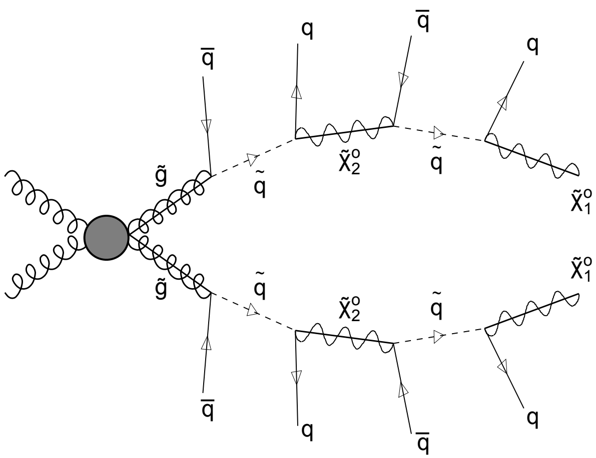
JET QUANTUM NUMBERS

Using Jet Substructure Workshop
April 24, 2013

Matthew Schwartz
Harvard University

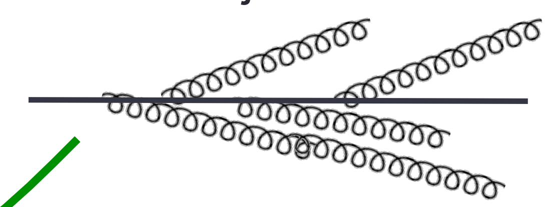
What is a jet?

Energetic quarks and gluons produced



Parton shower

Quarks and gluons "shower" to form jets



Jet algorithms: reconstruct parton momenta

As of 2007: **jet=parton**

Jets are not just 4-momenta!

- Jets have **substructure**
  - Hard subjets
  - Jet shapes
- Jets have **quantum numbers**
  - Flavor (up/down/strange/charm/bottom)
  - Electric charge $-\frac{2}{3}, -\frac{1}{3}, 0, \frac{1}{3}, \frac{2}{3}$
  - Color charge (quark or gluon)
  - Spin?
- Jets have **superstructure**
  - Color connections between jets
- Jets are **not partons**

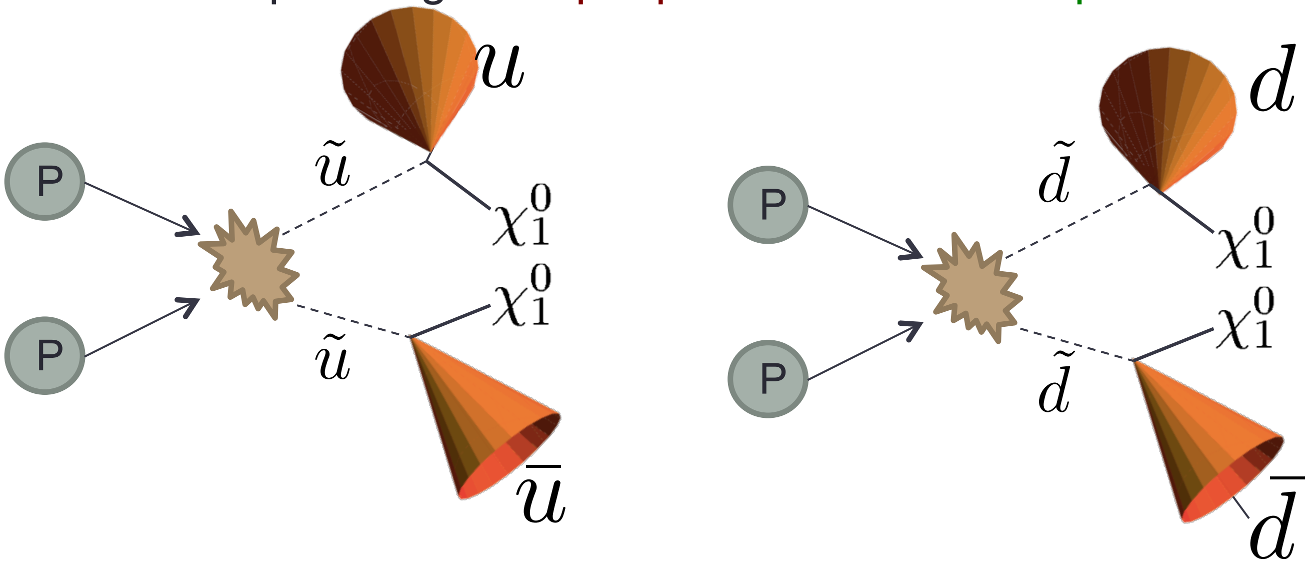
My talk today

ELECTRIC 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

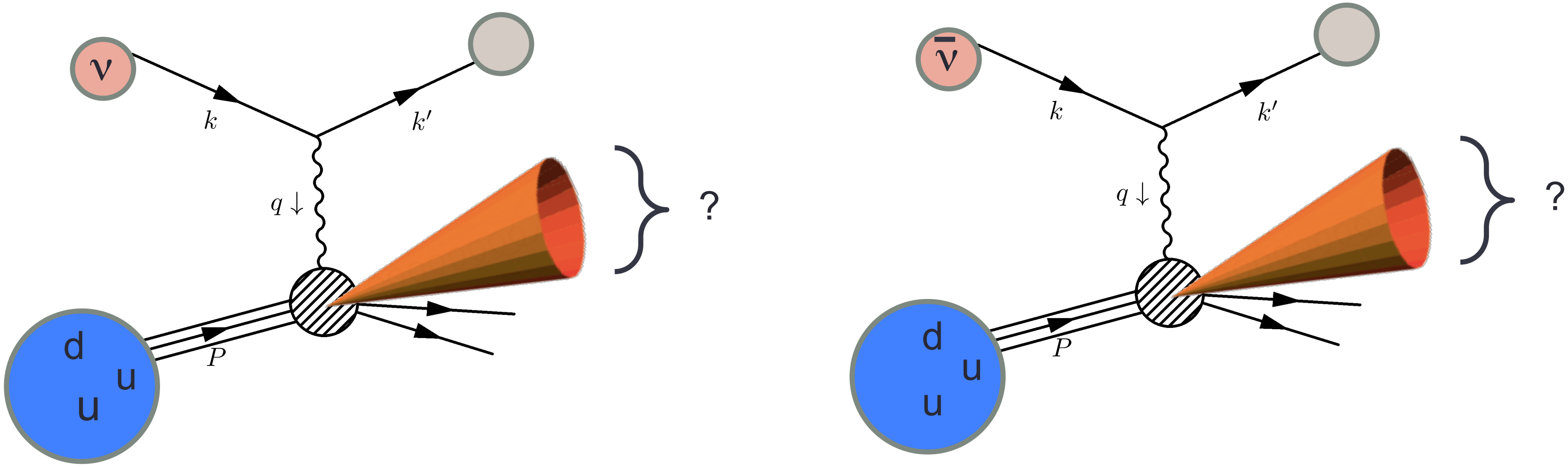


- **W prime** vs **Z prime**

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

Long history…

- Late 1970s: do quarks exist?
- Deep-inelastic neutrino-proton or anti-neutrino-proton scattering



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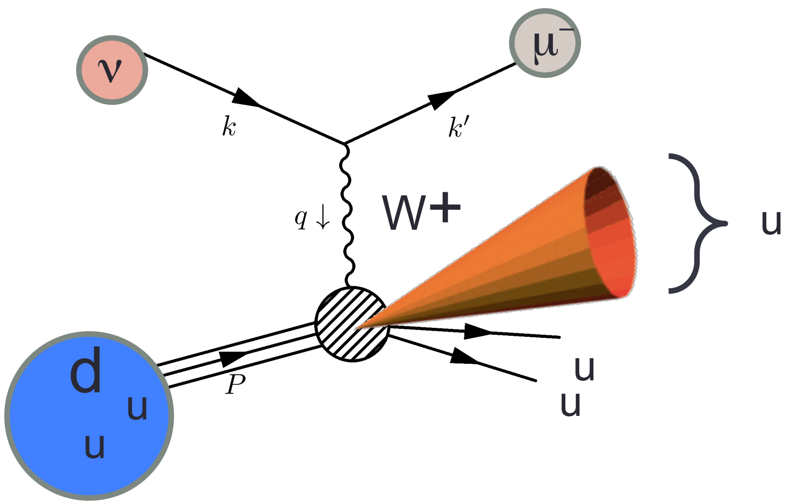
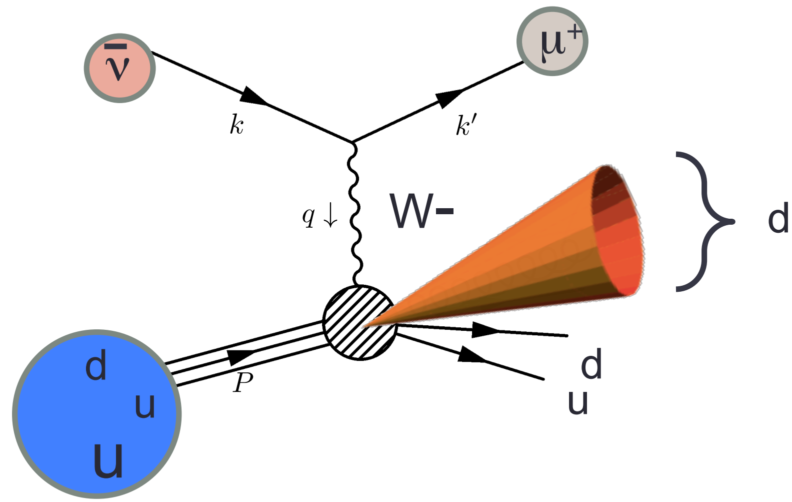




- Charge of jet is unambiguous

Long history…

Measured the energy-weighted **jet charge**:

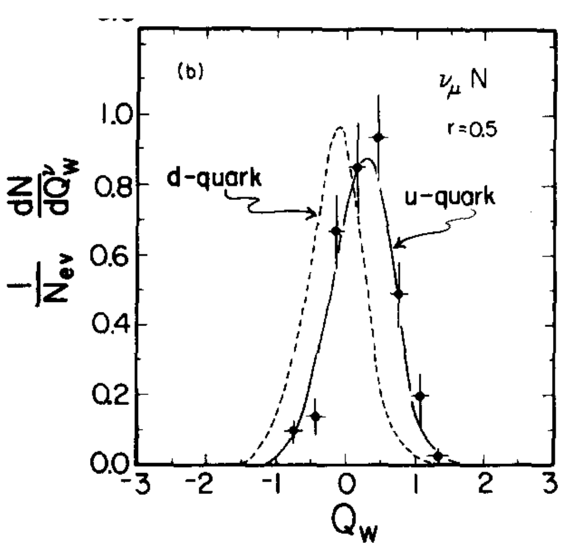
$$Q_\kappa^i = \frac{1}{E_{\text{jet}}} \sum_{j \in \text{jet}} Q_j (E_j)^\kappa$$

$1 \ll \kappa$ would include beam remnants

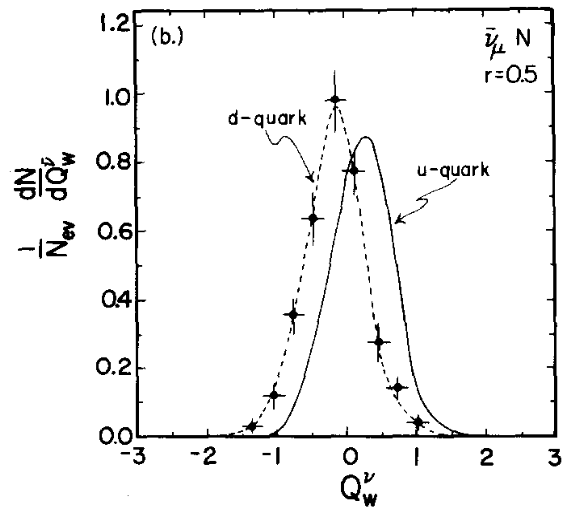
$1 \lesssim \kappa$ would let one particle dominate

- Suggested by Feynman and Field (1977)
- Early calculations in parton model (no QCD!)

Fermilab Data (1980)



neutrino ➔ up quark jet



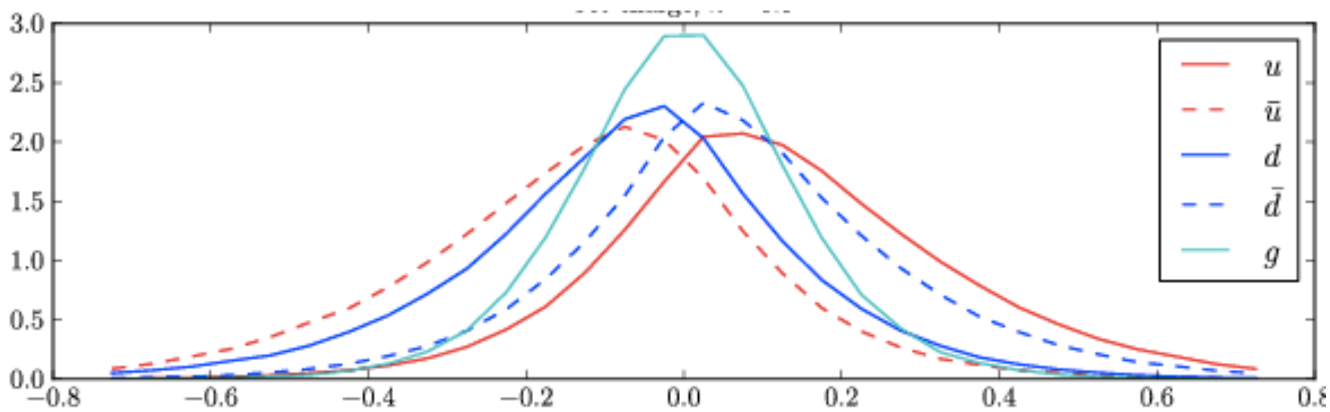
anti-neutrino ➔ down quark jet

Distinguishing charge $-\frac{2}{3}, -\frac{1}{3}, 0, \frac{1}{3}, \frac{2}{3}$

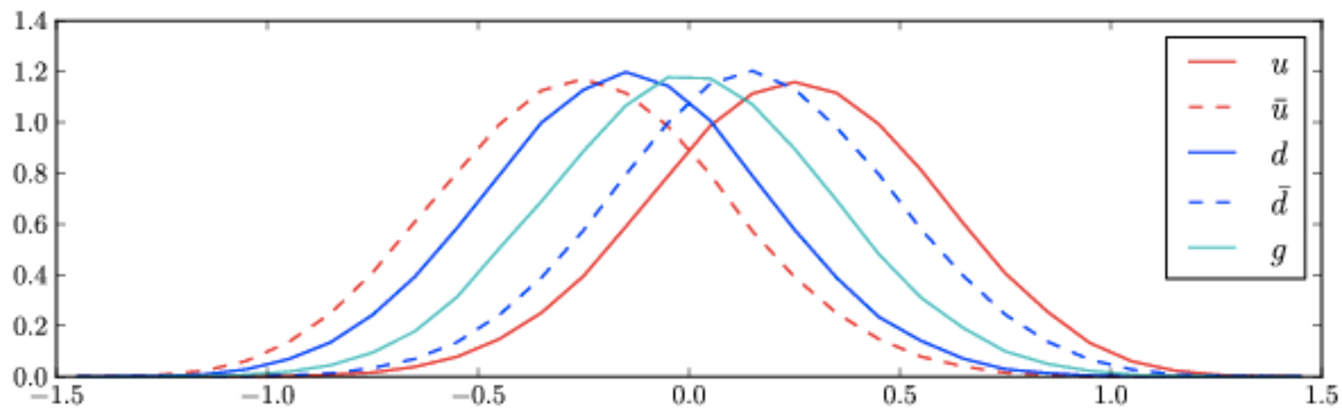
Krohn, Lin, MDS, Waalewijn
arXiv:1209.2421

Measure the p_T-weighted **jet charge**:

$$Q_\kappa^i = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{j \in \text{jet}} Q_j (p_T^j)^\kappa$$



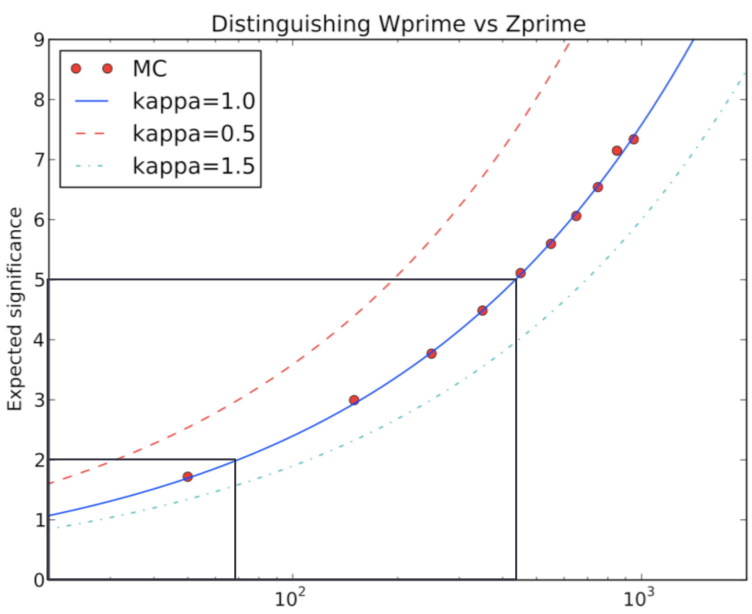
κ=1

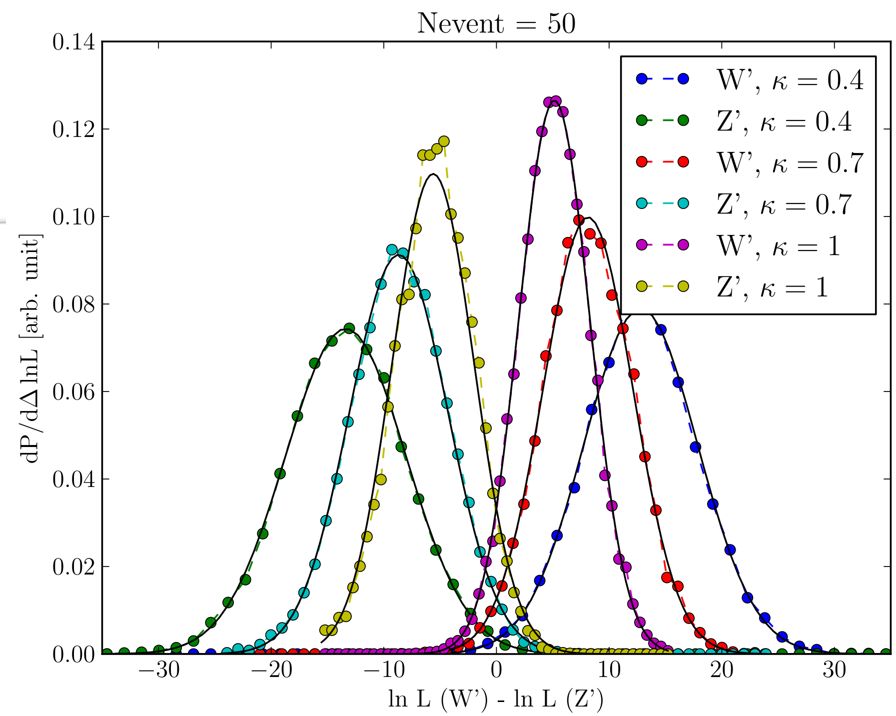


κ=0.5

Distinguishes W' from Z'

Log-likelihood distribution for 1 TeV resonance, various κ

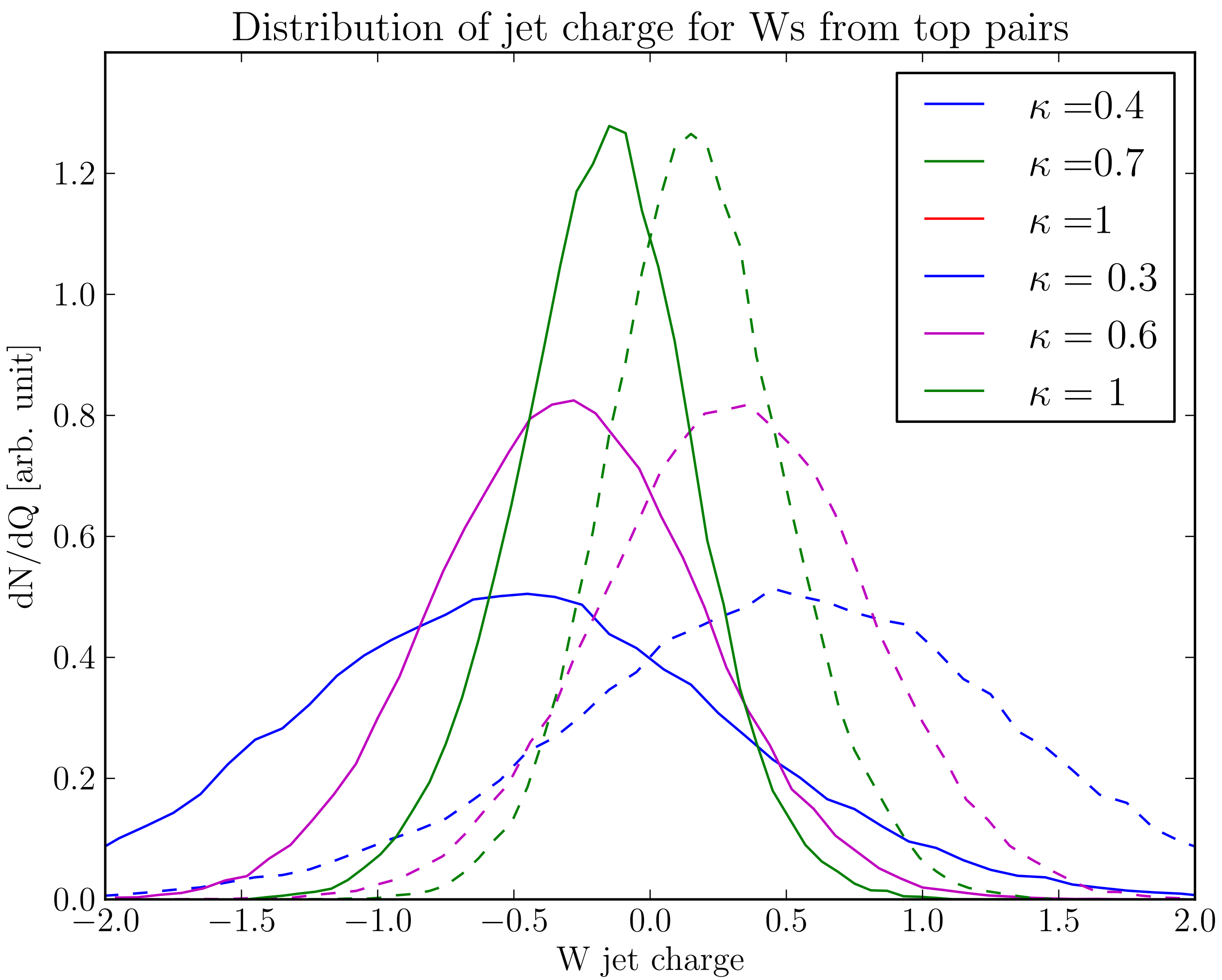




2σ with 30 events
5σ with 200 events

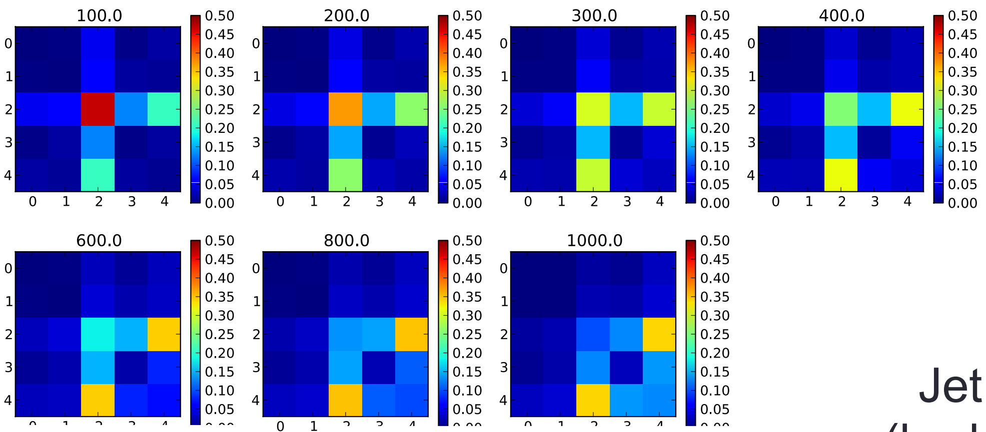
Calibrate with hadronic W's from tops

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

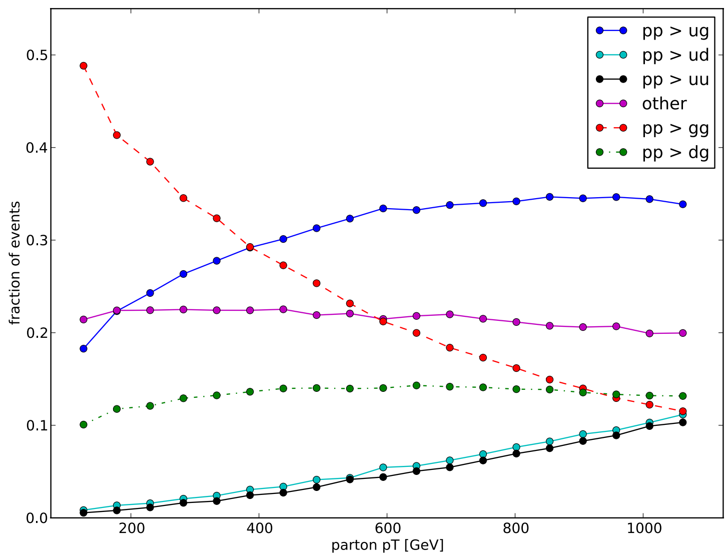


Dijets are good for something!

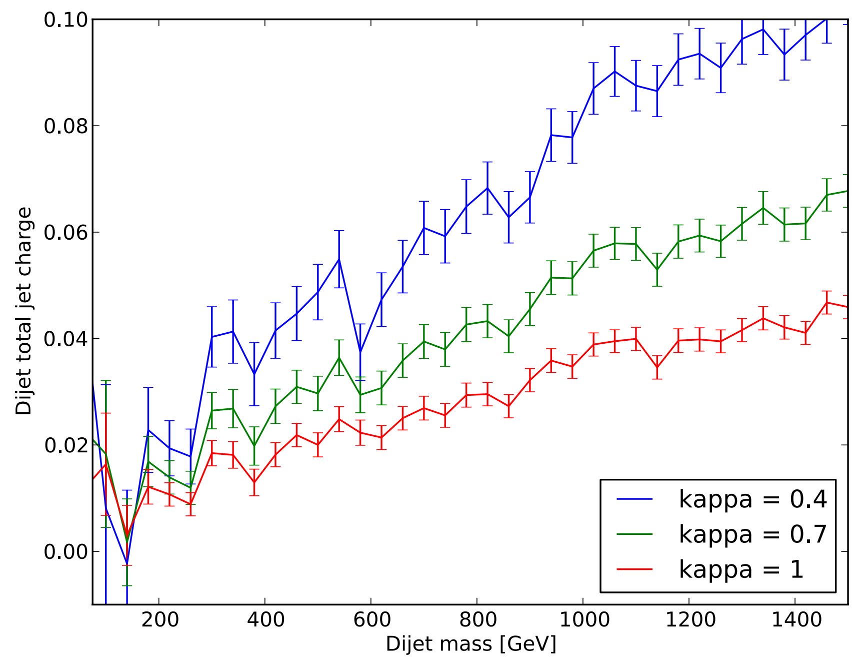
2D charges (parton level) for different pT



Fractions (parton level)



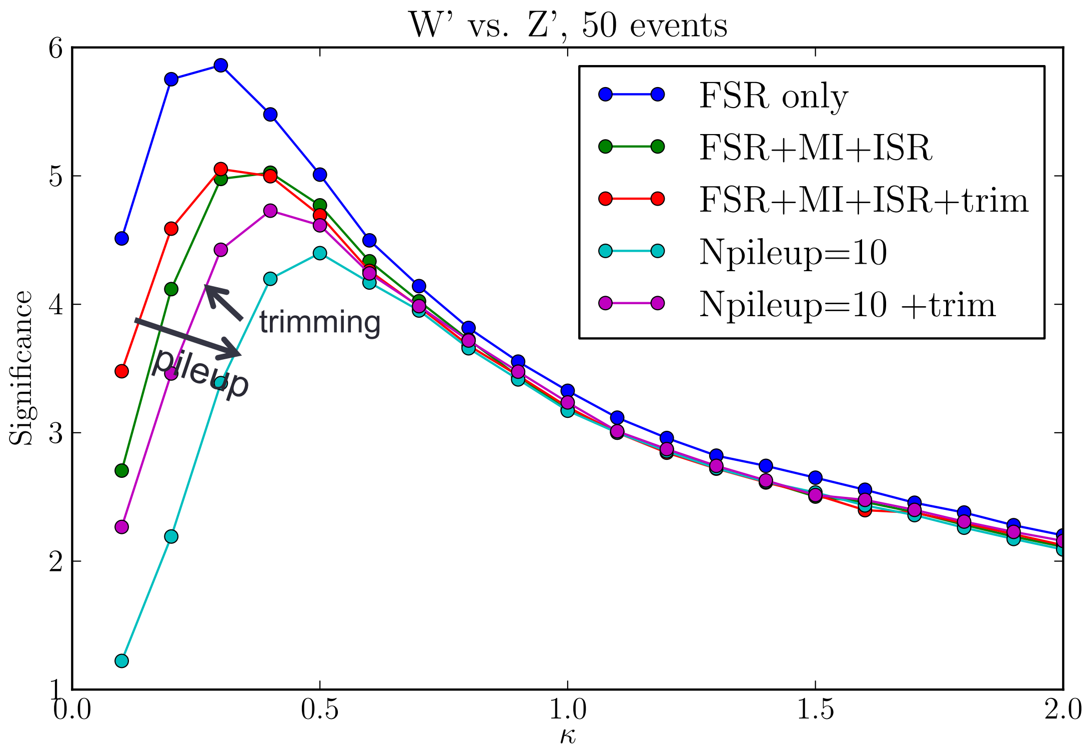
Jet charge (hadron level)



Contamination

Effect of multiple interactions/pileup not bad

- Tracks from primary interaction vertex part of motivation
- Could be extremely useful tool at high luminosity



Mean at width are calculable

$D_q^h(x,\mu)$ **Fragmentation function**

- Probability that parton q fragments to hadron h with energy fraction x

$$E_{\text{hadron}} = x E_{\text{parton}}$$

- Nonperturbative objects with perturbative evolution equations

Moments of fragmentation functions

$$\widetilde{D}_q^h(\nu,\mu) = \int_0^1 \mathrm{d}x\, x^\nu D_q^h(x,\mu)\,,$$

(prob. that emission is within jet)

Splitting functions within jet

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

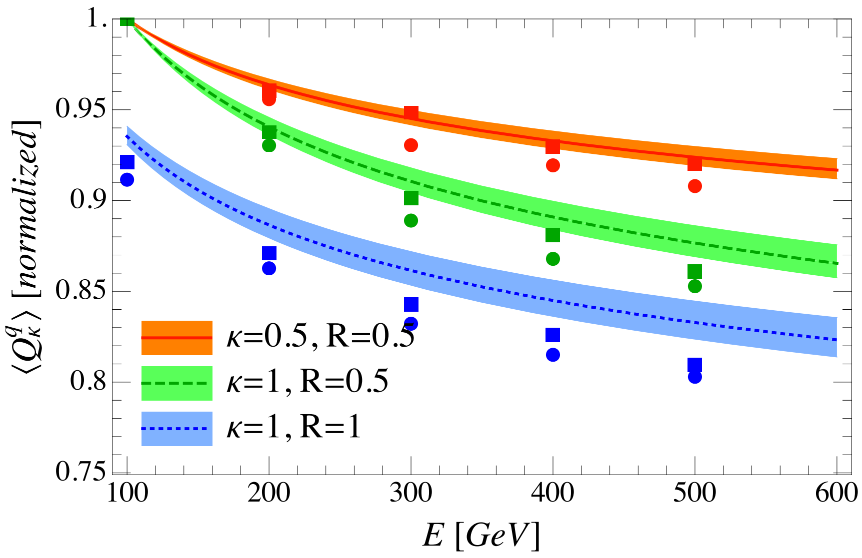
$$\langle \mathcal{Q}_\kappa^q \rangle = \frac{1}{16\pi^3} \frac{\widetilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{\mathcal{J}_q(E,R,\mu)} \sum_h Q_h \widetilde{D}_q^h(\kappa,\mu)$$

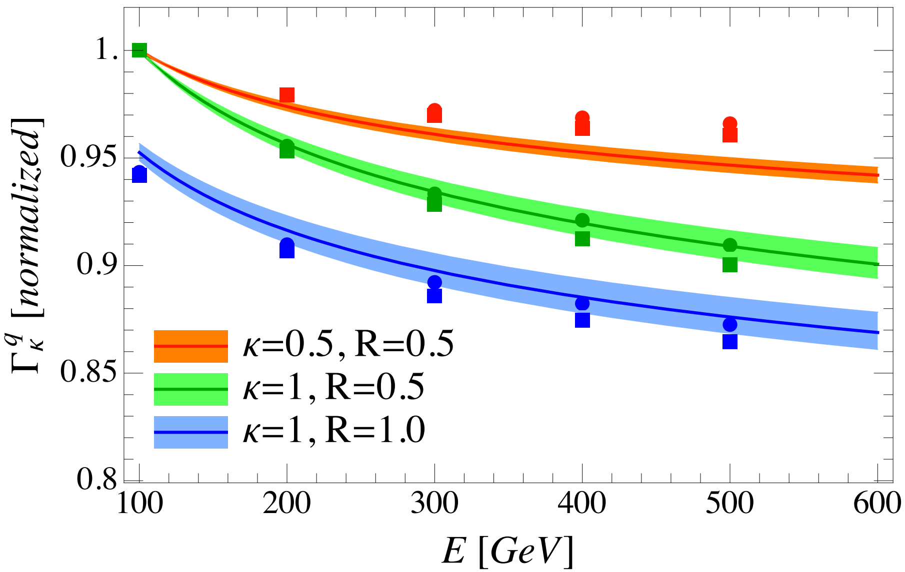
Jet function

Calculable

(Prob. of getting jet with E and R)

Mean and width evolution are calculable





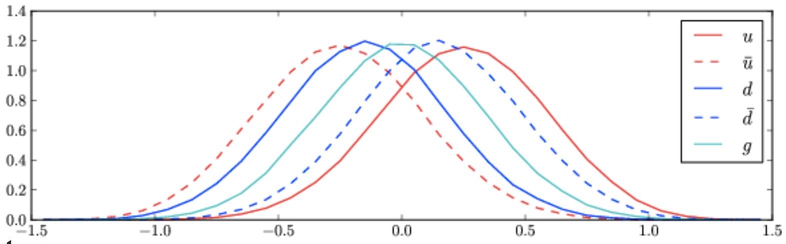
Krohn, Lin, MDS, Waalewijn
PRL (to appear)

- Moments of charge distribution
  calculable from moments of fragmentation functions

- **Evolution** of these moments tests **precision QCD**

Jet Charge Summary

- p_T weighted jet charge remarkably **useful** at LHC



- Uses **only tracks**
  - Insensitive to pileup
  - Can be used at high luminosity
- Most information in **average** and **width**

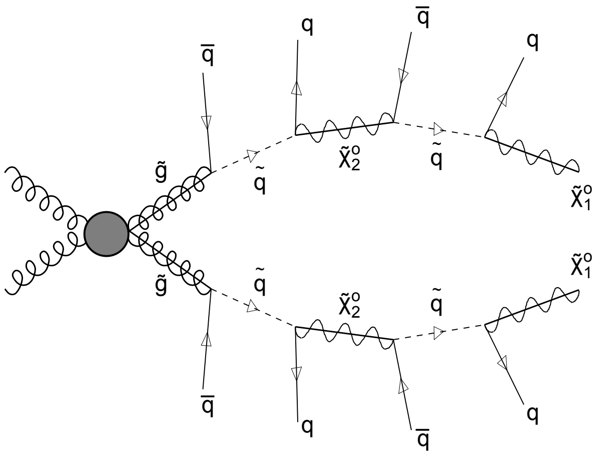
$$\langle \mathcal{Q}_\kappa^q \rangle \qquad (\Gamma_\kappa^i)^2 = \langle \mathcal{Q}_\kappa^i \rangle^2 - \langle (\mathcal{Q}_\kappa^i)^2 \rangle$$

- Can be **tested** on W jets from top decays
- Can be **tested** on dijets
  - Quark/Gluon/Flavor content measurable (statistically)
  - Compare Pythia and Herwig
  - Compare evolution to precision QCD

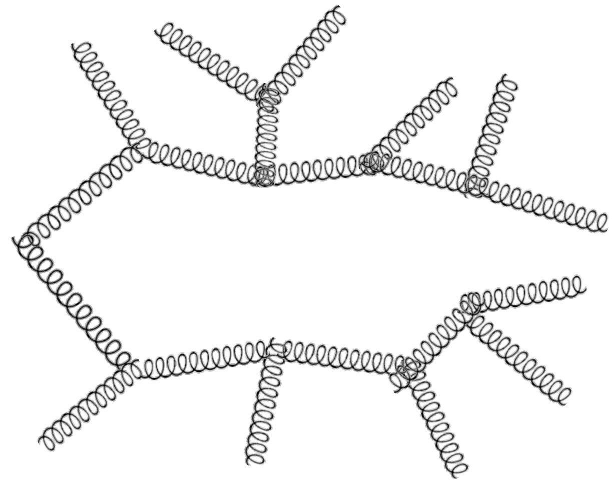
QUARKS VS GLUONS

QCD charge: quark or gluon

New physics mostly **quark jets**



Backgrounds mostly **gluon jets**



- Low level quark and gluon differences already used in
  - b-tagging
  - Jet calibration
- Is it possible to distinguish **quarks** from **gluons** on an **event-by-event basis**?

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. Using monte carlo, **how can we distinguish Q from G**?

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

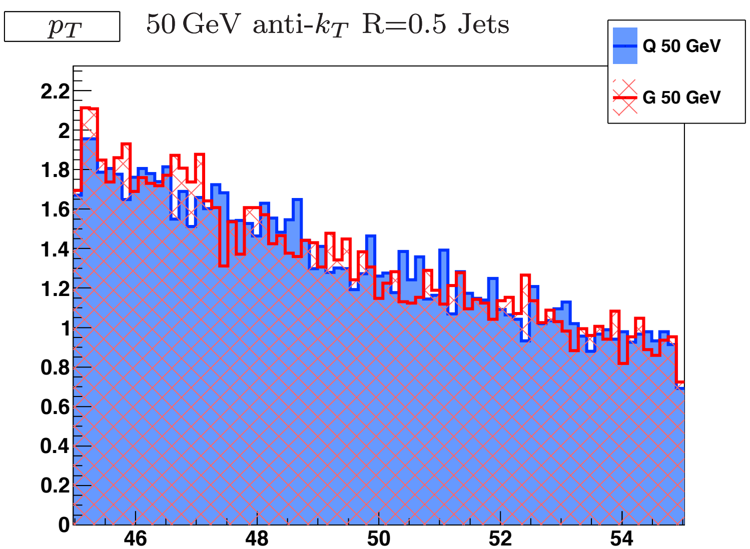
   Gallichio and MDS JHEP (to appear)

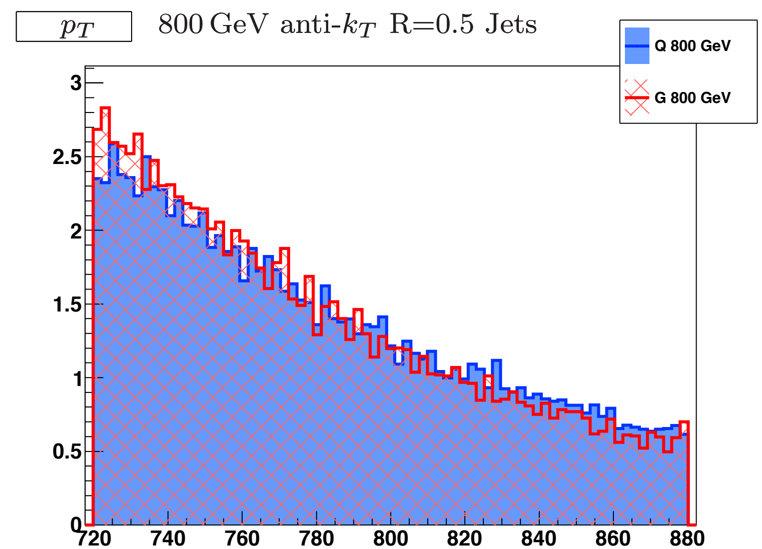
2. How can we **validate on data**?
   - Where do we find pure samples of quark and gluon jets?

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

Generating samples is delicate

- Quarks and gluons with similar pT at parton level
  -> quark jets with larger pT (on average)
- Start with samples with 20% window, with quarks slightly higher
- Keep only samples within 10% of nominal jet pT





Decouples pT from jet properties

We looked at 10,000 variables

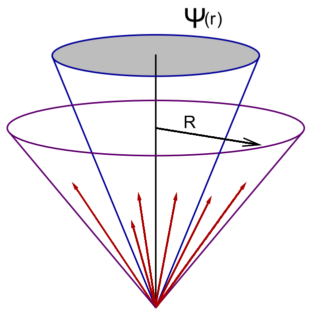
The menu, including varying jet size

- 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

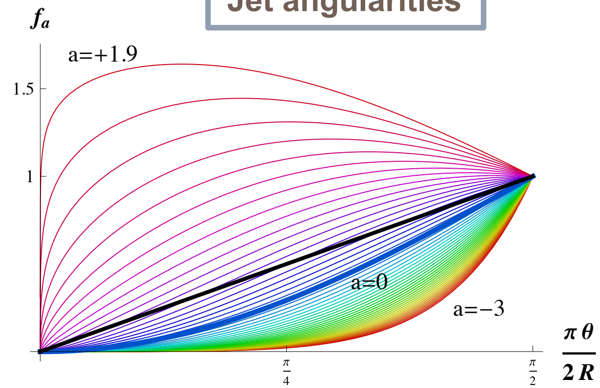
Show http://jets.physics.harvard.edu/qvg

Quark and gluon jet substructure

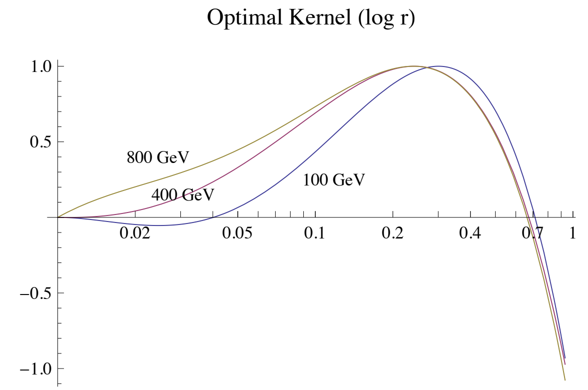
Integrated/differential "Jet Shape"



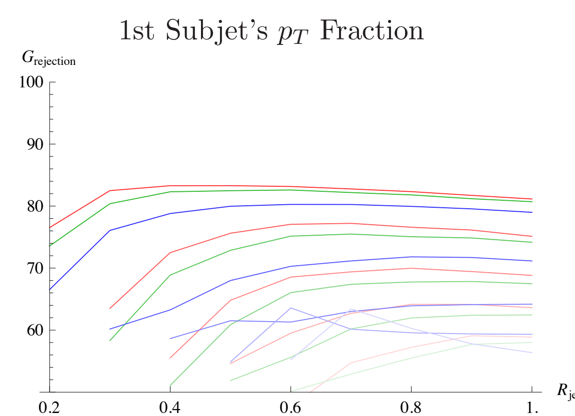
Jet angularities



Iteratively optimized radial profile

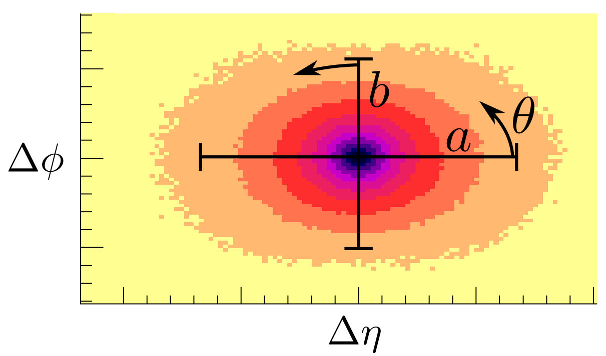


Subjet counts and properties



Properties of Covariance tensor

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

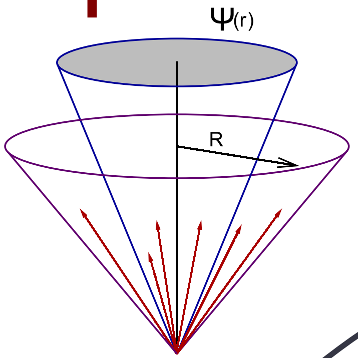


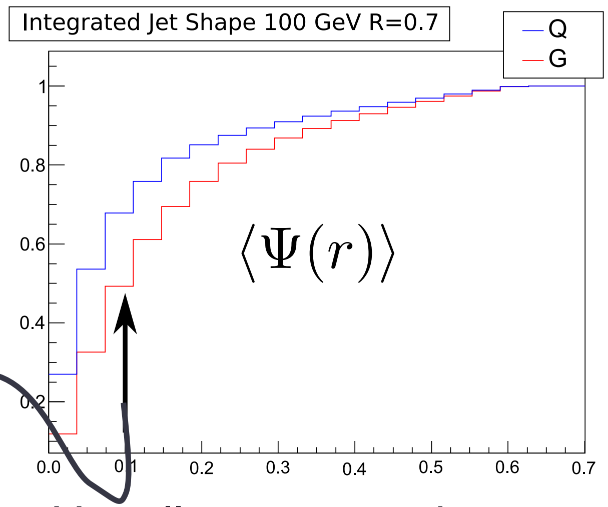
Combination of Eigenvalues

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

Integrated jet shape

$$\Psi(r) = \int_0^r \frac{p_T(r')}{p_T^{jet}} dr' \ .$$

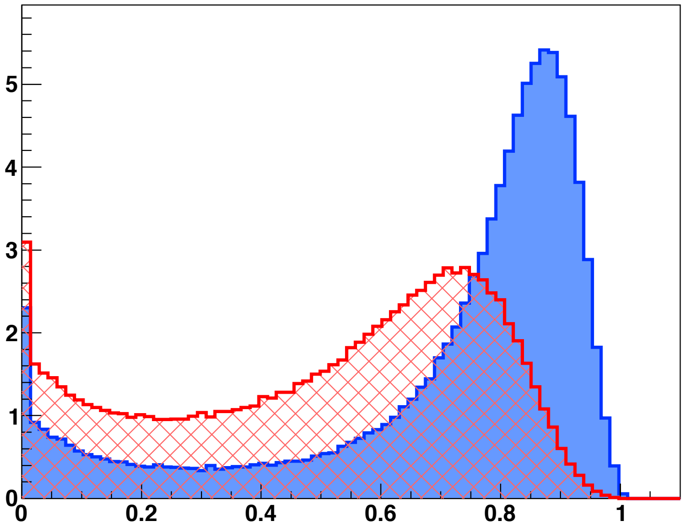




- distribution for each r

Usually measure the average

Distributions for r=0.1



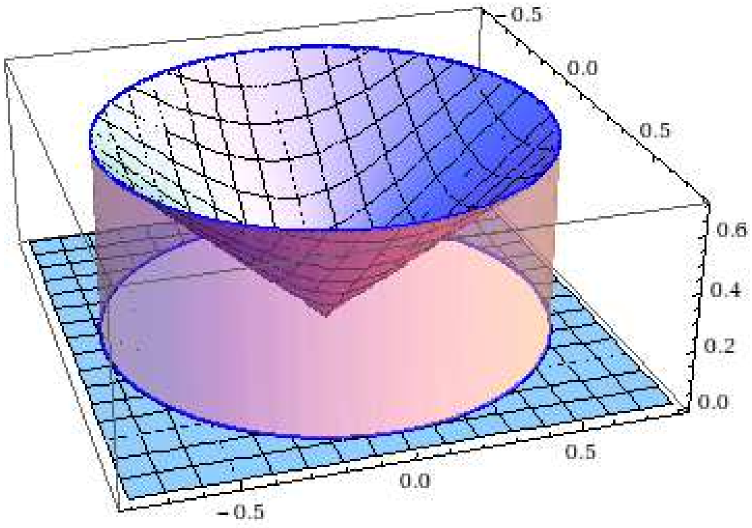
Much more information in the distributions:

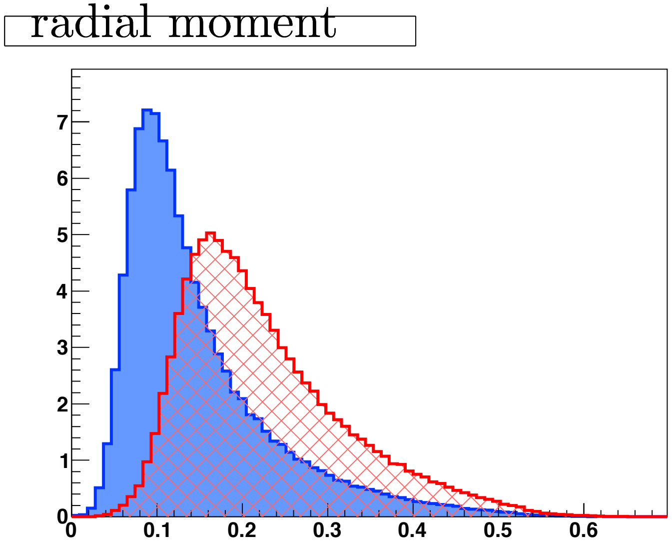
- *Don't just measure the average*

Girth

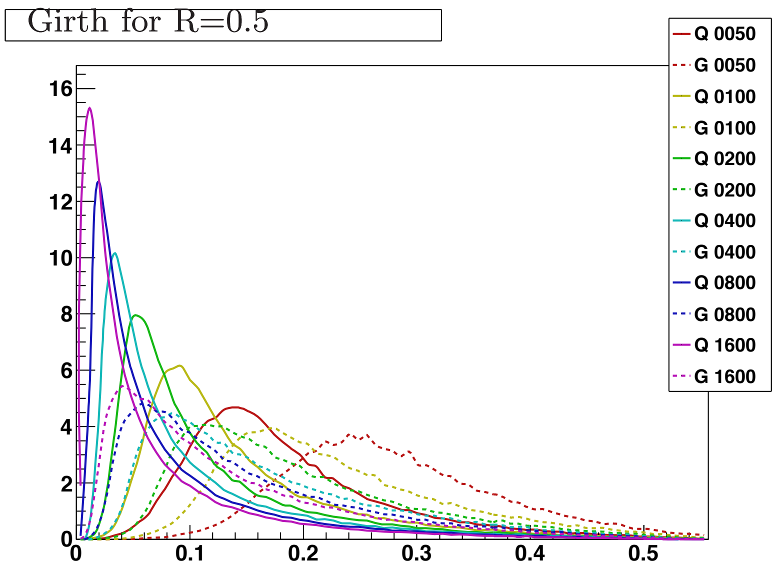
Weight p_T deposits by distance from jet center

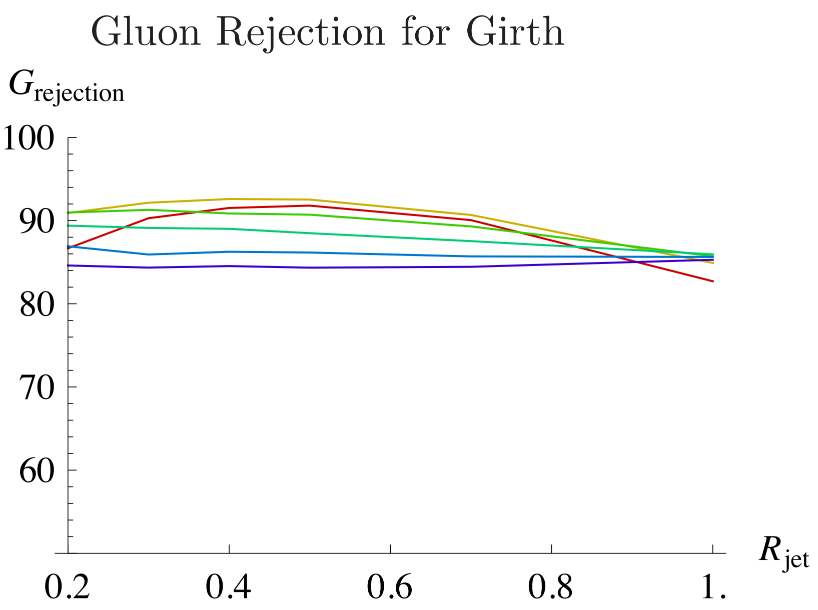
Radial Moment, or Girth : $$g = \frac{1}{p_T^{jet}} \sum_{i \in \text{jet}} p_T^i |r_i|$$



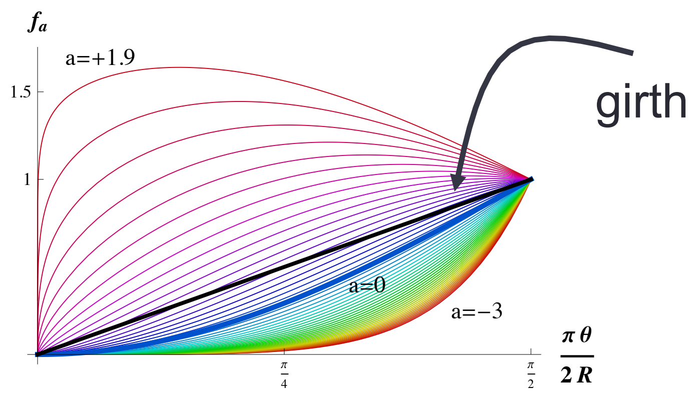


Girth


Girth for R=0.5
Q 0050
G 0050
Q 0100
G 0100
Q 0200
G 0200
Q 0400
G 0400
Q 0800
G 0800
Q 1600
G 1600
0
2
4
6
8
10
12
14
16
0.1
0.2
0.3
0.4
0.5


Gluon Rejection for Girth
$G_{\text{rejection}}$
100
90
80
70
60
0.2
0.4
0.6
0.8
1.
R_{jet}

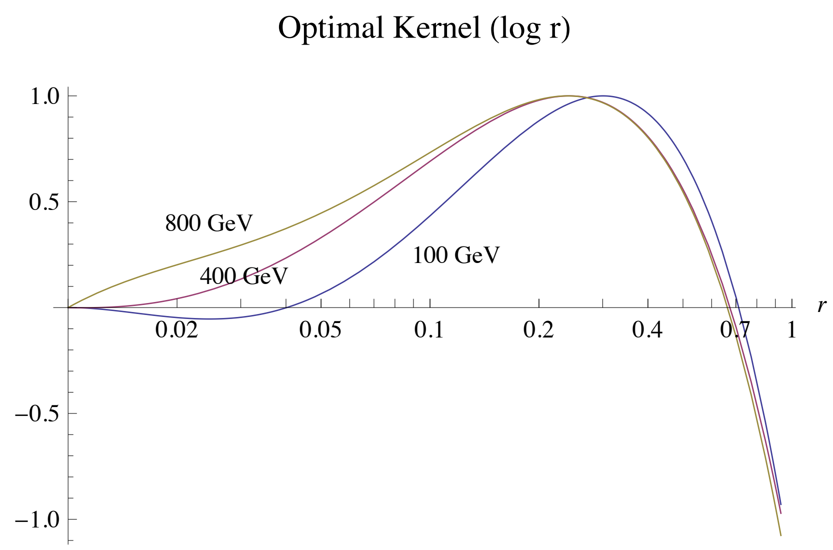
Angularities

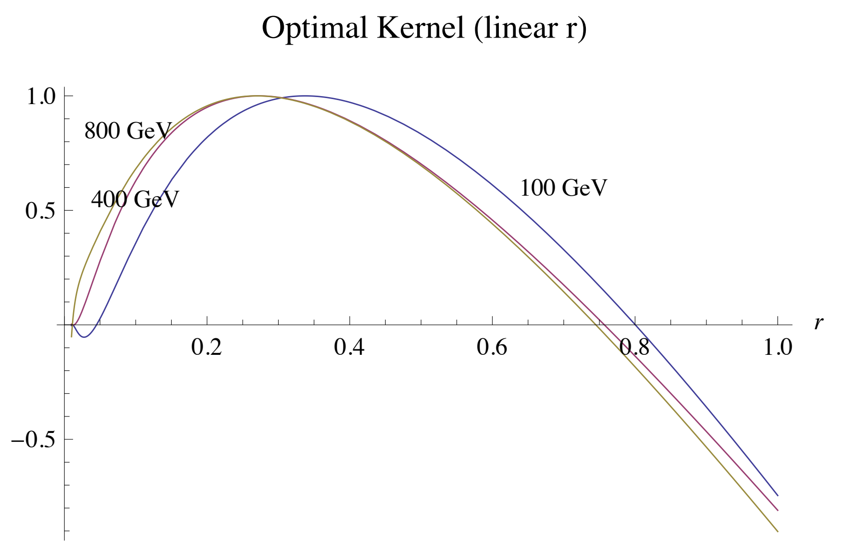


Any radial weighting
Is a jet shape

Most general jet shape

Optimize the shape with a spline; nodes determined by simulated annealing



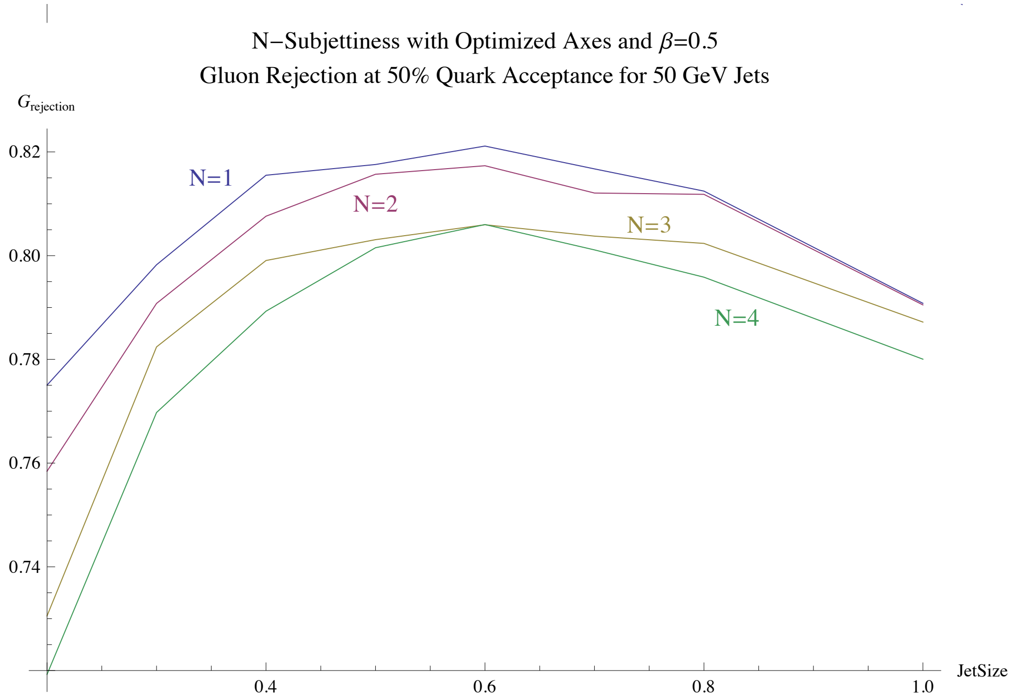


All shapes work about the same – just use girth

N-subjettiness

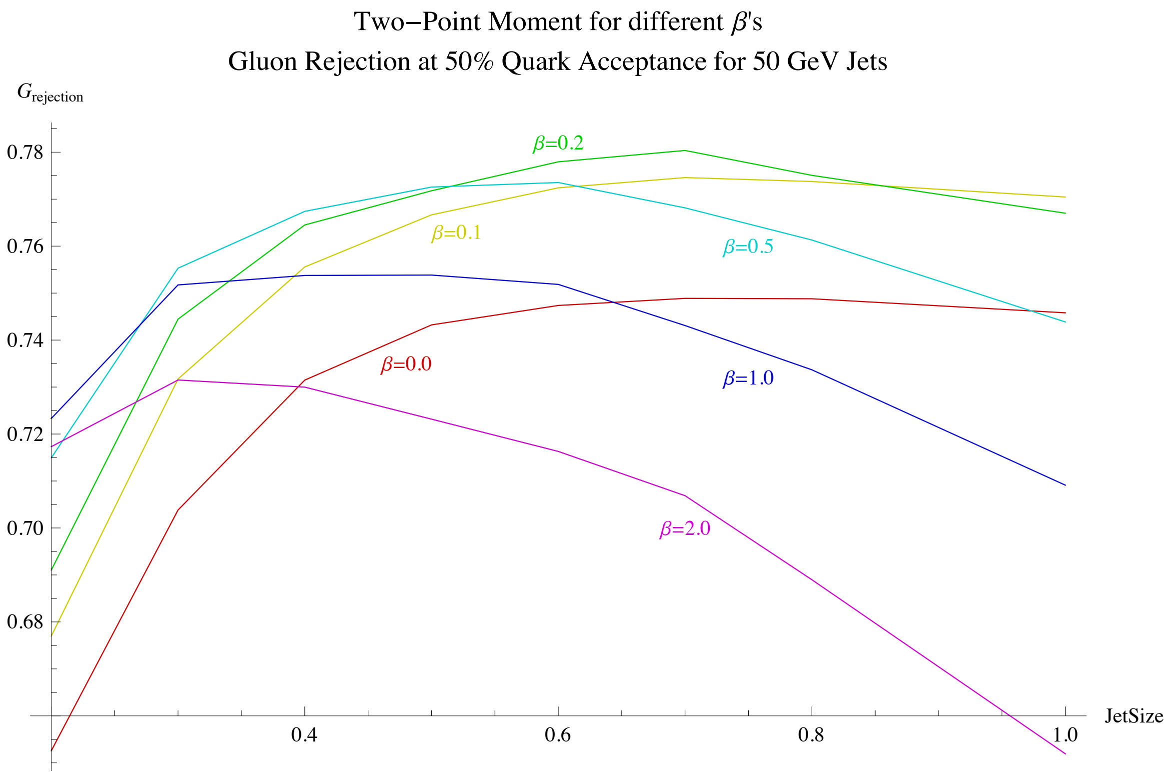
- 1,2 and 3-subjettiness comparable
- Highly correlated, and differences within errors
- $\beta \sim \frac{1}{2}$ works slightly better

$$\tau_{N,\beta} = \frac{1}{d_0} \sum_{J=0}^{N} \sum_{k \in \mathrm{subjet}_J} p_{T,k} \left(\Delta R_{J,k}\right)^{\beta} ,$$



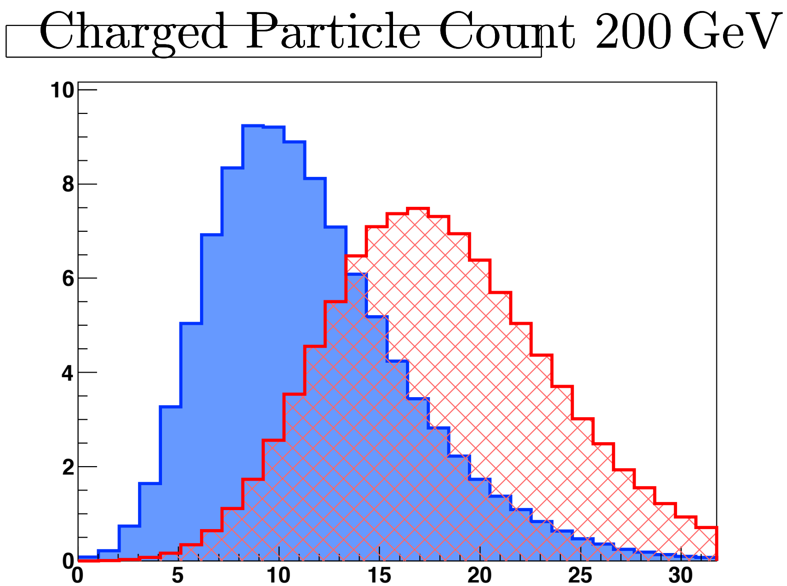
2-point moment

$$T_\beta = \frac{1}{(p_T^{\text{jet}})^2} \sum_{i\in\text{jet}} \sum_{j\in\text{jet}} p_T^i\, p_T^j\, \Delta R^\beta$$

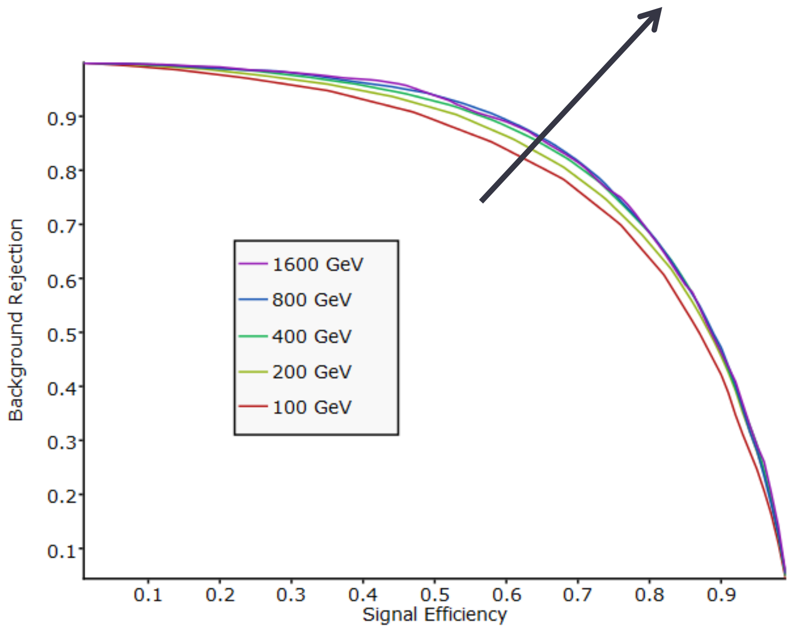


- Comparable to best variables (Girth/n-subjettiness)
- Fairly uncorrelated with count variables

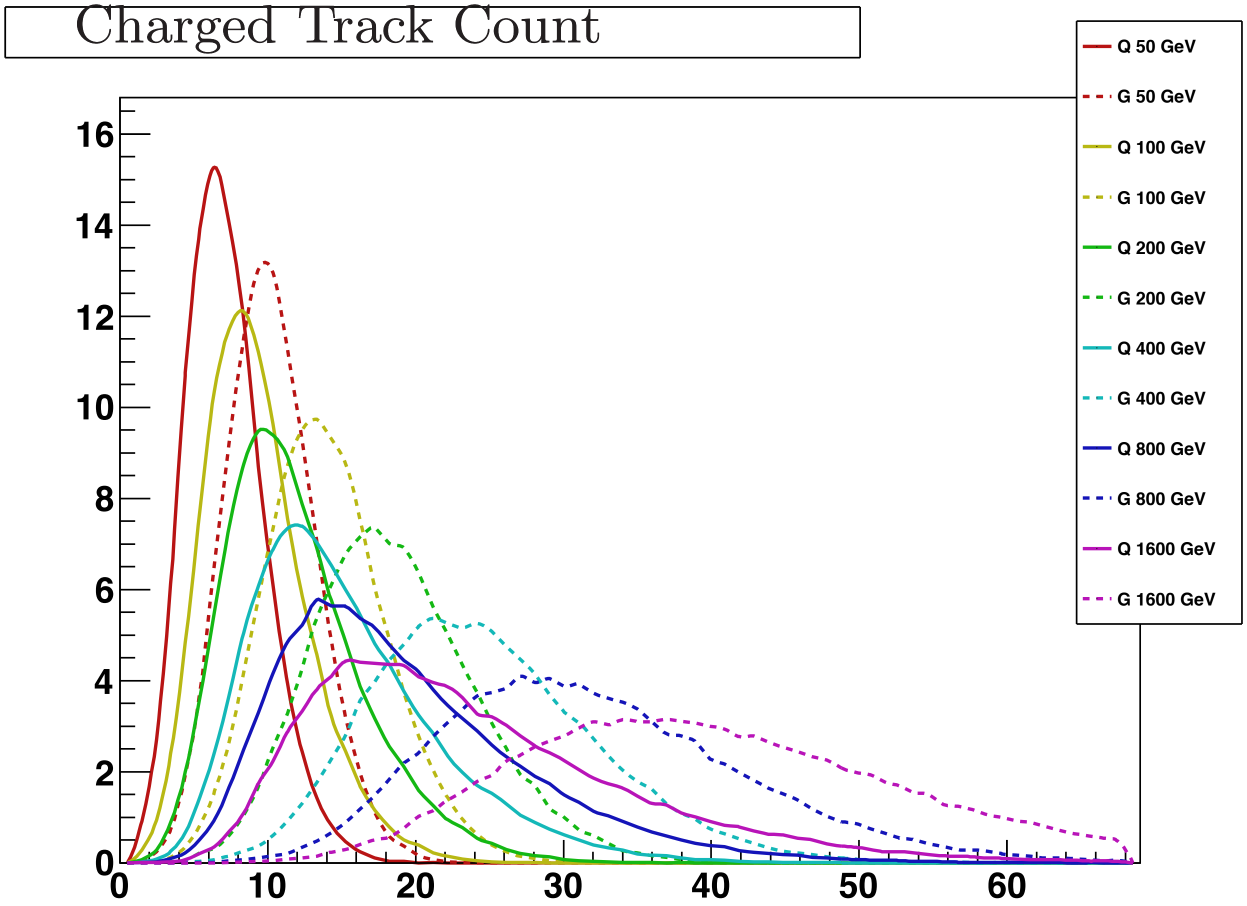
Charged Particle Count



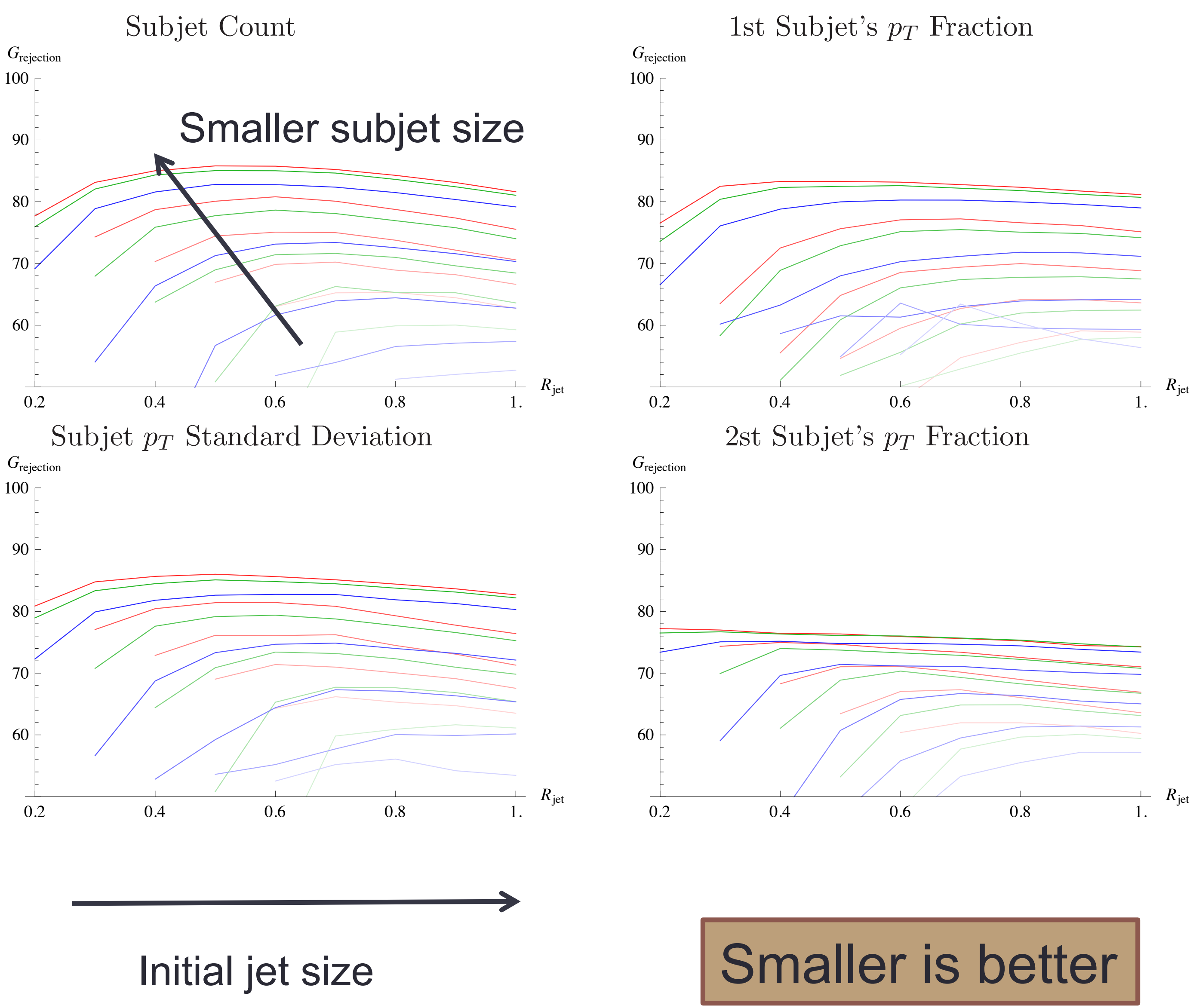
Higher p_T



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


Charged Track Count
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
Q 50 GeV
G 50 GeV
Q 100 GeV
G 100 GeV
Q 200 GeV
G 200 GeV
Q 400 GeV
G 400 GeV
Q 800 GeV
G 800 GeV
Q 1600 GeV
G 1600 GeV

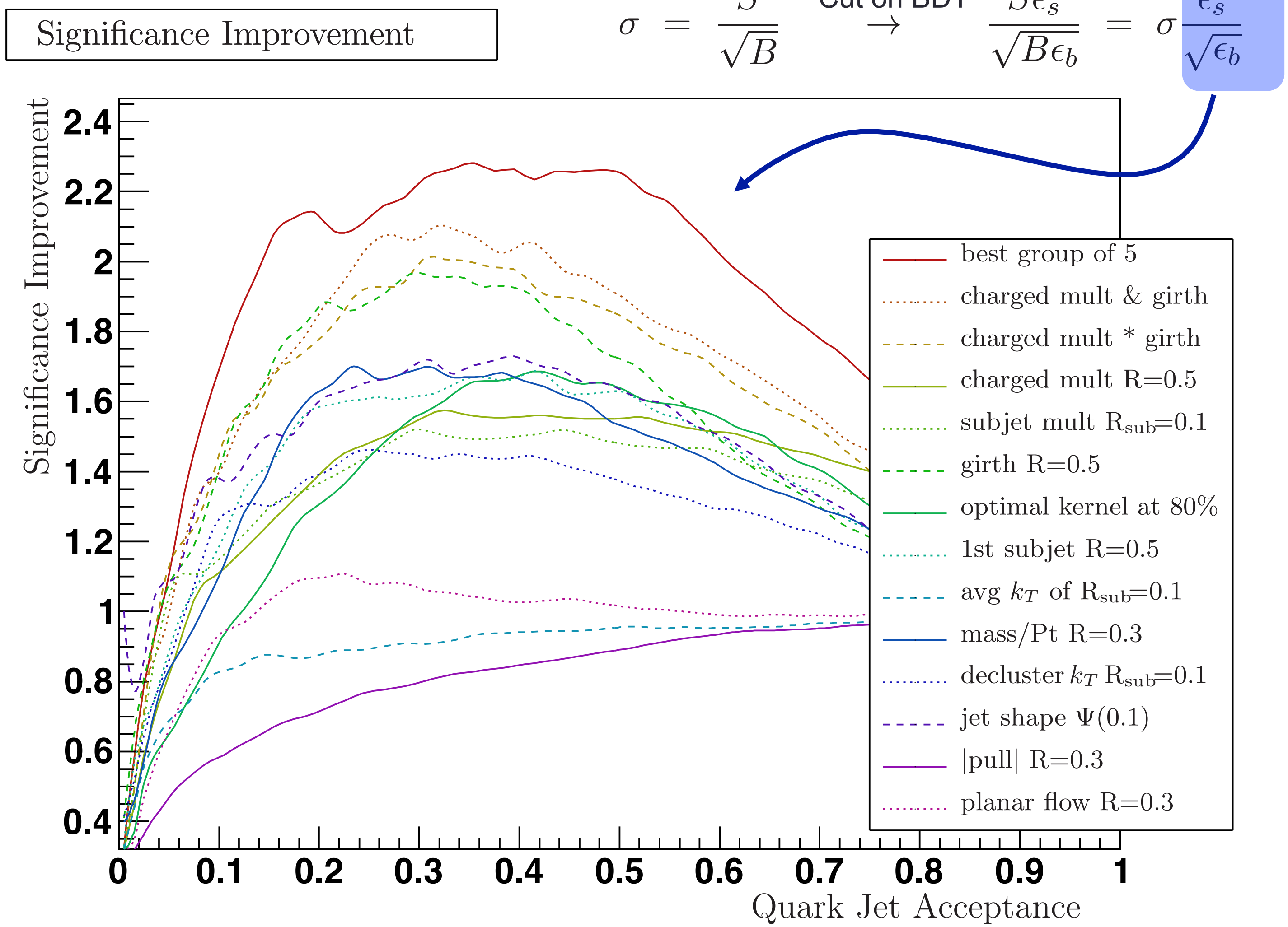
Gluon rejection as a function of initial jet size



Smaller is better

Quark and gluon jet substructure

$$\sigma = \frac{S}{\sqrt{B}} \xrightarrow{\text{Cut on BDT}} \frac{S\epsilon_s}{\sqrt{B\epsilon_b}} = \sigma\frac{\epsilon_s}{\sqrt{\epsilon_b}}$$



We looked at 10,000 variables

Using pythia, all hadrons, the best two variables in Pythia are

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

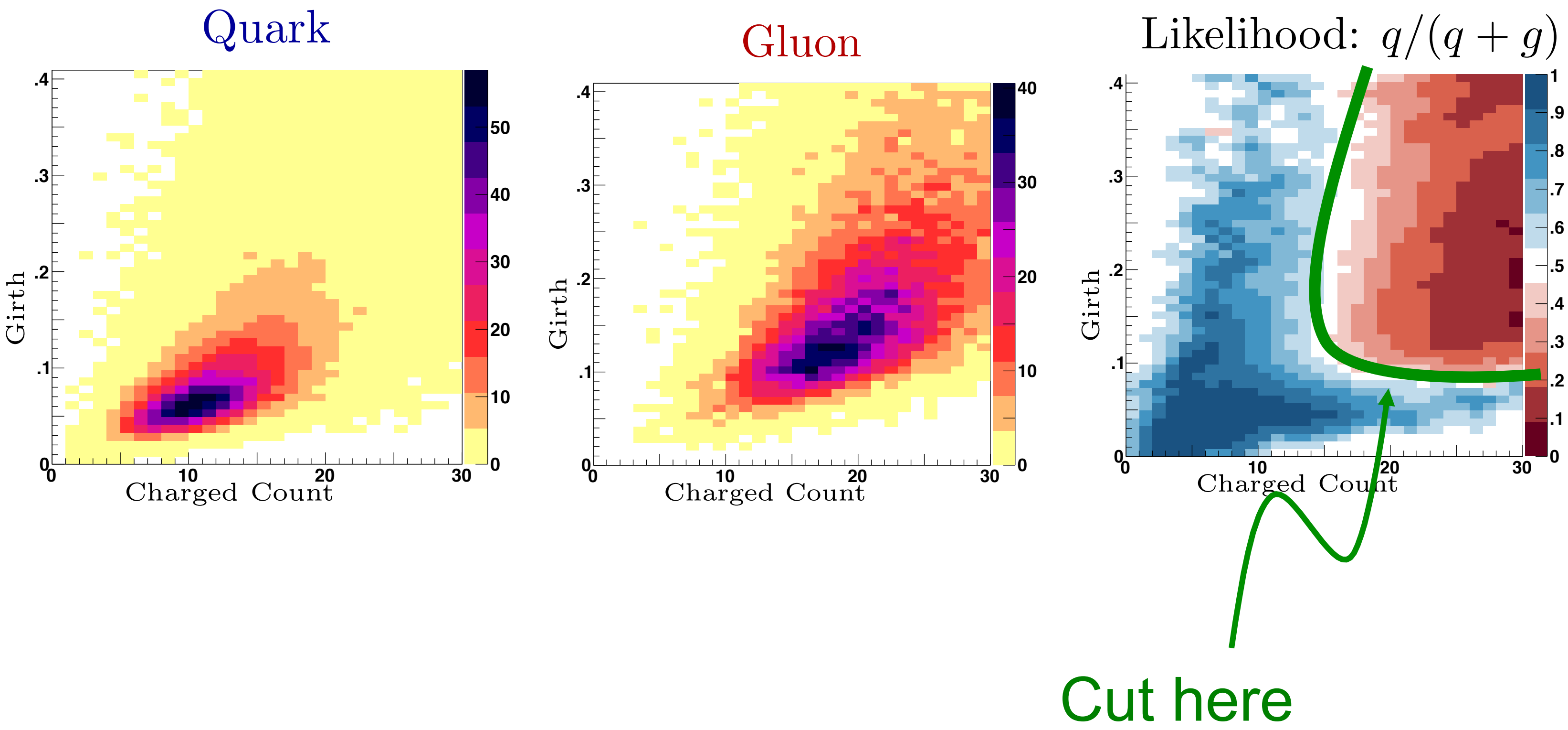
and

2. Linear radial moment (girth)
   - Similar to jet broadening

Herwig less clear (more below)

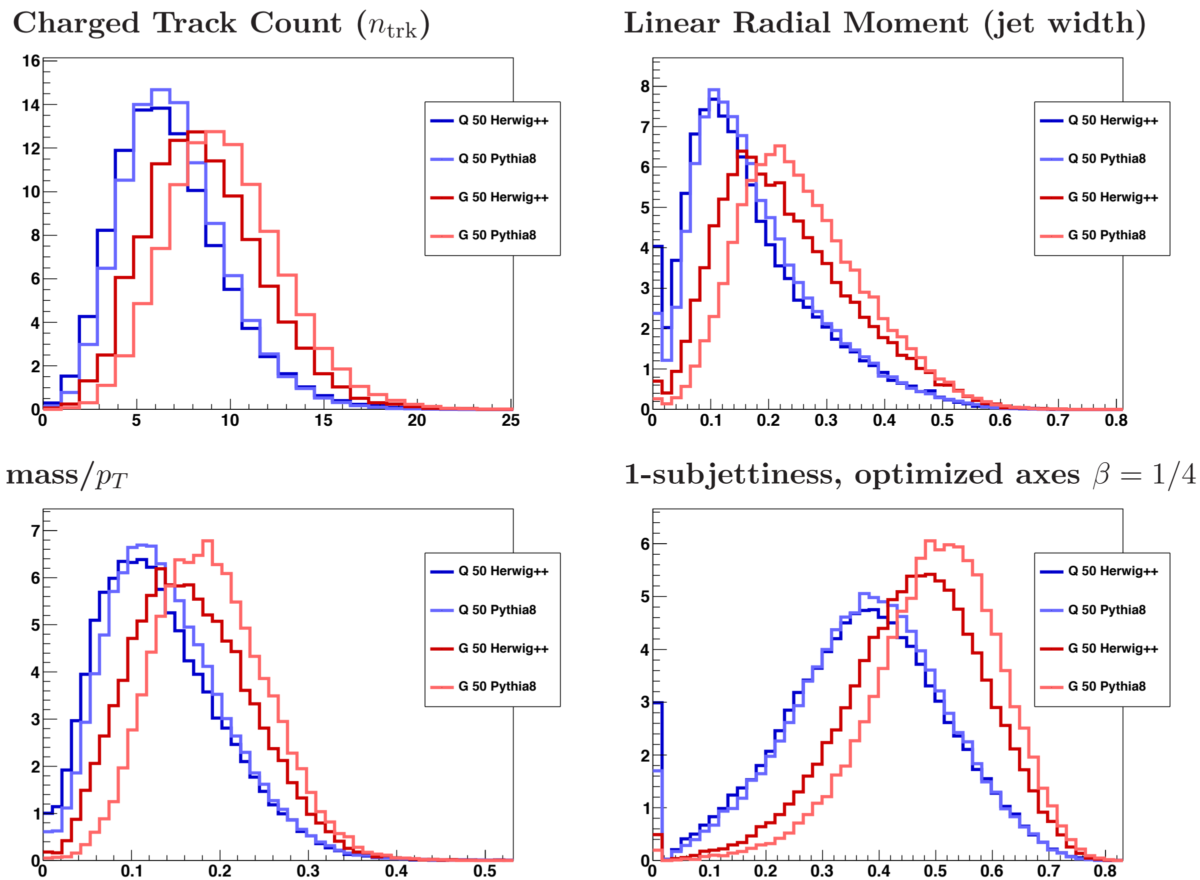
Show http://jets.physics.harvard.edu/qvg

2D distributions



- Keep 50% of quark jets
- Reduce gluon jets by a factor of 8 (to 12.5%)

Pythia vs Herwig



- Pythia and Herwig qualitatively similar
- Discrimination power with Herwig ++ universally worse

Quark and gluon tagging: results

	Gluon Efficiency % at 50% Quark Acceptance	50 GeV Particles P8	50 GeV Particles H++	50 GeV Tracks P8	50 GeV Tracks H++	200 GeV Particles P8	200 GeV Particles H++	200 GeV Tracks P8	200 GeV Tracks H++
Single variables	2-Point Moment β=1/5	8.7*	17.8*	13.7*	22.8*	8.3	15.9	13.2	19.6
	1-Subjettiness β=1/2	9.3	18.5	14.2	22.9	7.6	16.2	12.3	19.4*
	2-Subjettiness β=1/2	9.2	18.6	13.9	23.6	6.8	15.7*	9.8	18.7
	3-Subjettiness β=1	9.1	19.3	14.6	24.4	5.9*	16.7	8.6*	19.5
	Radial Moment β=1 (Girth)	10.3	20.5	16.1	24.9	11.2	18.9	15.3	21.9
	Angularity $a = +1$	10.3	20.0	15.8	24.5	12.0	19.3	14.0	21.6
	Det of Covariance Matrix	11.2	21.2	18.1	27.0	9.4	20.9	13.5	24.6
	Track Spread: $\sqrt{< p_T^2 >}/p_T^{\mathrm{jet}}$	16.5	25.3	16.5	25.3	9.3	20.1	9.3	20.1
	Track Count	17.7	26.4	17.7	26.4	8.9	21.0	8.9	21.0
	Decluster with k_T, ΔR	15.8	24.5	20.1	28.4	13.9	20.1	16.9	23.4
	Jet m/p_T for R=0.3 subjet	13.1	25.9	16.3	27.7	11.9	24.2	14.8	26.2
	Planar Flow	28.7	34.4	28.7	34.4	39.6	42.9	39.6	42.9
	Pull Magnitude	37.0	39.0	32.9	35.6	30.6	30.2	29.6	30.6
Pairs of variables	Track Count & Girth	9.9	20.1	13.4	23.2	7.1	17.3	7.7*	18.7
	R=0.3 m/p_T & R=0.7 2-Point β=1/5	7.9*	17.7	12.2*	22.1	5.7	14.4*	8.5	17.9
	1-Subj β=1/2 & R=0.7 2-Point β=1/5	8.5	17.3*	12.9	22.1	6.0	14.6	8.6	17.7*
	Girth & R=0.7 2-Point β=1/10	12.6	21.9	12.6	21.9*	9.2	18.0	9.2	18.0
	1-Subj β=1/2 & 3-Subj β=1	8.9	18.0	14.0	23.2	5.6*	15.0	8.4	18.4
3,4,5 variables	Best Group of 3	7.5	17.0	11.0	20.9	4.7	14.0	6.9	16.6
	Best Group of 4	7.1	16.7	10.6	20.5	4.5	13.7	6.2	16.3
	Best Group of 5	6.9	16.4	10.4	20.0	4.3	13.3	6.1	15.9

Quark and Gluon tagging

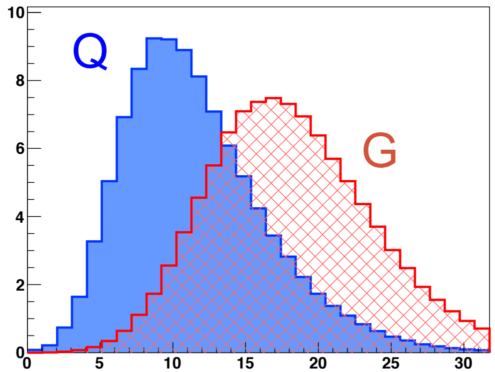
- Discrimination easier at **higher p_T**
- Using **all particles** works better than just **charged tracks**
- 80-90% gluon rejection at 50% quark acceptance is realistic
- **Pythia** gives bigger Q/G difference than **Herwig**

Quark and Gluon tagging summary

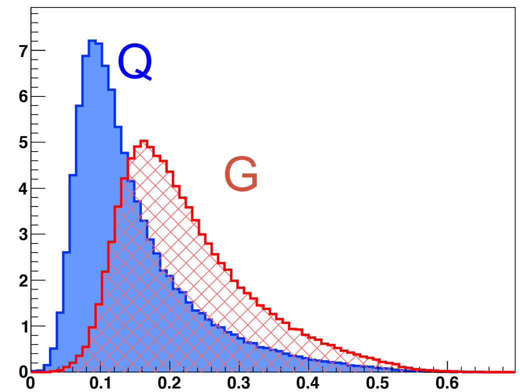
- Discrimination easier at **higher p_T**
- Using **all particles** works better than just **charged tracks**
- 80-90% gluon rejection at 50% quark acceptance is realistic
- **Pythia** gives bigger Q/G difference than **Herwig**
- **Herwig** efficiencies look more like data

Full sim (ATLAS)

Charged particle count



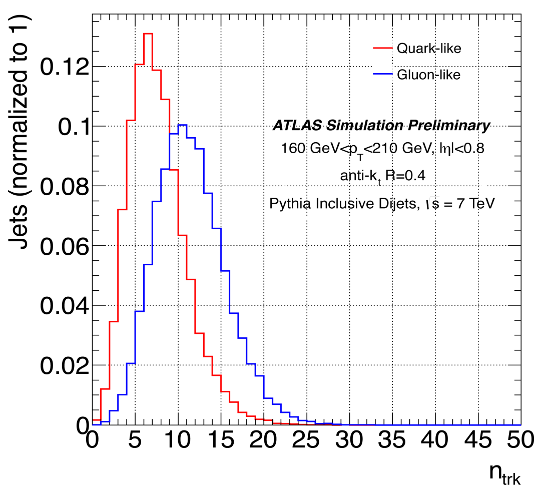
Linear radial moment (girth/track width)



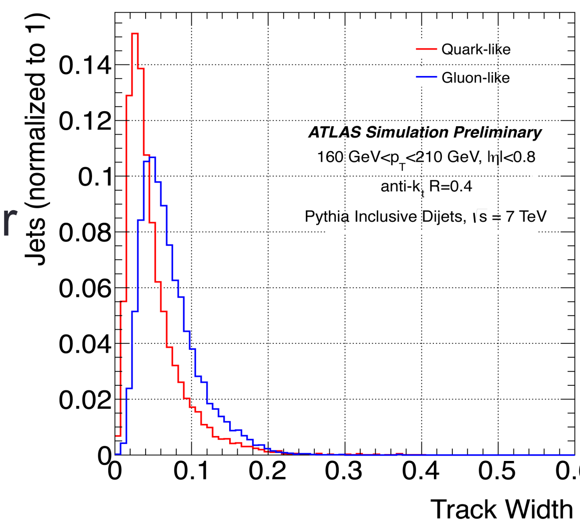
$$= \frac{1}{p_T^{jet}} \sum_{i\in\text{jet}} p_T^i |r_i|$$

PYTHIA

Colors backwards
(sorry)

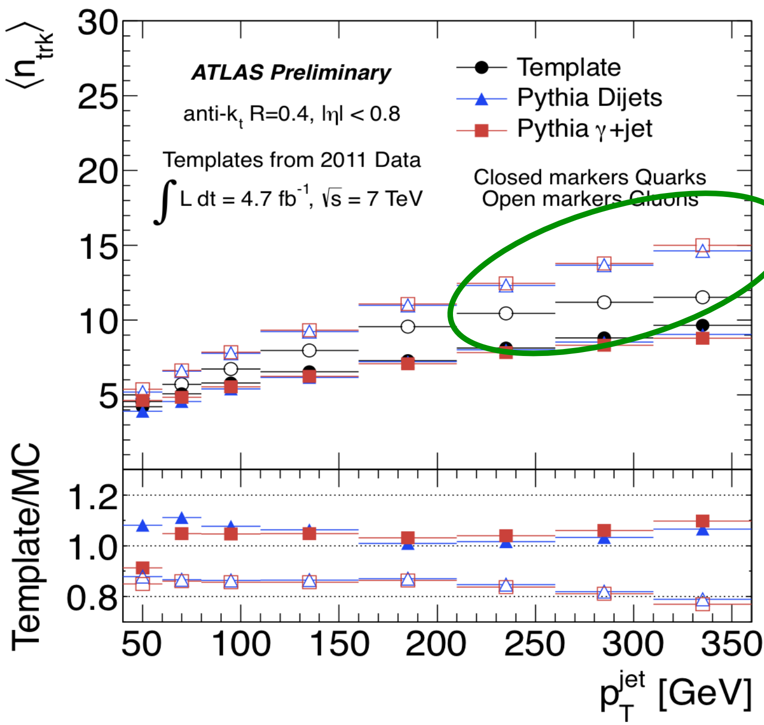


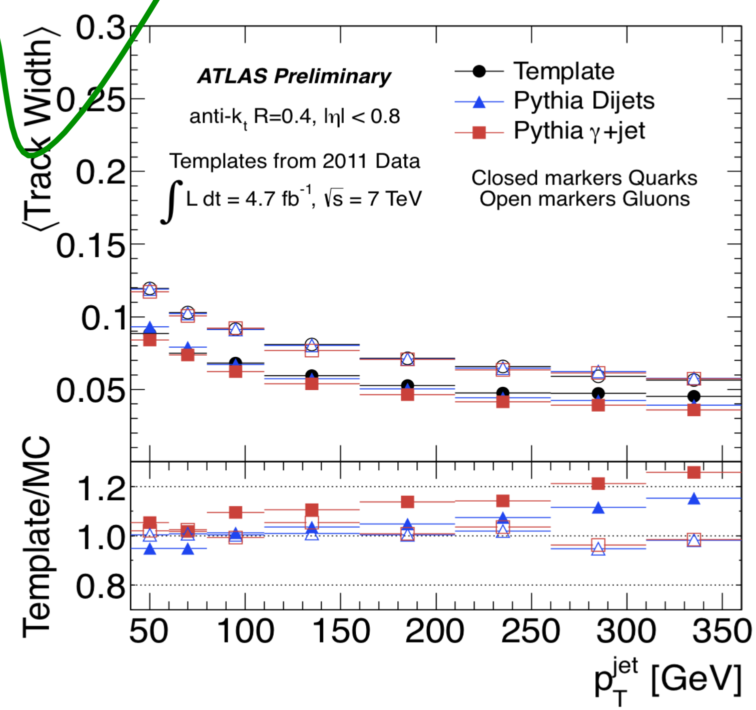
ATLAS
Full detector
simulation



Data (July 2012)

Data and pythia do not agree
For charged particle multiplicity





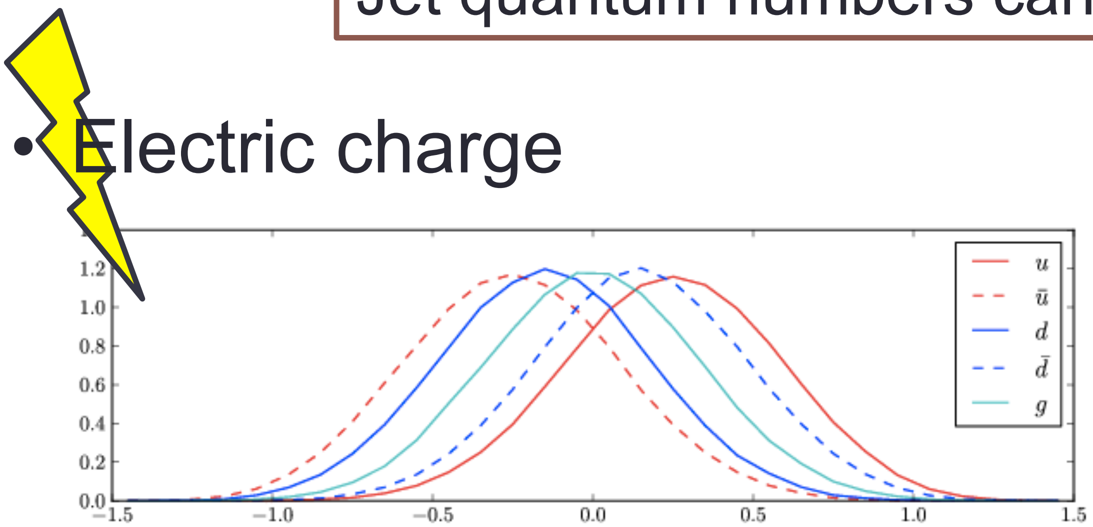
	Quark acceptance	Gluon acceptance
Pythia 8	50%	17%
Herwig ++	50%	26%
Data	50%	25%

Future of Q vs G needs
more data and better theory

Summary

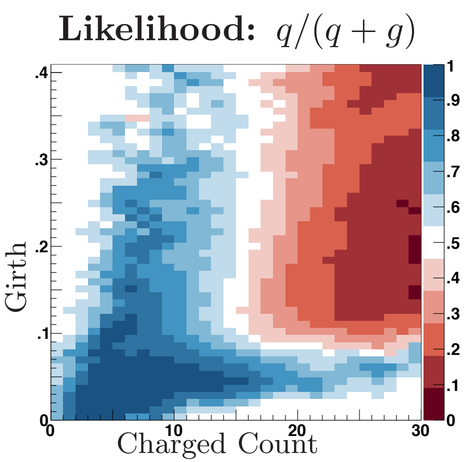
Jet quantum numbers can be measured

- Electric charge



- Can validate on W's from top decays
- Test on dijets
- Calculate scale and R dependence in QCD
- (Relatively) insensitve to pileup

- Color charge (QvG)



- Challenging, but doable
- 80% Gluon at 50% quark
- Monte Carlos limited