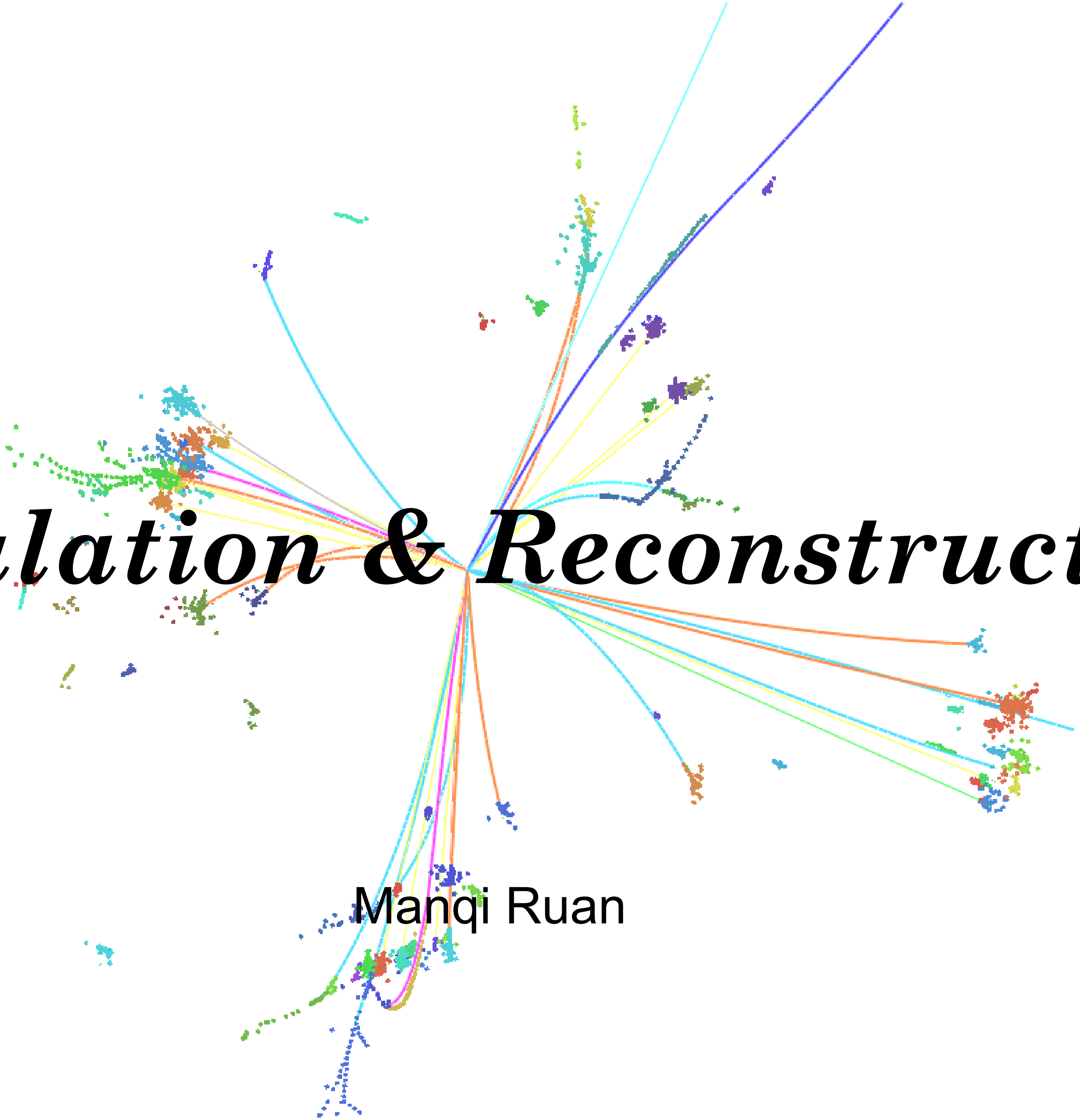
Simulation & Reconstruction



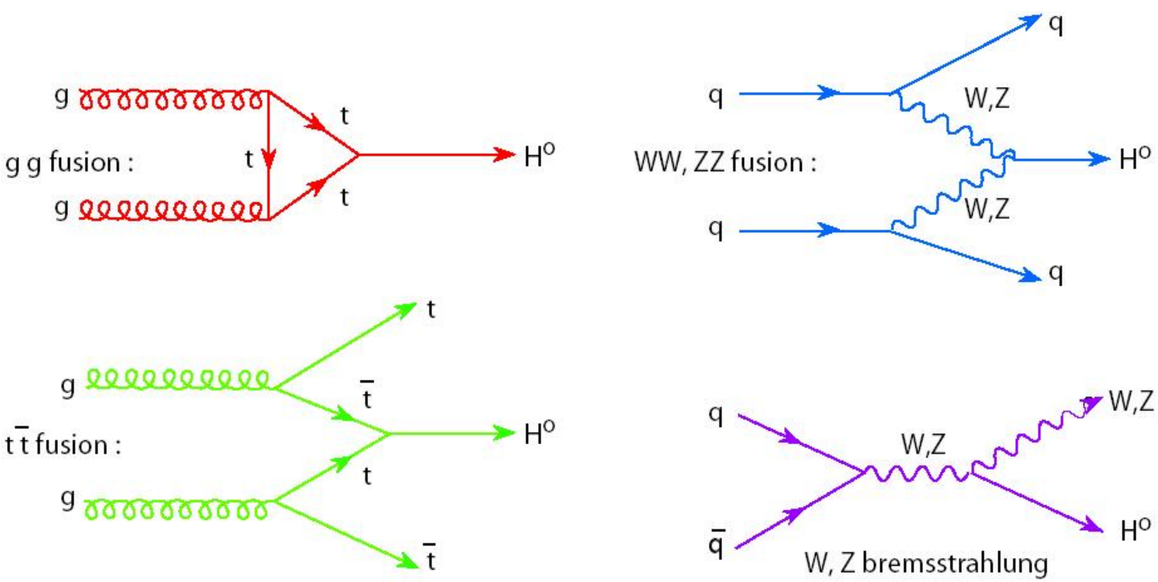
Manqi Ruan

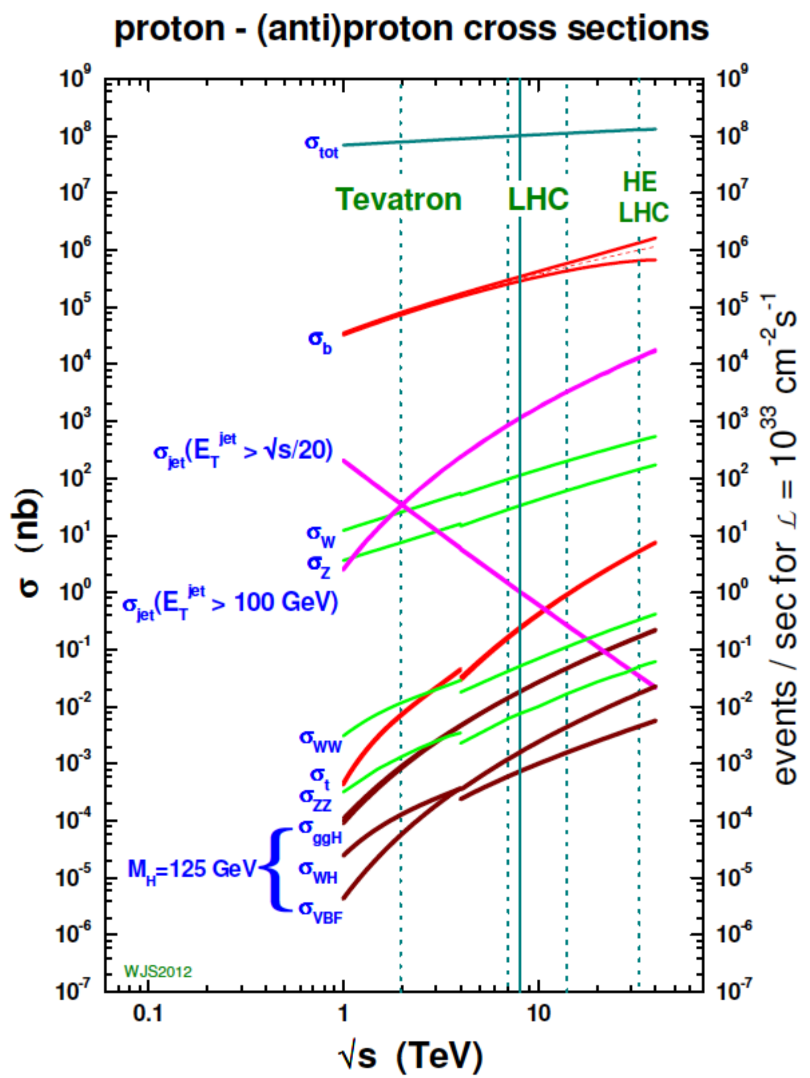
Outline

- Physics Motivation
- Simulation & Reconstruction: General picture
- Reconstruction: from hit to objects
  - Tracking
  - **Clustering**
  - Matching & Final state particle Reconstruction;
  - **lepton identification**
  - Photon reconstruction
  - Tau reconstruction
  - Jet Reconstruction & Flavor Tagging
- Applied to physics analysis
- Summary


Higgs...

Higgs @ LHC



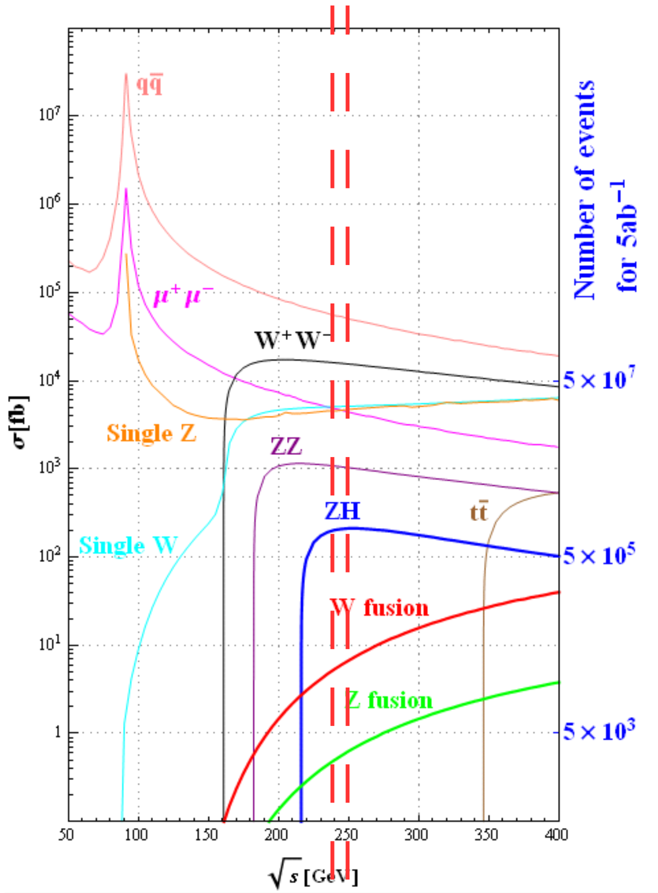


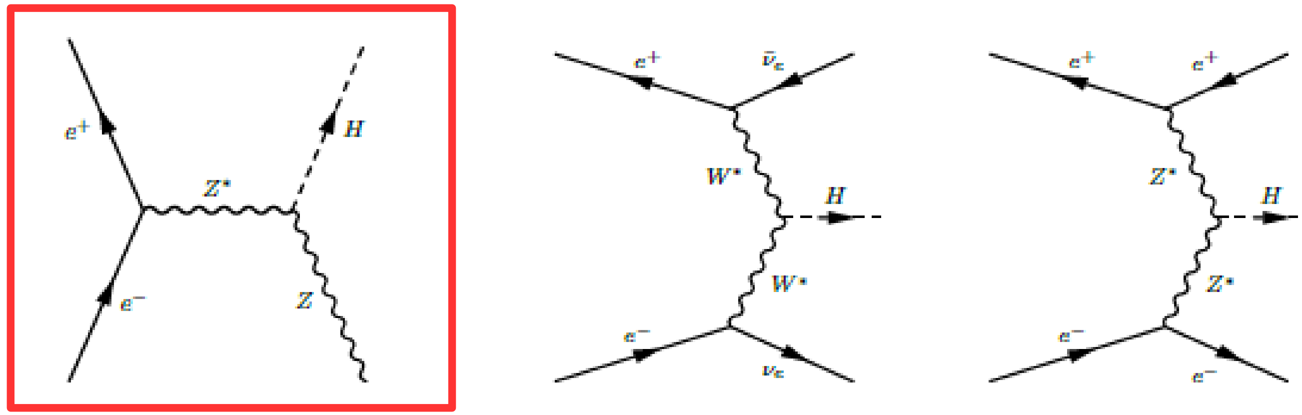
PP collider: High productivity but low finding efficiency
~already 10^6 Higgs in Run 1 data...

Higgs signal: found via the decay final states.

$$\sigma(AA \rightarrow H \rightarrow BB) \sim g^2(HAA) g^2(HBB)/\Gamma_{total}$$

Higgs @ CEPC

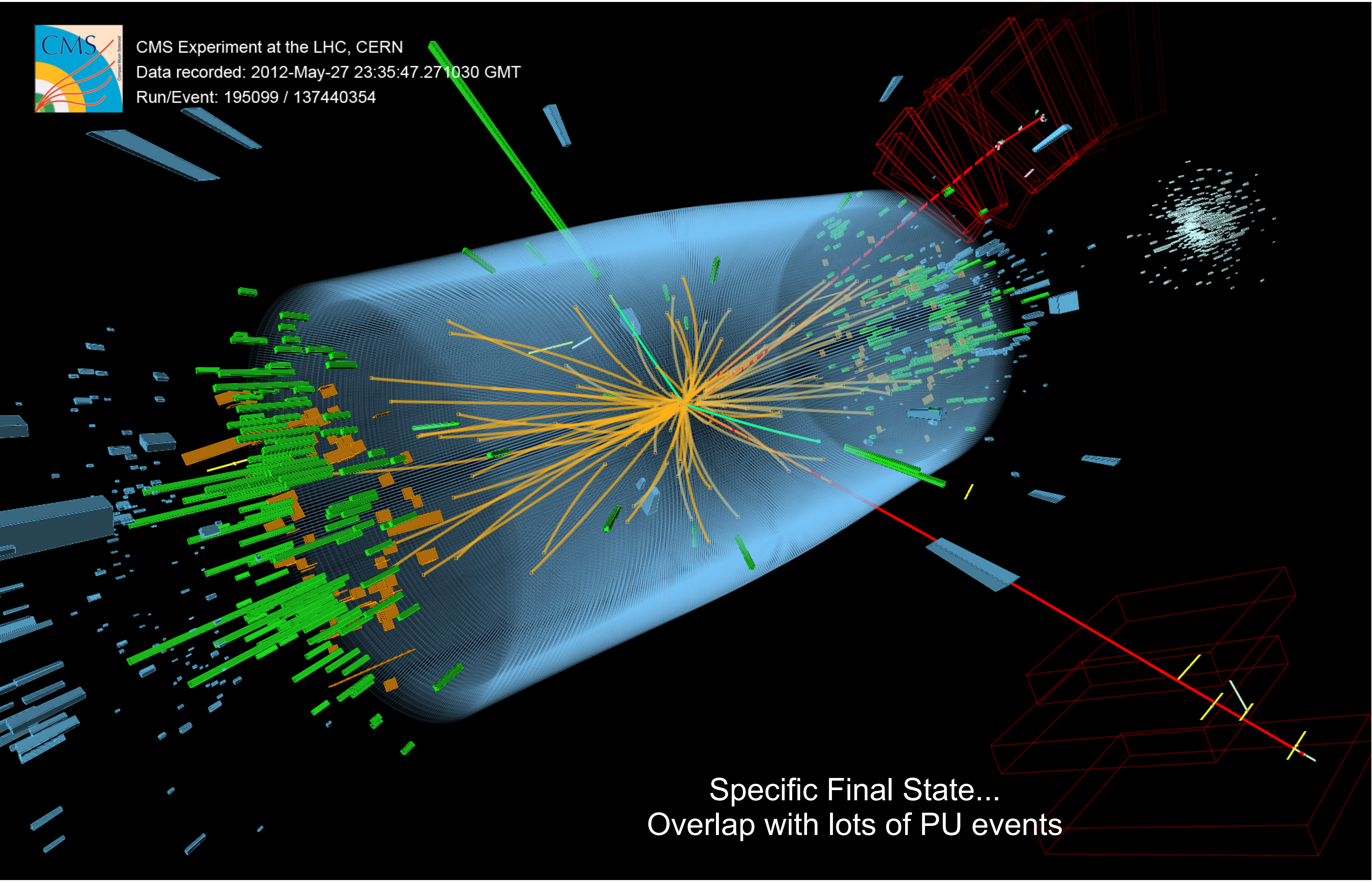


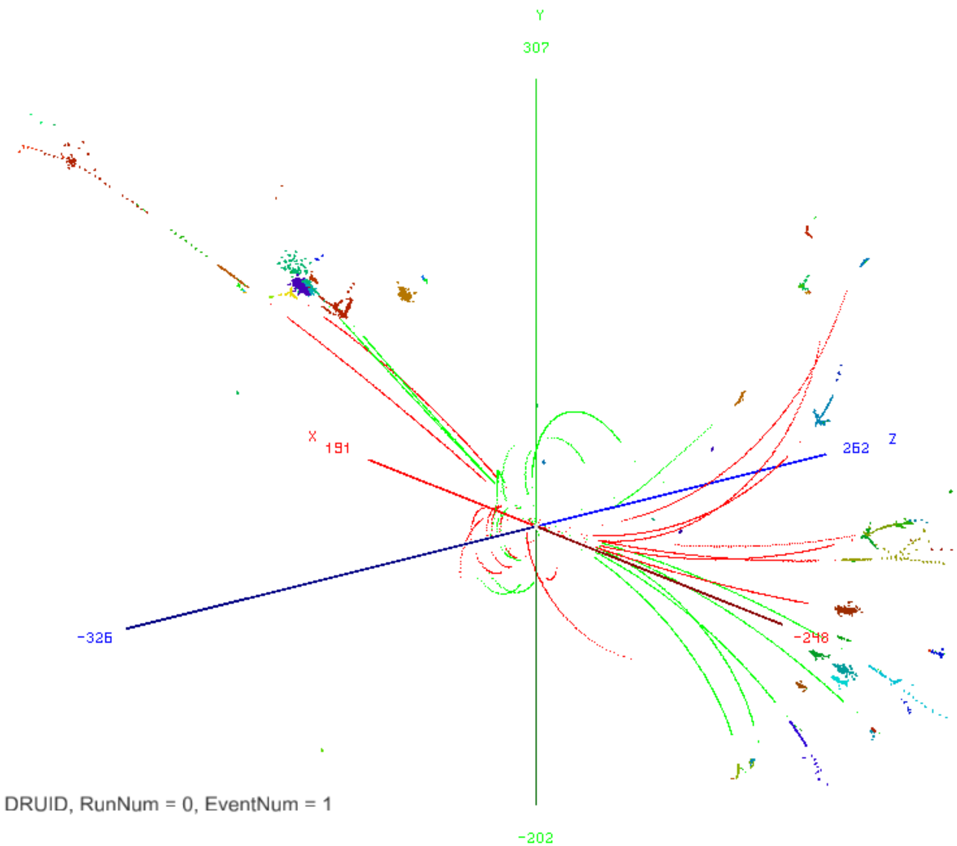


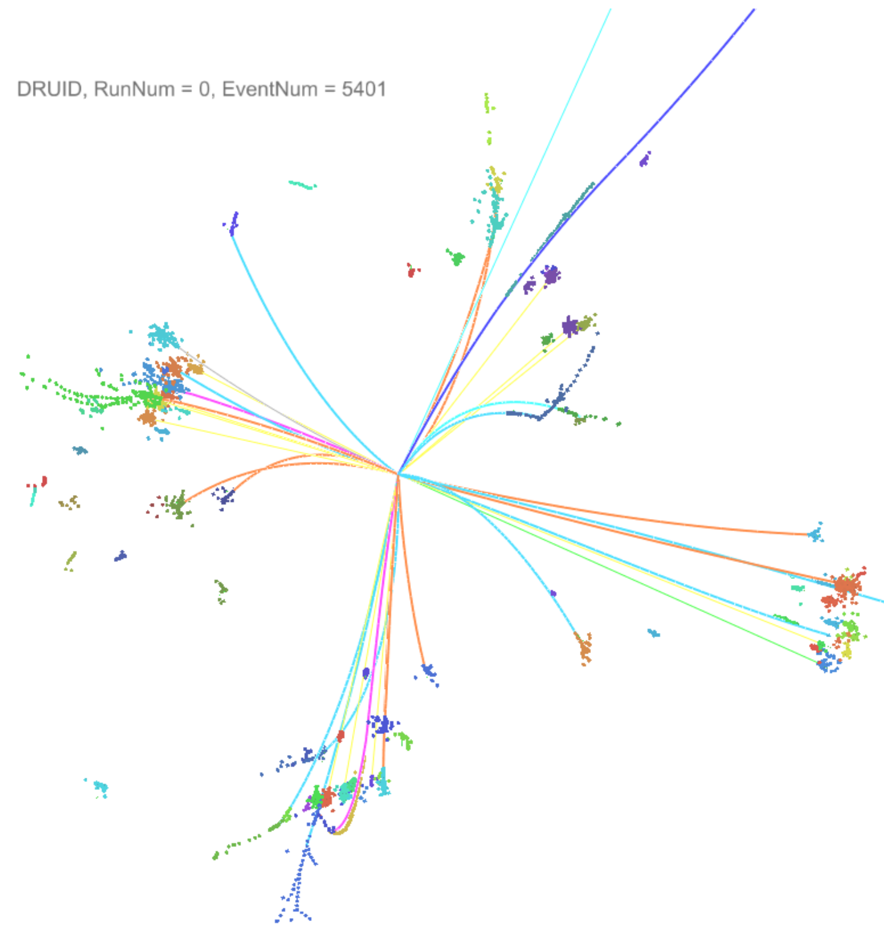
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

CEPC: 1 M Higgs boson in a clean environments

Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H->X))
Derive: Higgs width, branching ratios & absolute value of coupling constants

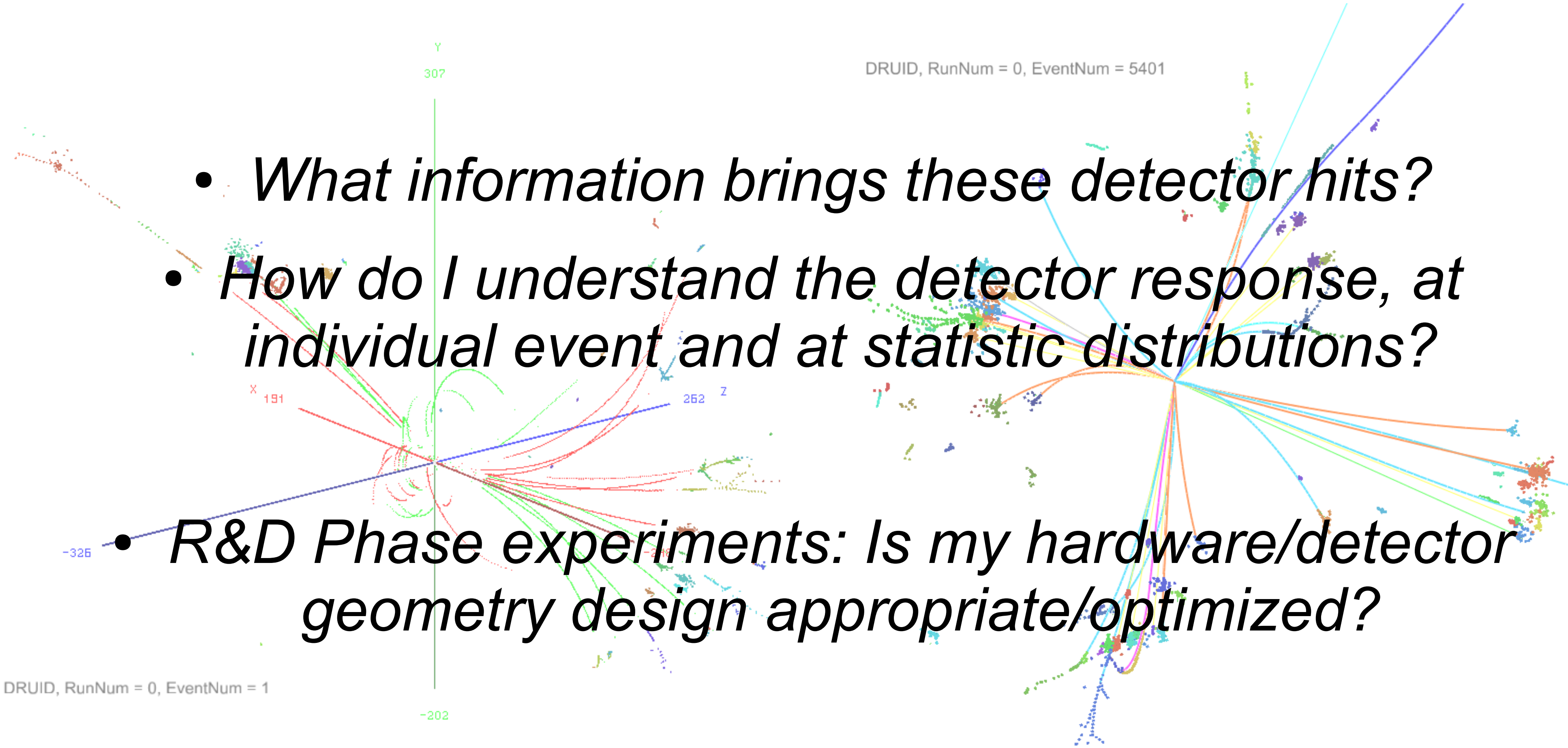

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
Specific Final State...
Overlap with lots of PU events





Sim Higgs @ CEPC

Questions...



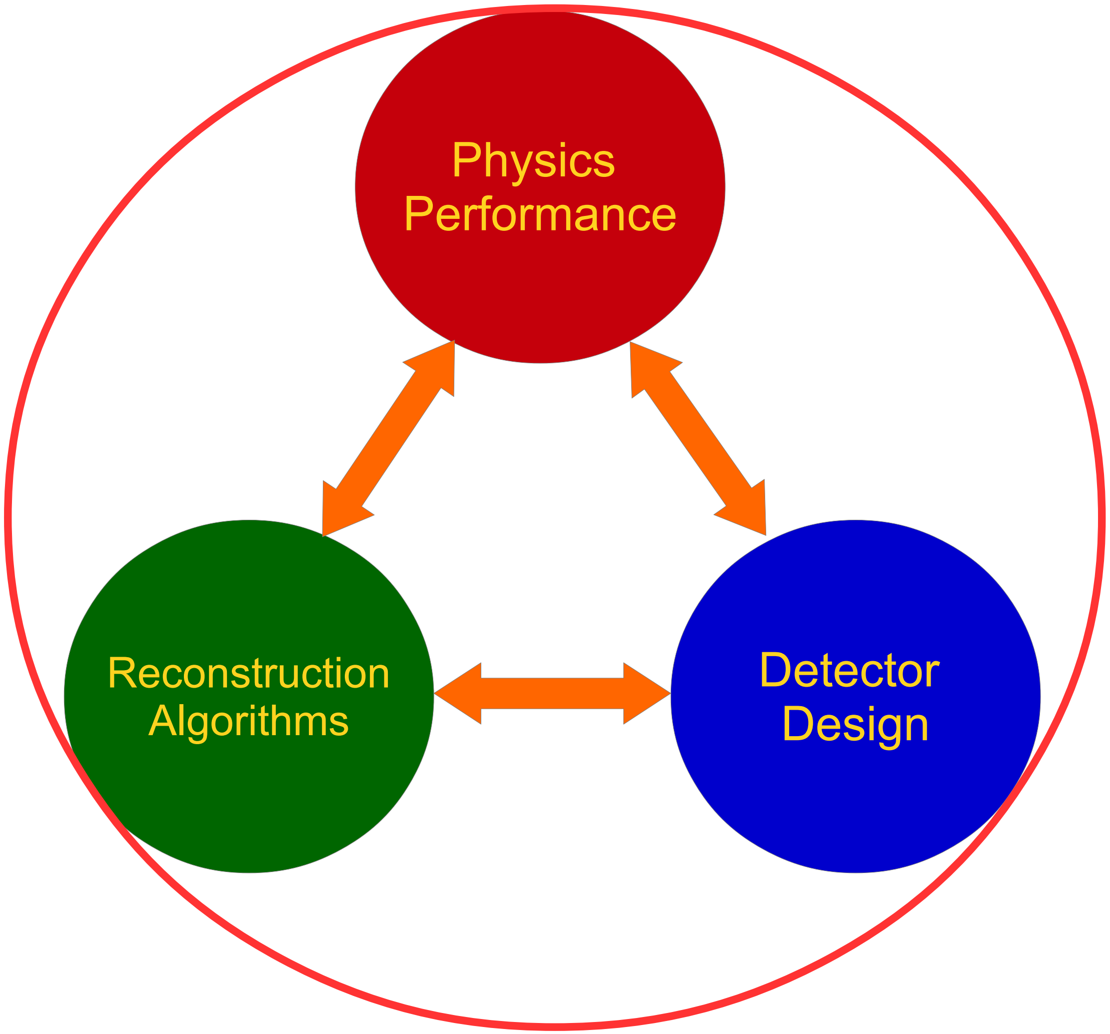
- *What information brings these detector hits?*
- *How do I understand the detector response, at individual event and at statistic distributions?*

- *R&D Phase experiments: Is my hardware/detector geometry design appropriate/optimized?*

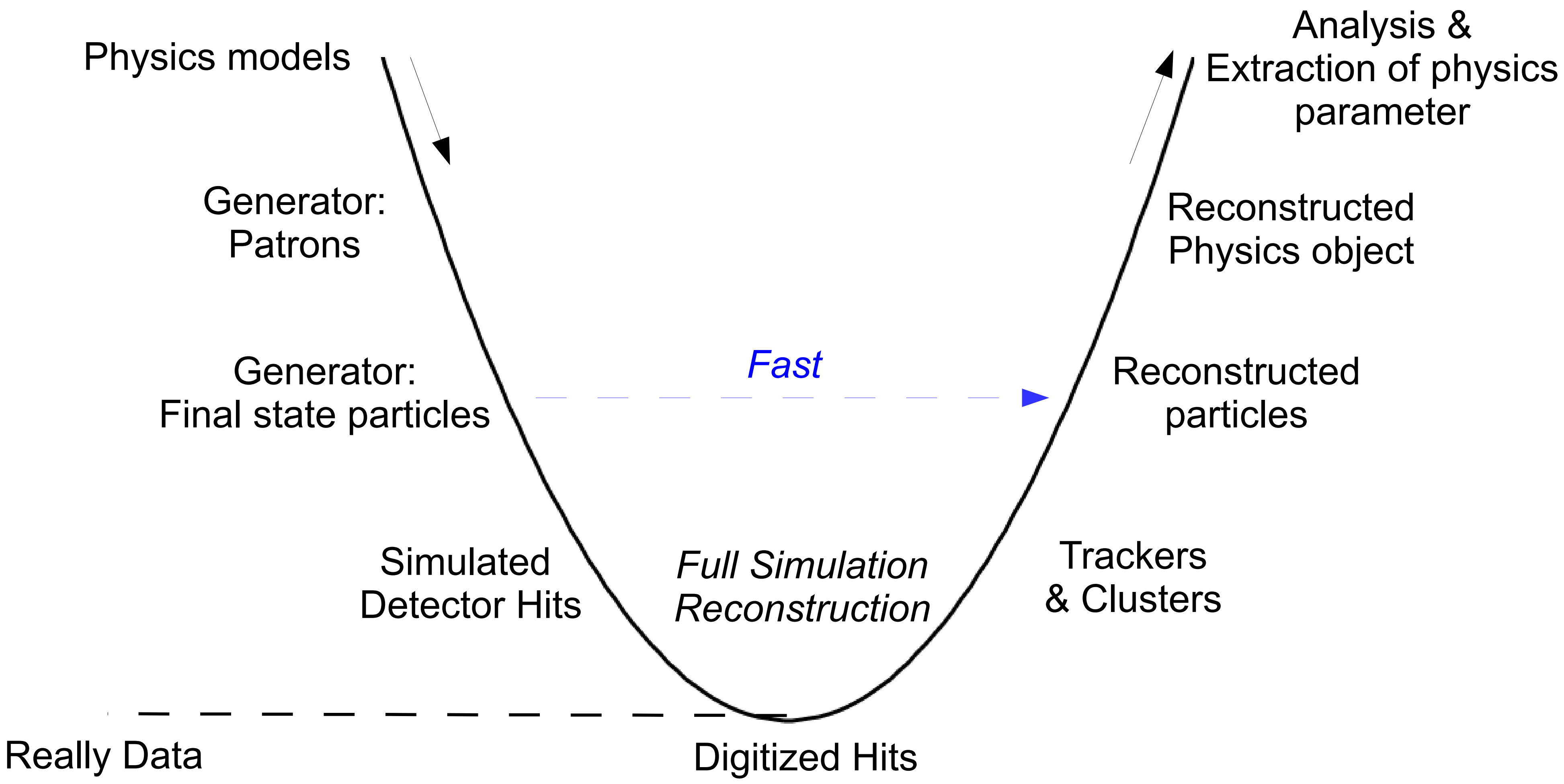
- *Portal to the Answer:* ***Simulation & Reconstruction***

Objectives

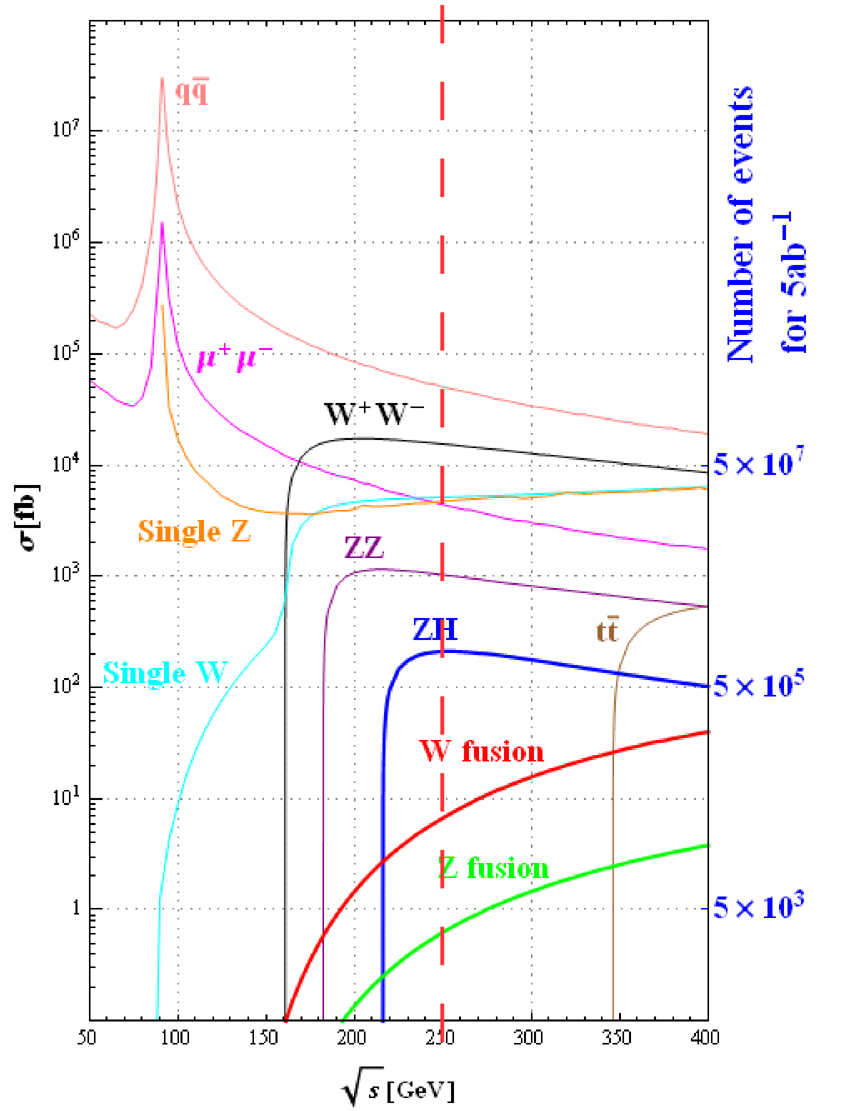
- **Explore & Demonstrate the Physics Potential**
- **Deliver the optimized detector design**
- **Develop the mandatory simulation/reconstructio n Chain**

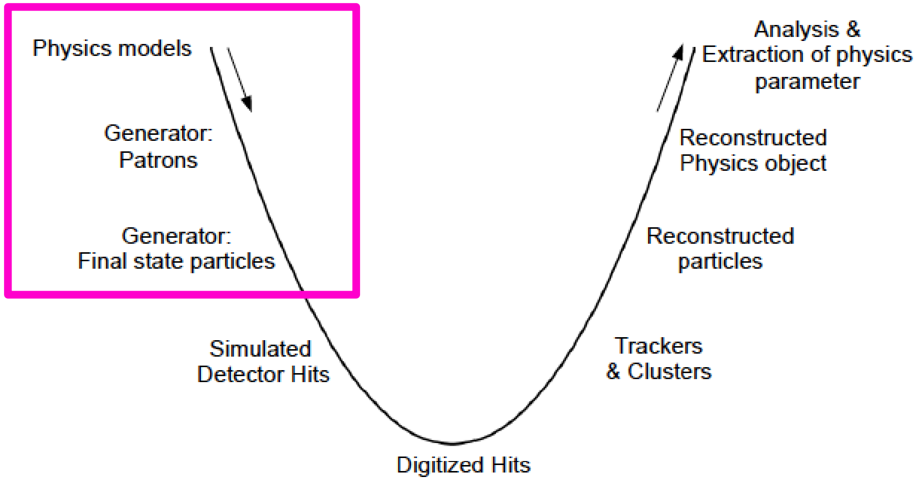


Data flow


Physics models
Analysis &
Extraction of physics
parameter
Generator:
Patrons
Reconstructed
Physics object
Fast
Generator:
Final state particles
Reconstructed
particles
Simulated
Detector Hits
Full Simulation
Reconstruction
Trackers
& Clusters
Really Data
Digitized Hits

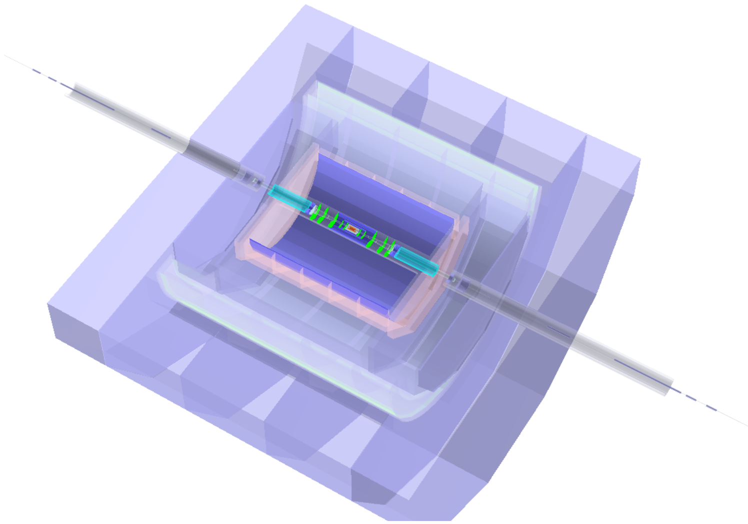
Generator

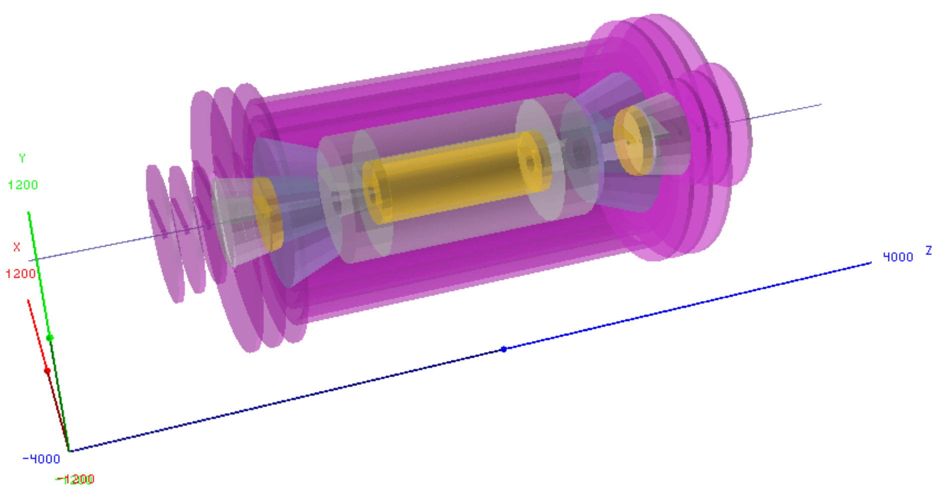


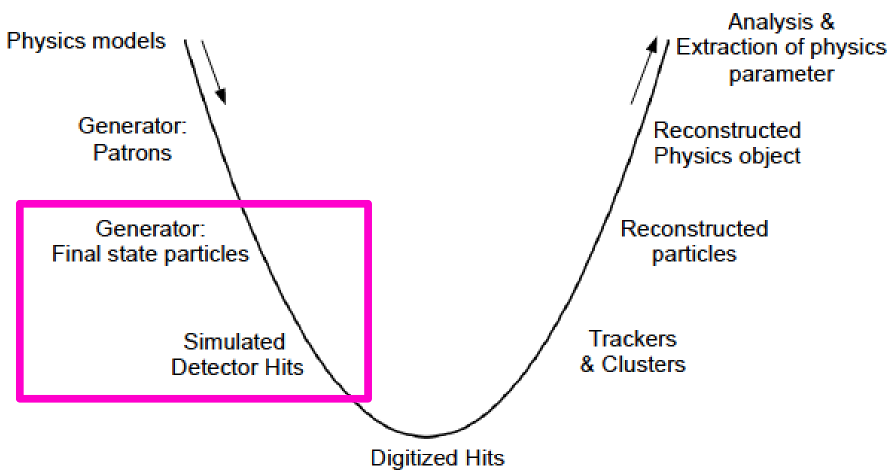


- Dedicated CEPC Samples at 250 c.m.s & adequate beam parameter setting
- SM sets (4f + 2f + Higgs): Whizard
- Exotics: Madgraph
- *Fragmentation: pythia*
- *etc*

Geant 4 Full Simulation



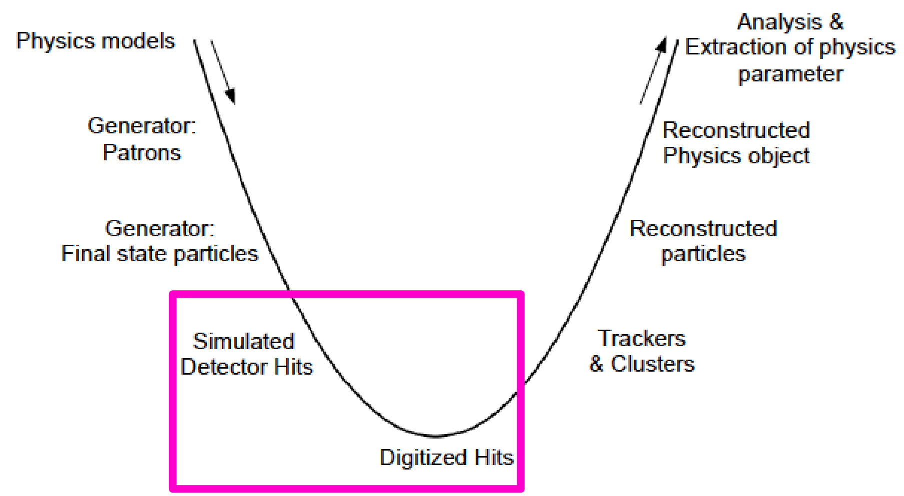


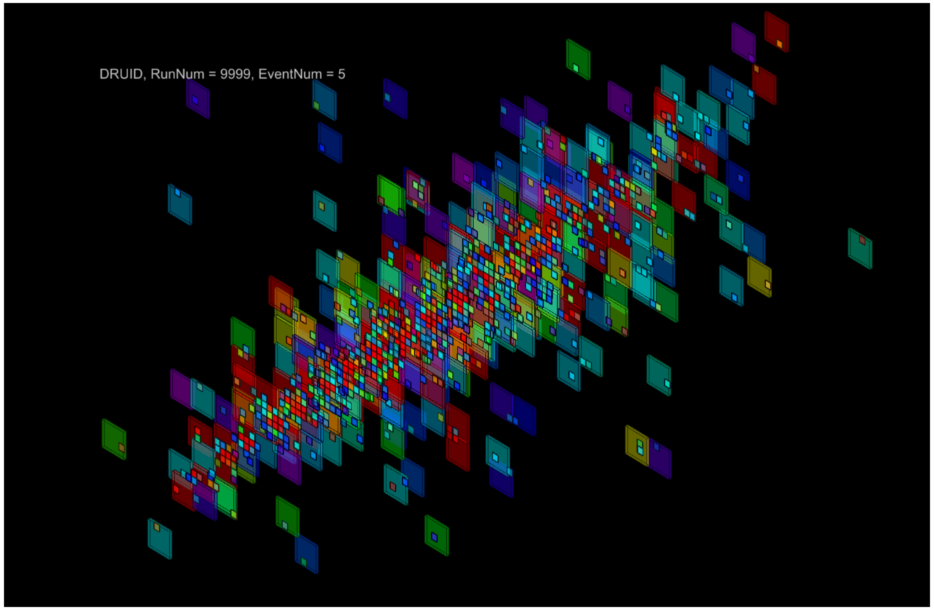


- Organize the material (sensors, absorber, mechanics...) into virtual detector
- Calculate the energy deposits at each sensor volume, for a physics event
  - How different particles, at different energy interact with different material -> Geant 4

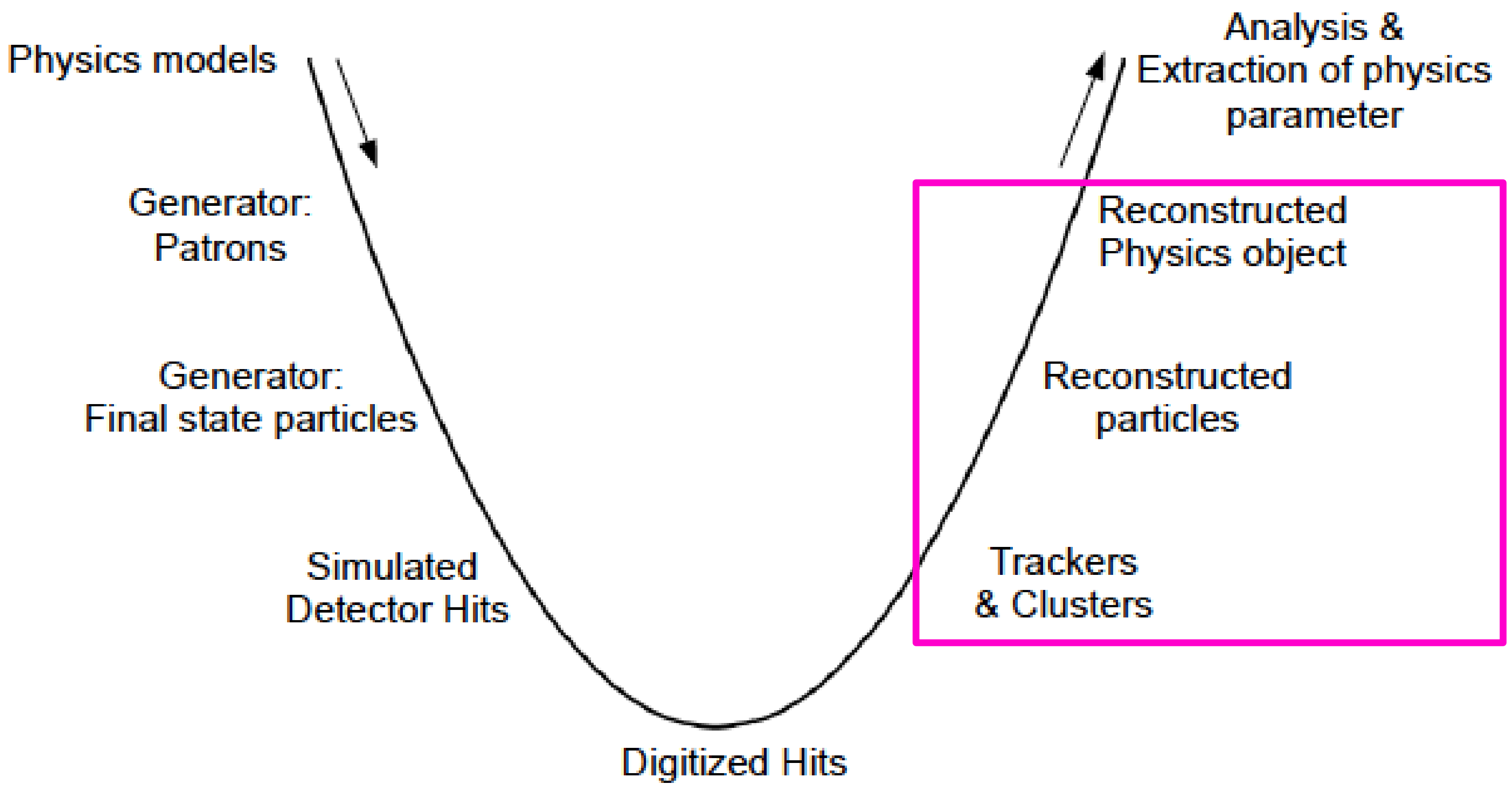
Digitization

- Digitization: from deposited energy to ADC value
  - Include geometry defects, noise, linearity, saturation...
  - Characteristic of hardware performance: essential for detector optimization
- Trackers: using ILD Software
- Calorimeter: using G2CD
  - Modeling of charge deposition & spatial distribution
  - Digitize to different cell size

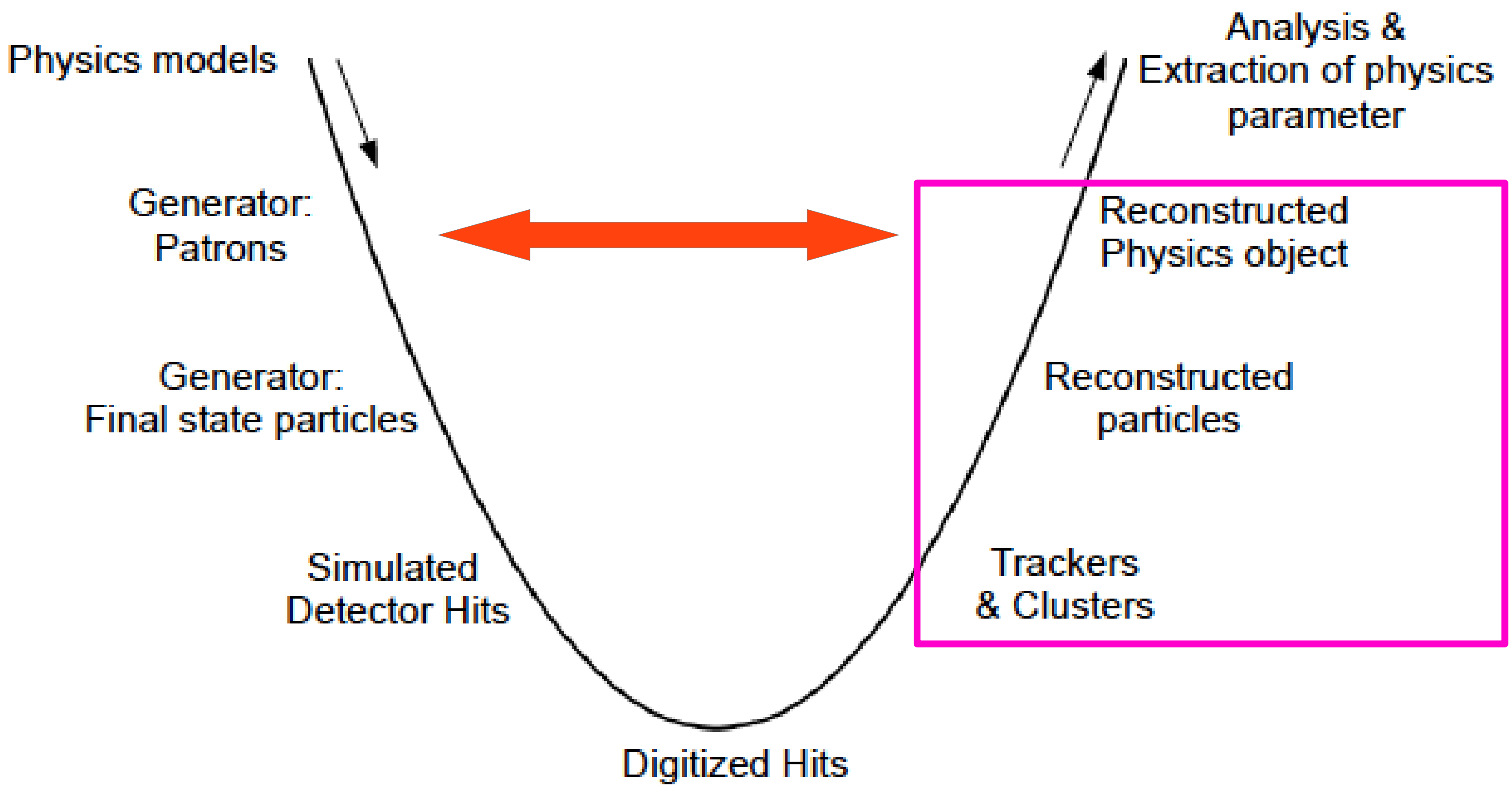




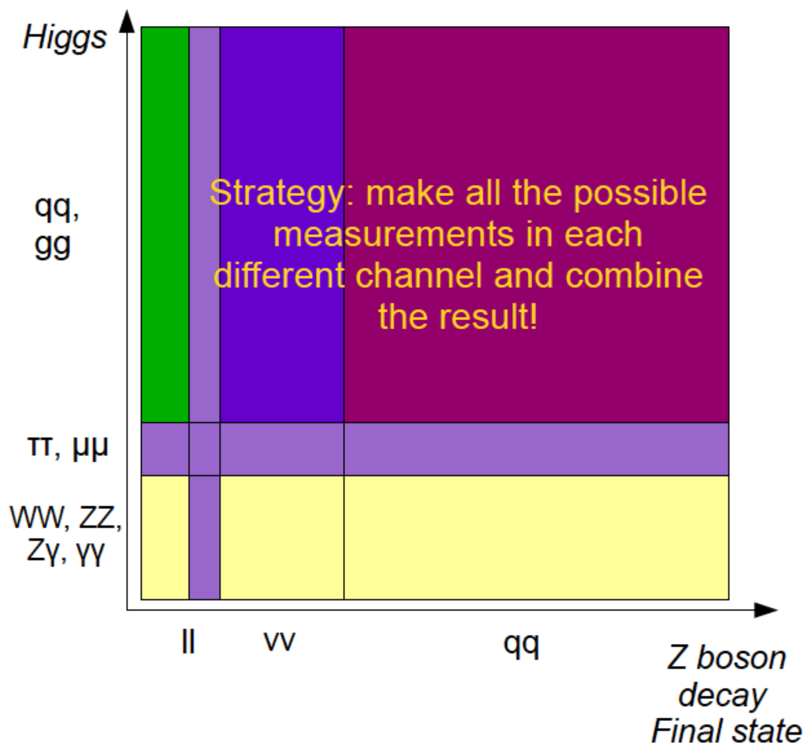
Reconstruction

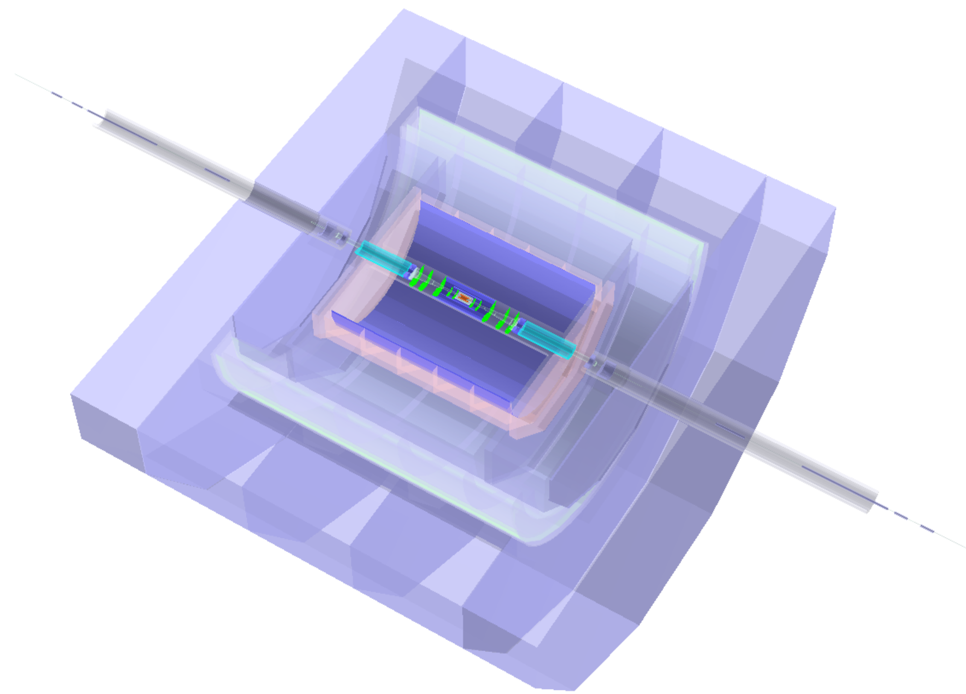


Reconstruction



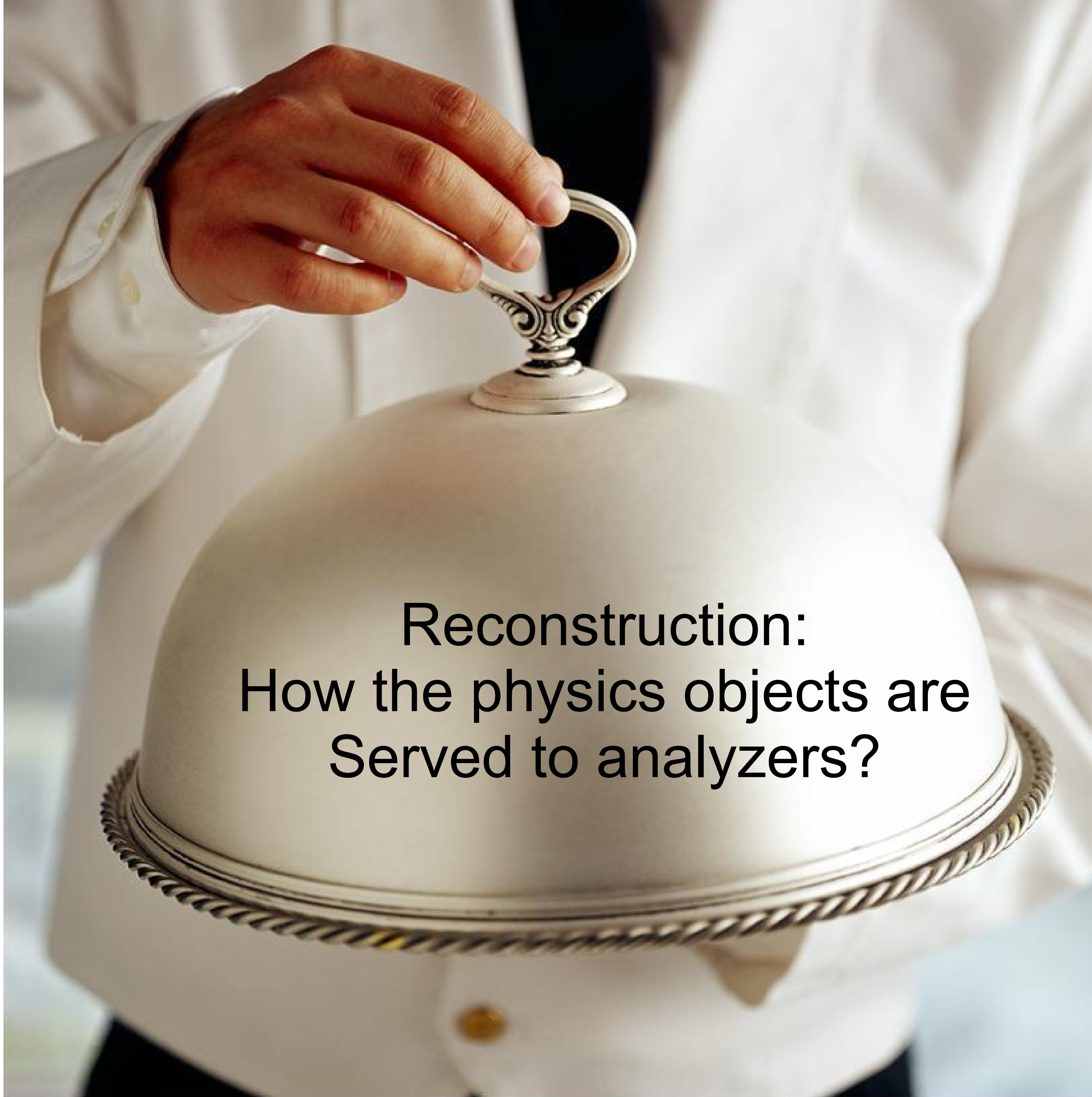
CEPC Conceptual detector, developed from ILD



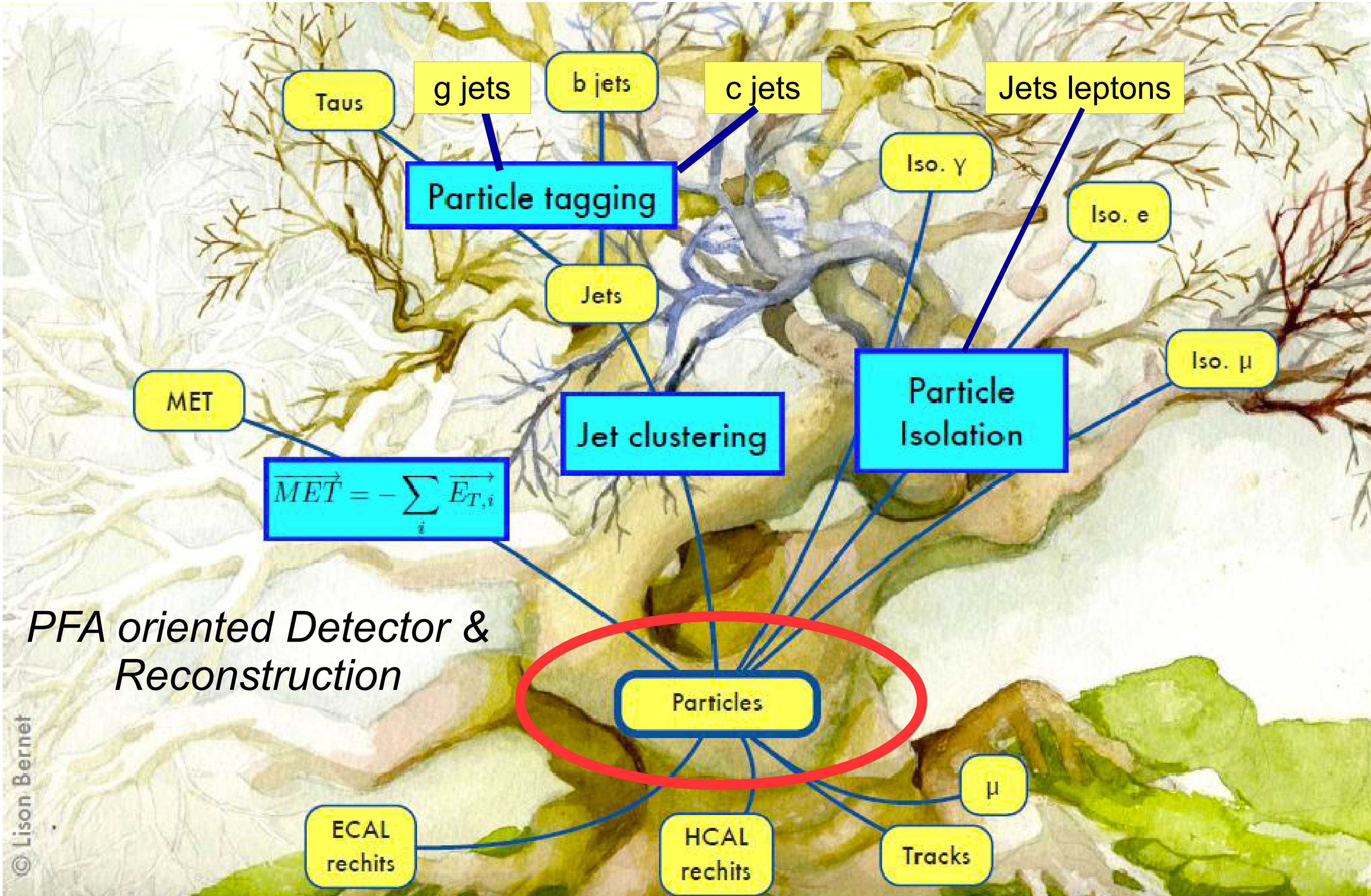


A detector reconstruct all the physics object (lepton, photon, tau, Jet, MET, ...) with high efficiency/precision

High Precision VTX located close to IP: b, c, tau tagging
High Precision Tracking system: $\delta(1/Pt) \sim 2*10^{-5}(GeV^{-1})$
PFA oriented Calorimeter System (~o(10^8) channels): Tagging, ID, Jet energy resolution, ect



Reconstruction:
How the physics objects are Served to analyzers?


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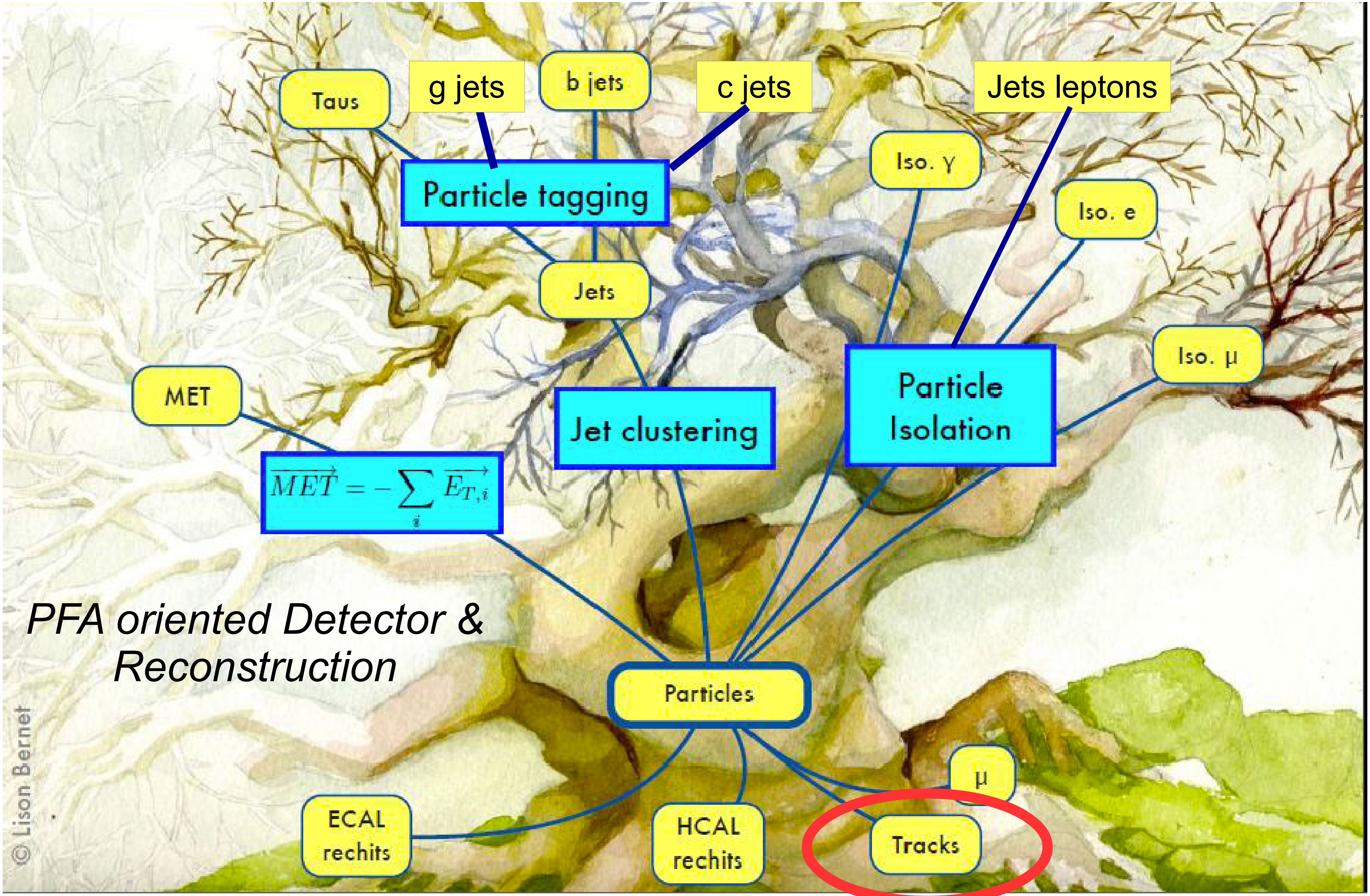
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
μ
ECAL rechits
HCAL rechits
Tracks
© Lison Bernet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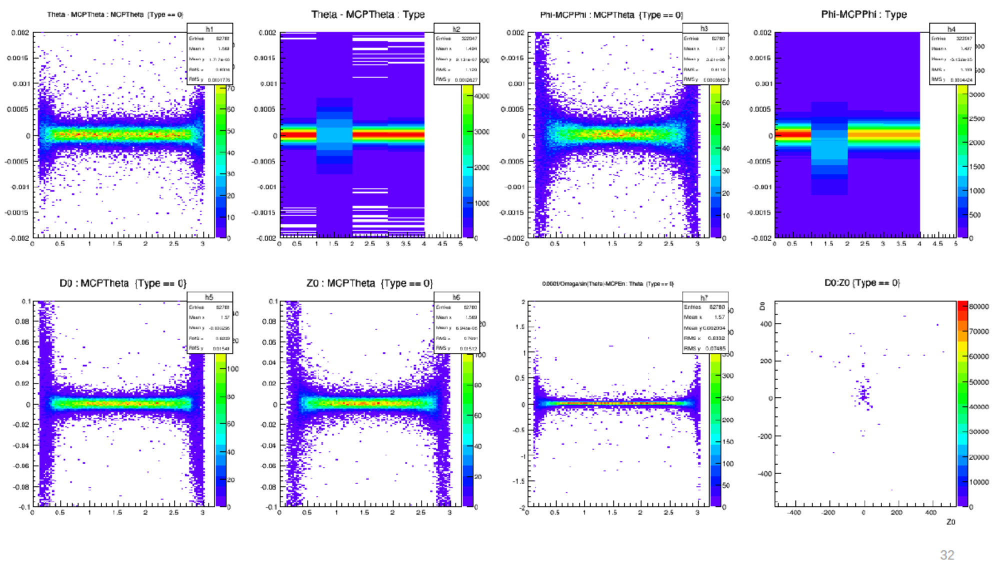
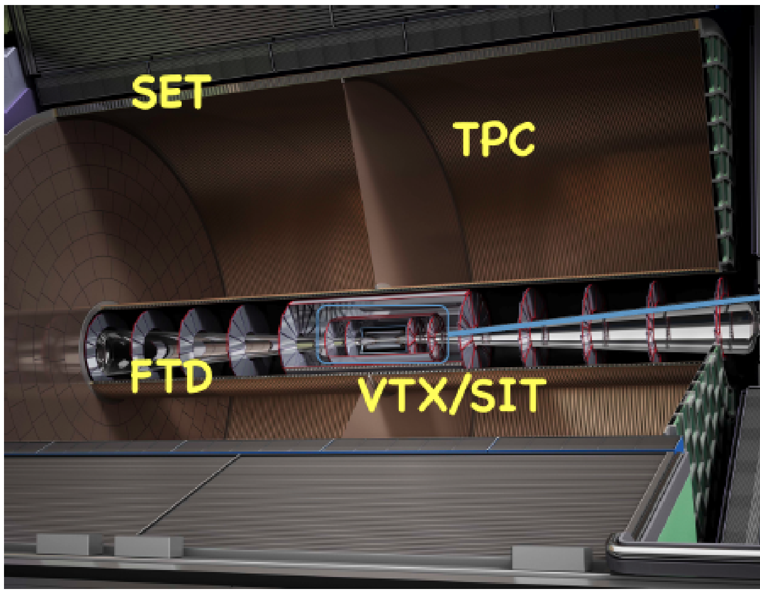
Tracking

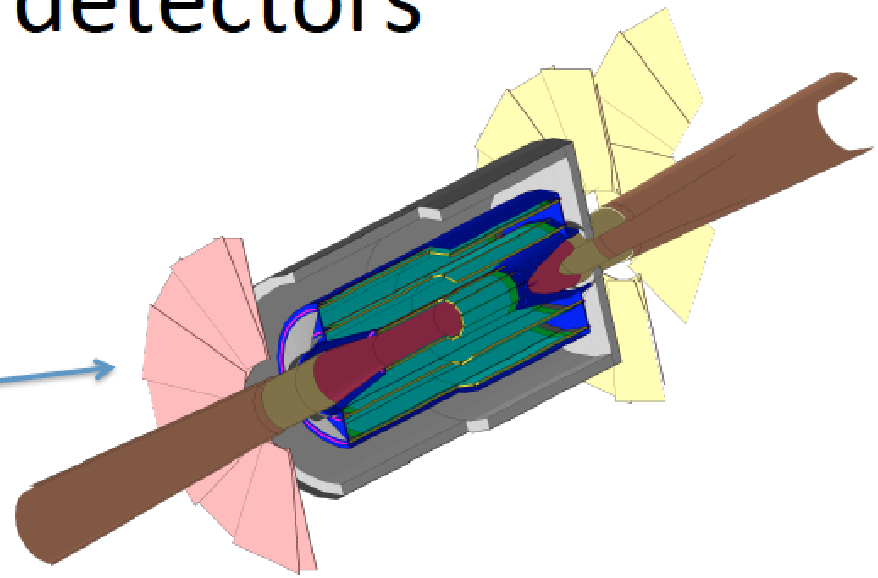
- Describe the trajectory of a charged particle by a helix
- Find the Helix (Can be challenging)
  - Efficiency of finding...
- Measure the Helix:
  - Closest point to the IP: (D0, Z0)
  - Theta Angle
  - Phi Angle
  - Curvature (Omega)

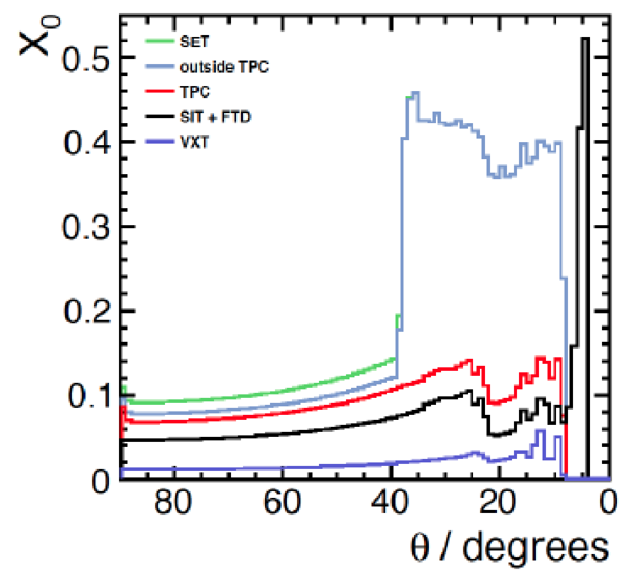


- Objective: for any geometry, produce & understand the track response:
  - Track efficiency & multiplicity
  - Differential resolution of D0, Z0, Phi, TanLambda(Theta), Omega(P_T)

Tracking detectors







Detector	Point Resolution
VTX	$\sigma_{r\phi,z} = 2.8\mu m$ (layer 1) $\sigma_{r\phi,z} = 6.0\mu m$ (layer 2) $\sigma_{r\phi,z} = 4.0\mu m$ (layers 3-6)
SIT	$\sigma_{\alpha_z} = 7.0\mu m$ $\alpha_z = \pm 7.0^\circ$ (angle with z-axis)
SET	$\sigma_{\alpha_z} = 7.0\mu m$ $\alpha_z = \pm 7.0^\circ$ (angle with z-axis)
FTD *Pixel*	$\sigma_r = 3.0\mu m$ $\sigma_{r_\perp} = 3.0\mu m$
FTD *Strip*	$\sigma_{\alpha_r} = 7.0\mu m$ $\alpha_r = \pm 5.0^\circ$ (angle with radial direction)
TPC	$\sigma^2_{r\phi} = (50^2 + 900^2 \sin^2\phi + ((25^2/22) \times (4T/B)^2 \sin\theta)\ (z/\text{cm}))\ \mu m^2$ $\sigma^2_z = (400^2 + 80^2 \times (z/\text{cm}))\ \mu m^2$ where ϕ and θ are the azimuthal and polar angle of the track direction

L. Bo

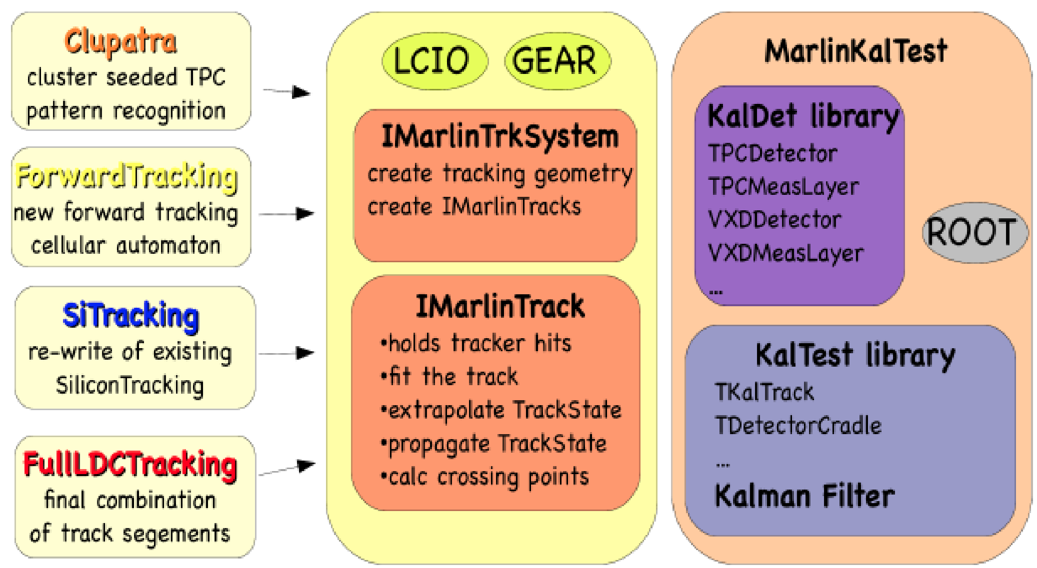
Tracking algorithm

- **ForwardTracking**
  - new standalone forward tracking package – uses:
  - Cellular Automaton for track finding
  - Hopfield networks to arbitrate between candidates w/ mutual hits)
  - SubsetProcessor to find consistent set w/ tracks from SiliconTracking

Clupatra

- Seed: nearest neighbor clustering, outside-in direction
- road search based on the Kalman filter and track extrapolation
- track segments from curling particles are merged, using a coarse circle
- split tracks are merged by Kalman filter

- **SiliconTracking**
  - brute force triplet search in stereo angle sectors based on a set of seed-layer-triplets
  - road search based on helix fit
  - attach leftover hits
  - refit



- **FullLDCTracking**
  - combines track from TPC – SiTracking – ForwardTracking
  - based on track parameter compatibility
  - adding spurious leftover hits
  - final track fit

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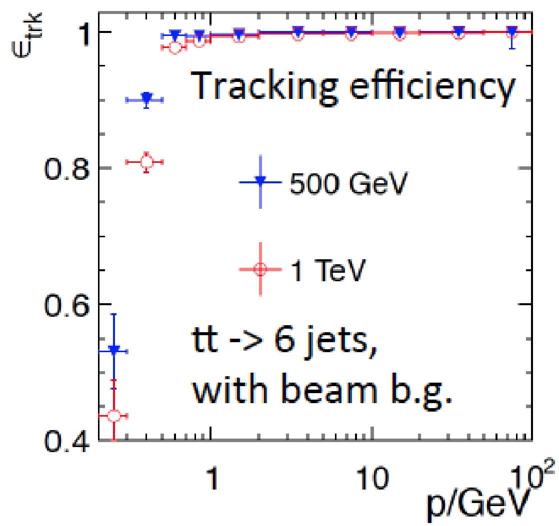
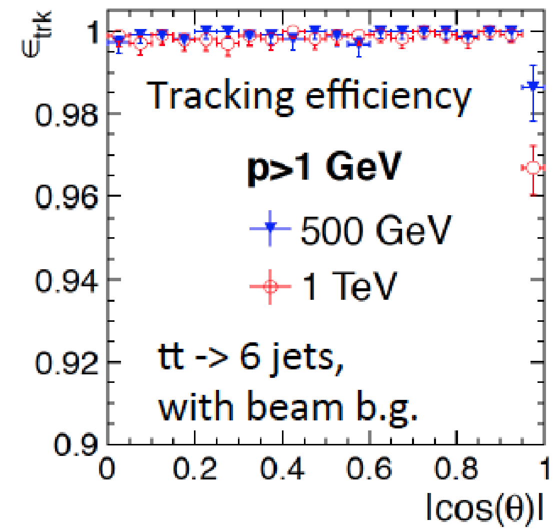
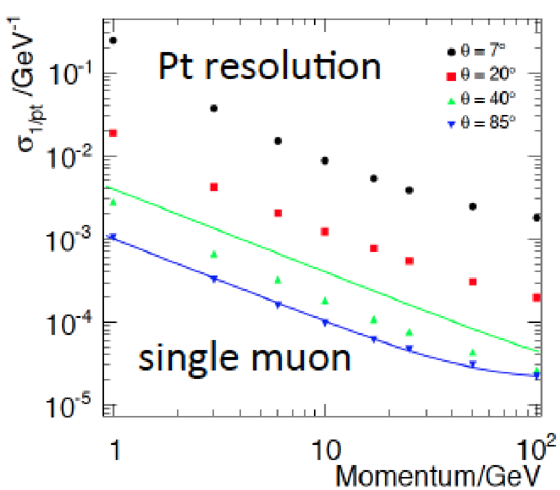
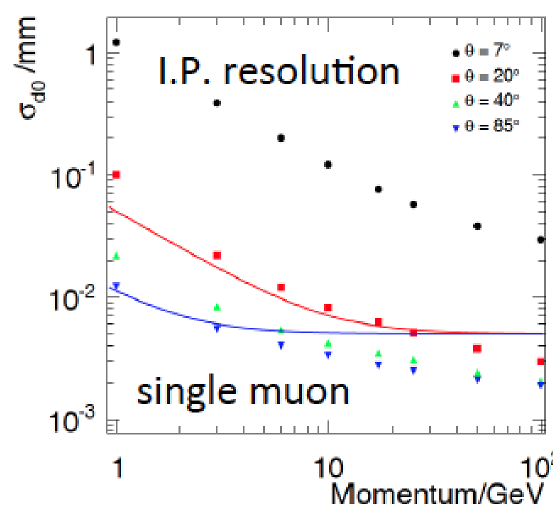
Tracking performance









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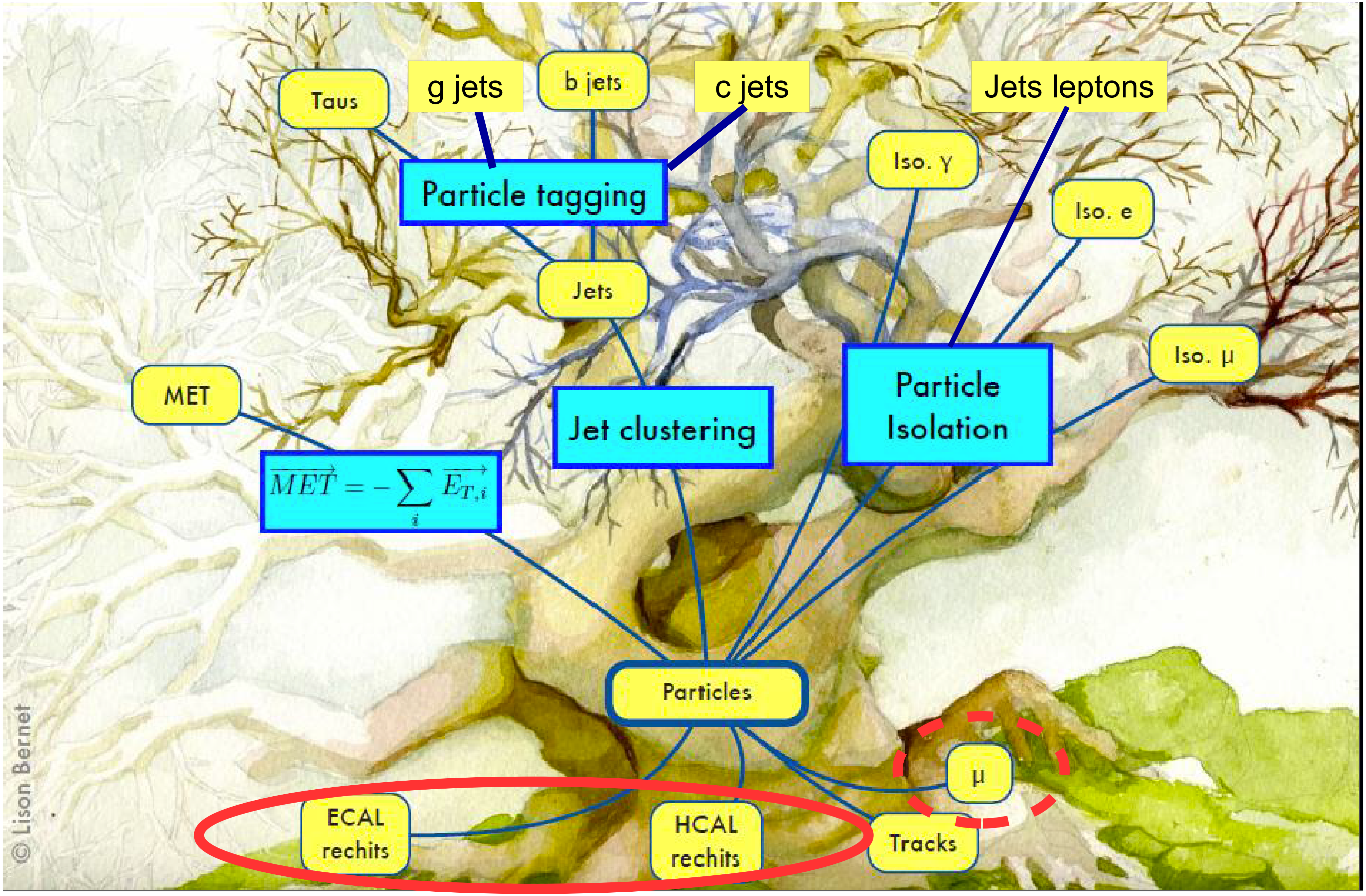
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Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
Particles
μ
ECAL rechits
HCAL rechits
Tracks
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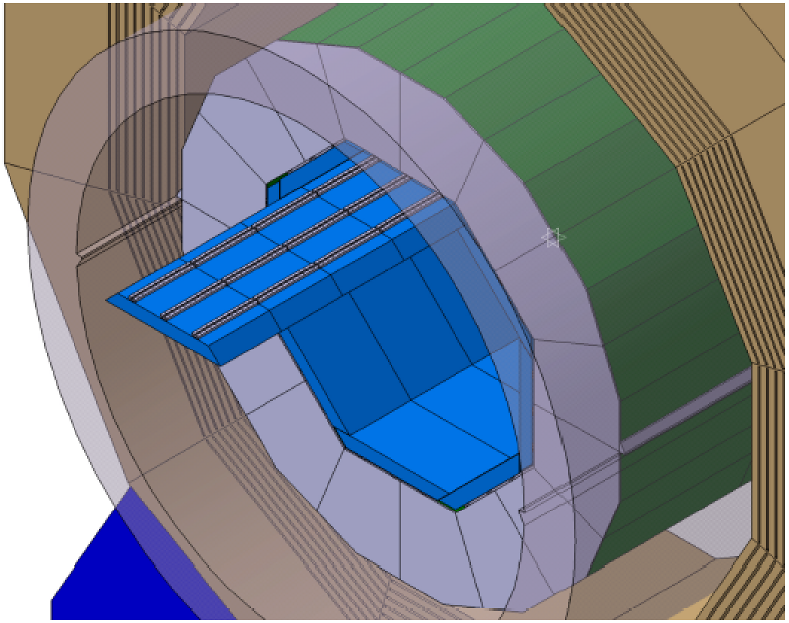
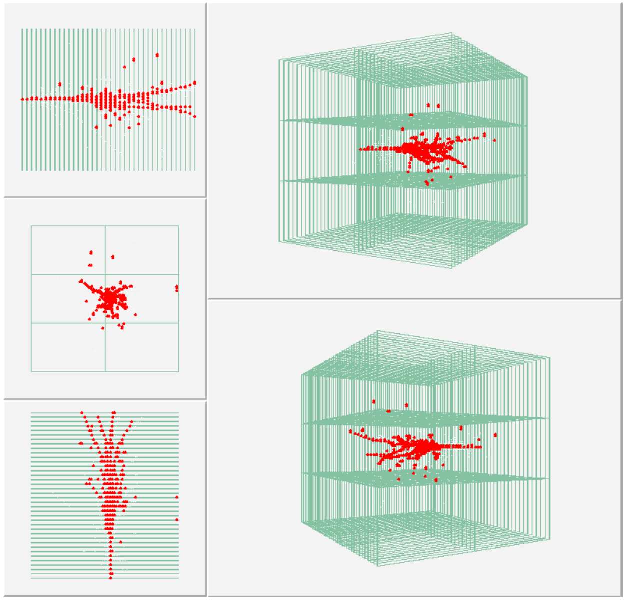
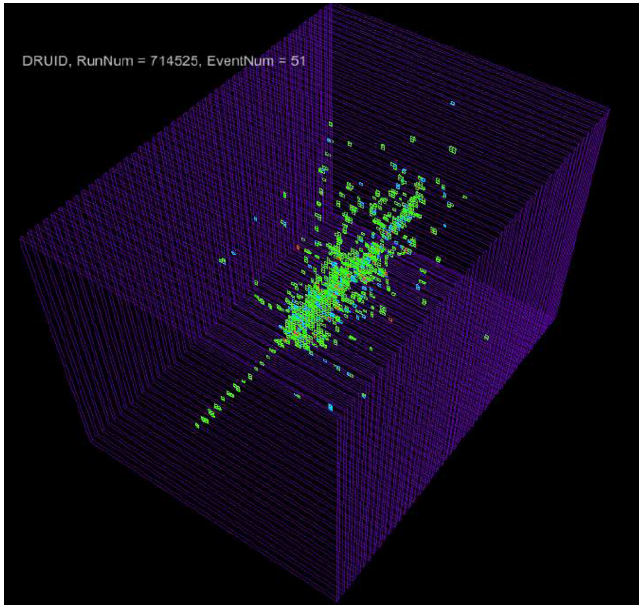
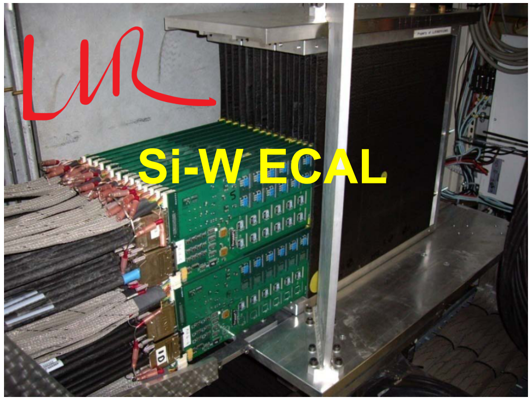
Clustering: ultimate goal ~ 1-1 correspondence between particles incident the calorimeter and the reconstructed calorimeter cluster...

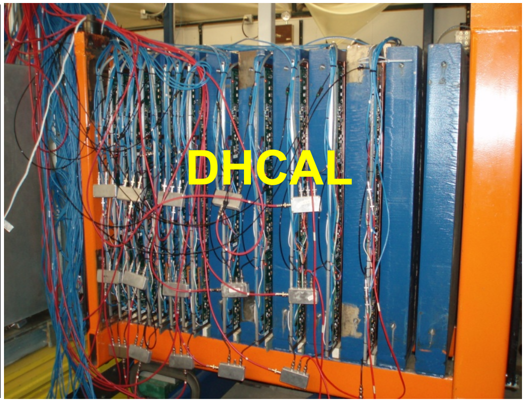
Calorimeter R&D for ILD







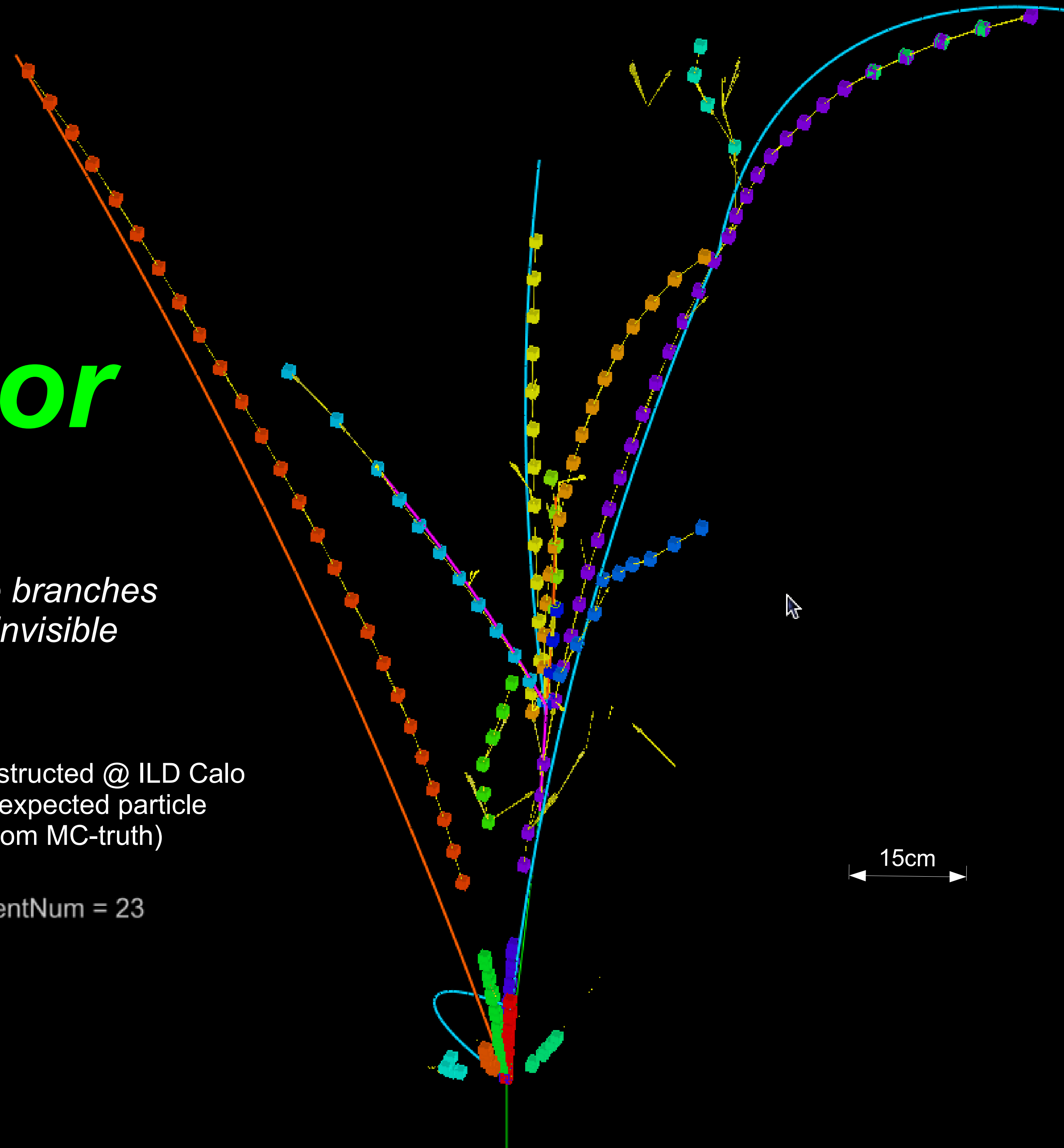




Ultra high granularity ~ 1 channel cm^{-3}. 3d, 4d or 5d image...

Arbor

Except some branches might be invisible

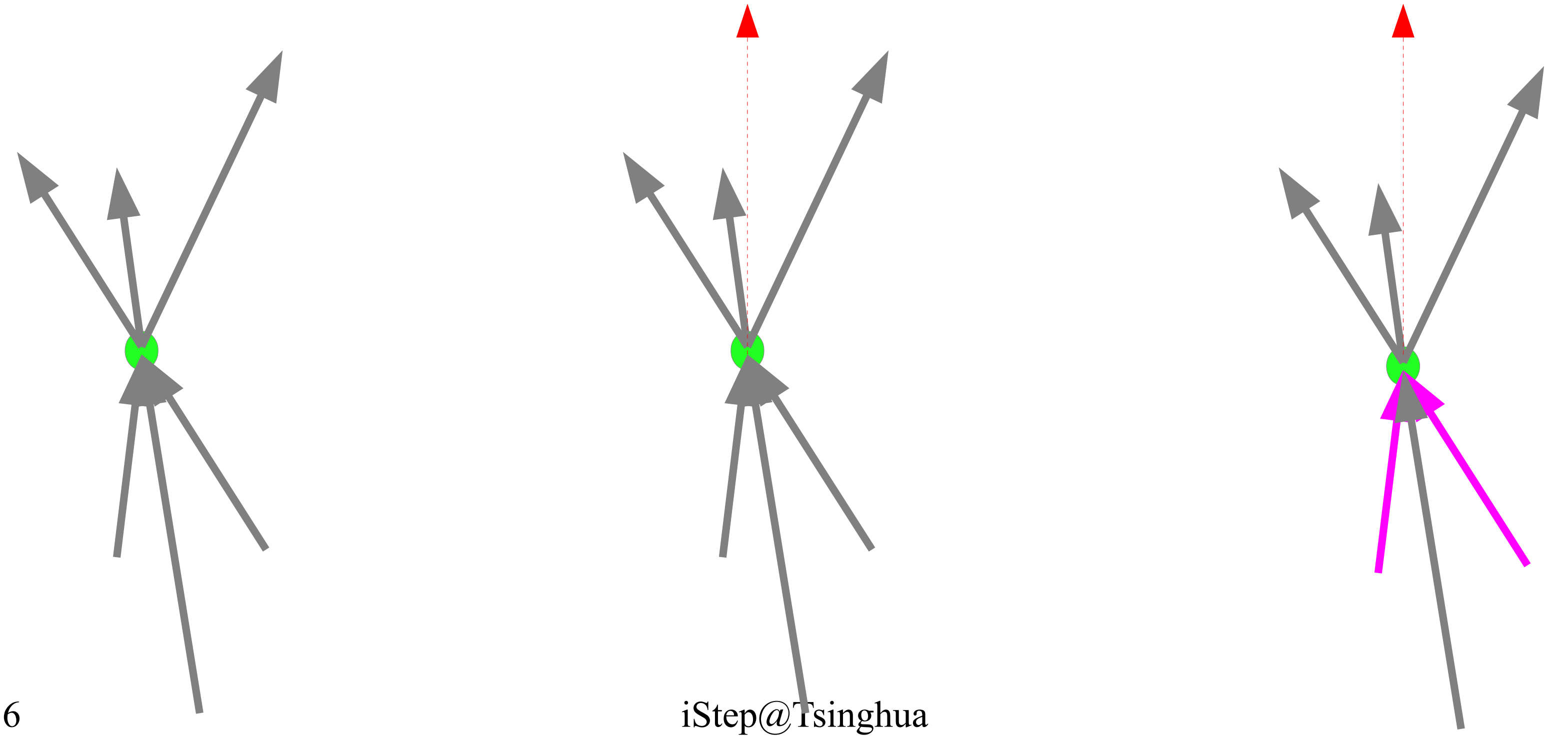


20 GeV Klong reconstructed @ ILD Calo
Curves indicating expected particle trajectories (from MC-truth)

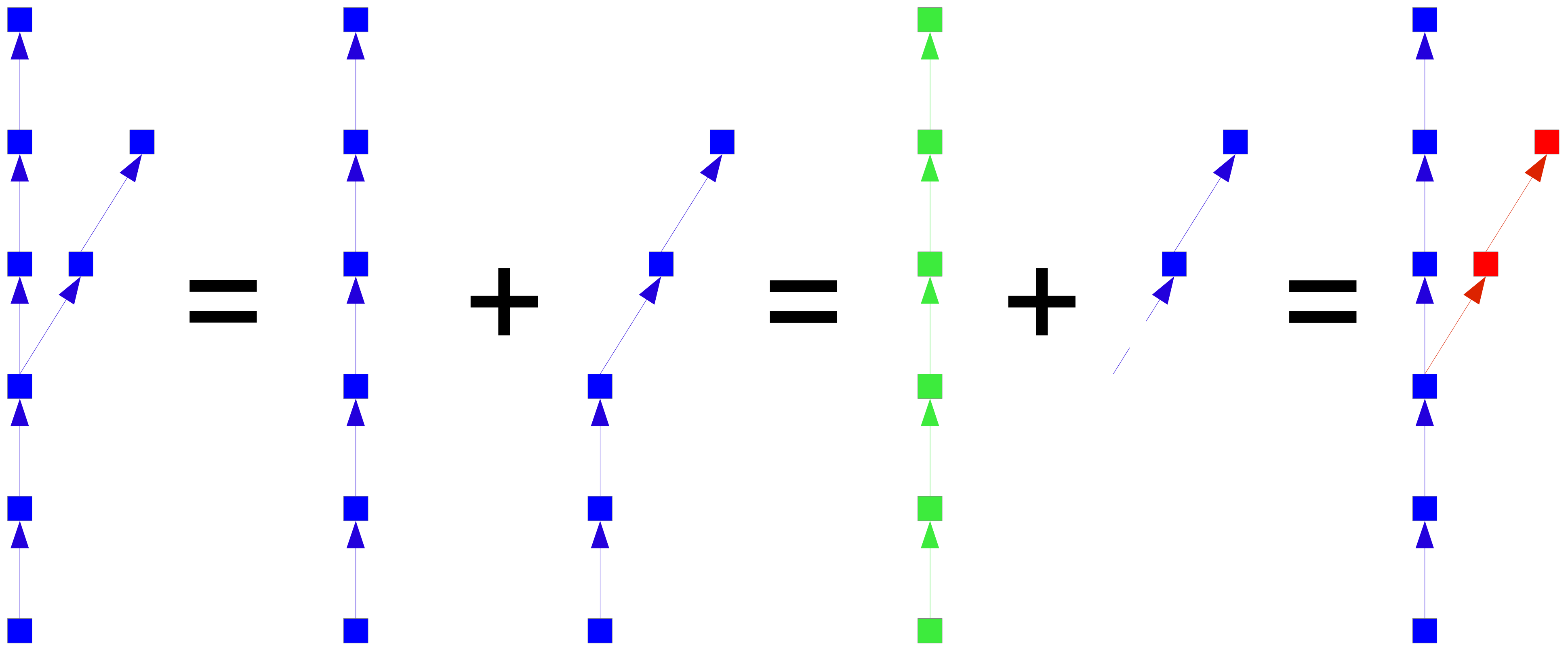
DRUID, RunNum = 0, EventNum = 23

Algorithm: hits→connector set

- Preparation: hits cleaning, pre-clustering, etc
- Create connector set between hits
  - Create all possible connectors (according to geometry constrains)
  - Clean: keep at most one connector end at a given hit
  - Iterate: change geometry constrain, add new connectors, and clean

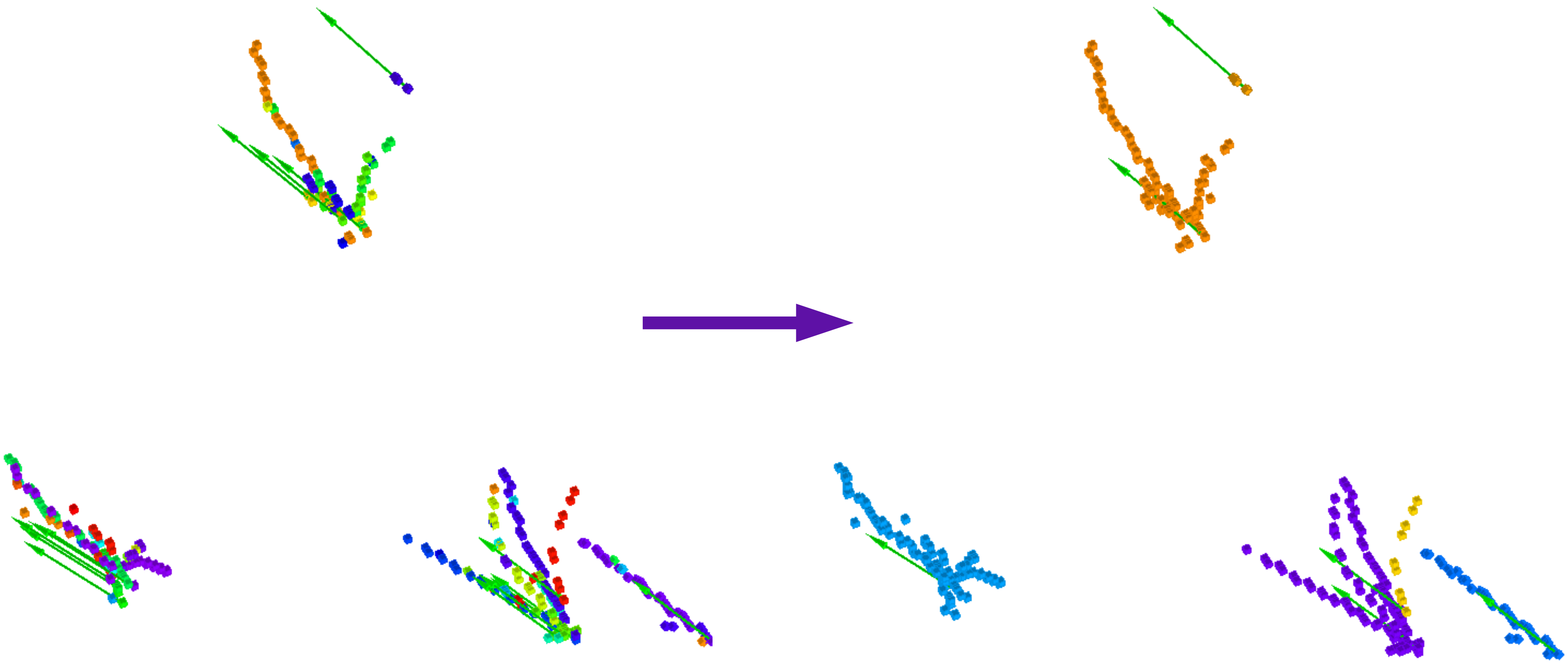


Algorithm: connector → branch

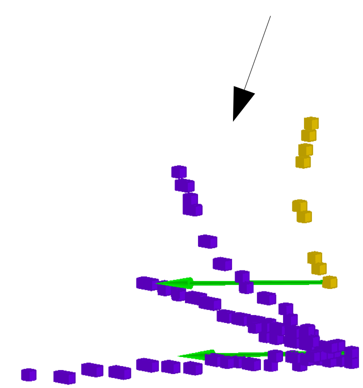


- Tag the unique branch set from connectors
  - Create all the possible branches (*from leaves to seed*)
  - Loop the branches with length order, flag hit, end the branch at the flagged hits

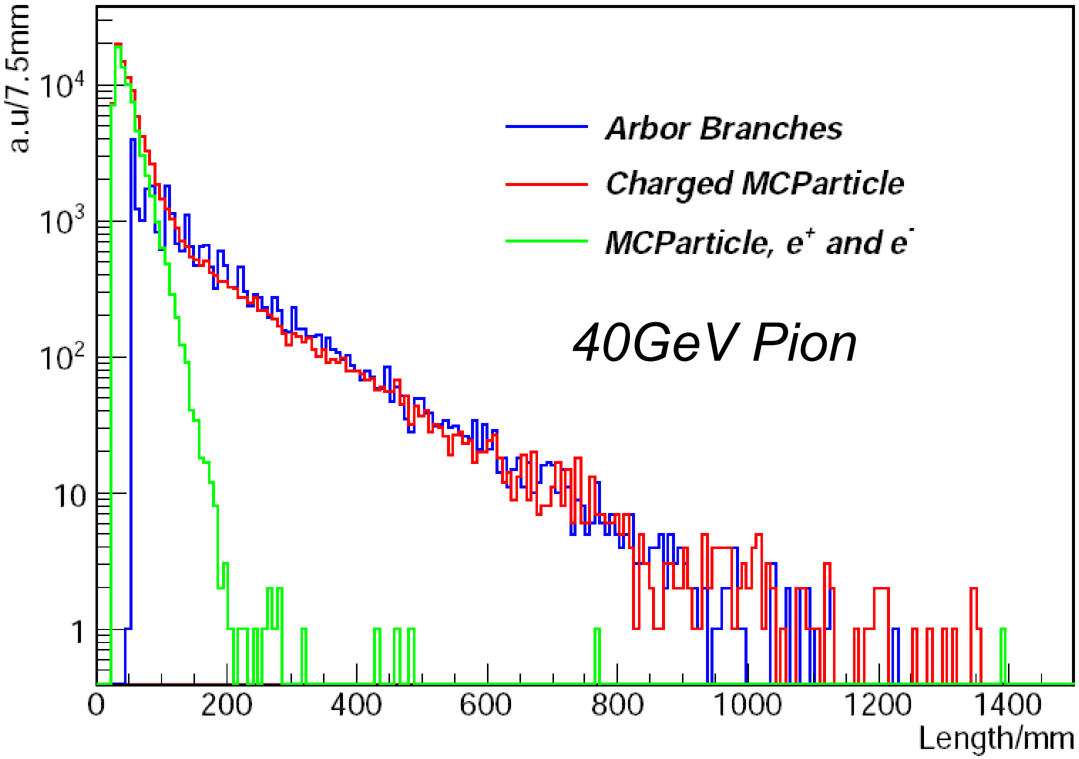
Algorithm: branch→tree

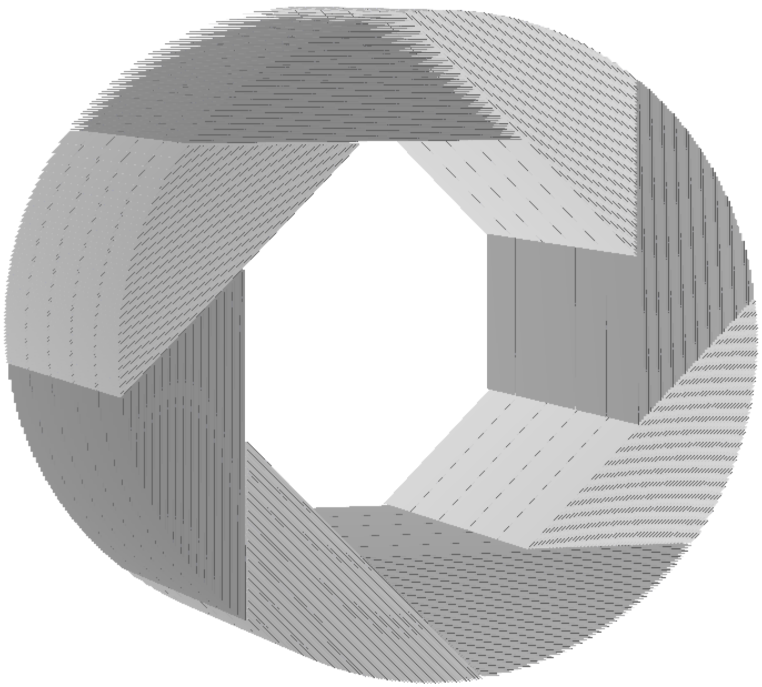


- Link branches to trees according to spatial distances
  - *Point distance, curve distance, projective distances...*



Validation: Arbor Branch Length (ABL) Vs MC Truth

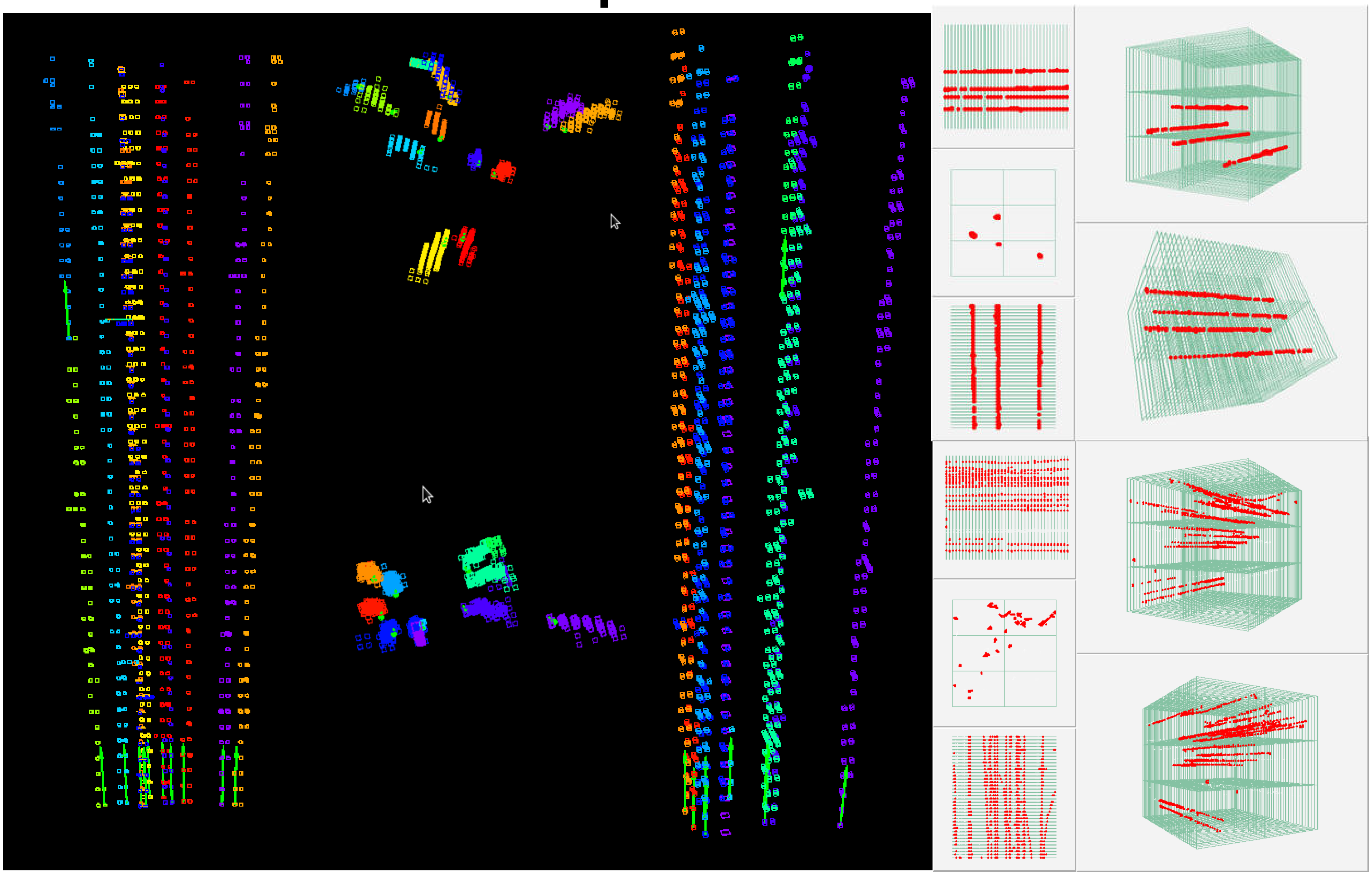




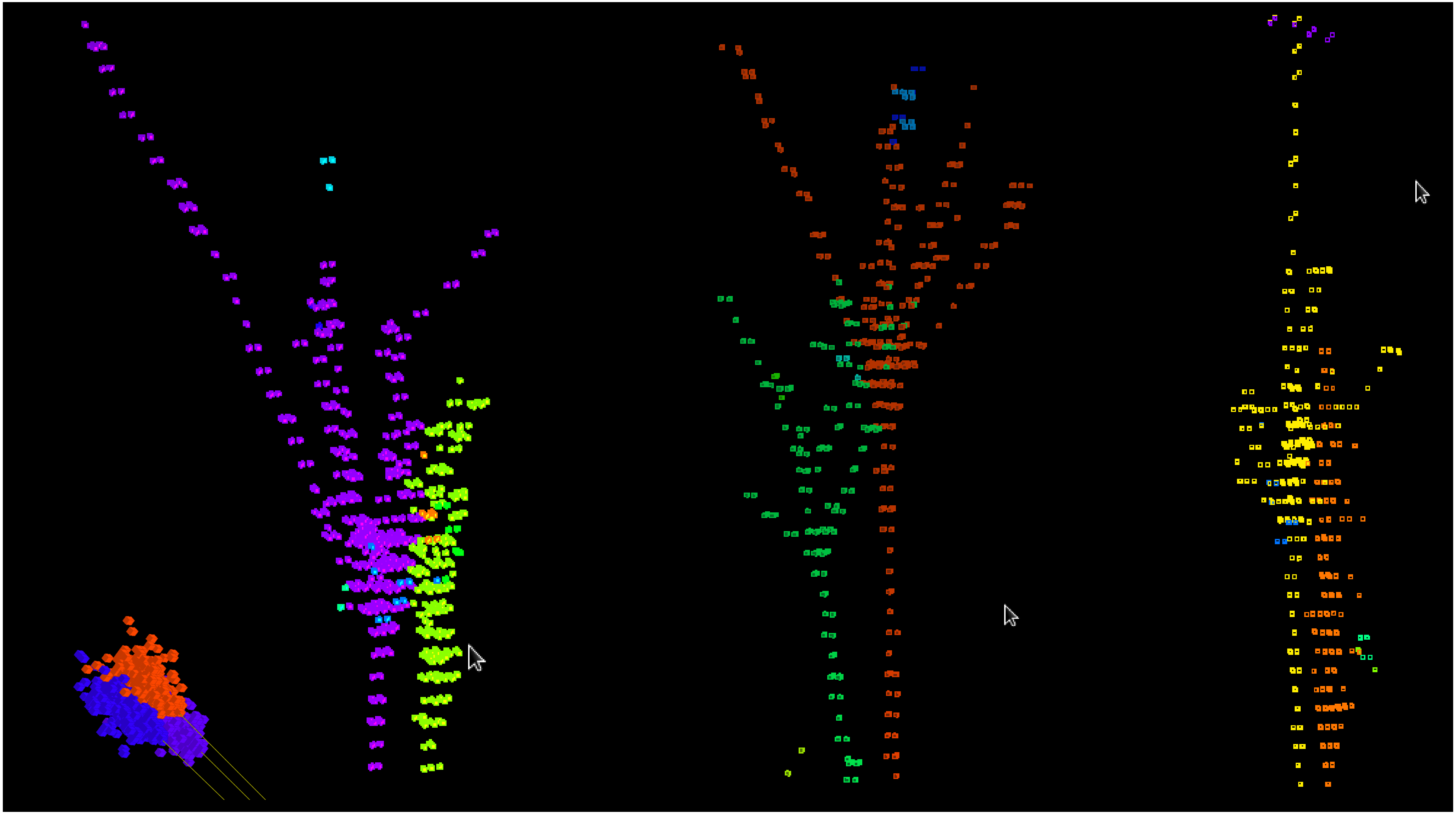
Arbor: successfully tag sub-shower structure

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 neighbouring cells

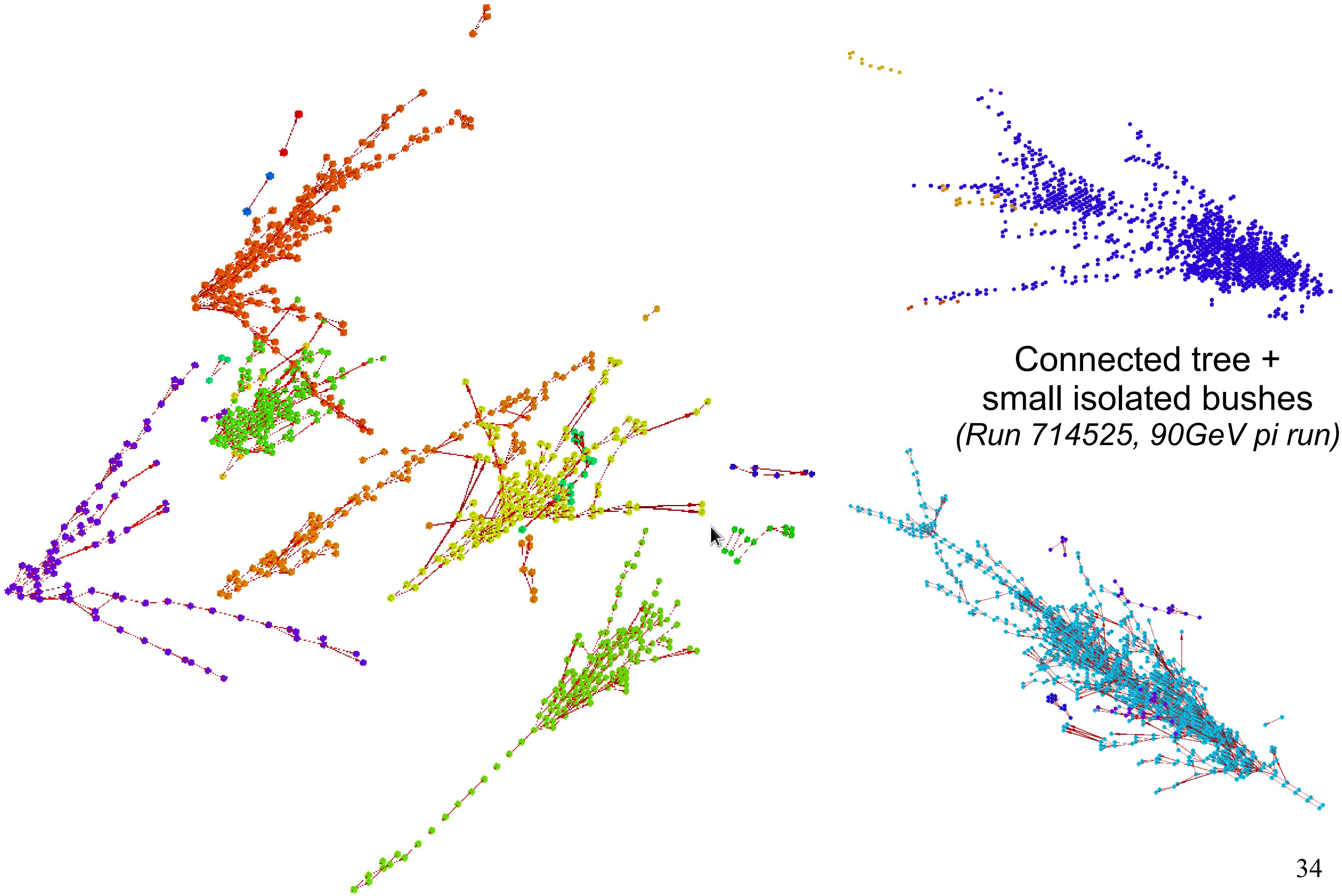
Separation: multiple muon



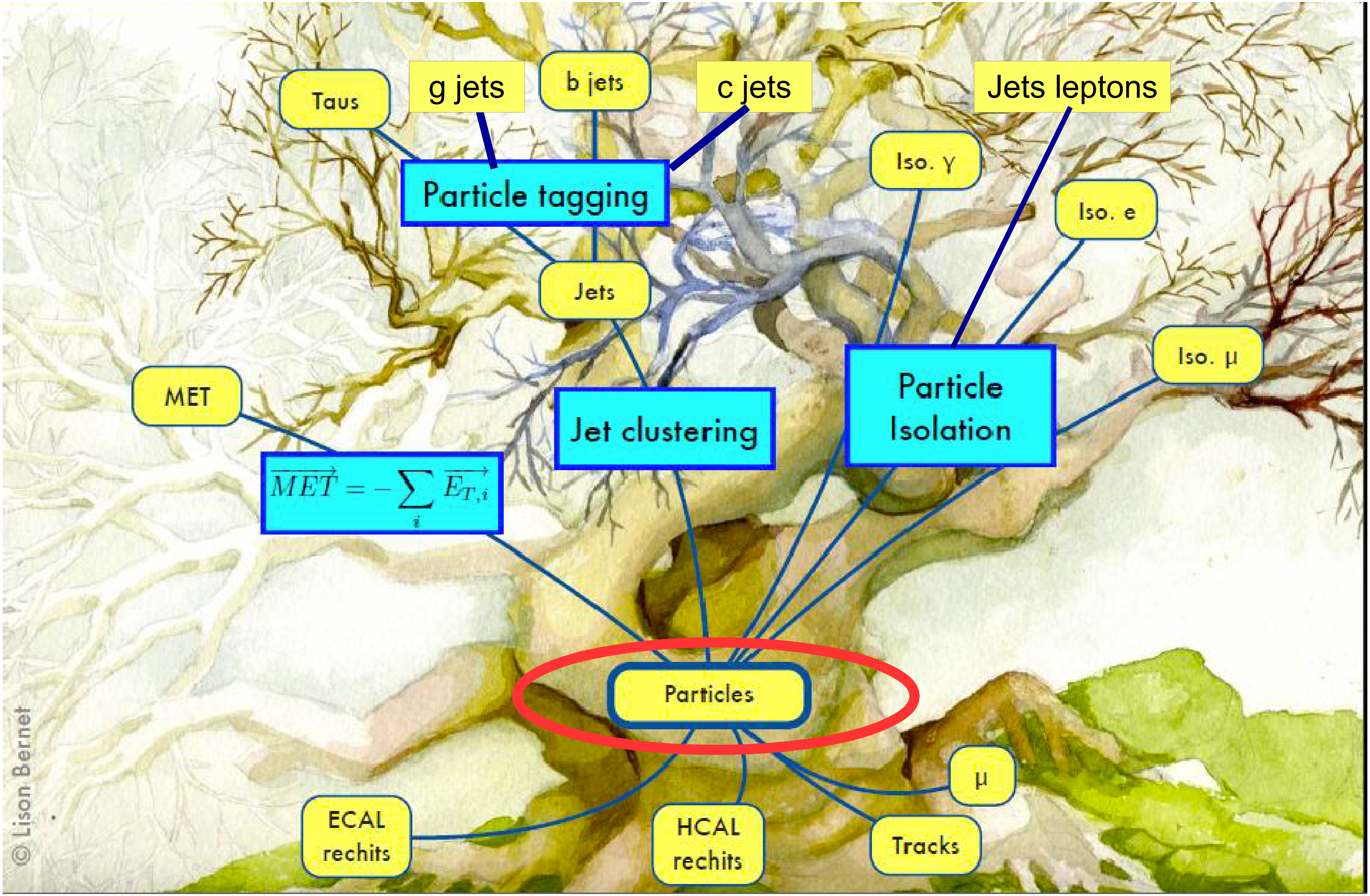
Separation: overlay showers



Test beam data



Connected tree +
small isolated bushes
(Run 714525, 90GeV pi run)


Taus
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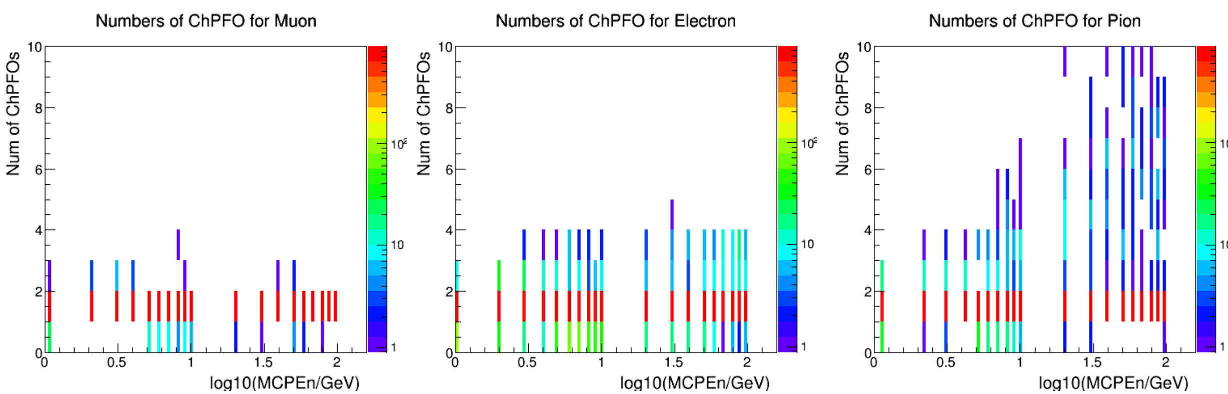
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
Particles
μ
ECAL rechits
HCAL rechits
Tracks
© Lison Bernet

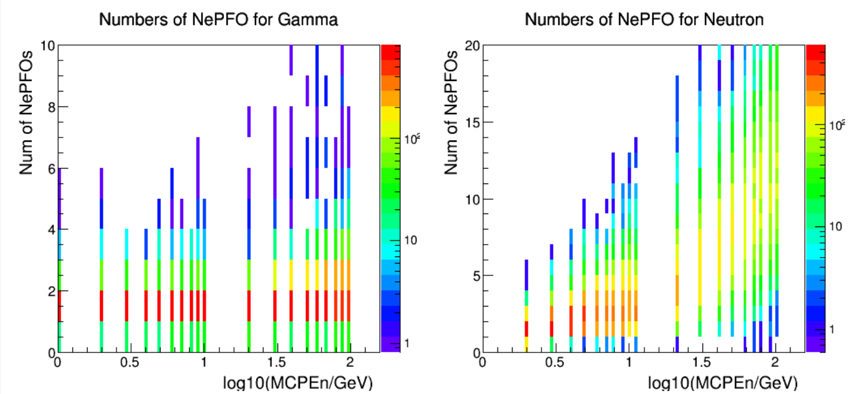
Track Cluster Matching

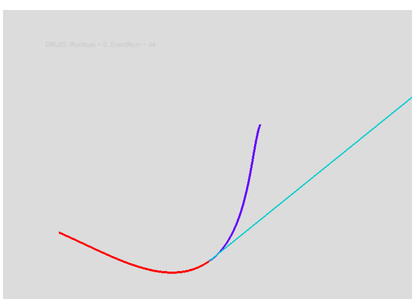
- <Track, Cluster>: Charged particle
- <Track, Multiple Clusters>: The Cluster is artificially split, Or it's a charged particle with pre-interactions before reaching the calorimeter
- <Track, No Cluster>: Wrongly constructed track, detector dead zone, or Low energy tracks
- <No Track, Cluster>: Neutral Particle
- ...

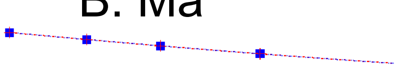
- *Straight forward idea – lots of efforts in implementation...*

Arbor @ single particle

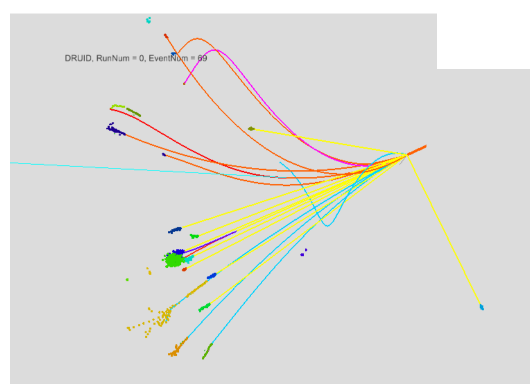


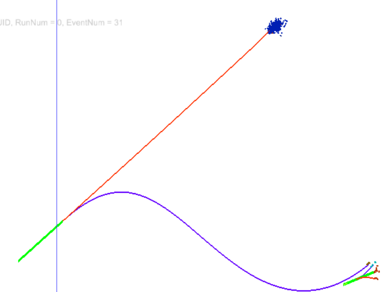


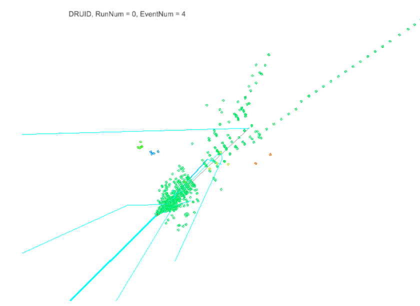


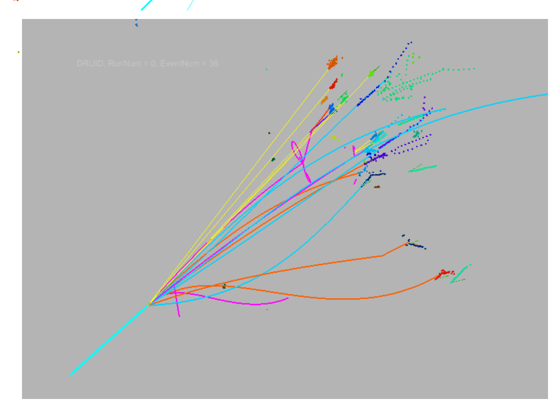


B. Ma





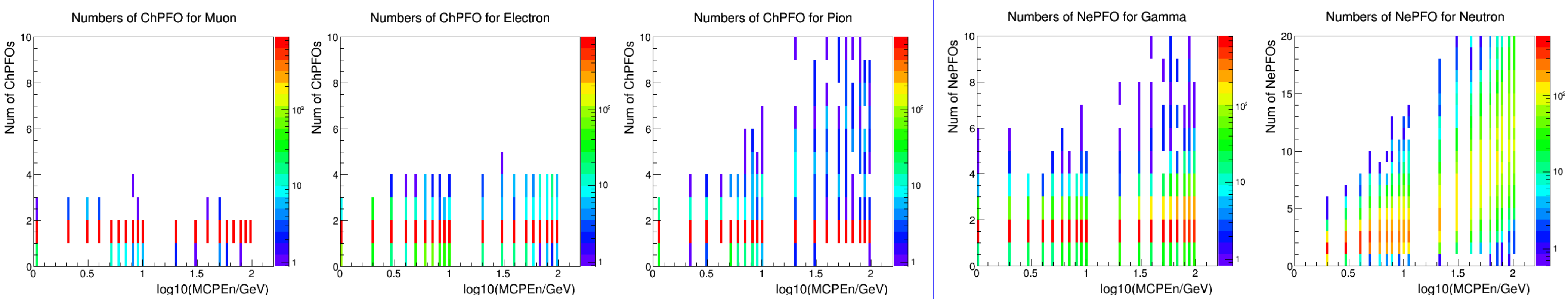


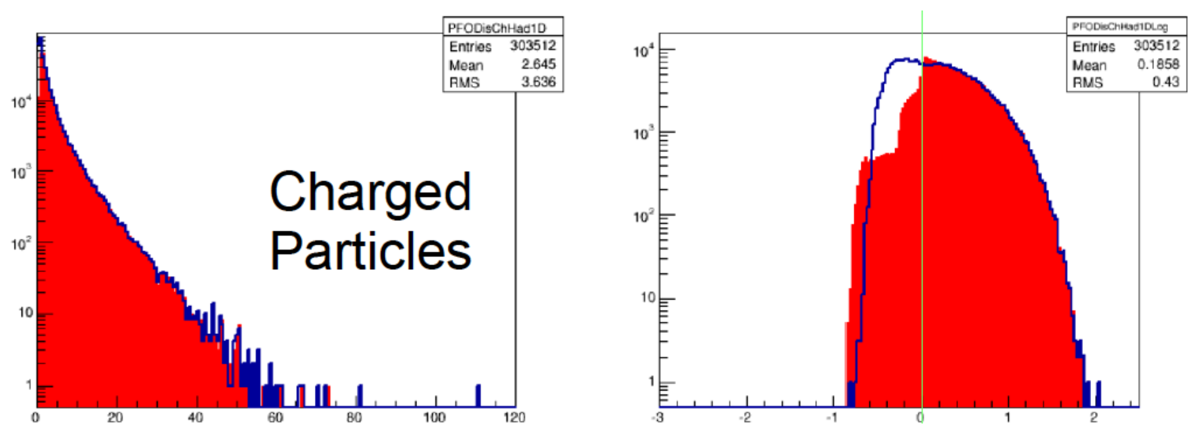


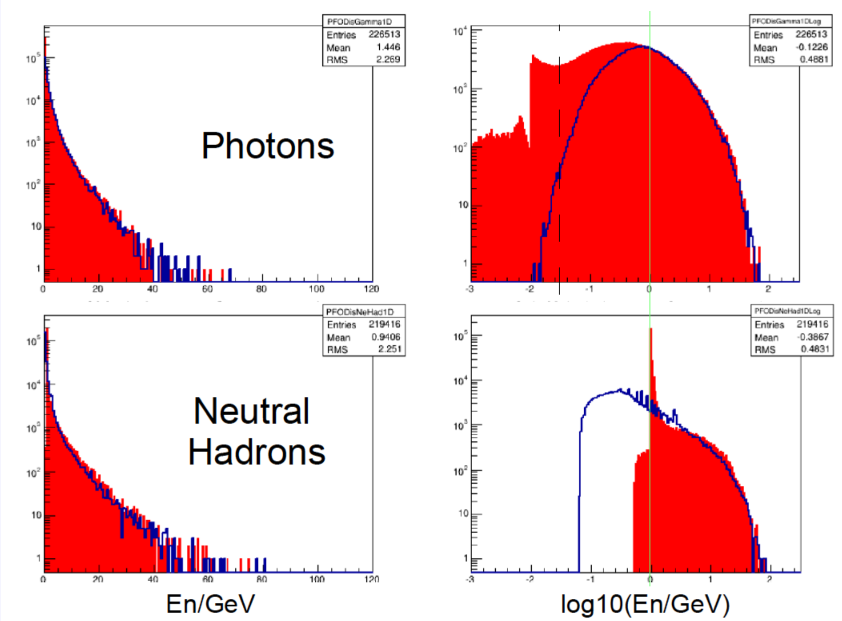
Charged

Neutral

Arbor @ single particle

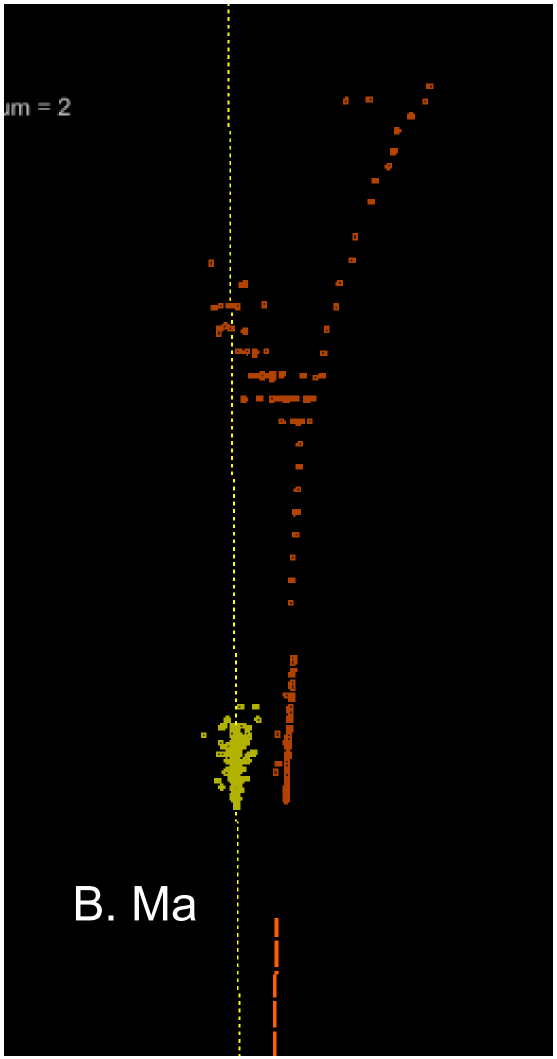


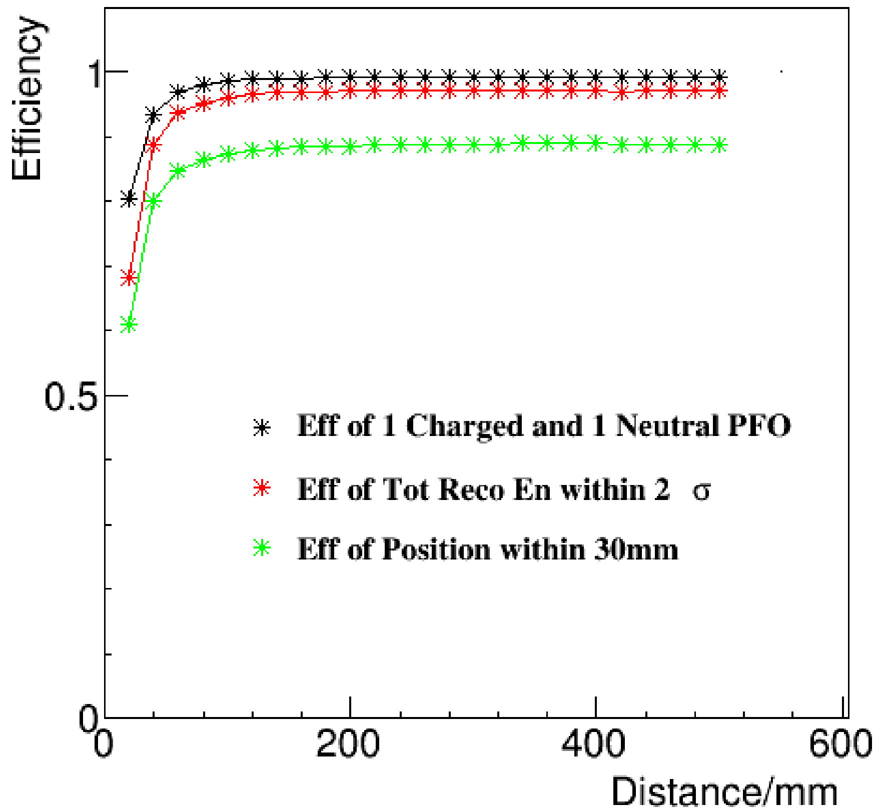


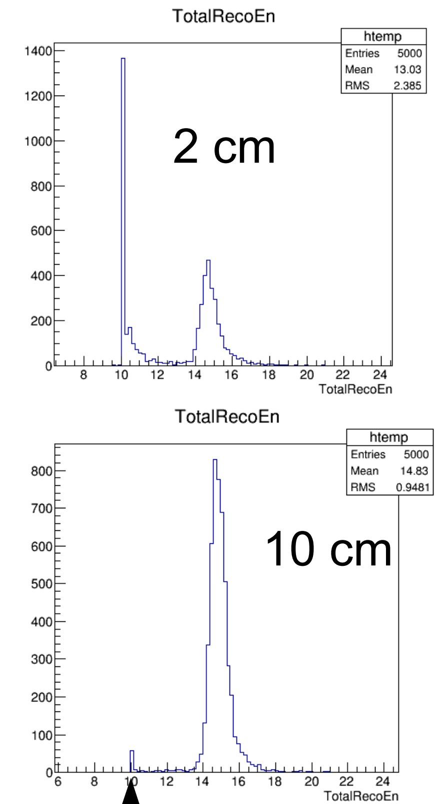


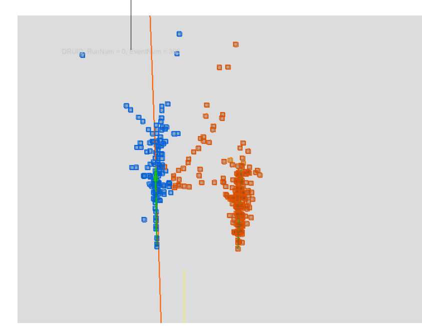
B. Ma

Separation

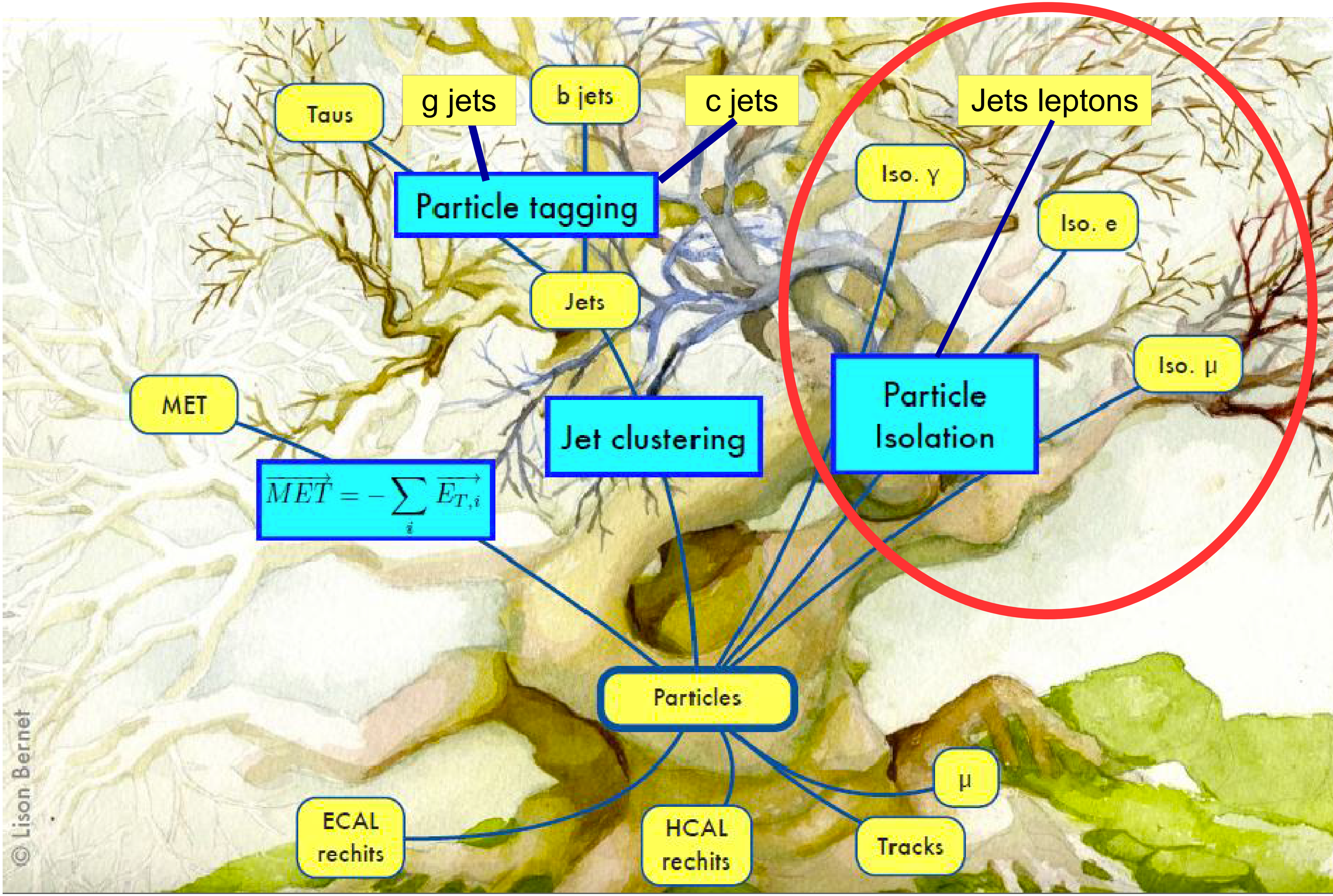






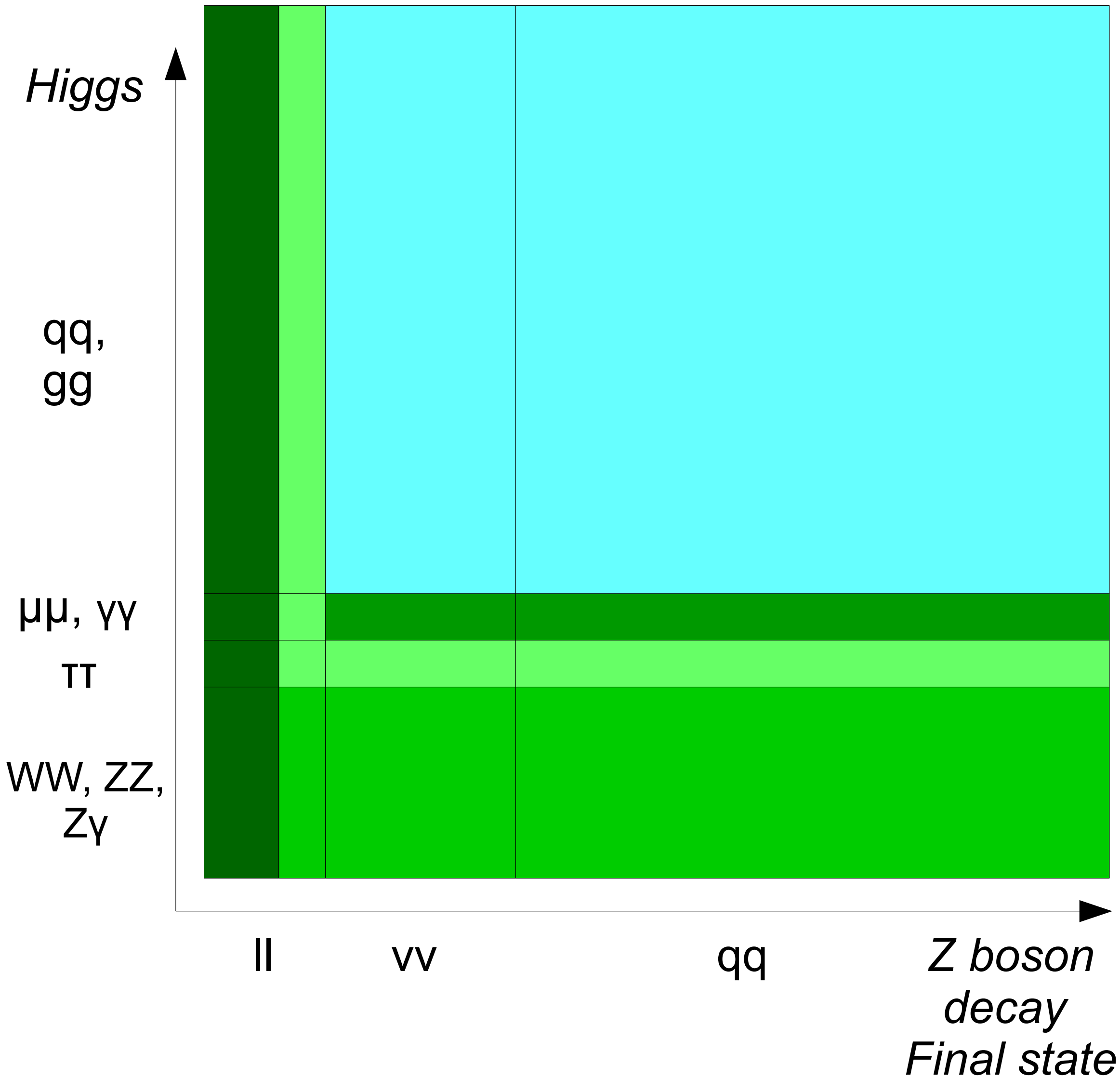


Tiny inefficiency: bridging effect by fragments



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

Lepton ID



Essential

Signal Classification & Background rejection.

Almost everything you want to measure at electron-positron collider...

Higgs:

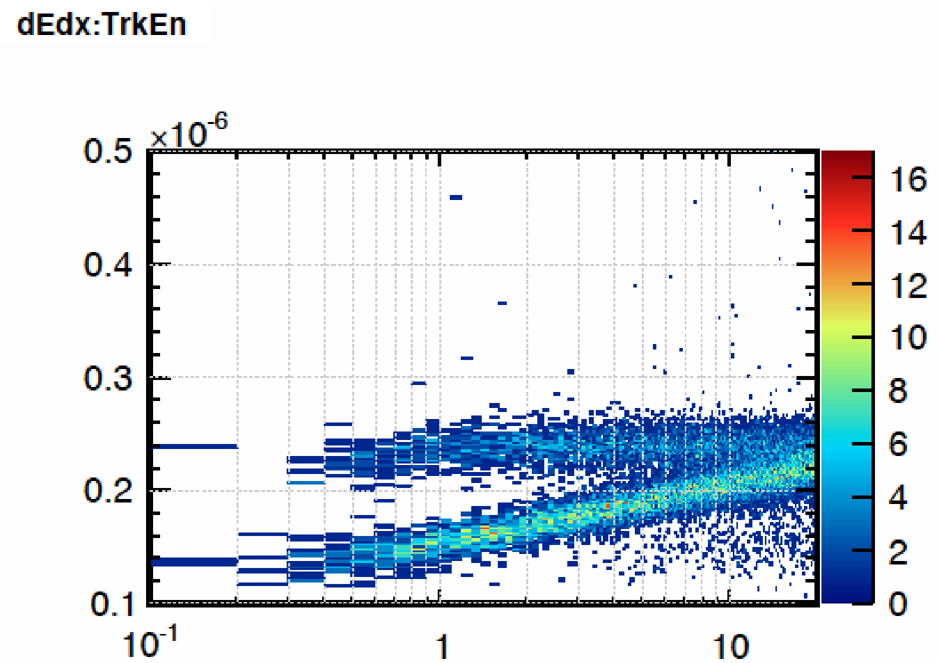
Even for H->bb, cc, gg measurement, the lepton number provides useful information for b/c tagging

ε^e_e	P^e_μ	P^e_π	P^e_{udf}
P^μ_e	ε^μ_μ	P^μ_π	P^μ_{udf}
P^π_e	P^π_μ	ε^π_π	P^π_{udf}

PID Variables: tracks

- **dE/dx**: For a track in TPC, the distribution of energy loss per unit of depth follows the **Landau distribution**.

- The dE/dx of a track used here is actually the **average** of this value but after **vetoing tails** at the two edges of Landau distribution [10%–70%]



D. Yu

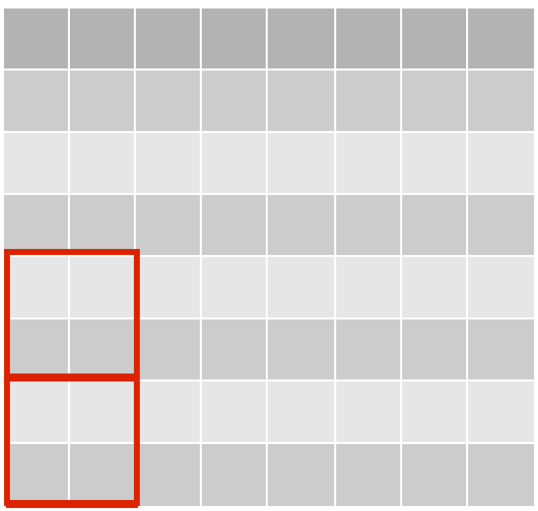
PID Variables: Other Calo

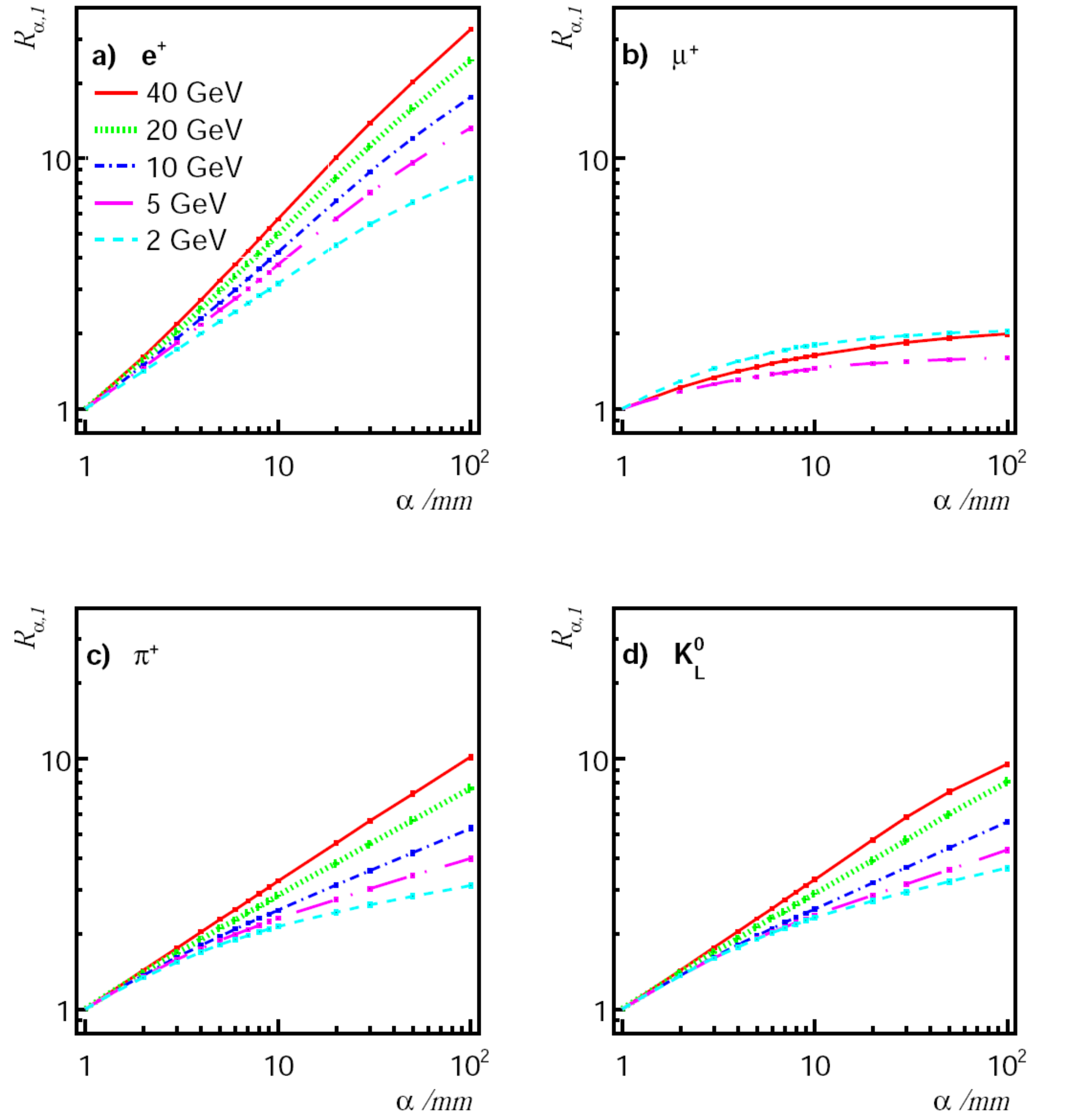
- **Energy Distribution**:
  - the proportion of energy deposit **in ECAL**: **EcalEn**
  - energy deposit in the **first 10 layers** in ECAL: **EEClu_L10**
  - energy deposit in a cylinder around the incident direction within a **radius of 1 R_M** and **1.5 R_M** : **EEClu_r, EEClu_R**
- Spatial **Hits Information**:
  - **number of layers** hit by the shower: **ECALHit, HCALHit**
  - **number of hits** in the **first 10 layers** of ECAL: **NH_ECALF10**
  - the **maximum distance** between a **hit** and the **helix**: **MaxDisHel**
  - the **maximum** and **average distance** between a **hit** and **axis of the shower** (defined by the 1st hit and the COG): **maxDisHtoL, avDisHtoL**
  - the **depth of COG**, and the **depth of shower** defined as the **depth** of the **inner most** hit and the **outer most** hit: **graDepth, CluDepth, MinDepth**

Fractal dimension of particle shower

$$FD_\beta = \left\langle \frac{\log(R_{\alpha,\beta})}{\log(\alpha)} \right\rangle + 1.$$

$$R_{\alpha,\beta} = N_\beta / N_\alpha.$$



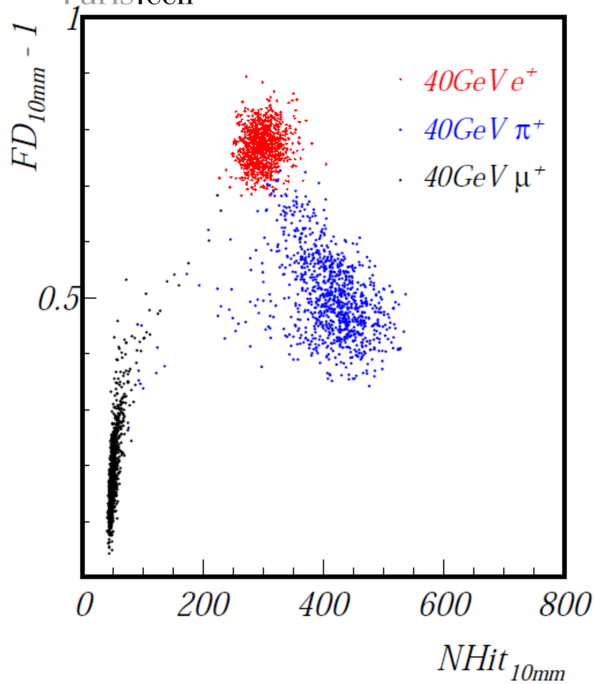


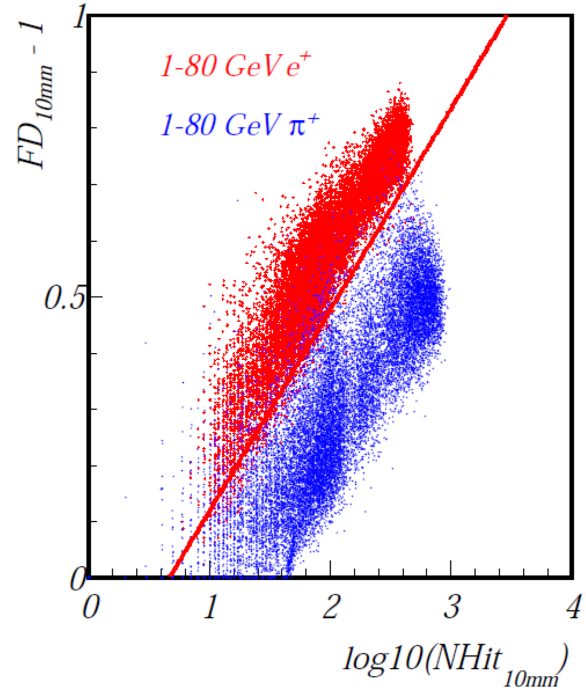
Ultimate cell size: 1mm

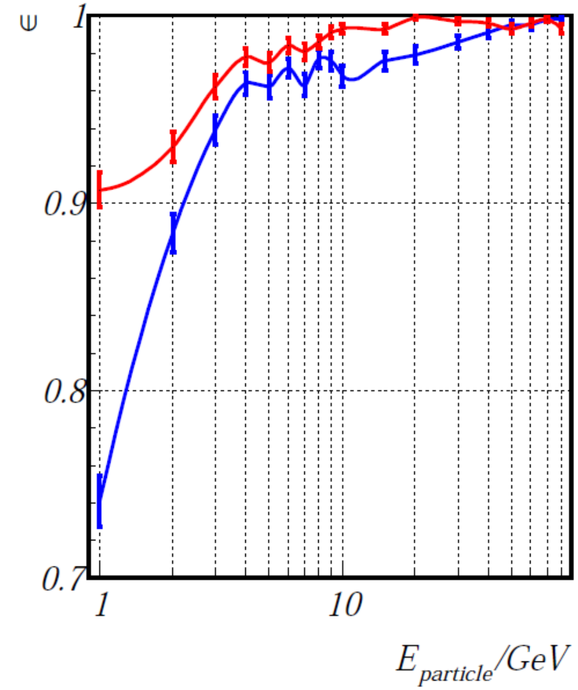
Resize cell: 2 – 10, 20, 30, 50, 60, 90, 120, 150 mm.

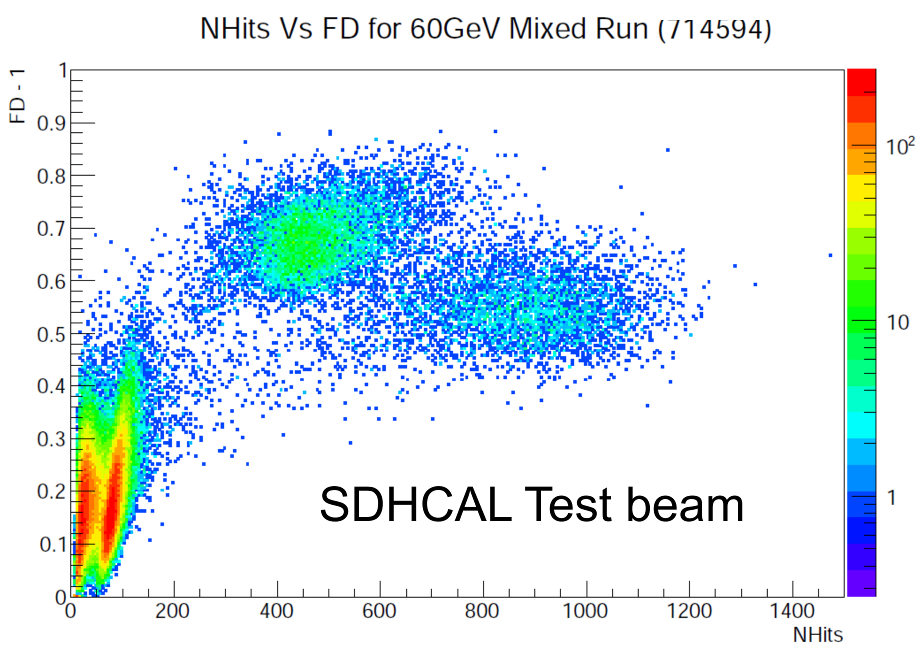
Sample: particle gun events at ILD SDHCAL

Application: PID, etc









	e^+	μ^+	π^+
e^+	100%	0	0
μ^+	0	99.5%	0.5%
π^+	1.7%	1.4%	96.9%

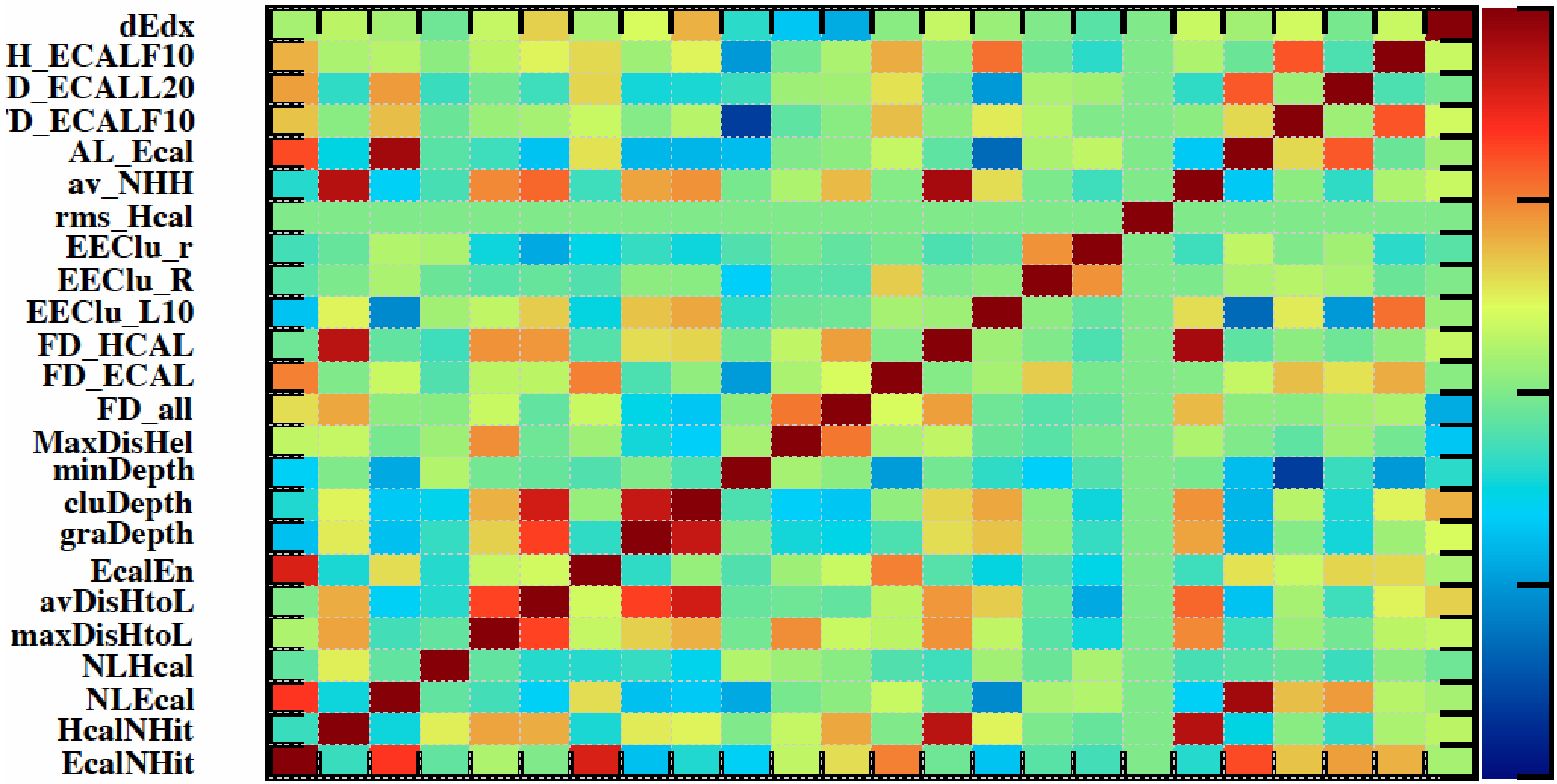
FD: transverse information

Promising PID over full energy range
Event classification at test beam

TMVA Correlation Matrix

10GeV Muon(root-6.04)

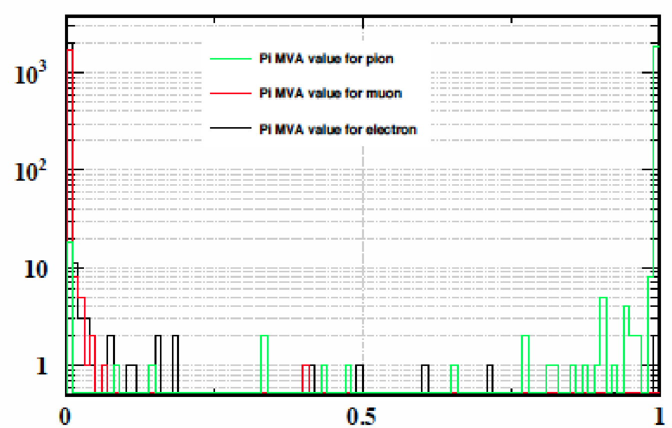
D. Yu



TMVA BDTG

- Samples: (e, mu, pi) x (1, 2, 3, 5, 7, 10, 20, 30, 40, 50, 70 GeV) x (10000 events)
- Method: TMVA BDTG selected as “best” (vs likelihood, etc.)
- Catalog： TMVA Value for three catalogs: e, mu, pi
- Classification :
  - mvaVal_*>0.5
  - otherwise “undefined pid” (very rare)

BDTG Value mvaVal_pi
for 10GeV pi, e, mu



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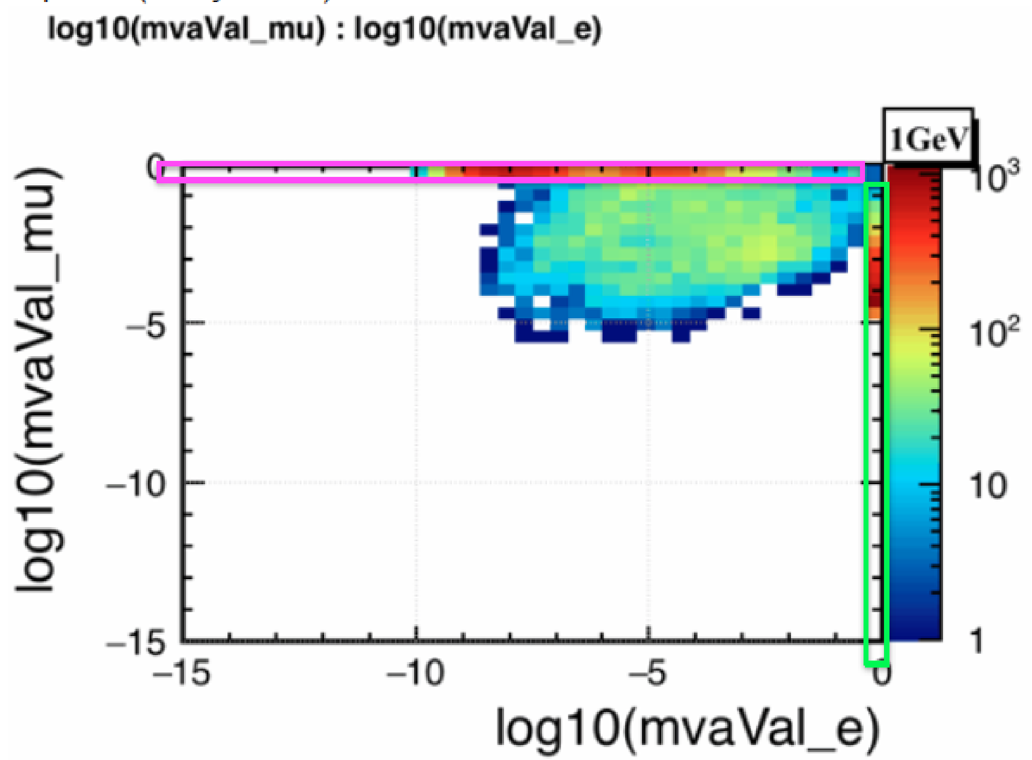
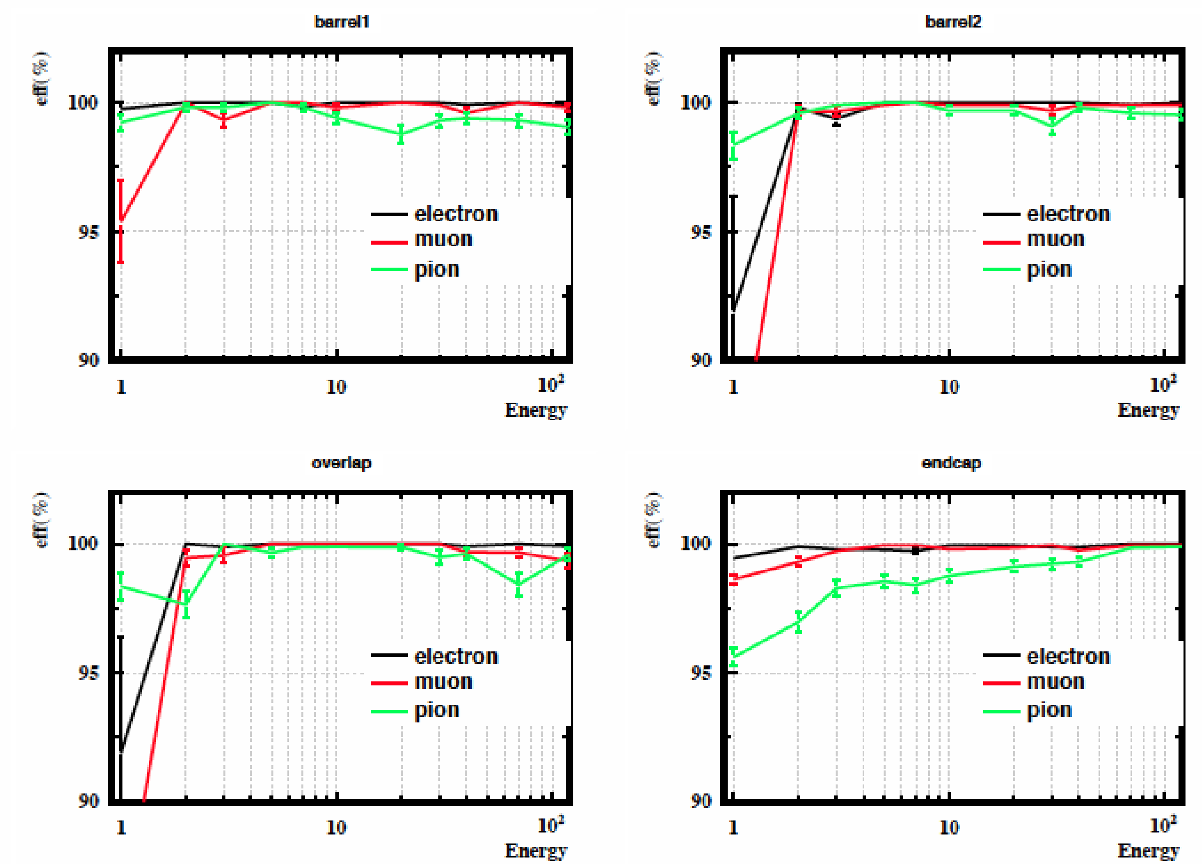


Efficiency & Mis-tagging

- PID efficiency for e, mu, pi at different detector regions



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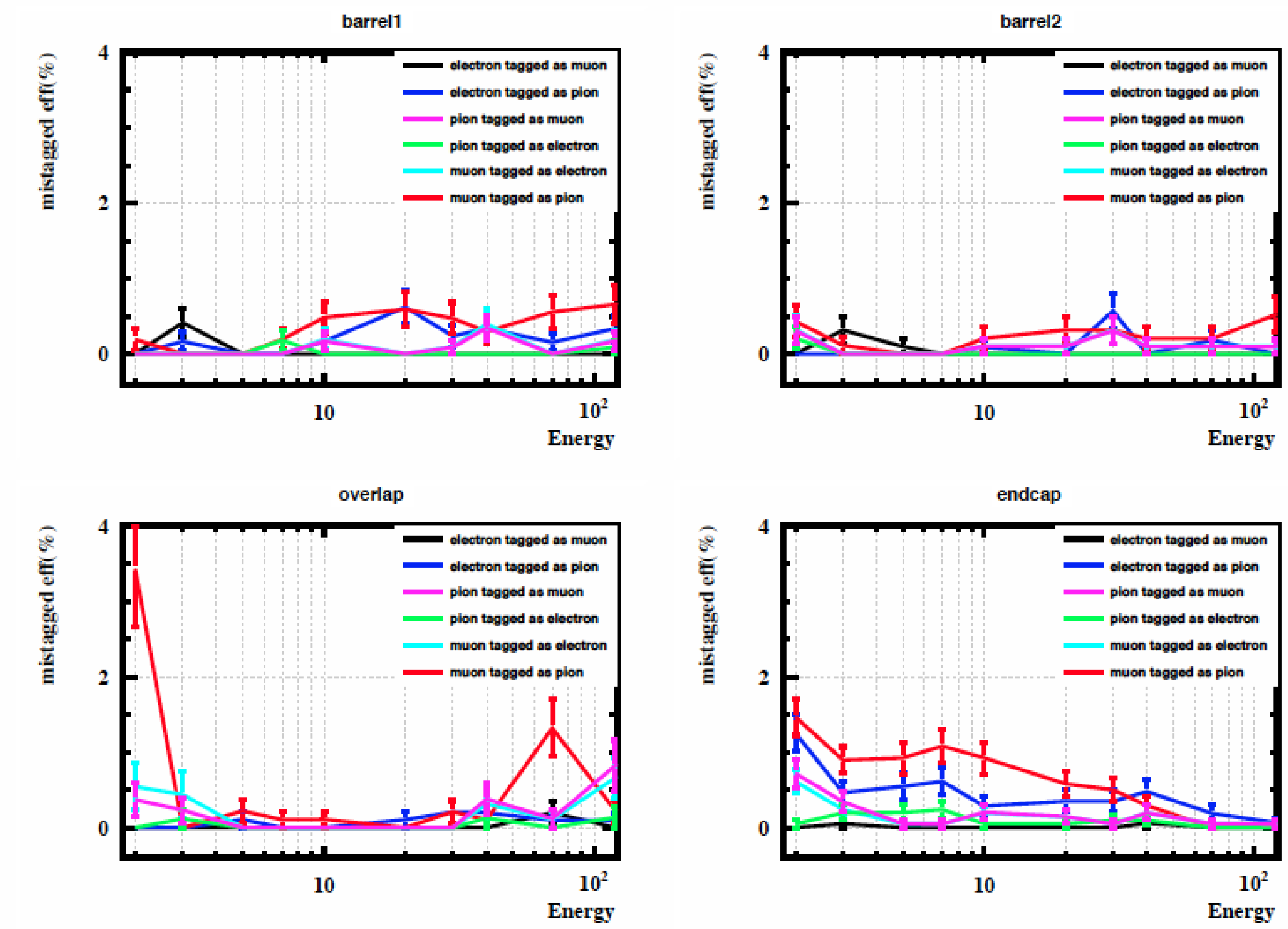
- endcap is the best region (more statistics for low energy)
- combined efficiency: about 98% for pion higher than 3GeV
- muon & electron: even better

Efficiency & Mis-tagging

- PID efficiency for e, mu, pi at different detector regions



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Result

ε^e_e	P^e_μ	P^e_π	P^e_{udf}
P^μ_e	ε^μ_μ	P^μ_π	P^μ_{udf}
P^π_e	P^π_μ	ε^π_π	P^π_{udf}

Table 2 Migration Matrix at 40 GeV (Barrel1)

	e^-	μ^-	π^+
e^-	99.91 ± 0.08	0.08 ± 0.03	0
μ^-	0	99.60 ± 0.19	0.39 ± 0.19
π^+	0.34 ± 0.17	0.25 ± 0.14	99.39 ± 0.22

P_udf negligible...

- At E > 3GeV && Non Overlap region, Lepton Id efficiency ~ 99.9%, Pion Id efficiency ~ 98.5%

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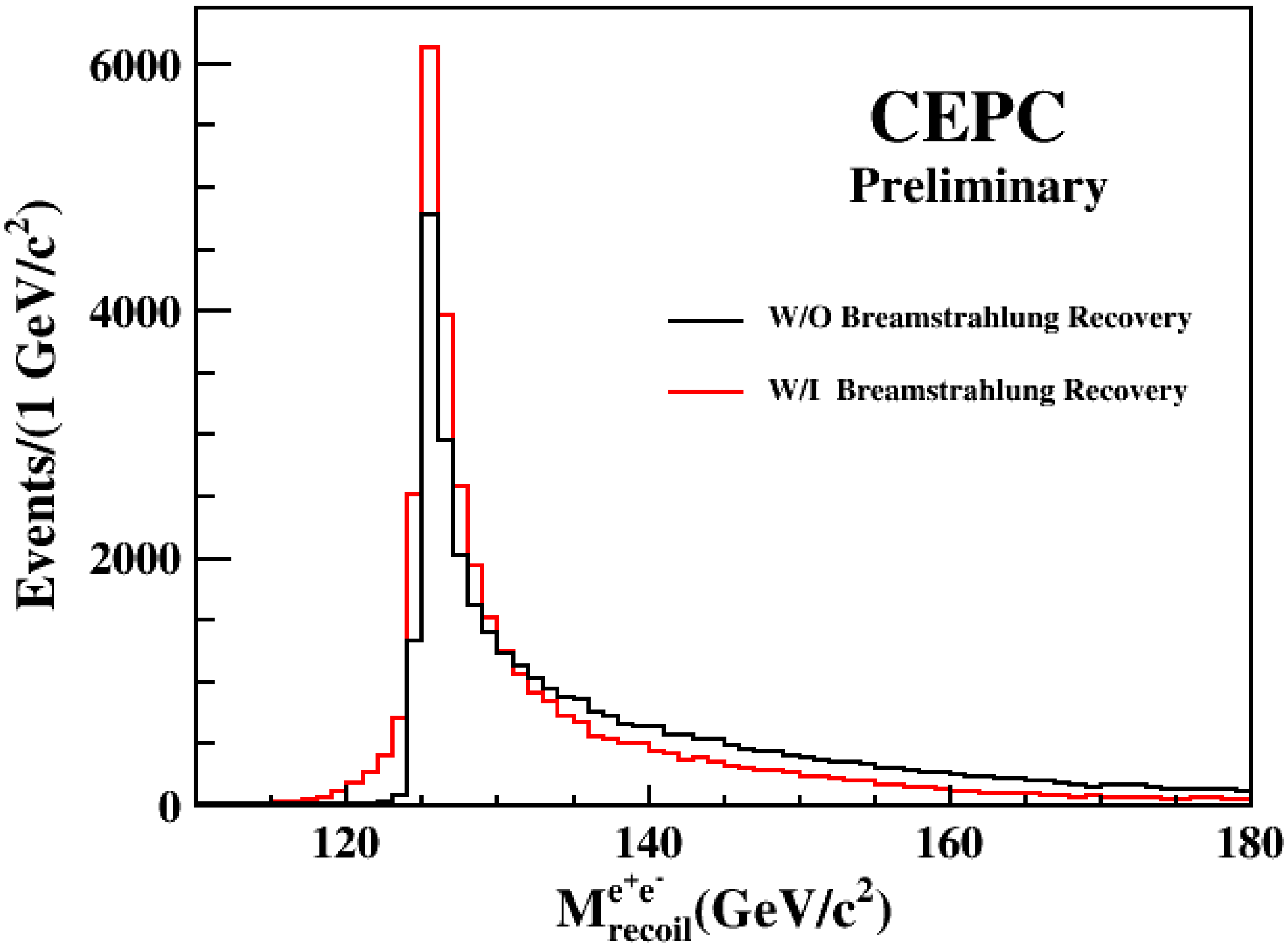
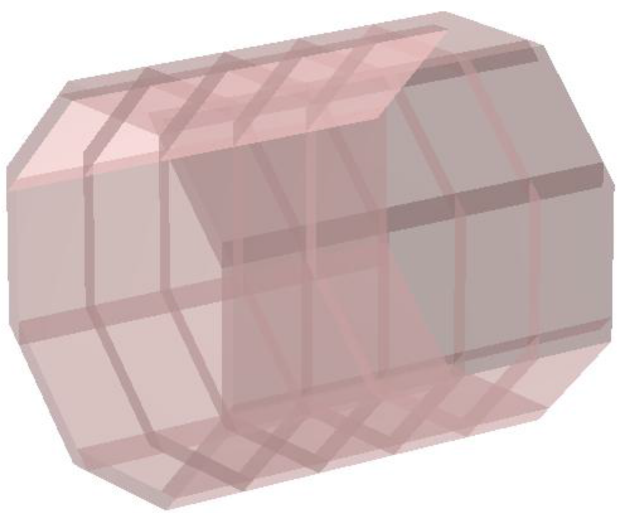
Bremsstrahlung photon recovery of electron/positron



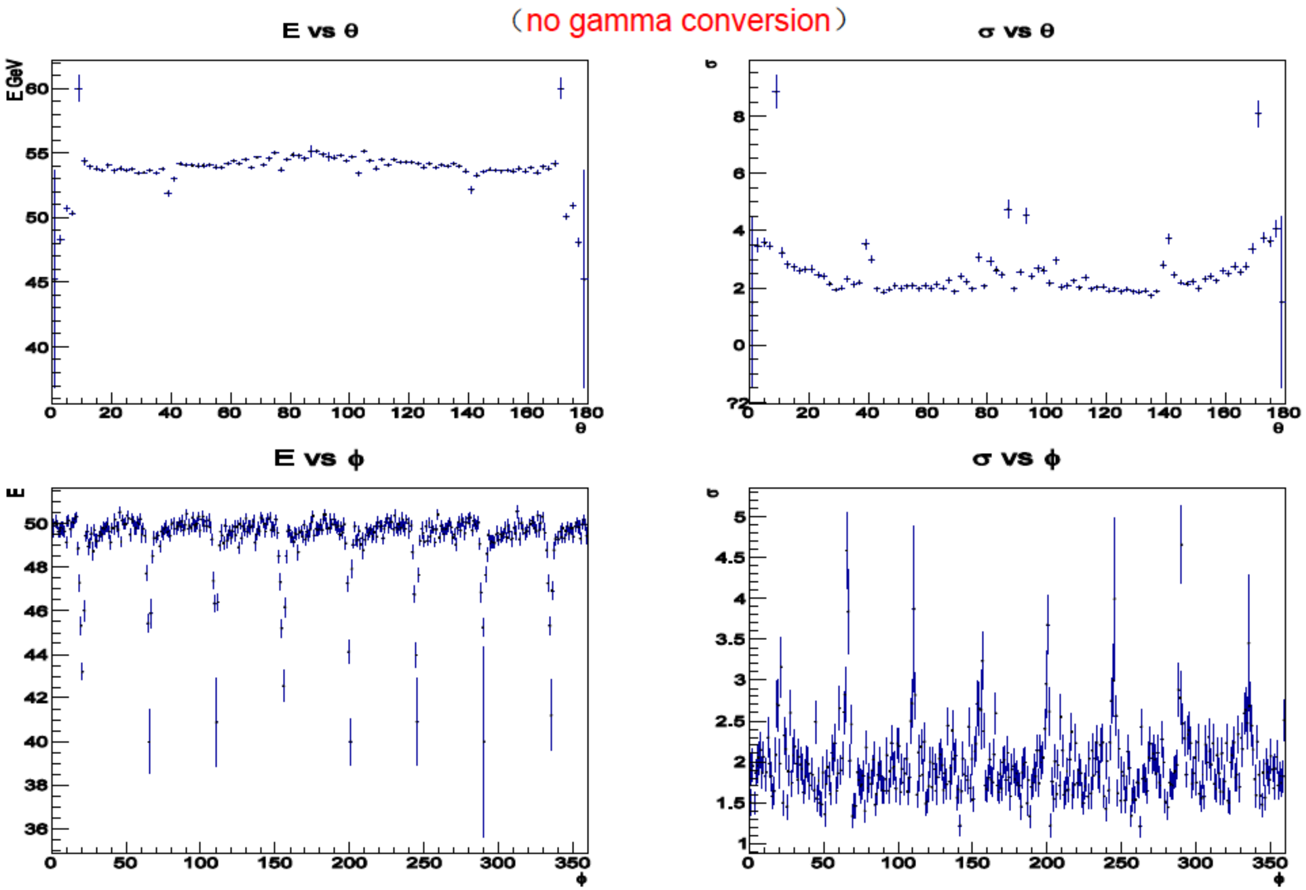
- *Developed by Zhenxing, Binsong, Wanglei, etc*

Arbor: photon reconstruction



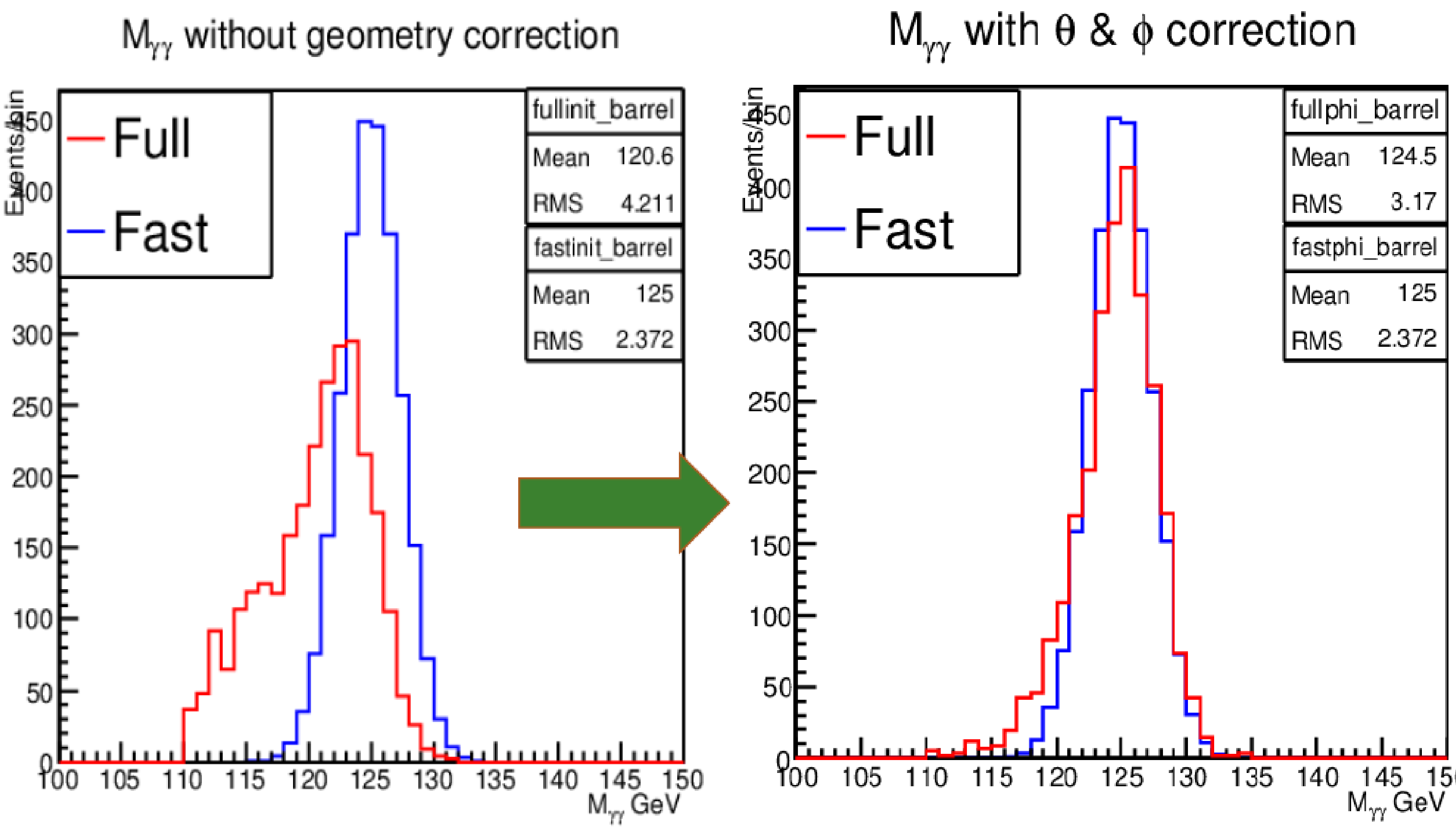
ECAL Barrel of ILD/CEPC_v1

F. Wang, etc



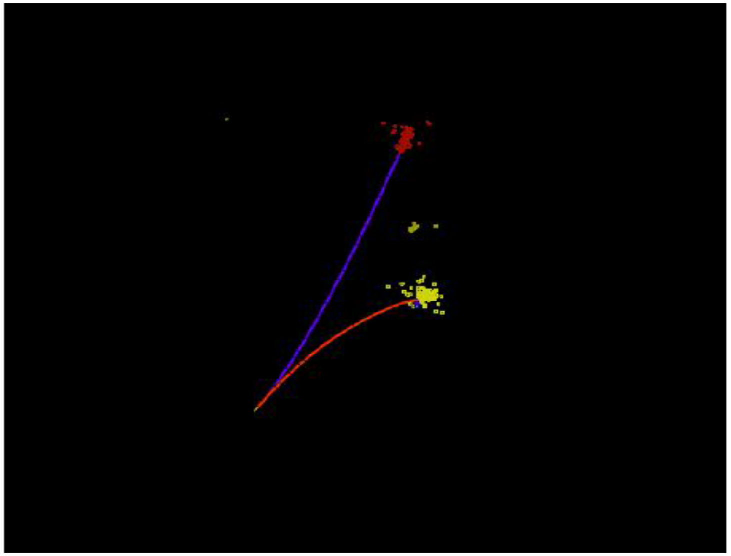
Angular Correlation of EM Shower energy response

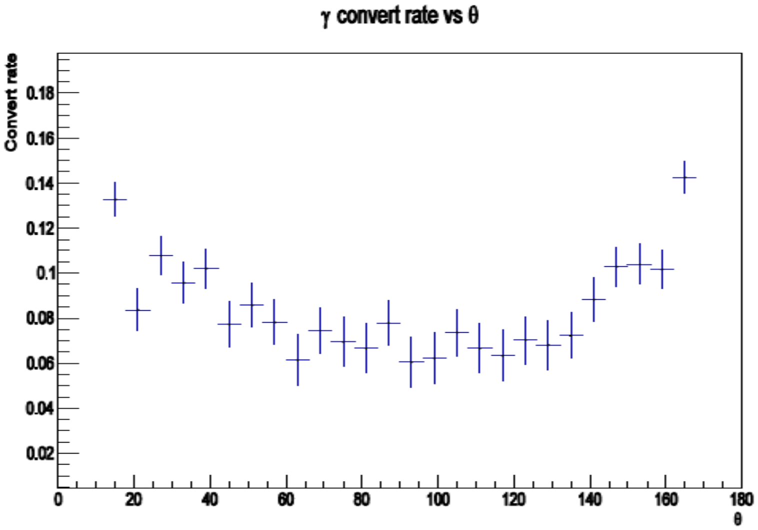
Arbor: photon reconstruction

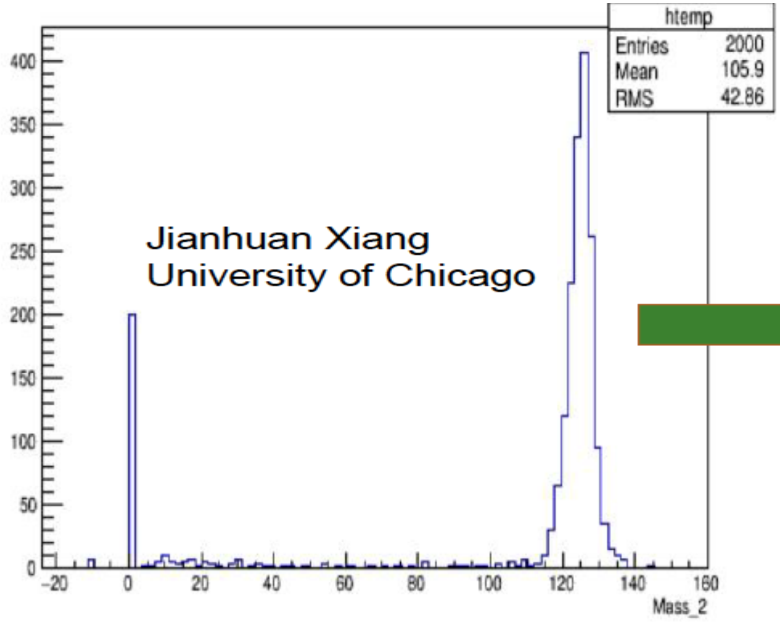


F. Wang

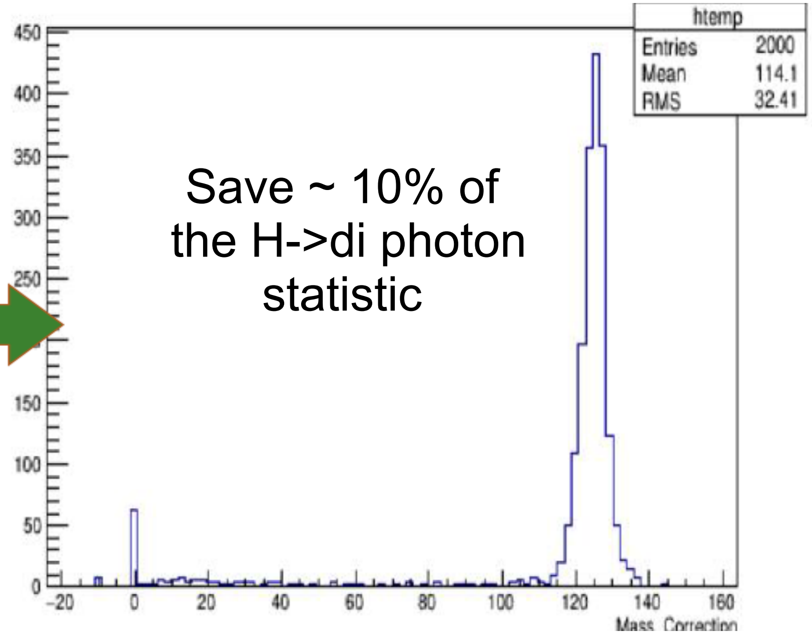
Photon conversion & recovery



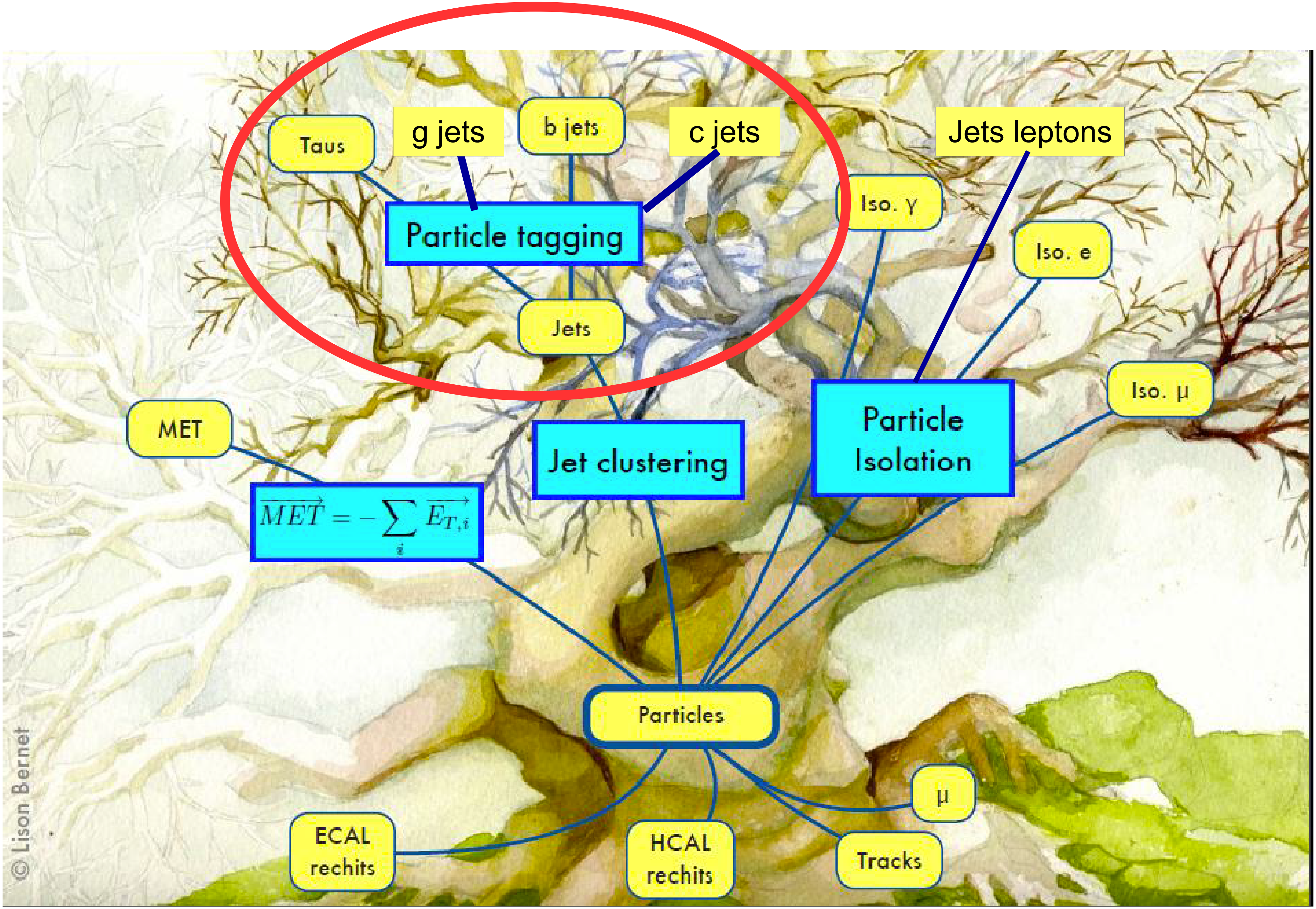




Jianhuan Xiang
University of Chicago

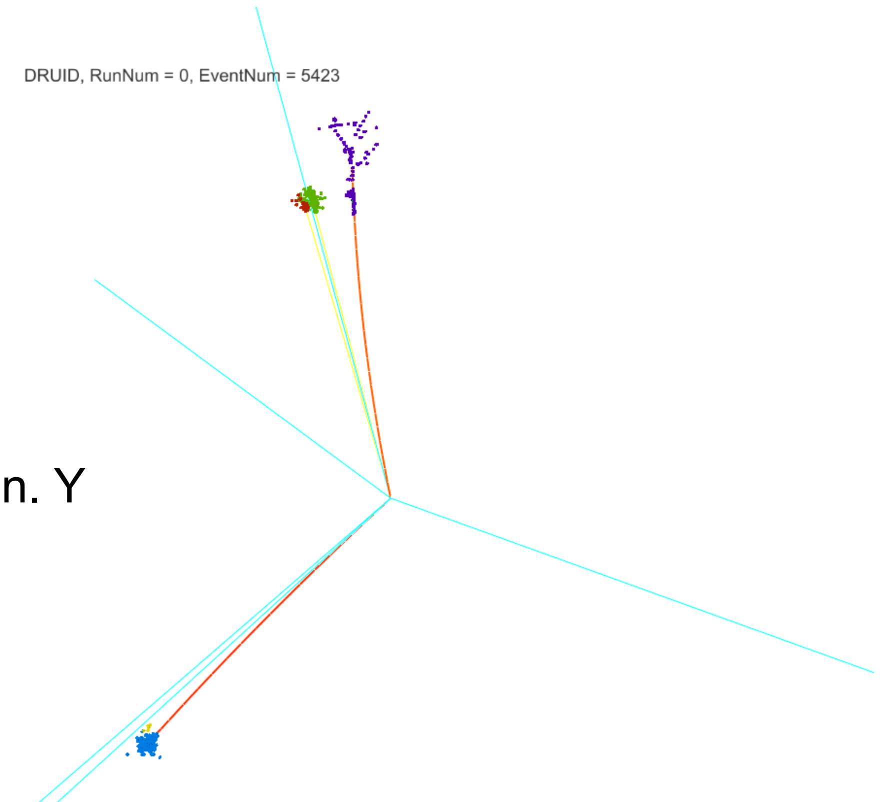


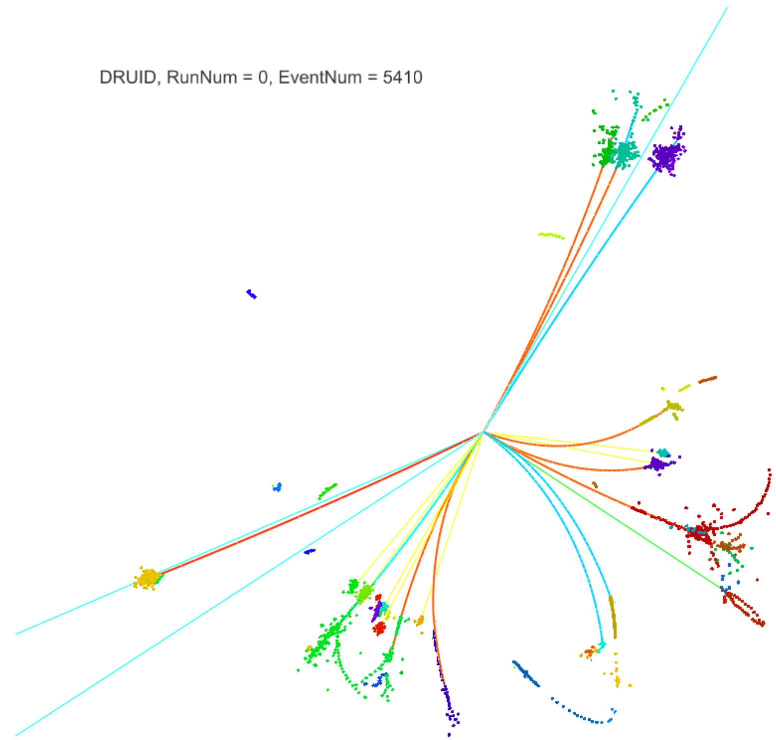
Save ~ 10% of the H->di photon statistic


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

Arbor: Tau reconstruction

Dan. Y



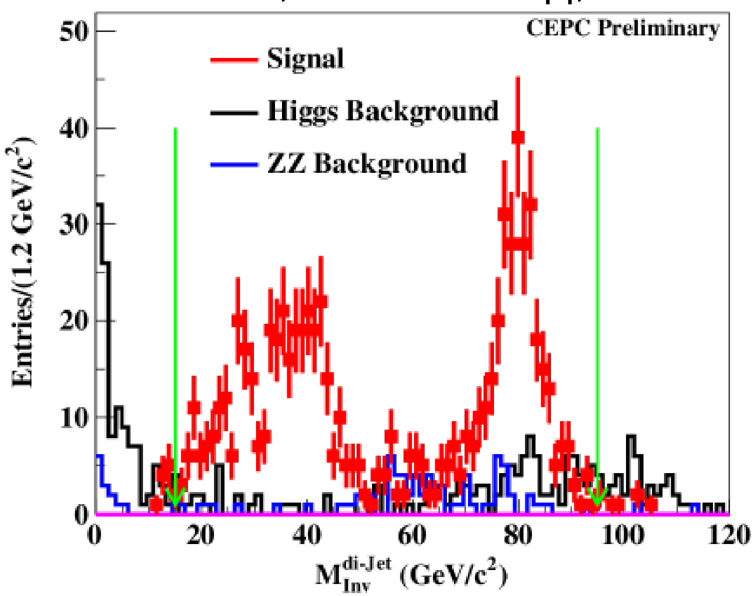


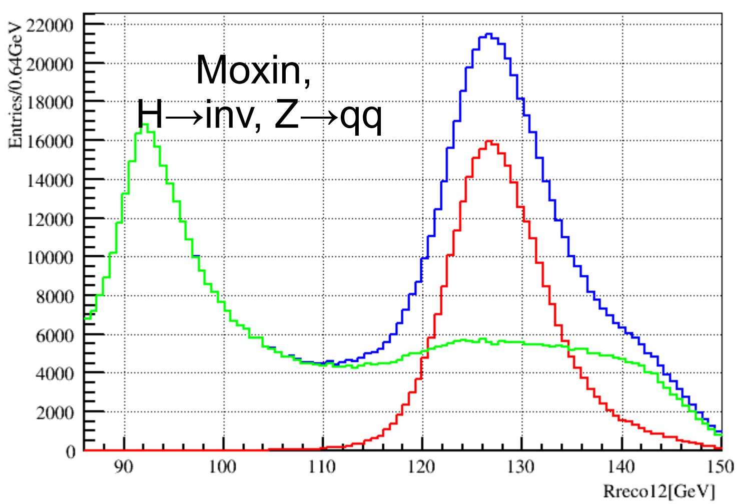
To be covered soon...

- 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→tautau event finding, with llH and vvH final state. The remaining bkgrds are H→WW/ZZ→leptonic/tau final state
  - More detail: see Gang's talk

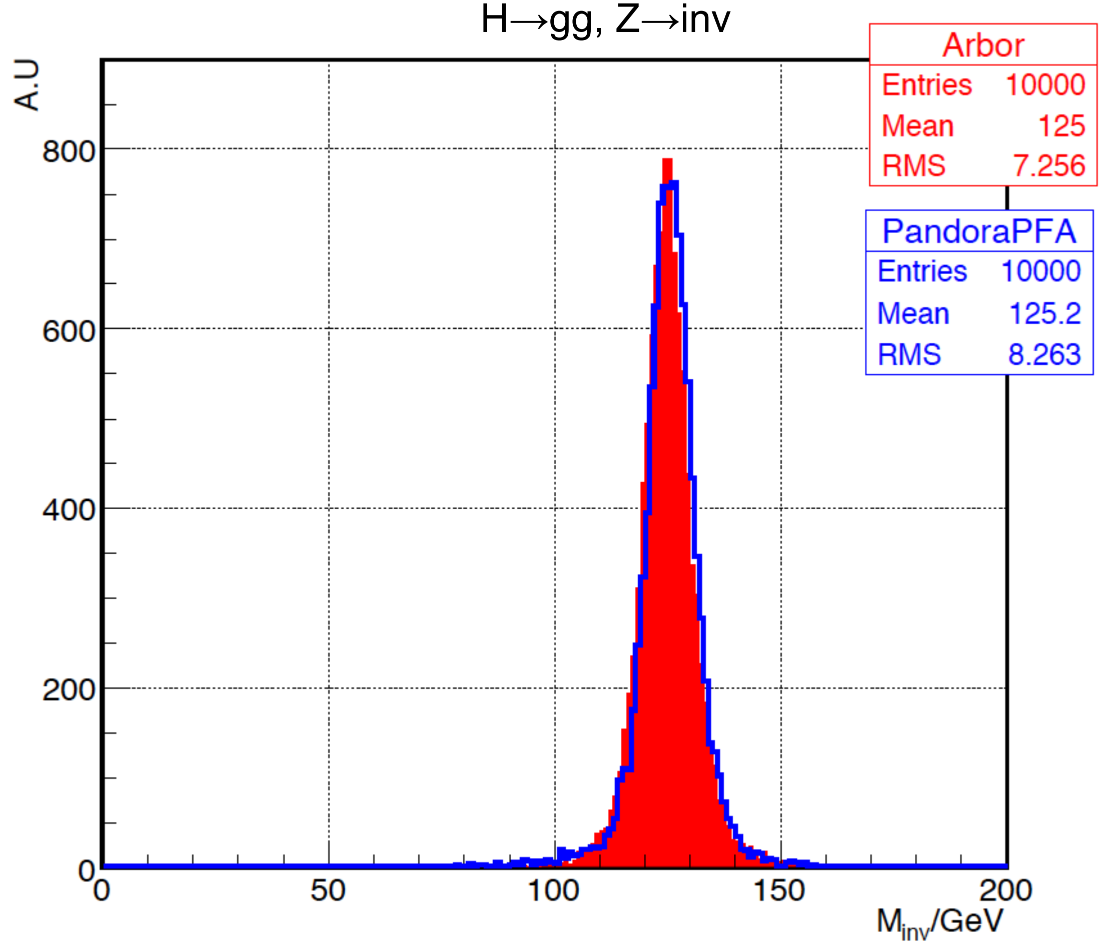
Arbor: JER/MET

Liao libo, H→WW*→lvqq, Z→ll



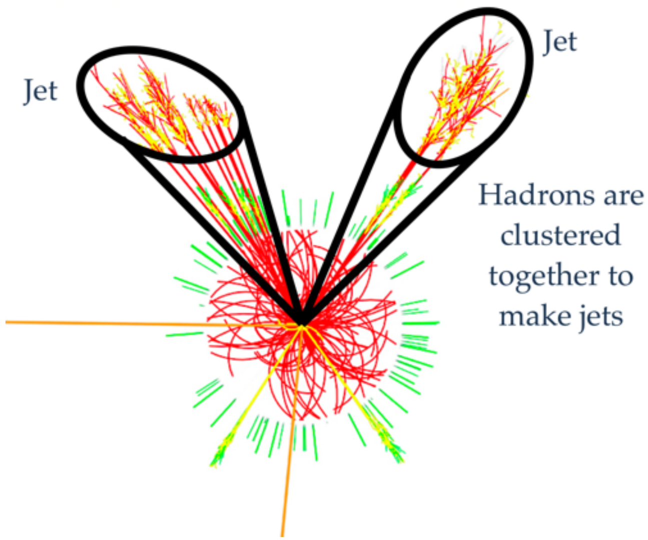


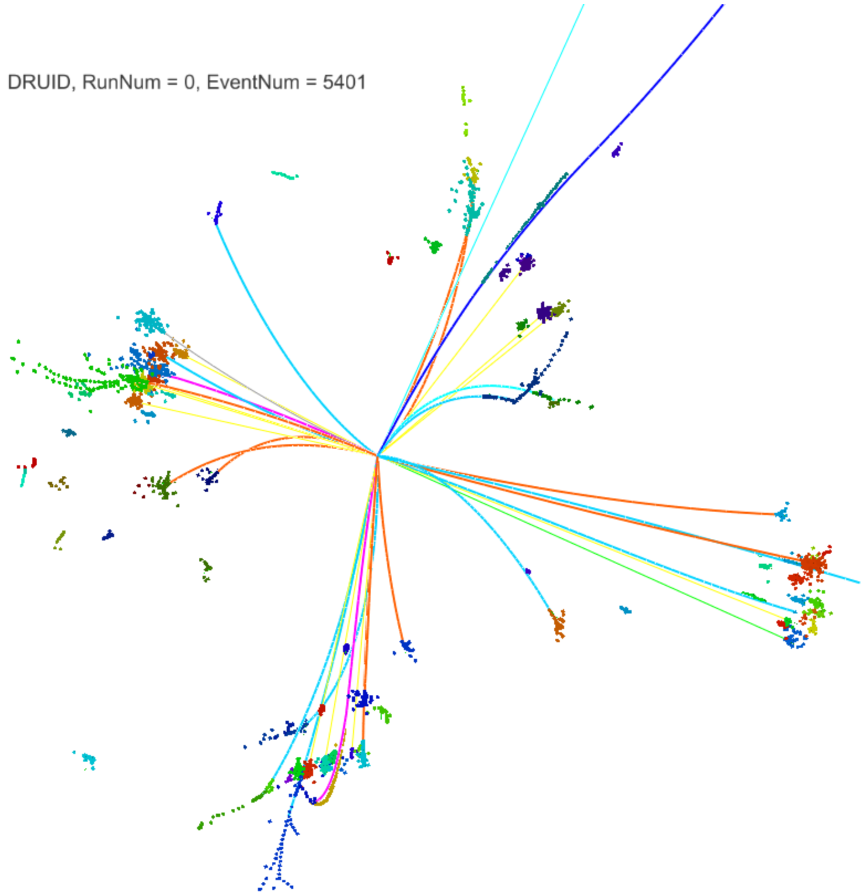
H→gg, Z→inv



- MET: usually no ambiguity;
- Jet: Highly depending on Jet clustering if #Jet > 2...

Jet Clustering

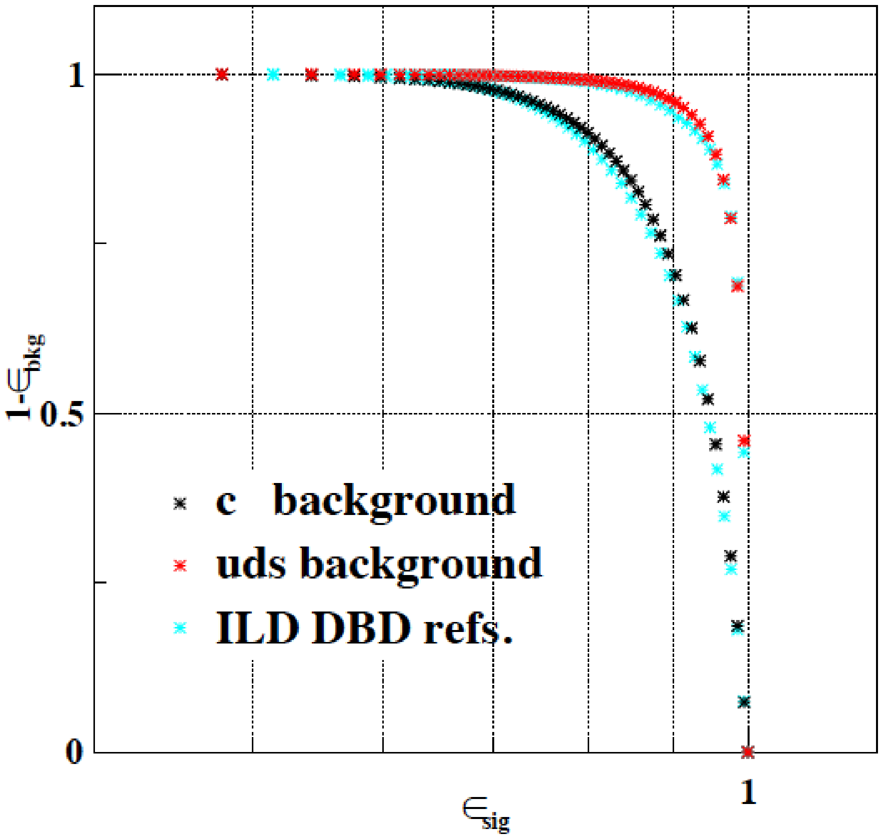


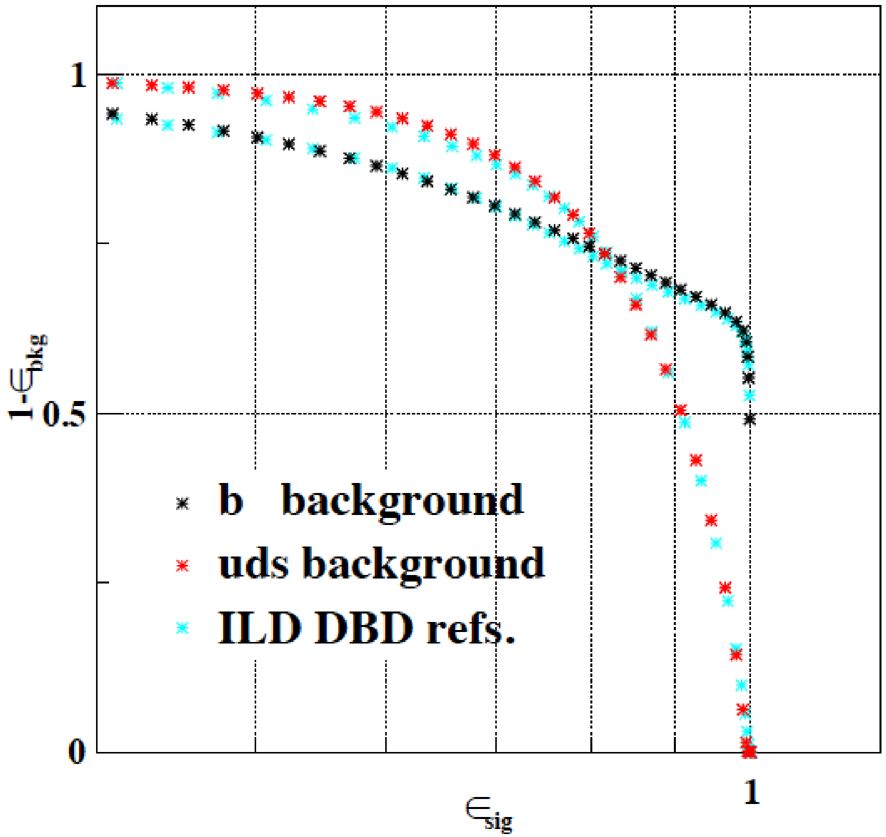


Distance definition & Thresholds;

Two strategy: Fix the threshold and let Number of Jets floating;
Force the events into given number of jets.

Flavor Tagging

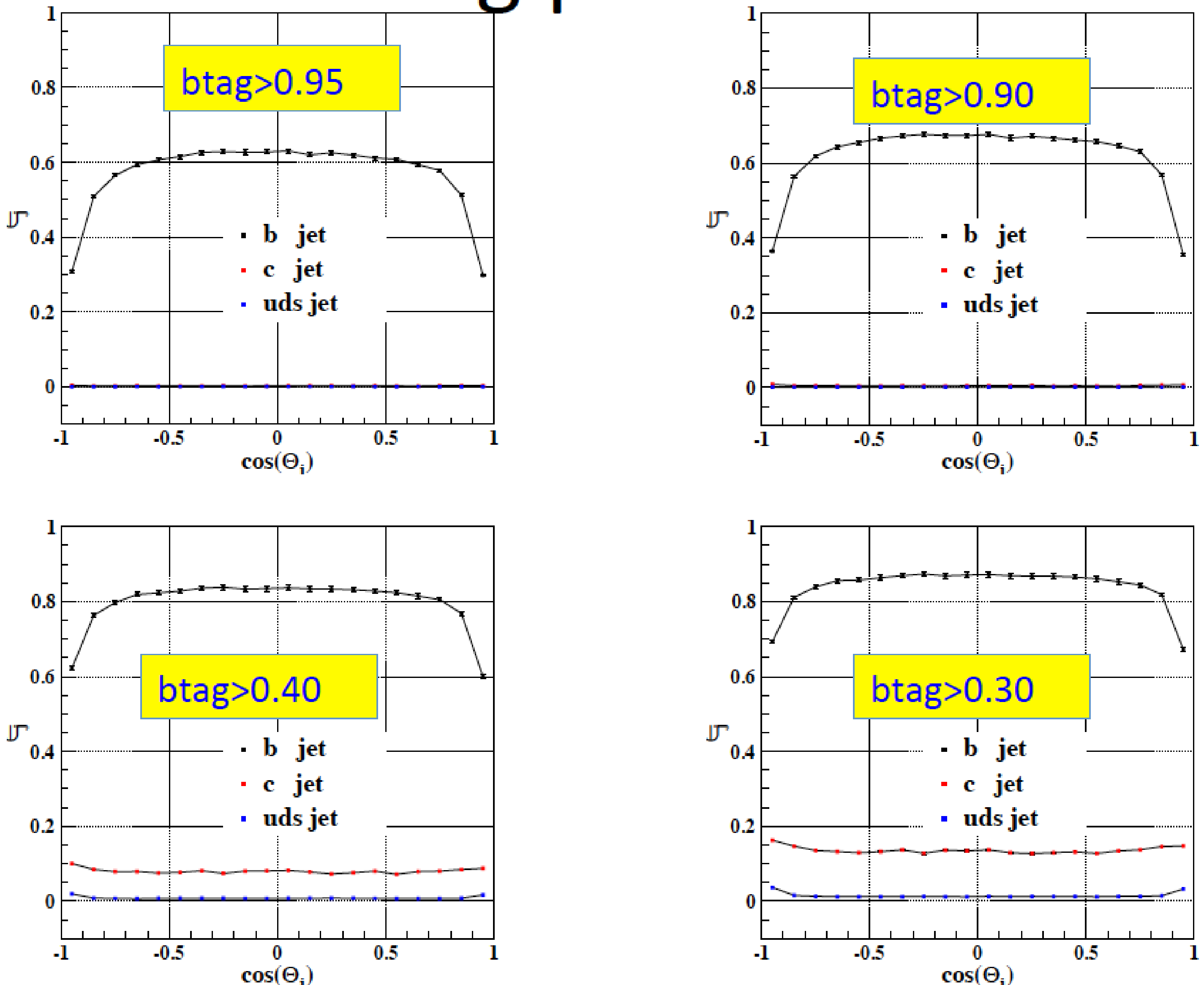




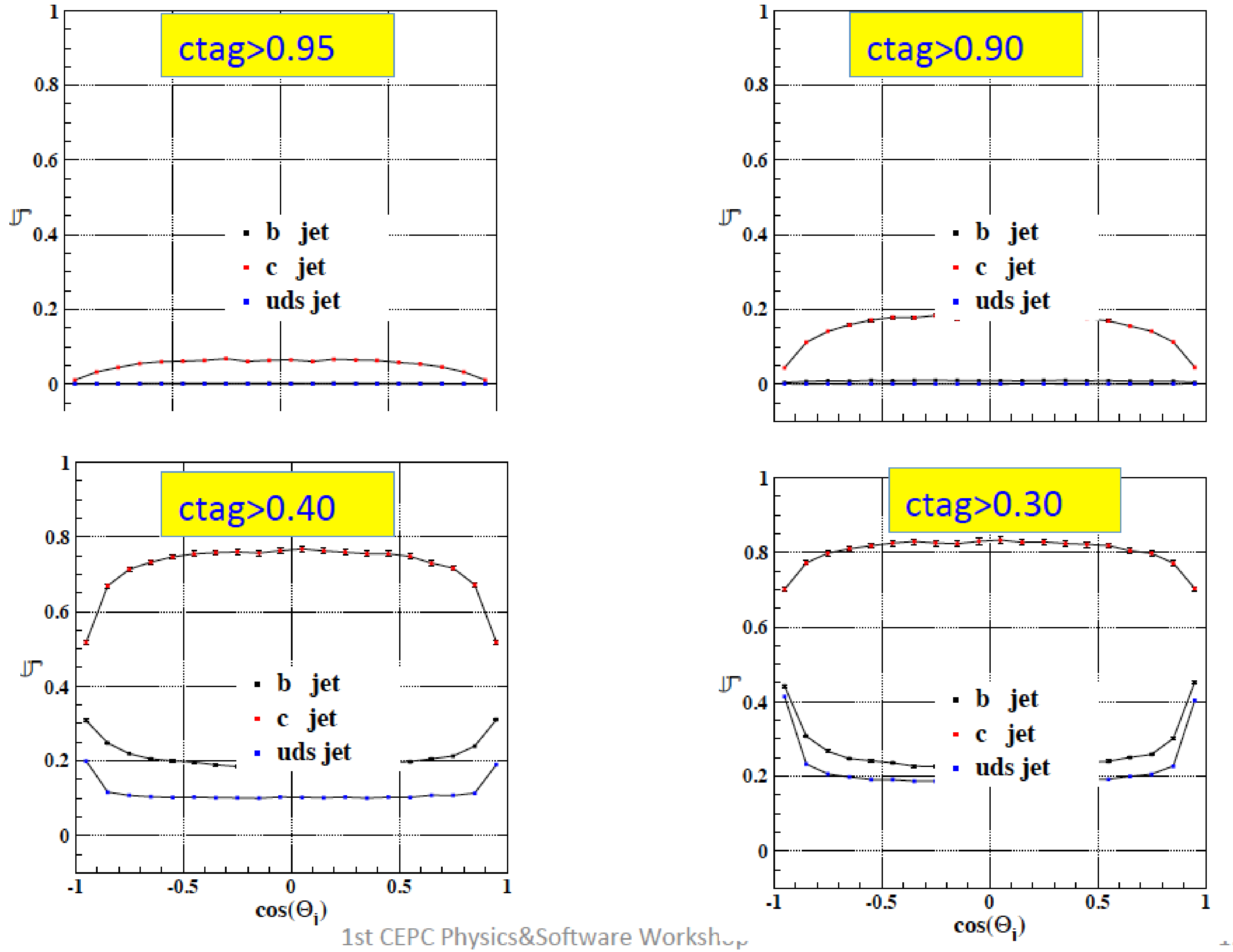
G. Li, etc, using
LCFIPlus packages

TMVA based method from ILC Study:
http://indico.ihep.ac.cn/event/5592/contribution/16/material/slides/0.pdf

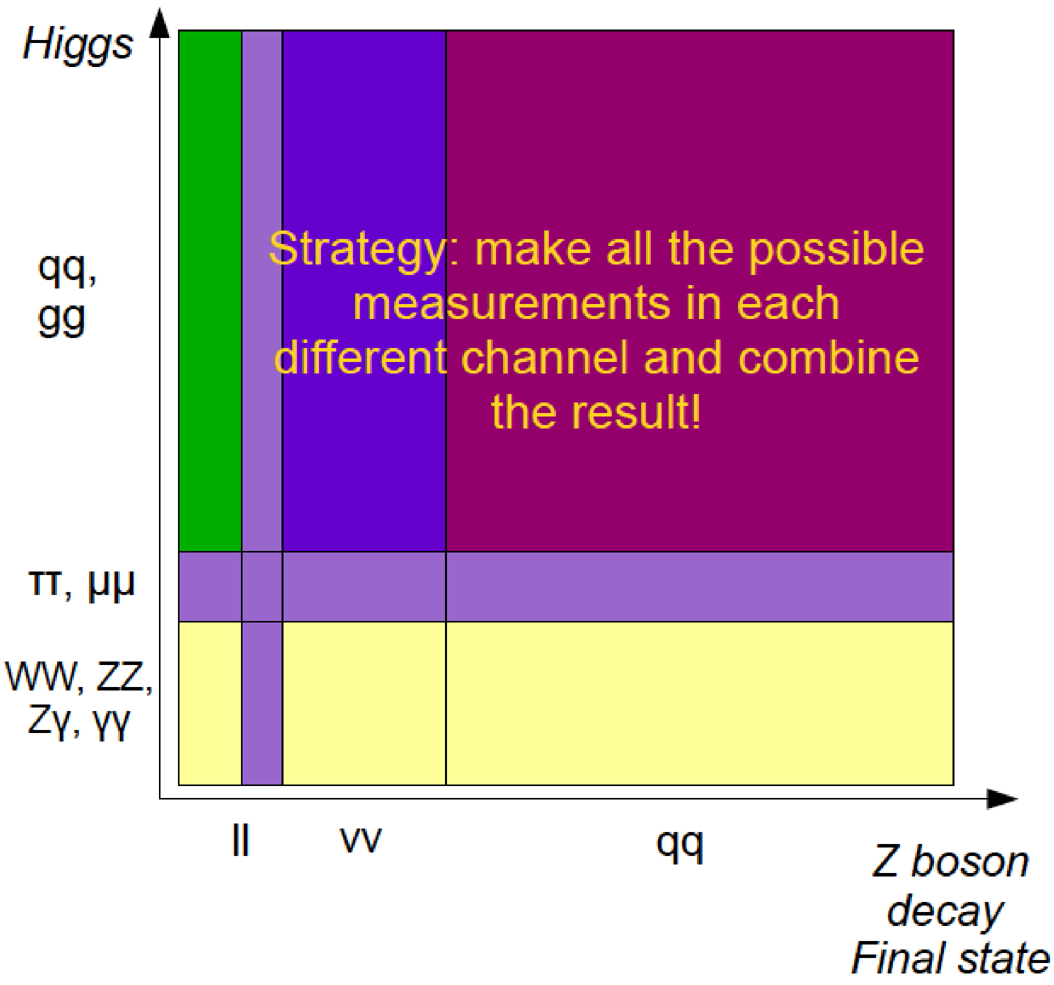
btag performance

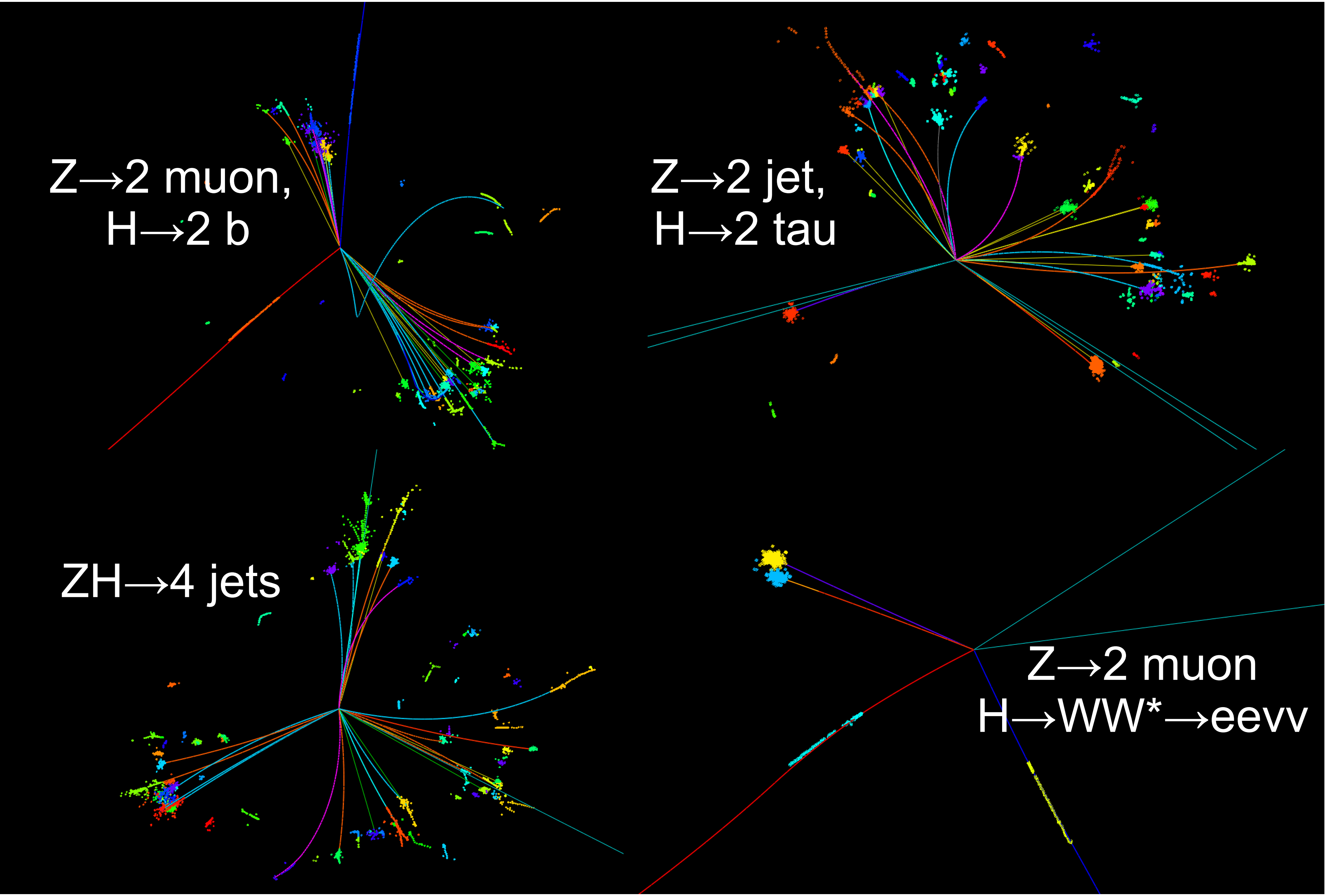


ctag performance



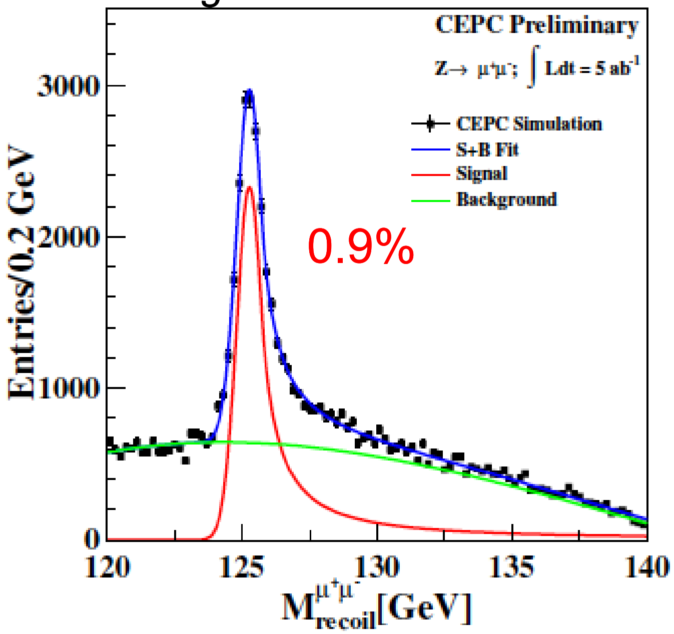
Applied to physics analysis...

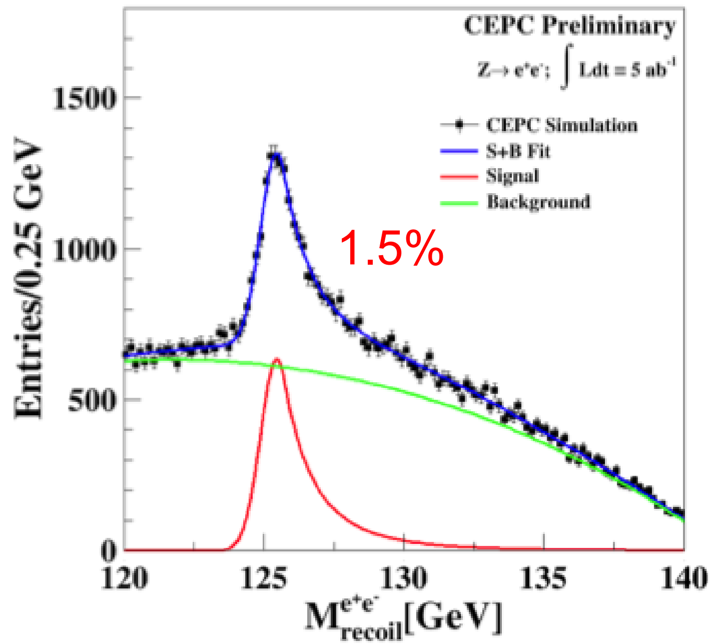


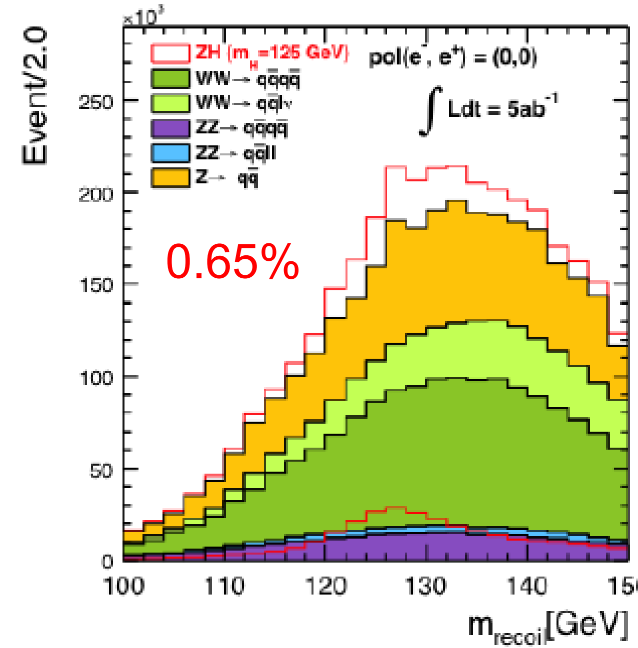

Z→2 muon,
H→2 b
Z→2 jet,
H→2 tau
ZH→4 jets
Z→2 muon
H→WW*→eeνν

Model-independent measurement of σ(ZH)

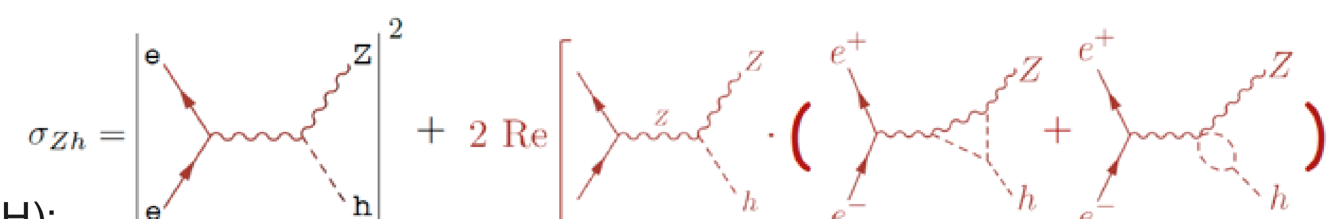
Zhenxing Chen







- Recoil mass method. Combined precision:
  δσ(ZH)/σ(ZH) = 0.5% -
  δg(HZZ)/g(HZZ) = 0.25%



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- In-direct measurement on g(HHH): ~60% in 7 para fit and ~ 70% in 10 para fit

- *M. McCullough, 1312.3322*

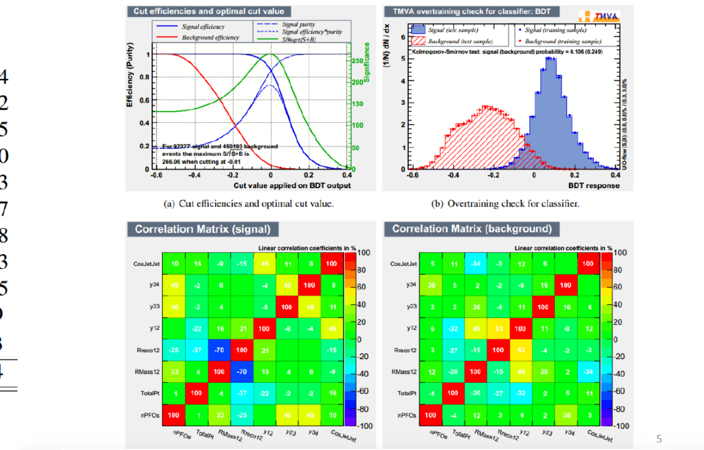
Workflow for Br(H->bb, cc, gg) measurements

Yu Bai, Boyang, Hao Liang, Shuyang Hu, Zhenxing Chen, etc

2. Selection

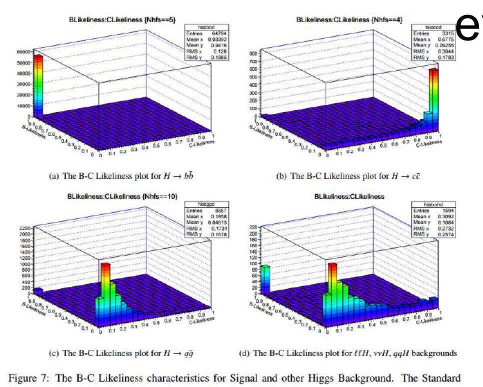
Cut Definition	*Sig.*	*qq*	*qqnn*	*qqln*	*xxh*
FSClasser output	148955	25M	183687	3698817	63194
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	148808	23M	163088	3439927	58882
$110 < E_{\mathrm{total}} < 150$	132561	10M	125878	705357	34215
$P_T > 19$	126006	34198	116314	627602	32300
Isolation lepton veto	123586	33775	115867	327206	23773
$100 < M_{\mathrm{inv}} < 135$	117845	9506	10420	162511	21277
$70 < M_{\mathrm{rec}} < 125$	111886	7521	10045	110426	20458
$0.15 < y_{12} < 1$	111353	7405	9702	101797	19983
$y_{23} < 0.06$	105078	6644	8456	69313	14495
$y_{34} < 0.008$	100117	6504	7878	58532	6899
$-0.98 < \cos(\theta^{(2\mathrm{jets})}_{\mathrm{included}}) < -0.4$	97277	5178	5365	33293	6273
BDT > -0.01	76666	344	118	69	1594
Significance	**265.20**				
Efficiency	**51.5%**				

3. BDT & final results

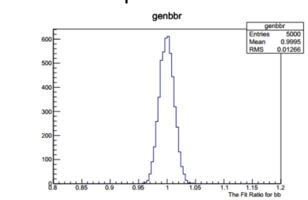


Flavor tagging

vvH events

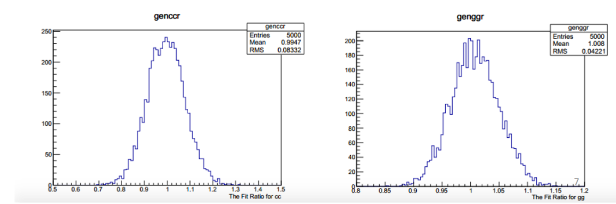


Template fit



Template: 2000 fb-1
Data: 500 fb-1
Fit Times: 5000

No SM bkg in template fit, since no full simulation



	Rbb		Rcc		Rgg		Comments
	CEPC, 5ab-1	ILC, 250fb-1	CEPC	ILC	CEPC	ILC	
mumuH	0.89%	3.3%	9.5%	22.6%	7.0%	33.0%	Full Simulated Sig + Bkg (Bkg using pre-selection technology)
eeH	1.3%	3.8%	11.8%	26.8%	10.6%	31.3%	
qqH	0.25%	1.5%	12.2%	10.2%	18.8%	13.1%	
vvH	0.4%	2.0%	2.7%	11.0%	1.3%	14.0%	Full Sim Sig + Fast Sim Bkg for event selection; No SM Bkg for Template fit
combined	0.2%	1.0%	2.5%	6.9%	1.3%	8.5%	

Br(H->ZZ)

	Z->ll	taus	vv	qq
ZZ*->4q	888	444	2.64k	9.24k
2v + 2q	508	254	1.51k	5.29k
2l + 2q	170	85	508	1778
4v	73	36	216	756
2l + 2v	49	24	145	508
4l	8	4	24	86
X + tau	120	60	356	1246

ZZZ*	Yield	pre_selection	event-category	main_bkg	accuracy(expected)
μμvvjj	256	243	118	zz_sl,h->ww*	12.9%
μμjjvv			125	zz_sl,h->bb,h->ww*	(> 25%)
eevvjj	264	179	91	sze_sl,h->ww*	15.8%
eejjvv			88	sze_sl,h->ww*,h->bb	(> 25%)
vvμμjj	306	293	144	zz_sl,h->ww*	11.0%
vvjjμμ			149	zz_sl,h->bb,h->ww*	12.9%
vveejj	302	252	118	sze_sl,h->ww*	21.3%
vvjjee			134	sze_sl,h->ww*,h->bb	(> 25%)
qqμμvv	271	237	115	h->ww*,h->tautau,zz_sl,,ww_sl	(> 25%)
qqvvμμ			122	h->ww*,h->tautau,zz_sl,,ww_sl	(> 25%)
qqeevv	255	230	107	h->ww*,h->tautau,sze_sl,,sw_sl	(> 25%)
qqvvee			123	h->ww*,h->tautau,sze_sl,,ww_sl	(> 25%)

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Accuracies
μμ + qq + vv: 7.0%
ee + qq + vv: 12.7%

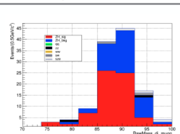
Combined accuracies: 6.1%

ZZZ*->eevvjj

	sig	zh_bkg	qq	zz_sl	ww_sl	sw_sl	sze_sl
Yield	264	34484	99874234	2681457	25773352	17361538	6850366
event category	179	22972	1961	108	206	4441	61209
event category	91	1791	53	20	81	792	2915
final	71	40	0	2	0	7	4

- Pre_selection:
- e+e- variant mass (75,105)
- e+e- recoil mass(115,165)
- each lepton >2Gev
- pt of e pair > 10Gev

event-category
missing mass > jets' invariant mass



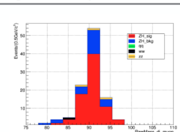
accuracy:15.8%

ZZZ*->μμvvjj

	sig	ZH_bkg	qq	ww_sl	zz_sl
Yield	256	34356	99874234	25773352	2681457
event category	209	27536	862	1174	24548
event category	118	1916	16	282	944
final	81	24	0	1	4

- Pre-selection:
- μ+μ- variant mass (80,100)
- μ+μ- recoil mass(120,160)
- each lepton >2Gev
- pt of μ pair > 10Gev

event-category
missing mass > jets' invariant mass



accuracy:12.9%

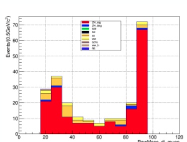
ZZZ*->vvjjμμ

	sig	ZH_bkg	zz_sl	ww_sl	qq
Yield	306	237668	2681457	25773352	99874234
pre-selection	293	8357	12868	120649	12890
event category	149	8062	12616	117435	12833
final	82	3	19	8	1

- Preselection-requirements:
- visible mass (0,180)
- visible energy (0,180)
- 2 same-flavour lepton > 2 Gev

event-category
leptons' invariant mass > jets'

accuracy:12.9%



ZZZ*->vvμμjj

	sig	ZH_bkg	zz_sl	ww_sl	qq
Yield	306	237668	2681457	25773352	99874234
pre-selection	293	8357	12868	120649	12890
event category	144	295	252	3214	57
final	97	4	7	7	0

- Preselection-requirements:
- visible mass (0,180)
- visible energy (0,180)
- 2 same-flavour lepton > 2 Gev

event-category
leptons' invariant mass > jets

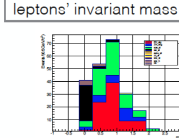
accuracy:11.0%

ZZZ*->vveejj

	sig	zh_bkg	sze_sl	sw_sl	ww_sl
Yield	302	20951	6850366	17361538	25773352
pre-selection	252	17241	86582	43805	110432
event category	118	733	46883	2765	1062
final	65	4	35	27	9

- Preselection-requirements:
- visible mass (0,180)
- visible energy (0,180)
- 2 same-flavour lepton > 2 Gev

event-category
leptons' invariant mass > jets'



accuracy:21.3%

Result:
final state =μμ+vv+jj
7.02%

final state = ee+vv+jj
12.7%

Br(H->WW)

Libo Liao, etc

WW*\νZ	ll	taus	vv	qq
4q	6.91K	3.45K	19.74K	69.1k
lvqq	4.53K	2.27K	12.94K	45.3k
lvlv	745	377	2.13K	7.45K
tau+X	3.2K	1.60K	9.14K	32.0K

Normalize to 5 ab^{-1}

Full Simulation: Z->di muon; H->WW*
4q: ~3%
eevv; 17.6%, eμvv: 9.8%, μμvv: 14.7%
μvqq: 4.1%, evqq: 4.0%

Z->di electron on processing

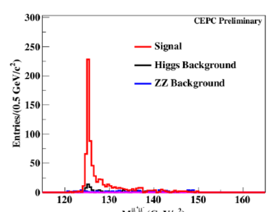
Fast Extrapolation: 1.6%
Total Combination: ~ 1.0%

Analysis result

Category	Signal	ZH	ZZ	Single Z
Total	2215	32291	5499688	7788916
$N_{ZPole}=2; N_{Isolep}=1; N_{Jets}=2; l=\mu$	988	1667	508	0
$80\ \mathrm{GeV}/c^2 < M_{Inv}^{\mu^+\mu^-} < 100\ \mathrm{GeV}/c^2$	879	1455	296	0
$120\ \mathrm{GeV}/c^2 < M_{Rec}^{\mu^+\mu^-} < 150\ \mathrm{GeV}/c^2$	853	1412	170	0
$M^2_{Missing} < 2000\ \mathrm{GeV}^2/c^4$	837	1074	142	0
$E_\mu > 15$ GeV	741	292	93	0
$15\ \mathrm{GeV}/c^2 < M_{Rec}^{di-Jet} < 95\ \mathrm{GeV}/c^2$	724	129	78	0
$\lvert\delta E_{Jets}\rvert < 60$ GeV	717	86	73	0

Table 5: Cut chain of semi leptonic decay of $H \to WW^* \to \mu\nu qq$

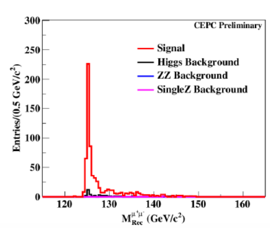
$H \to WW^* \to \mu\nu qq$



Category	Signal	ZH	ZZ	Single Z
Total	2215	32291	5499688	7788916
$N_{ZPole}=2; N_{Isolep}=1; N_{Jets}=2; l=e$	864	881	83	824
$80\ \mathrm{GeV}/c^2 < M_{Inv}^{\mu^+\mu^-} < 100\ \mathrm{GeV}/c^2$	774	738	52	472
$120\ \mathrm{GeV}/c^2 < M_{Rec}^{\mu^+\mu^-} < 150\ \mathrm{GeV}/c^2$	755	717	31	314
$M^2_{Missing} < 2000\ \mathrm{GeV}^2/c^4$	743	406	11	308
$10\ \mathrm{GeV} < E_e < 70$ GeV	699	227	6	210
$15\ \mathrm{GeV}/c^2 < M_{Rec}^{di-Jet} < 95\ \mathrm{GeV}/c^2$	676	90	3	99
$N_{Remain} > 6$	670	65	3	4
$\lvert\delta E_{Jets}\rvert < 60$ GeV	663	43	1	1

Table 4: Cut chain of semi leptonic decay of $H \to WW^* \to e\nu qq$

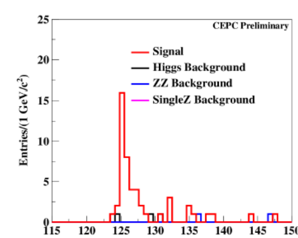
$H \to WW^* \to e\nu qq$



$H \to WW^* \to \mu\nu\mu\nu$

Category	Signal	ZH	ZZ	Single Z
Total	348	34624	5499688	7788916
$N_{ZPole}=2; N_{Isolep}=2; l=\mu$	77	129	5309	0
$80\ \mathrm{GeV} < M_{Inv}^{\mu^+\mu^-} < 100$ GeV	73	124	4143	0
$120\ \mathrm{GeV} < M_{Rec}^{\mu^+\mu^-} < 150$ GeV	66	118	2548	0
$N_{Remain} < 3$	66	56	2442	0
$10\ \mathrm{GeV} < M_{Inv}^{\mu^+\mu^-} < 65$ GeV	58	46	411	0
$40\ \mathrm{GeV} < E_{Missing} < 100$ GeV	55	26	231	0
$\sqrt{(\frac{D0}{sigD0})^2 + (\frac{Z0}{sigZ0})^2} < 5$	54	7	226	0
Total $P_T > 20$ GeV	52	3	3	0

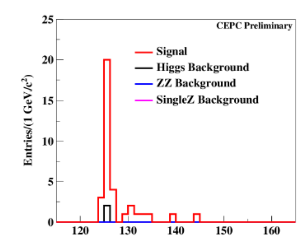
Table 2: Cut chain of $\mu\mu$ final state



$H \to WW^* \to e\nu e\nu$

Category	Signal	ZH	ZZ	Single Z
Total	348	34624	5499688	7788916
$N_{ZPole}=2; N_{Isolep}=2; l=e$	61	114	4	1807
$80\ \mathrm{GeV} < M_{Inv}^{\mu^+\mu^-} < 100$ GeV	53	105	2	1165
$120\ \mathrm{GeV} < M_{Rec}^{\mu^+\mu^-} < 150$ GeV	52	101	1	726
$N_{Remain} < 3$	51	60	0	692
$10\ \mathrm{GeV} < M_{Inv}^{e^+e^-} < 65$ GeV	49	47	0	49
$35\ \mathrm{GeV} < E_{Missing} < 100$ GeV	49	27	0	31
$\sqrt{(\frac{D0}{sigD0})^2 + (\frac{Z0}{sigZ0})^2} < 6$	39	4	0	24
Total $P_T > 20$ GeV	36	4	0	0

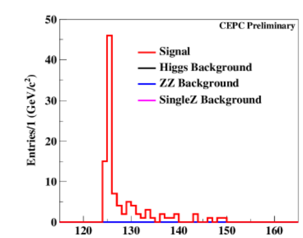
Table 3: Cut chain of ee final state



$H \to WW^* \to e\nu\mu\nu$

Category	Signal	ZH	ZZ	Single Z
Total	348	34624	5499688	7788916
$N_{ZPole}=2; N_{Isolep}=2; l_1=e, l_2=\mu$	147	136	32	1
$80\ \mathrm{GeV} < M_{Inv}^{\mu^+\mu^-} < 100$ GeV	134	119	21	0
$120\ \mathrm{GeV} < M_{Rec}^{\mu^+\mu^-} < 150$ GeV	130	117	15	0
$N_{Remain} < 3$	130	89	3	0
$10\ \mathrm{GeV} < M_{Inv}^{e\mu} < 65$ GeV	123	79	3	0
$35\ \mathrm{GeV} < E_{Missing} < 110$ GeV	123	68	2	0
$\sqrt{(\frac{D0}{sigD0})^2 + (\frac{Z0}{sigZ0})^2} < 4$	105	0	0	0

Table 1: Cut chain of $e\mu$ final state



DRUID, RunNum = 0, EventNum = 5401

Higgs width measurement

- $g^2(HXX) \sim \Gamma_{H\to XX} = \Gamma_{total} * Br(H\to XX)$
- Branching ratios: determined simply by
  - σ(ZH) and σ(ZH)*Br(H→XX)
- Γ_{total} : determined from:
  - From σ(ZH) ($\sim g^2(HZZ)$) and σ(ZH)*Br(H→ZZ) ($\sim g^4(HZZ)/\Gamma_{total}$)
  - From σ(ZH)*Br(H→bb), σ(ννH)*Br(H→bb), σ(ZH)*Br(H→WW), σ(ZH)
    - *Would be good to have some data at E > 250 GeV*
- Therefore: at CEPC Higgs program (240-250 GeV operation), Γ_{total} become the bottle neck of the coupling fit once Br(H→XX) is measured more precisely: Br(H→tautau, WW, bb,cc, gg)

Result

$$\Gamma_h \propto g_Z^2 \frac{\sigma_Z^{\text{inc}} \sigma_{Wb}}{\sigma_{ZW} \sigma_{Zb}}$$ WW method

$$\Gamma_h = \frac{(g_A^2)^2}{(g_A^2 g_A^2/\Gamma_h)} \propto g_A^2 \frac{\sigma_A^{\text{inc}}}{\sigma_{AA}};$$ ZZ method

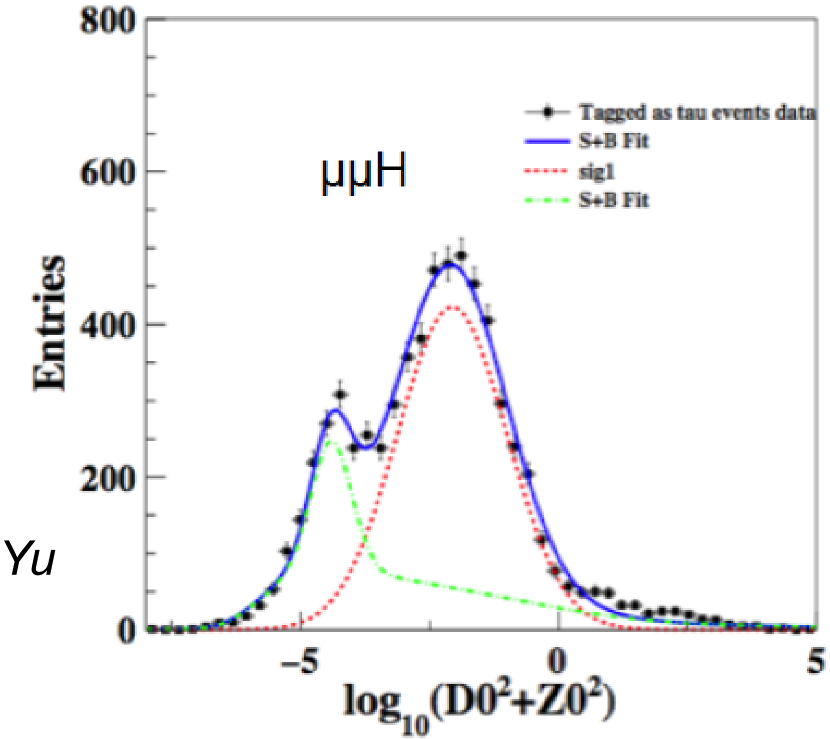
O_1	σ_{ZH}	0.5% from pre-CDR
O_2	$\sigma_{ZZ} = \sigma_{ZH} \times Br(H \to ZZ^*)$	4.3% extrapolated from TLEP
O_3	$\sigma_{Wb} = \sigma_{\nu\nu H} \times Br(H \to bb)$	2.8% from pre-CDR
O_4	$\sigma_{ZW} = \sigma_{ZH} \times Br(H \to WW^*)$	1.38% latest result from Libo's work combined with the result extrapolated from ILC result (1.5% at PreCDR)
O_5	$\sigma_{Zb} = \sigma_{ZH} \times Br(H \to bb)$	0.28% from pre-CDR

Total Higgs width relative precision

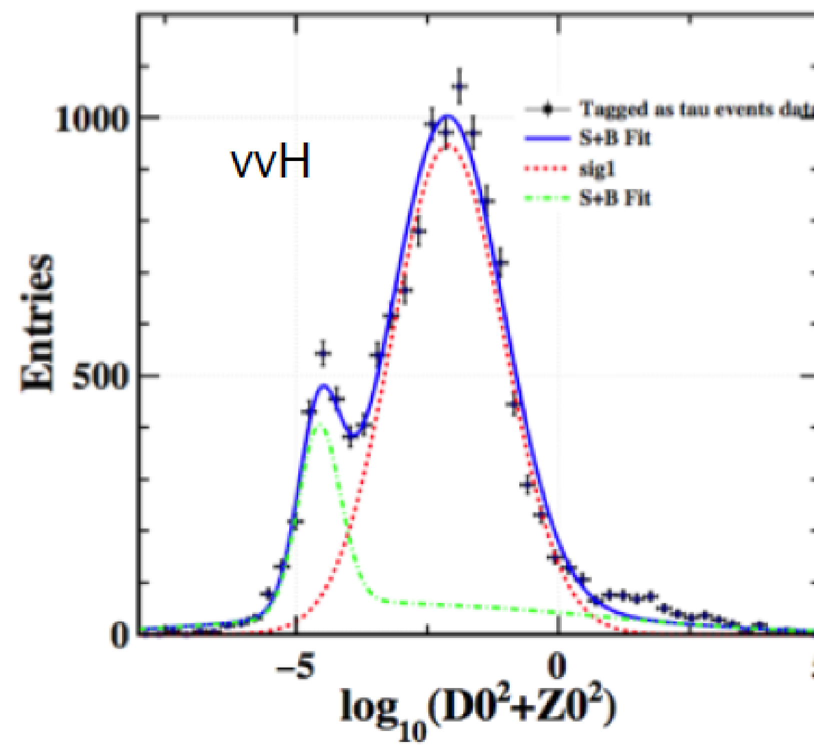
ww method	3.3%
zz method	4.4%

Yuqian Wei

H->di tau



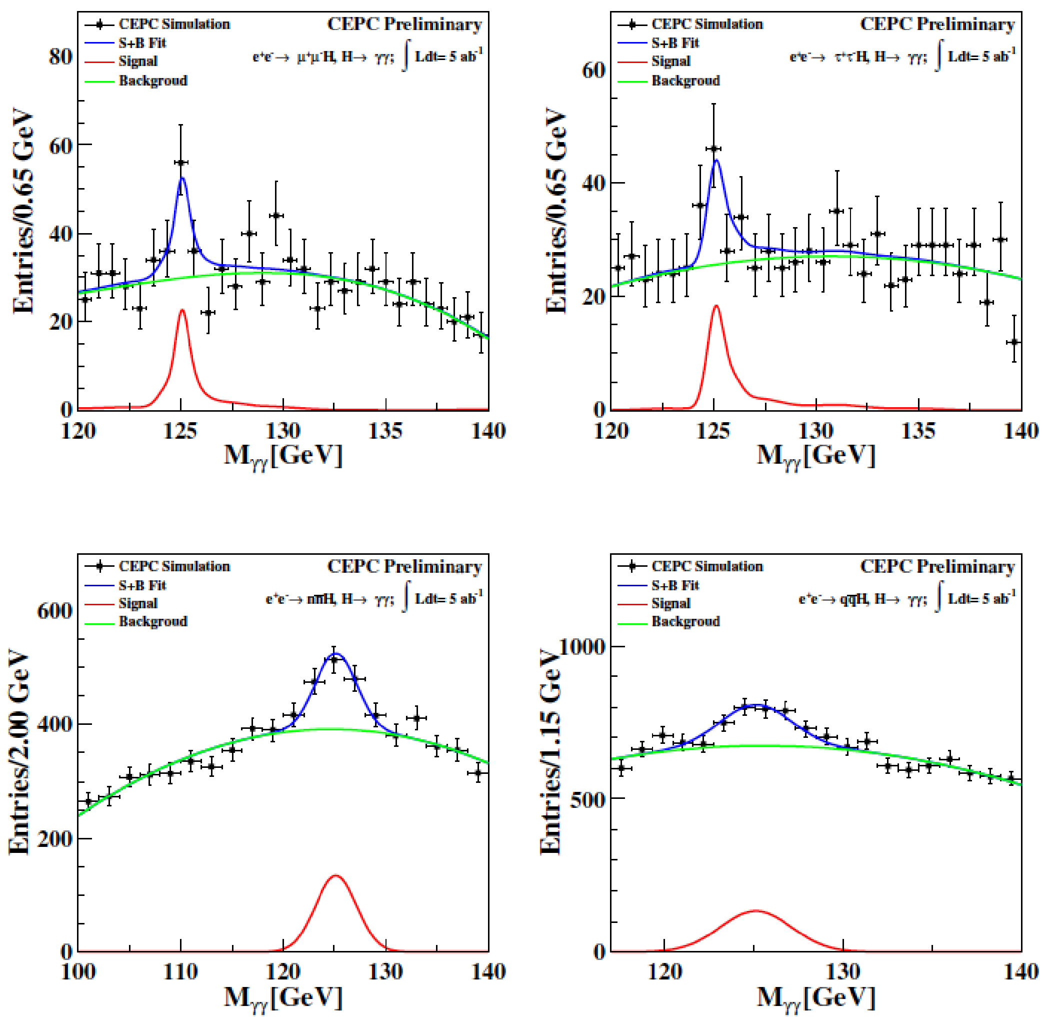
Dan Yu



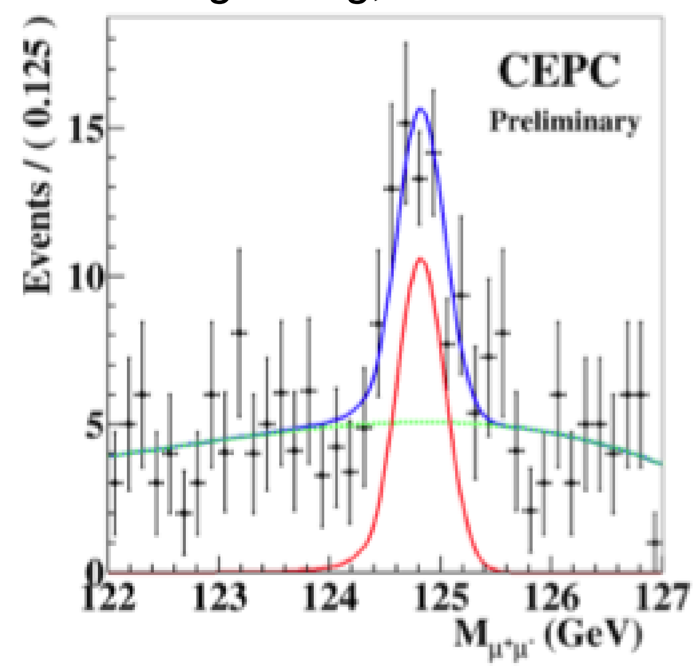
- Without other SM background, relative accuracy
  - μμH channel: 2.6%
  - vvH channel: 1%
- *Common background samples will soon be provided...*

Higgs rare decay

Feng Wang, Jianhuan Xiang, etc



Binlong Wang, Zhenwei Cui

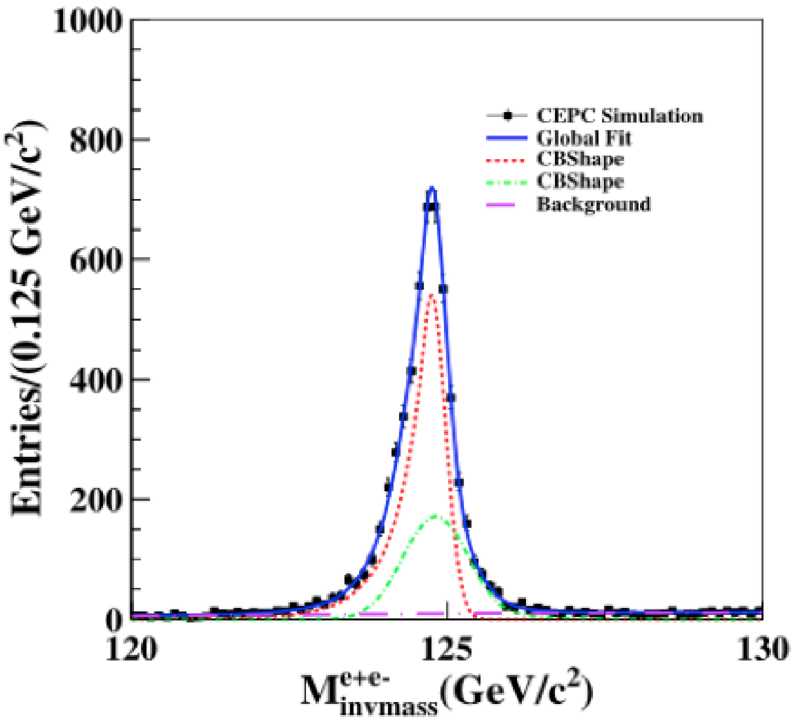


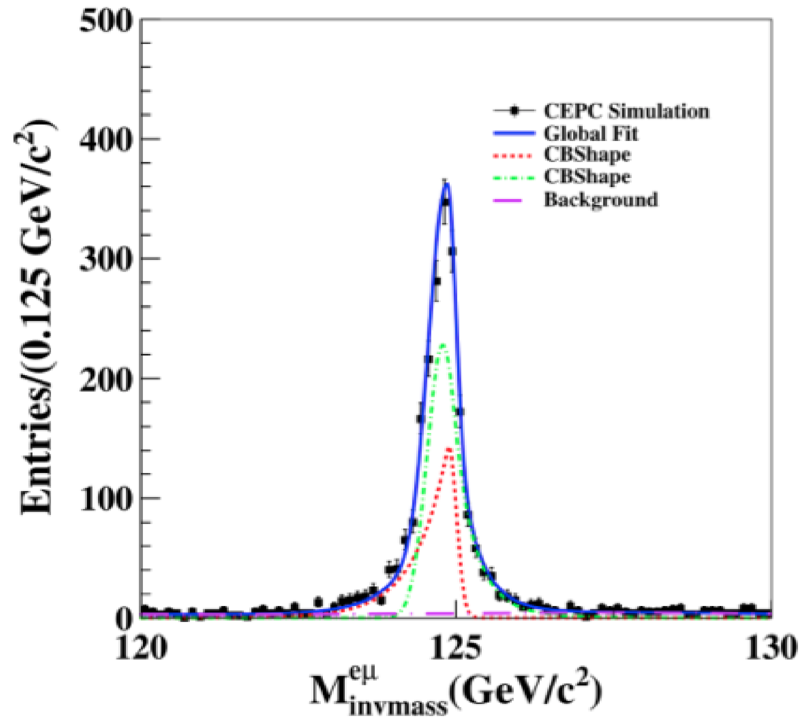
Br(H→γγ):
photon identification efficiency
& ECAL intrinsic resolution

Br(H→μμ):
Muon identification & Track
Momentum resolution

Uplimit of Br(H->ee) & Br(H->emu)

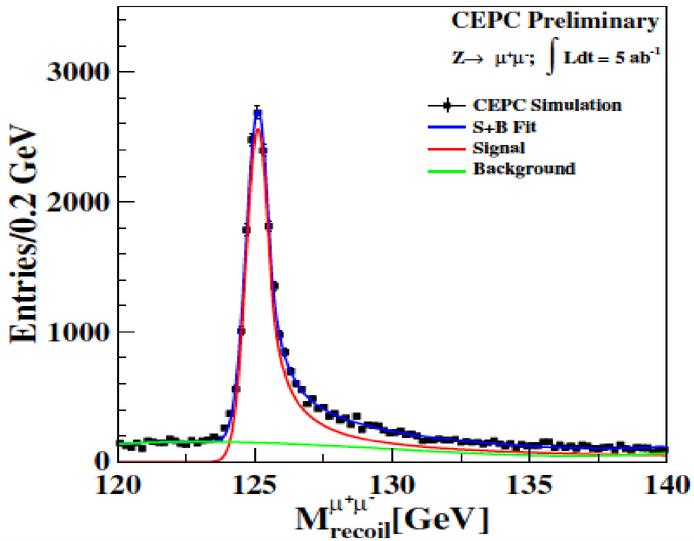
Lei Wang

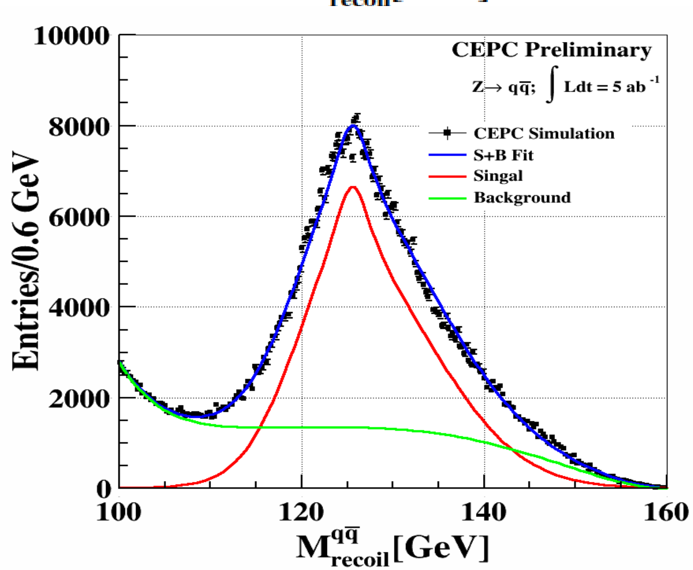




95% up limit: Br(H->ee) = 1.7e-4;
Br(H->emu) = 1.2e-4;

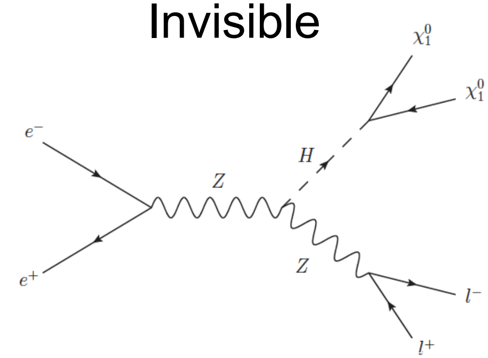
Higgs invisible/exotic decays



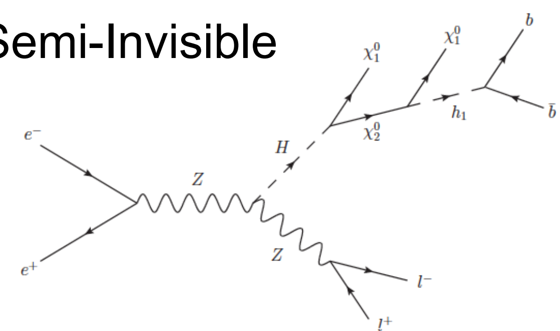


Zhenxing Chen
Xin Mo
Jiawei Wang
Kevin, etc

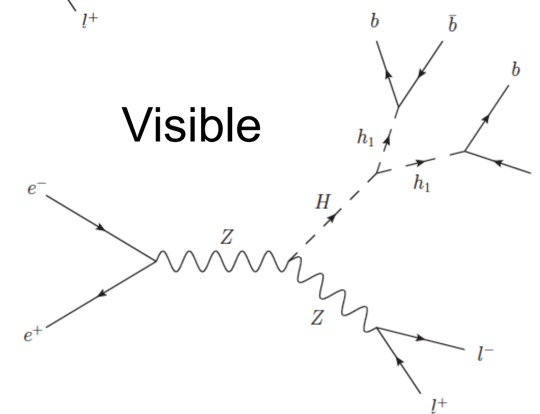
Invisible



Semi-Invisible



Visible



Constrain the final state recoil to Z boson: probe the Higgs invisible/exotic decays
Br(H->inv) are limited to 0.28% at 95% CL

Several benchmark exotic decay verified: 5-sigma deviation expected at Br(H->exo) of 0.1%

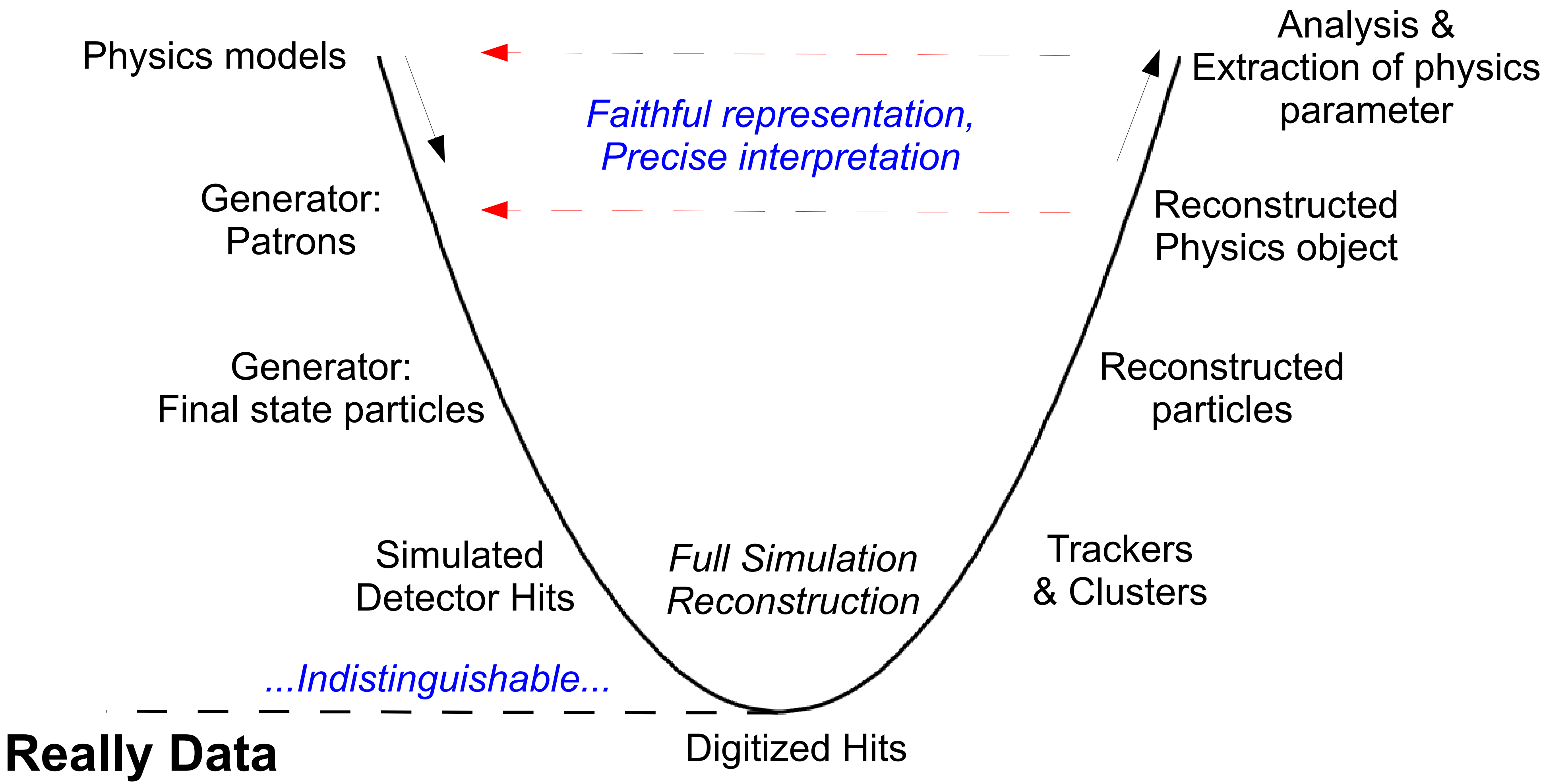
Sim & Recon

- Indisponsable tool
  - Interpret the experimental data
  - Explore the physics potential
  - Design-optimize the detector/facility

- Bridge between Theory/Pheno, Accelerator & Detector Hardware

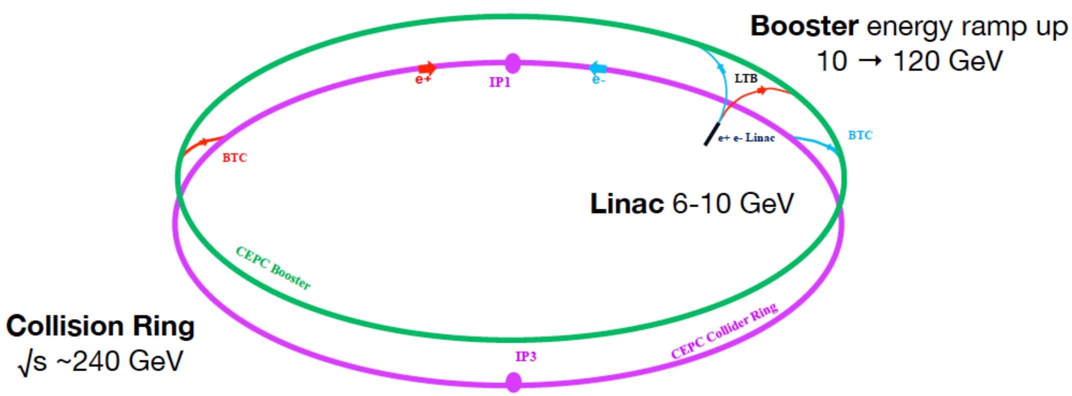
- Intelligence of the detector

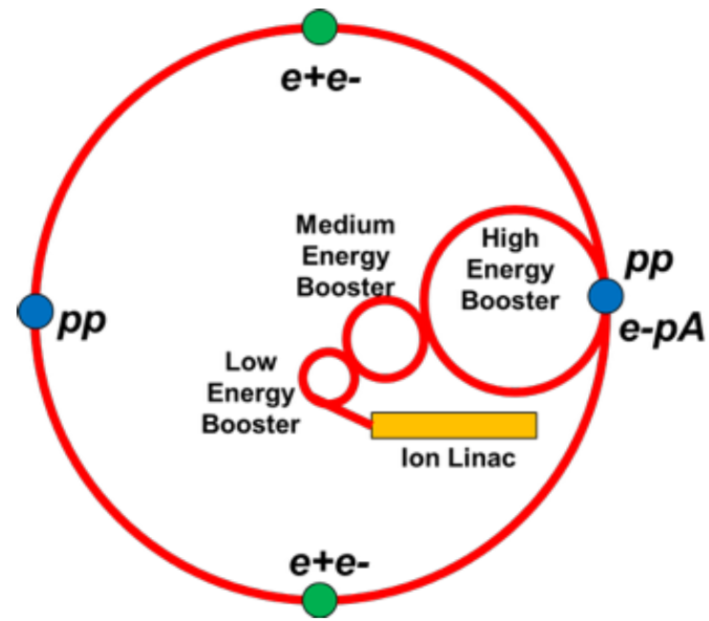
Summary


Physics models
Analysis &
Extraction of physics
parameter
Faithful representation,
Precise interpretation
Generator:
Patrons
Reconstructed
Physics object
Generator:
Final state particles
Reconstructed
particles
Simulated
Detector Hits
Full Simulation
Reconstruction
Trackers
& Clusters
...Indistinguishable...
Really Data
Digitized Hits

Backup

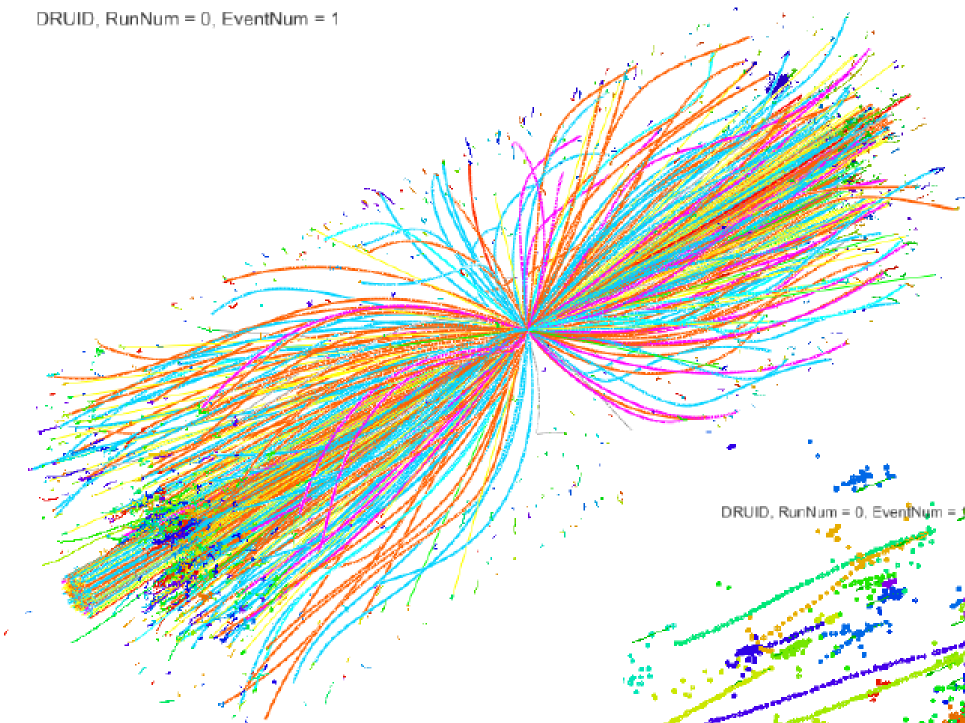
CEPC-SPPC

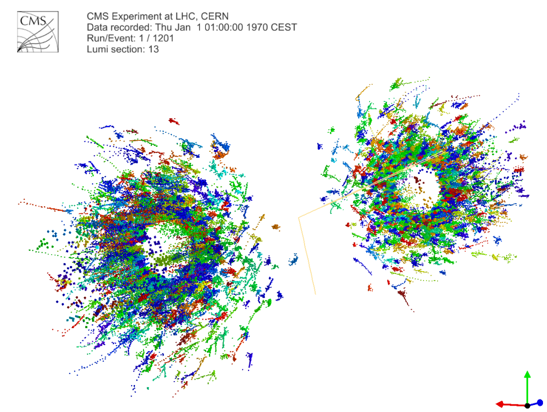




- Electron-positron collision phase
  - Higgs factory: collision at ~240 - 250 GeV center-of-mass energy, Instant luminosity ~ $2*10^{34}$ $cm^{-2}s^{-1}$, 1M clean Higgs event at 2 IP over 10 years
  - Z pole operation for precise EW measurement
- Proton-Proton collision phase
  - center-of-mass energy constrained by tunnel circumference and high-field dipole
  - Peak luminosity ~ $1*10^{35}$ $cm^{-2}s^{-1}$ (*ArXiv: 1504.06108, discussion on needed Luminosity*)
- Tunnel circumference: 54 km in the baseline design. Longer tunnel to be evaluated.

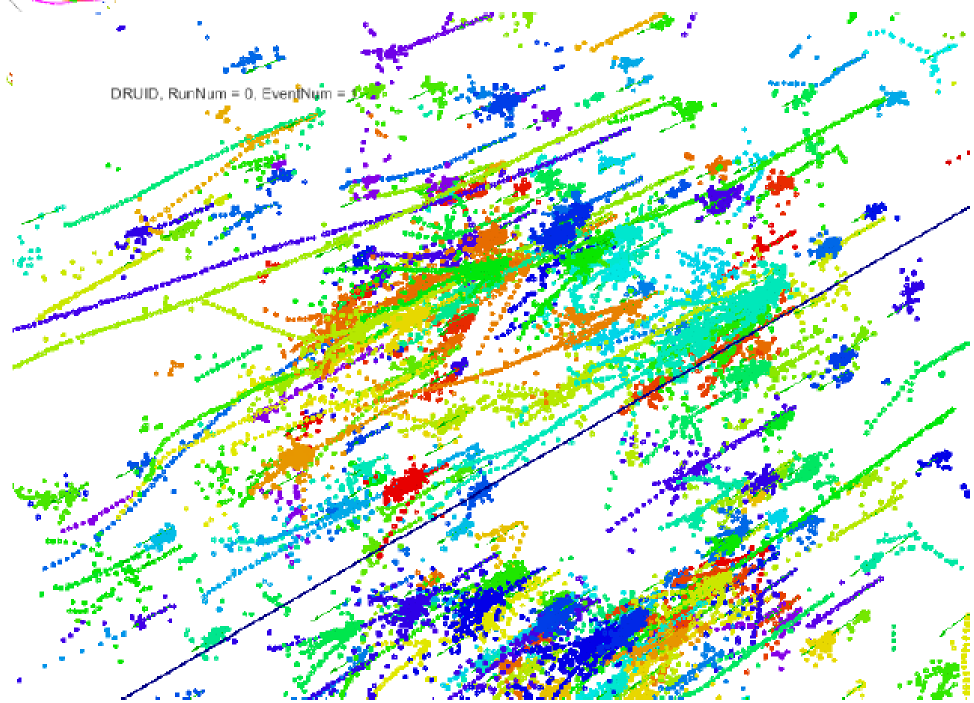
KD algorithm boost: $N^2 \rightarrow N\log(N)$





Messy
Environments

Overlap 20
Min-bias events



CEPC Event: speed up by 1 order of magnitude