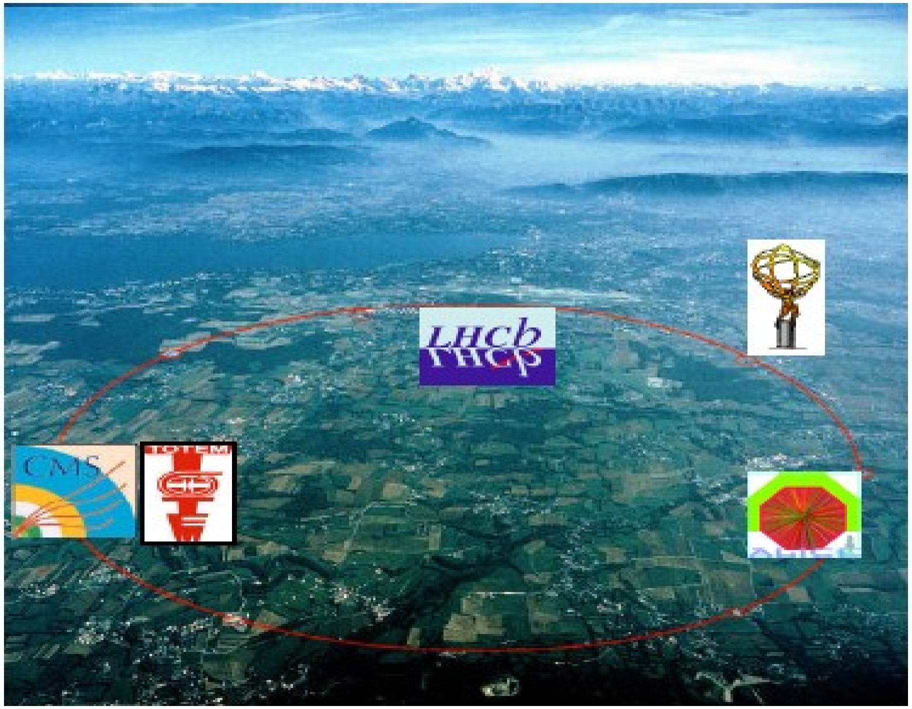
Physics with first fb^{-1}

at Large Hadron Collider

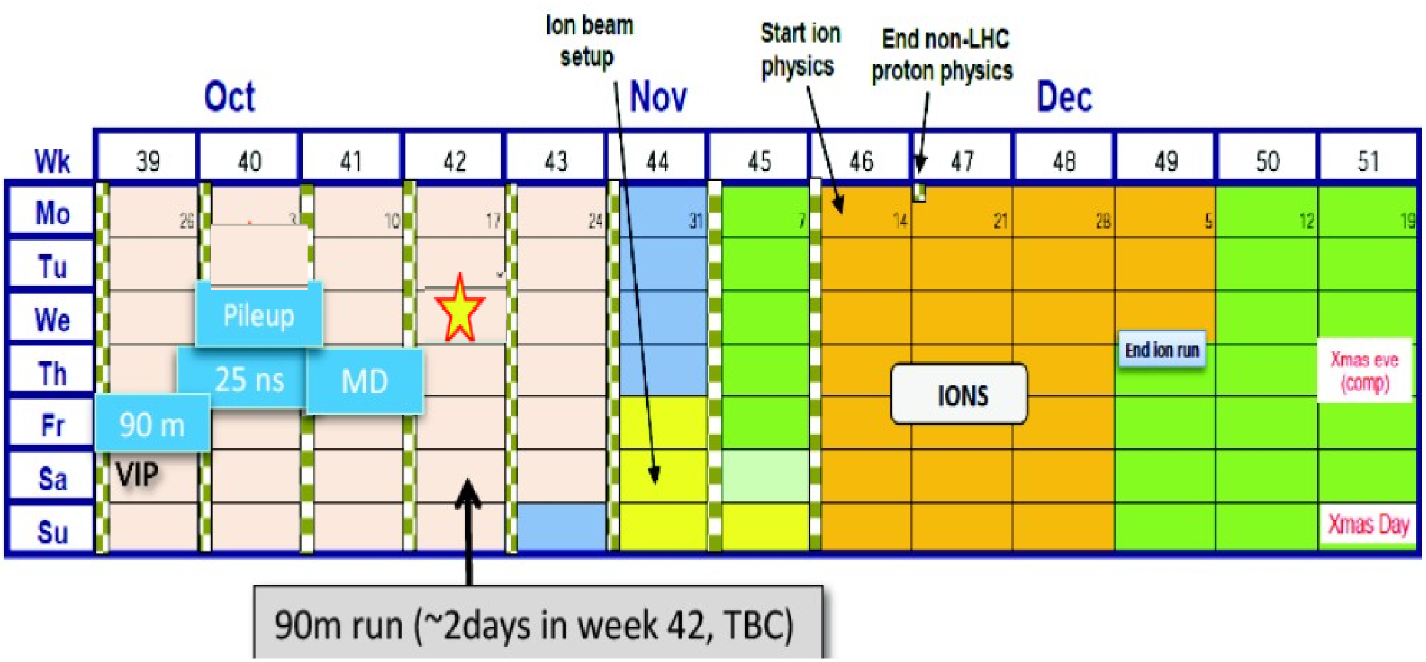
Today:

- **Inelastic cross-section**
- **Soft QCD**
- **Hard QCD**
  - **Jets**
  - **Photons**



News from last week(s)

- Close to 5fb^{-1} delivered by LHC



Plan

- Amazing how much could have been done with only 36pb^{-1} data accumulated in 2010: numbers of results are still in the pile-line but already theory is being tested quantitatively.... and is holding its own (unfortunately)

19.10 Hard QCD

9.11 W,Z inclusive, asymmetry, W/Z + heavy flavours

23.11 Top physics

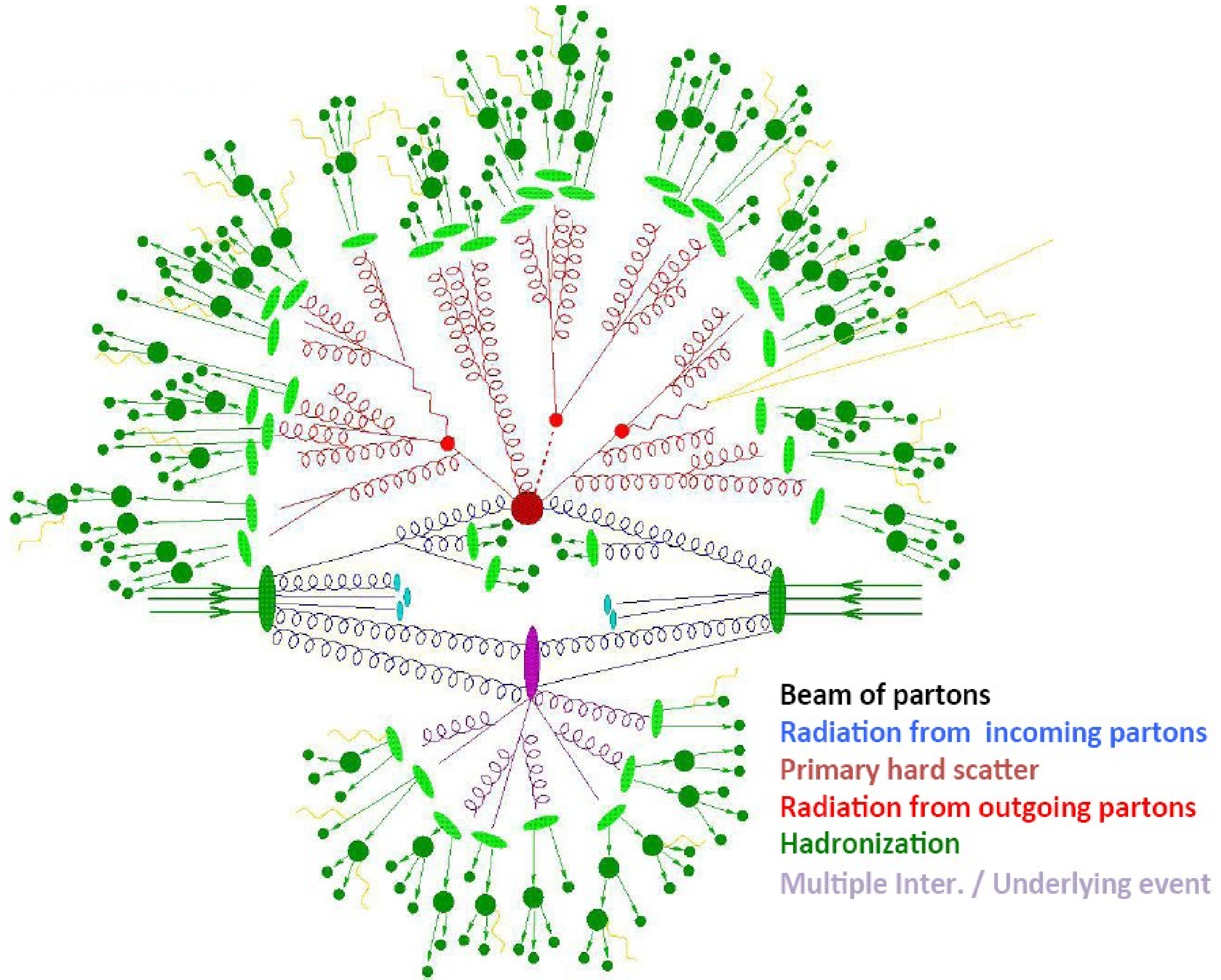
30.11 Diboson production and TGS couplings

7.12 B-physics and heavy ions

4.01 Higgs boson… where we are?

18.01 What's new from New Physics searches?

Typical pp collision



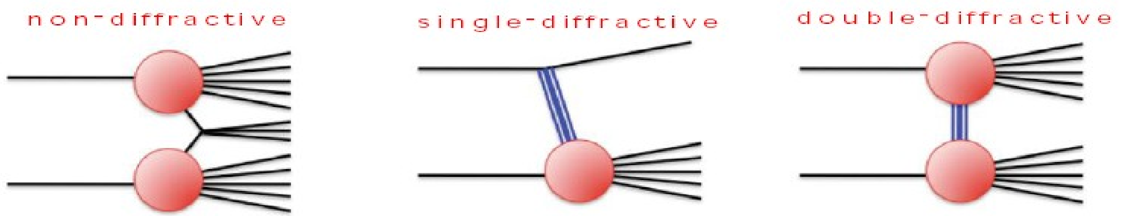
Inelastic pp collisions

p-p interactions are dominated by soft (low momentum transfer) QCD processes

Soft QCD can not be predicted using perturbative QCD model!

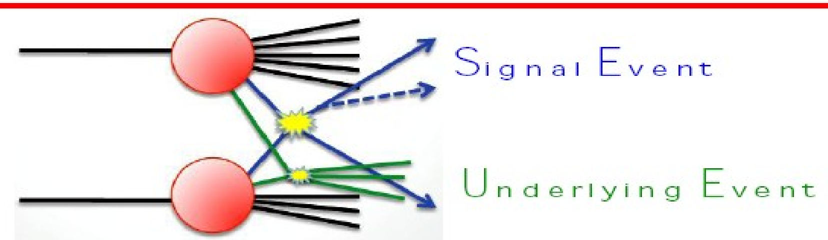
Rely on phenomenological models that need to be tuned to data

Inelastic pp collisions are the result of a combination of non-diffractive and diffractive p-p processes: $\sigma_{total\text{-}inelastic} = \sigma_{sd} + \sigma_{dd} + \sigma_{nd\text{-}inelastic}$



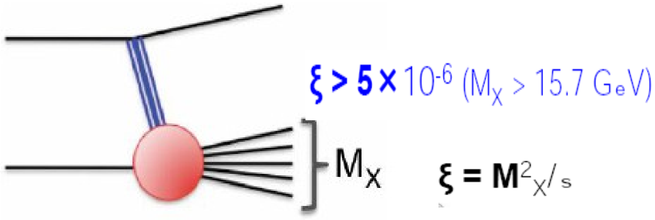
<u>Knowledge on soft-QCD processes needed:</u>

- To model pileup (up to ~20 p-p interactions per bunch crossing)
- To model the soft processes occuring in the *Underlying Event*
- Affects E_T^{miss} resolution, lepton ID, jet reconstruction, ...

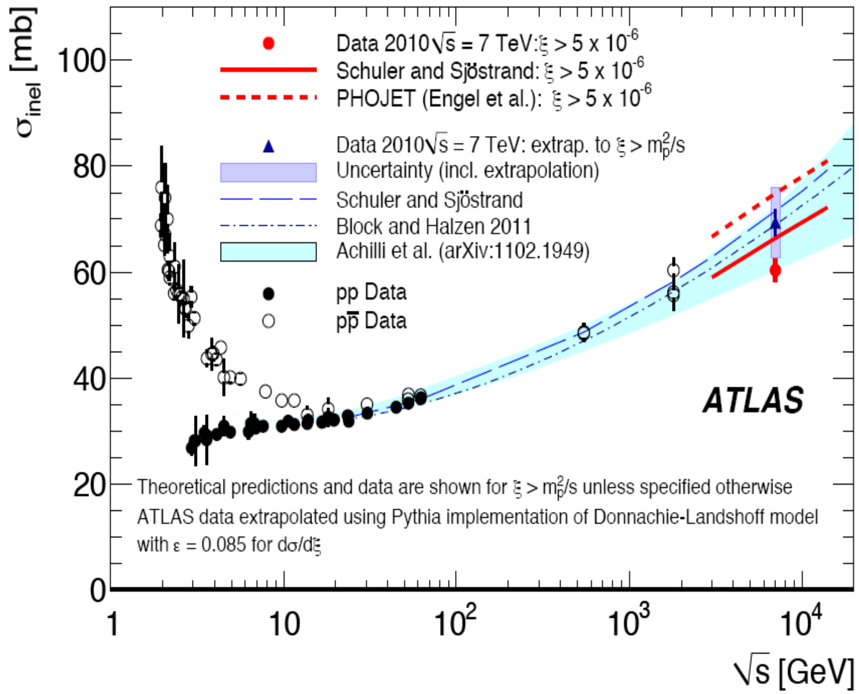


Total inelastic pp cross-section

$$\sigma(\xi > 5 \cdot 10^{-6}) = 60.3 \pm 0.05\,(\text{stat.}) \pm 0.5\,(\text{sys.}) \pm 2.1\,(\text{lumi})\,\text{mb}$$
$$\sigma_{inel} = 69.1 \pm 2.4\,(\text{exp.}) \pm 6.9\,(\text{extr.})\,\text{mb}$$



- Using MBTS trigger miss only elastic (pp->pp) and low mass diffraction (pp->pX)
- Measure fiducial cross-section
- After 5-10% extrapolation obtain total inelastic cross-section

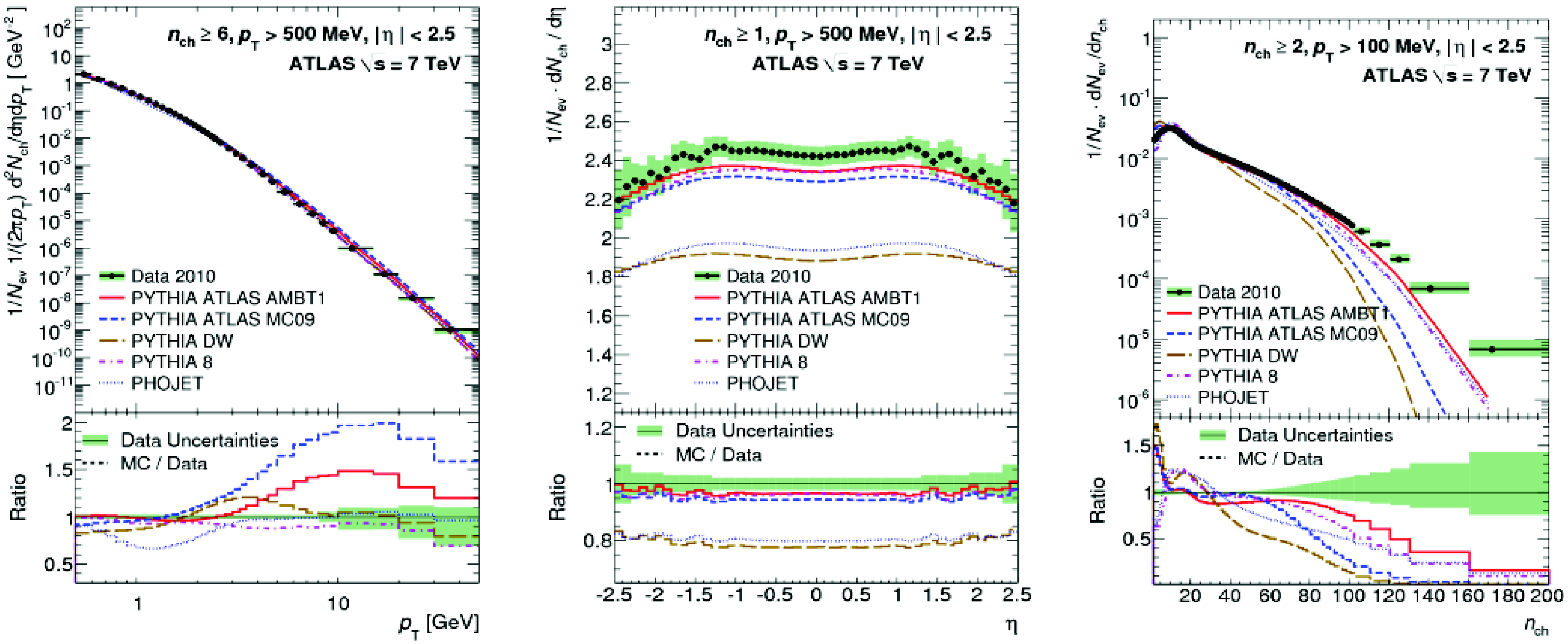


Total syst error: 3.5%
Dominant syst. error:
luminosity measurement 3.4%

$\sigma(\xi > m_p^2/s)$ [mb]	
ATLAS Data 2010	$69.4 \pm 2.4(\text{exp.}) \pm 6.9(\text{extr.})$
Schuler and Sjöstrand	71.5
PHOJET	77.3
Block and Halzen	69
Ryskin *et al.*	65.2 – 67.1
Gotsman *et al.*	68
Achilli *et al.*	60 – 75

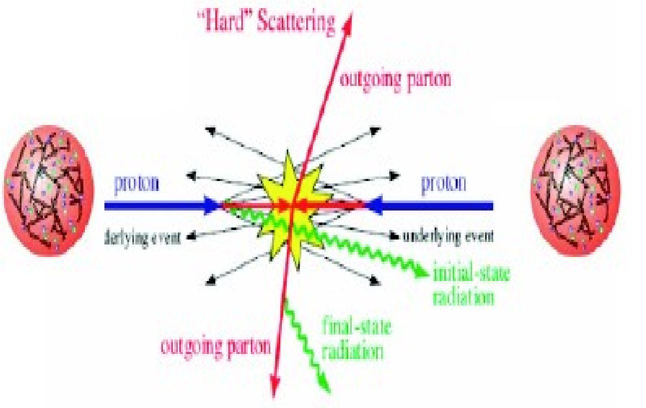
Soft QCD: Charged particles multiplicities

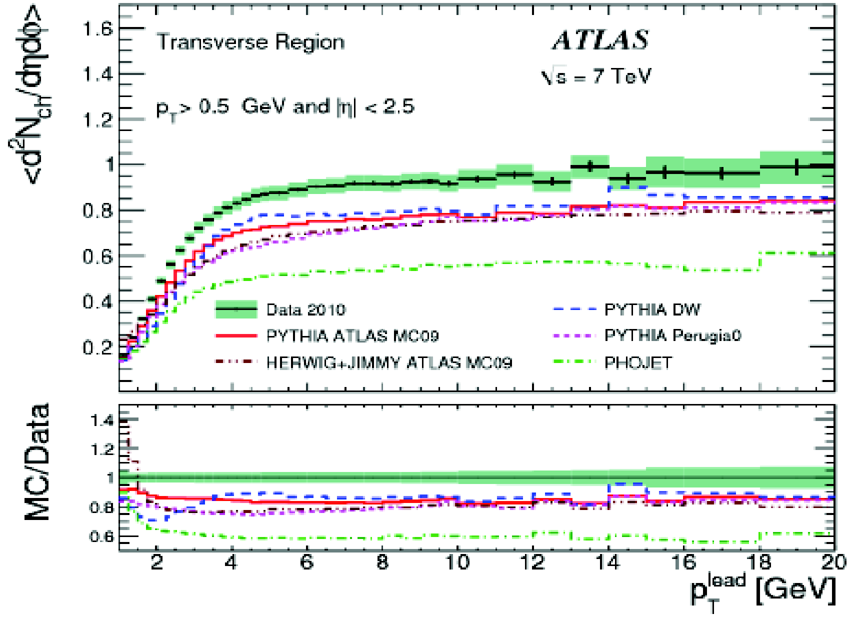
- Extremely precise data
- Also measured for diffraction enhanced/suppressed samples
- Up to 200 tracks per event
- No MC fully describe data, tunes are in progress

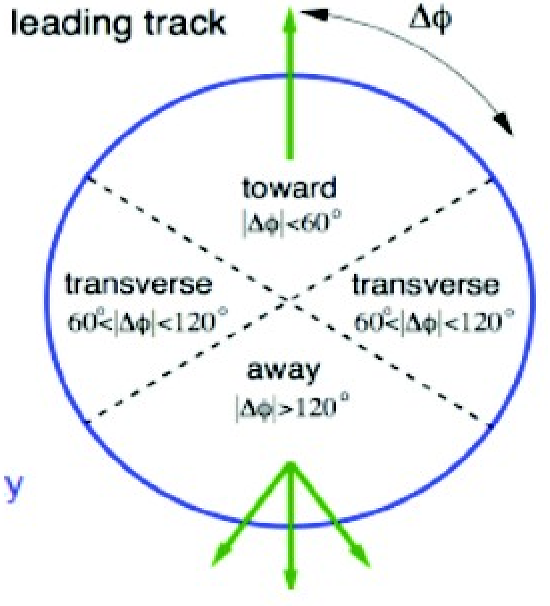


The underlying event

- Transverse region particularly sensitive to multiple (parton) int's.
- All commonly used MC models predict too little transverse activity

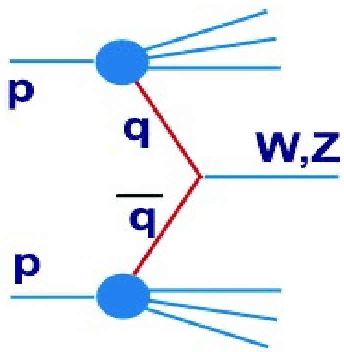


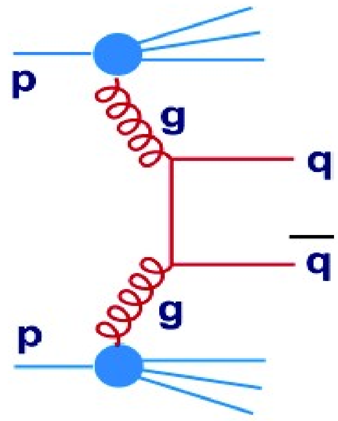


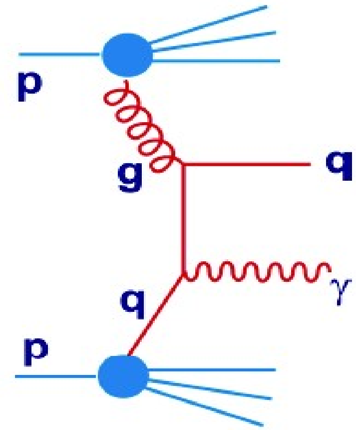


QCD hard scattering processes

- EW gauge bosons Di-jets Direct photons



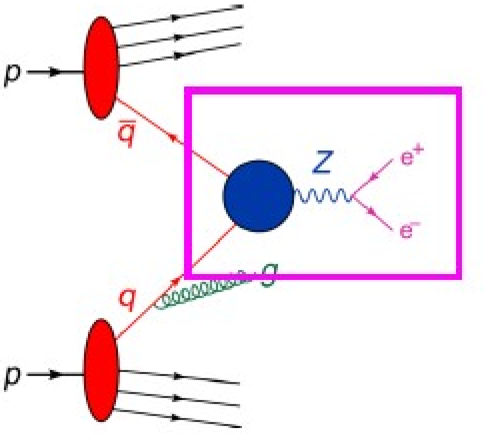




- Measuring those processes test our understanding of:
  - Partonic structure of protons
  - QCD scattering via calculations of N(NLO)
  - Hadronisation/underlying event
  - What makes a good jet algorithm
  - Data driven background estimates for rare processes

QCD factorisation and parton model

- Asymptotic freedom guarantees that as short distances (large transverse momenta) partons in the proton are almost free
- Sampled ”one at a time” in hard collisions
  - QCD improved parton shower model



Parton distribution function:
prob. of finding parton a in proton 1, carrying fraction x_1 of its momentum

“suitable” final state

factorization scale
(“arbitrary”)

$$\sigma^{pp\to X}(s;\alpha_s,\mu_R,\mu_F) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1,\alpha_s,\mu_F)\, f_b(x_2,\alpha_s,\mu_F) \times \hat{\sigma}^{ab\to X}(sx_1x_2;\alpha_s,\mu_R,\mu_F)$$

Partonic cross section, computable in perturbative QCD

partonic CM energy^2

renormalization scale
(“arbitrary”)

Short-distance cross-section in perturbation theory

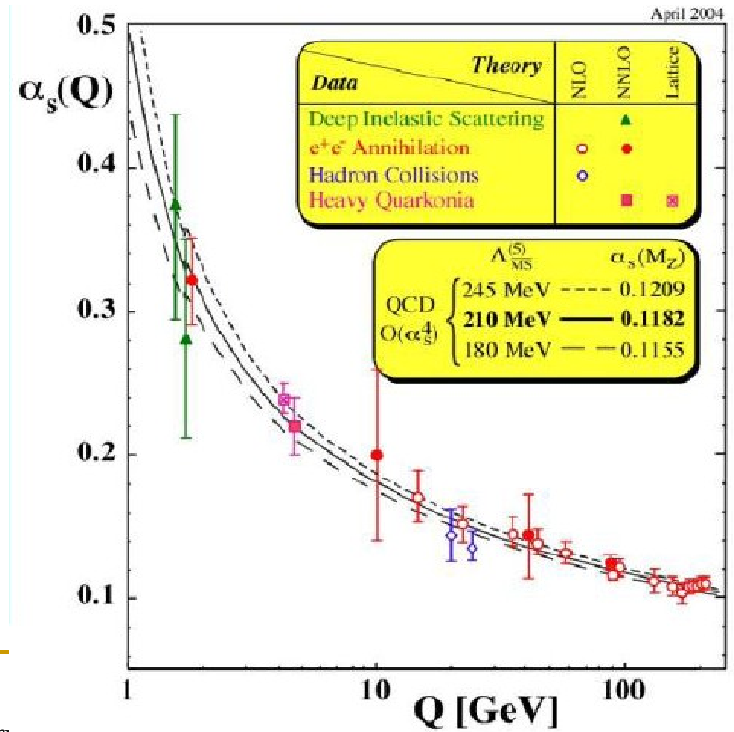
$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) \;=\; [\alpha_s(\mu_R)]^{n_\alpha} \left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi} \hat{\sigma}^{(1)}(\mu_F, \mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F, \mu_R) + \cdots \right]$$

LO NLO NNLO

- Leading-log predictions only qualitative due to poor convergence of the expansion in $\alpha_s(\mu)$
- Traditional estimate error bands by varying combined renormalisation and factorisation scales

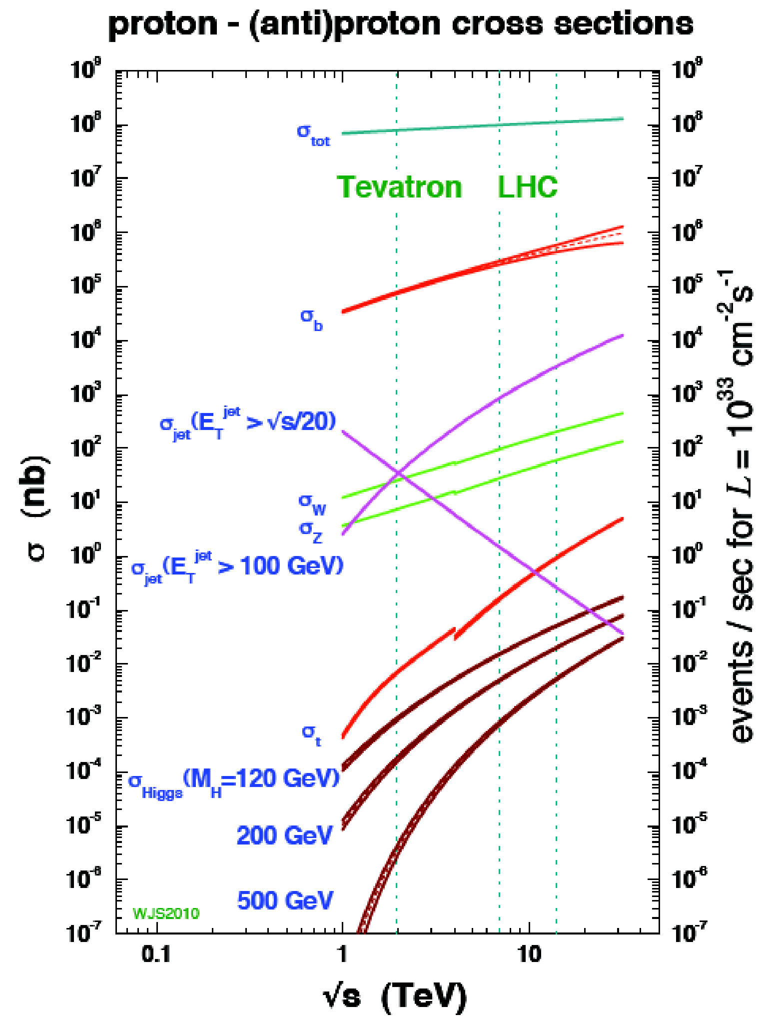
$$\mu_R = \mu_F = \mu$$

from ½ to 2 times the typical scale



Available predictions

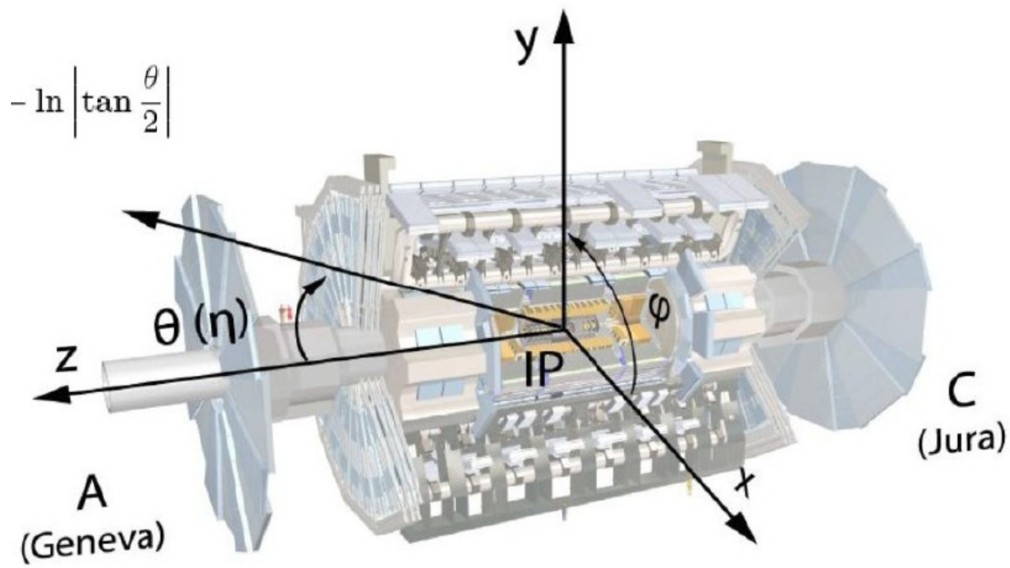
- Accurate predictions for dijet production, W/Z/gamma + jets production at the LHC are available
  - Monte Carlo event generators
    - NLO + parton shower (MC@NLO, POWHEG)
    - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
  - Parton level codes for distributions at NLO
- Modern parton distribution functions

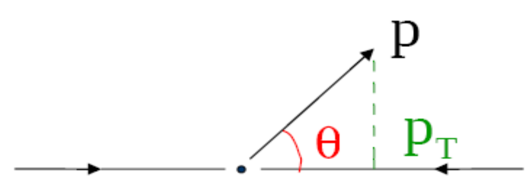


ATLAS Detector

THE ATLAS DETECTOR IS REALLY BIG!

- Length : $\sim$ 46 m
- Radius : $\sim$ 12 m
- Weight : $\sim$ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables





Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

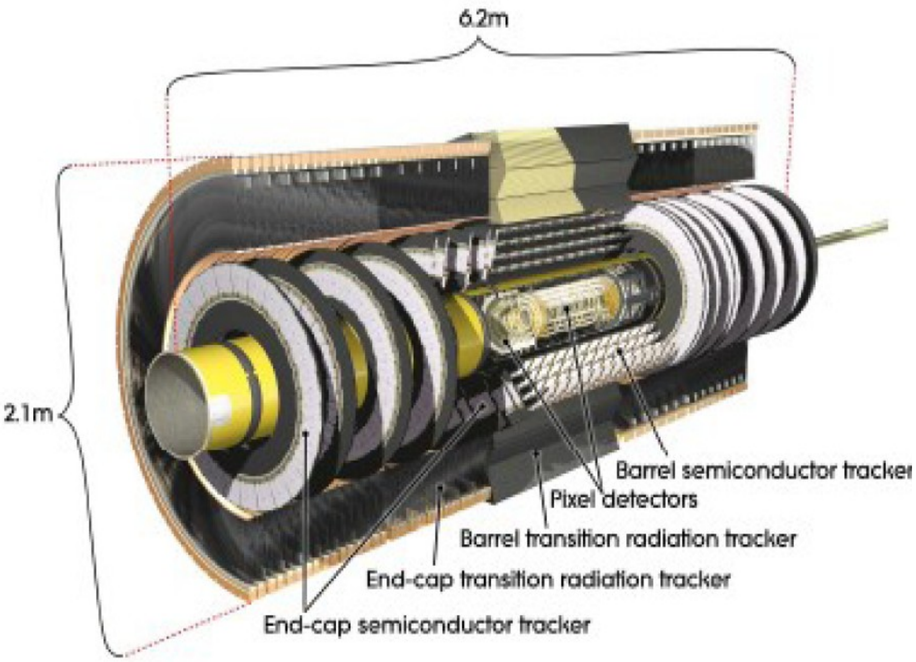
Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

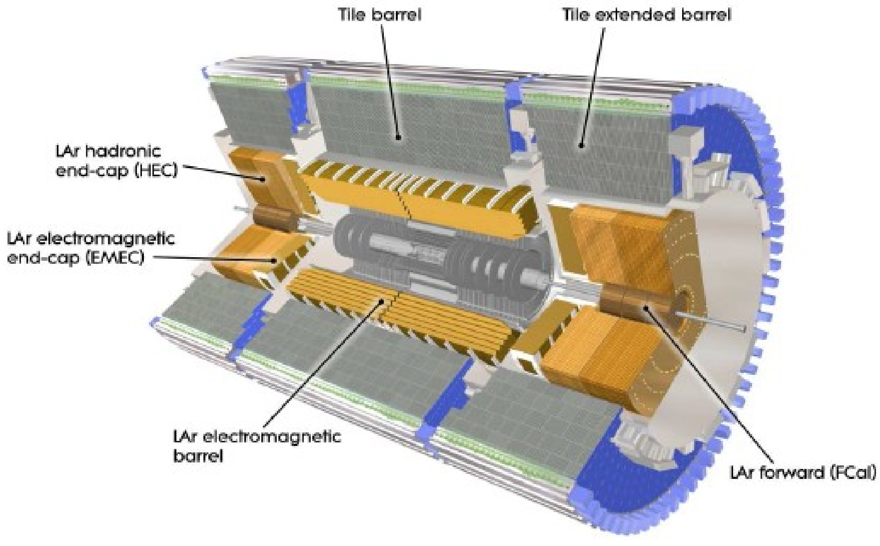
ATLAS Inner Detector



The inner detector $|\eta| < 2.5$ consists of

- Pixel detectors, semi-conductor tracker (SCT), transition radiation tracker
  - $\approx$ 87 million readout channels
  - Immersed in 2T solenoidal magnetic field
- Resolution of $\sigma/p_T = 5 \times 10^{-4} \oplus 0.015$

ATLAS Calorimeters



Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
- Transverse and longitudinal sampling $\approx$ 200000 readout cells up to $|\eta| < 4.9$

Electromagnetic Calorimeters:

- Fine granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in central region
- Energy resolution $10\%/\sqrt{E}$

Hadronic Calorimeters:

- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in central region, less segmented in forward region
- Energy resolution $50\%/\sqrt{E} \oplus 0.03$

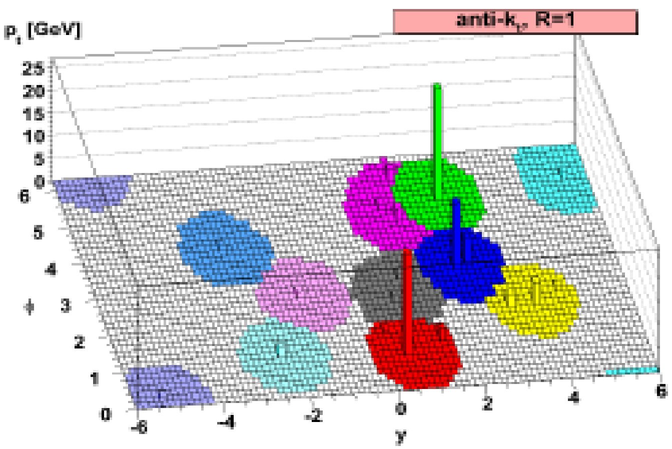
Jet reconstruction in ATLAS

- Jet finding: from partons/particles/energy deposits to jet

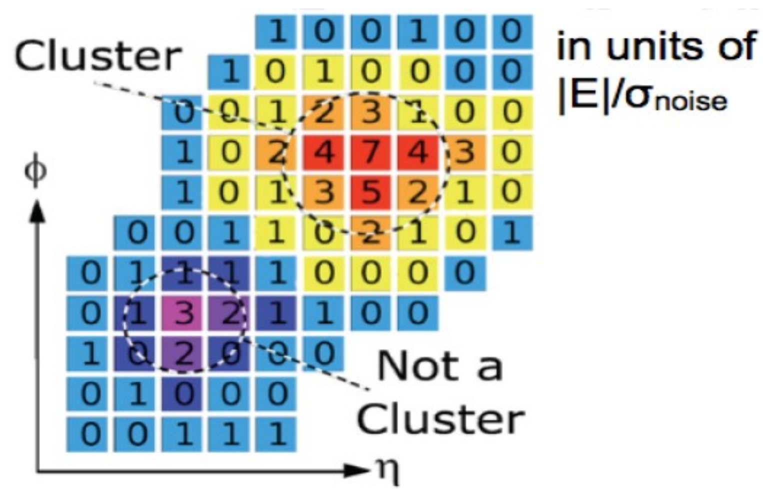
Energy deposits → noise-suppressed **3D clusters**:
exploit transverse and longitudinal calorimeter segmentation

Jet inputs clustered with anti-k_T algorithm:

- Infrared safe, collinear safe (⇒ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6

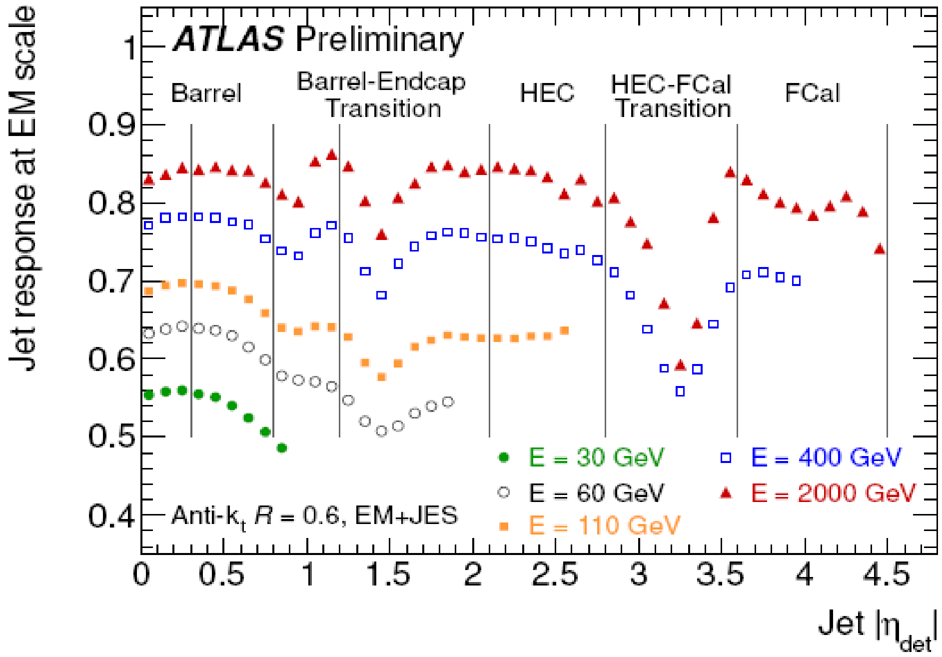


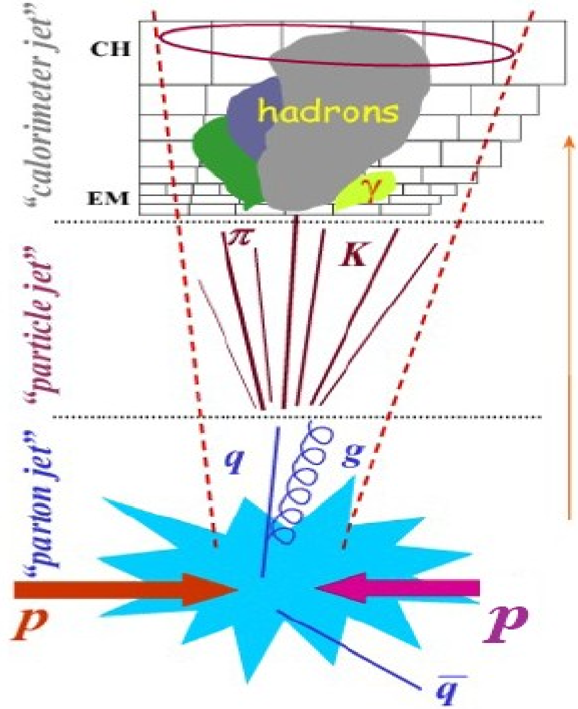
[Cacciari, Salam, Soyez JHEP 0804:063,2008]



Jet reconstruction in ATLAS

- Jet calibration:restore the jet energy scale (JES) starting from the EM energy scale





Transitions between separate calorimeters evident.

η-dependent jet calib corrects for response diffs in η

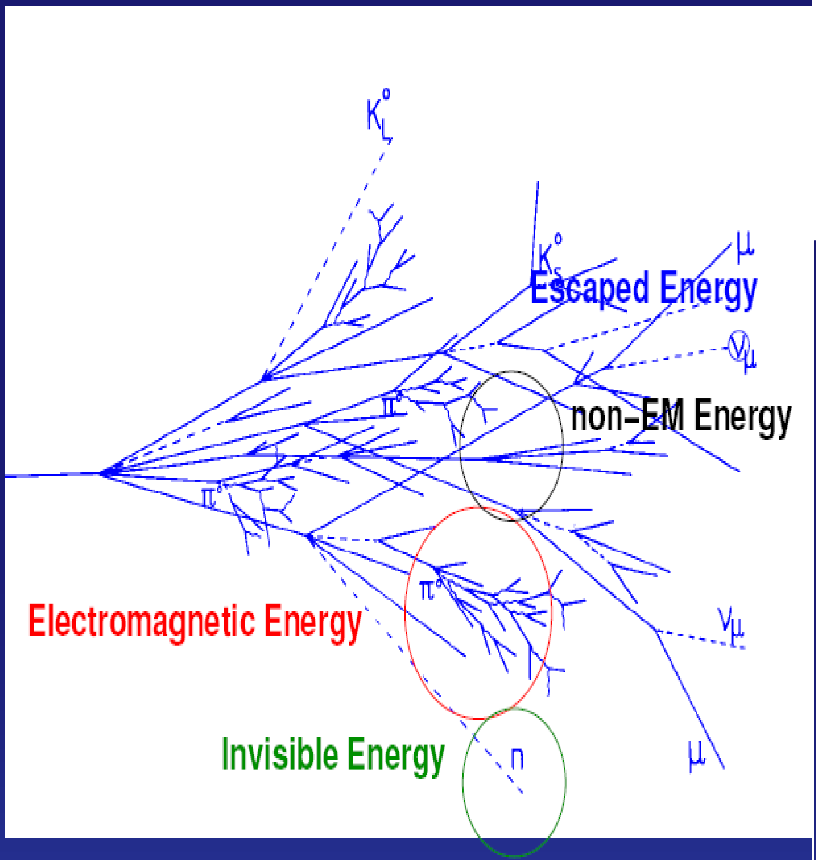
Calorimeter jet response needs to be corrected for :

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

$\Rightarrow$ calibrate the jet kinematics to the hadronic scale

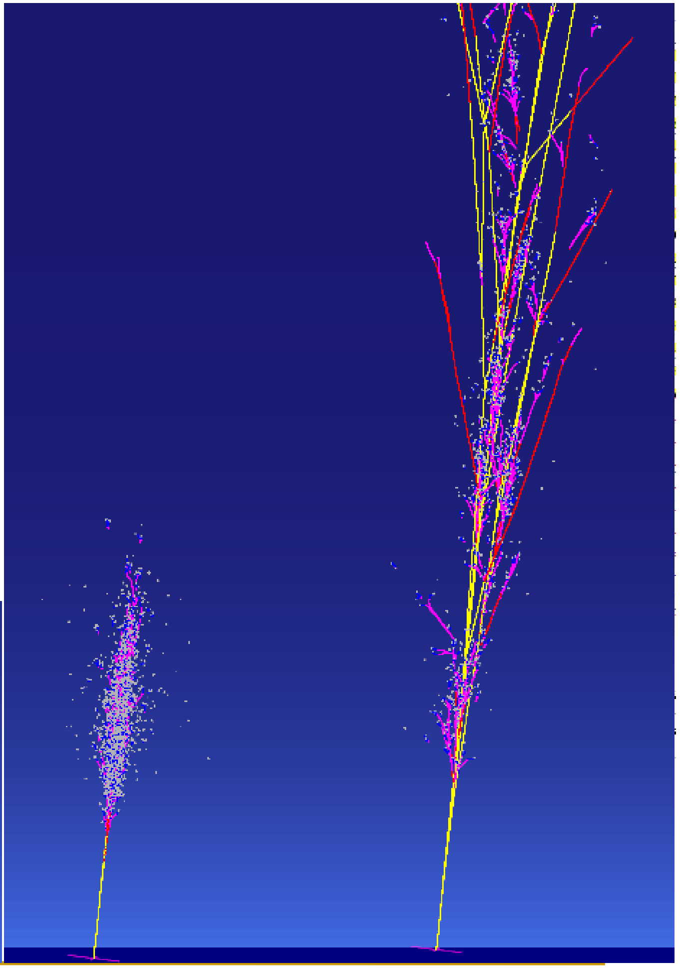
A hadronic shower consists of

- EM energy (e.g. $\pi^0 \to \gamma\gamma$) $O(50\,\%)$
- visible non-EM energy (e.g. dE/dx from $\pi^\pm, \mu^\pm$, etc.) $O(25\,\%)$
- invisible energy (e.g. breakup of nuclei and nuclear excitation) $O(25\,\%)$
- escaped energy (e.g. ν) $O(2\,\%)$



each fraction is energy dependent and subject to large fluctuations

50 GeV showers of electron (left) and pion (right) in iron

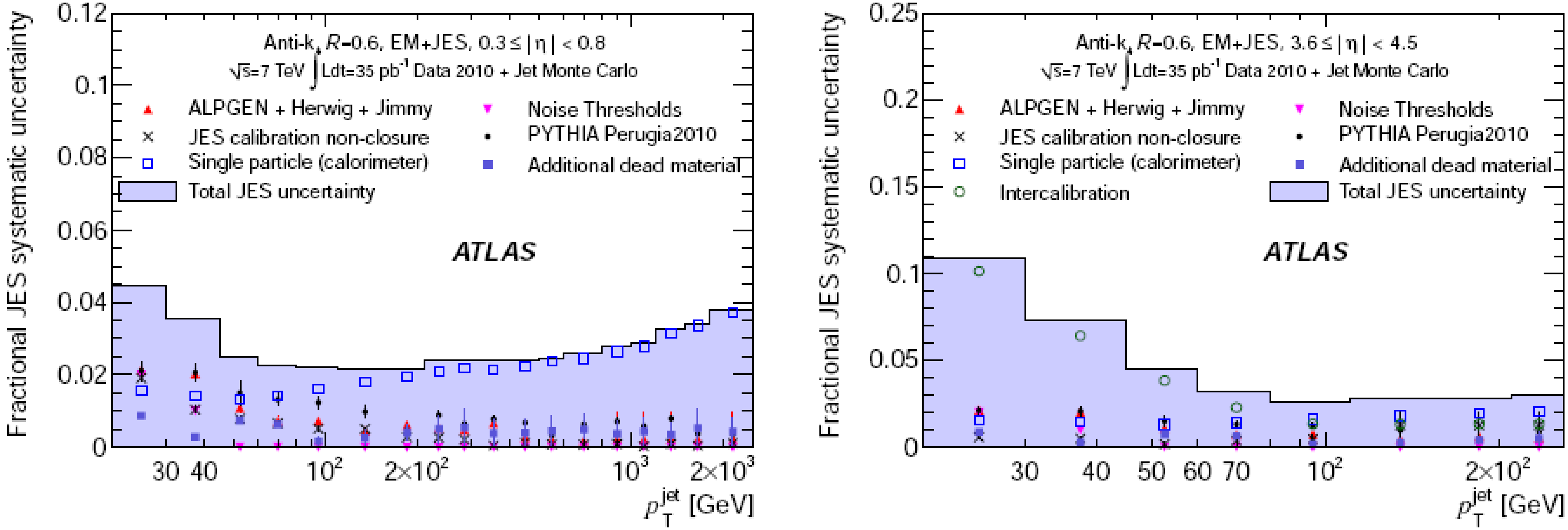


invisible energy is the main source of the non-compensating nature of hadron calorimeters

hadronic calibration has to account for the invisible and escaped energy and deposits in dead material and ignored calorimeter parts

Jet energy calibration

- Jet measurements require calibration of the jet energy scale
  - Derives a calibration which restores average JES with (η,E)-dependent calibration constants from MC



Central region $(|\eta| < 0.8)$, $60 < p_T < 800$ GeV $< 2.5\%$

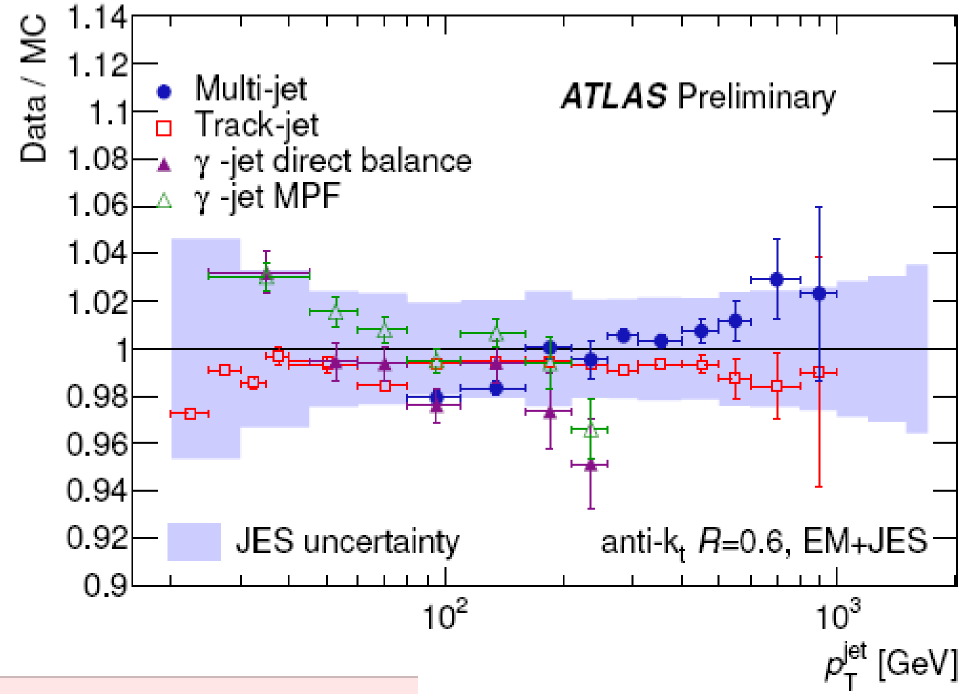
Forward region $(3.6 < |\eta| < 4.5)$, $p_T > 20$ GeV $< 12\%$

Jet energy calibration

- In-situ techniques used to validate JES and its uncertainty
  - Use well calibrated objects as reference for jet p_T
  - Compare calibrated JES in data and Monte Carlo simulation

Techniques used in ATLAS:

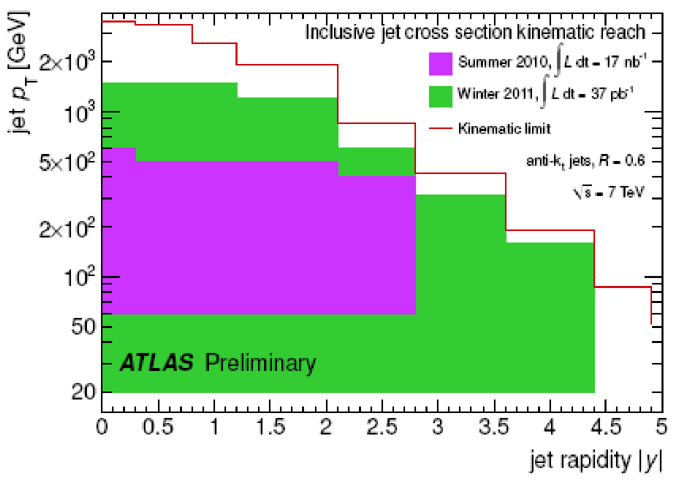
- Balance high p_T jet with recoil system (*Multi-jet / MJB*)
- γ-jet direct p_T balance
- Missing-E_T projection fraction (*MPF*)
- Compare calorimeter jets to track-jets
- $Z \to ee$-jet p_T balance (2011 only)

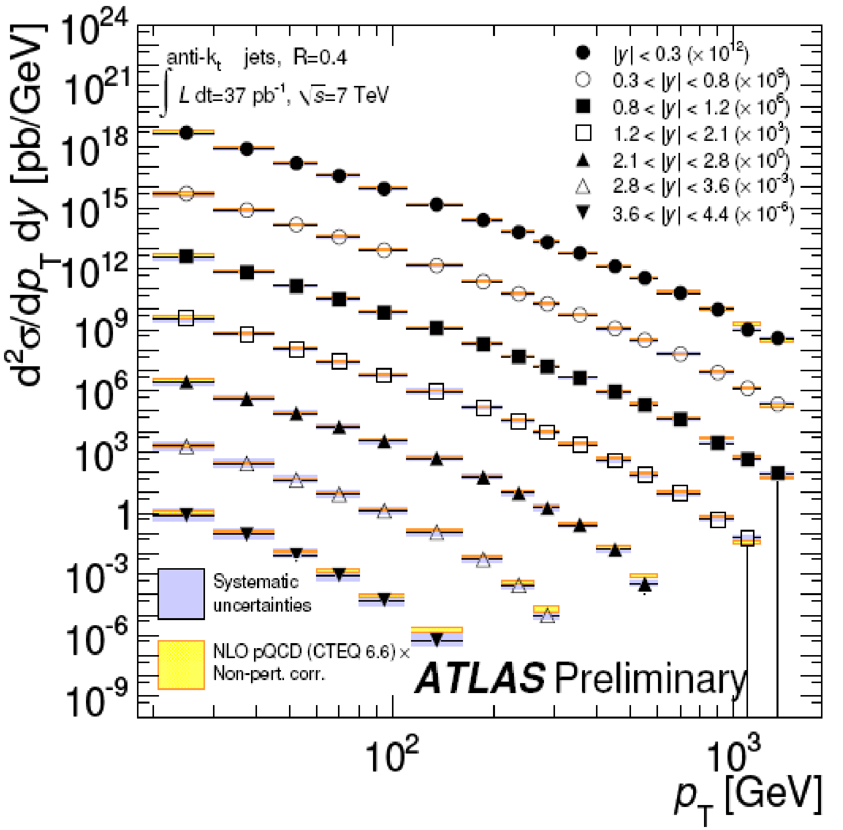


ATLAS goal for jet energy scale uncertainty: **1%**

Inclusive jet cross-section

Using 37 pb^{-1} pb of data, increasing the kinematic range of previous measurements

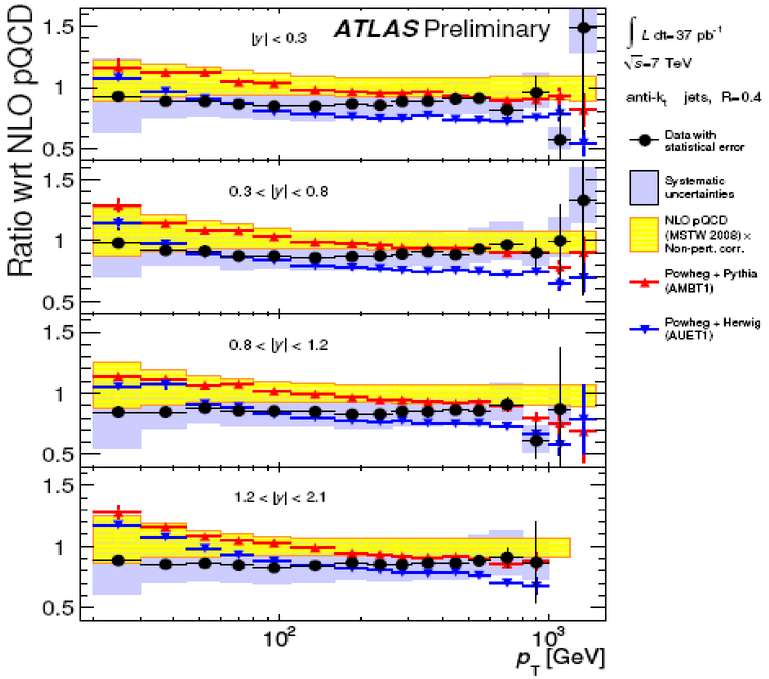


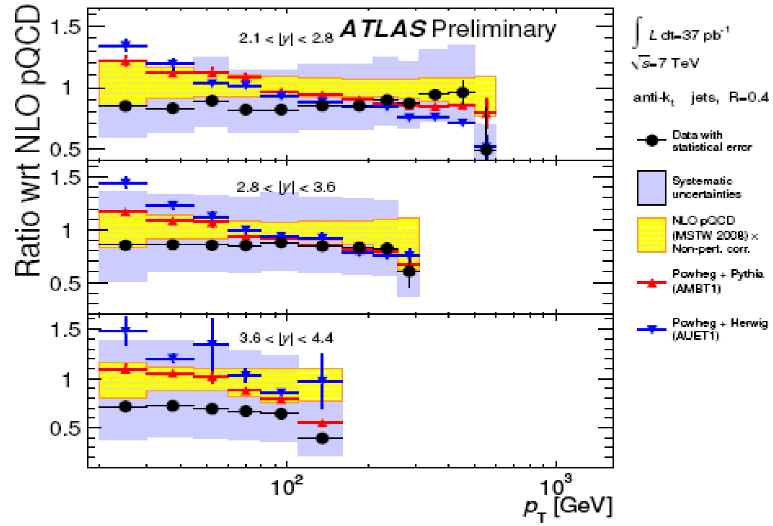


- Cross section out to $|y| < 4.4$
- p_T up to 1.5 TeV

Comparison of data to NLO pQCD predictions with CTEQ 6.6.

Inclusive jet cross-section





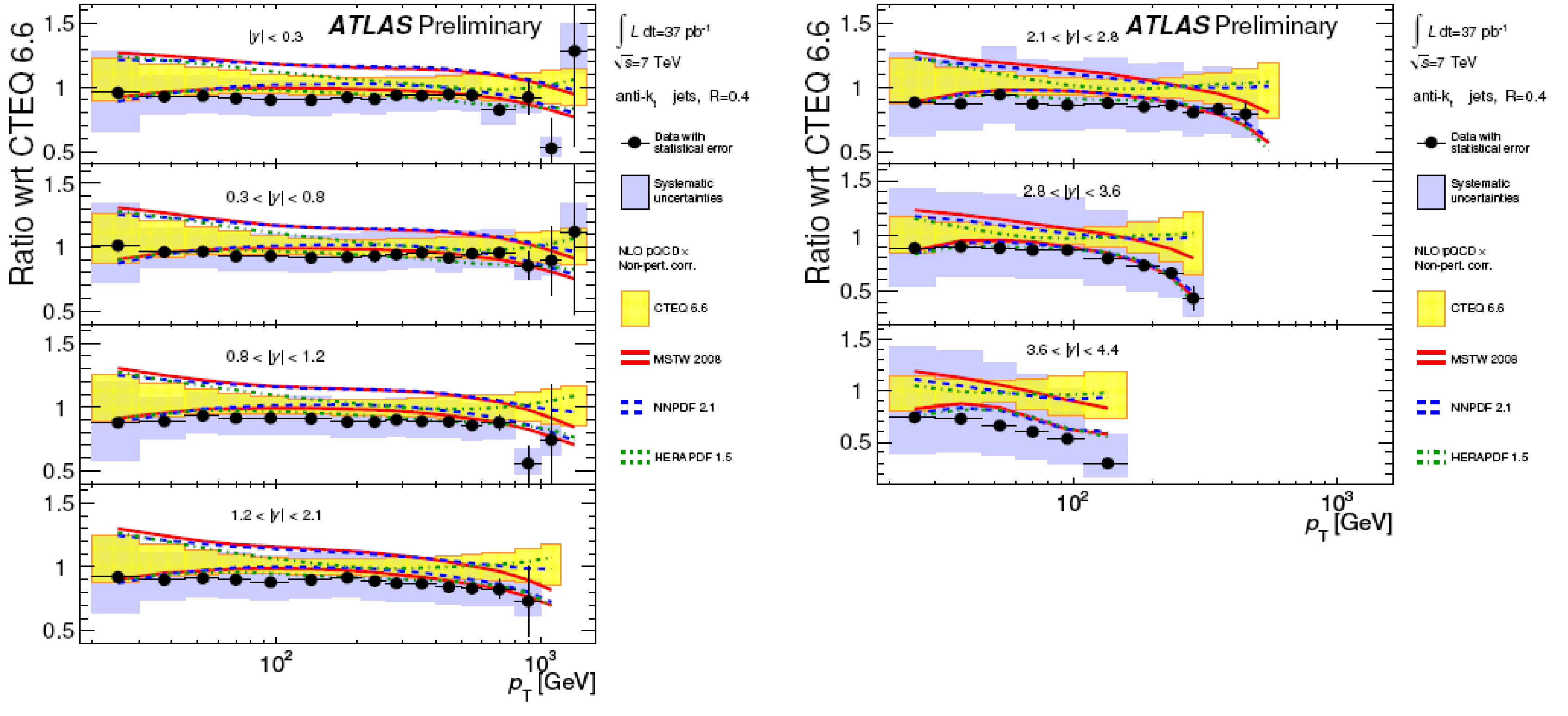
Powheg predictions are consistent with data and NLOJet++, with present uncertainties

Trend for Powheg to predict different slope to cross section

Prediction w.r.t NLOJet++ MC

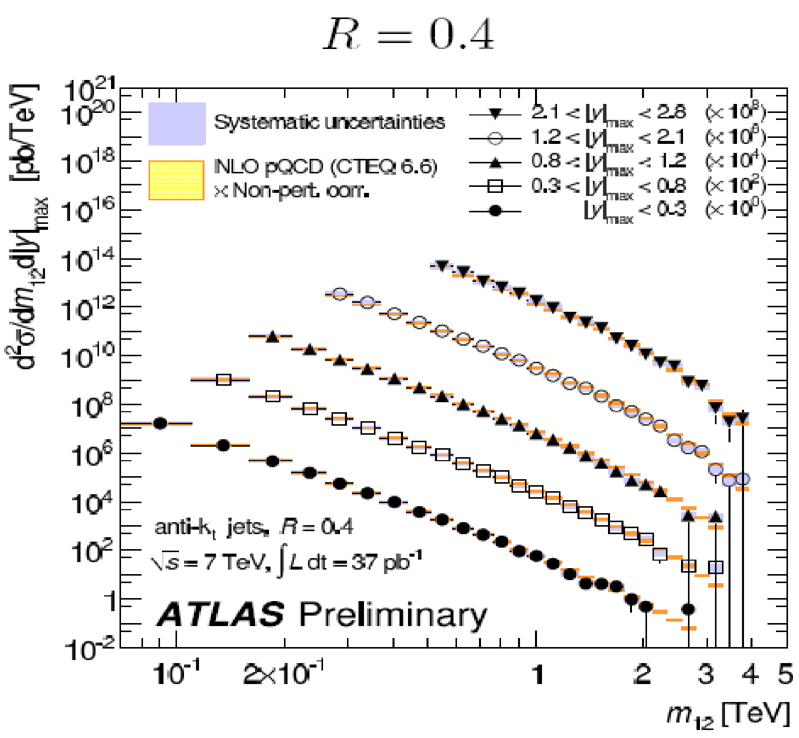
$AMBT1$, $AUET1$ are different detector tunes

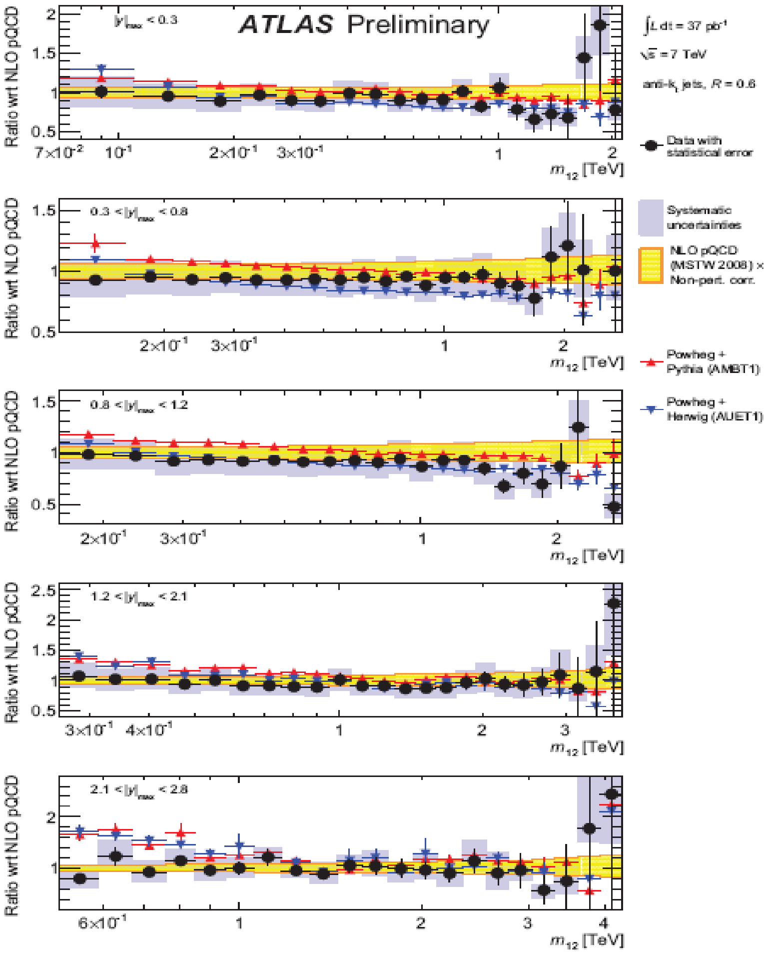
Inclusive jet cross-section



Ratio of inclusive jet cross section measurement in data and MC, with various PDFs

Dijet cross-section



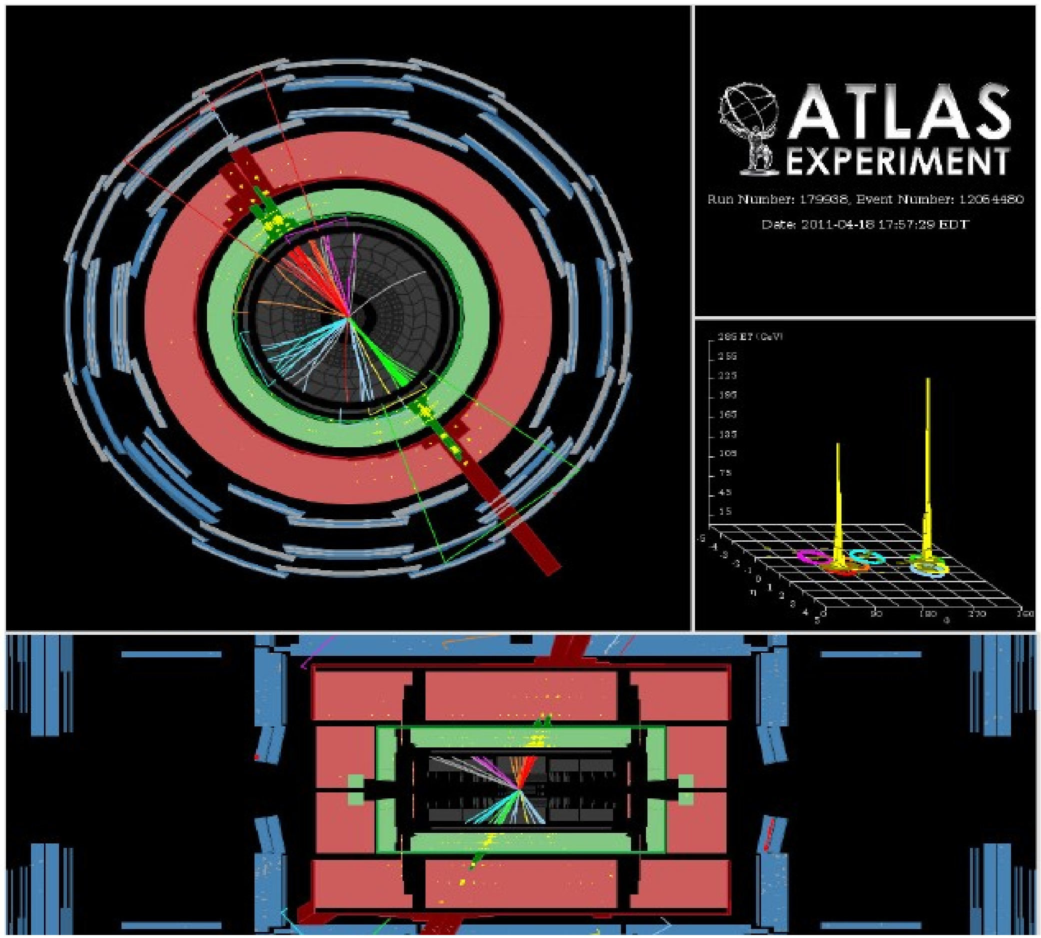


Observing masses up to 4.1 TeV, new energy range!

Powheg systematically predicts higher cross sections at low mass, and lower prediction at high mass, than NLOJet++

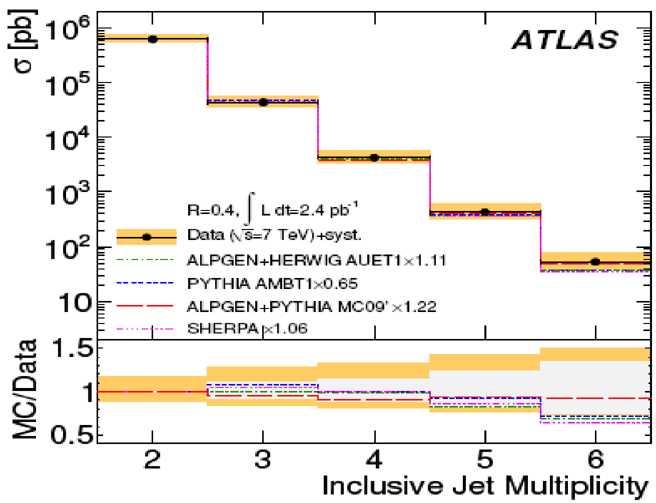
ATLAS high mass dijet event

2011 data event with dijet mass of 4040 GeV



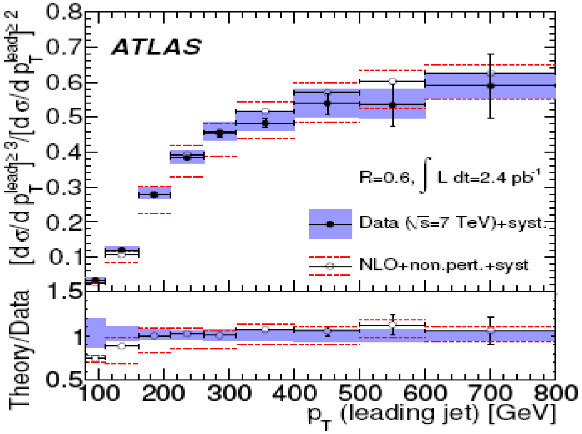
Multi jet cross-section

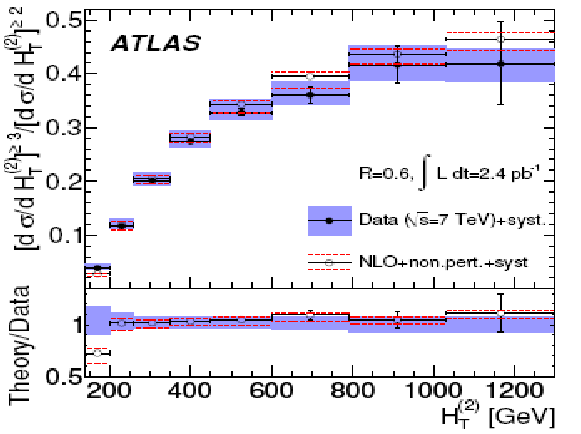
- Fundamental and direct test of QCD
- Main systematics: JES and "close-by jets" effect



Find ALPGEN better describes data

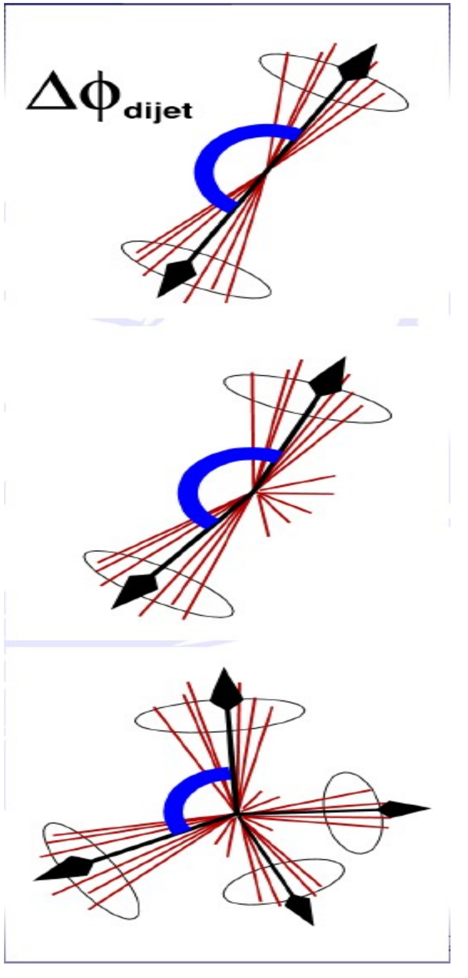
Ratio σ(3-jet)/σ(2-jet) much smaller uncertainties





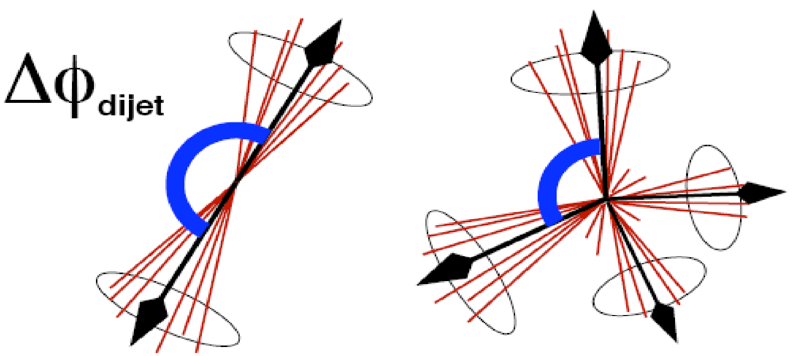
Studies of higher order QCD radiation

- Azimuthal decorrelations in dijet events and distribution of energy within jets sensitive to QCD radiation structures
  - Probing higher order QCD radiation
  - Main systematics: cluster energy scale (separate from JES) and unfolding

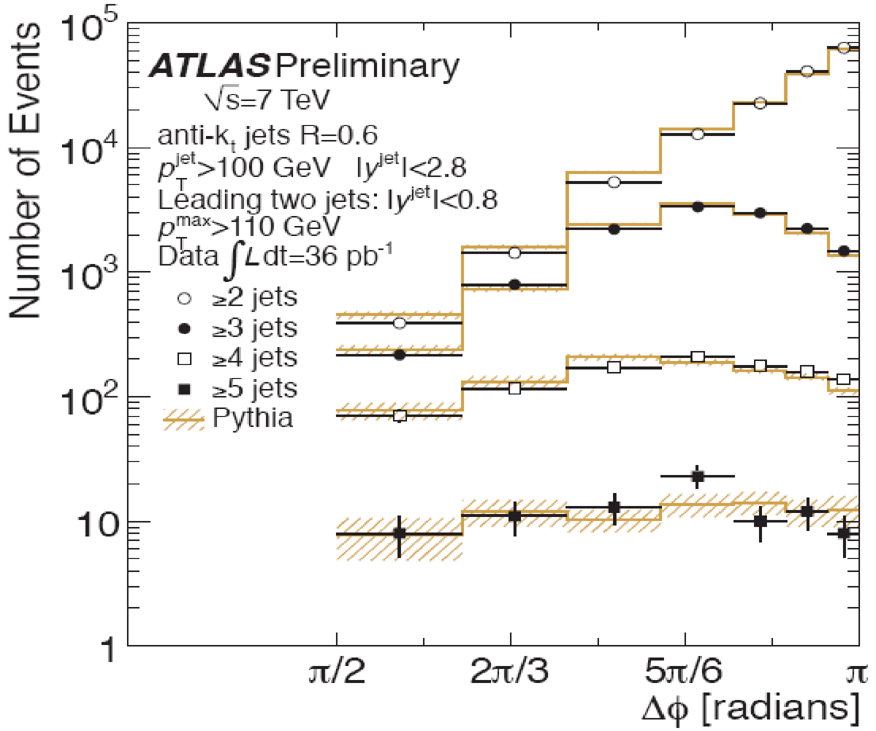


Azimuthal decorrelations

- Complementary to multi-jet cross section measurement.
- Pure di-jets have azimutal angle Φ between jets equal to π.
- With additional hard radiation, i.e. extra jets, phi becomes smaller.

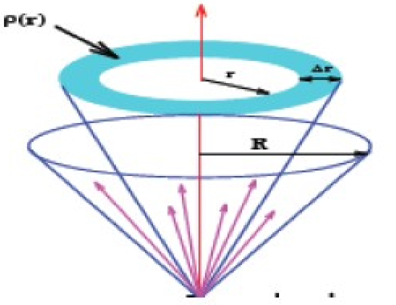


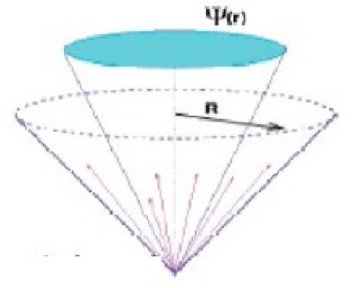
- Requiring additional jets flattens distribution.



Jet substructure

- Jets are both complete 4-vectors and complex composite objects.
- At LHC energy decays of top, W, etc decays can be collimated into one jet
- Knowledge of the internal jet substructure is important in distinguishing these decays from gluon or quark initiated jets
- Internal structure of energetic jets is mainly dictated by emission of multiple gluons from primary parton
  - Calculable in pQCD





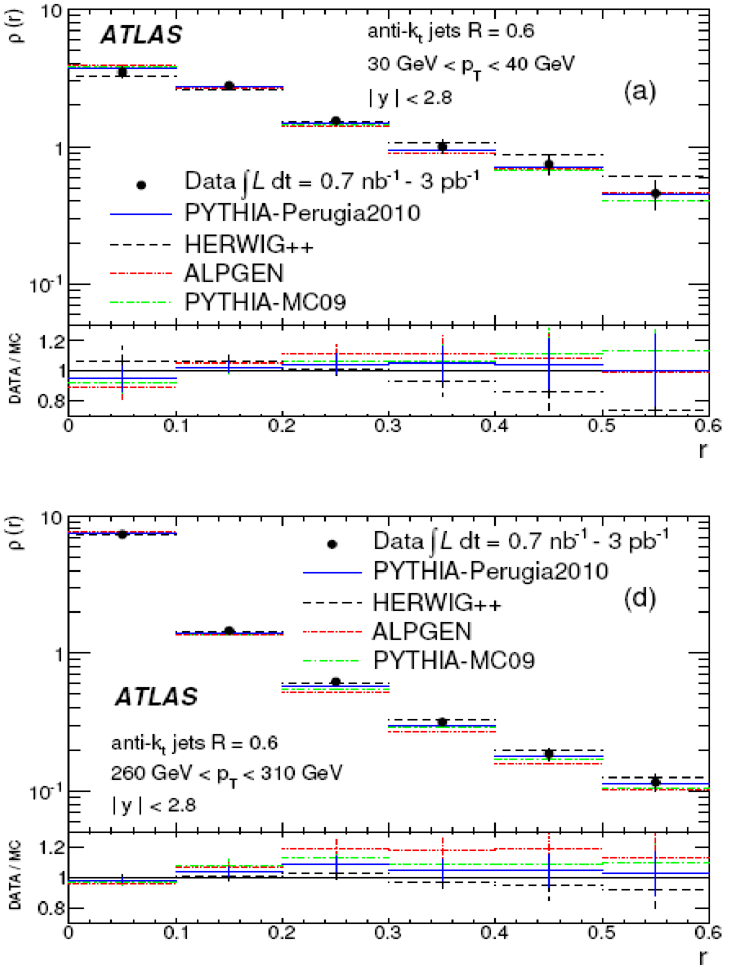
Differential jet shape

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\Sigma_{jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}, \Delta r/2 \leq r \leq R - \Delta r/2 \qquad (1)$$

Integral jet shape

$$\Psi(r) = \frac{1}{N_{jet}}\Sigma_{jet}\frac{p_T(0,r)}{p_T(0,R)}, 0 \leq r \leq R \qquad (2)$$

Jet substructure

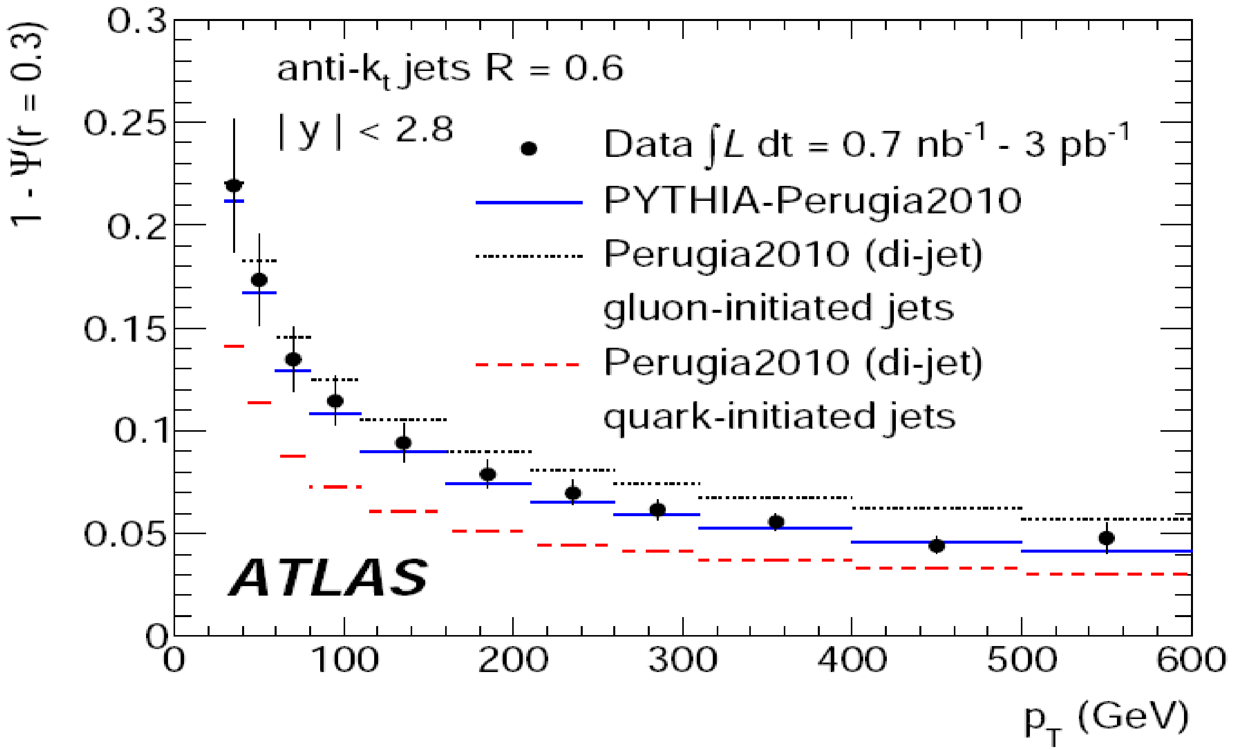


Differential jet shapes vs jet p_T, integrated over $|y| < 2.8$

- As expected, jet narrows with increasing p_T
- Data compared to various MC predictions
  - PYTHIA-Perugia2010
  - PYTHIA-MC09
  - Herwig++
  - Alpgen (with Herwig+Jimmy)
- General agreement, although Herwig++ predicts jets too narrow

Jet substructure

Jet substructure studies have matured well beyond comparisons of quark- and gluon-initiated jets in event generators:



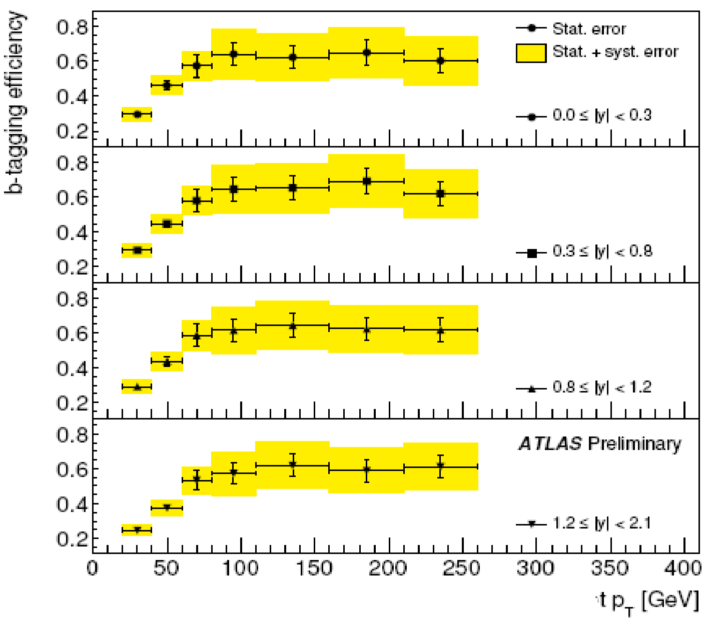
b-jet cross-section

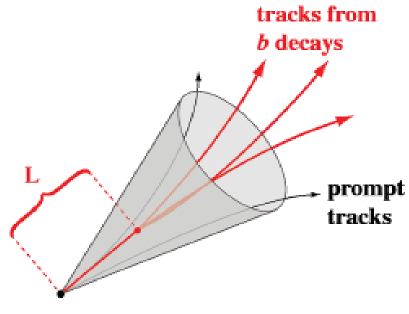
b-jet tagger "SV0"

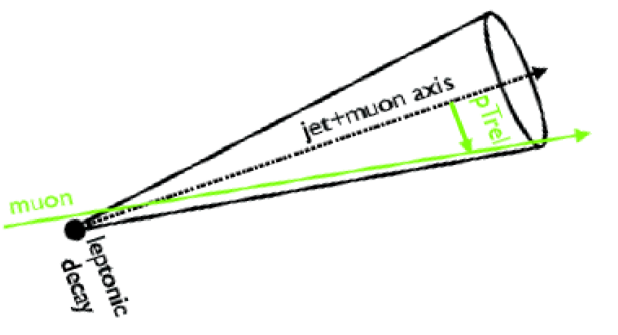
- Iterative secondary vertex seeding from track pairs
- separation power from decay length significance

Also tag *b*-jets with muon decay

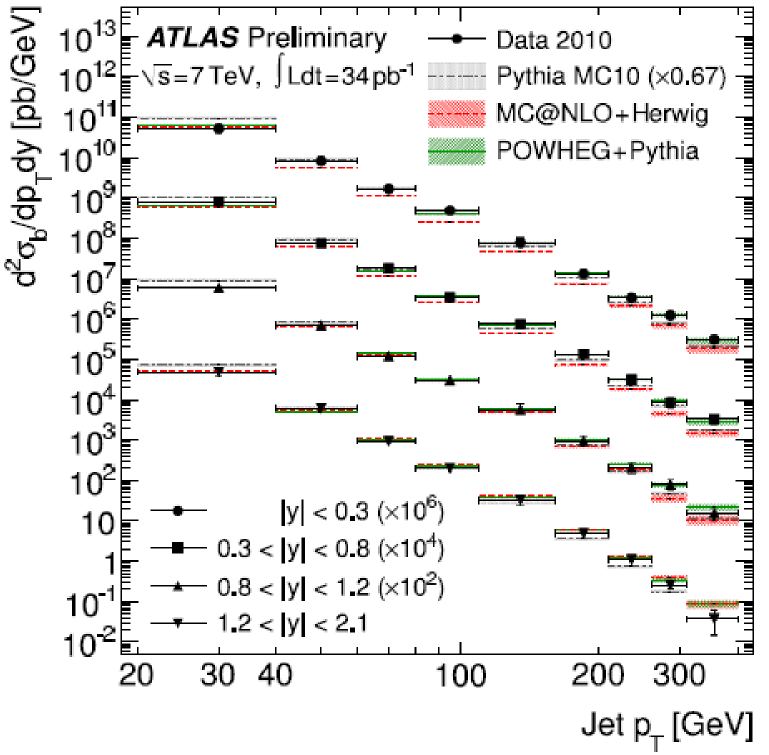
- Determine the relative distance between jet axis and muon
- Fit templates for *b*-jet contribution

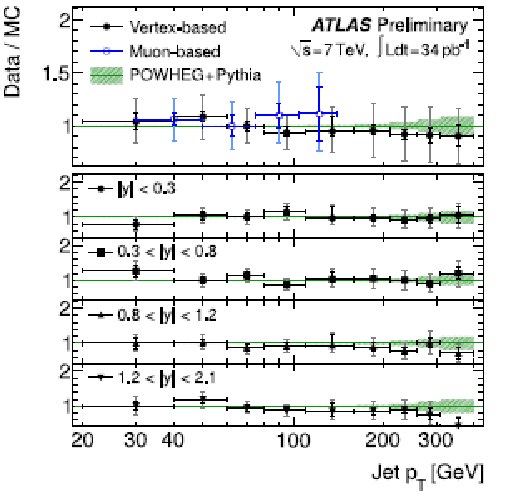


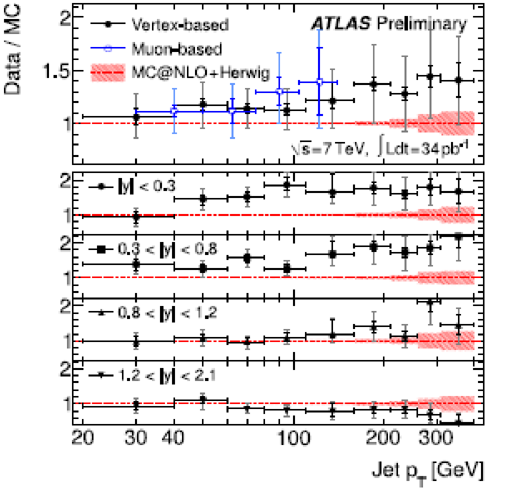




b-jet cross-section

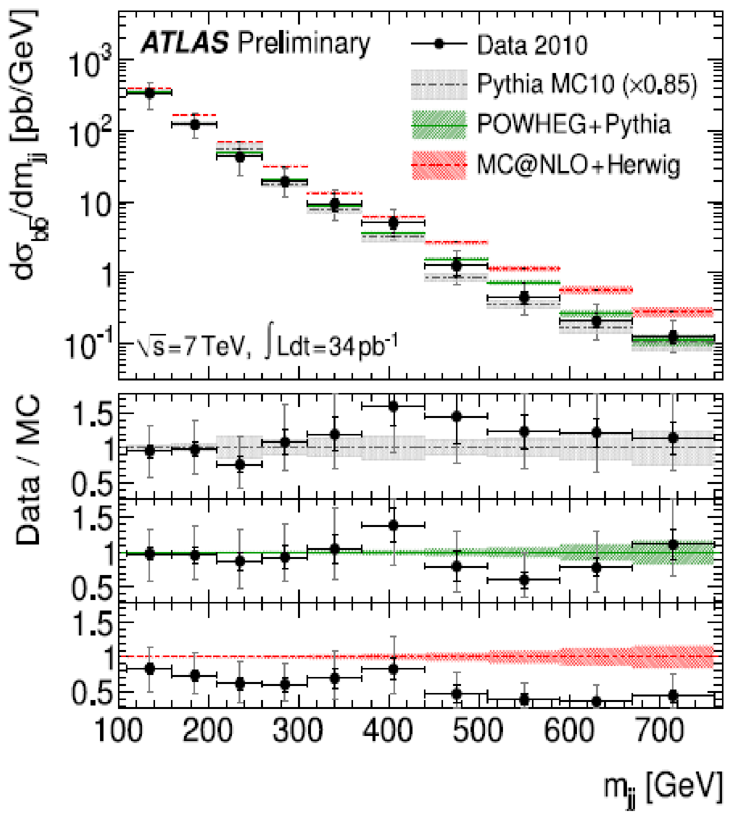




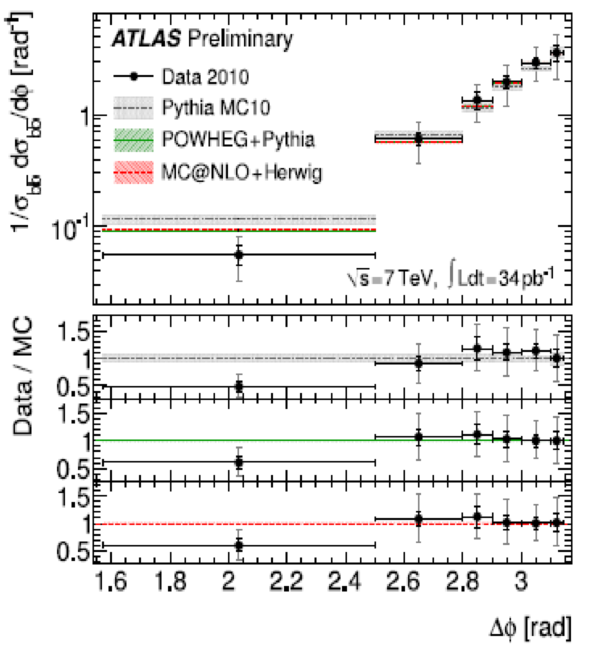


- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

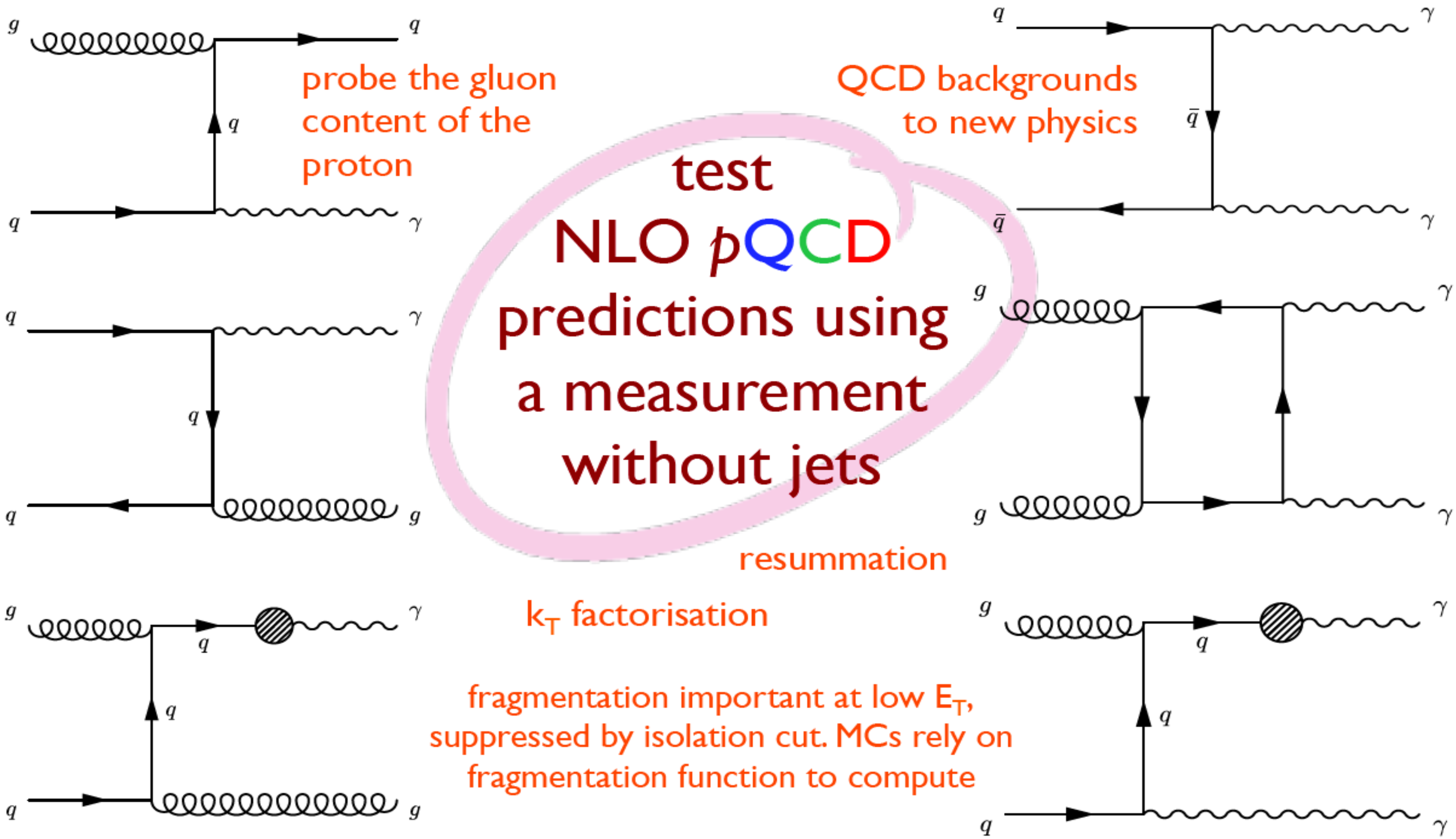
Inclusive bb-jet cross-section



- PYTHIA MC10 and Powheg show good agreement
- MC@NLO does not model the data, especially at high dijet mass

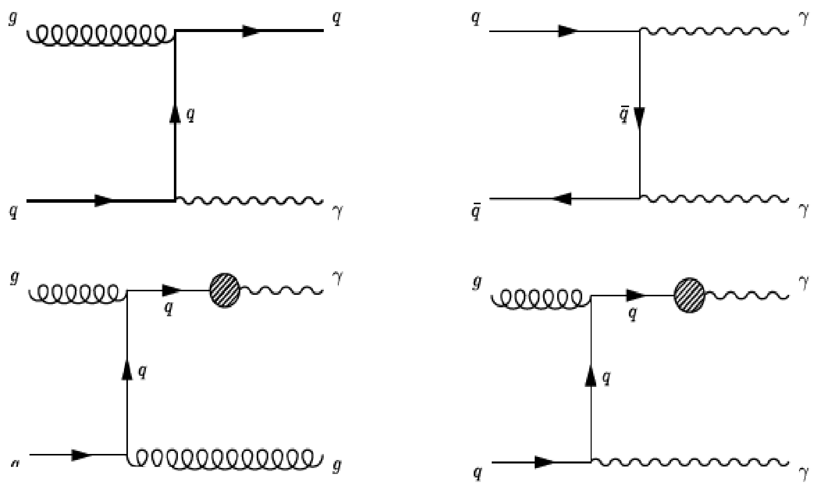


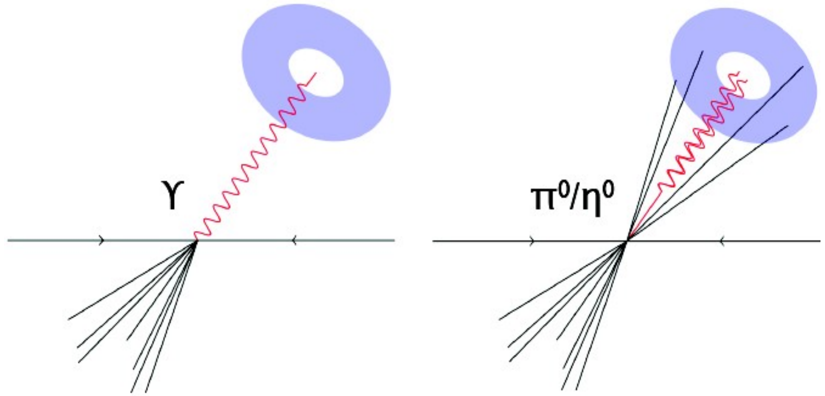
Why measure prompt photons?



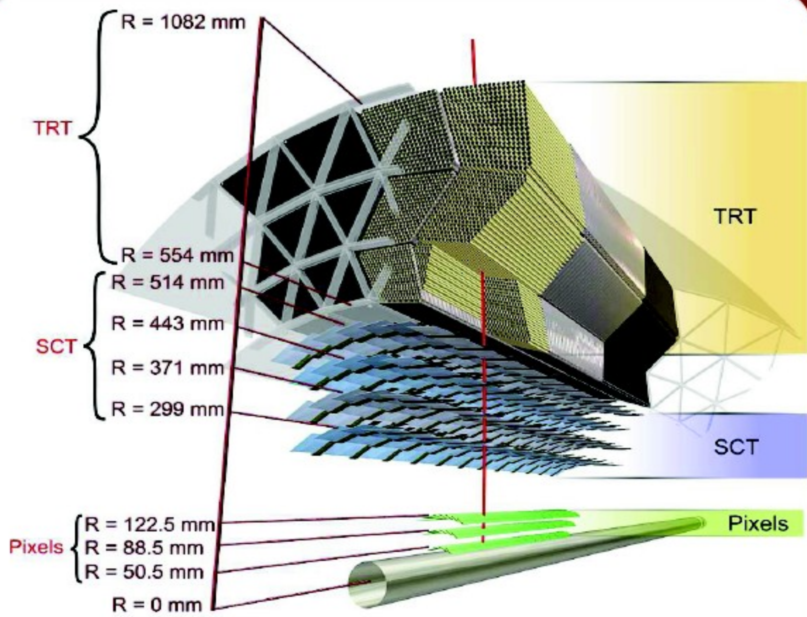
Prompt and isolated photons

- Prompt:
  - Direct from the hard scattering
  - Parton fragmentation more important at low E_T
- Isolated:
  - Isolation criteria to reduce bgd from QCD jets
    - Photons from neutral meson decay in jets
  - Reduced fragmentation component:
    - ~30% reduction at 15 GeV
    - <10% above 35 GeV

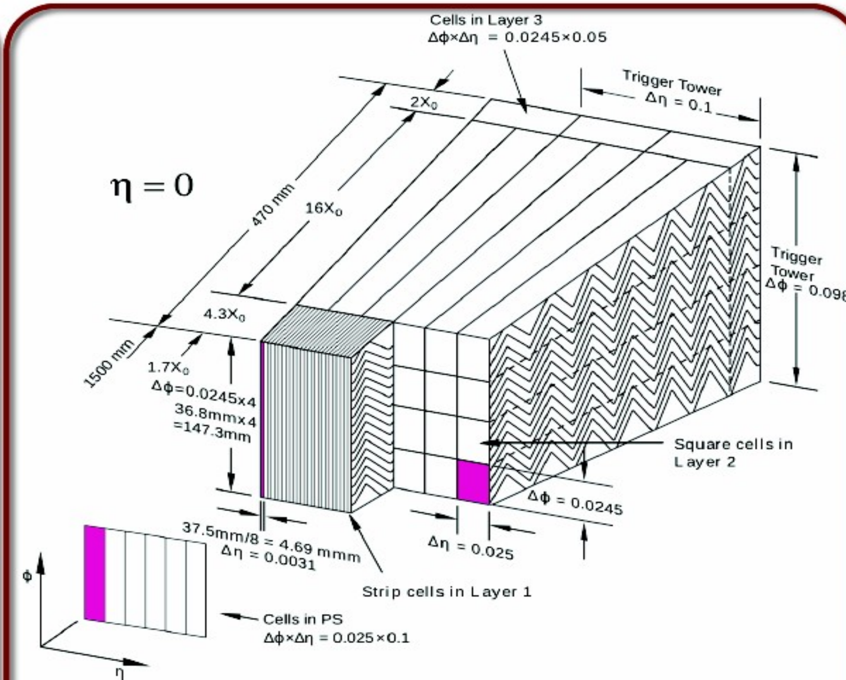




Measuring photons with ATLAS

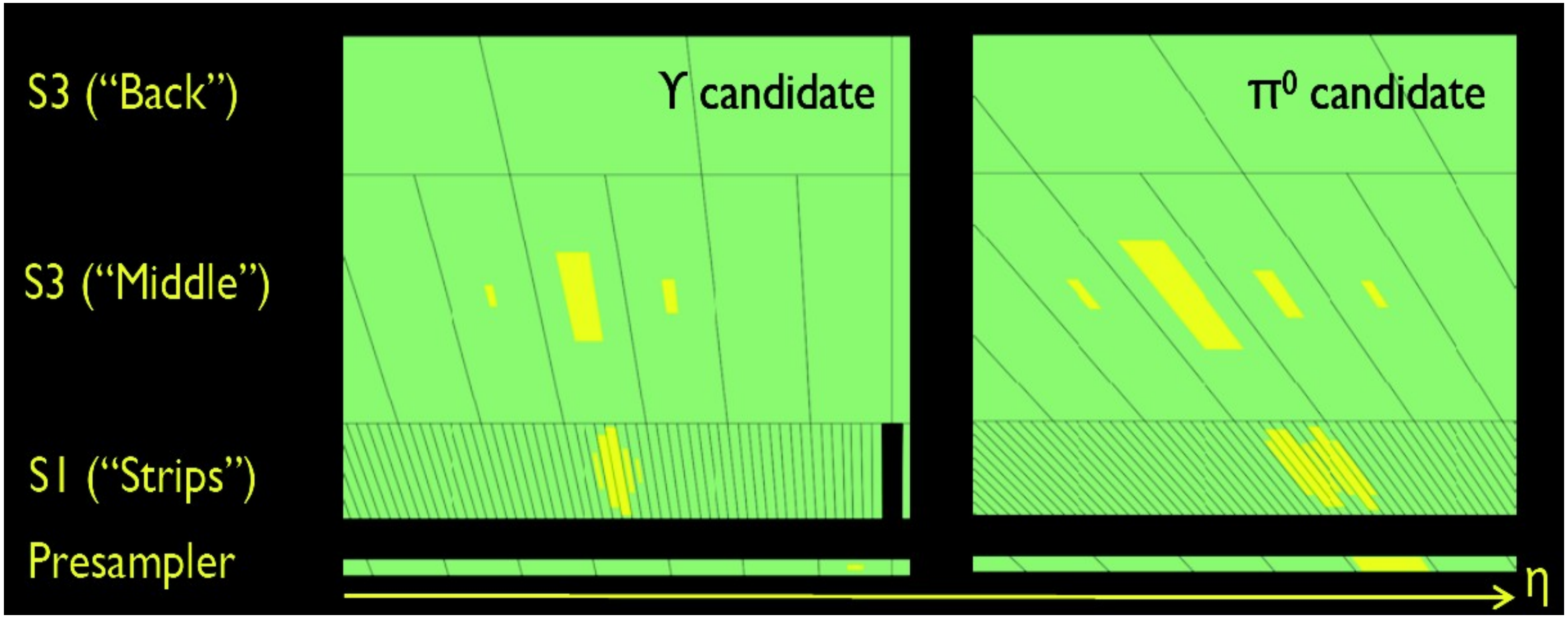


- Inner detector
  - ✓ track charged particles
  - ✓ measure transition radiation
  - ✓ e/γ discrimination
  - ✓ γ conversion reconstruction

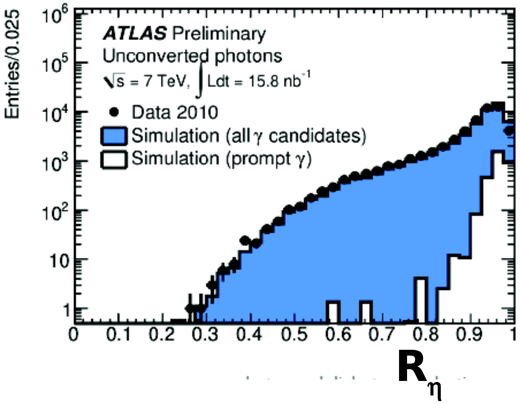


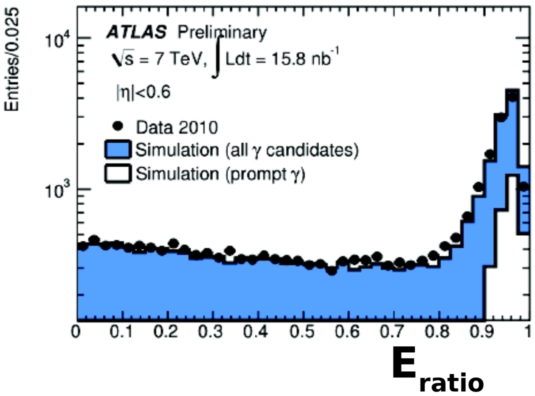
- Pb-LAr EM calorimeter
  - ✓ η/φ/longitudinal segmentation
  - ✓ fine granularity in 1st layer up to η<2.37
  - ✓ γ energy and direction
  - ✓ γ/π⁰ separation (EM shower moments)

Photon identification

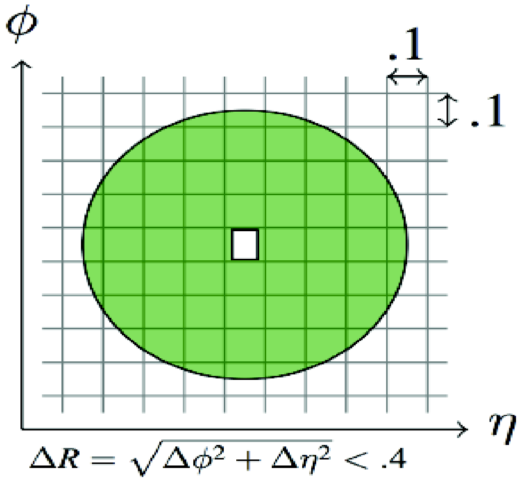


- loose and tight selection
- optimised separately for unconverted and converted photons

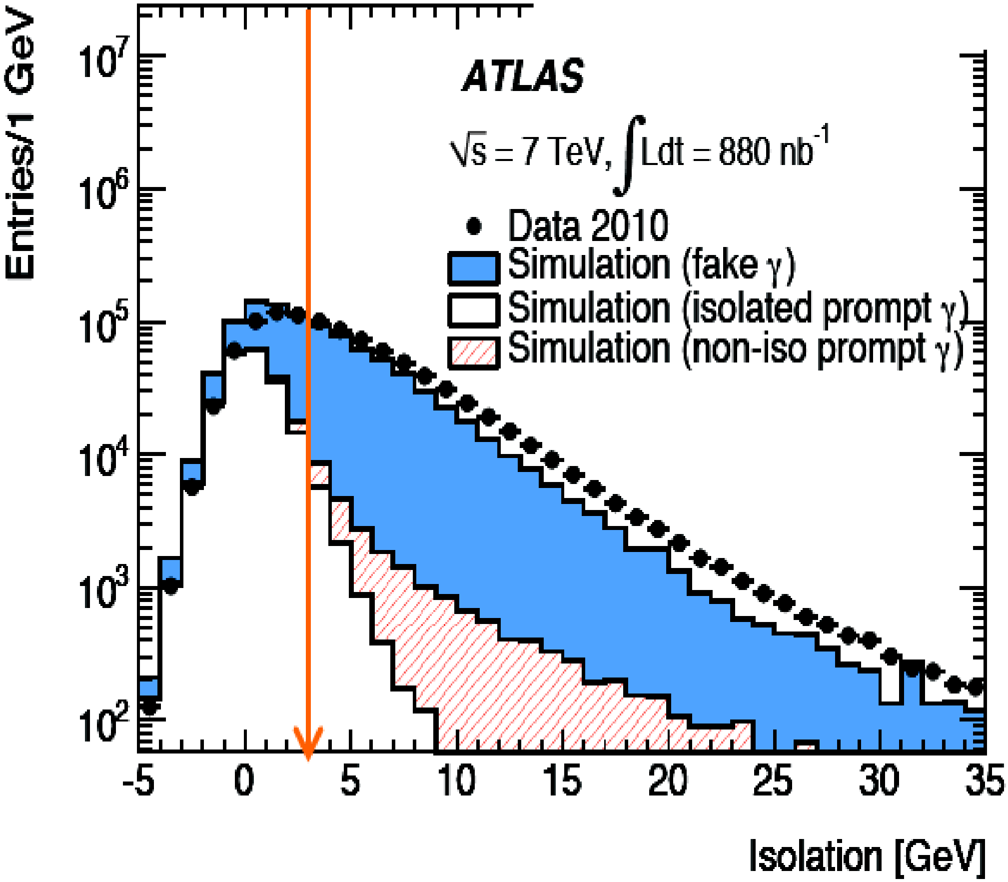




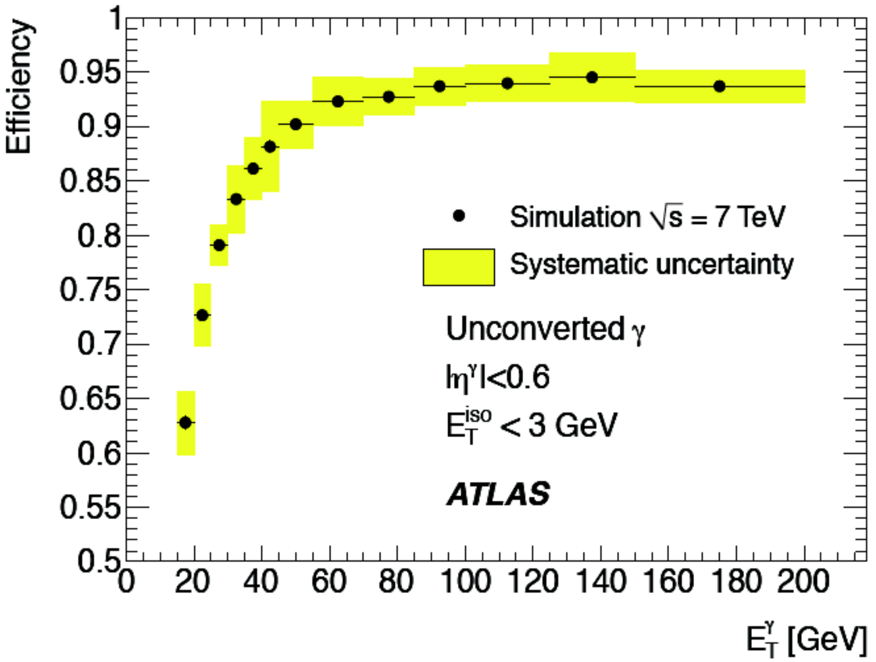
Photon isolation

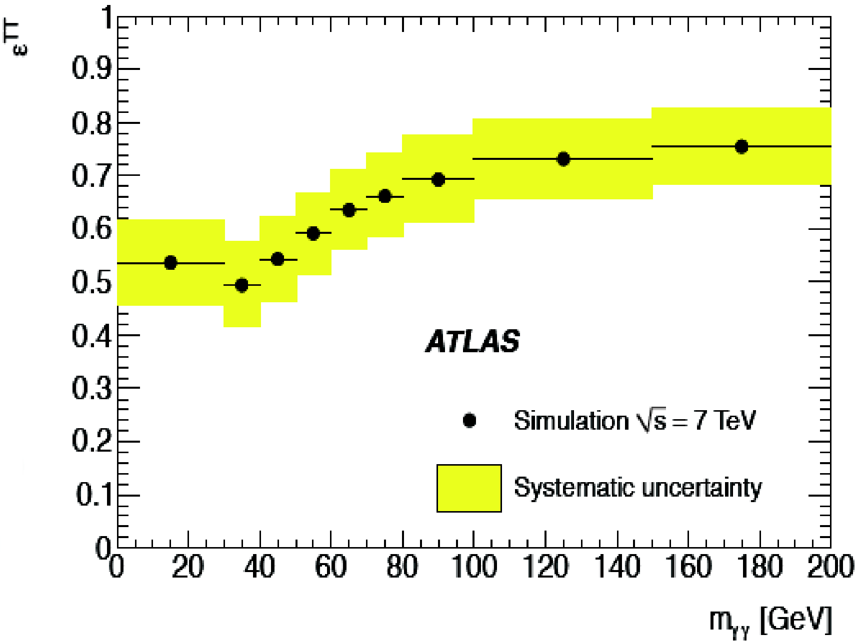


- Define isolated photon comparable to theory
- Isolation corrected event-by-event for leakage, pile-up, underlying event. Average 450-550 MeV



Photon identification efficiency

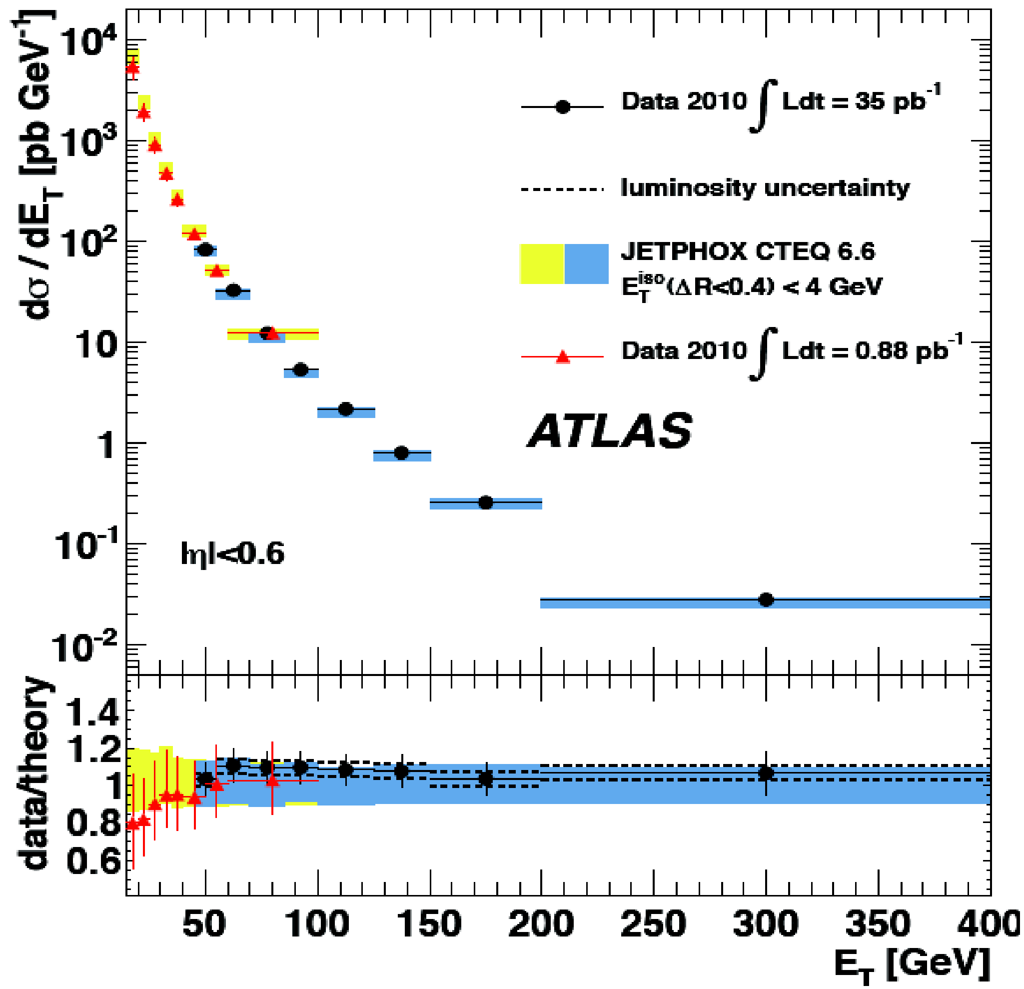




- **From MC, corrected for Data/MC discrepancies**
- Separately for converted and non-converted γ
- Combined in $\gamma\gamma$ spectrum according to $\gamma\gamma$ E_T spectrum and conversion composition

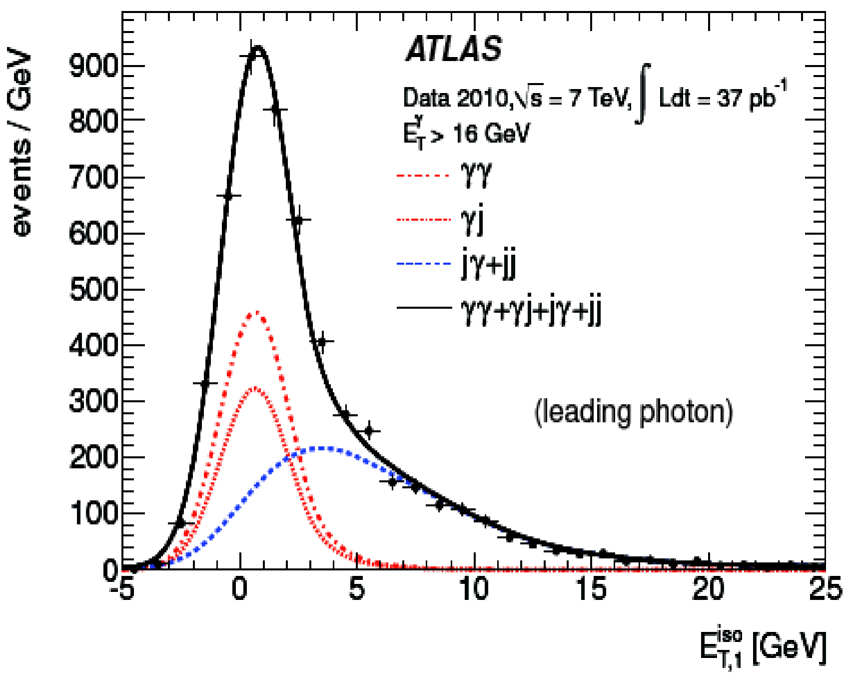
Inclusive cross-section

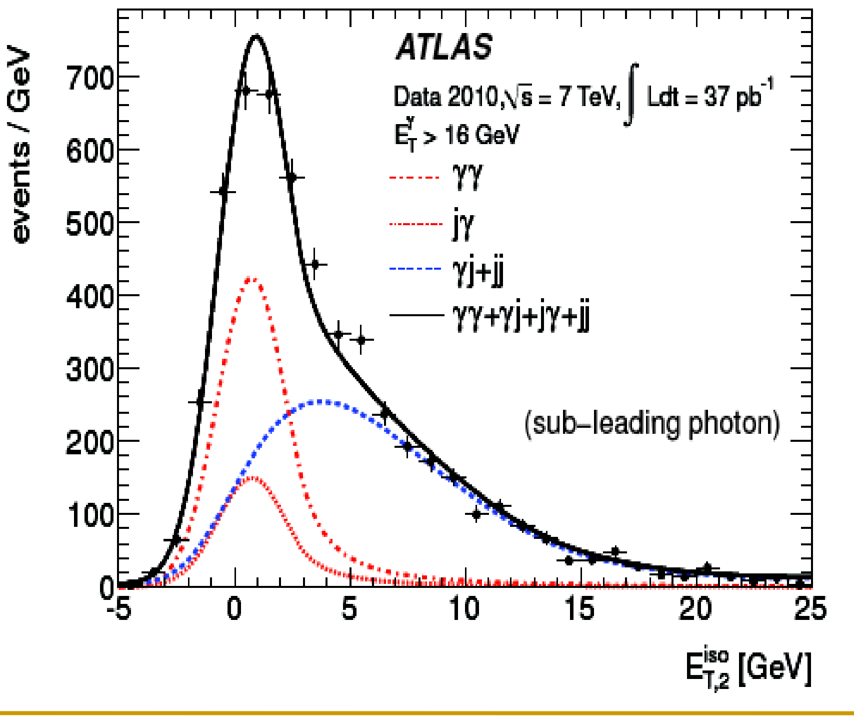
- Measured in 4 rapidity ranges
- Here example for central barrel



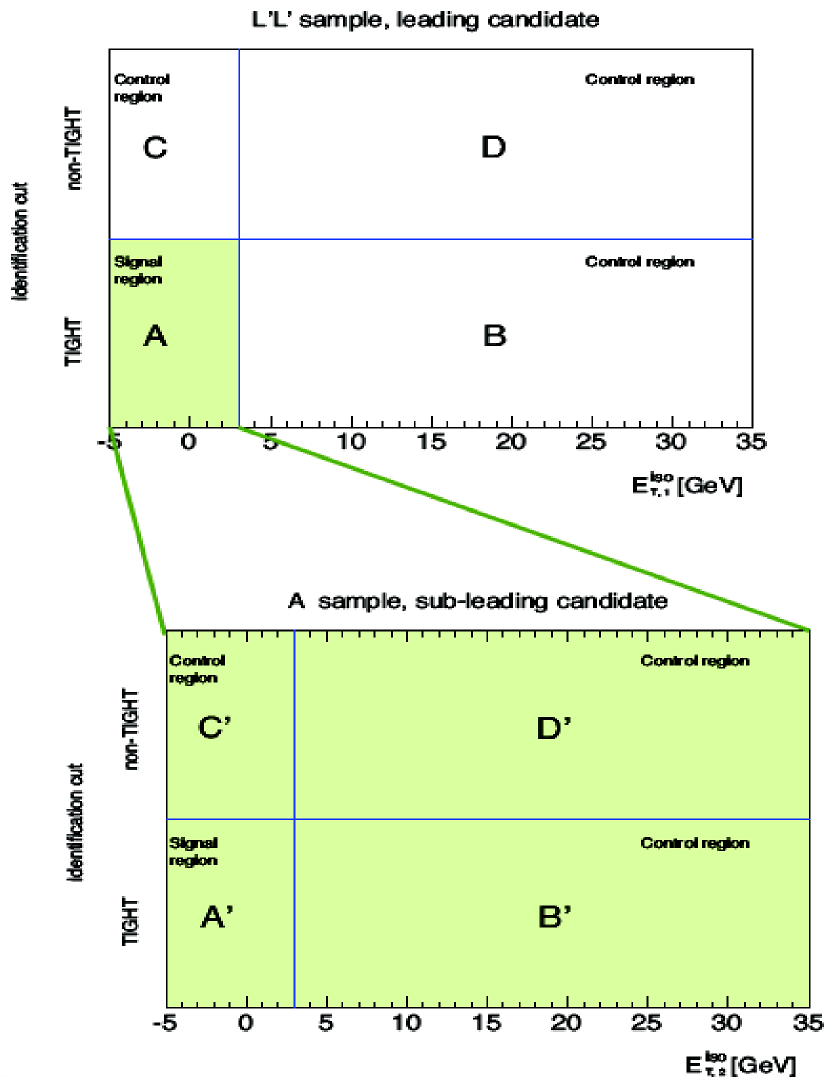
Diphoton cross-section

- Background estimated with two methods:
  - ABCD method: extrapolate from the bgd enriched control regions
  - here shown example of 2D template fit





ABCD method



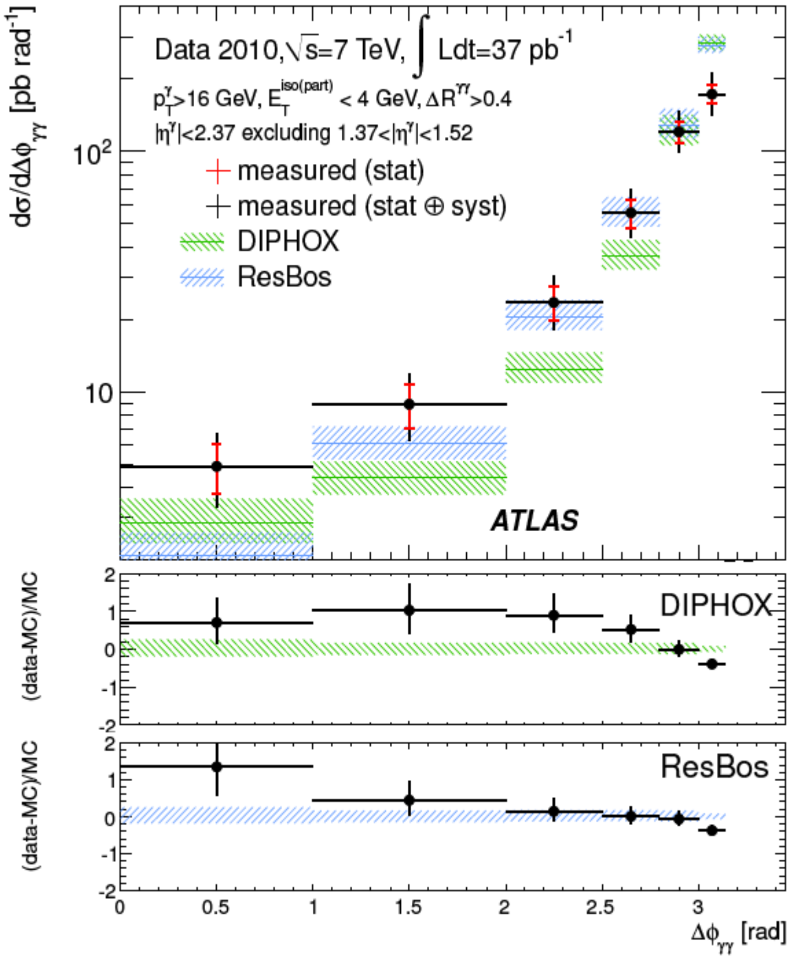
$$N^A_{\text{sig}} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A} \frac{M^A}{M^B}$$

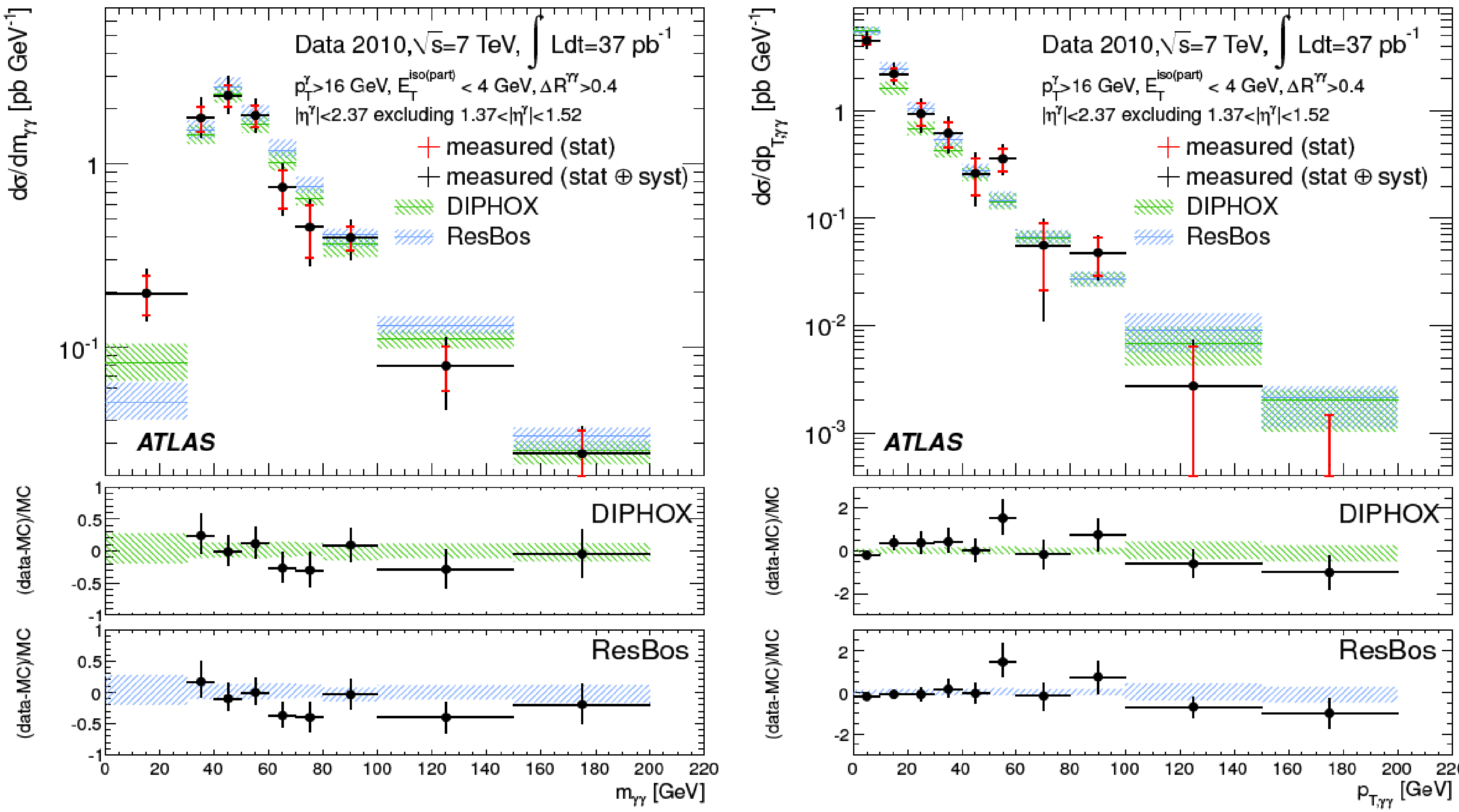
- Signal purity > 90% for E_T>50 GeV
- Main systematic uncertainties:
  - MC inputs (corrections to isolation definition)
  - Bgd control region definition

Isolated di-photon cross-section

- Measured with 2010 data (35pb-1) production cross-section for isolated photons and isolated di-photons
  - Isolation energy corrected event-by-event for pileup and UE
  - Data driven background subtraction
- Results in good agreement with TH pQCD predictions, some differences observed
  - Inclusive production at low ET (fragmentation, k_T factorisation)
  - Azimuth separation for diphoton production (resummation)



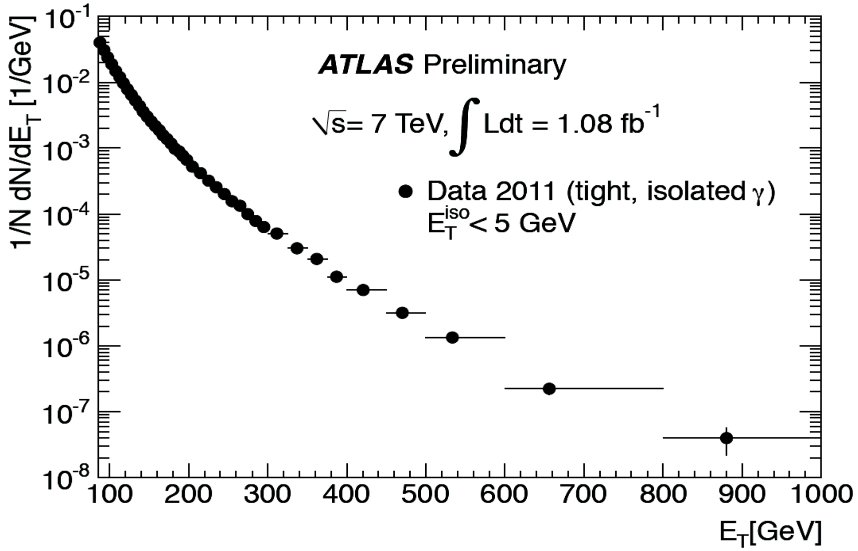
Isolated di-photon cross-section

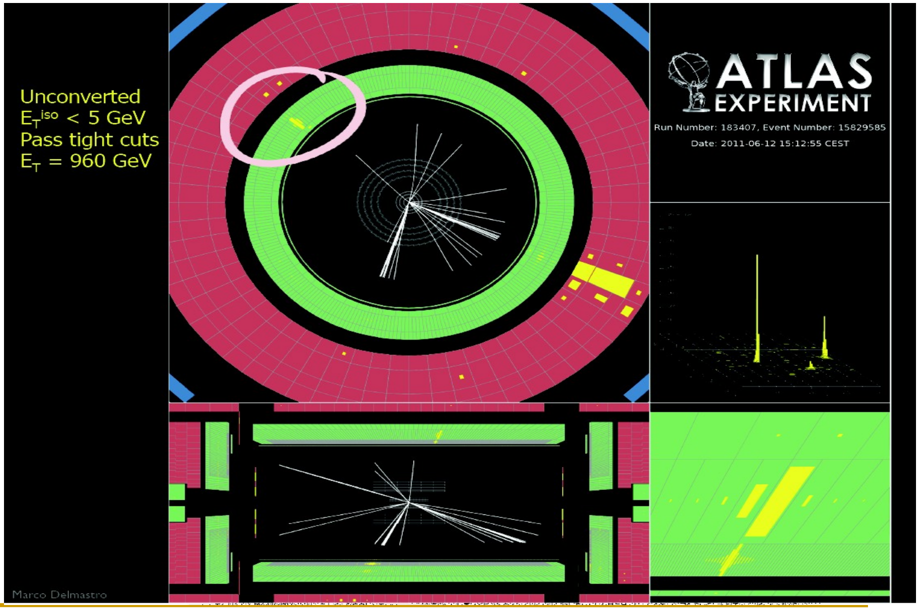


Looking forward 2011 data

- More than $4fb^{-1}$ collected already
  - Photon + (heavy flavour) jets
  - Inclusive photons at very high E_T
  - Di-photons at high mass
  - Double/triple differential cross-sections and ratios

E_T^{γ} = 960 GeV





Summary

- The LHC era allowed us to verify QCD in new kinematic regimes, good testing ground for predictions
- Current understanding of detectors allows to do precision QCD measurements.
- Already now data allows to discriminate between different MC predictions (theoretical models)

Plan

- Amazing how much could have been done with only 36pb^{-1} data accumulated in 2010: numbers of results are still in the pile-line but already theory is being tested quantitatively.... and is holding its own (unfortunately)

9.11 W,Z inclusive, asymmetry, W/Z + heavy flavours

23.11 Top physics

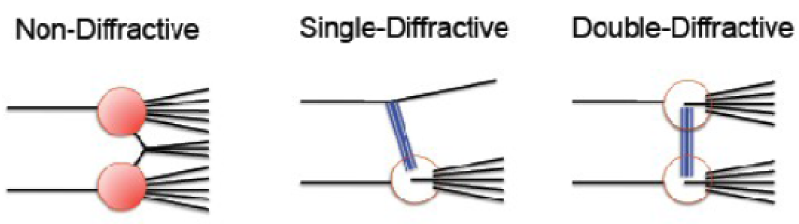
30.11 Diboson production and TGS couplings

7.12 B-physics and heavy ions

4.01 Higgs boson... where we are?

18.01 What's new from searches?

Minimum Bias Analysis



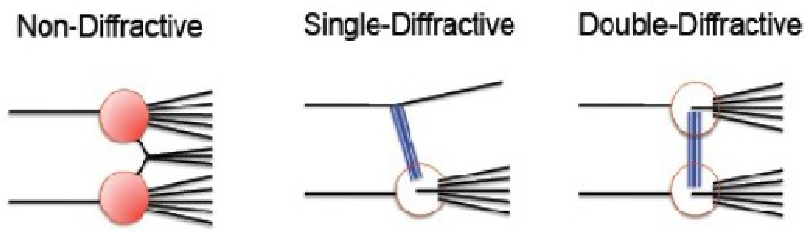
Observables:

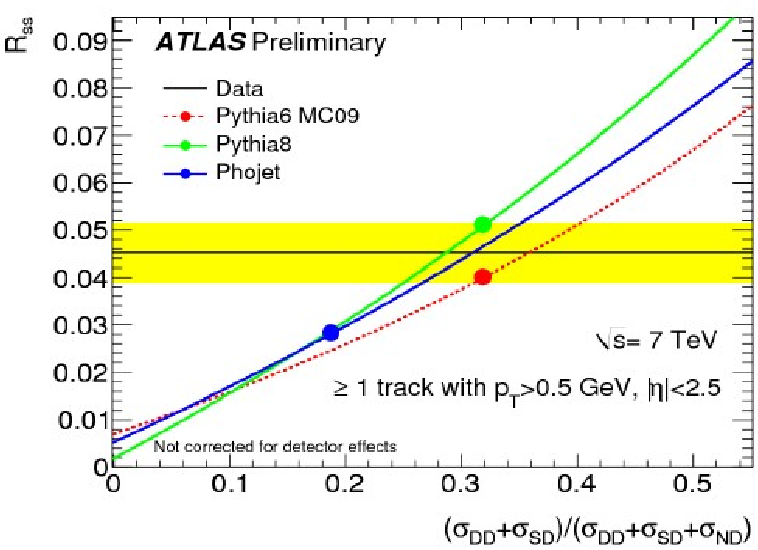
- Charged particle multiplicity:
  $1/N_{evt}.dN_{evt}/dN_{ch}$ vs. N_{ch}
- Charged particle p_T distrubution:
  $1/N_{evt}.dN_{evt}/dp_T^2$ vs. p_T
- Charged particle η (pseudorapidity) distrubution:
  $1/N_{evt}.dN_{evt}/d\eta$ vs. η
- Mean p_T vs. number of charged particles:
  $<p_T>$ vs. N_{ch}

Pythia: **non-diffractive**, **single-diffractive**, **double-diffractive** events generated

- Pythia6 ATLAS MC09:
  - tuned to the Tevatron 0.63 – 1.96 TeV underlying events and minimum-bias data
- Pythia6 Perugia0:
  - soft QCD tuned to CDF and CERN minimum-bias data
- Pythia6 DW:
  - tuned to CDF Run II UE and Drell-Yan data
- Pythia6 AMBT1 (**ATLAS Minimum Bias Tune 1**):
  - tuned to preliminary results of ATLAS minimum bias data at 0.9, 7 TeV, $N_{ch} \geq 6$, $p_T > 500$ MeV
- Pythia8:
  - improved colour-reconnection model
  - produces harder p_T and N_{ch} spectra
- Phojet:
  - an alternative model based on pomeron exchange
- Herwig+Jimmy:
  - alternative MC model + multiparton interaction model

Diffractive enchanced Minimum-Bias studies





- A colour singlet (pomeron) exchange, proton breaks up or proton dissociates (one or both)
- The colour change absence → rapidity gaps, **single sided activity**
- Events with hits only in one side of the MBTS selected
- Ratio of single sided activity R_{SS} (ratio of single-sided events to all events with MBTS hits) – indication of the diffractive events
- Each of MC models requires about 30% of diffractive components