Overview of QCD Studies at the LHC

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KAIST-KAIX Workshop for Future Particle Accelerators
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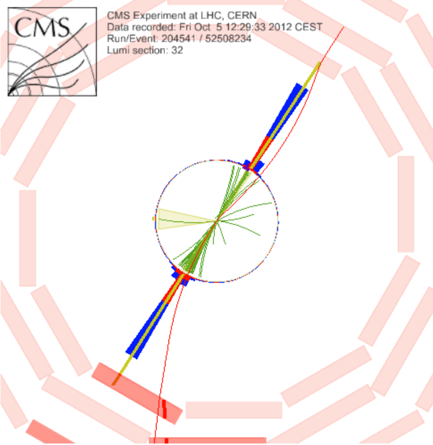
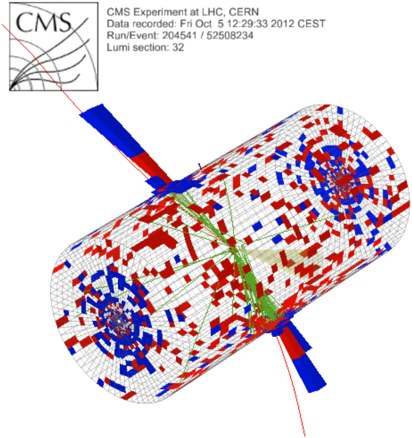
An Event Display

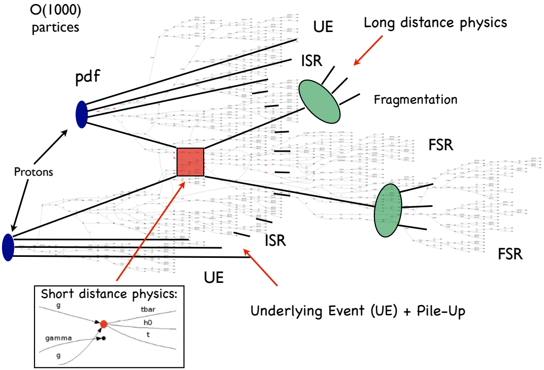




- Quarks and gluons are charged under QCD color
- Bare quarks and gluons not observed, instead see collimated *jet* of hadrons after *showering*

CMSPublic/PhysicsResultsEXO12059

Introduction

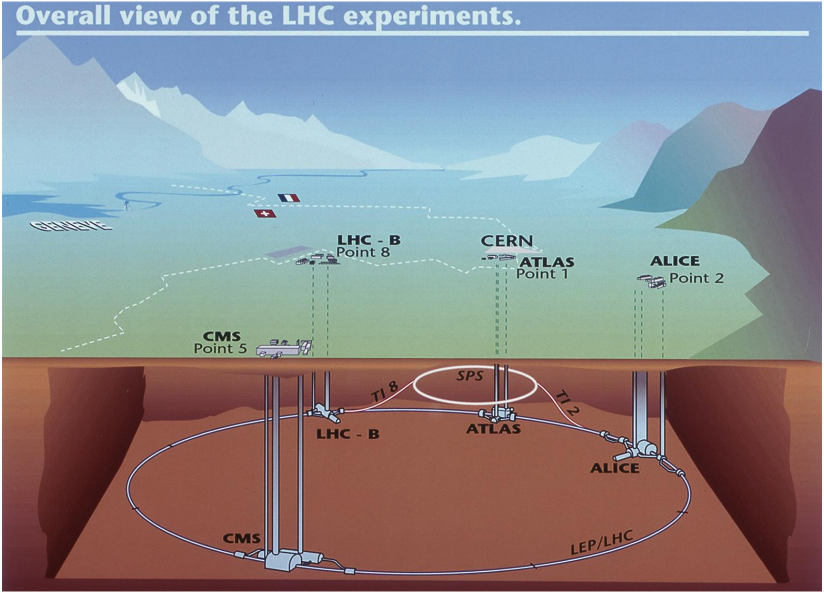


- QCD at colliders is a complex multi-scale problem
  - Every event at LHC involves QCD, can only cover a subset of results
- CMS and ATLAS study many aspects of QCD, in ever-increasing levels of detail, will give a taste of Run II results
- Papers referenced in this talk: arXiv:1711.02692, arXiv:1605.04436, arXiv:1712.05471, arXiv:1902.04374, arXiv:1711.08341, arXiv:1807.05974, arXiv:1903.02942, arXiv:1808.07340, arXiv:1807.02810

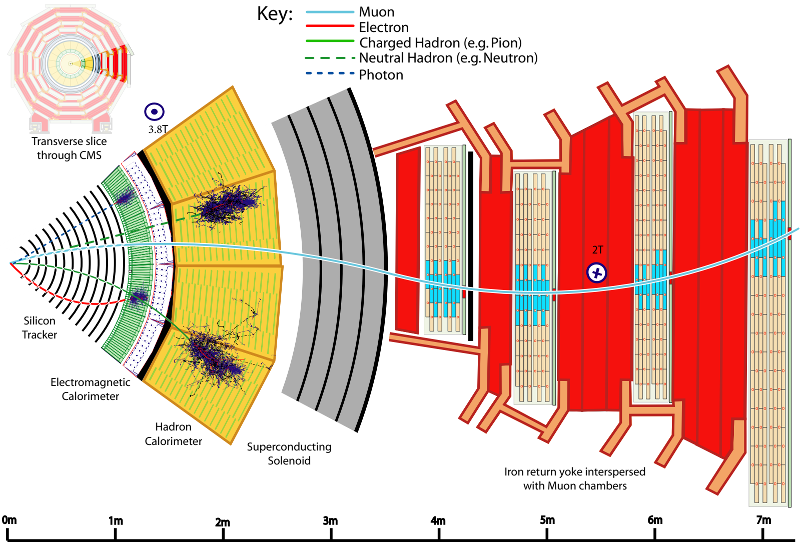
Figure from arXiv:1901.10342

Contents

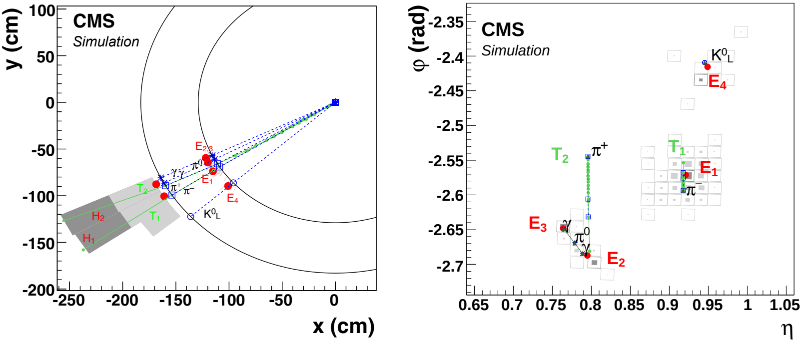
LHC


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

The CMS Detector



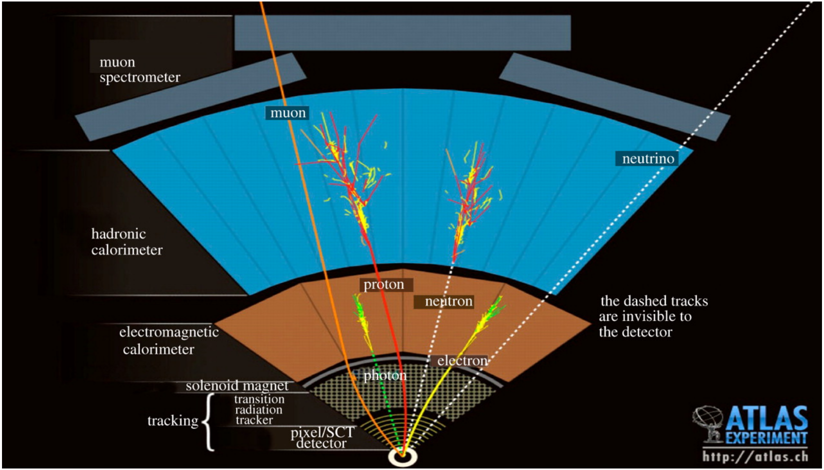
CMS Jet Reconstruction



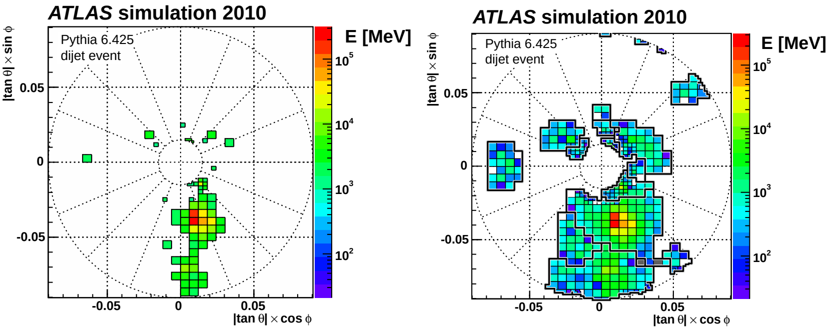
- Inc CMS, information from all detectors combined together giving *particle flow* output, used as input to jet algorithms
- Can use CHS "Charged-Hardon Subtraction" or PUPPI "Pileup Per Particle Identification" weights to reduce effects of pileup
- Small additional pile-up corrections and jet energy scale corrections (based on data analysis) applied

arXiv:1706.04965

The ATLAS Detector



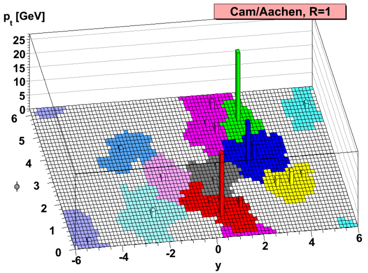
ATLAS Jet Reconstruction

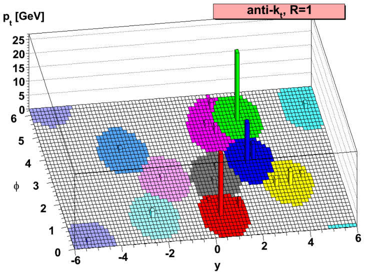


- In ATLAS, jet reconstruction uses 3D topological clusters built from energy deposits in the calorimeter cells
  - Topoclusters corrected to EM shower response
  - Pileup corrections applied, and energy-η dependent jet energy corrections to recover *particle jet* energy
  - Further corrections based on e.g. N_{trk} to reduce fluctuations from particle composition

arXiv:1603.02934

Jet Types and Sizes

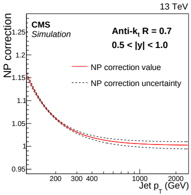


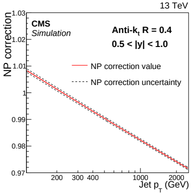


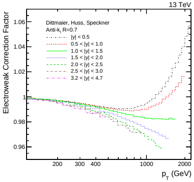
- For Run II:
  - ATLAS and CMS unified *default* jet reconstruction, anti-kt algorithm with $R = 0.4$
  - In Run I, ATLAS used $R = 0.4$ default, CMS defaulted to $R = 0.5$
- Various non-standard jet types/sizes, reclustering, grooming techniques being explored by both collaborations
  - Pileup reduction, non-perturbative soft energy deposit removal, substructure studies, boosted object ID studies

arXiv:1901.10342

Double-Differential Inclusive Jet Distributions





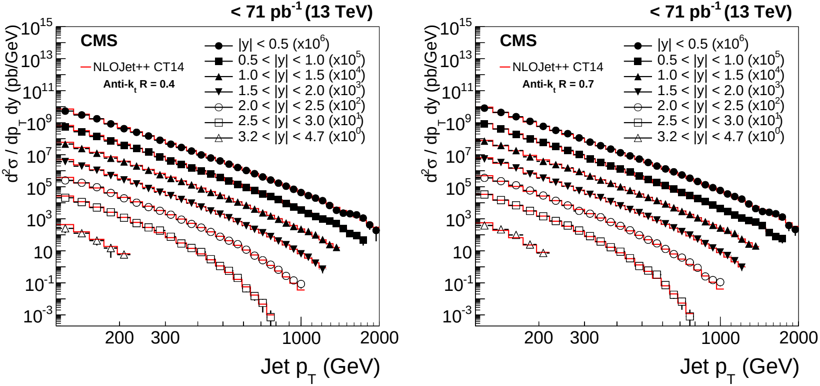


arXiv:1605.04436

- Simplest thing you might think to do is to count jets and compare to theoretical prediction
- CMS and ATLAS do this dividing jets by jet p_T and absolute rapidity $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$
- The collaborations compare to NLO predictions
- Requires non-perturbative (NP), EW corrections
  - $C^{\mathrm{NP}} = \frac{d\sigma^{\mathrm{PS+HAD+MPI}}/dp_T}{d\sigma^{\mathrm{PS}}/dp_T}$
- Jets are the most common hard event in LHC, jet triggers are *prescaled*
  - Only a fraction of the triggered events are kept

HLT path	p_T range (GeV)
PFJet_60	114–133
PFJet_80	133–220
PFJet_140	220–300
PFJet_200	300–430
PFJet_260	430–507
PFJet_300	507–638
PFJet_400	638–737
PFJet_450	>737

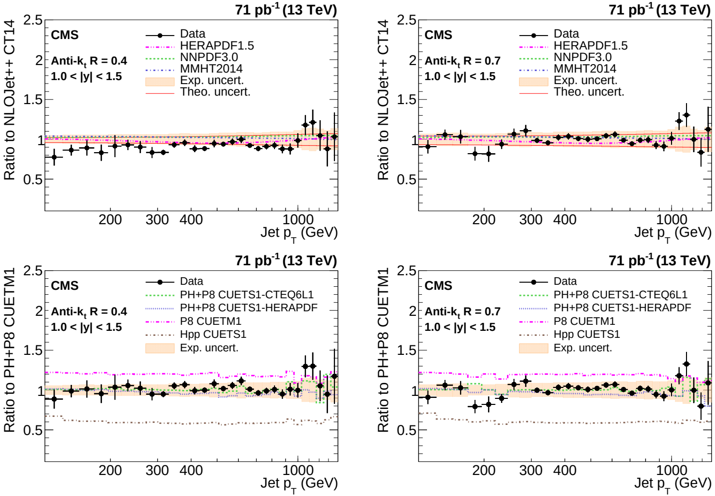
Double-Differential Inclusive Jet Distributions



- Double differential cross section as a function of jet p_T and rapidity
  - "< 71 pb^{-1}" triggers increase with changing conditions
- Key test of perturbative QCD, over 14 orders of magnitude in x-sect
  - Comparison to NLOJet++ with non-perturbative/EW corrections
- Inclusive jet spectrum with anti-kT jets: (Left) R=0.4 (Right) R=0.7

arXiv:1605.04436

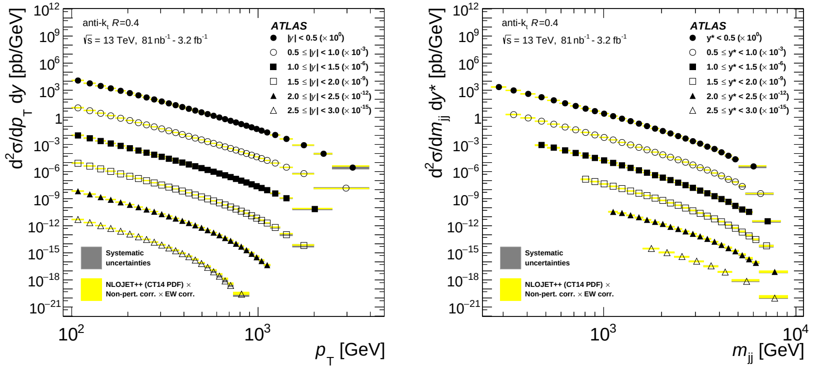
Double-Differential Inclusive Jet Distributions



- NLOJet++ overestimating R=0.4 by ≈5%, doing well with R=0.7
- NLO event generators matched to parton shower models both R

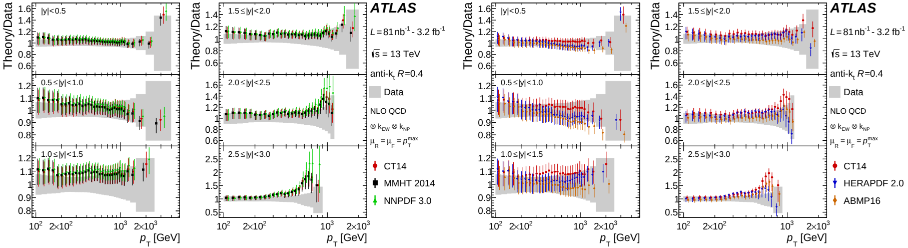
arXiv:1605.04436

Double-Differential Inclusive Jet Distributions



- Double differential cross section as a f^n of jet p_T and rapidity
- Double differential cross section as a f^n of $y^* = |y_1 - y_2|/2$ and m_{jj}
- Comparison to NLOJet++ with non-perturbative/EW corrections
  - Nb. CMS multiplying with positive exponents, ATLAS uses negative

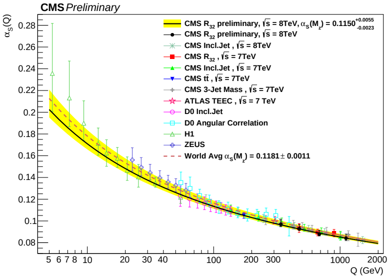
arXiv:1711.02692



- As for CMS, central value for NLOJet++ + corrections overestimates data (R=0.4)
  - Nb. ATLAS has theory/data whereas CMS preferred data/theory
- Prediction for various PDF sets shown

arXiv:1711.02692

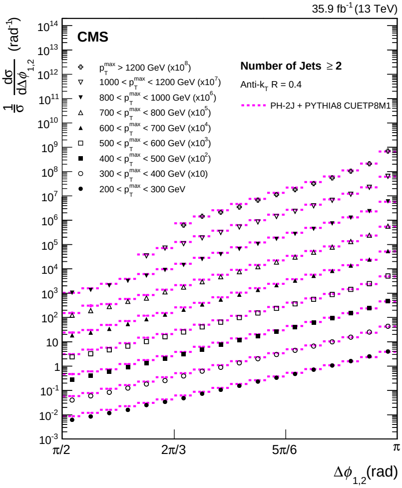
Measurement of α_S from multi-jet events



- Inclusive 2-jet and 3-jet cross-sections are measured as a f^n of avg. p_T
  - $\sqrt{s} = 8$ TeV, 19.7 fb^{-1}, anti-kT jets with $R = 0.7$
- From a fit of the ratio of 3- to 2-jet x-sect. $\alpha_S(M_Z)$ is inferred
- Find $\alpha_S(M_Z) =$ $0.1150 \pm 0.0010(exp) \pm 0.0013(PDF) \pm 0.0015(NP)^{+0.0050}_{-0.0000}(scale)$
  - Consistent with world average

CMS-PAS-SMP-16-008

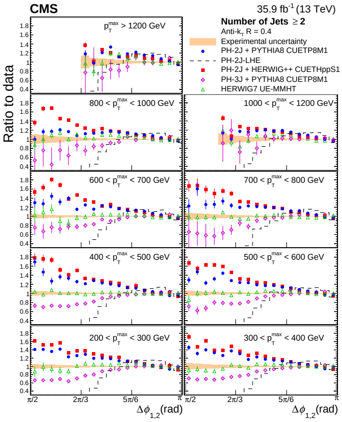
Azimuthal correlations for inclusive 2-jet events

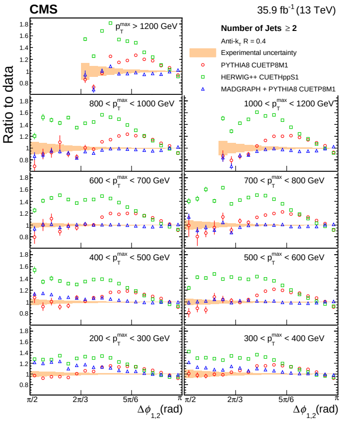


arXiv:1712.05471

- In the dijet topology, final partons back-to-back in the transverse plane
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{1,2}}$ azimuthal correlation between the two jets with largest p_T, as a fn of leading jet p_T
- Interesting tool to test predictions of multijet production
- Covers $\pi/2 < \Delta\phi_{1,2} < \pi$
  - $\Delta\phi_{1,2} < \pi/2$ has large $t\bar{t}$ and W/Z+jet backgrounds

Azimuthal correlations for inclusive 2-jet events

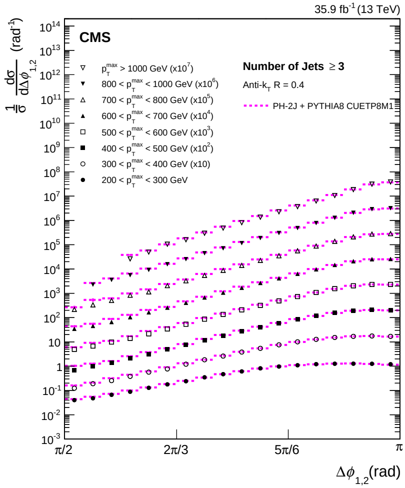


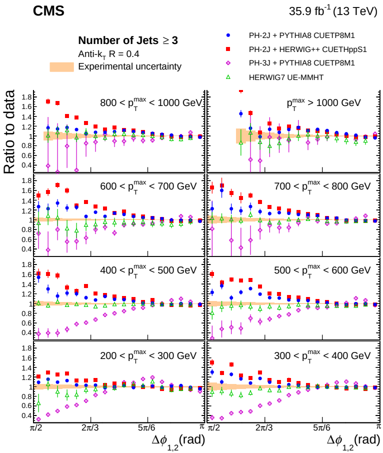


- NLO predictions, PH=POWHEG
- LO predictions right, MG includes MLM-matched LO $2 \to 2, 3, 4$
- Herwig7 gives best description of data
    - Uses MC@NLO method of matching versus PowHeg method

arXiv:1712.05471

Azimuthal correlations for inclusive 3-jet events

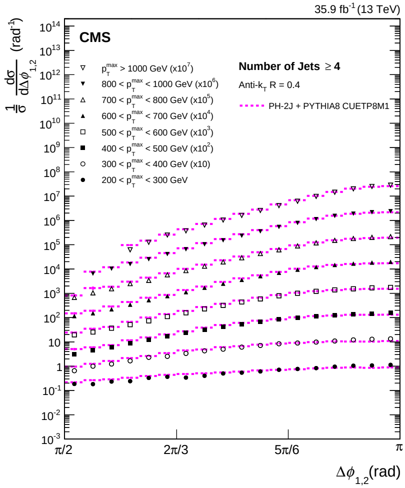


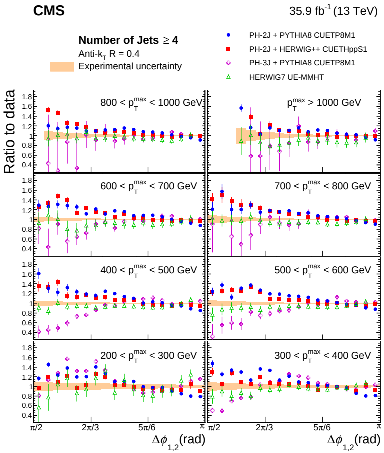


- Requiring 3 jets flattens the $\Delta\phi$ distribution
- Herwig7 still gives best results

arXiv:1712.05471

Azimuthal correlations for inclusive 4-jet events

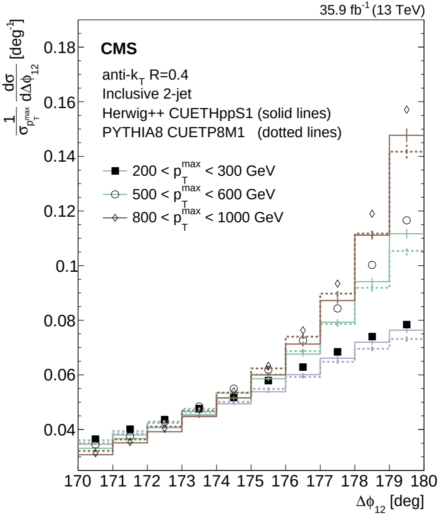




- Four-jets further flattens the distributions
- Herwig7 still gives best description of the data

arXiv:1712.05471

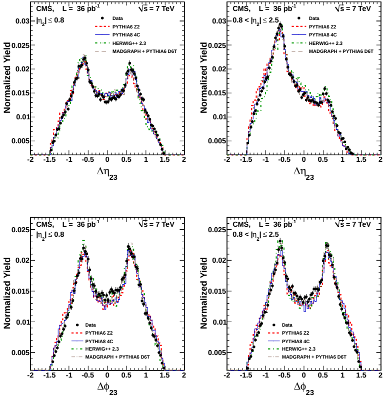
Azimuthal correlations in nearly back to back topologies

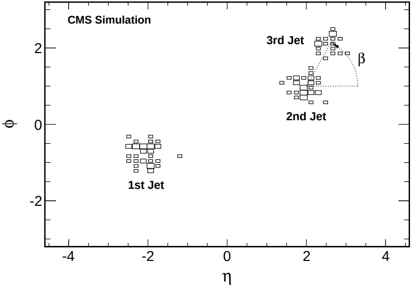


arXiv:1902.04374

- Nearly back-to-back topologies allows a more precise test different resummation strategies
  - Requires more detailed understanding of the effects of soft gluons
- More back-to-back as p_T increases
- 2-jet and 3-jet inclusive distributions measured
  - No prediction precisely modelling the distributions simultaneously currently

Color Coherence (7 TeV)

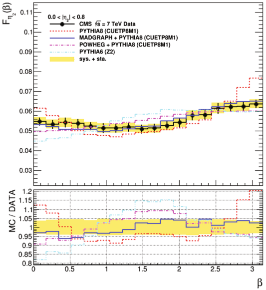


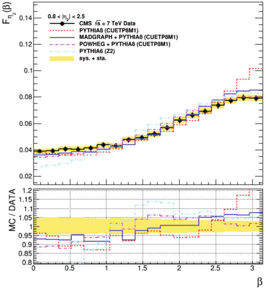


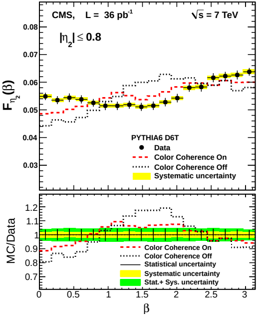
- $\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$
  - In presence of color coherence effects, should have β=0, 3rd jet lies on the event plane, while β=$\pi/2$, out of plane radiation suppressed
- Measured in in trijet events requiring $M_{12} > 220$ GeV, $p_{T1} > 100$ GeV

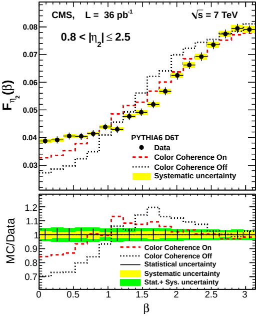
arXiv:1311.5815

Color Coherence (7 TeV)









- Turning PYTHIA6 color coherence parameter off decreases
- Newer MCs (left) describe the effect better
  - In particular, Madgraph with LO $2 \rightarrow 3$ diagrams improves description

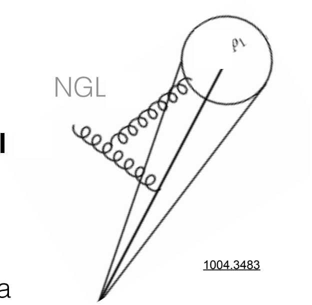
(top) arXiv:1311.5815, (left) https://doi.org/10.3938/jkps.70.465

Soft Drop

What is soft drop?

2

- Soft drop is a **jet grooming** algorithm
  - Removes soft and wide angle radiation from a jet
- Formally insensitive to **non-global logarithms**
  - Jet substructure observables amenable to precision calculations for the first time at a pp collider



- Particularly important because JSS observables are dominated by **resummation** and **not fixed-order**

Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

The soft drop algorithm

3

Take a jet clustered with e.g. anti-kt

↓

Re-cluster it with C/A

↓

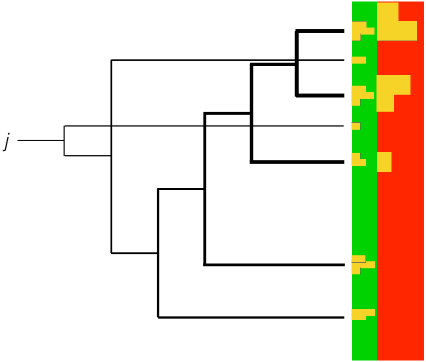
Traverse the clustering tree backwards

↓

If a branch point satisfies the soft drop condition, stop.

↓

Otherwise remove the softer branch and continue down the harder branch.



anti-kt: clusters hardest radiation first

Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

The soft drop algorithm

4

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↓

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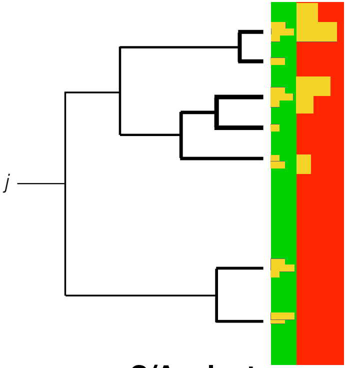

C/A: clusters closest radiation first

Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

The soft drop algorithm

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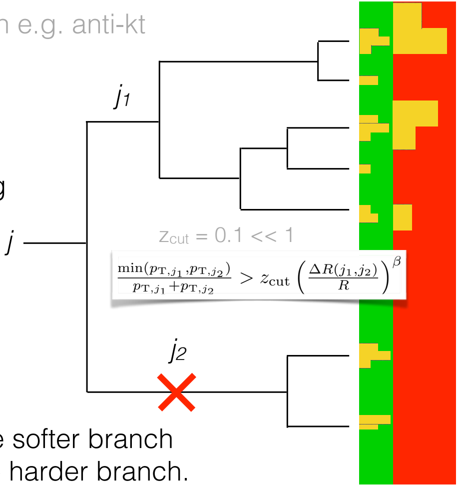

$$\frac{\min(p_{\mathrm{T},j_1}, p_{\mathrm{T},j_2})}{p_{\mathrm{T},j_1}+p_{\mathrm{T},j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R(j_1,j_2)}{R}\right)^{\beta}$$

Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

The soft drop algorithm

6

Take a jet clustered with e.g. anti-kt

↓

Re-cluster it with C/A

↓

Traverse the clustering tree backwards

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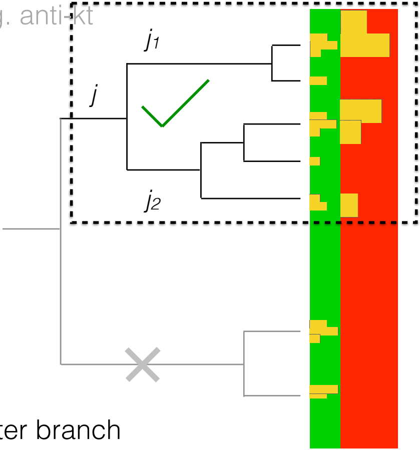
Otherwise remove the softer branch and continue down the harder branch.



Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

The soft drop jet mass

- Measuring the soft drop jet mass:

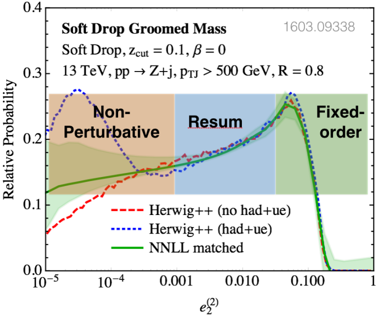
  $(m_{jet})^2 = (\Sigma E)^2 - (\Sigma p)^2$

- More precisely, we are measuring $\rho^2 = m^2/p_T^2 = e_2^{(2)}$,
- Using dijet events, with $p_T > 600$ GeV
- Simultaneously unfolding in p_T and ρ, but bin final result inclusively in p_T
- Larger β means less grooming
  - Studying 3 different values of β

The soft drop mass has recently been calculated to NNLO + NNLL

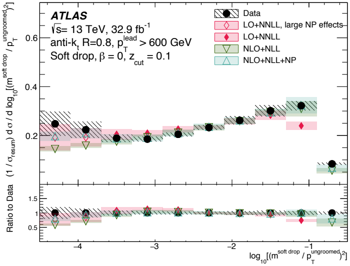
z_{cut} resummation: 1704.02210

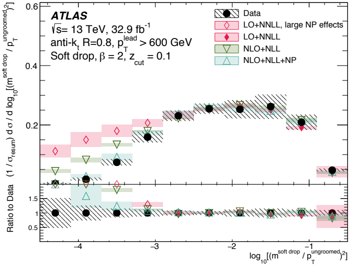
NNLO+NNLL: 1603.06375, 1603.09338



Slides from: ATL-PHYS-SLIDE-2018-196; soft drop: arXiv:1402.2657

Soft drop jet mass at 13 TeV

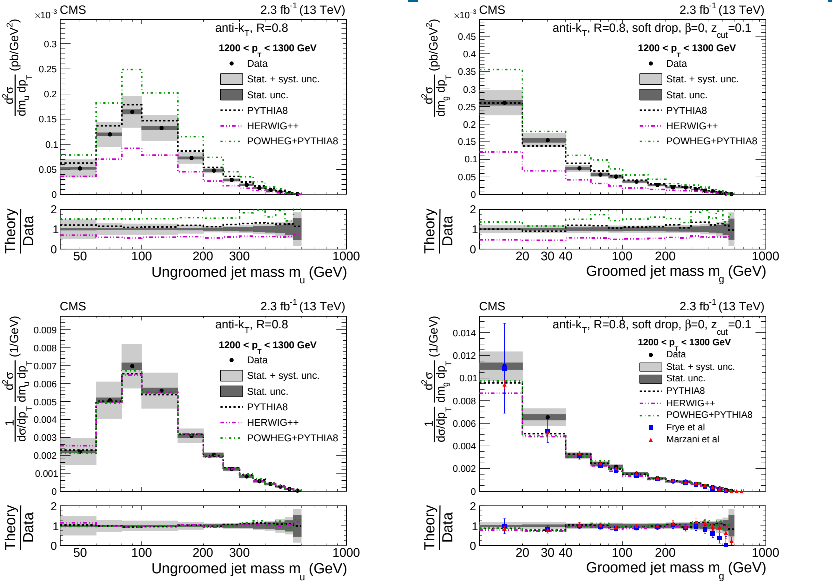




- Soft drop algorithm removes soft emission, underlying event
  - Soft drop condition: $z = \frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$
  - Smaller β removes more soft particles
- *Dimensionless mass* $\rho = m^{\text{soft drop}} / p_T^{\text{ungroomed}}$, only weak p_T dependence
  - Groomed p_T collinear unsafe when $\beta = 0$
  - Nb. large off-diagonal terms in unfolding matrix
- Comparing β=0 (left) and β=2 (right) to various calculation schemes
- For large β the impact of non-perturbative effects becomes large

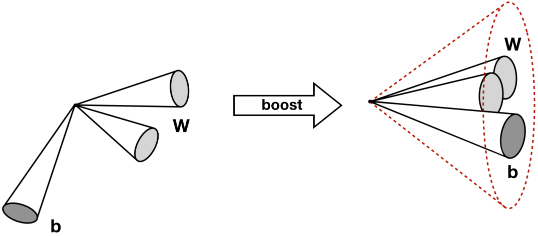
arXiv:1711.08341

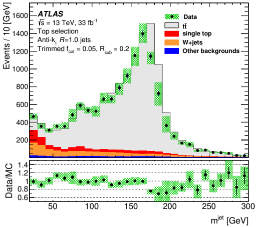
Diff. jet σ fn. of jet mass



arXiv:1807.05974

Jet substructure at 13 TeV



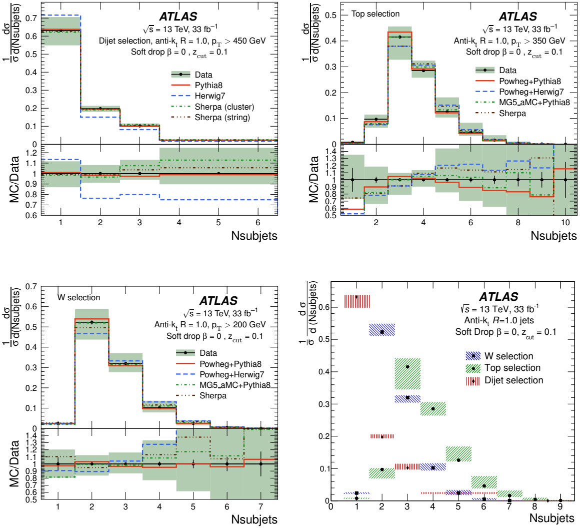


low top quark p_T high top quark p_T

- At high p_T, quark jets from W/top can merge
  - Interest in using substructure as a way to tag *boosted* objects
- Compare substructure properties of high p_T jets in:
  - Dijet events: two trimmed anti-k_T R=1.0 jets with $p_T > 200$ GeV
    - Trimming: find R=0.2 subjets and remove if $p_T^{sub}/p_T^{fat} < f_{cut} = 0.05$
    - Use leading p_T jet for further study if $p_T > 450$ GeV
  - High Top and W jets in $t\bar{t}$ events
    - Require isolated muon to tag semi-leptonic top events
    - Top jet: anti-k_T R=1.0 jet with $p_T > 350$ GeV , mass > 140 GeV
    - W jet: anti-k_T R=1.0 jet with $p_T > 200$ GeV , $60 <$ mass < 100 GeV
- Mass shift: "due to the lack of in situ calib. of jet mass, and to jet mass scale unc. in the detector-level plots"

Fig. from arXiv:1712.01391, plot from arXiv:1903.02942

Jet substructure at 13 TeV



arXiv:1903.02942

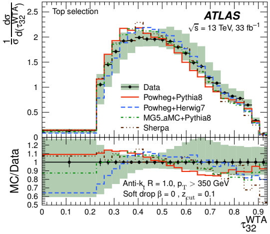
- Start from anti-k_T R=1.0 jets, trimmed (fat jet)
- Apply soft-drop procedure
- $N_{subjets}$: number of R=0.2 k_T subjets with $p_T > 10$ GeV reconstructed from the parent fat-jet
- Subjet distributions peak at 1 for dijet jets, 2 for W jets, 3 for top jets

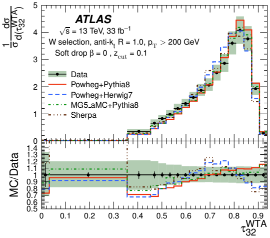
$$\tau_0 = \sum p_{T_i} R,$$

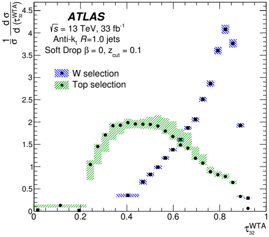
$$\tau_1 = \frac{1}{\tau_0} \sum p_{T_i} \Delta R_{1,i}$$

$$\tau_2 = \frac{1}{\tau_0} \sum p_{T_i} \min(\Delta R_{1,i}, \Delta R_{2,i})$$

$$\tau_3 = \frac{1}{\tau_0} \sum p_{T_i} \min(\Delta R_{1,i} \ldots \Delta R_{3,i})$$

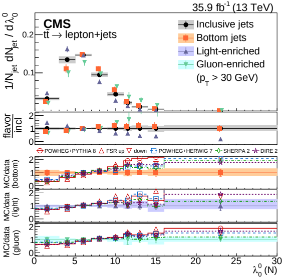


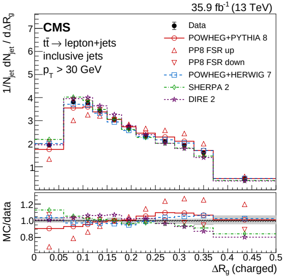


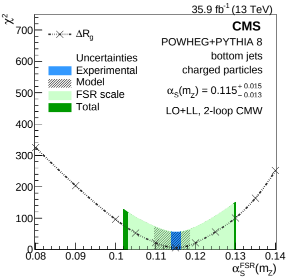


arXiv:1903.02942

- N-subjetiness: compatibility with N subjets
- Find exactly N subjet seeds with k_T algorithm, then calculate p_T sum of weighted distance to nearest subjet
- $\tau_{32} = \tau_3/\tau_2$: distinguish between 3 vs 2 subjets
  - 3-jet structure (top) should be lower



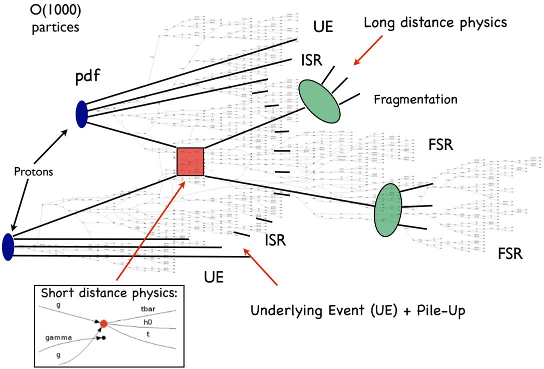




- Non-boosted semi-leptonic $t\bar{t}$ topology, anti-k_T R=0.4 jets
- Extensive study of jet substructure observables including differentiating bottom, light quark and gluon jets
  - Bottom from b-tagging, light quarks from $W \to qq'$ reconstruction
  - $\lambda_0^0(N)$ number of charged particles in jet
  - ΔR_g angle between groomed subjets
- Use measurements to tune $\alpha_S^{FSR}(M_Z)$ to improve data/MC description

arXiv:1808.07340

Summary: end where we began



- QCD is a complex theory involving multiple scales
- The LHC is using new tools and old to test the theory and continue to improve its modelling
- Interplay between experiment and theory moving our understanding forward