Vector meson production in ultraperipheral collisions: accessing the small-x gluon

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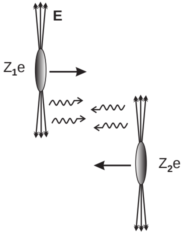
Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC, February 14, 2017

Content

Content

Ultraperipheral collision as a deep inelastic scattering

$b \gtrsim 2R_A$: strong interactions are suppressed



J. Nystrand et al, nucl-ex/0502005

1. Nucleus creates a (real) photon flux $n(\omega)$
2. Photon-nucleus scattering

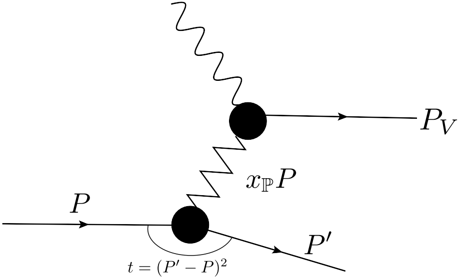
$$\sigma^{AA \to AA+V} \sim n(\omega) \sigma^{\gamma A \to VA}(\omega)$$

Interesting QCD part: high-energy γ-nucleus or γ-proton scattering.

Diffractive vector meson production as a probe of small x

Exclusive production of vector meson

$$\gamma p \to Vp$$
$$\gamma A \to VA$$

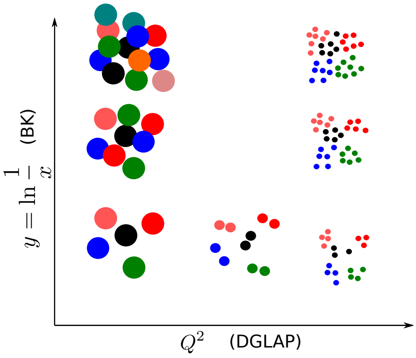


Pocket formula for diffraction (2-gluon exchange)

$$\frac{\mathrm{d}\sigma^{\gamma^* H \to VH}}{\mathrm{d}t} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{\text{em}} M_V^5} \left[\mathbf{xg(x, Q^2)}\right]^{\mathbf{2}}$$

- Diffraction is very sensitive to (small-x) gluons!
- UPC is $\gamma - p$ or $\gamma - A$ collision
  - Nuclear DIS before the EIC era - and at very high energies!

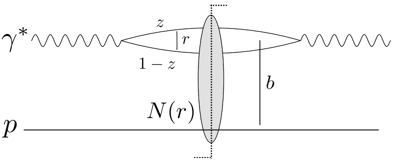
QCD at high energy: Color Glass Condensate



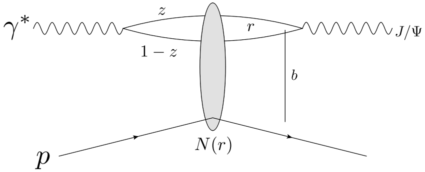
- CGC = QCD at high energies
- x (energy) dependence: BK/JIMWLK (perturbative)
- Saturation of gluon density at small x
- Saturation scale Q_s^2

Natural framework to describe high energy scattering.

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
- ...

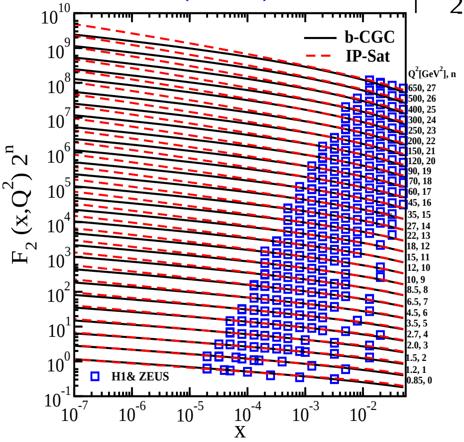
Non-perturbative input from a fit to HERA F_2 data.

IPsat model and DIS

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

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

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

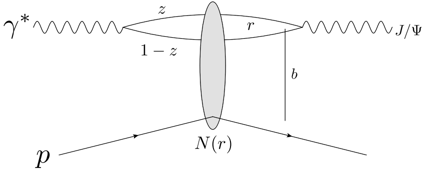


Rezaeian et al, 1307.0825

- DGLAP evolved gluon distribution $xg(x,\mu^2)$
- Proton profile T_p Gaussian
- Very good agreement with structure function data
- Generalization for nuclei: $S_A(r,b,x) = \prod_{i=1}^{A} S_p(r, b - b_i, x)$
- Extremely good description of the precise HERA data

Diffractive vector meson production

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



Diffractive scattering amplitude

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

- Fourier transfer from impact parameter to transverse momentum Δ $\to$ access to spatial structure

Still need to average over target configurations!

Coherent diffraction = target remains intact

Target is at the same quantum state before and after the scattering (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**

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 proportional to the amount of fluctuations in the impact parameter space

Cross section for incoherent γA diffraction: T. Lappi, H.M, 1011.1988

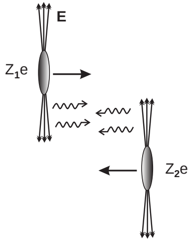
Content

1. Background

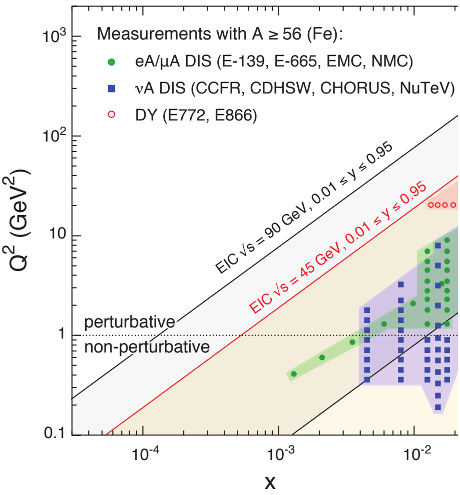
2. Pb+Pb collisions

3. p+Pb collisions

Going to small x with nuclei

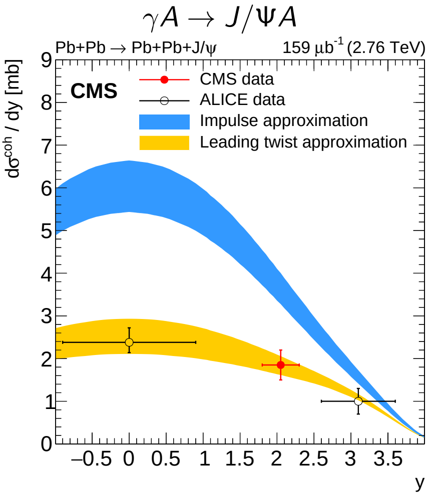


EIC white paper



- Currently there is basically no small-x nuclear DIS data
- Momentum fraction $x = M_V e^y / \sqrt{s}$
- Midrapidity J/Ψ at the LHC: $x \sim 10^{-3}$
- Forward J/Ψ at the LHC $x \sim 10^{-2}$ and $x \sim 10^{-5}$

Signal of nuclear effects seen in γA diffraction

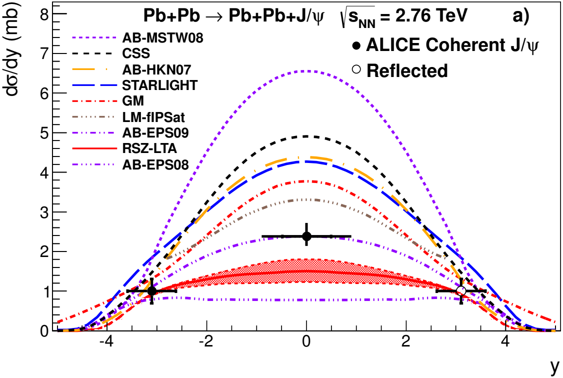


CMS, 1605.06966

Impulse approximation = scaled γp

- Clear nuclear effects seen (e.g. saturation, shadowing)

Coherent diffraction, model comparison

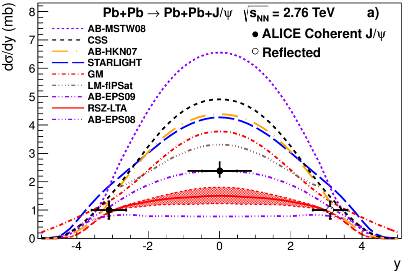


ALICE, 1305.1467

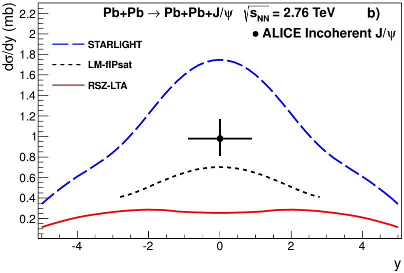
Shadowing/saturation needed, compare e.g.
AB-MSTW08 and AB-EPS09 (nuclear pdf) / LM-fIPsat (saturation)

Coherent and incoherent diffraction

Coherent



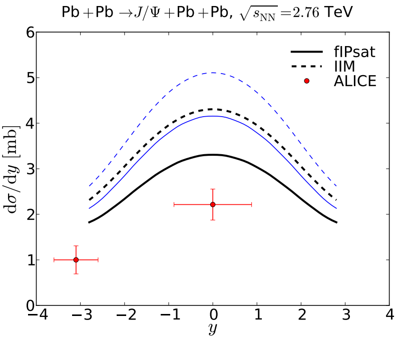
Incoherent



Dipole model calculation (LM-fIPsat): ok simultaneous description

- More LHC data coming
  - $\sqrt{s} = 5.02\,\mathrm{TeV}$: x dependece of the gluon density
  - Spectra differentially in $t \to$ Geometric structure and fluctuations
  - **QM2017:** Neutron tagging $\Rightarrow$ large x/small x separation

This is becoming precision physics (linear scale!)



T. Lappi, H.M., 1301.4095

"Theory uncertainties" are still large

- Dipole-nucleus amplitude
  - No nuclear DIS data to fit
  - But other data, e.g. R_{pA}
- Vector meson wave function (thin-thick lines)
  - Constrained mainly by the leptonic decay width = wave function at origin!
- Large phenomenological corrections
  - Especially skewedness (2 gluons, $x \ll x'$) is large, $\sim 50\%$
- NLO???

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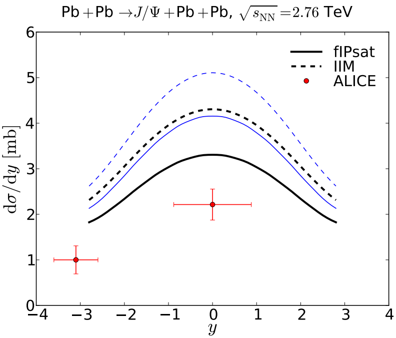

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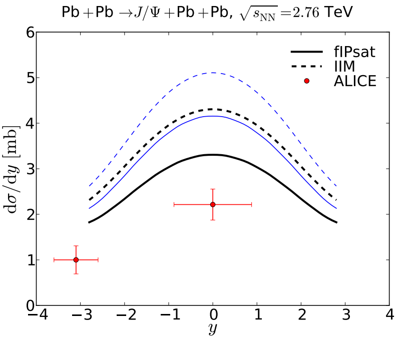

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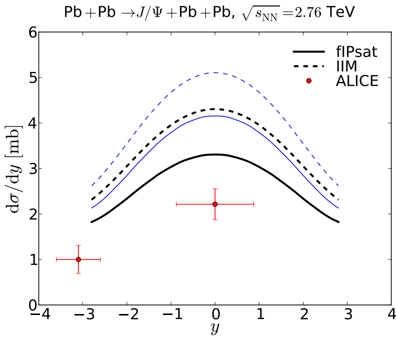

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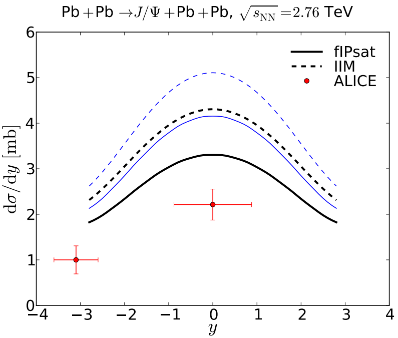

T. Lappi, H.M., 1301.4095

- Model uncertainties mainly affect normalization, not rapidity (Bjorken-x) dependence.(?)

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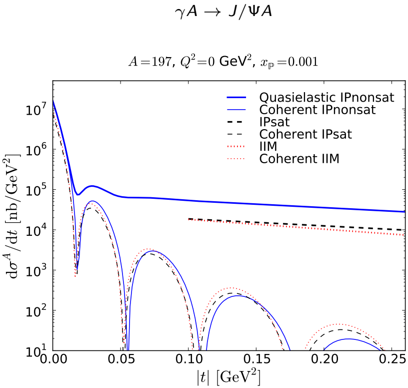
More differential measurements in the near future



T. Lappi, H.M., 1011.1988

Solid line: no saturation

Dashed lines: with saturation

Measure differentially in vector meson momentum $t = -\Delta^2$

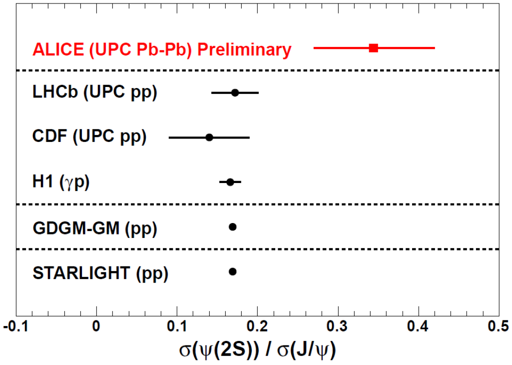
- Incoherent: more sensitive to saturation effects
  - **QM2017, CMS:** No/small incoherent cross section at small x!
  - Qualitatively predicted:

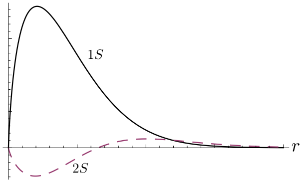
    T. Lappi, H. M., 1011.1988
- Coherent: extract transverse density profile of the small-x gluons in the nucleus

  Toll, Ullrich, 1211.3048

Excited states: $\Psi(2S)/J/\Psi$

Species dependence could test our understanding of the wave function





ALICE, 1508.05076

Qualitative agreement with dipole model: node effect is damped at large Q_s^2 (contribution from large dipoles is suppressed).

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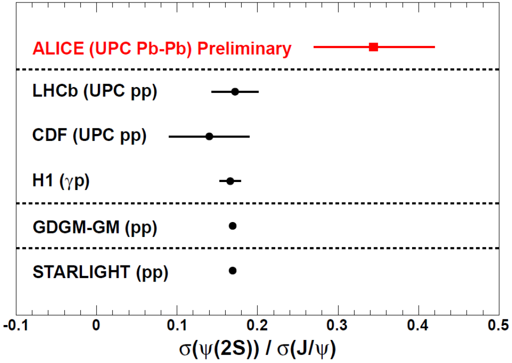
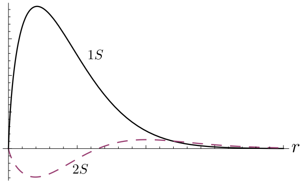


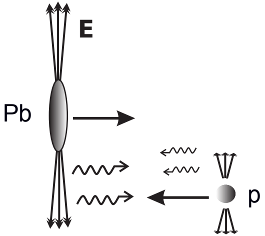


ALICE, 1508.05076

Qualitative agreement with dipole model: node effect is damped at large Q_s^2 (contribution from large dipoles is suppressed).

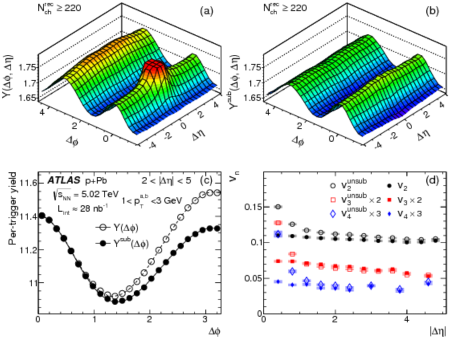
QM2017: $\sigma(2S)/\sigma(J/\Psi) = 0.166 \pm 0.011$

Content



Photon flux $\sim Z^2$

- Ultraperipheral pA collision $\approx \gamma p$ collision
- Access small-x structure of the proton



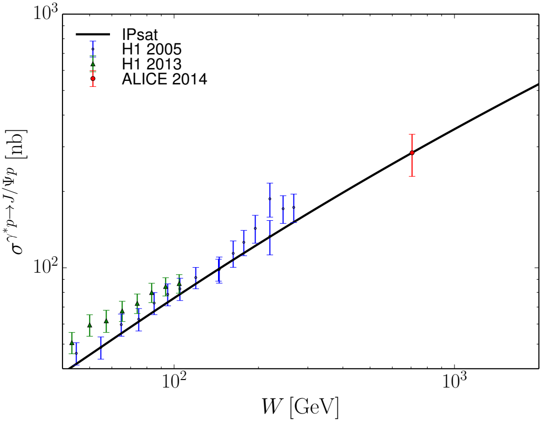
Collective phenomena seen in pp&pA

- Have to understand role of the initial state geometry
- Diffraction: average structure and fluctuations

ATLAS, arXiv:1409.1792

Diffraction at the TeV scale

Total coherent diffractive cross section



Total coherent cross section follows the same W^γ power law as HERA

- No significant saturation effect expected, described by IPsat

Proton structure fluctuations

Recall:

- Coherent diffraction probes average structure
- Incoherent diffraction is sensitive to amount of fluctuations

Strategy

Simultaneous description of HERA coherent and incoherent data allow us to constrain event-by-event proton structure 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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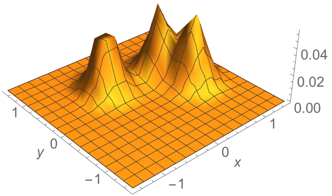
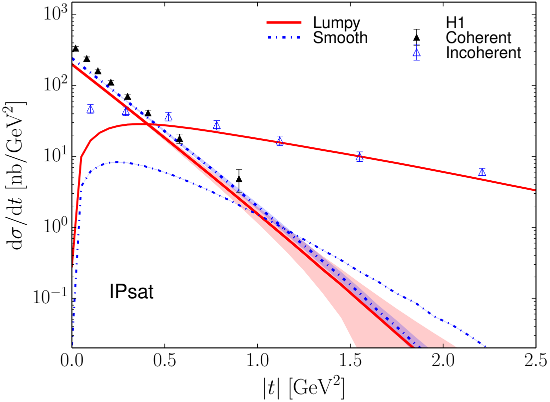
Now proton = 3 overlapping hot spots.

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

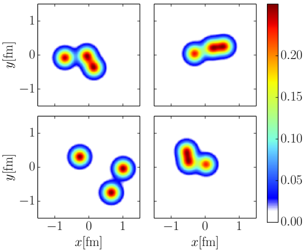




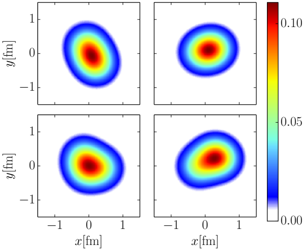
H.M, B. Schenke, PRL 117 (2016), 052301 and PRD94 (2016), 034042

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

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



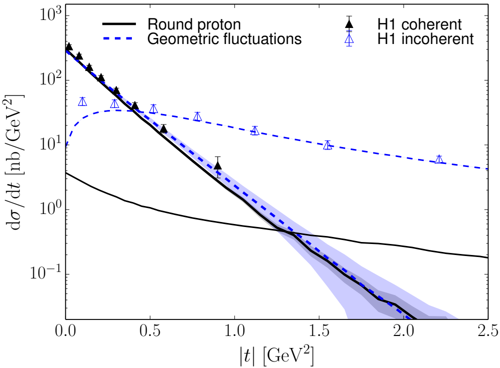
Smooth: $B_{qc} = 1.0$, $B_q = 3.0$

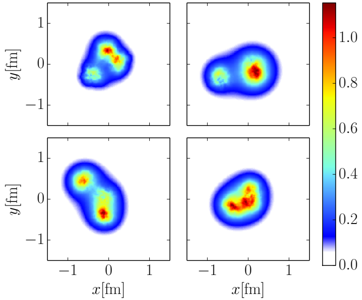


Units: GeV^{-2}

IP-Glasma and HERA data

Include color charge fluctuation, parameters fitted to H1 data



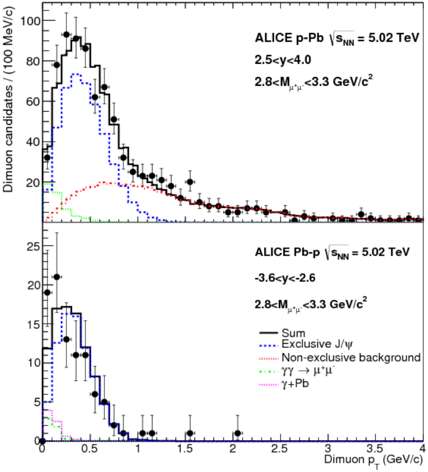


H.M., B. Schenke, PRD94 (2016), 034042

- Initial condition for pA hydro, good description of v_2 and v_3 data!

Towards smaller x / larger W in γp

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



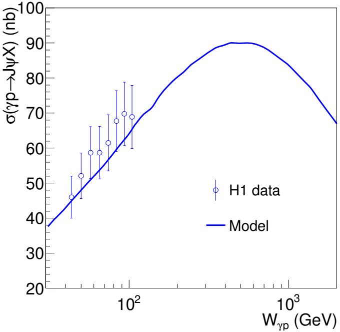
$x \sim 10^{-2} \to 2 \cdot 10^{-5}$

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

ALICE arXiv:1406.7819

Proton smoothening at small x?

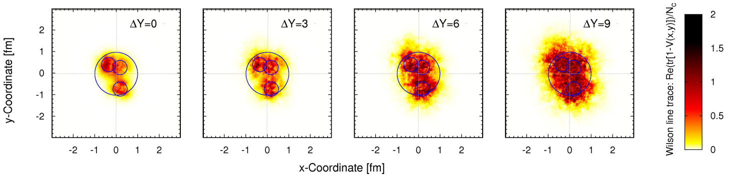
Cepila, Contreras, Takaki (1608.07559): Number of constituent quarks $\sim x^a(1 + b\sqrt{x})$, parameters fitted to HERA data



- Qualitatively expect incoherent cross section to decrease at high W
- Still expect to see significant incoherent contribution at $\sim$ 1 TeV

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)

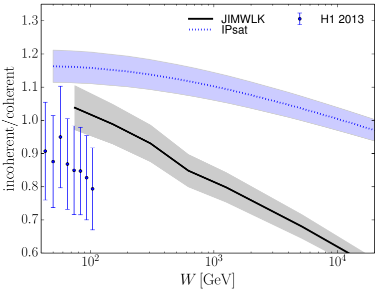


B. Schenke, S. Schlichting, Phys.Lett. B739 (2014) 313-319

- Proton grows
- Proton gets smoother

Energy evolution of diffractive J/Ψ production

Work in progress / preliminary (qualitative results at this point)



- Incoherent cross section grows more slowly
  - Proton gets smoother
  - Dipole must not scatter off other constituent quarks (included in IPsat calculation T. Lappi, H.M., 1011.1988)
- We would expect to still see a large incoherent contribution at $W \sim 700\,\mathrm{GeV}$

Conclusions

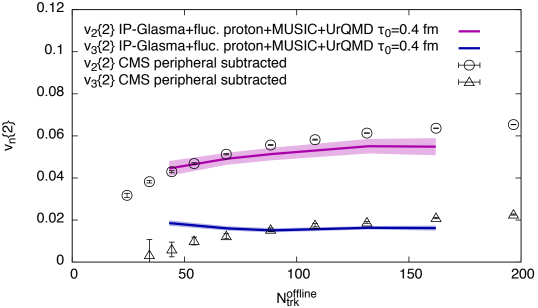
- UPC: diffractive vector meson production at very high energy
- CGC calculations compatible with both coherent and incoherent J/Ψ measurements form the LHC
- Signatures of saturation/shadowing in heavy ion collisions
  - Still largish model dependence
- pA collisions: study proton structure at high energies
  - Description of HERA data requires large proton structure fluctuations
  - LHC pA data hints for smoothening at small x
  - Fluctuations applied to hydro calculations of pA collisions: good description of the v_n measurements (backup)
- Lots of new data coming!

BACKUPS

Hydro calculations with proton fluctuations from HERA

Hydro numbers

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

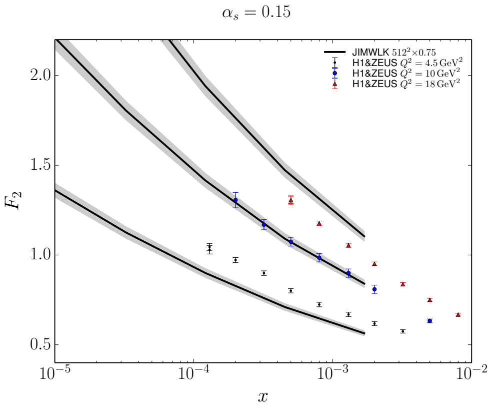


Large v_2 and v_3 at largest centrality bins reproduced well.

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

Constrain evolution speed

Work in progress / preliminary



- F_2 data at $Q^2 = 4.5 \ldots 18\,\mathrm{GeV}^2 \sim M^2_{J/\Psi}$ constrain α_s
- MV model does not give exactly correct Q^2 dependence

Adding color charge fluctuations: IP-Glasma

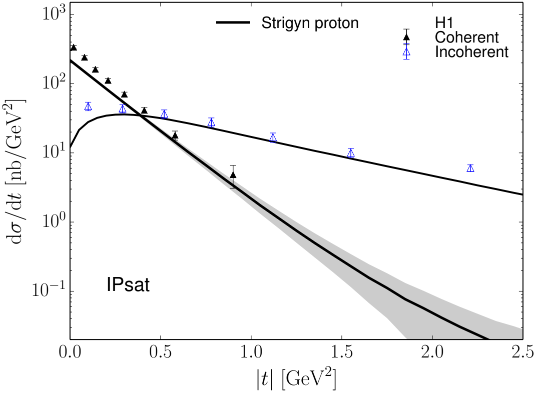
- Obtain saturation scale $Q_s(x_T)$ from IPsat (with fluctuations)
- MV-model: Sample color charges, density $\sim Q_s(x_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

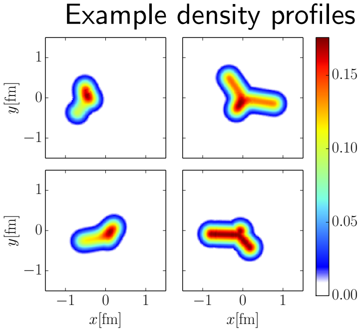
$$V(x_T) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(x^-, x_T)}{\nabla^2 + m^2}\right)$$

- 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

Lumpiness matters, not details of the density profile

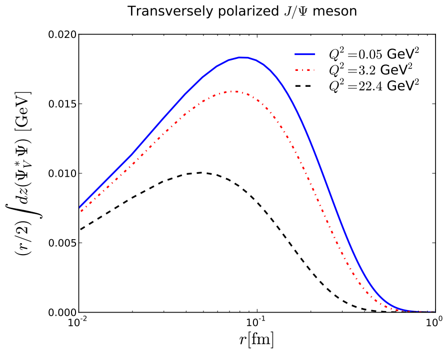
3 valence quarks that are connected by "color flux tubes" (Gaussian density profile, width B_q). Also good description of the data

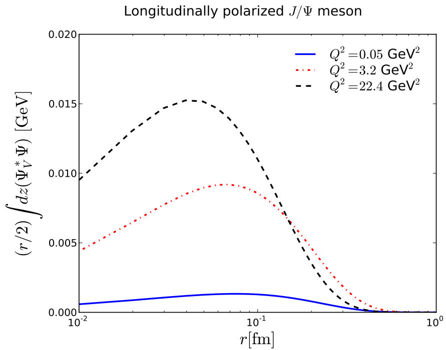




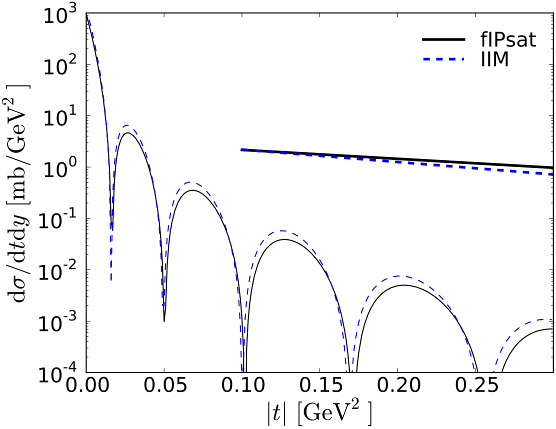
H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911

Wave function overlap in J/Ψ production:





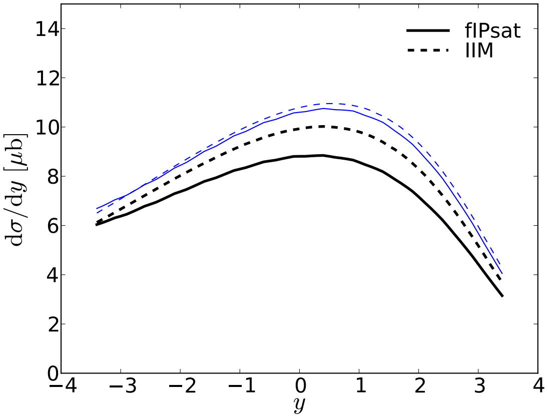
Differential cross section



T. Lappi, H. Mäntysaari, 1301.4095

Assuming proton profile function $T_p(b) \sim e^{b^2/(2B_p)} \Rightarrow$ incoherent cross section $\sim e^{-B_p t}$: probes spatial distribution of gluons in proton!

pA prediction



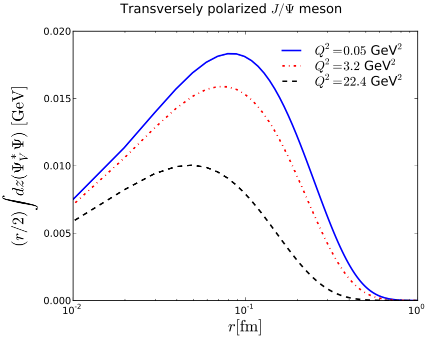
T. Lappi, H. Mäntysaari, 1301.4095 CMS frame

As the photon flux $\sim Z^2$, dominant process is the one where the nucleus emits the photon $\Rightarrow$ probes mostly proton structure.

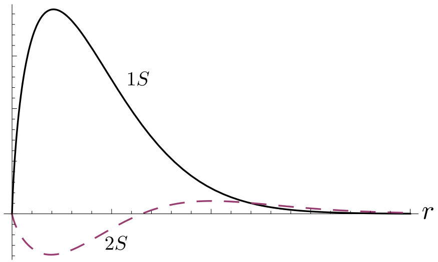
Vector meson wave functions

$\gamma^* \to q\bar{q}$ can be computed from QED, but $q\bar{q} \to$ vector meson requires some modelling, parameters fit to reproduce decay width.

Excited states: $\Psi(2S)$ wave function has a node (orthogonal to J/Ψ).
Cross section $\sim \int \mathrm{d}^2 r \Rightarrow$ large suppression compared to J/Ψ



Radial overlap:



Generalization for nuclei

S matrix $\sim$ probability not to scatter [recall: $S = 1 - N$]:

$$S_A(r, b, x) = \prod_{i=1}^{A} S_p(r, b - b_i, x)$$

Average over nucleon configurations

$$\langle \mathcal{O}(\{b_i\}) \rangle_N = \int \prod_{i=1}^{A} \left[\mathrm{d}^2 b_i \, T_A(b_i) \right] \mathcal{O}(\{b_i\})$$