Ultraperipheral collisions and low-x physics

T. Lappi

University of Jyväskylä

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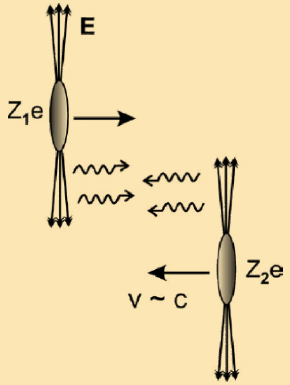
Ultraperipheral collisions

Highly charged heavy nucleus:
source of photons

- Quasi-real photons $Q^2 = 0$
- Photon flux & polarization calculable

$\Longrightarrow$ High energy γ+A, $\gamma + p$, $\gamma + \gamma$
available at LHC & RHIC

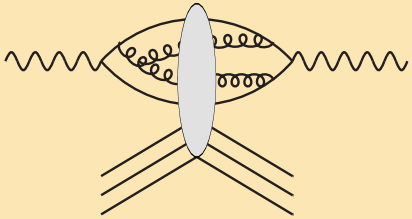


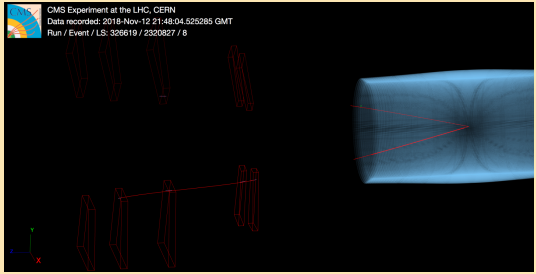
Outline

This talk: small-x — mostly related to UPC

- Dipole picture of DIS, the CGC: recent developments
- Exclusive processes in collinear factorization
- Vector meson production in UPC
- Other UPC measurements

(Trying to point out related talks at DIS2021, apologies for the ones I missed!)



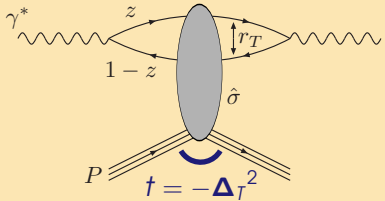


Dipole picture of DIS, CGC

The dipole picture of DIS

Small x in target rest frame: DIS dominated by QCD components of virtual photon

"Dipole cross section" =
elastic forward scattering amplitude of $q\bar{q}$ dipole.



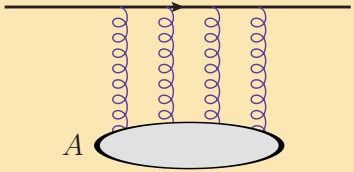
$$\sigma_{\text{dip}}(x,\mathbf{r}_T) = 2\int \mathrm{d}^2\mathbf{b}_T \mathcal{N}(x,\mathbf{r}_T,\mathbf{b}_T) \quad ; \quad \int \mathrm{d}^2\mathbf{b}_T e^{i\boldsymbol{\Delta}_T\cdot\mathbf{b}_T}$$

Predictive power: From **same amplitude** calculate different DIS processes

- Total $\gamma^* p/\gamma^* A$: $\sigma_{\text{tot}}^{\gamma^* H} = |\Psi(\gamma^* \to q\bar{q})|^2 \otimes \sigma_{\text{dip}}$ (Optical theorem) $(\otimes \equiv \int_0^1 \mathrm{d}z\, \mathrm{d}^2\mathbf{r}_T)$
- Inclusive diffraction: $\frac{\mathrm{d}\sigma^{\gamma^* H\to X+H}}{\mathrm{d}t} = \frac{1}{4\pi}|\Psi(\gamma^* \to q\bar{q})|^2 \otimes |\mathcal{N}(\boldsymbol{\Delta}_T)|^2$,
- Exclusive vector mesons: $\frac{\mathrm{d}\sigma^{\gamma^* H\to VH}}{\mathrm{d}t} = \frac{1}{4\pi}|\Psi(\gamma^* \to q\bar{q}) \otimes \mathcal{N}(\boldsymbol{\Delta}_T) \otimes \Psi^*(q\bar{q}\to V)|^2$
- **+** inclusive particle production and correlations in pp, pA, AA

Dipole cross section in CGC

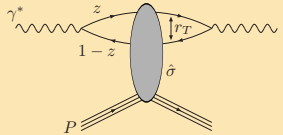
High energy/small x: scattering amplitude is eikonal Wilson line in strong **color field**



$$U(\mathbf{x}_T) = P \exp\left\{ ig \int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-) \right\}$$

- CGC: dipole cross section is Wilson line correlator

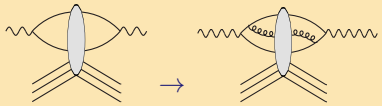
$$\sigma_{\mathrm{dip}}(\mathbf{r}_T) = 2 \int \mathrm{d}^2\mathbf{b}_T \frac{1}{N_c} \mathrm{Tr} \left\langle 1 - U^\dagger\left(\mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) U\left(\mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right) \right\rangle$$



- Sources for color field: large x partons
- Gluon saturation built in as unitarity requirement

Talk Dumitru: Color charge correlations in the proton at moderately small x

NLO calculations in CGC: recent progress



$$\sigma \sim \overbrace{\mathcal{O}(1)}^{\text{LO}} + \overbrace{\mathcal{O}(\alpha_s \ln 1/x)}^{\text{LL}} + \overbrace{\mathcal{O}(\alpha_s)}^{\text{NLO}} + \overbrace{\mathcal{O}(\alpha_s^2 \ln 1/x)}^{\text{NLL}}$$

- BK/JIMWLK evolution Balitsky, Chirilli 2008, Grabovsky, Lublinsky, Mulian et al 2012
  + collinear resummations Iancu, Triantafyllopoulos et al $\sim$ 2015
- Total DIS cross section $m_q = 0$ Balitsky, Chirilli 2010, Beuf 2011-2017, HERA fit Hänninen et al 2020
  Talk Hänninen: Next-to-Leading Order Dipole Picture fits to HERA data
  Also inclusive $\gamma + 2j$ Roy, Venugopalan 2019
- Diffractive dijets in DIS Boussarie et al 2014
- Exclusive light vector mesons (with PDA's) Boussarie et al 2016

Under way

- Exclusive quarkonium (with NRQCD) Escobedo, T.L. 2019, Penttala et al 2020, 2021
  Talks Escobedo: The dipole picture and the NR expansion, Penttala: Higher-order corrections ...
- Diffractive structure functions
- Total DIS cross section with massive quarks Beuf, T.L., Paatelainen

+ Much related activity in hadron production in fwd rapidity hh-collisions

Photon wavefunction at NLO

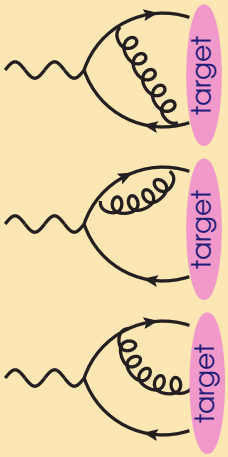
- Dipole picture approach: light-cone quantize photon
- Basic building block: light cone wave function for $\gamma^* \to q\bar{q}$

$$|\gamma*\rangle_D = |\gamma*\rangle_B + \psi^{\gamma\to q\bar{q}}\,|q\bar{q}\rangle_B + \psi^{\gamma\to q\bar{q}g}\,|q\bar{q}g\rangle_B + \dots$$

- Last frontier of perturbation theory at 1 loop: Hamiltonian perturbation theory in LC gauge
- Recently major technical progress
  - $\gamma^*_{T,L} \to q\bar{q}$ for massless quarks: Beuf 2016, Paatelainen et al 2017
  - $\gamma^*_L \to q\bar{q}$ with quark mass: Beuf, T.L. Paatelainen 2021, γ_T soon
  - Similar $q \to qg$: Iancu, Mulian 2020

Note no "CGC" in $\psi^{\gamma\to q\bar{q}}$ (This is $\sim$ impact factor for γ^*)
But crucial for CGC calculations (Combined with tree level $\gamma^* \to q\bar{q}g$)

- F_2, F_L Fit to HERA Hänninen 2020
- Exclusive: $\gamma^{(*)} + A \to V.M. + A$ L polarization Mäntysaari, Penttala 2021
- F_L^c, soon F_2^c, $F_{2,L}^D$



Vector meson wave functions

Vector meson light cone wavefunctions

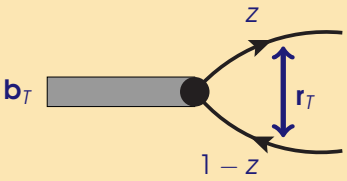
- Several phenomeonological parametrizations
- Solve nonrelativistic bound state equation

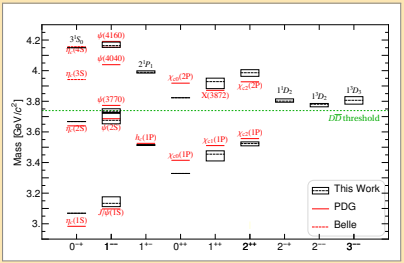
  Krelina, Nemchik et al
- BLFQ: Nonpertubative bound state LCWF with AdS-motivated confining potential

  Y. Li, P. Maris, X. Zhao, J. P. Vary et al
- Nonrelativistic QCD: Expansion around $m_q = \infty$ with nonpert. coefficients from data, available at NLO

  M. Á. Escobedo and T.L. 2019,
  T.L., H. Mäntysaari and J. Penttala 2020
  H. Mäntysaari and J. Penttala 2021

Talks Escobedo, Penttala.
Also need NRQCD in inclusive: see talk Taels





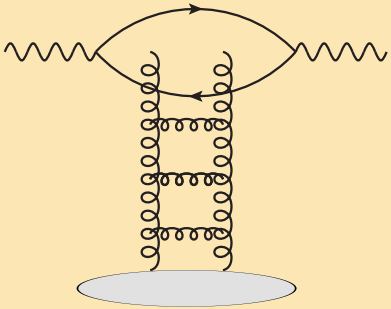
(BLFQ fit Li, Maris, Zhao, Vary 2015)

Collinear factorization picture

Dipole cross section in the dilute limit

Connection to pdf's

- σ_{dip}: **elastic** scattering amplitude:
  color neutral state out
  $\Longrightarrow$ Exchange vacuum quantum numbers;
  "pomeron"
- Simplest color neutral QCD state: 2 gluons
- 2-gluon exchange in amplitude
  $\sim$ 1-gluon cross section
  $\Longrightarrow$ gluon distribution



Perturbative estimate; valid for small dipoles

$$\sigma_{\text{dip}}(\mathbf{r}_T) = \frac{\pi^2}{N_c}\alpha_s(\mu^2)xg(x,\mu^2)\mathbf{r}_T{}^2$$

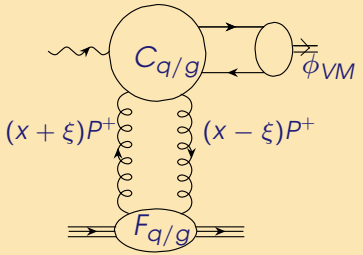
GPD factorization

At NLO "rough estimate" not enough.
Collinear factorization

Coefficient function

$$\mathcal{A} \sim \int_{-1}^{1} dx \left[\overbrace{C_g(x,\xi)}\, F_g(x,\xi) + \sum_{q=u,d,s} \overbrace{C_q(x,\xi)}\, F_q(x,\xi) \right] \phi_{VM}$$

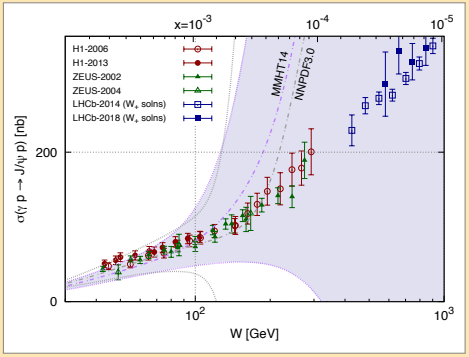
Generalized Parton Distribution



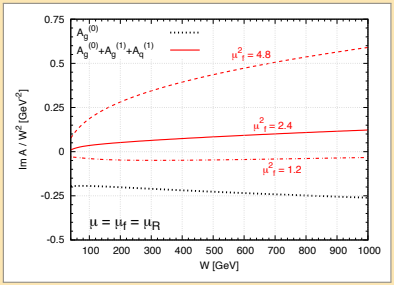
- Collinear distributions: strongly ordered transverse momenta
- Two-gluon exchange: keep track of longitudinal momenta $x+\xi$, $x-\xi$
- Relate GPD to PDF at small x: "Shuvaev transform"
- So far fully nonrelativistic meson wavefunction

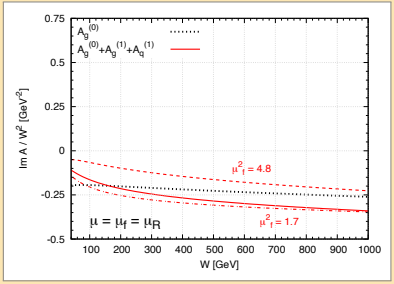
From exclusive vector mesons to PDF's

- NLO corrections large
  (can change sign of amplitude)
- Scale dependence now getting resolved
  Jones et al
- First comparisons with existing PDF's available



(Figures C. Flett et al arXiv:1912.09128)





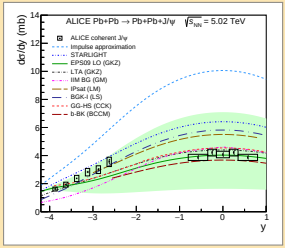
Vector mesons

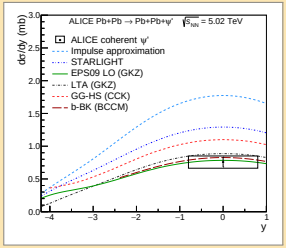
Coherent vector meson data

Mainstay of UPC program: vector meson exclusive photoproduction

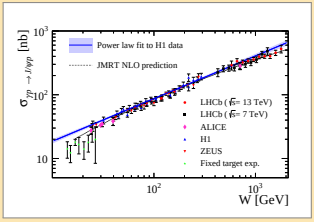
- Initially statistics-limited, but measurements more detailed all the time

Talks:
– Pozdnyakov: Coherent photoproduction of ρ^0 vector mesons in ultra-peripheral Pb-Pb and Xe-Xe collisions with ALICE
– Schmidke: J/Psi production in ultra-peripheral heavy-ion collisions at RHIC
– Luszczak: Coherent photoproduction of J/Ψ in nucleus-nucleus collisions in the color dipole approach – an update.





(ALICE $\gamma + A \to J/\Psi + A$ & $\gamma + A \to \Psi' + A$)



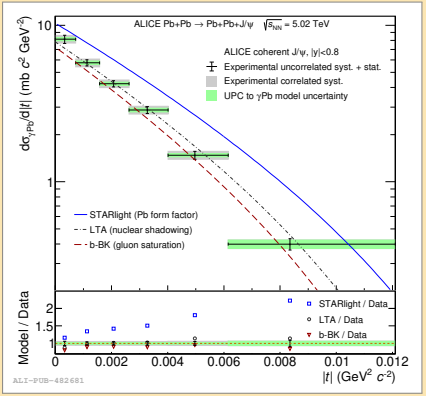
(LHCb $\gamma + p \to J/\Psi + p$ vs. W)

t-distribution in coherent $\gamma + A \to J/\Psi + A$

ALICE arXiv:2101.04623

- These are very small numbers!
  Extracted from J/Ψ decay leptons
  (cannot measure scattered nucleus)
- EIC will have larger t;
  (But how does precision compare?)
- Generally interesting steep t-distribution.
  Qualitatively expected from saturation
  (but b-BK has saturation and is not steep enough. . .)

Talk Krelina: Momentum transfer dependence of heavy quarkonium electroproduction

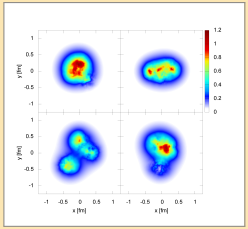


Target breakup: Good-Walker picture

Coherent = target intact:

$\Longrightarrow$ Average gluon density

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



Incoherent = target breakup:

$\Longrightarrow$ Fluctuations of gluon density

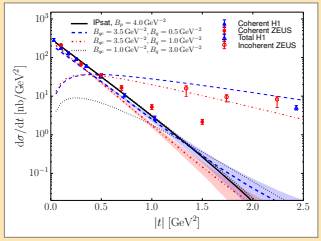
$$\frac{\mathrm{d}\sigma^{\gamma^* A\to VA^*}}{\mathrm{d}t} \sim \left\langle\left|\mathcal{N}\right|^2\right\rangle_{\mathrm{N}} - \left|\langle\mathcal{N}\rangle_{\mathrm{N}}\right|^2$$

Transverse imaging of nucleon & nucleus: measure both!

Talks

– Mäntysaari: Gluon imaging using azimuthal correlations in diffractive scattering at the Electron-Ion Collider

– Toll: Intranuclear fluctuations in eA collisions with Sartre

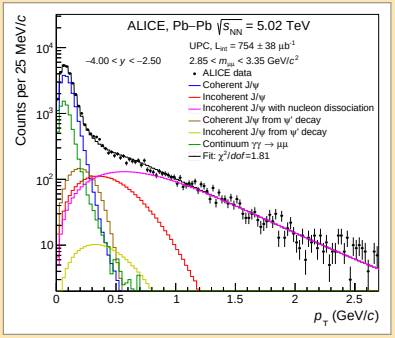


(HERA data & IPsat model)

Nuclear breakup data

At LHC (& EIC): do not measure recoil nucleus

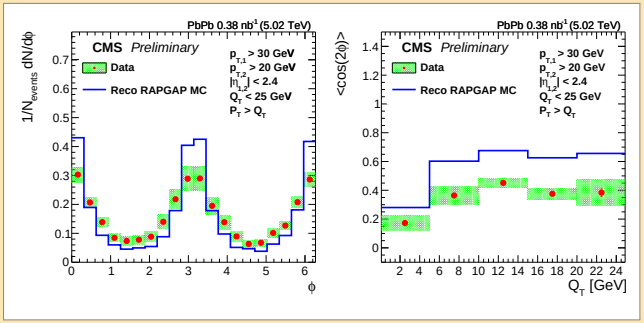
- LHC experiments separate by template fitting t-distribution
- Want to see more of these turned into incoherent cross sections!
- Protons at EIC: can measure recoil and separate (what about $\gamma + p$ @LHC ?)
- Nuclei at EIC: can we understand breakup **?**



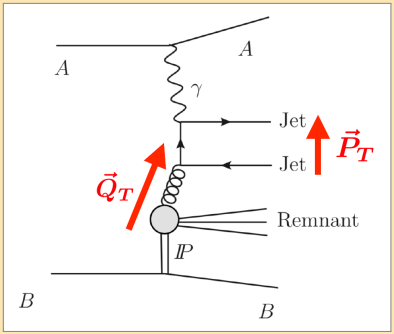
Talk Wan Chang: Investigations of coherent production background and eA collision geometry using forward particles at the EIC

Other UPC measurements

Exclusive dijets in $\gamma + A$



(CMS-PAS-HIN-18-011)



- Access to TMD, gluon polarization, Wigner
- LHC: can go to large p_T
- EIC: kinematics more limited

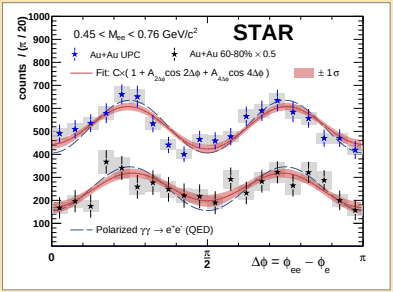
$\mathbf{Q}_T = \mathbf{p}_{T1} + \mathbf{p}_{T2}$
$\mathbf{P}_T = \frac{1}{2}(\mathbf{p}_{T1} - \mathbf{p}_{T2})$
$\varphi = \varphi_{\mathbf{Q}_T, \mathbf{P}_T}$

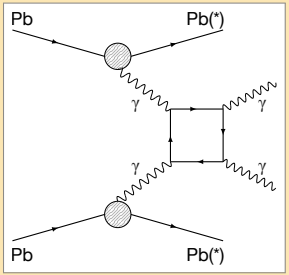
Talks:
– Salazar Searching for gluon saturation in forward dijet/dihadron measurements at the EIC
– Helenius Photoproduction of diffractive dijets in Pythia 8

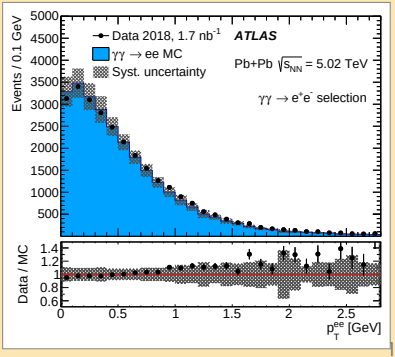
Non-QCD final states

- $\gamma + \gamma \to \gamma + \gamma$
- $\gamma + \gamma \to \ell^+\ell^-$
- New physics searches
- Understand photon flux, polarisation, k_T-depedence

Talk Harland-Lang: Physics from Photons at the LHC



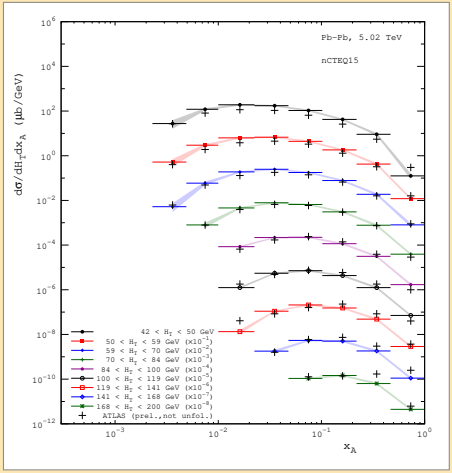




Inclusive: dijets

- ATLAS measurement of $\gamma + A \to 2j + X$
- Preliminary data from 2017; would be good to see this finalized!
- Here, pQCD vs. unfolded data

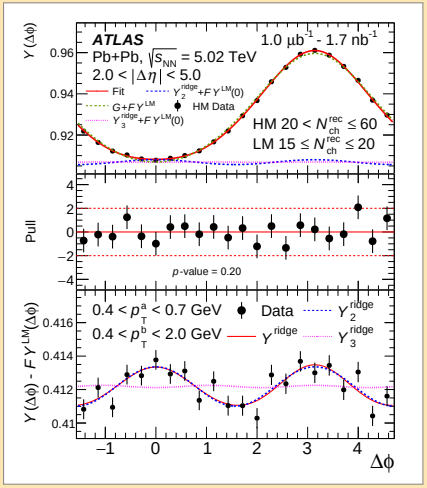
Talks
– Guzey: Inclusive and diffractive dijet photoproduction in ultraperipheral heavy ion collisions at the LHC
– Flore: NLO inclusive J/Ψ photoproduction at large PT at HERA and the EIC



(Guzey, Klasen 2018)

Inclusive: azimuthal anisotropy

- Hadronic, component in photon
  $\Longrightarrow$ like a ρ-meson-nucleus collision
- Look for collective phenomena as in a heavy ion collision
- HI-type analysis: N_{ch} classes, in high N_{ch} collisions extract "flow" modulation in $\Delta\phi$-correlation



(ATLAS, arXiv:2101.10771)

Conclusions

- Lots of theory advances recently going to NLO
  both in dipole and collinear pictures
- New high energy $\gamma - p$, $\gamma - A$ measurements from LHC and RHIC
  $\Longrightarrow$ Access to gluon content & geometry of the nucleus and nucleon
- Strong complementarity with EIC
  - UPC: higher energy, but $Q^2 \approx 0$ $\Longrightarrow$ heavy quark or jet to stay perturbative
  - EIC: leverarm in Q^2 turns new final states into perturbative probes