Initial-state in heavy-ion collisions: Theory summary

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Summary: speakers

≈ 15 theory talks in "Initial state"

- *Nuclear PDF*: Helenius, Khalek, Kusina, Paakkinen, …
- *Low x in e-A*: Beuf, Hänninen, Mäntysaari, …
- *p-A, A-A*: Armesto, Jalilian-Marian, Mace, Mazeliauskas, Mrowczynski, Venugopalan, …

A few talks have already been featured in Plenary section;
they will not appear here

Summary: covered subjects

- Precision DIS: structure functions; photon, charm & bottom production
- Nuclear PDF: new methods, new constraints from current facilities, and possible constraints from feature facilities
- Saturation/Color Glass Condensate framework for gluon & photon production in hadronic collisions
- New ideas: Heavy quark transport in Glasma, Beyond conventional evolution
- Future facilities: nuclear structure & saturation
- Practical implementations: – small x evolution to DIS and input for hadronic collisions and UPC; – thermalization in A-A collisions at weak coupling; – two gluon production within dilute-dense CGC

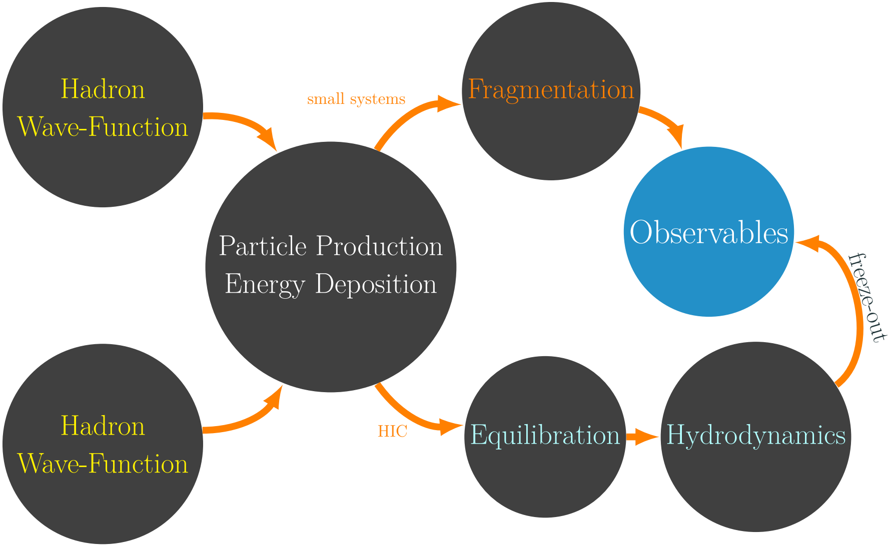
Heavy ion collisions

HIC create most optimal environment for probing Quark-Gluon Plasma

- Transport coefficients (η/s,ζ/s,$\hat{q}$)
- Thermalization
- ...
- Equation of state (CP)
- Running coupling $\alpha_s(T, \mu)$

Requires detailed understanding of initial state

High energy hadron collisions: multi-step process



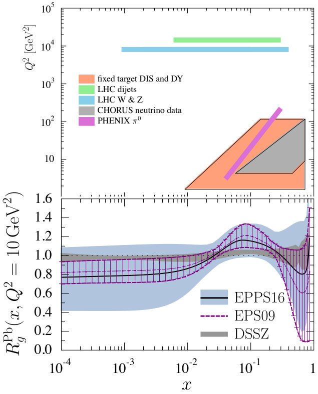
Hadron Wave-Function: nPDF

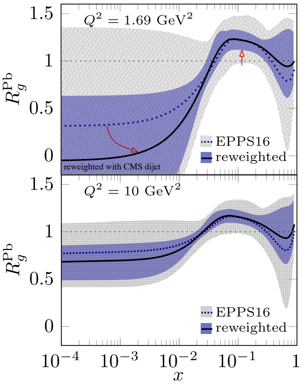
- Nuclear PDF $\neq$ superposition of nucelon PDFs
  $\rightsquigarrow$ sensitivity to partonic structure of nucleus
- Important for extracting perturbative QGP properties
- Tension with experimental data may indicate onset of saturation

nPDF: new constraints from LHC dijets 5 TeV

- Dijet data $\rightsquigarrow$ reduction of EPPS16 gluon uncertainty
- Data seems to favour rather deep shadowing
- Faster implementation for global analysis: Neural Network for nuclear PDF

Khalek: Wed 9:00





Paakkinen: Wed 11:25

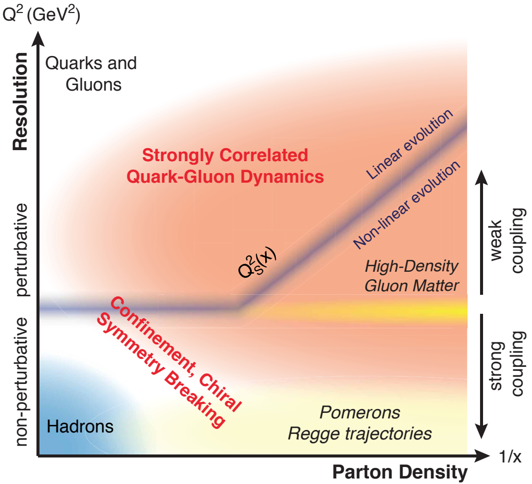
- AFTER@LHC: fixed target mode to constrain large-x content of nuclei

Kusina: Wed 11:45

High energy phase diagram of QCD

- Bulk of particle production is at small $p_\perp \rightsquigarrow$ small $x \sim \frac{p_\perp}{\sqrt{s}} e^{-y}$
- QCD matter at high parton densities
- Weakly coupled, but non-perturbative: $g \to 0,\ gA^\mu \sim 1$

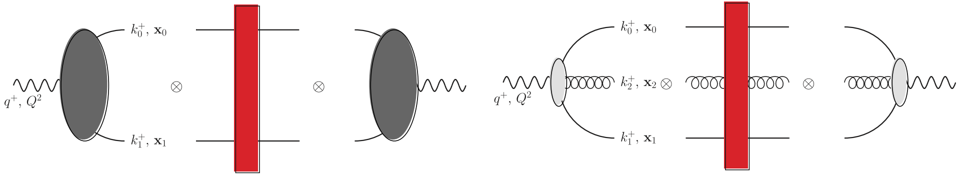
  Müller: Mon 14:00
- BK & JIMWLK to account for multiple rescattering
- Use DIS to fix parameters, apply to hadronic collisions: NLO/NLL DIS



Venugopalan: Tue 10:45

E. Aschenauer et al, arXiv:1708.01527

DIS factorization:



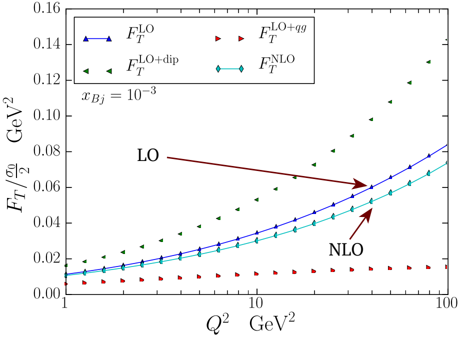
Beuf: Tue 9:00 **Hänninen: Tue 9:20**

DIS: small-x

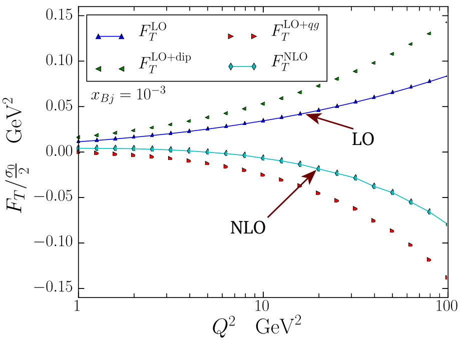
Two schemes (both are formally NLO) DIS structure functions:

Hänninen: Tue 9:20

“Unsubtracted”



“Subtracted”



- Moderate corrections at NLO
- Positive NLO structure functions

- Significant corrections at NLO
- Negative NLO structure functions

▷ No good fits yet...

▷ Ultimate goal is NLO + NL Log resummation; need for consistent factorization

DIS: massive quarks

Beuf: Tue 9:00

- Charm and bottom production $\rightsquigarrow$ massive quarks

- Standard approach: Light Cone Perturbation Theory

- 30 year-old puzzle: beyond LO with massive quarks:

  Mustaki et al, PRD43 (1991)

  - Anomalous dimension for m_q renormalization is different from covariant PT ?!
  - Nontrivial gluon mass renormalization ?!

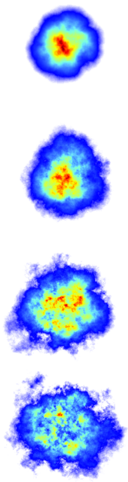
- New UV divergence in k^+ $\rightsquigarrow$ it matters how you apply Dimensional Regularization for terms with this UV divergence!

- Poincaré invariant regularization leads to resolution of the puzzle; LCPT calculation consistent with covariant PT

- Important input for small-x phenomenology: NLO DIS with massive quarks

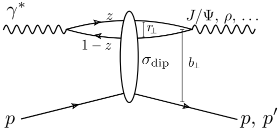
DIS input for p-A

$x = 10^{-2}$

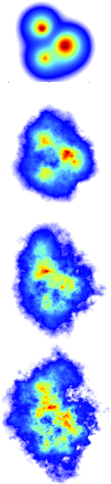


$x = 10^{-4}$

- Diffraction: sensitivity to gluon distribution $\sim (xG)^2$



$W = 75$ GeV



$W = 680$ GeV

- (In)Coherent vector meson production to constraint average proton density and its fluctuations
- IP-SAT model: Saturation is in model's parametrization:

$$N(\mathbf{r}, \mathbf{b}, x) = 1 - \exp\left[-\#\, \mathbf{r}^2 g(x, \mu^2)\, T_p(\mathbf{b})\right]$$

- To include saturation dynamics: JIMWLK evolution

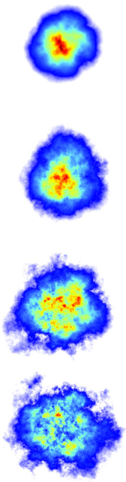
$$N\left(\mathbf{x}-\mathbf{y}, \frac{1}{2}(\mathbf{x}+\mathbf{y}), x\right) = 1 - \mathrm{Tr}\left[V_x(\mathbf{x}) V_x^\dagger(\mathbf{y})\right] / N_c$$

- Fix parameters at one energy (x_0); predict at higher energies ($x < x_0$)

Mäntysaari: Tue 9:40

DIS input for p-A

$x = 10^{-2}$

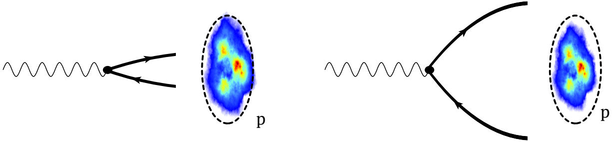


$x = 10^{-4}$

- However there are difficulties:
  - Gluon emission kernel is scale invariant $\rightsquigarrow$ Coulomb tail

    Introduce non-perturbative IR cut-off m
  - Evolution speed in LO JIMWLK

    Reduce α_s or include running coupling corrections
  - Large dipoles

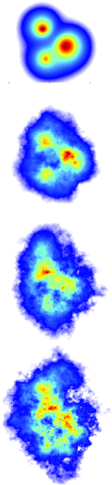


Use observables not sensitive to large r;

or/and set $N(r > R_p) \to 1$ for large r^2 as in IP-SAT

Non-perturbative physics: Coulomb tails & large dipoles ?!

$W = 75$ GeV

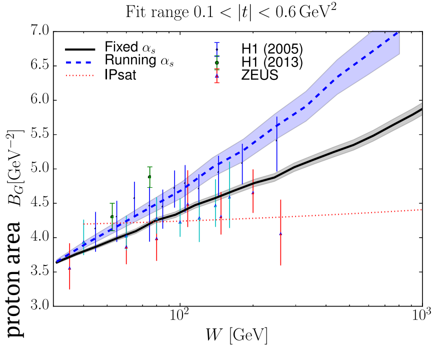


$W = 680$ GeV

Mäntysaari: Tue 9:40

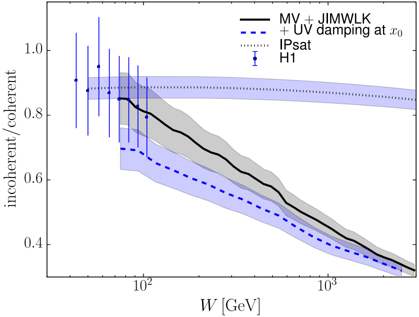
DIS input for p-A

- ▷ Size fixed at $W = 30$ GeV
- ▷ Evolution speed fixed by charm-F2



- ▷ Running α_s: faster evolution at long distances

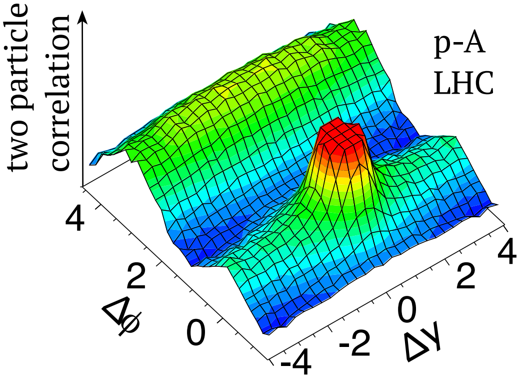
- ▷ Incoherent/coherent cross section ratio compatible with H1 data
- ▷ Insensitive to contributions from large dipoles



- ▷ Parameters fixed at $W = 75$ GeV

▷ Significant deviation from IP-SAT model

Mäntysaari: Tue 9:40

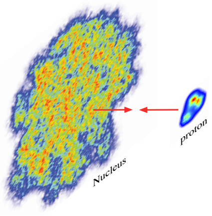


What is the origin of apparent collectivity?

What do initial state correlations at weak coupling tell us?

Armesto: Th 9:20 **Mace: Th 9:40**

Long range rapidity correlations and the ridge: analytics

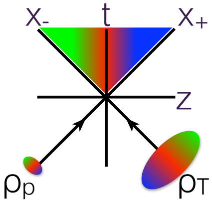


- p/d/He^3-A in dilute-dense approximation: $\rho_p(k)/k^2 \ll 1$

$$\frac{dN}{d^2k}[\rho_p,\rho_T] \sim g^2\rho_p^2 f_1(\rho_T) + g^4\rho_p^3 f_2(\rho_T) + \cdots \; ; \; \frac{d^2N}{d^2k_1 d^2k_2} = \left\langle \frac{dN}{d^2k_1}\frac{dN}{d^2k_2} \right\rangle_{p,T}$$

Does not require solving τ-evolution in Classical Yang Mills numerically

- Rather simple structure of strict dilute-dense limit $g^2\rho_p^2 f_1(\rho_T)$ is amendable to analytical analysis under reasonable approximation
- Two-particle **correlated** production
  - Bose enhancement in projectile, suppressed by $1/N_c^2$
  - HBT correlations, suppressed by $1/N_c^2$
  - Classical effects (a-la domains), suppressed by $1/N_c^2$ and by $1/S_\perp$ of the projectile



- **Quantum effects dominate in gluon correlations**

Armesto: Th 9:20 **Mace: Th 9:40**

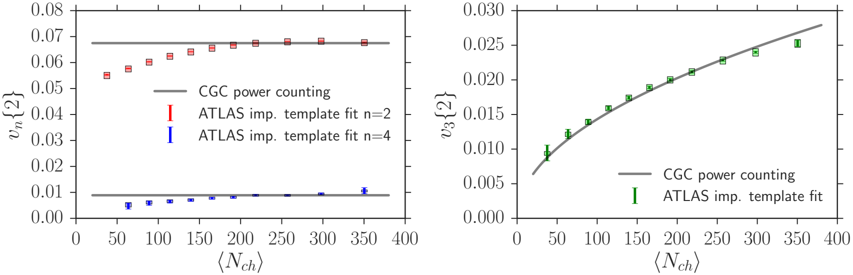
- To kill all of it, take the limit $N_c \to \infty$ and recover "IP-Jazma" (1808.01276)

Long range rapidity correlations and the ridge: analytics

- Tour de force analytical calculation: three-gluon correlations function
- Although expressions are complicated,
  Emerging structure of fully correlated production is transparent:
  - ▷ HBT of three gluons
  - ▷ Bose Enhancement of 3 gluons in projectile
  - ▷ HBT of 2 gluons + Bose Enhancement in projectile

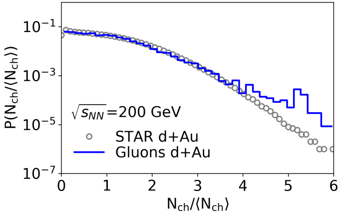
⇑ Armesto: Th 9:20; Mace: Th 9:40 ⇓

- Approximate scaling with multiplicity in p-A: $v_{\rm even}\{2\} \sim N_{\rm ch}^0$ & $v_{\rm odd}\{2\} \sim N_{\rm ch}^{1/2}$

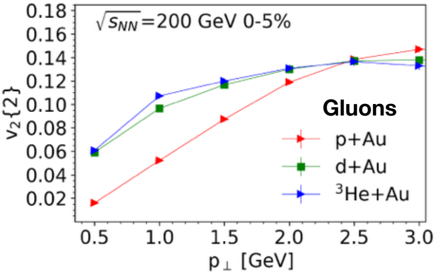


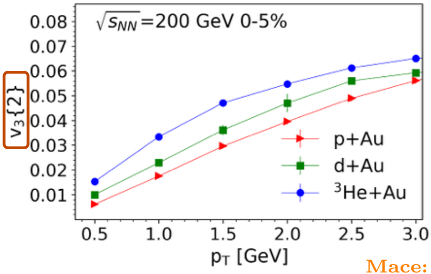
Long range rapidity correlations and the ridge: numerics

- Numerical implementation:
  - Data-guided approach similar to IP-Glasma model
  - Nucleon position fluct. both in projectile and target
  - Subnucleonic color charge density by IP-SAT
  - Parameters are fixed by DIS + $P(N_{\rm ch})$ for d-A



System size dependence at RHIC captured by CGC/ Reasonable agreement with experiment





Mace: Th 9:40

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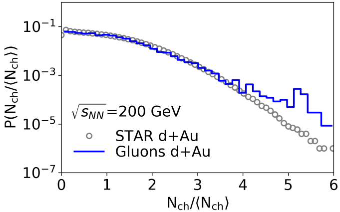
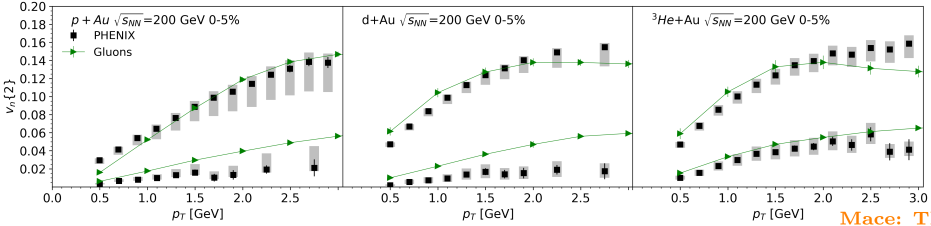


System size dependence at RHIC captured by CGC/ Reasonable agreement with experiment

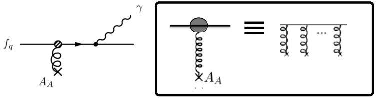


Mace: Th 9:40

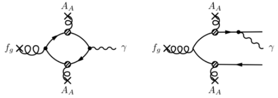
Particle production: q + $\bar{q}$ + photon

- Leading order: quark scatters off target field and produce photon
- Next to leading order: gluon produces $q+\bar{q}$; emission of photon
- Also includes correlated dijet-photon production

LO:



NLO:



unintegrated gluon distribution

Target forward dipole amplitude

$$\frac{d\sigma^{\text{NLO}}}{d^2\boldsymbol{k}_{\gamma\perp}d\eta_\gamma} = S_\perp \sum_f \frac{\alpha_e \alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)} \int_{\eta_q \eta_p} \int_{\boldsymbol{q}_\perp \boldsymbol{p}_\perp \boldsymbol{k}_{1\perp} \boldsymbol{k}_\perp} \frac{\varphi_p(Y_p, \boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2} \tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{k}_\perp) \tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{P}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_\perp)$$
$$\times \left[2\tau_{g,g}(\boldsymbol{k}_{1\perp};\boldsymbol{k}_{1\perp}) + 4\tau_{g,q\bar{q}}(\boldsymbol{k}_{1\perp};\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp}) + 2\tau_{q\bar{q},q\bar{q}}(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp};\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp})\right],$$

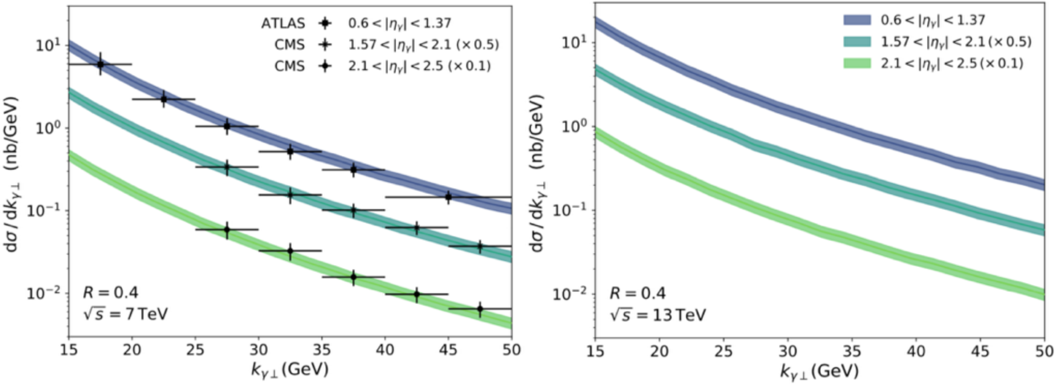
▷ NLO dominates at high energy due to large gluon density

▷ Large $k_\perp \gg Q_s$ to recover $k_\perp$ factorization

▷ and collinear factorization

Venugopalan: Tue 10:45

Particle production: q + $\bar{q}$ + photon



- ▷ Proton-proton collisions
- ▷ Saturation corrections are about 10%
- ▷ Expected to be larger in p-A!

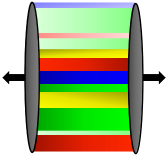
▷ k-factor to match this NLO calculation to experiment $= 2.4 \rightsquigarrow$ need for NNLO

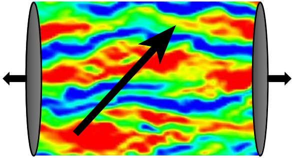
▷ Explore similar processes in DIS first: Inclusive photon+dijet (NLO+NLL)

Venugopalan: Tue 10:45

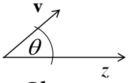
Non-equilibrium transport of heavy quarks through Glasma

- HIC: according to CGC collision induces Glasma field – strong mostly classical chromodynamic fields.
- How do heavy quarks propagate through the Glasma?
- Fokker-Planck equation of heavy quarks interacting with classical chromodynamic fields





$dE/dx, \hat{q}?$



Glasma

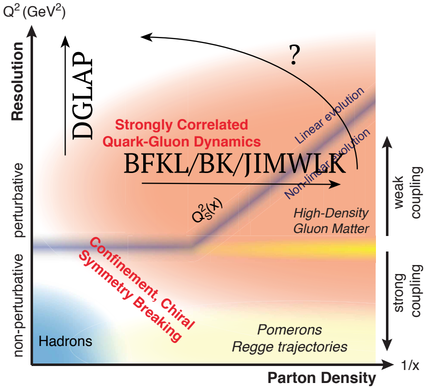
$$\begin{cases} -\dfrac{dE}{dx} = 14\cos^2\theta \left[\dfrac{\text{GeV}}{\text{fm}}\right] \\ \hat{q} = 33\left(\sin^2\theta + \sin\theta\right) \left[\dfrac{\text{GeV}^2}{\text{fm}}\right] \end{cases}$$

Typical values extracted from experiment

$$\begin{cases} -\dfrac{dE}{dx} = 1.0 - 3.0 \left[\dfrac{\text{GeV}}{\text{fm}}\right] \\ \hat{q} = 1.5 - 7.0 \left[\dfrac{\text{GeV}^2}{\text{fm}}\right] \end{cases}$$

Mrówczyński: Tue 12:05

Can we combine non-linear small x evolution and DGLAP?



- Account for one hard scattering – a first step towards unifying JIMWLK with DGLAP?!
- Previously: double integral equation that contains both NLx BFKL and NLO DGLAP (Ciafaloni, Colferai, Salam, Stasto, . . .)

Jalilian-Marian: Th 9:00

Conclusions

- A lot of new results/significant progress in initial state and pre--equilibrium dynamics since Hard Probes '16
- Reaching new precision: NLO+NLL in DIS with heavy quarks and photons
- Practical implementations for QCD effective kinetic theory, two particle correlations in dilute-dense CGC, and JIMWLK evolution in DIS
- A few new ideas put forward; a few old puzzle resolved & a lot of new goals set


BACKUP

What is the origin of high multipliicty events

- Saturation/CGC: gluon multiplicity fluctuations in projectile
  - Valence color charge fluctuations in (non-local) MV model

    $\rightsquigarrow$ Liouville potential

  - Small x evolution of the above

    $\rightsquigarrow$ increasing width of the potential

  - $\approx$ negative binomial probability distr. for produced gluons
- Gluon fragmentation $\rightsquigarrow$ multiplicity fluctuations?!
- What does strong coupling SYM tells us?
  - Single point functions a-la $\langle T^{\mu\nu} \rangle$ are not sufficient
  - Two point functions are rare… $\langle T^{00}(x) T^{00}(y) \rangle$

Theory approaches to particle production/scattering

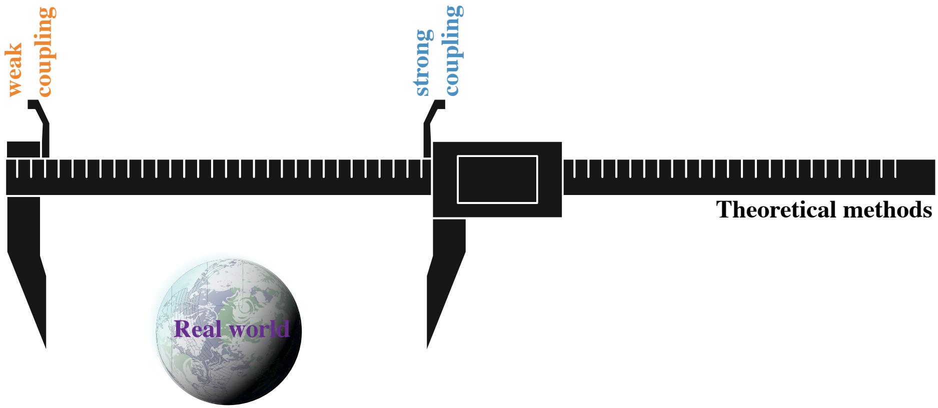
‘

▷ **Saturation/CGC framework:** highly occupied QCD at weak coupling
$g \to 0,\ gA \sim 1$

talks by Armesto, Jalilian-Marian, Mäntysaari, Mace, Mazeliauskas, Mrowczynski, Venugopalan, ...

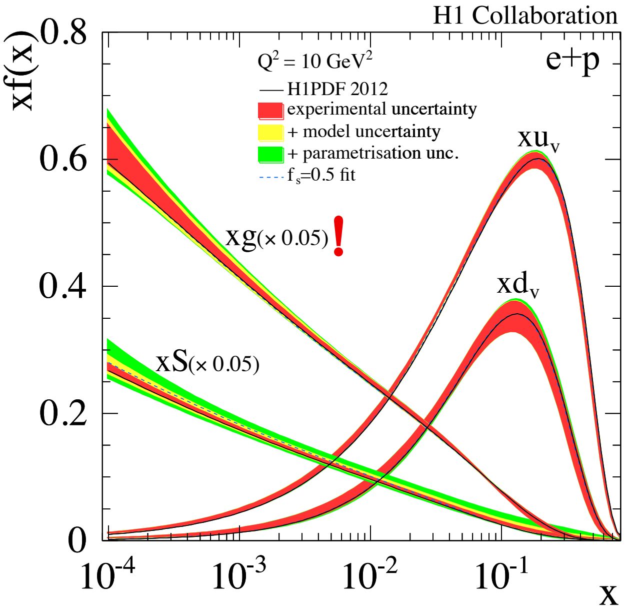
▷ **Holography:** duality between strongly coupled SYM and classical gravity in AdS
$g^2 N_c \to \infty,\ N_c \to \infty$

Theory grip on reality



- At best, theoretical methods can only bracket real world
- Some degree of extrapolation/modelling is required

Gluon density at small x

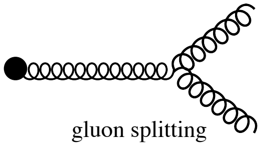


Evolution equations:radiation dominated regime

- BFKL equation resums powers of $\alpha_s \ln \frac{1}{x}$; no multiple rescattering

$$\frac{\partial}{\partial \ln \frac{1}{x}} N(x, k^2) = \alpha_s N_c \; K_{\rm BFKL} \otimes N(x, k^2)$$

I. Balitsky, V. Fadin, E. Kuraev, & L. Lipatov, '78



- Emission of new gluons as x decreases; the emission is proportional to N

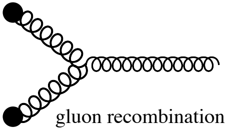
- Gluon density increases without bound

violating quantum mechanical black disk limit for total cross section

Evolution equations: nonlinear regime

- At small x, parton recombination modifies evolution (large N_c)

$$\frac{\partial}{\partial \ln \frac{1}{x}} N(x,k^2) = \alpha_s N_c \; K_{\mathrm{BFKL}} \otimes N(x,k^2) - \alpha_s N_c \; N^2(x,k^2)$$



I. Balitsky,'96; Yu. Kovchegov '99

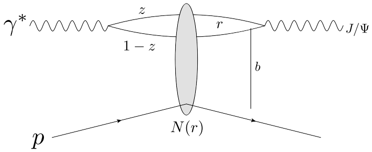
- Emission of new gluons as x decreases; emission is proportional to N

- Recombination $\rightsquigarrow$ reduction of gluon number in wave function

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

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

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

Average over configurations

Coherent diffraction:
Target proton remains in the same quantum state
Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\ \mathcal{A}^{\gamma^* p \to Vp}\ |^2$$

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

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

Variance, measures the amount of fluctuations!

: average over target configurations [N(r, **b**)]

BK and Black Disk Limit