Diffractive scattering from CGC

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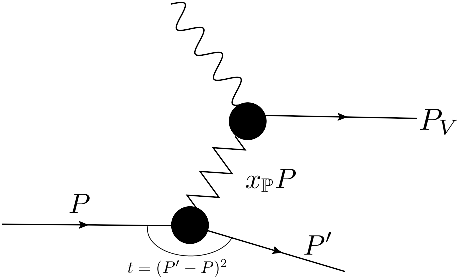
Why diffraction

Exclusive production of vector meson/dijet/diffracive system

$\gamma + A \to V + A$

$\gamma + A \to \text{jet}_1 + \text{jet}_2 + A$

$\gamma + A \to M_X + A$

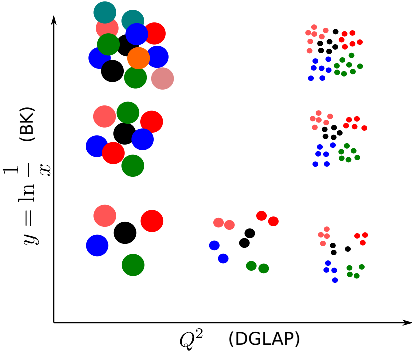


Pocket formula for VM production (2-gluon exchange)

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

- Diffraction is very sensitive to (small-x) gluons!
- Measure t (conjugate to impact parameter) ⇒ access to geometry

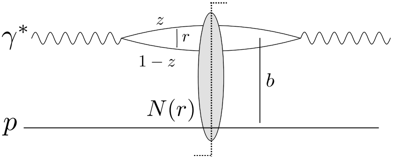
QCD at high energy: Color Glass Condensate

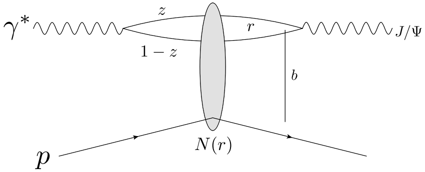


- CGC = QCD at high energies
- x (energy) dependence: BK/JIMWLK (perturbative)
- Saturation of gluon density at small x at scale Q_s^2

Natural framework to describe high energy scattering, which probes QCD in the non-linear regime

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

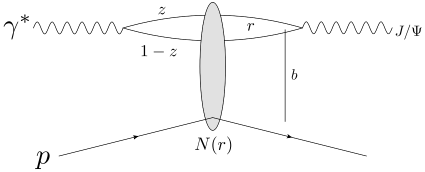
- DIS
- Diffraction
- Particle spectra in pp/pA
- ...

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

Probe of the geometry: exclusive J/Ψ production

High energy factorization:

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



Diffractive scattering amplitude

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

- Impact parameter is the Fourier conjugate of the momentum transfer → Access to the spatial structure
- Total F_2: forward elastic scattering amplitude ($\Delta = 0$) for $V = \gamma$

Average over target configurations

Coherent diffraction:

Target remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle|^2$$

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

Variance, measures the amount of fluctuations ("*lumpiness*")!

$\langle\,\rangle$: average over target configurations [N(r, **b**)]

Average over target configurations

Coherent diffraction:

Target remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle|^2$$

Incoherent/target dissociation:

Total diffractive − coherent cross section

Target breaks up

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}^{\gamma^* A \to VA}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle|^2$$

Variance, measures the amount of fluctuations ("*lumpiness*")!

$\langle\,\rangle$: average over target configurations [N(r, **b**)]

Lessons from HERA

Dipole model fits to DIS data

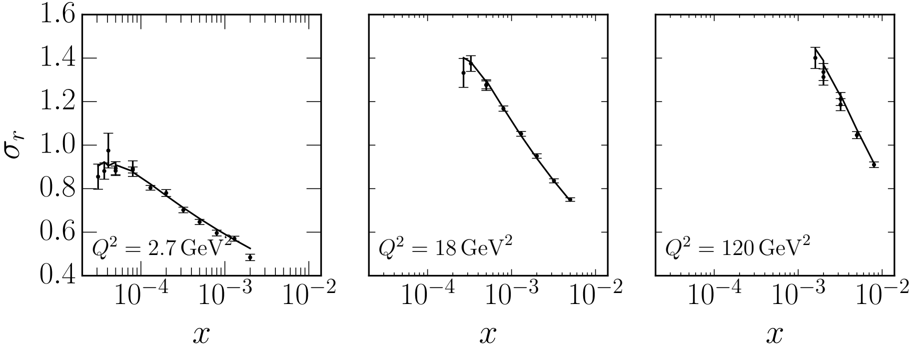
Succesfull fits to precise σ_r data, different forms for the dipole N

- IPsat: parametrized x dependence and geometry, matching to DGLAP

  Kowalski, Teaney 2003, Rezaeian et al, 2012, Mäntysaari, Zurita 2018,...

- Perturbative small-x evolution equations (BK, JIMWLK), usually without impact parameter profile (no diffraction)

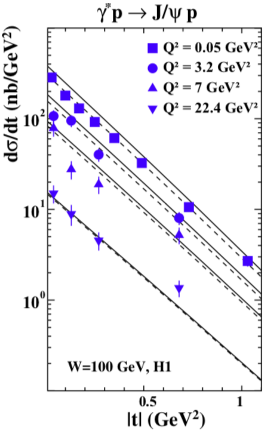
  Albacete et al 2009, Albacete et al 2010, Berger, Stasto, 2012, Lappi, Mantysaari 2013, Mantysaari, Schenke 2018

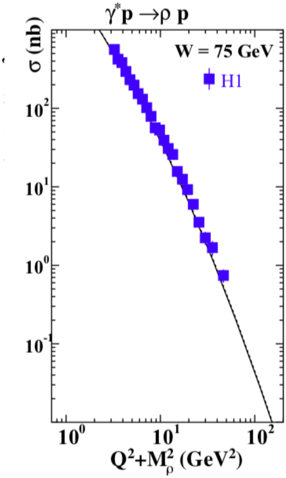


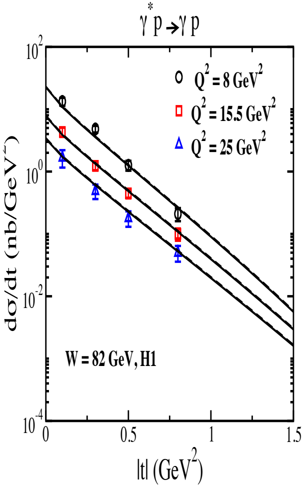
Simultaneous description of exclusive scattering

IPsat parametrization fitted to structure function data:

- Good description of the exclusive $J/\Psi, \rho, \phi, \gamma$ production data







Rezaeian et al, 1212.2974

Beyond the round proton

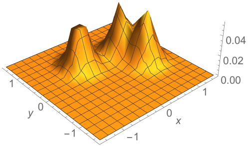
Recall: coherent cross section $\sim$ average, incoherent $\sim$ variance
$\Rightarrow$ need event-by-event fluctuating $N(\mathbf{r},\mathbf{b})$

Constituent quark inspired picture

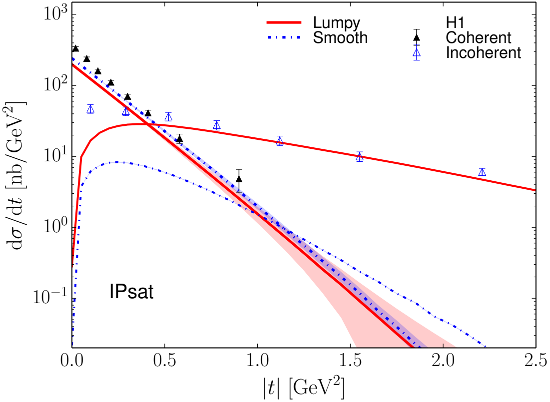
- Sample hot spot substructure
- Geometry and density fluctuations see also Mark's talk on Tue
- Use constraints from coherent and incoherent cross sections (average profile and amount of fluctuations)

Mantysaari, Schenke 2016, 2017, Cepila, Contreras, Takaki 2017, 2018

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



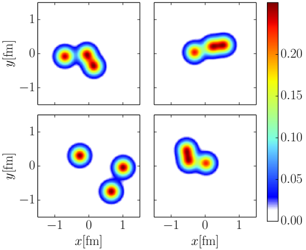
HERA data for $\gamma + p \to J/\Psi + p$



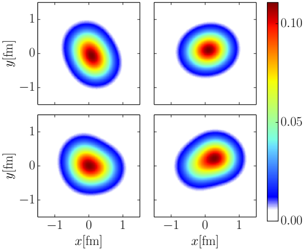
H.M, B. Schenke, PRL 117 (2016), 052301 and PRD94 (2016), 034042

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

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



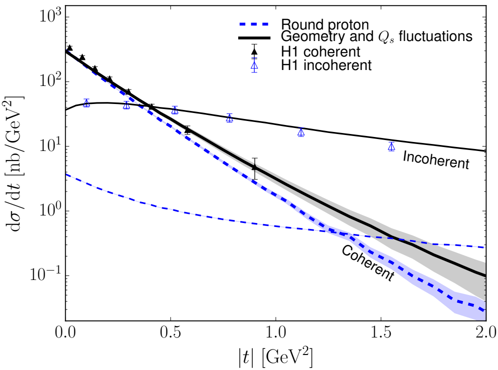
Smooth: $B_{qc} = 1.0, B_q = 3.0$

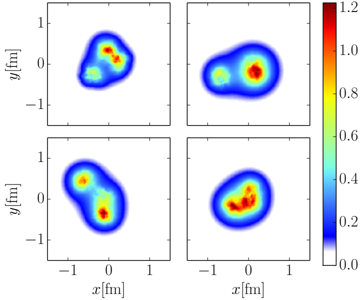


Units: GeV^{-2}

Beyond IPsat

Include color charge fluctuation, solve Yang-Mills equations ⇒ Wilson lines





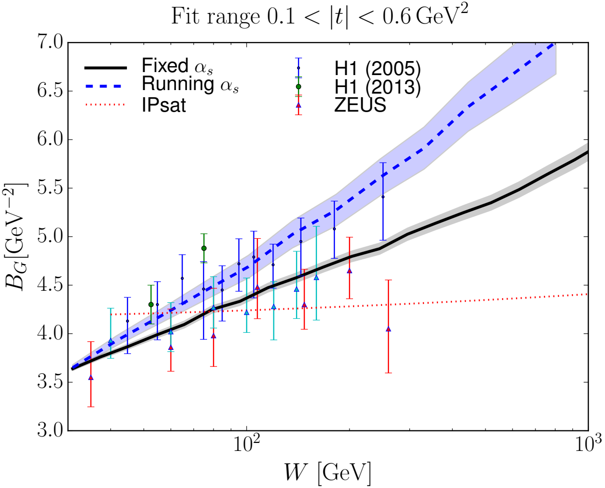
H.M., B. Schenke, PRD94 (2016), 034042

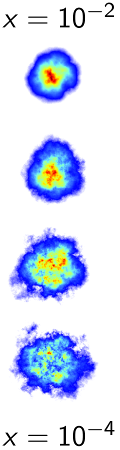
- MV model with *b* dependence, similarly as in "IP-Glasma"
- Initial condition for pA hydro, good description of v_2 and v_3 data!

H.M, Schenke, Chun, Tribedy, 1705.03177

Energy evolution from CGC (round proton)

Size fixed at $W = 30\,\mathrm{GeV}$, α_s and Λ_{QCD} fixed by charm-F_2



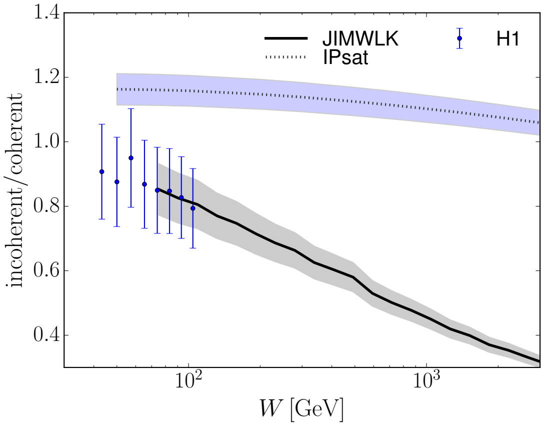


Running α_s: faster evolution at long distance scales. $r_{\mathrm{RMS}} \approx \sqrt{2B_G}$

H.M, B. Schenke, 1806.06783

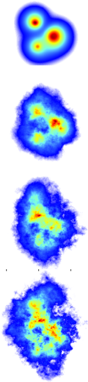
Energy evolution from CGC → smoother proton

Take proton configurations at $W = 75\,\mathrm{GeV}$ and evolve by solving perturbative JIMWMLK evolution equation H.M, B. Schenke, 1806.06783



IR and α_s by charm-F_2 data

$W = 75$ GeV:

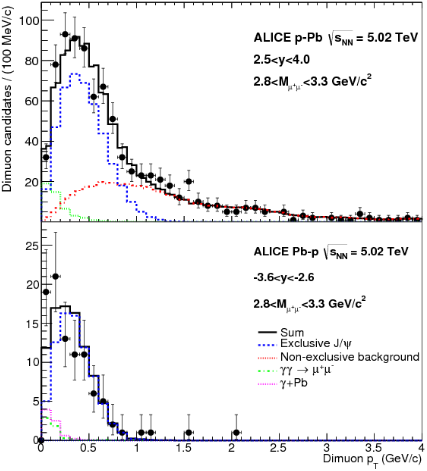


$W = 680$ GeV

H.M, B. Schenke, 1806.06783

Compatible with ALICE data

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



ALICE arXiv:1406.7819

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

- Incoherent cross section not observed at small x
- Signature of smoothening at small x?
    - Smooth transition at intermediate W

      ALICE, QM2018
- Proton grows, diffractive slope $B_p : 4\,\mathrm{GeV}^{-2} \to \sim 6.7\,\mathrm{GeV}^{-2}$

So far so good

Excellent description of a large variety of HERA data.

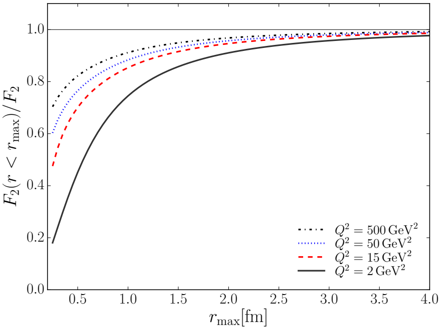
But still large theory uncertainties

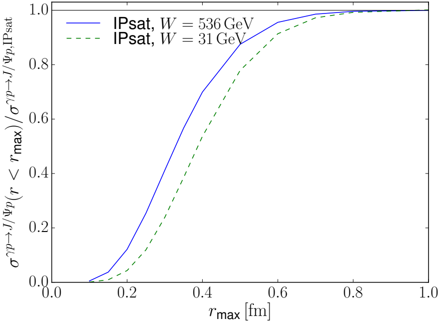
- Significant contribution from dipoles $r \gtrsim 1/\Lambda_{\mathrm{QCD}}$ (more soon)
- Vector meson wave function $\Rightarrow \sim 50\%$ uncertainty
- Skewedness ($x_1 \ll x_2$) $\Rightarrow \sim 50\%$ phenomenological correction
- Higher order corrections (Boussarie, Wed Nov 7)

Description of large dipoles

Even at high Q^2 significant fraction of F_2 comes from dipoles $r \gtrsim 1.5\,\mathrm{fm}$
Diffractive J/Ψ production: need to include up to $\sim 0.7\,\mathrm{fm}$

- Note that $R_{\text{proton}} \sim 0.5\,\mathrm{fm}$



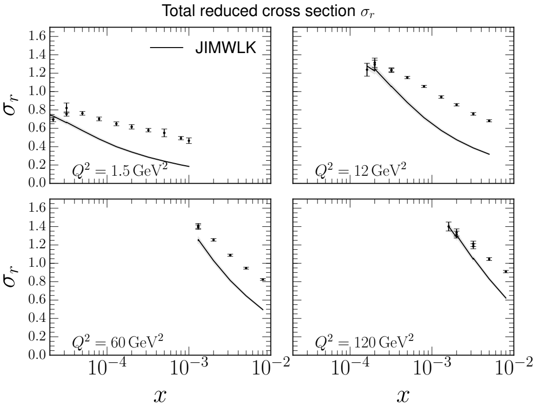


In IP-sat they scatter with probability 1, not the case with JIWMLK

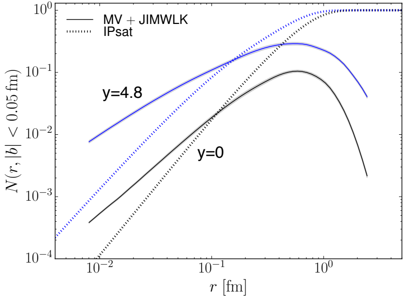
H.M, P. Zurita 1804.05311 , H.M, B. Schenke 1806.06783

Small-x evolution and impact parameter dependence

Initial condition for JIMWLK from charm F_2 data (not sensitive to large r)


Total reduced cross section σ_r

H.M, B. Schenke, 1806.06783

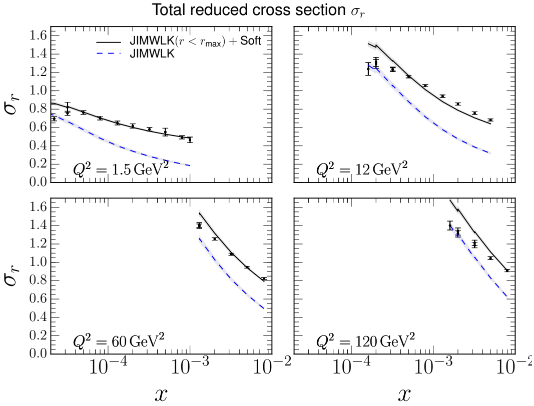


- Total σ_r underestimated (and diffractive cross sections)

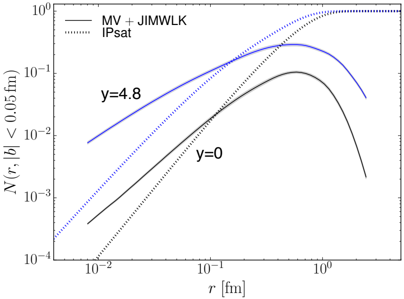
More about large dipole contributions: H.M, P. Zurita, 1804.05311

Small-x evolution and impact parameter dependence

Initial condition for JIMWLK from charm F_2 data (not sensitive to large r)



H.M, B. Schenke, 1806.06783

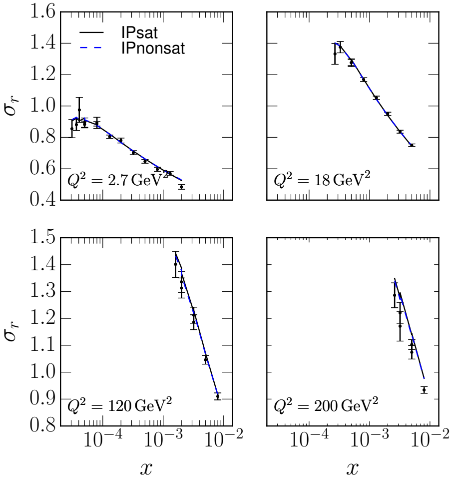


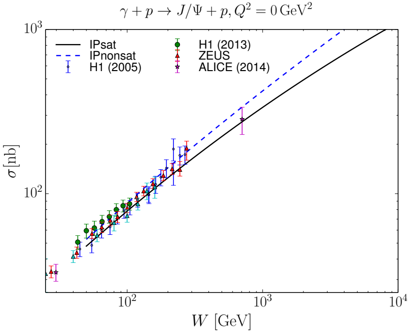
- Total σ_r underestimated (and diffractive cross sections)
- Here: add *non-perturbative* contribution:
  $N(r > R_p) = 1$ Berger, Stasto, 1106.5740
- Comparison to IPsat: differences when $r \gtrsim R_{\text{proton}}$

Higher densities with nuclear targets

Searching for saturation effects

Saturation models describe precise HERA data accurately
Same quality can be obtained with linearized models (here "IPnonsat")





IPsat and IPnonsat fitted to the same σ_r data

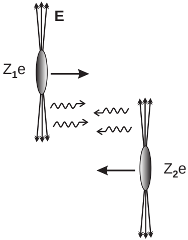
H.M, P. Zurita, 1804.05311

Need higher gluon densities than accessible in $\gamma + p$

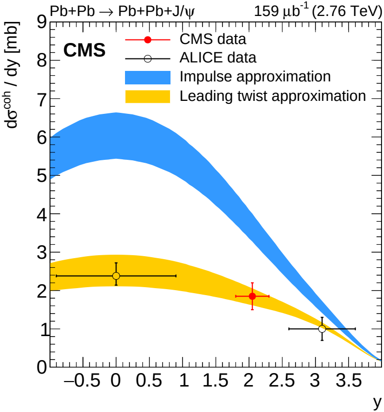
Diffraction off nuclei

- Enhance saturation effects: $Q^2_{s,A} \sim A^{1/3} x^{-\lambda}$ (increasing A is cheaper than decreasing x)
- Varying A at the EIC $\Rightarrow$ probe different Q_s^2 ranges

Already data from UPCs

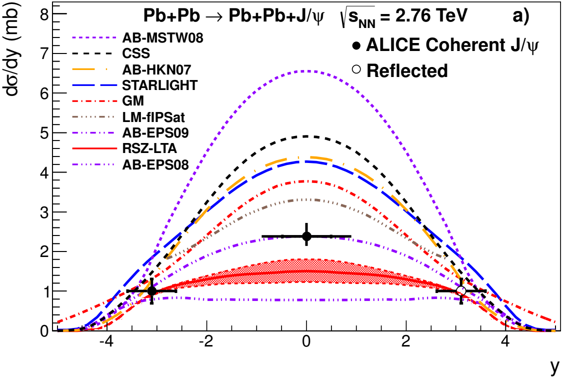


- Momentum fraction $x = M_V e^y / \sqrt{s}$



Clear nuclear effects: impulse approximation is scaled $\gamma + p$

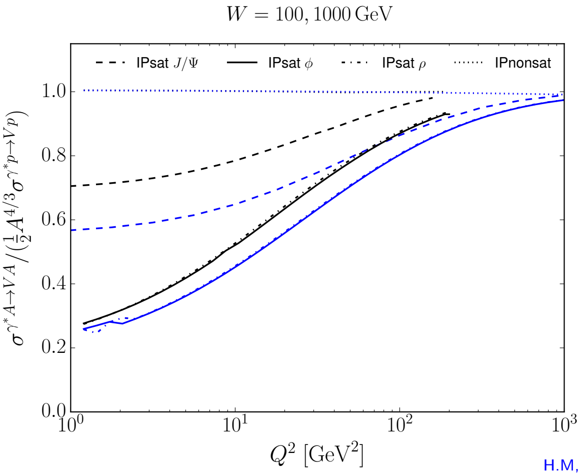
Coherent diffraction, model comparison



ALICE, 1305.1467

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

Large nuclear suppression in vector meson production



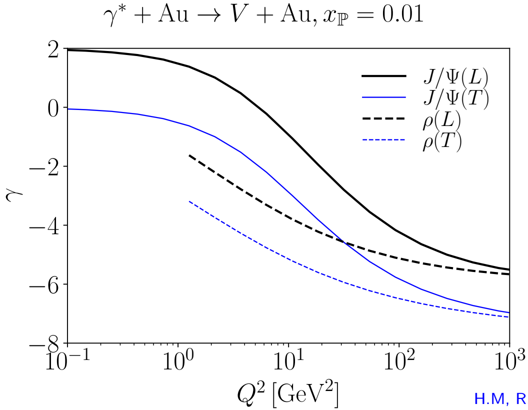
H.M, P. Zurita, 1804.05311

- Especially for heavy mesons expect large nuclear effects
- No suppression with linear IPnonsat parametrization
- Q^2 and A scan at the EIC!

Q^2 lever arm: dilute ↔ transition

High $Q^2 =$ dilute region, saturation effects become visible when $Q^2 \lesssim Q_s^2$

For example: write $\sigma^{\gamma^* \mathrm{Au} \to V + \mathrm{Au}} \sim Q^\gamma$

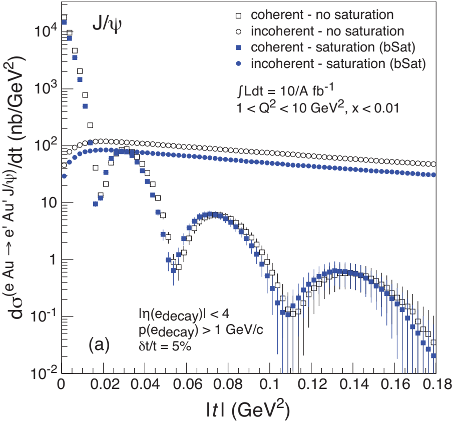


H.M, R. Venugopalan, 1712.02508

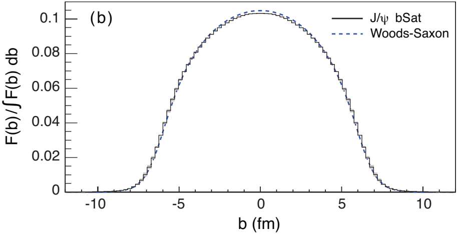
Large effects especially for J/Ψ for which can go to $Q^2 = 0$
But need high energy (Q^2 lever arm) to see the transition

Extract nuclear geometry

Full EIC simulation with expected uncertainties in $\gamma + A \to J/\Psi + A$



Coherent J/Ψ spectra $\Rightarrow$ FT
$\Rightarrow$ Density profile



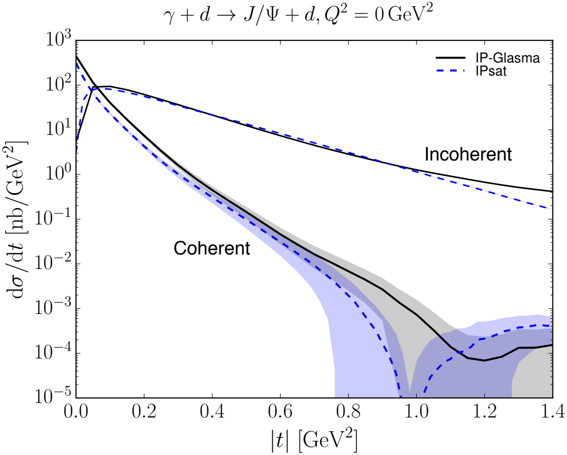
Extract transverse density profile of small-x gluons

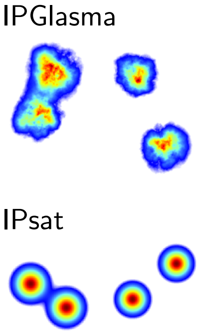
T. Toll, T. Ullrich, 1211.3048

Small nuclei: where are the small-x gluons located

Nucleon positions from Hulthen wave function

IP-Glasma: add color charge fluctuations and (regulated) Coulomb tails



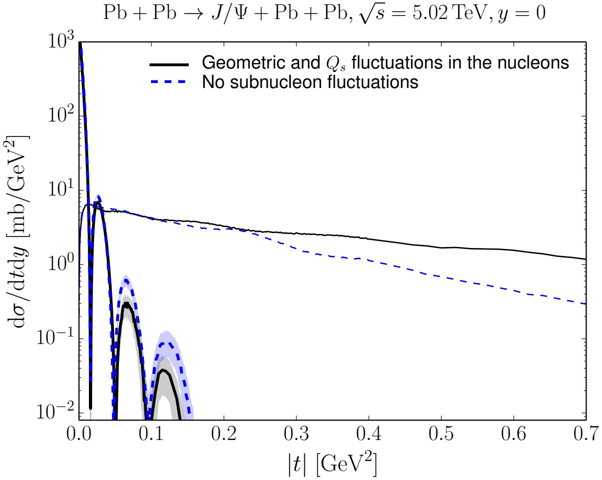


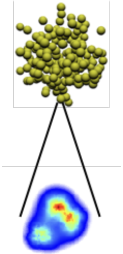
Preliminary

H.M, B. Schenke, in preparation

Fluctuations at different length scales

- Small $|t|$: long length scale, fluctuating nucleon positions
- Large $|t|$: short length scale, fluctuating nucleon substructure





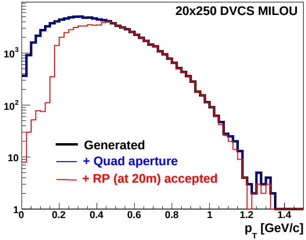
H.M, B. Schenke, 1703.09256

Centrality in diffraction?

Incoherent diffraction: largish p_T kick on small area

- Nucleon scatters off other nucleons on its way out
- More "ballistic nucleons" in central events
- Also nucleons when nucleus decays from excited state
  But with different p_T spectra (thermal in TRF)

"Ballistic protons": end up in the roman pot
⇒ centrality estimator

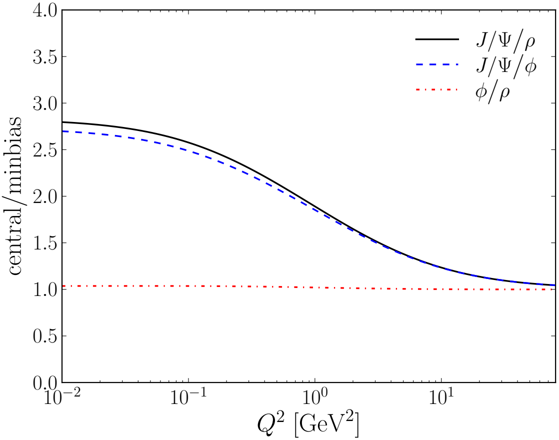


Centrality in diffraction

Larger saturation scale in central events

- Expect to see larger suppression for lighter mesons
- Centrality dependence of Q_s^2

$\gamma + A \to V_1/V_2 + A^*, x_{\mathbb{P}} = 0.005$



Vector meson ratio in central / minbias events

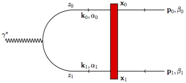
- Light mesons more suppressed at $Q^2 \lesssim Q_s^2$

H.M, T. Lappi, R. Venugopalan,

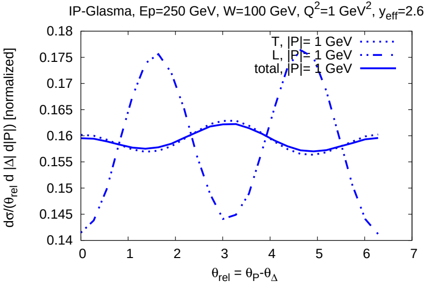
Phys.Rev.Lett. 114 (2015), 082301

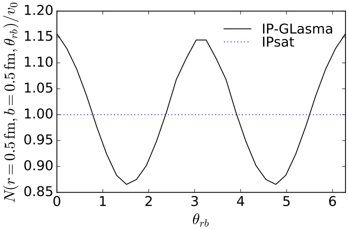
More differential: diffractive dijets

- Two transverse momenta (sum and difference)
  $\Rightarrow$ more detailed probe
- Cross section $\sim$ Wigner distribution Hatta, et al, 1601.01585
- Dependence on dipole orientation (compute from MV)



Altinoluk et al, 1511.07452





Momentum sum-difference angle: $v_2 \neq 0$
IPsat: $v_2 = 0$, no dependence on θ_{rel}

$\sphericalangle(\vec{r}, \vec{b})$: v_2 in IP-Glasma
IPsat: no dependence on θ_{rel}

H.M, N. Mueller, B. Schenke, in progress

EIC era, some thoughts

Complementarity of very high-energy $\gamma - p$ and $\gamma - Pb$ UPC
… and EIC with Q^2 and A lever arm

Possiblitities

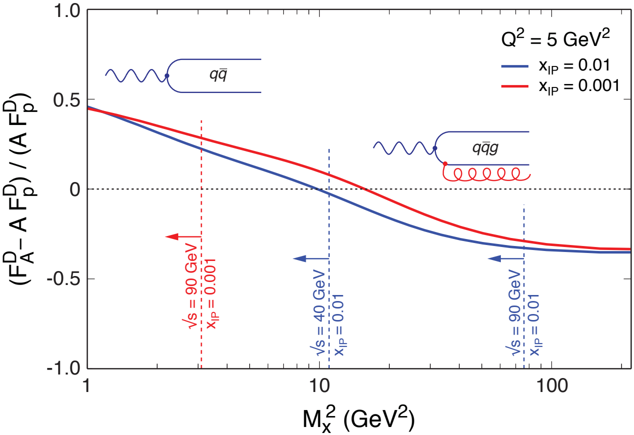
- See clean saturation phenomena
- Precision studies of saturation effects in nuclei at NLO
- Map vector meson wave functions (Q^2 and Q_s^2 [A] lever arm helps)
- Extract Wigner distributions
- Understand confinement (large dipoles, evolution of p or d to small x)
- Inclusive diffraction, large diffractive/total cross section ratio
- Can we do centrality (inclusive or diffractive)

Interesting fundamental physics on its own
+ necessary input to LHC heavy ion physics program

BACKUPS

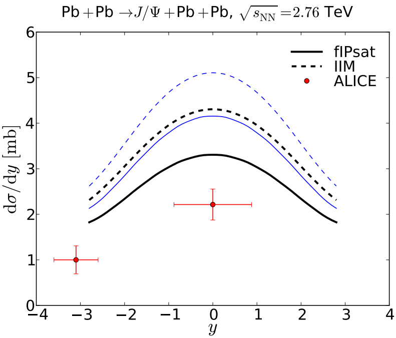
Inclusive diffraction

Higher Fock states are suppressed in the black disk limit



E. Aschenauer et al, 1708.01527, based on Kowalski,Lappi, Marquet,Venugopalan 0805.4071

This is becoming precision physics (linear scale!)



T. Lappi, H.M., 1301.4095

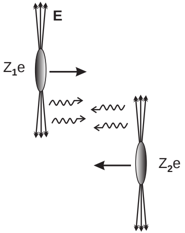
- Model uncertainties mainly affect normalization, not rapidity (Bjorken-x) dependence.(?)

"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???

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

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

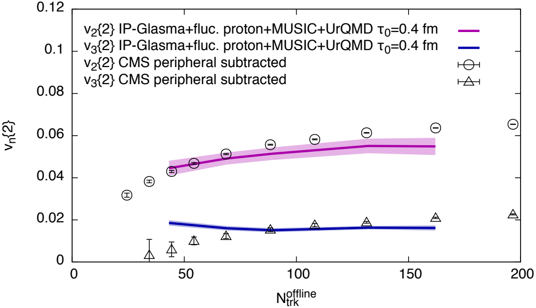
Interesting QCD part: high-energy γ-nucleus or γ-proton scattering.

Fluctuating protons in pA collisions

Hydro calculations with proton fluctuations from HERA

Hydro numbers

- $\tau_0 = 0.4$ 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.

H.M, B. Schenke, C. Shen, P. Tribedy, 1705.03177

Dipole amplitude from IP-Glasma

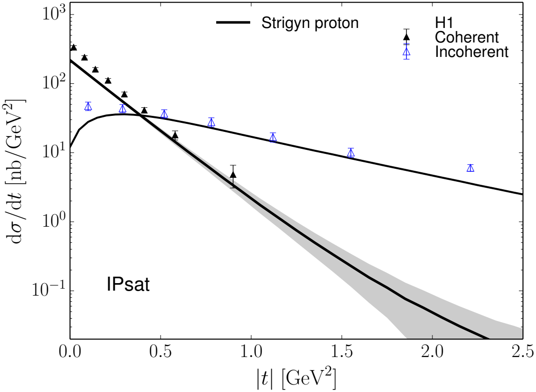
- Obtain saturation scale $Q_s(x_T)$ from IPsat (with fluctuations)
- MV-model: Sample color charges, density $\sim Q_s(x_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

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

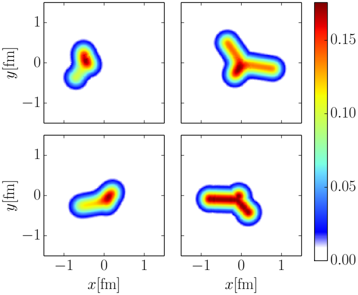
- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr}\, V(x_T) V^\dagger(y_T)/N_c$
- Fix parameters B_{qc}, B_q and m with HERA data

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



Example density profiles



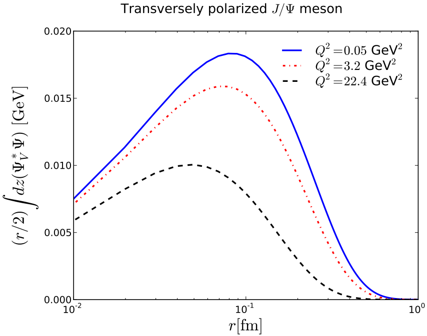
H.M, B. Schenke, PRD94 034042

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

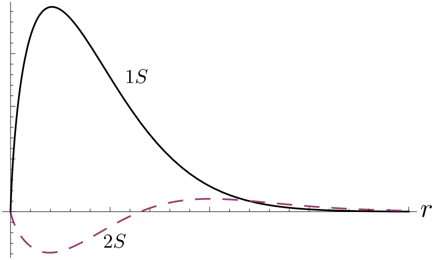
Vector meson wave functions

$\gamma^* \to q\bar{q}$ 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 (IPsat)

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

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