Probing the nuclear structure at small x with e+A collisions

Cyrille Marquet

Theory Division - CERN

Dominguez, CM and Wu (2009)

CM, Xiao and Yuan (2009)

Albacete and CM (2010)

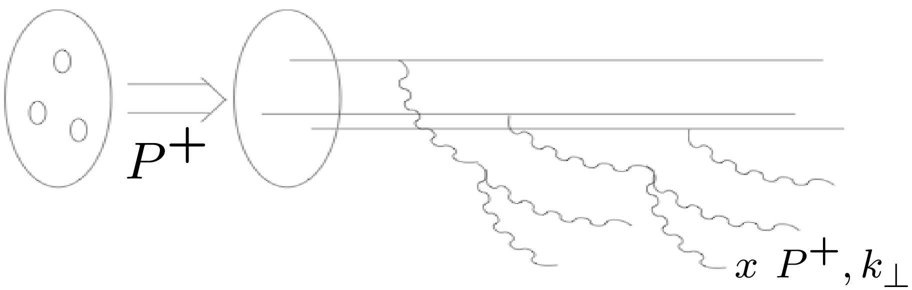
Dominguez, CM, Xiao and Yuan (2011)

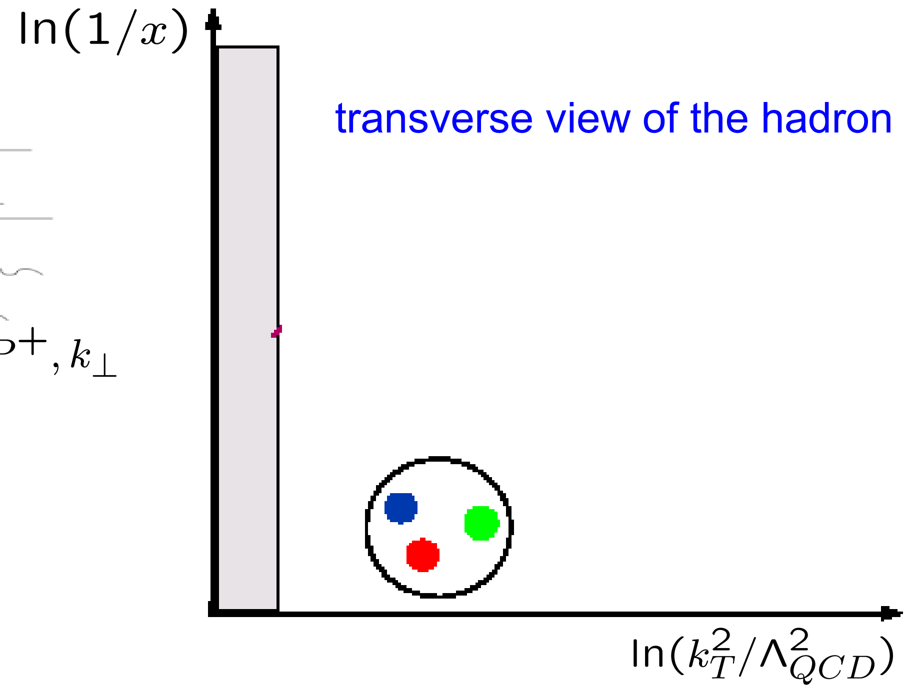
Outline

- Introduction to small-x physics
- DIS structure functions at small x
  - integrated parton distributions
- Semi-inclusive DIS at small x
  - k -dependent parton distribution
- Di-hadron production in DIS at small x
  - gluon (momentum) correlations
- Coherent vs incoherent diffractive VM production
  - b-dependent parton distributions
  - gluon (spatial) correlations

The hadron wave function in QCD

$$|\text{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T >> \Lambda_{QCD}\,,\, x \leq 1\rangle + |k_T >> \Lambda_{QCD}\,,\, x << 1\rangle$$





The dilute regime

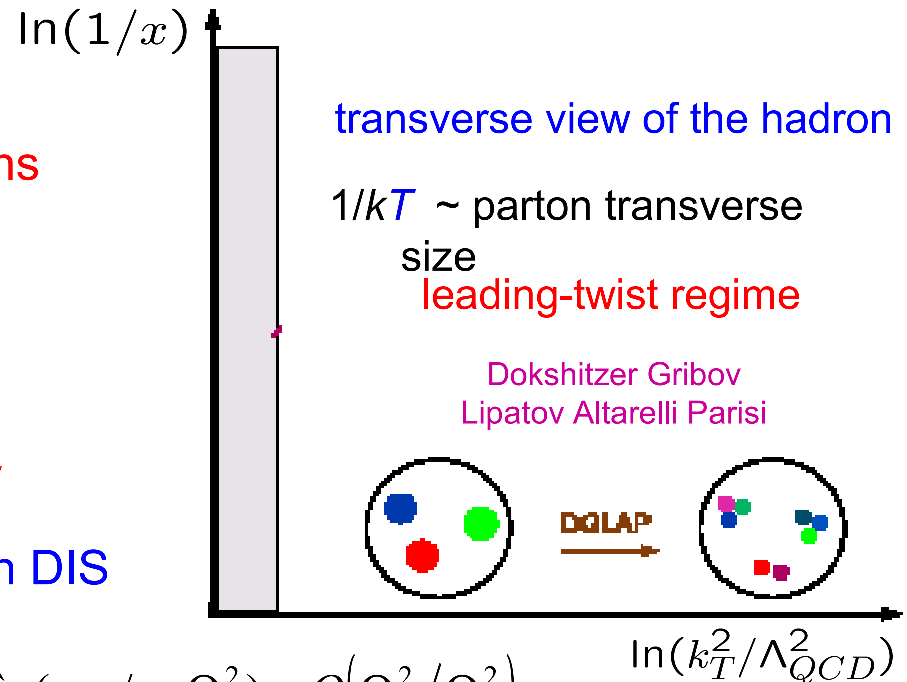
$$|\text{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T >> \Lambda_{QCD}\,,\, x \le 1\rangle + |k_T >> \Lambda_{QCD}\,,\, x << 1\rangle$$

hadron = a dilute system of partons

evolution: as k_T increases,
the hadron gets more dilute

the partons interact incoherently

for instance, the total cross-section in DIS



transverse view of the hadron

$1/k_T$ ~ parton transverse size

leading-twist regime

Dokshitzer Gribov Lipatov Altarelli Parisi

$$\sigma_{DIS}(x_{Bj},Q^2) = \sum_{partons\ a} \int_{x_{Bj}}^{1} dx\, \phi_{a/p}(x,Q^2)\hat{\sigma}_a(x_{Bj}/x,Q^2) + O\left(Q_0^2/Q^2\right)$$

parton density — partonic cross-section — higher twist $\longrightarrow \dfrac{(A/x)^{1/3}}{Q^2}$

not valid if *x* is too small when the hadron becomes a dense system of partons

The saturation regime

$$|\mathrm{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T >> \Lambda_{QCD}\,,\, x \le 1\rangle + |k_T >> \Lambda_{QCD}\,,\, x << 1\rangle$$

the separation between the dilute and dense regimes is caracterized by a momentum scale:

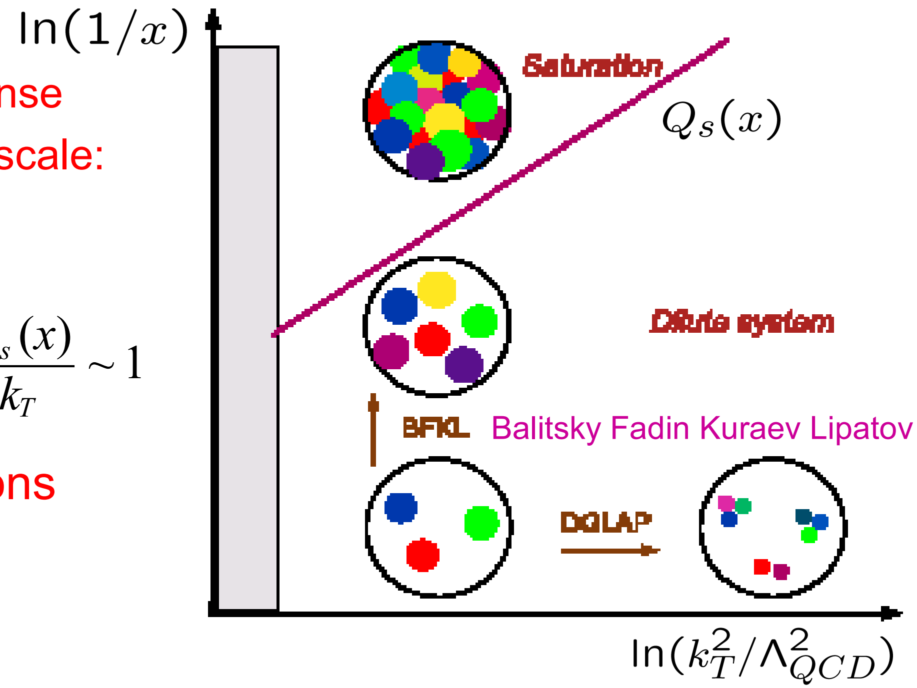
the saturation scale $Q_s(x)$

in the saturation regime, higher-twists are important: $\frac{\Lambda_{QCD}}{k_T} << 1\,,\ \frac{Q_s(x)}{k_T} \sim 1$

hadron = a dense system of partons

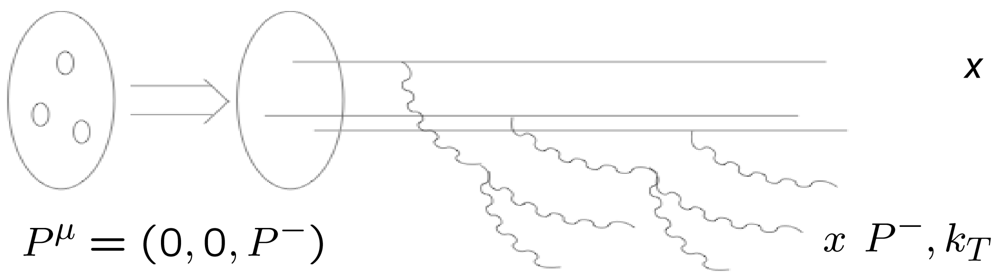
evolution: as *x* decreases, the hadron gets more dense

in the saturation regime,
the evolution becomes non linear
the partons interact coherently



the saturation regime of QCD:
- non-linear yet weakly-coupled
- describes the collective behavior of partons in the nuclear wave function

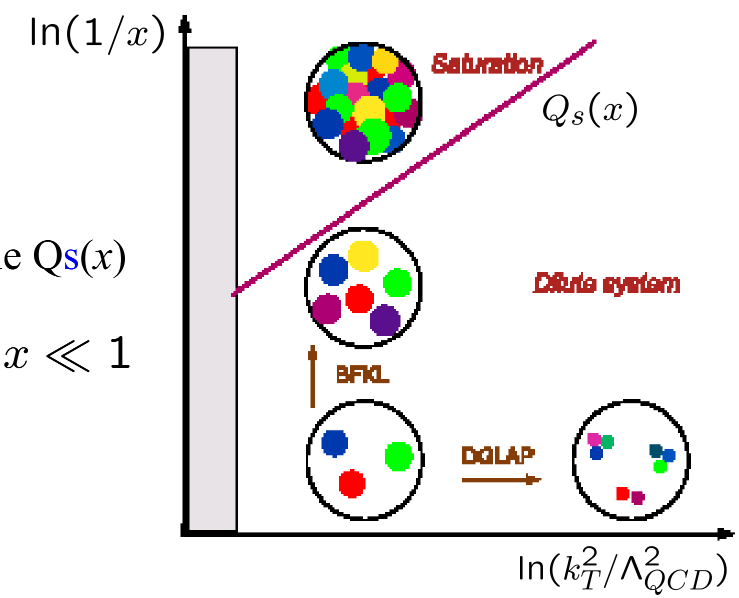
Map of parton evolution in QCD



x : parton longitudinal momentum fraction

kT : parton transverse momentum

the distribution of partons as a function of *x* and *kT* :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger *kT* (and a more dilute hadron)

BFKL evolution to smaller *x* (and denser hadron)

dilute/dense separation characterized by the saturation scale Qs(*x*)

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

$\rho \sim \dfrac{xf(x, k_\perp^2)}{\pi R^2}$ gluon density per unit area

it grows with decreasing x

$\sigma_{rec} \sim \alpha_s / k^2$ recombination cross-section

recombinations important when $\rho\ \sigma_{rec} > 1$

the saturation regime: for $k^2 < Q_s^2$ with $Q_s^2 = \dfrac{\alpha_s x f(x, Q_s^2)}{\pi R^2}$

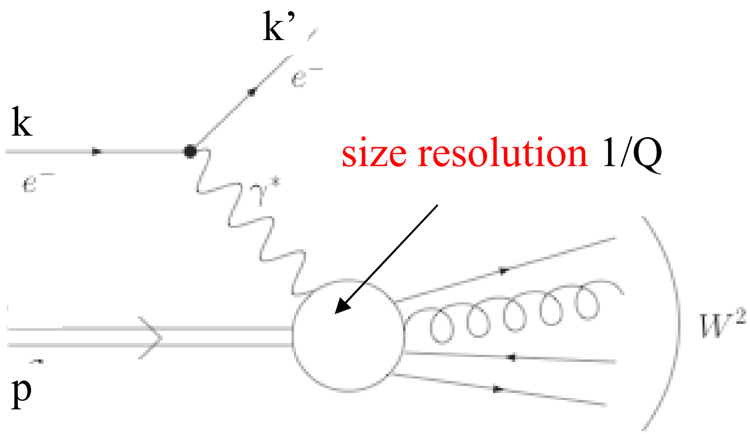
this regime is non-linear

yet weakly coupled

$\alpha_s(Q_s^2) \ll 1$

DIS structure functions at small x

Kinematics, structure functions



lh center-of-mass energy
S = (*k*+*p*)

γ^*h center-of-mass energy
W = (*k*-*k*'+*p*)

photon virtuality
Q = - (*k*-*k*') > 0

$$x = \frac{Q^2}{2p.(k-k')} = \frac{Q^2}{W^2 - M_h^2 + Q^2}$$

$$y = \frac{p.(k-k')}{p.k} = \frac{Q^2/x}{S - M_h^2}$$

x ~ momentum fraction of the struck parton

y ~ W^2/S

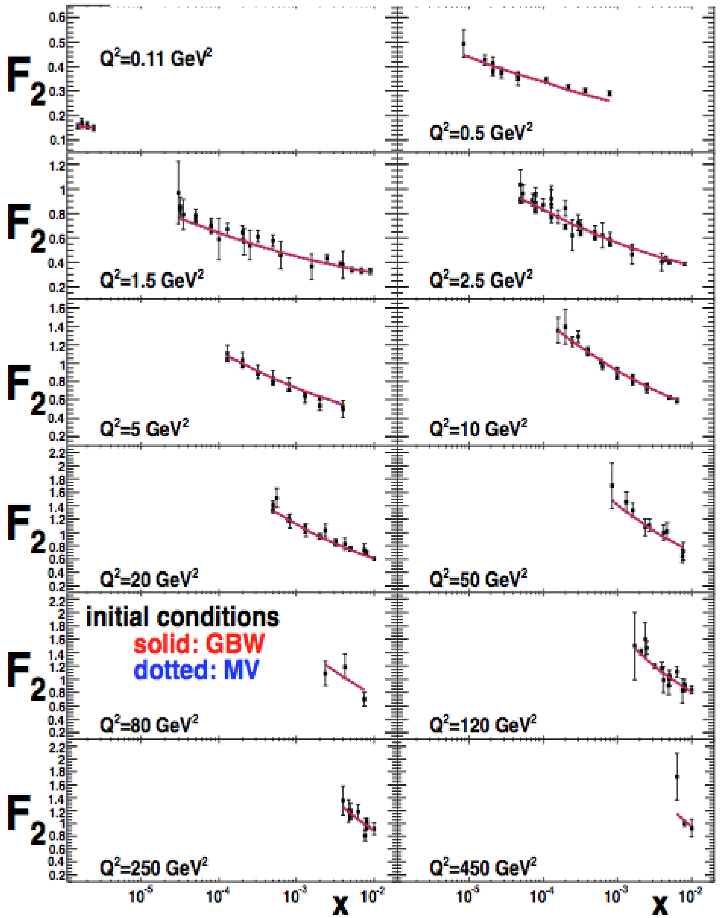
- the measured cross-section

$$\frac{d^2\sigma^{eh\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

experimental data are often shown in terms of $\sigma_{tot}^{\gamma^*h\to X} = \sigma_T^{\gamma^*h\to X} + \sigma_L^{\gamma^*h\to X} = \frac{4\pi^2\alpha_{em}}{Q^2}F_2$

DIS off the proton

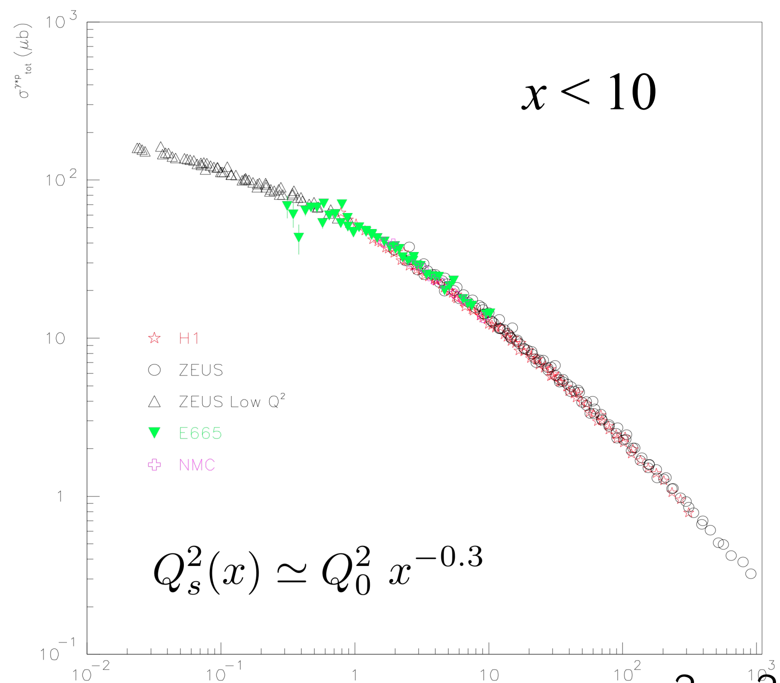
Albacete, Armesto, Milhano and Salgado (2009)



rcBK fit (~ 850 points) $\chi^2/\mathrm{dof} = 1.1$

Stasto, Golec-Biernat and Kwiecinski (2001)

$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



$\tau \equiv Q^2/Q_s^2(x)$

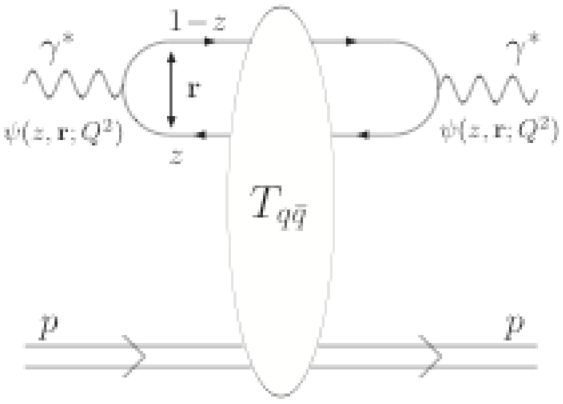
geometric scaling seen in the data, but scaling violations are essential for a good fit

The dipole factorization in DIS

- the cross section at small x

Mueller (1990), Nikolaev and Zakharov (1991)

$$\sigma_{T,L}^{\gamma^* p\to X} = 2\int d^2r\, dz\, |\psi_{T,L}(z,\mathbf{r};Q^2)|^2 \underbrace{\int d^2b\, T_{q\bar{q}}(\mathbf{r},\mathbf{b},x_B)}$$



overlap of $\gamma^* \to q\bar{q}$
splitting functions

dipole-hadron cross-section
computed in the CGC
or with dipole models

Balitsky and Chirilli

the existing CGC phenomenology is still based on the leading log approximation,
F_2 and F_L will be the first observables where NLL will be available for practical analysis

- estimating the importance of saturation

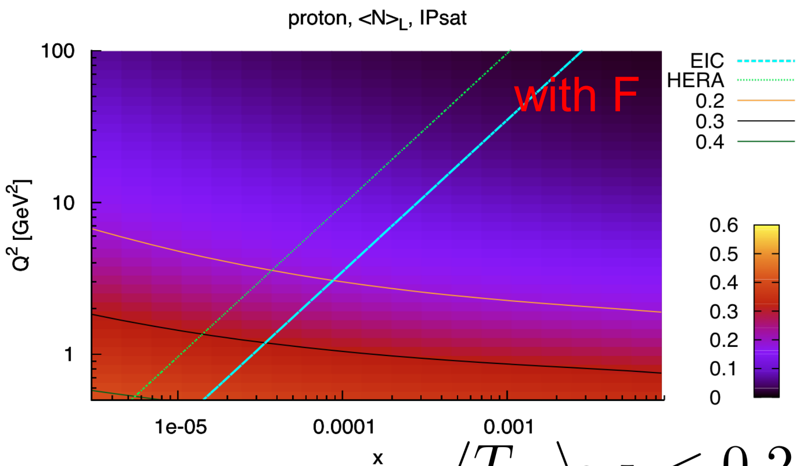
Diehl and Lappi

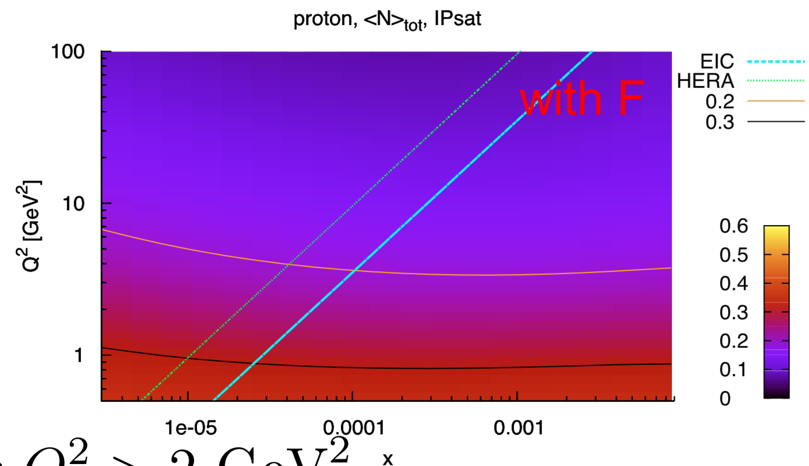
$$\langle T_{q\bar{q}}\rangle_{2,L}(x,Q^2) = \frac{\int d^2r dz\ |\psi_{2,L}(z,\mathbf{r};Q^2)| \int d^2b\ T_{q\bar{q}}^2(\mathbf{r},\mathbf{b};x)}{\int d^2r dz\ |\psi_{2,L}(z,\mathbf{r};Q^2)| \int d^2b\ T_{q\bar{q}}(\mathbf{r},\mathbf{b};x)}$$

average dipole scattering amplitude $\langle T_{q\bar{q}}\rangle_{T,L} < 0.6-0.7$ and not 1 because of b int

Average strength of scattering

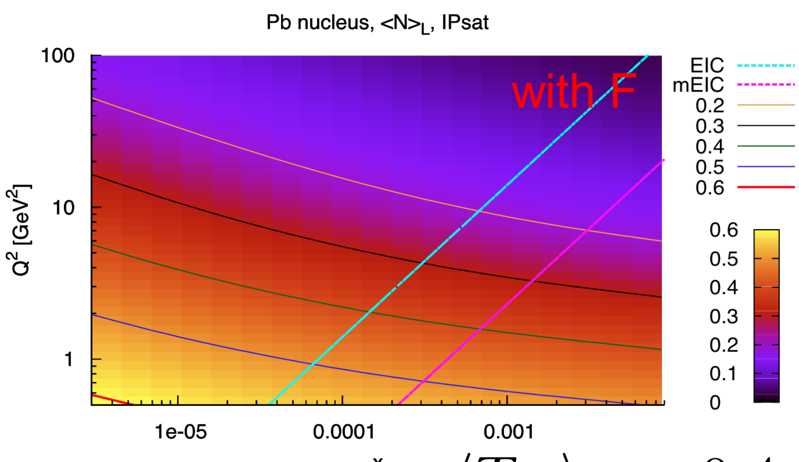
- off the proton

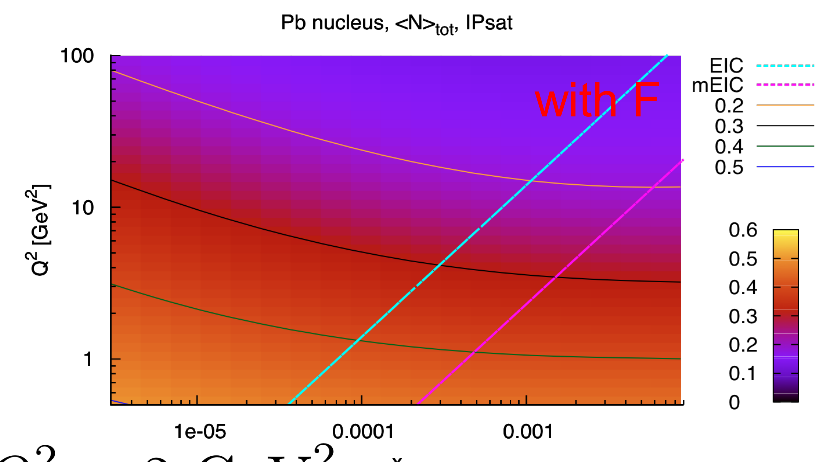




$$\langle T_{q\bar{q}} \rangle_{2,L} < 0.25 \text{ for } Q^2 > 2 \text{ GeV}^2$$

- off the nucleus



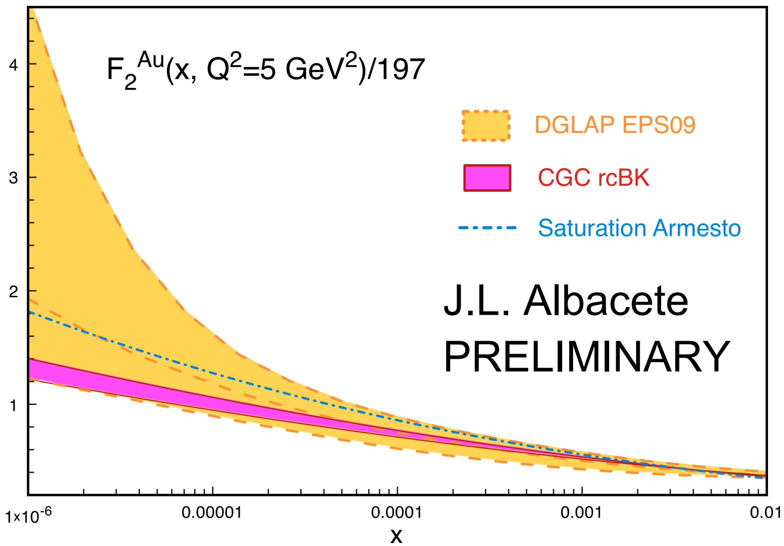


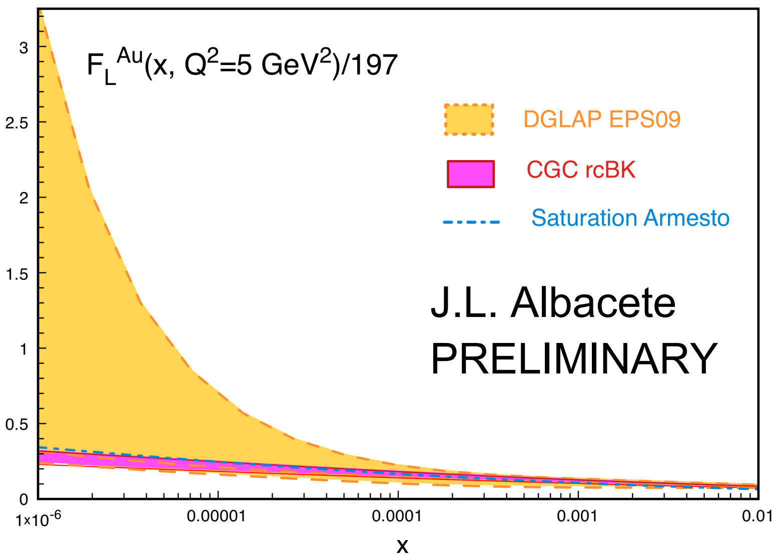
$$\langle T_{q\bar{q}} \rangle_L \simeq 0.4 \text{ for } Q^2 = 2 \text{ GeV}^2$$

Expectations for e+A

- using the small-x QCD evolution

extrapolating from relatively large-x data, the non-linear QCD evolution can predict the structure functions



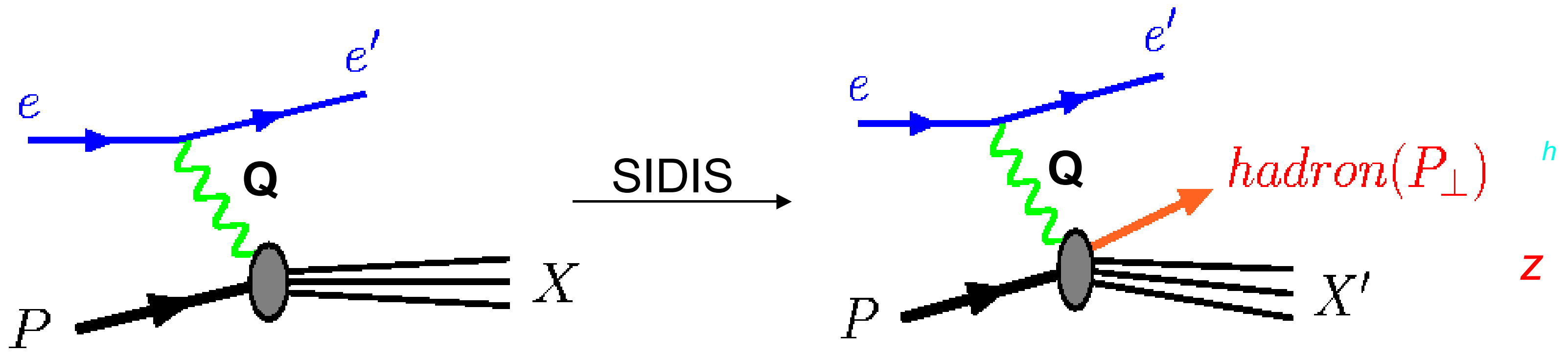


still this need to be checked with data, it is not absolutely clear that the CGC is already applicable in the x range where one starts the evolution

the CGC initial conditions for heavy-ion collisions are based on such extrapolations too

Semi-inclusive DIS
(or single-hadron production)

The dipole factorization in SIDIS

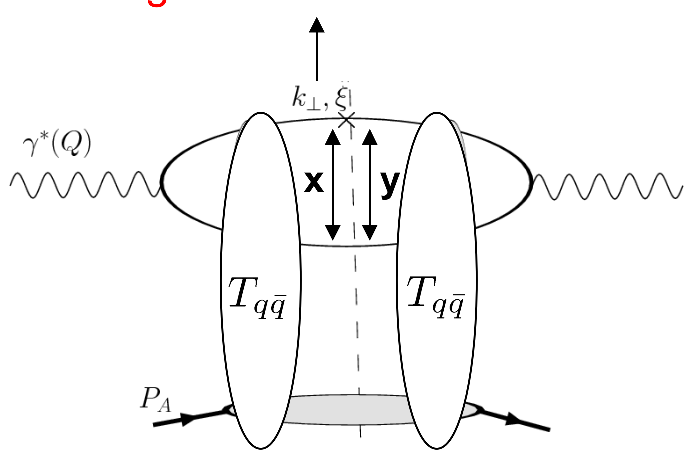


- the cross section at small x

$$\Phi(\xi, \mathbf{x}, \mathbf{y}; Q^2) = \psi(\xi, \mathbf{x}; Q^2)\psi^*(\xi, \mathbf{y}; Q^2)$$

dipoles in amplitude / conj. amplitude

fragmentation into hadron



$$\frac{d\sigma^{\gamma^* p \to hX}}{dz_h d^2 P_\perp} = \frac{d\sigma_{T,L}^{\gamma^* p \to qX}}{d\xi d^2 k_\perp}\left(k_\perp = \frac{\xi}{z_h} P_\perp\right) \otimes D_{h/q}(z_h/\xi)$$

$$\frac{d\sigma_{T,L}^{\gamma^* p \to qX}}{d\xi d^2 k_\perp} = \int \frac{d^2x}{2\pi}\frac{d^2y}{2\pi}\, e^{-ik_\perp\cdot(\mathbf{x}-\mathbf{y})}\Phi_{T,L}(\xi, \mathbf{x}, \mathbf{y}; Q^2)\int d^2b\, [T_{q\bar{q}}(\mathbf{x}, x_B) + T_{q\bar{q}}(\mathbf{y}, x_B) - T_{q\bar{q}}(\mathbf{x}-\mathbf{y}, x_B)]$$

McLerran and Venugopalan, Mueller, Kovchegov and McLerran (1999)

Cross section in momentum space

- the lepto-production cross section

$$\frac{d\sigma(ep\to e'hX)}{d\mathcal{P}} = \frac{\alpha_{em}^2 N_c}{2\pi^3 x_B Q^2}\sum_f e_f^2 \int_{z_h}\frac{dz}{z}\frac{D(z)}{z^2}\int d^2b\, d^2q_\perp \overbrace{F(q_\perp,x_B)\,\mathcal{H}\left(\xi=\frac{z_h}{z},k_\perp=\frac{P_\perp}{z}\right)}^{k_T \text{ factorization}}$$

phase space $d\mathcal{P} = dx_B dQ^2 dz_h dP_\perp^2$

the unintegrated gluon distribution

$$F(q_\perp,x_B) = \int \frac{d^2r}{(2\pi)^2}\, e^{-iq_\perp\cdot\mathbf{r}}[1-T_{q\bar{q}}(\mathbf{r},x_B)]$$

F.T. of photon wave function

$\epsilon_f^2 = \xi(1-\xi)Q^2$

massless quarks

$$\mathcal{H}(\xi,k_\perp) = \left(1-y+\frac{y^2}{2}\right)(\xi^2+(1-\xi)^2)\left|\frac{k_\perp}{k_\perp^2+\epsilon_f^2}-\frac{k_\perp-q_\perp}{(k_\perp-q_\perp)^2+\epsilon_f^2}\right|^2 \qquad \text{photon T}$$

$$+(1-y)4\xi^2(1-\xi)^2Q^2\left(\frac{1}{k_\perp^2+\epsilon_f^2}-\frac{1}{(k_\perp-q_\perp)^2+\epsilon_f^2}\right)^2 \qquad \text{photon L}$$

The x evolution of the u-pdf

- the Balitsky-Kovchegov (BK) evolution

Balitsky (1996), Kovchegov (1998)

$$\frac{d}{dY}f_Y(k) = \underbrace{\bar{\alpha}\int\frac{dk'^2}{k'^2}\left[\frac{k'^2 f_Y(k') - k^2 f_Y(k)}{|k^2 - k'^2|} + \frac{k^2 f_Y(k)}{\sqrt{4k'^4 + k^4}}\right]}_{\text{BFKL}} - \bar{\alpha} f_Y^2(k)$$

$$Y = \ln\left(\frac{1}{x}\right)$$

$$\bar{\alpha} = \frac{\alpha_s N_c}{\pi}$$

non-linearity important when the gluon density becomes large

here $f_Y(k)$ is not exactly the u-pdf, but a slightly modified F.T. of $T_{q\bar{q}}$

$$f_Y(k) = \int\frac{d^2r}{2\pi r^2}\; e^{ik.\mathbf{r}}\; T_{q\bar{q}}(\mathbf{r}, Y)$$

BK evolution at NLO has been recently calculated

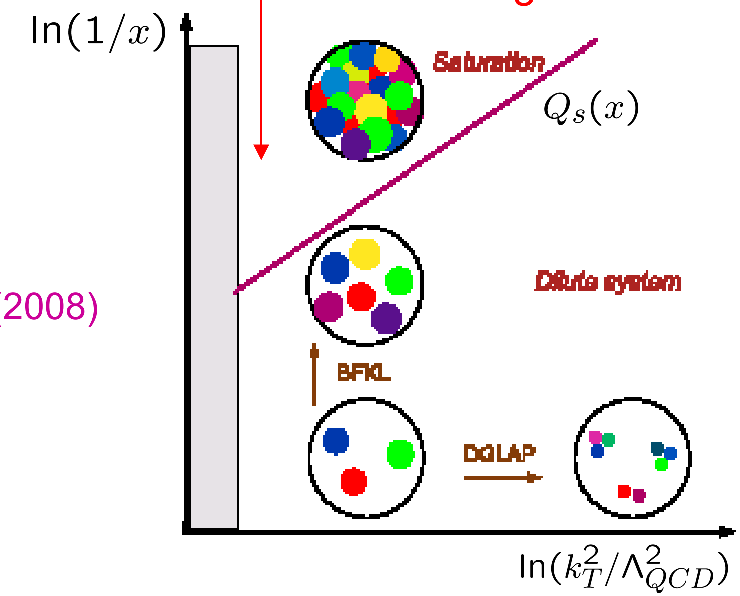
Balitsky-Chirilli (2008)

- in the saturation regime

the evolution of the u-pdf becomes non-linear

in general cross sections become non-linear functions of the gluon distribution

however, SIDIS is a special case in which the k_T-factorization formula written previously still holds



the distribution of partons as a function of x and k_T

Large-Q² limit of small-x result

- keeping the leading 1/Q term:

CM, Xiao and Yuan (2009)

$$\frac{d\sigma(ep\to e'hX)}{d\mathcal{P}}|_{P_\perp^2\ll Q^2}=\frac{\alpha_{em}^2N_c}{2\pi^3Q^4x_B}\sum_f e_f^2\left(1-y+\frac{y^2}{2}\right)\frac{D(z_h)}{z_h^2}\int d^2bd^2q_\perp F(q_\perp,x_B)A(q_\perp,k_\perp=P_\perp/z_h)$$

only transverse photons

simple function

$$A(q_\perp,k_\perp)=\int d\xi\left|\frac{k_\perp|k_\perp-q_\perp|}{(1-\xi)k_\perp^2+\xi(k_\perp-q_\perp)^2}-\frac{k_\perp-q_\perp}{|k_\perp-q_\perp|}\right|^2$$

- the saturation regime can still be probed

the cross section above has contributions to all orders in $Q_s^2/P_\perp^2$

even if Q^2 is much bigger than Q_s^2, the saturation regime will be important when $P_\perp^2\sim Q_s^2$

in fact, thanks to the existence of Q_s, the limit $|P_\perp|\to 0$ is finite,

and computable with weak-coupling techniques ($Q_s\gg\Lambda_{QCD}$)

eventually true at small x

TMD-pdf / u-pdf relation

- at small *x* and large Q^2

one recovers the TMD factorization formula, with

$$xq(x,k_\perp) = \frac{N_c}{4\pi^4}\int d^2b\, d^2q_\perp F(q_\perp,x)\left[1-\frac{k_\perp\cdot(k_\perp-q_\perp)}{k_\perp^2-(k_\perp-q_\perp)^2}\ln\left(\frac{k_\perp^2}{(k_\perp-q_\perp)^2}\right)\right]$$

TMD-pdf (for $xq(x,k_\perp)$)

u-pdf (for $F(q_\perp,x)$)

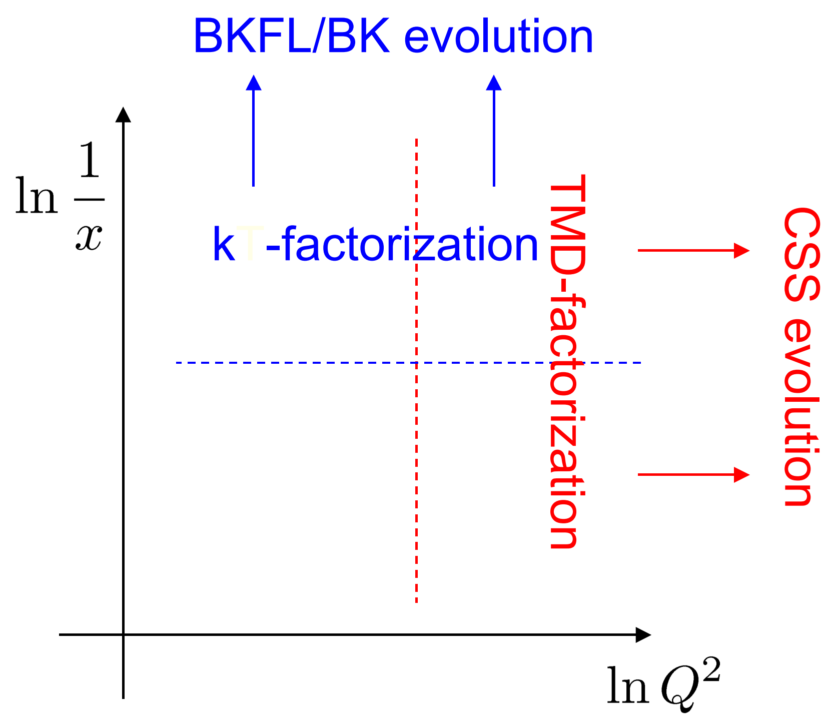
in the overlaping domain of validity,

TMD & k_T factorization are consistent

- the saturation regime

the TMD factorization can be used in the saturation regime, when $k_\perp^2 \sim Q_s^2$

there $xq(x,k_\perp) \to \mathrm{const.}$

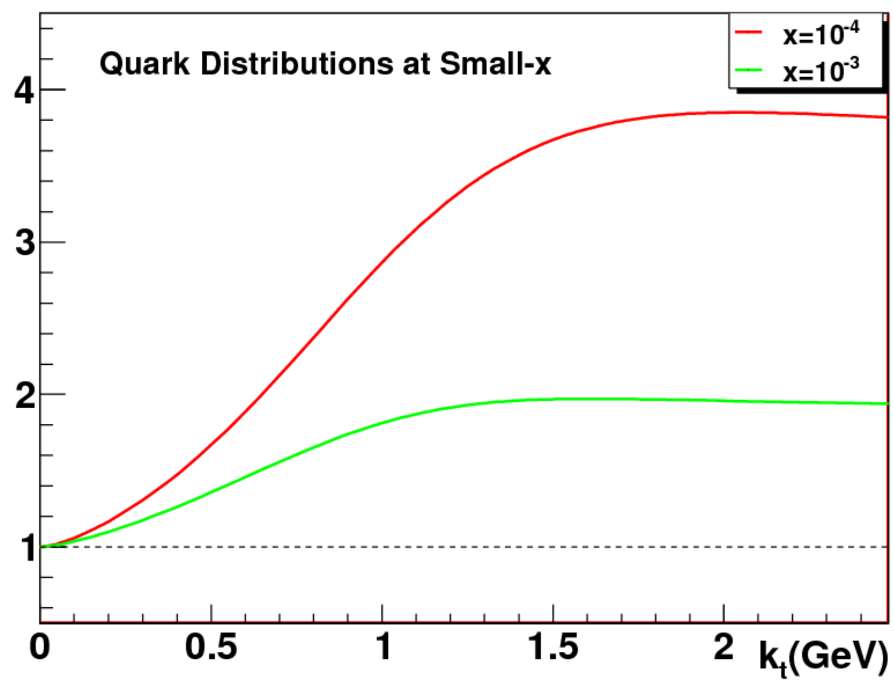


x evolution of the TMD-pdf

- from small *x* to smaller *x*

$$\frac{xq(x,k_\perp)}{x_0 q(x_0,k_\perp)}$$

$$x_0 = 10^{-2}$$



t

$$\frac{Q_s^2(x)}{Q_s^2(x_0)}$$

at large k

t

$$xq(x,0) = c$$

at small k

not full BK evolution here, but GBW parametrization

$$F(q_\perp, x) = e^{-q_\perp^2/Q_s^2(x)}/Q_s^2(x) \qquad Q_s^2(x) = (3.10^{-4}/x)^{0.28}\ \mathrm{GeV}^2$$

Golec-Biernat and Wusthoff (1998)

HERA data probe saturation

- ratio of SIDIS cross sections at two different values of *x*

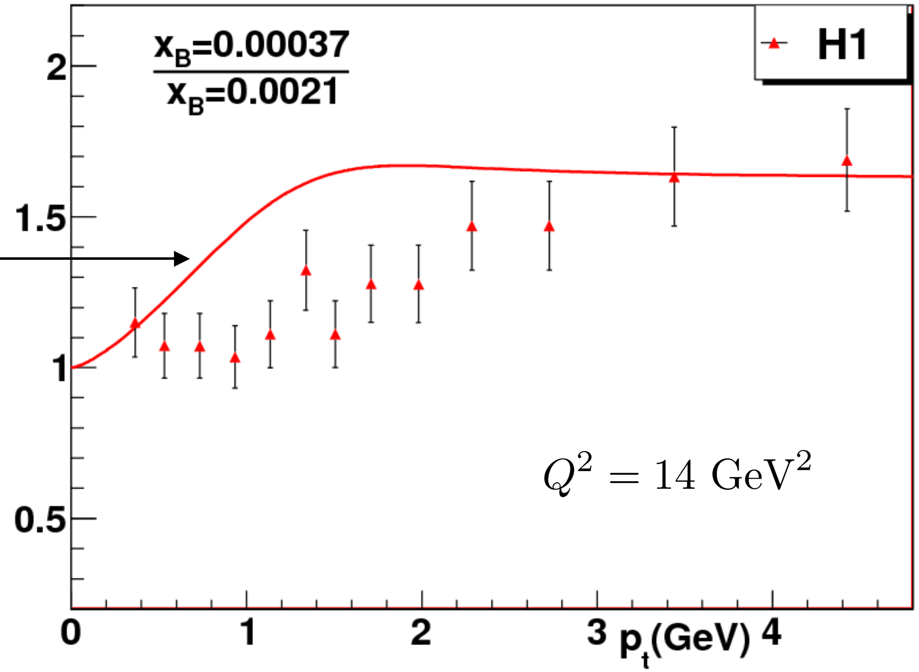
H1 collaboration (1997)

$$\frac{d\sigma(ep \to e'hX)}{d\mathcal{P}}\Big|_{\substack{x_B \ll 1 \\ Q^2 \gg P_\perp^2}} \simeq q(x_B, P_\perp)$$

our (crude) calculation

one can do much better with actual BK evolution and quark fragmentation

the data show the expected trend



- at future EIC's

the SIDIS measurement provides direct access to the transverse momentum distribution of partons in the proton/nucleus, and the saturation regime can be easily investigated

Di-hadron production in DIS

TMD factorization at large Q^2 ?

- non-universality of the TMD-pdf

the TMD distributions involved in di-jet production and SIDIS are different

Bacchetta, Bomhof, Mulders and Pijlman (2005)
Collins and Qiu, Vogelsang and Yuan (2007)
Rogers and Mulders, Xiao and Yuan (2010)

breaking of TMD factorization:

one cannot use information extracted
from one process to predict the other

in this approach the breaking of TMD factorization is a problem

- is there a better approach ? at small-x, yes

in the Color Glass Condensate (CGC)/dipole picture, we also

notice that k_T factorization is broken, but this is not an obstacle

we can consistently bypass the problem,
and define improved pdfs to recover universality

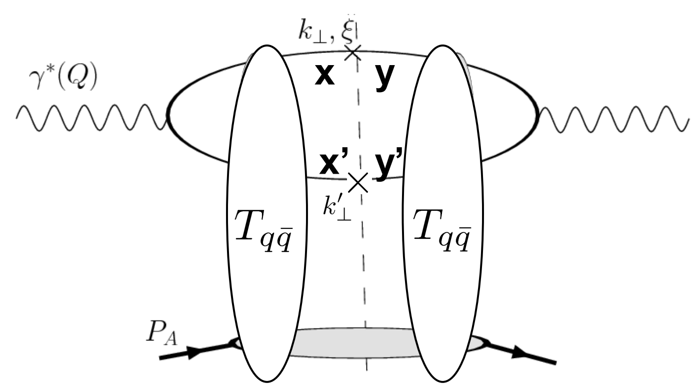
Dominguez, CM, Xiao and Yuan (2010)

No k_T factorization at small-x

- the di-jet cross section in the dipole picture

$$\frac{d\sigma_{T,L}^{\gamma^* p\to q\bar{q}X}}{d^2k_\perp d^2k'_\perp} = \int \frac{d^2x}{2\pi}\frac{d^2y}{2\pi}\frac{d^2x'}{2\pi}\frac{d^2y'}{2\pi}\, e^{-ik_\perp\cdot(\mathbf{x}-\mathbf{y})}e^{-ik'_\perp\cdot(\mathbf{x}'-\mathbf{y}')}\int d\xi\;\Phi_{T,L}(\xi,\mathbf{x}-\mathbf{x}',\mathbf{y}-\mathbf{y}';Q^2)$$
$$\times\left[T_{q\bar{q}}(\mathbf{x}-\mathbf{x}',x_B)+T_{q\bar{q}}(\mathbf{y}-\mathbf{y}',x_B)-T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{y}',\mathbf{y},x_B)\right]$$

because of the 4-point function $T_{q\bar{q}\bar{q}q}$, there is no k_T factorization (unless saturation and multiple scatterings can be safely neglected)



- SIDIS was a special case

in SIDIS, the $k'_\perp$ integration sets **x'**=**y'**,
and then $T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{x}',\mathbf{y},x_B) = T_{q\bar{q}}(\mathbf{x}-\mathbf{y},x_B)$

this cancellation of the interactions involving the spectator antiquark in SIDIS is what led to k_T factorization

with dijets, this does not happen, and as expected,

the cross section is a non-linear function of the u-pdf

Constraining the 4-point function ?

unlike most observables considered in DIS, di-hadrons probe more

than the dipole scattering amplitude, it probes the 4-point function

$$T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{y}',\mathbf{y},x_B)$$

only in special limits it can be simplified, such as $|k_\perp + k'_\perp| \ll |k_\perp|\ ,|k'_\perp|$

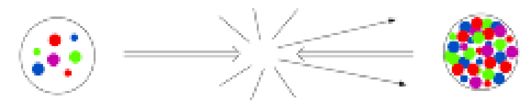
Dominguez, Xiao and Yuan (2010)

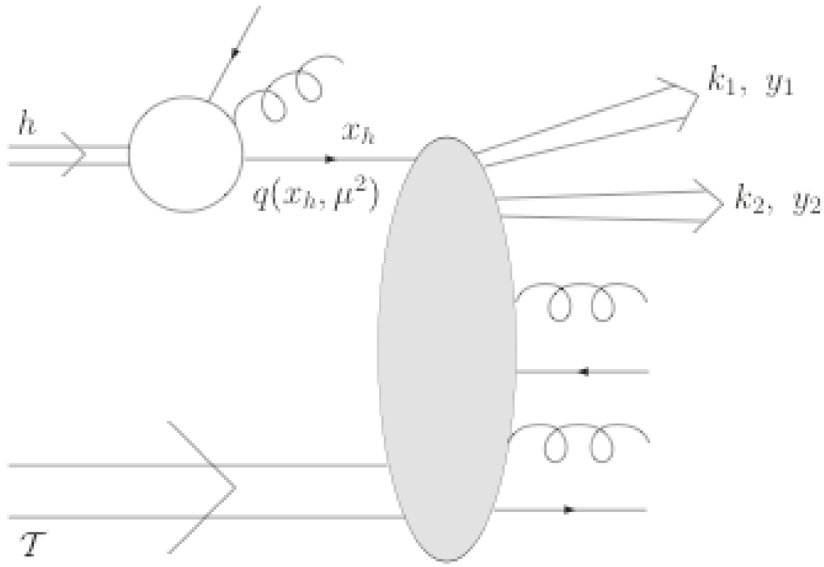
we expect to see the same effect in e+A vs e+p
than the one discovered in d+Au vs p+p collisions at RHIC

the same 4-point function is involved in the d+Au case
but the e+A measurement could help constrain it better
the background will be much smaller than in d+Au for instance

Forward di-hadron production

in p+A type collisions $x_A = \dfrac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$





the CGC cannot be described by a single gluon distribution

CM (2007)

the saturation regime is better probed compared to single particle production

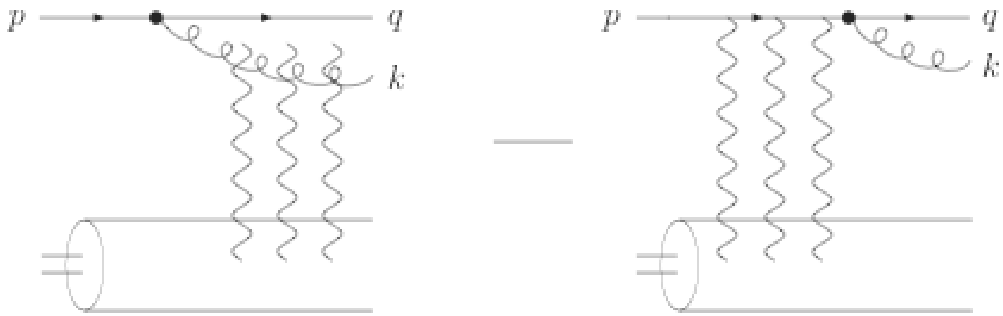
$$\frac{d\sigma^{dAu\to h_1 h_2 X}}{d^2k_1 dy_1 d^2k_2 dy_2}$$

is sensitive to multi-parton distributions, and not only to the gluon distribution

no kT factorization

$\dfrac{d\sigma^{dAu\to h_1 h_2 X}}{d^2k_1 dy_1 d^2k_2 dy_2}$ involves 2-, 4- and 6- point functions

The two-particle spectrum



b: quark in the amplitude
x: gluon in the amplitude
b': quark in the conj. amplitude
x': gluon in the conj. amplitude

collinear factorization of quark density in deuteron

Fourier transform $k_\perp$ and $q_\perp$ into transverse coordinates

$$\frac{d\sigma^{dAu\to qgX}}{d^2k_\perp dy_k d^2q_\perp dy_q} = \alpha_S C_F N_c\, x_d q(x_d,\mu^2)\int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2b}{(2\pi)^2}\frac{d^2b'}{(2\pi)^2}\; e^{ik_\perp.(\mathbf{x}'-\mathbf{x})}e^{iq_\perp.(\mathbf{b}'-\mathbf{b})}$$

$$\left|\Phi^{q\to qg}(z,\mathbf{x}-\mathbf{b},\mathbf{x}'-\mathbf{b}')\right|^2\Big\{S^{(4)}_{qg\bar{q}g}[\mathbf{b},\mathbf{x},\mathbf{b}',\mathbf{x}';x_A]-S^{(3)}_{qg\bar{q}}[\mathbf{b},\mathbf{x},\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]$$

$$-S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A]+S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}$$

pQCD $q \to qg$ wavefunction

interaction with hadron 2 / CGC

$$z=\frac{|k_\perp|e^{y_k}}{|k_\perp|e^{y_k}+|q_\perp|e^{y_q}}$$

n-point functions that resums the powers of $g_s A$ and the powers of $\alpha_s \ln(1/xA)$

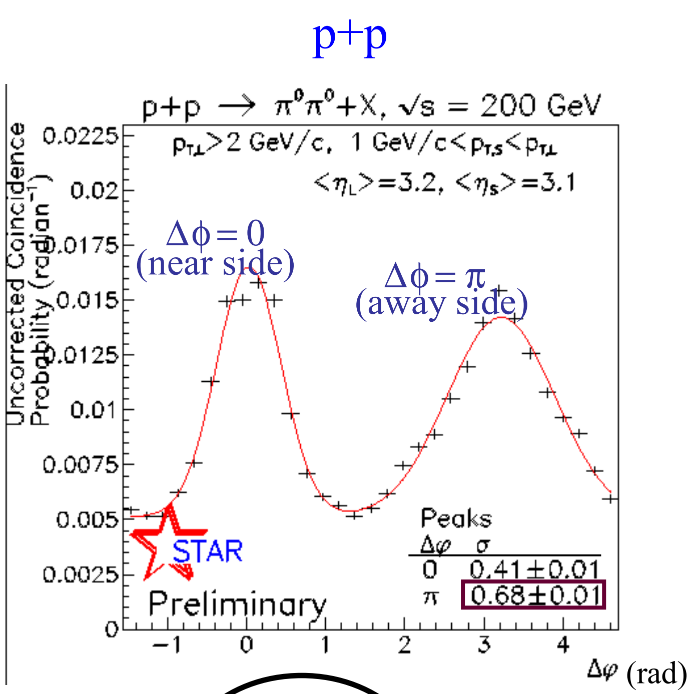
computed with JIMWLK evolution at NLO (in the large-Nc limit), and MV initial conditions

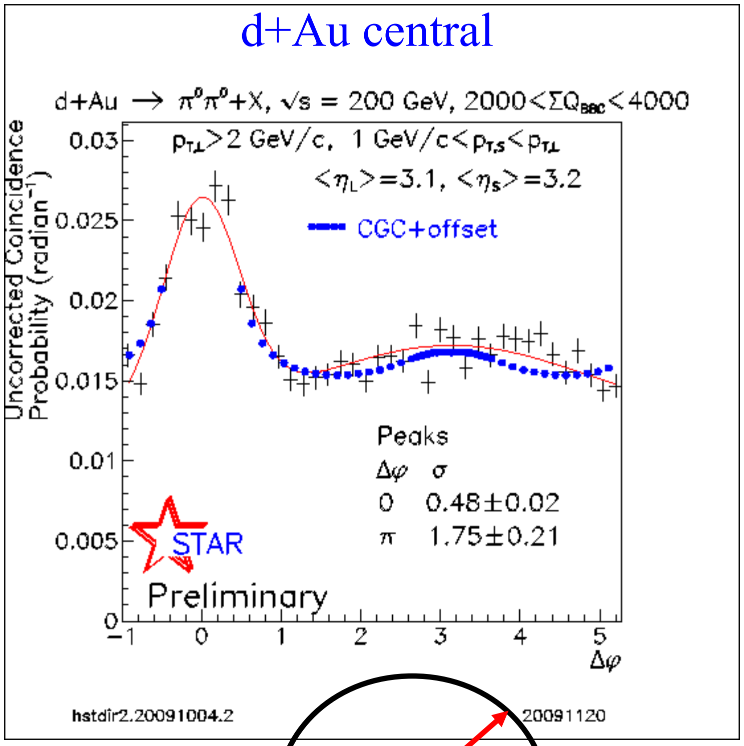
no parameters

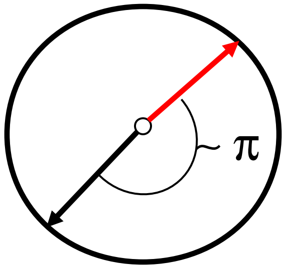
Di-hadron p_T imbalance in d+Au

- comparison of CGC calculations with RHIC data

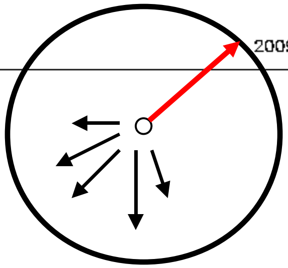
Albacete and CM (2010)







this happens at forward rapidities, but at central rapidities, the p+p and d+Au signal are almost identical

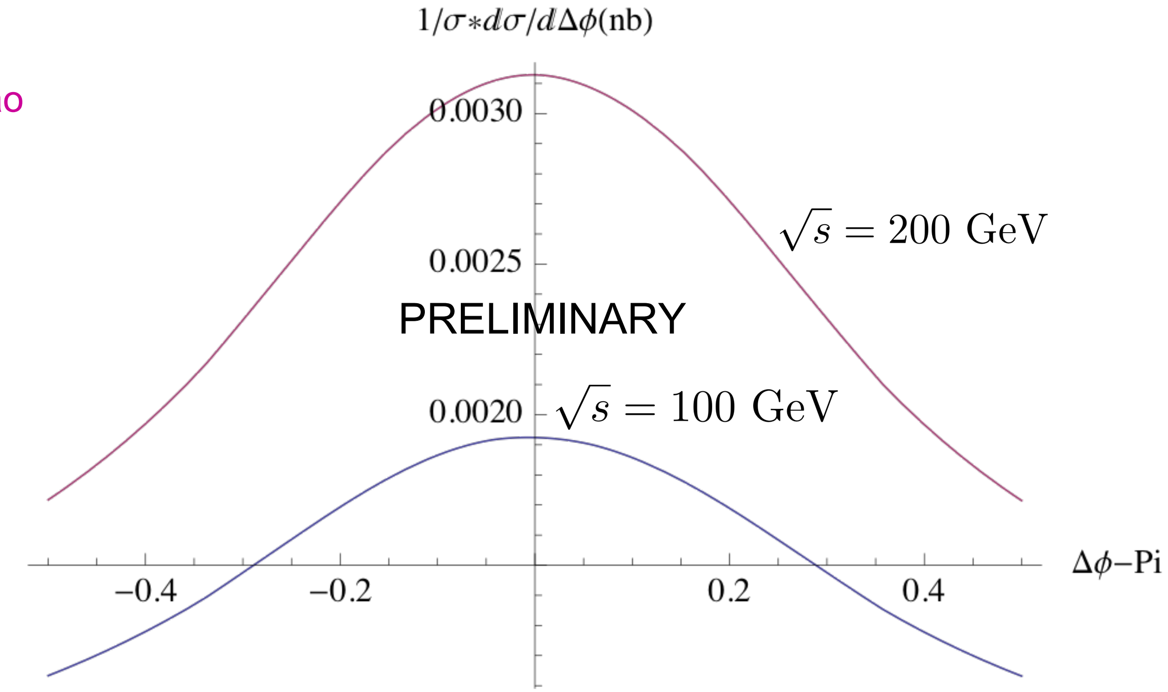


Di-hadron p_T imbalance in e+A

- the di-hadron cross section in the small momentum imbalance limit

$$|k_\perp + k'_\perp| \ll |k_\perp|\ ,|k'_\perp|$$

Xiao



not e+A vs e+p but rather e+A at two different energies

About the CGC calculation

- in the large-Nc limit, the cross section is obtained from

$$S^{(4)} = \frac{1}{N_c}\left\langle \mathrm{Tr}(W_{\mathbf{x}} W^\dagger_{\mathbf{y}} W_{\mathbf{u}} W^\dagger_{\mathbf{v}})\right\rangle_{x_A} \text{ and } S^{(2)} = \frac{1}{N_c}\left\langle \mathrm{Tr}(W_{\mathbf{x}} W^\dagger_{\mathbf{y}})\right\rangle_{x_A}$$

the 2-point function is fully constrained
by e+A DIS and d+Au single hadron data

- in principle the 4-point function should be obtained from an evolution equation (equivalent to JIMWLK + large Nc)

Jalilian-Marian and Kovchegov (2005)

- in practice one uses an approximation that allows to express $S^{(4)}$ as a (non-linear) function of $S^{(2)}$

CM (2007)

even though the knowledge of S is enough to predict the
T

forward dihadron spectrum, there is no k factorization:
the cross section is a non-linear function of the gluon distribution

this approximation misses some leading-Nc terms Dumitru and Jalilian-Marian (2010)

Coherent vs incoherent diffraction in DIS (or diffraction without/with target dissociation)

VM production at small x

- the diffractive cross section

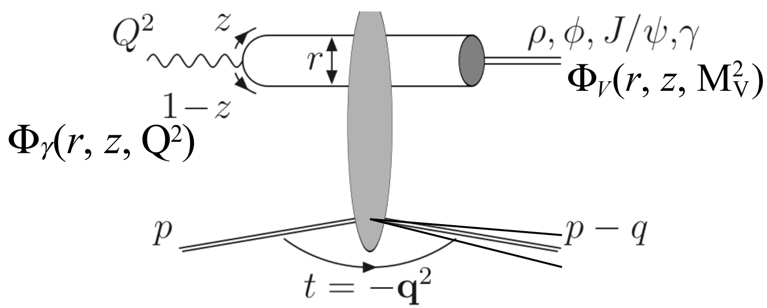
amplitude

conjugate amplitude

$$\frac{d\sigma^{\gamma^* p\to VY}}{dt}=\frac{1}{4\pi}\int d^2r d^2r' \underbrace{\varphi(\mathbf{r},\mathrm{Q}^2,\mathrm{M}_\mathrm{V}^2)\varphi^*(\mathbf{r}',\mathrm{Q}^2,\mathrm{M}_\mathrm{V}^2)}_{\text{overlap functions}}\int d^2b d^2b' e^{iq_\perp.(\mathbf{b}-\mathbf{b}')}\left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b})T_{q\bar{q}}(\mathbf{r}',\mathbf{b}')\right\rangle_x$$

r : dipole size in the amplitude

r’ : dipole size in the conjugate amplitude



target average at the cross-section level:
contains both broken-up and intact events

one needs to compute a 4-point function,
that gives access to gluon correlations

- the exclusive part

obtained by averaging at the level of the amplitude:

$$\left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b})T_{q\bar{q}}(\mathbf{r}',\mathbf{b}')\right\rangle_x \to \left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b})\right\rangle_x \left\langle T_{q\bar{q}}(\mathbf{r}',\mathbf{b}')\right\rangle_x$$

probes b dependence: $$\frac{d\sigma^{\gamma^* p\to Vp}}{dt}=\frac{1}{4\pi}\left|\int d^2r\, \varphi(\mathbf{r},\mathrm{Q}^2,\mathrm{M}_\mathrm{V}^2)\int d^2b\, e^{iq_\perp.\mathbf{b}}\left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b})\right\rangle_x\right|^2$$

Coherent diffraction

- the dipole-nucleus cross-section

Kowalski and Teaney (2003)

$$T^{p}_{q\bar{q}}(r,b,x) = 1 - e^{-f(r,x,b)}$$

$$\Downarrow$$

$$T^{A}_{q\bar{q}}(r,b,x) = 1 - e^{-\sum_i f(r,x,b-b_i)}$$

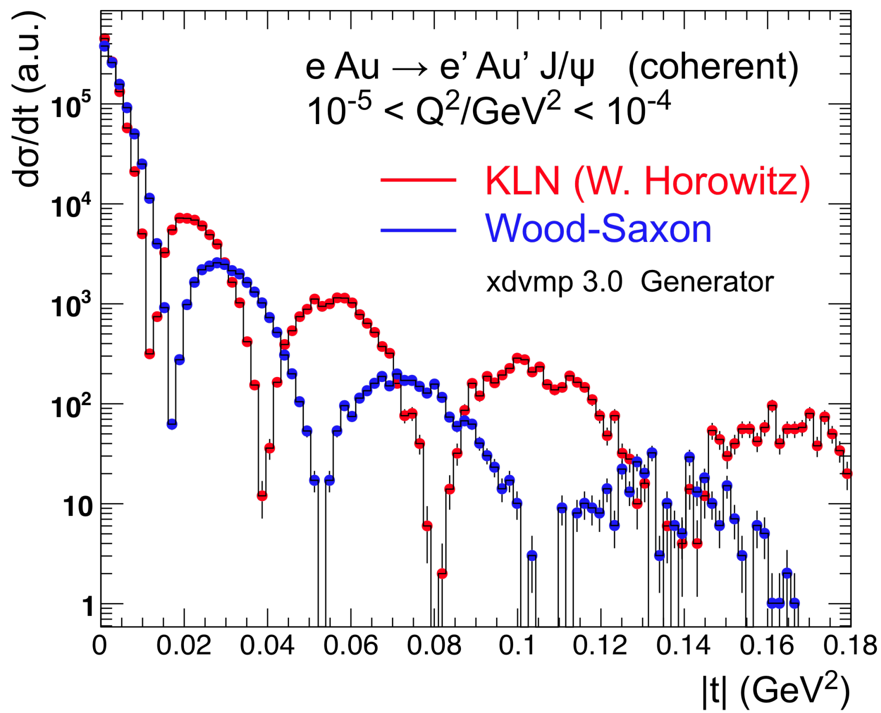
$T_A(\{b_i\})$ ← position of the nucleons

averaged with the Wood-Saxon distribution

assumption of independent nucleons not compatible with QCD non-linear evolution

Horowitz, Toll and Ullrich

large incoherent contribution not shown



compared with CGC-inspired gluon distribution (KLN): differences are seen and are big enough to be tested (need 50 MeV resolution on momentum transfer)

Incoherent diffraction (proton case)

Dominguez, CM and Wu (2009)

- as a function of t

exclusive production:

the proton undergoes elastic scattering

dominates at small |t|

diffractive production :

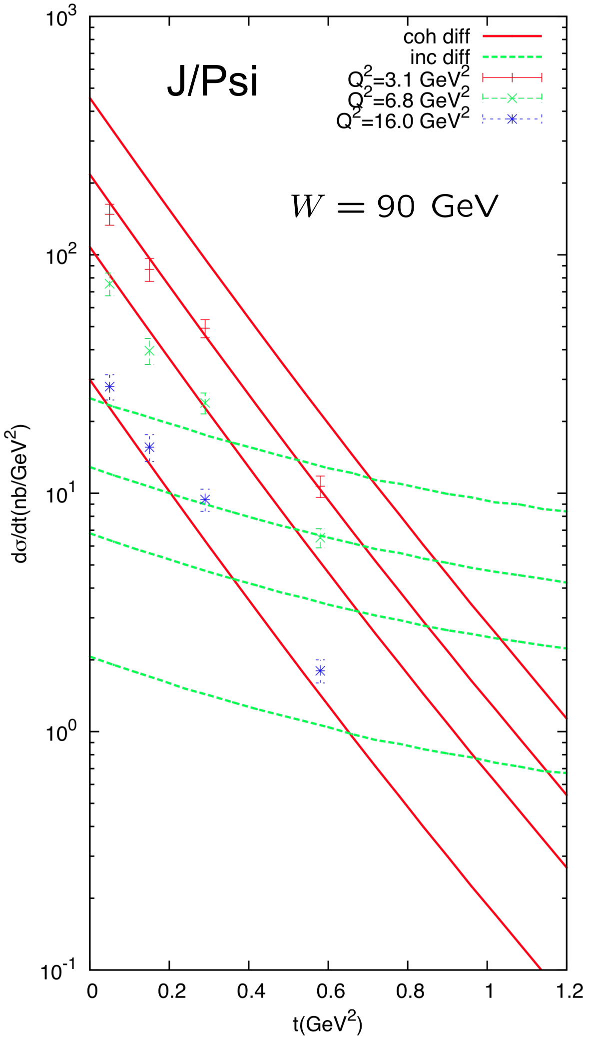
the proton undergoes inelastic scattering

dominates at large |t|

- two distinct regimes

exclusive
→ exp. fall at -t < 0.7 GeV
diffractive
→ power-law tail at large |t|

the transition point is where the data on exclusive production stop



From protons to nuclei

- qualitatively, one expects three contributions

exclusive production is called coherent diffraction

the nucleus undergoes elastic scattering, dominates at small |t|

intermediate regime (absent with protons)

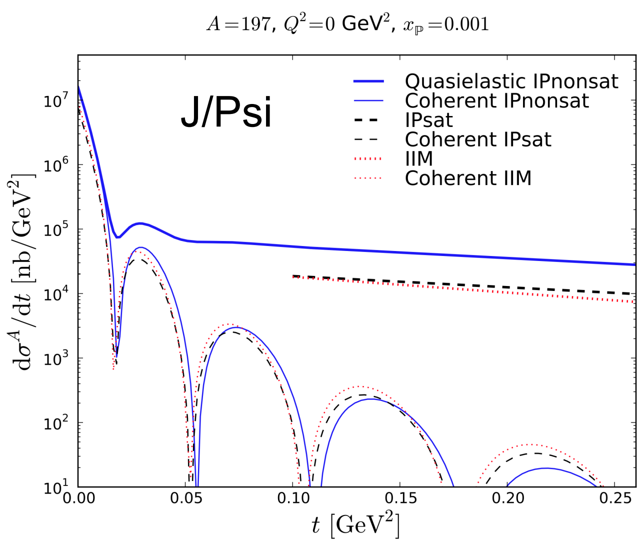
the nucleus breaks up into its constituents nucleons, intermediate |t|

then there is fully incoherent diffraction

the nucleons undergo inelastic scattering, dominates at large |t|

- three regimes as a function of t:

coherent diffraction
→ steep exp. fall at small |t|
breakup into nucleons
→ slower exp. fall at 0.02 < -t < 0.7 GeV
incoherent diffraction
→ power-law tail at large |t|



Lappi and Mantysaari (2010)

Conclusions

- very little is known about the structure of heavy nuclei at small-x
  - only for inclusive structure functions we have data at moderate x
  - SIDIS and exclusive VM production data are at high x or for light nuclei
  - diffractive structure functions have never been measured
- e+A collisions are ideal to learn about this
  - so far we have expectations using small-x QCD evolution
  - the CGC initial conditions for HIC are based on these expectations
  - but this needs to be checked with data
- what are crucial measurements ?

  - SIDIS & di-hadrons: the k dependence of the gluon distribution
  - coherent diffraction: the impact-parameter dependence
  - incoherent diffraction: correlations between small-x gluons