Gluon Tagging and Quark & Gluon Samples

How well can we do at the 7 TeV LHC?

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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

Gluon Tagging Motivation

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

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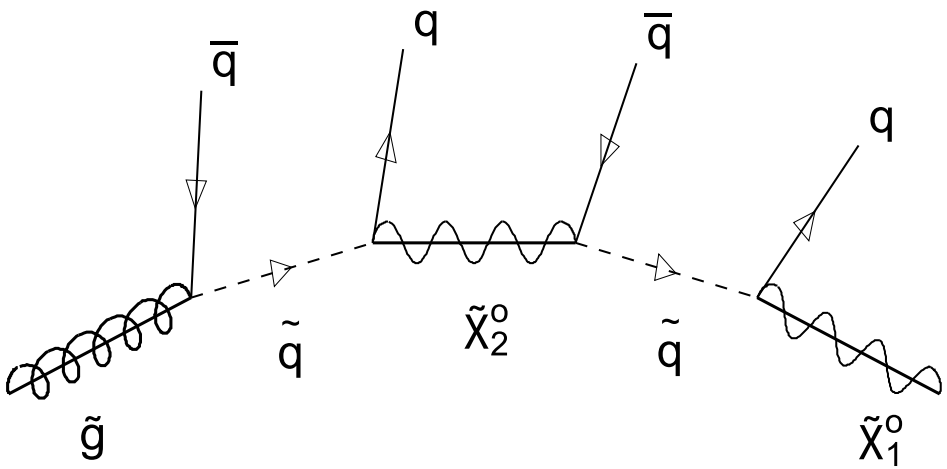
- 8-jet Gluino event: $pp \to \tilde{g}\tilde{g}$ and each $\tilde{g} \to q\bar{q}\chi_1^0 + q\bar{q}\chi_2^0$



Tagging is especially important without W, Z, γ, $\ell^{\pm}$, B-Tags, or $\not{E}_T$

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 $c\bar{s}$
- Vector Boson Fusion
- Q & G Jets as backgrounds to boosted top, W, H, etc.

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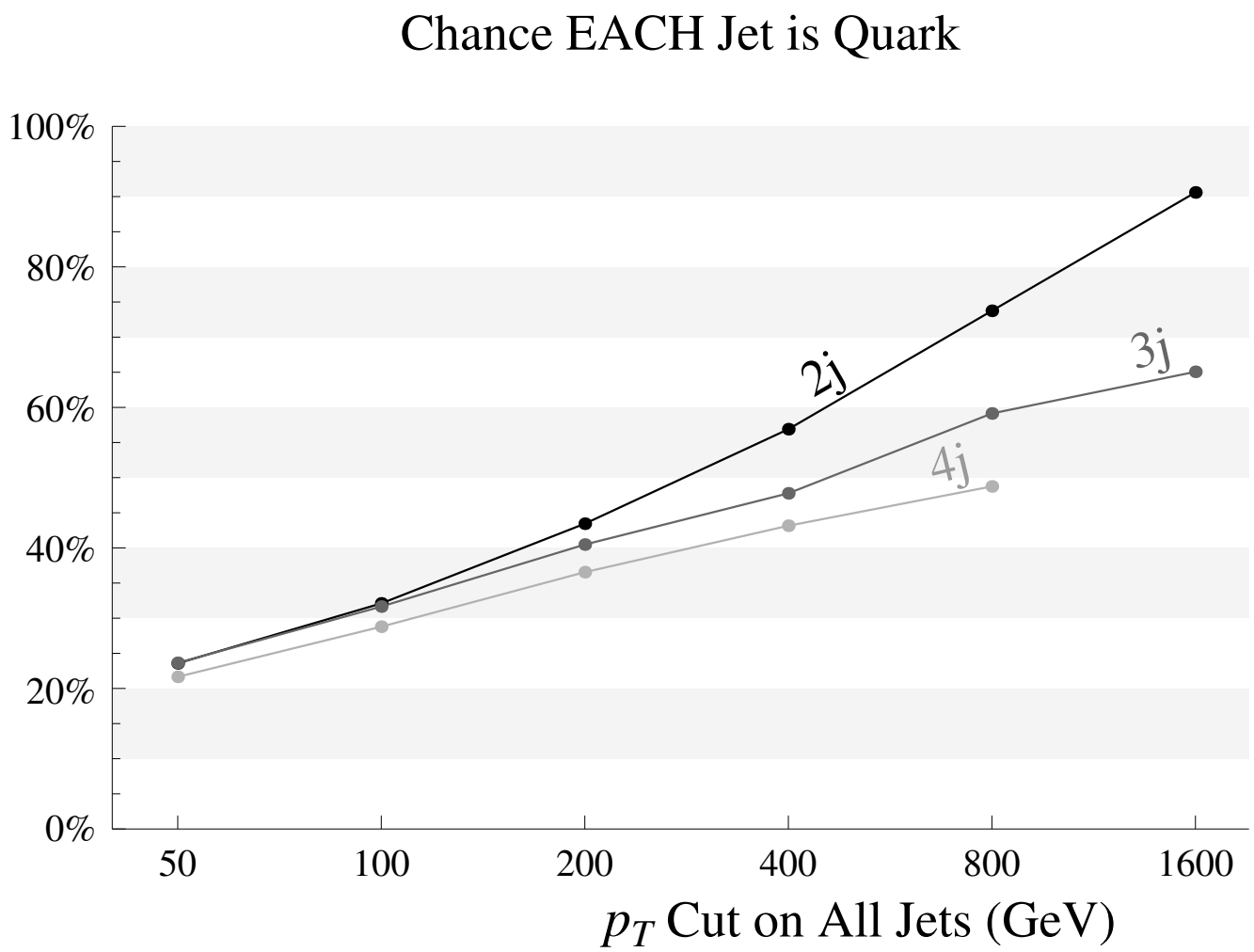
NOTE!
LEP found b-jets look more like gluon jets than light quark jets
(in terms of size and particle count)

Eventually combine Gluon-Tagging with B-Tagging and τ-Tagging

But There's a Lot of Glue to Get Stuck In

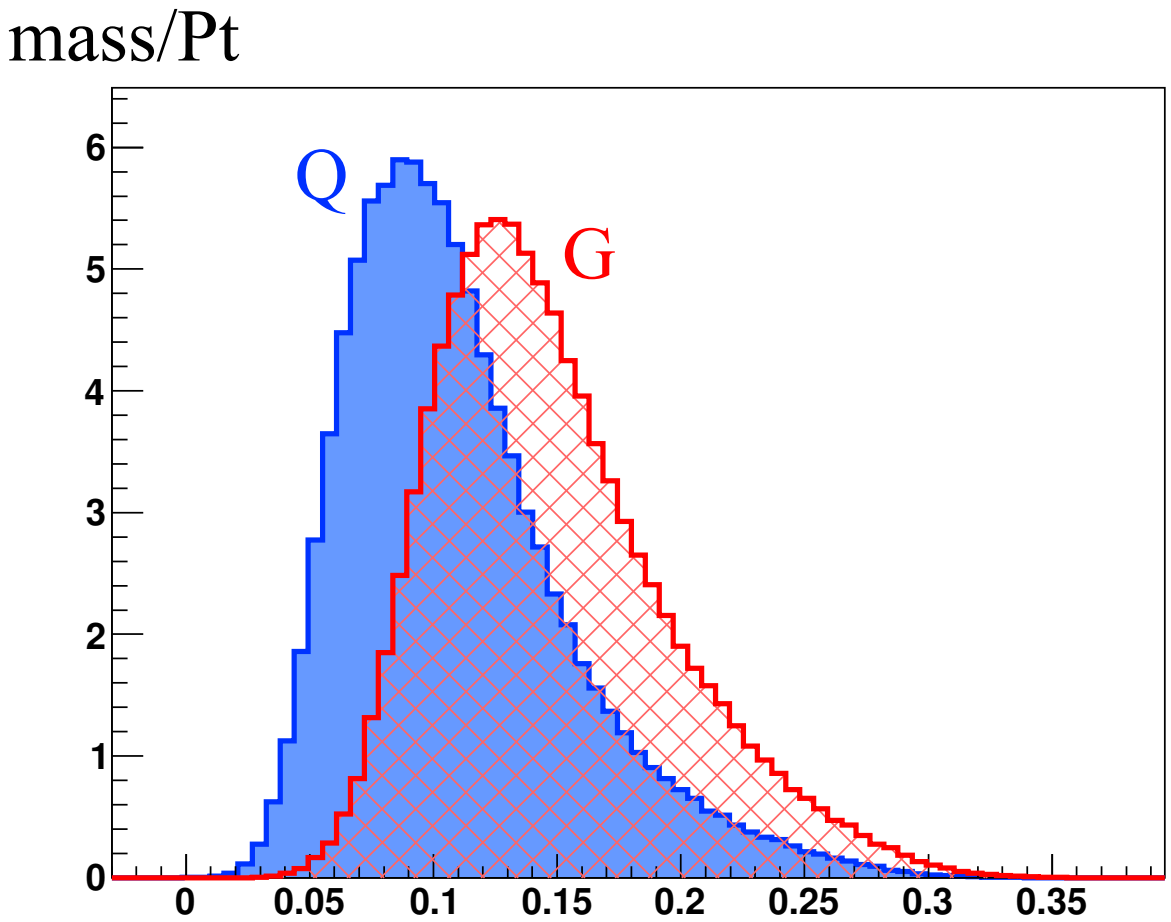


So chance that all 4 jets $\gtrsim 100\,GeV$ are quark: $(30\%)^4 = 0.8\%$

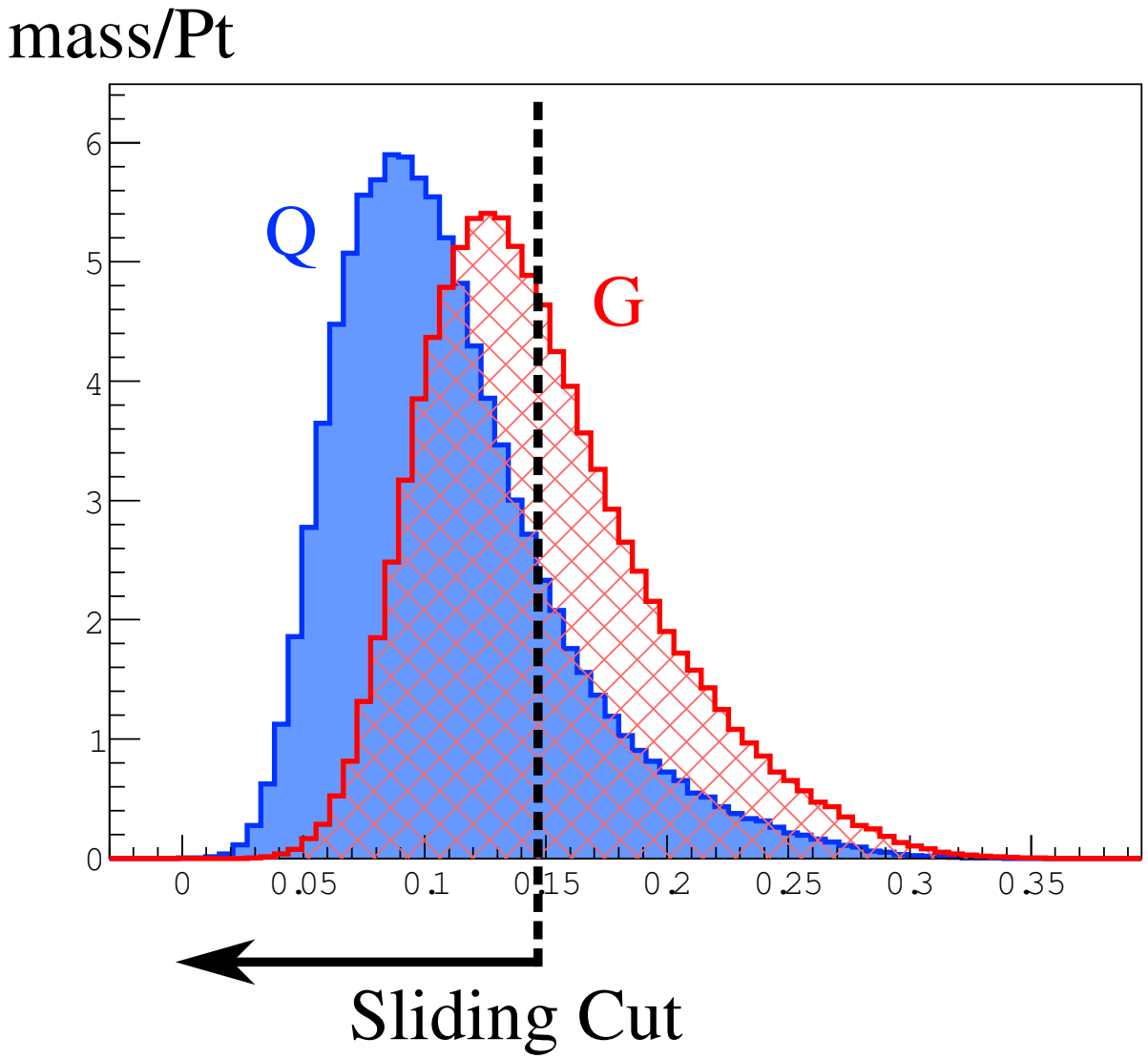
The Gluon Tagger

Jet Mass as an Example Observable

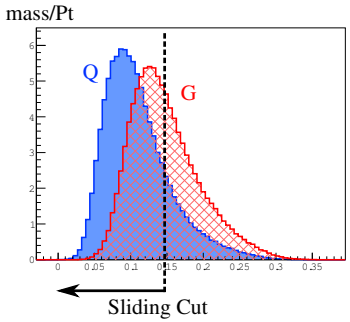
- Normalizing by p_T (200 GeV in this sample) generalizes better.

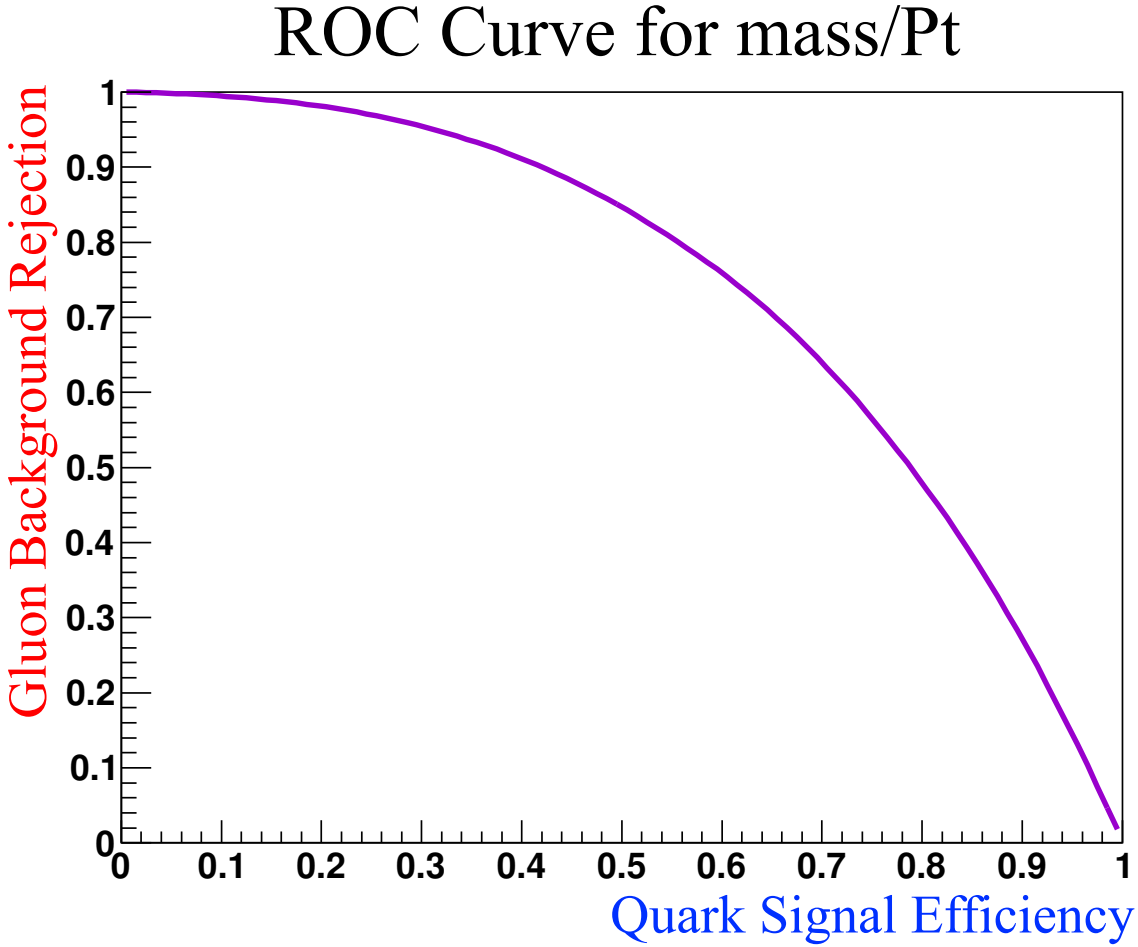


Evaluating the Observable: Sliding Cut

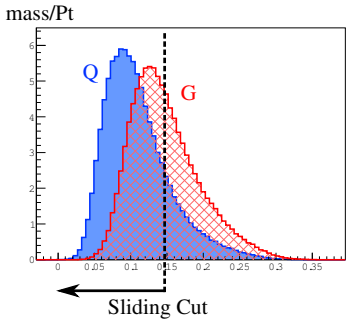


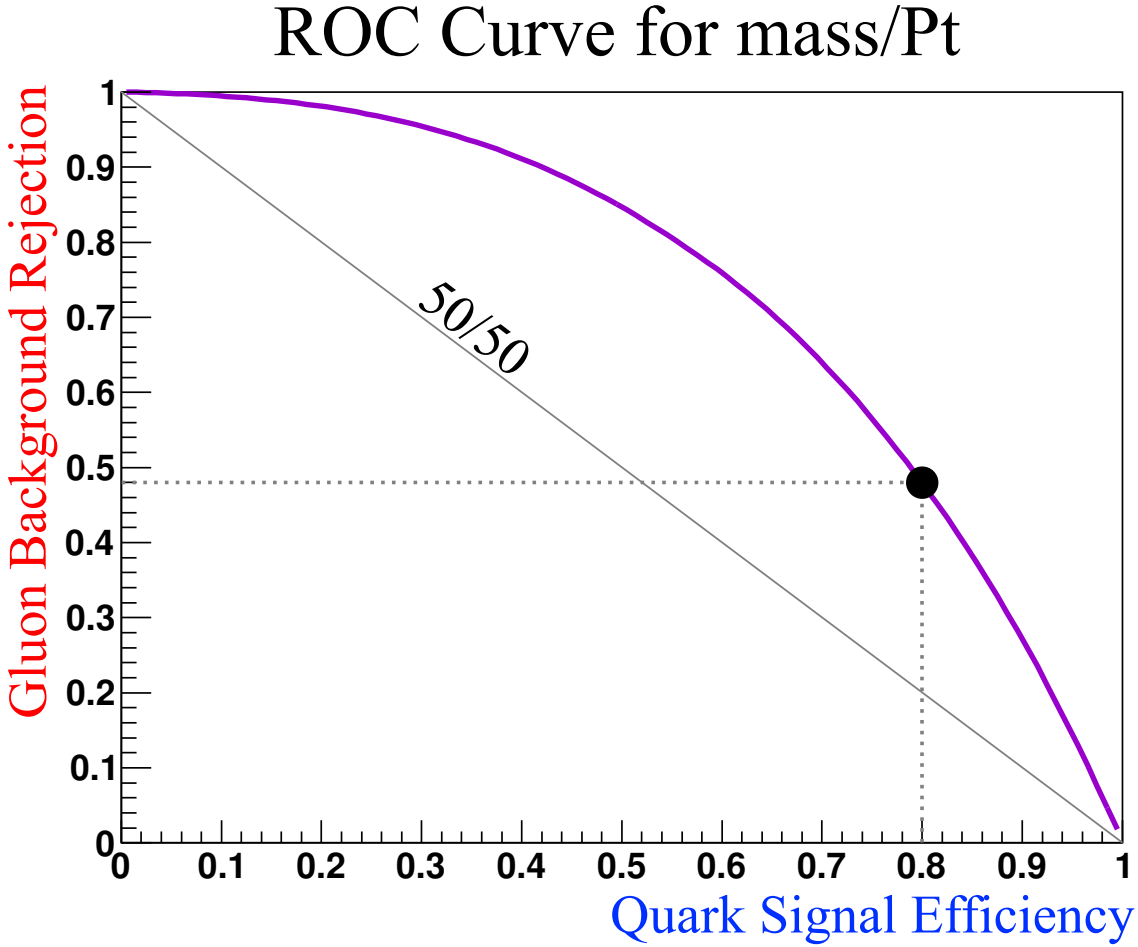
ROC Curve


mass/Pt
Q
G
Sliding Cut

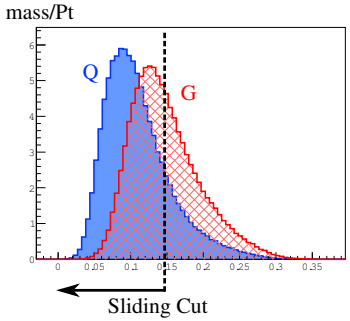

ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

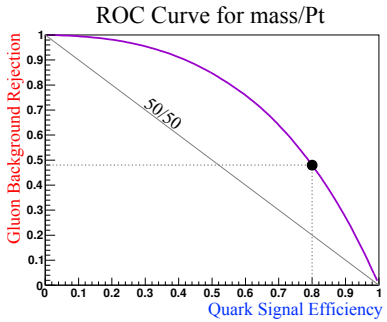
ROC Curve

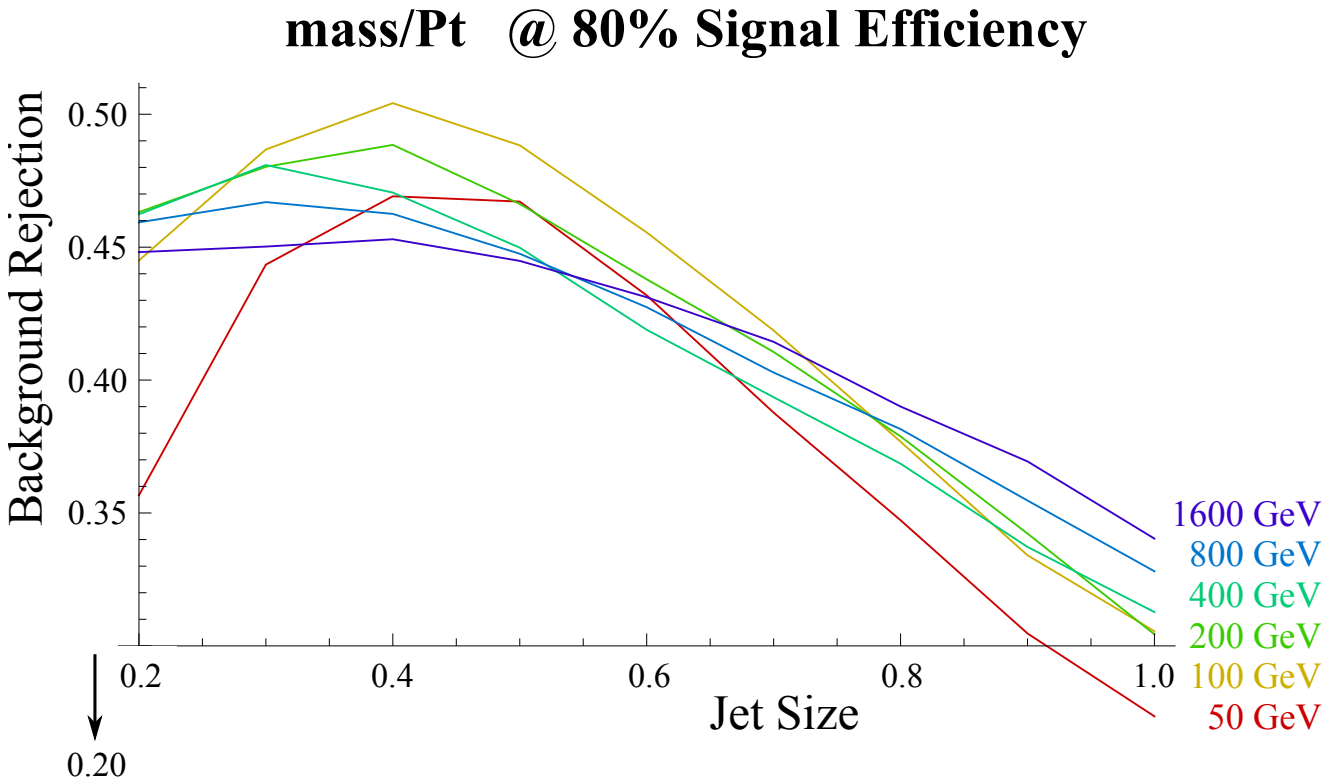

mass/Pt
Q
G
Sliding Cut


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







Gluon adjoint's C_A vs Quark fundamental's C_F

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

Lore: quark jet first emits a gluon, and then it dominates the cascade.

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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).

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

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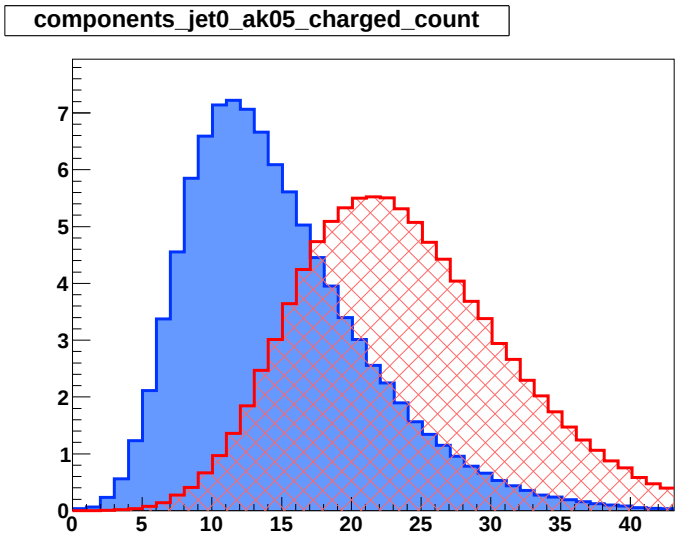
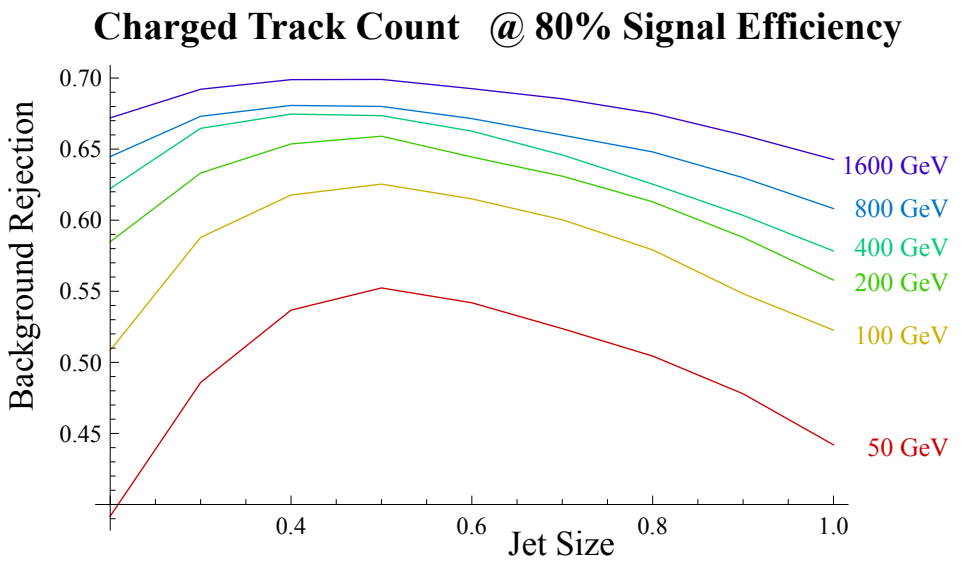
Multiplicity of *any* particle in a gluon jet should be $C_A/C_F = 9/4$ times greater (confirmed at LEP).

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

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

Charged Particles Count



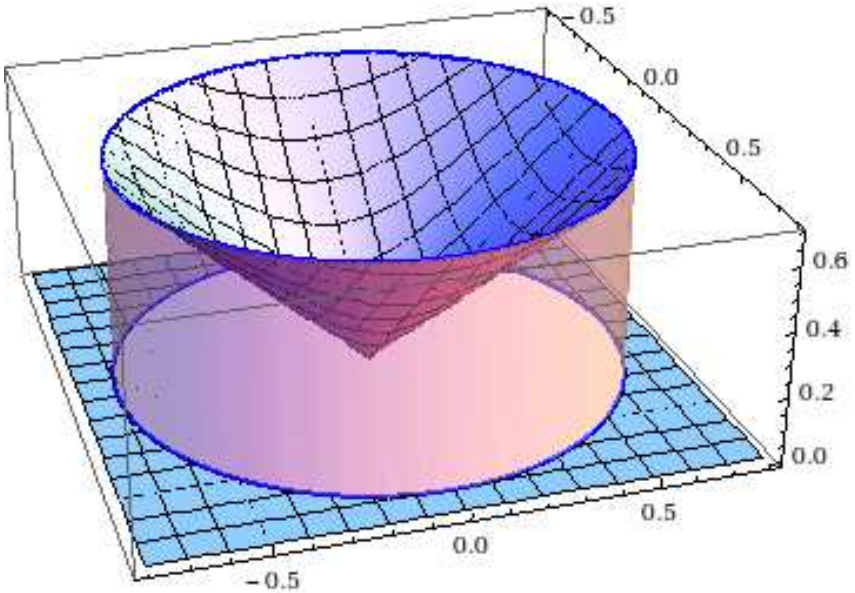


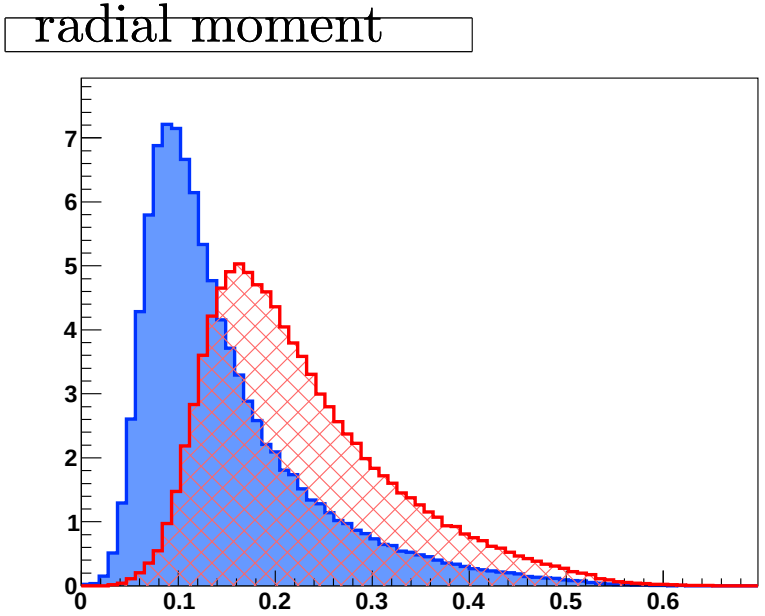
Higher p_T means more charged tracks and more 'time' to establish C_A/C_F.

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

Weight p_T deposits by distance from jet center

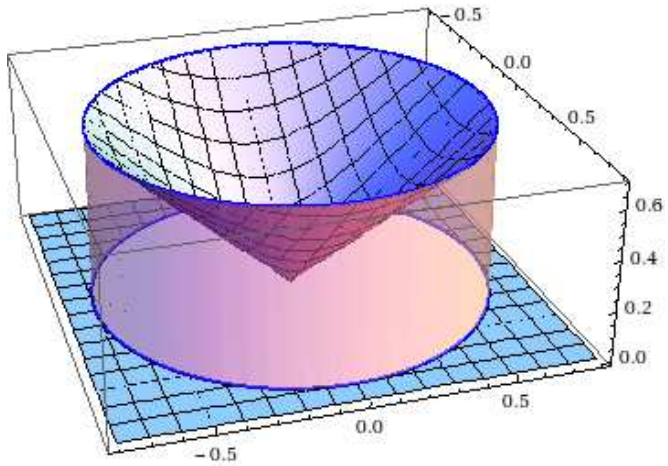
$$\text{Radial Moment, or Girth :} \qquad g = \frac{1}{p_T^{jet}} \sum_{i \in \text{jet}} p_T^i |r_i|$$



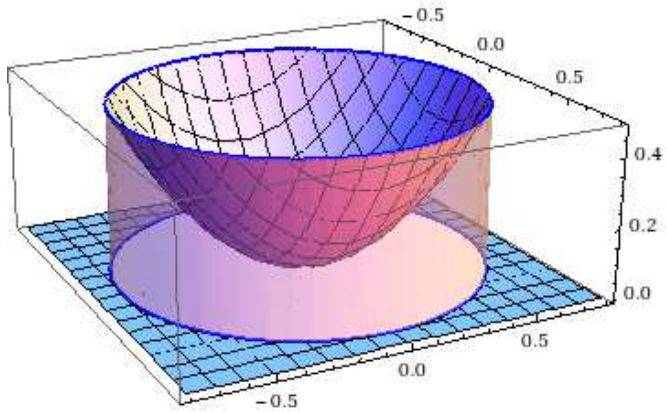


Radial Moments and Their Kernels

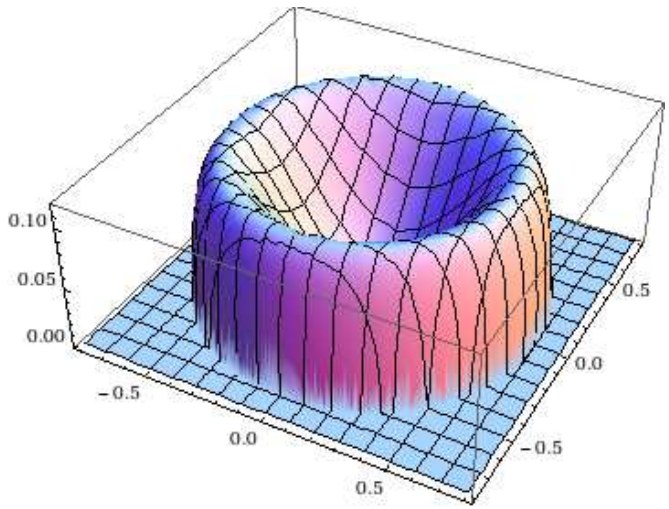
Linear Moment



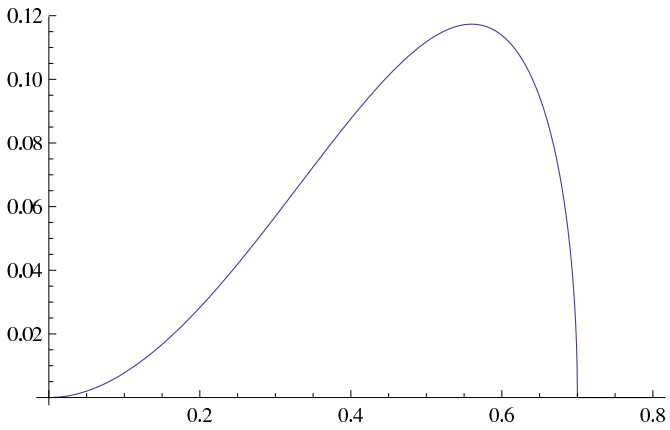
Quadratic Moment



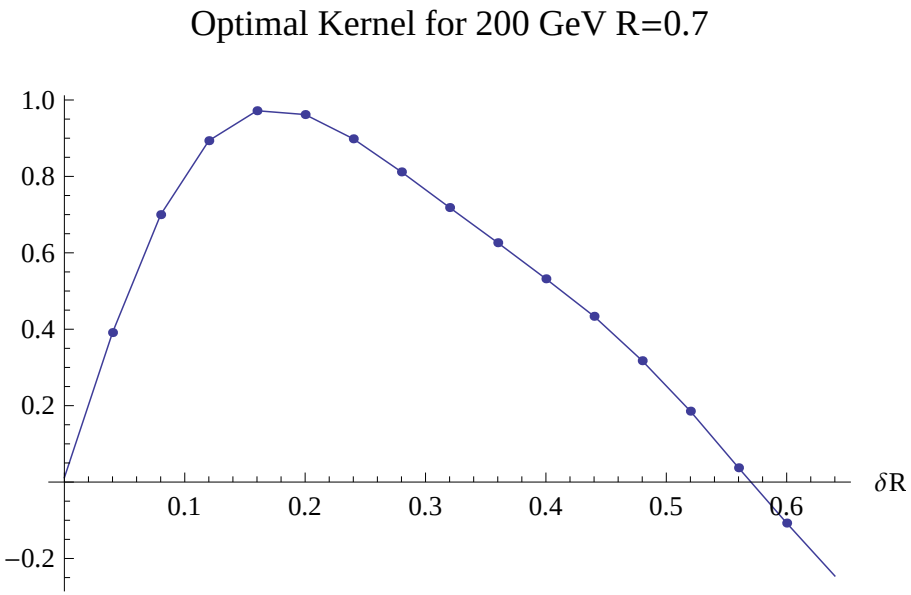
Tapered Moment

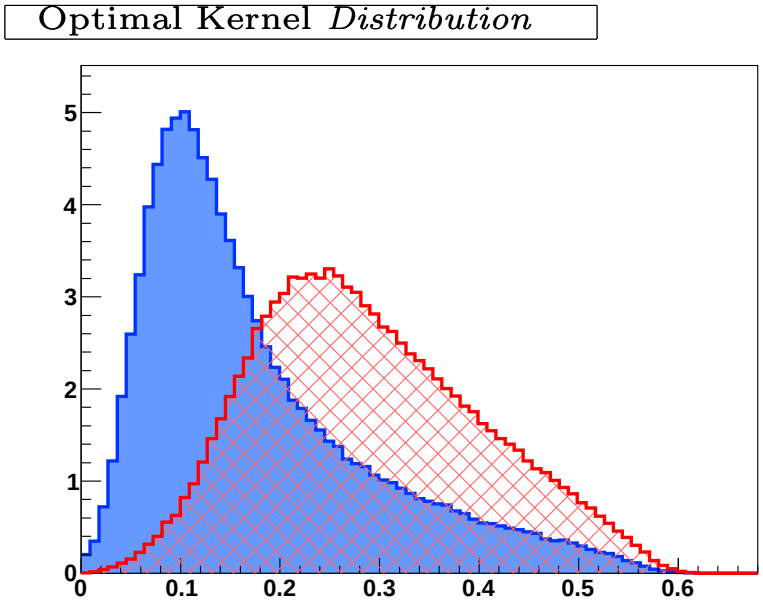


Tapered Radial Kernel



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.

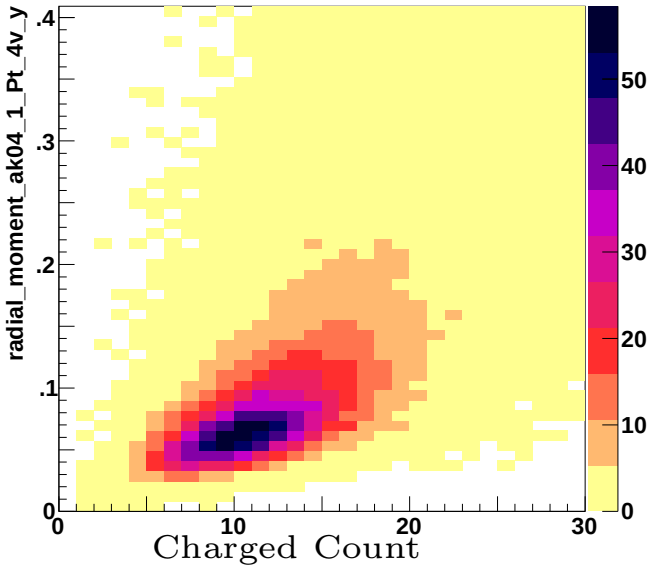
Types of Variables

The menu, including varying jet size

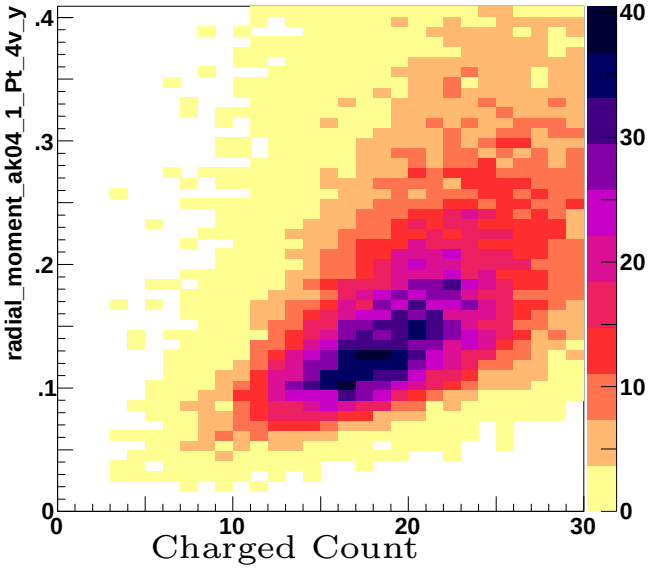
- Distinguishable particles/tracks/subjets
  - multiplicity, $\langle p_T \rangle$, σ_{p_T}, $\langle k_T \rangle$,
  - charge-weighted p_T sum
- Moments
  - mass, girth, broadening
  - angularities
  - optimal kernel
  - 2D: pull, planar flow
- Subjet properties
  - Multiplicity for different algorithms and R_{sub}
  - First subjet's p_T, 2nd's p_T, etc.
  - Each subjet's mass
  - Splitting k_T scale

Combining Variables: Girth vs Charged Count

Quark



Gluon



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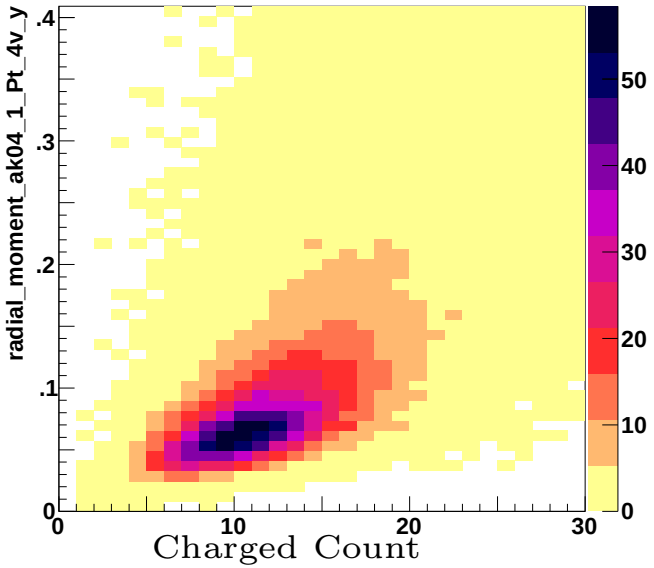
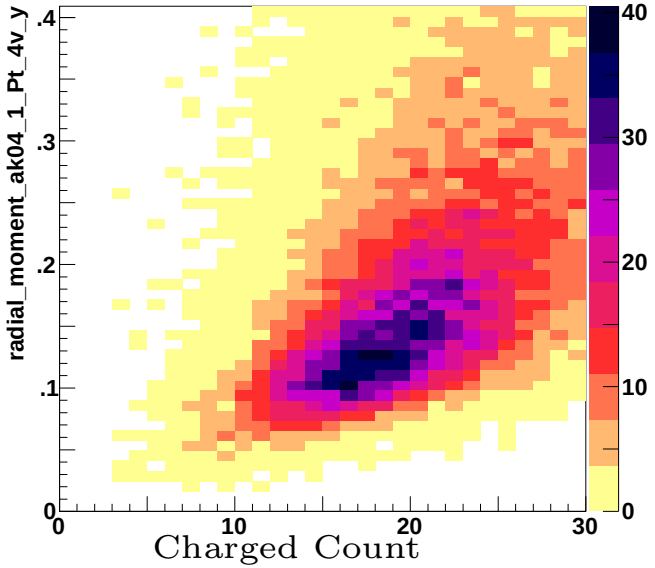
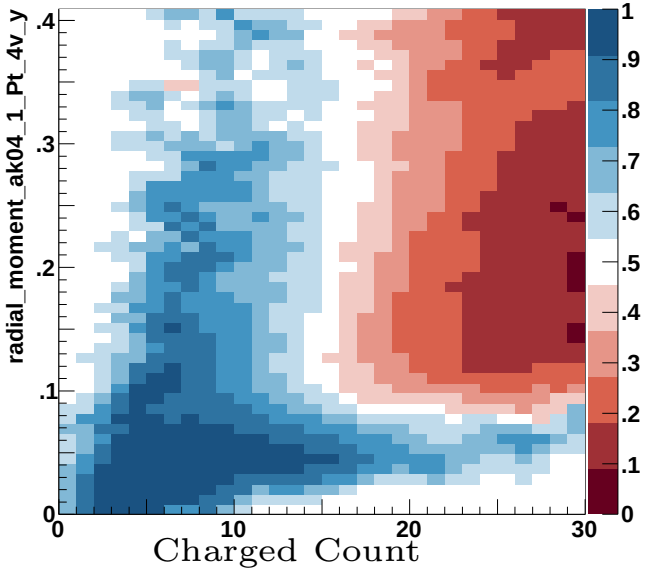


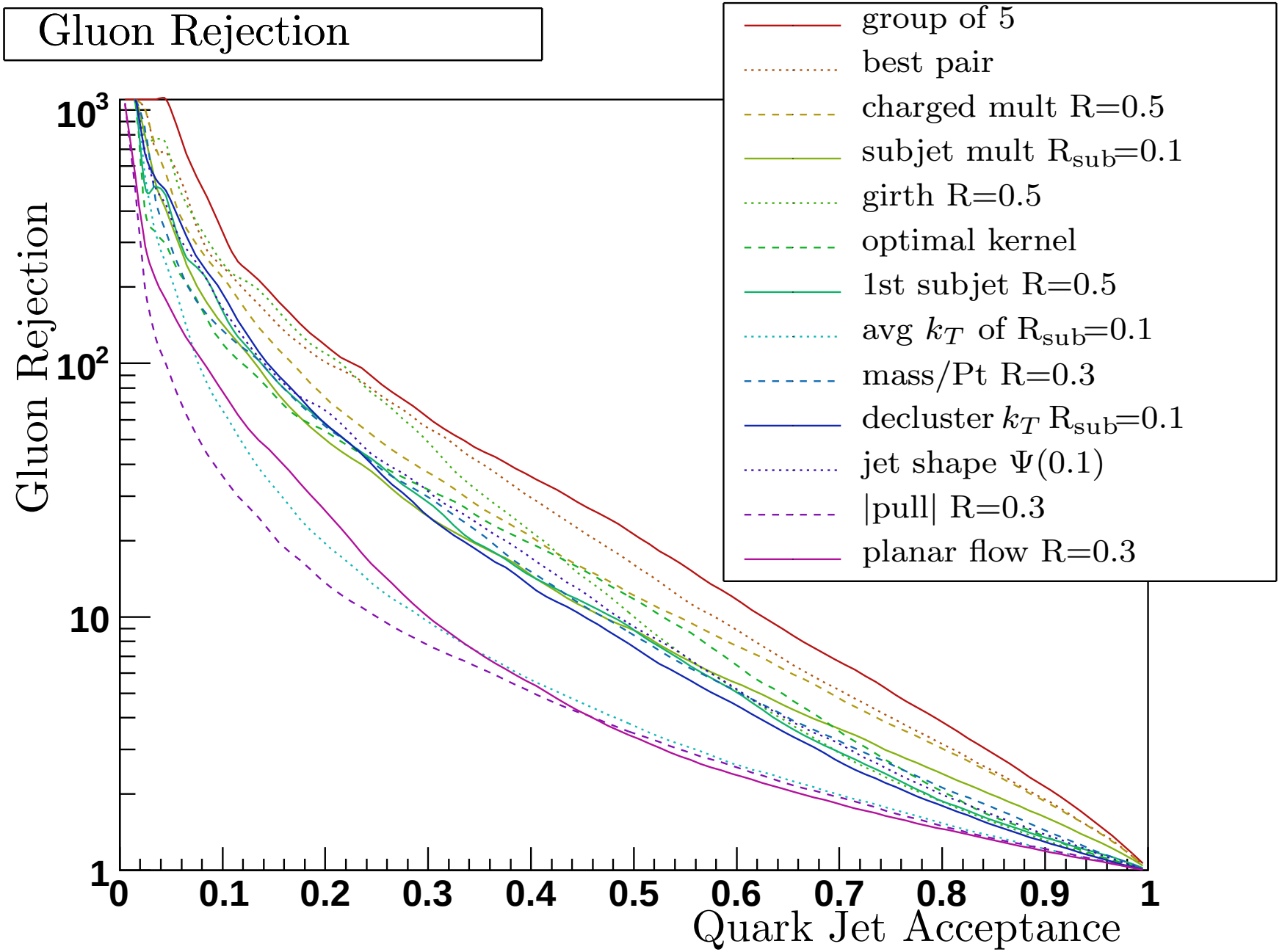
Gluon



Likelihood: $q/(q+g)$



Best Variables in Each Category for 200 GeV 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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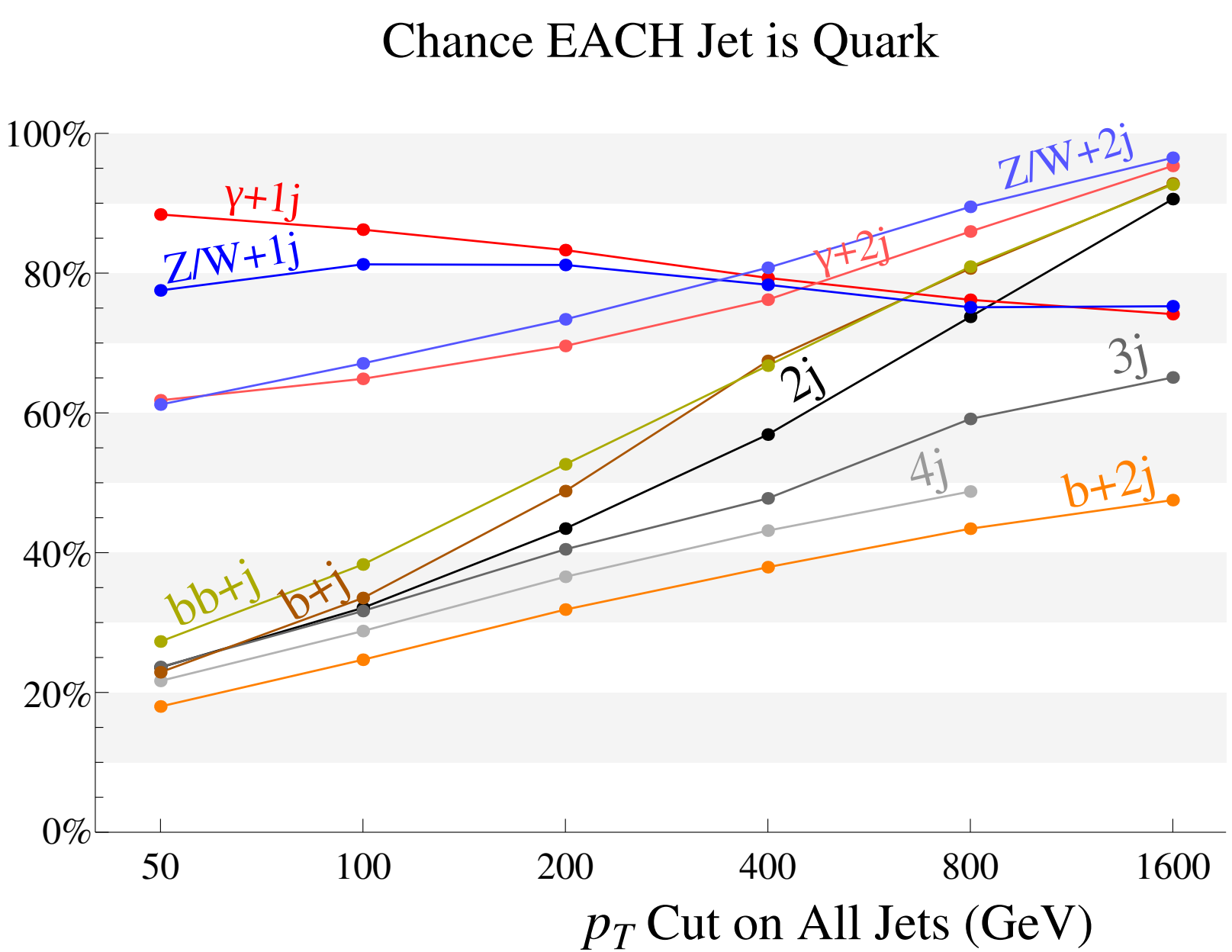
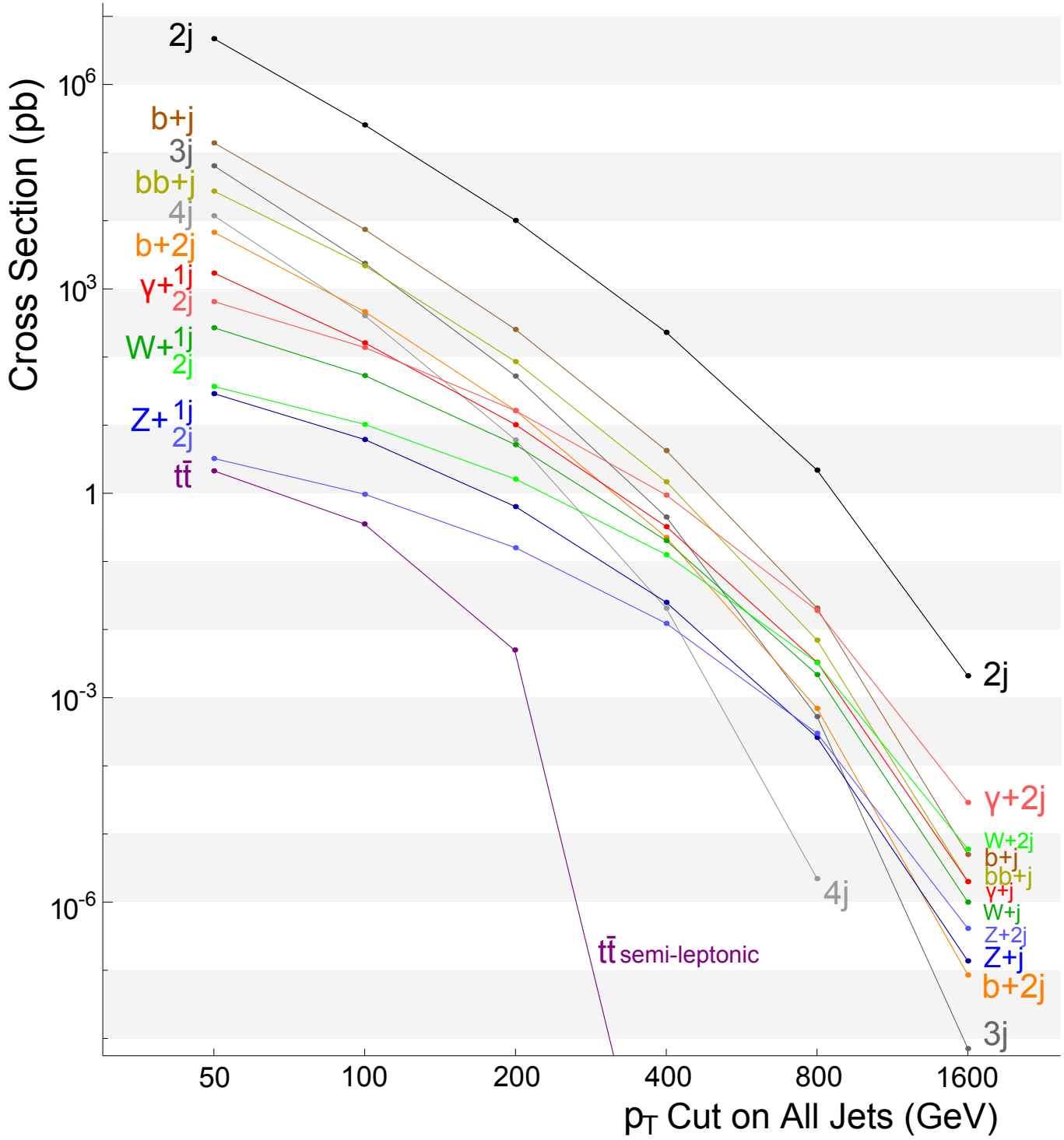
For 4-jets, all of these get raised to the 4th for glue-heavy background.
Differences in these variables are worth verifying & calculating.

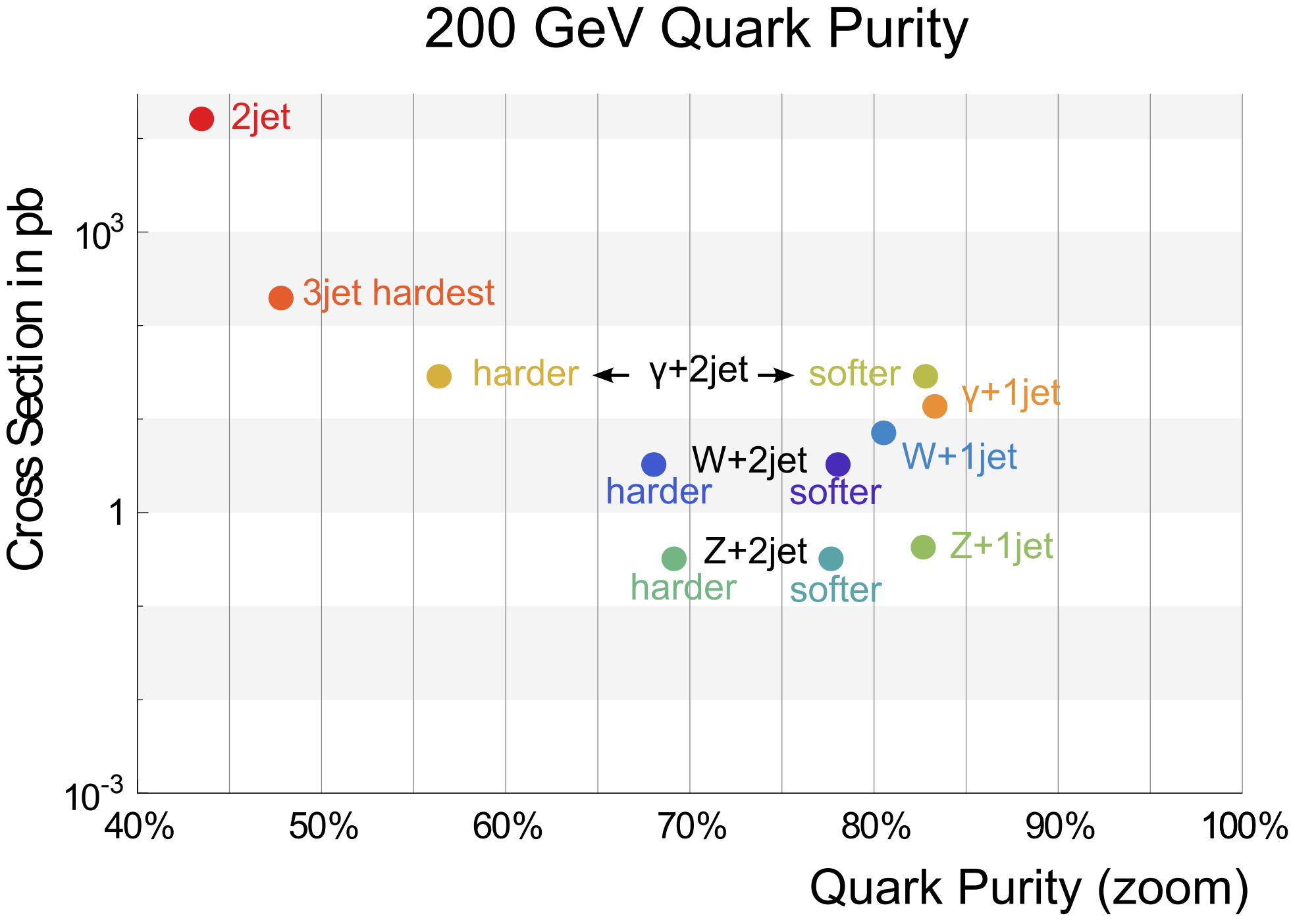
Finding Pure Samples of Quark and Gluon Jets

(more in Matt Schwartz's Talk)

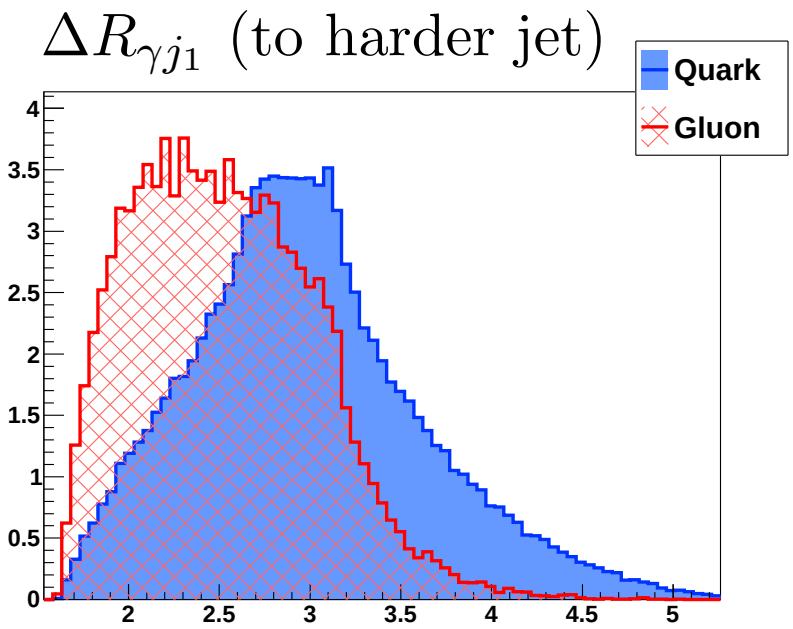
Starting Samples

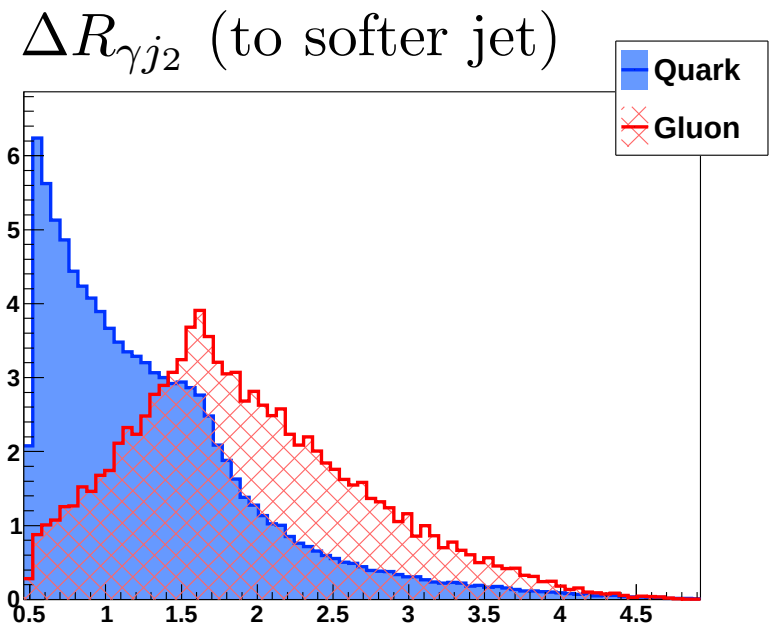



Cross Section (pb)
10^6
10^3
1
10^{-3}
10^{-6}
2j
b+j
3j
bb+j
4j
b+2j
γ+1j 2j
W+1j 2j
Z+1j 2j
tt̄
2j
γ+2j
W+2j
b+j
bb+j
γ+j
W+j
Z+2j
Z+j
b+2j
3j
4j
tt̄ semi-leptonic
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)

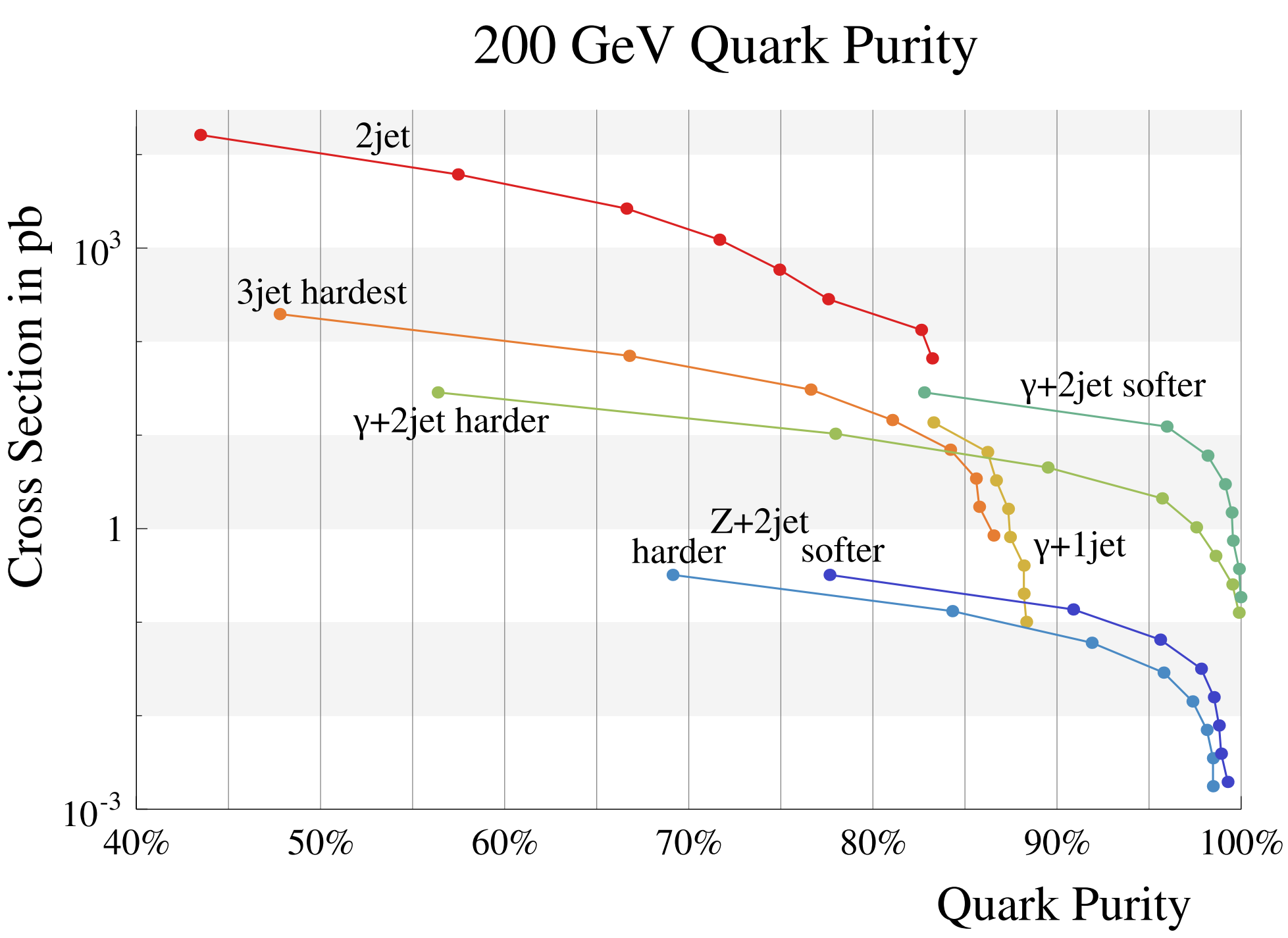

200 GeV Quark Purity
2jet
3jet hardest
harder
γ+2jet
softer
γ+1jet
W+2jet
W+1jet
harder
softer
Z+2jet
Z+1jet
harder
softer
Cross Section in pb
10^3
1
10^-3
40%
50%
60%
70%
80%
90%
100%
Quark Purity (zoom)

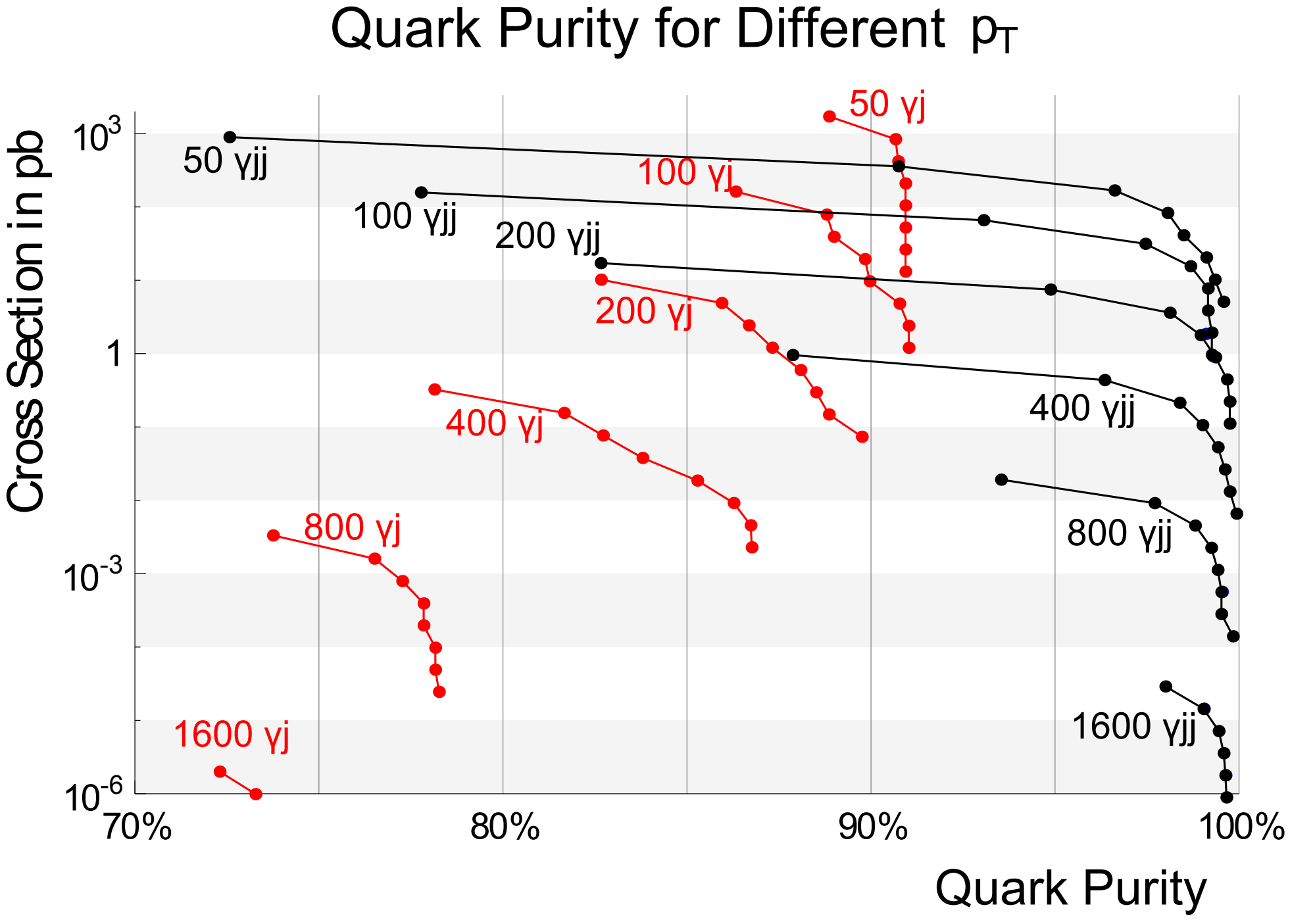
Quark Purification in γ+2jet: Look at Softer Jet

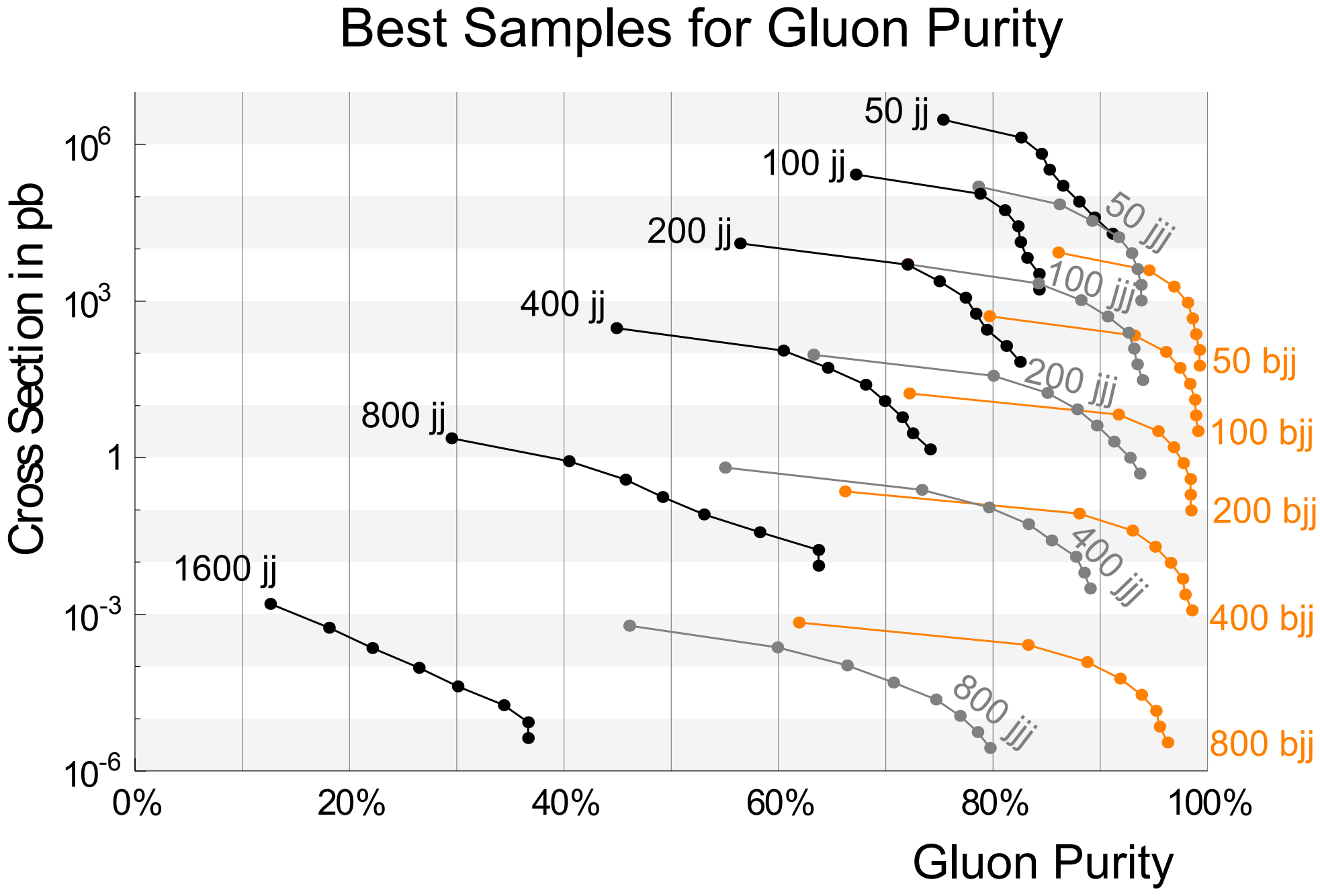




When the softer jet is quark, The photon is often radiated off of it, rather then the harder jet.


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


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


Best Samples for Gluon Purity
Cross Section in pb
10^{6}
10^{3}
1
10^{-3}
10^{-6}
0%
20%
40%
60%
80%
100%
Gluon Purity
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

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- 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

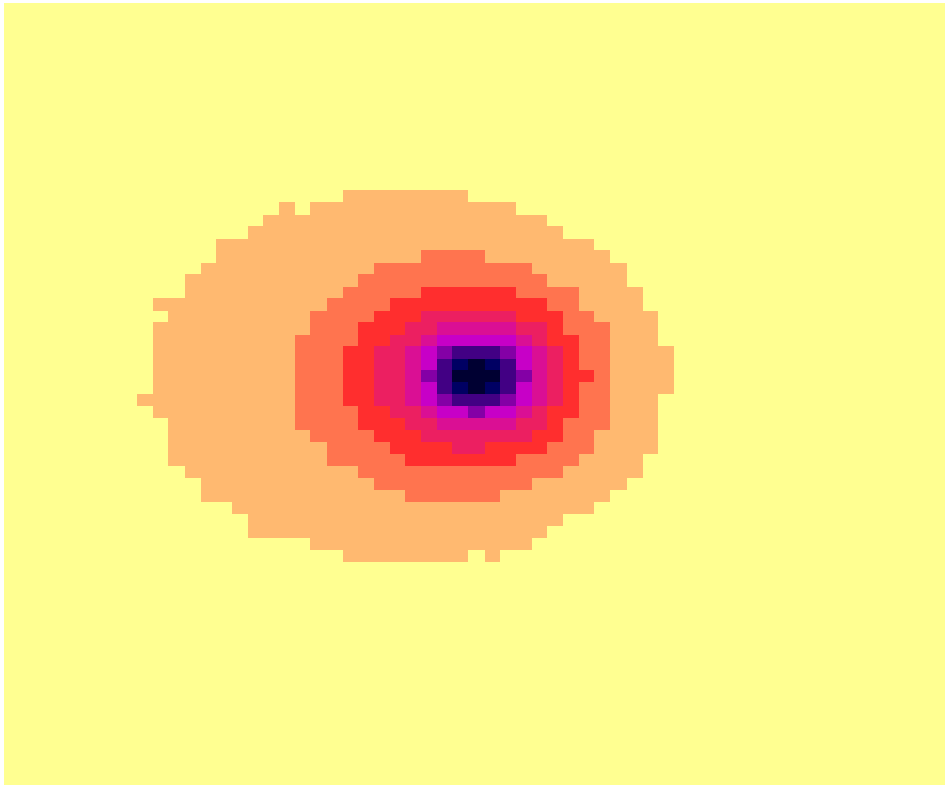
Now go forth and use these tools for good.... Thanks!

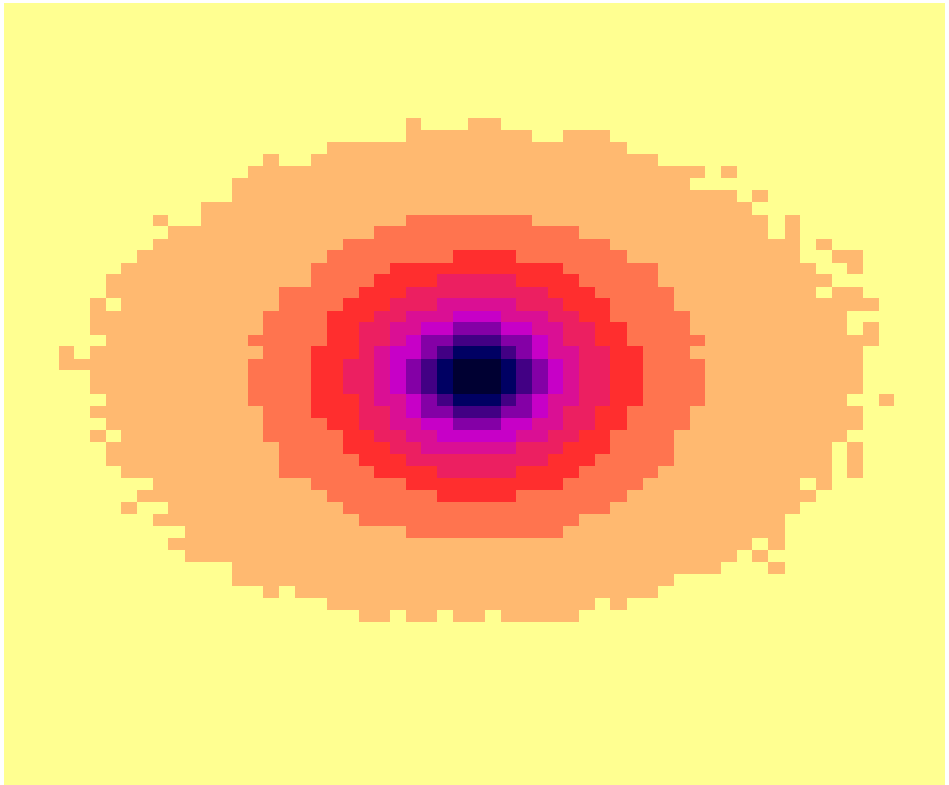
Backup

In case waving my hands proves insufficient ...

Visual Differences

Accumulate 3 million back-to-back dijet events



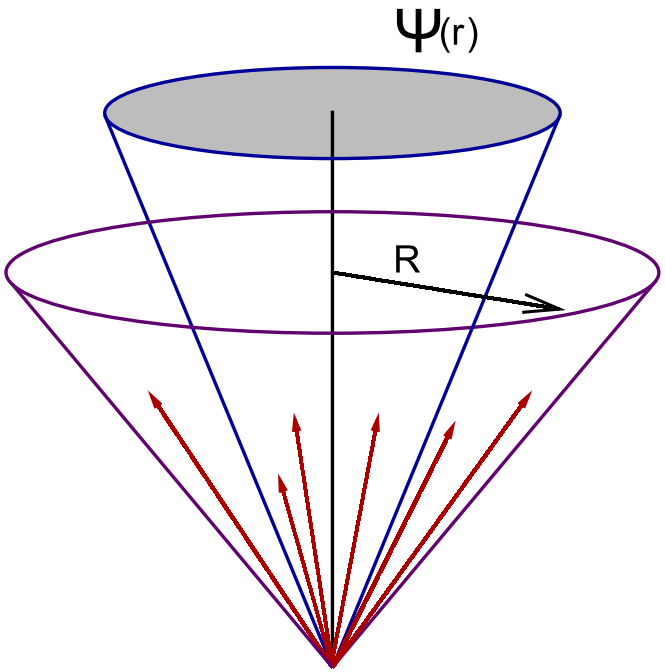


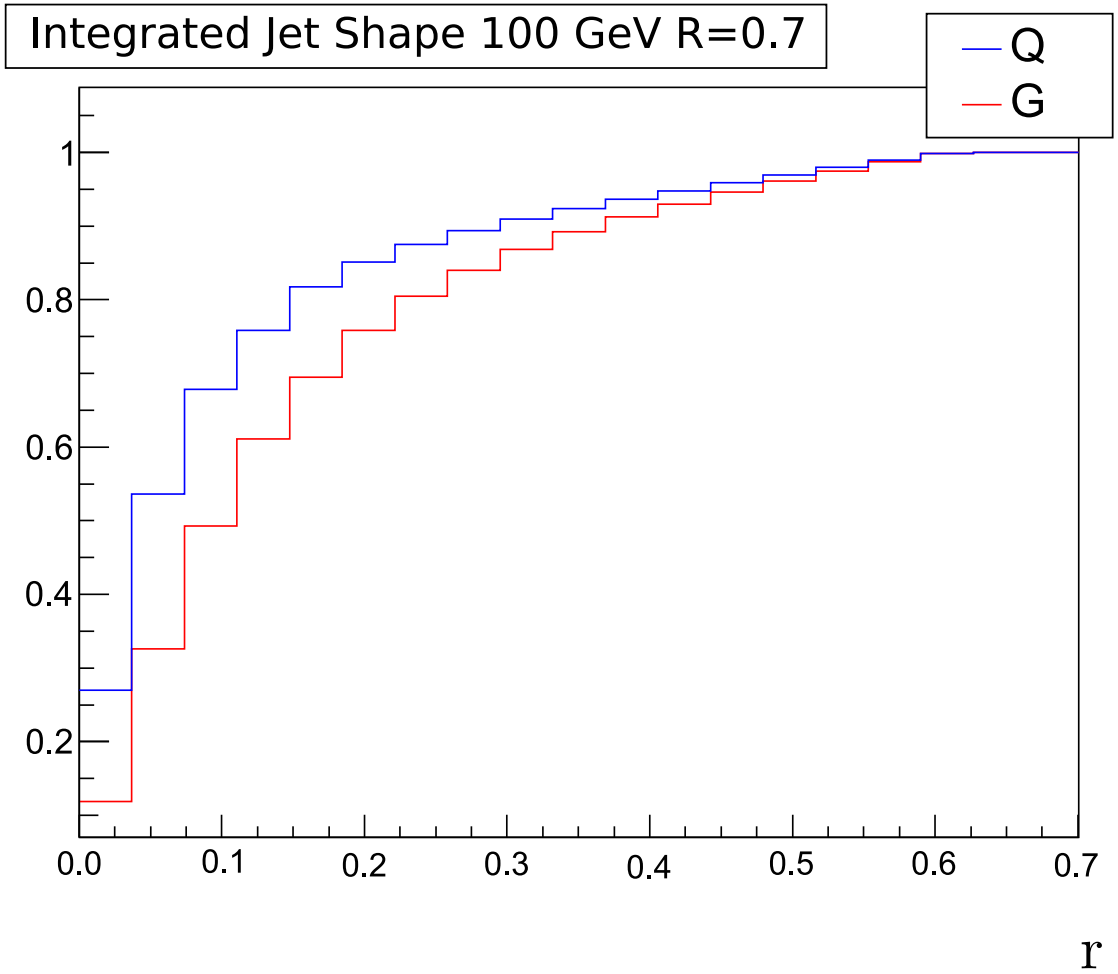
Quark Jets

Gluon Jets

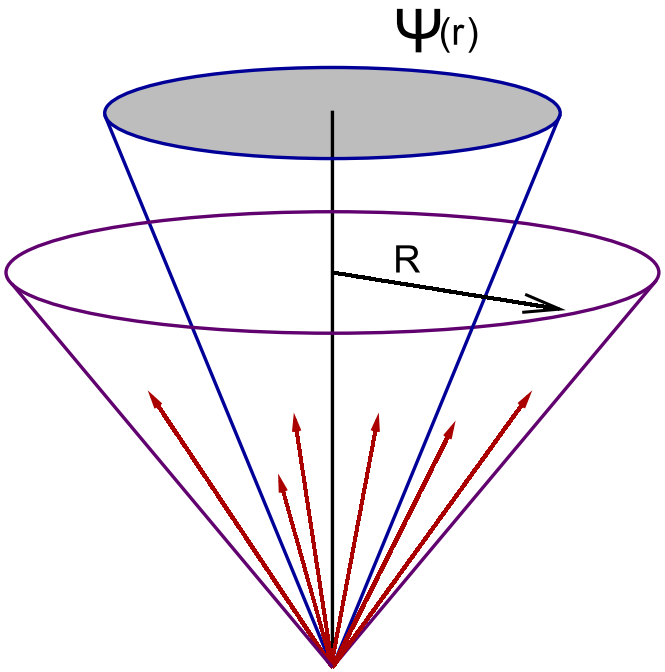
(Same total amount of p_T, which is hidden by logarithmic color bands.)

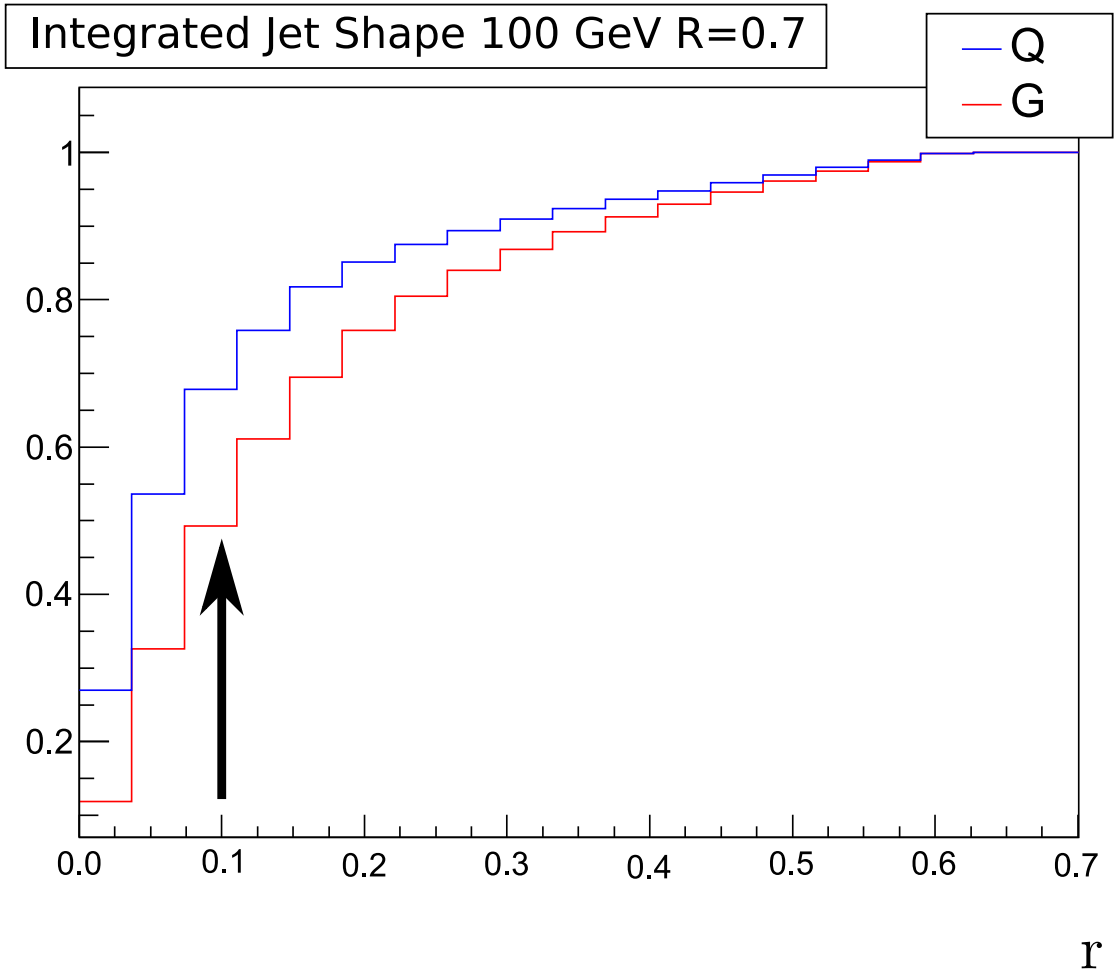
Jet Shape


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

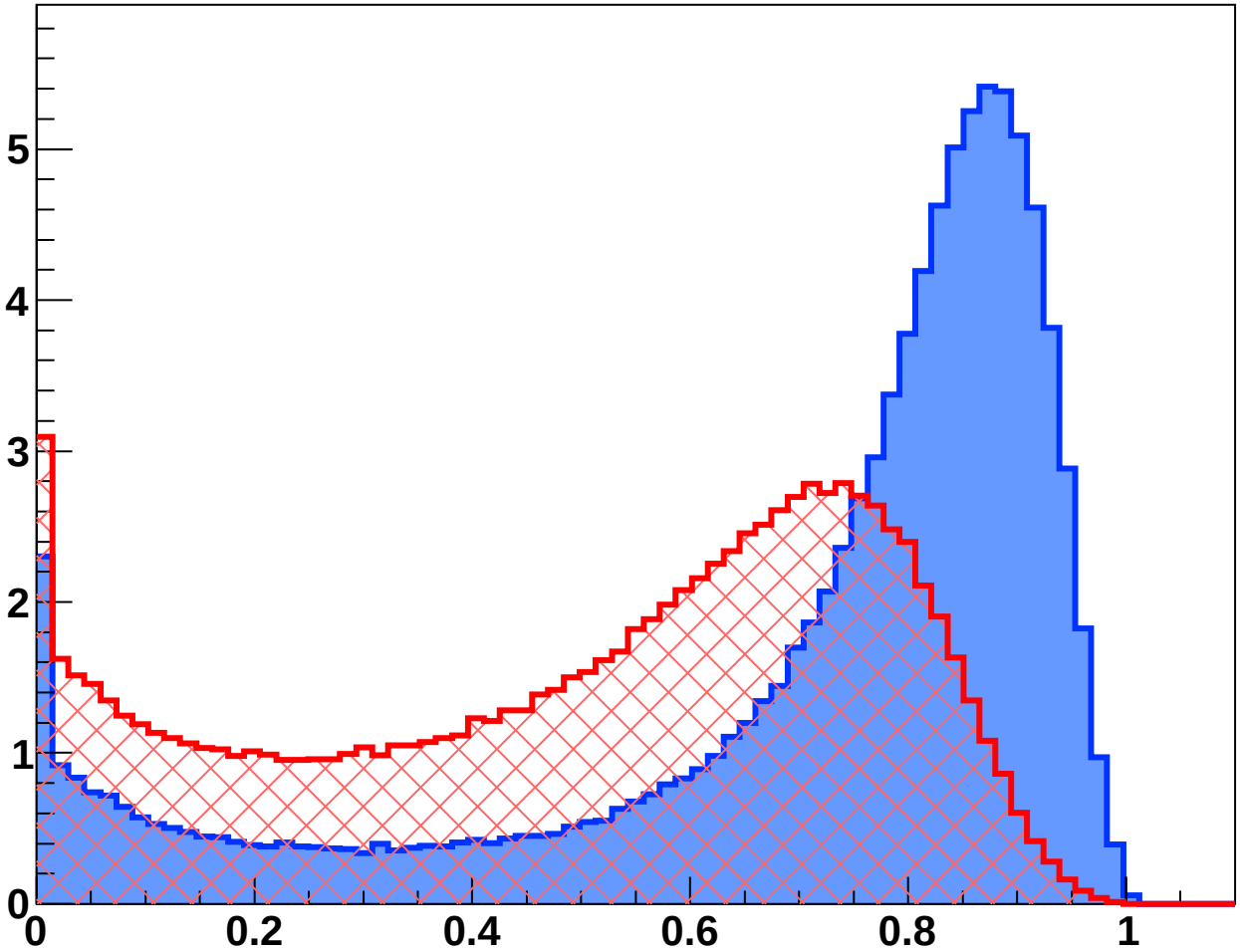
Jet Shape


Ψ(r)
R


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

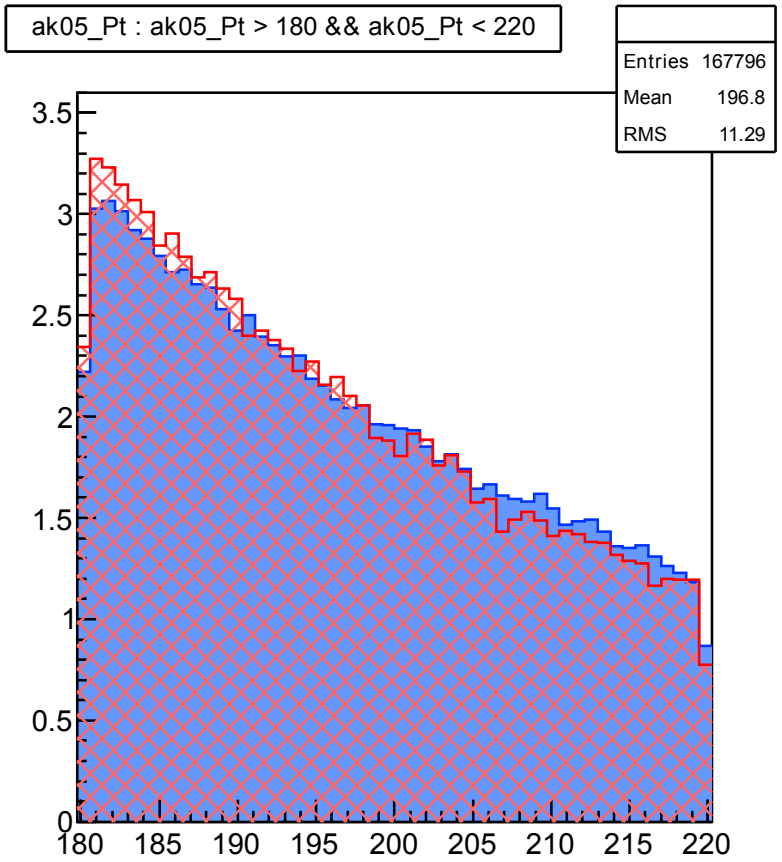
Jet Shape *Distribution* vs *Average*

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

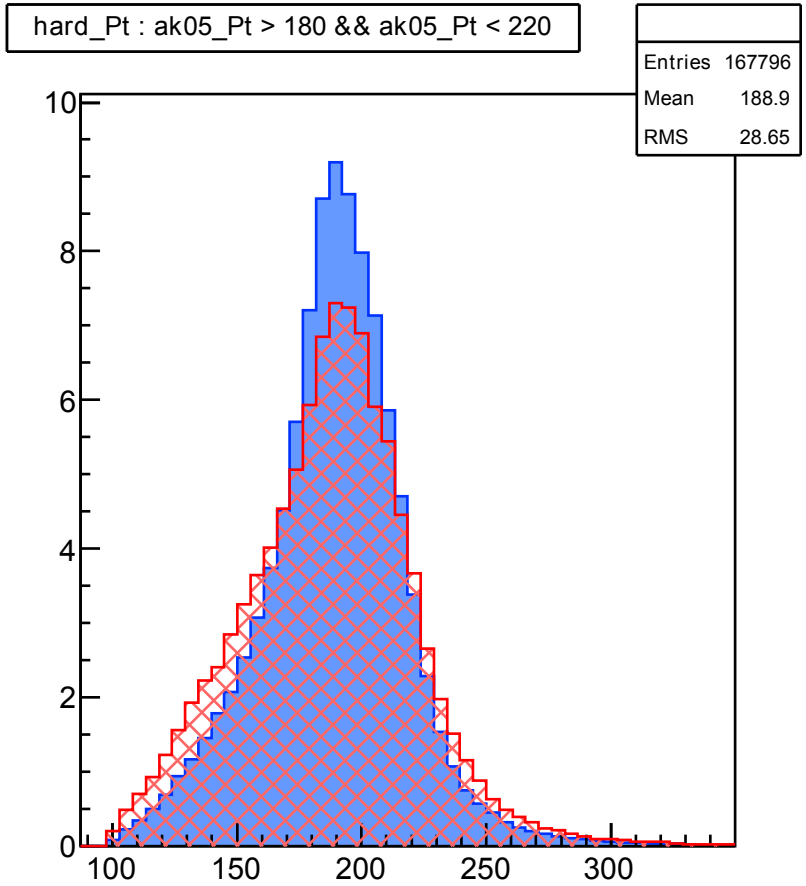


- Distribution is *not* narrow gaussian around average
- Correlations *between* shapes is also useful

Event Generation

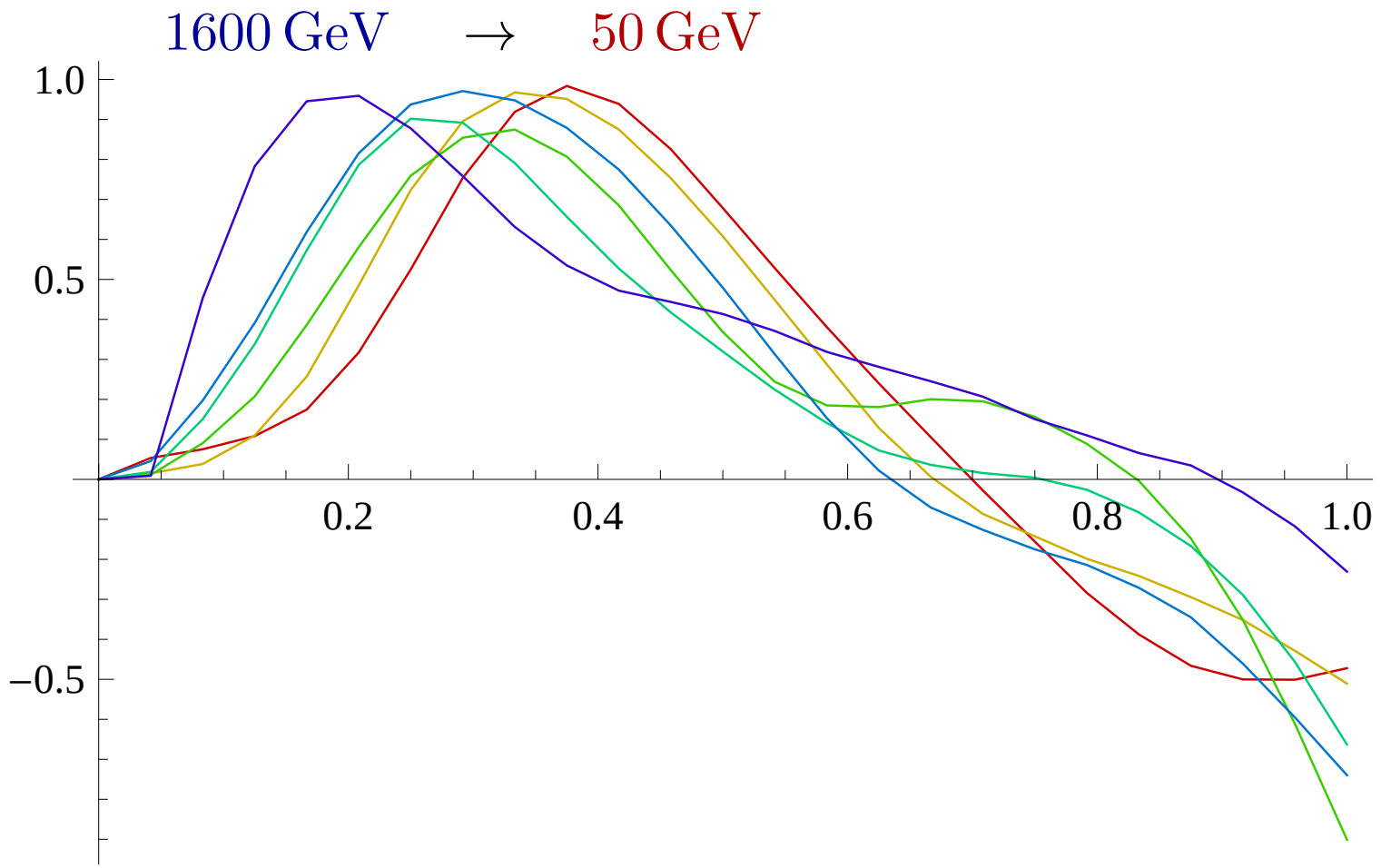


Jet p_T: anti-k_T R=0.5



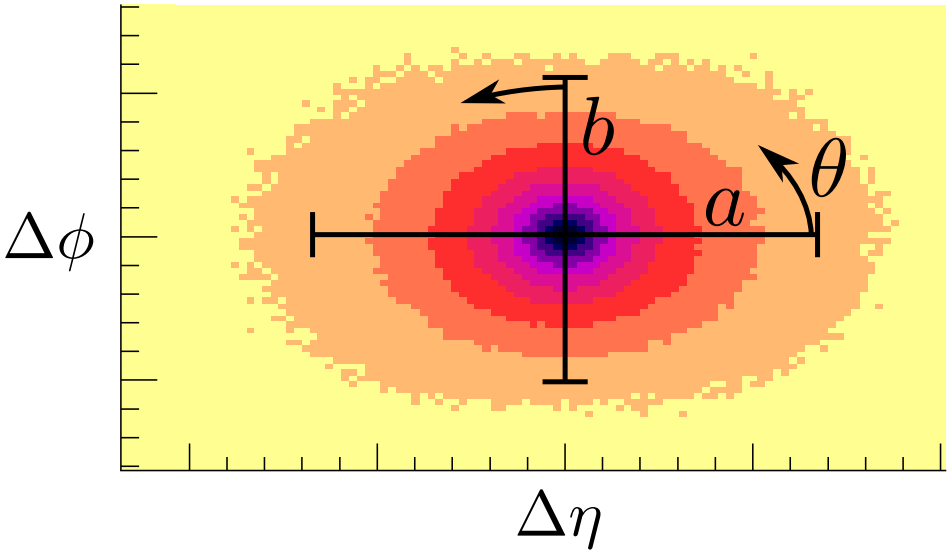
Hard Parton p_T

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



Moment of Inertia / Covariance / Eccentricity

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



Moment of Inertia / Covariance / Eccentricity

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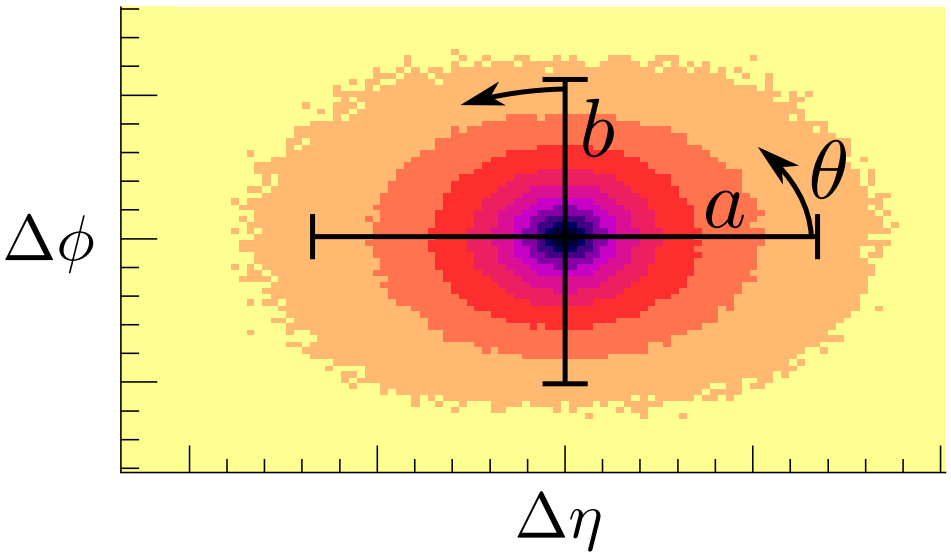


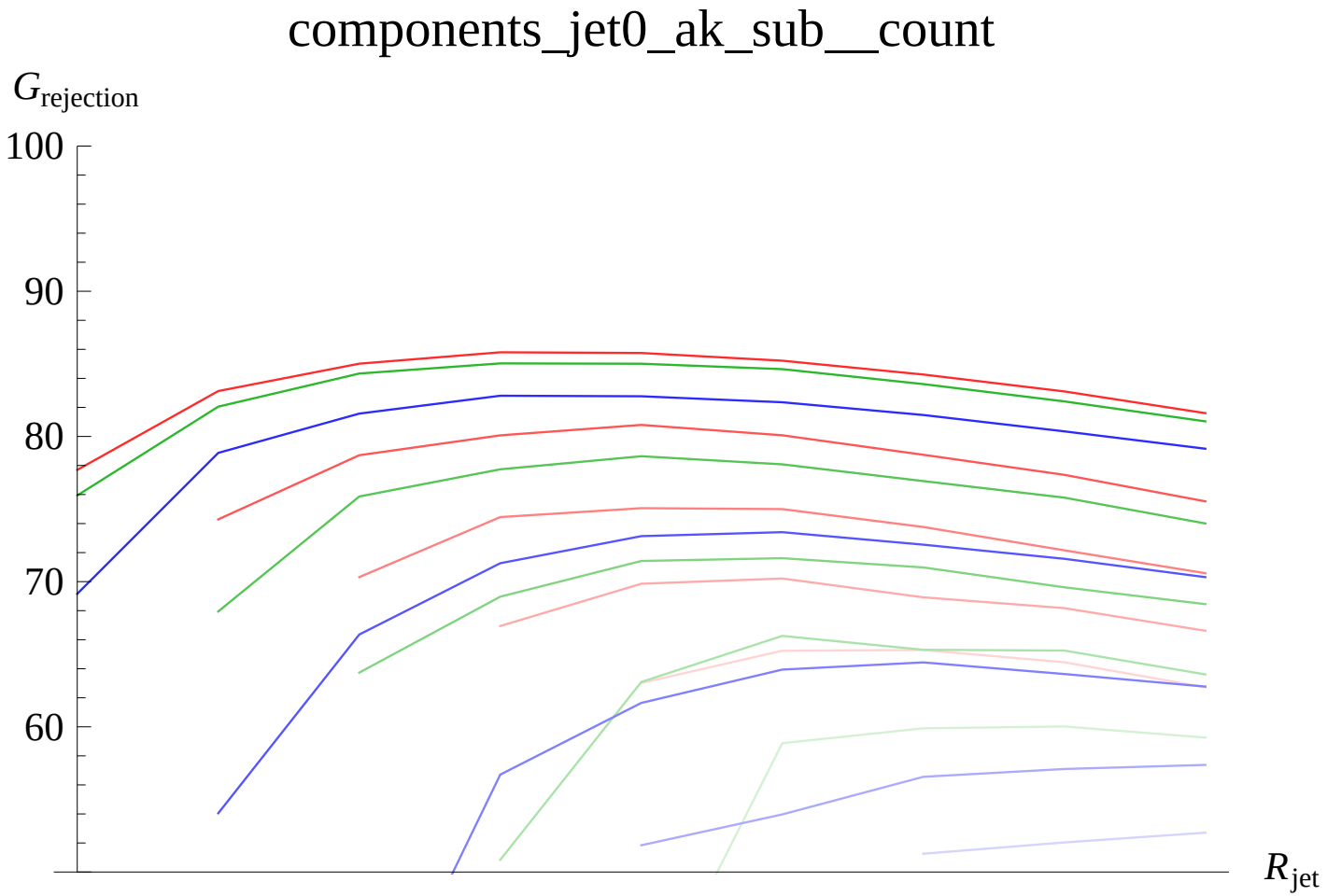
Combination of Eigenvalues

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

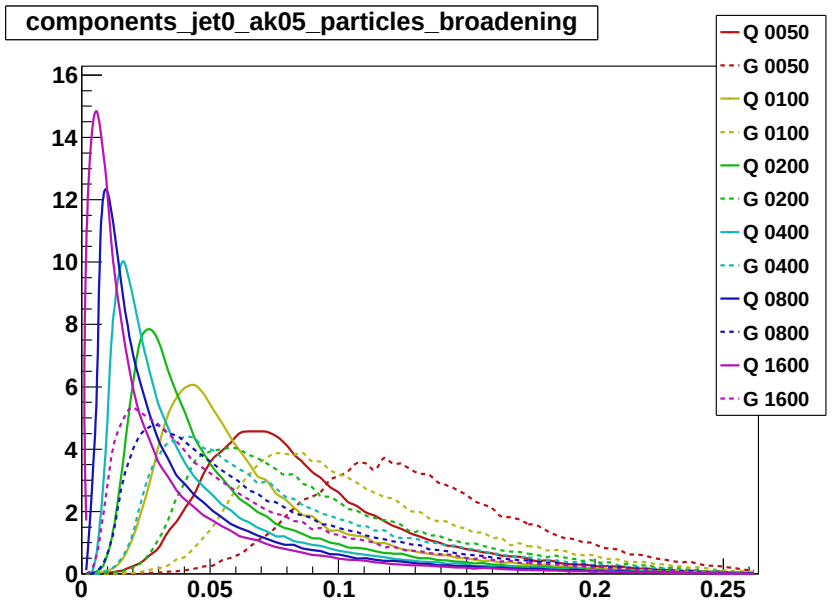
- Different Jet sizes ($R = 0.1, 0.2, 0.4, 0.7, 1.0, 1.4, ...$)
- Different Jet definitions (anti-kt, kt, CA, SisCone)
- Different Generators: Pythia vs Herwig
- Different Samples: Dijet vs γ+jet vs 8-Jets
- Different Subjet sizes and types
- Different Powers in the various moments
- Charged Tracks or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

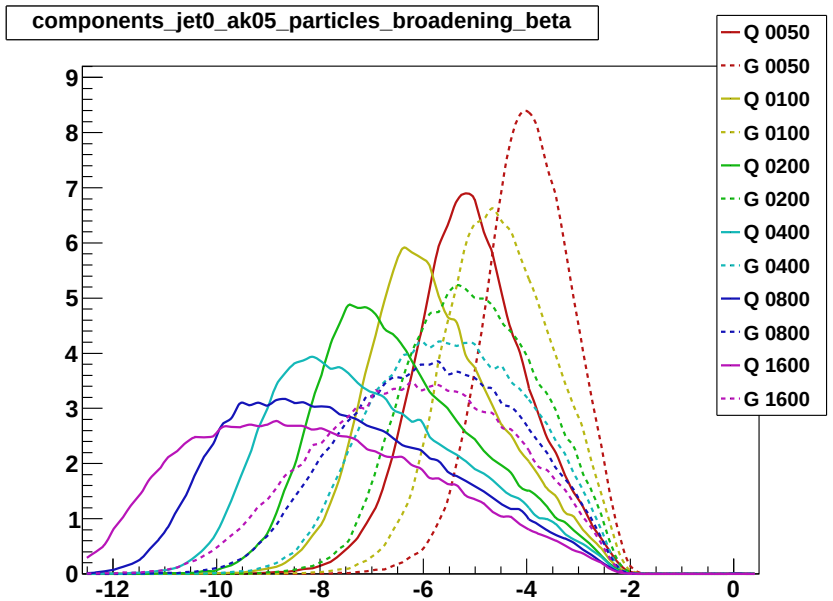
And different variables are better for different Jet p_T ranges.

Jet Broadening

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

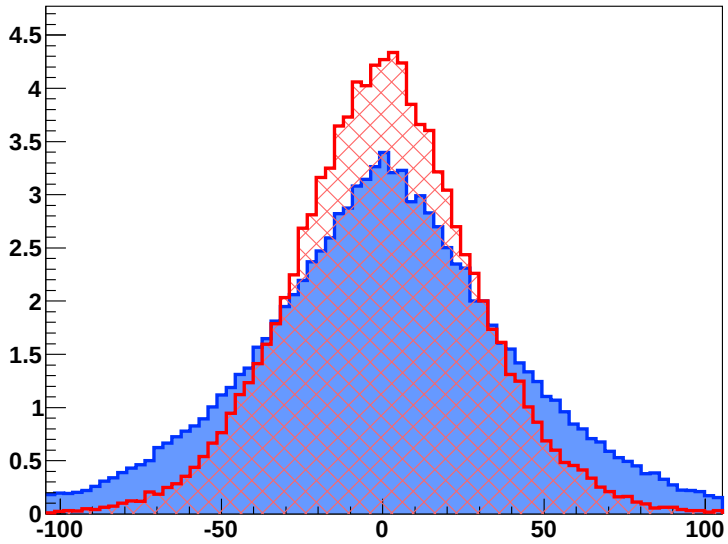
$$B_{\text{jet}} = \frac{\sum_i |\vec{p}_i \times \hat{n}_{\text{jet}}|}{\sum_i |\vec{p}_i|} = \frac{\sum_i |\vec{k}_T i|}{\sum_i |\vec{p}_i|}$$



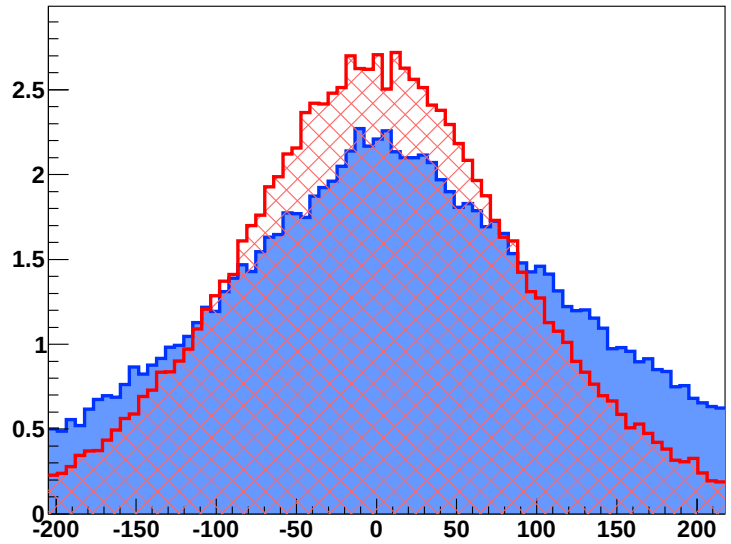


Charge Weighted by p_T

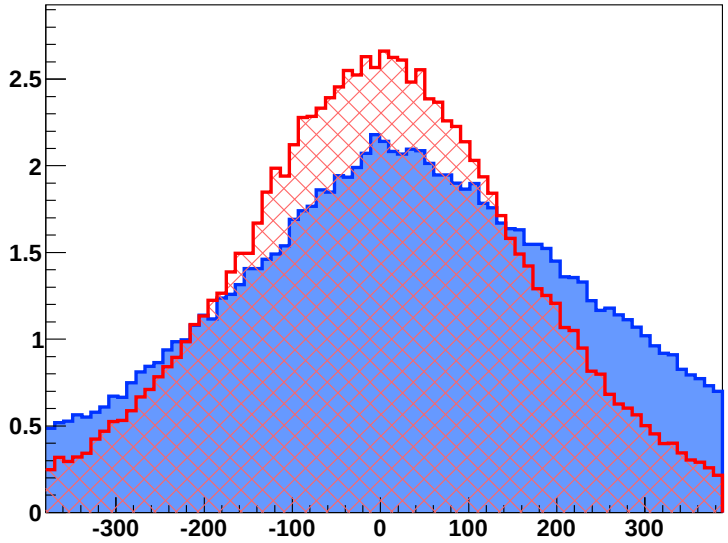
50 GeV



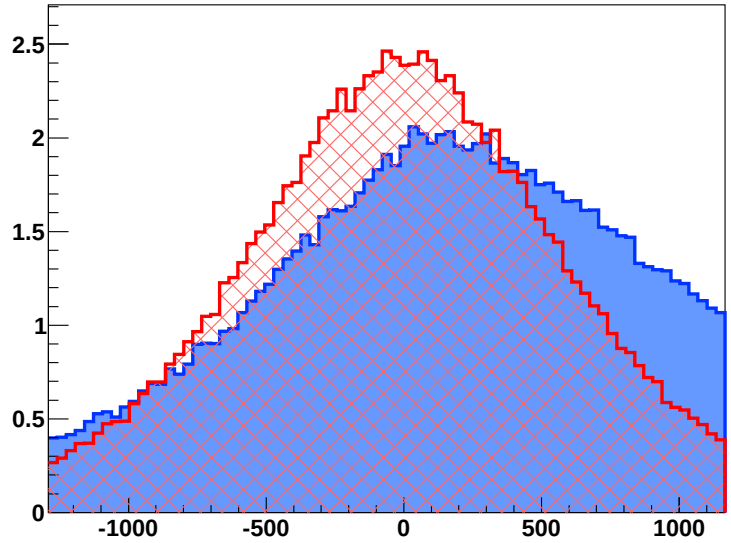
200 GeV



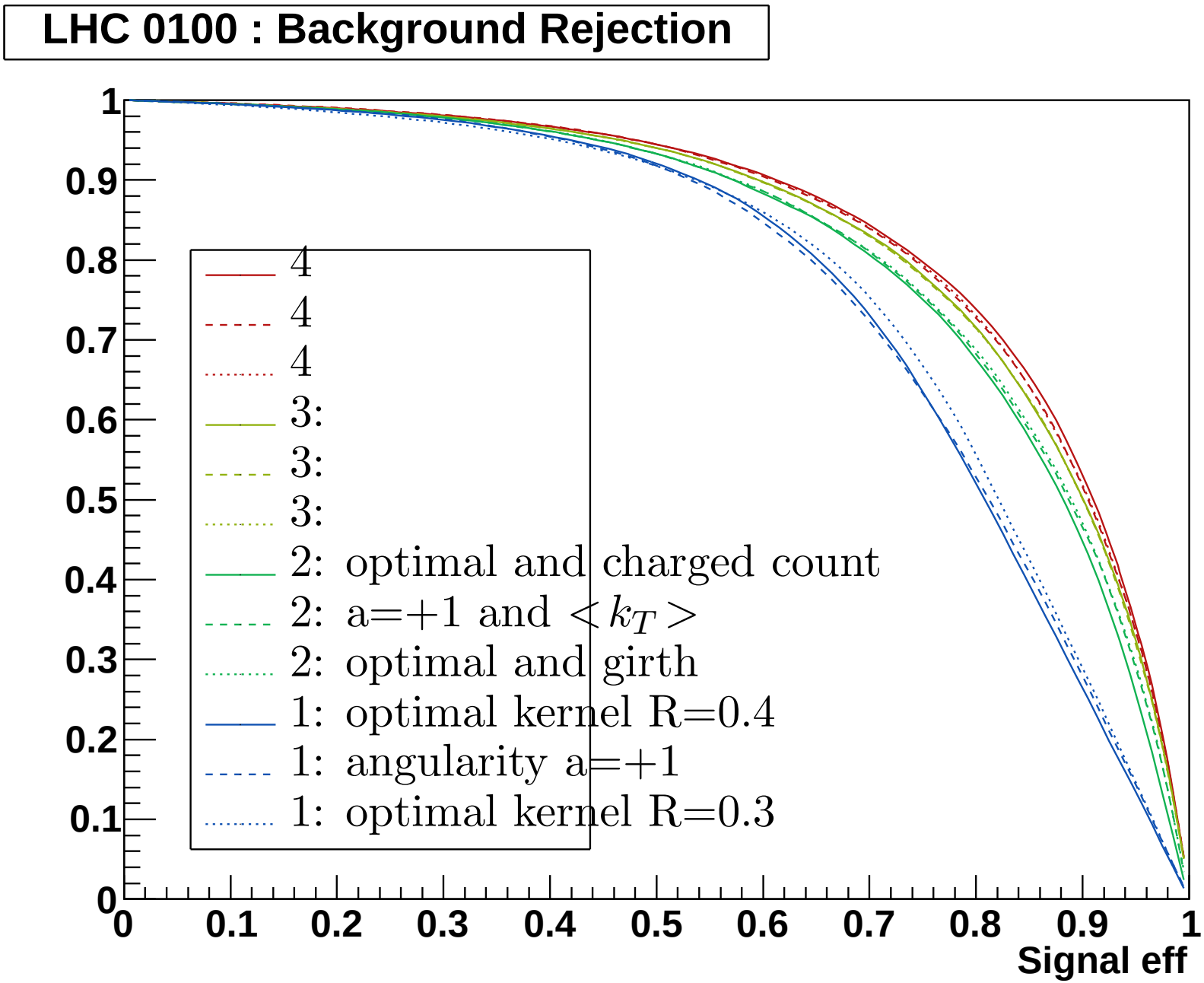
400 GeV



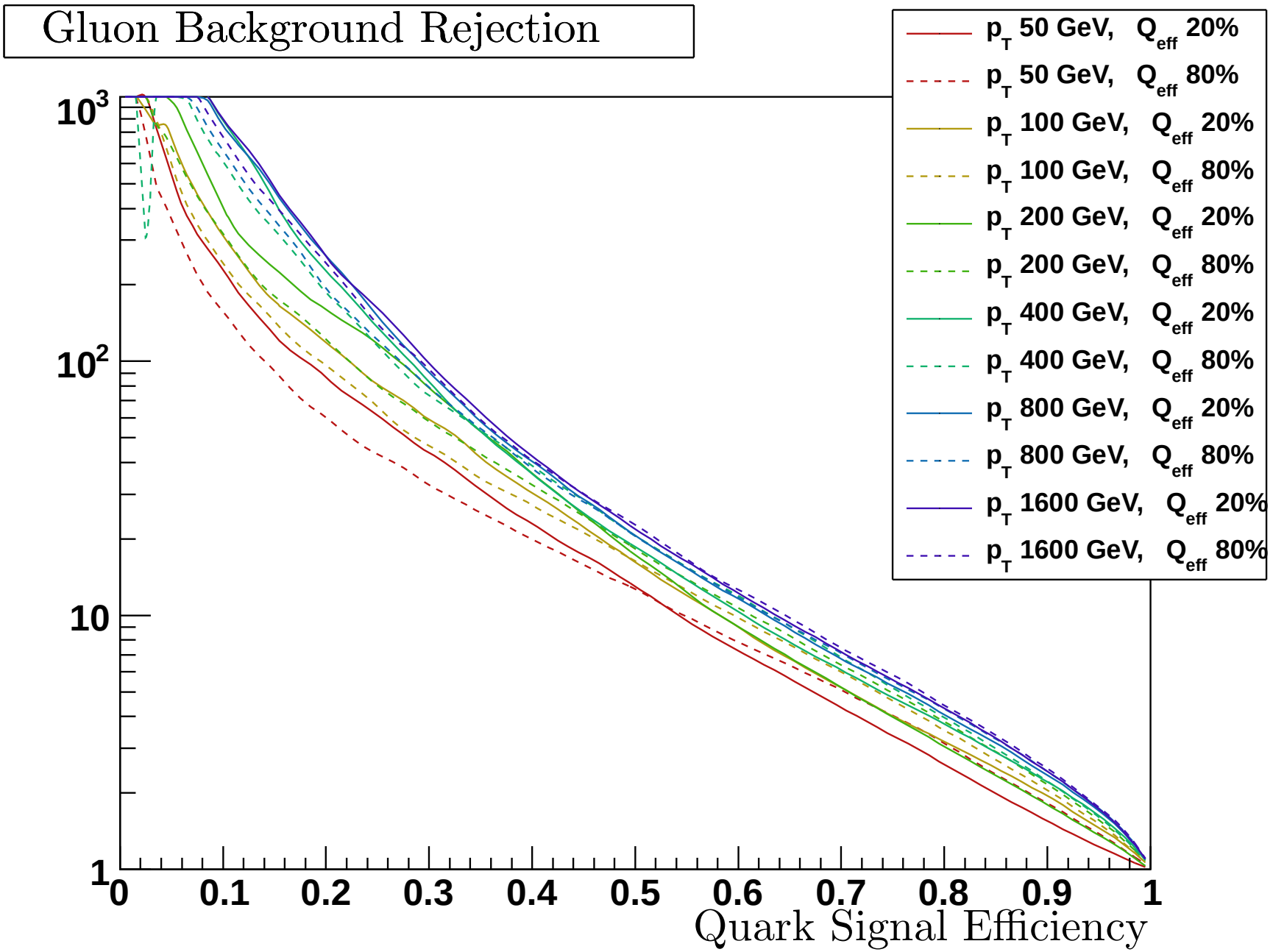
1600 GeV



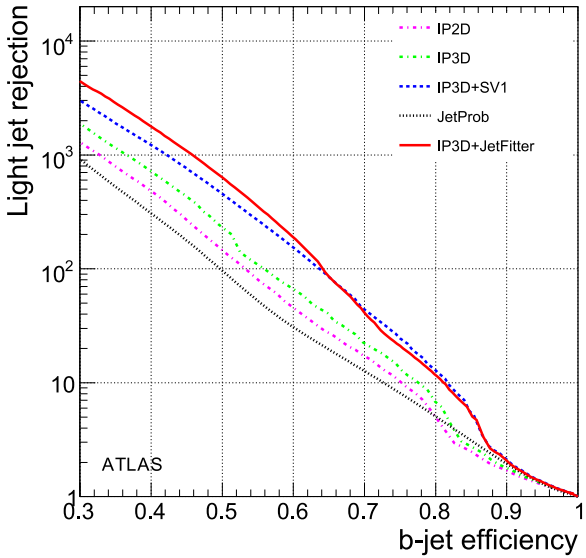
ROC Curves for Best Combinations



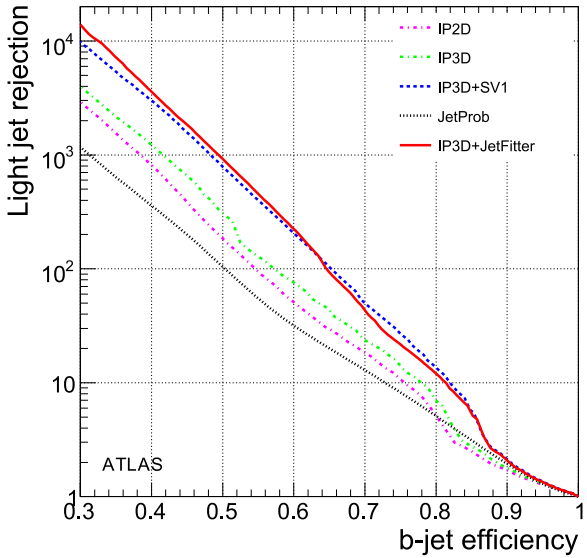
Final Results: Best Pairs



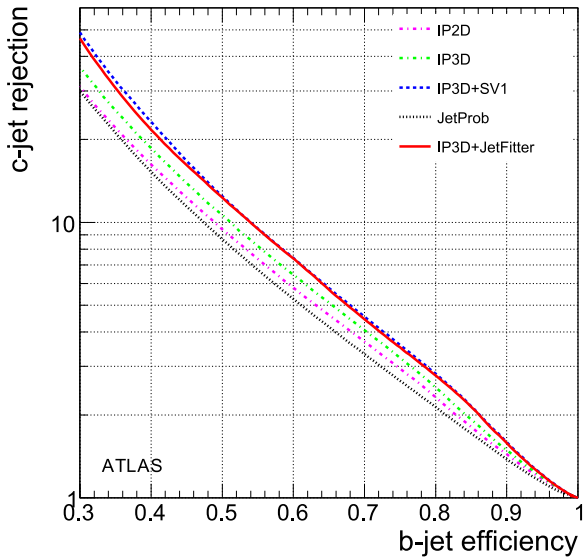
Compare to ATLAS B-Taggnig



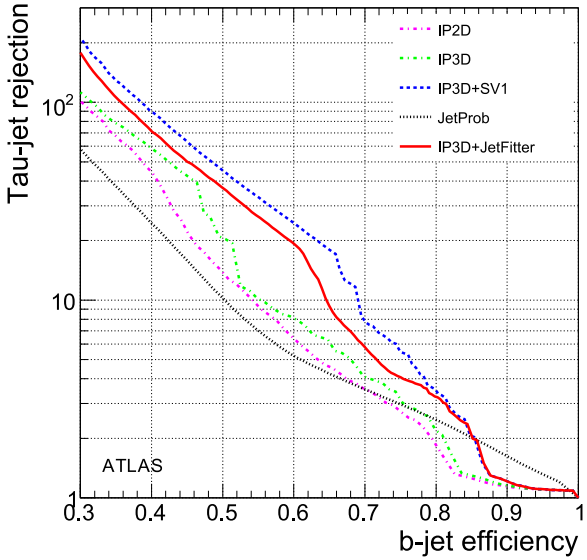
(a) Non-purified light jets



(b) Purified light jets

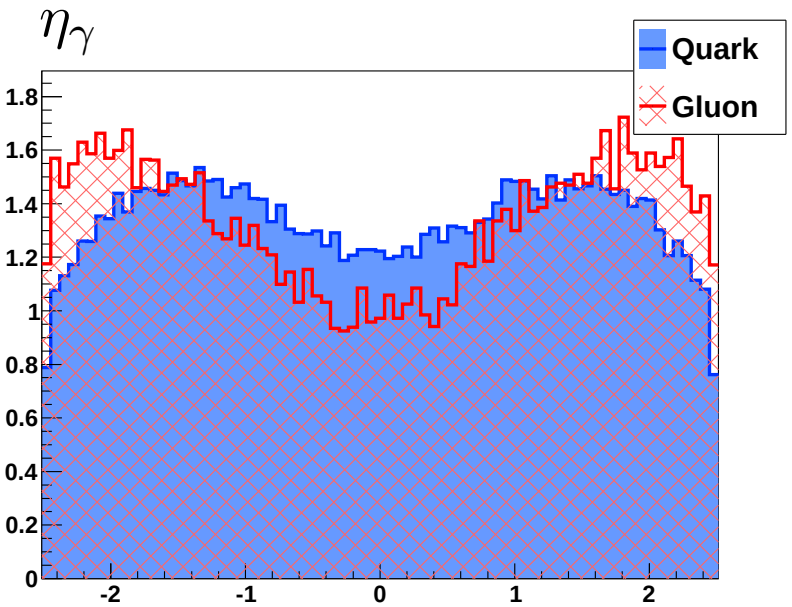


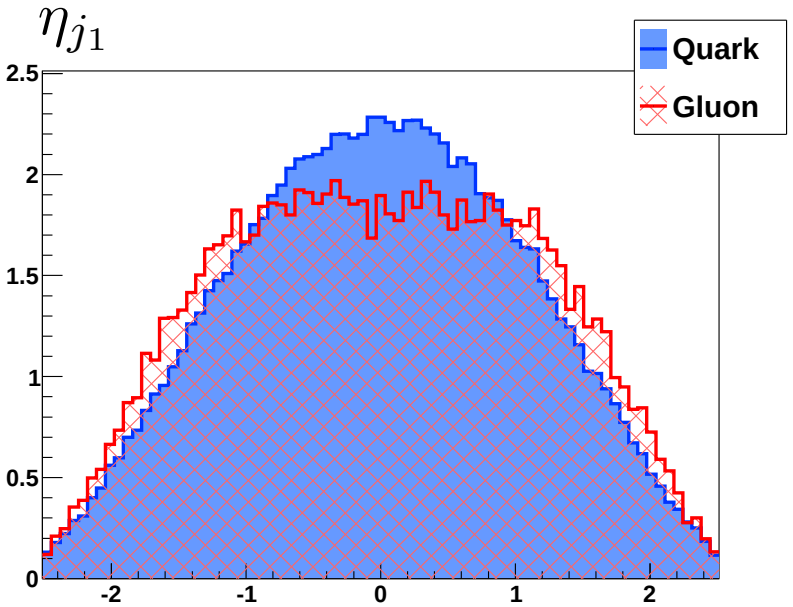
(c) c-jets



(d) τ-jets

Quark Purification in γ+2jet: Look at Softer Jet



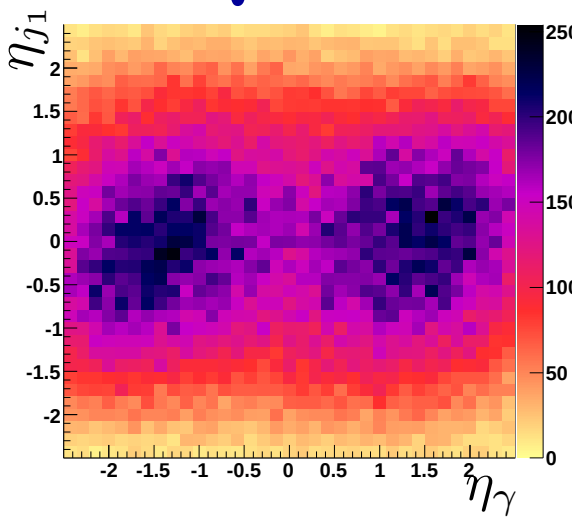


Other useful kinematics (?)

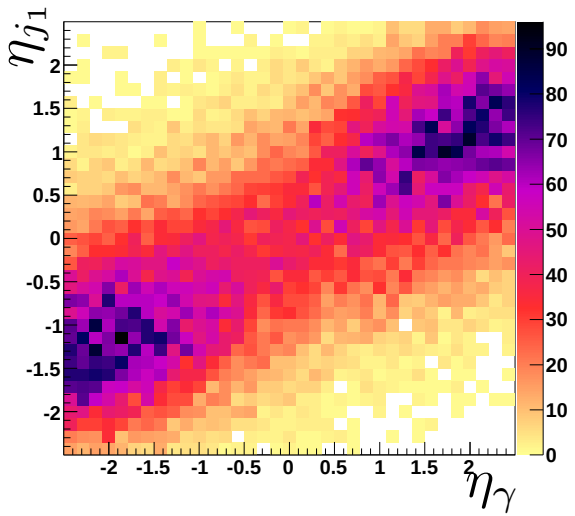
Quark Purification in γ+2jet: Look at Softer Jet

2D version of the same

Quark



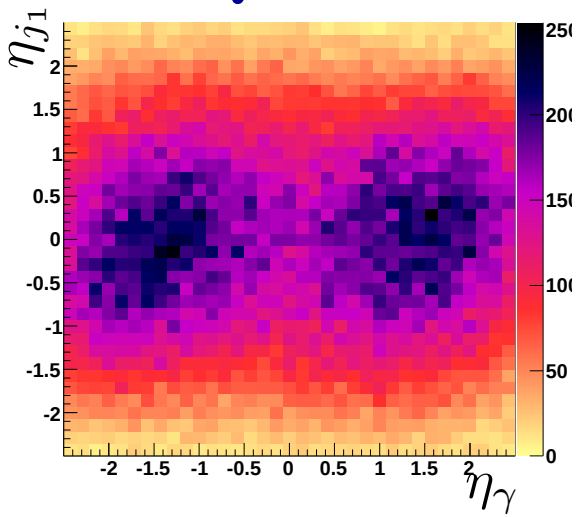
Gluon



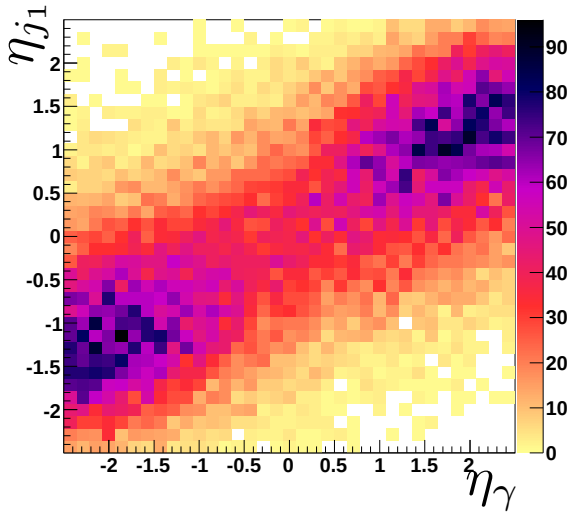
Quark Purification in γ+2jet: Look at Softer Jet

2D version of the same

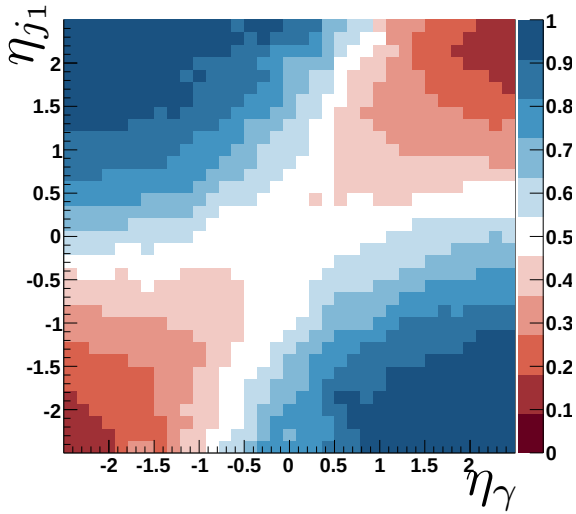
Quark



Gluon



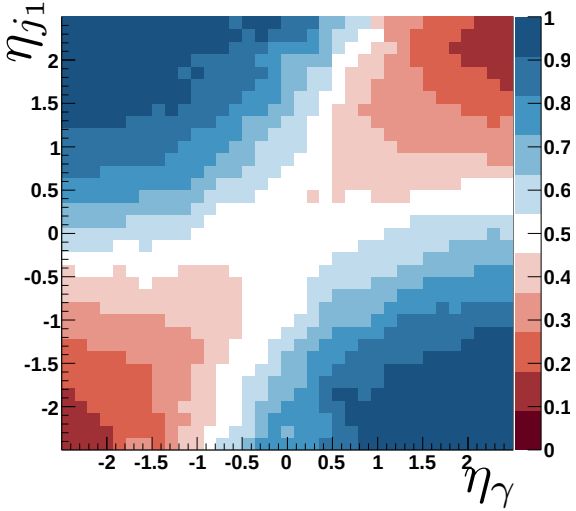
Likelihood

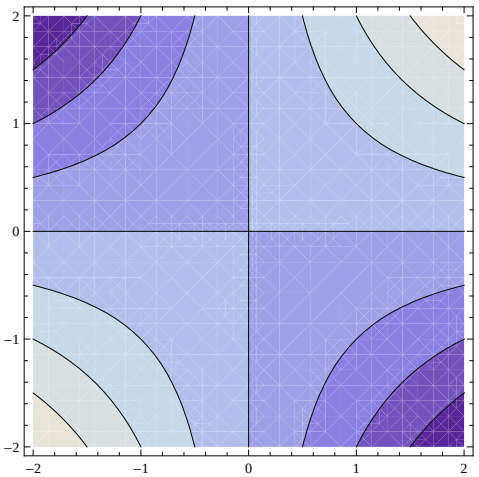


Quark Purification in γ+2jet: Look at Softer Jet

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

Likelihood

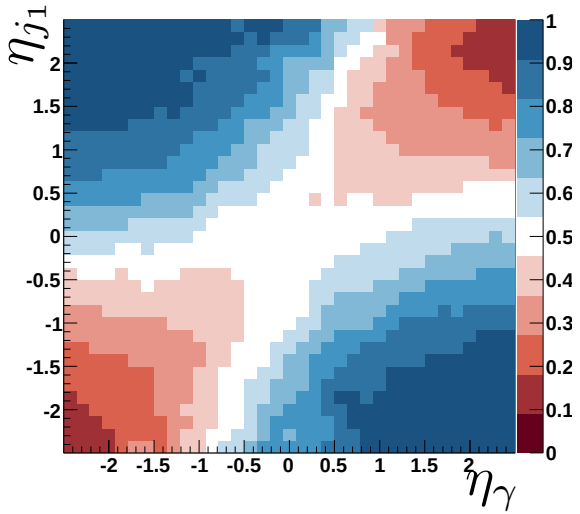


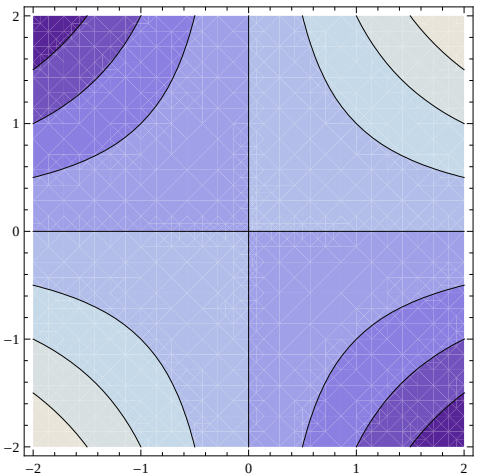


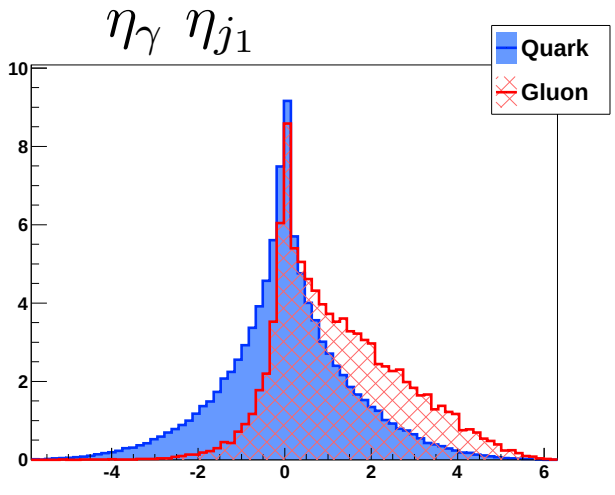
Quark Purification in γ+2jet: Look at Softer Jet

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

Likelihood

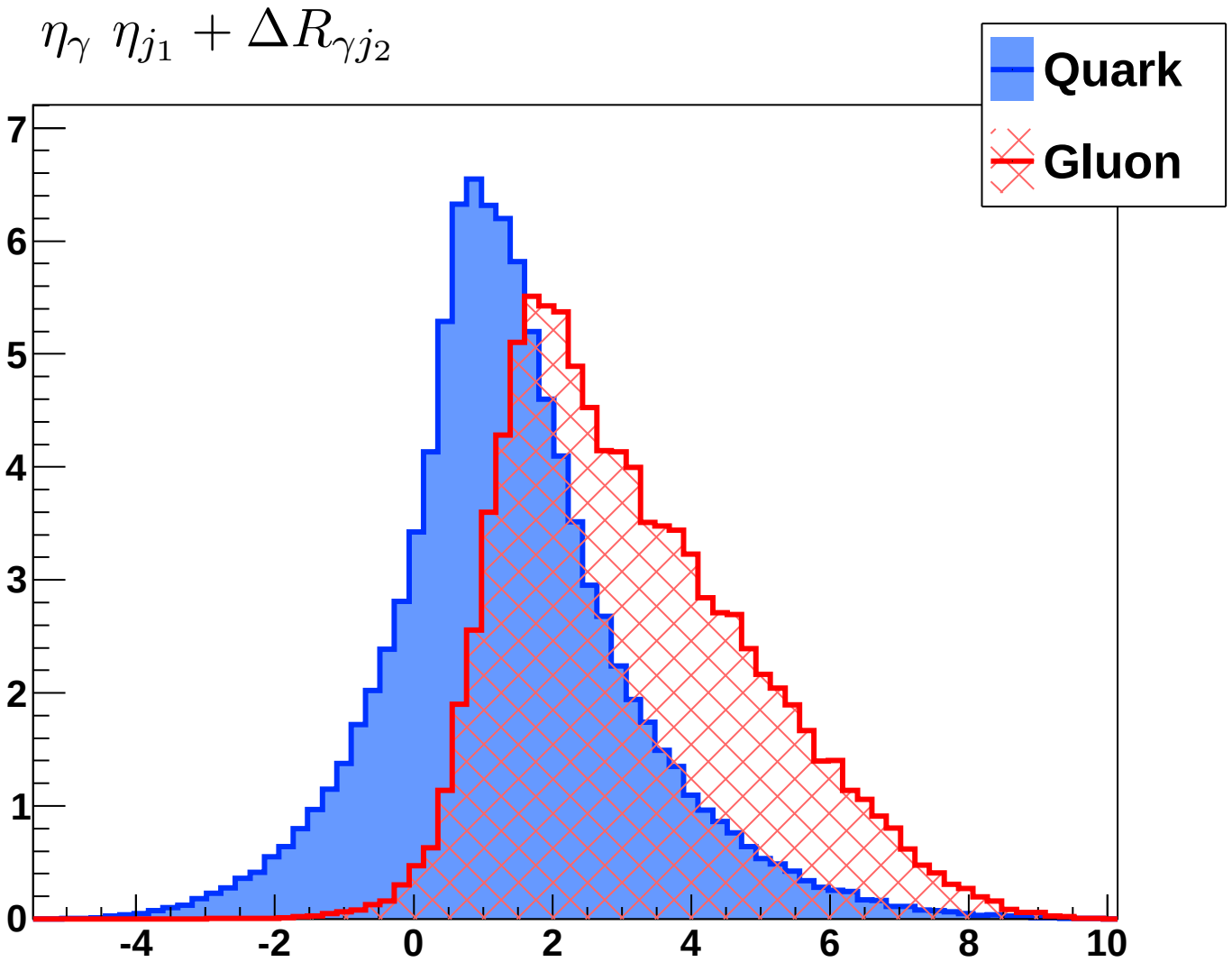






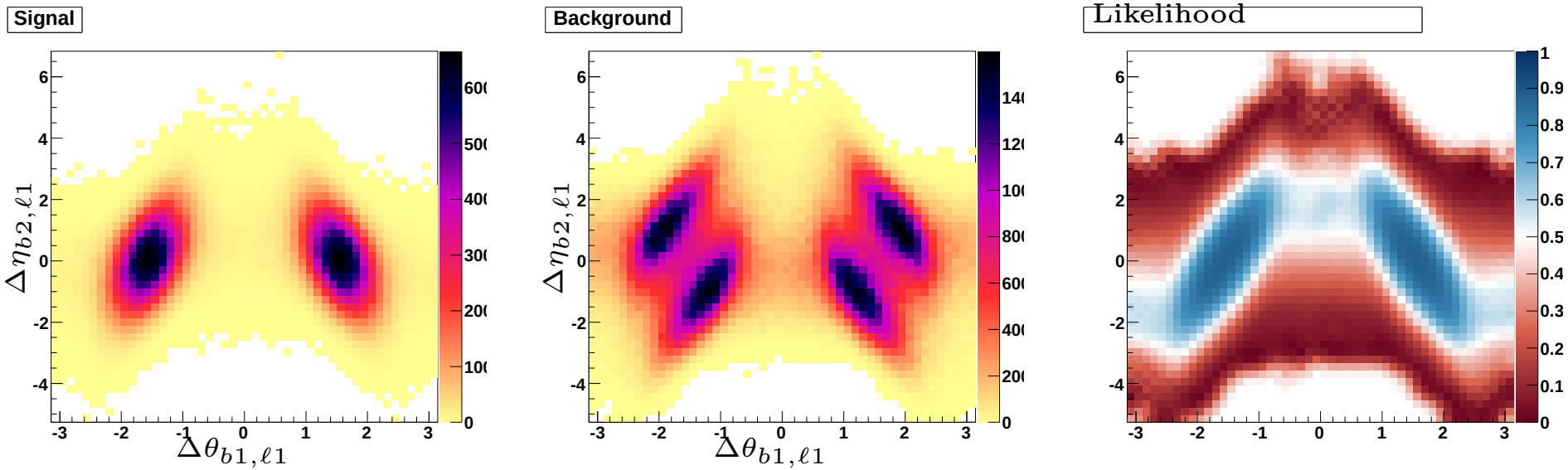
Quark Purification in γ+2jet: Look at Softer Jet

Do it again to find an even better combination

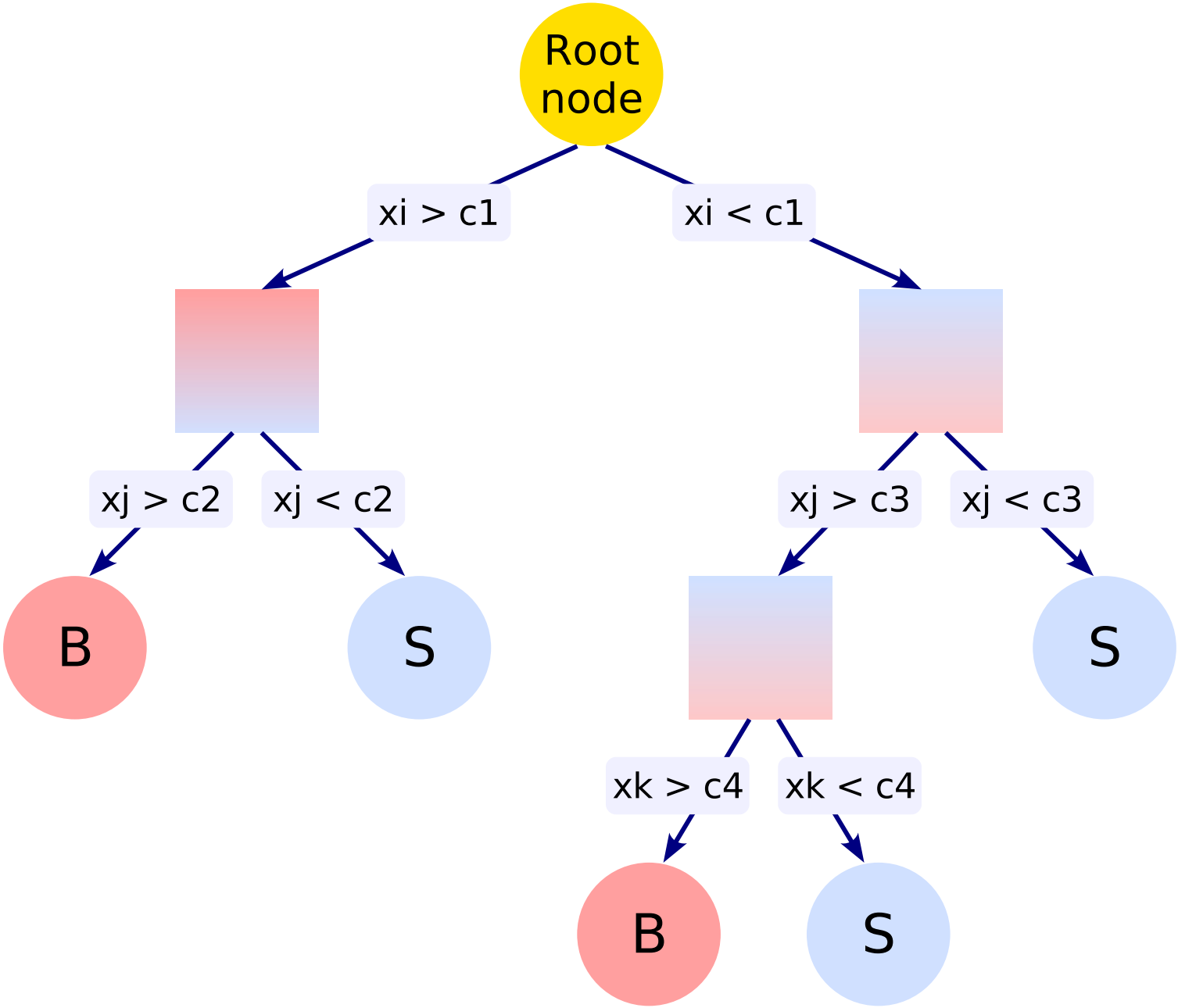


Automating the process with Boosted Decision Trees

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

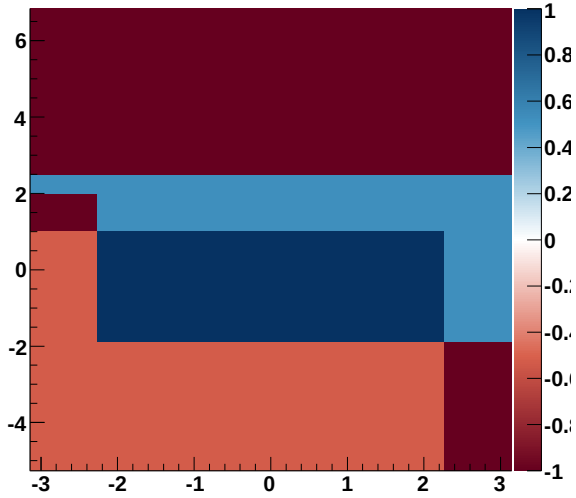


Automating the process with Boosted Decision Trees

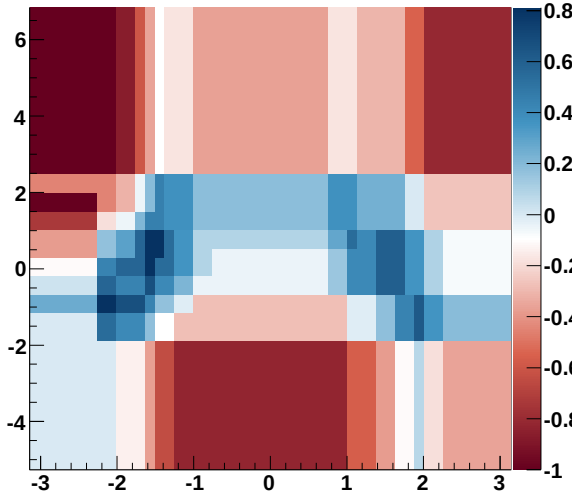


Do **Not** ***Fear*** Boosted Decision Trees

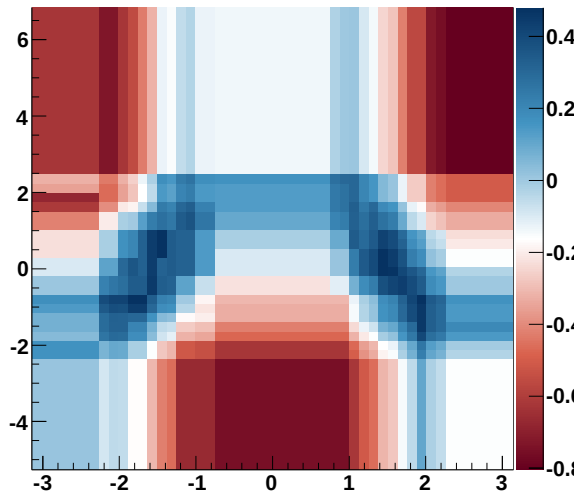
BDT 2



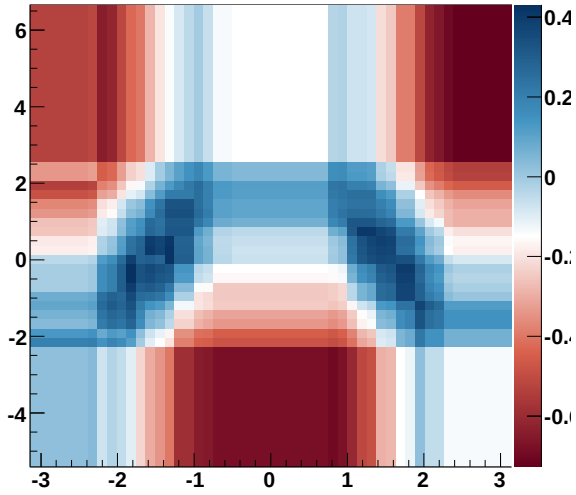
BDT 8



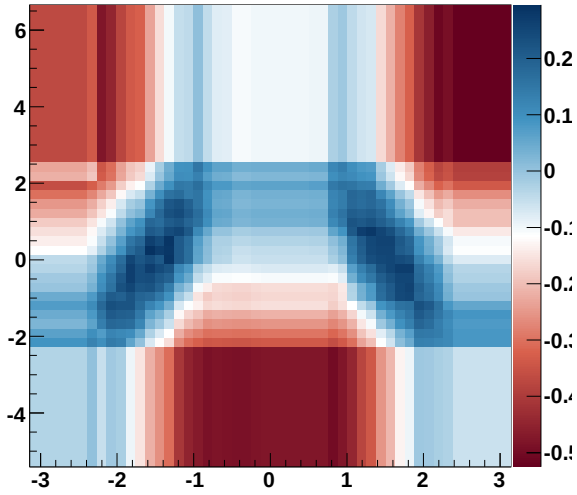
BDT 32



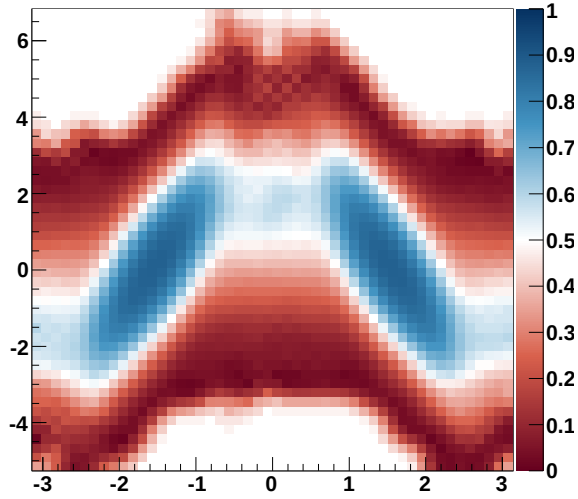
BDT 64

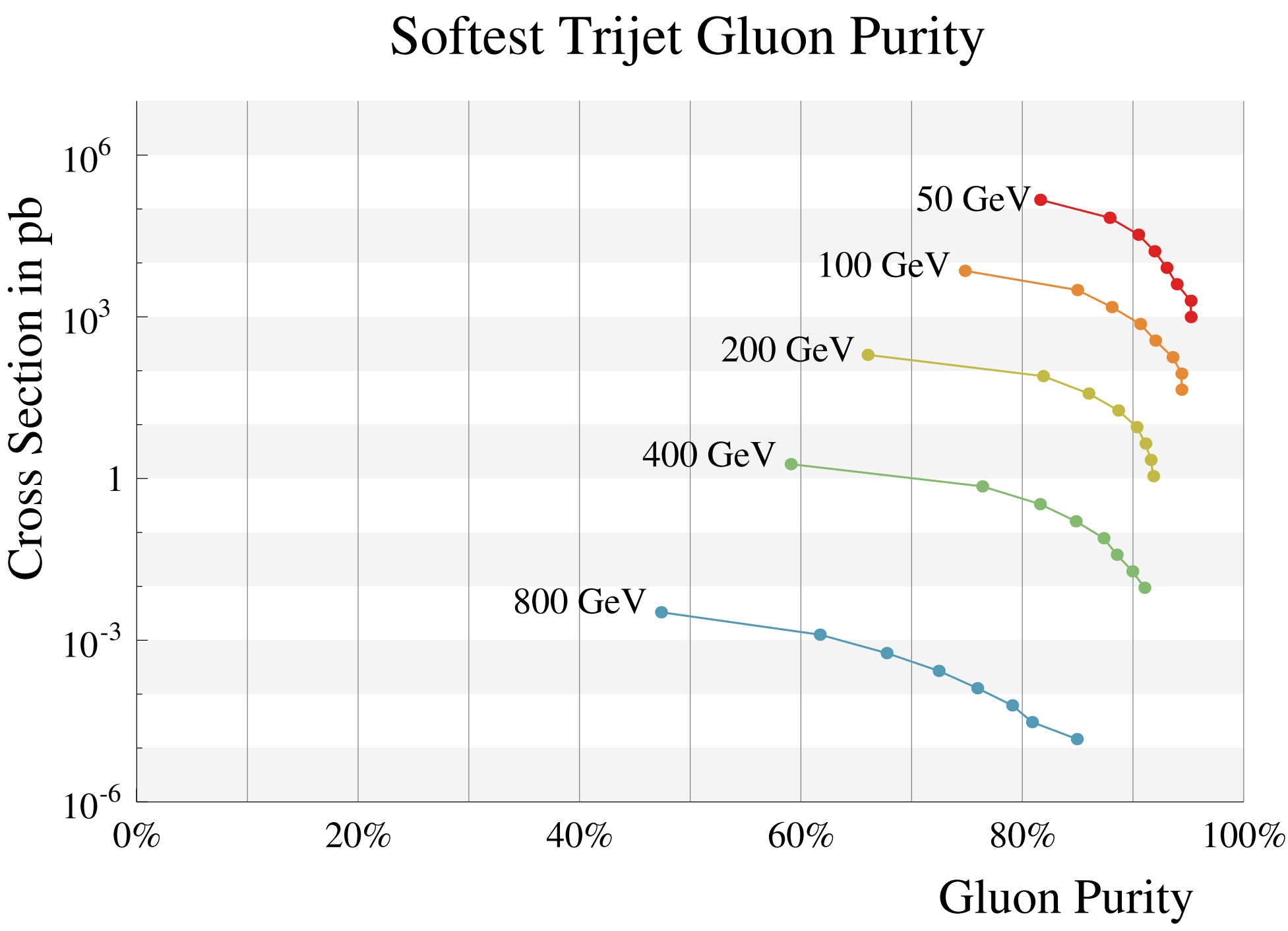


BDT 256

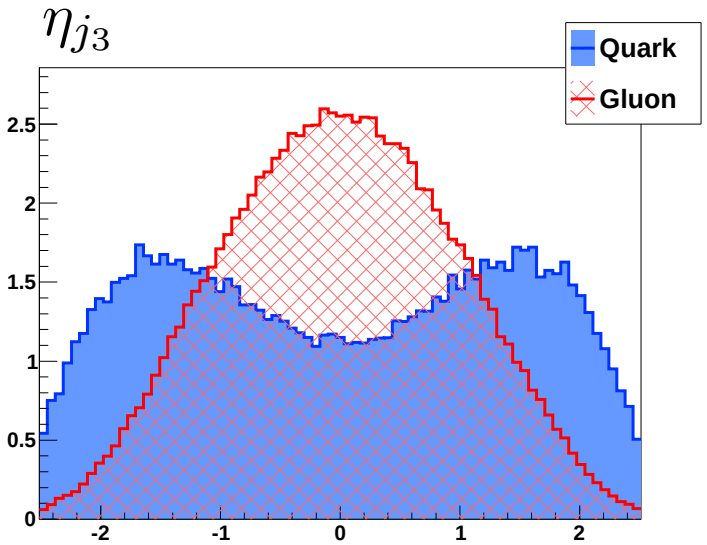


Likelihood

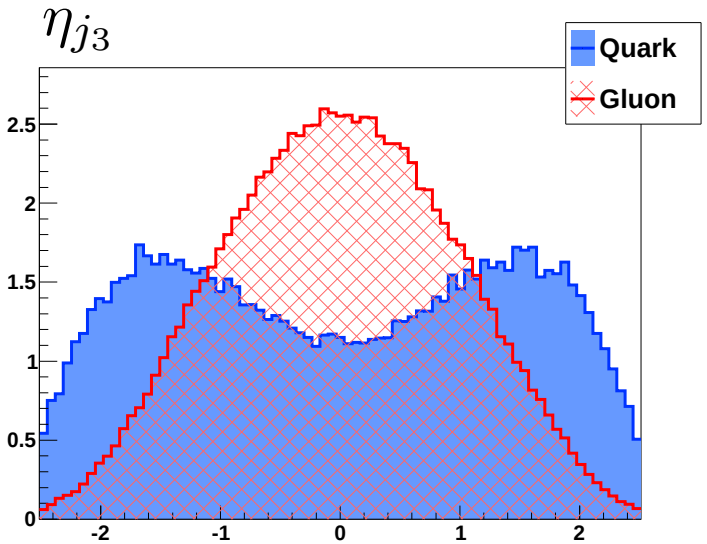



Softest Trijet Gluon Purity
Cross Section in pb
10^{6}
10^{3}
1
10^{-3}
10^{-6}
50 GeV
100 GeV
200 GeV
400 GeV
800 GeV
0%
20%
40%
60%
80%
100%
Gluon Purity

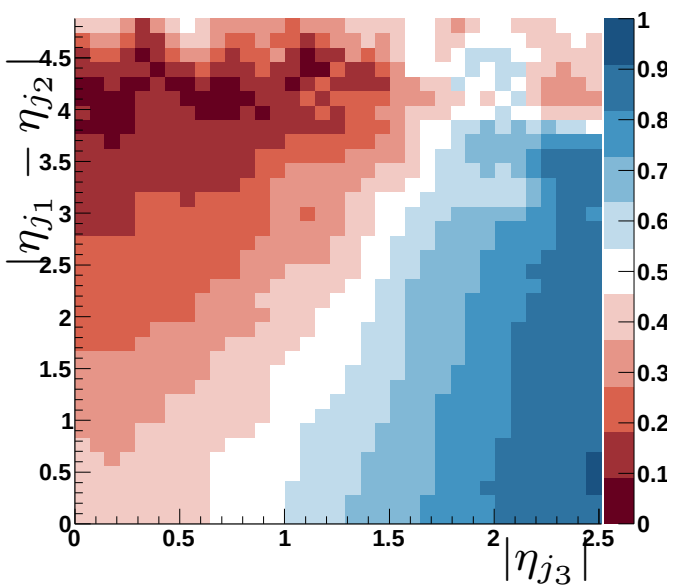
Gluon Purification: Lesson about Harsh Cuts

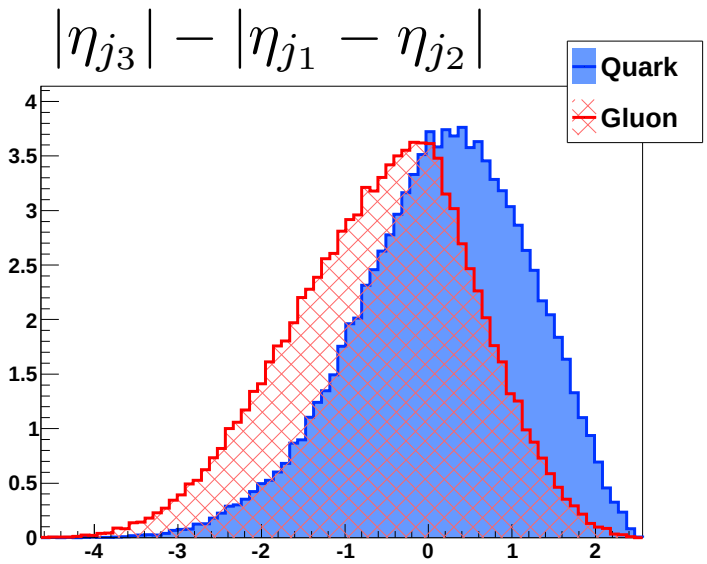


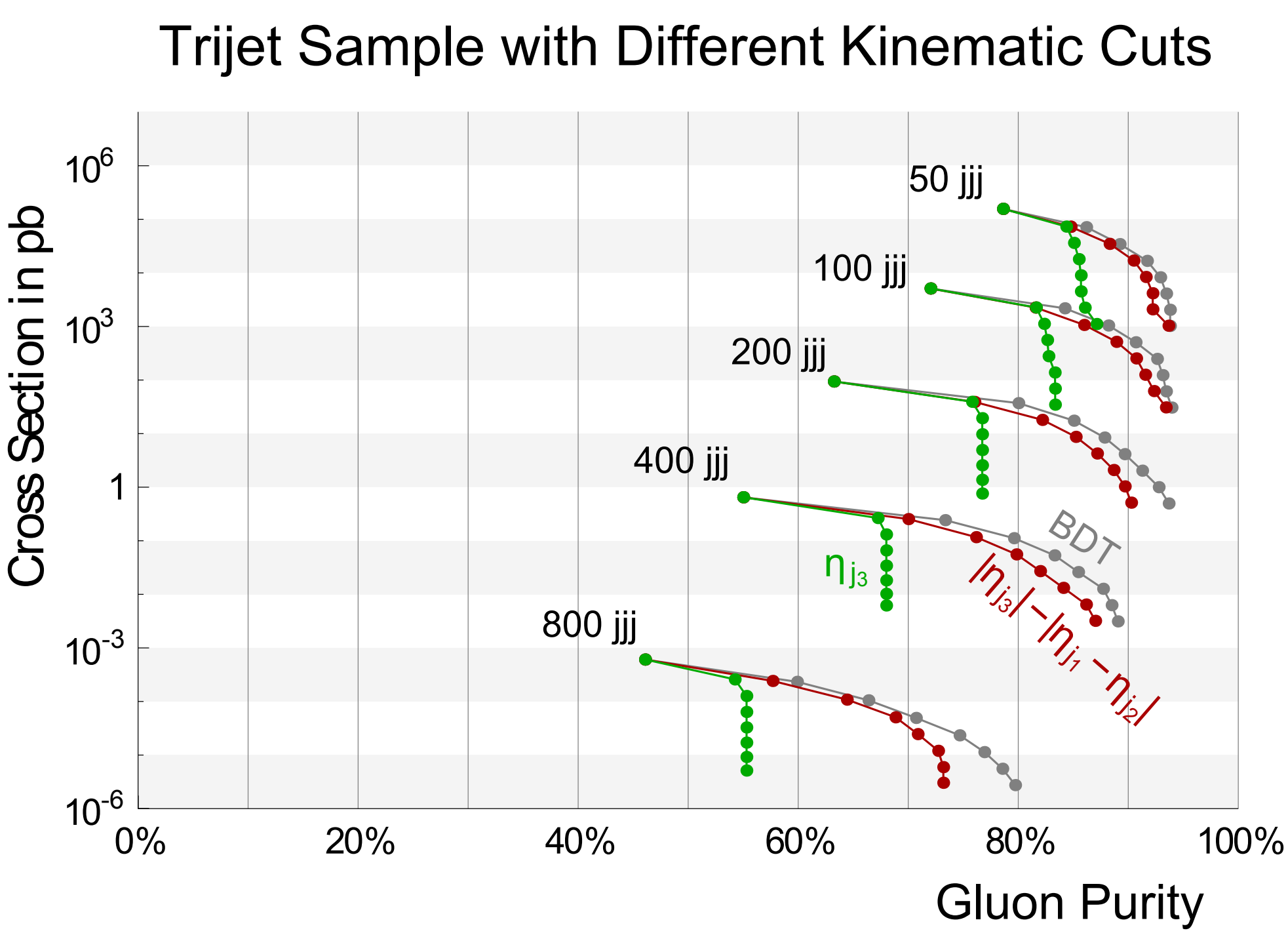
Gluon Purification: Lesson about Harsh Cuts



Likelihood






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}
$|\eta_{j_3}| - |\eta_{j_1} - \eta_{j_2}|$