On the ATHENA HCAL

Miguel Arratia (UCR),
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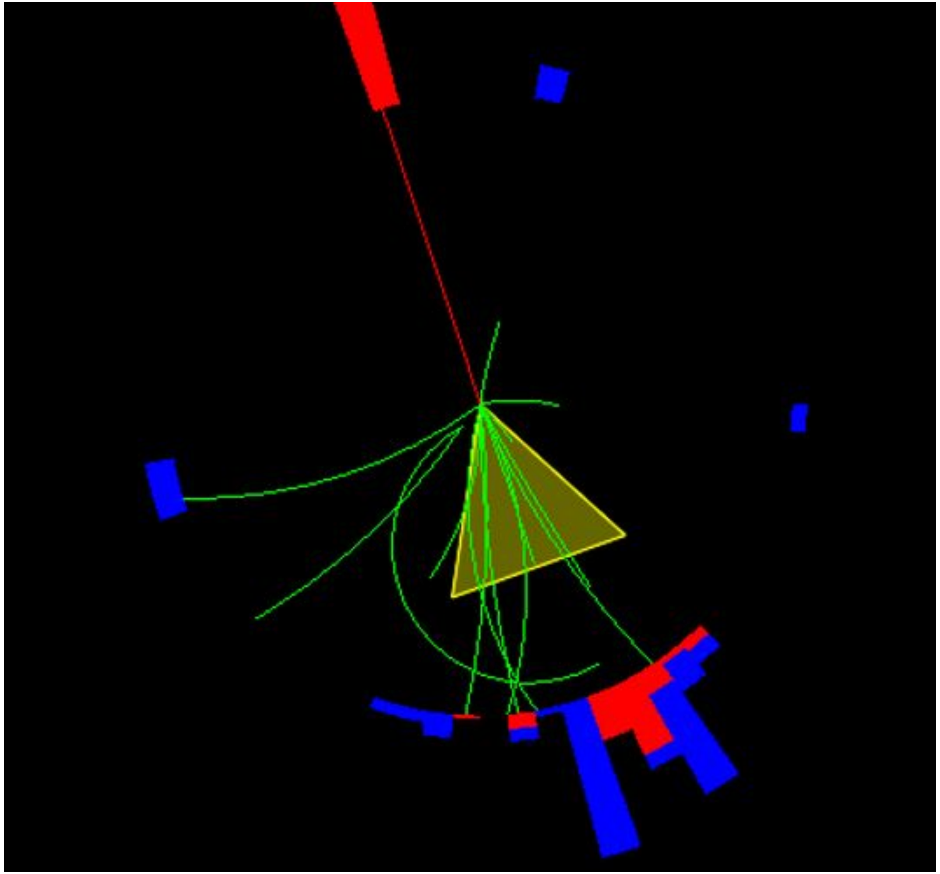


Measuring the "hadronic final state" is essential to

1) Reconstruct DIS variables in neutral-current DIS (lepton alone not enough)
2) Reconstruct DIS variables in charged-current DIS (neutrino in final state)
3) Jets, MET, event shapes, gaps, etc.

All are HFS measurements so the distinction between points 1), 2) and 3) is artificial and not useful.

"Jet performance" is critical for a big chunk of the EIC program.
It is not an option or luxury.

For what do we want HCAL?

- Not to “compete with tracker”.
- It is to **fully reconstruct ~100% of the hadronic final state.**
- With tracker + EMCAL you get only ~90%, which is not enough for accurate measurements (jets, missing energy & hadronic reconstruction).
- **The ~10% reminder of neutral hadrons, measured with EMCAL+HCAL, dominates the jet energy resolution (and MET)**
  That is, tracker performance is irrelevant.
  More specifically, the dominant source is the “confusion” term that arises from subtraction of charged-particle energy from HCAL to estimate neutral hadron energy.

Combining HCAL, ECAL and tracker info
I.e. energy-flow reconstruction

- One needs to subtract charged-particles energy from HCAL readings to not double count.

- This is not as simple as taking tracker info and subtracting from HCAL energy
Challenge: charged particles can shower before HCAL (e.g in cryostat)

- Having **good estimate of the energy loss of charged hadrons *BEFORE* they reach the HCAL** is important for energy-flow reconstruction.
This is where ECAL and HCAL granularity play a role.

- Our ability to determine whether a HCAL cluster is significant or not (i.e. whether it reveals a neutral hadron or not) is a key driver of resolution

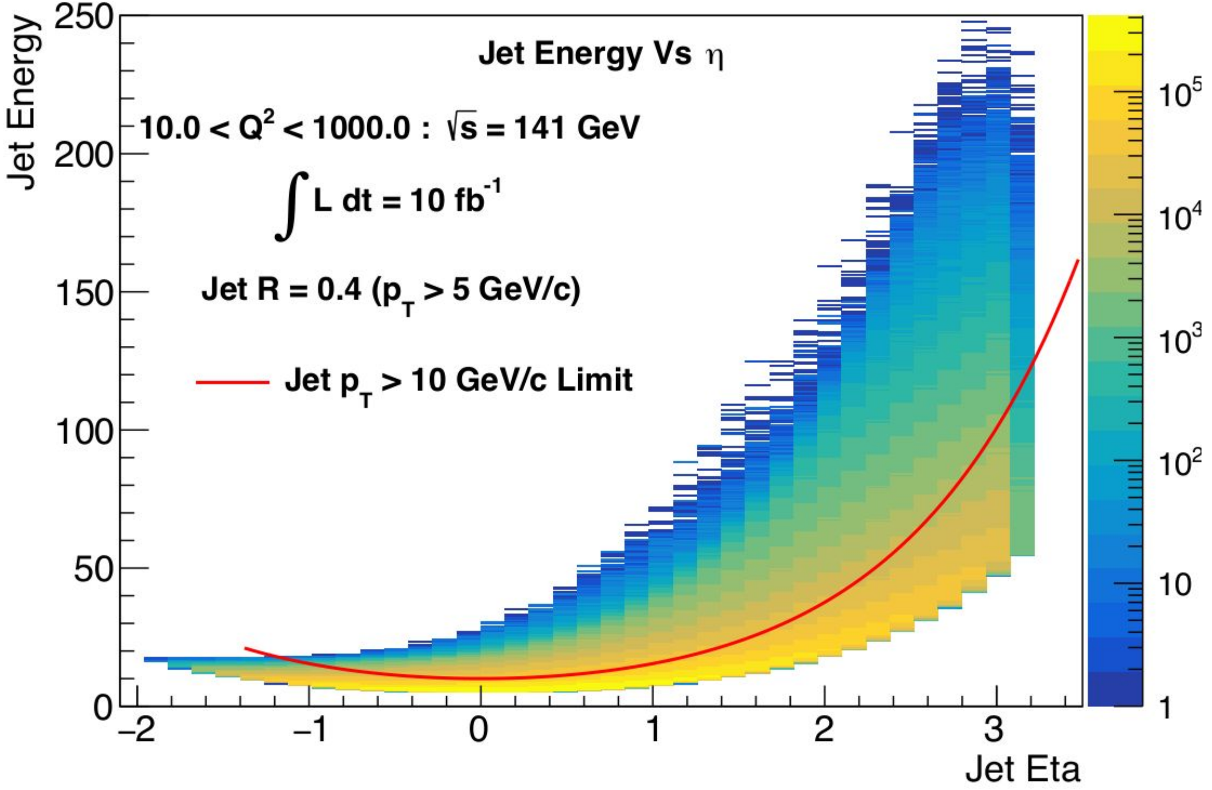
Previous successful examples of e-flow reco which ****<u>are relevant for EIC energies</u>****

- **ALEPH at LEP**. Relevant energy: jet pT ~45 GeV. (~ half Z)
  Jet energy resolution achieved: ~60%/sqrt(E)..

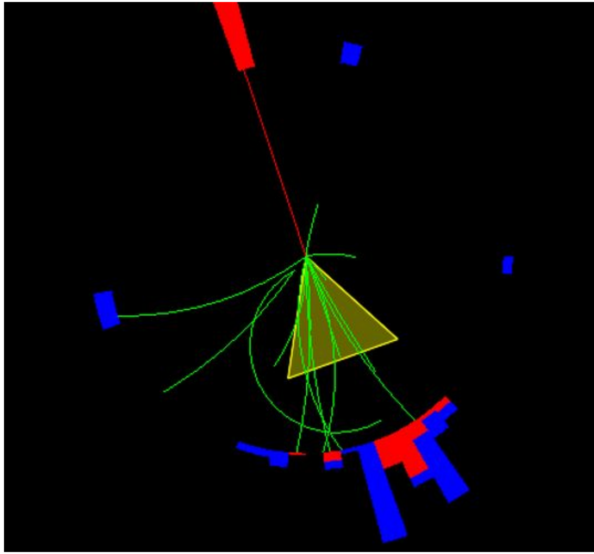
- **H1 at HERA.** Range: from pT ~ 5 GeV to pT~100 GeV
  Jet energy resolution achieved ~50%/sqrt(E) + 5%.
  Jet energy scale uncertainty achieved: 1.0% for E>10 GeV.

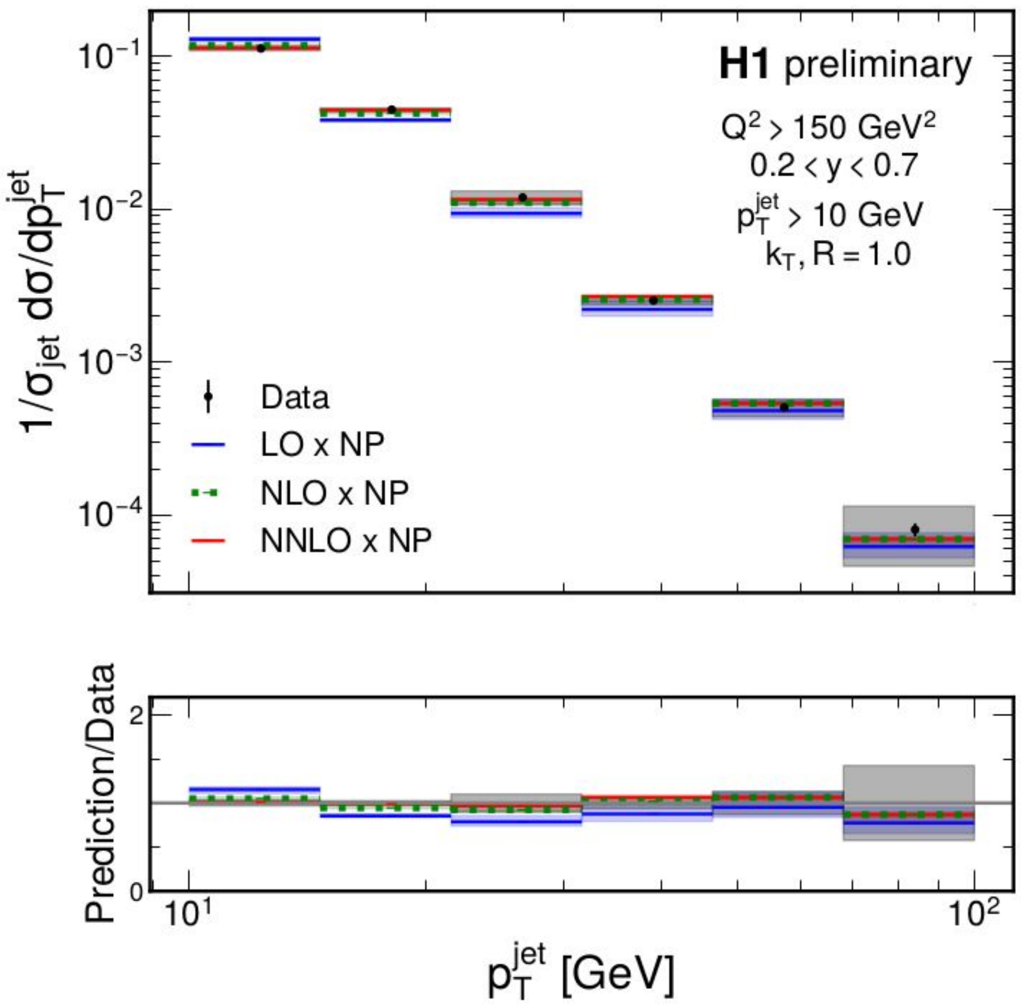
We want to apply it to ATHENA at EIC. From pT~5 GeV to pT ~50 GeV
Goal = 1.0% JES uncertainty down to 10 GeV (like H1 & ZEUS)

EIC



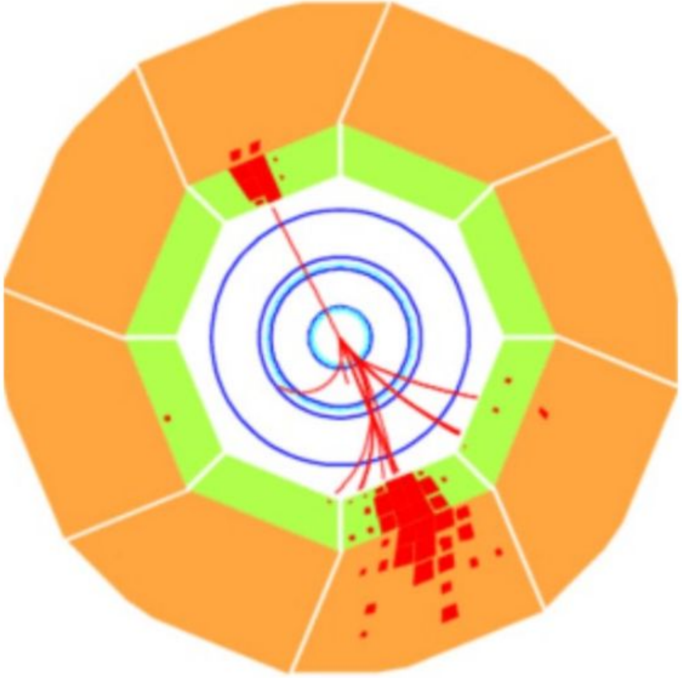
Jet Energy Vs η
10.0 < Q² < 1000.0 : √s = 141 GeV
∫ L dt = 10 fb⁻¹
Jet R = 0.4 (p_T > 5 GeV/c)
Jet p_T > 10 GeV/c Limit
Jet Energy
Jet Eta



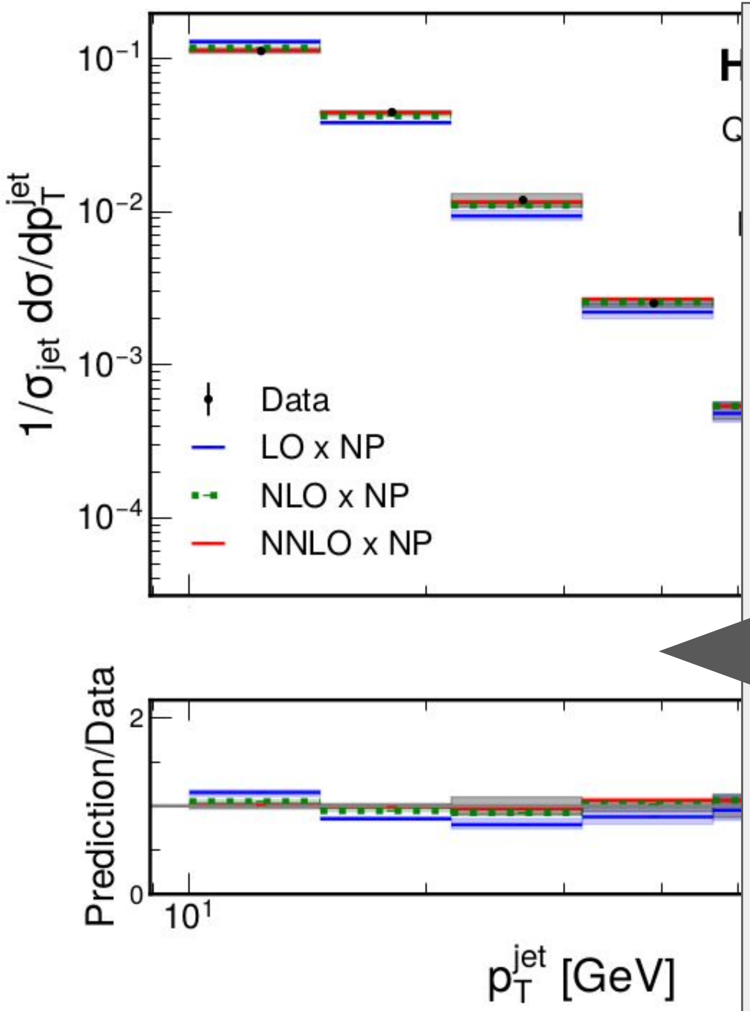


H1 preliminary
$Q^2 > 150$ GeV^2
$0.2 < y < 0.7$
$p_T^{jet} > 10$ GeV
k_T, R = 1.0
Data
LO x NP
NLO x NP
NNLO x NP
$1/\sigma_{jet}\, d\sigma/dp_T^{jet}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Prediction/Data
2
0
10^1
10^2
p_T^{jet} [GeV]

HERA

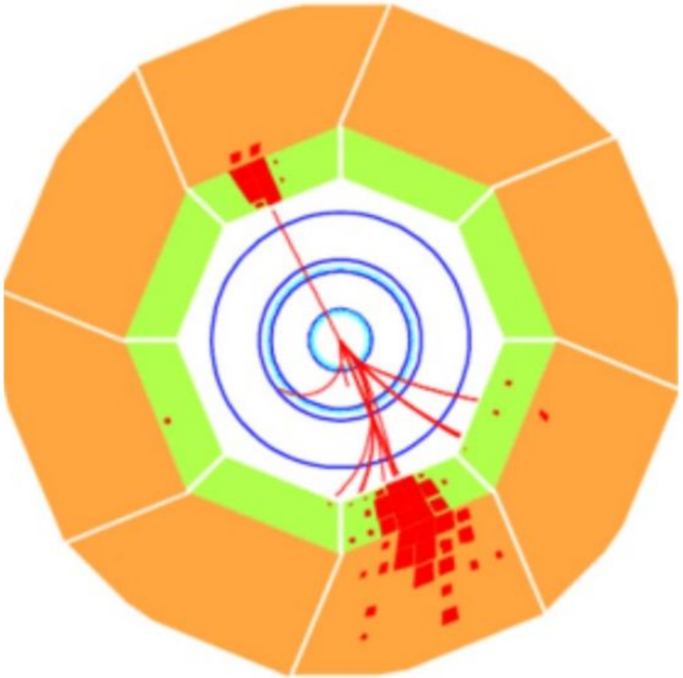


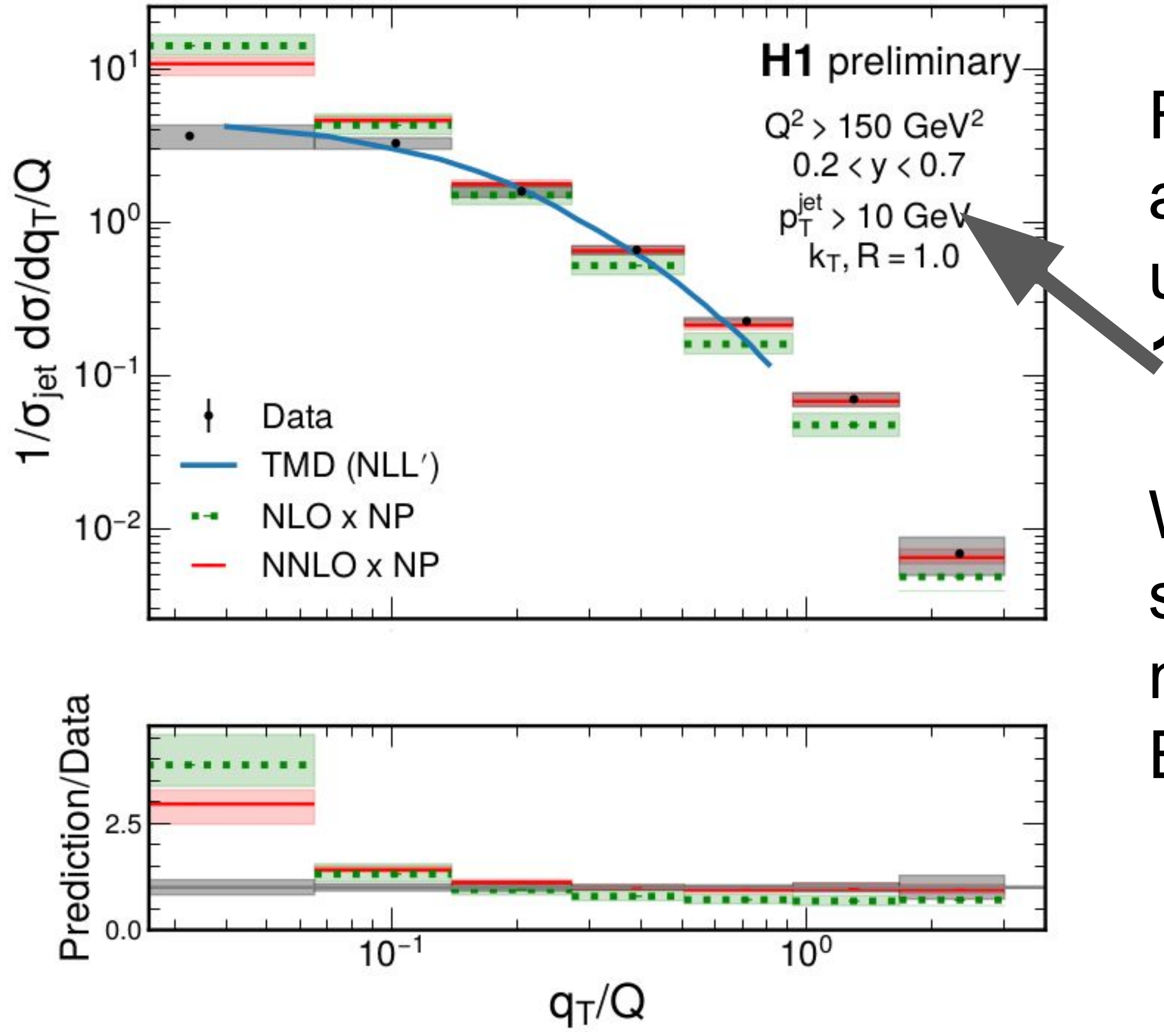
HERA



This is beyond the range of EIC.

That is, there is still a very large overlap

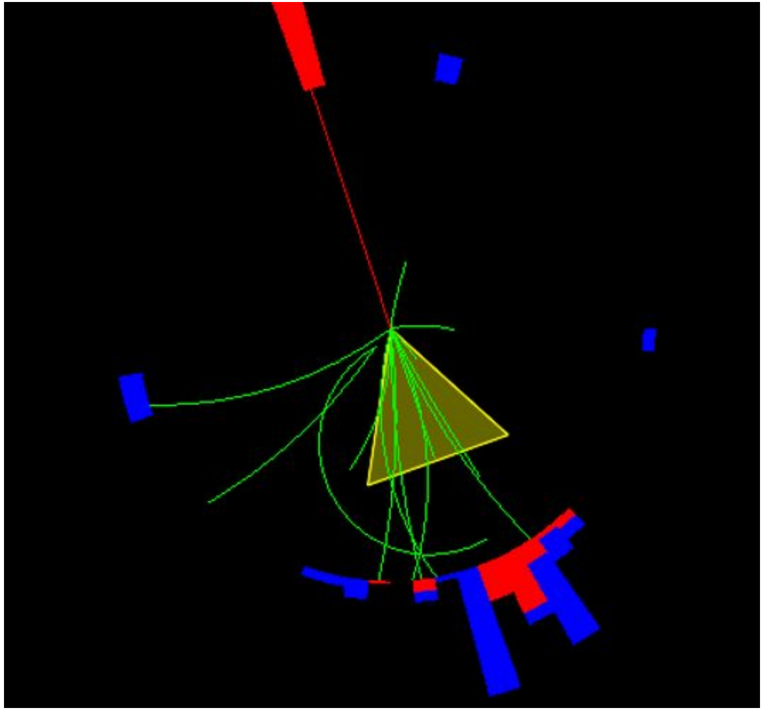


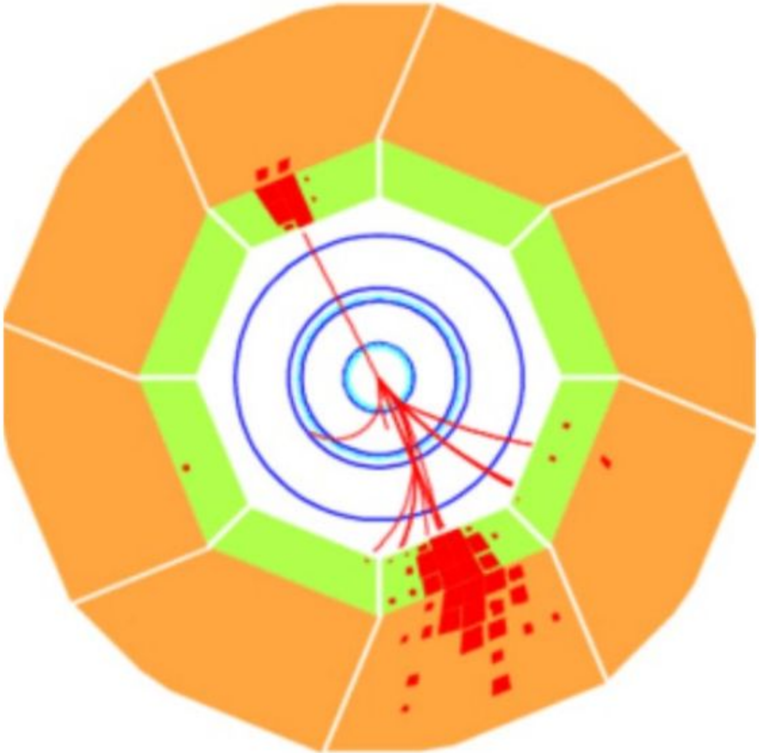


For example, this is a measurement that uses **10 GeV jets.**

We want and can do similar measurements at EIC

What can we learn from H1?





H1 did employ AI-assisted "software compensation": Smaller correction, smaller uncertainty

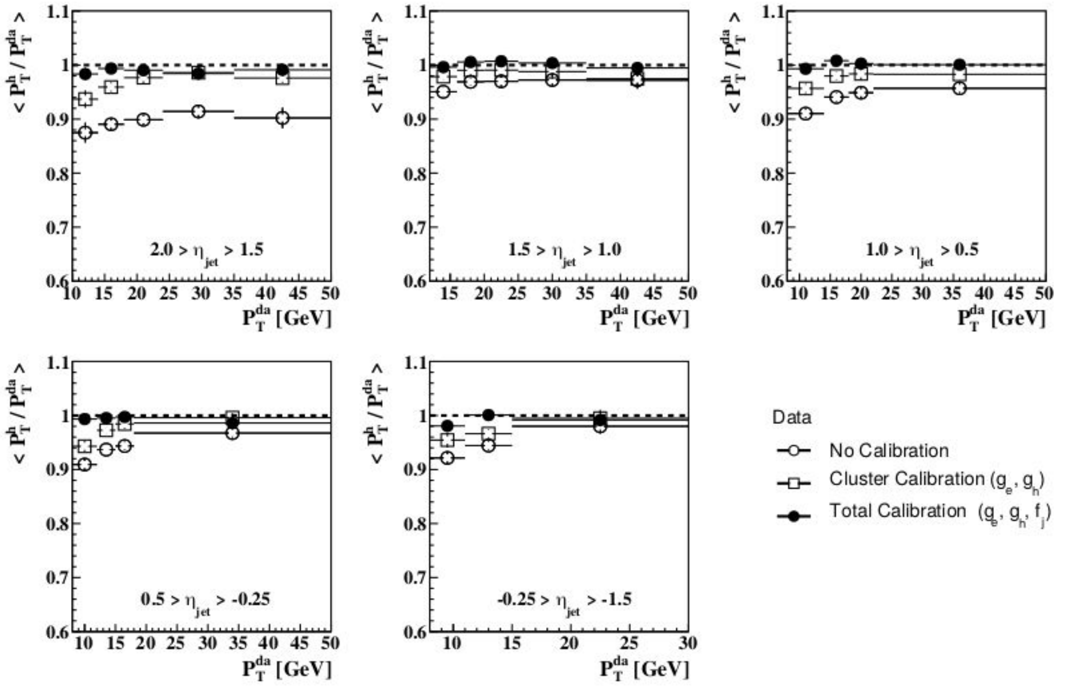


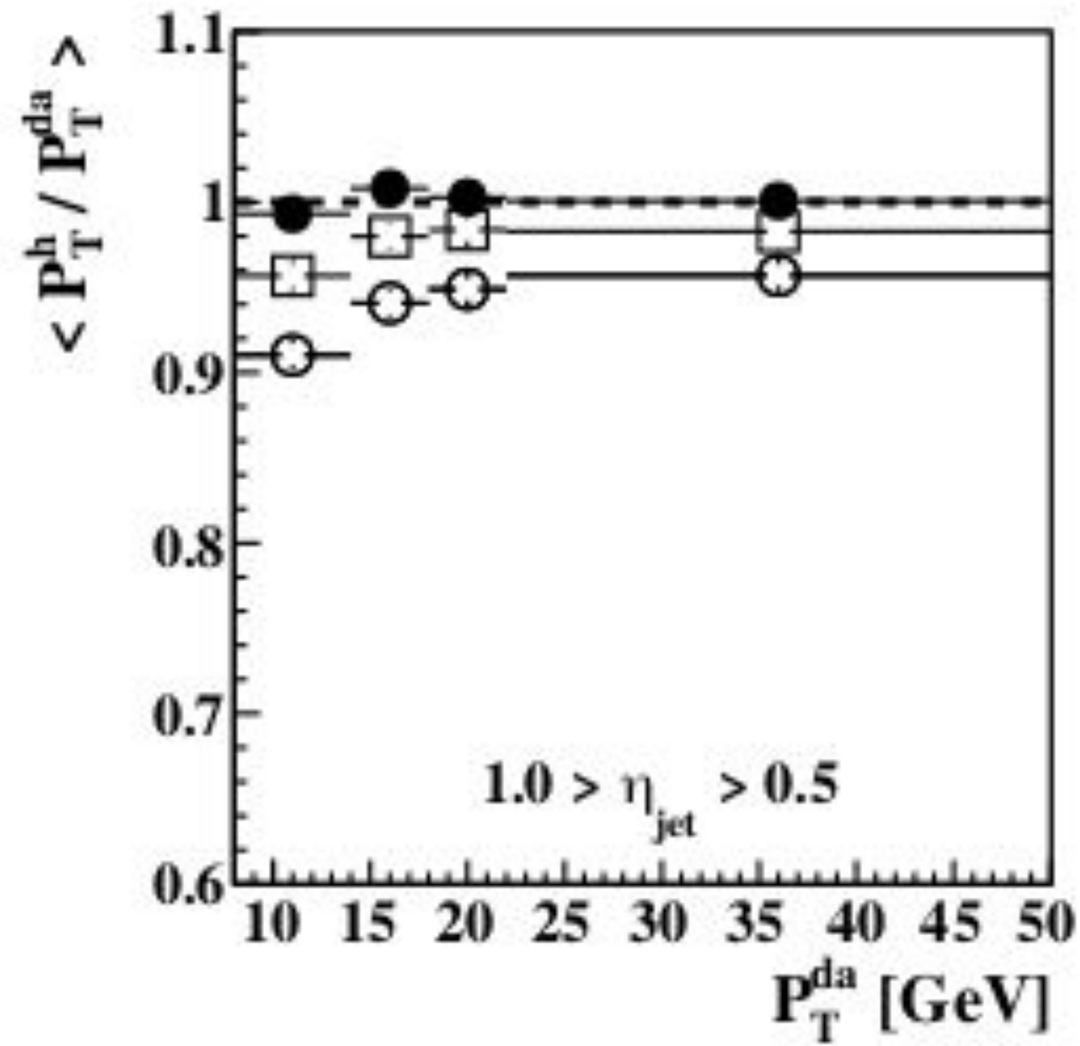
Figure 8.10: Mean values of the P_T-balance distributions as function of P_T^{da} in bins of η_{jet}. Shown are results obtained prior to the calibration (open circles), with the cluster

1.0% JES uncertainty, down to 10 GeV (this is truly remarkable)

NN exploits fine segmentation of LAr calorimeter.

HCAL had 4-6 layers

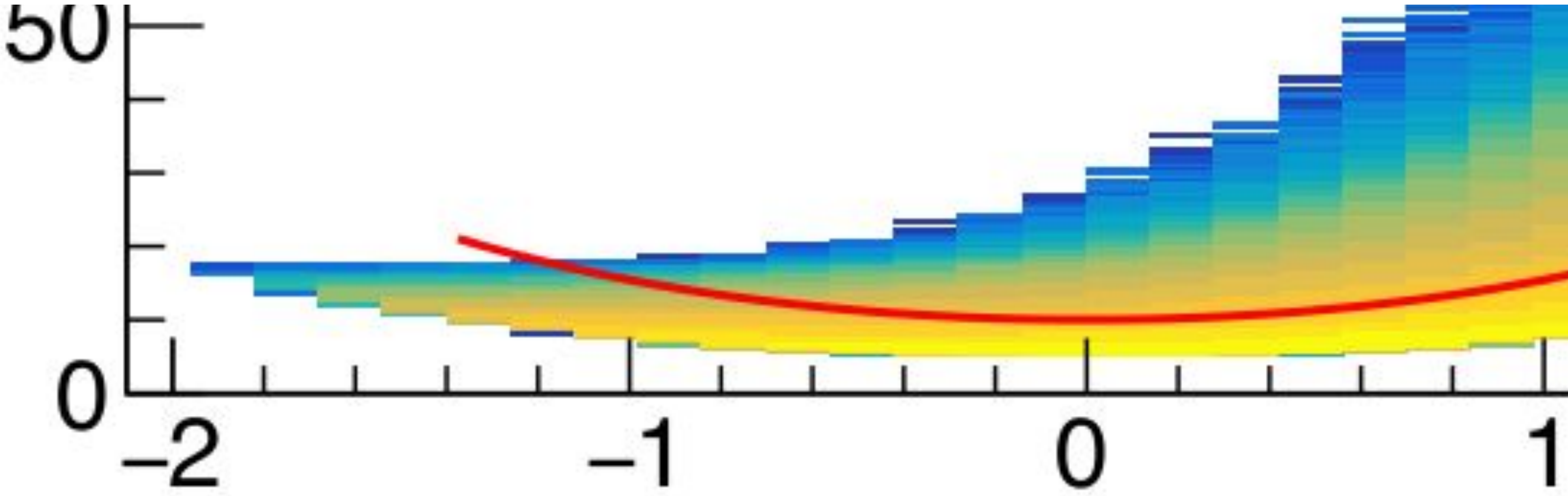
Roman Kloger thesis (Hamburg U.)



Note the pT range here for mid rapidity.

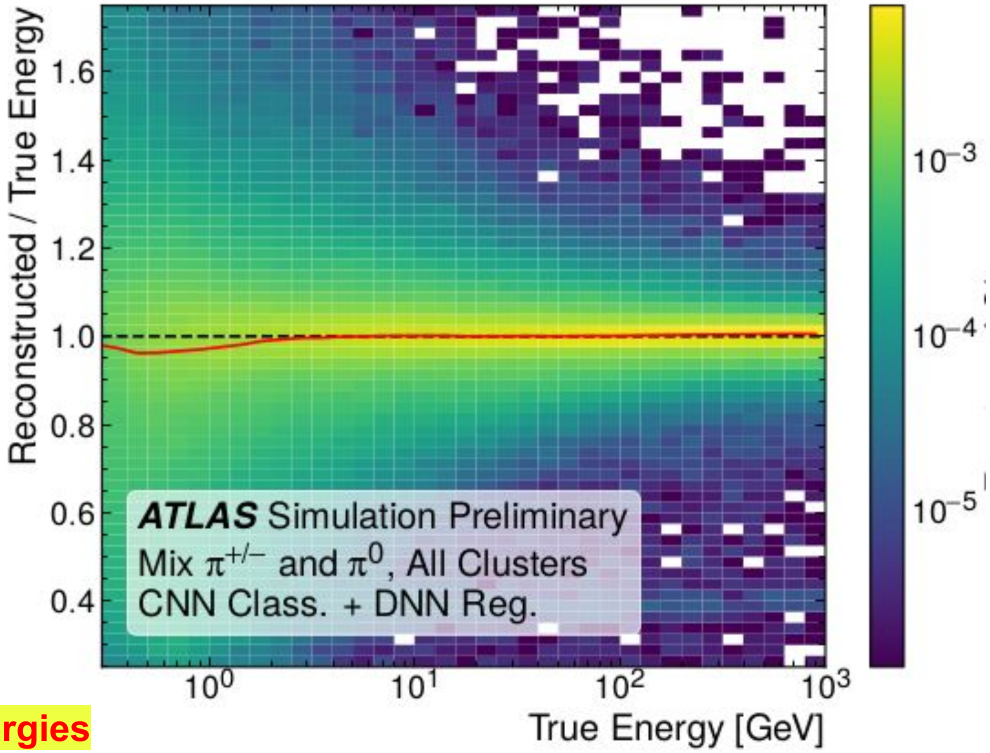
This overlaps with EIC barrel

EIC Barrel



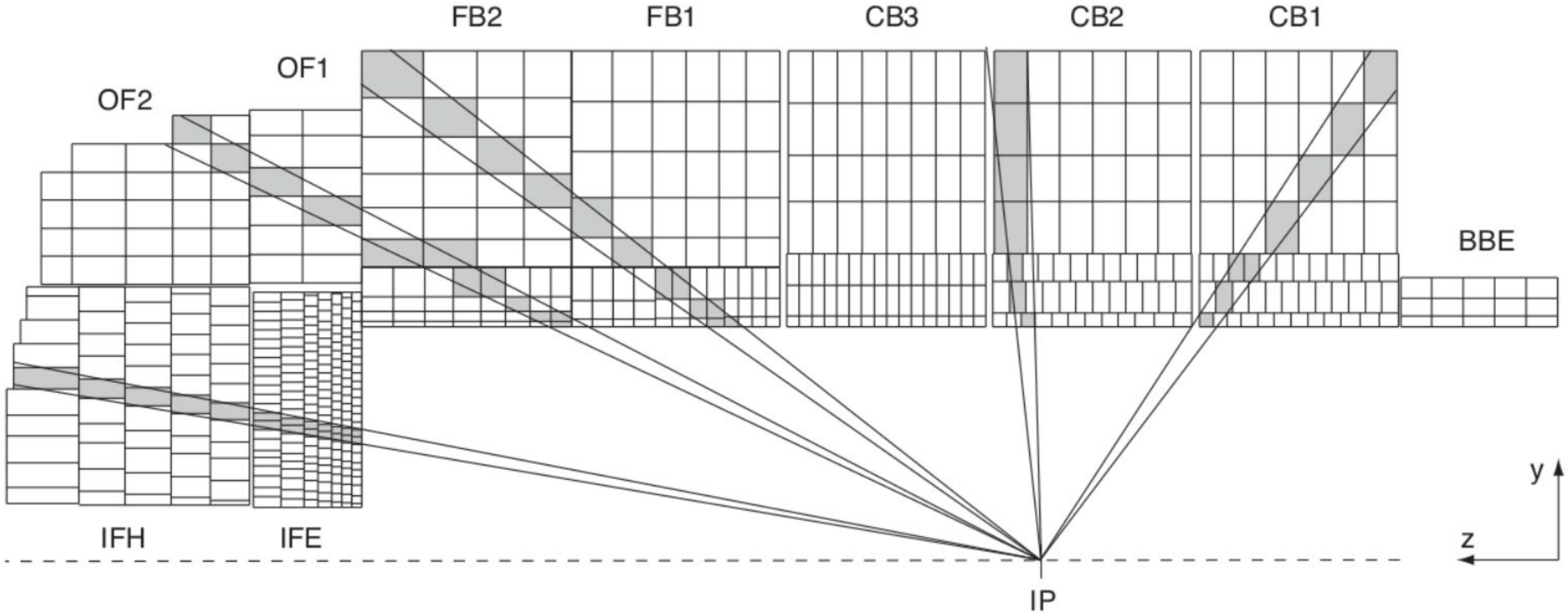
The AI4Calofield has moved on quite a bit since ten years ago, e.g:

ATL-PHYS-PUB-2020-018



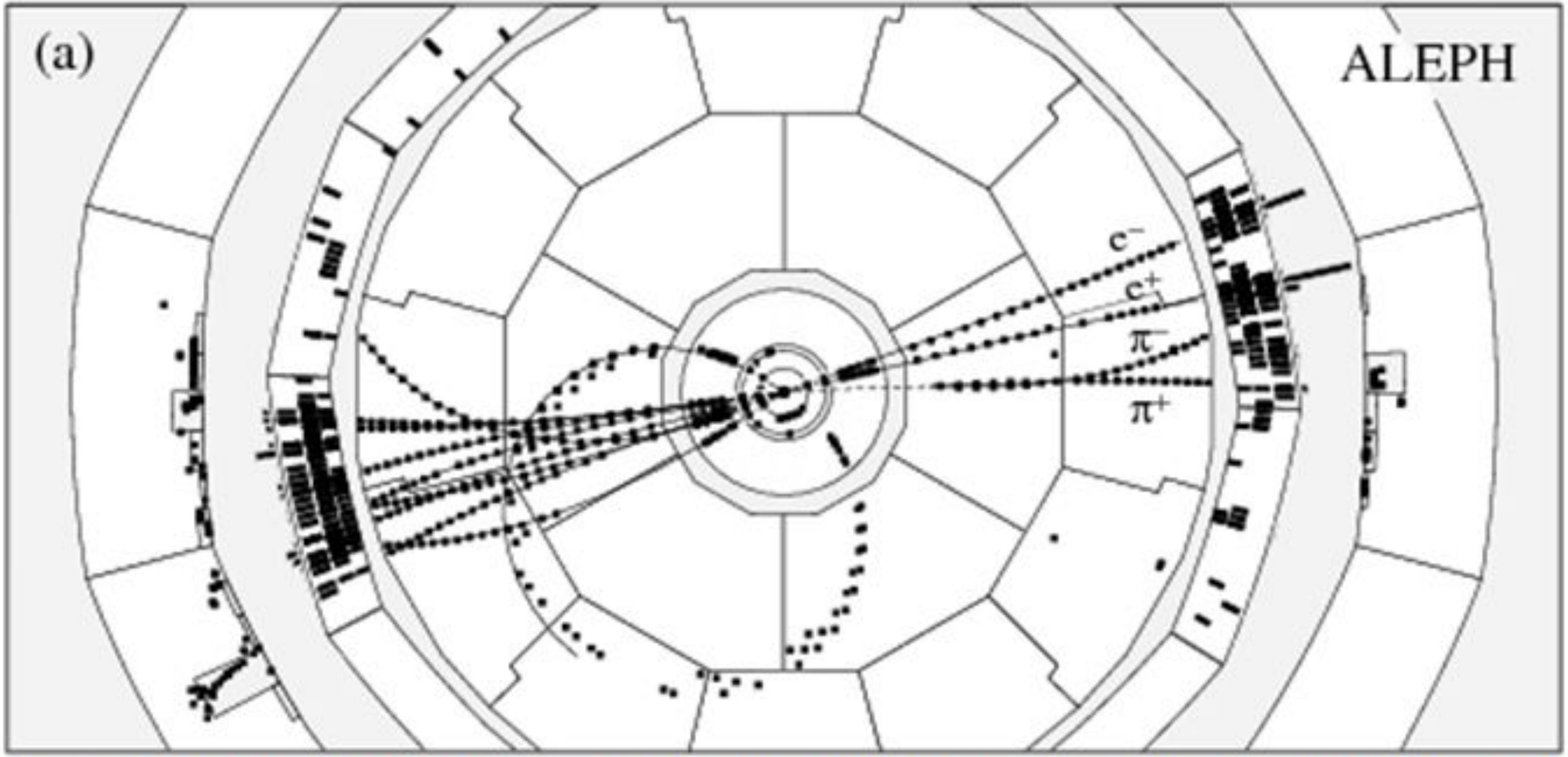
EIC Relevant energies

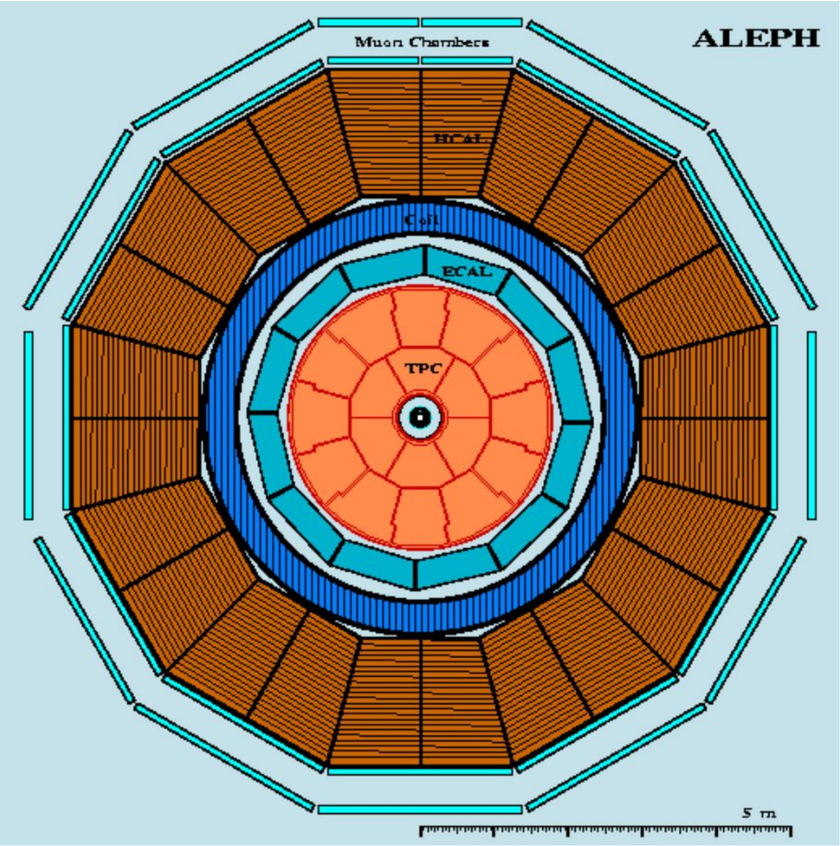
H1 LAr :very high segmentation, all inside solenoid.
I know, this is unrealistic for ATHENA, but I think we should consider potential of affordable granularity for “software compensation”



What lesson can we learn from ALEPH@LEP?

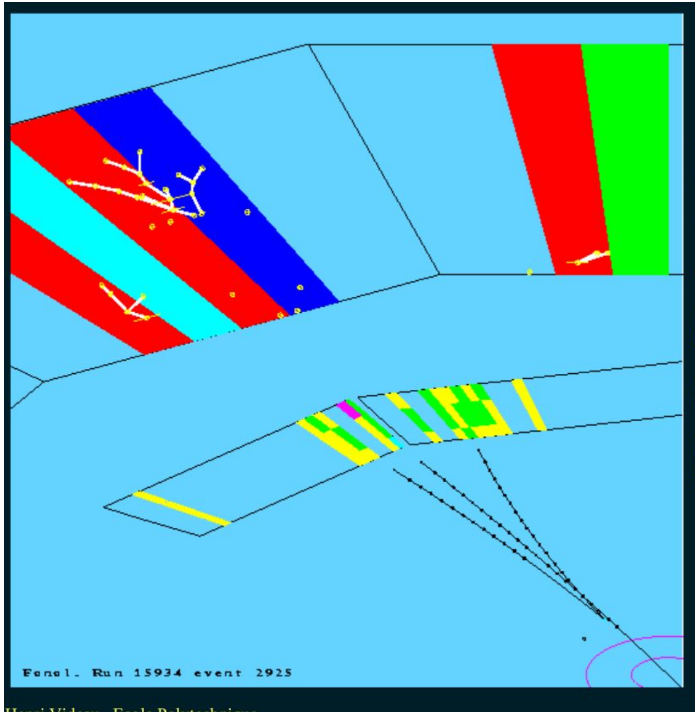
(after all, they invented energy-flow reco, and optimized for jets energies of ~40 GeV)





HCAL with decent transverse segmentation
+streamer info longitudinally.

Similarly, “KLM” might work for ATHENA?



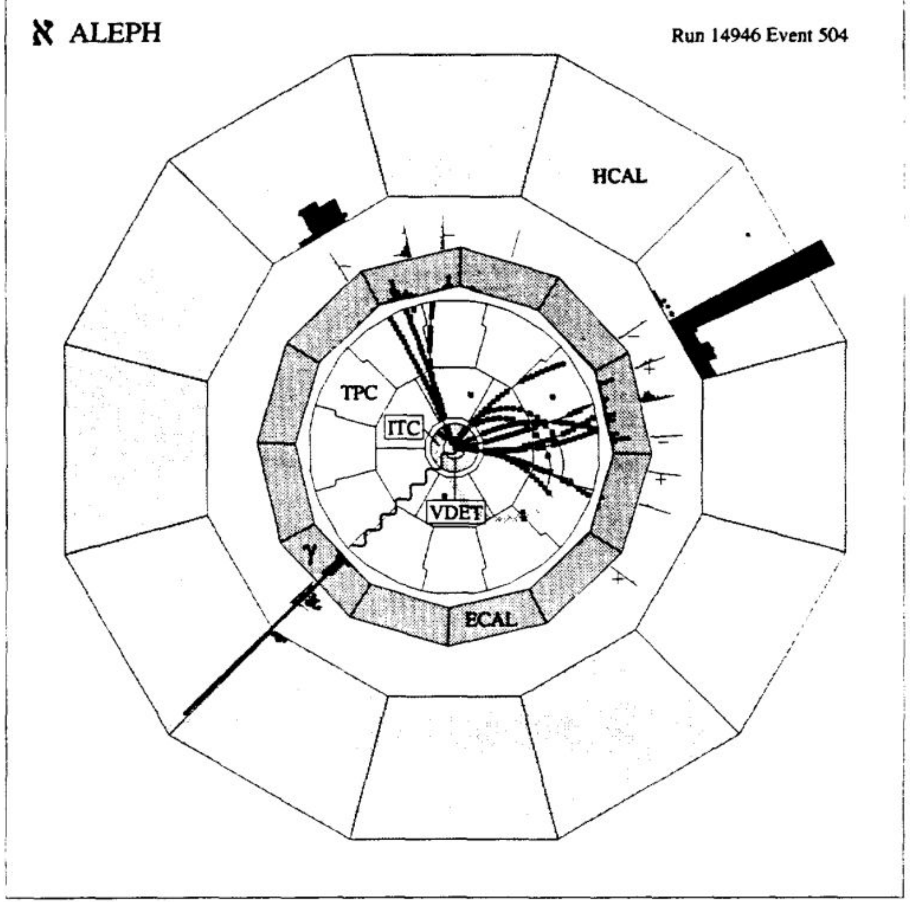


Figure 28: An hadronic event accompanied by an isolated, energetic photon, represented by a wiggly line, carrying an energy of (30.8 ± 1.1) GeV. The mass recoiling against the photon is $(52.0 \pm 1.9)\ \mathrm{GeV}/c^2$, while the visible mass of the hadronic system is $(53.6 \pm 4.9)\ \mathrm{GeV}/c^2$.

Comparison of barrel HCAL specs

	Energy res (with ECAL).	Transverse granularity	Longitudinal granularity	Tech	Has any section inside solenoid?
ATHENA	?? (85%/sqrt(E)?	?? 2.8 degrees? (10 x10 cm2)?	?? 3 layers?	?? Fe/Sc?	?? No
H1	50%/sqrt(E)	7.6 degrees (20x20 cm2)	4-6 layers	LAr	Yes, all
ALEPH	85%/sqrt(E)	3.7 degrees	1 (+23 streamer layers)	Fe/streamer tube	No
sPHENIX	85%/sqrt(E)	5.7 degrees	None	Fe/Sc	No (or yes if iHCAL)

Summary

- EIC hadronic reconstruction requires energy-flow reconstruction to rely exploit great tracker and ECAL res.
- HCAL plays an important, crucial role in energy-flow reconstruction.
- Transverse and longitudinal segmentation are important, not just energy resolution.
- Previous experiments such as H1 and ALEPH are good and contrasting examples of successful application of energy-flow, at energies that are relevant for EIC energies.
- ATHENA design must consider algorithms that will be used for reconstruction (e-flow) and calibrations (software compensation). Consider upgrades (staged longitudinal segmentation readout?)

Backup

ALEPH Calorimeters

ECAL	ALEPH
Absorber	Pb
Detector	Wire chamber
$\mathbf{X_0}$	22 (4,9,9)
Granul.	0.8^0
σE/E a	0.18
σE/E b	-
σE/E c	0.009
σE/E (%) @50 GeV	2.7

HCAL	ALEPH
Absorber	Fe
Detector	Stream tubes
Λ	7.16
Granul.	3.7^0
σE/E a	0.85
σE/E b	-
σE/E c	-
σE/E (%) @50 GeV	12

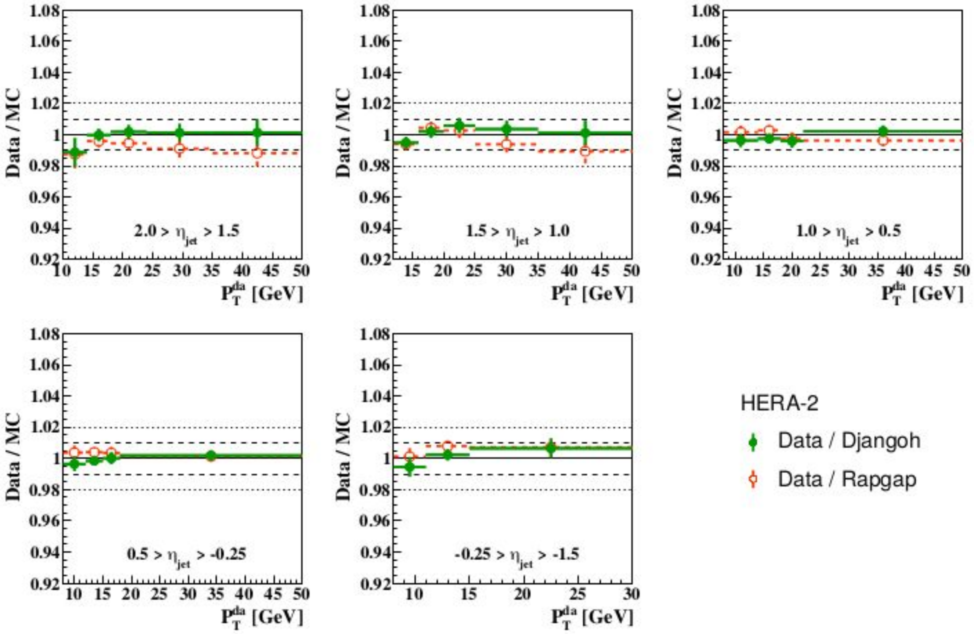
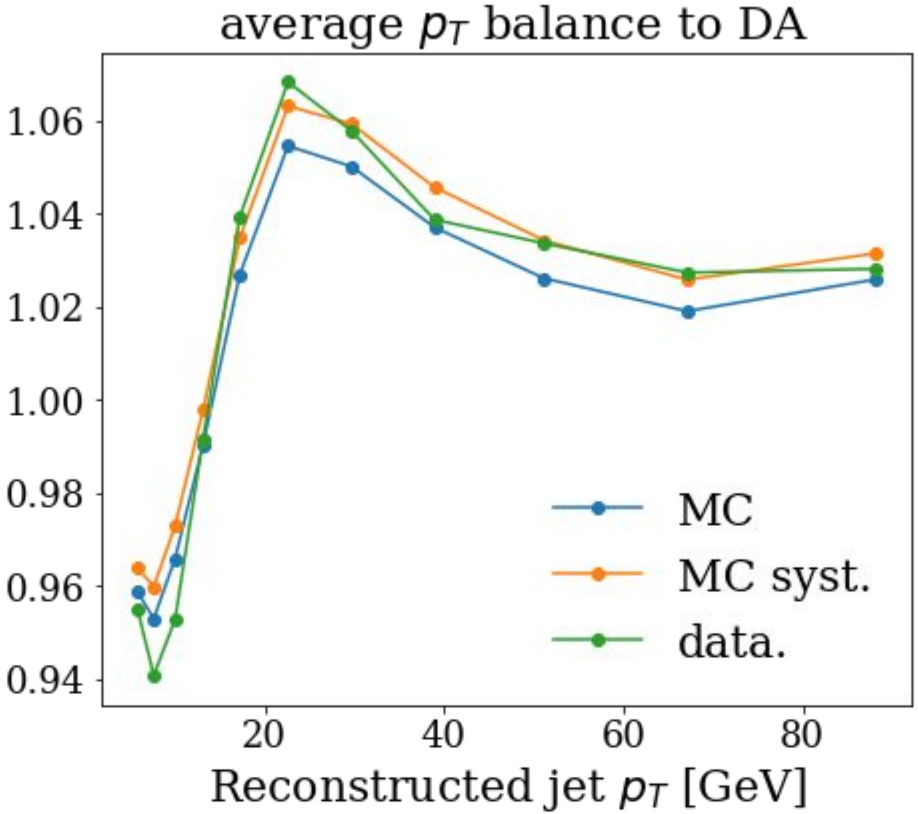


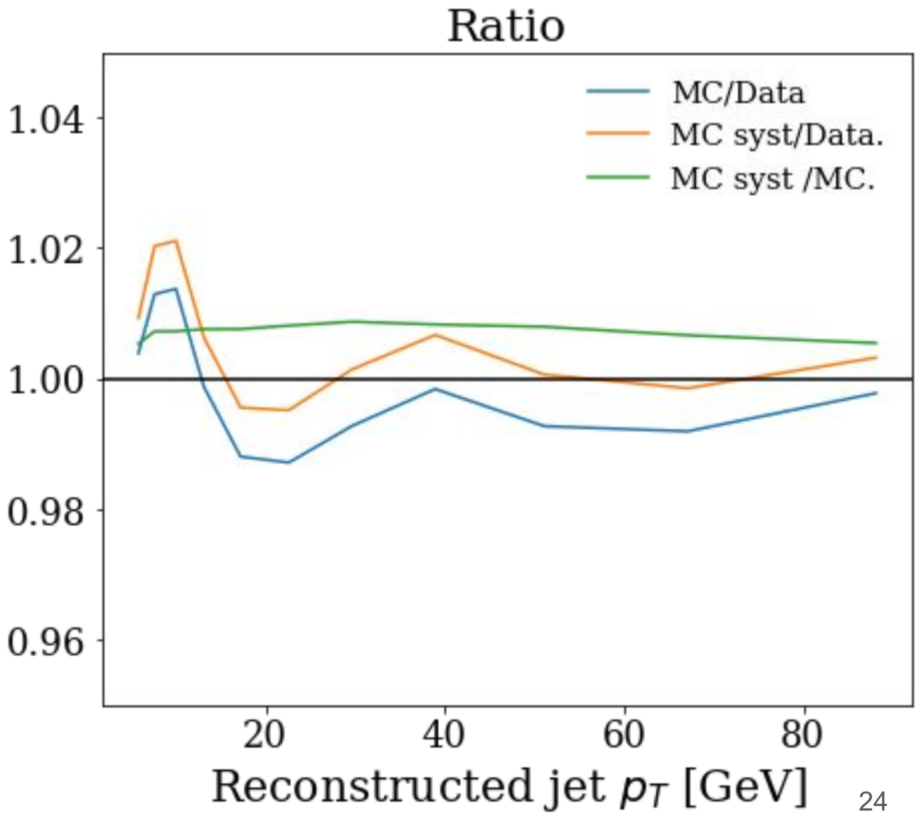
Figure 8.12: Double-ratio of the P_{T}-balance as function of $P_{\mathrm{T}}^{\mathrm{da}}$ in η_{jet} bins corresponding to figure 8.11. The dashed (dotted) line represents a 1% (2%) deviation.

Calibrate hadronic final state
In data and in MC separately
using the same method that
relies on balance to lepton
(really double angle method)

Systematic uncertainty is
Taken from the data/MC
agreement

Jet Calibration (H1)





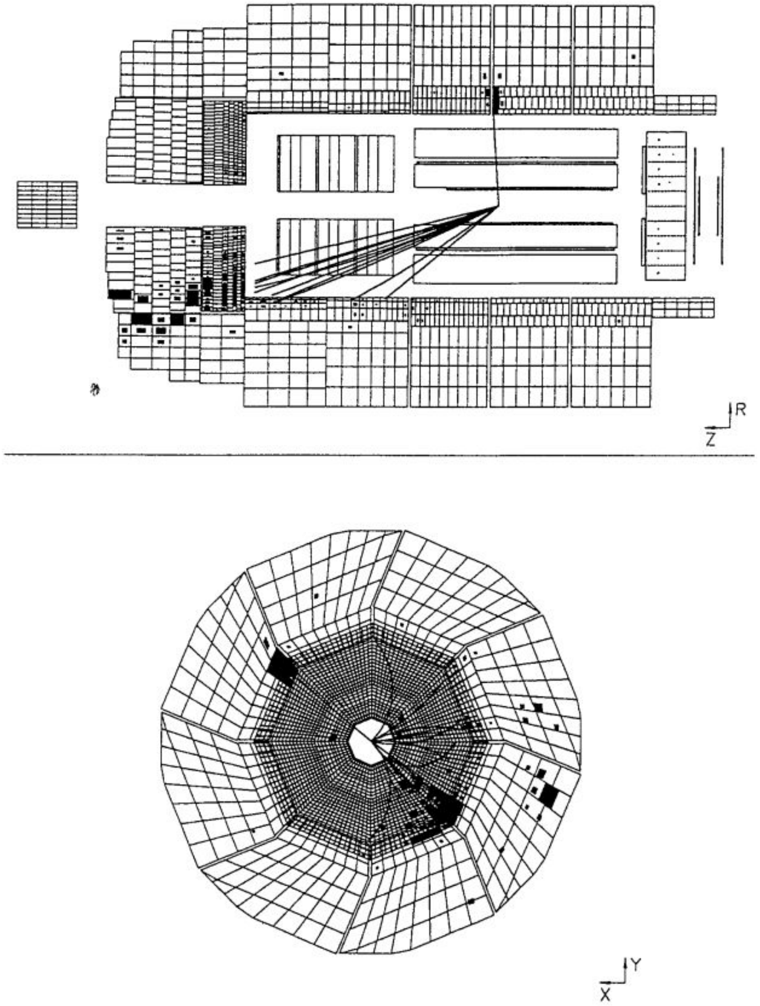


Fig. 31. One of the first deeply inelastic neutral current events recorded with the H1 calorimeter ($Q^2 = 2600\ \mathrm{GeV}^2$).