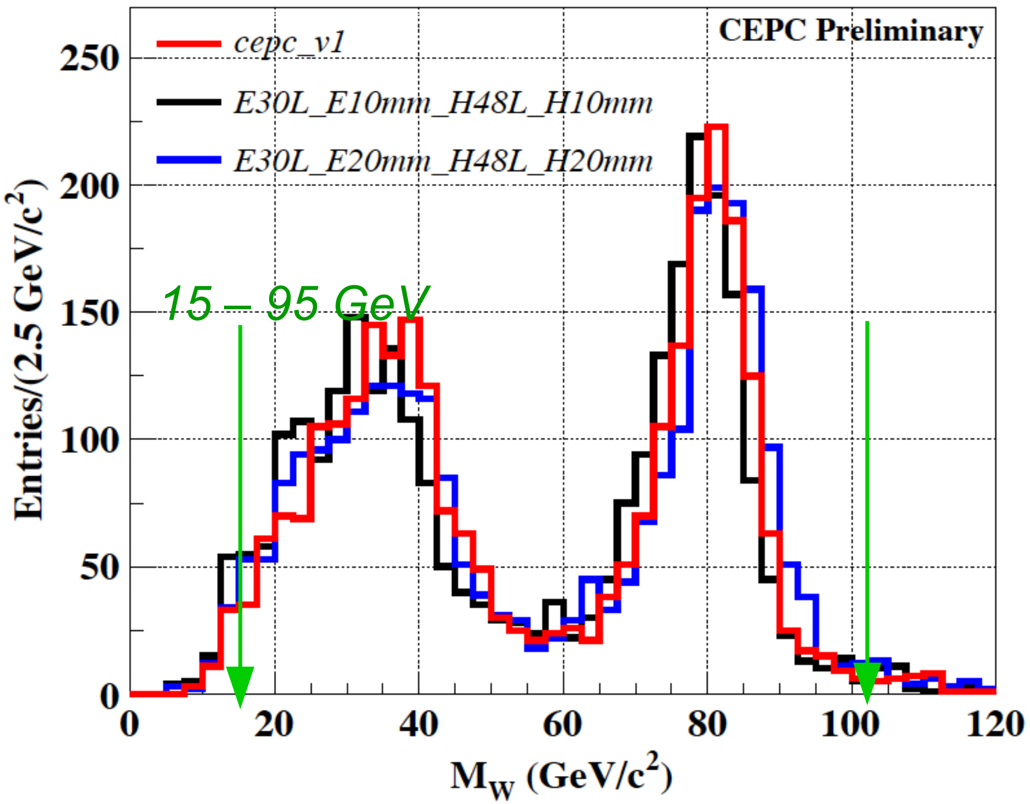
KD algorithm enhanced, speed ~ o(Nlog(N)). Promising at pp

Identify Goal

Thanks

Br(H→WW) @ 10mm/20mm Cell size





Br(H→WW) via vvH, H→WW*→lvqq

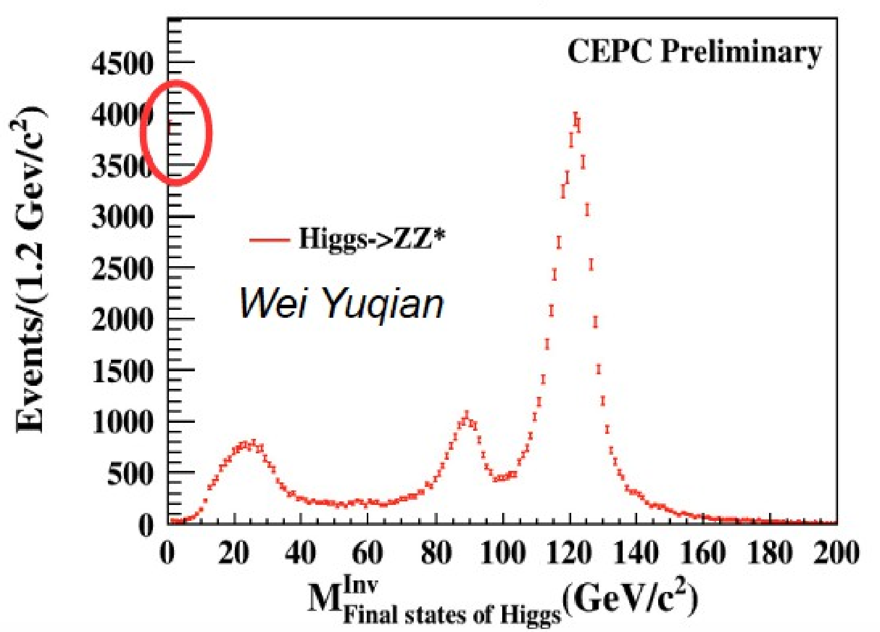
No lose in the object level efficiency;
JER slightly degraded, ~ 5/10% at 10/20 mm
(*ill. behaviors: stay to be tuned*)

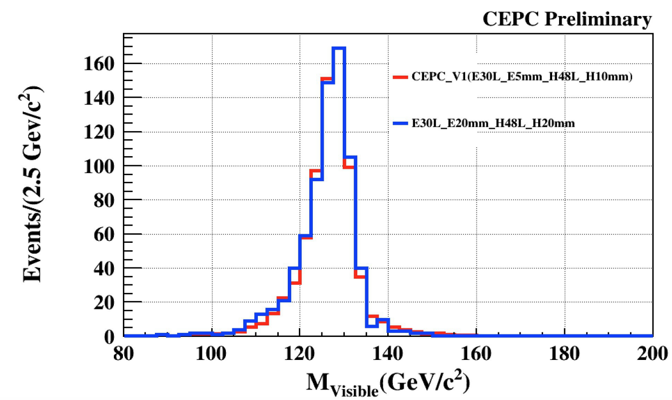
Over all: event reco. efficiency varies ~1%

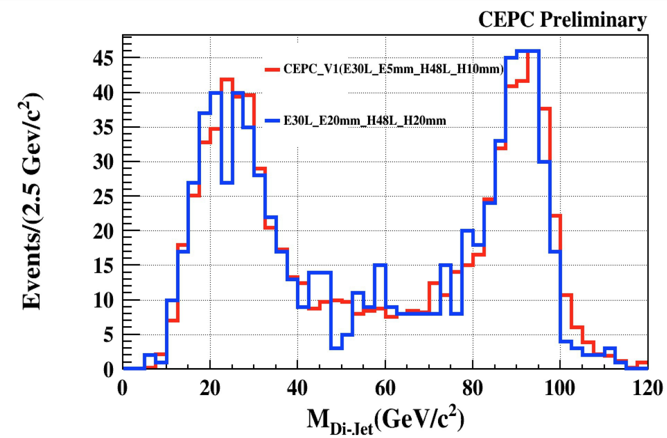
	Simu.	Recon.	Efficiency
CEPC_v1	2885	2783	96.5%
TG1	2878	2814	97.8%
TG2	2878	2807	97.5%

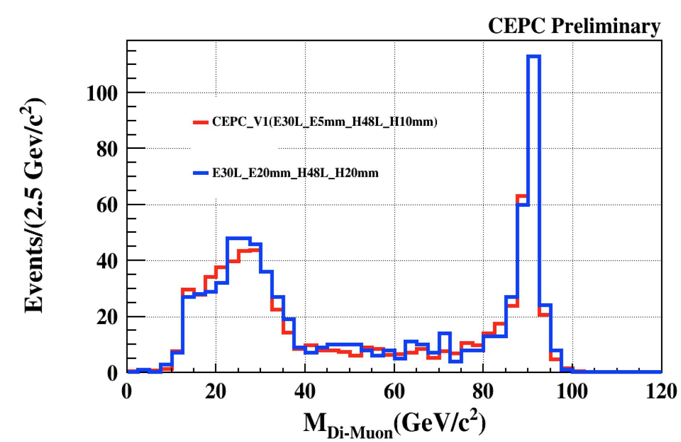
TG1: E30L_H48L_10mm, TG2: E30L_H48L_20mm

Br(H→ZZ) @ 10mm/20mm Cell size







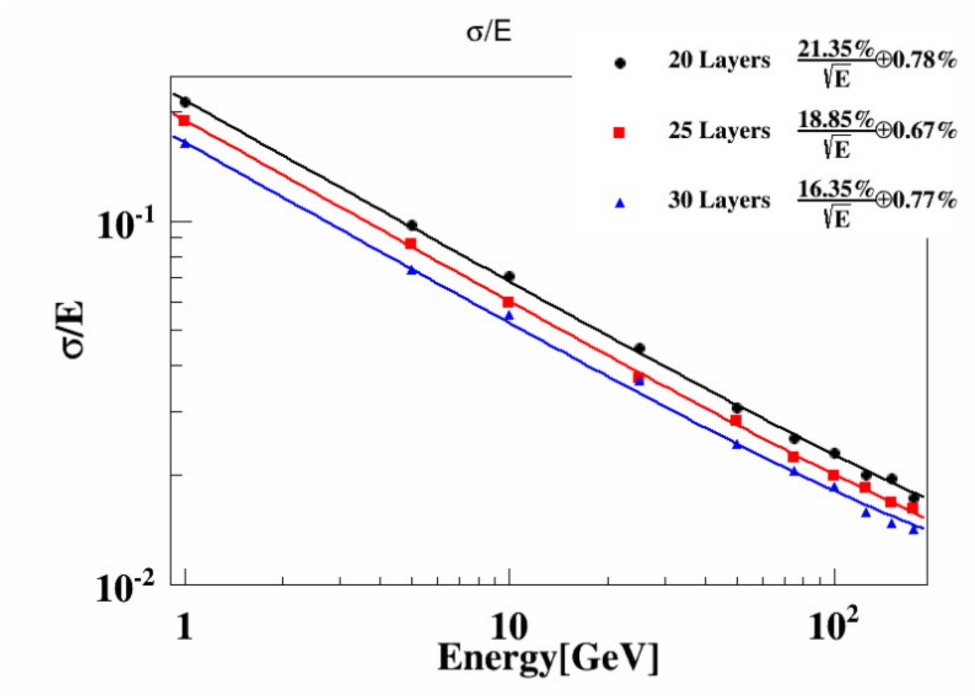


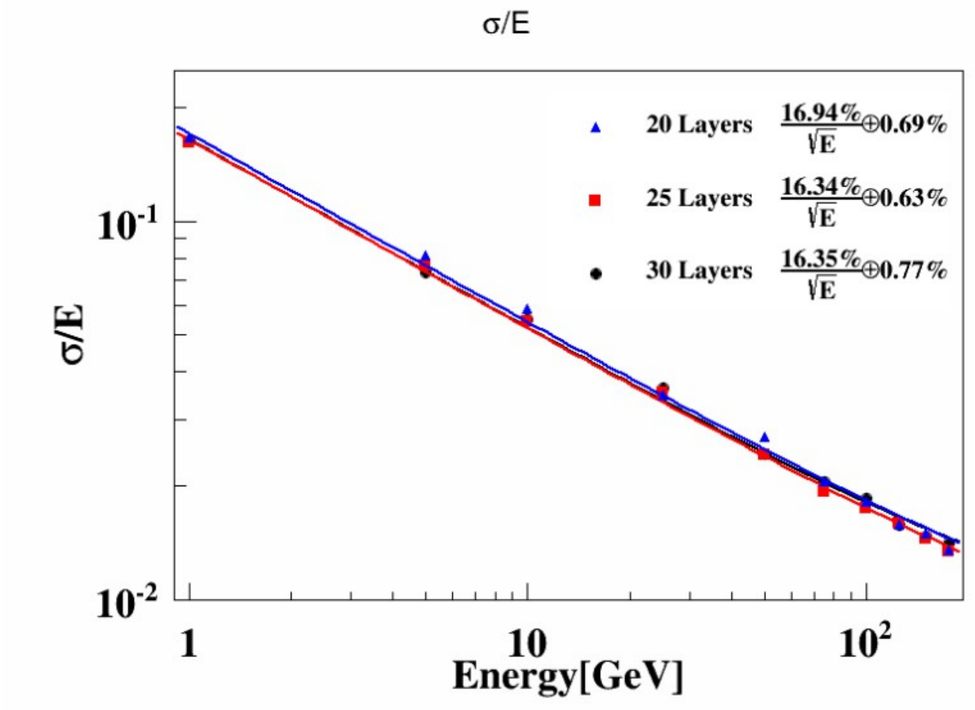
Br(H→ZZ) via vvH, H→ZZ*→llqq

Over all event reco. efficiency reduced ~2%

	Events	Recon.	Efficiency
CEPC_v1	4143	3957	95.5%
TG2	808	754	93.3%

Longitudinal: #Layer & Si Thickness



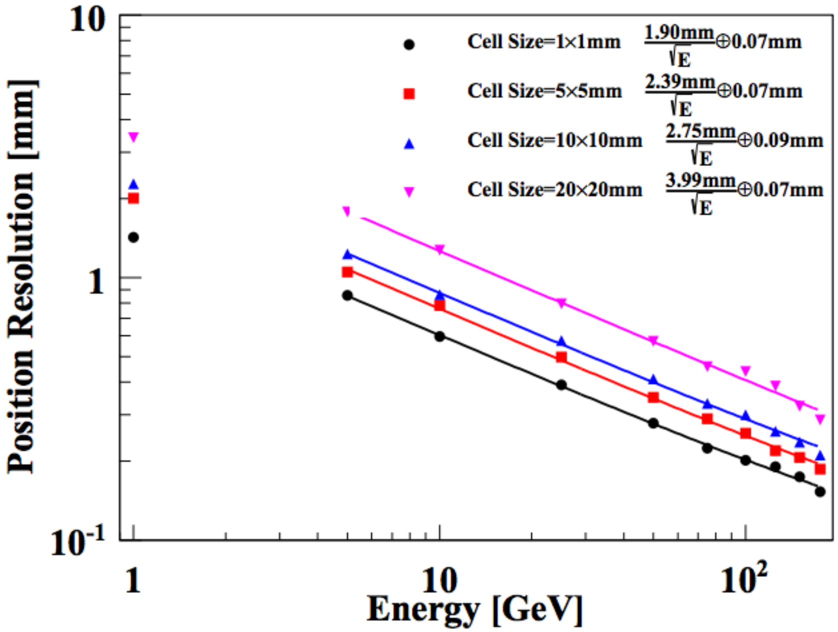


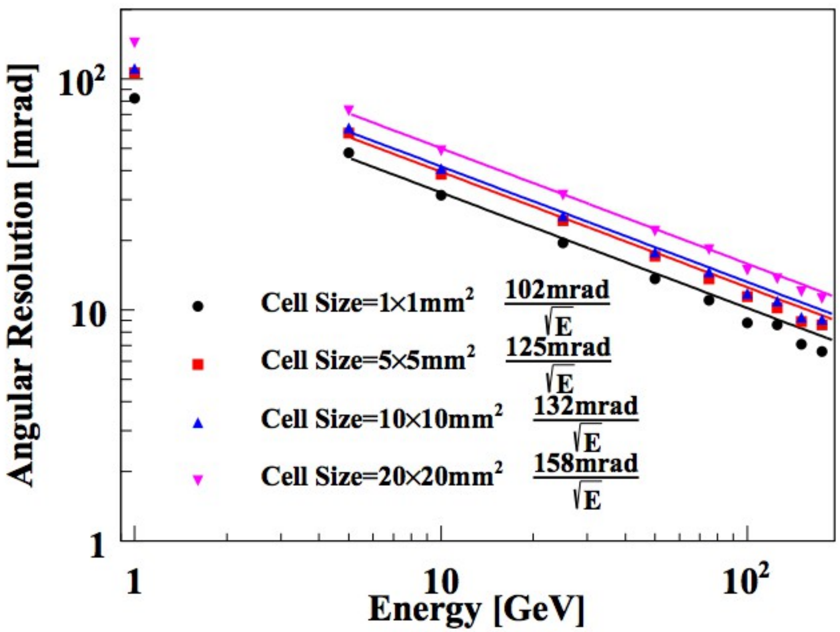
Performance @ Photon with E > 1 GeV:

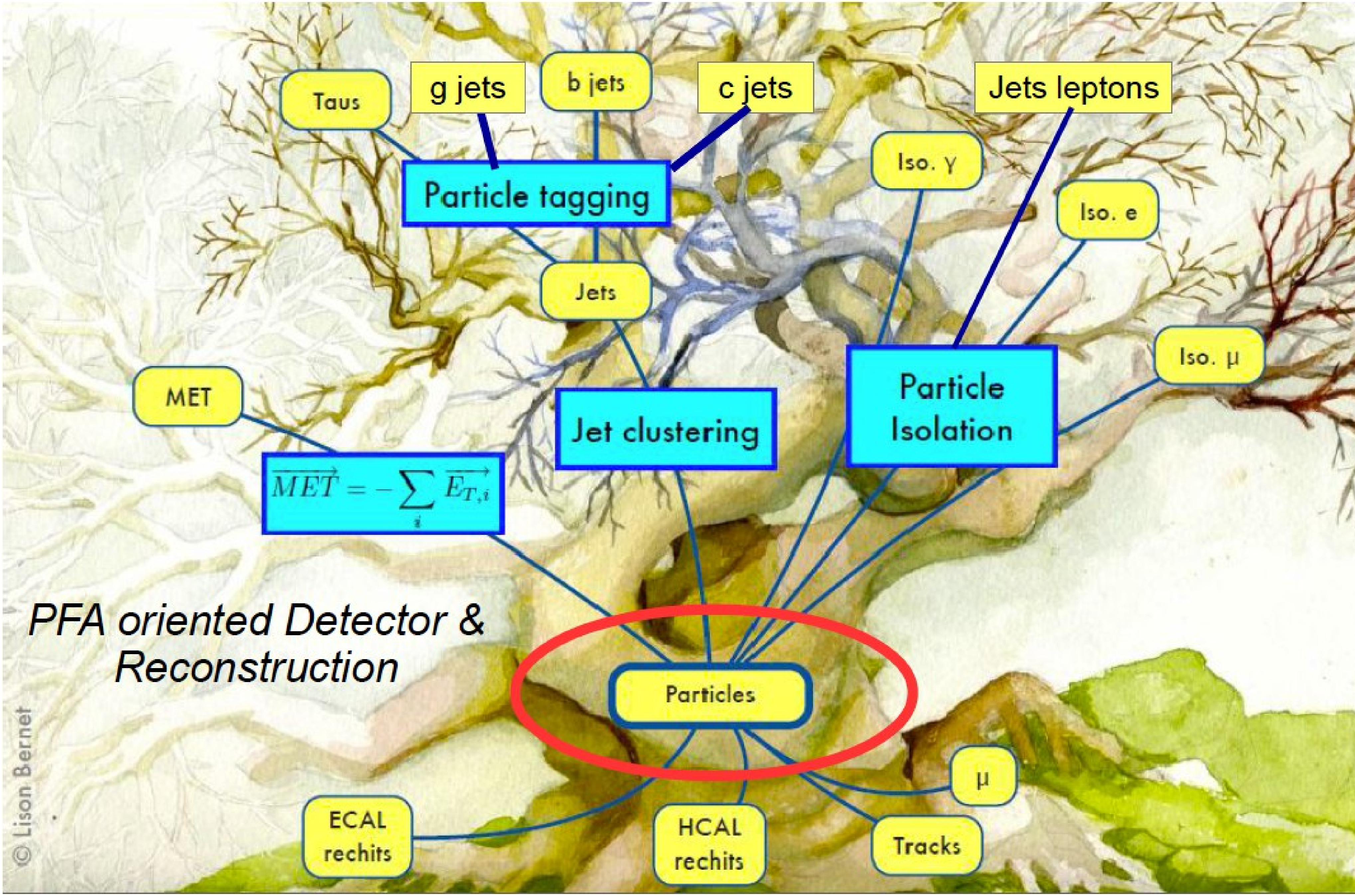
Energy Resolution is comparable at:

20 * 1.5 mm Si + 4.5 mm W
25 * 1 mm Si + 3.6 mm W
30 * 0.5 mm Si + 3 mm W

Impact of Cell Size: Position/Angular

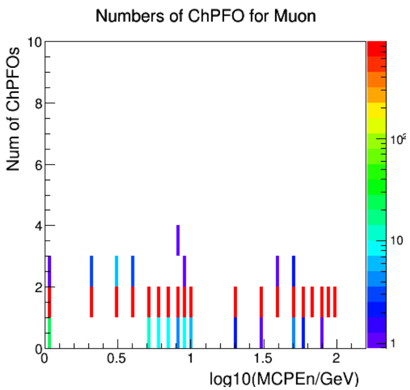


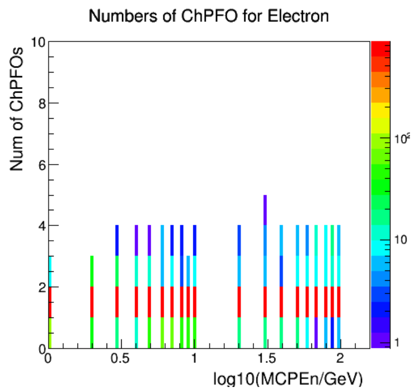


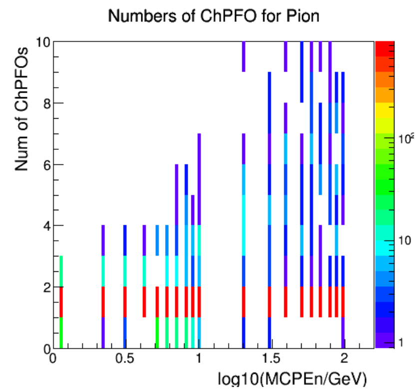


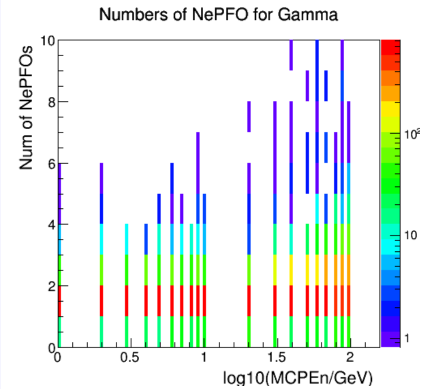
Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
Iso. μ
MET
Jet clustering
Particle
Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector &
Reconstruction
Particles
μ
ECAL
rechits
HCAL
rechits
Tracks
© Lison Bernet

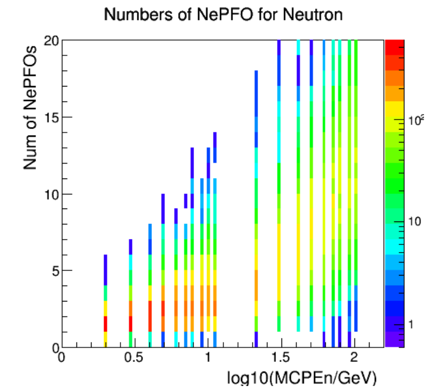
Arbor @ single particle

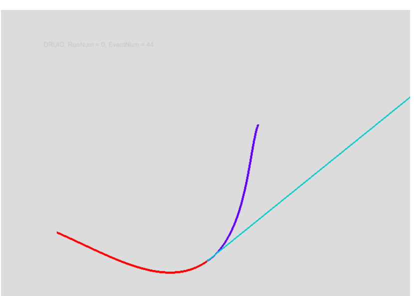


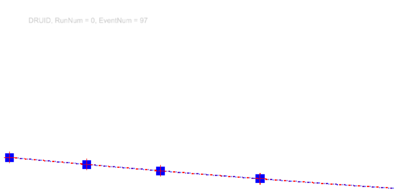


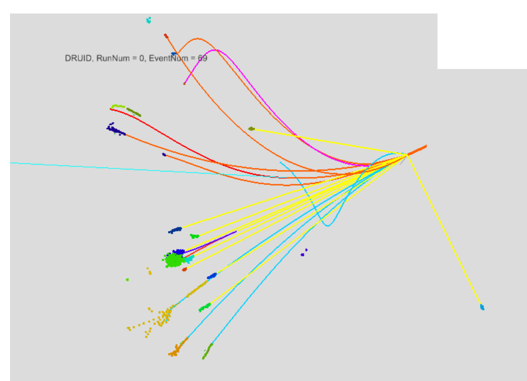


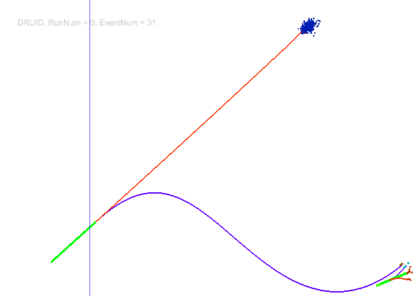


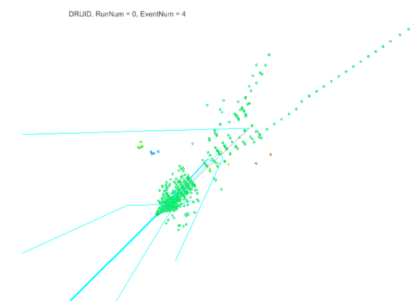


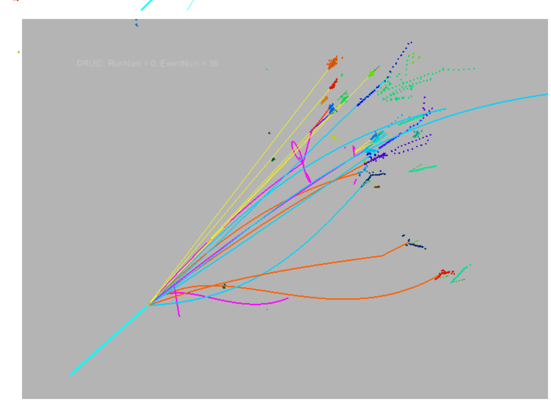






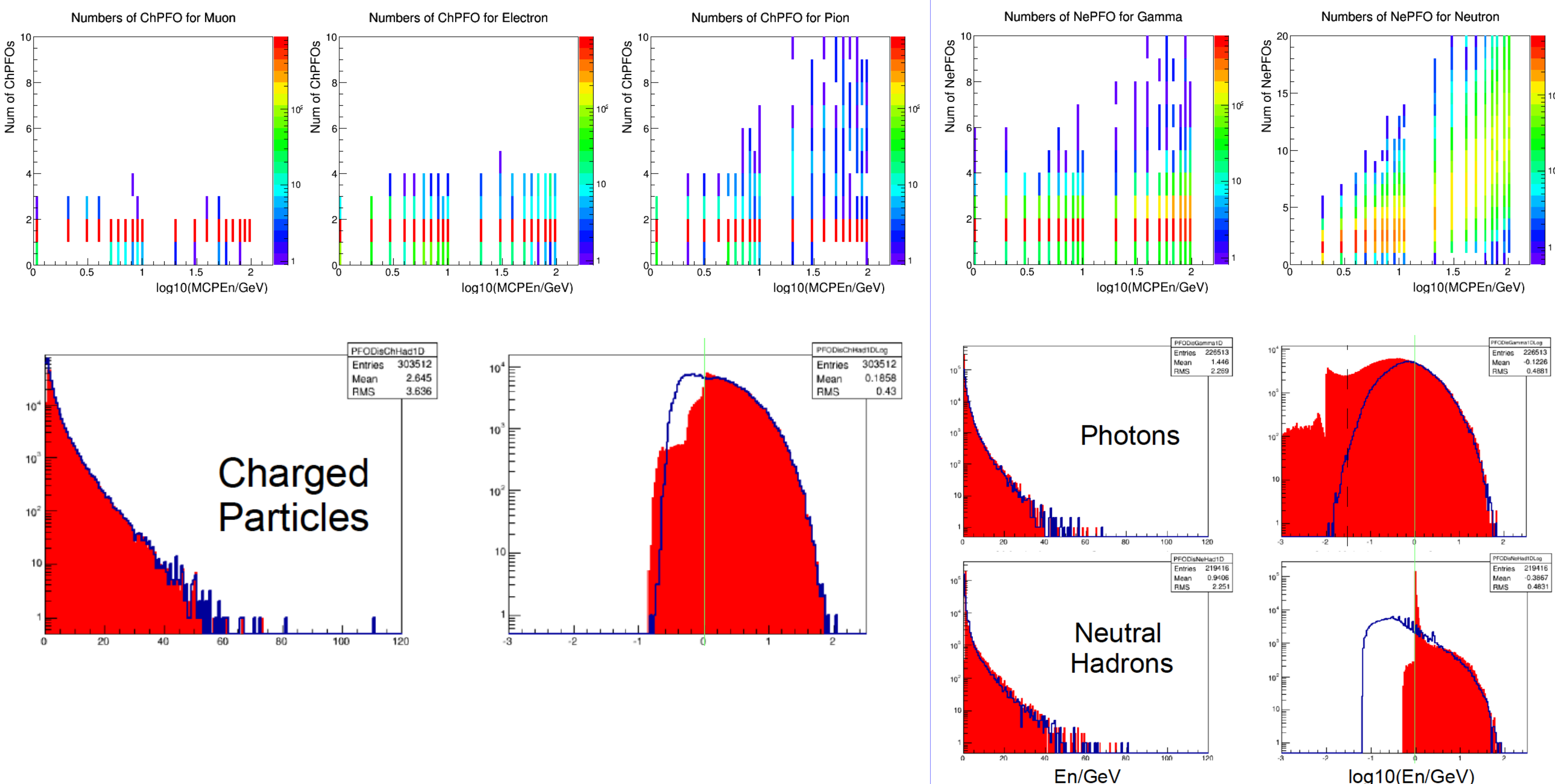




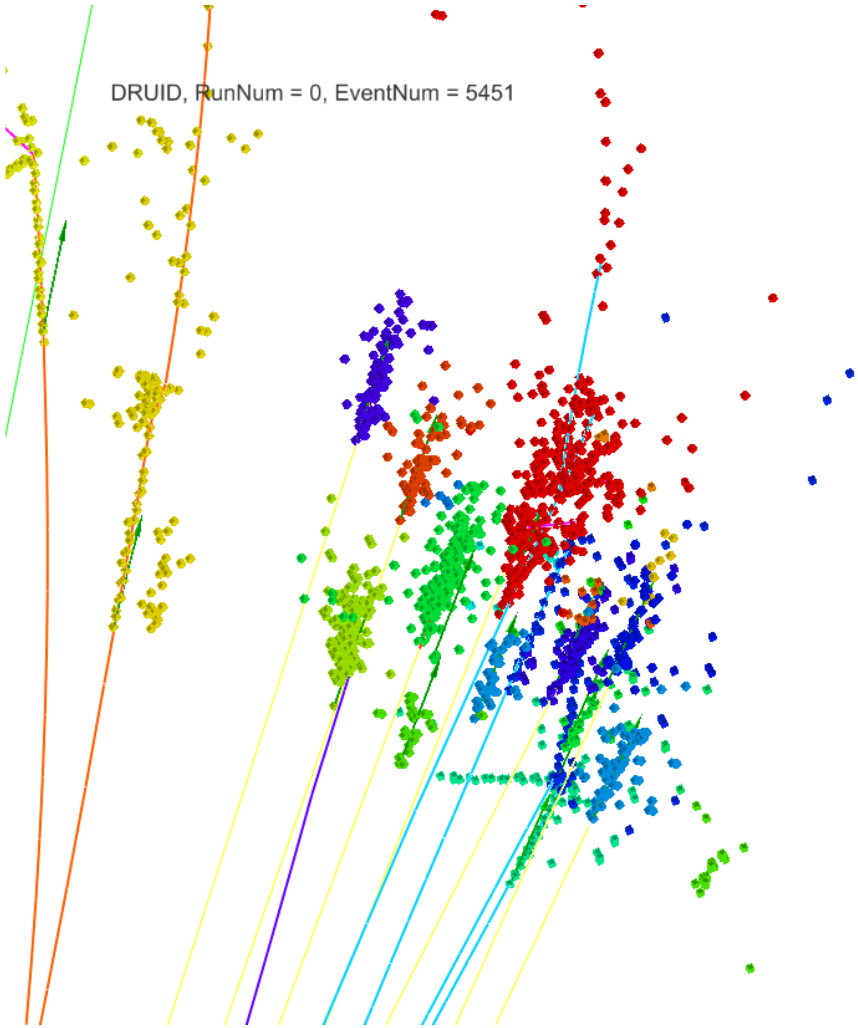


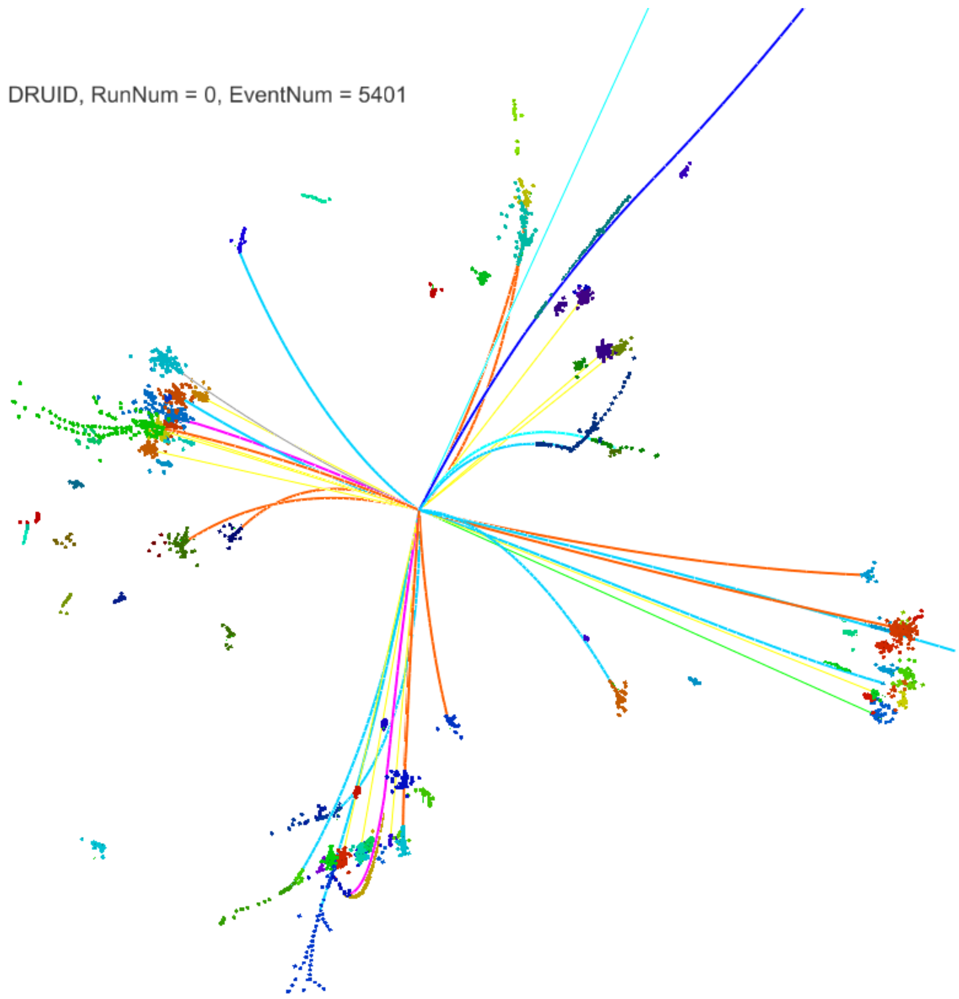
Charged *Neutral*

Arbor @ single particle



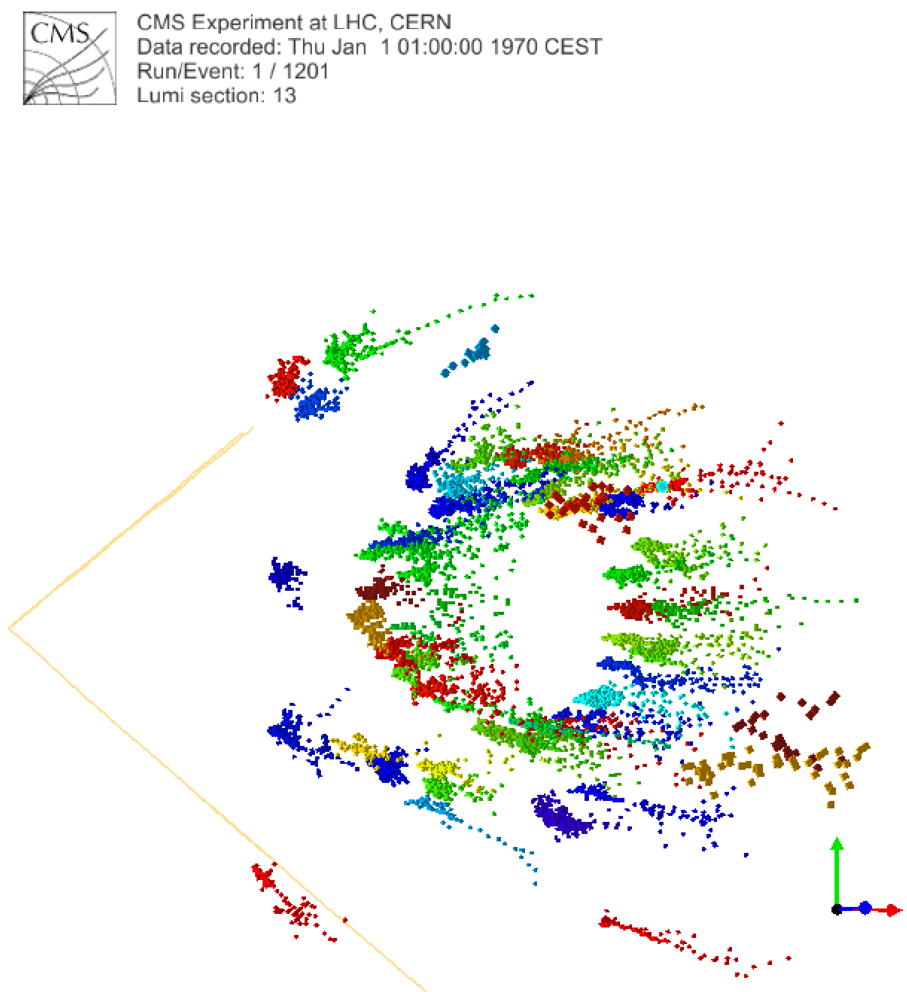
Separation: Jets



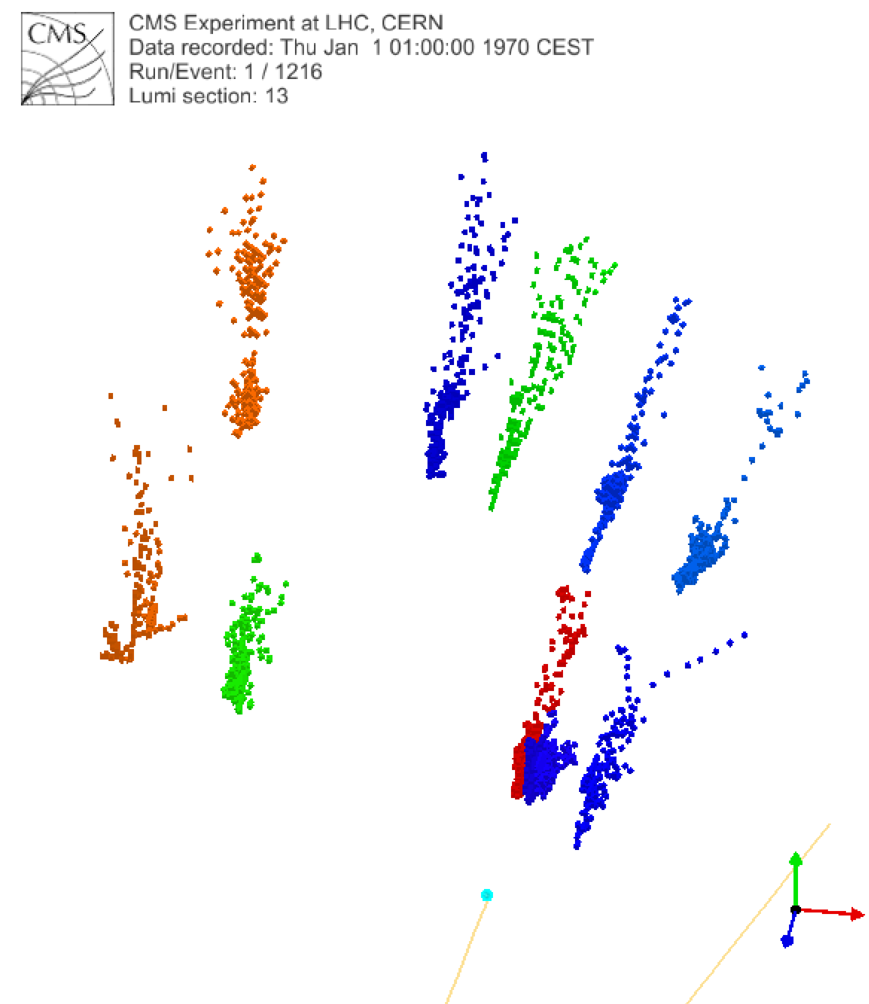


Separation: Key for PFA

Tau Tagging @ 140PU



En > 15 GeV Clusters



En > 30 GeV Clusters