Multijets, Jet Shapes, Substructure and Radiation Between Jets in CMS

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on behalf of CMS

SM@LHC 2012, April 10-13, Copenhagen

Outline

- Introduction
- Jet Shapes and Substructure
- Measurements with Forward Jets
- 3-jet to 2-jet Ratio

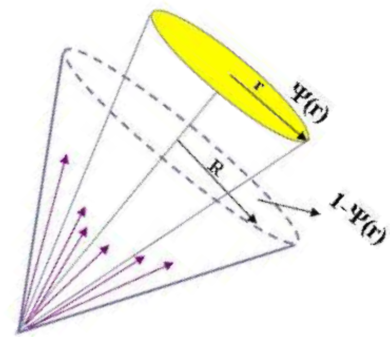
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

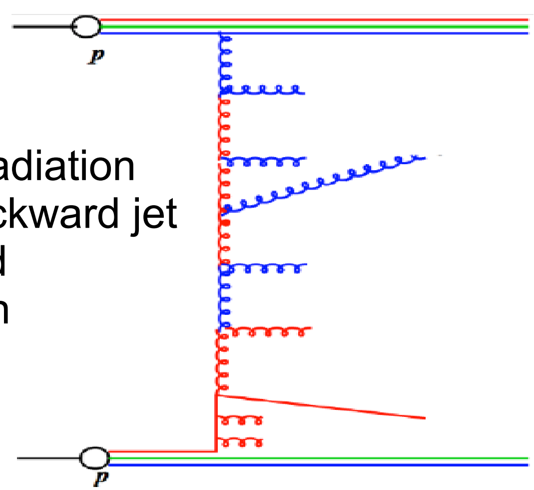
Motivation for multijets, jet shapes, substructure and radiation between jets

→ Different means of testing QCD.

Jet substructure and jet shapes:

- Gain knowledge of parton to jet transition
- Dependence on parton type (gluon vs quark jet)
- Sensitivity to higher orders in α_s
- Jet properties well described by QCD models at Hera and Tevatron. Test extrapolation of QCD to LHC energies.





Measurements with forward jets:

- Sensitivity to correlations and additional radiation between the forward jet and central or backward jet
- Large rapidity separation between forward and central region → open up for radiation
- Search for effects beyond DGLAP

3-jet over 2-jet ratio (central jets):

- Only presented measurement with explicit selection of N>2 jets
- Probe perturbative QCD and test validity of MC models.

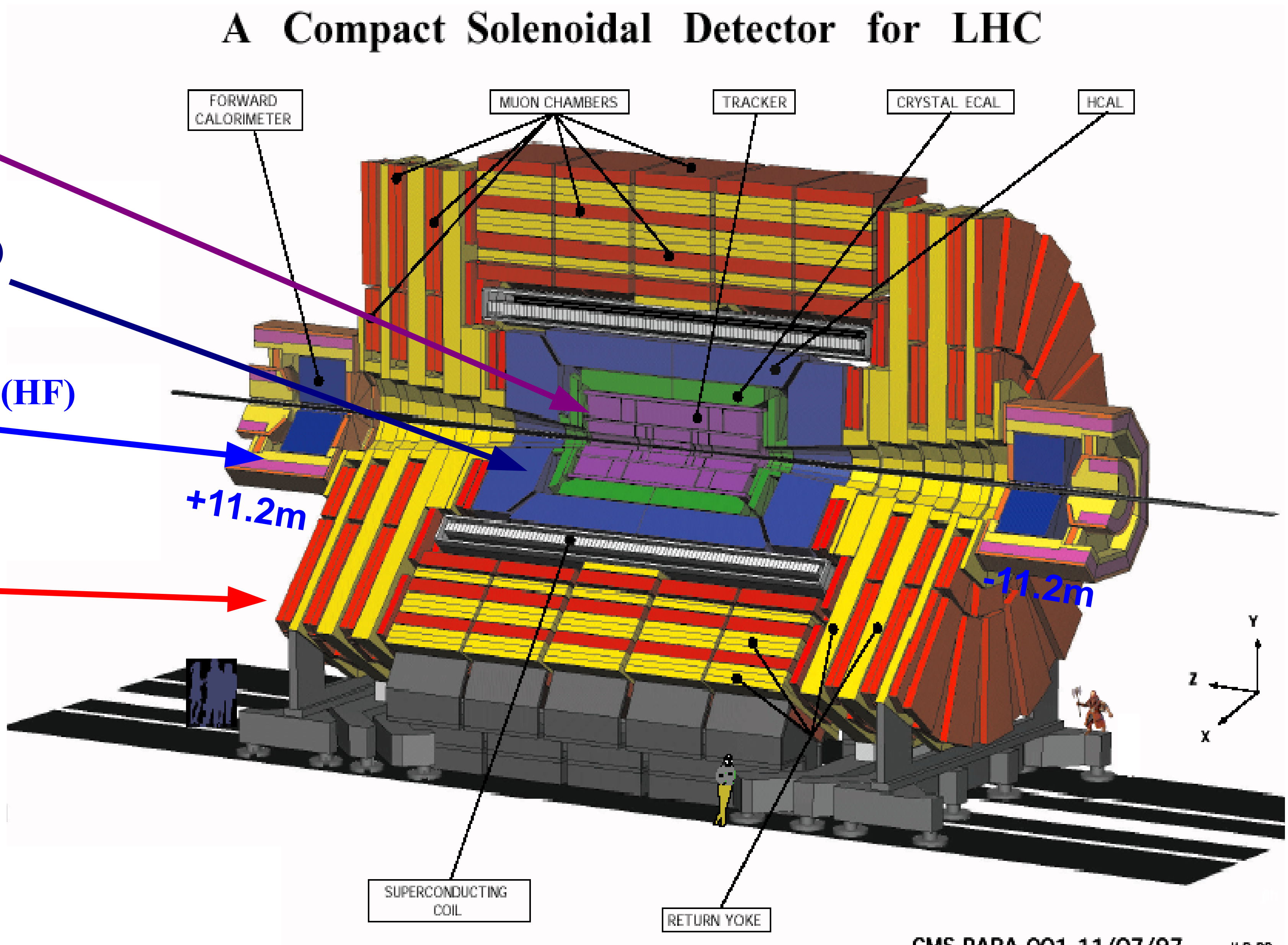
The CMS Detector

Trackers
$|\eta| < 2.5$

Calorimeters
(EM and Hadronic)
$|\eta| < 3.0$

Hadronic Forward (HF)
Calorimeters
$2.9 < |\eta| < 5.2$

Muon Chambers
$|\eta| < 2.5$



Basic Selection

Each presented measurement is based in 2010 data (low pile-up) collected at √s=7 TeV.
The integrated luminosities for respectively measurement is written in the plots.

Selections

Minimum-bias trigger – a signal in either of the beam pickups (BPTX), and coincidence hits in the Beam Scintillator Counters (BSC) → Non-single diffractive events

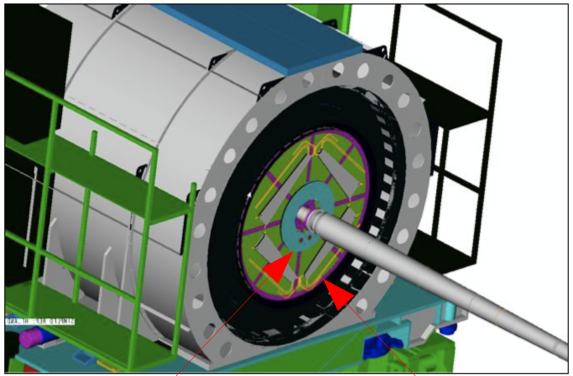
in combination with

A single jet trigger or a combination of single jet triggers → trigger efficencies close to 100%.

and additional cuts for

- High quality primary vertex
- Beam halo and beam background reductions

The detailed jet selections varies for the different analyses and are written for respectively measurement



Jet Transverse Structure

Jet Transverse Structure

Event and jet selection:

- Anti kt-algorithm, R=0.7
- Di-jet events with $p_{t,jet}$>20 GeV on the leading jet, and $p_{t,jet}$>10 GeV on the subleading jet.
- Jets with $p_{t,jet}$>20 GeV and $|\eta|<1$ included in the measurement.

Main observables:

- Number of charged particles inside the jet, N_{chrg}

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- Jets with $p_{t,jet}$>20 GeV and $|\eta|$<1 included in the measurement.

Main observables:

- Number of charged particles inside the jet, N_{chrg}
- The charged particle transverse jet shape, δR^2, a *measure of the width of the jet*.

  Use ϕ_C and η_C – the p_t weighted averages of ϕ_i and η_i the charged particles in the jet.

  Calculated the average distance between the particles and ϕ_C and η_C

$$\langle \delta\phi^2 \rangle = \frac{\sum_{i\epsilon \mathrm{jet}} (\phi_i - \phi_C)^2 \cdot p_{T,i}}{\sum_{i\epsilon \mathrm{jet}} p_{T,i}} \quad \langle \delta\eta^2 \rangle = \frac{\sum_{i\epsilon \mathrm{jet}} (\eta_i - \eta_C)^2 \cdot p_{T,i}}{\sum_{i\epsilon \mathrm{jet}} p_{T,i}}$$

  Use the sum as a measure of the width of the jet: $\delta R^2 = \langle \delta\phi^2 \rangle + \langle \delta\eta^2 \rangle$

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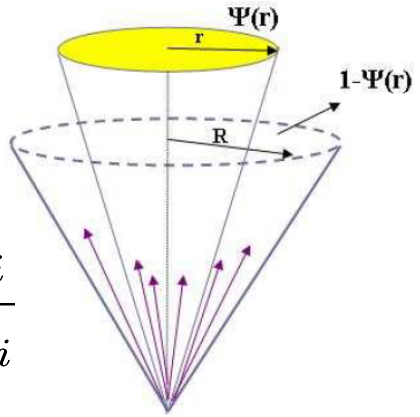
  Use the sum as a measure of the width of the jet: $\delta R^2 = \langle\delta\phi^2\rangle + \langle\delta\eta^2\rangle$

- The integrated jet shape: Average fraction of the jet transverse momentum inside a cone with radius $r = \sqrt{(\phi - \phi_C)^2 + (\eta - \eta_C)^2}$

$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$

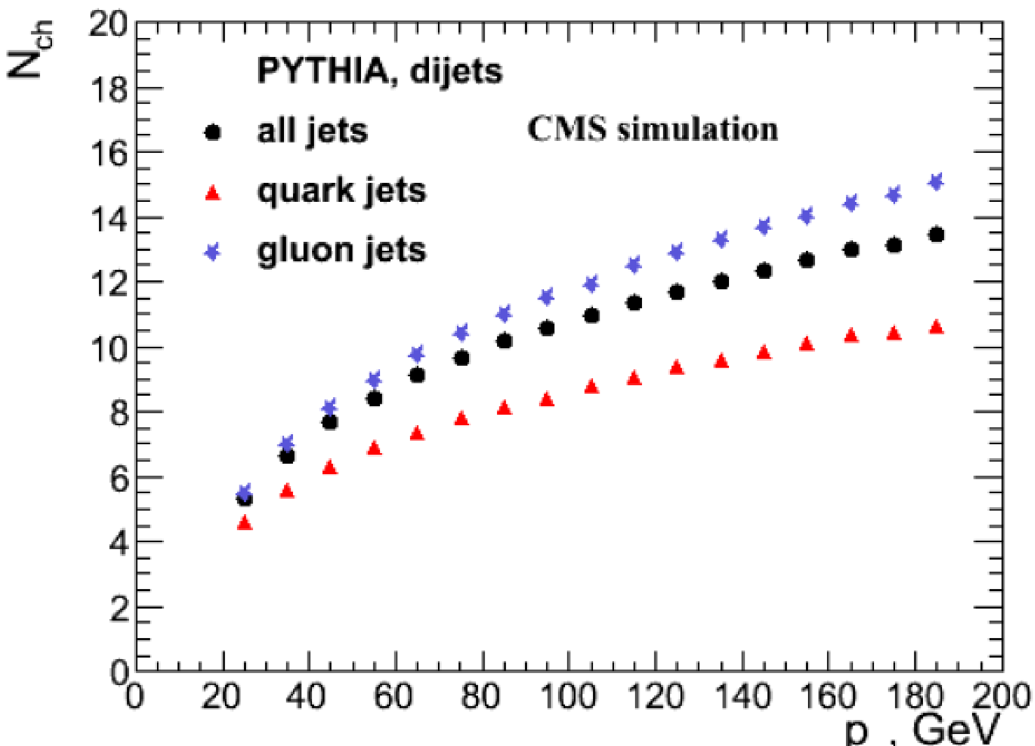


Jet Transverse Structure

Monte Carlo

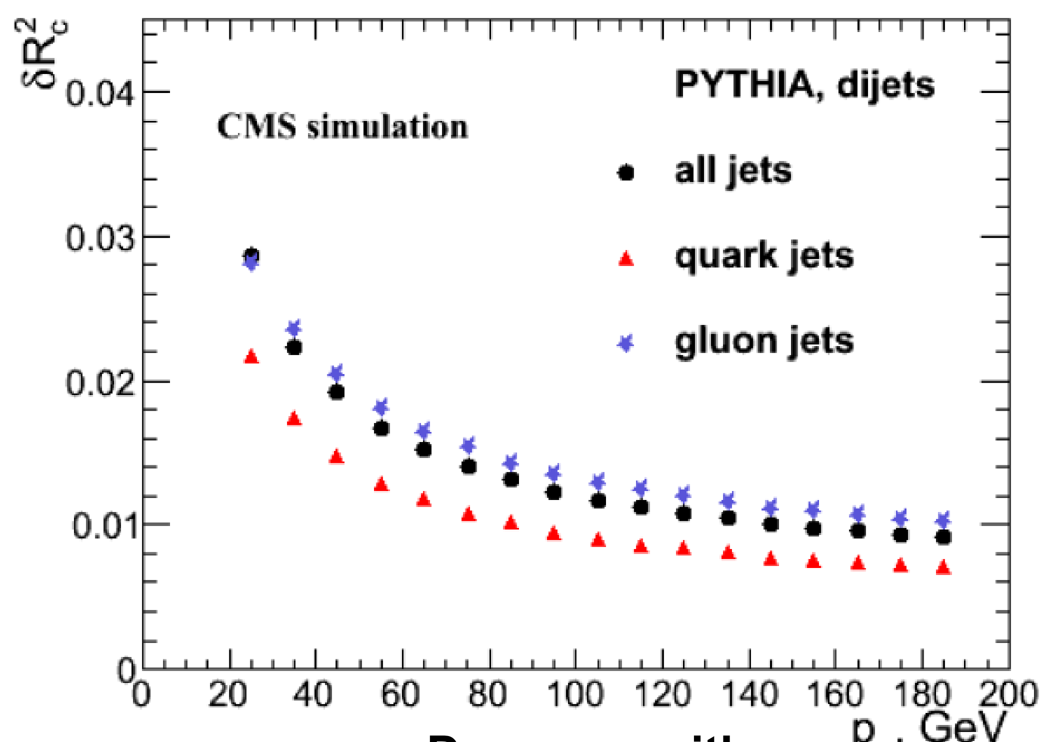
possibility to separate quark and gluon jets

The charged particle multiplicity in a jet



Increase with p_T

The charged particle transverse jet shape ~ width



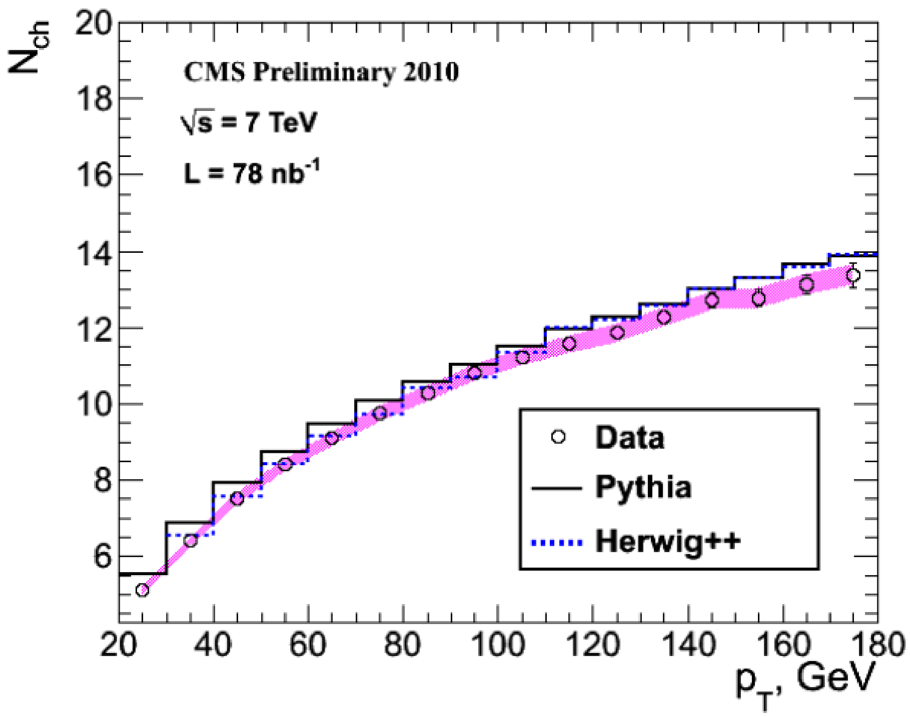
Decrease with p_T

Gluon jets are typically somewhat broader and contains more particles then quark jets, due to the higher color charge of the gluon.

Jet Transverse Structure

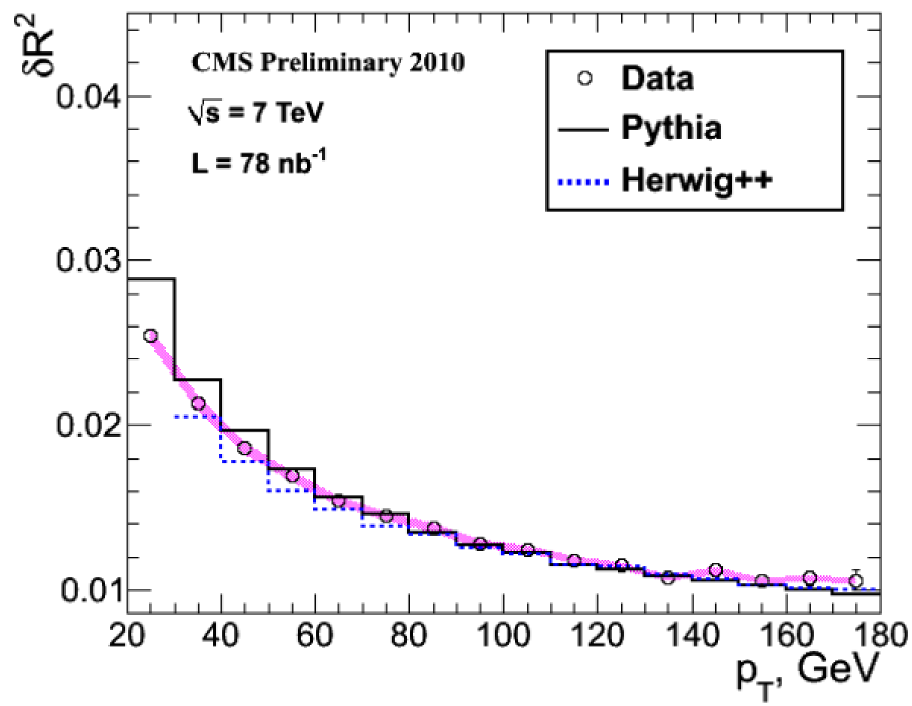
Data

The charged particle multiplicity in a jet



- N_{ch} - Descent describtion of data by MC.
- Herwig++ slightly better at low $p_{t,jet}$

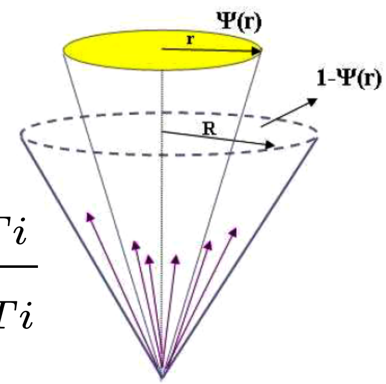
The charged particle transverse jet shape



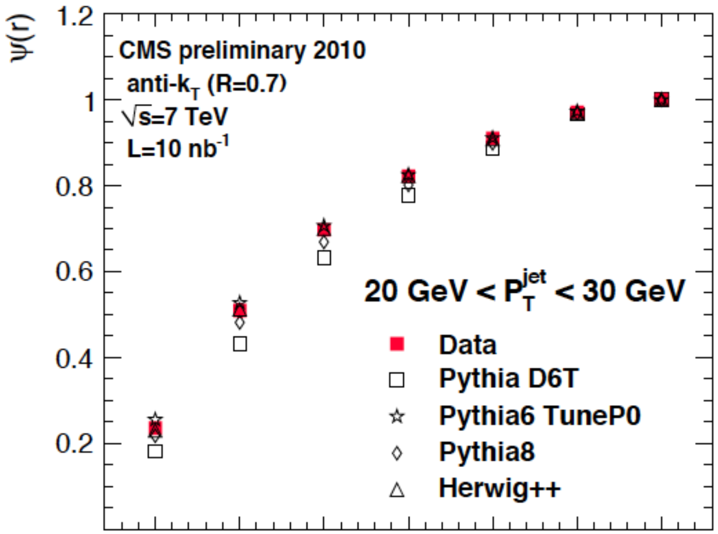
- At high $p_{t,jet}$, data relatively well described by the MC.
- At low $p_{t,jet}$, Pythia6 somewhat broader than data, Herwig++ somewhat narrower than data

Jet Transverse Structure

The integrated jet shape: Average fraction of the jet transverse momentum inside a cone with radius $r = \sqrt{(\phi - \phi_C)^2 + (\eta - \eta_C)^2}$

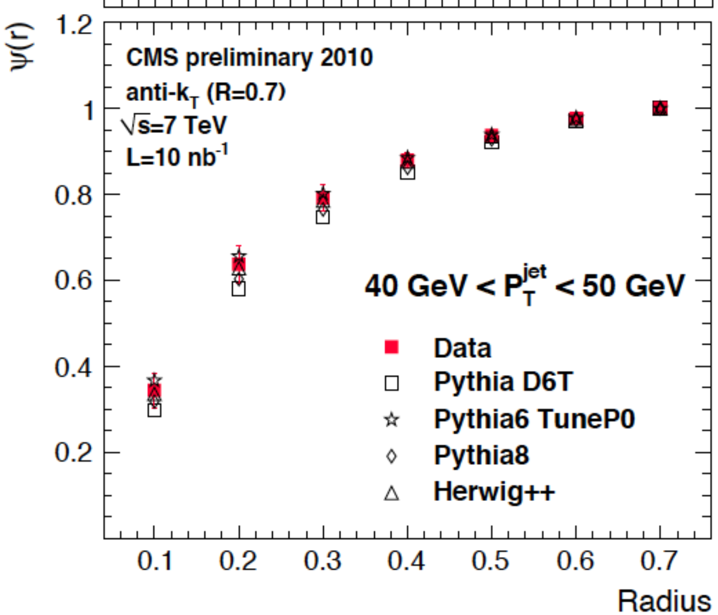


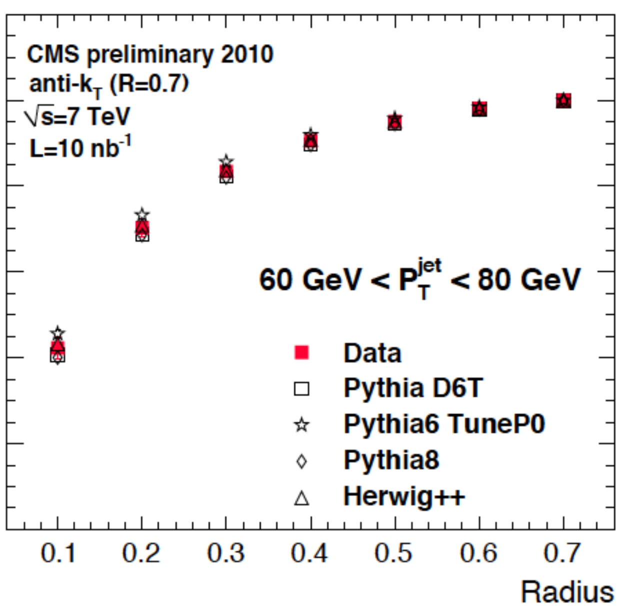
$$\psi(r) = \frac{\sum_{r_i < r} p_{Ti}}{\sum_{r_i < R} p_{Ti}}$$

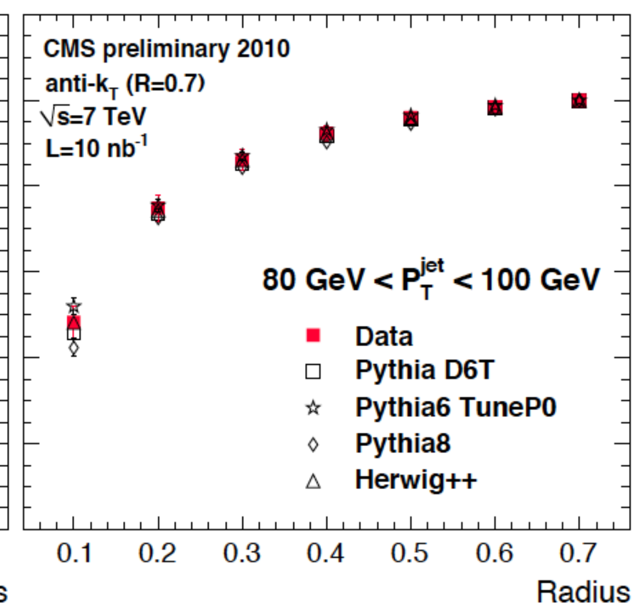


Approaches 1 by construction → Differences between data and MC show up at low radius.

As before, somewhat larger difference at low $p_{t,jet}$.







Subjet Multiplicity in Dijet Events

Subjet Multiplicity

Data and Selection:

Dijet events with both jets $p_{t,jet}$>97 GeV and |y|<1 or 1<|y|<2

Jets defined with **k_t-algorithm (R=0.6)**: High sensitivity to softer object, in opposite to the anti-kt algorithm.

Definition of mean subjet multiplicity

Reminder – the k_t-algorithm:

1) For each pair of objects *(i,j)* find $d_{ij} = min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{0.6^2}$

where ΔR_{ij} is the distance in y-*Φ* space: $\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta\phi_{ij})^2}$

2) If d_{ij} is less than the beam distance, $d_{ij} < d_{ib} = p_{Ti}^2$, merge the objects, otherwise define it to be a final jet.

3) Repeat until only final jets

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2) If d_{ij} is less than the beam distance, $d_{ij} < d_{ib} = p_{Ti}^2$, merge the objects, otherwise define it to be a final jet.

3) Repeat until only final jets

Subjets*:*

Repeat the kT-jet algorithm with all jet constituents until $d_{ij} > d_{cut} = y_{cut} \cdot p_T^2(jet)$

The remaining jets defined as subjets.

Mean subjet multplicity – the average number of subjets per jet: $\langle M\rangle(y_{\mathrm{cut}}) = \frac{1}{N_{\mathrm{jet}}}\sum_{jets} M(y_{\mathrm{cut}})$

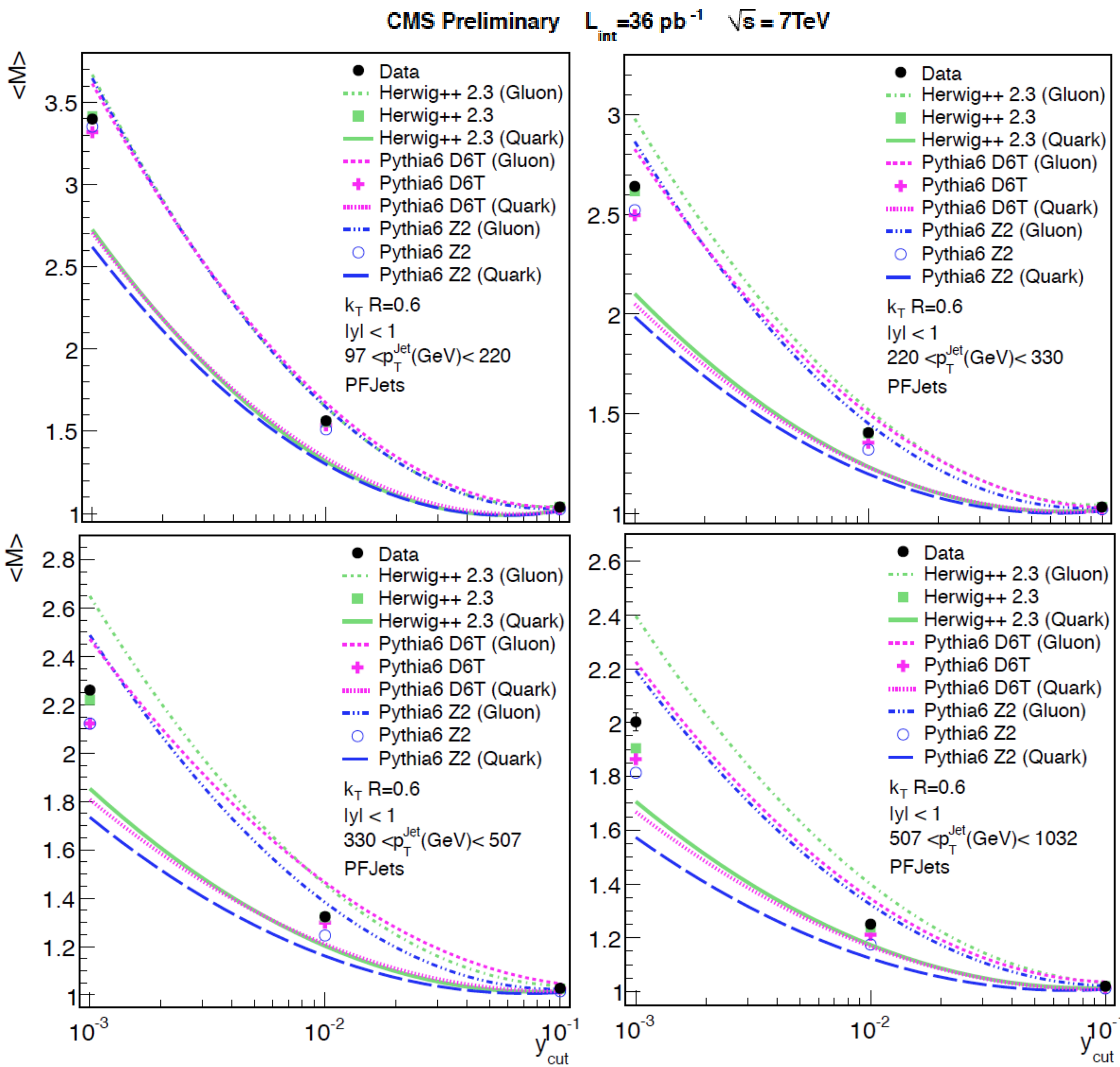
The number of subjets depends on the resolution parameter y_{cut}.

Subjet Multiplicity

CMS-PAS-QCD-10-041

<M> vs. y_{cut} in bins of p_t

- $y_{cut}=10^{-1}$ **gives <M>=1 which is the jet itself.**
- **Low $p_{t,jet}$: Good description data.**
- **Difference between data and MC increases with pt.**
- **Larger sensitivity of the average subjet multiplicity to the jet originating parton at low y_{cut}.**
- **In the next figures $y_{cut}=10^{-3}$**

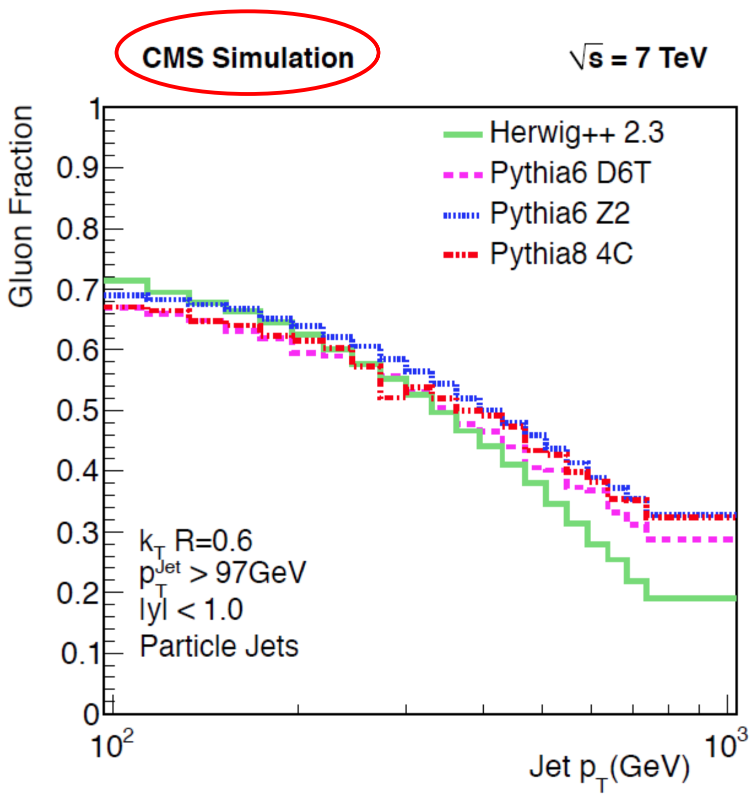


Gluon vs Quark Jets

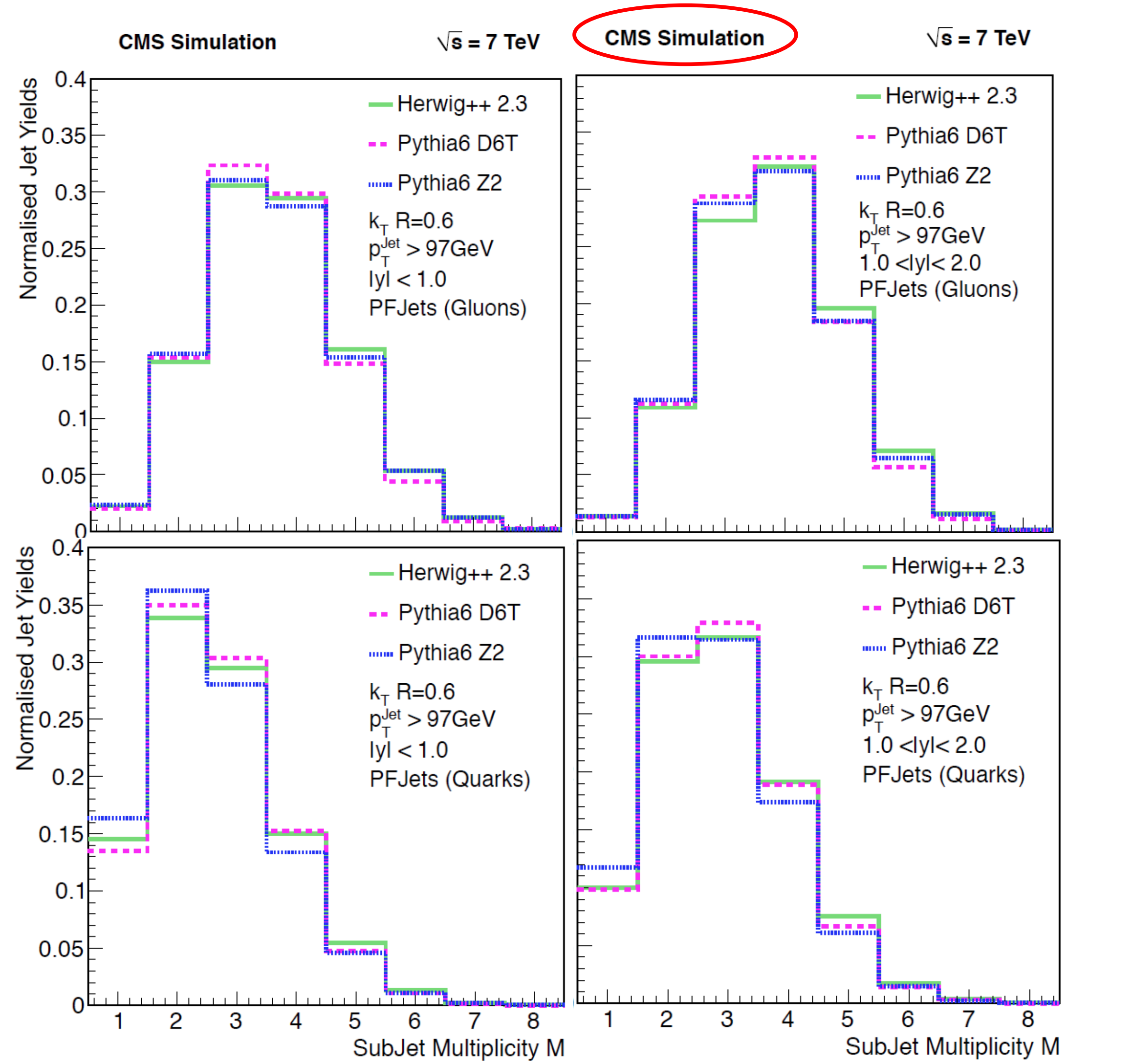
CMS-PAS-QCD-10-041

Monte Carlo

possibility to separate quark and gluon jets



Fraction of gluon jets decreases with $P_{t,jet}$

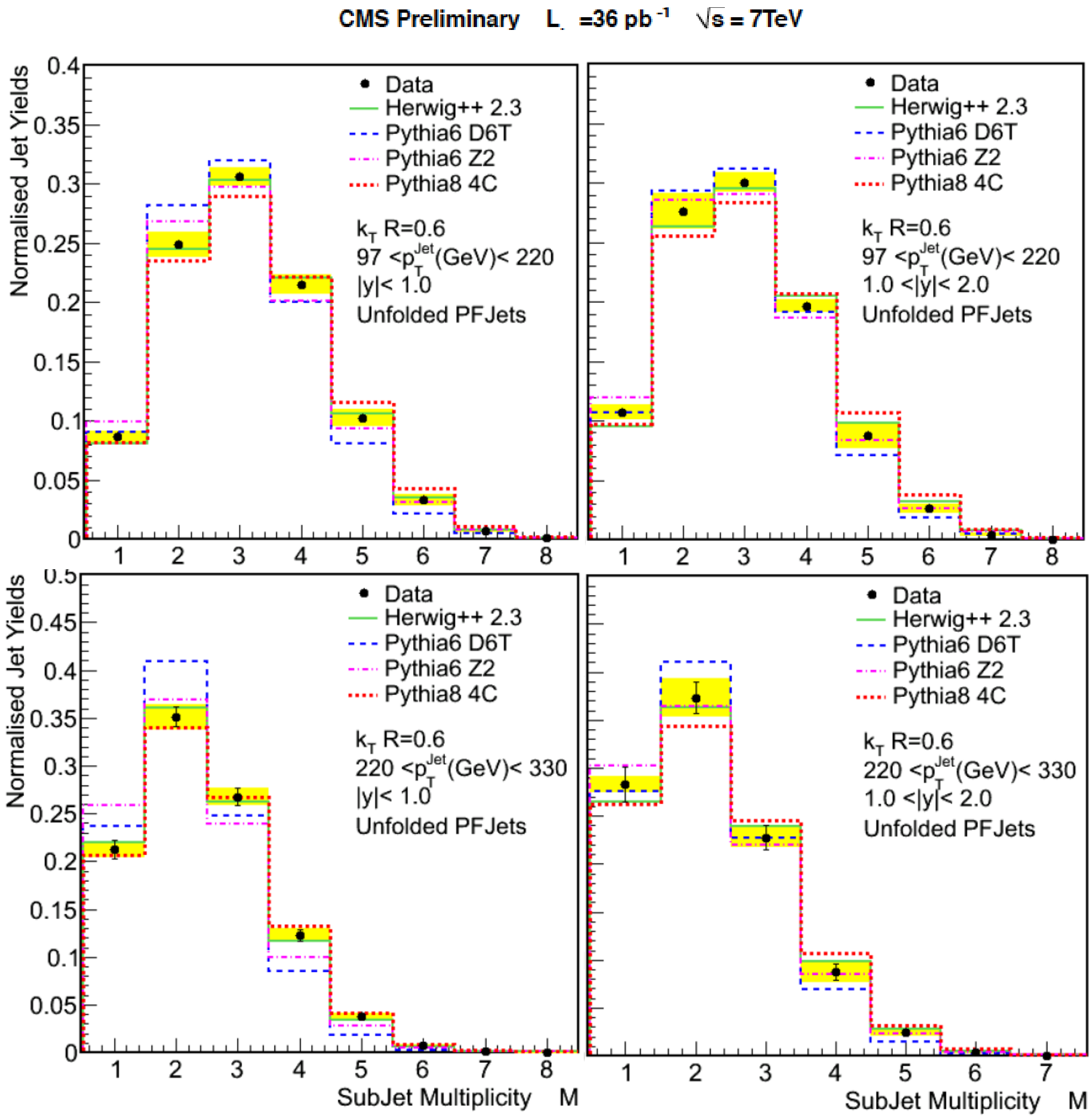


Subjet multiplicity different for quark and gluon jets.
Difference not completely washed out by detector effects.

Subjet Multiplicity

<M> in bins of $p_{t,jet}$ and <y>

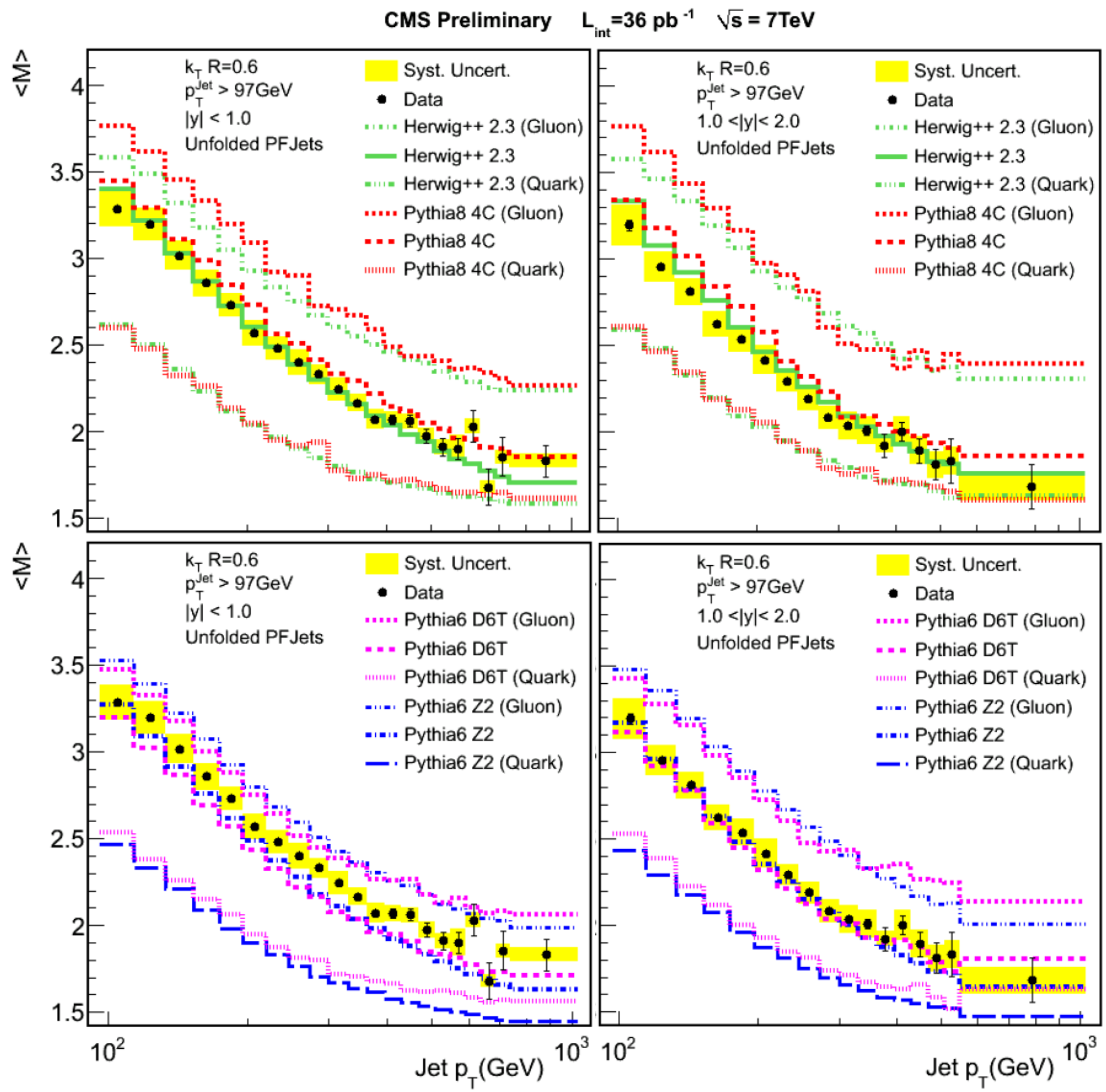
- **Lower subjet multiplicity at high $p_{t,jet}$ - more quark jets (c.f. previous slide)**
- **Somewhat higher sub-jet multiplicity for more central jets - independent of jet type (c.f. previous slide)**
- **Best description by Herwig++.**
- **Pythia8 (4C) OK**
- **Pythia6 worst, but show tune dependence**



Subjet Multiplicity vs $p_{t,jet}$

$p_{t,jet}$ vs subjet multiplicity

- <M> decrease with increasing $p_{t,jet}$, and is somewhat lower for less central jets, i.e. a higher degree of collimation with increasing $p_{t,jet}$
- Larger contribution from quark jets at high $p_{t,jet}$.
- Herwig++ best
- Pythia8 (4C) close
- Pythia6 fails slightly for both tunes (D6T and Z2) Small tune dependence.



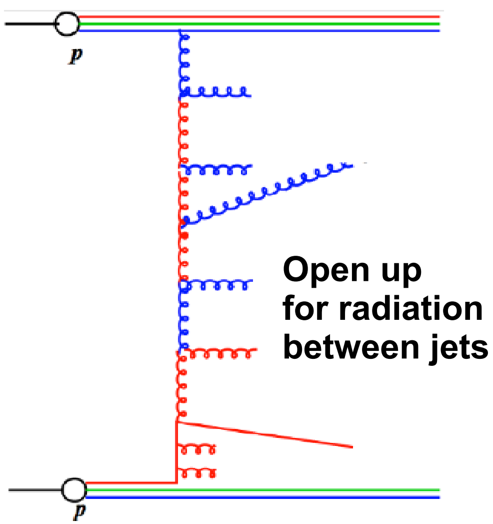
Forward and Forward+Central Jet Cross sections

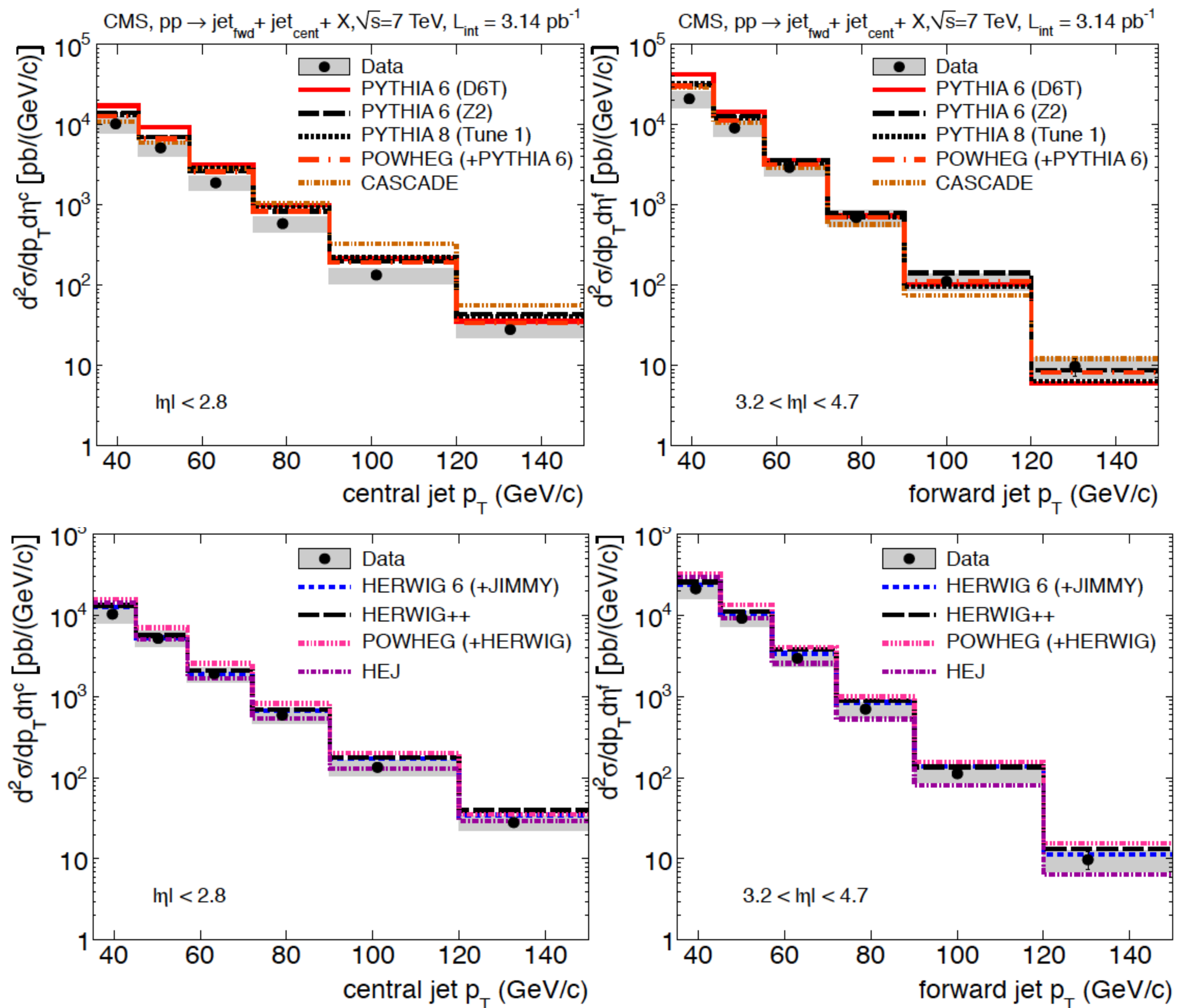
Forward+Central Jets

CMS-FWD-11-002, arXiv:1202.0704

Events with at least one jet with
- **3.5<|η|<4.7**
- **$p_{t,jet}$>35 GeV**

and one central jet with
- **|η|<2.8**
- **$p_{t,jet}$>35 GeV**





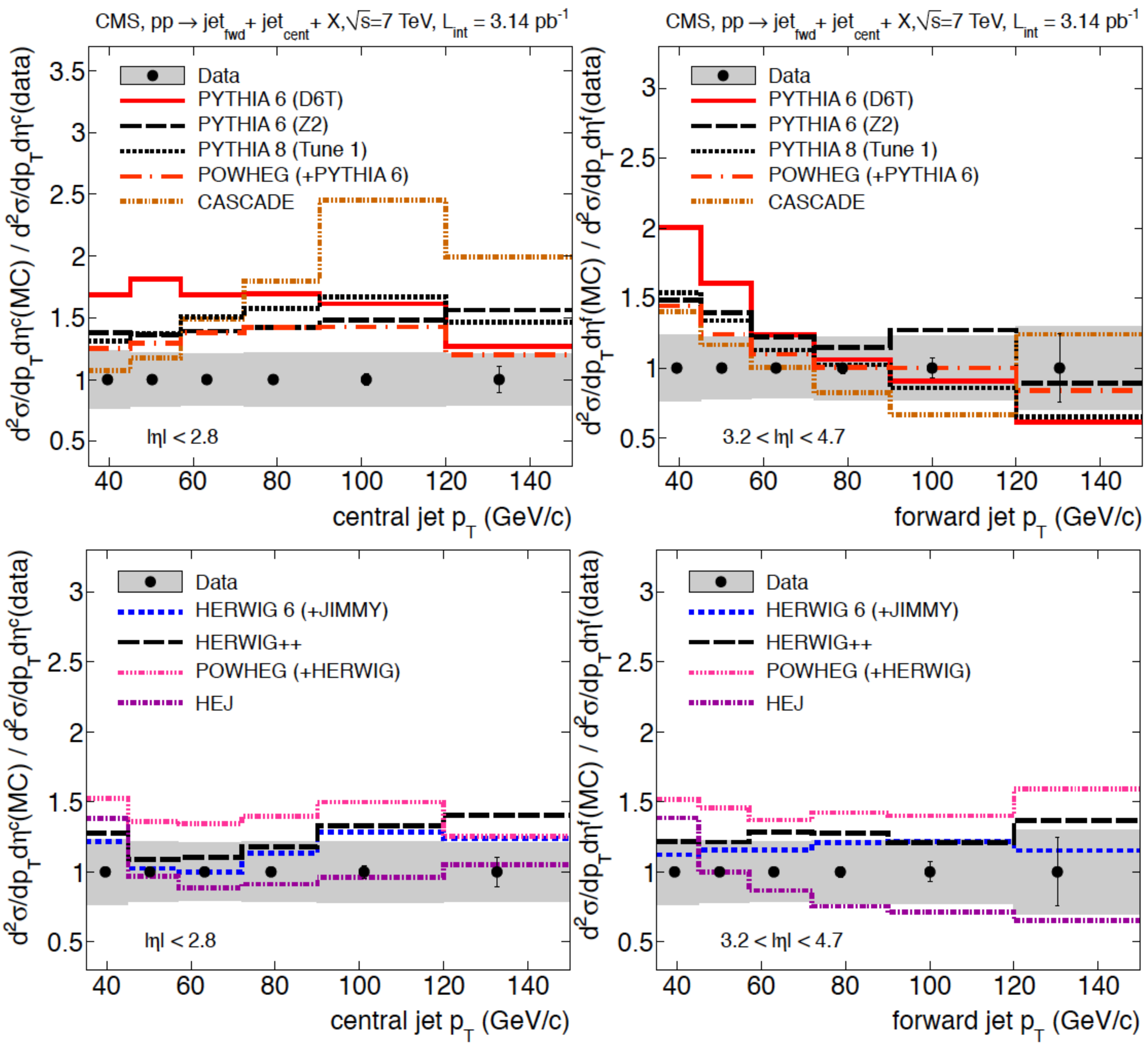
- **Forward jet cross-section somewhat steeper than central jet cross-section.**

- **Comparison to several generators. (ratios on next slide)**

Forward+Central Jets

CMS-FWD-11-002, arXiv:1202.0704

- **Difference in MC description of data between the forward and the central jet.**
- **Largest shape difference for forward jet.**
- **Pythia6 and Pythia8, as well as CCFM based CASCADE problem with normalization of the central jet and shape of the forward jet.**
- **Herwig6, Herwig++, and the BFKL inspired MC HEJ are the best.**

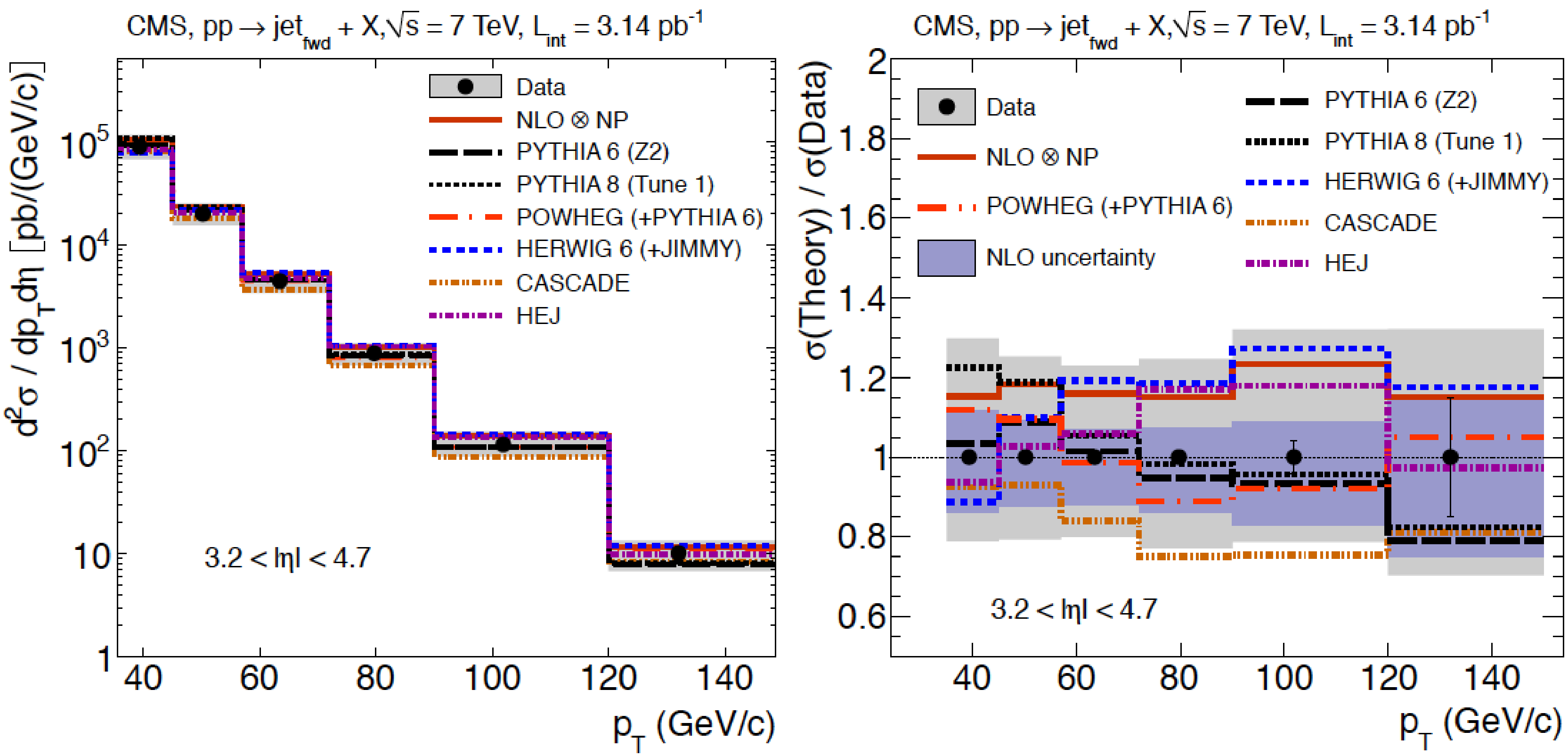


Inclusive Forward Jet Measurement

CMS-FWD-11-002, arXiv:1202.0704

Inclusive forward jet measurement better described.

Events with at least one jet with 3.5<|η|<4.7 and $p_{t,jet}$>35 GeV



- All predictions describe the data within the uncertainties.
- NLO prediction (NLOJET++) too high, but agrees with the data within the large theoretical and experimental uncertainties.
- NLO+PS (POWHEG+PYTHIA6) best.

Ratios of Dijet Production

Inclusive over Exclusive Di-jet Cross-section

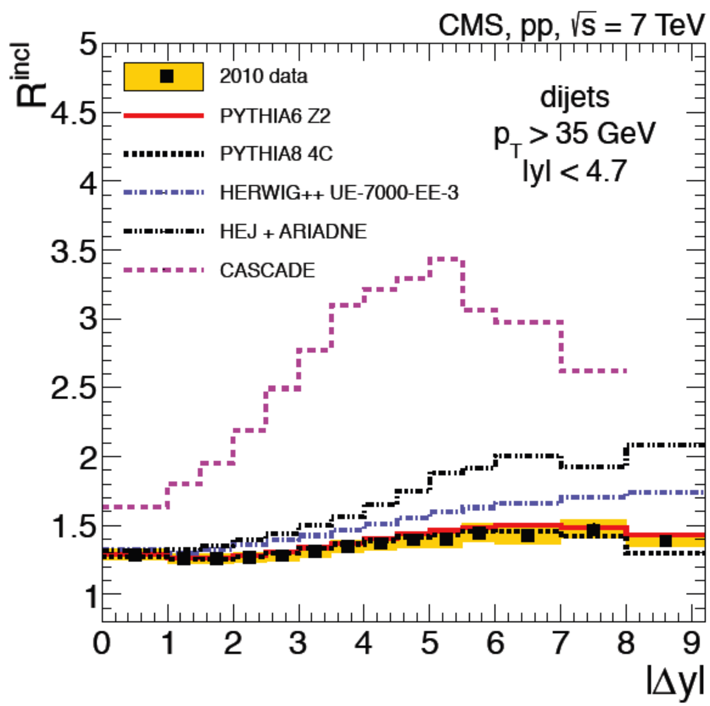
Jets reconstructed with the anti-kT algorithm (R=0.5) and selected with:
$p_{t,jet}$>35 GeV and $|\eta_{jet}|$<4.7

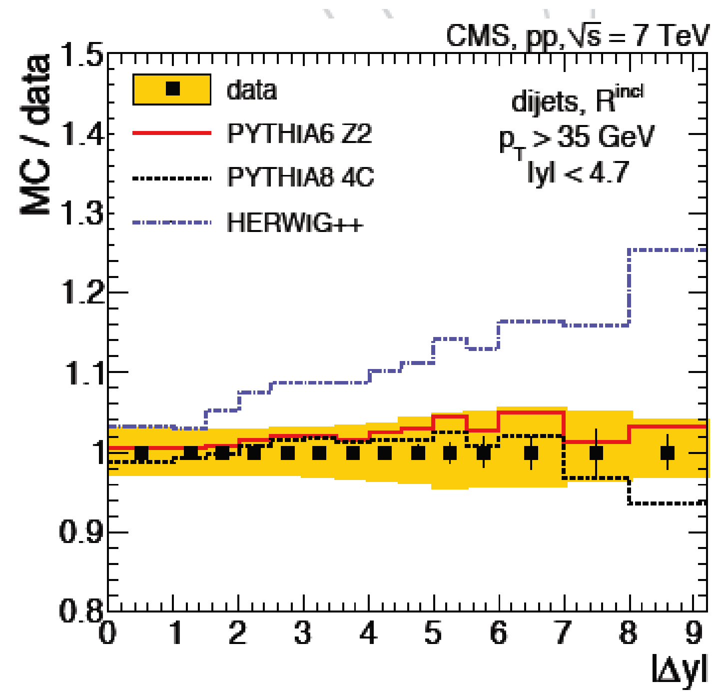
Inclusive jets: **All jet pairs in the events considered**
Mueller-Navelet jets: Most forward and backward jet in the inclusive sample
Exclusive jets: **Events with two jets**

Measure ratios as a function of rapidity difference between jets, Δy

$$\boxed{R = \frac{\sigma_{dijet}(\text{inclusive})}{\sigma_{dijet}(\text{exclusive})}}$$

$$R = \frac{\sigma_{dijet}(\text{MN})}{\sigma_{dijet}(\text{exclusive})}$$





- Increasing Δy → Larger phase space for radiation
- Pythia6 (Z2) and Pythia8 (4C) agree well with data
- Small influence of MPI (not shown)
- Herwig++ (EE3) and HEJ+Ariadne too high at high Δy
- Cascade off

Inclusive over the MN Di-jet Cross-section

Jets reconstructed with the anti-kT algorithm (R=0.5) and selected with:
$p_{t,jet}$>35 GeV and $|\eta_{jet}|$<4.7

Inclusive jets: **All jet pairs in the events considered**
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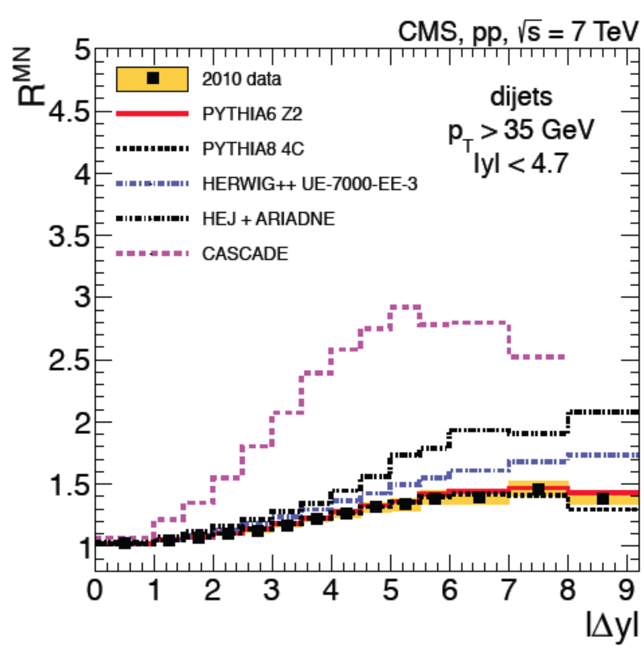
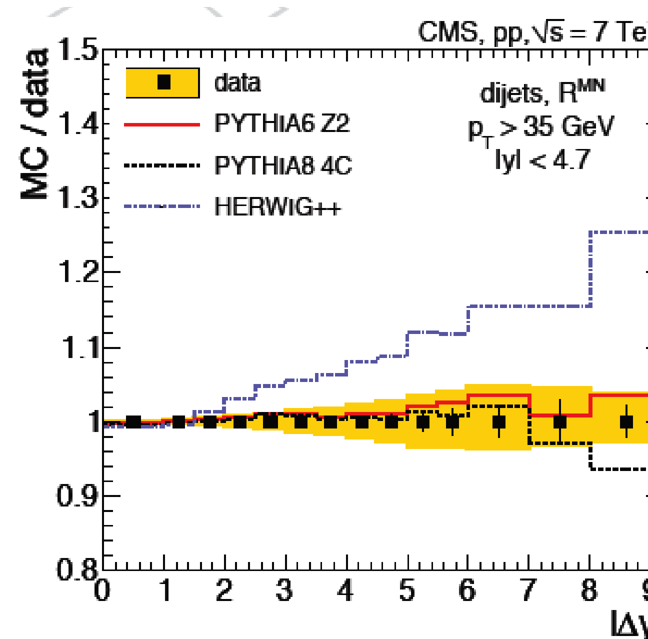




- Low Δy: Ratio(MN/exclusive) per definition *smaller* than Ratio(inclusive/exclusive)
- High Δy: Ratio(MN/exclusive) per definition *same* than Ratio(inclusive/exclusive)
- MC data comparison: exactly the same conclusion as on previous slide

General conclusion: No need for BFKL inspired models

3-jet to 2-jet Ratio

3-jet to 2-jet ratio in the central region

Jets are defined with the anti-kT algorithm with R=0.5, and required to have $\mathbf{p_{t,jet}>50}$ **GeV** and **|y|<2.5**.

The **ratio between events with $\mathbf{N_{jet}\geq 3}$ and $\mathbf{N_{jet}\geq 2}$, $\mathbf{R_{32}}$,** is measured as a function of total jet transverse momentum for all jets, $\mathbf{H_T}$:

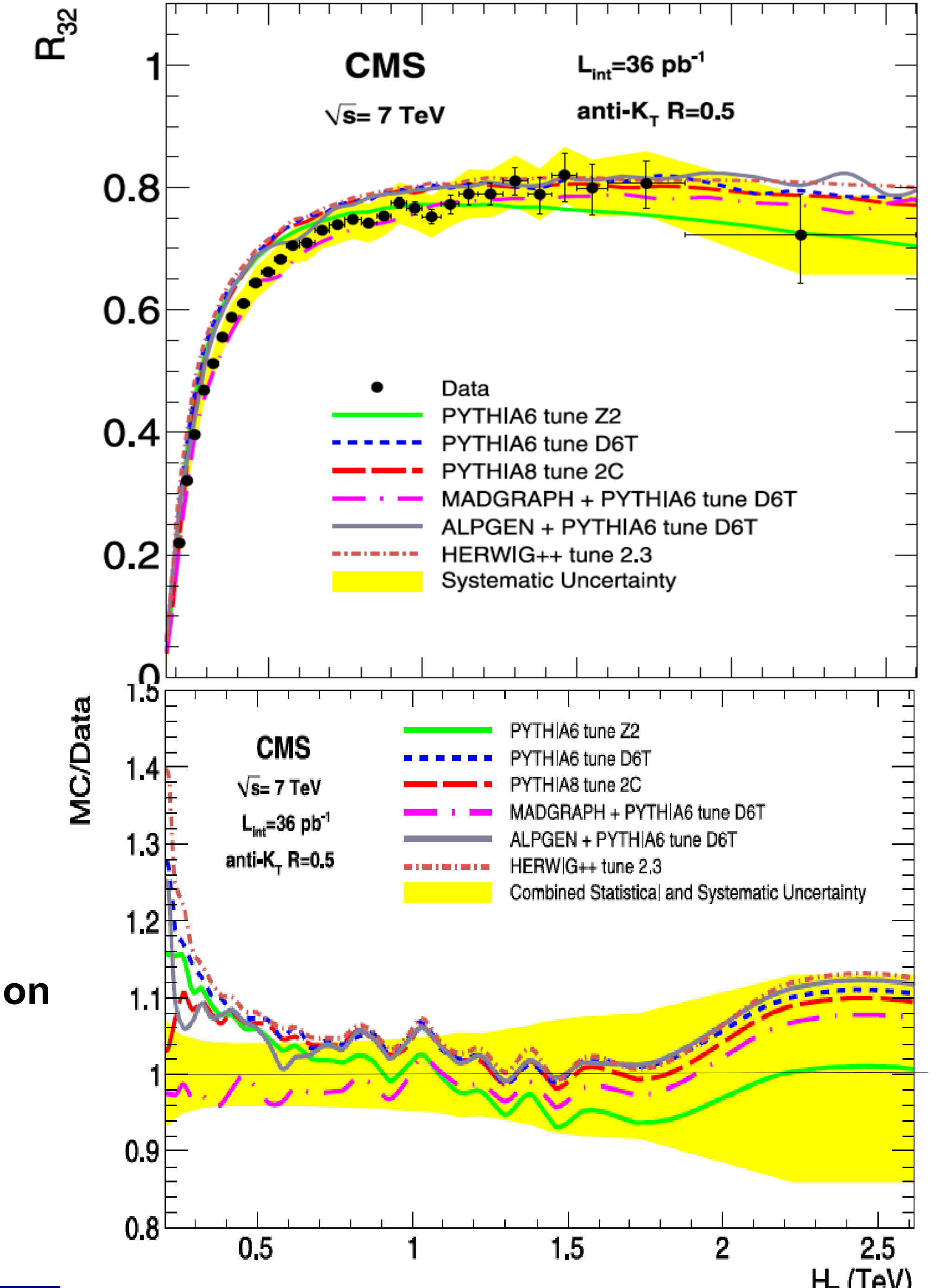
$$H_\mathrm{T} = \sum_{i=1}^{N} p_{\mathrm{T}i}$$

- **Low $\mathbf{H_T}$:**
  - **- Difficult for MC to describe data**
  - **- Shape difference between MCs**

- **High $\mathbf{H_T}$:**
  - **- Large uncertainty, all MC describes data**
  - **- All MC roughly the same shape**

- **Large tune and model dependence over the hole range in $\mathbf{H_T}$**

- **MADGRAPH+PYTHIA6 (D6T) best. The only prediction that described the data over the whole range in $\mathbf{H_T}$.**



Summary

Summary

- **Jet substructure**
  - Overall quite good description of measurement by tested MC models.
  - Some sensitivity to tunes and models, but nothing striking.
  - Different jet shapes and substructure between gluon and quark jets. Largest contribution to measurement from gluon jets.

- **Forward jet measurement**
  - Larger experimental and theoretical uncertainties compared to the jet substructure measurement.
  - Forward+central jet measurement difficult to understand.
  - Dijets with very large rapidity separation: Collinear factorization ok.

- **3-jet over 2-jet ratio for central jets**
  - Low H_T – interesting region – difficulties to describe data – large tune and model sensitivity.

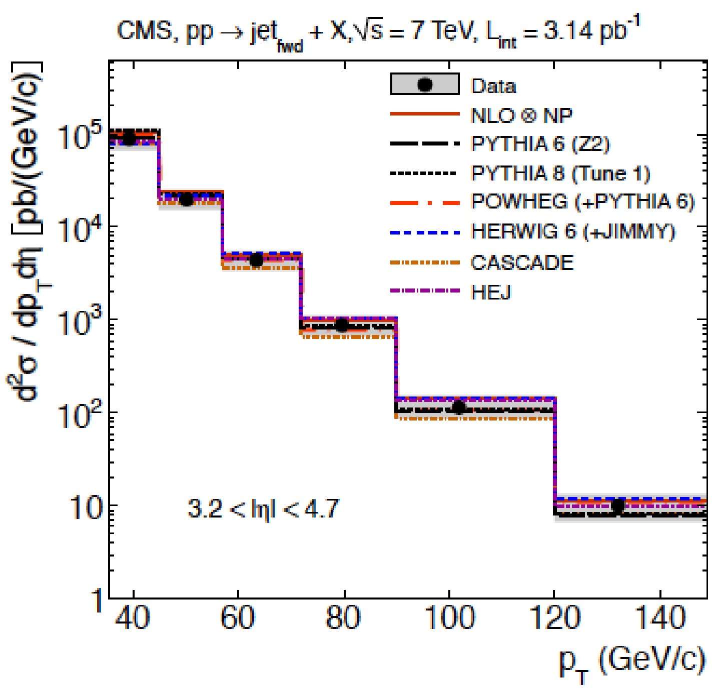
BACK UP

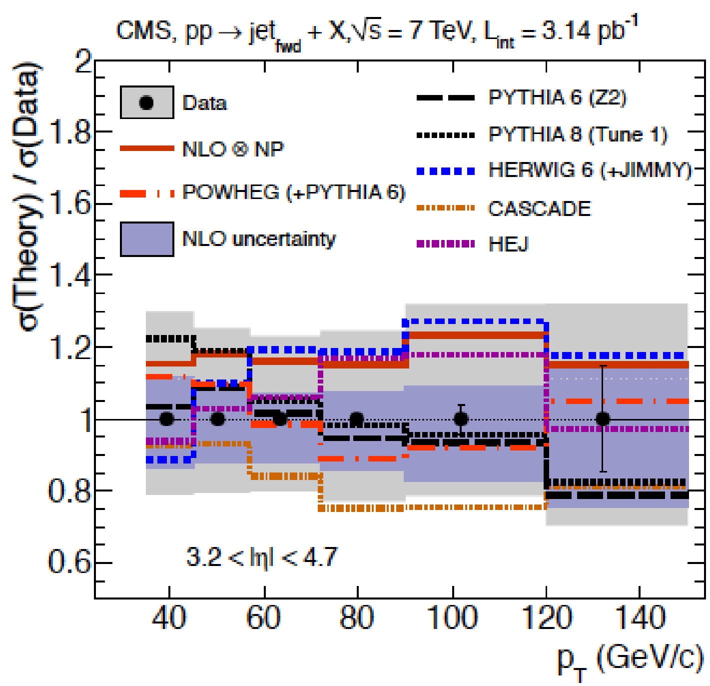
Forward Jet Measurement

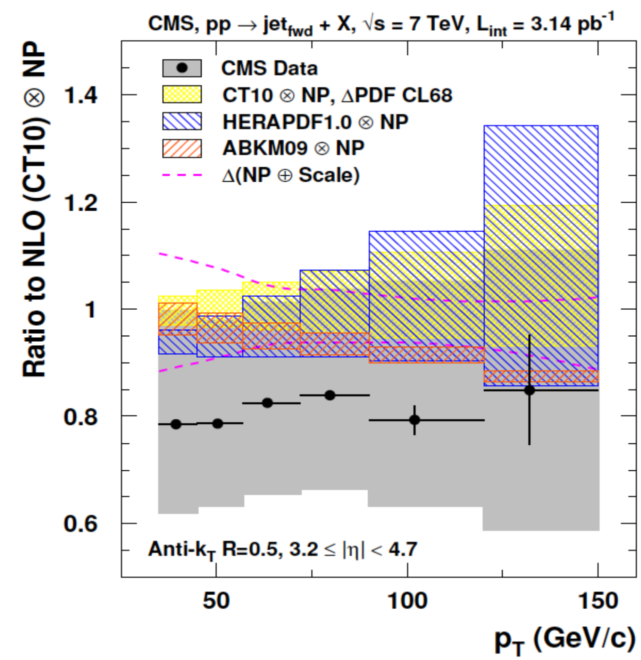
CMS-FWD-11-002, arXiv:1202.0704

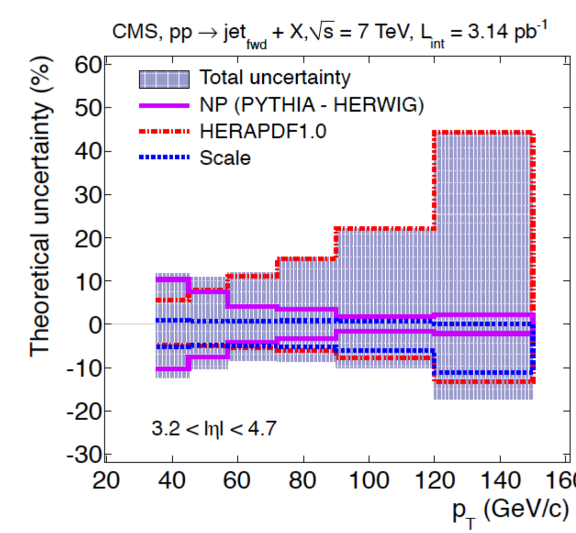
Selection: Events with at least one jet with

- $3.5<|\eta|<4.7$
- $p_{t,jet}>35$ GeV









- **All predictions describe the data within the uncertainties.**
- **NLO prediction (NLOJET++) too high, but agrees with the data within the large theoretical and experimental uncertainties.**
- **Fairly large uncertainty on the NLO calculations:**

High $p_{t,jet}$: dominated by the PDF uncertainty

Low $p_{t,jet}$: dominated by model dependence of the non-pertubative corrections