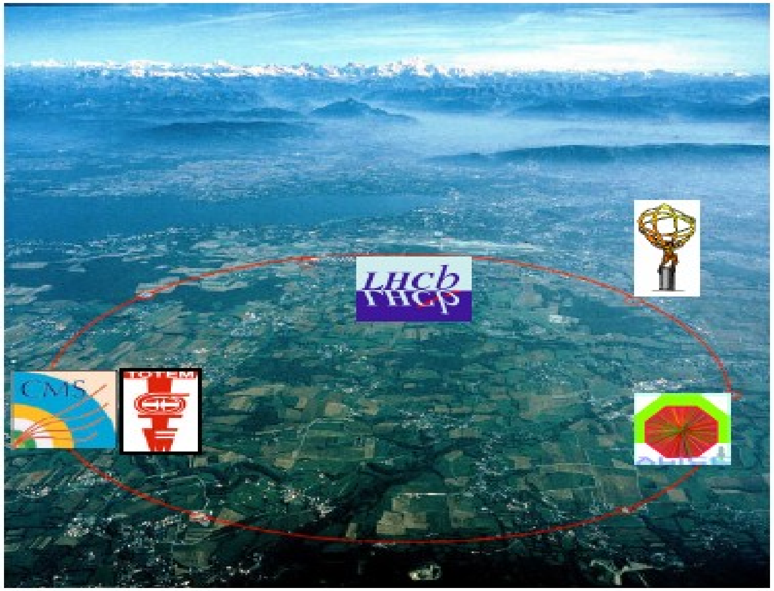
Physics Program
of the experiments at
Large Hadron Collider

- **Hard QCD**
  - **Jets**
  - **Photons**

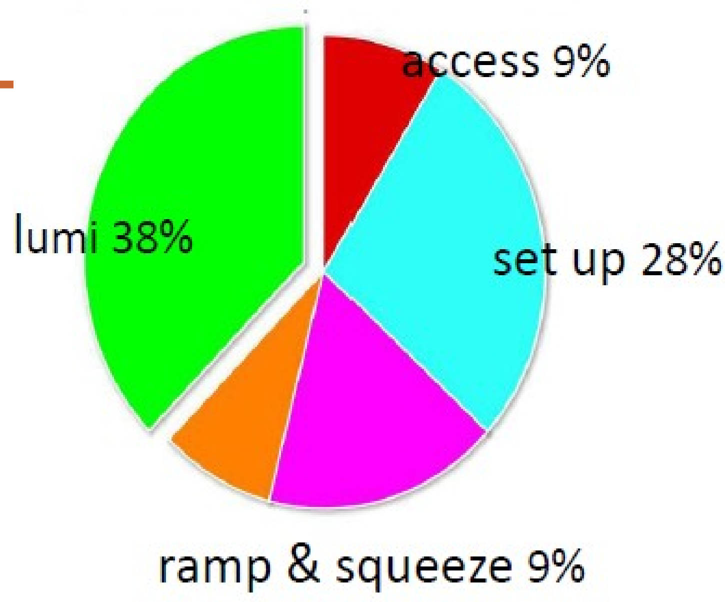


News of last week

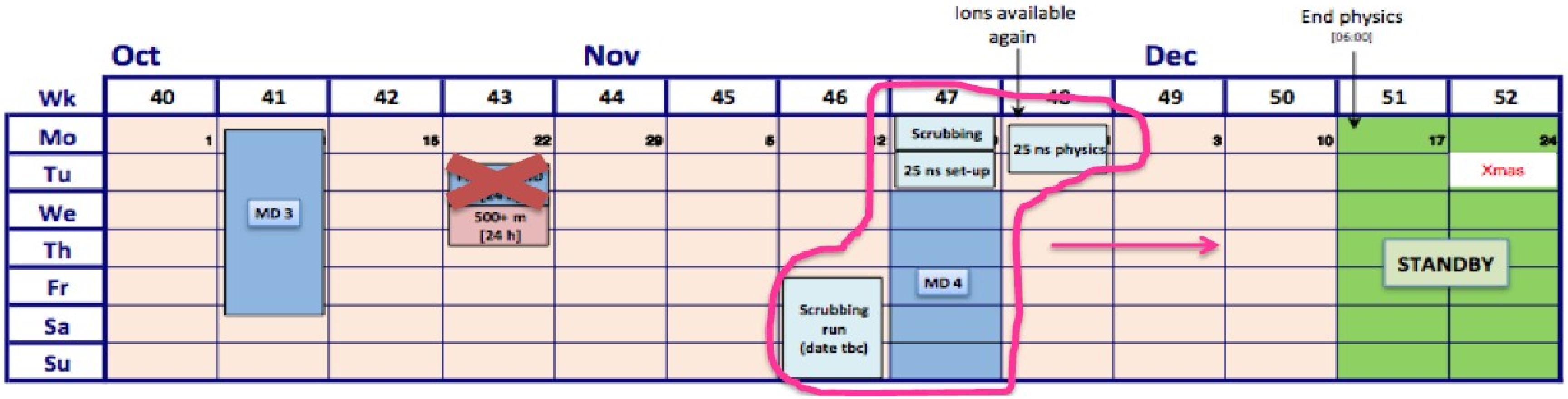
Very good week, with nice and long fills …

Delivered luminosity in the last 7 days: 1.14 fb-1 !!

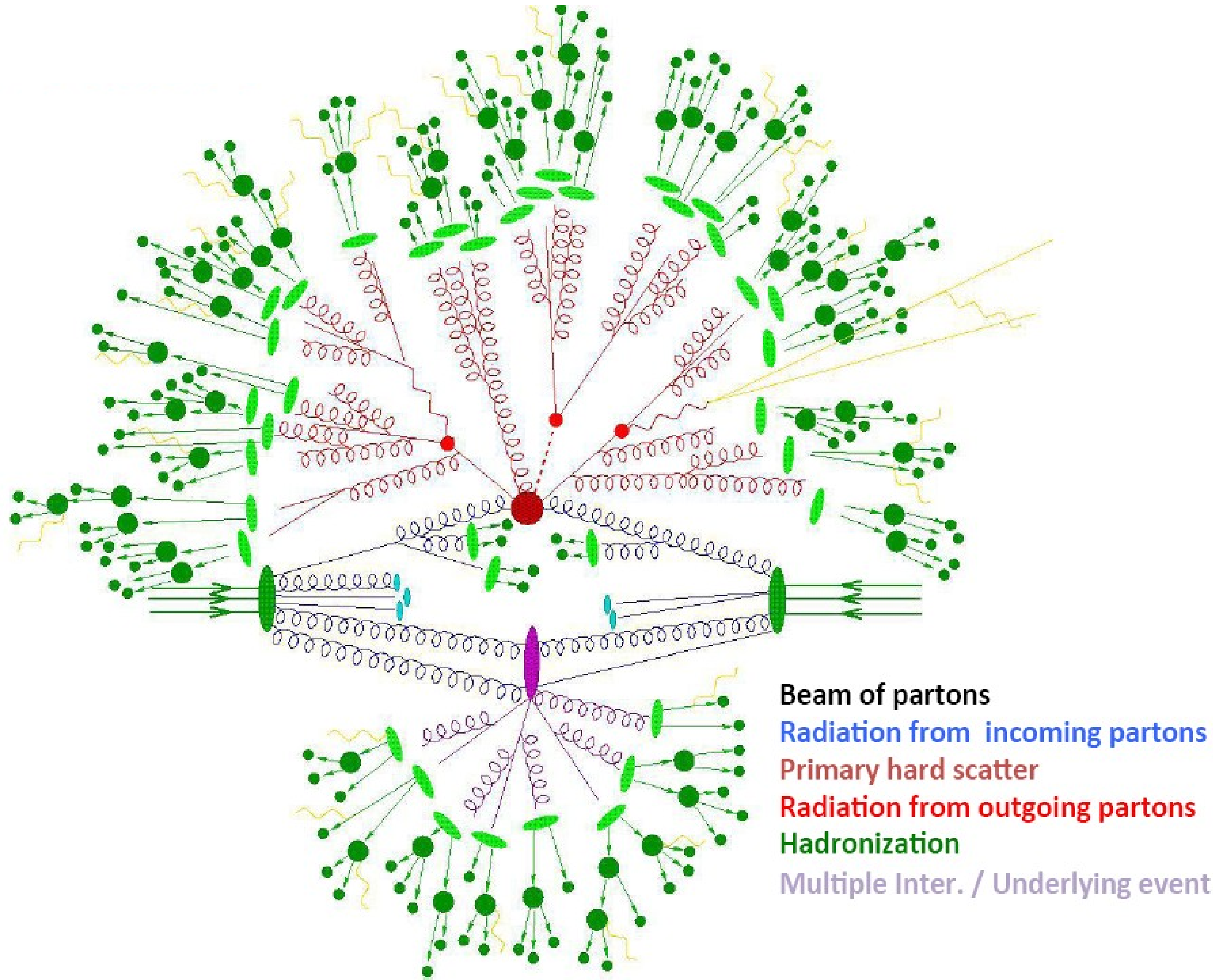
38% of the time spent in stable beams.



News on the Schedule

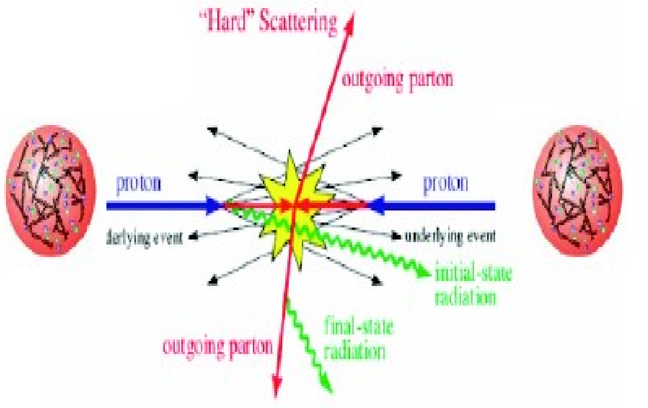


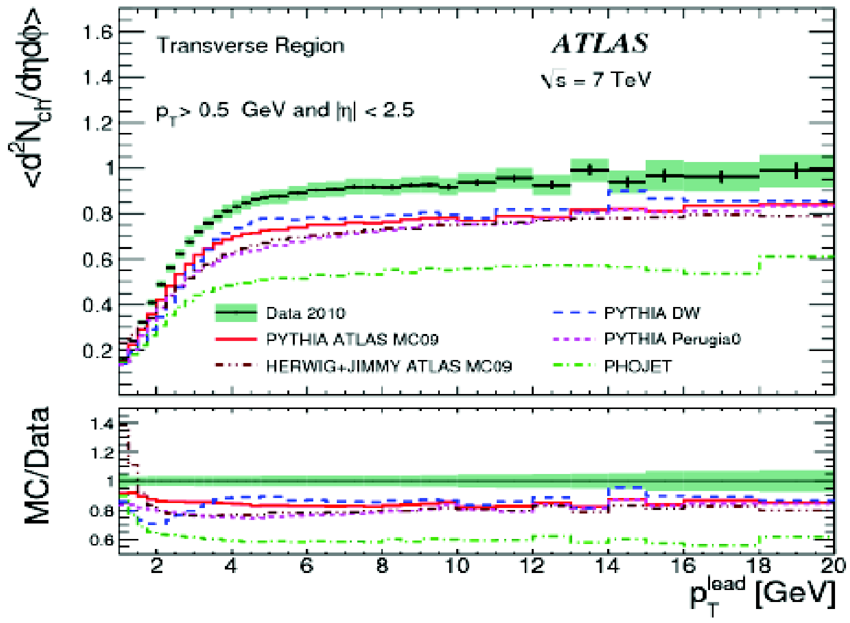
Typical pp collision

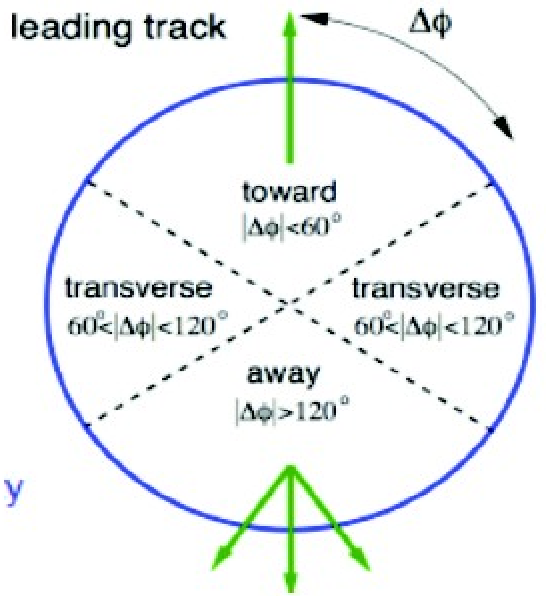


The underlying event

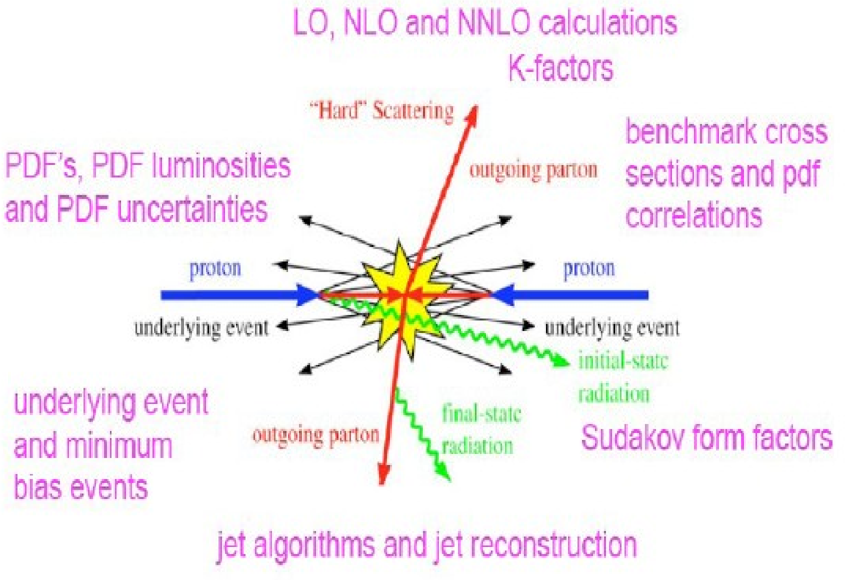
- Transverse region particularly sensitive to multiple (parton) int's.
- All commonly used MC models predict too little transverse activity

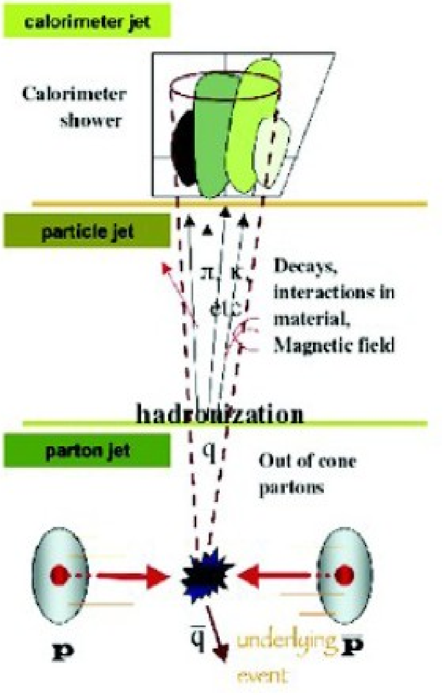






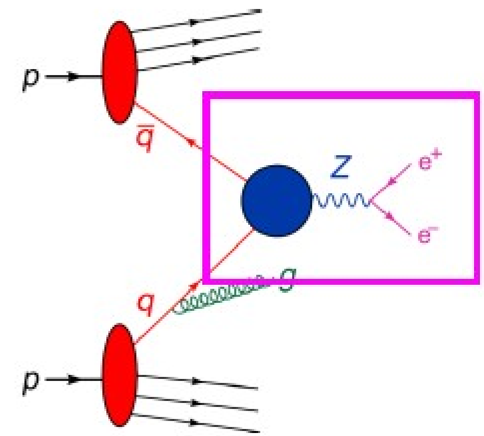
Understanding cross-section at LHC





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



“suitable” final state

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

factorization scale (“arbitrary”)

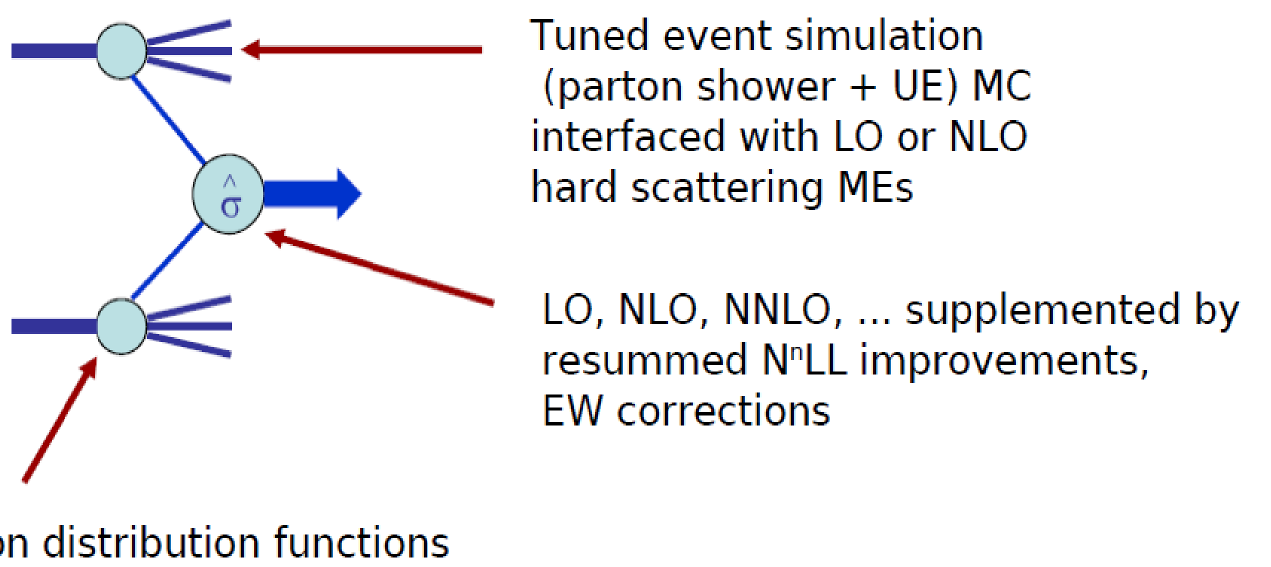
$$\sigma^{pp\to X}(s;\alpha_s,\mu_R,\mu_F) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1,\alpha_s,\mu_F)\, f_b(x_2,\alpha_s,\mu_F) \times \hat{\sigma}^{ab\to X}(sx_1x_2;\alpha_s,\mu_R,\mu_F)$$

Partonic cross section, computable in perturbative QCD

partonic CM energy²

renormalization scale (“arbitrary”)

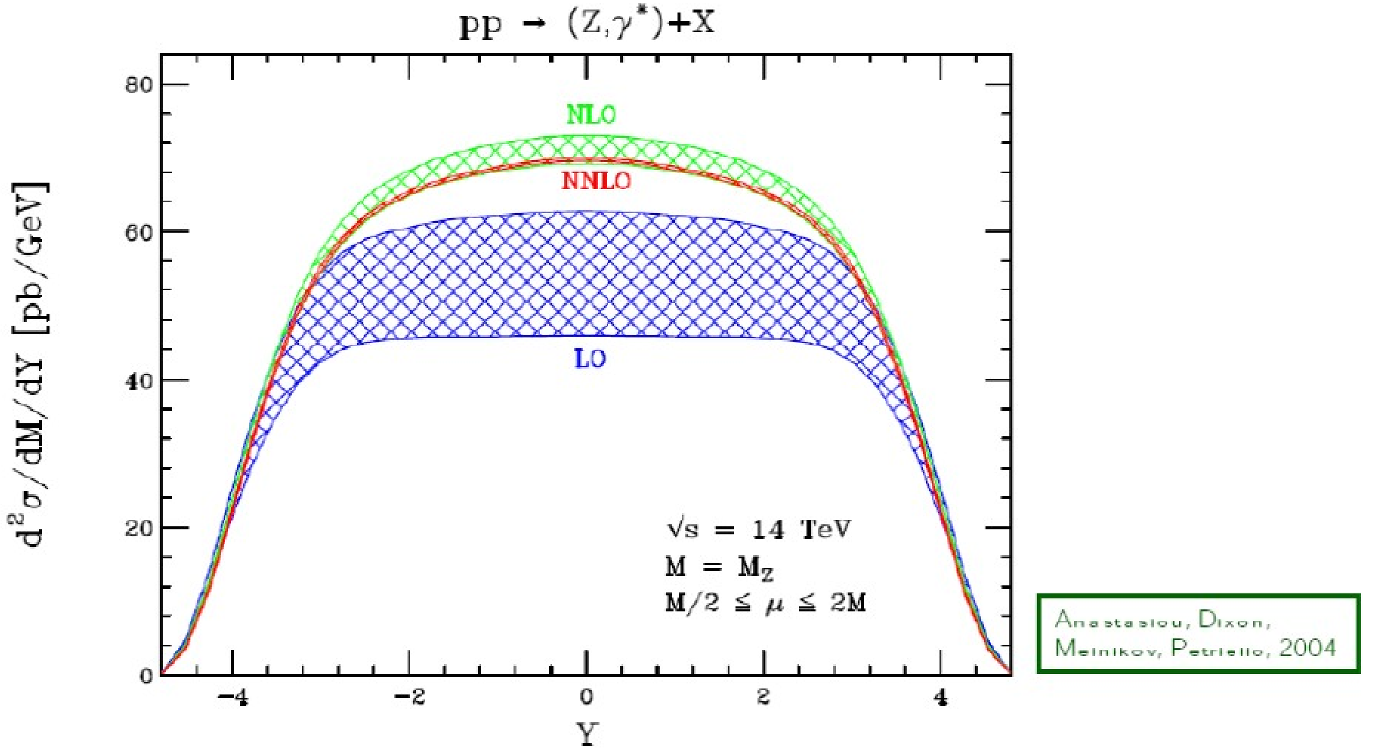
Perturbative QCD in the LHC era



- The QCD factorisation theorem for hard scattering (short distance) inclusive processes

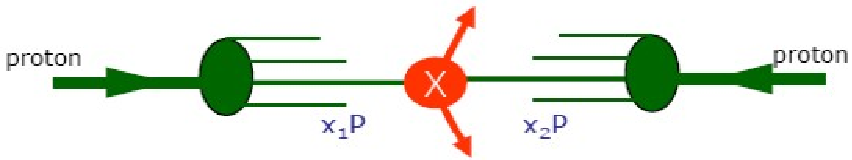
$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

The impact of NLO



- Shown only scale variation μ_R and μ_F

Parton distribution functions

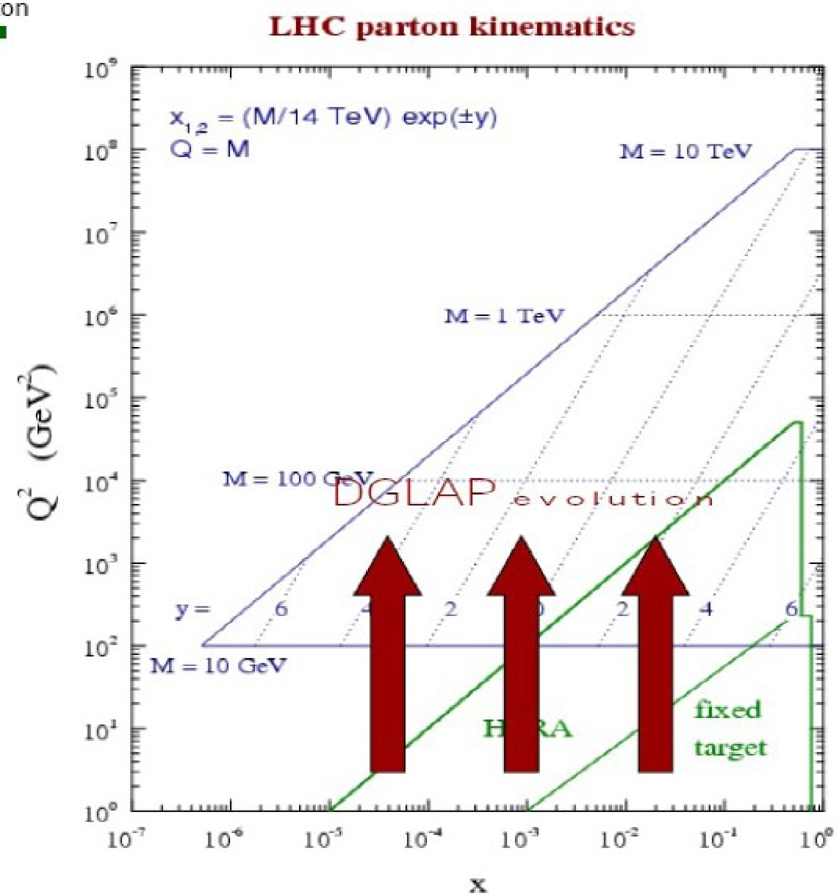


Momentum fraction x_1, x_2 determined by mass and rapidity of X.

- x dependence of $f_i(x,Q^2)$ determined by "global fit" to deep inelastic scattering and other data, Q^2 dependence determined by DGLAP equations:

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{q_iq_j}(y,\alpha_S)\, q_j\left(\frac{x}{y},Q^2\right) + P_{q_ig}(y,\alpha_S)\, g\left(\frac{x}{y},Q^2\right)\right\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq_j}(y,\alpha_S)\, q_j\left(\frac{x}{y},Q^2\right) + P_{gg}(y,\alpha_S)\, g\left(\frac{x}{y},Q^2\right)\right\}$$



How PDF's are obtained?

- Choose a factorisation scheme (e.g. MSbar), and an order of perturbation theory (LO, NLO, NNLO) and a starting scale Q_0 where pQCD applies (e.g. 1-2 GeV).
- Parametrise quark and gluon distributions at Q_0, e.g.

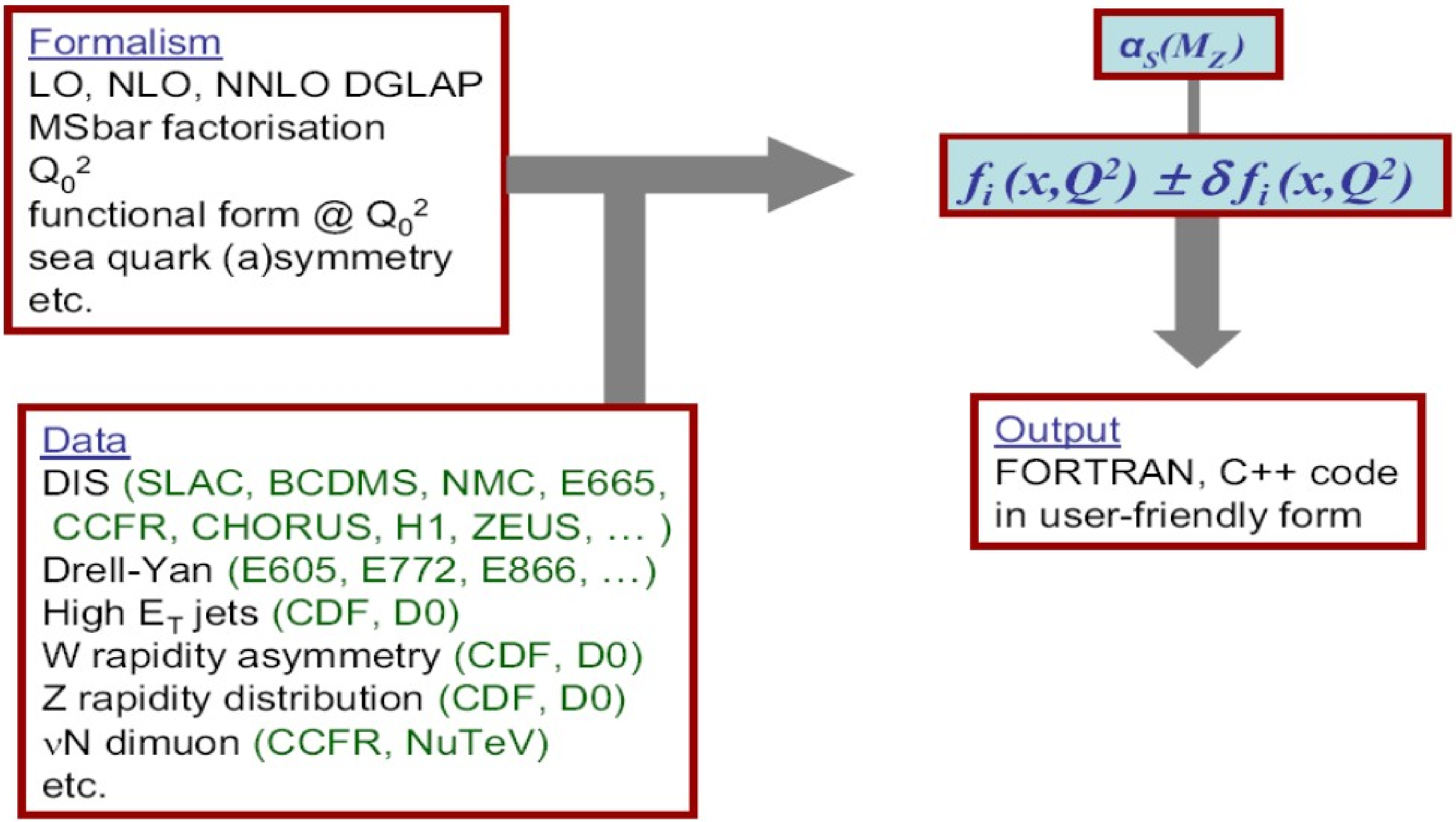
$$f_i(x, Q_0^2) = A_i x^{a_i}[1 + b_i\sqrt{x} + c_i x](1-x)^{d_i}$$

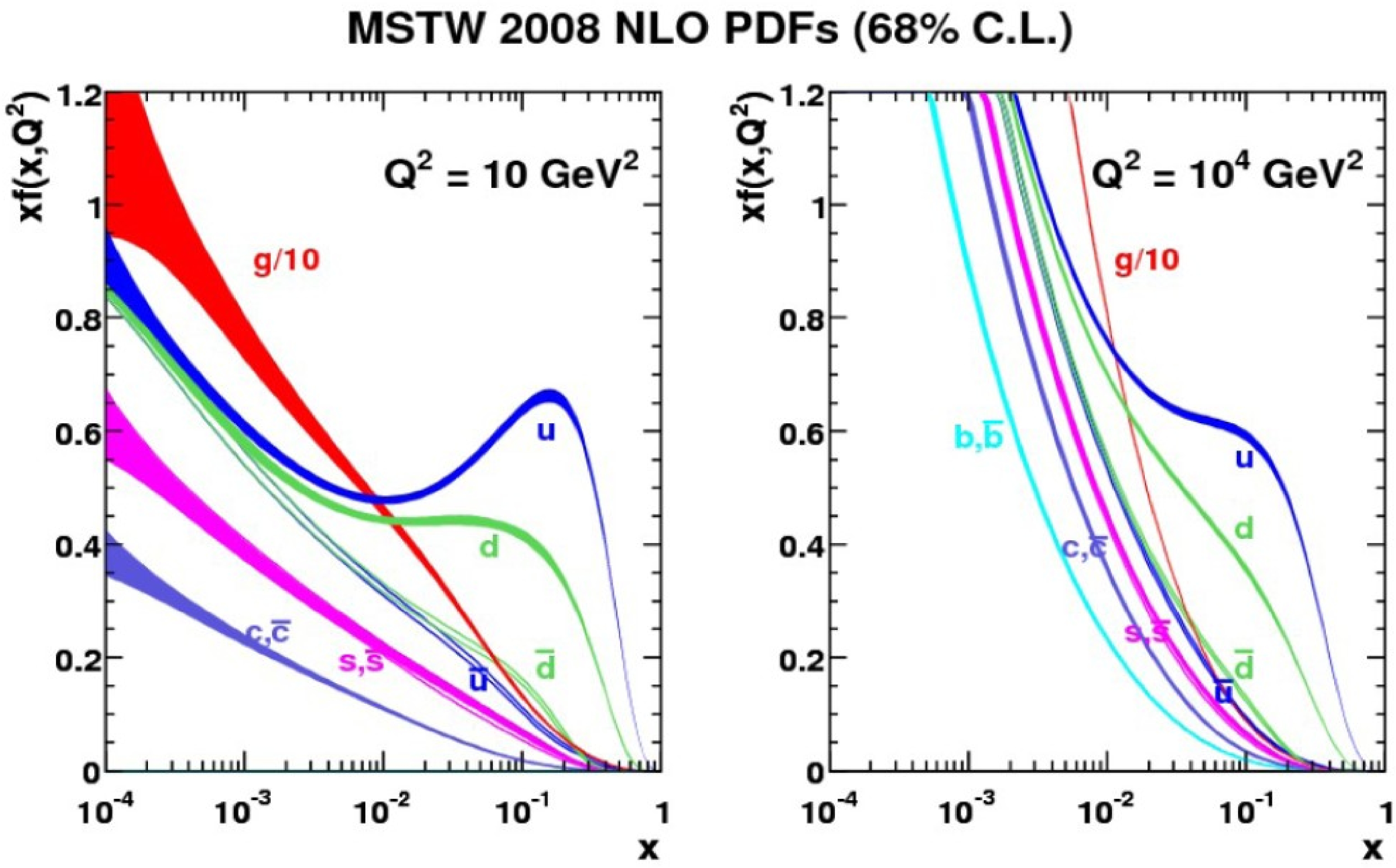
- Solve DGLAP equations to obtain the pdfs at any x and $Q>Q_0$; fit data for parameters (A_i, a_i, ...α_s)
- Approximate the exact solutions (e.g. interpolation grids, expansions in polynomials etc), just output "global fit" is available for users

```
SUBROUTINE PDF(X,Q,U,UBAR,D,DBAR,...,BBAR,GLU)
```

input | output

Anatomy of global PDF fit





MSTW 2008 NLO PDFs (68% C.L.)
xf(x,Q²)
Q² = 10 GeV²
g/10
u
d
d̄
ū
s,s̄
c,c̄
x
Q² = 10⁴ GeV²
b,b̄

HERA + ATLAS global PDF fits

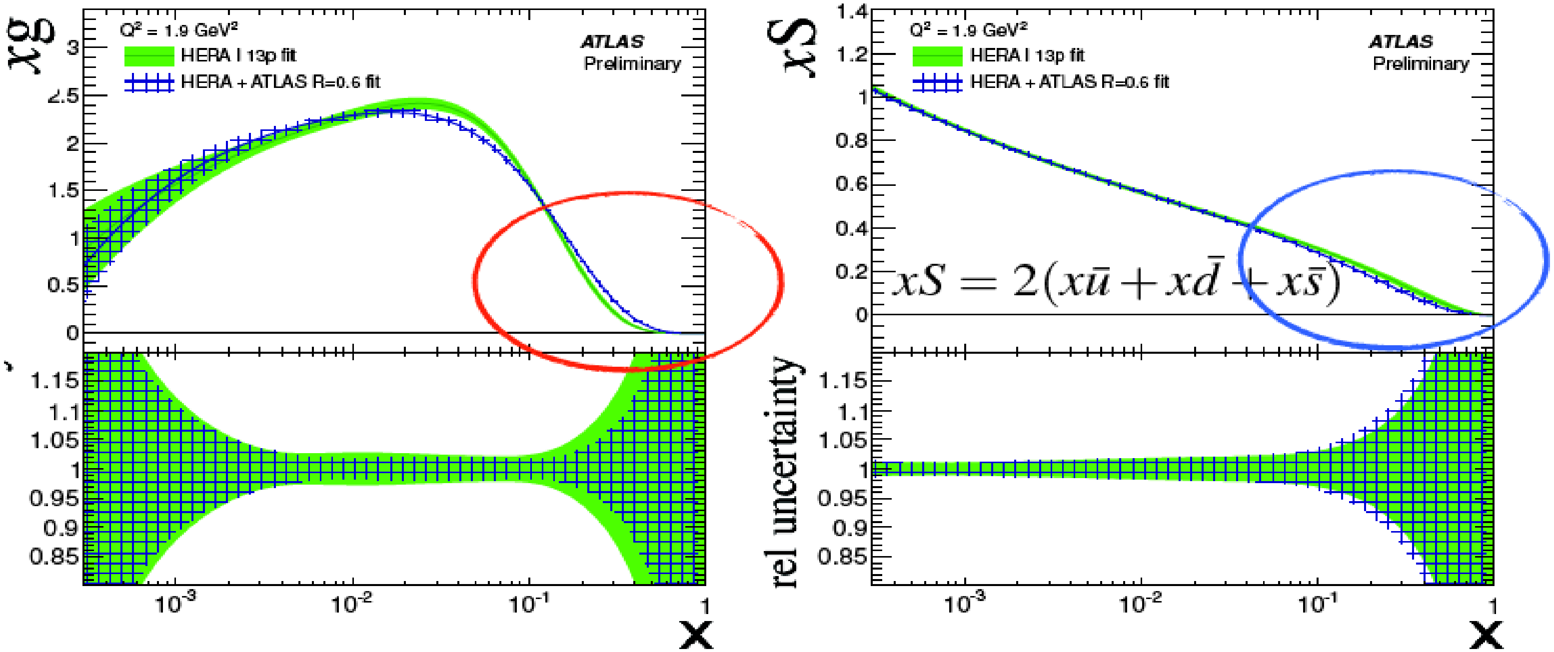
Different centre-of-mass energies probe different x and Q^2 values for the same p_T and rapidity ranges.

➡ Increased sensitivity to PDFs expected when both sets of jet cross section data are analyzed together

After inclusion of the ATLAS jet data:

➡ gluon distribution (xg) tends to be harder with a reduction in the uncertainty

➡ sea quark distribution (xS) tends to be softer for high x resulting in a larger uncertainty



Short-distance cross-section in perturbation theory

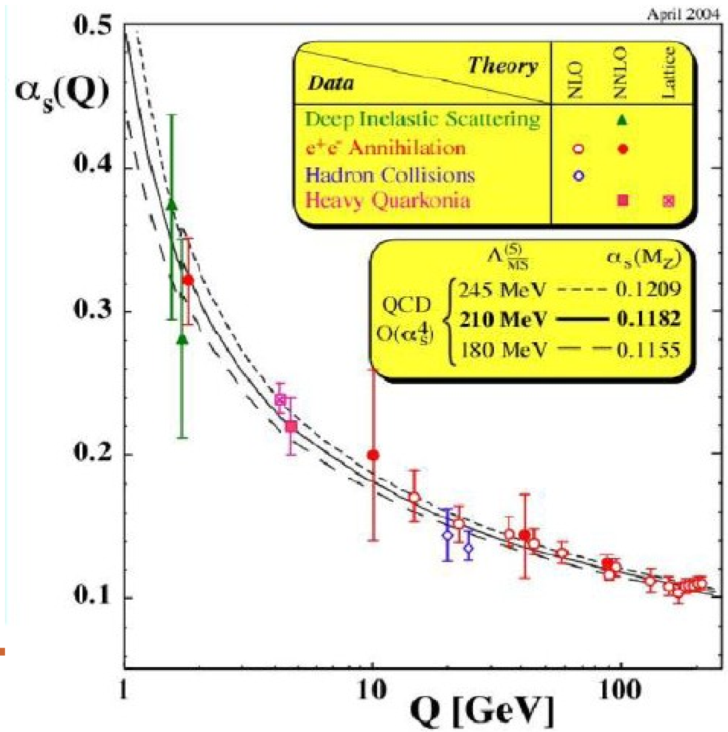
$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) = [\alpha_s(\mu_R)]^{n_\alpha} \left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi} \hat{\sigma}^{(1)}(\mu_F, \mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F, \mu_R) + \cdots \right]$$

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

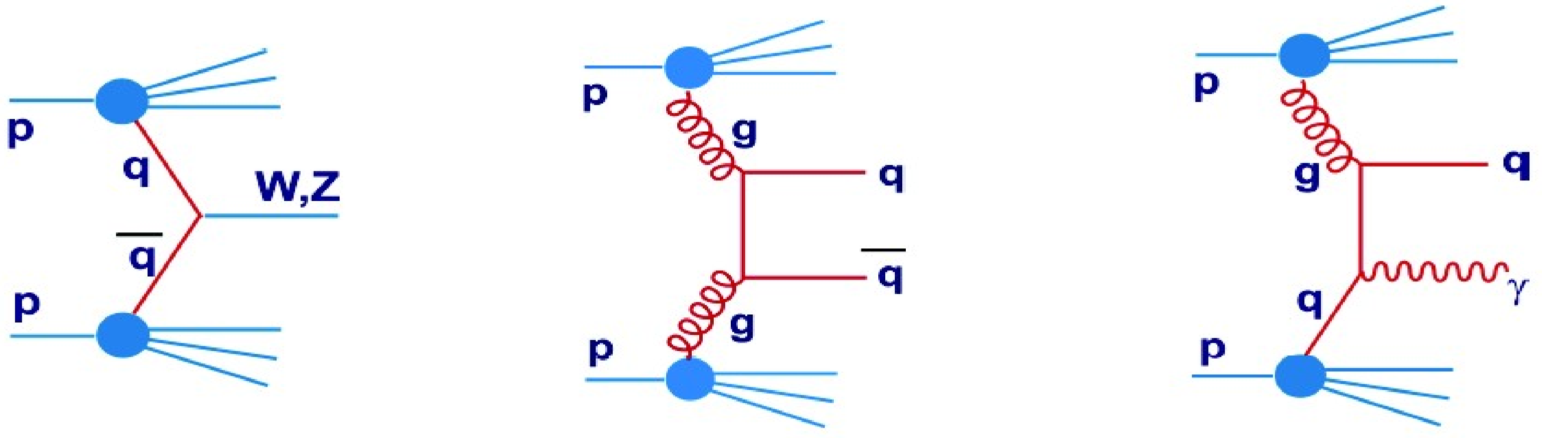
$$\mu_R = \mu_F = \mu$$

from ½ to 2 times the typical scale



QCD hard scattering processes

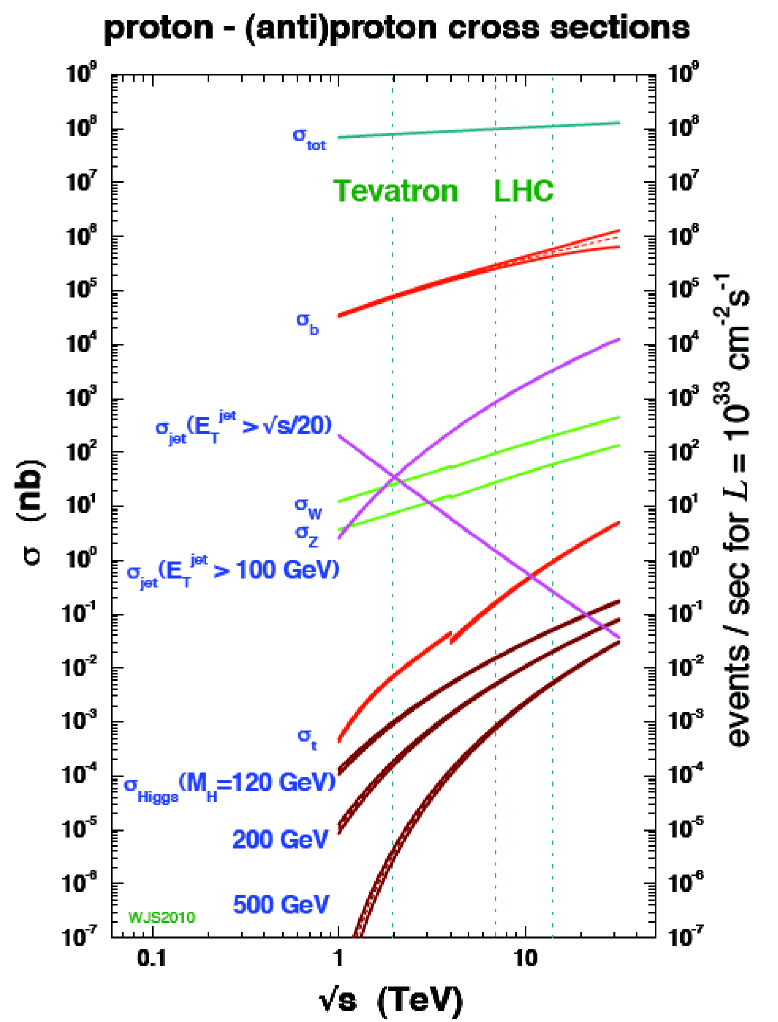
- EW gauge bosons   Di-jets   Direct photons



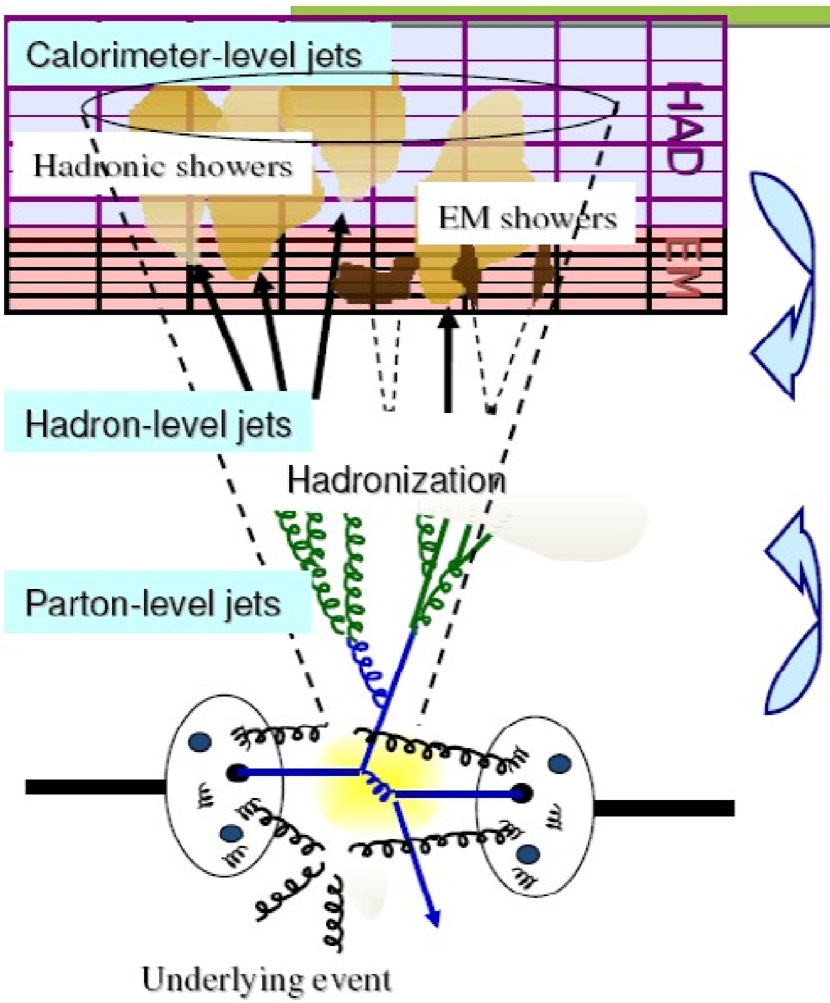
- Measuring those processes test our understanding of:
  - Partonic structure of protons
  - QCD scattering via calculations of N(NLO)
  - Hadronisation/underlying event
  - What makes a good jet algorithm
  - Data driven background estimates for rare processes

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



Inclusive jet production



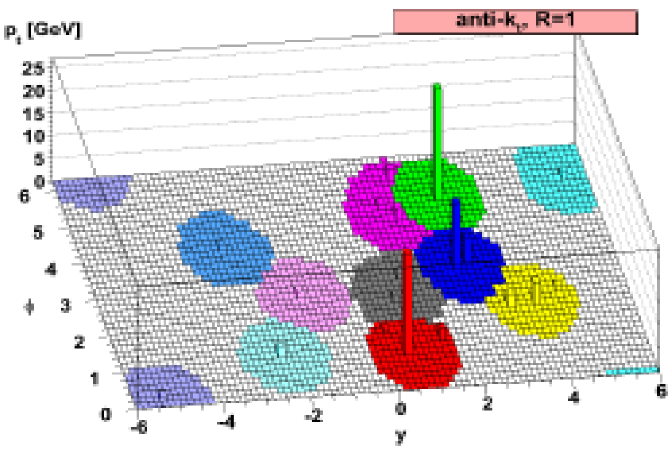
Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)

Jets are collimated spray of particles originating from parton fragmentation.
→ To be defined by an algorithm

Jet reconstruction in ATLAS

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

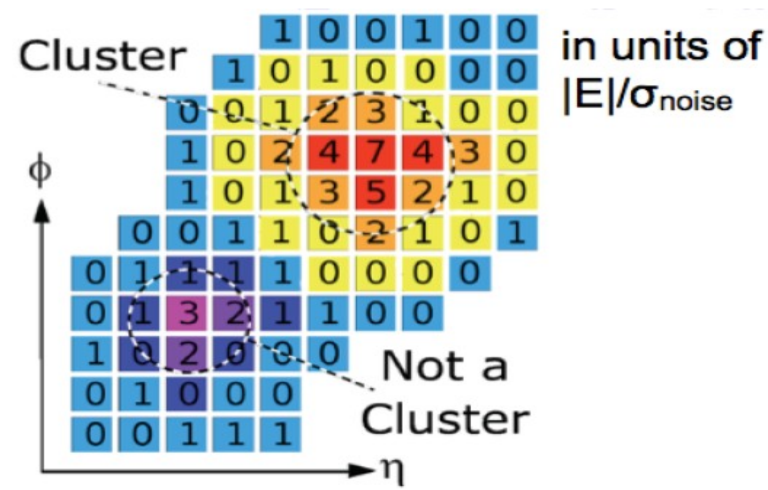


[Cacciari, Salam, Soyez JHEP 0804:063,2008]

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

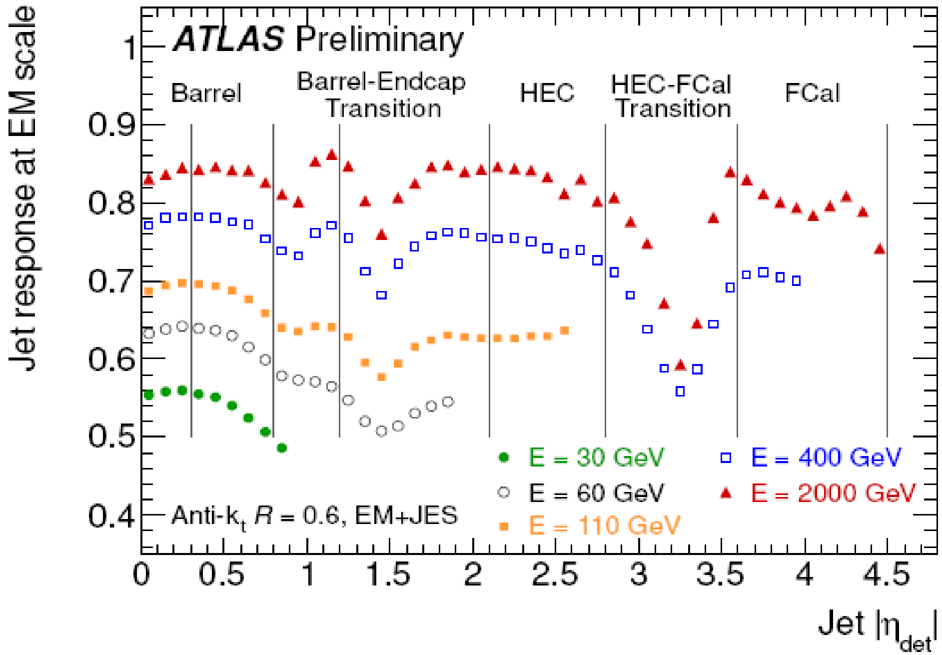
Jet inputs clustered with anti-k_T algorithm:

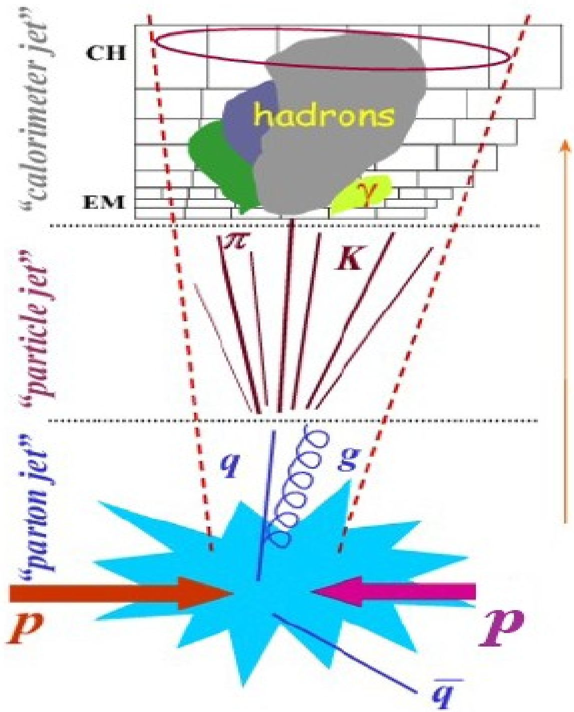
- Infrared safe, collinear safe ($\Rightarrow$ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6



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

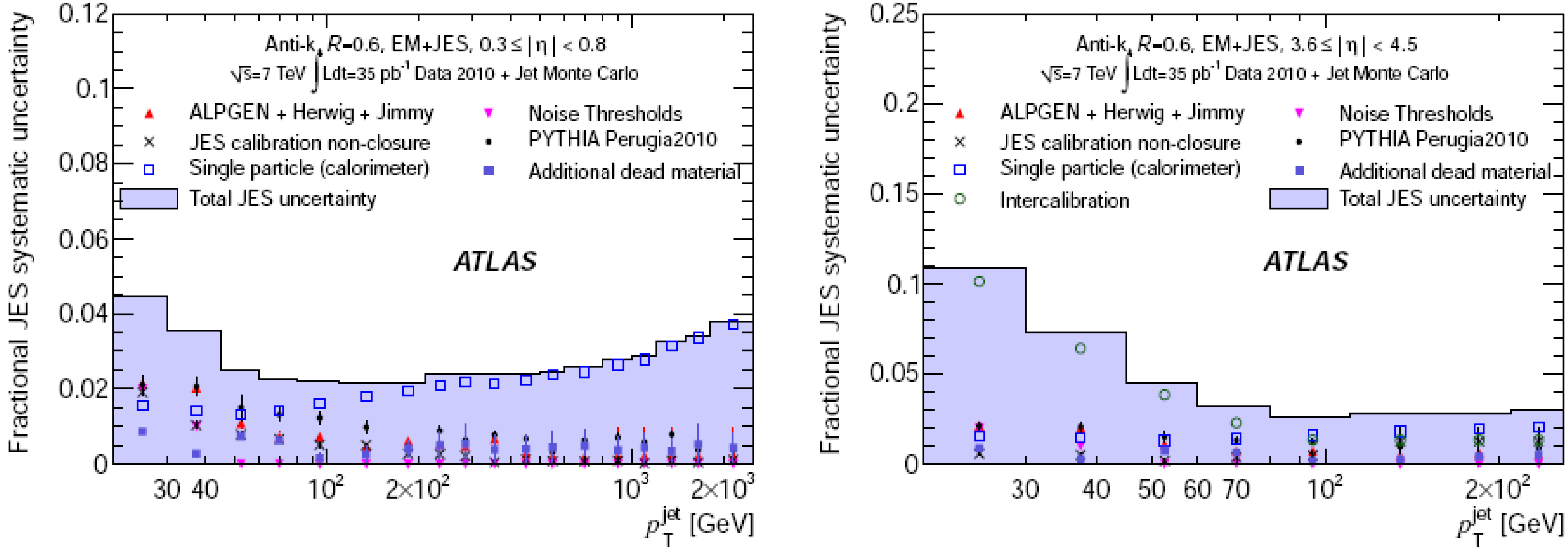
Calorimeter jet response needs to be corrected for :

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

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

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 $< 2.5\%$

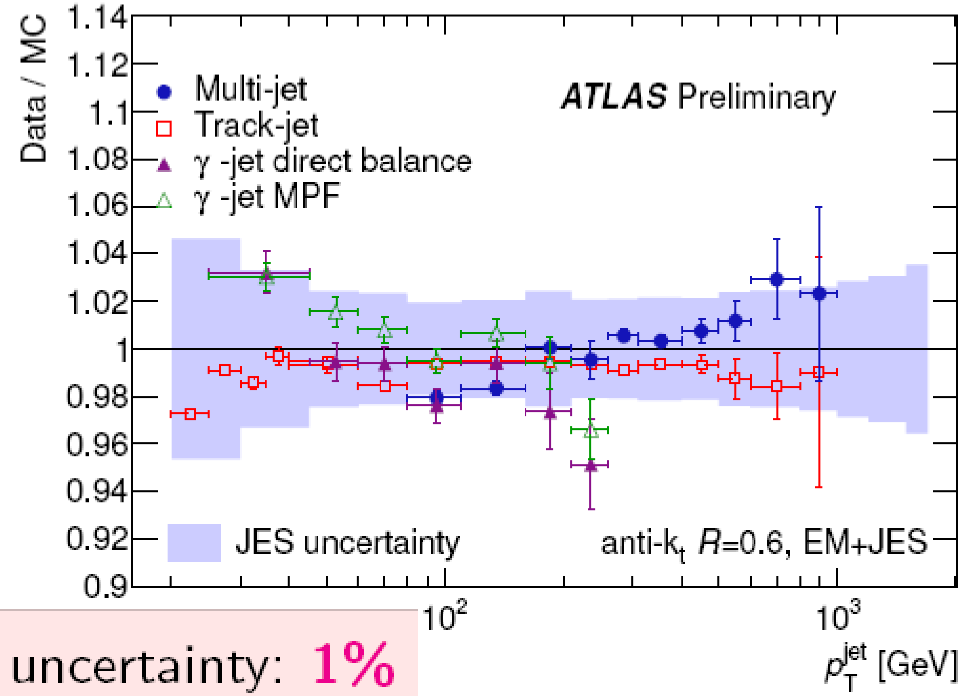
Forward region $(3.6 < |\eta| < 4.5)$, $p_T > 20$ GeV $< 12\%$

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)

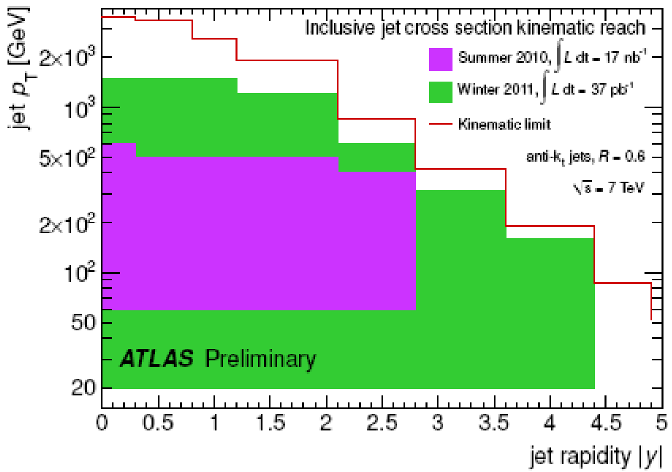


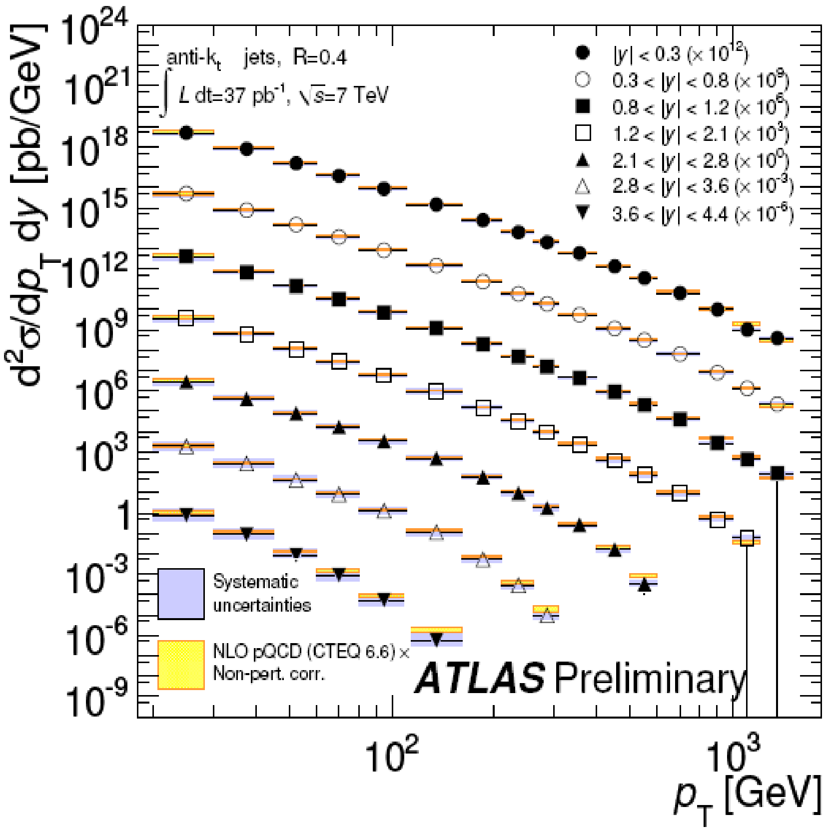
ATLAS goal for jet energy scale uncertainty: **1%**

Achieved with 2011 data in central region !!!

Inclusive jet cross-section

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

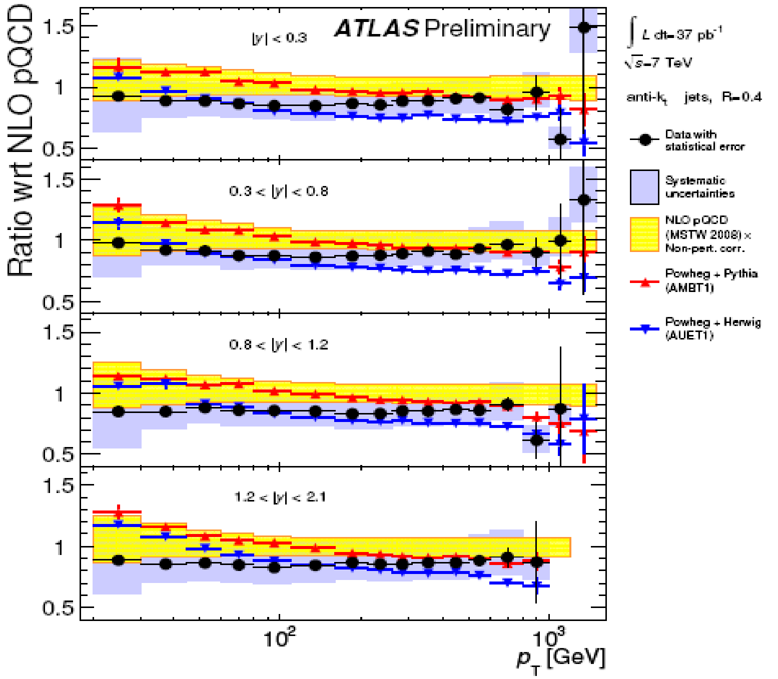


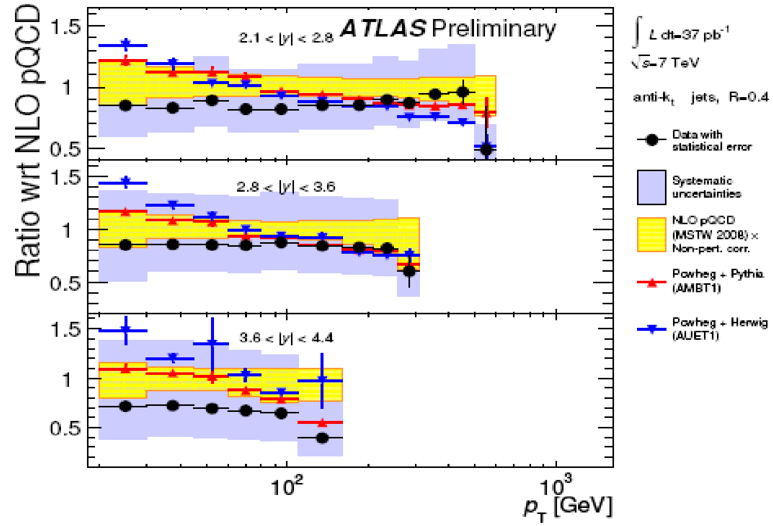


- Cross section out to $|y| < 4.4$
- p_T up to 1.5 TeV

Comparison of data to NLO pQCD predictions with CTEQ 6.6.

Inclusive jet cross-section



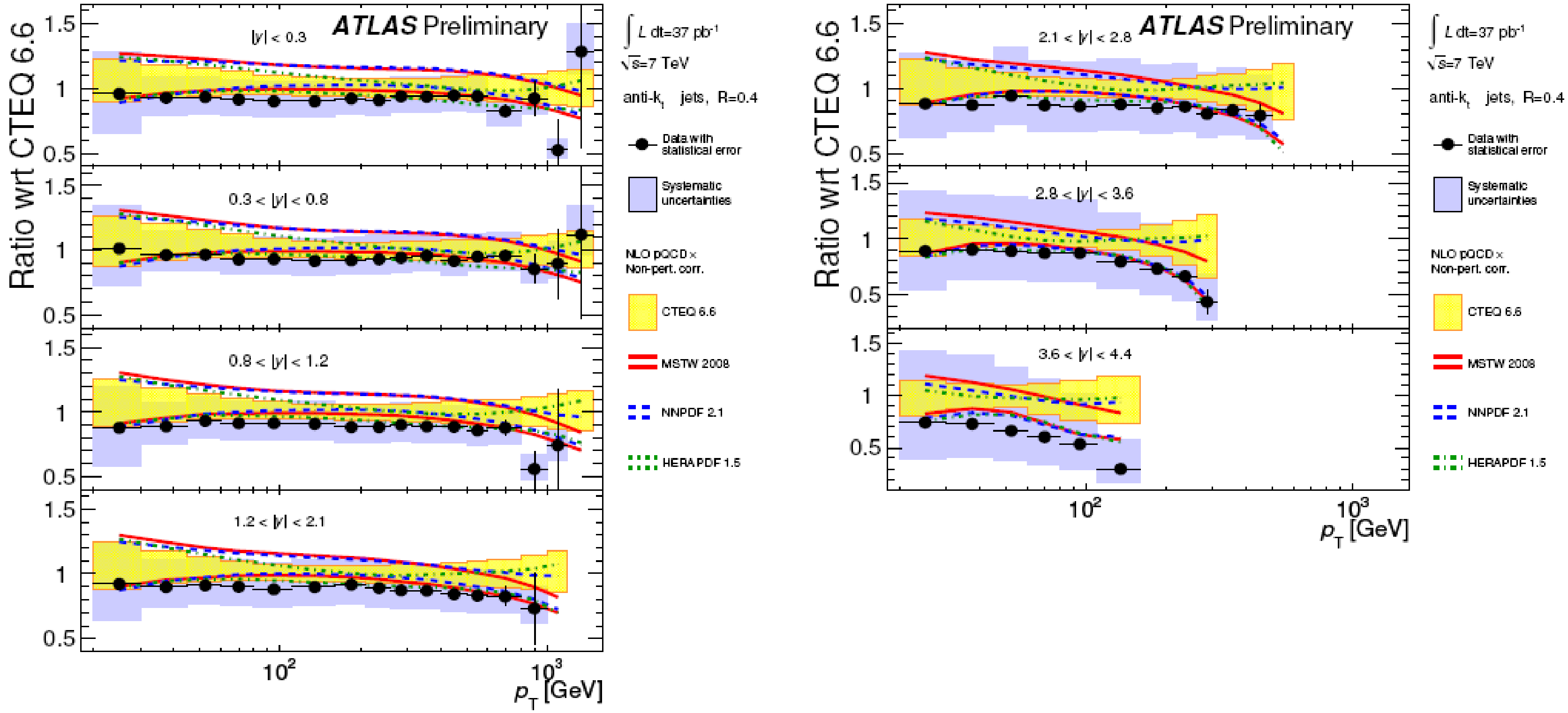


Prediction w.r.t NLOJet++ MC

$AMBT1$, $AUET1$ are different detector tunes

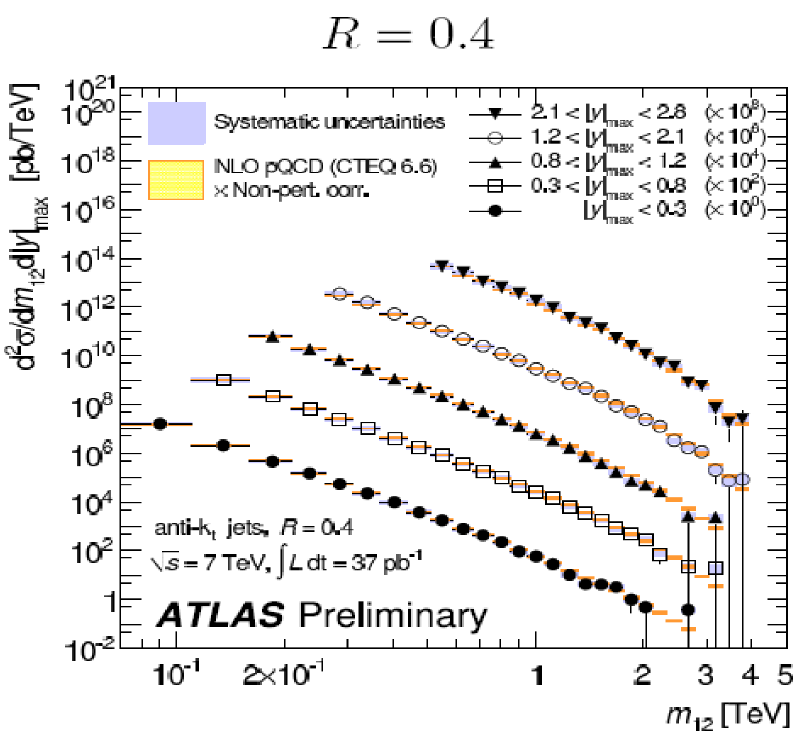
Powheg predictions are consistent with data and NLOJet++, with present uncertainties
Trend for Powheg to predict different slope to cross section

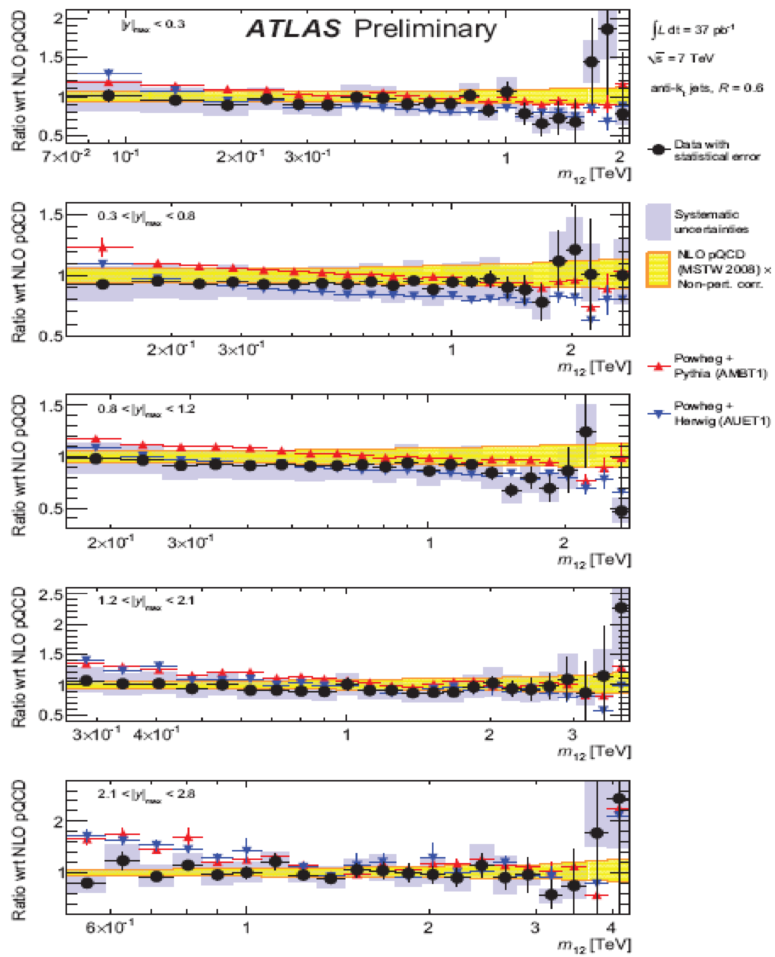
Inclusive jet cross-section



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

Dijet cross-section



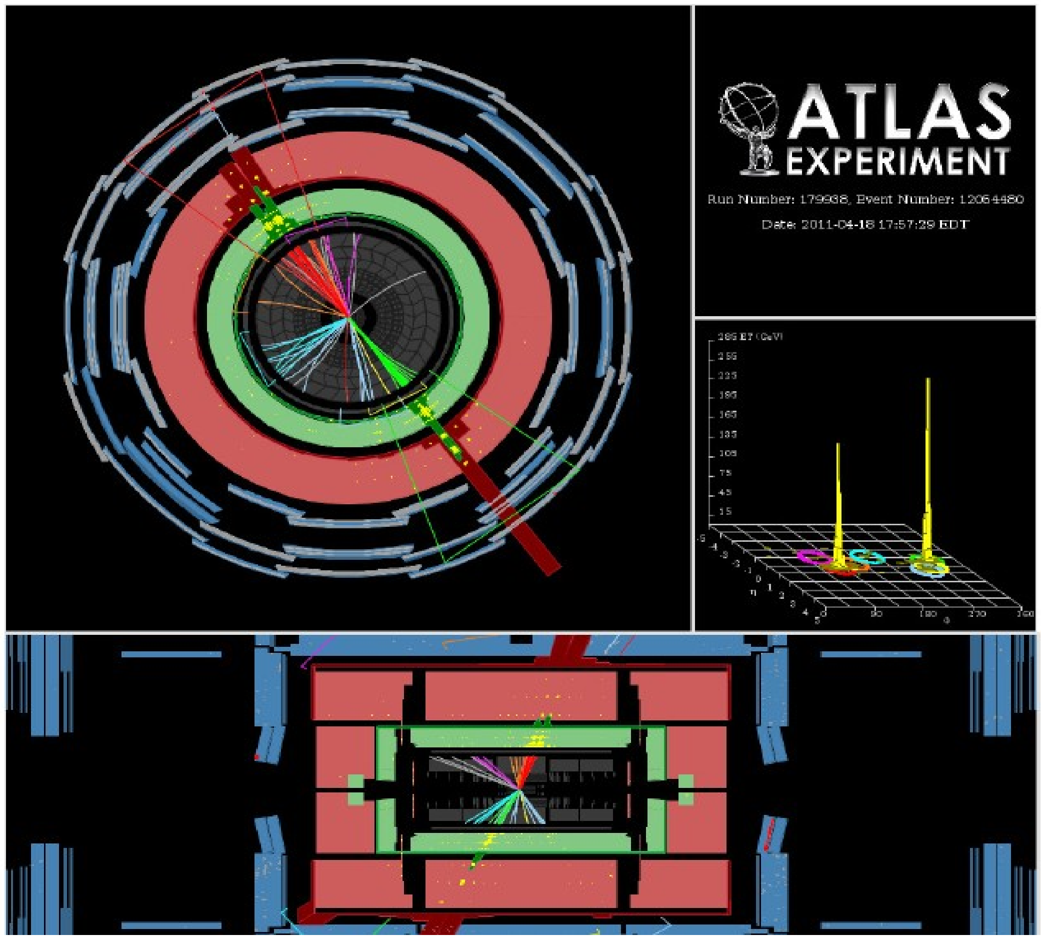


Observing masses up to 4.1 TeV, new energy range!

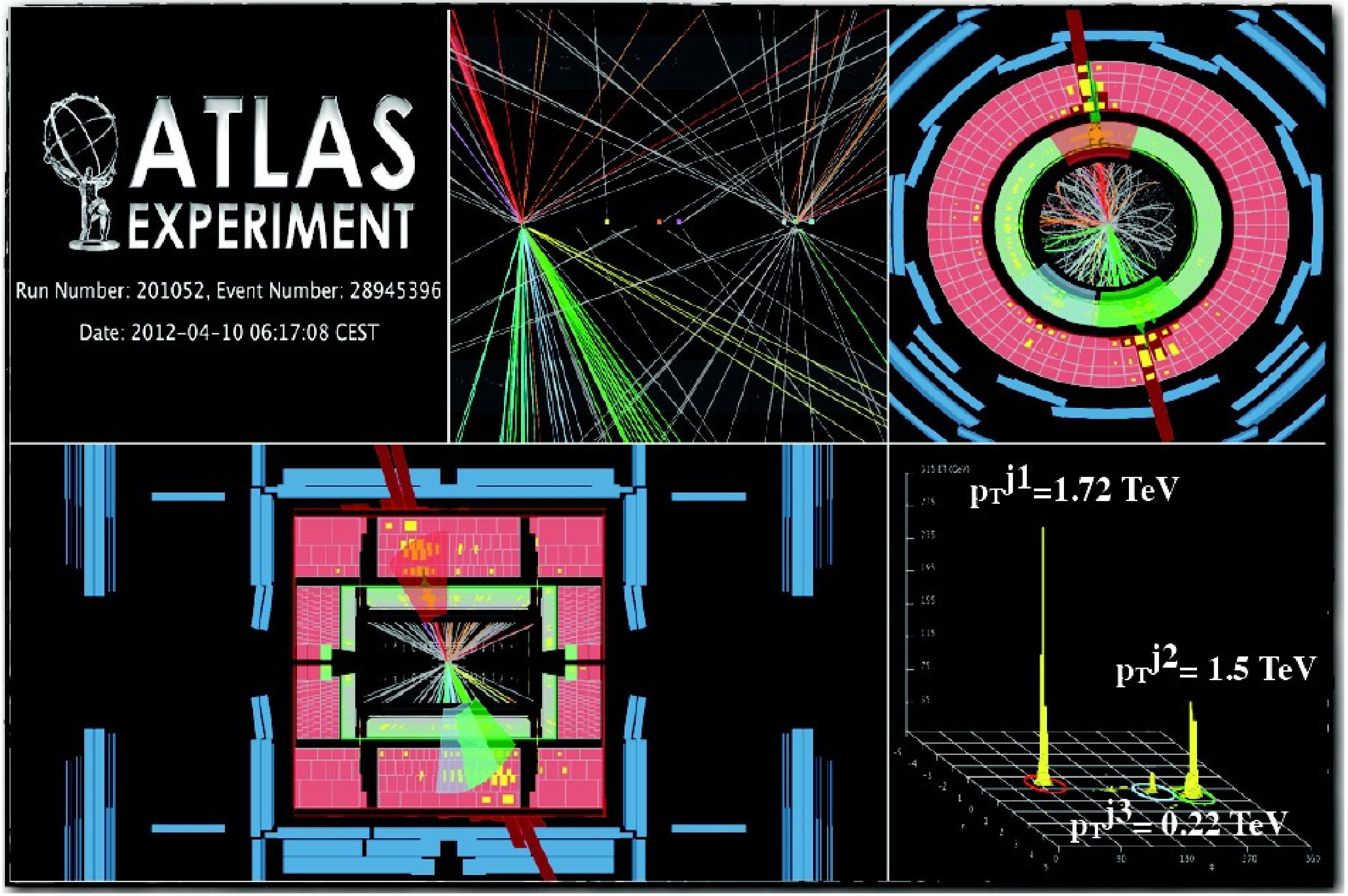
Powheg systematically predicts higher cross sections at low mass, and lower prediction at high mass, than NLOJet++

ATLAS high mass dijet event

2011 data event with dijet mass of 4040 GeV

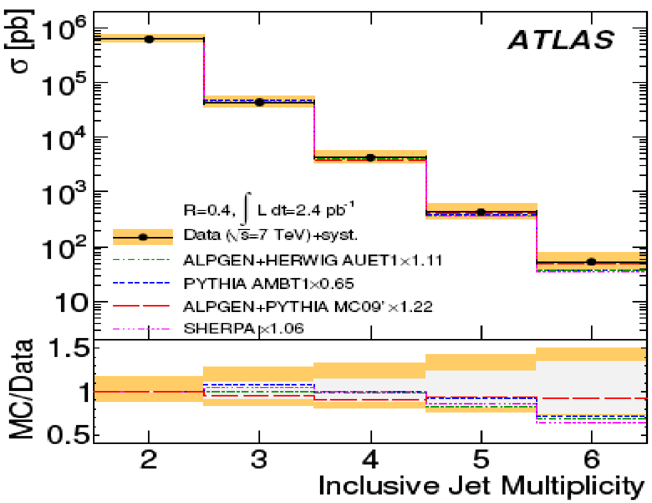


ATLAS high E_T jets



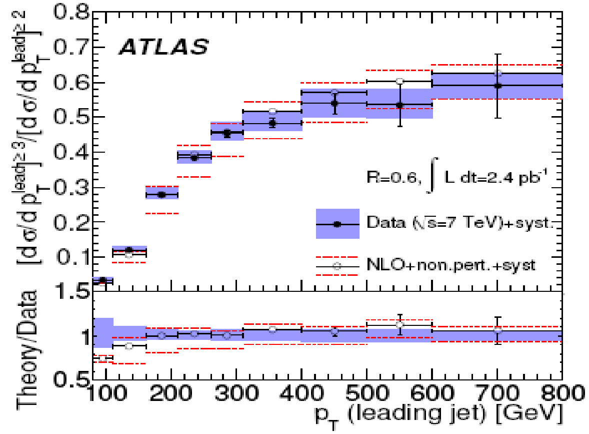
Multi jet cross-section

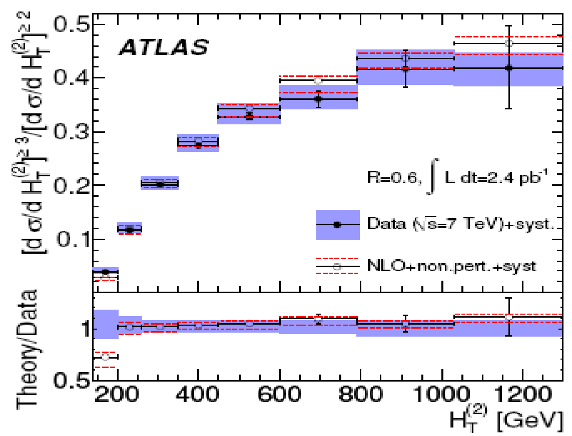
- Fundamental and direct test of QCD
- Main systematics: JES and "close-by jets" effect



Find ALPGEN better describes data

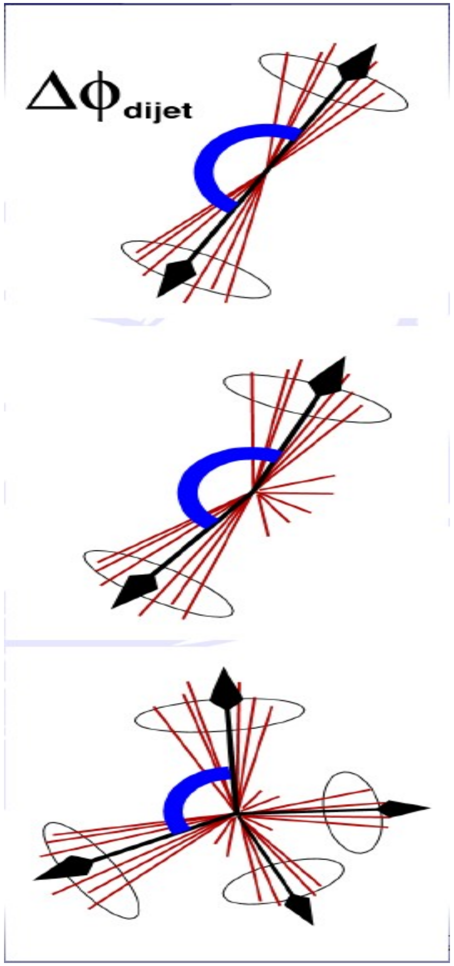
Ratio σ(3-jet)/σ(2-jet) much smaller uncertainties





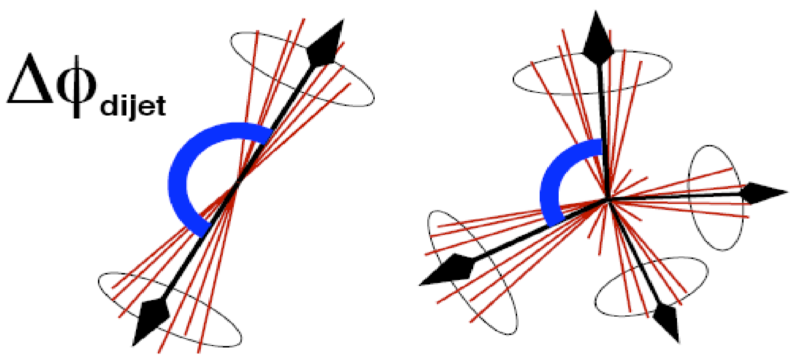
Studies of higher order QCD radiation

- 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

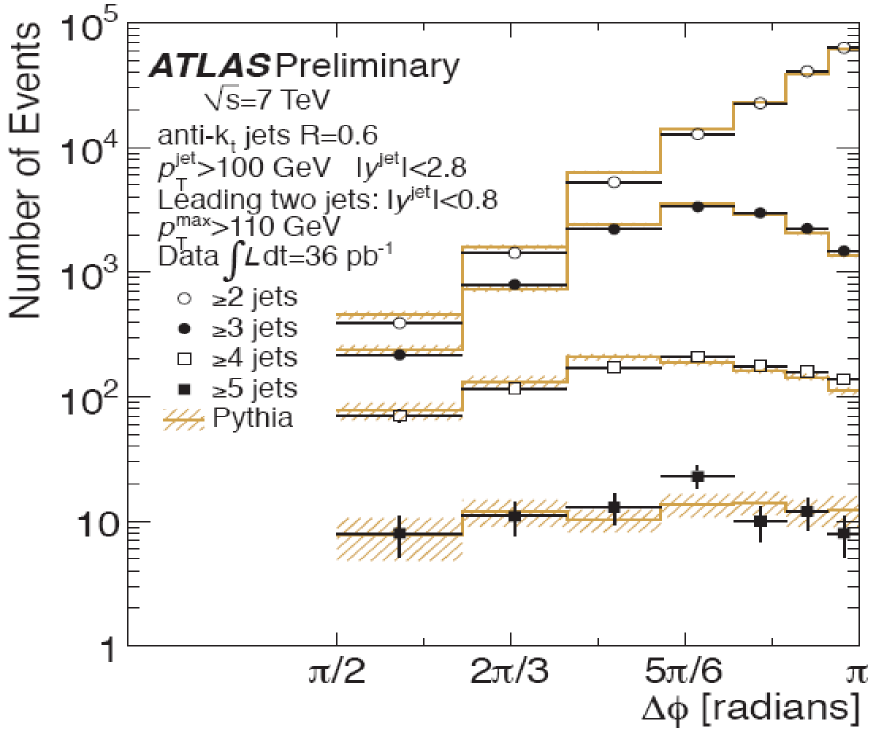


Azimuthal decorrelations

- 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.

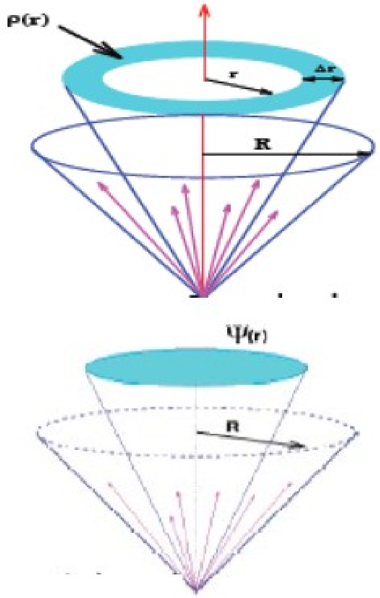


- Requiring additional jets flattens distribution.



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



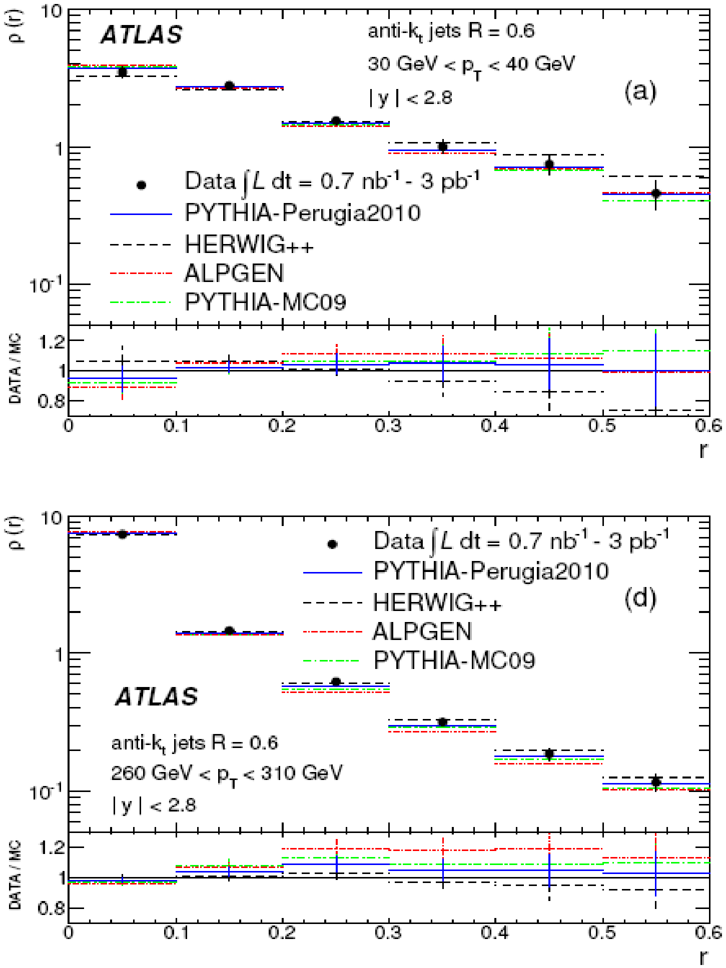
Differential jet shape

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

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

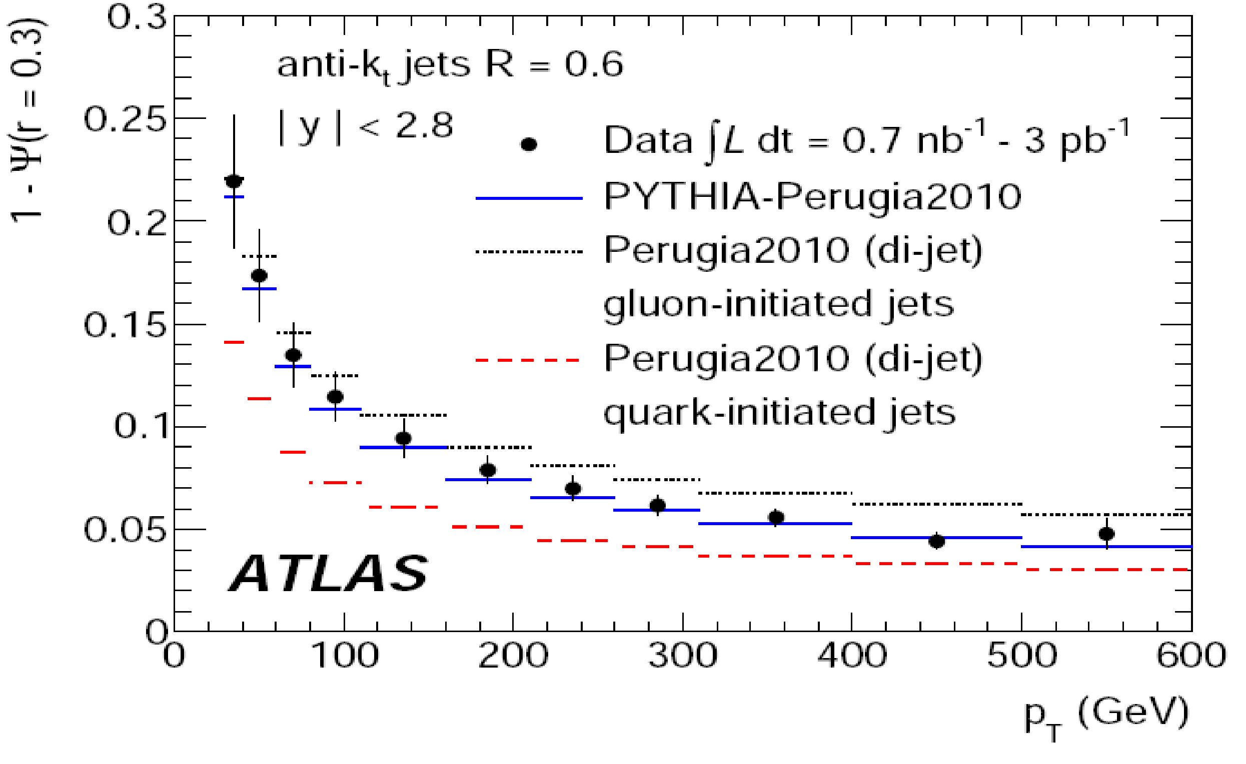


Differential jet shapes vs jet p_T, integrated over $|y| < 2.8$

- 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:



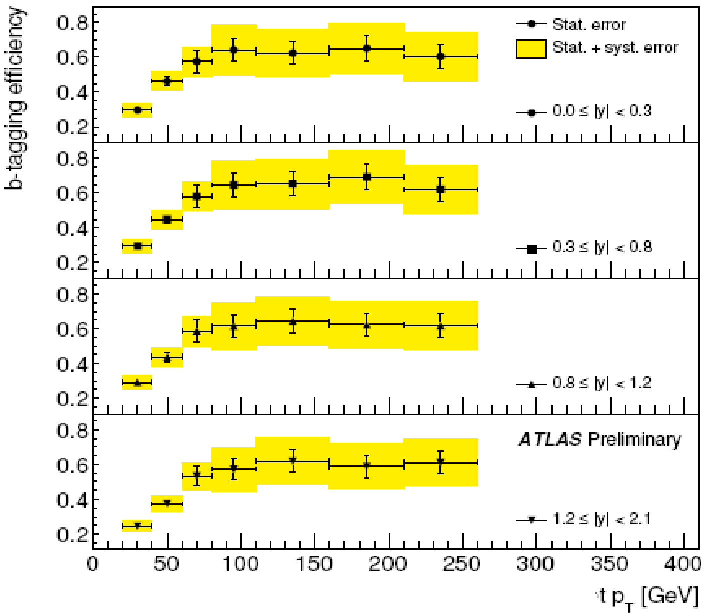
b-jet cross-section

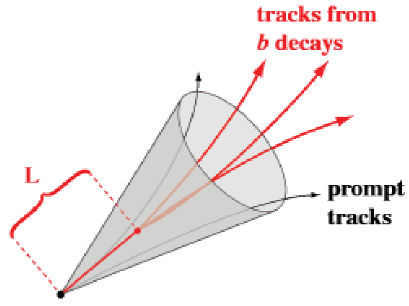
b-jet tagger "SV0"

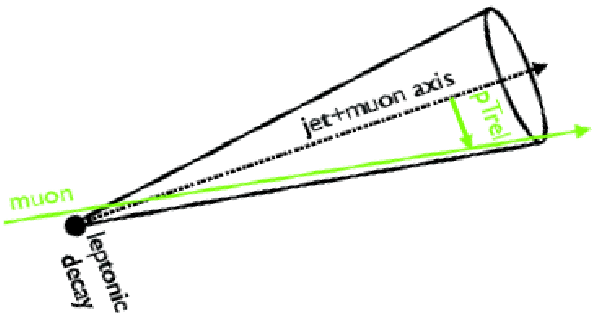
- Iterative secondary vertex seeding from track pairs
- separation power from decay length significance

Also tag b-jets with muon decay

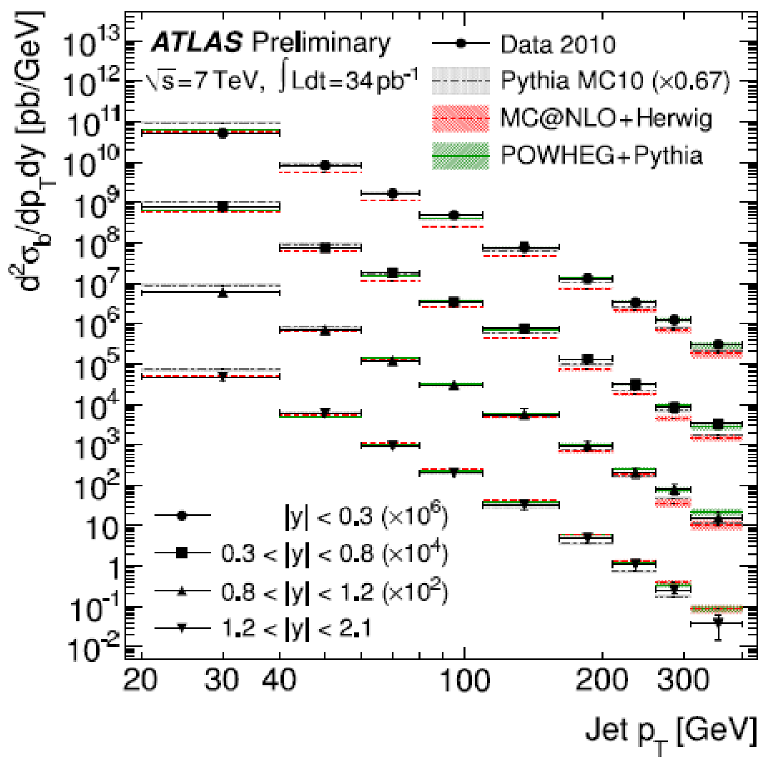
- Determine the relative distance between jet axis and muon
- Fit templates for b-jet contribution

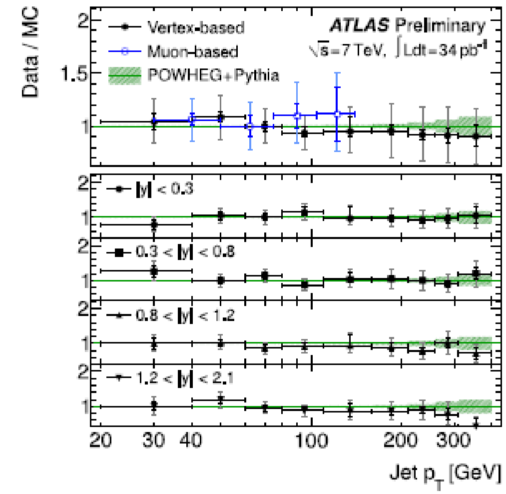


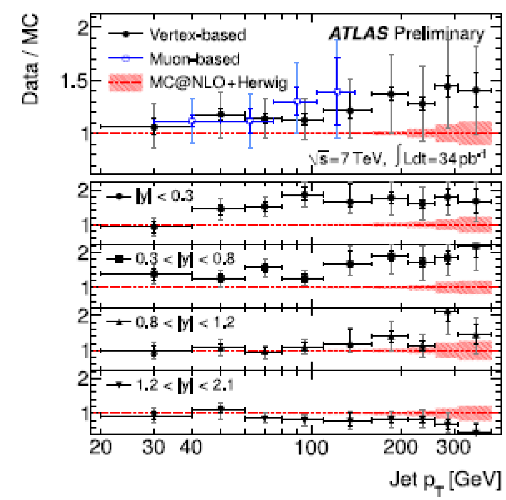




b-jet cross-section

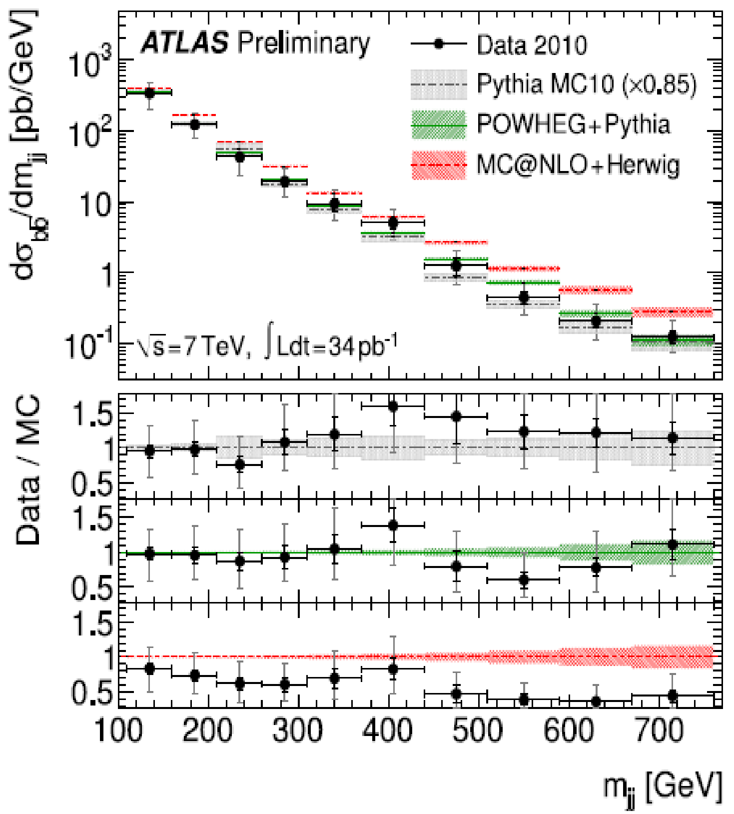




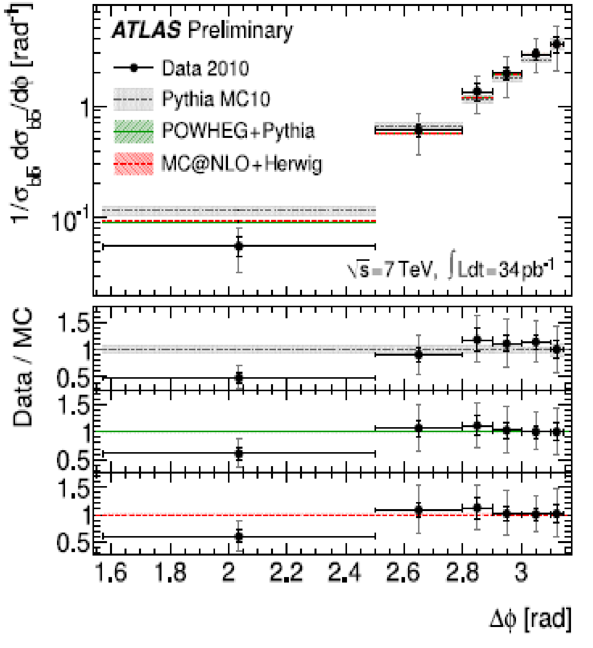


- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

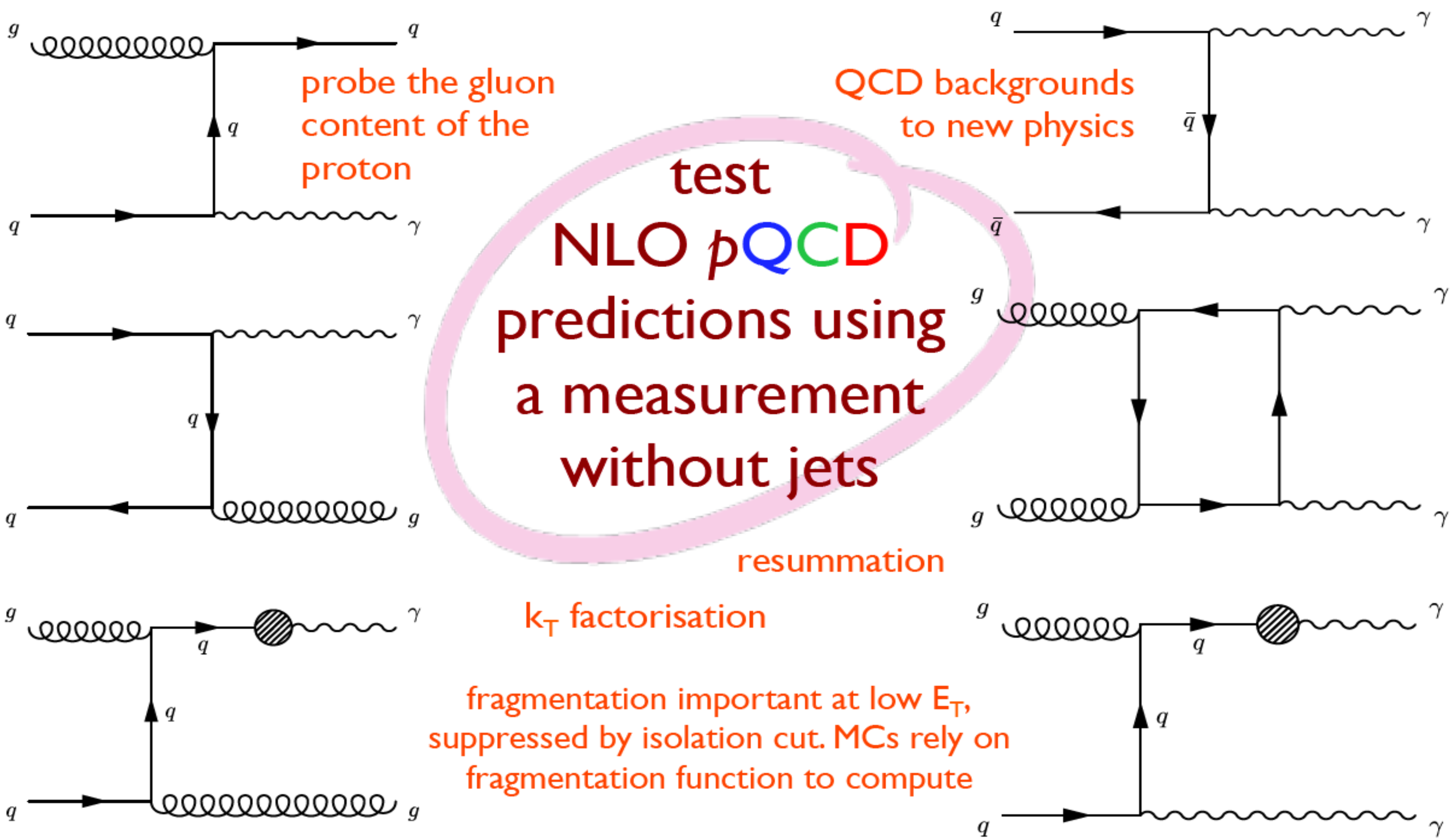
Inclusive bb-jet cross-section



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

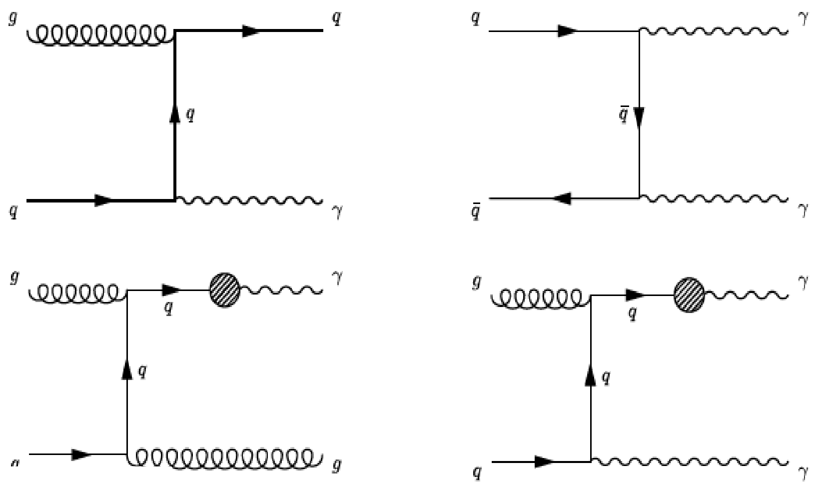


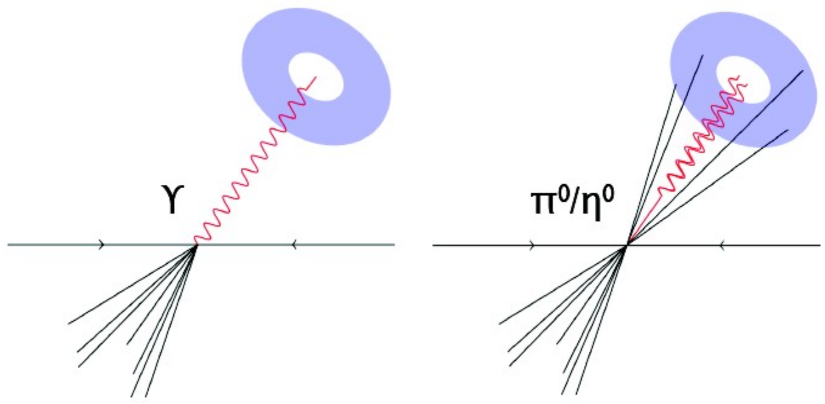
Why measure prompt photons?



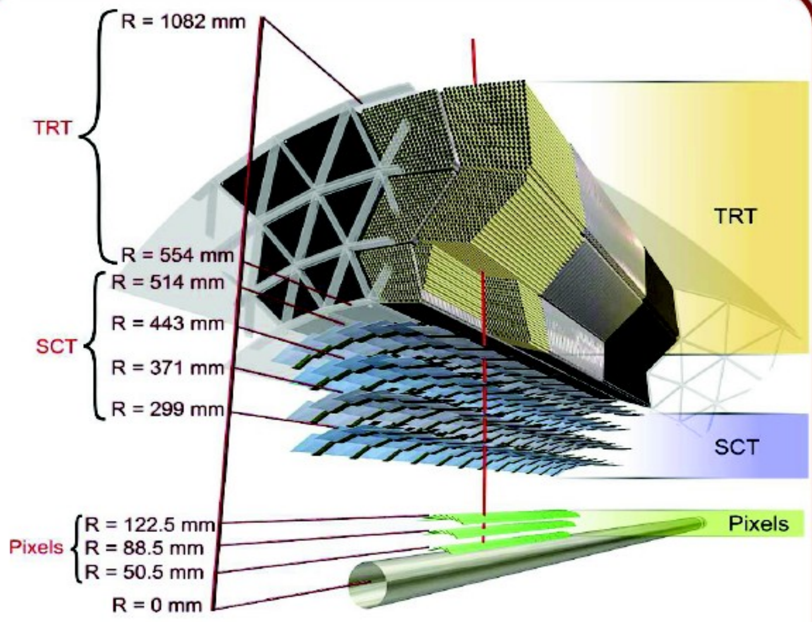
Prompt and isolated photons

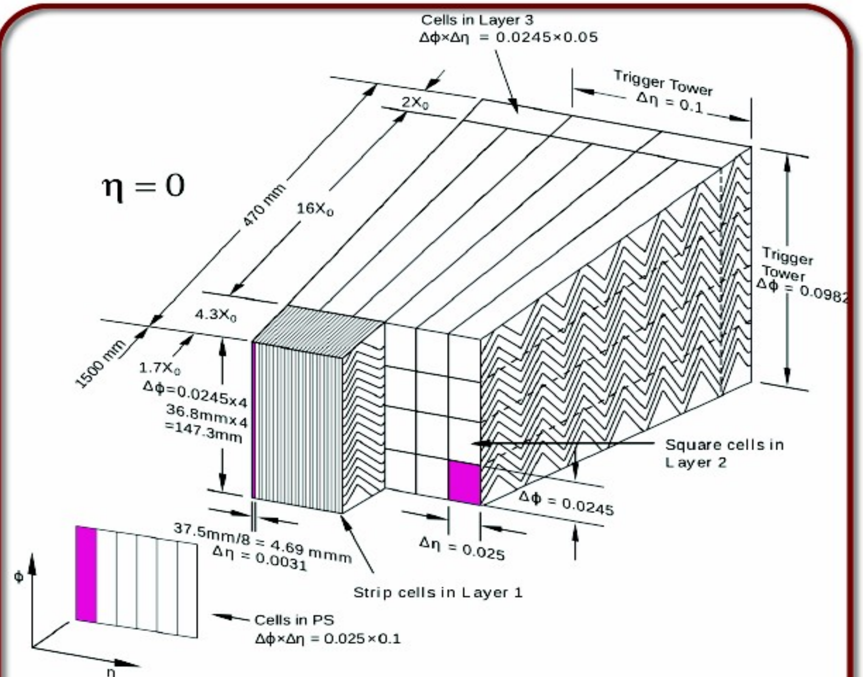
- Prompt:
  - Direct from the hard scattering
  - Parton fragmentation more important at low E_T
- Isolated:
  - Isolation criteria to reduce bgd from QCD jets
    - Photons from neutral meson decay in jets
  - Reduced fragmentation component:
    - ~30% reduction at 15 GeV
    - <10% above 35 GeV





Measuring photons with ATLAS

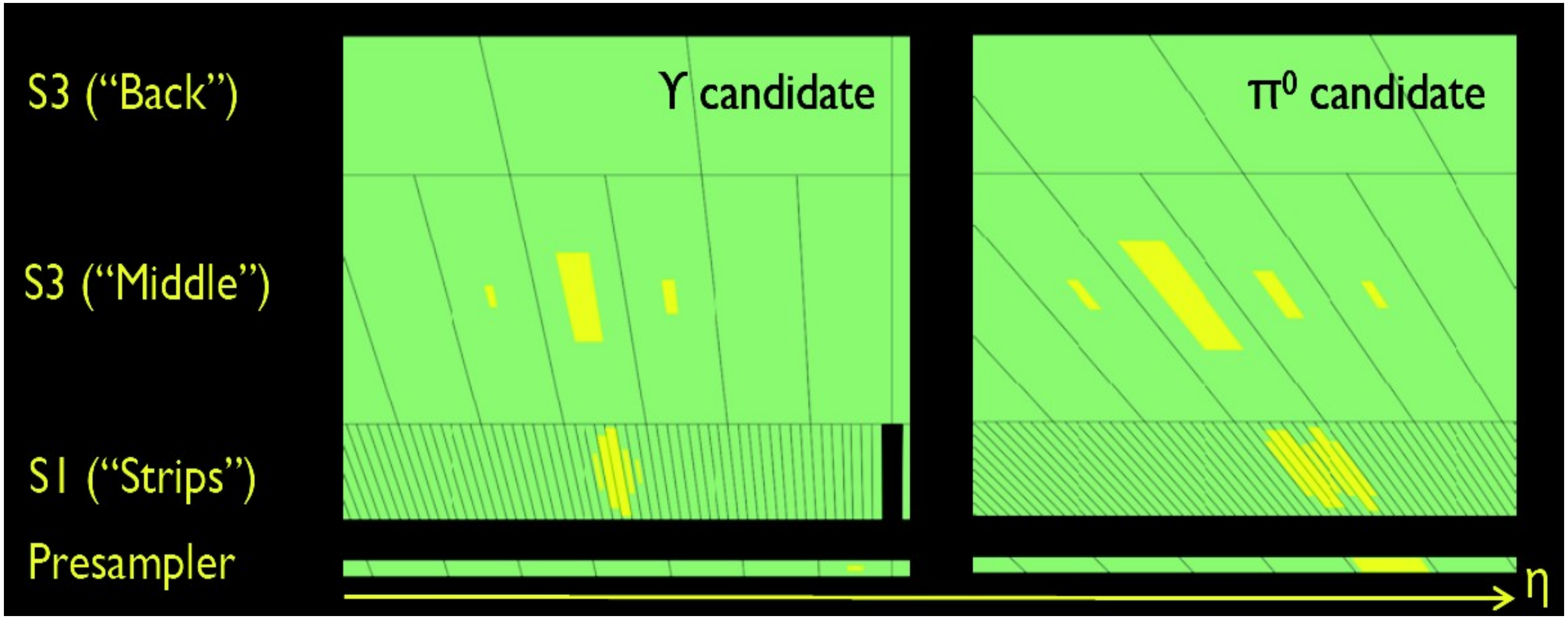




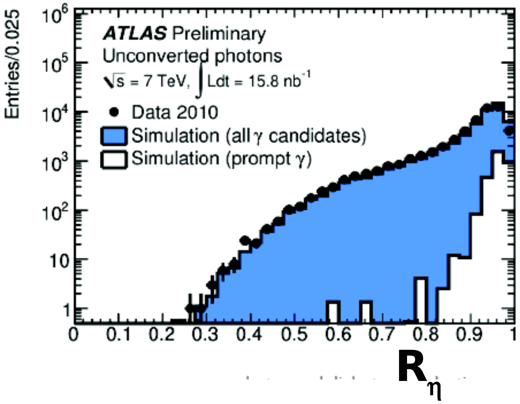
- Inner detector
  - ✓ track charged particles
  - ✓ measure transition radiation
  - ✓ e/γ discrimination
  - ✓ γ conversion reconstruction

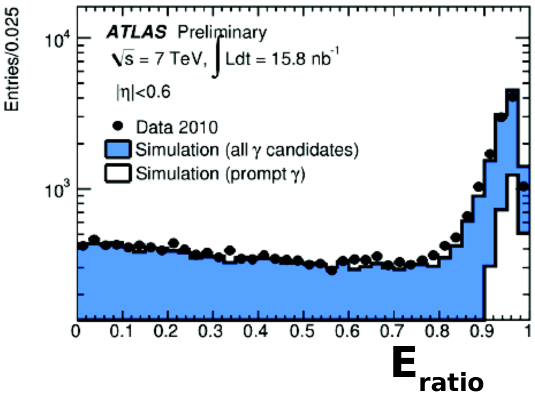
- Pb-LAr EM calorimeter
  - ✓ η/φ/longitudinal segmentation
  - ✓ fine granularity in 1st layer up to $\eta<2.37$
  - ✓ γ energy and direction
  - ✓ γ/π^0 separation (EM shower moments)

Photon identification

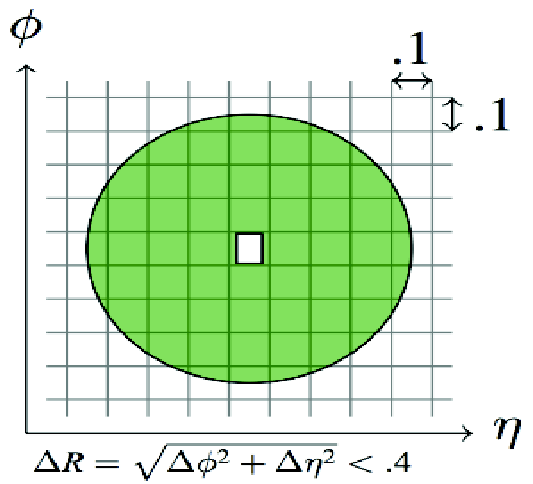


- loose and tight selection
- optimised separately for unconverted and converted photons

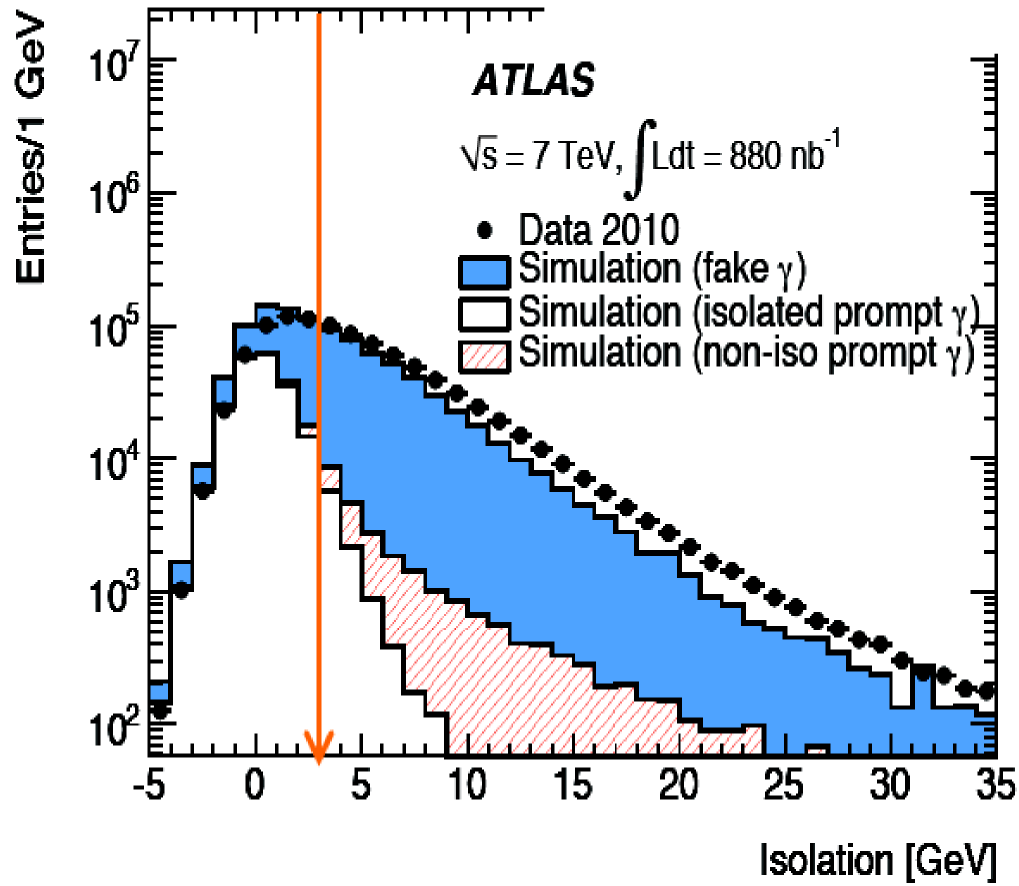




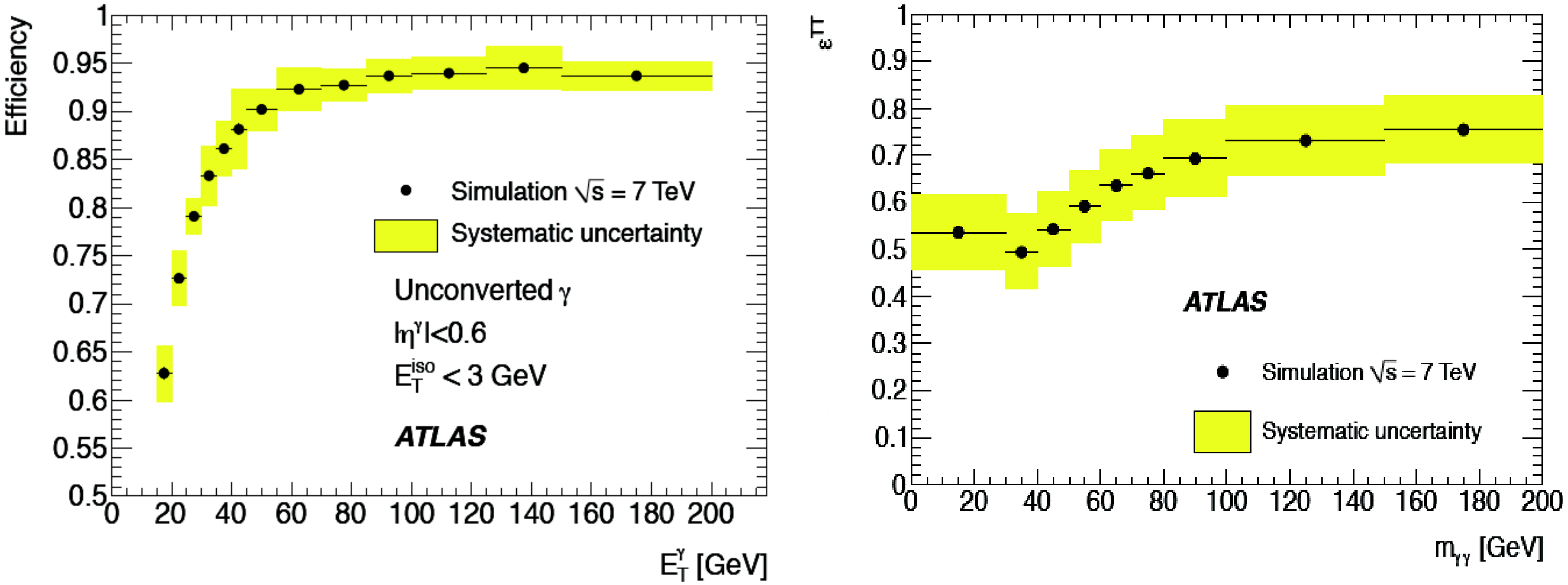
Photon isolation



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



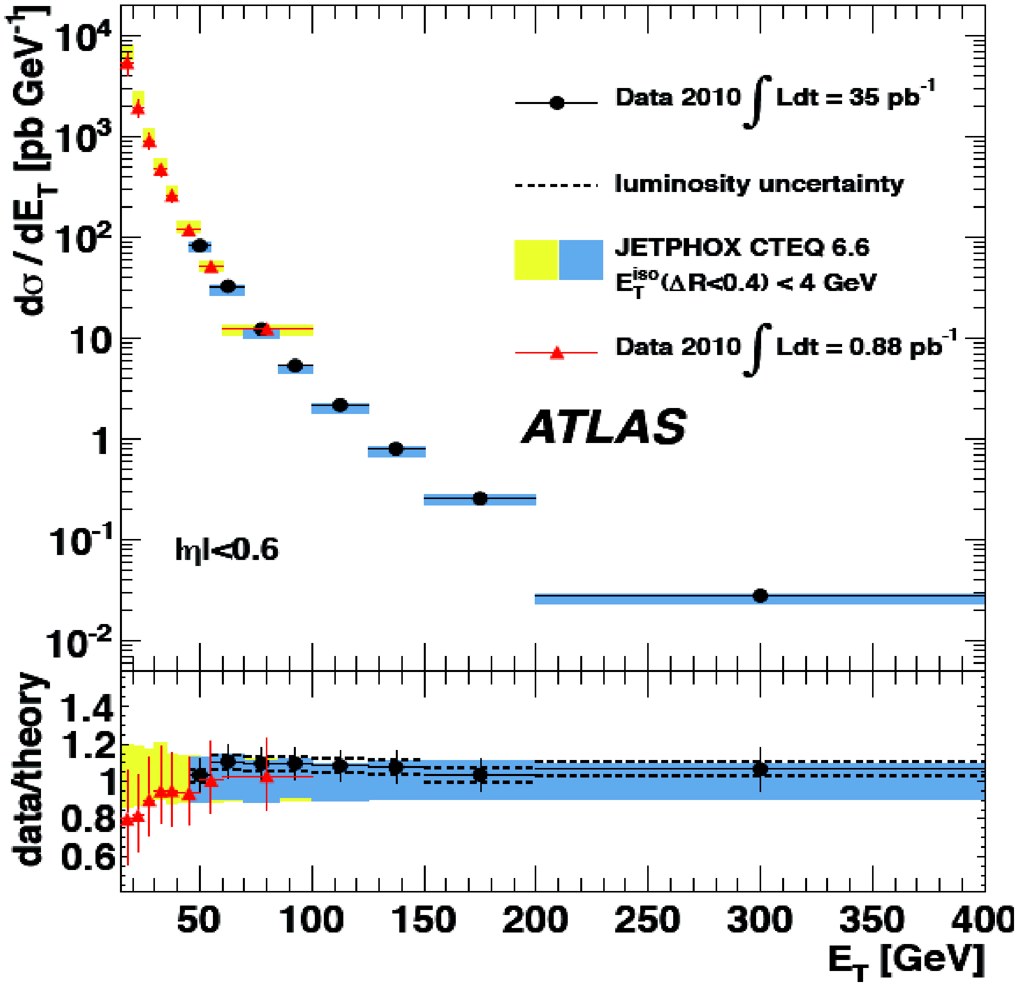
Photon identification efficiency



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

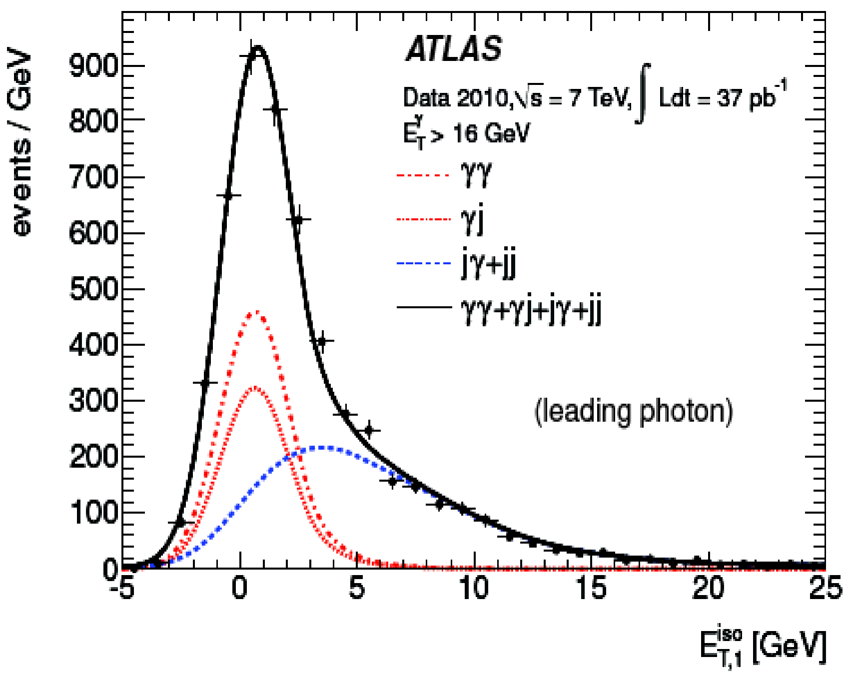
Inclusive cross-section

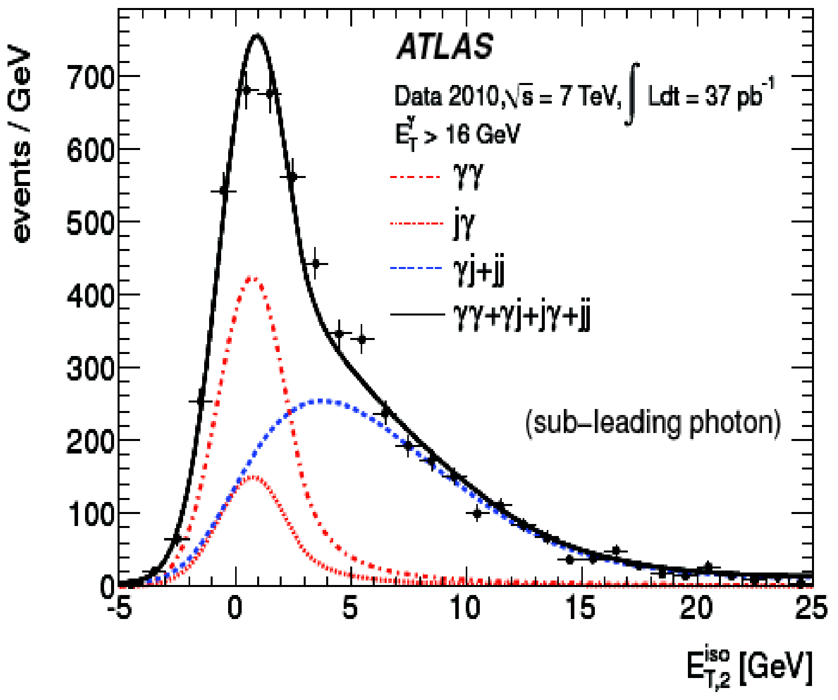
- Measured in 4 rapidity ranges
- Here example for central barrel



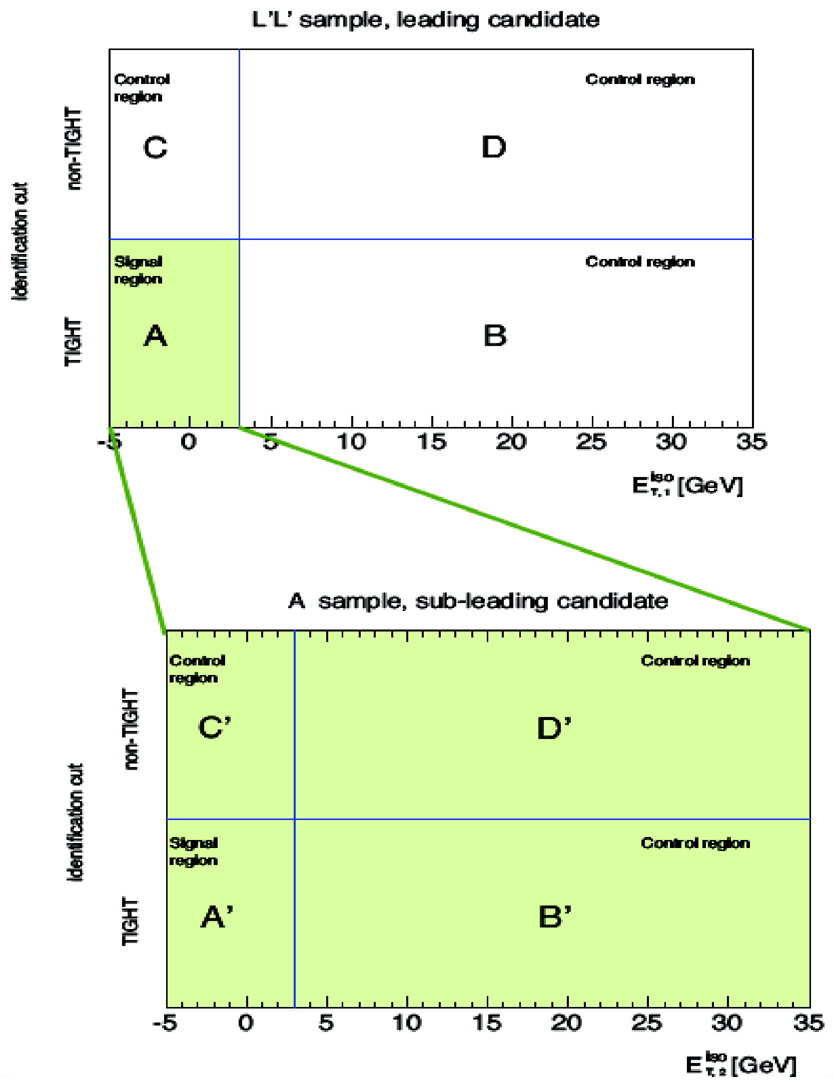
Diphoton cross-section

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





ABCD method



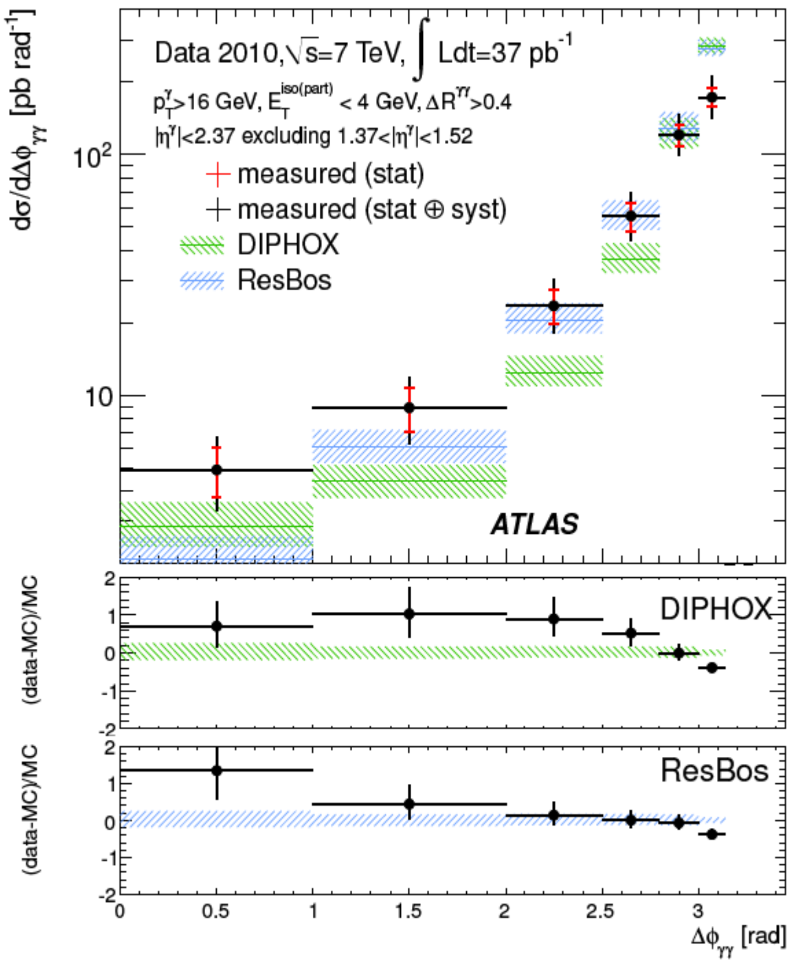
$$N^A_{\mathrm{sig}} = N^A - N^B \frac{M^A}{M^B}$$

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

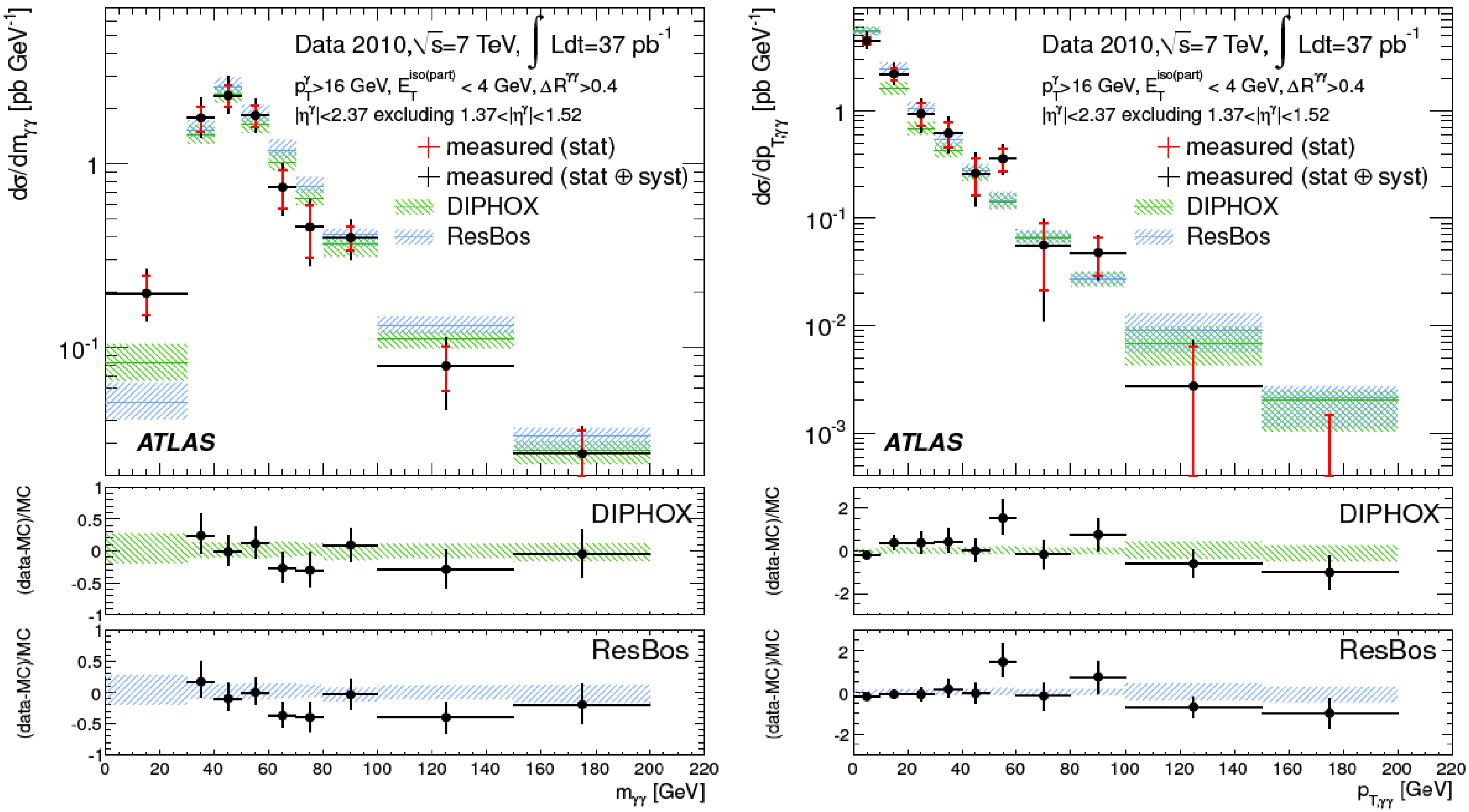
- Signal purity > 90% for E_T>50 GeV
- Main systematic uncertainties:
  - MC inputs (corrections to isolation definition)
  - Bgd control region definition

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



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)

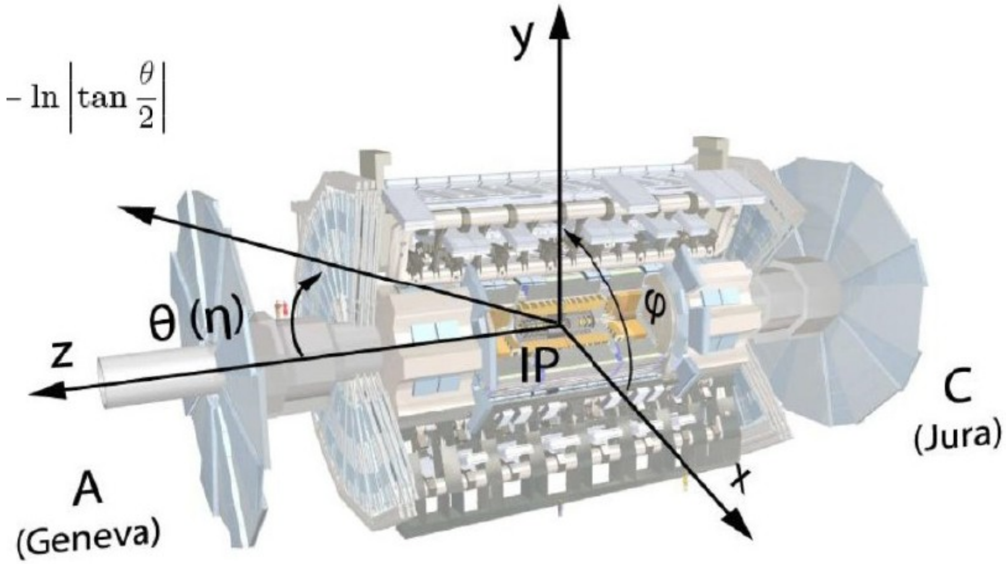
Next topics

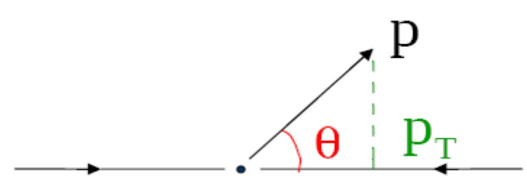
- 7.11 - W, Z bosons: inclus. cross-sections, W/Z+jets
- 14.11 – W, Z bosons:precise measurements
- 21.11 – Top: xsection, mass
- 28.11 – Dibosons and anomalous couplings
- 5.12, 12.12 - **Higgs**
- 19.12 – **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme

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)

$$p_T = p \sin\theta$$

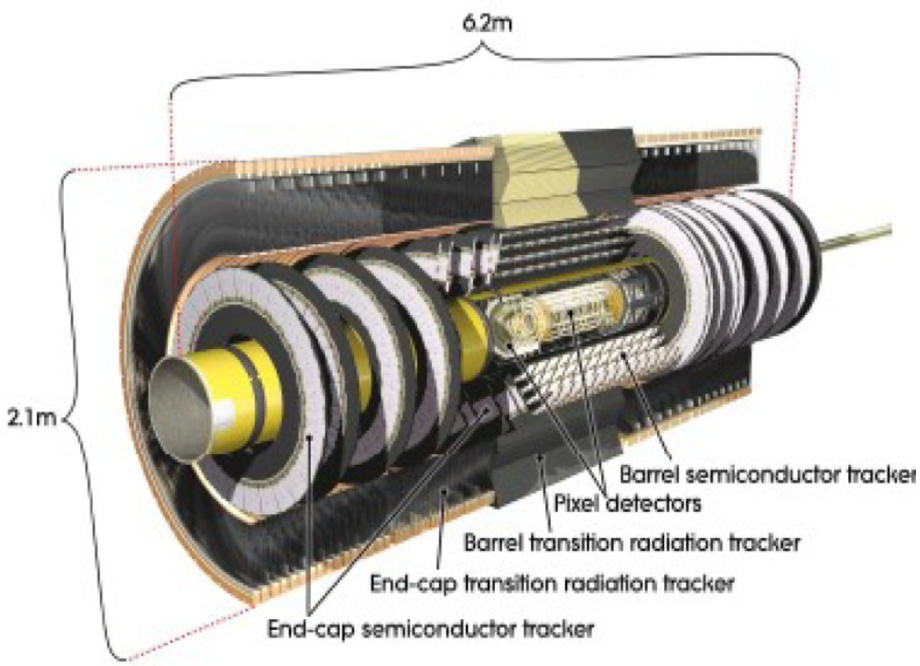
Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

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

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

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

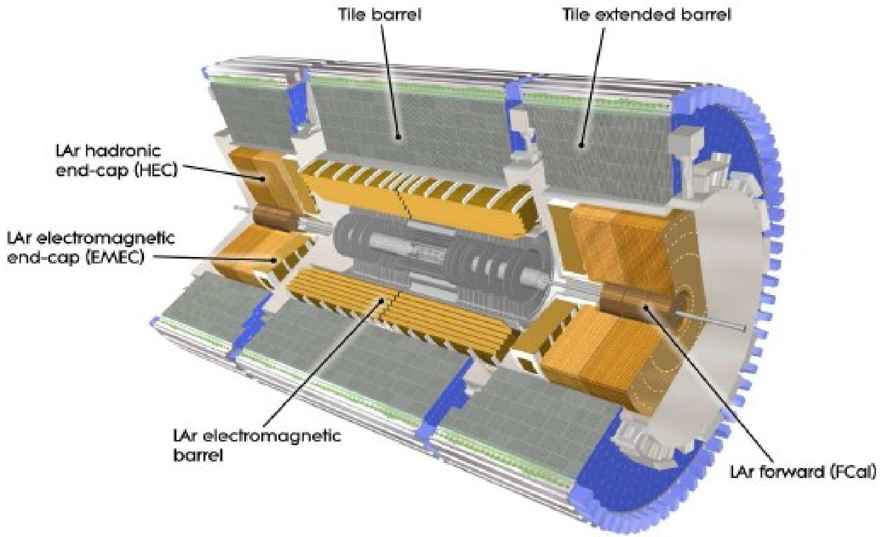
ATLAS Inner Detector



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 $50\%/\sqrt{E} \oplus 0.03$