Neutral Hadrons in the Barrel

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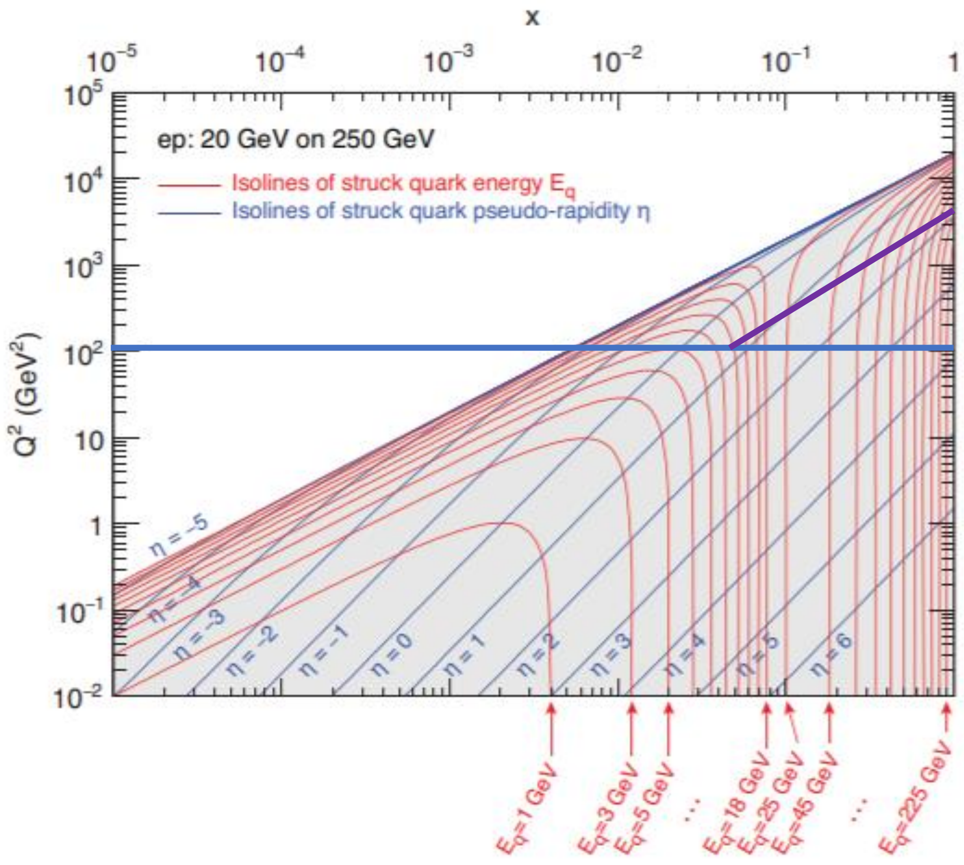
Calo WG 9/13/21

Framing the Discussion

- My physics interests (and much of the YR) live at high Q^2, high y
  - This is where pQCD predictions are typically most precise
    - Precise predictions require equally (or more) precise experiments to test them
  - EIC will have unprecedented statistics here, more than HERA in a large region!
- This phase space depends crucially on hadronic reconstruction in the barrel
  - For jets, CC, and inclusive physics
    - Bad hadronic reconstruction in the barrel is very problematic for CC DIS
  - Even larger phase space region goes to the barrel in e+A due to reduced hadron energy



I'm happy to discuss the physics case more, if necessary

Magnet Design

- Materials collected from magnet material excel sheet
  - Looks like solenoid.xml pulls from this sheet
  - Material interaction lengths from PDG
- Historically, no collider experiment has ever put a “proper” HCal beyond such a thick magnet
  - Muon detectors or tail catchers only
  - H1: (HCal inside magnet) set a requirement on their magnet thickness of $\leq .6\ \lambda_0$ to allow them to catch tails/muons with good efficiency
  - BaBar: Set magnet thickness requirement of $\leq .25\text{-}.4\ \lambda_0$ to ID neutrals
  - ALEPH: Required $\leq .4\ \lambda_0$
- Based on thickness, expect ~2% of high-energy hadrons to make it past Ecal+Magnet without showering (at mid-rapidity)

	Radial distance(mm)	Int. Lengths
SS	325	1.909742625
Cu	155	1.011749347
NbTi	27	0.1125
Total		3.033991973
	Int. L at Thickest	
	4.0269348	

Quite surprised to see this, majority of material in current model is non-magnetic stainless steel S235 (λ_0 ~ 17 cm)

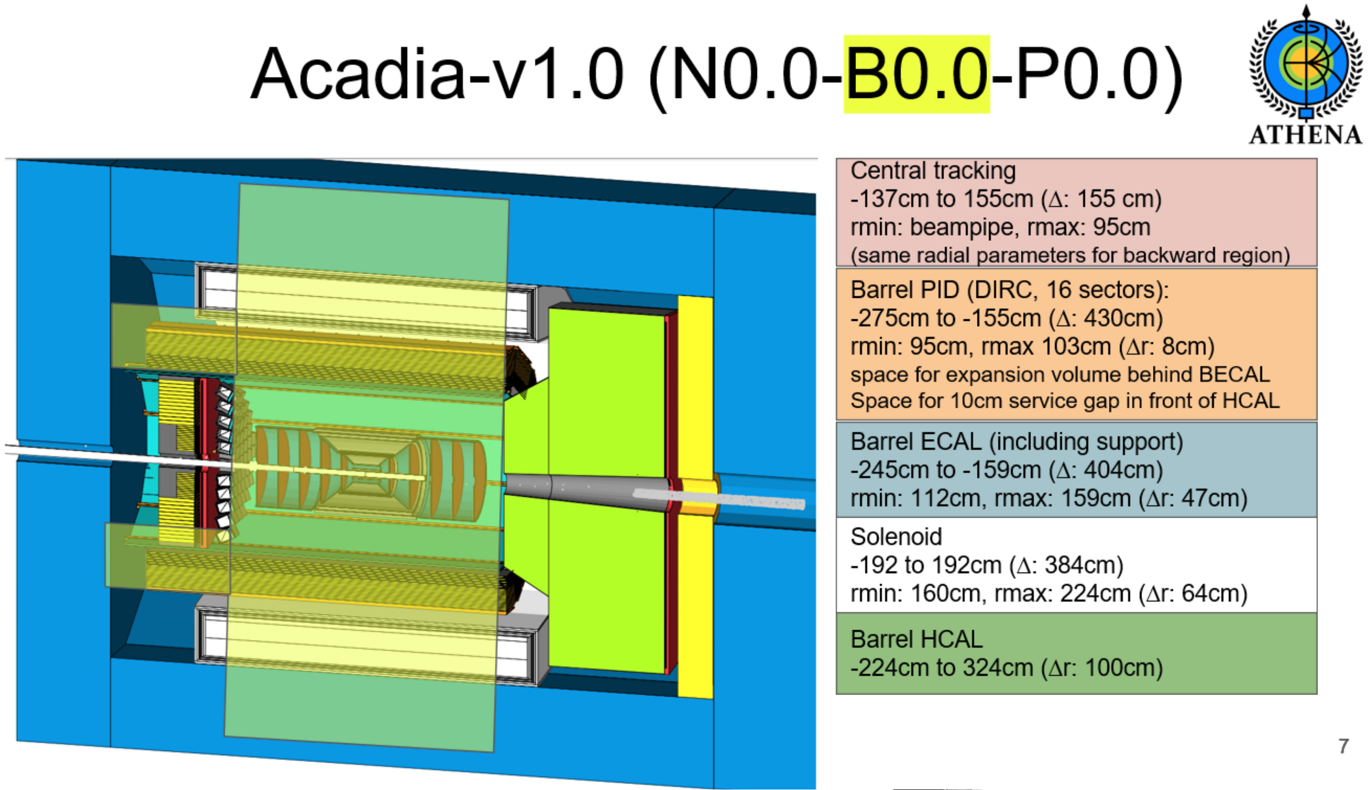
Copper from coil itself is 1 λ_0

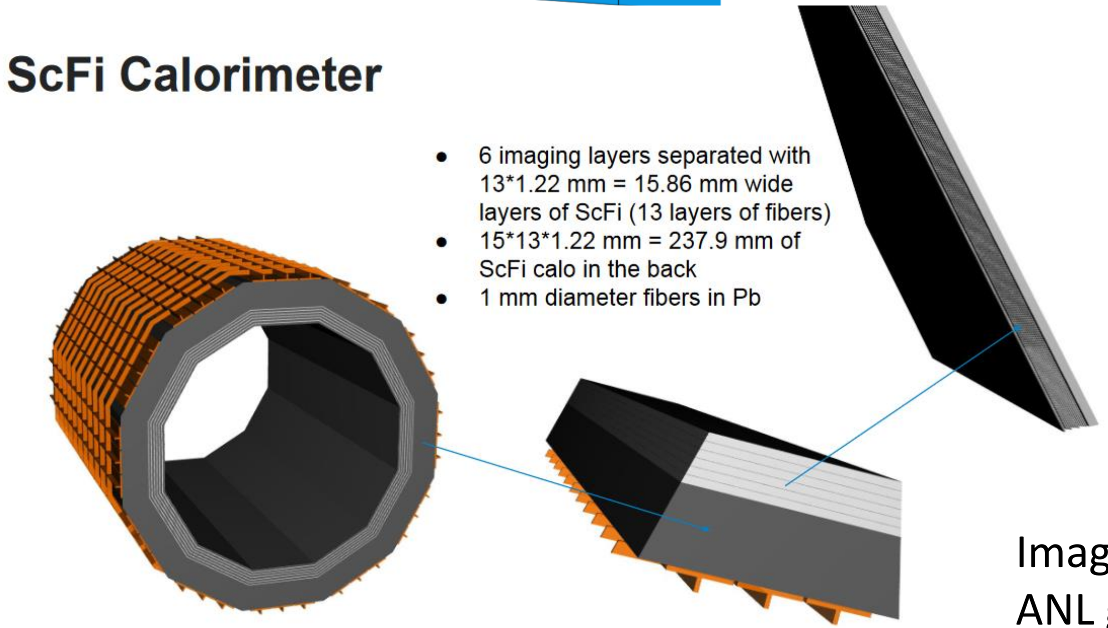
	Radial distance	Int. Lengths
SS	125	0.734516394
Cu	155	1.011749347
NbTi	27	0.1125
Al	200	0.503778338
Total		2.362544079
	Int. L at Thickest	
	3.135740323	

Thinner option, Al overbind (not in sim)

What's there now?

- Barrel ECal is so-called "hybrid"
  - AstroPix silicon layers with Pb/scintillating fibers running in-between
  - Outside the last silicon layer, Pb/SciFi with fibers running parallel to the beam a la KLOE
- Barrel HCal is 10cm x 10 cm scintillator between steel
- Magnet is as described earlier





Images from ANL group

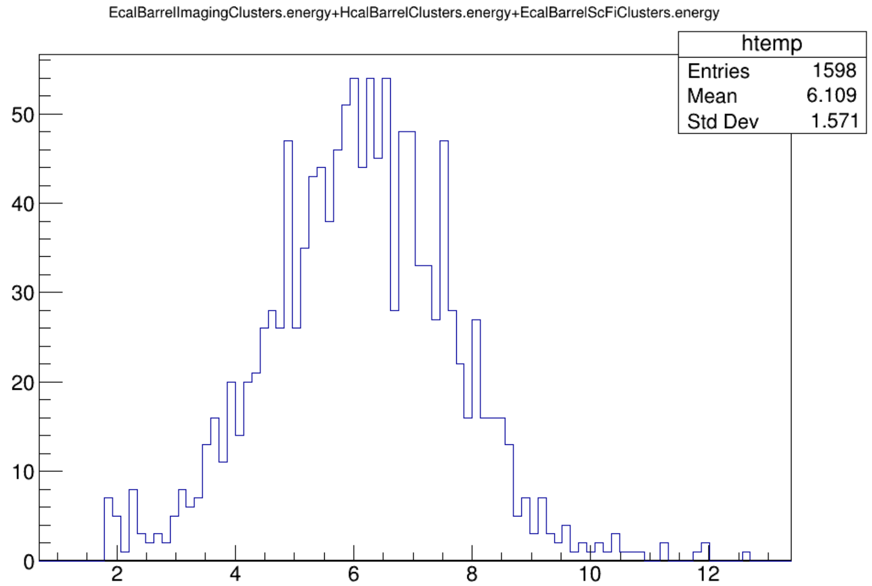
Full Sim Reco Results

- Please interject if I'm misinterpreting results
  - I haven't looked in-depth at the code used for the reconstruction
- In the data format if there's no cluster, the energy entry is left unfilled
  - Not filled with 0, so when directly drawing in ROOT a plot of the sum of EcalSciFi+EcalImaging+Hcal it only plots points which have all 3 entries filled
  - May lead to some misleading results for resolution, hard to gauge detection efficiency

20 GeV K_L SciFi Imaging

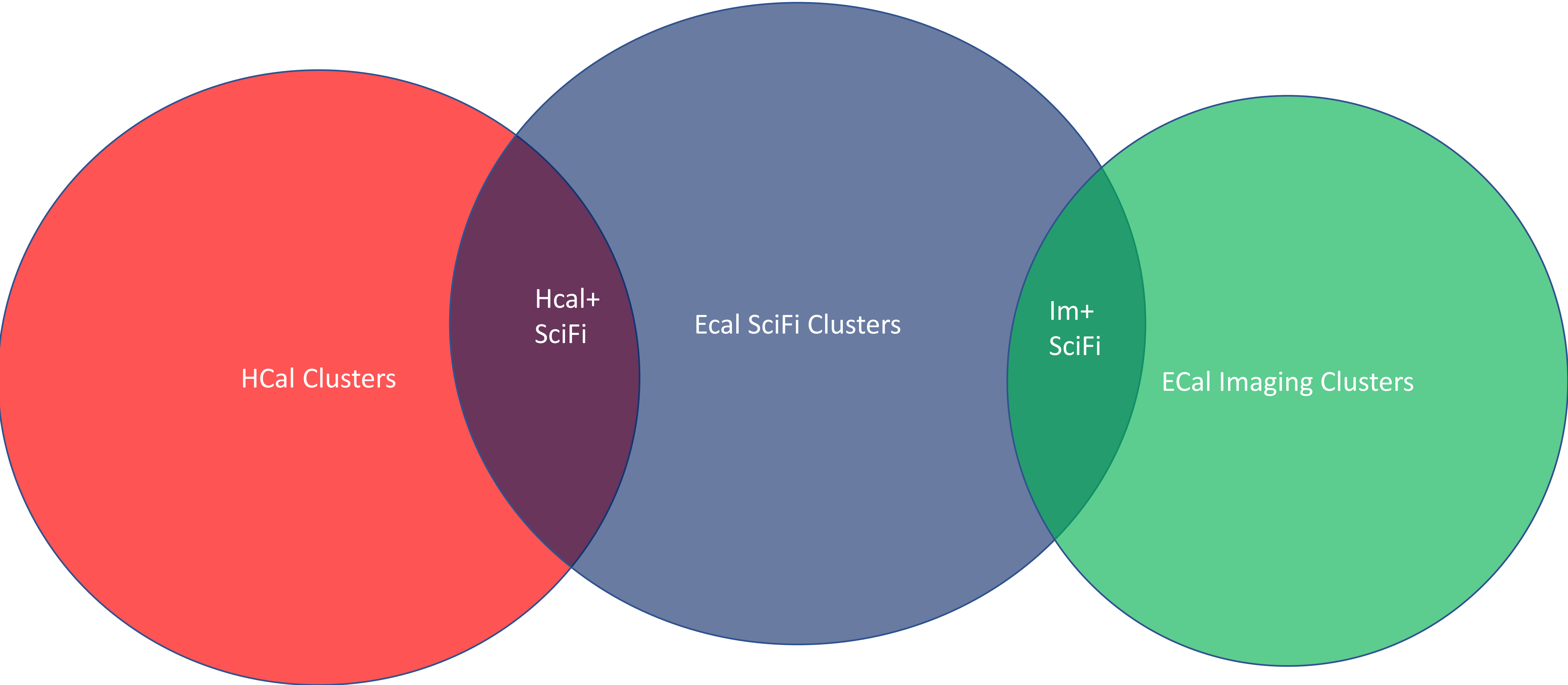
Row	Instance	HcalBarre	EcalBarre	EcalBarre
0	0		17.284151	9.0576734
0	1			0.2873802
1	0		21.082780	11.316175
2	0		16.849378	
3	0		18.772605	3.6546840
4	0		2.4567558	
5	0		20.863412	6.5761132
5	1		0.5719503	
6	0		19.435823	
7	0		17.776001	1.5590604
8	0		0.2746572	
9	0		15.540548	1.5707118
10	0		7.2686867	
10	1		0.3896910	
11	0	7.3518447		
12	0			
13	0		16.812416	3.1569187
14	0		2.0538775	

1M particles fired, only 1k events where all 3 calo had clusters



Want fraction of particles fired that leave at least one cluster in a calorimeter

ROOT evaluates unfilled entry in Draw() selector to FALSE, so sum number of individual events with one cluster in each calorimeter and remove double counting – Effectively no events with exclusive Hcal+Imaging overlap



Average Clusters per Particle (first pass on efficiency)

- NB: K_L can produce multiple (up to 6) ECal clusters
  - Decays to 3 pi^0 in flight
- N Clusters increases with energy
- This is not so useful in terms of efficiency

Species	**$N_{clusters}/N_{particles}$ HCal**	**$N_{Clusters}/N_{particles}$ ECal SciFi**	**$N_{Clusters}/N_{particles}$ Ecal Imaging**
100 MeV K_L	.0001	.34	.020
500 MeV K_L	.0007	.54	.016
1 GeV K_L	.0011	.77	.029
2 GeV K_L	.0066	.86	.053
5 GeV K_L	.029	.94	.22
10 GeV K_L	.068	.98	.41
20 GeV K_L	.15	1.04	.51

“Efficiency” (Fraction with > 0 Clusters)

Attempt to deconvolute efficiency from $N_{clusters}$

At 20 GeV (quite rare in DIS at EIC), only 15% of K_L leave a cluster in Hcal

K_L mean free path longer than neutrons

Could also be that some of the lower energy K_L are decaying before the Ecal, cτ ~ 4 meters, let’s look at neutrons instead

Species	Hcal	Ecal SciFi	Ecal Imaging	Hcal+SciFi	SciFi+ Imaging	Total Frac. with > 0 clusters
500 MeV K_L	0.000075	0.52	0.016	0.00009	0.009	0.526985
1GeV K_L	0.001	0.72	0.028	0.0004	0.023	0.7256
5GeV K_L	0.029375	0.7875	0.18125	0.00625	0.18125	0.810625
10GeV K_L	0.07	0.8	0.3	0.0021	0.3	0.8679
20GeV K_L	0.15	0.8	0.32	0.08	0.32	0.87

“Efficiency” (Fraction with > 0 Clusters)

- Neutron efficiency even lower than K_L except at 20 GeV
  - Less likely to interact in the Ecal at lower energies
  - K_L Decays easier to detect

- Sanity Check: $e^{-4} \sim .02$, $e^{-2} \sim .14$
  - Showers in magnet can still leave energy in Hcal
  - If a shower can longitudinally extend by 2 λ_0, then results are sensible
  - Would naively expect even less coming out of magnet than seen here

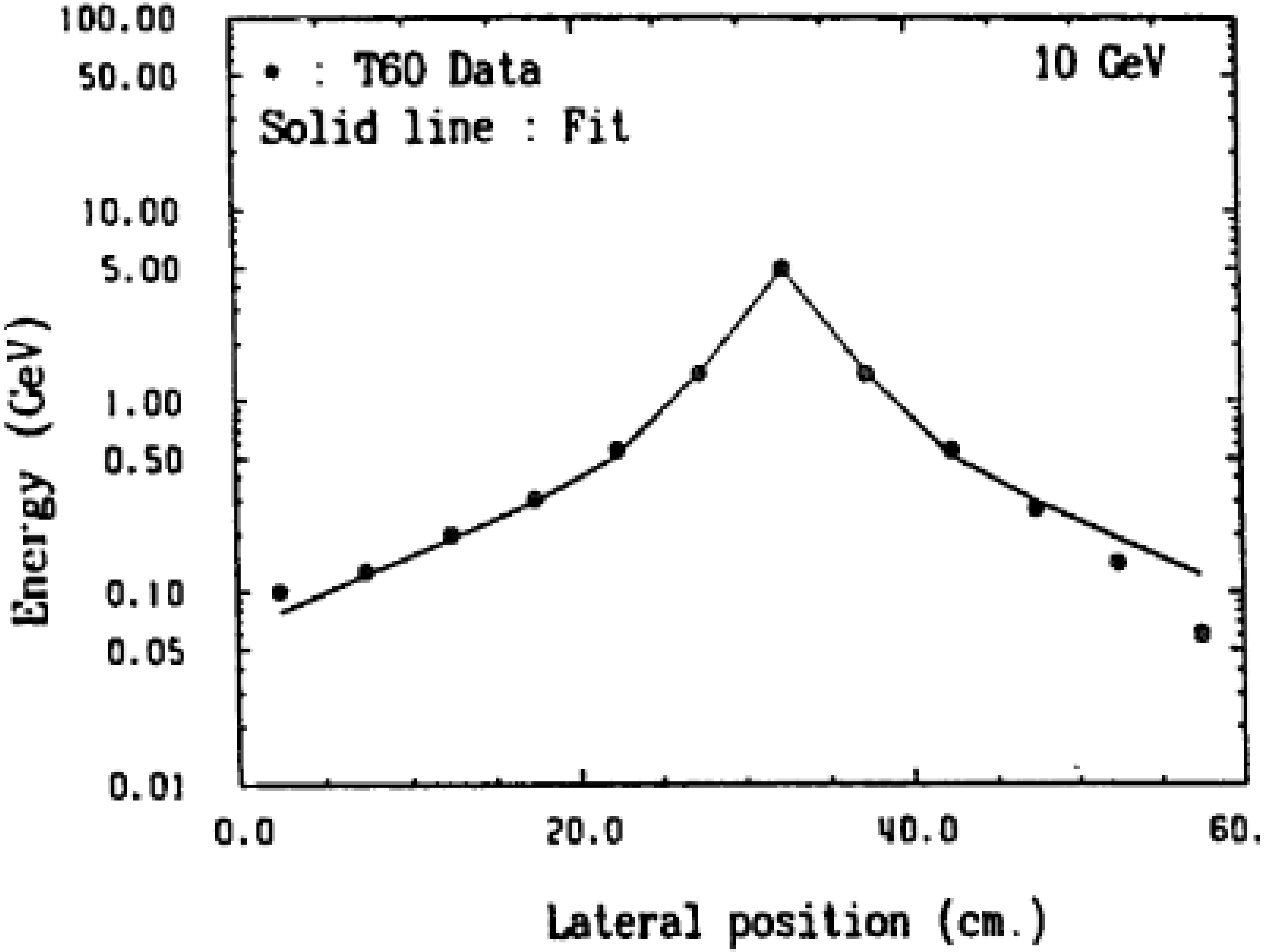
Species	Hcal	Ecal SciFi	Ecal Imaging	Hcal+SciFi	SciFi+ Imaging	Total fraction with > 0 clusters
500 MeV neutron	0.00001	0.14	0.0004	0	0.000006	0.140394
1 GeV neutron	0.0016	0.393	0.001229	0.00001	0.000678	0.395141
5 GeV neutron	0.028	0.76	0.1	0.078	0.1	0.71
10 GeV neutron	0.08	0.79	0.25	0.031	0.25	0.839
20 GeV neutron	0.175	0.81	0.31	0.087	0.31	0.898

Low energy hadrons are surprising

Conclusions

- Current HCal sees clusters from < 10% of 10 GeV neutrons
    - Can't measure energy, very inefficient neutral ID
- A few options:
    - 1. Say that the EMCal is good enough for handling neutral hadrons, don't build BHCal
        - I have a set of slides on this, can present them now or just post to indico
    - 2. Reduce the material of the magnet, keep BHCal
        - A request: Could SWG do a quick run where they change SS in magnet to aluminum and shoot 10 GeV neutrons?
        - Should test if Al will make things alright, easiest change integration-wise
    - 3. Beef up the EMCal so that it has a better response to hadrons, don't build BHCal
        - Up to experts to decide how to do this, if it's possible
        - I'll be happy to analyze the DD4HEP data from another EMcal model

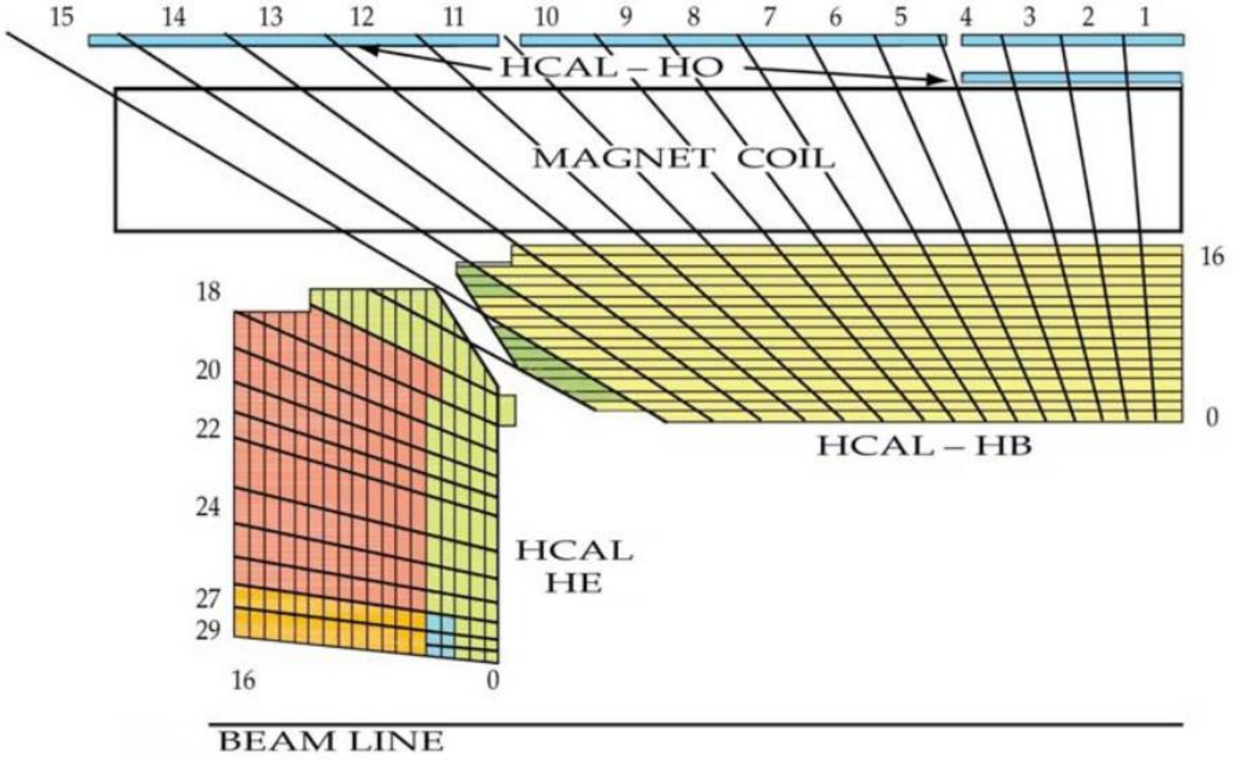
Backup

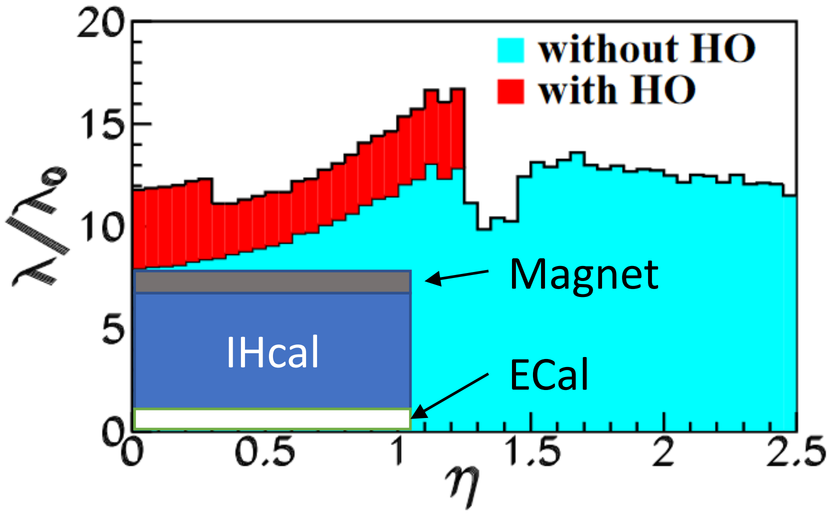


100.00
50.00
10.00
5.00
1.00
0.50
0.10
0.05
0.01
• : T60 Data
Solid line : Fit
10 GeV
Energy (GeV)
0.0
20.0
40.0
60.
Lateral position (cm.)

Case Study: CMS

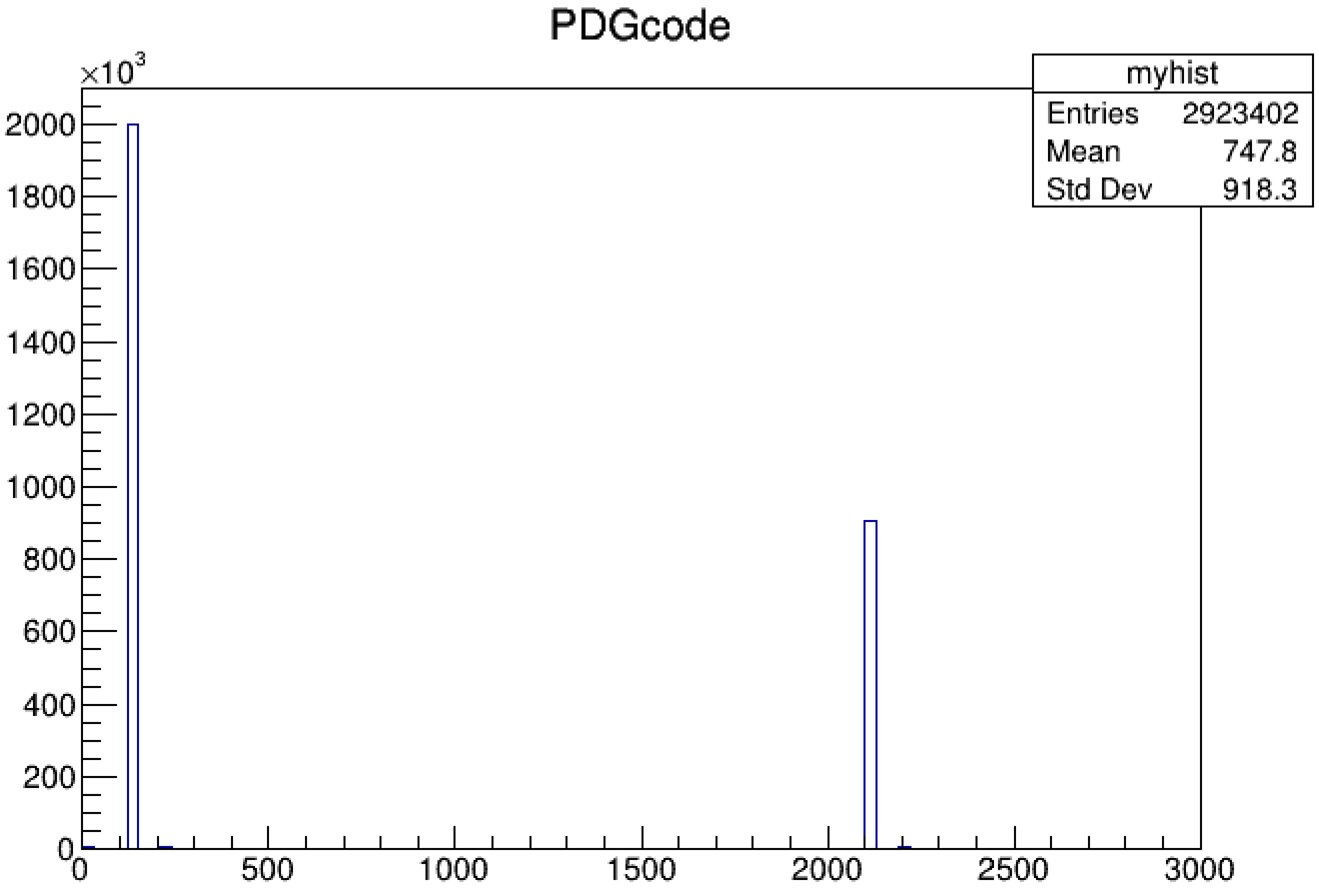
- Inner Hcal is 5.82 λ
  - Energies obviously much higher, ~ 2 orders of magnitude
- Magnet ID: 5.945 m, OD: 6.9m
  - Radial extent of ~50 cm vs. 64 cm for ATHENA
  - CMS magnet is $\frac{1.4}{sin\theta}$ int. length
  - 1.4λ @ eta = 0, 2.8λ @ eta = 1.3
- CMS needs as much material as possible to absorb hadrons before muon detectors for muon ID -> Thick magnet has a benefit
  - No such benefit for EIC, thicker magnet only hurts





Neutrons in Kaon Sample

- Not one of the normal kaon decay products

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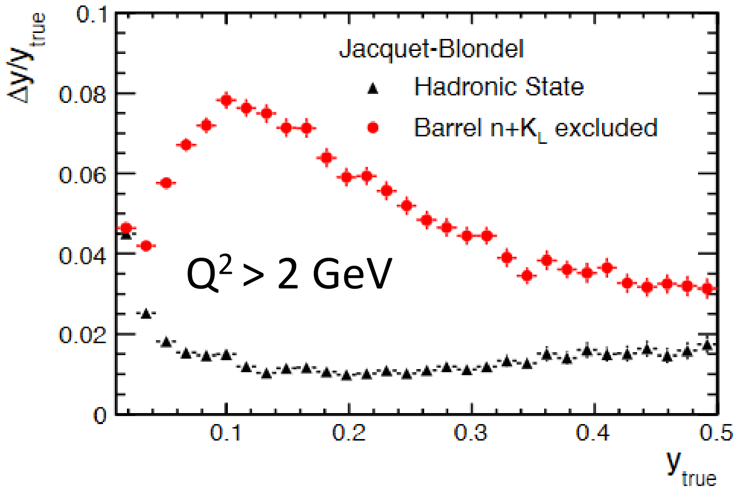
Physics Considerations - Inclusive

$$y_{JB} = \frac{\sum(E - p_z)}{2E_e}$$

Using final hadronic state in -4<η<4



At $Q^2 = 2$, few hadrons in the barrel

At high Q^2 (> 100), impact of missing neutral energy in the barrel will be much larger

- Total amount of E-P_z = $2E^e_i$
  - For EIC (at highest E_i^e!) this is 36 GeV
  - Quantity is conserved
- Enters directly kinematic reconstruction with hadron, e-sigma, sigma, I-sigma methods
- Crucial quantity for vetoing QED ISR, acceptance losses, photoproduction
    - ISR independent methods will incorrectly assume beam electron energy
  - Almost all HERA DIS analyses include cut on E-P_z
- In barrel, E-P_z is maximized (P_z small)
  - Losing a neutron with 4 GeV is a 14% loss in total E-P_z at EIC!

Neutral ID

- Such a thick magnet will also impact ability to even ID neutral hadrons (BaBar, Belle reasoning)
  - Even with .25 λ magnet, neutral efficiency plateau is only ~85% due to early interactions
  - Belle, BaBar measure single neutral hadrons, not in jets along with many charged+neutral hadrons
- Belle and BaBar needed only to ID neutrals because the B decay channel is overconstrained
  - Not the case in jets at EIC
  - Lepton-jet imbalance is a key observable
- Current ATHENA barrel HCal will have low neutral-ID efficiency due to material upstream, no ability to measure energy
- Reconstructing DIS kinematics via all non-electron methods requires measurement of hadronic energy flow, charge tagging not enough

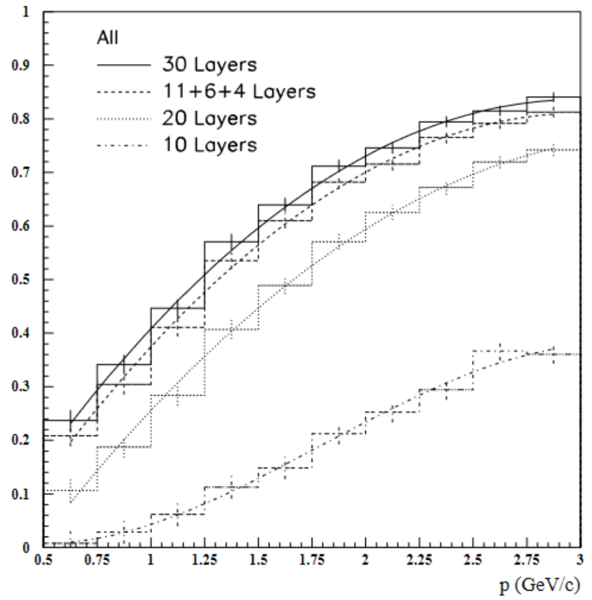
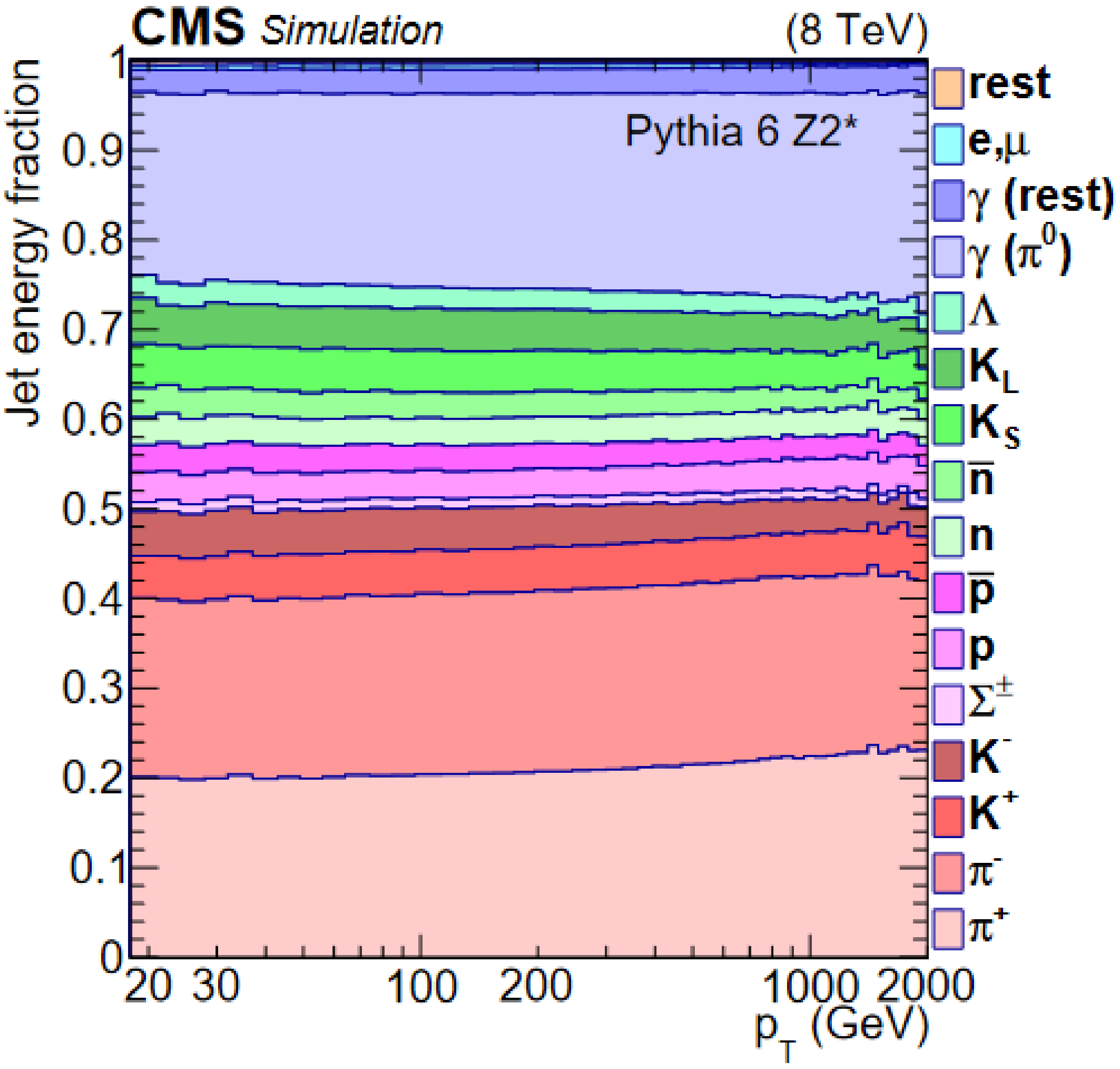


Figure 8-16. *Efficiency for detecting K_L^0s as a function of momentum. The different sets of points represent different segmentations of the flux return iron. A solution with 21 active planes with graded separation is compared.*



CMS Simulation
(8 TeV)
Pythia 6 Z2*
Jet energy fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
30
100
200
1000
2000
p_T (GeV)
rest
e,μ
γ (rest)
γ (π^0)
Λ
K_L
K_S
$\bar{n}$
n
$\bar{p}$
p
$\Sigma^\pm$
K^-
K^+
π^-
π^+