The possibilities of studying the fragmentation of Quark and Gluon jets in pp and HI collisions at LHC

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• **What motivates us**
  • Differences between Quark and Gluon jets and what they mean

• **History of studying Quark and Gluon jets**
  • Results from LEP and Tevatron, limitations of measurements

• **How can we ID the jets**
  • Data-driven method to identify jets

• **Jets at ALICE at LHC**
  • Jet reconstruction at ALICE, γ-jet and 3-jet events
  • HI perspectives
What motivates us to study quark and gluon jets separately

Jets are produced in hard scatterings of partons of colliding particles/ions

Emerging from the very early stages of collisions they are ideal to study

Early stages of collisions Hadronisation processes Particle production

These questions can be addressed through the study of fragmentation properties of quark and gluon jets
Quark and Gluon Jets

Quark and gluon jet carry different colour factors

\[ \frac{C_A}{C_F} = \frac{9}{4} = 2.25 (Q \rightarrow \infty) \]

The colour factors are proportional to the probability a parton radiates soft gluon

Gluons branch more easily and are expected to form

Higher multiplicity jets

Broader jets

Jets with softer fragmentation function
Quark and Gluon Jets

Particle production differences:

- Gluons
- **Baryon production**
- Quarks
- **Meson production**

Higher multiplicity jets

Broader jets

Jets with softer fragmentation function
The differences in the frag. properties of q/g jets must naturally be represented in the experimentally studied variables

- identified hadron spectra, multiplicity, R(AA)

**Variables connected to jet-properties study**

- Jet-shape, charged multiplicity
- Fragmentation functions
- Identified hadron spectra
History of studying Quark and Gluon jets

- First studies looking at properties of jets were conducted in $e^+e^-$ (LEP)


Qualitative differences were observed
• **4-jet events**
  - Angles between 2-momenta planes
• **Event shape**
  - Thrust
• **Q/G separation**
• **3-jet events**

The results of the methods have been combined to average $C_A$ and $C_F$

$$
\overline{C_A} = 2.89 \pm 0.03\text{(stat.)} \pm 0.21\text{(syst.)}
$$

$$
\overline{C_F} = 1.30 \pm 0.01\text{(stat.)} \pm 0.09\text{(syst.)}
$$
Identified particles in Q/G jets have been measured as well.

Relative proton abundance in gluon jets has been observed.

All measurements at LEP have been performed in vacuum.

In hadron-hadron and heavy-ion collisions we face the challenge to test QCD in a dense environment.

http://arXiv.org/abs/hep-ex/0106063v1
**TEVATRON**
- Jets identified in di-jet and γ-jet events based on the expected fraction of gluon jets at certain di-jet invariant mass
- Multiplicities were compared

\[
\frac{N_g}{N_q} = r = 1.6 \pm 0.2
\]

*Method sensitive to misidentification. High fraction of gluon jets both in di-jet and γ-jet events in proton-antiproton col.*
At high $p_T$, the $p/\pi^+$ ratios can be directly compared to results from quark jet fragmentation as measured in $e^+ + e^-$ collisions by DELPHI \cite{29}, indicated by the dotted-dashed line in Fig. 4(a). The $p/\pi^+$ ratio measurements in d+Au and Au+Au collisions are higher than in quark jet fragmentation. This is likely due to a significant contribution from gluon jets to the proton production, which have a $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio up to two times larger than quark jets \cite{30}. A similar comparison cannot...
JET INTERACTION WITH MEDIUM

mid $p_T$ hadron yield enhanced
⇒ Coalescence of hard partons from jets with soft partons from medium


COLOR CHARGE EFFECT OF PARTON ENERGY LOSS

The observed ordering of $R_{AA}$ of identified hadrons is consistent with predictions from calculations including jet flavor conversion in the hot dense medium

Wei Liu, Che Ming Ko, Ben-Wei Zhang

Beijing, 2012
Our studies

- Over the past 2 years we tried to look at how the event-type, or the jet-type respectively influences the final particle spectra in MC

- First we were looking w/o jet-finders afterwards we approached the issue by simulating experimental techniques and were primarily looking for the possibilities to distinguish Q/G jets
Antiparticle/particle ratios

QQ, QG:
\( \bar{u} \) and s suppressed w.r.t u
\( \Rightarrow \) towards higher \( p_T \)
antiparticle/particle ratio drops
Antiparticle/particle ratios

Gluon production dominates spectra, difference in quark production vanish

⇒ ratios levels at 1
p/π, p/K
Different point worth mentioning:

The gluon contribution to the ratios changes to lower values with energy (0.3 - 0.25).

Ratio from all prod.channels on the other hand at ~ TeV energies stays the same (~ 0.25).

! Important to look at separate prod.channels for tuning purposes as well.

? PYTHIA tunes parameters may lead to underestimation of proton production in the gluon channel when looking at the full event.

**Event shape selection:**

- $T > 0.9$ - anisotropic (2-Jet like)
- $T < 0.9$ - isotropic (3-Jet like)

Ratios for all production channels

3-Jet events – additional hard gluon radiation

Effect $\sim$ 20-40 %

Effect stronger for pions
What are the limitations

- Our understanding of what jet is limited by our experimental definition of jet – Jet Finding algorithm
- We have prior expectations to how we expect gluons and quarks to fragment into particles. This expectations are embedded into MC generators. Method designed on MC - BIASED
Can we overcome them?

✗ Our understanding of what jet is limited by our experimental definition of jet – Jet Finding algorithm

✔ We have prior expectations to how we expect gluons and quarks to fragment into particles. This expectations are embedded into MC generators. Method designed on MC – BIASED
How to ID the different partons?

• Use their properties
• Separate “clean” production channels for the production of Q/G
  – G: 3-jet events
  – Q: gama-jet
• Pythia 6, Perugia-0, pp@7TeV
• **Jet-jet**
  – **10 Million events**
• **γ-jet events**
  – **1 Million events**
• anti-kT algorithm, R = \{0.4\}
• |η| < 0.5, at least 3 charged particles
• Variables: **R(90%)**; size of sub-cone containing 90% of jet's energy
3-jet events practically overlap with the jet-jet distribution – gluon dominated sample

Gamma-jet events have smaller average R90, which is the demonstration of the fact, that quarks are narrower than gluons.
Cross-section falls with a smaller (power-law) exponent
- $n = 5.9$ (LHC) / 8 (RHIC)
- Reduced sensitivity to energy scale
- Reduced selection bias on fragmentation

Different $x_f$ range
- LHC: 0.02 - 0.2
- RHIC: 0.15 – 0.45

LHC (RHIC) gluon (quark) dominated
How is the average value influenced by the quark and gluon jets?

\[ \Delta R = R_{90} - \langle R_{90} \rangle \]

*We select bin:*

Jet \( p_T = (34;44) \)

*Determine cut:*

**Q:** \( \Delta R = (-0.04, 0) \)

**G:** \( \Delta R = (0., 0.04) \)
Whereas the **gluons are dominating the positive side of the distribution**, the **quarks dominate the negative values of ΔR**. However, the **“quark sector” is highly contaminated by gluons.**
The selected quarks are compared to MC quarks and gluons. We see that even we have high contamination in our selection, we selected “quark-like” and “gluon-like” jets.

Bias in our variable? Let's look at other variables then.
Good agreement up to 20 GeV. Better agreement for quarks than for gluons.
As we go higher in pT the $z$ becomes larger and we enter region were we weren't successful in the first place.
We want to perform our study in ALICE experiment because of its great PID capabilities.

Although acceptance is not ideal for jet-study, the recent preliminary results show, the experimental setup is suitable.
Jets with ALICE at LHC

Reconstructed Jets UA1 Cone R = 0.4:
Jet 1: $\eta = 0.02$, $\phi = 306^\circ$, $p_T = 71$ GeV, Tracks 15
Jet 2: $\eta = 0.84$, $\phi = 132^\circ$, $p_T = 47$ GeV, Tracks 9
$\Delta \phi = 174^\circ$
Total Tracks 108

Q/G jets in pp and HI
Sona Pochybova
Beijing, 2012

A. Morsch, Mexico 2010

HMPID 3-jet event study with HMPID
**Detectors for jet reconstruction**

- **ITS+TPC+(TOF, TRD)**
  - Charged particles $|\eta| < 0.9$
  - Excellent momentum resolution up to 100 GeV/c ($\varphi/p < 6\%$)
  - Tracking down to 100 MeV/c
  - Excellent Particle ID and heavy flavor tagging

- **EMCal**
  - Energy from neutral particles
  - Pb-scintillator, 13k towers
  - $\varphi = 107\%$, $|\eta| < 0.7$
  - Energy resolution $\sim 10\%\sqrt{E_\gamma}$
  - Trigger capabilities

**HMPID**

$|\eta| < 0.5$, $\Delta\varphi = 57$

PID in $3\text{ GeV} < p_T < 5\text{ GeV}$

**VHMPID extension planned**

**PHOS**

$|\eta| < 0.12$, $\Delta\varphi = 100$

17k det. channels
Jet reconstruction algorithms

Jet definition

\[ \{ p_i \} \rightarrow \{ j_k \} \]

- particles, 4-momenta, calorimeter towers, ....
- + parameters (usually at least the radius R)
- + recombination scheme

Cacciari, Salam
In order to work properly jet algorithms should be

- **Infrared safe** (for the calculation to converge)
  - soft emission shouldn’t change jets
collinear splitting shouldn’t change jets

- **Fast** (if many particles have to be clustered)
  - In order to be realistically applicable at detector level

These (and other) requirements were widely acknowledged as early as 1990
(Snowmass accord)

Perhaps quite surprisingly, they had not yet been met in 2005

A calorimeter is of course always infrared safe.
You need these properties not so much to find jets, but to be able to calculate them in pQCD
**Sequential recombination algorithms**

bottom-up approach: combine particles starting from **closest ones** in some distance measure. Repeat until few left: call them jets

Work because of mapping closeness $\Leftrightarrow$ QCD divergence

Examples: $k_t$, Cambridge/Aachen, …. Loved by $e^+e^-$, ep and theorists

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**Cone algorithms**

top-down approach: find coarse regions of energy flow.

How? Find **stable cones** (i.e. their axis coincides with sum of momenta of particles in it)

Work because QCD only modifies energy flow on small scales

Examples: JetClu, MidPoint, ….. Loved by pp and (fewer) theorists
How do the jet-finding algorithms work?

Clustering jet finders

1. Calculate ‘distances’
   - $d_{ij}$ between all particles $i$ and $j$
   - $d_{iB}$ between $i$ and beam

2. Find smallest of $d_{ij}$ and $d_{iB}$
   - If $d_{ij}$ is smallest, recombine $i$ and $j$
   - If $d_{iB}$ is smallest call $i$ a jet

3. Goto step 1 if anything’s left

Two variants (& one parameter, $R$)

- **$k_t$ jet finder** [1991]
  
  \[
  d_{ij} = \min(k_{ti}^2, k_{tj}^2) \Delta R_{ij}^2, \quad d_{iB} = k_{ti}^2 R^2
  \]

- **Cambridge/Aachen** [1998]
  
  \[
  d_{ij} = \Delta R_{ij}^2, \quad d_{iB} = R^2
  \]

Cone jet finders e.g.

1. Create a seed (3-vector) from the direction of each input particles (possibly, implement a way to specify a smaller list of seeds to save processing time i.e. calo clusters)

2. For each seed, $s$, create a cone in $\eta-\phi$ space of radius $R$ (get by the parameter radius around the seed axis such that a particle, $p$, with

\[
(\eta_p - \eta_s)^2 + (\phi_p - \phi_s)^2 < R^2
\]

is defined to be inside the cone.

3. Then combine every particle in this cone into a jet using a $p_\perp$ recombination scheme as described in section 2.5.2 of the KtJet paper.

4. Now create a new cone around this jet’s axis and repeat step 3. If the new jet’s axis is collinear with the previous axis then the jet is stable and it is added to the list of meta-jets, otherwise the process is repeated until either a stable jet if found or a maximum number of iterations is reached.

5. The next stage is to enforce infra-red safety, to repeat steps 4-6 with a new net of seeds in between every pair of jets, $i$, $j$, found above if $i$ and $j$ are between 1 and 2 cone radii apart i.e.

   \[
   R^2 < (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 < (2R)^2
   \]

   then:

   \[
   \eta_s = \frac{\eta_i + \eta_j}{2} \quad \phi_s = \frac{\phi_i + \phi_j}{2}
   \]

6. Next any jets with $p_\perp$ less than a pre-defined parameter (usually of order 5 GeV) are removed from the list.

7. Then for each jet in the list, if the sum of the $p_\perp$ of any particles in the jet which are shared with a higher $p_\perp$ jet in greater than some fraction, ovlim, of the jet’s $p_\perp$, then remove the jet from the list.

8. Next for each particle that is still more than one jet, remove the particle from all but the closest jet to particle’s direction, i.e. the jet with the smallest $\Delta(\eta_{ij}^2 + \Delta \phi_{ij}^2)$.

9. Finally step 6 is repeated.

[from W. Plano]
3-Jet and γ-jet yields

Ntrig: 700 M. Events (1st year of running)

σ (inel): 69 mb

\[ \frac{1}{\sigma_{\text{ine}}} \frac{d\sigma}{dp_T} = \frac{1}{N_{\text{trig}}} \frac{dN}{dp_T} \]

Both three-jet events and gamma-jet events are rare – need to be patient and wait for statistics

The gamma-jet cross-section much lower than three-jet events

\[ 3\text{-jet, } p_T > 10 \text{ GeV/c } \sim 10^5 \]
How about HI?

• Is it possible to perform differentiation of quark and gluon jets in the HI environment?

• **QM 2011:**
  • CMS and ATLAS observed, that the part of jets we can reconstruct has the same fragmentation as the jets in pp
So, there is a hint that we can use this approach even in HI.
Summary

- Studying the fragmentation of Quark and Gluon jets gives us access to understand the fragmentation processes and particle formation.

- **ALICE** – excellent PID capabilities up to 5 GeV/c and extensions are planned (VHMPID).

- ID is challenging.
  - **MC not good to use** – BIAS
  - **3-jet, γ-jet events** – rare events

- HI – recent studies show a possibility for ID.
Summary

- Seems we cannot distinguish q/g jets on jet-by-jet basis, rather we select “quark-like” and “gluon-like” jets
- We can study structural properties of these jets, such as FFs and particle spectra and their ratios
- The reference samples of quarks and gluons from γ-jet and 3-jet events are essential