EXPERIMENTAL ASPECTS OF JETS

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22/07/2014 – HASCO Goettingen

MOTIVATION

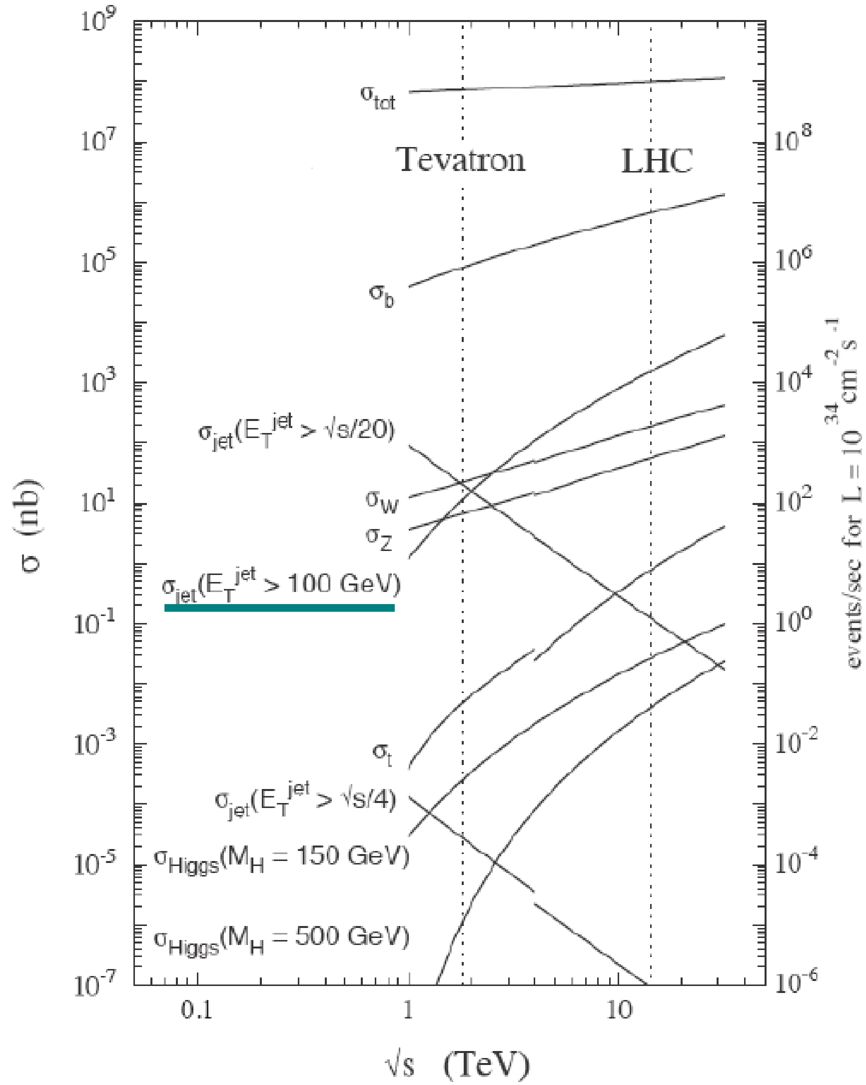
Why jets?

Large Hadron Collider:
Quark and gluon (→ jet) factory

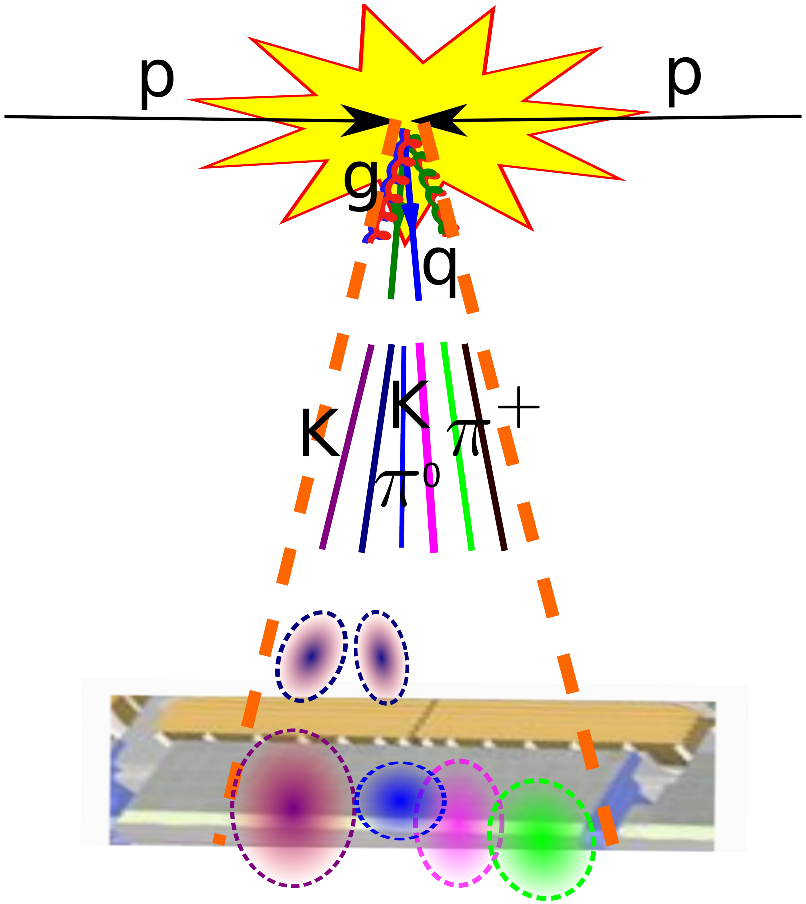
Use **jets for measurements:**
Understand backgrounds,
test reconstruction
and performance with early data

Use **jets for searches:**
Abundant probes for new physics

...but first of all:
How do we identify and measure jets?



THE ANATOMY OF A JET



Parton level

Quarks and gluons
from the hard scattering

Particle level

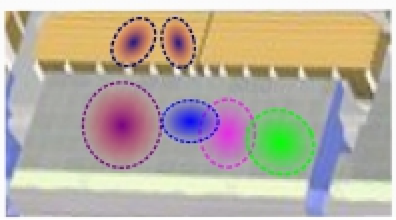
Particles from the hadronization of
quarks and gluons

Calorimeter level

Energy deposited in the calorimeters

Experimental Jets, Part 1: Jet Finding and Calorimeters

Energy deposits in calorimeters



ATLAS Calorimeters

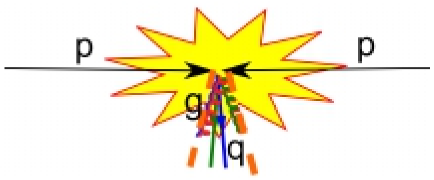
⇒

Jet reconstruction

jet finding

calibration

⇒



Outline

Recap of jet algorithms

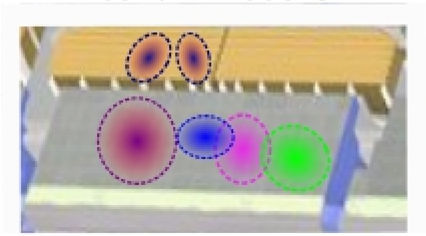
- The need for a jet algorithm
- Recap of jet algorithms
- Algorithms used at the LHC

Detectors for jets

- Basics of hadronic interactions
- Calorimeter basics
- ATLAS and CMS in brief

EXPERIMENTAL JETS, PART 2: JET CALIBRATION AND PERFORMANCE

Energy deposits in calorimeters



ATLAS Calorimeters

⇒

Jet reconstruction

jet finding

calibration

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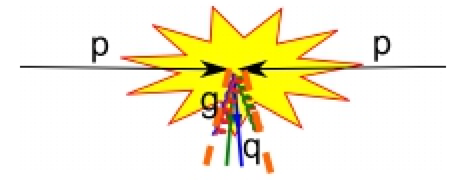


Outline

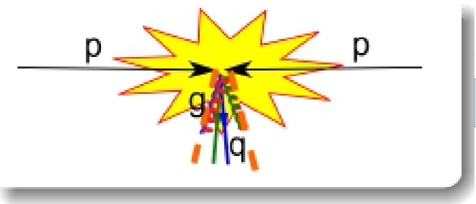
Concepts of jet calibration and performance

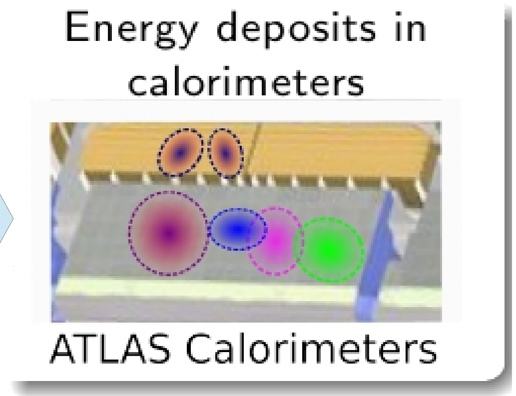
- Jet response and resolution
- Missing transverse momentum
- Jet performance tools
- Jet identification

Jet calibration and performance in ATLAS and CMS

- Pile-up subtraction
- JES calibrations
- Jet performance and uncertainty

EXPERIMENTAL JETS, PART 3: JET MEASUREMENTS AND SEARCHES





(note: this did not happen yet)

Outline

Measurements of jets

- Inclusive jet / dijet jet cross section
- Three jet cross section
- Top mass measurement

Jet searches

- Dijet resonance search
- Dark matter searches
- TTBar resonances

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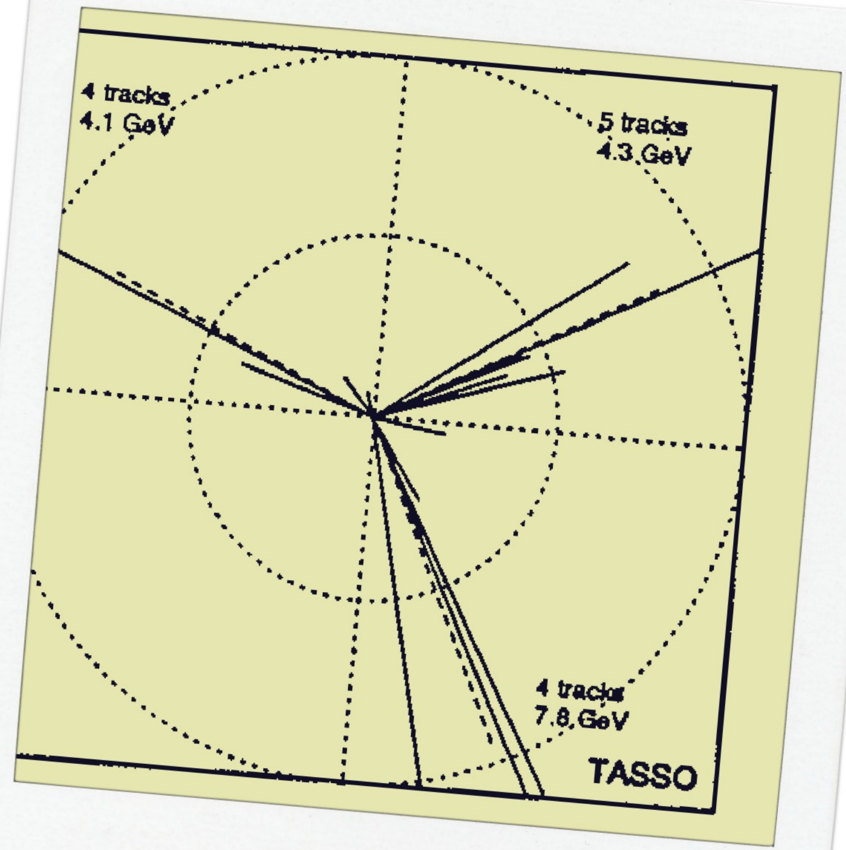
ATLAS EXPERIMENT

1 - JET ALGORITHMS AND CALORIMETERS



One of the first observed gluon jets

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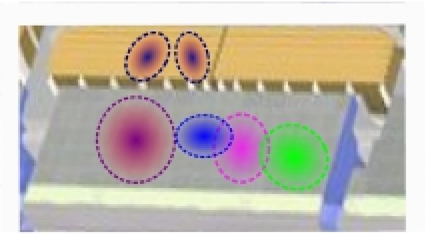
EXPERIMENTAL JETS, PART 1: JET FINDING AND CALORIMETERS

Energy deposits in calorimeters



ATLAS Calorimeters

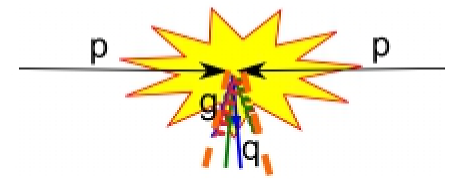
⇒

Jet reconstruction

jet finding

calibration

⇒



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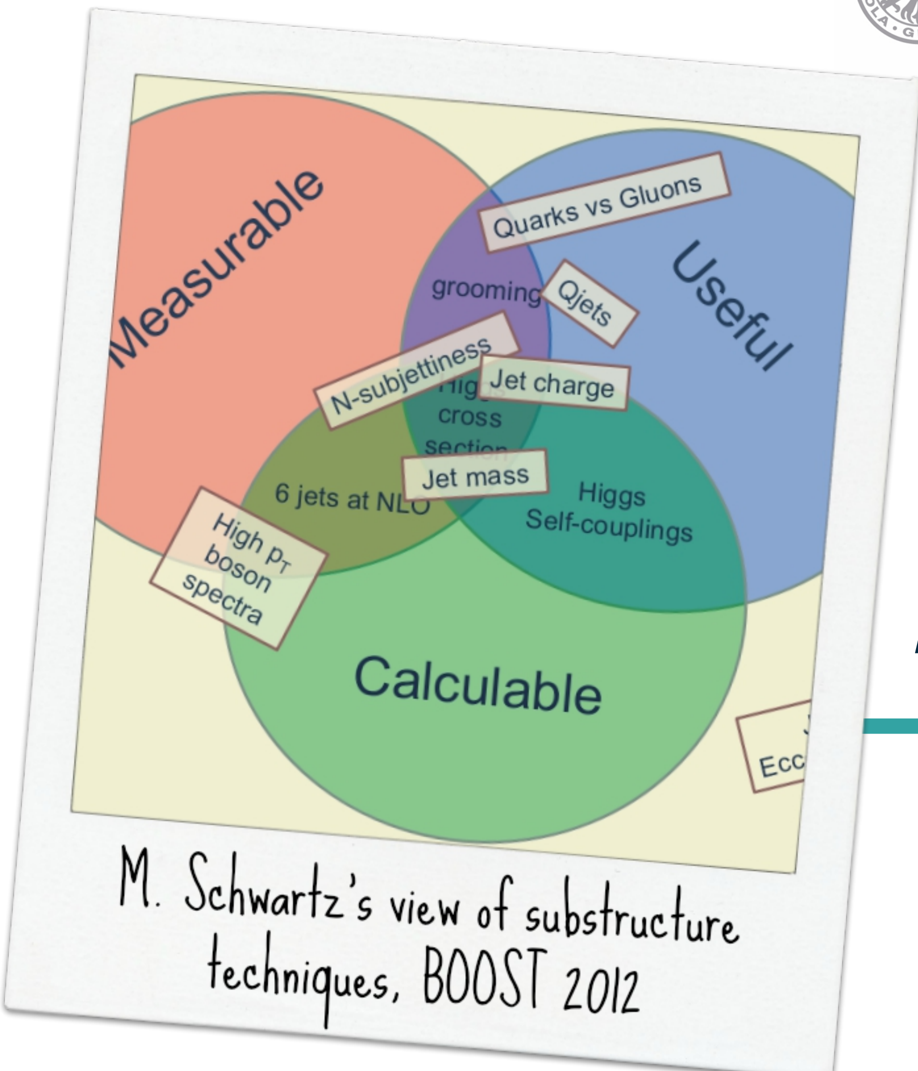

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ATLAS EXPERIMENT

1.1 - REMINDER OF JET ALGORITHMS AND JET SUBSTRUCTURE

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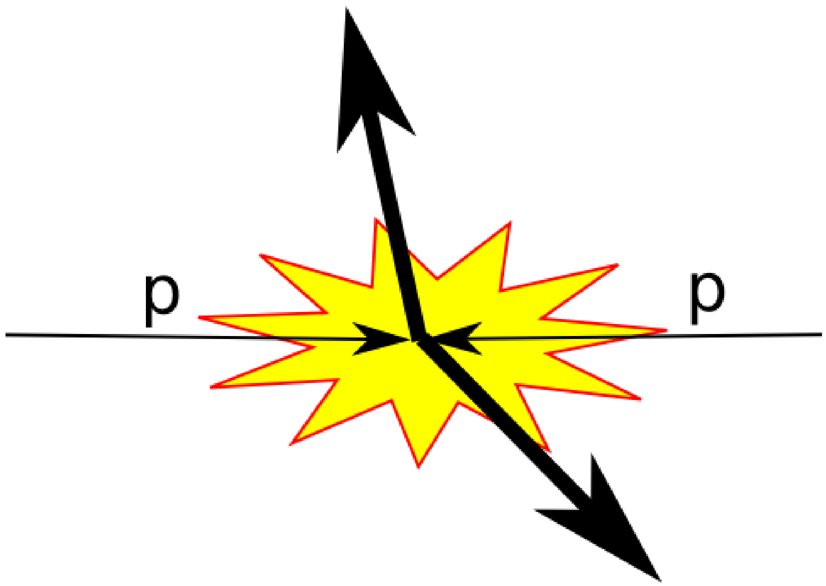
THINK ABOUT A LHC COLLISION

Collision of two protons → two highly energetic objects are produced

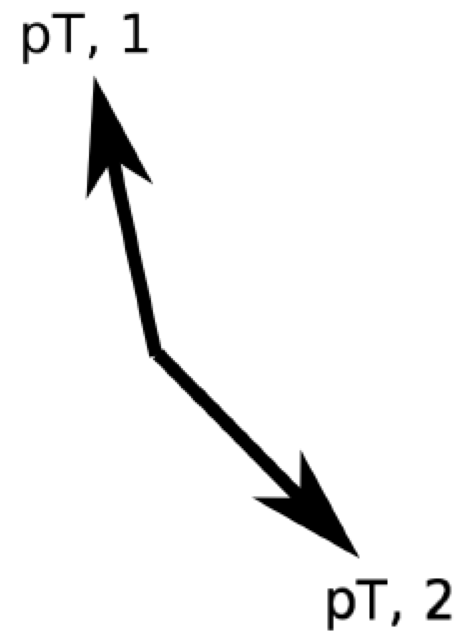
high-pT jets



Chaos from order, order from chaos?

A high-p_T dijet event: how we see it

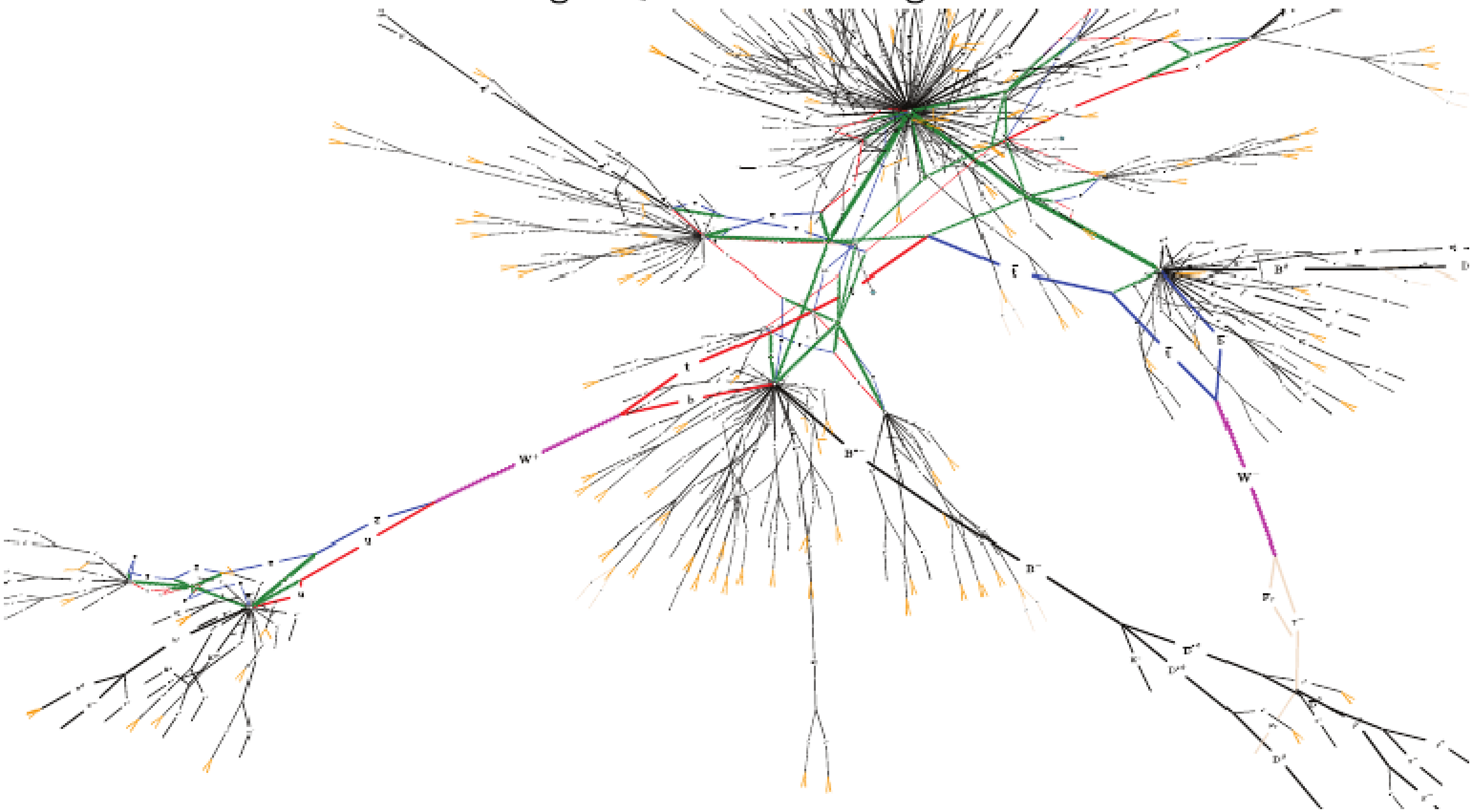
...from the back of an envelope...



Chaos from order, order from chaos?

A high-p_T dijet event: how we see it

...according to QCD from a MC generator...

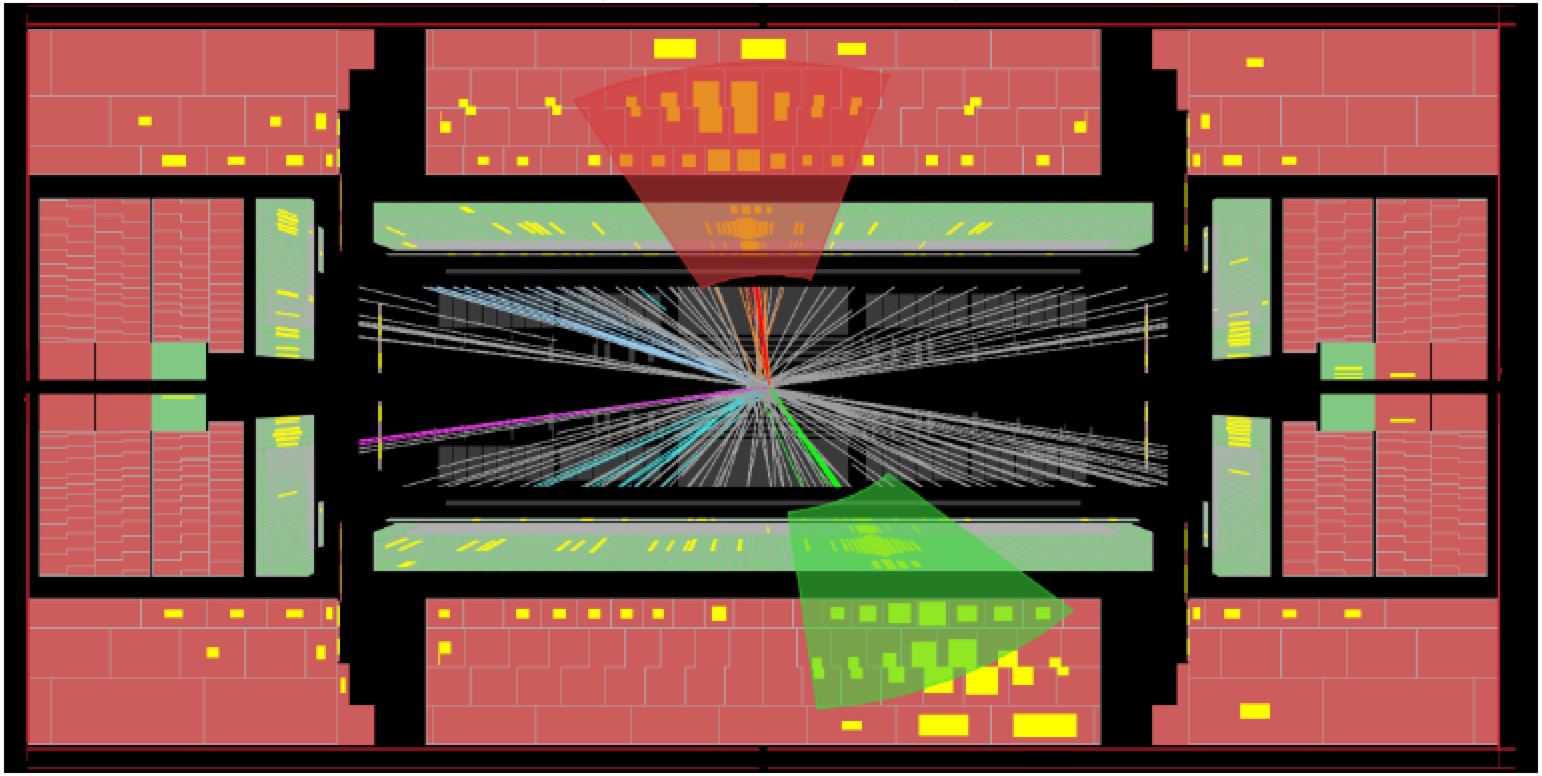


I cheated: this is a semileptonic $t\bar{t}$ event from MCViz, but you get the idea

Chaos from order, order from chaos?

A high-p_T dijet event: how we see it

...in the ATLAS calorimeter...

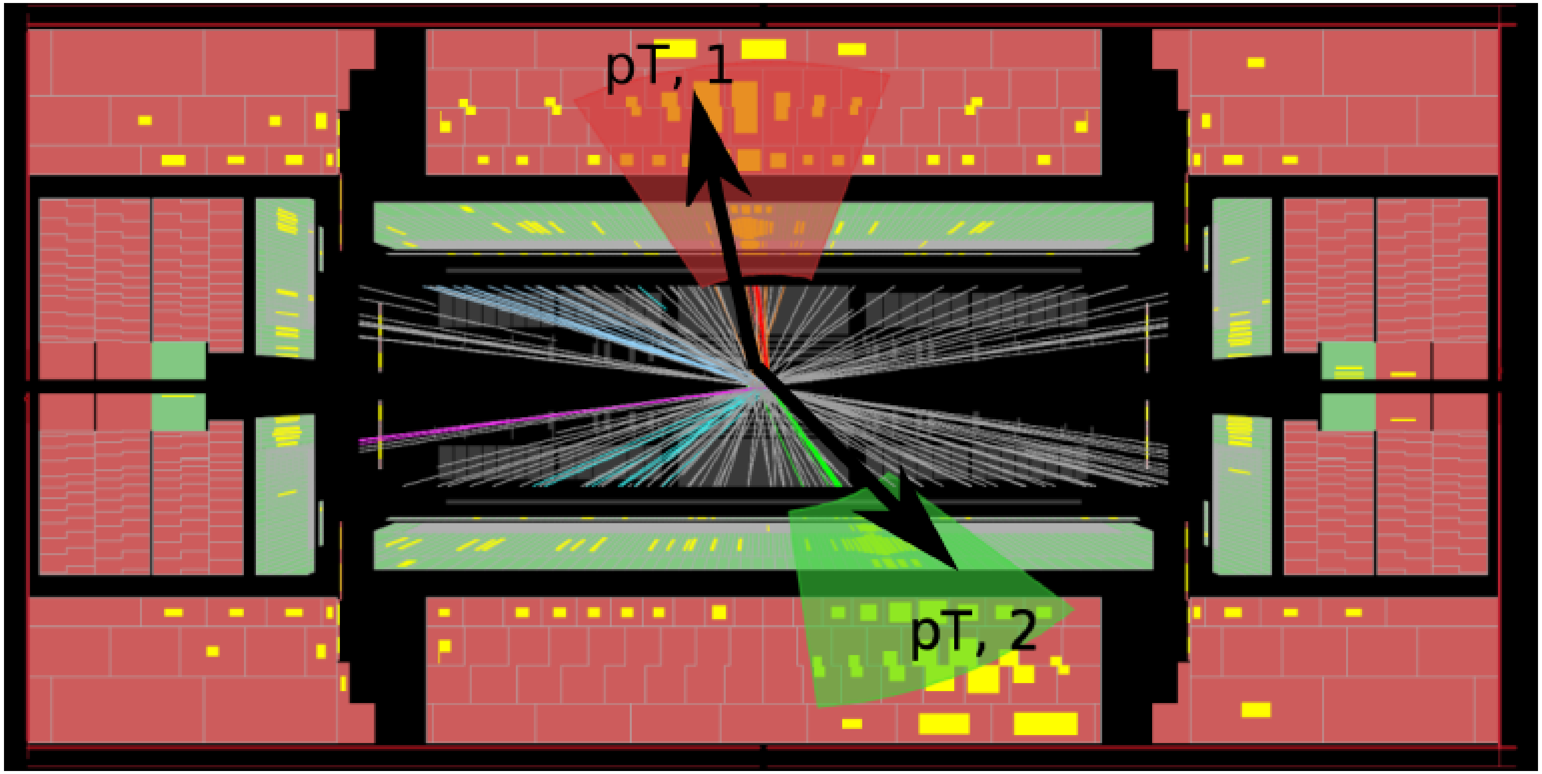


Note: some 'cleaning' already performed: ATLAS topological clustering algorithm

Chaos from order, order from chaos?

A high-p_T dijet event: how we see it

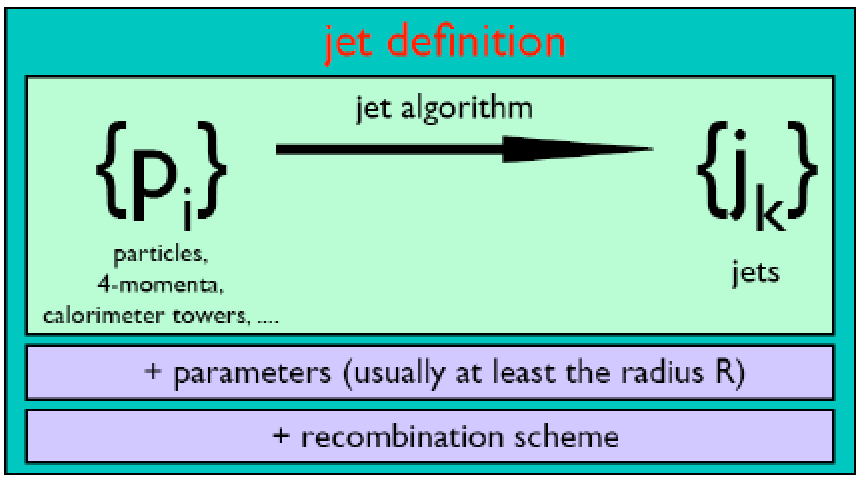
...after applying a jet algorithm.



JET ALGORITHMS FOR LHC EXPERIMENTALISTS

Goal: kinematics of jet ↔ kinematics of underlying physics objects
Use a jet algorithm to cluster objects into a jet

Les Houches 2007 proceedings, arXiv:0803.0678



From M. Cacciari, MPI@LHC08

Apply same jet definition
to objects on different levels:

1. Partons
2. Particles
   → Truth Jets
   (only particles from the hard scattering)
3. Calorimeter objects
   (ATLAS: Topoclusters)
   → Reconstructed Jets
4. Tracks
   → Track Jets
5. A combination of calorimeter and tracking information (CMS)
   → Particle Flow Jets

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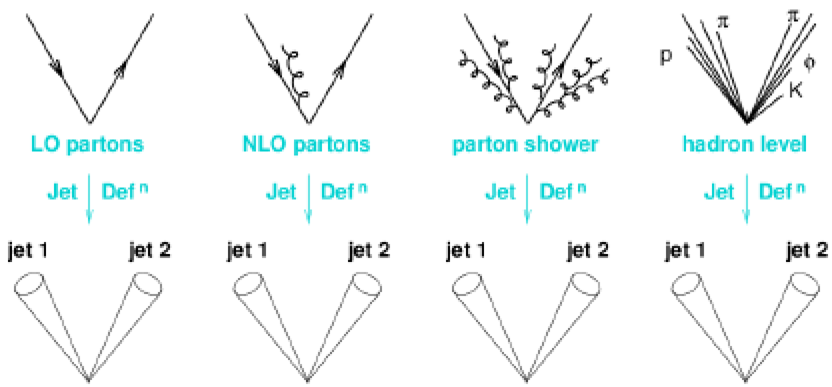

From G. Salam, MCNet School 2008

Apply same jet definition
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JET ALGORITHMS: WISHLIST

No right jet algorithm

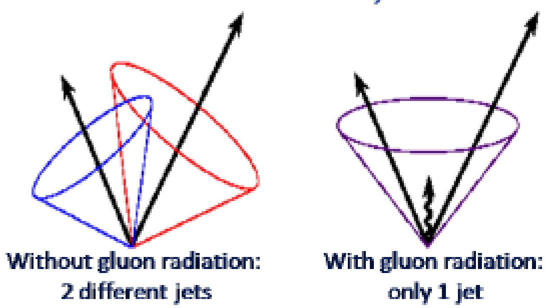
Different processes ↔ different algorithms / parameters

(we'll see more of this later...)

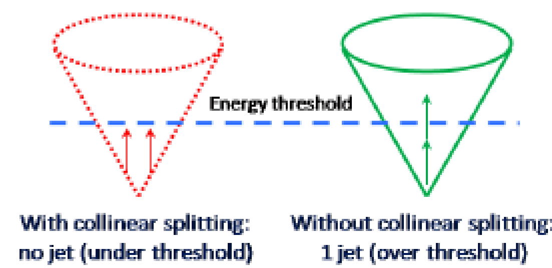
Requirements:

1. Theoretically well behaved → no α_s dependence of jet configuration:

Infrared safety



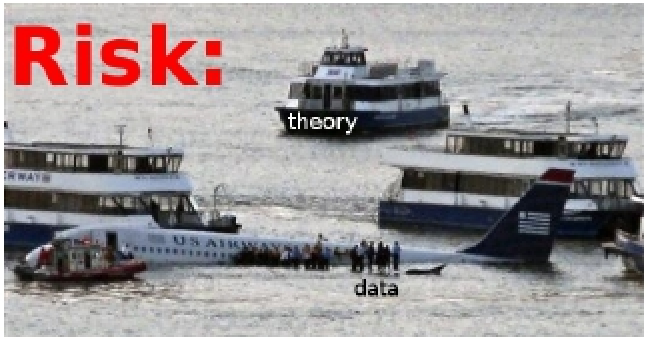
Collinear safety



2. Computationally feasible → fast
3. Detector independent

SAFETY WARNINGS

Crucial to analyse data with infrared / collinear safe jet algorithm!



Theory matters:

Among consequences of IR unsafety:

	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC_{mp}-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO (→ NNLO)
$W/Z + 1$ jet	LO	NLO	NLO	NLO
3 jets	none	LO	LO	NLO [nlojet++]
$W/Z + 2$ jets	none	LO	LO	NLO [MCFM]
m_{jet} in $2j + X$	none	none	none	LO

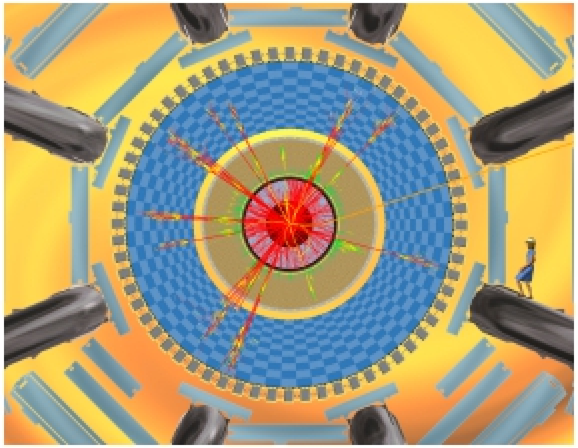
NB: $30 – 50M investment in NLO

From G. Salam, MCNet School 08

IMPLEMENTATION OF JET ALGORITHMS

Goal: kinematics of jet ↔ kinematics of underlying physics objects
Use a jet algorithm to cluster objects into a jet

Basic algorithm: event display + physicist



"Everyone knows a jet when they see it"

Note: don't try this at home when the LHC is running

...but what is really needed for communicating results:

1. full specification of algorithm and parameters → how to group objects
2. recombination scheme → how to merge objects characteristics
3. treatment of overlapping jets (if any) → how to avoid double counting

Popular jet algorithms for experimentalists

Cone-based algorithms

- Cone in $y - \phi$ space around object momentum vector
- Jet = objects in cone

Available on the (ATLAS and CMS) market:

- ATLAS Cone unsafe!
- Seedless Infrared Safe Cone (SISCone)

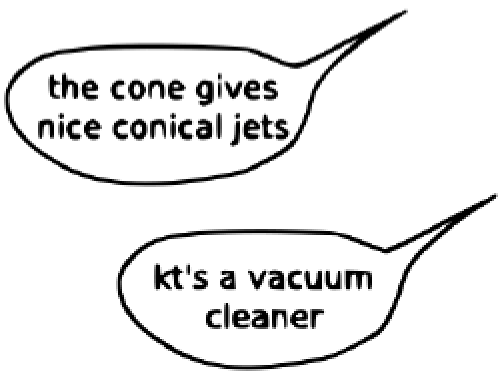
Sequential recombination algorithms

- Group objects based on minimum relative distance
- Jet = grouped objects

Available on the (ATLAS and CMS) market:

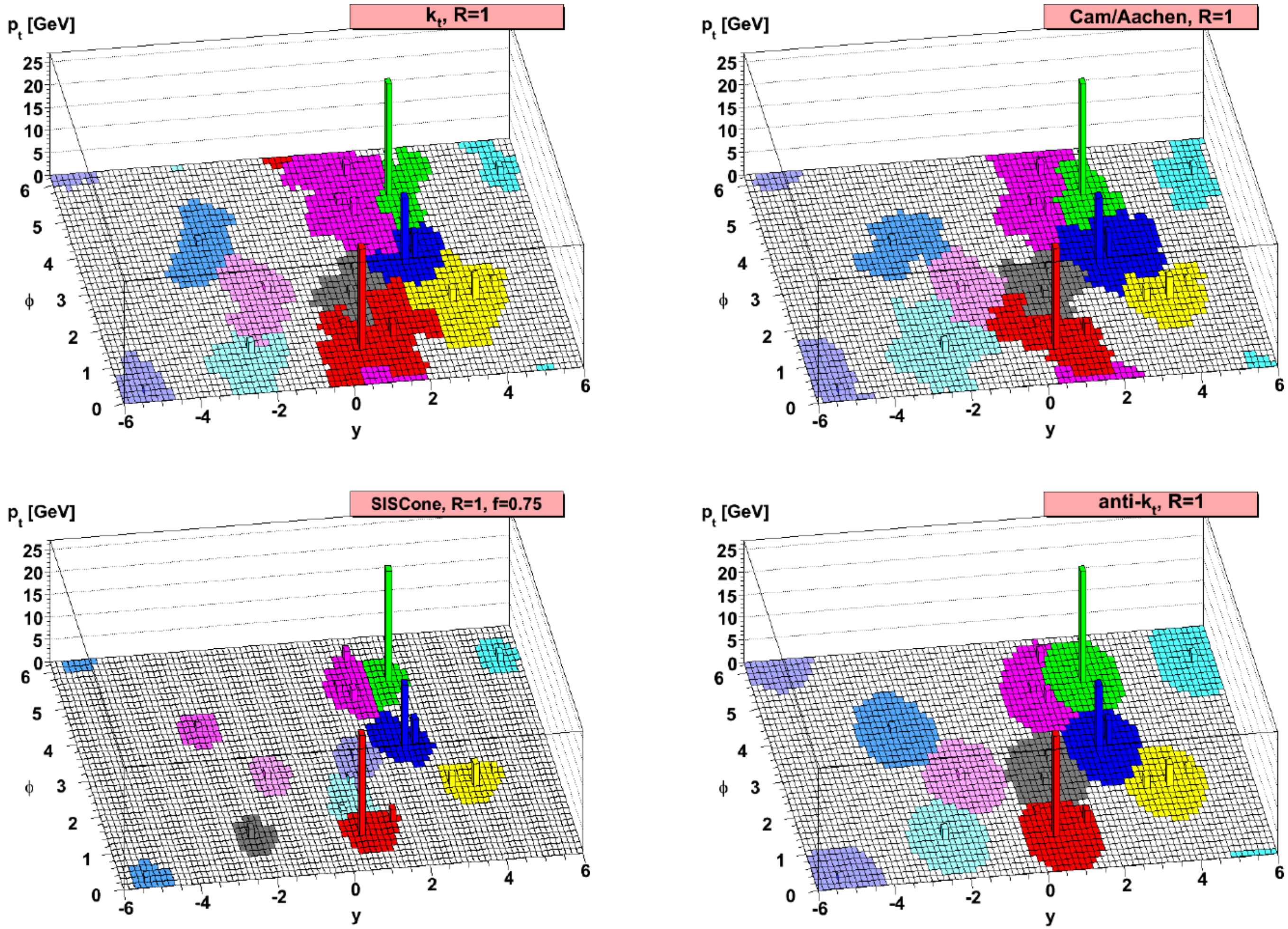
- K_t
- Cambridge-Aachen
- Anti-K_t

What algorithms for data?



From G. Salam, MCNet School 2008

Does the jet algo make a difference? Yes.



http://arxiv.org/abs/0802.1189

Sequential recombination algorithm: kt

Algorithm specification: k_t

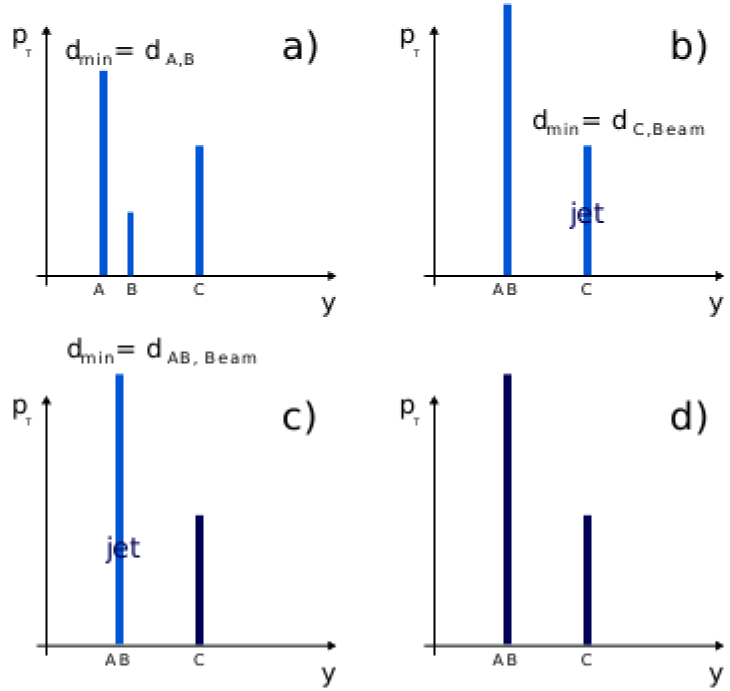
- $d_{i,j} = min(p_{T,i}^2, p_{T,i}^2)\frac{\Delta R^2}{D^2}$;
  $d_{i,Beam} = p_{T,i}^2$
- D : algorithm parameter (≈ weight for angular distance ΔR)
- Iterate:

1. For every pair of objects i, j calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else i is a jet, remove it from list [a]

- Recombination starts from soft objects

[a] ATLAS default: inclusive algorithm

Idea:



ATLAS EXPERIMENT SEQUENTIAL RECOMBINATION ALGORITHM: C/A

Algorithm specification: Cambridge-Aachen

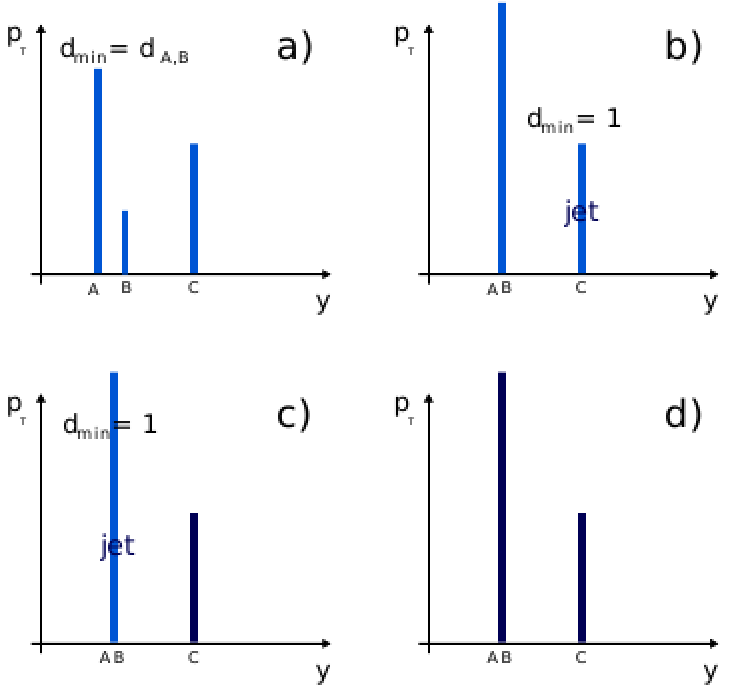
- $d_{i,j} = \frac{\Delta R^2}{D^2}$; $d_{i,Beam} = 1$
- D : algorithm parameter
- Iterate:

1. For every pair of objects i, j calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else i is a jet, remove it from list [a]

- Distance-based recombination

[a] ATLAS default: inclusive algorithm

Idea:



SEQUENTIAL RECOMBINATION ALGORITHM: ANTI-KT

Algorithm specification: Anti-k_t

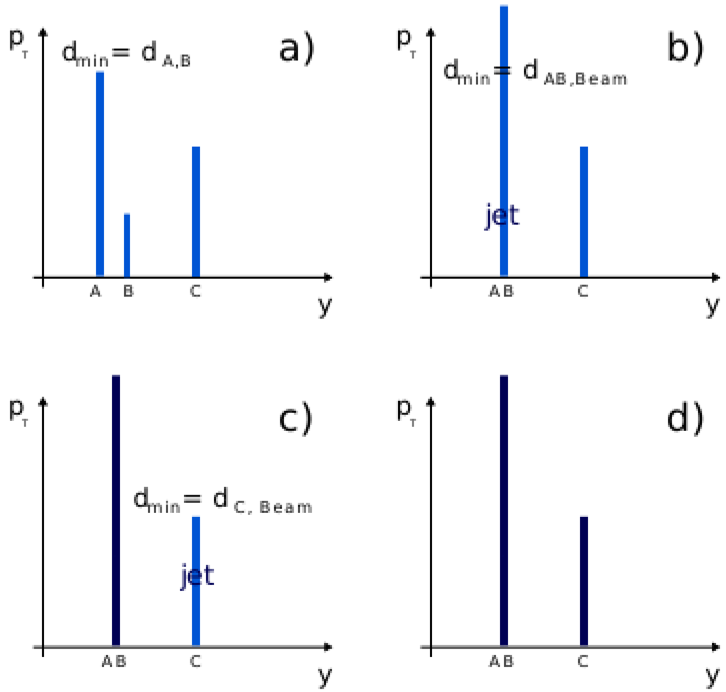
- $d_{i,j} = min(\frac{1}{p^2_{T,i}}, \frac{1}{p^2_{T,i}})\frac{\Delta R^2}{D^2}$;
  $d_{i,Beam} = \frac{1}{p^2_{T,i}}$
- D : algorithm parameter
- Iterate:

1. For every pair of objects i, j calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else i is a jet, remove it from list [a]

- Recombination starts from hard objects

[a] ATLAS default: inclusive algorithm

Idea:



THE PRACTICAL DEMONSTRATION

I WILL NEED 10 VOLUNTEERS...
...SOME TALL, SOME SHORT

ATLAS EXPERIMENT More advanced: choices, choices

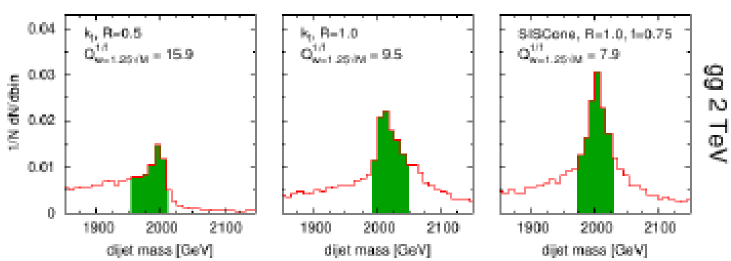
Decision: choice of jet algorithm distance parameter (R)

"It's all fun and games until someone loses a hard constituent"

Example figures from original jetography paper arXiv 0810.1304:
Quantifying the performance of jets, G. Salam, J. Rojo, M. Cacciari

Advantages of wider distance parameters (large-R):

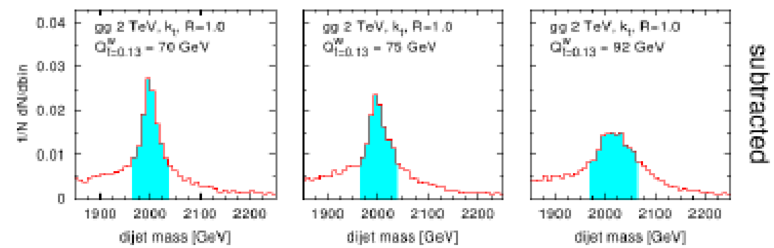
- Captures more QCD radiation:
  → Smaller non-perturbative corrections when comparing data to theory
  → Better mass resolution for dijet resonances



Dijet mass for resonance decaying into two gluons: improvement in resolution when increasing radius

Disdvantages of wider distance parameters (wider jets):

- Captures more of anything else:
  → extra energy not from hard scattering (calorimeter noise, other pp collisions)

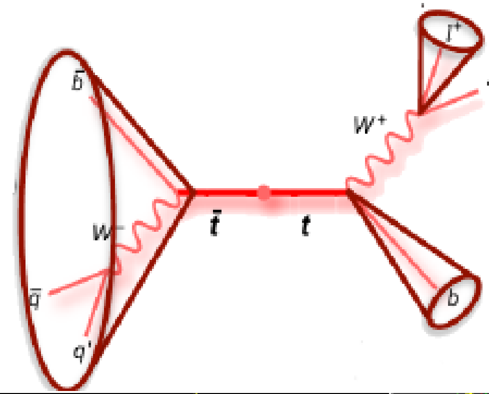


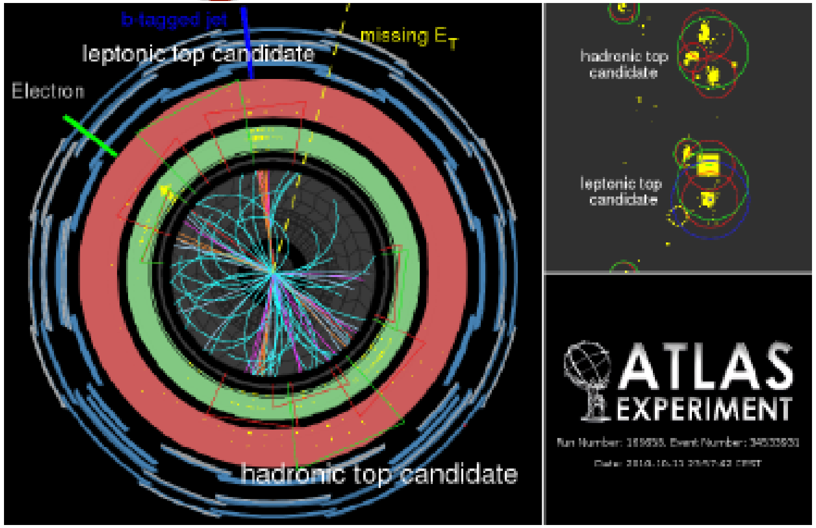
Dijet mass for resonance decaying into two gluons, large-radius: deterioration in resolution when increasing pile-up as in left to right plot

- with large kinematic boost, decay products of heavy objects more collimated
  ...can we use this to our advantage?
  Yes, with jet substructure!

ATLAS EXPERIMENT Short introduction to fat jets

Example: boosted top candidate





[ATLAS-CONF-2011-073]

When to make fat jets:

When more objects (e.g. from a decay) are collimated due to kinematic boost:

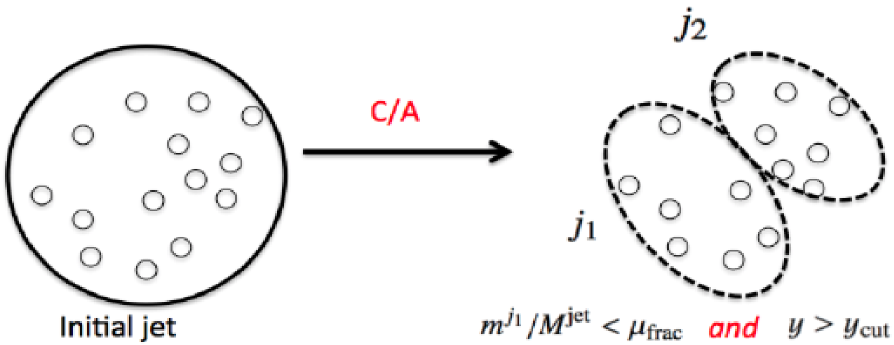
- collect everything in a large-R (fat) jet
- probe substructure of this large-R jet (e.g. sub-jets)

How to use fat jets:

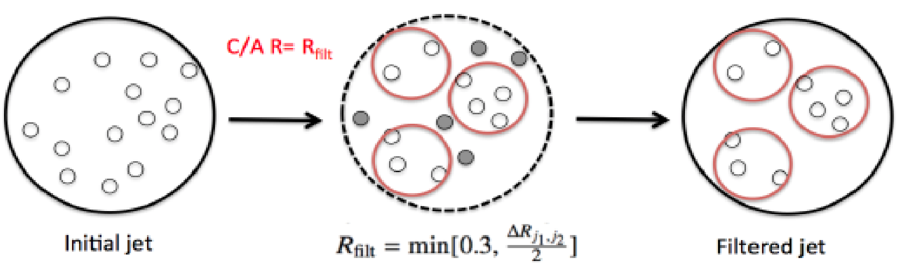
- exploit jet grooming techniques to:
  - separate QCD jets from jets from boosted objects decays (background rejection)
  - make jets more resilient to radiation/pile-up
- use jet mass as a handle for mass of heavy object (e.g. W, or top)

A famous grooming algorithm: *BDRS*

1. Find Cambridge/Aachen R=1.2 jets
2. Undo last step of jet algorithm and obtain two proto-jets $(j1, j2)$
3. Only keep C/A jets where:
   - significant difference between original jet and $j1$: $m^{j1}/m^{C/A\ jet} < \mu_{frac}$
   - symmetric splitting between $j1, j2$: $y = \frac{min[(p_T^{j1})^2, p_T^{j2})^2]^2}{m^{C/Ajet}} \Delta R^2_{j1,j2} > y_{cut}$

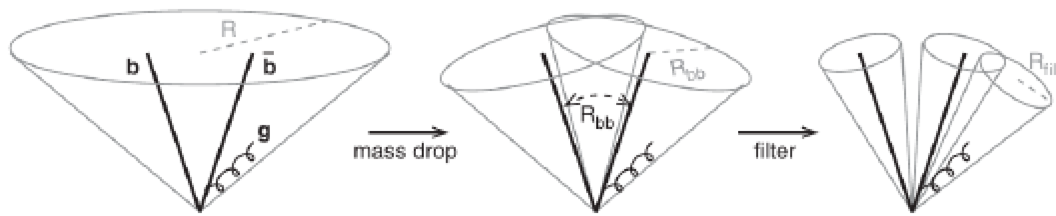


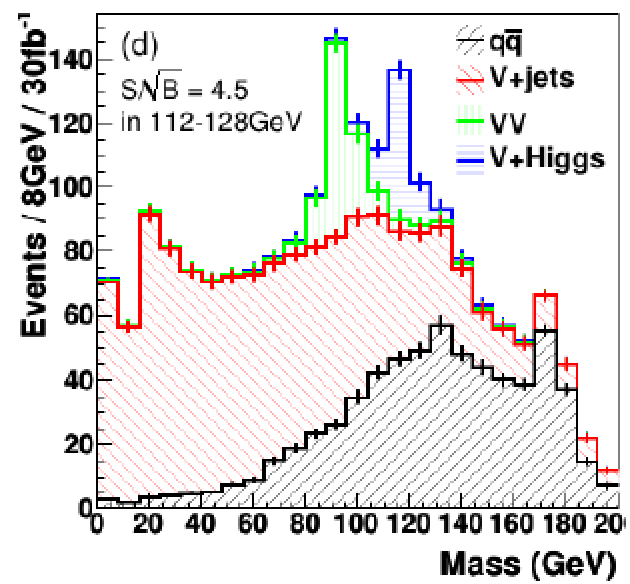
4. Recluster constituents of the jet using C/A with distance parameter=R_{filt}, only keep three hardest subjets



ATLAS EXPERIMENT What is it useful for?

It could be useful for Higgs decay in $b\bar{b}$ (overwhelming background):





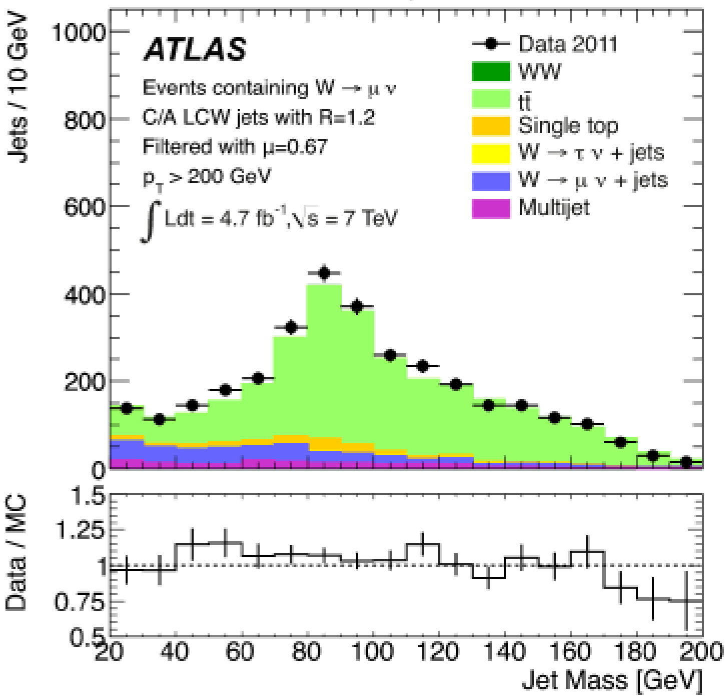
Frequently Asked Questions

- Is it really useful for boosted Higgs?
  We'll know at the LHC @ 14 TeV
- Is it useful for ATLAS analyses?
  Yes, we'll see this later

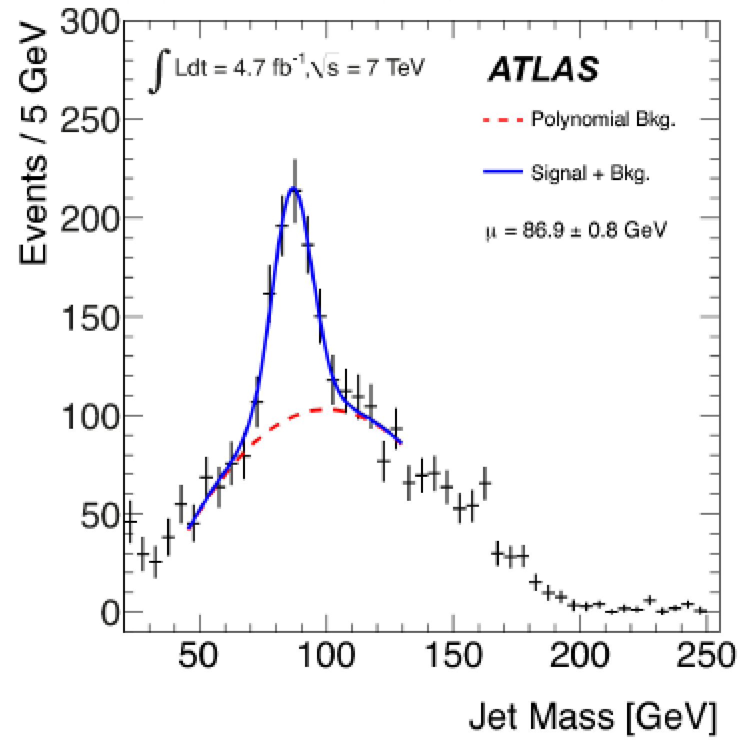
ATLAS EXPERIMENT JET MASS

Mass of single fat, groomed jet: handle on mass of heavy boosted objects ⇒ a well known standard candle can be used to set mass scale in data

Mass distribution for C/A split/filtered jets in $W \to l\nu$, with $p_{T,W} > 200$ GeV

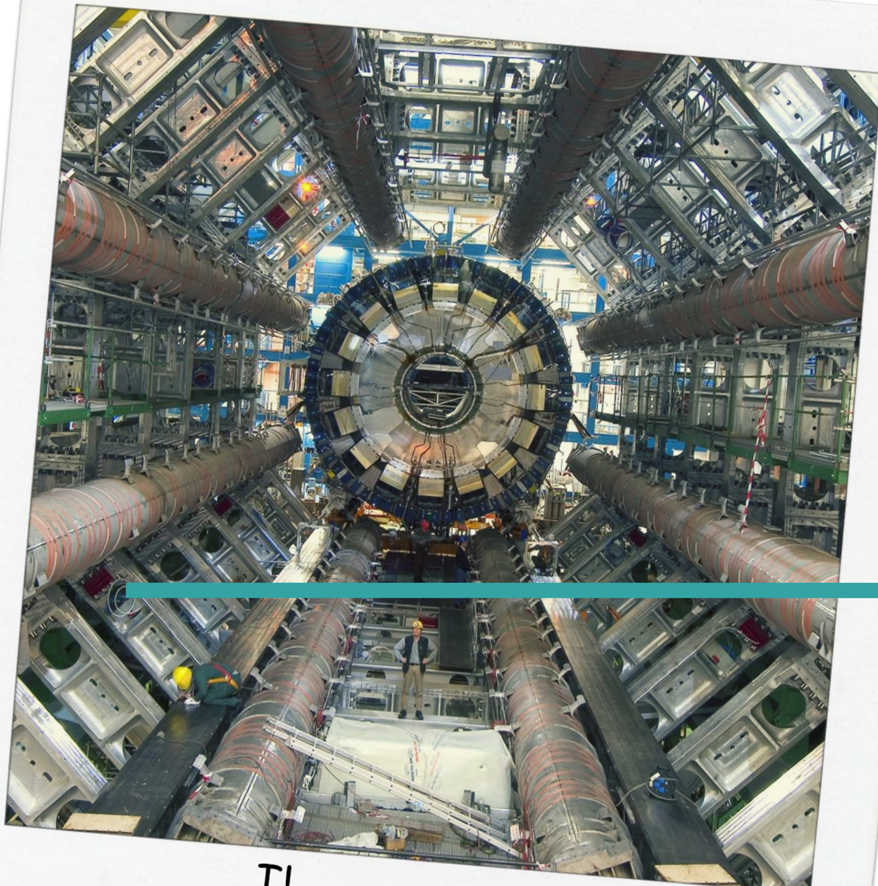


Fit to the W mass distribution in 2011 data



5' for questions up to here

1.2 - THE ATLAS AND CMS CALORIMETERS



The installation of the ATLAS calorimeters

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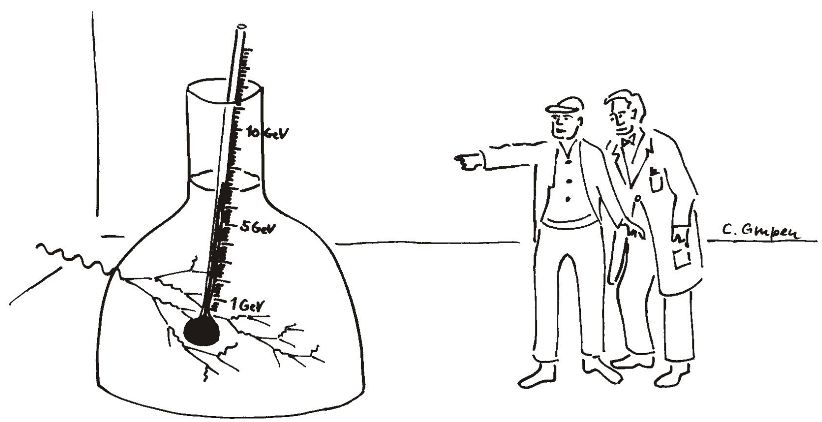
ATLAS EXPERIMENT How does a *calor*-imeter work?

Particle **interaction** → energy loss → energy released in calorimeters
→ energy measured through **active** material

E.g.: excitation of material → de-excitation photons → collection and amplification of photons → electrical impulses

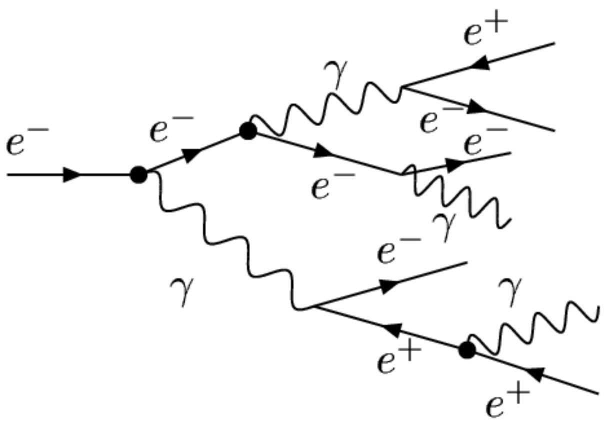
EM-force: e.g. ionization and radiation
Strong and weak force: interactions with nuclei of calorimeter material



"Look, our new total absorption calorimeter!"

ATLAS EXPERIMENT Calorimeter basics: particle showers

Electromagnetic showers



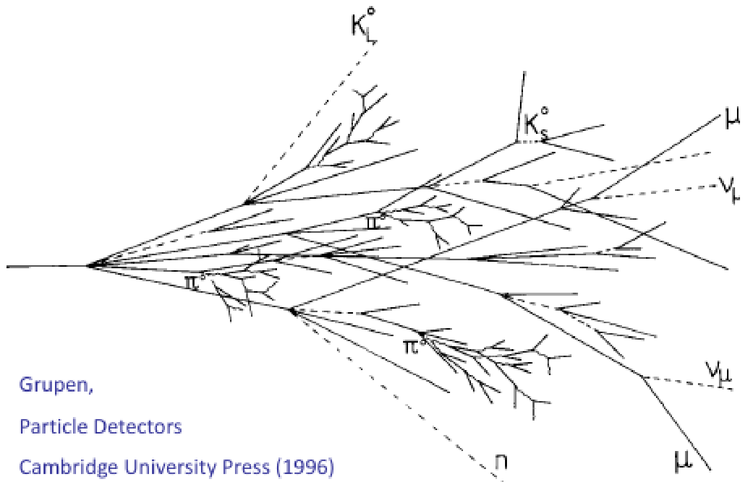
Processes involved (high E):

- Pair production
- Photon radiation by electrons

Particles involved:

- Electrons
- Photons

Hadronic showers



Grupen,
Particle Detectors
Cambridge University Press (1996)

Processes involved:

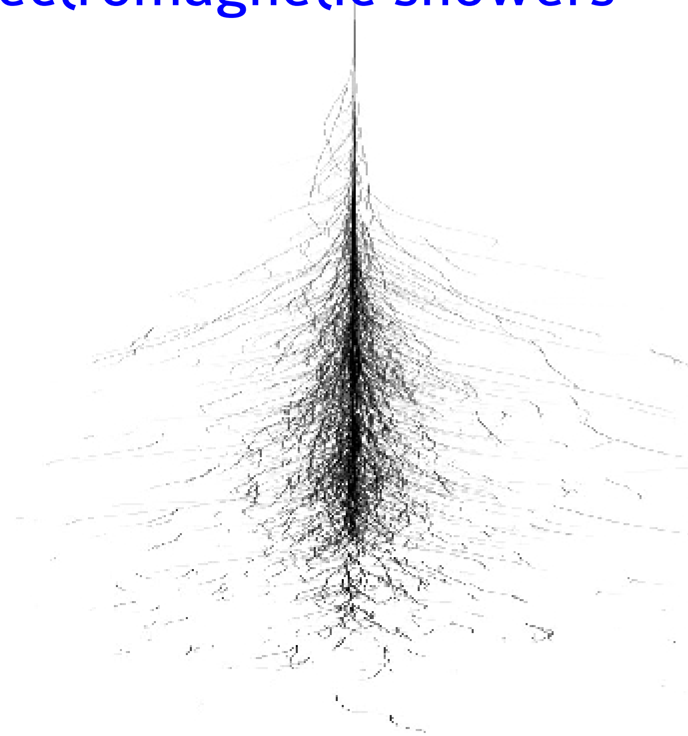
- Nuclear interactions, de-excitations...

Particles involved:

- Baryons and mesons (mostly pions)
- Photons and electrons (EM-component)
- Muons and Neutrinos
(~ invisible to calorimeters!)

ATLAS EXPERIMENT Calorimeter basics: particle showers

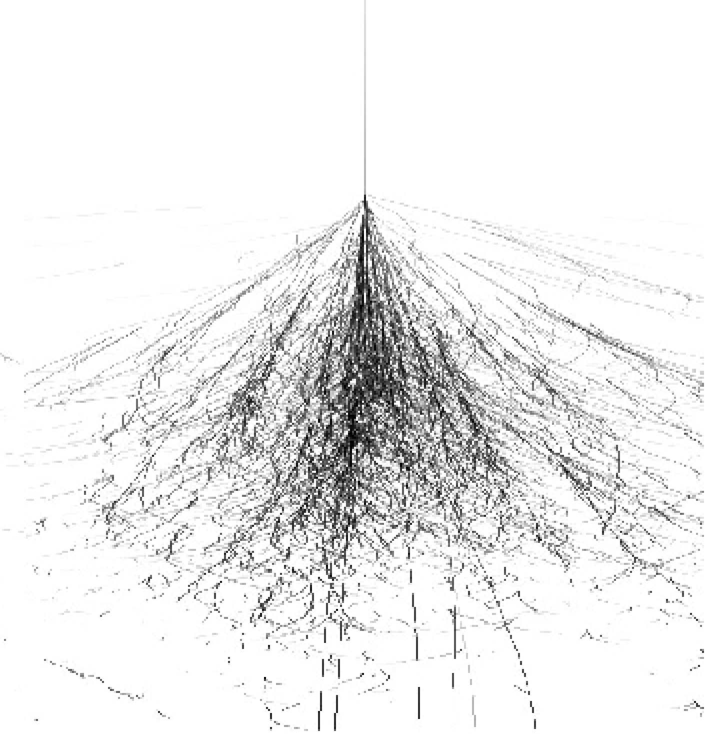
Electromagnetic showers



Gamma shower

Narrower, shorter shape

Hadronic showers



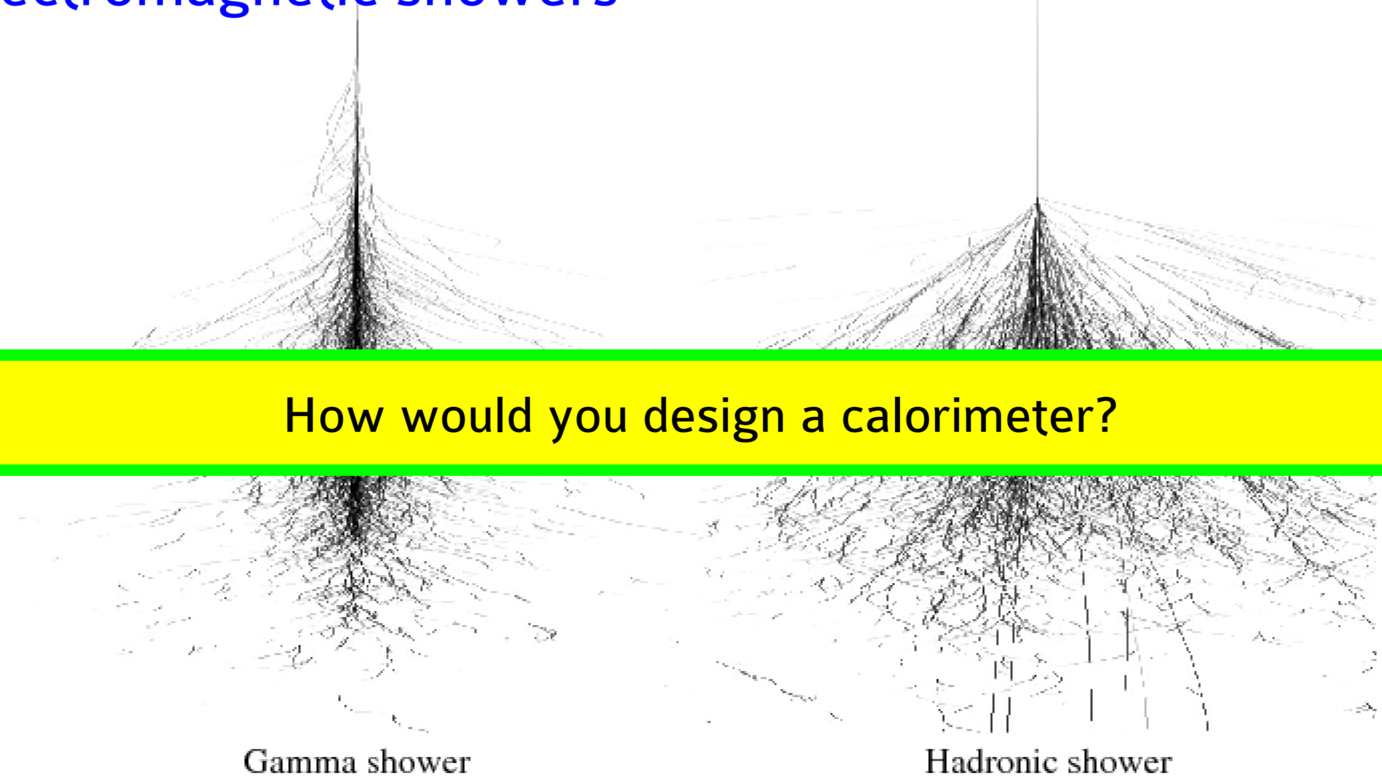
Hadronic shower

Longer, wider shape
More fluctuations in energy and shape

ATLAS EXPERIMENT Calorimeter basics: particle showers

Electromagnetic showers

Hadronic showers



How would you design a calorimeter?

Narrower, shorter shape

Longer, wider shape
More fluctuations in energy and shape

ATLAS EXPERIMENT CALORIMETER DESIGN

Electromagnetic calorimeter

Shorter shower → more compact

Can afford to be ***homogeneous***
- measure all energy in active material
(e.g. scintillating crystal)

Response = energy measured / original particle energy

All particles have ~ the same response (they all interact through EM force, no invisible particles)

Hadronic calorimeter

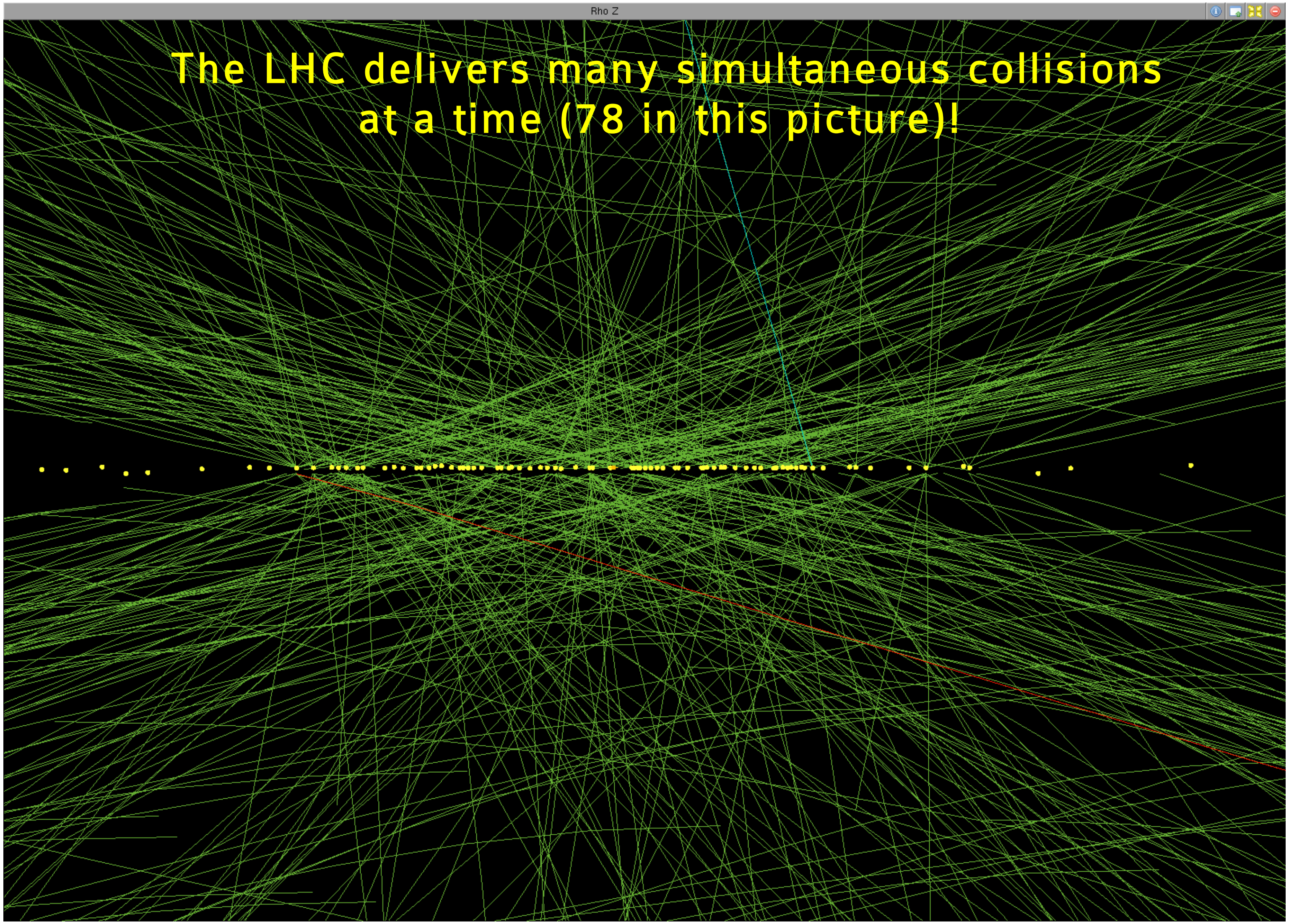
Longer showers → bigger calorimeter

Usually: ***sampling*** calorimeters
- absorb energy in passive material (e.g. iron)
- measure part of it in active material

In principle, **not all particles have the same response**: hadronic showers containing muons/neutrinos/slow neutrons will deposit **less energy**

→ need to **calibrate** hadronic showers differently (alternative: compensating calorimeters, see further reading)

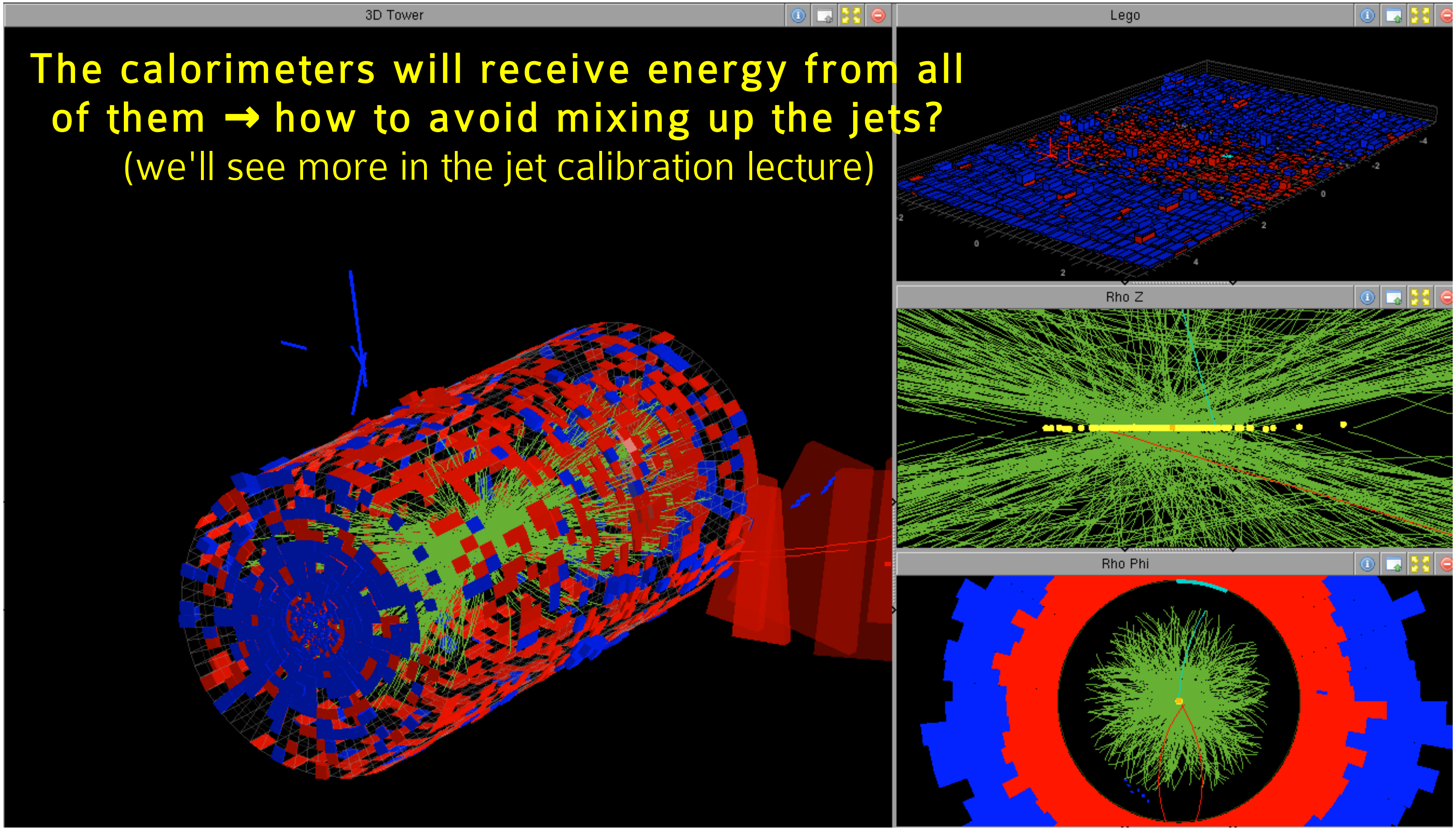
TOO MANY ENERGY DEPOSITS: PILE-UP



ATLAS EXPERIMENT Too many energy deposits: pile-up

The calorimeters will receive energy from all of them → how to avoid mixing up the jets?

(we'll see more in the jet calibration lecture)

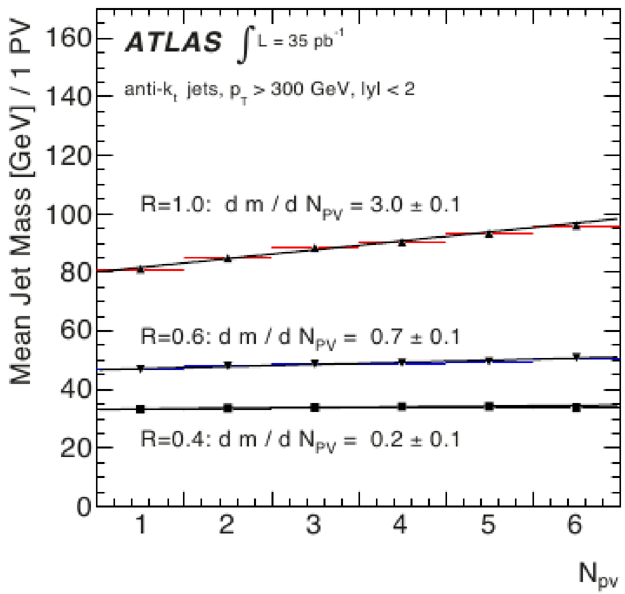


What is jet grooming also useful for: pile-up

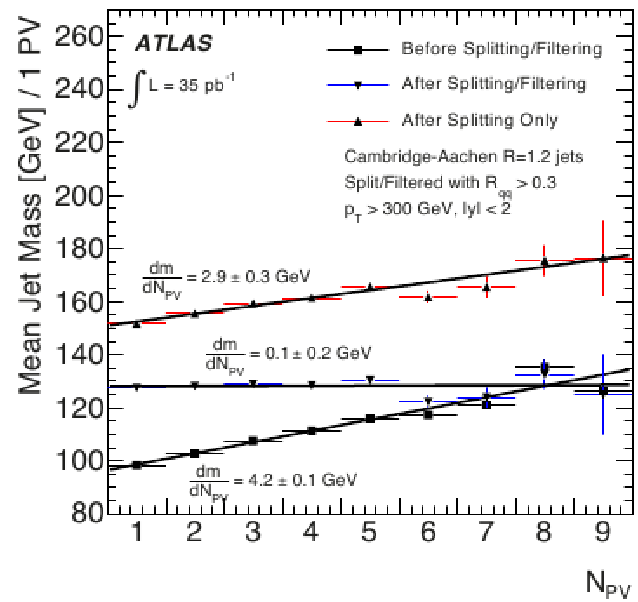
Original aim of jet filtering algorithms [arXiv 0802.2470]:
"filter away UE contamination
while retaining hard perturbative radiation from the Higgs decay products"

(extra energy proportional to number of additional interactions)

Impact of pile-up for anti-k_T jets as a function of R



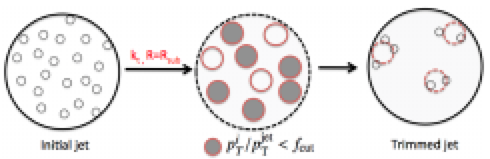
Impact of pile-up for C/A jets R=1.2, before and after filtering



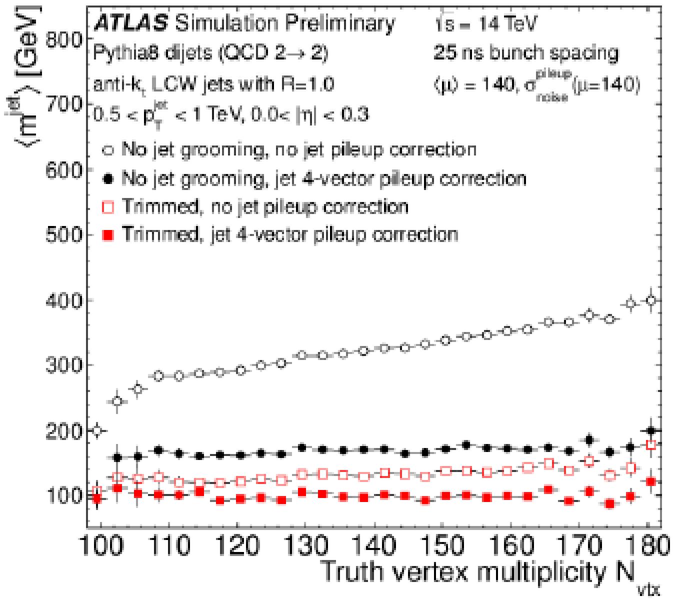
Technique can be employed to reduce impact of pile-up

ATLAS EXPERIMENT More pile-up → obese jets?

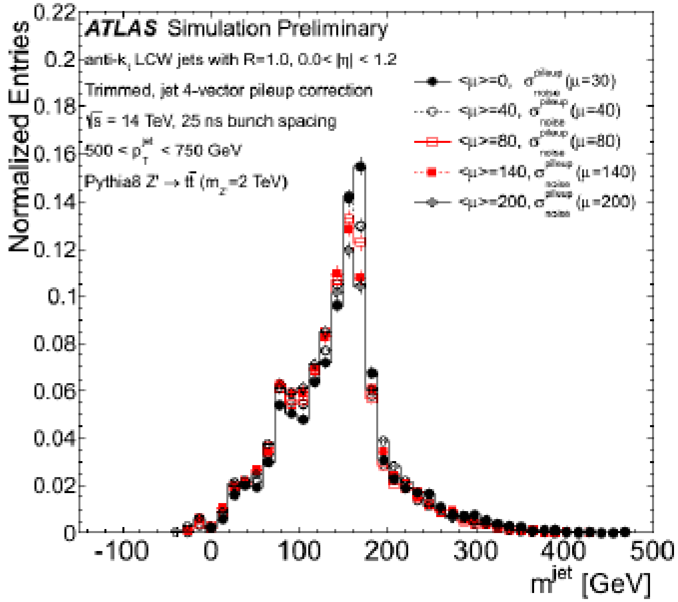
High-luminosity LHC (14 TeV, after Run-II): number of additional interactions (μ) could go up to 140 and more
$\Rightarrow$ will jet substructure techniques still work?



Simulated impact of pile-up on QCD jet mass for R=1.0 anti-k_T jets



Simulated impact of pile-up on $Z' \to t\bar{t}$ jet mass for R=1.0 anti-k_T jets



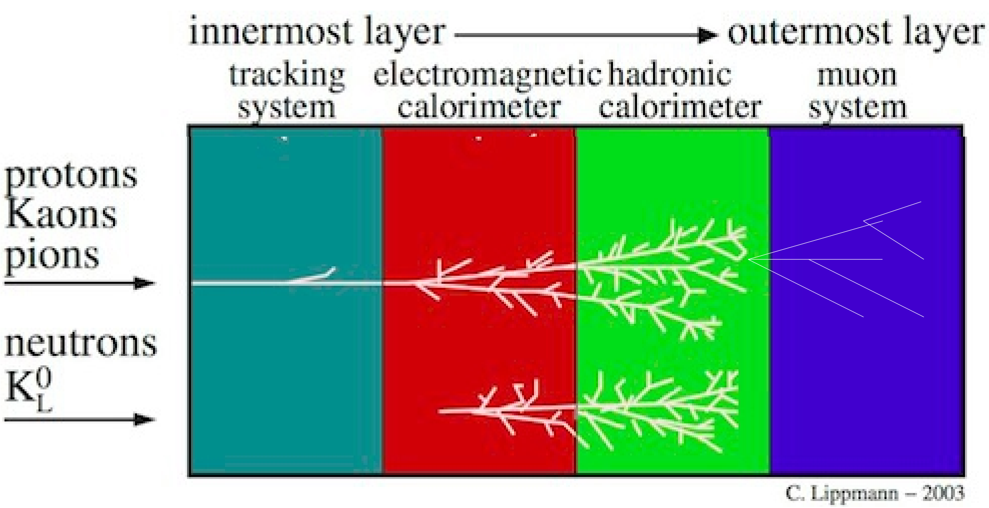
Need both trimming and pile-up correction, but it will work!

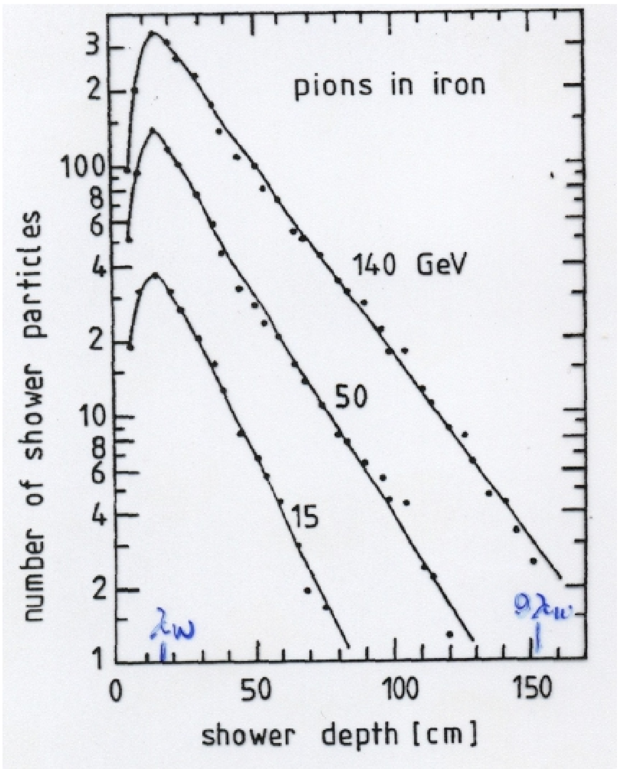
TOO MUCH ENERGY: LEAKAGE (PUNCH-THROUGH)

If shower longer than calorimeter → leakage

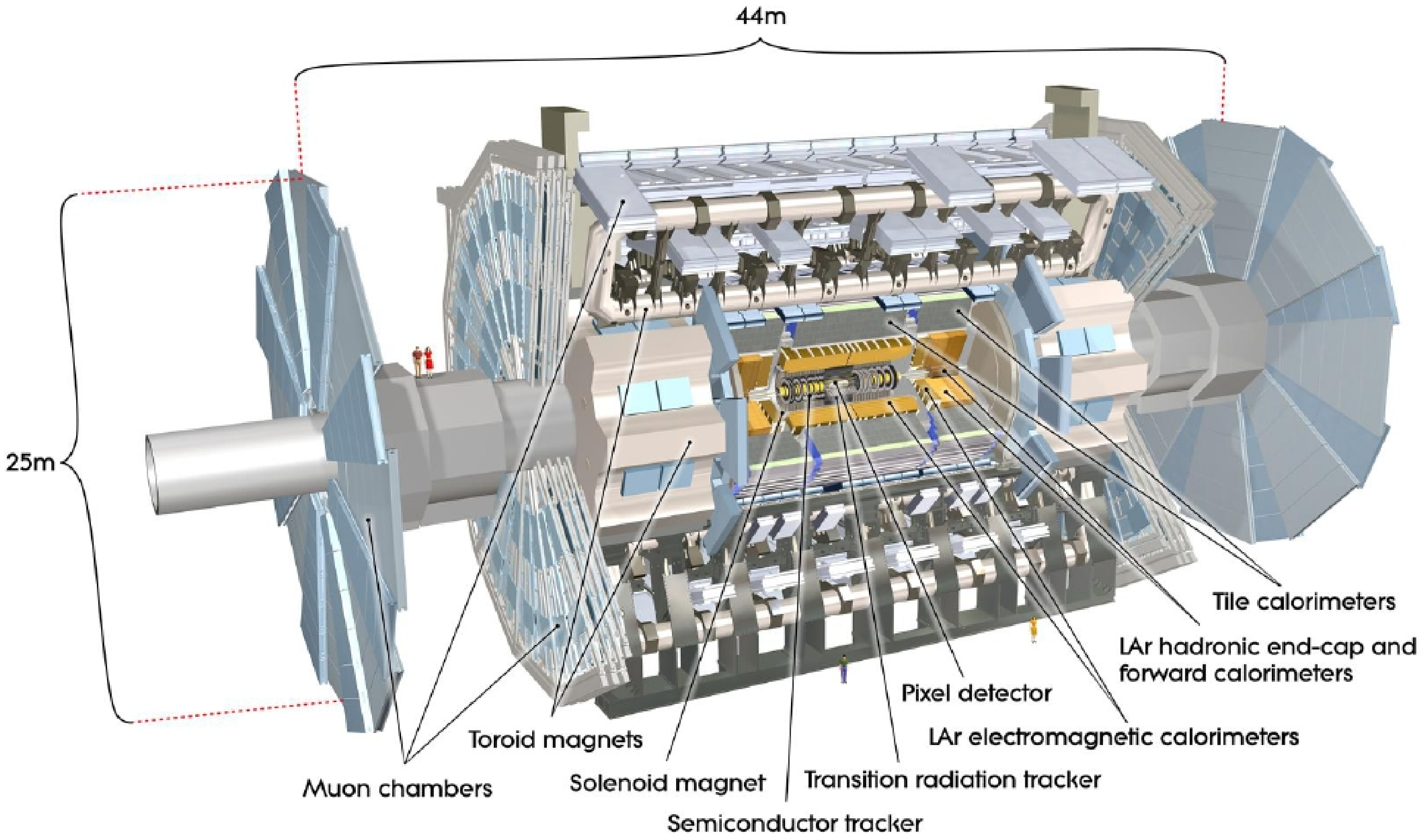
Collection of energy from hadronic showers: **statistical process**, this may happen (or calorimeter might just be too short to contain all shower → design considerations!)

Hint: hits in the muon chambers





THE ATLAS DETECTOR

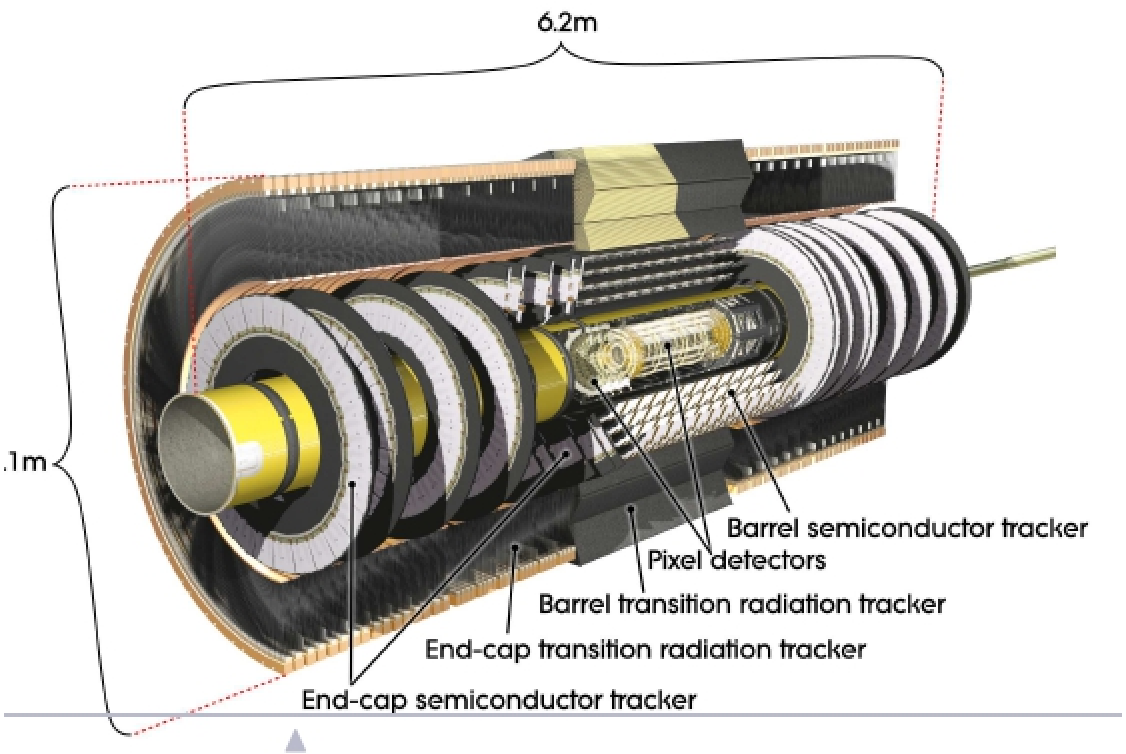


Important for jets: inner detector, calorimeter system, (muon spectrometer)

THE ATLAS INNER DETECTOR

Inner detector

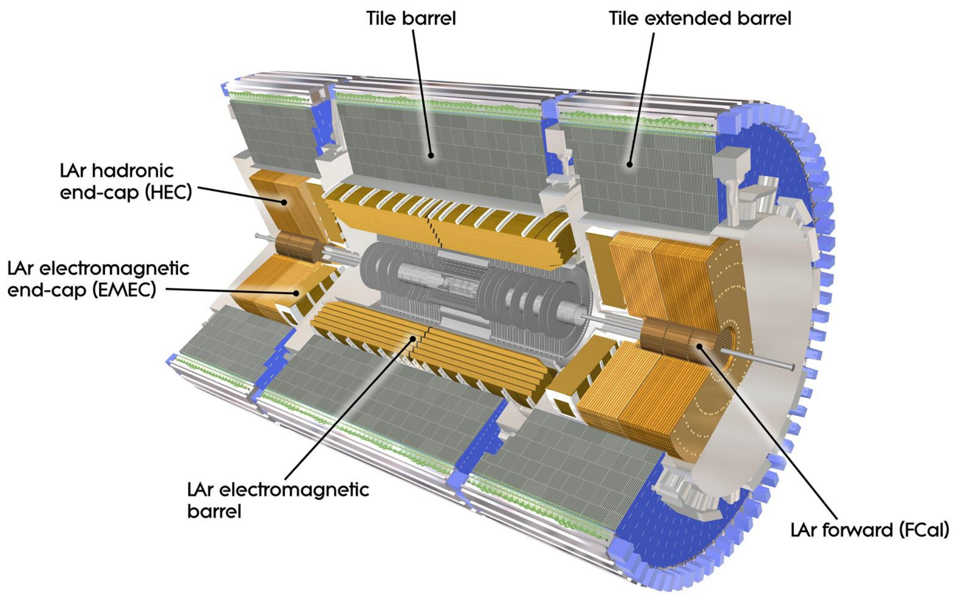
- Pixel detectors, semiconductor tracker (SCT), transition radiation tracker
    - $\approx$ 87M readout channels, coverage up to $|\eta|$ <2.5
    - Immersed in 2T magnetic field from solenoid



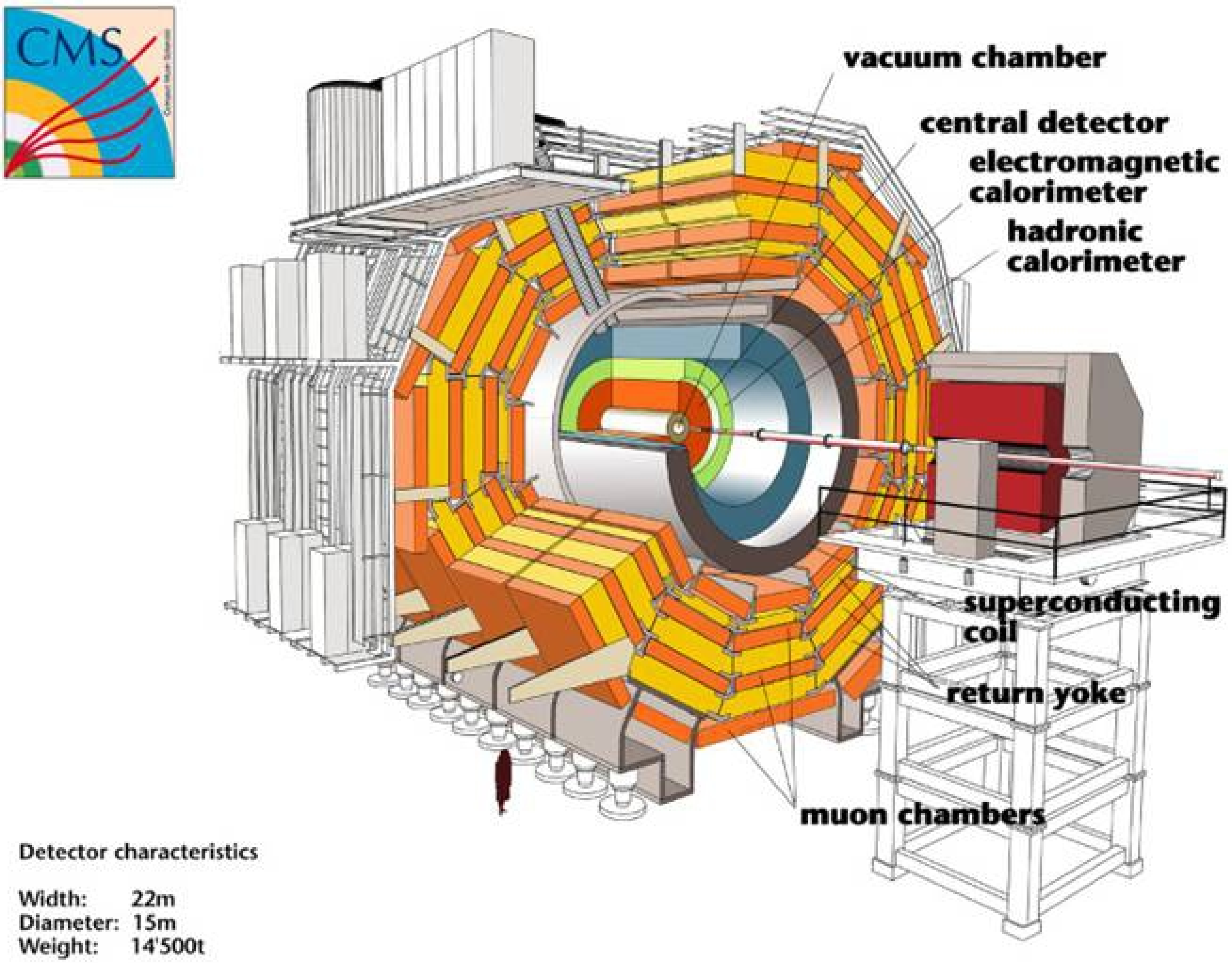
THE ATLAS CALORIMETERS (1)

Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
  - transverse and longitudinal sampling
  - very fine granularity: $\approx$ 200 000 readout cells up to $|\eta| < 4.9$
- Energy deposits grouped in noise-suppressed 3D topological clusters
  noise definition includes pile-up and electronic noise



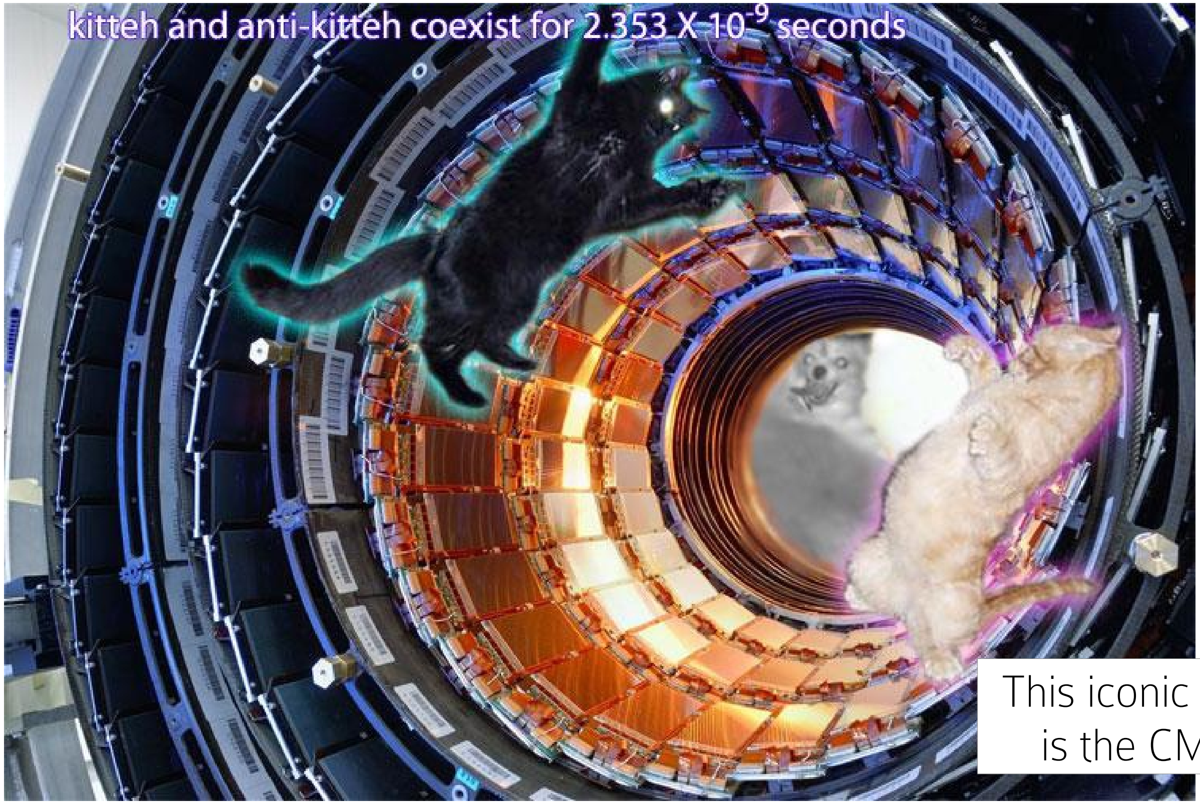
The CMS detector



THE CMS INNER DETECTOR

Inner detector

Only silicon detectors: pixels (close to interaction points) and strips
200 m^2 of silicon within 4T magnetic field from solenoid



This iconic background is the CMS tracker

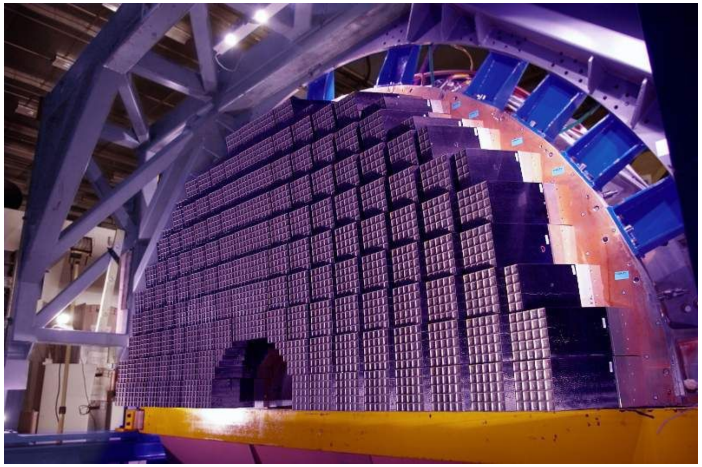
THE CMS CALORIMETERS

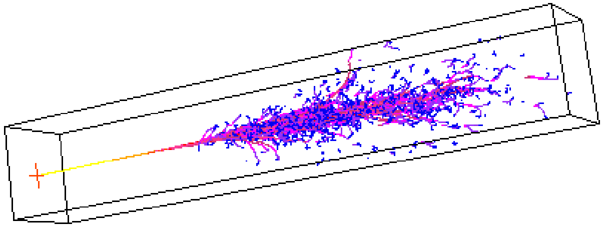
Electromagnetic calorimeter (ECAL)

Homogeneous crystal calorimeter
Pre-shower calorimeter to distinguish electrons from photons
~ 78000 read-out channels

Hadronic calorimeter (HCAL)

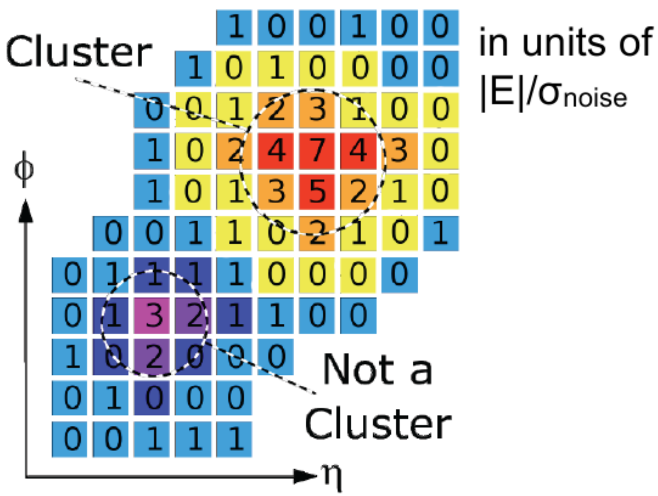
Sampling calorimeter
Active material: plastic scintillator
Absorber: steel or brass (Russian navy!)





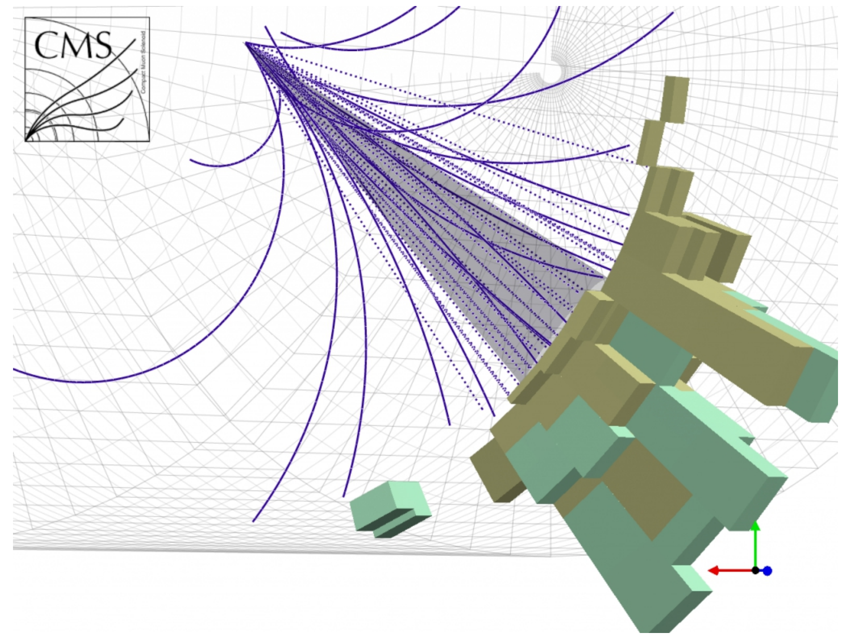
MAIN INPUTS TO JET ALGORITHMS AT THE LHC

ATLAS: Topological clusters



3-dimensional groups
of cells containing energy deposits

CMS: A combination of charged particle tracks and energy deposits



ATLAS and CMS:

Simulated stable particles (*truth jets*)

Only tracks from charged particles (*track jets*)

How to catch a jet: ATLAS jet triggers

The ATLAS trigger system

- 3-tier system (Level-1, Level-2, Event Filter)
- Reduces data intake from ≈ o(10) MHz to ≈ 300 Hz
- Jet triggers: allow for rejection of fakes at L2, anti-k_T jets at the event filter

ATLAS jet triggers (Summer 2011):

1. Minimum Bias Scintillators (MBTS)
2. Single-jet triggers (central and forward)
3. Multijet triggers
4. Topology based triggers
5. Combination triggers

[ATL-DAQ-PROC-2011-034]

Trigger chains currently running unprescaled	Thresholds L1 (GeV)	Thresholds L2 (GeV)	Thresholds EF (GeV)	Rates for 1×10^{33} cm^{-2}s^{-1} L1 (Hz)	Rates L2 (Hz)	Rates EF (Hz)
Inclusive single-jet chains						
1 central jet	75	95	240	275	160	2.8
1 forward jet	75	95	100	3.9	1.1	0.6
Inclusive multi-jet chains						
3 central jets	3×50	3×70	3×75	12	4.9	4.2
5 central jets	5×10	5×25	5×30	60	7.9	3.0
Topological and combination chains						
1 central "fat" jet, anti-k_T $R = 1.0$	75	95	240	275	160	2.7
2 forward jets with $\Delta\eta > 5$	2×30	2×50	2×55	2.2	<0.5	<0.5
1 central jet + E_T^{miss}	50 + 20	70 + 20	75 + 45	711	338	20
1 central jet with $H_T > 350$	75	95	100	275	160	11

5' for questions up to here + 10' break

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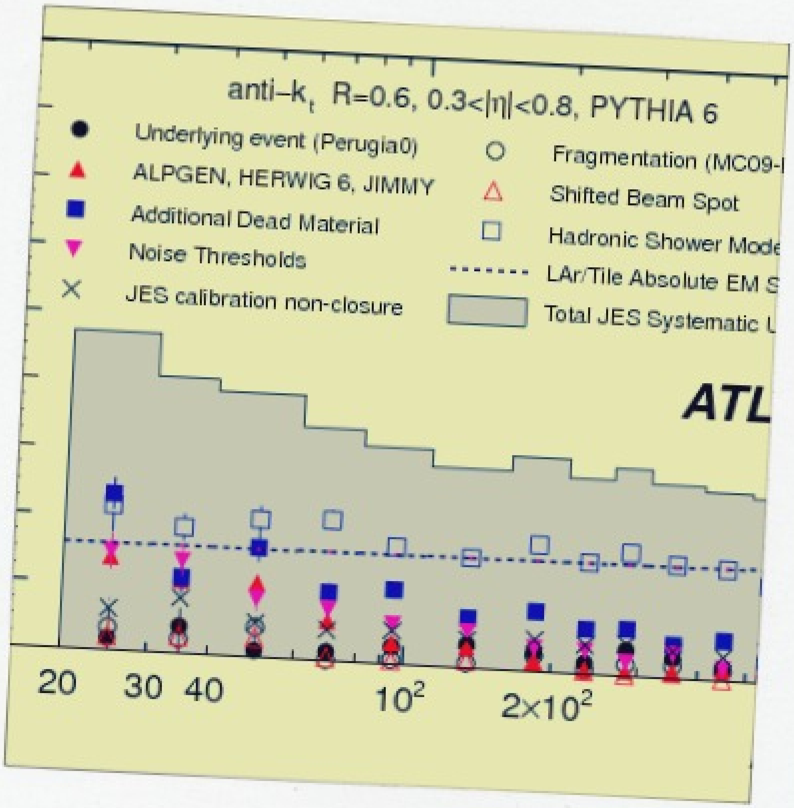
ATLAS EXPERIMENT



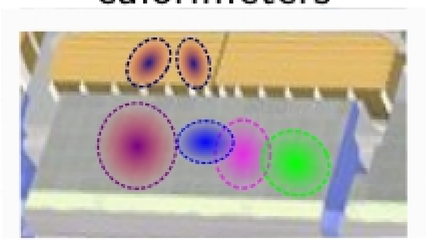
First ATLAS JES uncertainty (2010)

2 - JET CALIBRATION AND PERFORMANCE

22/07/2014 – HASCO Goettingen

EXPERIMENTAL JETS, PART 2: JET CALIBRATION AND PERFORMANCE

Energy deposits in calorimeters



ATLAS Calorimeters

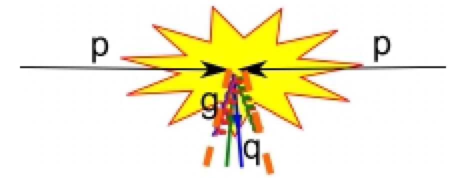
⇒

Jet reconstruction

jet finding

calibration

⇒



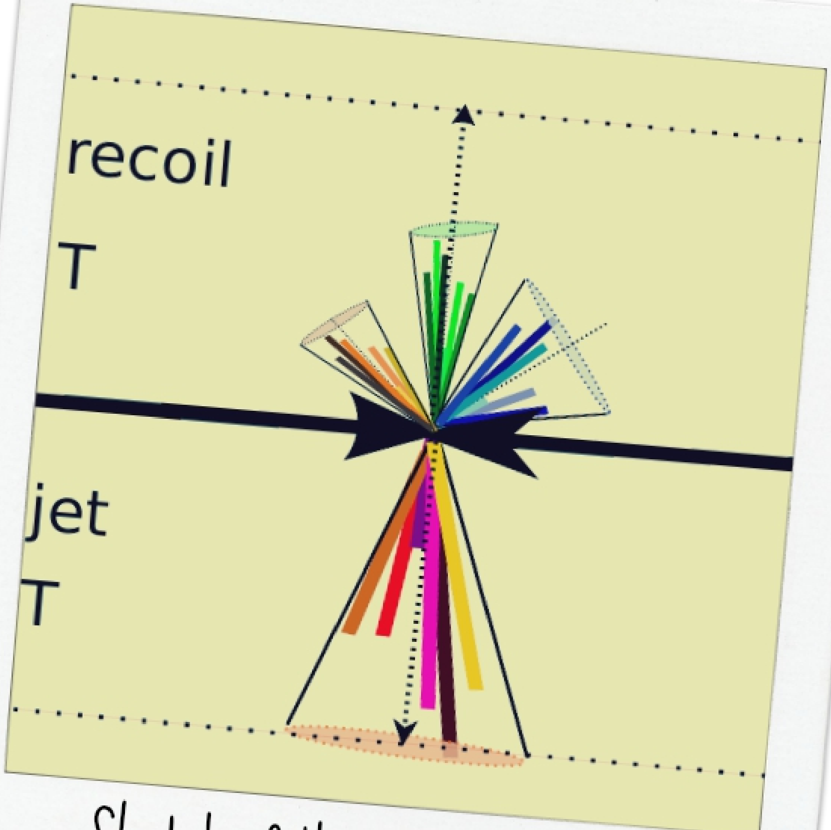
Outline

Concepts of jet calibration and performance

- Jet response and resolution
- Missing transverse momentum
- Jet performance tools
- Jet identification

Jet calibration and performance in ATLAS and CMS

- Pile-up subtraction
- JES calibrations
- Jet performance and uncertainty



Sketch of the multijet balance jet calibration technique

2.1 - SOME NOTIONS OF JET CALIBRATION AND JET PERFORMANCE

22/07/2014 – HASCO Goettingen

ATLAS EXPERIMENT RESPONSE AND RESOLUTION

How will a calorimeter react to a particle?

Thought (blackboard) experiment (1):

shoot 10000 pions of E=100 GeV in our calorimeter

Draw the energy distribution of the jets

(assuming one pion per jet)

Response and Resolution

How will a calorimeter react to a particle?

Thought (blackboard) experiment (2):

Our calorimeter is non-compensating

there is inactive material (a tracker!) in front of it

Not all the shower is captured by the jet

There is extra energy due to pile-up (...)

What happens to our energy distribution?

ATLAS EXPERIMENT Response and resolution

How will a calorimeter react to a particle?

Thought (blackboard) experiment (3):

There are fluctuations in the shower properties

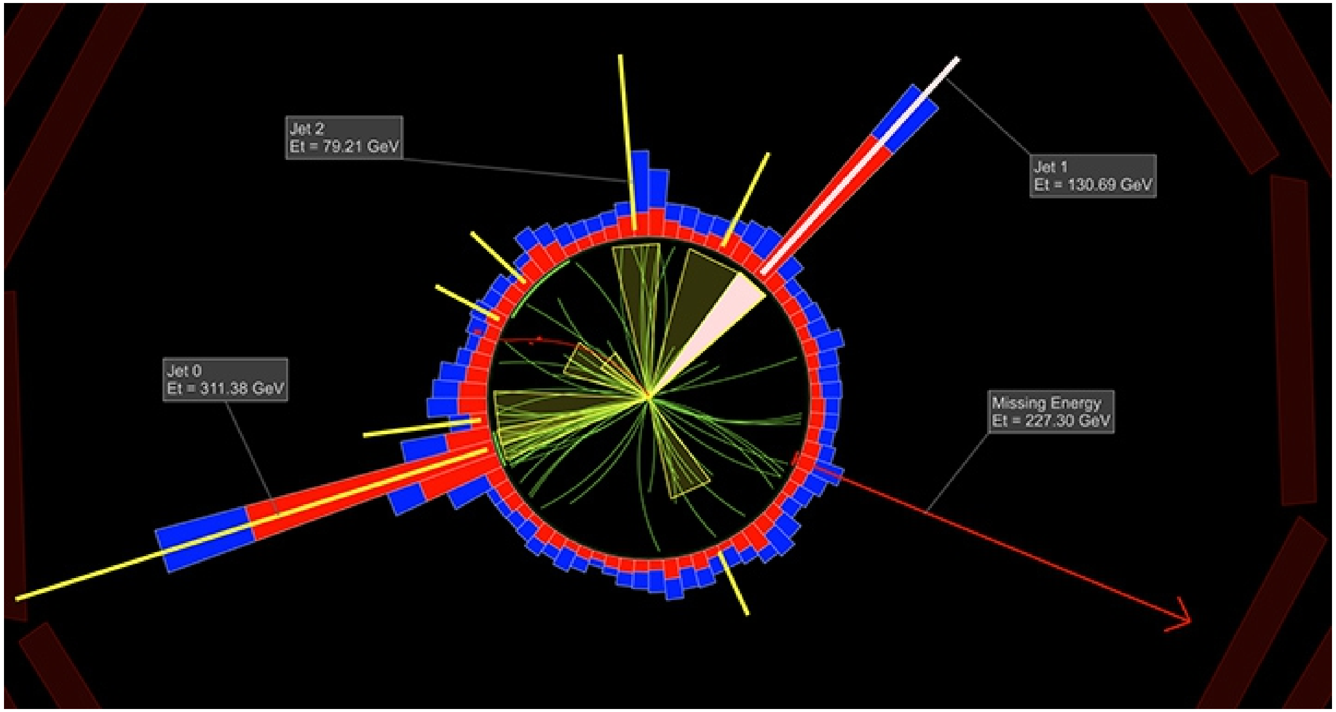
→ fluctuations in the collected energy

There is leakage (punch-through)

What happens to our energy distribution?

RELATED: MISSING TRANSVERSE MOMENTUM

Missing transverse momentum: particles escaping undetected…but also mismeasured jets!

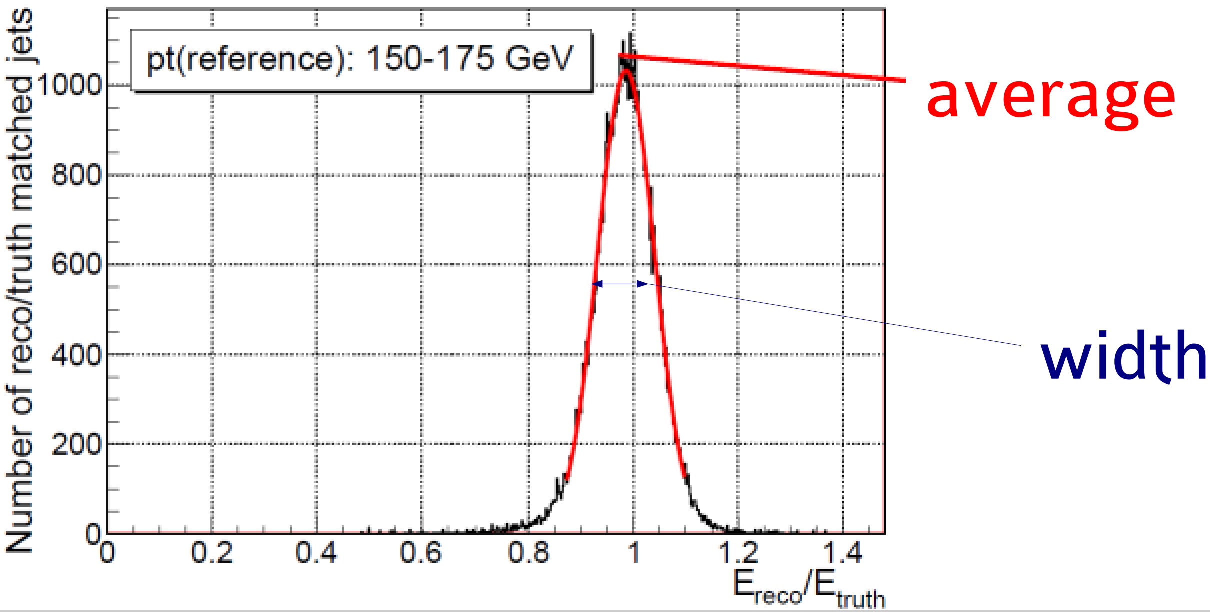


Jet energy response and resolution need to be well performing and well understood to discover e.g. SUSY

ATLAS EXPERIMENT Response and resolution

How will a calorimeter react to a particle?

Divide original jet energy by measured jet energy:
average → jet response
width → jet resolution



ATLAS EXPERIMENT Parameterisation of jet energy resolution

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

Typical:

A: 0.5 – 1.0 [Record:0.35]
B: 0.03 – 0.05
C: few %

http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/

ATLAS EXPERIMENT JET PERFORMANCE

How to **quantify** the performance of jets?

compare the **jet** to a reference object:

- linearity (response) $L = \frac{K_{Reco}}{K_{Reference}}$
- resolution $R = \frac{\sigma(K_{Reco})}{K_{Reco}}$
- purity [a] $P = \frac{N_{Reco,Matched}}{N_{Reco}}$
- efficiency [b] $E = \frac{N_{True,Matched}}{N_{True}}$

[a,b] only available in MC comparison

with K: kinematic quantity (e.g. E, p_T)

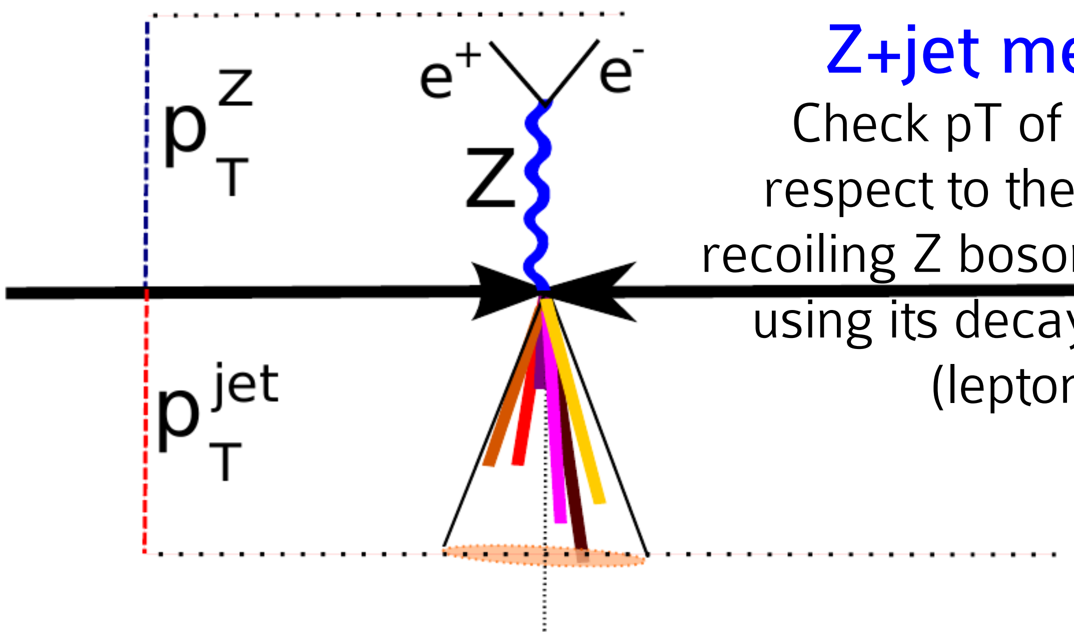
Compare different calibrations and corrections

Extract uncertainties from systematic comparisons of performance plots (and kinematic distributions)

Reference object: true jet, track jet, better calibrated object

Checking jet performance *in-situ* using well-calibrated objects

Exploit **better calibrated objects** **recoiling against jet** to test jet energy scale and resolution

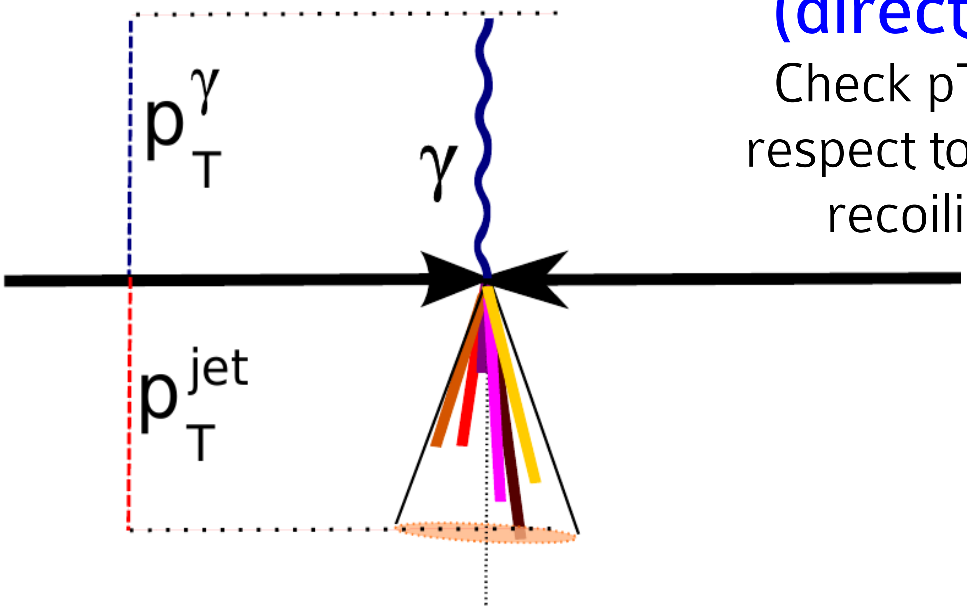


Z+jet method

Check pT of jets with respect to the pT of the recoiling Z boson, measured using its decay products (leptons)

CHECKING JET PERFORMANCE *IN-SITU* USING WELL-CALIBRATED OBJECTS

Exploit **better calibrated objects** **recoiling against jet** to test jet energy scale and resolution



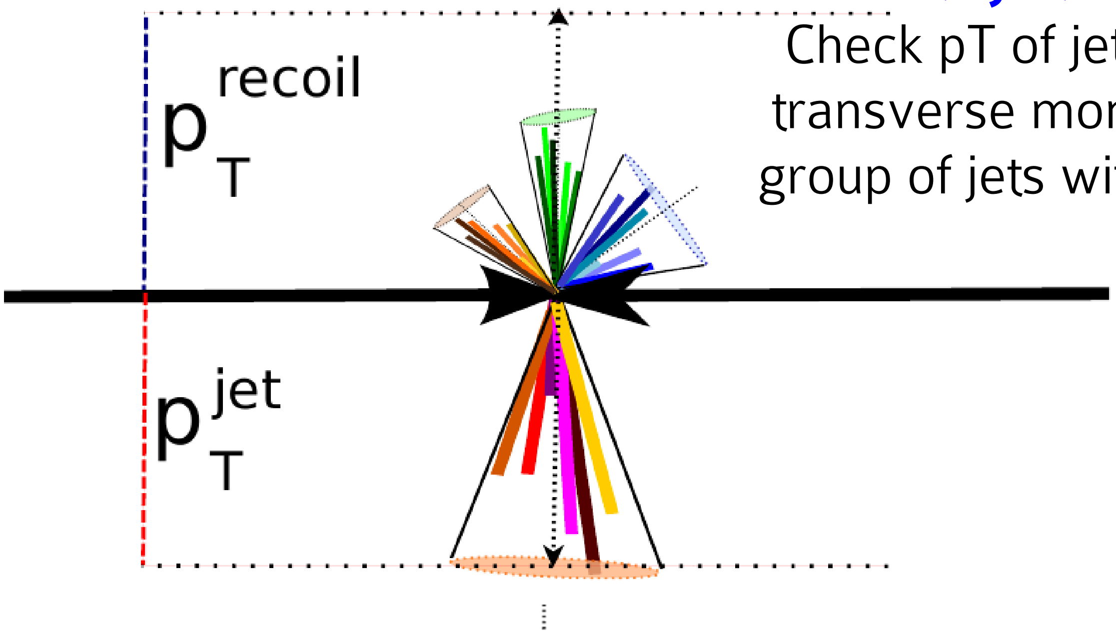
photon+jet method (direct balance)

Check pT of jets with respect to the pT of the recoiling photon

Alternative: missing transverse momentum projection fraction (MPF)

CHECKING JET PERFORMANCE *IN-SITU* USING WELL-CALIBRATED OBJECTS

Exploit **better calibrated objects** **recoiling against jet** to test jet energy scale and resolution

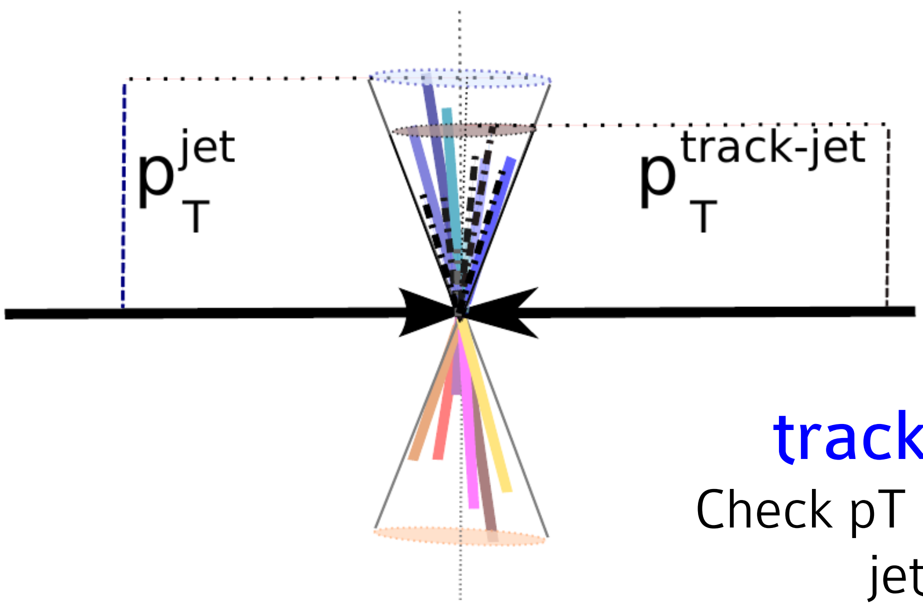


Multi-jet balance

Check pT of jet with high transverse momentum vs group of jets with lower pT

CHECKING JET PERFORMANCE *IN-SITU* USING WELL-CALIBRATED OBJECTS

Exploit **better calibrated jets** **of the same origin as our jet** to test jet energy scale and resolution

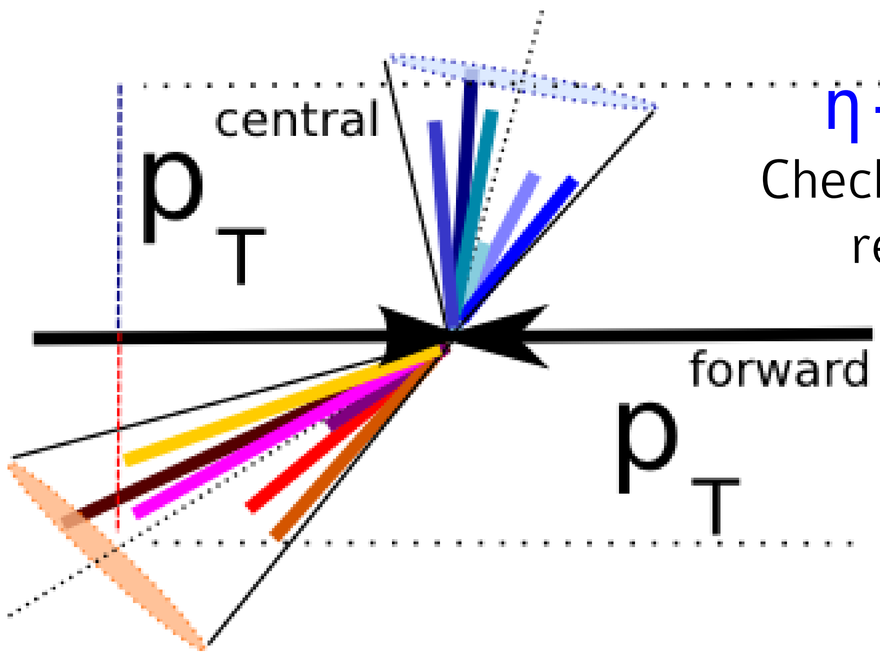


track-jet method

Check pT ratio of calorimeter jet vs track jet

CHECKING JET PERFORMANCE *IN-SITU* USING WELL-CALIBRATED OBJECTS

Exploit **better calibrated objects** **recoiling against jet**
to test jet energy scale and resolution

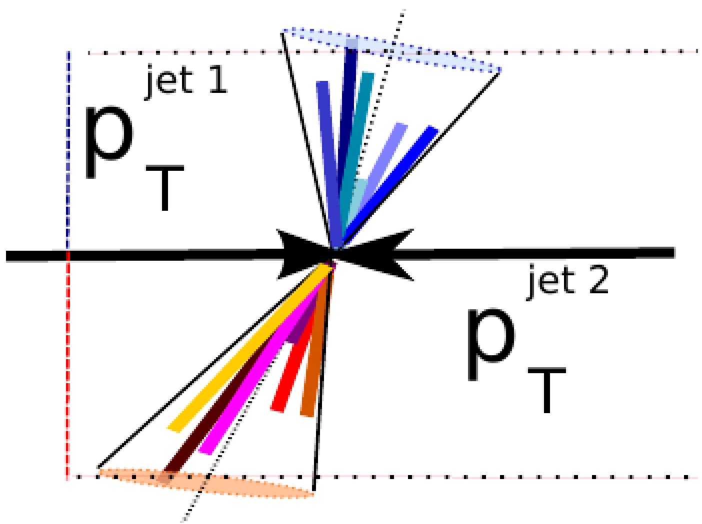


η - intercalibration

Check pT of forward jets with respect to central jets

IN-SITU RESOLUTION

Exploit **better calibrated objects** **recoiling against jet**
to test jet energy scale and resolution



Alternative: bisector method

pT-balance

Width of pT asymmetry distribution is connected to width of pT distribution

$$A = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

Assuming $p_T^2 \sim p_T^1$

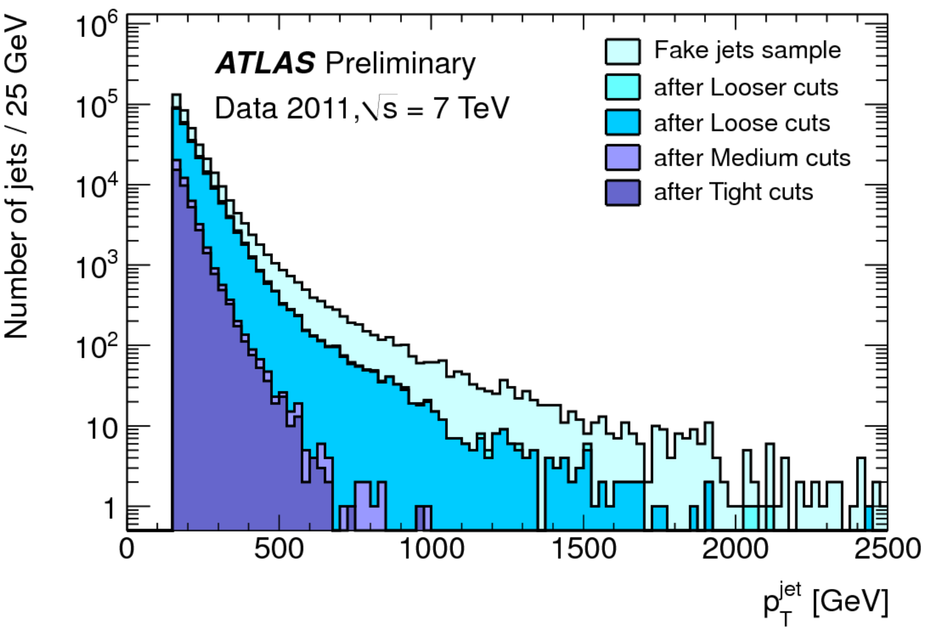
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{2}\sigma_A$$

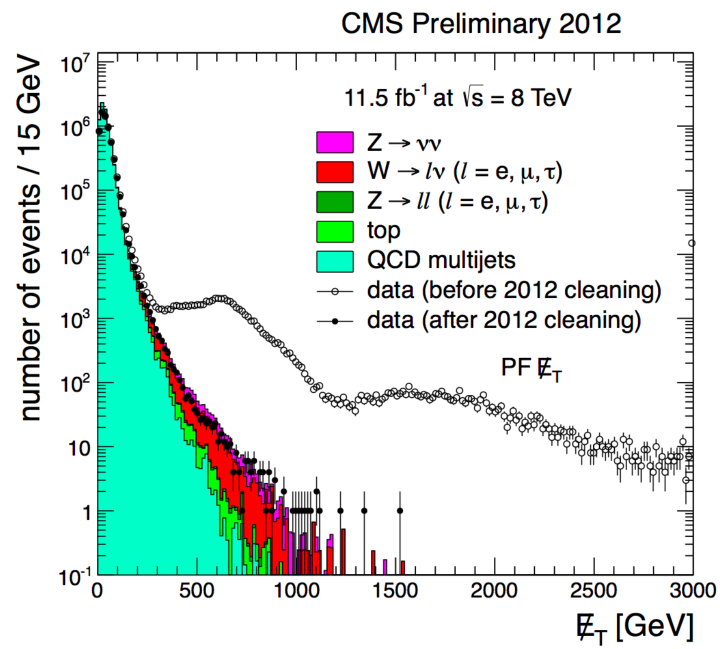
ATLAS EXPERIMENT JET IDENTIFICATION

Energy deposits in calorimeters → jet

But: energy deposits in calorimeters != always real jets

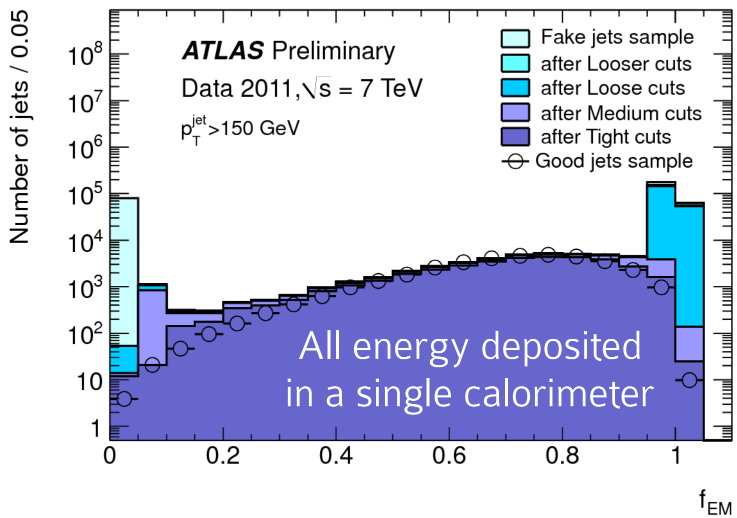
→ experiments need criteria to remove fake jets

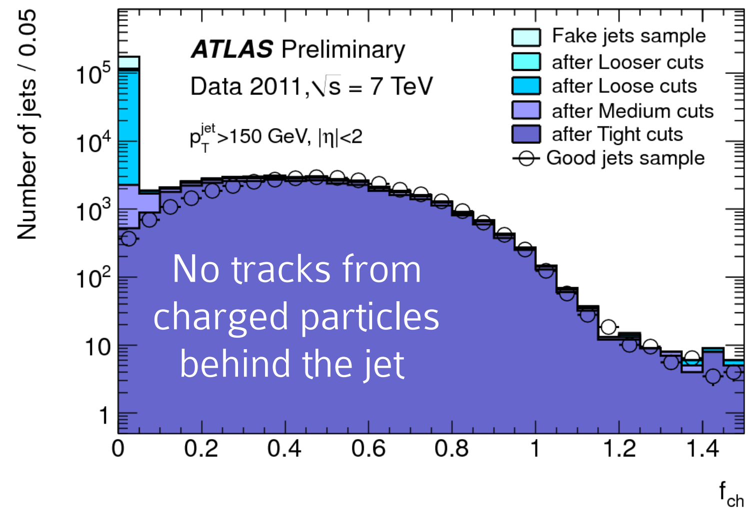


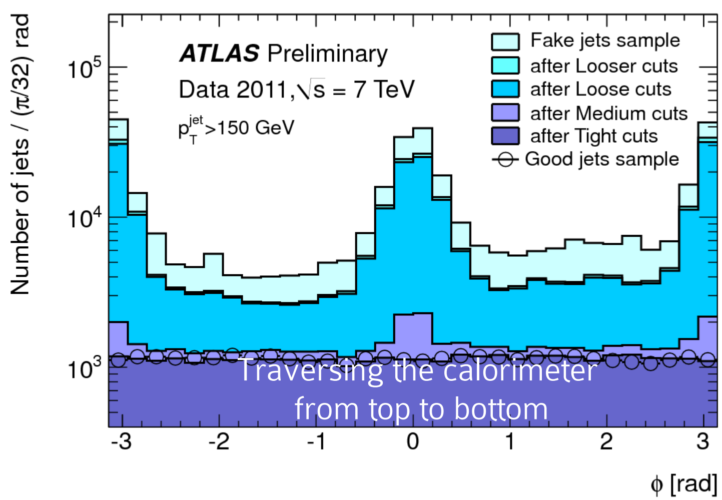


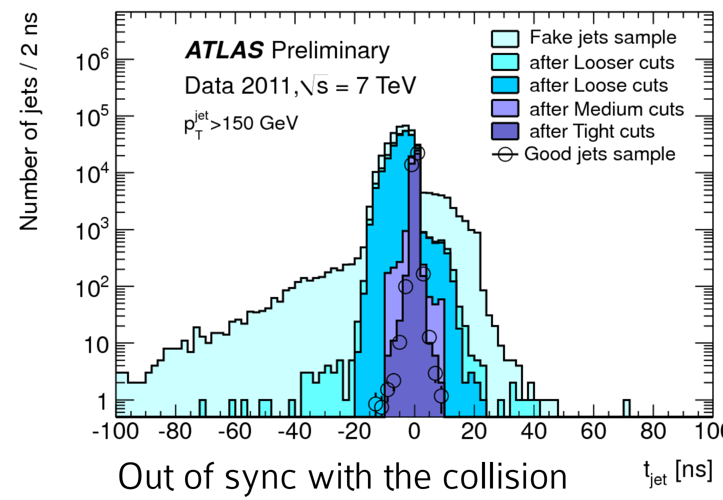
ATLAS EXPERIMENT JET IDENTIFICATION

Characteristics of fake jets include:



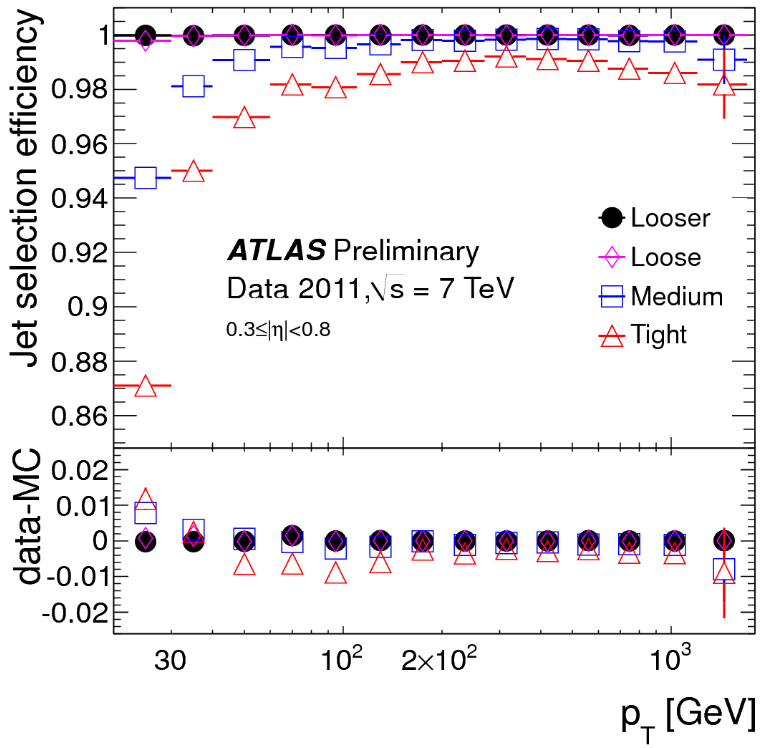






JET IDENTIFICATION: PERFORMANCE

Cuts with various 'tightness': **inefficiency** (= cutting good jets) vs **purity** (= cutting all bad jets)



Most analyses use looser/loose working points

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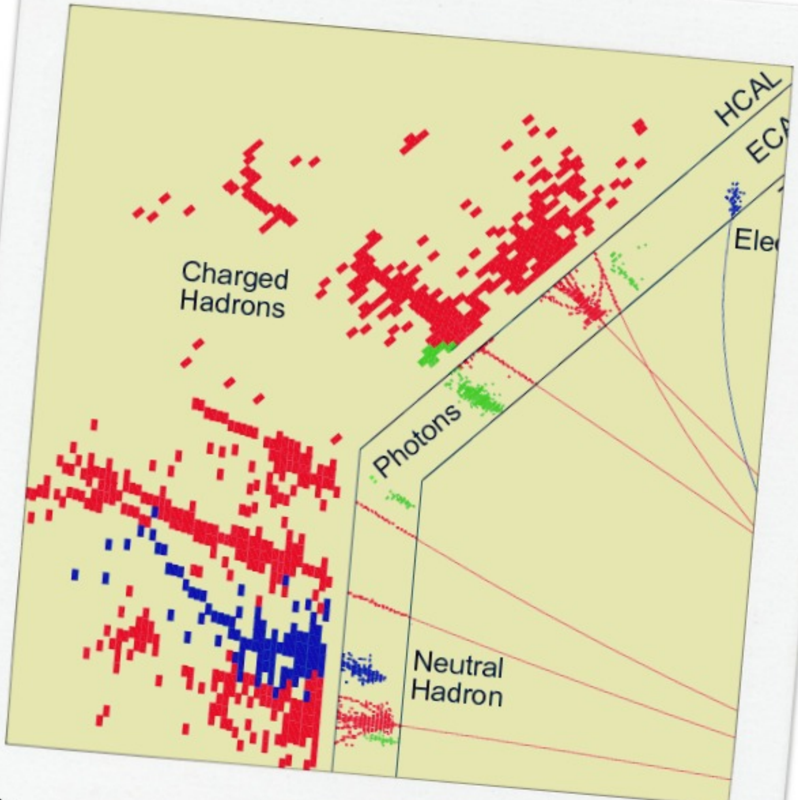
ATLAS EXPERIMENT

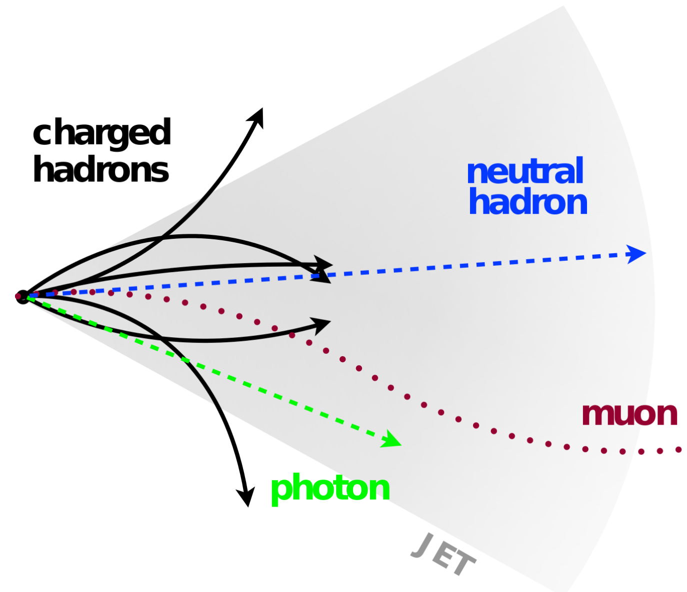


Example event, input to particle flow

2.2 - JET CALIBRATION AND PERFORMANCE, IN LHC DATA

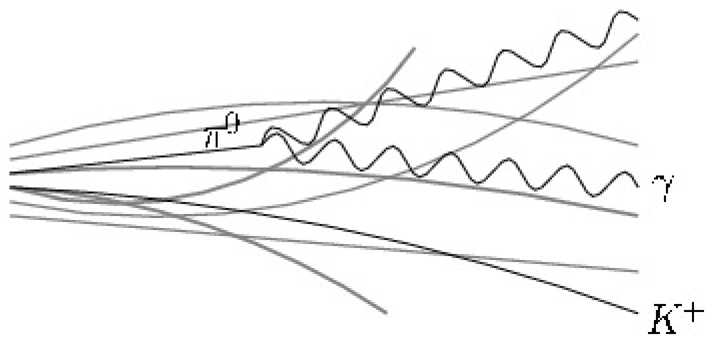
22/07/2014 – HASCO Goettingen

RECAP: FORMATION OF JETS IN ATLAS AND CMS



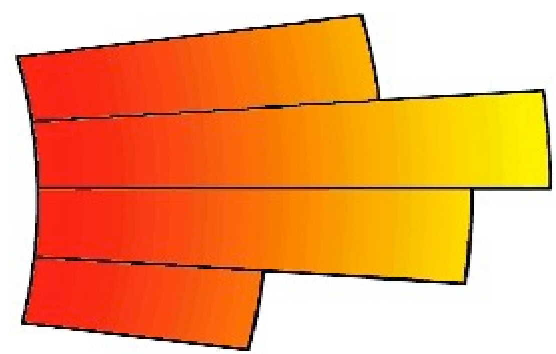
CMS: particle flow jets
using both tracking and calorimeter info

parton level jet



particle level jet

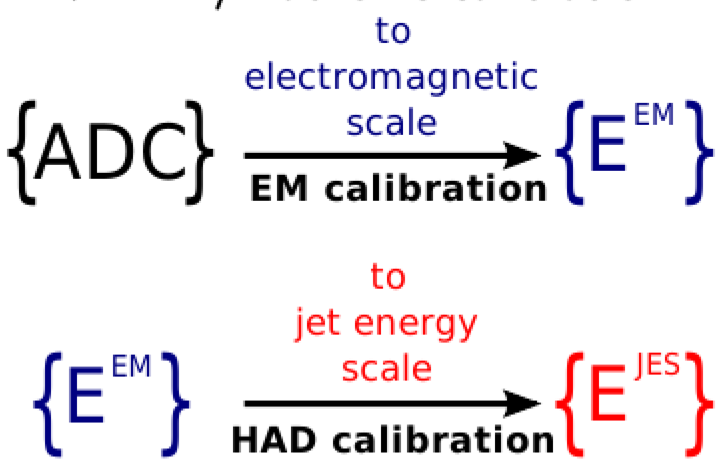
ATLAS: calorimeter jets
using topological clusters as input



calorimeter level jet

JET CALIBRATION IN A NUTSHELL

Measure **energy** from **readout signal**
→ **EM / hadronic calibration**



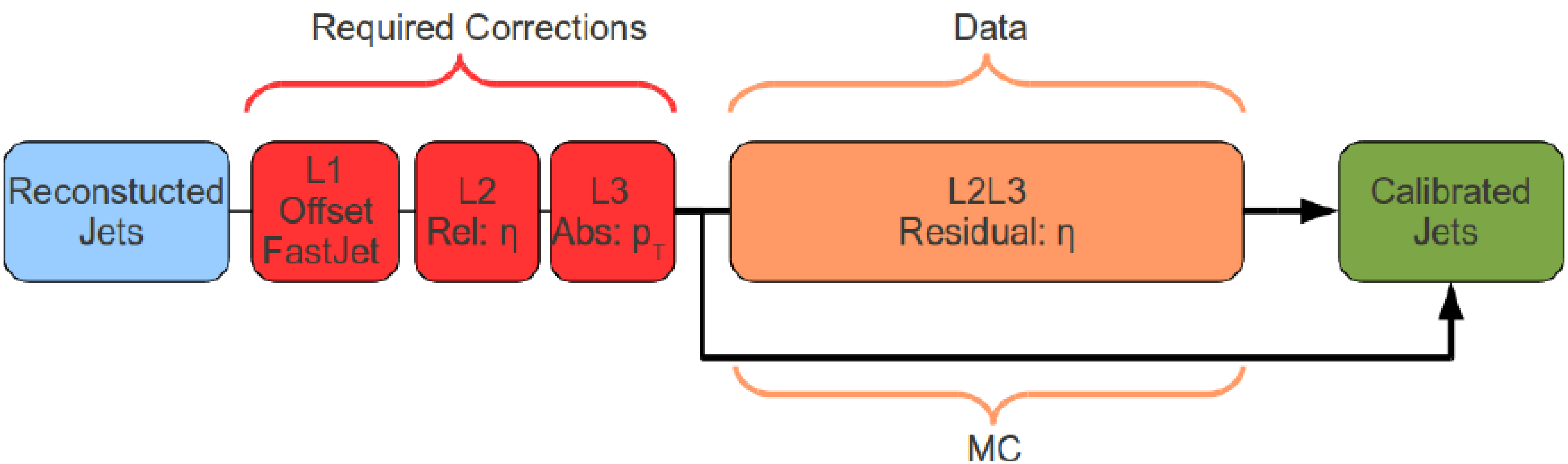
Calorimeter jet response corrected for:

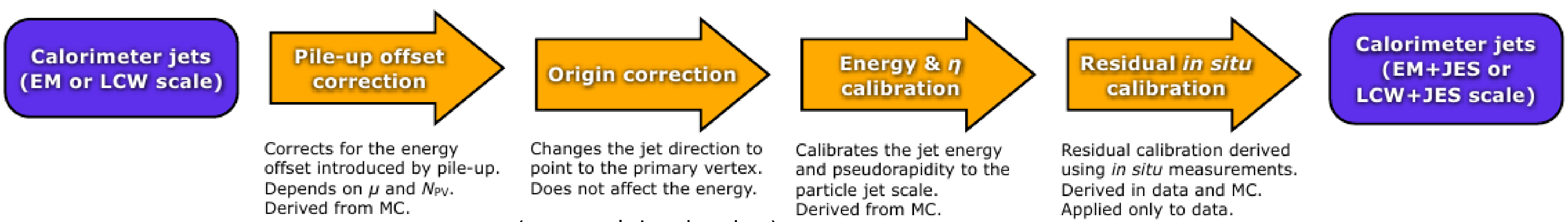
- **Non-compensating** calorimeters
- **Inactive** material
- **Out-of-cone** effects

Further calibration steps:

- **pile-up correction** to remove extra energy from multiple interactions
- correction based on **in-situ balance** techniques (e.g. γ+jet)

JET CALIBRATION FOR ATLAS AND CMS





(not explained today)

ATLAS EXPERIMENT PILE-UP SUBTRACTION

Two kinds of pile-up:

in-time (extra interactions within same LHC bunch crossing)
→ add "diffuse radiation" to jet
out-of-time (different bunch crossings)
→ may affect calorimeter signal and energy reconstruction

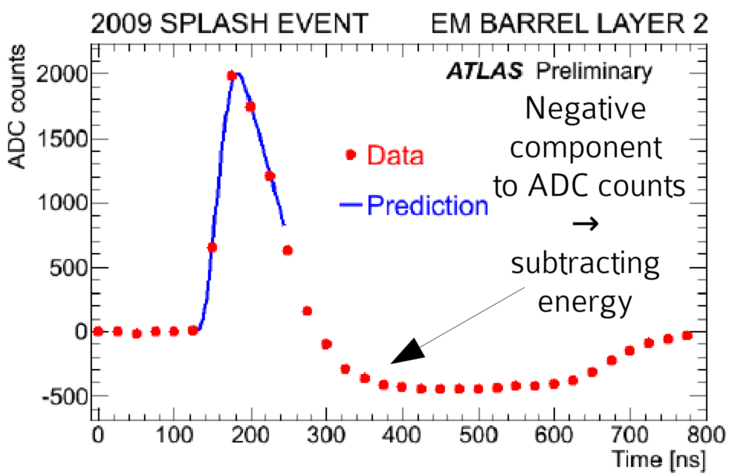
In-time pile-up

CMS and ATLAS: event-by-event subtraction of in-time pile-up component based on **jet area**
Additional/alternative "**offset**" correction for residual effects, based on simulation or on uncorrelated area (outside jet) in same event

Cross-checks using **track jets** (can select only tracks from primary vertex)
Also: methods to **reject spurious pile-up jets** by checking tracks from PV exist (*JVF* method)

Out-of-time pile-up

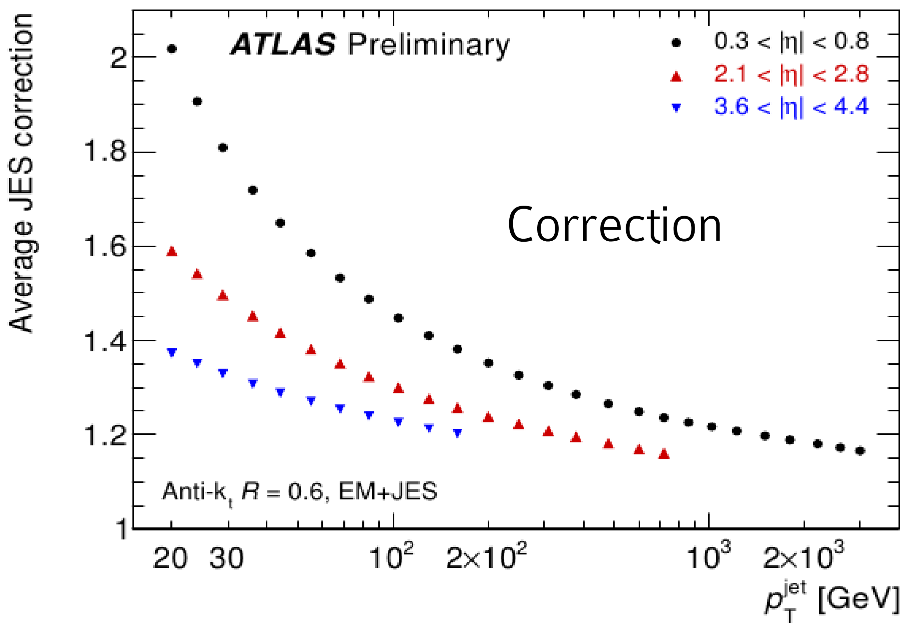
ATLAS: calorimeters designed to cancel in-time and out-of-time components (bunch crossings every 25 ns)



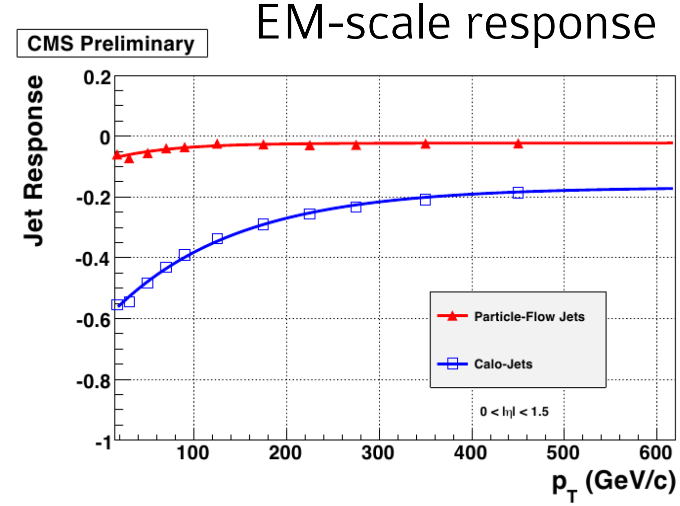
JES correction for ATLAS and CMS

Main correction: from **EM** scale to **hadronic** scale

Generally based on MC simulation:
derive calibration constants from **response** of reconstructed jet after full detector simulation wrt truth jet



EM-scale response

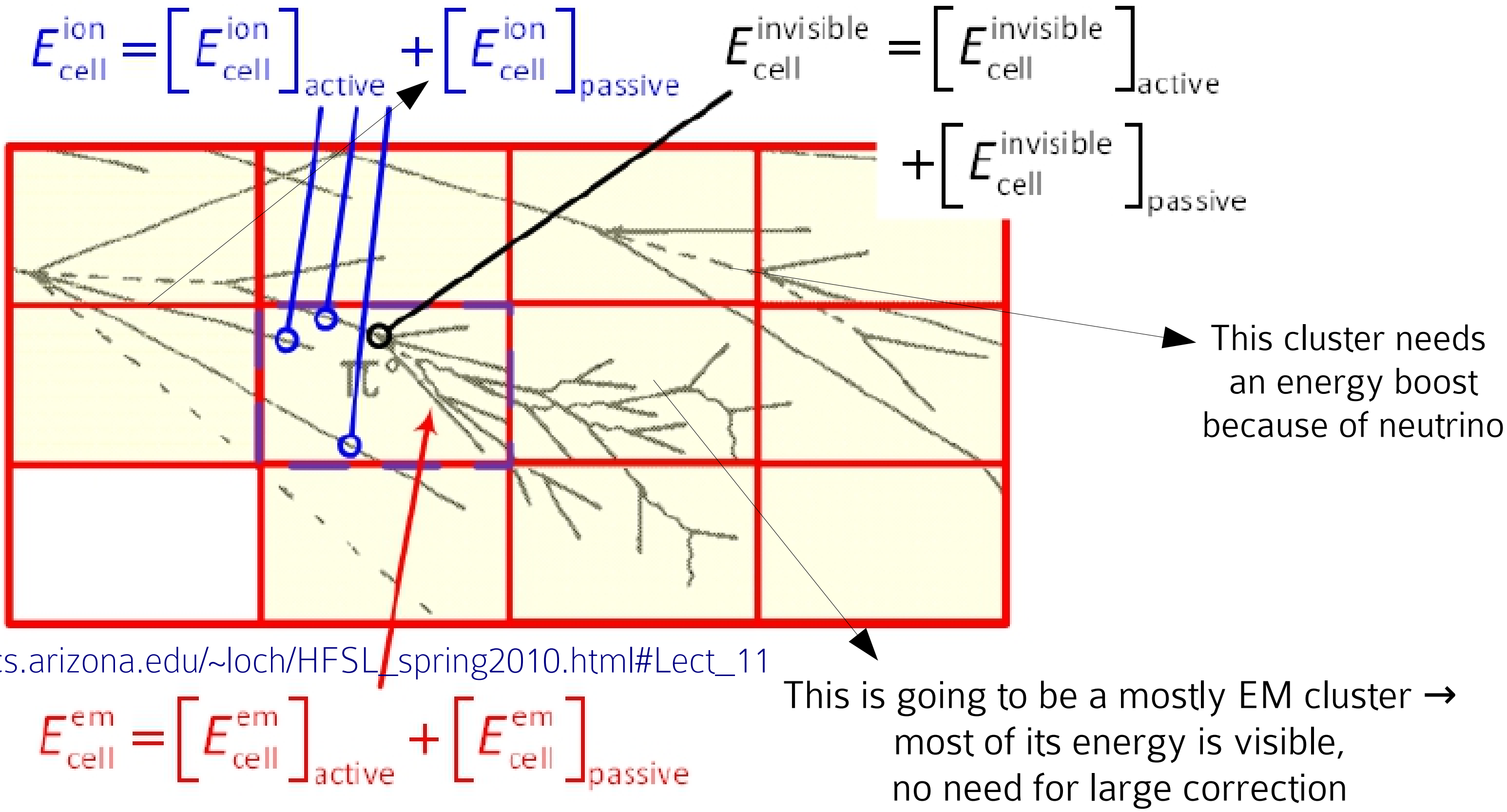


Can be refined using other **properties of jets**

The correction increases with energy as there are more neutral pions in the shower at high-pT→ EM component enhanced

ATLAS EXPERIMENT Calibration of topocluster: local calibration

Topoclusters are designed to **follow shower development**
→ they contain information on EM/HAD content, can be exploited in calibration



http://atlas.physics.arizona.edu/~loch/HFSL_spring2010.html#Lect_11

ATLAS EXPERIMENT Calibration of topocluster: local calibration

Calibrate clusters to had scale based on energy density and shape, apply correction factor to cluster **before jet formation**

Local calibration also accounts for energy losses due to dead material and out-of-cluster

JES calibration (smaller) accounts for remaining effects:

http://atlas.physics.arizona.edu/~loch/HFSL_spring2010.html#Lect_11

$$E^{jet}_{true} = E^{calo}_{dep} + E^{loss}_{mag} + E^{loss}_{low} + E^{loss}_{leak} + E^{loss}_{out} - E^{gain}_{UE \otimes PU} - E^{gain}_{env}$$

E^{calo}_{dep}	energy deposited in the calorimeter within signal definition
E^{loss}_{mag}	charged particle energy lost in solenoid field
E^{loss}_{low}	particle energy lost in dead material
E^{loss}_{leak}	energy lost due to longitudinal leakage
E^{loss}_{out}	energy lost due to jet algorithm/calorimeter signal definition
$E^{gain}_{UE \otimes PU}$	energy added by underlying event and/or pile-up
E^{gain}_{env}	energy added by response from other nearby particles/jets

only source of signal!

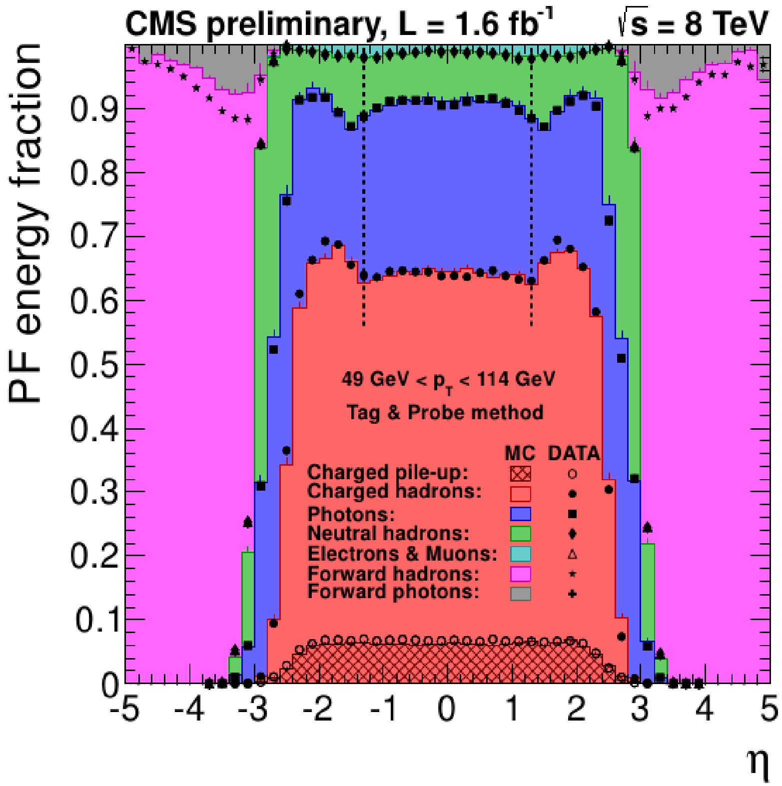
ATLAS EXPERIMENT PARTICLE FLOW DETAILS

Aim: reconstruct all particles in the collisions (!), feed them to jet algorithm
→ exploit all information from all subdetectors

Make a list of "elements":
tracks, energy deposits, muons

Associate elements together, each element is a particle:
e.g. extrapolate tracks to calorimeter, find corresponding cluster
→ charged hadron

For each particle, optimally combine information from various subdetectors:
e.g. charged hadrons: use more precise tracker when possible



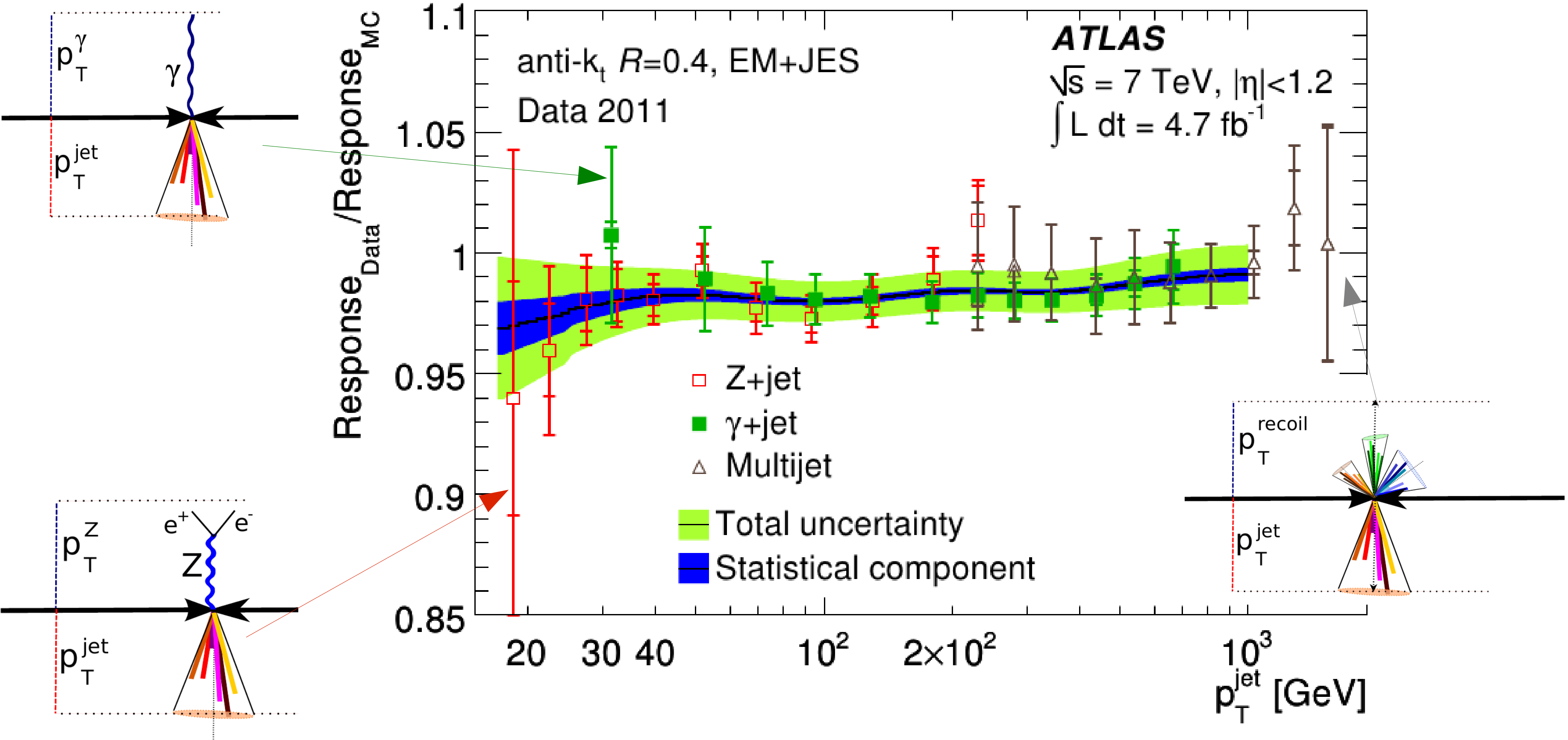
Improvements in reconstruction efficiency, resolution wrt using calorimeter alone

IN-SITU CALIBRATION

Use **well-measured objects** to **check the scale** of the **calibrated jets**

Compare balance in data and MC → combine, correct for differences

Alternative: *absolute* calibration, but e.g. theoretical uncertainties are a problem



ATLAS EXPERIMENT IN-SITU CALIBRATION

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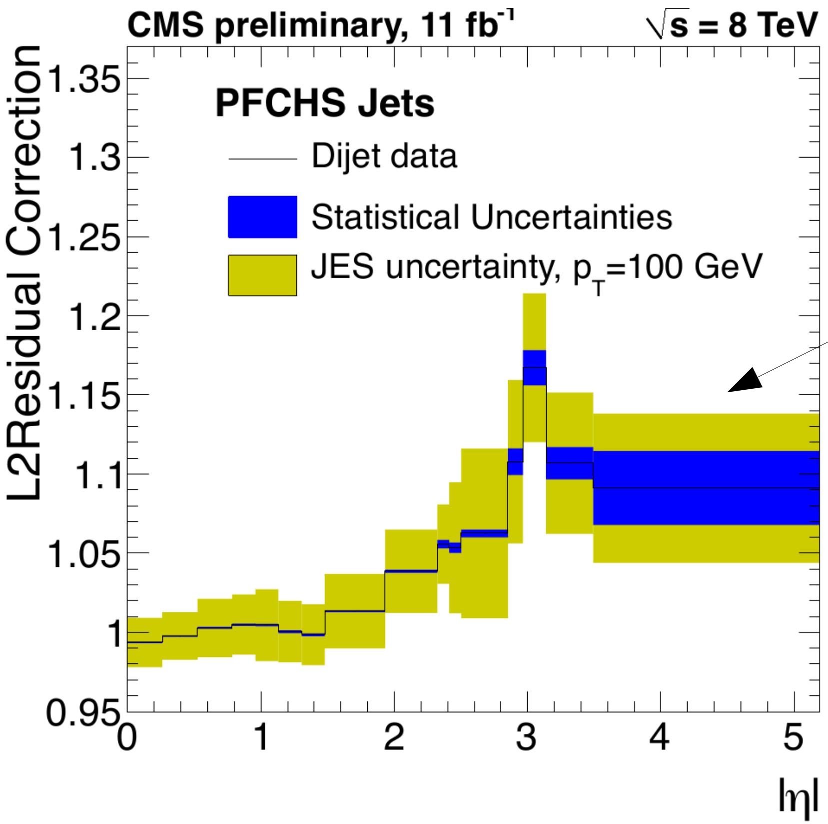
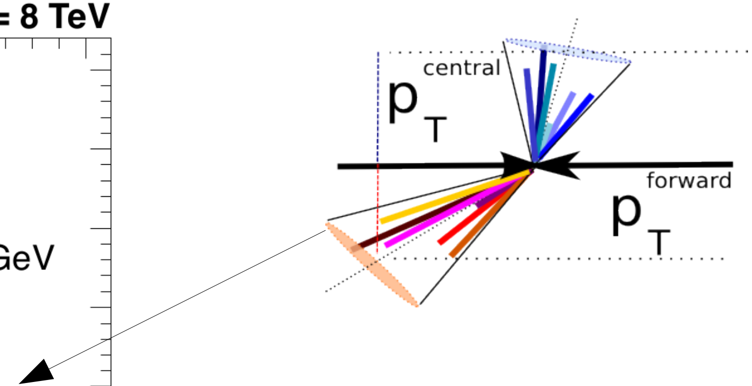


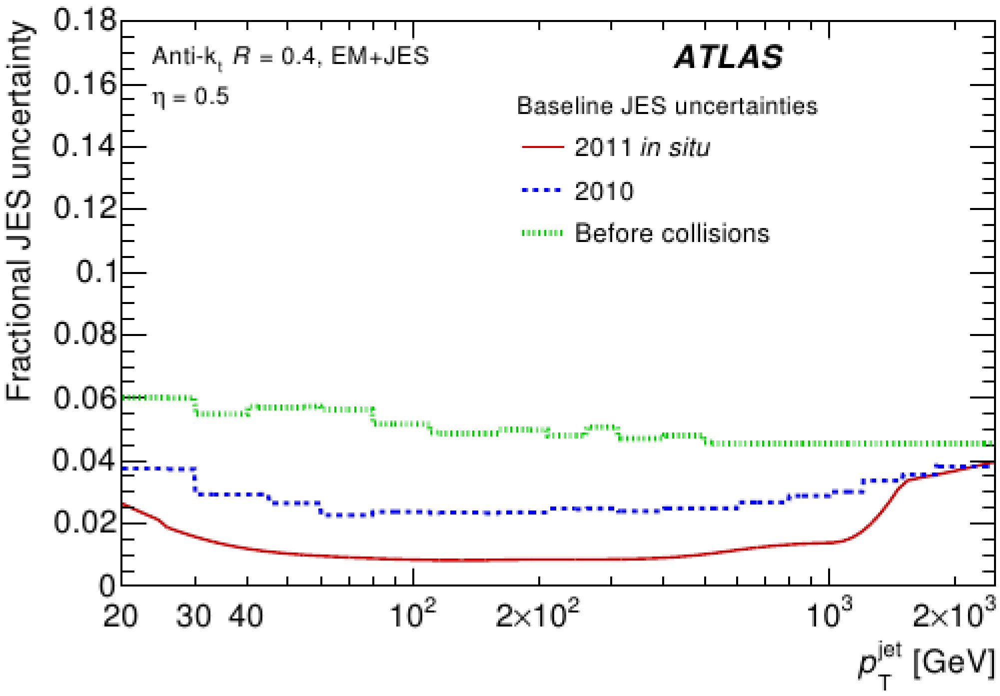


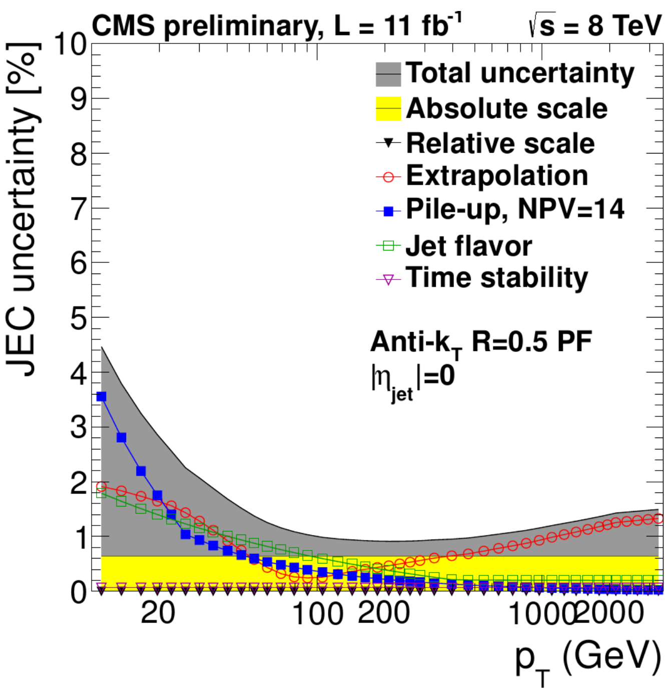
JET ENERGY SCALE UNCERTAINTY

How well do we know the energy of a jet?

→ **systematic uncertainty** on the **jet energy scale**

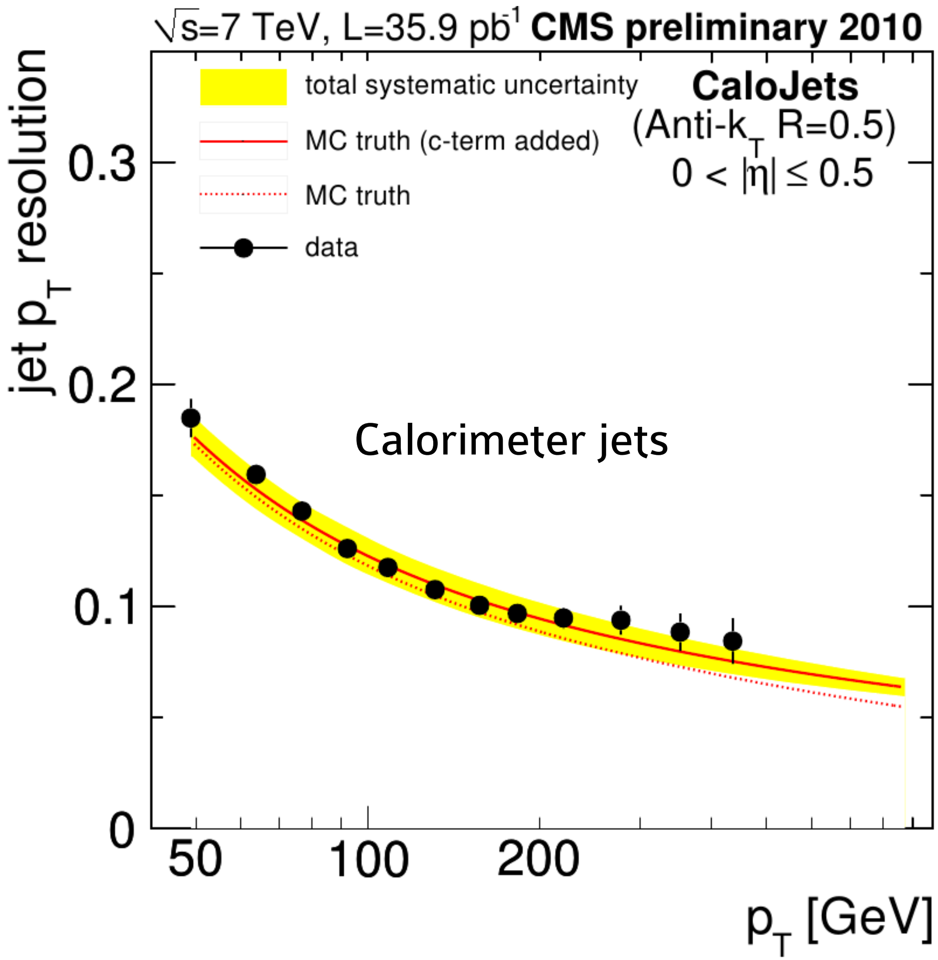
Milestone of **1% "baseline" JES uncertainty** reached by ATLAS and CMS **after 1 year of data**

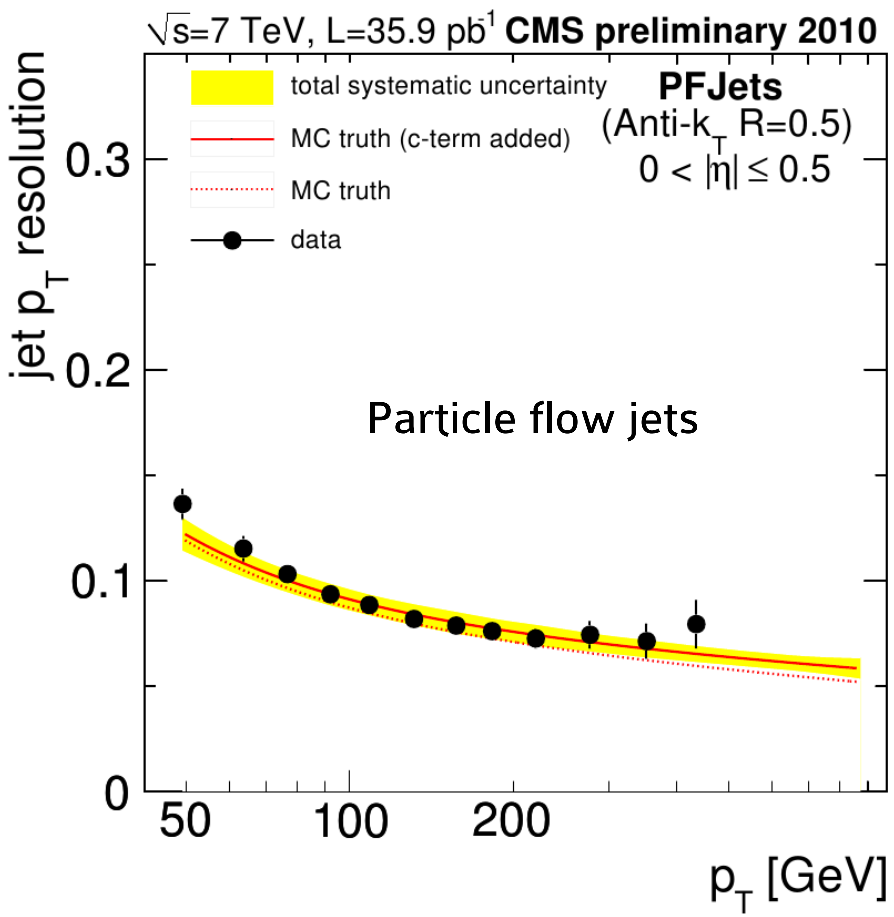




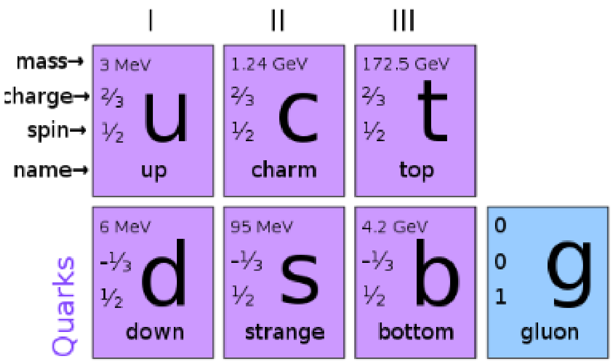
JET ENERGY RESOLUTION AND ITS UNCERTAINTY

How well do we calibrate jets → **jet energy resolution**





QUARK/GLUON/HEAVY FLAVOR DISCRIMINATION



Different properties of quark initiating the jet
→ different properties/performance of jets

Can we distinguish them? Yes

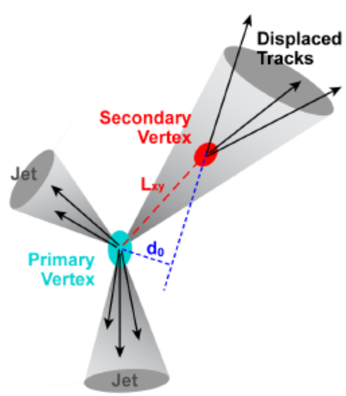
1. light quark vs gluon jets
2. light vs heavy flavor jets

Useful for physics analysis (signal vs background)

b-tagging:

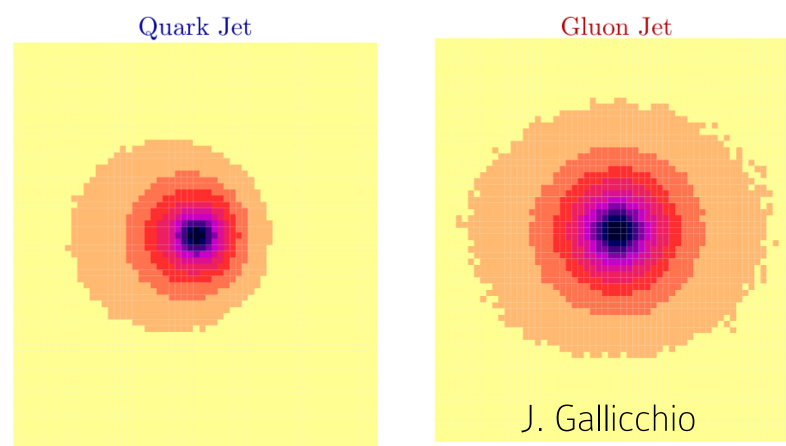
Exploit long lifetime of b-hadrons:
- reconstruct secondary vertex
- use track impact parameters

Sketch from D0 single top public page



quarks and gluon tagging:

Exploit different fragmentation:
- gluon jets wider than quark jets
- more charged particles for gluon jets



5' for questions up to here

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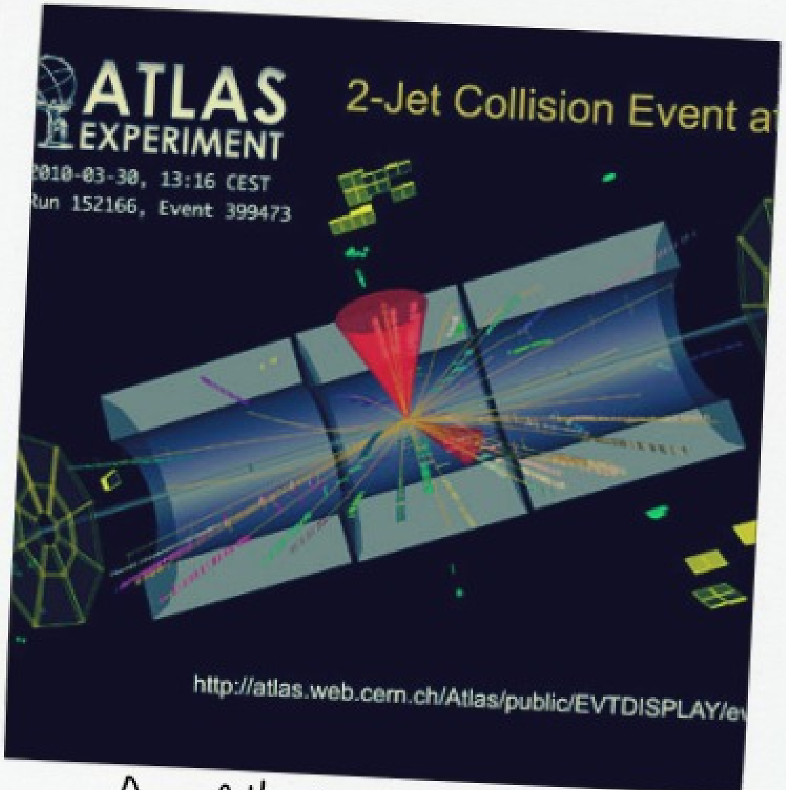
ATLAS EXPERIMENT



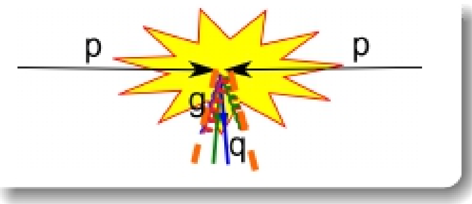
One of the first dijet events observed in ATLAS

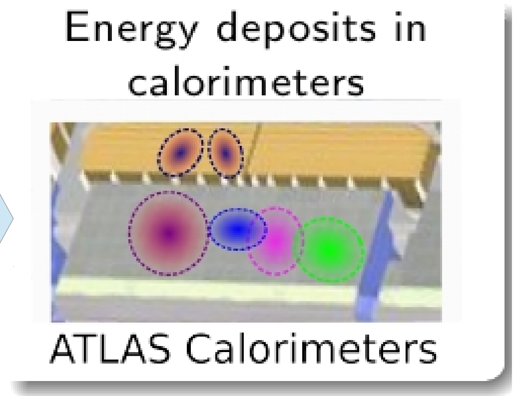
3 - SEARCHES AND MEASUREMENTS WITH JETS

22/07/2014 – HASCO Goettingen

EXPERIMENTAL JETS, PART 3: JET MEASUREMENTS AND SEARCHES

Only a tiny fraction shown today





(note: this did not happen yet)

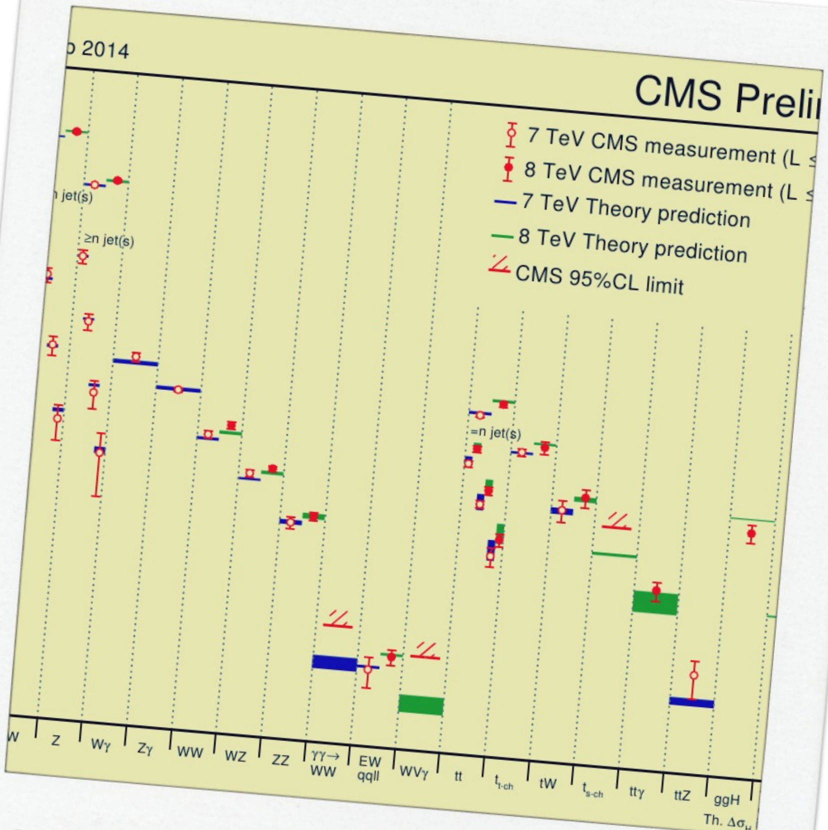
Outline

Measurements of jets

- Inclusive jet/dijet cross section
- Three jet cross section
- Top mass measurement

Jet searches

- Dijet resonance search
- Dark matter searches:
  - mono-jet
  - mono-W

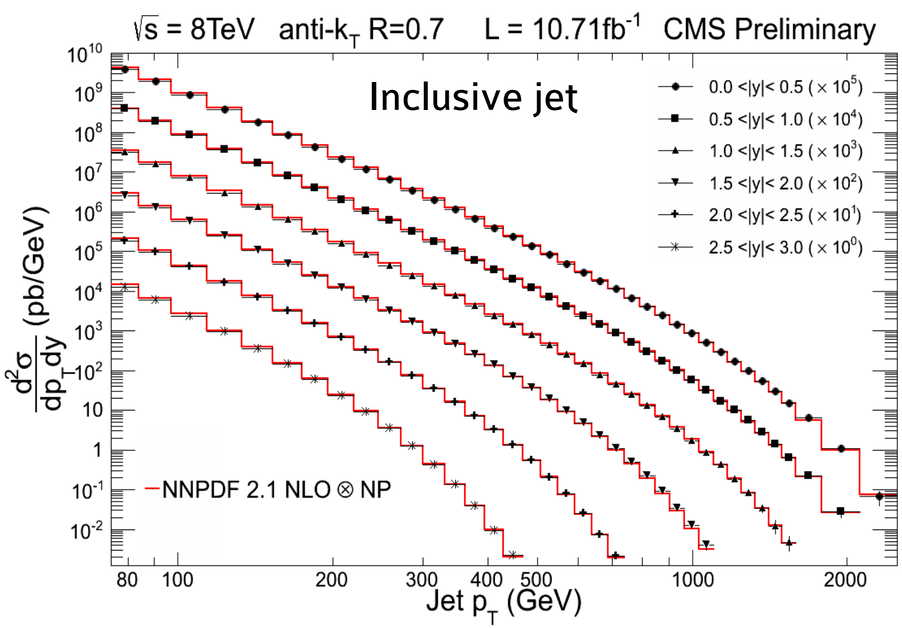


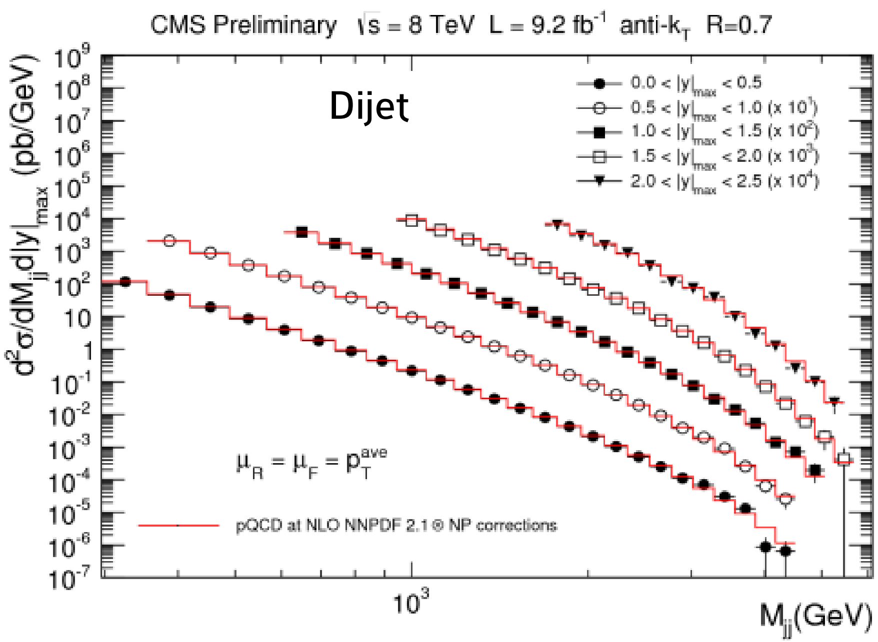
The Standard Model as seen by CMS

3.1 – MEASUREMENTS WITH JETS

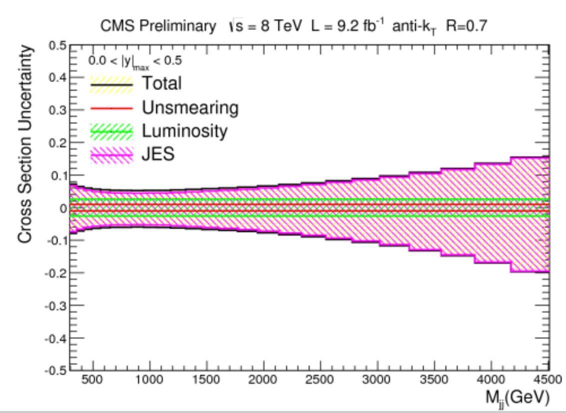
THE INCLUSIVE JET/DIJET CROSS SECTION

Measure **cross section of jet events** as a function of jet pT and rapidity
Measure **cross section of dijet events** as a function of invariant mass and separation





JES/JER uncertainty:
main experimental systematics



THE INCLUSIVE JET/DIJET CROSS SECTION

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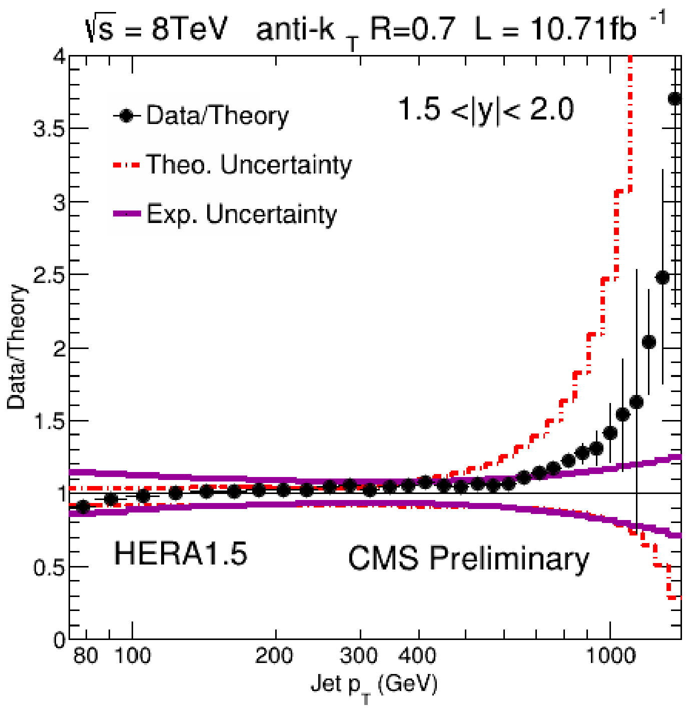
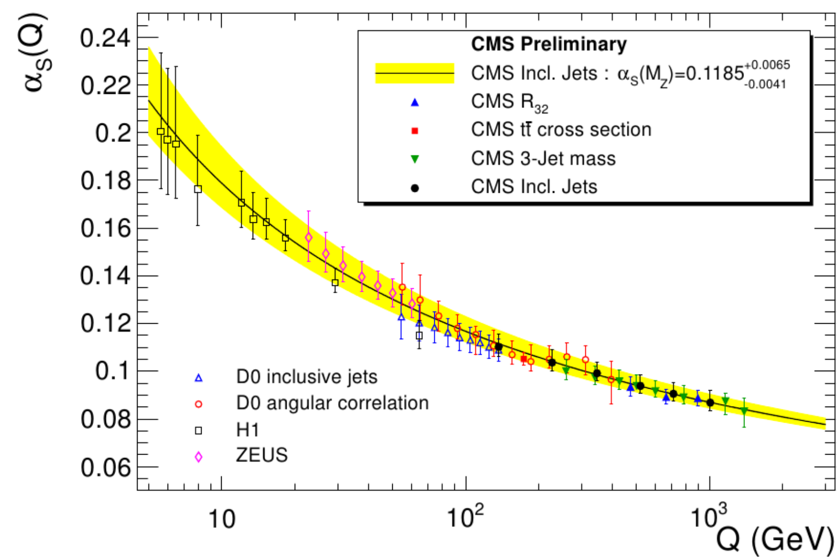
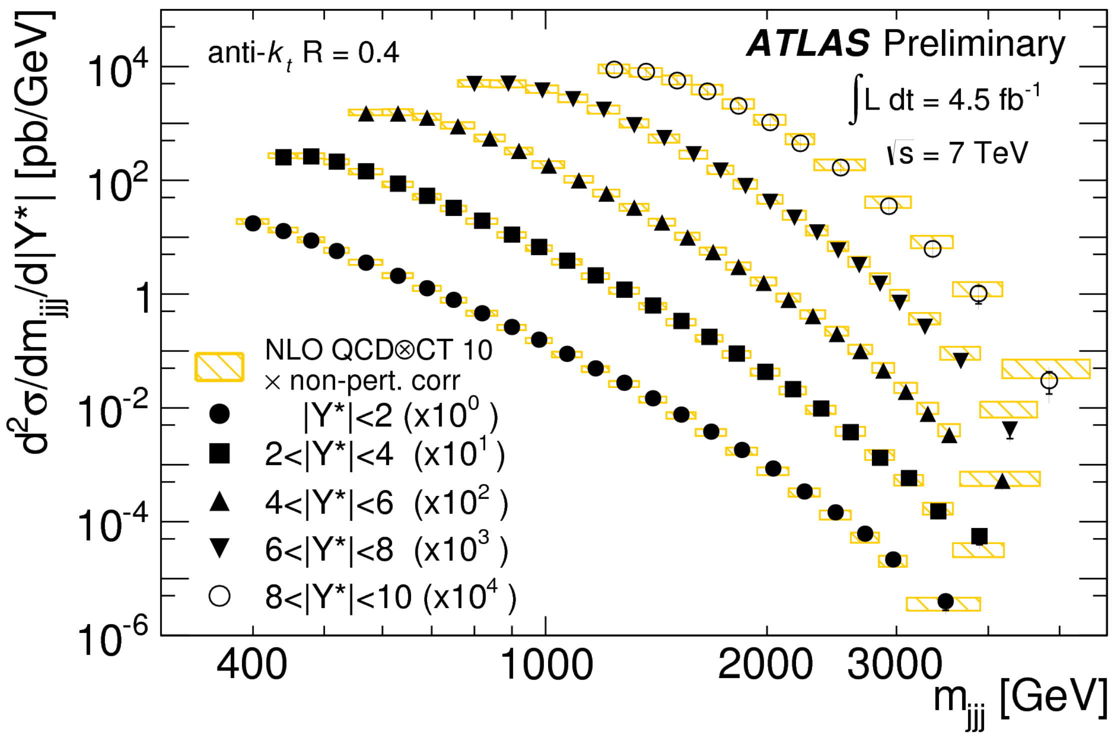


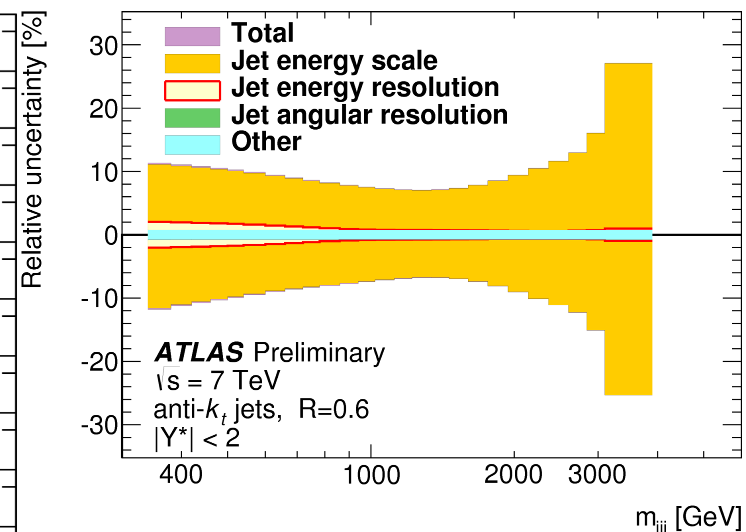


Measurements can **constrain theory:**
help determination of **strong coupling constant** and **parton distribution functions**

THREE JET CROSS SECTION

Measure **cross section of three-jet events** as a function of **invariant mass of three leading jets** and their **separation**



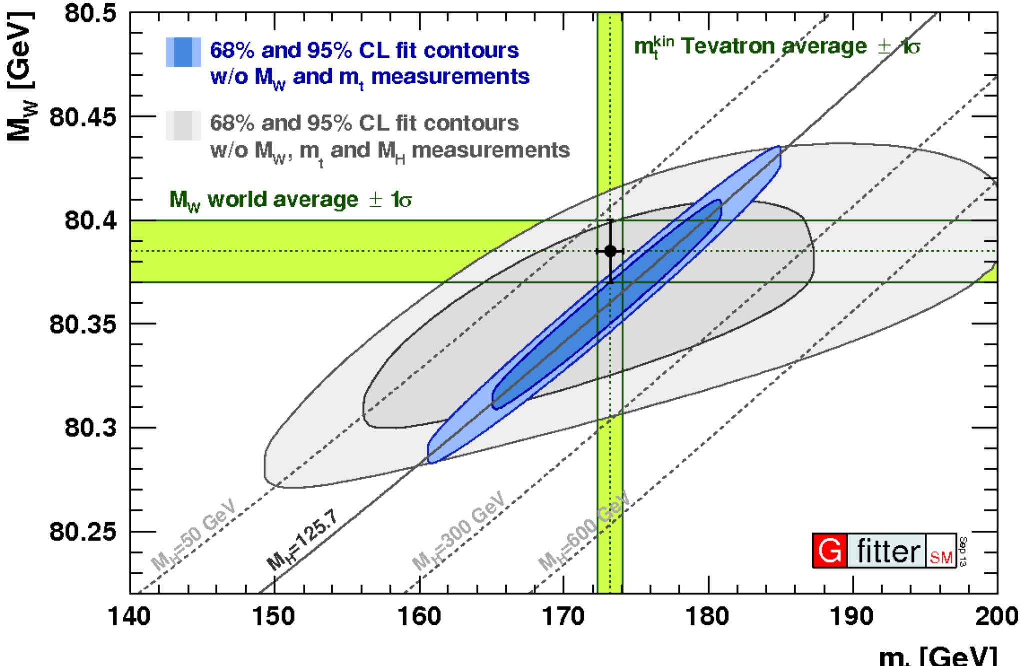


JES/JER uncertainty:
main experimental systematics

Measurement will be useful to check and improve parton distribution function fits

ATLAS EXPERIMENT TOP QUARK MASS

- LHC: top factory → surpass Tevatron statistics
- Top quark crucial to understand consistency of SM parameters (link between H, W and top mass)
    - Implications on New Physics constraints



JES uncertainty: one of the main experimental unc.
knowing the JES well → knowing the top mass well!

LHC/Tevatron NOTE

ATLAS-CONF-2014-008
CDF Note 11071
CMS PAS TOP-13-014
D0 Note 6416

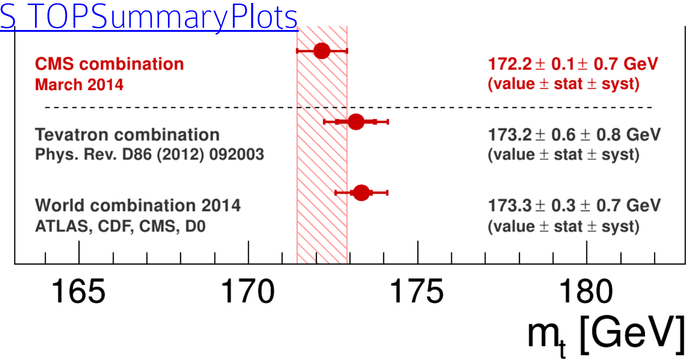
March 17, 2014

http://arxiv.org/abs/1403.4427

First combination of Tevatron and LHC measurements of the top-quark mass

M_{top} = 173.3±0.3(stat)±0.7(syst) GeV

CMS TOPSummaryPlots

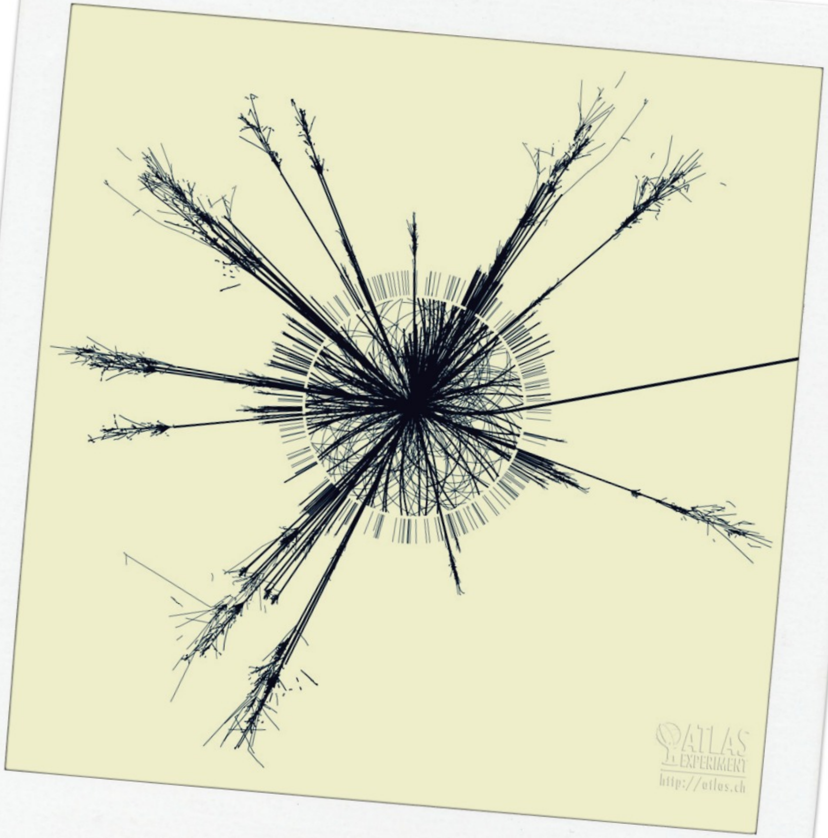


M_{top} = 172.2±0.1(stat)±0.7(syst) GeV

http://arxiv.org/abs/1405.1756 FERMILAB-PUB-14-123-E

Precision measurement of the top-quark mass in lepton+jets final states

M_{top} = 175.0±0.6(stat)±0.5(syst) GeV



A simulated black hole event in ATLAS

3.2 - SEARCHES WITH JETS

22/07/2014 – HASCO Goettingen

ATLAS EXPERIMENT DIJET "BUMP SEARCH"

Jets: most copiously produced high-pT objects at the LHC
→ new physics could show up early in jet signatures

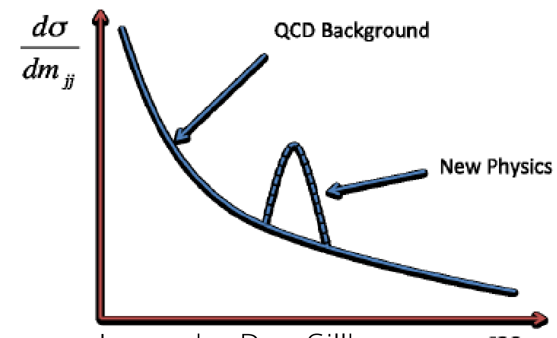
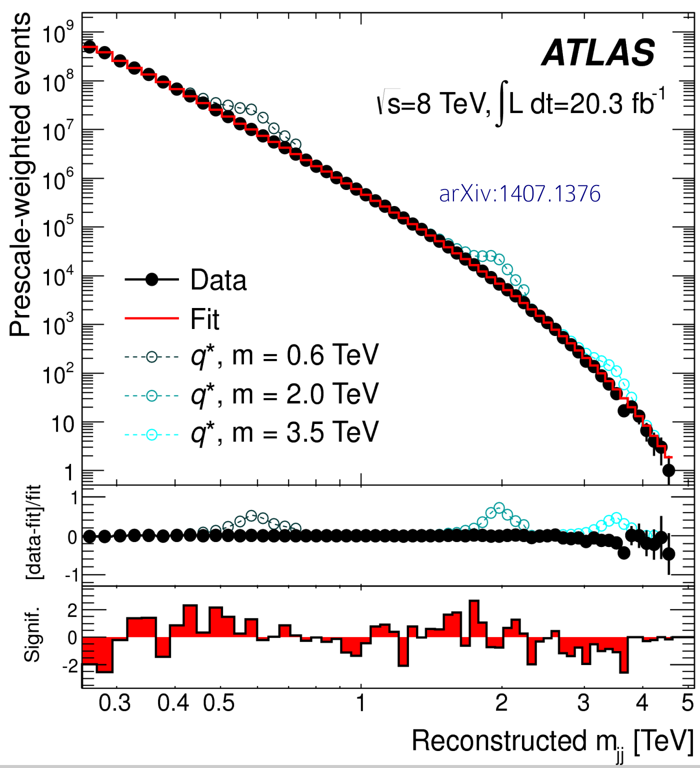


Image by Dag Gillberg

New particles → new resonances

If resonance decays hadronically:
Bump in the **invariant mass spectrum** of two central, leading jets



Background estimation: **smooth fit to data**

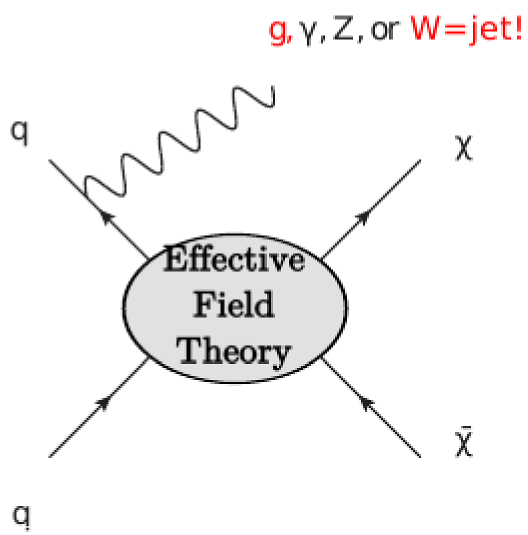
Crucial to have **jet performance** under control to discover new particles!

No evidence of signal →
constraining TeV-scale masses for many new particles

ATLAS EXPERIMENT Search for monojets/mono-W

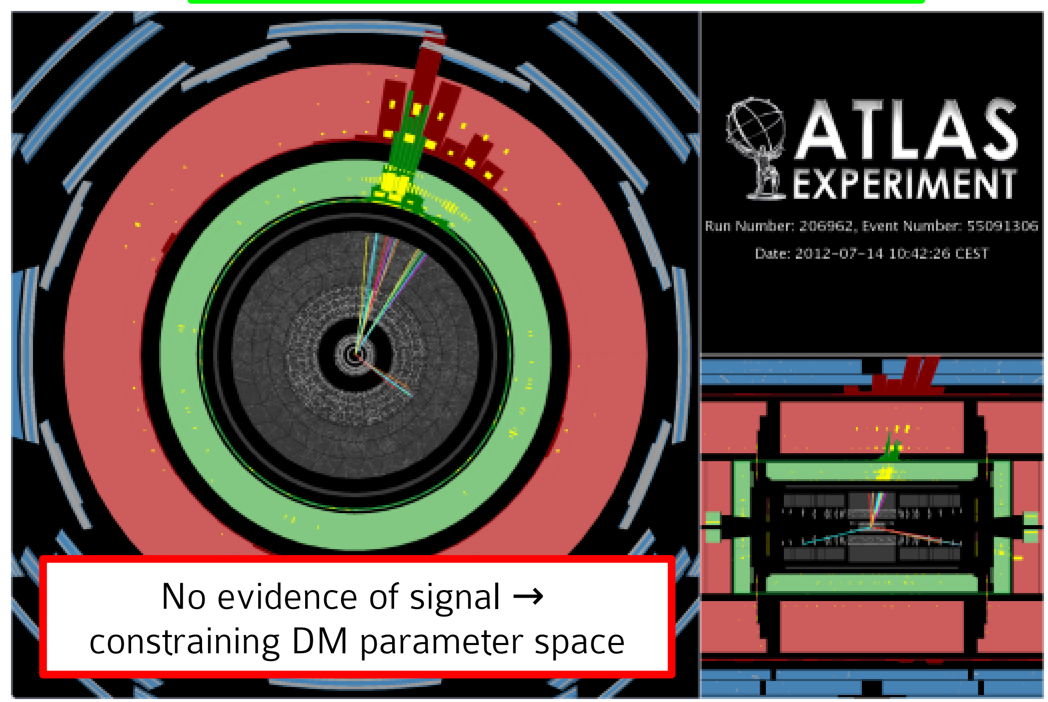
From cosmological and astroparticle experiment observations:

≈ 95% of the universe is (directly or indirectly) evident but unexplained:
dark matter and **dark energy**



LHC experiments have a shot at finding a particle candidate for **dark matter**:
dark matter interacts gravitationally ⇒ could it interact **weakly**?

Mono-jet: look for excess of jets with high pT, high missing transverse momentum
(after careful jet identification!)

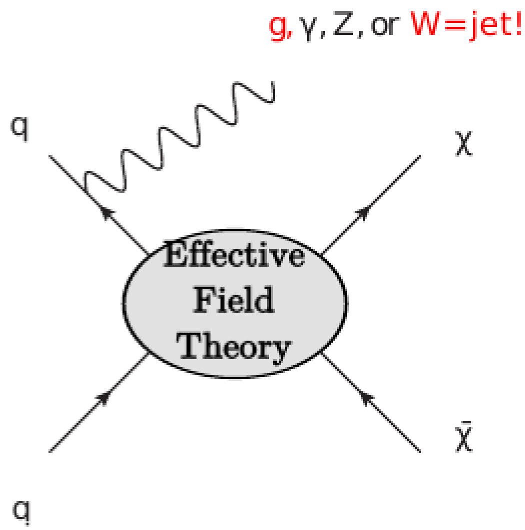


No evidence of signal → constraining DM parameter space

ATLAS EXPERIMENT SEARCH FOR MONOJETS/MONO-W

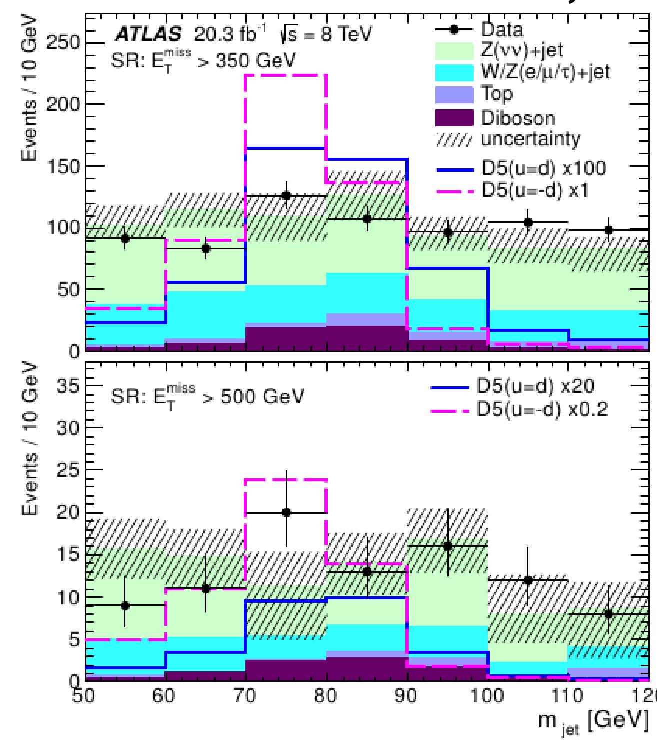
From cosmological and astroparticle experiment observations:

$\approx$ 95% of the universe is (directly or indirectly) evident but unexplained:
dark matter and **dark energy**



LHC experiments have a shot at finding a particle candidate for **dark matter**:
dark matter interacts gravitationally $\Rightarrow$ could it interact **weakly**?

Mono-W: use fat. groomed jets (C/A BDRS) to reconstruct the entire W decay into a jet



No evidence of signal → constraining DM parameter space

5' for questions up to here

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FACULTÉ DES SCIENCES

ATLAS EXPERIMENT

4. LET'S RECAP EVERYTHING FOR TODAY

22/07/2014 – HASCO Goettingen

JET ALGORITHMS AND CALORIMETERS

Jet algorithms

Most used jet algorithm at the LHC: Anti-kT
No perfect jet algorithm/perfect set of parameters, as long as theoretically safe
Use *fat jets* when objects are boosted and their decay products are collimated

Calorimeters

Basic principles:

- exploit interactions of particle with matter. Try to stop particle: energy release → detection and measurement
- hadronic and electromagnetic showers: differences
- hadronic and electromagnetic calorimeters: differences

ATLAS and CMS calorimeters: design → inputs to jet algorithms
The influence of pile-up: extra energy (not always), corrected for offline
Calorimeter leakage (punch-through): influence on response (mean) and resolution (width of the distribution E_{reco}/E_{true})

ATLAS EXPERIMENT Jet calibration and performance

Concepts of jet calibration and performance

In-situ techniques: test JES and JER using well-calibrated objects balancing jet
Missing transverse momentum, affected by deterioration in JER
Jet identification: check timing, EM energy fraction, number of tracks of jet...to be sure!

Jet calibration in action: ATLAS and CMS

Formation of jets in ATLAS and CMS: topocluster jets vs particle flow jets
Pile-up subtraction: first step event-based, then overall correction
JES calibration: compensate the calorimeter with software
Details on JES calibration:
- Topocluster calibration
- Particle-flow formation

Jet performance and Jet Energy Scale

Measurements and searches with jets

Measurements with jets

Inclusive jet / dijet cross section, three-jet cross section ↔ Importance of understanding experimental performance to compare with theory (and improve it)

Top mass measurement ↔ JES uncertainty main experimental uncertainty,
need to reduce / take care of correlations in combination

Searches with jets

Dijet resonance search ↔ "smooth" JES assumption in background estimation
Mono-jet search ↔ jet identification and removal of fakes crucial
Mono-W search ↔ use substructure technique to select jets containing W boson

Thanks for your attention! + resources

For any questions: find me around or via e-mail
caterina DOT doglioni AT cern DOT ch

Simple overview of calorimeters
http://dorigo.wordpress.com/2008/04/06/calorimeters-for-high-energy-physics-experiments-part-1/
Lectures on detectors and calorimeters
http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/
http://atlas.physics.arizona.edu/~loch/HFSL_spring2010.html
LHC detector papers
http://jinst.sissa.it/LHC/
CMS JES paper
http://iopscience.iop.org/1748-0221/6/11/P11002/
ATLAS JES paper
http://arxiv.org/abs/1406.0076
CMS public jet/MET results
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME
ATLAS public jet/MET results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissPublicResults
CMS Standard Model results on jets
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP#Jet_Production
ATLAS Standard Model results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Jet_Physics
CMS Exotica results
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
ATLAS Exotics results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults