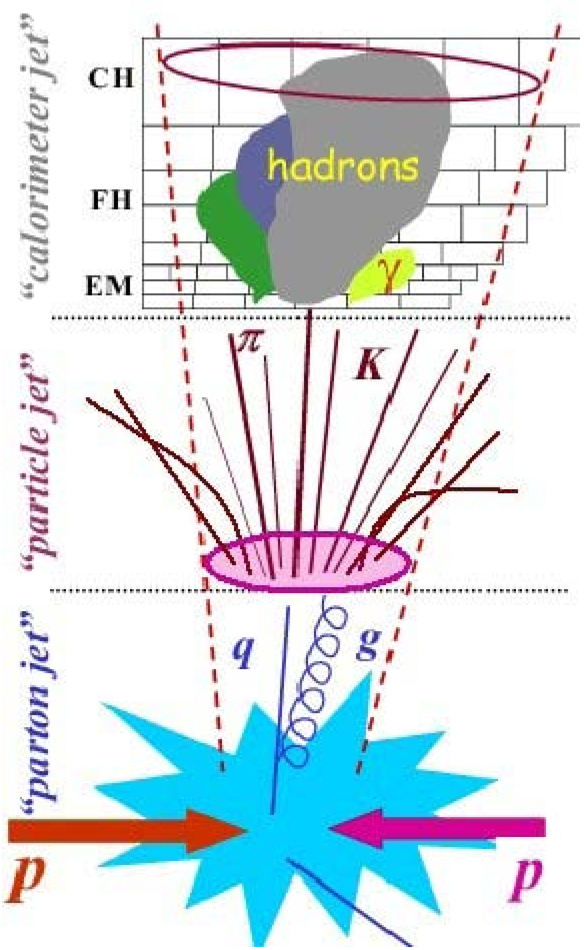
QCD Jets at the LHC

Leonard Apanasevich
University of Illinois at Chicago

on behalf of the ATLAS and CMS collaborations

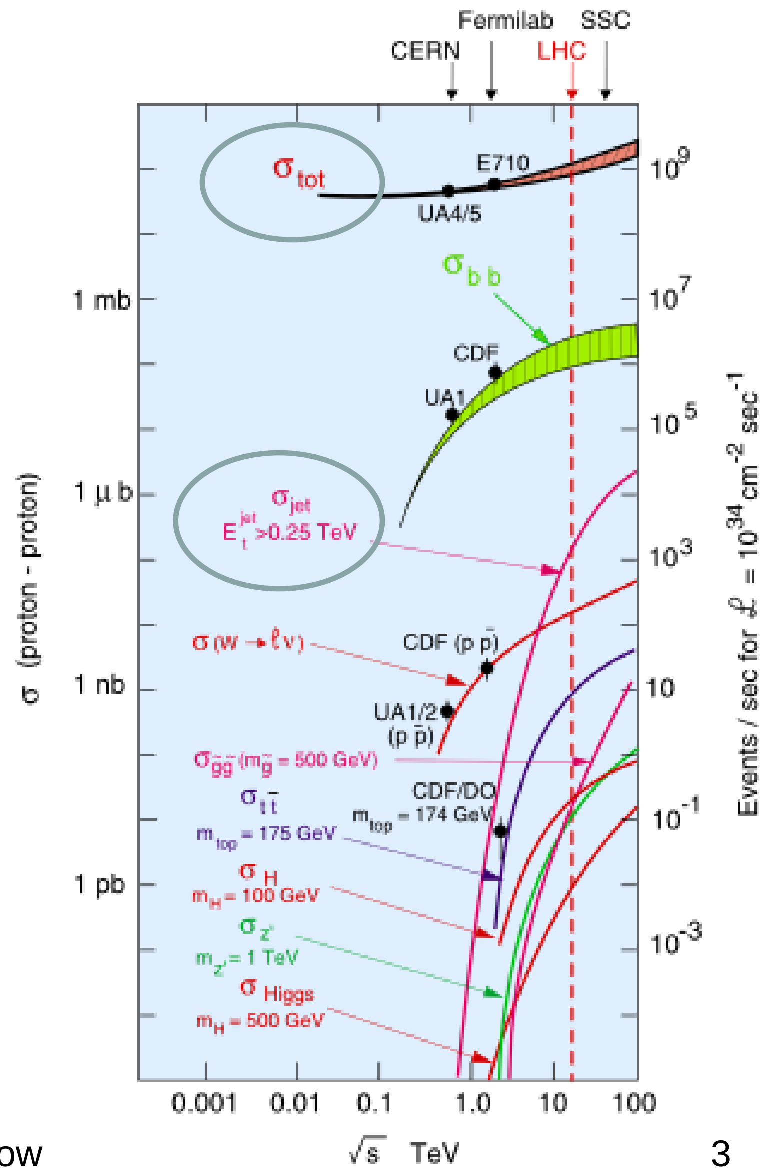
Outline

- Physics at the LHC
- Jet Reconstruction and Performance
  - Clustering Algorithms
  - Energy Scale Calibration
  - Energy Resolution
  - Focus will be on in-situ methods
- Jet Measurements
  - Underlying Event
  - Jet Shapes
  - Dijet Angular Decorrelation
  - Inclusive Jet Cross Section
  - Dijet Mass and Ratio
  - Dijet Angular Distribution
  - Event Shapes
  - Multi-Jets

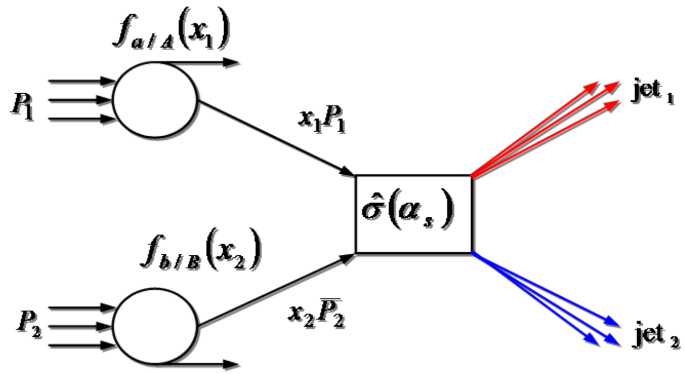


Physics at the LHC

- Total cross section ~100-120 mb
- The goal at startup is to re-establish the standard model (i.e., QCD, SM candles) in the LHC energy regime
  - σ(pT>250 GeV)
    - 100x higher than Tevatron
  - Electroweak
    - 10x higher than Tevatron
  - Top
    - 100x higher than Tevatron
- Jet measurements at LHC are important:
  - confront pQCD at the TeV scale
    - constrain PDFs
    - probe α_s
  - important backgrounds for SUSY and BSM searches
  - sensitive to new physics
    - quark substructure, excited quarks, dijet resonances, etc.
- QCD processes are not statistics limited!



High p_T Jets at the LHC



$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a\, f_{a/A}(x_a,\mu) \int dx_b\, f_{b/B}(x_b,\mu) \frac{d\hat{\sigma}}{dP_T}$$

N_{jets} / pb^{-1} |y|<1.3

Sqrt(s)	pT>0.5 TeV	pT>1 TeV
10	320 / pb^{-1}	5 / pb^{-1}
14	860 / pb^{-1}	20 / pb^{-1}

N_{dijets} / pb^{-1} $|\eta_1|, |\eta_2|<1.3$

Sqrt(s)	M_{jj}>1.4 TeV	M_{jj}>2TeV
10	50 / pb^{-1}	7.4 / pb^{-1}
14	140 / pb^{-1}	20 / pb^{-1}

For comparison, corresponding numbers from the Tevatron:

N_{jets} / pb^{-1} |y|<0.8

Sqrt(s)	pT>0.5 TeV	pT>1 TeV
2	0.05 / pb^{-1}	—

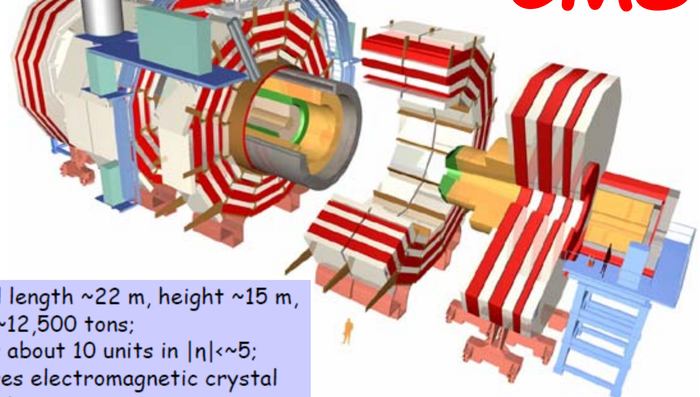
N_{dijets} / pb^{-1} $|\eta_1|, |\eta_2|<2.4$

Sqrt(s)	M_{jj}>1 TeV	M_{jj}>2TeV
2	0.03 / pb^{-1}	—

Jet Reconstruction at CMS and ATLAS

- Jet algorithms considered:
  - Seedless Cone, R=0.5, 0.7
  - KT, D=0.4, 0.6
  - Iterative Cone, R=0.5 (used in the trigger)
- Jet types:
  - Calorimeter jets (towers input).
  - JetPlusTrack (combined calorimeter and tracker information).
  - Particle Flow jets (particles input).
  - Track jets (track input).

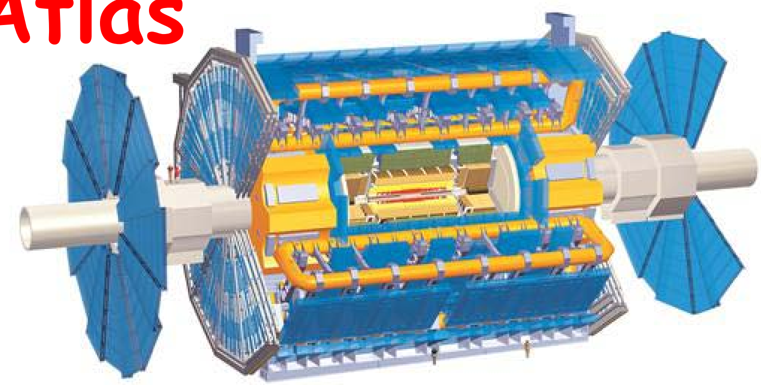
CMS



- overall length ~22 m, height ~15 m, weight ~12,500 tons;
- covers about 10 units in |η|<~5;
- features electromagnetic crystal calorimetry;
- features hadronic scintillator calorimetry (typical e/h ≈1.3-1.5)

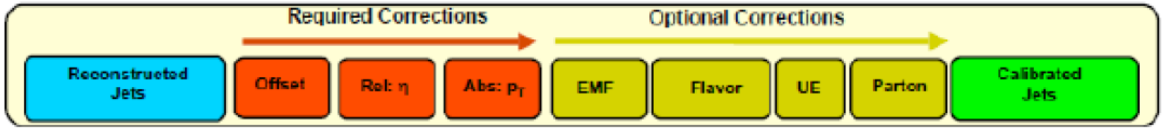
- Jet algorithms considered:
  - Anti KT, D=0.4, 0.6
  - Seeded Cone, R=0.4, 0.7
  - Seedless Cone, R=0.4, 0.7
  - KT, D=0.4, 0.6
- Jet types:
  - Calorimeter jets (towers or topological cell clusters input).
  - Energy Flow jets (combined calorimeter and tracker information).
  - Track jets (track input).

Atlas



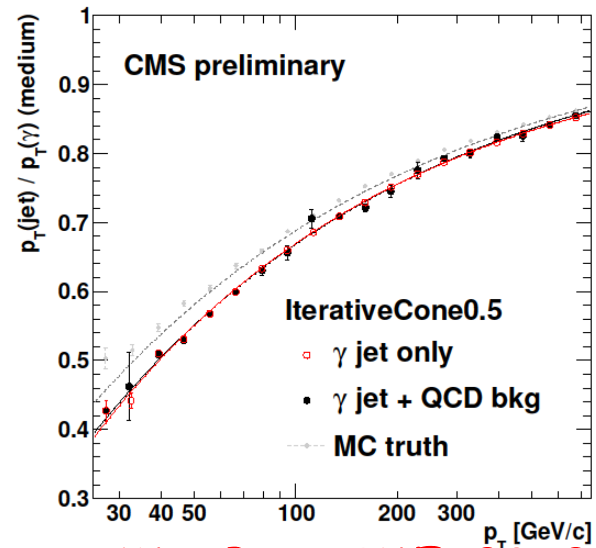
- overall length ~45 m, height ~22 m, weight ~7,000 tons;
- covers about 10 units in |η|<~5;
- features electromagnetic and hadronic liquid argon calorimetry (e/h≈1.4);
- features hadronic scintillator calorimetry (e/h≈1.4);

Jet Energy Calibration at CMS

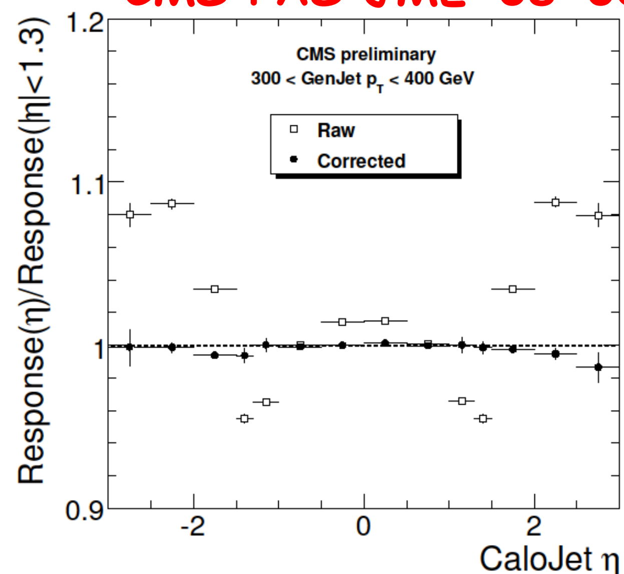


- Factorized approach (like Tevatron):
  - offset correction (removes pile-up and noise contribution)
  - relative correction (flattens the jet response in pseudorapidity)
  - absolute correction (flattens the jet response in p_T)
- Data driven approach:
  - Di-jet balancing
  - γ+jet, Z+jet balancing
- Optional corrections:
  - electromagnetic fraction dependence
  - flavor dependence
  - parton level
  - underlying event
- Systematic uncertainty ~10% at startup, improving with accumulating luminosity

CMS PAS JME-09-004



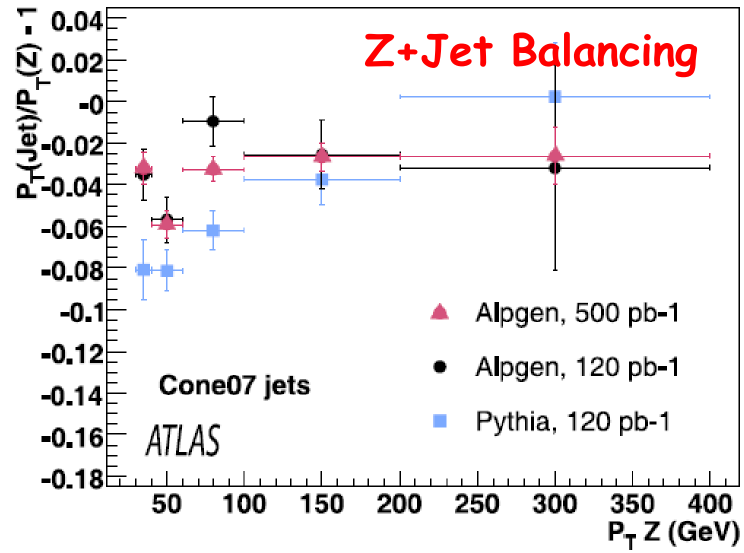
CMS PAS JME-08-003

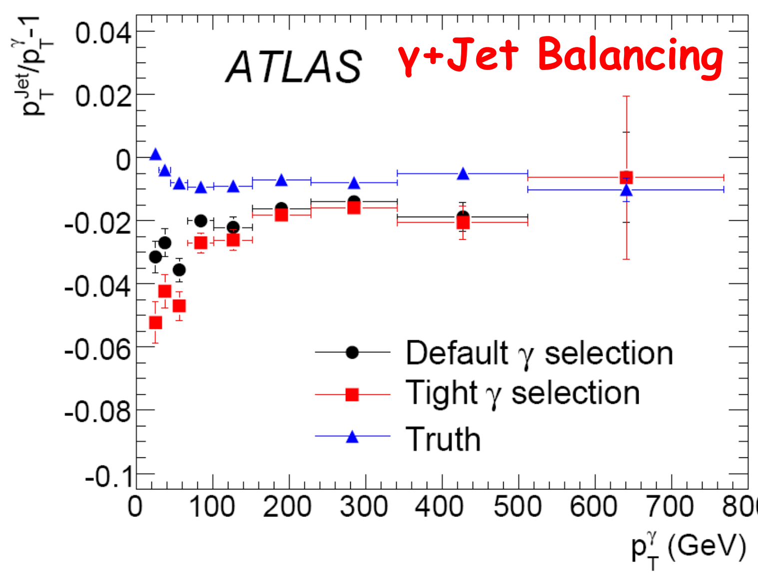


Jet Energy Calibration at ATLAS

EM or Hadronic scale jets
↓
Phi/Eta inter-calibration
↓
<u>Offset:</u> noise, out-of-time pileup, in-time pileup
↓
Relative Eta correction
↓
Absolute Energy Scale
↓
Particle-level calibrated jets

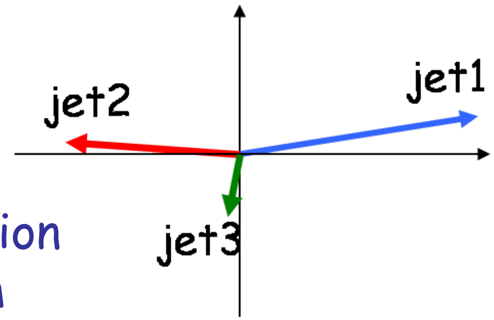
- Jet calibration procedure starts with calorimeter cells that have been calibrated using test-beam electron data
  - This is the called EM scale
- *A* comprehensive calibration program using MC simulation is then applied to correct for non-compensation and dead material effects
  - This defines the hadronic scale
  - These methods have been validated using test-beam single pion data.
- Depending on how well the early data agrees with the MC simulation, in-situ methods will start directly from EM-scale or hadronic scale





CERN-OPEN-2008-020

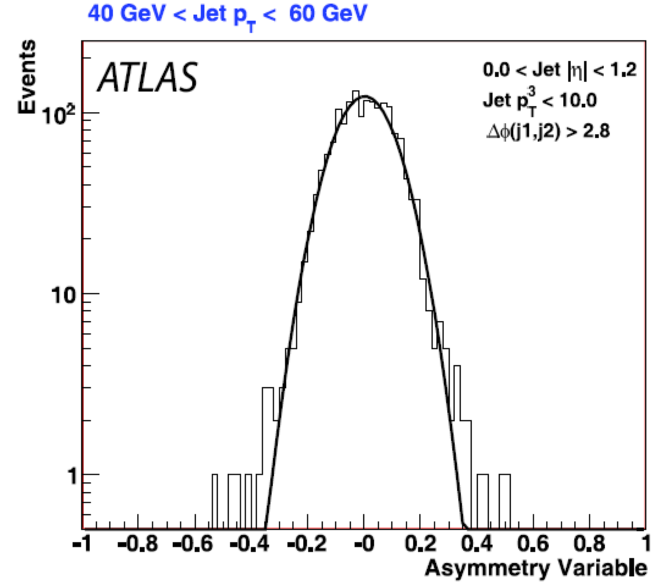
Jet Resolution at ATLAS and CMS

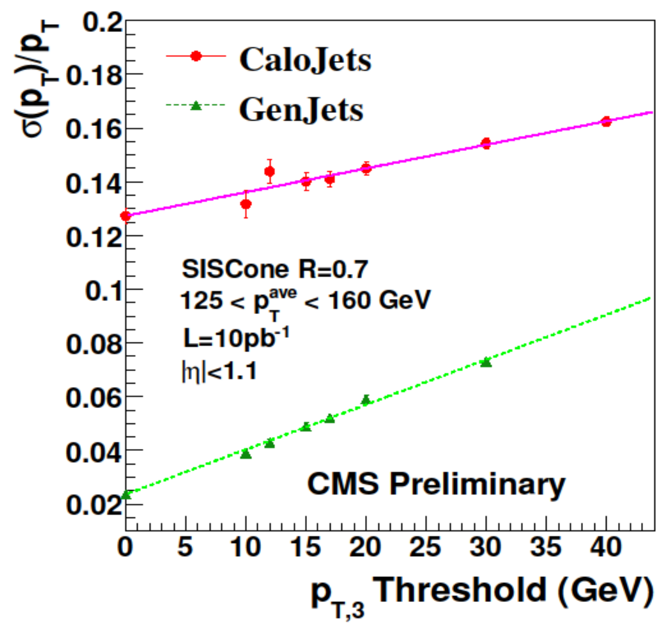


- The Asymmetry method is a data-driven technique for measuring the jet p_T resolution and is based upon momentum conservation in the transverse plane
  - Developed and used at D0
- The jet p_T resolutions are derived from the width of the asymmetry distributions between two leading jets

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})} \qquad \left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

- Contributions from additional jets are removed by applying various threshold cuts on the 3rd jet and extrapolate to the p_T^{jet3} = 0 GeV limit





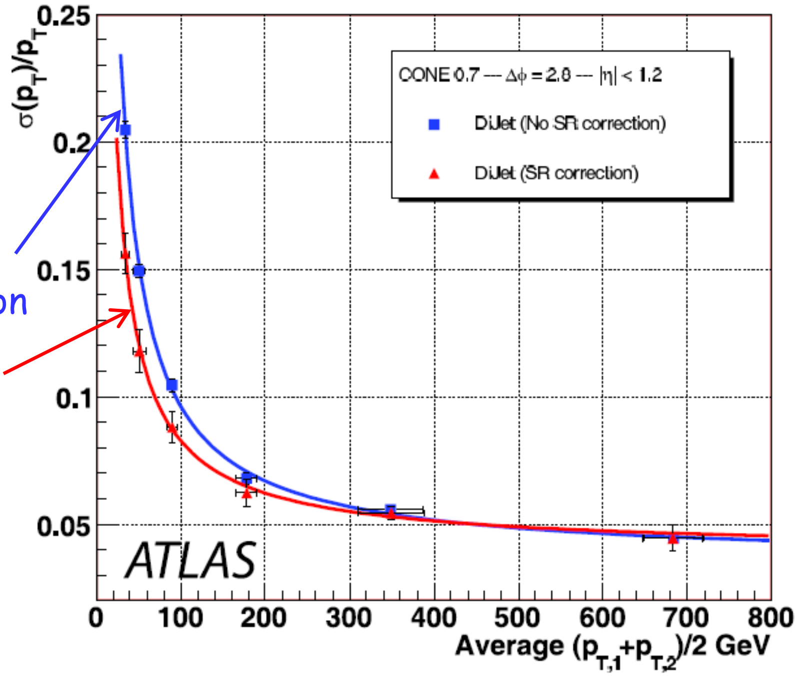
Jet Resolution at ATLAS and CMS

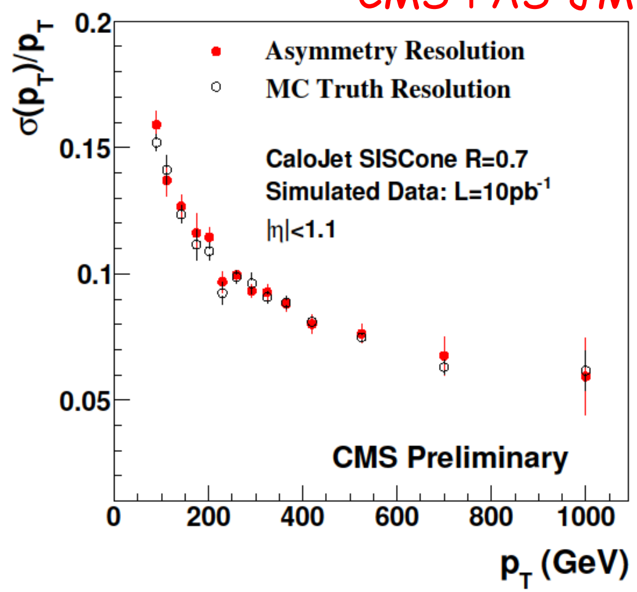
CMS-PAS-JME-09-007

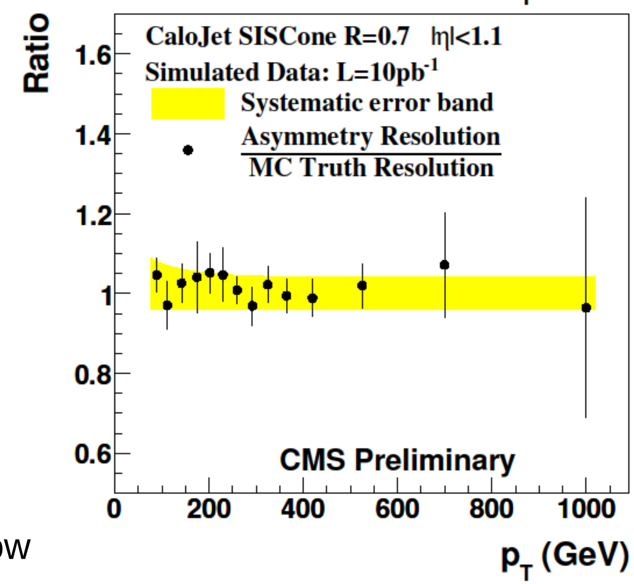
CERN-OPEN-2008-020

No corr. for soft radiation

corrected



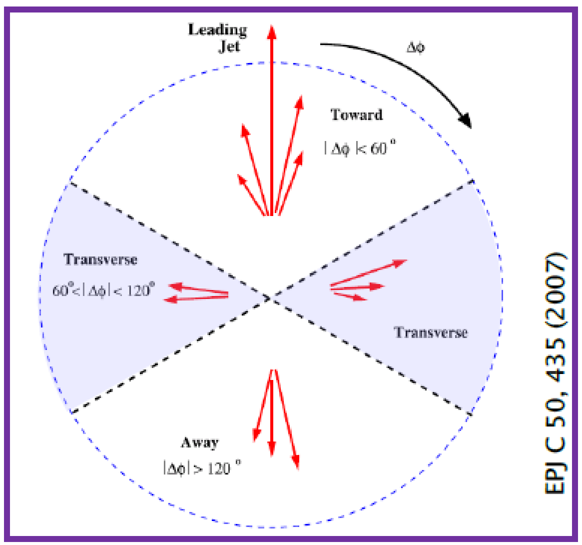


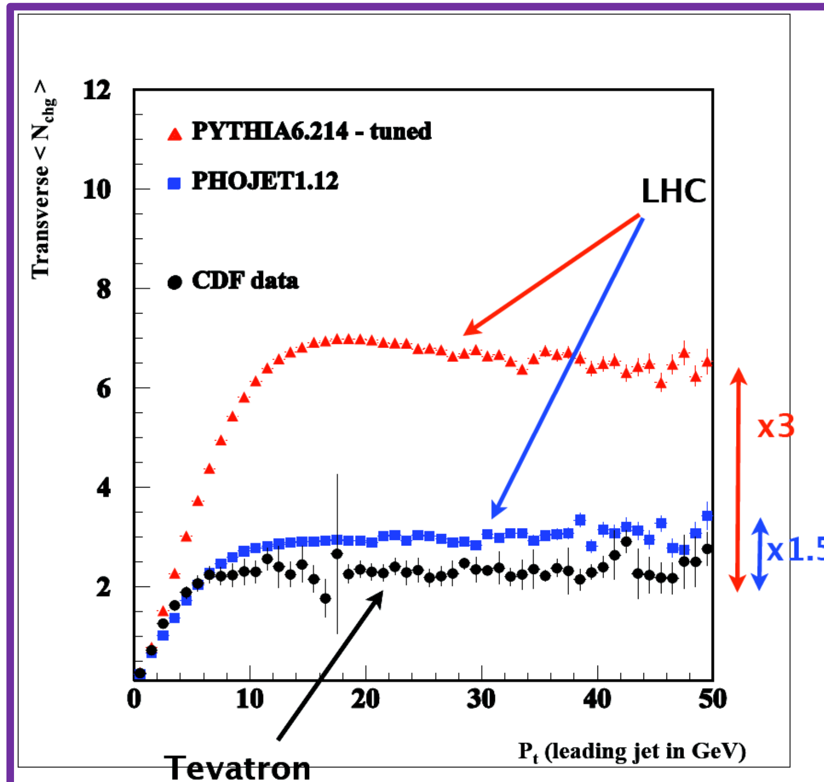


QCD Jet Measurements

Underlying Event

- Study of the track multiplicity and p_T density in "transverse" jet region
  - CDF approach
  - Measurement used to tune MC event generators at the Tevatron
  - Naïve re-scaling of Tevatron will not work

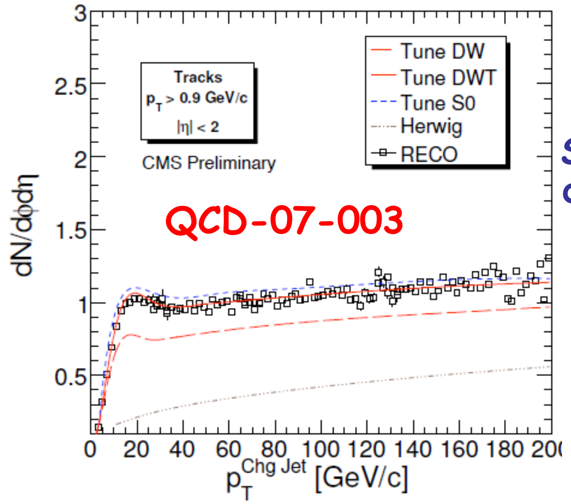




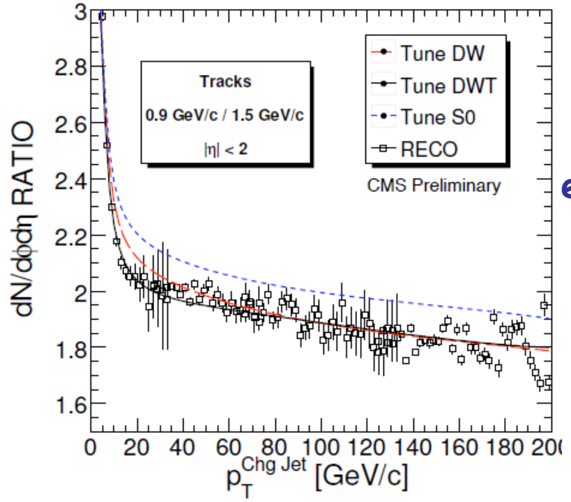
Large model dependence on LHC predictions from Tevatron data

Underlying Event

CMS

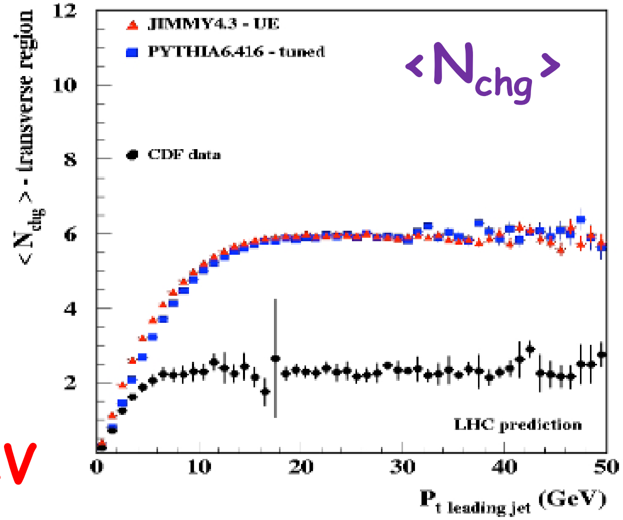


Sensitivity to different MC tunes



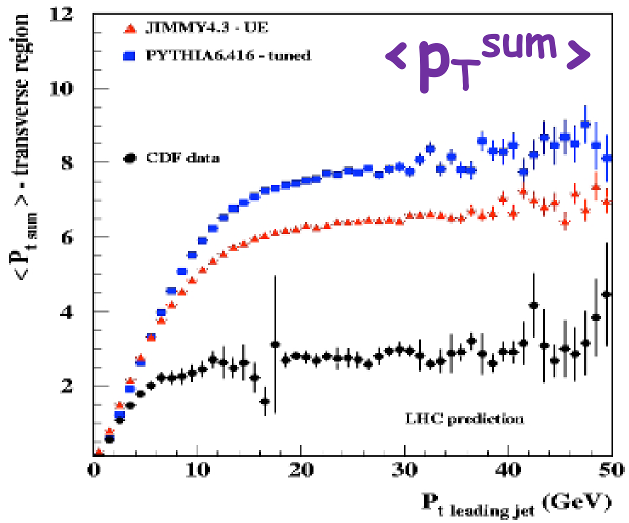
Reduced systematic effects with ratio: 0.9/1.5

ATLAS



Tuned-Pythia and Jimmy predict same particle density

$\sqrt{s}$ = 14 TeV

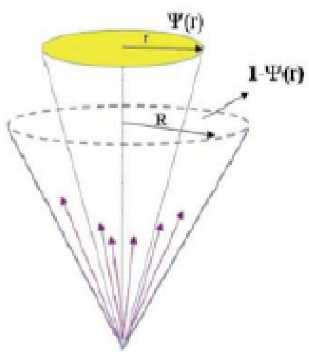


Tuned-Pythia predicts harder particles than Jimmy

Integrated Jet Shape

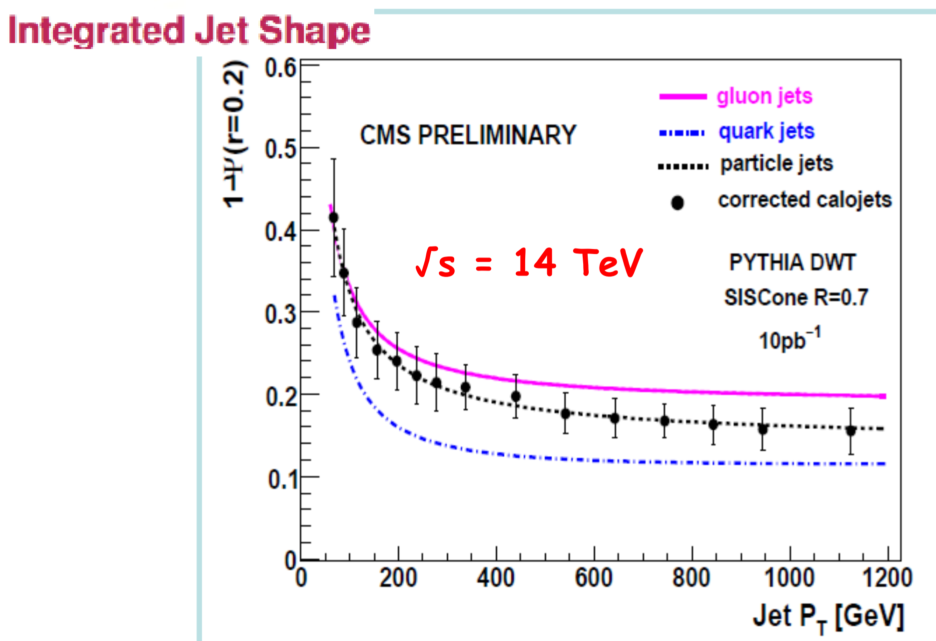
CMS PAS QCD-08-005

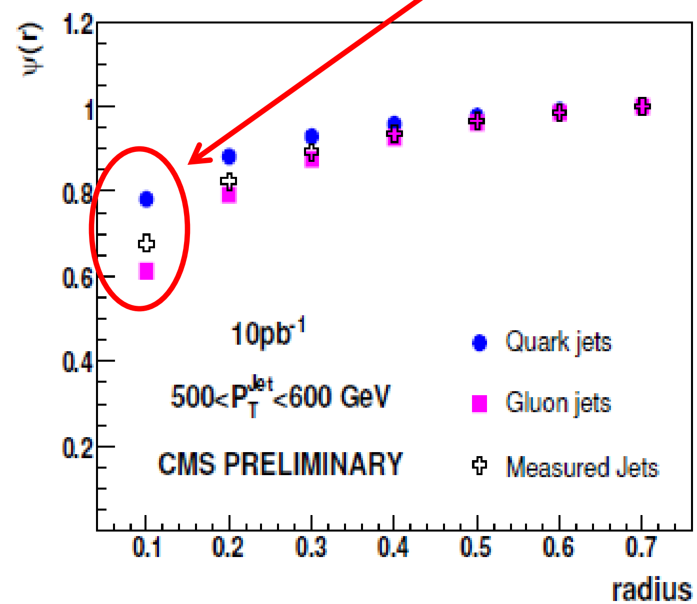
$$\Psi(r)=\frac{1}{N_{jets}}\sum_{jets}\frac{P_T(0,r)}{P_T^{jet}(0,R)}$$



- Jet shapes probe the transition between a parton produced in the hard process and the observed spray of hadrons
- Sensitive to the quark/gluon jet mixture
- Test of parton shower event generators at non-perturbative levels
- Useful for jet algorithm development and tuning

Quark jets narrower than gluon jets



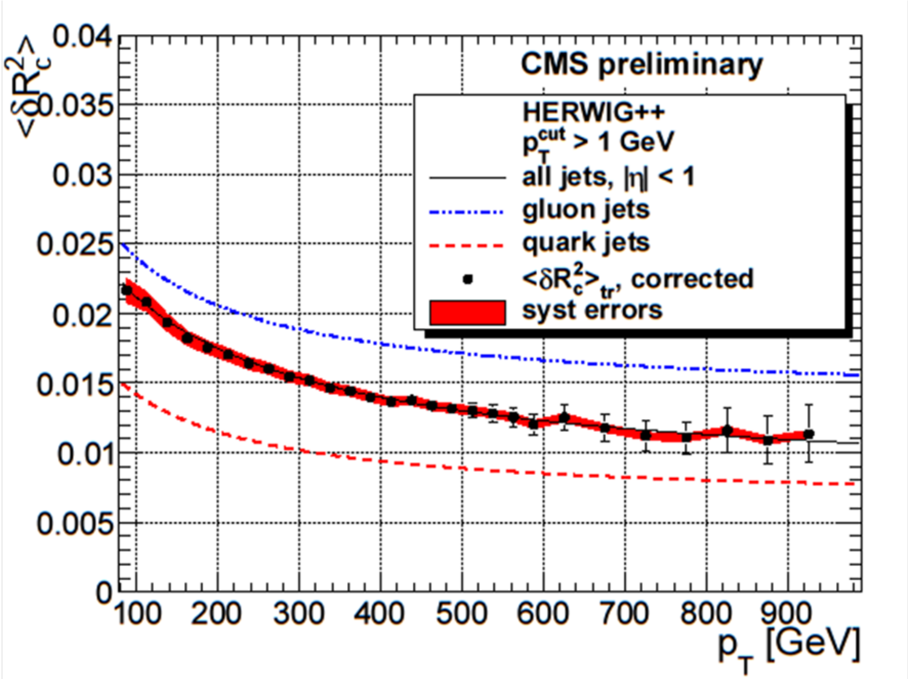


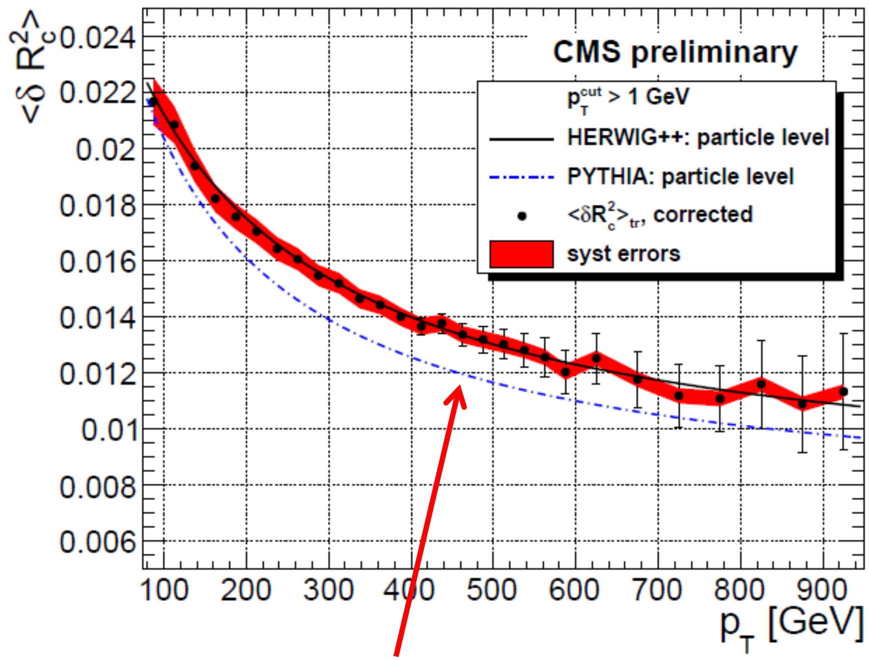
Jet Structure: 2nd Moment of P_T Radial Distribution

CMS PAS QCD-08-002

- Complementary method to study jet structure
- Potentially improved systematic uncertainties
  - Largest uncertainty is from energy scale calibration

$$\delta R^2_{jet}(p_T) = \frac{\sum_{C^*} \Delta R^2(C^*, jet) * p_T^{C^*}}{p_T^{jet}}$$





Differences observed between Herwig and Pythia

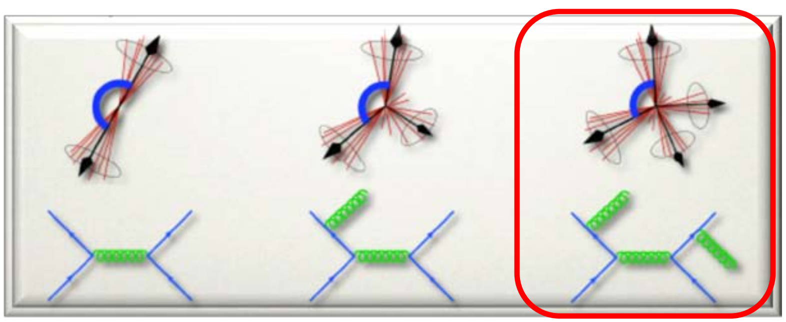
Dijet Angular Decorrelation

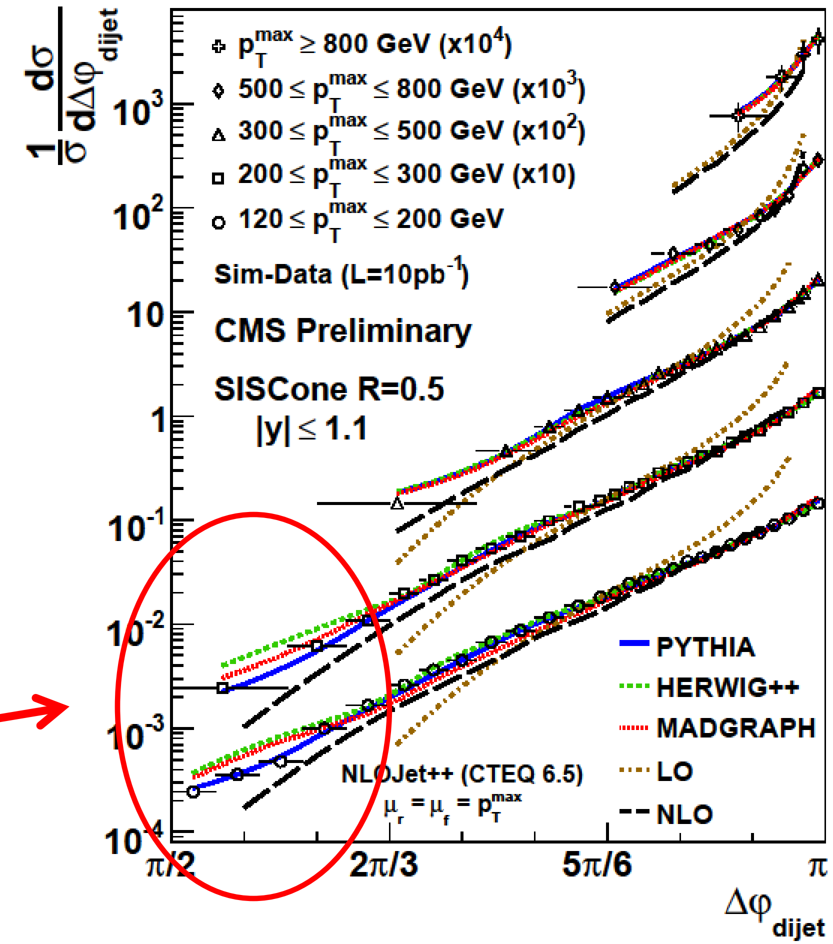
CMS PAS QCD-09-003

- Measurement of the azimuthal angle between the two leading jets.
- $\Delta\varphi$ distribution of leading jets is sensitive to higher order radiation w/o explicitly measuring the radiated jets
- Shape Analysis:

$$f\left(\Delta\varphi_{\text{dijet}}\right) = \frac{1}{\sigma_{\text{dijet}}} \left| \frac{d\sigma_{\text{dijet}}}{d\Delta\varphi_{\text{dijet}}} \right|$$

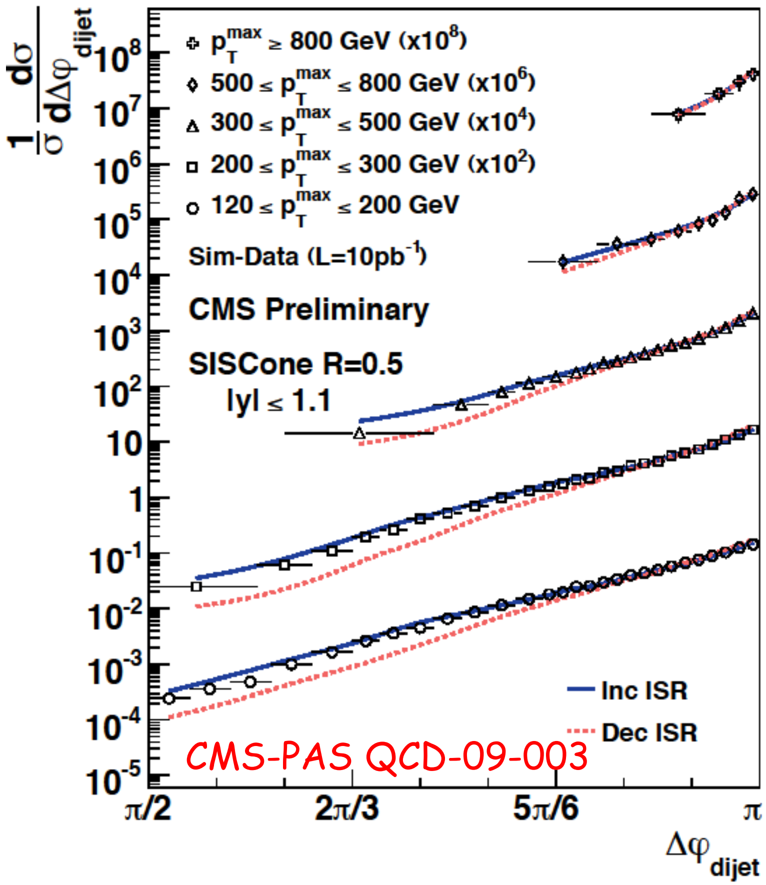
  - Reduced sensitivity to theoretical (hadronization, underlying event) and experimental (JEC, luminosity) uncertainties



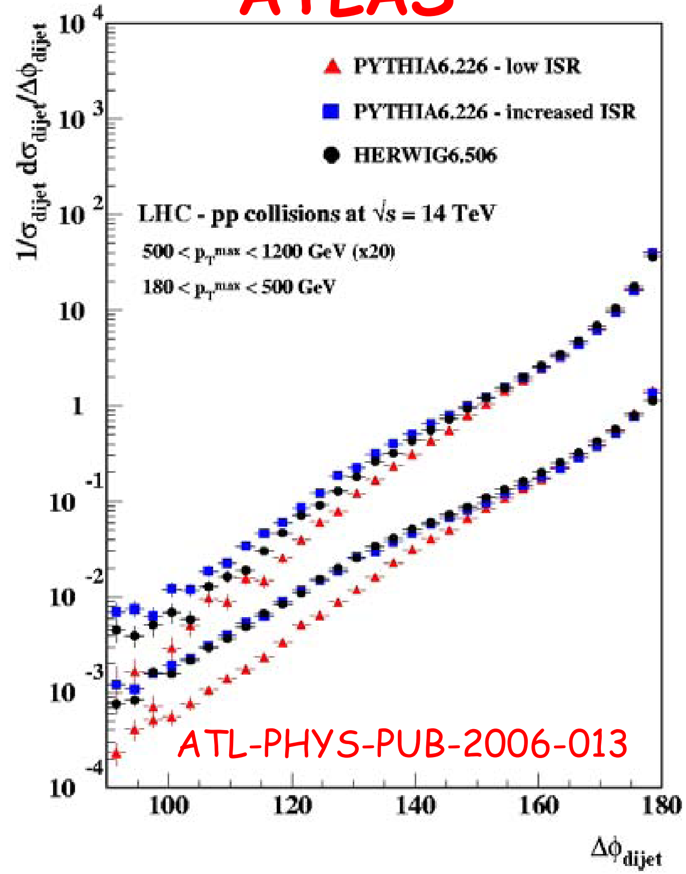


Dijet Angular Decorrelation (ii)

CMS



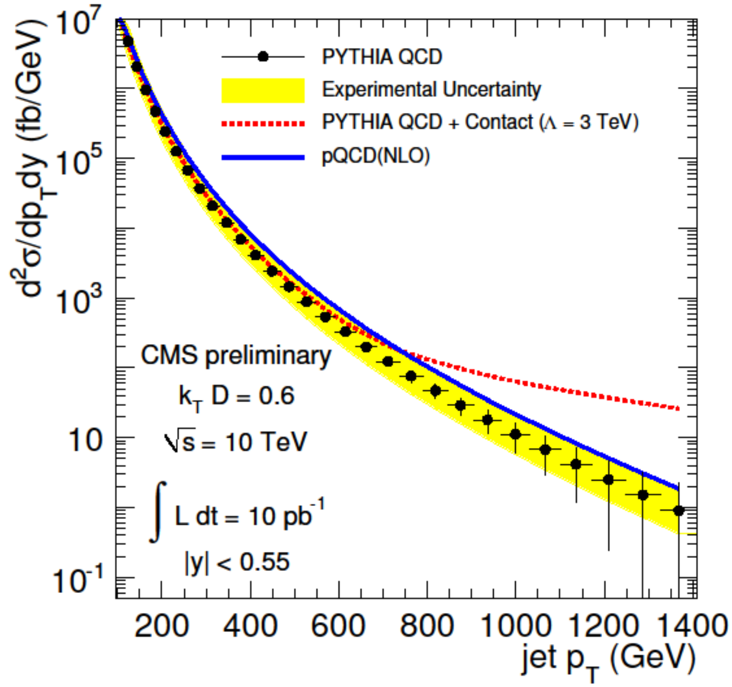
ATLAS

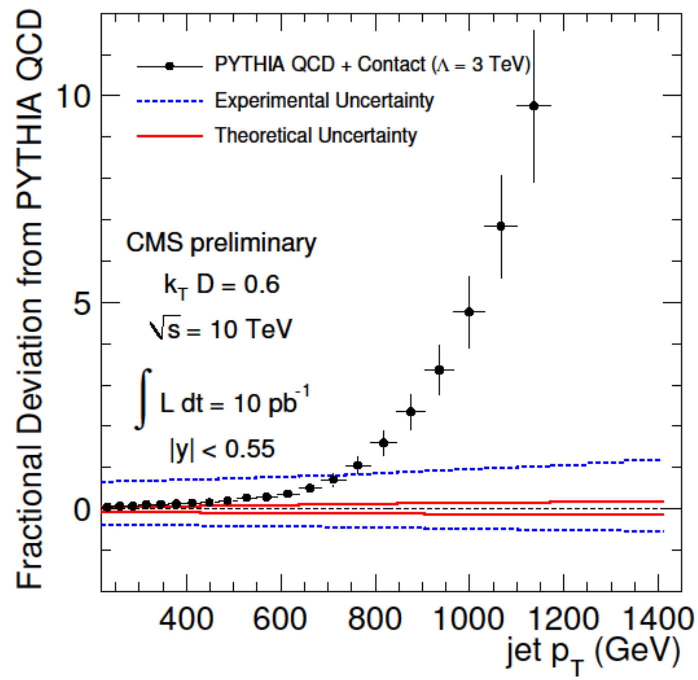


- Early measurement shown to be useful for tuning phenomenological parameters (ISR) in MC event generators
- Systematic uncertainties dominated by jet energy scale and jet energy resolution effects

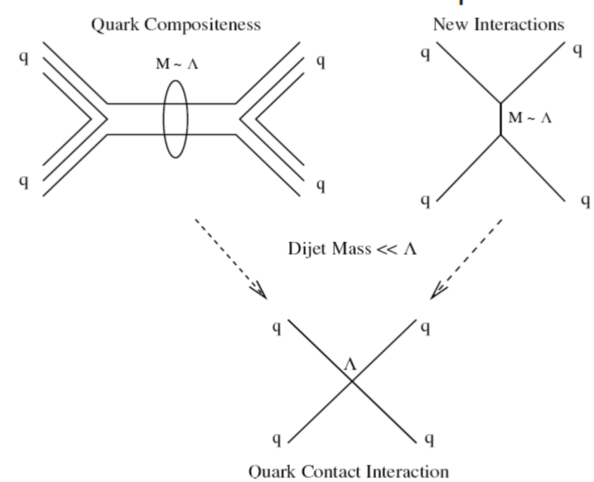
Inclusive Jet Cross Section

CMS PAS QCD-08-001





- Important jet commissioning measurement
- Can probe contact interactions beyond the Tevatron reach (2.7 TeV) with 10 pb^{-1} at 10 TeV
- Main uncertainty: Jet energy scale
  - assume 10% on day 1
- Can be used to constrain PDF's



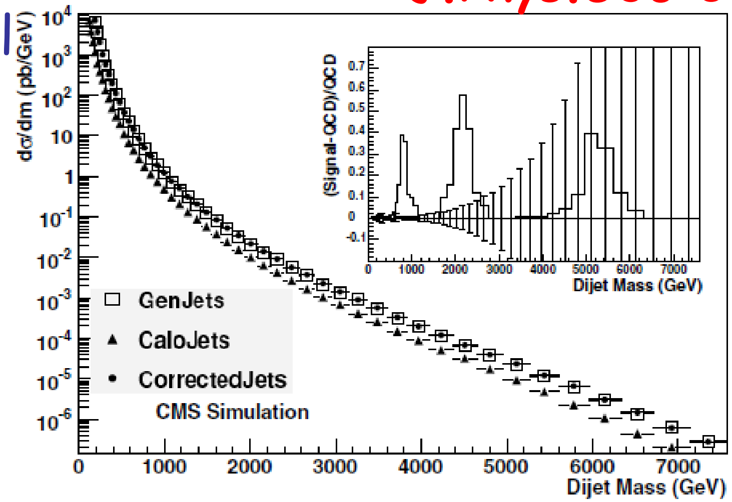
Dijet Mass and Ratio

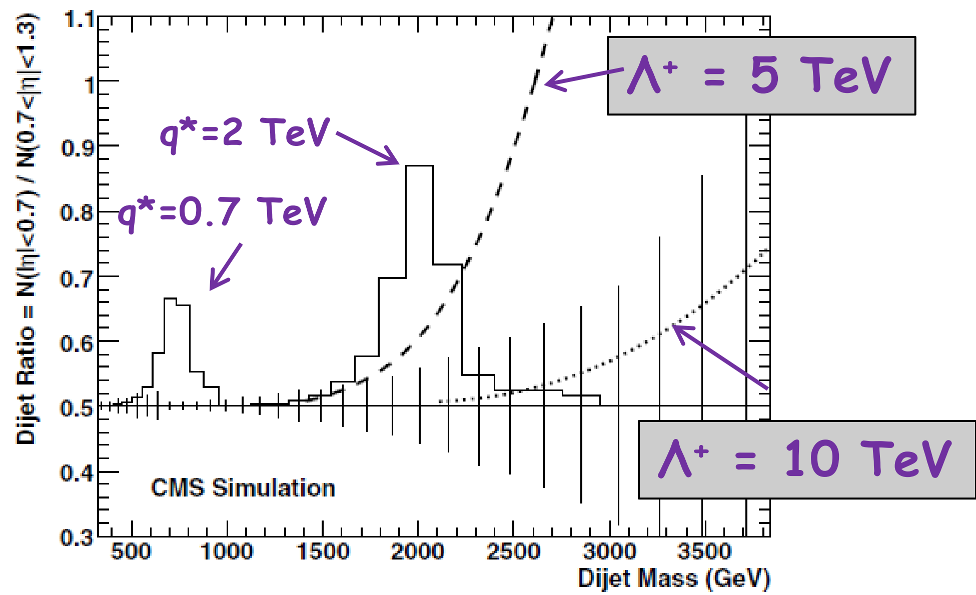
- The dijet mass distribution will be used to search for dijet resonances
- The dijet ratio is a simple measure of dijet angular distributions
  - N(|η|<0.7)/N(0.7<|η|<1.3)
  - Sensitive to contact interactions and dijet resonances
    - With ~100 pb-1 @ 14 TeV; discovery potential up to Λ = 7 TeV
- Dijet ratio has low systematic uncertainties and is a precision test of QCD at startup

J.Phys.G36:015004,2009

$\sqrt{s}$ = 14 TeV

L= 100 pb^{-1}





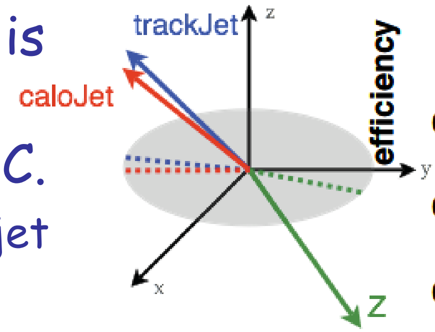
Summary

- LHC will start producing collisions this year!
- After 20 years of R&D, construction, and installation the ATLAS and CMS detectors are ready for data
- First steps: understand detector performance with beam and re-establish the SM
- First measurements will be on QCD analyses
- Small amount of data will be enough to exceed the Tevatron reach
- Rich QCD program at startup and beyond
- New physics might be around the corner!

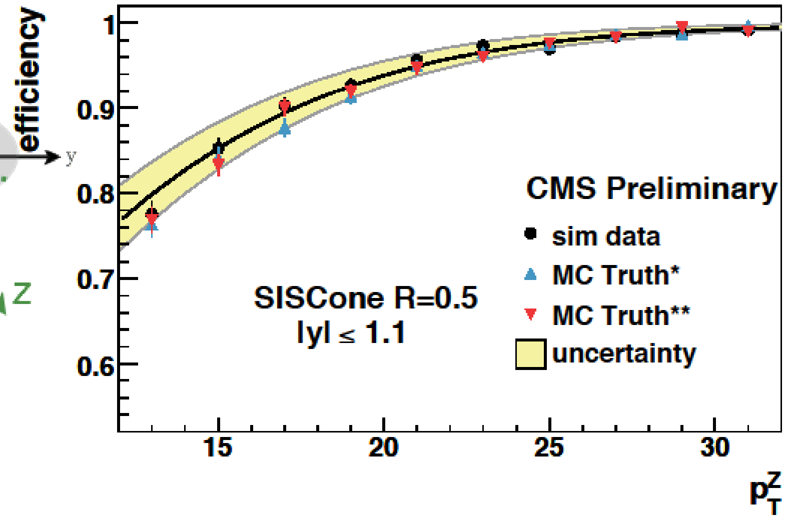
Backup Slides

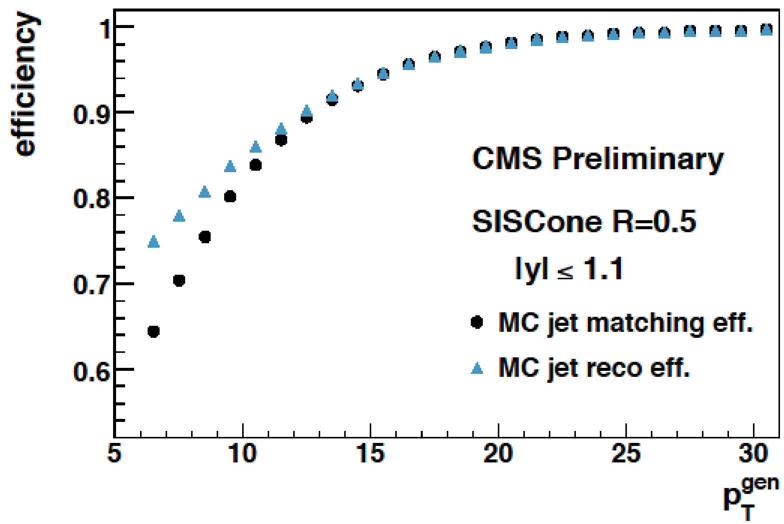
Jet Reconstruction Efficiency at CMS

- A tag and probe method is used to calculate the efficiency in data and MC.
  - Use Z(→μμ)+jet, Z(→ee)+jet or γ+jet events



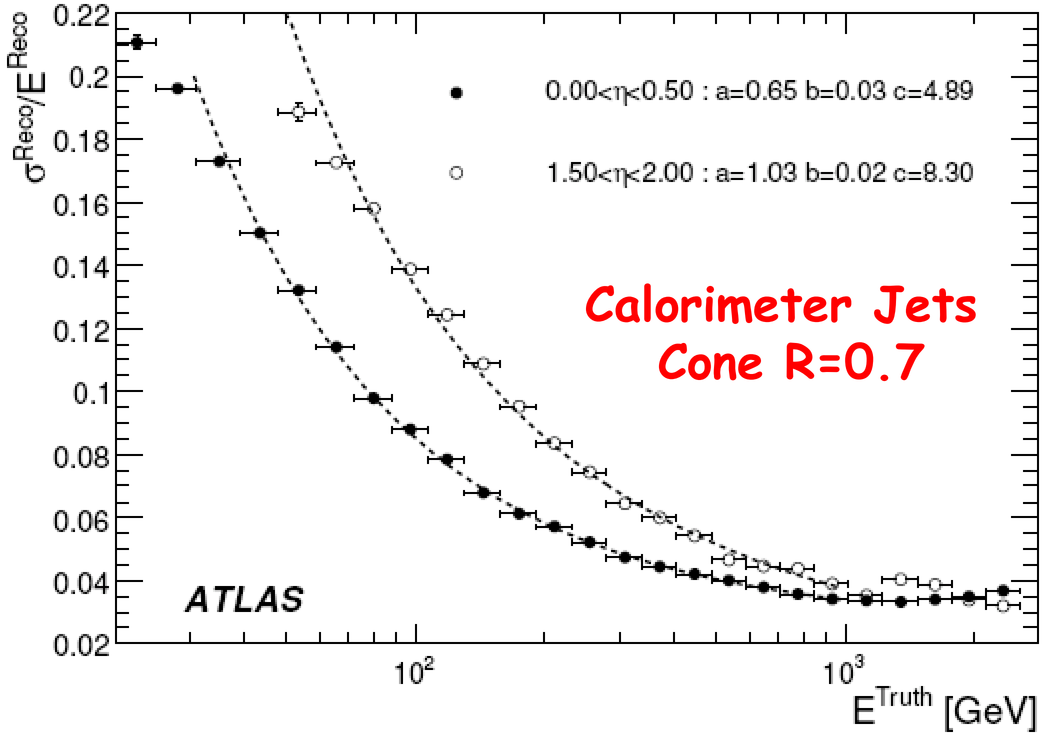
- If the matching efficiency from data is found to disagree with the MC efficiency, then the MC will be adjusted to match the data distributions
- The true calorimeter jet reconstruction efficiency is obtained by removing the effects of the position resolution on the ΔR matching procedure from the corrected MC jet matching efficiency





Jet Resolution at ATLAS

CERN-OPEN-2008-020

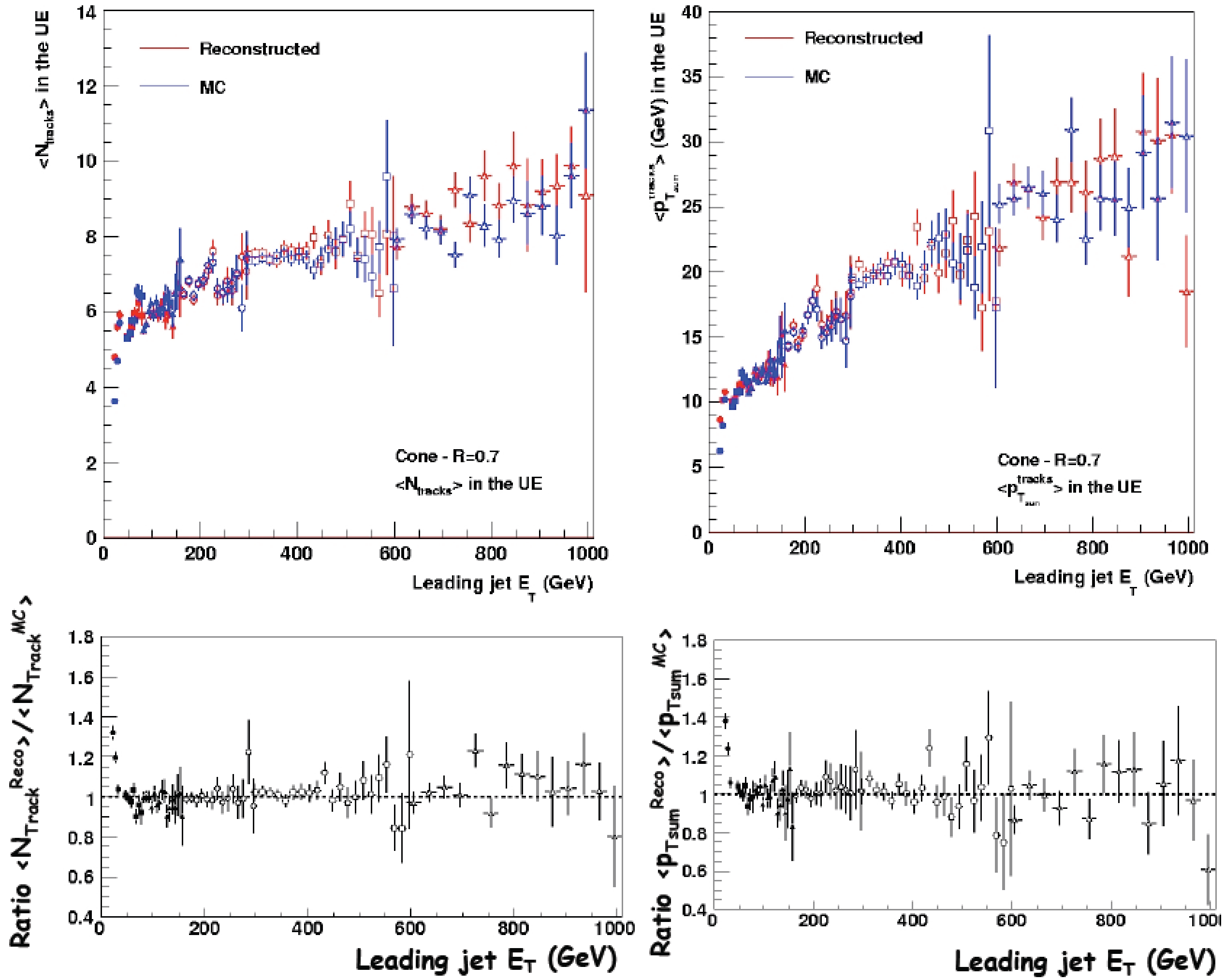


Jet Energy Resolution from MC Truth

- Energy calibrated using "H1-style" cell signal weighting

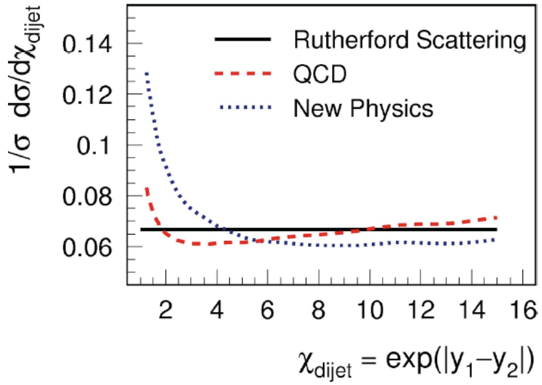
Underlying Event at ATLAS

Good agreement between reconstructed and generated variables

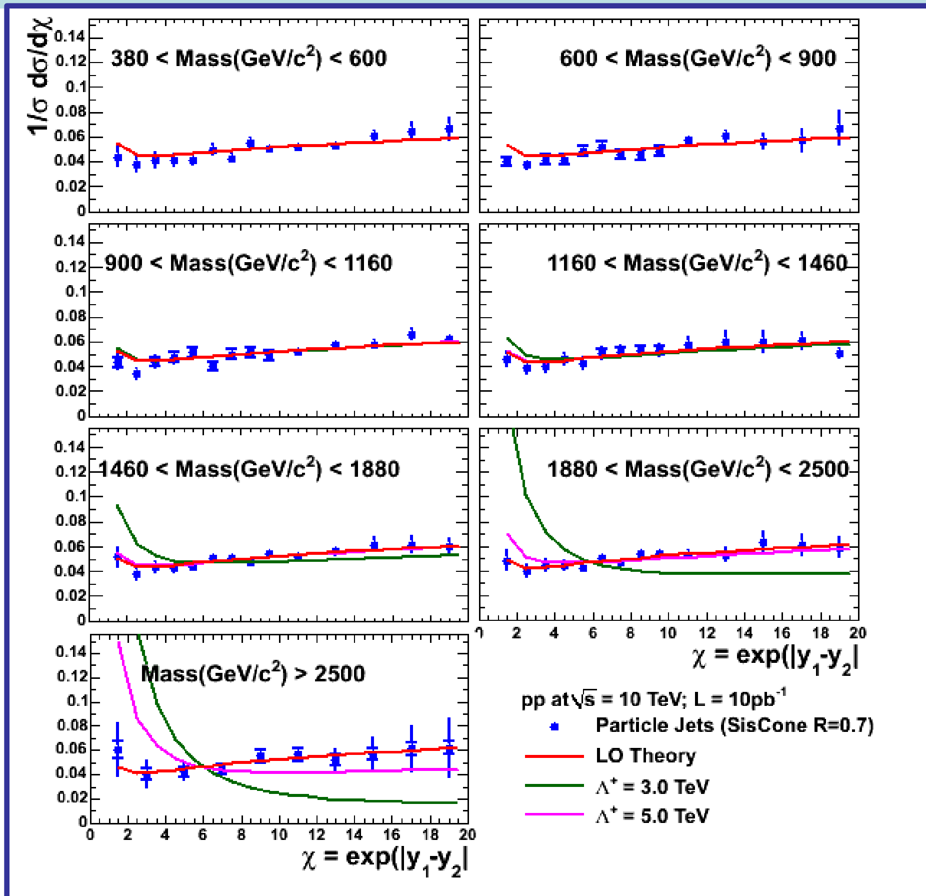


Dijet Angular Distribution

- Angular distributions sensitive to new physics



- Insensitive to PDFs
- Reduced sensitivity to detector effects
- Errors dominated by JES



$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda_c^2} \qquad \left(\frac{\hat{u}}{\Lambda_c^2}\right)^2$$