Constructing & Using a Quark/Gluon Tagger

How well can we do at the 7 TeV LHC?

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UC Davis

27 March 2012

Outline

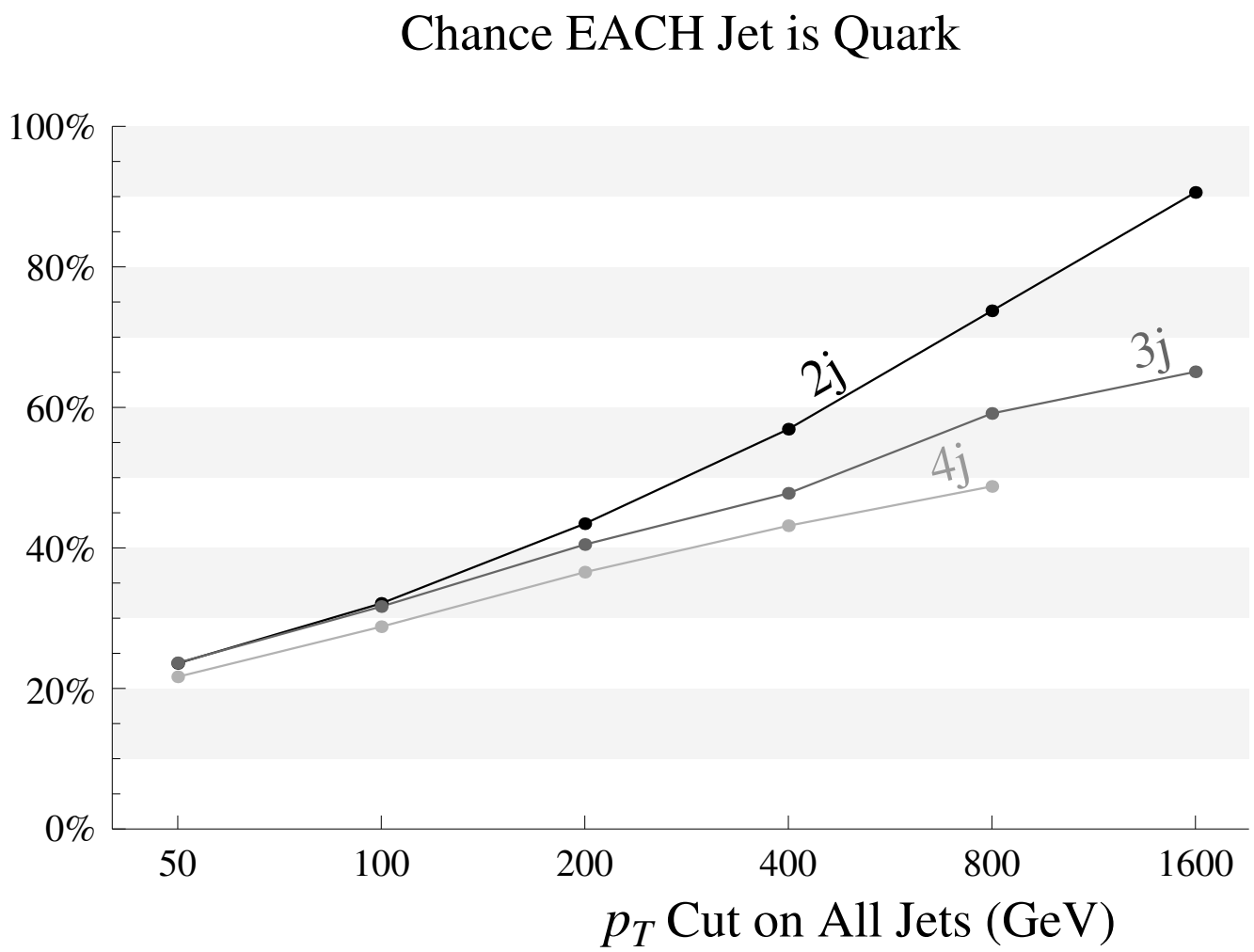
1. **Big Motivation:** Reject Gluey LHC Backgrounds
2. **The Tagger:** Observables and Performance
3. **Verification:** Finding Pure Samples of Quark and Gluon Jets

"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 $\gtrsim 100\,\text{GeV}$ are quark $\approx (30\%)^4 \approx 1/125$

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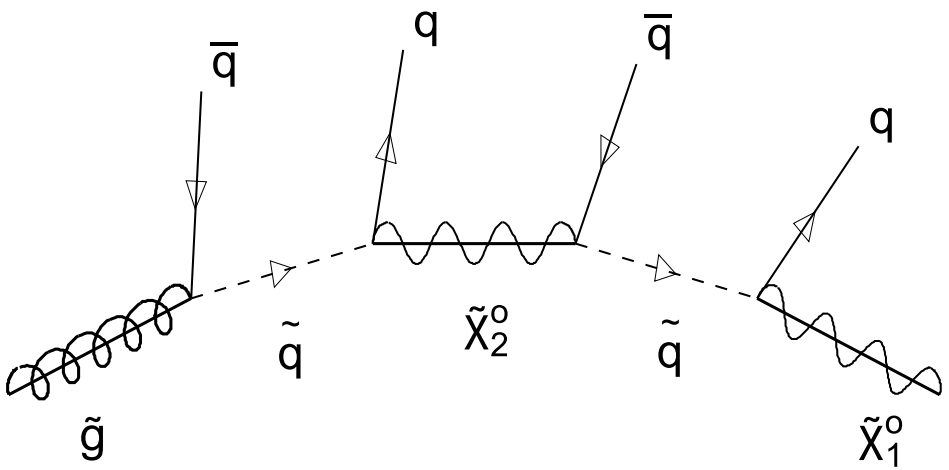

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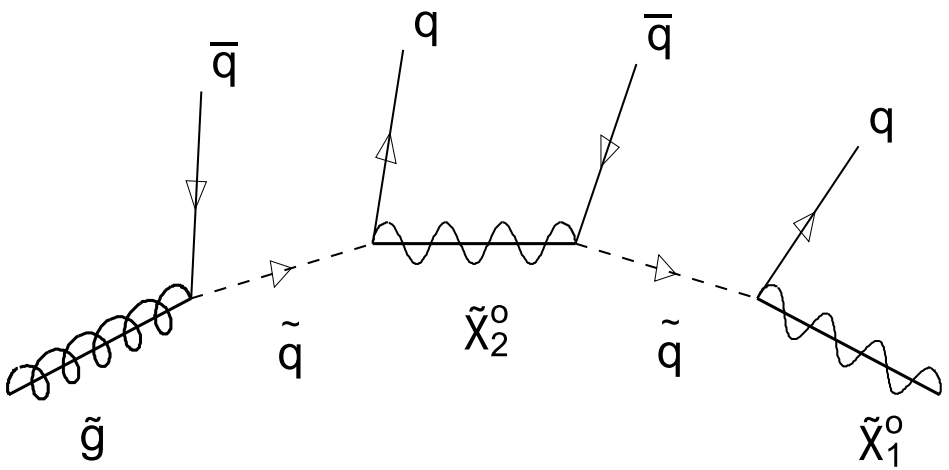

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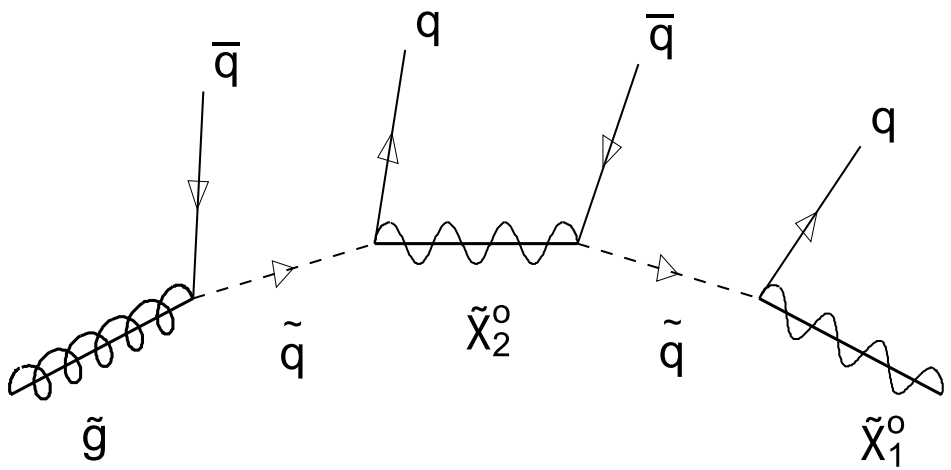

- Higgs $H^+ \to c\bar{s}$ (for charged Higgs mass between τ and top mass)
- Measure Z' coupling to hadrons (or find a leptophobic Z')

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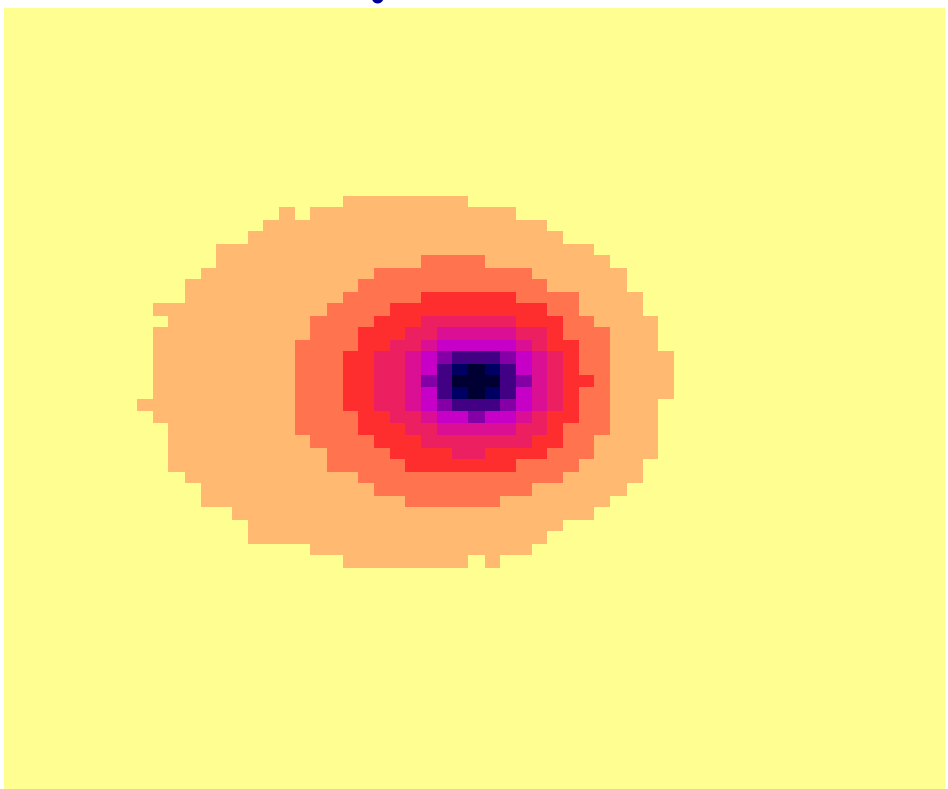
Must combine Quark/Gluon-Tagging with B-Tagging and τ-Tagging.

The Quark/Gluon Tagger

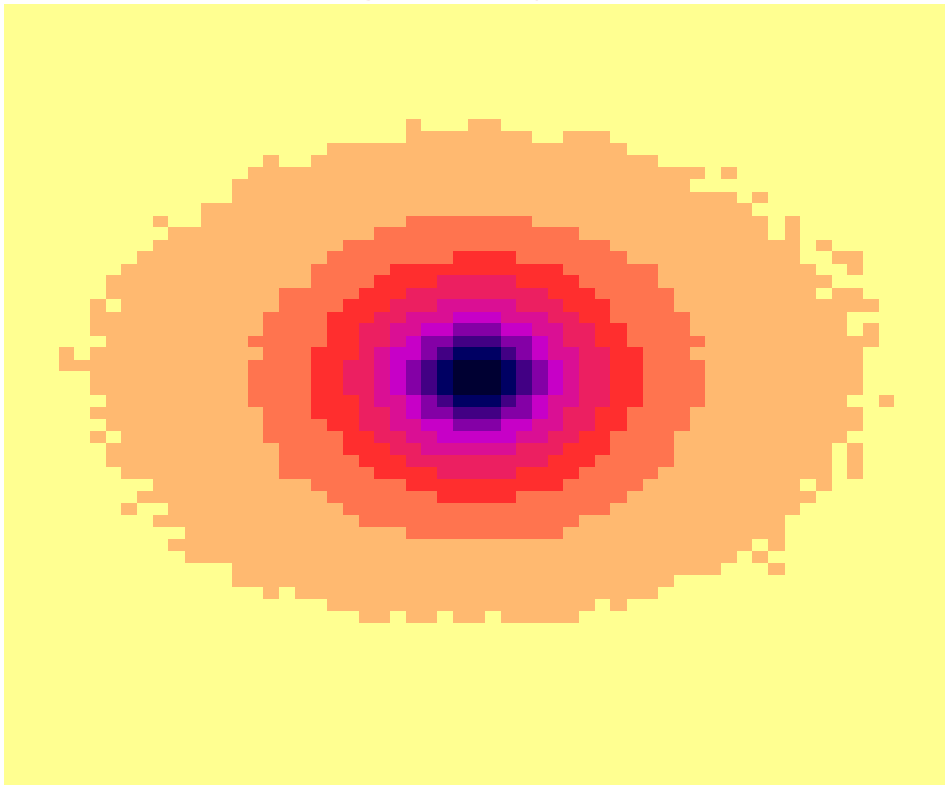
Visual Differences

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.)

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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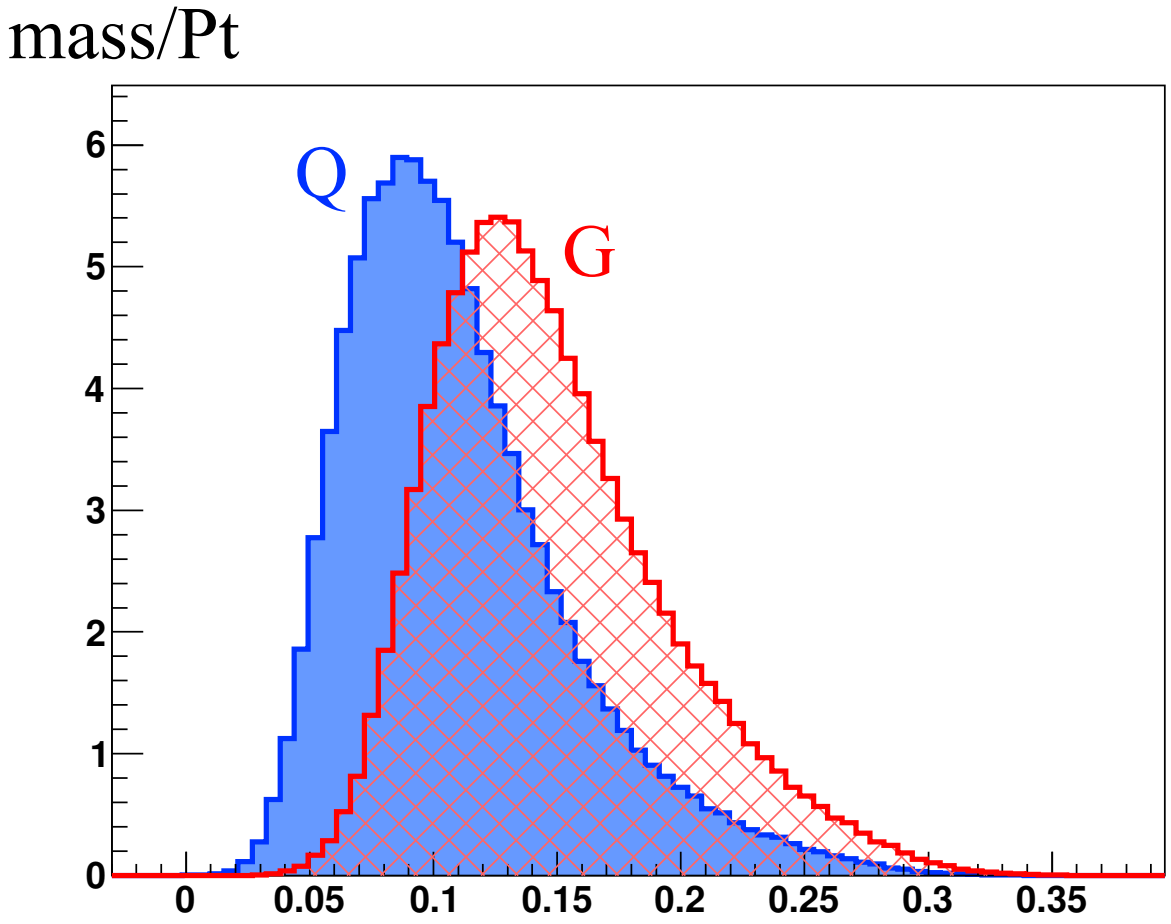
Average Jet Mass in the small angle limit:

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

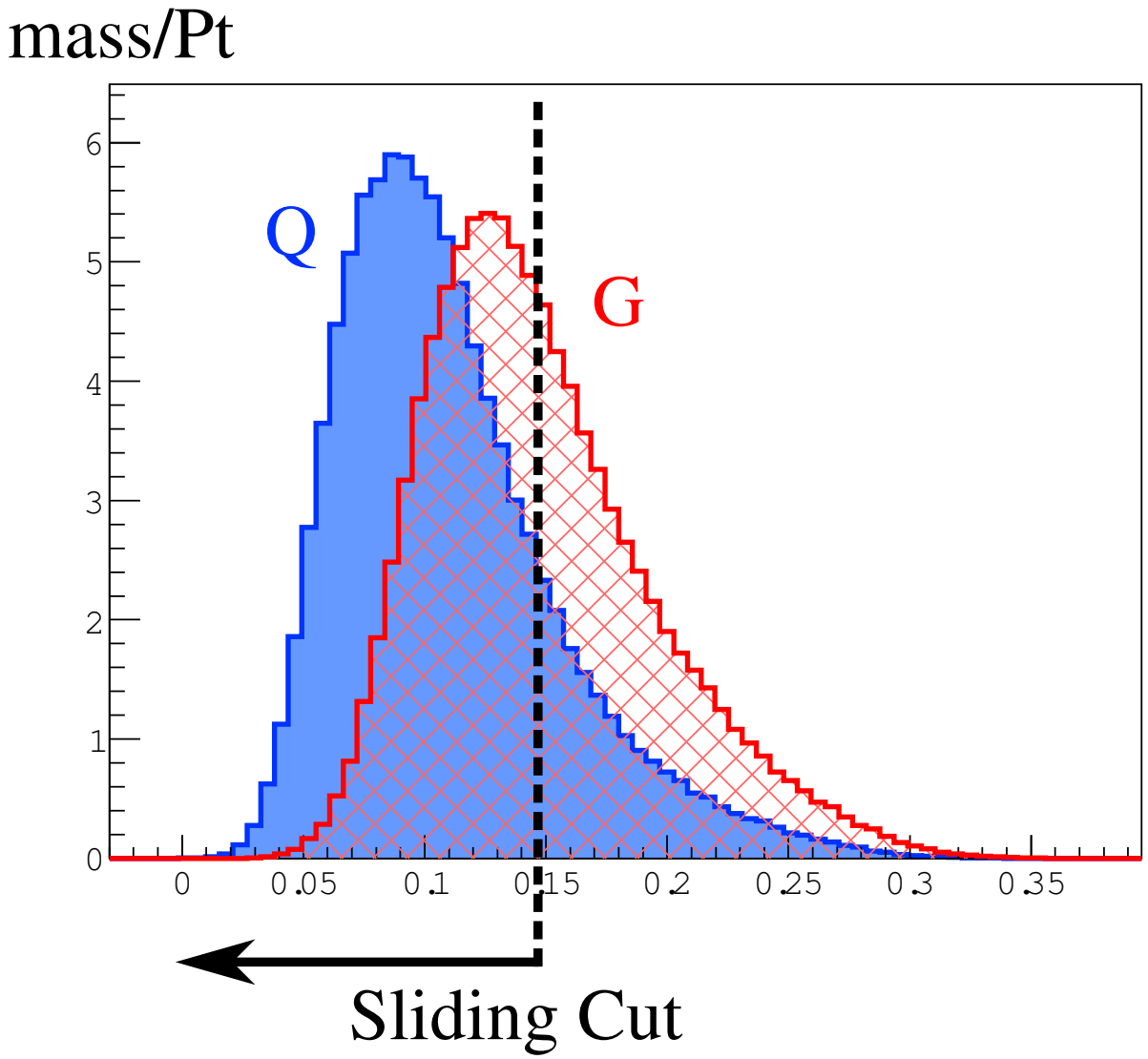
Distribution of Jet Mass....

Jet Mass as an Example Observable

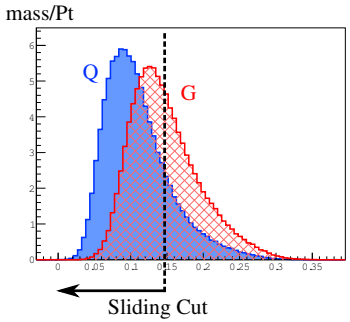
- Normalizing by p_T (200 GeV in this sample) generalizes better.
- All distributions normalized to equal area.

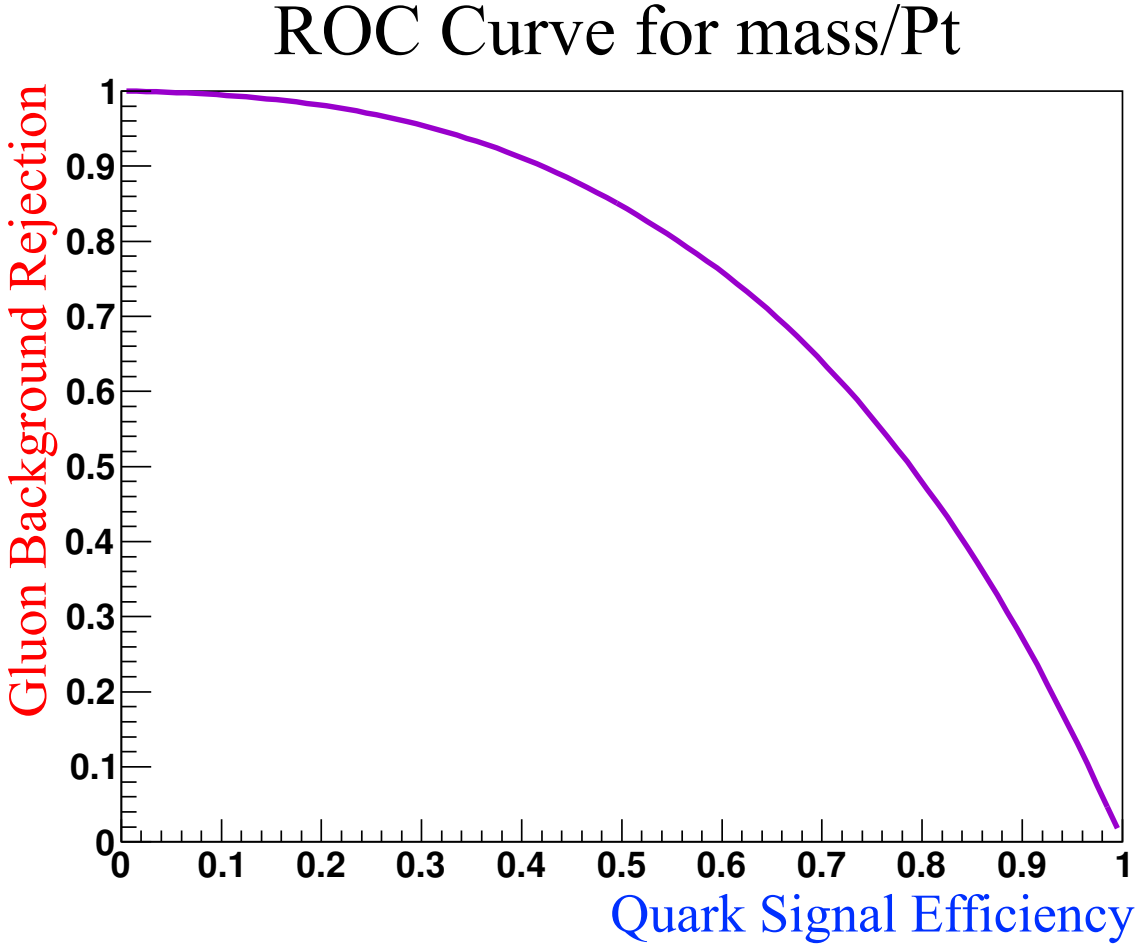


Evaluating the Observable: Sliding Cut

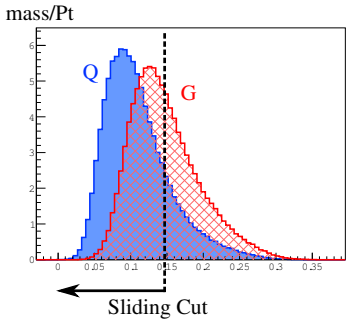


ROC Curve


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
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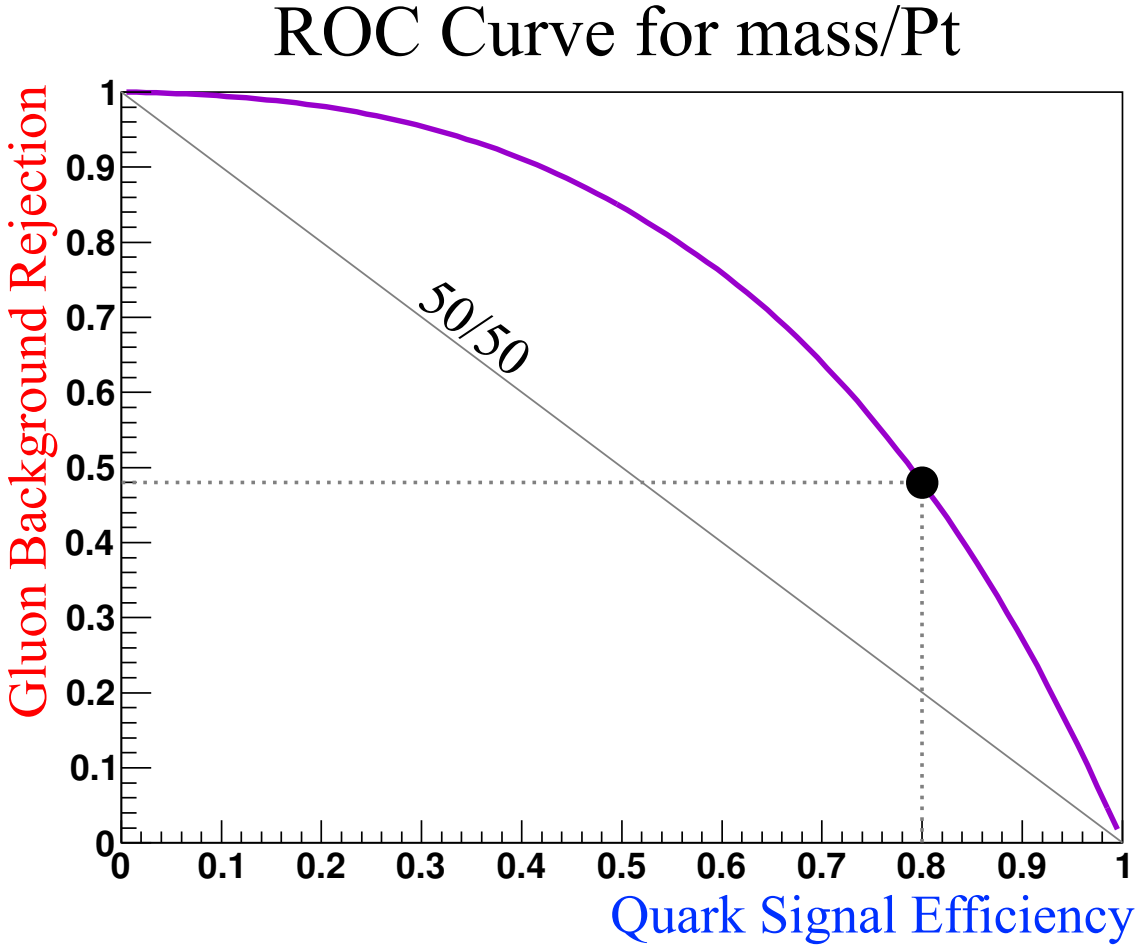
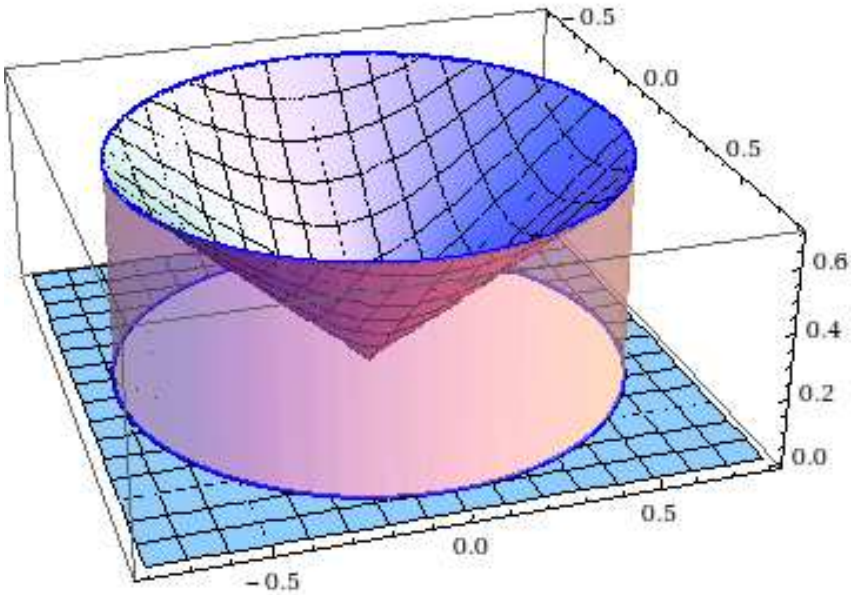

ROC Curve for mass/Pt
Gluon Background Rejection
Quark Signal Efficiency
50/50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

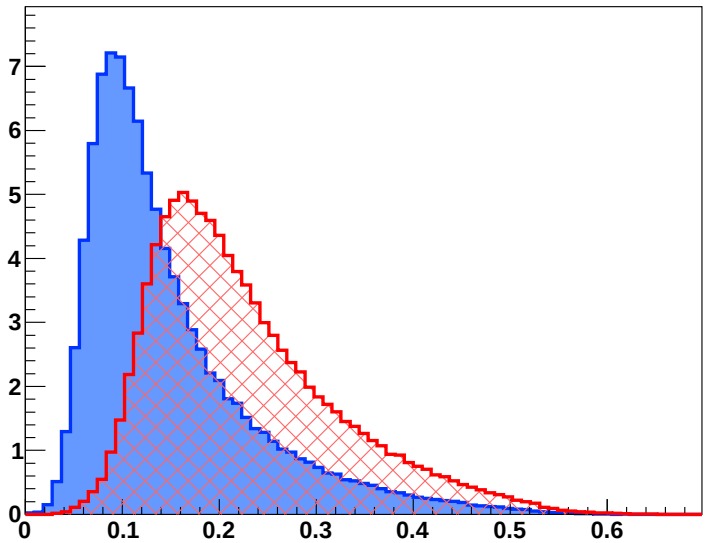
Radial Moment – a measure of the "girth" of the jet

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 Moment for 100 GeV



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

Gluon adjoint's C_A vs Quark fundamental's C_F

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

Brief Theory II — Particle Count

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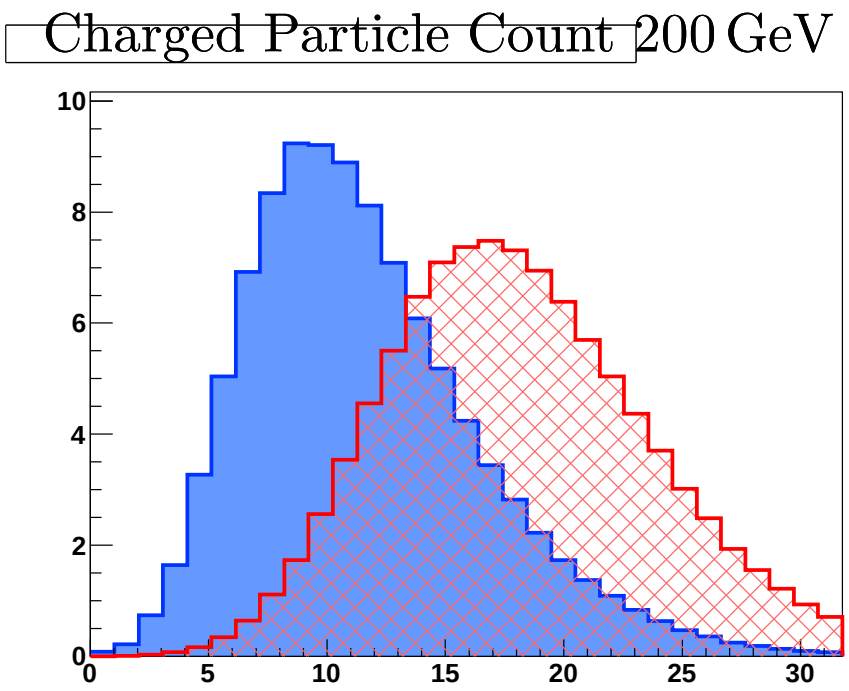
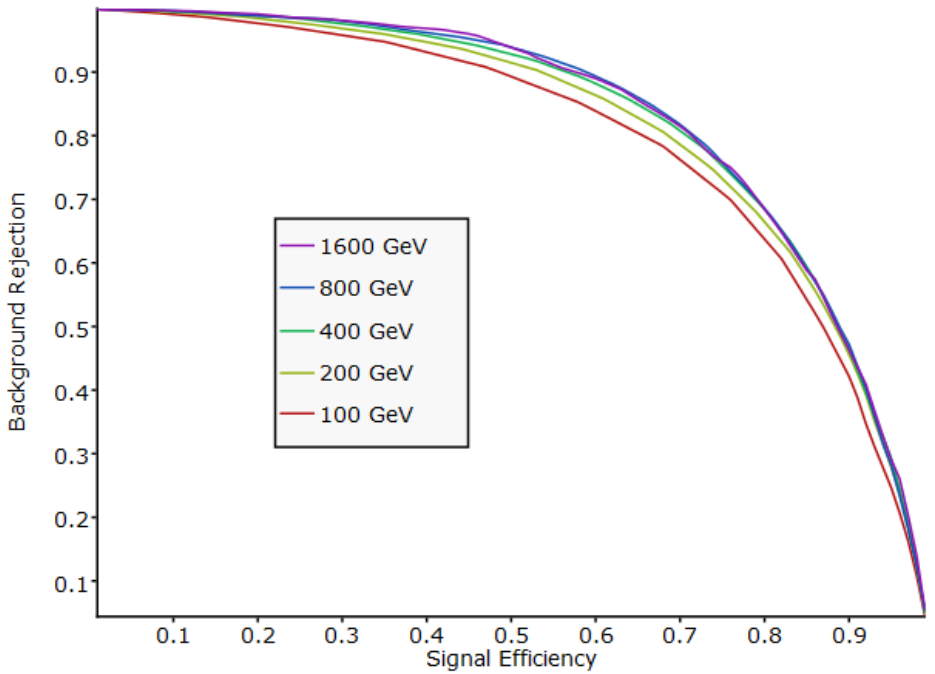
$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F} \qquad \frac{\sigma_g^2}{\sigma_q^2} = \frac{C_A}{C_F}.$$

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

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

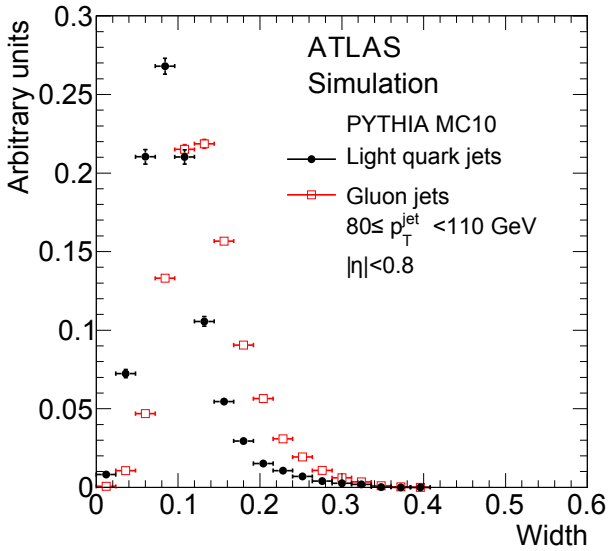
Charged Particles Count

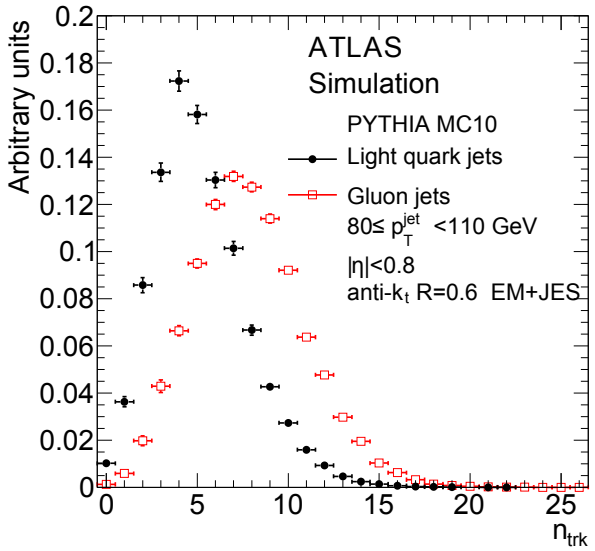


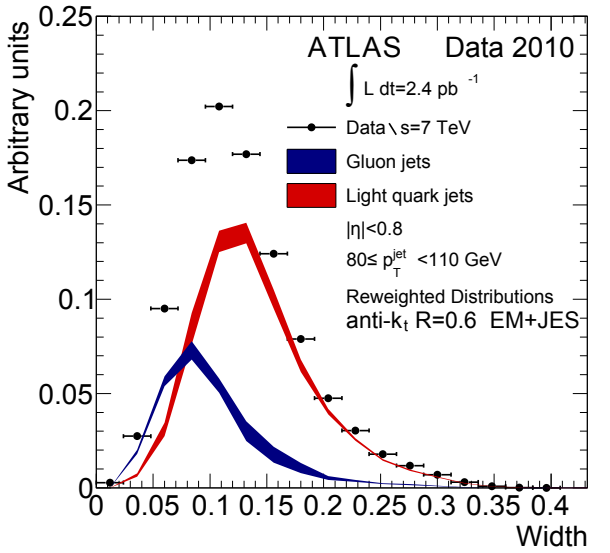


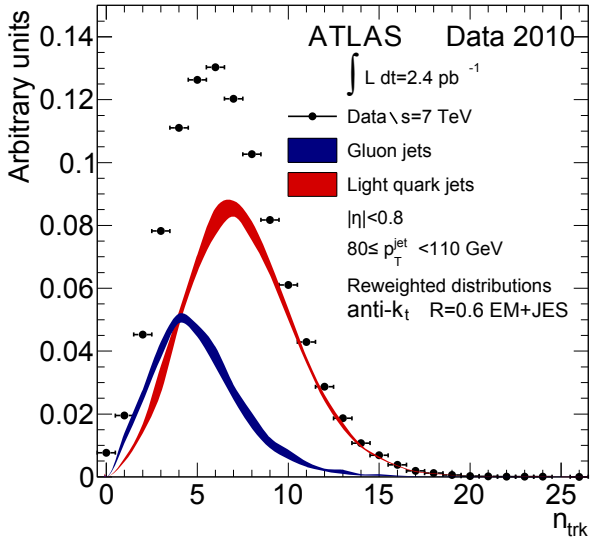
Higher p_T means more tracks and more 'time' to establish C_A/C_F.

ATLAS Measurements









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

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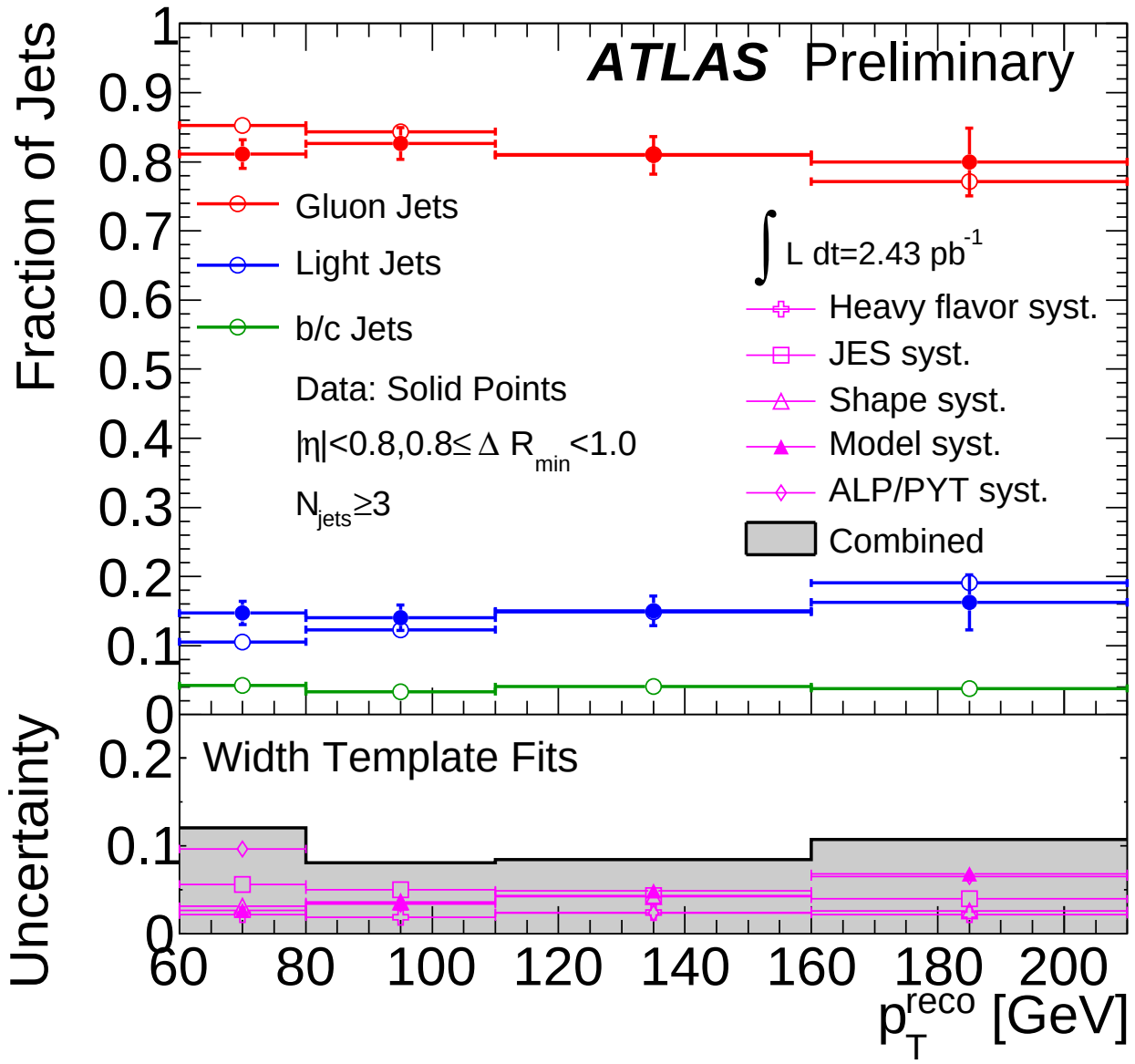


(from "Light-quark and Gluon Jets..." ATLAS-CONF-2011-053)

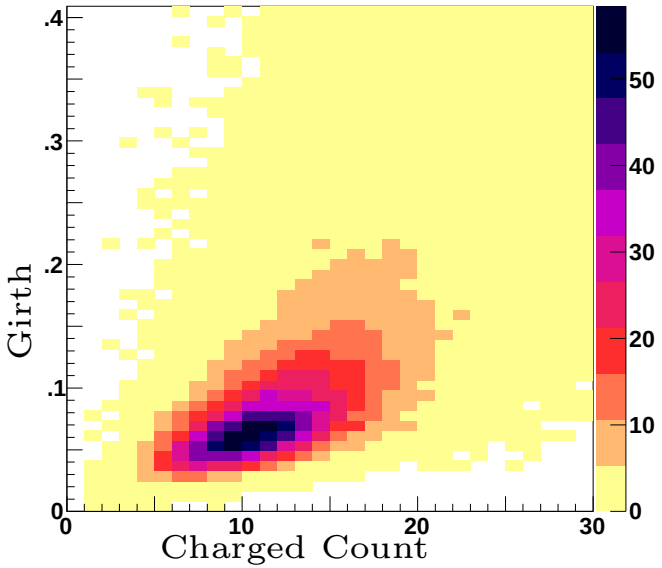
Types of Variables

The menu, including varying jet size

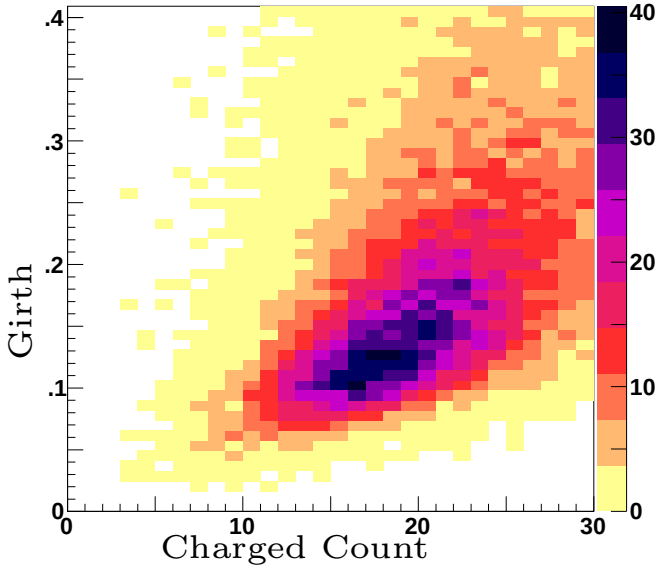
- Distinguishable particles/tracks/subjets
  - multiplicity, $\langle p_T \rangle$, σ_{p_T}, $\langle k_T \rangle$,
  - charge-weighted p_T sum
- Moments
  - mass, girth, jet broadening
  - angularities
  - optimal kernel
  - 2D: pull, planar flow
- Subjet properties
  - Multiplicity for different algorithms 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

Quark



Gluon



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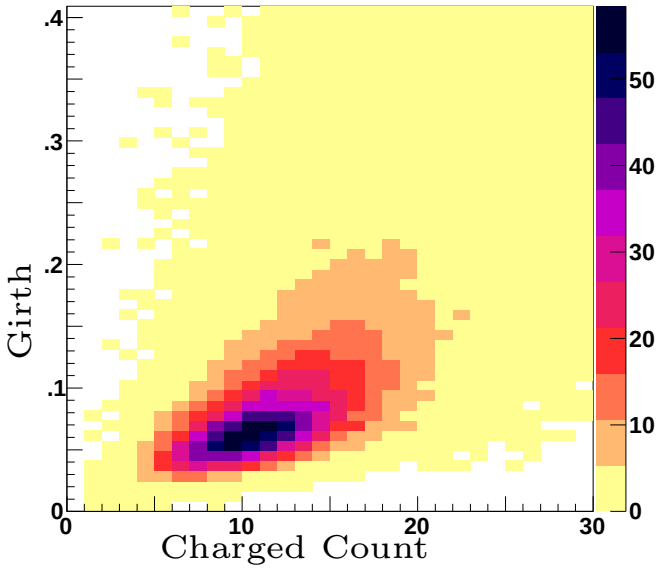

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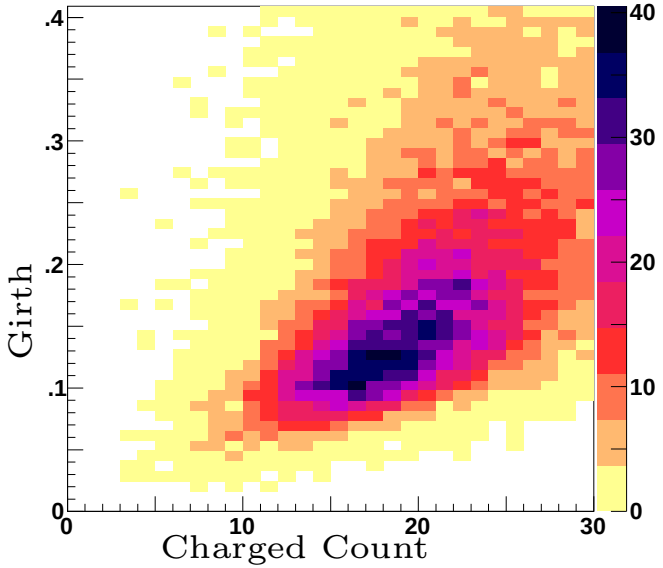
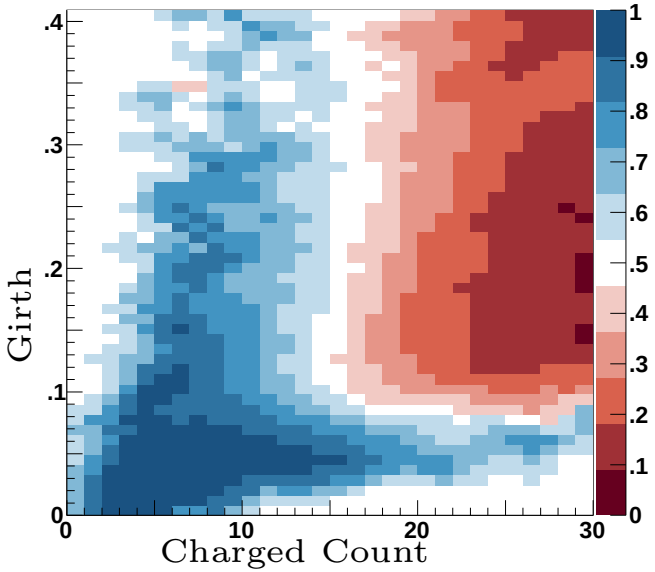
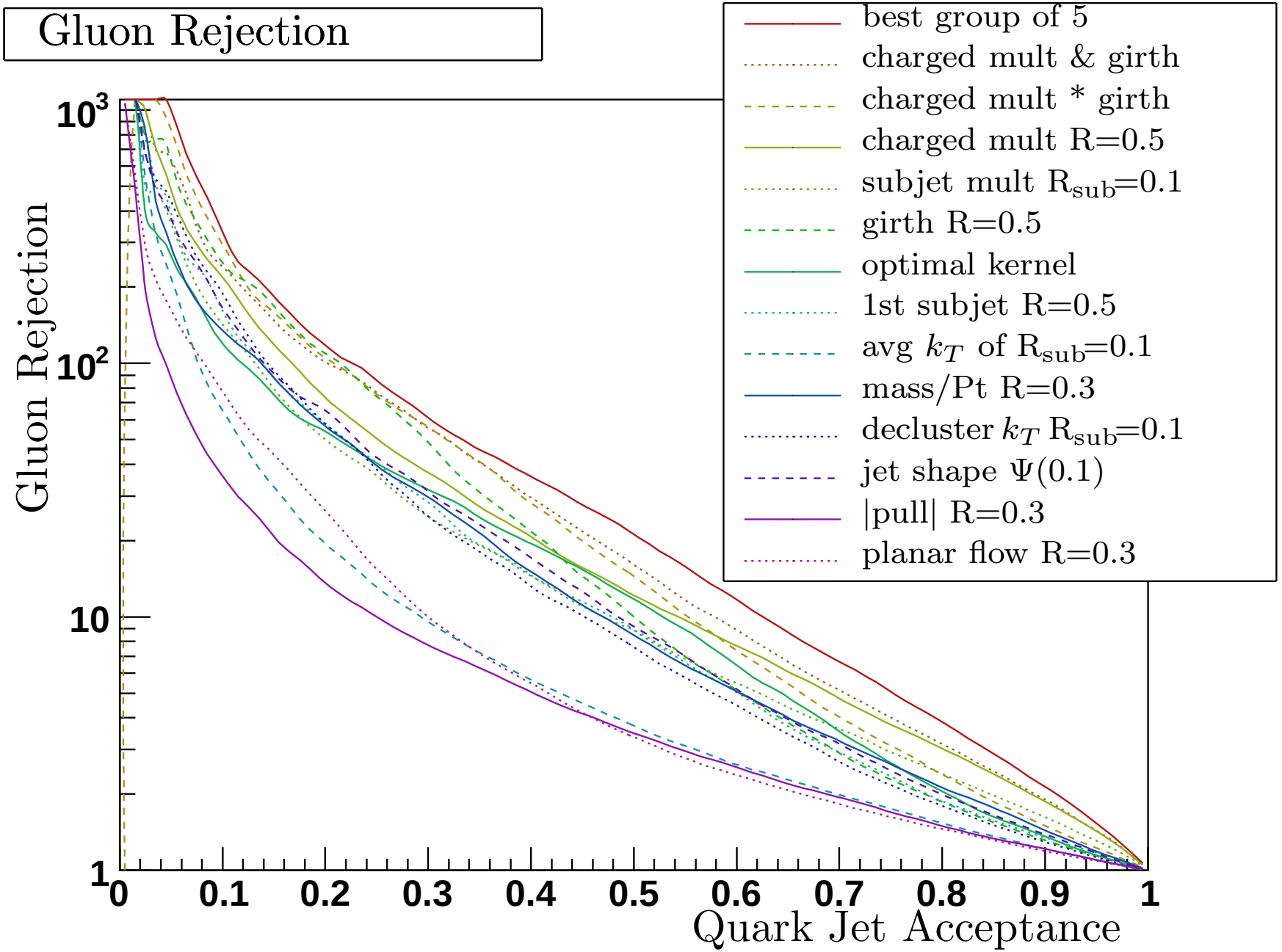


Likelihood: $q/(q+g)$



Best Variables in Each Category for 200 GeV Jets



Summary and Use of the Tagger

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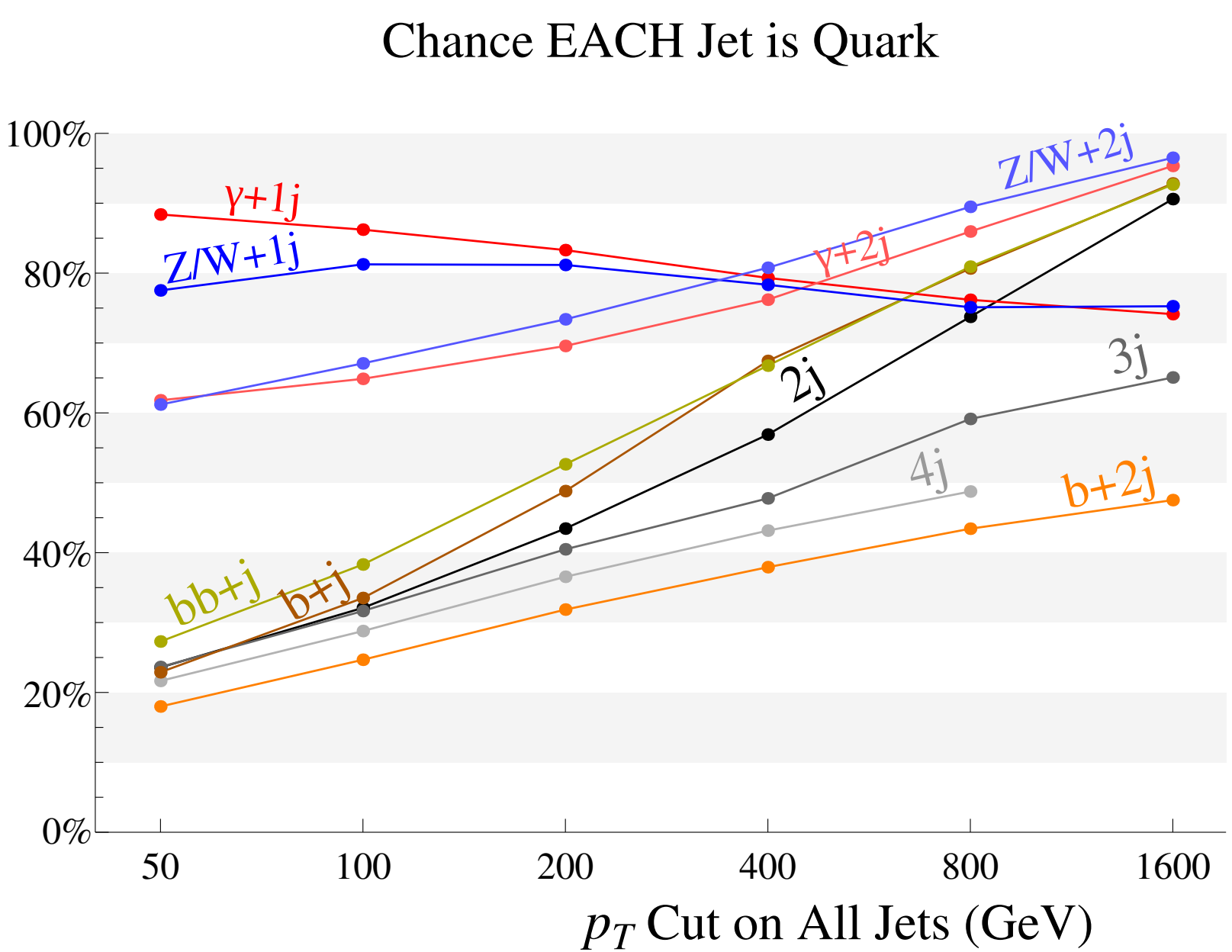
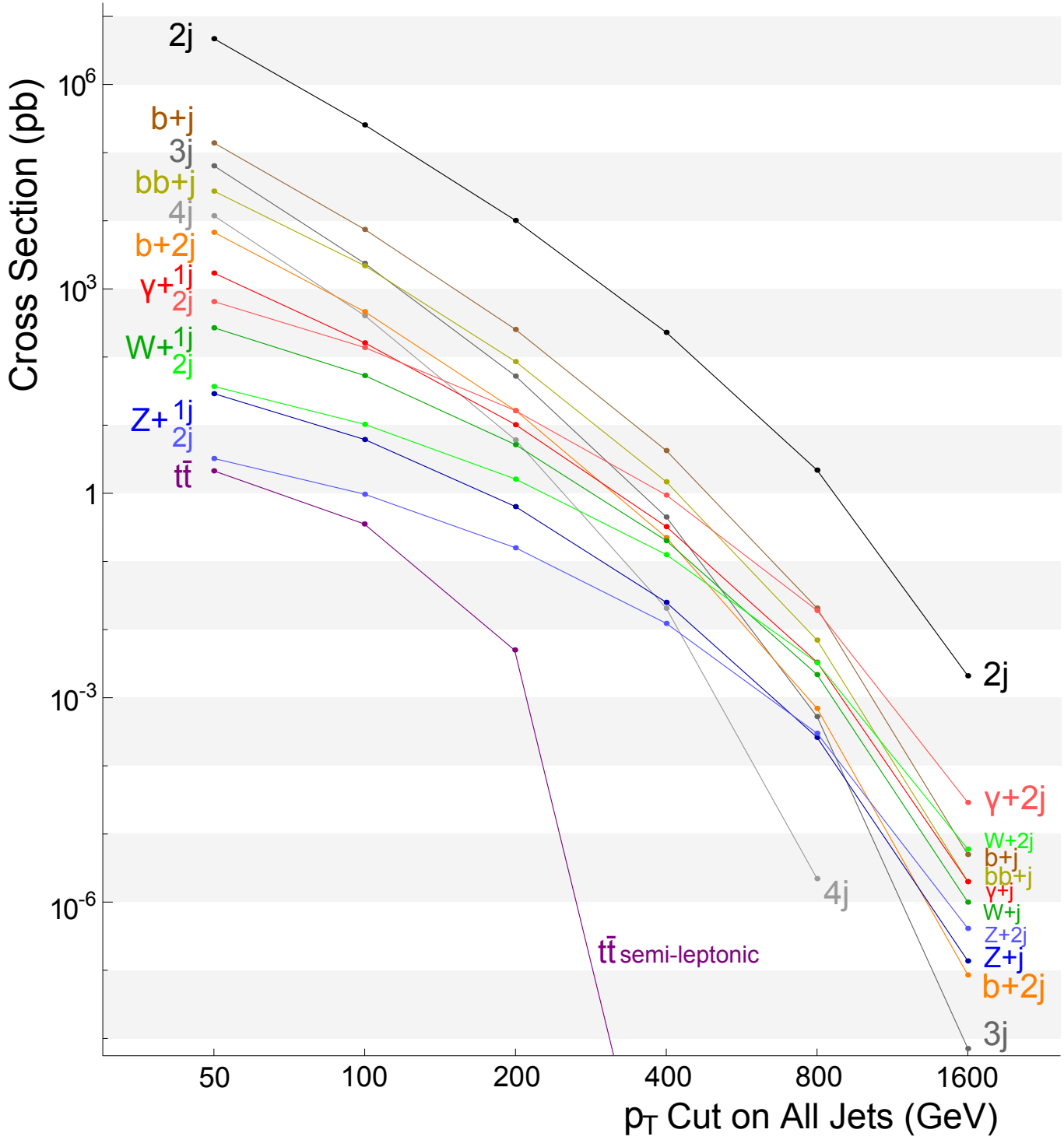
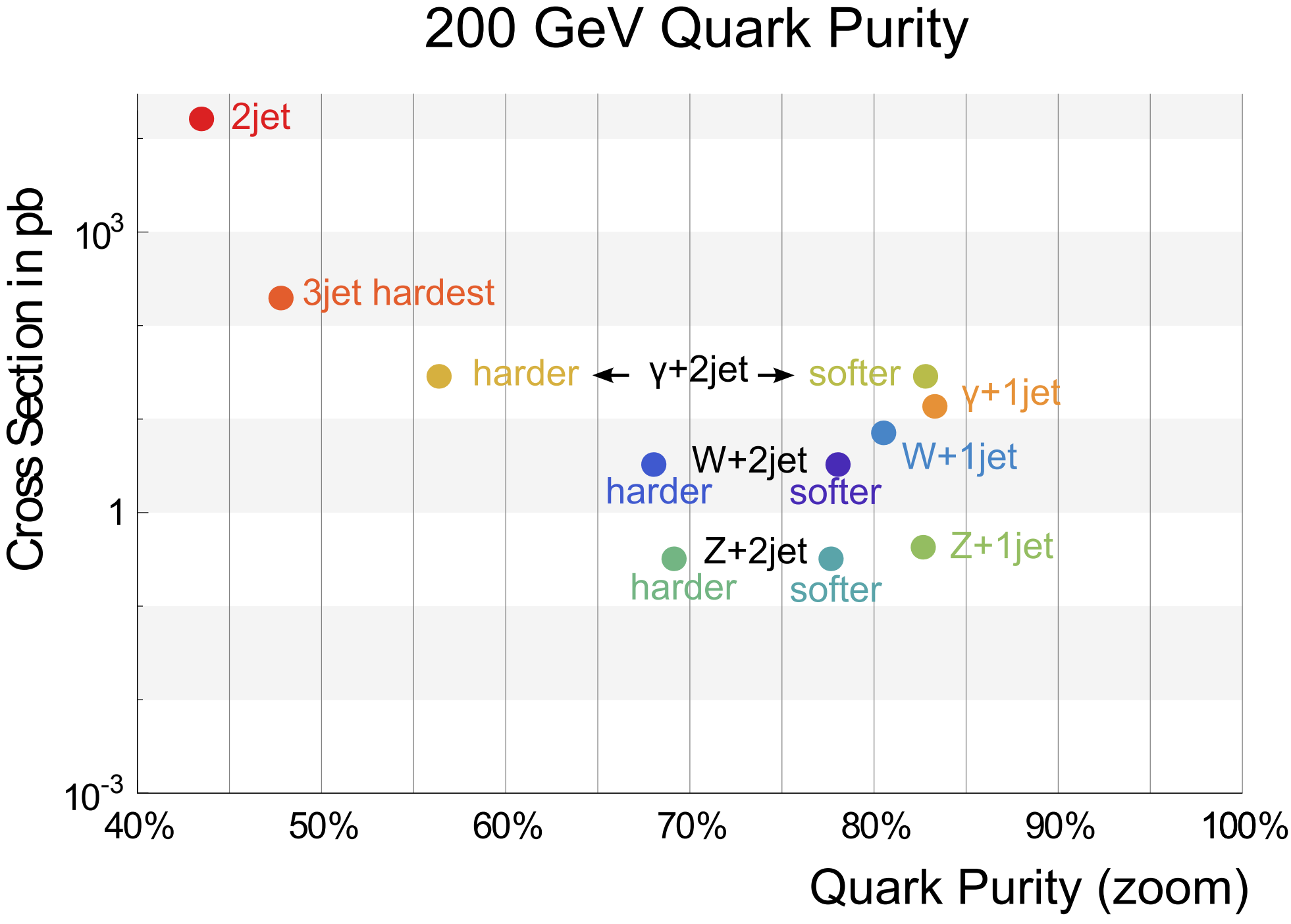
For the 8 quark gluino example, significance improvement is 14.8!

Finding Pure Samples of Quark and Gluon Jets

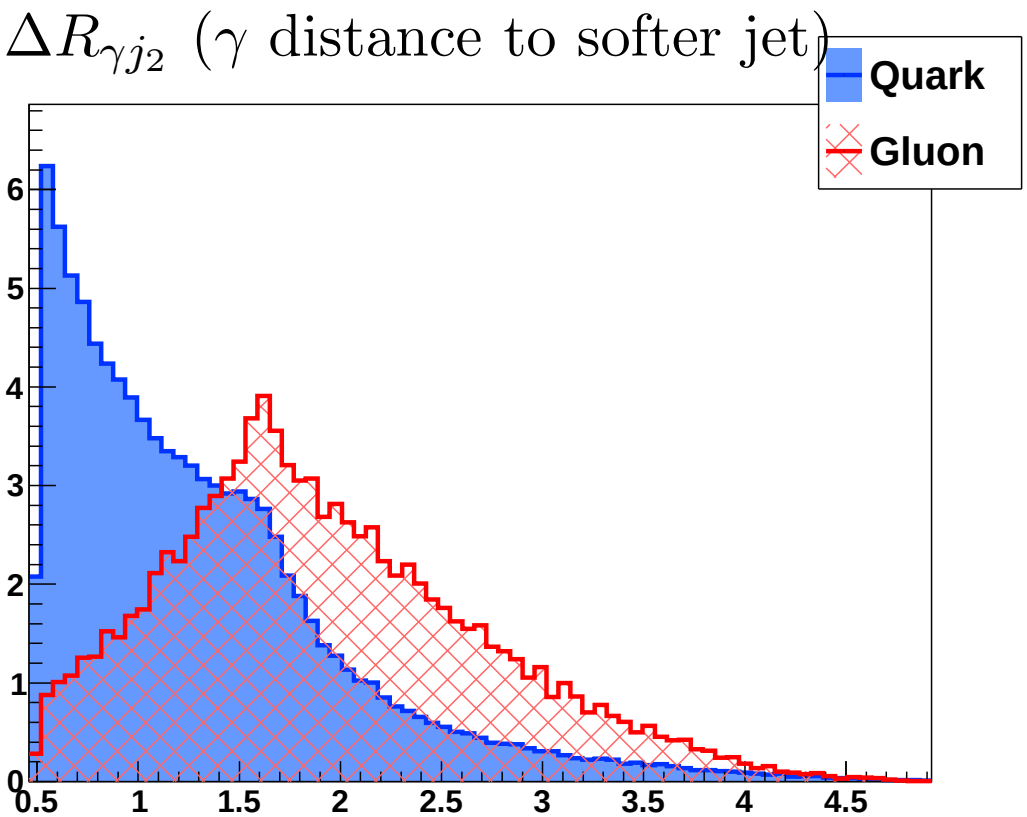
Starting Samples



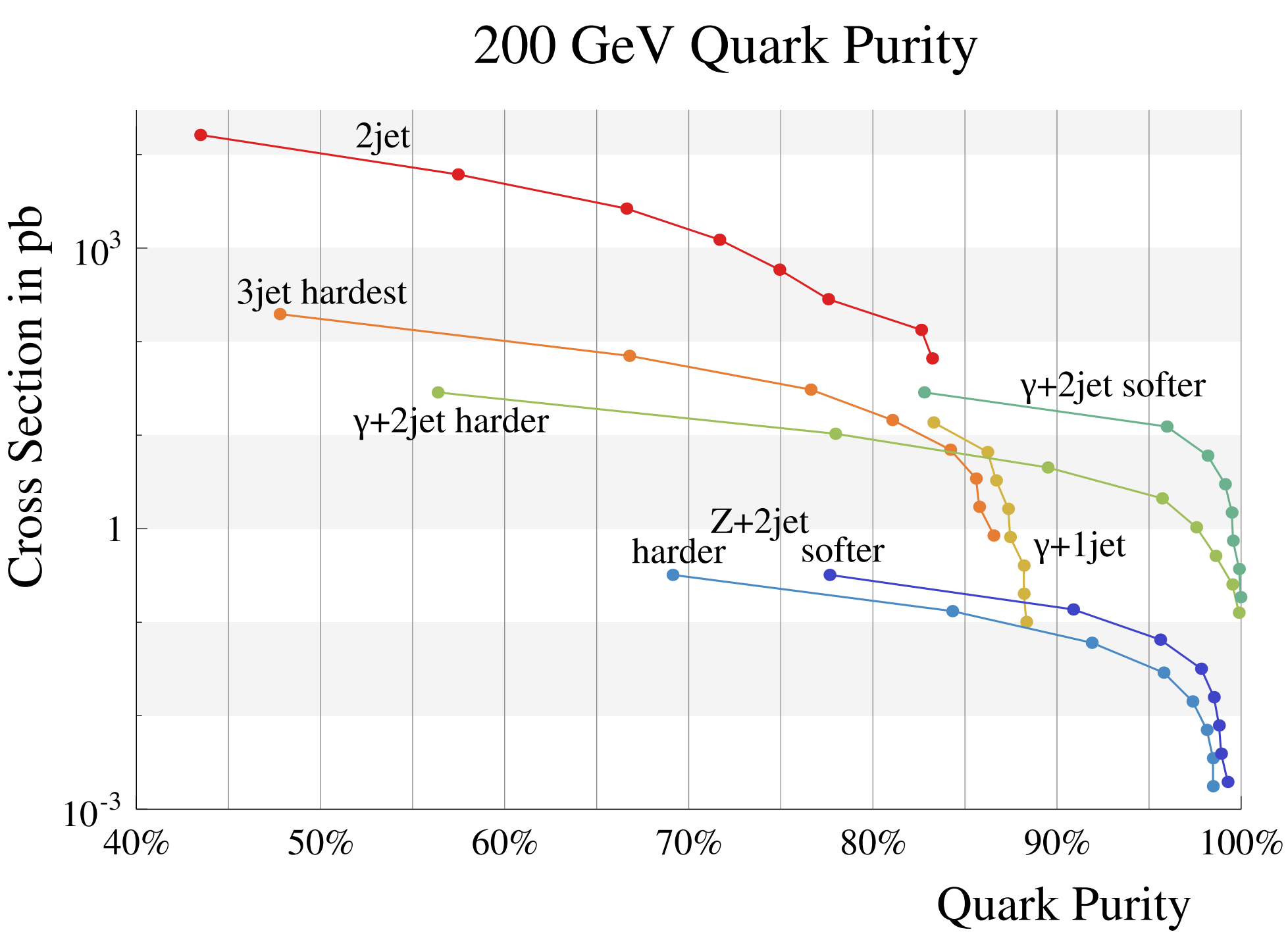

Cross Section (pb)
10^6
10^3
1
10^{-3}
10^{-6}
2j
b+j
3j
bb+j
4j
b+2j
γ+1j 2j
W+1j 2j
Z+1j 2j
tt̄
2j
γ+2j
W+2j
b+j
bb+j
γ+j
W+j
Z+2j
Z+j
b+2j
3j
4j
tt̄ semi-leptonic
50
100
200
400
800
1600
p_T Cut on All Jets (GeV)

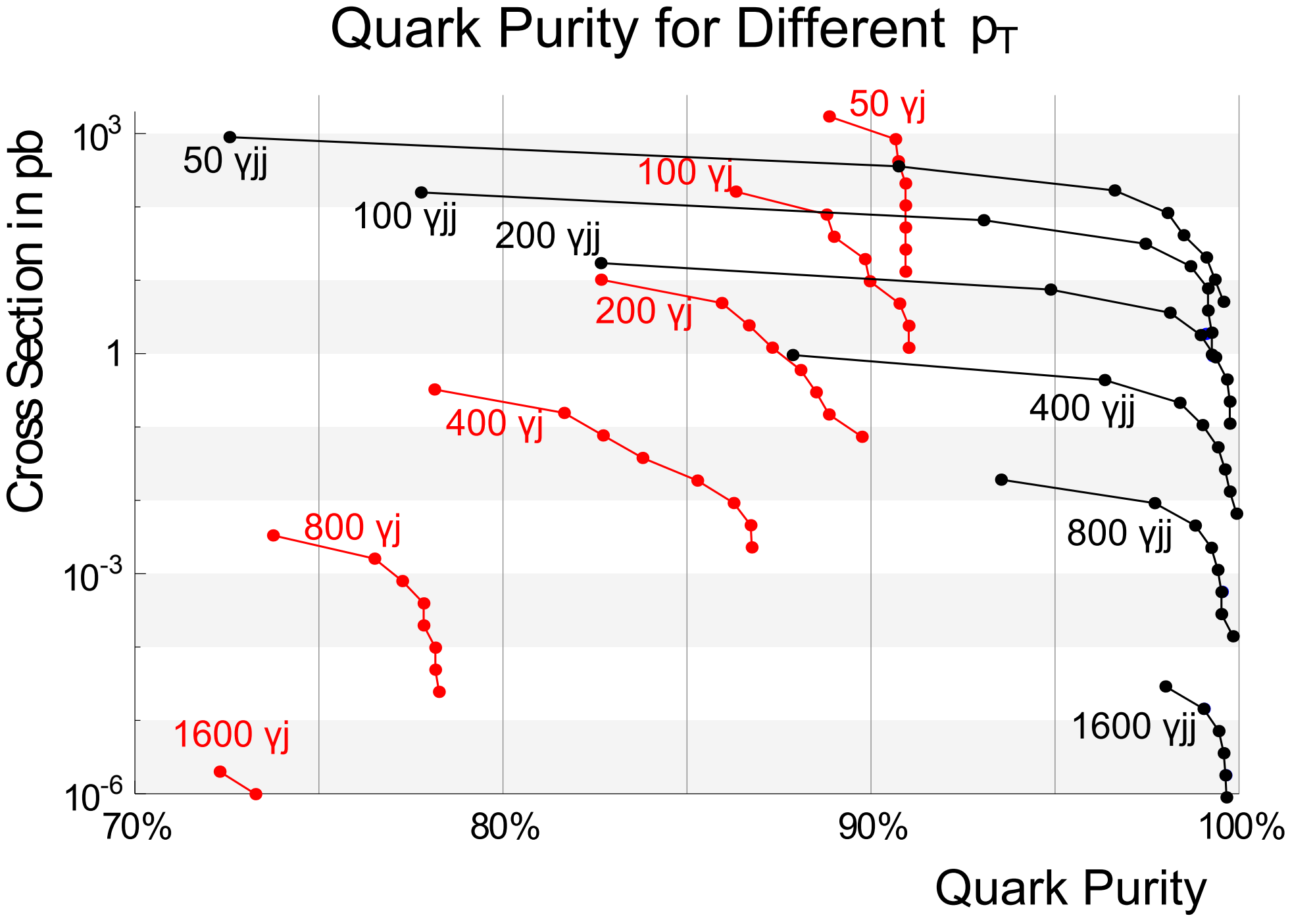

200 GeV Quark Purity
2jet
3jet hardest
harder
γ+2jet
softer
γ+1jet
W+2jet
W+1jet
harder
softer
Z+2jet
Z+1jet
harder
softer
Cross Section in pb
10^3
1
10^-3
40%
50%
60%
70%
80%
90%
100%
Quark Purity (zoom)

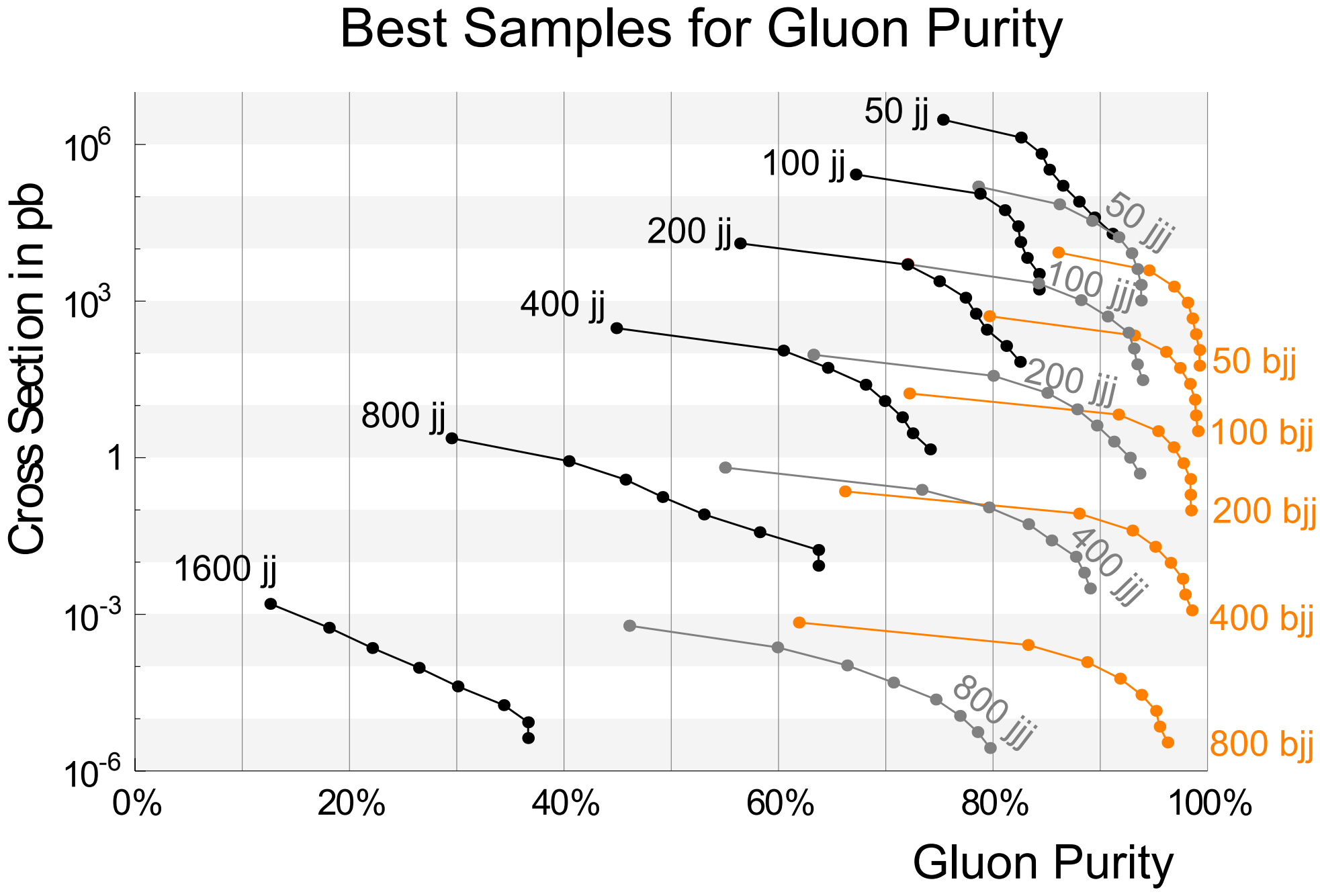
Quark Purification in γ+2jet



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
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- ATLAS is already measuring these properties.
- Keep these techniques in your toolchest.

Thanks!

Backup

In case waving my hands proves insufficient ...

QCD Jet Flavor Theory

Is Flavor Meaningful Beyond Leading Order?

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Claim: Nothing can go wrong that wouldn't also destroy the event's meaning/usefulness/interpretation.

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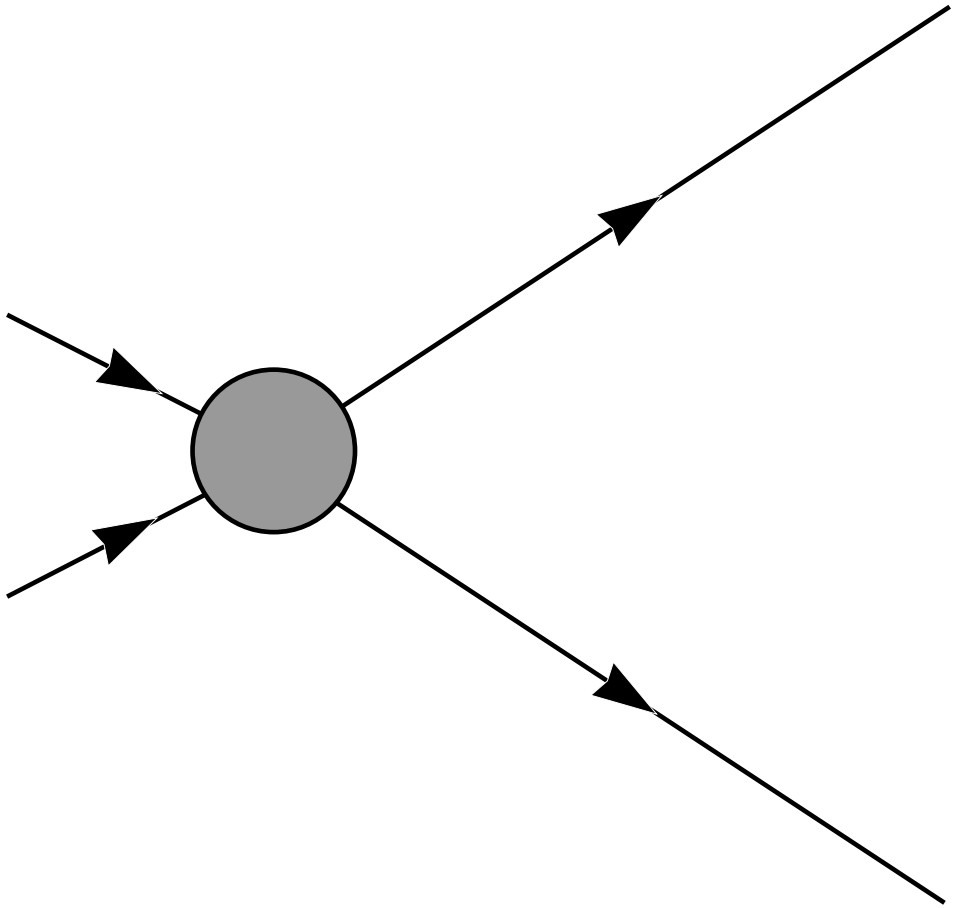
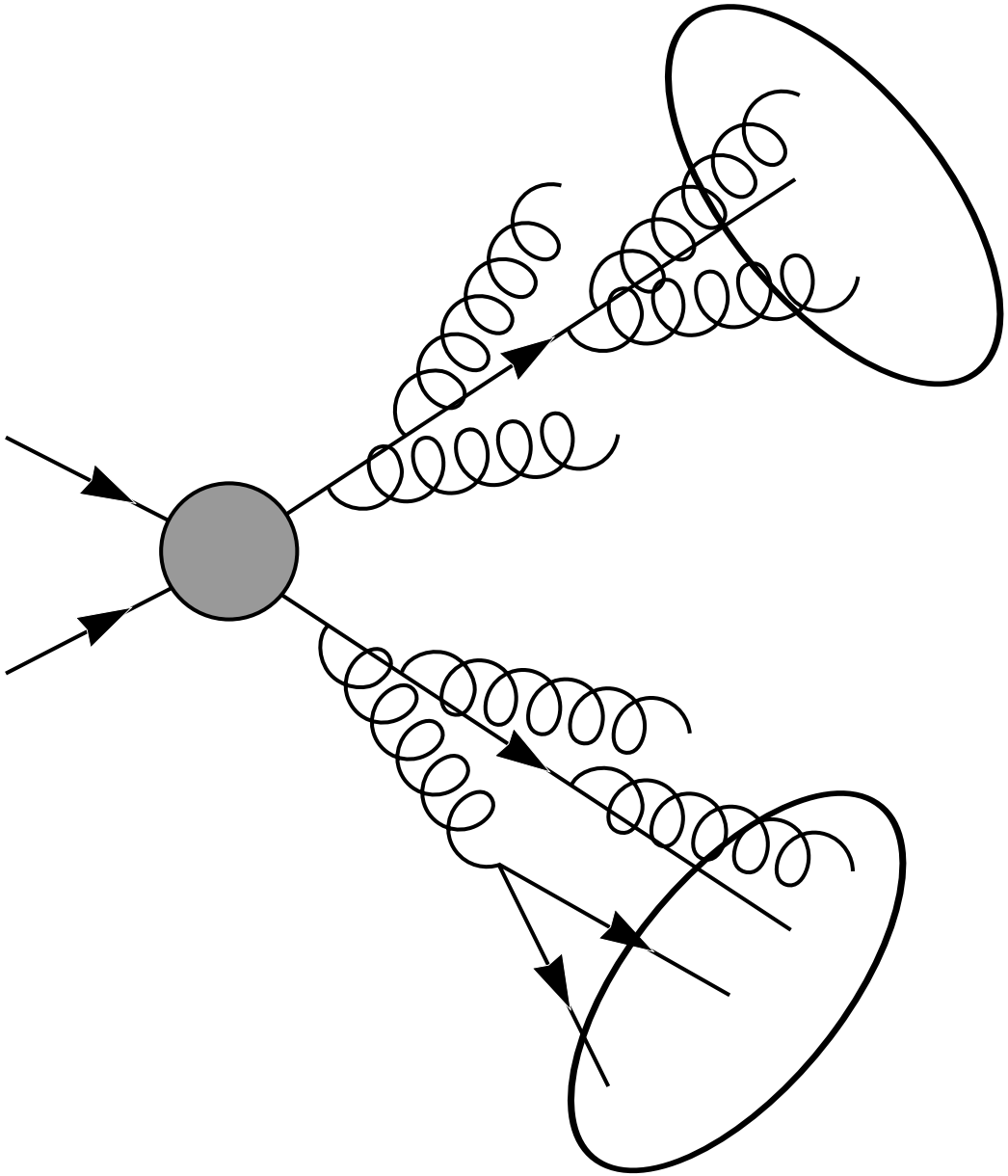
So flavor is *no more dangerous* theoretically than *any time* jets are used as a proxy for hard partons.

(All of this is sperate from measurement resolution.)

Example of 2 Quark Jets



Standard Parton Shower



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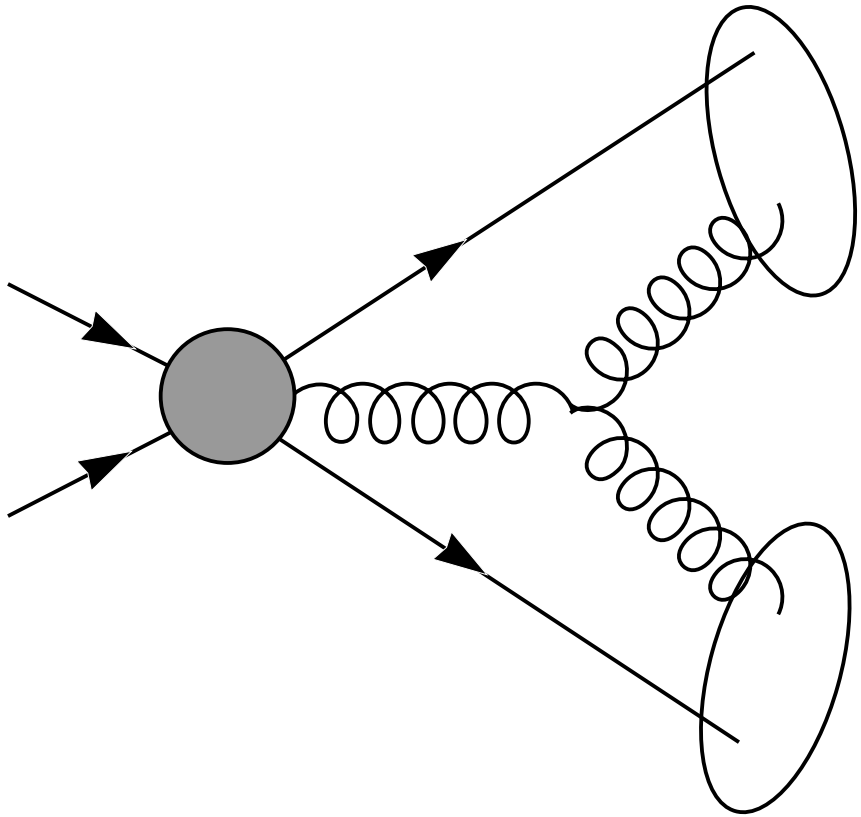

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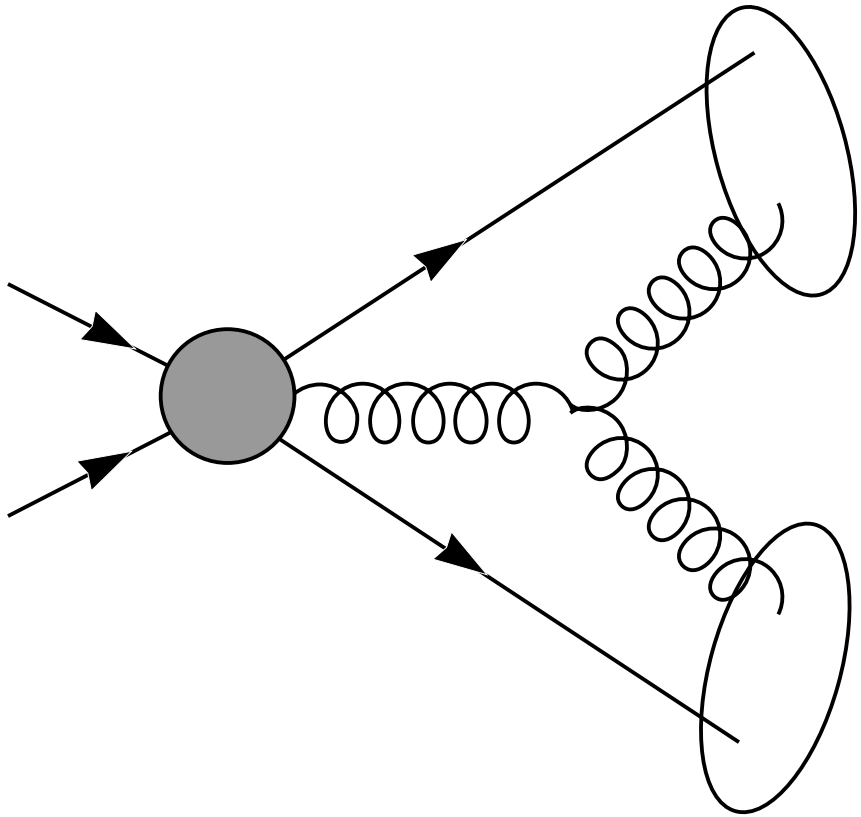

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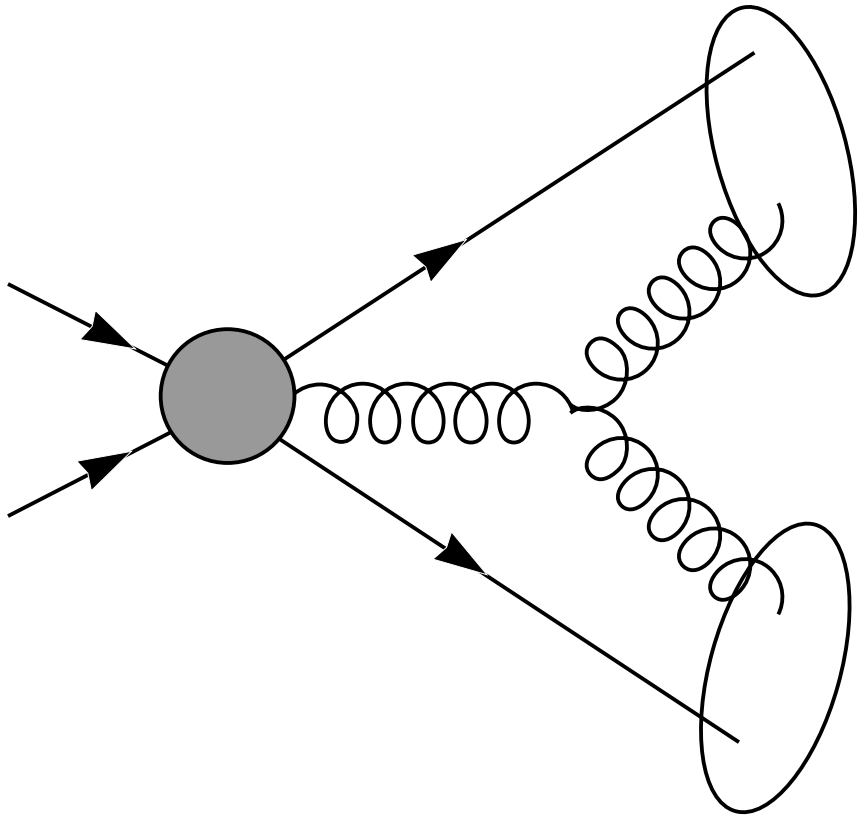

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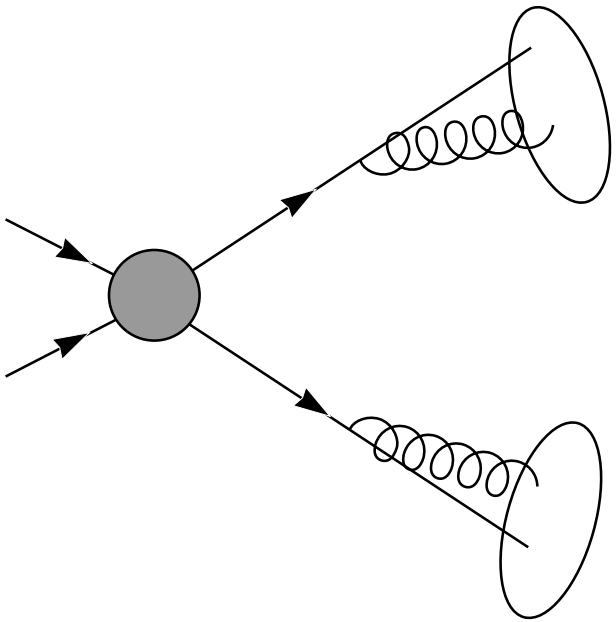
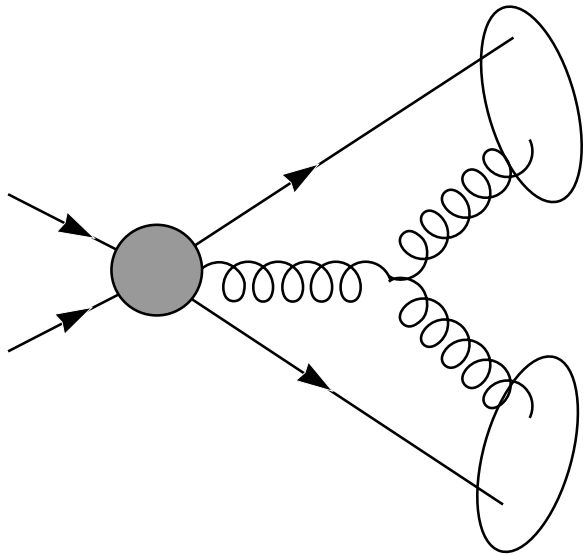
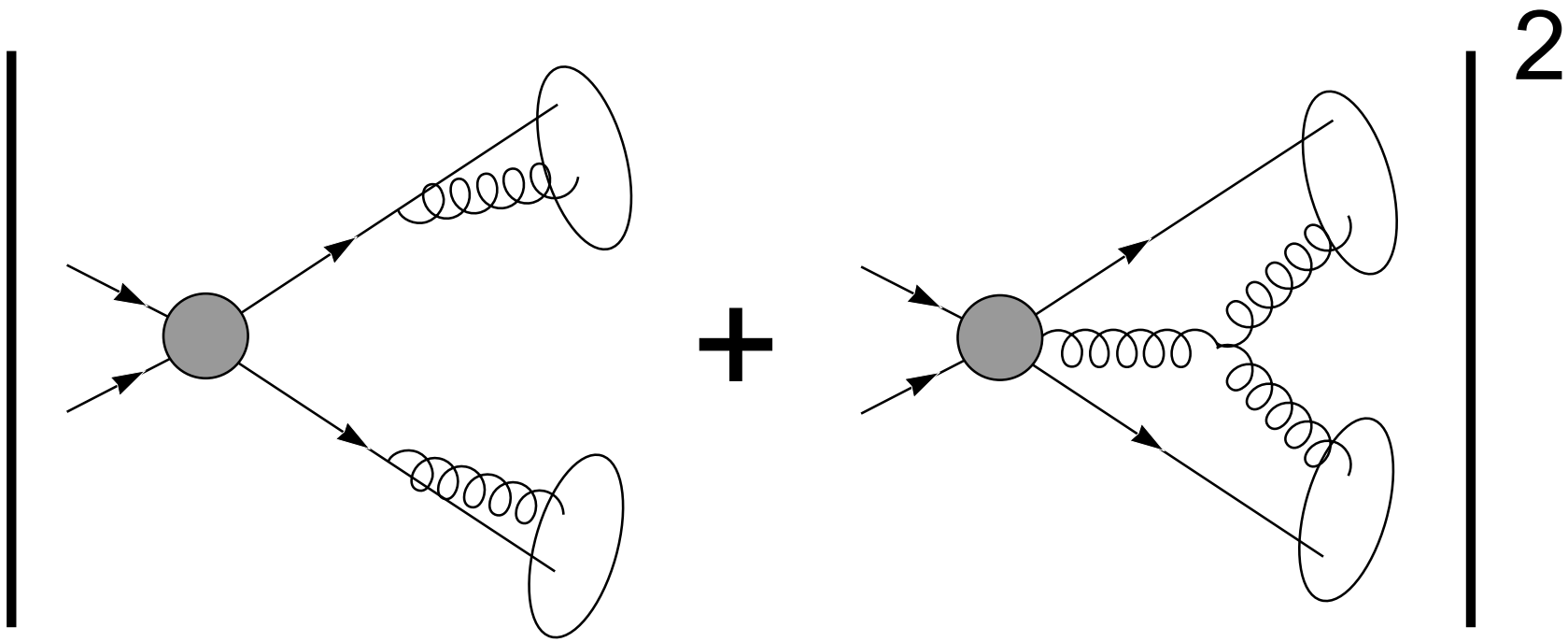
If they were b's, a B-Tag wouldn't mean they're useful for $H \to b\bar{b}$.

Perturbation Theory: Ambiguity and ...





... Quantum Indistinguishability



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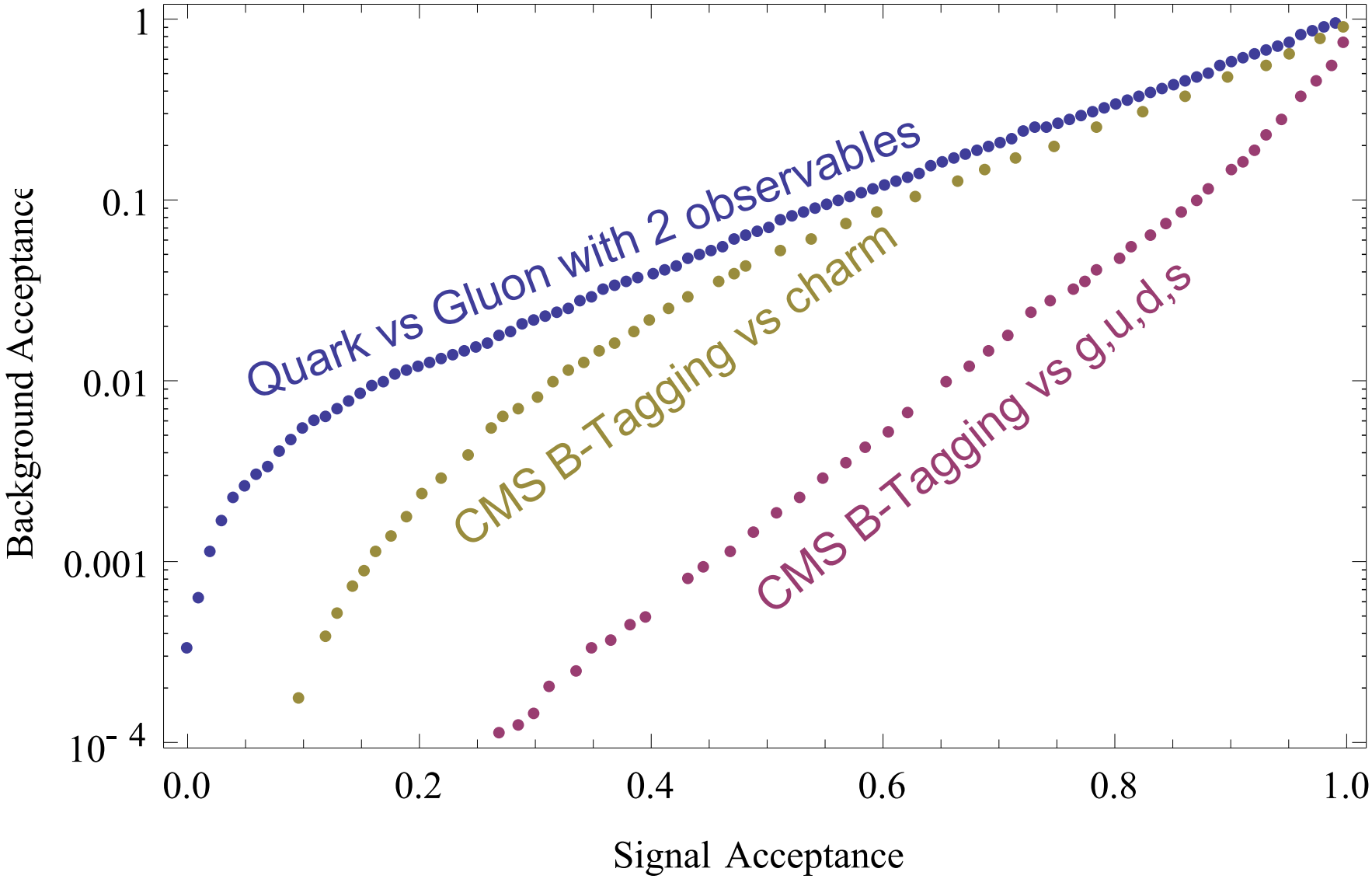
Whatever is most useful to separate real signals from real backgrounds.

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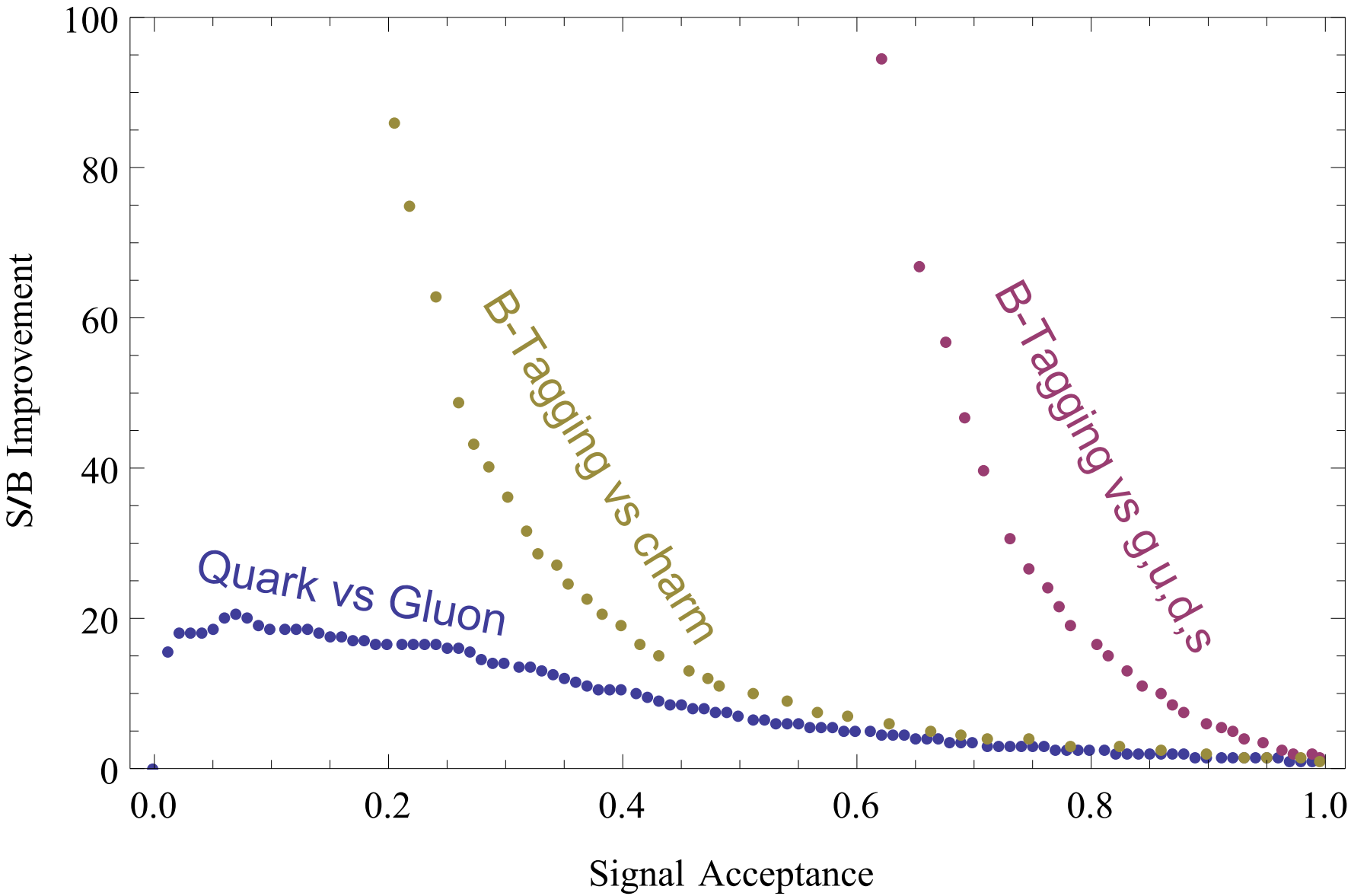
If you start with S signal events and B background events,

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

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

Comparison to B-Tagging



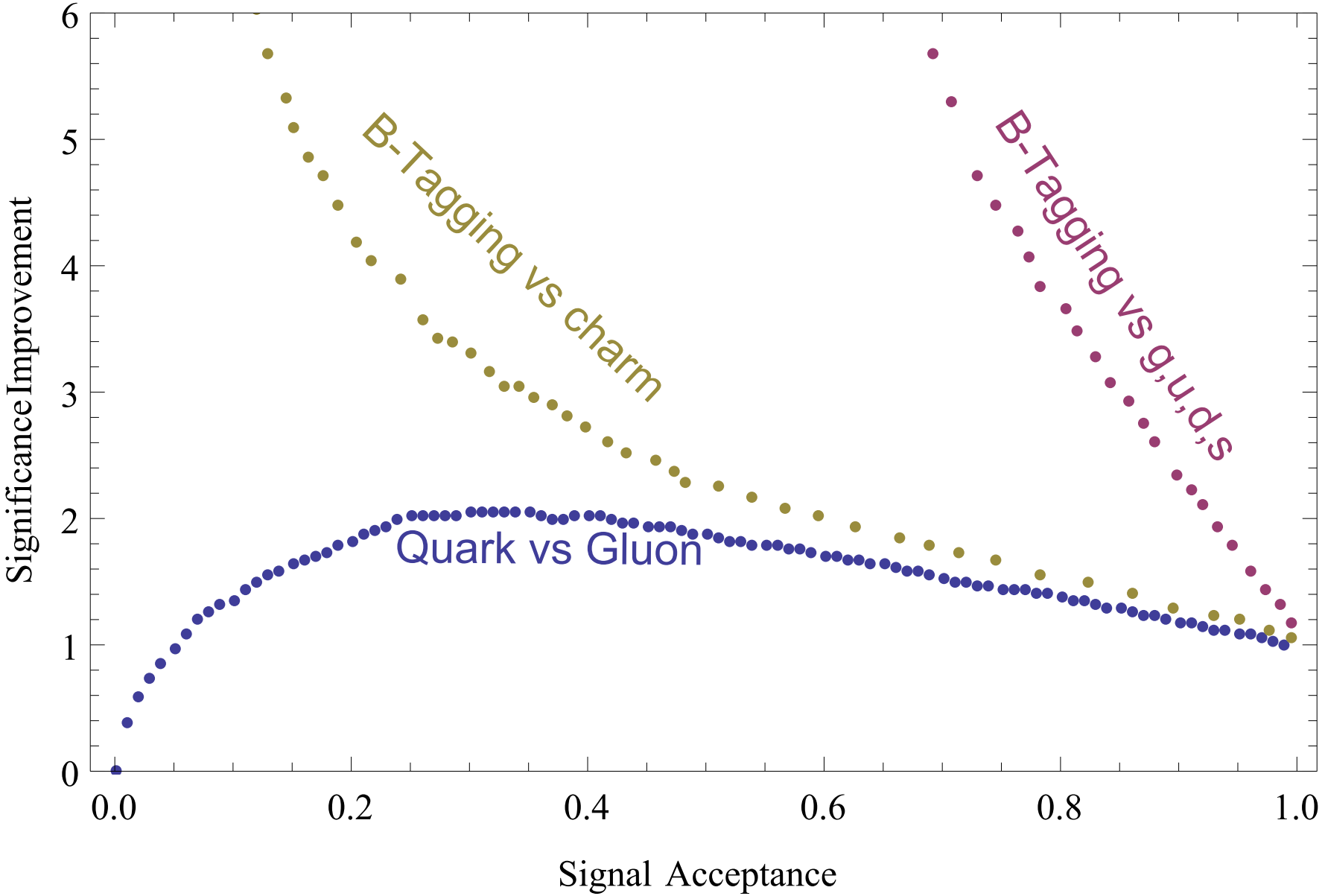
Cutting, S/B, and $S/\sqrt{B}$

Improvement in statistical significance scales differently

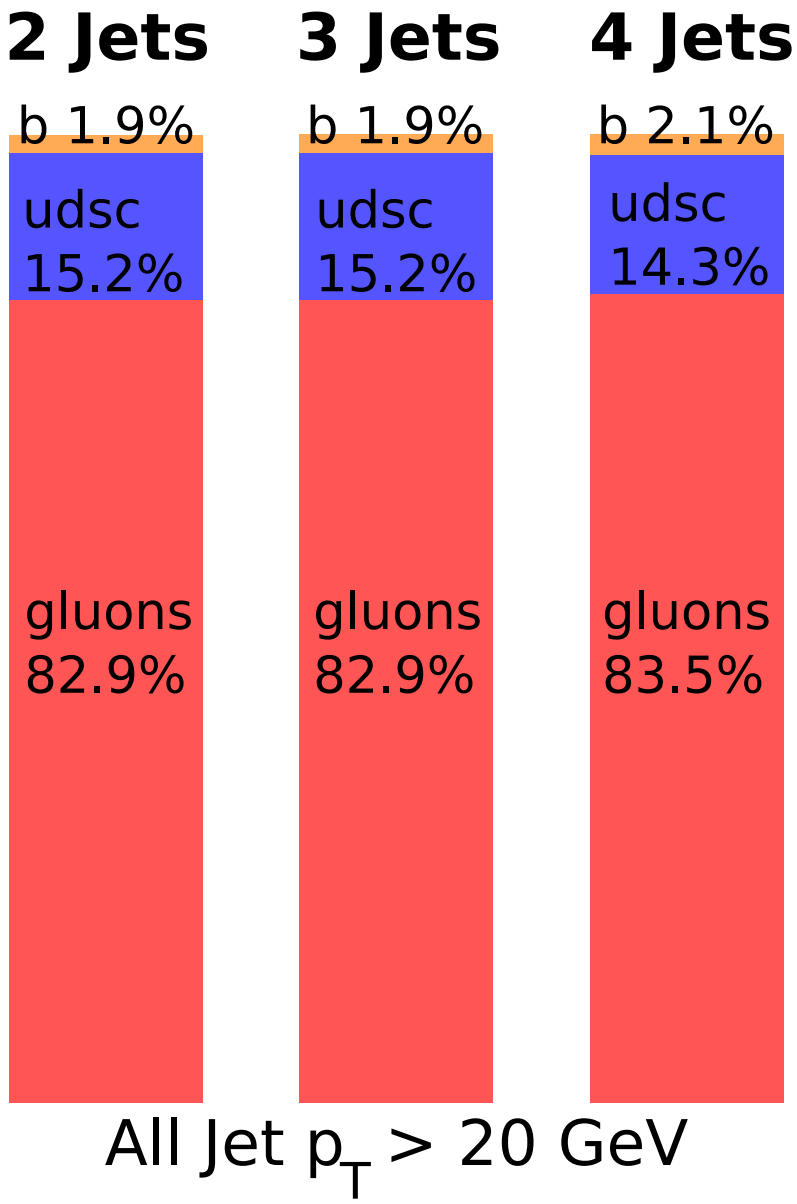
$$\sigma = \frac{S}{\sqrt{B}} \quad \rightarrow \quad \frac{S\epsilon_s}{\sqrt{B\epsilon_b}} = \sigma\frac{\epsilon_s}{\sqrt{\epsilon_b}}$$

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

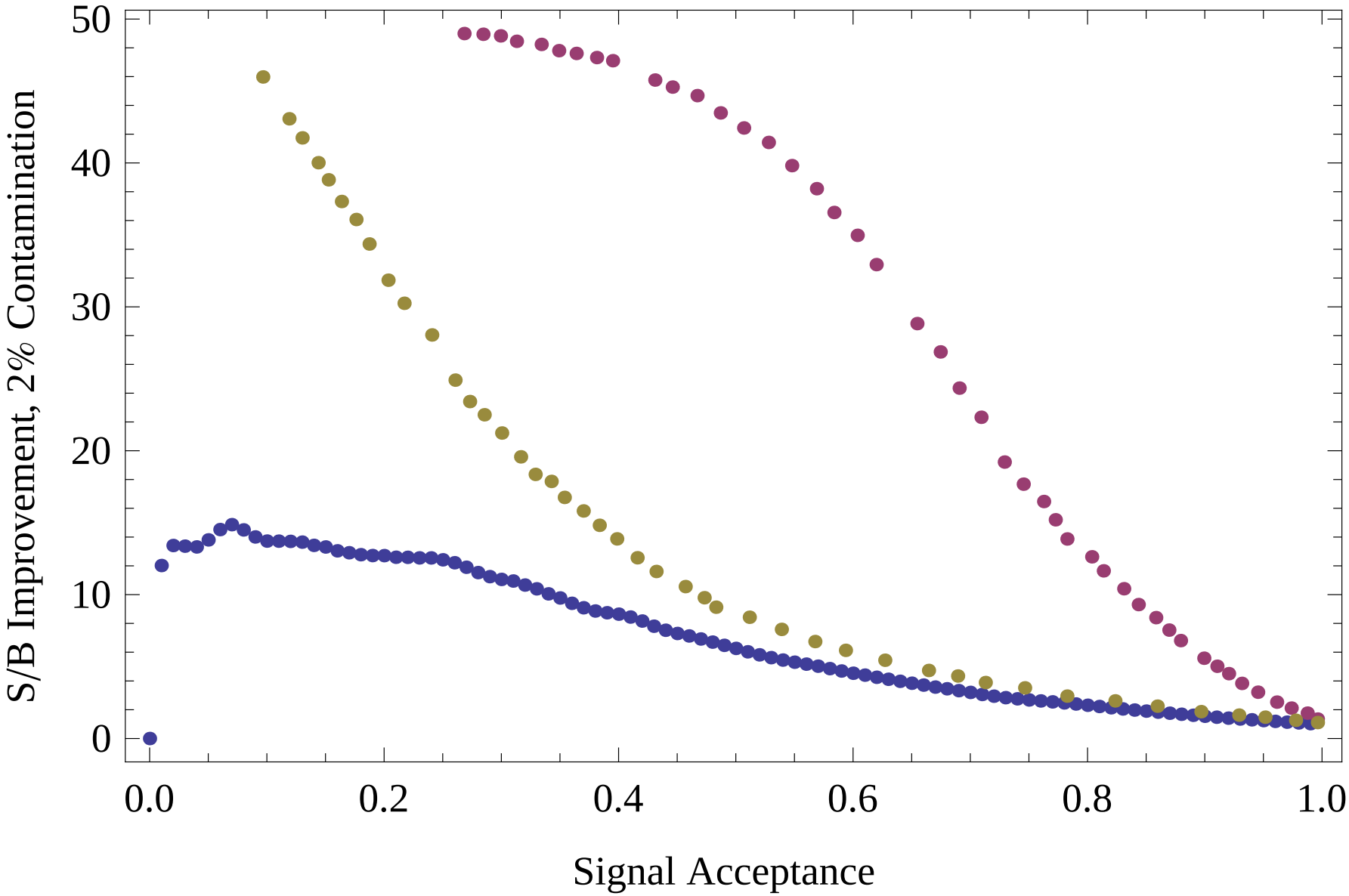
Comparison to B-Tagging



But Backgrounds Contain B's and Quarks! (e.g. QCD)



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



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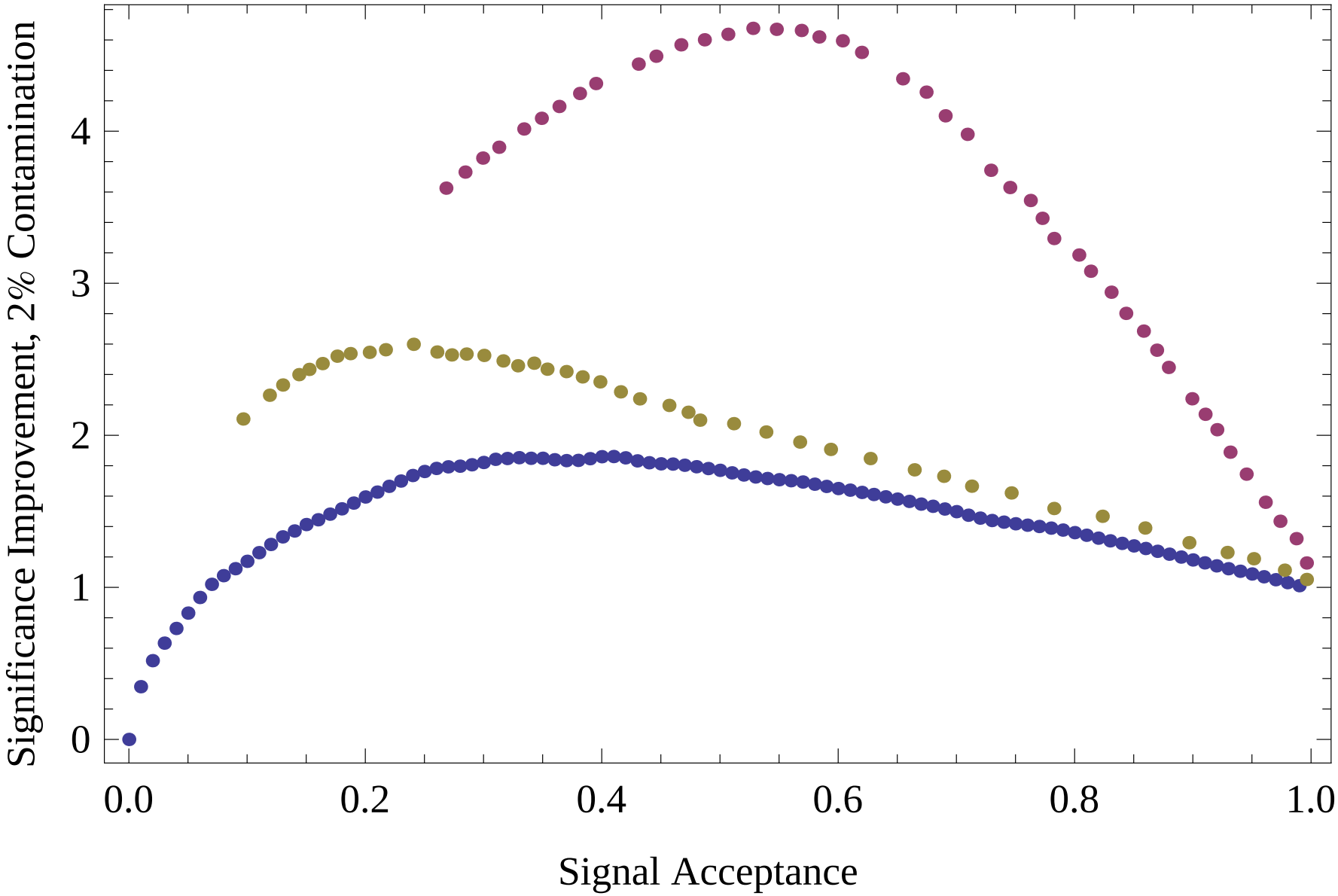
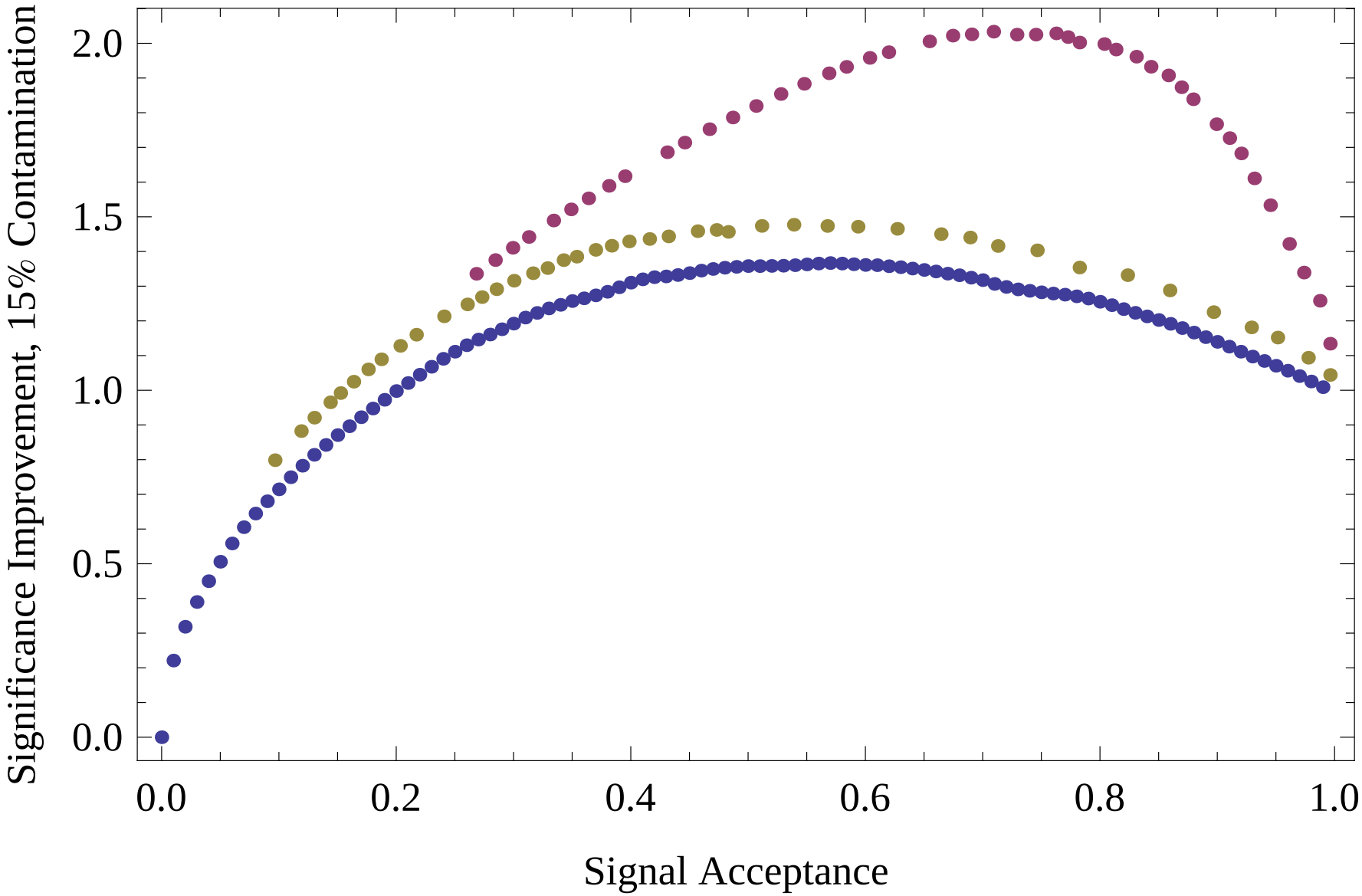
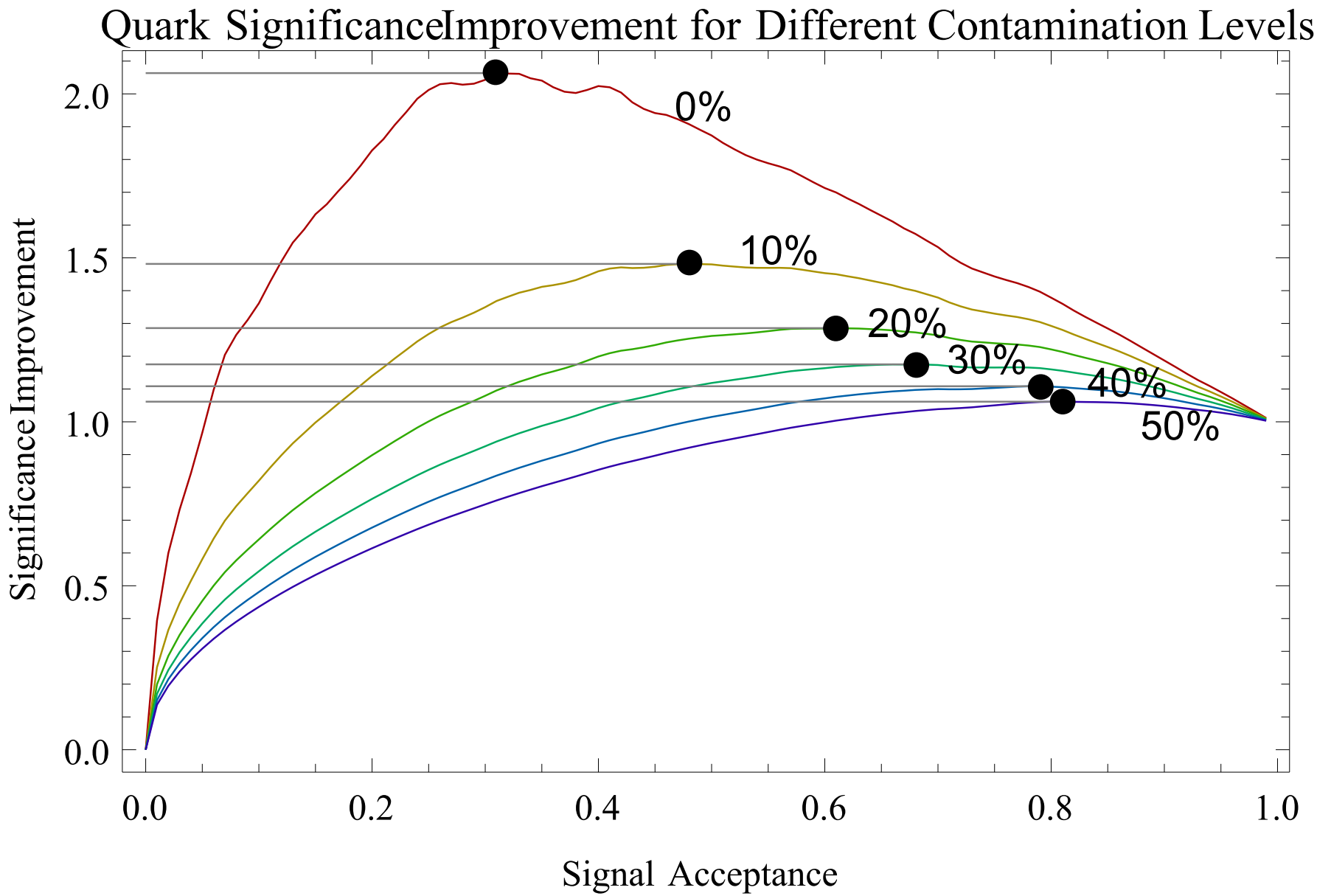


Background Contains 15% 'Signal' flavor (Q-case)



Operating Points that Maximize Quark Significance



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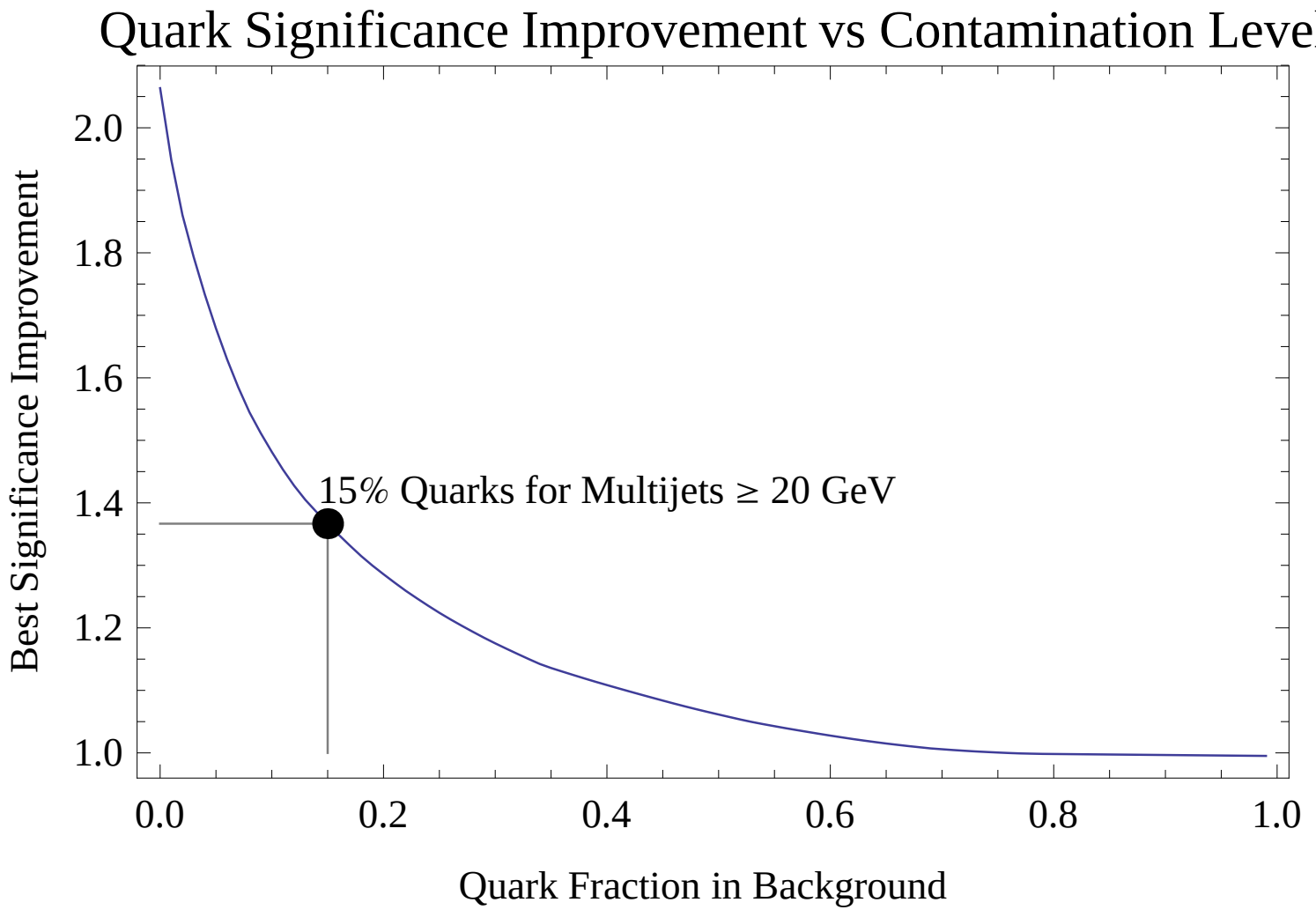

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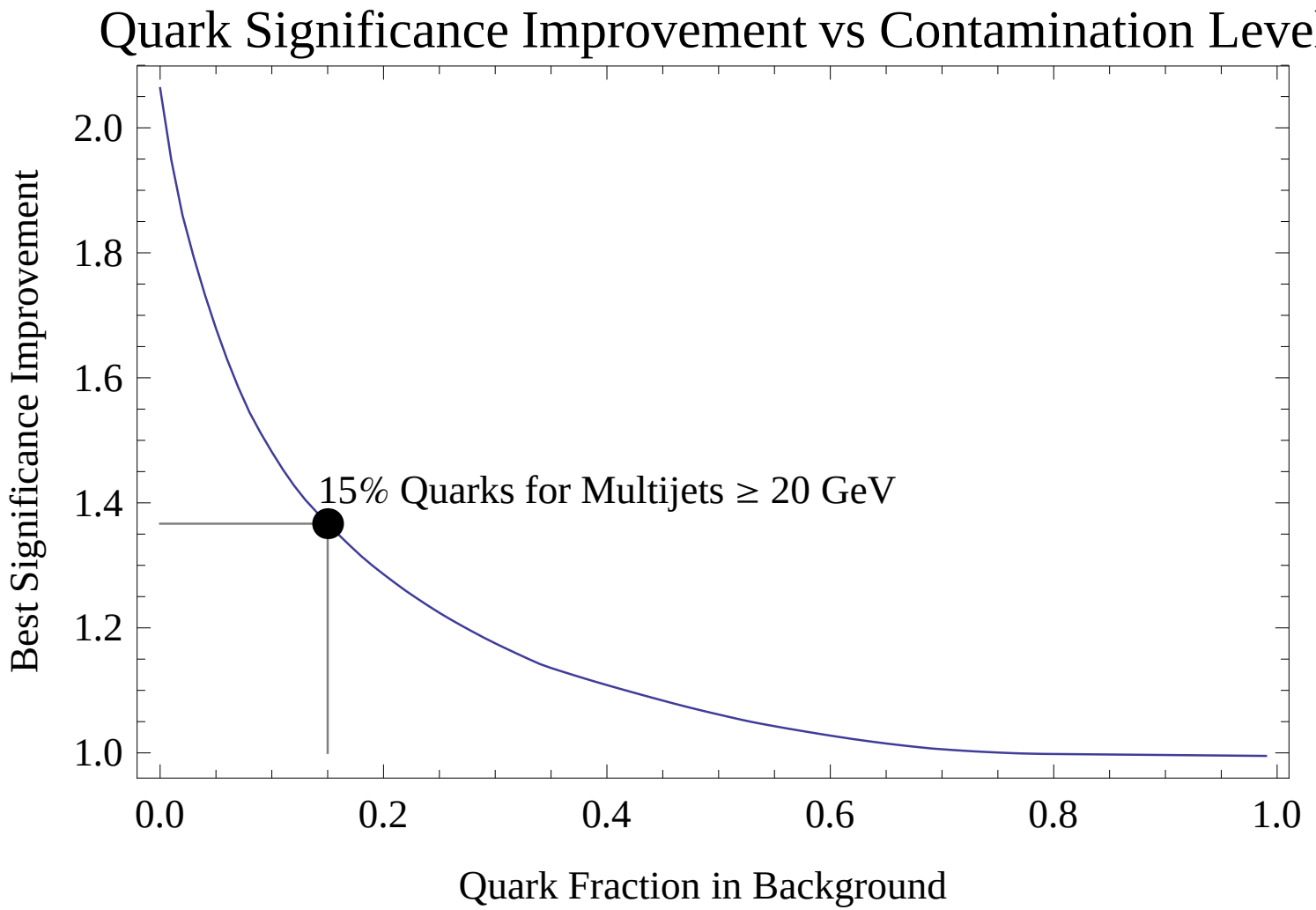

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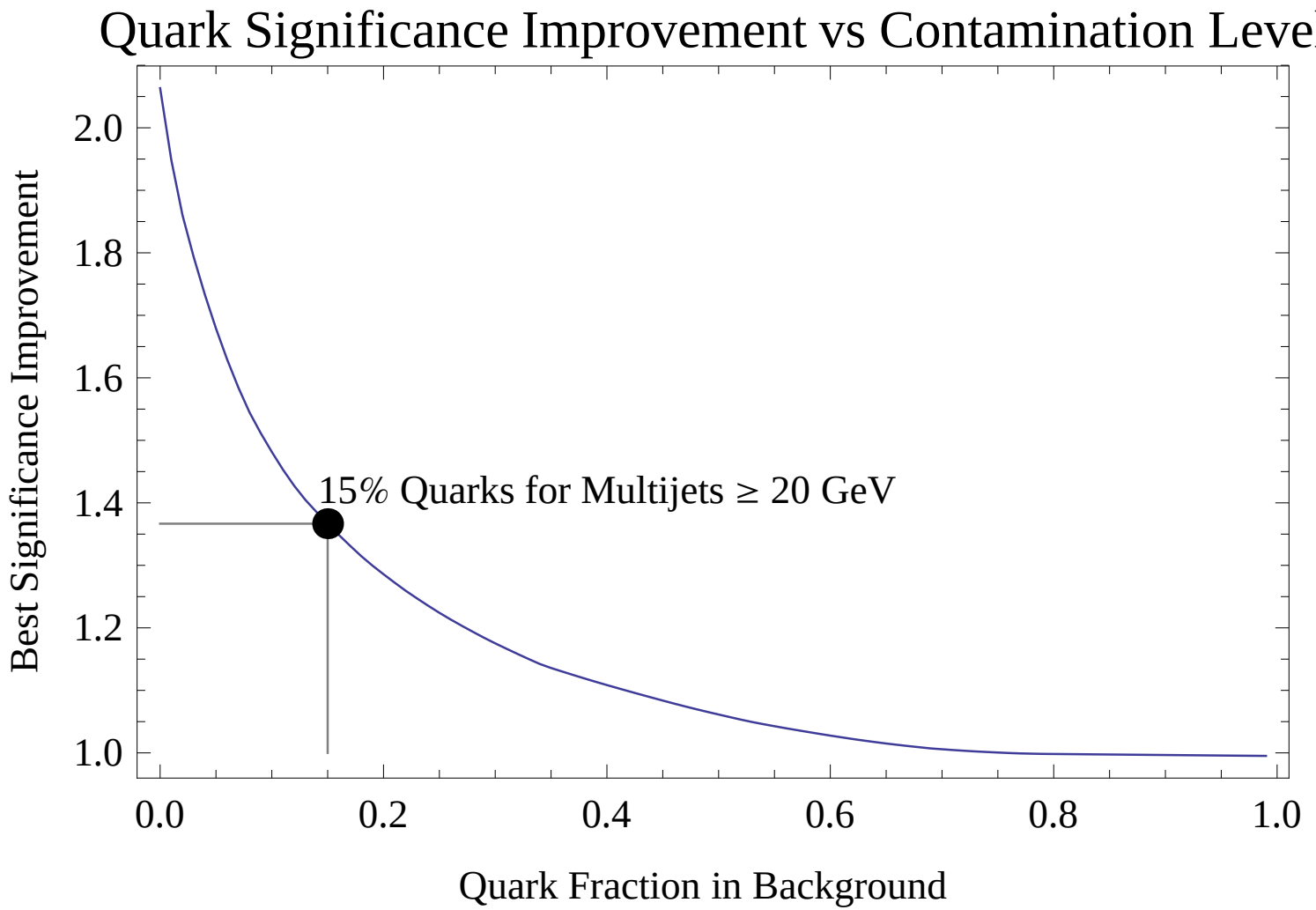

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For the 8 quark gluino example, significance improvement is 12.2.

Different Quark Jet Fractions