Jets in Experiment

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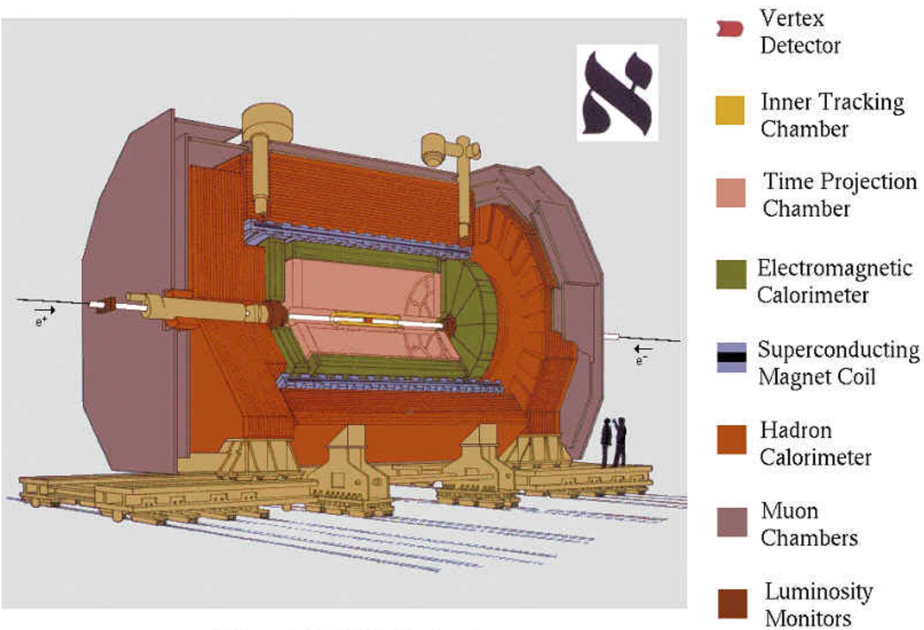
September 22nd, 2016

How are jets detected experimentally?

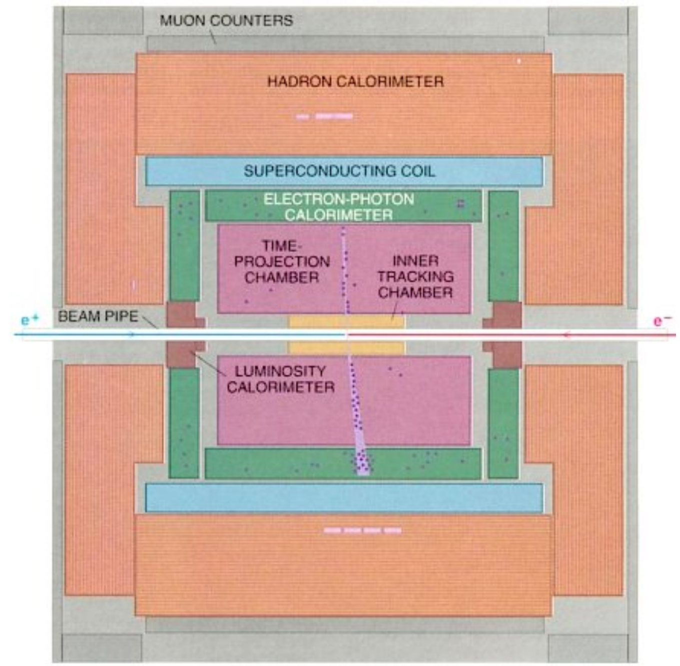
How do we correct for experimental effects?

This is not a review of experimental results.
For that, have a look, e.g., at my talk from QM 2015

The classic onion design



The ALEPH Detector

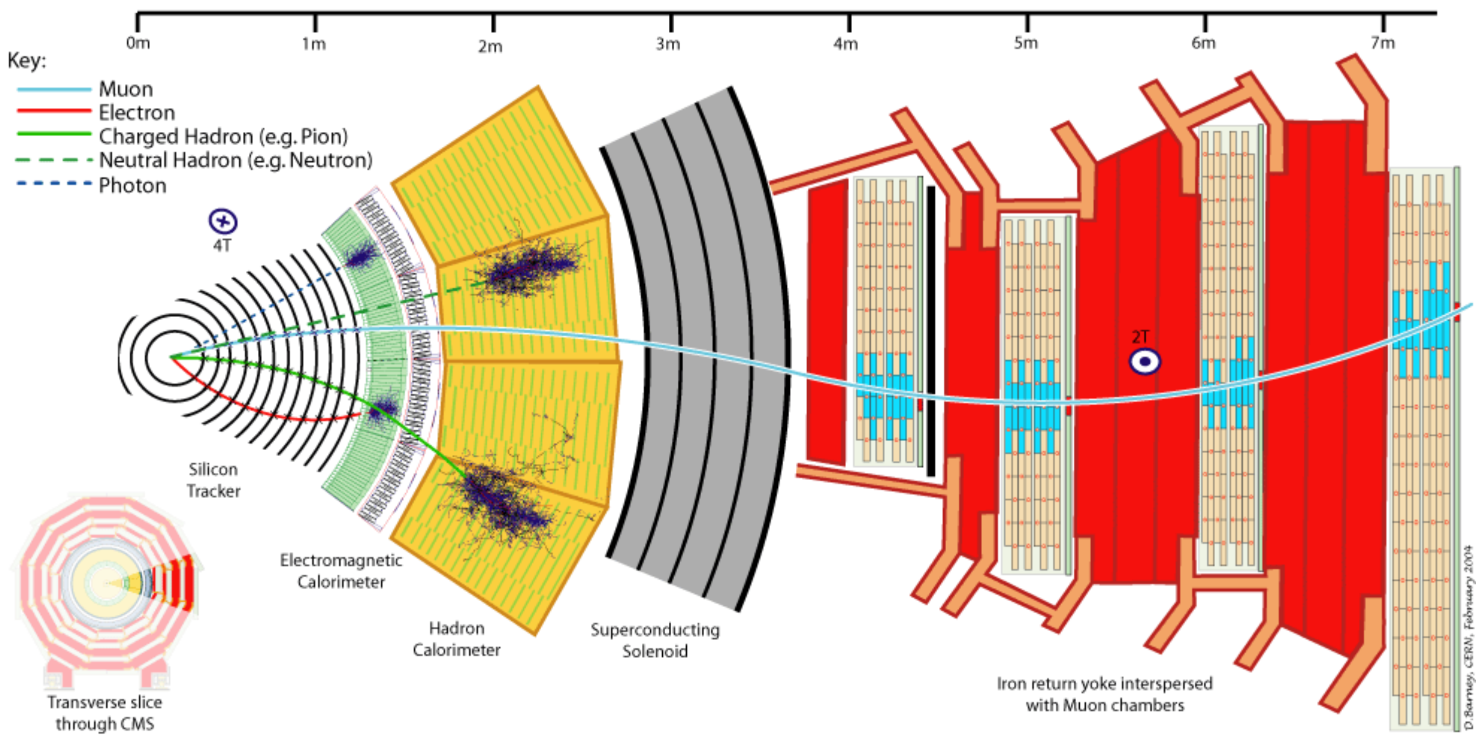


- Tracking
- Electromagnetic calorimeter
- Hadronic calorimeter
- Muon detectors

+ Large acceptance (hermetic)

→ All types of particles detected, including neutrinos via missing E_T

Particle signatures



Four types of detectors identify 5 types of particles: h^+, h^0, γ, e, μ
Detector technologies vary, but always the same basic principle
→ ionization, then charge or light collection

Calorimeters are for jets

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

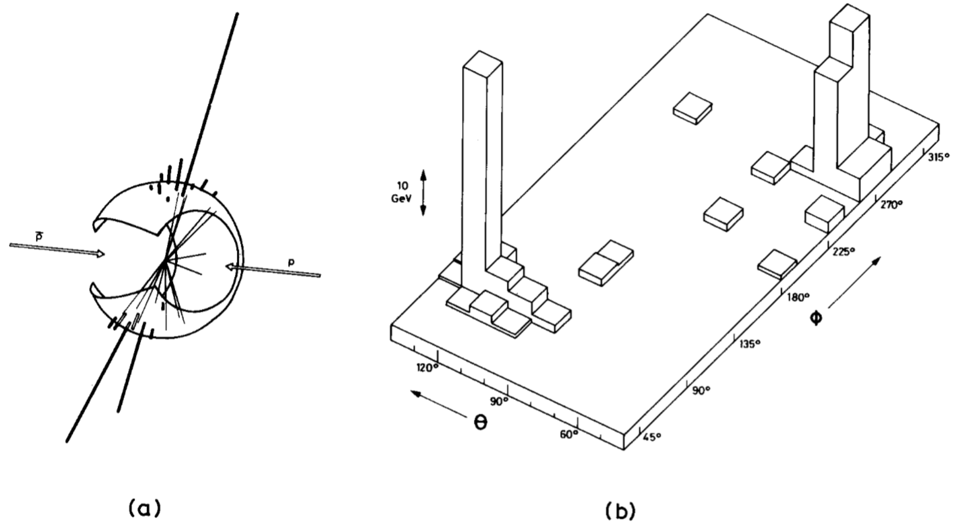


Fig. 4. Configuration of the event with the largest value of ΣE_T, 127 GeV (M = 140 GeV): (a) charged tracks pointing to the inner face of the central calorimeter are shown together with cell energies (indicated by heavy lines with lengths proportional to cell energies). (b) the cell energy distribution as a function of polar angle θ and azimuth ϕ.

First observation of jets in hadron collisions by UA2
→ based on calorimetry
(no B field!)

- Calorimetry = Total absorption
- Typically use light collection (scintillation or cherenkov)
- Shower penetration ~ ln(E) → compact

Issues w/ jet measurements

Many of the modern issues already encountered in 1983

Calorimeter design challenges:

It is found that hadrons deposit a significant fraction of their energy in the EM calorimeter. Due to nuclear effects, the response to hadrons of the combined EM and hadron calorimeter is smaller than its response to EM showers of the same energy.

Underlying event subtraction:

The transverse energy of a jet is defined as: $E_T(\text{jet}) = \Sigma E_T(\text{windows}) - \Sigma E_T(\text{background})$, where the background subtraction is done for every event assuming that the transverse energy density (per unit of η) of the soft background within the window is the same as its average outside the window.

Jet energy corrections:

Comparison of the resulting jet E_T spectrum with the generated one yields a correction factor for each E_T bin. The global correction factor for $d\sigma/dE_T$ is 1.1, essentially independent of E_T.

The UA1 experiment

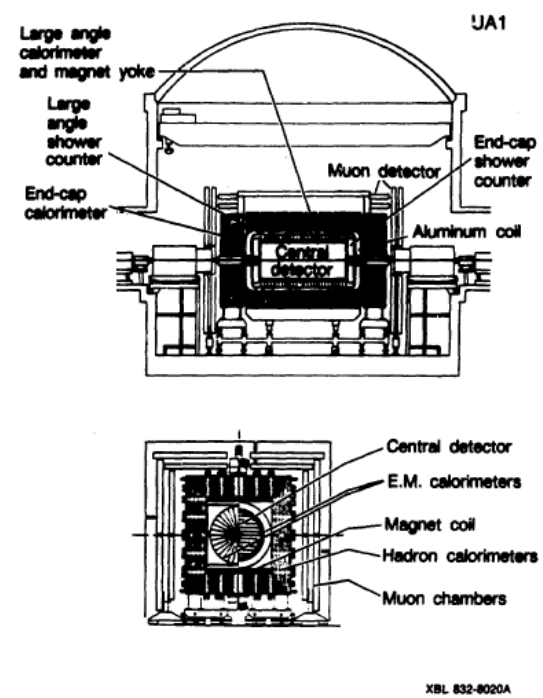


Fig. 8. Longitudinal and end view of the UA1 experiment at CERN.

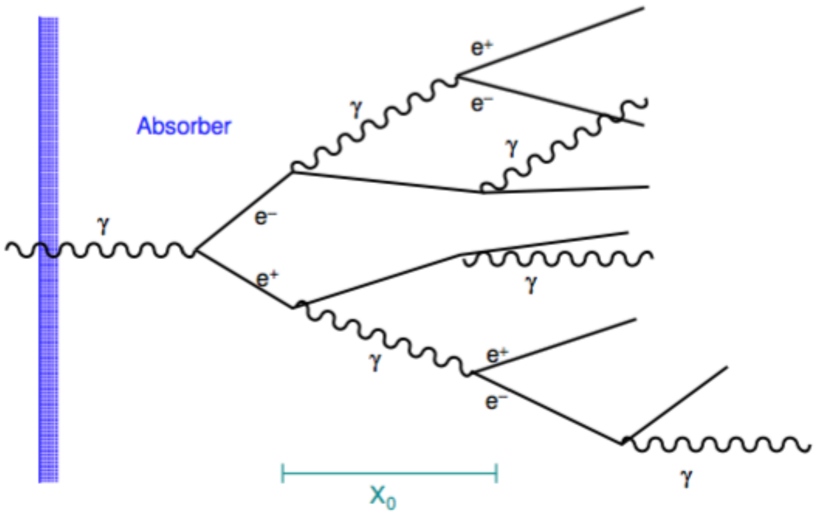
“Calorimetry for a 4π RHIC detector”

To appear in the
Proceedings of the Second RHIC Workshop,
LBL, Berkeley, Calif., USA, May 1987

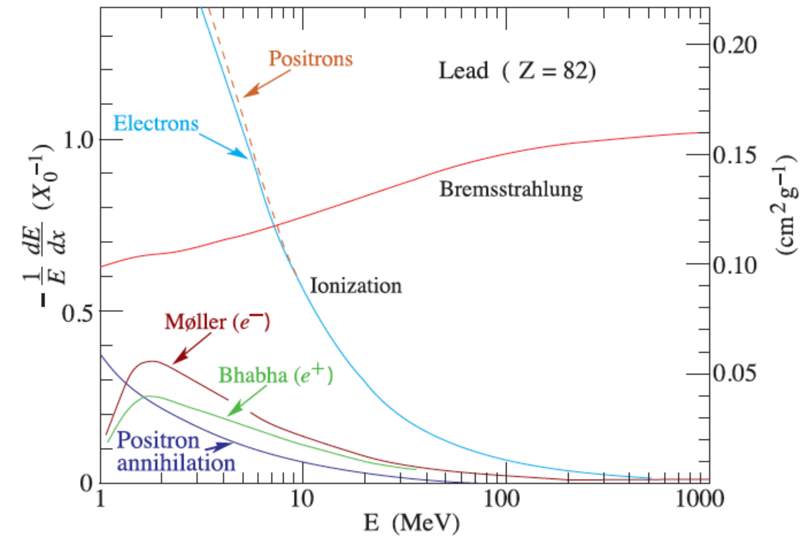
The role of full solid angle (4π) calorimetry at RHIC is, we believe, very different from that at other very high energy colliders. At e^+e^-, ep and pp or $p\bar{p}$ colliding beam machines at SLC/LEP energies and above, high resolution calorimetry [5] has become of crucial importance for measuring jets, which trace the partons in energy and direction. In contrast the physics program at RHIC, as far as we can see today, is oriented more towards large distance phenomena (confinement, phases of matter etc.). As such our main aim is to study hadronic matter at very high temperatures and densities over extended volumina. The subset of most central, most opaque nuclear collisions which have the best chance of generating such conditions may be selected by requiring large transverse energy E_T (summed over all final state particles) in a calorimeter.

The physics of calorimeters

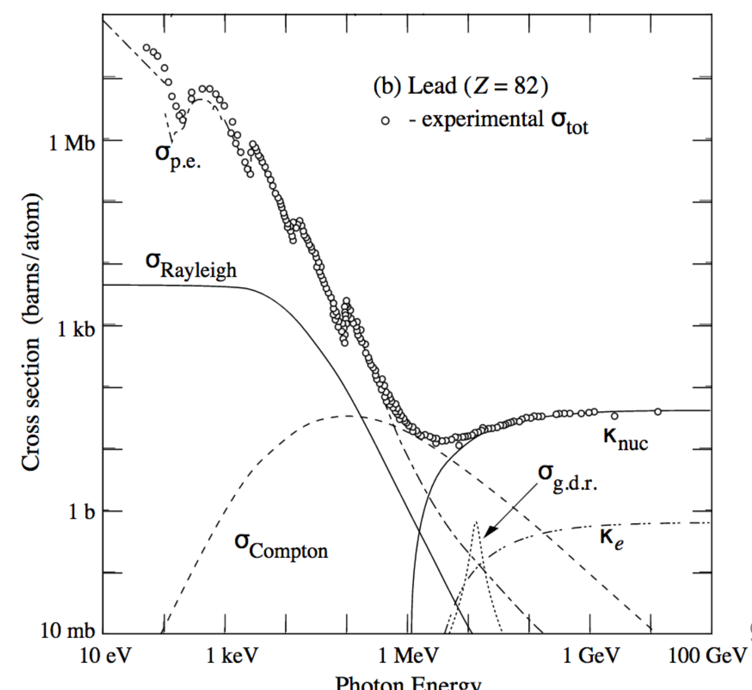
EM showers



Electrons



Photons

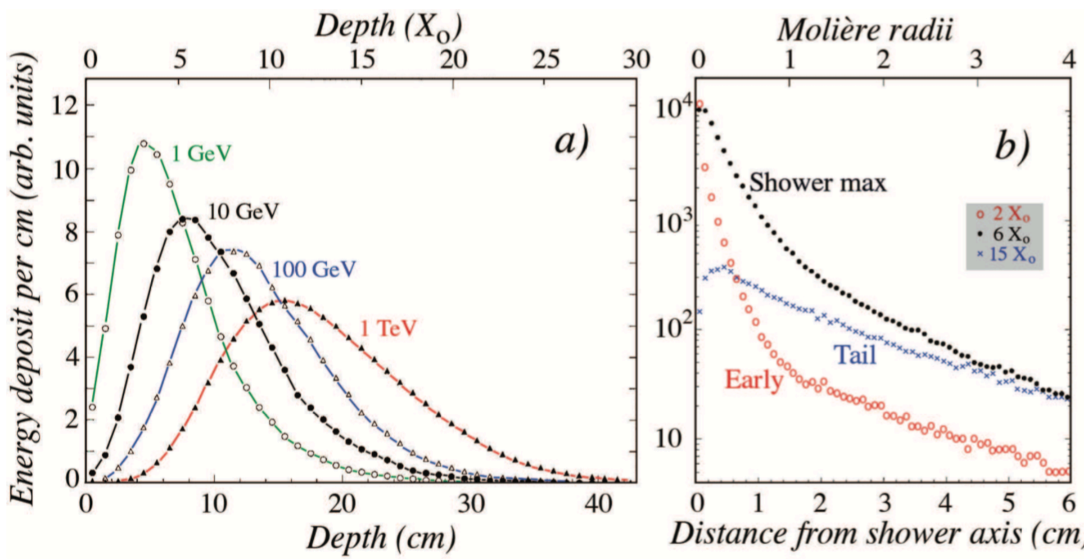


- Shower multiplication: pair production and brems, dominant > 10 MeV, E independent above 1 GeV
- Shower evolution
  - e: Below critical energy, E_c~10 MeV, ionization dominates (basis for signal detection)
  - γ: Photoelectric effect takes over at ~ 1 MeV
- Radiation length X_0
  - $\langle E(x)\rangle = E_0 \exp(-x/X_0)$
  - $\langle I(x)\rangle = I_0 \exp(-7/9\ x/X_0)$
- Typical X_0 of O(1 cm) and 20 X_0s → EM calos are thin!

Properties of EM showers

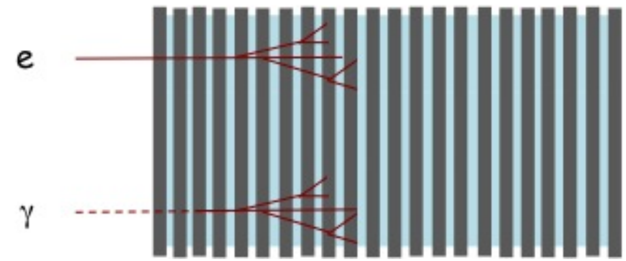
- Radiation length $$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$
- Critical energy $$E_c^{\mathrm{Gas}} = \frac{710\ \mathrm{MeV}}{Z+0.92} \quad \left[E_c^{\mathrm{Sol/Liq}} = \frac{610\ \mathrm{MeV}}{Z+1.24} \right]$$
- Molière radius: transverse size (90% containment) $$R_M = \frac{21\ \mathrm{MeV}}{E_c} X_0$$
- Shower max $$t_{\max} \propto \ln(E_0/E_c)$$

e's in copper:

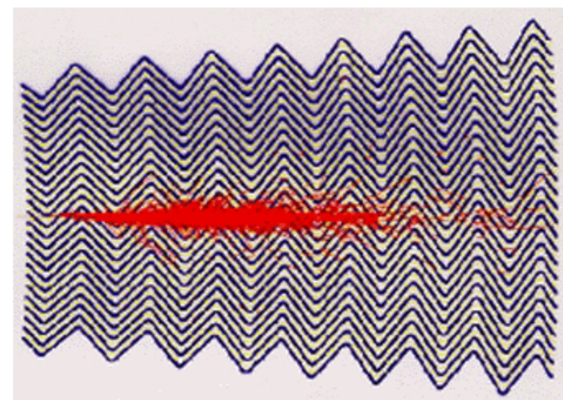


Sampling calorimeters

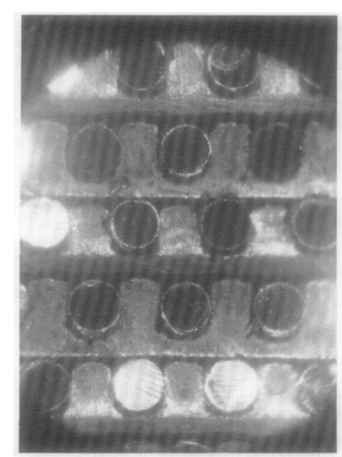
- Two components
  - High Z absorber, often Pb
  - Active material
    - Plastic scintillators
    - Nobel gas / liquid, typically argon
- Various geometries
  - Alternating slabs (sandwich)
  - Alternate geometries to minimize charge collection time and remove cracks



Sandwich



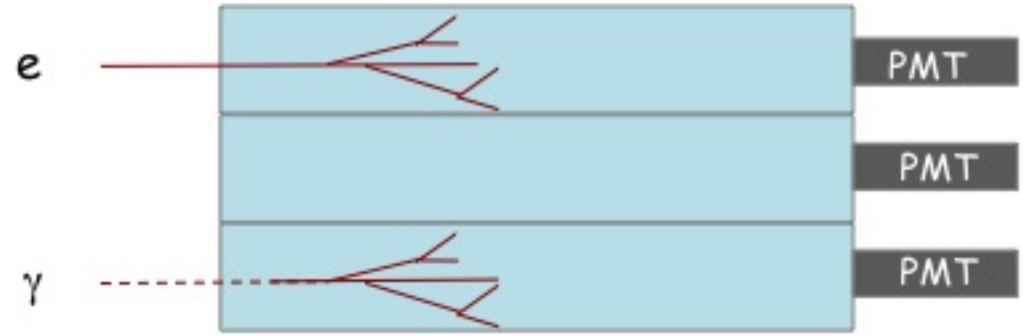
Accordion
ATLAS lAr



H1 SpaCal

Homogenous calorimeters

- Same material absorbs and produces signal
  - Scintillating crystals, e.g., PbWO4 (CMS, PHOS)
  - Cherenkov light, e.g, PHENIX lead-glass
- Pros: Better resolution, can be compact
- Cons: Expensive, no longitudinal segmentation

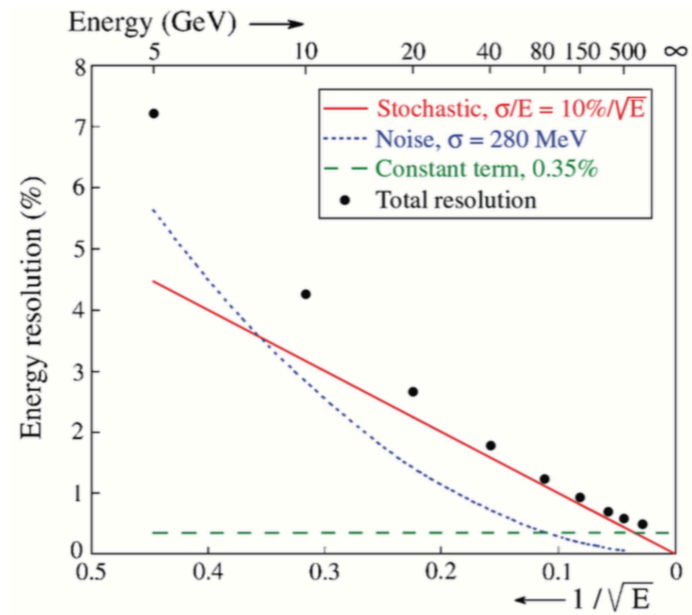


Energy resolution of calo's

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

ATLAS ECAL

- a = stochastic (intrinsic): Shower, signal, and sampling fluctuations
- b = noise: electronics, pile-up
- c = constant: shower leakage, cracks / dead area, inhomogeneity, inter-calibration



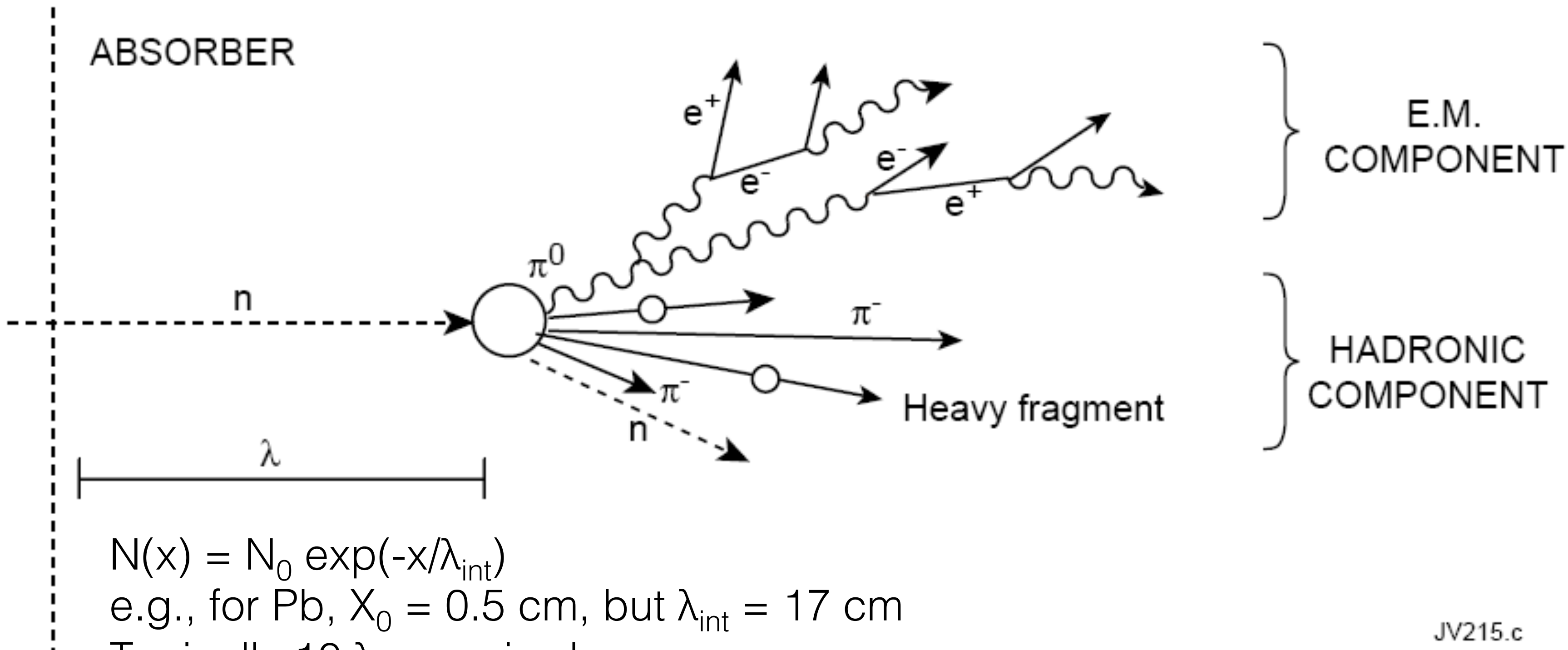
Typically, b relevant at low energy, while c limits high energy performance

EM calo's in HI expt's

Expt	Type	Resolution	X_0s	Coverage	Tower size	Notes
ALICE EMCAL	Sampling	$7\%/\sqrt{E} \oplus 1.5\%$	20	$\sim\pi$ $\eta<0.7$	6 cm	
ALICE PHOS	Homogenous	$3\%/\sqrt{E} \oplus 1\%$	20	$\pi/5$ $\eta<0.12$	2 cm	
ATLAS	Sampling	$10\%/\sqrt{E} \oplus 0.5\%$	22	2π $\eta<3$	~6 cm	Longitudinal segment.
CMS	Homogenous	$3\%/\sqrt{E} \oplus 0.5\%$	25	2π $\eta<3$	2 cm	
LHCb	Sampling	$10\%/\sqrt{E} \oplus 1\%$	25	2π $2<\eta<5$	4-12 cm	Pads and pre-shower
PHENIX PbSc	Sampling	$8\%/\sqrt{E} \oplus 1.5\%$	18	$3/4\pi$ $\eta<0.35$	5 cm	
PHENIX PbGl	Homogenous	$6\%/\sqrt{E} \oplus 1\%$	16	$\pi/4$ $\eta<0.35$	4 cm	
STAR	Sampling	$14\%/\sqrt{E} \oplus 1.5\%$	18	2π $\eta<1$	10 cm	Shower max, pre-shower

Quoting barrel properties, endcaps usually worse
Plenty of other considerations, e.g, timing, radiation-hardness

Hadronic showers



$N(x) = N_0 \exp(-x/\lambda_{int})$
e.g., for Pb, X_0 = 0.5 cm, but λ_{int} = 17 cm
Typically 10 λ_{int} required
→ hadron calorimeters much thicker than EM (& always sampling)

- First relativistic component produces charged and neutral pions
  → neutral pions produce EM component ("one way street")
- Followed by (non-relativistic) various nuclear reactions
- Hadronic showers characterized by large fluctuations (EM fraction, nuclear reactions, etc.) → poor resolution compared to EM showers

Nuclear reactions

A. Spallation: Fast hadron ejects nucleons, which collide w/ other nuclei
Protons (~ 100 MeV) produces ionization

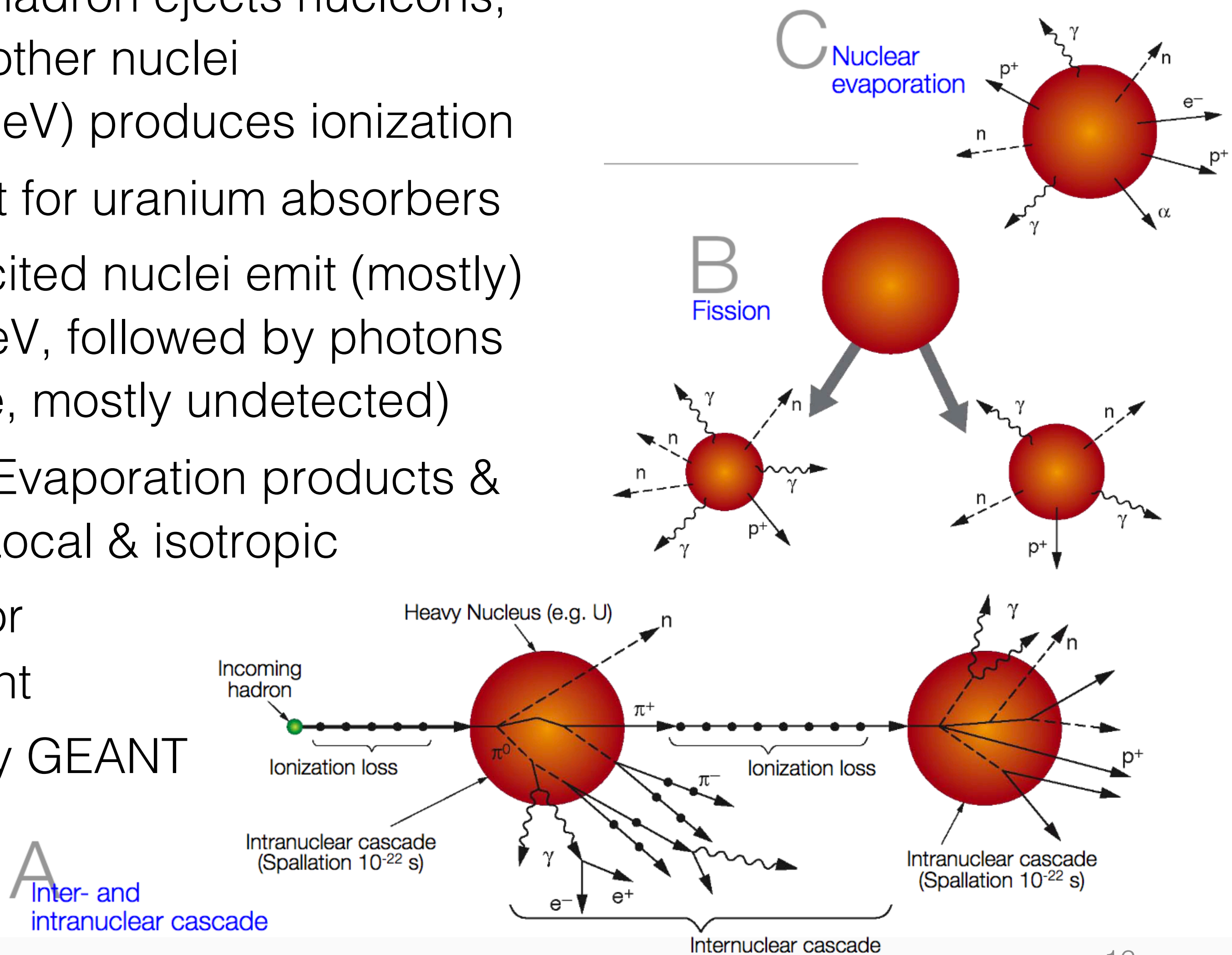
B. Fission: Relevant for uranium absorbers

C. Evaporation: Excited nuclei emit (mostly) neutrons, ~10 MeV, followed by photons (both short-range, mostly undetected)

- Invisible energy: Evaporation products & binding energy. Local & isotropic

→ Lower response for non-EM component

- Poorly modeled by GEANT



EM vs hadronic response

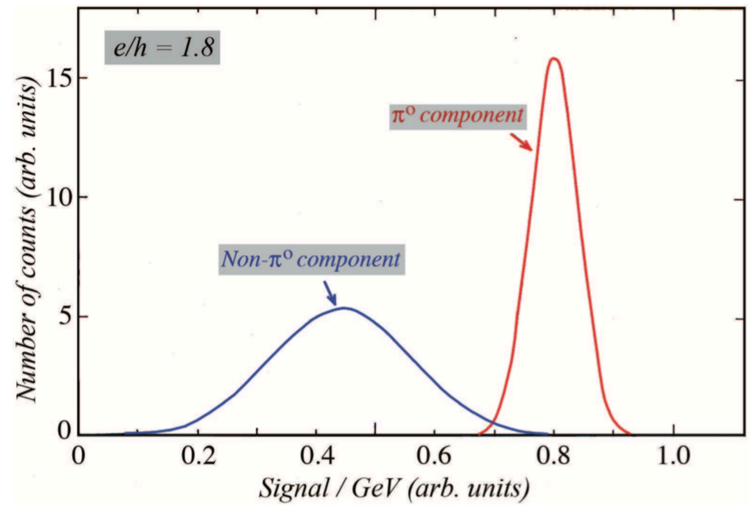
- e/h typically less than 1
- Measured with e/π

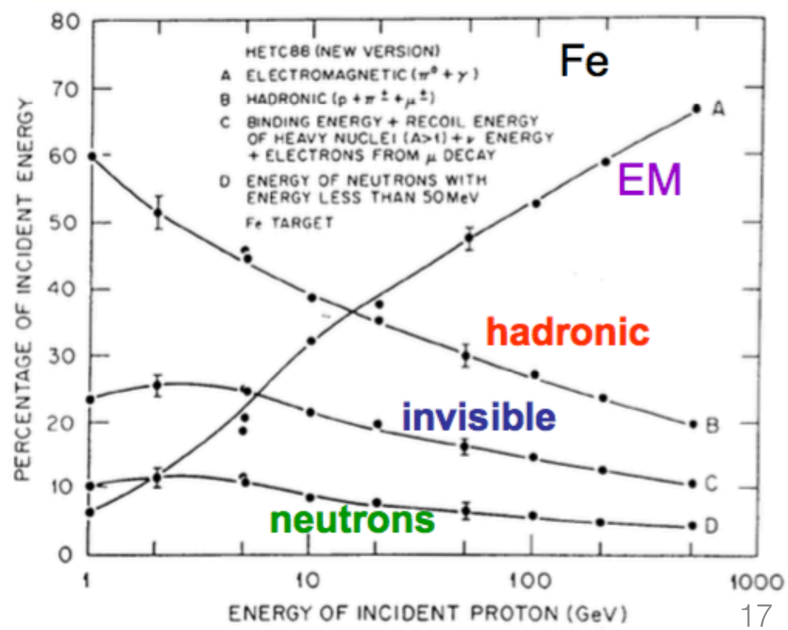
$$\frac{e}{\pi} = \frac{e}{h}\left(\frac{1}{1 + f_{\mathrm{EM}}(e/h + 1)}\right)$$

- Varies w/ energy,

  f_{EM} = 0.1 E(GeV)

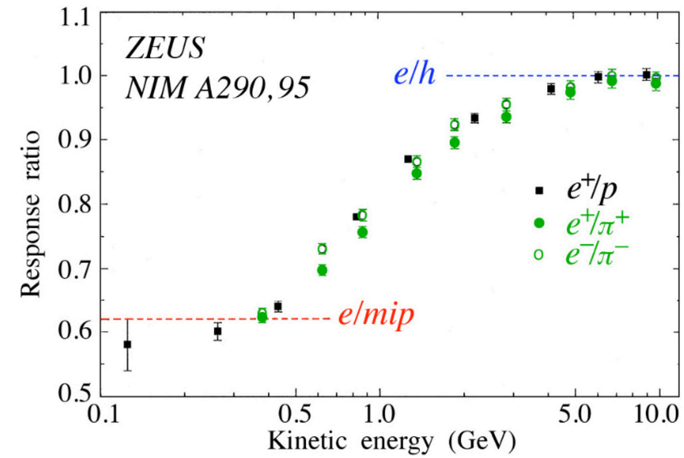
- Consequences
  - Non-linear response
  - Limits energy resolution (constant term)

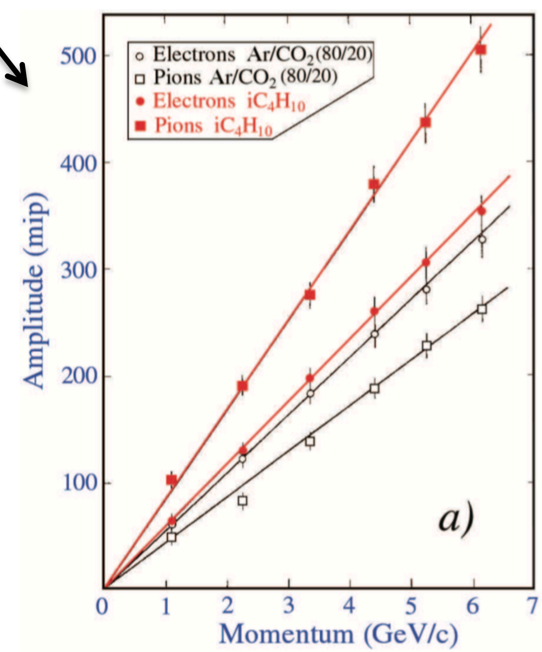




Compensation (e/h = 1)

- e/h can be tuned via choices of materials and sampling fraction
  - Boost hadronic response
    - Fission w/ uranium absorbers
    - Hydrogen-rich active materials (recover slow neutrons)
  - Suppress EM response w/ high Z absorber, photo-electric effect ~Z^5
  - Also, software compensation: determine f_{EM} by shower shape, particularly longitudinal
- Low E always non-linear, consequence of sampling → calorimeters not optimal for bulk observables



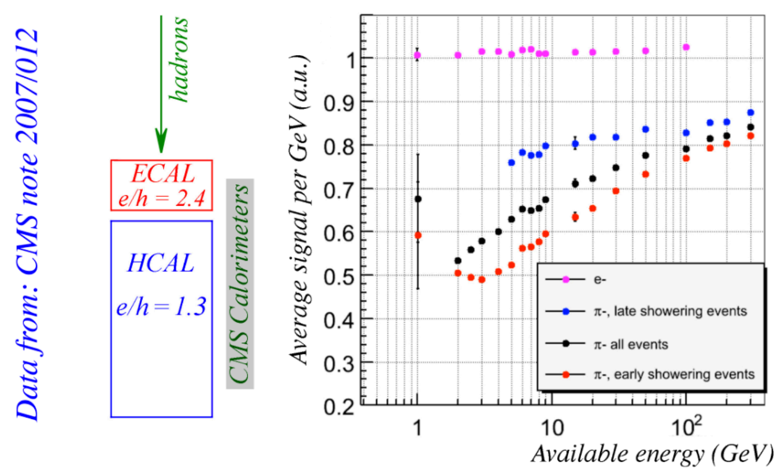


Hadron calo’s in “HI” expt’s

Expt	Resolution	λ_I	Coverage	Tower size	e/h	Notes
ATLAS	$50\%/\sqrt{E} \oplus 3\%$	10	2π, $\eta<5$	20 cm	1.4	
CMS	$100\%/\sqrt{E} \oplus 5\%$	7	2π, $\eta<5$	100 cm	1.3	+tail catcher
LHCb	$80\%/\sqrt{E} \oplus 10\%$	5.6	2π, $2<\eta<5$	13-26 cm		

- Compare to ZEUS (e/h=1): $\sigma/E = 35\%/\sqrt{E} + 2\%$
- Compensation requires long signal integration window, would have been challenging for the LHC due to rate

Hadron resolution depends on combined ECAL + HCAL



What about tracking devices?

- Several varieties: silicon (pixel, strip), gaseous (transition radiation tracker, wire chambers)
- Vary in material budget, speed, precision
- Pros: Precise, linear, $\sigma(p) / p \sim p$
- Cons depend on device, but some combination of:
  - Fake tracks / poor resolution at high p_T
  - Losses, algorithmic or in material
  - Speed / uniformity
- Not sufficient alone for jets → neutral fraction fluctuates
- However, essential for modern jet measurements
  - Pile-up mitigation, calo noise rejection
  - Combined with calorimeters à la Particle flow
  - Jet calibration w/ track jets
  - Essential for flavor identification (quark vs glue & b-tagging)

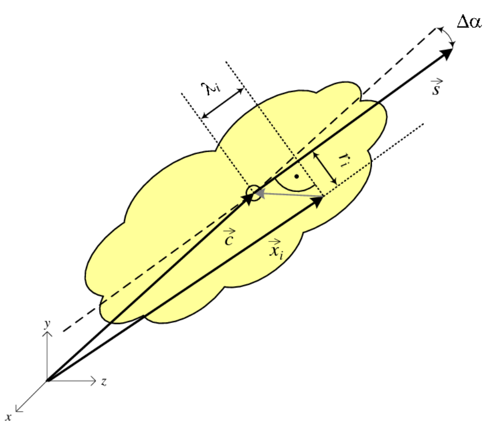
Jet calibrations

- How do we make the correspondence between detector objects and particle level jets?
  - Particles are measured w/ finite resolution
  - They overlap and add non-linearly in our detector
- Two strategies:
  - Local calibrations: Use calo segmentation or tracking information to compensate/mitigate calo non-linearity
  - Jet-level calibrations: Correct at jet level, taking into account data-simulation differences

Local calibrations

Topological clusters (ATLAS)

- Clustering algo, robust against noise and PU*
  - Seeds: $E_{cell} > 4\ \sigma_{noise}$
  - Join seeds with all neighbors (adjacent in 3d)
  - Growers: $E_{cell} > 2\ \sigma_{noise}$ → Take growers' neighbors as well
  - Others merged only if direct neighbors (else thrown out)
  - Split clusters w/ > 1 local maxima
- Cluster properties
  - Geometrical moments: Location, direction, size
  - "Signal moments": Significance, density, EM fraction



$\vec{c}$ *centre of gravity of cluster, measured from the nominal vertex* $(x = 0, y = 0, z = 0)$ *in ATLAS*

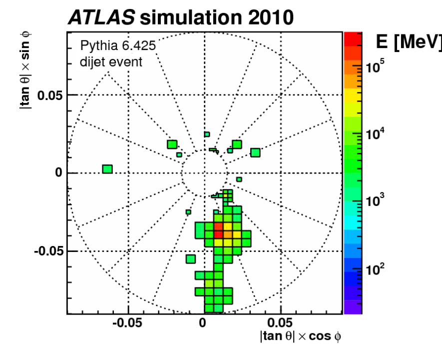
$\vec{x}_i$ *geometrical centre of a calorimeter cell in the cluster, measured from the nominal detector centre of ATLAS*

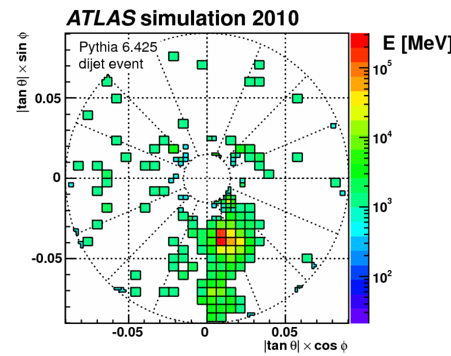
$\vec{s}$ *particle direction of flight (shower axis)*

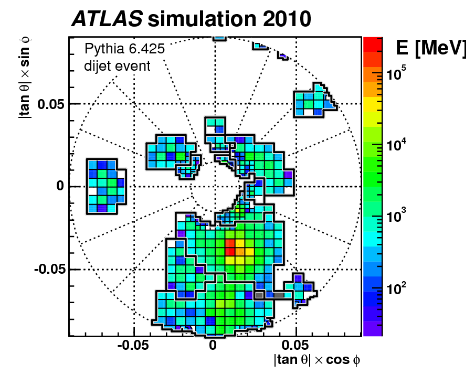
$\Delta\alpha$ *angular distance* $\Delta\alpha = \angle(\vec{c}, \vec{s})$ *between cluster centre of gravity and shower axis* $\vec{s}$

λ_i *distance of cell at* $\vec{x}_i$ *from the cluster centre of gravity measured along shower axis* $\vec{s}$ $(\lambda_i < 0$ *is possible)*

r_i *radial (shortest) distance of cell at* $\vec{x}_i$ *from shower axis* $\vec{s}$ $(r_i \geq 0)$







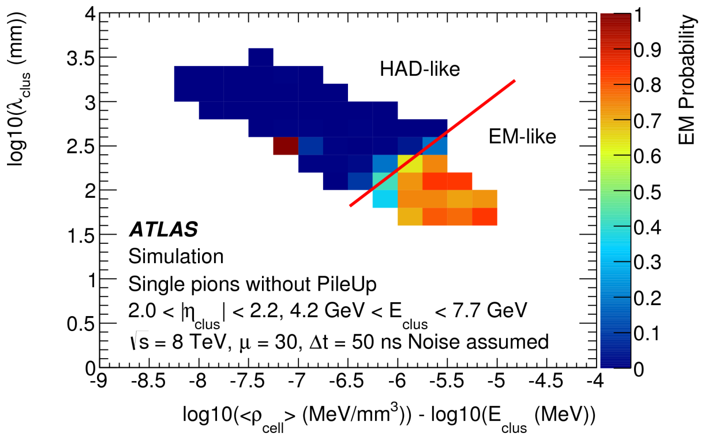
*Calo readout such that PU appears as add'l noise fluctuations

Cluster calibrations

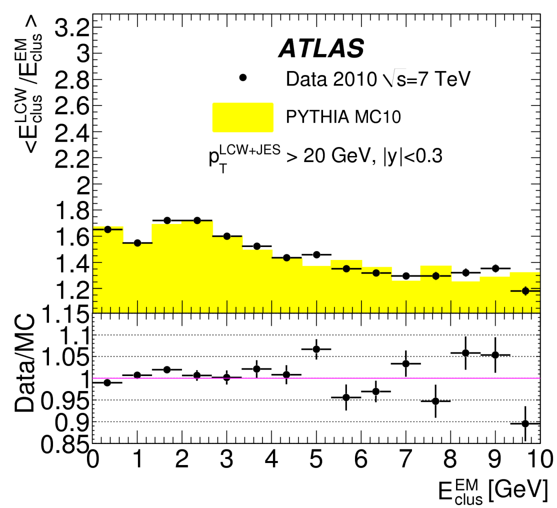
- "Local cell weighting" (LCW):
  Use cluster properties to correct for instrumental effects

1. EM/HAD classification
   - Overall cluster correction, depending on shower depth and density
   - Further, weight individual cells depending on type, location, and energy
2. Out-of-cluster: based on "lost" cells within an envelope
3. Dead / leakage: Search for adjacent inactive regions & calibrate based nearby energy deposit

EM/HAD cluster classification



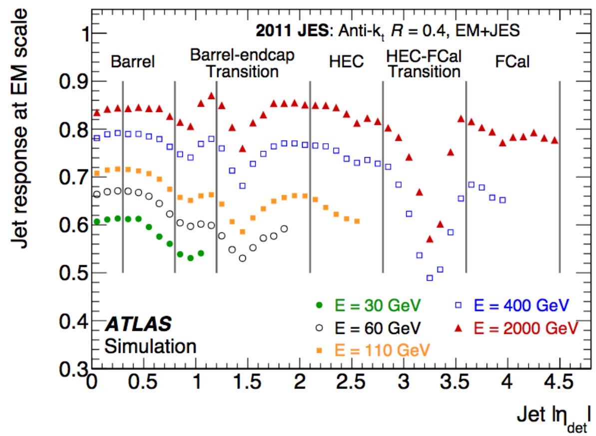
Mean cluster corrections

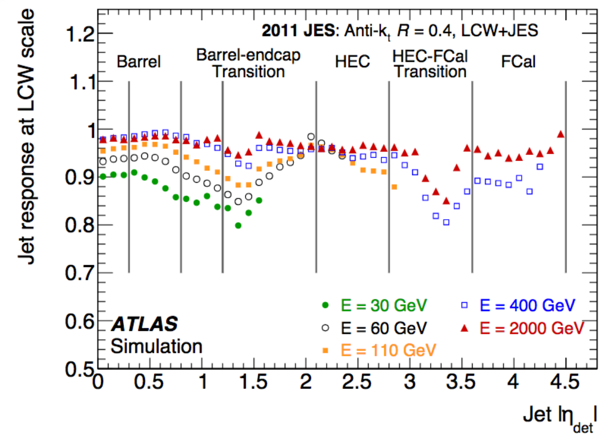


Jets w/ LCW clusters

Baseline: assume all clusters are EM

LCW calibrations



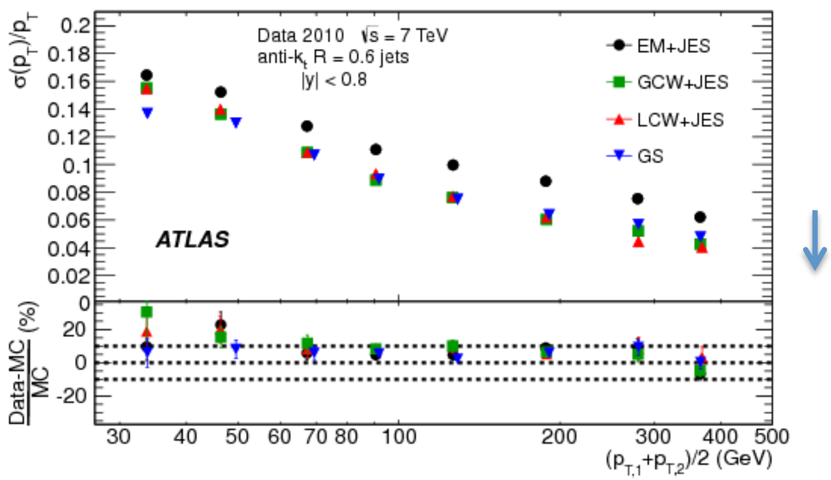


Response:

- Larger response compared to EM scale
- More uniform across jet eta and energy

Resolution:

- Improved by ~20%
- Good data/MC agreement

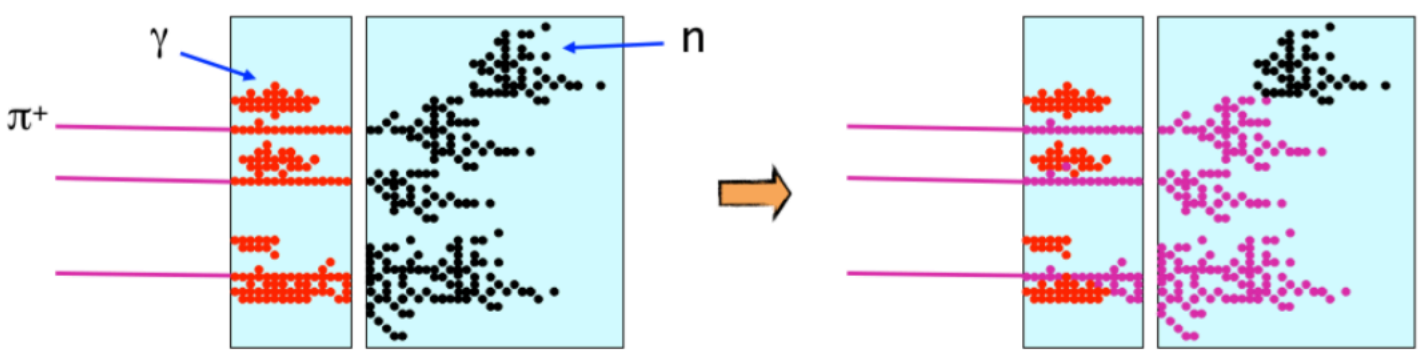


Particle flow (CMS)

- Charged hadrons comprise ~60% of jets, best measured w/ tracker

Component	Detector	Energy Fract.	Energy Res.	Jet Energy Res.
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\,E_j$	$10^{-4}\,E^2_{X^{\pm}}$	$< 3.6 \times 10^{-5}\,E_j^2$
Photons (γ)	ECAL	$\sim 0.3\,E_j$	$0.15\,\sqrt{E_\gamma}$	$0.08\,\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\,E_j$	$0.55\,\sqrt{E_{h^0}}$	$0.17\,\sqrt{E_j}$

- A PF algorithm combines calorimeter and tracker information
- The trick is to minimize double counting, while resolving all particles

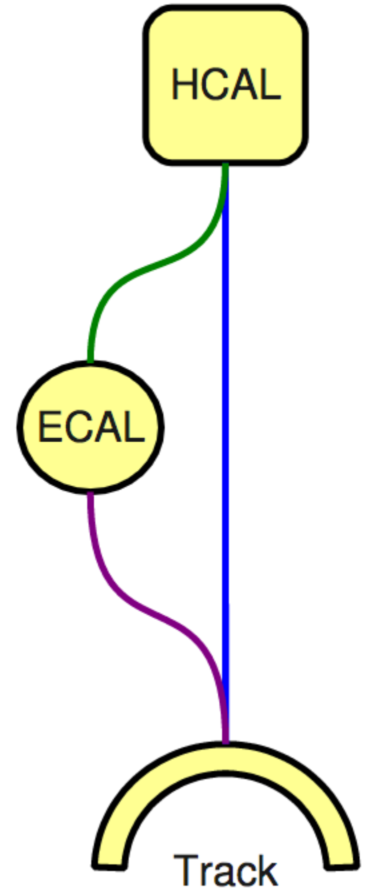


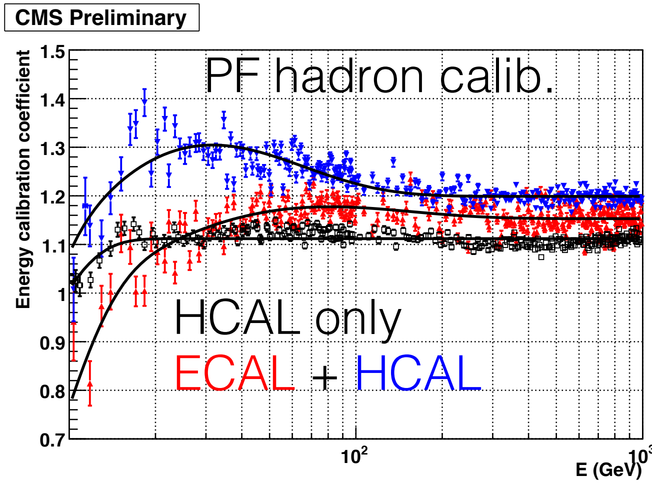
$E_{JET} = E_{ECAL} + E_{HCAL}$ $\quad$ $E_{JET} = E_{TRACK} + E_\gamma + E_n$

Particle flow in CMS

1. Topological calo clustering (2d)
2. Linking “elements” into “blocks”:
   - Track-cluster: extrapolate tracks to expected calor depth. <= 1 HCAL cluster per block. HCAL-ECAL: η-ϕ envelope around HCAL cell
3. Resolve, based on compatibility:
   - If track E = calo E (within uncertainties) → PF charged hadron
   - If track E > calo E: Progressively remove poor quality tracks
   - If track E < calo E: excess turned into neutrals
   - Unlinked calo clusters become neutrals

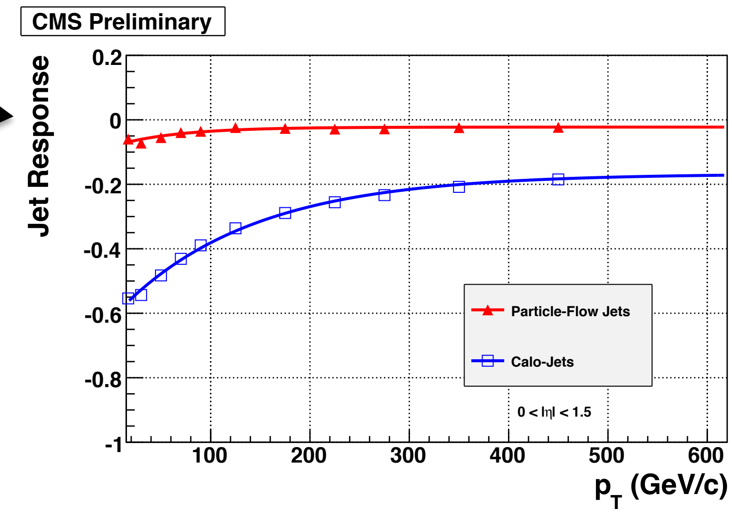
Calo clusters associated to charged and neutral hadrons are calibrated using isolated track data

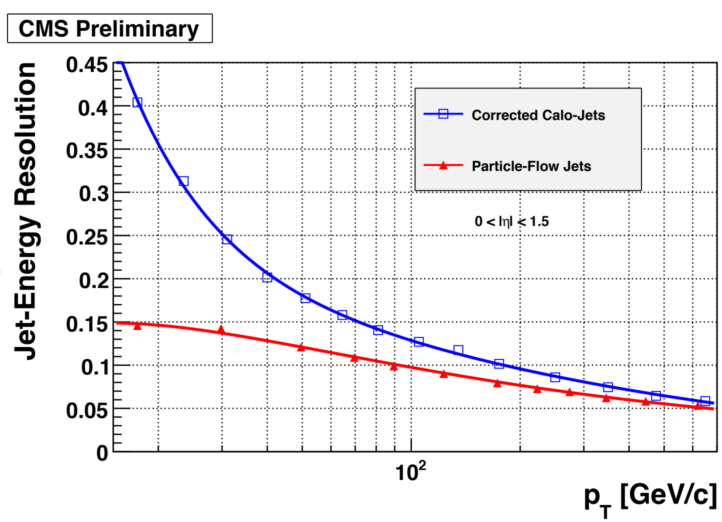


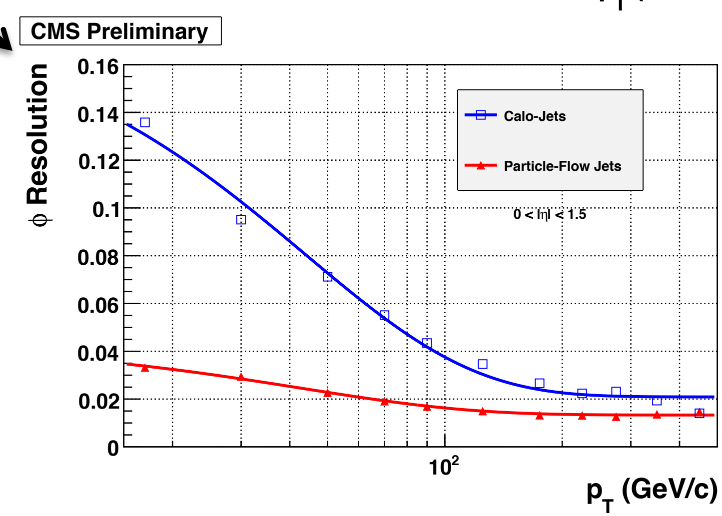


PF performance in CMS

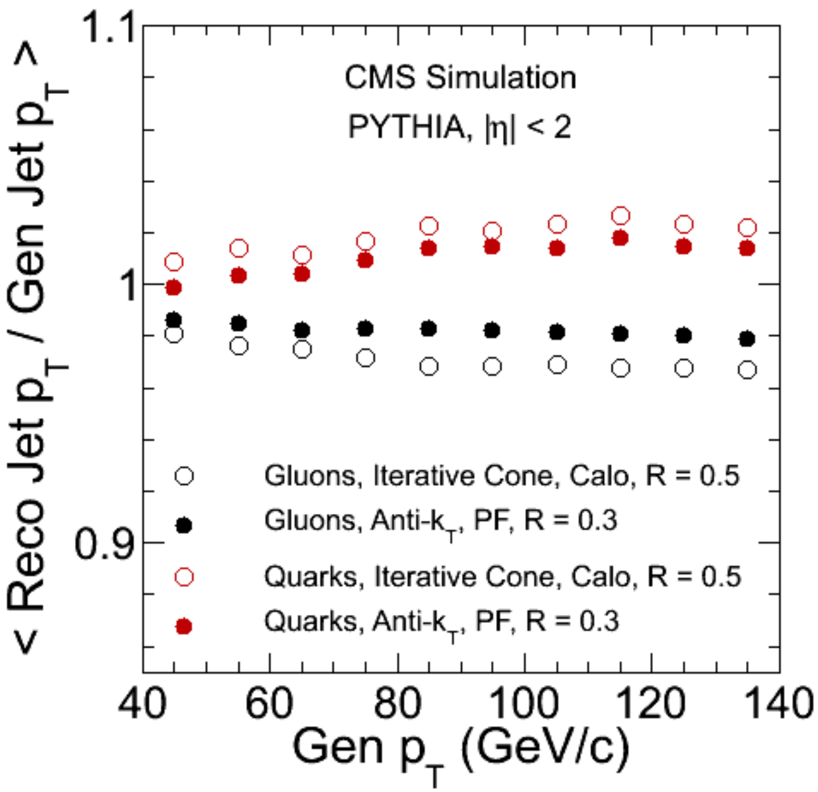
- Response: Captures more of raw jet p_T
- Energy resolution: Improved at low p_T, converges to calo behavior at high p_T
- Pointing resolution vastly improved







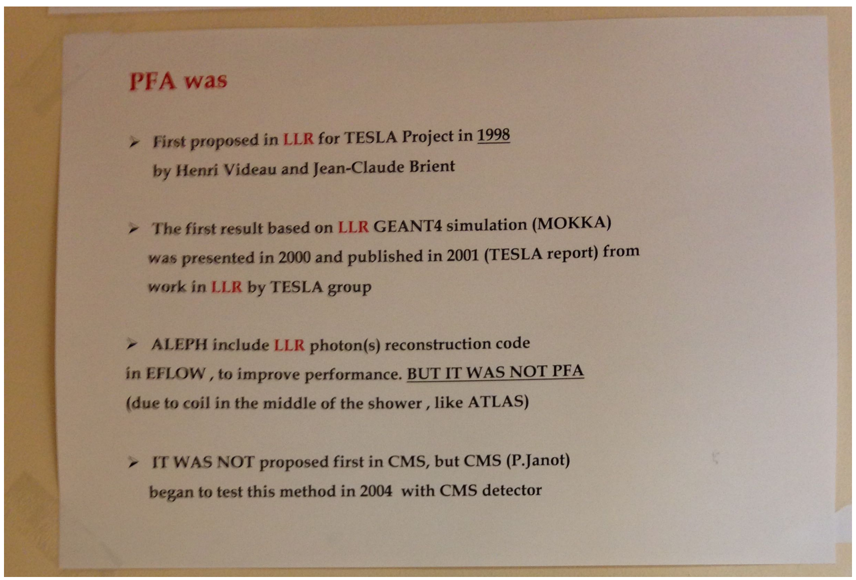
Flavor dependence

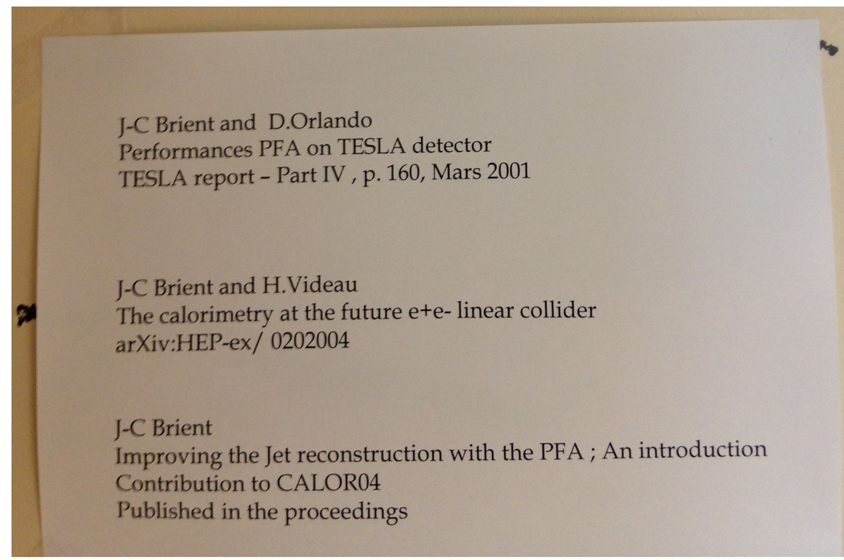


- Response tends to be lower for gluon jets due to calo non-linearity
- Gluon jet fragmentation poorly modeled by generators
- Generator dependence reduced for PF, compared to calo

History of PF

… as seen on the next to the door of my lab director, Jean-Claude Brient





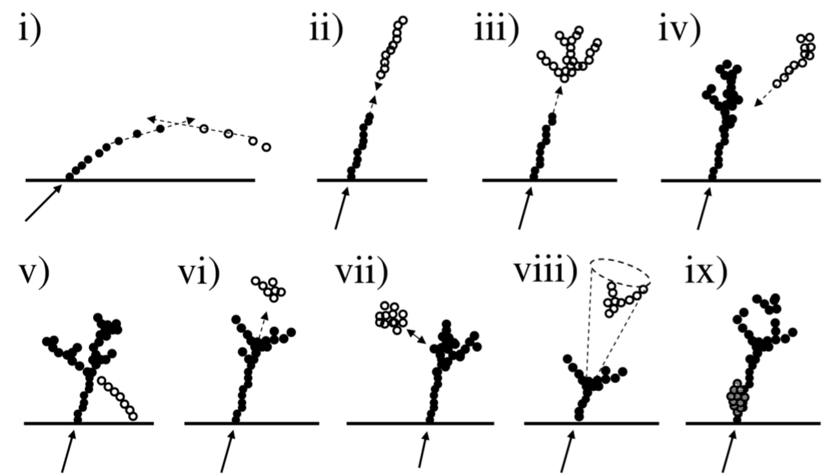
Particle flow was not invented by CMS
In fact, CMS is not really an ideal PF detector

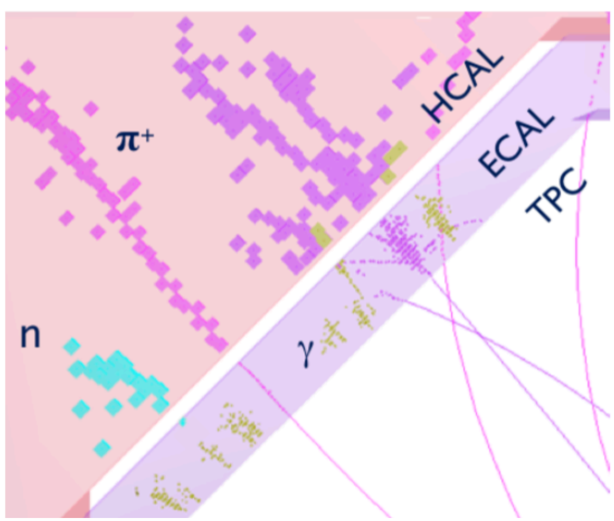
Particle flow calorimetry

High granularity calorimeters

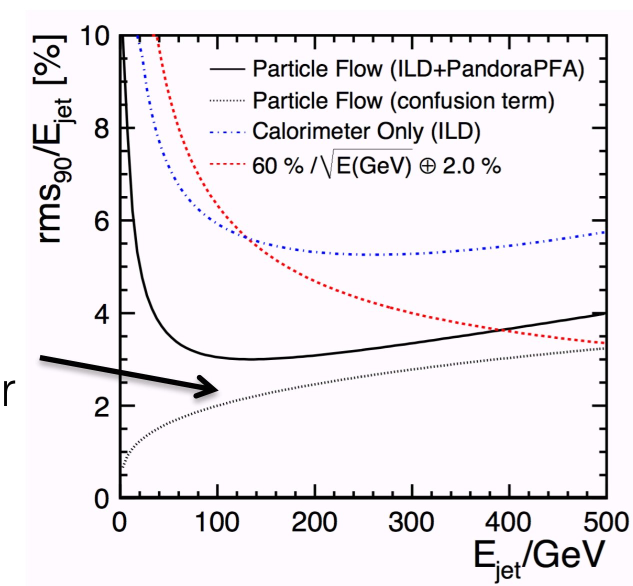
- ~ 1 cm cell size x 10s of layers
- Silicon as active material
- Examples
  - CALICE prototypes
  - CMS endcap upgrade (LS3)

Topological linking rules offered by high granularity in *Pandora*



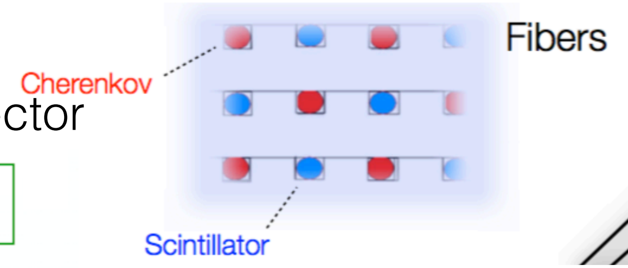


"Confusion" limiting factor in resolution



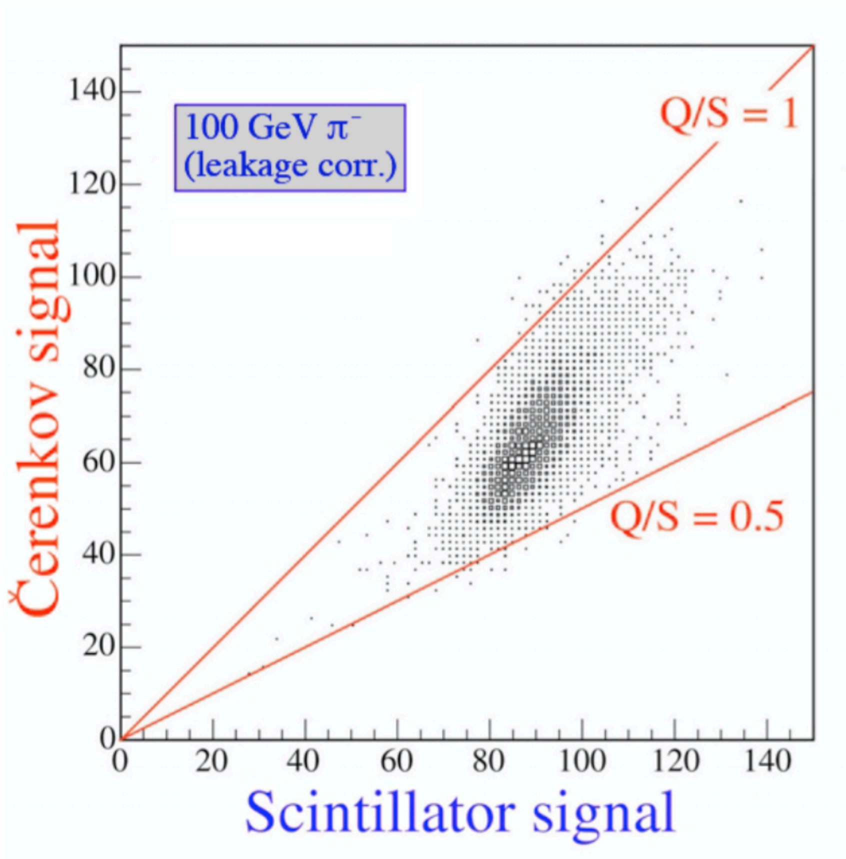
Dual-Readout Method (DREAM)

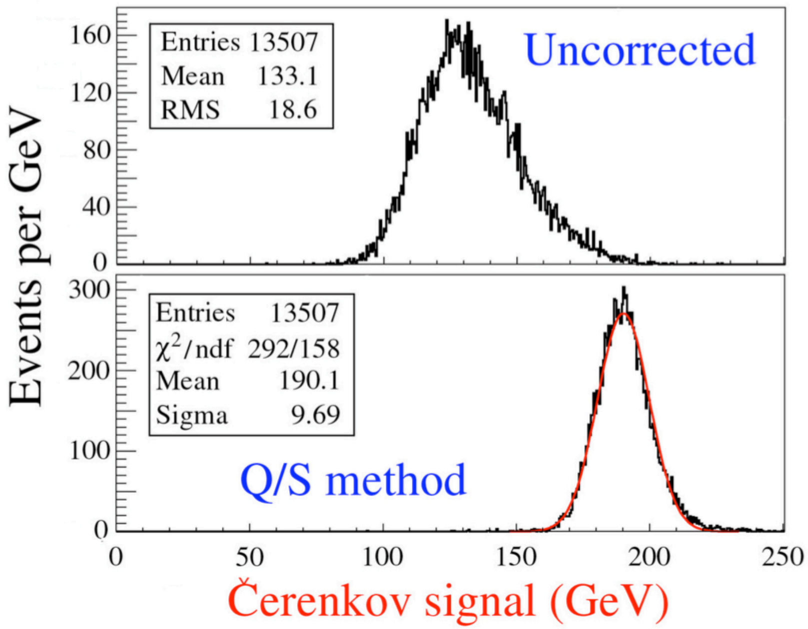
Concept: Only EM component radiates Cherenkov light
→ Use both scintillation and Cherenkov in the same detector



$$E = \frac{S - \chi Q}{1 - \chi}$$

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$$

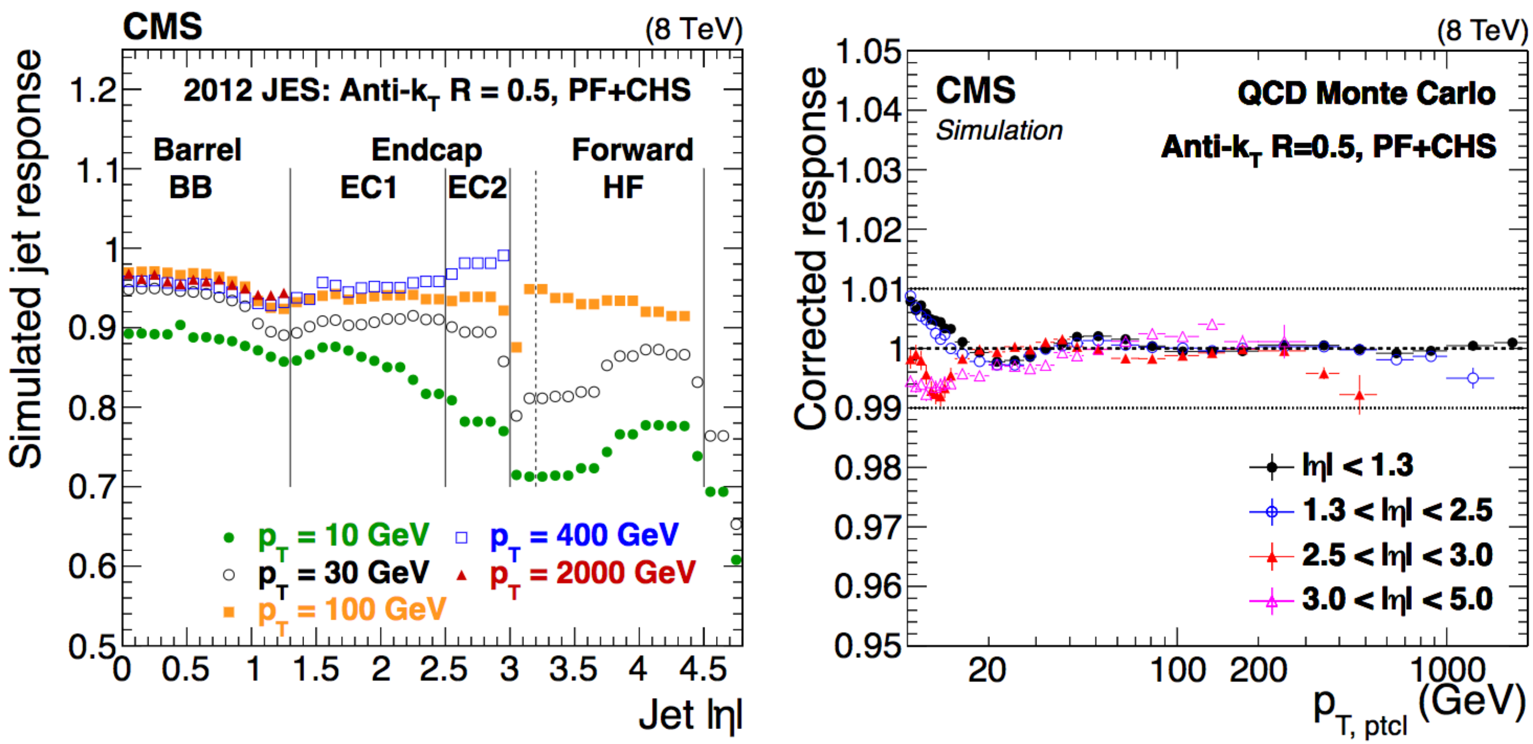




Small prototype tested w/ cosmic ray showers
Observed excellent linearity, improved resolution (limited by leakage)

Jet-level calibrations,
aka, jet-energy corrections (JEC)

MC based corrections



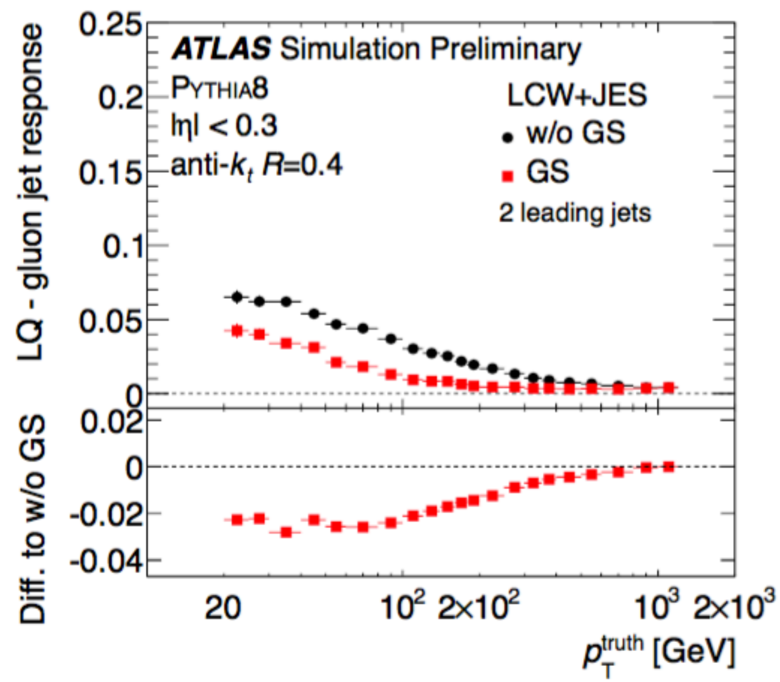
Not much to it …

For a given generated p_T, force the measured $\langle p_T \rangle$ to match

“Global sequential” calibrations

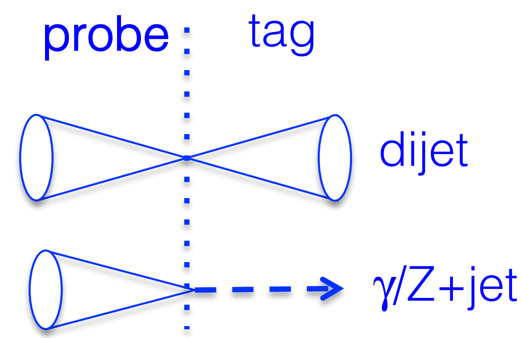
(ATLAS)

- Response depends on jet fragmentation pattern
- Flavor of initiating parton a key driver
  → gluon jets wider and higher multiplicity (softer)
- MC calib’s derived for specific mix of quarks & gluons
- Flavor dependence
  - Degrades resolution
  - Increase jet systematics
  - Also relevant for quenching
- Calibration variables
  - Track multiplicity
  - Track jet width $$width_{\mathrm{trk}} = \frac{\sum_{i} p_{\mathrm{T}}^{i} \Delta R(i,\mathrm{jet})}{\sum_{i} p_{\mathrm{T}}^{i}},$$
  - # of muon segments
    (related to calo leakage)



In-situ corrections

- Idea: Account for data-MC differences in calibrations
  - Generator: fragmentation, hadronization, etc.
  - Simulation: detector response, material effects, etc.
- Strategy: Exploit (leading order) balancing
  - Relative inter-calibration vs η w/ dijets
  - Absolute calibrations w/ γ+jet and Z+jet

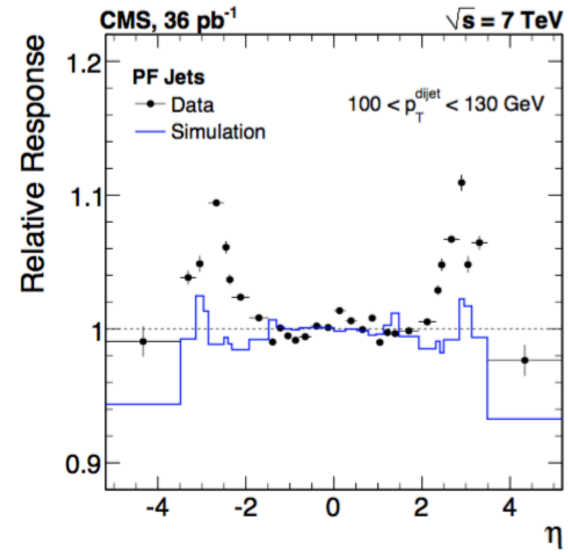


- Two methods:
  - p_T (direct) balancing: balance btwn the 2 objects
  - Missing p_T fraction (MPF): balance w/ recoil of the entire event using missing E_T
- but objects don't *exactly* balance, e.g., FSR
  - ATLAS: use tight kinematic cuts
  - CMS: scan vs. next highest jet and extrapolate (next slide)

Dijet relative correction

Compare tag jet (η<1.3) to probe jet (scanned in η)

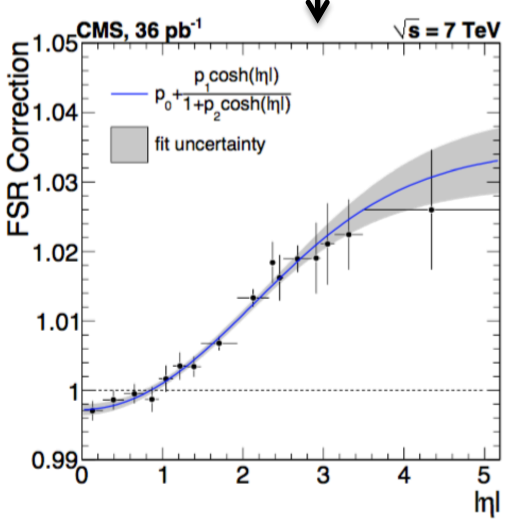
$$R_{\mathrm{rel}}^{p_{\mathrm{T}}} = \frac{1+\langle\mathcal{A}\rangle}{1-\langle\mathcal{A}\rangle}, \quad \text{where} \quad \mathcal{A} = \frac{p_{\mathrm{T,probe}} - p_{\mathrm{T,tag}}}{2p_{\mathrm{T,ave}}},$$



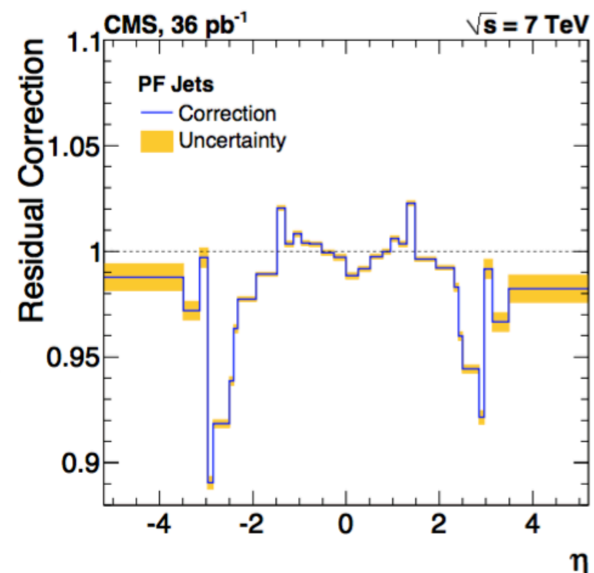
Veto on 3rd jet w/ α < 0.2, where $\alpha = p_{T,3}/p_{T,ave}$

Correct to α = 0, using a straight-line extrapolation:

$$k_{\mathrm{FSR}}(\alpha=0.2) = \frac{\left(\frac{R_{\mathrm{rel}}^{\mathrm{data}}(\alpha\to 0)}{R_{\mathrm{rel}}^{\mathrm{MC}}(\alpha\to 0)}\right)}{\left(\frac{R_{\mathrm{rel}}^{\mathrm{data}}(\alpha<0.2)}{R_{\mathrm{rel}}^{\mathrm{MC}}(\alpha<0.2)}\right)}$$



Apply k_{FSR}, & take data/MC:



Absolute calibrations

Method 1: p_T (direct) balance → $R_{\text{jet},p_T} = \frac{p_{\text{T,jet}}}{p_{\text{T,ref}}}$, ref = γ or Z

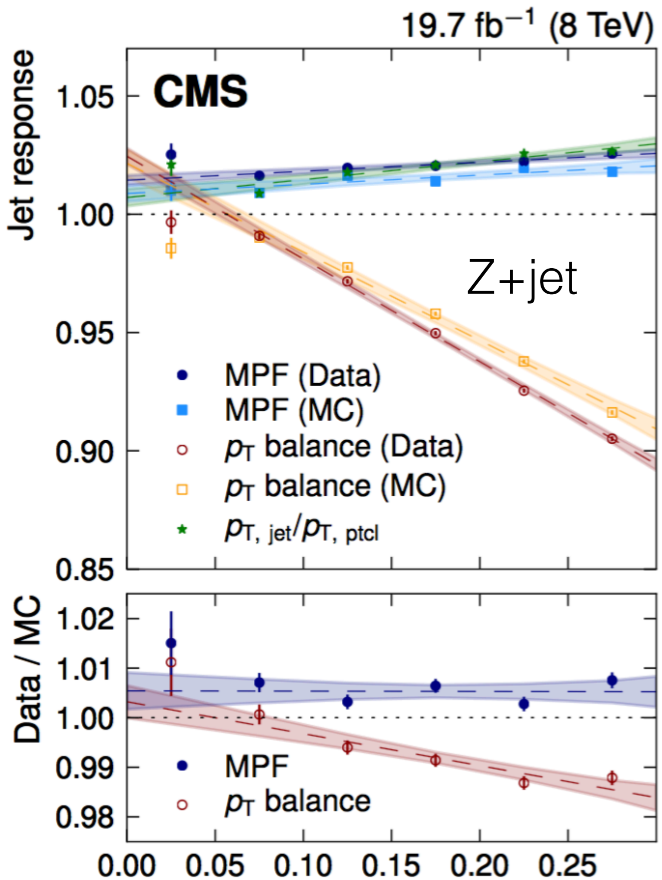
Method 2: Missing p_T fraction (MPF)

$$\vec{p}_T^{\,ref} + \vec{p}_T^{\,recoil} = 0$$

$$R_{ref}\vec{p}_T^{\,ref} + R_{recoil}\vec{p}_T^{\,recoil} = -\vec{\cancel{E}}_T$$

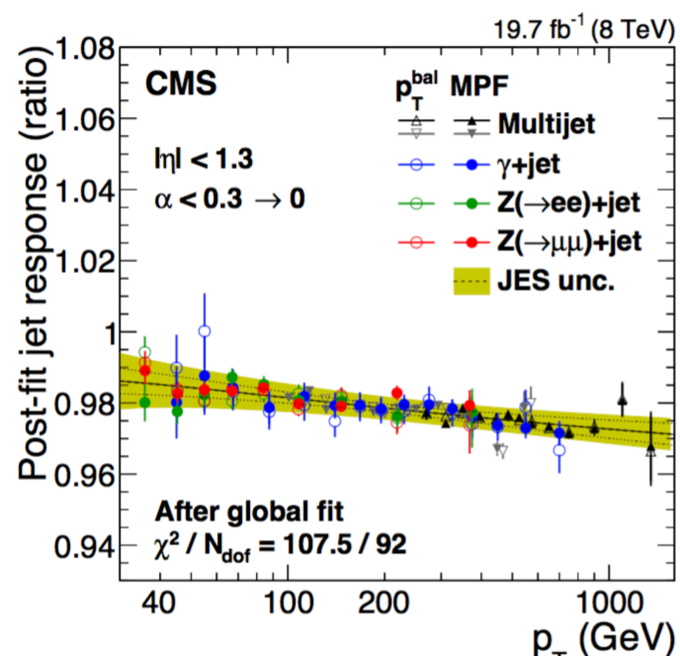
$$R_{MPF} = 1 + \frac{\vec{\cancel{E}}_T \vec{p}_T^{\,ref}}{(\vec{p}^{\,ref})^2}$$

$R_{ref} << R_{recoil}$



$= p_T^{jet}/p_T^Z$

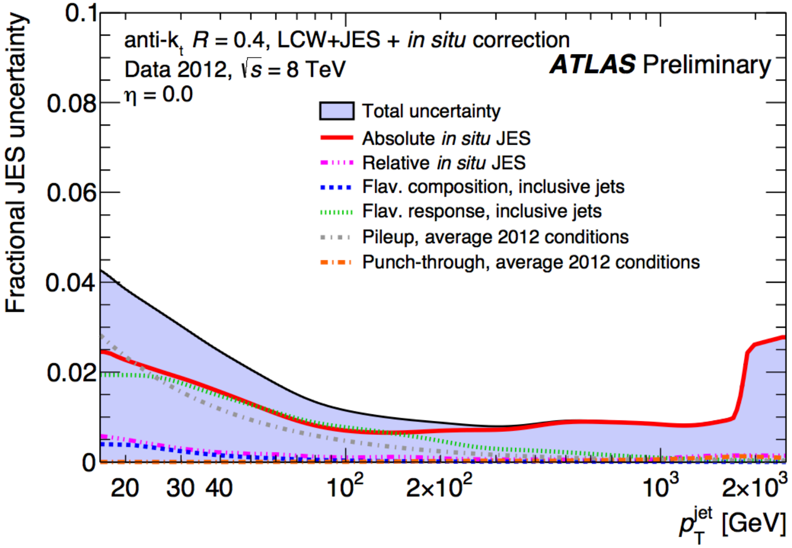
Data/MC, w/ other channels:



1-2%!

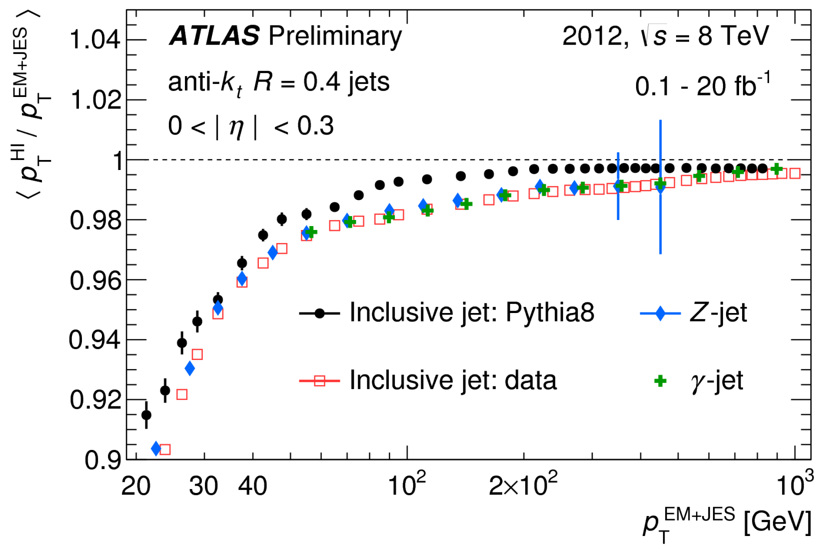
JES uncertainties

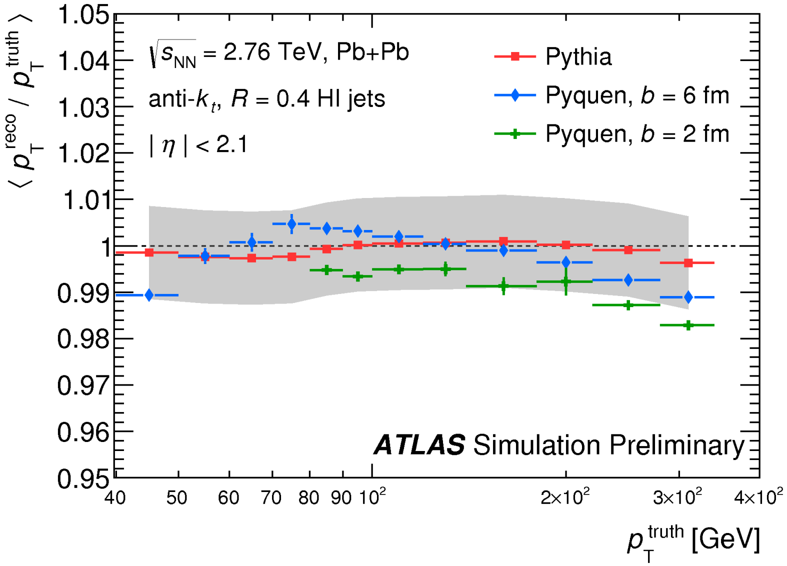
- In-situ calibrations
  - Single particle response (testbeam vs. collisions)
  - Modeling (Pythia vs. Herwig)
  - Reference objects, e.g. γ E–scale
  - + others
- Pile-up uncertainty
  - Track-jets (ATLAS)
  - Zero bias (CMS)
- Flavor uncertainties
  - <u>Composition</u> of calibration sample (e.g., Z+jets) vs. inclusive jets
  - <u>Response</u> of gluons jets from different generators



What about heavy ions?

- Issue #1: In-situ (balancing) methods don't work b/c of quenching
  Also use a different jet reconstruction (mainly UE subtraction)
- Solution: pp cross calibration
  - HI vs. pp algo response
  - Data vs. MC (double ratio)

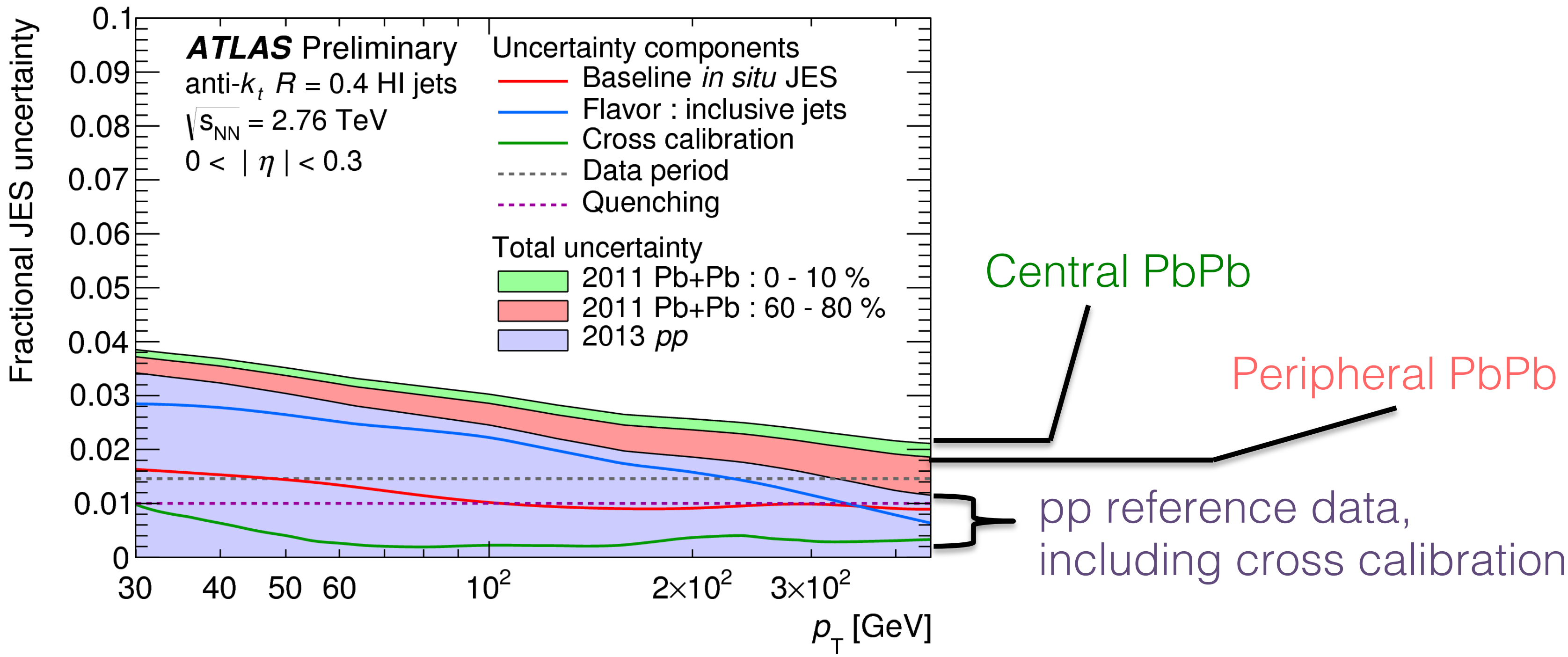




Issue #2: Quenching could modify response
Solution: Check w/ generator (Pyquen) tuned to match fragmentation in PbPb data

Issue #3: time dependence of calo response (pp vs HI run)
Solution: Compare track-jets to calo jets in the two runs (not shown)

JES uncertainties for heavy ions



3-4% jet energy scale uncertainty in PbPb!

We are in the era of precision jet measurements in heavy ions!

Summary

- Calorimeter non-linearity is *the* main challenge to measuring jets
- Mitigation of this effect achieved with “local” techniques such as software compensation and particle flow
- Subsequent calibration of jets revolves around correcting the response, most importantly with in-situ techniques
- Plenty of things I didn’t speak about: underlying event subtraction, resolution effects, etc., etc.

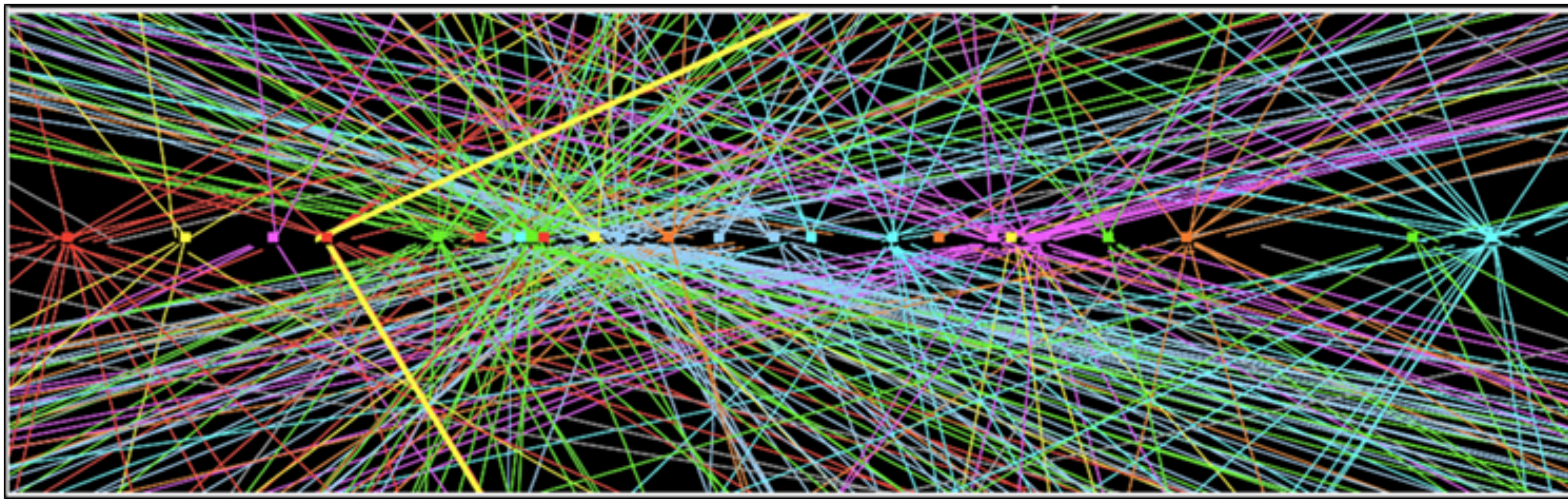
Enjoy the conference!

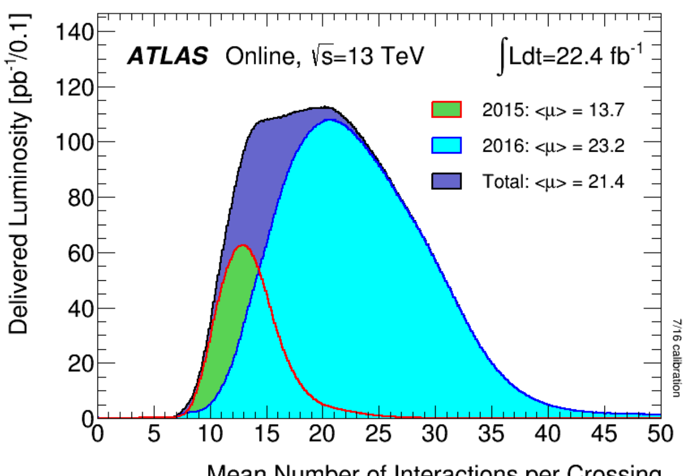
Backup

Underlying event subtraction

- Jet-by-jet: The FastJet ρ * jet area
  - Standard approach in pp and for ALICE
  - Addl' instrumental effects sometimes added "by-hand"
- Tower-by-tower: ATLAS & CMS HI approach
  - Iterative: Evaluate <E>/tower, find jets, re-evaluate <E>/tower
  - ATLAS: Includes flow modulation & uses longitudinal segmentation
  - CMS: "Noise suppression": over-subtract to balance negatives
- Particle-by-particle
  - Grooming techniques: typically for substructure analysis
  - Constituent subtraction: extension of the ρ * jet method
  - Charged hadron subtraction & PUPPI (pile-up)

Pileup





In-time PU = multiple vertices

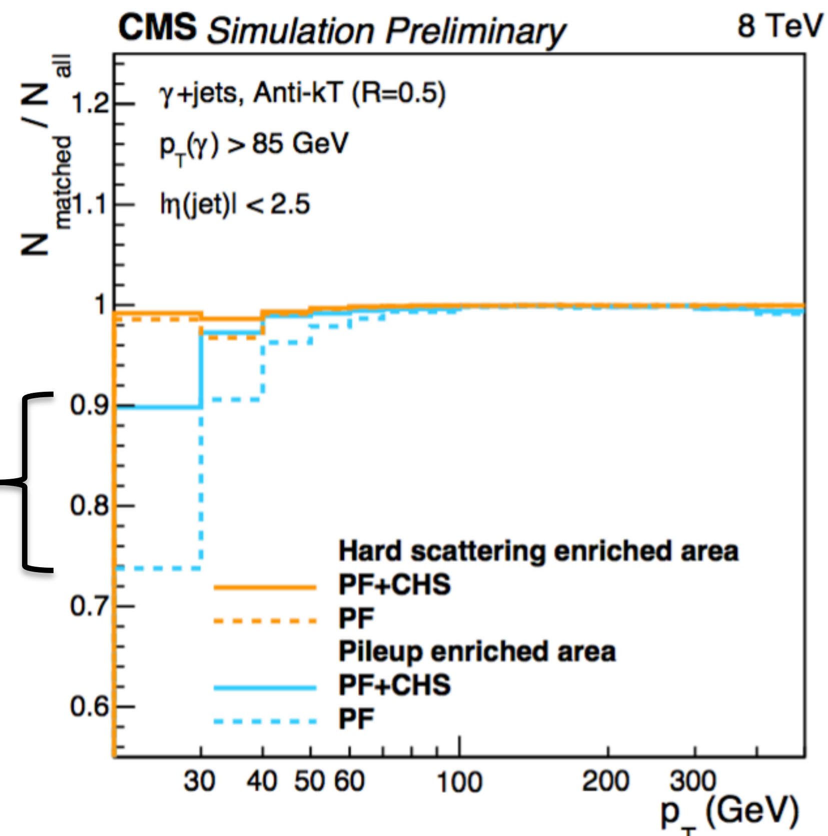
Out-of-time PU = Residual calo energy (afterglow)

Heavy-ion underlying event resembles in-time PU, <u>except</u> all particles from a single vertex

Charged hadron subtraction

PU enriched area: γ+jet $\Delta\phi < 1$
Hard scattering enriched:
γ+jet $\Delta\phi > 3$ & p_T(jet) > 0.2 $p_T(\gamma)$

- Extension of CMS PF
  - Leading vertex (LV) highest sum p_T^2
  - Tracks associated to a unique vertex
  - Tracks associated to PU vertices subtracted (including calo E)
- See also ATLAS Jet-vertex fraction



60% of PU jets removed

PUPPI

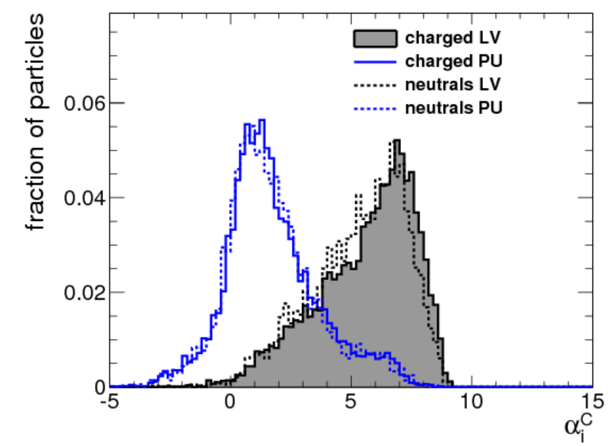
PileUp Per Particle Identification

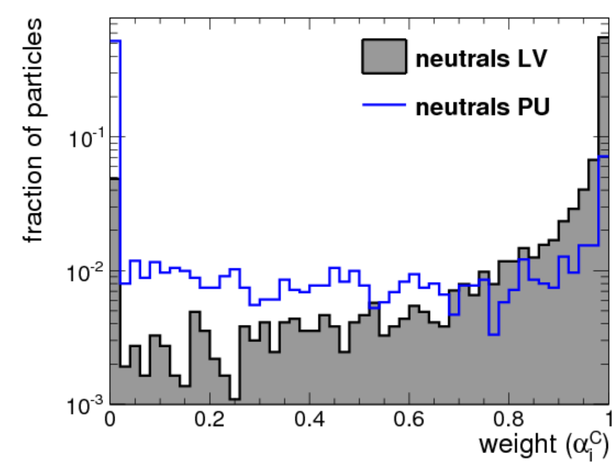
- Concept: Determine probability for particle to come from PU based on neighboring activity
- Method:
  - Metric α, based on local density

$$\alpha_i = \log \sum_{j \in \text{event}} \xi_{ij} \times \Theta(R_{\min} \le \Delta R_{ij} \le R_0), \qquad \text{where } \xi_{ij} = \frac{p_{Tj}}{\Delta R_{ij}}.$$

  - Determine α_{PU} from non-leading vertex tracks
  - Scale particle 4-vectors by weight, using median ($\bar{\alpha}_{PU}$) and RMS (σ_{PU})

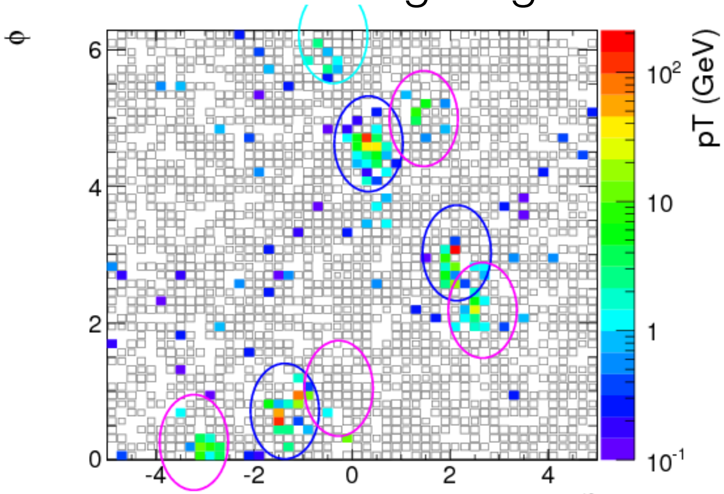
$$\chi_i^2 = \Theta(\alpha_i - \bar{\alpha}_{\rm PU}) \times \frac{(\alpha_i - \bar{\alpha}_{\rm PU})^2}{\sigma_{\rm PU}^2}, \qquad w_i = F_{\chi^2,\mathrm{NDF}=1}(\chi_i^2),$$



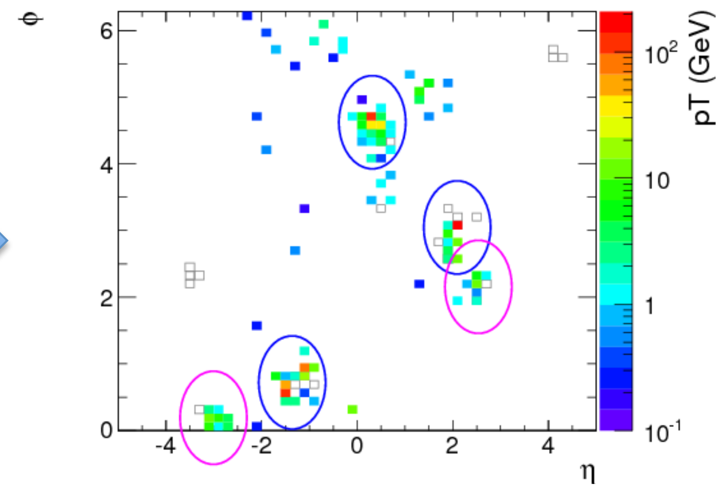


PUPPI performance in 80 PU*

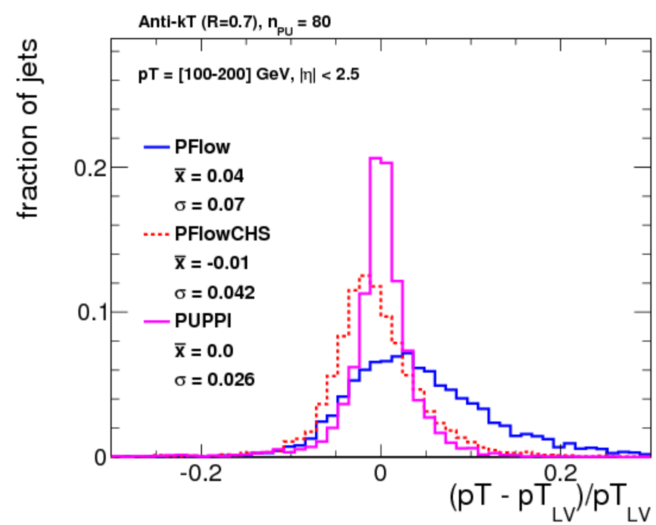
Before weighting



After weighting



- "Resolution" defined w.r.t. jet reco'd from particles from leading vertex
- Clear improvement visible compared to all particles and charged-hadron-subtracted jets



* For a detector w/ perfect tracking and 0.1 x 0.1 calo granularity

Unfolding detector resolution

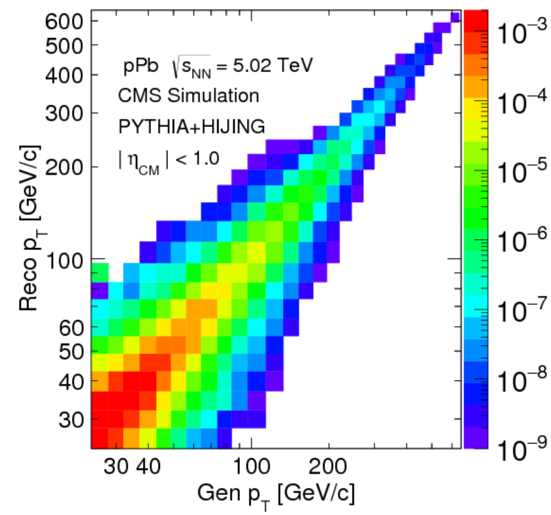
Convolution:

$$f_{meas}(b) = \int R(b\,|\,y) f_{true}(y)\,dy$$

$$\Rightarrow \quad \hat{A}y = b$$

Matrix notation

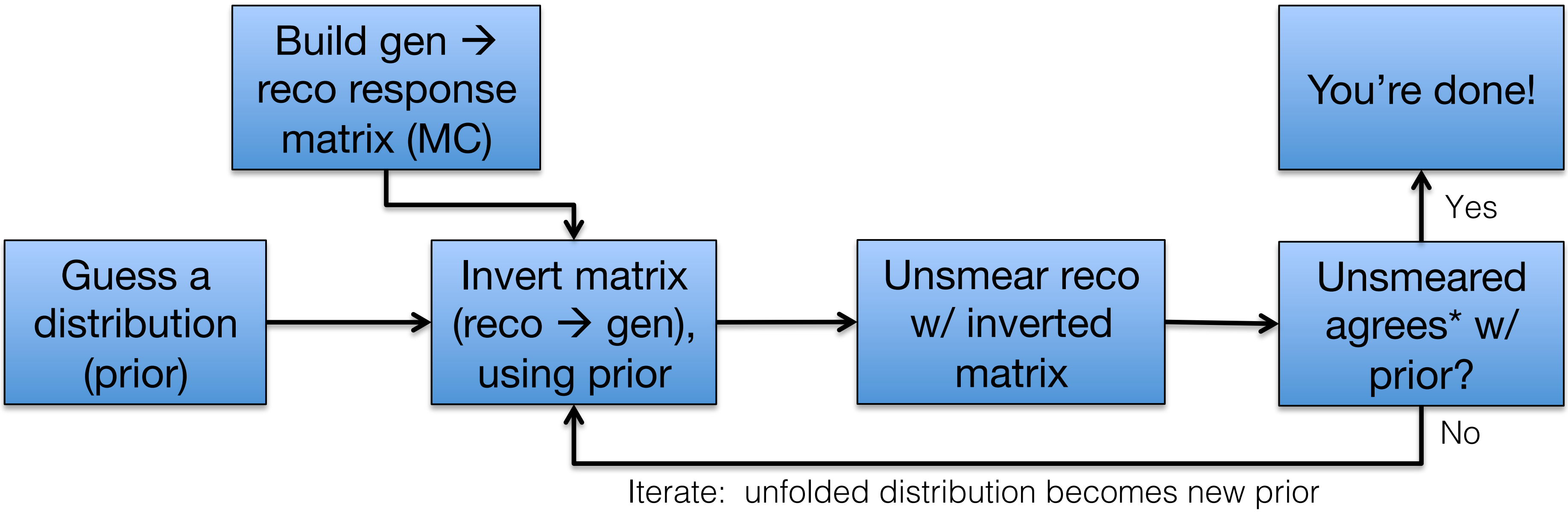
- True (binned) distribution related to measured one by *response matrix*
- Inversion of matrix an *ill-posed* problem → instable against small variations, e.g., from statistical uncertainties
- *Regularization* includes additional constraints, damps fluctuations
- Commonly used methods
  - Iterative Bayesian (d'Agostini)
  - Singular Value Decomposition (SVD)
- Both implemented in *RooUnfold*



Unfolding matrix pPb

- Care required to set regularization parameter
- Refolding and toy MC essential to validate procedure
- Smearing theory sometimes a useful alternative

D'Agostini for dummies



- A good prior helps (MC gen distribution often not a bad choice)
- Prior allows a well-determined matrix inversion, you already know the answer!
- Operationally: scale each slice of response matrix such that projection is prior

* Understanding when to stop iterating is the whole trick. Procedure only converges up until a point, which should be determined in advance