Jet substructure measurements in CMS

Christophe Royon
University of Kansas, Lawrence, USA
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Contents

- Generalized angular studies in dijet and Z+jet (arXiv:2109.03340, JHEP 01 (2022) 188)
- **NEW:** Measurement of primary Lund jet plane density at 13 TeV (CMS-PAS-SMP-22-007; theory: F. Dreyer, G. Salam, G. Soyez, arXiv:1807.04758)
- **NEW:** Measurement of energy correlators (CMS-PAS-SMP-22-015)

What is jet substructure?

- Jet constituents are mapped onto physically meaningful observables
- We can distinguish between fragmentation functions (we identify the leading hadrons), the classic jet shapes (such as thrust), and groomed variables (where we want to remove the effects of soft gluon emissions for instance during hadronization)

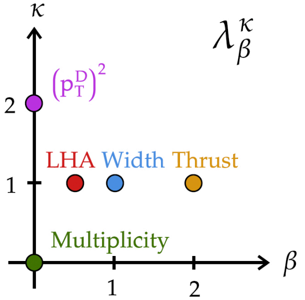
New variables: Generalized angular properties in Z+jet and dijets

- New observables

$$\lambda_\beta^\kappa = \Sigma_i z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$
$$z_i = \frac{p_{Ti}}{\Sigma_j P_{Tj}}$$

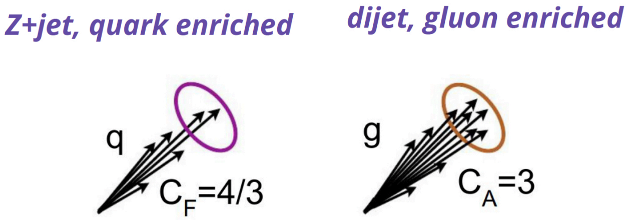
z_i is jet fractional transverse momentum carried by i

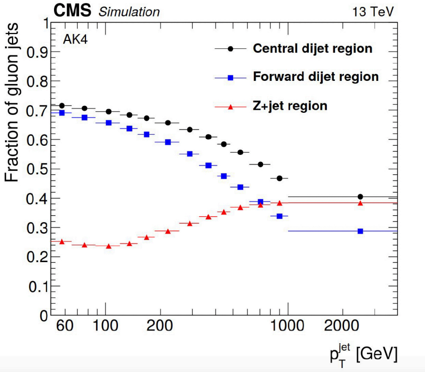
- $\Delta R_i = \sqrt{(\Delta y_i)^2 + (\Delta\phi_i)^2}$ between the jet axis and the jet constituent
- β and κ parameters controlling momentum and angular distributions



- We will study: Les Houches Angularity $\lambda^1_{0.5}$, width λ^1_1, thrust λ^1_2, multiplicity λ^0_0, $(p_T^D)^2$ λ^2_0

Distinguishing between gluon and quark components: Dijets and $Z + jet$

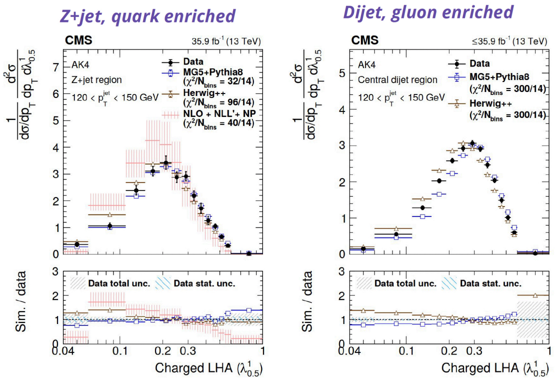




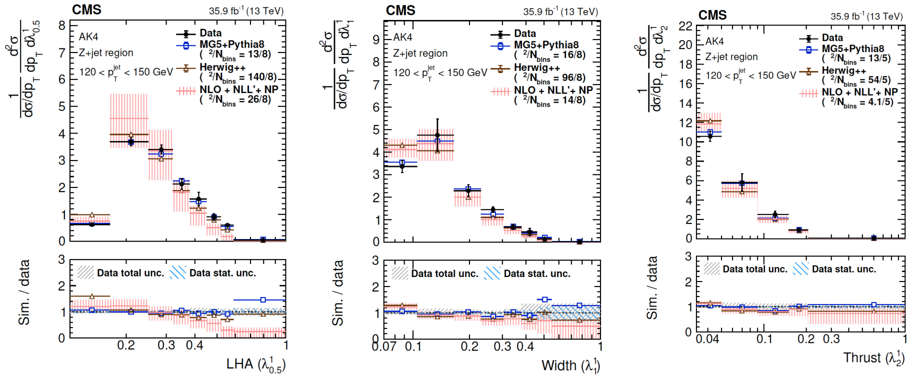
- Quark enhanced sample: Z+jet
- Gluon enhanced sample: dijets, especially for central dijets

- Allows to distinguish between quark and gluon jets

Example of Les Houches angularity distribiution

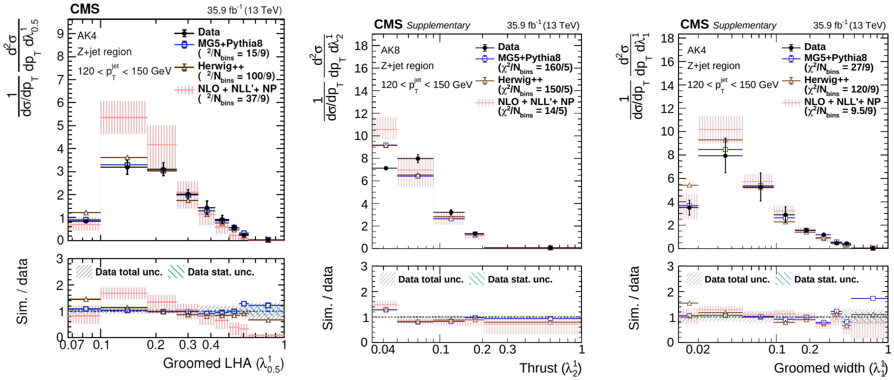


- Example of Les Houches angularity observable: $\kappa = 1$, $\lambda = 0.5$
- Data unfolded to particle level
- MG5+PYTHIA and HERWIG++ describe quark-enriched data well, and envelop the gluon-enriched data
- For Z+jet: resummation at NLL matched to fixed-order NLO matrix elements, with NP corrections from Sherpa, not in perfect agreement



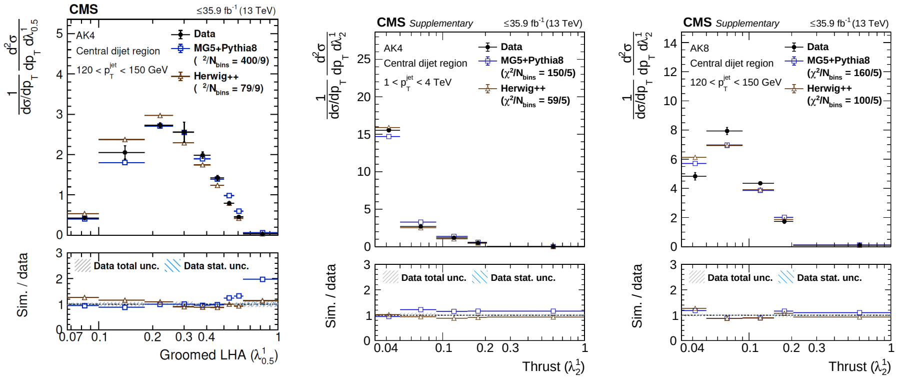
- We increase the β value for fixed κ: increase the weight of angular effects
- The more weight is given to angular scale, the better agreement of theory with data

Groomed generalized angularities in $Z + jet$ events



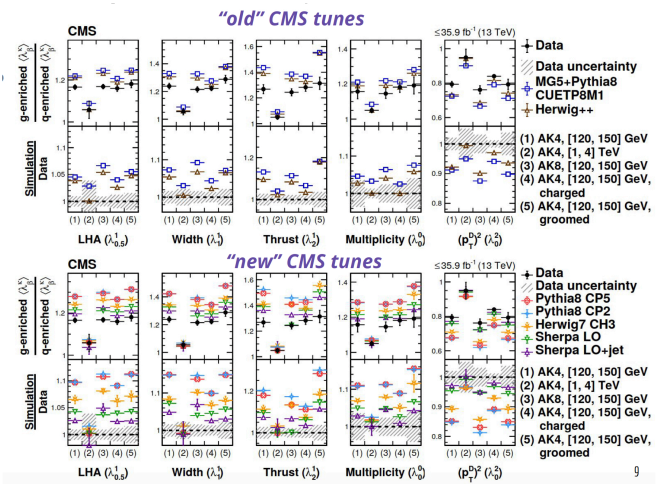
- We increase the β value for fixed κ: increase the weight of angular effects
- Soft-drop grooming to remove soft, wide-angle radiation
- Tension at small β =0.5 persists, related to hard collinear splittings description?

Groomed generalized angularities in dijet events



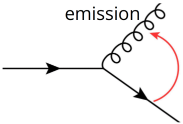
- We increase the β value for fixed κ: increase the weight of angular effects
- Reasonable agreement between theory with data

Dijet/Z+jet ratio

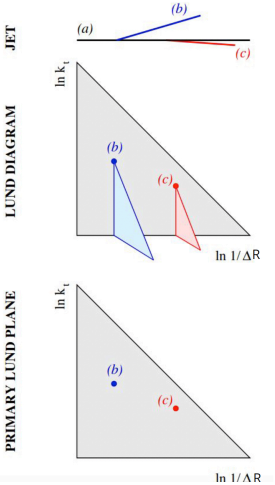


- Experimental uncertainties partially cancel in dijet/Z+jet ratio
- LO+PS overestimate the g-enriched/q-enriched ratio
- g-enriched / q-enriched ratio is better modelled with "old" PYTHIA8 and HERWIG7 CMS tunes
- Angular measurements are fundamental to tune further MC and to understand better gluon radiation from QCD

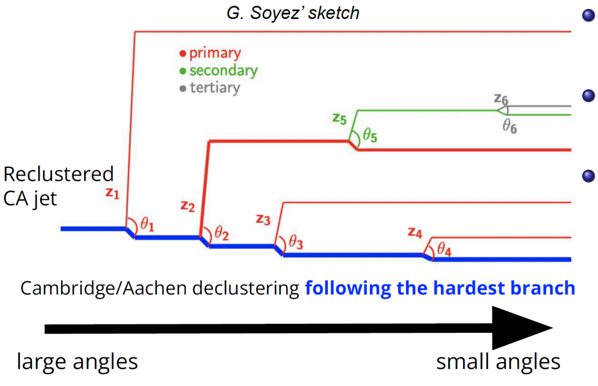
Lund jet plane analysis: Visualizing the phase-space of QCD splittings



- Lund planes are a 2D representation of the phase-space of 1→2 splittings
  - Splitting angle $\Delta R = \sqrt{(y_{soft} - y_{hard})^2 + (\phi_{soft} - \phi_{hard})^2}$
  - Relative transverse momentum of emission k_T
- Logs of k_T and $1/\Delta R$ used for Lund plane axes
- Lund planes used for parton shower calculations and jet substructure techniques developments
- Experimentally: Possibility to construct an experimental proxy for Lund diagrams using iterative jet declustering (Lund jet plane)



Constructing the Lund jet plane



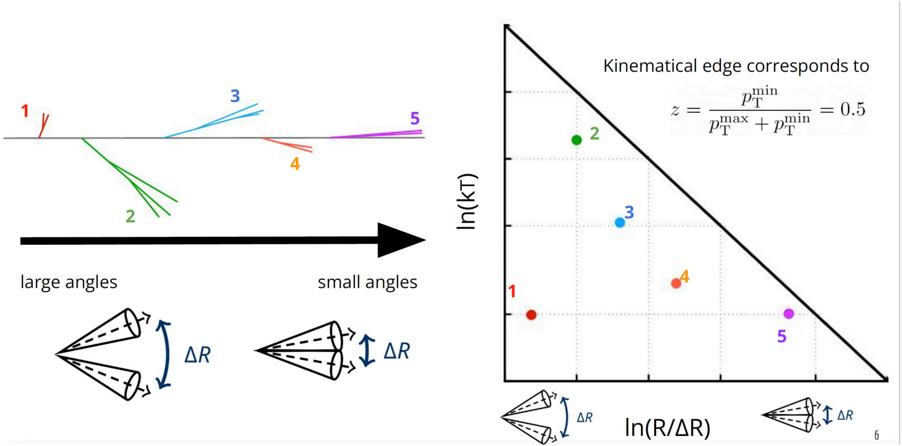
- Constituents of anti-k_T jets are reclustered with the Cambridge/Aachen (CA) algorithm

- CA sequentially combines the pairs of protojets with strict angular ordering
- The CA jet is then declustered iteratively (large to small angles)
- Transverse momentum k_T and splitting angle ΔR of soft subjet (emission) relative to hard subjet (core) are measured at each step

$$\Delta R = \sqrt{(y_{soft} - y_{hard})^2 + (\phi_{soft} - \phi_{hard})^2}$$
$$k_T = p_T \Delta R$$

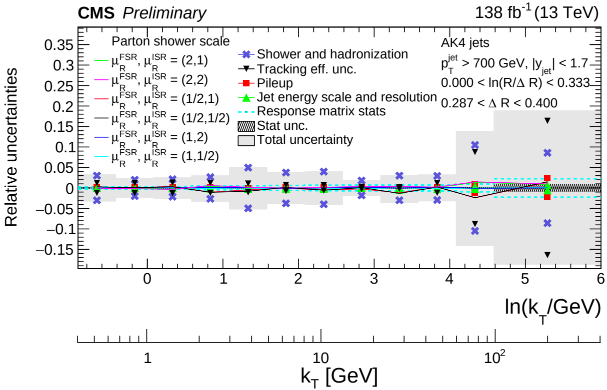
where p_T is for the subjet

- Iterate until the core is a single particle

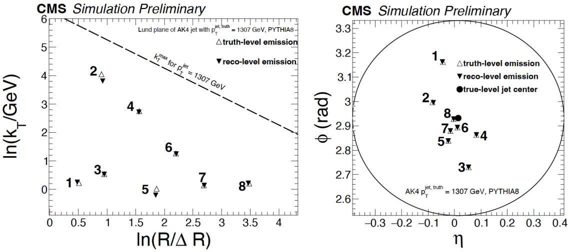


- A given jet is represented as a number of points in the Lund plane

Systematic uncertainties



- Leading uncertainty: Shower and hadronization models (2-7% in the bulk, 10% at kinematical edge)
- Tracking reconstruction uncertainties: 1-2% in bulk, 10-20% at kinematical edge
- Subleading uncertainties <1%
  - Parton shower scale
  - Response matric statistics
  - Jet energy scale and resolution
  - Pile up modeling

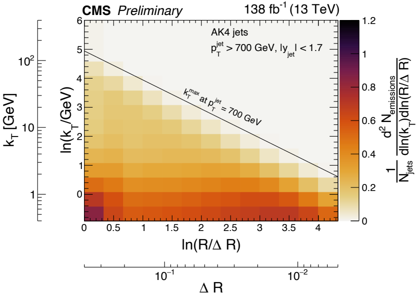


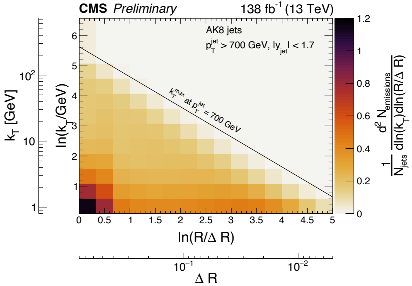
- Corrections to particle level (down to $p_T \sim 0$ of charged particles for jet constituents)
- Multidimensional unfolding of Lund jet plane (p_T^{jet}, k_T, ΔR)

- PYTHIA8 CP5 chosen as nominal and MC-based corrections derived from geometrically matched truth-level and det-level splittings. Uniquely matched pairs are considered. Matches with smaller ΔR take precedence
- Matching window:

$$(\Delta R)^2 = (\eta_{true} - \eta_{det})^2 + (\phi_{true} - \phi_{det})^2$$

Unfolded primary Lund jet plane density

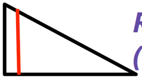




- Measurements of the primary Lund jet plane performed for $R = 0.4$ and for the first time $R = 0.8$ corrected to particle level by CMS
- Plateauing of emissions at high k_T, growth of emissions at low k_T as expected from the dependence of emission density with α_S

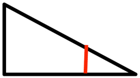
Lund jet plane density: log k_T dependence

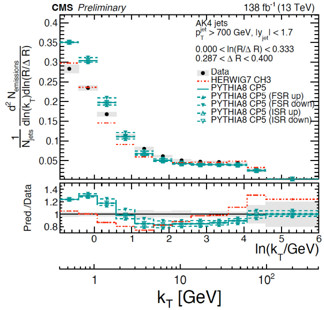
Large angle emissions

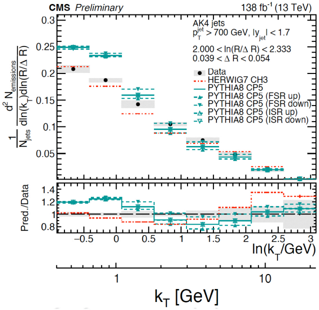


R=0.4 results (R = 0.8 in backup)

Small angle (collinear limit)

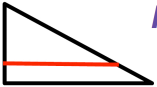






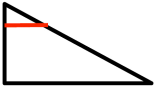
- Primary Lund jet plane density projected onto the log k_T axis
- Large splitting angles left and small splitting angles right
- PYTHIA8 CP5 overestimates the number of emissions by 15-20%, Data favors FSR down in parton shower region
- HERWIG 7 CH3 in better agreement with data

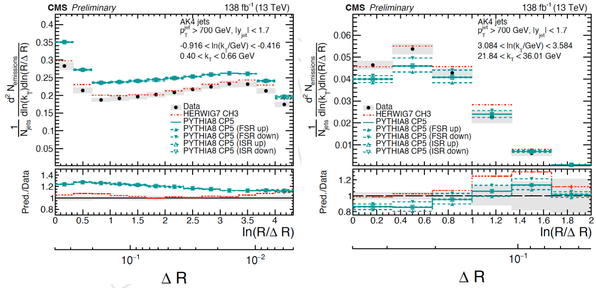
R=0.4 results (R = 0.8 in backup)



Low-k_T
(hadronization + MPI)

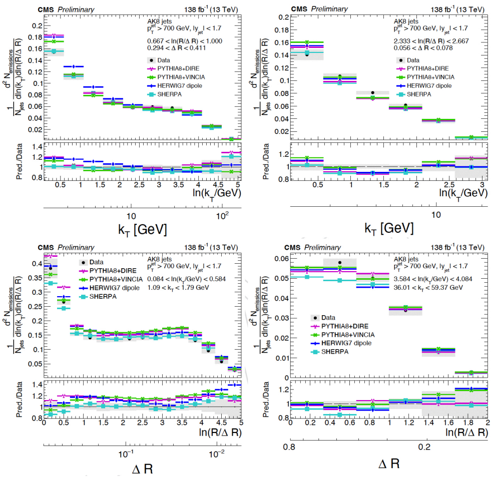
High-k_T
(perturbative region)





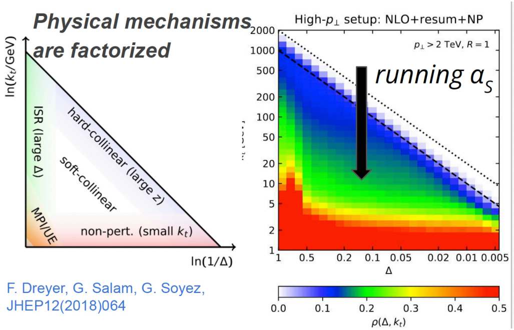
- Primary Lund jet plane projected onto the log $R/\Delta R$ axis
- Soft splittings (left) and hard splittings (rigfht)
- Low (resp. large) k_T splitting populates the whole (resp. wide) angle radiation region
- PYTHIA8 CP5 overshoots data by 25-35% at low k_T, better description for hard emissions

Lund jet plane density: model dependence



- PYTHIA8 with VINCIA or DIRE models in agreement with data within a few % except at high k_T
- SHERPA and HERWIG7 with dipole showers describe the data within 5-10% including at high k_T
- Comparison between data and HERWIG7 (different choices of recoil scheme of angular ordered shower); choose the recoil scheme in angular ordered parton showers in a region where quark and gluon fragmentations play an important role
- Goal to achieve NLL accuracy in next generation of parton showers

Lund jet plane density: sensitivity to α_S



F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

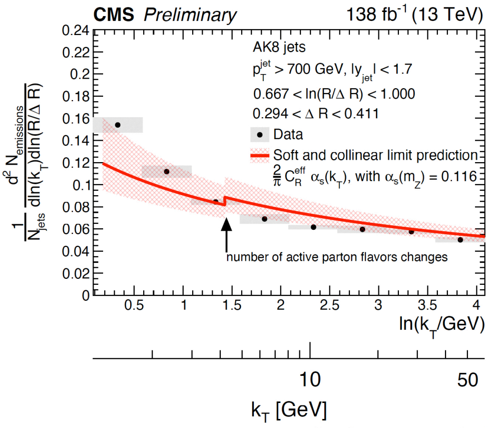
- Measurement of the jet-averaged density of emissions

$$A = \frac{1}{N_{jets}} \frac{d^2 N_{emissions}}{dlogk_T dlog(R/\Delta R)}$$

- In the soft and collinear limit of pQCD, it scales with α_S

$$A \sim \frac{2}{\pi} C_R \alpha_S(k_T)$$

- Running of $\alpha_S(k_T)$ sculpts the Lund plane density. (C_R: color factor, $C_A = 3$, $C_F = 4/3$)
- Measurement can be used to improve MC generators and test pQCD calculations

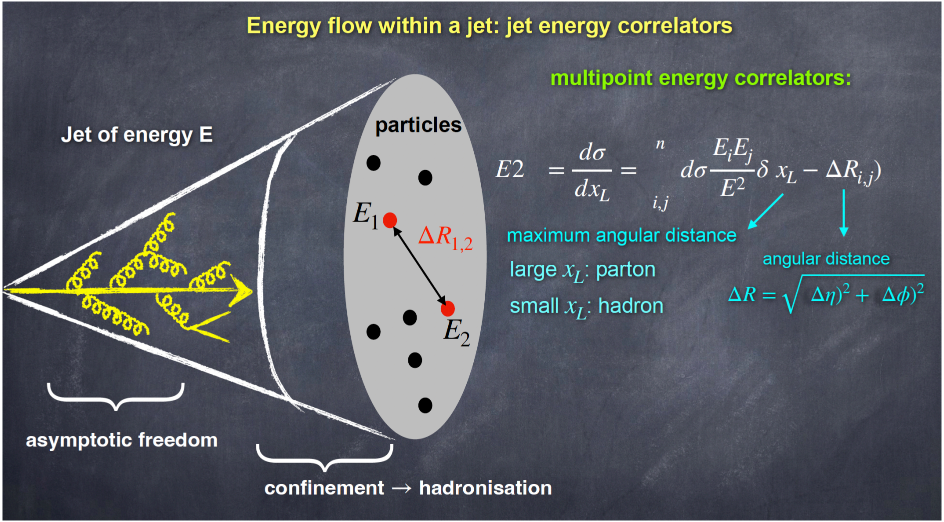


- Soft and collinear limit prediction

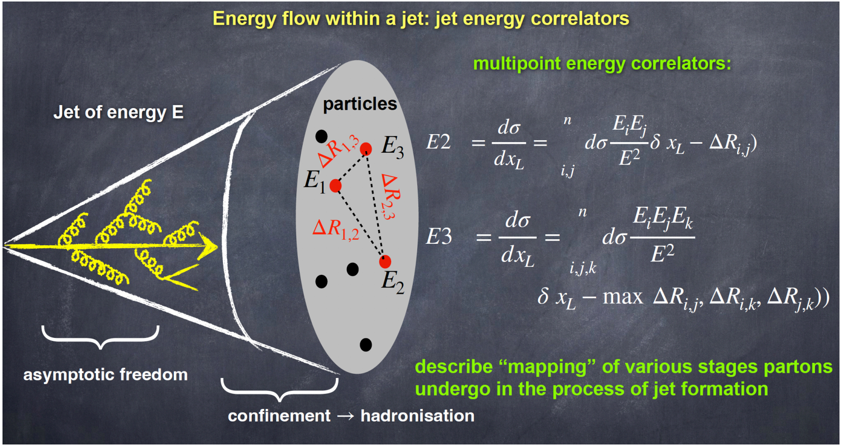
$$\frac{1}{N_{jets}} \frac{d^2 N_{emissions}}{d \log k_T d \log(R/\Delta R)} \sim \frac{2}{\pi} C_R \alpha_S(k_T)$$

- Compute soft and collinear limit prediction predictions with simplified assumptions ($\alpha_S(M_Z) = 0.116$, 1-loop β function)
- Qualitative illustration of effect of running coupling in the jet substructure

Probing partonic time evolution: correlators

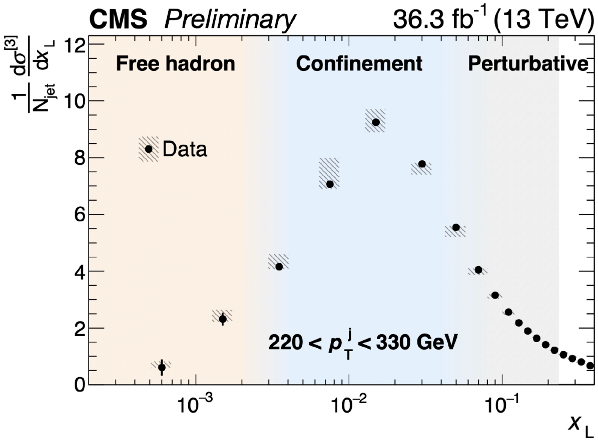


Probing partonic time evolution: correlators



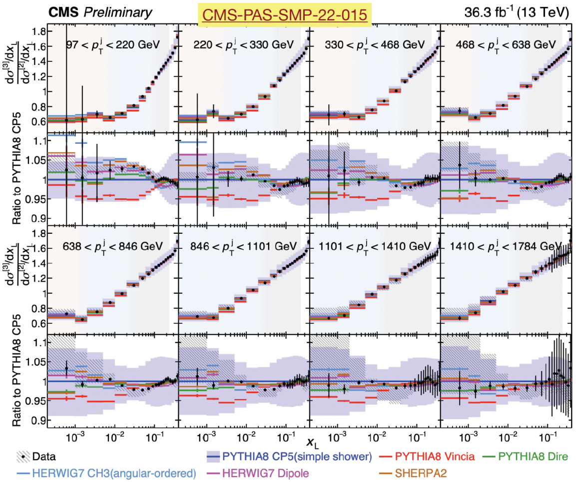
Theory: Chen, Moult, Zhang, and Zhu, arXiv:2004.11381; Lee, Meçaj, and Moult, arXiv:2205.03414, Chen, Gao, Li, Xu, Zhang, and Zhu, arXiv:2307.07510

Illustration of partonic time evolution



- Data: 2016, dijets with anti-k_T with $R = 0.4$, integrated luminosity : 36.3 fb^{-1}
- Phase space: $|y| < 2.1$, $97 < p_T^{jet} < 1784$ GeV (8 bins), $p_T^{particle} > 1$ GeV
- Detector-level to particle level: Bayesian unfolding in 3D (x_L, p_T^{jet}, weight)
- Different regions in x_L
  - Low x_L (largest ΔR between the 2 or 3 particles): non-interacting hadrons, power-law scaling
  - medium x_L: region where quarks and gluons are confined
  - large x_L: quantum interactions of quarks and gluons

Energy correlator ratio: unfolded E3C/E2C vs MC simulation



- No MC completely agrees with data, but almost fine within systematics
- Largest differences between data and MC in non-perturbative region
- Systematic uncertainties: varying renormalization and factorization scales, PDF uncertainties, parton shower models, UE models
- Extract the slope of E3C/E2C vs p_T^{jet}
- CMS-PAS-SMP-22-015

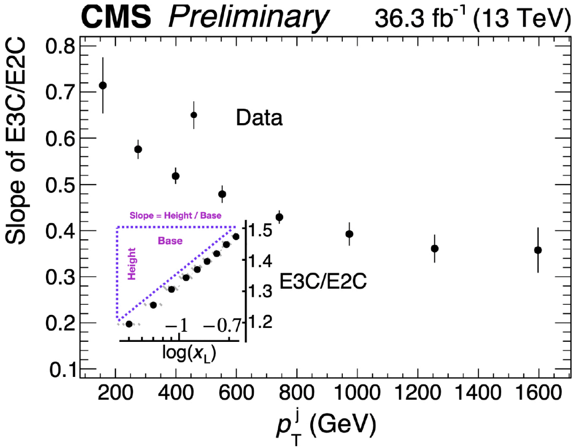
Extraction of α_S

- Extraction of α_S via the E3C to E2C ratio
- E3C/E2C ratio

$$\frac{E3C}{E2C} \sim \alpha_S(Q) \ln x_L + O(\alpha_S^2)$$

where $Q \sim x_L p_T^{jet}$ (energy scale at which the transition between free hadrons and perturbative region occurs)

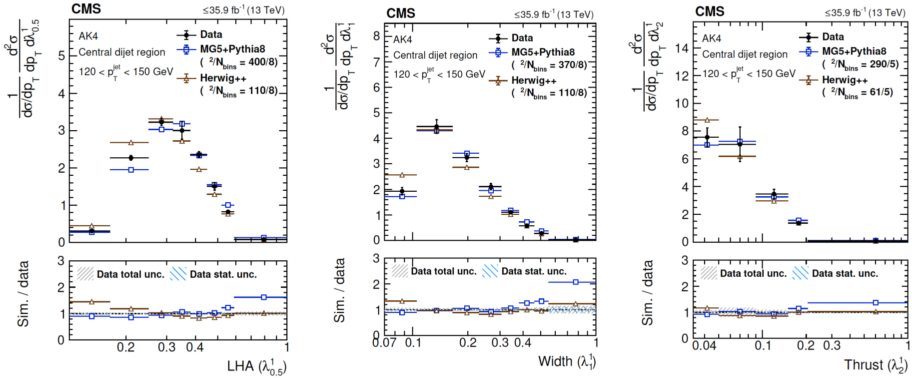
- Slope of ratio proportional to α_S



Conclusion

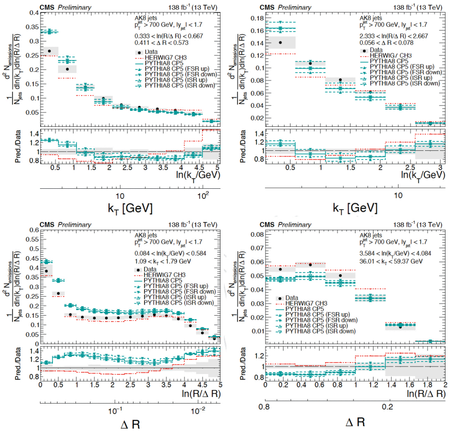
- Measurements of jet substructure sensitive to basic building blocks of QCD
- Valuable input for a better understanding of quark-jet and gluon-jet substructure from Z+jet and dijet events
- Visualize the phase space of QCD splittings using the primary Lund jet plane
- Improve our understanding of QCD and the description of data by MC, goal of achieving NLL accuracy in next generation of parton showers
- Time evolution of partons illustrated in substructure measurements

Ungroomed generalized angularities in dijet events



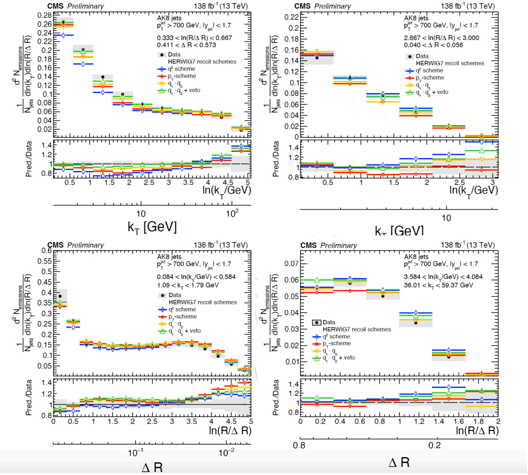
- We increase the β value for fixed κ: increase the weight of angular effects
- Reasonable agreement between theory with data

Lund jet plane density for AK8 jets



- $\log k_T$ and $\log R/\Delta R$ dependence for AK8 jets

Lund jet plane density: recoil scheme dependence



- Comparison between data and HERWIG7 predictions with different choices of the recoil scheme of its angular ordered shower
- q^2 scheme shows largest discrepancy with data, while p_T scheme is better
- $q_1.q_2$ leads to a better description, and even better $q_1.q_2 + veto$ scheme, same as at LEP
- Lund jet plane data can help choosing the recoil scheme in angular ordered parton showers in a region where quark and gluon fragmentations play an important role
- Goal to achieve NLL accuracy in next generation of parton showers

Energy correlator ratio vs NNLL

- Unfolded E3C/E2C vs NNLL
- $\alpha_S(M_Z) = 0.1229 + 0.0040 - 0.0050$