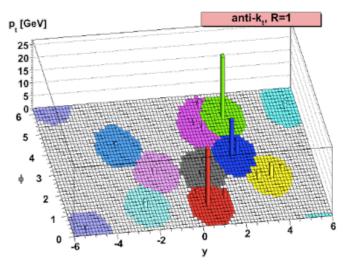
NEW IDEAS IN JET PHYSICS

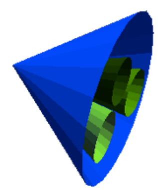
Matthew Schwartz
Harvard University

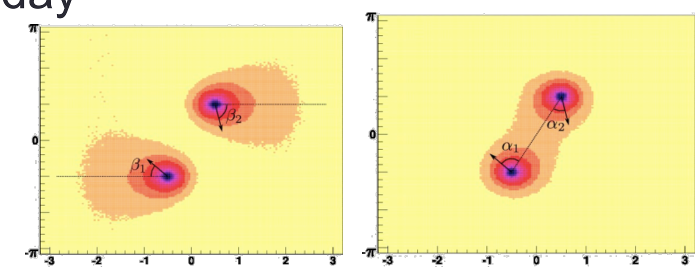
Jets at the LHC

- Jet physics is entering a **golden era**
  - No matter what the LHC sees, we will need jets to figure out what it is:
    Supersymmetry? Extra dimensions? Higgs boson?
  - The LHC is studying jets with unprecedented precision

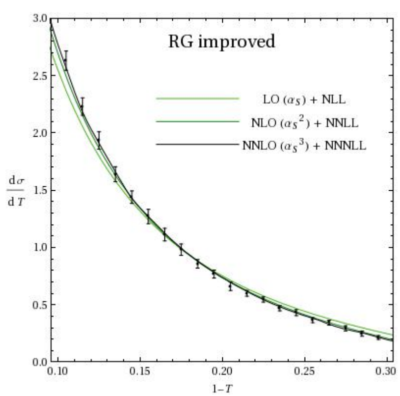
- New ways to use jets are being invented every day

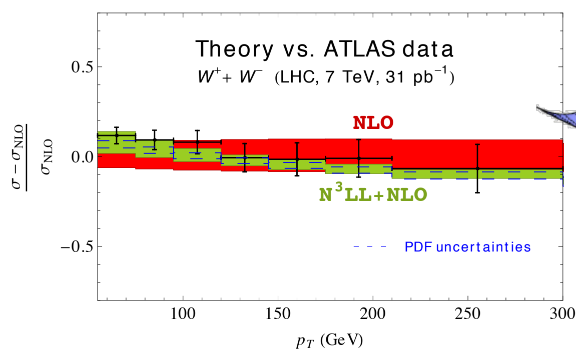


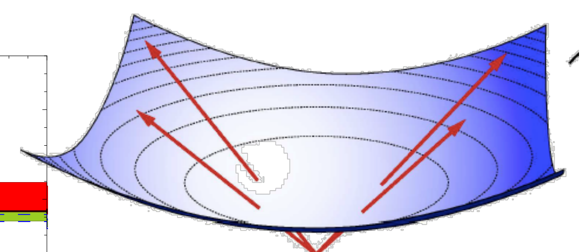




- New theoretical tools are being developed to calculate jet properties







Jet physics I’m interested in

- Jet substructure
- Color flow
- Quark vs gluon jets
  - Gluon tagging
  - Calibration
- Jet charge
- Q-jets
- Jet mass
- N-subjettiness
- Jet physics from static charges in AdS

Jet physics I'm interested in

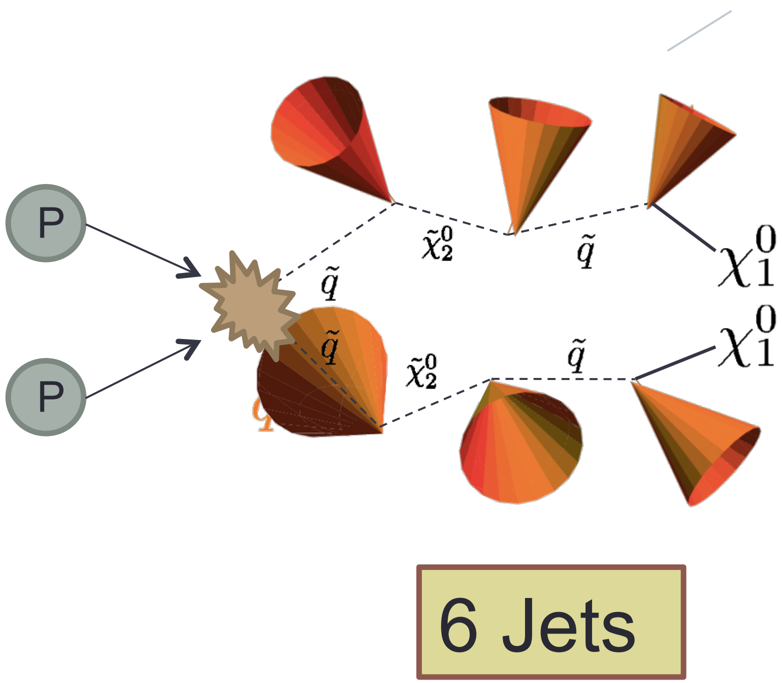
- Jet substructure
  Kaplan, Rehermann, MDS, Tweedie **Phys.Rev.Lett.** 101 (2008) 142001
  Cui, Han, MDS, **JHEP 1107 (2011) 127**
- Color flow
  Gallichio and MDS **Phys.Rev.Lett.** 105 (2010) 022001
- Quark vs gluon jets
  - Gluon tagging
    Gallichio and MDS **Phys.Rev.Lett.** 107 (2011) 172001
  - Calibration
    Gallichio and MDS **JHEP** 1110 (2011) 103
- Jet charge
  Krohn, Lin, MDS, Waalewijn,, in preparation
- Q-jets
  Ellis, Hornig, Roy, Krohn, MDS **Phys.Rev.Lett.** 108 (2012) 182003
- Jet mass
  Becher, Chien, Kelley, Schabinger, Zhu, various
- N-subjettiness
  Feige, MDS, Stewart Thaler, arXiv:1204.3898
- Jet physics from static charges in AdS
  Chien, MDS, Simmons-Duffin, Stewart, **Phys.Rev. D85 (2012) 045010**

Why study jets at the lhc?

New physics at the LHC is expected to be jet-heavy

- Even if new physics is first discovered with leptons, need jets to tell us what it is!

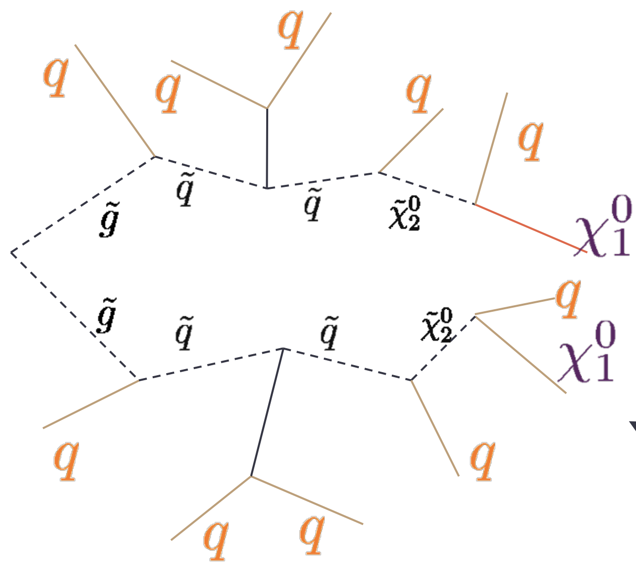
Example: Supersymmetry



Interpreting jets

We want to see quarks and gluons:

We observe jets:



QCD

Can we **invert** ?

Reality: **this** exists

Assumption: **this** exists

Jet-to-parton map

- Find jet momenta
- Set quark momenta = jet momenta

What is wrong with the jet-to-parton map?

It treats jets as 4-vectors

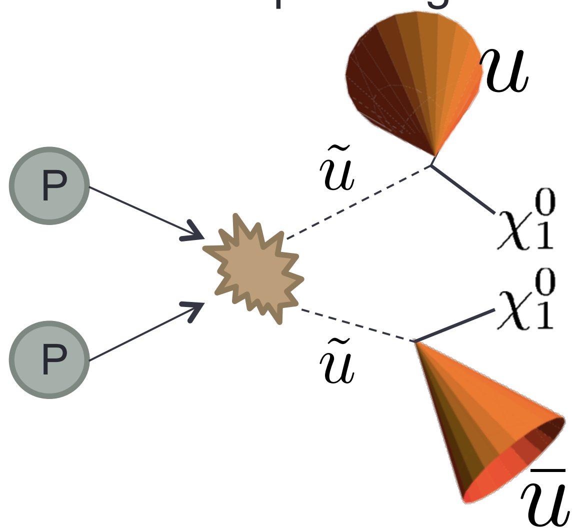
- Jets have **color** , and color connections
  - Used by D0 (published) and ATLAS (Boost 2012, hopefully)
- Quark and gluon jets may be different
  - **New physics** is **quark heavy**, backgrounds are **gluon heavy**
  - Although difficult, quark and gluon discrimination could be extremely useful
- Jets have **charge**
- Jets from boosted objects have **substructure**
  - E.g. top-tagging from boosted top jets – used by CMS!
  - Boosted Higgs searches
  - N-subjettiness

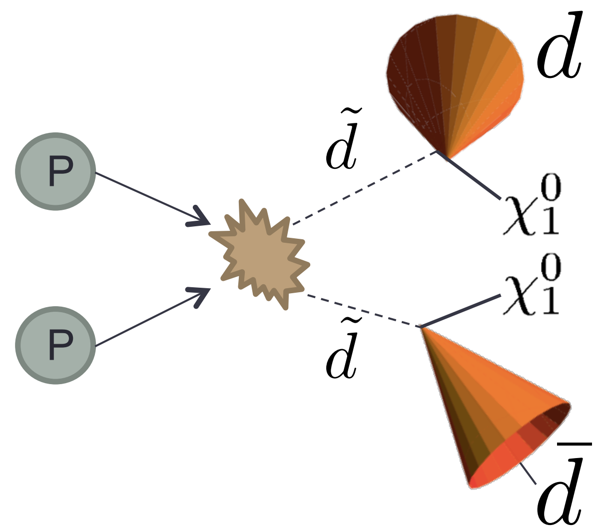
JET CHARGE

Jet charge

Can the charge of a jet be measured?

- Could distinguish **up-quark** jets from **down-quark** jets
  - Could help distinguish up squarks from down squarks





- **W prime** vs **Z prime**

- Many many uses for characterizing new physics (if seen)

How to measure

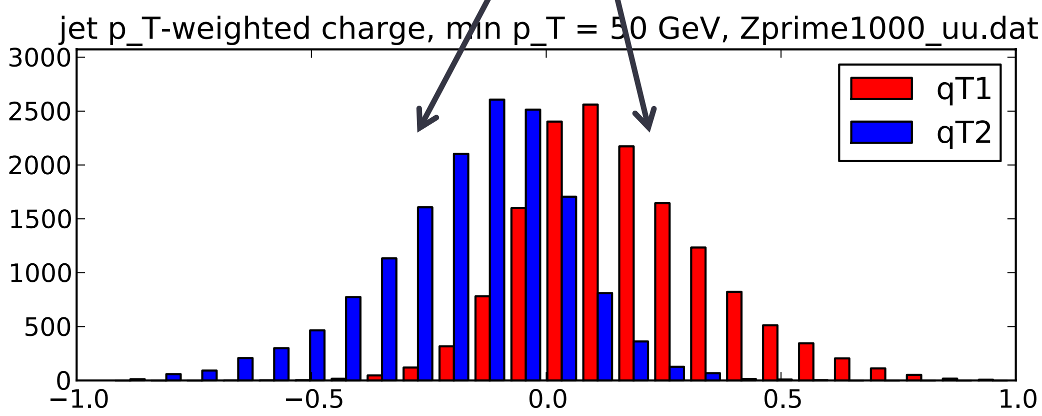
Work in progress with
David Krohn, Tongyan Lin
and Wouter Waalewijn

We consider the energy-weighted **jet charge**:

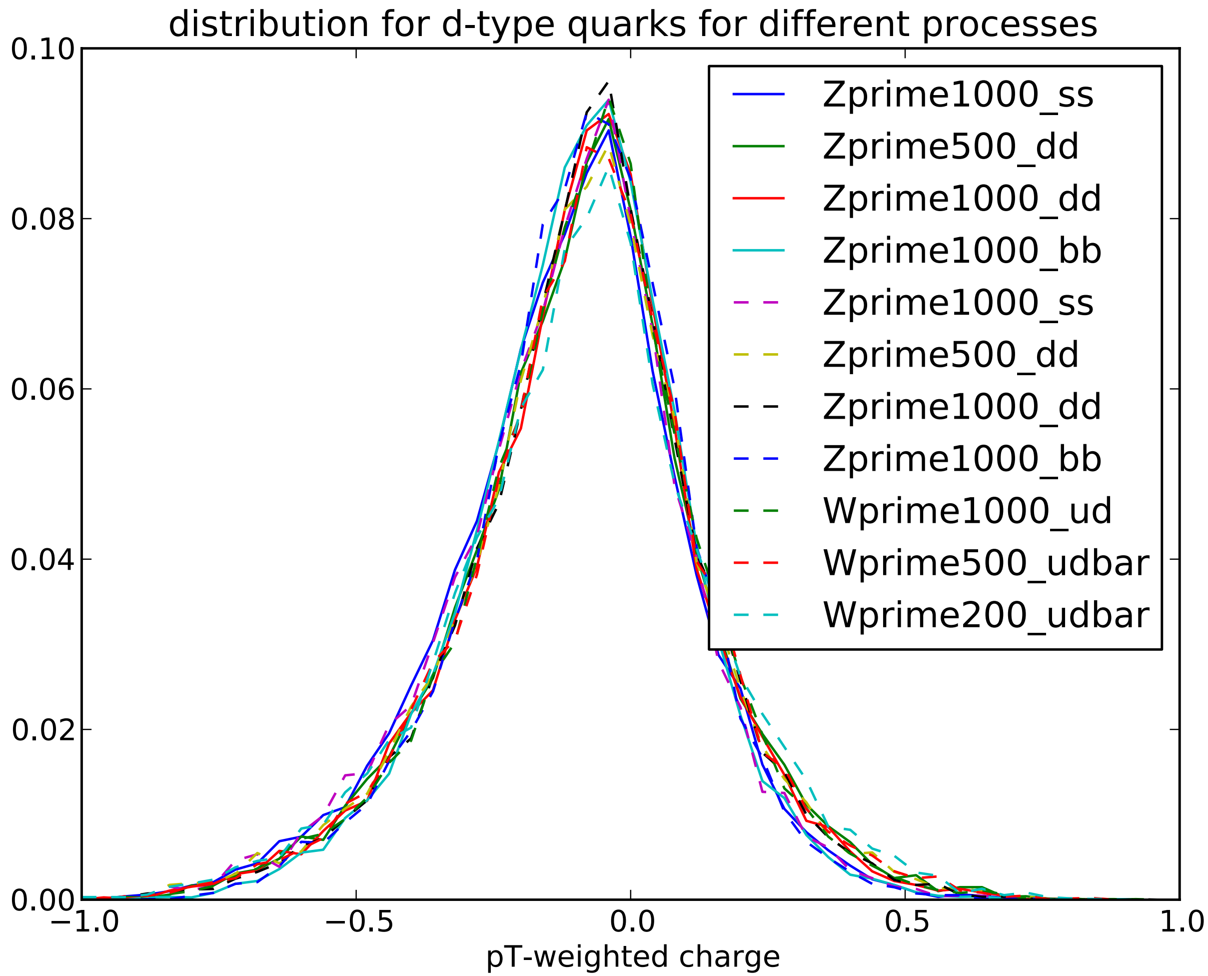
$$\mathcal{Q}_\kappa^i = \frac{1}{E_{\rm jet}} \sum_{j \in {\rm jet}} Q_j (E_j)^\kappa$$

- Long history at e+e- colliders and deep-inelastic scattering
- Can it work at the LHC?

$$Z' \to \bar{u}u$$

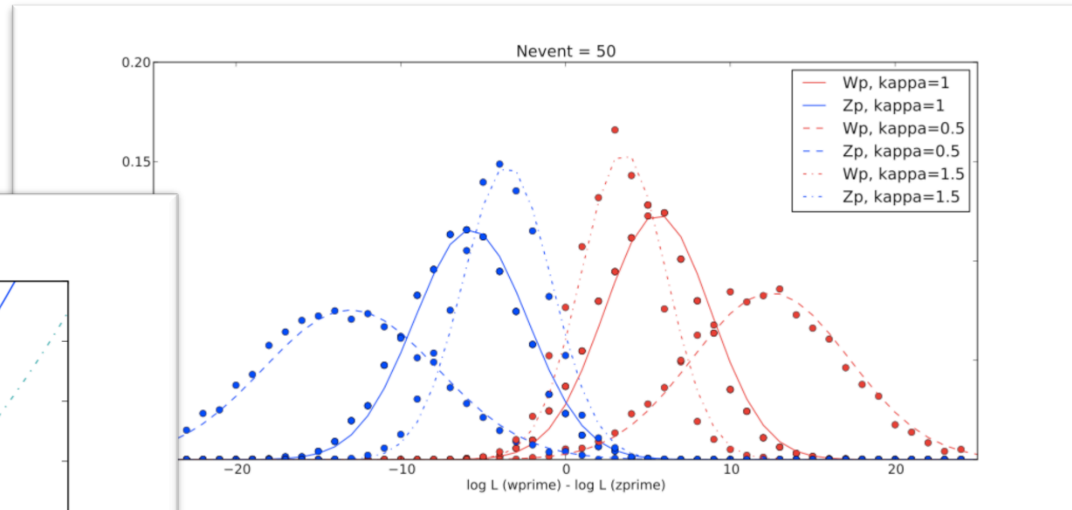


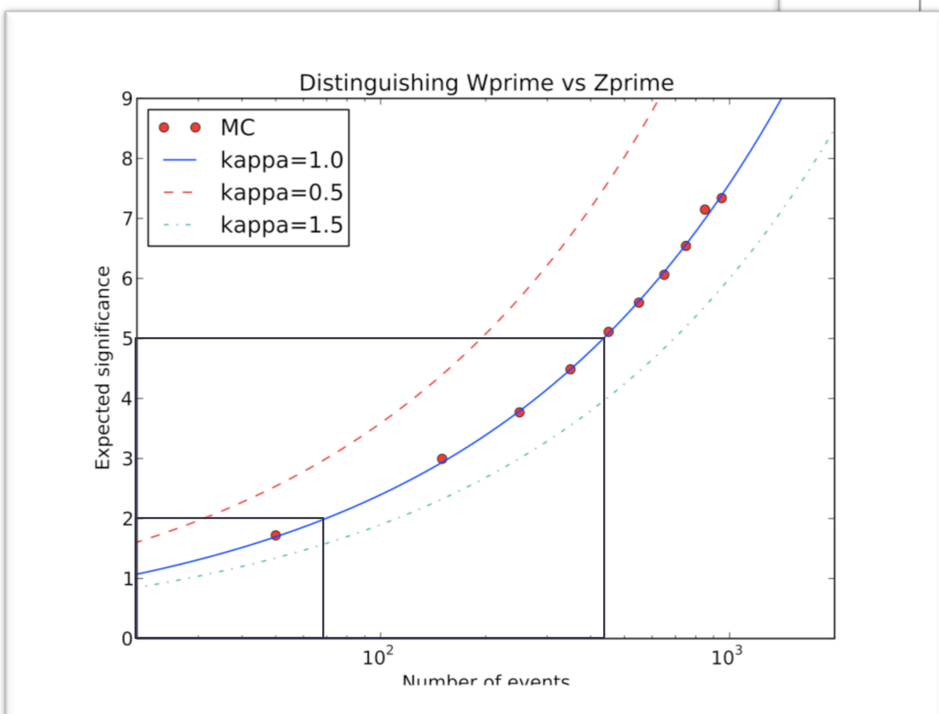
Consistent among flavors



Distinguishes W ' from Z '

Log-likelihood distribution for 1 TeV resonance, various κ

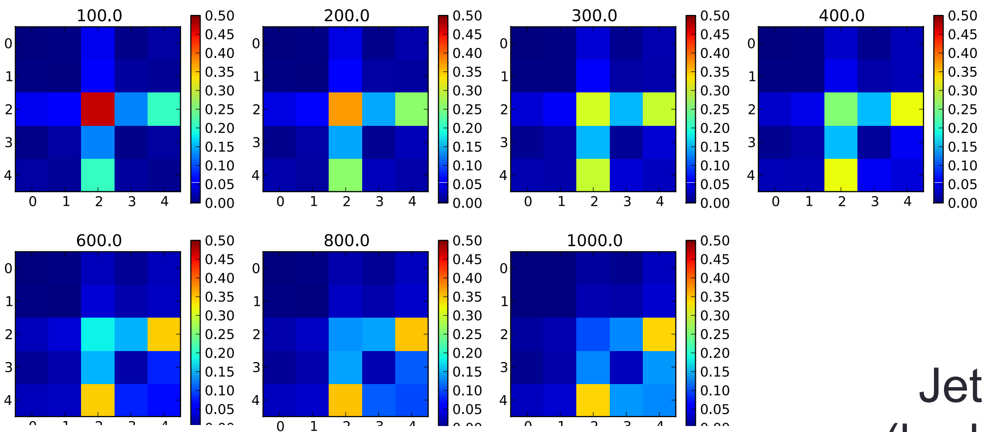




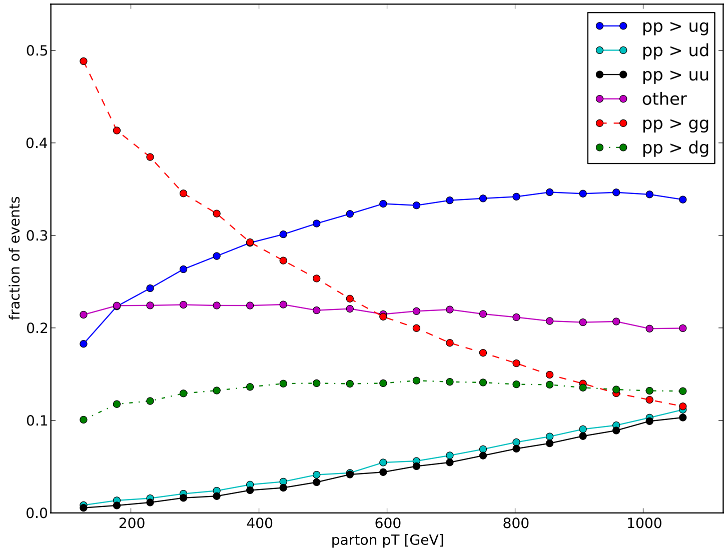
2σ with 30 events
5σ with 200 events

Calibrate on standard model

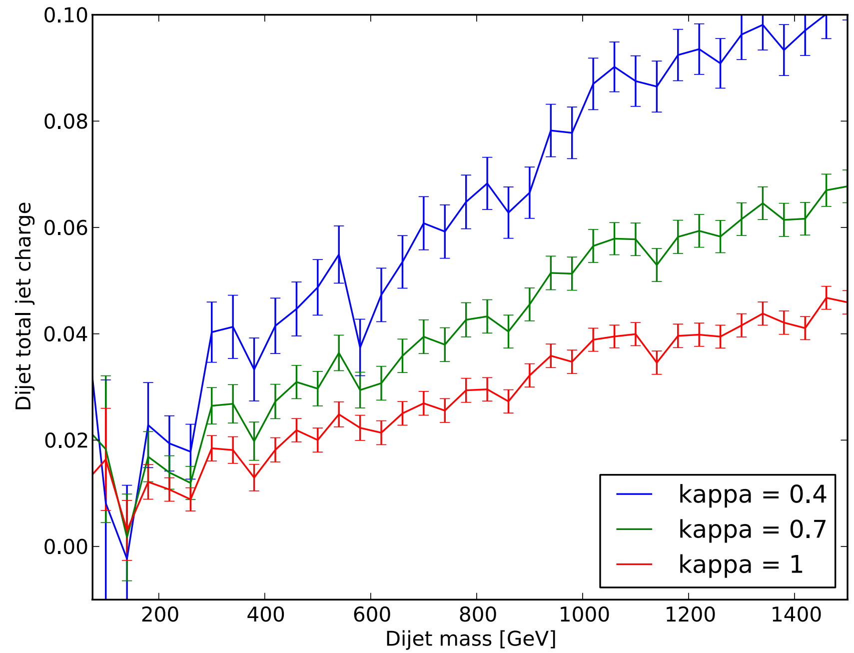
2D charges (parton level)
for different pT



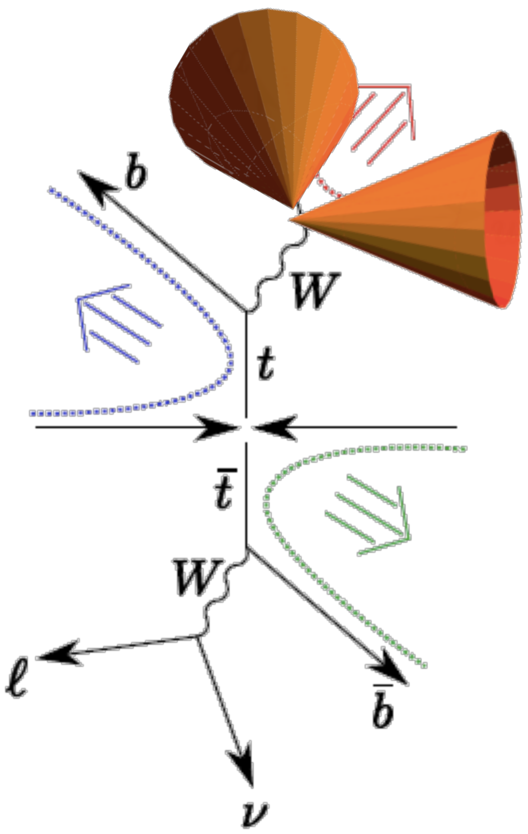
Fractions
(parton level)



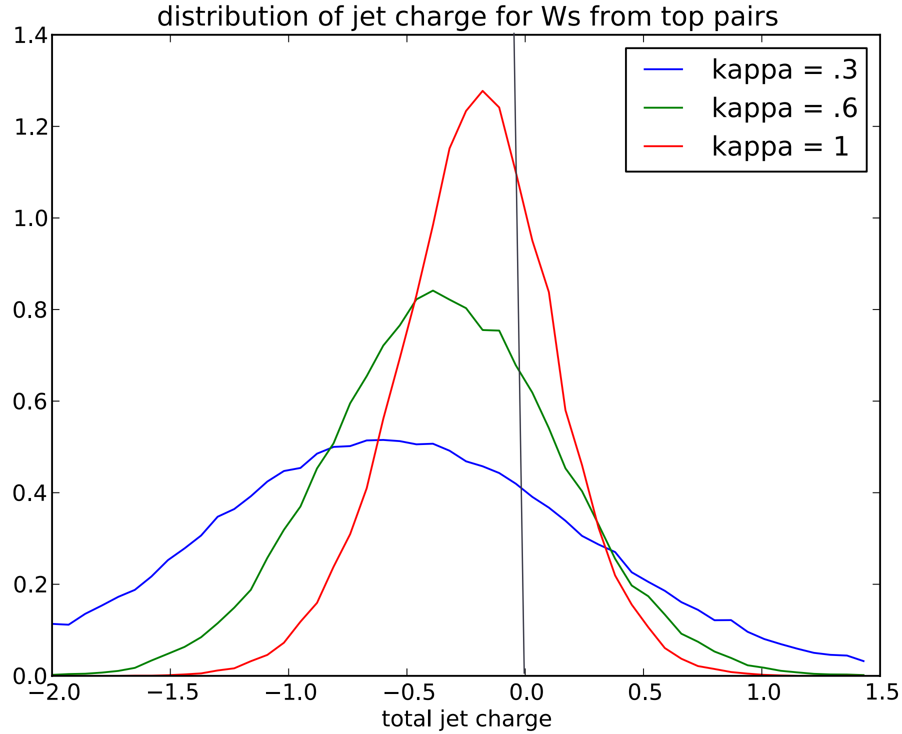
Jet charge
(hadron level)



Test on top quarks



Measure sum of jet charges from W decay products



Calculate in QCD

Mean jet charge

$$\langle \mathcal{Q}_\kappa^i \rangle = \frac{1}{16\pi^3} \frac{\widetilde{\mathcal{J}}_{ij}(E,R,\kappa,\mu)}{\mathcal{J}_i(E,R,\mu)} \sum_h Q_h \widetilde{D}_j^h(\kappa,\mu)$$

Fragmenting jet functions

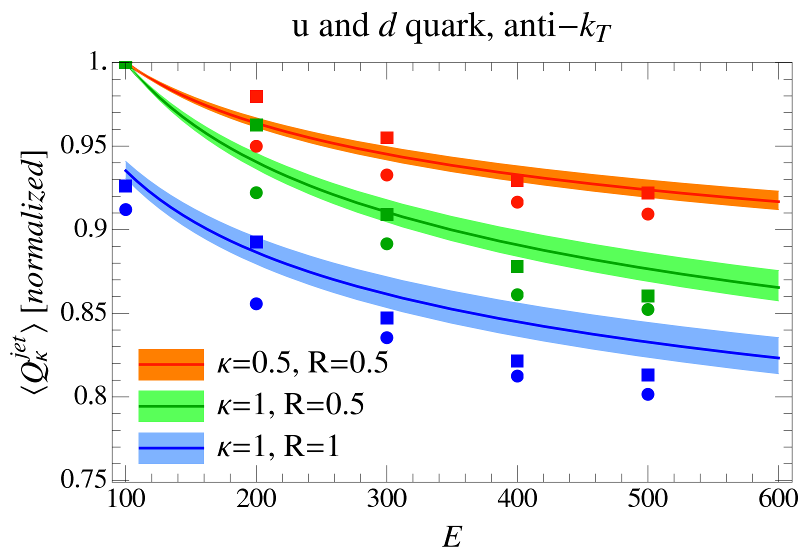
Fragmentation functions

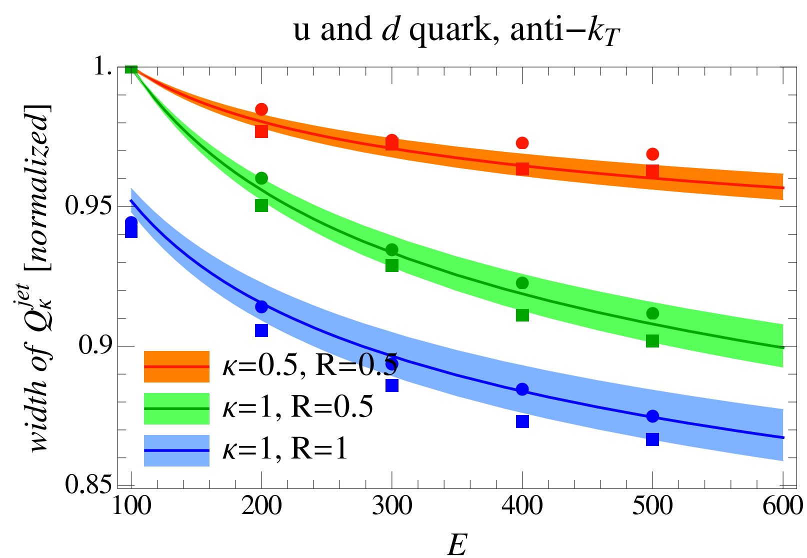
Width of jet charge

$$\langle (\mathcal{Q}_\kappa^i)^2 \rangle = \sum_j \frac{\tilde{\mathcal{J}}_{ij}(E,R,2\kappa,\mu)}{2(2\pi)^3 J_i(E,R,\mu)} \sum_h Q_h^2 \tilde{D}_j^h(2\kappa,\mu) +$$

$$\int \mathrm{d}z_1\, \mathrm{d}z_2\, z_1^\kappa z_2^\kappa \sum_{h_1,h_2} Q_{h_1} Q_{h_2} \frac{\mathcal{G}_i^{h_1 h_2}(E,R,z_1,z_2,\mu)}{2(2\pi)^3 J_i(E,R,\mu)}$$

Dihadron fragmentation functions





- Good agreement with Pythia
- Systematically improvable

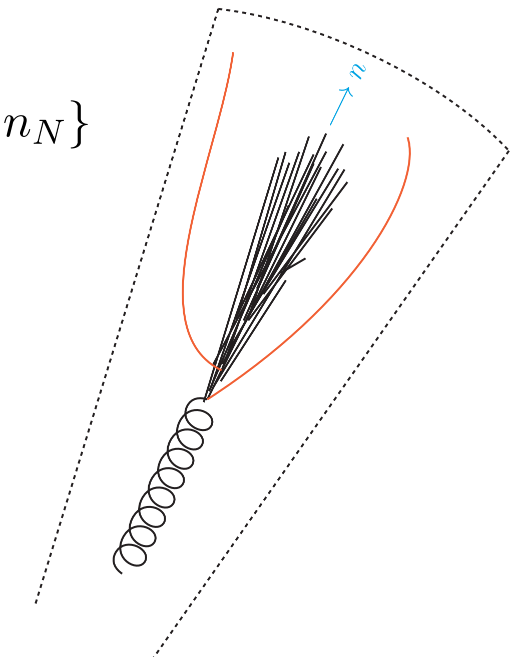
N-SUBJETTINESS

N-subjettiness

$$\mathcal{T}_N \equiv \min_{n_1,\ldots,n_N} \sum_{j\in J} \min\{p_j \cdot n_1, \ldots, p_j \cdot n_N\}$$

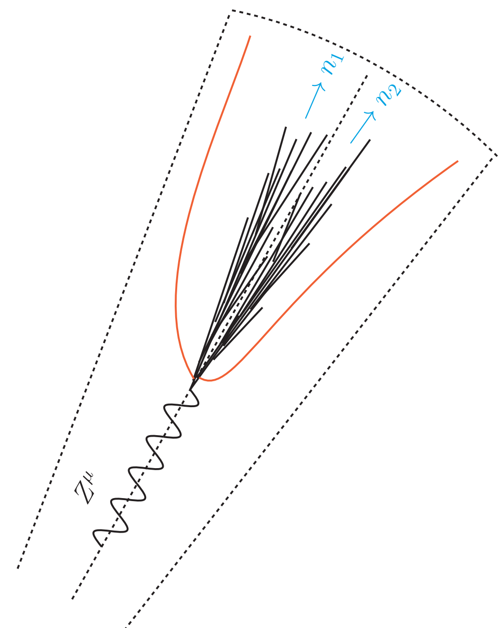
$$\mathcal{T}_1 \approx \frac{m_J^2}{2E_J}$$

$$\mathcal{T}_2 \approx \frac{m_1^2}{2E_1} + \frac{m_2^2}{2E_2}$$



QCD jet

(all τ_n small)



Boosted W/Z jet

(small τ_2, large τ_1)

$$\mathcal{T}_2/\mathcal{T}_1$$

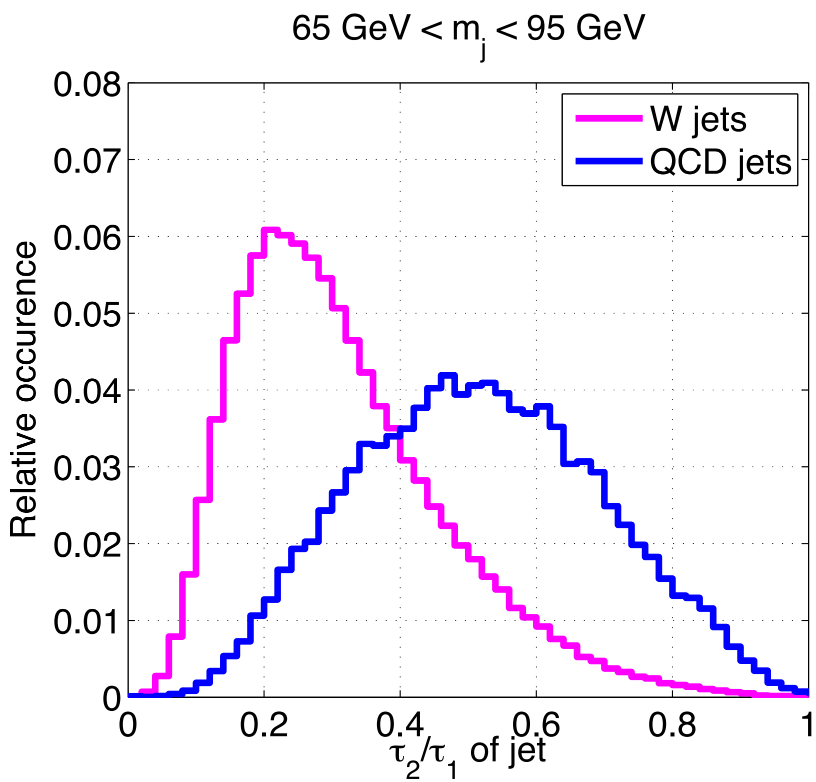
Good discriminant

Ratio τ_2/τ_1

Useful for distinguishing boosted W jets from QCD jets

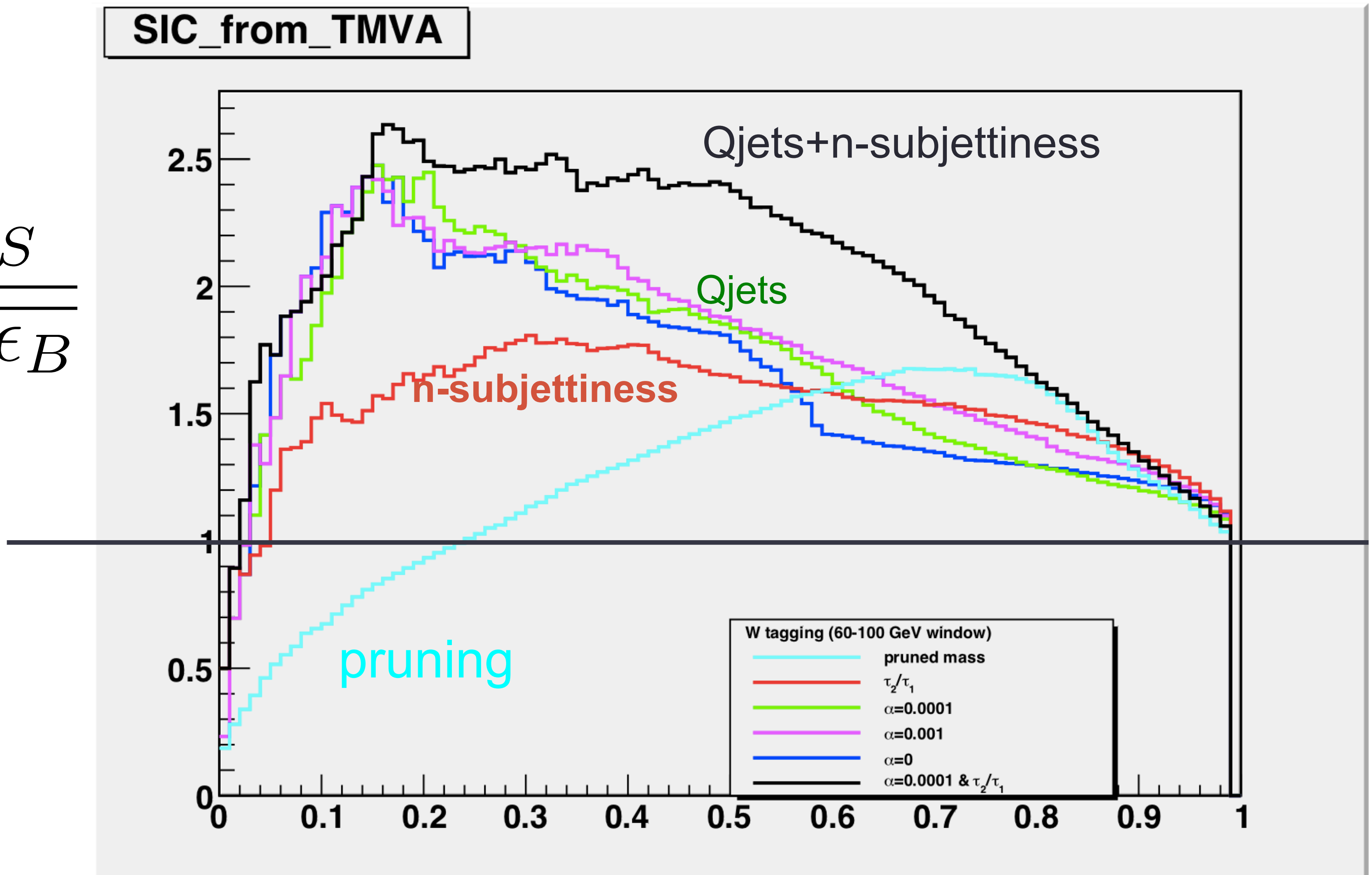
$$\mathcal{T}_2 \approx \frac{m_1^2}{2E_1} + \frac{m_2^2}{2E_2}$$

$$\mathcal{T}_1 \approx \frac{m_J^2}{2E_J}$$



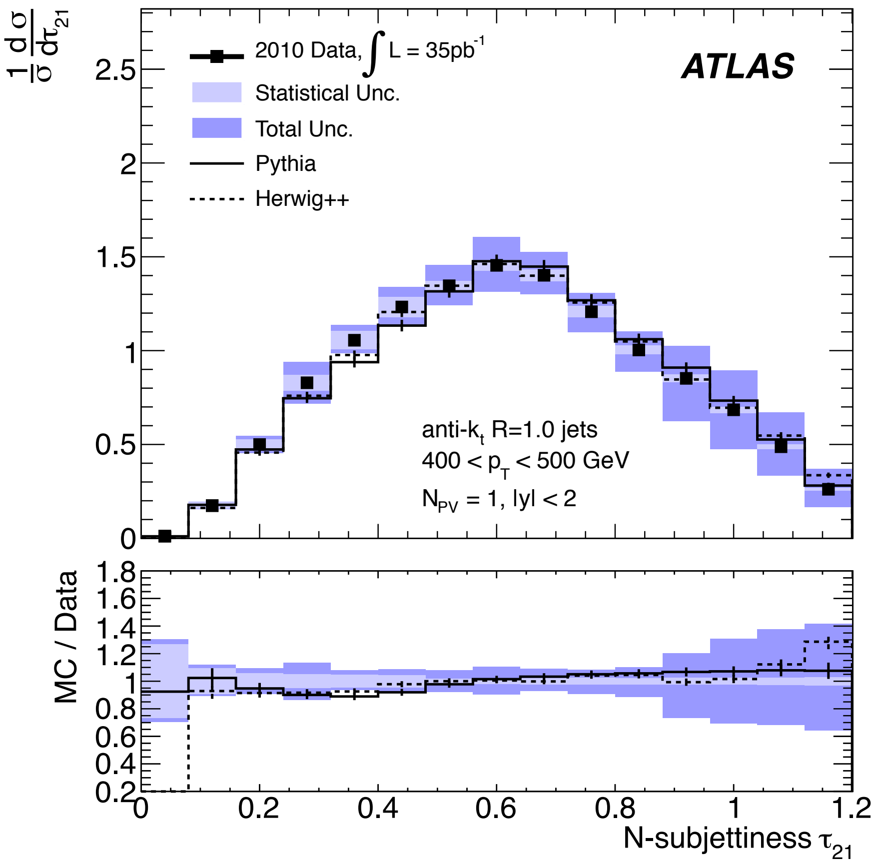
Not as good as Qjets (see Tuhin's talk)

$$\frac{\epsilon_S}{\sqrt{\epsilon_B}}$$



Already measured by ATLAS

(March 20, 2012)



With more data,
could be a precision observable.

Can we calculate n-subjettiness
more accurately then Pythia and Herwig
using **QCD**?

Factorization formula

Work done with
Iain Stewart, Jesse
Thaler and Ilya Fiege

Soft function

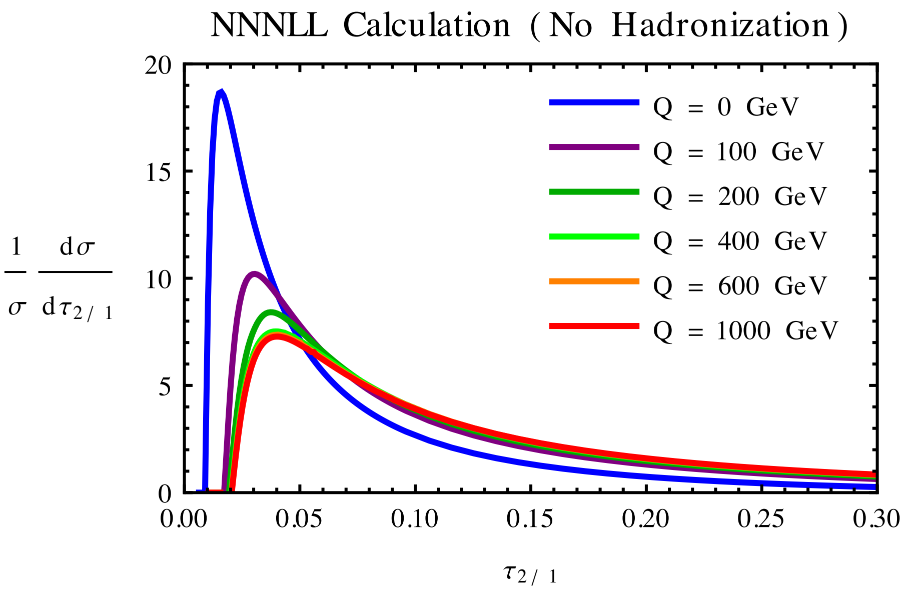
Hard function

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\mathcal{T}_{2/1}} = H\int \frac{d\cos\theta}{2}\int ds_1 ds_2 dk_1 dk_2\, S(k_1, k_2, \{n_i\}, \mu)$$
$$\times\, J(s_1,\mu)J(s_2,\mu)\delta\Big(\mathcal{T}_{2/1} - \frac{k_1+k_2}{\mathcal{T}_1} - \frac{s_1E_2+s_2E_1}{2E_1E_2\mathcal{T}_1}\Big)$$

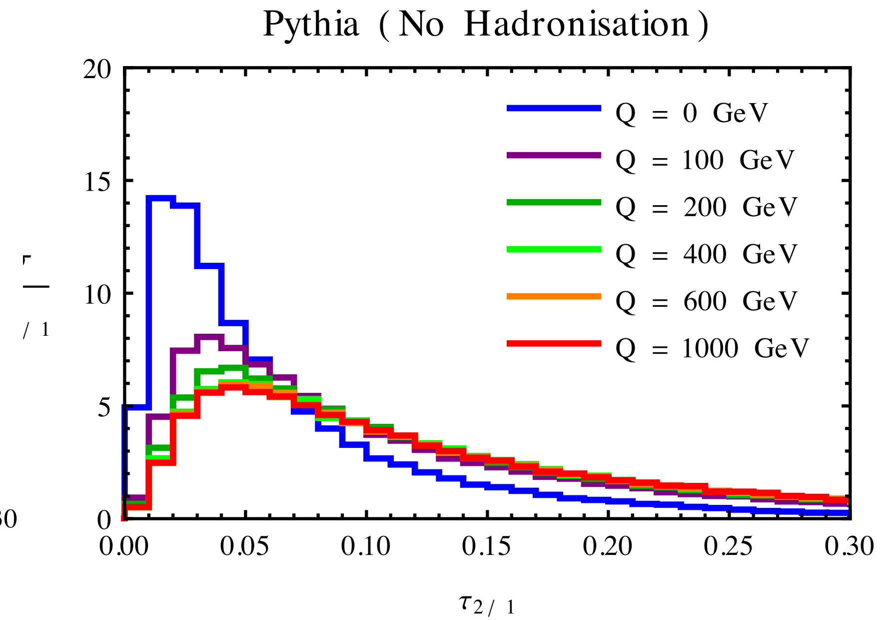
Jet function

Based on factorization for n-jettiness (Stewart, Tackmann, Waalewijn)

Results

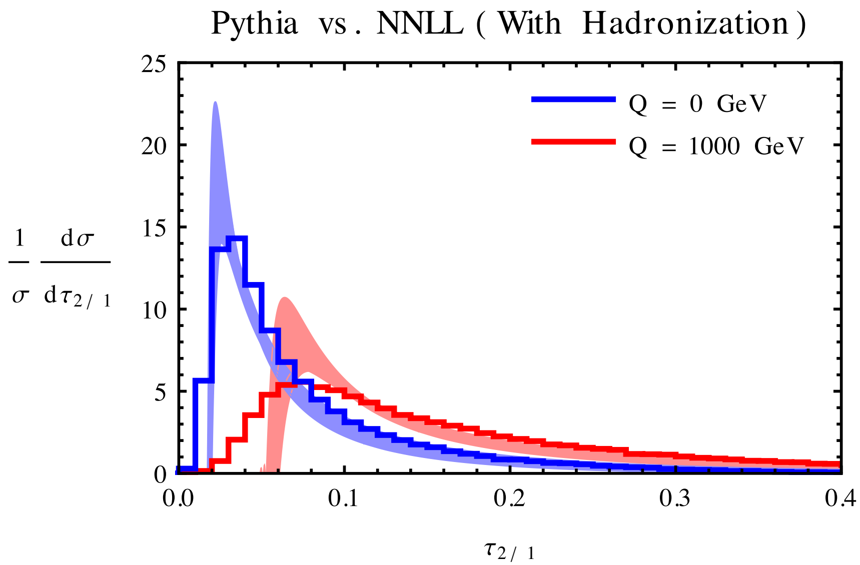


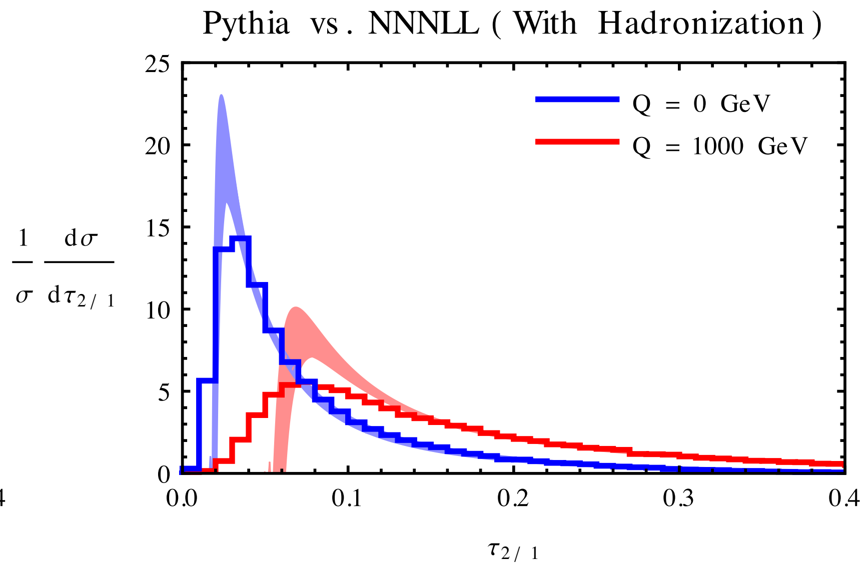
NNNLL Calculation (No Hadronization)
$\frac{1}{\sigma}\frac{d\sigma}{d\tau_{2/1}}$
20
15
10
5
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$\tau_{2/1}$
Q = 0 GeV
Q = 100 GeV
Q = 200 GeV
Q = 400 GeV
Q = 600 GeV
Q = 1000 GeV



Pythia (No Hadronisation)
20
15
10
5
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$\tau_{2/1}$
Q = 0 GeV
Q = 100 GeV
Q = 200 GeV
Q = 400 GeV
Q = 600 GeV
Q = 1000 GeV

Compare to Pythia





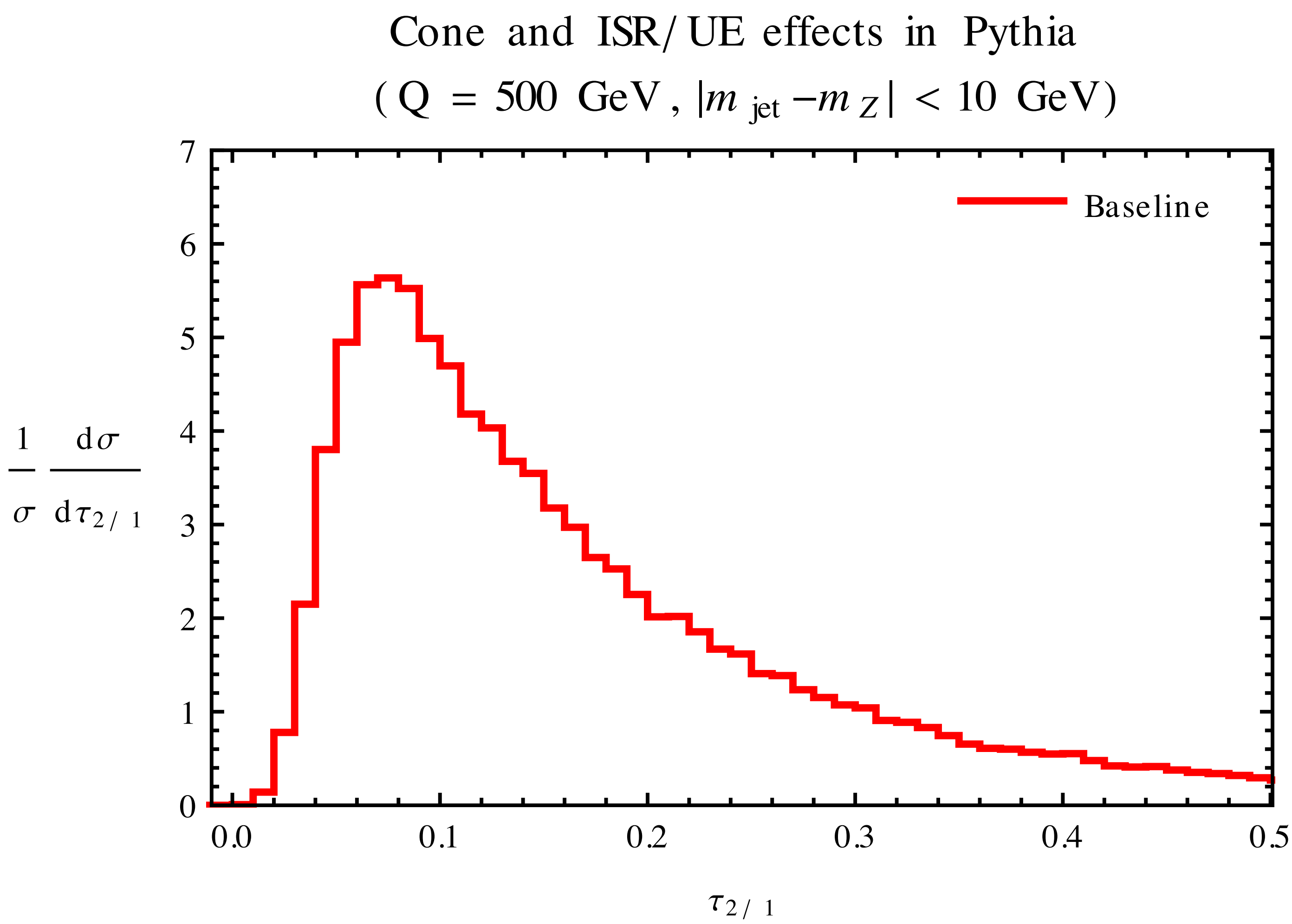
Corrections

Real events have

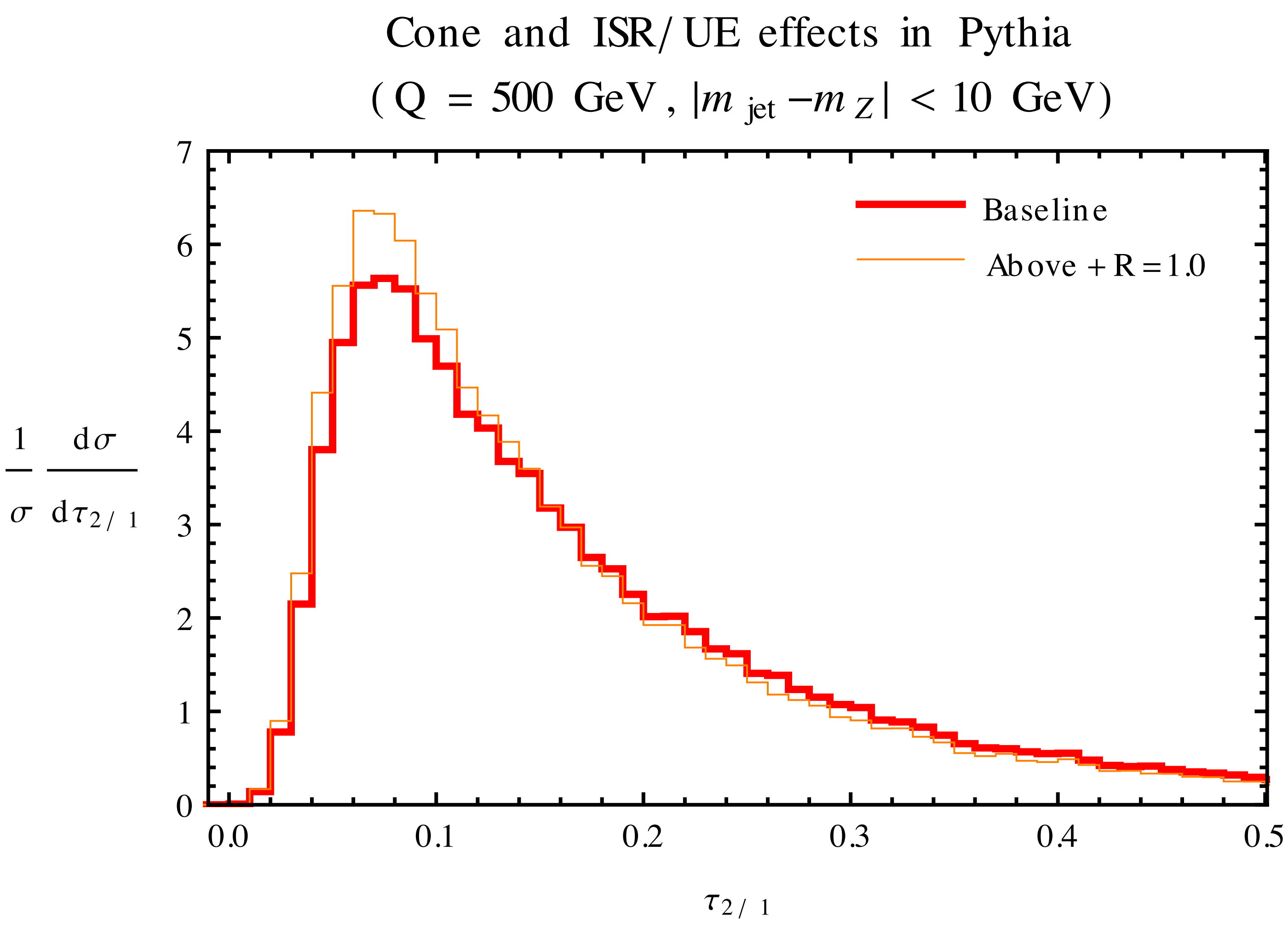
- initial state radiation (ISR)
- Final state radiation (FSR) from other jets
- Underlying event (UE)
- Jet algorithm and size dependence

Power corrections?

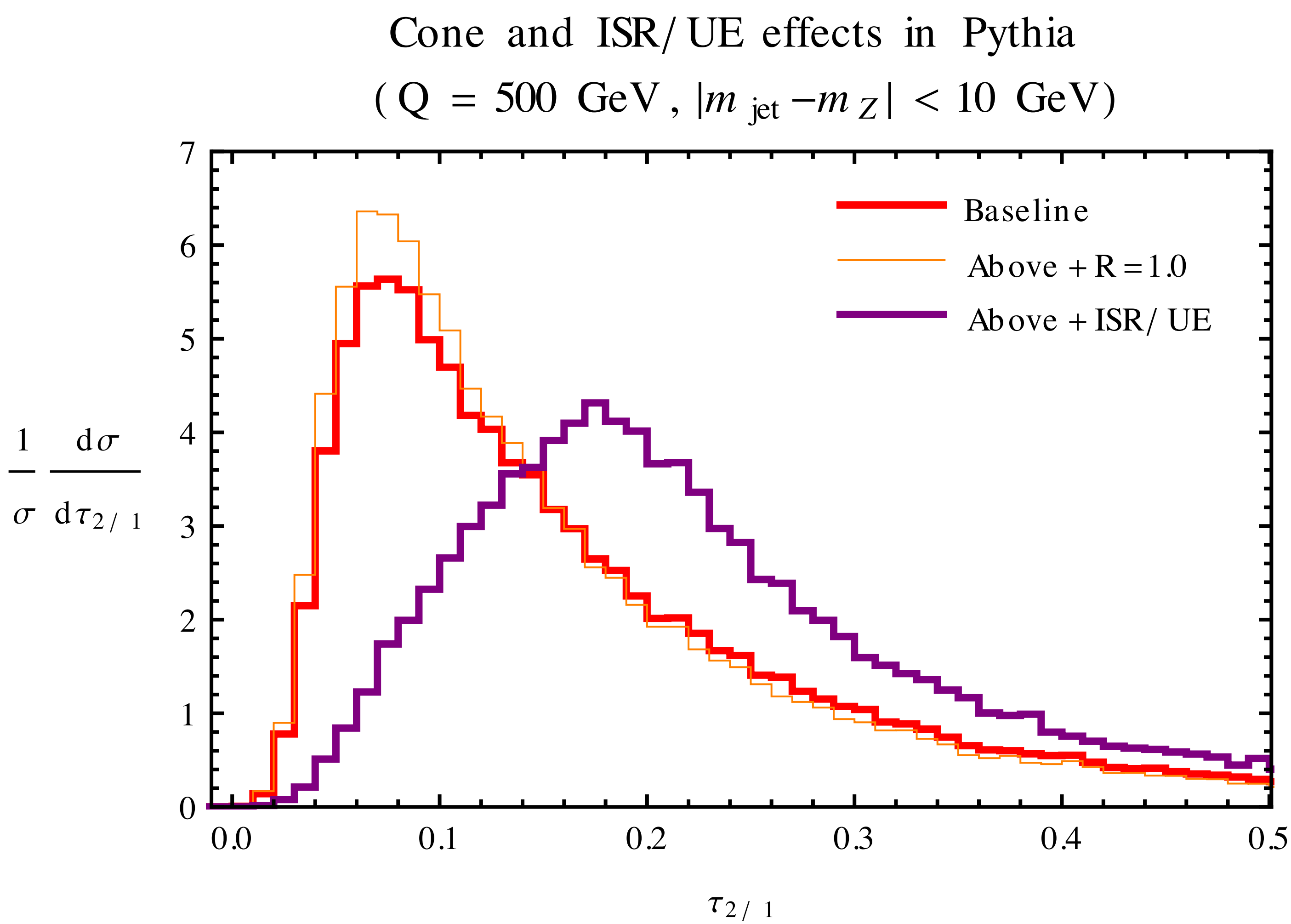
Cone and ISR/UE



Cone and ISR/UE



Cone and ISR/UE



Corrections

Real events have

- initial state radiation (ISR)
- Final state radiation (FSR) from other jets
- Underlying event (UE)
- Jet algorithm and size dependence

Power corrections?

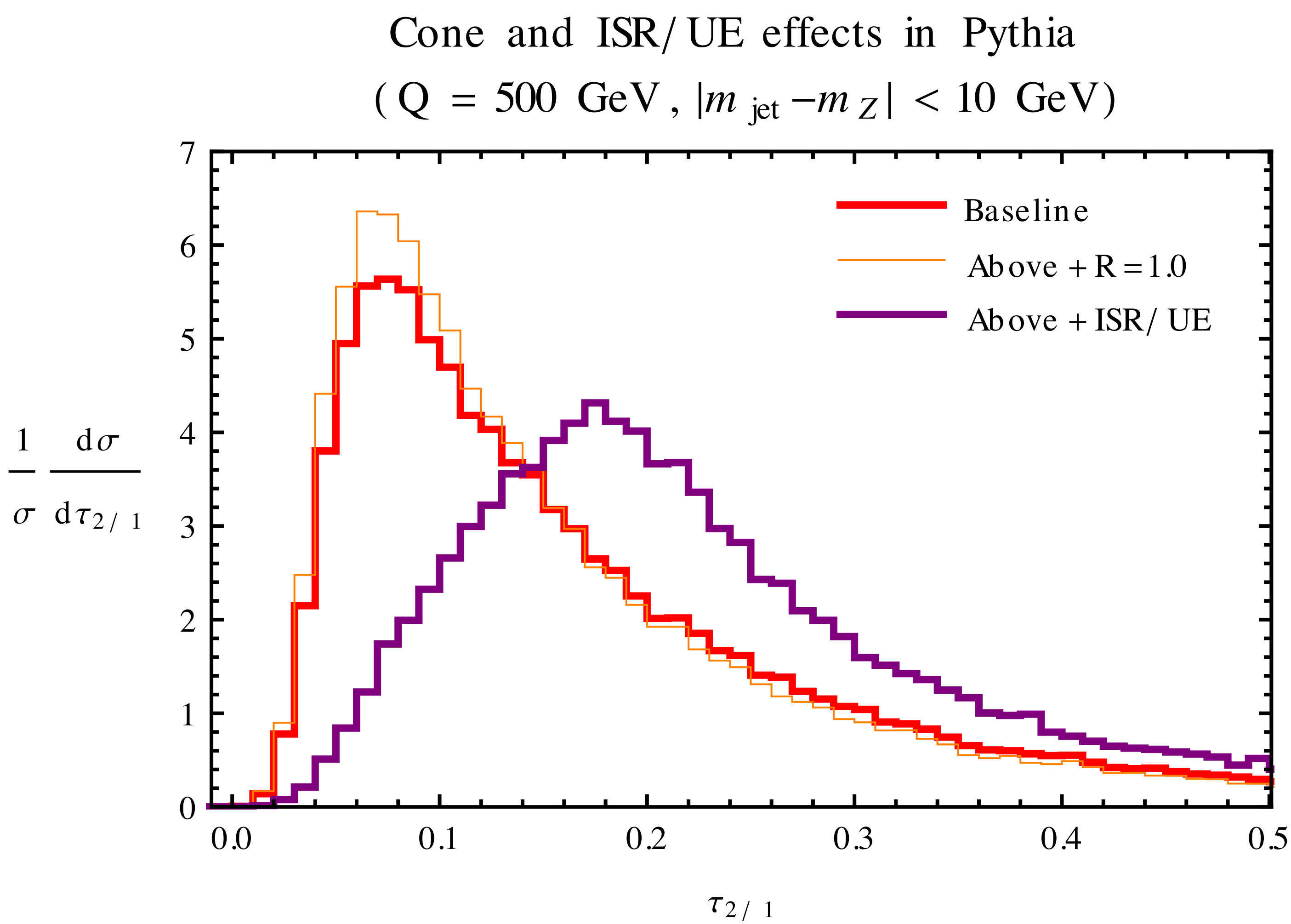
Key to corrections:

- At large boost, these shift τ_1 and τ_2 in the same way
- For W-jets, $\tau_1 = m_W$ at parton level → we know $\Delta\tau$

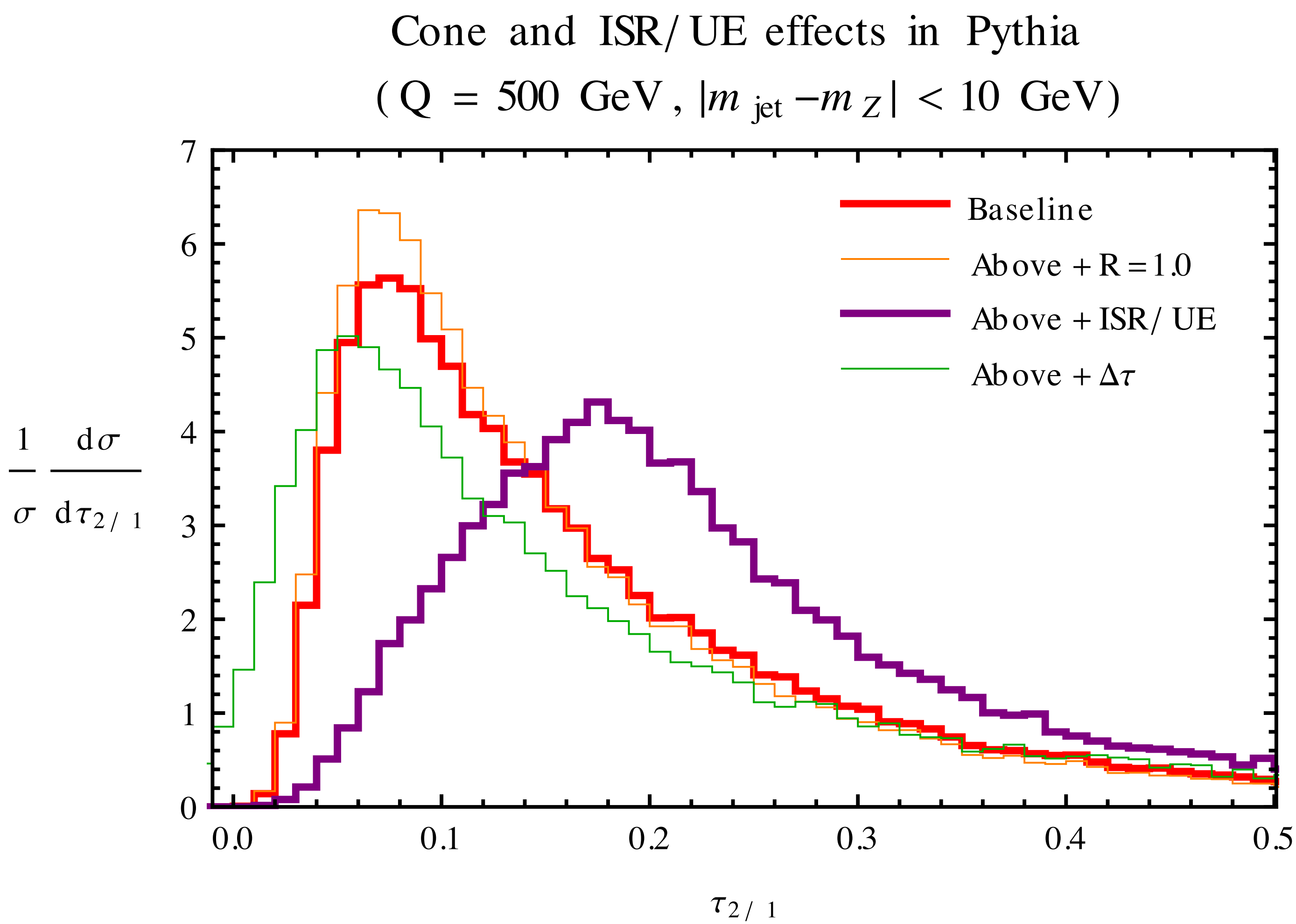
Slightly modified observable:

$$\tau_{2/1} \equiv \frac{\mathcal{T}_2 - \mathcal{T}_1 + \widehat{\mathcal{T}}_1}{\mathcal{T}_1 - \mathcal{T}_1 + \widehat{\mathcal{T}}_1} = \frac{\mathcal{T}_2 - \Delta\tau}{\mathcal{T}_1 - \Delta\tau} \quad \Longrightarrow \quad (\tau_{2/1})_{ISR/UE} \sim 1/Q$$

Cone and ISR/UE



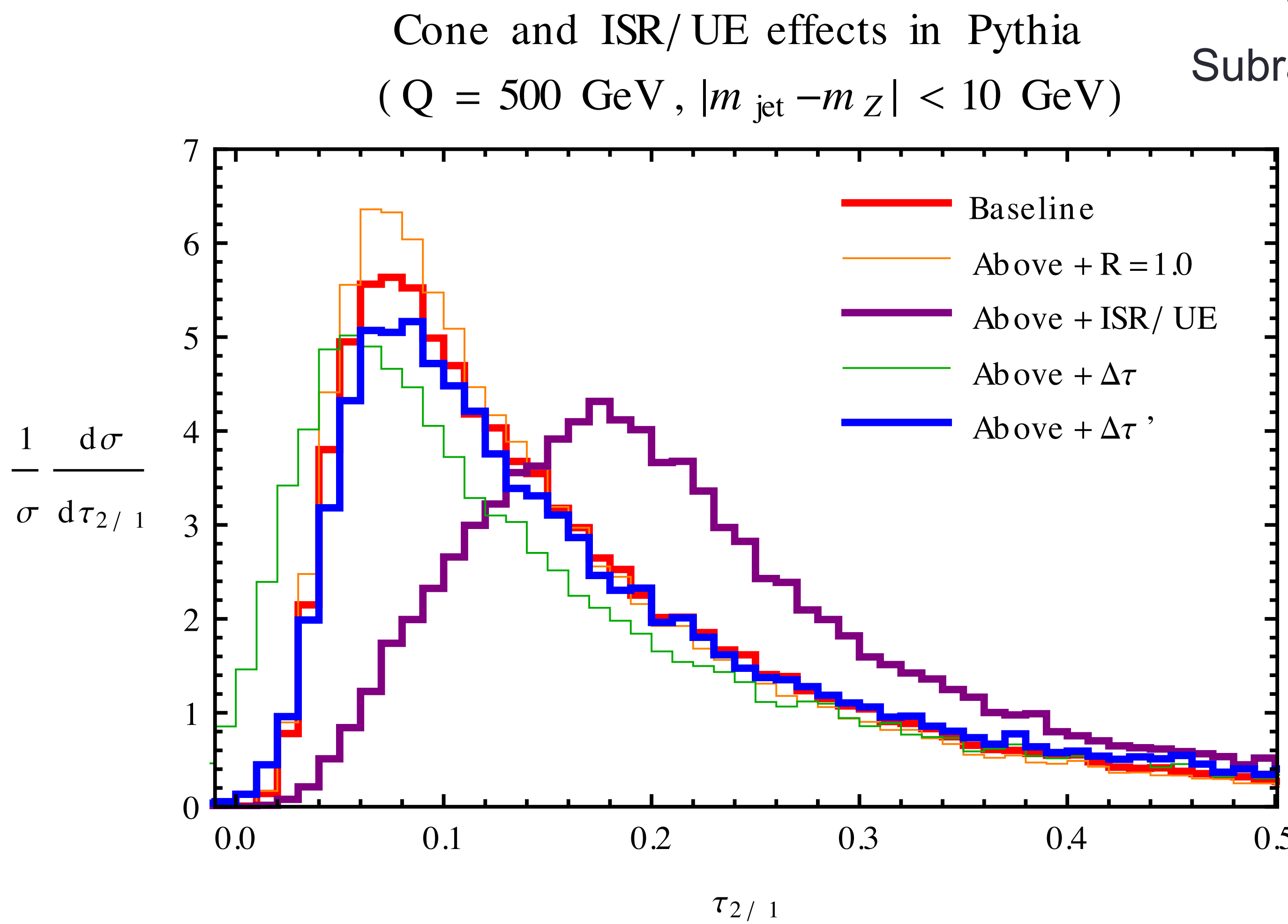
Cone and ISR/UE



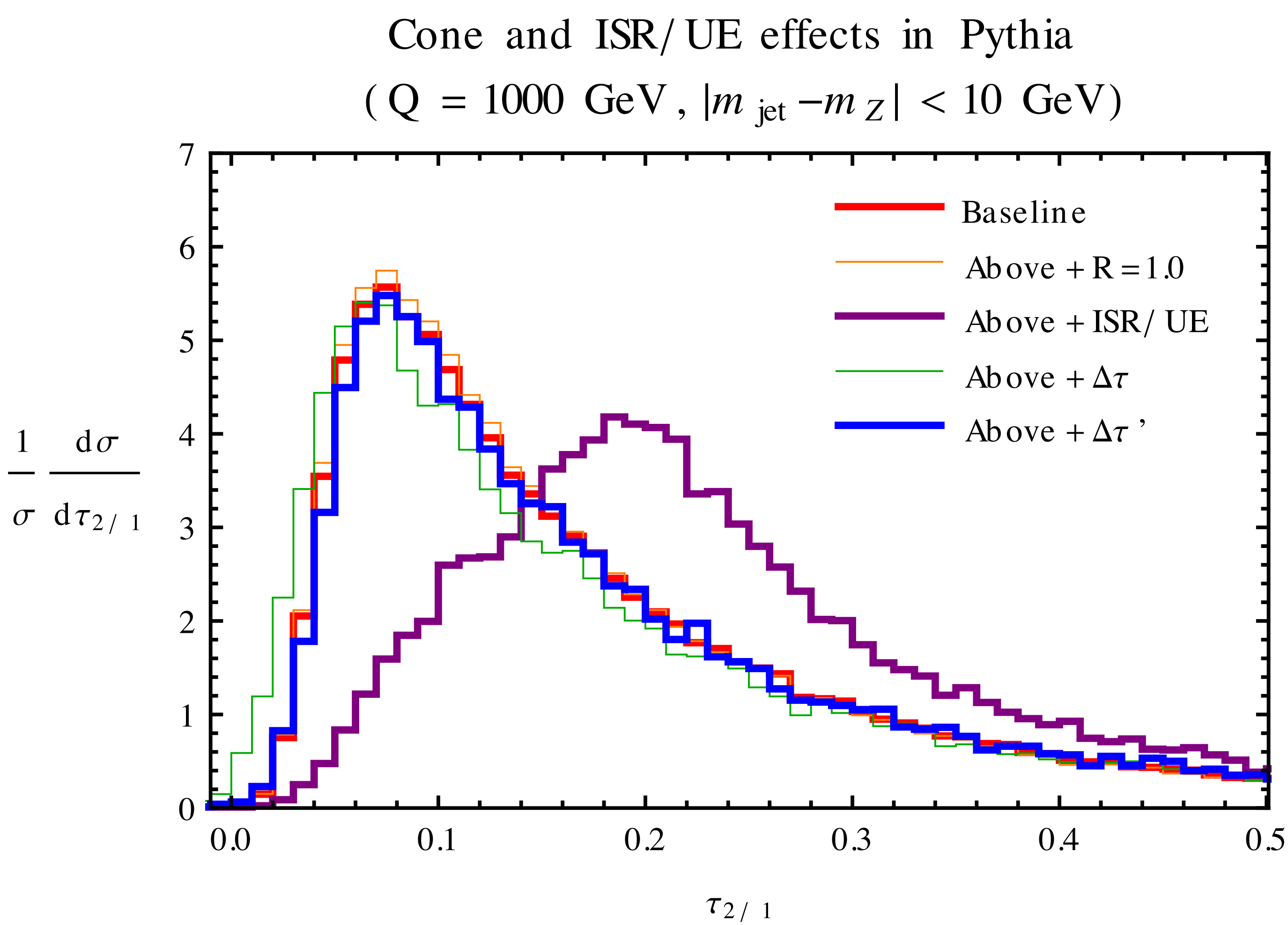
Cone and ISR/UE

$$\Delta\tau' = \Delta\tau\left(1 - \frac{\pi m_Z}{2Q}\right)$$

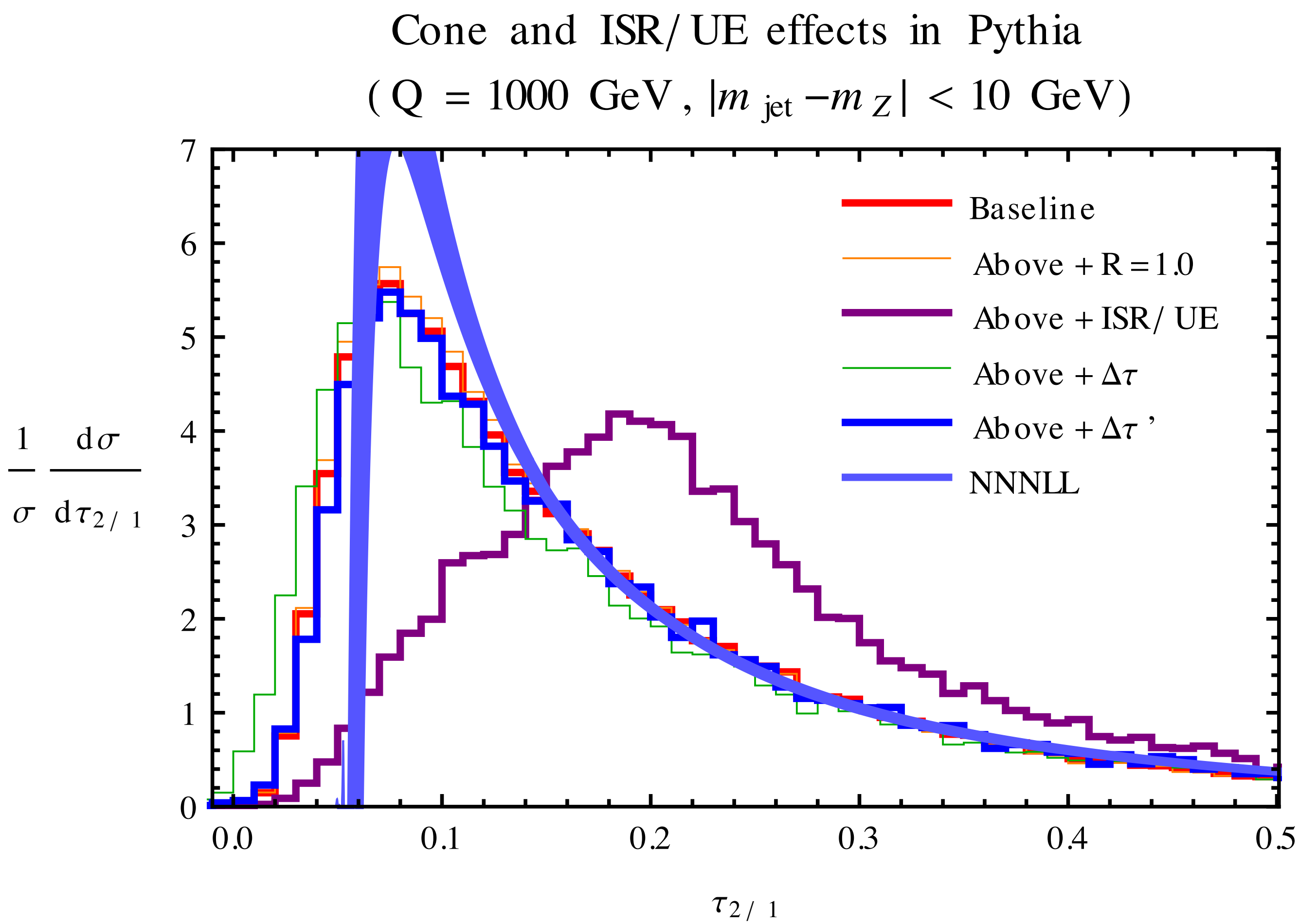
Subract off average



Cone and ISR/UE



Cone and ISR/UE



QUARKS VS GLUONS

Quark versus Gluon jets

Work done with
Jason Gallicchio

Subtle subject

- Monte Carlo event generators
  may not be trustworthy

- Some data from LEP, but ATLAS and CMS can measure much better

Two parts

1. Assuming Pythia is correct, **how can we distinguish Q from G**?

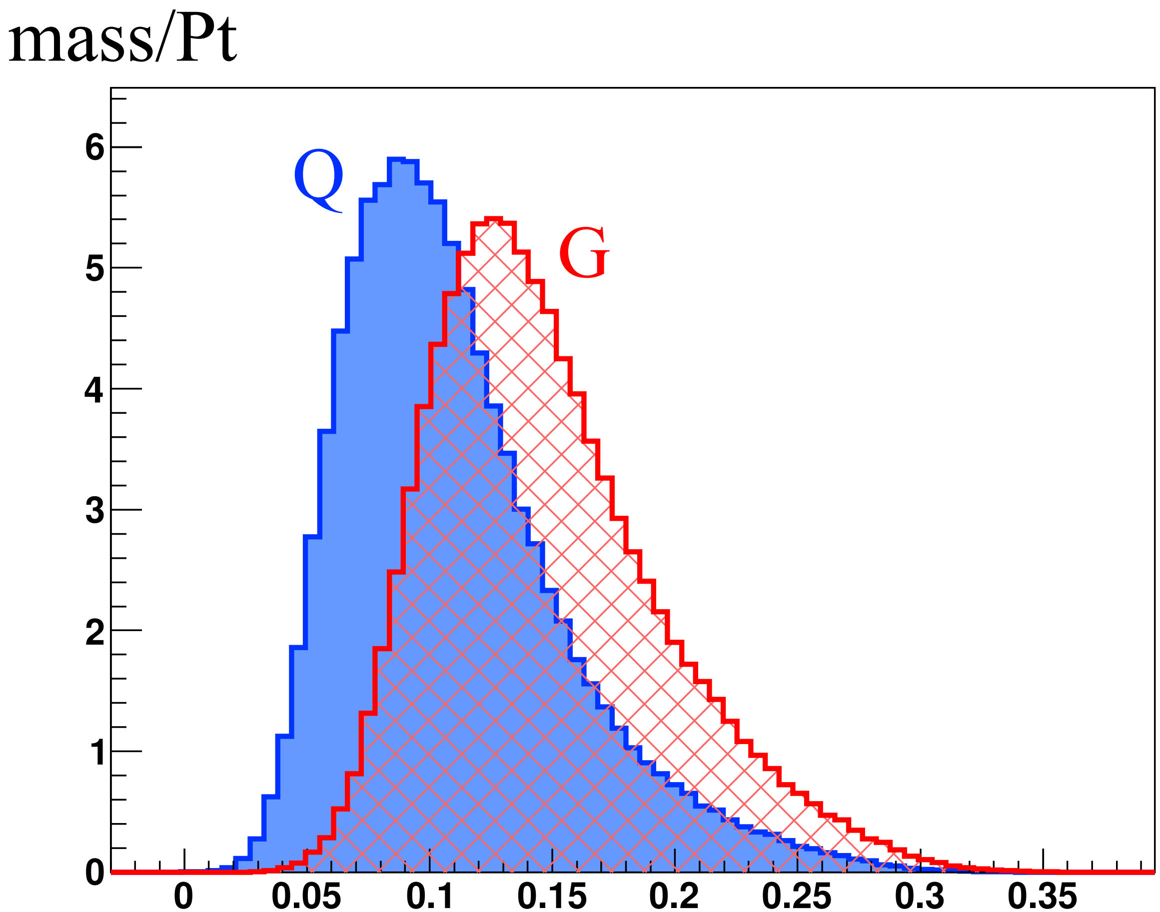
   Gallichio and MDS **Phys.Rev.Lett.** 107 (2011) 172001

2. How can we **validate on data**?
   - Where do we find pure samples of quark and gluon jets?

   Gallichio and MDS **JHEP** 1110 (2011) 103

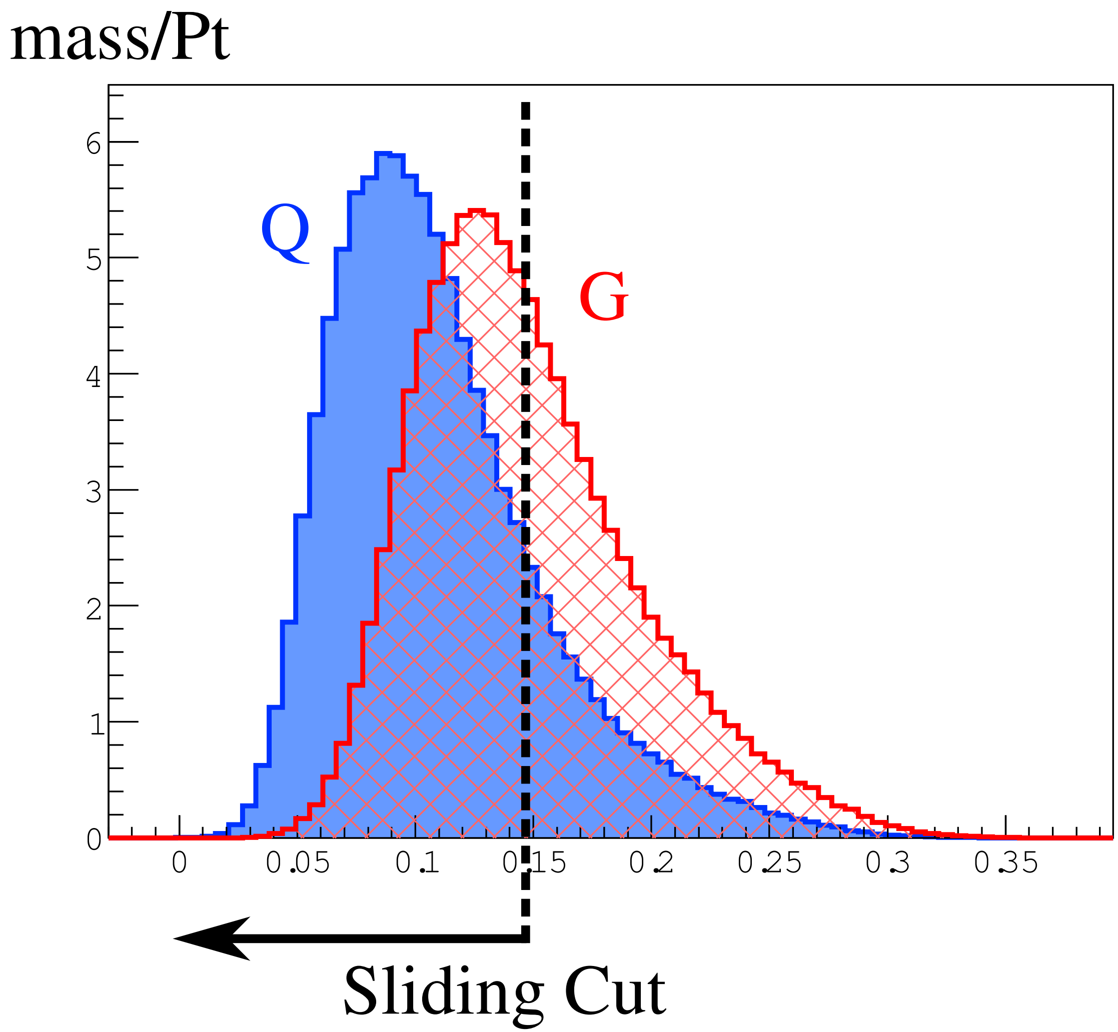
How to compare variables?

- Look at distributions of each variable, normalized to equal area



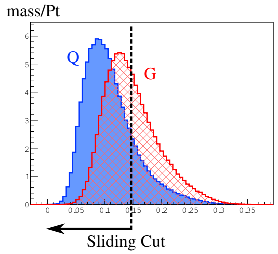
How to compare variables?

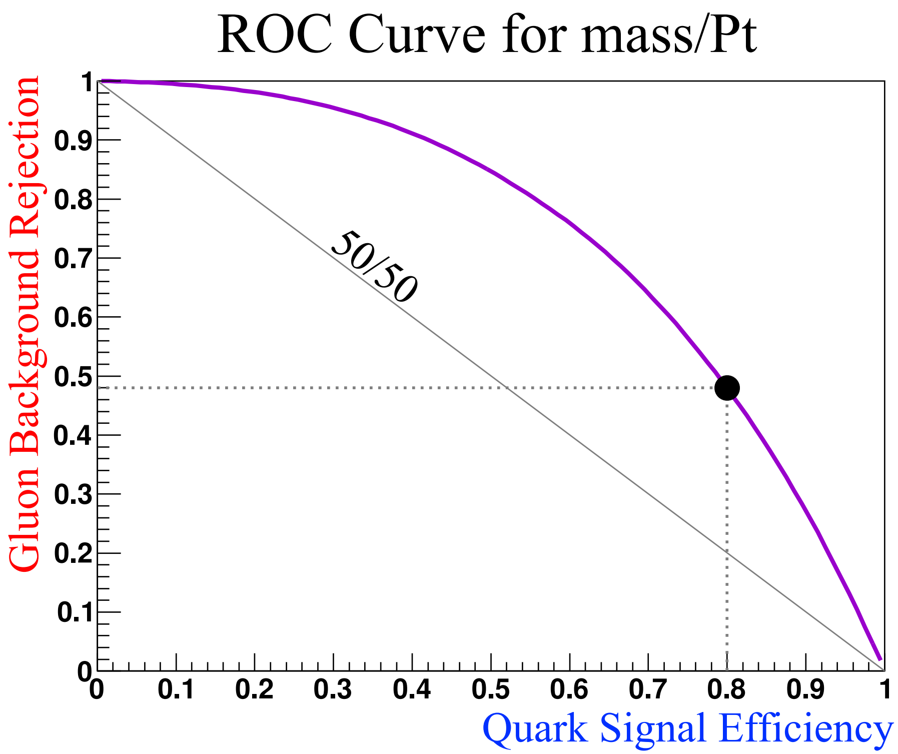
- Look at distributions of each variable, normalized to equal area
- Look at efficiencies as a function of sliding cut



How to compare variables?

This generates the "Receiver Operator Characteristic" (ROC)



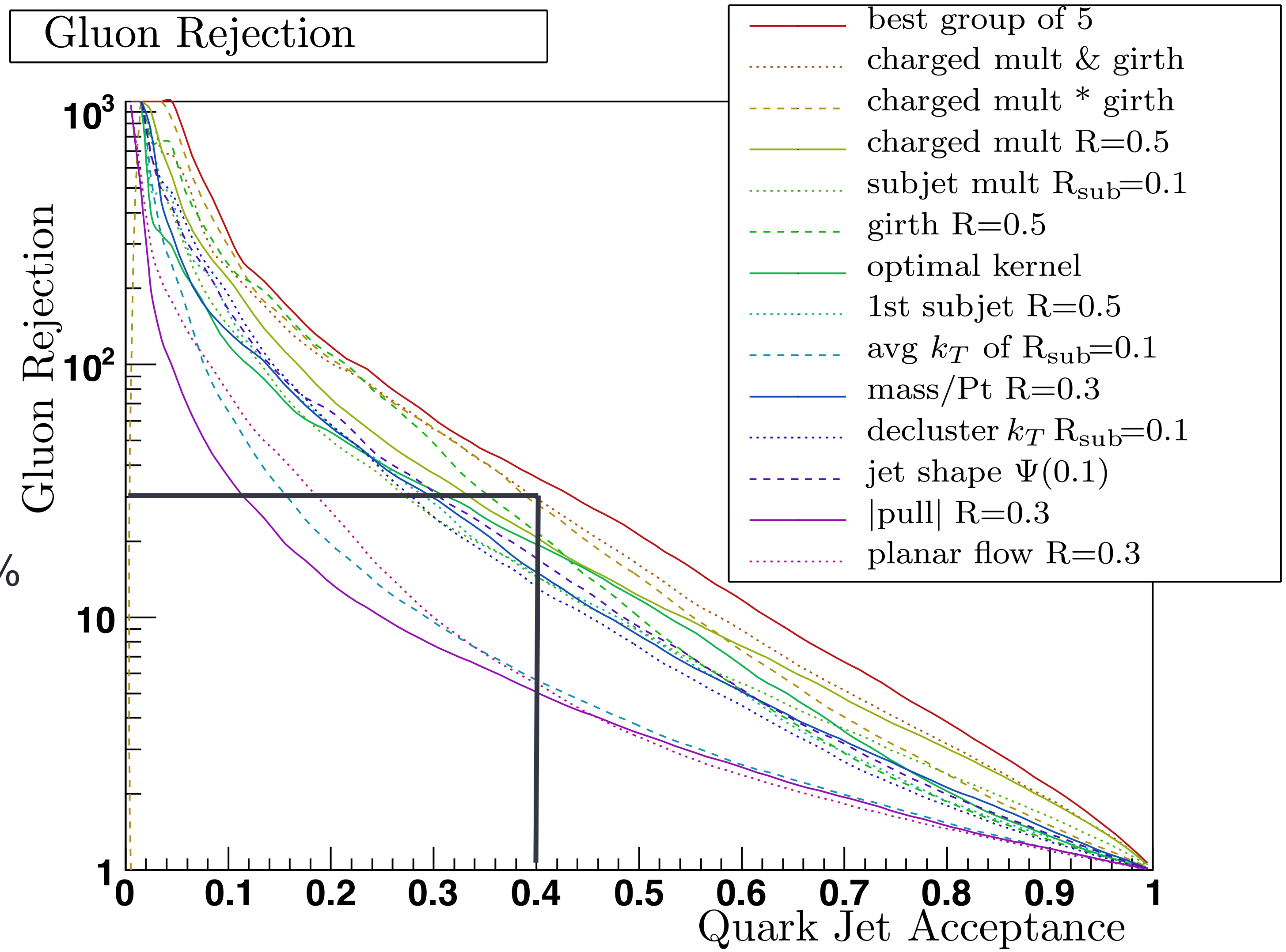


We looked at 10,000 variables

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

Show http://jets.physics.harvard.edu/qvg



1/30 = 3%
gluon

40% quarks

We looked at 10,000 variables

Best 2 were

1 Charged particle count

- Better spatial and energy resolution works better
  - e.g. particles > topoclusters > calorimeter cells > subjets

and

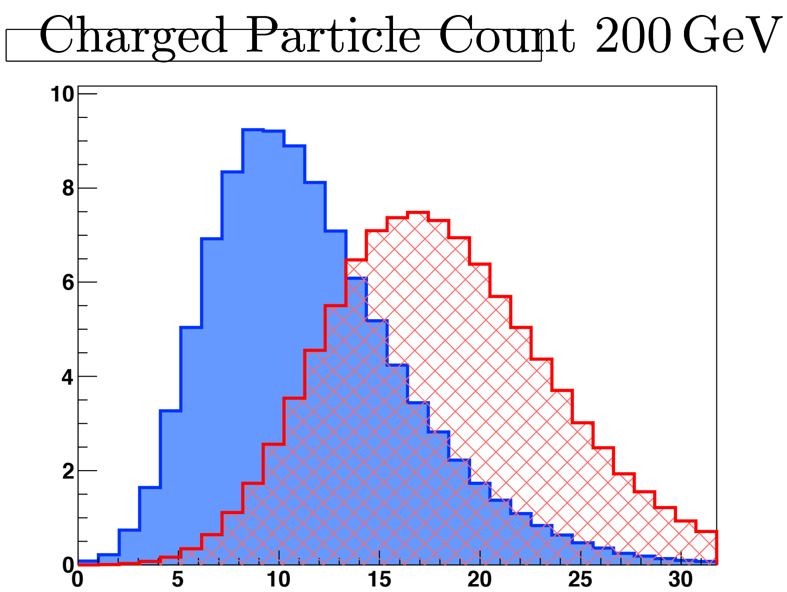
2 Linear radial moment (girth)

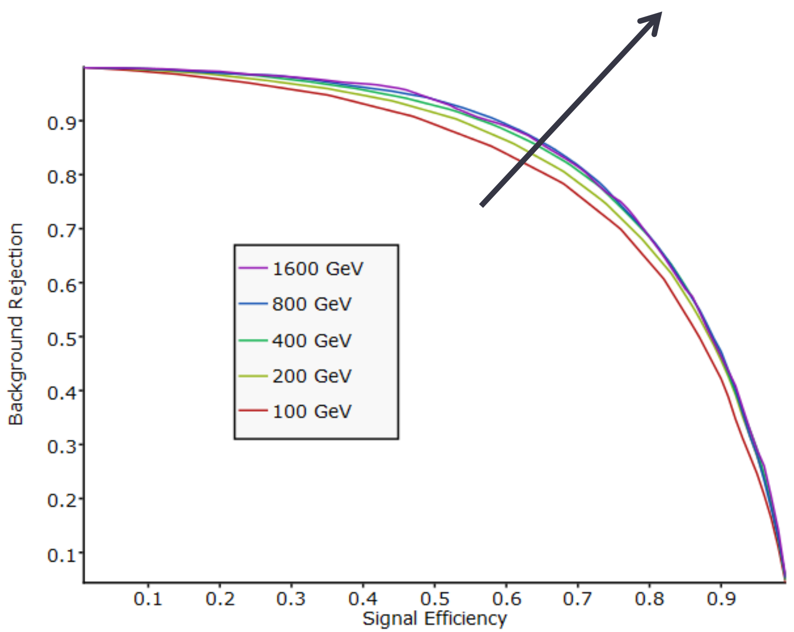
- Similar to jet broadening

Show http://jets.physics.harvard.edu/qvg

Charged Particle Count

Higher p_T



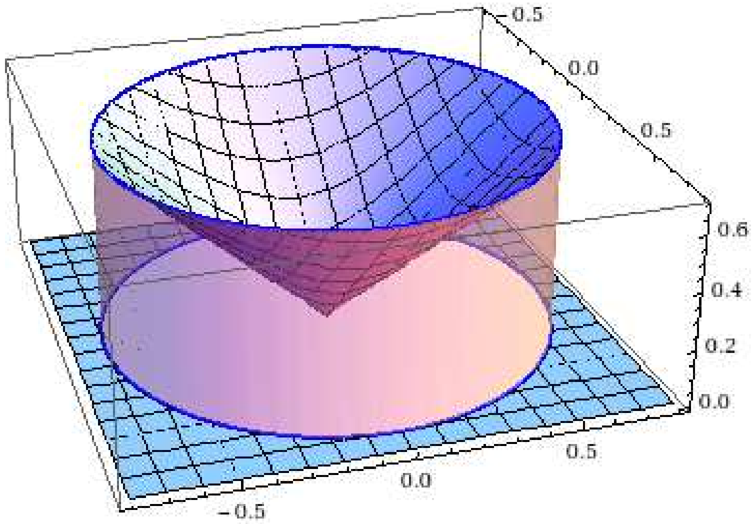


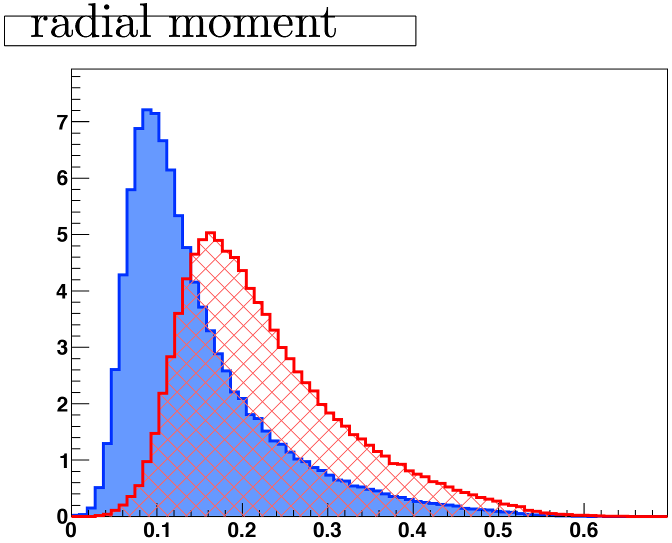
Higher p_T means more tracks and more 'time' to establish C_A/C_F.

Girth

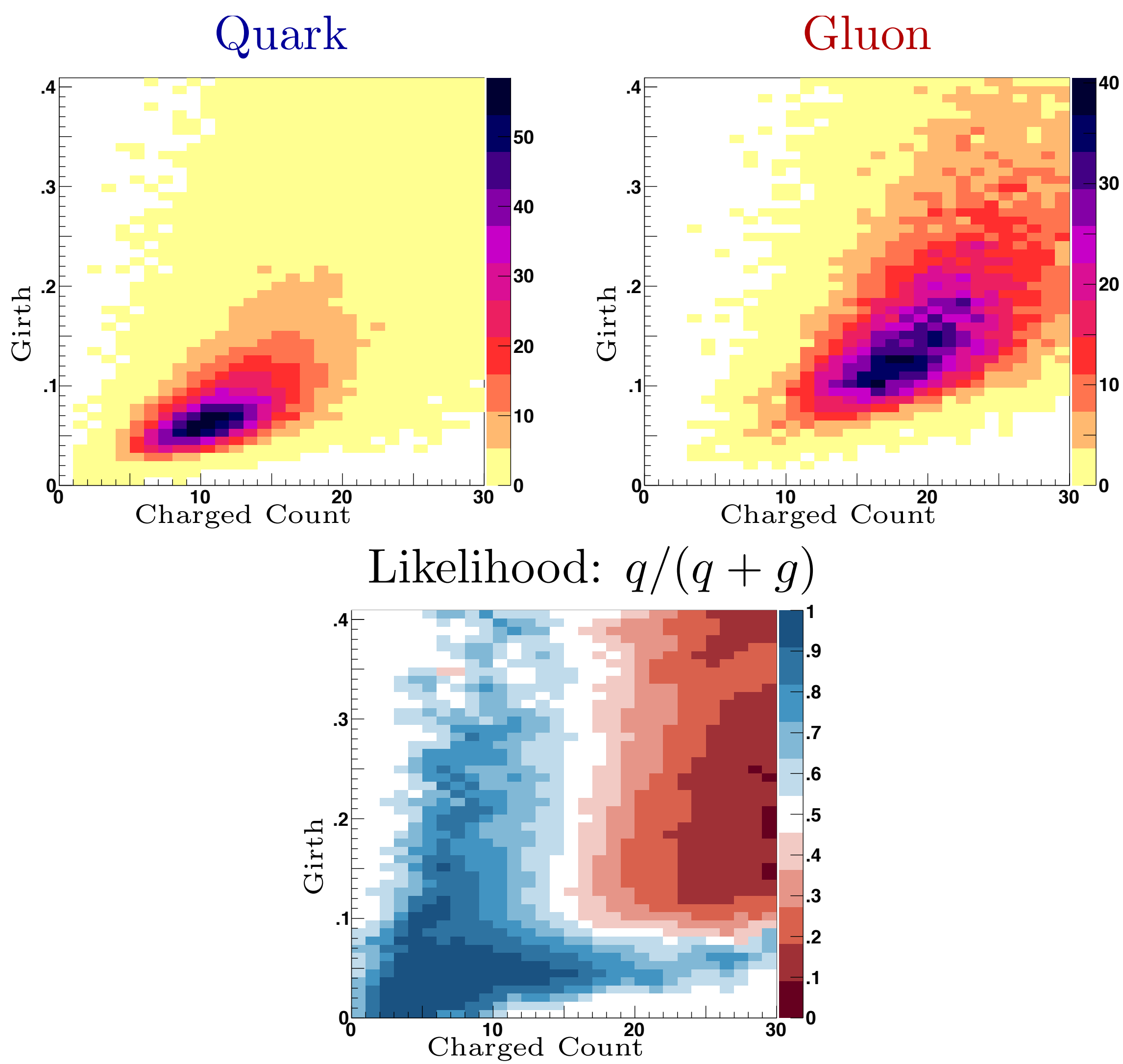
Weight p_T deposits by distance from jet center

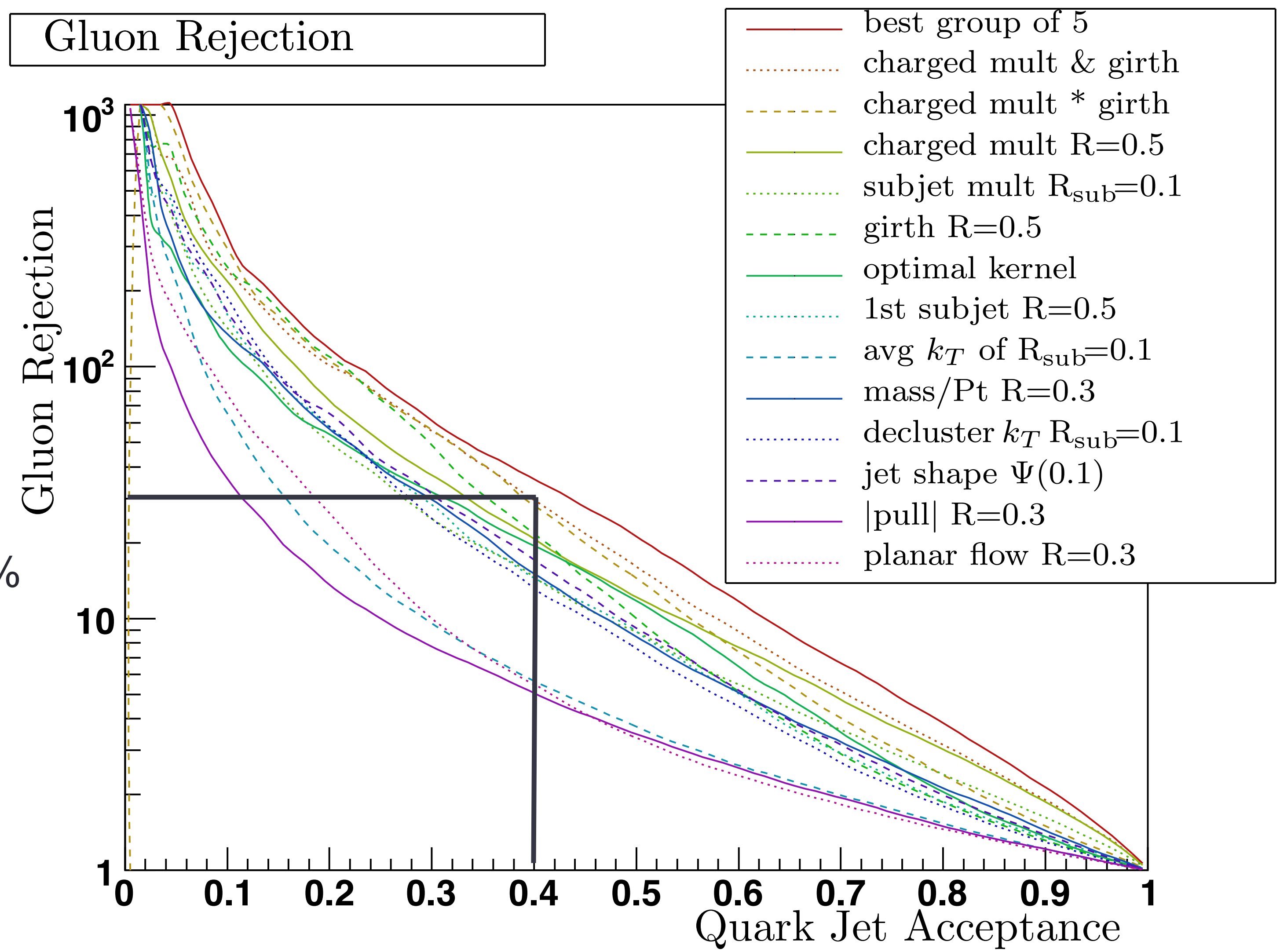
Radial Moment, or Girth : $$g = \frac{1}{p_T^{jet}} \sum_{i \in \mathrm{jet}} p_T^i |r_i|$$





2D distributions show that they are fairly uncorrelated

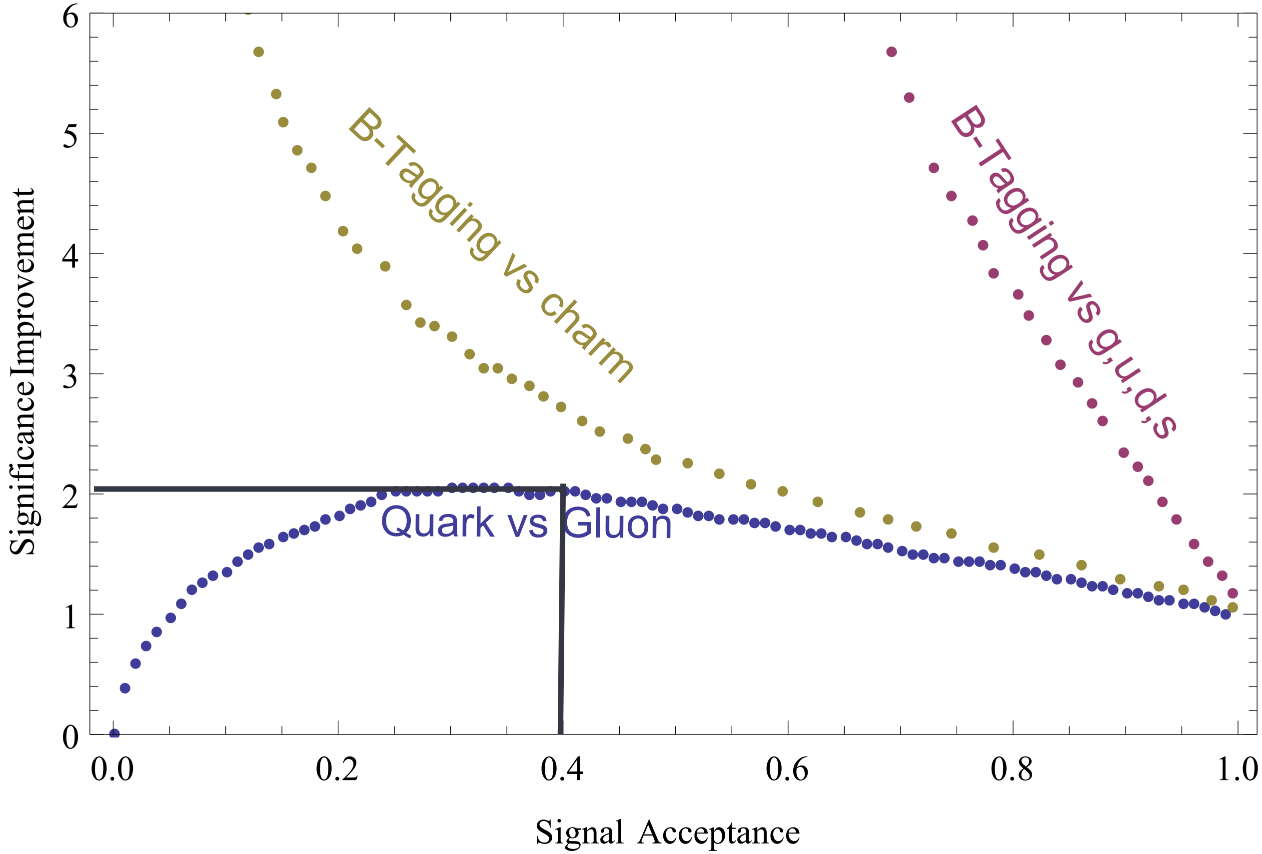




1/30 = 3%
gluon

40% quarks

Result



Significance Improvement of $$\frac{0.4}{\sqrt{1/30}} = 2.19$$

Conclusions

"These are not your daddy's jets" -- Steve Ellis

The **LHC is so great** that we can go **well-beyond the jet-to-parton map**

- Detectors can measure jet **substructure**
- Need to look at substructure to find new physics in huge backgrounds

Beyond the jet-to-parton map

- **Jet charge**
  - Measureable, calculable and useful
- **N-subjettiness**
  - Measureable, calculable and useful as well
- **Quark** jets and **gluon** jets distinguishable: 40% Q vs 3% G
  - Charge particle count and linear radial moment work best
  - Calculable (beyond Pythia)?
- ???

A lot of new data is coming soon (by Boost 2012 hopefully)