Non-perturbative QCD Dynamics at LHC and Beyond – an Experimentalist's View

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SnowMass2021

EF05: QCD and strong interactions: Precision QCD

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CERN

Preliminaries

This talk is not a comprehensive review…

- … due to lack of time and …
  - Restricted to jets in proton (pp) collisions at the LHC
    - Some remarks regarding HL-LHC – high lumi operations
  - Mostly latest findings and present day hot topics
- … a bias towards ATLAS results
  - Better personal overview
    - After >25 years with this experiment
  - Not an intentional disregard of e.g. CMS, LHCb, ALICE, …
    - They are all producing great QCD (and other) results

Focus on experimental aspects in hadronic final state reconstruction

- Highly selective
  - Modelling issues in jet reconstruction performance and SM jet measurements
- Some comments on possible future R&D
  - Parton shower (fragmentation & hadronization) and underlying event (multiple parton interactions, MPI) tuning

This talk

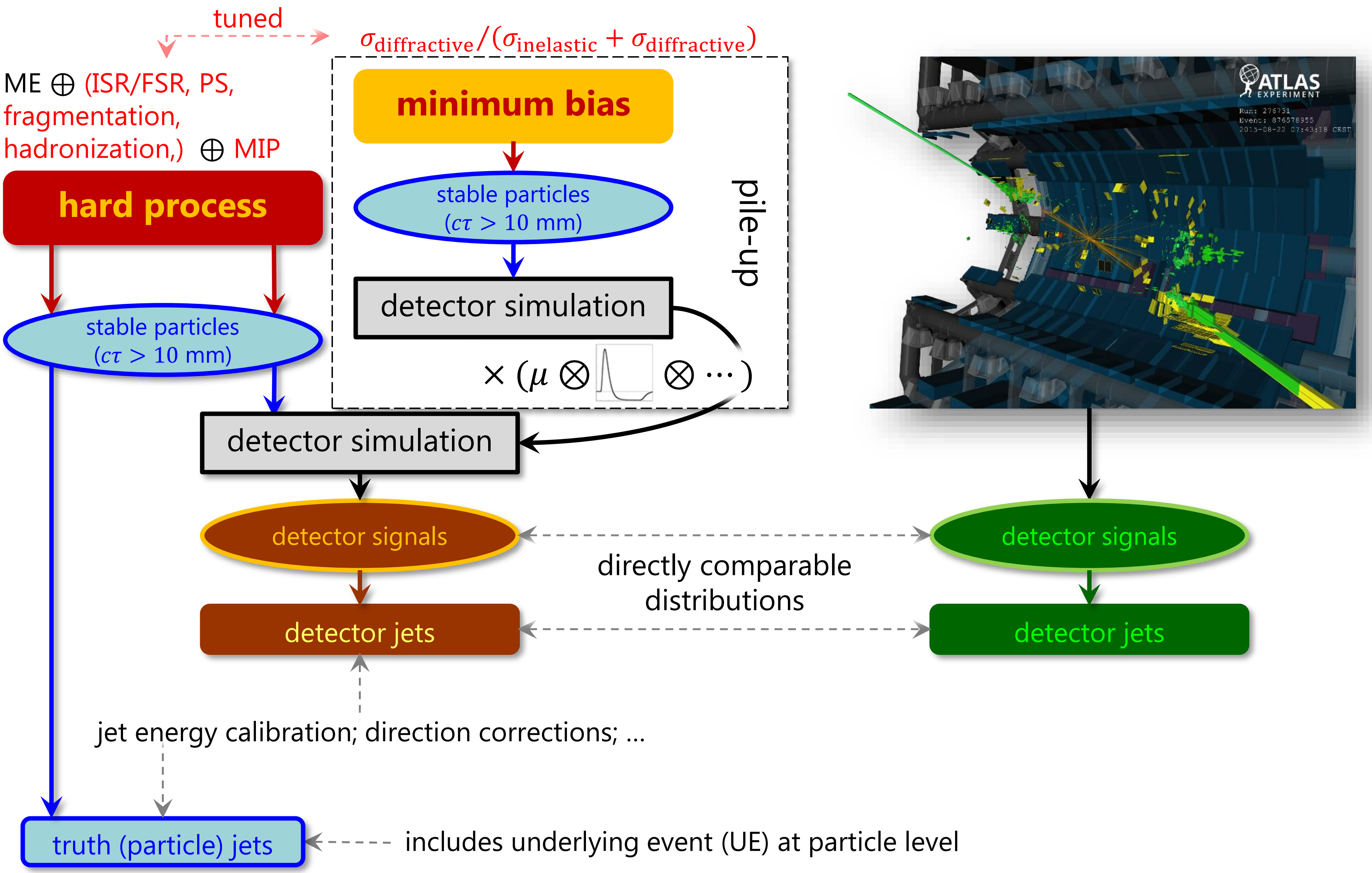
Role of soft emissions in jet reconstruction precision

- Small-R jets
  - Anti-k_t with $R = 0.4$ – standard tools for measurements & searches
  - Underlying event (UE) contribution and pile-up (PU) mitigation
- Large-R jets (most popular configurations)
  - Anti-k_t with $R = 0.8$ $R = 1.0$ – tools for tagging heavy particle decays
  - Constituent level pile-up suppression & jet grooming

Modeling parton emissions at all(?) scales

- Tuning efforts
  - Selected recent results
- Observations from measurements
  - Jet mass and substructure observables
  - Event shapes
- Some ideas on moving on
  - Input to tuning
  - Inclusive measurements of emissions in jets at ~all scales
- QCD at softer scales
  - Exploring energy-energy correlations in jets

Soft QCD Contribution to Jet Reconstruction



Jet Reconstruction Sequence in ATLAS

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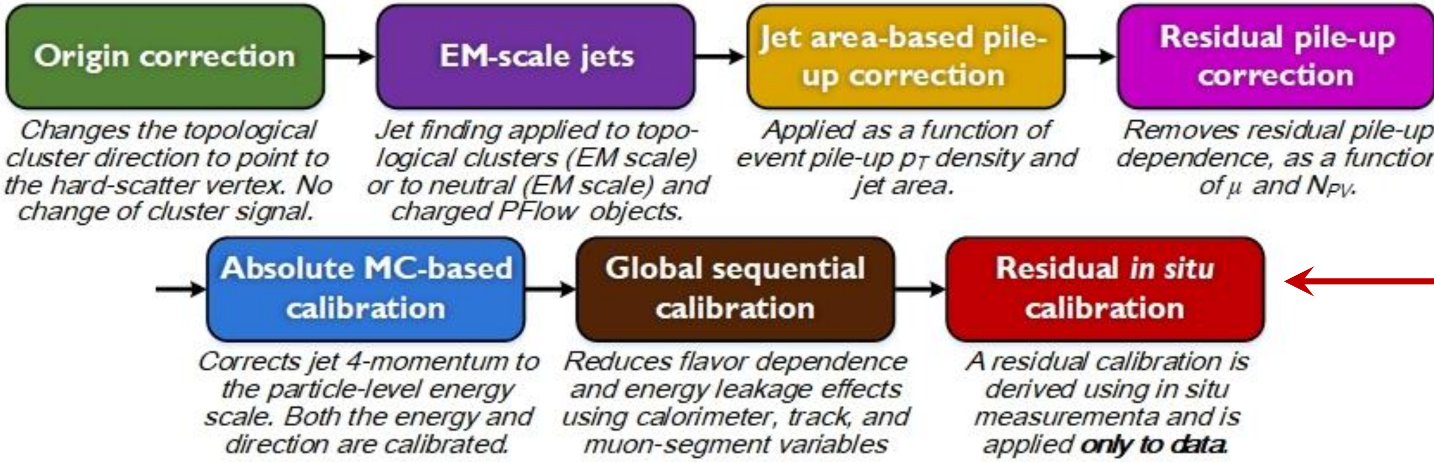
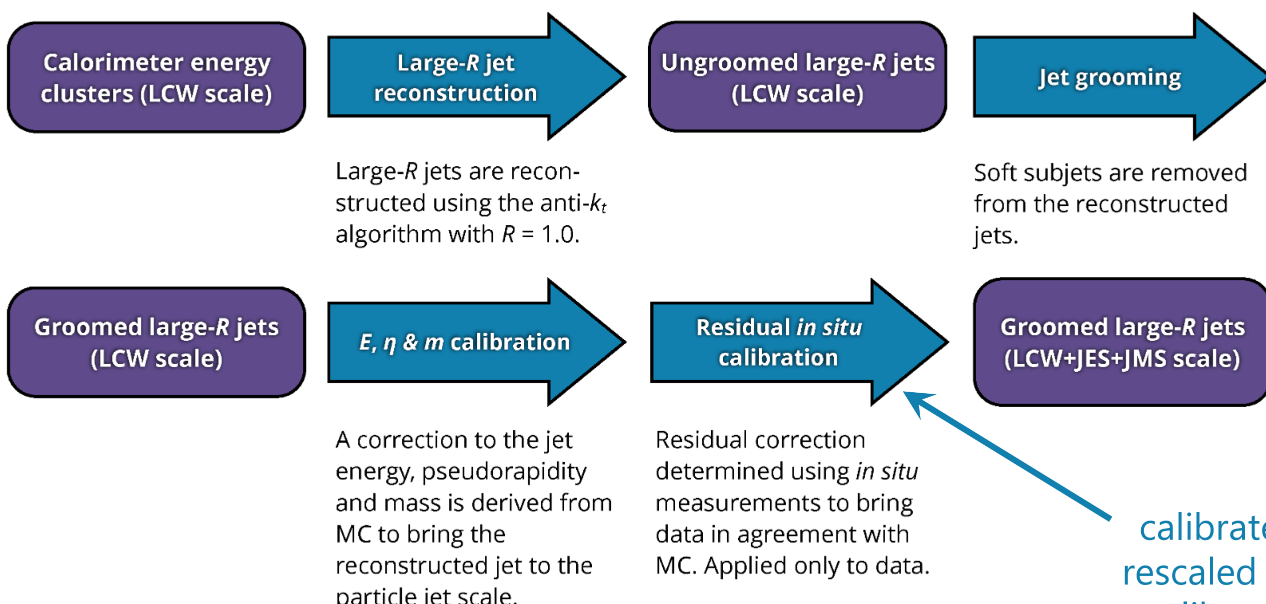
Anti-k_t $R = 0.4$



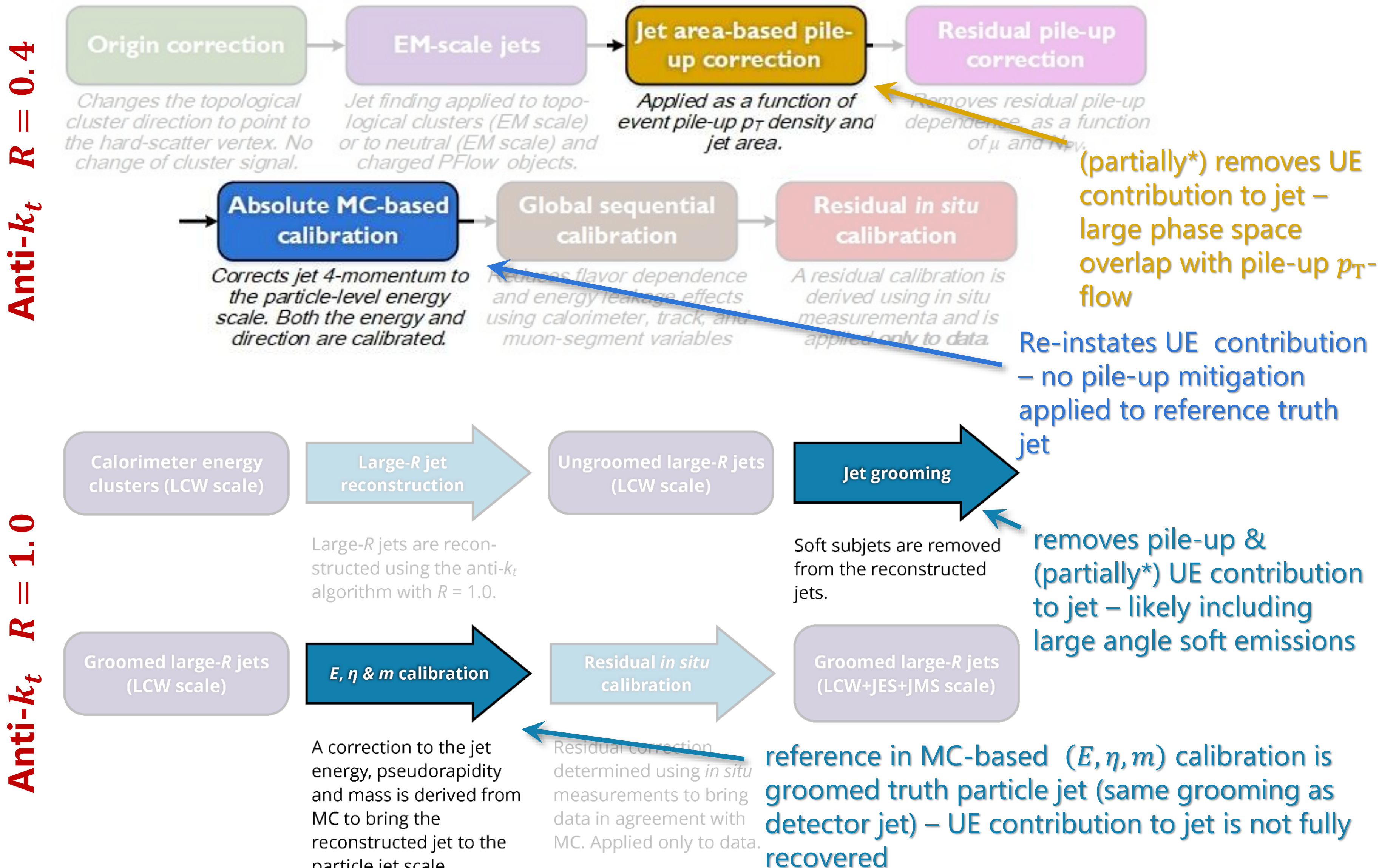
calibrates p_{T} - $(E, \vec{p})$ rescaled

Anti-k_t $R = 1.0$



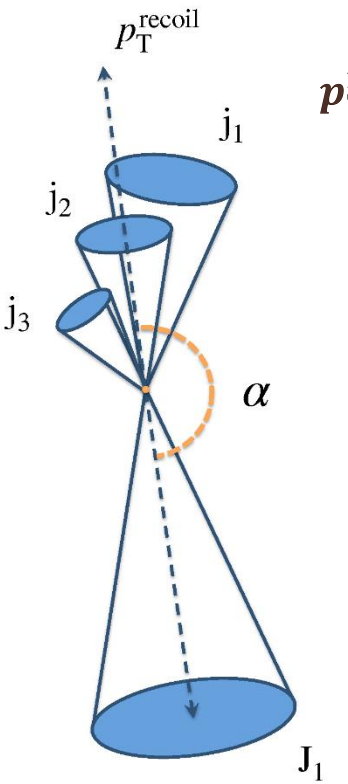
calibrates p_{T} and m – first $(E, \vec{p})$ rescaled by p_{T}-calibration, then m calibrated & p_{T} rescaled with E unchanged

Jet Reconstruction Sequence in ATLAS



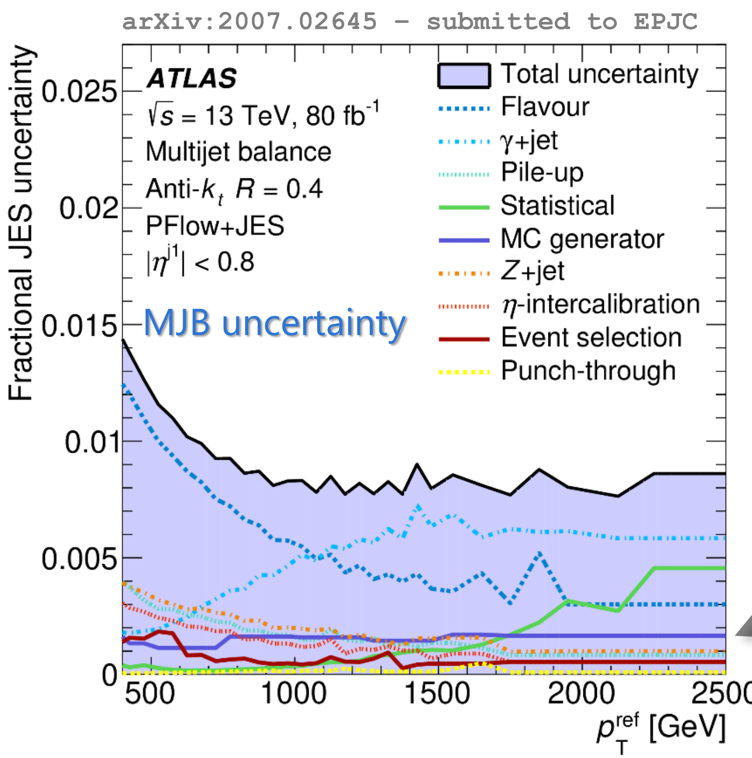
*the stochastic nature of most grooming techniques including the jet-area-based pile-up suppression leads to the removal of an unknown amount of the UE contribution to the jet.

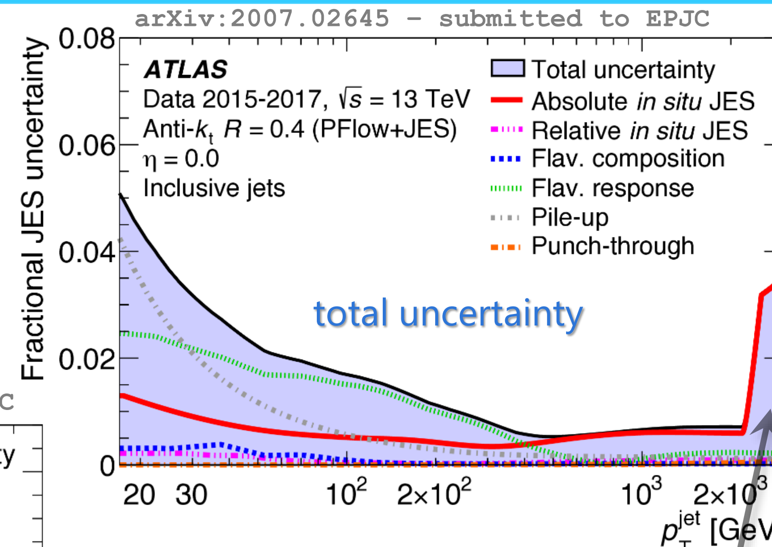
Jet Calibration Uncertainties



multi-jet balance

$$p_T^{\mathrm{ref}} = p_T^{\mathrm{recoil}} = \left| \sum_{\mathrm{recoil}} \vec{p}_T^{\,\mathrm{jet}} \right|$$





Uncertainties from modelling

Arise from differences between MC generators

Little contribution to total uncertainty even in most sensitive high jet-p_T region

Constituent Level Pile-up Suppression

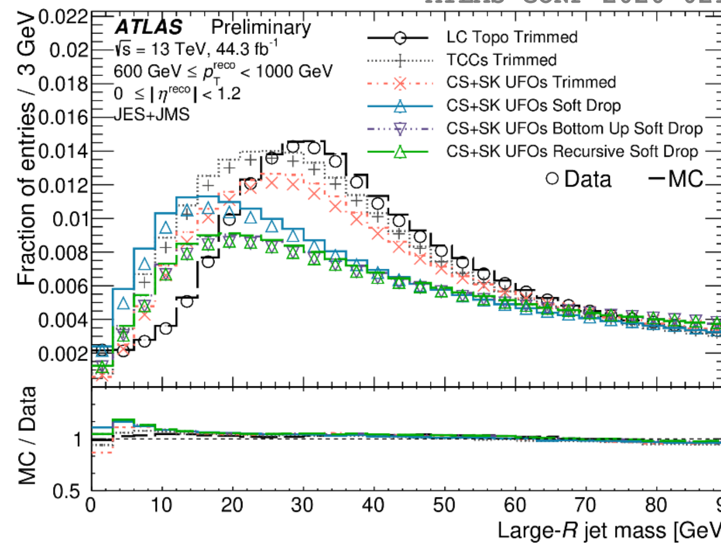
Remove pile-up from input signal

- Attractive for large-R jets …
  - Improve precision and resolution in measurements using structural (p_{T}-flow) jet information (e.g. for tagging heavy particle decays)
- … and event shapes
  - Recovering/extracting soft signal contributions to $E_{\mathrm{T}}^{\mathrm{miss}}$ in the presence of pile-up
- Non-jet context
  - Stochastic approach to remove diffuse emissions from pile-up – no correlation to hard scatter interactions
  - Local pile-up density measures with various area definitions (Voronoi-area-based, constituent subtraction with ghosts, SoftKiller, PUPPI…)
  - Combination of approaches – ConstituentSubtraction + SoftKiller (CS+SK) increase efficiency

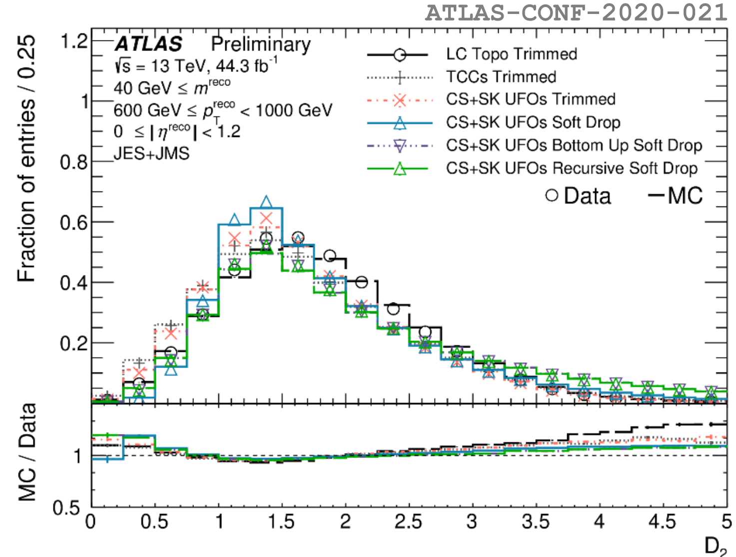
Combination with jet substructure reconstruction

- Jet grooming (e.g. SoftDrop)
  - Reduces sensitivity to soft emissions in already biased input signals
- Enhanced sensitivity to harder structure
  - Popular tagger inputs are jet mass & ratio of 2-point to 3-point energy-energy correlation functions D_2

ATLAS-CONF-2020-021



ATLAS-CONF-2020-021



Underlying Event Tunes ATLAS Run 2

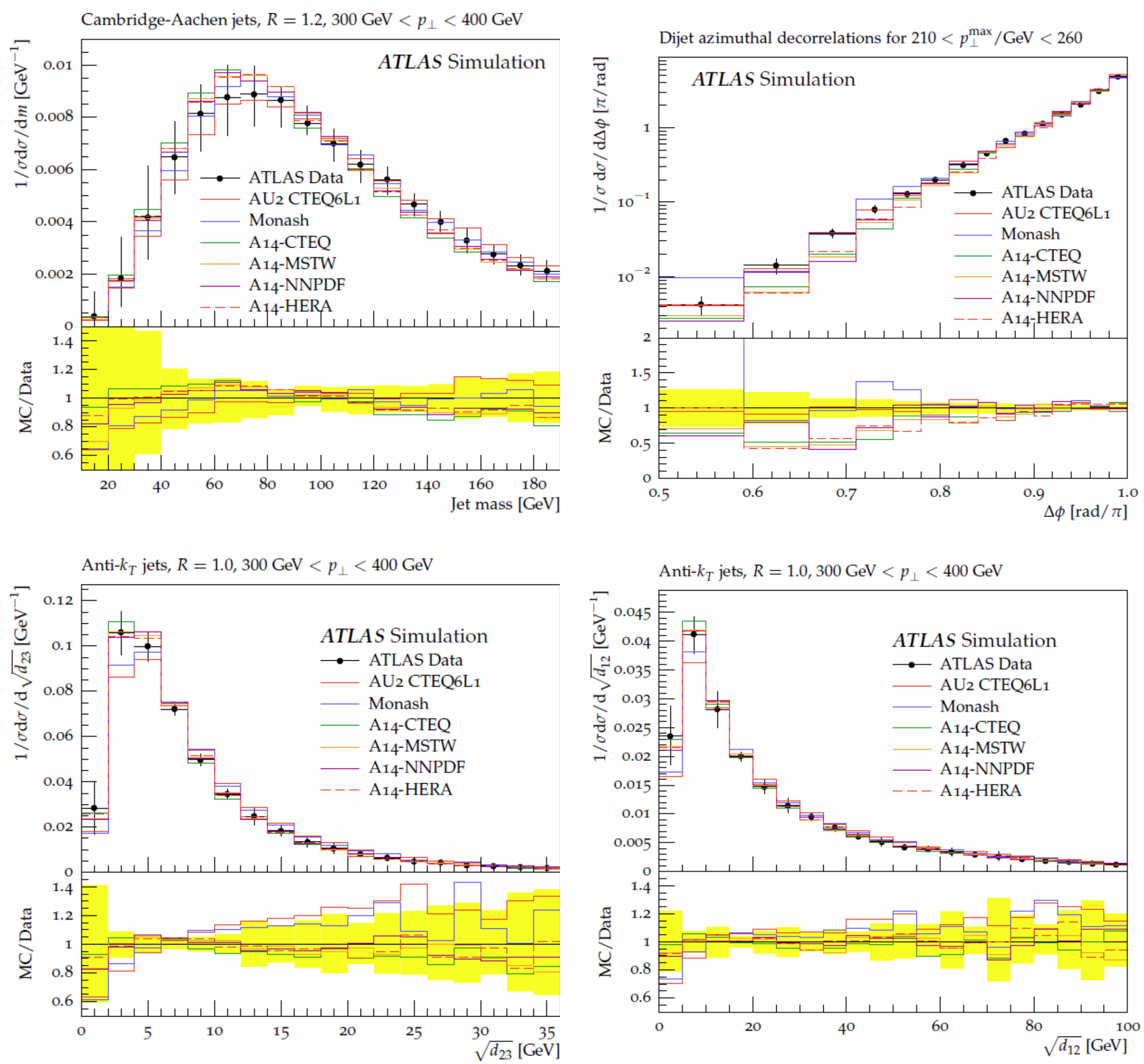
Most recent ATLAS tune: A14 (pp at $\sqrt{s} = 7$ TeV)

- Underlying event
  - Evolution of transverse activity with hardest track & calorimeter jets
- Parton shower
  - Jet structure – track jet properties, jet masses & substructure variables, jet shapes in inclusive jet and $t\bar{t}$ final states
- Additional emissions beyond LO $2 \rightarrow 2$
  - Dijet azimuthal de-correlation
  - Gap jet fraction in $t\bar{t}$ final states
  - 3/2 jet ration
  - Z-boson p_{T}

Performs well in Run 2

- Used for all physics analysis in pp collisions at $\sqrt{s} = 13$ TeV

ATLAS-PHYS-PUB-2014-021

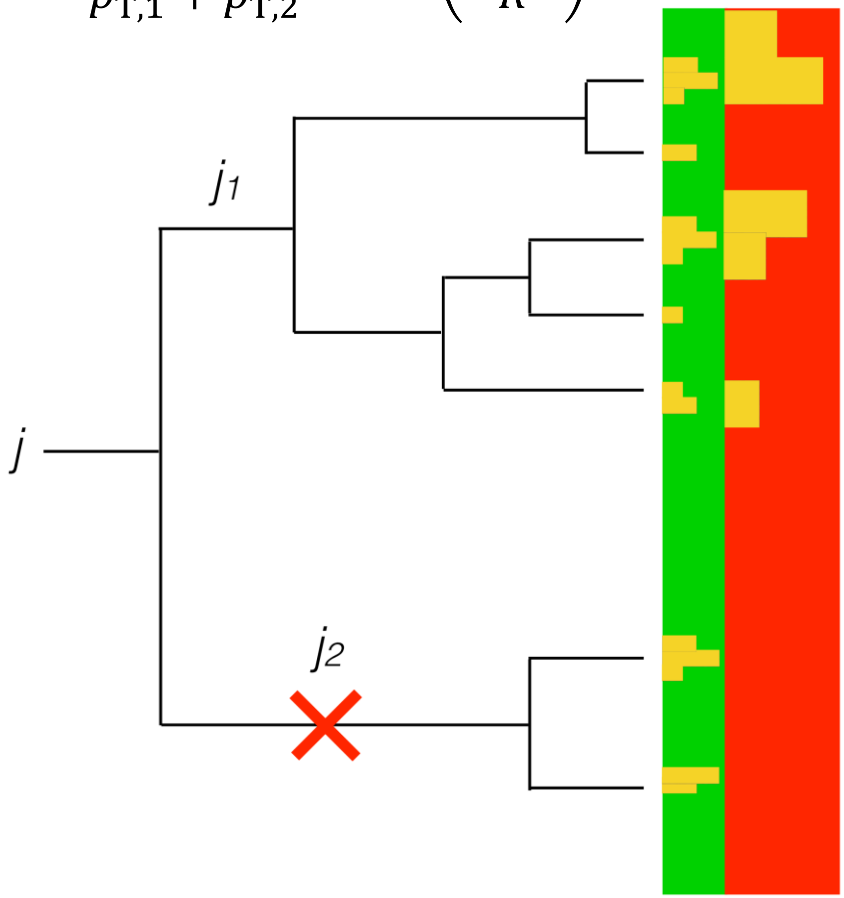


SoftDrop

Remove soft wide angle emissions from jet

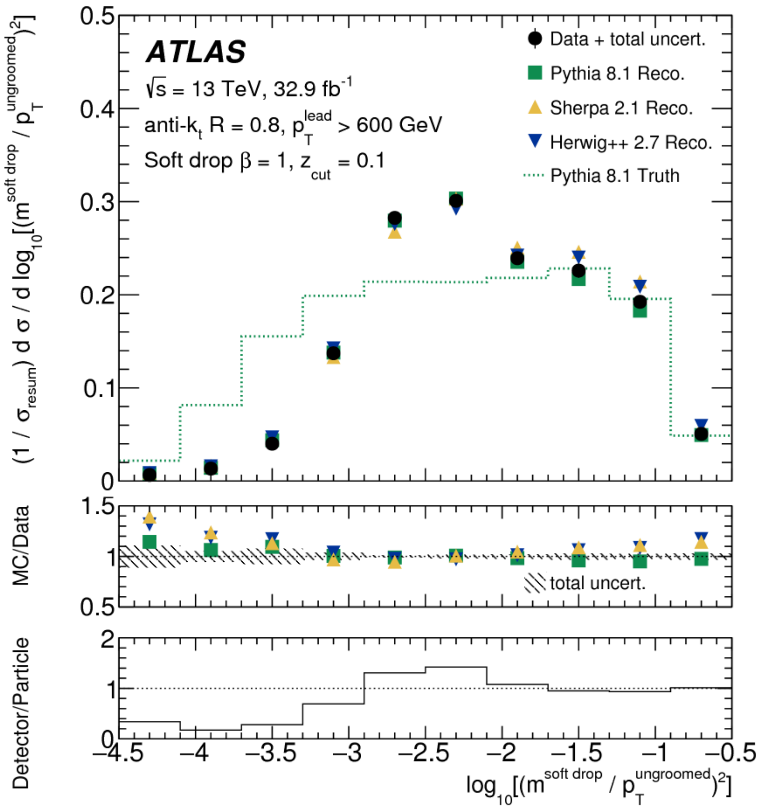
- Traverses jet clustering history
  - Drops branches reflecting wide angle soft radation
  - Insensitive to nonglobal logarithmic corrections – removes radiation leaving the jet cone and emit particles back into the cone
- SoftDrop variables
  - Mass, p_{T} balance of splitting, angular distance of emission
  - Found to be calculable to NLL and NNLL accuracy
  - Excellent agreement with data in regions where calculations are accurate
  - Non-perturbative effects prominent theoretical uncertainty – dominate higher order effects
- Free parameters z, β, jet radius R
  - Regulate sensitivity to radiation scales

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

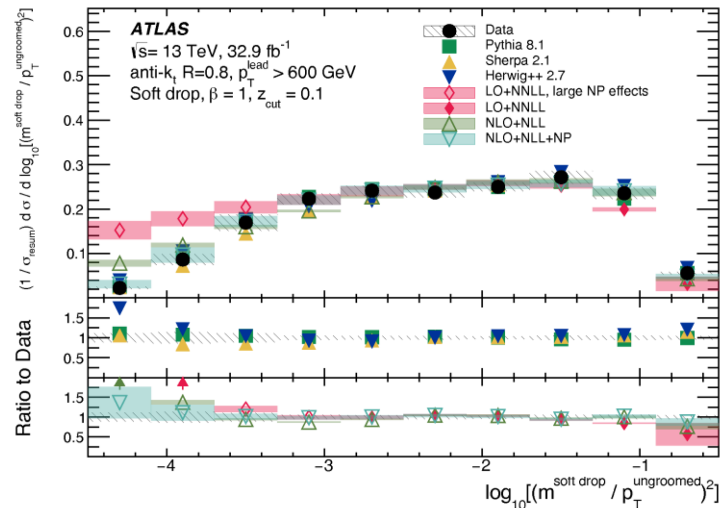


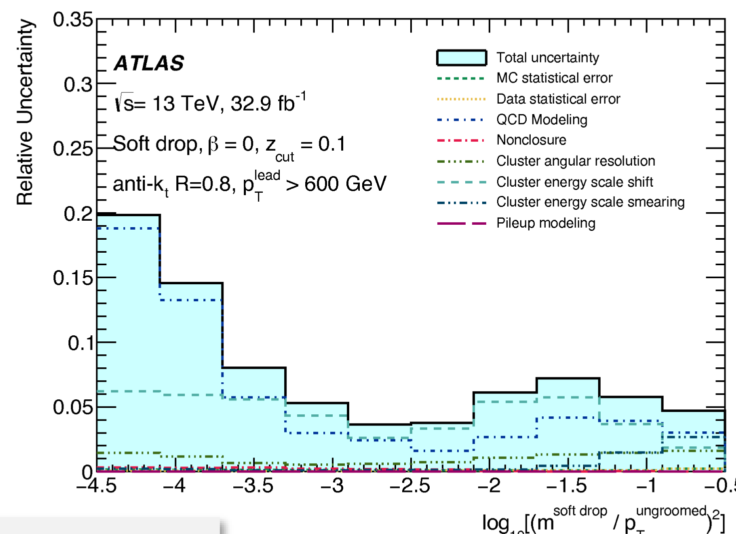
Soft Drop Mass Measurement

Detector-level …



… unfolded measurements





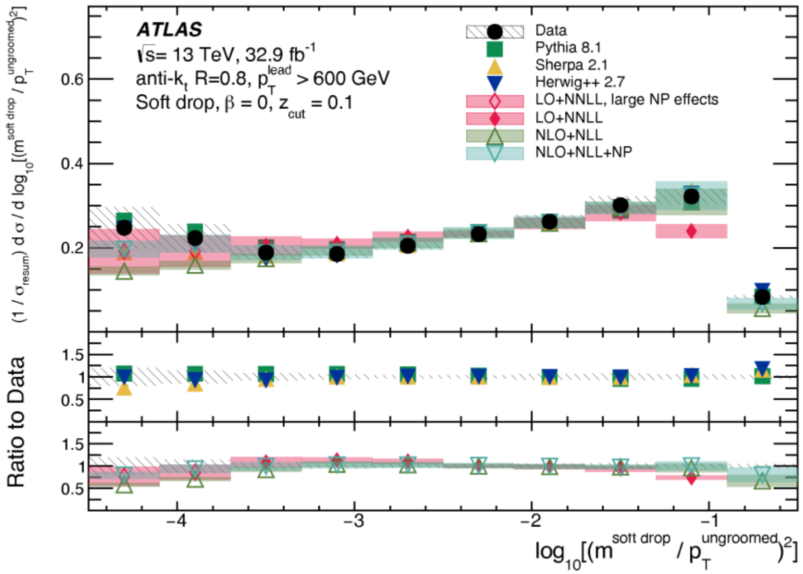
Systematic uncertainties ⟶

arXiv:1711.08341 (2017)

Soft Drop Mass – Interpretation

$\beta = 0$

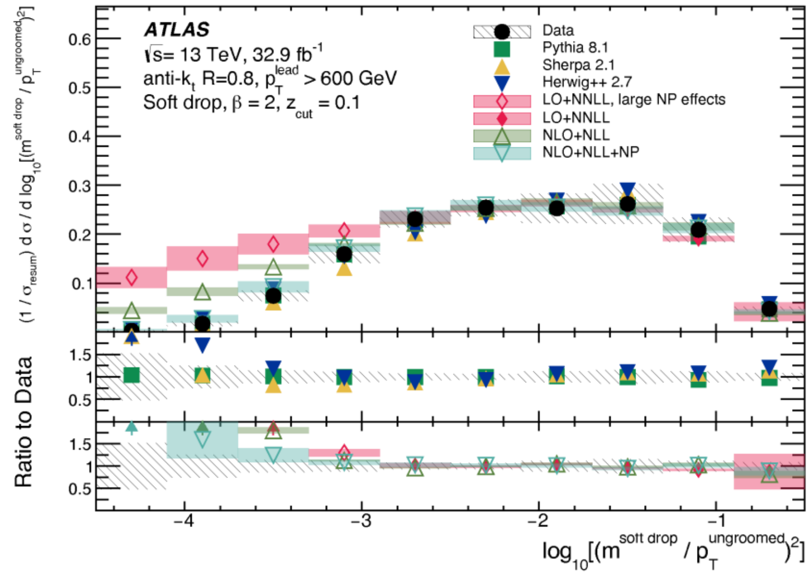
Removes soft→collinear radiation



arXiv:1711.08341 (2017)

$\beta = 2$

Removes soft radiation



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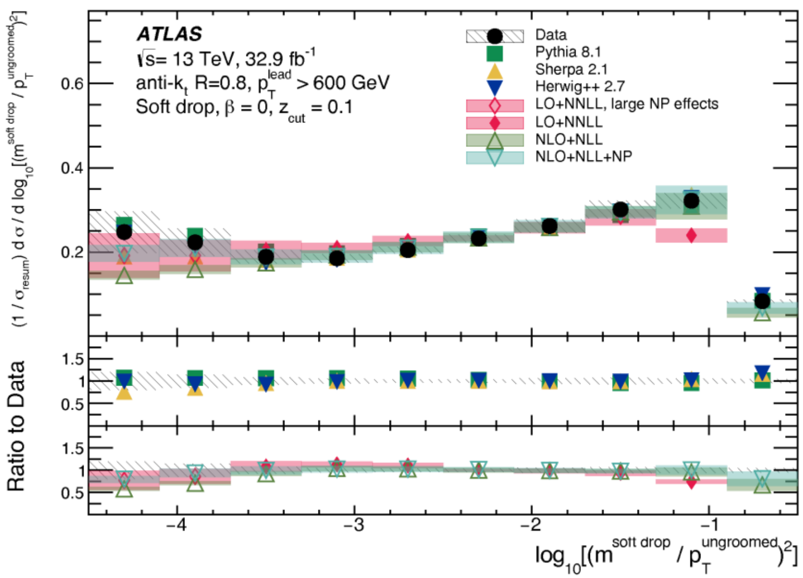
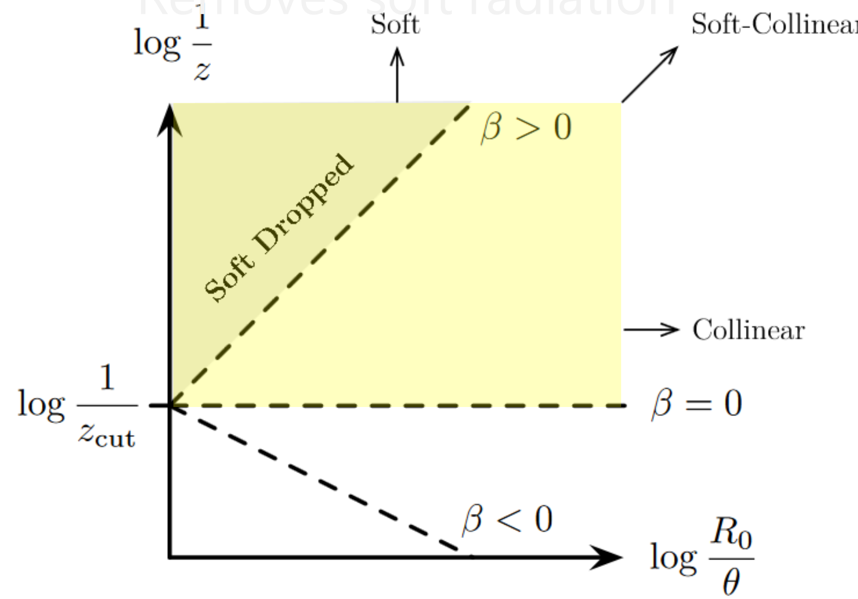


$\beta = 2$

Removes soft radiation



 Peter Loch – *Snowmass EF05* August 3, 2020

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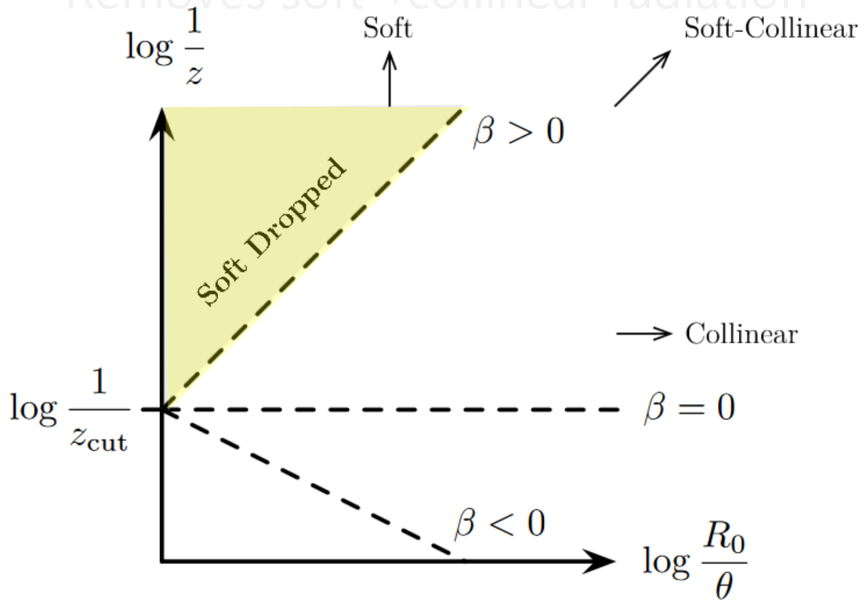
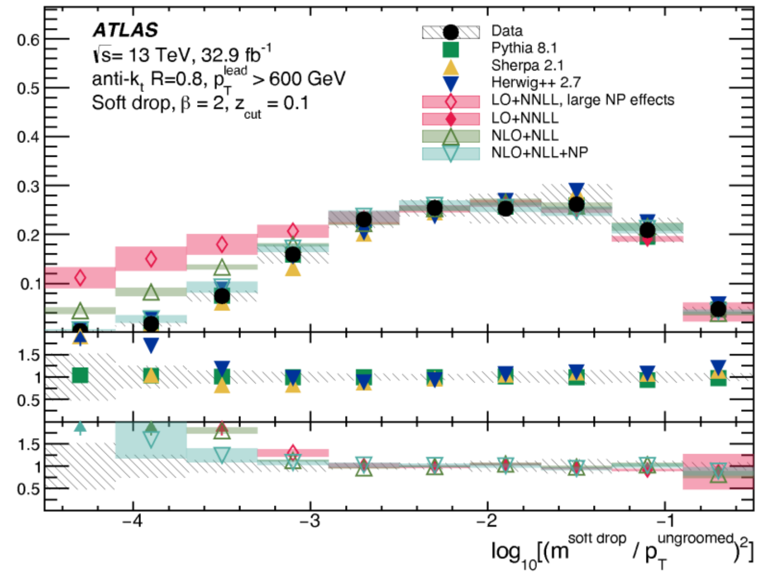


$\beta = 2$

Removes soft radiation



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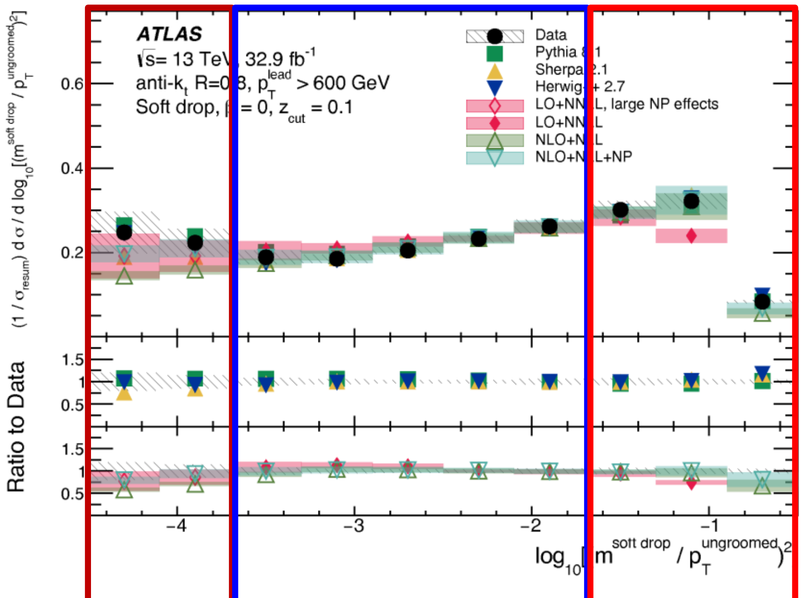
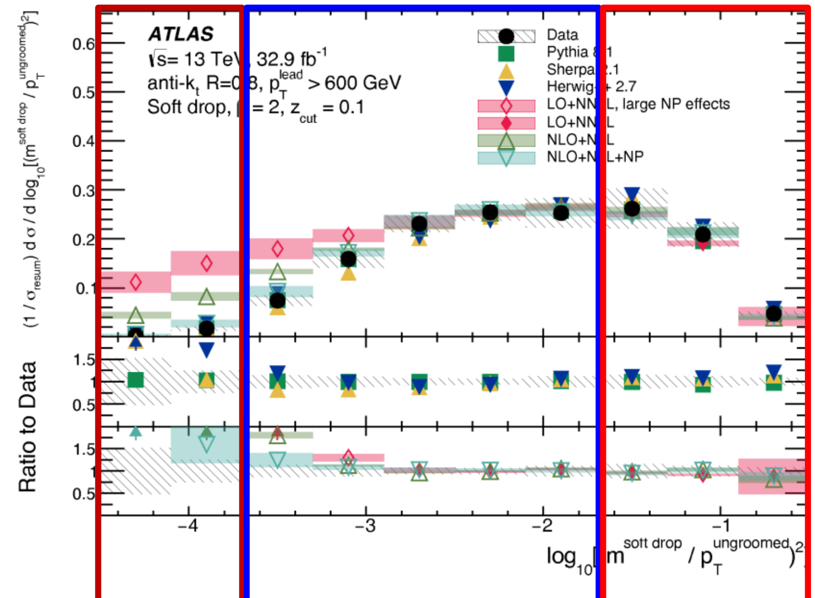


$\beta = 2$

Removes soft radiation



< −3.7 non-perturbative regime

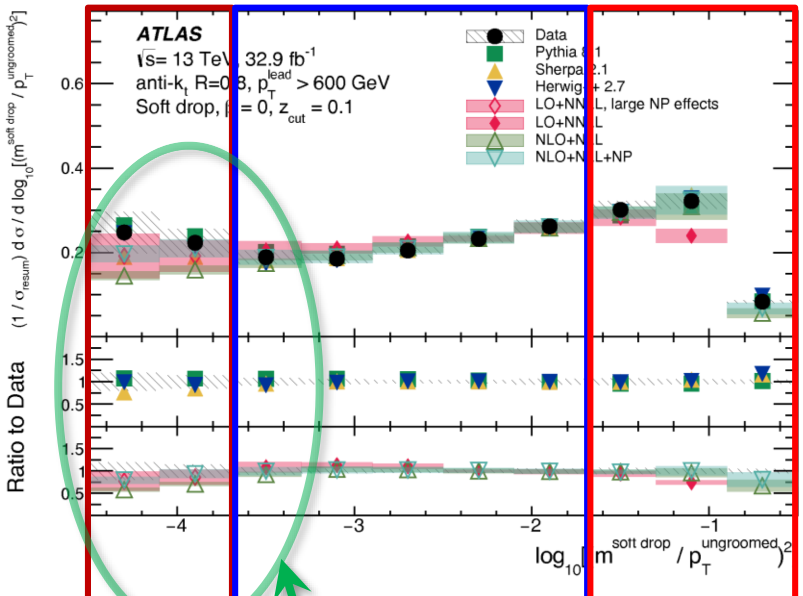
−3.7 → −1.7 resummation region

> −1.7 fixed order regime
(large angle gluon emission)

Soft Drop Mass – Interpretation

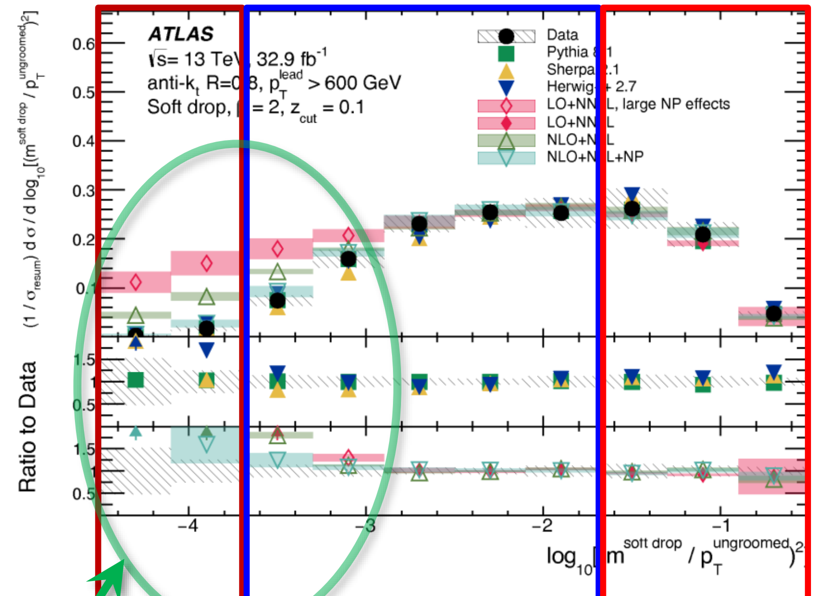
$\beta = 0$

Removes soft→collinear radiation



$\beta = 2$

Removes soft radiation



Larger disagreements for less inclusive ($\beta = 2$) soft contribution removal

(large angle gluon emission)

More on SoftDrop Variables

ATLAS Coll., Phys.Rev.D 101 052007 (2020)

Updated results …

- More SoftDrop variables
  - p_{T}-balance of splitting $z_g = \min(p_{\mathrm{T},j1}, p_{\mathrm{T},j2})/(p_{\mathrm{T},j1} + p_{\mathrm{T},j2})$
  - Opening angle of splitting $r_g = \sqrt{(y_1 - y_2)^2 + (\varphi_1 - \varphi_2)^2}$
- Calorimeter & track-based analyses
  - Updated/new systematic uncertainties

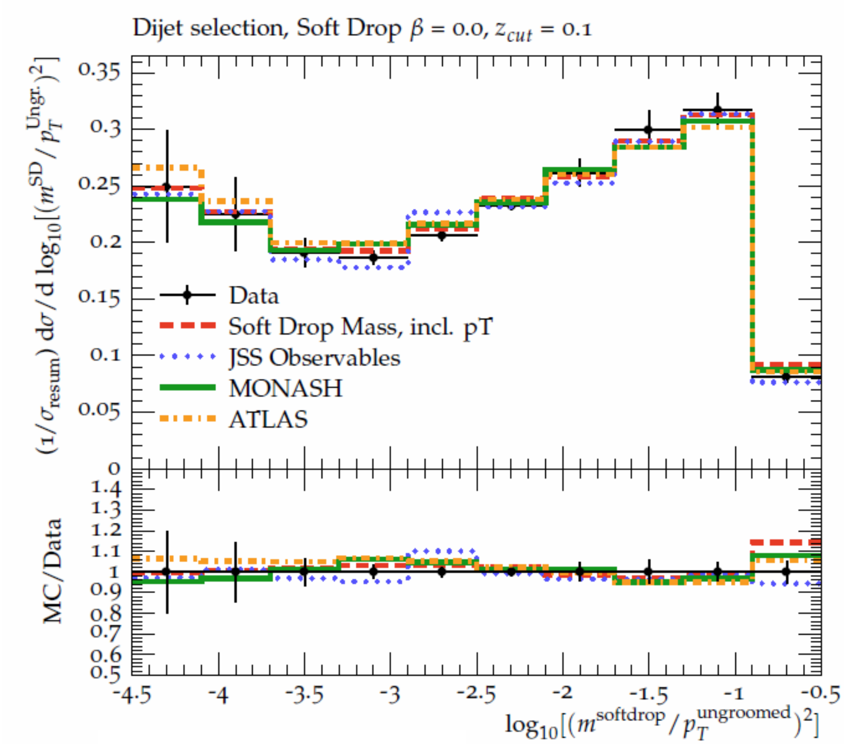
… provide a deep look in to the dynamics of jet formation

- Evaluation of splitting history at various angular and momentum scales

TeV@Les Houches 2019

- Use of (SoftDrop) substructure observables in tuning
  - SoftDrop mass from studies at Les Houches 2019
  - Promising first investigation

arXiv.2003.01700



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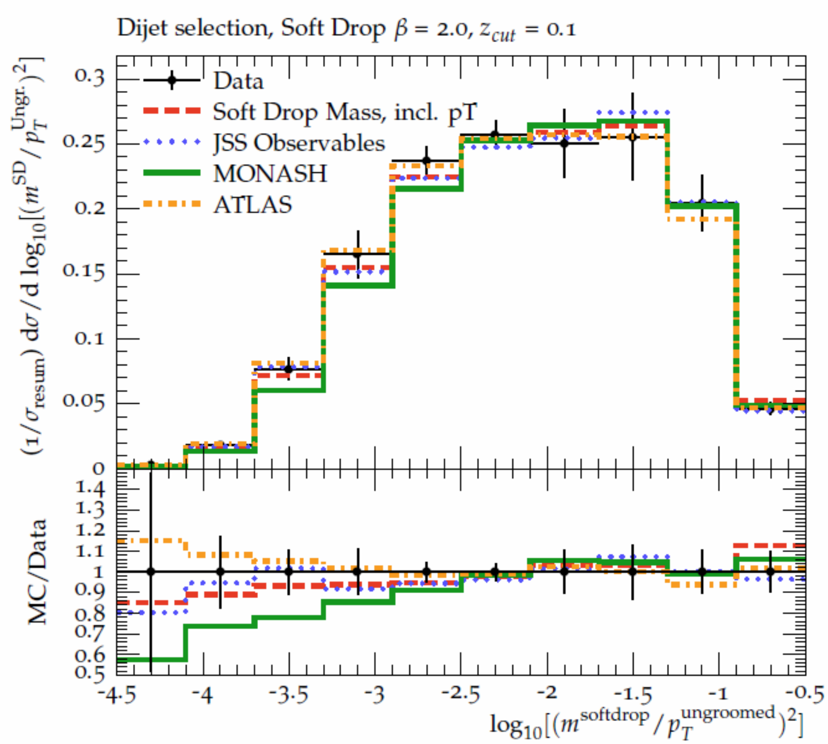


Hadronic Event Shapes with Jets

Event shapes with jets

arXiv:2007.12600 [hep-ex]

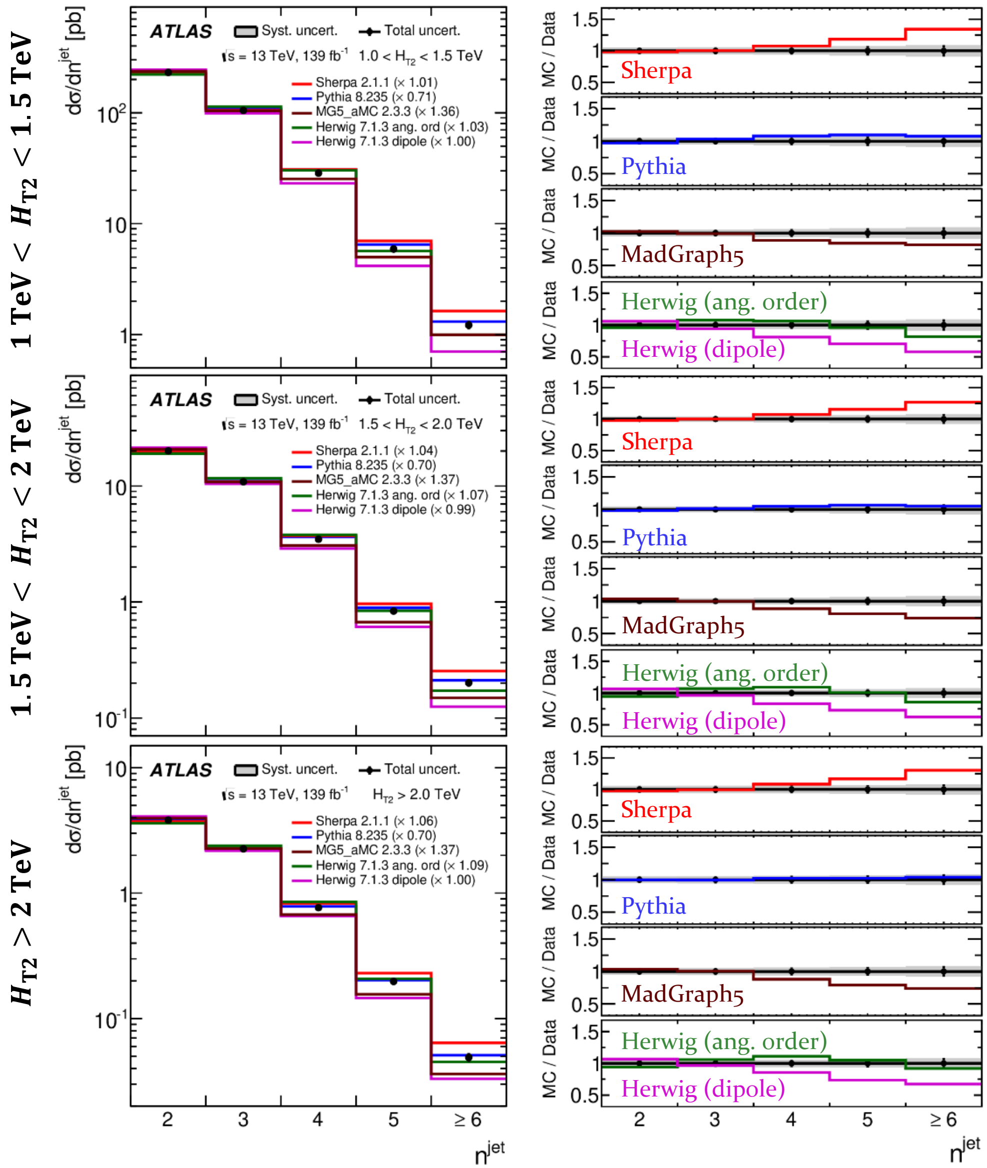
- Proxy for energy flow shapes in collision event
  - Measurement tests prediction power of fixed-order calculations, parton shower modeling, etc.
- Clear expectation values for given topology
  - Shapes vanish for 2 → 2 processes with perfect forward-backward (back-to-back in transverse plane) symmetry – at maximum for uniform energy (transverse momentum) distribution
- Probe for multi-jet energy flow at highest scales
  - $\mathcal{O}(\text{TeV})$ for $\sqrt{s} = 13$ TeV
  - Evaluated in multi-jet final states ($n^{\text{jet}} \geq 2$) as function of hardness of interaction
    - Representative observable for interaction activity is $H_{\text{T2}} = p_{\text{T}}^{\text{lead}} + p_{\text{T}}^{\text{sublead}}$

Measurement

- Jet and event selection
  - Consider only fully calibrated anti-k_t jets with $R = 0.4$ clustered from particle flow objects with $p_{\text{T}}^{\text{jet}} > 100$ GeV, $|\eta^{\text{jet}}| < 2.4$
  - Multi-jet events with $n^{\text{jet}} \geq 2$,
  - $H_{\text{T2}} > 1$ TeV selected
- Presentation of results
  - Differential cross-sections as ratio to fiducial cross section $\sigma(n^{\text{jet}} \geq 2)$
    - $1/\sigma(n^{\text{jet}} \geq 2)\, d\sigma/d\{T_{\perp}, T_m, S_{\perp}, A, C, D\}$ in $(H_{\text{T2}}, n^{\text{jet}})$ bins*
  - Unfolded data is compared to various Monte Carlo generators

*see additional material for description of all used event shape observables

Modeling of Jet Multiplicities



arXiv:2007.12600 [hep-ex]

Fiducial cross section

- Measured as function of n^{jet}
  - Evaluated in same three regions of H_{T2} used for event shape measurements – provides normalization

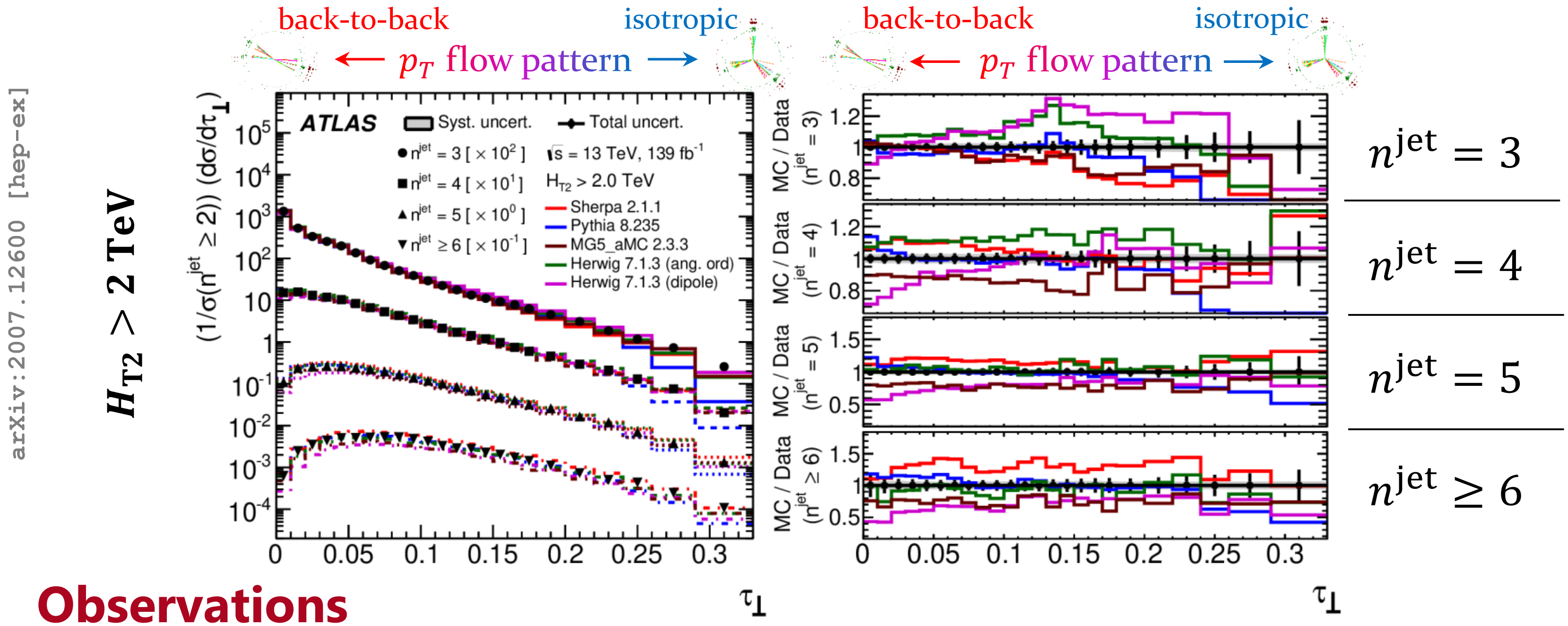
Modeling $d\sigma/dn^{\mathrm{jet}}$ shapes

- Pythia 8.235
  - $2 \rightarrow 2$, LO accuracy
  - Generally good agreement for all n^{jet}
- Sherpa 2.2.1
  - $2 \rightarrow \{2,3\}$, LO accuracy (multi-leg)
  - Overestimation (increasing) for $n^{\mathrm{jet}} > 4$
- Herwig 7.1.3 (angular ordered PS)
  - $2 \rightarrow 2$ NLO accuracy, $2 \rightarrow 3$ LO
  - Good description with slight underestimation for $n^{\mathrm{jet}} \geq 6$
- Herwig 7.1.3 (dipole PS)
  - $2 \rightarrow 2$ NLO accuracy, $2 \rightarrow 3$ LO
  - Good description for low n^{jet}, underestimation for higher n^{jet}
- MadGraph5_aMC 2.3.3
  - $2 \rightarrow \{2,3,4\}$ NLO accuracy
  - Good description for low n^{jet}, underestimation for higher n^{jet}

Modeling normalization

- Well predicted at low n^{jet}
  - Only small differences between models
- Large spread in normalization at high n^{jet}
  - Sherpa predicts 30% more than data
  - Herwig (dipole PS), MadGraph predict 30% less

Transverse Thrust with Jets



Observations

- Evolution with increasing hardness of interaction
  - More events with more isotropic flow at softer interactions (lower H_{T2})
  - Increasing H_{T2} yields increased contribution from events with close to back-to-back flow patterns

Comparisons to models

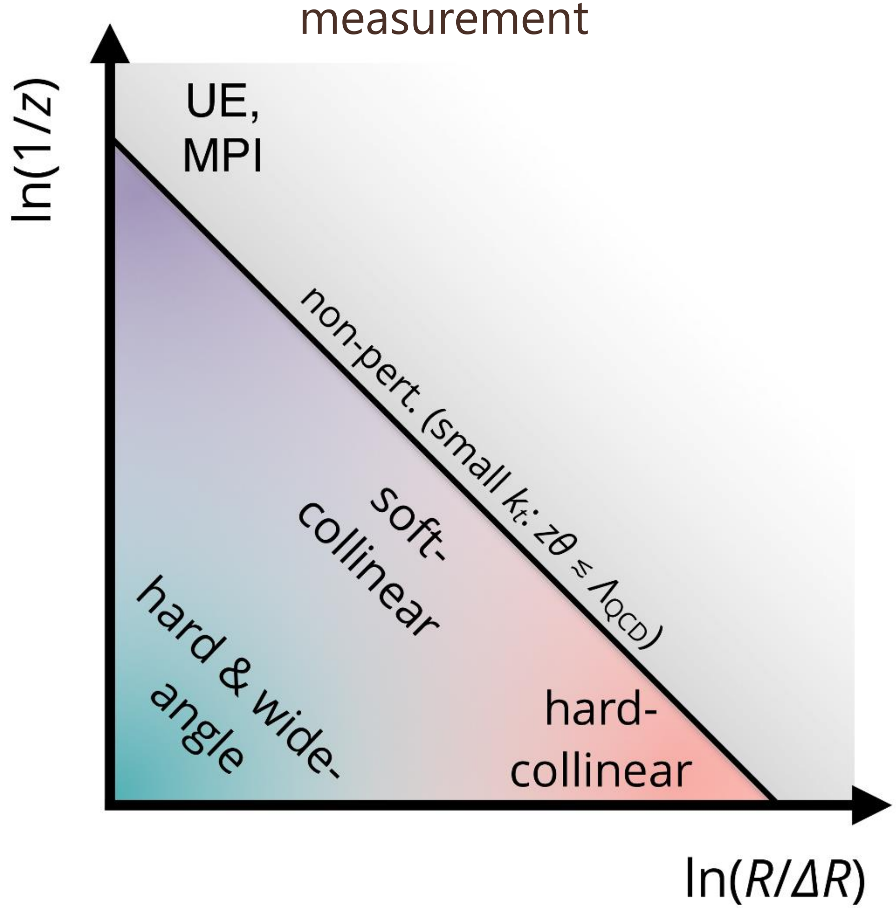
- Evaluation of predictions
  - Generally fewer isotropic events in MC than in data at low n^{jet} – better agreement at higher jet multiplicities
- Shapes of cross sections
  - None of the considered MC generators gives good description in full phase space
  - Similar distribution shapes at high n^{jet} from all considered model

New Measurements for Tuning?

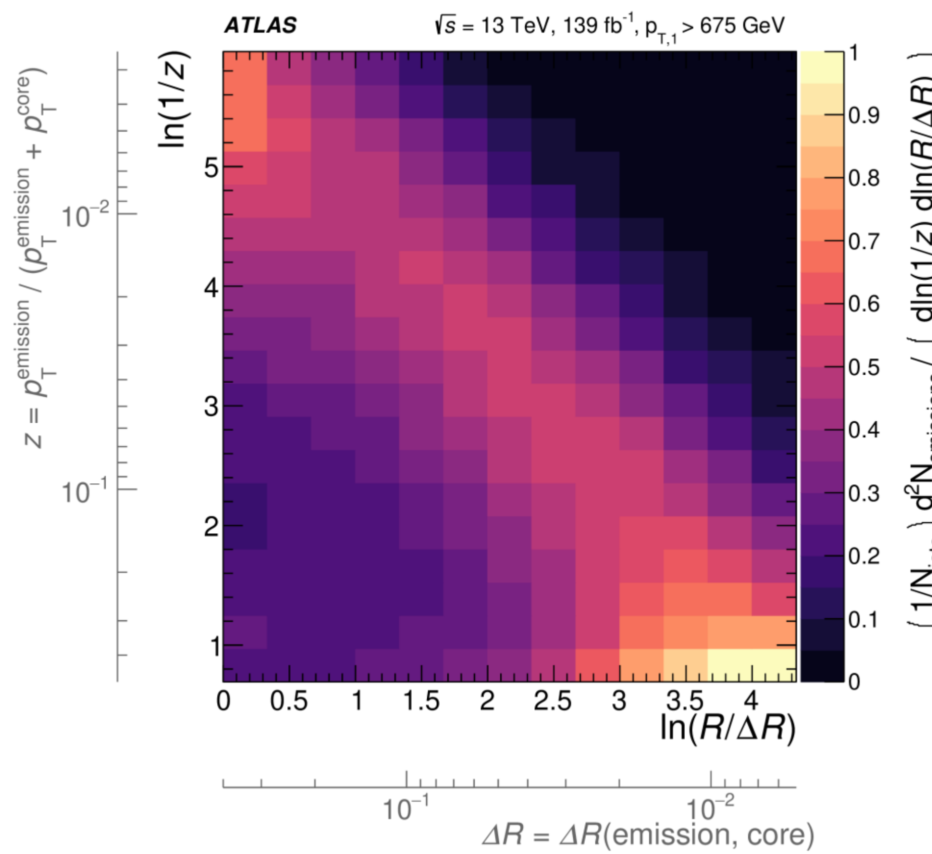
LundPlane with tracks

Phys.Rev.Lett. 124, 222002

- 2-dim image of radiation pattern in jet
  - Wide range of emission angles and radiated energies in one measurement

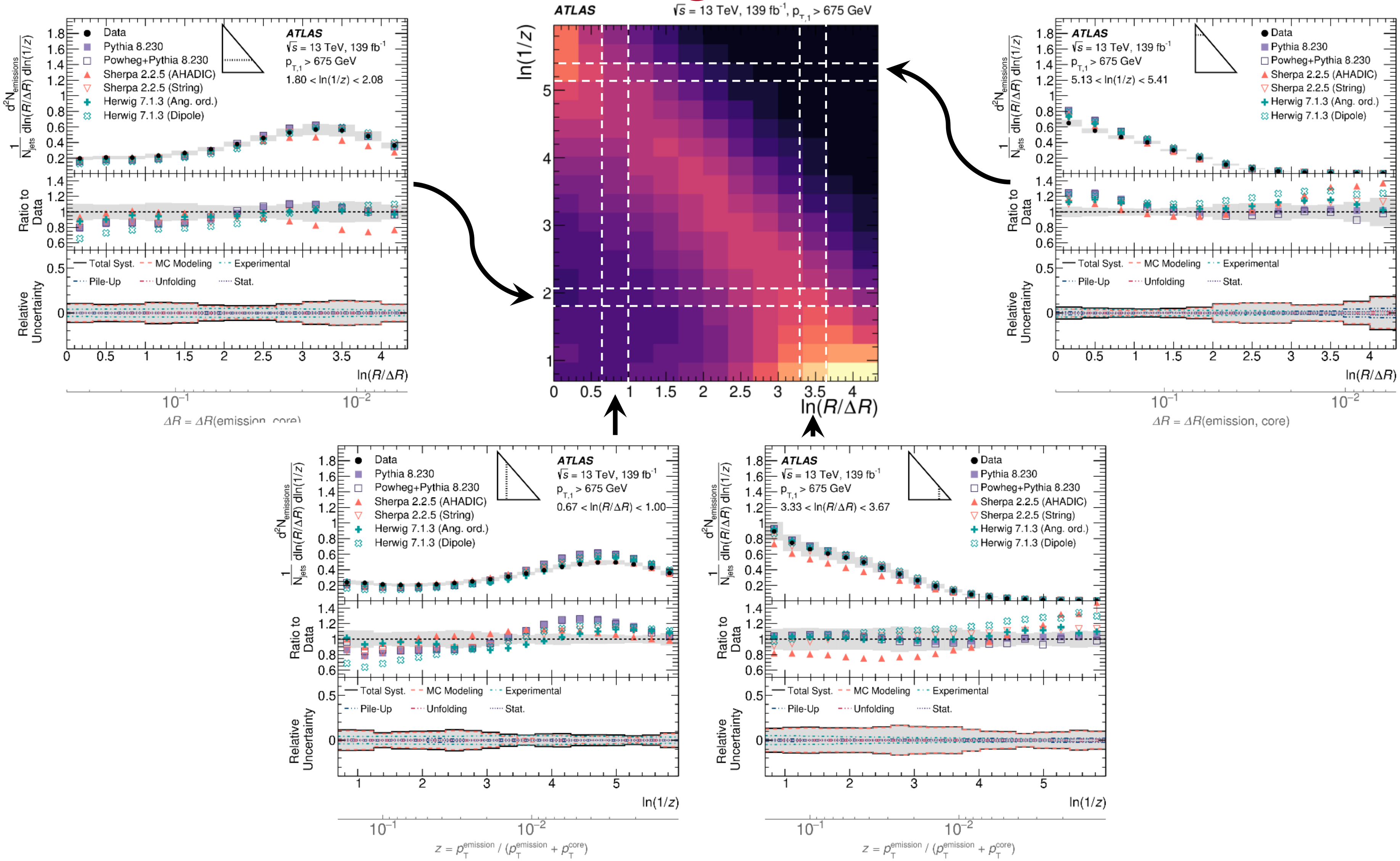


Particle level unfolded from track image



LundPlane Measurements for Tuning?

Compare emission modeling



How About Energy-Energy Correlations?

Adjust sensitivity to scales of emission

Energy-energy correlations

Employs N-point energy correlation functions between jet constituents

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

0-point corr. $\mathrm{ECF}(0,\beta) = 1$

1-point corr. $\mathrm{ECF}(1,\beta) = \sum_{i\in\mathrm{jet}} p_{\mathrm{T}i}$

2-point corr. $\mathrm{ECF}(2,\beta) = \sum_{i<j\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} \left(R_{ij}\right)^{\beta}$

3-point corr. $\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} p_{\mathrm{T}k} \left(R_{ij}R_{ik}R_{jk}\right)^{\beta}$

4-point corr. $\mathrm{ECF}(4,\beta) = \sum_{i<j<k<l\in\mathrm{jet}} p_{\mathrm{T}i}\, p_{\mathrm{T}j} p_{\mathrm{T}k} p_{\mathrm{T}l} \left(R_{ij}R_{ik}R_{il}R_{jk}R_{jl}R_{kl}\right)^{\beta}$

Larkoski, Salam, Thaler, JHEP 1306(2013) 108

How About Energy-Energy Correlations?

Adjust sensitivity to scales of emission

Energy-energy correlations

Employs N-point energy correlation functions between jet constituents

$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$

Double-ratios indicate jet source

Generally $C_N^{(\beta)} = (\mathrm{ECF}(N+1,\beta)\mathrm{ECF}(N-1,\beta))/ECF(N,\beta)^2$

$C_1^{(\beta)}$ is useful for quark/gluon separation for small $\beta \simeq 0.2$ – exploits different soft radiation patterns (uses 2-point correlations)

$C_2^{(\beta)}$ helps with boosted W/Z/H identification with $\beta \simeq 0.5$ better for high mass and $\beta \simeq 2$ better for lower mass resonances – at a fixed p_{T} (uses 3-point correlations)

$C_3^{(\beta)}$ distinguishes QCD jets from boosted top quarks best for $\beta \approx 1-2$ (uses 4-point correlations)

How About Energy-Energy Correlations?

Adjust sensitivity to scales of emission

- Energy-energy correlations
  - Employs N-point energy correlation functions between jet constituents
  - $\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in\mathrm{Jet}}\left(\prod_{a=1}^{N} p_{\mathrm{T}i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$

Experimentally challenging for soft QCD measurements

- Track only measurement
  - Small effect by pile-up – tracking in dense environments at HI-LUM?
- Calorimeter only measurement
  - Soft energy flow in jet distorted by pile-up – constituent level pile-up mitigation may hurt sensitivity to soft emissions…
- Particle flow measurement
  - Charged response equal to track measurement – neutral response may not help much…
- Could be studied with Run 2/3

Conclusions & Outlook

Access to soft emissions in hard objects

- Exploring regions of non-perturbative QCD experimentally at high precision
  - Looking inside of jets helps to increase understanding of radiation patterns → input to tunes and validation of new models/calculations
- Experimental limitations
  - Pile-up adds diffuse emissions on top of the hard scatter
  - Track-based measurements
  - Constituent-level pile-up mitigation in particle flow measurements

Hard emission modeling not too well controlled

- ATLAS analysis of event shapes
  - More work needed on the side of calculations – or matching calculations with tuned parton showers and MPI?
- May be an issue in multi-jet searches…

Soft QCD effects

- Several new observables available
  - Testing of tuning, evaluation of achievable precision and biases?
  - Tuning using 1-dim distributions of jet shapes and structure is already established
- Tuning to ≥2 dim "images"
  - Machine learning in soft QCD tuning seems a very interesting route to follow – exploration of otherwise had to determine correlations, ranking of observables by
  - Frameworks like Professor are already performing multi-dimensional fits, as far as I know…

Additional Material

Hadronic Event Shapes With Jets

Event shapes with jets

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Event shape	Name	Comments
$T_\perp$	Transverse thrust	$\tau_\perp = 1 - T_\perp$, $0 \leq \tau_\perp < 1 - 2/\pi$, $\tau_\perp \nearrow \Rightarrow$ back-to-back topology
T_m	Transverse thrust, minor component	$0 \leq T_m < 2/\pi$, $T_m \nearrow \Rightarrow$ increased energy flow outside of plane spanned by thrust and beam axes
$S_\perp$	Transverse sphericity	from eigenvalues $\{\mu_k\}$ of transverse sphericity tensor $\mathcal{M}_{xy}$, $S_\perp = 2\mu_2/(\mu_1 + \mu_2)$, $0 \leq S_\perp \leq 1$, ↓ back-to-back, ↑ isotropic
A	Aplanarity	from eigenvalues $\{\lambda_k\}$ of sphericity tensor $\mathcal{M}_{xyz}$, $A = \frac{3}{2}\lambda_3$, $0 \leq A \leq 1$, $A \nearrow \Rightarrow$ event less planar
C	3-jet observable	$C = 3(\lambda_1\lambda_1 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$, $C = 0$ for $n^{\text{jet}} < 3$, $0 < C \leq 1$ for $n^{\text{jet}} > 2$
D	4-jet observable	$D = 27(\lambda_1\lambda_2\lambda_3)$, $0 \leq D \leq 1$, $D = 0$ if all jets are in same plane

Event Shape Variables

Linearized Sphericity Tensor

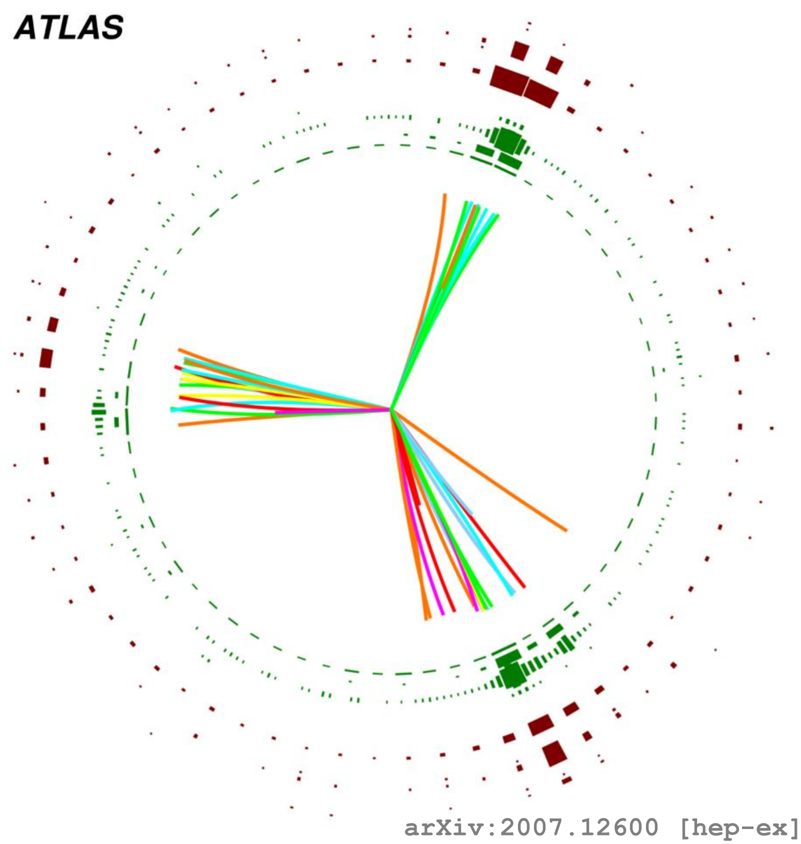
$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

Transverse Linearized Sphericity Tensor

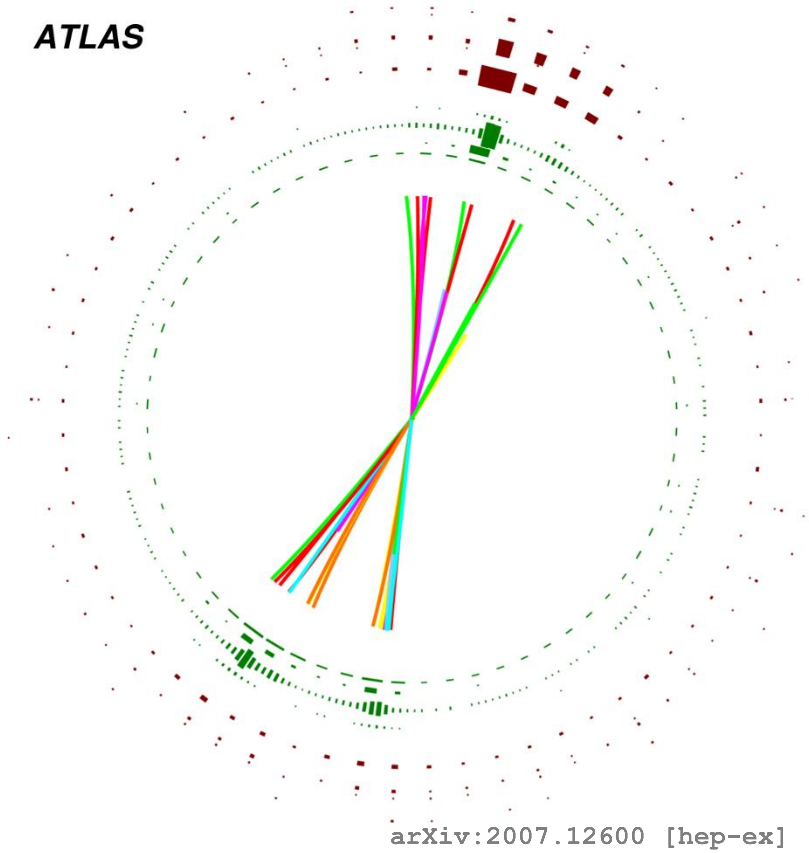
$$\mathcal{M}_{xy} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix}$$

Hadronic Event Shapes with Jets

Examples: transverse thrust & transverse sphericity

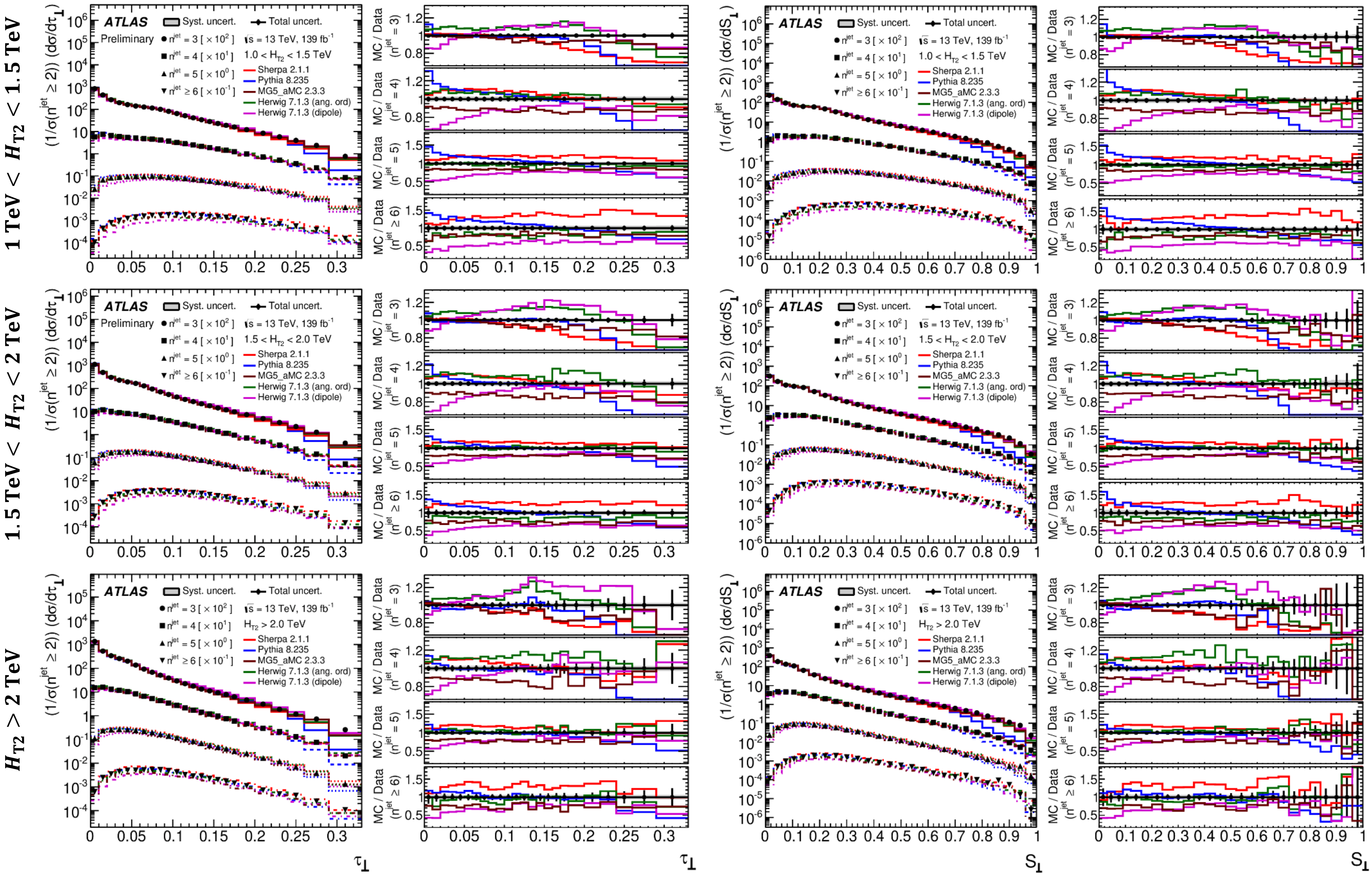


$n^{\text{jet}} = 3$, high values of $\tau_{\perp} = 1 - T_{\perp}$ and $S_{\perp}$



$n^{\text{jet}} = 5$, low values of $\tau_{\perp}$ and $S_{\perp}$

Hadronic Event Shapes: $\tau_{\perp}(H_{\mathrm{T2}}, n^{\mathrm{jet}})$, $S_{\perp}(H_{\mathrm{T2}}, n^{\mathrm{jet}})$



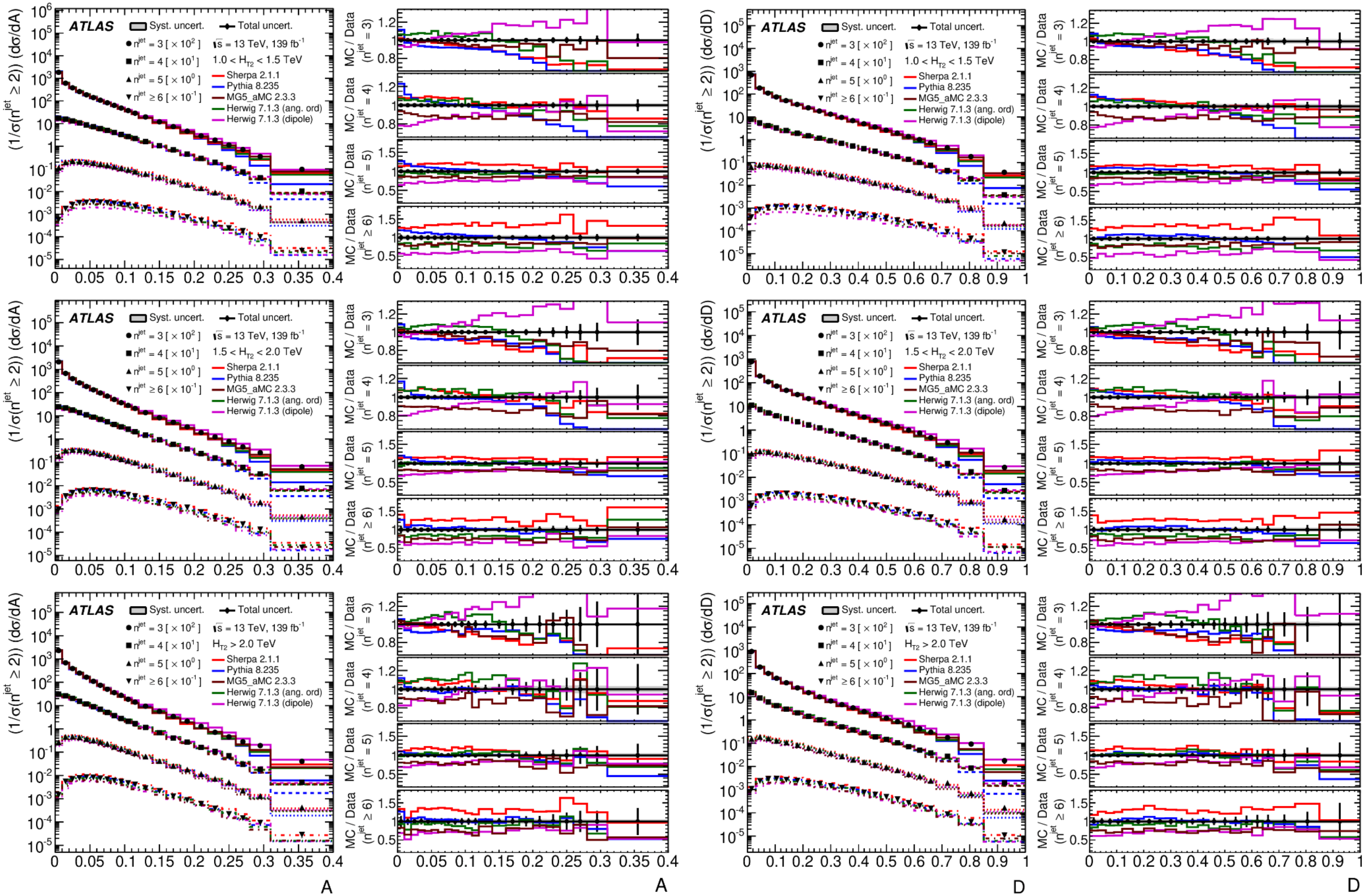
arXiv:2007.12600 [hep-ex]

Hadronic Event Shapes: $A(H_{T2}, n^{jet})$, $D(H_{T2}, n^{jet})$

$1\ \text{TeV} < H_{T2} < 1.5\ \text{TeV}$

$1.5\ \text{TeV} < H_{T2} < 2\ \text{TeV}$

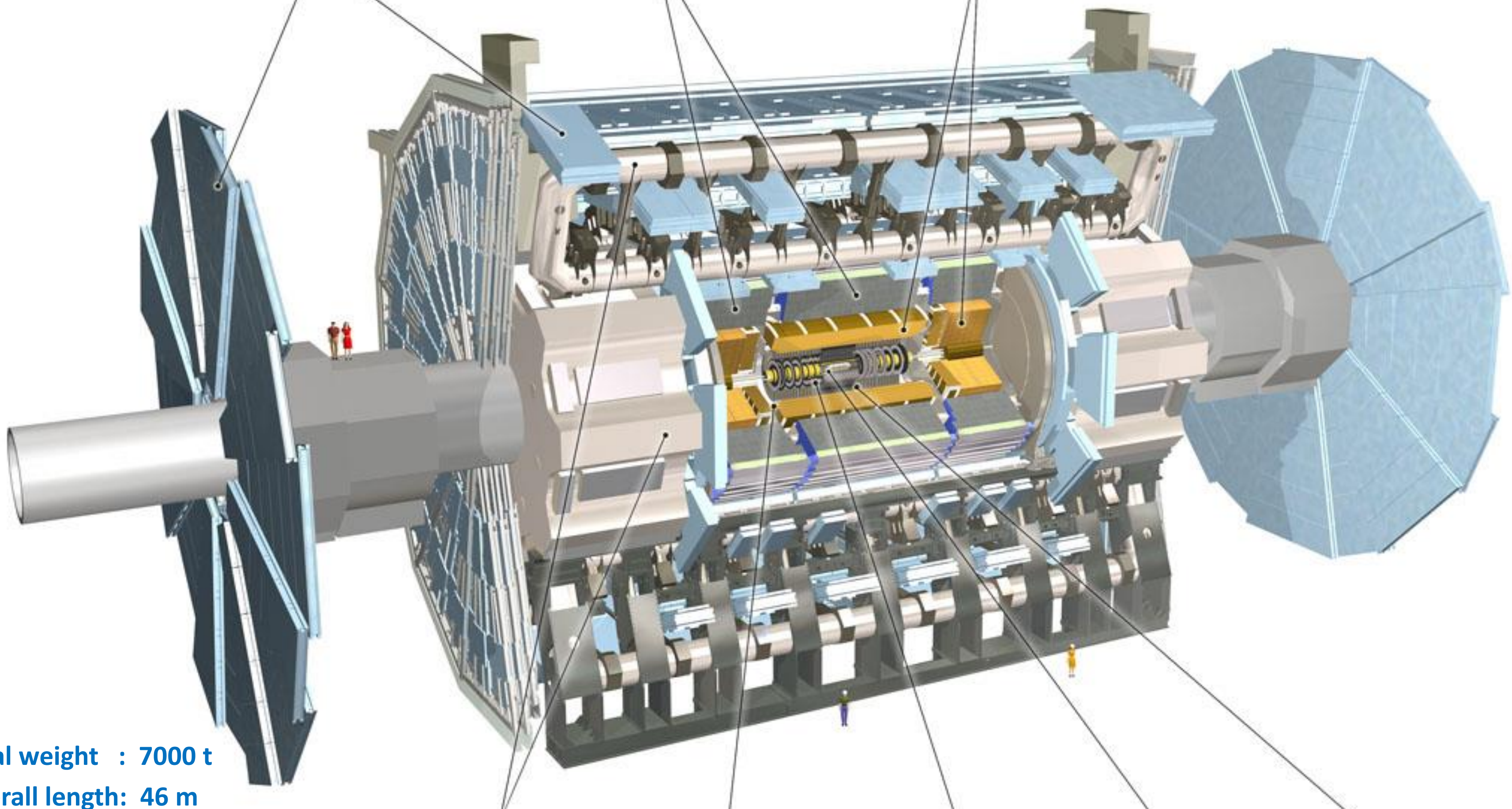
$H_{T2} > 2\ \text{TeV}$



arXiv:2007.12600 [hep-ex]

ATLAS at the LHC

A multi-purpose detector system



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + (varying) toroid field

Detectors for Hadronic Final State Reconstruction

Calorimeters

- Provides principal signals for $e^{\pm}/\tau^{\pm}$ and jet kinematics – and other measurements
  - Full coverage within $|\eta| < 4.9$ with depth $\gtrsim 10\ \lambda_{\text{int}}$
- Highly segmented for energy flow measurements (~188,000 cells)
  - High granularity in $\Delta\eta \times \Delta\varphi = 0.025 \times \pi/128$ (central EM)
  - Up to seven depth layers (*samplings*)

Inner detector

- Provides charged particle tracks and vertices
  - Coverage $|\eta| < 2.5$
- Jet energy calibration refinement
  - Provides vertex for jet origin correction/jet vertex association/jet vertex tagging (JVT)
  - Flavor/fragmentation sensitive response measures – mitigation of jet flavor response dependencies
- Particle flow
  - Replace charged response in calorimeter with kinematics from well-measured tracks
- Missing transverse momentum soft contributions
  - Tracks not used or associated with (hard) reconstructed particles and jets

Muon spectrometer

- Reconstructed muons
  - Contribution to missing transverse momentum reconstruction
- Track segments
  - Proxy for energy leakage behind a jet