Saturation and forward jets in proton-lead collisions at the LHC

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Based on H. M, H. Paukkunen,
Phys. Rev. D 100 (2019), 114029 `arXiv:1910.13116 [hep-ph]`

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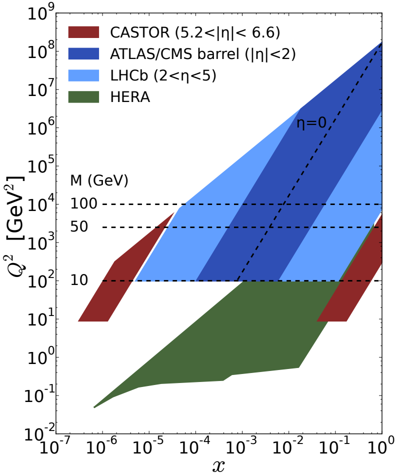
Initial Stages 2021

Motivation: forward calorimeter at CMS



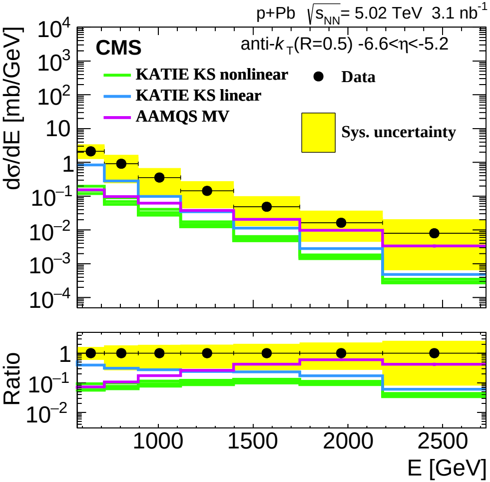
- CMS has a forward calorimeter at $5.2 < \eta < 6.6$
- Inclusive scattering: $x_A \sim p_T e^{-y}/\sqrt{s}$
  $\Rightarrow$ potential to probe very small $x \sim 10^{-6}$
- CASTOR data range $E_{\text{jet}} \sim 500 \ldots 2500\text{GeV}$
- Promising kinematics: $p_T \sim Q_{s,A}$

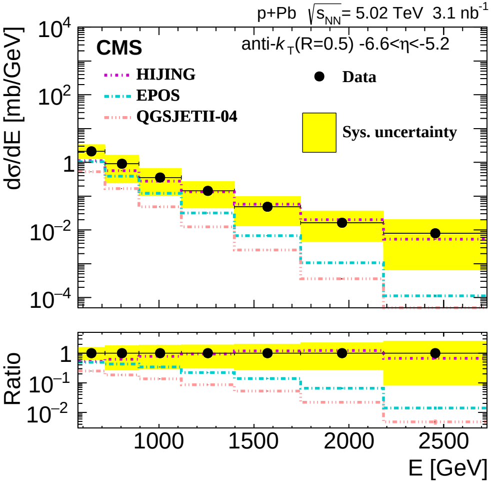
Left: Castor acceptance in the x, Q^2 plane in pp collisions at $\sqrt{s} = 13$ TeV.

$\Delta y \sim 0.5$ rapidity shift is required in p+Pb

CMS, 2011.01185

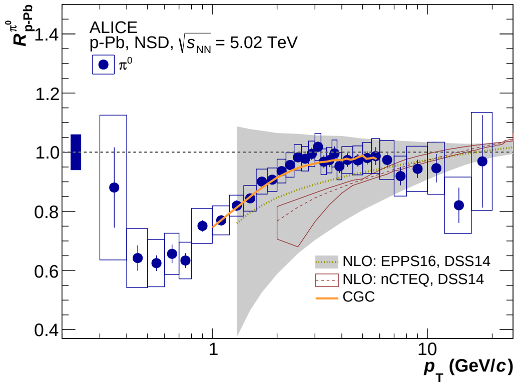
CASTOR p+Pb data (proton towards CASTOR)





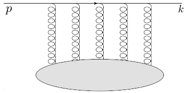
Difficult dataset for many model calculations (HIJING is doing ok). Also Pb+p data available. Can we see saturation effects in this data?

Forward particle production from CGC



Excellent description of e.g. LHC R_{pA} data

Based on T. Lappi, H.M, 1309.6963, ALICE 1801.07051



- LO: $1 \to 1$ process: $q + A \to q + X$
- Quark picks up Wilson line $V(\mathbf{x})$.
- Conjugate amplitude: pick $V^\dagger(\mathbf{y})$
- Cross section $\sim$ FT of the dipole $S = \frac{1}{N_c} \mathrm{Tr}\, V^\dagger(\mathbf{y}) V(\mathbf{x})$ to momentum space $\tilde{S}(\mathbf{p})$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y \mathrm{d}^2\mathbf{k}} \sim \frac{\sigma_0}{2} x f_i(x, \mu^2) \tilde{S}(\mathbf{k}, x).$$

- S: BK evolution in x, IC from HERA
  Generalized to nuclei T. Lappi, H.M, 1309.6963

Jet production

- CASTOR measures total E, and has no y segmentation
- Independently produced jets may be seen as one (*merged*, total E measured)
- MPI processes important! LO: higher order processes neglected
- Probability to have j partonic scattering processes: Poisson

$$p_j(\mathbf{b}) = e^{-T(\mathbf{b})\sigma} \frac{[T(\mathbf{b})\sigma]^j}{j!}$$

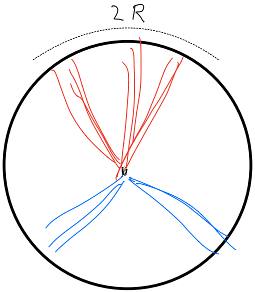
Total jet production cross section

$$\frac{\mathrm{d}\sigma^{pp}_{\mathrm{MPI}}}{\mathrm{d}E} = \int \mathrm{d}^2\mathbf{b} \sum_{j=1}^{\infty} p_j(\mathbf{b}) \prod_{i=1}^{j} \left[\frac{1}{\sigma} \int \mathrm{d}E_i \frac{\mathrm{d}\sigma}{\mathrm{d}E_i} \right] \times \sum_{\text{measured}} \delta(E - E_{\text{measured}}).$$

Note: not all j jets are merged and measured!
Generalized to nuclei:

$$\left[\frac{1}{\sigma} \int \mathrm{d}E_i \frac{\mathrm{d}\sigma}{\mathrm{d}E_i} \right] \to \left[\frac{1}{N_{\text{tot}}(\mathbf{b})} \int \mathrm{d}E_i \frac{\mathrm{d}N(\mathbf{b})}{\mathrm{d}E_i} \right]$$

Jet merging

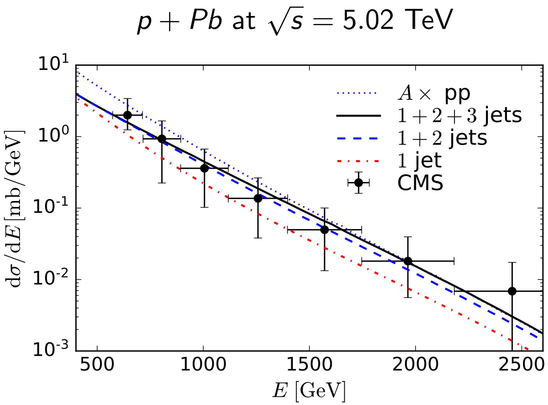


$C_{n=3}(k=2)$

Total 5 jets, $n=3$ of which seen as one (merged), other $k=2$ jets do not contribute to the measured energy

- MPI: individual jets have independent azimuthal angles
- Some of the jets are produced close to each other in azimuthal angle $\rightarrow$ merged
- MPI cross section modified:
  Probability to produce n merged and k unmerged jets $C_n(k)$:
  - Sample n jets in a jet (cone R), probability $2R/(2\pi)^{n-1}$
  - Other k: random azimuthal angle
  - None of the k jets can be closer than R to any merged n jets
- At given n sum over all k
- Detailed modified MPI cross section:
  H.M, H. Paukkunen, 1910.13116 or backup

Comparison to pA data

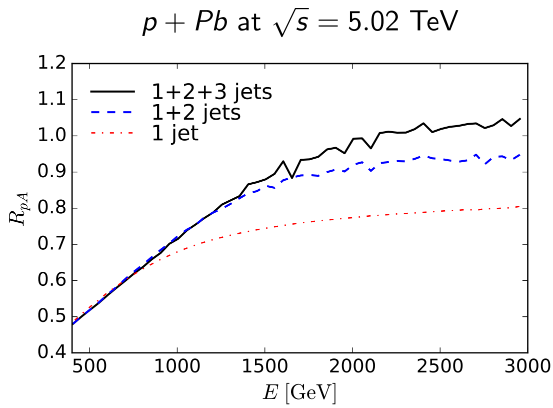


H.P, H.M, 1910.13116. CMS-CASTOR data: 1812.01691.

- Good agreement with CMS-CASTOR data
- For comparison: a scaled *pp* result
  - Significant nuclear effects at small E
- $n = 2$ merged jets gives a numerically important contribution
- $n = 3$ (or more) merged jets is only a small correction
- Results summed over any number k of non-merged jets

Note: jet energy measured in the lab frame

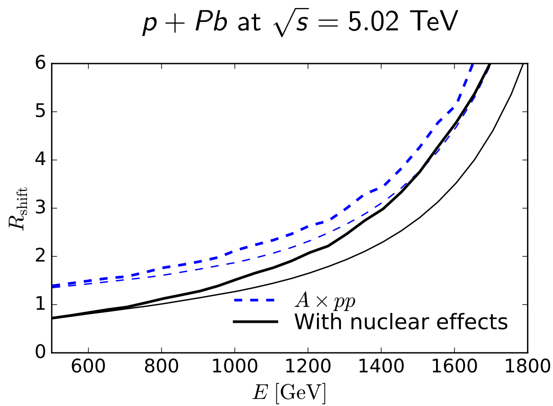
Nuclear suppression factor – magnitude of saturation effects



- Significant nuclear suppression at small E
- Merged jet production effects at high E
  $\Rightarrow$ Robust prediction for large saturation effects at small E
- MPIs are more important in p+Pb
  $\Rightarrow R_{pA} > 1$ at large E
- However, pp reference would be needed in the same kinematics...

H.P, H.M, 1910.13116

Nuclear suppression factor – magnitude of saturation effects



H.M, H. Paukkunen, 1910.13116

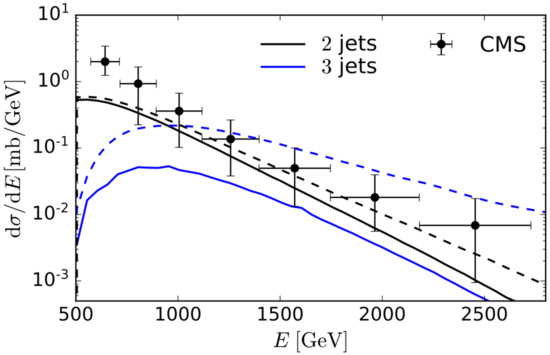
- Proton reference at same $\sqrt{s}$ w/o boost

$$R_{\text{shift}} = \frac{\mathrm{d}\sigma^{p+A \to i+X} / \mathrm{d}E(y_{\text{shift}} = 0.465)}{A \mathrm{d}\sigma^{p+p \to i+X} / \mathrm{d}E(y_{\text{shift}} = 0)}.$$

- Compare solid (nuclear effects) and dashed ($A \times pp$) calculations: Significant saturation effect!
- Thick lines: full calculation ($n = 1, 2, 3$)
  Thin lines: no merged jets, $n = 1$
  Small difference, robust prediction at small E

Large x in the proton

$p + Pb$ at $\sqrt{s} = 5.02$ TeV



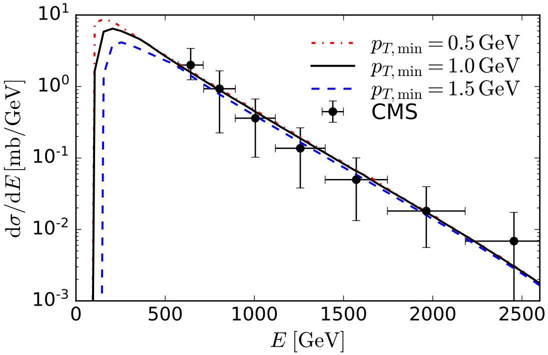
- Forward rapidity: x in the proton ~ 0.1
- Kinematical constraint: $\sum_{i=1}^{n} x_i < 1$
- Implemented using an effective multi parton distribution function (see backup)
- Large effect at $n \gtrsim 3$ merged jets:
  Solid: with $\sum_i x_i < 1$
  Dashed: no kinematical constraint
- Results summed over any number of non-merged jets

H.P, H.M, 1910.13116. CMS-CASTOR data: 1812.01691.

Longitudinal momenta of the k non-merged jets neglected, their spectra is peaked at small p_T

Dependence on minimum p_T cut

$p + Pb$ at $\sqrt{s} = 5.02$ TeV



H.M, H. Paukkunen, 1910.13116. CMS-CASTOR data: 1812.01691

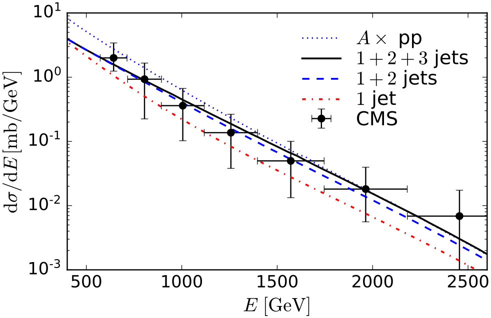
- MPI probability depends on integrated cross section σ: recall Poisson

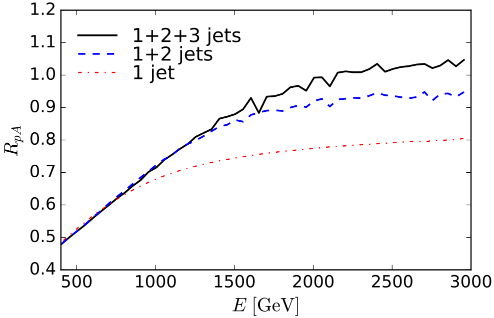
$$p_k(\mathbf{b}) = e^{-T(\mathbf{b})\sigma} \frac{[T(\mathbf{b})\sigma]^k}{k!}$$

- Regularized by lower p_T cut
  $\Rightarrow$ dependence on the regulator $p_{T,\min}$
- Results insensitive on this cut in the interesting kinematics

Conclusions

- Calculate forward jet energy spectra from CGC
- MPI processes are important (total energy is measured)
- Expect large saturation effects ($R_{pA} \sim 0.5$) in the CASTOR kinematics
- CGC calculation including MPI processes compatible with the CMS-CASTOR data
- Currently large data uncertainties, but calculation with non-linear nuclear effects preferred





Backups

Multi parton scattering explicitly

"Merge 1", $n = 1$

$$\frac{d\sigma^{pp,1}_{\text{MPI}}}{dE} = \int d^2\mathbf{b} e^{-\sigma T(\mathbf{b})} T(\mathbf{b}) \times \frac{d\sigma}{dE} \sum_{k=0} \frac{[\sigma T(\mathbf{b})]^k}{k!} C_1(k)$$

Probability $C_n(k)$ n jets merged, k not

2 parton scattering: effective DPDF

$$\frac{1}{2} x_i x_j \left(f_i(x_i) f_j\left(\frac{x_j}{1-x_i}\right) + f_i\left(\frac{x_i}{1-x_j}\right) f_j(x_j) \right)$$

$n > 2$ merged jets similarly

"Merge 2", $n = 2$

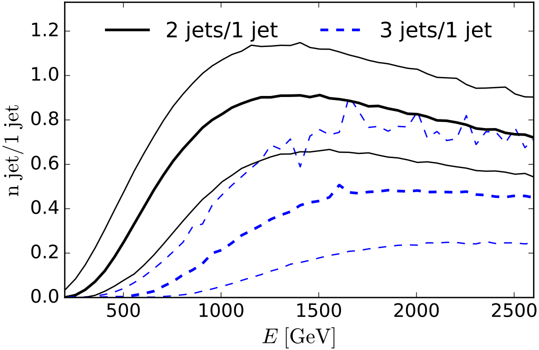
$$\frac{d\sigma^{pp,2}_{\text{MPI}}}{dE} = \frac{1}{2!} \int d^2\mathbf{b} e^{-\sigma T(\mathbf{b})} T^2(\mathbf{b}) \times \sum_{k=0} \frac{[\sigma T(\mathbf{b})]^k}{k!} C_2(k) \times \int dE_1 dE_2 \delta(E_1 + E_2 - E) \frac{d\sigma}{dE_1} \frac{d\sigma}{dE_2}.$$

Note: no requirements for k jets, one gets

$$\frac{d\sigma^{pp,2}_{\text{MPI}}}{dE} \xrightarrow{C_2(k)=\frac{2R}{2\pi}} \int dE_1 dE_2 \delta(E_1 + E_2 - E) \times \left(\frac{2R}{2\pi}\right) \frac{1}{2\sigma_{\text{eff}}} \frac{d\sigma}{dE_1} \frac{d\sigma}{dE_2},$$

Importance of multijet production

n merged jet production cross section normalized by $n = 1$ jet production

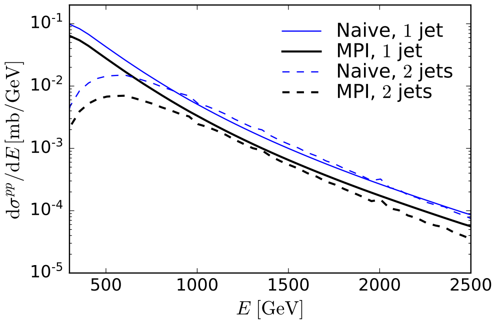


$p + Pb$ at $\sqrt{s} = 5.02$ TeV

- Summed over all k not merged jets
- $n = 2$ merged jets: order 1 contribution
  - Two small-E jets easier than one high-E
- $n = 3$ merged jets: only $\sim 20\%$ contribution on top of $1 + 2$ merged jets
  - Phase space suppression
- Thin lines: different min-p_T cut (later)

H.P, H.M, 1910.13116

Constrained azimuthal distribution



Naive = no constraints for the azimuthal angles of the k unmerged jets H.P, H.M, 1910.13116

$p + p$ at $\sqrt{s} = 13$ TeV

- If no requirements for the azimuthal distribution of k jets, we recover standard single, double etc. parton scattering formula
- Black lines: part of the phase space forbidden (otherwise would be merged)
- Significant effect on the cross section