Recent QCD results from LHC experiments

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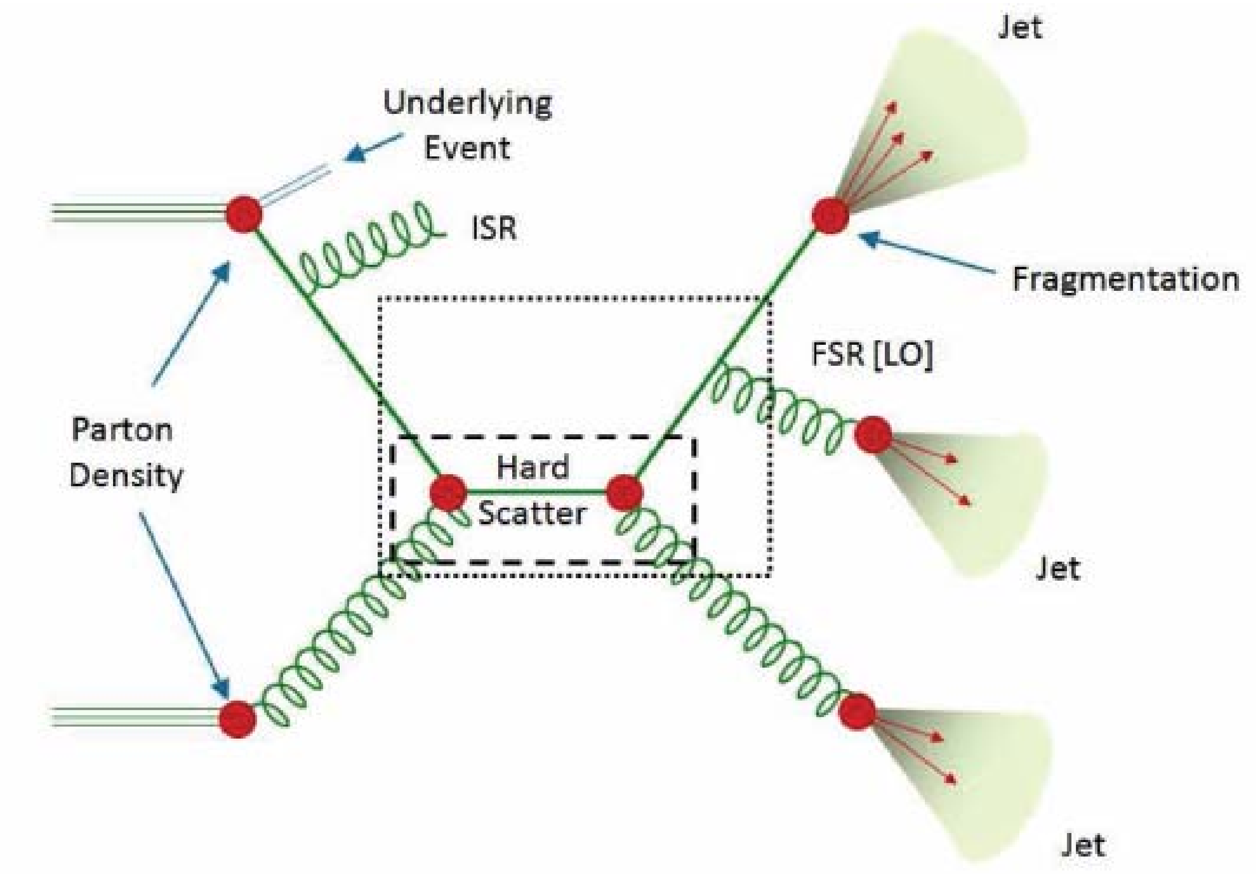
Introduction

- Hard scatter of constituents from initial state hadrons to final state partons
  - Initial state characterized by parton density functions (PDF's)
    - Initial state hadrons are bound states; remnants appear as underlying event
  - Final state partons seen as hadrons
  - LO description of hard scatter is insuficient to describe data
    - Challenging calculation: NLO, NNLO?
- QCD studies at LHC benefit from years of study at other facilities
  - Especially the Tevatron where many problems are similar
  - Also e±p (HERA), e+e- (LEP,..), and fixed target experiments
    - Confirmed underlying theory and measured many parameters
    - Measured parton density functions and tested their evolution
- Powerful software tools for describing expectations
  - LO matrix elements plus parton showers and hadronization (Pythia, Herwig, Sherpa)
  - Matrix element descriptions + parton showers (Alpgen, Sherpa)
  - Full fixed order NLO calculations (MCFM, NLOJet++)
  - Full fixed order NLO + parton showers (MC@NLO, POWHEG)

Introduction



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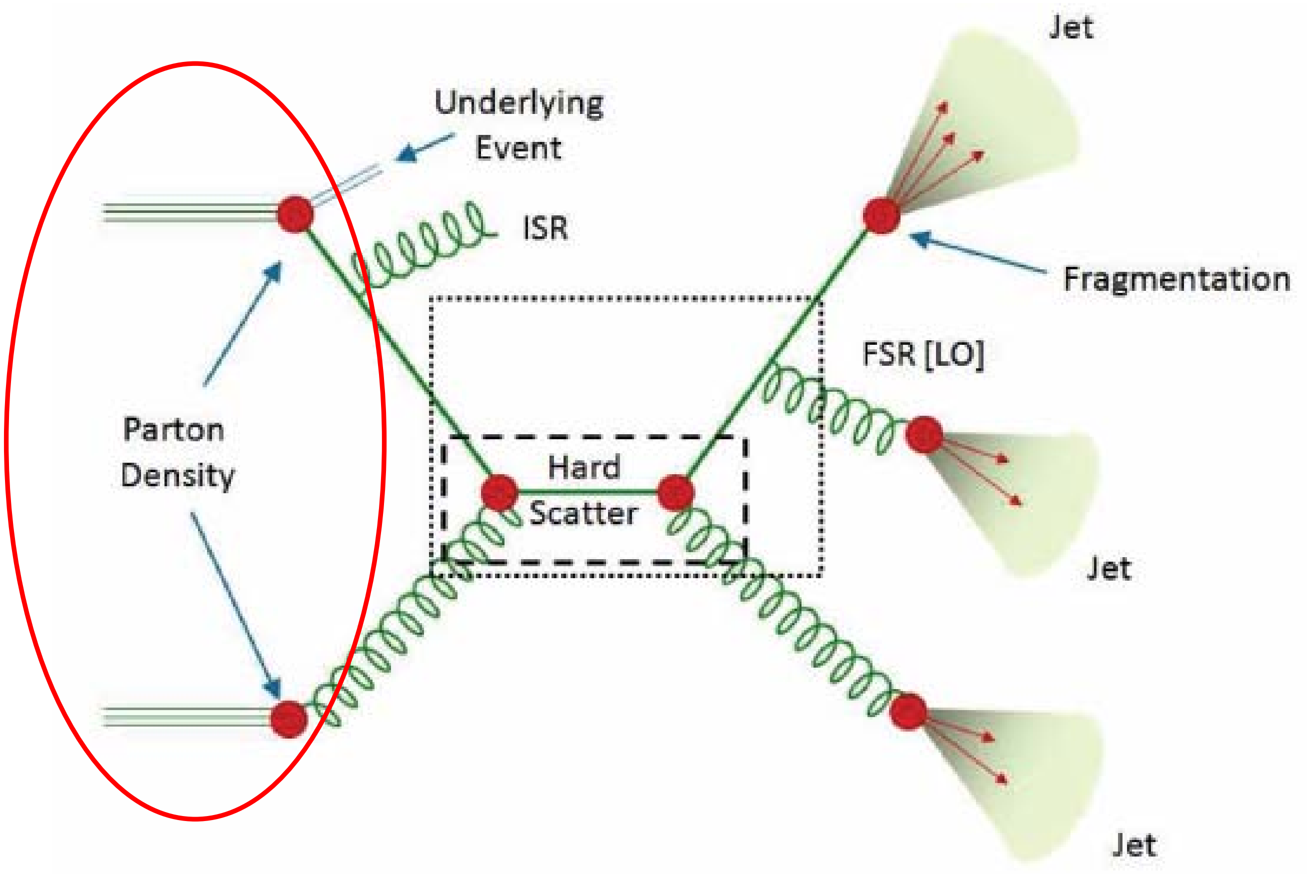
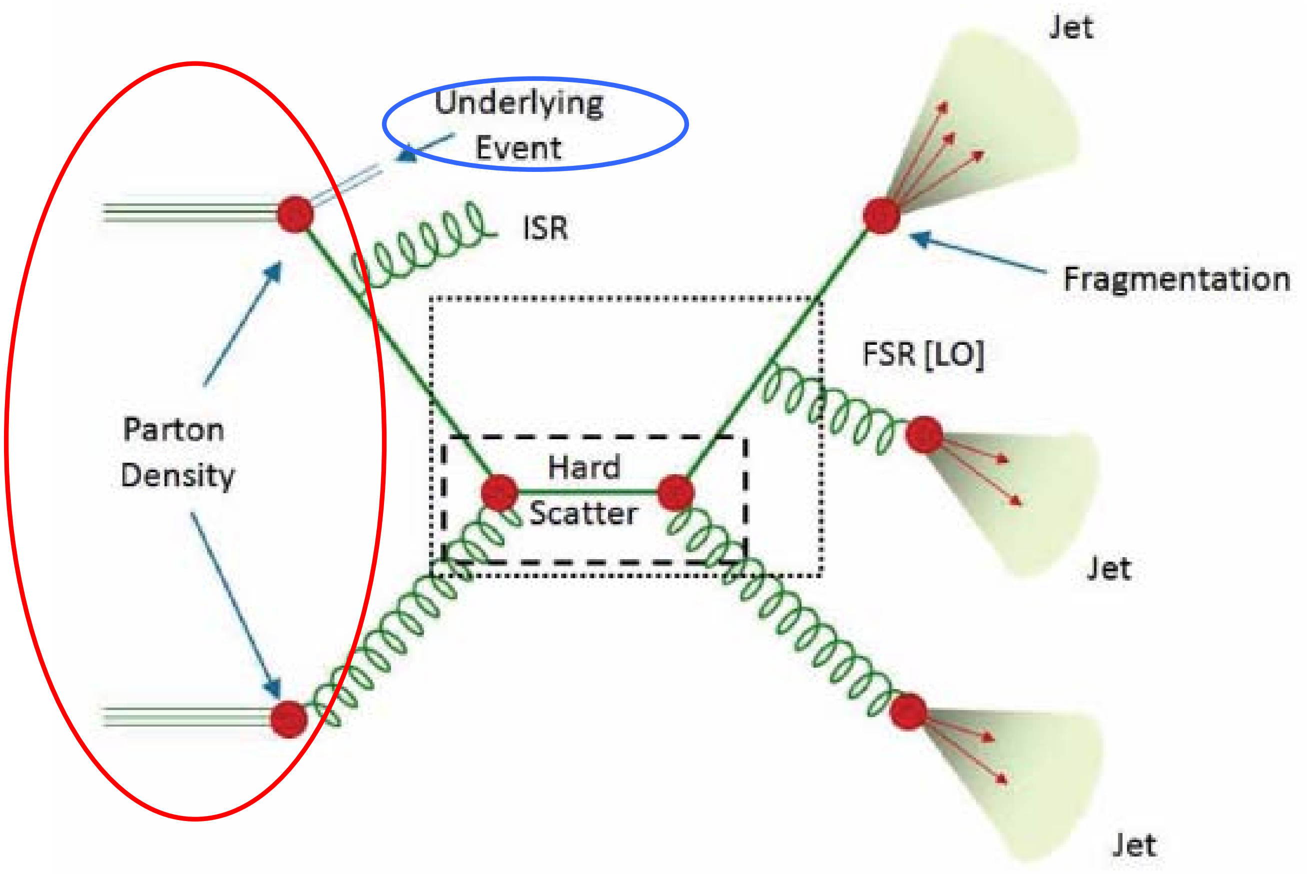


PDF's

Introduction

PDF's



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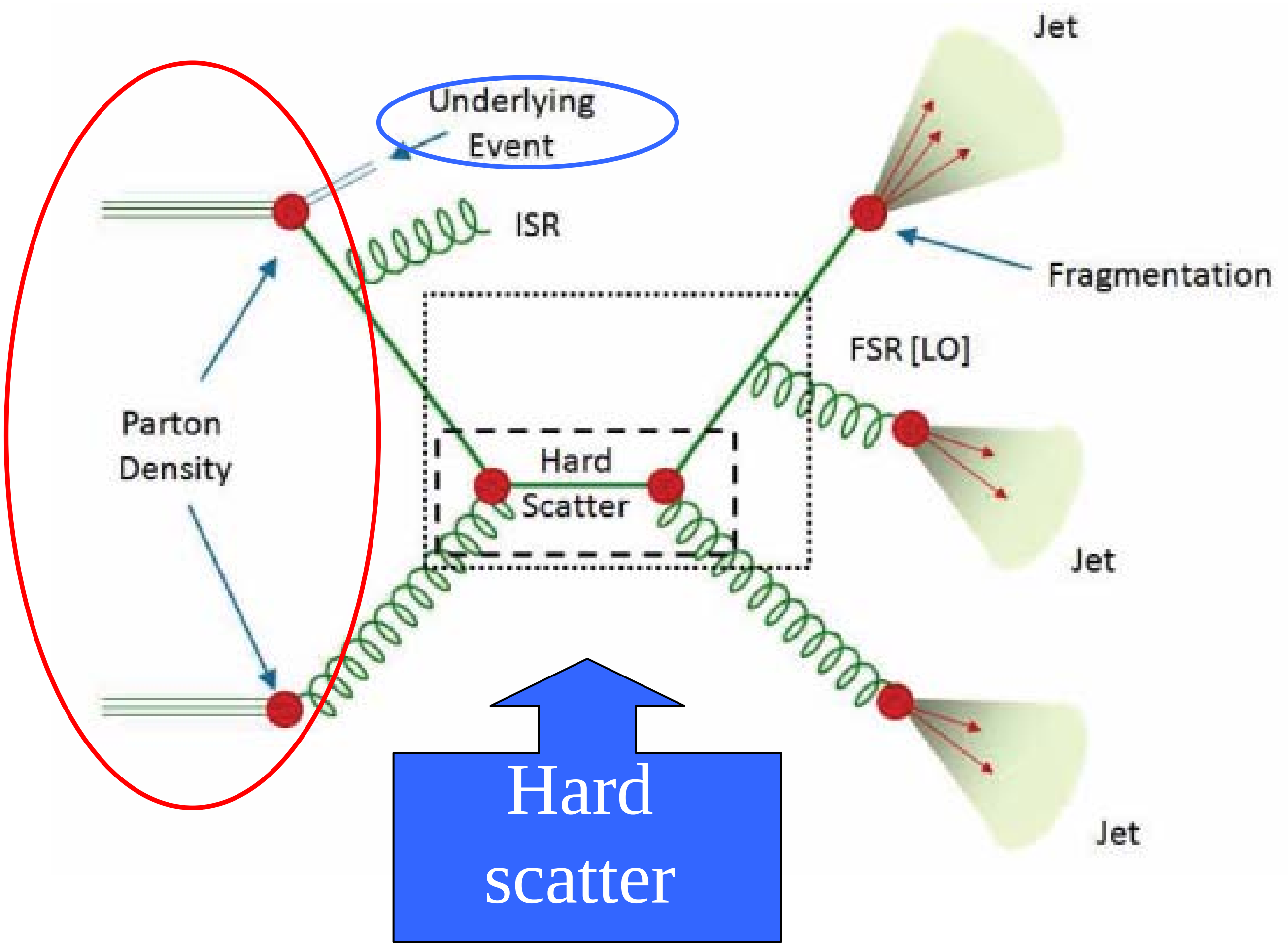
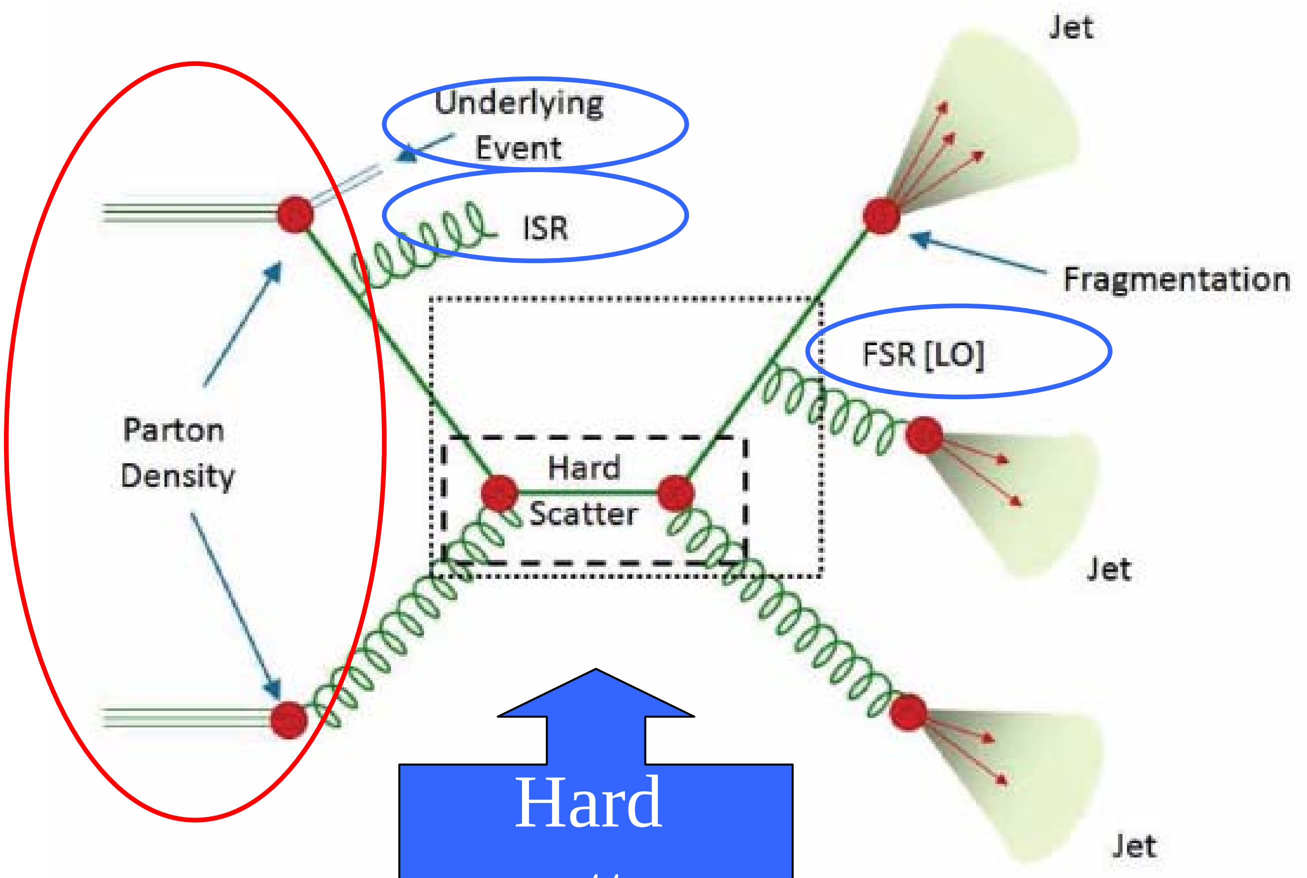


PDF's

Hard scatter

Introduction



PDF's

Hard scatter

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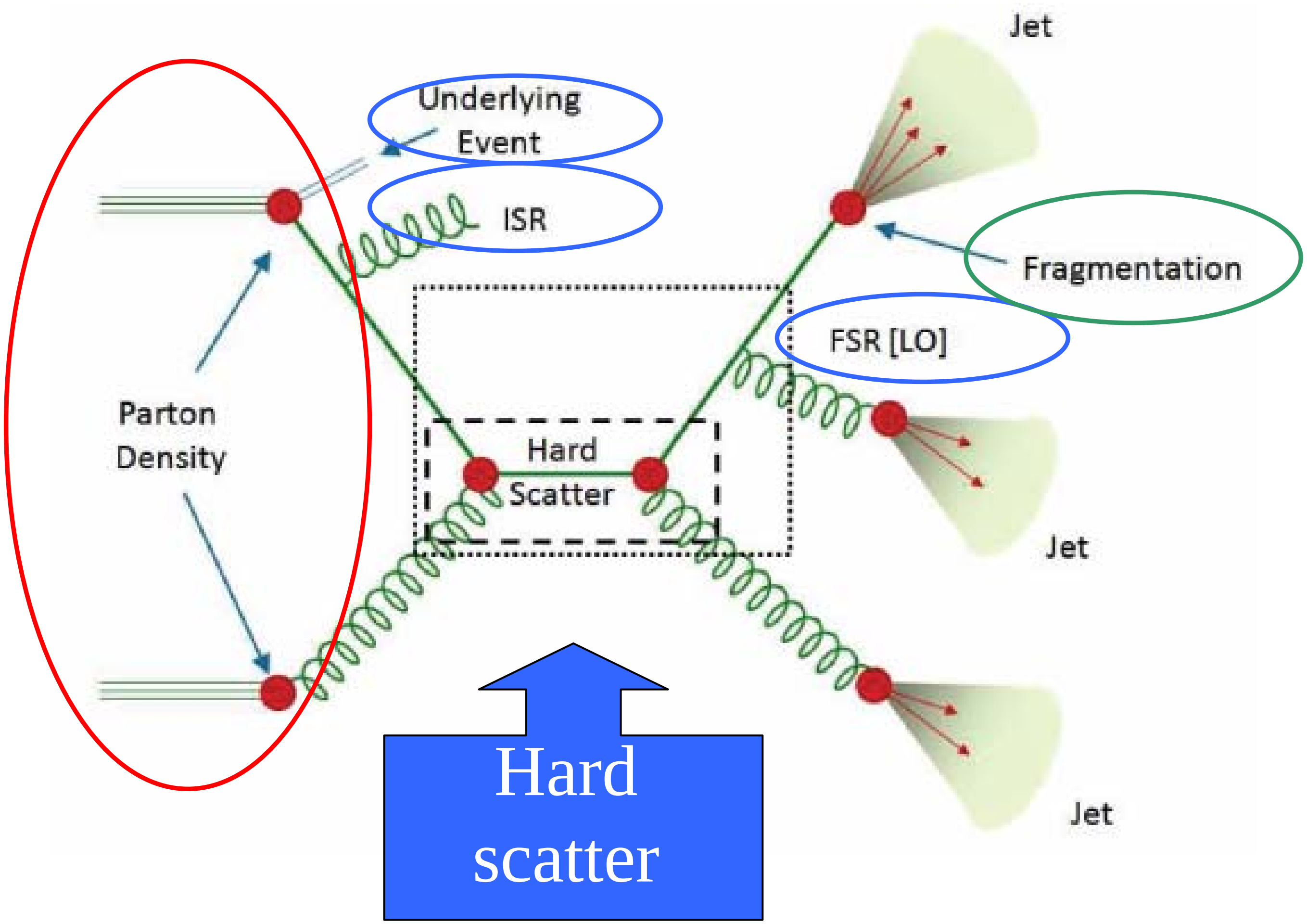

PDF's

Hard scatter

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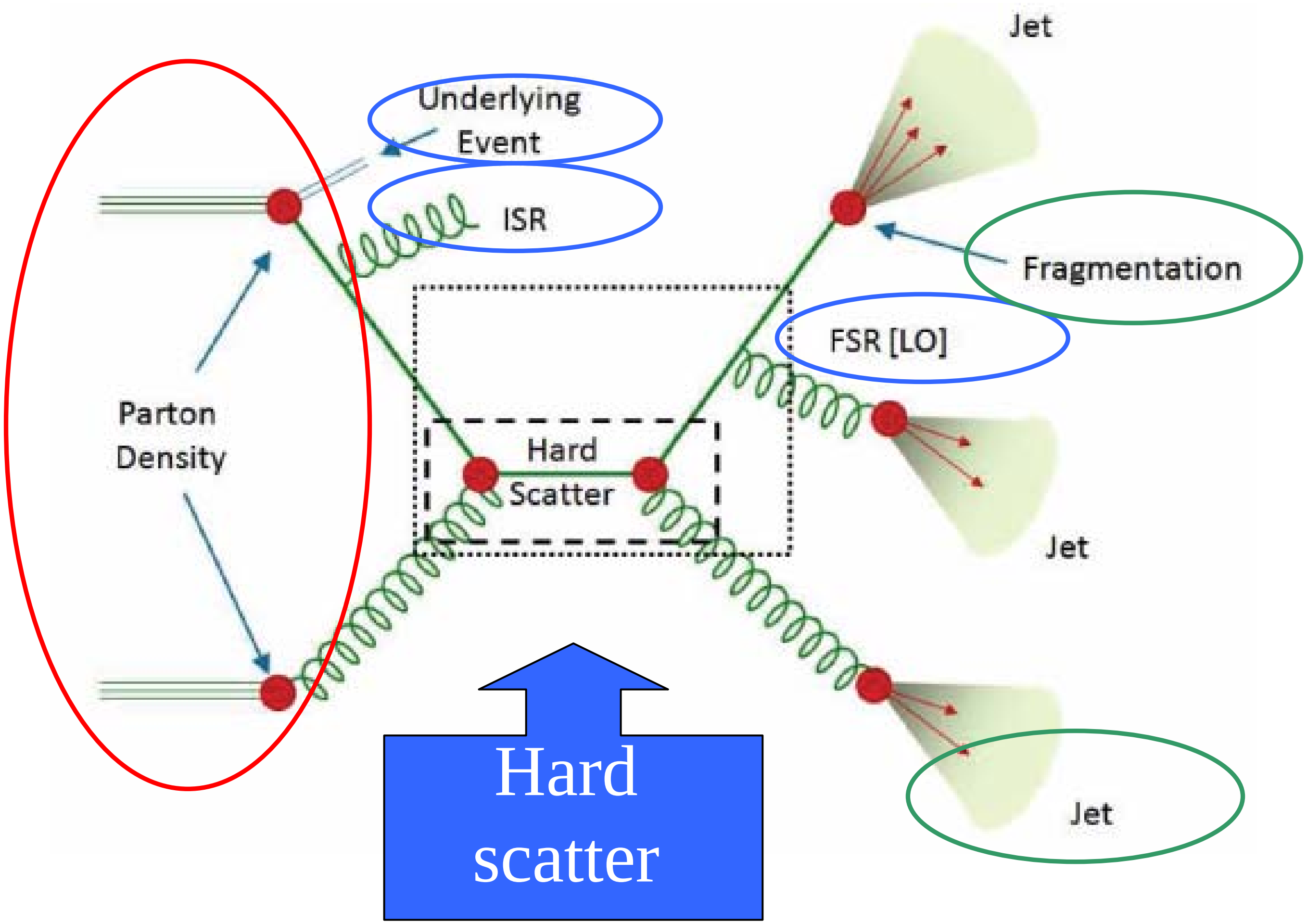


PDF's

Hard scatter

Introduction

The challenge:

- Final states at hadron colliders dominated by QCD processes
- Almost any new physics involves QCD
  - Created from protons constituents
  - Parton density functions needed
- Final states usually involve quarks and gluons (i.e. hadron jets)
- A major background for new physics production is often QCD
  - huge cross section
- Better understanding of QCD=> improved sensitivity to new physics

Outline

Perturbative QCD:

- Jet properties
- Inclusive Jet cross sections
- Dijet cross sections
- Multijet production
- W/Z + Jets
- Isolated prompt photons

Non perturbative QCD:

- Underlying Event
- Minimun Bias

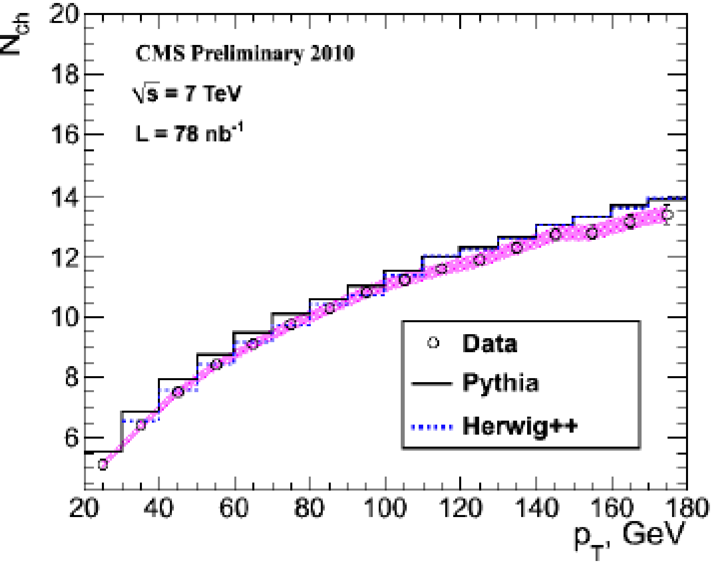
Conclusions

Jet Properties

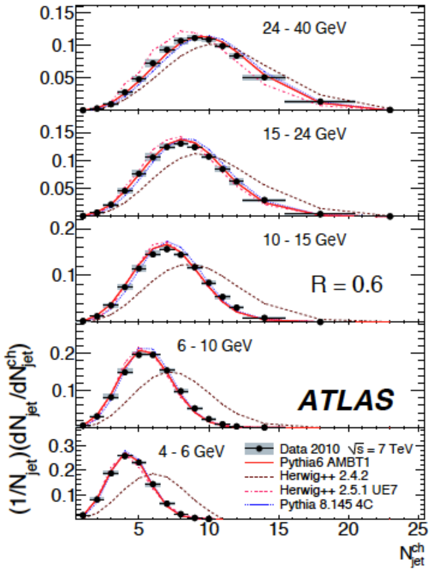
- Need to study MC description of jets: important for QCD measurements

Mean charged particle multiplicty vs jet p_T

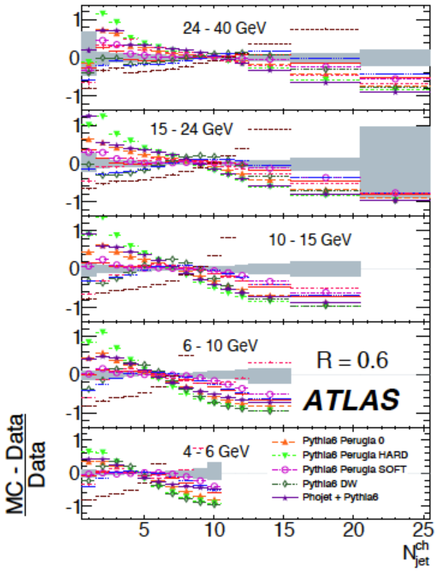
- Uncertainties from p_T migration associated with jet energy scale



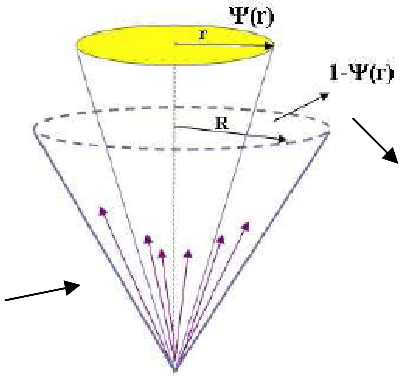
Multiplicity distributions for five intervals of jet p_T

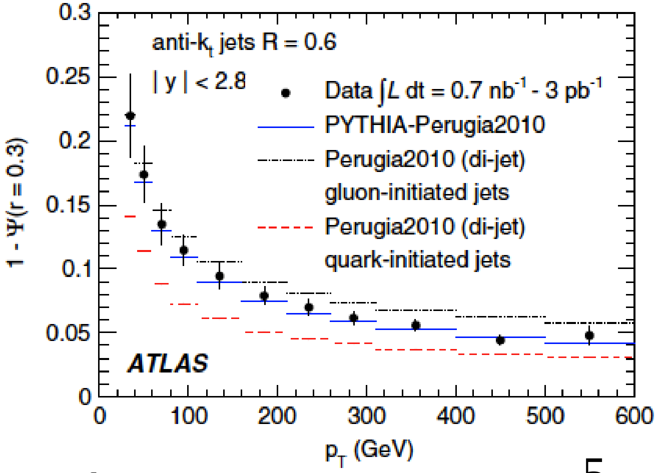


Comparisons with Pythia tunes



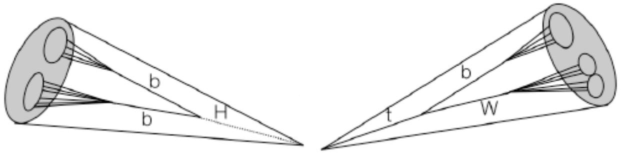
Energy density in tail of jet (r > 0.3) vs jet p_T



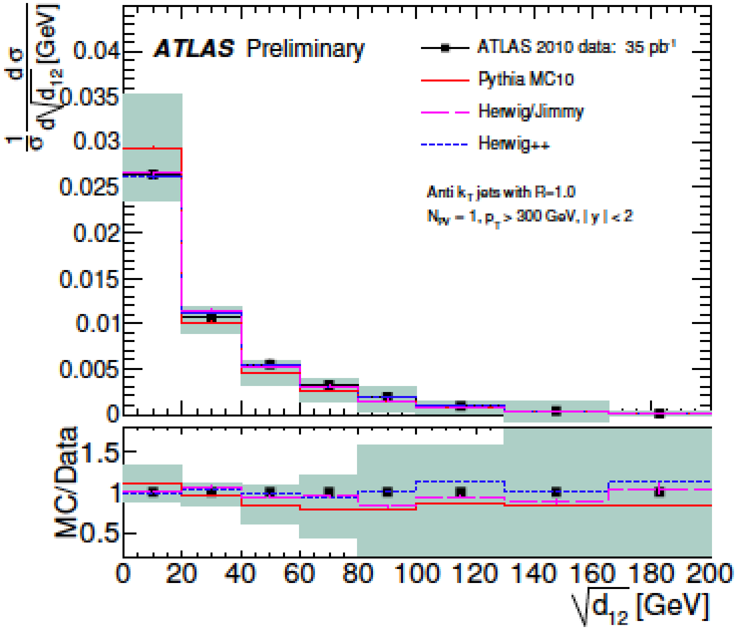


Jet Properties

- **Jets may contain interesting substructure**
  - **boosted decays of heavy particles**
    - **high mass jets with near-symmetric sub-jets**
  - **QCD jets develop mass from gluon radiation**
    - **gives asymmetric sub-jets**
  - **can substructure be identified?**
    - **very active area for studies at high p_T**



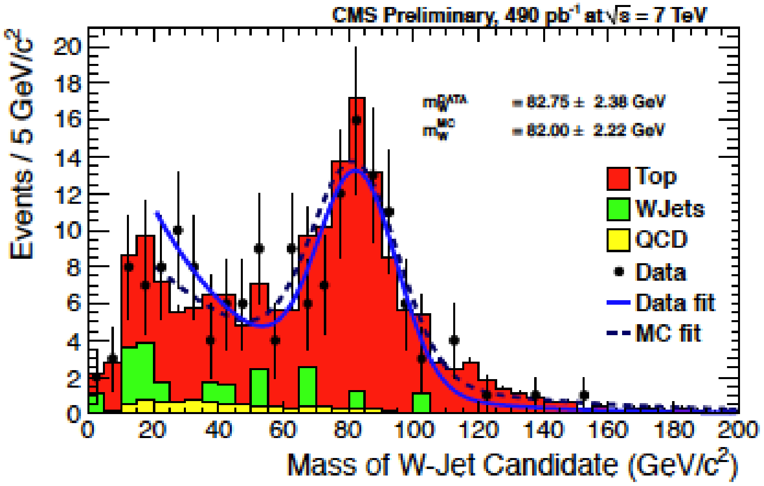
algorithms for measuring “fat” jets as applied to QCD jets
Consider large anti-kt jets (R=1) and splitting scale of final two elements of the cluster $\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2})\delta R_{12}$



Measured splitting scale for final cluster in QCD anti-kt jets
Typical scale ~ 30 GeV

Jet Properties

CMS looks in similar direction: use of algorithms for boosted top tagging and W tagging with jet pruning to search for $Z' \to t\bar{t}$



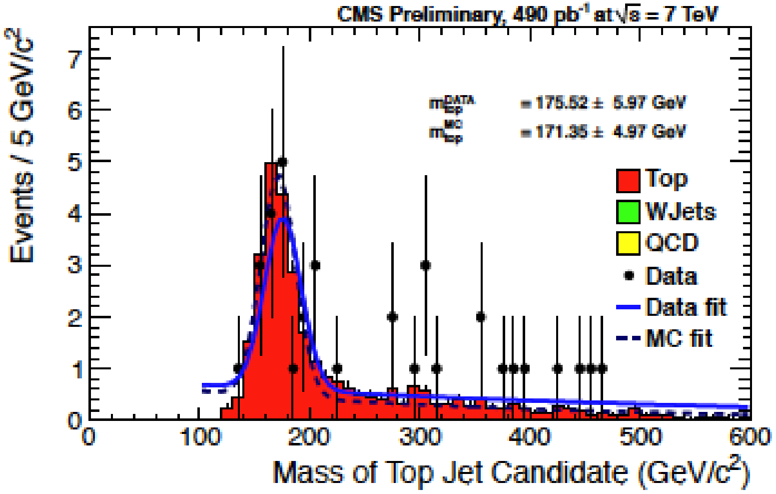
Calibrate using boosted W jets from t-tbar events with semi-leptonic decay

$$t\bar{t} \to \ell \nu b + q q' b$$

Lepton defines one hemisphere

W from jets in opposite hemisphere.

At least 1 jet with p_T > 200 GeV



Cambridge-Aachen jets with R=0.8

Jet pruning applied.

At least 1 tagged b jet

Good agreement of data with MC.

Mass of hadronic W decay plus additional jet.

Inclusive Jet Cross Section

- Anti-K_T jet algorithm standard for ATLAS & CMS:
- Soft particles first cluster with hard ones before among themselves

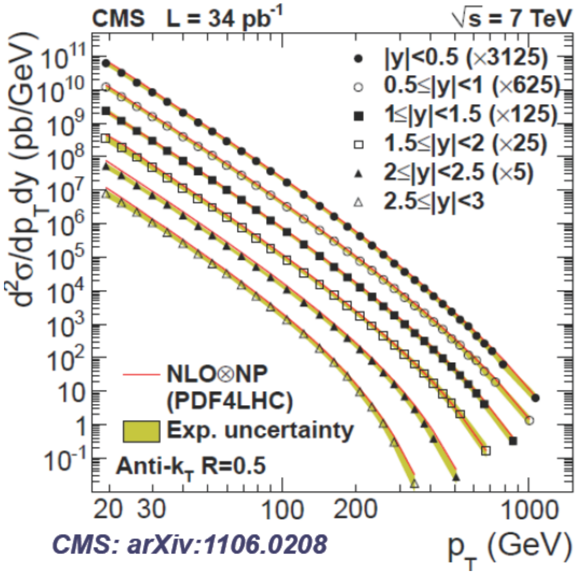
P_t up to 1 TeV, |y|<4.7. Cross sections vary by 10^{10} over the Pt range measured

Both expts. compare with NLOJET++ ⊗ NP effects

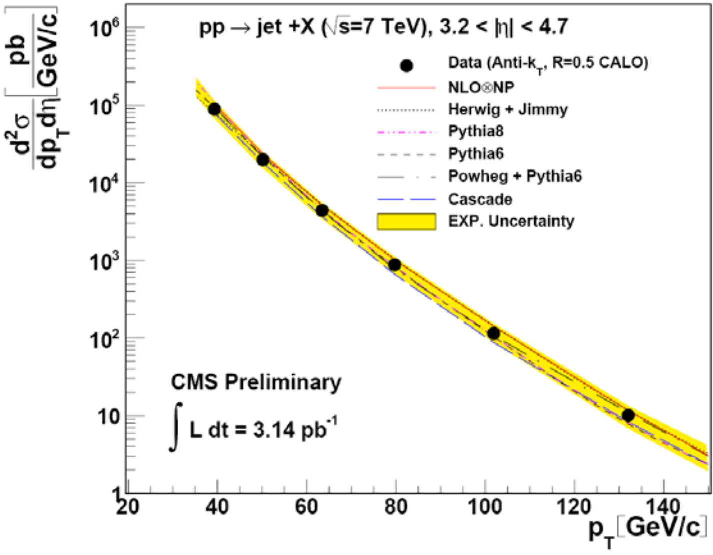
Pdfs (baseline)
- ATLAS: CTEQ6.6
- CMS: PDF4LHC

Experimental syatematic uncertainties ~10-20%

Both experiments agree with predictions within uncertainties.

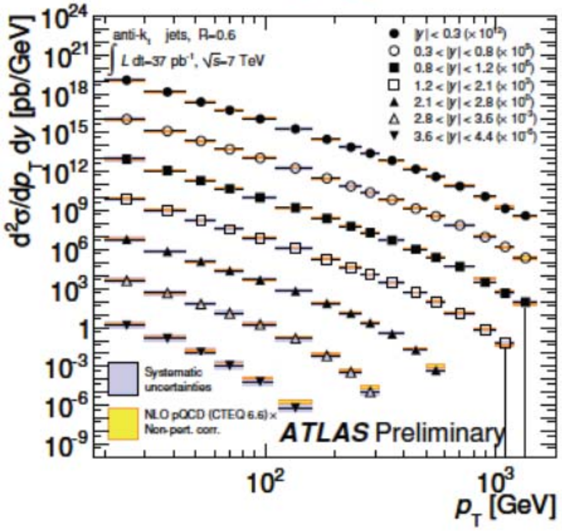


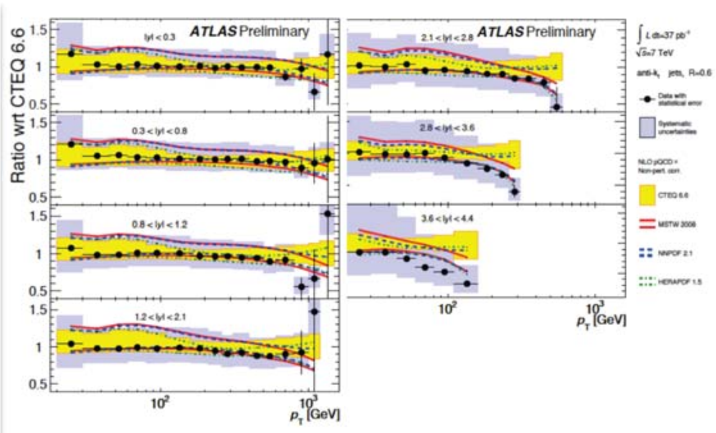
CMS: arXiv:1106.0208



CMS: PAS FWD-10-003

ATLAS



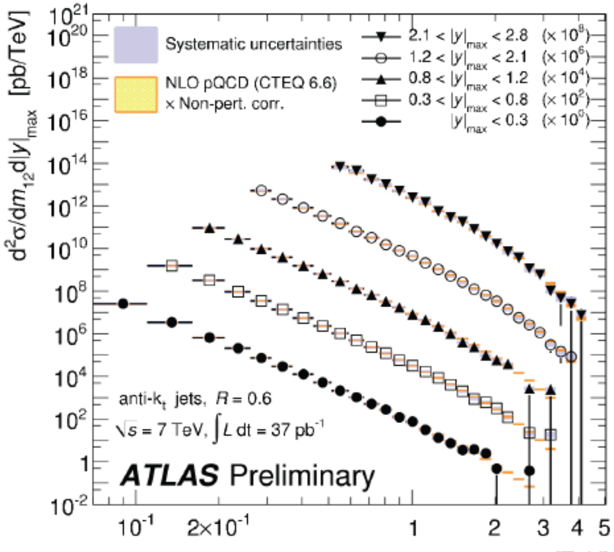


Dijet cross section

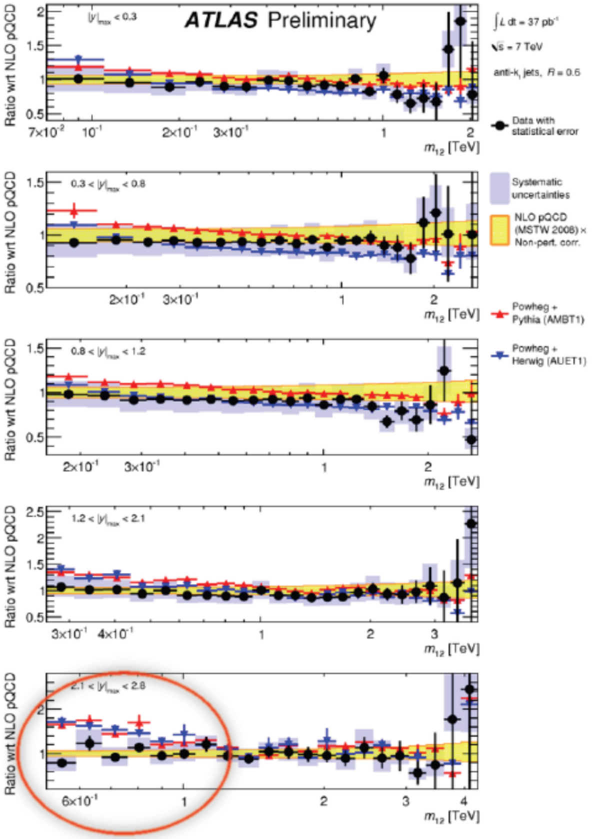
Dijet cross section as function of M_{JJ} and $|y|_{max}$

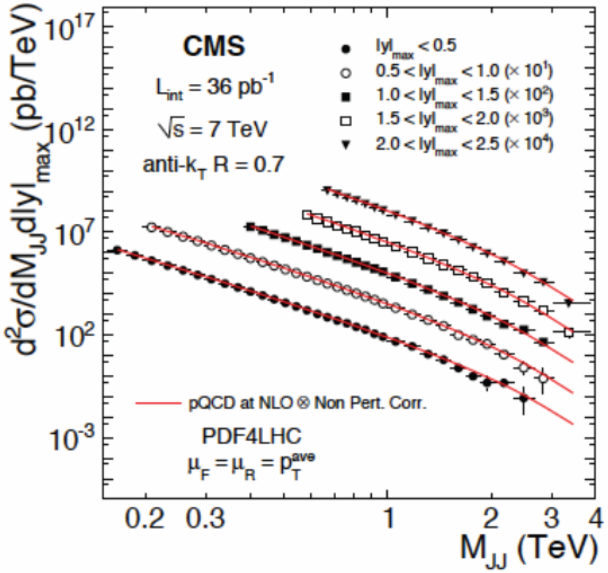
M_{JJ} up to 4 TeV in 5 intervals of $|y|_{max}$

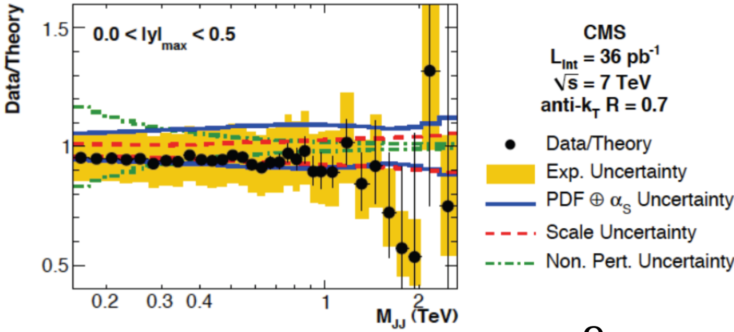
Data and predictions in good agreement with uncertainties of 10-15%



ATLAS: CONF-2011-047

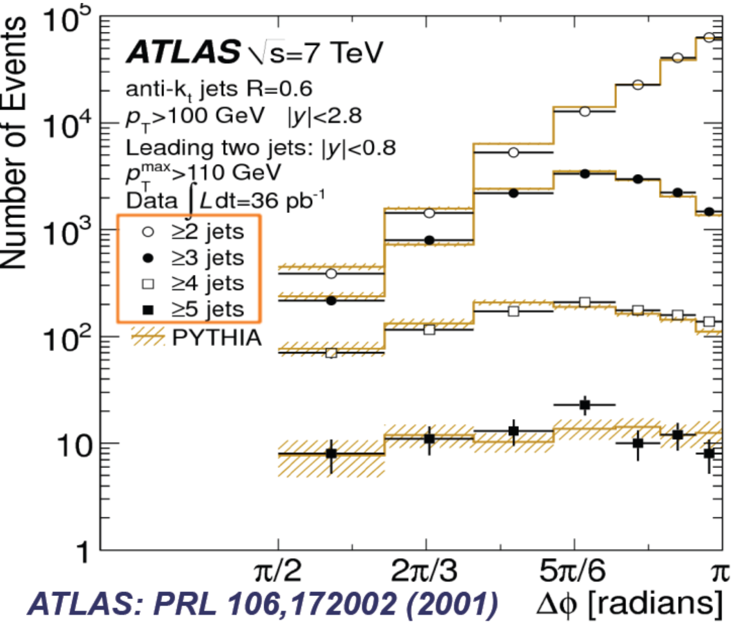






Dijet cross section

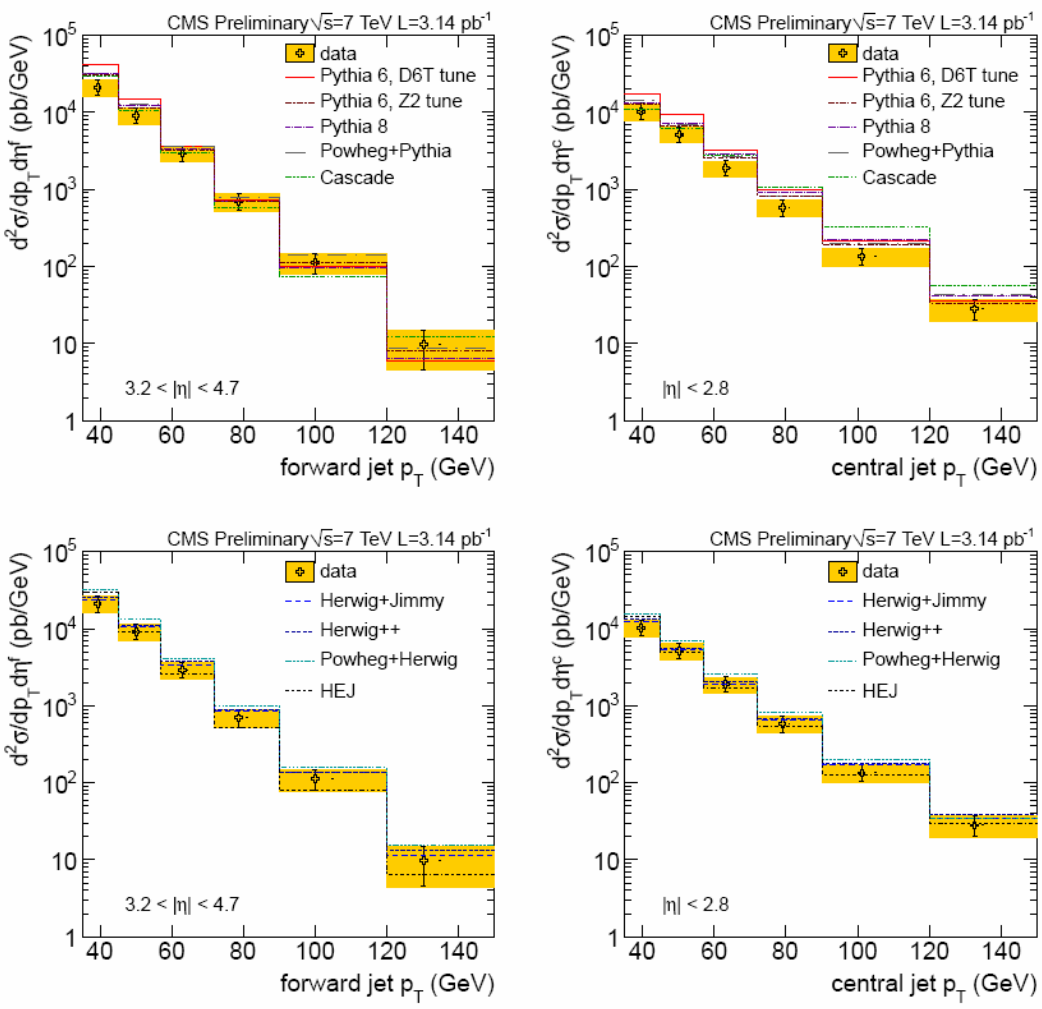
Azimuthal Dijet Distributions



ATLAS: PRL 106,172002 (2001)

Pythia tunes overestimate the jet spectra when requiring simultaneous production of central-forward jets

Cross section measurement for a forward-central dijet production



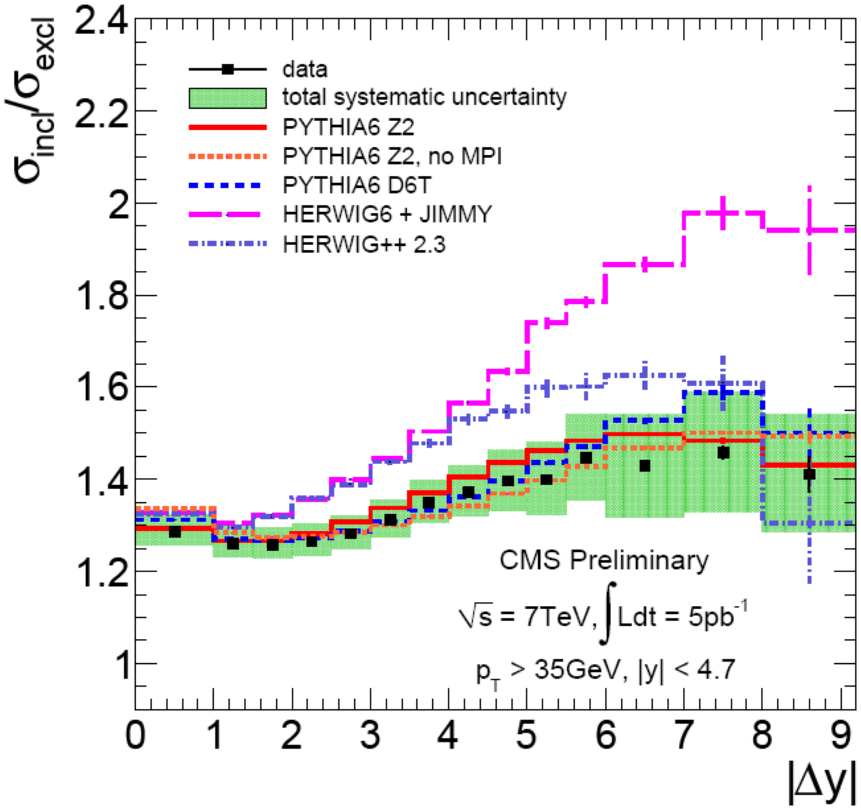
CMS: PAS FWD-10-006

Dijet production

Inclusive to exclusive dijet cross section ratio for jets with P_t>35 GeV and |y|<4.7 as function of their rapidity separation measured by CMS

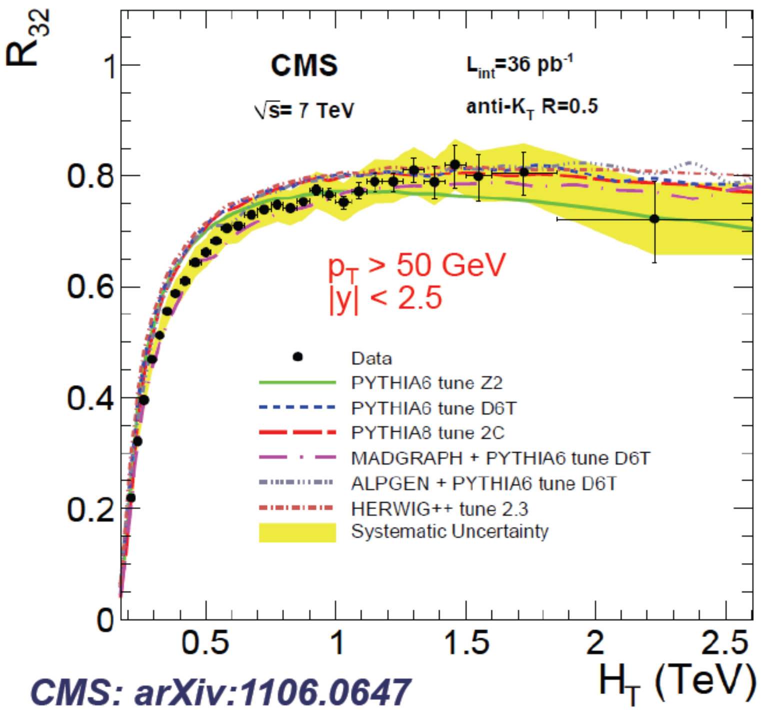
Inclusive cross section is 1.2-1.5 times larger than the exclusive one

Good agreement between data and PYTHIA6 predictions

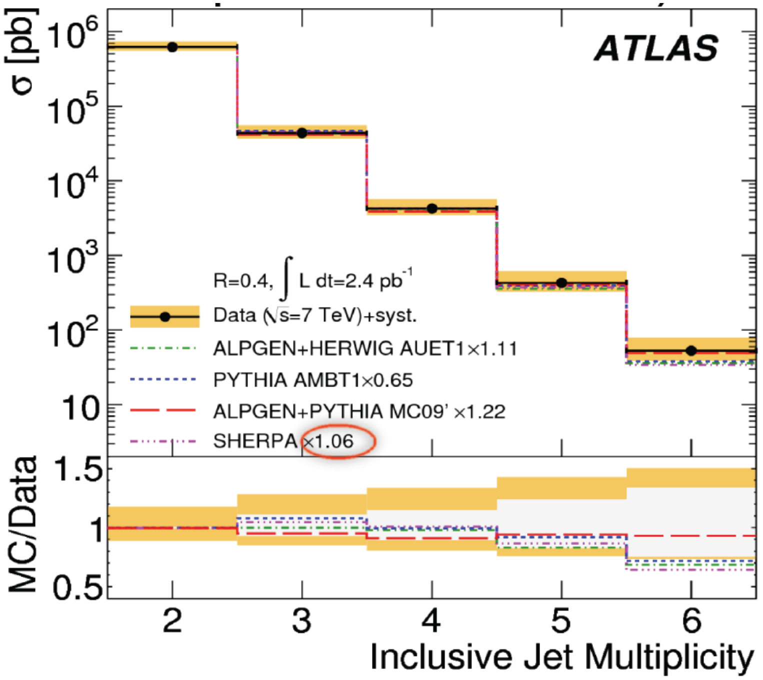


CMS: PAS FWD-10-014

Multijet production



CMS: arXiv:1106.0647



CMS results for

$(d\sigma_{3j}/dH_T)/(d\sigma_{2j}/dH_T)$

vs $H_T = \sum_{i=1}^{N} p_{Ti}$

for p_T> 50 GeV

$|y|$ < 2.5

Madgraph agrees well over full range

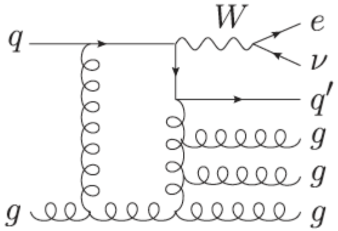
ATLAS results for σ_{nj}
leading jet p_T> 80 GeV,
other jets p_T> 60 GeV, $|y|$ < 2.8

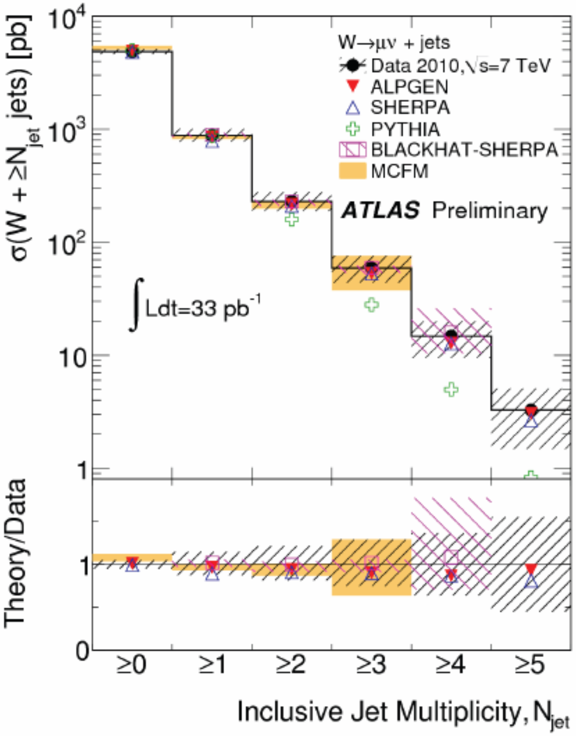
Predictions scaled to 2-jet cross section and compared for n > 2.
Dominant systematic JES

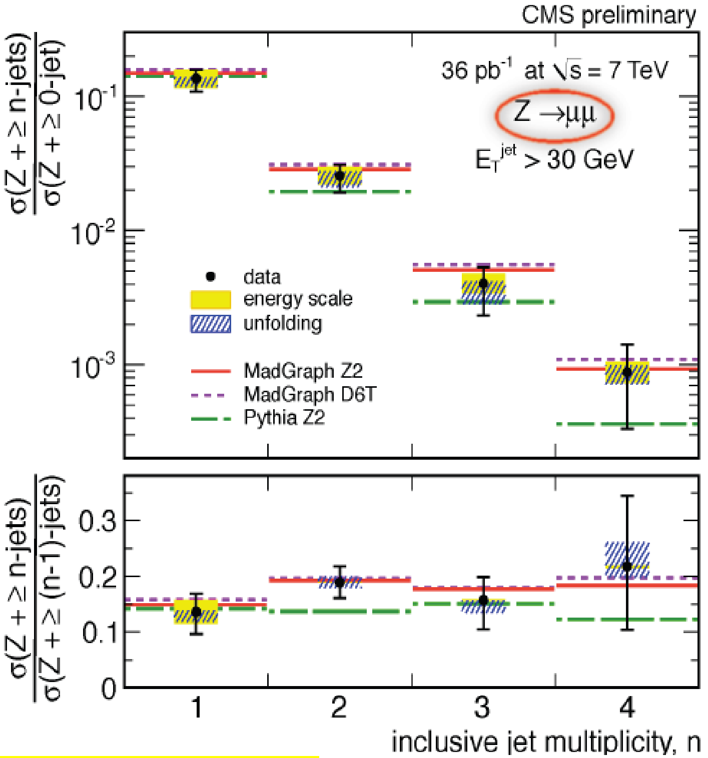
SHERPA provides best normalization

W/Z + Jets

- Important background in many channels (top, Higgs, BSM)
- Confronts pQCD predictions; offer a test of tree-level generators: MadGraph, ALPGEN, SHERPA



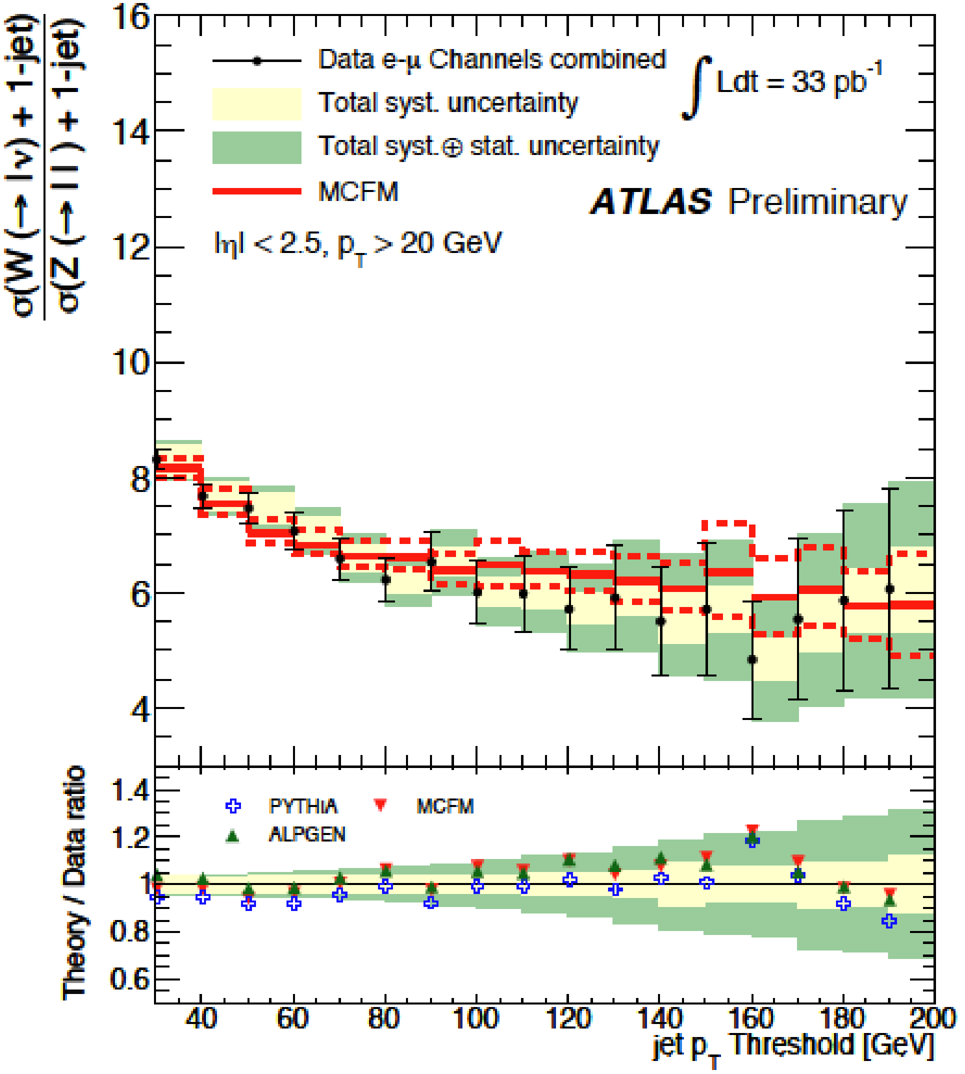




- Good agreement with MadGraph/ALPGEN and NLO MCFM and BLACKHAT+SHERPA
- Poor agreement with Pythia

W/Z + Jets

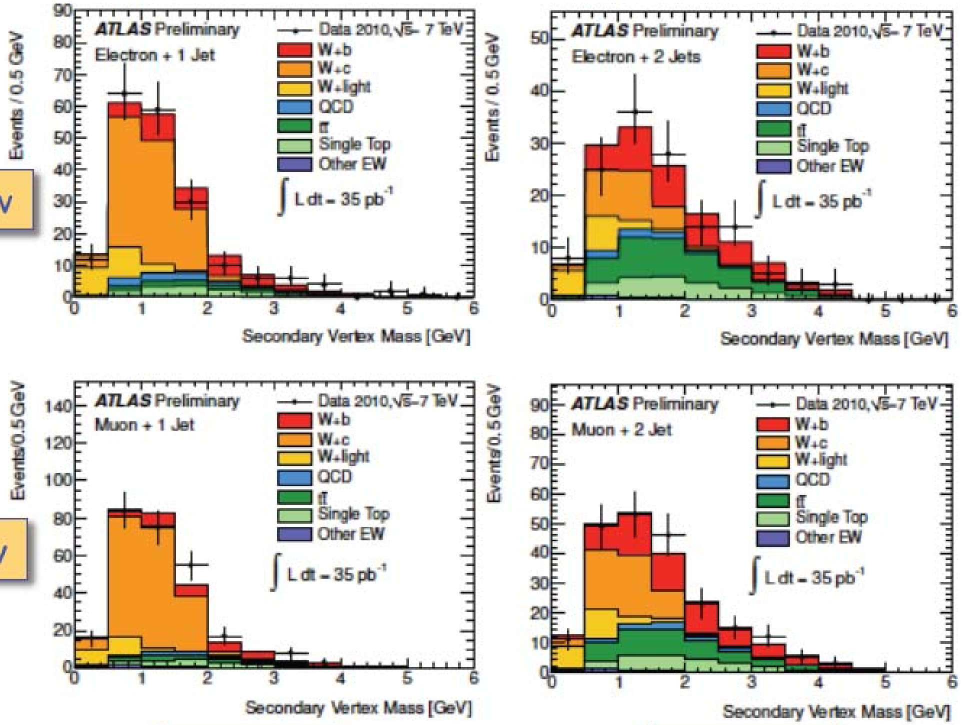
- Ratio $\sigma(W+n\text{-jet})/\sigma(Z+n\text{-jet})$ less sensitive to systematic uncertainties
    - pdfs and energy scales
    - experimental jet energy scale and resolution
    - new physics might upset ratio
- Measured by ATLAS for $n = 1$ vs p_T threshold for counting jets
- good agreement with NLO predictions
    - overall uncertainty is 4% for $p_T > 30$ GeV
    - will gain from higher statistics
    - largest systematic is boson reconstruction
    - can also extend to higher n



W/Z + b

- Important background for many searches (Higgs, SUSY, top)

- Measured by ATLAS using 2010 data sample
  - studied W + 1 jet and W + 2 jets
  - b tagging similar to Z + b case



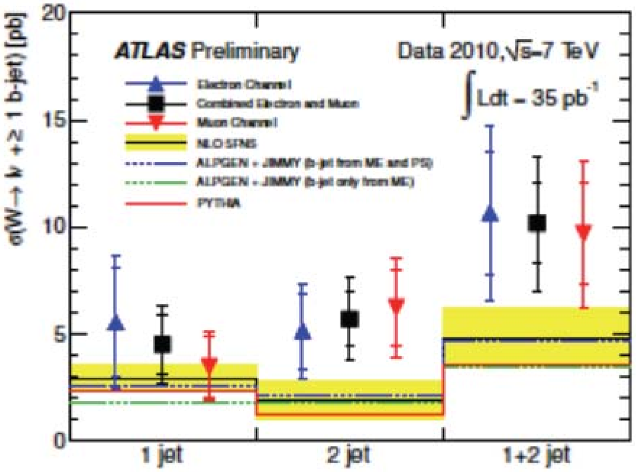
W→eν

W→μν

W + 1 jet

W + 2 jet

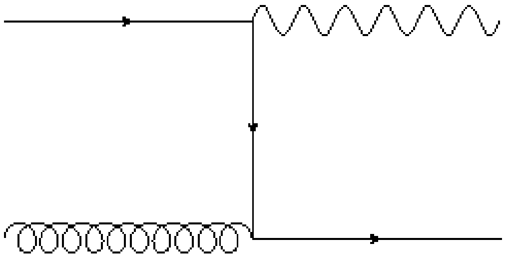
Results from e and μ combined. Measurements ~1.5σ above NLO prediction.
Largest effect in 2-jet channel.



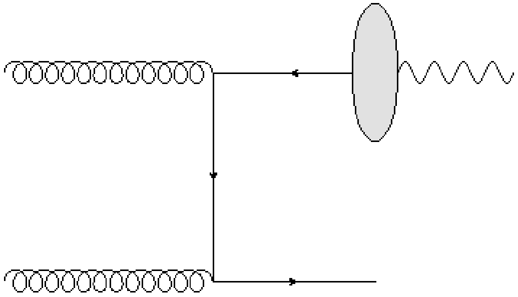
Isolated prompt photons

- A traditional channel for testing perturbative QCD
  - photons are direct or from parton fragmentation
    - define isolation cone around photon to constrain second source

both components computed at NLO and implemented in JETPHOX Monte Carlo



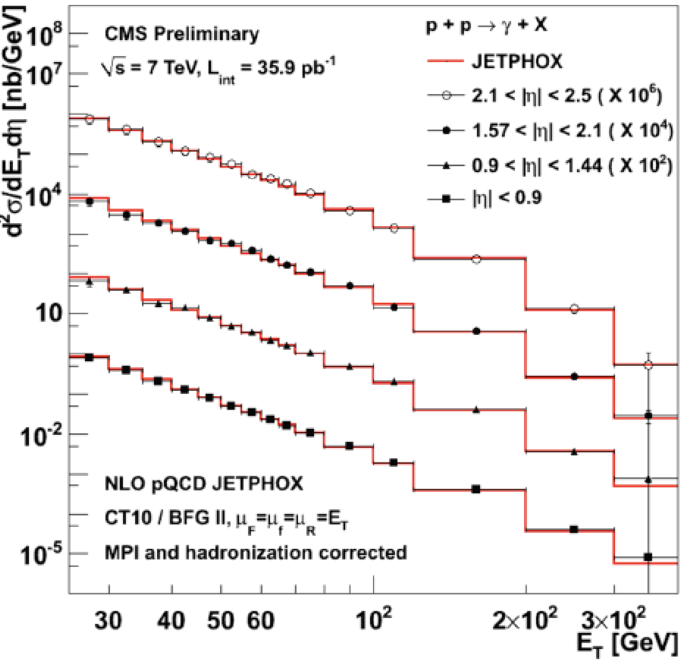
Typical "direct" production term. Dominant at LHC.

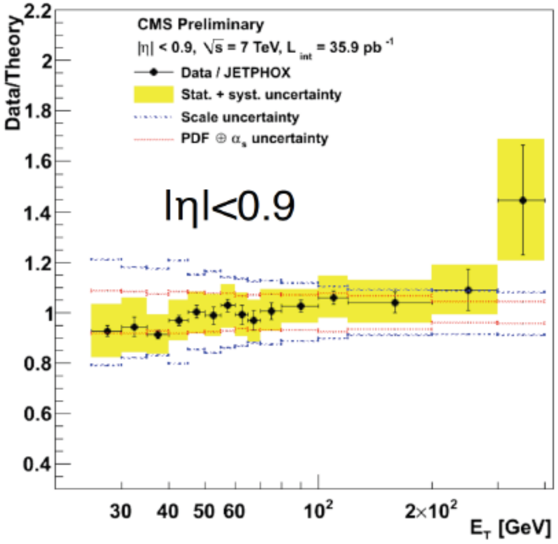


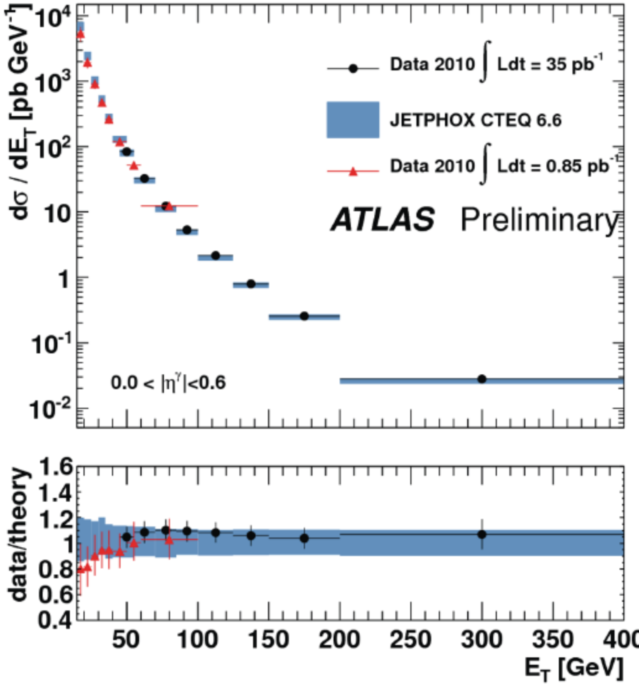
Typical fragmentation production process.

- Important to understand photon production at LHC
  - Important in many new physics searches (Higgs, SUSY, …)
- Nice measurement to showcase EM calorimeter and photon detection

Isolated prompt photons





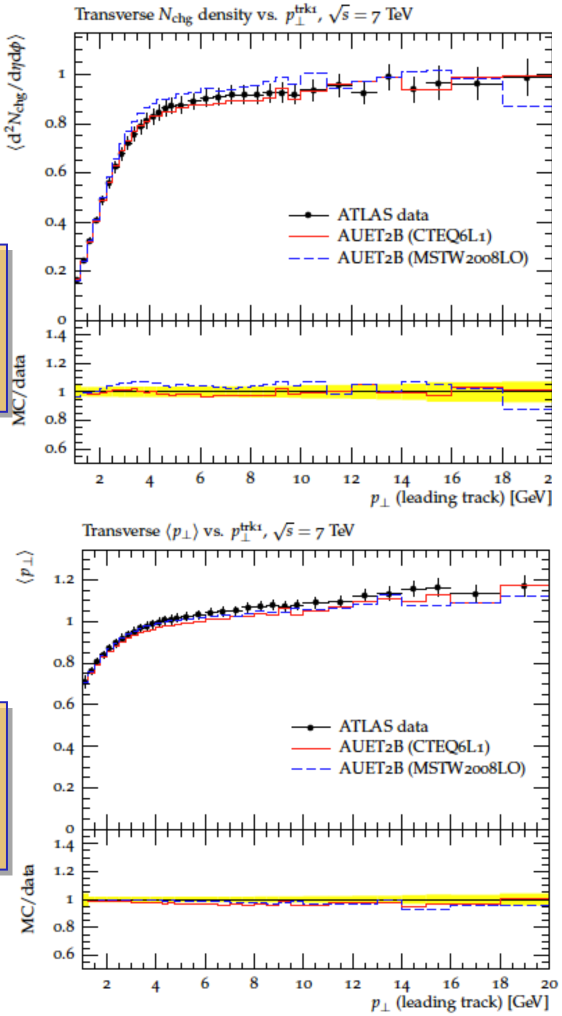


- **Data/theory: Good agreement with NLO QCD**
- **Experimental uncertainties ≥ PDF uncertainty**
- **Theory scale uncertainty > PDF uncertainty**

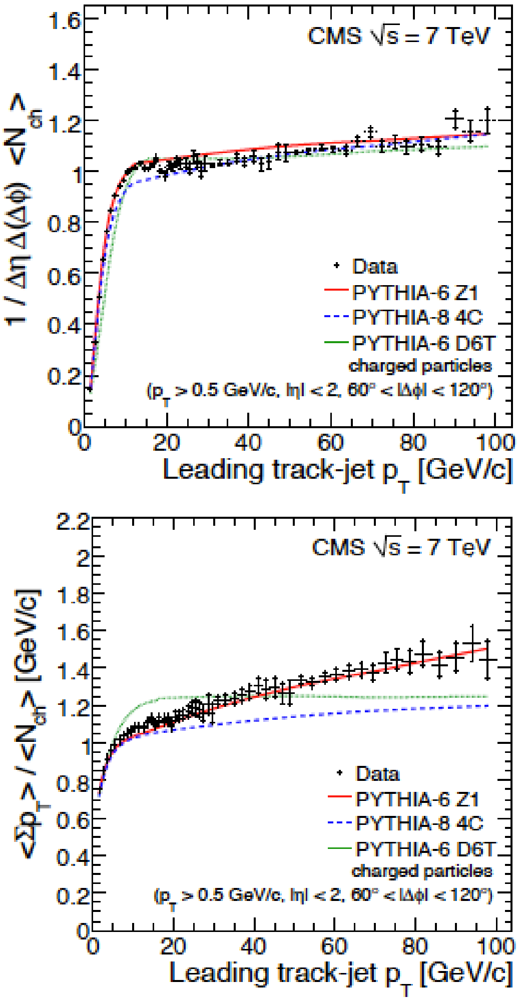
Nonperturbative QCD: Underlying Event

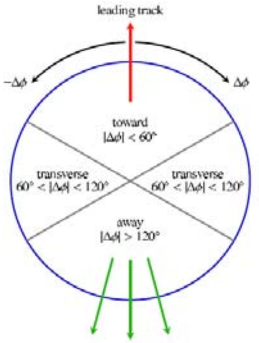
- Look at properties in 60° azimuthal wedge transverse to leading track

N_{chg} density vs p_T of leading tk



$\langle p_T \rangle$ of chg tks vs p_T of leading tk





Results in good agreement:
- between experiments
- with underlying fit.

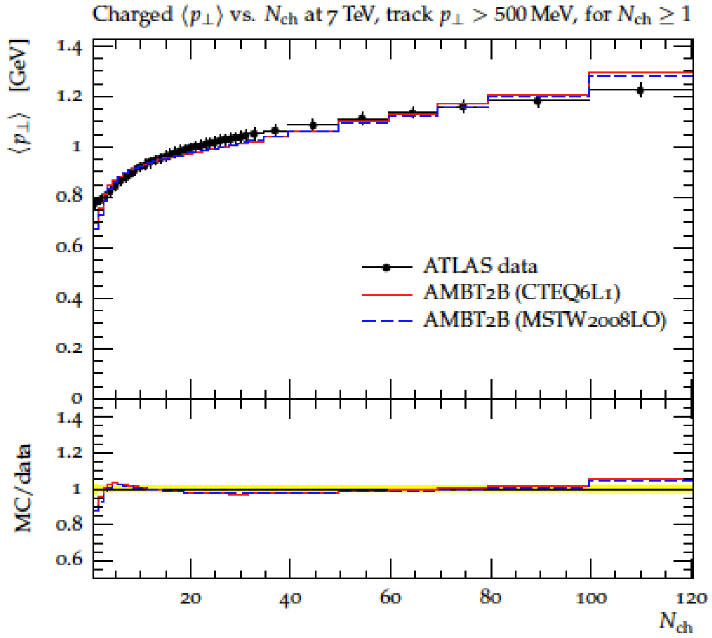
Rapid rise with p_T
Plateau above p_T ~ 5 GeV

ATLAS: 1 < pT < 20 GeV

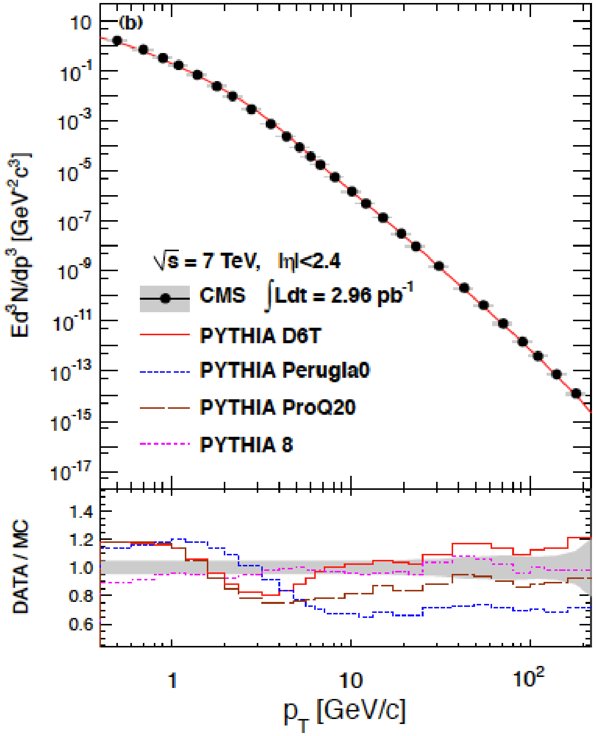
CMS: 1 < pT < 100 GeV

Nonperturbative QCD: Minimum Bias Events

- Most of the total cross section. Currenty 6 MB interactions/crossing but ultimately ~25
  - charged track characteristics
  - models based on colored string fragmentation



$\langle p_T \rangle$ vs multiplicity for p_T > 500 MeV (after MC tuning)



p_T spectrum (from CMS)

Conclusions

- An remarkable number of interesting new results
  - both from CMS and ATLAS experiments
- Common QCD software tools unify the work and are essential for understanding the data
- Most QCD predictions in good agreement with experiments
  - current level of precision is 10-15% on data and theory
    - precision of the measurements is likely to improve

      detectors become better understood

      large event samples allow more detailed systematic studies
  - we look forward to studies at higher Q^2 or shorter distance scales through larger data sets and higher energy
  - updated pdfs which include LHC results are expected

BACKUP

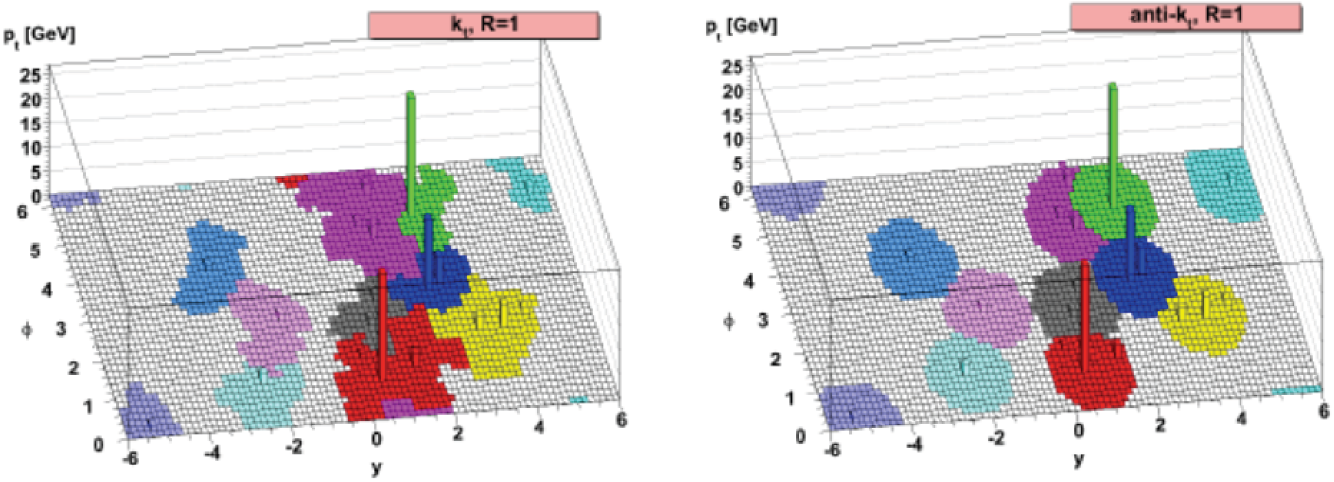
kT and anti-kT Jet Algorithms

- define for each proto-jet its “beam distance” $d_{iB} = k_{Ti}^{n}$

  and for each pair of pro-jets their “separation”

  $d_{ij} = \min(k_{Ti}^{n}, k_{Tj}^{n}) \frac{\Delta R_{ij}^{2}}{R^{2}}$ where $\Delta R_{ij}^{2} = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$

  and R^2 is a specified size scale of order unity
- if $d_{ij} < d_{iB}$ combine proto-jets *i* and *j*; otherwise, define *i* as a jet and remove it from the list
- k_T algorithm corresponds to $n = 2$ (favors clustering of soft proto-jets)
- anti-k_T corresponds to $n = -2$ (favors clustering of hard proto-jets)
- both algorithms are infrared and collinear safe



M. Cacciari, et al.
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