SUBJET STRUCTURE IN p-p COLLISIONS AT LHC ENERGIES

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Master Of Philosophy

CENTRE OF ADVANCED STUDY IN PHYSICS

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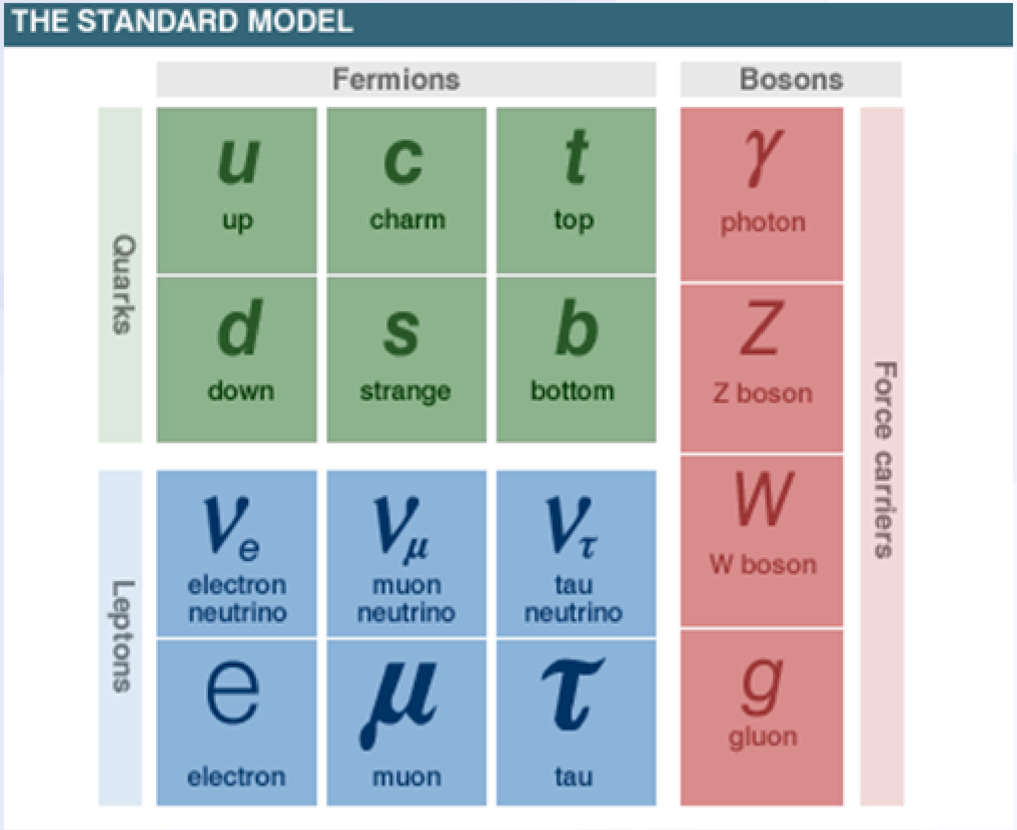
Outline

- The Standard Model
- Quantum Chromodynamics (QCD)
- Jets and Jet algorithms
- Subjets
- Simulations and Tools
- Motivation
- Determination of C_A/C_F ratio
- Data Sample and Selection cuts
- Results
- Conclusions

The Standard Model

- Model to describe the fundamental particles and their interactions.
- Fundamental particles :
  - Quarks (q)
  - Leptons
  - Mediators
- Three Generations.

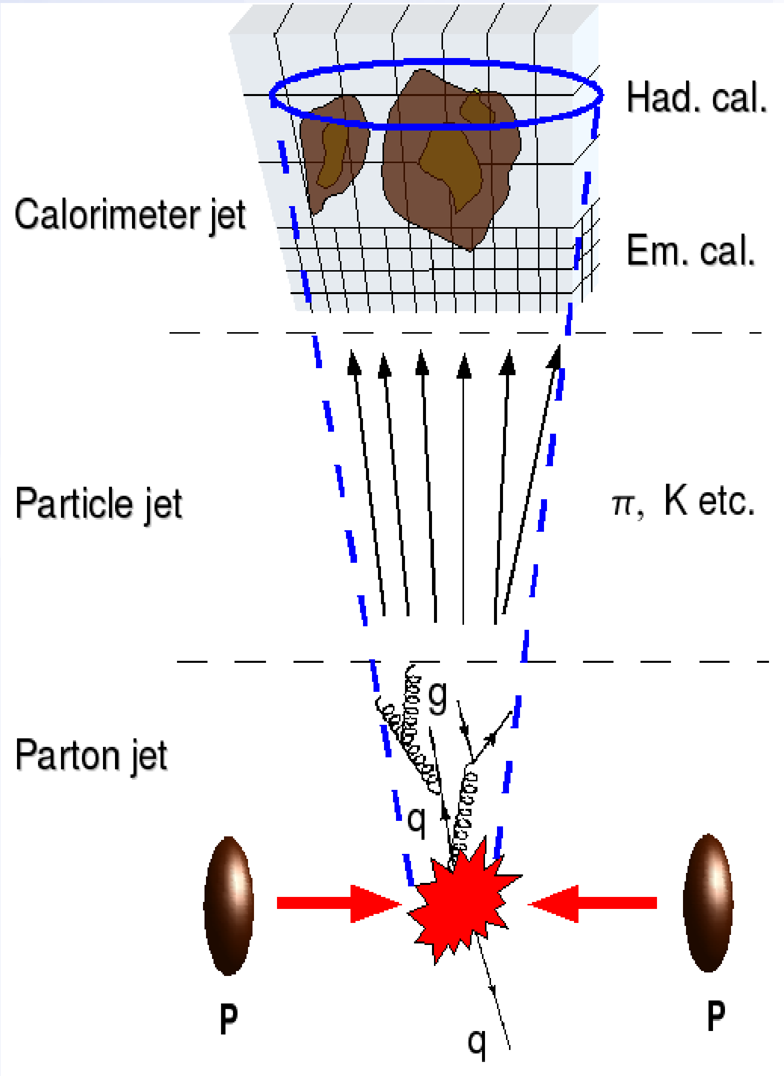


Quantum Chromodynamics (QCD)

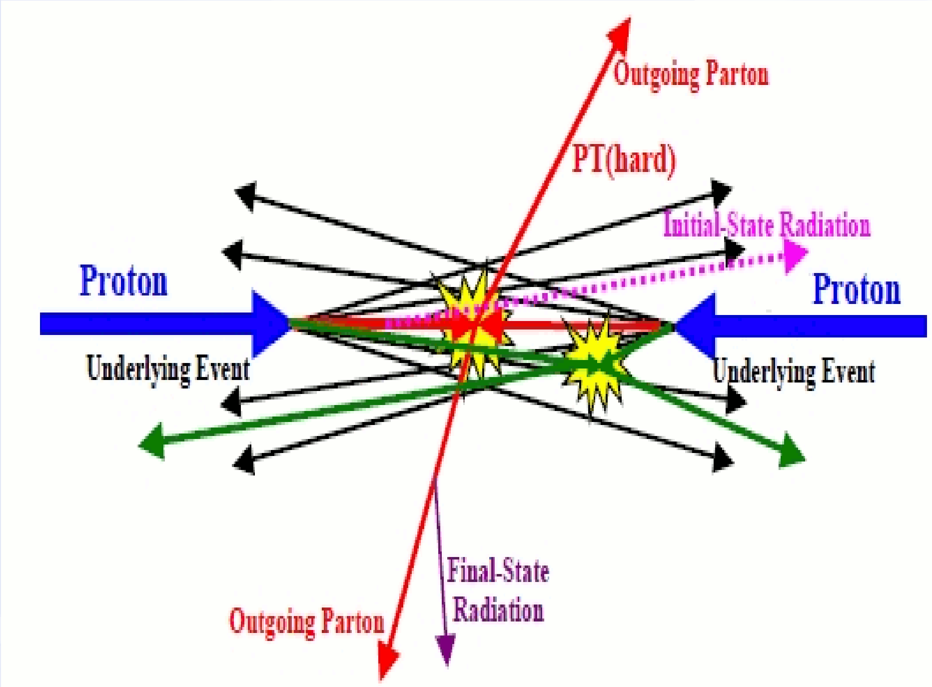
- QCD : a theory to describe the strong interactions between the quarks.
- Exchange of gluons.
- Color charge.
  - Quarks and gluons : colored.
  - Hadrons – baryons (qqq) and mesons ($q\bar{q}$) : colorless.
- Properties :
  - Confinement – at low energies.
  - Asymptotic freedom – at high energies.

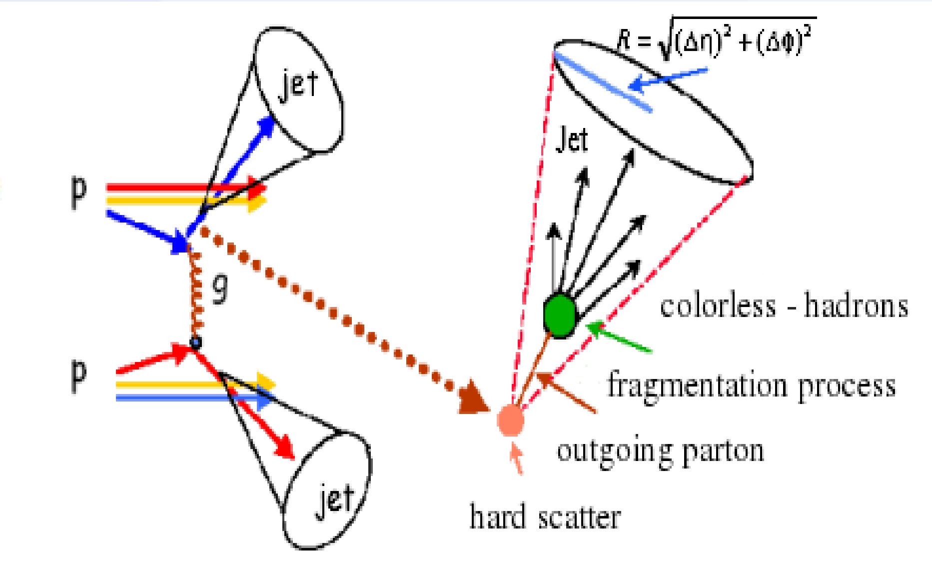
Jets

- Initial p-p collision produces outgoing partons (q and g).
- Fragmentation, decay and hadronization produces charged particles in the form of collimated bunches of stable hadrons.
- Resulting electrons, photons and hadrons deposit energy in the calorimeter.
- Jets are the observable objects to relate experimental observations to theory predictions formulated in terms of partons.
- The kinematic properties of the jet (p_T,η,Φ) can be associated to the kinematic properties of original partons produced from hard scattering process.



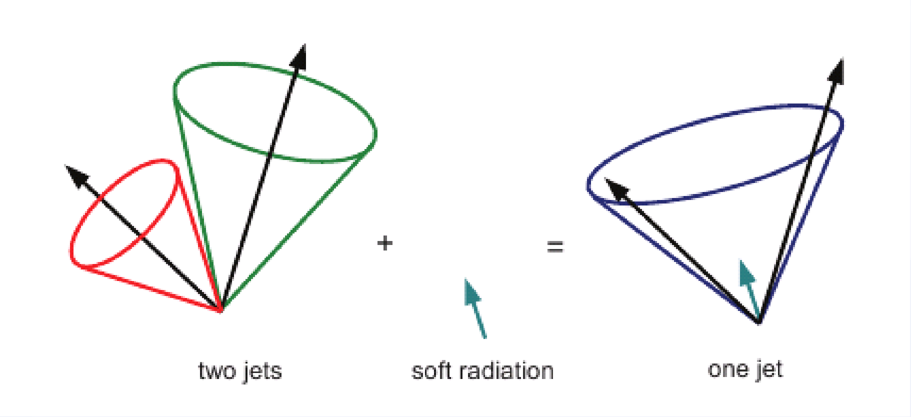
- Initial state radiation (ISR) : incoming parton emits a gluon : extra jets, $P_T \neq 0$.
- Final state radiation (FSR) : outgoing parton emits a gluon : extra jets.
- Remnants of protons interact producing low E_T particles (UE).
- Collisions between more than one p-p pair : Multiple interactions.
- Collisions between more than one parton within each incoming proton : double parton interactions.
- 2->2 scattering: Two partons are produced from the collision of a parton in each of the incoming hadrons.
- Each outgoing parton forms one jet.



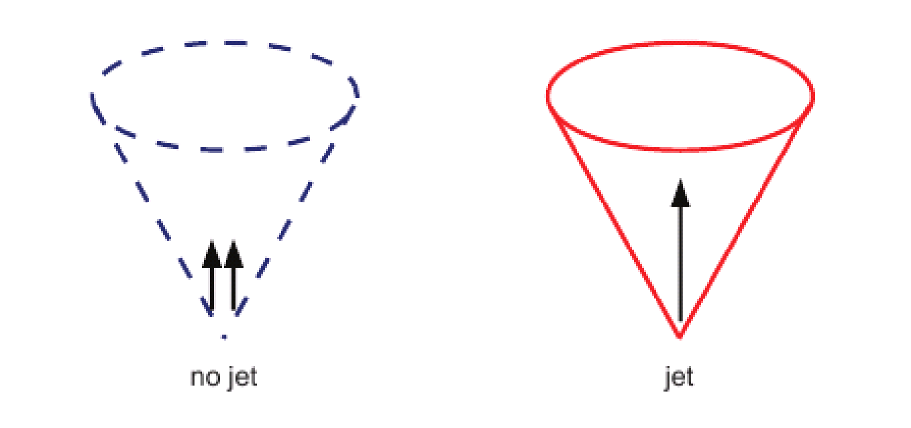


Jet Algorithms

- A jet algorithm defines how signals in the detector (experimental) or partons (theory) are grouped into jets.
- A "good" jet algorithm requires :
  - Finite perturbative results in theoretical calculations.
  - Equivalent at parton, particle, detector levels.
  - Detector-independent.
  - Uses minimum computer resources.
  - Easily calibrated.



- Infrared safety : addition of a infinitely soft gluon should not change the number of jets.
- Collinear safety : replacing any parton with a collinear pair of partons should not change the number of jets.



Two main types of jet algorithms :

- Cone algorithms
  - Rely on the spatial separation of the particles .
  - Infrared and collinear unsafe.
- Sequential algorithms
  - Focus on the closeness in momentum space.
  - Infrared and collinear safe.
  - k_T
  - Cambridge/Aachen
  - Anti-k_T

Subjets

- Provides an insight into the transition between partons produced in the hard scattering process and the experimentally observable jets of hadrons.
- The subjets in a particular jet are defined by re-running the jet algorithm only on the particles assigned to a jet .
- The anti-k_T algorithm is less sensitive to details of the distribution of softer objects in an event (or within jets).
- With k_T algorithm, the clustering of the particles in a jet is terminated when all d_{ij} , d_{iB} are above the quantity d_{cut} given by $d_{cut} = y_{cut} p_T^2(\text{jet})$.
- In Cambridge/Aachen algorithm, after clustering with some given value of R, the constituents of a particular jet can be clustered into subjets by re-running the algorithm at a smaller radius, Reff = √(dcut) R.
- The number of subjets in a jet is the subjet multiplicity M.

Simulations and Tools

Monte Carlo Simulation : A computerized mathematical technique based on the use of random numbers and probability statistics to investigate problems.

- A powerful tool which makes a direct comparison between theory and the experiment.
- Monte Carlo programs such as HERWIG, PYTHIA are used today to reproduce all aspects of the events.
- All based on LO matrix elements + Leading Log Approximation.
- Include the effects of Initial and Final State radiation.
- Output of these programs is a list of particles (mostly hadrons) which can be fed into a detector simulation.

PYTHIA : The most widely used program to generate the high-energy physics.

- Previous versions PYTHIA6 were written in Fortran, PYTHIA8 represents a complete rewrite in C++. For this work, PYTHIA8 (version 8160).

FASTJET : a software C++ package which provides a broad range of jet finding and analysis tools in p-p and e+e- collisions, fast implementations of many sequential recombination and currently used cone algorithms.

- Also provides a uniform interface to external jet finders via a plug mechanism, tools for determining jet areas, to facilitate the manipulation of jet substructure, estimation of pileup and underlying-event noise levels etc.
- FastJet with version 3.0.3 was used.

ROOT : a set of Object-Oriented C++ frameworks created by Rene Brun and Fons Rademakers in CERN after the successful projects such as PAW (the Fortan based progarm).

- It consists of a huge C++ library provided with all the functionalities to handle and analyse large amounts of data. It includes histrogramming methods in 1,2 and 3 dimensions, curve fitting etc.

Motivation

- We present the Monte Carlo results on the jet substructure by defining an observable called subjet multiplicity.
- It is useful to discriminate between quark and gluon jets.
- The color factor ratio $C_A/C_F = 2.25$, with color factors[1] $C_A = 3$, $C_F = 4/3$, indicates that a gluon radiates more than a quark. So the number of subjets within a gluon jet are more than that in quark jet.
- In the present work, we have used subjet multiplicity to compare gluon jets to quark jets by ratio $r = \langle M_g \rangle - 1 / \langle M_q \rangle - 1$, where $\langle M_g \rangle$ and $\langle M_q \rangle$ are the average subjet multiplicities in gluon and quark jets respectively.
- The value of $r = 1$ implies that there is no difference between gluons and quarks whereas the value other than 1 expresses the differences between them.
- The similar samples of jets are compared at $\sqrt{s} = 7$ TeV and 10 TeV. At LHC, the study of p-p collisions at 7 TeV is possible and to study the collisions at 10 TeV will be possible after the shutdown in 2013.

[1] R.K. Ellis, W.J. Stirling *et al., "QCD and Collider Physics", Cambridge University Press (1996)*

Determination of C_A/C_F ratio

- M is the subjet multiplicity in a mixed sample of quark and gluon jets.

$$M = fM_g + (1 - f)M_q$$

- At $\sqrt{s}$ = 7 TeV and 10 TeV

$$M^7 = f^7 M_g + (1 - f^7)M_q$$

$$M^{10} = f^{10} M_g + (1 - f^{10})M_q$$

- The solutions (assuming sub-jet multiplicity independent of $\sqrt{s}$) are :

$$M_q = (f^{10}M^7 - f^7 M^{10})/(f^{10} - f^7) \qquad (1)$$

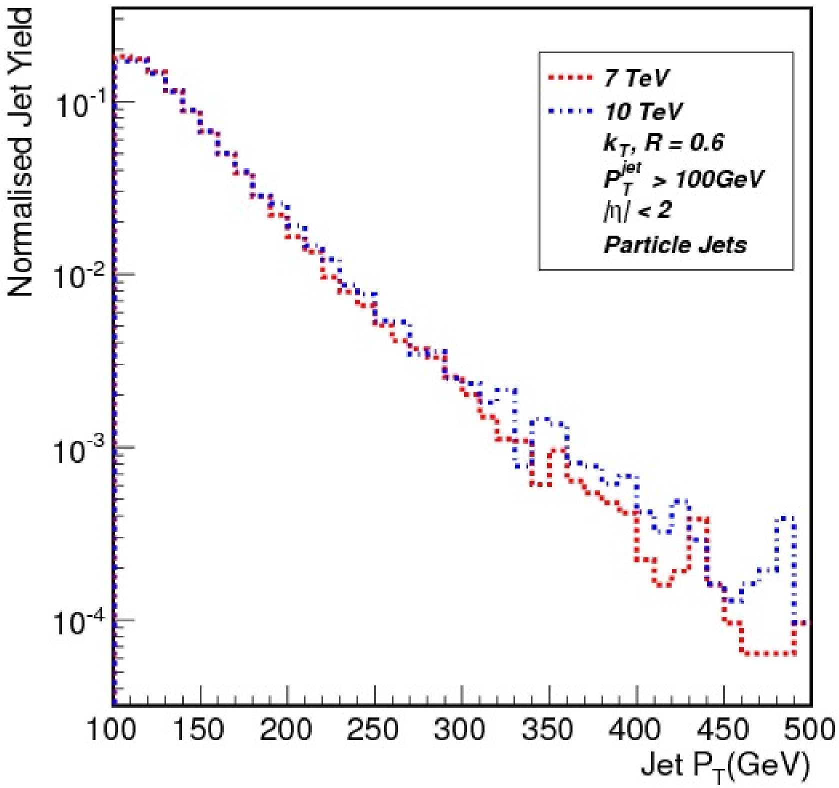
$$M_g = ((1 - f^7)M^{10} - (1 - f^{10})M^7)/(f^{10} - f^7) \qquad (2)$$

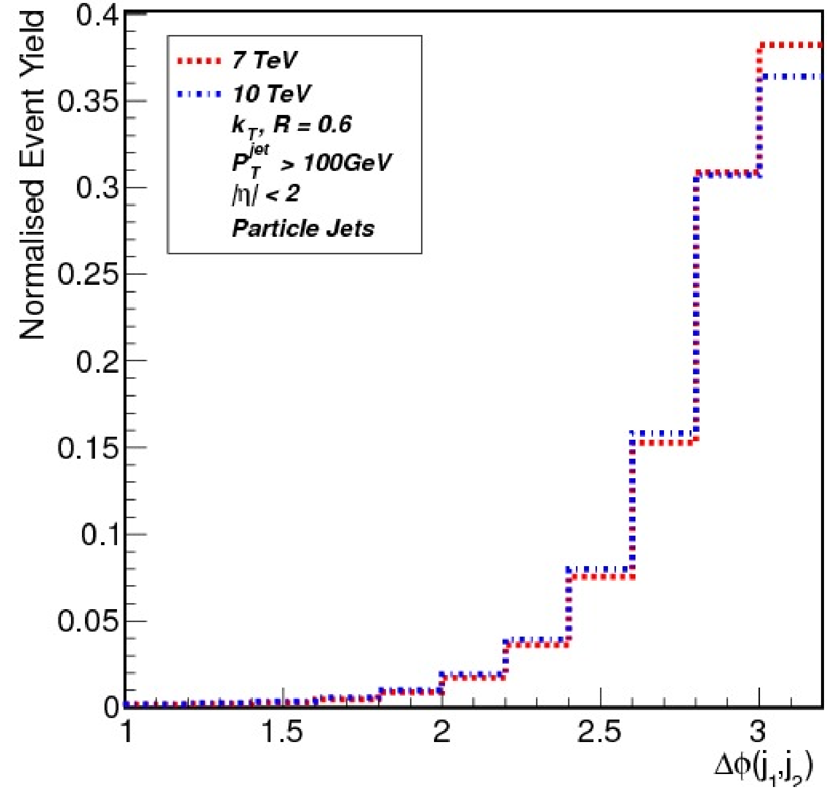
- The gluon jets are compared to the quark jets by having a ratio

$$r = < M_g > - 1 / < M_q > - 1$$

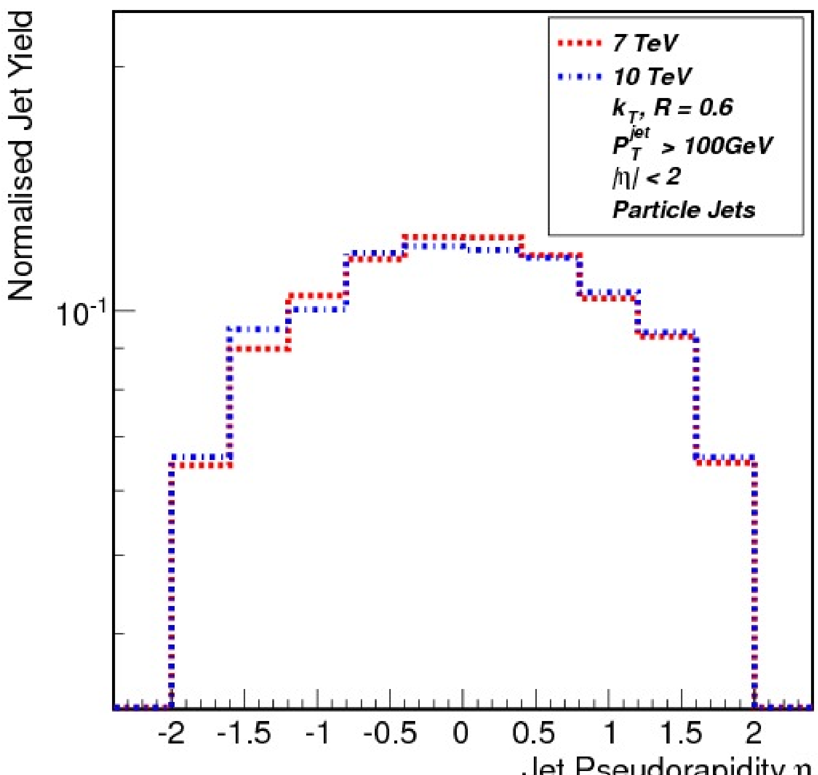
Data Sample and Selection Cuts

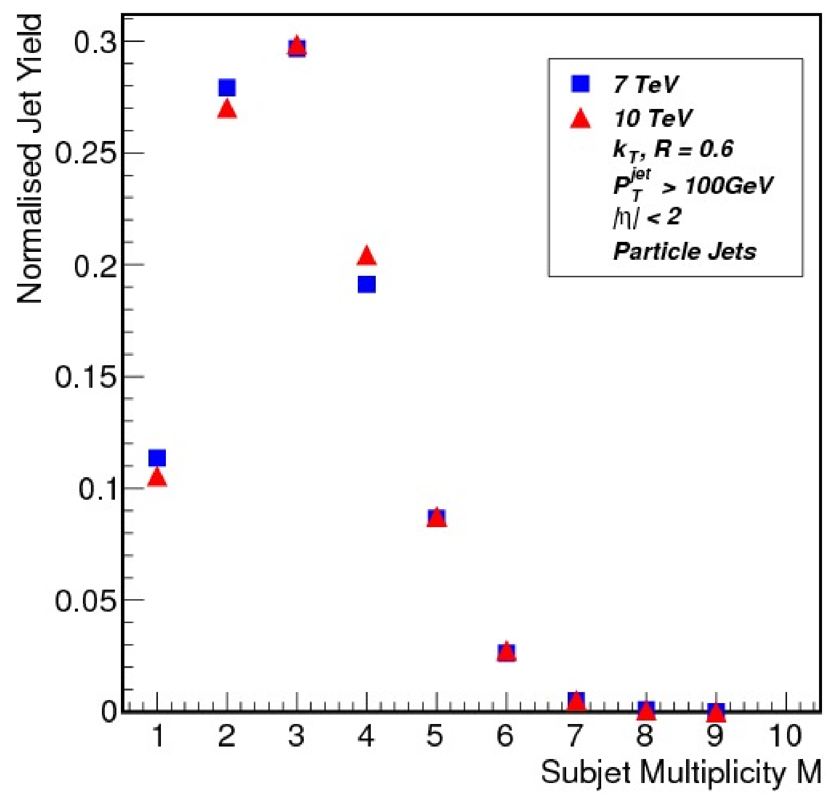
- Using PYTHIA8, 1 million events are generated at $\sqrt{s}$ = 7 TeV and 1 million events at $\sqrt{s}$ = 10 TeV in the pseudorapidity range $|\eta| < 2$.
- 1 million events are also generated in each separate bins of jet pseudorapidity $|\eta|$ which are 0.0 – 0.5, 0.5 - 1.0 , 1.0 - 1.5, and 1.5 - 2.0 for leading jets.
- A sample of dijet events in hard QCD 2 -> 2 scattering events, is defined by selecting the two jets leading in P_T in each event with the following selection cuts:
  - $P_T > 100$ GeV
  - $|\Delta\Phi(j_1,j_2) - \Pi| < 1.0$ (requiring them to be back-to-back in the azimuthal plane)
  - $|\eta| < 2$
  - $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2} < 0.4$
- For k_T algorithm, $\langle M \rangle$ is measured for R = 0.6 and $y_{cut} = 10^{-3}$. For Cambridge algorithm, $\langle M \rangle$ is studied by resolving the subjets with Rsub = 0.5 within a jet of size R = 1.0

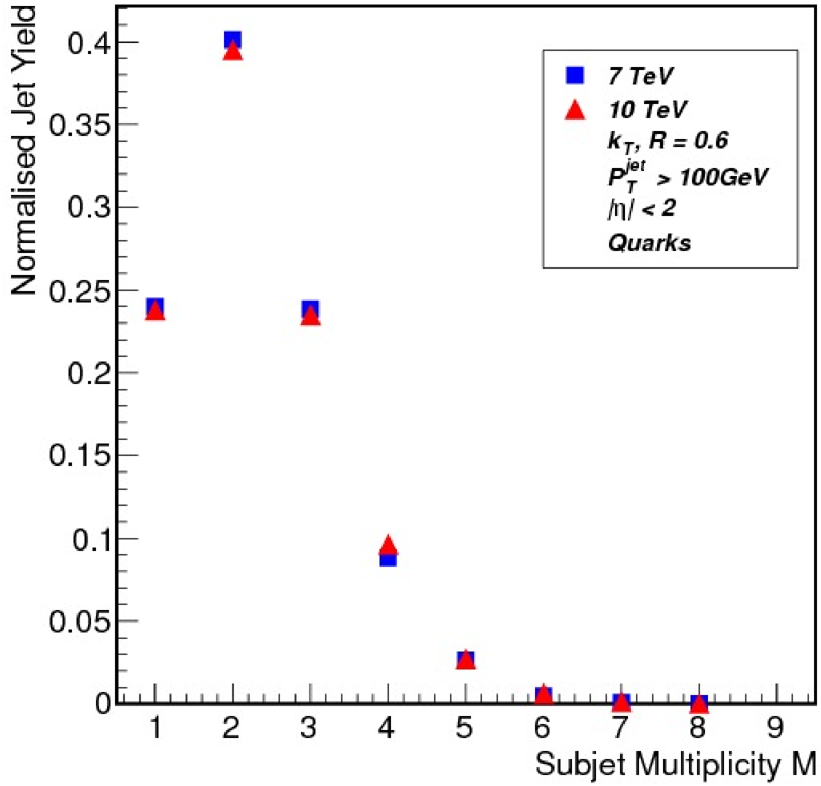

Normalised Jet Yield
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
|η| < 2
Particle Jets
Jet P_T(GeV)

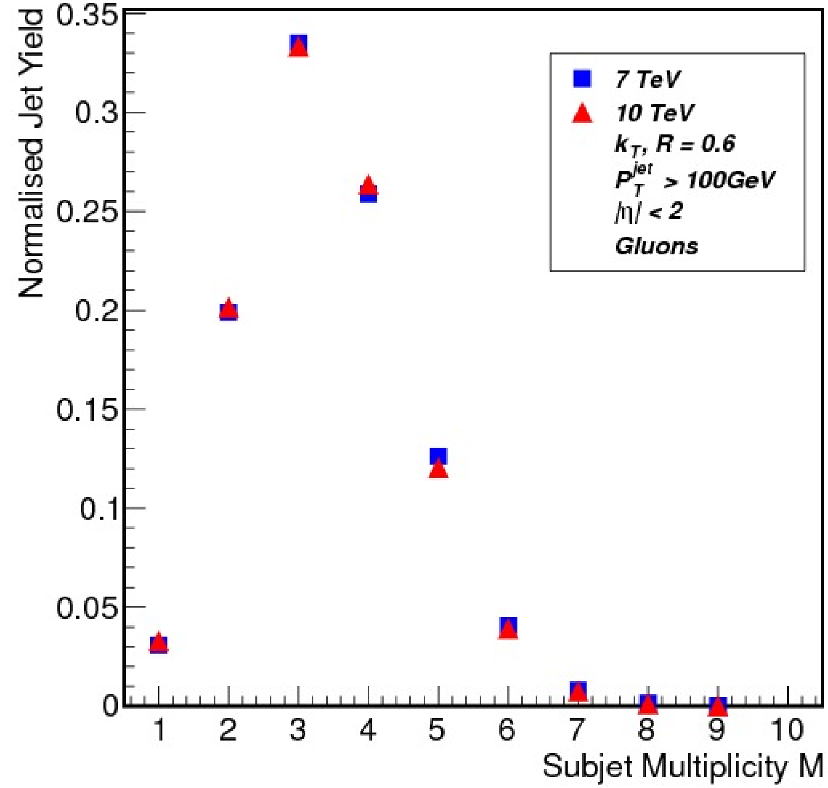

Normalised Event Yield
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
|η| < 2
Particle Jets
$\Delta\phi(j_1,j_2)$

k_T

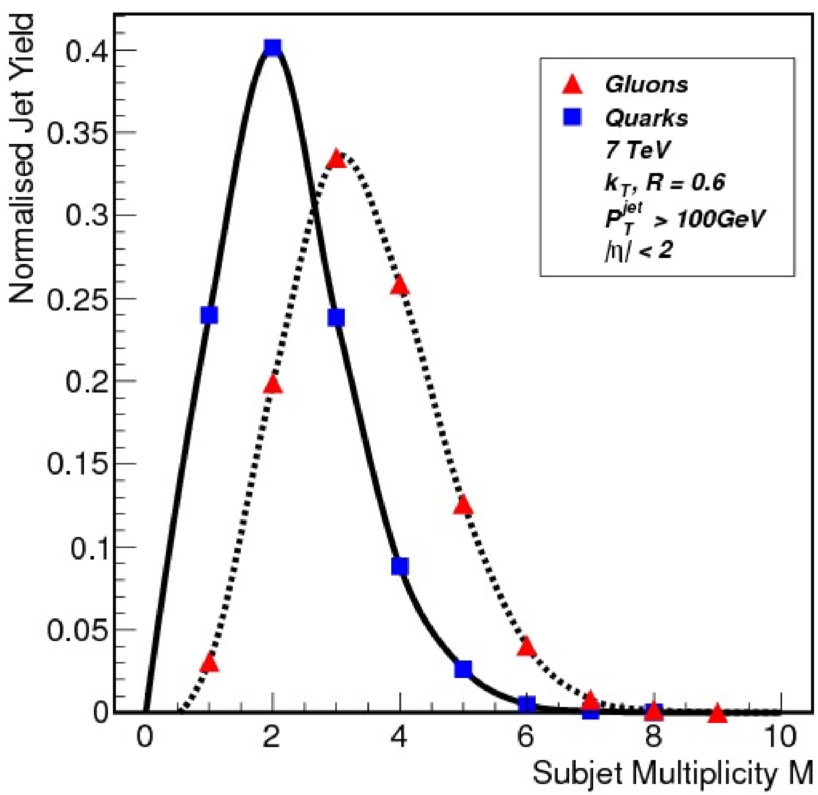

Normalised Jet Yield
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
|η| < 2
Particle Jets
Jet Pseudorapidity η


Normalised Jet Yield
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
|η| < 2
Particle Jets
Subjet Multiplicity M


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 2
Quarks


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 2
Gluons

k_T


Normalised Jet Yield
Subjet Multiplicity M
Gluons
Quarks
7 TeV
k_T, R = 0.6
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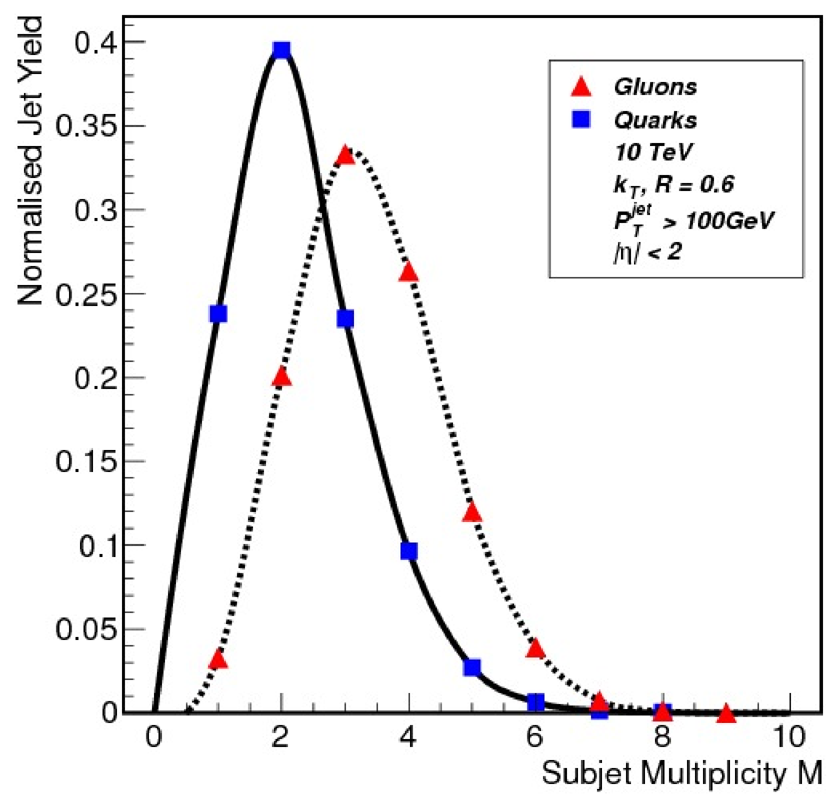
Normalised Jet Yield
Subjet Multiplicity M
Gluons
Quarks
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
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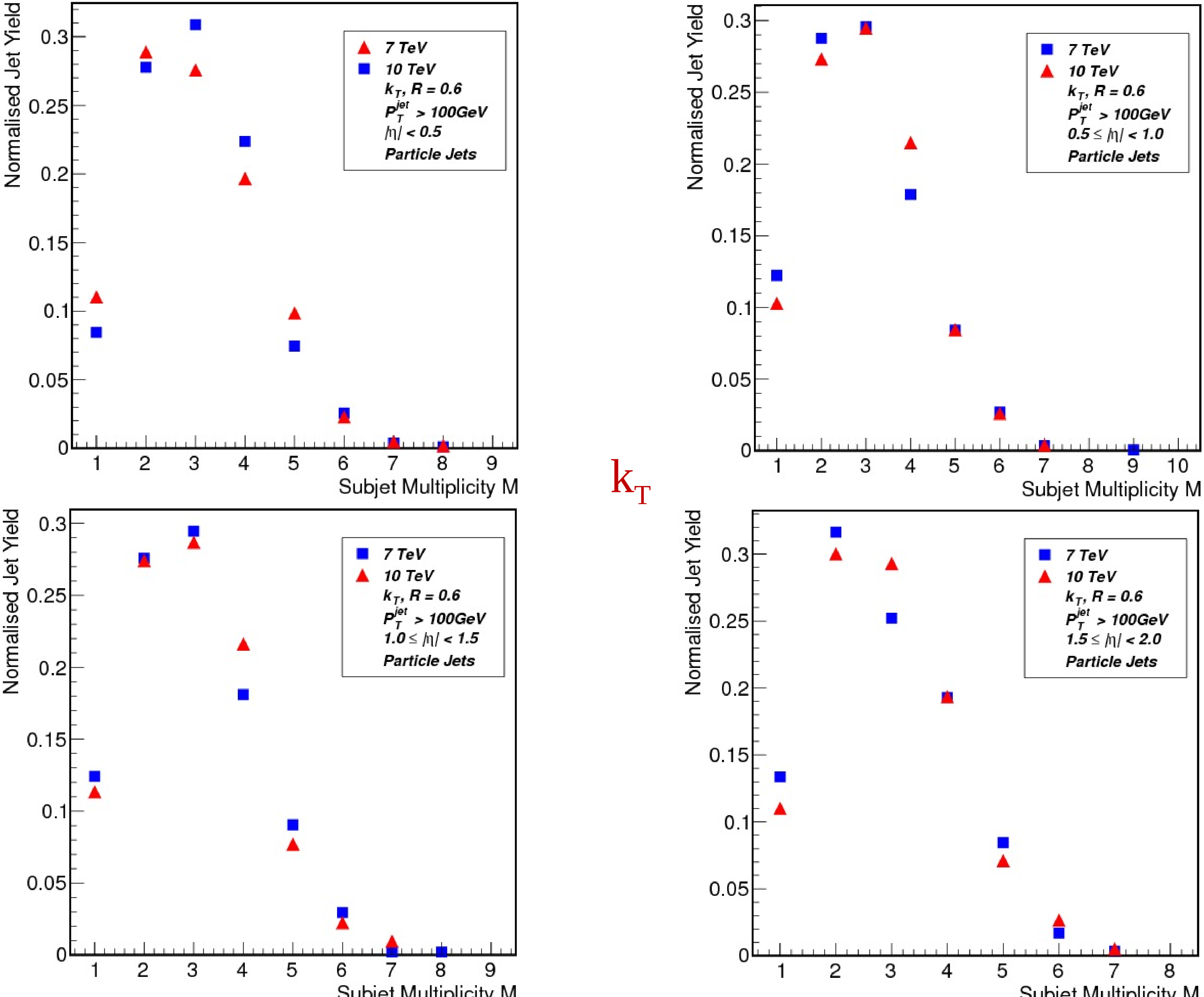
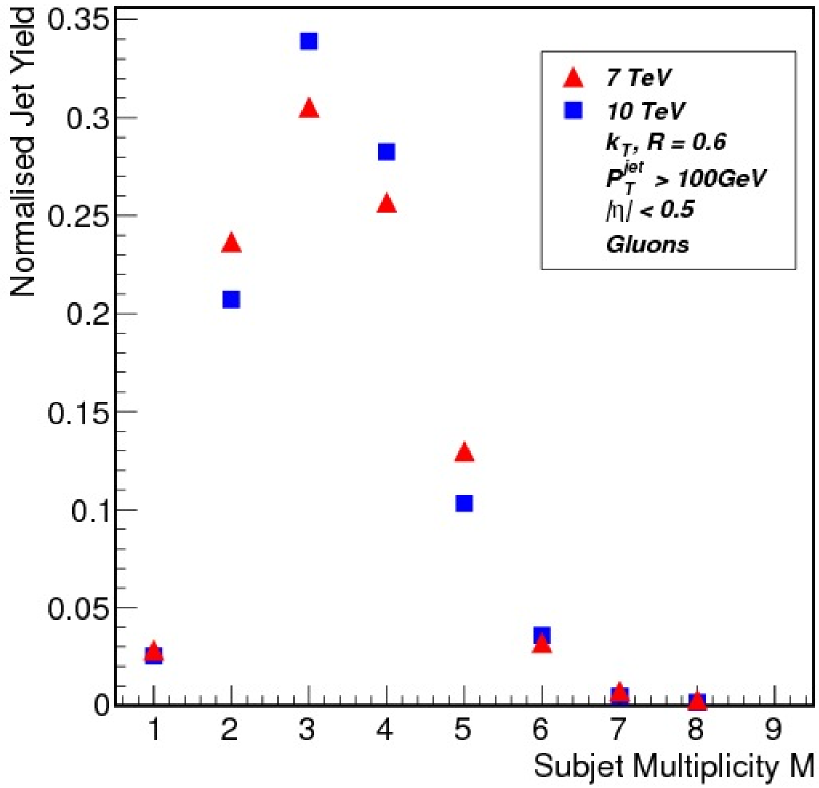

Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 0.5
$0.5 \leq |\eta| < 1.0$
$1.0 \leq |\eta| < 1.5$
$1.5 \leq |\eta| < 2.0$
Particle Jets
k_T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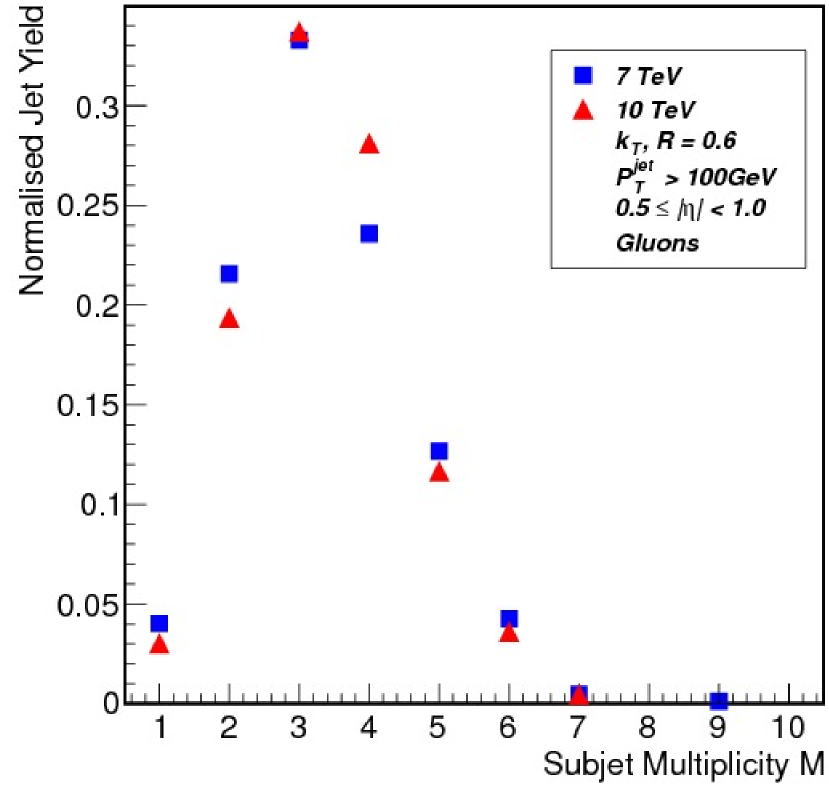
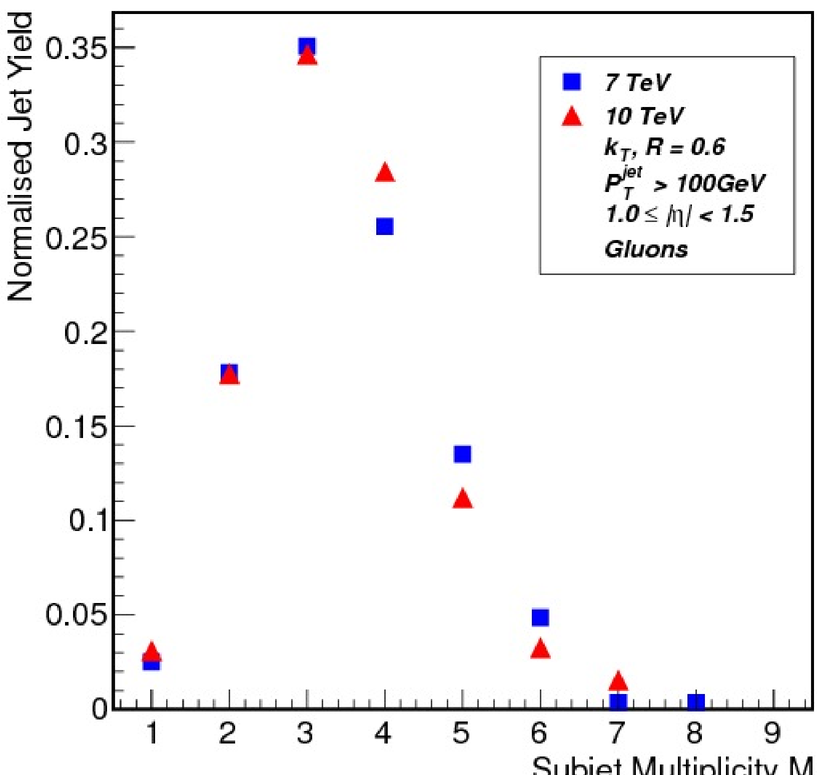
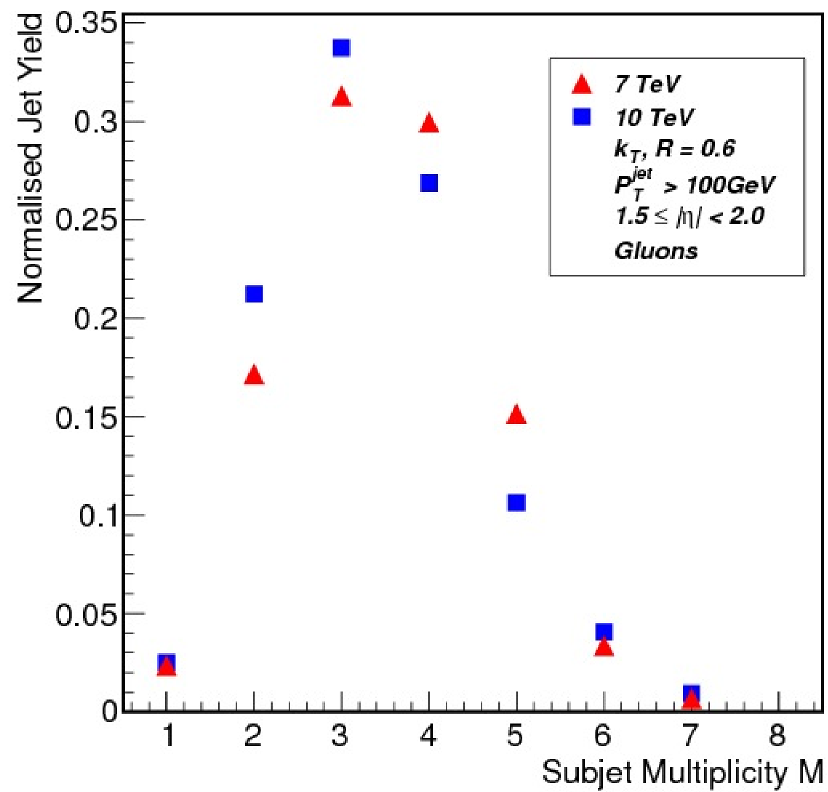
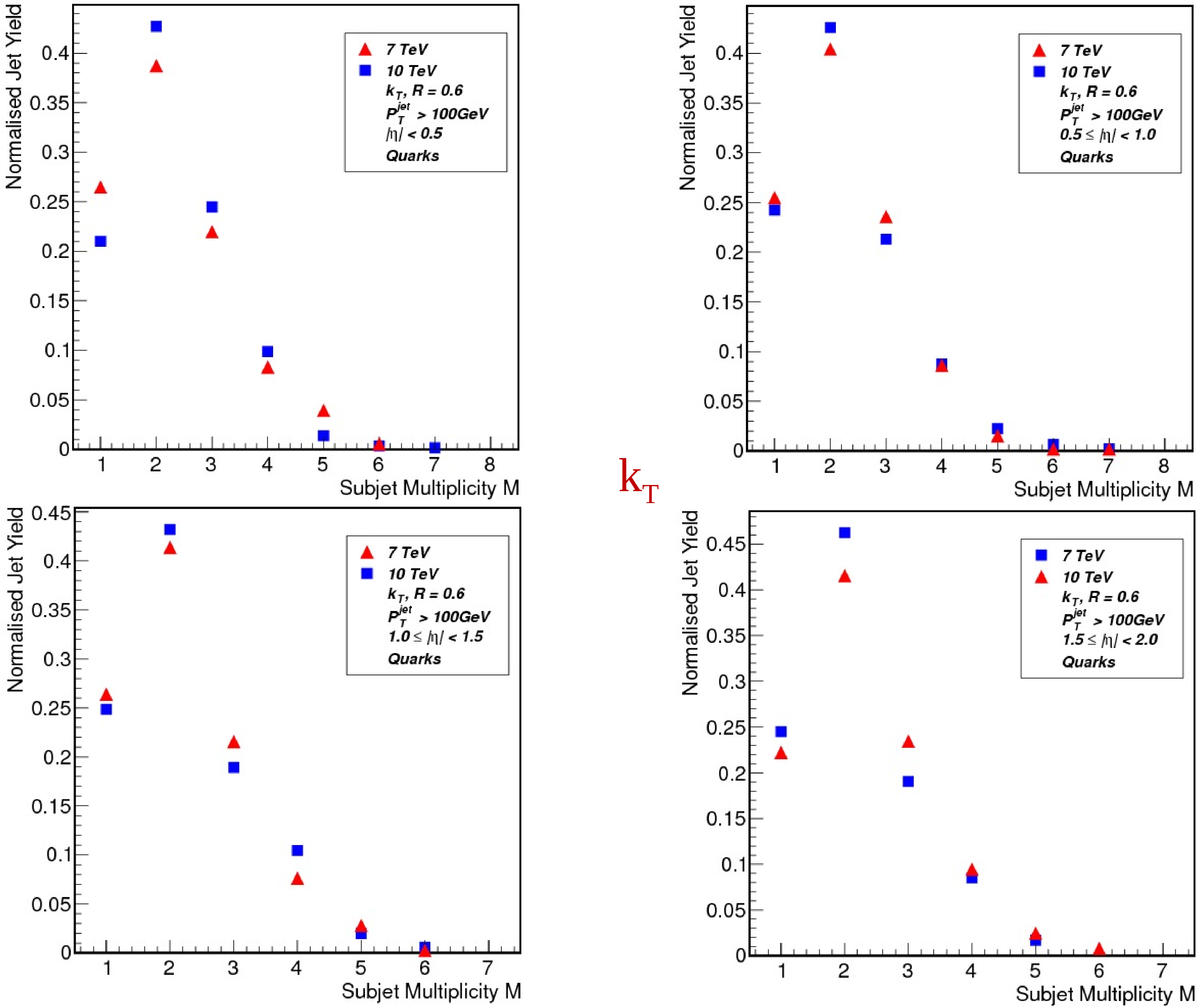
Gluons


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$0.5 \leq |\eta| < 1.0$
Gluons

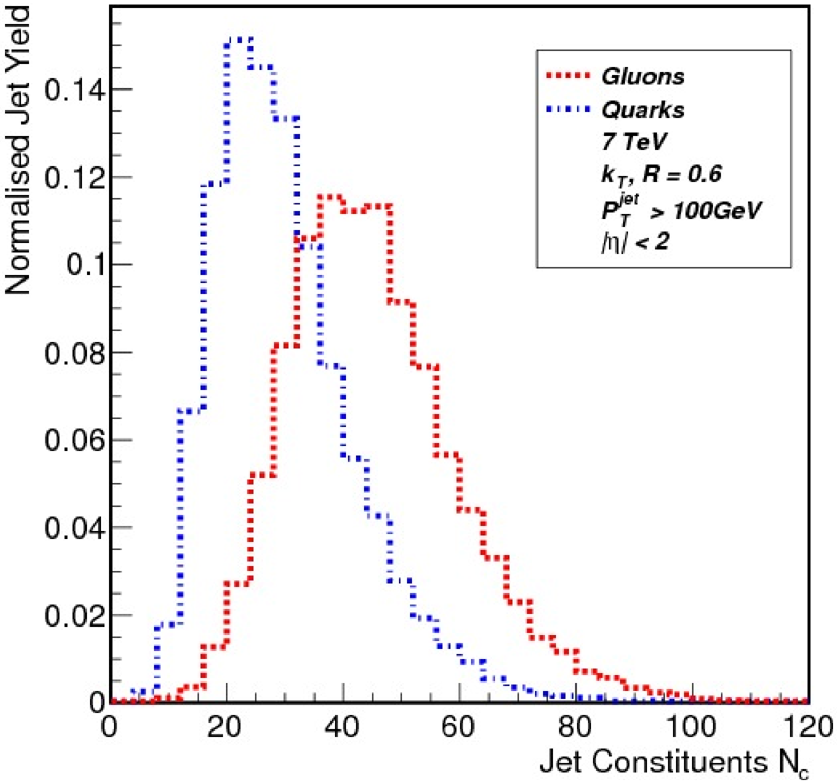
k_T


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$1.0 \leq |\eta| < 1.5$
Gluons

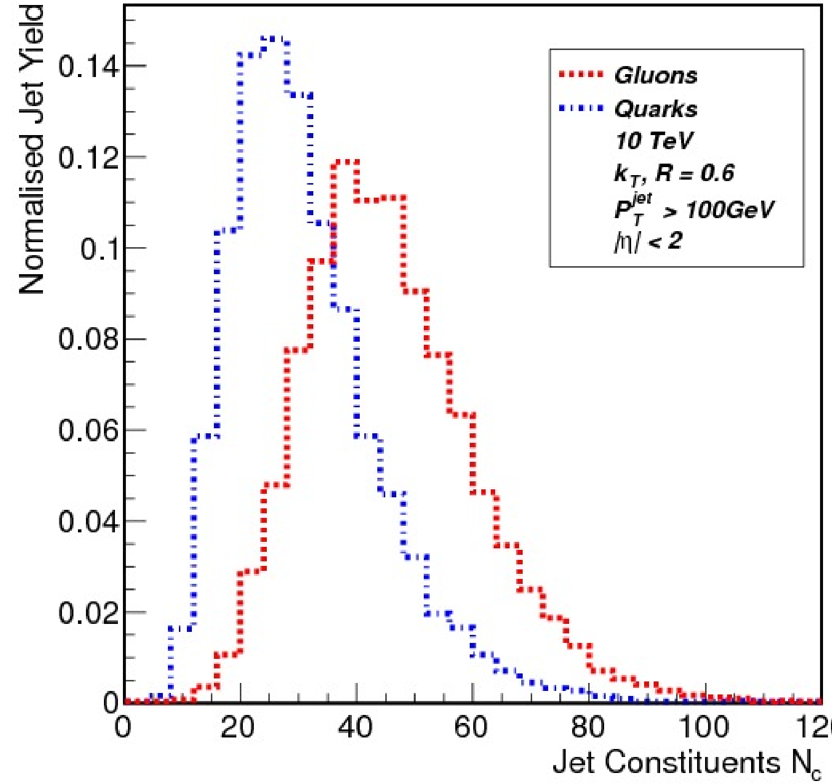

Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$1.5 \leq |\eta| < 2.0$
Gluons



Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 0.5
Quarks
$0.5 \leq |\eta| < 1.0$
$1.0 \leq |\eta| < 1.5$
$1.5 \leq |\eta| < 2.0$
k_T


Normalised Jet Yield
Jet Constituents N_c
Gluons
Quarks
7 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 2

k_T


Normalised Jet Yield
Jet Constituents N_c
Gluons
Quarks
10 TeV
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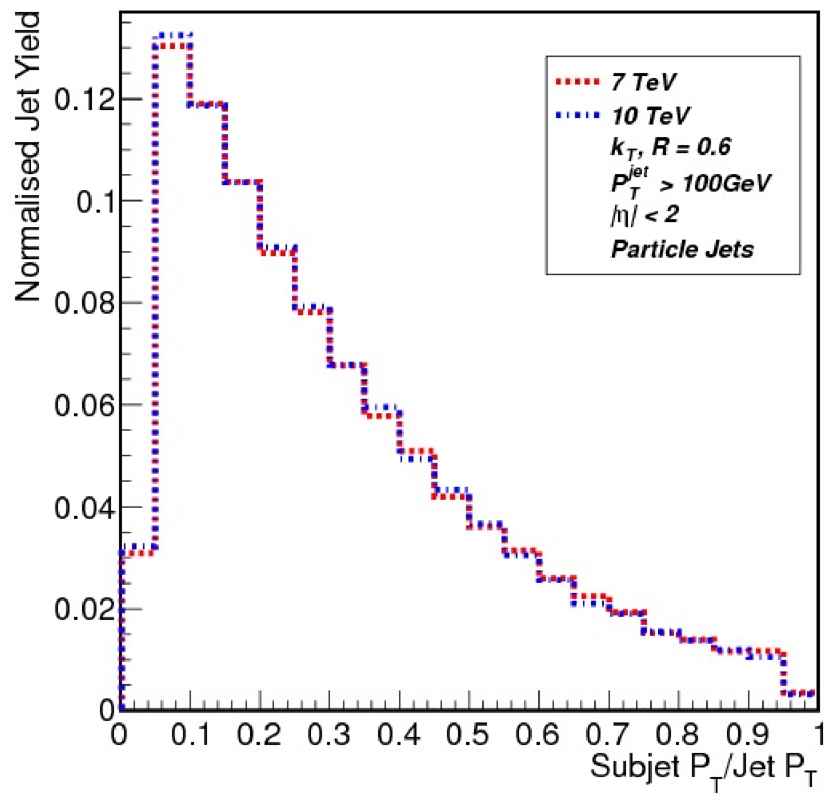
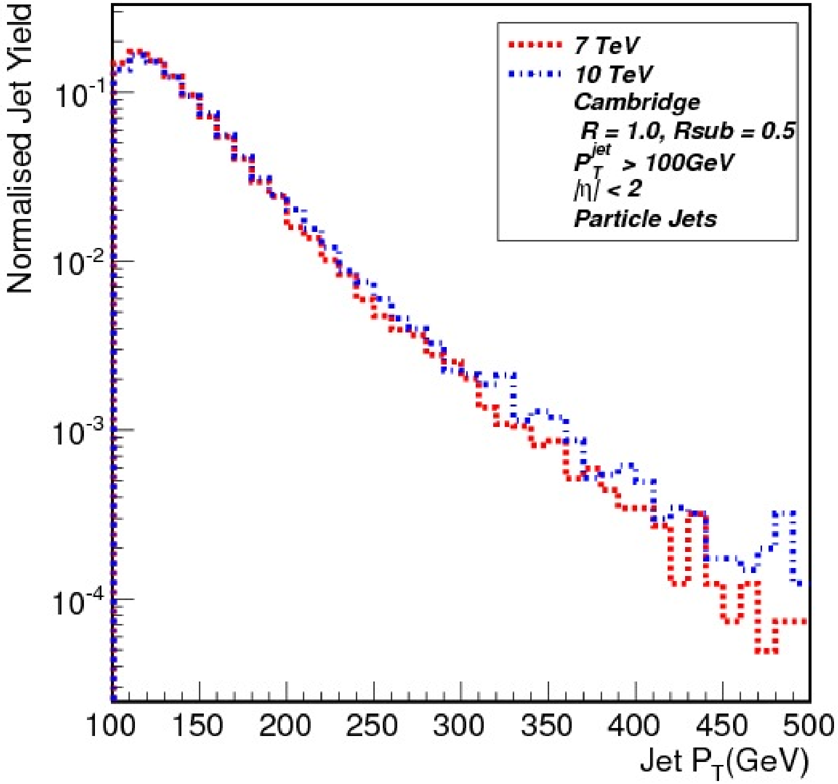
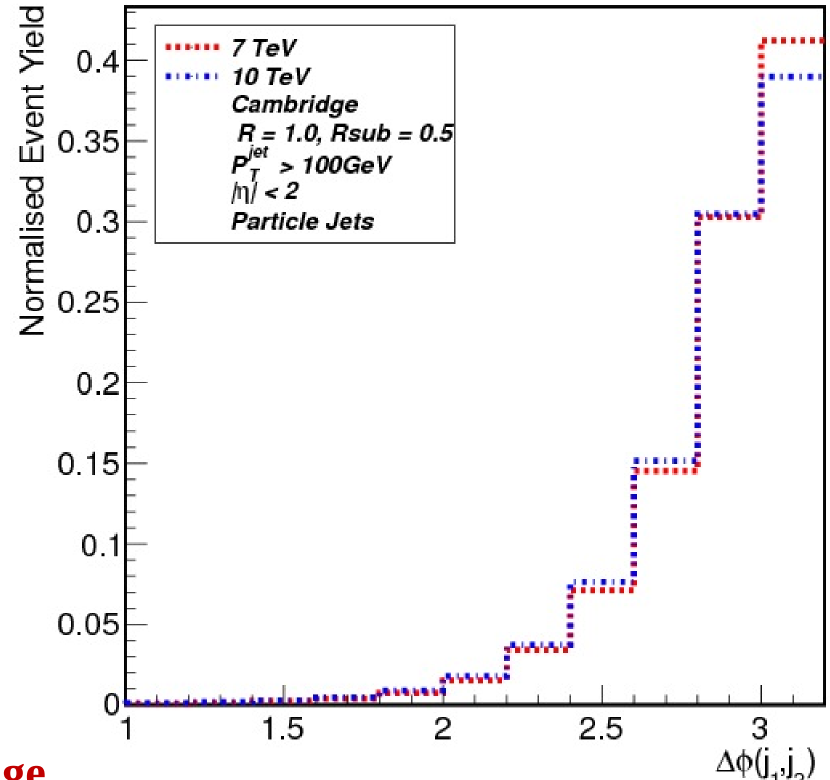

Normalised Jet Yield
Subjet P_T/Jet P_T
7 TeV
10 TeV
k_T, R = 0.6
P_T^{jet} > 100GeV
$|\eta|$ < 2
Particle Jets


Normalised Jet Yield
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$|\eta|$ < 2
Particle Jets
Jet P_T(GeV)


Normalised Event Yield
7 TeV
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P_T^{jet} > 100GeV
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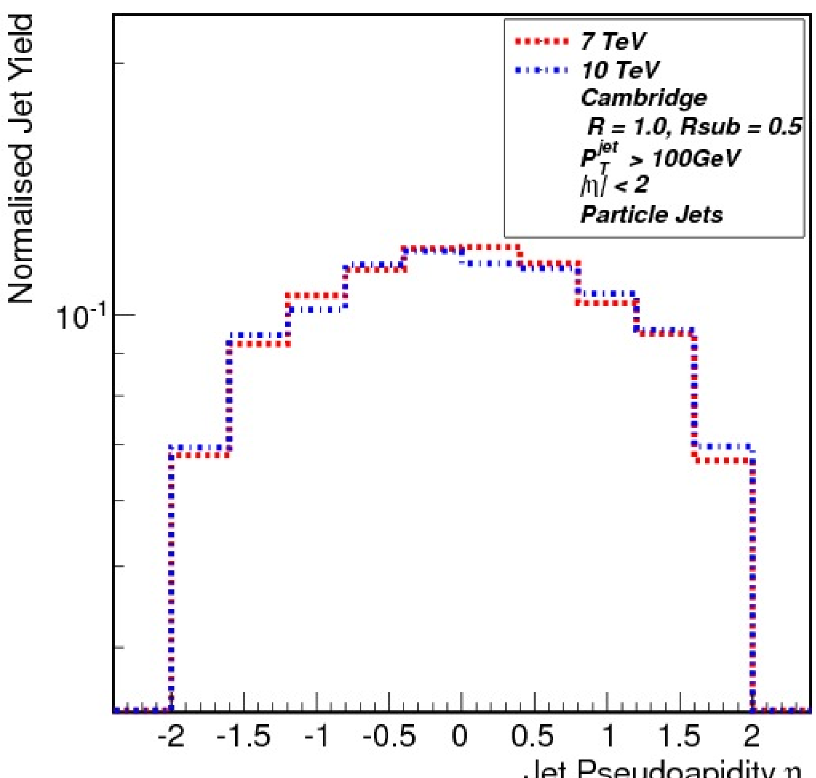
Particle Jets
$\Delta\phi(j_1,j_2)$

Cambridge


Normalised Jet Yield
7 TeV
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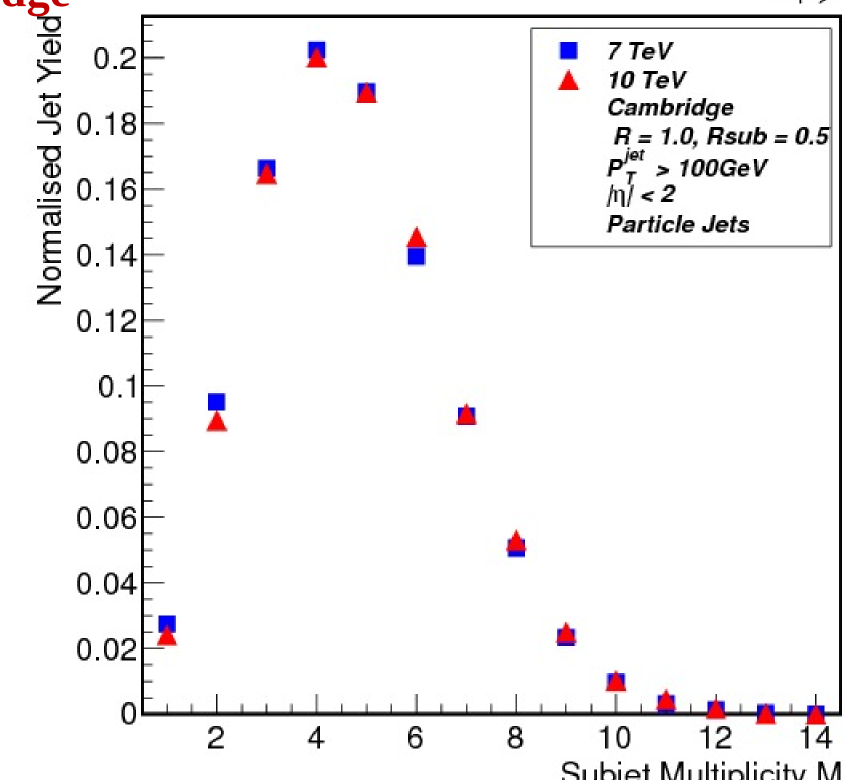
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$|\eta|$ < 2
Particle Jets
Jet Pseudoapidity η


Normalised Jet Yield
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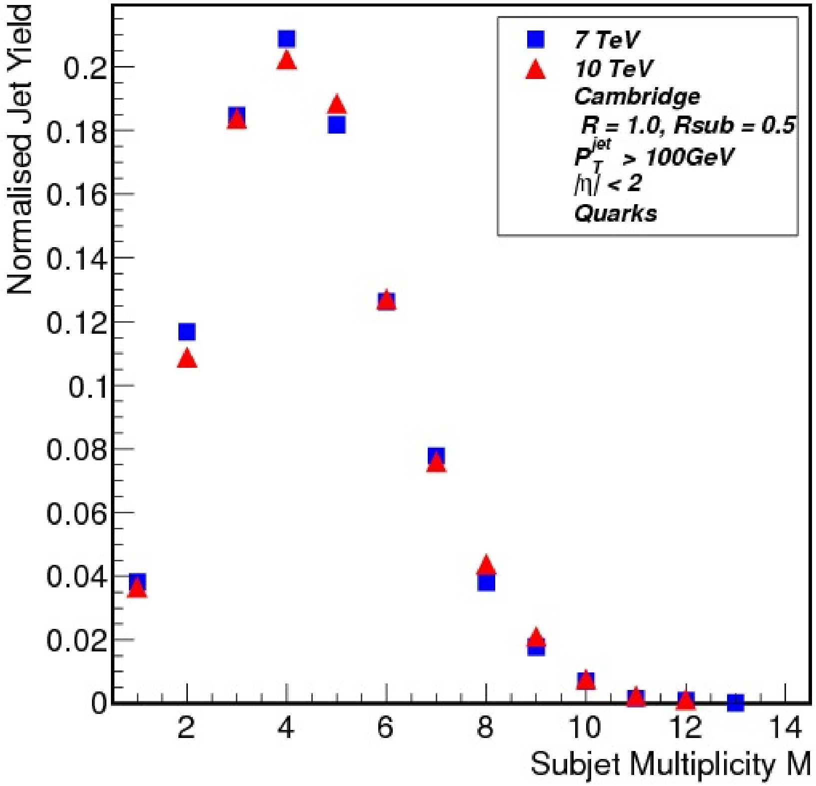
P_T^{jet} > 100GeV
$|\eta|$ < 2
Particle Jets
Subjet Multiplicity M


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
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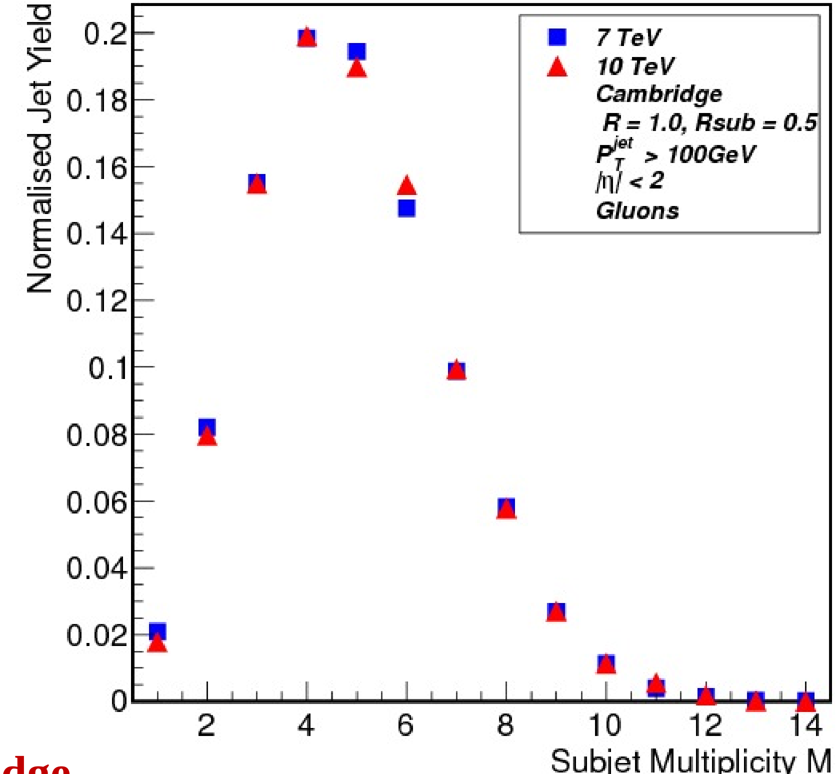
|η| < 2
Quarks


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
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R = 1.0, Rsub = 0.5
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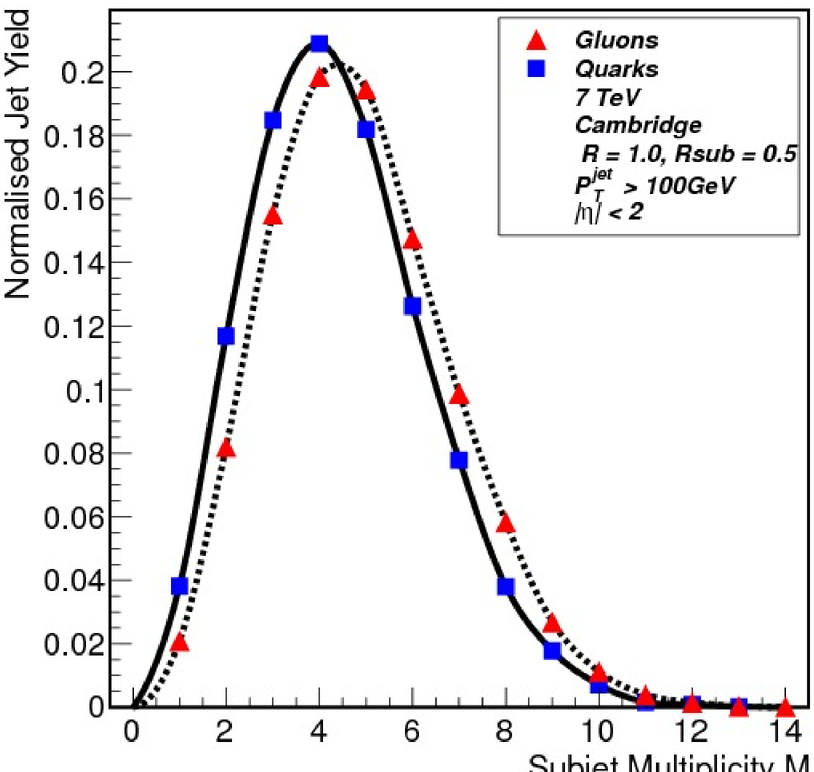
Gluons

Cambridge


Normalised Jet Yield
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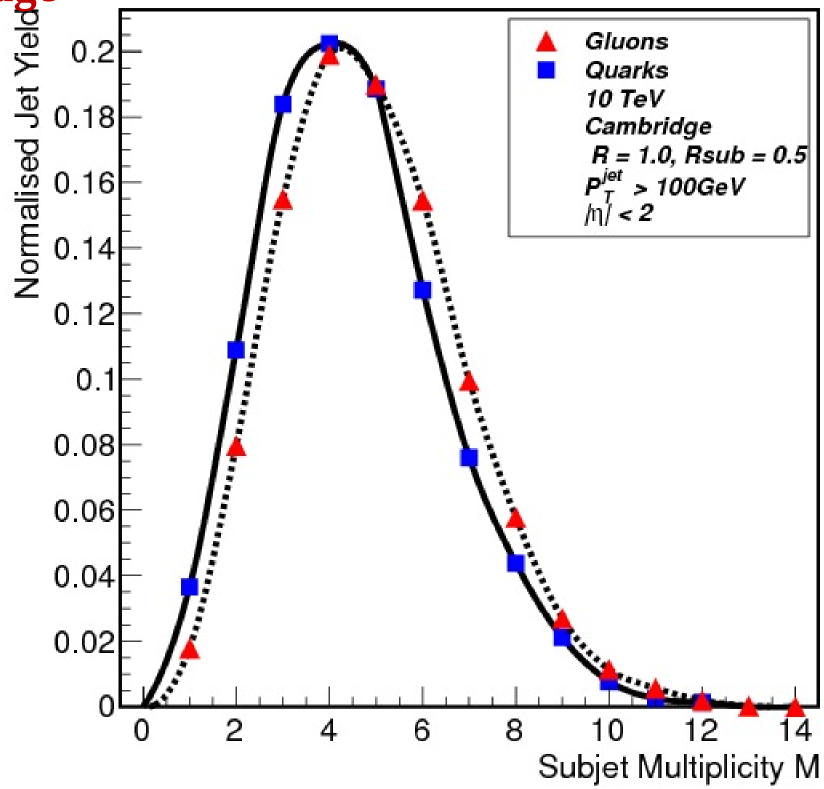
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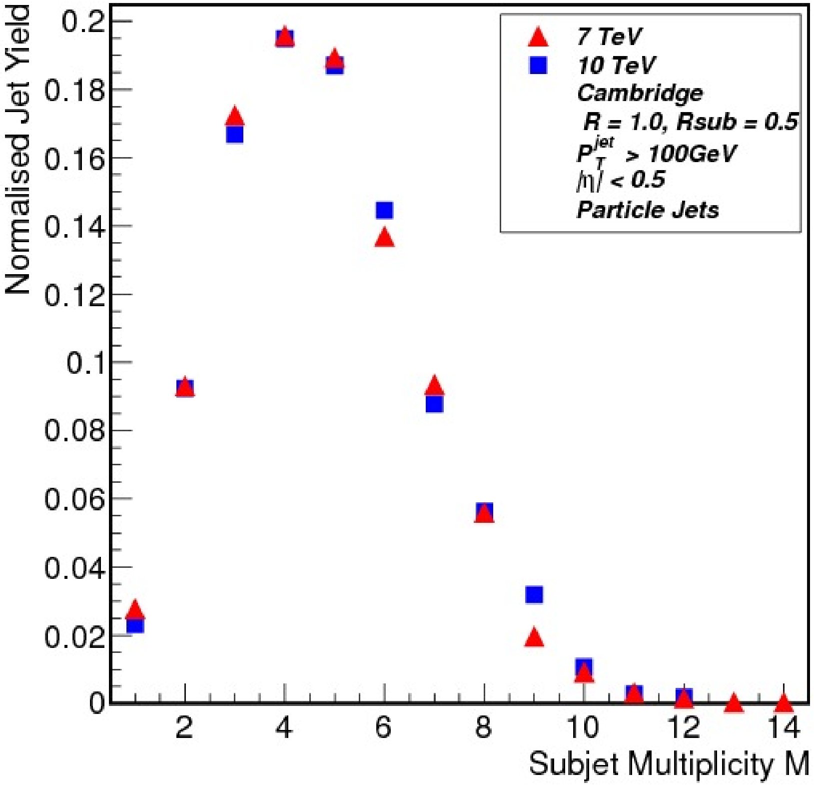
7 TeV
10 TeV
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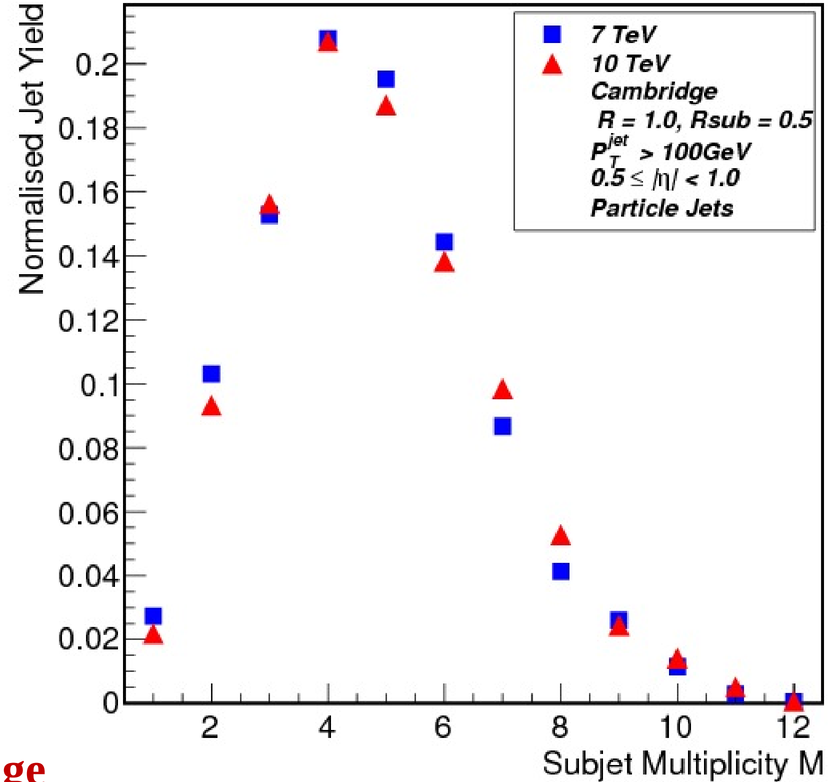
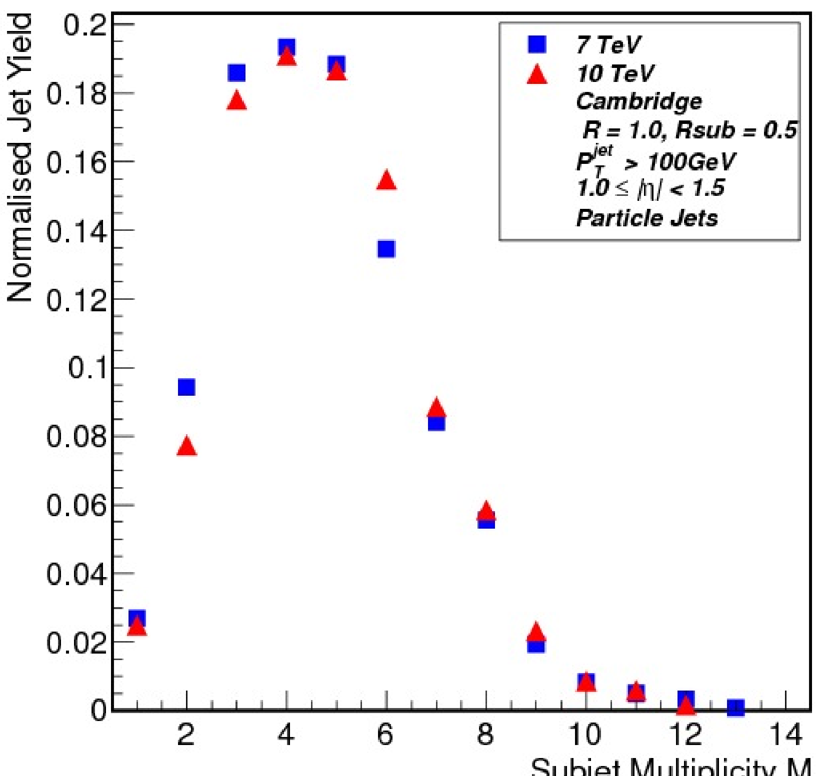
|η| < 0.5
Particle Jets
Normalised Jet Yield
Subjet Multiplicity M


7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
0.5 ≤ |η| < 1.0
Particle Jets
Normalised Jet Yield
Subjet Multiplicity M

Cambridge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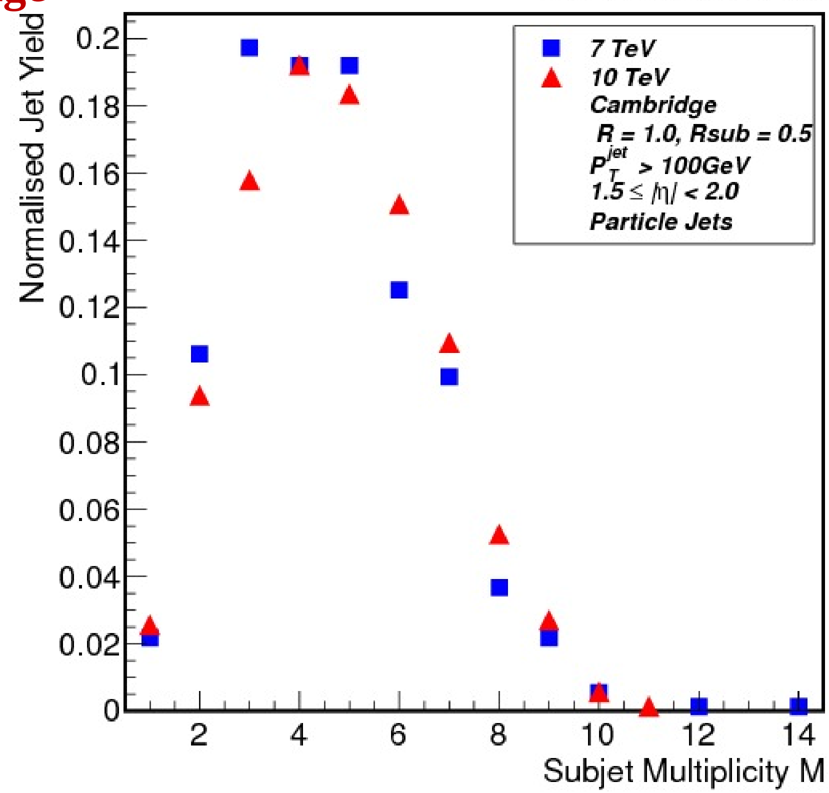
Normalised Jet Yield
Subjet Multiplicity M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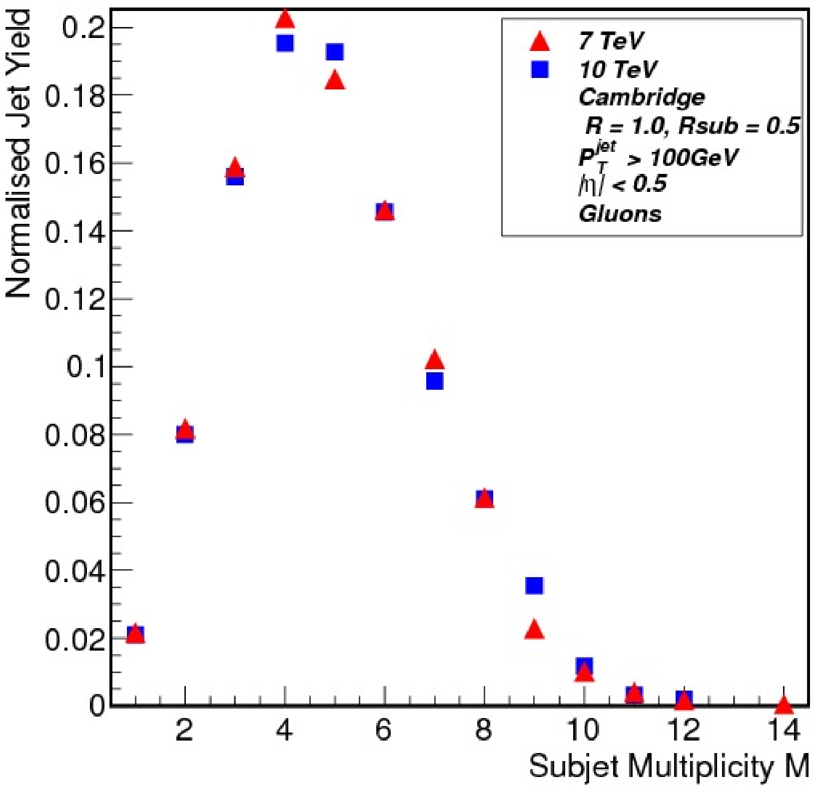
Particle Jets
Normalised Jet Yield
Subjet Multiplicity M


Normalised Jet Yield
Subjet Multiplicity M
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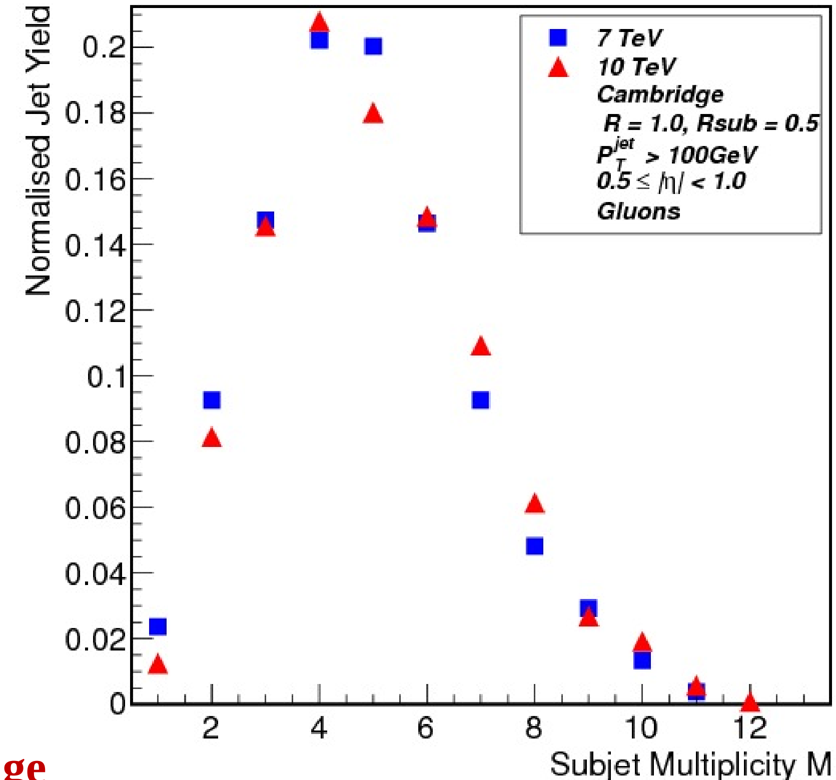
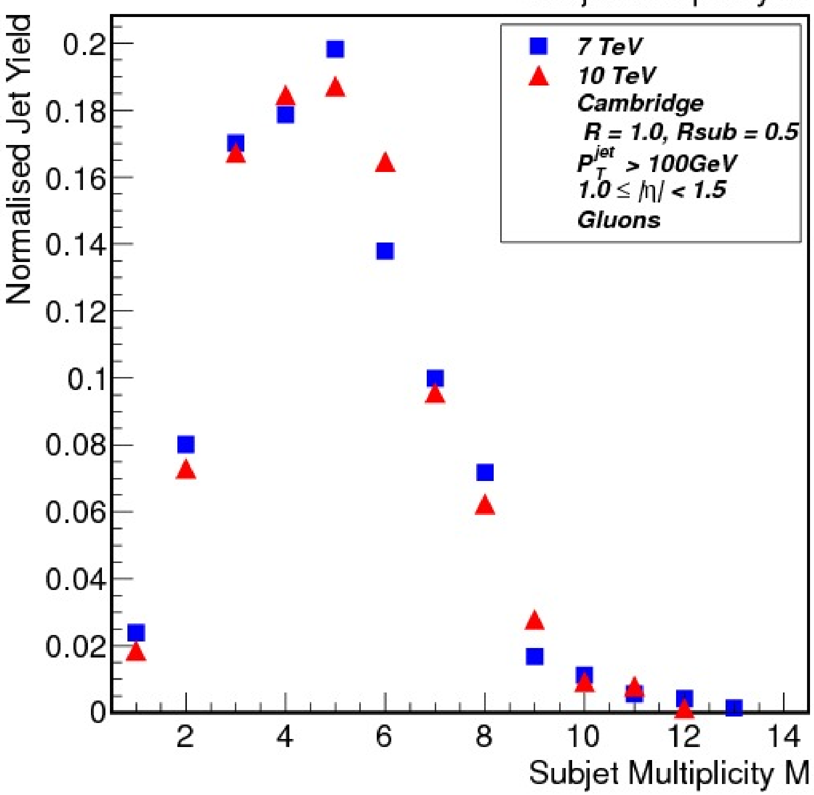
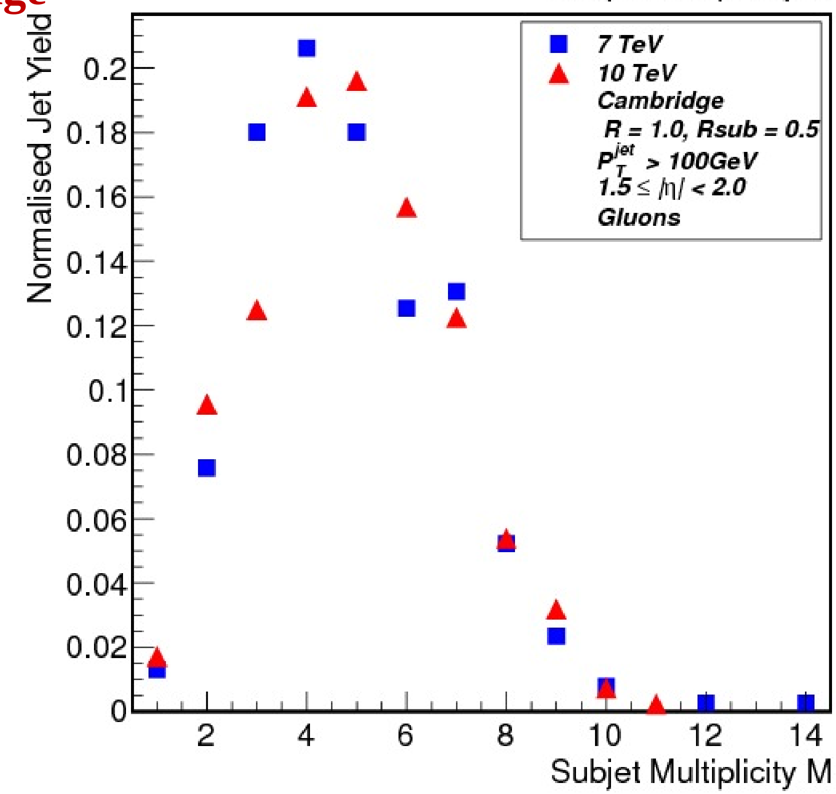
Gluons

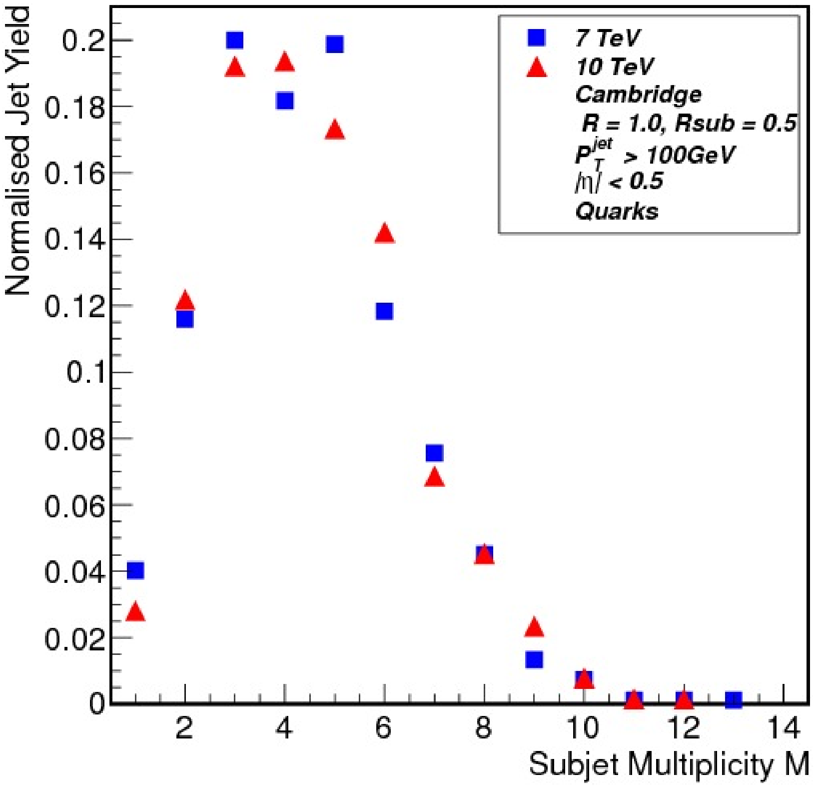

Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$0.5 \leq |\eta| < 1.0$
Gluons

Cambridge

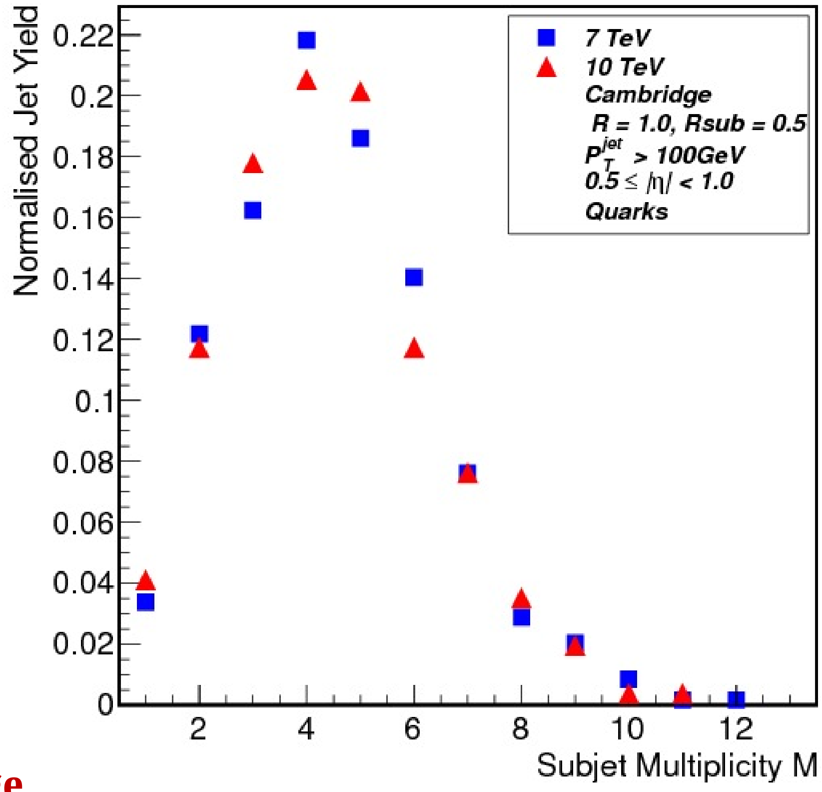

Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$1.0 \leq |\eta| < 1.5$
Gluons


Normalised Jet Yield
Subjet Multiplicity M
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$1.5 \leq |\eta| < 2.0$
Gluons

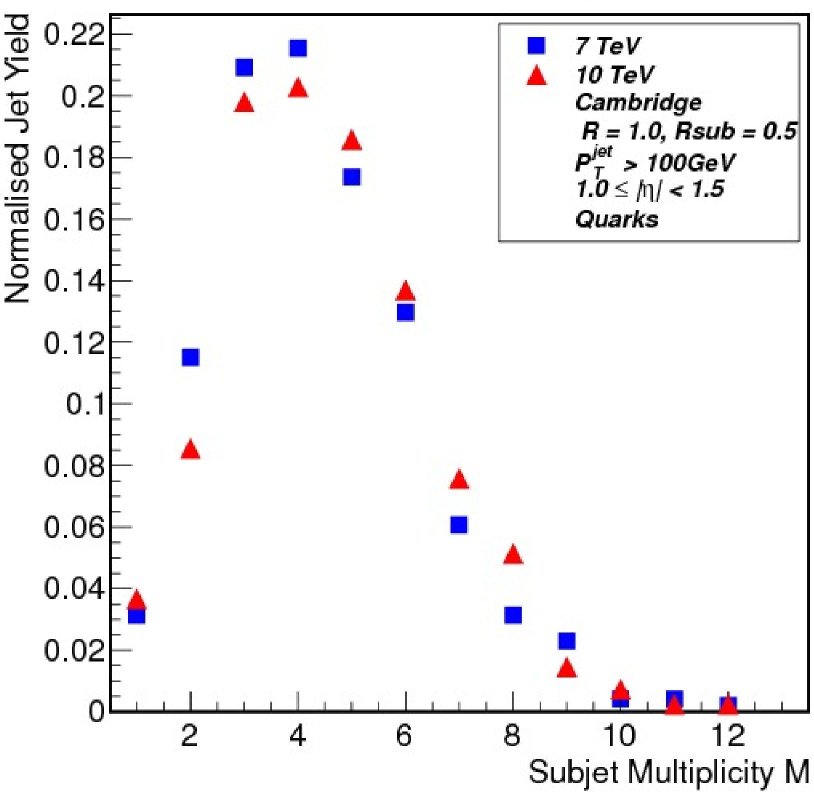
Cambridge



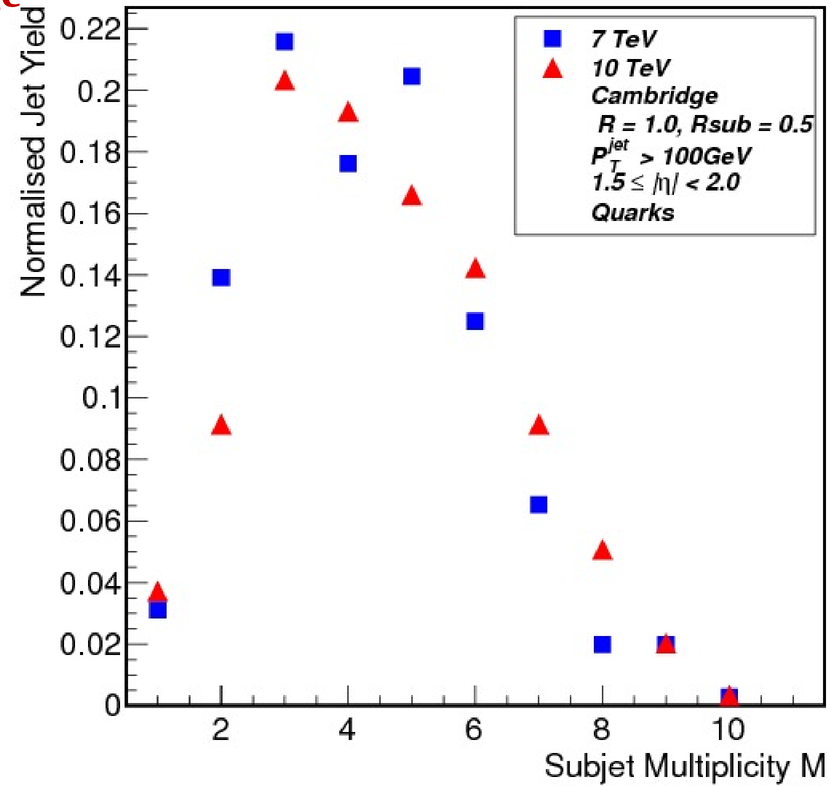
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$|\eta|$ < 0.5
Quarks
Normalised Jet Yield
Subjet Multiplicity M



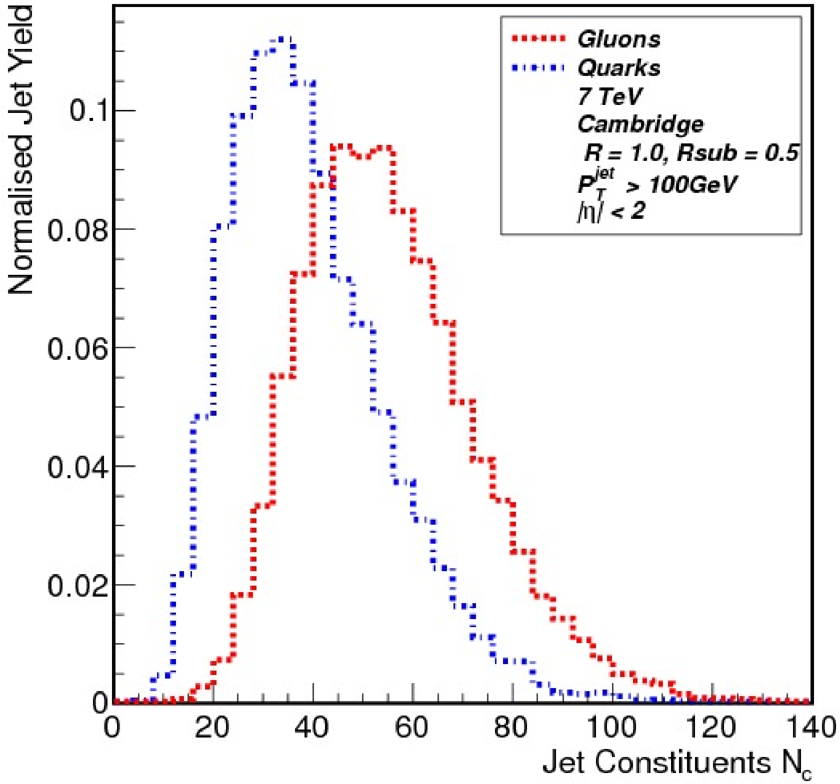
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$0.5 \leq |\eta| < 1.0$
Quarks
Normalised Jet Yield
Subjet Multiplicity M

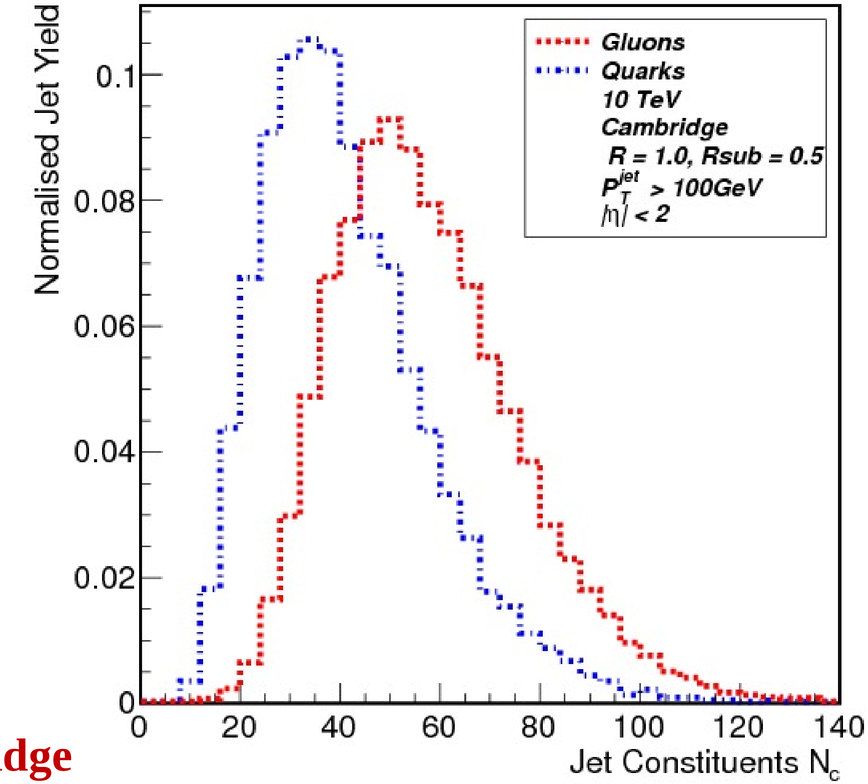


7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$1.0 \leq |\eta| < 1.5$
Quarks
Normalised Jet Yield
Subjet Multiplicity M

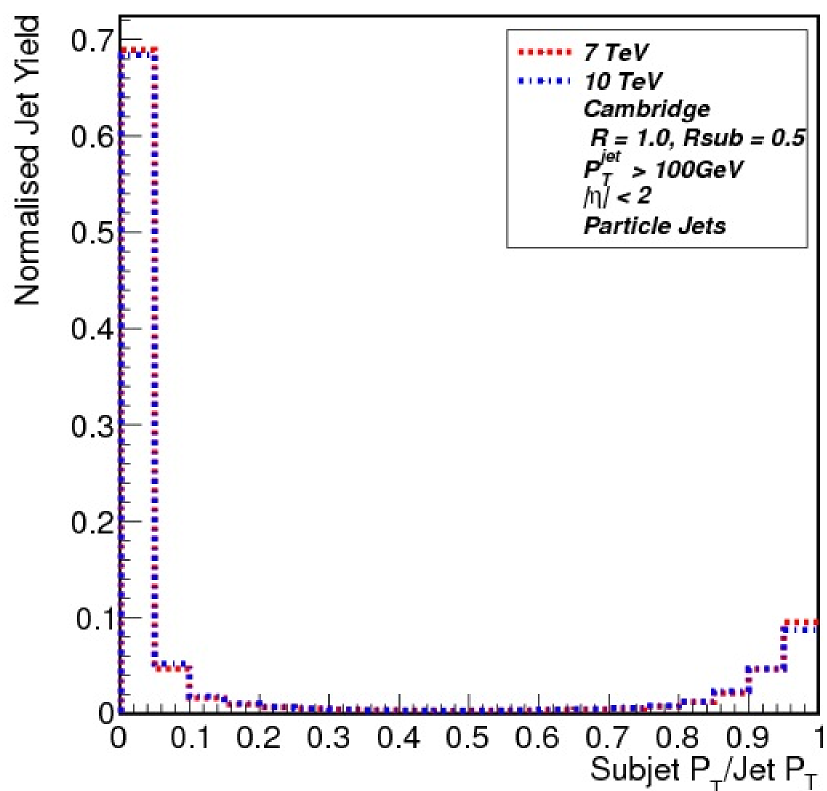


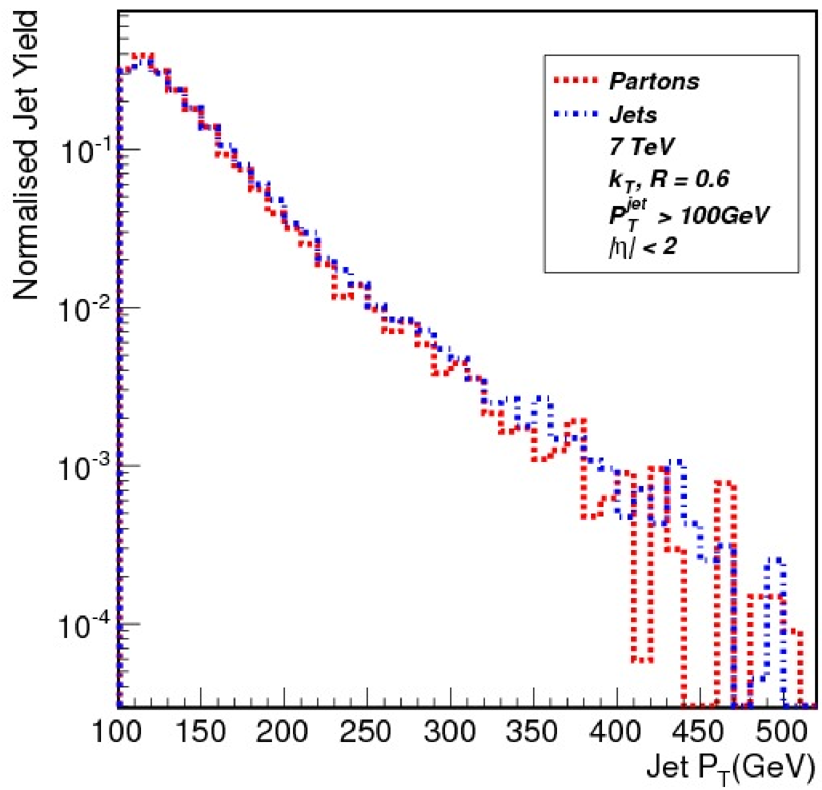
7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
$1.5 \leq |\eta| < 2.0$
Quarks
Normalised Jet Yield
Subjet Multiplicity M


Gluons
Quarks
7 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
|η| < 2
Normalised Jet Yield
Jet Constituents N_c

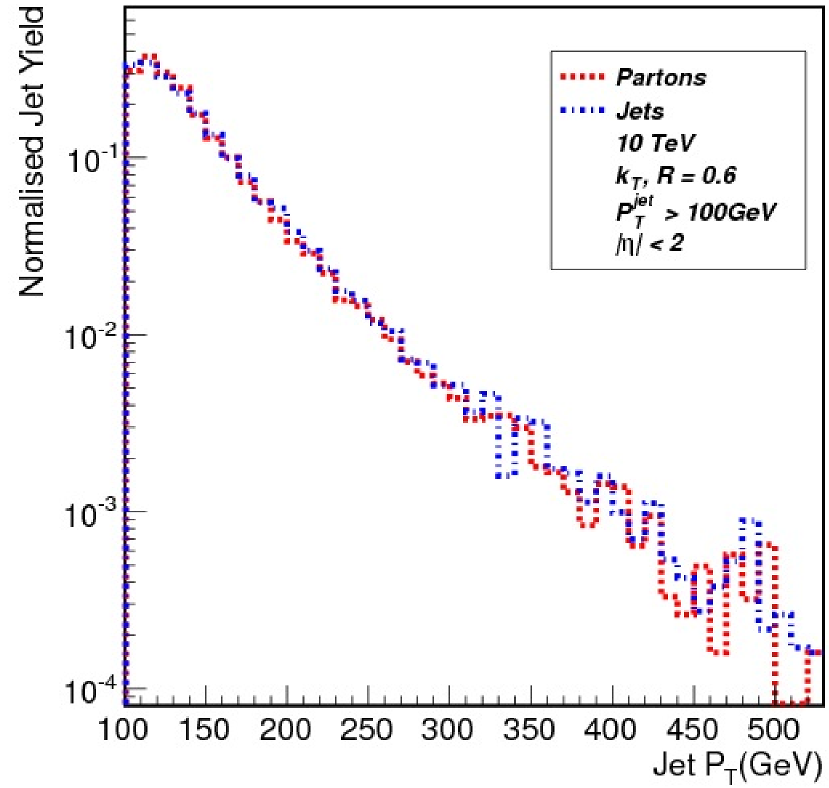

Gluons
Quarks
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
|η| < 2
Normalised Jet Yield
Jet Constituents N_c

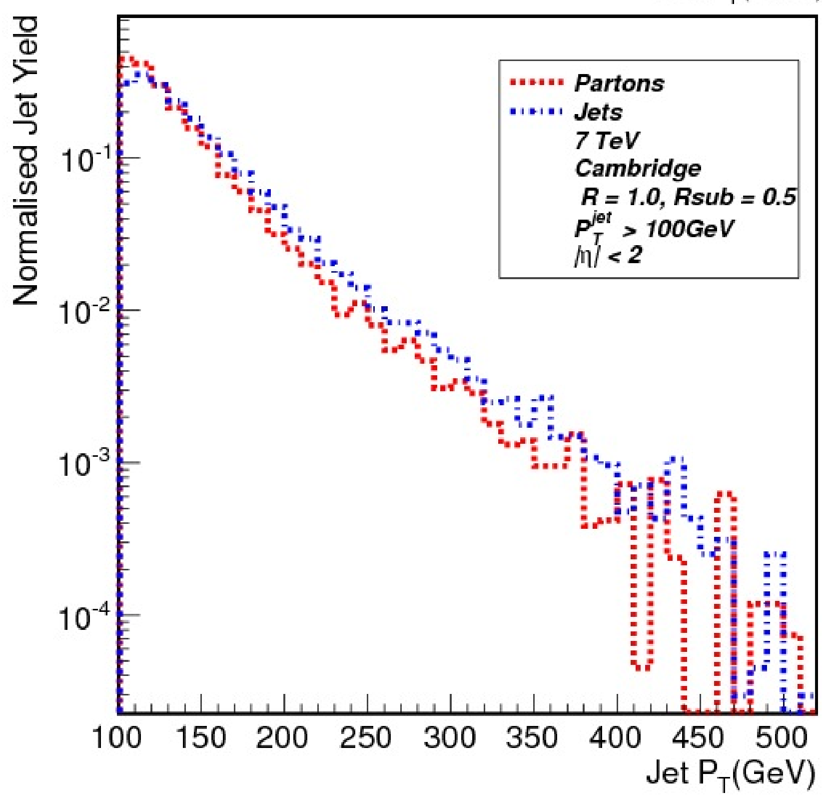
Cambridge


7 TeV
10 TeV
Cambridge
R = 1.0, Rsub = 0.5
P_T^{jet} > 100GeV
|η| < 2
Particle Jets
Normalised Jet Yield
Subjet P_T/Jet P_T

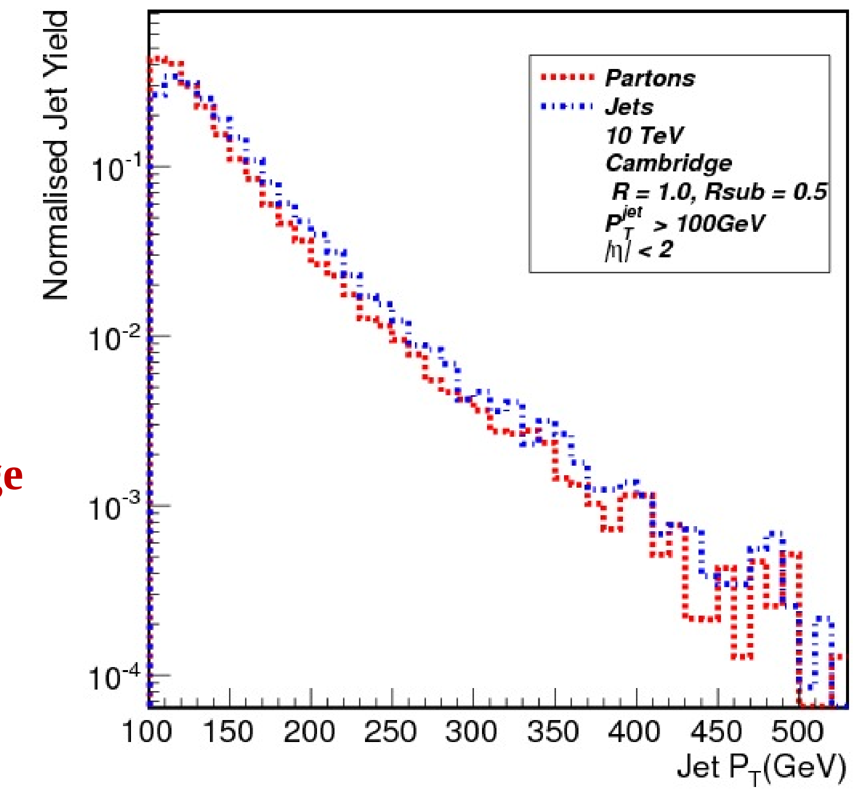


k_T





Cambridge



Results

Average subjet mutiplicity and ratio of color factor in the phase space $\|\eta\| < 2$ for k_T Algorithm						
	Gluon Jets		Quark Jets		$R = C_A/C_F$	Stat.
	<M>	Stat.	<M>	Stat.		
7 TeV	3.41	±0.026	2.28	±0.022	1.88	±0.023
10 TeV	3.39	±0.026	2.31	±0.024	1.83	±0.024
From eqns. (1) & (2)	3.37	±0.635	2.35	±0.755	1.76	±0.656

Average subjet mutiplicity and ratio of color factor in the phase space $\|\eta\| < 2$ for Cambridge Algorithm						
	Gluon Jets		Quark Jets		$R = C_A/C_F$	Stat.
	<M>	Stat.	<M>	Stat.		
7 TeV	4.89	±0.033	4.44	±0.038	1.13	±0.012
10 TeV	4.93	±0.032	4.52	±0.042	1.12	±0.013
From eqns. (1) & (2)	3.69	±1.329	5.69	±0.928	1.74	±0.688

Conclusions

- Study of p-p interactions at $\sqrt{s}$ = 7 TeV and 10 TeV.
- Selection of dijet events.
- Measurement of Subjet Multiplicity and calculation of color factor ratio

  using two algorithms : k_T and Cambridge.
- Better results with k_T than Cambridge.
- Color factor ratio r = 1.76 ± 0.66 with k_T and 1.74 ± 0.69 with Cambridge.

Experiments	C_A/C_F	Stat.	Sys.
D0 (2 jet events)	1.91	±0.04	±0.21
DELPHI(3 jet events)	1.74	±0.03	±0.10
L3(4 jet events)	1.84	±0.12	±0.36
OPAL(4 jet events)	2.11	±0.16	±0.28
DELPHI(4 jet events)	2.44	±0.34	±0.11
ALEPH(4 jet events)	2.20	±0.09	±0.13

Future Plans :

- Continue to reproduce this study

  using CMS experimental data.

THANK YOU

Sequential Algorithms

- Sequential Algorithms : work by defining a distance between pairs of particles and recombining the pair of closest particles successively.
- Never assign a particle to more than one jet.
- Infrared and collinear safe.
- Define a distance d_{ij} between two objects i,j :

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta R_{ij}^2 / R^2$$

where

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- and a distance d_{iB} between one object i and the beam direction B:

$$d_{iB} = k_{ti}^{2p}$$

- Find the minimum d_{min} of all the d_{ij} , d_{iB}

- If d_{min} is d_{ij} recombine i,j into a new single particle k, summing their four momenta by recombination scheme and go to step 1.
- If d_{min} is d_{iB} , declare particle i to be a final-state jet and remove it from the list.
- Repeat the procedure until no particles are left.
- Algorithms used in present analysis :
  - k_T algorithm
    - $p = 1$
    - Clustering involves soft particles
  - Cambridge/Aachen algorithm
    - $p = 0$
    - Clustering is energy independent
- Recombination scheme : E-scheme. $E = \Sigma E^i$; $k^i_{t,x,y,z} = \Sigma k^i_{t,x,y,z}$

Value of y_{cut}