Particles from the Colored Glass: diffraction, DIS and hadron production

Nuclear theory/RIKEN seminar

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Content

1. Baseline: DIS
2. Diffraction in DIS and AA
3. Single inclusive hadron production
4. From proton to nucleus

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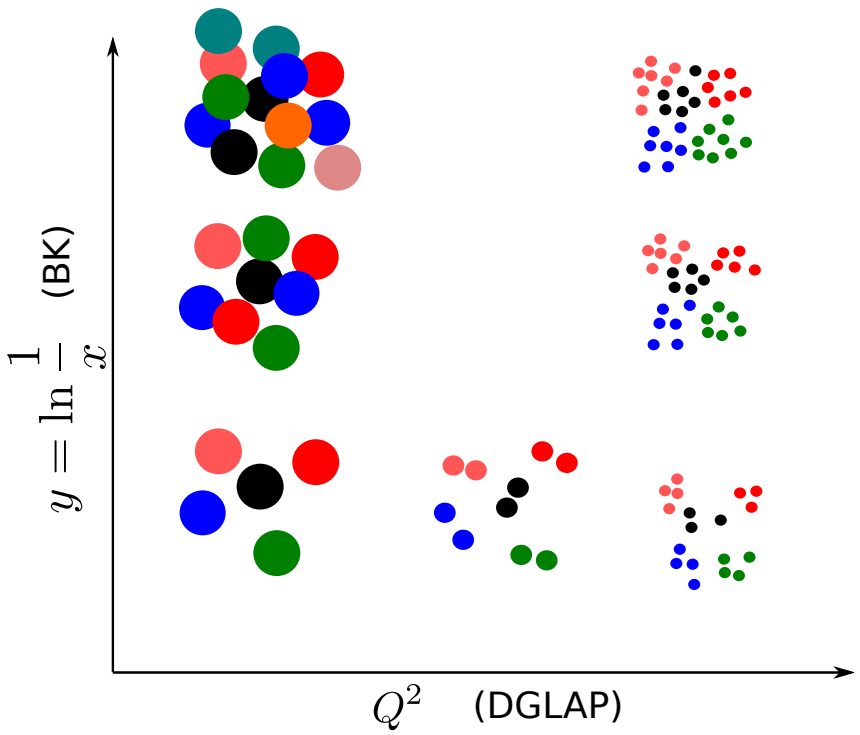
Introduction



- CGC: QCD at high energies
- Saturation phenomena described by CGC
- Evolution in x (energy): BK equation
- Saturation scale Q_s = characteristic momentum scale

Nuclear target (pA/eA collision) is interesting as $Q_s^2 \sim A^{1/3}$.

Setting up the baseline

CGC offers a consistent framework to describe small-x data.

- rcBK equation gives energy (Bjorken x) evolution
- Non-perturbative input: dipole amplitude at $x = x_0$

Compute

- DIS
- Diffractive DIS
- Single inclusive hadron production in pp and pA
- Dihadron correlations, ...

Fitting

Solve rcBK with modified MV model initial condition

$$N_p(r, y=0) = 1 - \exp\left[\frac{-(r^2 Q_{sp}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda_{\mathrm{QCD}}} + e_c \cdot e\right)\right],$$

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f)\ln\frac{4C^2}{r^2\Lambda_{\mathrm{QCD}}^2}}.$$

Compute σ_r (or F_2), assume factorizable proton impact parameter profile

$$\sigma_{T,L}^{\gamma^* p} = \sigma_0 \int \mathrm{d}z |\Psi_{\gamma^* \to q\bar{q}}^{T,L}|^2 N(r, y)$$

Fit Q_s^2, σ_0, C^2 and consider different models:

- MV with $\gamma \equiv 1, e_c \equiv 1$.
- MV$^\gamma$ with $e_c \equiv 1$, fit γ (AAMQS collaboration, arXiv:1012.4408).
- MV^e with $\gamma \equiv 1$, fit e_c (NEW).

Fit result

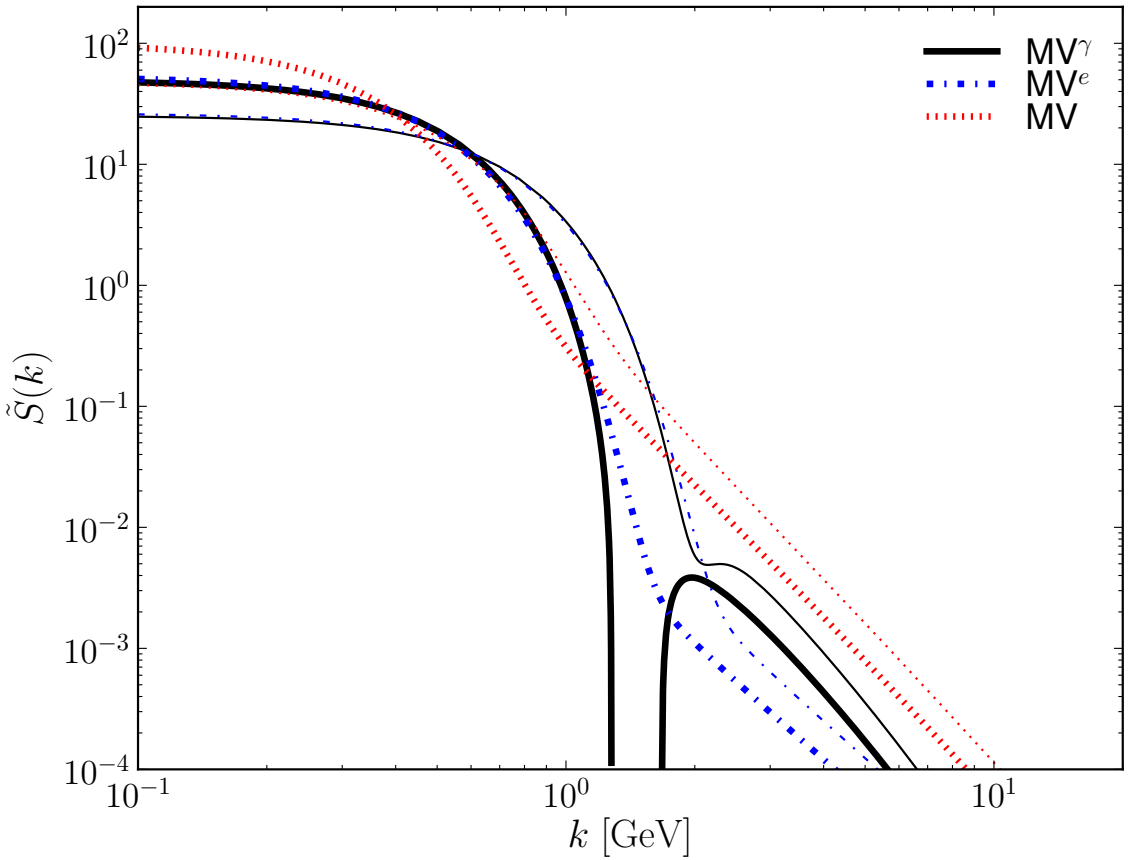
Fit to HERA σ_r data at $Q^2 < 50\,\mathrm{GeV}^2, x < 0.01$ (MV$^\gamma$ fit by AAMQS).

	$\frac{\chi^2}{\text{d.o.f}}$	Q_{s0}^2 [GeV^2]	Q_s^2 [GeV^2]	γ	C^2	e_c	$\sigma_0/2$ [mb]
MV	2.76	0.104	0.139	1	14.5	1	18.81
MV$^\gamma$	1.18	0.165	0.245	1.135	6.35	1	16.45
MV^e	1.15	0.060	0.238	1	7.2	18.9	16.36

- Much better fit with modified MV models.

- MV$^\gamma$: Fourier transform of $1 - N(r)$ ($\sim$ ugd) negative at large k
+ MV^e: Positive (next slide)
+ MV^e without γ is easier to generalize for nuclei.

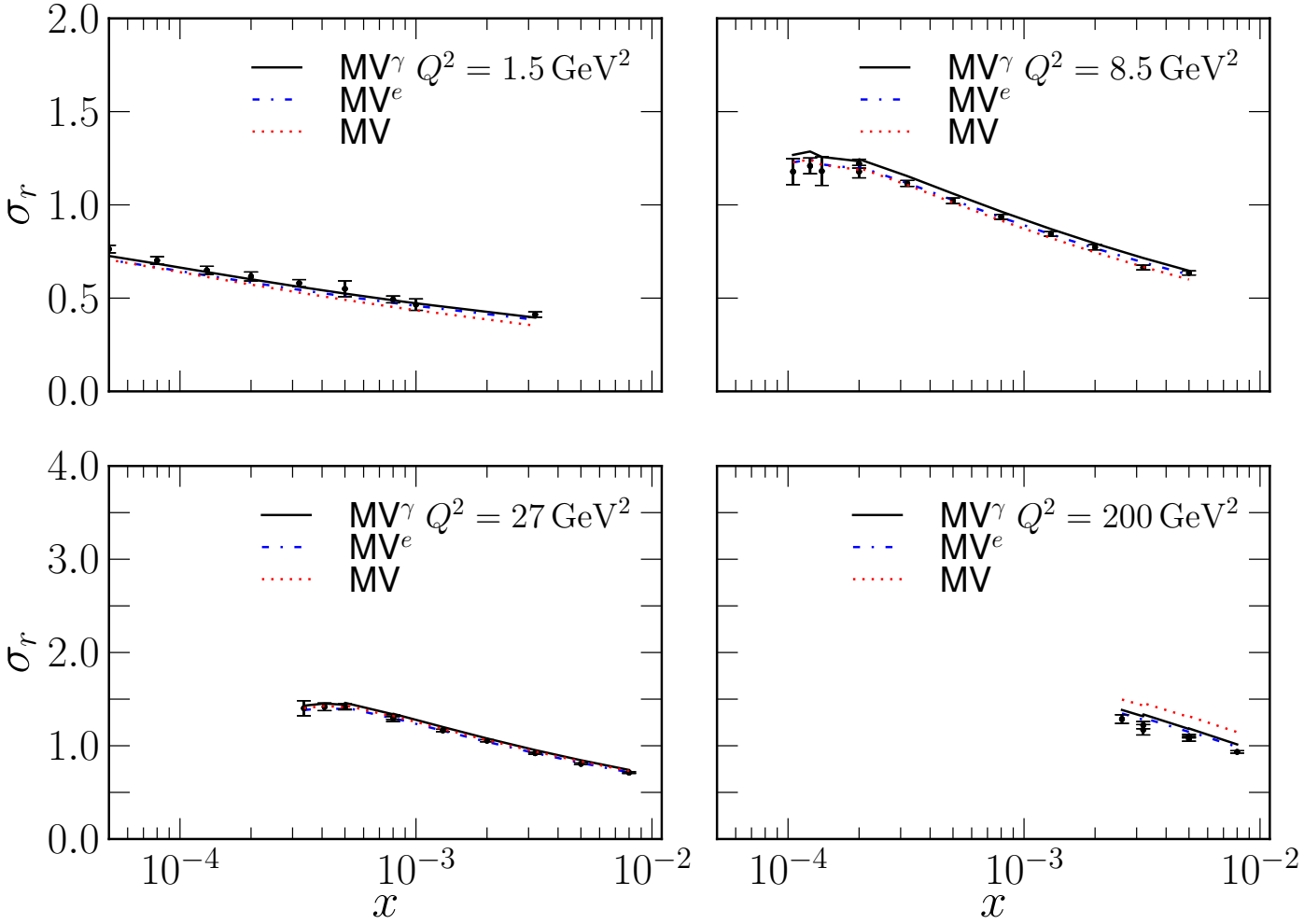
Fourier transform of the ICs



- Thick lines: fundamental representation, thin lines: adjoint

MV^e: smoother inteprolation between saturation region and large-k powerlaw behavior.

Fit result

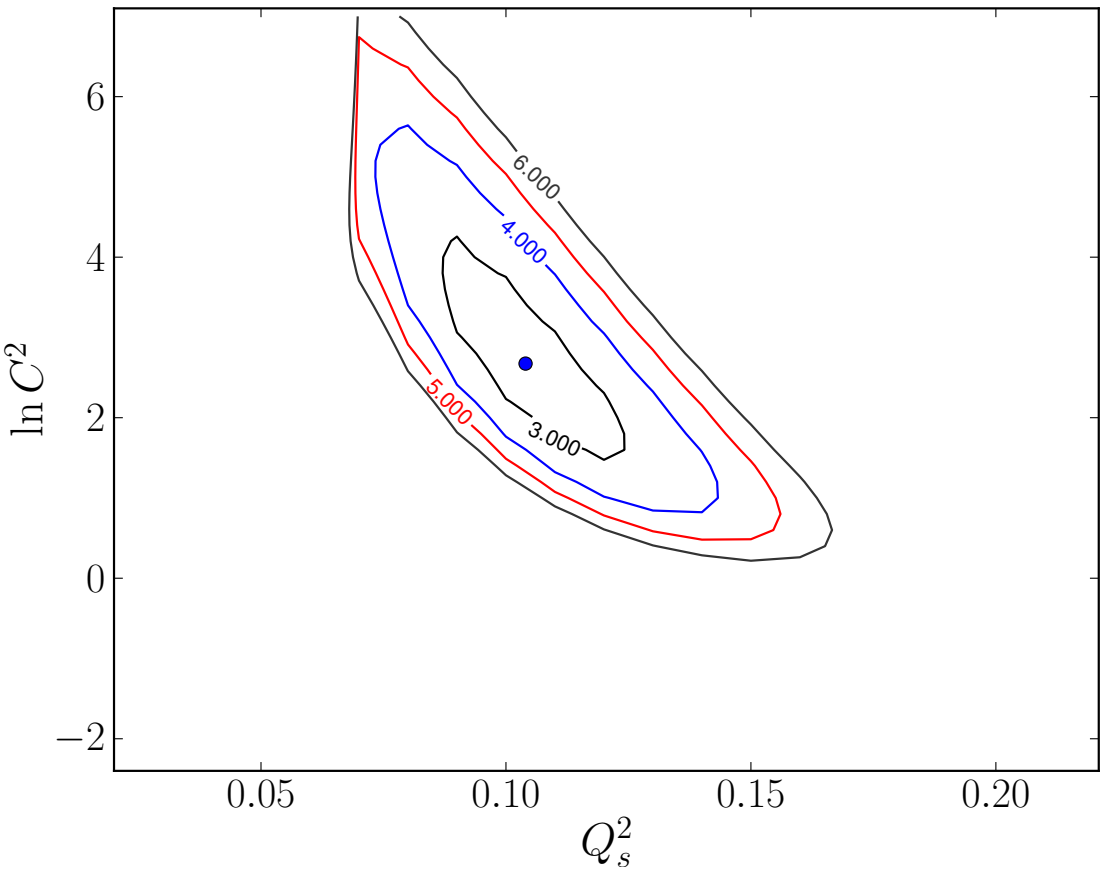


Fitted to $Q^2 < 50\,\mathrm{GeV}^2$ HERA data (arXiv:0911.0884)

Correlations

Fit parameters are correlated, analysis ongoing $\Rightarrow$ error sets for the dipole amplitude.

Example: χ^2/d.o.f for the MV model, Q_s^2 and C^2 are correlated:



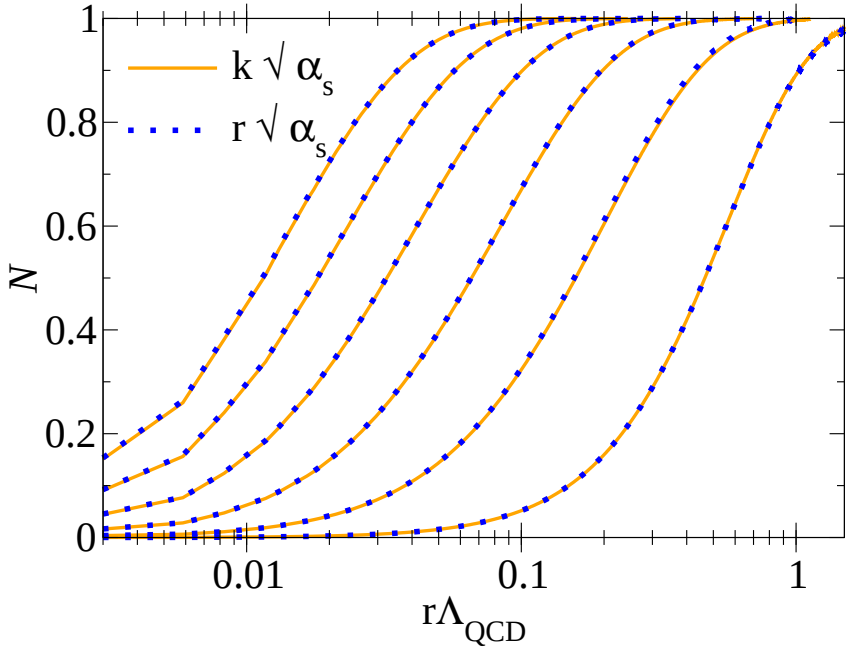
Value of Λ_{QCD}

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f)\ln\frac{4C^2}{r^2\Lambda_{\mathrm{QCD}}^2}}.$$

Fit result: $C^2 \sim 6$.
Analytically (Kovchegov, Weigert, 2007): $4C^2 = 4e^{-2\gamma_E}$
($\Rightarrow \Lambda_{\mathrm{QCD}} \sim 50\,\mathrm{MeV}$)
Numerical verification: T. Lappi, H.M. arXiv:1212.4825

Dipole amplitude at various y from JIMWLK

- Solid: $\alpha_s(k)$ (standard)
- Dashed: $\alpha_s(r)$, $4C^2 = 4e^{-2\gamma_E}$



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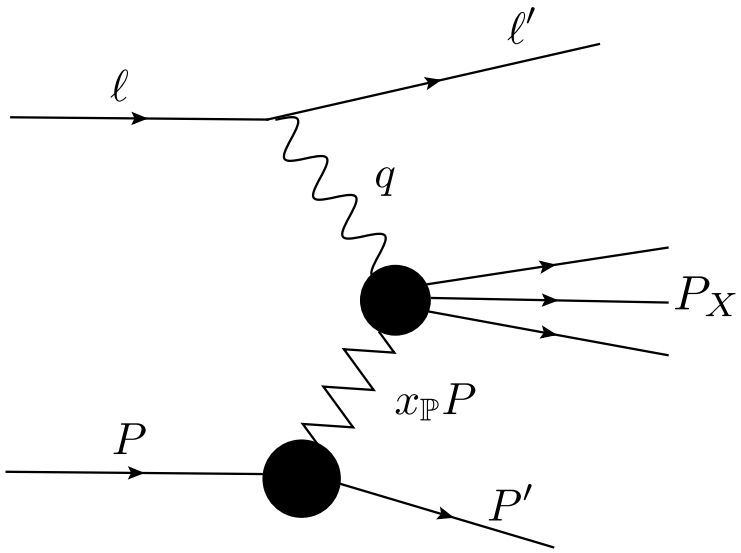
Diffraction

Diffraction

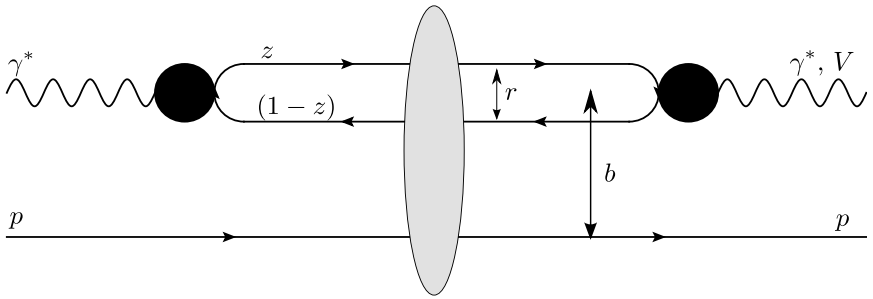
Scattering without exchange of quantum numbers ($=$ *color*) $\Rightarrow$ pomeron exchange



- $x_{\mathbb{P}}$: fraction of proton momentum carried by the pomeron.
- Probes impact parameter profile!

Diffraction from the CGC

Dipole picture:



$\gamma^* \to q\bar{q} \to V$, $q\bar{q}$ scatters elastically.

$$\mathcal{A}^{\gamma^* p}(x, Q, \Delta) = \int \mathrm{d}^2 r \int_0^1 \frac{\mathrm{d}z}{4\pi} \Psi_V^*(r, z, Q) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi(r, z, Q)$$

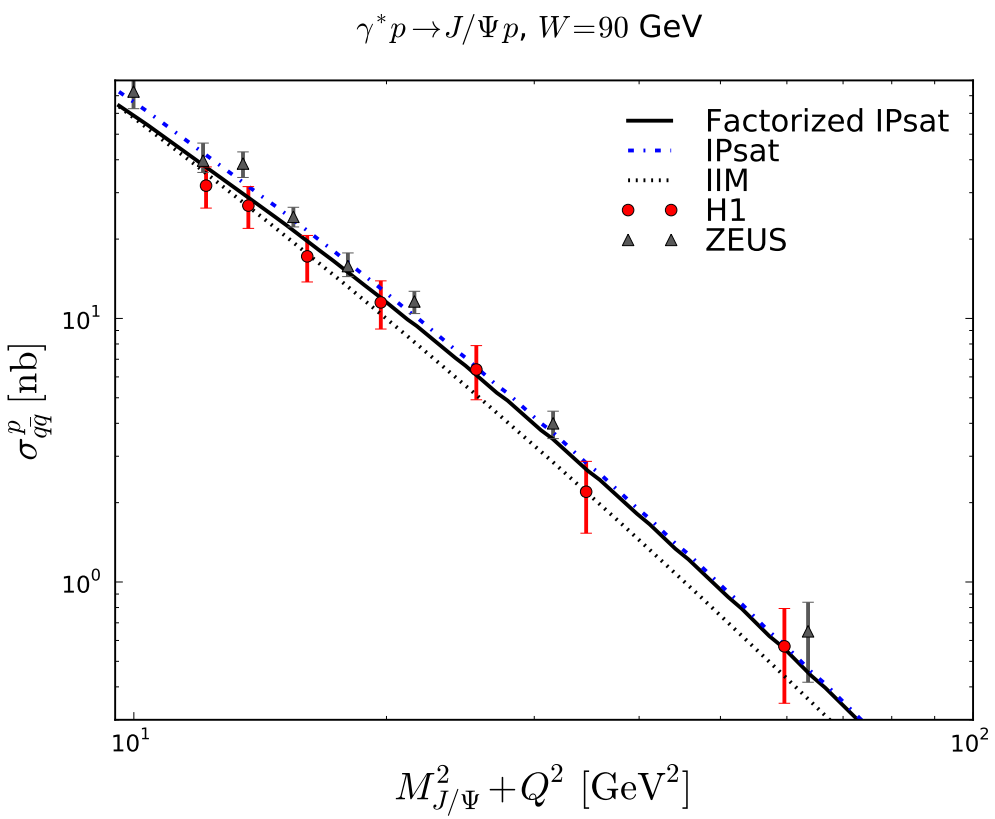
- Lifetime of the $q\bar{q}$ dipole is much longer than the interaction time.
- $\Psi^*\Psi$: virtual photon and vector meson wavefunction overlap
- $\mathcal{A}_{q\bar{q}}$: dipole-target scattering amplitude, $\sim \int e^{-ib\cdot\Delta}[1 - N(r, b)]$

Diffraction from the CGC

Diffraction requires impact parameter dependent dipole amplitude: IPsat

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

Parameters fit to *ep* data assuming gaussian proton profile T_p:



T. Lappi, H.M, 1011.1988

Factorized IPsat:
$N(r,b) = T_p(b) N(r)$

Diffraction off nuclei

Coherent (nucleus remains intact) and incoherent (nucleus can break up) diffraction.

- Quasielastic=coherent+incoherent:

$$\mathrm{d}\sigma^{\gamma^* A \to VA} \sim \langle |\mathcal{A}(x_{\mathbb{P}}, Q^2, \Delta)|^2 \rangle$$

- Coherent:

$$\mathrm{d}\sigma^{\gamma^* A \to VA} \sim |\langle A(x_{\mathbb{P}}, Q^2, \Delta) \rangle|^2$$

- Incoherent: variance/fluctuations (dominates at large $t = -\Delta^2$)

$$\mathrm{d}\sigma^{\gamma^* A \to VA*} \sim \langle |\mathcal{A}(x_{\mathbb{P}}, Q^2, \Delta)|^2 \rangle - |\langle A(x_{\mathbb{P}}, Q^2, \Delta) \rangle|^2$$

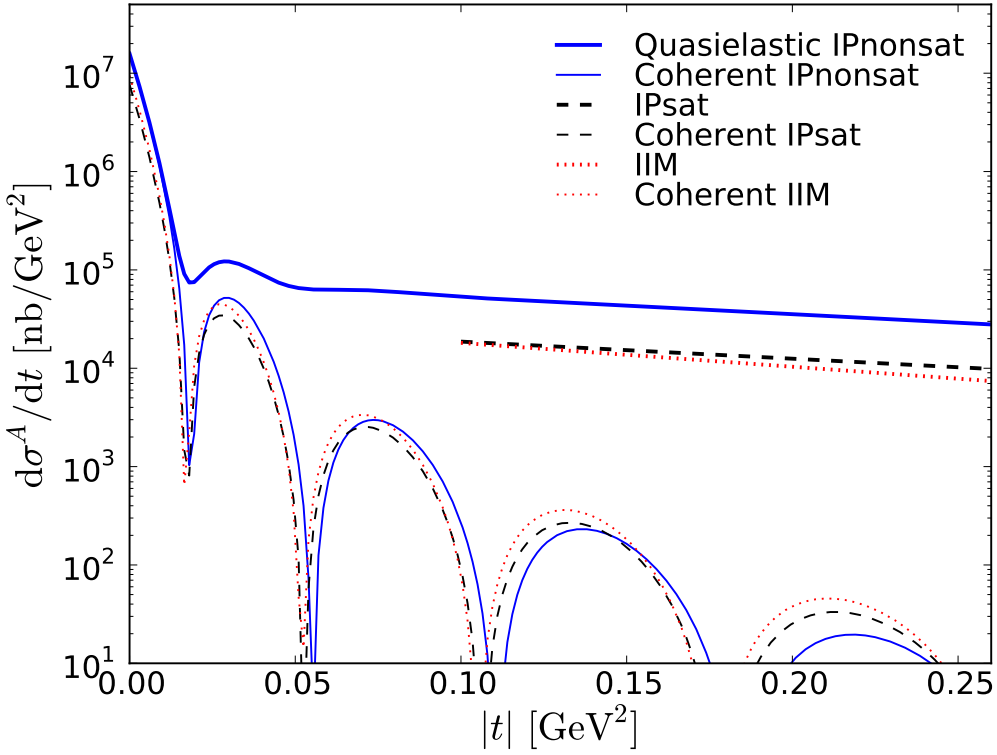
Average $\langle\rangle$ over nucleon positions.

Diffraction off nuclei

Saturation effects are clearly visible, IPnonsat=linearized IPsat ($N(r) \sim r^2$ at all r)

$\gamma A \to J/\Psi A$:

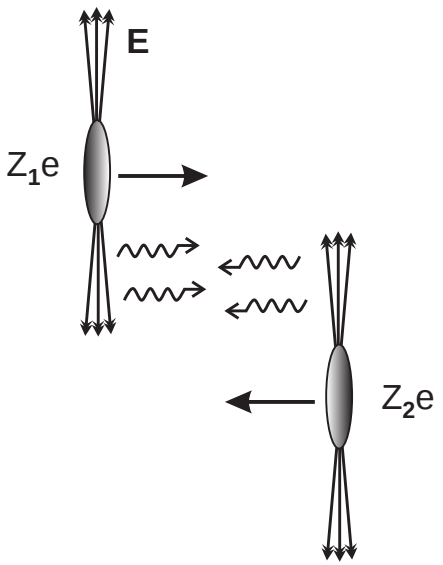
$A=197$, $Q^2=0$ GeV^2, $x_{\mathbb{P}}=0.001$



T. Lappi, H.M, 1011.1988

$\gamma - A$ collider

As we do not have EIC/eRHIC (yet), some other photon source is required
$\Rightarrow$ ultraperipheral AA collisions



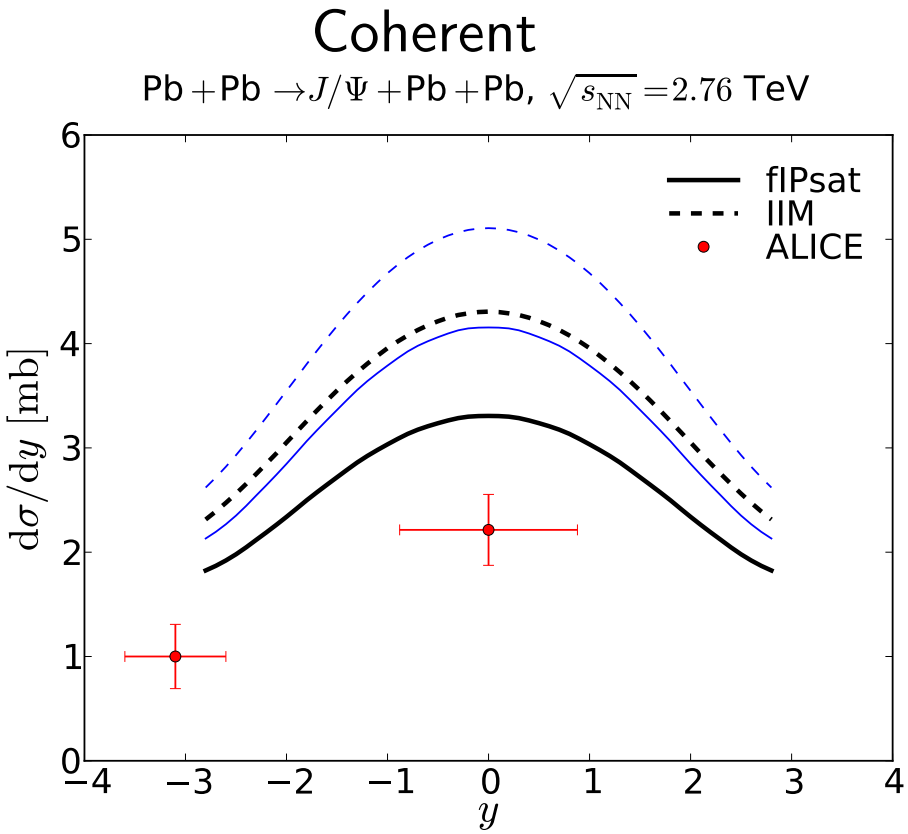
nucl-ex/0502005

$b \gtrsim 2R_A$: strong interactions suppressed, dominant process is $\gamma - A$.

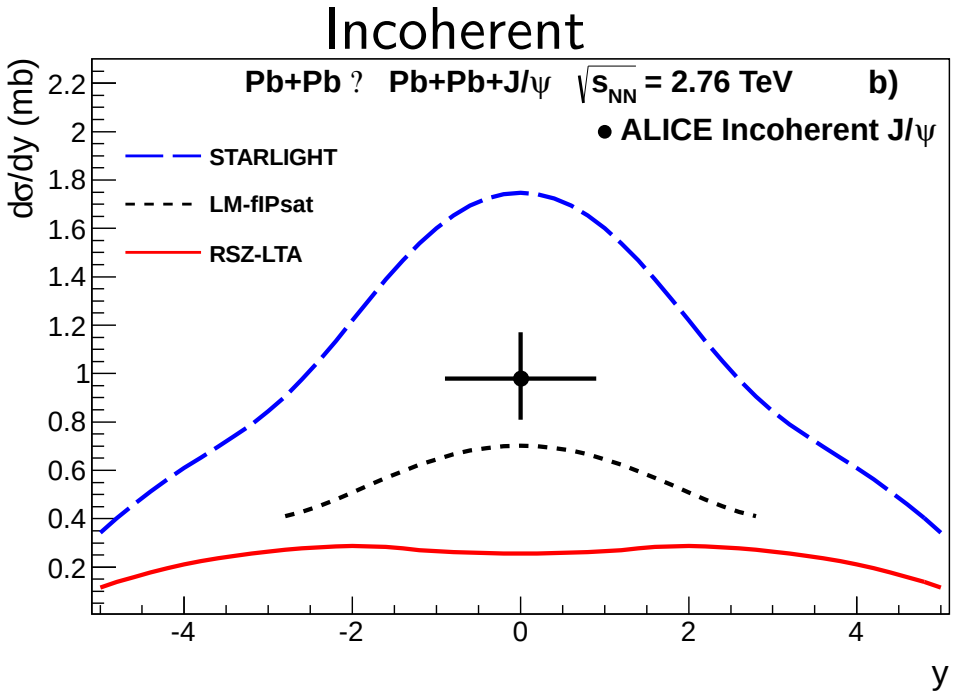
$$\sigma \sim \int \mathrm{d}\omega n(\omega)\sigma^{\gamma}(\omega),$$

where ω is the photon energy and $n(\omega)$ is the photon flux.

$\gamma - A$ diffraction



T. Lappi and H. Mäntysaari, 1301.4095



ALICE Collaboration, 1305.1467

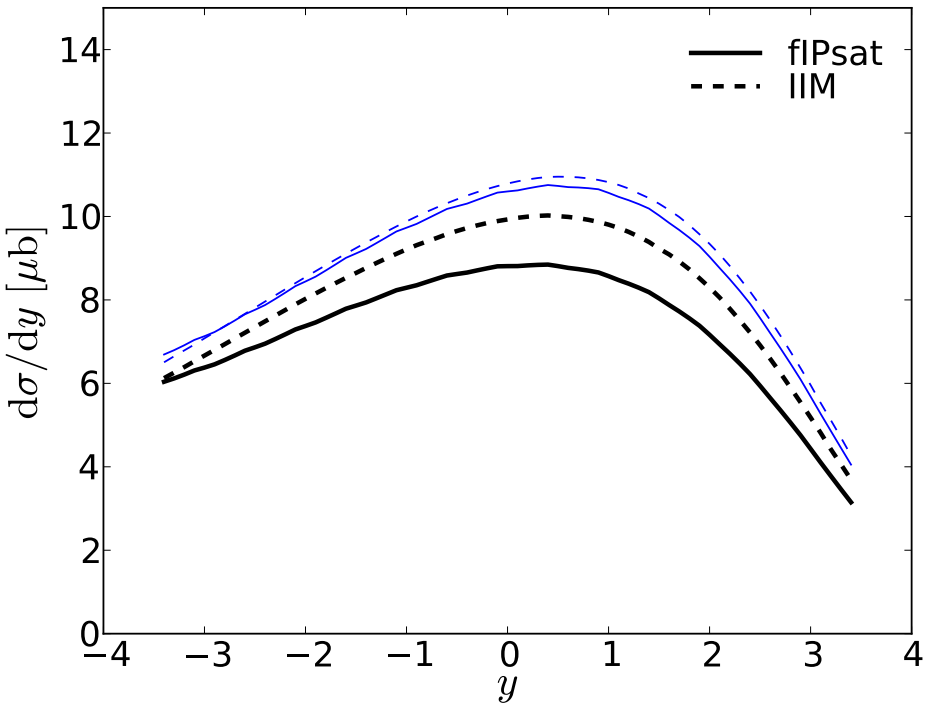
Data: ALICE 1209.3715 and talk by C. Mayer

Only parameters from HERA DIS!

Large theoretical uncertainties (skeweness correction, J/Ψ wavefunction)

Diffraction in pA

As the photon flux $\sim Z^2$, the dominant process is $\gamma p \to J/\Psi p$ scattering. Nucleus is the photon source.



T. Lappi, H.M., 1301.3715

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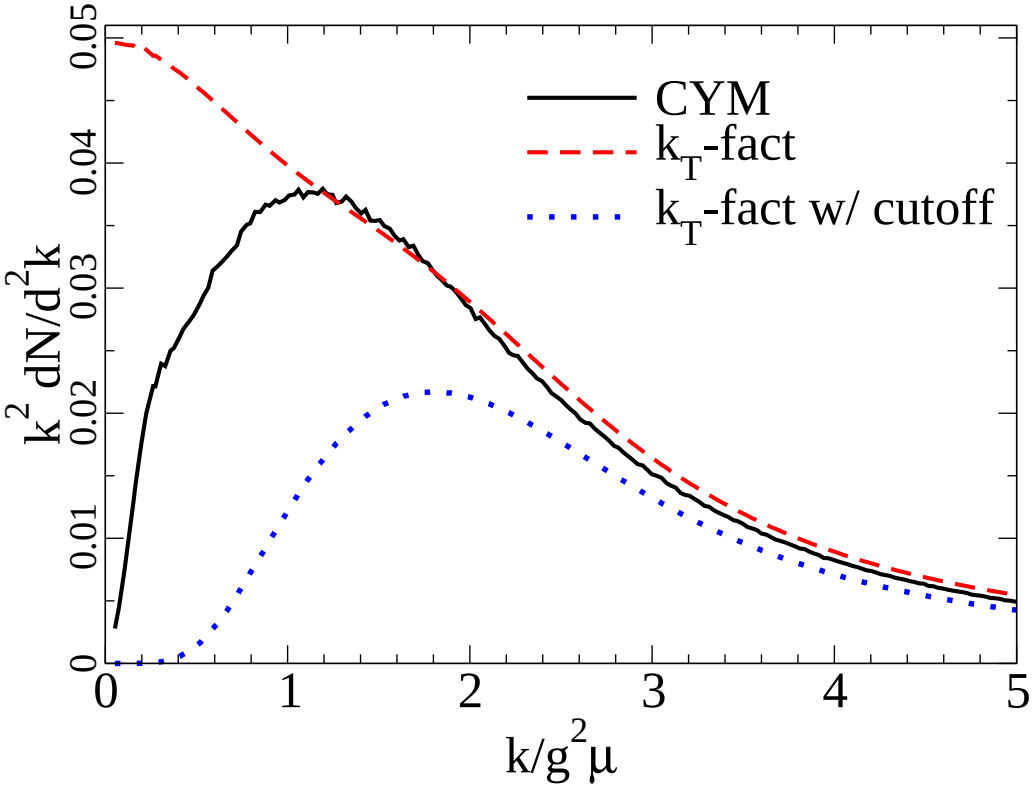
Single inclusive hadron production from CGC

Single inclusive particle production in pp using k_T factorization:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T \mathrm{d}y} = \frac{2\alpha_s}{C_\mathrm{F} p_T^2} \int \mathrm{d}^2 q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(k_T - q_T)}{(k_T - q_T)^2}$$

- Agrees with CYM for $p_T \gtrsim Q_s$
- φ_{x_1,x_2}: dipole (not WW) UGD of a hadron. $\varphi(k_T) \sim \frac{\sigma_0}{2} k^4 \int \mathrm{d}^2 r e^{ikr} [1 - N(r)]$



Blaizot, Lappi, Mehtar-Tani, arXiv:1005.0955

Single inclusive hadron production from CGC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T \mathrm{d}y} = \frac{2\alpha_s}{C_\mathrm{F} p_T^2} \int \mathrm{d}^2 q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(p_T - q_T)}{(p_T - q_T)^2}$$

Assuming that $p_T \gg Q_s$ we get the hybrid formalism (Note: $\varphi \sim \sigma_0/2 =$ proton DIS area).

$$\frac{\mathrm{d}N}{\mathrm{d}y \mathrm{d}^2 p_T} = \frac{\sigma_0/2}{\sigma_\mathrm{inel}} \frac{1}{(2\pi)^2} xg(x, Q^2) \tilde{S}(p_T),$$

where

$$xg(x, Q^2) = \frac{C_\mathrm{F}\sigma_0/2}{2\pi^2 \alpha_s} \int^{Q^2} \frac{\mathrm{d}^2 q_T}{(2\pi)^2} q_T^2 \tilde{S}(q_T),$$

(or e.g. CTEQ) and $\tilde{S}$ is Fourier transform of $1 - N(r)$ (adj. rep.).

Normalization factor

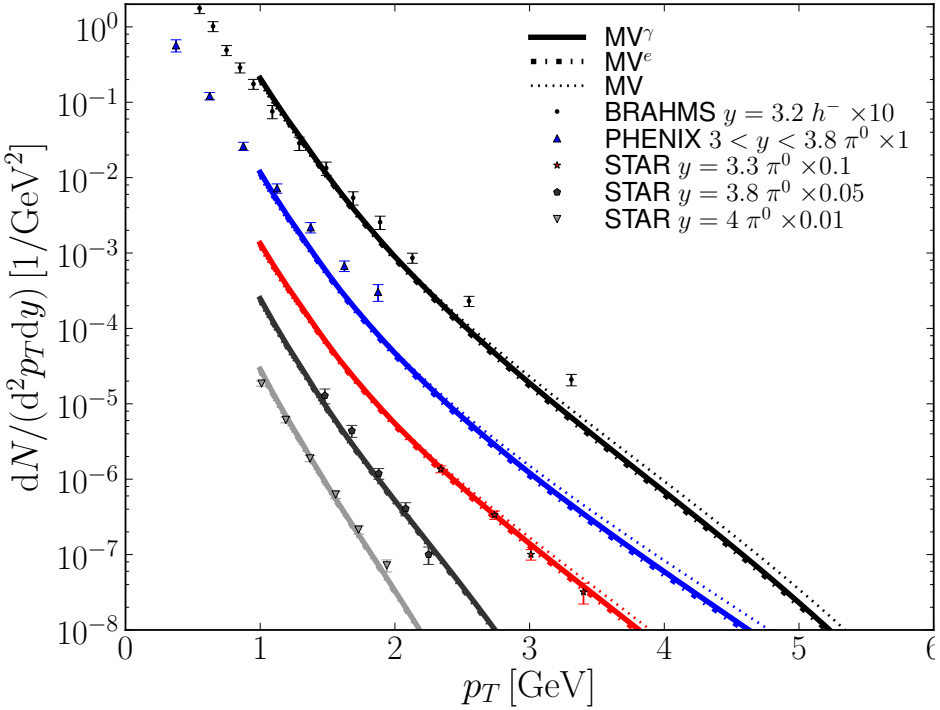
At RHIC (LHC) $(\sigma_0/2)/\sigma_\mathrm{inel} \sim 0.4$ (0.3)

Single inclusive hadron production from CGC

MV$^\gamma$ and MV^e models work with the LHC data, MV does not.

RHIC

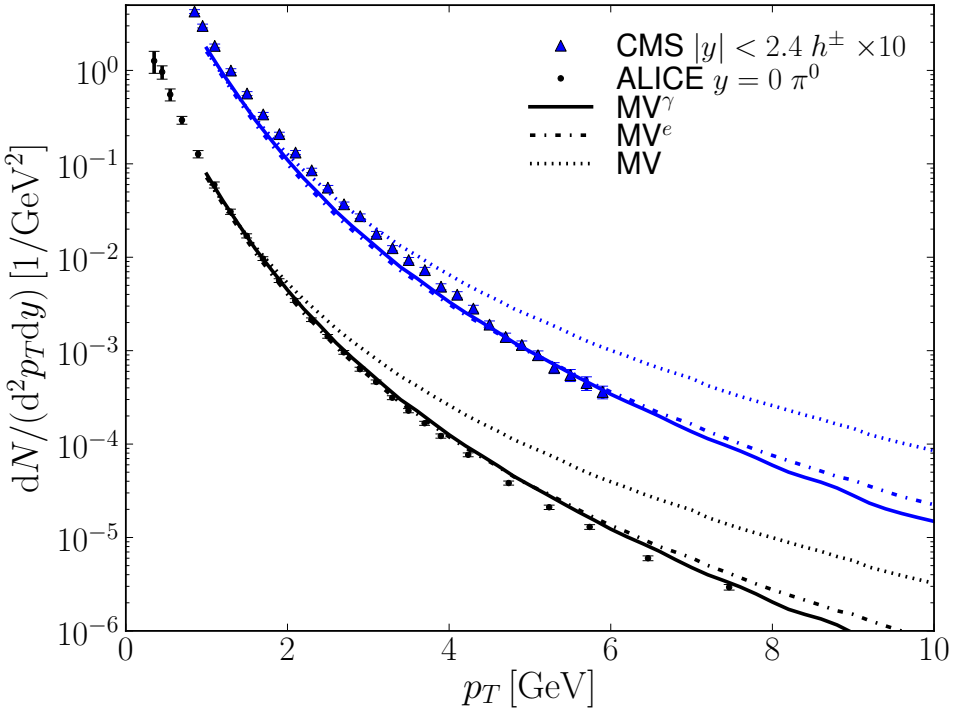
$p + p \to \pi^0/h^- + X$, $\sqrt{s} = 200\,\mathrm{GeV}$, $K = 2.5$



Hybrid formalism, LO CTEQ&DSS

LHC

$p + p \to \pi^0,\ h^\pm + X$, $\sqrt{s} = 7000\,\mathrm{GeV}$, $K = 1$



k_T factorization, LO DSS

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From proton to nucleus

Initial condition for nuclei: Glauber (dilute limit $\sigma^A_{\rm dip} \sim A\sigma^p_{\rm dip}$)

$$N_A(b,r) = 1 - \exp\left[-A T_A(b)\frac{\sigma_0}{2}\frac{(r^2 Q^2_{sp})^\gamma}{4}\ln\left(\frac{1}{\Lambda_{\rm QCD} r} + e_c \cdot e\right)\right].$$

No additional nuclear parameters

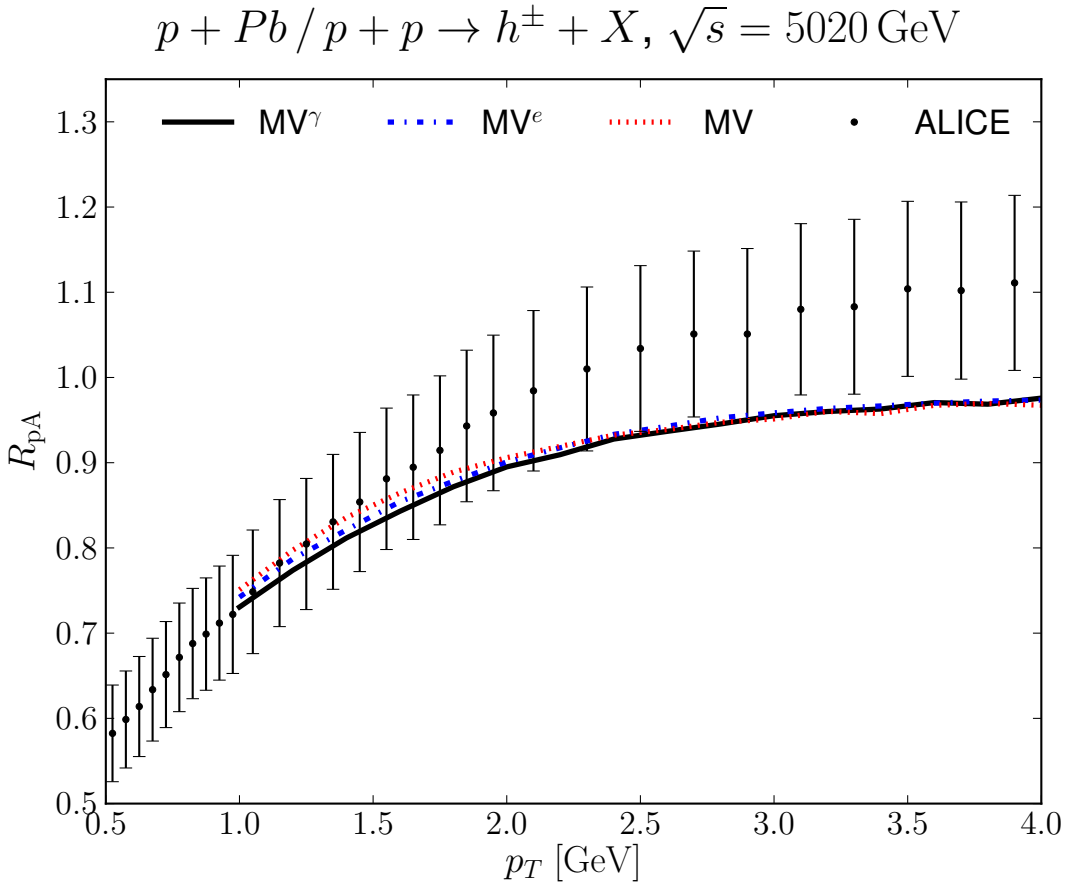
- σ_0 from DIS
- T_A: standard Woods-Saxon

$\Rightarrow$ prediction for $Q^2_s(b)$.

Note: average dipole cross section obtained by integrating over fluctuating nucleon positions.

From proton to nucleus R_{pA}

Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)

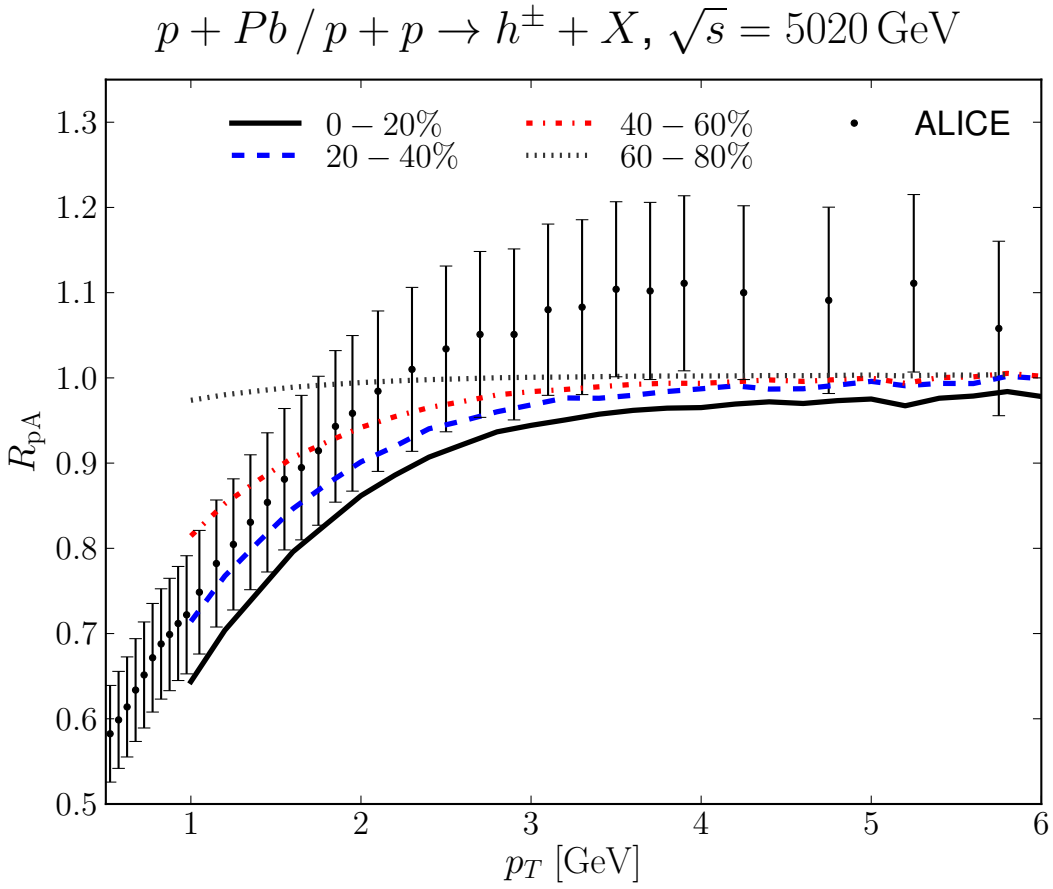


DATA: ALICE, 1210.4520

Minimum bias, basically no dependence on initial condition (MV model also works).

From proton to nucleus: R_{pA}, centrality dependence

Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)

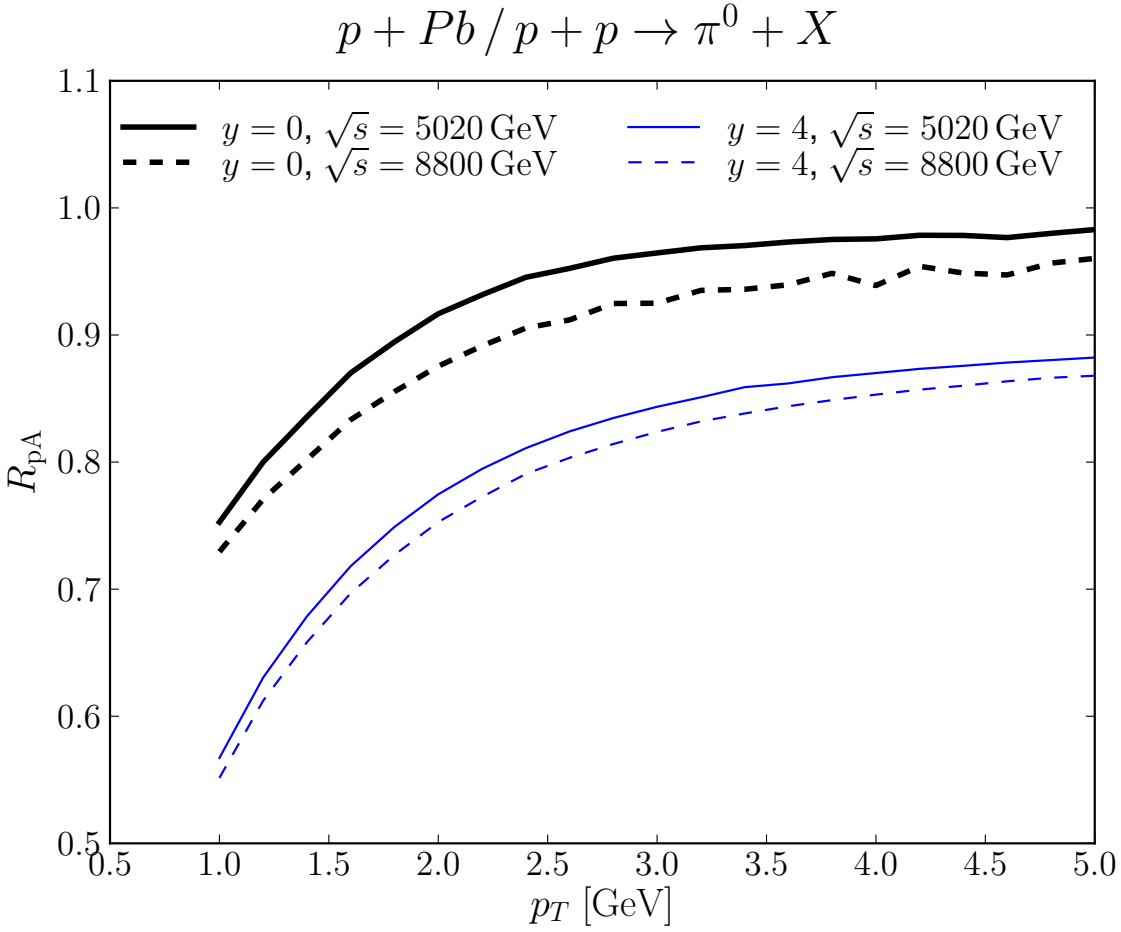


DATA: ALICE, 1210.4520

MV, MV$^{\gamma}$ and MV^{e} give $\approx$ same R_{pA}

Energy dependence of R_{pA}

Midrapidity $R_{pA} \to 1$ at large p_T independently of $\sqrt{s_{NN}}$!.

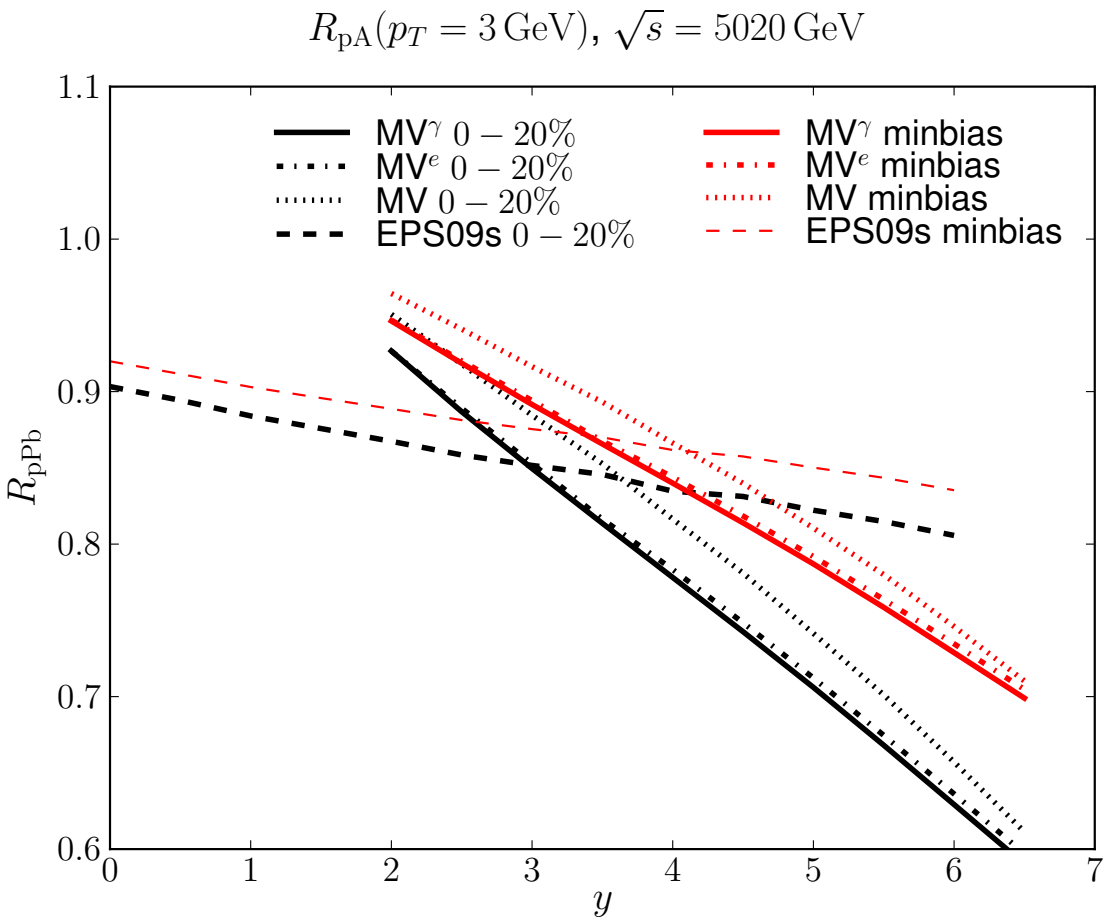


R_{pA} at $y = 0$ (k_T factorization) and at $y = 4$ (hybrid formalism)

CGC vs pQCD (EPS09s)

CGC predicts faster centrality and especially rapidity evolution than EPS09s-NLO pQCD

EPS09s calculations by I. Helenius



CGC: Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

Conclusions

- CGC offers a consistent framework to describe small-x observables
- New initial condition MV^e fitted to HERA data.
- MV model must be modified (include γ or e_c) in order describe LHC pp and pA spectra
- Diffractive DIS: probe impact parameter dependence
- Using only ep DIS as an input we compute single particle production in pp and pA.
- Centrality and rapidity dependent predictions for R_{pA}
  - Faster rapidity evolution than predicted by NLO pQCD calculations (EPS09s).

Future plans

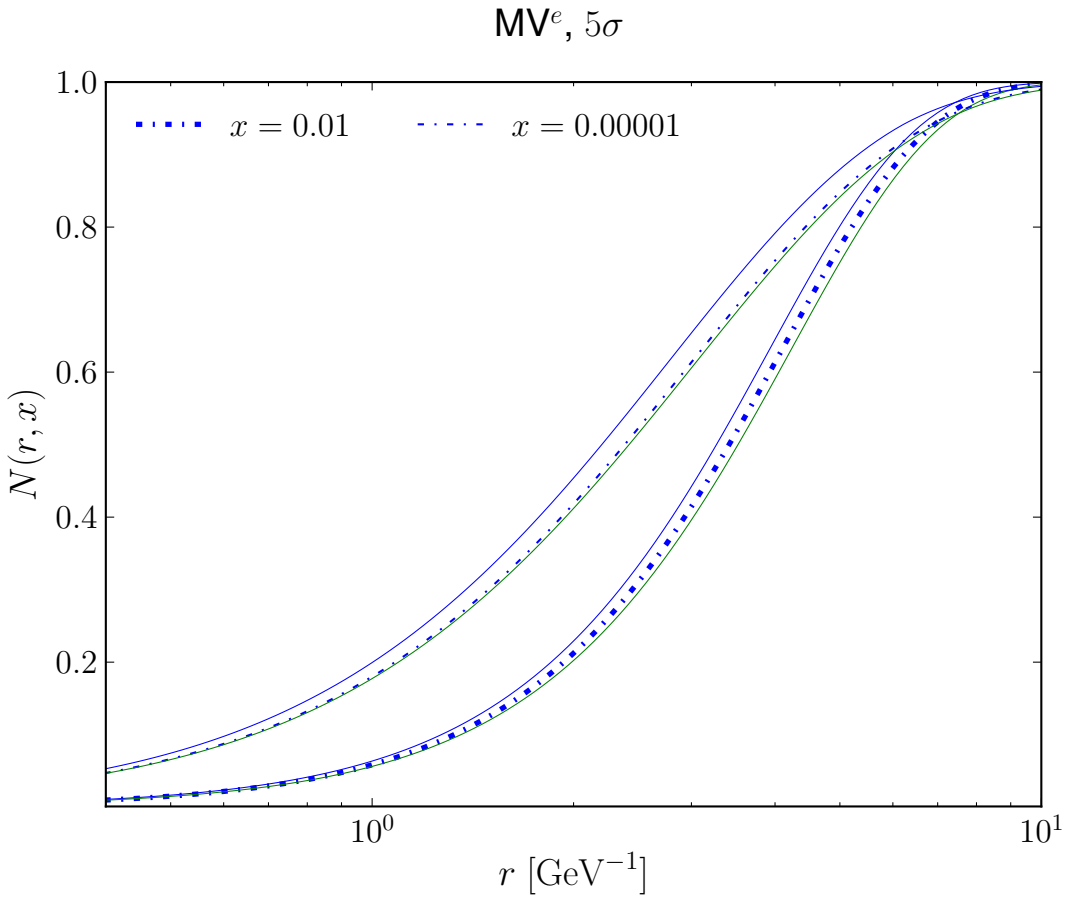
- Correlated statistical error analysis for HERA bk fit
- Numerical solution of the NLO BK
- Dihadron production at the LHC
- Diffraction? (ultraperipheral collisions?)

(some backup slides available...)

BACKUPS

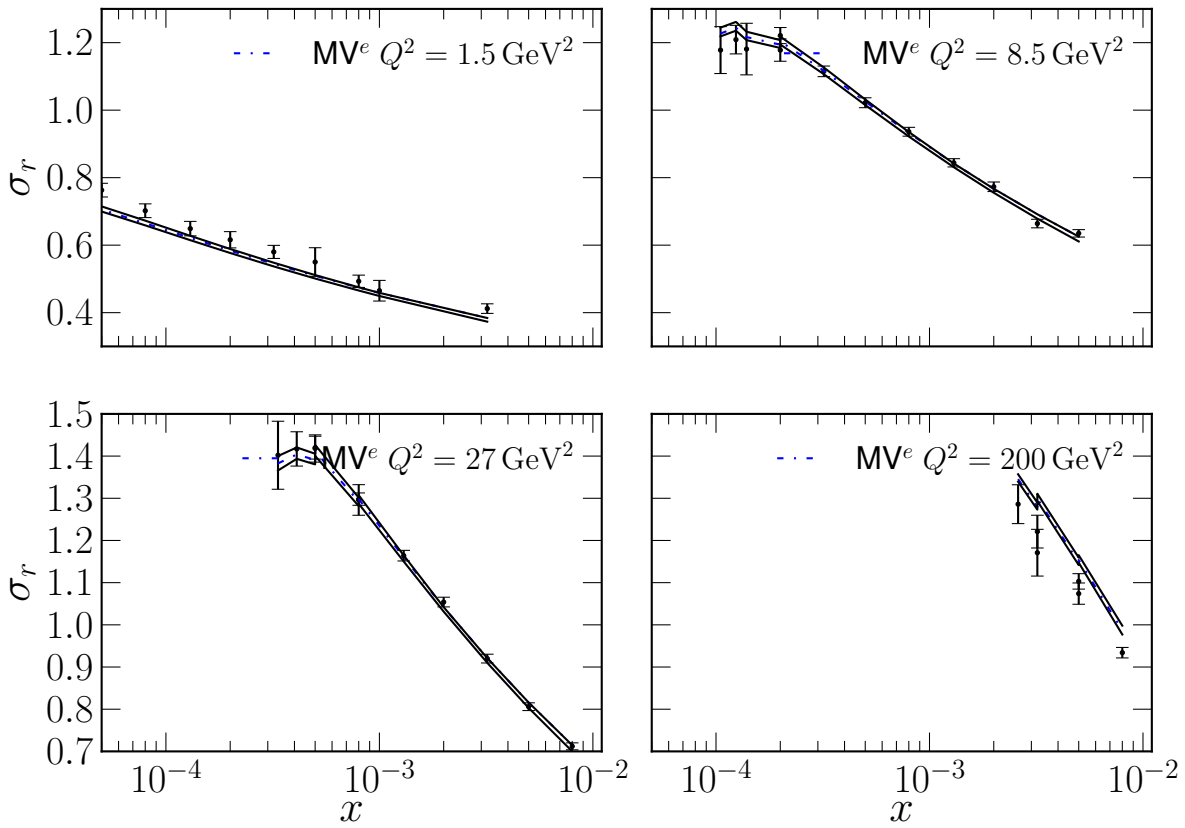
Correlation analysis, results

(Very) preliminary: Hessian method used to obtain errorsets for dipole amplitude at 5σ confidence level, MV^e initial condition.



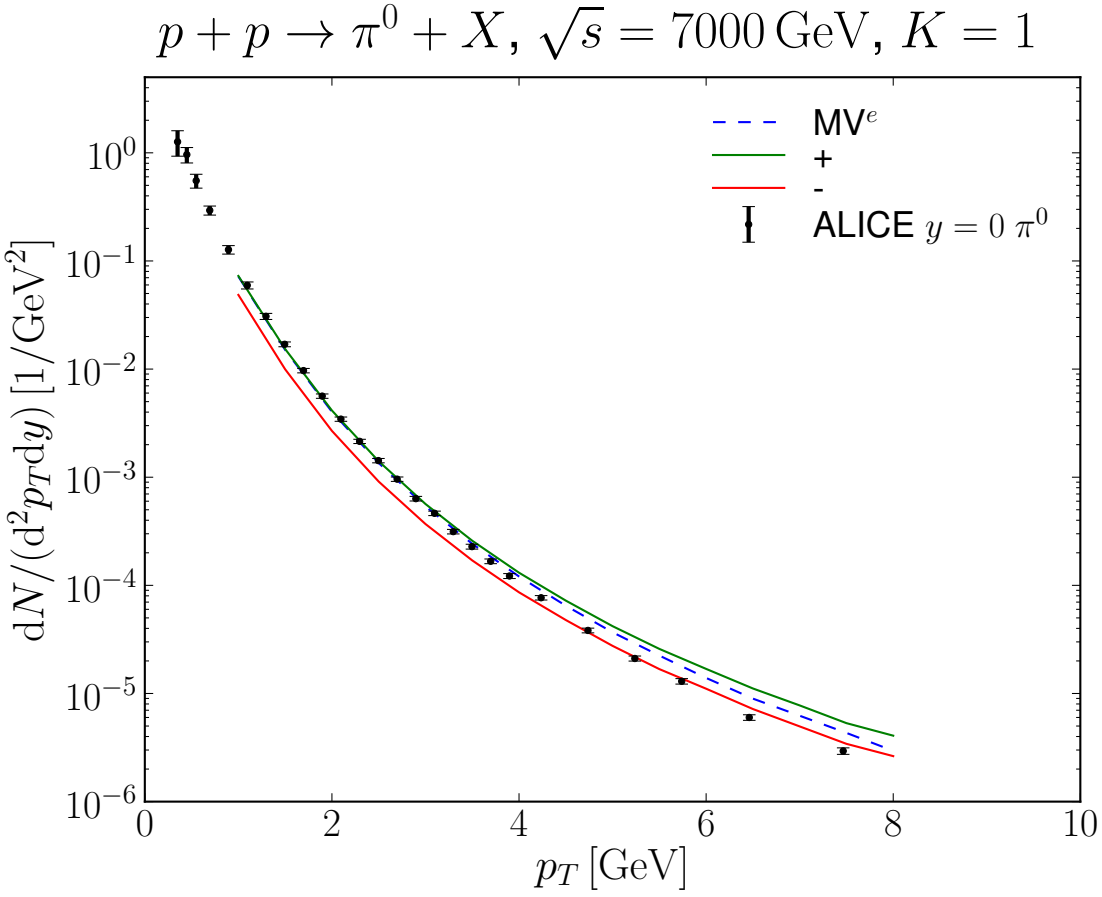
Correlation analysis, results

(Very) preliminary: Hessian method used to obtain errorsets for dipole amplitude at 5σ confidence level, MV^e initial condition.3



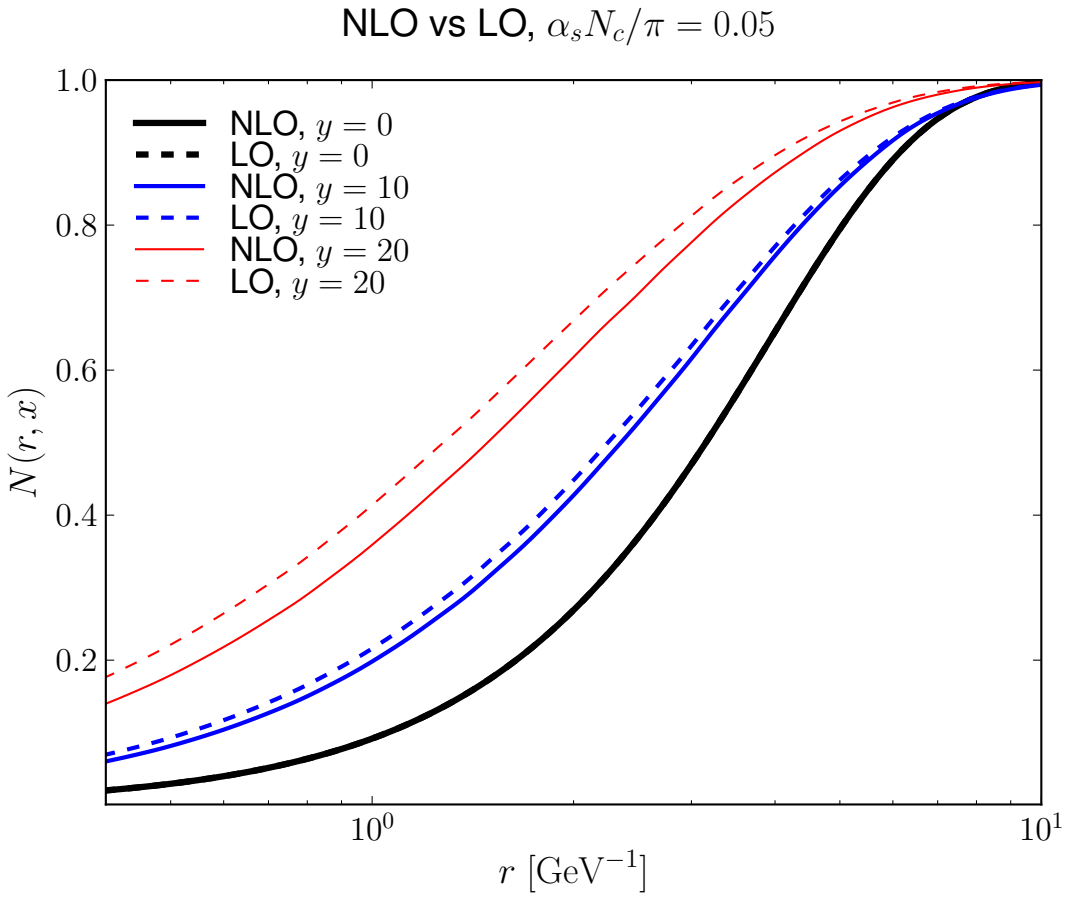
Correlation analysis, results

(Very) preliminary: Hessian method used to obtain errorsets

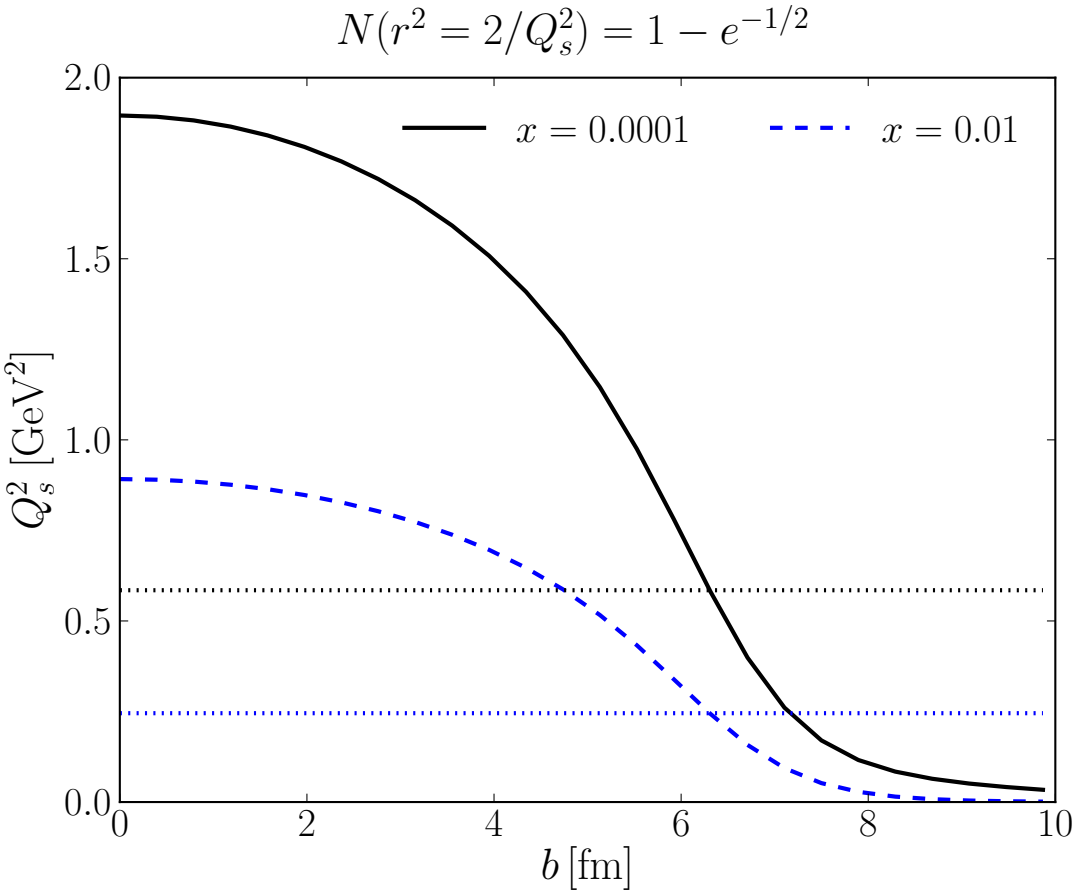


NLOBK

Numerical solution of the NLOBK equation (Balitsky, Chirilli, 0710.4330), very preliminary (large-N_c, $n_f = 0$).

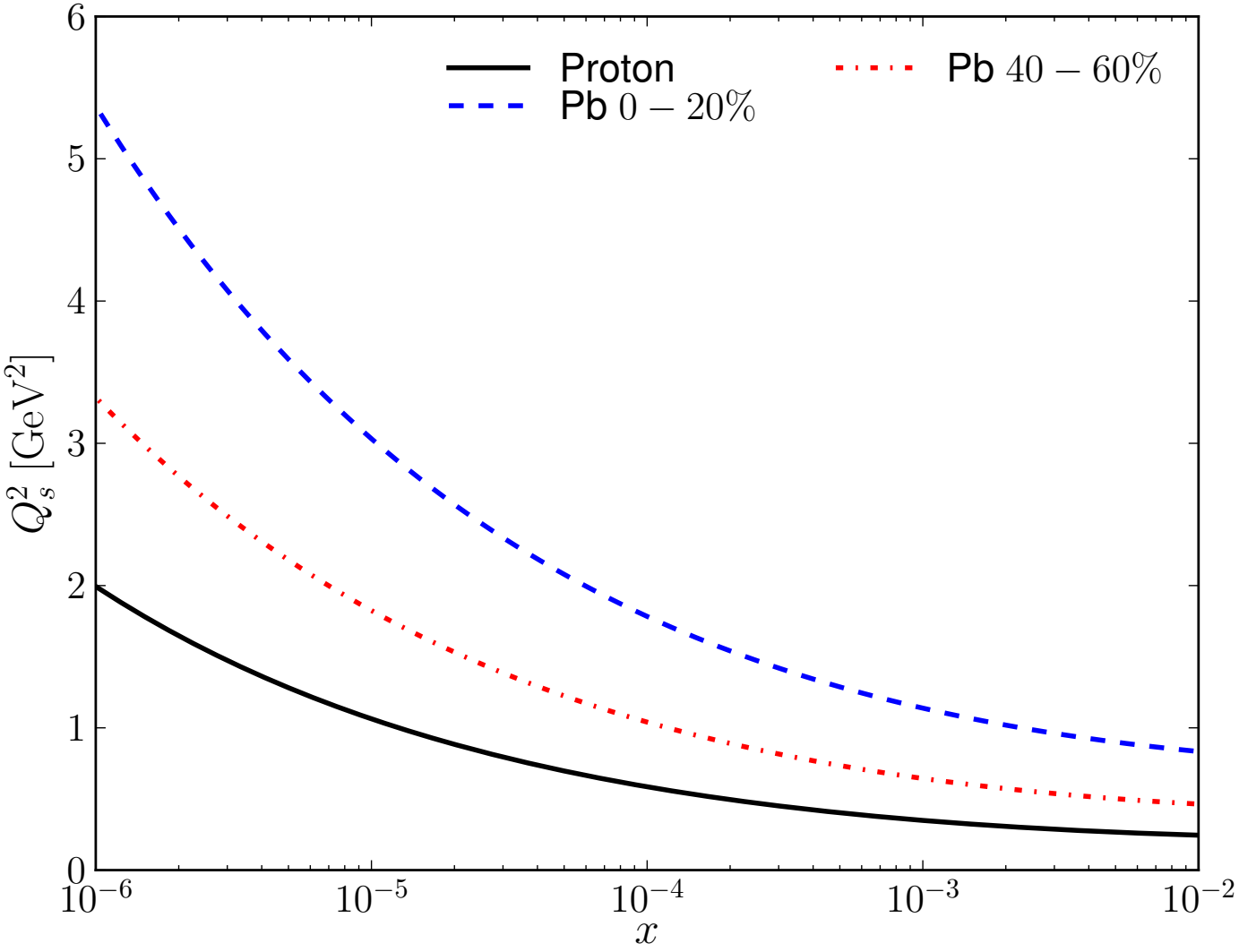


Impact parameter dependence of the saturation scale

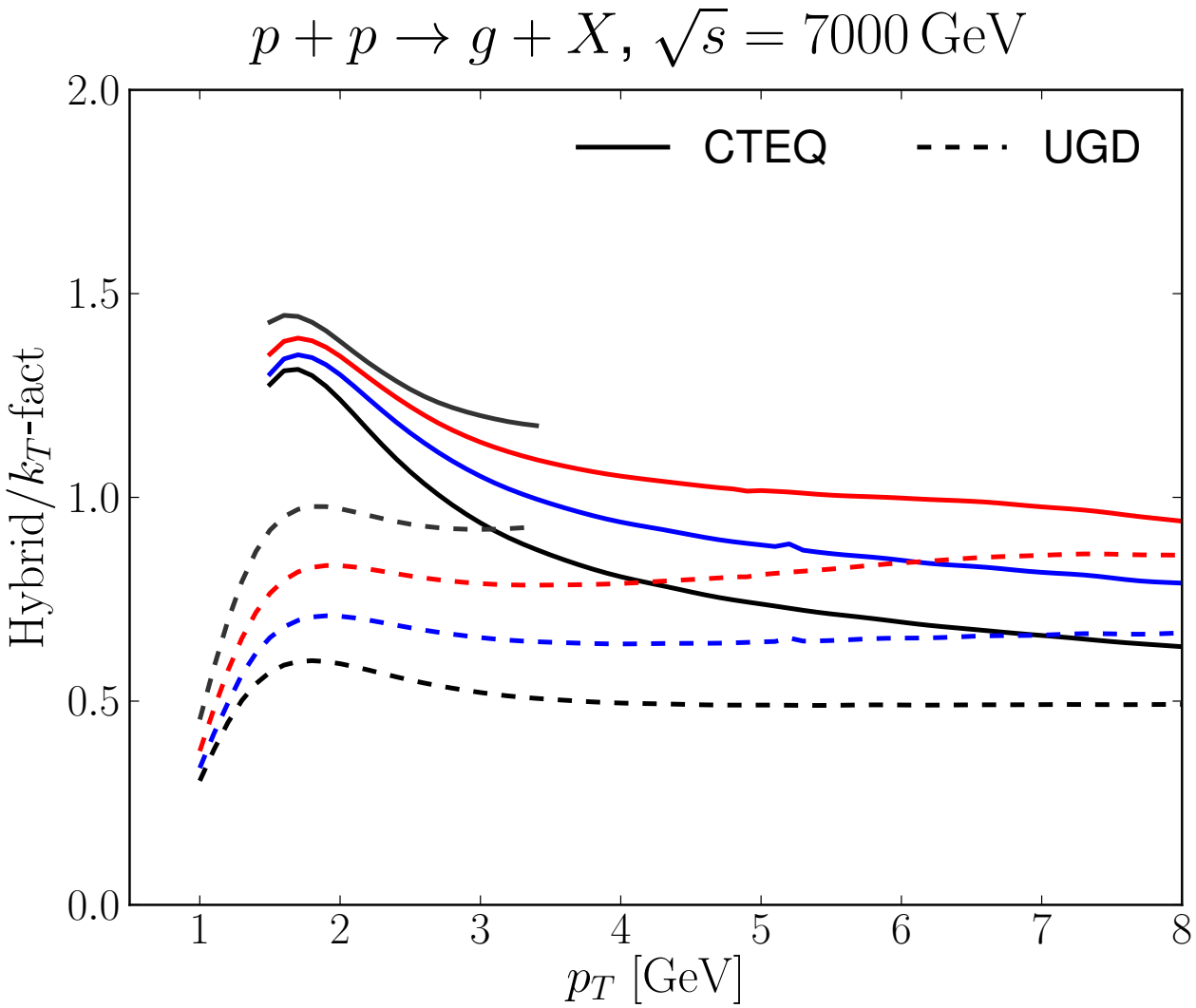


From proton to nucleus: saturation scale

$$N(r^2 = 2/Q_s^2) = 1 - e^{-1/2}$$

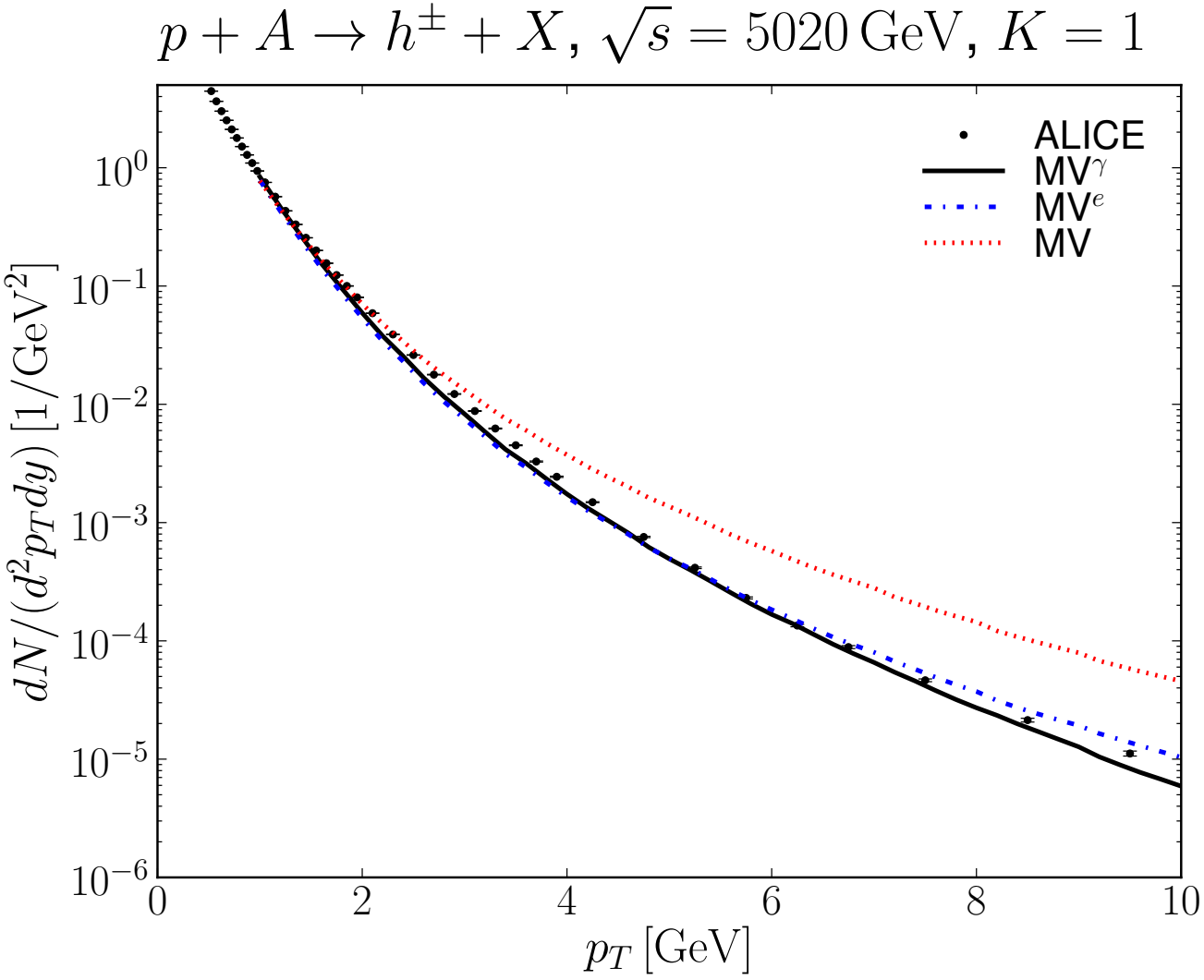


k_T factorization vs hybrid formalism



ALICE $p + Pb$ spectrum, k_T factorization

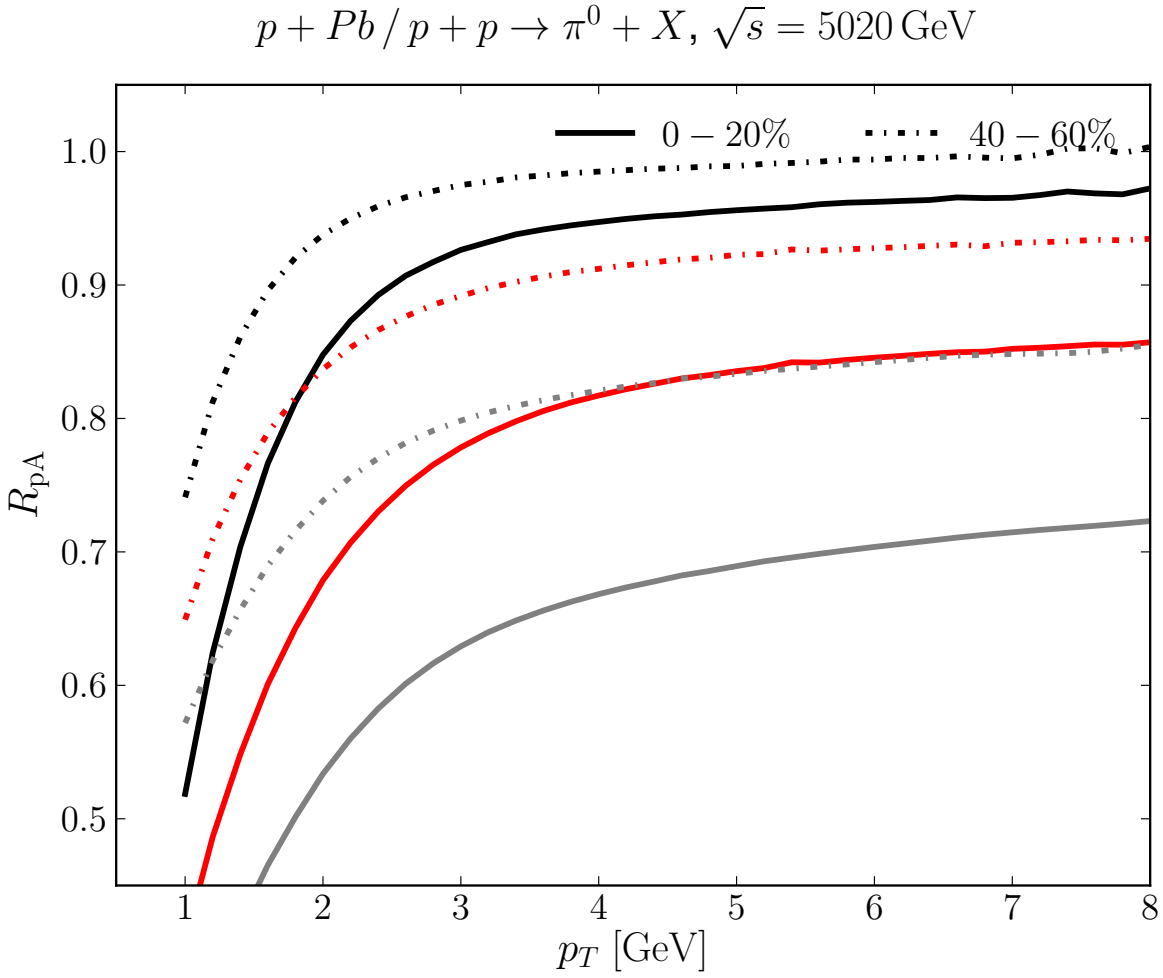
MV$^\gamma$ and MV^e model ICs work with ALICE data, MV does not.



k_T factorization, DATA: ALICE, 1210.4520

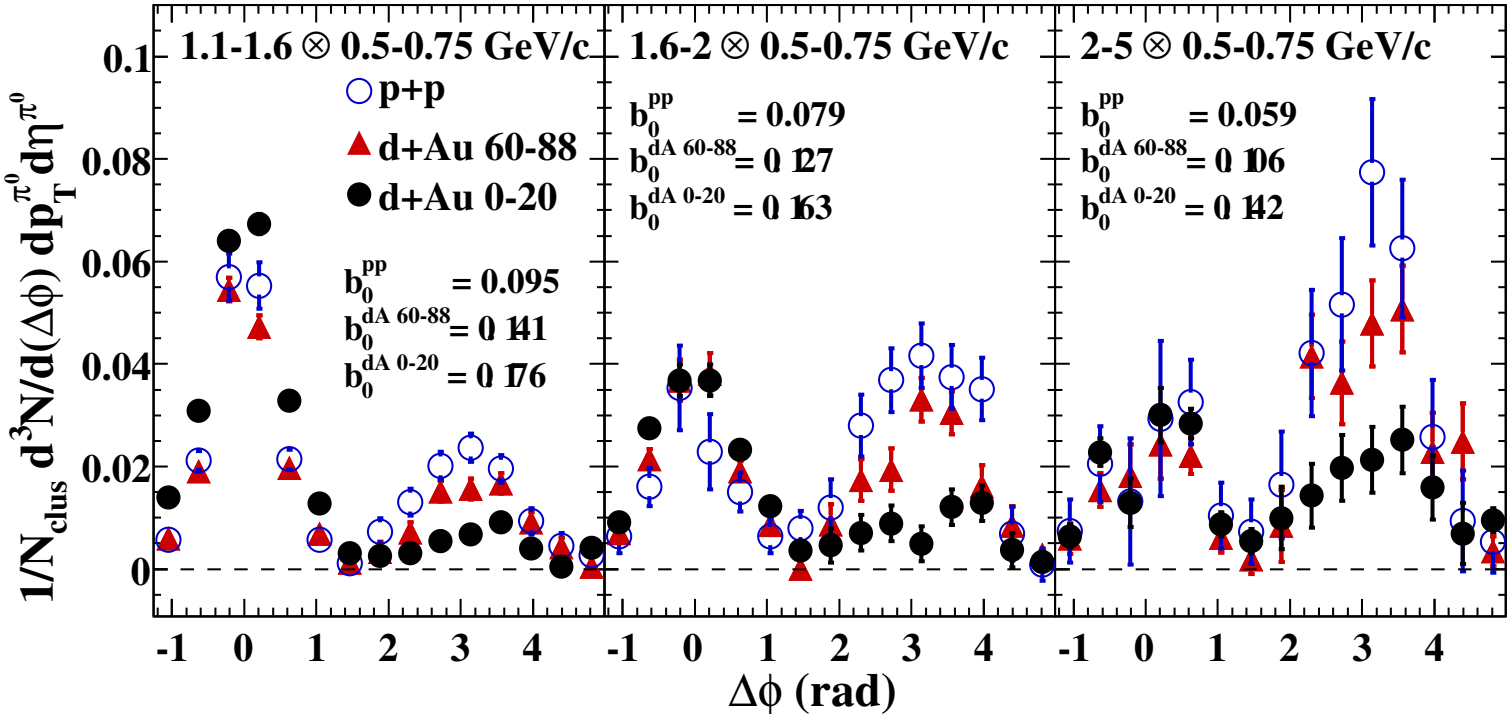
Rapidity dependence of R_{pA}: $0-20\%$ vs $20-40\%$

Centrality dependence increases at forward rapidities ($y = 2, 4, 6$)



Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

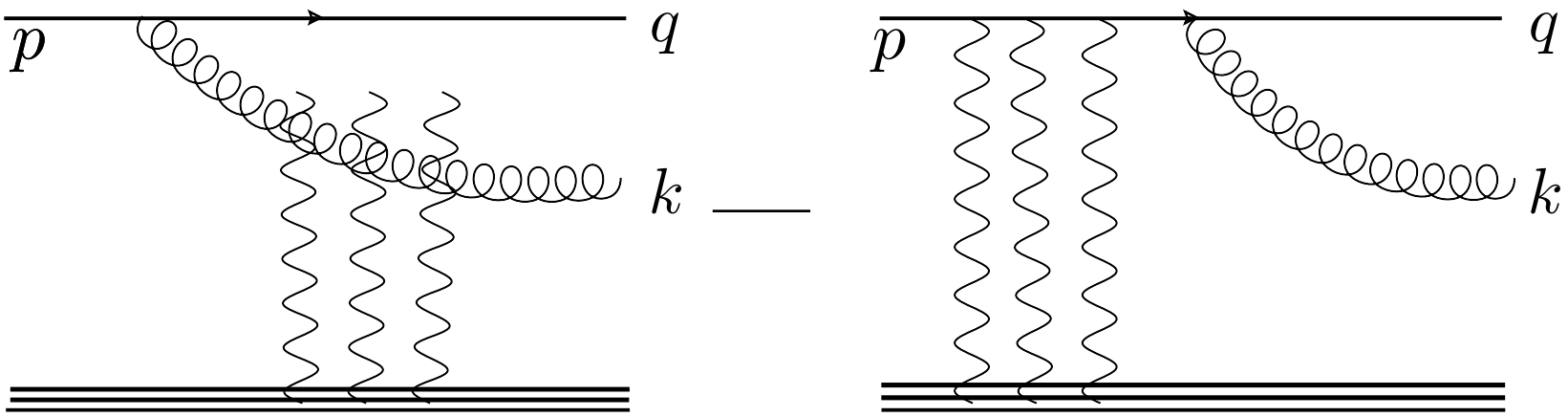
Dihadron production



PHENIX data (1105.5112): away side peak disappears when moving form p+p to central d+Au

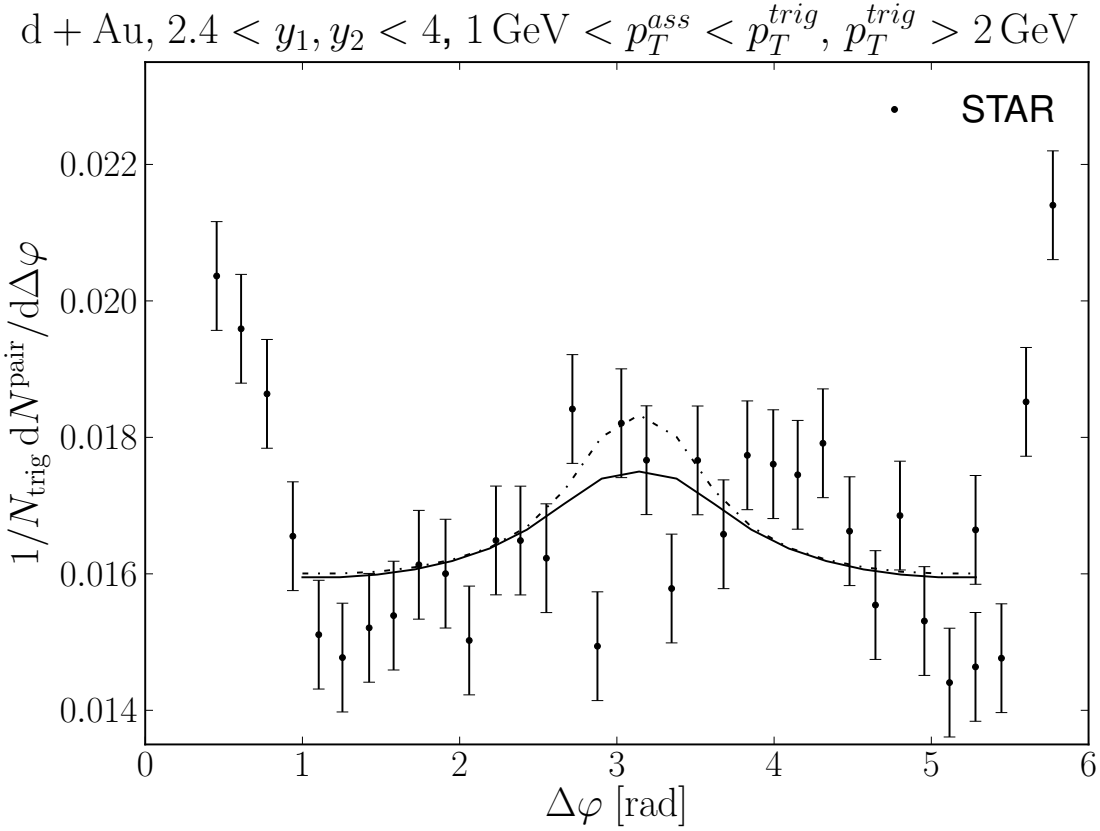
Dihadron production from CGC

CGC description: quark emits a gluon and scatters off the target.
Momentum transfer $\sim Q_s \Rightarrow$ explains disappearance of the away side peak



$$Q_s^2 \approx A^{1/3} \left(\frac{x}{x_0} \right)^{-0.3} Q_{s0}^2$$

Results: Coincidence probability



- Good description of central STAR data (pedestal from exp. data)
- Gaussian large-*Nc* approximation

T. Lappi, H.M, arXiv:1209.2853. data: PHENIX [1105.5112]