QCD at the high-energy frontier

T. Lappi

University of Jyväskylä, Finland

Spåtind Nordic Particle Physics Meeting, Gausdal 2020

Outline

Topic of this talk

- What does a proton/nucleus look like probed at $\sqrt{s} \gg p_T \gg \Lambda_{\mathrm{QCD}}$?

  (In practice $x \sim p_T/\sqrt{s}$, so small-x = high $\sqrt{s}$)
- Will argue: this is a weak coupling, but nonperturbative regime
- So how does one calculate cross sections?

  (For processes where a simple probe scatters off this complicated object)

Setup:

- High energy limit of Quantum Chromodynamics: gluon saturation
- Strong color fields & Wilson line
- Dilute-dense processes: orders in α_s and $\ln 1/x \sim \ln \sqrt{s}$

Details, recent work

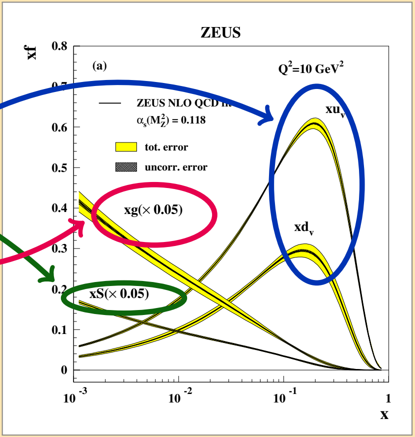
- Inclusive Deep inelastic scattering, at NLO
- Forward rapidity in proton-nucleus at NLO
- Exclusive processes, UPC

Parton distributions

Content of proton in DIS,
as measured by HERA

- "Valence": quantum numbers, energy
- "Sea" $q\bar{q}$ pairs
- Gluons: most (in numbers) $\sim x^{-0.3}$

(Recall: x = fraction of proton longitudinal momentum carried by parton)



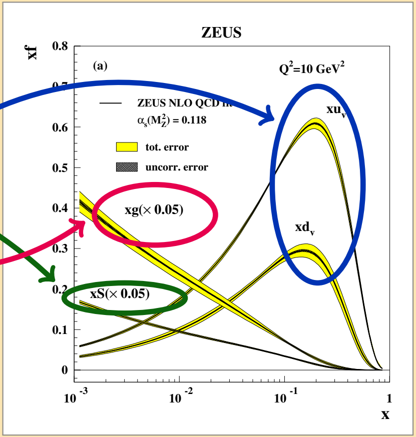
Parton distributions

Content of proton in DIS,
as measured by HERA

- "Valence": quantum numbers, energy
- "Sea" $q\bar{q}$ pairs
- Gluons: most (in numbers) $\sim x^{-0.3}$

Gluons dominate. Why?

(Recall: x = fraction of proton longitudinal momentum carried by parton)



Gluon saturation

What does a high enery proton look like? Parton model perspective

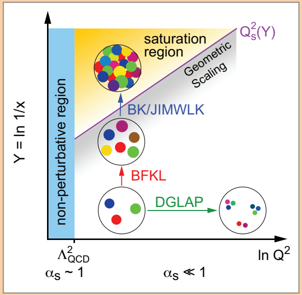
- Evolution with Q^2 $(\perp)$ or x $(\|)$: cascade of gluons
- Small x: phase space density of gluons large
  $\Longrightarrow$ nonlinear interactions, depending on
  - Size of one gluon $\sim 1/Q^2$
  - Transverse space available
  - Coupling

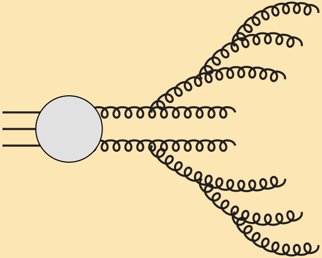
Gluon mergings matter when

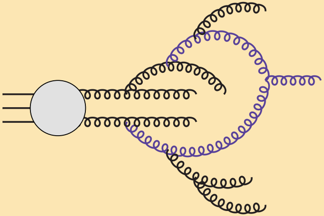
$$\pi R_p^2 \sim \alpha_s xG(x, Q_s^2)/Q_s^2$$

▼

Saturation "phase diagram":



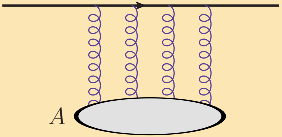




But don't calculate like this!

Eikonal scattering off target of glue

Instead of counting gluons, look at scattering amplitudes

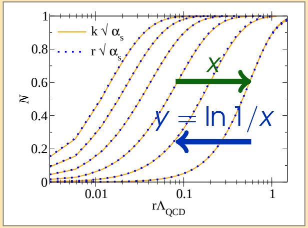


- Dilute probe through target color field
- At high energy interaction is eikonal, relevant degree of freedom is **Wilson line** (= scattering amplitude of colored parton)

$$V = \mathbb{P}\exp\left\{-ig\int^{x^+} \mathrm{d}y^+ A^-(y^+, x^-, \mathbf{x})\right\} \underset{x^+\to\infty}{\approx} V(\mathbf{x}) \in \mathrm{SU}(N_c)$$ coordinate space!

- Amplitude for color dipole

$$\mathcal{N}(r = |\mathbf{x}-\mathbf{y}|) = 1 - \left\langle \frac{1}{N_c}\operatorname{Tr} V^\dagger(\mathbf{x})V(\mathbf{y})\right\rangle$$

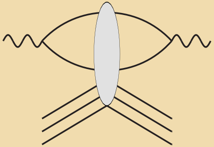


- In perturbative limit $\mathcal{N}(r) \sim \alpha_s [xG] r^2$ (xG = usual gluon pdf)
- **Saturation** = unitarity requirement for amplitude
  (built in as group theory constraint for $\mathrm{SU}(N_c)$)
- $1/Q_s$ is Wilson line $\perp$ **correlation length**

Power counting at small x

Dilute-dense process at LO

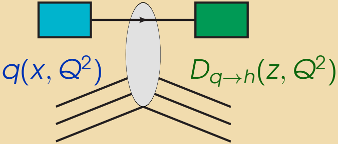
DIS



- $\gamma^* \to q\bar{q}$ dipole
  interacts with target color field
- Total cross section
  $2\times$Im-part of amplitude
- Exclusive & inclusive processes

"Dipole model": Nikolaev, Zakharov 1991
Fits to HERA data: e.g. Golec-Biernat, Wüsthoff 1998

Forward hadrons in pp/pA



- High x q/g from probe:
  collinear pdf
- $|\text{quark amplitude}|^2 \sim$ dipole
- Indep. fragmentation

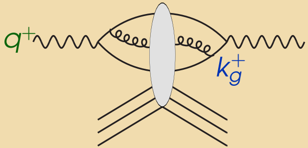
"Hybrid formalism" Dumitru, Jalilian-Marian 2002

Universality: both involve same dipole amplitude $\mathcal{N} = 1 - S$

Dilute-dense process at LL

Add one **soft** gluon: large logarithm of energy, i.e. $1/x$

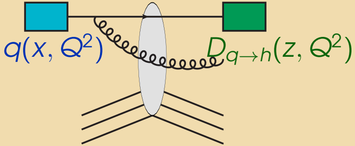
DIS



- Soft gluon: large logarithm

$$\alpha_s \int_{x_{Bj}} \frac{dk_g^+}{k_g^+} \sim \alpha_s \ln \frac{1}{x_{Bj}}$$

Forward hadrons



- Soft gluon $k^+ \to 0$: same large $\ln 1/x$
- Collinear gluon $k_T \to 0$:
  also DGLAP evolution of pdf, FF

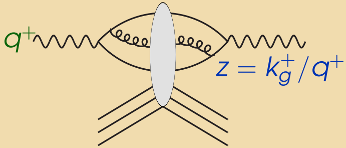
Dumitru et al 2005

Absorb large $\ln 1/x$ into renormalization of Wilson line:
JIMWLK equation, or **BK equation** for dipole Balitsky 1995, Kovchegov 1999
$\Longrightarrow$ RG evolution for amplitudes in energy (x or $\sqrt{s}$; cf DGLAP which is for pdf's in Q^2 or p_T)

Dilute-dense process at NLO

Add one gluon, but **not** necessarily soft

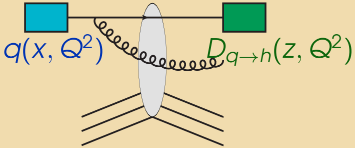
DIS



- DIS impact factor

Balitsky & Chirilli 2010, Beuf 2017

Forward hadrons



- NLO single inclusive

Chirilli et al 2011

- Leading small-k^+ gluon already in BK-evolved target
- Need to **subtract** leading log from cross section, (high energy) **factorization**

Schematically $$\sigma_{NLO} = \int \mathrm{d}z \Big[\overbrace{\sigma(z) - \sigma(z=0)}^{\sigma_{\text{sub}}} + \overbrace{\sigma(z=0)}^{\text{absorb in BK}} \Big] \quad z = \frac{k_g^+}{q^+}$$

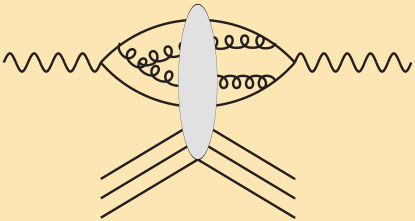
NLO to NLL

NLO evolution equation:

- Consider NNLO DIS
- Extract leading soft logarithm
- Lengthy calculation:

  Balitsky & Chirilli 2007

  $\Longrightarrow$ NLO BK/JIMWLK equation
- But additional resummations needed for practical phenomenology



(+ many diagrams at same order)

- $\alpha_s^2 \ln^2(1/x)$: two iterations of LO BK
- $\boxed{\alpha_s^2 \ln 1/x\text{: NLO evolution}}$
- α_s^2: part of NNLO impact factor (not calculated)

Summary: power counting in α_s & $\ln 1/x$; state of the art

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

Calculated at NLO/NLL

- JIMWLK/BK evolution Balitsky, Chirilli 2008, Grabovsky, Lublinsky, Mulian 2012
- Total DIS cross section $m_q = 0$ Balitsky, Chirilli 2010, Beuf 2011-2017
- Single inclusive particles in fwd rapidity hh-collisions Chirilli, Xiao, Yuan + others 2011 –
- Diffractive dijets in DIS Boussarie et al 2014
- Exclusive light vector mesons (with PDA's) Boussarie et al 2016

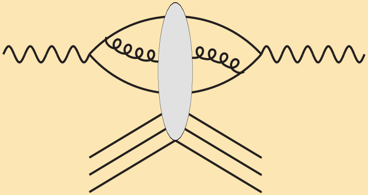
So far only LO/LL, but NLO/NLL under way:

- Forward rapidity dijets in pA Partial results: Mulian & Iancu, Ayala et al
- Diffractive structure functions
- Total DIS cross section with massive quarks
- Exclusive quarkonium in DIS/UPC (with NRQCD) T.L. Escobedo 2019

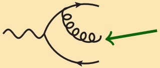
Benchmark processes at NLO:
DIS and fwd hadrons in pA

NLO calculations: Inclusive DIS

Balitsky, Chirilli 2010, Beuf 2011-2017



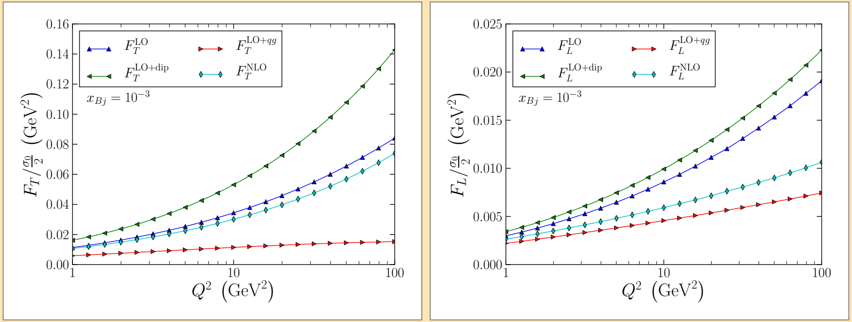
- At NLO need
  - Real: $q\bar{q}g$ state in dipole
  - Virtual: 1-loop corrections to the $\gamma^* q\bar{q}$-vertex
- Divergences cancel between real and virtual
- Massive quarks: in progress Beuf, T.L., Paatelainen
- Soft log factorized into BK evolution of target rest is NLO "γ^* impact factor"



$$\sigma_{L,T}^{qg,\text{sub.}} \sim \alpha_s C_\mathrm{F} \int_{z_1,\mathbf{x}_0,\mathbf{x}_1,\mathbf{x}_2} \int_{x_{Bj}/x_0}^{1} \frac{\mathrm{d}z_2}{z_2} \left[\mathcal{K}_{L,T}^{\text{NLO}}(z_2, X(z_2)) - \mathcal{K}_{L,T}^{\text{NLO}}(0, X(z_2)) \right].$$

DIS at NLO in dipole picture: 1st numerical implementation

Ducloué, Hänninen, T.L., Zhu 2017

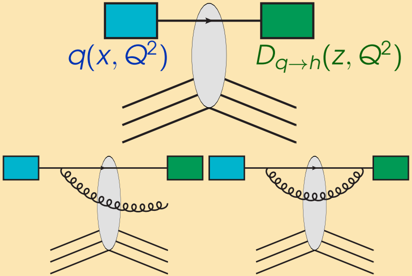


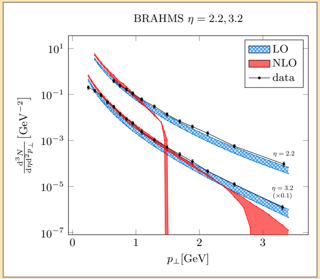
- NLO corrections of reasonable magnitude, after major cancellation between different terms
- Factorization procedure (still) somewhat naive, not good at large Q^2
- Starting point for comparison with HERA data, to replace existing LO dipole picture fits

NLO calculations: Particle production in forward pA

Particle production in forward pA:
"hybrid formalism"

- Quark/gluon from collinear pdf (large-x)
- 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"
- 1st result Stasto et al 2013 : NLO cross section negative at large p_T.
- This now understood as a problem with the "naive" factorization procedure: exactly as for DIS

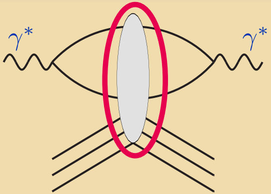




Exclusive DIS & UPC's

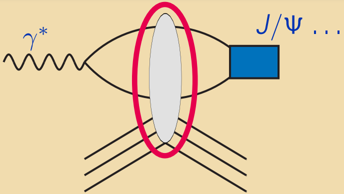
Exclusive processes in dipole picture

Total cross section



$\sigma_{tot} \sim$ forward elastic amplitude

Diffractive DIS



Exclusive $\sim$ |same amplitude|^2

Same dipole amplitude describes both

Unified description is a major advantage of the dipole picture

In hard scattering limit $\mathcal{N} \sim xg(x, Q^2) \implies$ often quoted formula

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

Exclusive DIS at NLO

Many possible final states

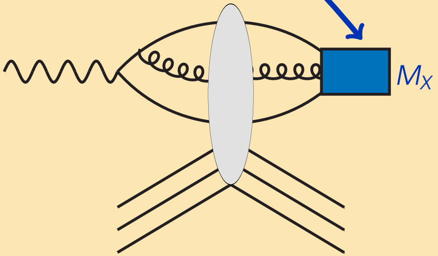
- Jets
- Vector mesons
- Any hadrons with fixed M_X ...

Known at NLO

- Dijets Boussarie et al 2014
- Exclusive light vector mesons
  PDA for meson Boussarie et al 2016

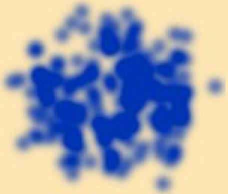
NLO calculations in progress

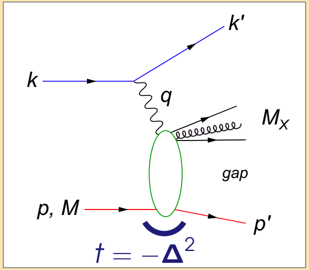
- Diffractive structure functions: fixed M_X
- Quarkonium, with NRQCD for meson
  Heavy quarks are important:
  allow $Q^2 = 0$ in weak coupling

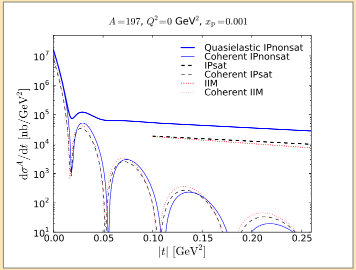


How to measure transverse geometry of gluons

Diffractive DIS gives Fourier transform of gluon distribution







$$\mathcal{N}(\mathbf{\Delta}) = \int \mathrm{d}^2\mathbf{b} e^{i\mathbf{b}\cdot\mathbf{\Delta}} \mathcal{N}(\mathbf{b})$$

Coherent target intact; measure **average** gluon distribution

$$-t \sim \frac{1}{R_A^2} \sim 0.01\mathrm{GeV}^2 \text{ (nucleus)}$$

Incoherent target breaks without color exchange: **fluctuations**

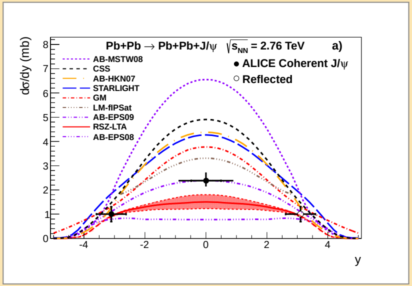
$$-t \sim \frac{1}{R_p^2} \sim 1\mathrm{GeV}^2 \text{ (nucleus} \to \text{nucleons)}$$

Both very important for QGP physics

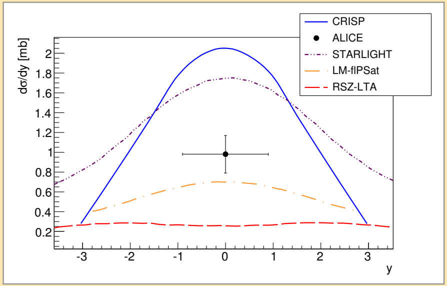
UPC results from LHC

- To understand b distribution need average **and** fluctuations: coherent **and** incoherent
- This is equally true for $\gamma^{(*)}A$ and $\gamma^{(*)}p$

Highest energy γ-p/A data so far: ultraperipheral collisions at LHC:



$\gamma A \to J/\Psi + A$ Eur. Phys. J. C **73** (2013) 2617



ALICE $\gamma A \to J/\Psi + A^*$

Plot from Phys. Rev. C **92** (2015) 064903

- $Q^2 = 0 \implies J/\Psi$ only at one scale: heavy quark mass.
- Q_s is p_T-scale: to study saturation dynamics need Q^2-dependence: EIC

Conclusions

QCD at the HE frontier

- Access to gluon saturation
- Resummation of large logs of energy into JIMWKL/BK evolution
- Moving to NLO
  - Loop calculations done for many processes
  - In $1/x$-evolution requires resummations
    & factorization needs to be consistent with these
    $\Longrightarrow$ challenges in implementation still being worked out
- Inclusive and exclusive processes in consistent framework
  - Small-x physics at EIC
  - Dilute-dense processes at LHC
  - Intial conditions of heavy ion collisions.