JET SUBSTRUCTURE AND THE STANDARD MODEL

ATLAS Standard Model Workshop

September 19, 2013

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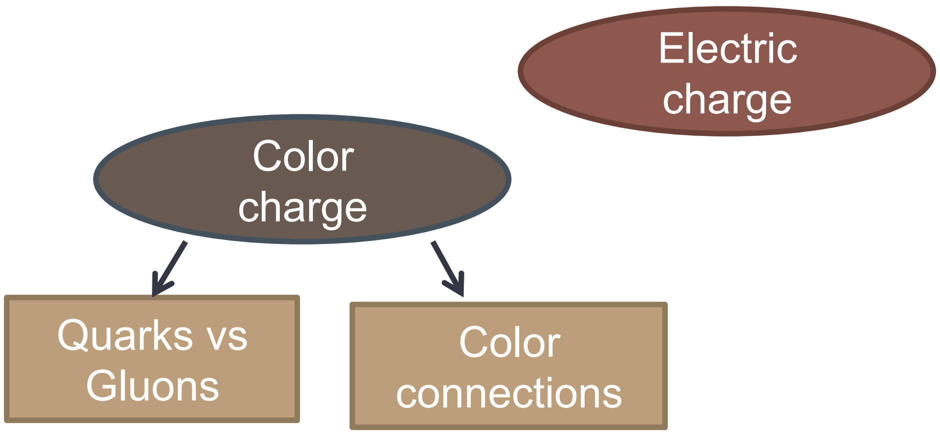
Two motivations

The July 5th problem

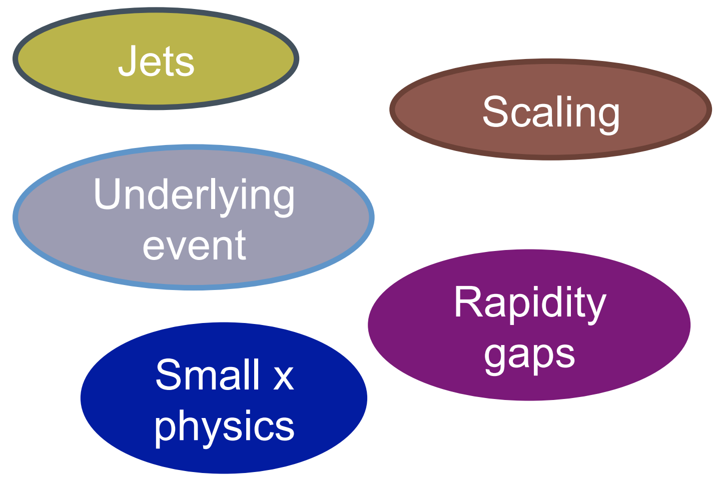
07-04-12: find the Higgs boson
07-05-12: measure everything about it
mm-dd-yy: find a new particle
mm-(dd+1)-yy: measure everything about it



Requires validation on Standard Model

Appreciating the The Standard Model

More than just **27 numbers**
Qualitatively new phenomena



Requires precision measurements
Requires precision calculations

Jet substructure

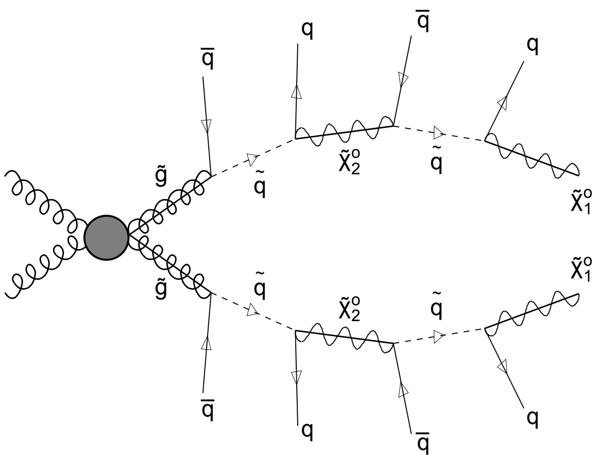
Lots of developments in jet substructure over the past 5 years

- Top-tagging
  - Johns Hopkins Tagger
  - Top template tagger
  - HEP top-tagging
- Jet grooming
  - Filtering
  - Trimming
  - Pruning
- Multijet events
- Pull
- ISR tagging
- Quarks vs Gluons
- Qjets
- Shower deconstruction
- Jet Charge
- N-subjettiness
- Jet cores
- W-tagging
- Dipolarity
- Modified mass drop
- Angularities
- N-point energy correlators
- Semi-classical clustering
- ….

Many methods tested on data.
Impressive agreement with full simulation.
Applications to BSM (e.g. Z' resonance searches)

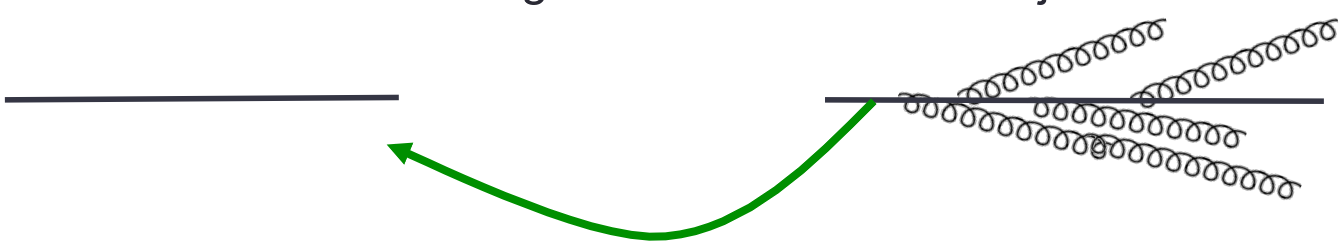
What is a jet?

Energetic quarks and gluons produced



Parton shower

Quarks and gluons “shower” to form jets



Jet algorithms: reconstruct parton momenta

As of 2007: **jet=parton**

A jet is a 4-vector. Just calibrate it (performance group).

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
  - Color charge (quark or gluon)
  - Spin (?)
- Jets have **superstructure**
  - Color connections between jets
- Jets are **not partons**
- Jets are not collections of hadrons

2007: A jet is a 4-vector. Just calibrate it.
2013: Jets are **sophisticated emergent phenomena** in the standard model

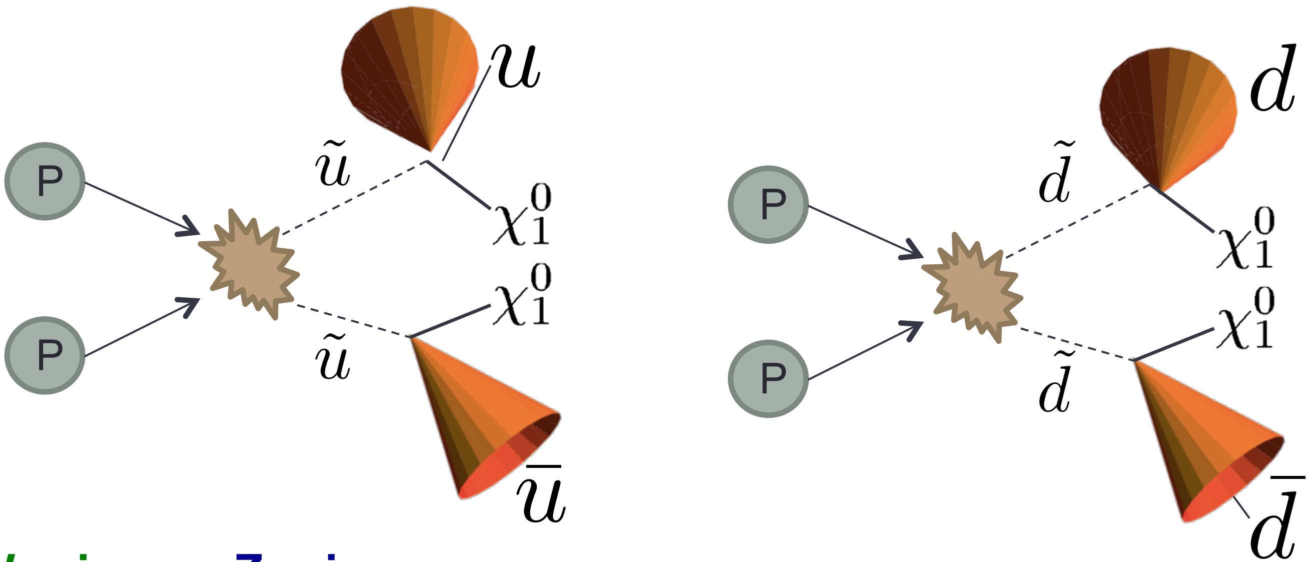
Lets study them for their own sake!

CASE STUDY: 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)

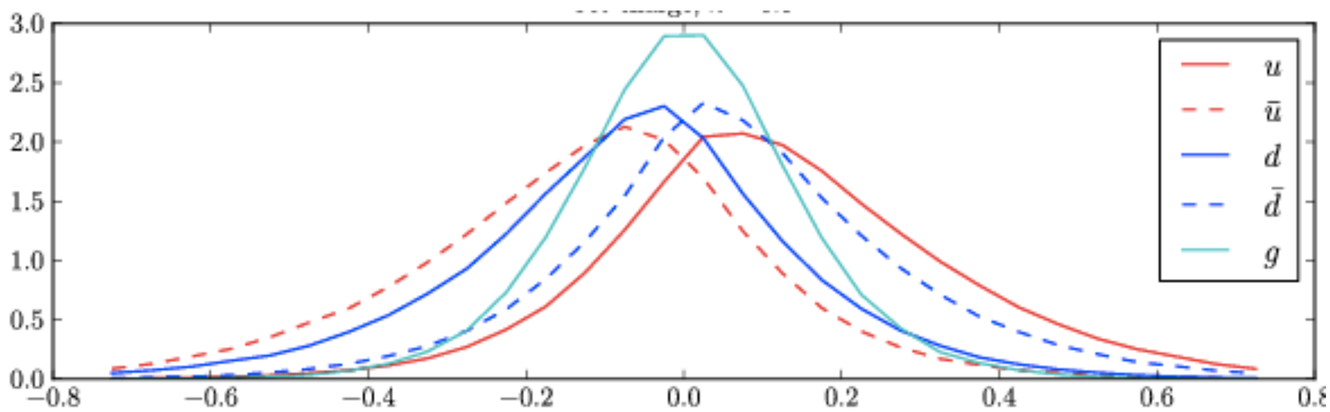
Distinguishing charge

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

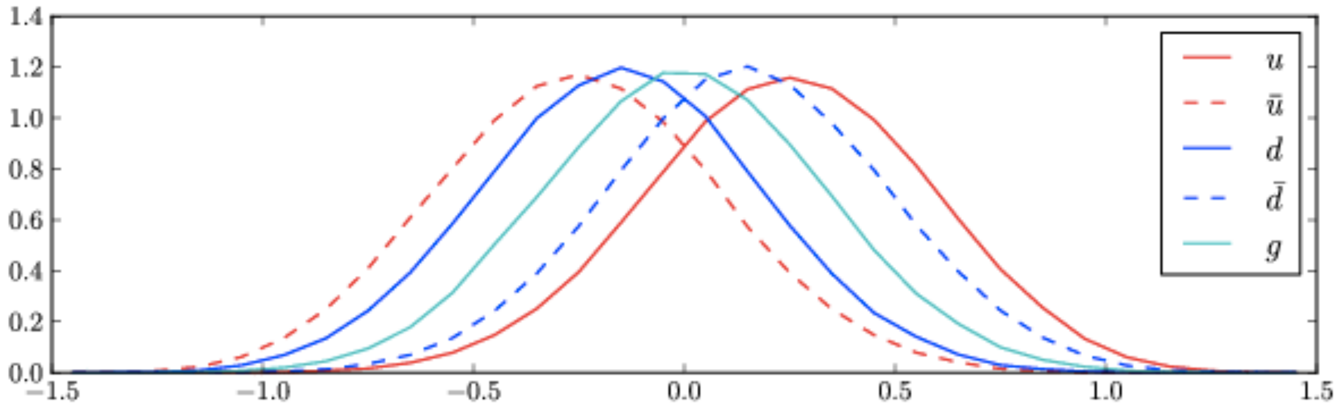
Measure the p_T-weighted **jet charge**:

Krohn, Lin, MDS, Waalewijn
Phys.Rev.Lett. 110 (2013) 212001

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



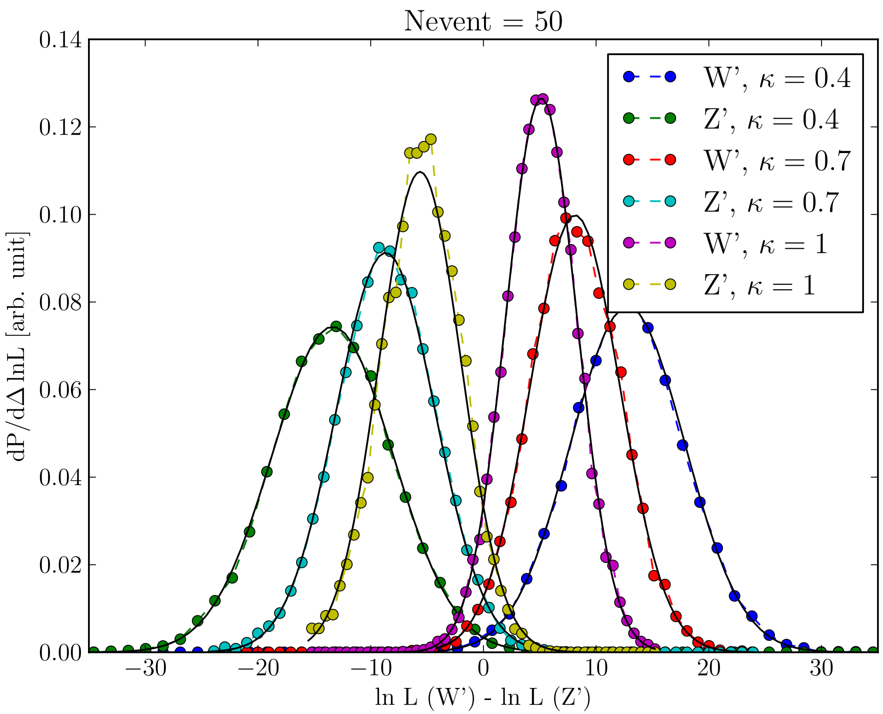
κ=1

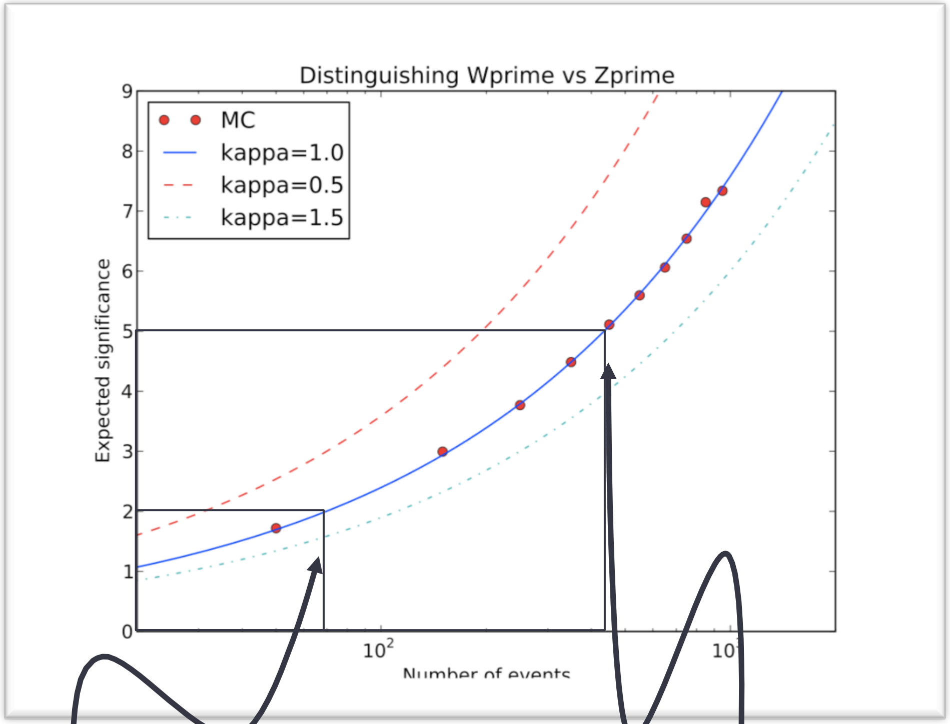


κ=0.5

Distinguishes W’ from Z’

Log-likelihood distribution for 1 TeV resonance, various κ

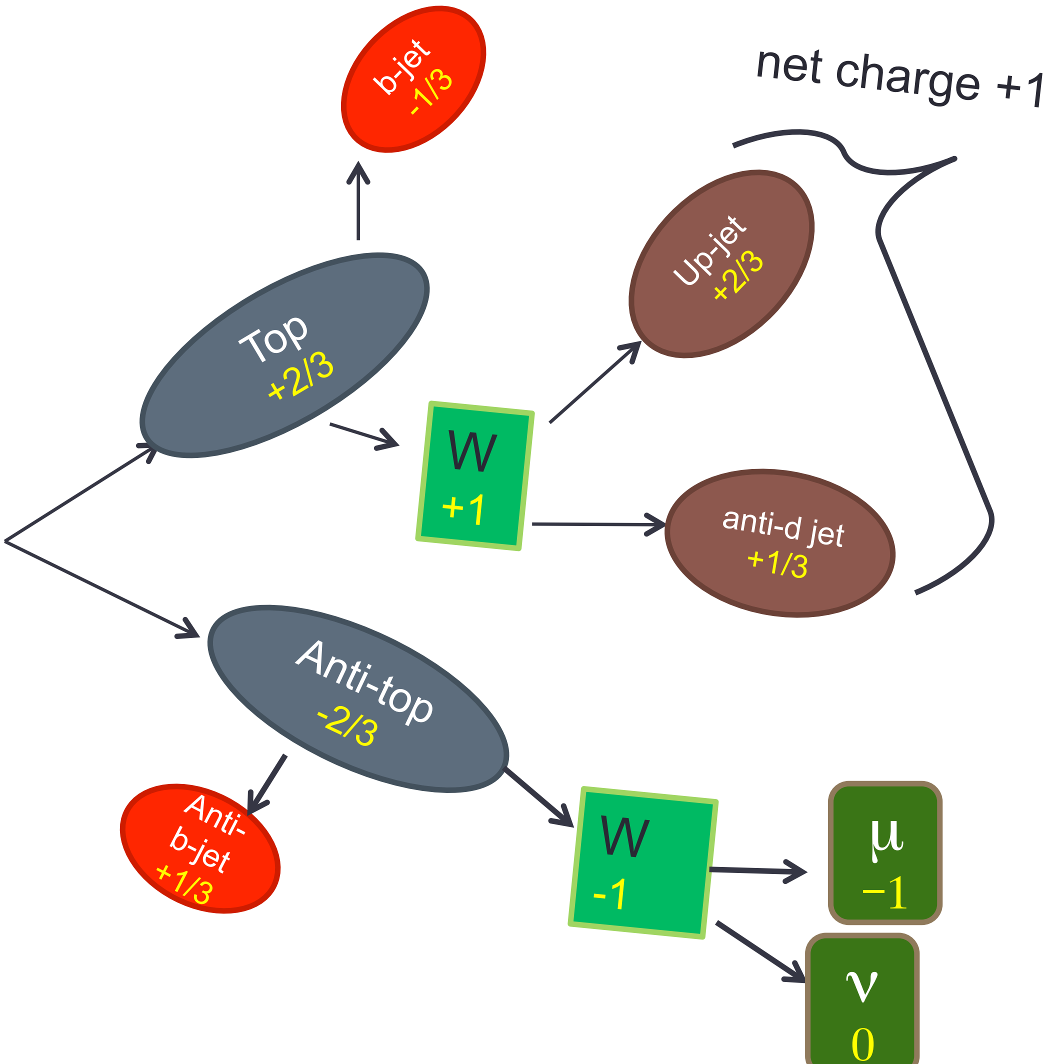


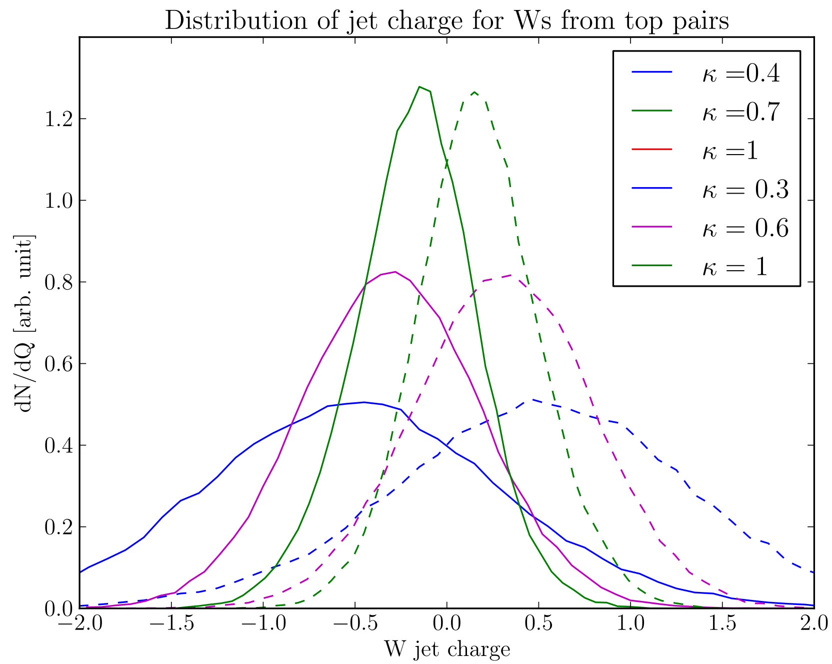


2σ distinction with 30 events

5σ discovery with 200 events

Can calibrate with hadronic W's from tops

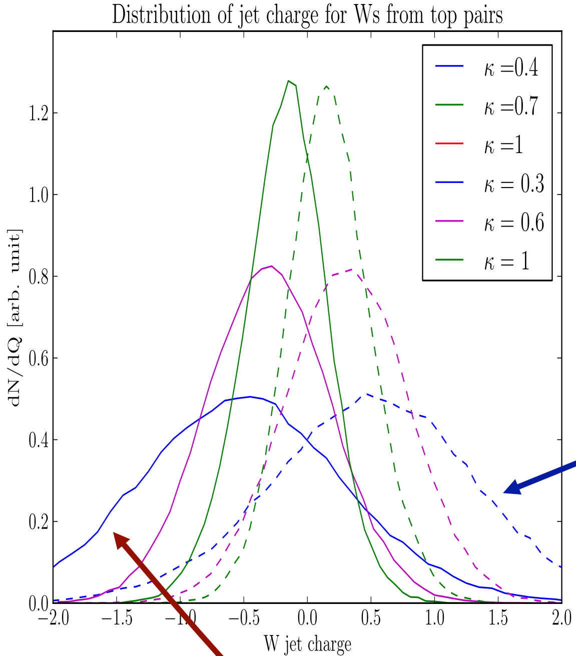




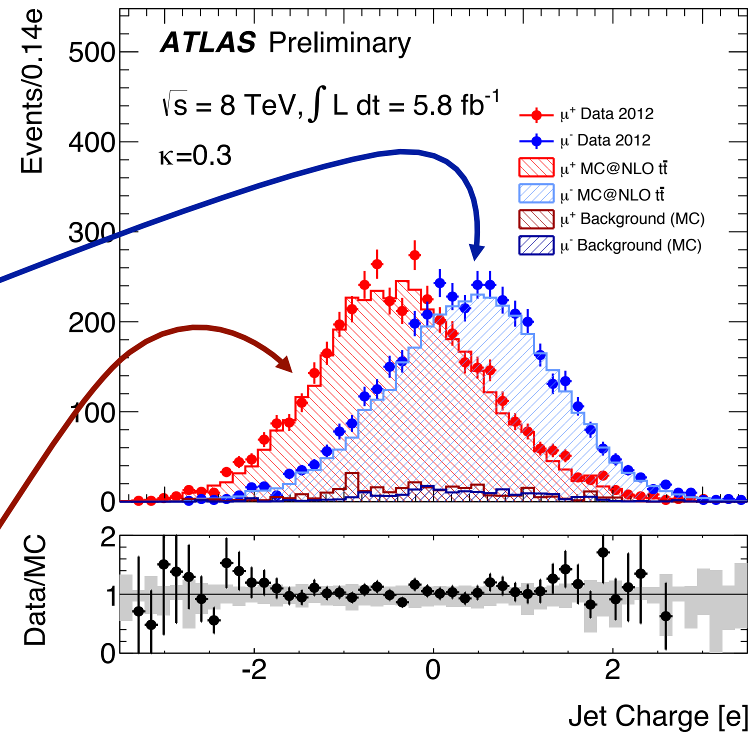
$$\mathcal{Q}_\kappa^i = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{j\in\text{jet}} Q_j (p_T^j)^\kappa$$

2013: measured in data by ATLAS!

Theory paper



ATLAS Conference note

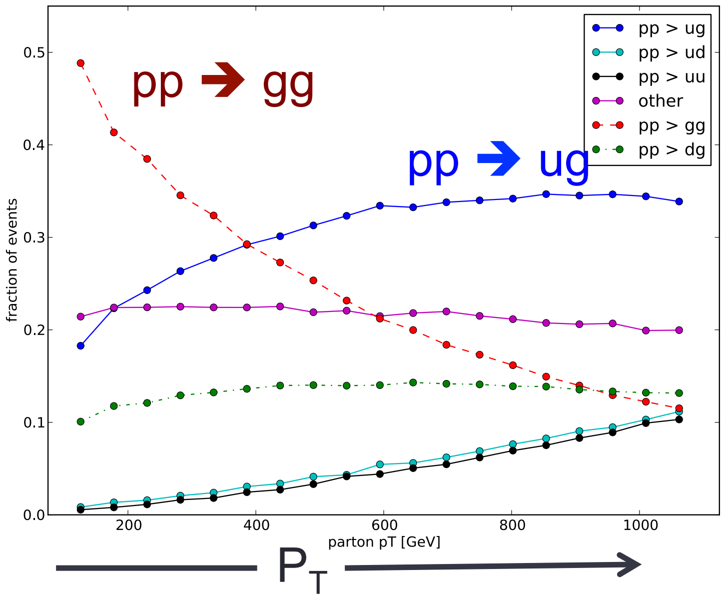


arXiv: **September, 2012**
Published: May 2013,
Phys.Rev.Lett. 110 (2013) 212001

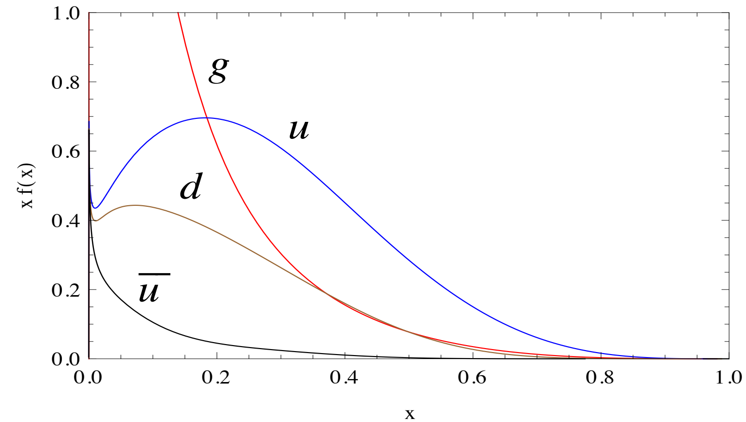
11 months

August, 2013

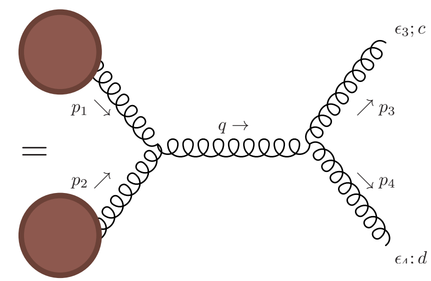
Dijets



Fractions for each channel (parton level)

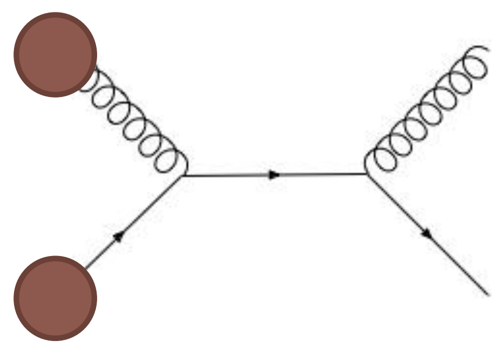


Small x: proton mostly gluon



pp → gg

Larger x: quark-gluon dominates

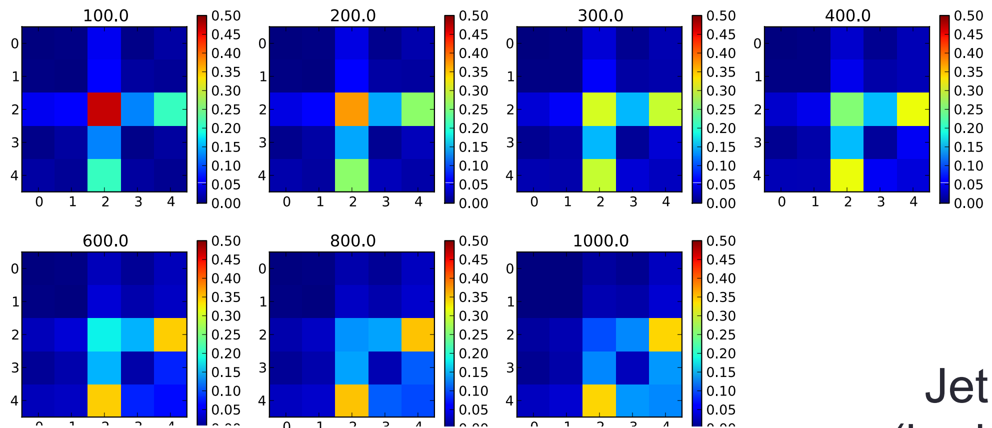


pp → ug

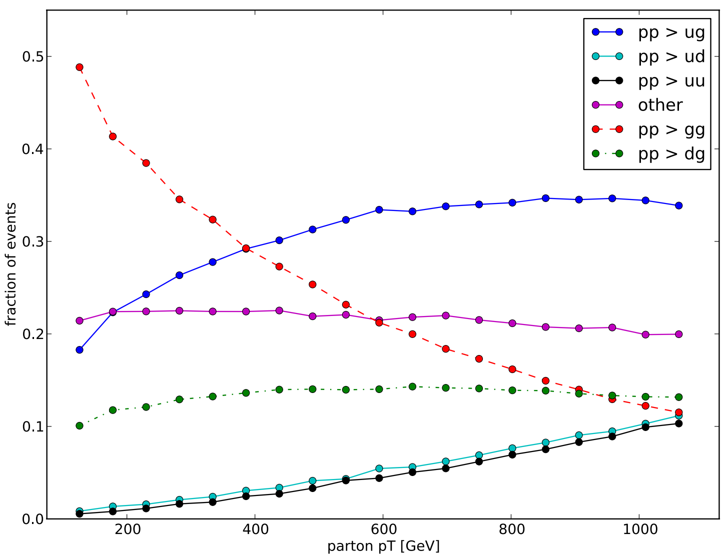
Valence quarks picked up at large x

Dijets: quarks at large x

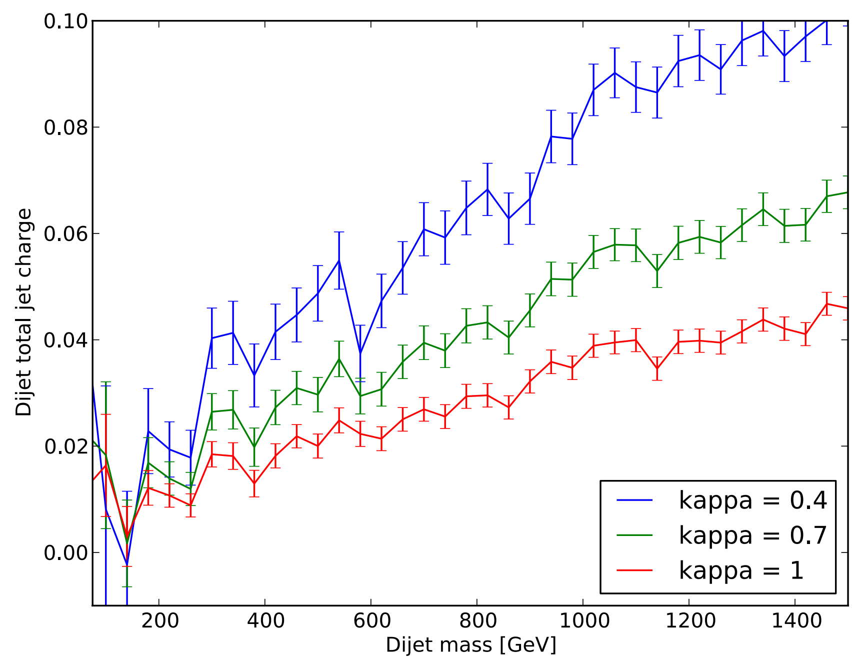
2D charges (parton level) for different pT



Fractions (parton level)

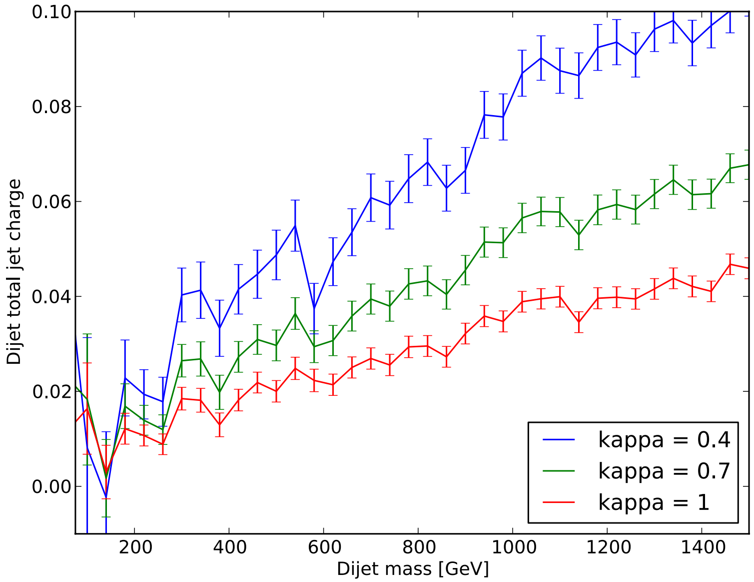


Jet charge (hadron level)

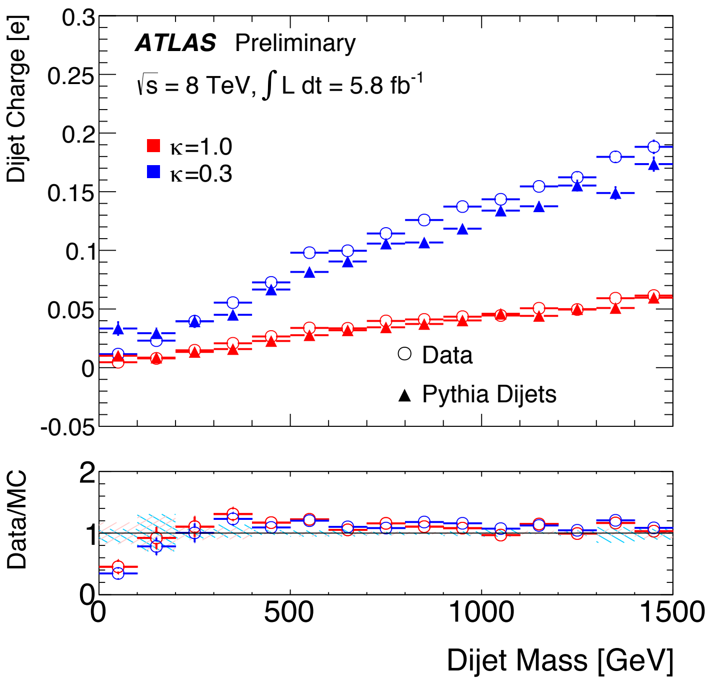


ATLAS data

Theory paper



ATLAS Conference note



Evidence of valence quarks in PDFs!
Quark charge measured without leptons
-- in pure QCD (dijet) events.

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

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

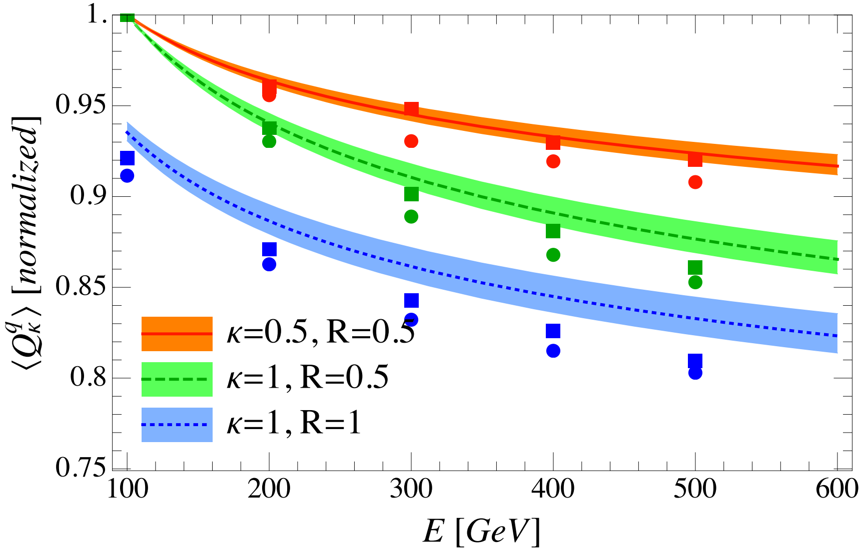
$$\langle \mathcal{Q}_\kappa^q \rangle = \frac{1}{16\pi^3} \frac{\widetilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{\mathcal{J}_q(E,R,\mu)} \sum_h Q_h \widetilde{D}_q^h(\kappa,\mu)$$

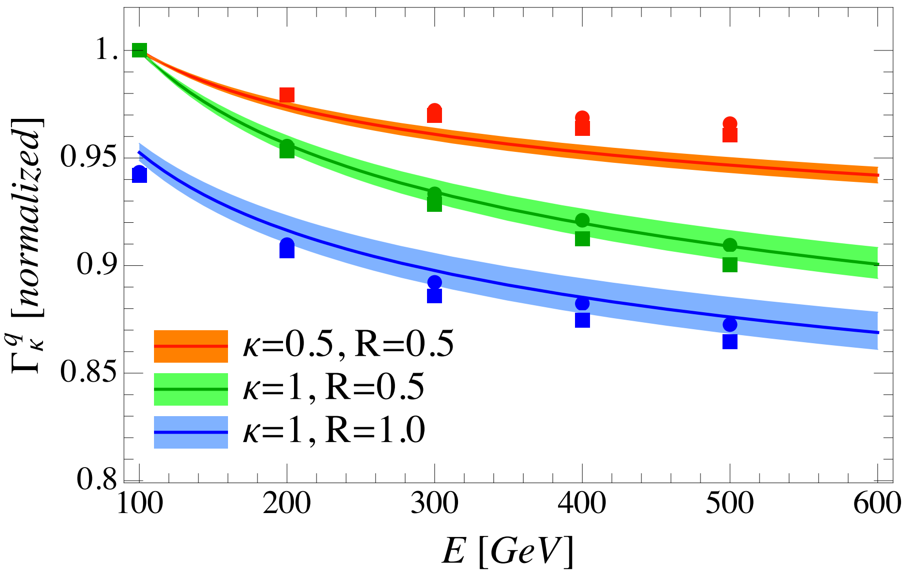
Jet function

Calculable

(Prob. of getting jet with E and R)

Mean and width evolution are calculable





Krohn, Lin, MDS, Waalewijn
Phys.Rev.Lett. 110 (2013) 212001

- Moments of charge distribution
  calculable from moments of fragmentation functions

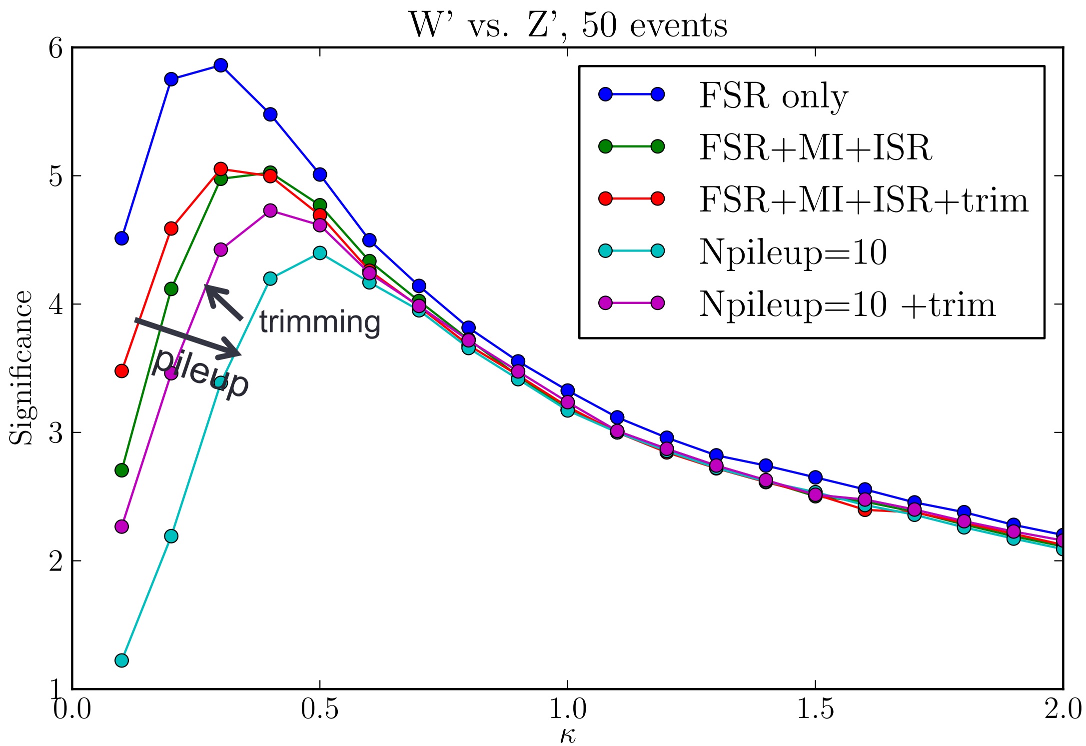
- **Evolution** of these moments tests **precision QCD**

  1. Verify dijet charge (2->2 cross sections and PDFs)
  2. Observe new form of scaling violation

Contamination

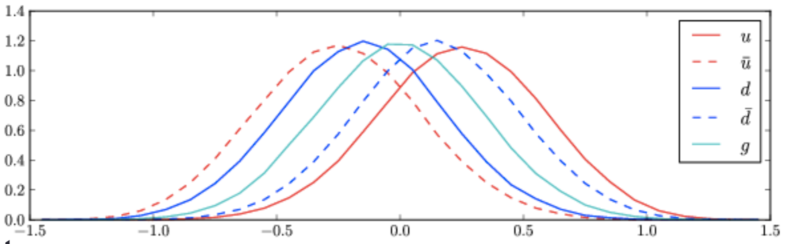
Effect of multiple interactions/pileup not bad

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



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**

$$\langle \mathcal{Q}_\kappa^q \rangle$$

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

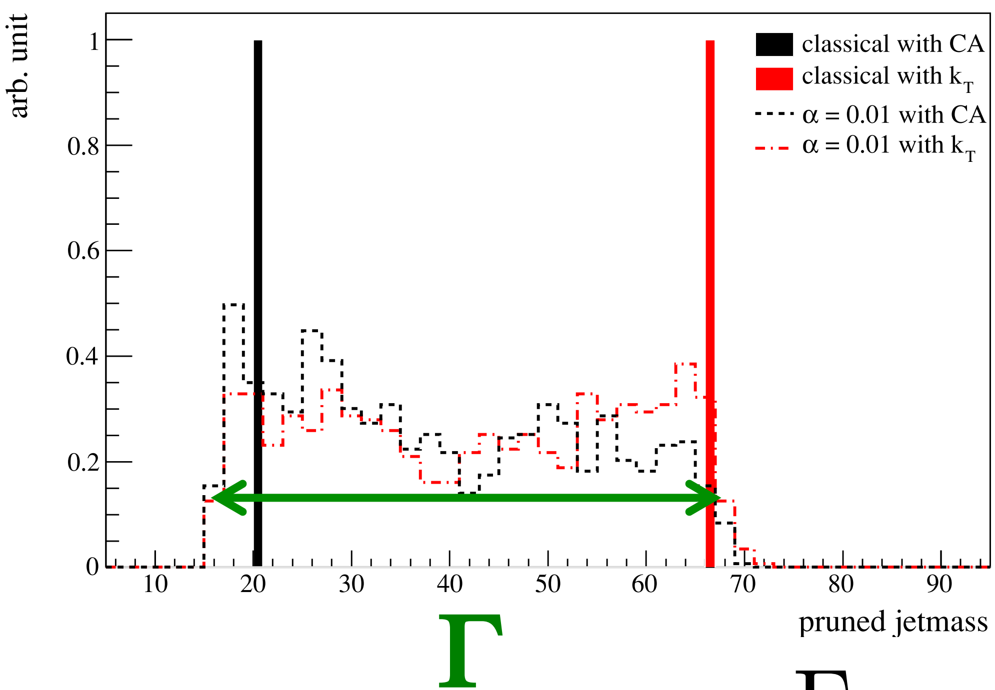
- Has been **validated** on W jets from top decays
- Has been **tested** on dijets
  - Quark/Gluon/Flavor content measurable (statistically)
  - Unfolded data will show
    - Tests precision QCD
    - Gluons are at small x, valence quarks at large x
    - First measurement of scaling violation in charge moments

OTHER IDEAS IN JET SUBSTRUCTURE

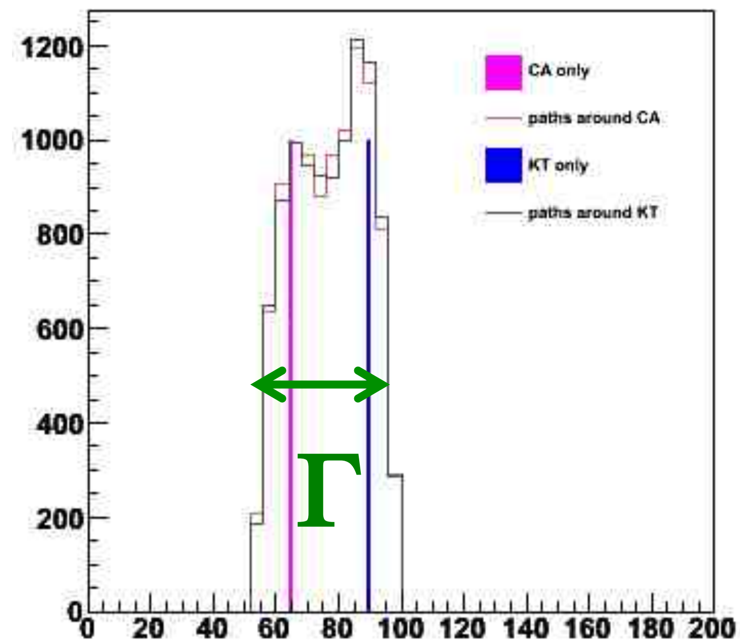
Qjets: sample multiple interpretations

Ellis,Hornig, Krohn, Roy, MDS
Phys.Rev.Lett. 108 (2012) 182003

QCD jets (one event)



W jets (one event)

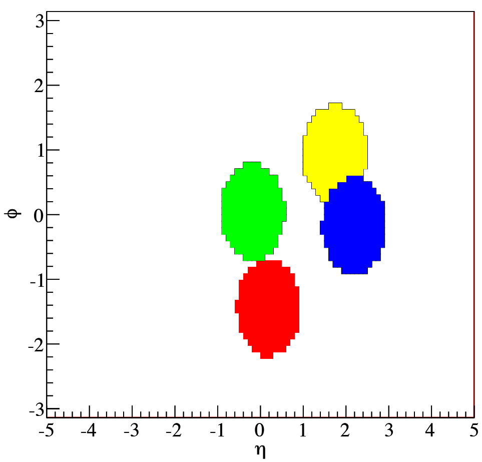


Volatility $\mathcal{V} = \frac{\Gamma}{\langle m \rangle}$ is a purely Q-observable

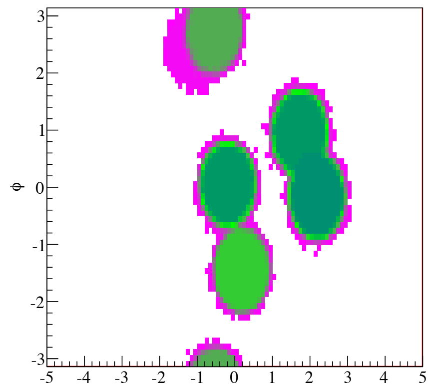
Jet Sampling: Qjets for ambiguous/ overlapping jets

Kahawala, Krohn, MDS
JHEP 1306 (2013) 006

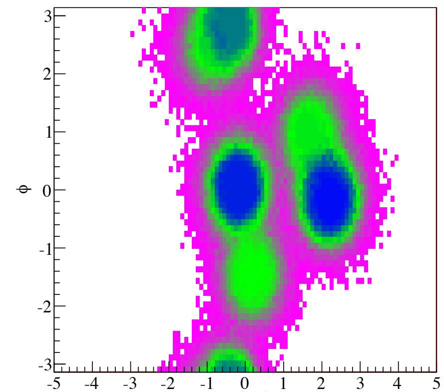
classical anti-k_T



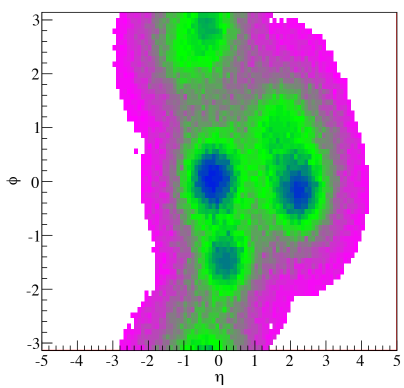
$\alpha = 10$



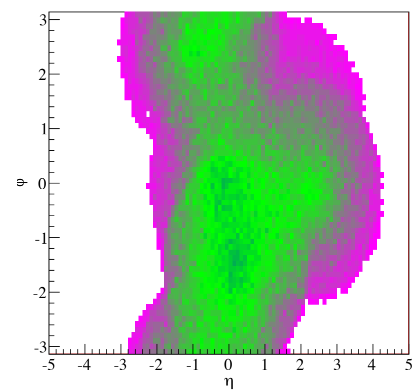
$\alpha = 1.0$



$\alpha = 0.1$

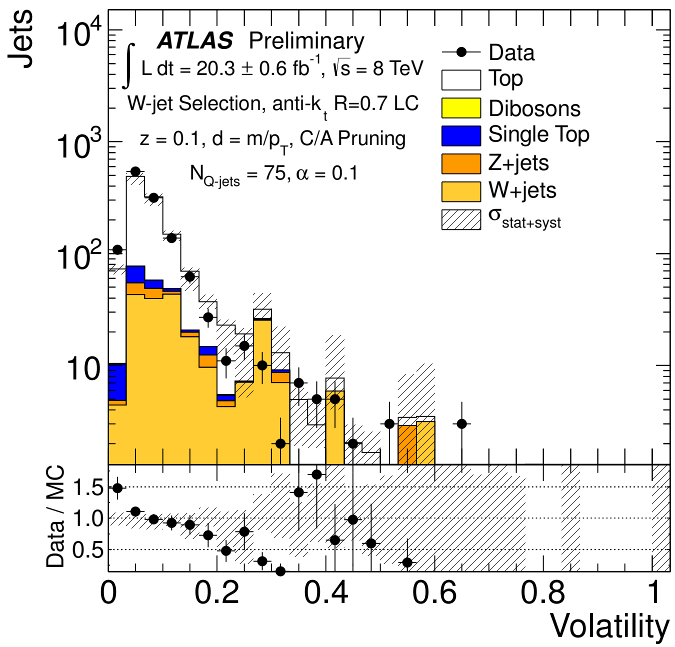


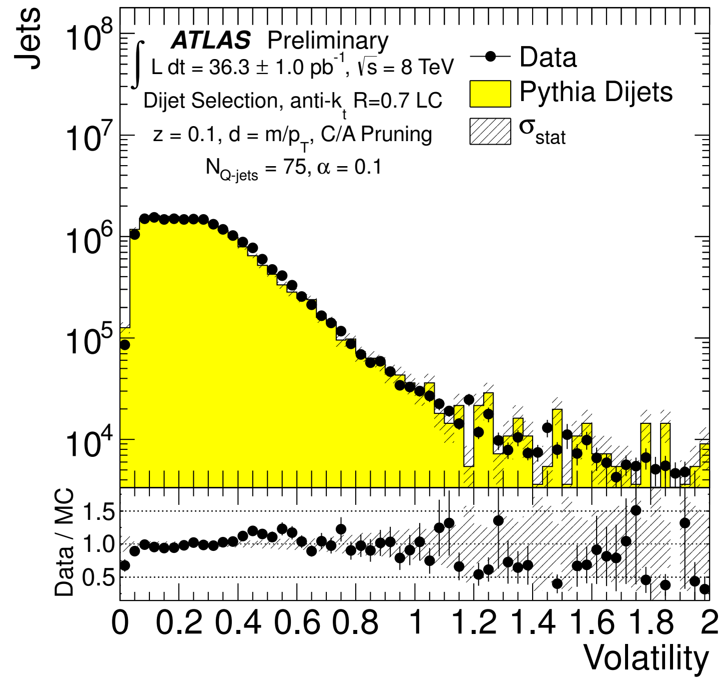
$\alpha = 0.01$



Measured in data

ATLAS-CONF-2013-087





Useful for top/W tagging
Useful for H -> bb
Distinguishes overlapping jets

Interesting standard model physics

Jet is not a parton

Jet is not a collection of hadrons!!

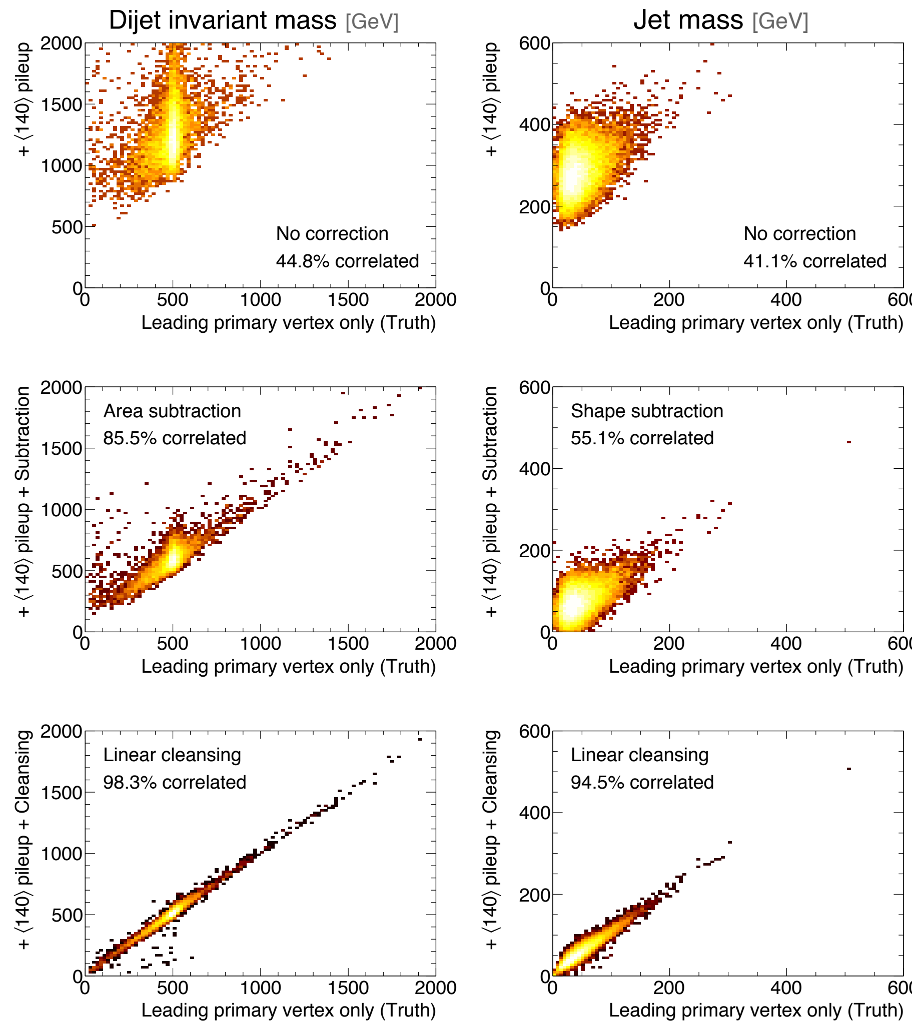
Jets are **sophisticated emergent phenomena** in the standard model

What is the **right way** to think about jets?

Pileup removal

will be **ESSENTIAL**
for precision QCD at high luminosity

140 pileup interactions



Existing methods

Jet area subtraction
Jet shape subtraction
Charged hadron subtraction
Jet vertex fractioning
Trimming
Pruning
Filtering

Work well at NPU = 20

Area/Shape subtraction

Jet Cleansing

(new method, Krohn, Low MDS, Wang)

Quark and gluon tagging

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

Gallichio and MDS JHEP 1304 (2013) 090

See also Larkoski, Salam and Thaler arXiv:1305.0007

Thaler and van Tilburg arXiv:1011.2268

Gluon Efficiency % at 50% Quark Acceptance	**50 GeV**				**200 GeV**			
	Particles		Tracks		Particles		Tracks	
	P8	H++	P8	H++	P8	H++	P8	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: $\sqrt{< p_T^2 >}/p_T^{\text{jet}}$	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

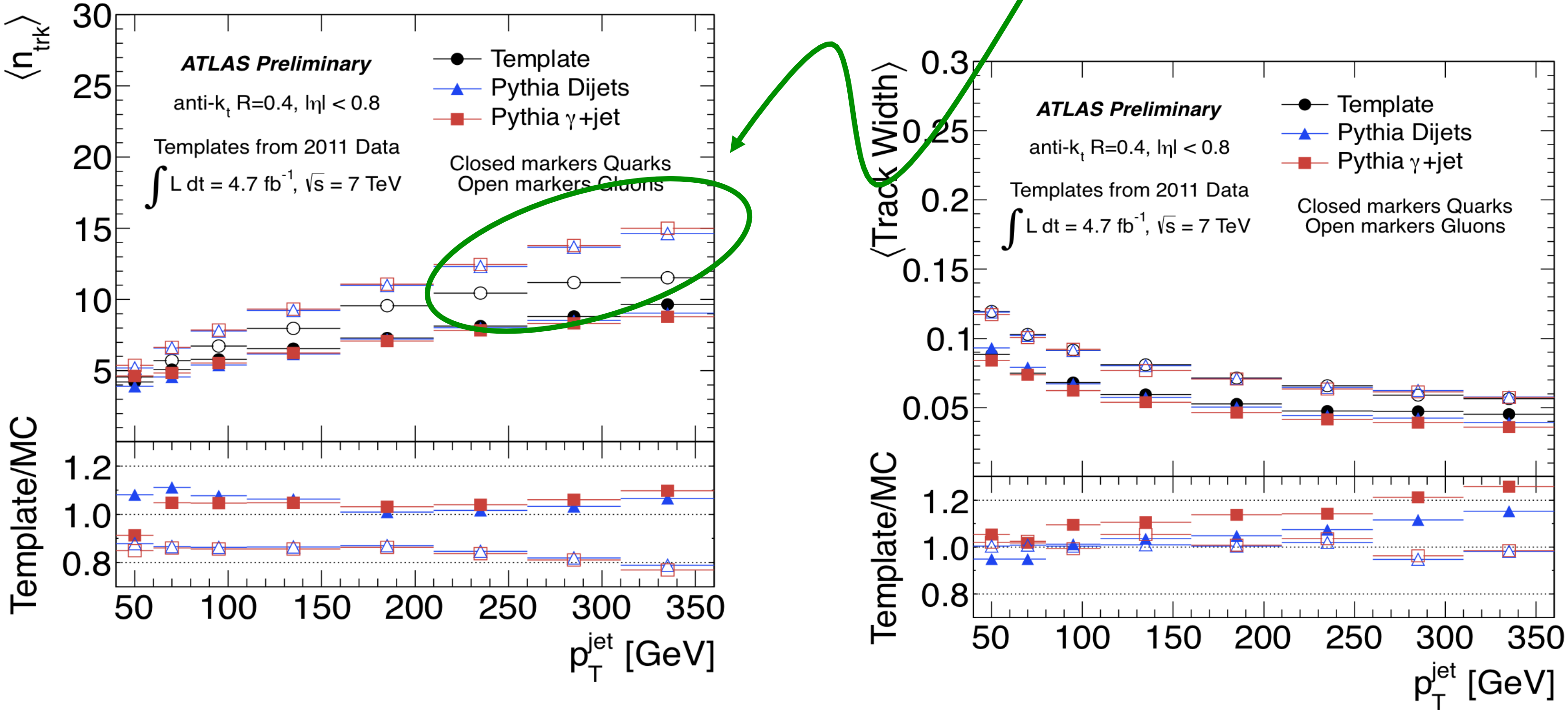
Quark and Gluon tagging

- Hard problem:
  Two equivalence classes → Shapes: Width/girth/2-point function; → Counts: # particles/subjets/
- 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**

ATLAS-CONF-2012-138

Data (Sep 2012)

Data and pythia do not agree
For charged particle multiplicity

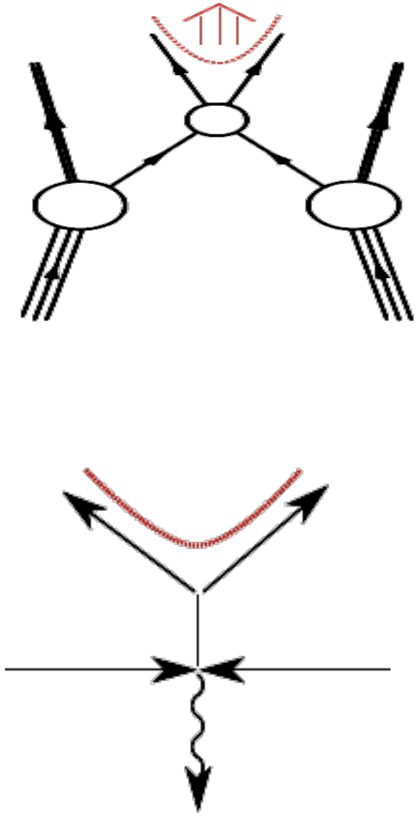


	Quark acceptance	Gluon acceptance
Pythia 8	50%	17%
Herwig ++	50%	26%
Data	50%	25%

Future of Q vs G needs
more data and better theory

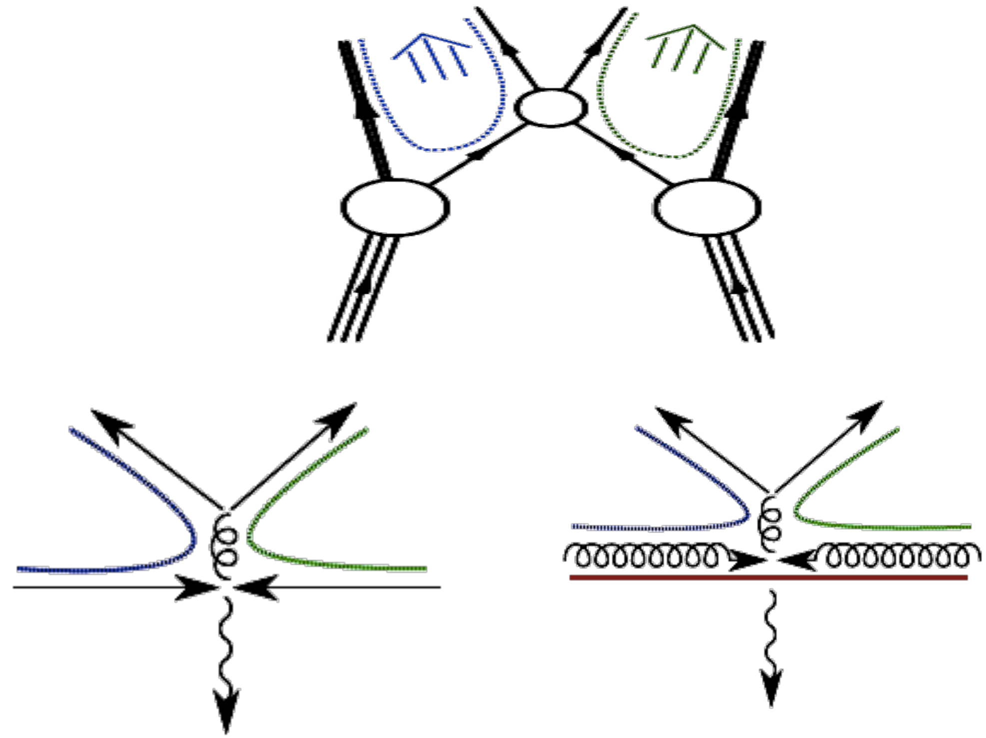
measuring Color flows in jets

Signal



$H \to b\bar{b}$

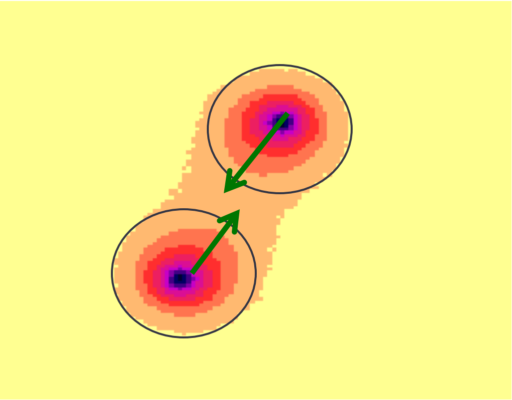
Background

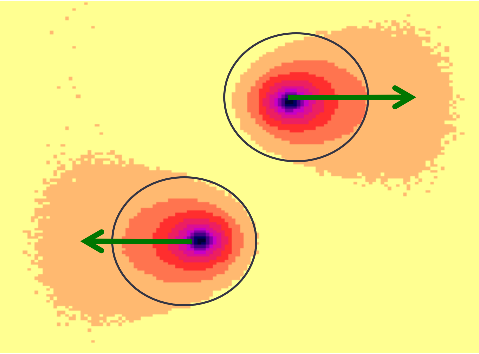


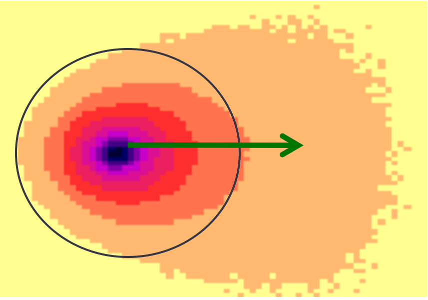
$q\bar{q} \to Zb\bar{b}$

$gg \to Zb\bar{b}$

Pull

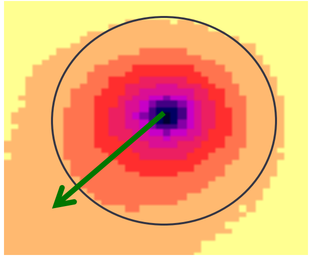




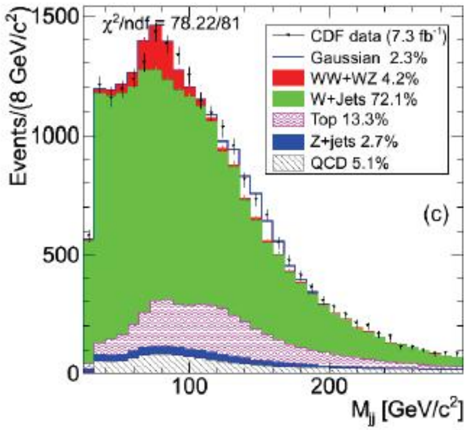


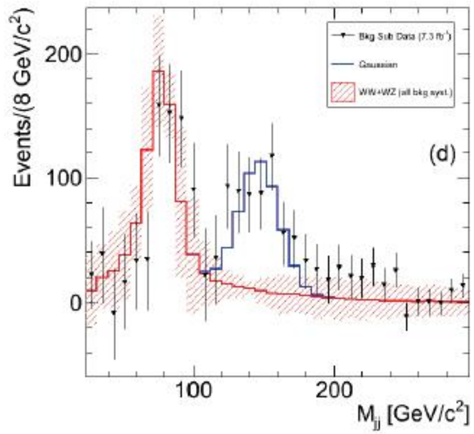
- Find **jets** (e.g. anti-k_T)
- Construct **pull vector** (~ dipole moment) on radiation in **jet**

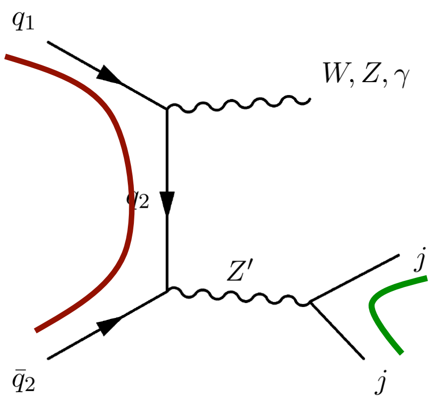
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \, \vec{r}_i$$



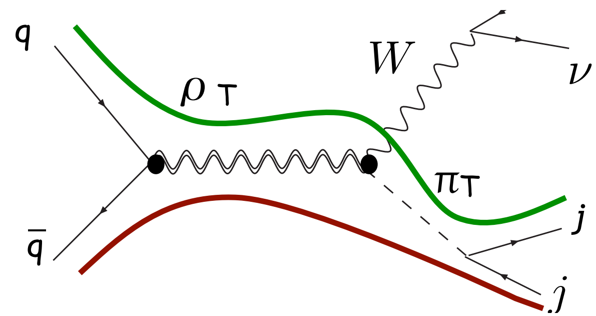
CDF dijet excess







t-channel



s-channel

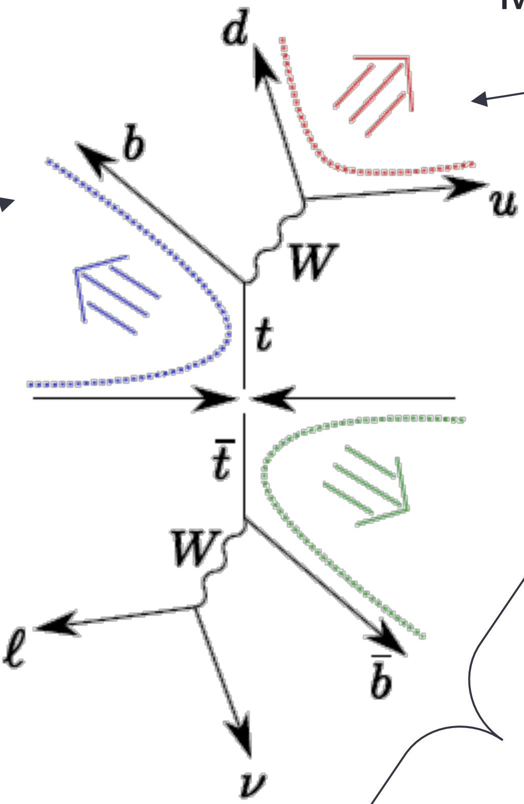
Measure color connections distinguishes s from t channel production

Must validate on Standard Model first

Validate on tops

b-tag

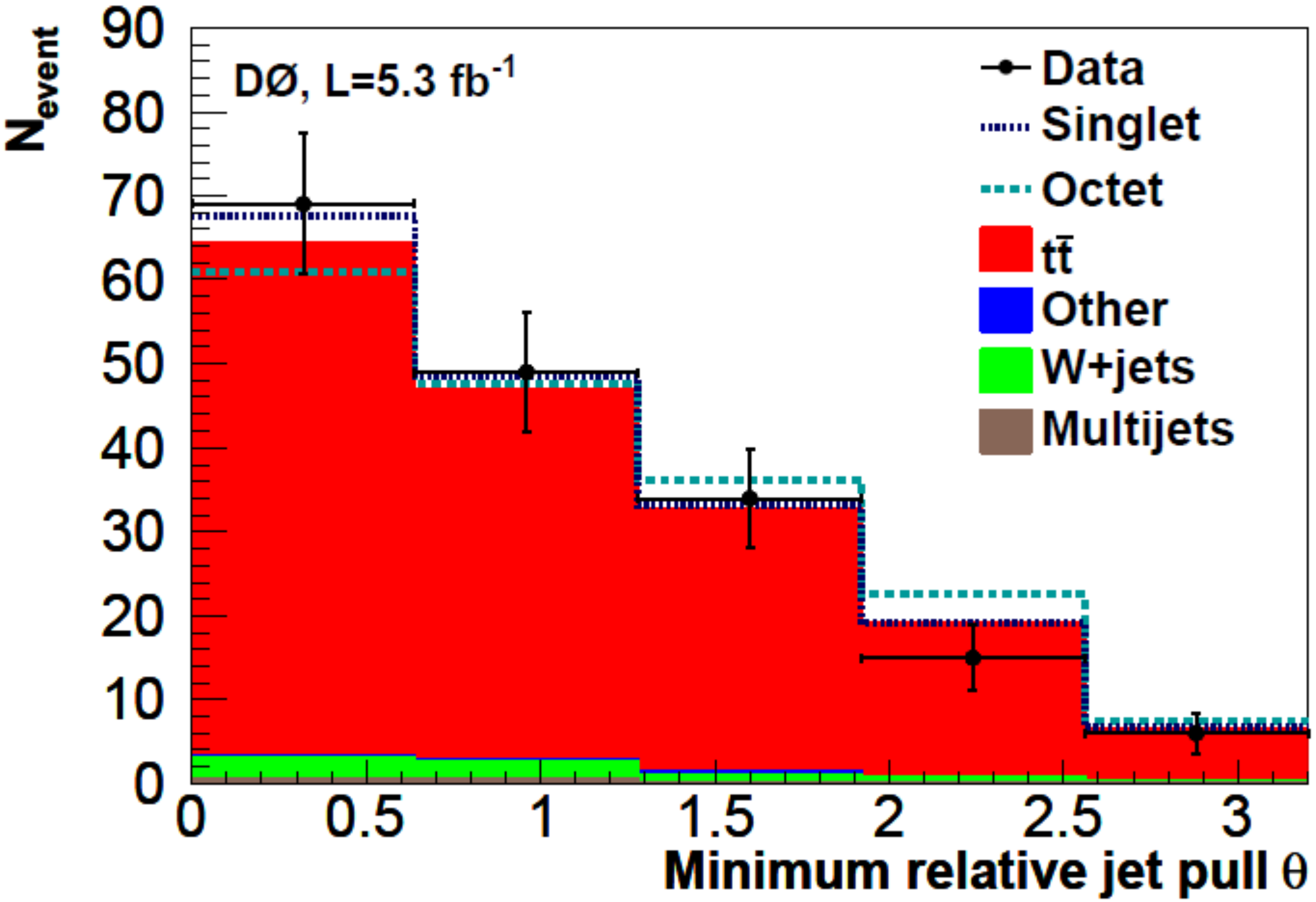
Measure pull



Clean top tag on leptonic side

D0 ruled out color octet W in top decays

Andy Haas and Yvonne Peters, hep-ex:1101.0648



Conclusions

The July 5^{th} problem → We want to have tools ready and validated **before** new physics is discovered

- e.g. jet charge
- color connections
- QvG
- …

Appreciating the The Standard Model ↓

2007: A jet is a 4-vector. Just calibrate it.
2013: Jets are **sophisticated emergent phenomena** in the standard model

Lets study them for their own sake!

Examples:

jet charge

- shows evidence for quarks and gluons in proton, at different x
- Mean charge scale-independent to leading order

  calculable scaling violation

Qjets/volatility

- Re-evaluate what a jet is.
- Wide open field, theoretically and experimentally

QUESTIONS FROM ATLAS

Scale uncertainties

- Several theorists suggest that factorization and normalization scale uncertainties on W+b predictions should be estimated by changing the scales by factors 4 and 1⁄4 (instead of the usual 2 and 1⁄2). This has become the standard procedure in comparing prediction with past W+b xsec measurements. Is this still justified?

Scale uncertainties

Why should scale variations predict uncertainties?

$$\sigma \sim \alpha_s(\mu) c_1 + \alpha_s^2(\mu)\left(c_1 \beta_0 \ln \frac{\mu}{Q} + c_2\right) + \cdots$$

Substitute in

$$\alpha_s(\mu) = \alpha_s(\mu_0) + \beta_0 \alpha_s \ln \frac{\mu_0}{\mu}$$

μ-dependence cancels

No dependence on μ if known exactly

Choose μ=Q to minimize large logs

$$\sigma \sim \alpha_s(Q) c_1 + \alpha_s^2(Q) c_2$$

Suppose c_2 is not known, but c_1 and β_0 are. How do we estimate c_2?

Varying around Q/2 < μ < 2Q

$$\sigma \sim \alpha_s(Q) c_1 \pm \alpha_s^2(Q) \underbrace{c_1 \beta_0 \ln 2}$$

2? 4? 100?

Gives a **number of order 1**

that appears **in the right place** where c_2 would in the cross section

Method works well for inclusive **single scale observables**

Scale uncertainties

Method works for inclusive **single scale observables**
No theory justification for most cross sections at LHC

N-jet production, W+jet production, Higgs+W with jet veto

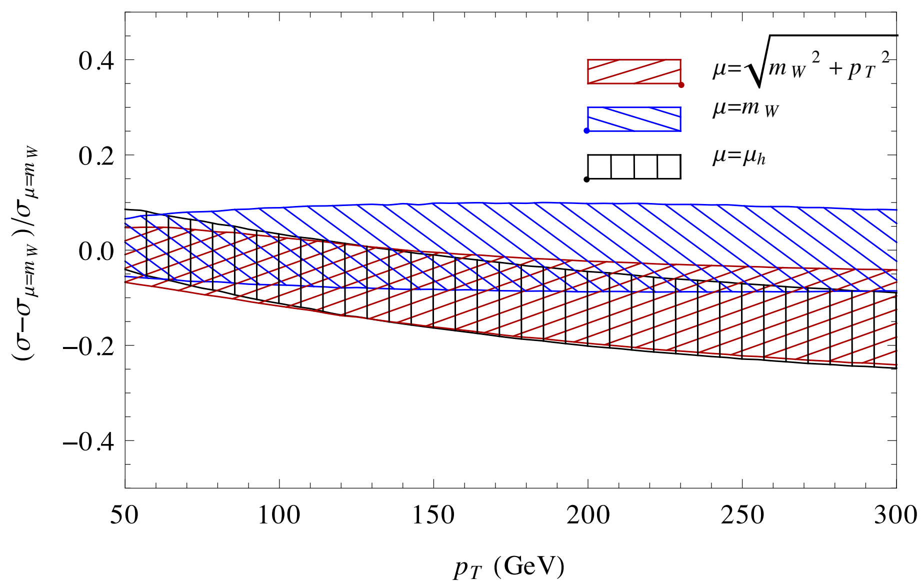
In these cases, we don't know what μ=Q means

1. Guess:

$$\mu = H_T$$
$$\mu = \sqrt{p_T^2 + m_W^2}$$
$$\mu = \max\{m_W, E_{\text{jet}}\}$$

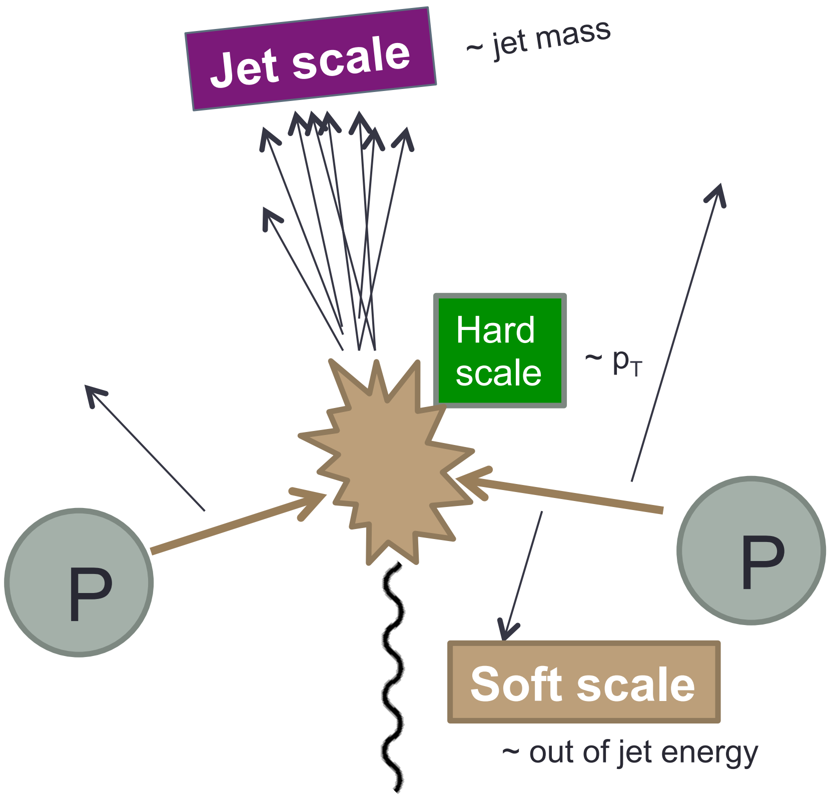
Pick one and vary by a factor of 2 or 4 or 100

Differences between parameterizations are larger than the individual variations



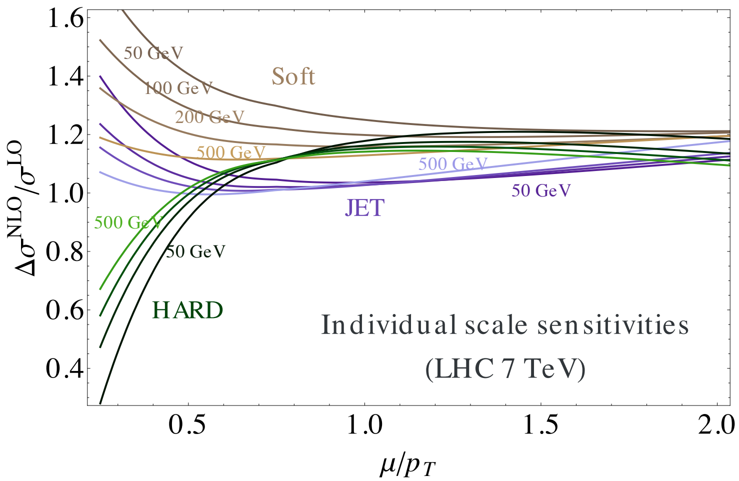
Becher, Lorentzen and **MDS**, Phys.Rev. D 86 (2012)

In some cases, we know the origin of the different scales

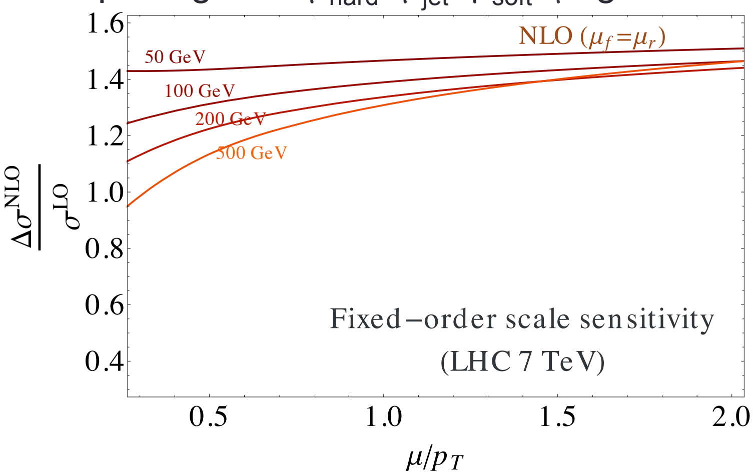


High p_T
W boson

Individual variation show extrema
(natural μ_{hard}, μ_{jet}, μ_{soft} scales, like Q)

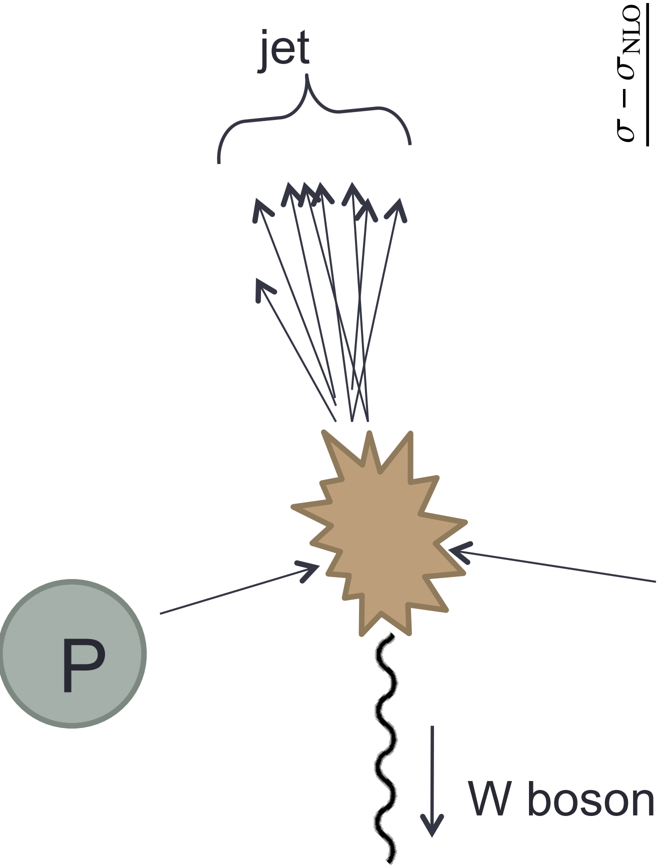


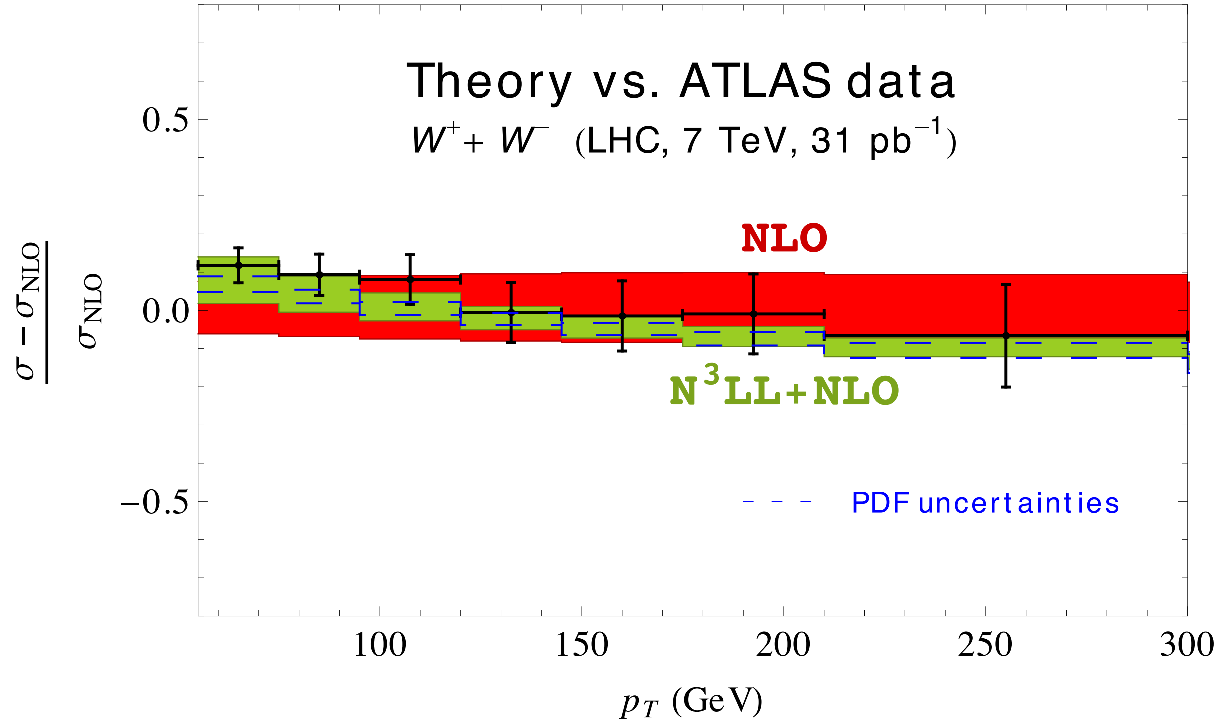
When put together $\mu_{hard}=\mu_{jet}=\mu_{soft}=\mu$ gives NLO



No natural μ at NLO (or NNNNLO). **Cannot set all scales equal**.

W + JET at the LHC





Becher, Lorentzen, and MDS, (2010, 2011, 2012, 2013 …)

Public code (PeTeR) for high-p_T W/Z

Scale setting

My recommendation:

Compare different parameterizations, including all relevant scales, rather than varying each by 2 or 4