Charged hadron multiplicities inside of jet:
Accessing Hadron Entropy?

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Entropy and Quantum Entanglement

Based on PhysRevD.95.114008:

- **Von Neumann Entropy in DIS:** Interpreted as the entropy of entanglement between the spatial region probed by Deep Inelastic Scattering and the rest of the proton.
- **Entanglement Entropy and Parton Multiplicity:** Assuming the hadron multiplicity is proportional to the multiplicity of color-singlet dipoles: relation between the parton structure function and the entropy of produced hadrons.

$$S_{\text{partons}} = \ln\left(xg\left(x, Q^2\right)\right) \equiv S_{\text{hadrons}}$$

Can we apply the same idea with the FF?

$$S_{\text{hadrons}} \overset{?}{\equiv} \ln\left(zD\left(z, \mu^2\right)\right)$$

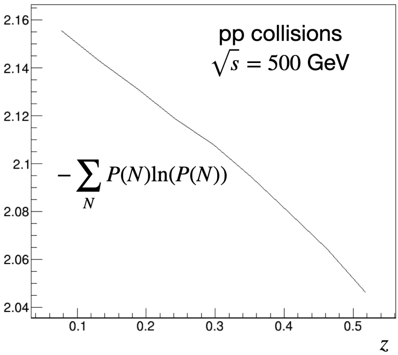
PYTHIA information

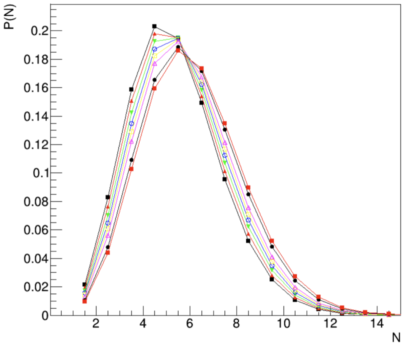
- pp collisions
- Hard QCD processes:
  1. gg to gg;
  2. gg to $q\bar{q}$.
- Anti-$k_\perp$ algorithm;
- Jet information:
  1. $R^{\text{Jets}} = 0.4$;
  2. $p_\perp^{\text{Jet}}$: not cut
- Initial-State Radiation (ISR): on/off
- Final-State Radiation (FSR): on/off

Observable:

Multiplicity: Charged-hadron number inside of jet, N.

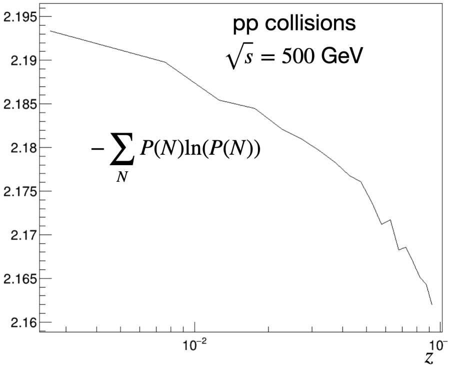
Multiplicity, z, and Entropy

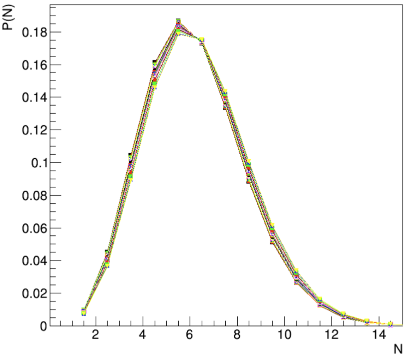




- **Left**: entropy vs z and **Right**: P(N) distributions
- At large $z \gtrsim 10^{-1}$: the entropy increases linearly

Multiplitic*y*, z and Entropy



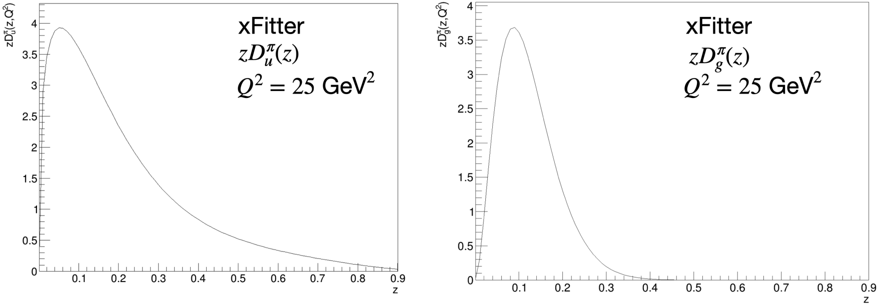


- **Left**: entropy vs z and **Right**: P(N) distributions
- At small $z \lesssim 10^{-2}$: the entropy seems to reach a plateau

Fragmentation Function

xFitter framework

$$D_i^{\pi^{\pm}}(z, Q_0) = \frac{\mathcal{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i, \beta_i+1]+\gamma_i B[2+\alpha_i, \beta_i+\delta_i+1]}$$



- **Left**: $zD_z^u(z)$ and **Right**: $zD_z^g(z)$ at NLO and Q^2= 20 GeV^2

Entropy and Fragmentation Function

Fragmentation Function used

- JAM at NLO for π
- NNPDF at NLO for π
- xFitter at (N)NLO for π

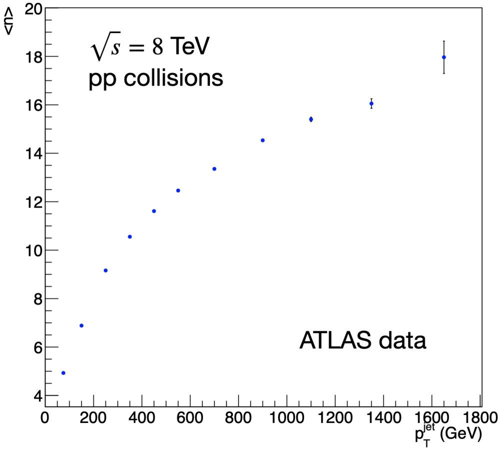
Our model:

$$S_{\langle n_{\mathrm{ch}}\rangle\left(p_{\mathrm{T}}^{\mathrm{jet}}\right)} = S_{q/g} + \ln\left(\int_{\left\langle z\left(p_{\mathrm{T}}^{\mathrm{jet}}\right)\right\rangle}^{1} dz D_{q/g}^{h}\left(z, p_{\mathrm{T}}^{\mathrm{jet}}\right)\right)$$

- Jets initiated by a *quark* or a *gluon*:
  $\rightarrow$ impacts the entropy differently
- z vs p_{T} is calculated using PYTHIA
- $\langle z\rangle$ is the relevant scale for the lower bound of the integral

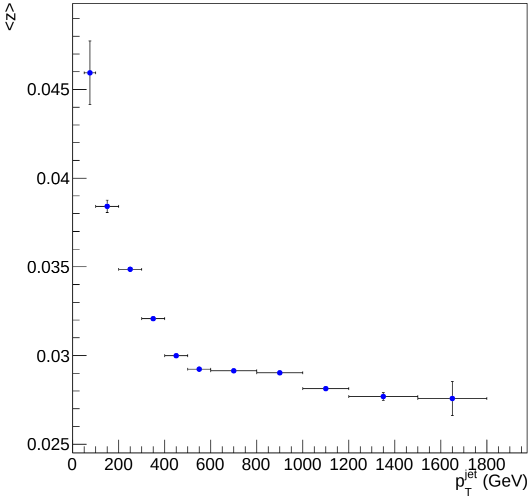
Multiplicity, Entropy and data

[ATLAS data, arvix 1602.00988]



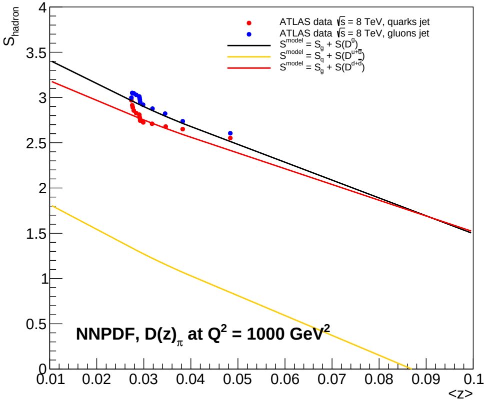
- $< n >$ as a function of $p_\perp^{jets}$: plateau at large $p_\perp^{jets}$
- $p_\perp^{jets}$ to z by using PYHTHIA simulation
- **Data from Jet initiated by quarks or gluons also available**

$< z >$ vs $p_{\perp}^{jets}$



- For each $p_{\perp}^{jets}$, we can determine a $< z >$ value
- Using the same binning, compared data

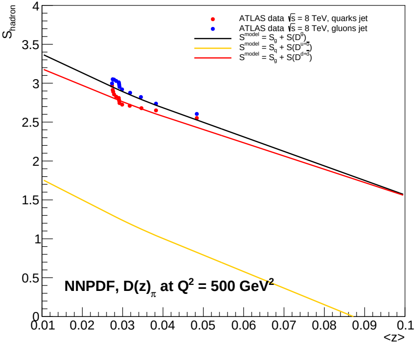
Entropy, Multiplicity and Fragmentation Function

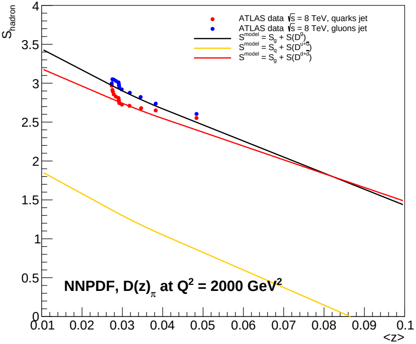


- S calculated using ATLAS data, P($< n >^{data}$, N)
- S calculated using $D(z)$ from NNPDF at $Q^2 = 1000$ GeV^2
- **Good agreement** between S_{data} and S^{model}

Entropy, Multiplicity and Fragmentation Function

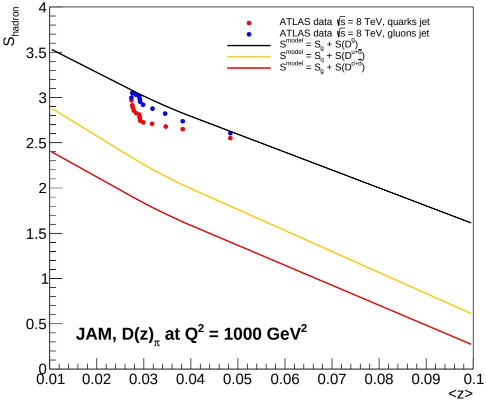
NNPDF Fragmentation Function





- Negligible dependence on Q^2

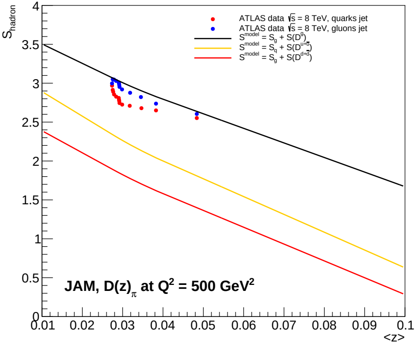
Entropy, Multiplicity and Fragmentation Function

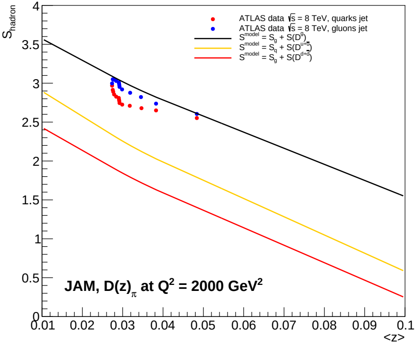


- S calculated using ATLAS data, P($< n >^{data}$, N)
- S calculated using $D(z)$ from JAM at $Q^2 = 1000$ GeV^2
- **Good agreement** between S_{data} and S^{model} *forgluons*

Entropy, Multiplicity and Fragmentation Function

JAM Fragmentation Function





- Negligible dependence on Q^2

Conclusion

→ **Objective:** prove the connection between entropy in jets and in confined matter

- ATLAS data at 8 TeV show lower multiplicities for quark- compared to gluon-initiated jets
- This directly impacts the entropy values
- Using the z vs p_T correlation from PYTHIA:
  → **a link between multiplicity data and quark/gluon fragmentation functions has been demonstrated**
- Very good agreement between data and NNPDF compared to JAM

→ **Next steps:** perform similar analysis for ATLAS data at 13 TeV and estimate uncertainties (quarks/gluons jet fraction, FF, z vs p_T correlation...)