Small x, diffraction, vector mesons

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DIS 2015, Dallas, TX

Outline

This talk:

- Introduction: Small-x DIS in different frames
  - Collinear factorization and dipole picture
  - Gluon saturation
- Advances in small-x theory
  - NLO in BK and applications
  - Connections to TMD factorization, spin physics
- Advances in experiment
  - Ultraperipheral collisions: high energy γ-p & γ-A

Disclaimer: personal bias in selection of topics!

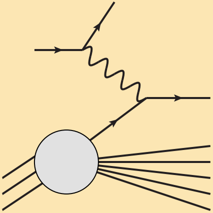
Subjects in WG2 not discussed in this talk:

- Soft diffraction in pp, CEP ... $\Longrightarrow$ several parallel talks in WG2 Goulianos, Brona, Cartiglia, Deile, Adamczyk, Albrow, Wallace
- Diffractive structure functions
- Holography Tan , neutrino processes Reinherz-Aronis, Asaadi, Tian

Introduction:

small x and saturation

DIS in IMF: collinear factorization

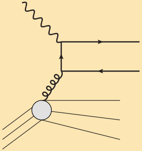


Usual collinear factorization picture:

- Proton, consisting of partons, moves at high energy
- Struck by γ^*: interaction time short $\Longrightarrow$ parton-parton interactions factorize
- Light cone quantized proton

QCD in collinear factorization

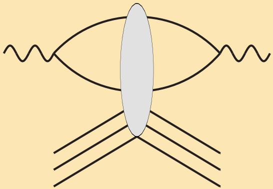
- LO $\gamma^* + q \to q$
- NLO: also γ^*+ parton $\to$ 2 partons + virtual
- High Q^2 logs resummed into DGLAP
- Only requires Q^2 and W^2 high separately



Nonperturbative physics parametrized by PDF's

DIS in dipole frame

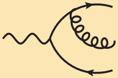
Same process, different frame: γ^* moving fast; not proton



- γ^* consists of partons
- Partons struck by target gluon field: interaction time short $\Longrightarrow$ structure of γ^* frozen

\+ Now we are light cone quantizing γ^*: a very clean object

QCD in dipole picture



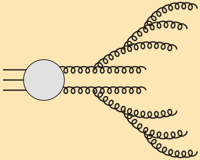
- LO: γ^* is only $q\bar{q}$ dipole
- NLO corrections: also include $\gamma^* \to q\bar{q}g$
- High W^2 logs resummed into BK/BFKL

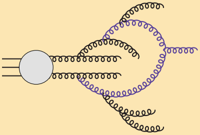
\- This is possible only when $W^2 \gg Q^2$ $\Longrightarrow$ difficult matching to valence region

Nonpert. physics parametrized by q/g+p scattering amplitudes

Gluon saturation in IMF: nonlinear interactions

- Evolution with Q^2 or x: cascade of gluons
- At some point phase space density of gluons large $\Longrightarrow$ nonlinear interactions
- When? Depends on
  - Size of one gluon $\sim 1/Q^2$
  - Transverse space available
  - Coupling



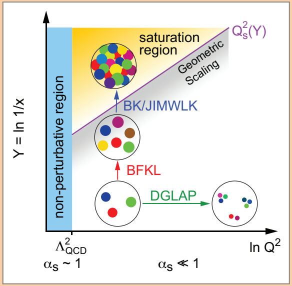


Saturation from gluon mergings

Nonlinear gluon interactions lead to

$$\pi R_p^2 \sim \alpha_s x G(x, Q_s^2)/Q_s^2$$

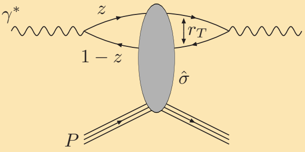
"Phase diagram":



WG2 talk Praszalowicz

(This is not a very convenient way to calculate!)

Gluon saturation in dipole picture: unitarity



- Proton described by dipole scattering amplitude $\mathcal{N}$, cross section $\sigma = 2\int d^2\mathbf{b}_T \mathcal{N}$
- Black disk limit: $\mathcal{N} \le 1$
- Dilute target $\Longrightarrow$ two gluon exchange:

$$\sigma \sim 2\pi R_p^2 \mathcal{N}(r) \sim \alpha_s r^2 xG(x, Q^2 \sim 1/r^2)$$

2-gluon exchange not valid for $Q^2 \sim \frac{1}{r^2} \lesssim Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R_p^2}$

Gluon saturation in dipole picture

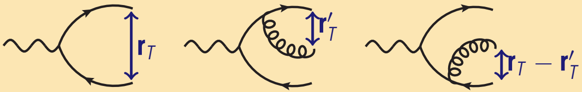
Gluon saturation appears as a unitarity constraint
$\Longrightarrow$ Must be built into formalism; not a result of dynamics.
Typically in CGC: eikonal interaction described by Wilson line

$$V = \mathbb{P}\exp\left\{-ig\int dx^+ A^-\right\} \quad \mathcal{N}(\mathbf{x}_T - \mathbf{y}_T) = 1 - \frac{1}{N_c}\left\langle \operatorname{Tr} V^\dagger(\mathbf{x}_T) V(\mathbf{y}_T)\right\rangle$$

Small x theory in the nonlinear regime

NLO evolution

What's going on today? WG2 talks: Lublinsky, Chirilli, Madrigal, Grabovskiy, TL



(Integrate over gluon; leading soft divergence gives evolution equation)

Balitsky-Kovchegov equation, ∼1995

$$\partial_y \mathcal{N}(\mathbf{r}_T) = \frac{\alpha_s N_c}{2\pi^2} \int d^2\mathbf{r}'_T \frac{{\mathbf{r}_T}^2}{{\mathbf{r}'_T}^2 (\mathbf{r}'_T - \mathbf{r}_T)^2} \left[\mathcal{N}_{\mathbf{r}'_T} + \mathcal{N}_{\mathbf{r}_T - \mathbf{r}'_T} - \mathcal{N}_{\mathbf{r}'_T} \mathcal{N}_{\mathbf{r}_T - \mathbf{r}'_T} - \mathcal{N}_{\mathbf{r}_T} \right]$$

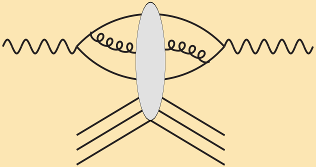
- Linear limit: BFKL: LO & NLO Talk: Hentschinski for recent progress
  - Resummation in Mellin space: Salam, Ciafaloni, Forte ...
- NLO BK equation Balitsky, Chirilli 2008
  - Direct solution shows same problems as NLO BFKL Talk TL
  - No Mellin space resummation for BK (nonlinear)
  - How to resum directly in coordinate space? Talk Madrigal
  - State of the art for phenomenology is still LO+running α_s
- BK is mean field approx for nonlinear term
  - Full correlations = Balitsky hierarchy = JIMWLK: LO 1997
  - NLO becoming reality: Talks: Lublinsky, Chirilli, Grabovskiy

NLO processes 1: DIS

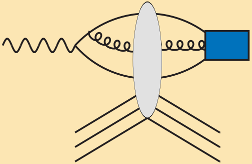
Not only evolution, but observables at NLO

DIS: NLO is $q\bar{q}g$ state in dipole:

- Soft log factorized into BK evolution of target
- Rest is NLO "γ^* impact factor"
- Derived Balitsky, Chirilli 2010, Beuf 2011
- Not applied yet



NLO corrections for exclusive processes?

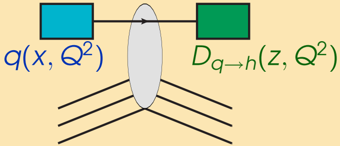


NLO 2: Particle production in forward pA

WG2 talks: Kovner, Stasto, Altinoluk, Kang, Wertepny

Particle production in forward pA:
"hybrid formalism"

- Quark/gluon from collinear pdf
  (large-x)
- LO: deflected by target field



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Particle production in forward pA: “hybrid formalism”

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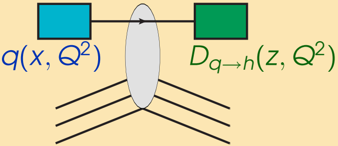
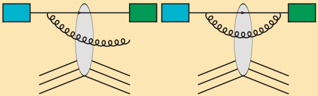
- LO: deflected by target field
- NLO: 1-loop virtual and radiative corrections
- 1-loop factorization formulae
  Chirilli, Xiao, Yuan 2011
  - Soft divergence: target BK
  - Collinear: DGLAP for pdf, FF
  - Rest: “hard function”





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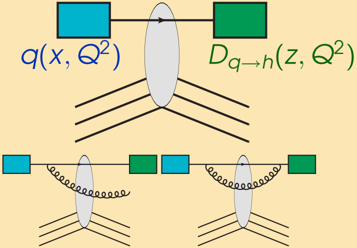
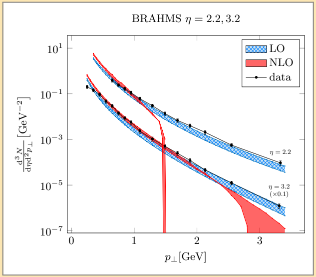
  - Soft divergence: target BK
  - Collinear: DGLAP for pdf, FF
  - Rest: "hard function"
- Result Stasto et al : NLO cross section negative at large p_T. Why? Expect many discussions this week Recent papers by Kang et al, Altinoluk et al





Connections to TMD & spin physics

WG2 talks: Kotko, Dumitru, Yuan, Tarasov

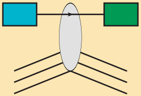
- TMD-distribution: conventional operator definition

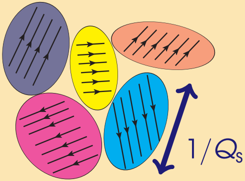
$$xG(x,\mathbf{k}_T) = \int \frac{dx^- \, d^2\mathbf{x}_T}{(2\pi)^3 P^+} e^{ixP^+x^- - i\mathbf{k}_T\cdot\mathbf{x}_T} \langle P|F^{+i}(x^-,\mathbf{x}_T)\mathcal{L}F^{+i}(0)|P\rangle$$

(Different gauge link $\mathcal{L}$ for different processes + generalizations for spin)

- Starting from Dominguez et al 2011 : systematically relate these to Wilson line correlators in CGC $\Longrightarrow$ very fruitful connections!

Example: azimuthal correlations WG2 talk Dumitru





- q/g sees target color E-field
- domains of size $\sim 1/Q_s$
- multiparticle azimuthal correlations: seen in pA expt!
- related to linearly polarized gluon distribution

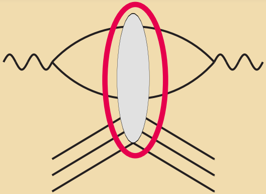
Exclusive processes,

vector mesons

Diffractive/exclusive processes in dipole picture

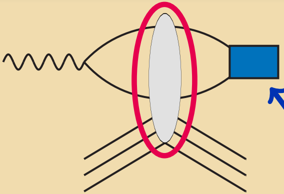
WG2 talks: Rezaeian, Gay-Ducati, Tuchin

Total cross section



$\sigma_{\mathrm{tot}} \sim$ forward elastic $q\bar{q}$-target amplitude (via optical theorem)

Diffractive DIS



Diffractive cross section $\sim$ |same amplitude|^2.

Same QCD-evolved amplitude describes both

Unified description is a major advantage of the dipole picture

- Vector mesons: also need meson light cone wavefunction
- Often quoted formula $\frac{d\sigma^{\gamma^* H \to VH}}{dt} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{\mathrm{em}} M_V^5} \left[xg(x, Q^2) \right]^2$ is the hard scattering limit of the dipole calculation.

Diffraction: proton target

WG2 talks: Scmitt, Adamczyk, Kovalchuk, Bussey

- ZEUS $\frac{\sigma(\Psi(2S))}{\sigma(J/\Psi)}$: important constraint for VM wave functions
  talk: Kovalchuk
- H1 & ZEUS diffractive dijets talks: Scmitt & Adamczyk
- ZEUS: diffractive isolated photons talk: Bussey

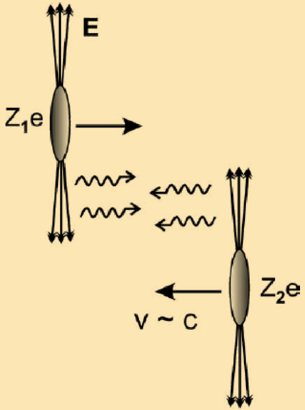
  $\Longrightarrow$ no wave function uncertainty, thus in principle cleaner

These + combined HERA σ^{D}_{tot} (slightly less recent) not yet fully utilized by small-x theory community

on my personal to do-list!

UPC: diffractive γ A at a hadron collider

- Range of strong interaction $\sim 1/m_\pi \sim 1$fm
- Range of electromagnetic force ∞
- Impact parameter $b > 2R_A$
  $\Longrightarrow$ **photon-nucleus** collision
- At LHC look for **exclusive** events: nucleus intact



$Q^2 = 0 \Longrightarrow$ to have hard scale must have heavy quark

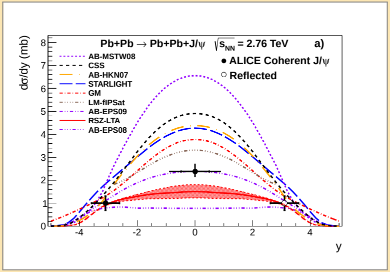
Would need an EIC to add a new Q^2-dimension to these results.

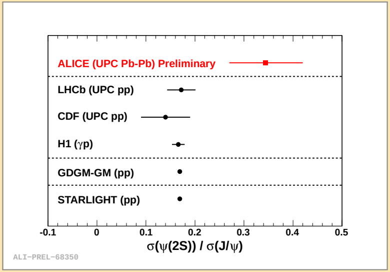
UPC: nuclear target

WG2 talks: Nystrand, Murray, Adam

UPC vector meson data from ALICE, LHCb (γp), CMS

- Rapidity $\sim$ gluon x
- J/Ψ, $\Psi(2S)$, most recently ρ_0, Υ (?)
  - Many species good for systematics of wave functions
  - ALICE $\sigma(\Psi(2S))/\sigma(J/\Psi)$ result very surprising! $\Longrightarrow$





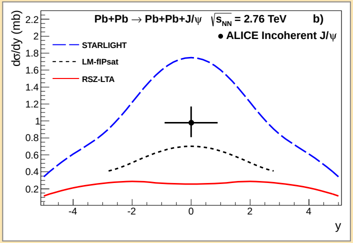
More to come

Many measurements still statistics limited.
$\Longrightarrow$ will improve with new LHC PbPb runs.

UPC: coherent, incoherent

WG2 talk: Ullrich

ALICE also has incoherent J/Ψ
= nucleus breaks up.



ALICE separates by $p_{T,J/\Psi}$

$$Q^2 = 0 \implies -t \approx p^2_{TJ/\Psi} = p^2_{TA}$$

- Coherent $-t \sim \frac{1}{R_A^2} \sim 0.01\text{GeV}^2$
- Incoherent $-t \sim \frac{1}{R_p^2} \sim 1\text{GeV}^2$

Underutilized constraint!
$\implies$ Rich physics topic at EIC

Coherent: average gluon density in transverse plane

$$\frac{d\sigma^{\gamma^* A \to VA}}{dt} = \frac{1}{4\pi} \left|\langle \mathcal{N} \rangle_N\right|^2$$

Incoherent: fluctuations of gluon density

$$\frac{d\sigma^{\gamma^* A \to VA^*}}{dt} \sim \left\langle |\mathcal{N}|^2 \right\rangle_N - \left|\langle \mathcal{N} \rangle_N\right|^2$$

- Interpretation explicit in SARTRE event generator,
  Ullrich & Toll
- TL, Mäntysaari, Venugopalan proposal
  Centrality selection in incoherent diff at EIC.

Conclusions

- Tremendous recent progress in small-x theory in the nonlinear regime:
  - Pushing calculations to NLO level
  - Exploring connections to spin, TMD physics

  But still a lot to do to turn ideas into precision phenomenology!
- While waiting for the EIC and LHeC, interesting data from:
  - UPC: vector mesons
  - Final HERA analyses

  These still need to be understood by the theory community