Diffractive vector meson production and initial state fluctuations in DIS

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7th Workshop of the APS Topical Group on Hadronic Physics

Based on: H.M., B. Schenke, PRL 117 (2016), 052301 and PRD 94 (2016), 034042
and work in progress with B. Schenke, P. Tribedy and C. Shen.

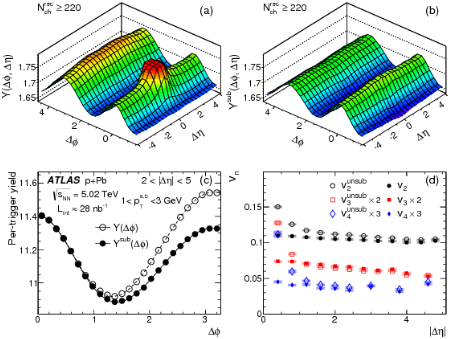
Motivation

A fundamental question

How are the quarks and gluons distributed in space inside the nucleon?

Practical applications

Initial state geometry is a necessary input for hydrodynamical simulations



ATLAS, arXiv:1409.1792

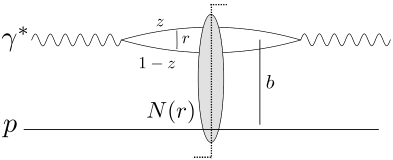
Collective phenomena seen in pp&pA

- Initial state geometry
  $\Rightarrow$ final state collectivity

Diffractive processes probe

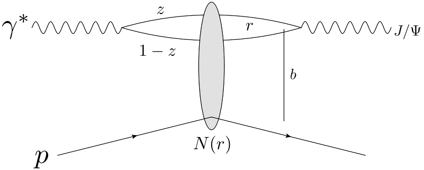
- Spatial density profile
- **Density fluctuations**

Deep inelastic scattering at high energy: dipole picture



Optical theorem:

$\sigma^{\gamma^* p} \sim$ dipole amplitude



$\sigma^{\gamma^* p \to Vp} \sim |\text{dipole amplitude}|^2$

Univesal dipole amplitude

Same universal QCD evolved dipole amplitude N appears in calculations of

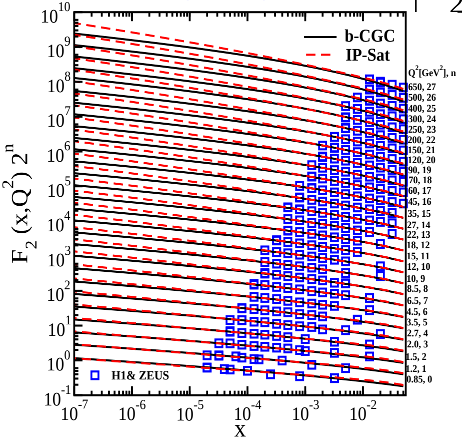
- DIS
- Diffraction
- Particle spectra in pp/pA
- ...

Dipole amplitude from HERA measurements

Use impact parameter dependent dipole amplitude (IPsat) fitted to HERA

(Kowalski, Motyka, Watt, 2006; Rezaeian et al, 2012)

$$N(r,x,b) = 1 - \exp\left[-\frac{\pi^2}{2N_c}\alpha_s xg(x,\mu^2)\,T_p(b)\,r^2\right]$$

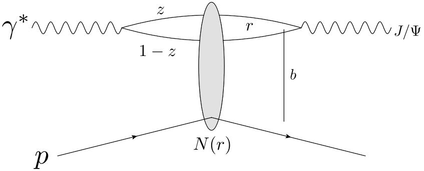


Rezaeian et al, 1307.0825

- DGLAP evolved gluon distribution $xg(x,\mu^2)$
- Proton profile T_p Gaussian
- Very good agreement with structure function data
- Good description of the precise HERA data

Diffractive vector meson production in dipole picture

1. $\gamma^* \to q\bar{q}$ splitting: $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically: $N(r, x, b)$
3. $q\bar{q} \to J/\Psi$: $\Psi^V(r, Q^2, z)$

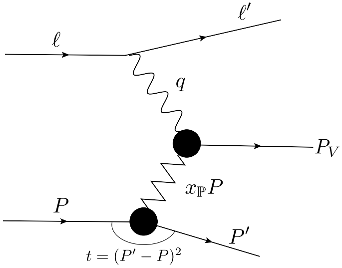


Diffractive scattering amplitude

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma*}\Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Fourier transfer from impact parameter to transverse momentum Δ → access to spatial structure
- Δ = transverse momentum of the vector meson

Exclusive vector meson production in DIS



Diffractive events: no exchange of color charge

- Target remains intact: *coherent diffraction*, small $|t|$. Probes average distribution of gluons.
- Target breaks up: *incoherent diffraction*, larger $|t|$. Sensitive to fluctuations.

Target: proton or nucleus

Coherent diffraction = target remains intact

Target is at the same quantum sate before and after the scattering:
$\langle\rangle$ = target average (Miettinen, Pumplin, PRD 18, 1978, ...)

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}(x, Q^2, t)\rangle|^2$$

with

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Coherent $t = -\Delta^2$ spectra is Fourier transfer of the **average density**

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Example: HERA data at $x \sim 10^{-3}$

For Gaussian profile $e^{-b^2/(2B)}$ gives $B = 4$ GeV^{-2}, corresponding to

$$\sqrt{\langle r_{\mathrm{2D}}^2 \rangle} = 0.56 \text{ fm}.$$

Incoherent diffraction = target breaks up

Total diffractive cross section − coherent cross section → target breaks up

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to V p^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}(x, Q^2, t)|^2 \rangle - \left| \langle \mathcal{A}(x, Q^2, t) \rangle \right|^2$$

with

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Incoherent cross section is variance ⇔ sensitive to fluctuations

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Constraints

Simultaneous description of coherent and incoherent data allows us to constrain the average shape and the amount of fluctuations

Constraining proton fluctuations

Start with a simple constituent quark inspired picture:

- Sample quark positions from a Gaussian distribution, width B_{qc}
- Small-x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations
- Dipole-target scattering: IPsat model fitted to F_2 data

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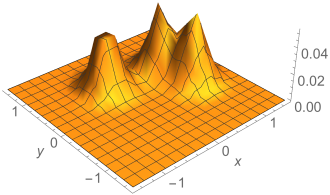
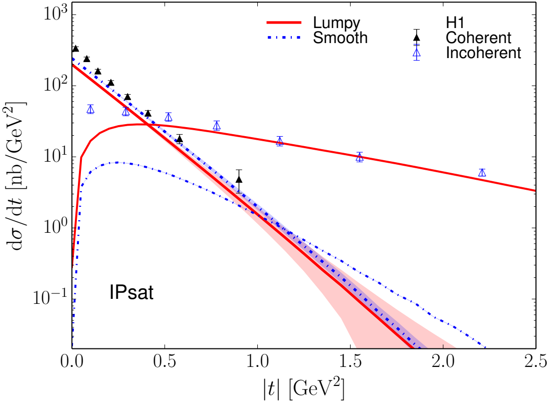
Now proton = 3 overlapping hot spots.

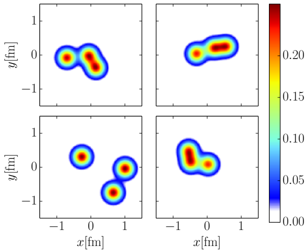
$$T_{\text{proton}}(b) = \sum_{i=1}^{3} T_q(b - b_i) \qquad T_q(b) \sim e^{-b^2/(2B_q)}$$



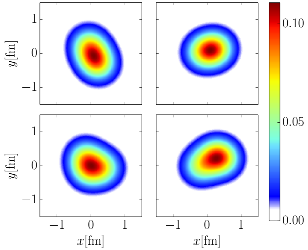
Constraining proton fluctuations in $\gamma + p \rightarrow J/\Psi + p^*$



Lumpy: $B_{qc} = 3.3, B_q = 0.7$



Smooth: $B_{qc} = 1.0, B_q = 3.0$

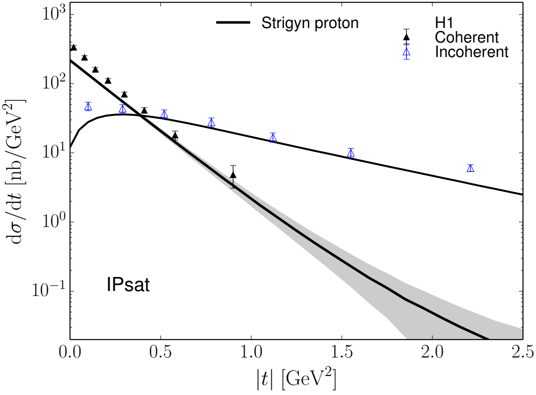


Units: GeV^{-2}

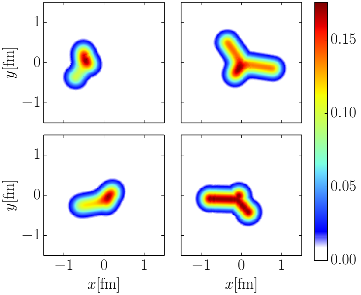
- H1 incoherent data requires large fluctuations
- Proton-photon center-of-mass energy $W = 75\mathrm{GeV}$, probing $x \approx 10^{-3}$

Lumpiness matters, not details of the density profile

3 valence quarks that are connected by "color flux tubes" (Gaussian density profile, width B_q). Also good description of the data



Example density profiles



H.M, B. Schenke, PRD94 034042

Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911

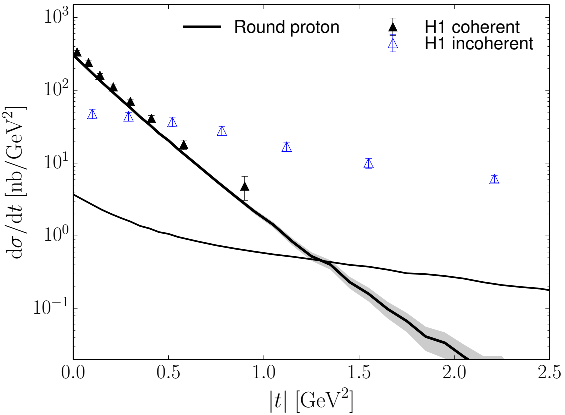
Adding color charge fluctuations: IP-Glasma

- Obtain saturation scale $Q_s(x_T)$ from IPsat (with fluctuations)
- MV-model: Sample color charges, density $\sim Q_s(x_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

$$V(x_T) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(x^-, x_T)}{\nabla^2 + m^2} \right)$$

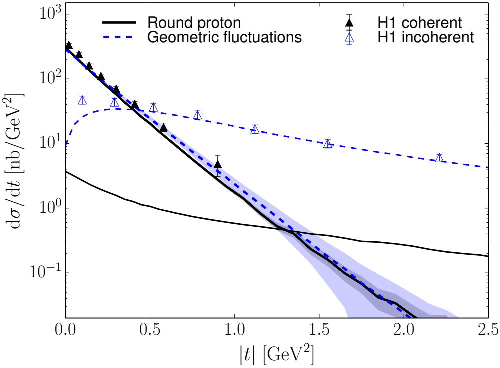
- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr}\, V(x_T) V^\dagger(y_T)/N_c$
- Fix parameters B_{qc}, B_q and m with HERA data

IP-Glasma and HERA data

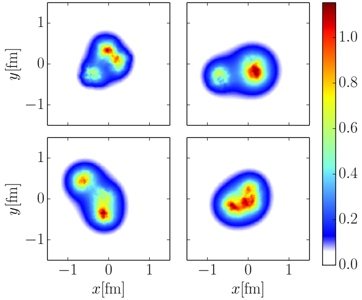


- Color charge fluctuations alone are not enough

IP-Glasma and HERA data



Parameters fitted to H1 data

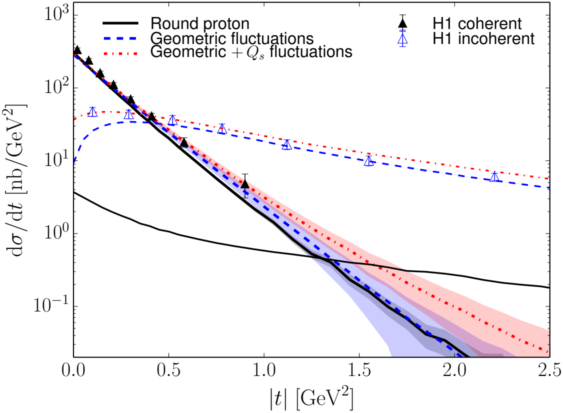


H.M., B. Schenke, PRD94 (2016), 034042

- Large geometric fluctuations are needed

IP-Glasma and HERA data, add Q_s fluctuations

- Allow Q_s of each constituent quark to fluctuate
- Constrained by *pp* multiplicity data (McLerran, Tribedy, arXiv:1508.03292)



- Q_s fluctuations improve description at small $|t| \sim$ large distance

Applications to pA collisions

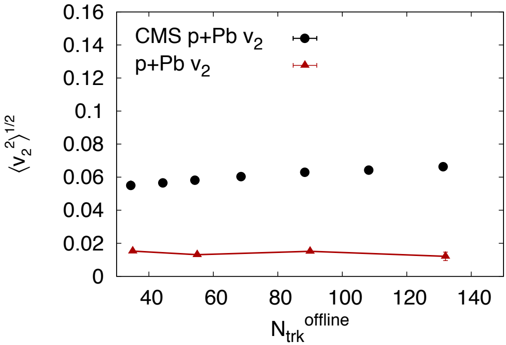
Large elliptic flow (v_2) seen in pA collisions

IP-Glasma with hydro works will with the AA data, apply to pA
Does it work?

First approach: round proton with only color charge fluctuations

B. Schenke, R. Venugopalan,

PRL113 (2014) 102301



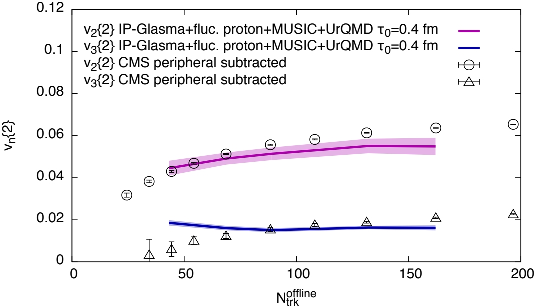
Color charge and Q_s fluctuations in the initial state do not create large enough flow harmonics to the final state

Fluctuating protons in pA collisions

Hydro calculations with proton fluctuations from HERA

Hydro details

- $\tau_0 = 0.4$ fm
- $T_{\text{fo}} = 155$ MeV
- Shear and bulk viscosity
- Initial $\pi^{\mu\nu}$
- $\eta/s = 0.2$

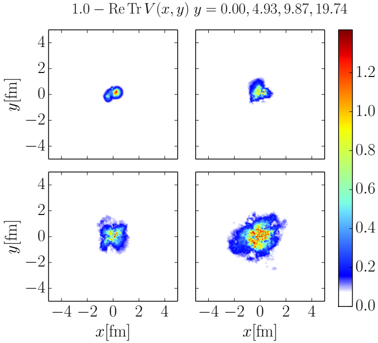


Large v_2 and v_3 at largest centrality bins reproduced well.

with B. Schenke, C. Shen, P. Tribedy, in preparation.

Evolution to small x (work in progress)

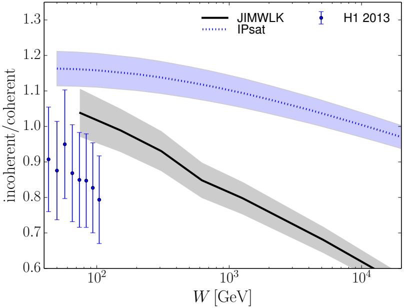
HERA data constrains proton structure at $x \sim 10^{-3}$.
Evolve to smaller x by perturbative CGC evolution equation (JIMWLK)



- Proton growth seen
- Smoothening of the overall geometry

Energy evolution of diffractive J/Ψ production

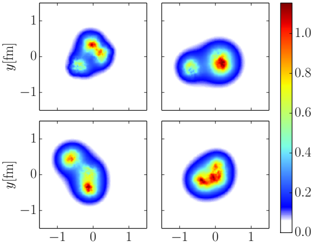
Work in progress (qualitative results at this point)

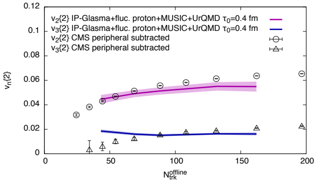


- Incoherent cross section grows more slowly
    - One contribution: proton becomes smoother
- Qualitatively in agreement with HERA data
- Ultraperipheral pA: ALICE does not see incoherent at $W \sim 700$GeV

Conclusions

- Coherent and incoherent diffraction combined probe proton
    - Density profile
    - Event-by-event density fluctuations
- Color charge fluctuations alone are not enough to describe HERA incoherent J/Ψ production data
    - Large geometric fluctuations of the proton density are needed
    - Saturation scale fluctuations improve description at small $|t|$
- Structure fluctuations constrained by HERA data
    - pA hydro calculations compatible with LHC data on v_n
- Next step: include small-x evolution in terms of JIMWLK equation





Backups

Saturation scale fluctuations

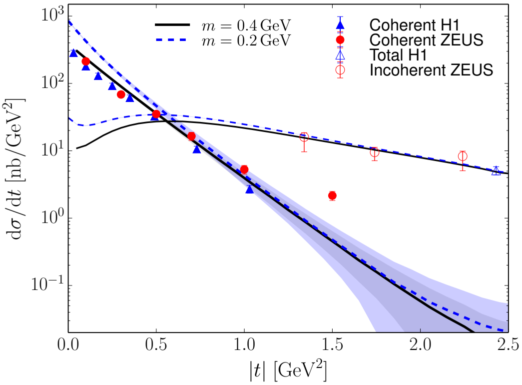
Saturation scale fluctuations ($p+p$ multiplicity distributions: $\sigma \sim 0.5$)

$$P(\ln Q_s^2/\langle Q_s^2\rangle) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{\ln^2 Q_s^2/\langle Q_s^2\rangle}{2\sigma^2}\right]$$

McLerran, Tribedy, arXiv:1508.03292: $p+p$ multiplicity distributions: $\sigma \sim 0.5$

- Shifted to keep average Q_s unchanged
- Allow Q_s^2 of each contituent quark to fluctuate
- If no geometric fluctuations, divide transverse space to $\sim 1/Q_s^2$ cells where Q_s^2 fluctuates

Insensitivity on infrared cutoff

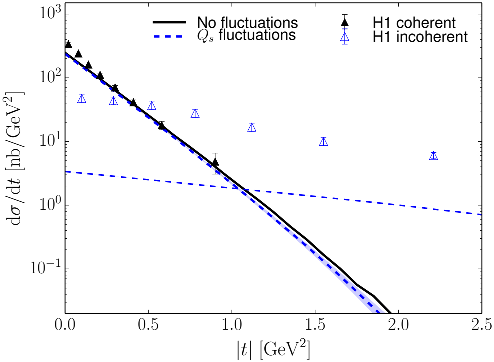


IP-Glasma: IR cutoff $m \sim \Lambda_{\mathrm{QCD}}$ to regulates long distance coulomb tails

- Proton size depends on m
- No sensitivity at large $|t|$

Saturation scale fluctuations w/o geometric fluctuations

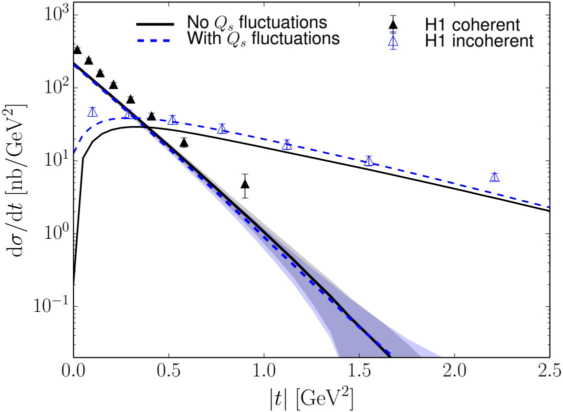
Allow Q_s^2 to fluctuate, $P(\ln Q_s^2/\langle Q_s^2\rangle) \sim \exp(-[\ln^2 Q_s^2/\langle Q_s^2\rangle]/2\sigma)$
Constrained by *pp* multiplicity fluctuations (McLerran, Tribedy, arXiv:1508.03292)



- Q_s fluctuations alone are not enough

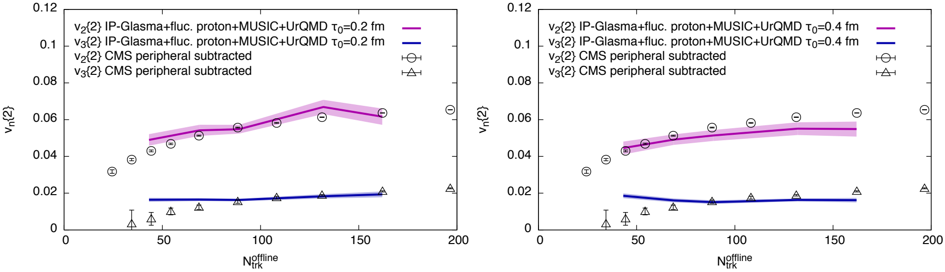
Saturation scale fluctuations + geometric fluctuations

Allow Q_s of each constituent quark to fluctuate separately (IPsat):



- Q_s fluctuations dominate incoherent cross section at small $|t|$ ($\sim$ large distance)

Dependence on τ_0

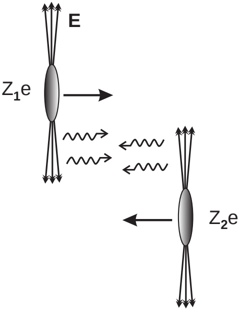


Towards smaller x / larger W

Diffractive DIS at the LHC: DIS at high energy!

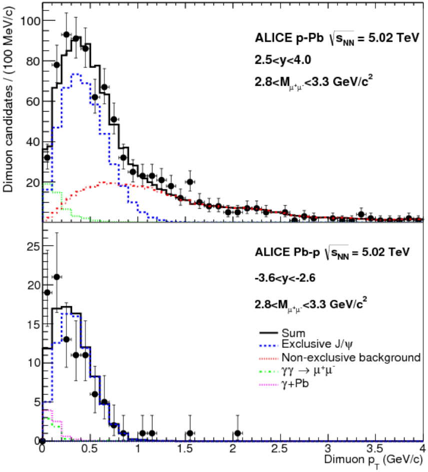
Ultraperipheral collisions ($b > R_1 + R_2$)

- Photon flux $\sim Z^2$
- Ultraperipheral PbPb collision $\approx$ high energy γA collision
- Ultraperipheral pA collision $\approx$ high-energy γp collision



Towards smaller x / larger W in γp

ALICE measurement in $\gamma + p \to J/\Psi + p(p^*)$ collisions



$x \sim 10^{-2} \to 2 \cdot 10^{-5}$

- Incoherent cross section not observed at small x
- Signature of smoothening at small x?
- Proton grows, diffractive slope B_p : 4GeV^{-2} $\to\sim$ 6.7GeV^{-2}

ALICE arXiv:1406.7819