CGC and forward physics

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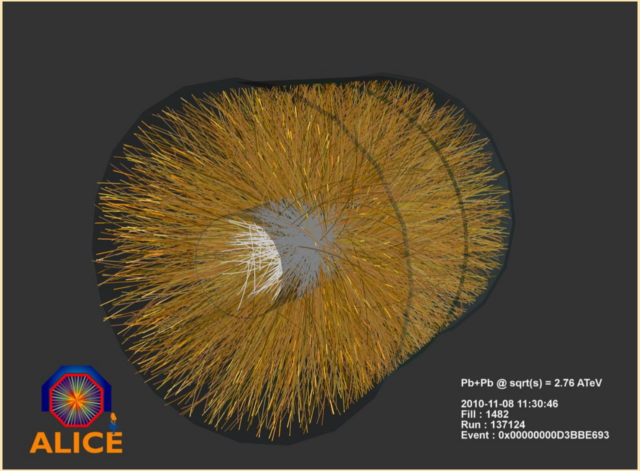
Outline

- Color Glass Condensate, saturation basics
- Forward scattering, NLO in CGC
- Non-flow particle correlations

Gluon saturation

A heavy ion event at the LHC

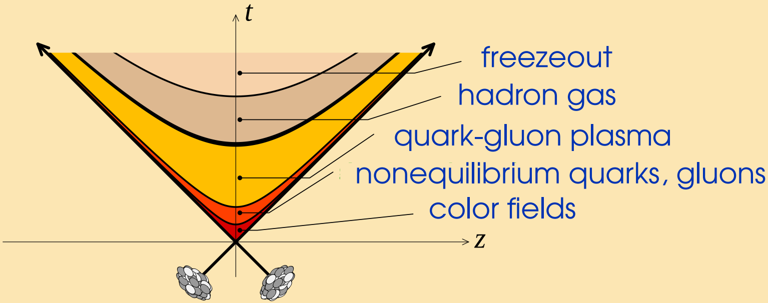


How does one understand what happened here?

Heavy ion collision in spacetime

The purpose in heavy ion collisions: to create QCD **matter**,
i.e. system that is large and lives long
compared to the microscopic scale

$$t \gg \frac{1}{T} \qquad L \gg \frac{1}{T} \qquad T > 200\text{MeV}$$



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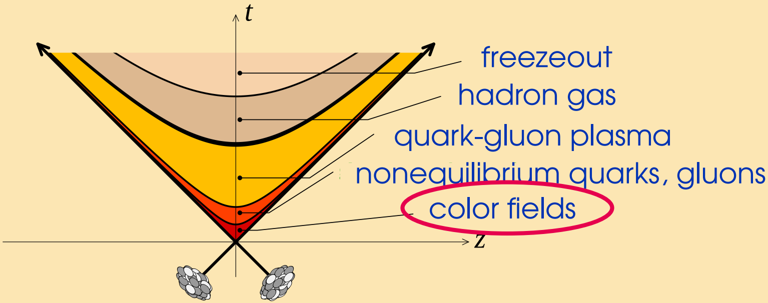

Concentrate here on the **earliest stage**

Gluon saturation, Glass and Glasma

Small x: the hadron/nucleus wavefunction is characterized by **saturation scale** $Q_s \gg \Lambda_{QCD}$.

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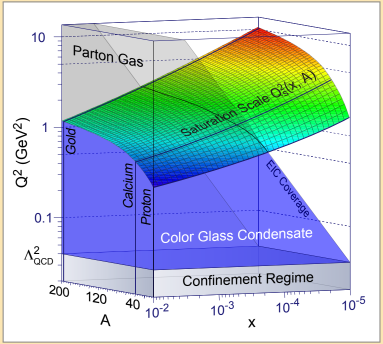
p$_T \sim Q_s$: strong fields $A_\mu \sim 1/g$

- occupation numbers $\sim 1/\alpha_s$
- classical field approximation
- small α_s, but nonperturbative



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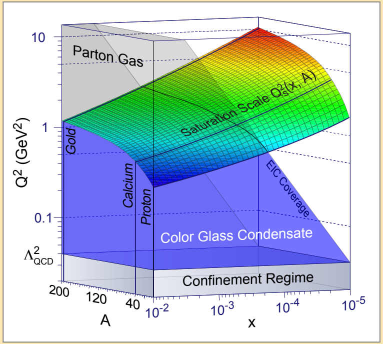

CGC: Effective theory for wavefunction of nucleus

- Large x = color charge ρ, **probability** distribution $W_y[\rho]$
- Small x = classical gluon field A_μ + quantum flucts.

Gluon saturation, Glass and Glasma

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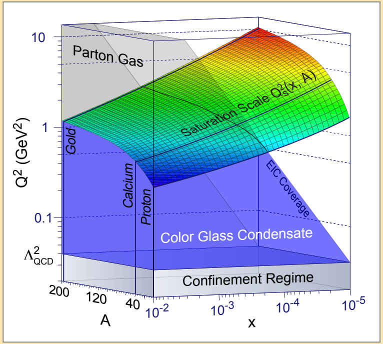

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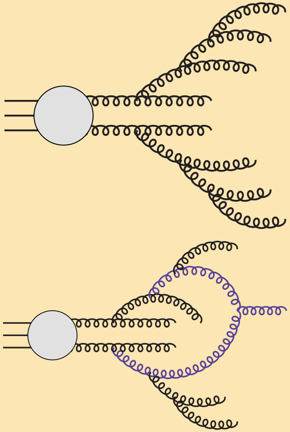
Glasma: field configuration of two colliding sheets of CGC. (Here $y \sim \ln \sqrt{s}$)

Gluon saturation in IMF: nonlinear interactions

Saturation when phase space density of gluons large

- Number of gluons $xG(x, Q^2)$
- Size of one gluon $\sim 1/Q^2$
- Transverse space available πR_p^2
- Coupling α_s



(LHC kinematics: $Q_s \approx 1$ .. 2GeV)

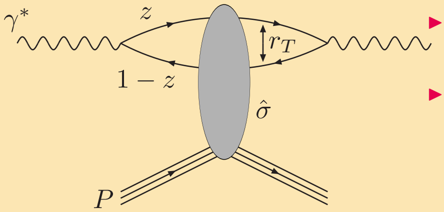
Estimate in terms of gluon numbers

Nonlinearities important when

$$\pi R_p^2 \sim \alpha_s xG(x, Q^2)\frac{1}{Q^2}$$

Solve for $Q^2 = Q_s^2$; "saturation scale"

Gluon saturation in dipole picture: unitarity



- Consider DIS, $q\bar{q}$ component of γ^*
- Scattering amplitude: unitarity limit $\mathcal{N} \leq 1$ (probability < 1)
- Two gluon exchange:

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

2-gluon exchange wrong when $Q^2 \sim \frac{1}{r^2} \lesssim Q_s^2 \sim \frac{\alpha_s xG(x, Q_s^2)}{\pi R_p^2}$ even if $\alpha_s(Q^2) \ll 1$

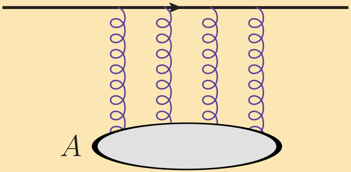
Gluon saturation in target rest frame

- Degree of freedom is scattering amplitude (not number of partons)
- Saturation appears as unitarity constraint

$\Longrightarrow$ Built into formalism; does not look dynamical.

Forward particle production

Eikonal scattering off target of glue



How to measure small-x glue?

- Dilute probe through target color field
- At high energy interaction is eikonal

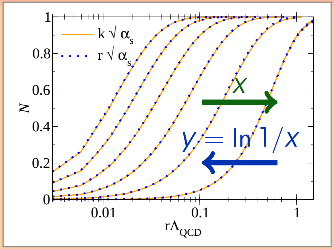
Eikonal scattering amplitude: Wilson line V

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

- Amplitude for color dipole

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

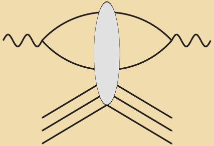
- $1/Q_s$ is Wilson line $\perp$ **correlation length**



Dilute-dense process at LO

Physical picture at small x

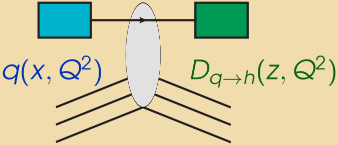
DIS



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

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

Forward hadrons in pA



- q/g from probe: collinear pdf
- $|\text{amplitude}|^2 \sim$ dipole
- Independent fragmentation
- Produced q/q p_T from target: $\sim Q_s$

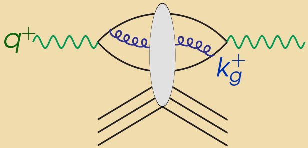
"Hybrid formalism"; Dumitru, Jalilian-Marian 2002

Both involve same dipole amplitude $\mathcal{N} = 1 - S$

Dilute-dense process at LL

Add one **soft** gluon: large logarithm of energy/x

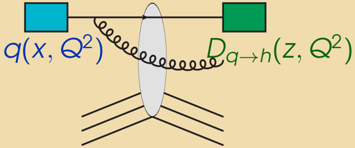
DIS



- Soft gluon: large logarithm

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

Forward hadrons



- Soft gluon $k^+ \to 0$: same large log
- Collinear gluon $k_T \to 0$: DGLAP evolution of pdf & FF

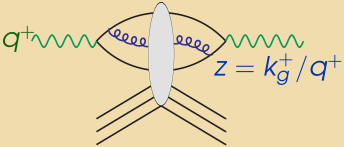
Dumitru et al 2005

Absorb large log into renormalization of target: **BK equation** Balitsky 1995, Kovchegov 1999

Dilute-dense process at NLO

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

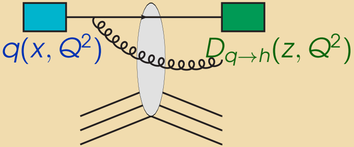
DIS



- DIS impact factor

  Balitsky & Chirilli 2010, Beuf 2017

Forward hadrons



- NLO single inclusive

  Chirilli et al 2011

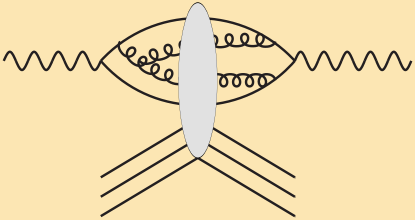
- Leading small-k^+ gluon already in BK-evolved target
- Need to **subtract** leading log from cross section:

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

NLO to NLL

NLO evolution equation:

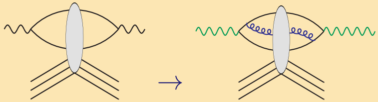
- Consider NNLO DIS
- Extract leading soft logarithm
- Lengthy calculation:
  Balitsky & Chirilli 2007
- But additional resummations needed for practical phenomenology



(+ many diagrams at same order)

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

NLO calculations in CGC: recent progress



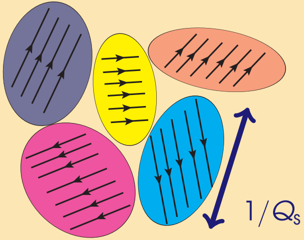
$$\sigma \sim \overbrace{\mathcal{O}(1)}^{\text{LO}} + \overbrace{\mathcal{O}(\alpha_s \ln 1/x)}^{\text{LL}} + \overbrace{\mathcal{O}(\alpha_s)}^{\text{NLO}} + \overbrace{\mathcal{O}(\alpha_s^2 \ln 1/x)}^{\text{NLL}}$$

- 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 ; massive quarks Beuf, T.L., Paatelainen 2021 Also inclusive $\gamma + 2j$ Roy, Venugopalan 2019
- Diffractive dijets in DIS Boussarie et al 2014 , Diffractive structure functions
- Exclusive light vector mesons (with PDA's) Boussarie et al 2016 Exclusive quarkonium (with NRQCD) Escobedo, T.L. 2019, Penttala et al 2020, 2021
- Single inclusive particles in fwd rapidity hh-collisions Chirilli, Xiao, Yuan + others 2011 –
- Forward rapidity dijets in pA Partial results: Mulian & Iancu, Ayala et al

Azimuthal correlations

Domains in the target color field

Physical origin for initial state particle correlations



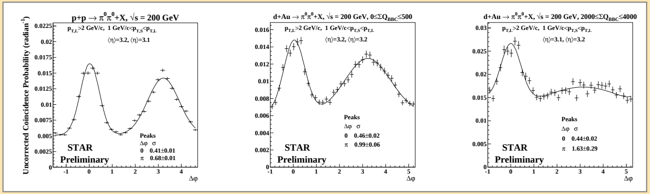
How is color field seen by individual quark?

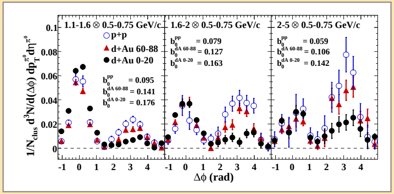
- Momentum transfer from target E-field
- "Domains" of size $\sim 1/Q_s$
  (Note actual calculation has Wilson lines, with correlation length, not explicit domains)
- Several probe particles inside domain: multiparticle azimuthal correlations.

- $\sim Q_s^2 S_\perp$ domains ($S_\perp$ = size of interaction area, πR_A^2, πR_p^2)
- $\sim {N_c}^2$ colors
- Relative correlation $\sim \frac{1}{{N_c}^2 Q_s^2 S_\perp}$ $\Longrightarrow$ stronger in small systems
- Both momentum & coordinate space $\Longrightarrow$ relevant for both flow & non-flow
- Next: 2 different kinds of "non-flow correlation"

Non-flow correlation 1: modified dijet

Saturation qualitatively explains striking RHIC results



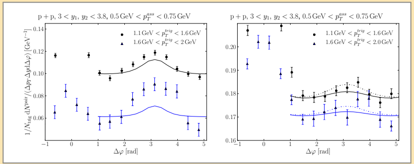


STAR, [arXiv:1102.0931]

PHENIX, [arXiv:1105.5112], PRL

However, jury is still out:

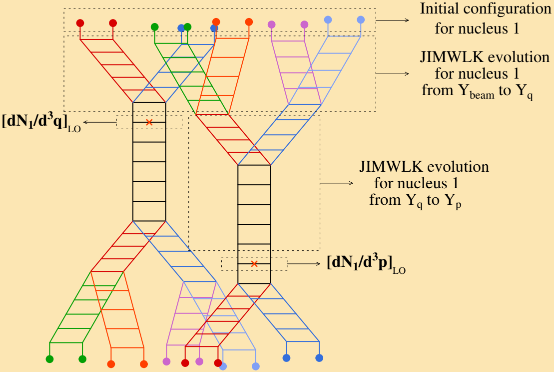
- Normalization: affected by $\Delta\varphi$-independent pedestal (careful: subtract vs. divide!)
- Peak width more sensitive to saturation
  — but affected by fragmentation
- Lot of effort in theory at NLO, but no NLO-data comparison yet



Non-flow correlation 2: purely multigluon

"Glasma graph," "ridge"

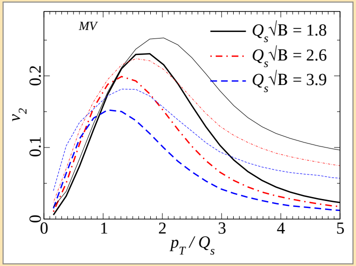
2 approaches with ultimately same origin for correlations (but not very transparently)



"Dense-dense" symmetric calculation: CYM or k_T-factorization approximation

Dilute-dense:

- Uncorrelated collinear quarks from probe
- Scatter from color field (same "hybrid formalism" as for single inclusive)



TL (arXiv:1501.05505 (hep-ph))

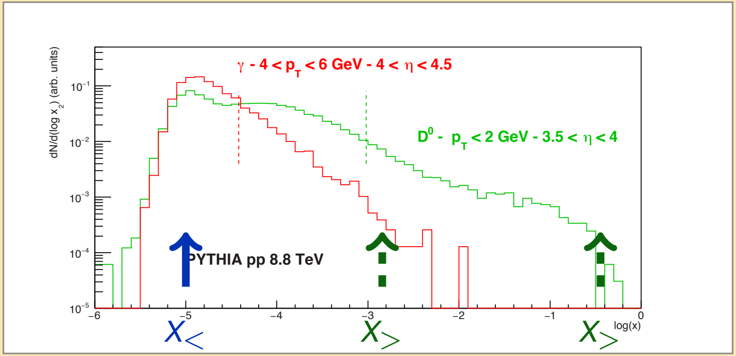
Conclusions

- Existence of gluon saturation: unambiguous consequence of unitarity
  — But: At what energy scale? In which observable? Less clear cut.
- Detailed probes of color fields: dilute-dense collisions:
  high energy DIS, forward rapidity pA
- Gluon fields contribute to correlation structure in high energy collisions: in coordinate space and directly in momentum space

Note on power counting and kinematics

Collinear $2 \to 2$ process, measure only 1 particle:

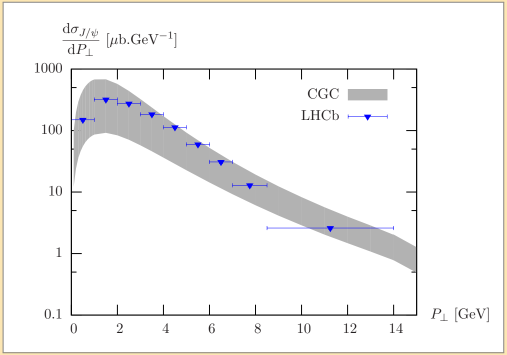
integral over large rapidity interval $\Delta y = \ln \frac{x_>}{x_<}$

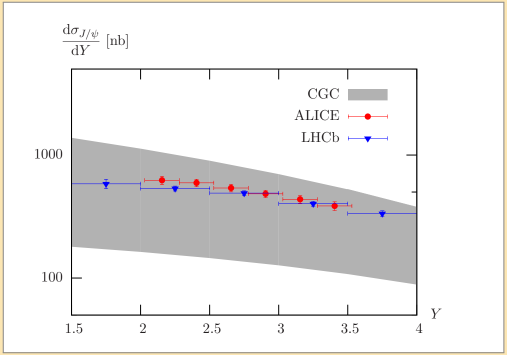


- In the CGC the power counting assumes $\alpha_s \ln \Delta y \sim 1 \implies$ integrated gluon absorbed into BFKL/BK/JIMWKL-evolved renormalized target at $x_<$
- The gluon recoil also gives intrinsic $\mathbf{k}_T \implies$ e.g. J/Ψ has p_T distribution at LO in CGC (vs. only at NLO in collinear)

Inclusive J/ψ in LHCb/ALICE kinematics

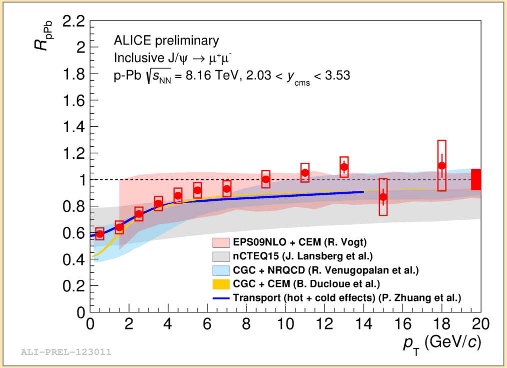
Cross sections for pPb Ducloué, T.L. Mäntysaari 1503.02789

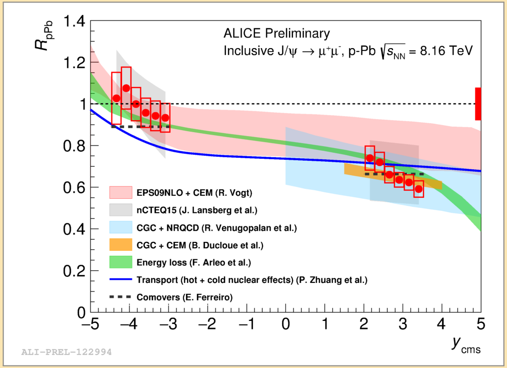




Most of normalization uncertainty from scale in collinear PDF, and in α_s

R_{pA} for inclusive J/ψ



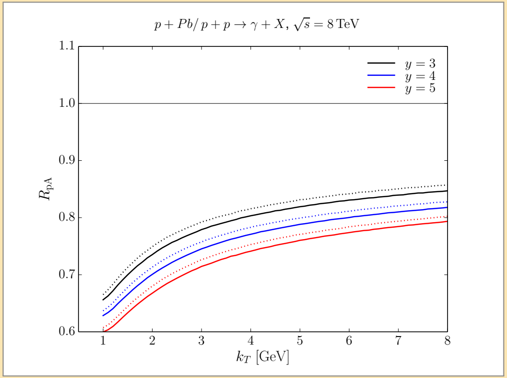


R_{pA}: scale uncertainty cancels

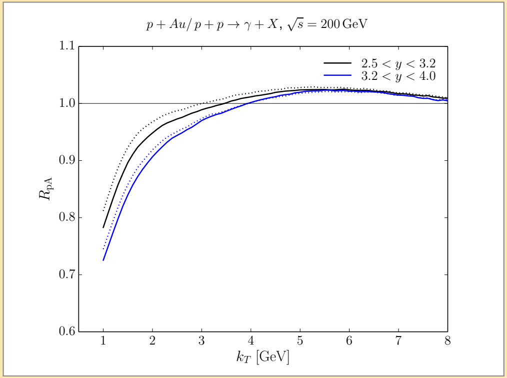
$\Longrightarrow$ determined by optical Glauber & value of Q_s (HERA)

Isolated photon R_{pA}

Ducloué, T.L. Mäntysaari, arXiv:1710.02206



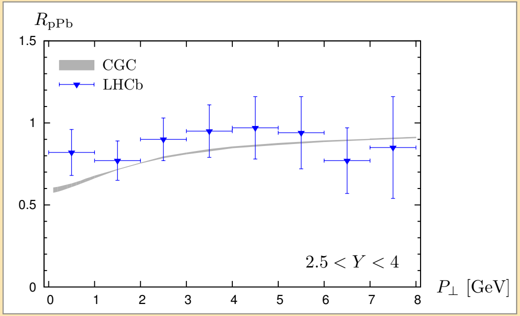
LHC energy



RHIC energy

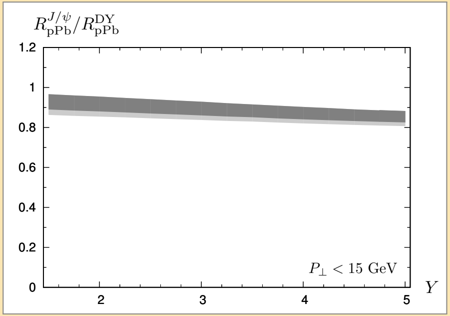
To see saturation effects at weak coupling p_T:
need LHC energy and preferrably fwd kinematics.

More R_{pA}'s: DY, D: very much same story



R_{pA} for D-mesons

Ducloué, T.L. Mäntysaari, `arXiv:1612.04585`

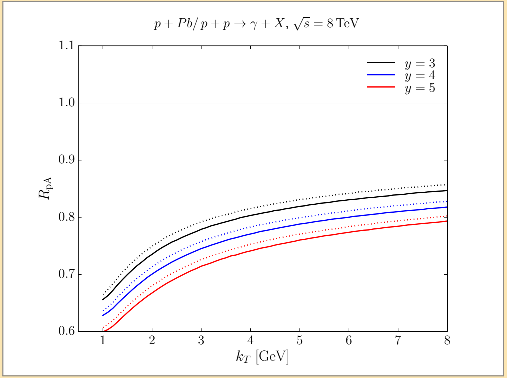


Double ratio of J/ψ to DY

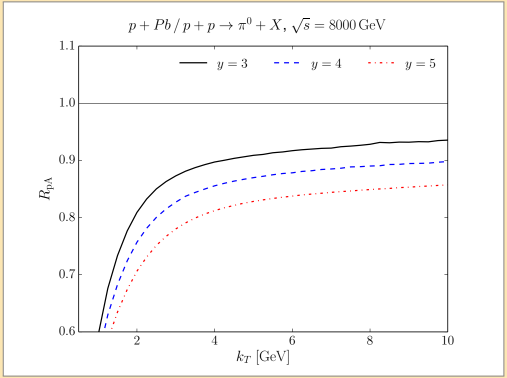
Ducloué `1701.08730`

(Cf. J/ψ energy loss models)

For comparison: light hadrons



Photons

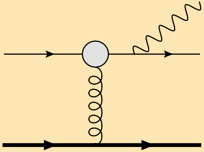


π^0: suppression not as large

Why is π^0 different?

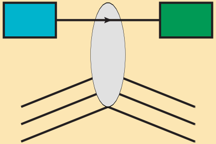
Largely artefact of CGC power counting.
LO CGC processes are

Photons



$1 \to 2$ kinematics:
even large photon k_T
can have target $k_T \sim Q_s$

Pions



$1 \to 1$ kinematics:
large pion p_T always from target $k_T \gg Q_s$
Becomes $1 \to 2$ at NLO

$\Longrightarrow$ suppression

(Eventually need to resum Sudakov)