JET PHYSICS

2012 Cargese summer school

August 27, 2012

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Outline

- Lecture 1: Jets and QCD
  - The physics of jets
  - Jets from perturbative QCD
  - Jet algorithms
  - Some data
- Lecture 2: Modern jet physics
  - Jet substructure
  - Jet grooming
  - Jet properties
    - Color flow
    - Jet charge
    - Quark and gluon jets
  - The future of jets

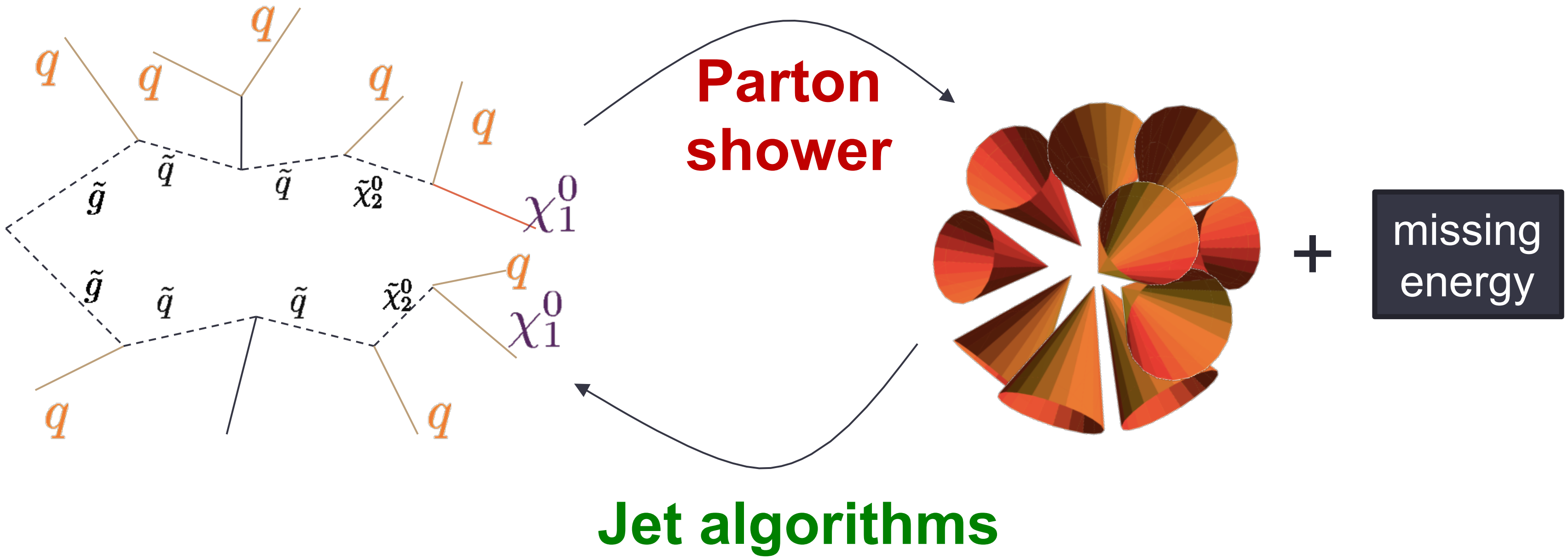
LECTURE 2
MODERN JET PHYSICS

JET SUBSTRUCTURE

Jet-to-parton map

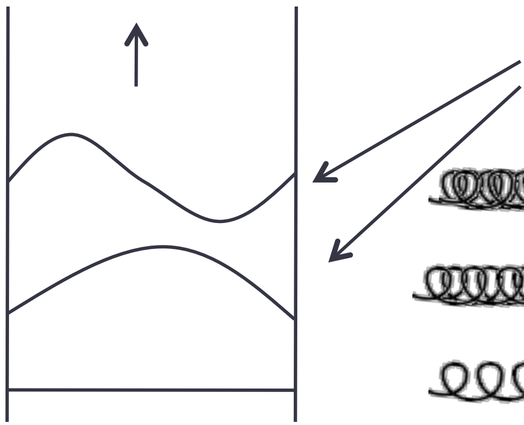
We want to see quarks and gluons:

We observe jets:

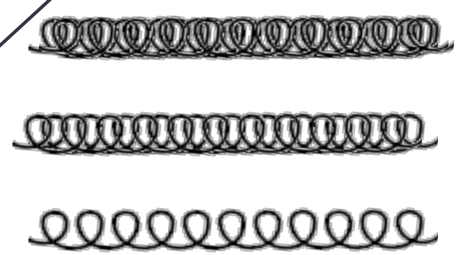


Application: resonance searches

Example: Tiny extra dimensions of space



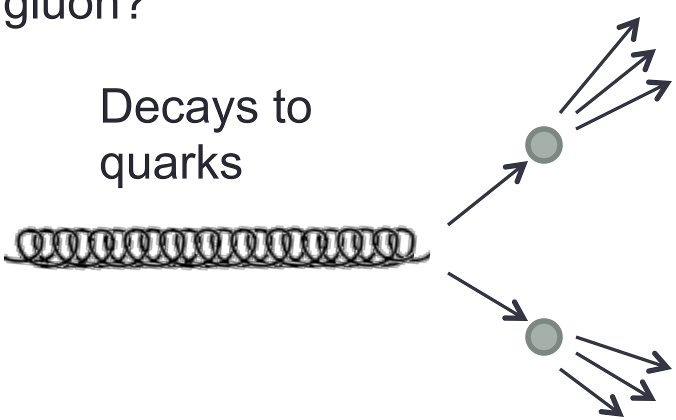
Higher harmonics have larger masses



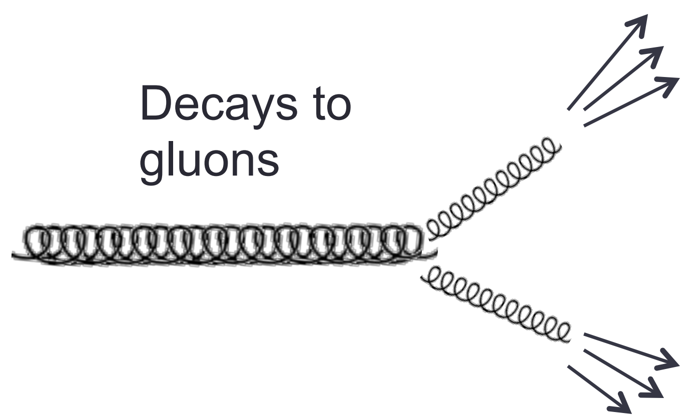
dijets

How do we see a heavy gluon?

Decays to quarks



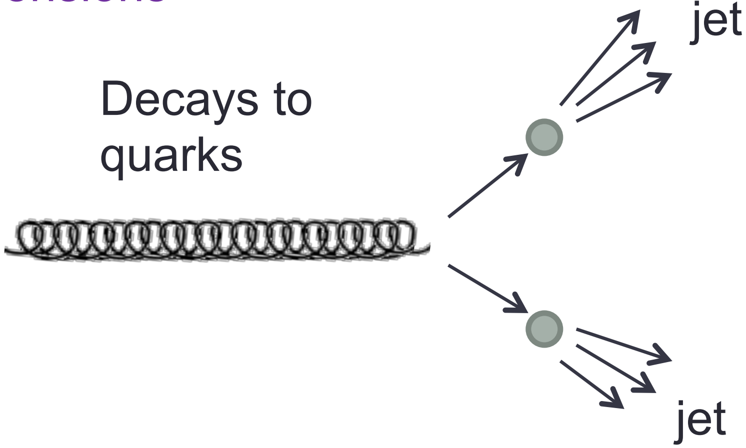
Decays to gluons



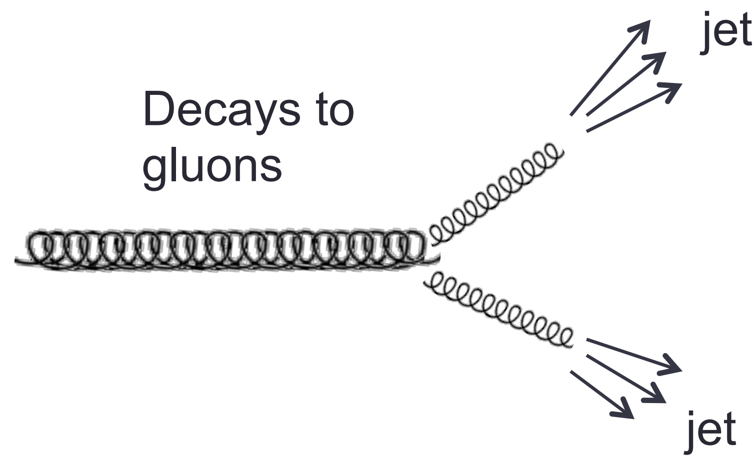
KK gluon searches

Heavy KK gluons from extra dimensions

Decays to quarks

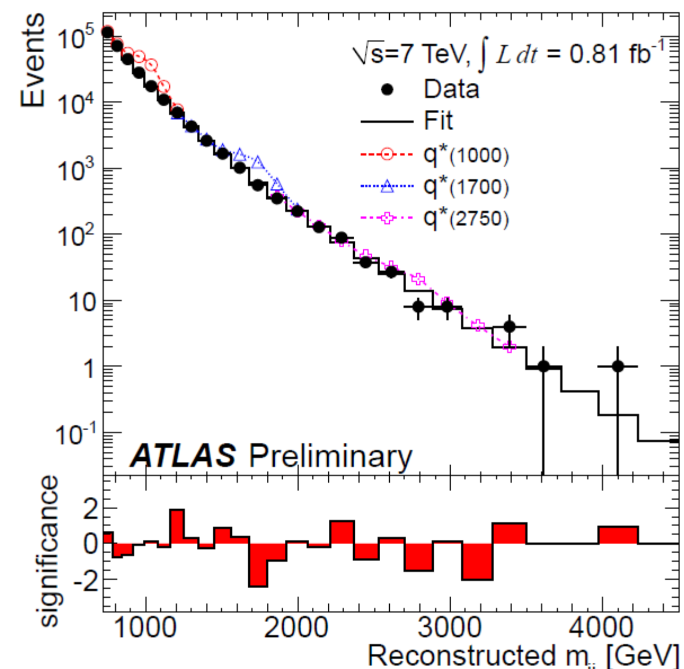


Decays to gluons



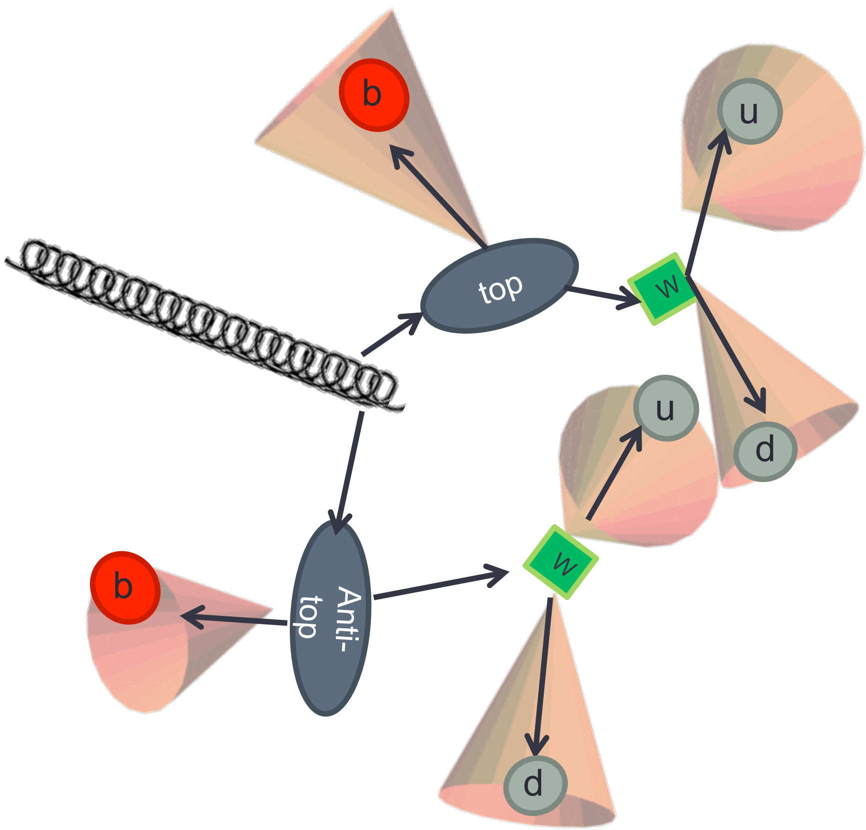
Dijet background from the standard model is enormous!

How else can we find KK gluons?

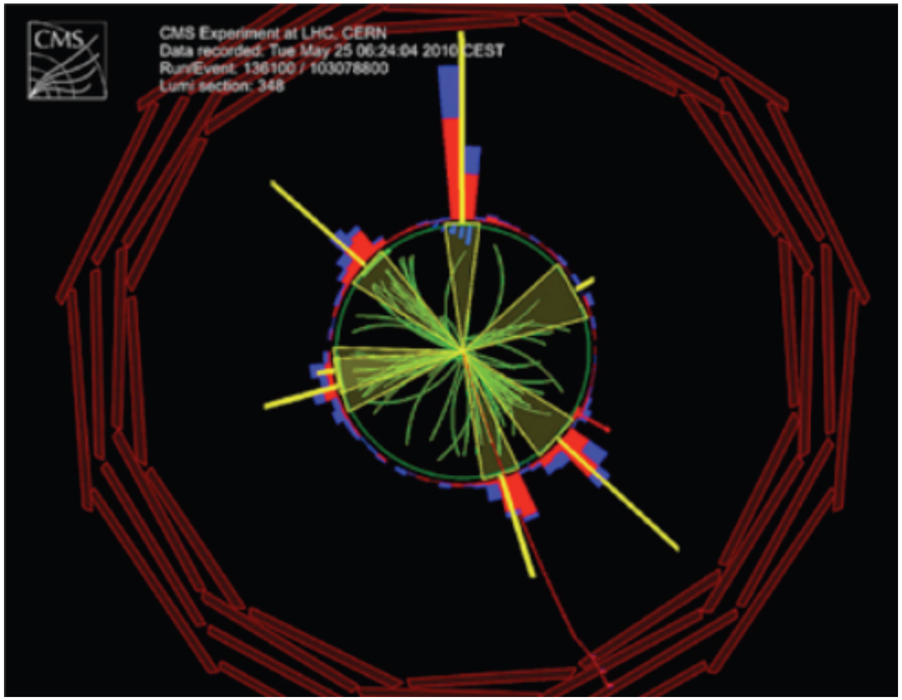


Other decay modes

Look at decays to top quarks:

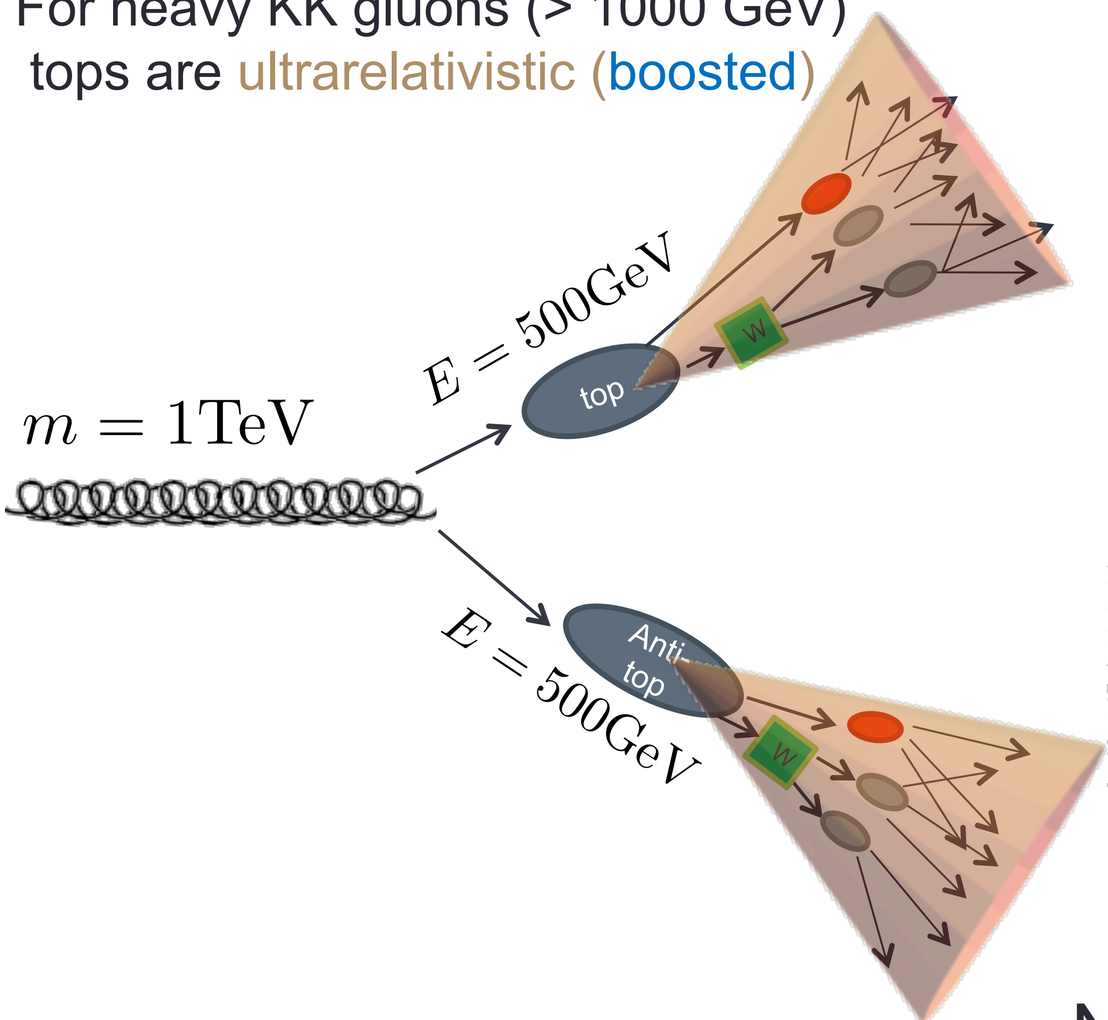


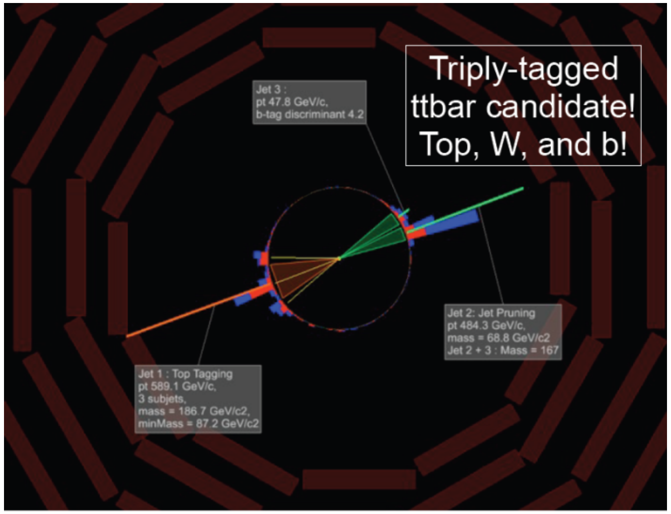
Looks like 6 Jets

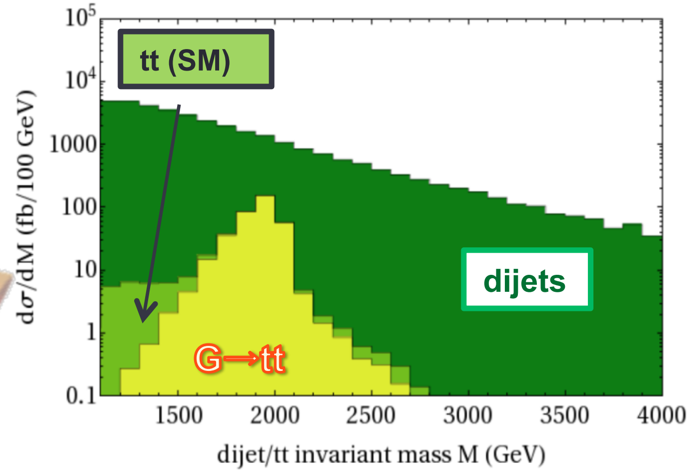


Problems at high mass

For heavy KK gluons (> 1000 GeV) tops are ultrarelativistic (boosted)





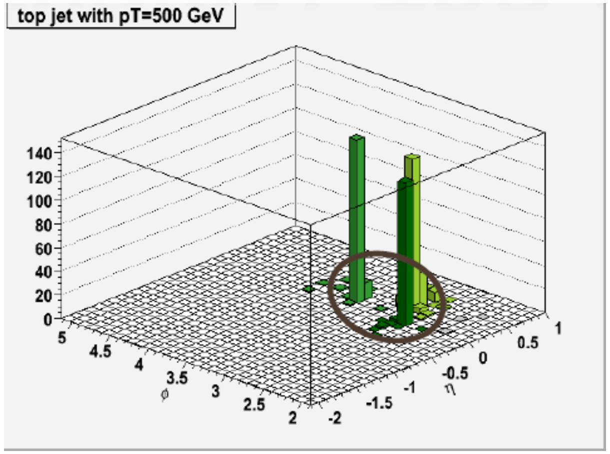


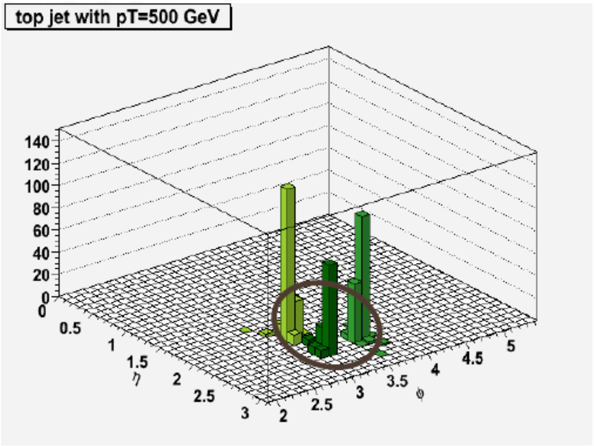
Now it looks like 2 jets!

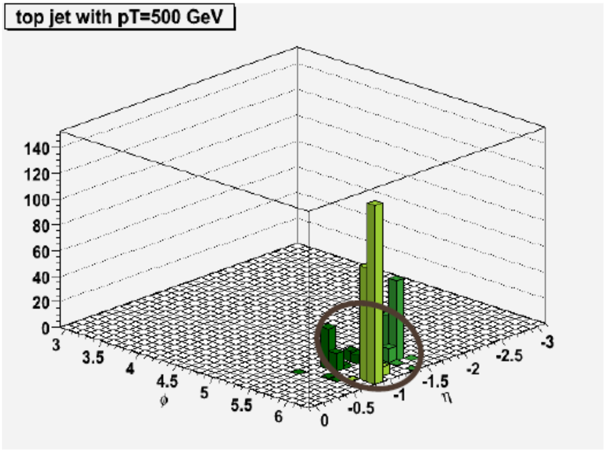
- Take **R large (R=1.0)** and you only get 2 jets not 6
- Take **R small (R=0.4)**, end up with too many tiny jets

Typical top jets

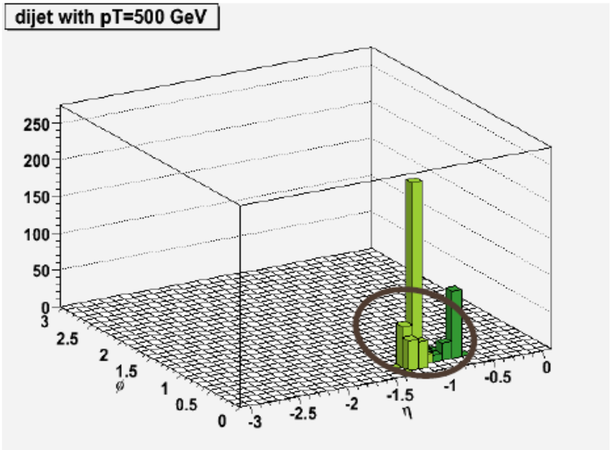
Moderate boost (P_T = 500 GeV)

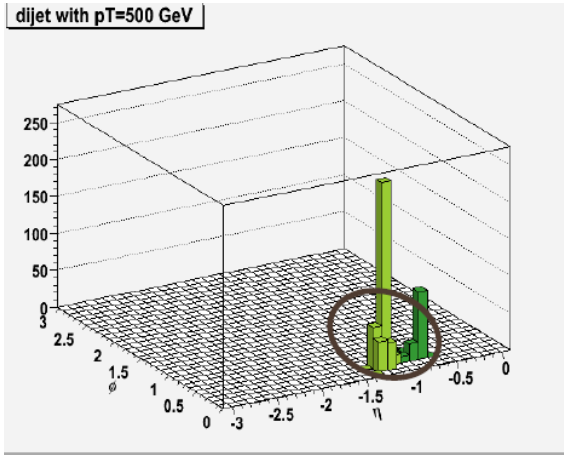


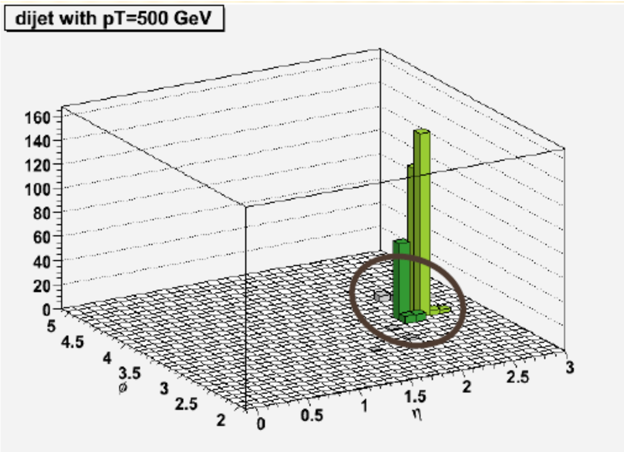




Typical background jets

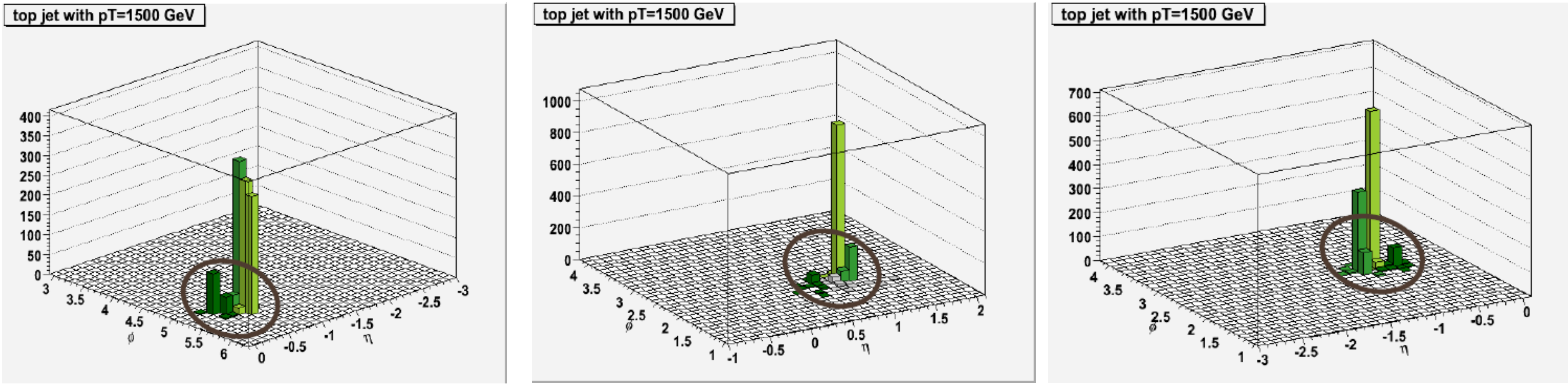




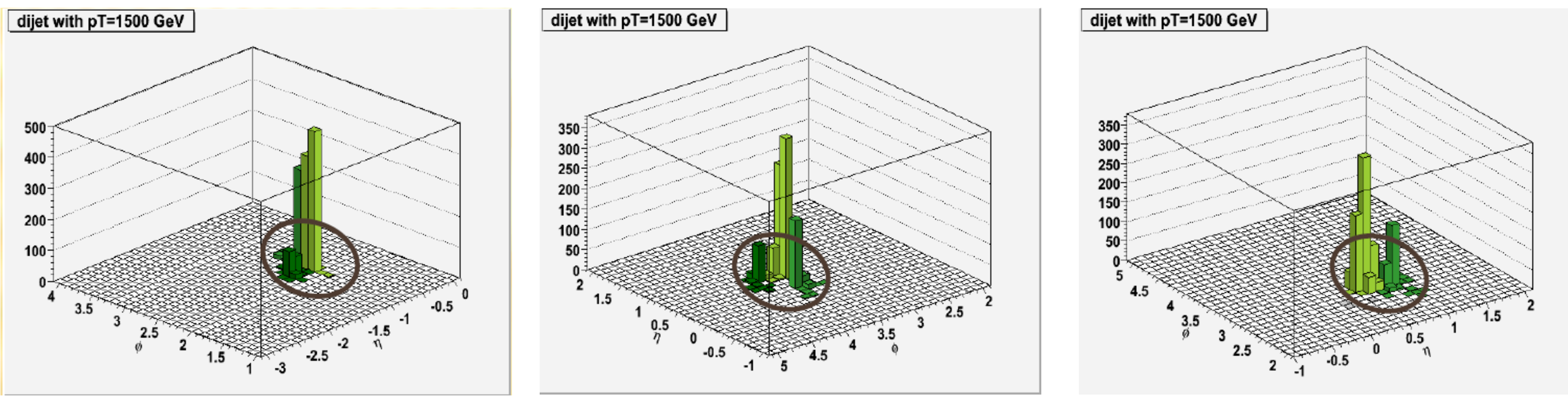


Typical top jets

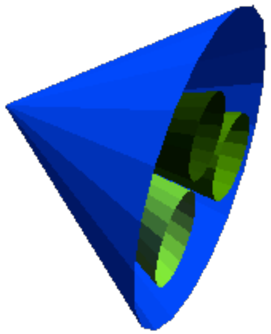
Large boost (P_T = 1500 GeV)



Typical background jets

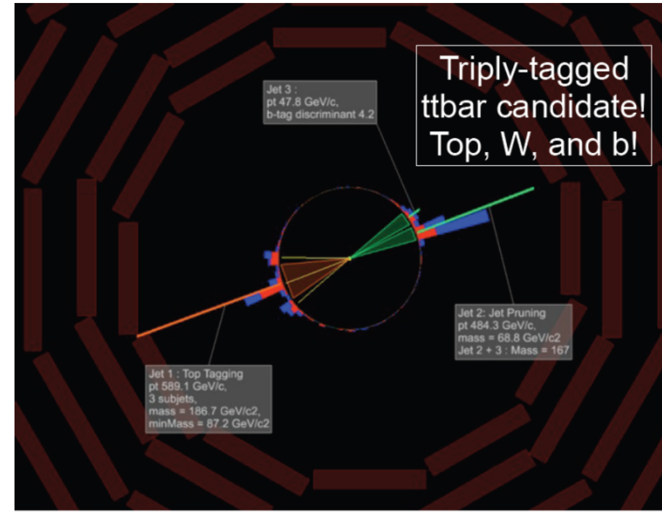


Jet substructure



New concept

Fat Jet

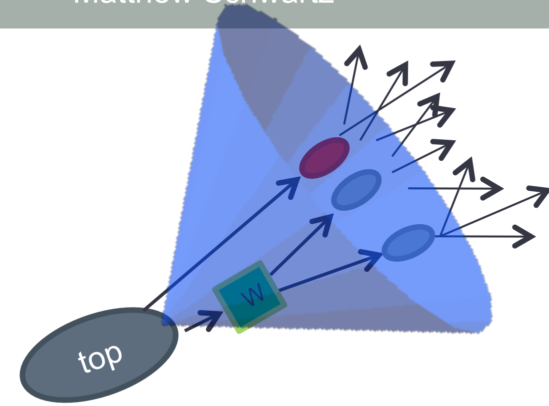


A jet is not a parton: it has **substructure**!

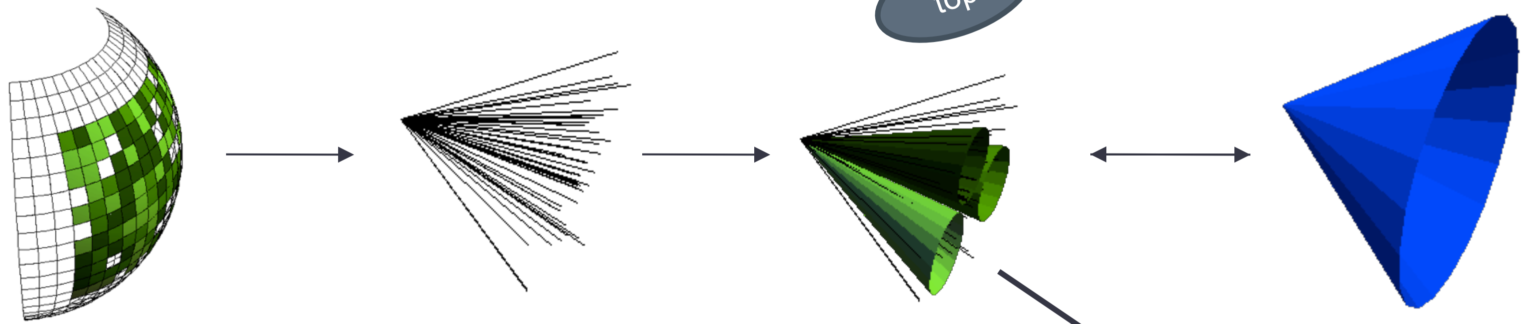
Quick history:

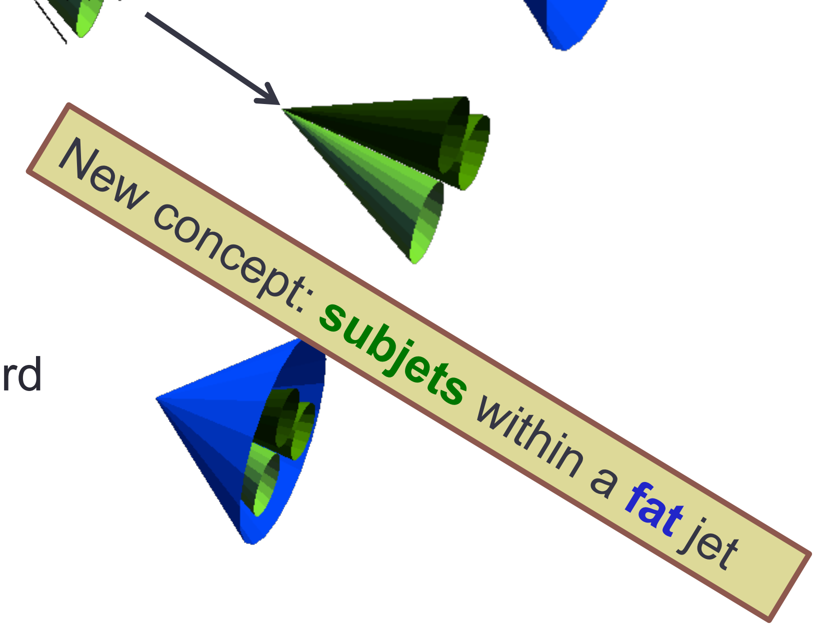
- M. Seymour : look within a jet (Z. Phys. C62 (1994) 127) (**1994**)
- Butterworth et al : boosted Ws in WW scattering (hep-ph/0201098) (**2002**)
- Butterworth et al : boosted Higgs (arXiv:0802.2470) (**2008**)
- Kaplan et al boosted tops (arXiv:0806.0848) (**2008**)
- 2008-today: hundreds of papers

Top-tagging



1. Find fat jets (R = 1.2)





2. Reverse clustering steps

3. Filter:
   - If clustered particle is soft, discard

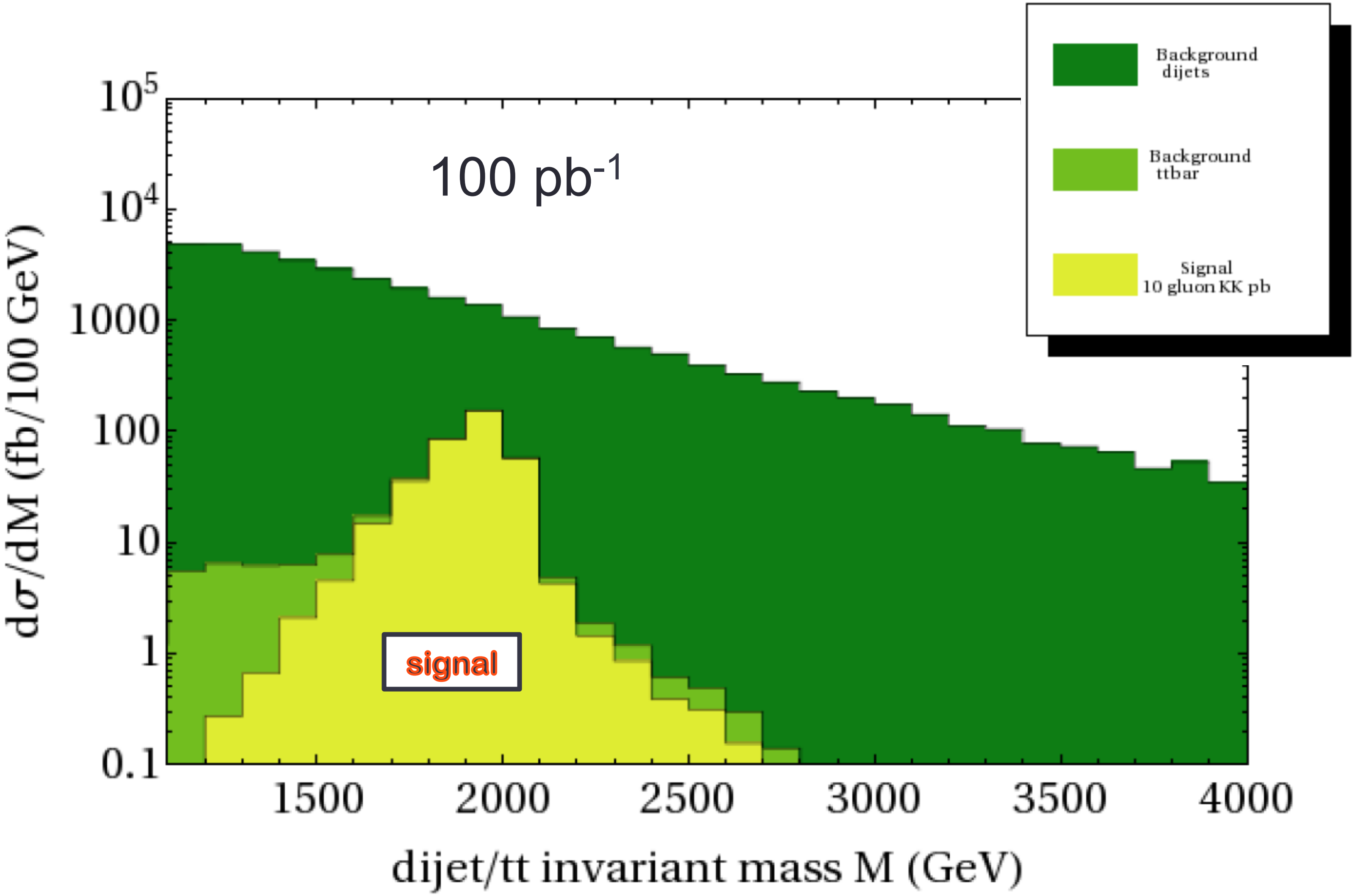
4. Top jets should have 3 subjets

5. Kinematic subjet cuts
   - W mass peak, top mass peak, and helicity angle

Hopkins top-tagger
Kaplan et al. arXiv:0806.0848

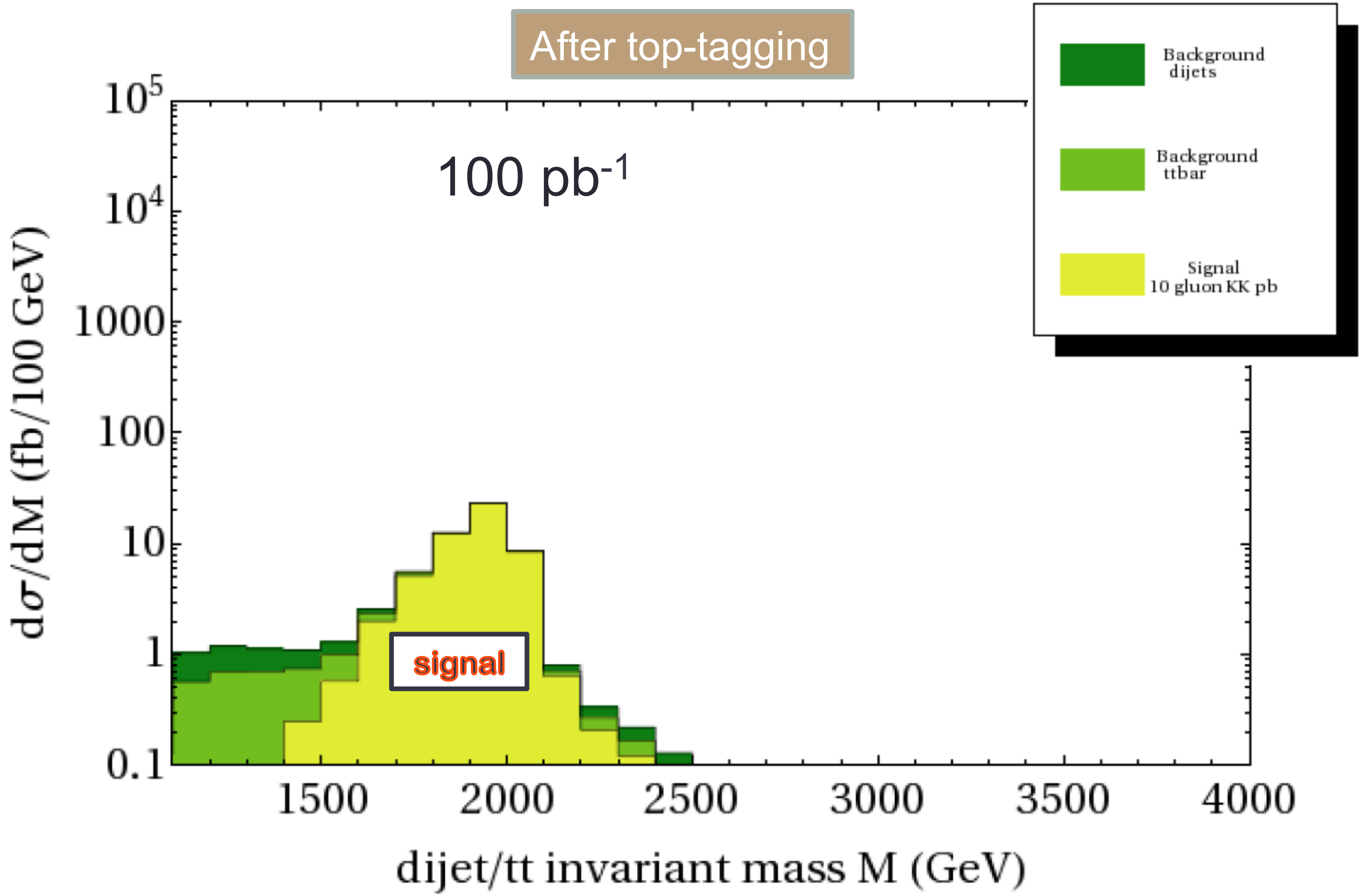
KK gluon

Hopkins top-tagger
Kaplan et al. arXiv:0806.0848



KK gluon

Hopkins top-tagger
Kaplan et al. arXiv:0806.0848

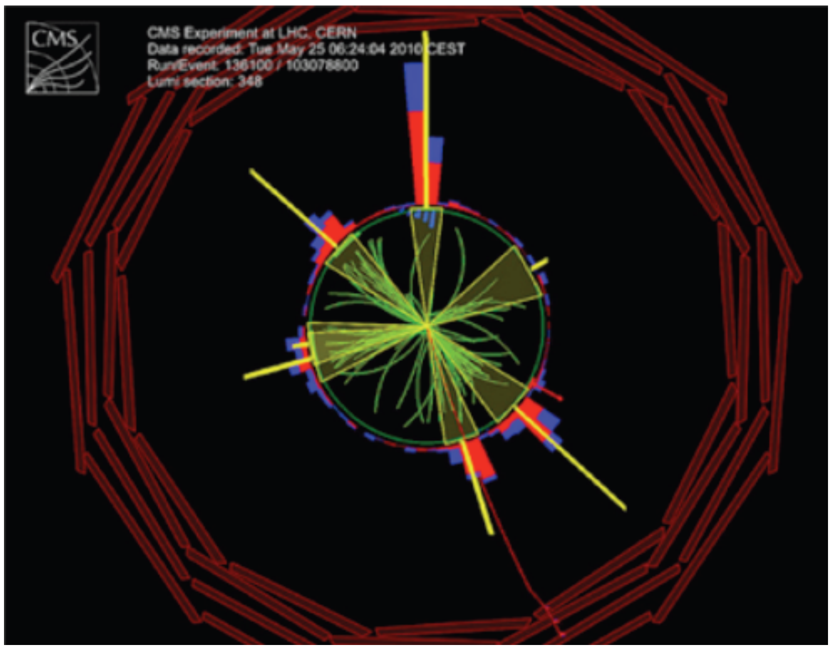


Top-tagging in data

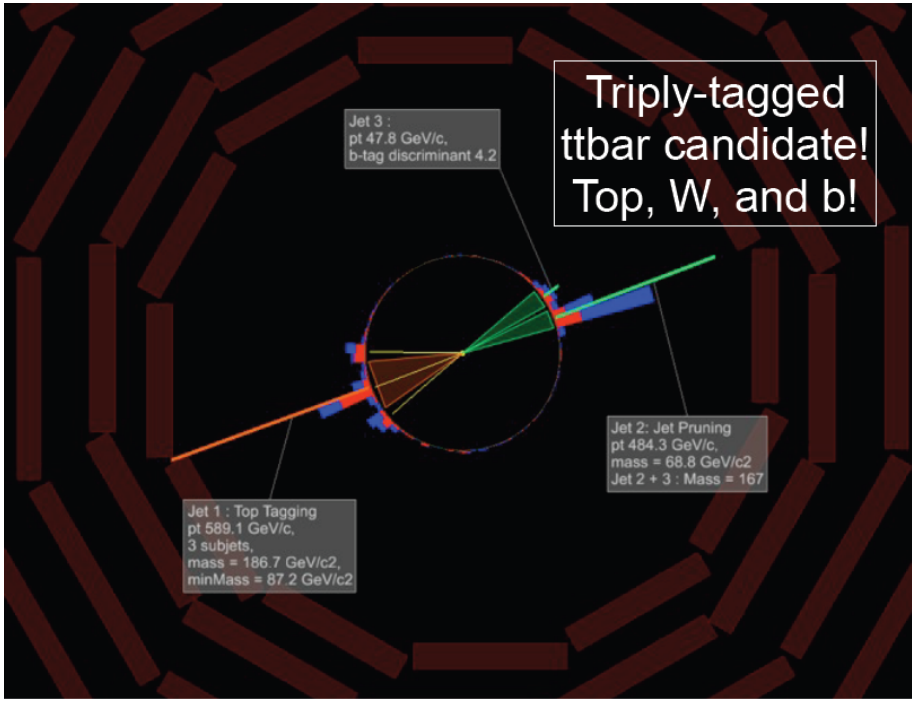
CMS, 2011

Top-antitop events

Unboosted

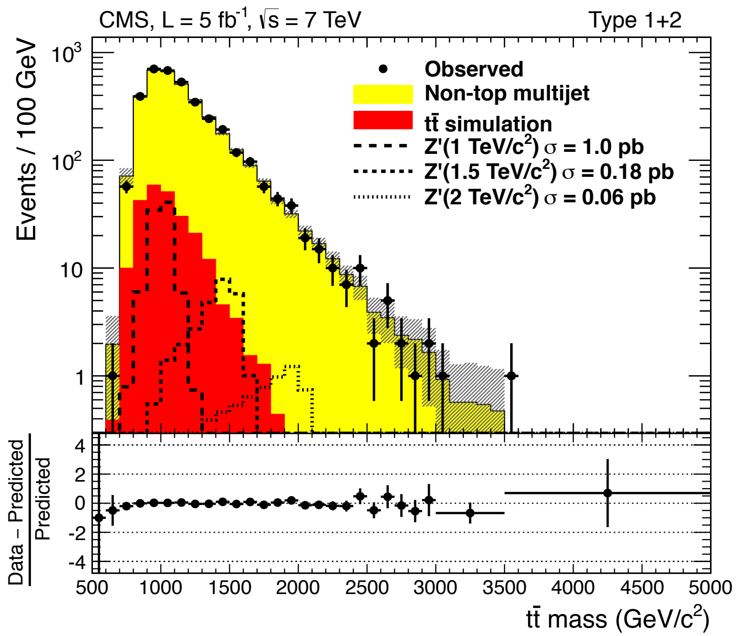


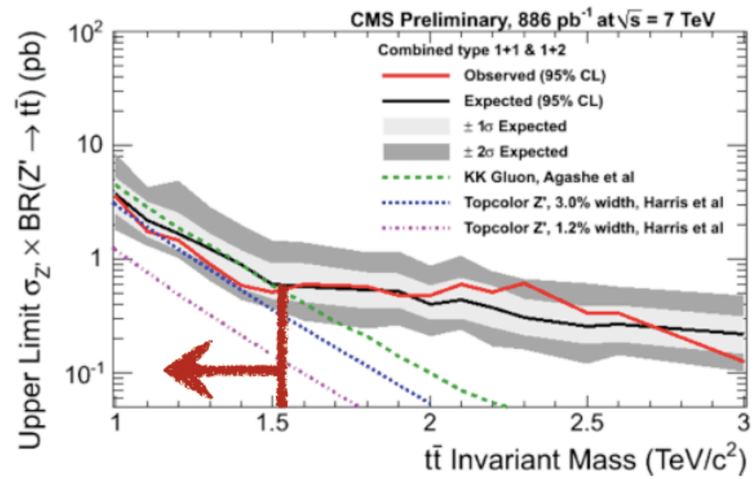
Boosted

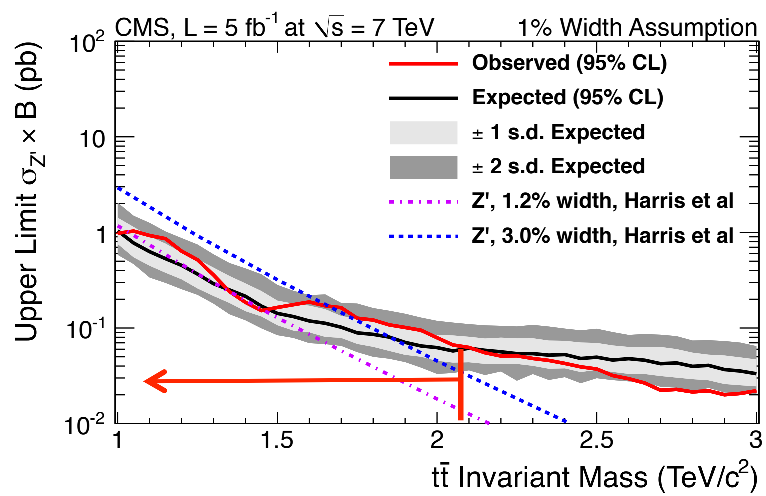


Top-tagging in data

Summer 2011: 0.8 fb^{-1} analyzed
resonances excluded to 1.5 TeV

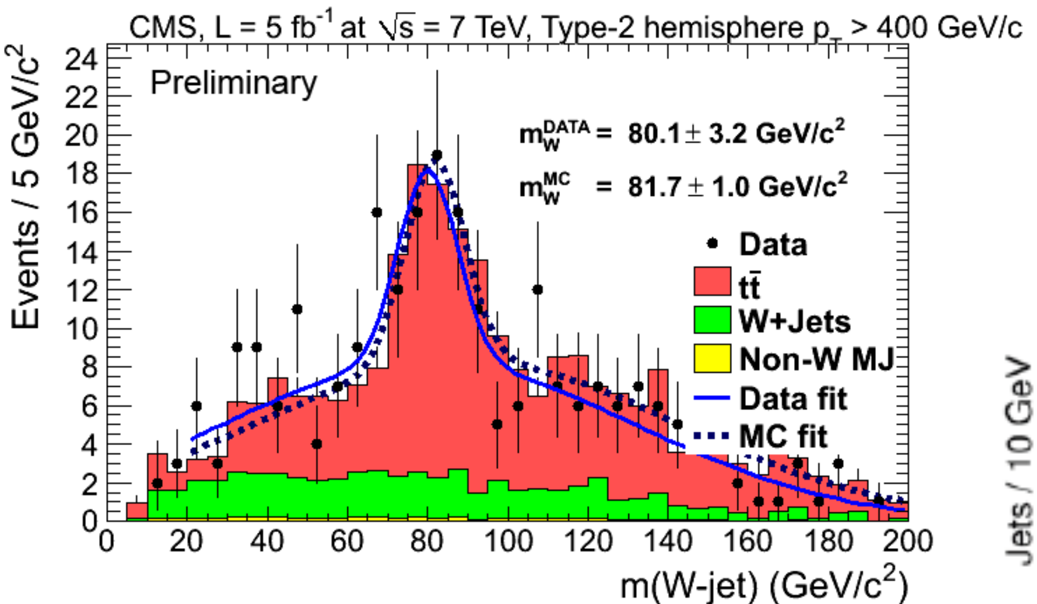






Spring 2012: 5 fb^{-1} analyzed
Resonances excluded up to 2.1 TeV

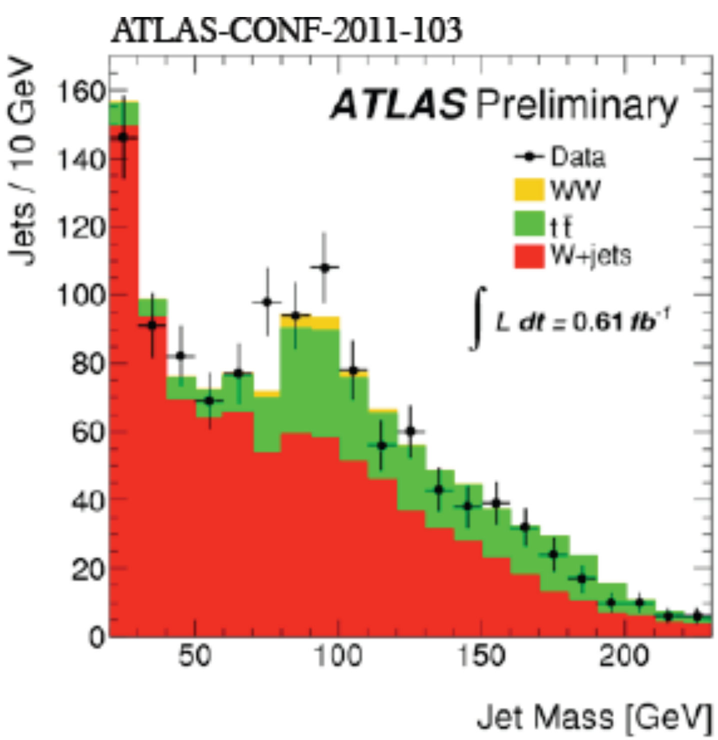
W boson in top jet



within filtered fat jets

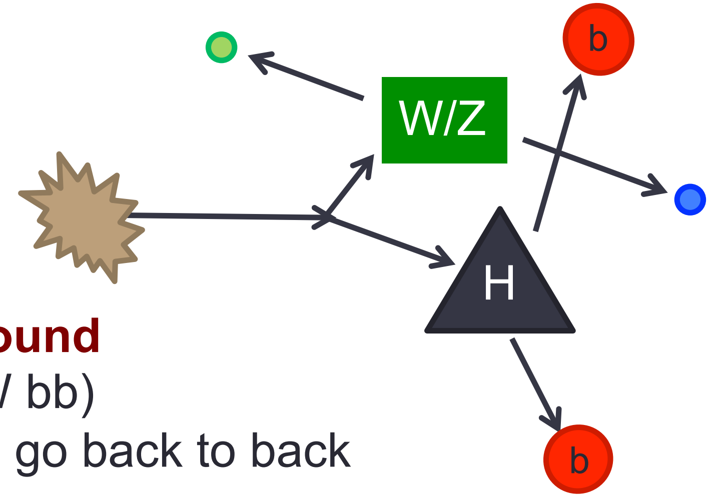
CMS (April, 2012)
arXiv:1204.2488

Atlas version
(less efficient algorithm)



BOOSTED HIGGS

Higgs to bb

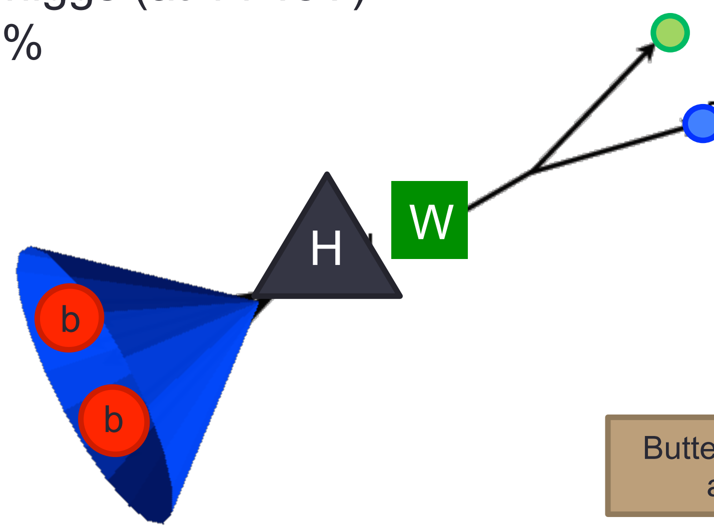


How can we measure the Hbb coupling?

- H + W/Z has **enormous** W/Z + bb **background**
- top background is also very large (tt -> WW bb)
- Z -> **neutrinos difficult** because neutrinos go back to back and there's no missing energy

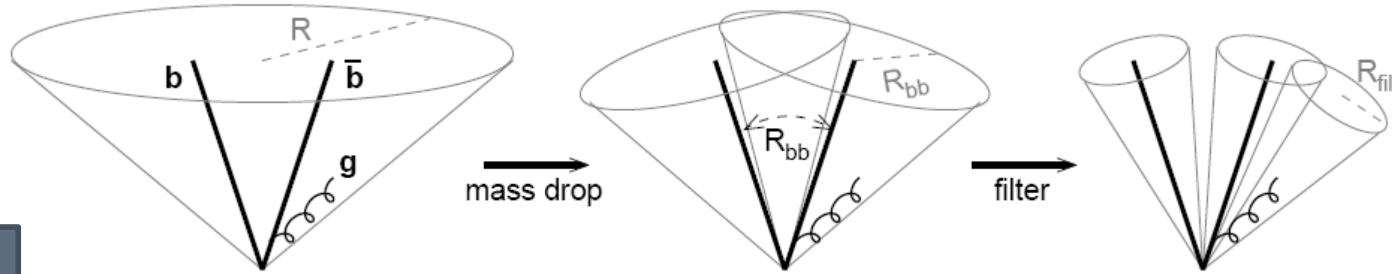
Go to boosted regime!

- Demand pT > 200 GeV for the higgs (at 14 TeV)
- Signal cross section drops to 5%
- W+jets drops to 0.1%
- Tops no longer a problem



Butterworth et al (BDRS)
arXiv:0802.2470

Boosted Higgs bosons



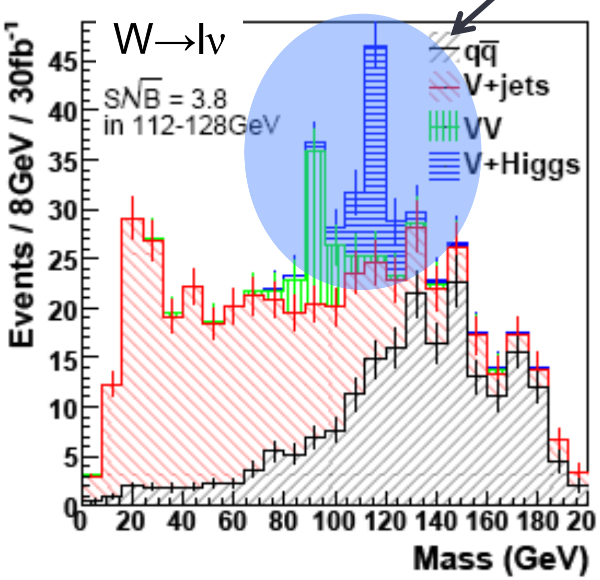
14 TeV 30 fb^{-1}

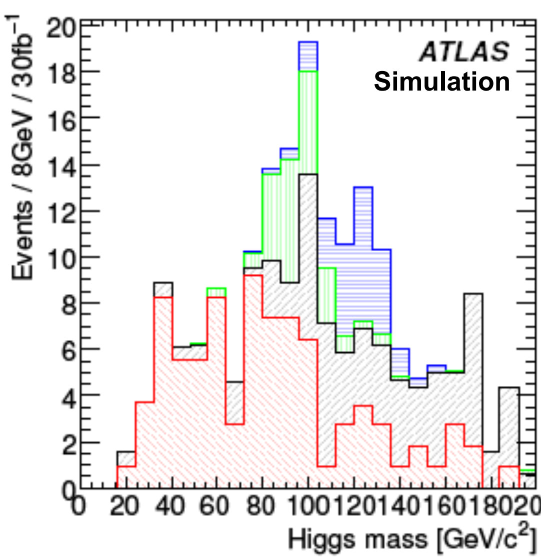
Parton level study
B's not decayed

Hadronic W peak
for validation

ATLAS
Full simulation

$S/\sqrt{B}$ = 3.0 at 30fb^{-1}





Not feasible at 8 TeV

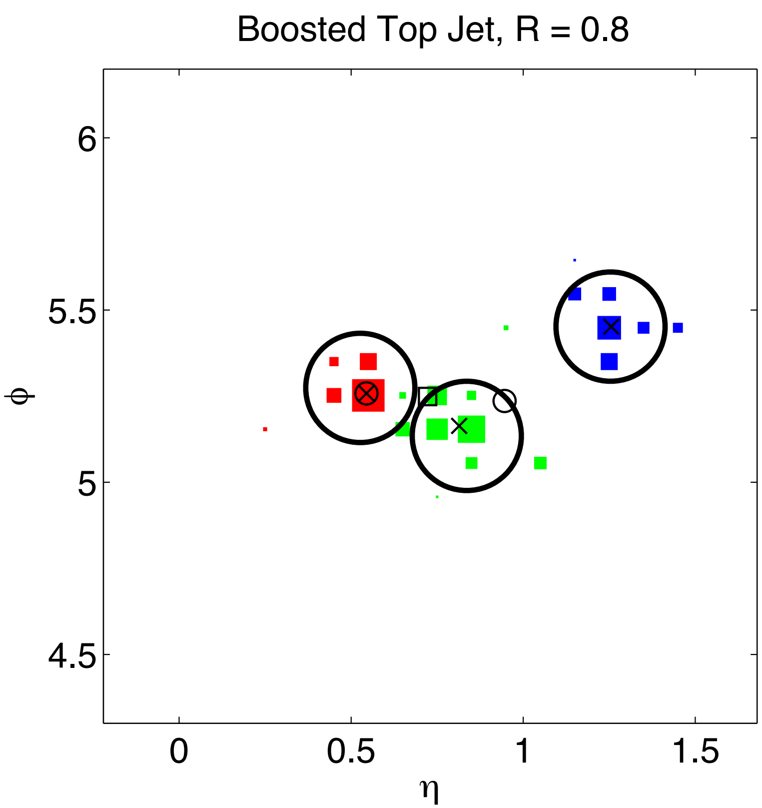
Possibly with 14 TeV data…

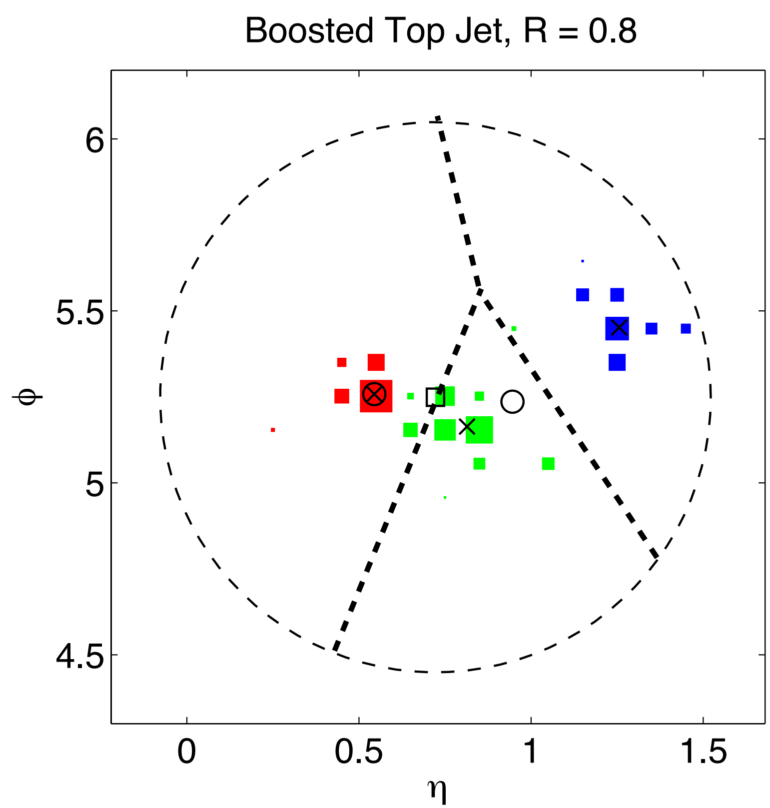
Butterworth et al (BDRS)
arXiv:0802.2470

N-SUBJETTINESS

N-subjettiness

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





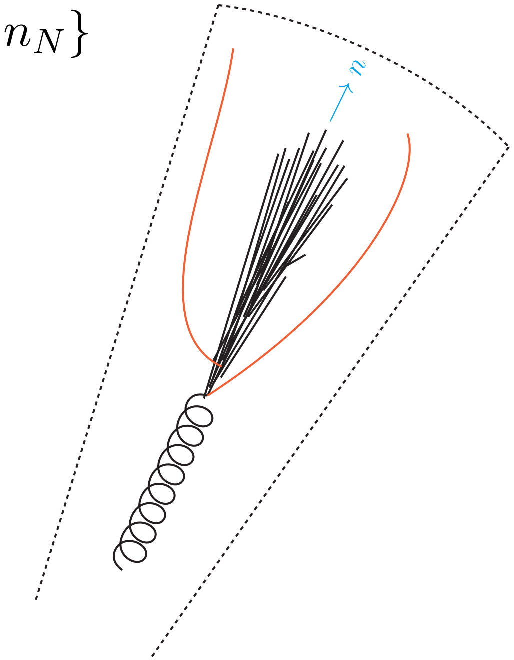
Finds subjets without fixed jet size

N-subjettiness

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

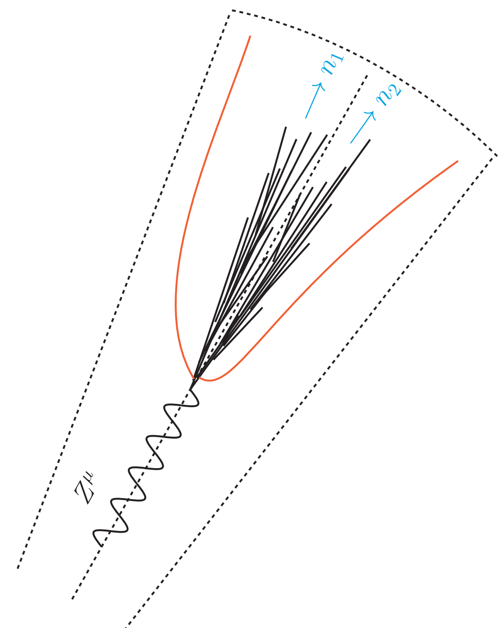
$$\mathcal{T}_1 \approx \frac{m_J^2}{2E_J}$$

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



QCD jet

(all τ_n small)



Boosted W/Z jet

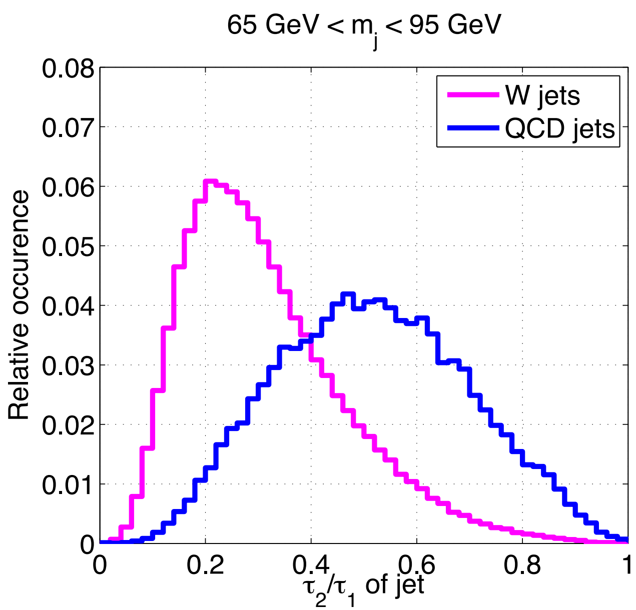
(small τ_2, large τ_1)

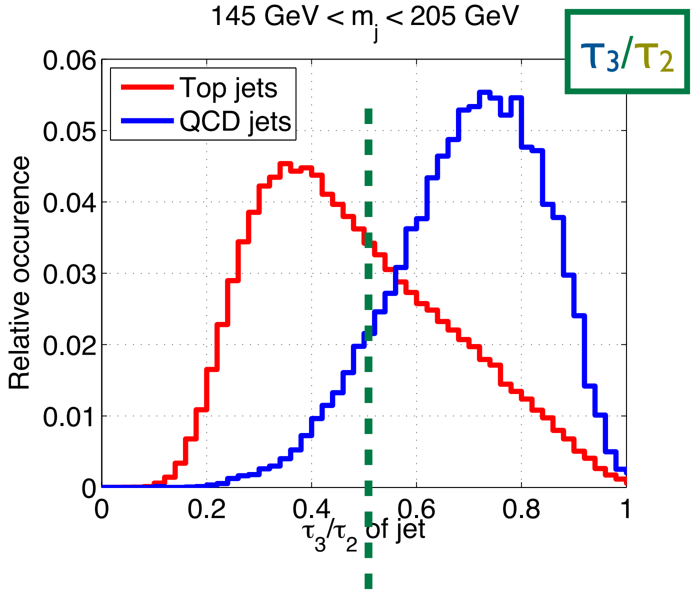
$$\mathcal{T}_2/\mathcal{T}_1$$

Good discriminant

Ratios τ_2/τ_1 and τ_3/τ_2

Useful for distinguishing boosted W or top jets from QCD jets





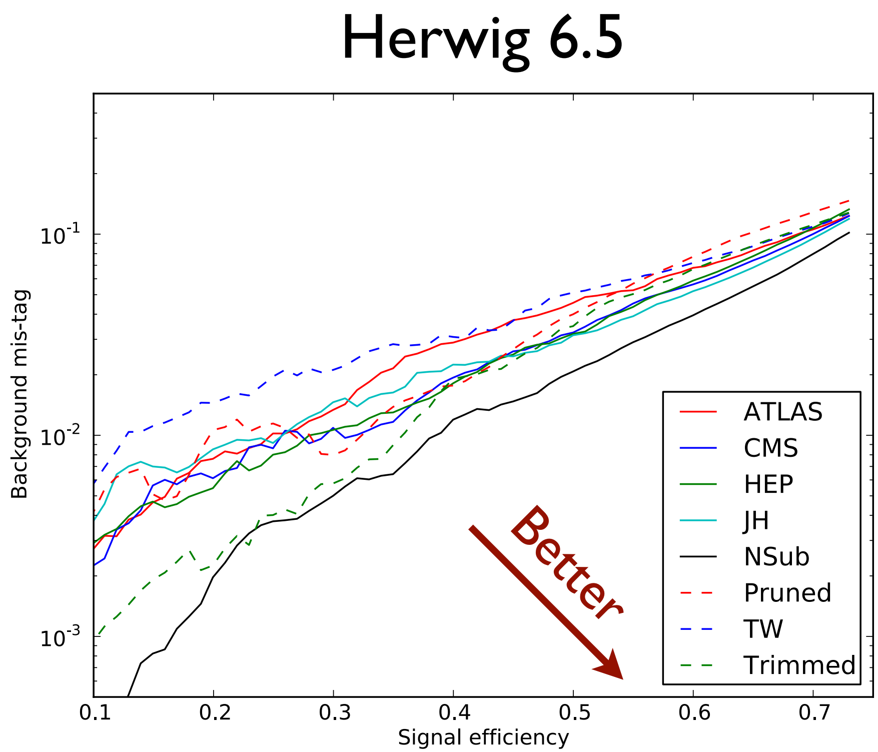
Flexible cut to adjust signal acceptance vs. background rejection

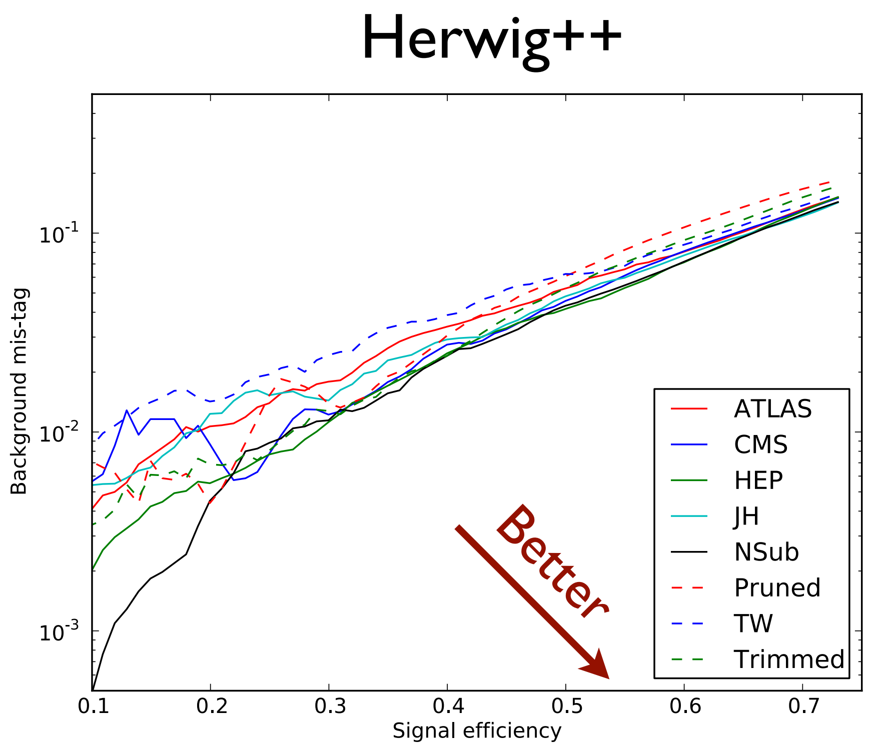
$$\mathcal{T}_1 \approx \frac{m_J^2}{2E_J}$$

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

$$\mathcal{T}_3 \approx \frac{m_1^2}{2E_1} + \frac{m_2^2}{2E_2} + \frac{m_3^2}{2E_3}$$

Top-tagging



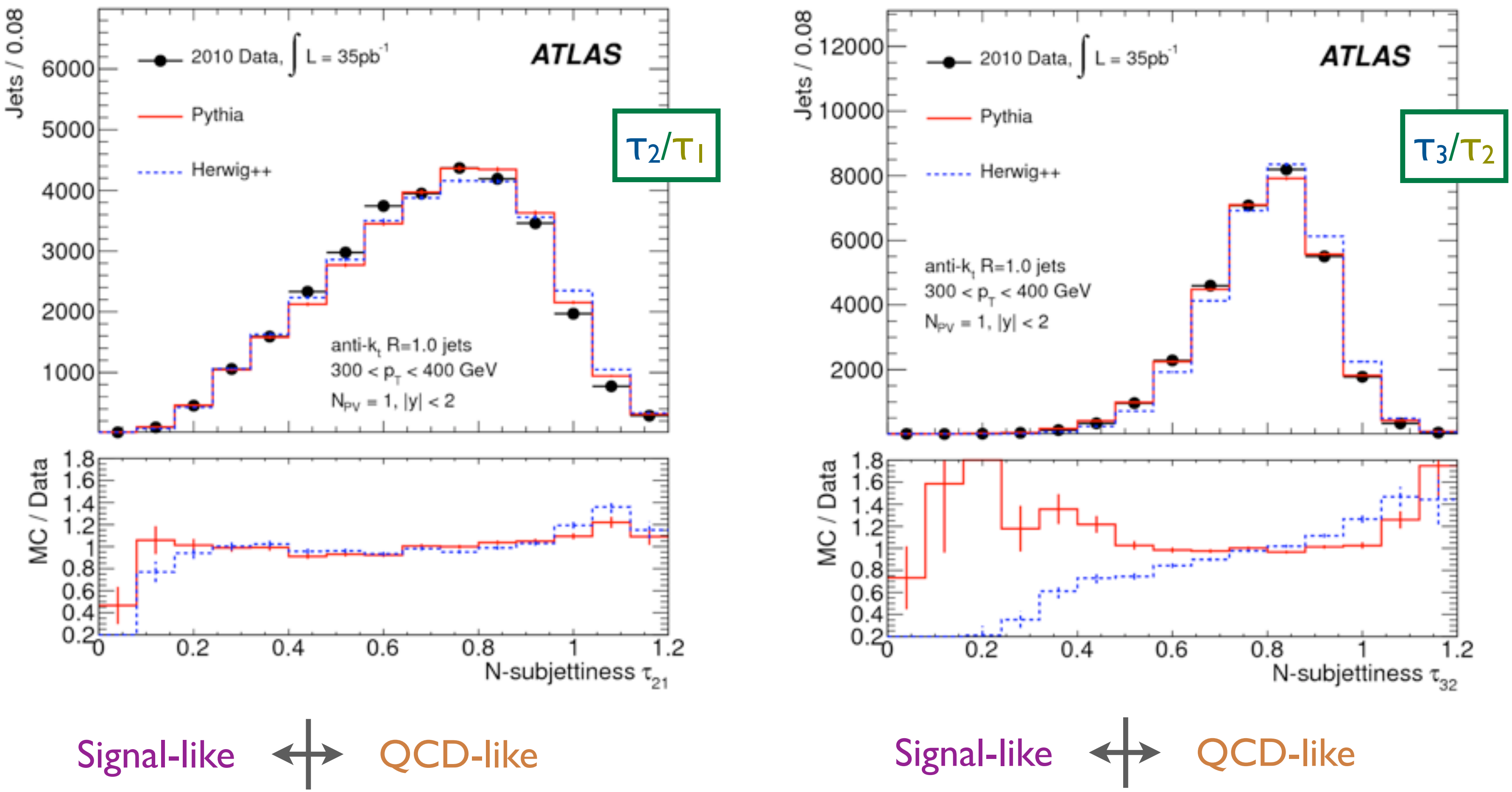


Single variable τ_3/τ_2 works well for top-tagging

- Simulations somewhat inconsistent

Atlas data (QCD only)

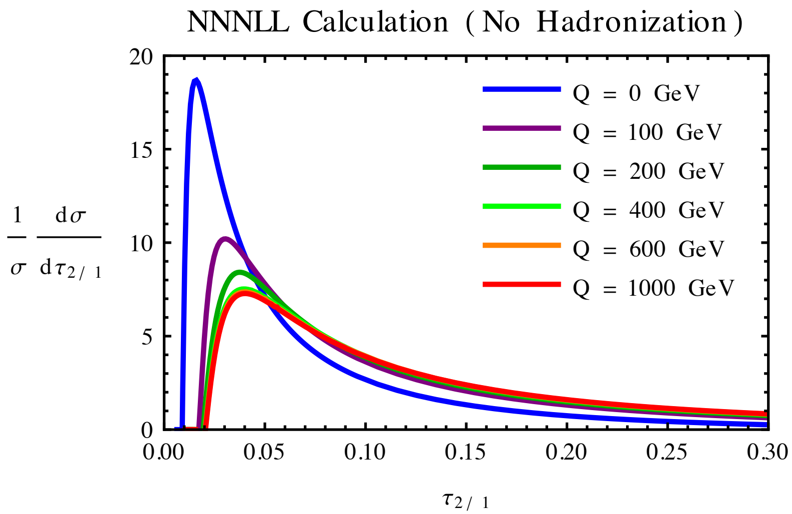
(March 20, 2012)

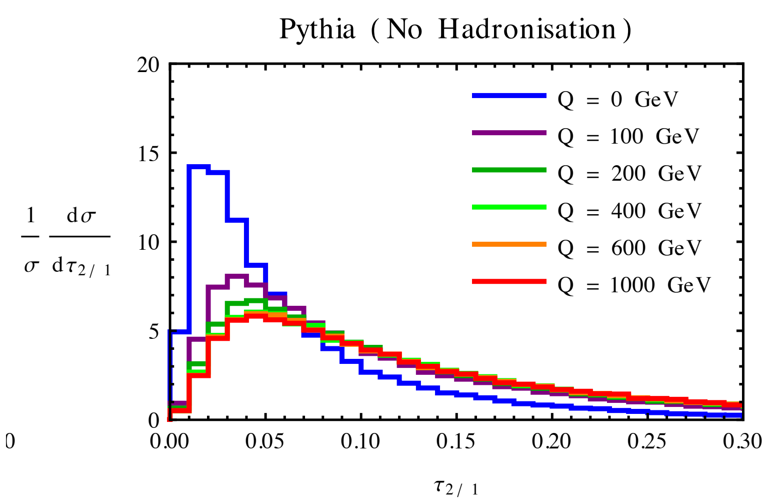


With more data, could be a precision observable.

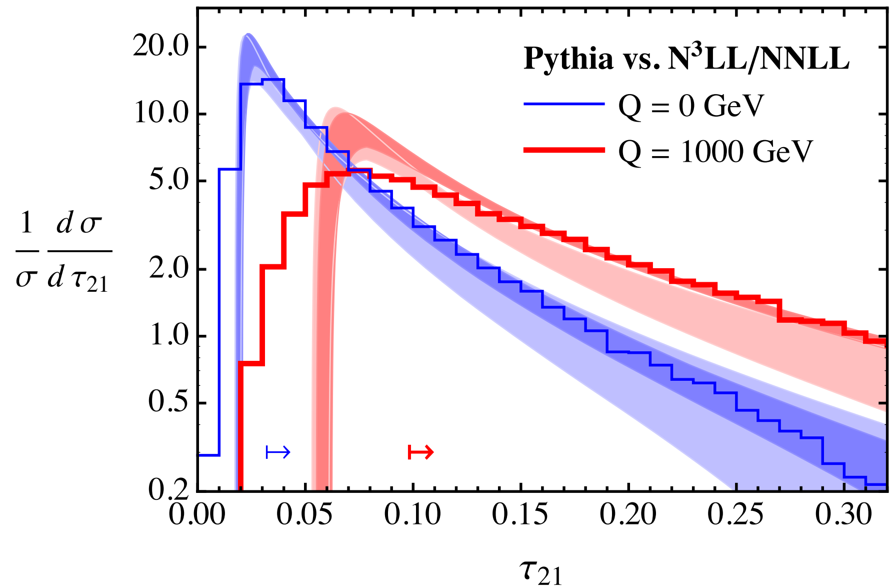
Comparison to theory

arXiv:1204.3898





Theory agrees well with pythia for W jets

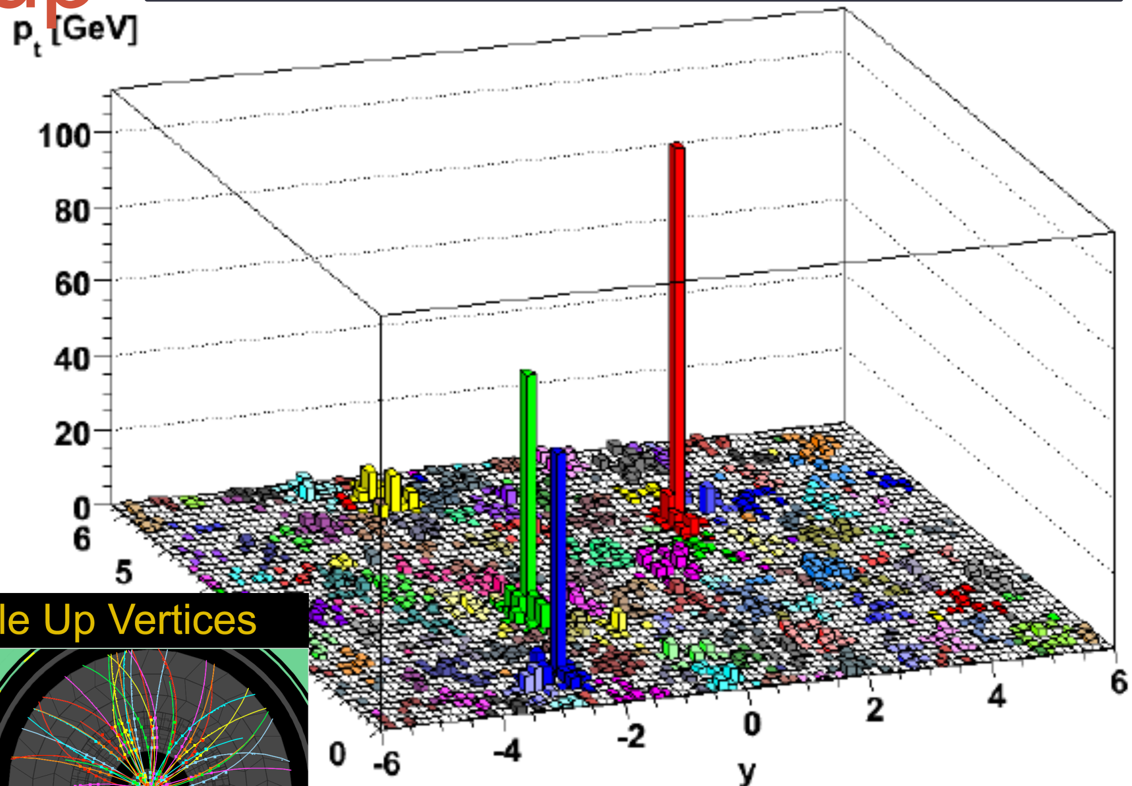


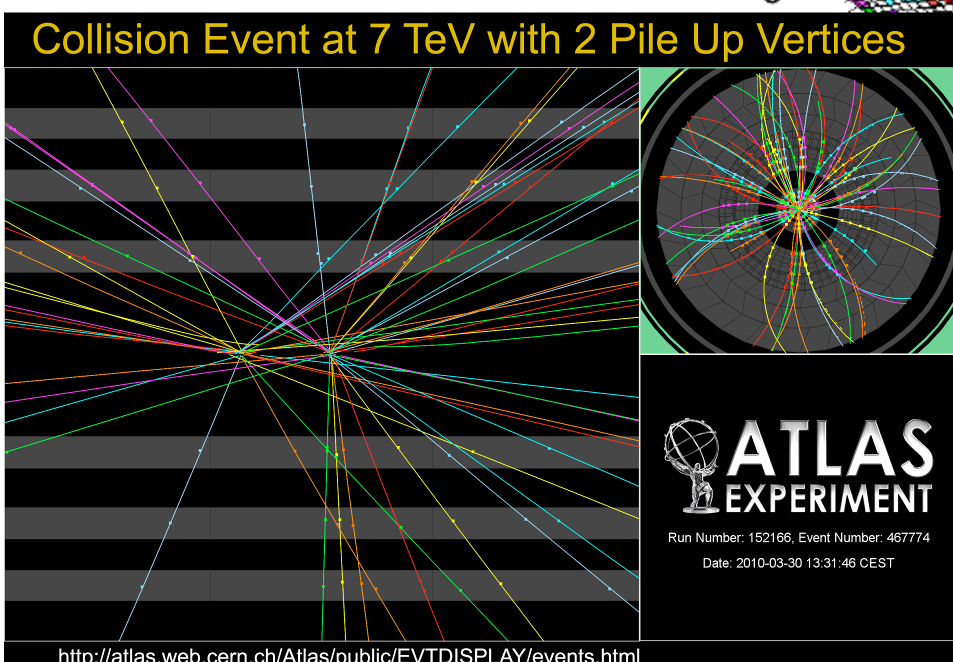
Can τ_N for QCD jets be calculated?

JET GROOMING

Jets with pileup

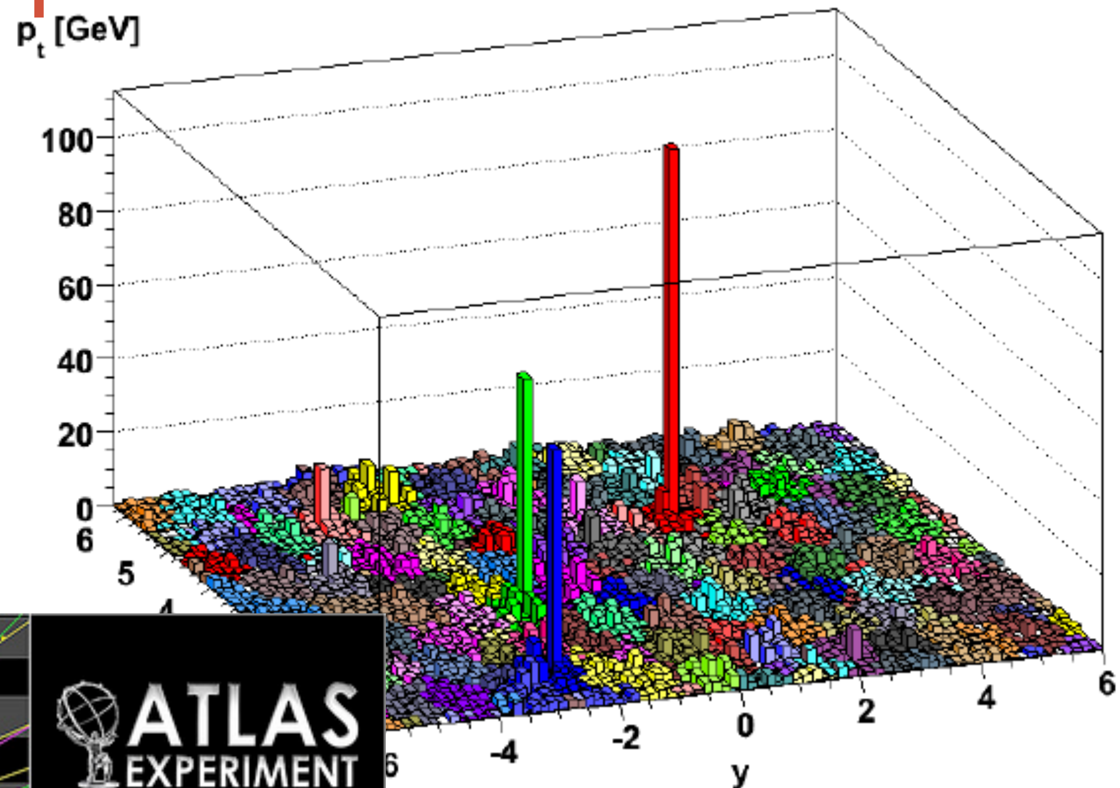
2010 pileup

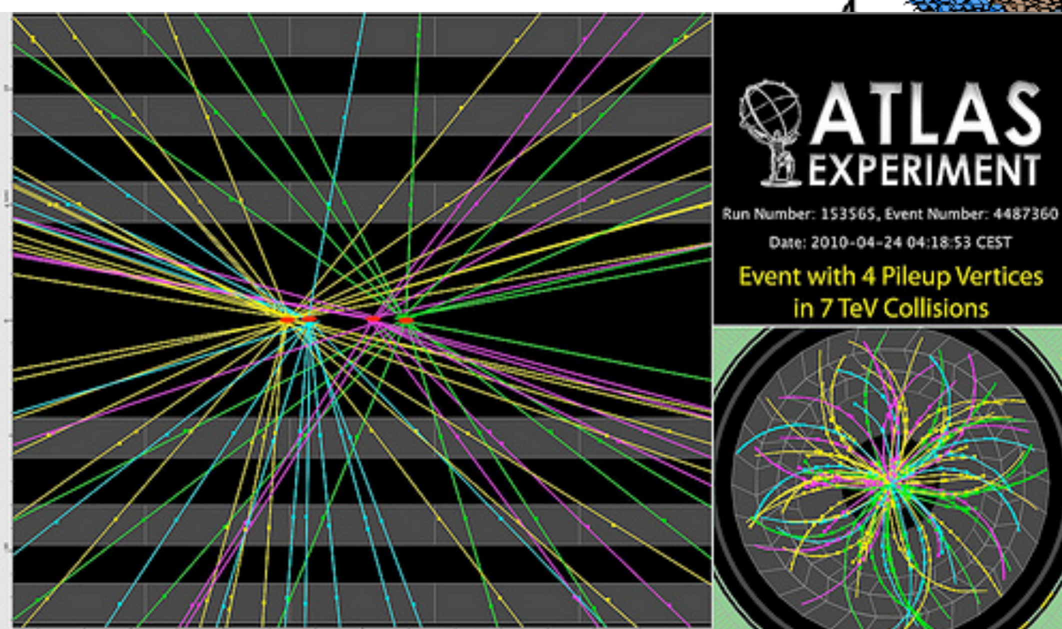




Jets with pileup

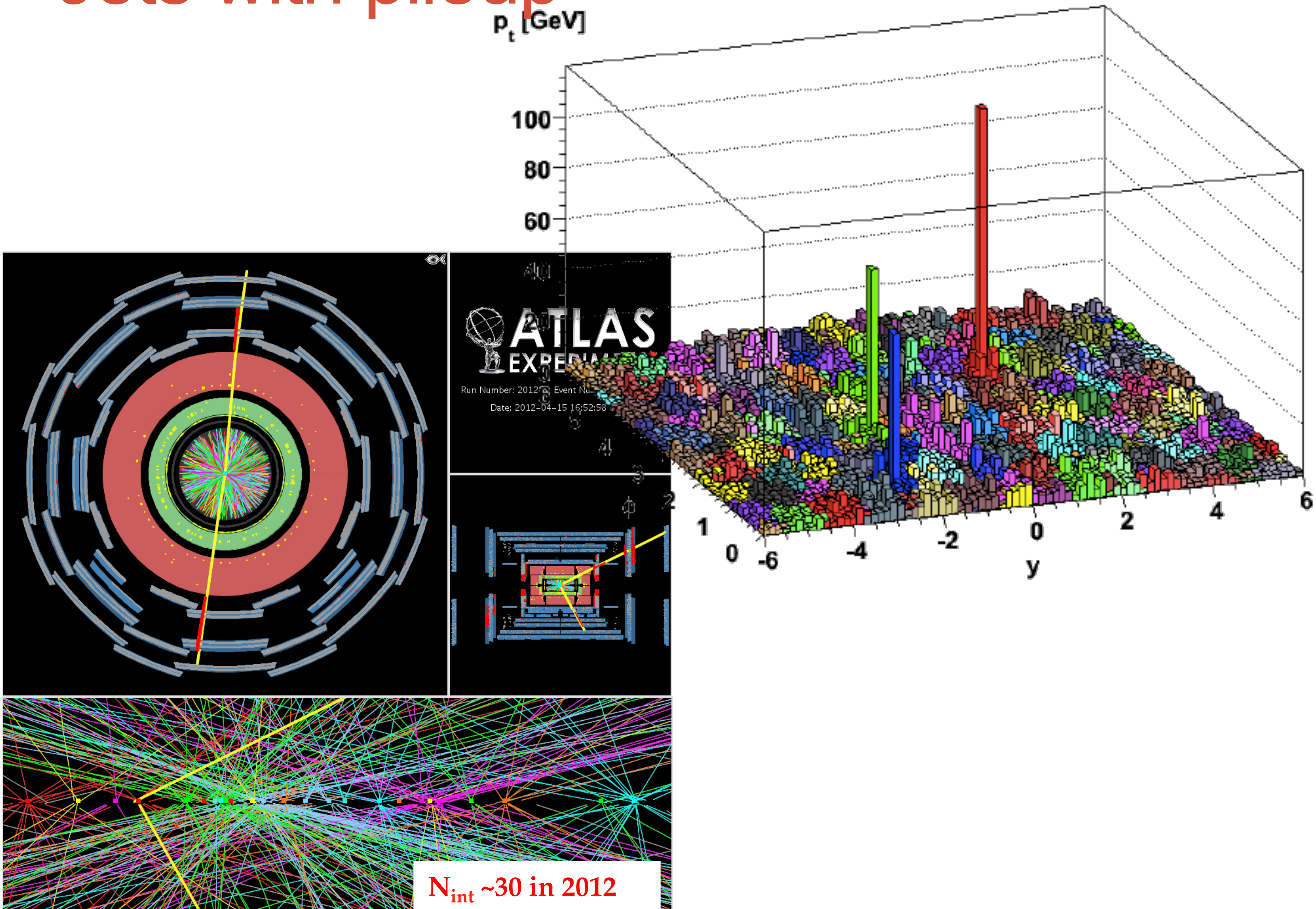
2011 pileup





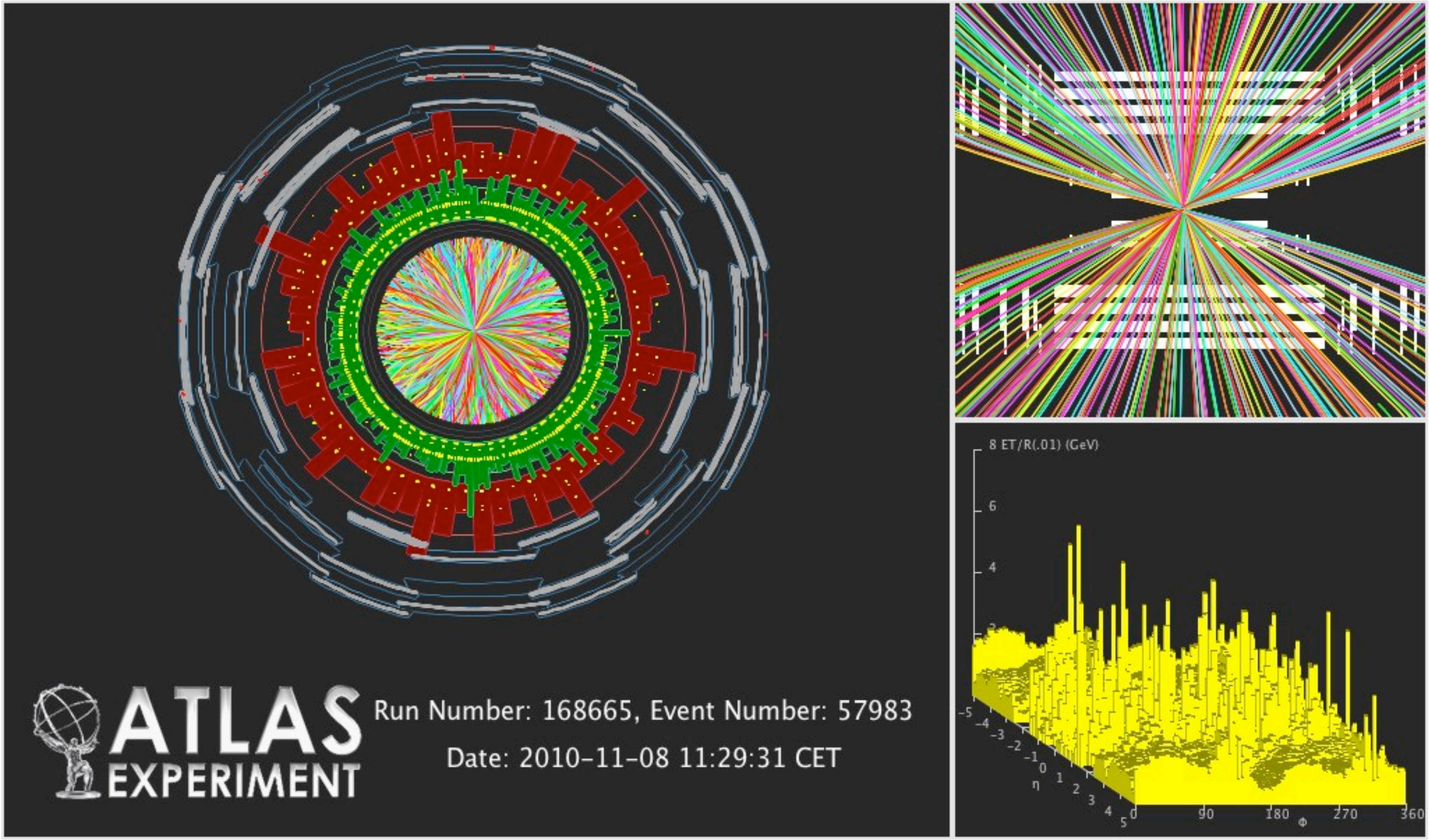
Jets with pileup

2012 pileup



Jets with pileup

2015 pileup?



(This is a heavy ion collision from 2010)

Jet grooming

Can we remove piluep without destroying the event?

Basic idea: remove soft radiation which is not collinear

Filtering (Butterwort et al 2008)

- Recluster fat jet into R=0.3 subjets
- Keep 3 hardest subjets

- ❑ Boosted Higgs
- ❑ Boosted top

Designed for C/A algorithm

Trimming (Krohn et al 2008)

- Recluster fat jet into R=0.3 subjets
- Keep subjets which have energy > 5% jet energy

- ❑ Parton momentum reconstruction
- ❑ Pileup removal

Designed for anti-k_T algorithm

Pruning (Ellis et al 2008)

- Undo clustering steps
- Cluster 1 with 2 if
  - E_1 , E_2 > 0.1 (E_1+E_2)
  - or R_{12} < 0.2
  - otherwise, drop softer of 1,2

- ❑ Jet mass searches
- ❑ Qjets

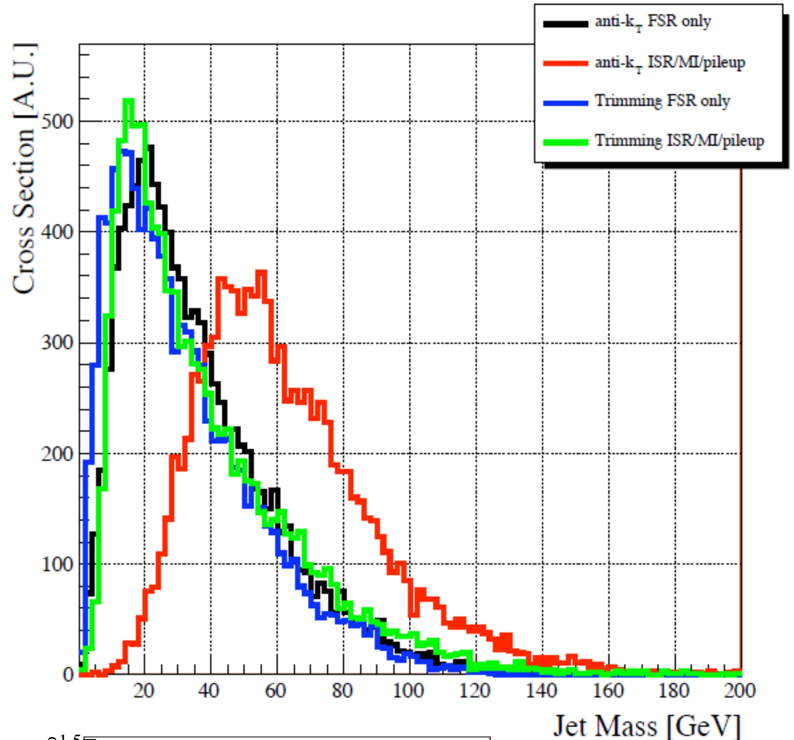
Designed for k_T algorithm

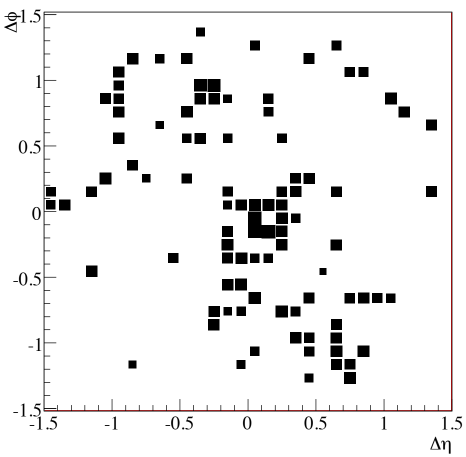
Oversimplified summary

- ❑ All help with jet substructure
- ❑ All help with pileup removal

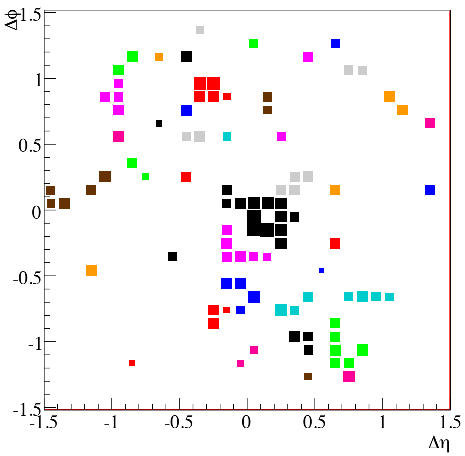
Trimming

1) Make seed jet with anti-k_T (R_0 large)
2) Recluster into subjets with k_T (R_0 small)
3) Remove subjets if $p_T < f_{cut}\, \Lambda_{hard}$
4) Kept subjets give trimmed jet

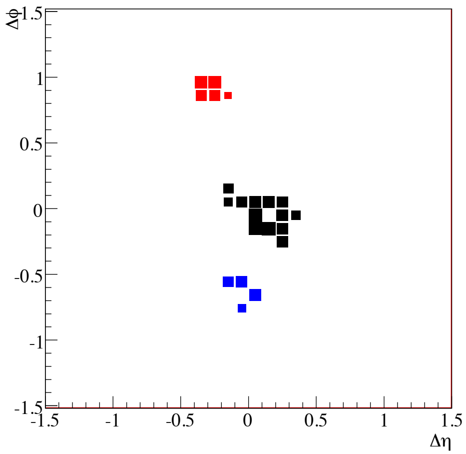




After anti-k_T $R_0 \sim 1.5$



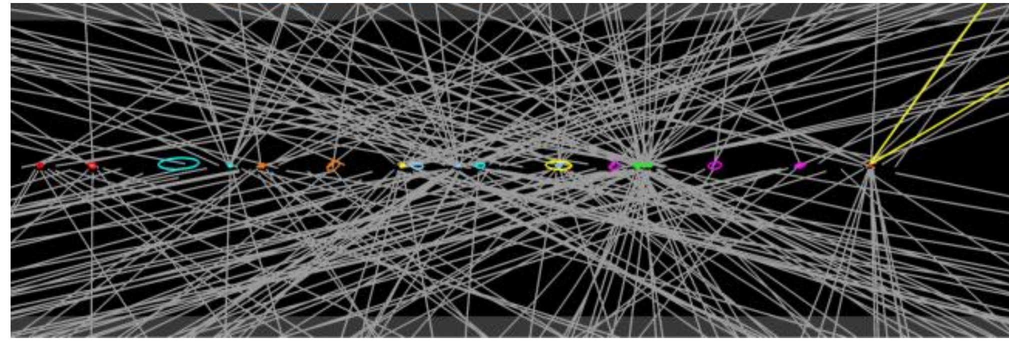
After k_T $R_0 \sim 0.2$



No subjets below 1% of total event p_T

Trimming

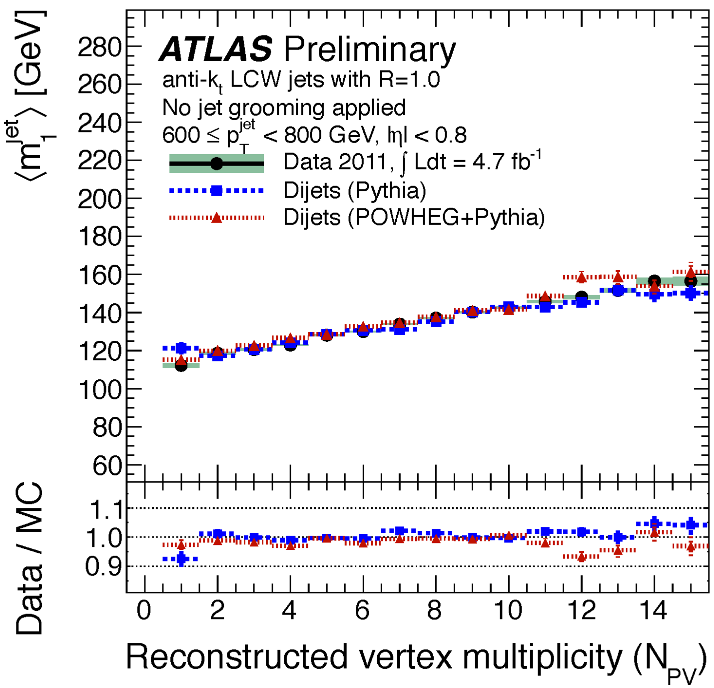
Helps experimentally
with pileup subtraction



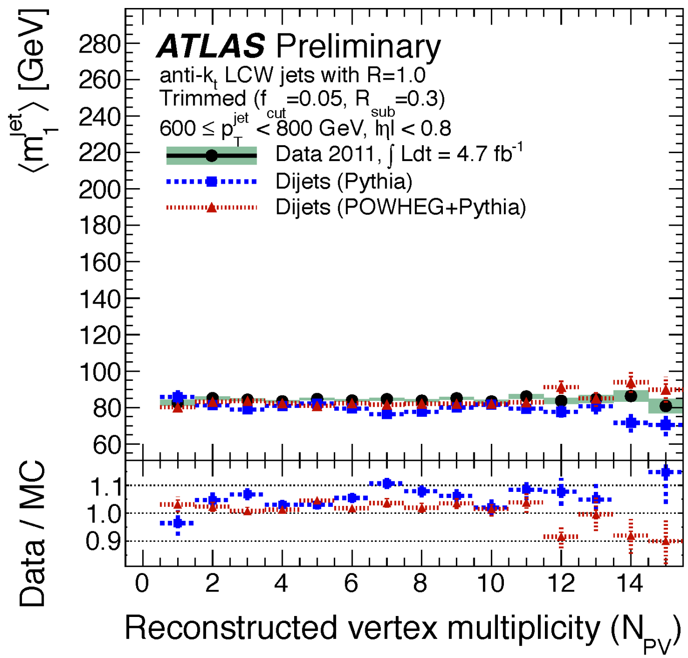
N_{PV} = 30

Jet mass dependence
On $N_{\text{Pileup-Vertices}}$

Before trimming

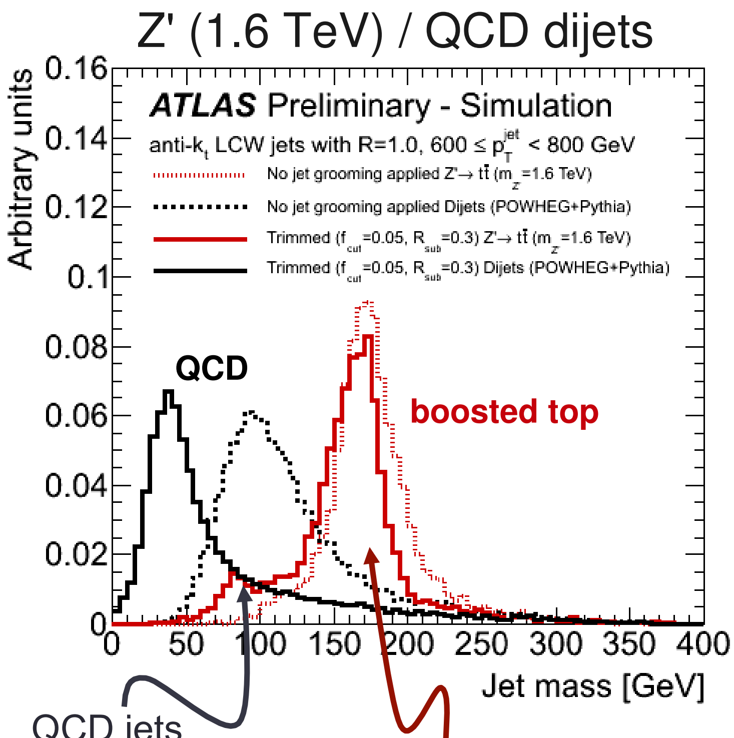


After trimming



Jet mass with grooming

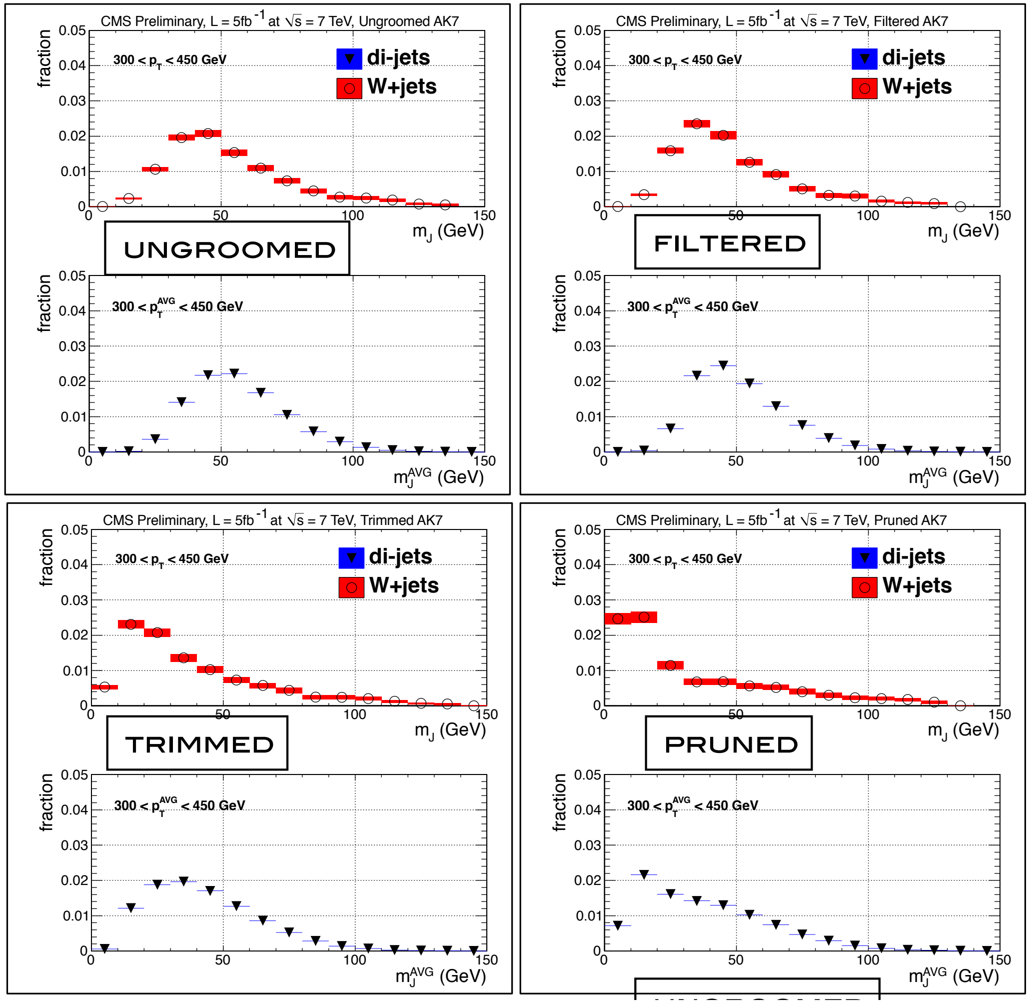
ATLAS simulation



QCD jets decimated by grooming

Top jets unaffected by grooming

CMS data (2012)

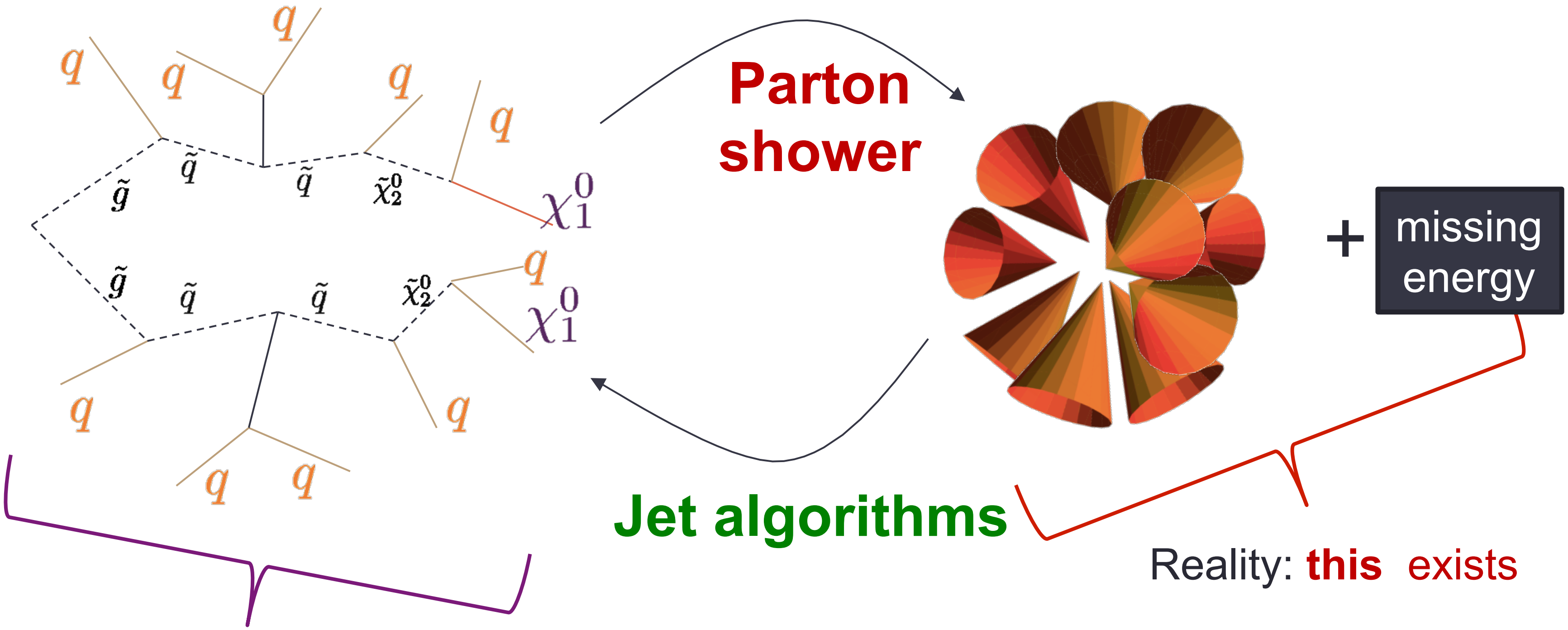


JET PROPERTIES

Jet-parton map

We want to see quarks and gluons:

We observe jets:



Reality: **this** exists

Assumption: **this** exists

What is wrong with the jet-parton map?

It treats jets as 4-vectors

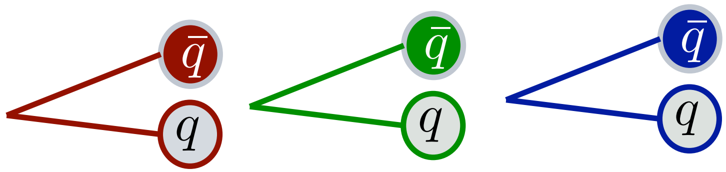
- Jets have **substructure**
  - Fat-jet boosted top/higgs searches
  - Can be groomed
- Jets have **superstructure**
  - **color** connections between jets
- Partons have quantum numbers
  - **Electric** charge
  - QCD charge (quark or gluon?)

} Can these be measured?

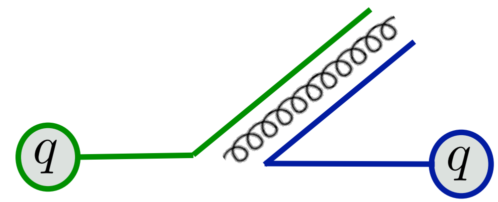
COLOR FLOW

Color coherence in soft radiation

3 quark color dipoles

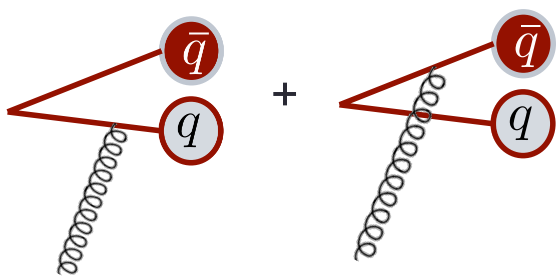


Gluons act like ends of 2 dipoles

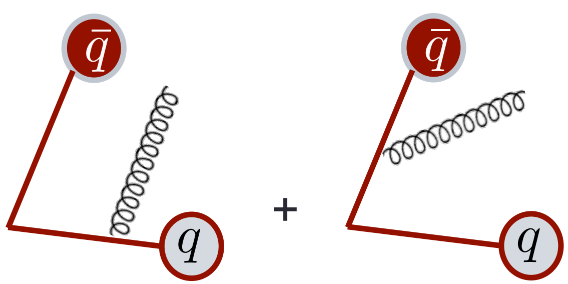


Accurate up to $1/N^2$ ~10% effects

Destructive interference



~ 0



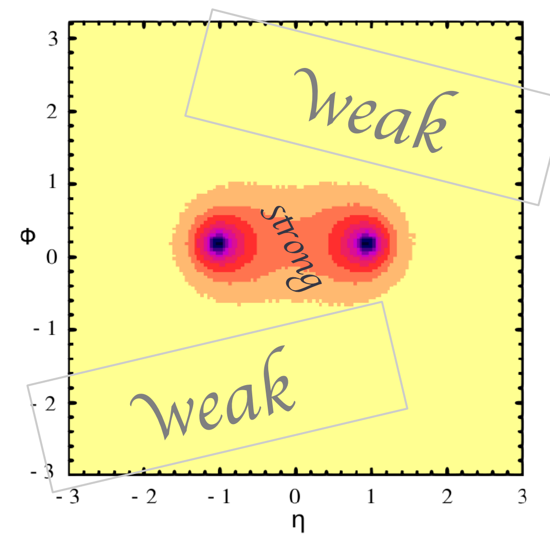
$\neq 0$

Constructive interference

Color coherence

⇕

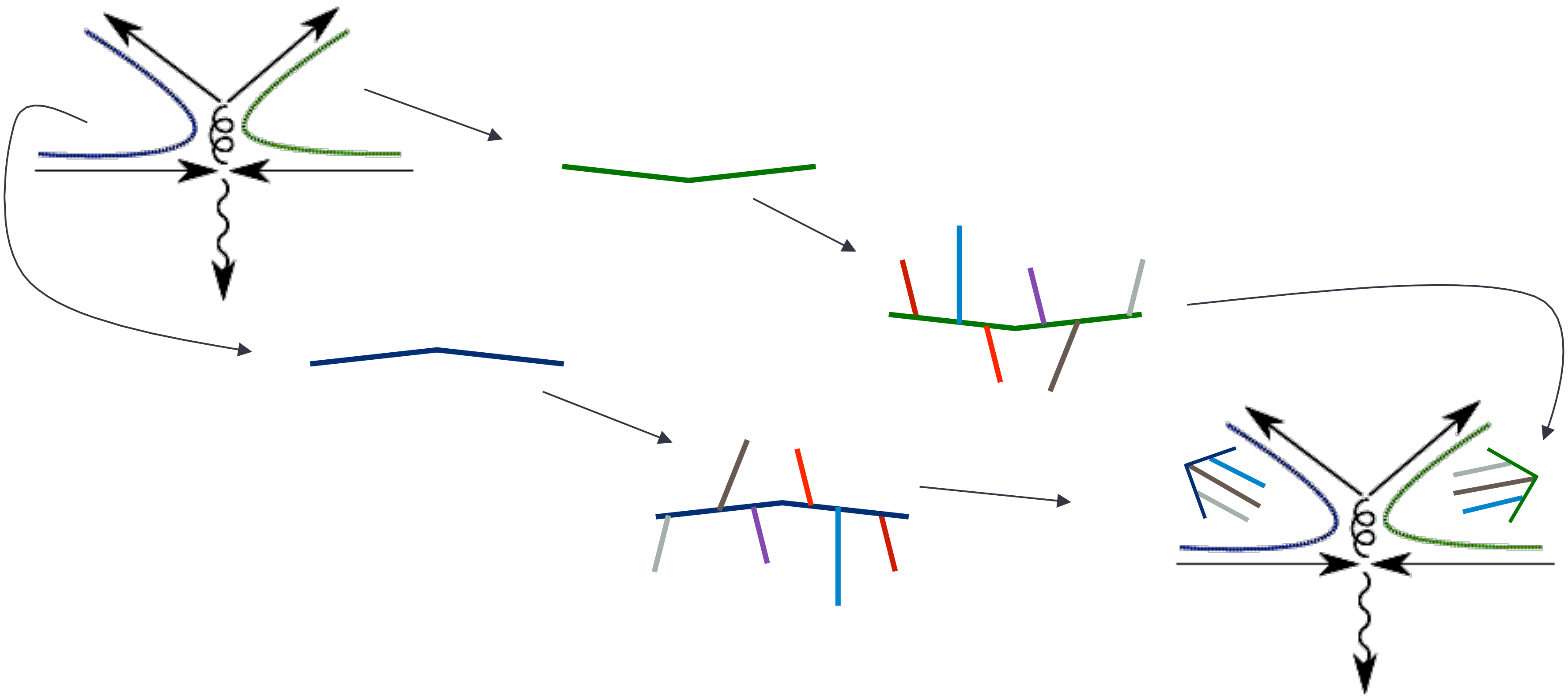
Angular ordering



Pythia simulation

Dipole shower

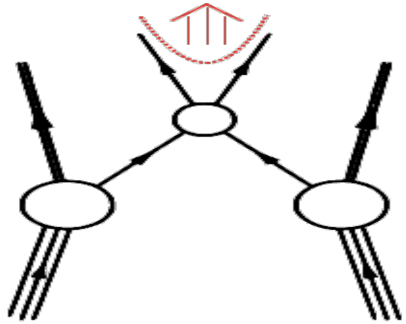
Dipole showers in its rest frame

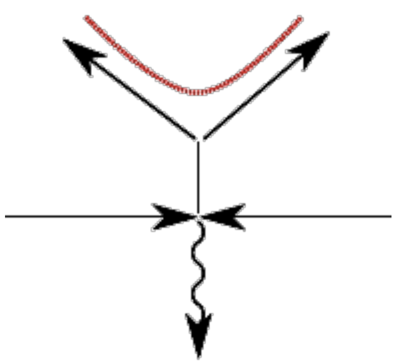


- Boost → **string showers** in **dipole-momentum** direction
- Alternative to angular ordering

Signal vs Background in H+W/Z

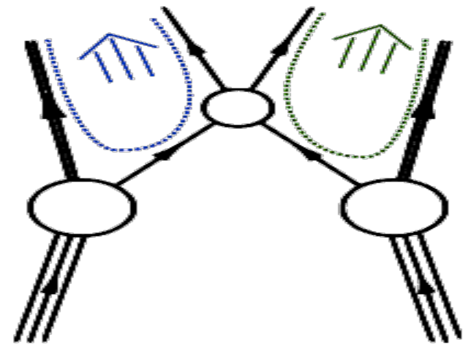
Signal

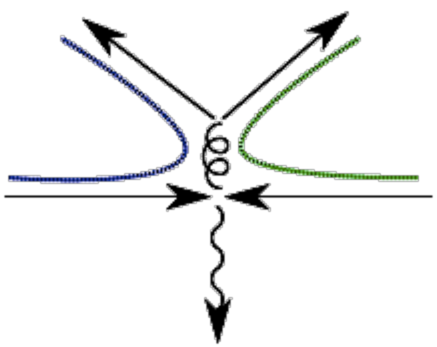




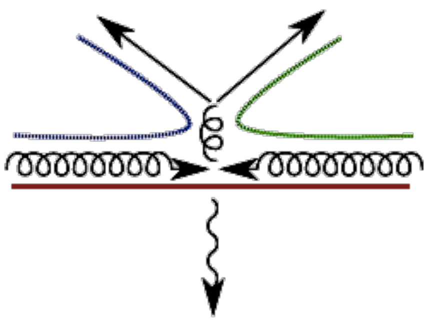
$H \to b\bar{b}$

Background



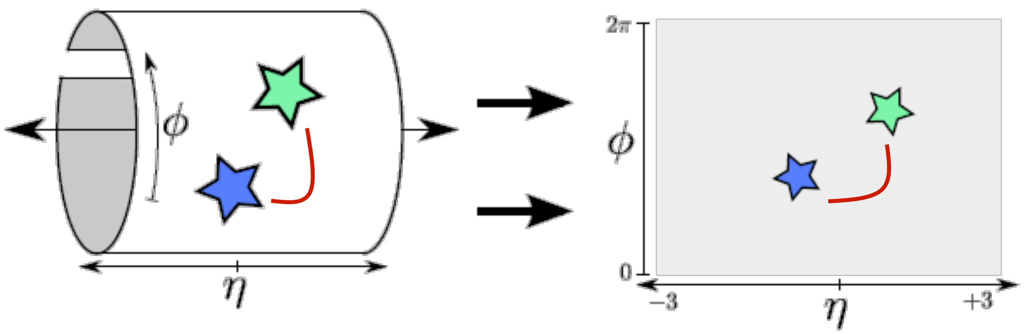


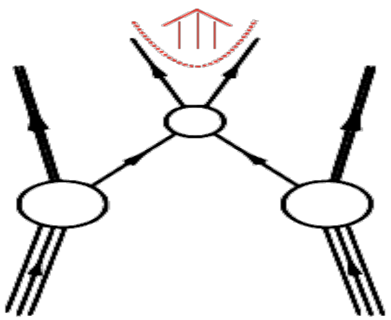
$q\bar{q} \to Zb\bar{b}$



$gg \to Zb\bar{b}$

How do they show up?



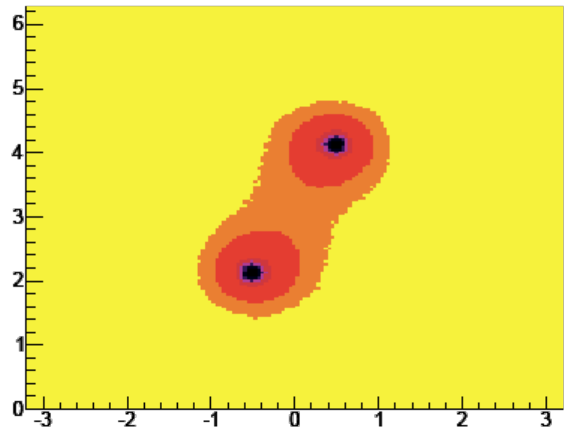


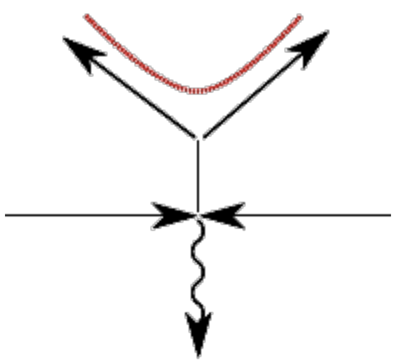
Shower same event
millions of times

Higgs:

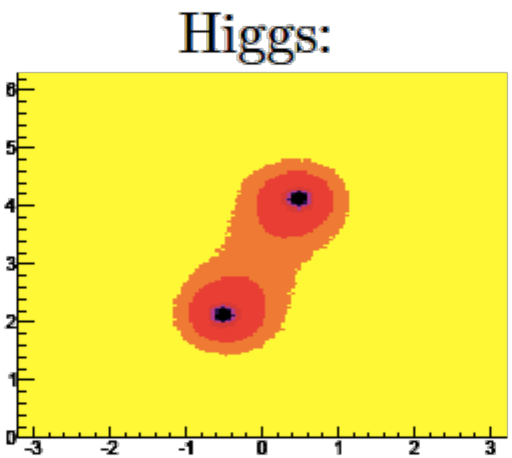
$\Delta\eta_{b\bar{b}} = 1$
$\Delta\phi_{b\bar{b}} = 2$

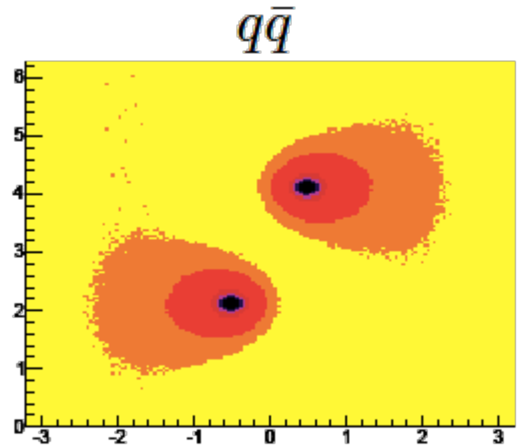
Add up E_T in each cell:

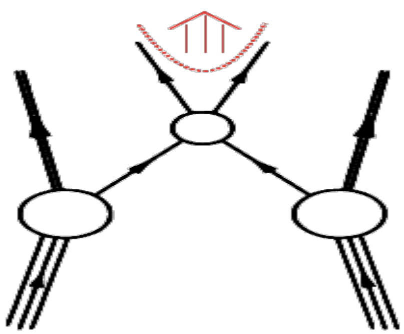


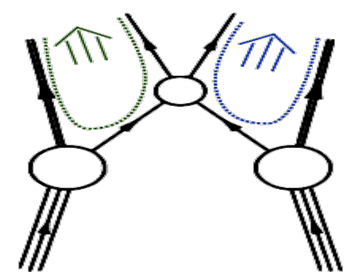


Signal vs background







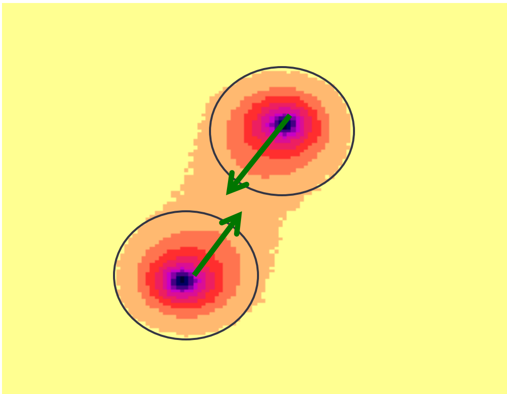


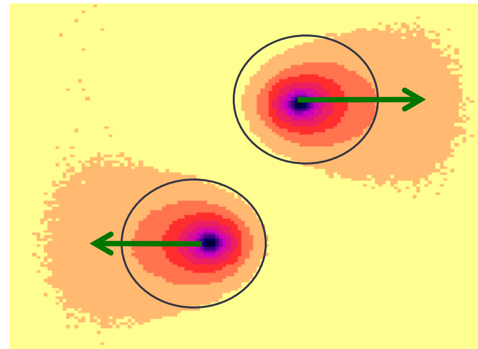
Signal (Higgs)
Color singlet

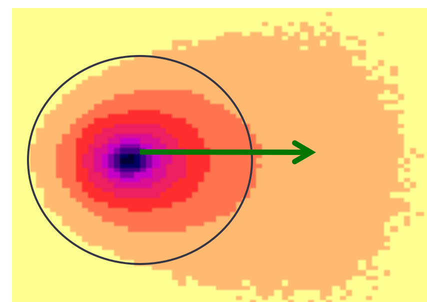
Background (QCD)
Color connected to beam

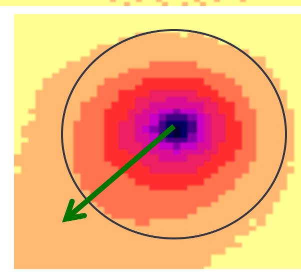
Pull

Gallichio et al. **Phys.Rev.Lett.** 105 (2010) 022001









- Find **jets** (e.g. anti-k_T)
- Construct **pull vector** (~ dipole moment) on radiation in **jet**

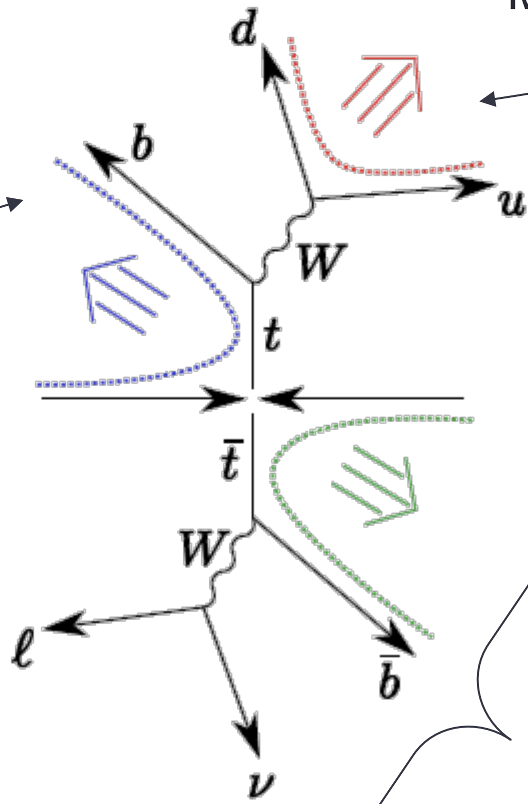
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \, \vec{r}_i$$

- Angle between pull vectors measures color connections

Can be validated on ttbar

b-tag

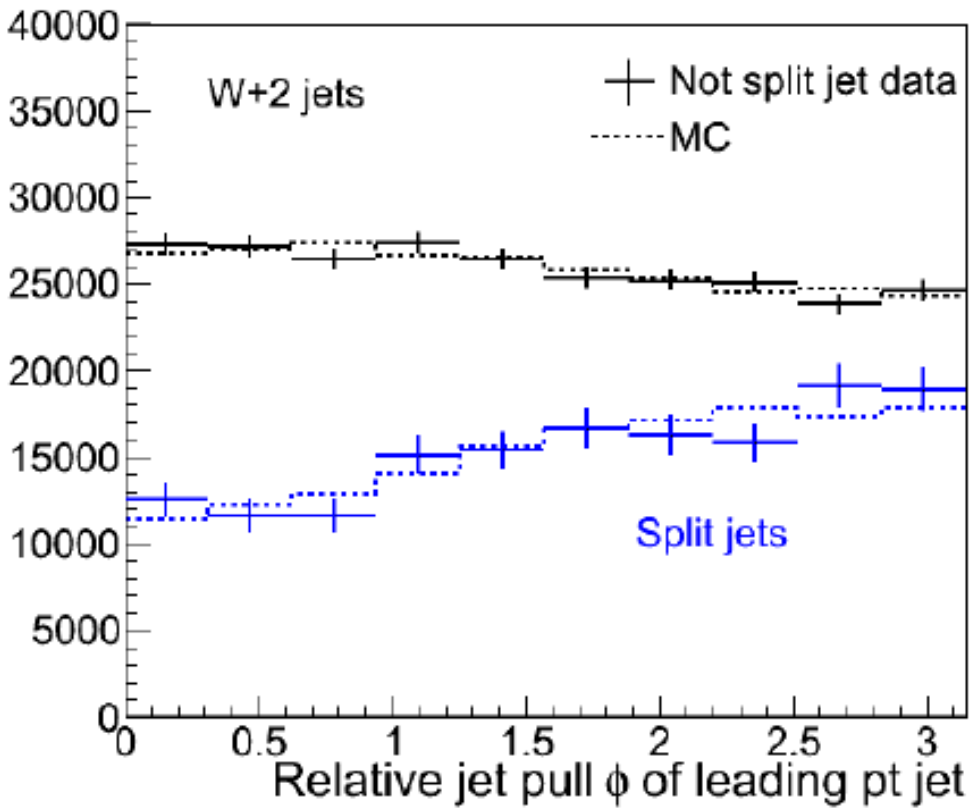
Measure pull



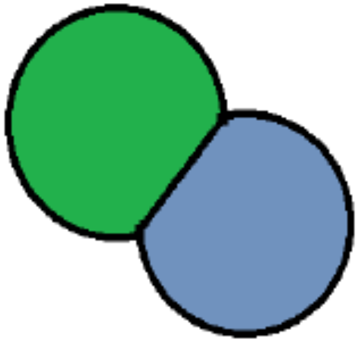
Clean top tag on leptonic side

Measured by D0 (2011)

D0 (arXiv:1101.0648)



Noise/pileup area smaller towards other jet!



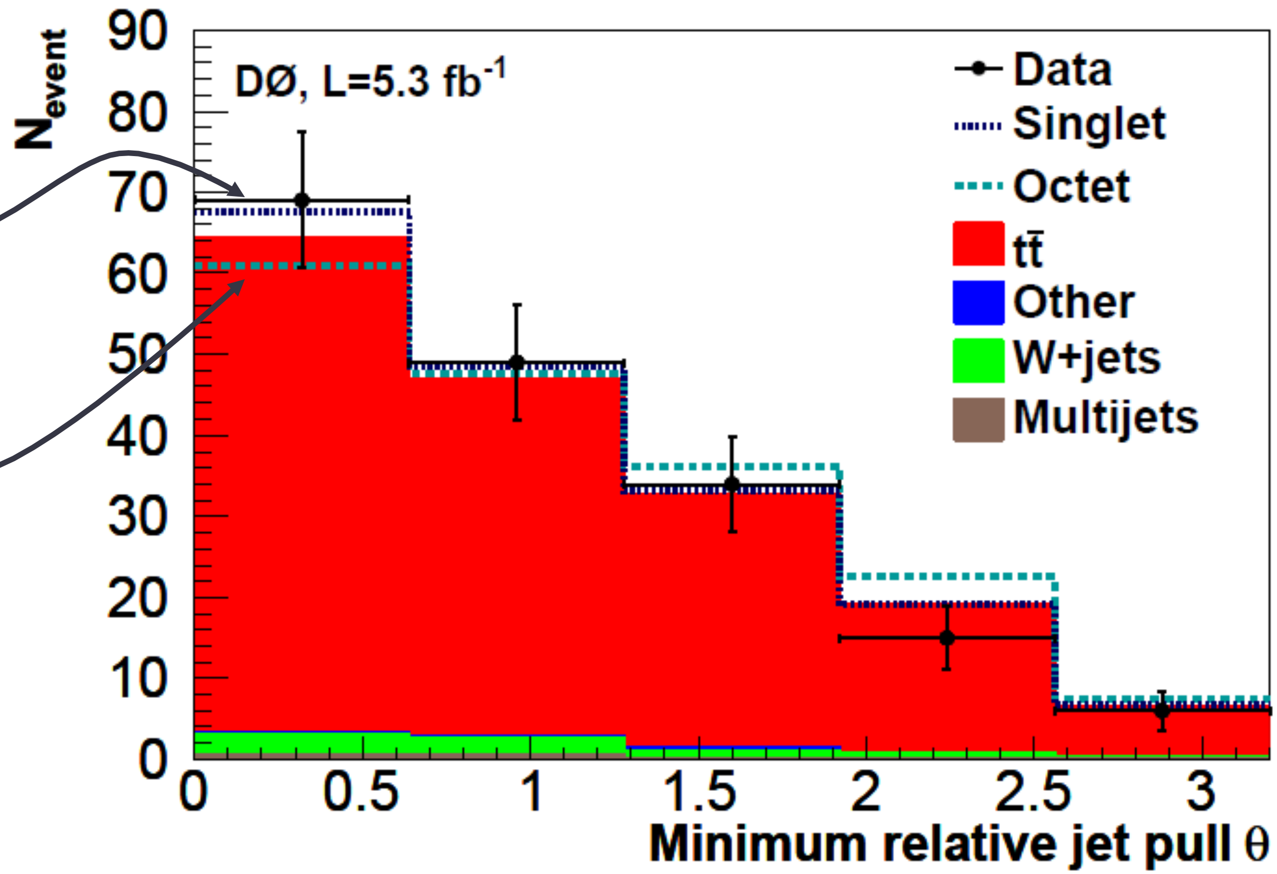
Cells are assigned to the *nearest jet*

Ruled out color octet W

D0 (arXiv:1101.0648)

W is color singlet

W is color octet

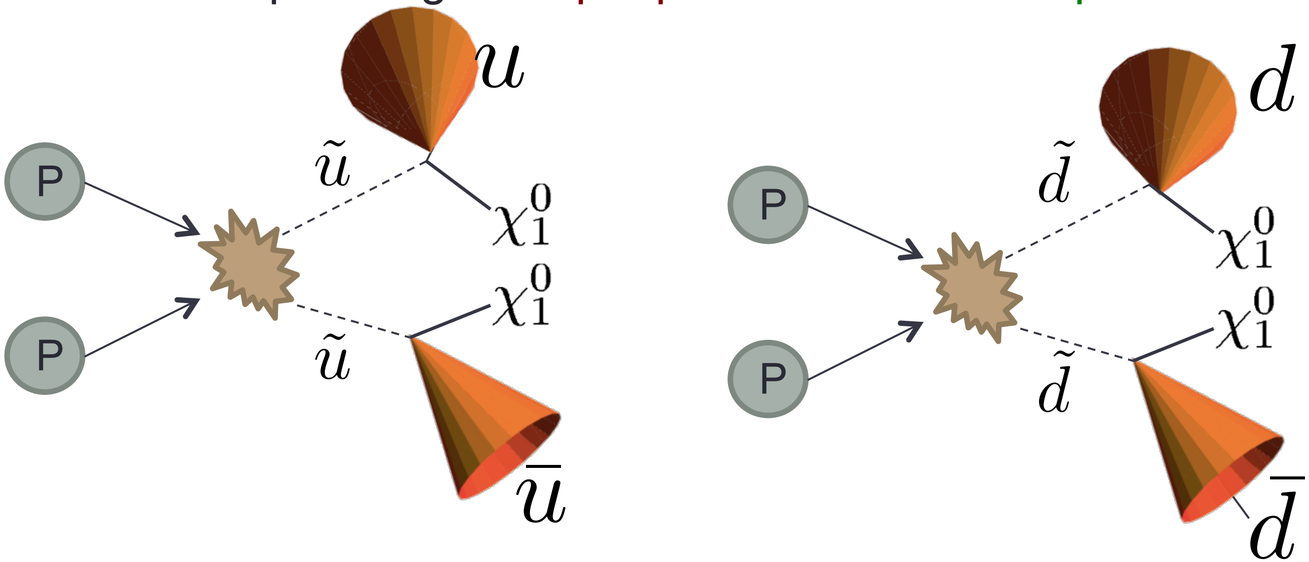


JET QUANTUM NUMBERS

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

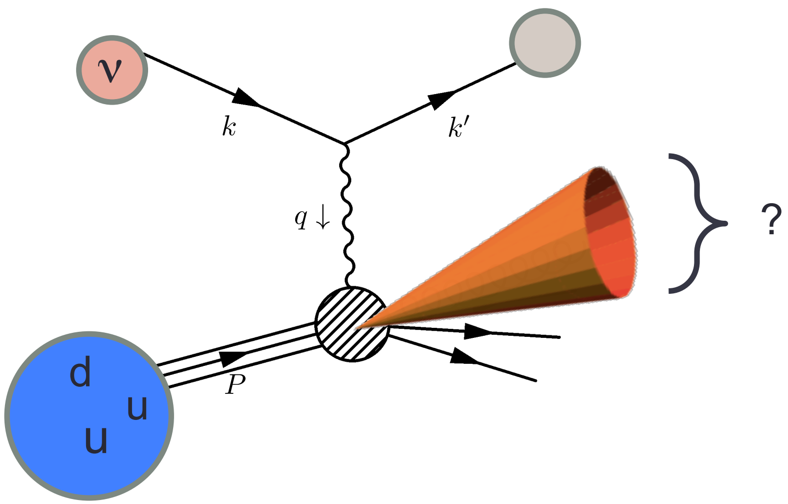


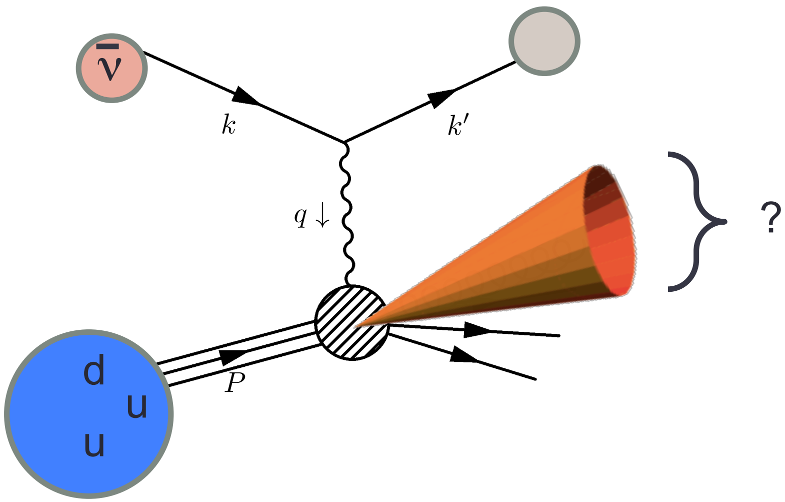
- **W prime** vs **Z prime**

- 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





Long history…

- Late 1970s: do quarks exist?
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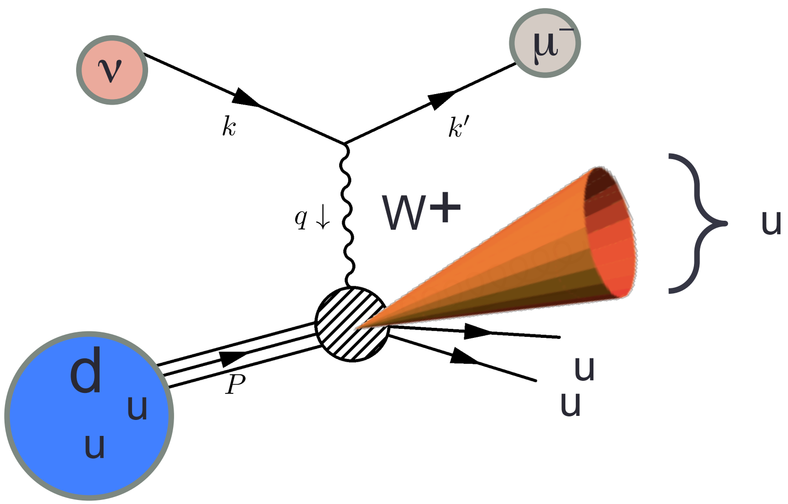
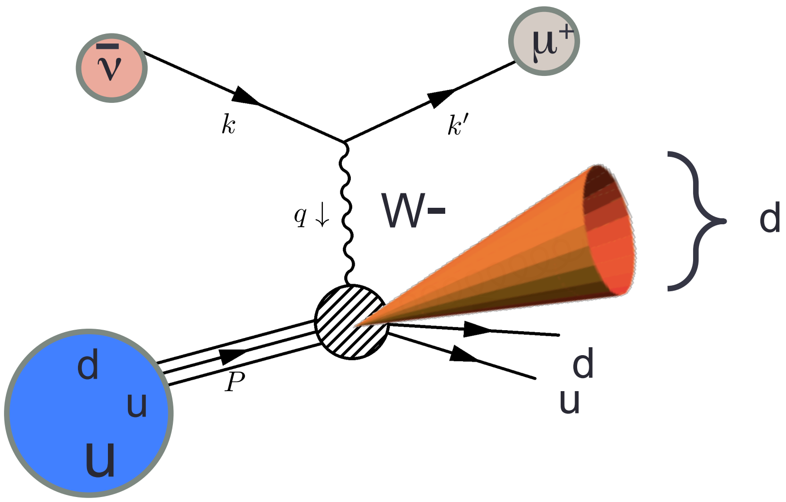




- Charge of jet is unambiguous

Long history…

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

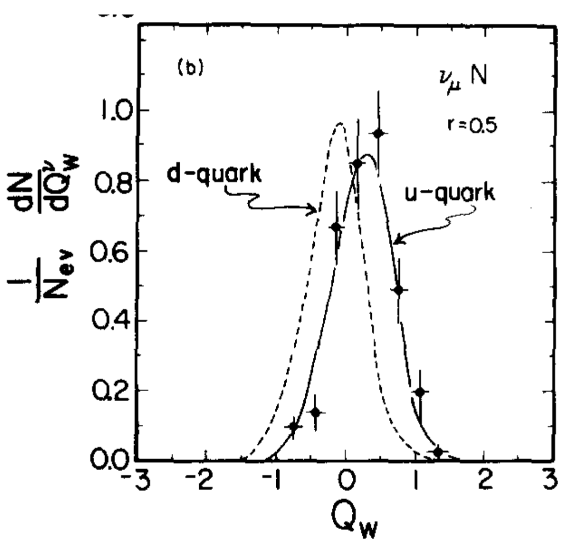
$$Q^i_\kappa = \frac{1}{E_{\text{jet}}} \sum_{j\in\text{jet}} Q_j (E_j)^\kappa$$

$1 \ll \kappa$ would include beam remnants

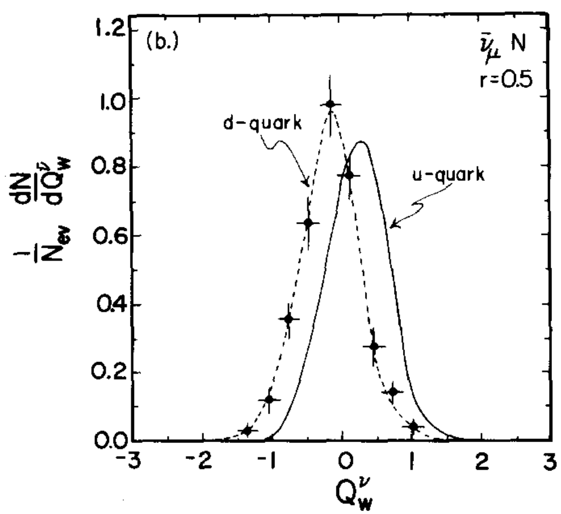
$1 \lesssim \kappa$ would let one particle dominate

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

Fermilab Data (1980)



neutrino ➔ up quark jet

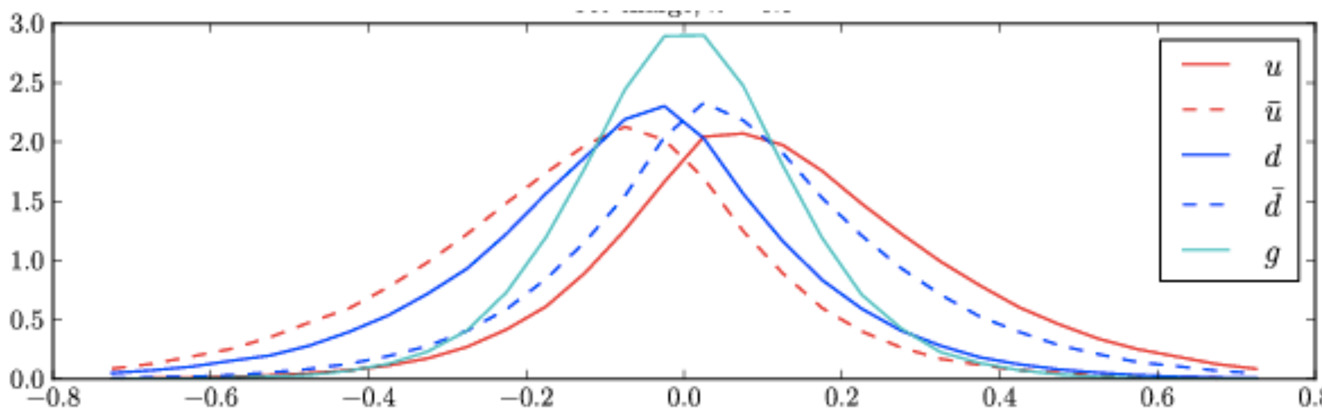


anti-neutrino ➔ down quark jet

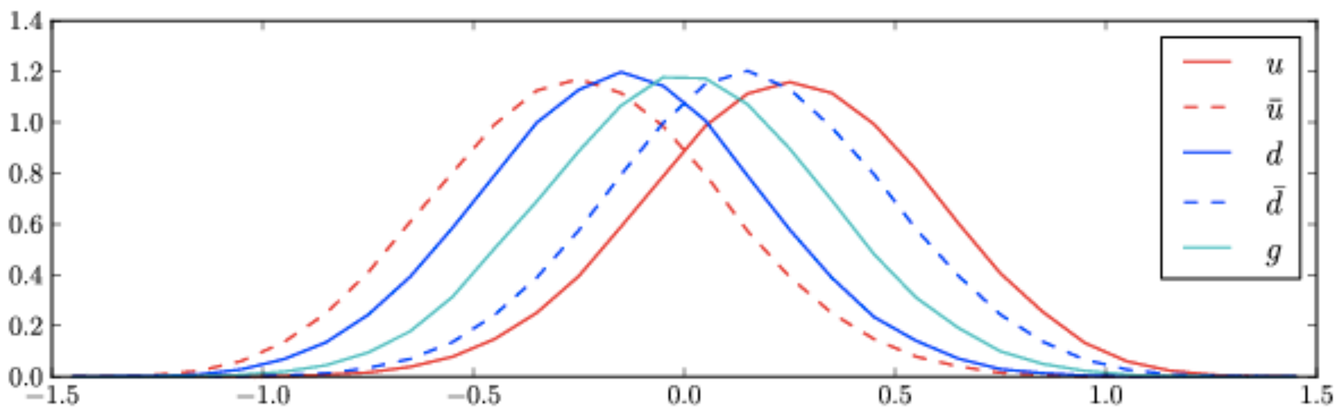
Can it work at the LHC?

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

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



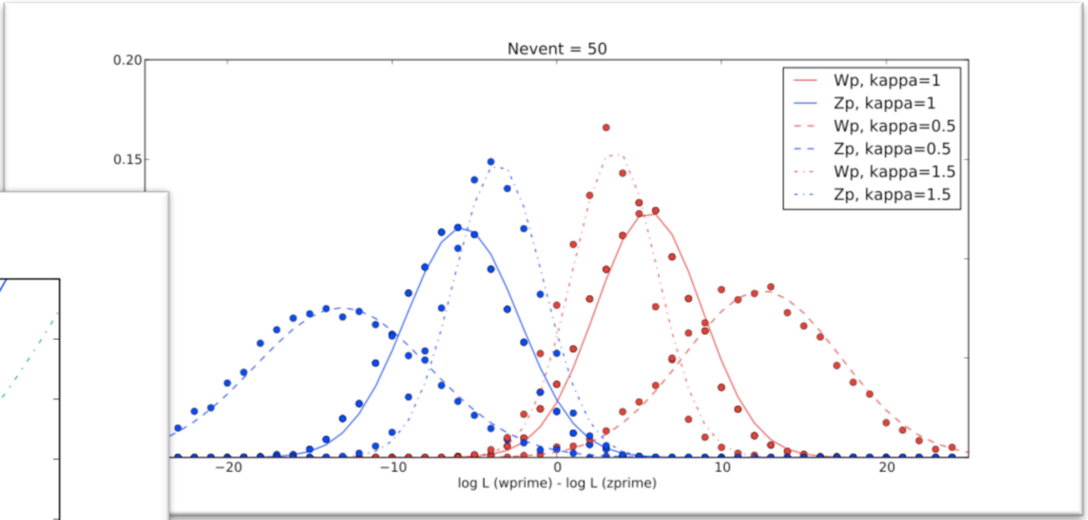
κ=1

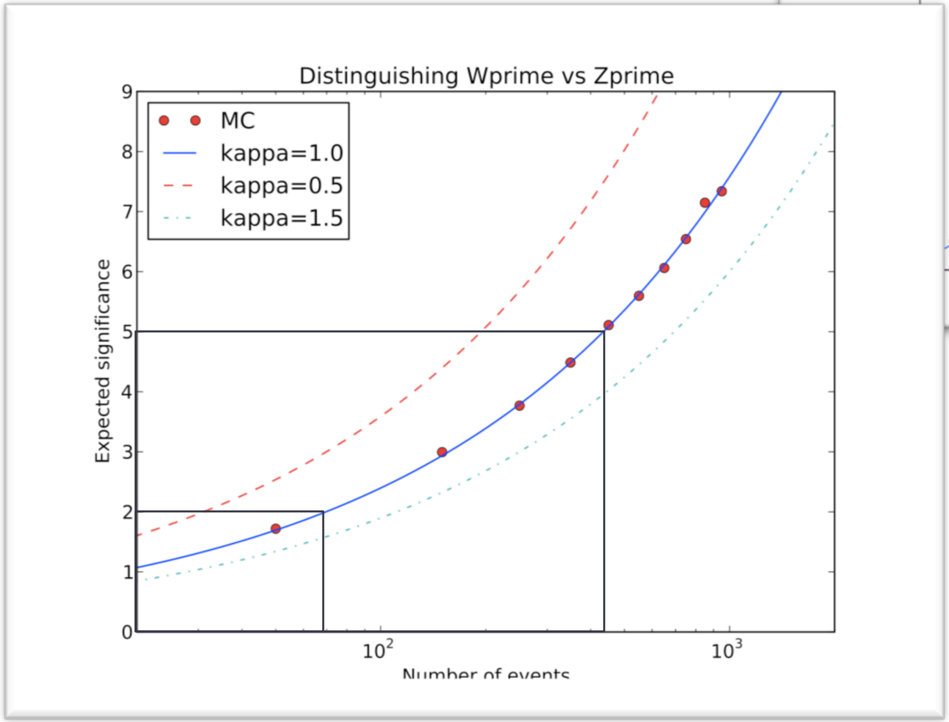


κ=0.5

Distinguishes W ' from Z '

Log-likelihood distribution for 1 TeV resonance, various κ

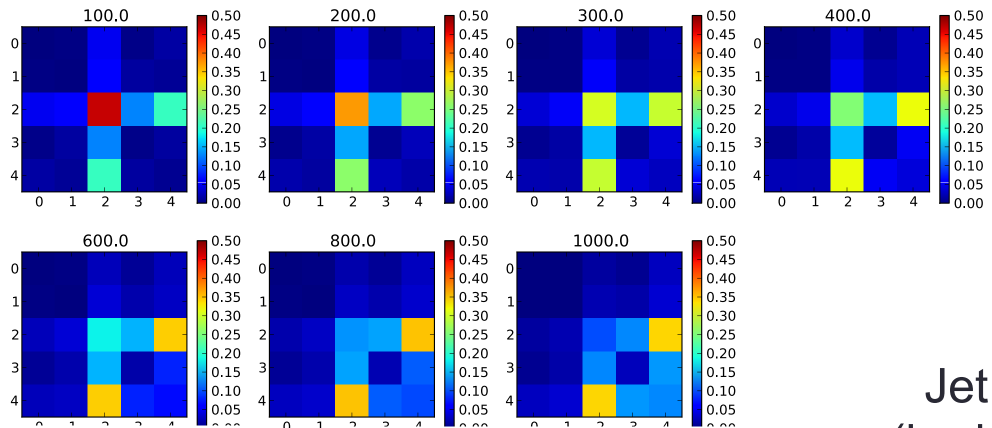




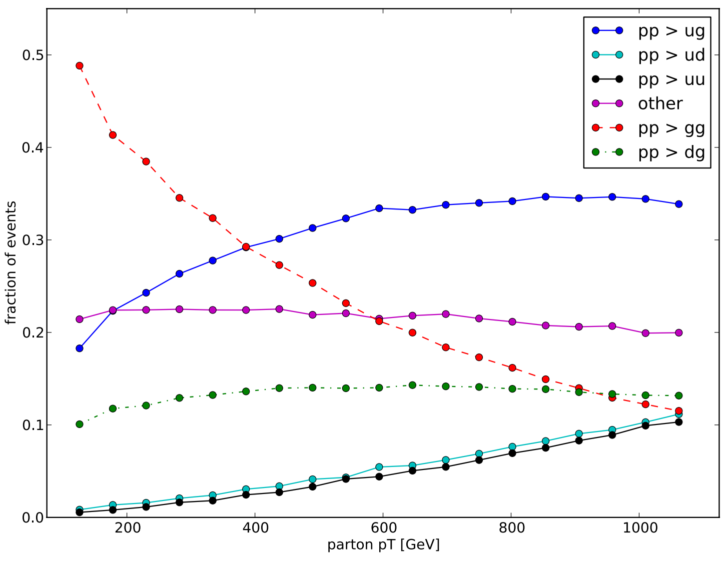
2σ with 30 events
5σ with 200 events

Calibrate on standard model

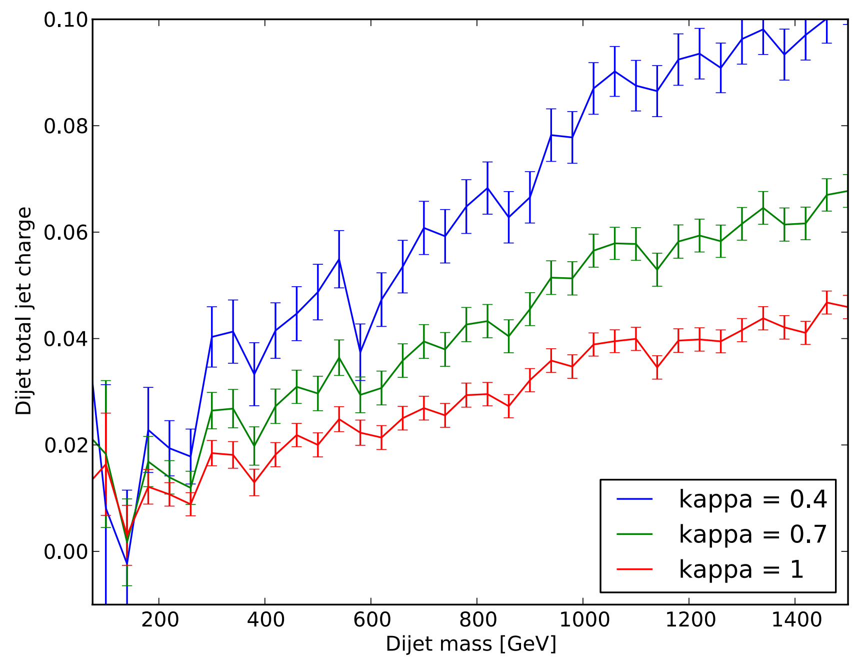
2D charges (parton level)
for different pT



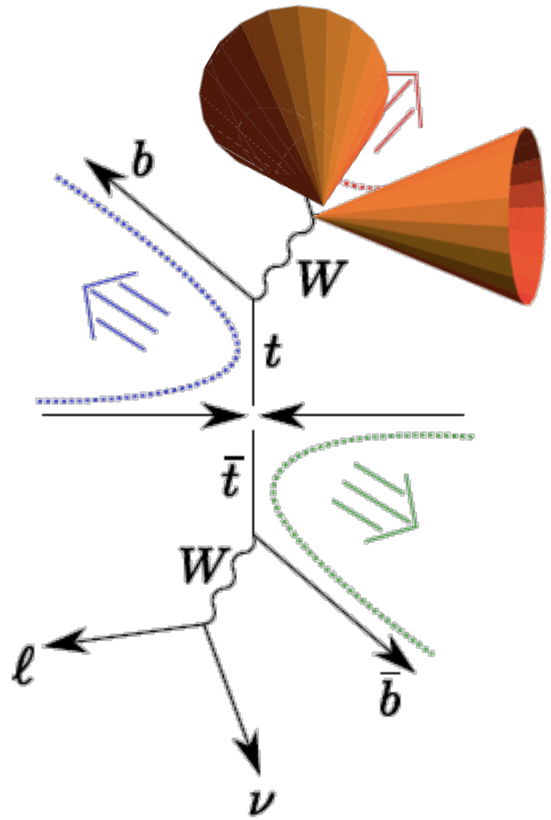
Fractions
(parton level)



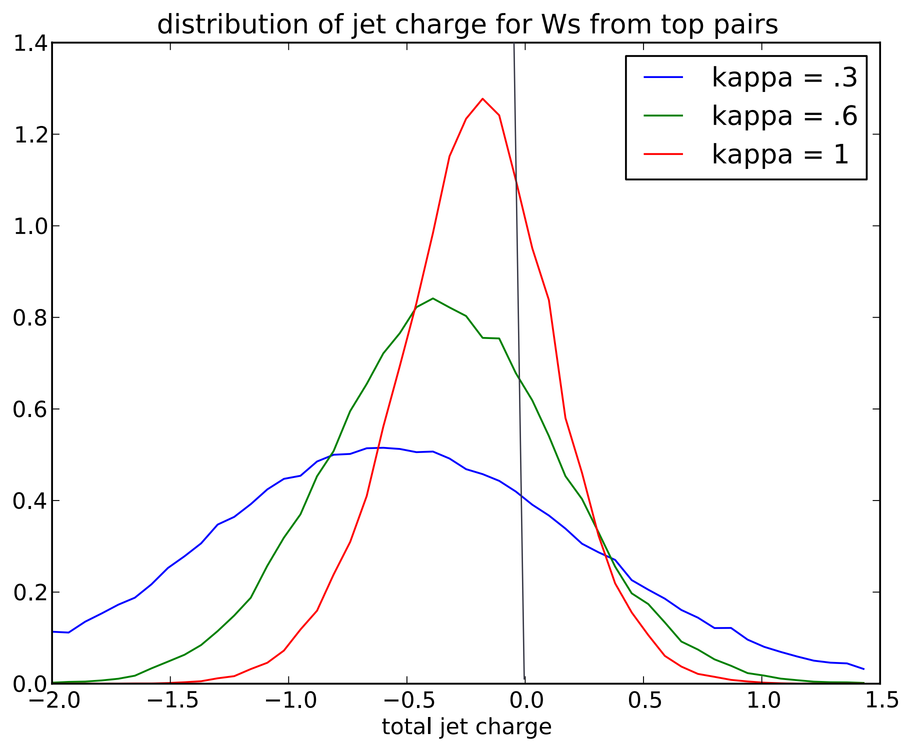
Jet charge
(hadron level)



Can also test on top quarks



Measure sum of jet charges from W decay products



Top Applications

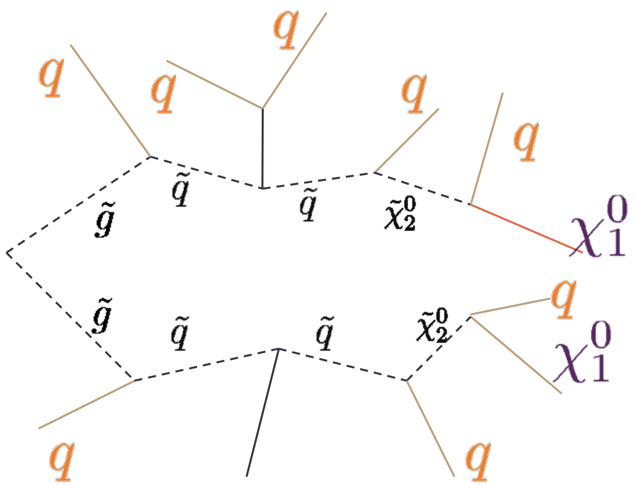
- Measure hadronic W charge
- Measure top charge
- Measure top polarization

Data

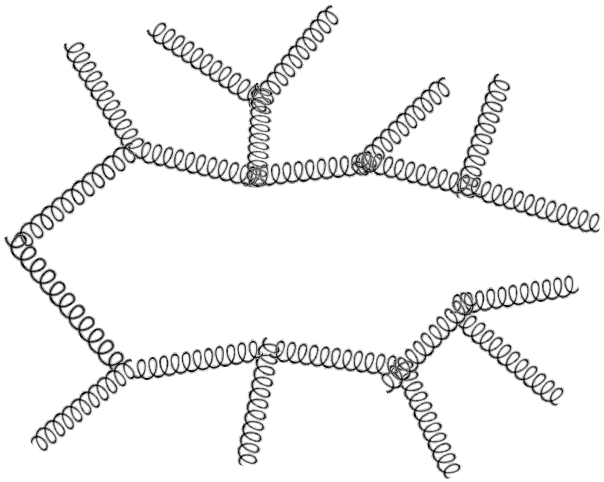
No LHC data yet

QCD charge: quark or gluon

New physics mostly **quark jets**



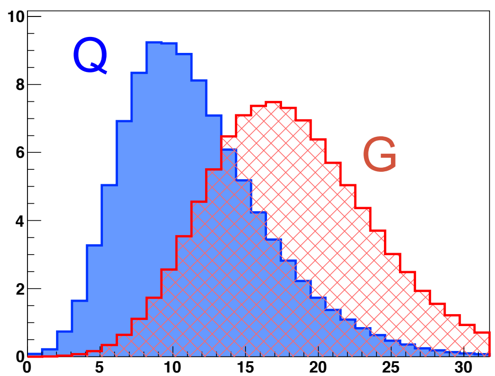
Backgrounds mostly **gluon jets**



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

Jet shape variables

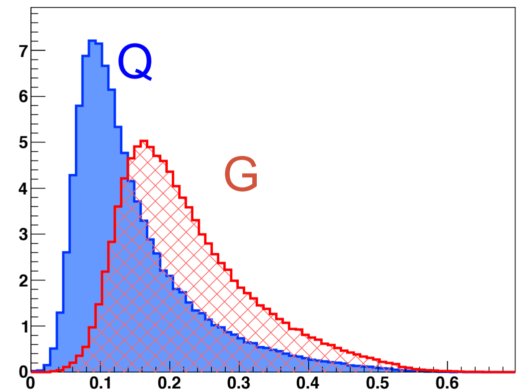
Charged particle count



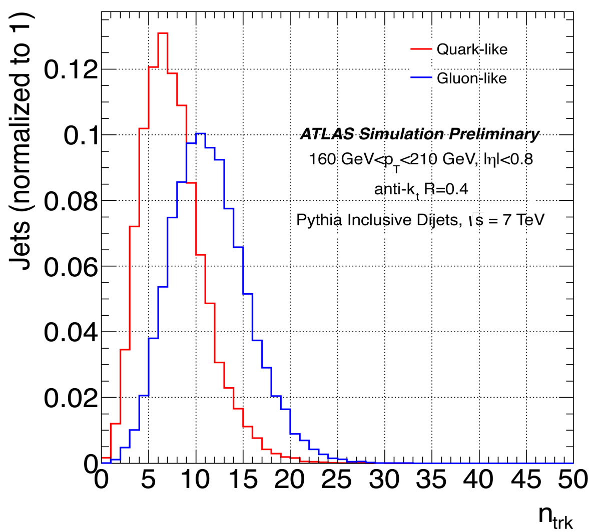
Colors backwards
(sorry)

PYTHIA

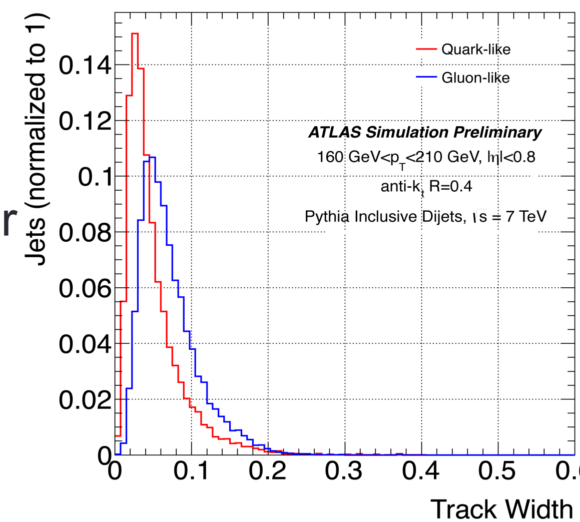
Linear radial moment (girth/track width)



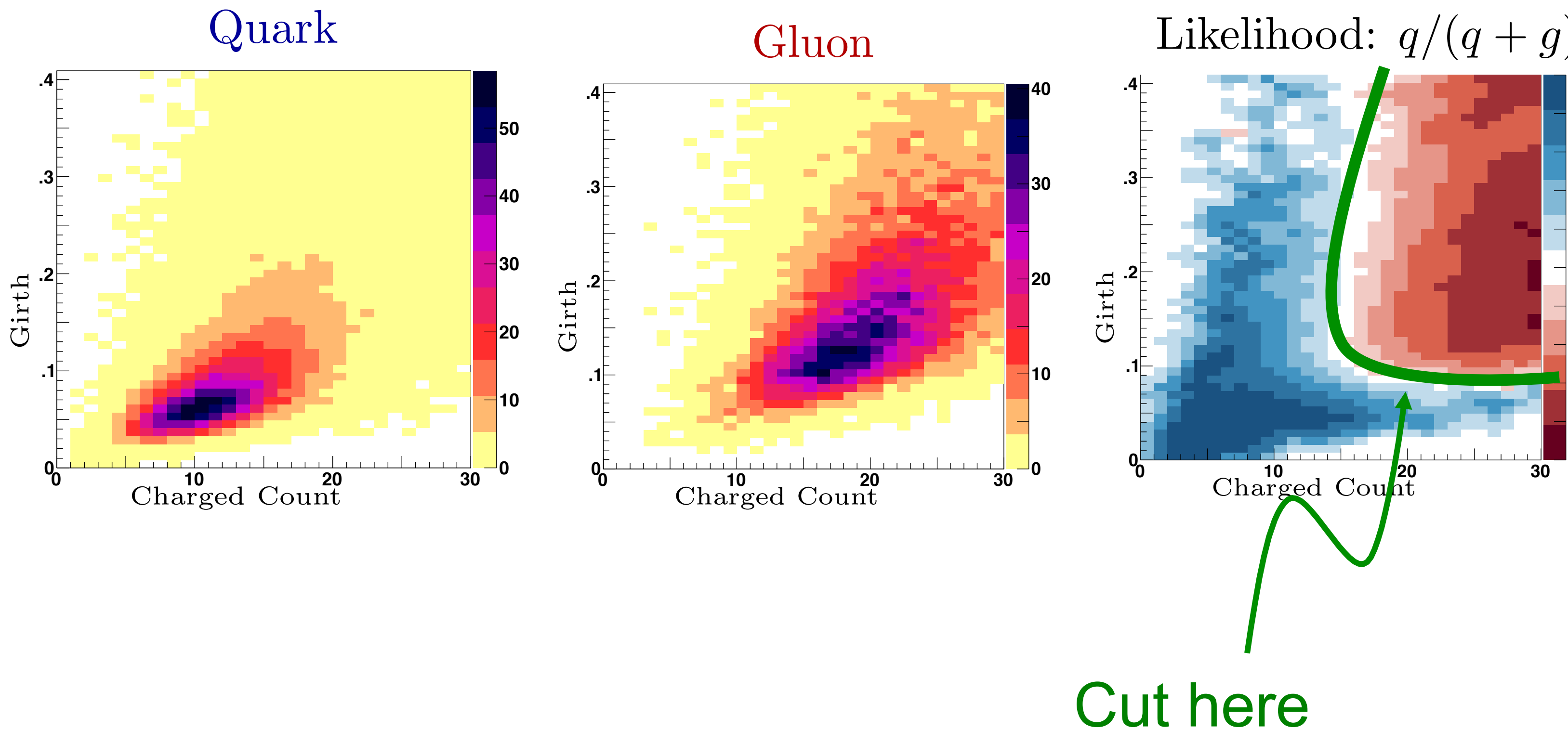
$$= \frac{1}{p_T^{jet}} \sum_{i\in \text{jet}} p_T^i |r_i|$$



ATLAS
Full detector
simulation



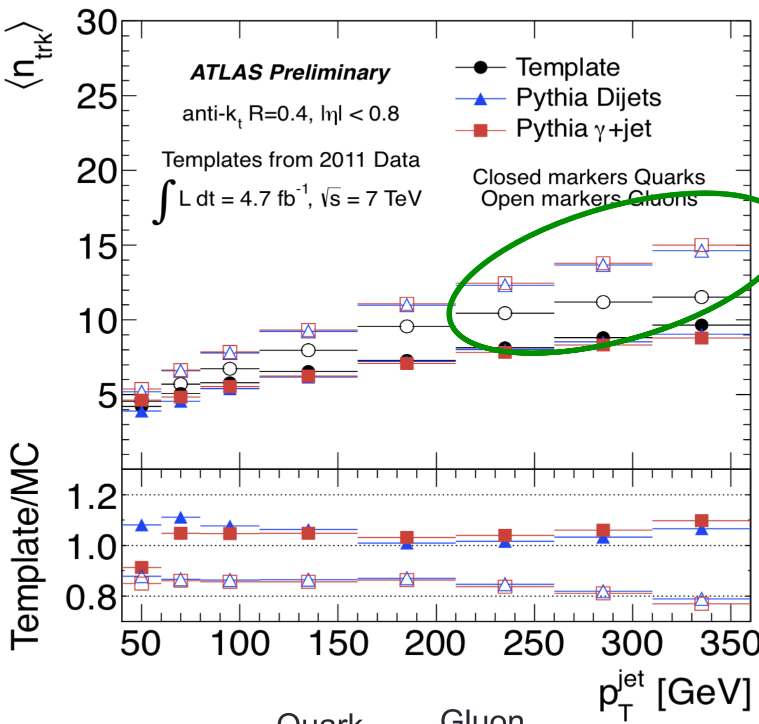
2D distributions

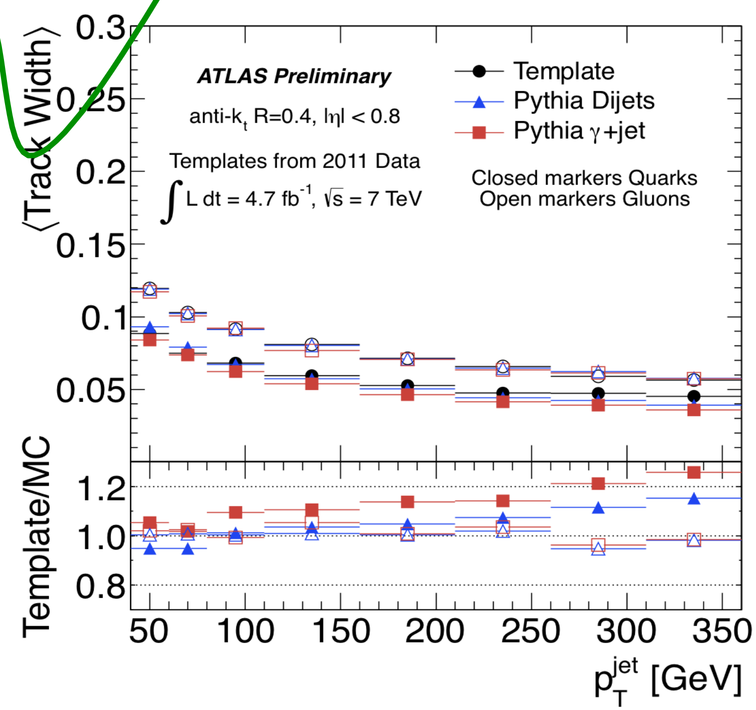


- Keep 50% of quark jets
- Reduce gluon jets by a factor of 8 (to 12.5%)

Data (July 2012)

Data and simulation do not agree
For charged particle multiplicity





	Quark acceptance	Gluon rejection
Simulation	50%	8
Data	50%	4

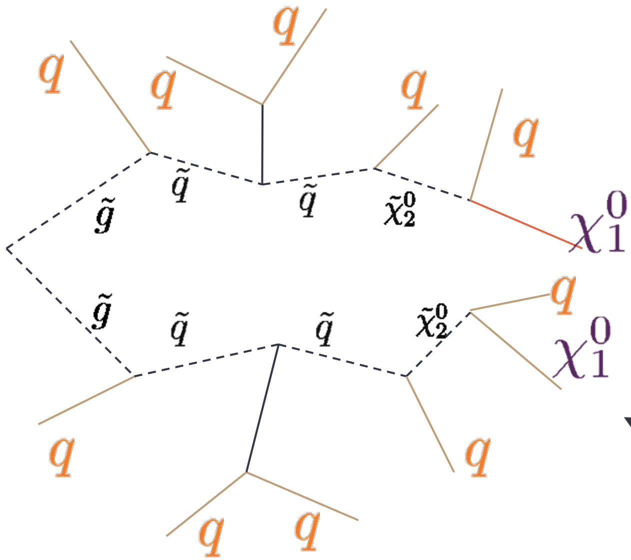
Factor of 2 worse gluon rejection in data than simulation

- Future of Q vs G needs better understanding

THE FUTURE OF JETS?

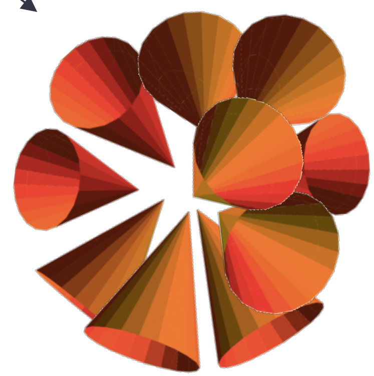
Jet-to-parton map

We want to see quarks and gluons:



Parton shower

We observe jets:



+ missing energy

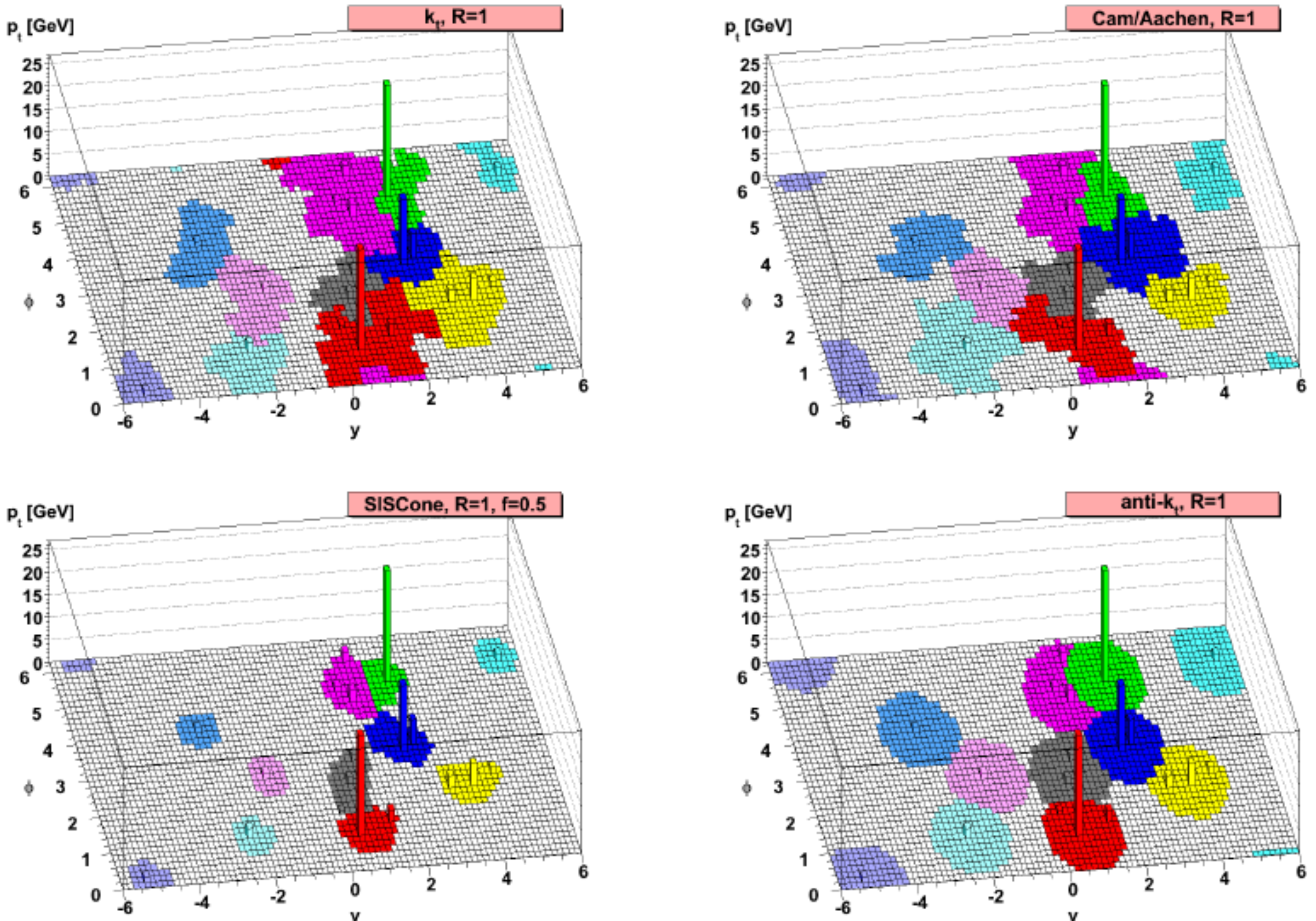
Jet algorithms

Reality: **this** exists

Assumption: **this** exists

Parton-shower is ***not* invertible**

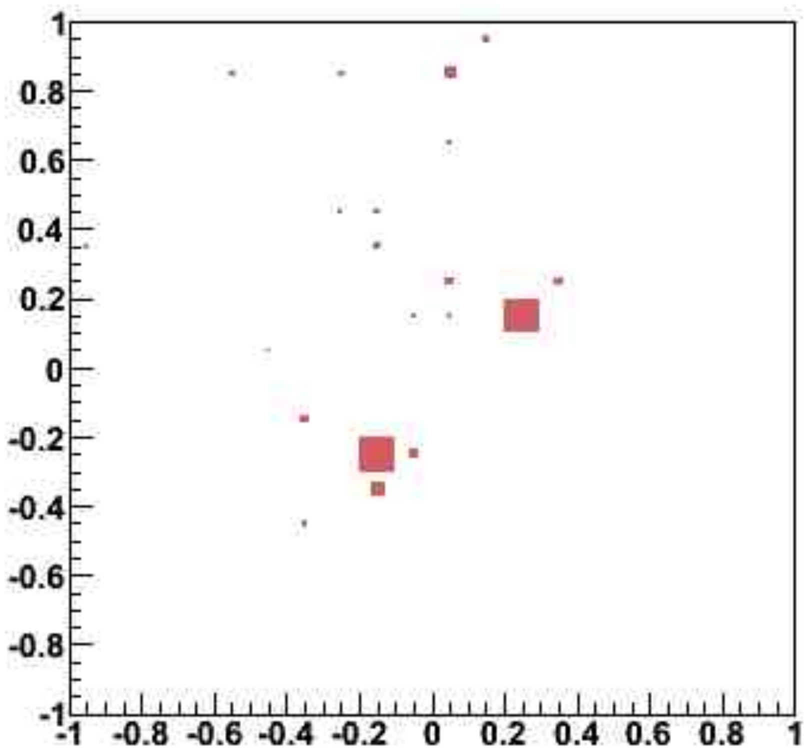
Different algorithms, different results

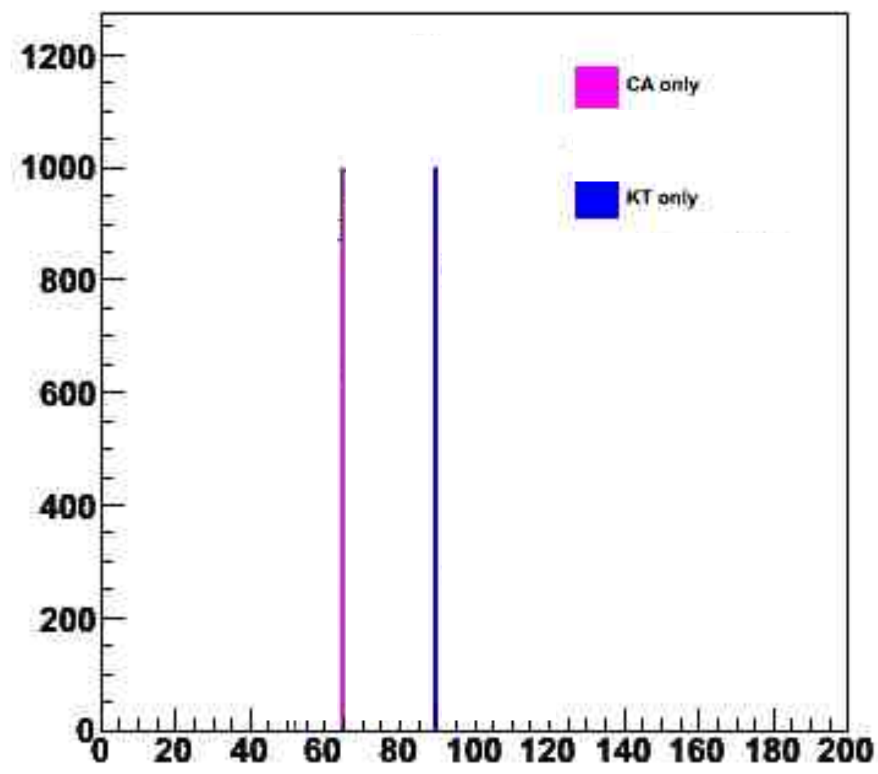


Cacciari, Salam, Soyez JHEP 0804:063 (2008)

e.g. reconstruct W invariant mass

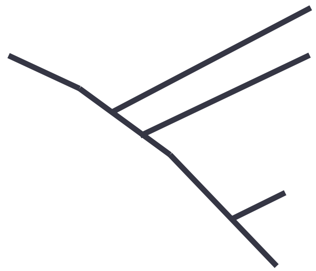
$$W \to \bar{q}q$$

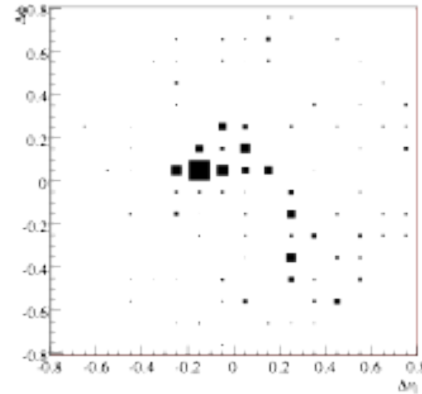




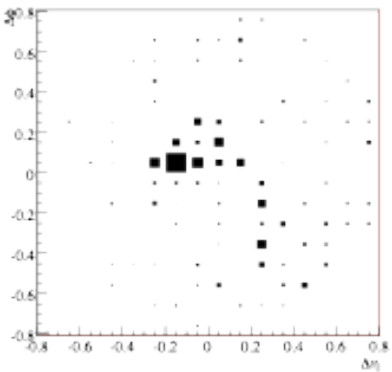
Parton shower is not invertible

Parton shower gives an event





What is the **inverse**?



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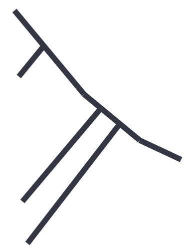
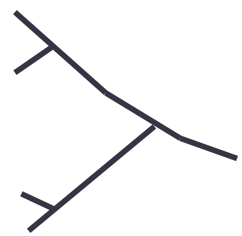
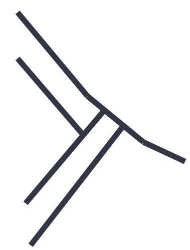


or



or



?

- Is there a way to have “fuzzier” jets
  which account for non-unique inverse?

One possibility: Qjets

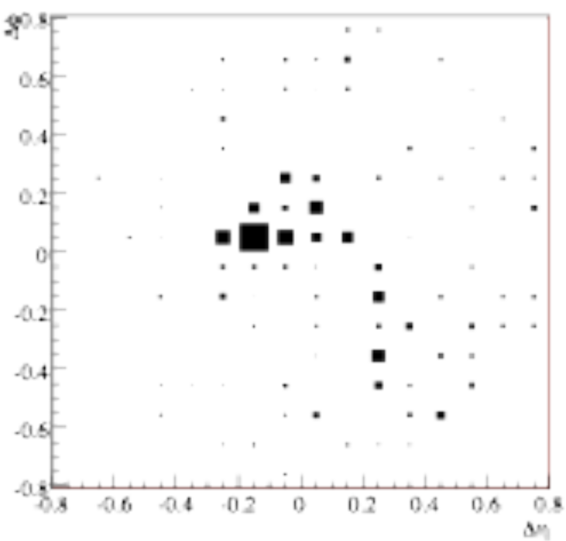
Ellis et al. arXiv:1201.1914

Add randomness into the jet algorithm

Instead of choosing smallest d_{ij}, choose pair with a probability

$$P \propto \exp(-\alpha d_{ij})$$

Generates **ensemble of trees** for **each event**



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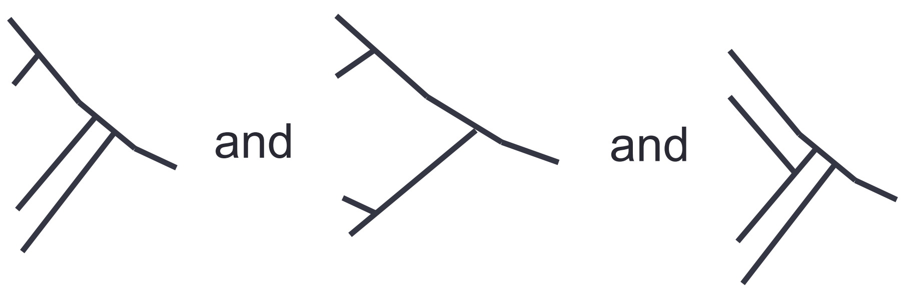


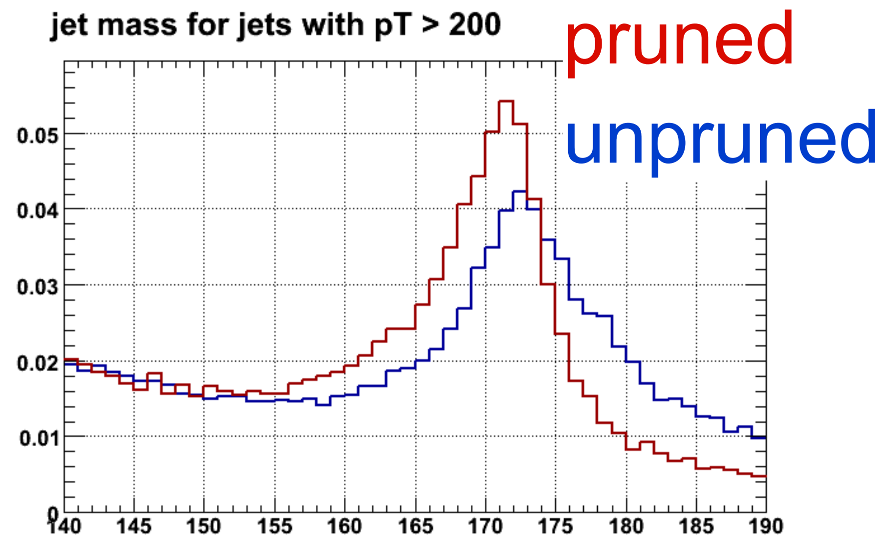
and and

What did we do with the Qjets?

As an example, we can **prune** them

- Pruning **discards** radiation in clustering that is **soft but not collinear**

$$z_{ij} \equiv \frac{\min\left(p_{T_i}, p_{T_j}\right)}{|\vec{p_{T_i}} + \vec{p_{T_j}}|} < z_{\text{cut}} \qquad \Delta R_{ij} > D_{\text{cut}}$$



Other variants **filtering** or **trimming** work similarly

Butterworth, Cox, Forshaw Phys.Rev. D65 (2002)

Krohn, Thaler, Wang JHEP 1002 (2010)

Pruned Qjets

- Construct 100 trees
  from each jet in each event

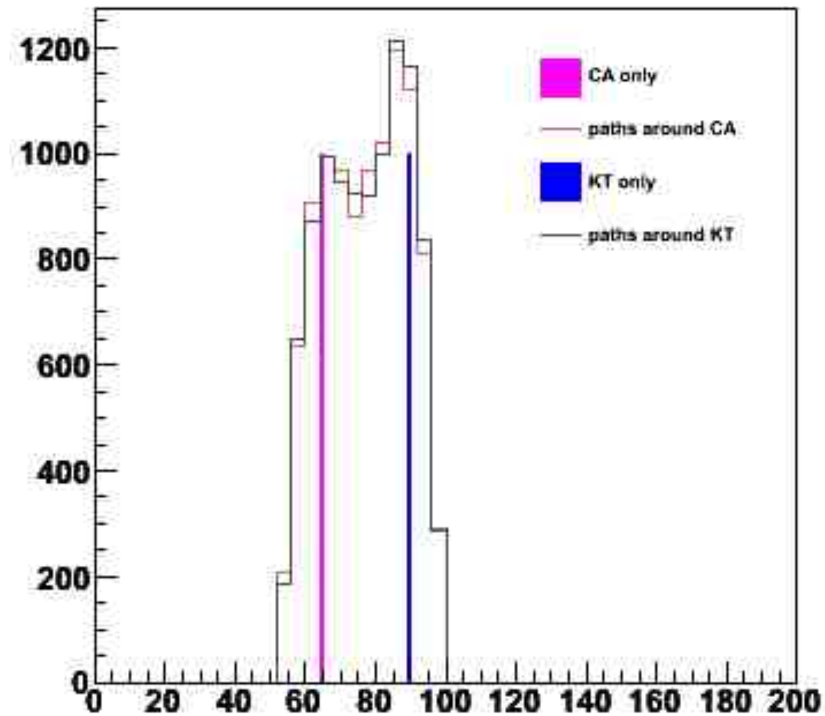
- Apply pruning to each tree

$$z_{ij} \equiv \frac{\min\left(p_{T_i}, p_{T_j}\right)}{|\vec{p_{T_i}} + \vec{p_{T_j}}|} < z_{\rm cut}$$

$$\Delta R_{ij} > D_{\rm cut}$$

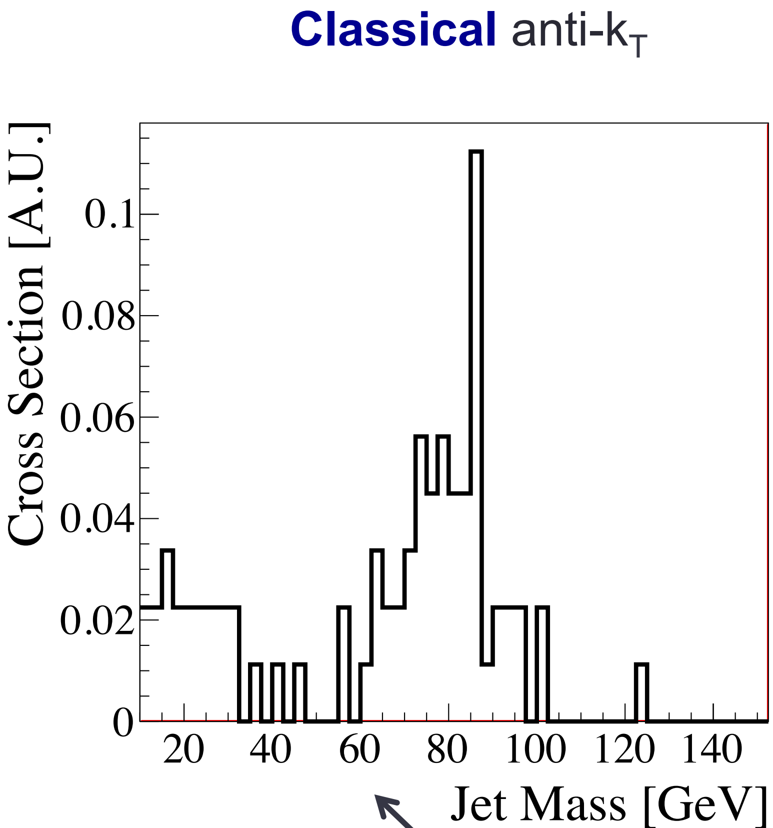
- Histogram resulting masses

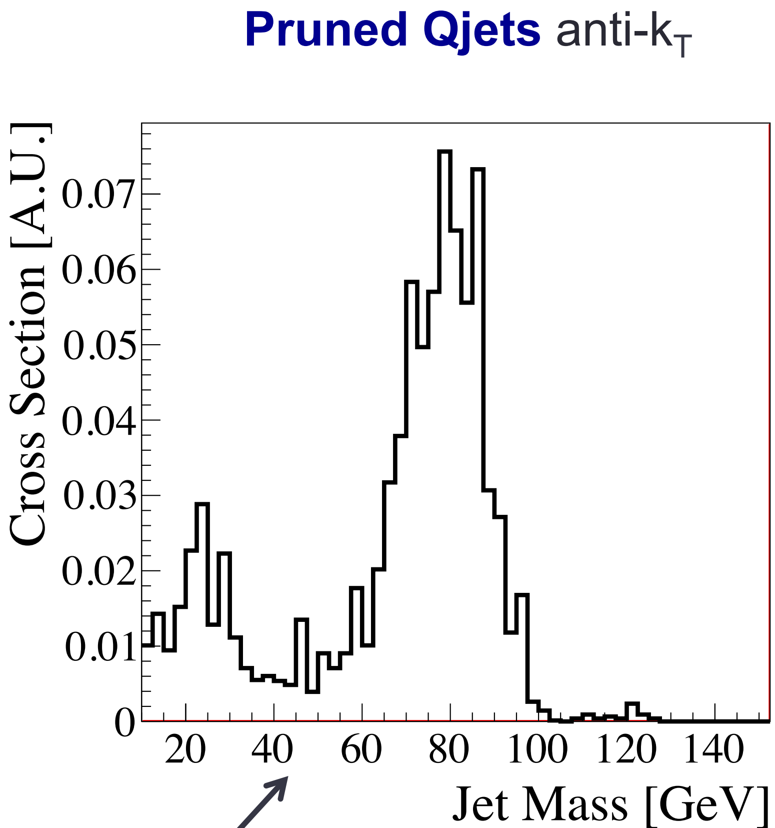
Event with a boosted W boson



This is ***one*** event

Distributions become much smoother





The same 100 events

Need fewer events for same precision

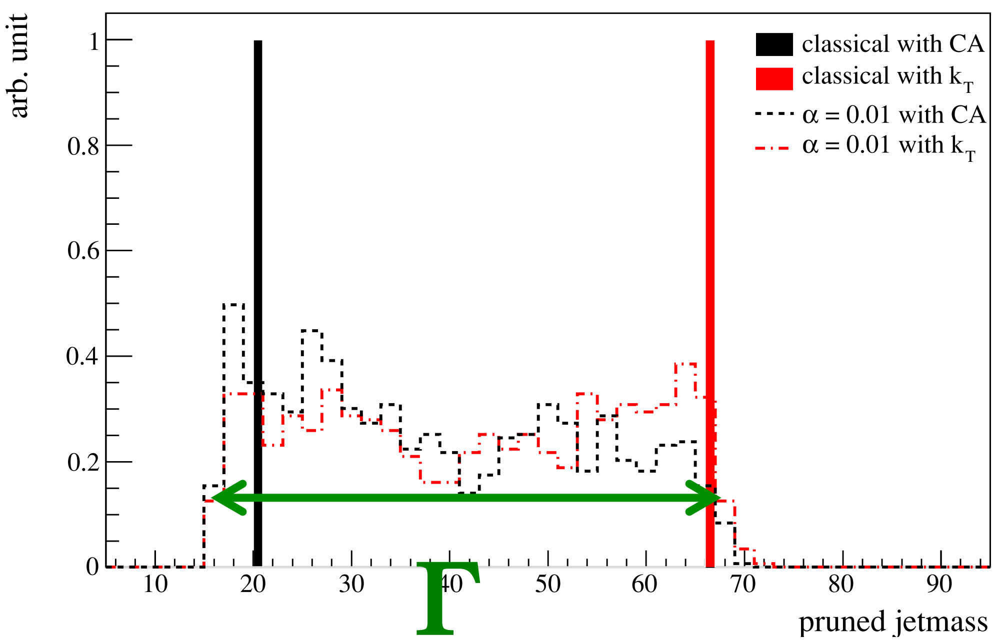
For example,
- Take 10 boosted W events (p_T>500)
- Construct jet mass
- Look at **variance** of the the **mean** W-jet mass over many pseudo-experiments

Algorithm	Mass uncertainty $\delta\langle m\rangle$	Relative Luminosity required
k_T	3.15 GeV	1.00
Qjets α=0	2.20 GeV	0.50
Qjets α=0.001	2.04 GeV	0.45

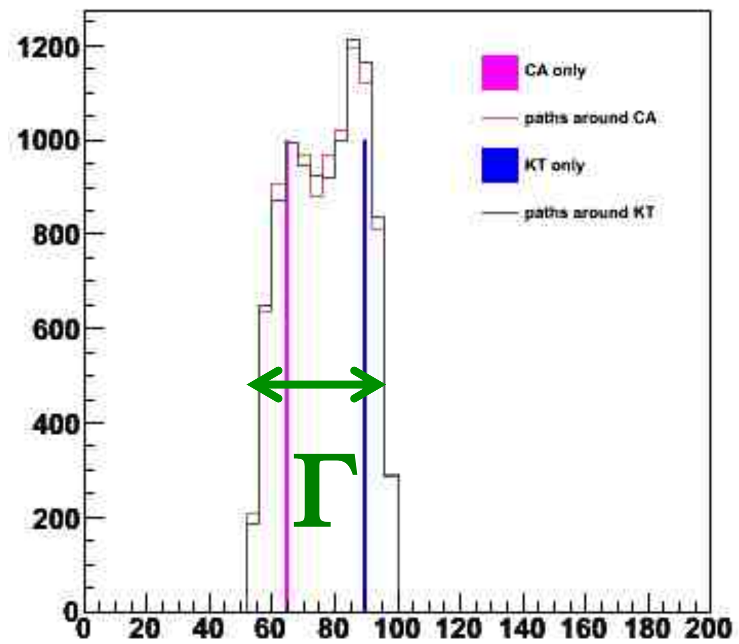
Qjets needs **half as much luminosity** as conventional jet algorithms

Signal vs background

QCD jets (one event)



W jets (one event)

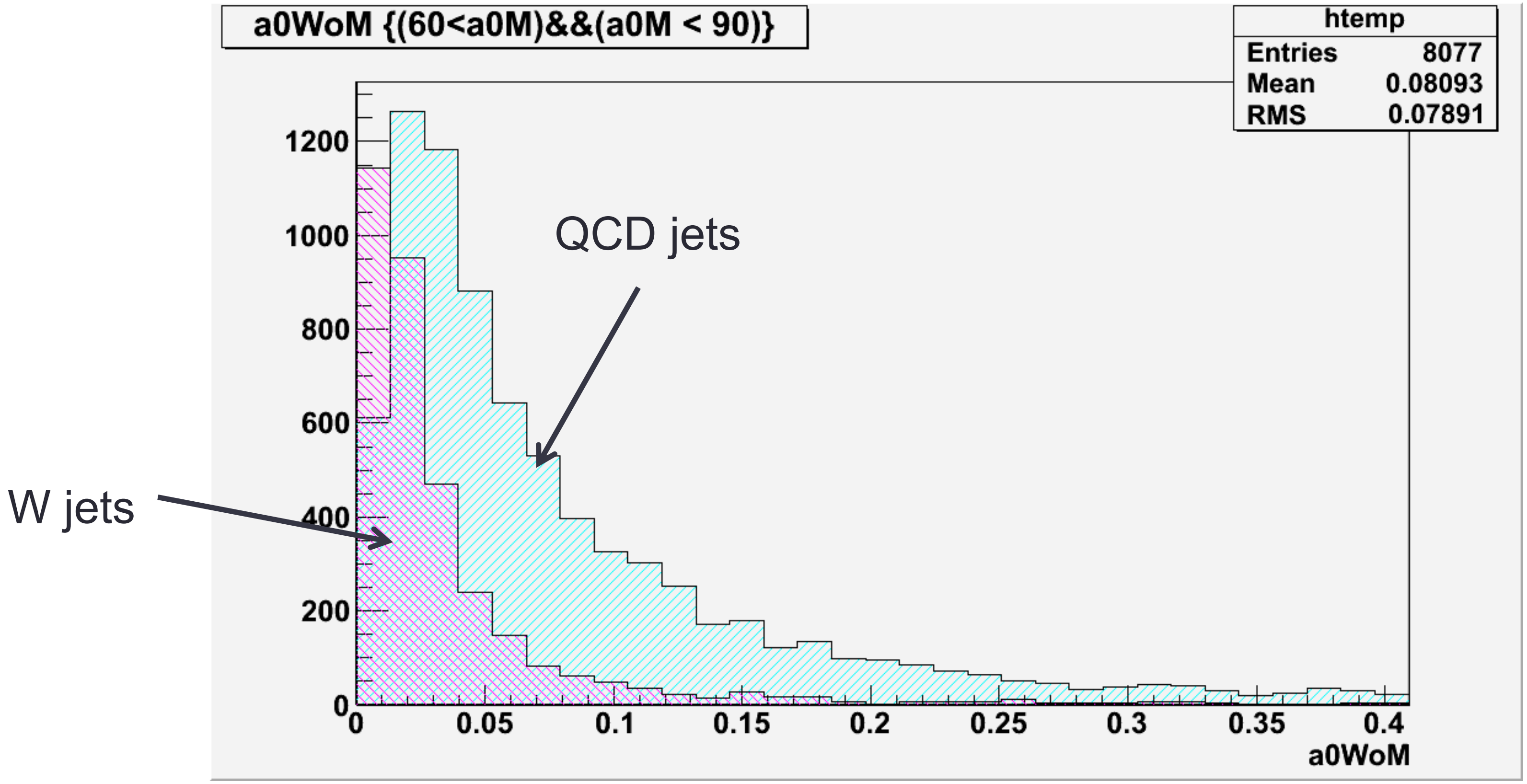


Volatility $\mathcal{V} = \frac{\Gamma}{\langle m \rangle}$ is a purely Q-observable

Volatility

$$\mathcal{V} = \frac{\Gamma}{\langle m \rangle}$$

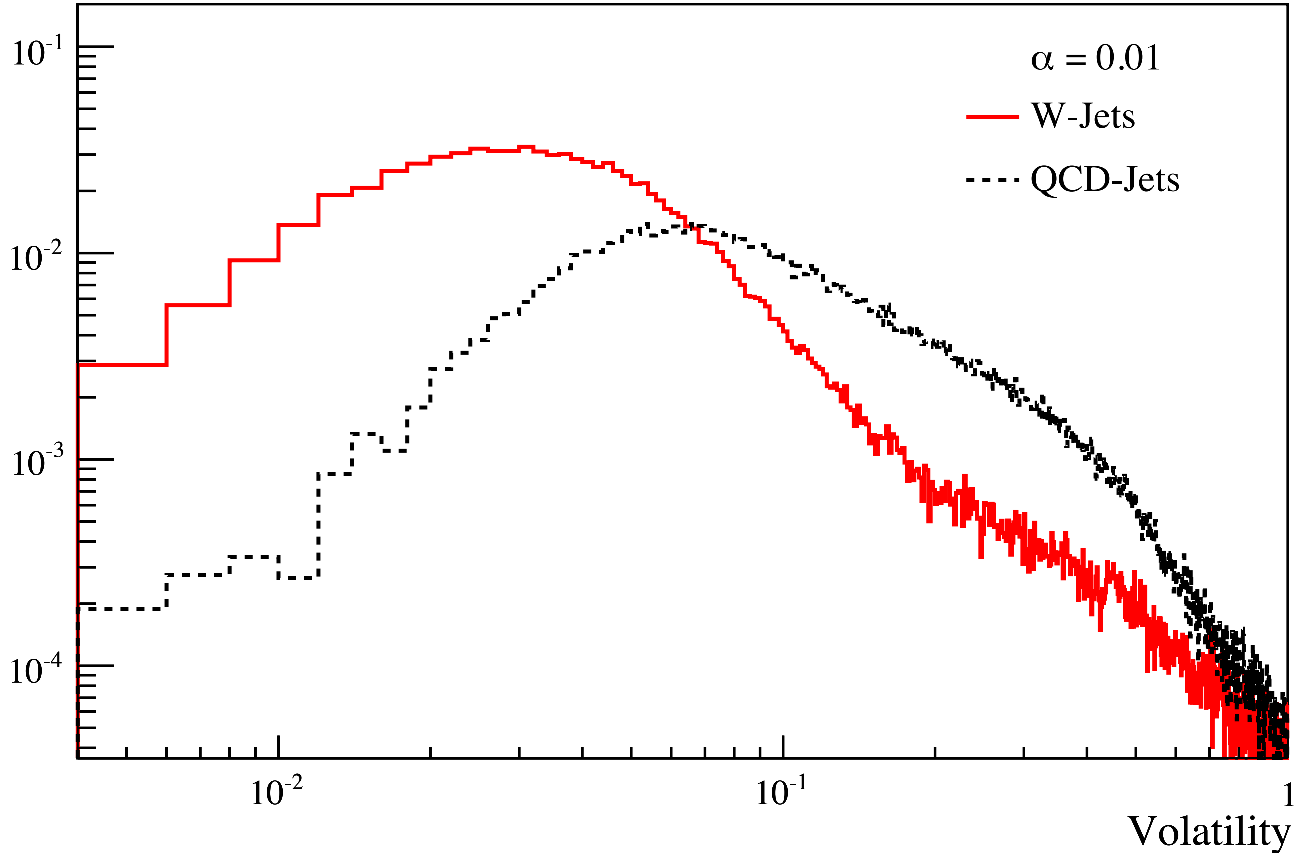
QCD jets are broader than boosted W jets



Volatility

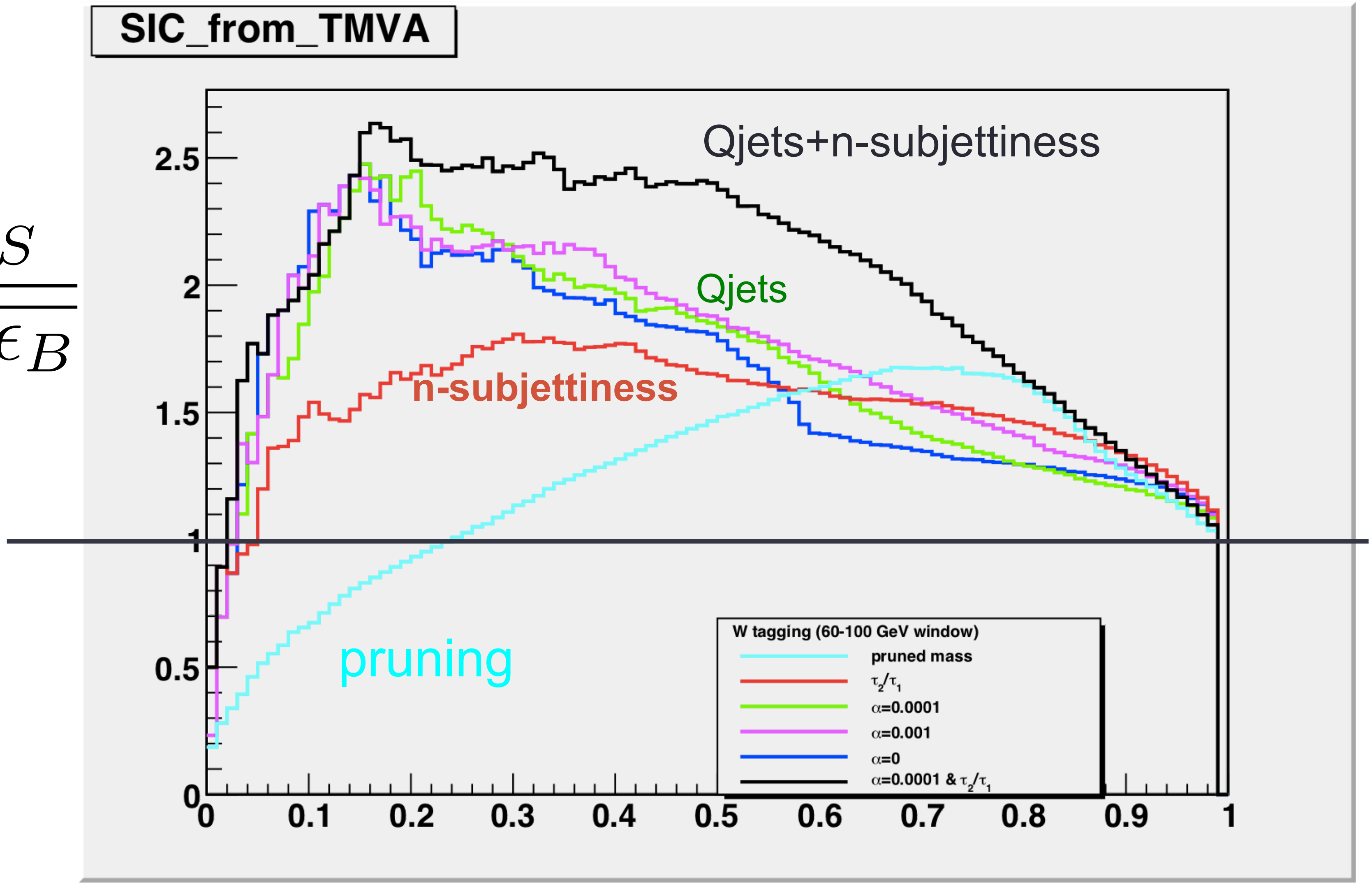
$$\mathcal{V} = \frac{\Gamma}{\langle m \rangle}$$

QCD jets are broader than boosted W jets



W-tagging: cut on volatility

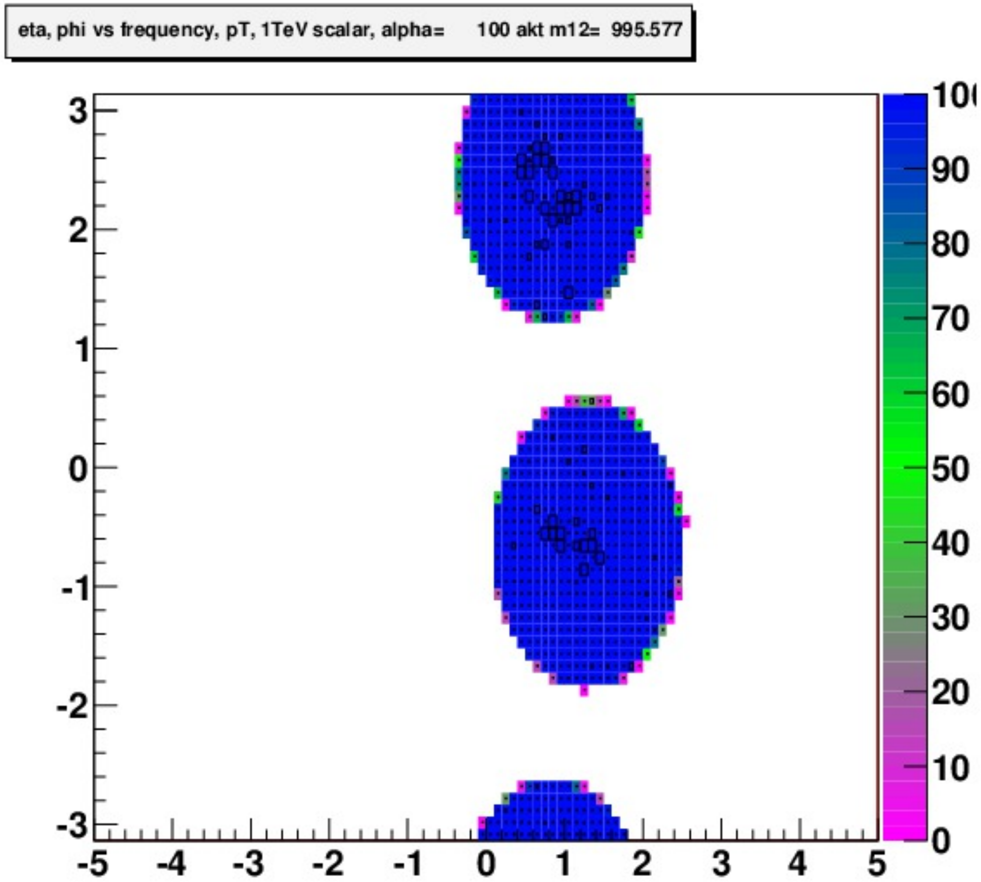
$$\frac{\epsilon_S}{\sqrt{\epsilon_B}}$$



Qjets on dijet events (no pruning)

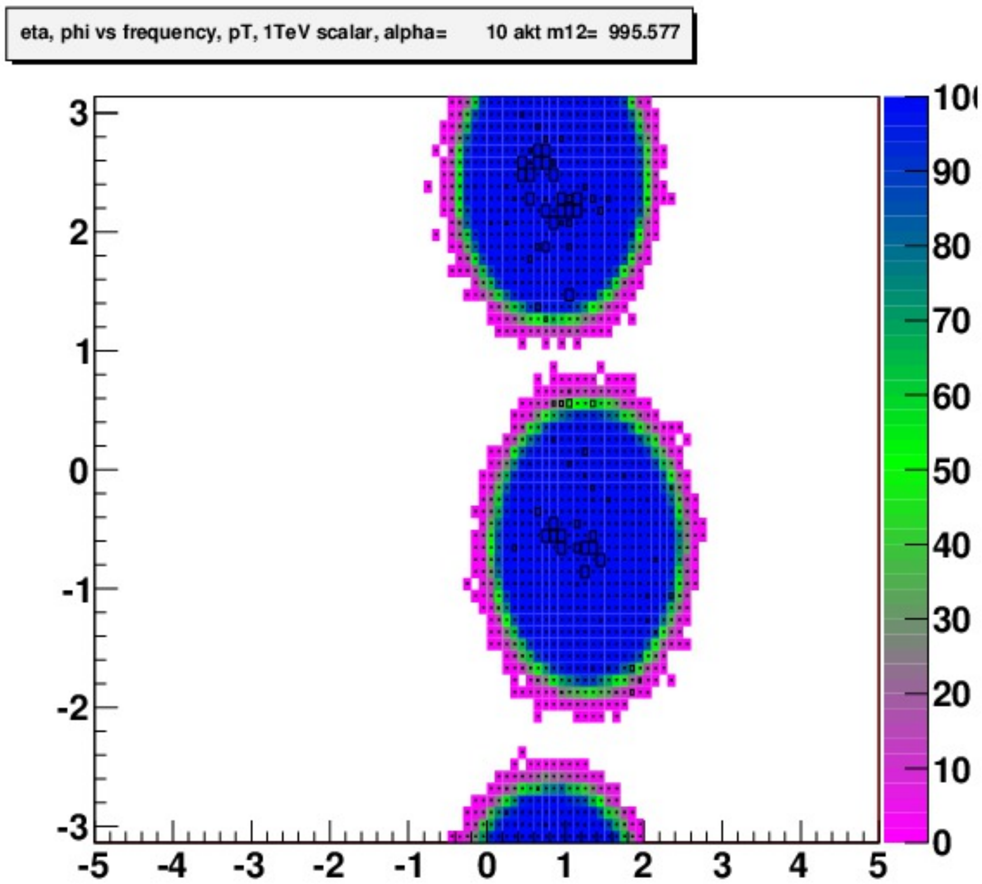
α = 100

(classical anti-kT)



Qjets on dijet events (no pruning)

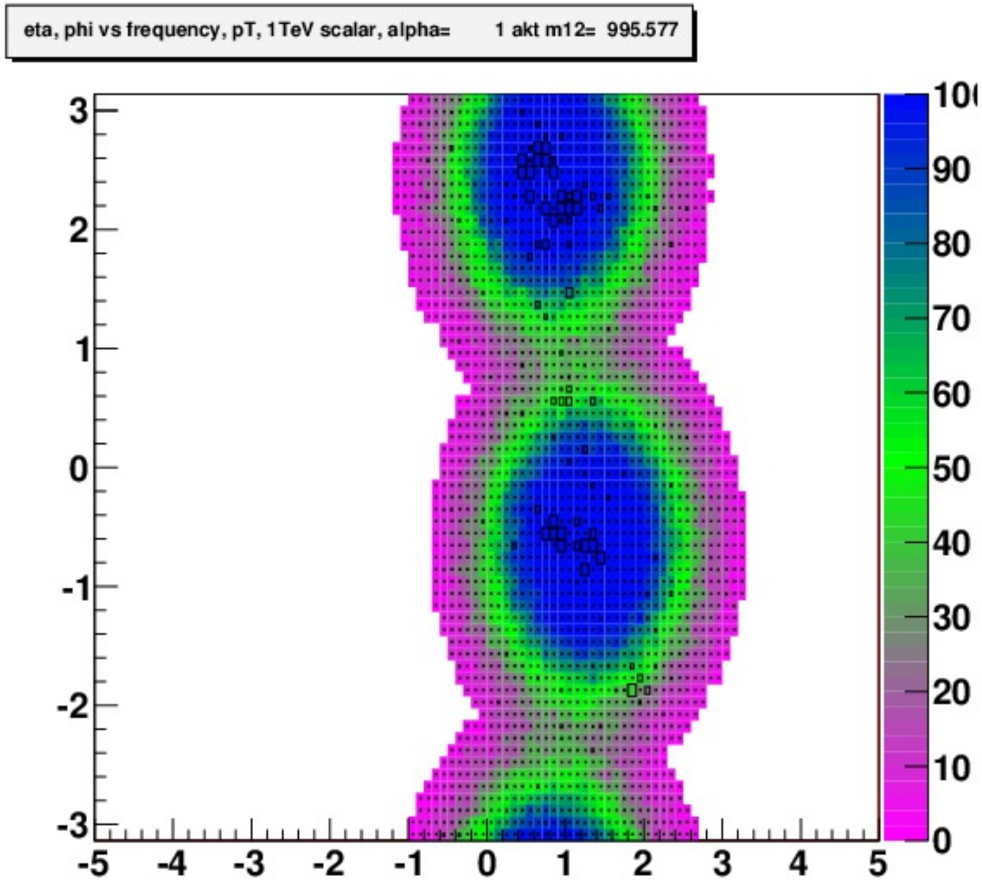
$\alpha = 10$



Work in progress, with D. Krohn and D. Kahawala

Qjets on dijet events (no pruning)

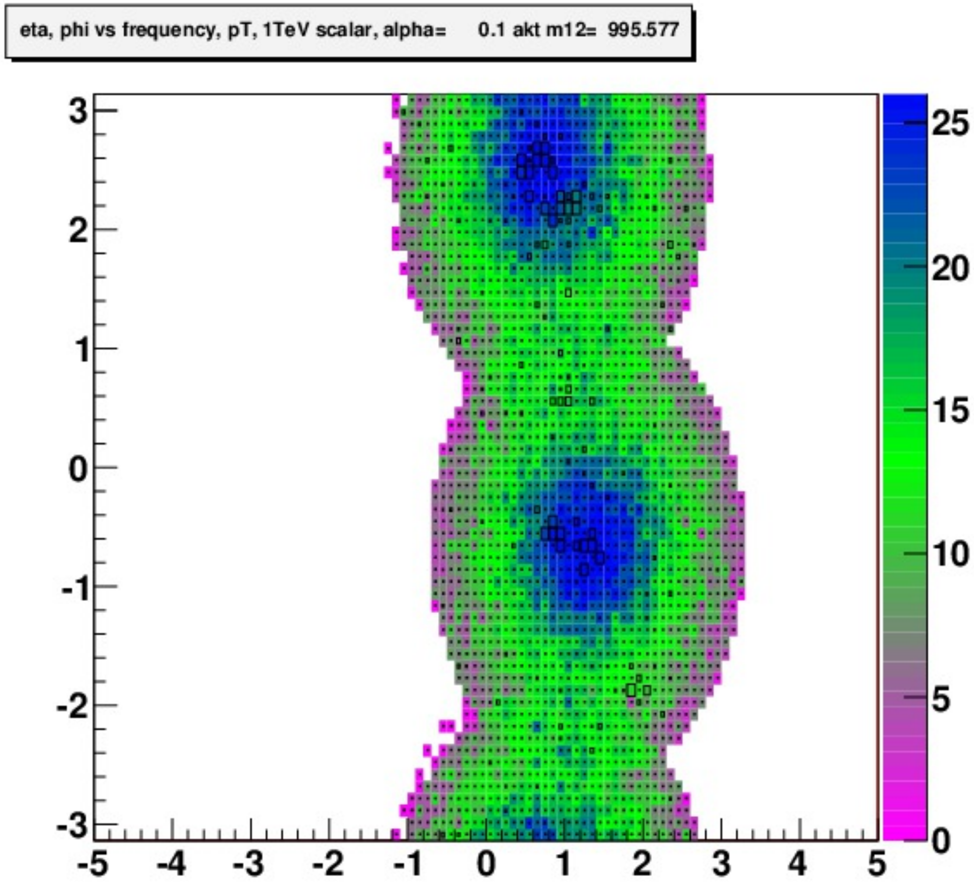
$\alpha = 1$



Work in progress, with D. Krohn and D. Kahawala

Qjets on dijet events (no pruning)

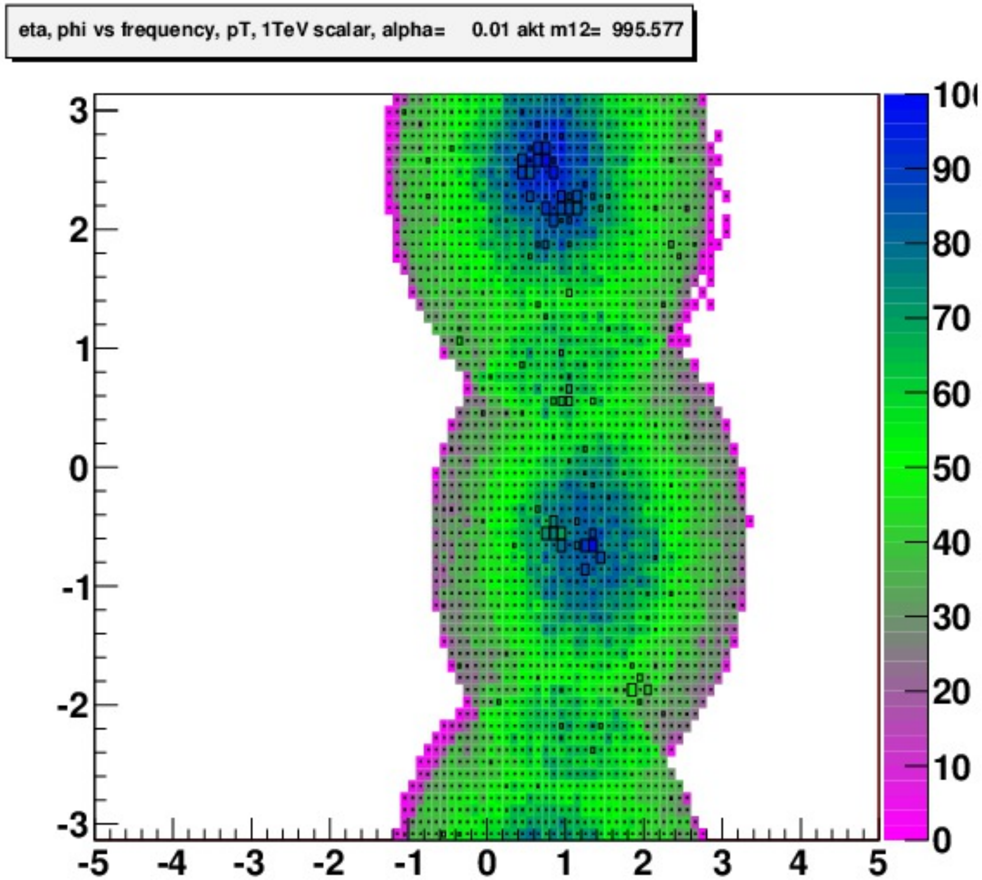
$\alpha = 0.1$



Work in progress, with D. Krohn and D. Kahawala

Qjets on dijet events (no pruning)

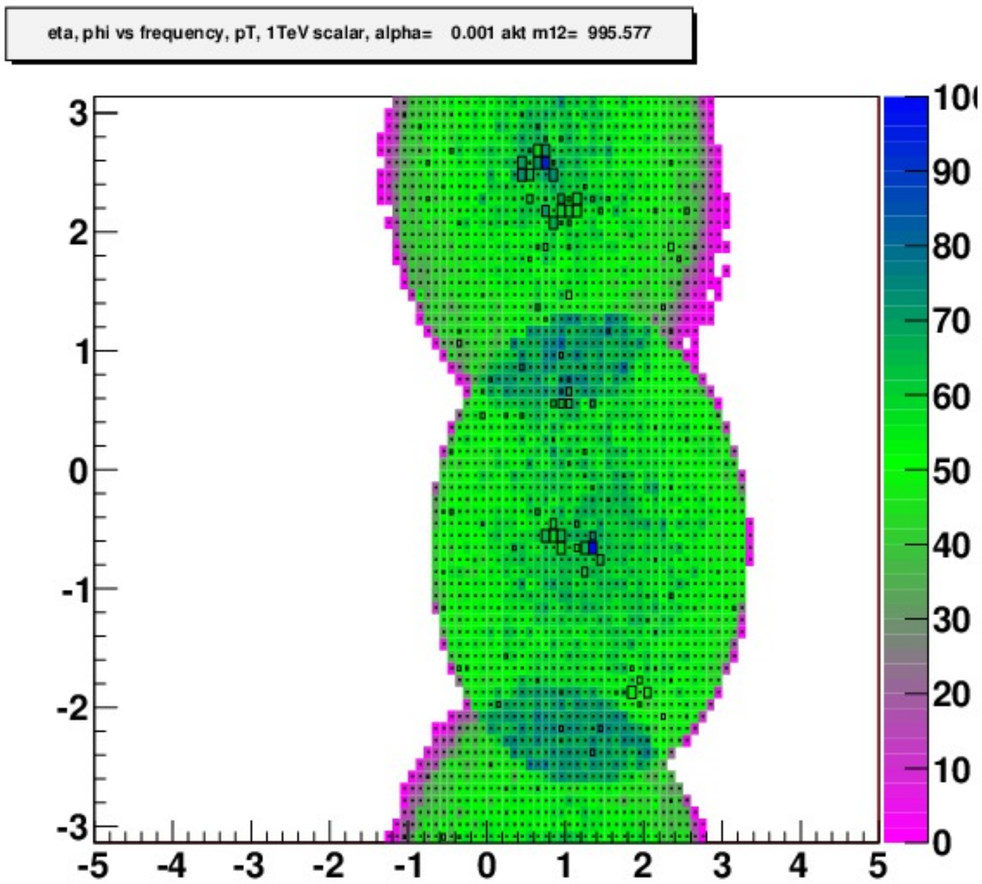
$\alpha = 0.01$



Work in progress, with D. Krohn and D. Kahawala

Qjets on dijet events (no pruning)

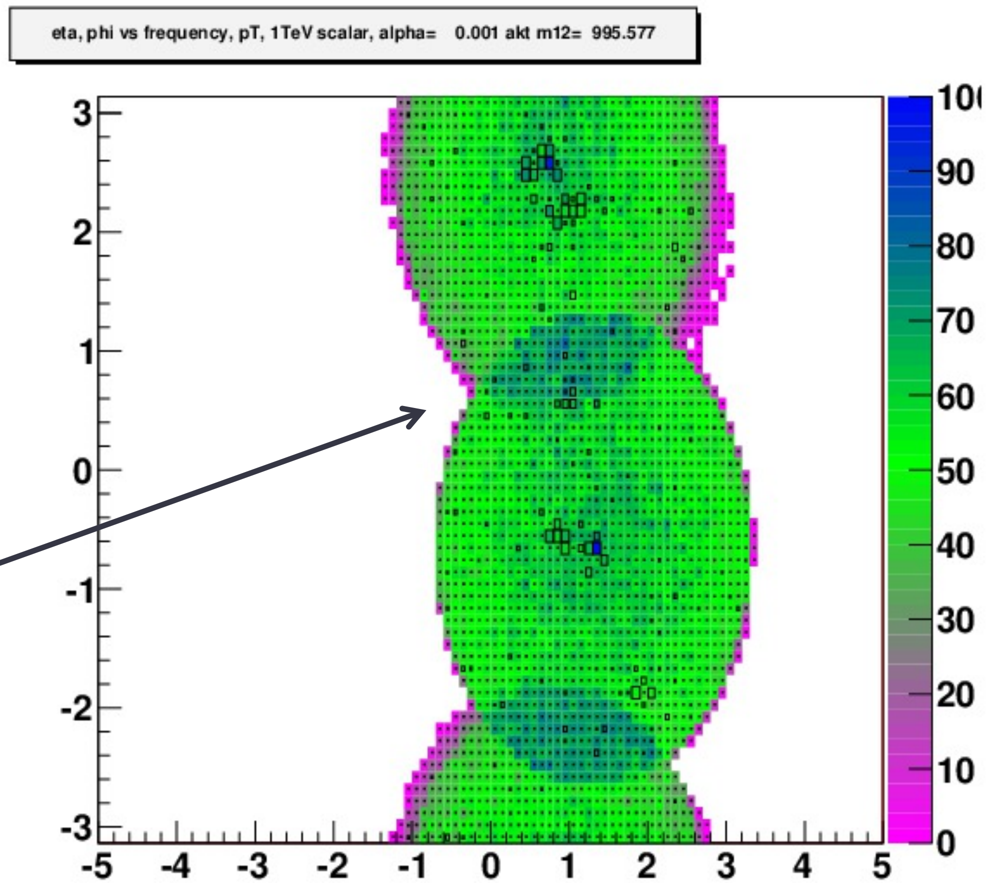
$\alpha = 0.001$



Work in progress, with D. Krohn and D. Kahawala

Qjets on dijet events (no pruning)

$\alpha = 0.001$

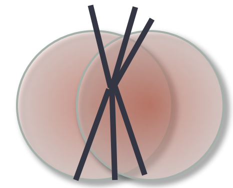


May help **resolve ambiguities** with **overlapping jets**

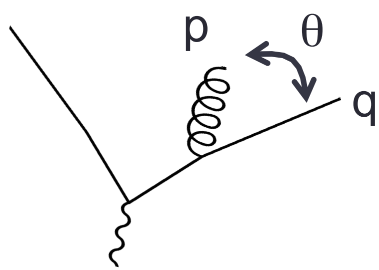
Work in progress, with D. Krohn and D. Kahawala

Summary from Lecture 1

- Jets exist because QCD is weakly coupled at short distances and strongly coupled at long distances



- Collinear and soft regions dominate cross sections

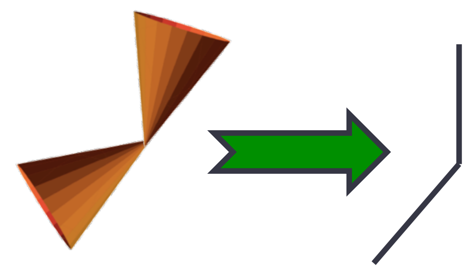


$$d\sigma = e^{-\int dP} dP$$

$$\sim e^{-\alpha \ln^2\left(\frac{\mu_1}{\mu_2}\right)} \left(\frac{\alpha_s}{2\pi}\frac{1+z}{1-z^2}\right) dz$$

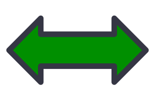
- Semi-classical approximation “Sudakov factors and splitting-functions” works excellently

- Jet algorithms reconstruct parton momenta from jets



- Different algorithms Different goals

Cone algorithms
Cambrideg/Aachen
k_T
Anti-k_T

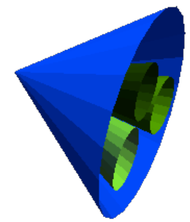


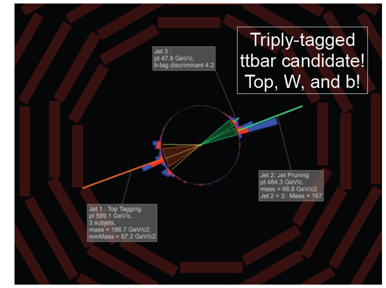
Reconstruct parton momenta
Infrared safe
Insensitive to pileup
Easy to calibrate experimentally

- Excellent agreement of theory with data

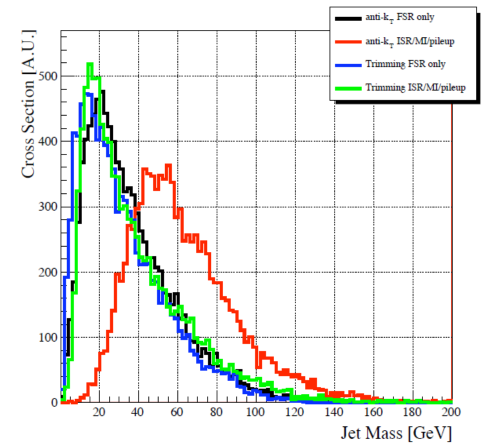
Summary from Lecture 2

- Jets have **substructure**
  - Top-tagging – CMS data
  - Boosted higgs for 14 TeV
  - N-subjettiness

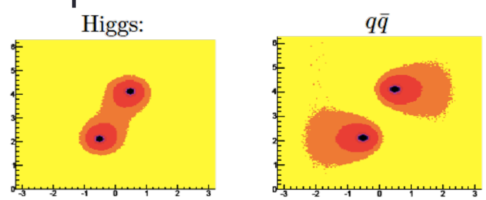




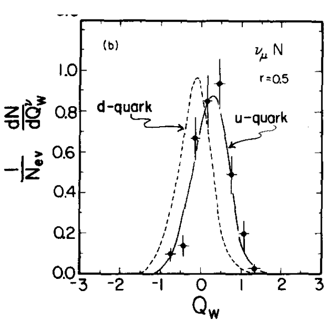
- Jets can be **groomed**
  - Trimming, Pruning and Filtering remove pileup
  - Allow better reconstruction of parton 4-momenta



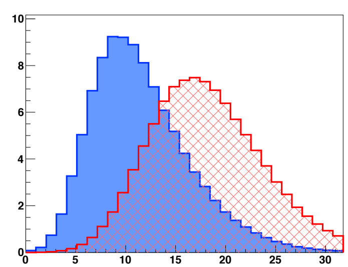
- Jets are not just 4-vectors
  - They have superstructure

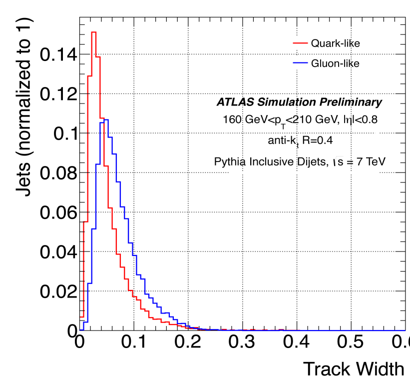


  - They have charge



and color





Jets and the LHC

- The LHC has much higher energy than any collider ever
  - More jets
  - Harder (more energetic) jets
  - More jet-like (collimated) jets

- LHC experiments can measure jets really well
  - Better energy resolution than Tevatron
  - Better spatial resolution than Tevatron
  - Can identify individual particles!!

Jet physics is entering a Golden Era

Revolution in the last 4 years

New experimental techniques

New ideas and algorithms

New theoretical methods

What will the future bring??