Constructing & Using a Quark/Gluon Tagger

How well can we do at the LHC?

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Outline

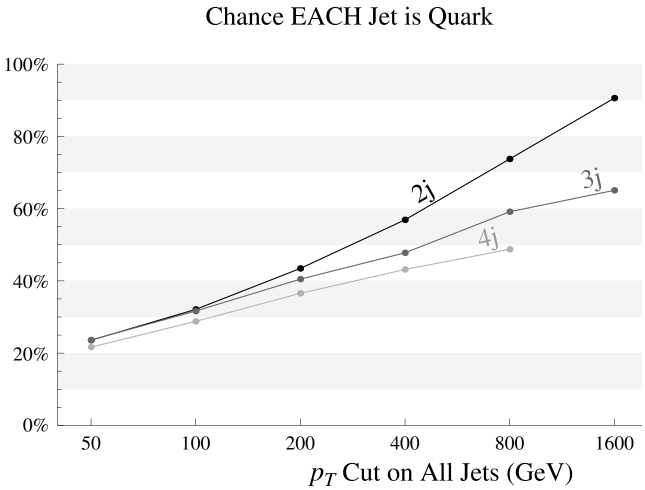
1. **Big Motivation:** Reject Gluey LHC Backgrounds
2. **The Tagger:** Observables and Performance
3. **Verification:** Finding Pure Samples of Quark and Gluon Jets
4. **Theory:** Meaningful to What Order?
5. **Using Flavor Taggers:** Acceptance/Rejection, S/B, Significance

"Quark and Gluon Tagging at the LHC" **arXiv:1106.3076**
"Pure Samples of Quark and Gluon Jets at LHC" **arXiv:1104.1175**

(with Matt Schwartz at Harvard)

Interactive Plots: `http://jets.physics.harvard.edu/qvg/`

There's a Lot of Glue to Get Stuck In (7 TeV LHC)



So chance that all 4 jets $\gtrsim 50\,\mathrm{GeV}$ are quark $\approx (21\%)^4 \approx 1/500$

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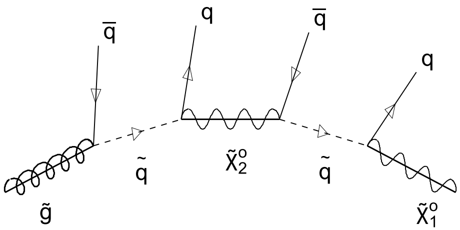

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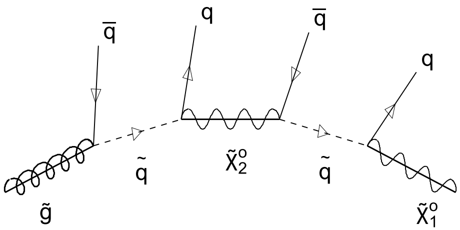

- Higgs $H^+ \to c\bar{s}$ (for charged Higgs mass between τ and t mass)

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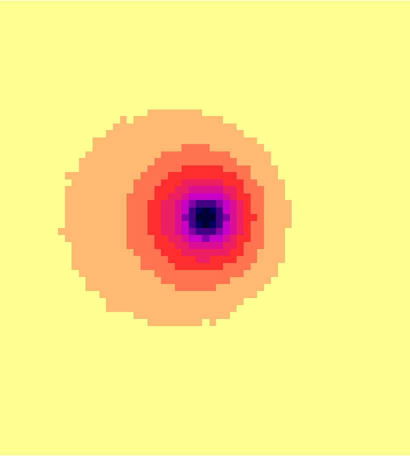
Must combine Quark/Gluon-Tagging with B-Tagging and τ-Tagging.

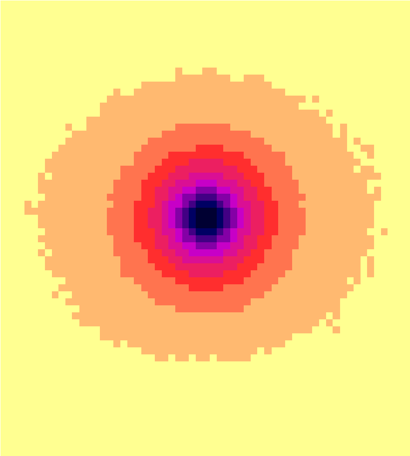
The Quark/Gluon Tagger

Same dijet event showered 3 million times. Accumulate $p_T(\eta, \phi)$:

Quark Jet

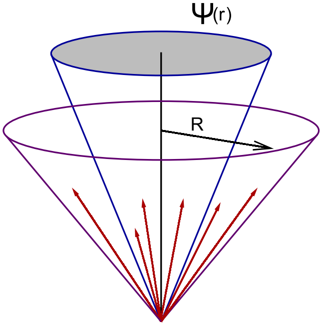


Gluon Jet

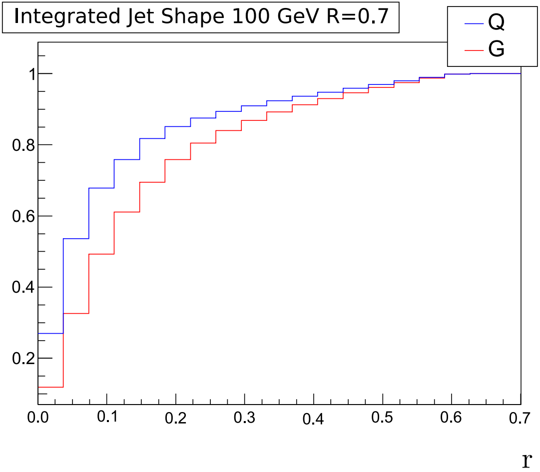


(Same total amount of p_T, which is hidden by logarithmic color bands.)

Jet Shape

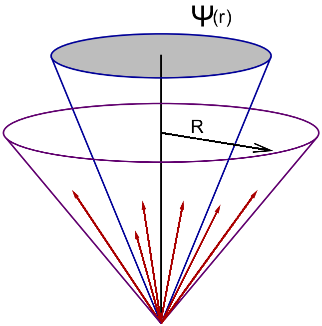


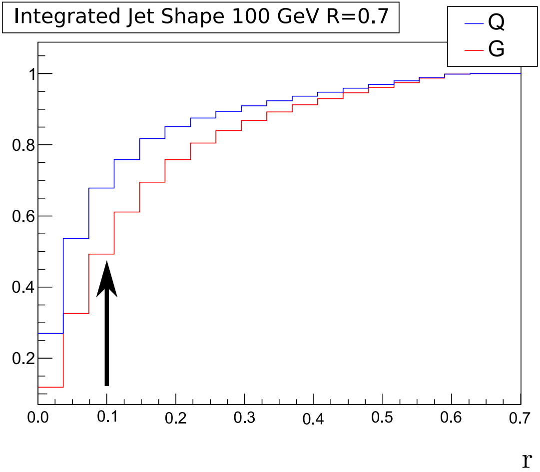
Ψ(r)
R



Integrated Jet Shape 100 GeV R=0.7
Q
G
1
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r

Jet Shape


Ψ(r)
R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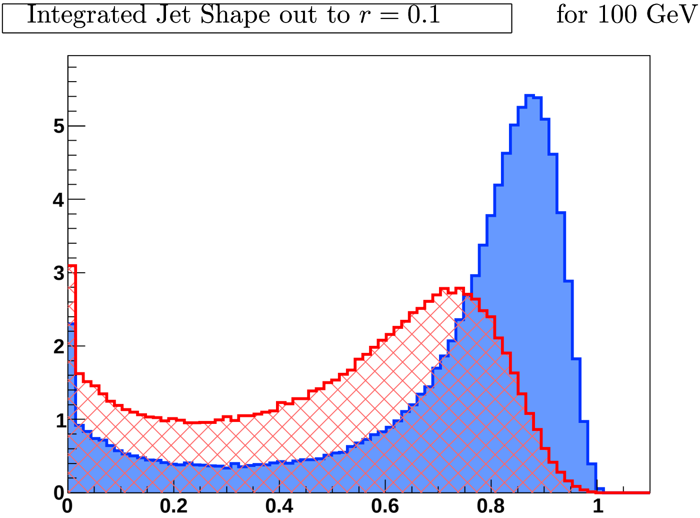
Q
G
1
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r

Jet Shape *Distribution* vs *Average*



- Distribution is *not* narrow gaussian around average
- Correlations *between* different r's might also be useful

Gluon has a greater effective color charge (squared) than quark:

Gluon adjoint's C_A vs Quark fundamental's C_F

$$\frac{C_A}{C_F} = \frac{9}{4}$$

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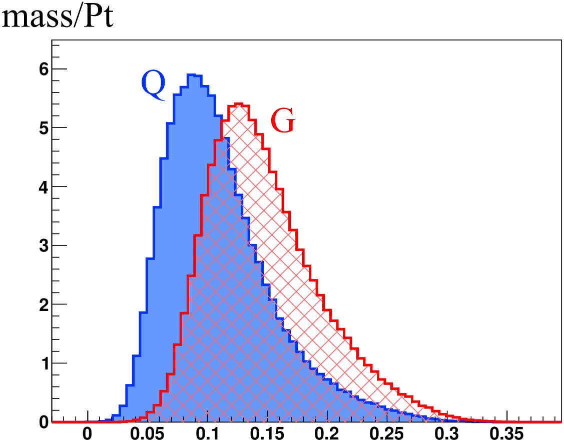
Average Jet Mass in the small angle limit:

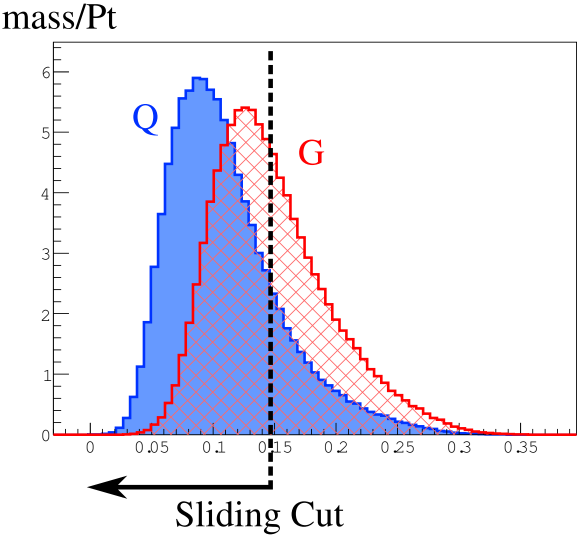
$$\langle M^2 \rangle = C \frac{\alpha_s}{\pi} \, p_T^2 \, R^2$$

Distribution of Jet Mass....

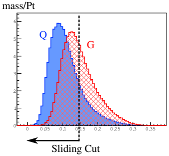
Jet Mass as an Example Observable

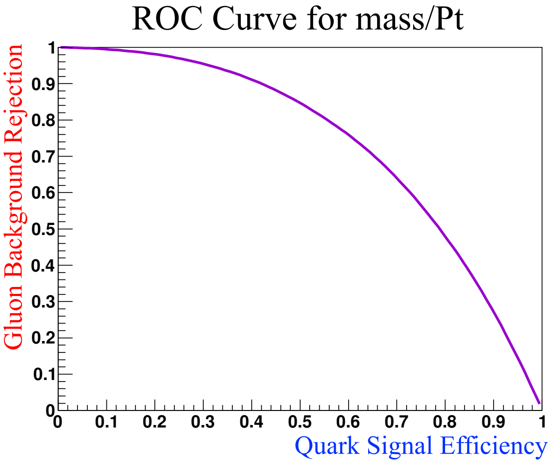
- Normalizing by p_T (200 GeV in this sample) generalizes better.
- All distributions normalized to equal area.



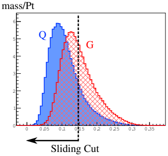

mass/Pt
6
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Q
G
Sliding Cut

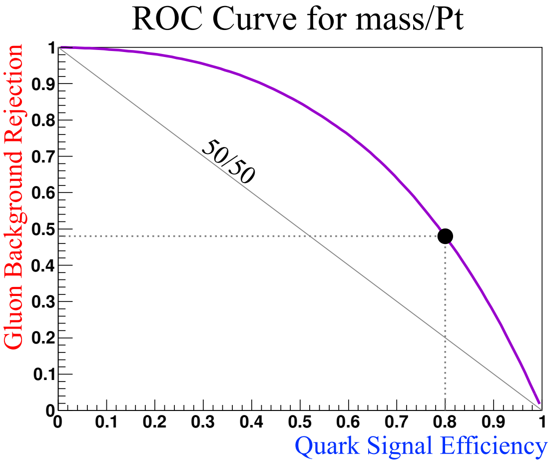
ROC Curve


mass/Pt
Q
G
Sliding Cut

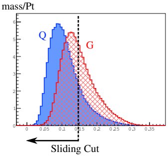

ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

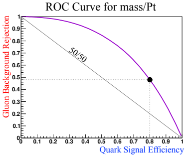
ROC Curve

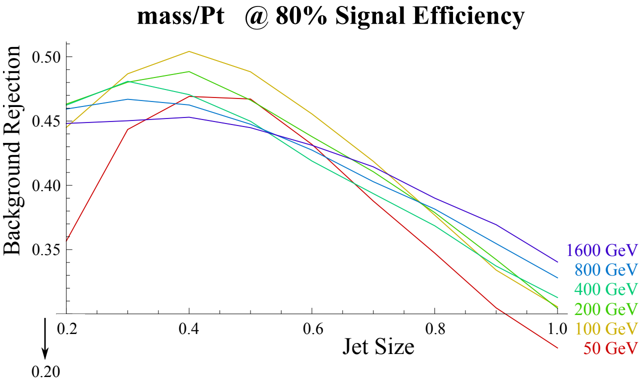

mass/Pt
Q
G
Sliding Cut


ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
50/50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Other Jet Sizes and p_Ts



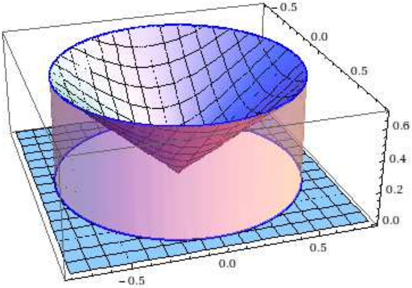


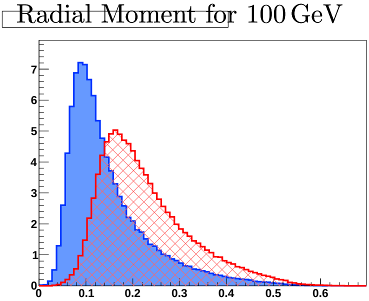


Radial Moment – a measure of the “girth” of the jet

Weight p_T deposits by distance from jet center

Radial Moment, or Girth : $$g = \frac{1}{p_T^{jet}} \sum_{i \in \text{jet}} p_T^i |r_i|$$





‘Jet Broadening’ is a similar LEP observable involving E and $\Delta\theta$.

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Multiplicity of *any* particle in a gluon jet should be $C_A/C_F = 9/4$ times greater (confirmed at LEP).

$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F}$$

Brief Theory II — Particle Count

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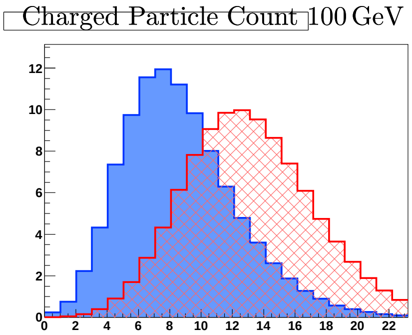
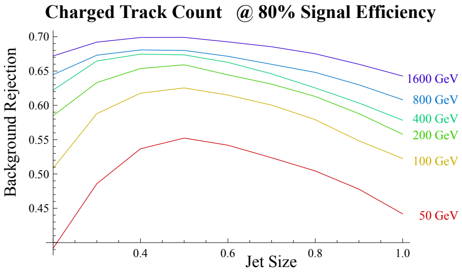
$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F} \qquad\qquad \frac{\sigma_g^2}{\sigma_q^2} = \frac{C_A}{C_F}.$$

(Calculated to N^3LO by Capella, et al. hep-ph/9910226)

Charged Particles Count



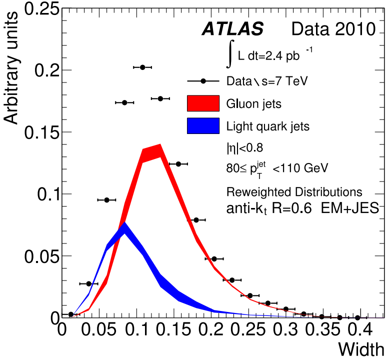


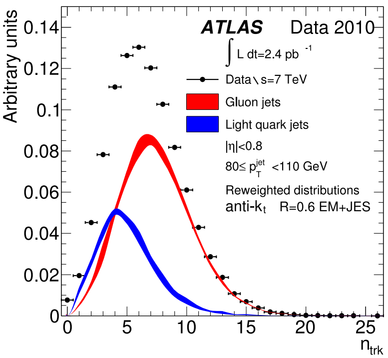
No detector simulation, but require charged particles $p_T > 1\,\mathrm{GeV}$.

Higher p_T means more tracks and more 'time' to establish C_A/C_F.

ATLAS Measurements

Data matches *correct* linear combination of pure quark + gluon.





from "Jet energy measurement with the ATLAS..." arXiv:1112.6426

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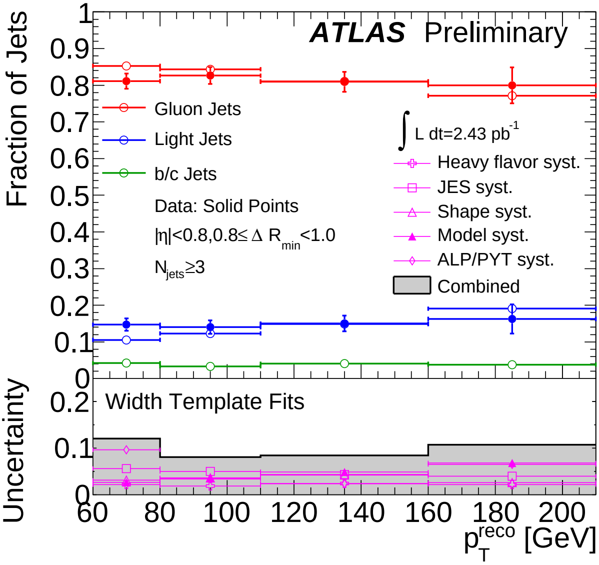


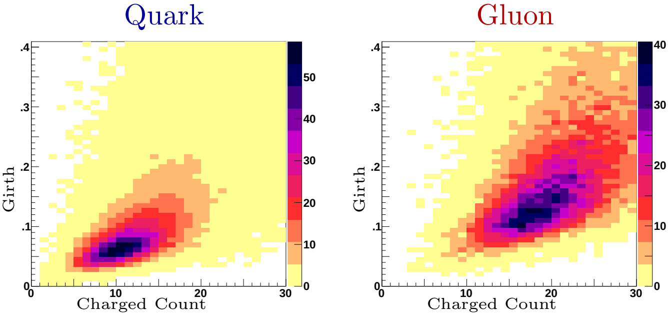
from "Light-quark and Gluon Jets..." ATLAS-CONF-2011-053

Types of Variables

The menu, including varying jet size

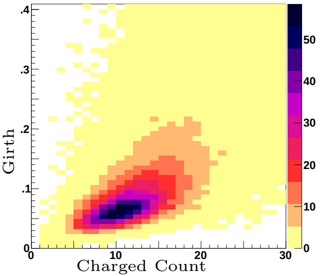
- Distinguishable particles/tracks/subjets
  - multiplicity, $\langle p_T \rangle$, σ_{p_T}, $\langle k_T \rangle$,
  - charge-weighted p_T sum
- Moments
  - mass, girth, jet broadening
  - angularities
  - optimal kernel
  - 2D: pull, planar flow
- Subjet properties
  - Multiplicity for different algorithms and R_{sub}
  - First subjet's p_T, 2nd's p_T, etc.
  - Ratios of subjet p_T's.
  - k_T splitting scale
- 2-Point Correlators (energy, p_T, possibly times $r^{\#}$, etc.)

Combining Variables: Girth and Charged Count

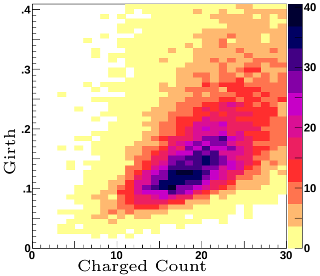


Combining Variables: Girth and Charged Count

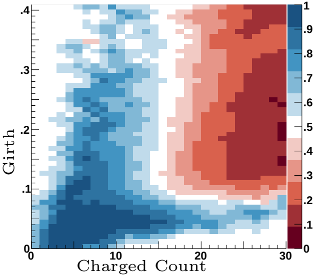
Quark



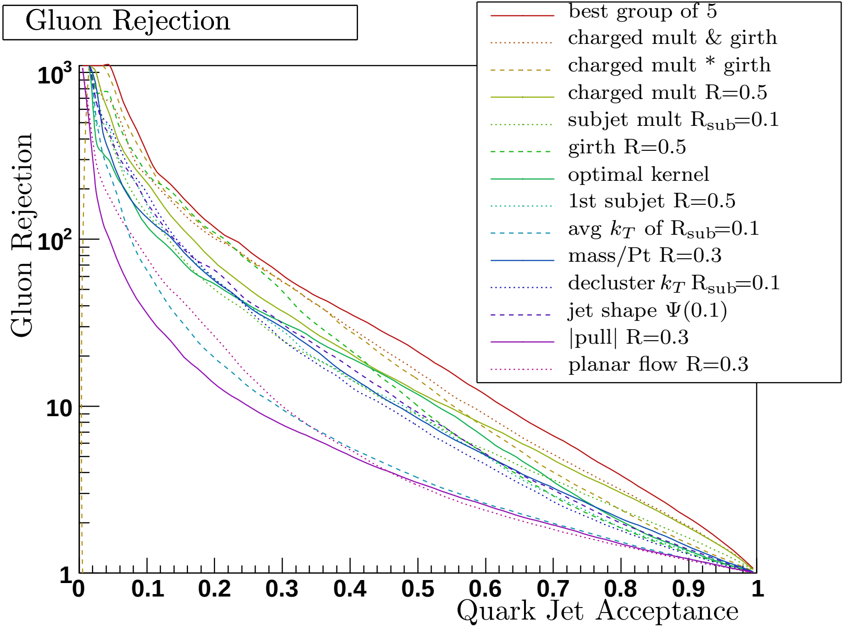
Gluon



Likelihood: $q/(q+g)$



Best Variables in Each Category for 200 GeV Jets



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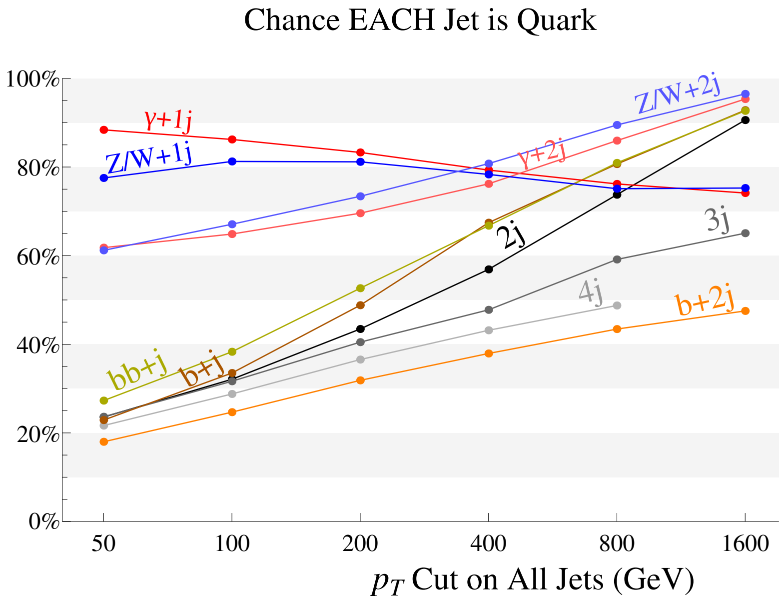
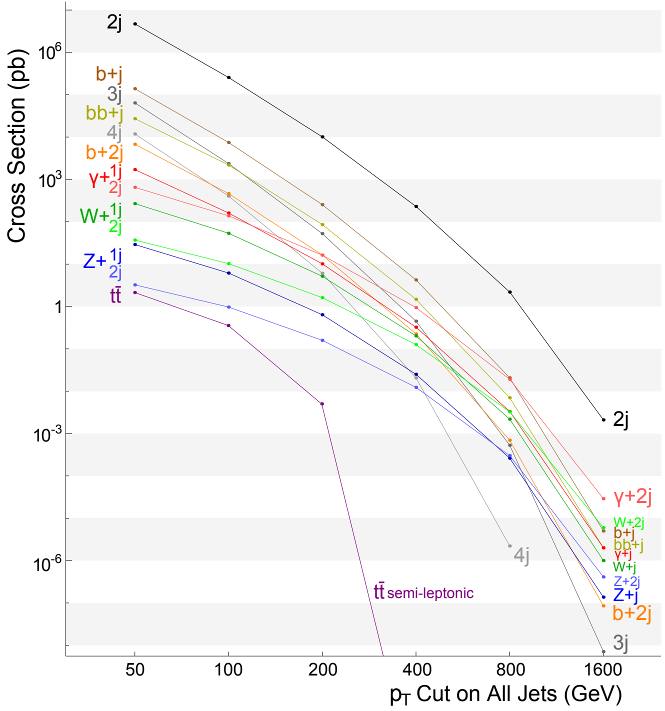
For the 8 quark gluino example, significance improvement is 14.8!

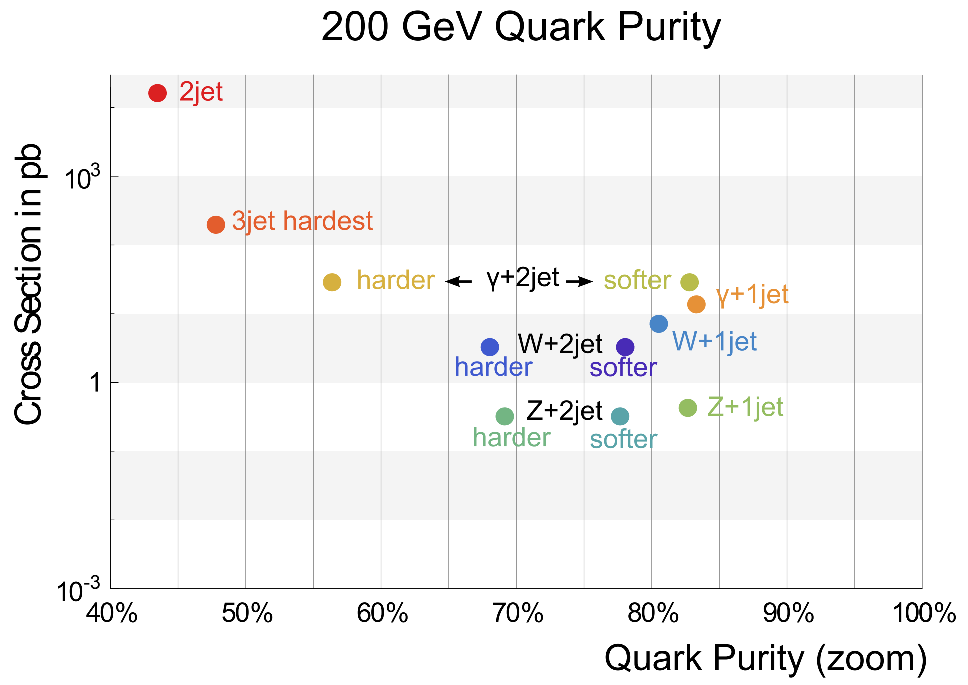
Finding Pure Samples of Quark and Gluon Jets

Starting Samples

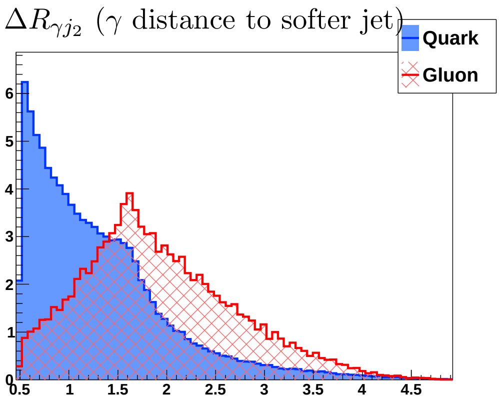




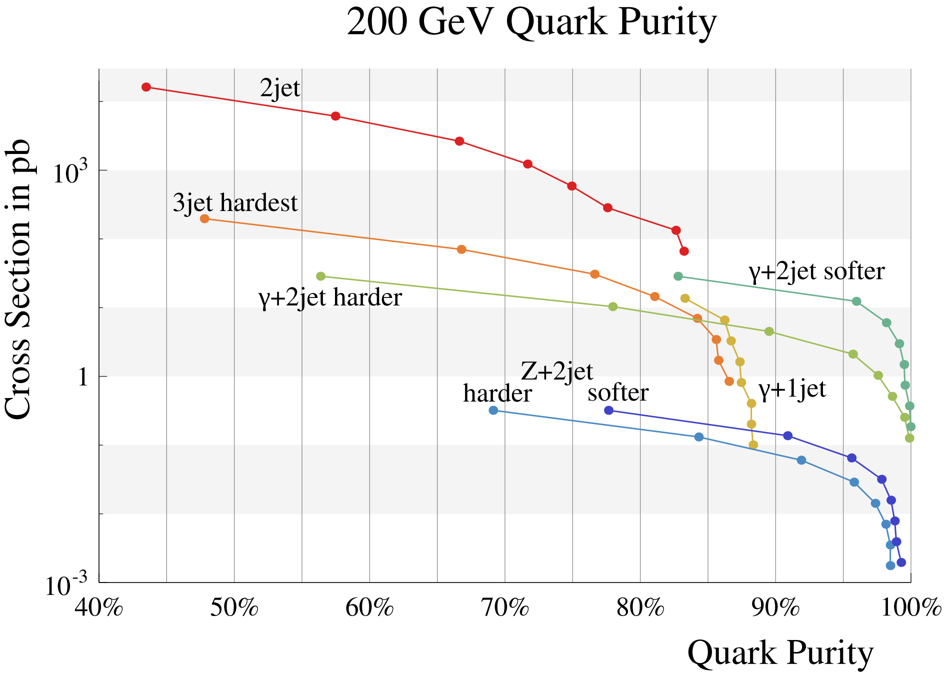
Cross Section (pb)
10^6
10^3
1
10^-3
10^-6
2j
b+j
3j
bb+j
4j
b+2j
γ+1j
2j
W+1j
2j
Z+1j
2j
tt̄
tt̄ semi-leptonic
2j
γ+2j
W+2j
b+j
bb+j
γ+j
W+j
Z+2j
Z+j
b+2j
3j
4j
50
100
200
400
800
1600
pT Cut on All Jets (GeV)


200 GeV Quark Purity
Cross Section in pb
Quark Purity (zoom)
10^3
1
10^{-3}
40%
50%
60%
70%
80%
90%
100%
2jet
3jet hardest
harder
γ+2jet
softer
γ+1jet
W+1jet
W+2jet
harder
softer
Z+2jet
Z+1jet
harder
softer

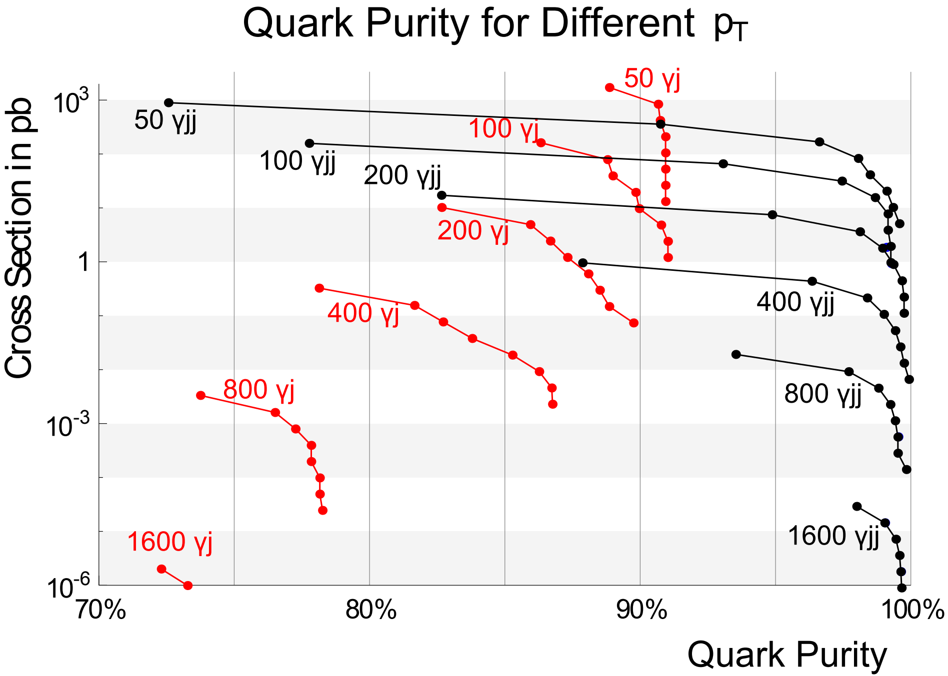
Quark Purification in γ+2jet



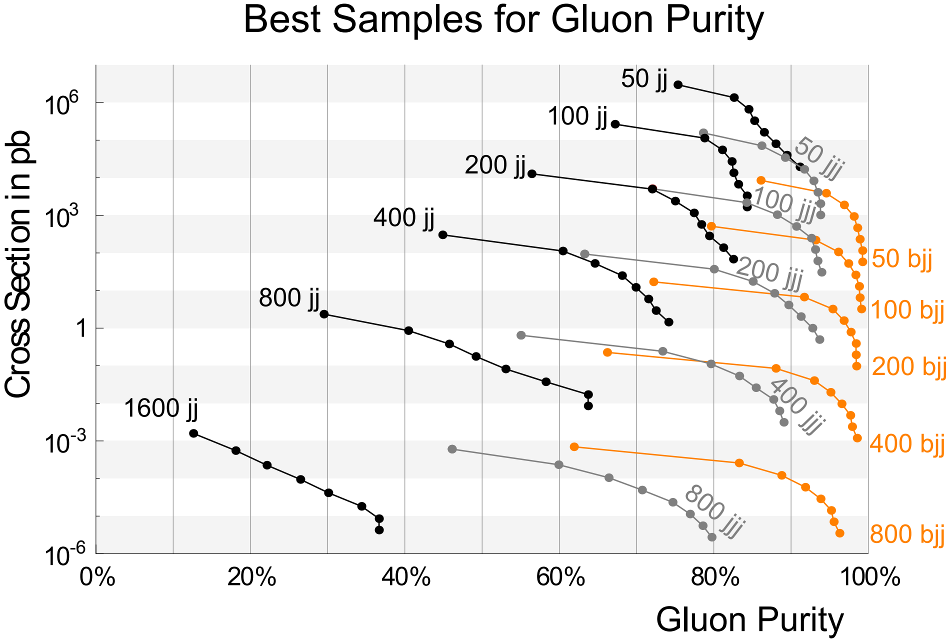
When the softer jet is quark, the photon is often radiated off of *it*, rather than the harder jet.



200 GeV Quark Purity
Cross Section in pb
10^3
1
10^{-3}
40%
50%
60%
70%
80%
90%
100%
Quark Purity
2jet
3jet hardest
γ+2jet harder
γ+2jet softer
Z+2jet
harder
softer
γ+1jet



Quark Purity for Different p_T
Cross Section in pb
Quark Purity
10^3
1
10^{-3}
10^{-6}
70%
80%
90%
100%
50 γj
100 γj
200 γj
400 γj
800 γj
1600 γj
50 γjj
100 γjj
200 γjj
400 γjj
800 γjj
1600 γjj



Best Samples for Gluon Purity
Cross Section in pb
Gluon Purity
10^6
10^3
1
10^{-3}
10^{-6}
0%
20%
40%
60%
80%
100%
50 jj
100 jj
200 jj
400 jj
800 jj
1600 jj
50 jjj
100 jjj
200 jjj
400 jjj
800 jjj
50 bjj
100 bjj
200 bjj
400 bjj
800 bjj

Summary of Finding Samples

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- ATLAS is doing so in samples of different 'known' quark/gluon fractions to back out 'pure' distributions.

QCD Jet Flavor Theory

Angle of Attack

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Claim: Nothing can go wrong that wouldn't also destroy the event's meaning/usefulness/interpretation, and those things are unlikely.

Extra Emissions?

Gluon emission:

- If it ends up in same jet (soft), this is exactly what determines the properties of the jet.
- If it creates its own jet (hard), it should have been modeled as a hard emission: ‘matching’

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Gluon splitting to quarks (light or b):

- If they end up in the same jet (soft), it's still a gluon jet.
- If they create their own jets (hard), these are quark (or b) jets.

Problem only when unrelated jets overlap.

What flavor is my Pythia jet!?

"What's the best way to find the *true* flavor of a random Pythia jet?"

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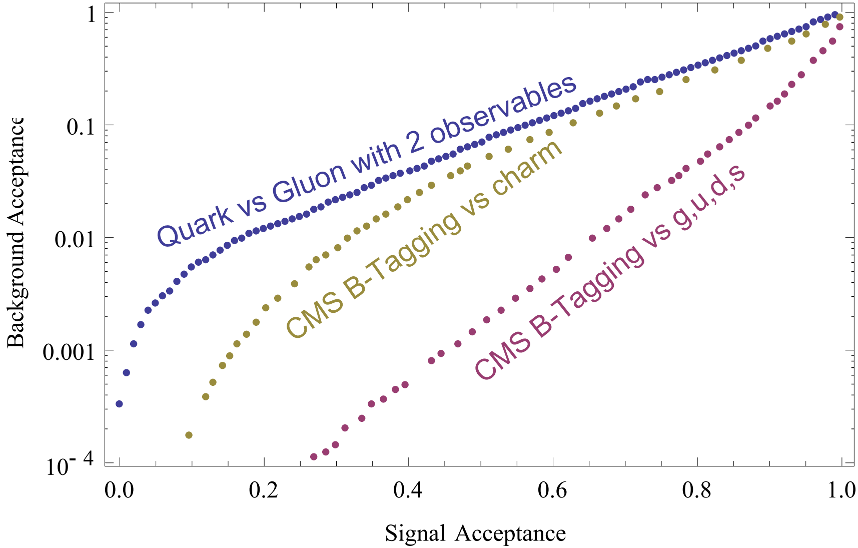
Whatever is most useful to separate real signals from real backgrounds.

Using Flavor Taggers

Cutting, S/B, and $S/\sqrt{B}$

Cutting gives some signal acceptance and some background acceptance.

Comparison to B-Tagging



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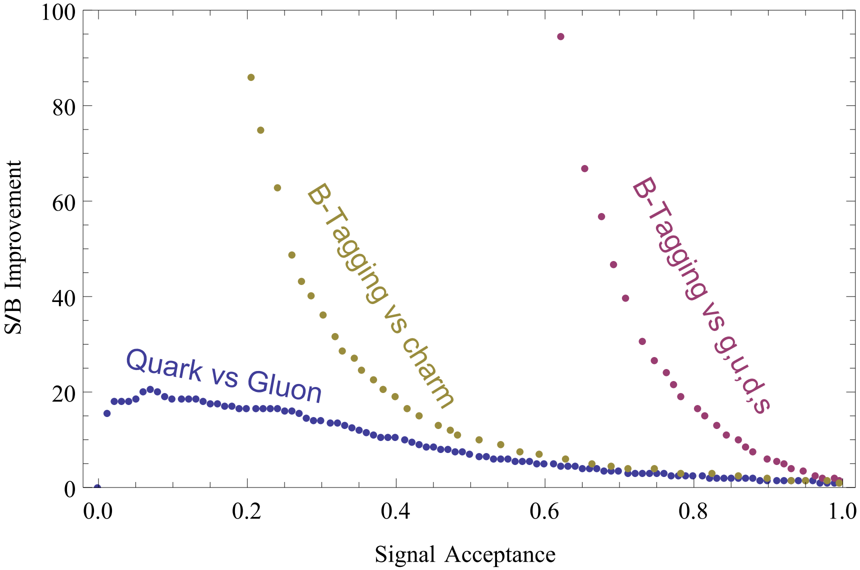
If you start with S signal events and B background events,

$$\frac{S}{B} \quad \rightarrow \quad \frac{S\epsilon_s}{B\epsilon_b} \quad = \frac{S}{B}\frac{\epsilon_s}{\epsilon_b}$$

Call $\frac{\epsilon_s}{\epsilon_b}$ the "S/B Improvement"

Comparison to B-Tagging



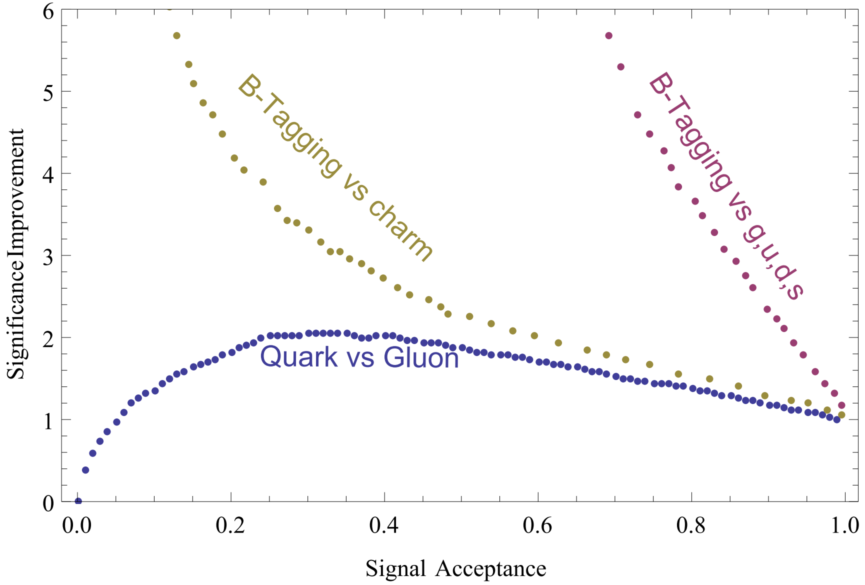
Cutting, S/B, and $S/\sqrt{B}$

Improvement in statistical significance scales differently

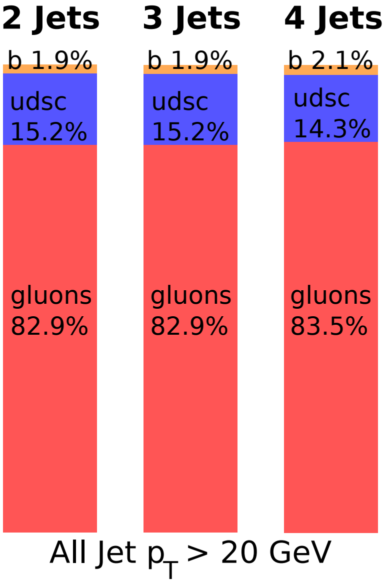
$$\sigma = \frac{S}{\sqrt{B}} \qquad \rightarrow \qquad \frac{S\epsilon_s}{\sqrt{B\epsilon_b}} = \sigma\frac{\epsilon_s}{\sqrt{\epsilon_b}}$$

Call $\frac{\epsilon_s}{\sqrt{\epsilon_b}}$ the "Significance Improvement"

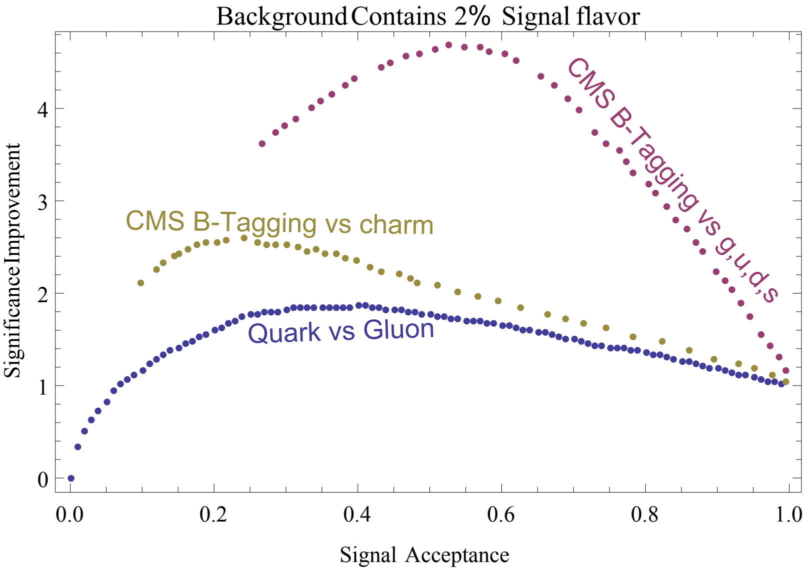
Comparison to B-Tagging



But Backgrounds Contain b's and light quarks!



Background Contains 2% 'Signal' flavor (B-case)



Background Contains 15% 'Signal' flavor (Q-case)