The Lund jet plane in ATLAS

LHC EW working group: jets & EW bosons meeting

Alex Sopio

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Introduction: The Lund jet plane (LJP)

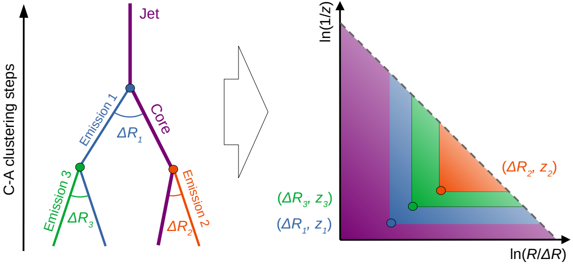
- Idea: reconstruct distribution of QCD radiation inside jet by constructing Lund Planes from proto-jets in CA algorithm.
- To reconstruct: calculate kinematic variables, eg

$$\underline{z} = \frac{p_T^e}{p_T^e + p_T^c}; \qquad \underline{\Delta R} = \sqrt{(y_e - y_c)^2 + (\phi_e - \phi_c)^2}; \qquad k_t = p_T^e \Delta R,$$

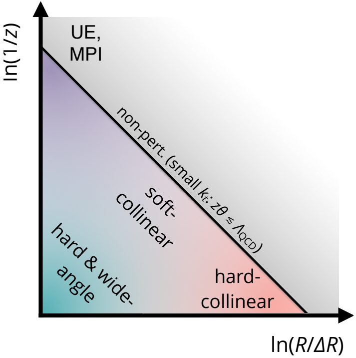
  for proto-jets e, c in each step where $p_T^e < p_T^c$.

- Plot LJP for angular + momentum variable. (Total number of emissions) / (total number of jets) gives the average emission density ρ_{LJP}.

- These *Lund Jet Planes* [Dreyer, 1807.04758] have many interesting features. Radiation of different origins is factorised across the plane.
- LJP relates closely to other jet substructure observables that are built from CA clustering sequences, e.g. the *Soft Drop* [Larkoski, 1402.2657,ATLAS, 1912.09837] jet mass which show similar behaviour.
- To leading order in QCD, the emission density is proportional to $\alpha_s(k_t)$.

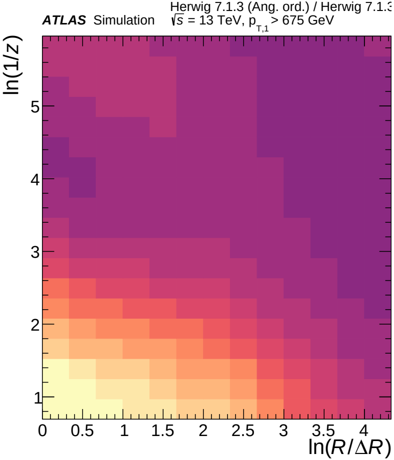


- Emissions of different scales and origins enter in different regions of the plane



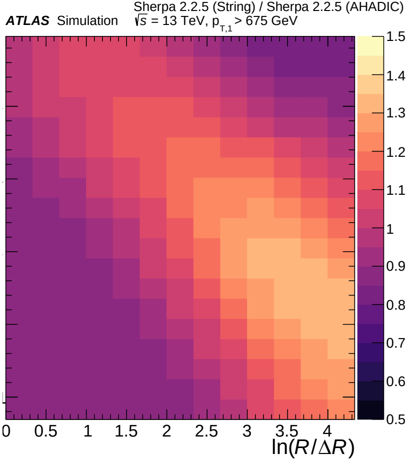
Parton shower

(Ang. ord. / Dipole)



Hadronization

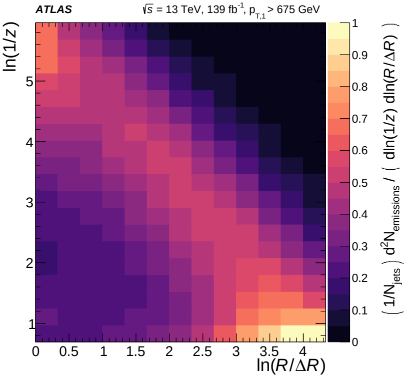
(Lund string / AHADIC)

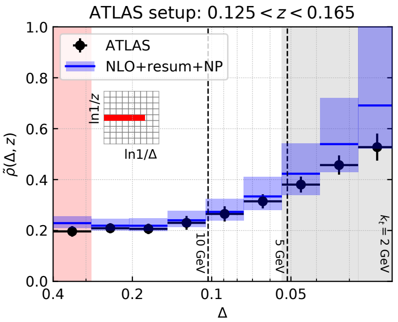


Source: EP-2020-030

First measurement of the LJP in dijets [EP-2020-030]

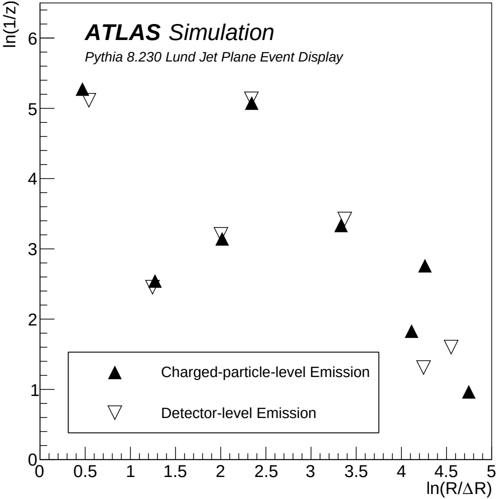
- First ever measurement of the Lund Jet Plane observable by ATLAS in dijet events [EP-2020-030].
- Uses the full ATLAS Run 2 dataset with lowest p_T un-prescaled single jet triggers. More than 29 million jets!
- Jets are reconstructed from calorimeter topoclusters using anti-k_T with $R = 0.4$.
- Event selections:
  - 2 jets, both $|\eta| < 2.1$
  - $p_T^{\text{leading}} > 675\,\text{GeV}$
  - Dijet balance: $p_T^{\text{leading}} < 1.5 \times p_T^{\text{sub-leading}}$
- LJPs are reconstructed for both jets. High jet p_T ensures good LJP resolution.
- Measurement was later compared to all-orger NLL resummations [Lifson, 2007.06578]. Good overall agreement, mismodelling at jet boundary due to CA-reclustering of anti-k_t jet.





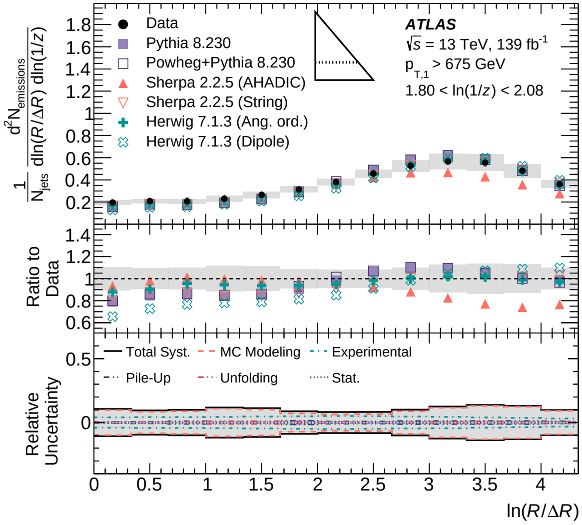
First measurement of the LJP in dijets [EP-2020-030]

- In the detector, the LJP is constructed from tracks to benefit from the high spatial resolution of the inner detector compared to the calorimeters.
- Tracks within a cone of size $R_{jet} = 0.4$ of the calibrated jets are collected and re-clustered using Cambridge-Aachen to calculate the LJP.
- The re-clustering of constituents of the jet has implications for the definition of the observable, specifically at the edges of the jet (wide ΔR).
- To make comparisons to MC, analytical predictions easy, the LJP is *unfolded*, i.e. corrected for detector effects, using the iterative Bayesian procedure (IBU) with 4 iterations.
- The correction requires matching detector-level LJP emissions with truth particles level ones in MC. Done using angular distance in detector space.



First measurement of the LJP in dijets [EP-2020-030]

- Uncertainty on the measurement is dominated by systematic sources. Detector affects difficult to resolve areas. Elsewhere: theoretical uncertainties, taking unfolding into account.
- No MC generator is able to describe all parts of the LJP.
- Best overall agreement for Herwig 7.1.3 w/ ang. ord. showers.
- Disagreements are most pronounced for: Herwig in large $z \times \Delta R$ region; Pythia in small z, large ΔR region; Sherpa large z, small ΔR.

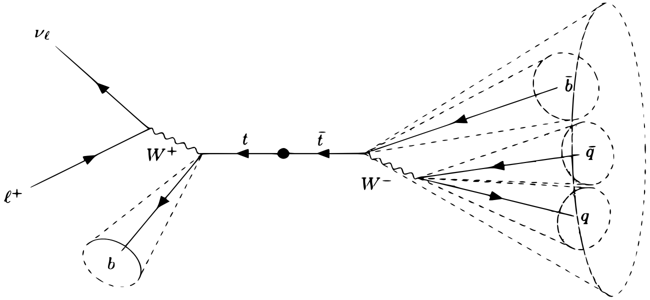


LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- Measuring LJP for the first time in jets initiated by boosted heavy particles, W, top, in semi-leptonic $t\bar{t}$ decays.
- W, top jets of particular interest due to: applications to tagging, top physics modelling, fragmentation of the b-quark

Semi-leptonic $t\bar{t}$ event pre-selection

- 1 trimmed ($R_{trim} = 0.2, f_{trim} < 0.05$) LCTopo $R = 1.0$ (large-R) jet with $p_T > 350$ GeV,
- 1 lepton with $p_T > 27$ GeV,
- $E^T_{miss} > 20$ GeV; $E^T_{miss} + M^T_W > 60$ GeV,
- at least 1 EMPFLow $R = 0.4$ (small-R) jet $p_T > 25$ GeV,
- at least 1 b-tagged (`DL1r:FixedCutBEff_77`) small-R jet,
- $\Delta R(lepton,\ bjet_1) < 1.5$.



LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- We consider the leading large-R jet in each event.
- A more challenging topology. Greater contributions from background, large number of detector systematic uncertainties eg. from tracks, large-R/small-R jets, leptons. Less stats than incl. dijets.
- The LJP is constructed from *ghost-matched* tracks to the large-R jet. More accurate matching than ΔR cone at edges of jet.
- We divide events into W-jet and top jet topologies, by applying cuts on the jet mass. For top jets, an additional b-tagged small-R jet must be contained within the large-R jet.
- No top or W tagging is applied to the large-R jets.

'top jet' selection

- $\Delta R(lepton,\ ljet) > 2.3$,
- $m_{ljet} > 140\,\text{GeV}$,
- $+1$ b-tagged $R = 0.4$ jet, $\Delta R(bjet_2,\ ljet) < 1.0$.

'W jet' selection

- $\Delta R(lepton,\ ljet) > 2.3$,
- $60\,\text{GeV} < m_{ljet} < 100\,\text{GeV}$,

LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- **Data** Full Run 2 dataset, $L_{\text{int}} = 140.1\,\text{fb}^{-1}$. Using fully efficient single-lepton triggers.

- **Signal $t\bar{t}$ MC**: Powheg NLO + Pythia 8.230, with total cross-section normalised to match NNLO predictions.

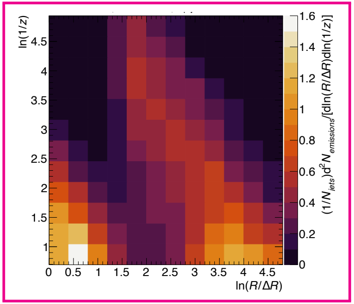
- **Background** contributions are estimated using MC predictions:
  - Single top Powheg+Pythia8 (w/ DR and DS)
  - W+ℓ+jets: Sherpa 2.2.1
  - $t\bar{t} + V$: aMcAtNlo + Pythia8
  - $t\bar{t} + H$: Powheg + Pythia8
  - Z+jets: Sherpa 2.2.1
  - Diboson: Sherpa 2.2.1

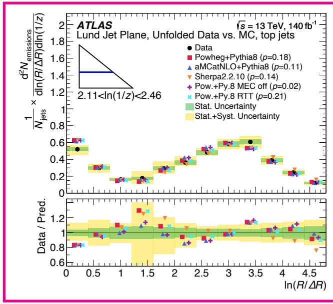
- "Fake" events background due to misreconstructed leptons estimated from data using the Matrix Method [ATLAS-CONF-2014-058].

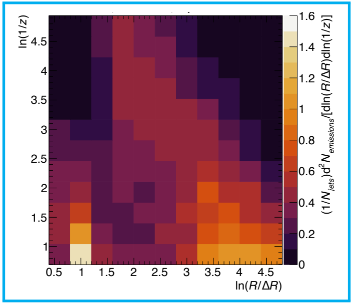
	Top jets		***W* jets**	
Sample	Events	Emissions	Events	Emissions
$t\bar{t}$	33 800 ± 3400	216 000 ± 22 000	28 000 ± 2900	164 000 ± 17 000
Single top	650 ± 170	4200 ± 1100	900 ± 1000	22 000 ± 6000
$t\bar{t} + V$	330 ± 50	2200 ± 300	330 ± 40	1850 ± 250
Fake leptons	230 ± 120	1400 ± 700	900 ± 400	5400 ± 2800
W + jets	110 ± 40	760 ± 290	1500 ± 600	9100 ± 3400
VV	12 ± 6	80 ± 40	170 ± 90	1000 ± 500
Z + jets	8 ± 4	47 ± 24	100 ± 50	800 ± 400
Total pred.	35 100 ± 3400	224 533 ± 22 000	35 000 ± 3100	204 000 ± 18 000
Data	29 328	189 902	28 686	166 533

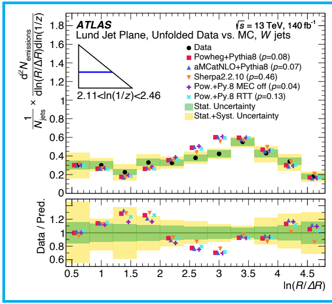
LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- LJPs for Top jets and W jets are presented separately.
- Unfold LJP to the particle level using Iterative Bayesian Unfolding with 4 iterations.
- Structure related to the top/W mass is observed in the lower-left corner of the LJP
- Unfolded distributions of the LJP are compared to a wide range of alternative $t\bar{t}$ MC configurations.
- Results could be useful for tuning $t\bar{t}$ MCs or developing and calibrating (see CMS-DP-2023-046) heavy particle jet taggers. $t\bar{t}$ events could also be investigated in future to measure LJP for b jets.



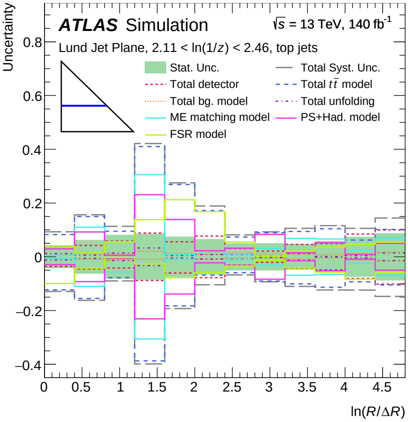


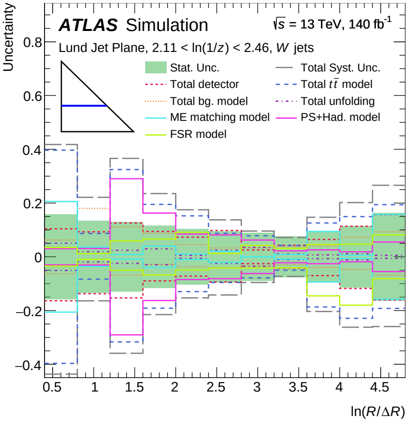




LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- Uncertainties range between 10 and 40%
- dominated by model systs: PS+hadronization, as well as ME matching & FSR in some areas.
- Substantial detector contributions from tracking at small ΔR.
- Background modelling uncertainties 5% in W jet selection, 1% in top jet selection



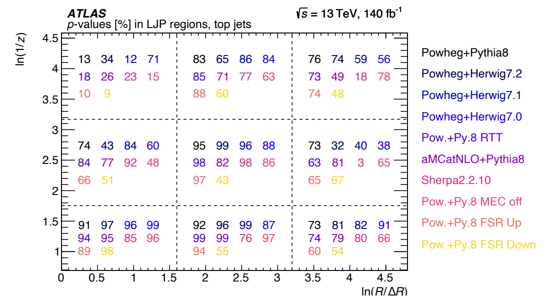


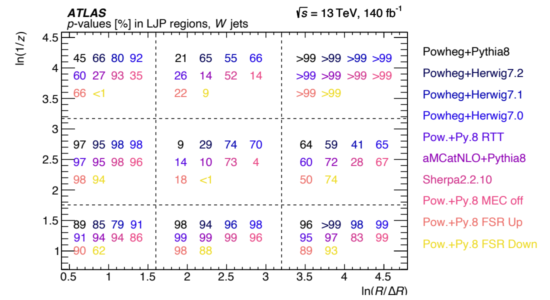
LJP for top and W jets in $t\bar{t}$ [EP-2024-169]

- Differences observed for various MC configurations. Observe disagreement globally (top: $p < 50\%$, W: $p < 1\%$) and locally in different regions for different MCs,eg.
  - Sherpa 2.2.10: narrow angle region, top jets
  - Pythia 8 (several versions): centre of plane, W jets

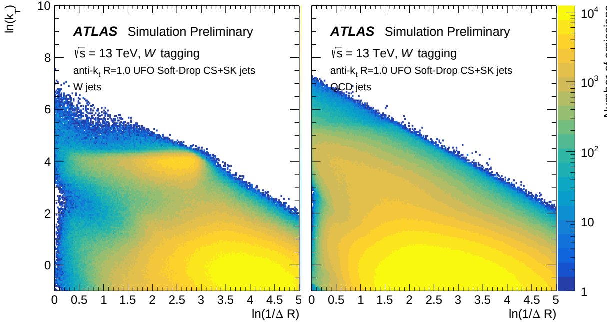
- Disagreement between data and MC are expected for this observable. Dijets measurement and Lund subjet multiplicity (see subsequent slides) observe $> 4\sigma$ differences in some bins.

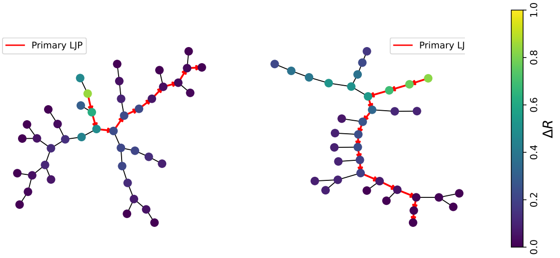
- Powheg+Pythia8, aMC@NLO+Pythia8, Powheg+Herwig differ more in centre of plane, Sherpa at narrow angles.

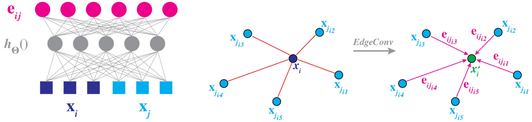




- The distinctive features of the LJP make it an interesting observable for jet tagging.
- Wide-angle splittings due to heavy particle decays clearly visible in the LJP. Quark and gluon jets can also be distinguished [Dreyer, 2112.09140].
- Can apply different types of neural networks to take advantage of these input shapes eg. conv. nets [Oliveira, 1511.05190], LSTMs [Dreyer, 1807.04758].
- Latest developments: graph neural networks [Dreyer, 2112.09140, Qu, 1902.08570] using the LJP coordinates on the full CA clustering tree as input features
- *LundNet* uses EdgeConv [Wang, 1801.07829] layers to perform convolutions along edges of graphs.

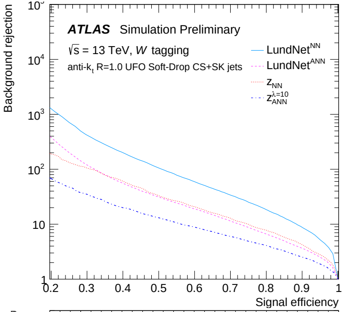


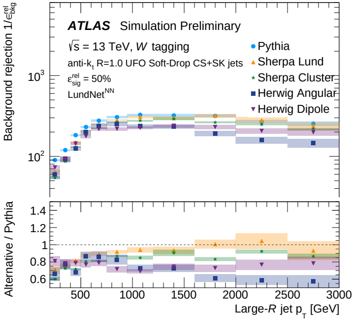




Graph neural network W tagger [PUB-2023-017]

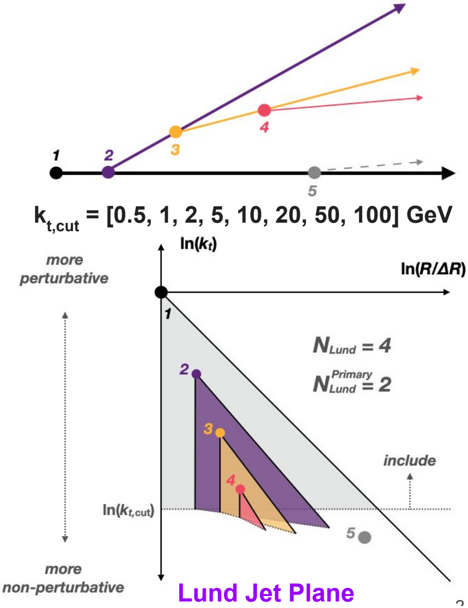
- Reconstruct LJP from *unified flow objects* (UFO): combined particle-flow + track-calo clusters. Combine ID and calo information for optimal jet reconstruction across a wide range of jet p_T.
- Outperforms ATLAS MLP and cuts-based methods $(m + D_2 + N_{trk})$ for high p_T jets.
- Comparable, or better, performance to other GNN approaches, eg. point-cloud like ParticleNet [Qu, 1902.08570].
- Tagger performance can be de-correlated from jet mass. Useful to avoid shaping of backgrounds.
- Challenges and possible improvements
  - Model dependence – soft bracnhings poorly described in MC.
  - Static graph structure. Could gain performance by recomputing between layers.





Lund subjet multiplicity [EP-2024-029]

- An LJP-derived multiplicity observable that captures the full branching nature of QCD. Hence, it is sensitive to higher-order effects that do not enter the primary LJP. Observable receives substantial soft contributions that we don't expect to be well-modeled.
- Observable is calculated by counting the number of subjets above a specified relative transverse momentum (k_t) in a jet's angular-ordered clustering history
- Average multiplicity is predicted by analytic resumations [Medves, 2212.05076] to NLO + NNDL accuracy [DL := 'double logarithms' $\propto (\alpha_{\rm S} \ln(k_t^{cut}/\sqrt{s})^2)^n$].
- Reconstructed using *ID tracks* ($p_{\rm T} > 500\,{\rm MeV}$) associated to $R = 0.4$ anti-k_t *Particle-flow jets*.
- Measured in $140.1{\rm fb}^{-1}$ of $13\,{\rm TeV}$ data in dijet events.
  - $p_{\rm T}^{j1} > 1.5 \times p_{\rm T}^{j2}$,
  - $p_{\rm T}^{j} > 120\,{\rm GeV}$
  - $|y_j| < 2.1$,
- Unfolded using IBU with 4 iterations.

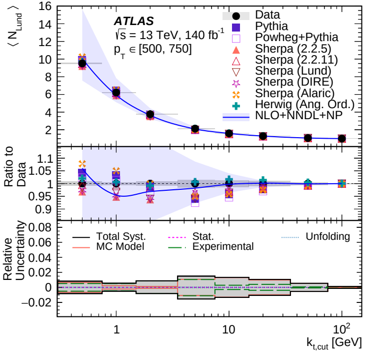


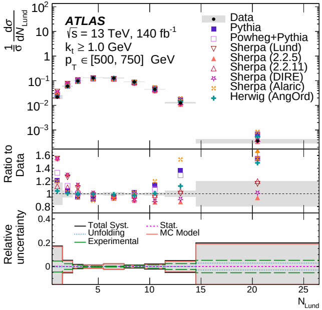
Lund subjet multiplicity [EP-2024-029]

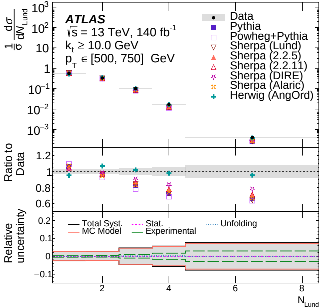
- Two types of Lund multiplicity measured in dijet events ($k_T > 1.0$,$k_T > 10.0$) for different p_T, η.
- Compared to latest analytical predictions, inclding new ALARIC parton shower [Höche, 2208.06057] (succeeds DIRE in SHERPA).

- HERWIG generally models the data best especially in perturbative regions, SHERPA variations do very well in non-perturbative regions. ALARIC overestimates $\langle N_{\mathrm{Lund}} \rangle$ at $k_T \lesssim 1\,\mathrm{GeV}$.
- Calculation agrees with the data within theory uncertainty
  - Non-perturbative effects dominate for $k_t < 5$ GeV
- Good experimental precision (5% to 30% uncertainty) and observed disagreement show measurement could be used to improve PS MCs.

Average multiplicity $\langle N_{\mathrm{Lund}} \rangle$







Summary

- The Lund jet plane is a powerful tool for both precision measurement and conventional JSS applications.
- Since its first measurement on ATLAS, new insights have been gained into hadronic jet formation, results inform MC modelling, improve jet tagging techniques, provide tests of SM parameters and access to new kinematic regions.
- LJP measurement in W and top jets applies observable for the first time to large-R heavy particle jets. Particularly relevant for tagging applications, including GNNs.
- The measurement of the *Lund subjet multiplicity* provides another precision test of QCD predictions and sensitivity to non-perturbative effects.

Questions

BACKUP

Theory: Lund planes

- Lund planes, or Lund diagrams first used by Andersson et al. to represent the available phase space of gluon emissions in a parton shower.
- The phase space is spanned by the range of available momenta (k_T or momentum fraction z) and emission angles (θ,y).
- When plotted on a log-log plot, Lund plane takes the shape of a triangle bounded by kinematic limits, eg. $k_T < \frac{1}{2}p_T^{jet}$ and continuum of very soft emissions.

[Andersson et al. Z. Phys. C 43, 625–632 (1989)]

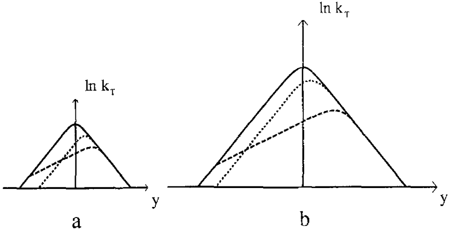


Fig. 5 a, b. The kinematically allowed region in the $y - \ln(k_T)$ plane. The dashed line is the upper limit for gluon radiation in our model (10). The dotted line is a line of equal suppression in the ordinary parton model

Theory: Lund Jet Planes

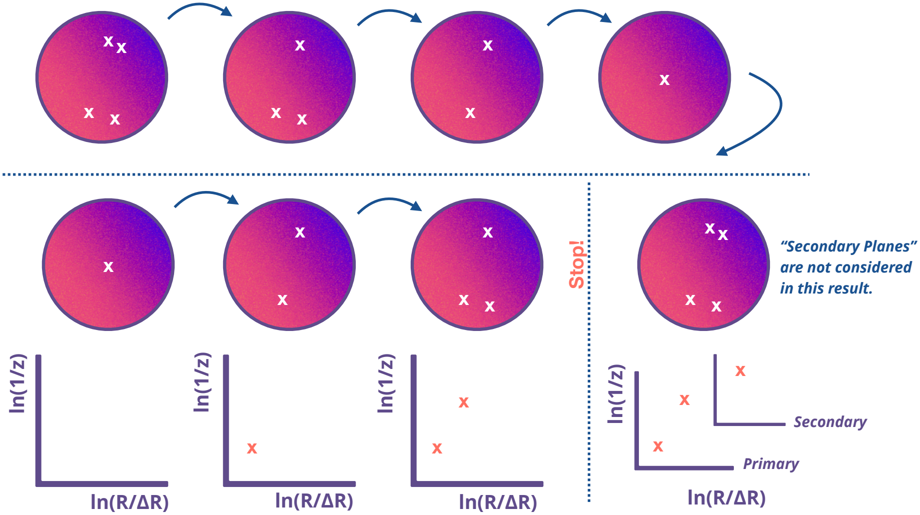
- Showering partons, splitting energy through subsequent gluon emissions, obey angular ordering: each emission is produced with a smaller angle than the previous one.
- The result is a spray of collimated QCD radiation: a jet!
- Jets at the LHC are usually reconstructed using sequential jet algorithms of the k_T-family.
- Particles in the detector are recombined pair-wise into proto-jets. Those are combined recursively into new proto-jets until a jet with a specified radius parameter R has been constructed.
- One variety, Cambridge-Aachen is angular ordered – like the parton showers in the Lund model.
- Idea: treat the clustering steps of the CA-algorithm like gluon emissions in a parton shower. Construct Lund planes for the 'emissions' $\rightarrow$ *Lund jet plane* (LJP).

Reminder: k_T-type jet algorithms

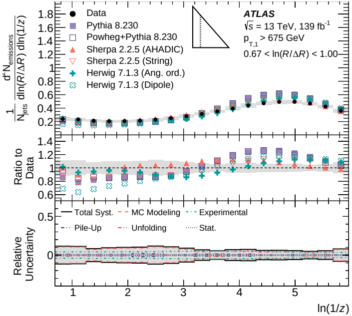
- For all final-state particles i, j:

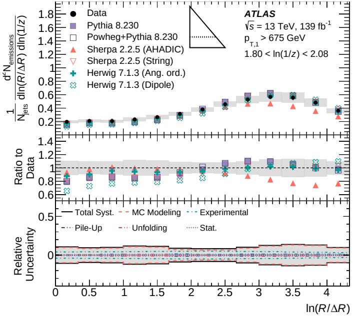
$$d_{ij} = min\left(p_{ti}^{2p}, p_{tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}; \quad d_{iB} = p_{ti}^{2p}$$

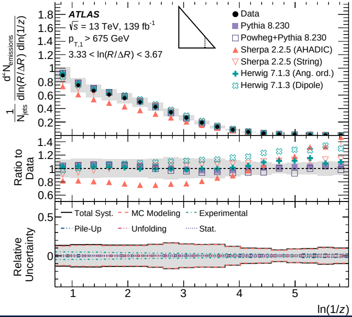
- $p \in \mathbb{Z}$ determines algorithm type:
  - $p = 0$: CA, $p = 1$: k_t, $p = 1$: anti-k_t
- Find minimum of all d_{ij}, d_{iB}.
  - If d_{ij} minimum: combine i,j, repeat
  - If d_{iB} minimum: terminate

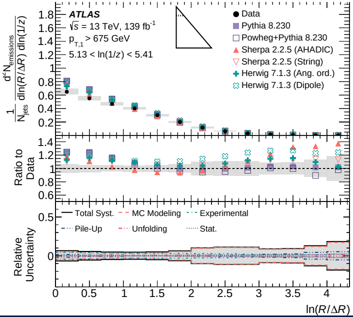

Stop!
"Secondary Planes" are not considered in this result.
ln(1/z)
ln(R/ΔR)
Secondary
Primary

LJP in dijets [EP-2020-030]: LJP slices

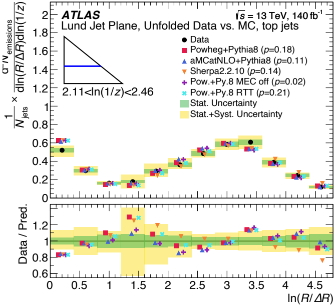


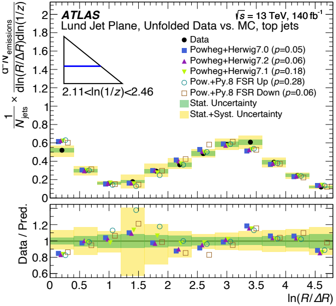


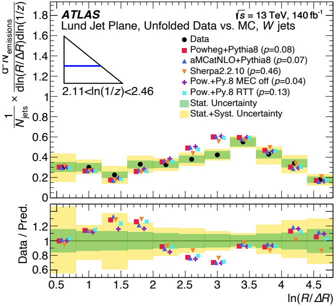


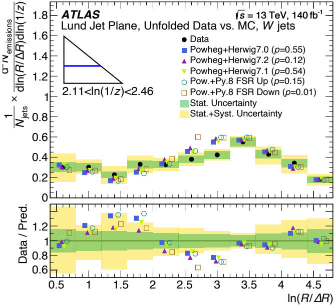


LJP in $t\bar{t}$ [EP-2024-169]: $\ln(R/\Delta R)$ slices

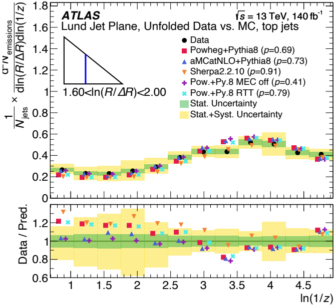


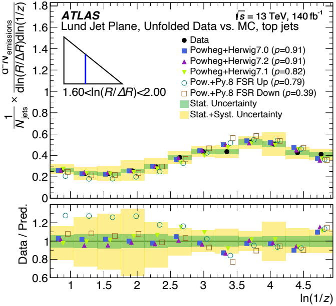


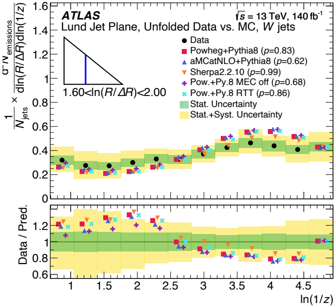


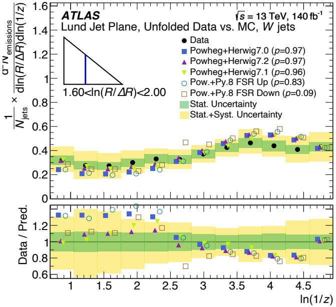


LJP in $t\bar{t}$ [EP-2024-169]: $\ln(1/z)$ slices









LJP in $t\bar{t}$ [EP-2024-169]: $\ln(1/z)$ uncertainty slices