Predictions for the Spatial Distribution of Gluons in the Initial Nuclear State

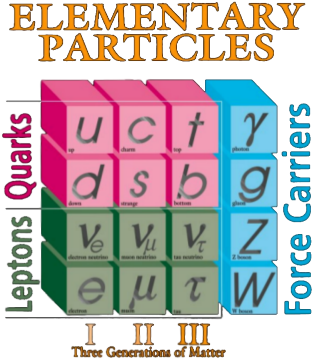
DGLAP vs. CGC

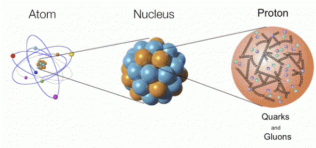
Greg Jackson
(With many thanks to Dr. W. A. Horowitz)

Department of Physics
University of Cape Town

greg@wam.co.za

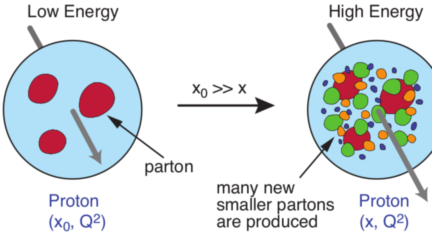
November 5, 2013





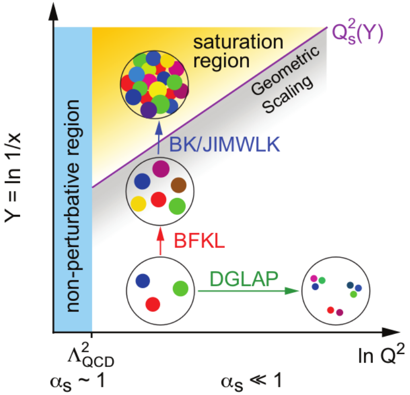
Example: **(HERA)**
elecron-proton collisions

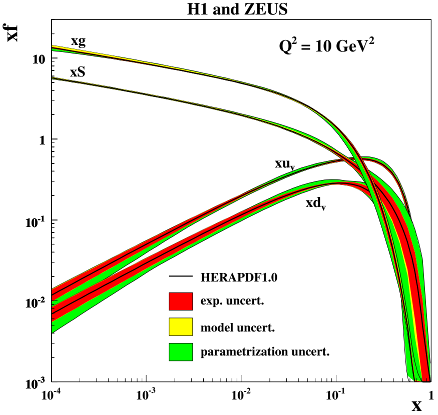
- Rapidity: $Y := \ln \frac{1}{x}$
- 'Resolution': $Q^2 := -q^2$



Motivation

QCD Phenomena: probe nuclear matter

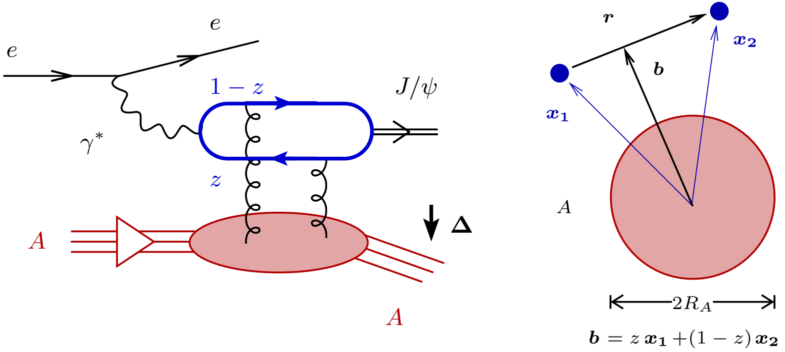




Excessive gluon production → "Saturation scale" Q_s^2

Exclusive Vector Meson Production

Electron scattering sensitive to *charge* distribution. We need sensitivity to *gluons*.



- The change in momentum of the nucleus, Δ, is measurable!
- Above is the LO two gluon exchange (t-channel process)

Putting the pieces together

Virtual photon (γ^*) fluctuates into a $q\bar{q}$

$\rightarrow$ Dipole interacts with A

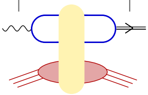
$\rightarrow$ $q\bar{q}$ recombines into vector meson (J/ψ)

Configuration space
$\leftrightarrow$ Momentum space

virtual photon wave function

vector meson

(Fourier trans)

$\mathcal{A}\Big($  $\Big)$

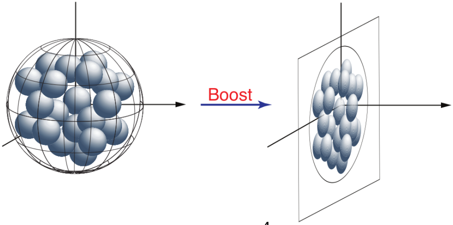
$$= \int \mathrm{d}^2\boldsymbol{r} \frac{\mathrm{d}z}{4\pi} [\Psi_V^* \Psi_\gamma](Q, \boldsymbol{r}, z)\, 2 \overbrace{\int \mathrm{d}^2\boldsymbol{b}\, e^{-i\boldsymbol{b}\cdot\Delta}}^{\text{(Fourier trans)}} \mathcal{N}(\boldsymbol{b}, \boldsymbol{r})$$

dipole interaction

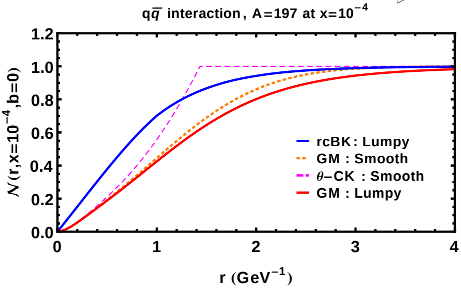
Scattering Amplitude $\Rightarrow$ cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi}|\mathcal{A}|^2$ where $t = -\boldsymbol{\Delta}^2$

Plan of attack: underlying physics?

Target becomes flattened into a pancake. We work in *transverse* space.



Overlapping nucleons



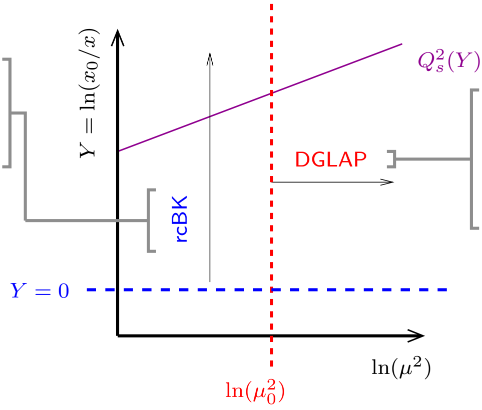
All geometry encoded in $\mathcal{N}(r, \boldsymbol{b})$

(represents interaction probability)

Pieced together under different assumptions.

Main model differences

Set ICs:
$\mathcal{N}(\boldsymbol{r}, Y = 0, \boldsymbol{b})$
evolve with rcBK



Ansatz for scale $\mu^2(r)$
then use GM formula
$\mathcal{N}(\boldsymbol{r}, Y, \boldsymbol{b})$
and DGLAP evolve xg

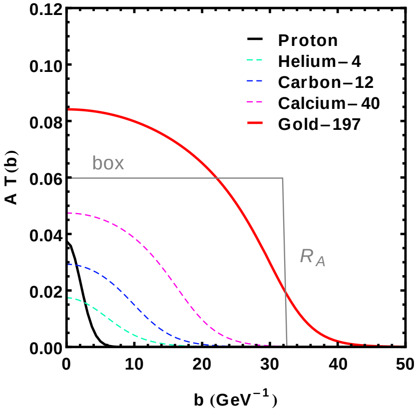
Transverse positions of the nucleons

Woods-Saxon: (normalised)

$$\rho_A(r) = \frac{N}{\exp[(r - R_A)/\delta] + 1}$$

Transverse distribution:

$$T_A(\boldsymbol{b}) := \int \mathrm{d}z \rho_A(\sqrt{z^2 + \boldsymbol{b}^2})$$



Single proton → (transverse) Gaussian blob:
("book" value $B_p = 4.25$ GeV^{-2})

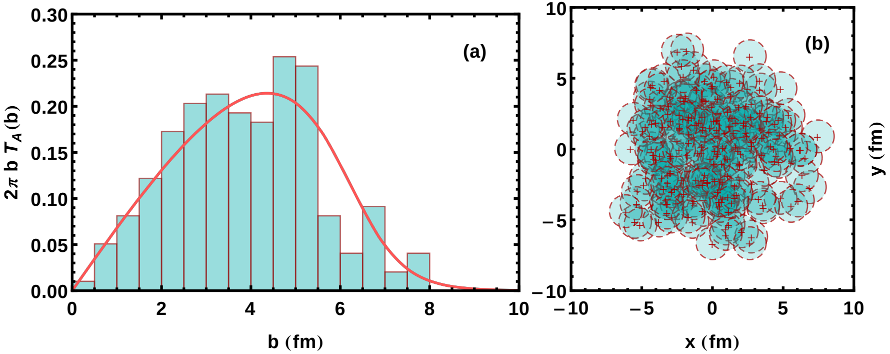
$$T_p(\boldsymbol{b}) = \frac{1}{2\pi B_p} e^{-b^2/(2B_p)}$$

rcBK Numerics

- Include non-linear QCD:
  Albacete & Dumitru, (2010), [arXiv:1011.5161[hep-ph]]

$N(\boldsymbol{b}) := \#$ of nucleons overlapping at $\boldsymbol{b}$

Generate ~ 1000 sets of nucleon coordinates $\{\boldsymbol{b}_1, \boldsymbol{b}_2, \ldots, \boldsymbol{b}_A\}$.



The Glauber-Mueller formula

Interaction **probability** given by $\mathcal{N}(\boldsymbol{r}, \boldsymbol{b})$: (should go to zero when $\boldsymbol{b}$ gets large enough)

The $q\bar{q}$ dipole passes through a gluon "cloud" and feels an effective *opacity*,

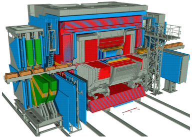
$$\Omega = r^2 \frac{\pi^2}{N_c} \alpha_s(\mu^2) x g(x, \mu^2) T(\boldsymbol{b})$$

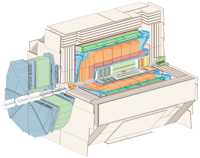
- Exponentiate for thick target (GM): $\mathcal{N}_1 = 1 - \exp\left(\frac{-\Omega}{2}\right) \leq 1$ ✓
  Mueller, Nucl. Phys. $\boldsymbol{B}$335, (1990), 115
- The LO 2 gluon exchange (CK): $\mathcal{N}_0 = \frac{\Omega}{2} \propto r^2 \rightarrow \infty$ (for large dipoles)
  Caldwell & Kowalski, Phys. Rev. $\boldsymbol{C}$81, (2010)
- Enforce boundedness $(\theta\text{-}CK)$: $\mathcal{N}_\theta = \mathcal{N}_0 \theta(1 - \mathcal{N}_0) + \theta(\mathcal{N}_0 - 1) \leq 1$ ✓

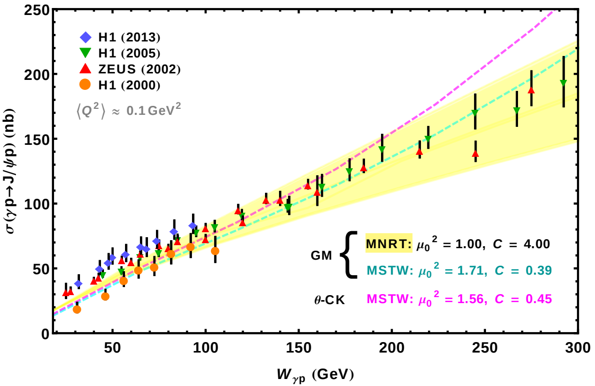
Constrain using $e + p$ experiments

"scale" depends on size r:

$$\mu^2(r) = \frac{C}{r^2} + \mu_0^2$$







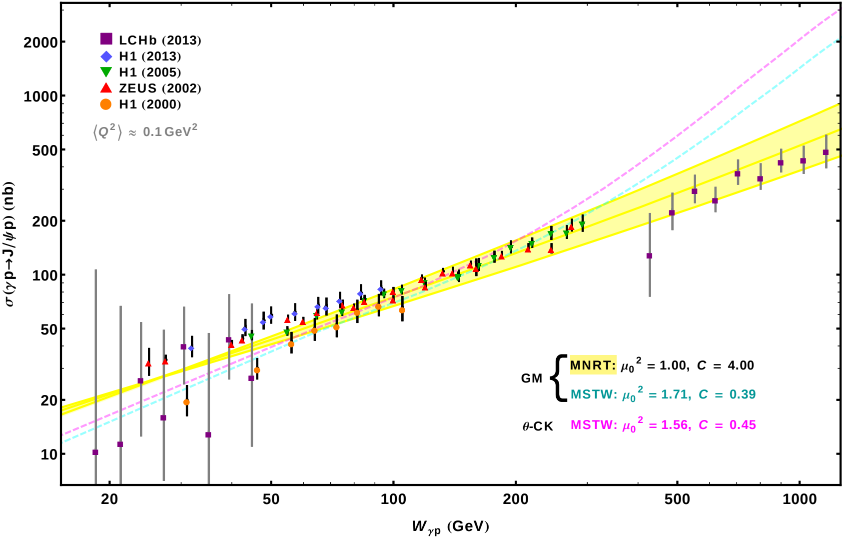
Get range of x values from invariant mass:

$$W^2 = \frac{(1-x)Q^2 + M_{J/\psi}^2}{x}$$

MSTW pdfs problematic!

Guzey & Zhalov,(2013) [arXiv:1307.4526 [hep-ph]]

Constrain using $e + p$ experiments



Glauber formula [nucleons to nuclei]

$$\Omega = r^2 \frac{\pi^2}{N_c} \alpha_s(\mu^2) x g(x,\mu^2) T(\boldsymbol{b})$$

- Average over nucleon coordinates $\{\boldsymbol{b}_i\}$:
  Lappi & Mäntysaari, Phys. Rev. C83, (2011)

- What can happen to the nucleus?

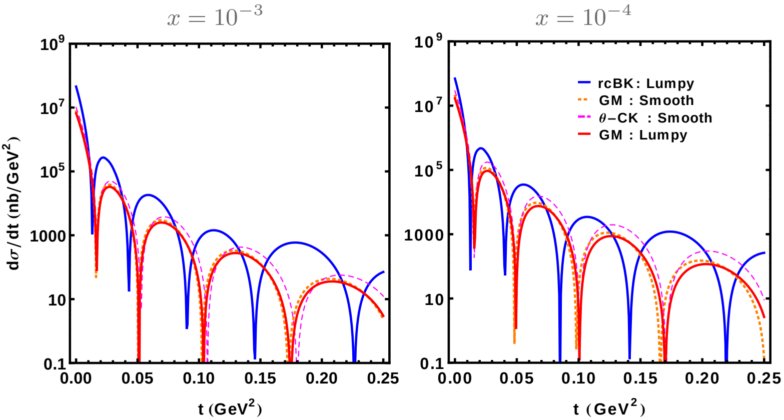
$$\begin{cases} T(\boldsymbol{b}) \to \overbrace{T_A(\boldsymbol{b})}^{\text{“Smooth”}} \\ T(\boldsymbol{b}) \to \underbrace{\sum_{i=1}^{A} T_p(\boldsymbol{b}-\boldsymbol{b}_i)}_{\text{“Lumpy”}} \end{cases}$$

$$\text{Coherent} : |\langle \mathcal{A} \rangle_N|^2 \qquad \text{Incoherent} : \langle |\mathcal{A}|^2 \rangle_N$$

$$\begin{aligned} \text{Coherent/elastic} &= \gamma^* A_0 \to J/\psi A_0 \\ \text{Incoherent/quasi-elastic} &= \gamma^* A_0 \to J/\psi A_n \end{aligned}$$

Model Comparison

EVMP: $\gamma^* A \to J/\psi A$ at $Q^2 = 0$ for ^{197}Au **(Coherent)**



(decreasing x) $\longrightarrow$

Measurable differences? Normalisation & peak/dip positions

Conclusion & Future Work

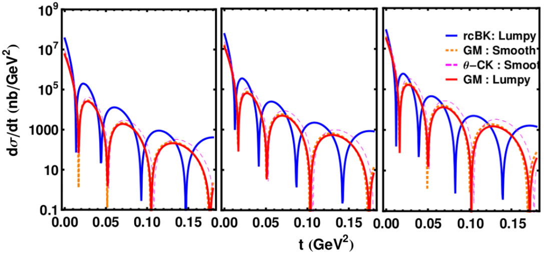
- $\frac{d\sigma}{dt}$ comparison from measurable differences @ future EICs
  - $\rightarrow$ Forward $t = 0$ changes by factor ~ 2
  - $\rightarrow$ Dip positions shift plus clear differences in maxima
  - $\rightarrow$ eRHIC (BNL) & ELIC (JLab)
- Use different canned nPDFs (MSTW artifact)
  - $\rightarrow$ EPS09 & EKS98 — Helenius et al, (2012), [arXiv:1205.5359 [hep-ph]]
  - $\rightarrow$ nCTEQ — Schienbein et al, Phys. Rev. **D80**, (2009)
- Include incoherent production (v. important for experiment)

$\sim$ *Thanks for your attention* $\sim$

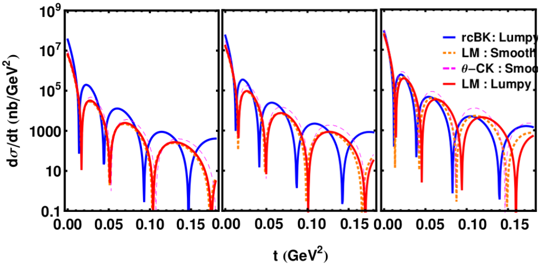
→ **Backup Slides**

MNRT vs MSTW

- Model comparison using MNRT07 for LM & θ-CK: 10^{-3}, 10^{-4}, 10^{-5}

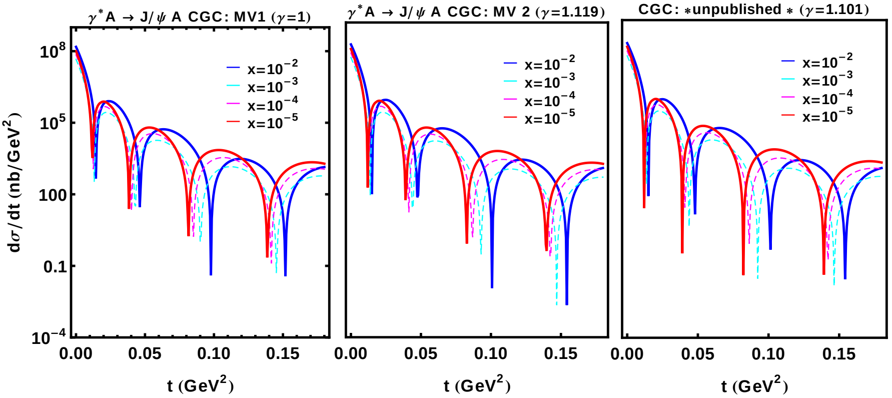


- Model comparison using MSTW for LM & θ-CK: 10^{-3}, 10^{-4}, 10^{-5}



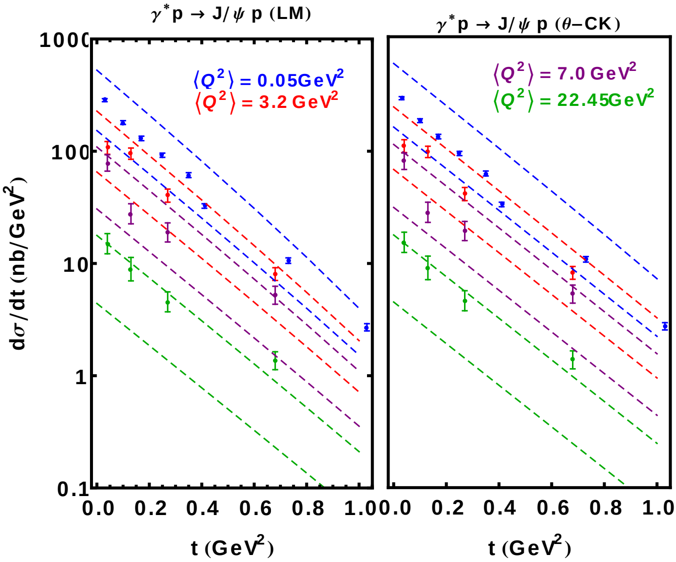
$\mathcal{N}(\boldsymbol{b})$ depends on the **overlap** $N(\boldsymbol{b})$

Albacete & Dumitru, (2010), [arXiv:1011.5161[hep-ph]]



$$\mathcal{N}(\boldsymbol{r}, Y=0, \boldsymbol{b}) \quad = \quad 1 - \exp\left[-\frac{(rQ_{s0}N(\boldsymbol{b}))^{2\gamma}}{4}\ln\left(\frac{1}{\Lambda r} + e\right)\right]$$

The shape of the proton [H1 & ZEUS]



The vector-meson photon overlap

$$
\begin{aligned}
\left[\Psi_V^* \Psi_{\gamma^*}\right]_L(\mathbf{r}, z, Q^2) &= e_c\sqrt{2N_c}\left[2z(1-z)Q\frac{K_0(\epsilon r)}{2\pi}\phi_L\right], \\
\left[\Psi_V^* \Psi_{\gamma^*}\right]_T(\mathbf{r}, z, Q^2) &= e_c\sqrt{2N_c}\left[(z^2+(1-z)^2)\left(\frac{-1}{m_c}\frac{\partial\phi_T}{\partial r}\right)\frac{\epsilon K_1(\epsilon r)}{2\pi} + \phi_T m_c\frac{K_0(\epsilon r)}{2\pi}\right]
\end{aligned}
$$

The wave functions $\phi_{L,T}$ are obtained through a short distance model GAUS-LC. The ansatz for the wave-function is in terms of its Fourier transform,

$$
\widetilde{\phi}_{L,T}(k,z) = N_{L,T}\, z(1-z)\exp\left[\frac{-k^2}{\omega_{L,T}^2}\right].
$$

The free parameters $N_{L,T}$ and $\omega_{L,T}$ are adjusted to reproduce the normalisation and decay width.

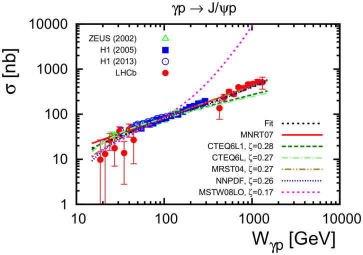
Kowalski & Teaney, Phys. Rev. **D68, (2003)**

MNRT07

Simple unintegrated gluon distribution $xg(x,\mu) \approx N x^{-\lambda}$

Martin et al, (2007), [arXiv:0709.4406 [hep-ph]]

For LO, take $\lambda = a + b \ln\left(\frac{\mu^2}{0.45\mathrm{GeV}^2}\right)$



	N	a	b	$\chi^2_{\min}/\mathrm{d.o.f.}$
LO	0.99 ± 0.09	0.051 ± 0.012	0.088 ± 0.005	0.9
NLO	1.55 ± 0.18	-0.50 ± 0.06	0.46 ± 0.03	0.8

Leading order contributions [included in GM]