Gluon Tagging and Quark & Gluon Samples

How well can we do at the 7 TeV LHC?

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Harvard

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Short Outline

- **Biggest Motivation:** Reject Gluey LHC Backgrounds
- **Part 1:** The Gluon Tagger
- **Part 2:** Finding Pure Samples of Quark and Gluon Jets

Other than "Wouldn't it be nice to know?"

Most *new physics* gives quark rather than gluon jets:

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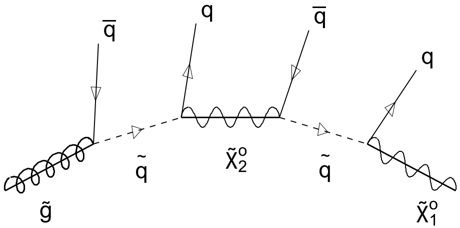

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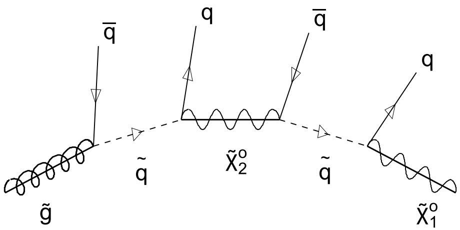

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Assignment: Your favorite example of gluon or non-b quark signals.

Motivation

Interesting *standard model physics* also tends to be quark-heavy

- Tops ($t\bar{t} \to$ 4 or 6 quarks)
- W's decaying hadronically (there's no b-tag): $W^+ \to u\bar{d}$ or $c\bar{s}$
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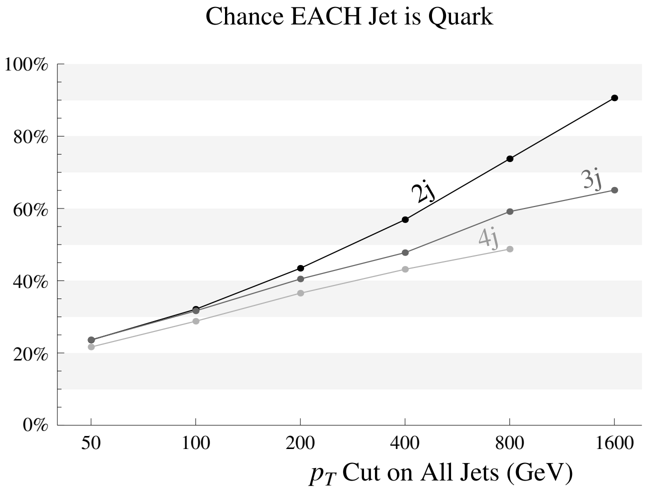
Eventually combine Gluon-Tagging with B-Tagging and τ-Tagging



So chance that all 4 jets $\gtrsim 100\,GeV$ are quark: $(30\%)^4 = 0.8\%$

Outline

- **Biggest Motivation:** Reject Gluey LHC Backgrounds
- **Part 1:** The Tagger
  - Example Observables: Jet Mass and Charged Track Count
  - Evaluating the power of observables: Background Rejection
  - Familiar presentation of 'Jet Shape' and its problems
  - Measuring 'size' of jets
  - Combining 2 or more observables
- **Part 2:** Finding Pure Samples of Quark and Gluon Jets

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What's different now than 20 years ago?

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- LHC is very jetty and *pp* is more gluey.
- The most difficult signals are buried under multi-jet events.

Goal

Which observables are useful:

- Individually?
- When combined?

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Interesting variables can be:

- Studied theoretically
- Verified experimentally

Differences in Quarks vs Gluons

- Color Charge: C_F vs C_A $\rightarrow$ jet mass, size, track count
- Color Connections: 1 vs 2 $\rightarrow$ eccentricity and pull
- Electrical Charge $\rightarrow$ charge-weighted track p_T
- Spin: 1/2 vs 1 $\rightarrow$ not explicitly used
- ...

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

Gluon adjoint's C_A vs Quark fundamental's C_F

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Brief QCD Showering Theory

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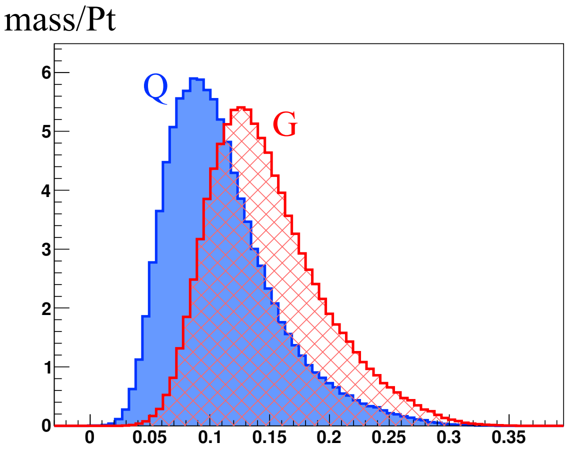
Jet Mass in the small angle limit:

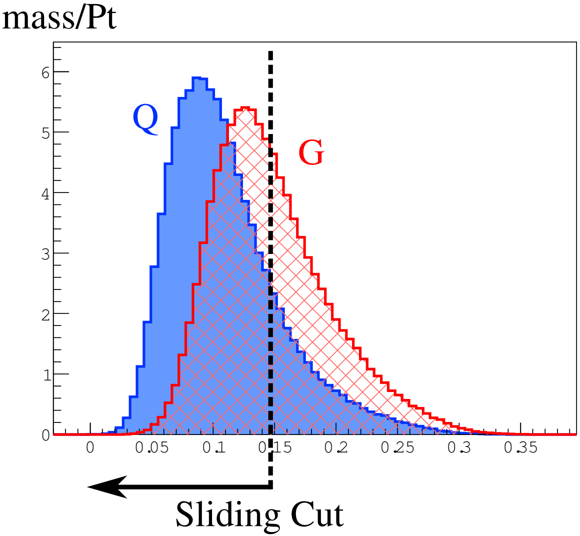
$$\left\langle M^2 \right\rangle = C \frac{\alpha_s}{\pi} p_T^2 R^2$$

where $C \sim C_A$ for gluon jets, and $\sim C_F$ for quark jets.

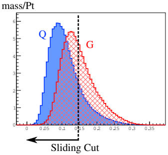
Jet Mass in Detail

- Normalizing by p_T (200 GeV in this sample) generalizes better.




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

ROC Curve


mass/Pt
Q
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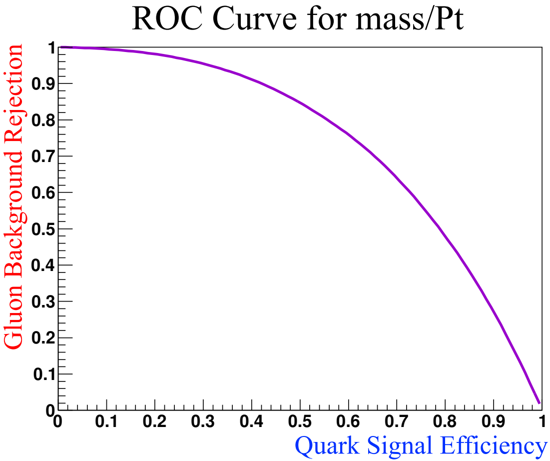
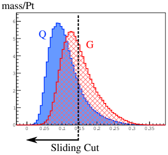

ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

ROC Curve


mass/Pt
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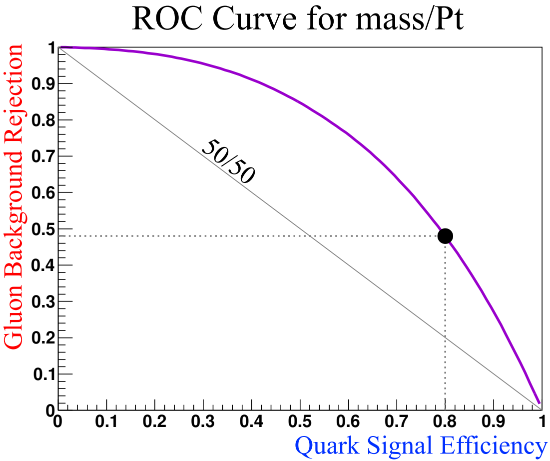
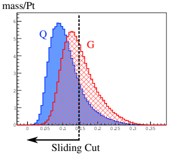
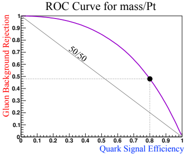
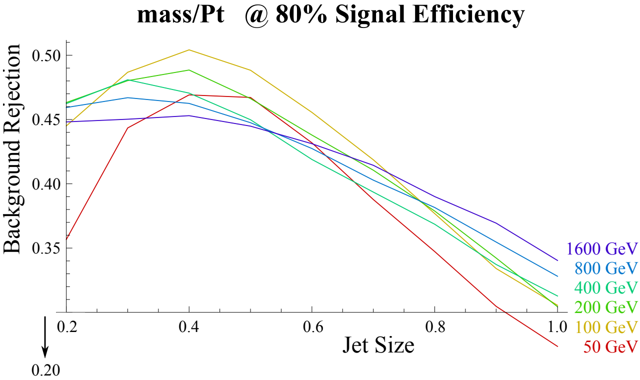

ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
50/50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Other Jet Sizes and p_Ts







Rather than showing $10 * 6 = 60$ ROC Curves, pick 80% point on each

Brief Theory II

Gluon adjoint's C_A vs Quark fundamental's C_F

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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).

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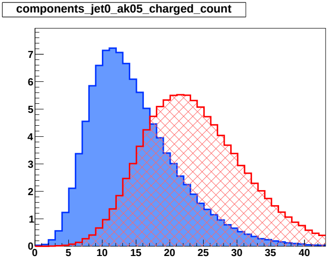
$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F} \qquad \frac{\sigma_g^2}{\sigma_q^2} = \frac{C_A}{C_F}.$$

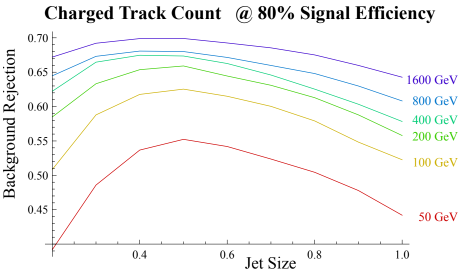
(Calculated to $\mathrm{N^3LO}$ by Capella, et al. hep-ph/9910226)

No detector simulation, but require charged particles $p_T > 500\,\mathrm{MeV}$.

Charged Particles Count

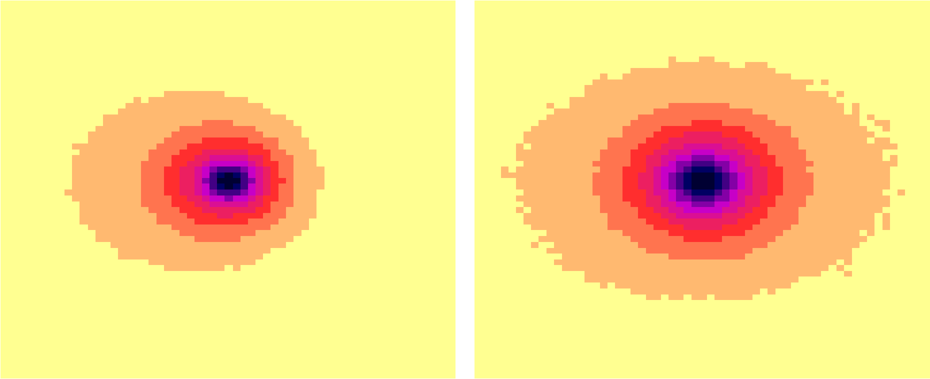
...this old favorite does quite well at high p_T:





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

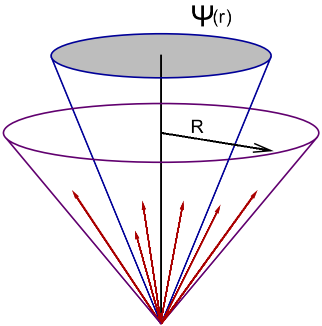
Accumulate 3 million back-to-back dijet events

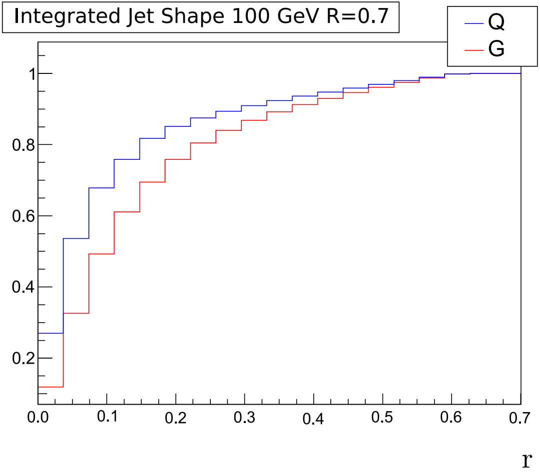


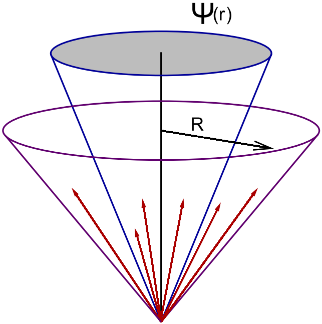
Quark Jets

Gluon Jets

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


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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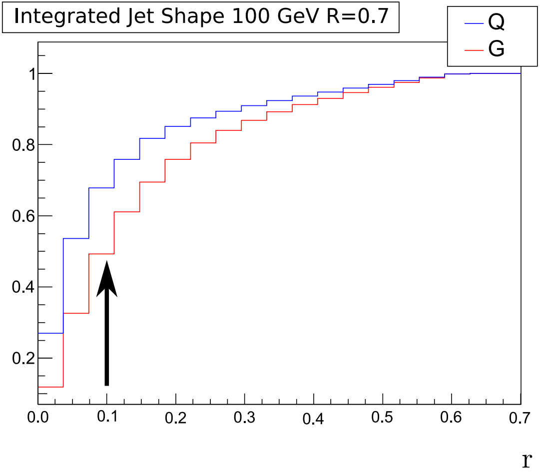
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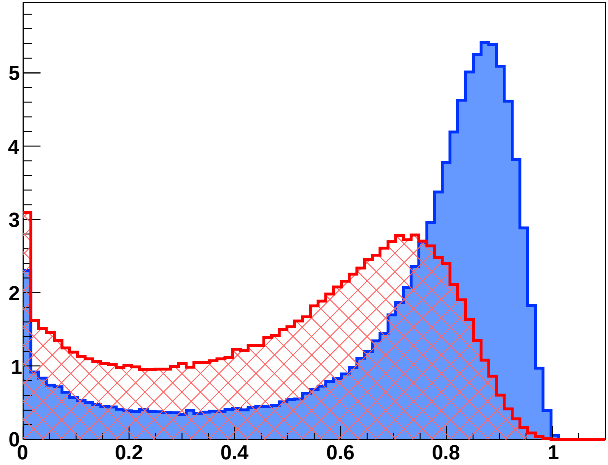
0.5
0.6
0.7
r

Jet Shape *Distribution* vs *Average*

Integrated Jet Shape out to $r = 0.1$ for 100 GeV

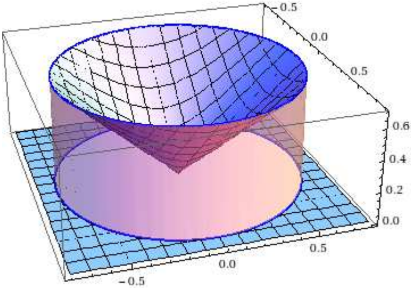


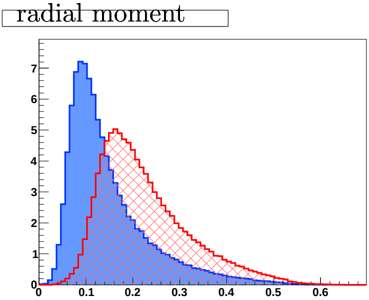
- Distribution is *not* narrow gaussian around average
- Correlations *between* bins is also useful

Radial Moment – a measure of the "girth" of the jet

Weight p_T deposits by distance from jet center

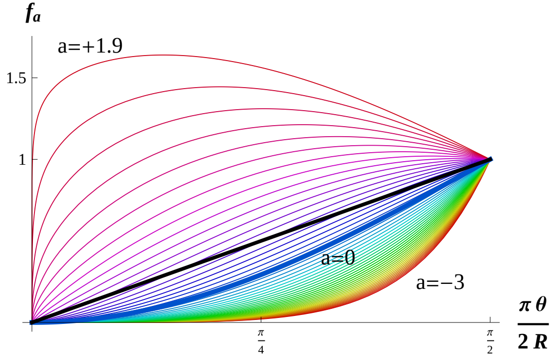
$$\text{Radial Moment, or Girth :} \qquad g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$



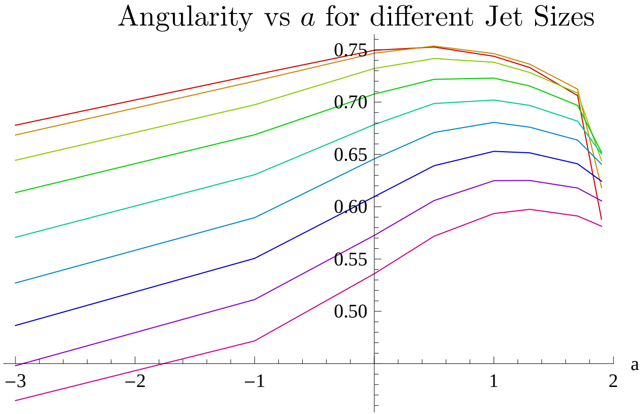


$$\text{Jet Angularities :} \qquad A_a = \sum_{i \in \text{jet}} E_i \ f_a(\theta)$$

$$f_a(\theta) = \sin^a\theta \ (1 - \cos\theta)^{1-a} \qquad \text{with } \theta = \frac{\pi |r_i|}{2R} \quad \text{or just } \theta$$

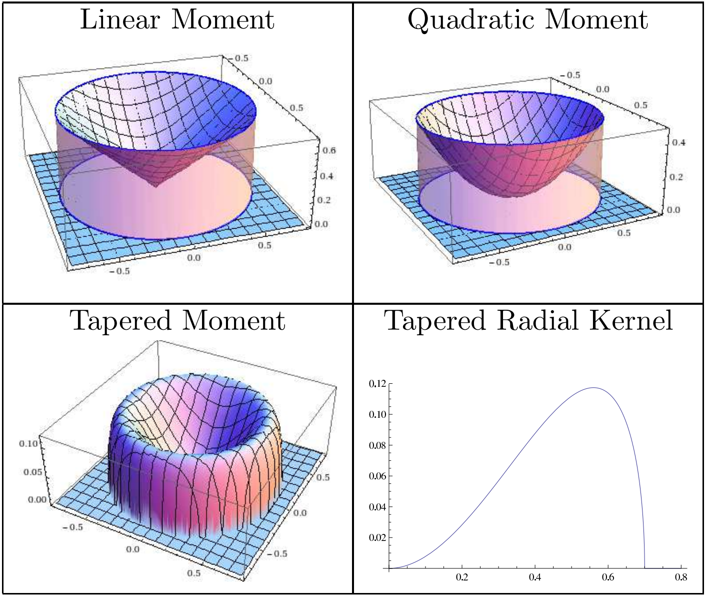


Normalization? none, mass, jet energy, jet p_T.

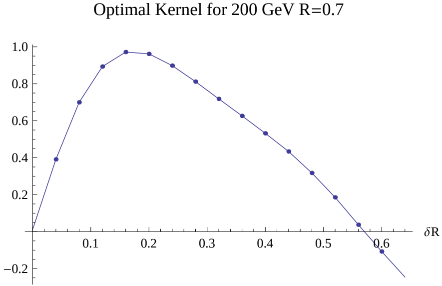


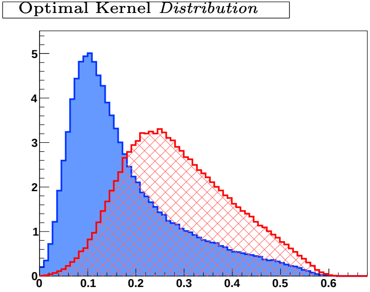
Small R=0.2 Jets (red) perform better than Large R=1.0 Jets (pink)

Radial Moments and Their Kernels



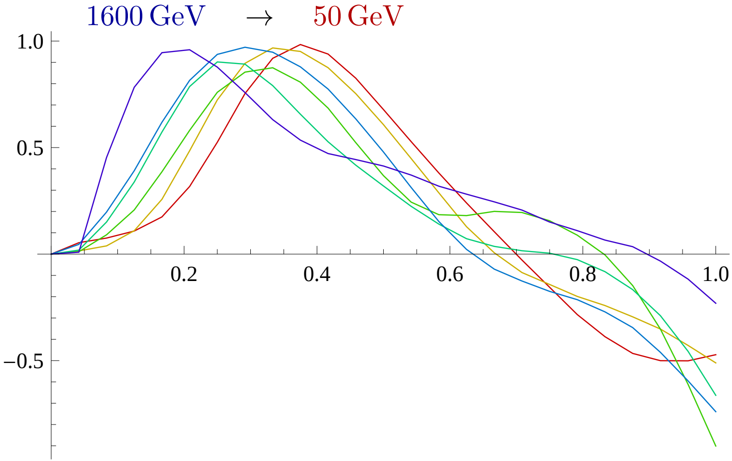
Optimal Kernel





- Positive kernel weights mean gluon-like.
- Overall vertical shift or scaling leads to same distribution.
- Quarks have most of their p_T near the center.

Optimal Kernel for different p_T's and $R = 1.0$

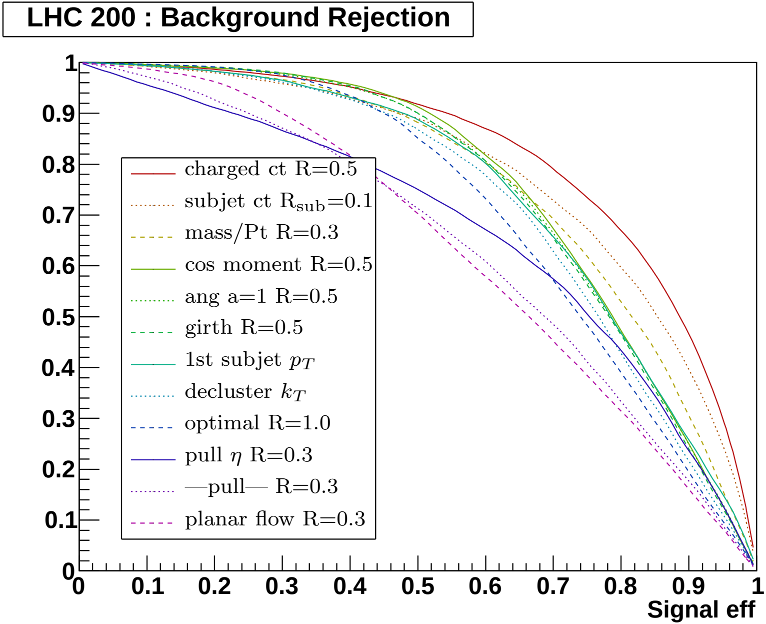


Types of Variables

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, 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.
  - Each subjet's mass
  - Splitting k_T scale

Best Variables in Each Category



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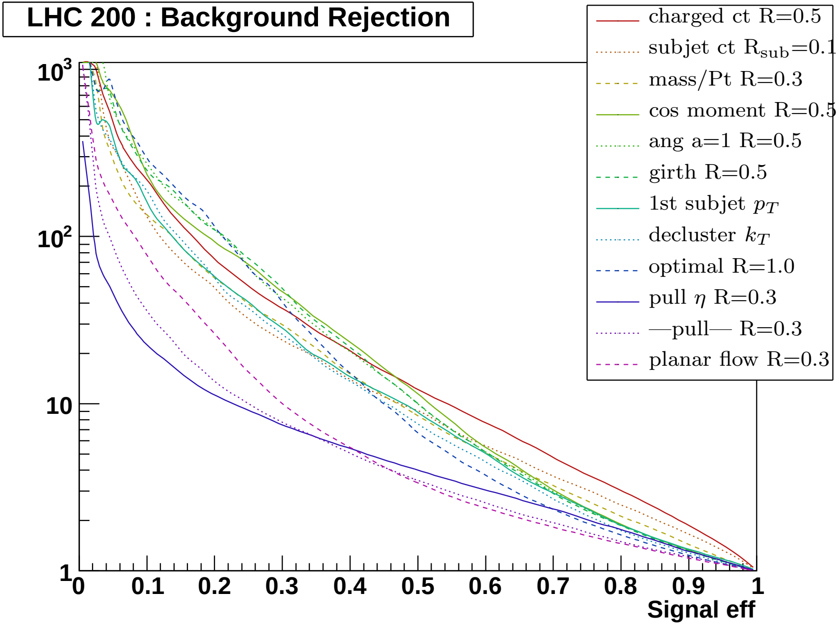

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- Keep only 40% of gluons while keeping 80% quarks
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- Optimize S/B?
- Optimize $S/\sqrt{B}$?

Cutting and $S/\sqrt{B}$

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Improvement in statistical significance scales differently

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

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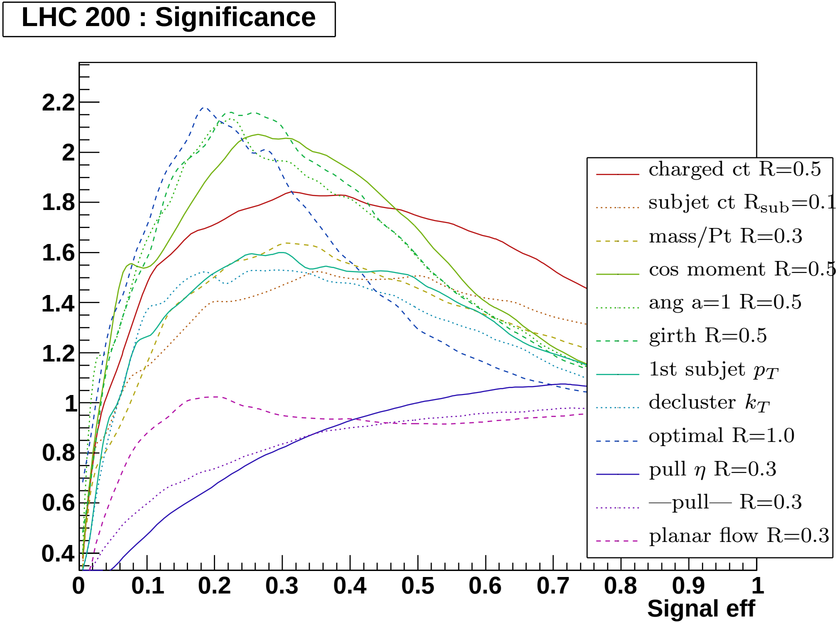
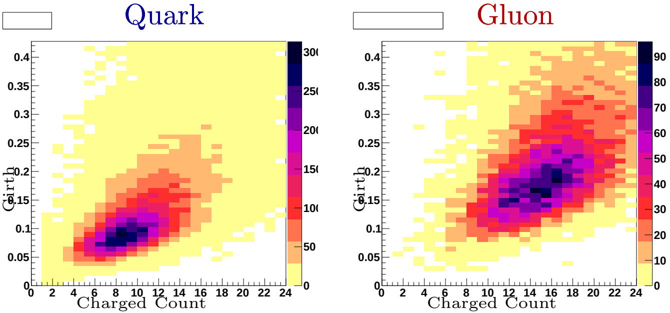
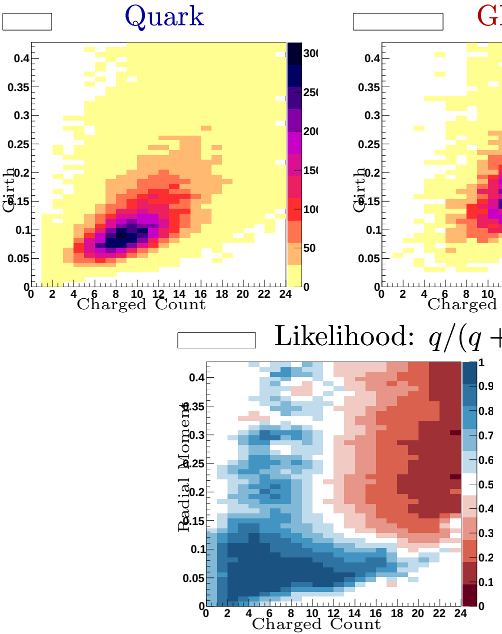
Cutting can improve significance only to a point...

Significance Improvements for Best Single Variables

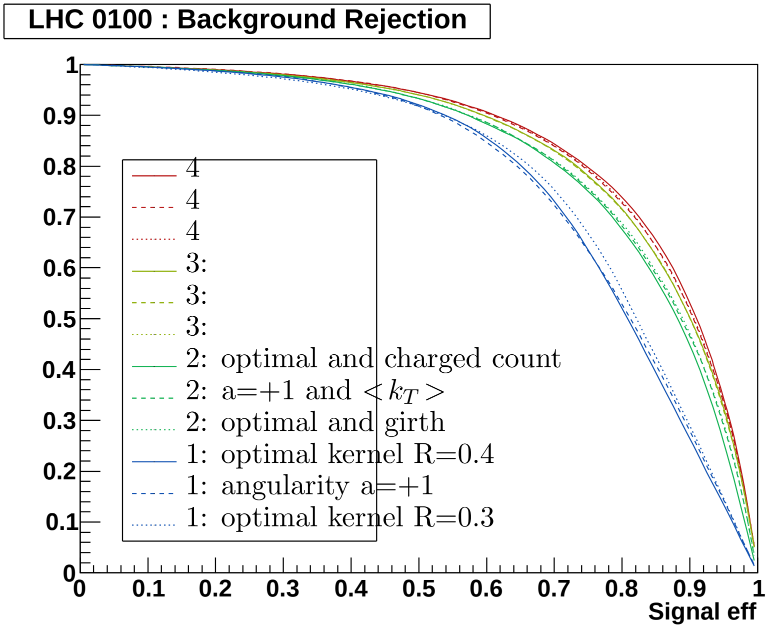


Combining Variables: Ex. Girth vs Charged Count

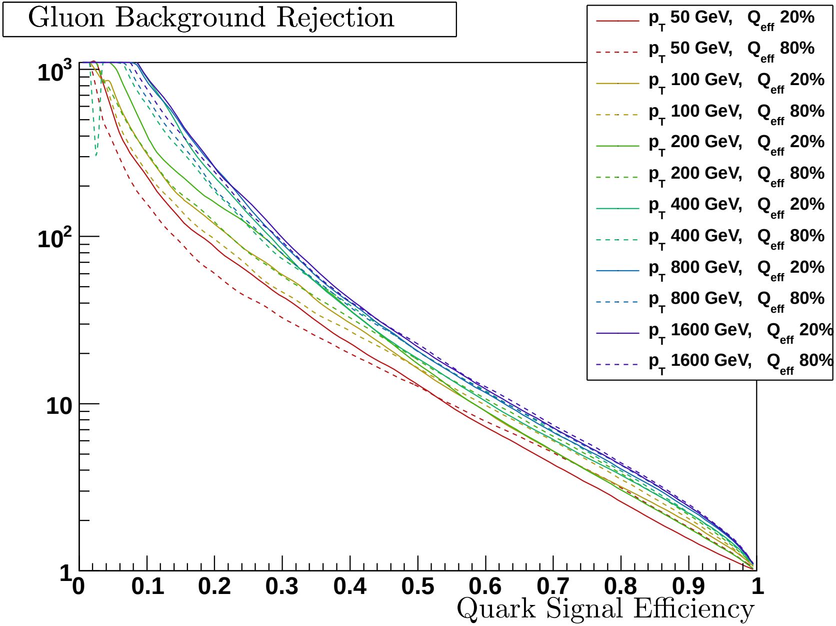



Quark
Gluon
Girth
Charged Count
Likelihood: $q/(q+g)$
Radial Moment

ROC Curves for Best Combinations



Final Results: Best Pairs



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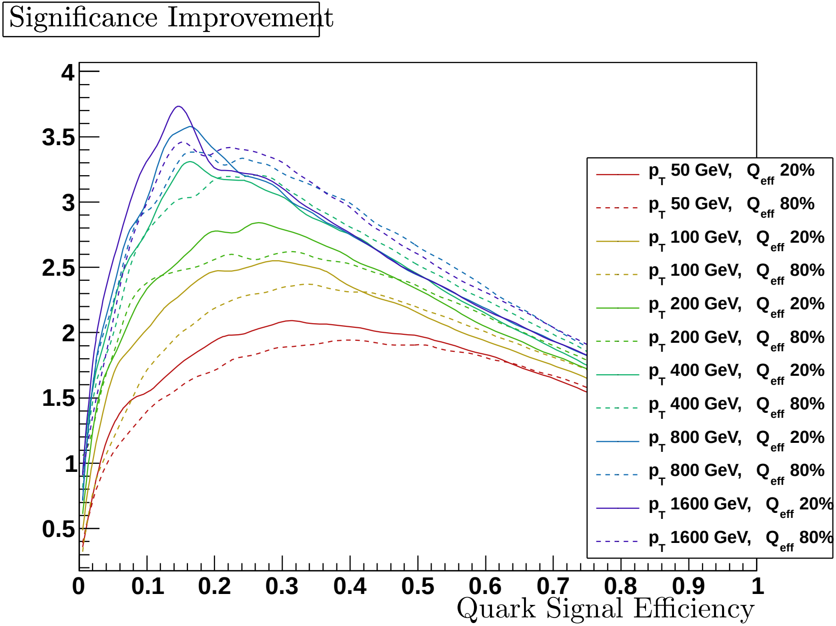

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TODO:

- Real Signals and Backgrounds (e.g. SUSY, $WW \to 4jet$)

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Differences in these variables are worth verifying & calculating.

TODO:

- Real Signals and Backgrounds (e.g. SUSY, $WW \to 4jet$)
- Use tagger to *measure* Q/G fraction (e.g. W+jets)

Summary of Gluon Tagging

Can reject 80% of gluons while keeping 80% quarks
Can reject 95% of gluons while keeping 50% quarks

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- Use tagger to *measure* Q/G fraction (e.g. W+jets)
- Encourage Atlas and CMS to squeeze out the most spatial resolution that they can.

Summary of Gluon Tagging

Can reject 80% of gluons while keeping 80% quarks
Can reject 95% of gluons while keeping 50% quarks

We can improve $S/\sqrt{B}$ on quark-only signals by a factor of 2x-3x.

For 4-jets, all of these get raised to the 4th for glue-heavy background.
Differences in these variables are worth verifying & calculating.

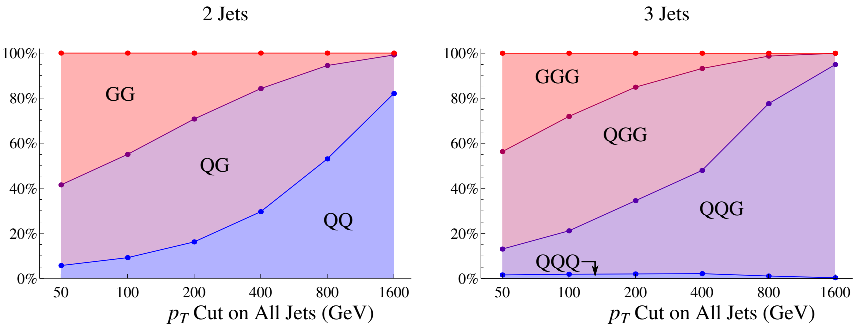
TODO:

- Real Signals and Backgrounds (e.g. SUSY, $WW \to 4jet$)
- Use tagger to *measure* Q/G fraction (e.g. W+jets)
- Encourage Atlas and CMS to squeeze out the most spatial resolution that they can.
- Integrate these variables into FastJet or SpartyJet.

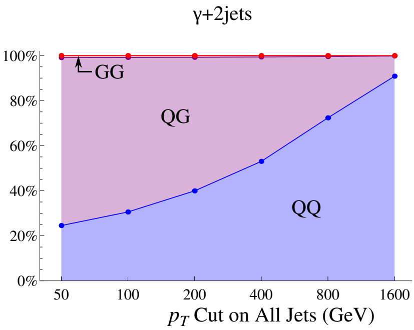
Outline

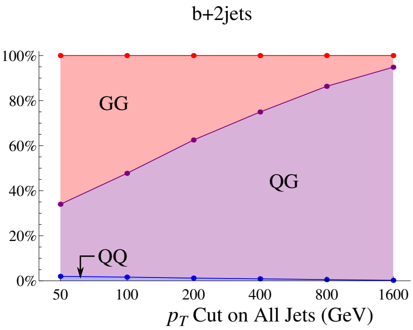
- **Biggest Motivation:** Reject Gluey LHC Backgrounds
- **Part 2:** The Gluon Tagger
- **Part 2:** Finding Pure Samples of Quark and Gluon Jets
  - Goal: High Purity with a high Cross Section
  - Use MADGRAPH tree-level samples
  - Find kinematic variables to cut on
  - 2D combinations and/or Multivariate Techniques
  - 99% Quark purity from γ+2jets
  - 95% Gluon purity from 3jets
  - **arXiv:1104.1175 [hep-ph]** with Matt Schwartz

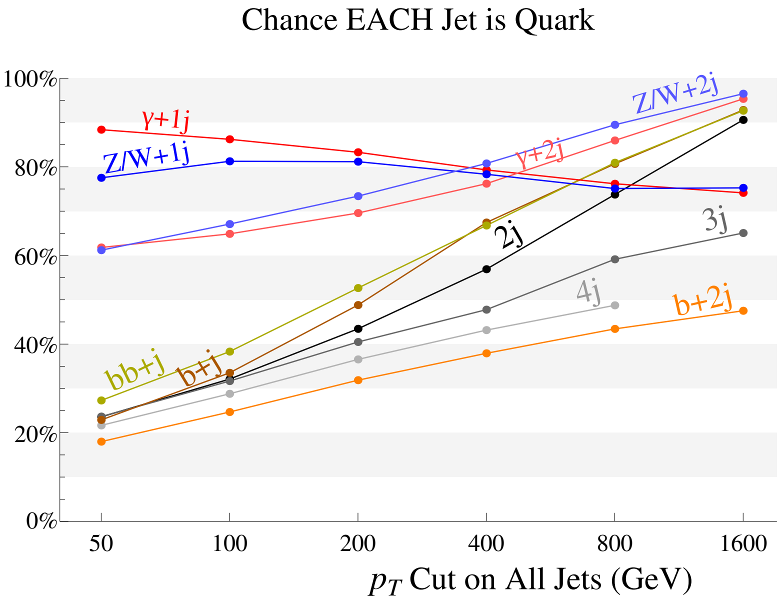
Detailed Multi-Jet Composition

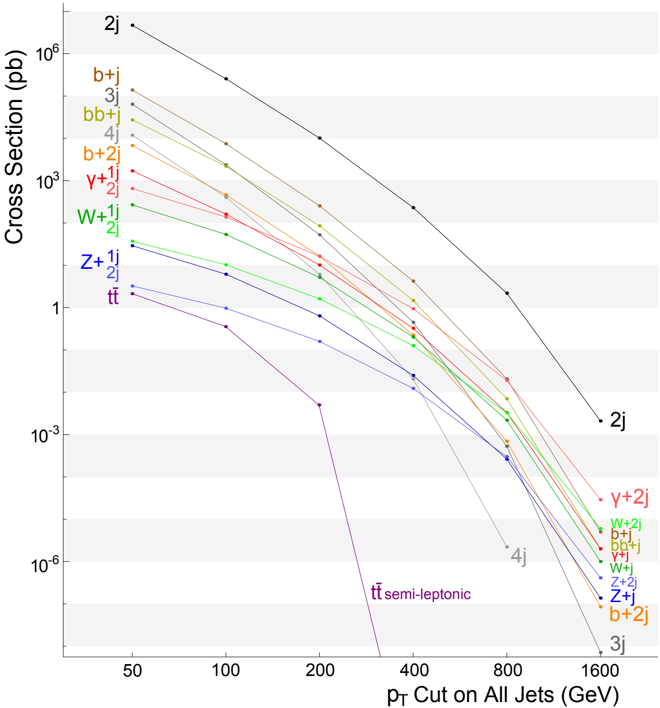


Result of Parton Distribution Functions

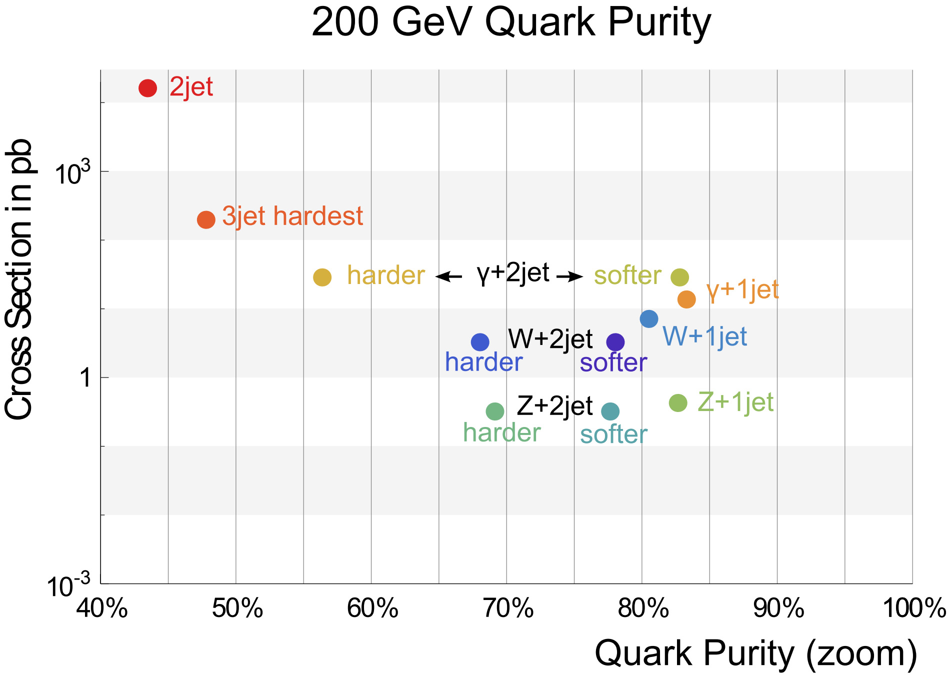

γ+2jets
100%
80%
60%
40%
20%
0%
GG
QG
QQ
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)


b+2jets
100%
80%
60%
40%
20%
0%
GG
QG
QQ
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)

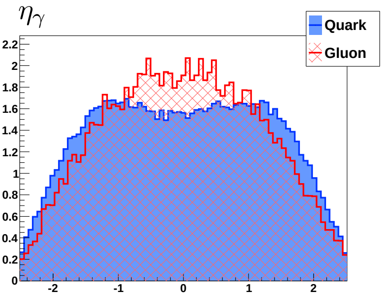

Chance EACH Jet is Quark
100%
80%
60%
40%
20%
0%
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)
γ+1j
Z/W+1j
Z/W+2j
γ+2j
2j
3j
4j
b+2j
bb+j
b+j

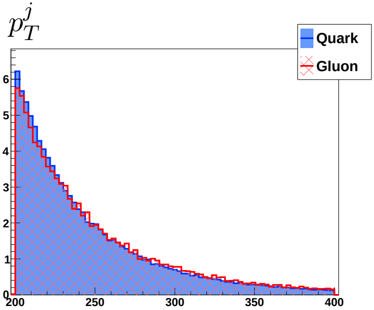


Cross Section (pb)
10^6
10^3
1
10^{-3}
10^{-6}
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)
2j
b+j
3j
bb+j
4j
b+2j
γ+1j
2j
W+1j
2j
Z+1j
2j
$t\bar{t}$
2j
γ+2j
W+2j
b+j
bb+j
γ+j
W+j
Z+2j
Z+j
b+2j
3j
4j
$t\bar{t}$ semi-leptonic


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

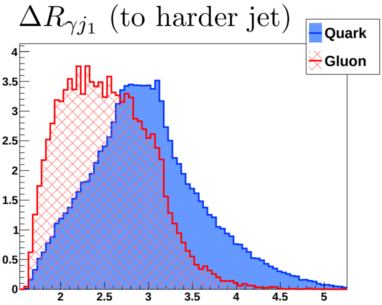
Quark Purification in γ+1jet

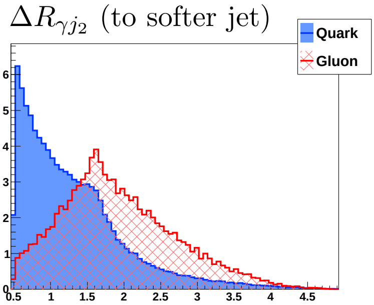




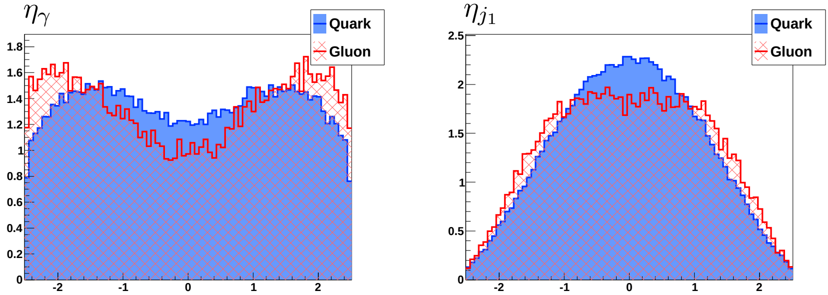
Kinematics are too similar to do much:

- $gq \to \gamma q$: Quark signal
- $q\bar{q} \to \gamma g$: Gluon background



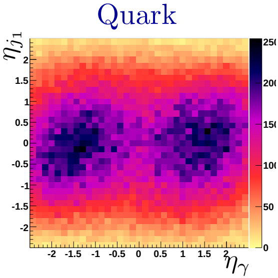


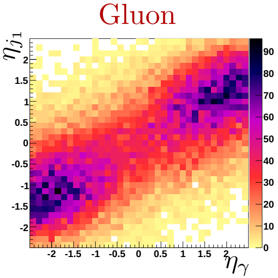
When the softer jet is quark, The photon is often radiated off of it, rather then the harder jet.



Other useful kinematics (?)

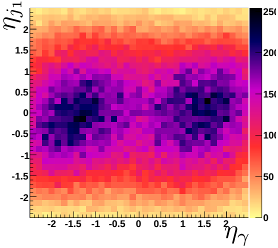
2D version of the same



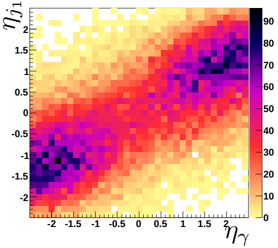


2D version of the same

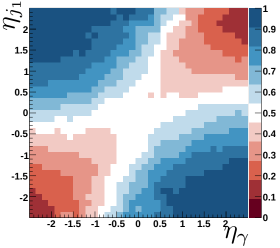
Quark



Gluon

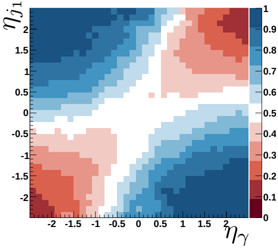


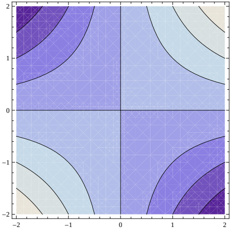
Likelihood



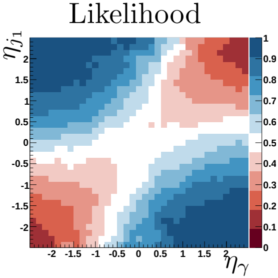
Approximating the Likelihood Contours with $f(x,y) = xy$

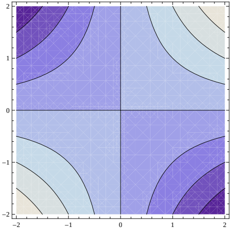
Likelihood

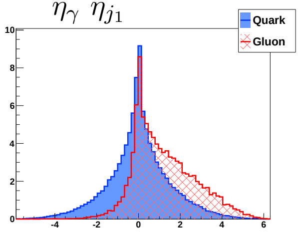




Approximating the Likelihood Contours with $f(x, y) = xy$

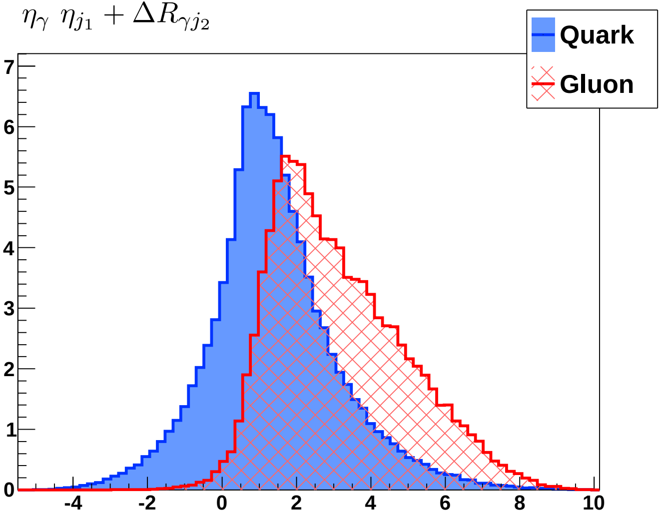




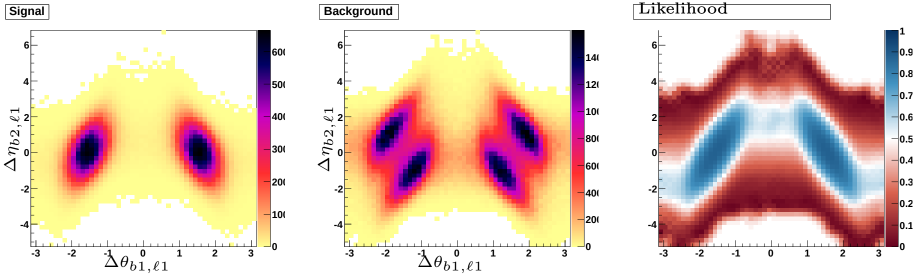


Do it again to find an even better combination

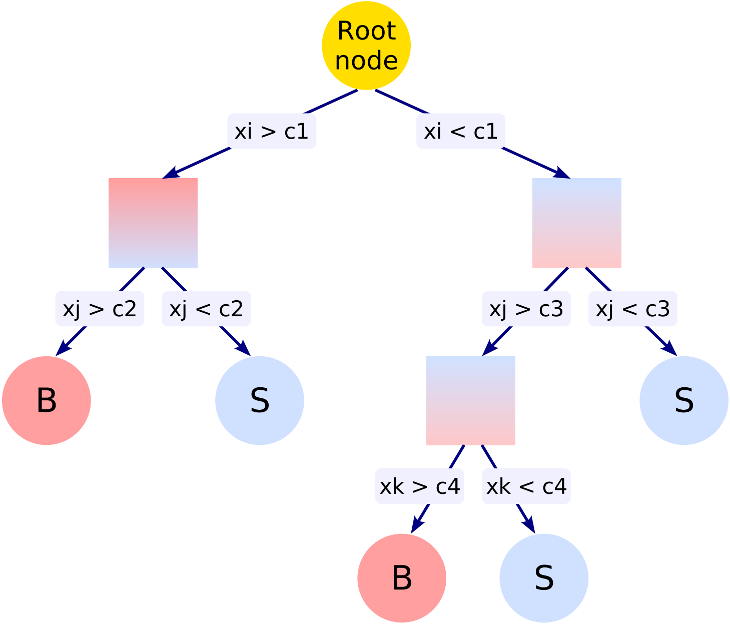
$\eta_\gamma \ \eta_{j_1} + \Delta R_{\gamma j_2}$



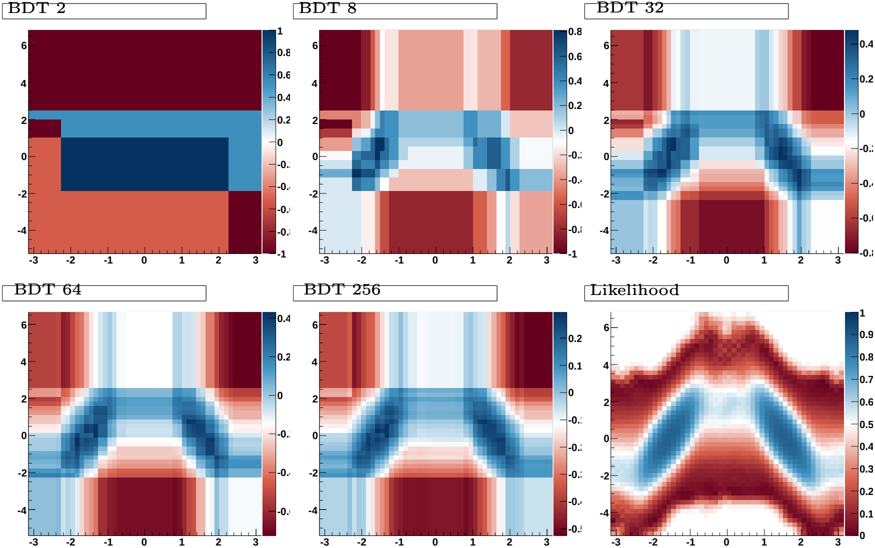
Some totally crazy illustrative example from my Higgs+Z work:

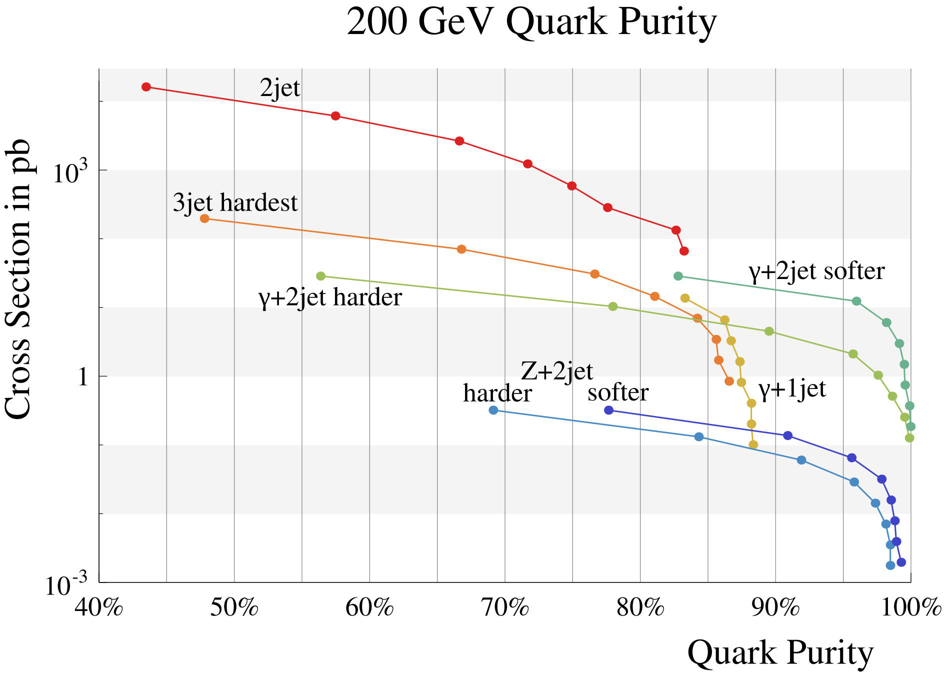


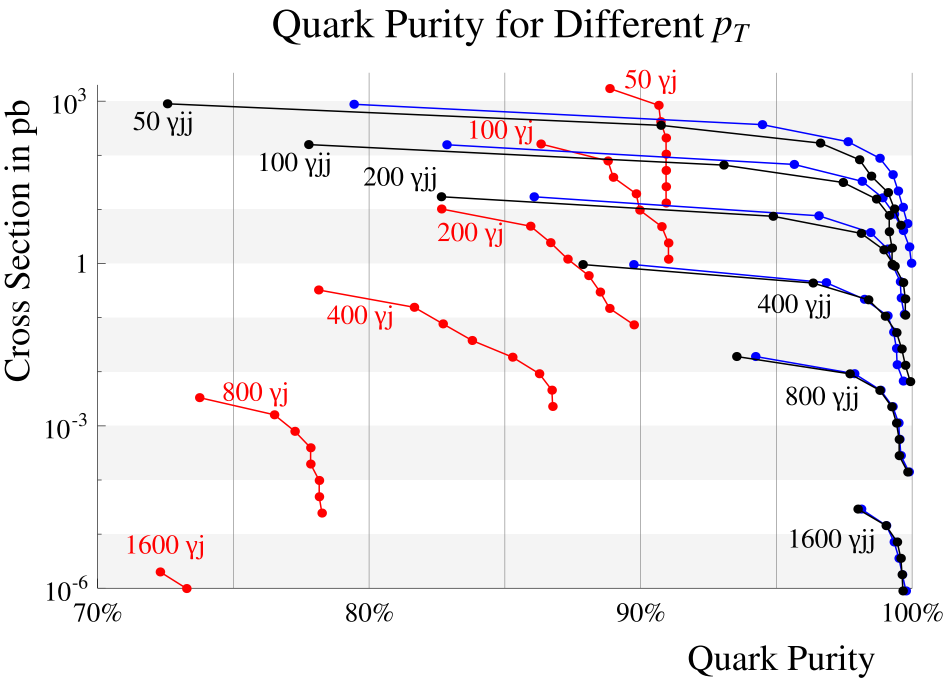
Automating the process with Boosted Decision Trees

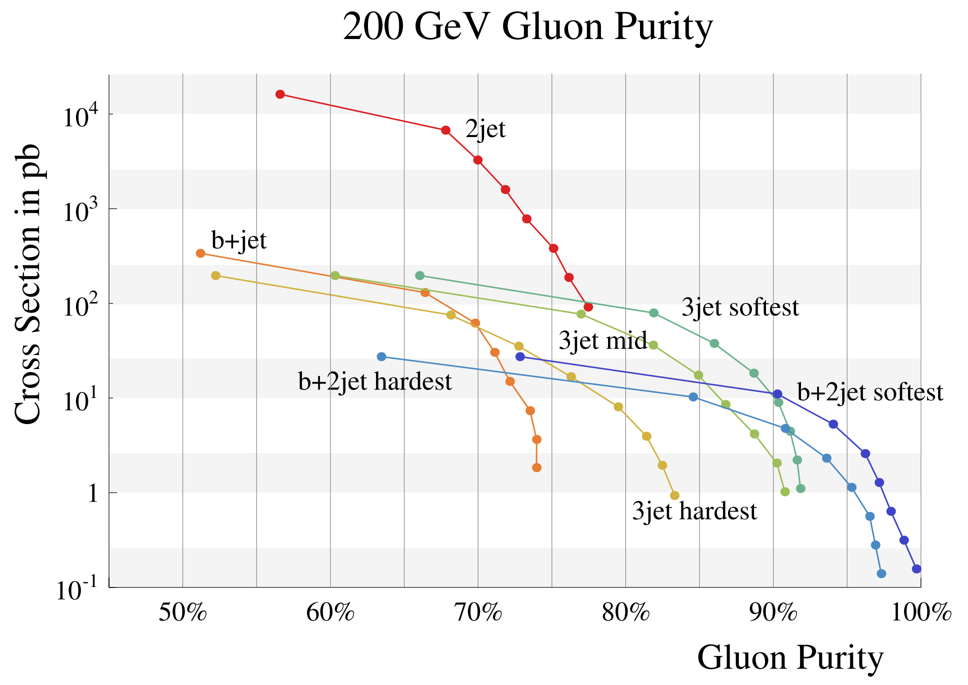


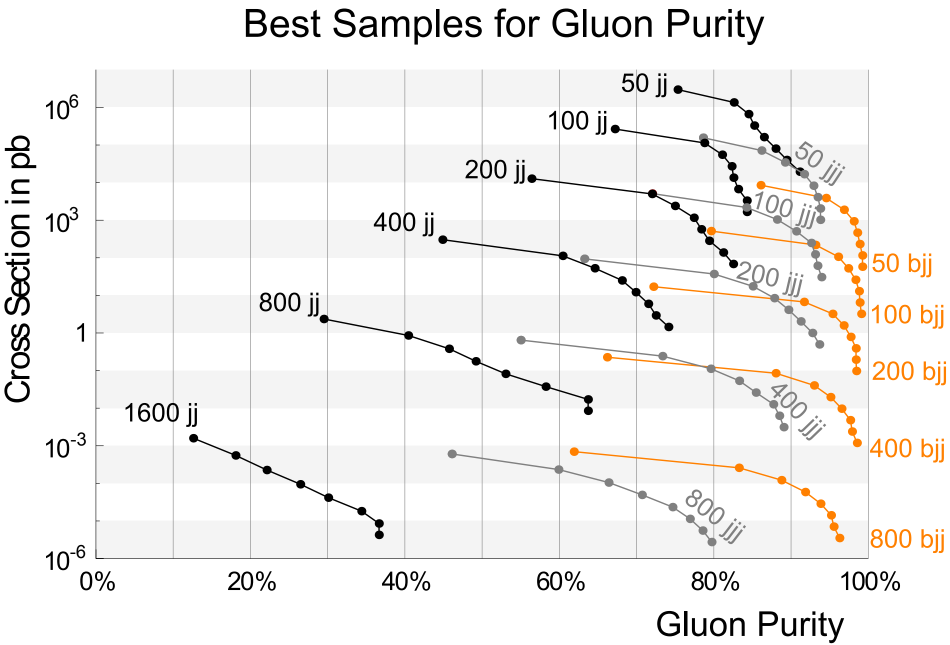
Do **Not** ***Fear*** Boosted Decision Trees




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


200 GeV Gluon Purity
Cross Section in pb
10^4
10^3
10^2
10^1
1
10^{-1}
2jet
b+jet
3jet softest
3jet mid
b+2jet hardest
b+2jet softest
3jet hardest
50%
60%
70%
80%
90%
100%
Gluon Purity



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

- Quark samples at 99% purity for γ+jet
- Gluon samples at 90%-95% purity for 3jets

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- Gluon samples at 95%-99% purity for b+2jets with perfect B-Tagging and B-Anti-Tagging

Summary of Finding Samples

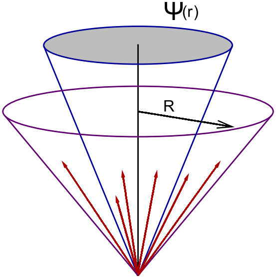
- Quark samples at 99% purity for γ+jet
- Gluon samples at 90%-95% purity for 3jets

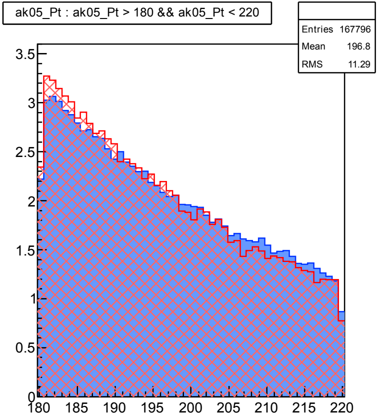
- Gluon samples at 95%-99% purity for b+2jets with perfect B-Tagging and B-Anti-Tagging

Now go forth and use these tools for good.... Thanks!

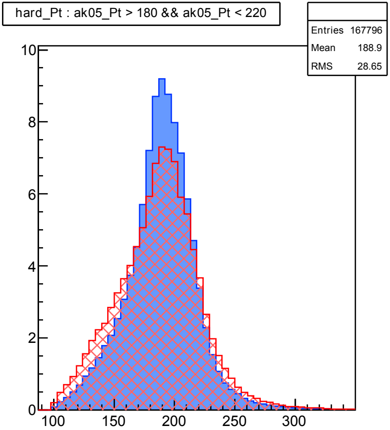
In case waving my hands proves insufficient ...

- Number of charged tracks
- Jet Shape (shown)
- LEP $e^+e^- \to Zg \to b\bar{b}g$





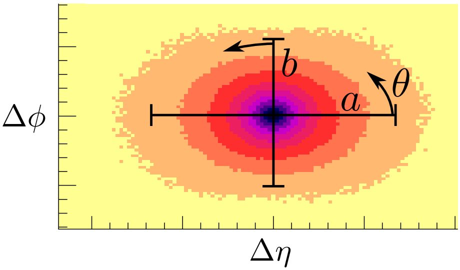
Jet p_T: anti-k_T R=0.5



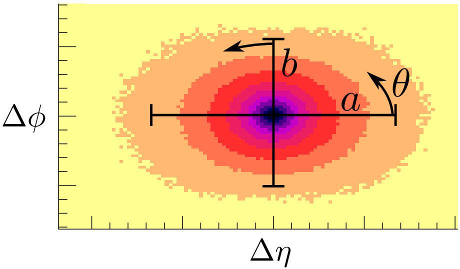
Hard Parton p_T

Moment of Inertia / Covariance / Eccentricity

Covariance Tensor: $\mathbf{C} = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} \begin{pmatrix} \Delta\eta_i\Delta\eta_i & \Delta\eta_i\Delta\phi_i \\ \Delta\phi_i\Delta\eta_i & \Delta\phi_i\Delta\phi_i \end{pmatrix}$



Covariance Tensor: $$\mathbf{C} = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} \begin{pmatrix} \Delta\eta_i \Delta\eta_i & \Delta\eta_i \Delta\phi_i \\ \Delta\phi_i \Delta\eta_i & \Delta\phi_i \Delta\phi_i \end{pmatrix}$$



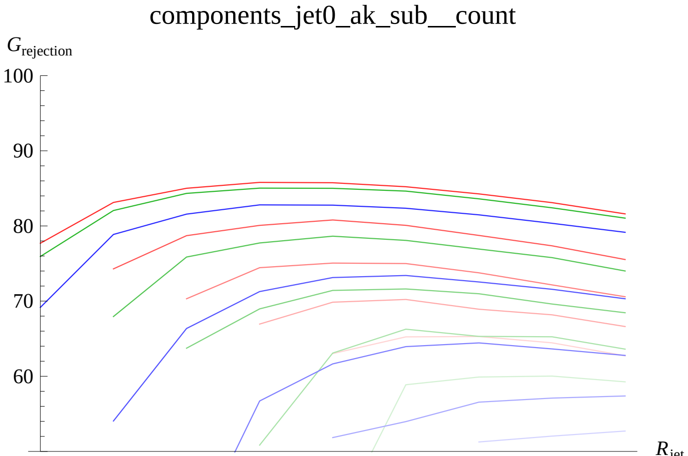
Combination of Eigenvalues

Girth:	$g = \sqrt{a^2 + b^2}$
Determinant:	$det = a \cdot b$
Ratio:	b/a
Eccentricity:	$\epsilon = \sqrt{a^2 - b^2}$
Planar Flow:	$pf = \frac{4ab}{(a+b)^2}$
Orientation:	θ

Not useful for Q vs G: first emission sets this shape, and has similar 2-body kinematics.

Subjets – Smaller is Better

- Subjet Algorithm: anti-k_T, CA, k_T
- Subjet Size: Darkest is $R_{\text{sub}} = 0.1$, lightest $R_{\text{sub}} = R_{\text{jet}}$



(Background Rejection at 50% Quark vs Initial Jet Size)

Explosion of Variables

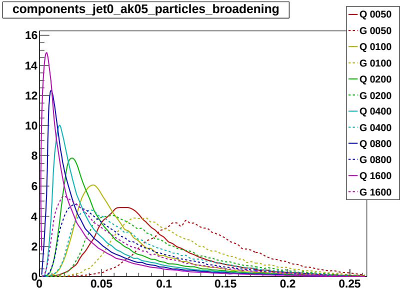
Explosion of Variables

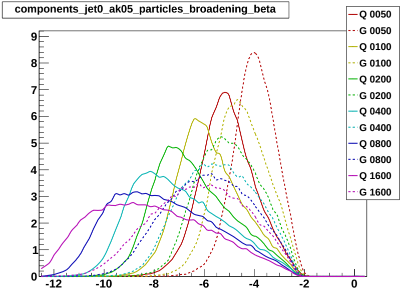
- Different Jet sizes ($R = 0.1, 0.2, 0.4, 0.7, 1.0, 1.4, ...$)
- Different Jet definitions (anti-kt, kt, CA, SisCone)
- Different Generators: Pythia vs Herwig
- Different Samples: Dijet vs γ+jet vs 8-Jets
- Different Subjet sizes and types
- Different Powers in the various moments
- Charged Tracks or Calorimeter deposits?

And different variables are better for different Jet p_T ranges.

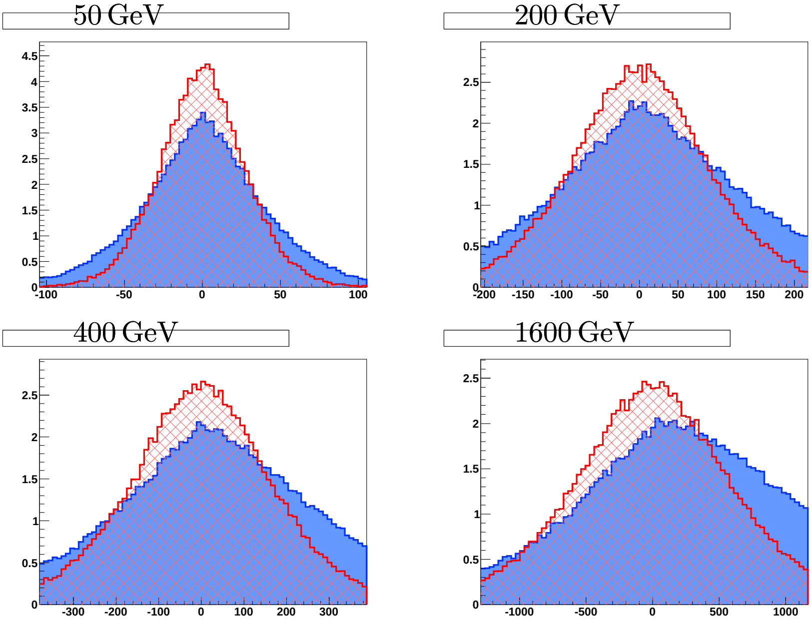
Jet Broadening similar to linear moment for small-angles: $k_T \approx p_T\, r$

$$B_{\text{jet}} = \frac{\sum_i |\vec{p}_i \times \hat{n}_{\text{jet}}|}{\sum_i |\vec{p}_i|} = \frac{\sum_i |\vec{k}_T i|}{\sum_i |\vec{p}_i|}$$

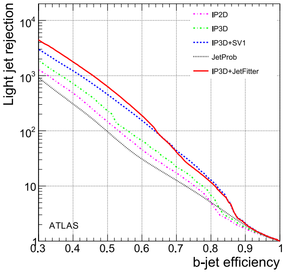




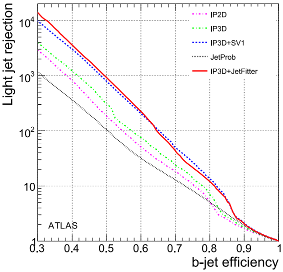
Charge Weighted by p_T



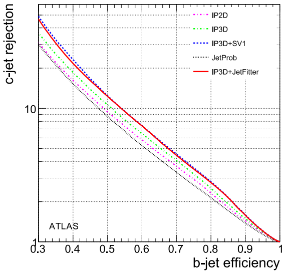
Compare to ATLAS B-Taggnig



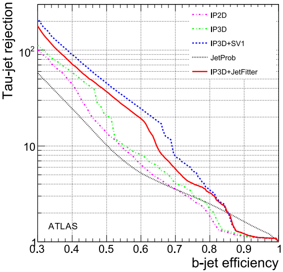
(a) Non-purified light jets



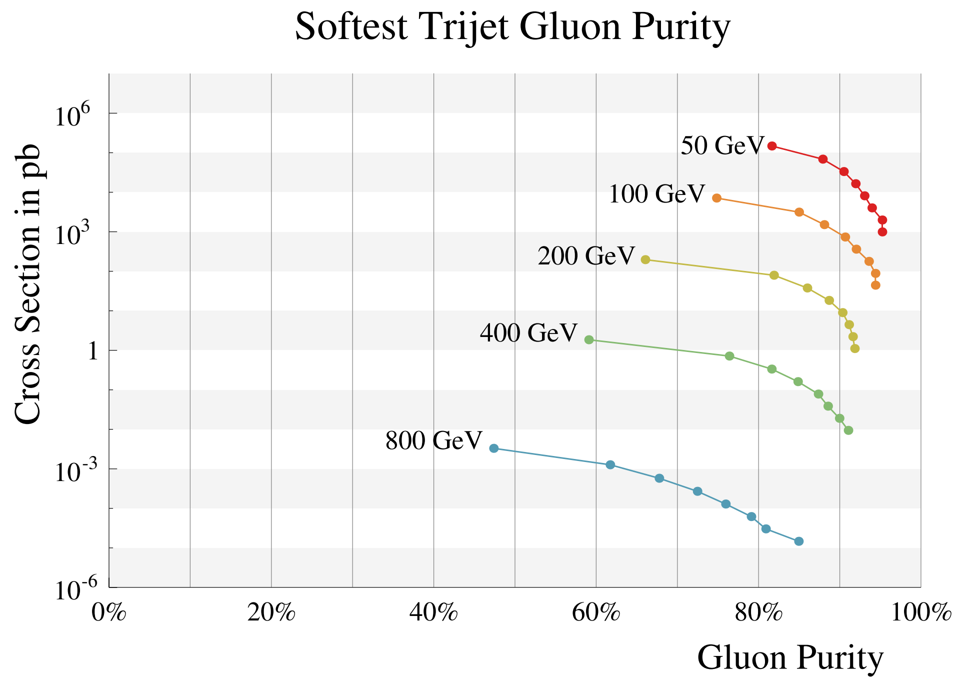
(b) Purified light jets



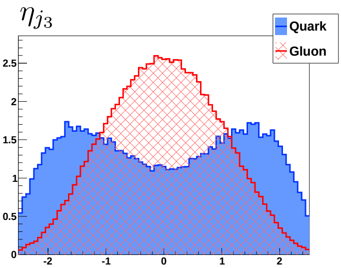
(c) c-jets



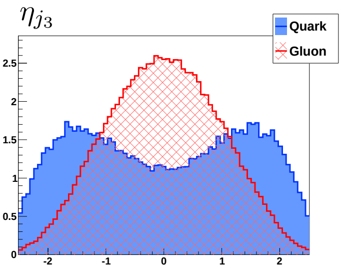
(d) τ-jets

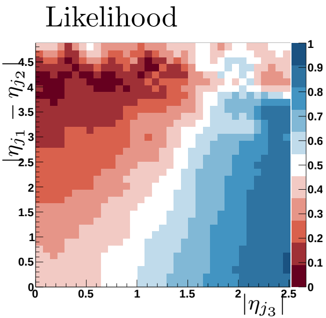

Softest Trijet Gluon Purity
Cross Section in pb
Gluon Purity
10^6
10^3
1
10^{-3}
10^{-6}
0%
20%
40%
60%
80%
100%
50 GeV
100 GeV
200 GeV
400 GeV
800 GeV

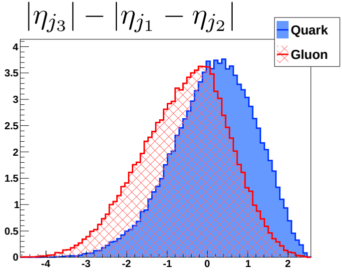
Gluon Purification: Lesson about Harsh Cuts

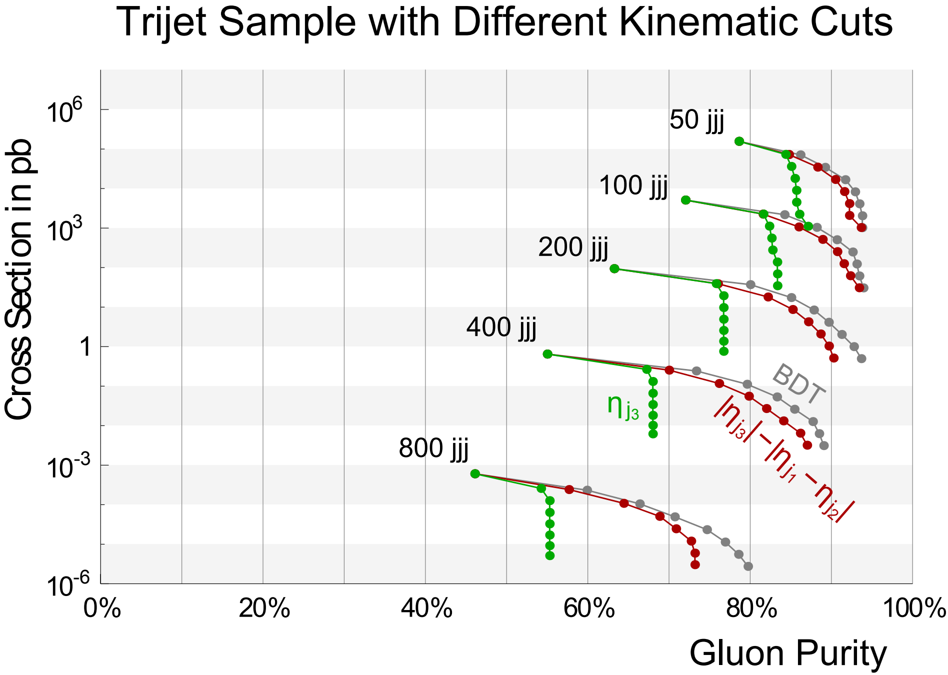


Gluon Purification: Lesson about Harsh Cuts









Trijet Sample with Different Kinematic Cuts
Cross Section in pb
10^6
10^3
1
10^{-3}
10^{-6}
0%
20%
40%
60%
80%
100%
Gluon Purity
50 jjj
100 jjj
200 jjj
400 jjj
800 jjj
BDT
η_{j_3}
$|\eta_{j_3}| - |\eta_{j_1} - \eta_{j_2}|$