Looking for BFKL resummation and saturation at the LHC

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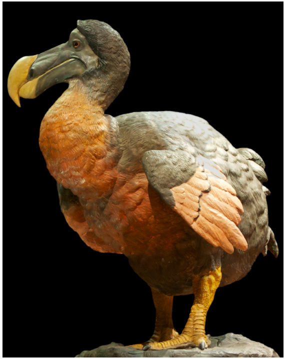
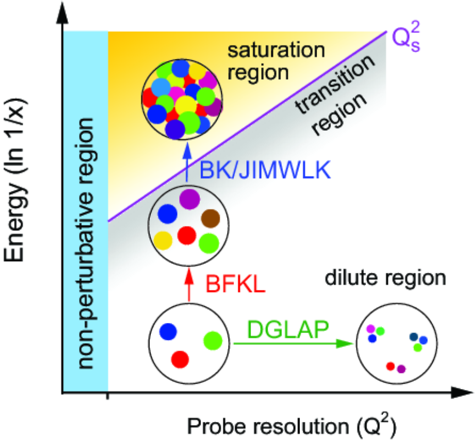


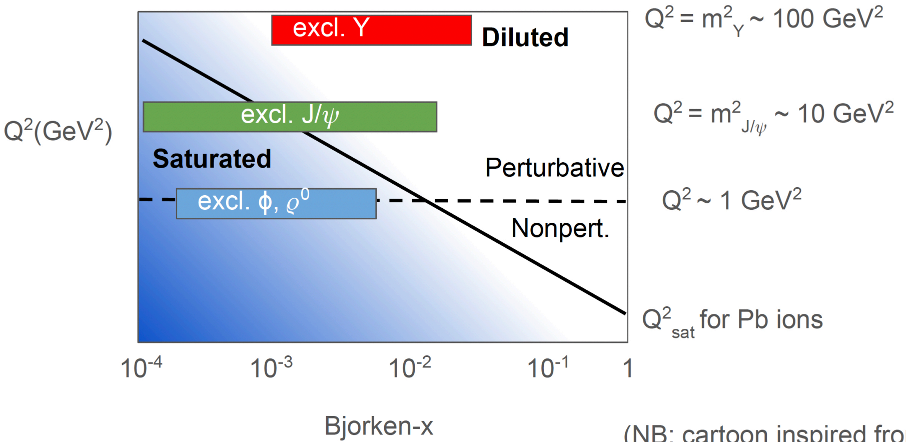
- Vector meson production (in collaboration with J. Penttala)
- Have we seen saturation in data at the LHC?
- Jet production in the very forward direction

Looking for BFKL resummation /saturation effects



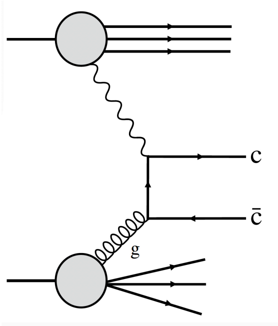
- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution Q^2, resums terms in $\alpha_S \log Q^2$ $\rightarrow$ resolving "smaller" partons at high Q
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy x, resums terms in $\alpha_S \log 1/x$ $\rightarrow$ Large parton densities at small x
- Saturation region at very small x
- Important to understand QCD evolution, parton densities

Looking for saturation effects: vector meson channel



(NB: cartoon inspired from Wei's plot)

Forward jets, J/Ψ, c and b productions: observables for saturation

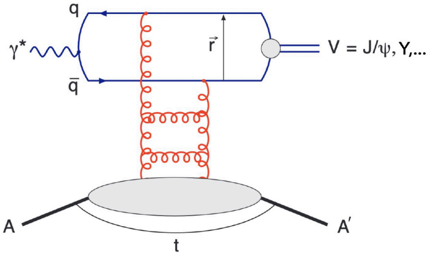


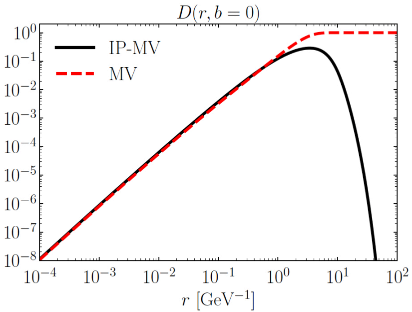
- What do we need to see saturation at the LHC?
- γPb c, b, J/Ψ are ideal probes for low-x physics

$$x = \frac{m_{c\bar{c}}}{\sqrt{s_{NN}}} \exp(-y_c)$$

- We can reach low x values of 10^{-4} or smaller
- We need a low scale (to be below Q_S), and this is why c or b where one can go to very low p_T or J/Ψ (low mass vector mesons) are ideal while still being in the perturbative region
- $d\sigma/dW$ is the best observable while $d\sigma/dy$ presents the difficulties to mix up low and high x

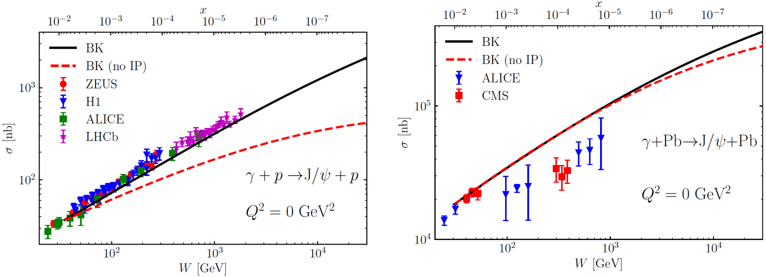
Looking for saturation: vector meson production





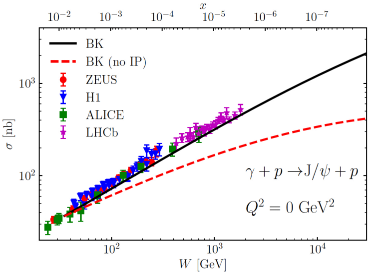
- Compute exclusive vector meson production in γp (HERA, EIC and pPb LHC) and γPb (EIC and Pb Pb LHC) where we probe the gluon density in p or Pb
- Saturation effects are expected to happen in Pb Pb, not in p Pb
- Computation: Factorize the $\gamma \to q\bar{q}$ part from the coupling to the proton: cross section proportional to $(xG)^2$ at LO
- Take into account b impact parameter dependence in dipole amplitude

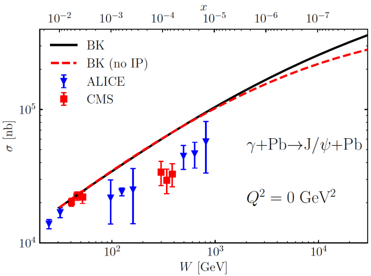
$$\partial_Y D(\mathbf{x}_0,\mathbf{x}_1,Y) = \int \mathrm{d}^2\mathbf{x}_2\, K_{\mathrm{BK}}(\mathbf{x}_0,\mathbf{x}_1,\mathbf{x}_2)\Big[D(\mathbf{x}_0,\mathbf{x}_2,Y)+D(\mathbf{x}_2,\mathbf{x}_1,Y)-D(\mathbf{x}_0,\mathbf{x}_1,Y)-D(\mathbf{x}_0,\mathbf{x}_2,Y)D(\mathbf{x}_2,\mathbf{x}_1,Y)\Big]$$



- Use Balitsky Kovchegov (BK) equation to describe the dipole evolution (so including saturation effects)

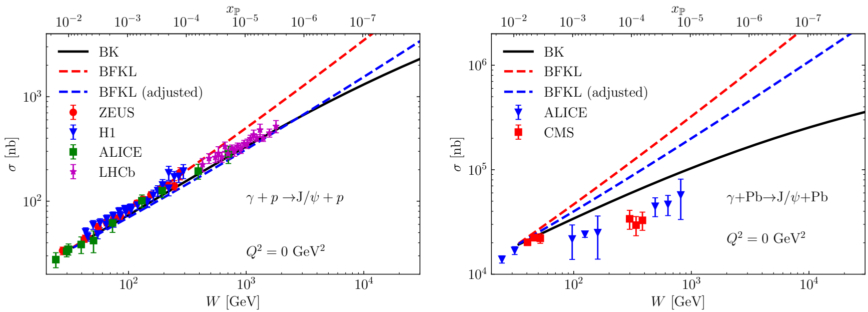
High energy evolution



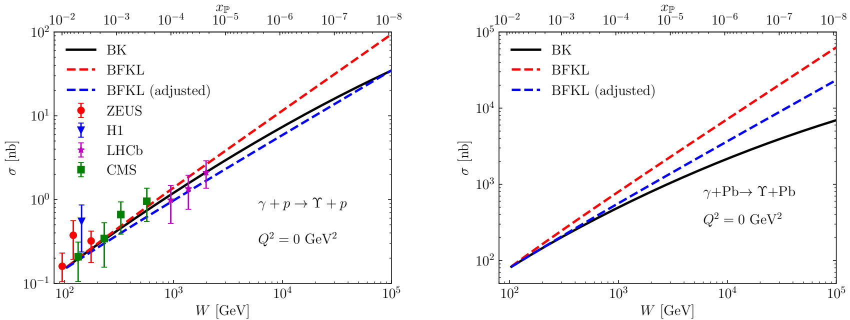


- Huge difference between taking into account b impact parameter dependence or not for γp (Penttala, Salazar)
- Much smaller differences for γPb: nucleus much larger than proton and neglecting impact parameter dependence is more justified
- Possibility to determine effects of saturation by neglecting the gluon recombination term in BK: equivalent of linear BFKL equation

Looking for saturation: J/Ψ vector meson production

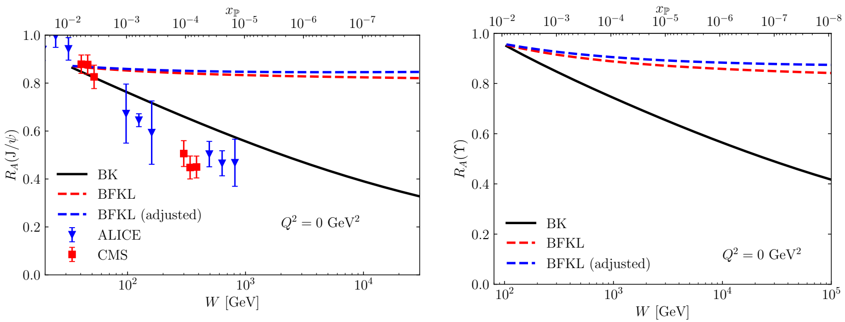


- BFKL and BK CGC predictions after taking into account b-dependence (J. Penttala, C. R.)
- J/Ψ production in pPb: small differences between BK and BFKL, BK slightly favored
- Large differences between BK and BFKL in PbPb collisions



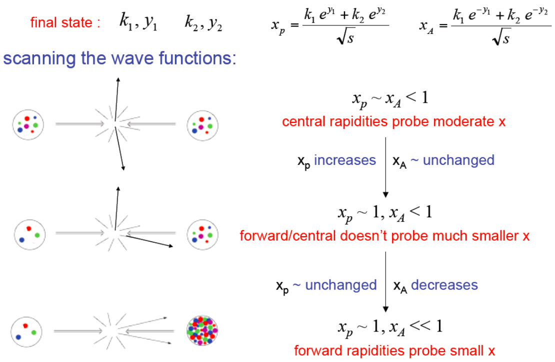
- Υ vector meson production: smaller differences between BFKL and BK in pPb or PbPb collisions
- Looking for additional observables: charm, etc

Looking for saturation: J/Ψ and Υ nuclear suppression factor



- Large nuclear suppression factor for J/Ψ in PbPb collisions
- Have we seen saturation in Pb Pb?
- Importance to have precise measurements of pp interactions as a reference at the same $\sqrt{s}$

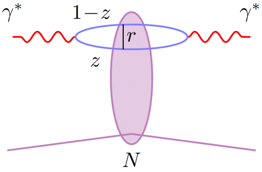
Saturation at the LHC using forward jets: Use pA and AA data



- If we want to see saturation effects, we need a dense object (Pb) and to go to very low x: measure jets in very forward direction
- Saturation effects: Measure two jets in very forward calorimeter (CASTOR in CMS, FOCAL project in ALICE)
- Use pp and pA runs (inclusive measurements, p and Pb are destroyed most of the time)
- Possibility to look for quark gluon plasma formation using $t\bar{t}$ production in PbPb

Dipole amplitude from HERA data

$$\sigma_{T,L}(x,Q^2) = 2\int \mathrm{d}z \int \mathrm{d}^2\mathbf{b}\,\mathrm{d}^2\mathbf{r}\left|\Psi^{\gamma}_{L,T}(Q^2,\mathbf{r})\right|^2 \mathcal{N}(\mathbf{r},\mathbf{b},x)$$
$$\Rightarrow \sigma_p \int \mathrm{d}z \int \mathrm{d}^2\mathbf{r}\left|\Psi^{\gamma}_{L,T}(Q^2,\mathbf{r})\right|^2 \mathcal{N}(\mathbf{r},x)$$



dipole-shockwave interaction schematic

- TMDs can be computed using either b-dependent or b-independent N

- We use AAMQS parametrization (A non-linear QCD analysis of new HERA data at small-x, ArXiv 1012.4408) (no impact parameter dependence)
- Factorisation of a photon into a $q\bar{q}$ dipole from the $q\bar{q}$ scattering off a dense nuclear target
- Balitsky Kovchegov equation to evolve the parton distributions at small x
- IPSat model to describe the impact parameter dependence (no BK evolution)
- Our model: mixture of AAMQS and IPSat

Dependence on impact parameter

$$S_\perp \mathcal{N}(\{G(r,x)\}) \to \int \mathrm{d}^2\mathbf{b} \mathcal{N}(\{G(r,x,b)\}) = \begin{cases} S_\perp \frac{\eta}{\sigma} \int \mathrm{d}^2\mathbf{b}\,(1 - exp[\sigma G(r,x) T(\mathbf{b})])\,, & T(b) > T_{\mathrm{min}} \\ 0, & \text{otherwise} \end{cases}$$

- We reintroduce the b dependence into the b-averaged dipole fits (parameters: η, σ, T_{min})
- For protons, choose (IPSat model hep-ph/0304189):

$$T_p(b) = \frac{exp(-b^2/2B_G)}{2\pi B_G}$$

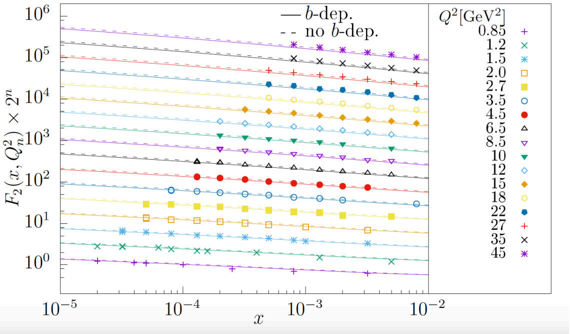
- For nuclei, sum of each proton and neutron gaussian thickness

$$T(b) = \Sigma_{i=1}^{A} T_{p/n}(b_i - b)$$

where the nucleon impact parameters (b_i's) are generated stochastically

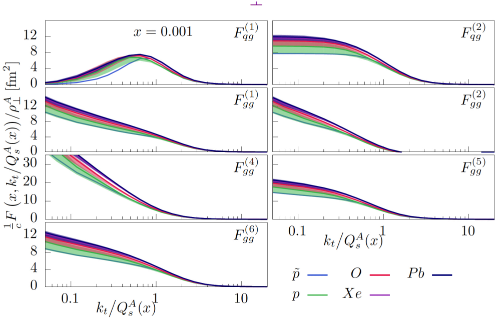
Matching b-dependent and independent proton TMDs: Recovering F_2 from HERA

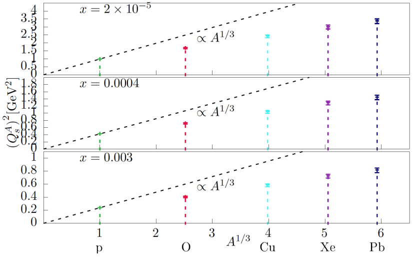
$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \left[\sigma_T(x, Q^2) + \sigma_L(x, Q^2)\right]$$



- Cross check of our model: get a good description of F_2 measurement at HERA
- Good description using either b-dependent or b-independent approaches, leads to same predictions

Use of nuclear Transverse Momentum Distributions (TMDs)



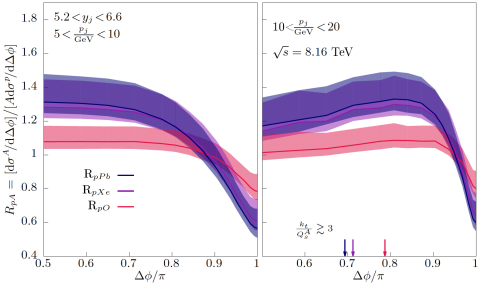


$(Q_s^A)^2$ (colored bars) *v.s.* $A^{1/3}Q_s^2$ (dashed) as func. of A

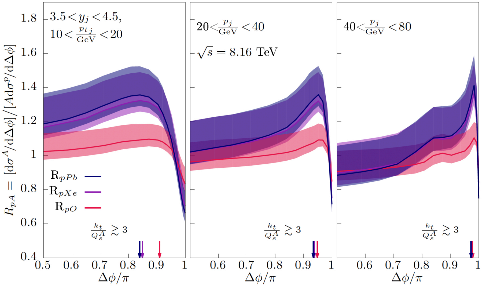
- Nuclear TMDs are calculated by swapping T_p and T_A
- Comparison between the saturation scales given by our model (using the b-dependence) and the naive one with the usual $A^{1/3}$ dependence: we get lower saturation scales

Nuclear modification factor

Nuclear mod. fac. in very forward Castor/Focal kinematics

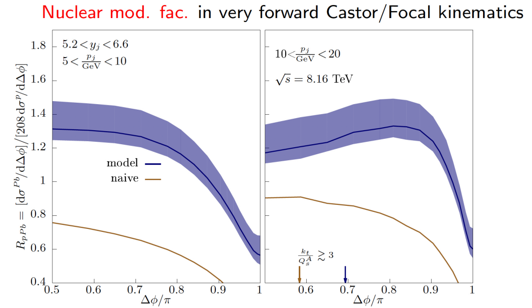


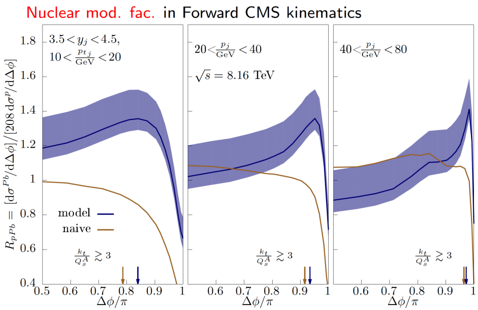
Nuclear mod. fac. in Forward CMS kinematics



- Nuclear modification factors for two detector configurations:
  - CASTOR/FOCAL kinematics: $5.2 < y_{jet}, < 6.6$ and p_T^{jet} 5 to 10 GeV, or 10 to 20 GeV
  - "Forward CMS" kinematics: $3.5 < y_{jet}, < 4.5$ and p_T^{jet} 10 to 20 GeV, 20 to 40 GeV or 40 to 80 GeV
- As expected, decorrelation more pronounced for higher y and lower p_T
- F. Deganutti, C. Royon, S. Schlichting, JHEP 01 (2024) 159

Nuclear modification factor: model versus naive saturation scale



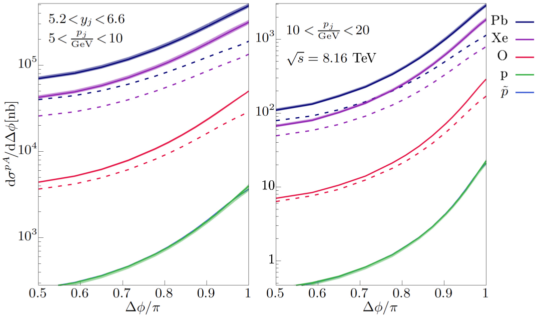


- As expected, large difference between model and naive saturation scales

Conclusion

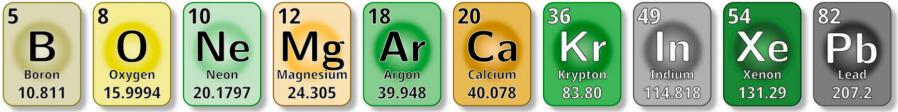
- Saturation at the LHC: use dedicated observables allowing to access low mass, low x such as very forward jets, vector meson (J/Ψ), c and b production
- **Have we seen already saturation at the LHC in J/Ψ production?**
- Predictions using impact parameter dependence on $\Delta\phi$ decorrelation between jets in the very forward direction (FOCAL)

Looking for saturation: very forward jet production



- Dedicated observables to look for saturation: particle/jet production in the forward region (F. Deganutti, C. Royon, S. Schlichting, JHEP 01 (2024) 159)
- Jet decorrelation predicted to be more pronounced for softer and higher rapidity jets
- Our model (including a full *b*-dependence calculation) predicts less decorrelation than using the naive scaling
- Can be tested using CASTOR (CMS) data or incoming FOCAL (ALICE) ones

Using different heavy ions at the LHC?



- Possibility to use lighter heavy ions at the LHC beyond run 4
- This would mean starting around 2035, so in overlap with the EIC
- Is it potentially interesting to compare for instance very forward jets, c and b production, J/Ψ and Υ production at higher energies of the LHC to see probably no saturation effects for light ions, and saturation for heavy ions?
- How much lumi would be needed?
- Can we measure Q_s for different ions using these data (and compare to EIC)?