Detector Performance Parameterisation

(with Delphes)

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FCC Hadron Detector Meeting
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Status

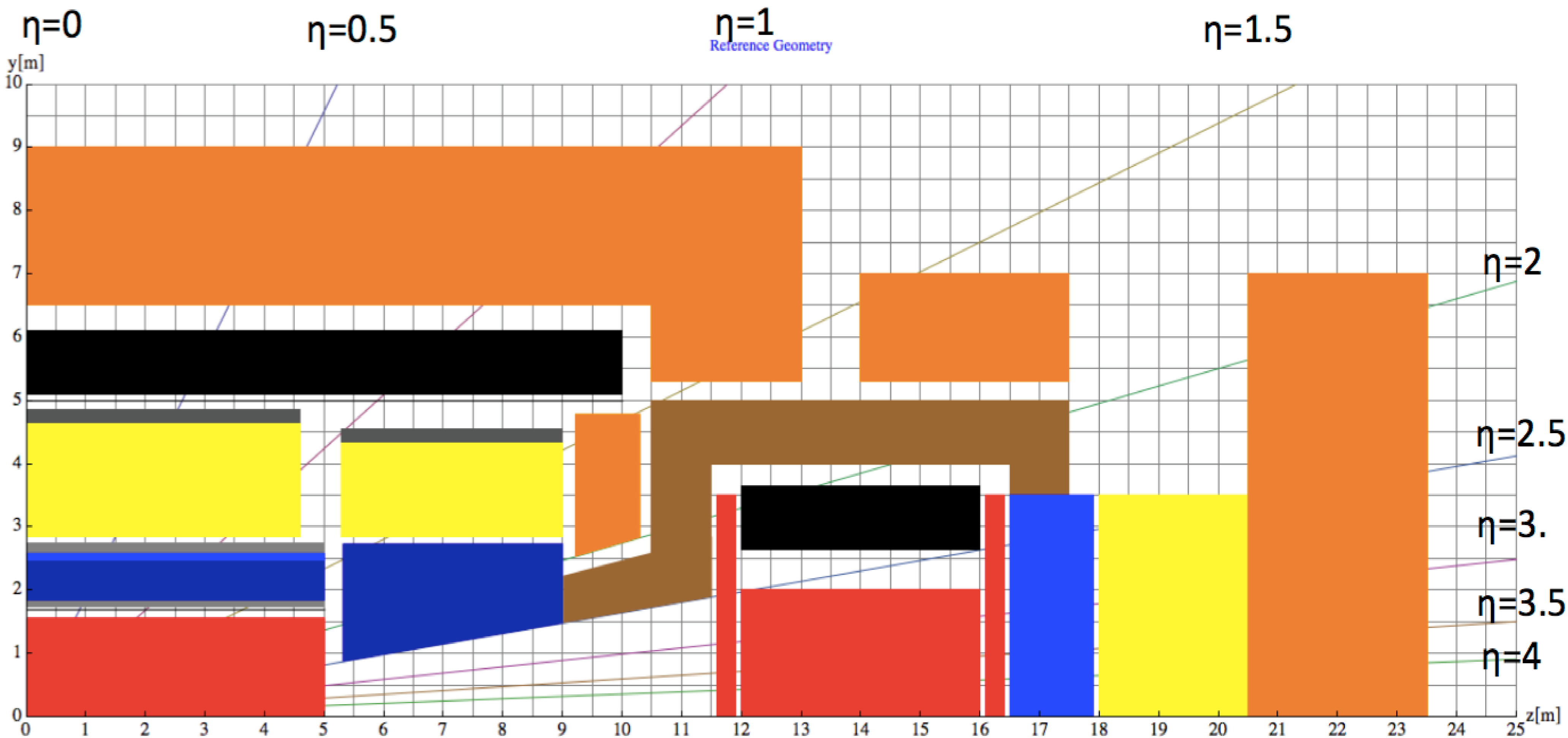
- Latest version of **FCC-hh detector layout** has been implemented in Delphes.
- FCC-hh card is available for beta-testing in Delphes Standalone mode (thanks to all for useful comments)
- Boosted Samples have been produced on HepSim repository (rfast005) [S.Chekanov]
- Compared to Delphes card implemented by H. Gray and F. Moortgat small changes have applied:

  - smaller detector/magnetic field

  - tracking/muon **resolution formulae** have been updated according to tkLayout parameterisation/analytical derivation

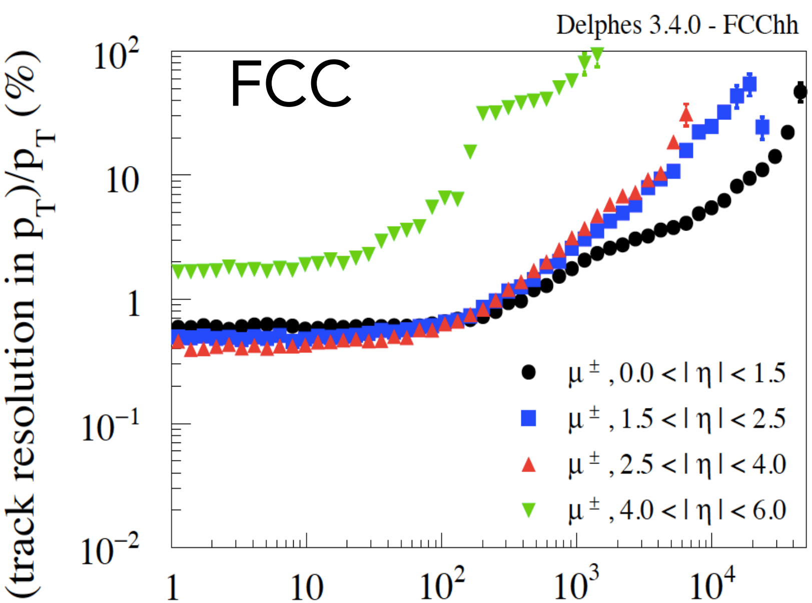
  - ECAL/HCAL layouts/resolution kept same
  - object (e-mu-gamma-b-tau) **efficiencies** also similar (with drop at high pT)

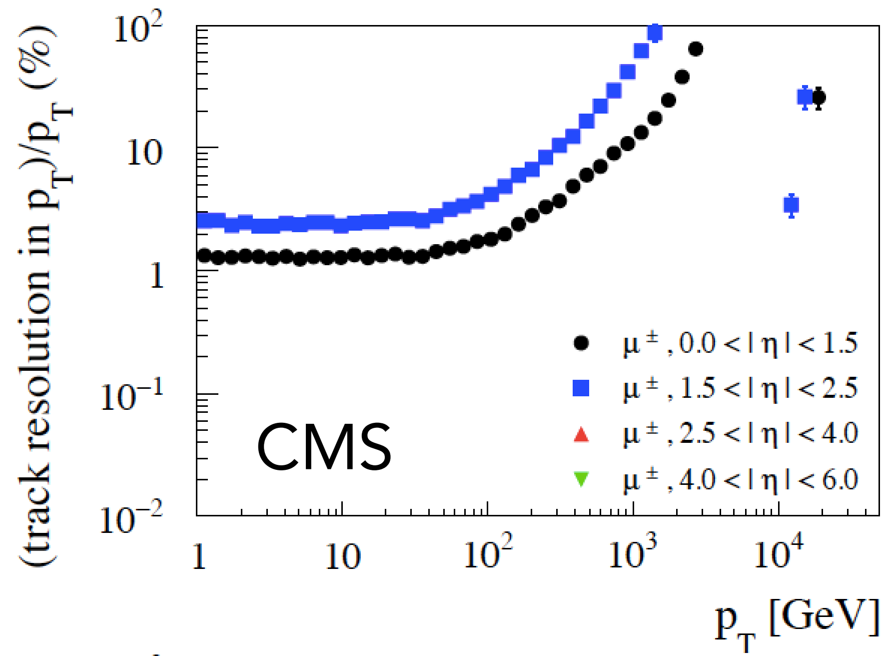
Detector Layout

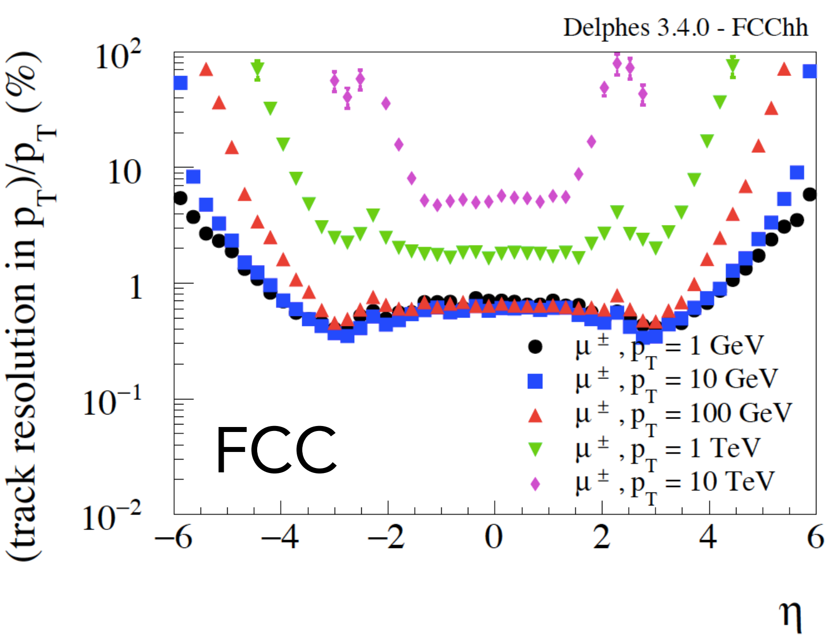


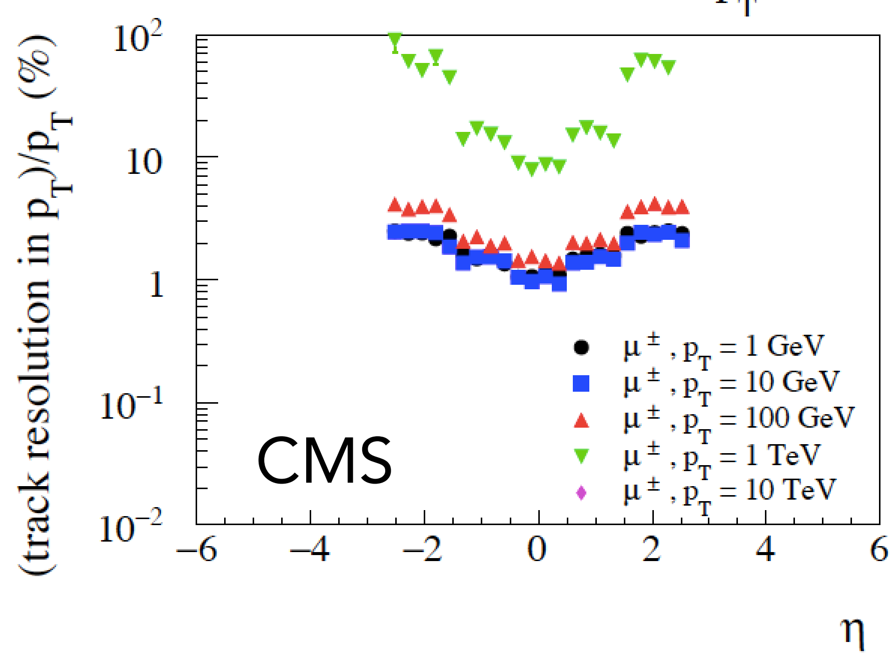
W. Riegler layout, proposed 13/08/2016

Muon Resolution

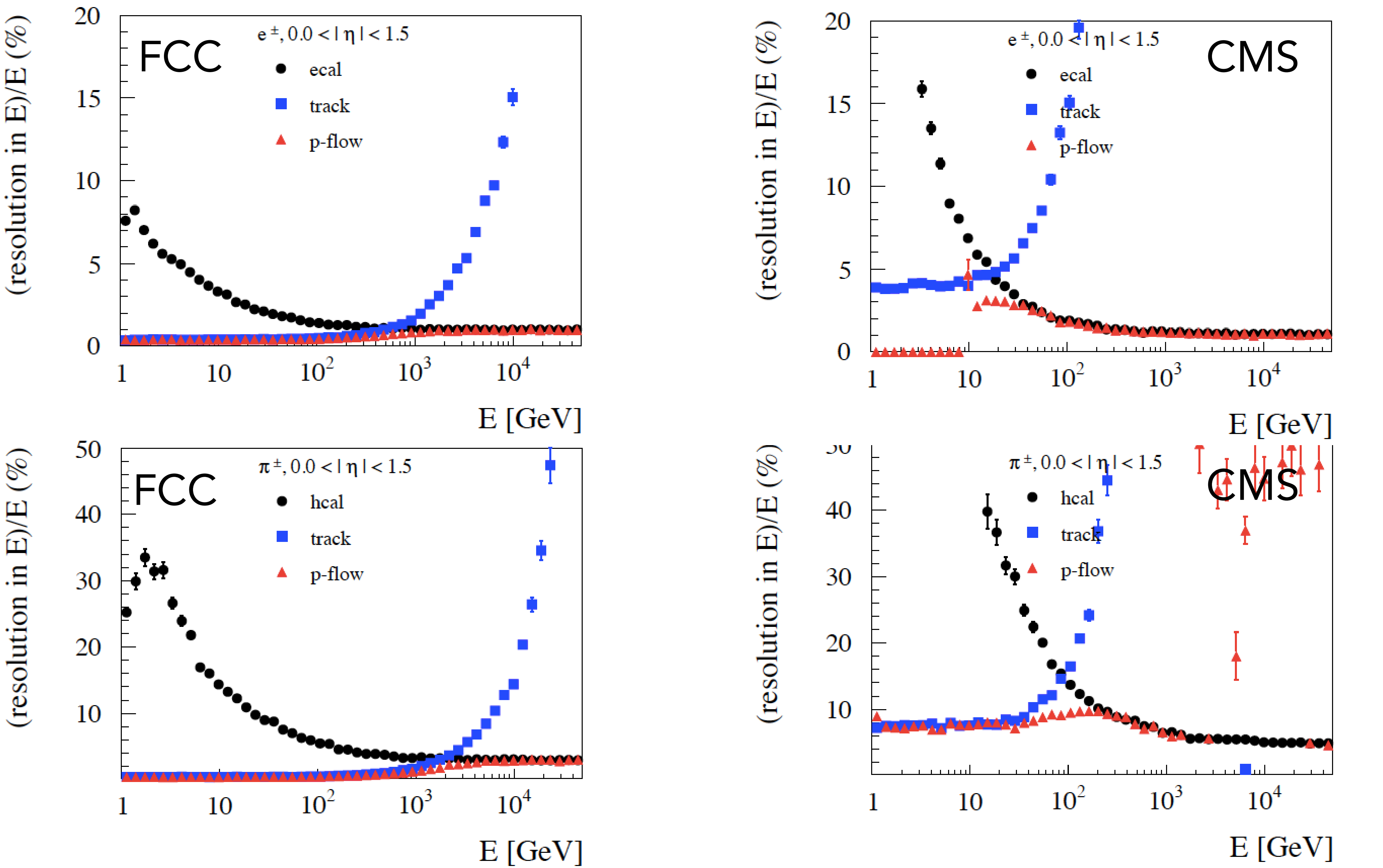




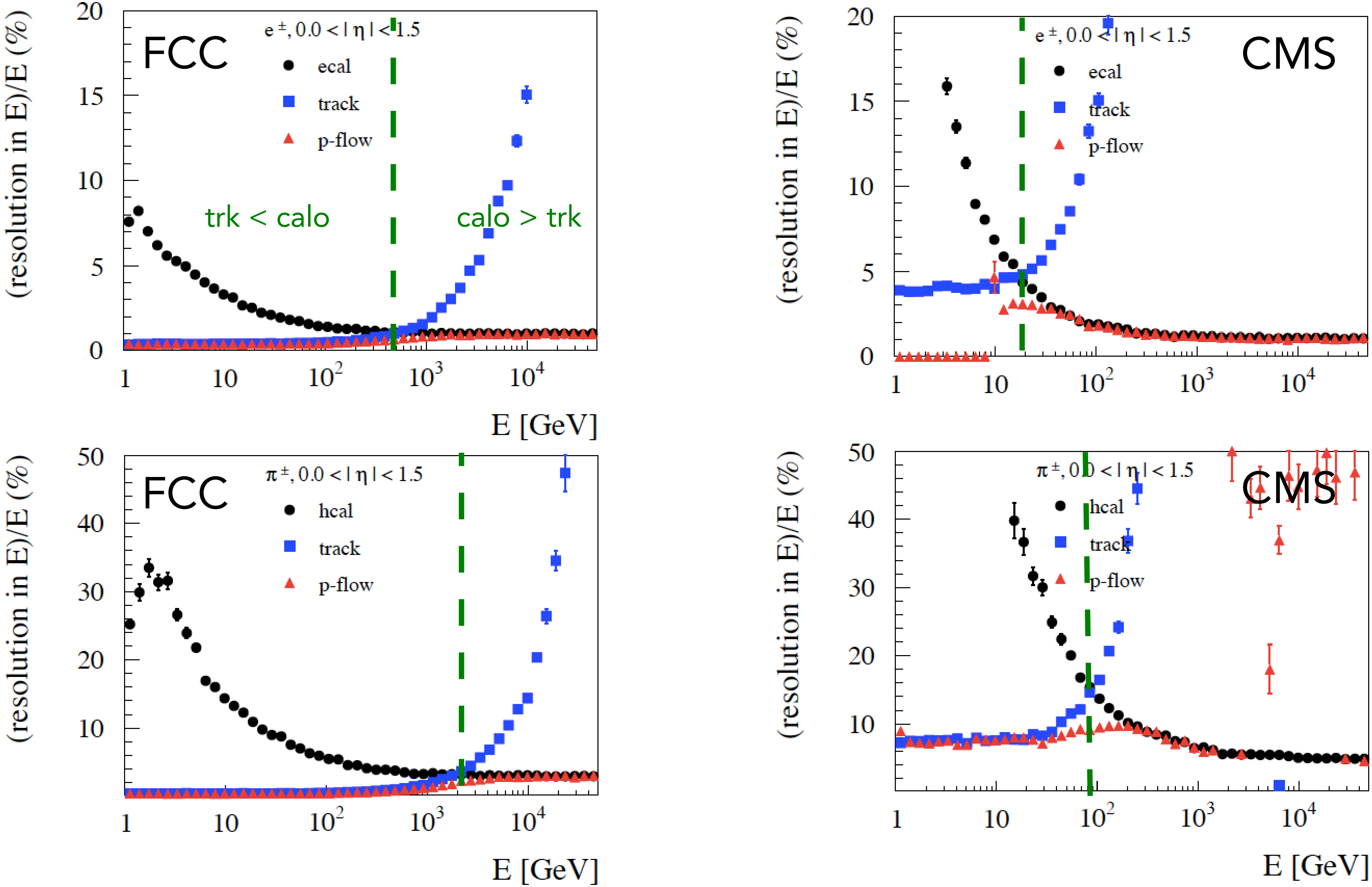




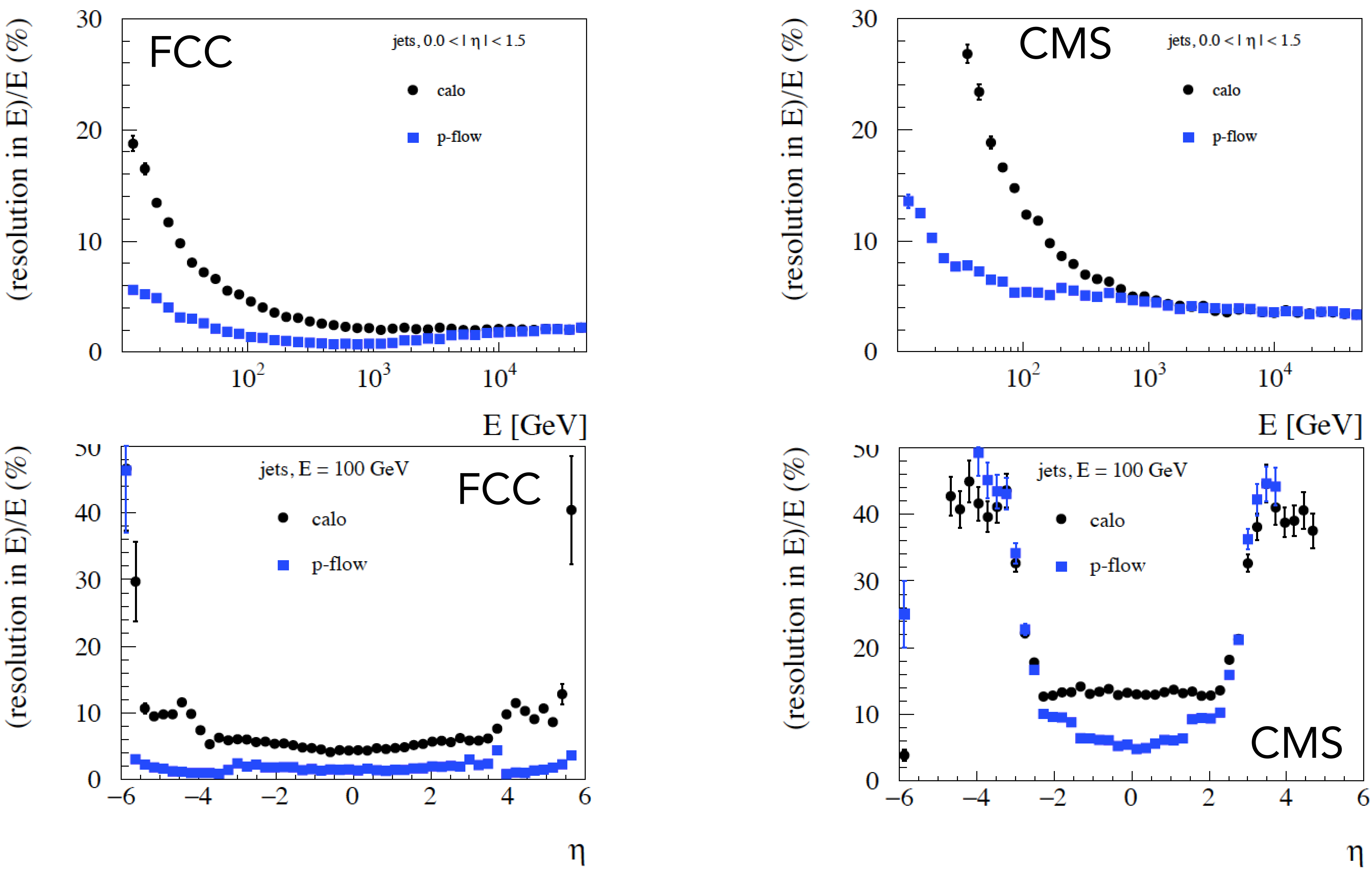
Particle-Flow (I)



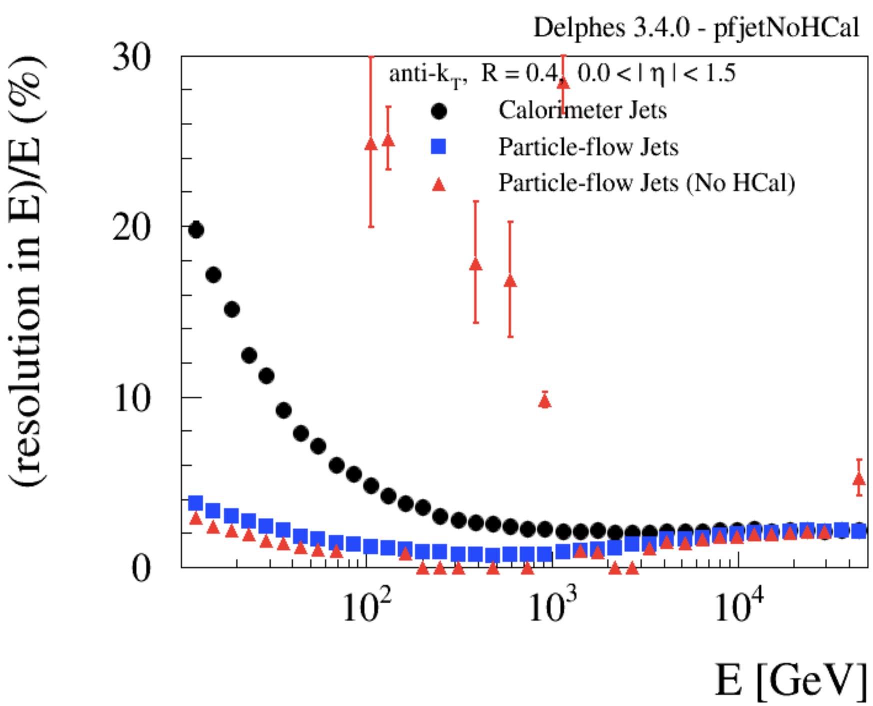
Particle-Flow (I)

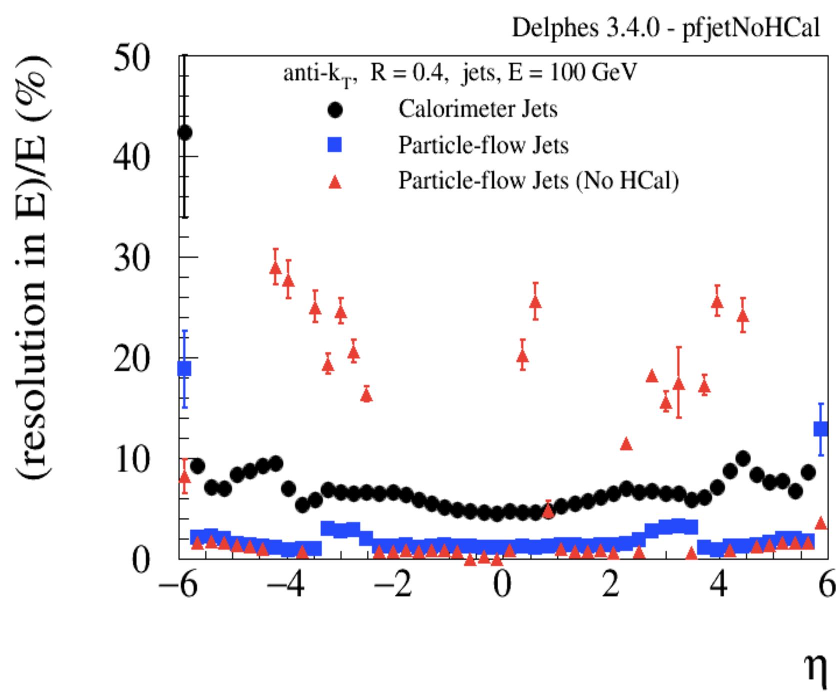


Particle-Flow (II)



Particle-Flow (No HCal)

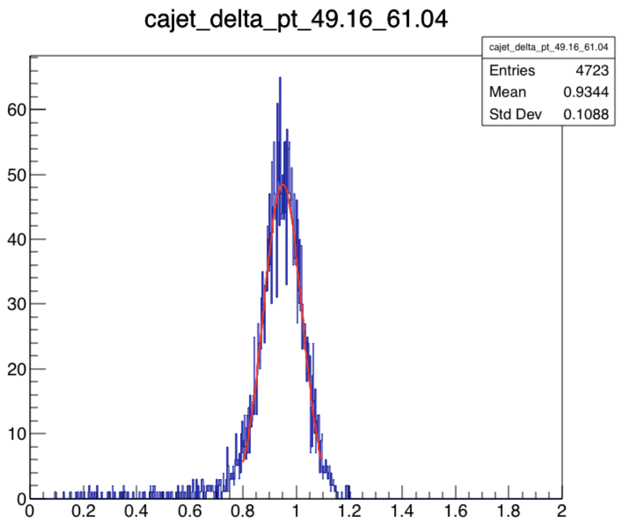




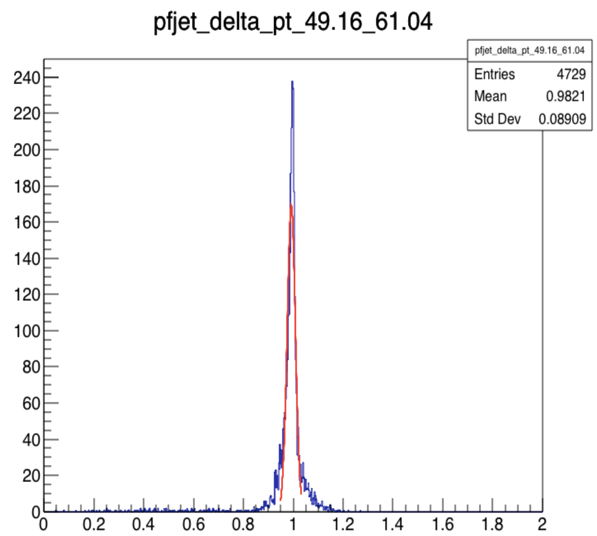
Particle-Flow (No HCal)

E = 50 GeV

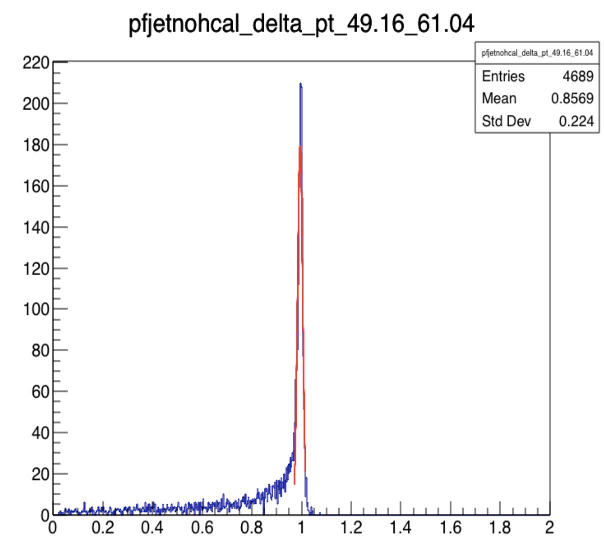
CaloJets



PFJets

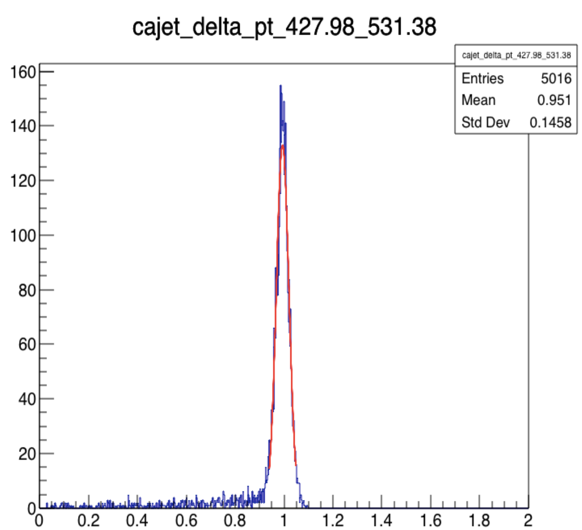
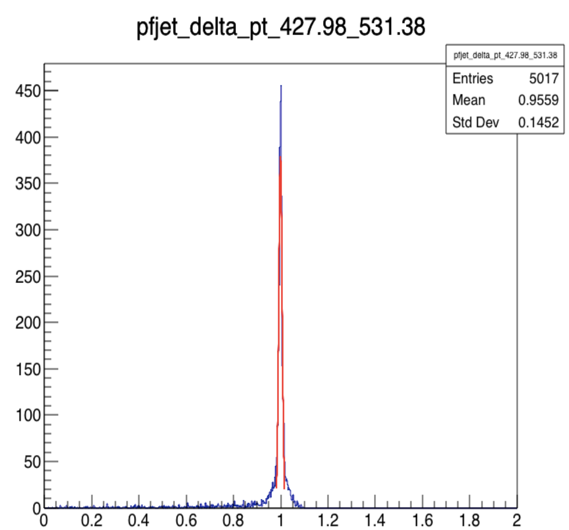
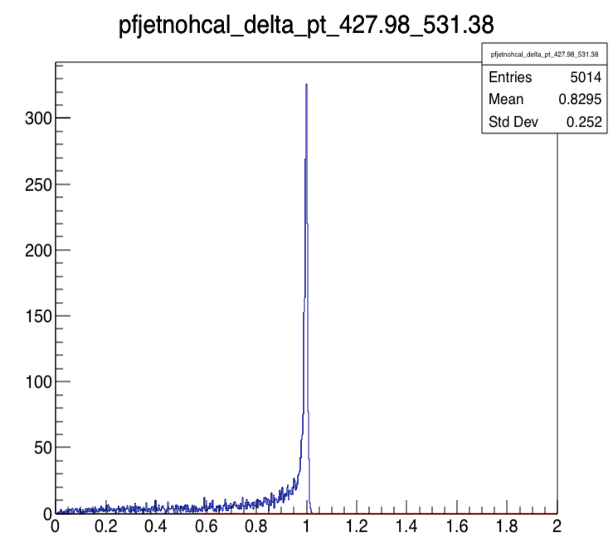


PFJets NoHCAL

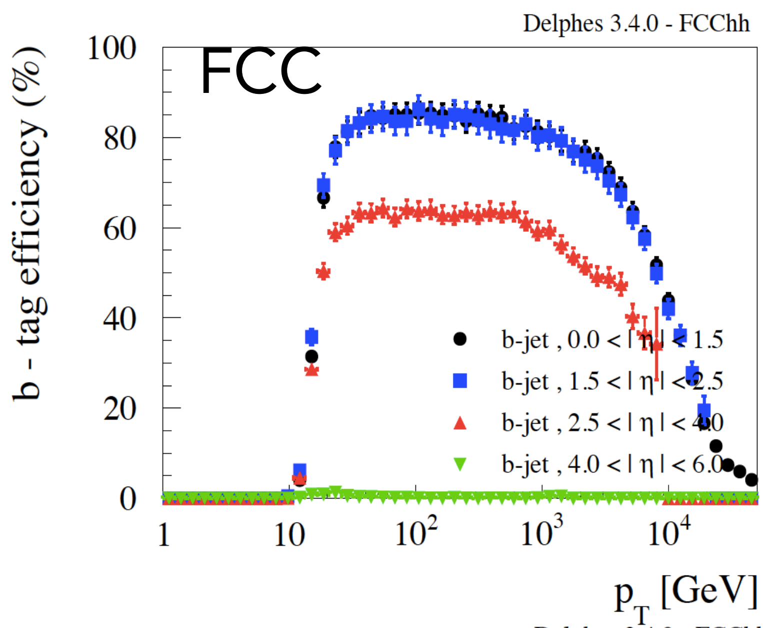


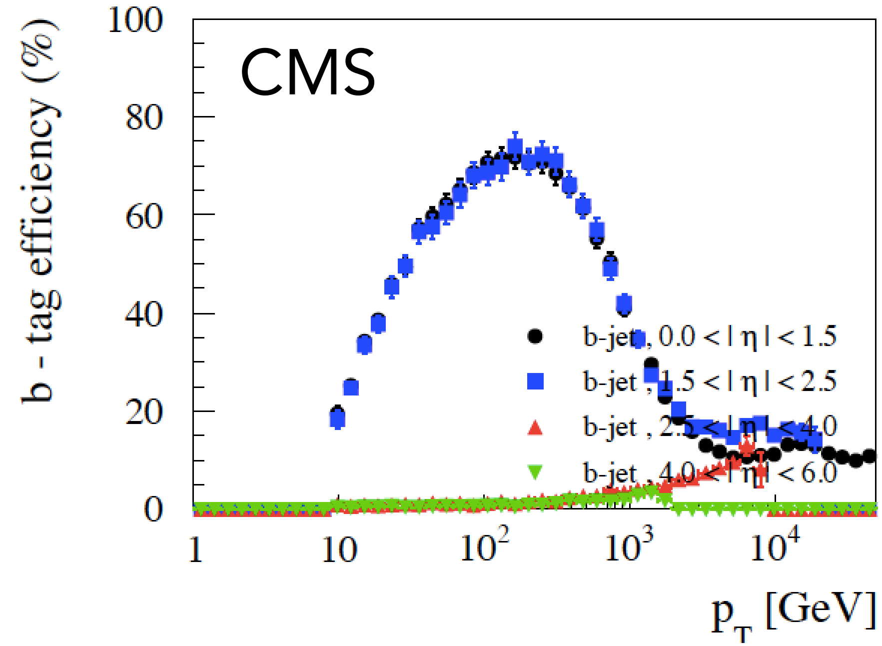
Particle-Flow (No HCal)

E = 500 GeV

CaloJets	PFJets	PFJets NoHCAL
		

B-Tagging


Delphes 3.4.0 - FCChh
FCC
b - tag efficiency (%)
b-jet , 0.0 < | η | < 1.5
b-jet , 1.5 < | η | < 2.5
b-jet , 2.5 < | η | < 4.0
b-jet , 4.0 < | η | < 6.0
p_T [GeV]


CMS
b - tag efficiency (%)
b-jet , 0.0 < | η | < 1.5
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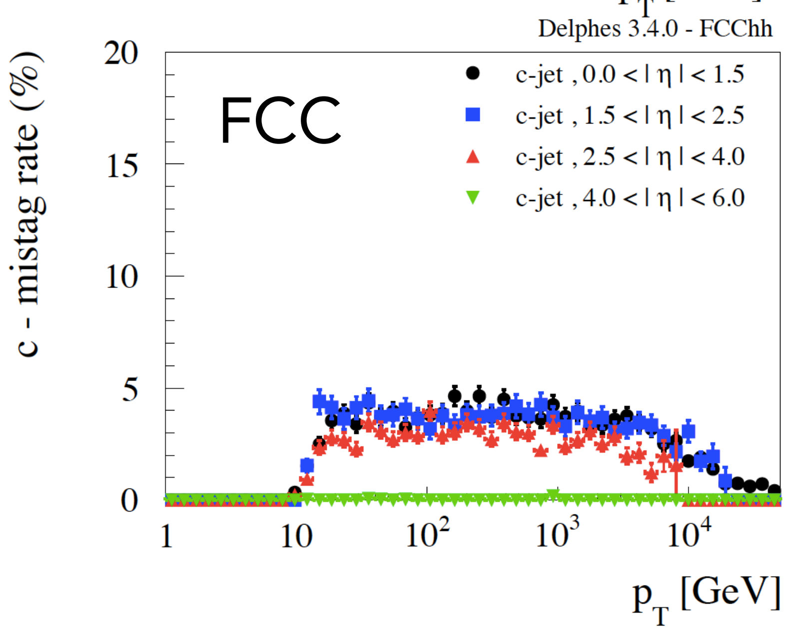
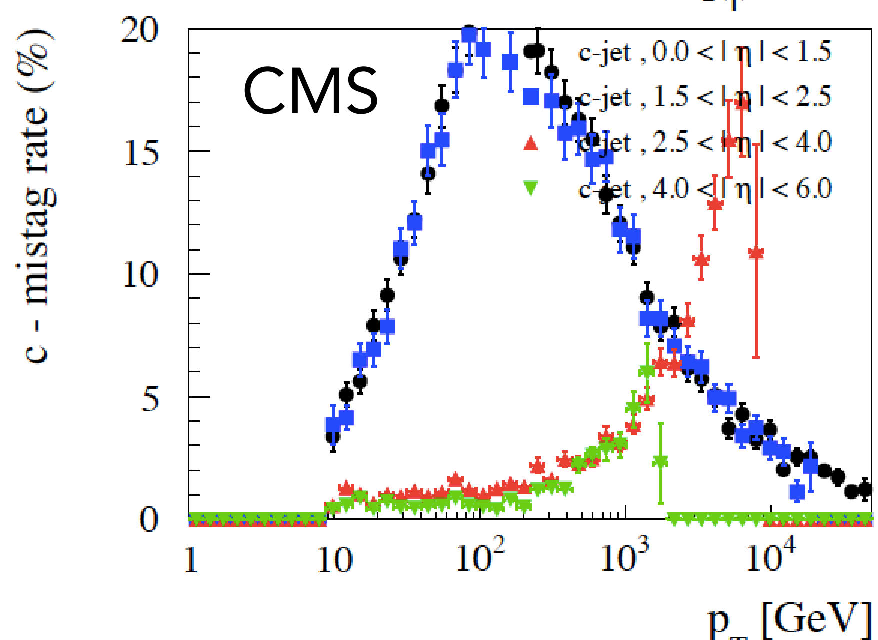
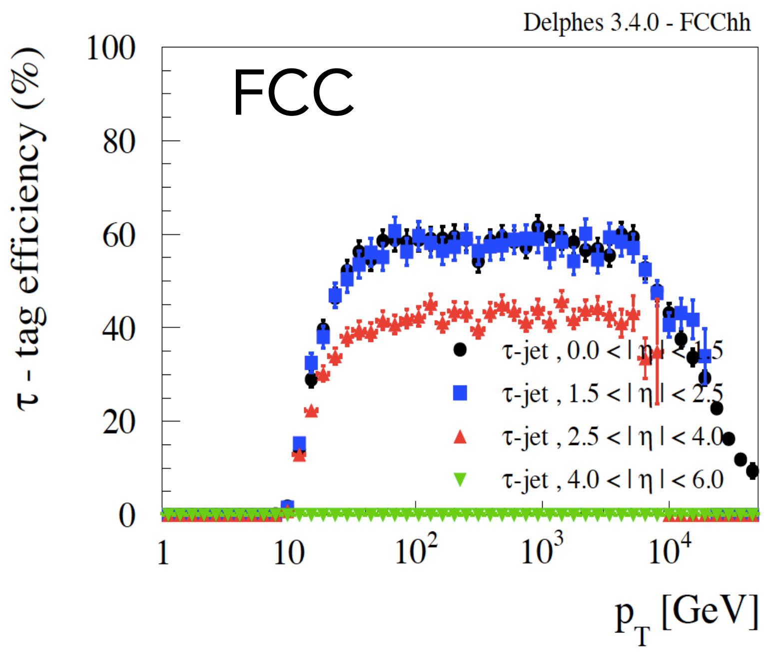
b-jet , 2.5 < | η | < 4.0
b-jet , 4.0 < | η | < 6.0
p_T [GeV]

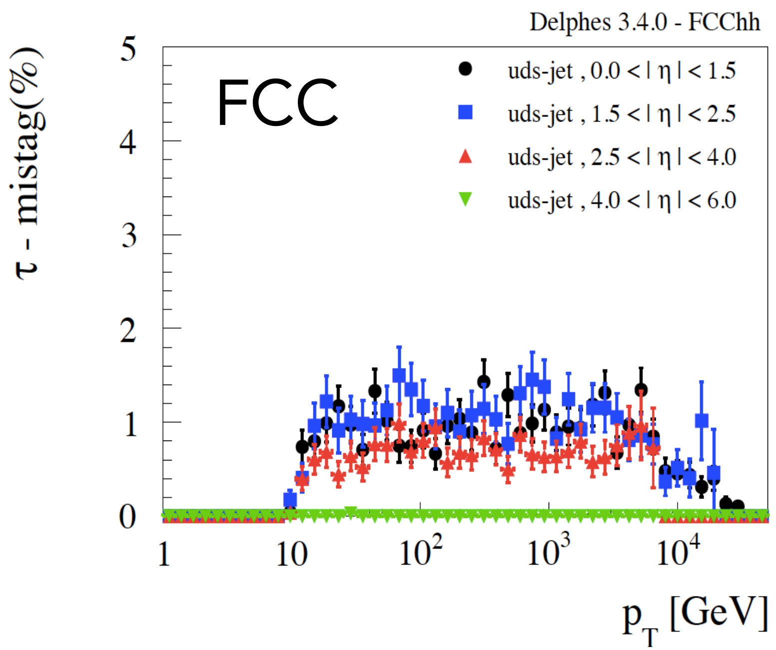

Delphes 3.4.0 - FCChh
FCC
c - mistag rate (%)
c-jet , 0.0 < | η | < 1.5
c-jet , 1.5 < | η | < 2.5
c-jet , 2.5 < | η | < 4.0
c-jet , 4.0 < | η | < 6.0
p_T [GeV]


CMS
c - mistag rate (%)
c-jet , 0.0 < | η | < 1.5
c-jet , 1.5 < | η | < 2.5
c-jet , 2.5 < | η | < 4.0
c-jet , 4.0 < | η | < 6.0
p_T [GeV]

Tau-Tagging



Delphes 3.4.0 - FCChh
FCC
τ - tag efficiency (%)
τ-jet , 0.0 < | η | < 1.5
τ-jet , 1.5 < | η | < 2.5
τ-jet , 2.5 < | η | < 4.0
τ-jet , 4.0 < | η | < 6.0
p_T [GeV]



Delphes 3.4.0 - FCChh
FCC
τ - mistag(%)
uds-jet , 0.0 < | η | < 1.5
uds-jet , 1.5 < | η | < 2.5
uds-jet , 2.5 < | η | < 4.0
uds-jet , 4.0 < | η | < 6.0
p_T [GeV]

Analysis Example

Example

- Start with a simple physics analysis:

Signal: $p\,p \rightarrow H \rightarrow 2\,e\,2\,\mu$

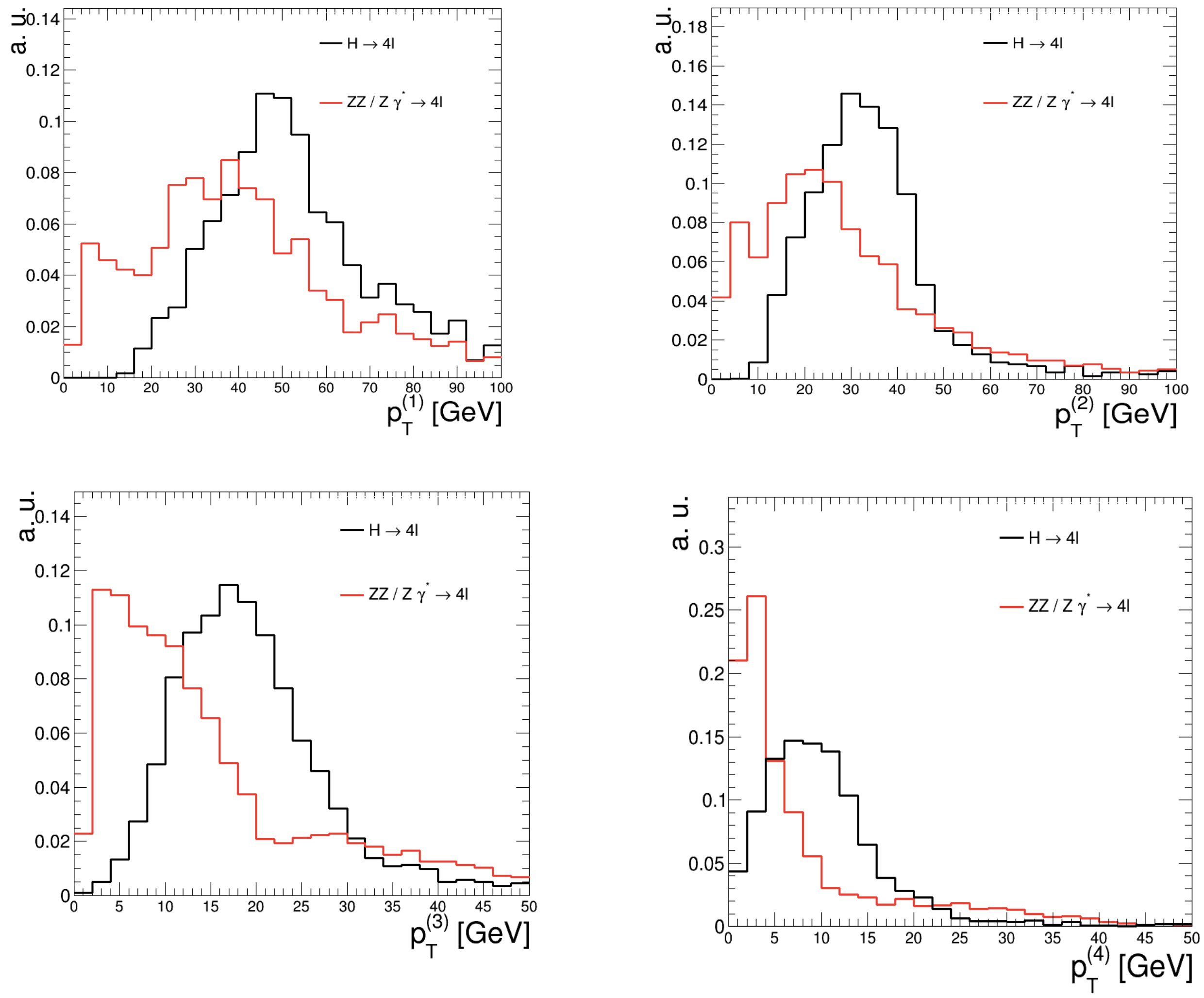
Background: $p\,p \rightarrow 2\,e\,2\,\mu$ ($m_{ll} > 5$ GeV)

- Workflow:

  - External LHE files produced with MG@LO
  - FCC-hh Delphes card interfaced with FCCSW
  - FCCSW runs Pythia8+Delphes and produces ROOT tree
  - analysis is implemented in HEPPY, which produces event selection/flat tree

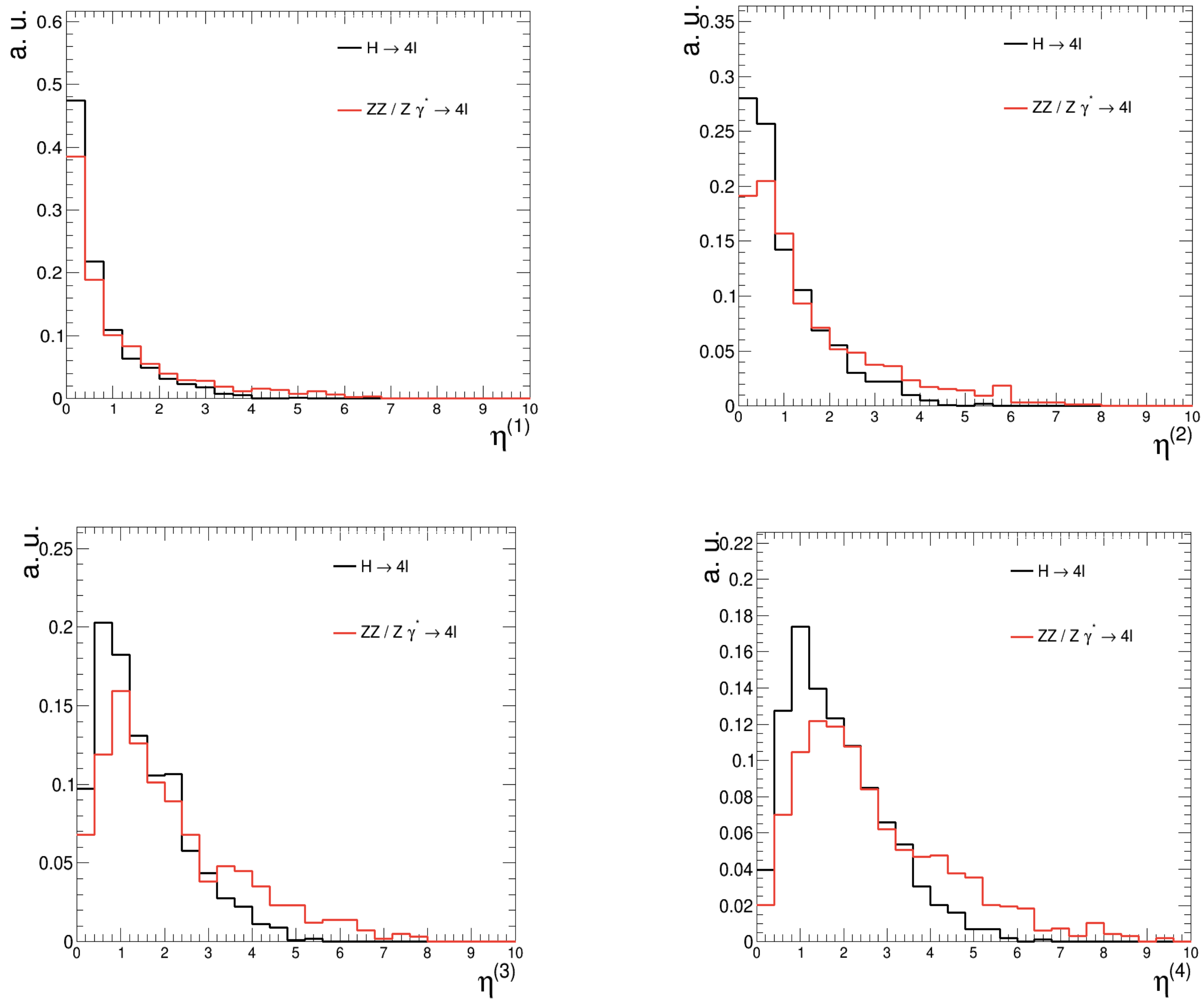
Gen Level (I)

p_T (l)



Gen Level (II)

η(l)



Event Selection

CMS inspired selection (can be certainly improved ...):

signal

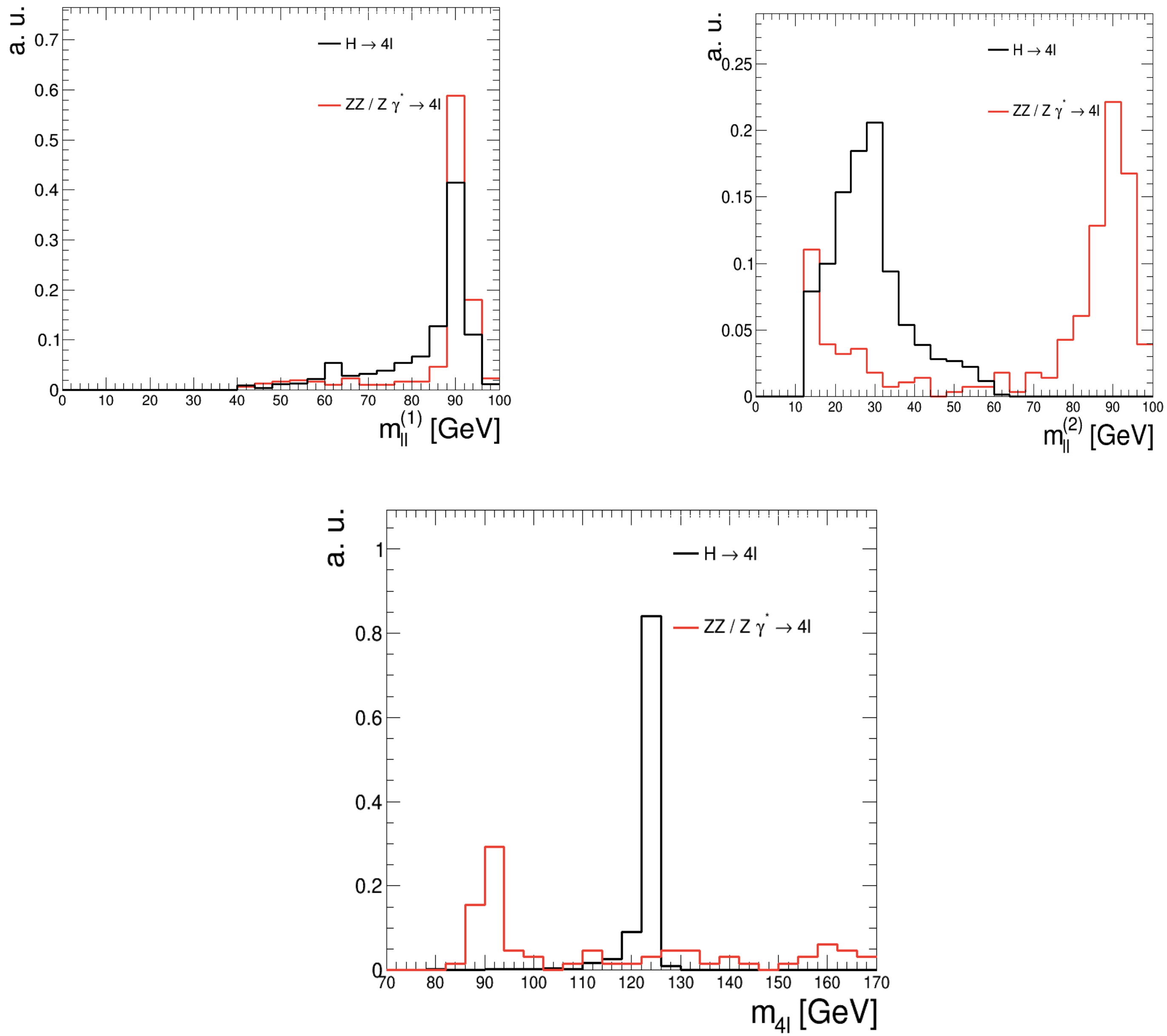
All events	2000	1.00	1.0000
At least two electrons with pT > 7	1115	0.56	0.5575
At least two muons with pT > 5	764	0.69	0.3820
At least one Z -> e+ e- candidates	764	1.00	0.3820
At least one Z -> mu+ mu- candidates	764	1.00	0.3820
40 < mZ1 < 120.	749	0.98	0.3745
12 < mZ2 < 120.	679	0.91	0.3395
Exactly two Z candidates	675	0.99	0.3375
leading lepton pT > 20	672	1.00	0.3360
sub-leading lepton pT > 10	671	1.00	0.3355

bkg

All events	2000	1.00	1.0000
At least two electrons with pT > 7	804	0.40	0.4020
At least two muons with pT > 5	447	0.56	0.2235
At least one Z -> e+ e- candidates	447	1.00	0.2235
At least one Z -> mu+ mu- candidates	447	1.00	0.2235
40 < mZ1 < 120.	423	0.95	0.2115
12 < mZ2 < 120.	307	0.73	0.1535
Exactly two Z candidates	306	1.00	0.1530
leading lepton pT > 20	301	0.98	0.1505
sub-leading lepton pT > 10	301	1.00	0.1505

Leptons $|\eta| < 6$!

Reco Level



Conclusions

- FCC-hh Delphes card validation plots have been shown
- Card is ready for use

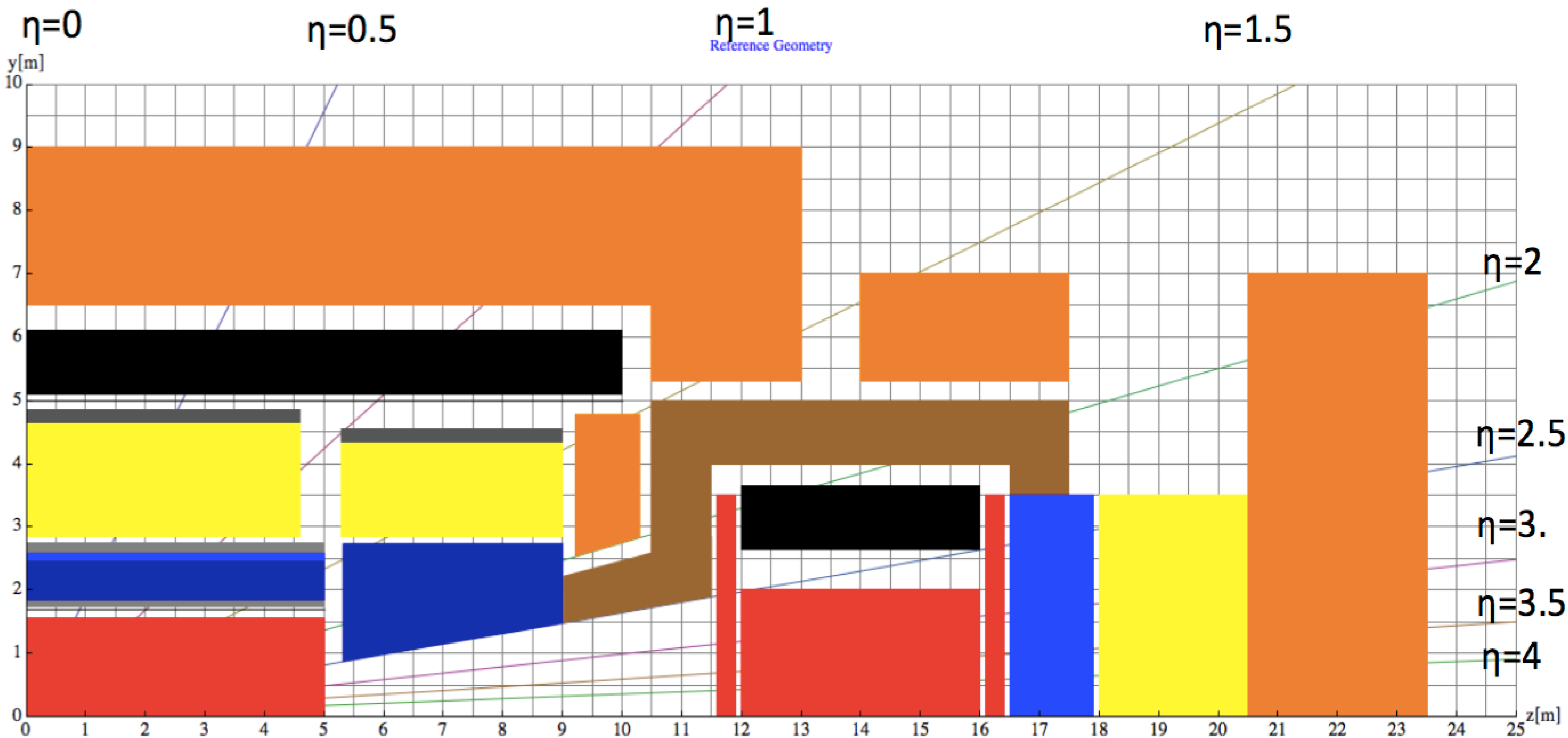
- Parameterisation and workflow tested on a simple physics analysis with low number of events, at LO

- FCCSW + Heppy provide user-friendly event generation + analysis framework
  --> workflow needs to be properly documented
  --> need to address:

  - LO/NLO generation (MG+Pythia8 generation within FCCSW)
  - setup user-friendly procedure for sending jobs in parallel

Back-up

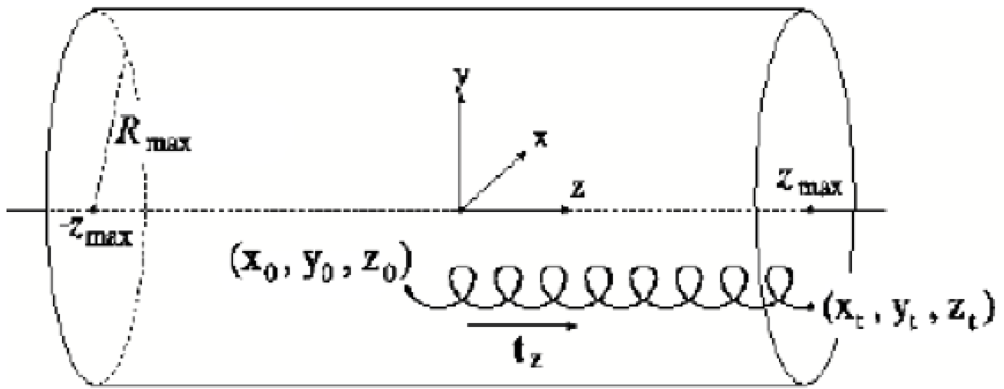
Detector Layout



W. Riegler layout, proposed 13/08/2016

Particle Propagation

- Propagation parameters FCC-hh (CMS):



  - magnetic field, B = 4T (4T)
  - radius, R = 1.5 m (1.29 m)
  - half-length, z_{max} = 5.0 m (3.0 m)

- Both tracker resolution and efficiency are provided as function of (p_T , eta, phi, p) and particle pdg Code.

  tracker resolution given by tkLayout,

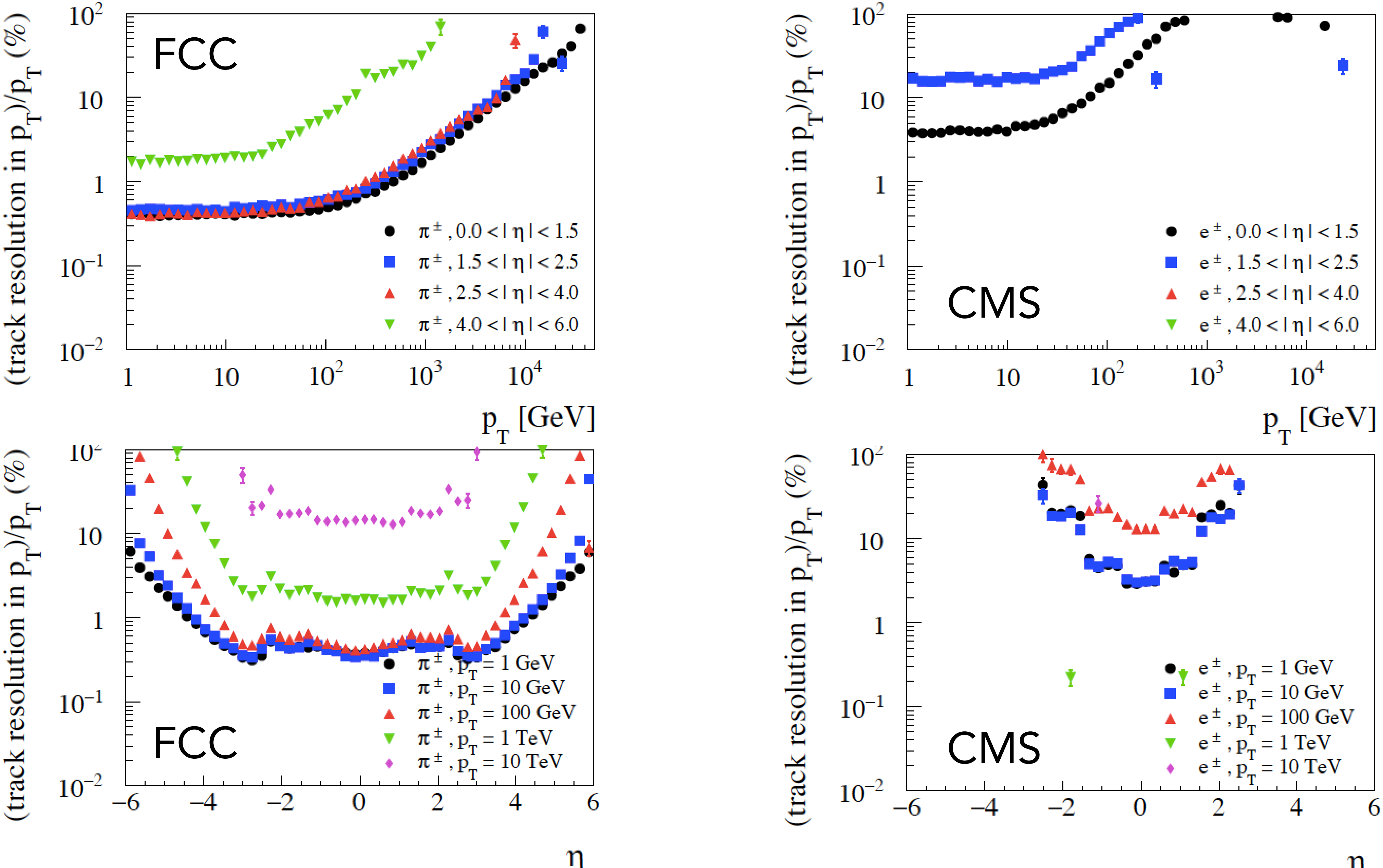
  efficiences are ad hoc for now (inspired by ALTAS, CMS).

- Muons are special, at this stage they are treated according to combined tracker + muon

  |eta| < 2: extended analytical resolution derived by Werner for eta = 0

  |eta| > 2: pure tracker resolution (tkLayout)

Tracking Resolution



Muon resolution

$$\sigma_y = \frac{1}{\sqrt{3}} L_{Calo}\, \theta_0$$

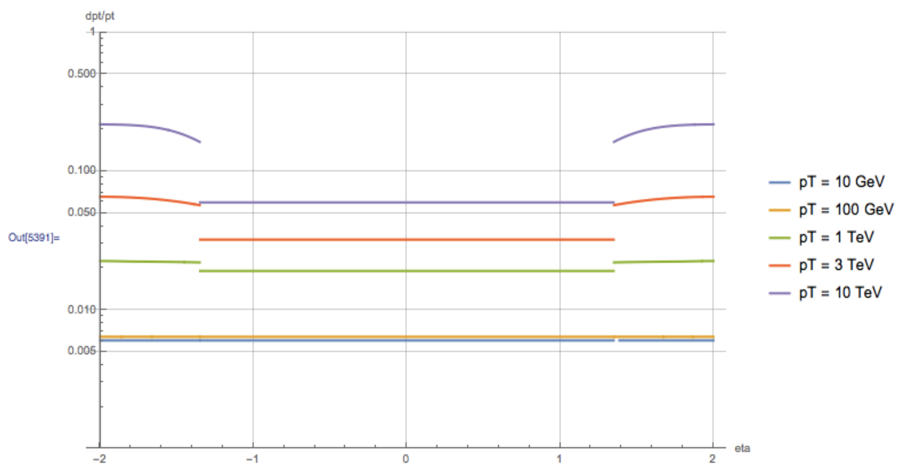
Muon System standalone $$\frac{\Delta p}{p} = \frac{2p}{0.3 L_1 B} \sqrt{\theta_0^2 + \sigma_{theta}^2} \qquad \theta_0 = \frac{0.0136}{\beta p [GeV/c]} \sqrt{\frac{L_{Calo}}{X0_{Calo}}} \left(1 + 0.038 \log \frac{L_{Calo}}{X0_{Calo}}\right)$$

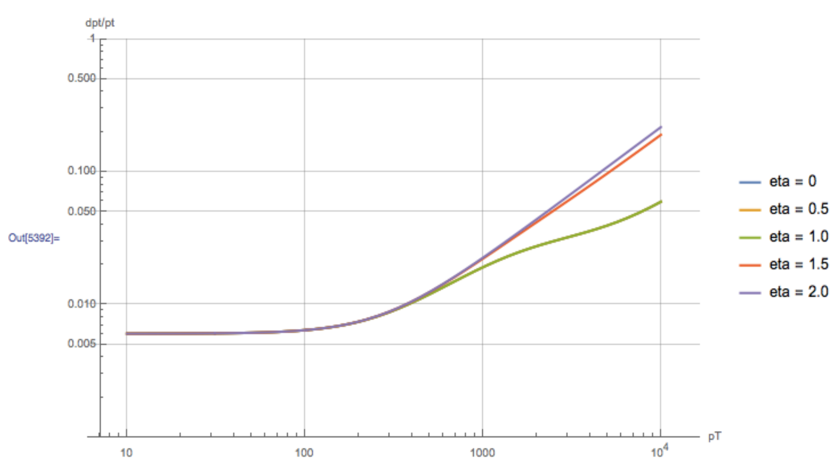
Inner Tracker $$\frac{\Delta p}{p} = \frac{p}{0.3B} \frac{\sigma}{L_0^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p}{0.3B} \frac{\sigma}{L_0^2} \sqrt{\frac{720}{N+5}} \quad N \gg 1$$

Combined $$\frac{\Delta p}{p} = \frac{p}{0.3B} \frac{\sigma_0}{L_0^2} \sqrt{\frac{720 N^3 (c_1 \sigma_0^2 + c_2 \sigma_1^2)}{(N+1)(N+2)(c_3 \sigma_0^2 + c_4 \sigma_1^2)}} \qquad (211)$$

$$\begin{aligned}
c_1 &= 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \\
c_2 &= L_0^2 (N+1)(N+2) \\
c_3 &= 3\left[L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N)\right] + 60N^3 \frac{L_1^4}{L_0^2} - 120N^3 \frac{L_1^3}{L_0} \\
c_4 &= L_0^2(N-1)(N+1)(N+2)(N+3)
\end{aligned}$$

Muon resolution





- $|\eta| < 1.35$

  sin(θ) dependence cancels out.
  -> resolution flat over η

- $1.35 < |\eta| < 2.0$

  jump due to muon station being closer

- $2.0 < |\eta| < 6.0$

  simply assume tracker resolution

Calorimetry

- ECAL/HCAL **segmentation is specified** in eta/phi coordinates

- Each particle that reaches the calorimeters **deposits a fraction of its energy** in one ECAL cell (f_{EM}) and HCAL cell (f_{HAD}), depending on its type:

particles	f_{EM}	f_{HAD}
e γ π^0	1	0
Long-lived neutral hadrons (K^0_S , Λ^0)	0.3	0.7
ν μ	0	0
others	0	1

- Particle energy is **smeared** according to the calorimeter cell it reaches with typical resolution:

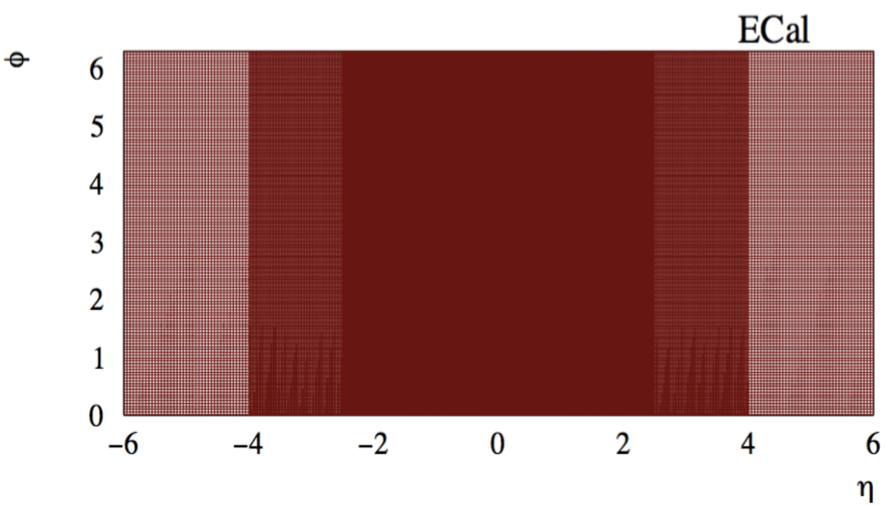
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S(\eta)}{\sqrt{E}}\right)^2 + \left(\frac{N(\eta)}{E}\right)^2 + C(\eta)^2$$

No Energy sharing between the neighboring cells
No longitudinal segmentation, no shower
No effect of magnetic field

ECAL (I)

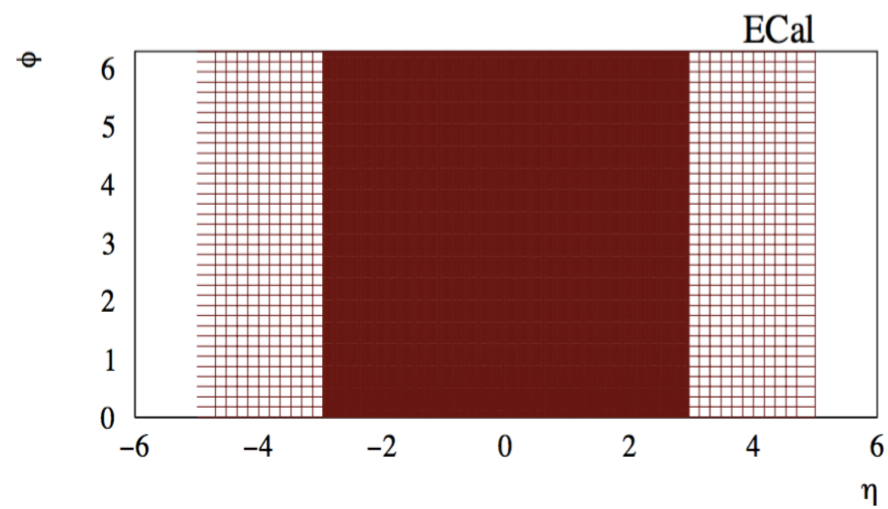
FCC

	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 2.5$	0.0125×0.0125	$\frac{10\%}{\sqrt{E}} + 1\%$
$2.5 < \lvert\eta\rvert < 4.0$	0.025×0.025	$\frac{10\%}{\sqrt{E}} + 1\%$
$4.0 < \lvert\eta\rvert < 6.0$	0.05×0.05	$\frac{10\%}{\sqrt{E}} + 1\%$

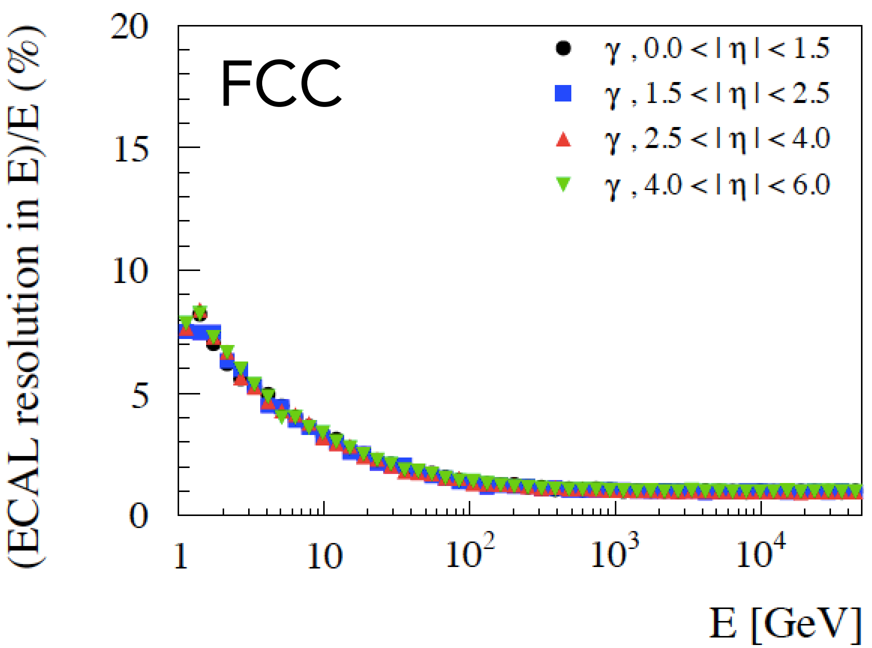


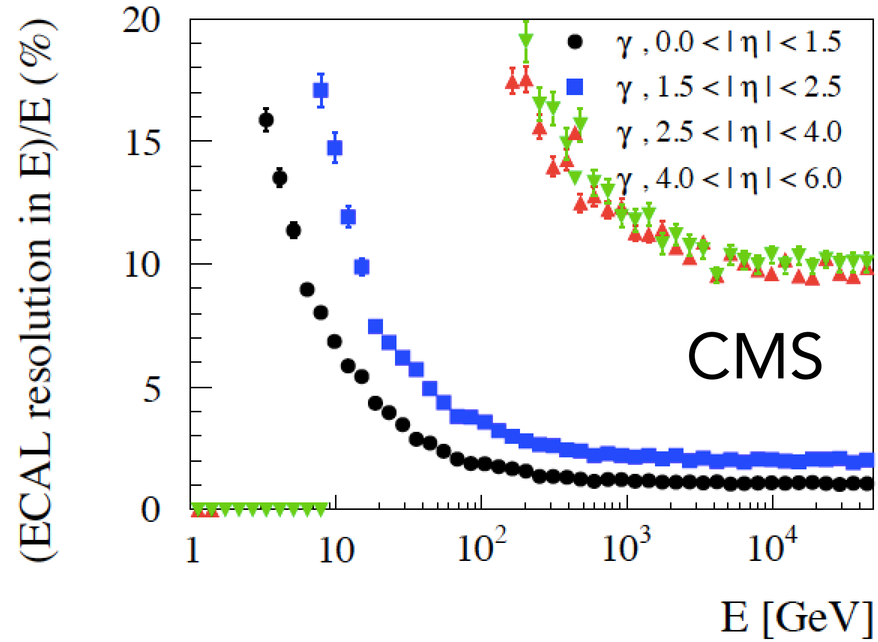
CMS

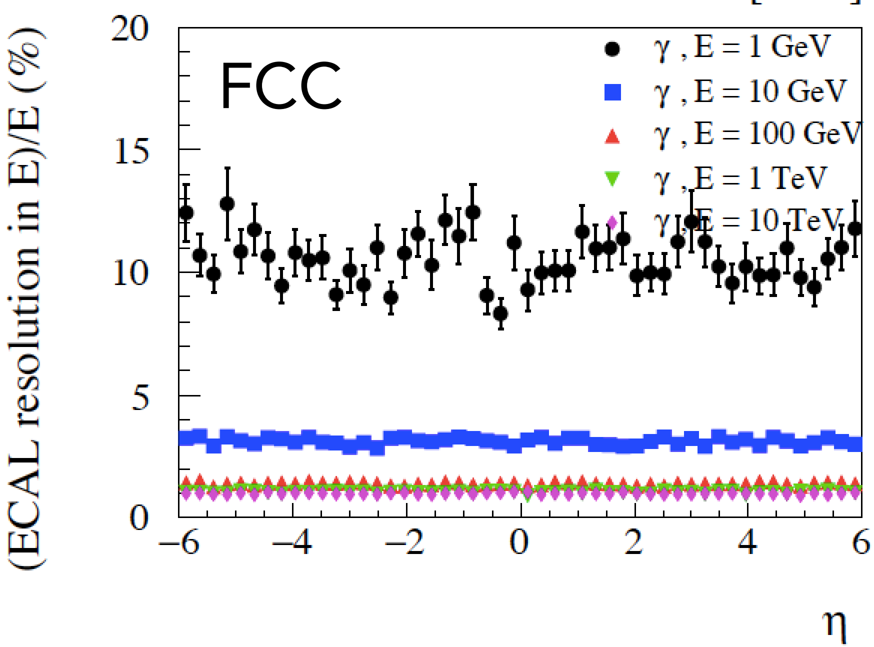
	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 1.5$	0.02×0.02	$\frac{11\%}{\sqrt{E}} + 1\%$
$1.5 < \lvert\eta\rvert < 2.5$	0.02×0.02	$\frac{11\%}{\sqrt{E}} + 1\%$
$2.5 < \lvert\eta\rvert < 5.0$	$0.175 \times (0.175 - 0.35)$	$\frac{270\%}{\sqrt{E}} + 13\%$

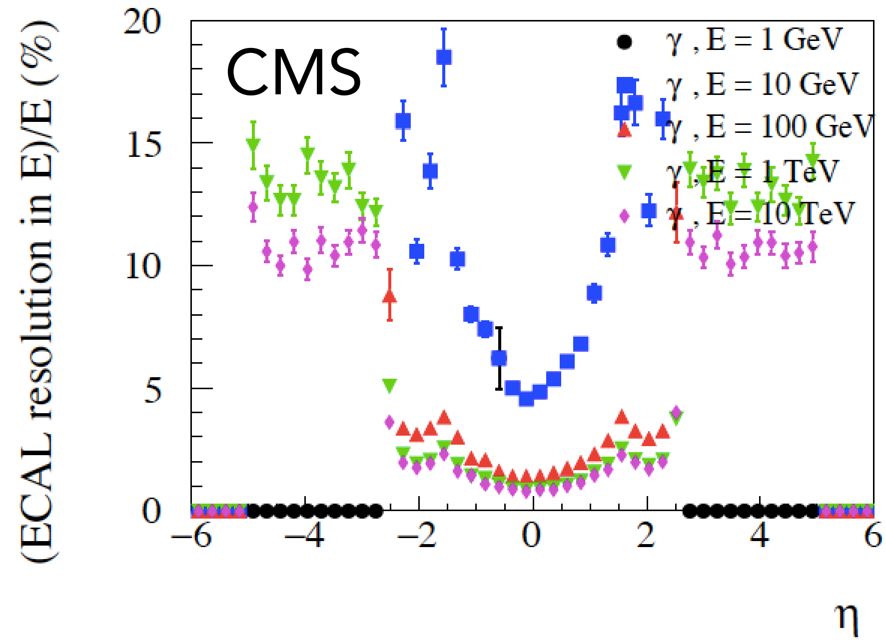


ECAL (II)


FCC
(ECAL resolution in E)/E (%)
E [GeV]
γ , 0.0 < | η | < 1.5
γ , 1.5 < | η | < 2.5
γ , 2.5 < | η | < 4.0
γ , 4.0 < | η | < 6.0


CMS
(ECAL resolution in E)/E (%)
E [GeV]
γ , 0.0 < | η | < 1.5
γ , 1.5 < | η | < 2.5
γ , 2.5 < | η | < 4.0
γ , 4.0 < | η | < 6.0

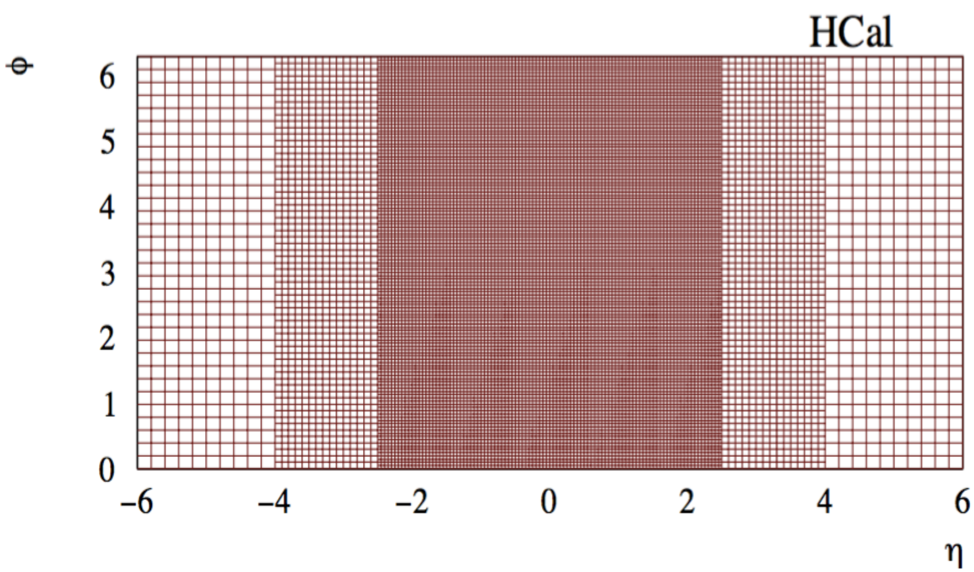

FCC
(ECAL resolution in E)/E (%)
η
γ , E = 1 GeV
γ , E = 10 GeV
γ , E = 100 GeV
γ , E = 1 TeV
γ , E = 10 TeV


CMS
(ECAL resolution in E)/E (%)
η
γ , E = 1 GeV
γ , E = 10 GeV
γ , E = 100 GeV
γ , E = 1 TeV
γ , E = 10 TeV

HCAL (I)

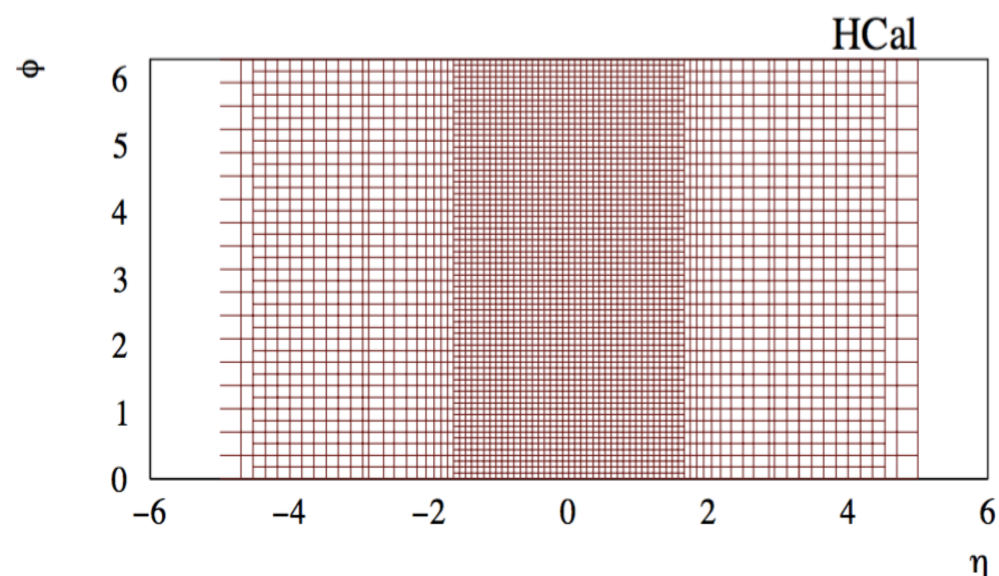
FCC

	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \|\eta\| < 2.5$	0.05×0.05	$\frac{50\%}{\sqrt{E}} + 3\%$
$2.5 < \|\eta\| < 4.0$	0.1×0.1	$\frac{50\%}{\sqrt{E}} + 3\%$
$4.0 < \|\eta\| < 6.0$	0.2×0.2	$\frac{100\%}{\sqrt{E}} + 5\%$

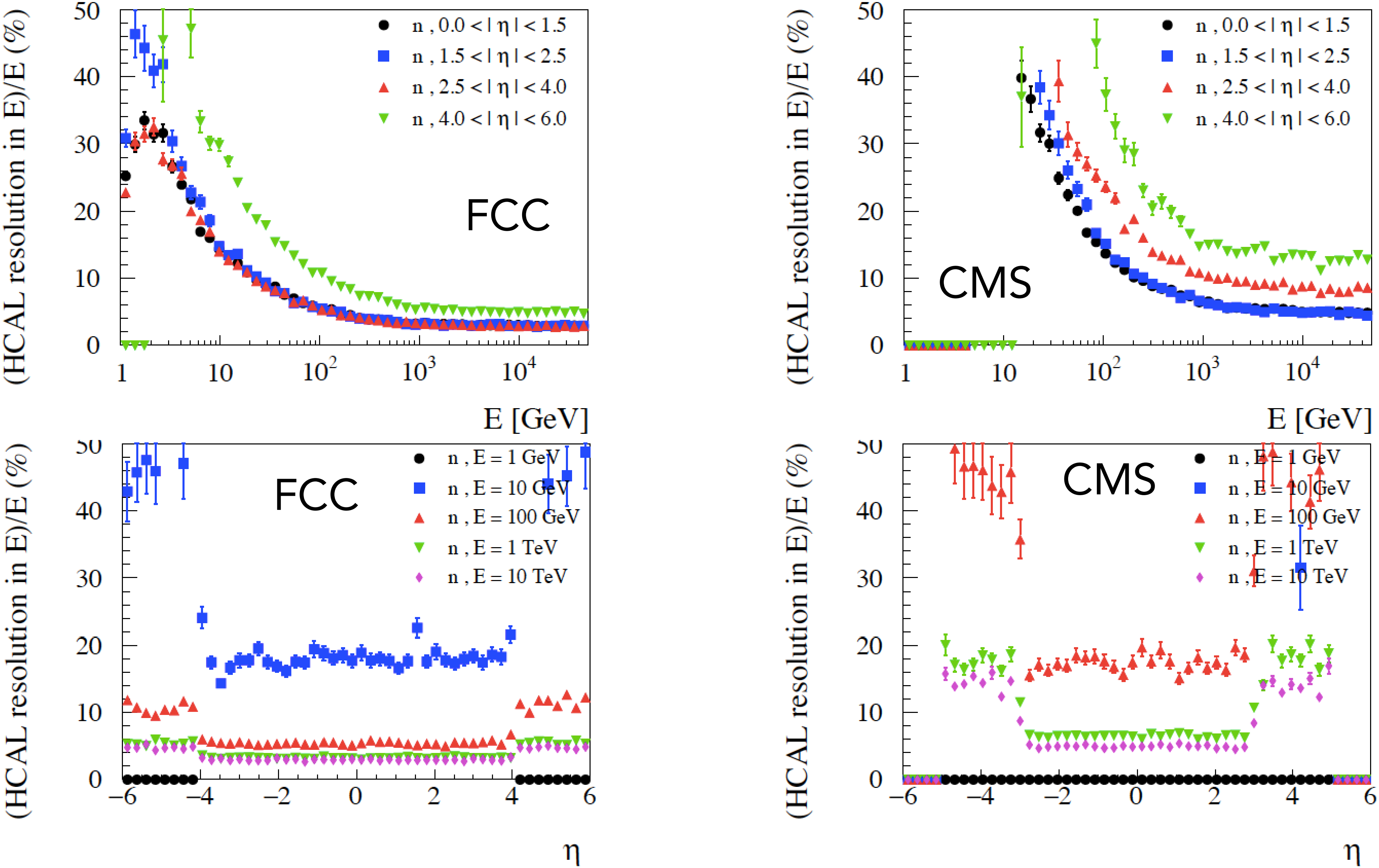


CMS

	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \|\eta\| < 1.5$	0.1×0.1	$\frac{150\%}{\sqrt{E}} + 5\%$
$1.5 < \|\eta\| < 3.0$	0.2×0.2	$\frac{150\%}{\sqrt{E}} + 5\%$
$3.0 < \|\eta\| < 5.0$	$0.175 \times (0.175 - 0.35)$	$\frac{270\%}{\sqrt{E}} + 13\%$



HCAL (II)



(HCAL resolution in E)/E (%)
n , 0.0 < | η | < 1.5
n , 1.5 < | η | < 2.5
n , 2.5 < | η | < 4.0
n , 4.0 < | η | < 6.0
FCC
CMS
E [GeV]
n , E = 1 GeV
n , E = 10 GeV
n , E = 100 GeV
n , E = 1 TeV
n , E = 10 TeV
η

Particle-Flow

- Idea: Reproduce realistically the performances of the Particle-Flow algorithm.

- In practice, in DELPHES use **tracking and calo** info to reconstruct high reso. input objects for later use (jets, E_T^{miss}, H_T)

→ If **σ(trk) < σ(calo) (low energy)**

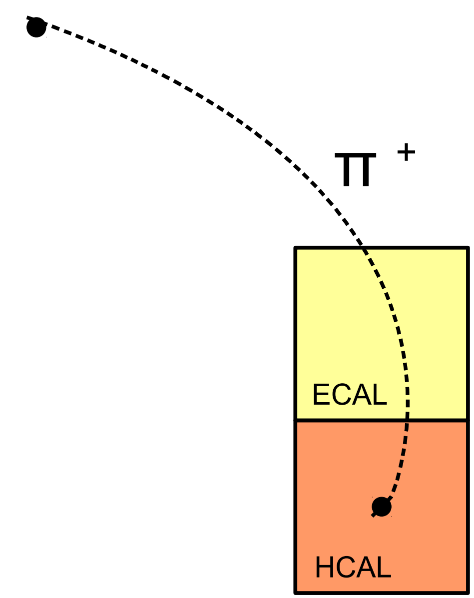
Example: A pion of 10 GeV

$E^{HCAL}(\pi^+) = 9$ GeV

$E^{TRK}(\pi^+) = 11$ GeV

Particle-Flow algorithm creates:

PF-track, with energy $E^{PF\text{-}trk} = 11$ GeV



Separate neutral and charged calo deposits has crucial implications for pile-up subtraction

Particle-Flow

- Idea: Reproduce realistically the performances of the Particle-Flow algorithm.

- In practice, in DELPHES use **tracking and calo** info to reconstruct high reso. input objects for later use (jets, E_T^{miss}, H_T)

→ If **σ(trk) < σ(calo) (low energy)**

Example: A pion of 10 GeV

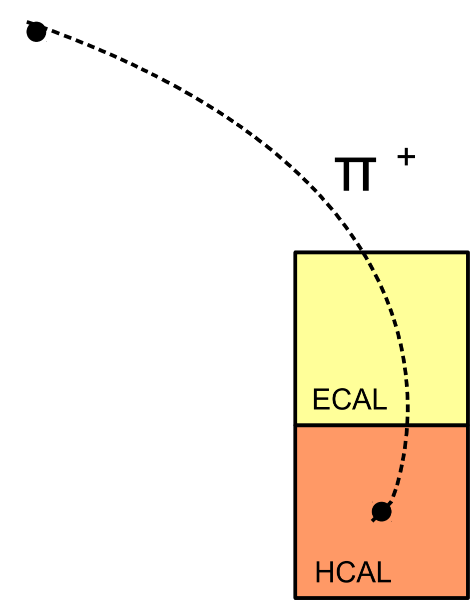
$E^{HCAL}(\pi^+) = 15$ GeV

$E^{TRK}(\pi^+) = 11$ GeV

Particle-Flow algorithm creates:

PF-track, with energy $E^{PF\text{-}trk} = 11$ GeV

PF-tower, with energy $E^{PF\text{-}tower} = 4$ GeV



Separate neutral and charged calo deposits has crucial implications for pile-up subtraction

Particle-Flow

DELPHES fast simulation

CERN

- Idea: Reproduce realistically the performances of the Particle-Flow algorithm.

- In practice, in DELPHES use **tracking and calo** info to reconstruct high reso. input objects for later use (jets, E_T^{miss}, H_T)

→ If **σ(trk) > σ(calo) (high energy)**

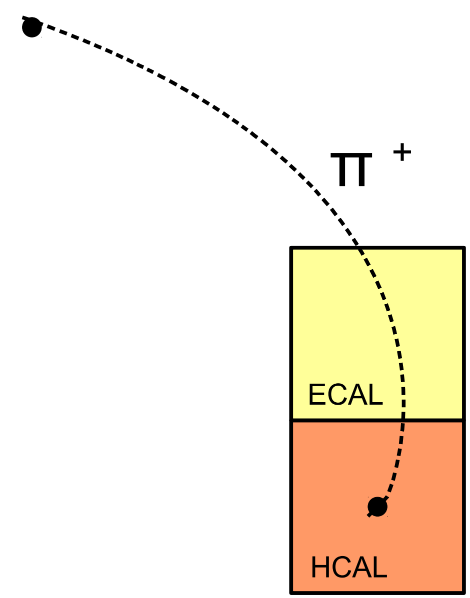
Example: A pion of 500 GeV

$E^{HCAL}(\pi^+)$ = 550 GeV

$E^{TRK}(\pi^+)$ = 400 GeV

Particle-Flow algorithm creates:

PF-track, with energy $E^{PF\text{-}trk}$ = 550 GeV
and no PF-tower



Separate neutral and charged calo deposits has crucial implications for pile-up subtraction