Jet Substructure Measurements Sensitive to Soft QCD effects with the ATLAS Detector

MPI@LHC, Shimla, 12th December 2017

Lily Asquith for the ATLAS collaboration

ATLAS EXPERIMENT

THE ROYAL SOCIETY

UNIVERSITY OF SUSSEX

Introduction

Two recent ATLAS measurements of substructure observables sensitive to soft QCD effects:

Measurement of the k_t splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

Constrain and tune MC generators (hard perturbative modeling and soft hadronic activity)

arXiv:1704.01530 STDM-2015-14 Published in JHEP08 (2017) 026

A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Perturbative region: constrain calcs
Non-perturbative: constrain MC generators

arXiv:1711.08341 STDM-2017-04. Submitted to PRL

Jet Reconstruction for Substructure

- Both measurements use **iterative recombination** jet reconstruction procedures to identify different types of jets, whose histories contain information useful to identify their substructure.
- The inputs to jet reconstruction algorithm are the four-momenta of either **charged particle tracks**, **clusters of energy** in the calorimeter, or **truth particles**.

1. Make a list of input four momenta, and define all possible pairs.
2. Find the smallest dij of all pairs, and combine that pair.
3. Repeat.

$d_{ij} = \min(k_{Ti}^{n}, k_{Tj}^{n})\, dR_{ij}$

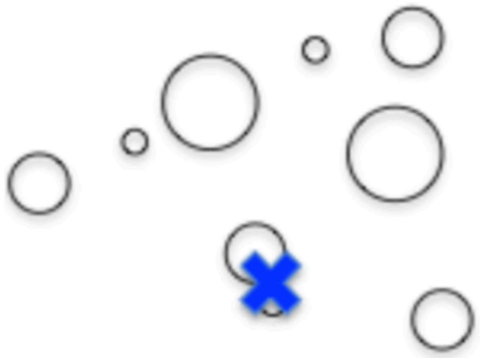
- If n=-2 : choose the softer k_T in the pair
- If n=0 : ignore the k_T
- If n=2: choose the harder k_T in the pair

Different n = different smallest d_{ij}

Jet algorithms refresher

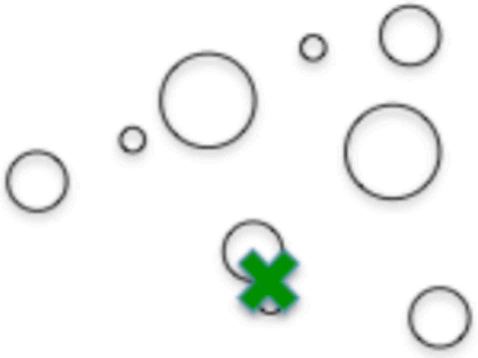
kT ($d_{ij} \propto p_T^2$)

soft+close



CA ($d_{ij} \propto p_T^0$)

close



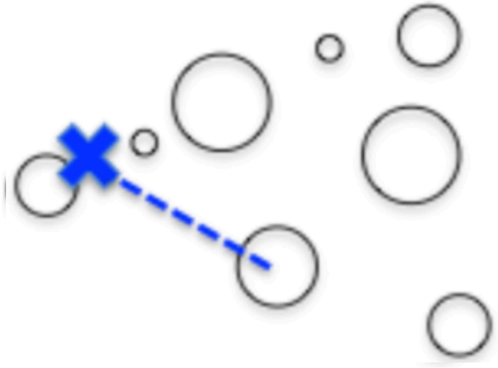
anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)

hard+close

Jet algorithms refresher

kT ($d_{ij} \propto p_T^2$)

soft+close



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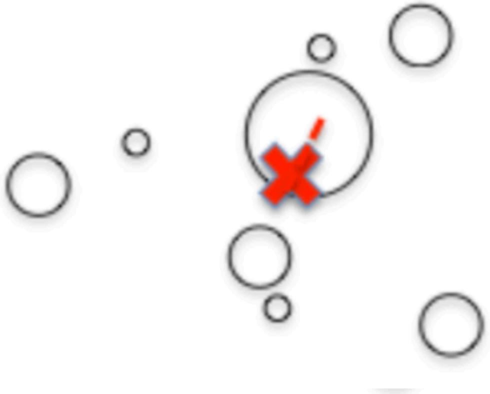

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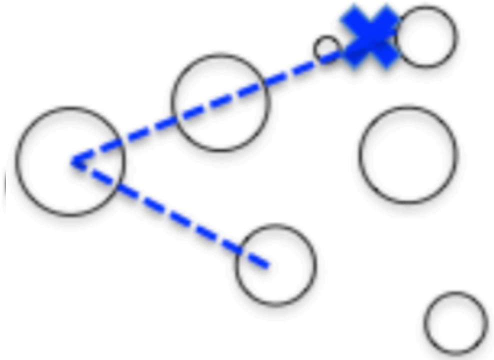

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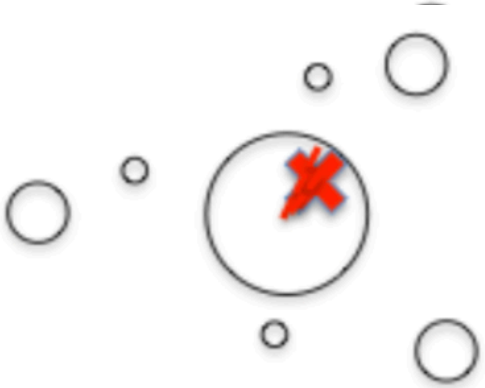

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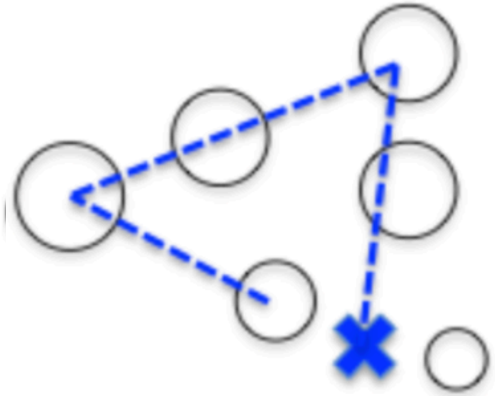

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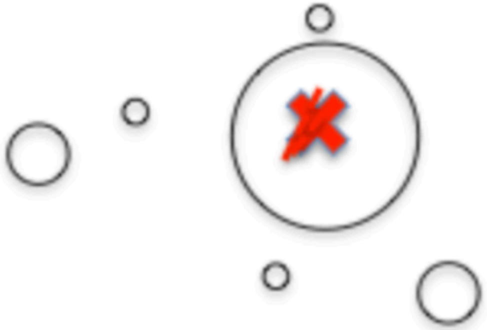
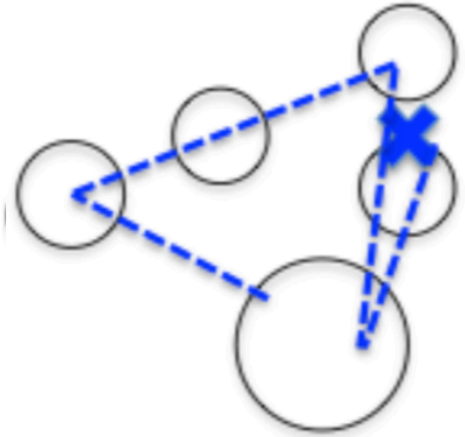


ANIMATION 5/12

Jet algorithms refresher

kT ($d_{ij} \propto p_T^2$)

soft+close



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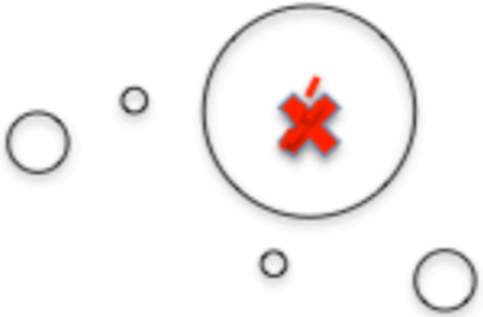

Jet algorithms refresher

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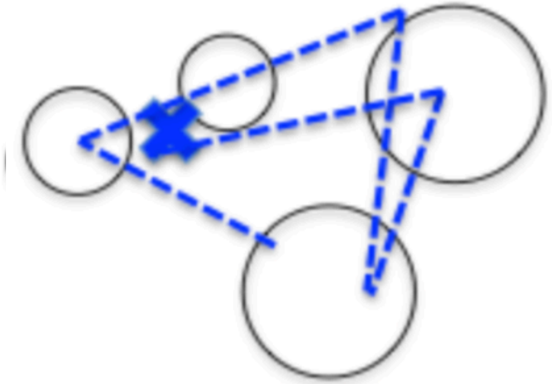

CA ($d_{ij} \propto p_T^0$)
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anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)
hard+close

ANIMATION 7/12

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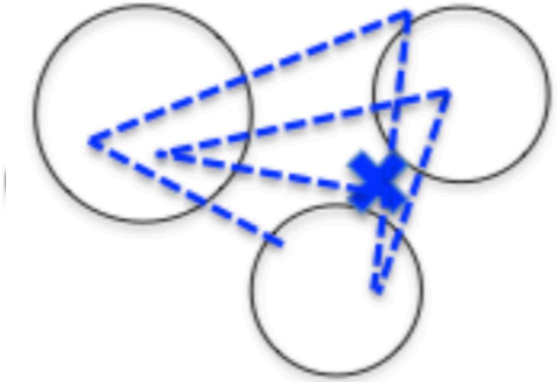

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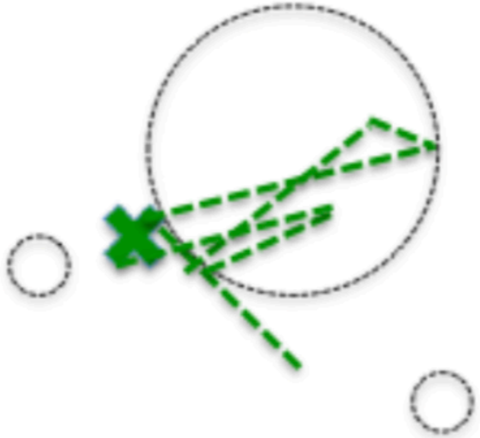

anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)

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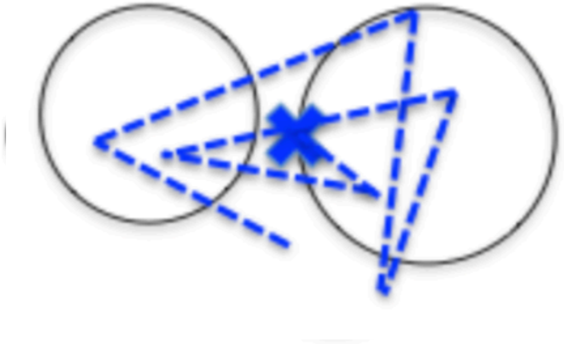

CA ($d_{ij} \propto p_T^0$)

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anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)

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Jet algorithms refresher

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soft+close

CA ($d_{ij} \propto p_T^0$)
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anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)
hard+close

The final jet

Jet algorithms refresher

kT ($d_{ij} \propto p_T^2$)

soft+close

CA ($d_{ij} \propto p_T^0$)

close

anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)

hard+close

Back up one step

Jet algorithms refresher

kT ($d_{ij} \propto p_T^2$)
soft+close

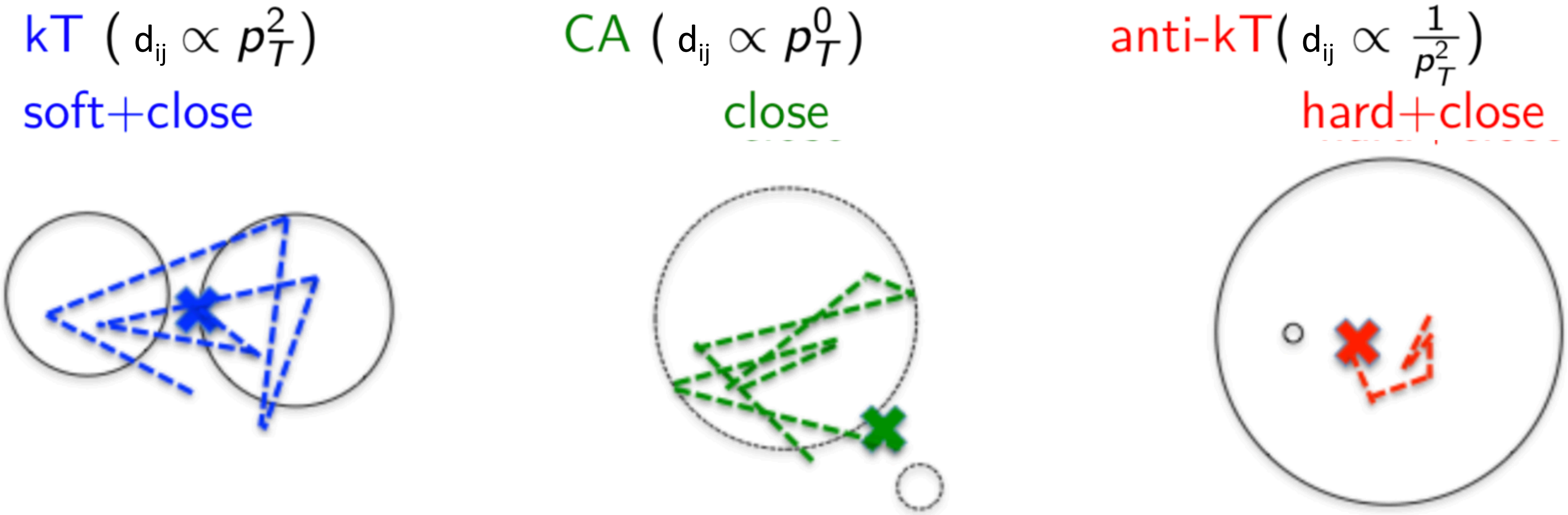
CA ($d_{ij} \propto p_T^0$)
close

anti-kT($d_{ij} \propto \frac{1}{p_T^2}$)
hard+close

Back up one step

ANIMATION 12/12

Jet algorithms refresher



The penultimate stage in the jet clustering epitomizes the difference between the algorithms: if there is hard underlying structure then kT and CA have the ability to spot it.

Measurement of the k_{t} splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8\,$TeV with the ATLAS detector

arXiv:1704.01530 STDM-2015-14 Published in JHEP08 (2017) 026

Splitting Scales

Measurement of the k_t splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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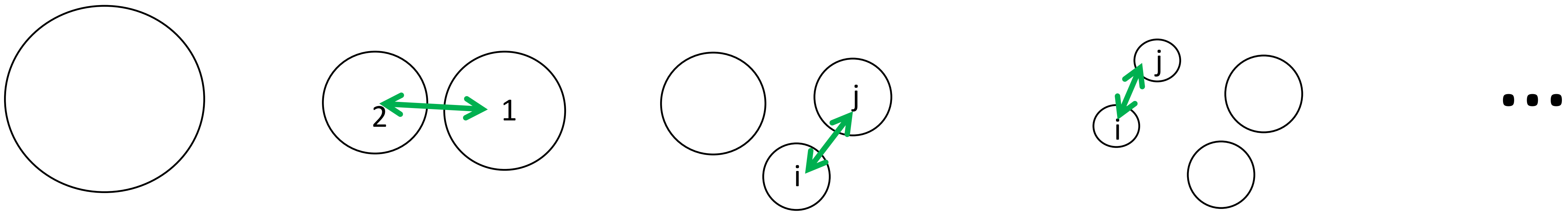
Measurement uses k_t algorithm (soft+close first = hard+wide last) with tracks as input.

$$d_{ij} = \min(k_{Ti}^2, k_{Tj}^2)\, dR_{(ij)}$$

$\sqrt{d_0} = p_T$ $\sqrt{d_1} = p_{T2} \times dR_{(1,2)}$ $\sqrt{d_2} = \min(p_{Ti},p_{Tj}) \times dR_{(i,j)}$ $\sqrt{d_3} = \min(p_{Ti},p_{Tj}) \times dR_{(i,j)}$



= final track-jet pT

Note that soft / collinear splittings have low values of $\sqrt{d_i}$

Event Selection

Measurement of the k_t splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

arXiv:1704.01530 STDM-2015-14 Published in JHEP08 (2017) 026

Run 1 8 TeV dataset : 20.2/fb

Aim to select $Z_{\ell\ell}$ +jets events at high purity, examine splitting scales in jets.

Track-jets are used to reduce uncertainties.

SHERPA 1.4.3

	$Z \to e^+e^-$		$Z \to \mu^+\mu^-$	
Process	Events	Contribution [%]	Events	Contribution [%]
QCD Z + jets	5 090 000	98.93 %	7 220 000	99.40 %
Multijet	42 000	0.81 %	25 000	0.34 %
Electroweak Z + jets	5 350	0.10 %	7 340	0.10 %
Top quarks	6 190	0.12 %	8 440	0.12 %
$W(W)$	1 100	0.02 %	1 460	0.02 %
$Z \to \tau^+\tau^-$	1 100	0.02 %	1 700	0.02 %
Total expected	5 150 000	100.00 %	7 260 000	100.00 %
Total observed	5 196 858		7 349 195	

~12M events in data with ~99% purity.

Iterative Bayes unfolding to particle-level applied to data - background.

Unfolded Data v. Calculations

Measurement of the k_t splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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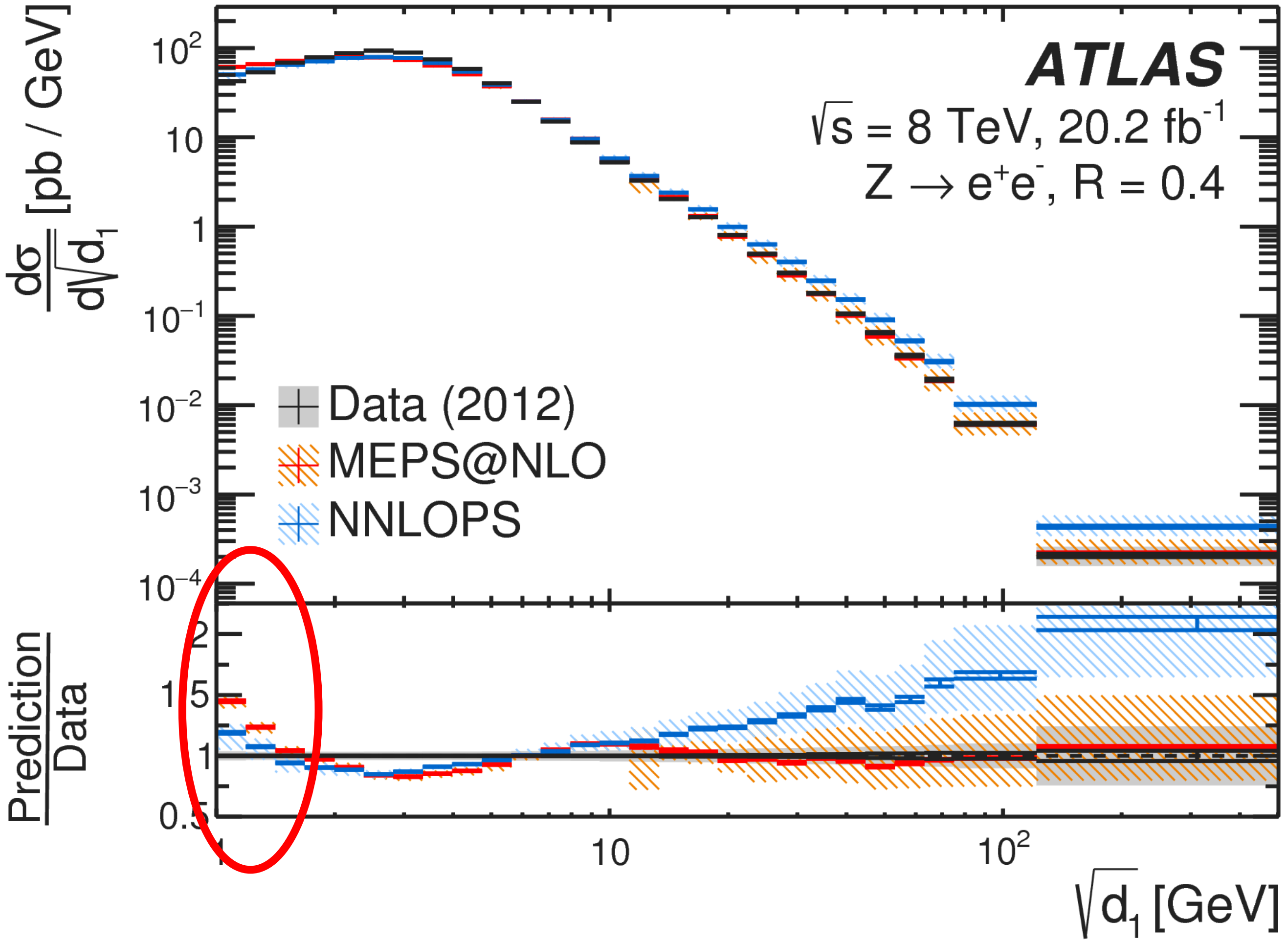
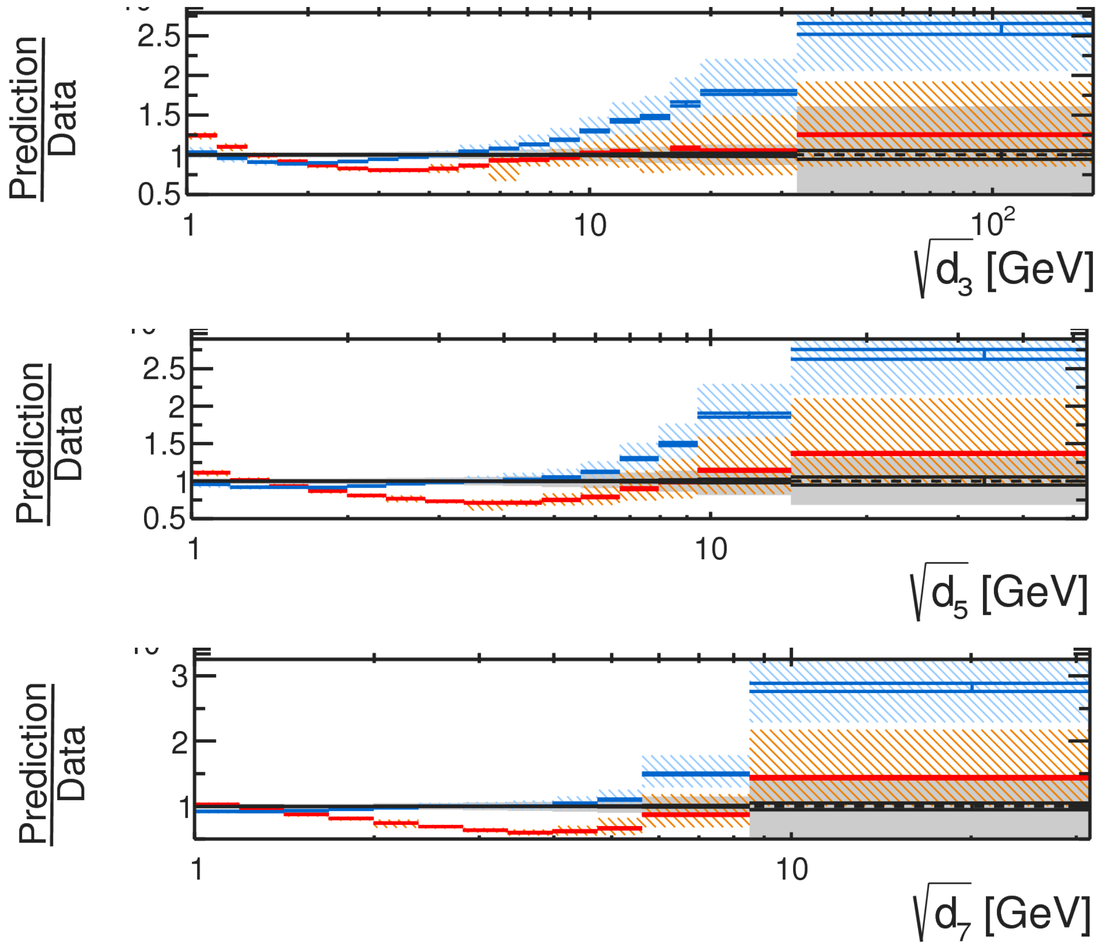


LEADING EIGHT SPLITTING SCALES MEASURED



Fixed order calculations not really helping for very low masses

A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

arXiv:1711.08341 STDM-2017-04. Submitted to PRL

Soft Drop Jet Mass

A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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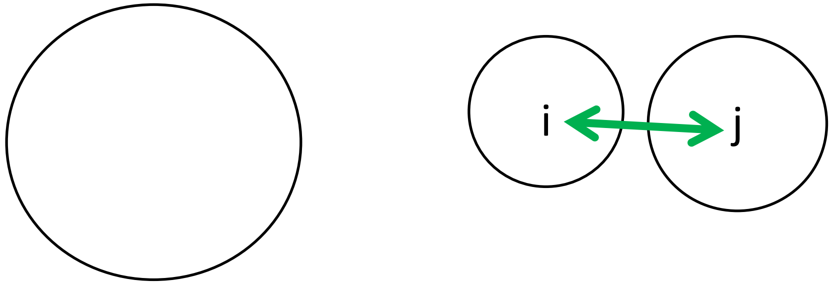
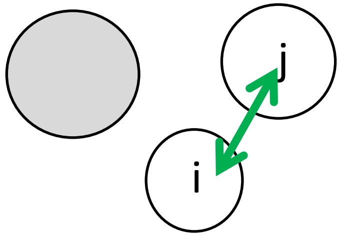
Measurement uses CA algorithm **R=0.8** with calibrated energy clusters as inputs.

$$\min(p_{Ti},p_{Tj}) / (p_{Ti} + p_{Tj}) \;>\; 10\% \left(\frac{dR_{ij}}{R}\right)^{\beta} \;\;?$$

yes → **Both pieces kept, algorithm finished.**

no → **Remove softer piece, repeat**





Larger values of β : more likely to pass criteria : less radiation removed.

When algorithm terminates, mass of resulting ‘groomed’ jet **m** is used.
The $\mathbf{p_T}$ of the ungroomed jet is then used in the denominator of the soft drop mass variable :

$$\log_{10}\left(\frac{\mathbf{m}}{\mathbf{p_T}}\right)^{2}$$

Event Selection

A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Run 2 13 TeV dataset : 32.9/fb

Aim is to select dijet events (high-p_T ensures full trigger efficiency), and examine the soft drop masses of the jets.

Trigger:

Dijet trigger 600 GeV

Offline selection:

Two anti-k_t R=0.8 jets, the leading one with p_{T1}>600 GeV, second with $p_{T2} > \frac{2}{3} p_{T1}$, $\eta < 1.5$

anti-k_t R=0.8 jets used for event selection, then the constituents are reclustered with CA R=0.8.

Soft Drop Jet Mass Measurement

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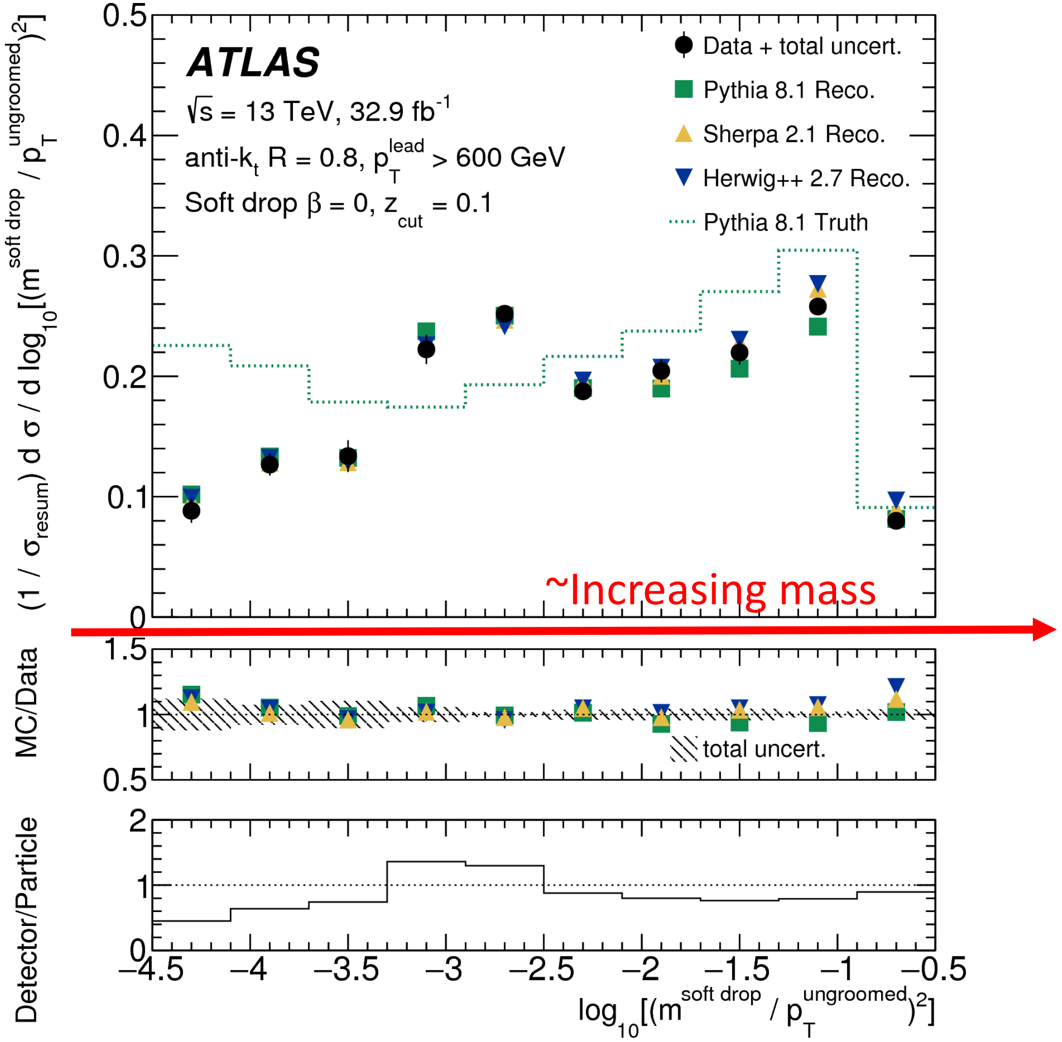
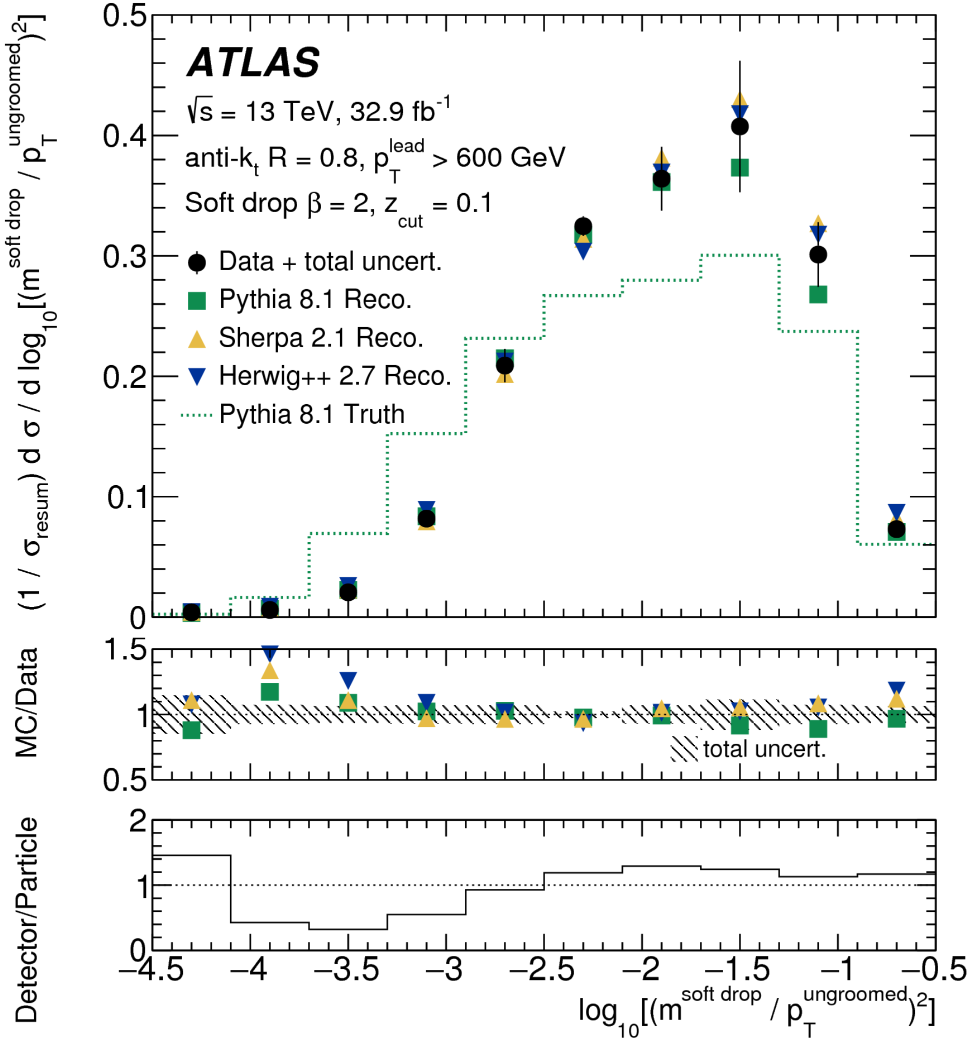
β =0 : more soft radiation removed



β =2 : less soft radiation removed



Data v. Calculations

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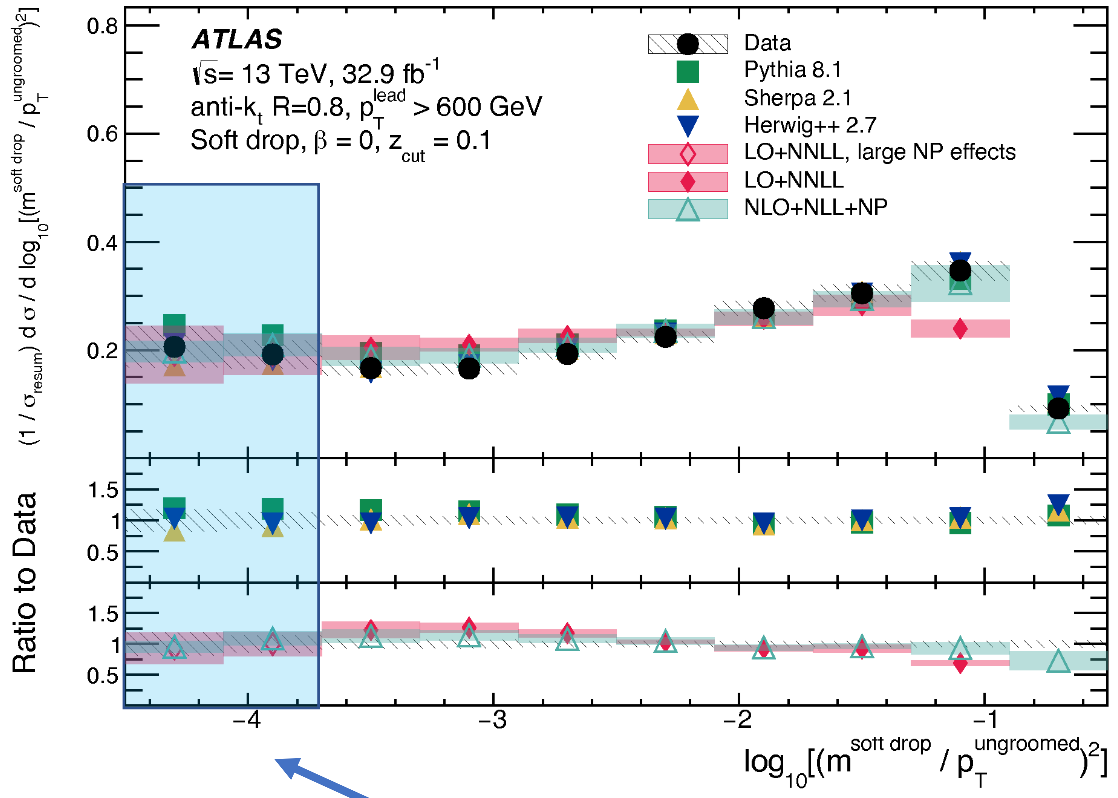
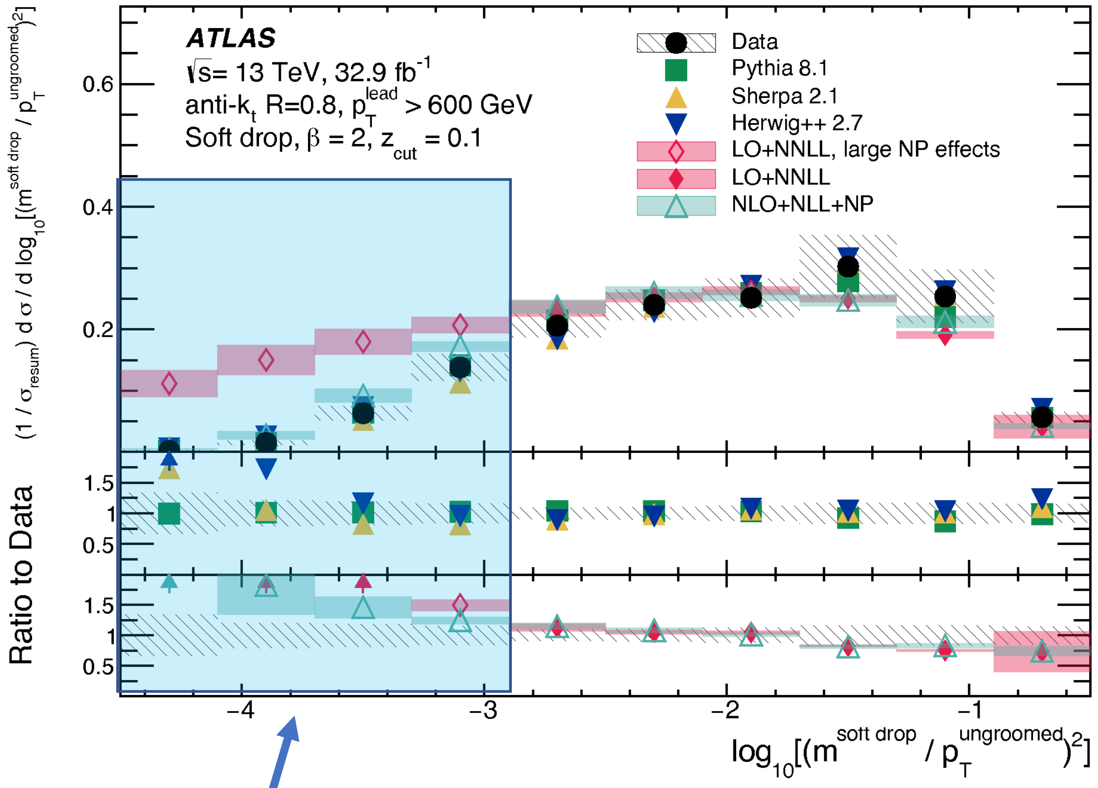
Iterative Bayesian unfolding to particle-level applied to data.





NP effects are expected to be large

Uncertainties

A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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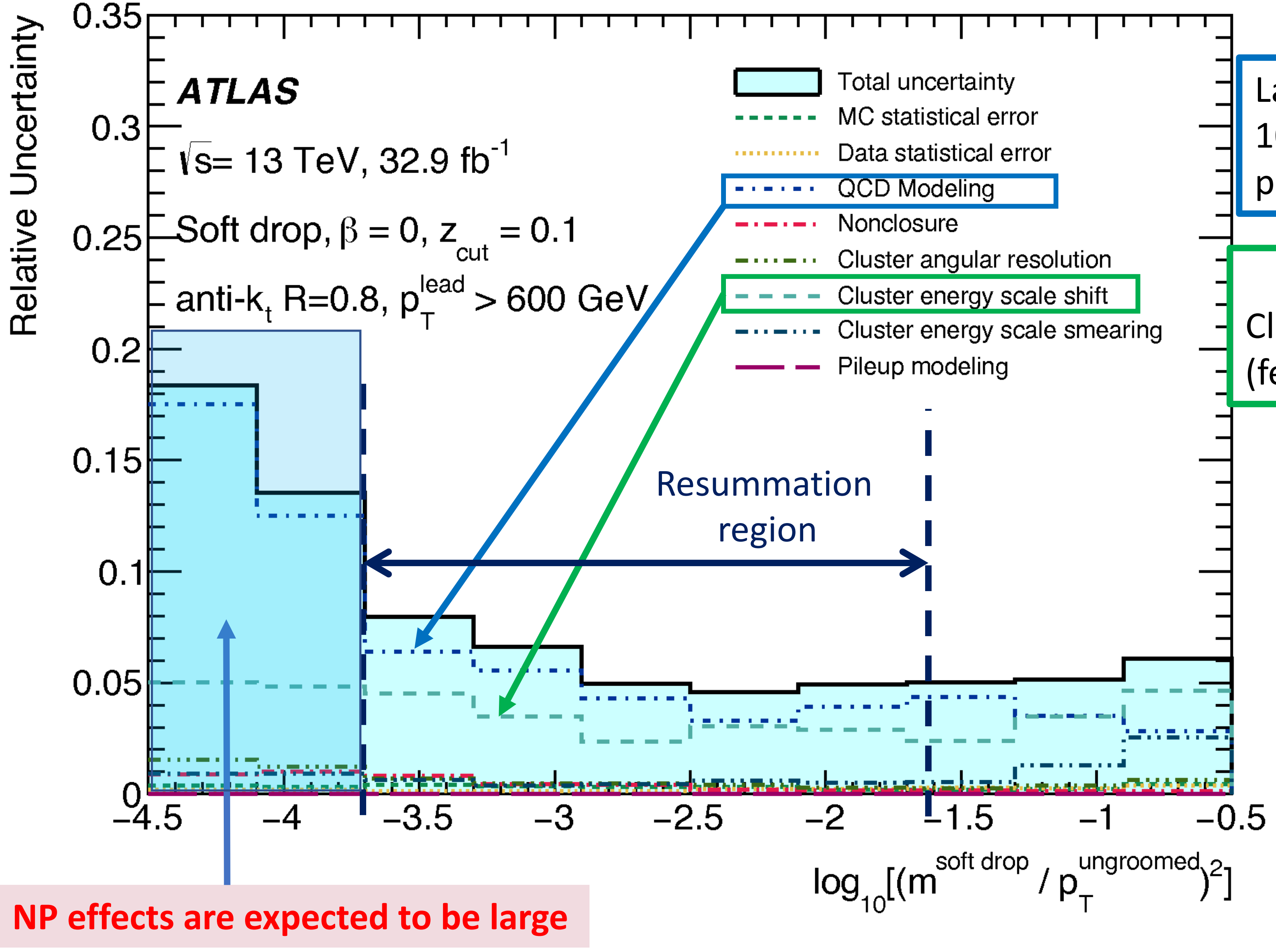

Largest uncertainty is QCD modeling 10-20%, biggest where NP effects a problem.

Cluster Energy Scale is largest at low values (few clusters)

Summary

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Perturbative region: constrain calcs
Non-perturbative: constrain MC generators

Soft drop mass shows particular promise for looking in detail at soft QCD.

..thank you for your attention.

ADDITIONAL MATERIAL

kT splitting event selection

- **Trigger:**
- Opposite-charge electron or muon pair targeting $Z_{\ell\ell}$
- **Offline selection:**
- Tracks: p_T>400 MeV, eta<2.5, >=1pixel, >=5 SCT, chi2<3, d0 < 1mm, z0xsin <0.6mm
- Electrons: must be Isolated, pT>25 GeV, eta<*2.4*7 (excluding 1.37-1.52)
- Muons: (combined) must be pT>25 GeV, eta<*2.4,*
- Isolation: (pT in dr<0.2 < 10% pT muon and pT in dr<0.2 < 13% pT electron
- Zll mass: 71-111 GeV

Analysis Sample

Measurement of the k_t splitting scales in $Z \to \ell\ell$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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~5M signal events with ~99% purity.

Z+jets normalised to NNLO prediction (PhysRevD.69.094008)

SHERPA 1.4.3 up to 4 LO hard emissions,CT10

POWHEG + Pythia6

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Total expected	5 150 000	100.00 %	7 260 000	100.00 %
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Estimated from data

Tt backgrounds normalised to NNLO in QCD, incl resum of soft gluons in NNLL (PhysRevLett.110.252004) (PhysRevD.83.091503)

Iterative Bayesian unfolding to particle-level applied to background-subtracted data.

Data v. Calculations

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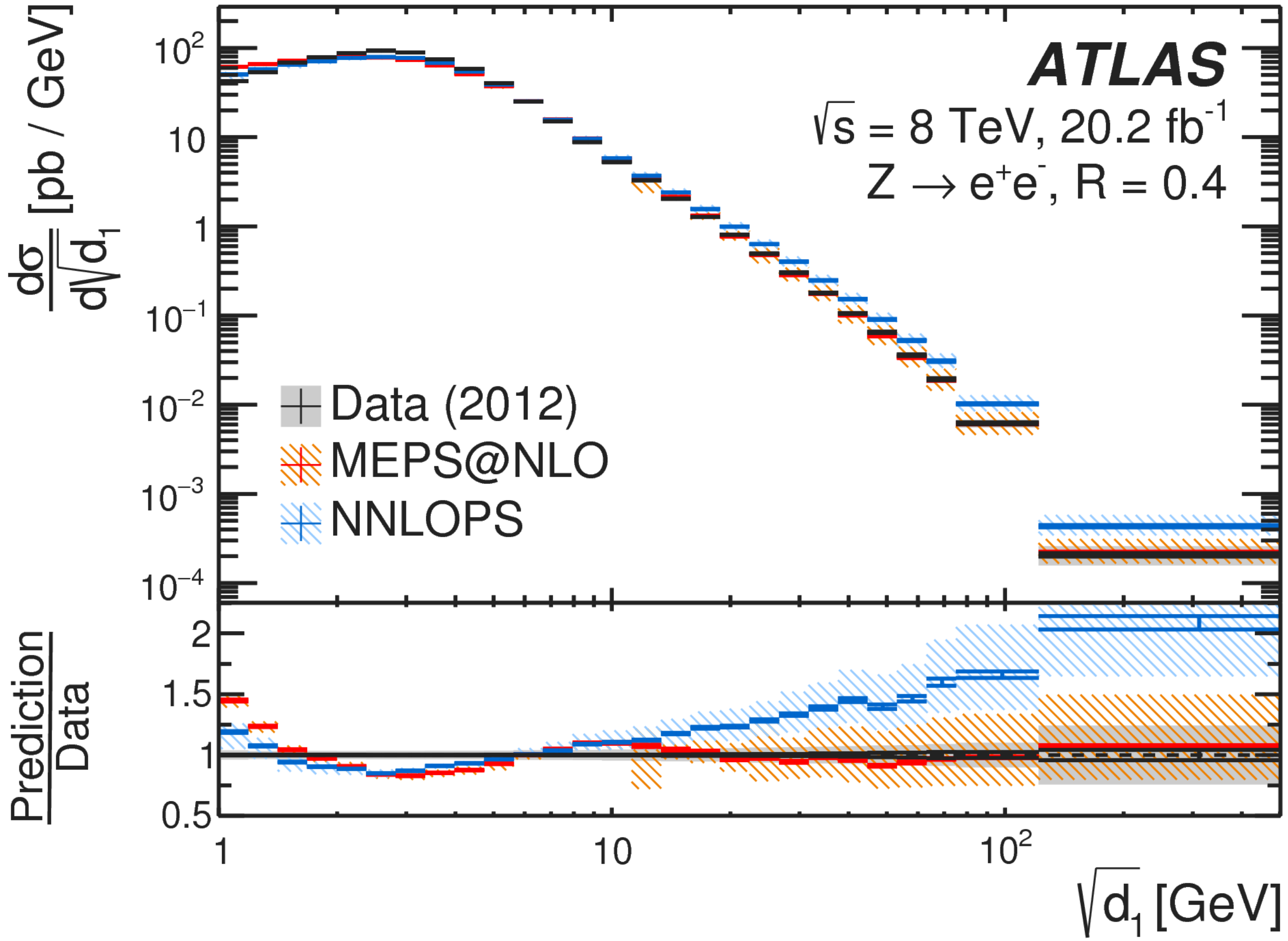
MEPS@NLO : SHERPA v2.2.1, 2(4) partons at N(LO) (Comix and OpenLoops) PDF: NNPDF3.0nnlo

NNLOPS : POWHEG-BOX (DY@NNLOPS and MiNLO) (showering by Pythia 8.185, monash tune) PDF: PDF4LHC15nnlo



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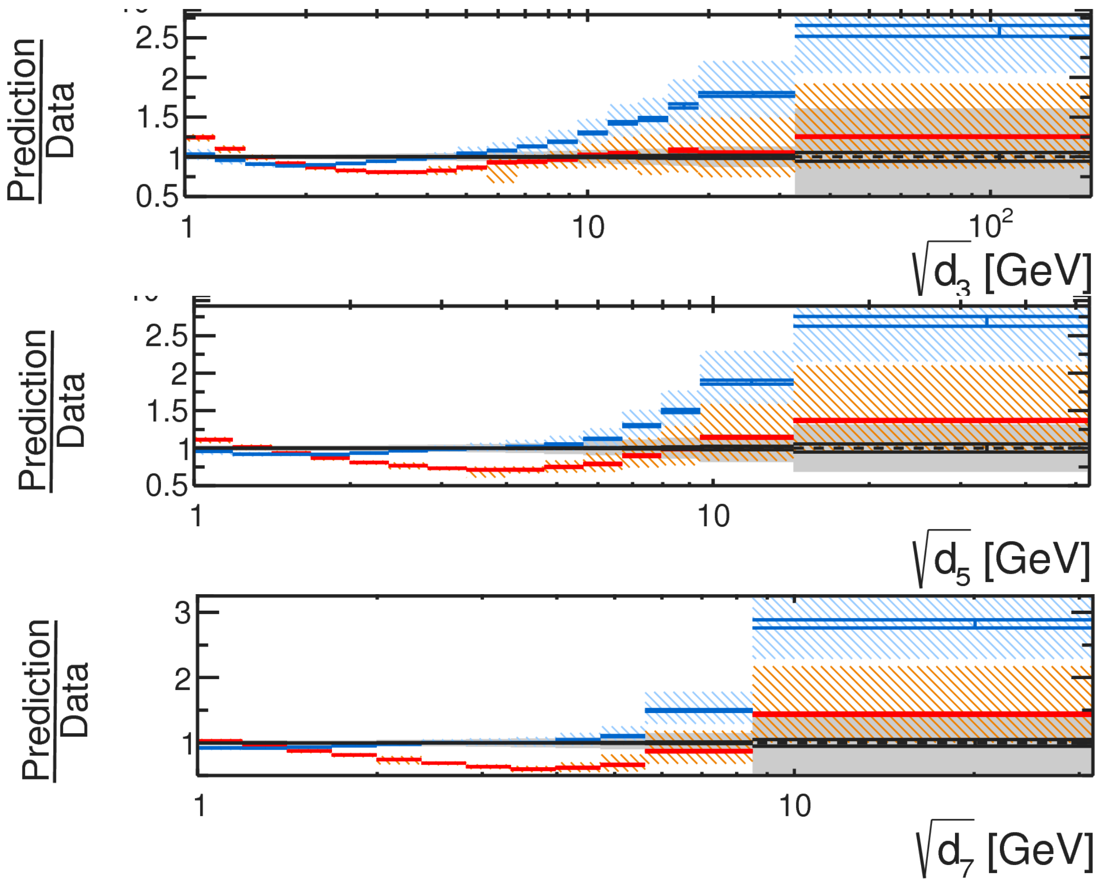

Uncertainties

3-10% uncertainty over most of range

Steeper rise (to ~15%) for subleading splitting scales

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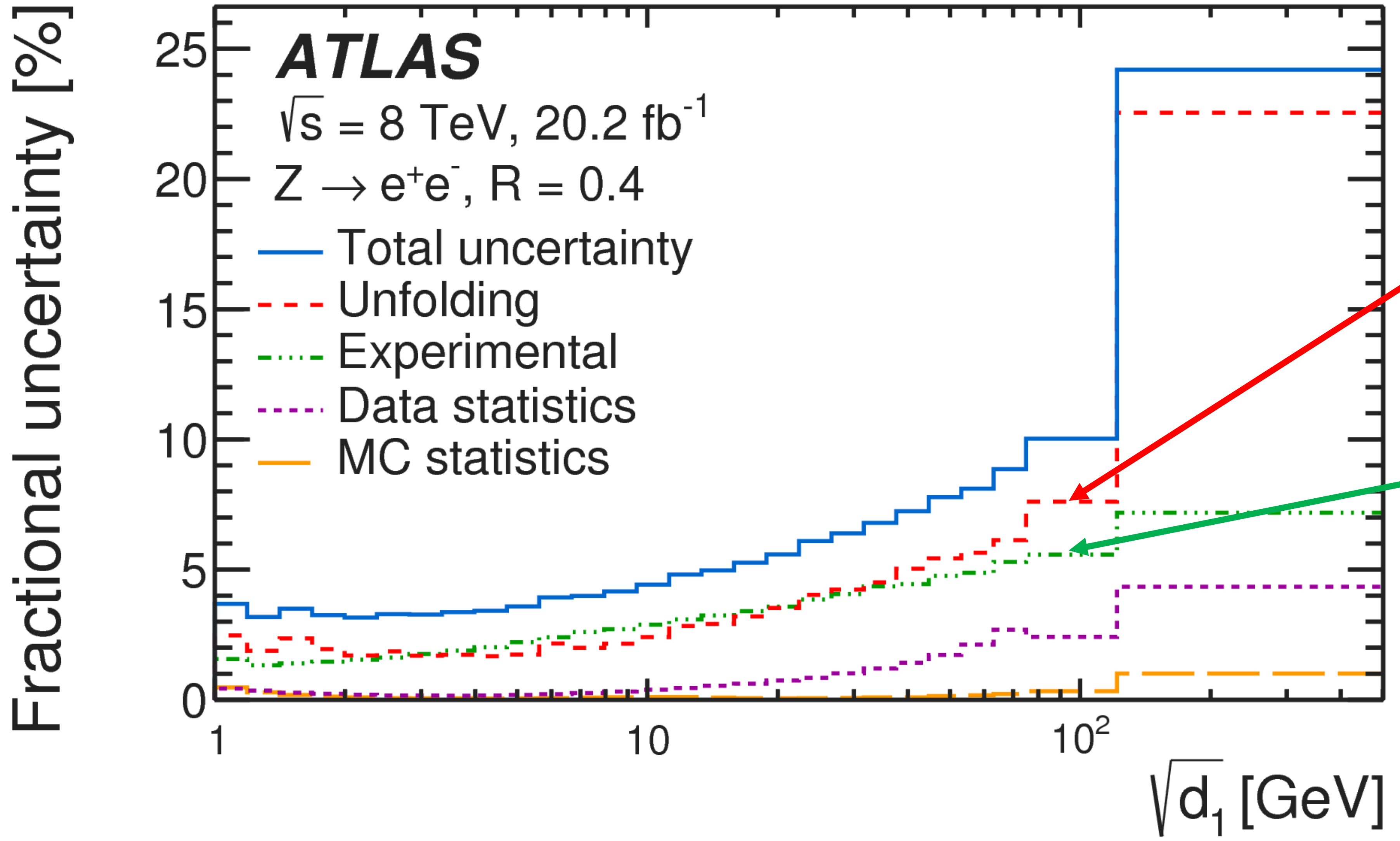

Total : Includes 1.9% luminosity

Closure, number of iterations, prior.

Tracking, pileup, event selection