Measurement of the associated production of direct photons and jets with the Atlas experiment at LHC

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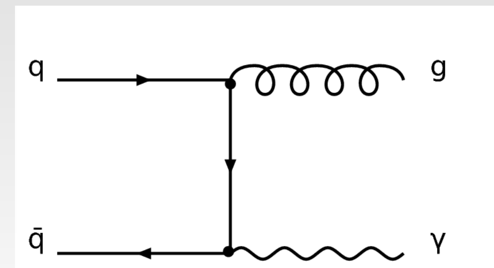
Outline

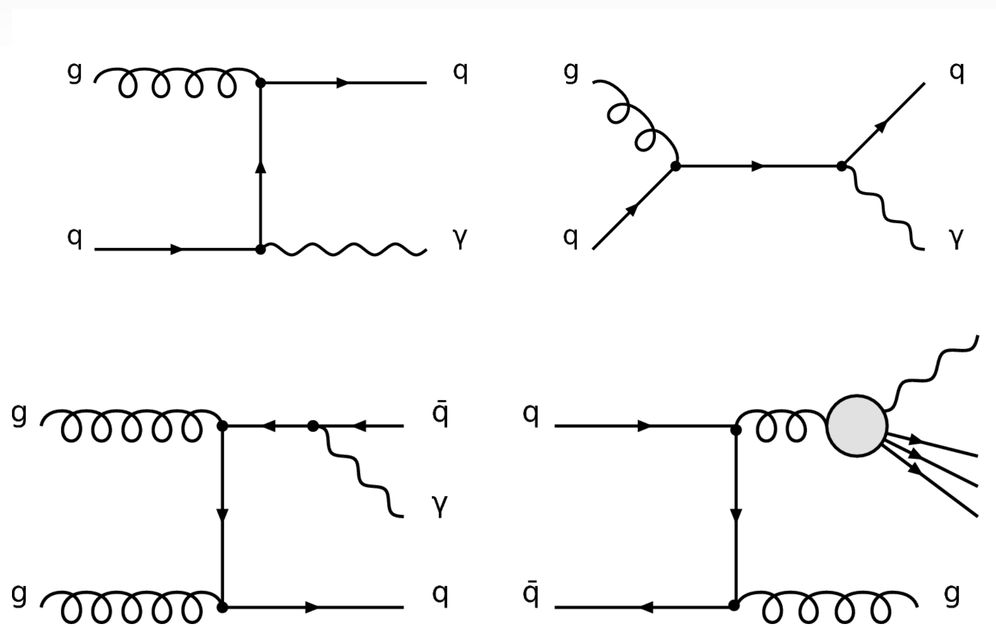
- Introduction
  - The direct photon channel
  - The Atlas experiment
  - Jets at Atlas
- Calorimeter response to hadrons
  - The TileCal stand-alone test beam
  - Validation of the Monte Carlo simulation
- Photon + Jet physics
  - Measurement of the associated production cross section
  - Validation of the jet calibration in Atlas

The direct photon channel

The direct photon channel

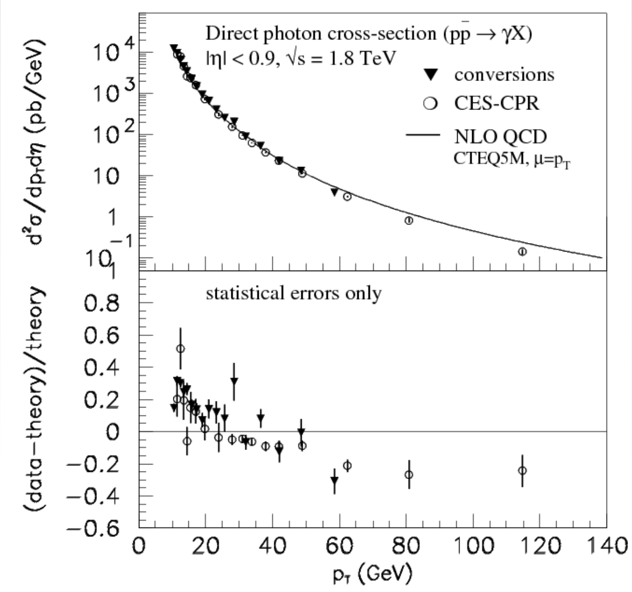


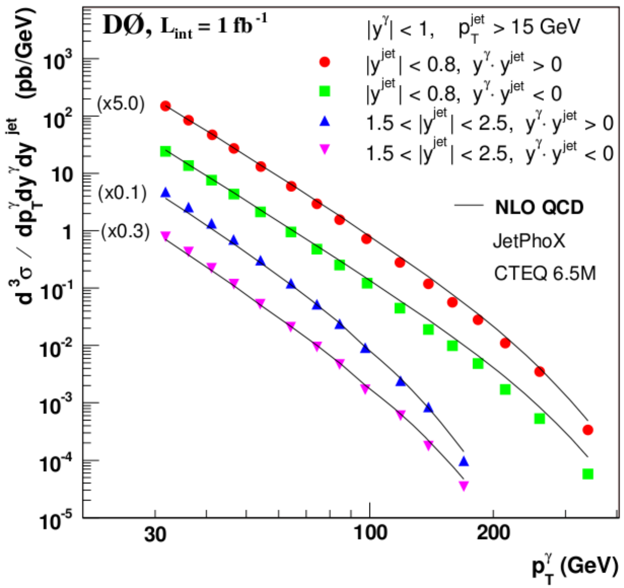
- Final state photons at p-p colliders
- 2 $\alpha\alpha_s$ diagrams
  - $q\bar{q}$ annihilation (~10%)
  - “Compton” scattering (~90%)
  - Bremsstrahlung



The direct photon channel

- Direct photon production in hadronic interactions observed for the first time at ISR
- Latest measurements at Tevatron: CDF (inclusive cross section) and D0 (jet-photon relative direction)
- Both experiments use transverse momentum balancing to set or validate the jet energy scale
- σ (LHC@7TeV)=6xσ(Tevatron)



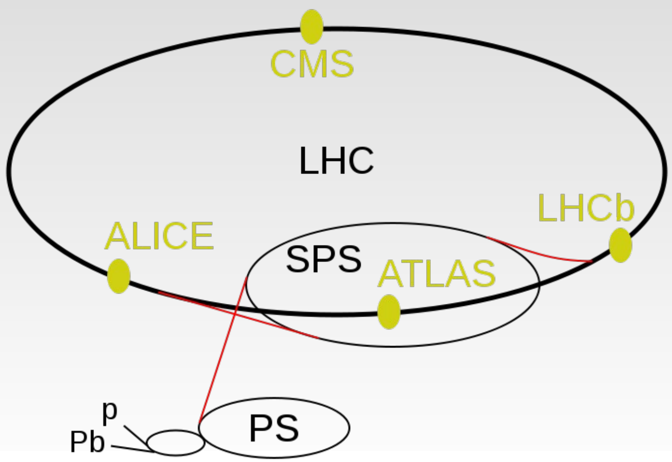


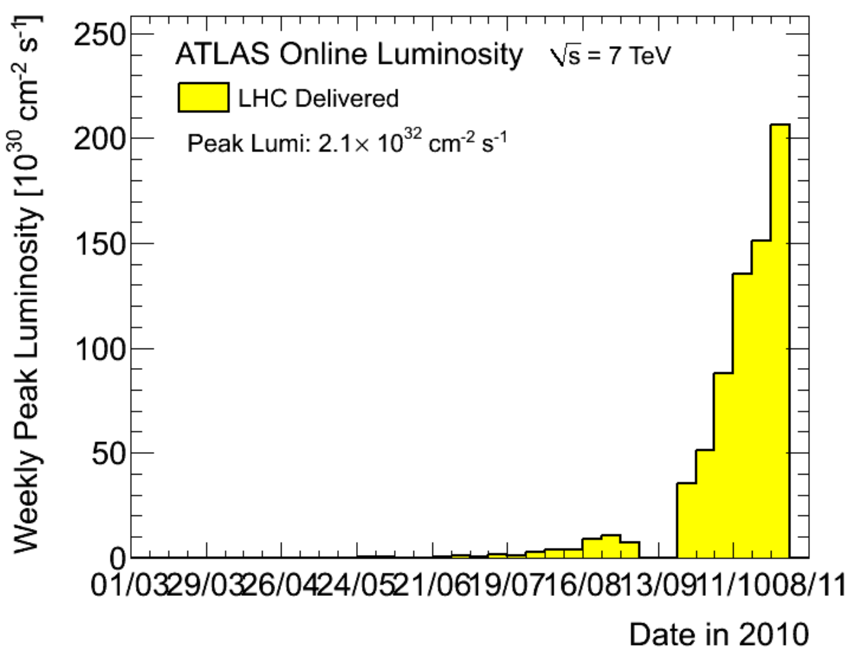
Summary

- Very interesting physics channel
- Backgrounds for many new physics searches
- Direct access to gluon PDF
- Transverse momentum balancing can be used in jet calibration

The LHC accelerator and the Atlas detector

The LHC accelerator





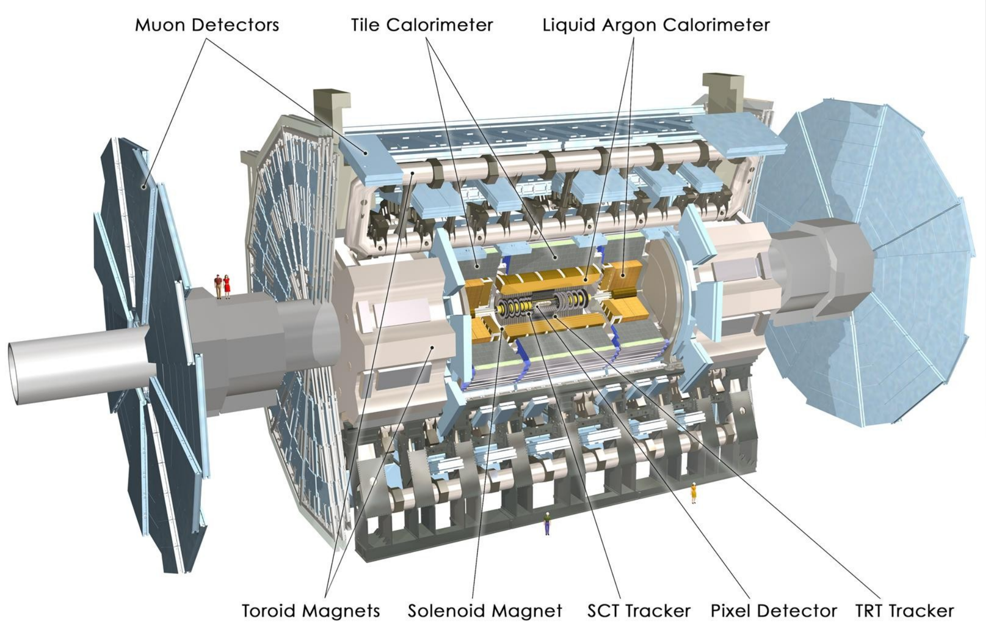
Parameters	
Design c.m. energy (TeV)	14
Current c.m. Energy (TeV)	7
Design bunch spacing (ns)	25
Current bunch spacing (ns)	50
Protons per bunch	10^{11}
2010 peak luminosity ($cm^{-2}s^{-1}$)	10^{32}
2011 peak luminosity ($cm^{-2}s^{-1}$)	10^{33}
Design luminosity ($cm^{-2}s^{-1}$)	10^{34}
Luminosity lifetime (h)	10

The Atlas experiment

- Central solenoidal B field (2T) + external toroidal B field (max 4T)
- Muon spectrometer
  - MDT/CSC
  - RPC/TGC (trigger)

$|\eta| < 2.7$

$\frac{\Delta P_T}{P_T}(P_T = 1 \text{ TeV/c}) = 10\%$



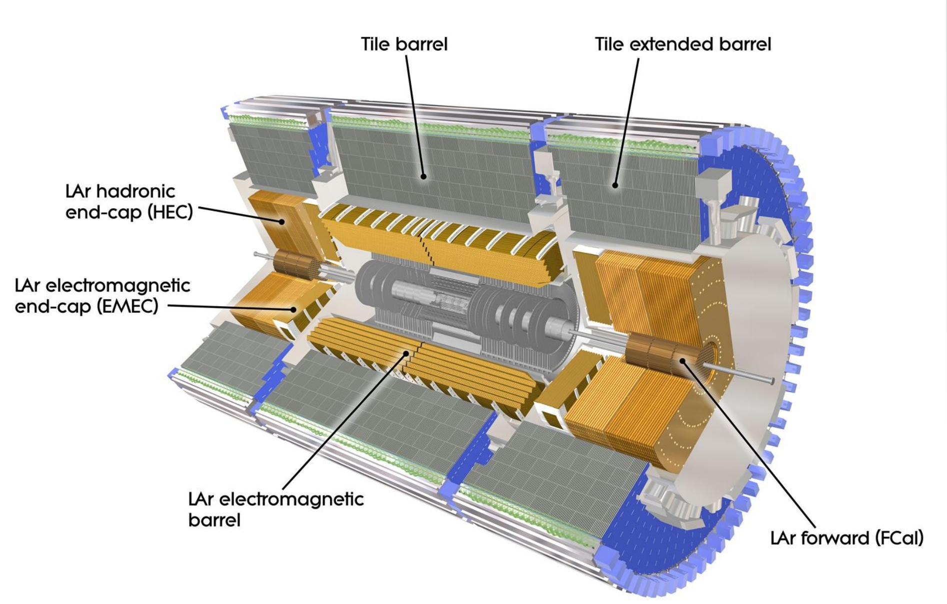
- Central tracker

$|\eta| < 2.5$

$\frac{\Delta p_T}{p_T}(p_T = 100 \text{ GeV}) = 4\%$

The Atlas calorimeters

	EM Barrel	TileCal
Tech.	Cu/LAr	Fe/sci.
coverage	$\|\eta\| < 1.4$	$\|\eta\| < 1.3$
Min. depth	24 X_0 (~1λ)	9 λ
$\Delta\eta \times \Delta\phi$ (mid.)	0.025 x 0.025	0.1 x 0.1
σ (E=100 GeV)	1.2%	6%
Linearity	0.2%	1%
Uniformity	0.5%	2.4%
e/h	1.5	1.36



	EndCap	Forward
tech	Cu/LAr	Cu-W/LAr
coverage	$1.4 < \|\eta\| < 3.2$	$3.1 < \|\eta\| < 4.9$
Min. depth	~20 X_0 + 9 λ	9.5 λ
$\Delta\eta \times \Delta\phi$ (mid.)	0.025 x 0.025	0.2 x 0.2

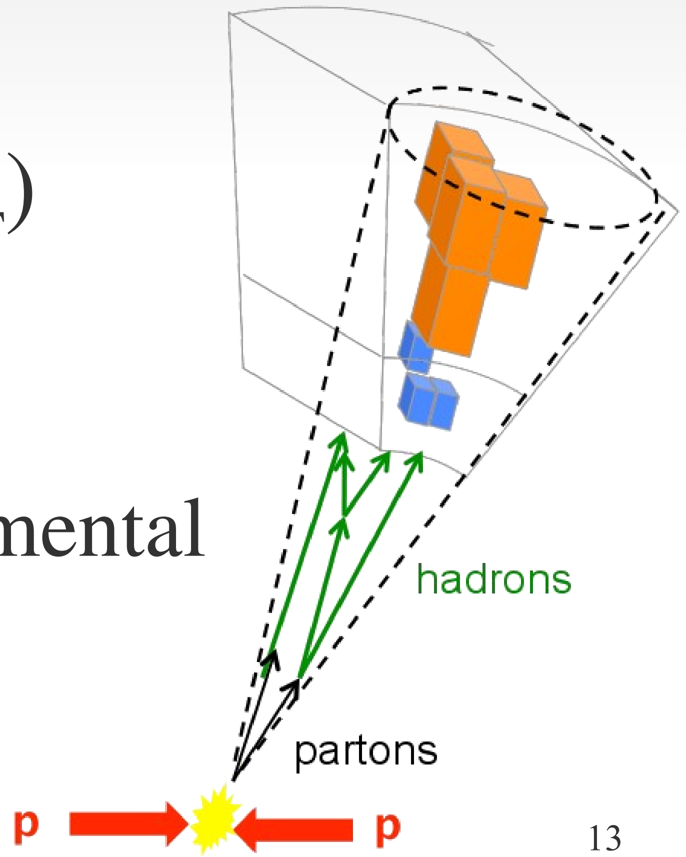
Summary

- Atlas is a general purpose experiment at LHC
- Precision SM measurements
- Discovery: Higgs and beyond
- Calorimeters:
  - Good energy resolution and linearity for em and hadronic particles
  - Non compensating → need calibration procedure to correctly measure jet energy

Jets at Atlas

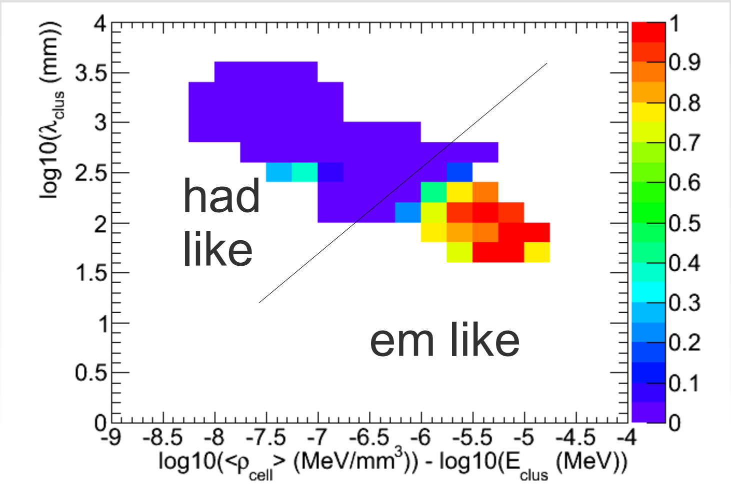
Jet algorithms

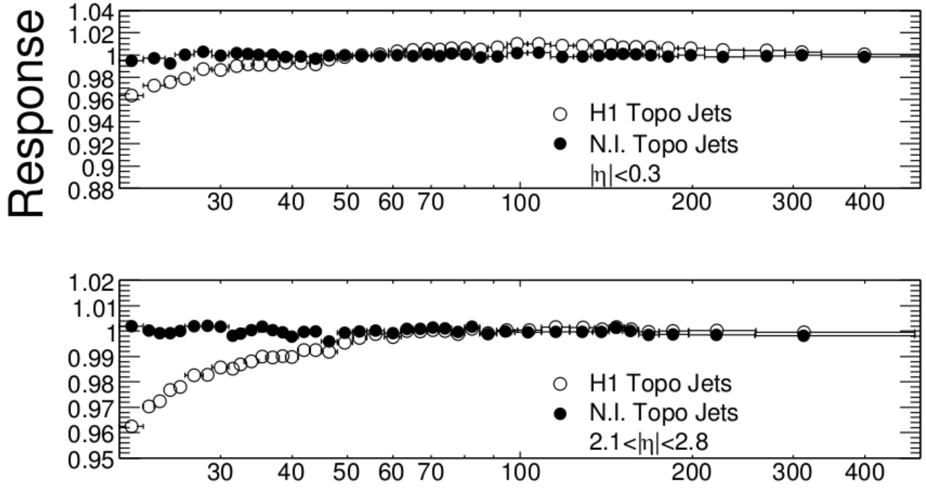
- A jet is a collection of four vectors (MC particles, calorimeter topo-clusters)
- Algorithms: Iterative cones, sequential recombination (k_T)
- Anti-k_T (R= 0.4 – 0.6)
  - Good theoretical and experimental properties



Jet calibration

- Reference energy: particle jet (jet reconstructed on MC final state)
- Non compensating calorimeters, out-of-cone, dead material, UE...
- Calibration methods:
  - Jet Energy Scale
  - Global Cell Weights
  - Local Cell Weights





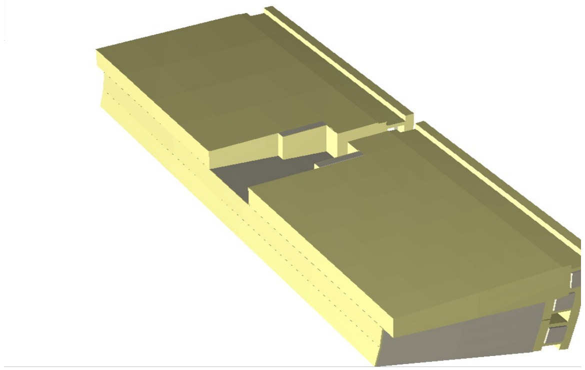
The TileCal stand alone test beam

Motivation

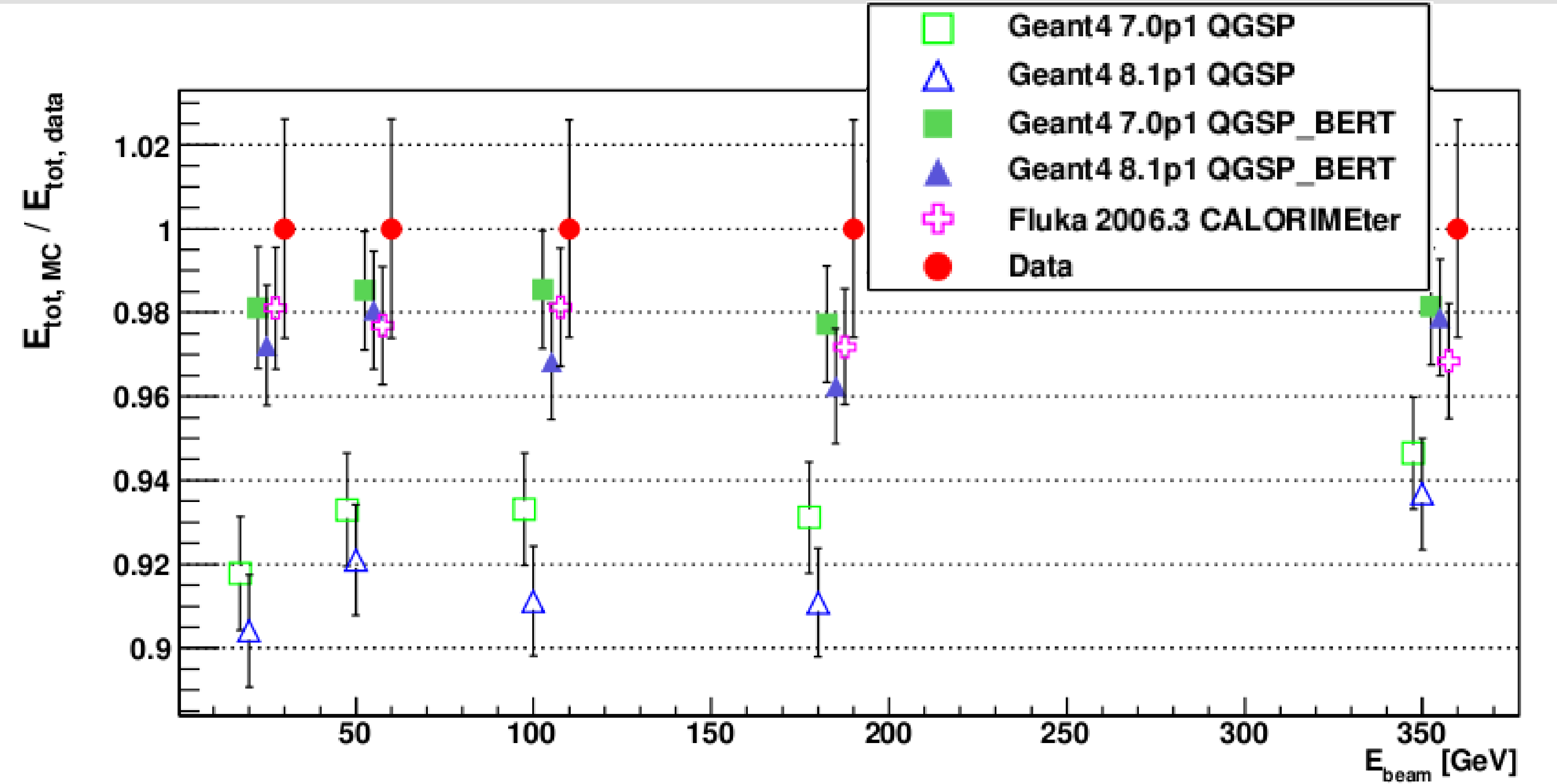
- The response of a calorimeter to hadrons (and jets) is non-linear because of non compensation
- A (Monte Carlo based) calibration procedure is needed to recover linearity and improve resolution
- MC simulation is tuned and validated against test beam measurement

The TileCal stand alone test beam

- TileCal stand alone test beam
  - e, μ, π (E = 20 – 350 GeV)
- Validation of the Geant4 and Fluka MC simulations
  - Geant4 v7.0 e v8.1 (QGSP e QGSP_BERT)
  - Fluka 2006.3 CALORIMEter
- π, p at θ = 20° (η~0.35)



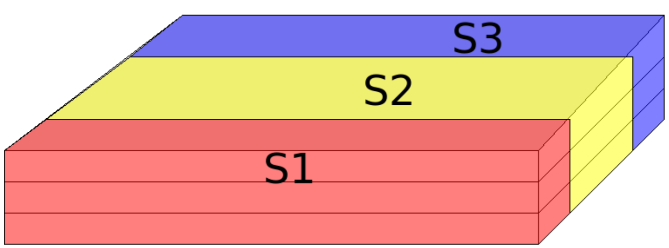
Calorimeter response and resolution

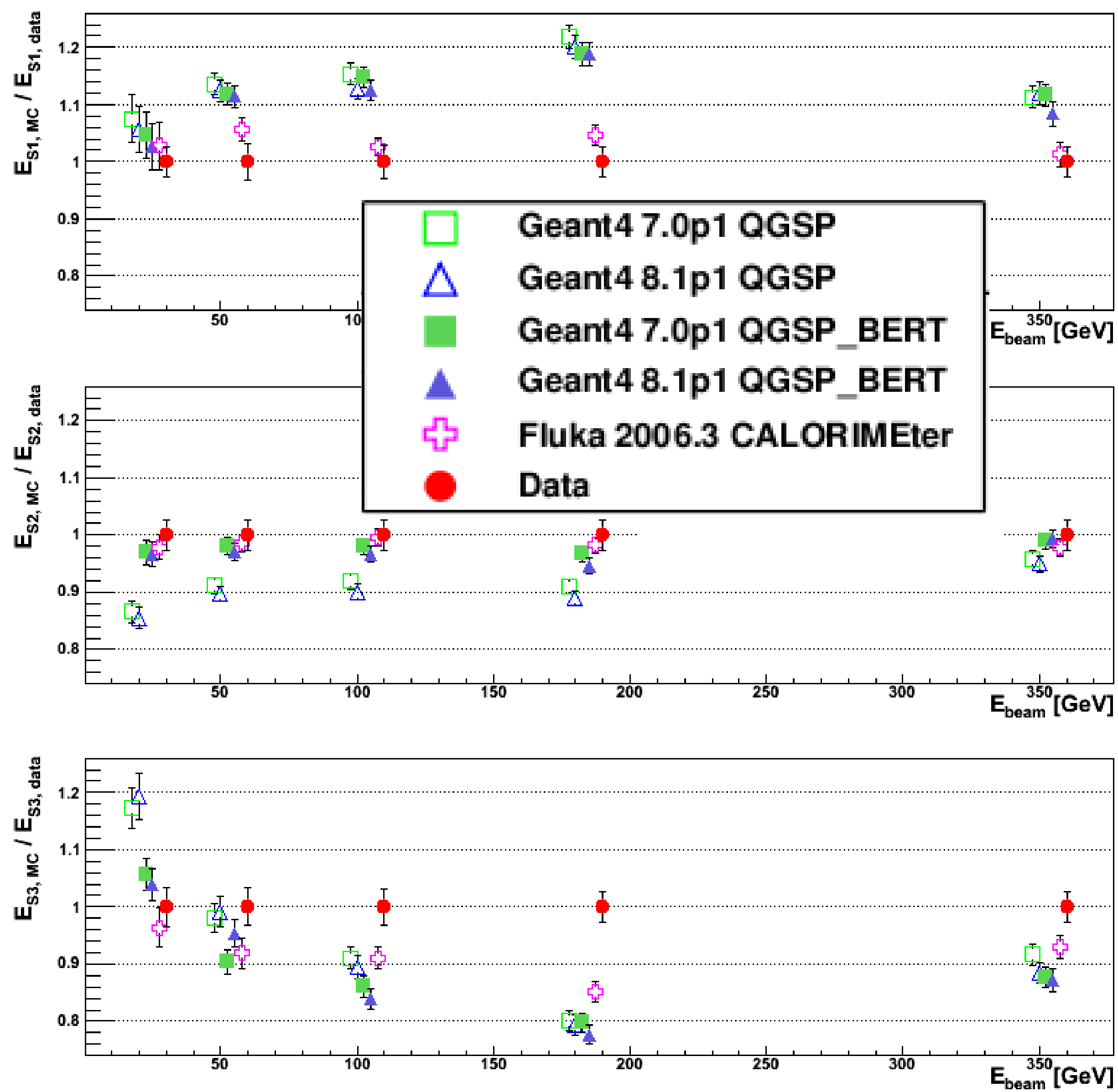


- Good results for Fluka and Geant4 with the Bertini cascade

Longitudinal and lateral shower shape

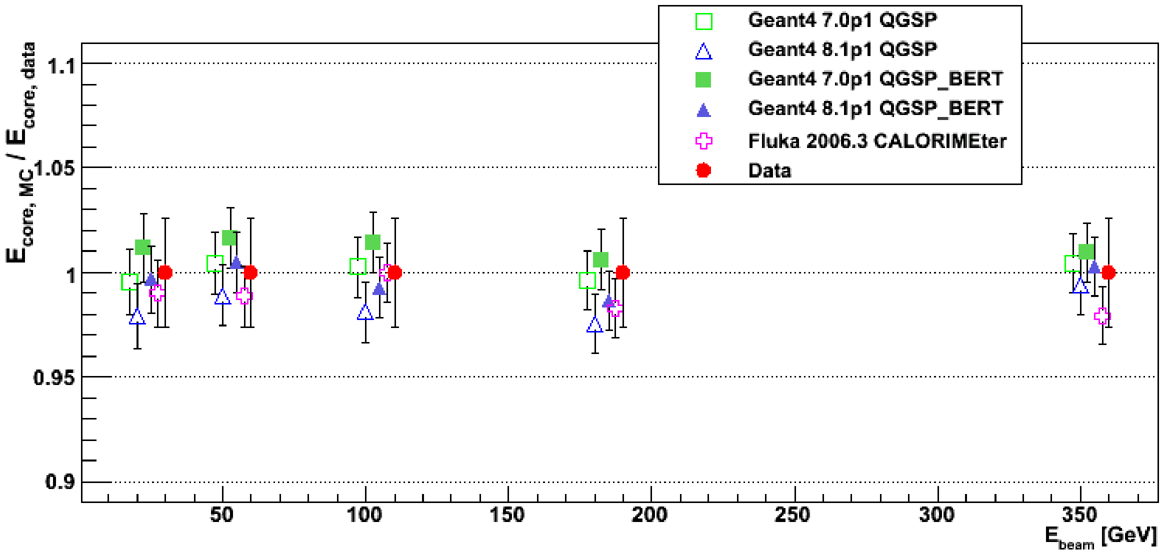
- Geant4 showers develop too early
- Bulk is ok
- All MC showers are too short

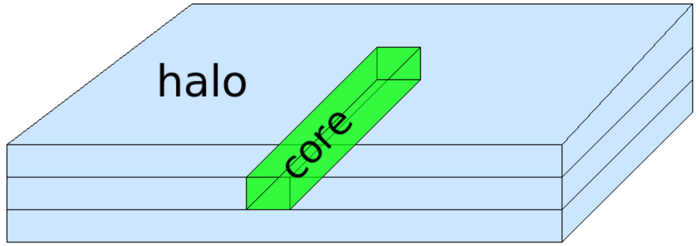


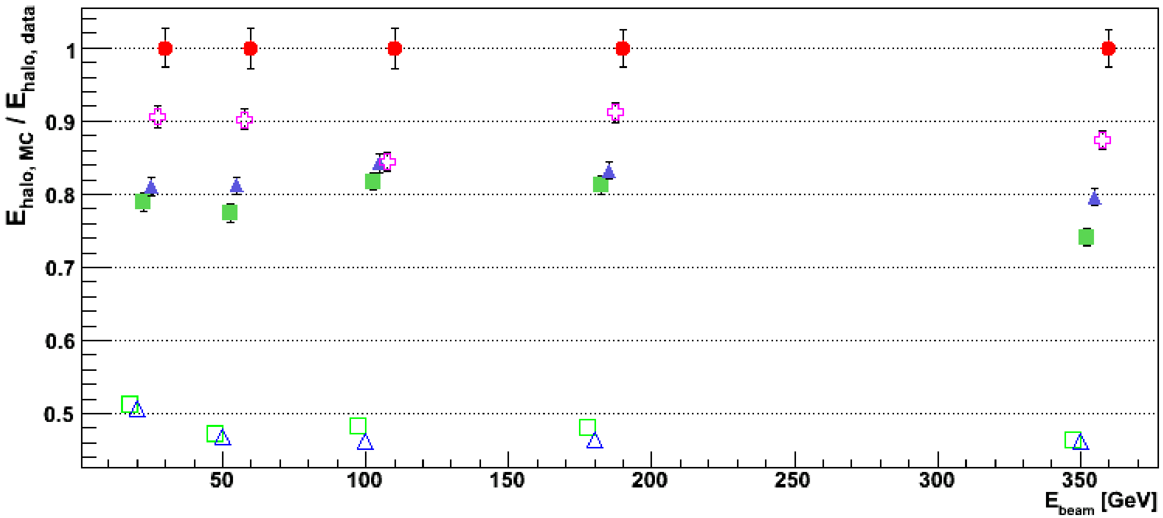


Lateral shower shape

- Core is ok
- All simulations predict too little energy in the halo







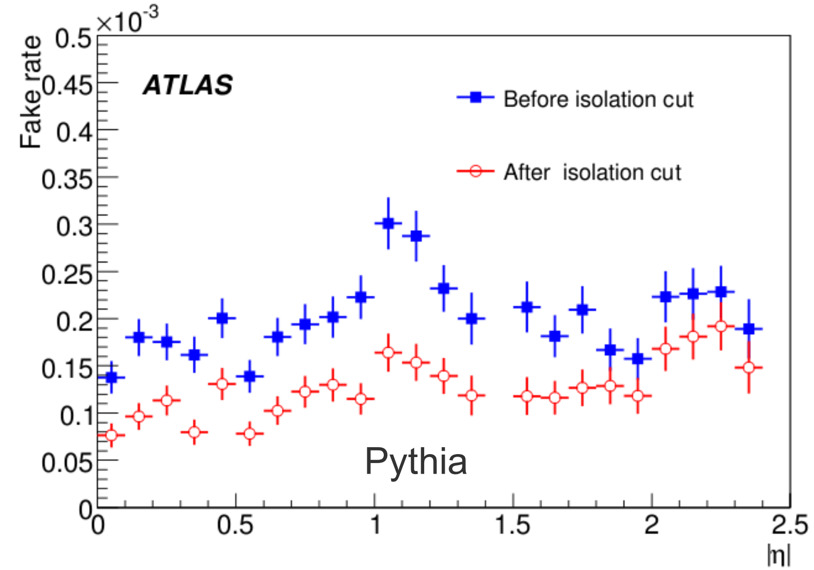
Summary

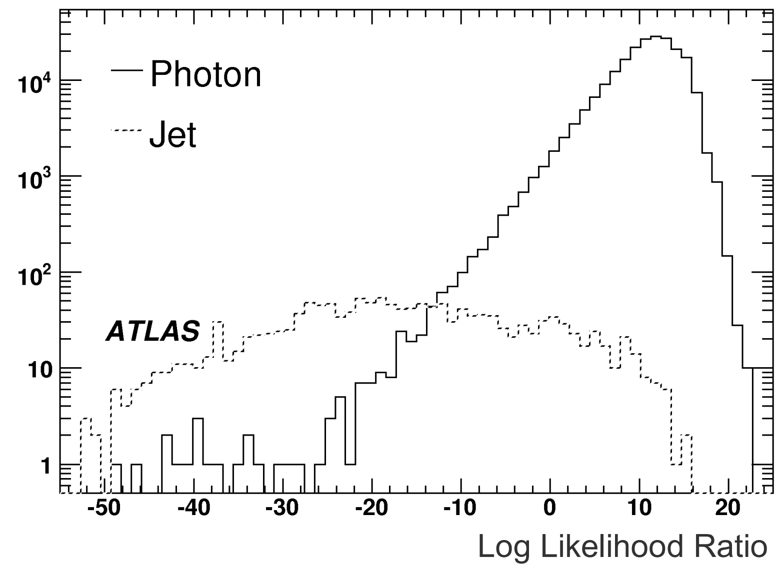
- The Bertini intra-nuclear cascade mechanism is the clear winner (default for Atlas now)
- Several area where Geant4 (and Fluka) needs to improve to match experimental data
- This study, together with many others, motivated several improvements in subsequent versions of Geant4

The photon + jet associated production cross section

Photon identification

- Good tracker coverage and efficiency: γ/e up to η=2.5
- Different corrections for converted/unconverted γ
- First layer of the LAr calorimeter highly segmented to assist γ/π^0 separation
- Tight and Loose selections based on several shower shape and isolation variables

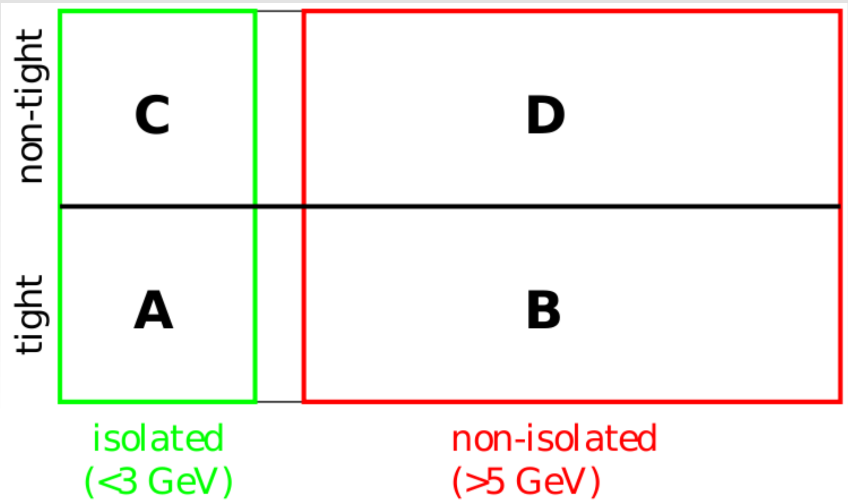


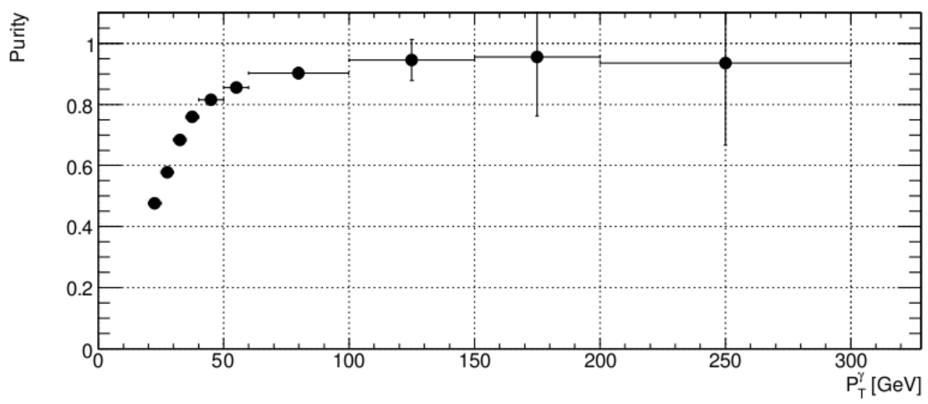


Dataset and event selection

- 38 pb^{-1} of data analysed (2010 statistics)
- Low threshold photon trigger (15 GeV)
- Several quality cuts:
  - vertex position and number of tracks pointing to it
  - Problematic LAr calorimeter regions
  - Bad jets
- Kinematic selection:
  - γ: $p_T > 20$ GeV, $|\eta| < 1.37$
  - Jets: $|\eta| < 2.8$ ($|\eta| < 0.8$ central, $1.8 < |\eta| < 2.8$ forward)

Selection purity





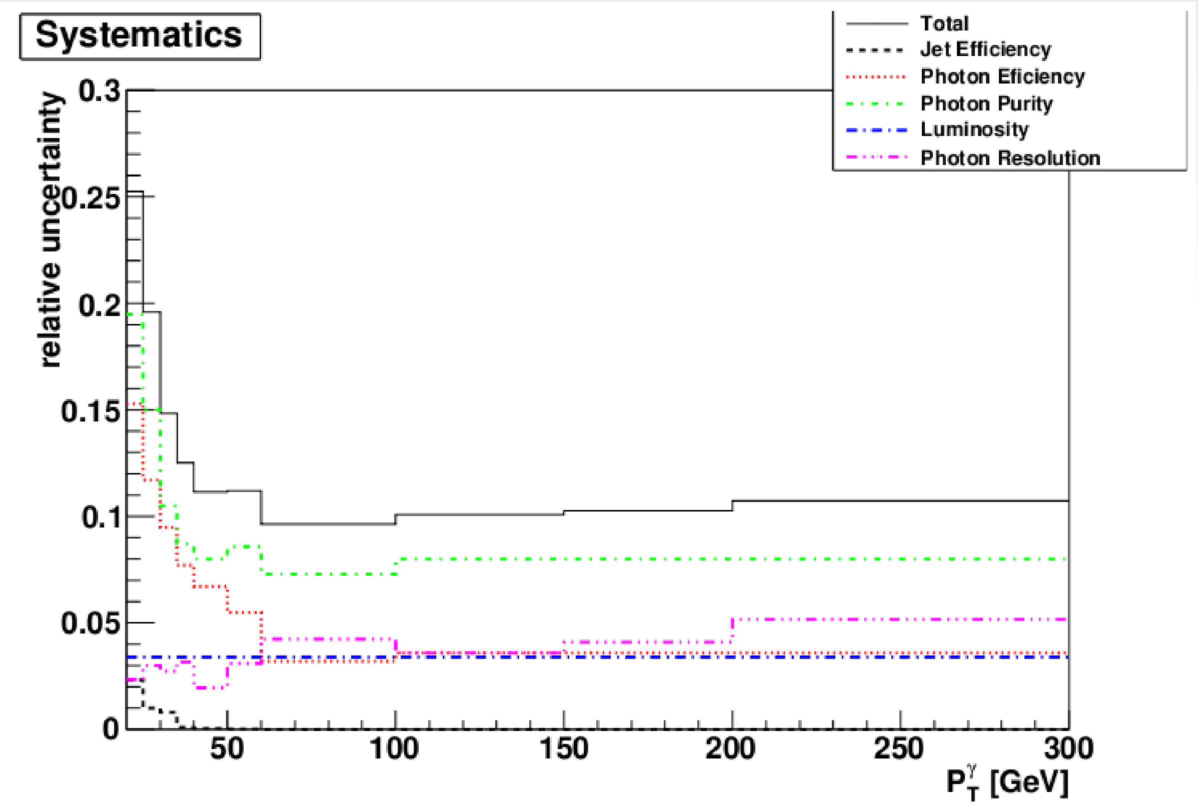
- Side-band method to estimate residual background
- B, C, D defined by cut reversal

$$N_A^{bg} = N_C^{bg} \frac{N_B^{bg}}{N_D^{bg}} \simeq N_C \frac{N_B}{N_D}$$

- Better than 90% after 60 GeV

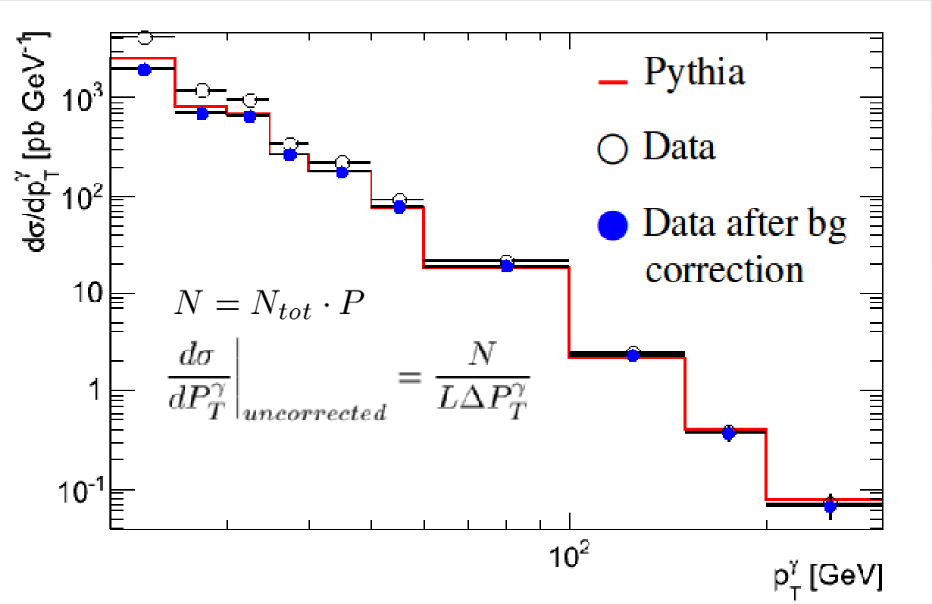
Systematic uncertainties

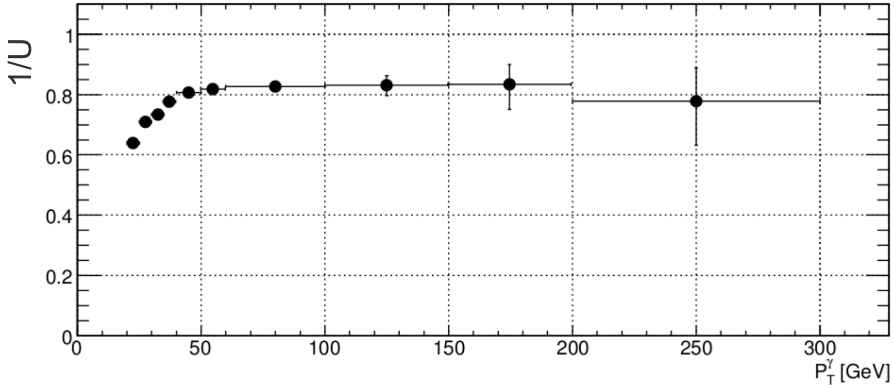
- Photon purity/efficiency:
  cut variation and
  photon shower shape
  variation
- Photon energy scale:
  assumed ~ 1%
- Photon resolution: MC
- Jet efficiency: MC
- Luminosity determination
  with dedicated
  measurements



Background and efficiency corrections

- Background: from side band measurements
- Efficiency: use MC to compute bin-by-bin unfolding coefficients

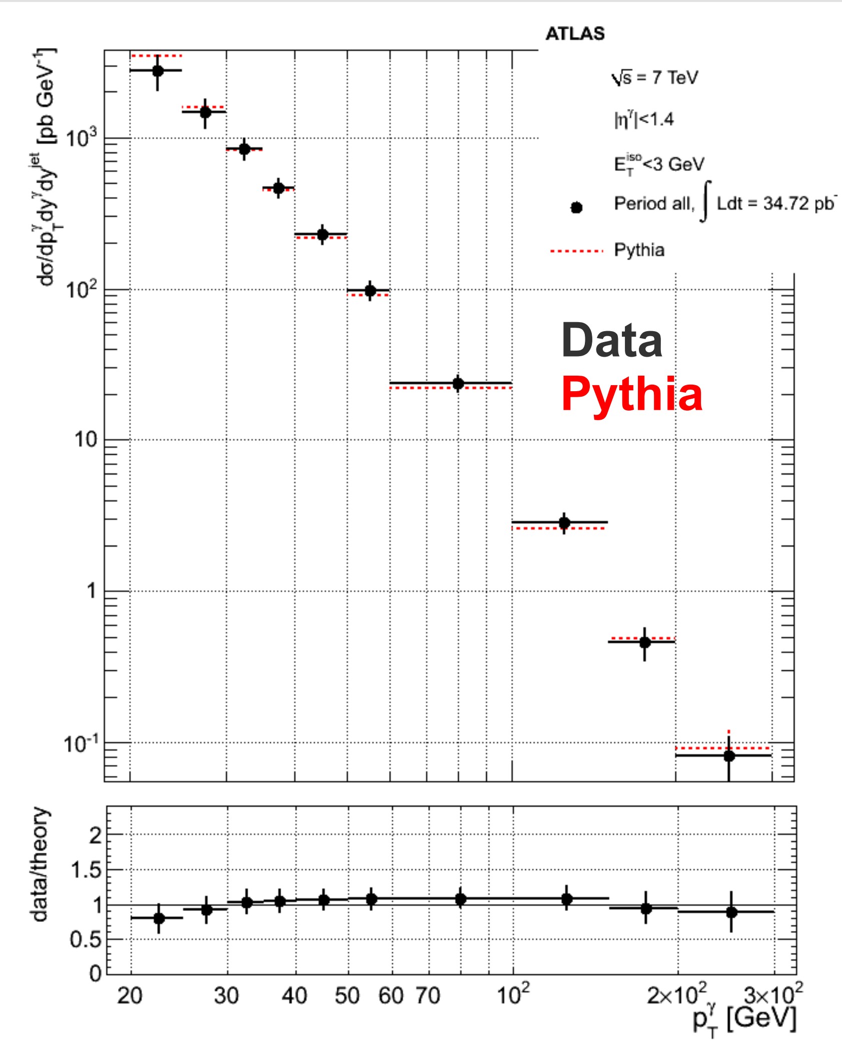




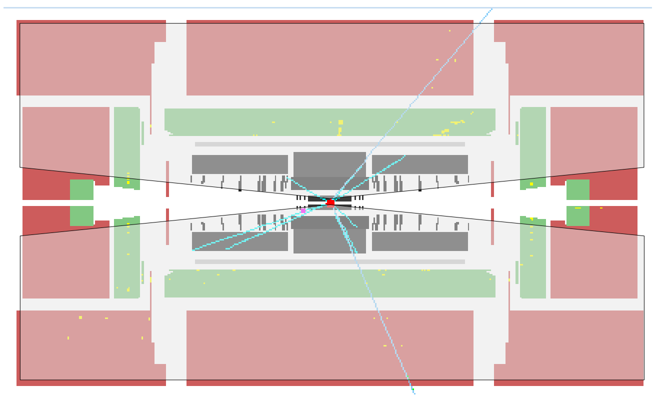
$$\frac{d\sigma}{dP_T^\gamma} = \frac{N}{L\Delta P_T^\gamma} U$$

$$U(p_T) = \frac{\left.\frac{d\sigma}{dP_T^\gamma}\right|_{\text{truth}}}{\left.\frac{d\sigma}{dP_T^\gamma}\right|_{\text{MC, allcuts}}}$$

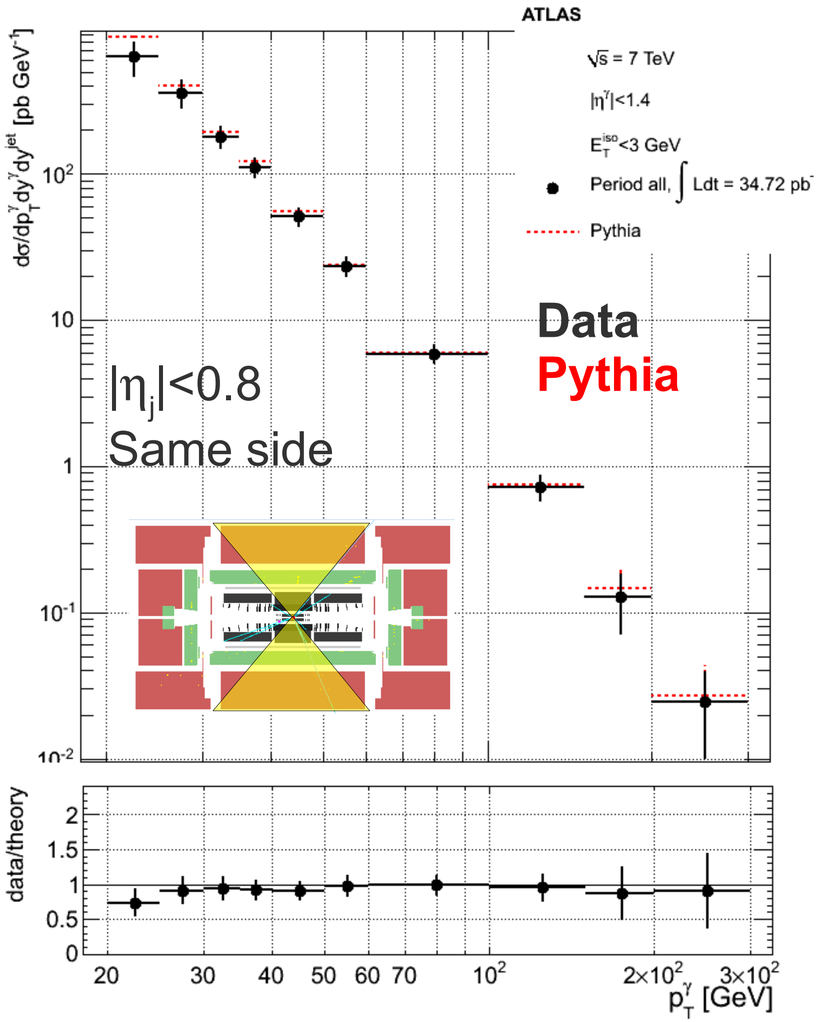
Inclusive cross section

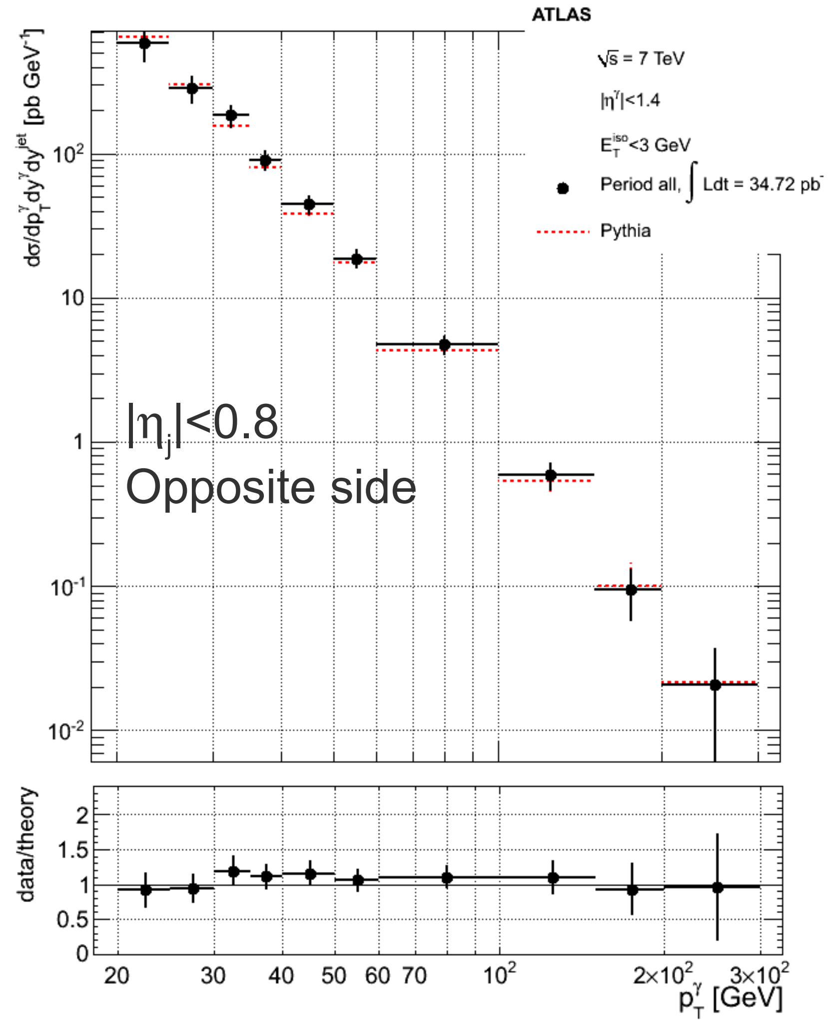


- All jets with |η| < 2.8
- All photons with |η| < 1.37

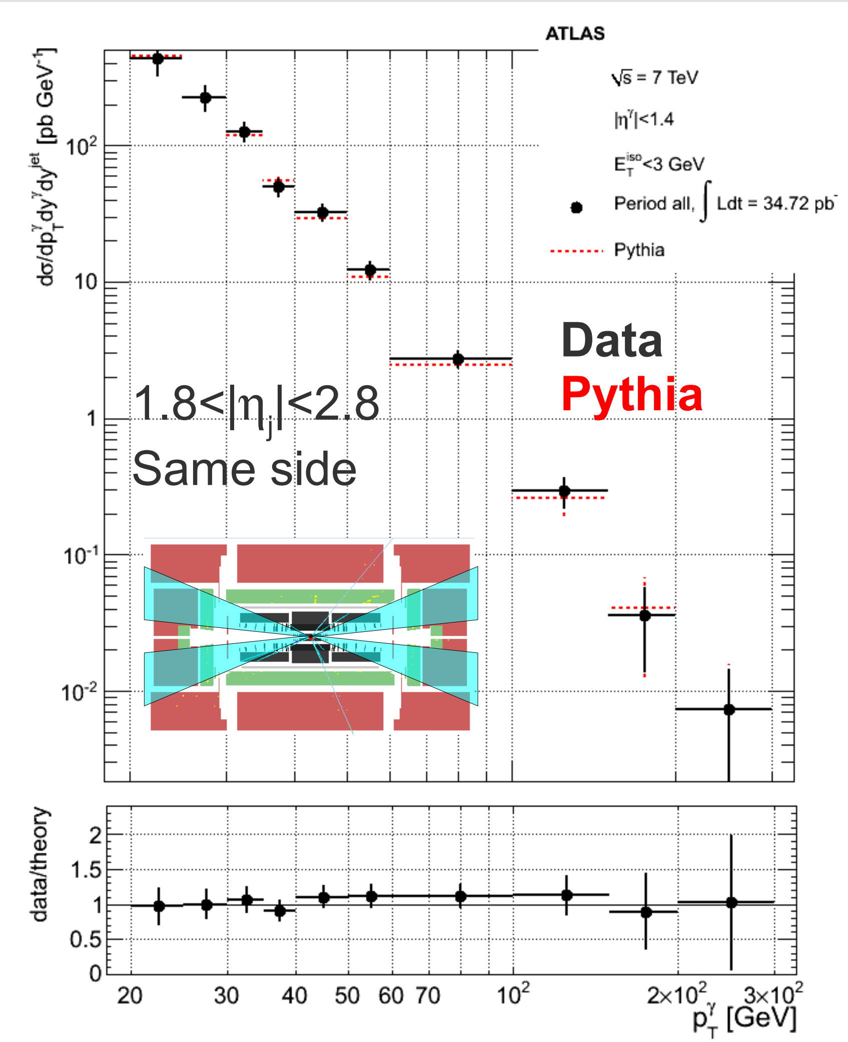


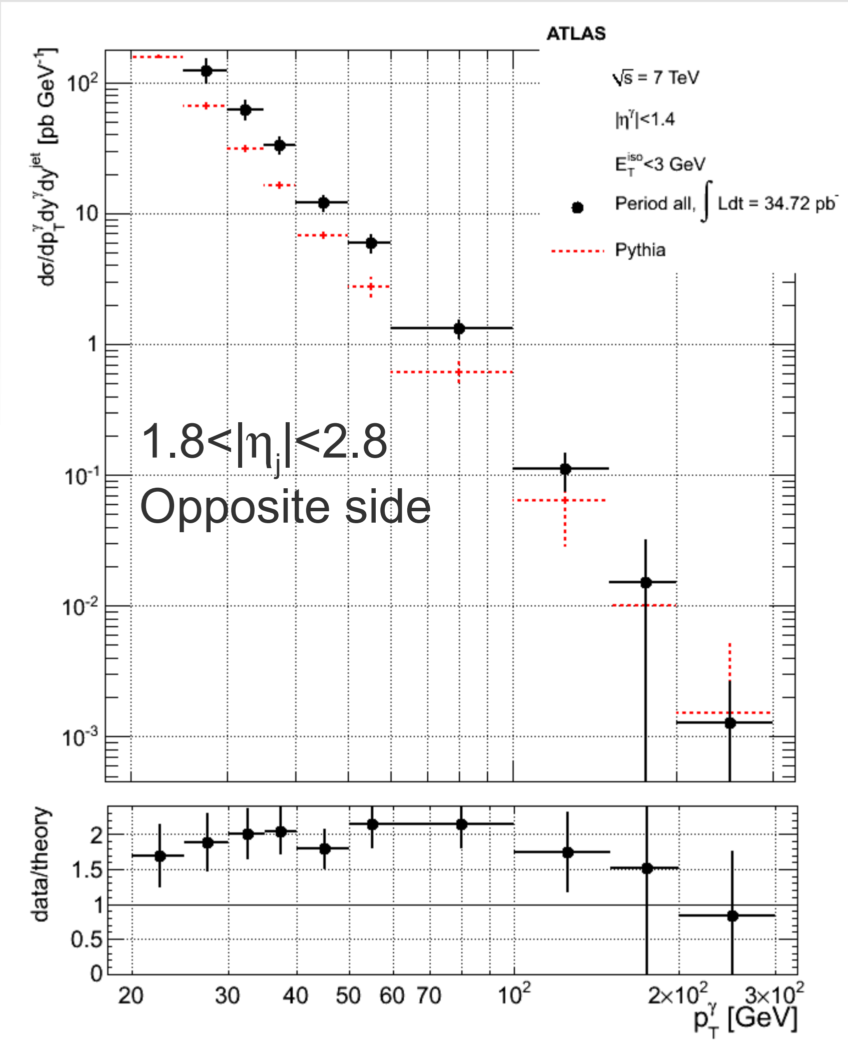
Central jets cross sections





Forward jets cross sections





Summary

- First measurement of the photon+jet associated production cross section at Atlas
- Good agreement with Pythia MC simulation with the exception of data sample with the largest rapidity gap (need NLO MC)

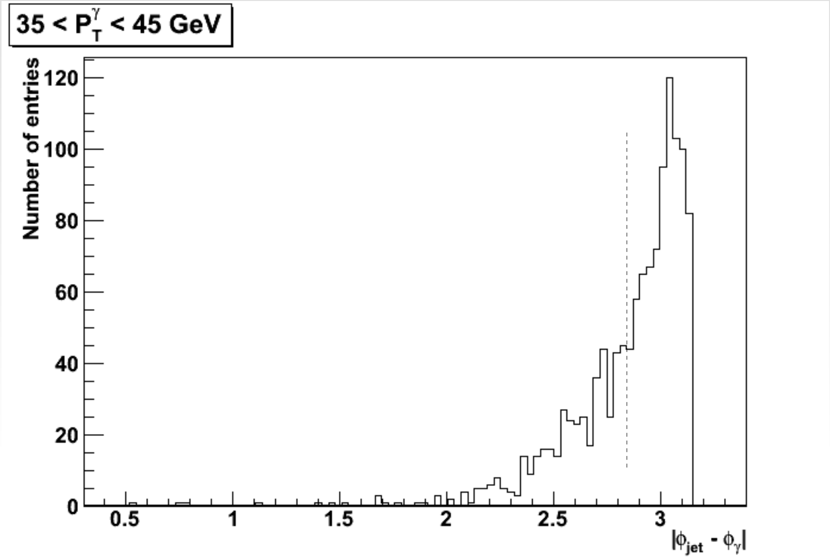
Jet energy scale validation using photon + jet events

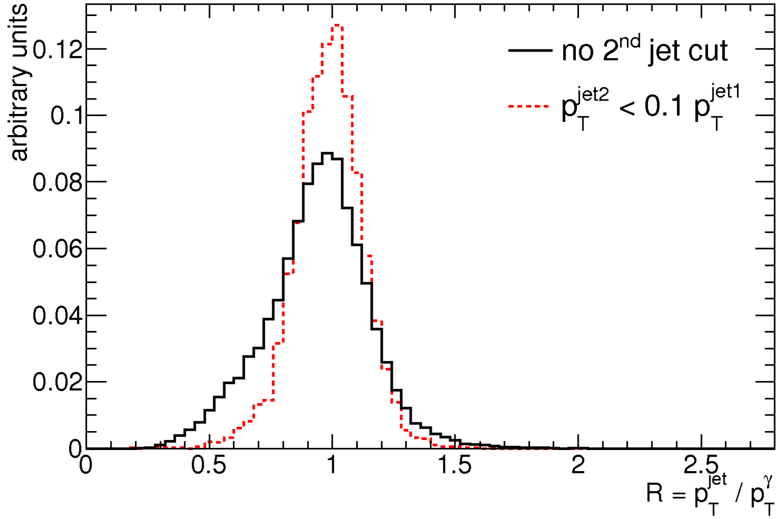
Motivation

- Calorimeter response to photon is well understood
- Use transverse momentum balancing to obtain an independent measure of the jet energy
- In-situ validation of the MC based calibration schemes

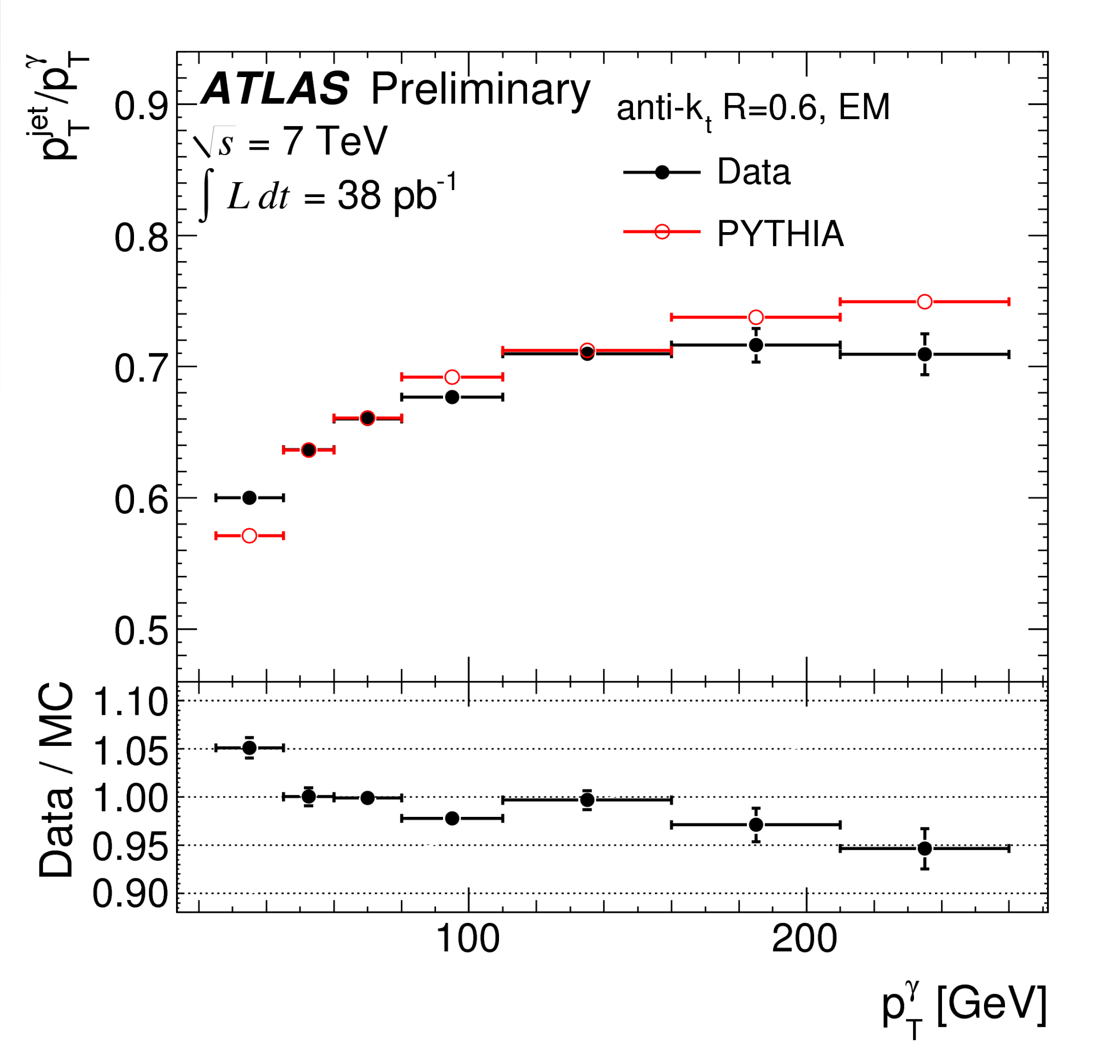
Selection performance and systematics

- Same selection as previous analysis
  - $|\eta_{jet}| < 1.2$
- Soft radiation cuts
  - $\Delta\phi > \pi - 0.2$
  - $p_{T,j2} / p_{T,j1} < 10\%$





Data – MC comparison (uncalibrated jets)

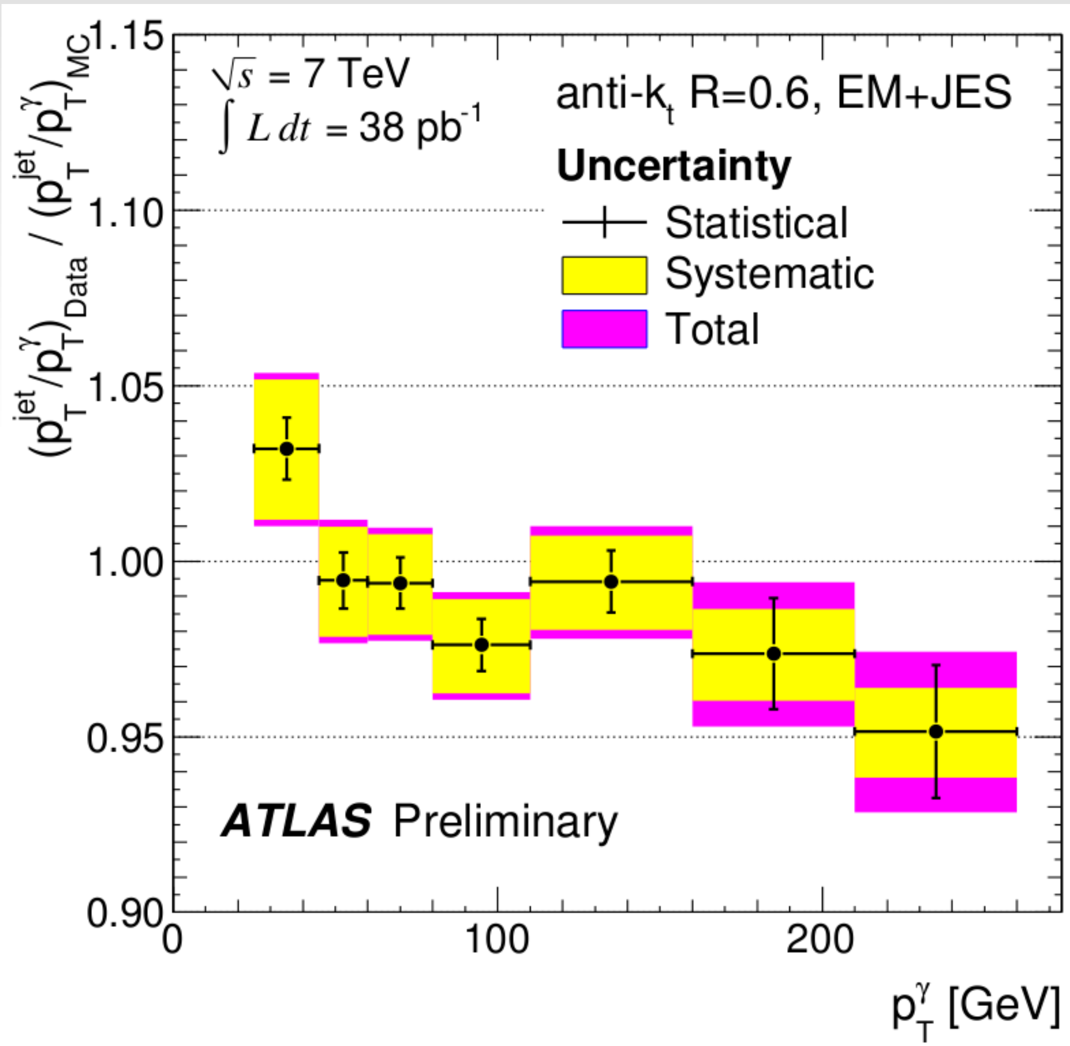


Systematic uncertainties over the Data/MC ratio

p_T^γ range (GeV)	systematics (%) (45, 60)	systematics (%) (110, 160)
Photon Energy Scale	$^{+0.5}_{-0.3}$	$^{+0.5}_{-0.3}$
Dijet Background	± 1.0	± 0.4
Soft Radiation	± 0.8	± 0.9
In-time Pile-up	± 0.8	± 0.8
Total Systematic Uncertainty	$^{+1.6}_{-1.5}$	$^{+1.4}_{-1.3}$

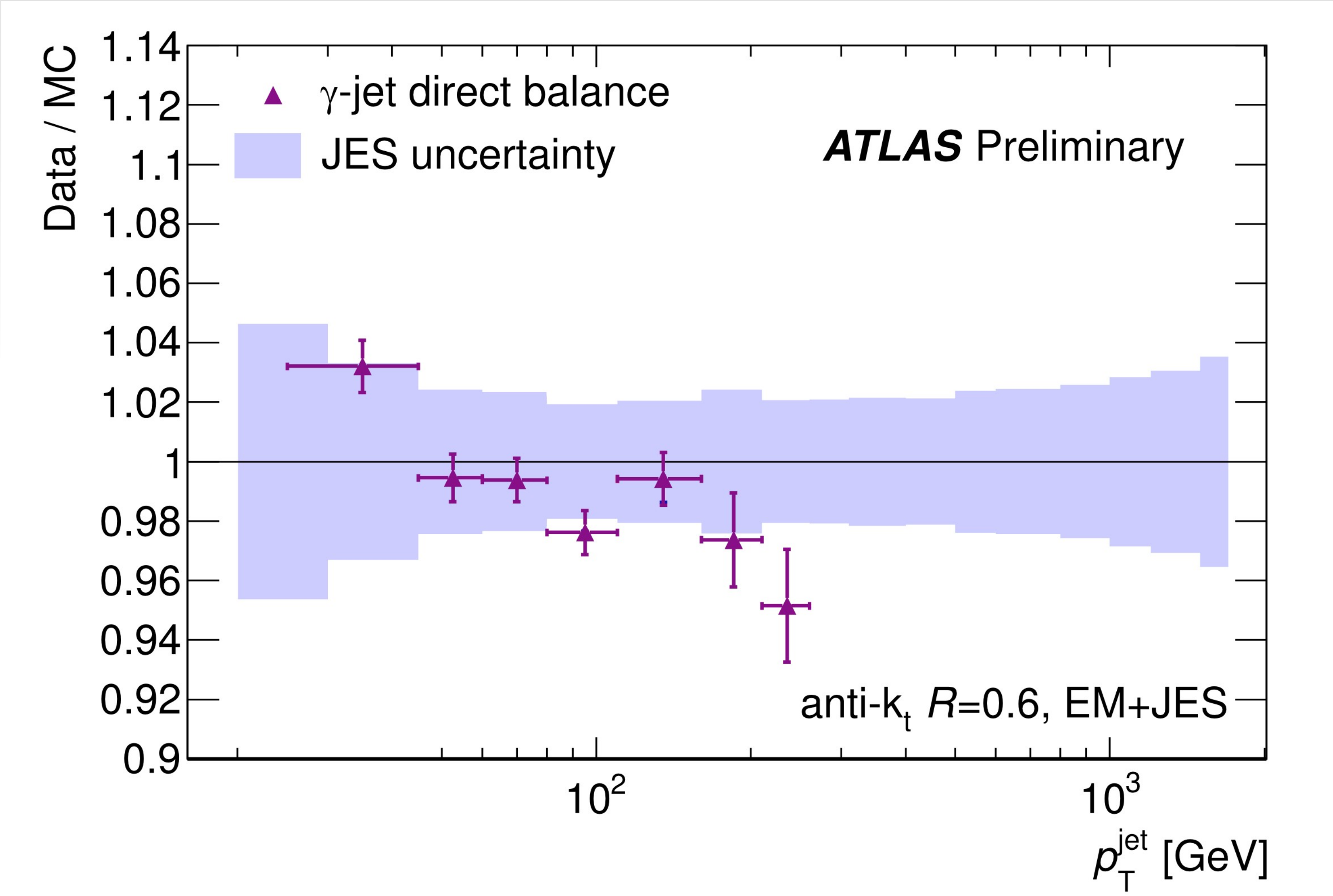
- Photon energy scale: estimated with $Z \rightarrow ee$
- QCD background: side-bands method
- Soft radiation: cut variation
- Pile up: require only 1 vertex in event

Validation of the EM+JES calibration scheme



- Data / MC ratio for the EM+JES scheme
- JES uncertainty constrained within 5%
- Similar results for other calibrations

Validation of the JES uncertainty



Summary

- Validation of the Atlas MC simulation
- Verification of the MC based jet calibration
  - All the 3 methods developed by the collaboration have been validated
- Systematic uncertainty of the method is below 2% for $p_T > 45$ GeV

Conclusions

- Investigate jet calibration in several key aspects
  - Validation (and tuning) of the Geant4 MC simulation
  - Verification of the Atlas MC simulation
  - Cross check of the jet calibrations schemes
- The in-situ validation of the JES is an essential ingredient of many results that Atlas has produced (and will produce) in 2011
- First measurement of the cross section for the associated production of photons and jets

The End

The gluon density inside the proton

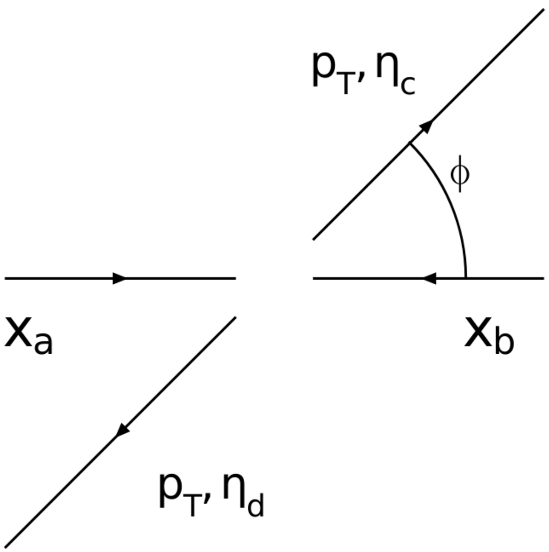
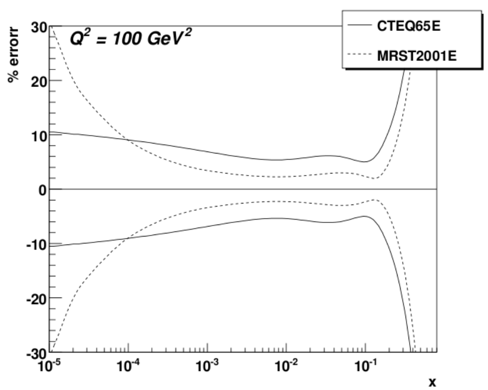


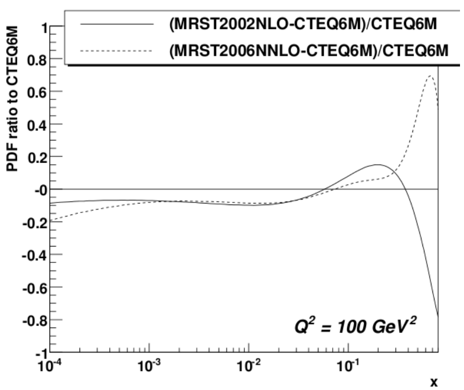
Figure 2.4: Generic 2 body scattering.

$$x_{min} = \frac{x_T e^{-\eta_\gamma}}{2 - x_T e^{\eta_\gamma}}$$

$$x_T = 2p_T/\sqrt{s}$$

- Gluon PDF determined via DIS + sum rule
- x_{min} is most likely the x of the gluon
- In the low p_T - high η LHC will be sensible to x ~ 10^{-3} - 10^{-4}





The gluon content of the proton

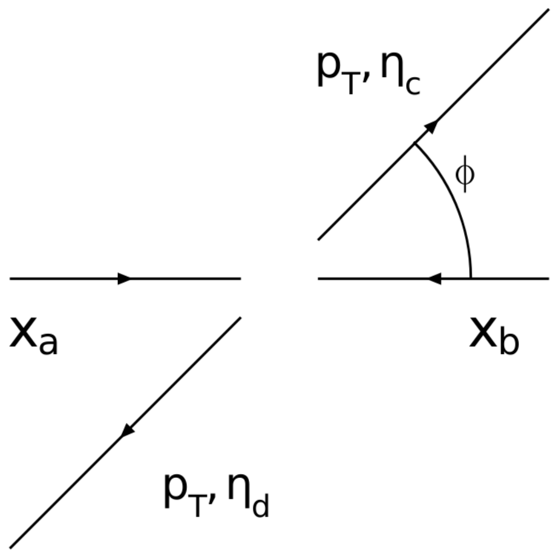
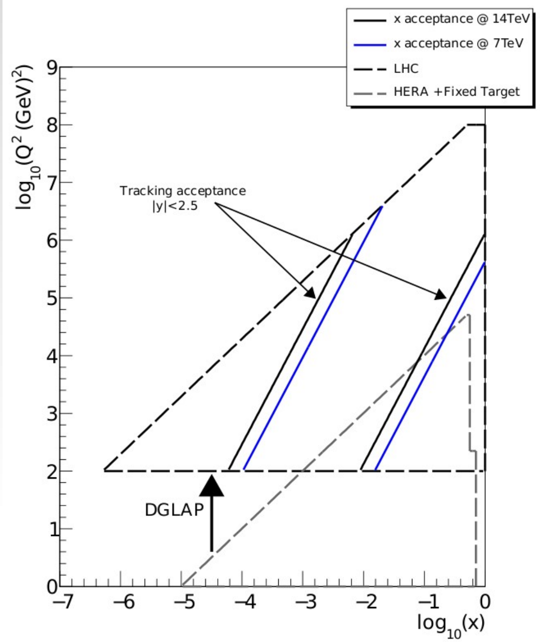


Figure 2.4: Generic 2 body scattering.



$$x_a = \frac{x_T}{2}(e^{\eta_c} + e^{\eta_d})$$

$$x_b = \frac{x_T}{2}(e^{-\eta_c} + e^{-\eta_d})$$

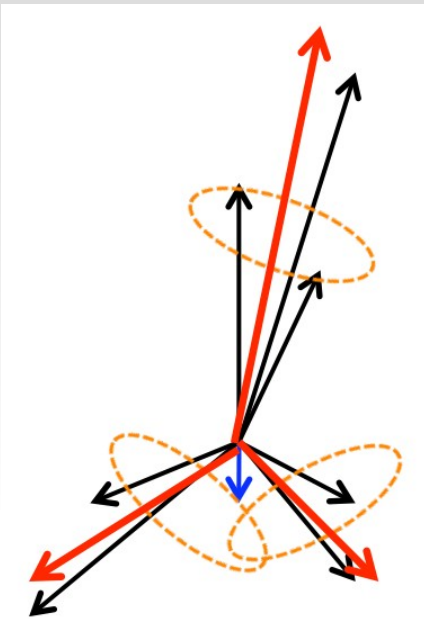
$$x_{min} = \frac{x_T e^{-\eta_\gamma}}{2 - x_T e^{\eta_\gamma}}$$

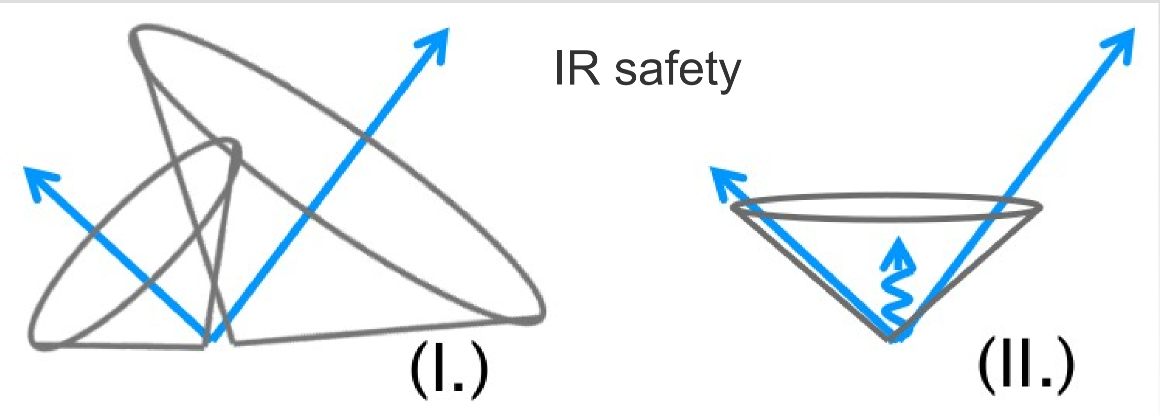
$$x_T = 2p_T/\sqrt{s}$$

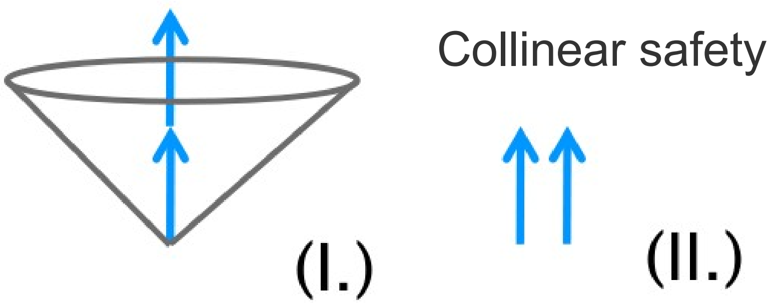
$$gq \to \gamma q \quad : \quad -\frac{\pi\alpha\alpha_s e_q^2}{3\hat{s}^2}\left(\frac{\hat{t}}{\hat{s}} + \frac{\hat{s}}{\hat{t}}\right)$$

$$q\bar{q} \to \gamma g \quad : \quad \frac{8\pi\alpha\alpha_s e_q^2}{9\hat{s}^2}\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}}\right)$$

IR and colinear safeness







Iterative cone algorithms

- Combination:
  - Progressive removal
  - Split and merge
  - Seedless
- Unsafe or computationally intensive
- Dark towers

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 < R^2$$

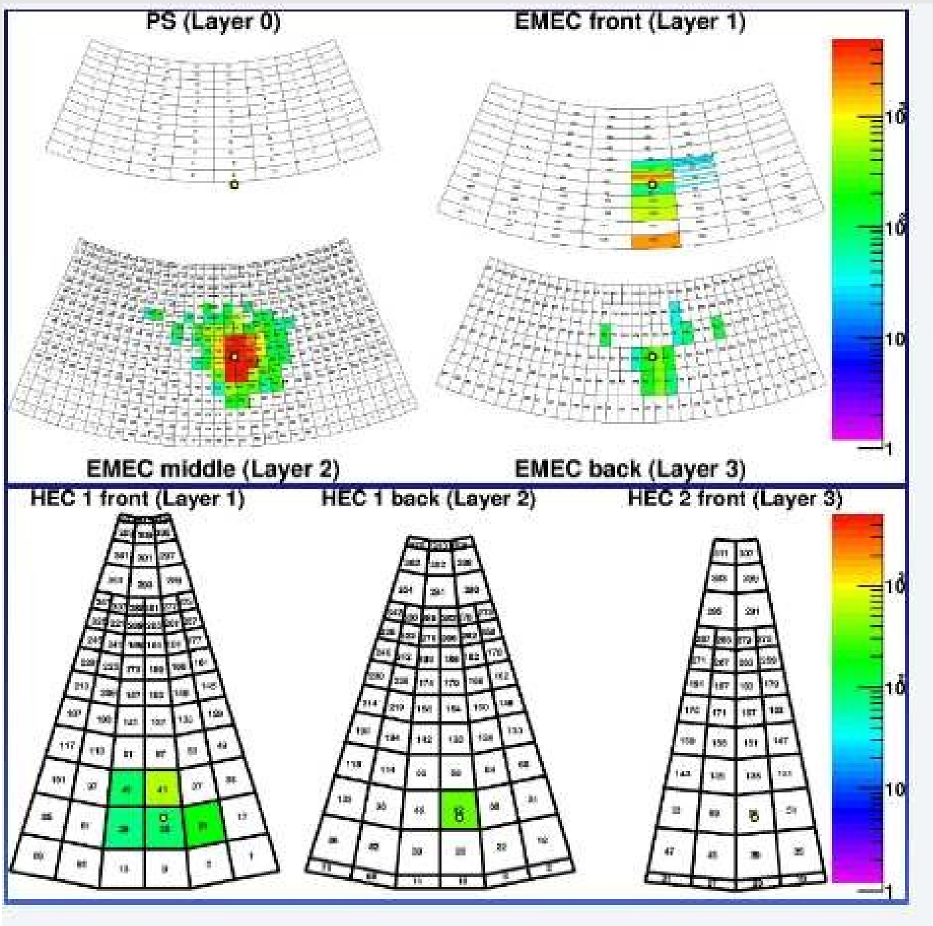
Sequential recombination algorithms

- Merge if $d_{ij} < \min(d_{ii}, d_{jj})$
- Parameters:
  - k_T: p = 1
  - Cambridge/Aachen: p = 0
  - Anti-k_T: p = -1
- Theoretically safe
- R = 0.4 – 0.6

$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{ii} = k_{T,i}^{2p}$$

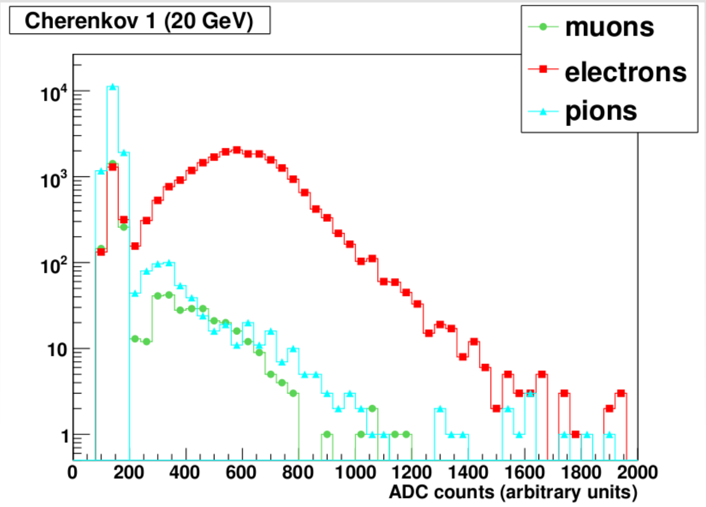
Calorimetric topo-clusters

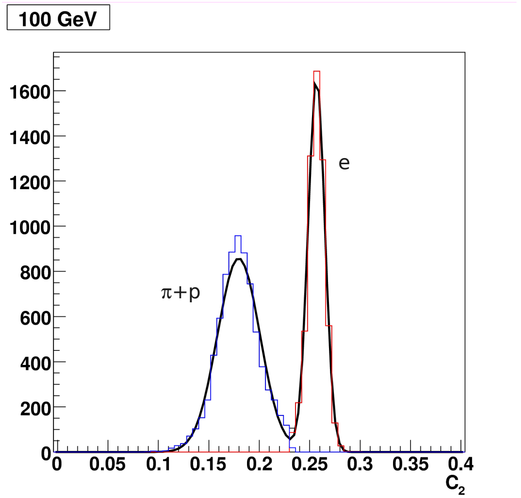


- 4-2-0 clustering scheme to group calorimetric cells
- Split merge procedure based on local minima/maxima

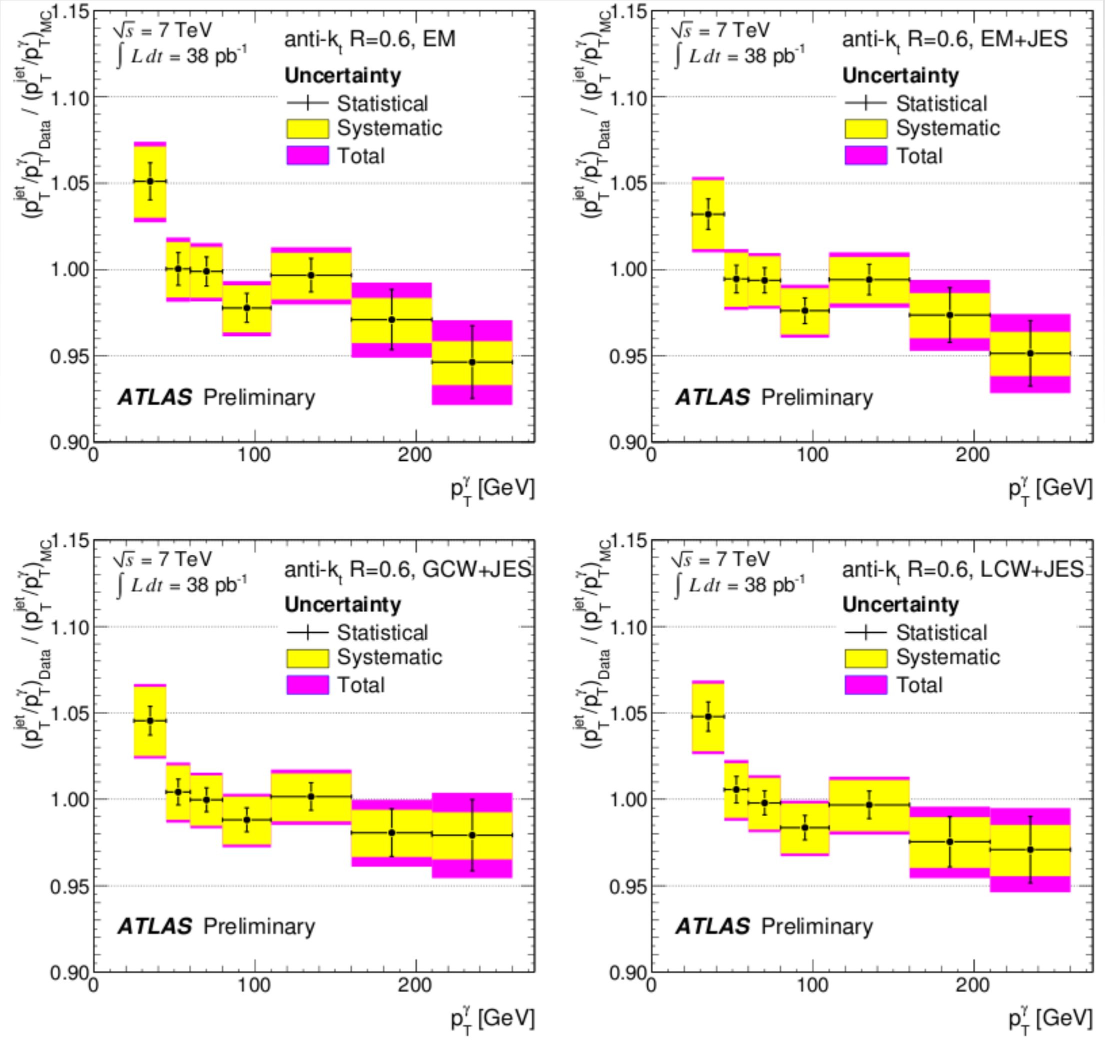
Particle identification

- e/π separation
  - Cherenkov (20 GeV)
  - Calorimetric selection (systematics!)
- π/p separation:
  - Cherenkov (50 GeV)
- Residual contamination reproduced in MC simulations

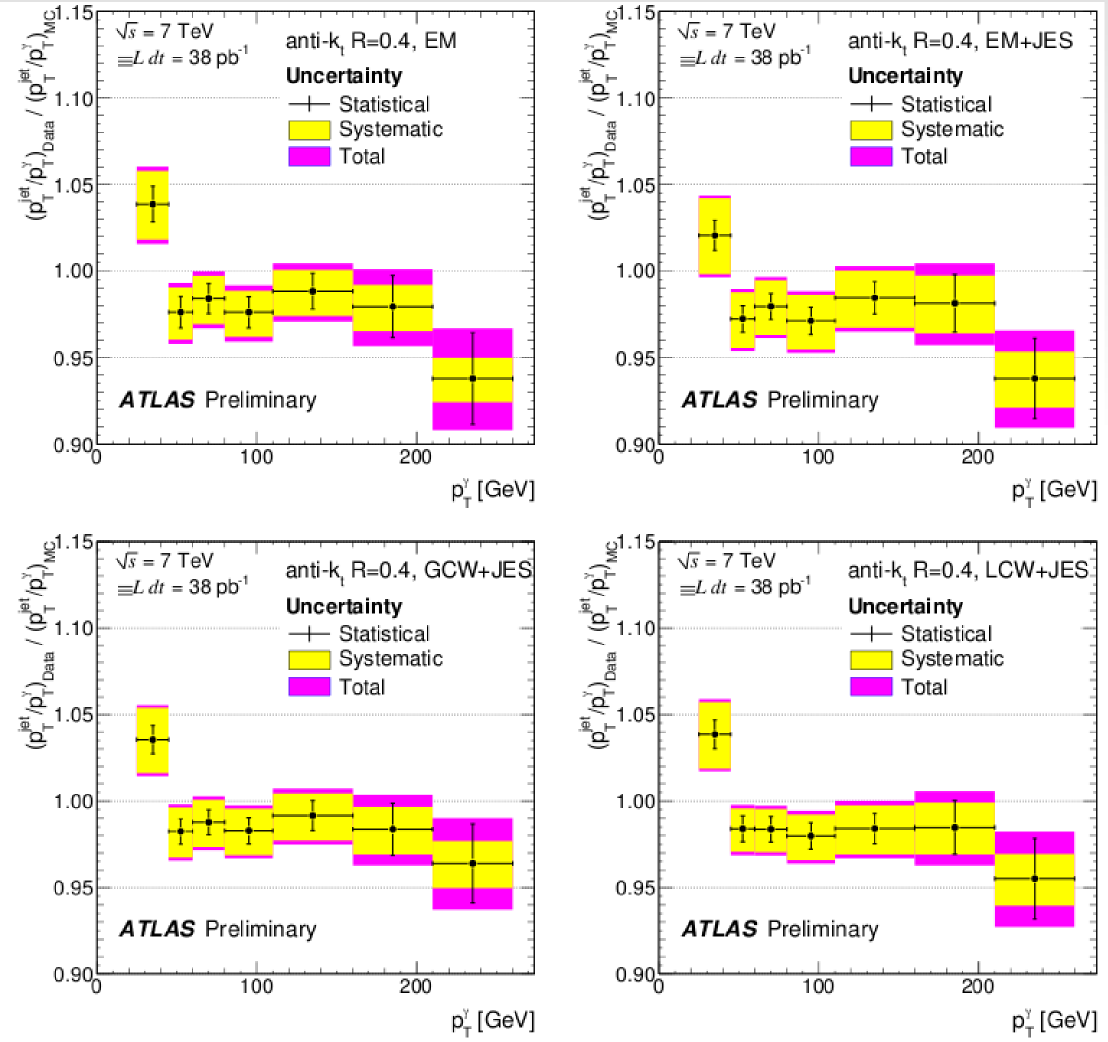




Validation of the jet energy scale calibration anti-k_T 0.6

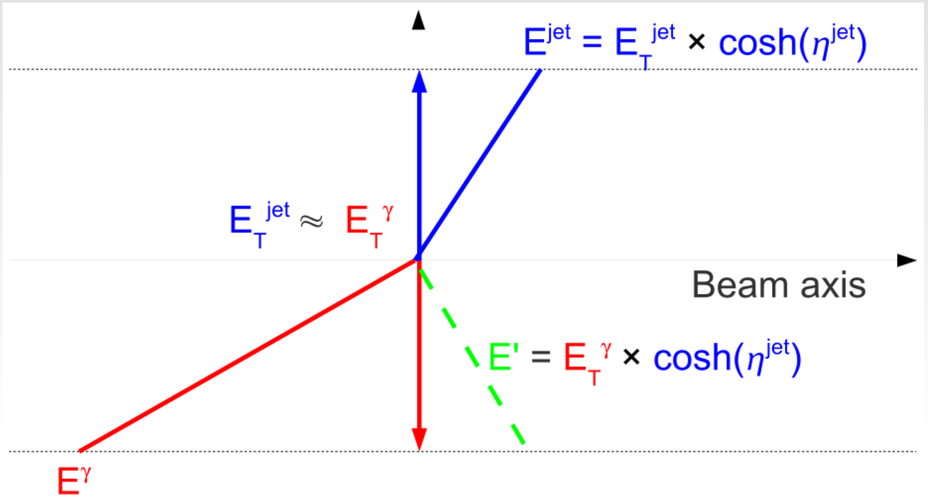


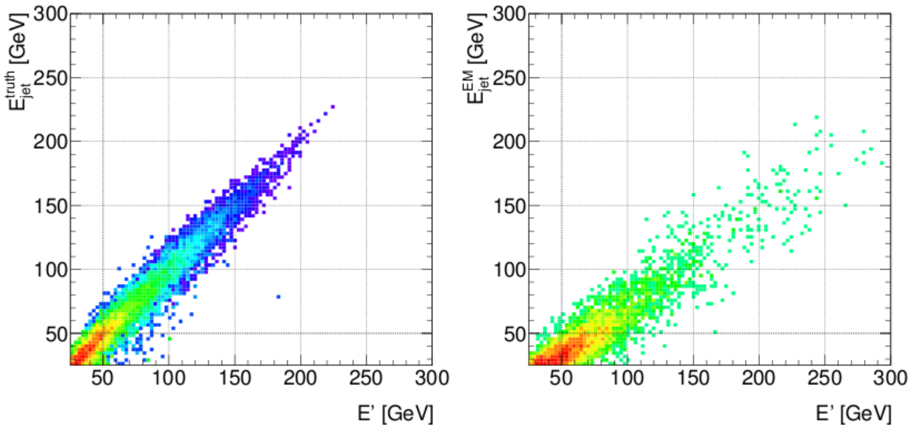
Validation of the jet energy scale calibration anti-k_T 0.4



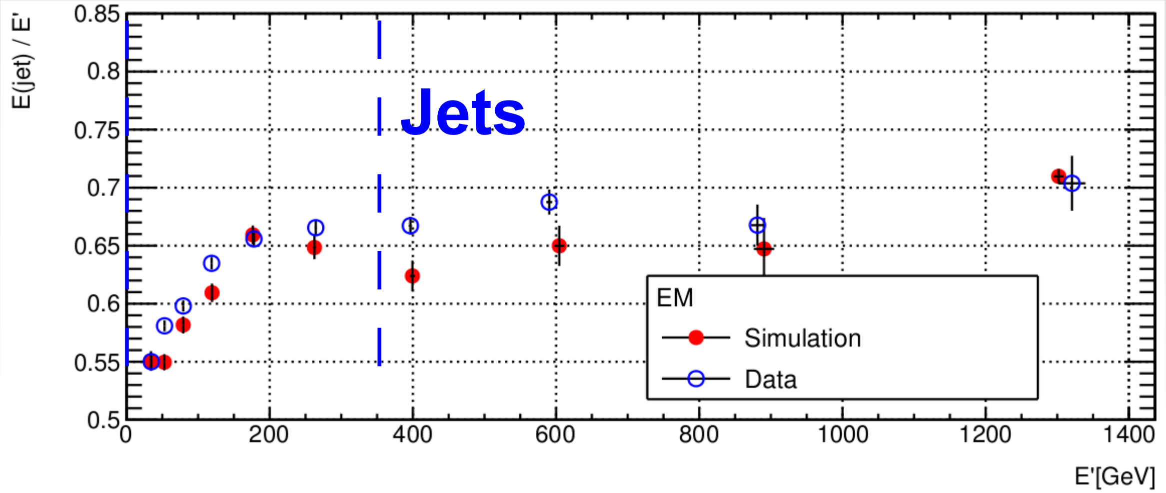
Calorimeter response to jets

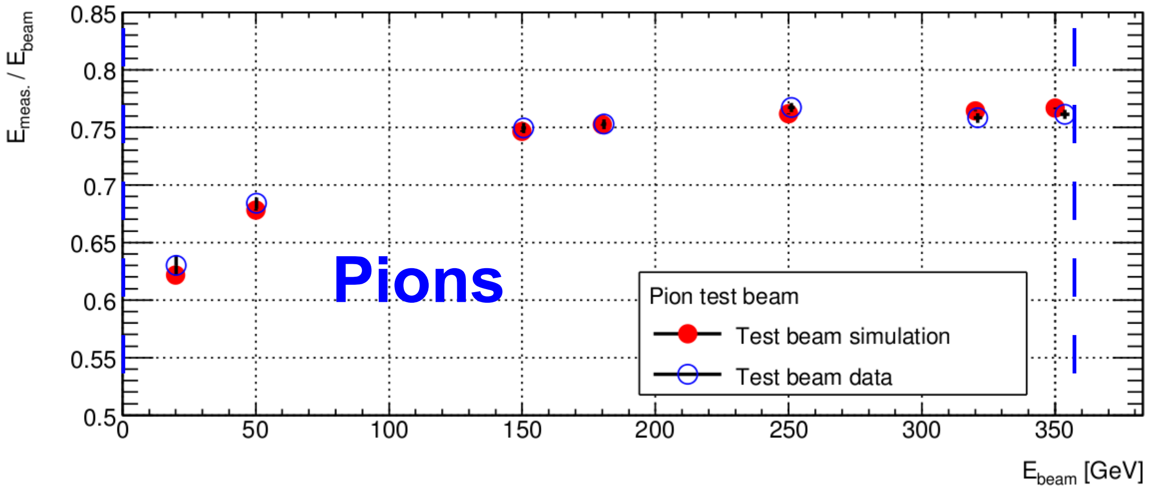
- Project the photon pT on the jet direction to estimate the true jet energy
- Measure the calorimeter response to jets





Calorimeter response to jets





Validation of the JES uncertainty