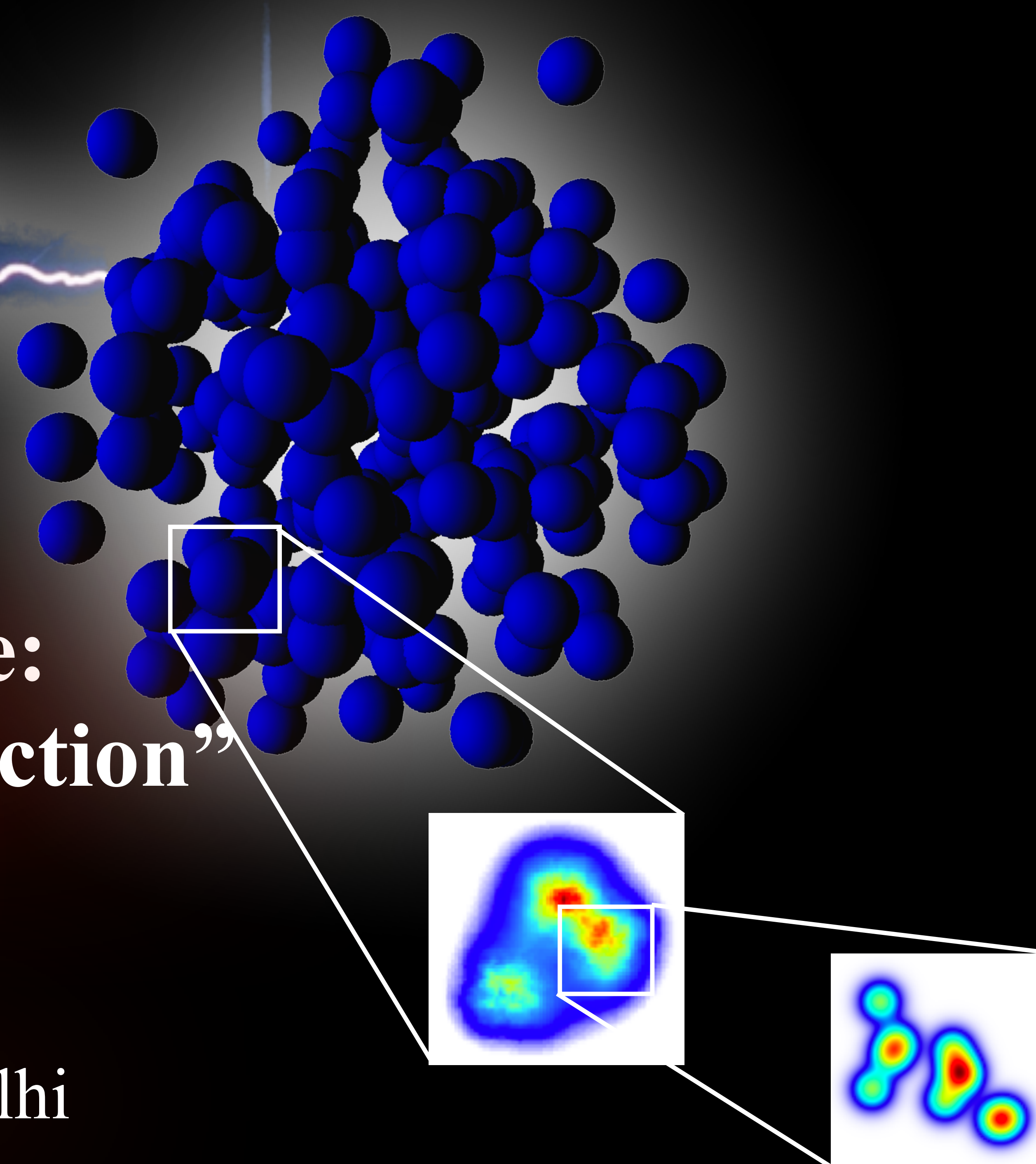
“The initial gluon profile: Lessons from exclusive diffraction”

DAE-HEP 2022

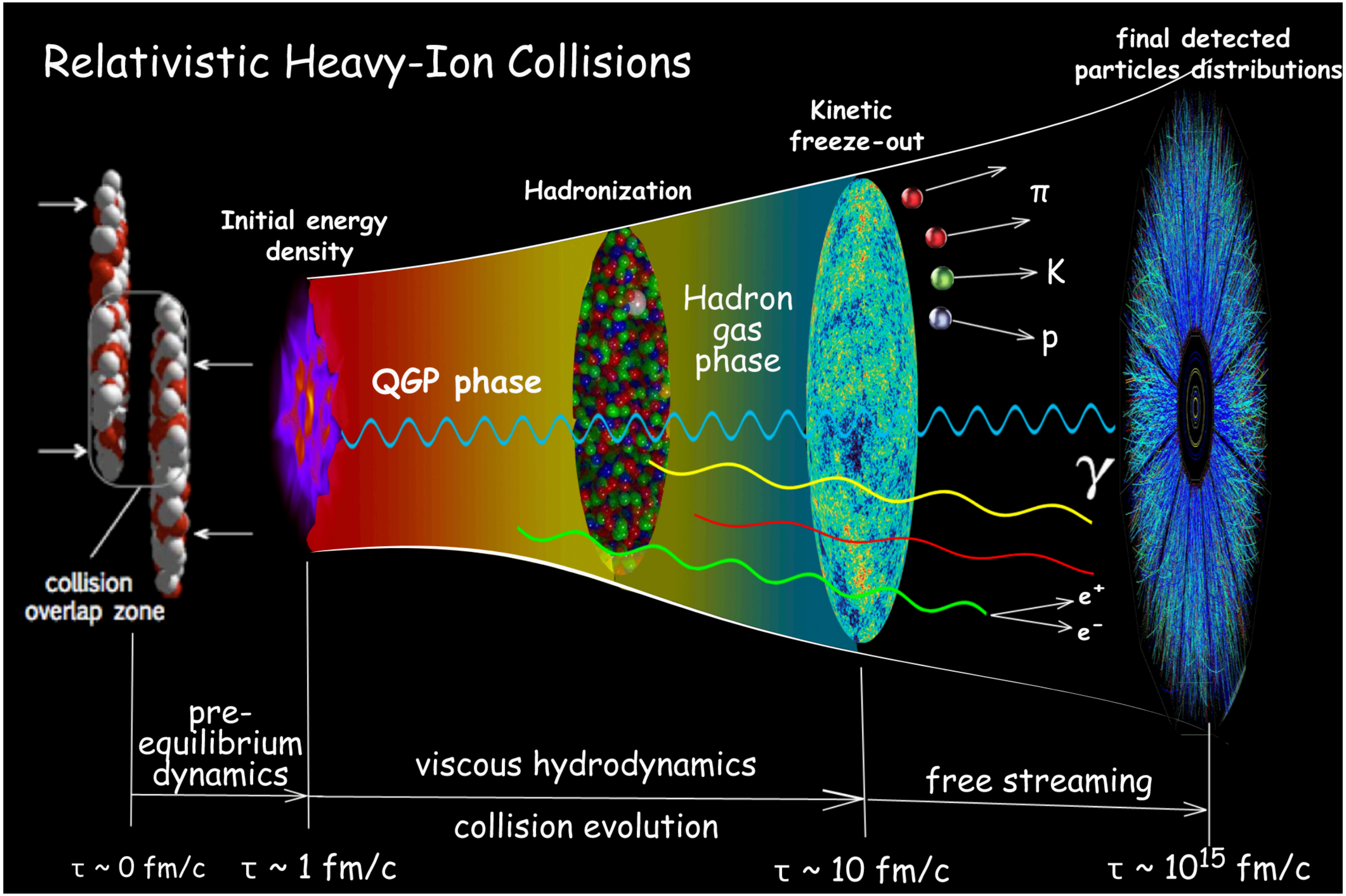
December 12, 2022

Tobias Toll
Indian Institute of Technology Delhi

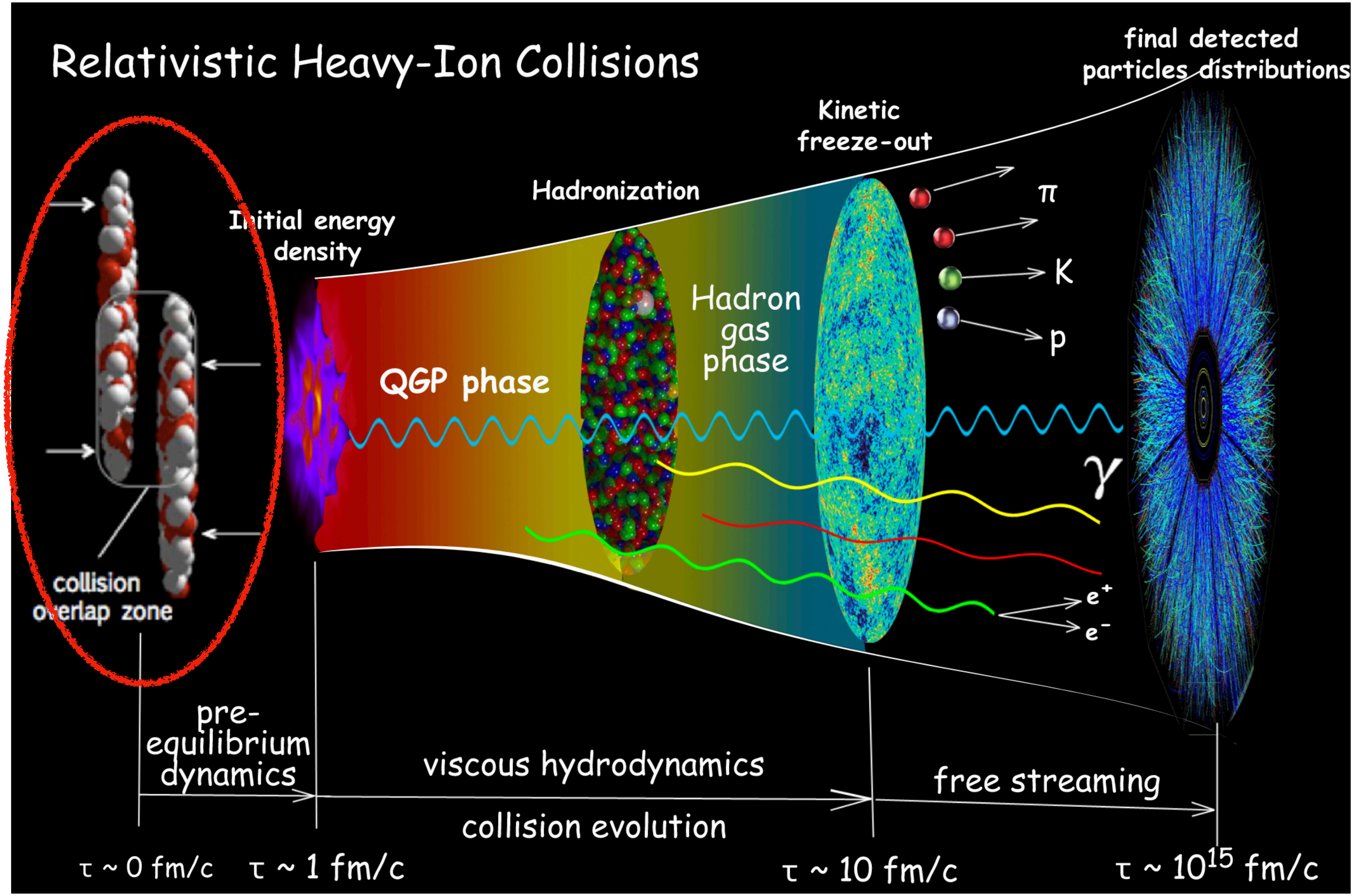


Part I:
Why the intial state is important

"Standard model of Heavy Ion Collisions"



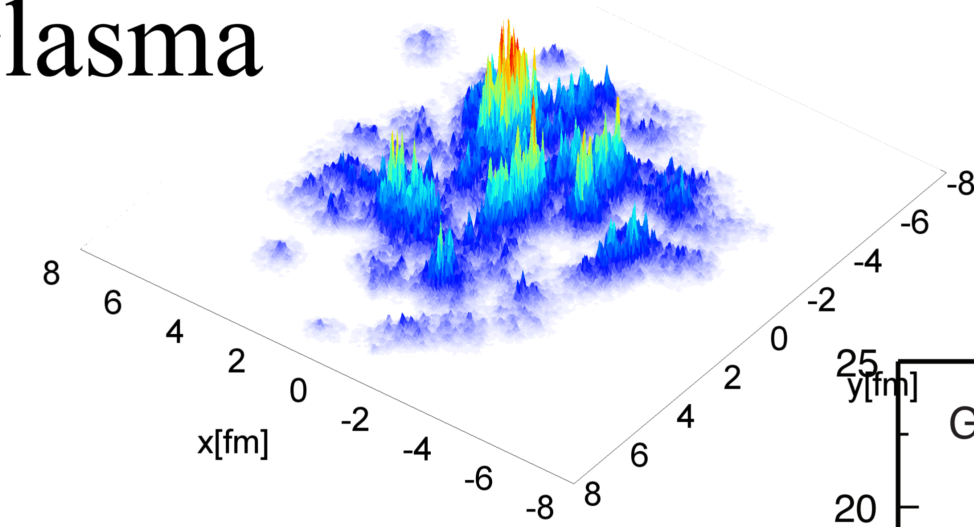
"Standard model of Heavy Ion Collisions"



All late time observables depend on the initial state. There is no accurate measurement of the initial state at high energies (small *x*)

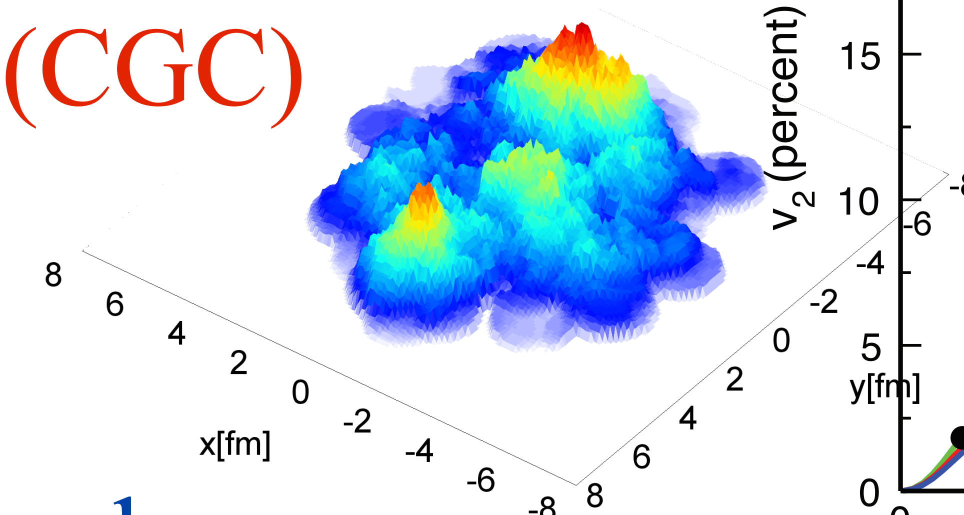
What is η/s?

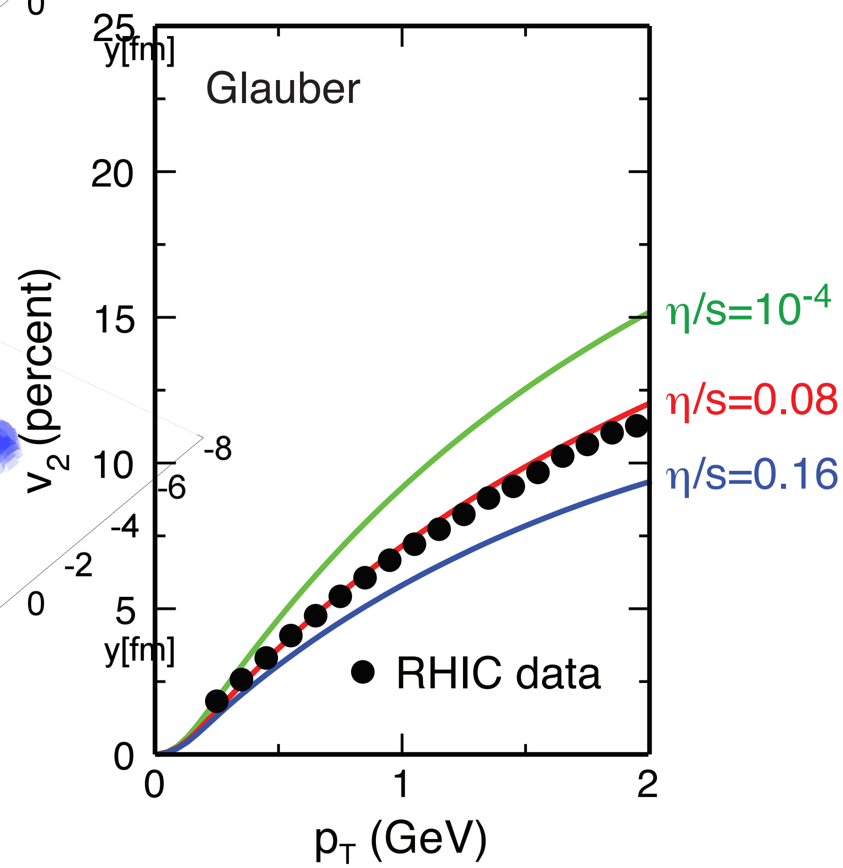
IP-Glasma

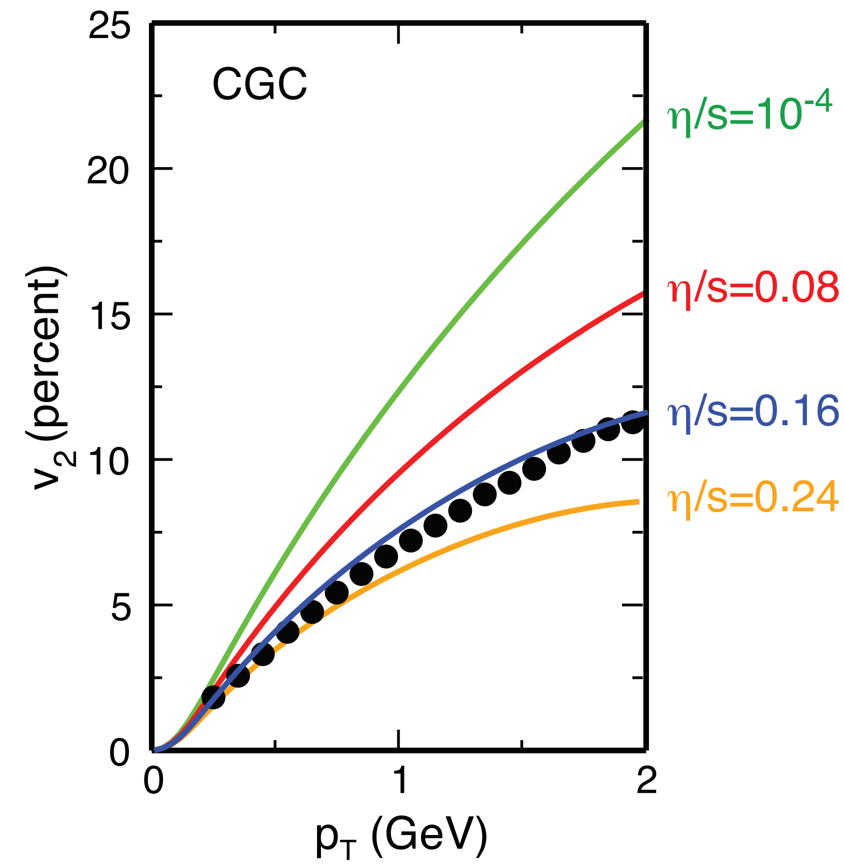


$1/(4\pi) \sim 0.08$

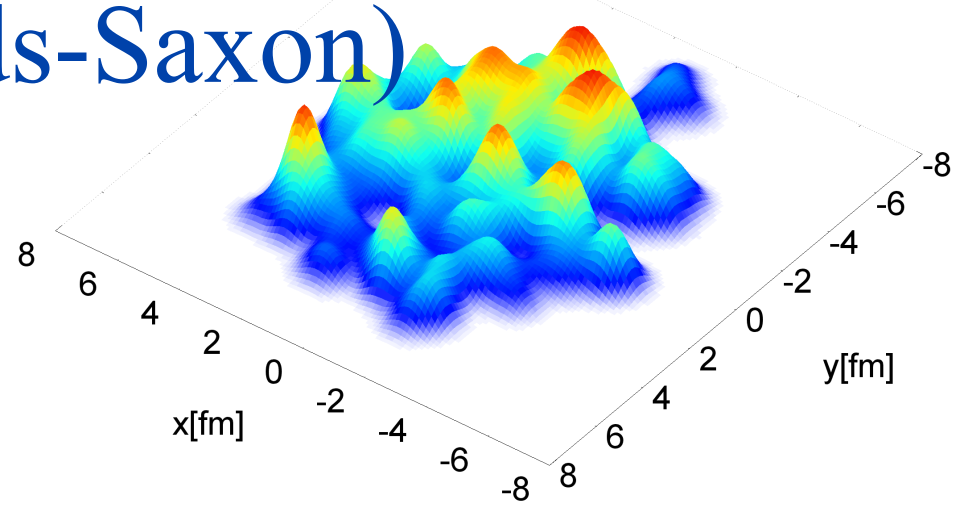
KLN(CGC)







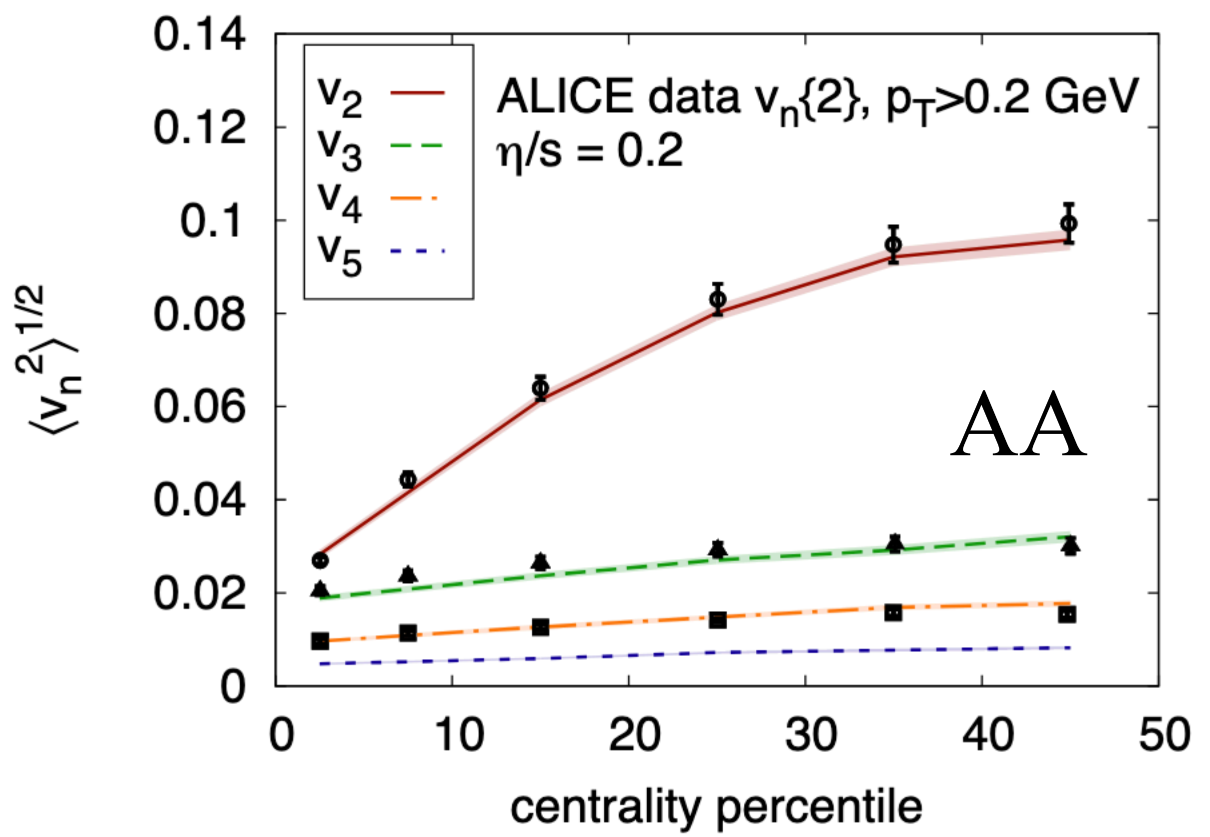
Glauber (Woods-Saxon)



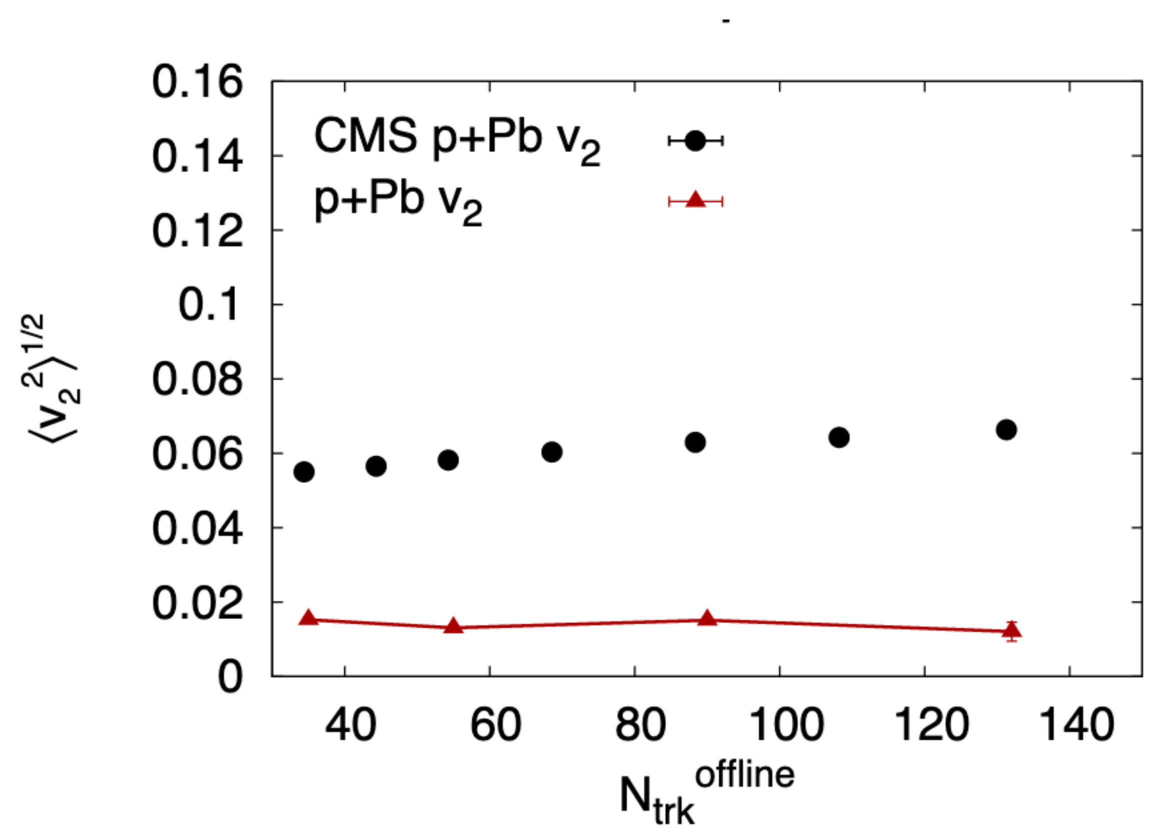
Different initial states= different fluctuation scales

AA vs. *pA*

IP-Glasma+Hydro



Gale et al, 1209.6330



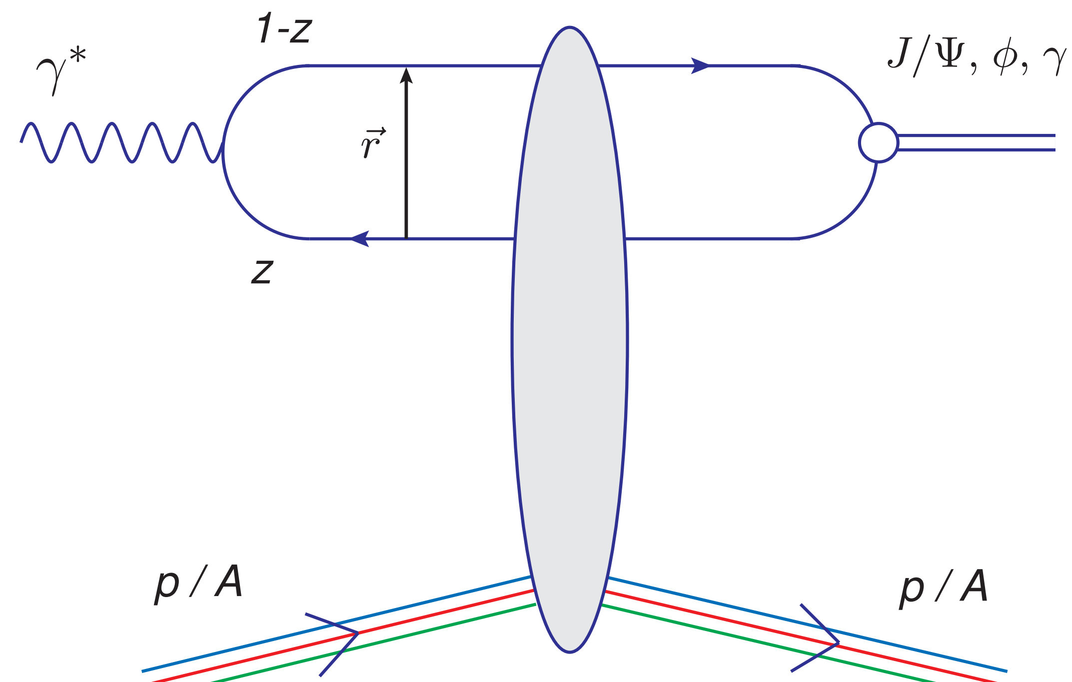
Schenke, Venugopalan, 1405.3605

Large elliptic flow seen in *p*-Pb collisions
Hydro calculation fail to describe this.

Part II:
Accessing the transverse initial state

H. Kowalski, L. Motyka, G. Watt, Phys.Rev.D 74 (2006) 074016, arXiv: hep-ph/0606272

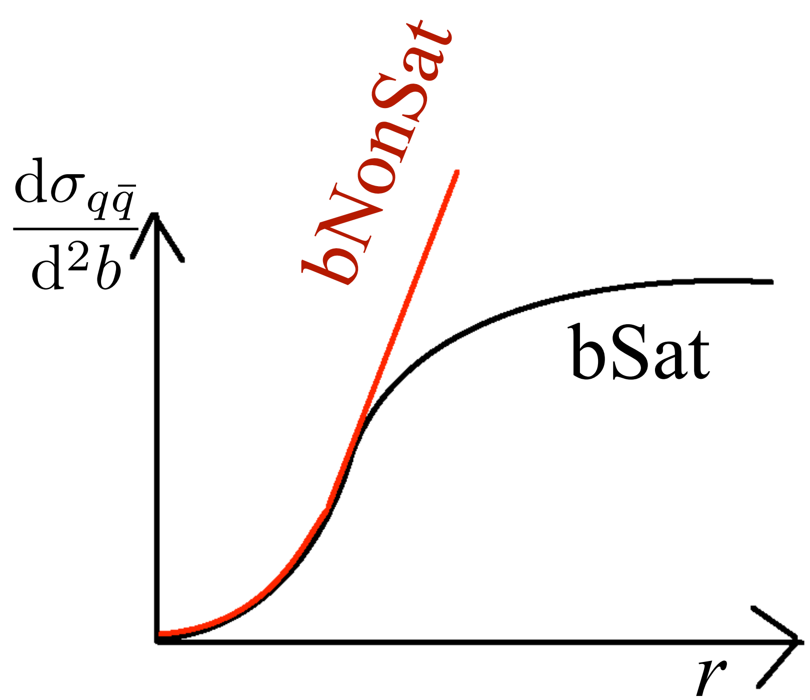
Exclusive diffraction in the Dipole Model



$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi} \left| \mathscr{A}^{\gamma^* p \to Vp}_{T,L} \right|^2$$

$$t = -\Delta^2$$

$$\mathscr{A}^{\gamma^* p \to Vp}_{T,L}(x_{I\!P}, Q^2, \Delta) = i \int 2\pi r dr \int \frac{dz}{4\pi} \int d^2\vec{b} \left(\Psi_V^* \Psi\right)(r,z) J_0([1-z]r\Delta) e^{-\vec{b}\cdot\vec{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2\vec{b}}(x_{I\!P}, r, \vec{b})$$



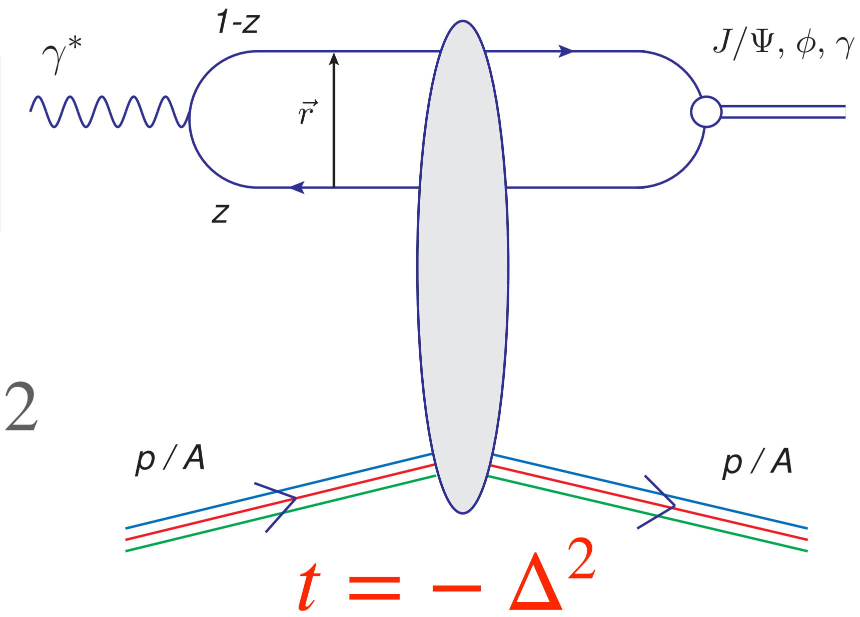
$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)\right)\right]$$

$$\frac{d\sigma^{\mathrm{nosat}}_{q\bar{q}}}{d\mathbf{b}} = \frac{\pi^2}{N_C} r^2 \alpha_S(\mu^2) x g(x,\mu^2) T(b)$$

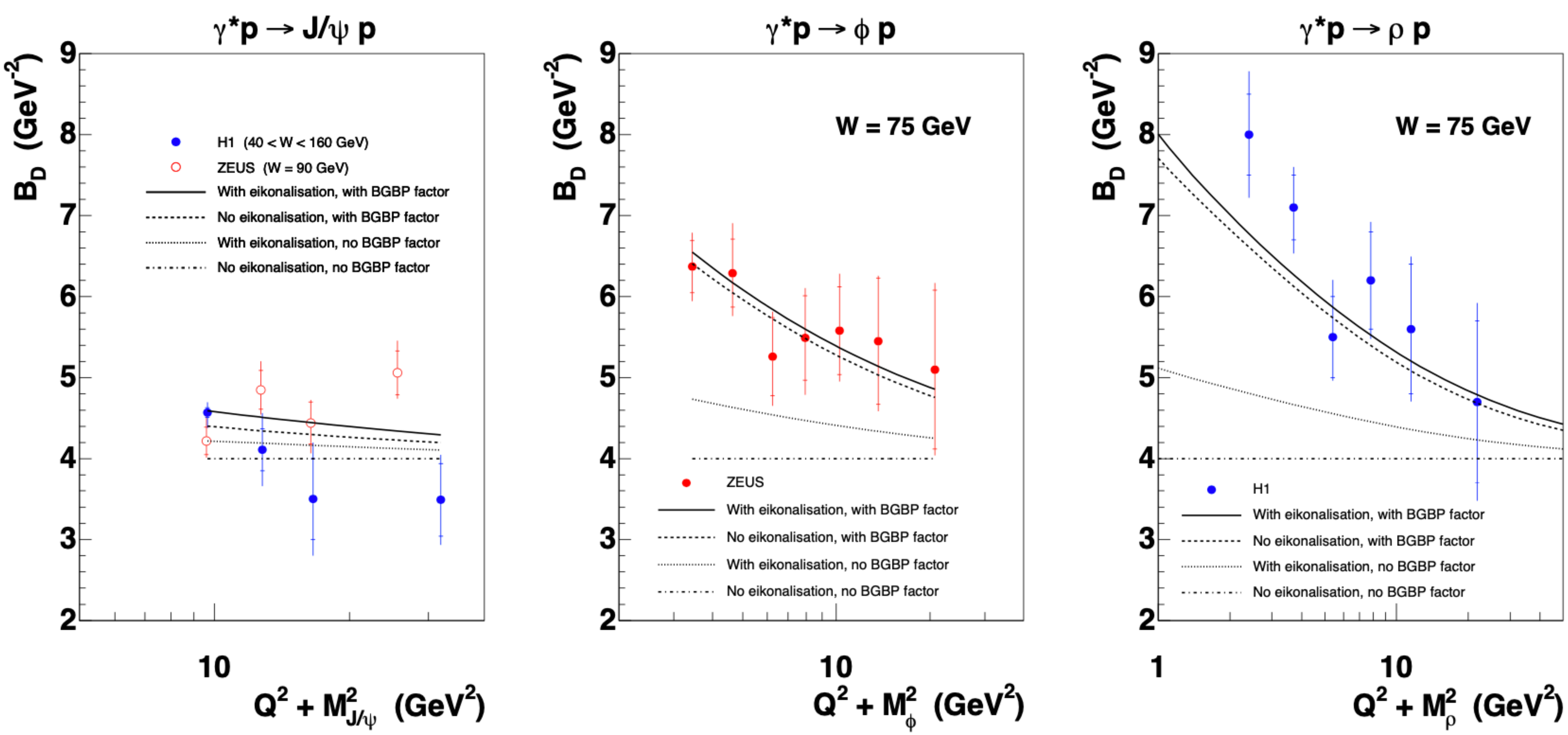
H. Kowalski, L. Motyka, G. Watt, Phys.Rev.D 74 (2006) 074016, arXiv: hep-ph/0606272

Exclusive diffraction in the Dipole Model

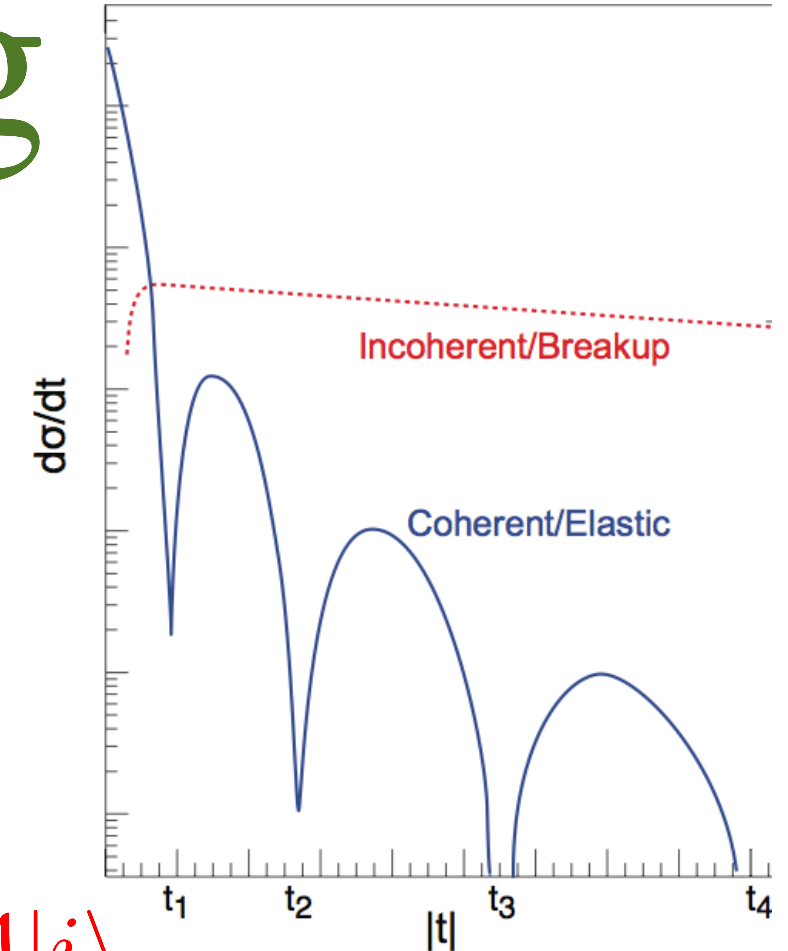
$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)\right)\right]$$



$$T_p(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}} \quad B_G = 4\ \mathrm{GeV}^{-2}$$



Incoherent Scattering



Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

complete set

$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \langle i \left| |\mathcal{A}|^2 \right| i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - |\langle \mathcal{A}\rangle|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} |\langle \mathcal{A}\rangle|^2$$

The nucleus as a collection of nucleons

TT, Thomas Ullrich
Phys.Rev.C 87 (2013) 2, 024913, arXiv: 1211.3048
Comput.Phys.Commun. 185 (2014) 1835-1853 arXiv:1307.8059

Independent scattering approximations:

$$1-\frac{1}{2}\frac{\mathrm{d}\sigma^{(p)}_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b}) = \prod_{i=1}^{A}\left(1-\frac{1}{2}\frac{\mathrm{d}\sigma^{(A)}_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, |\vec{b}-\vec{b}_i|)\right)$$

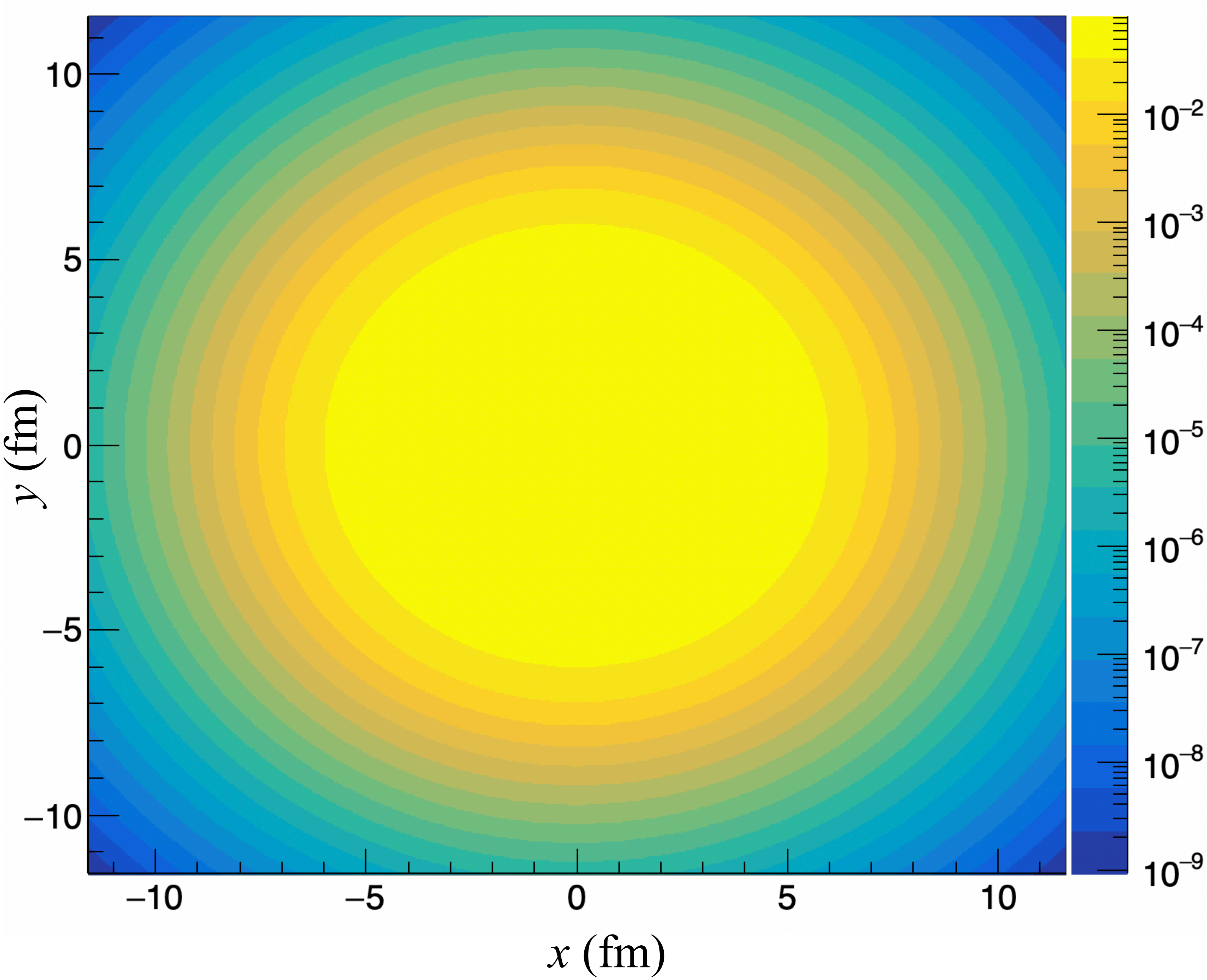
$$\frac{1}{2}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b}) = 1-\exp\left(\frac{\pi^2}{2N_C}r^2\alpha_S(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T_p(|\vec{b}-\vec{b}_i|)\right)$$

$$T_A(\vec{b}) = \int \mathrm{d}z\frac{\rho_0}{1+\exp\left(\frac{\sqrt{\vec{b}^2+z^2}-R_0}{d}\right)}$$

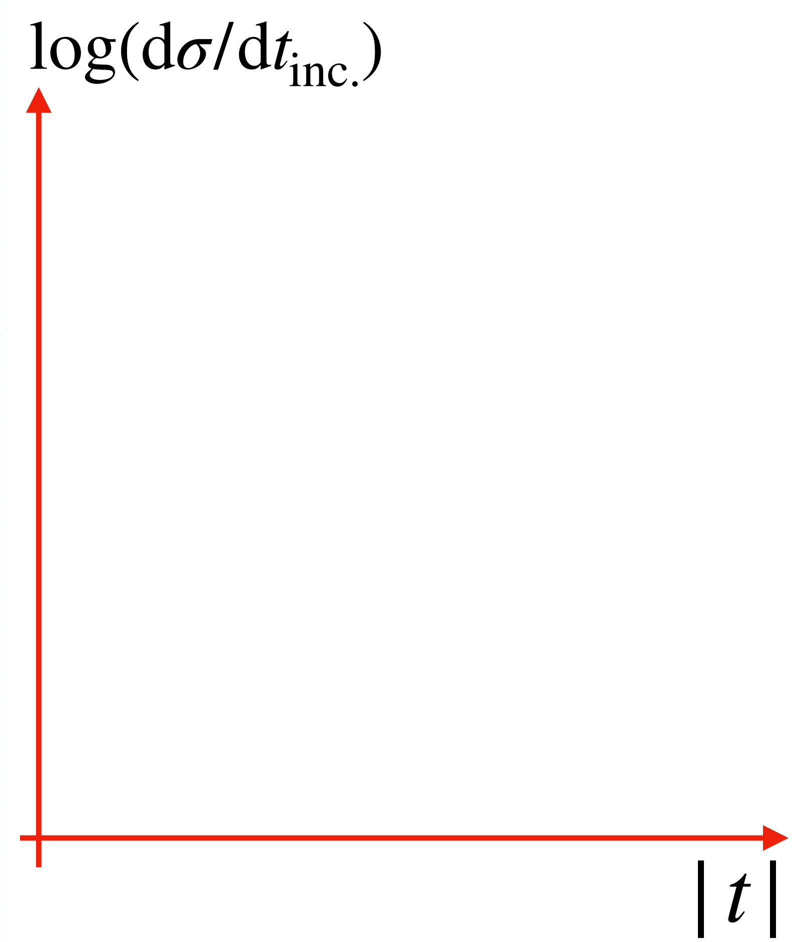
$$T_A(\vec{b}) = \sum_{i=1}^{A}T_p(|\vec{b}-\vec{b}_i|)$$

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

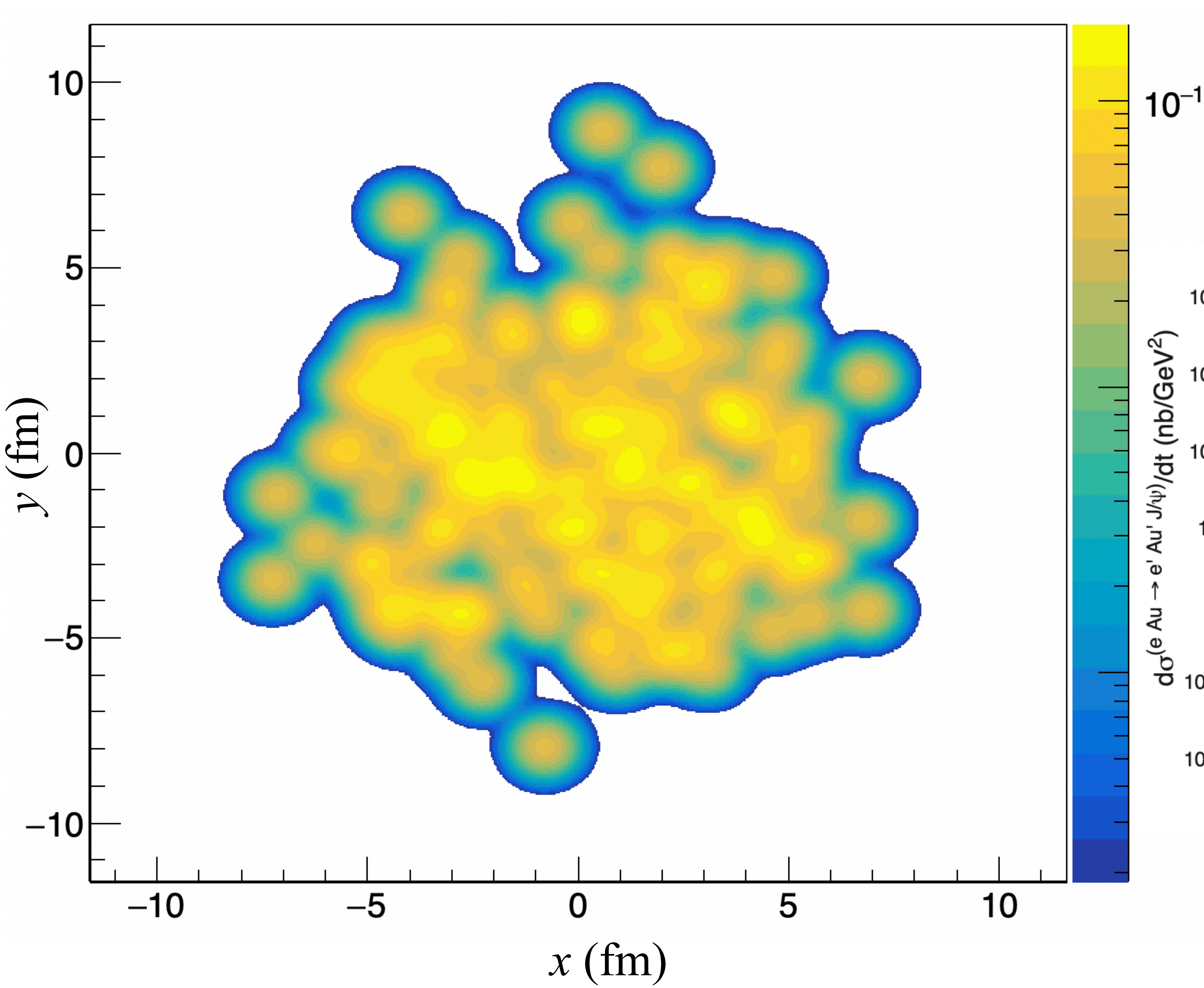
Into the heavy nucleus



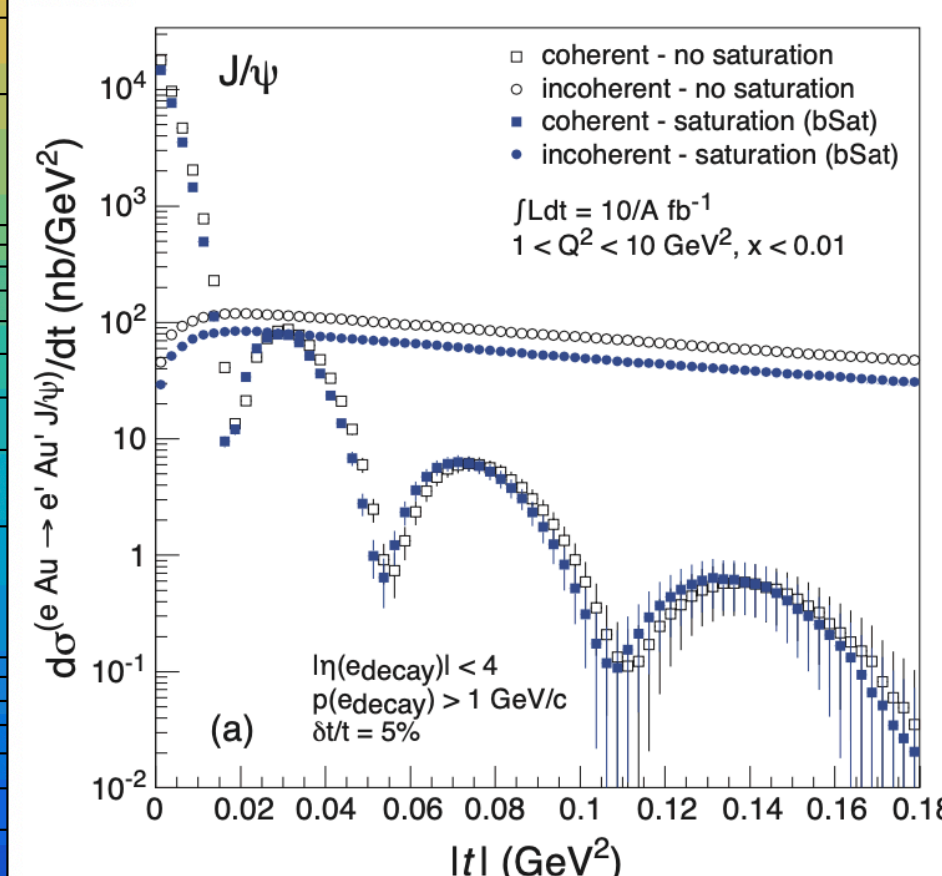
$|t| = 0$



Into the heavy nucleus

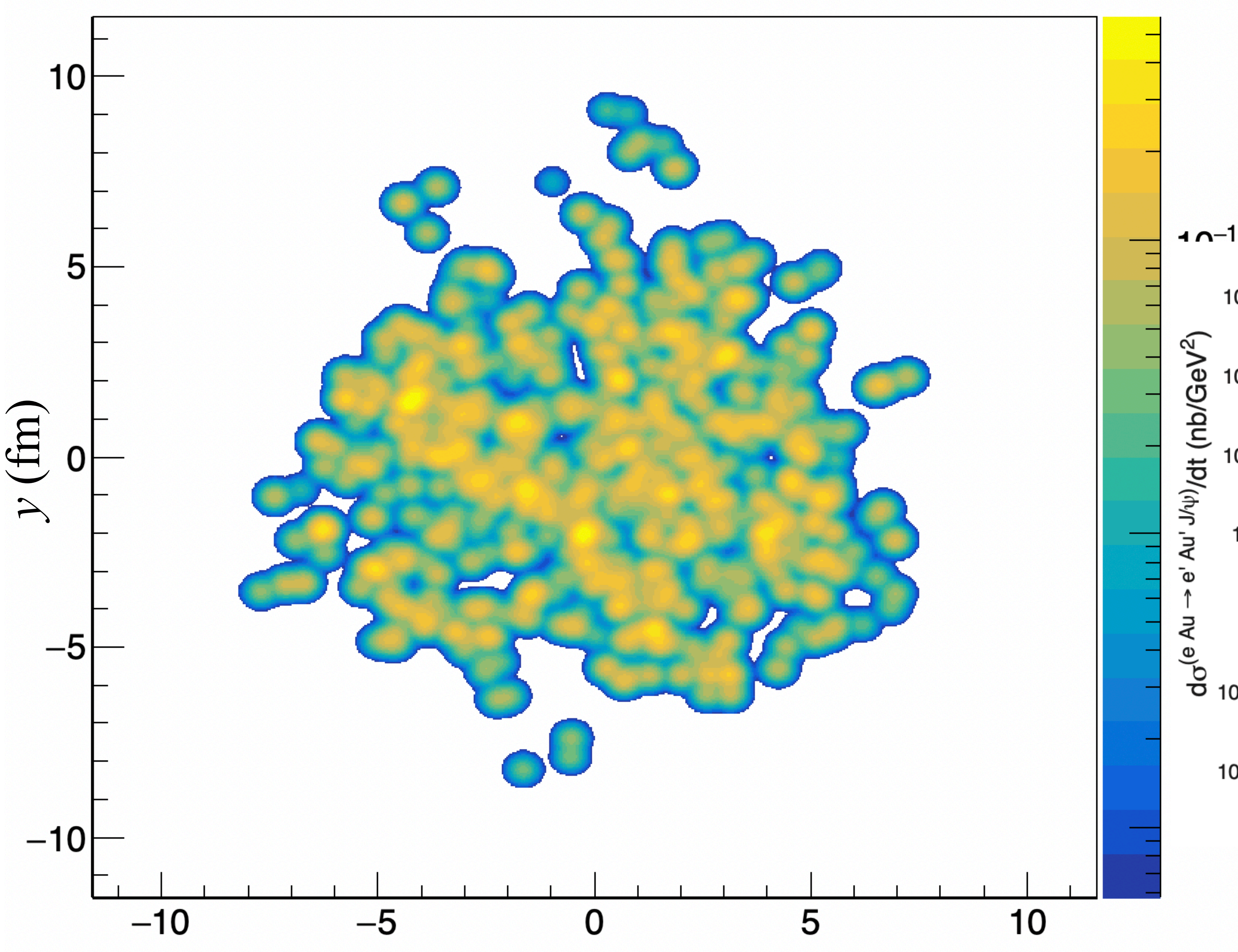


$|t| \lesssim 0.2\ \mathrm{GeV}^2$

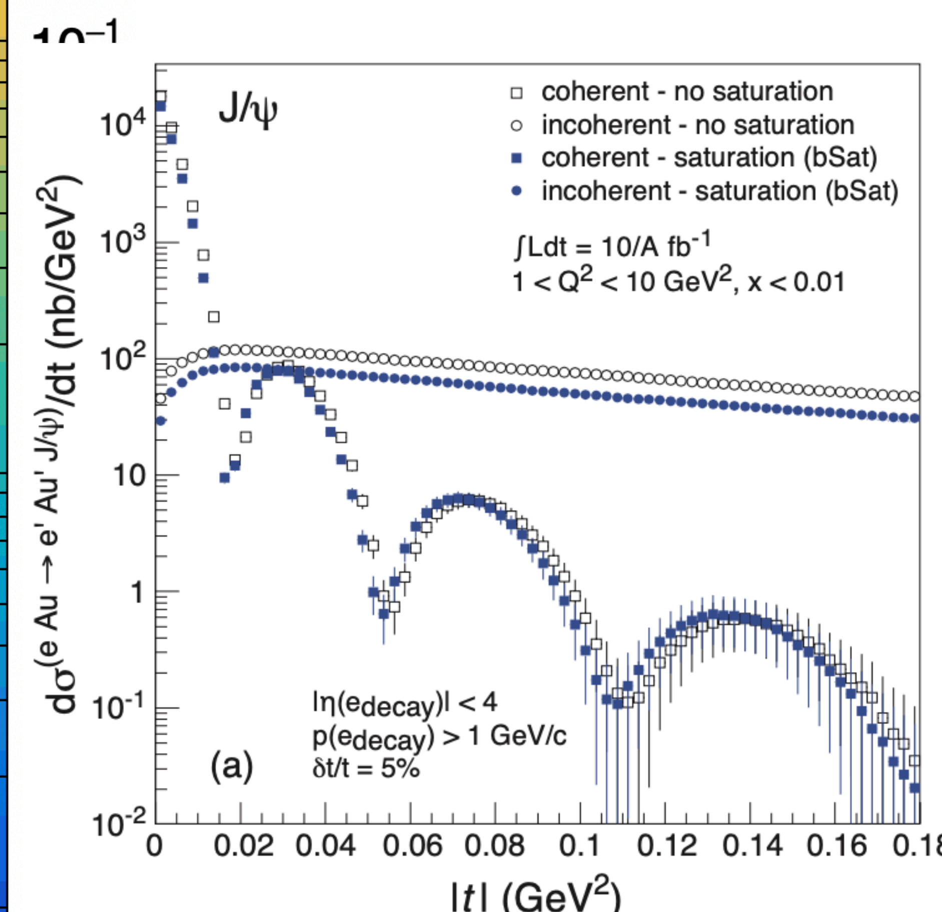


$|t|$

Into the heavy nucleus



$0.2 \lesssim |t| \lesssim 2\ \mathrm{GeV}^2$



$|t|$

Hotspot model for incoherent *ep*-scattering

$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

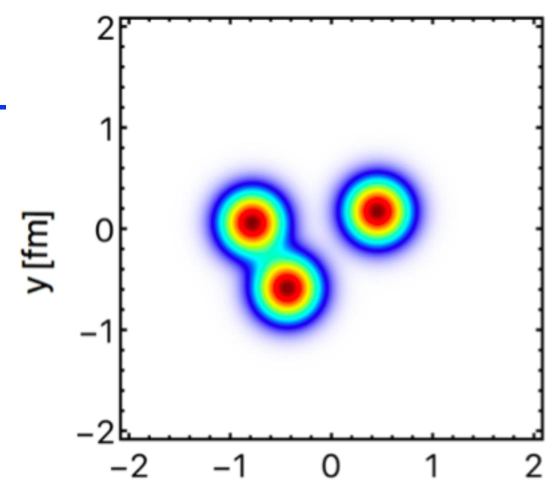
$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^6$$

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

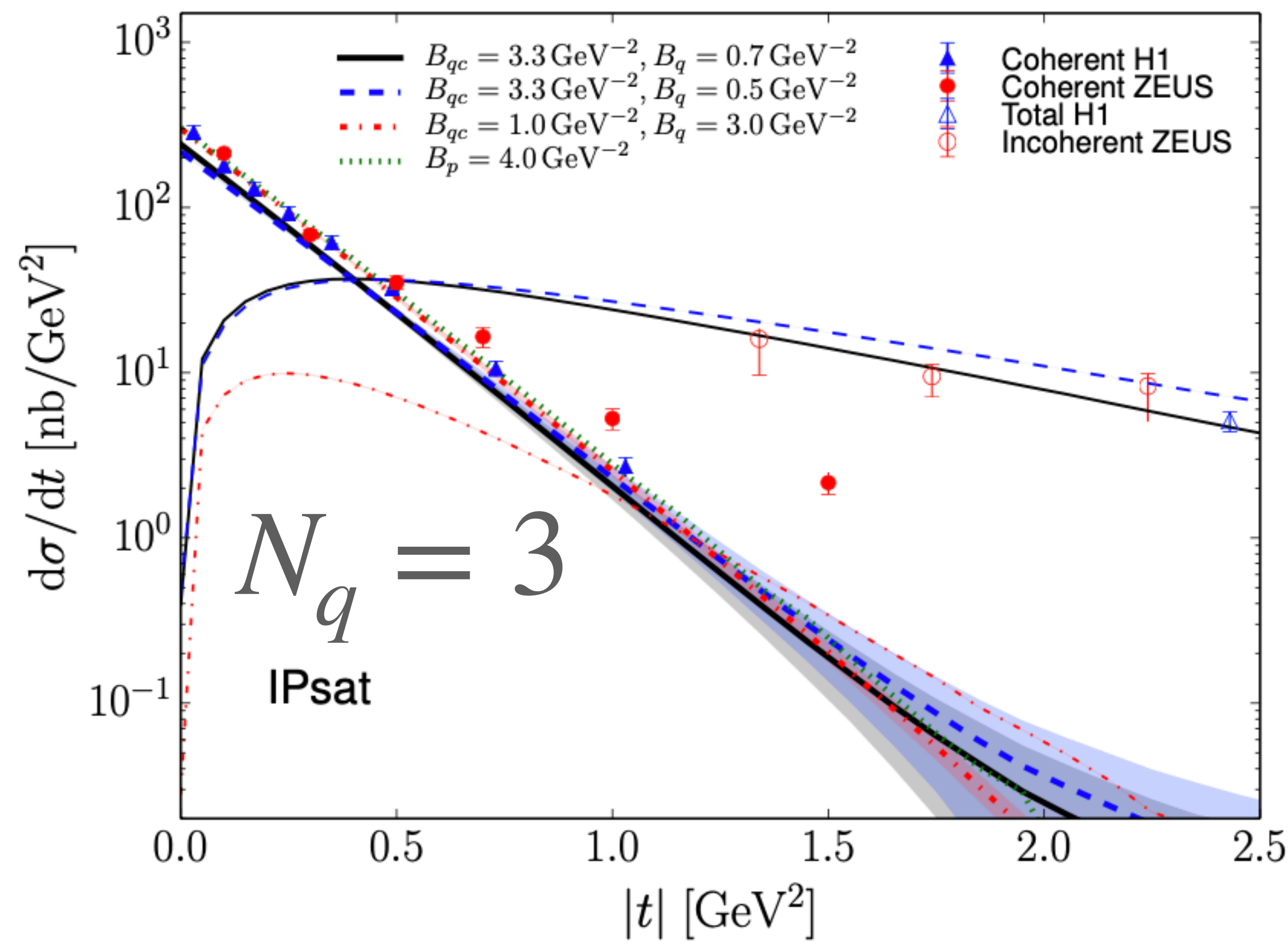
$$T_p(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}}$$

↓

$$T_p(b) = \frac{1}{2\pi N_q B_q} \sum_{i=1}^{N_q} e^{-\frac{(\vec{b}-\vec{b}_i)^2}{2B_q}}$$



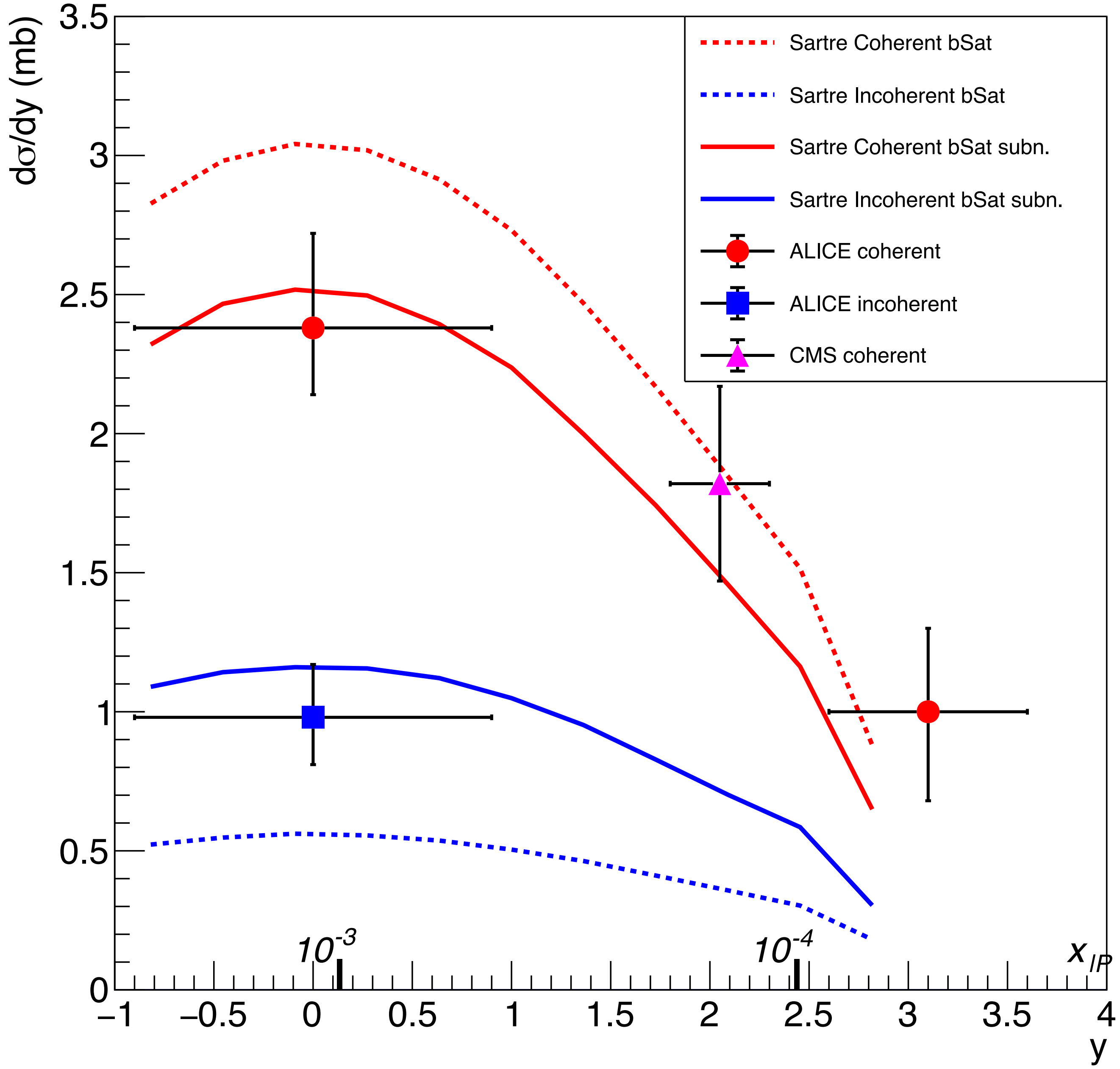
$\vec{b}_i$ with a Gaussian distribution of width B_{qc}



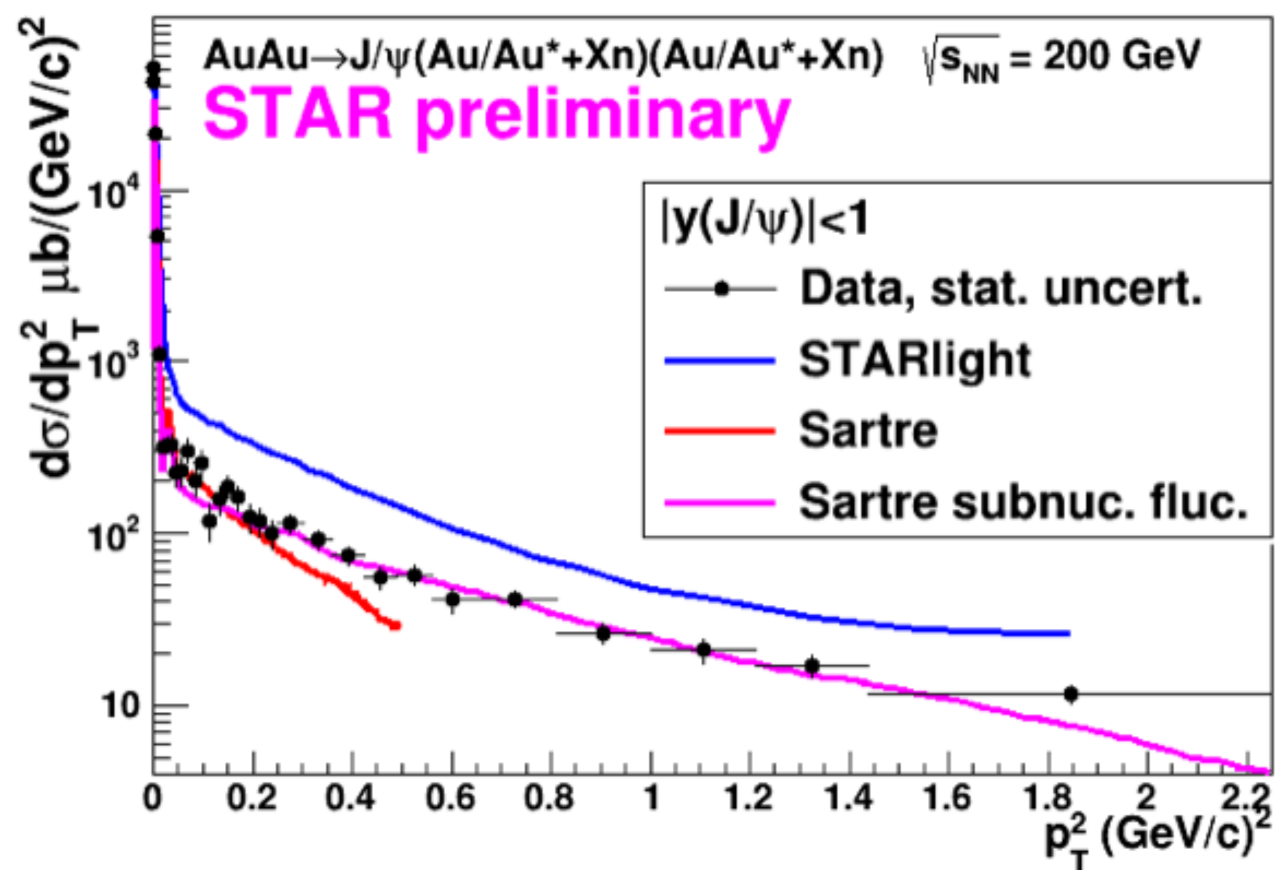
H. Mäntysaari and B. Schenke Phys. Rev. Lett., 117(5):052301, 2016.

Also: large scale (small $|t|$) saturation scale fluctuations. Affects small $|t|$, one more parameter.

A-A UPC at the LHC & RHIC



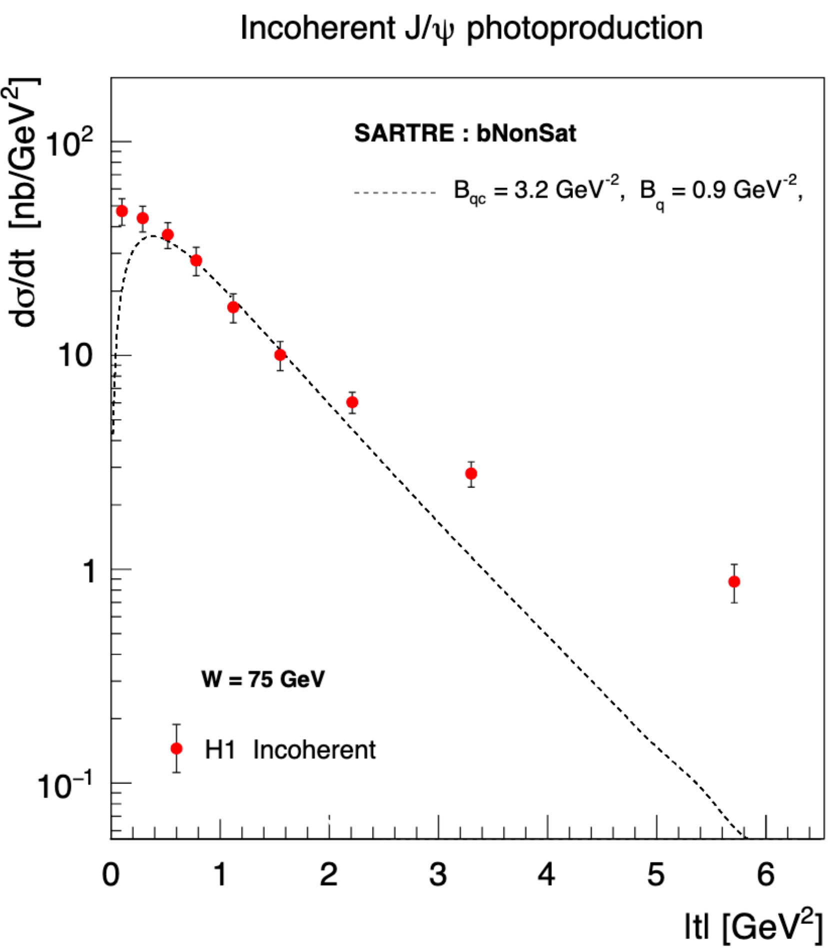
TT: SciPost Phys.Proc. 8 (2022) 148

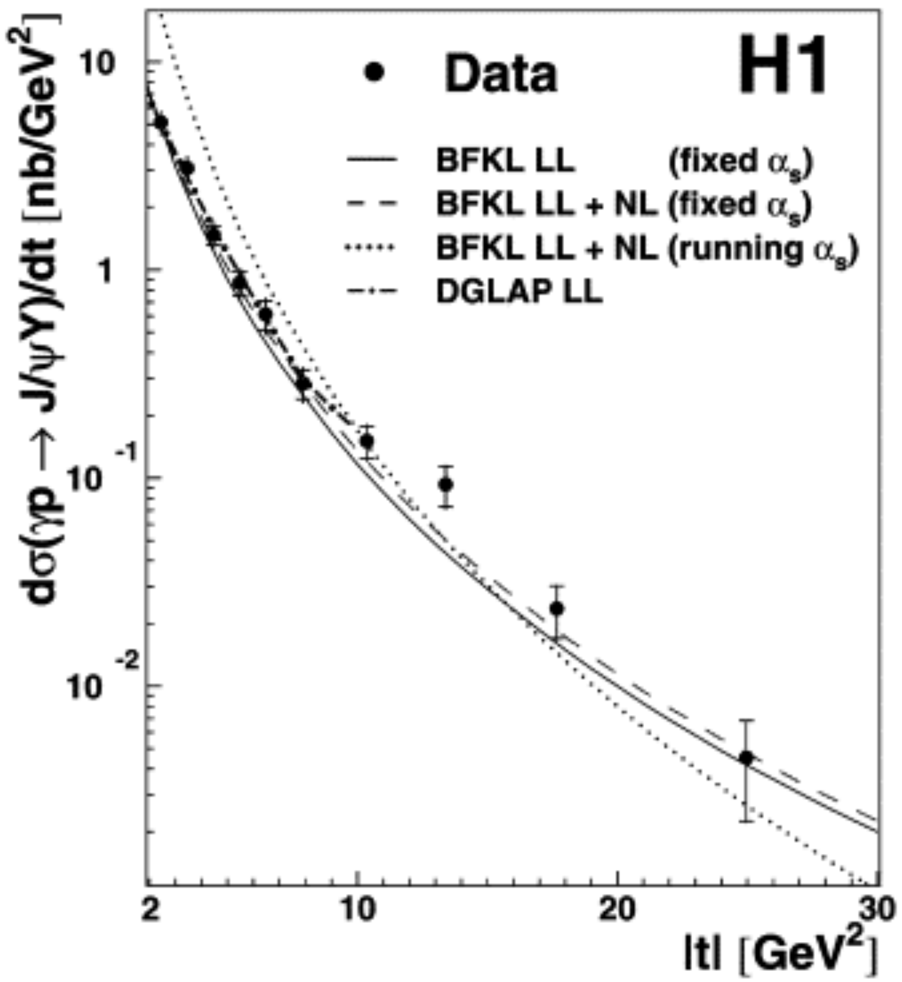


Eventhough coherent events dominate, the large $|t|$ tails have a significant effect on the cross sections!

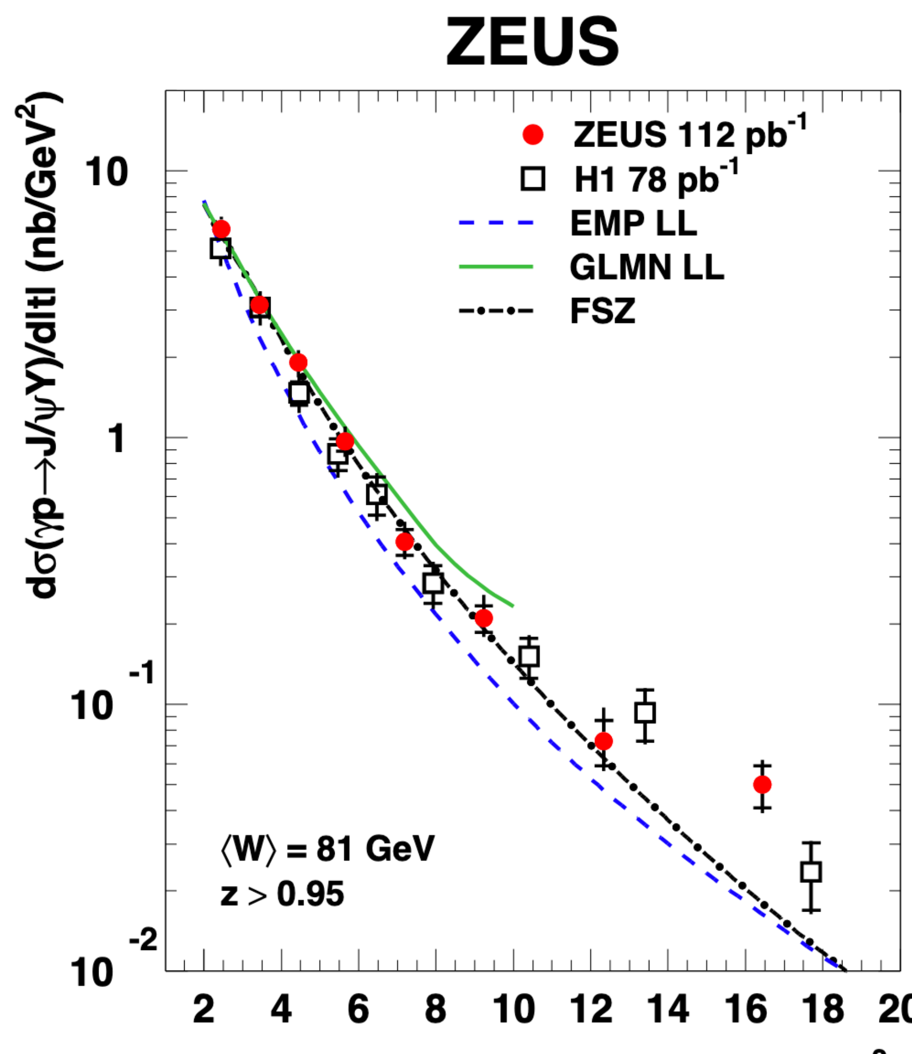
Subnucleon structure becomes important for $|t| > 0.2$ GeV^2

Hotspot Model shortcomings





Phys. Lett. B 568 (2003) 205–218



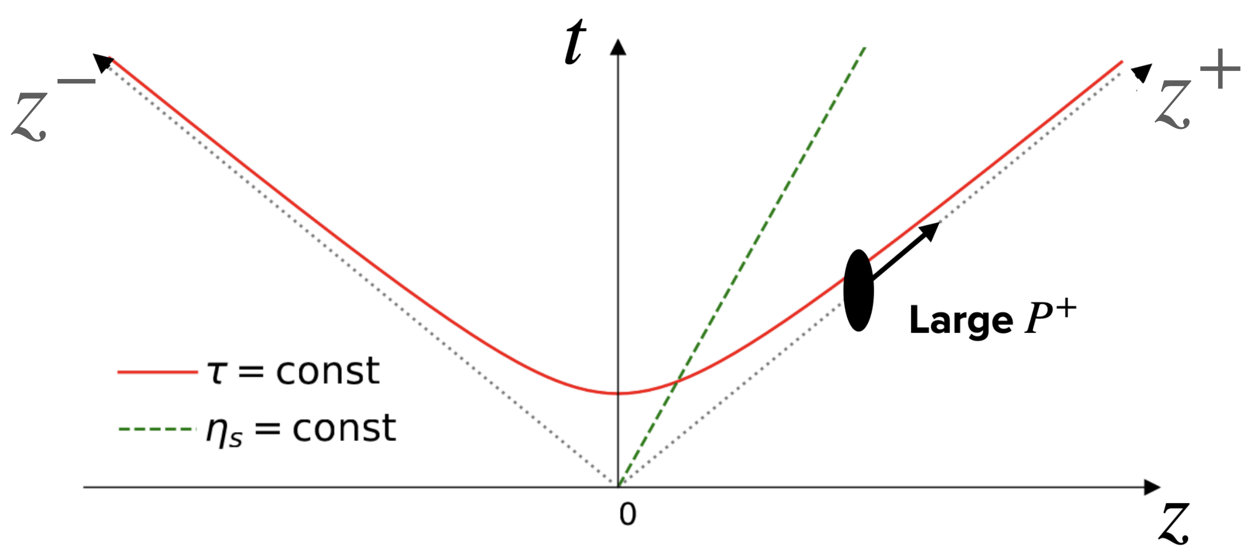
JHEP 05 (2010) 085

Non-perturbative phenomenology. Only valid for $|t| \lesssim 1$ GeV^2.
What about larger $|t|$?

Part III:
Two pictures of the transverse gluon

1: Color Charge Sources,
The Color Glass Condensate

The Color Glass Condensate Picture



Probe moving in z^- direction
Target moving in z^+ direction

Hadronic target moving with large P^+ probed at scale $x_0 P^+$ where $x_0 \ll 1$

Partons inside target have momenta $k^+ = xP^+$

Localisation of partons: $\Delta z^- \sim \frac{1}{k^+} = \frac{1}{xP^+}$

Spatial resolution of probe: $\frac{1}{x_0 P^+}$

Time evolution of partons:

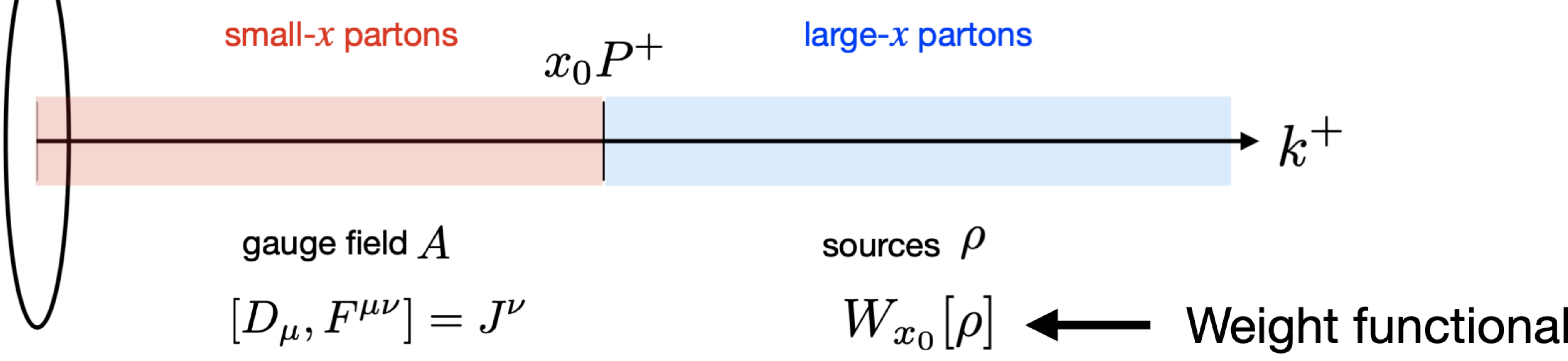
$$\tau = \sqrt{2z^+z^-} \approx \Delta z^+ \sim \frac{1}{k^-} = \frac{2k^+}{k_T^2} = \frac{2xP^+}{k_T^2}$$

Time resolution of probe:

$$\tau \approx \frac{2x_0P^+}{k_T^2} < \frac{2x_0P^+}{k_T^2}$$

For $x > x_0$, partons appear fully localised in z^- and static in z^+.
Treat these partons as sources of small-x fields.

The Color Glass Condensate Picture



Large x partons act as sources for small x gluons.

Need to model the weight functional, e.g. McLerran-Venugopalan Model:

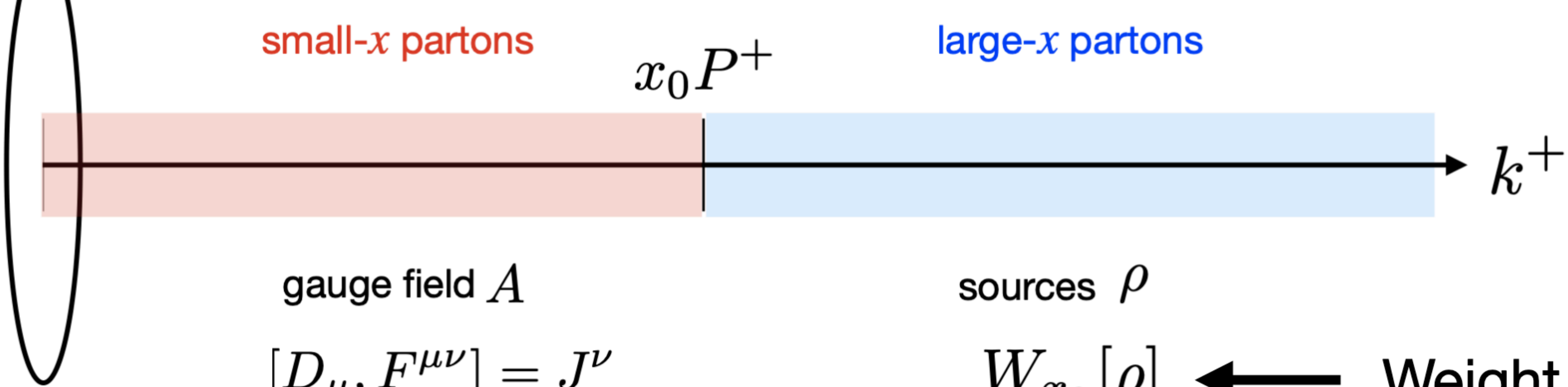
$$W_{x_0}[\rho] = \mathcal{N} \exp\left(-\frac{1}{2} \int \mathrm{d}x^- \mathrm{d}^2 x_T \frac{\rho_a^2(x^-, x_T)}{\lambda_{x_0}(x^-)} \right)$$

Central limit theorem: Assume Gaussian correlations of sources, large nucleus, independently fluctuating.

This is the basis for IP-Glasma (as seen earlier)

However: this picture combines very well with the hotspot model!

The Color Glass Condensate Picture



$$[D_\mu, F^{\mu\nu}] = J^\nu \qquad W_{x_0}[\rho] \longleftarrow \text{Weight functional}$$

$$T_p(b) = \frac{1}{2\pi N_q B_q} \sum_{i=1}^{N_q} e^{-\frac{(\vec{b} - \vec{b}_i)^2}{2B_q}}$$

Locate the source colour charges around the locations b_i of the hotspots and let them fluctuate event-by-event:

$$\left\langle \rho^a(\vec{x}) \right\rangle_{\text{CGC}} = 0, \qquad \left\langle \rho^a(\vec{x})\rho^b(\vec{y}) \right\rangle_{\text{CGC}} = \sum_{i=1}^{N_q} \mu^2\left(\frac{\vec{x} + \vec{y}}{2} - b_i\right)\delta^{(2)}(\vec{x} - \vec{y})\delta^{ab}$$

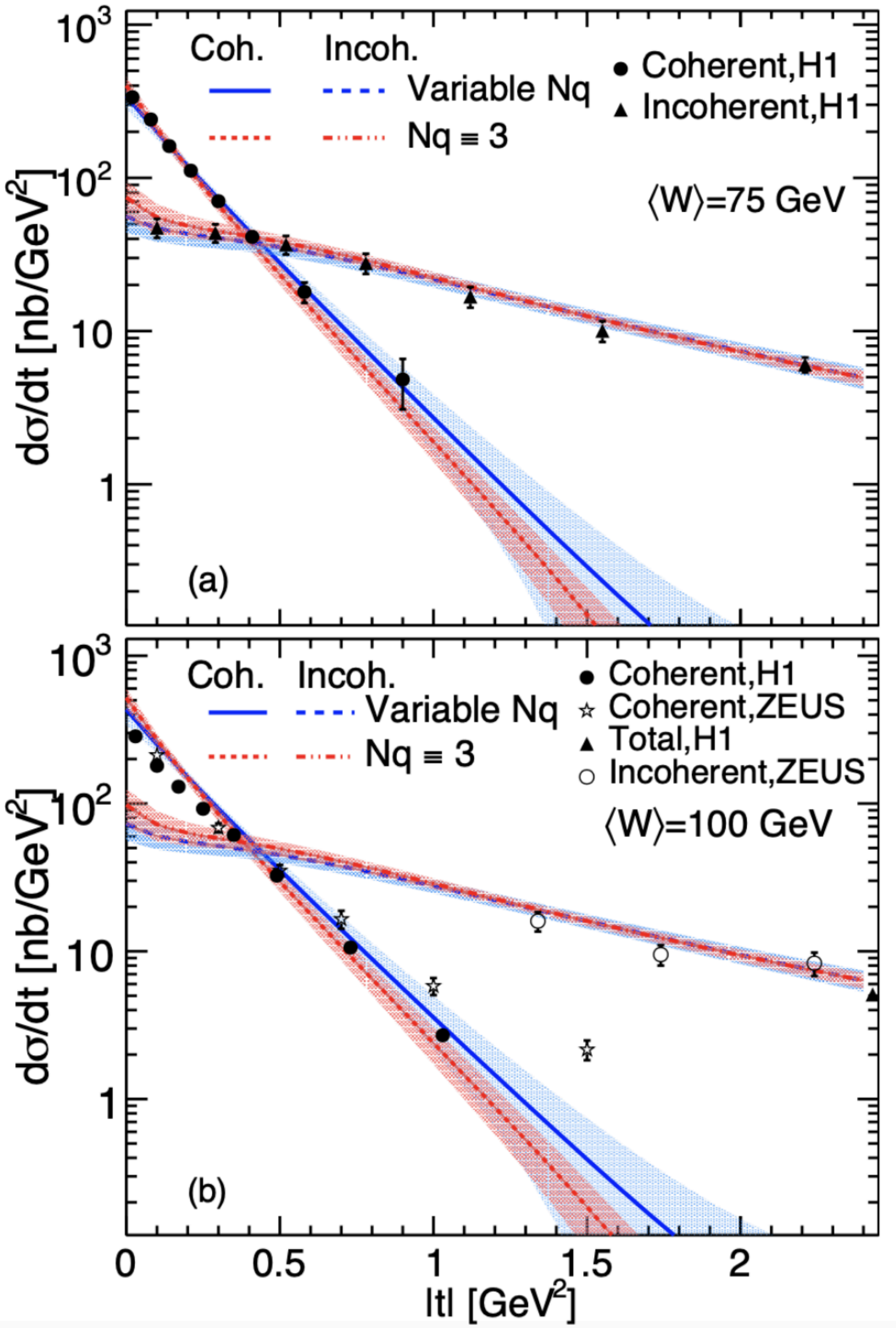
Hotspot profile: $\mu^2(\vec{x}) = \frac{\mu_0^2}{2\pi r_H^2} e^{-\frac{\vec{x}^2}{2r_H^2}}$

Small $|t|$ hotspot model acts as a starting distribution for the CGC nucleon.

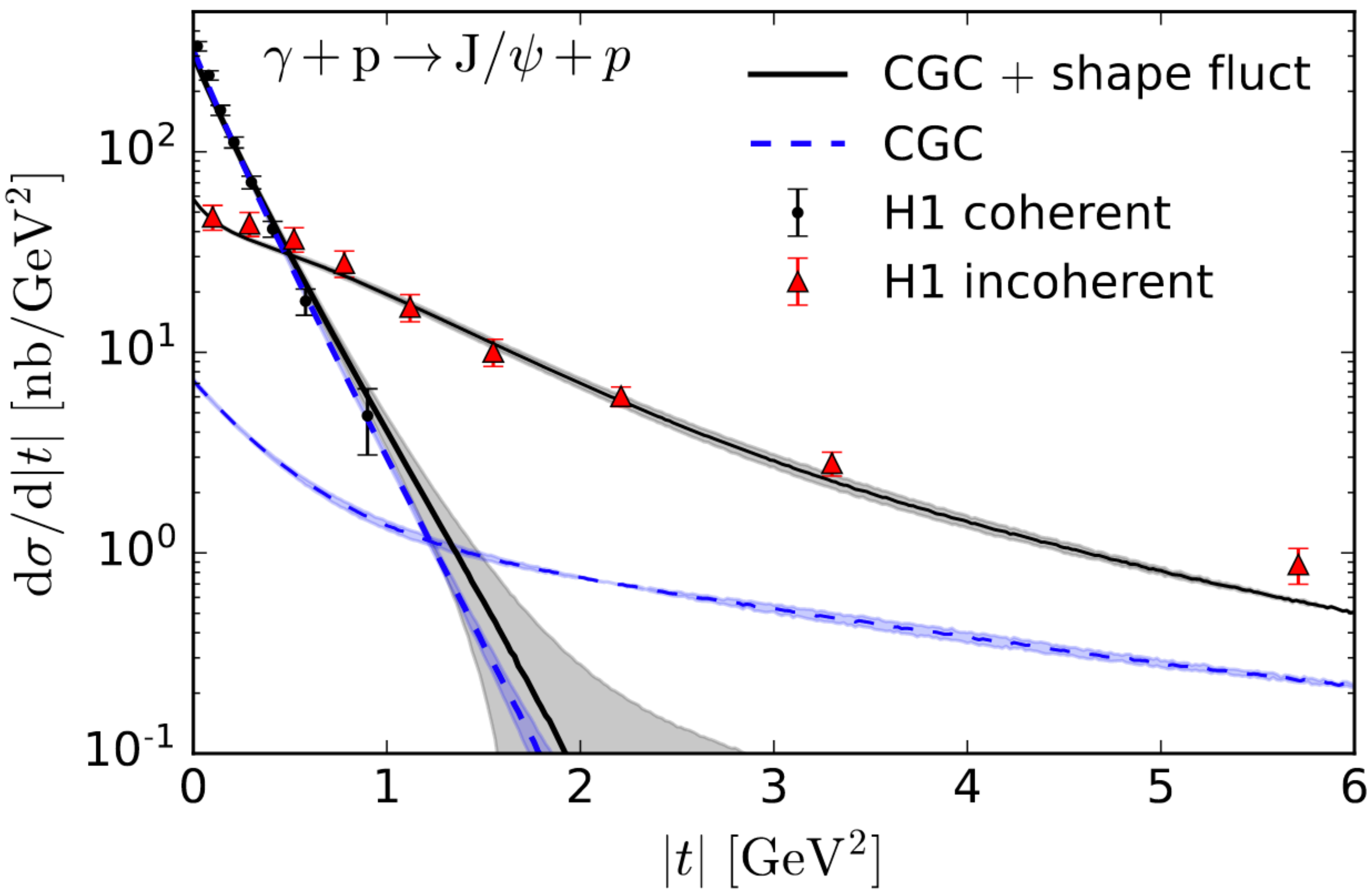
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
H. Mäntysaari, B. Schenke, Phys.Rev. D94 (2016) 034042

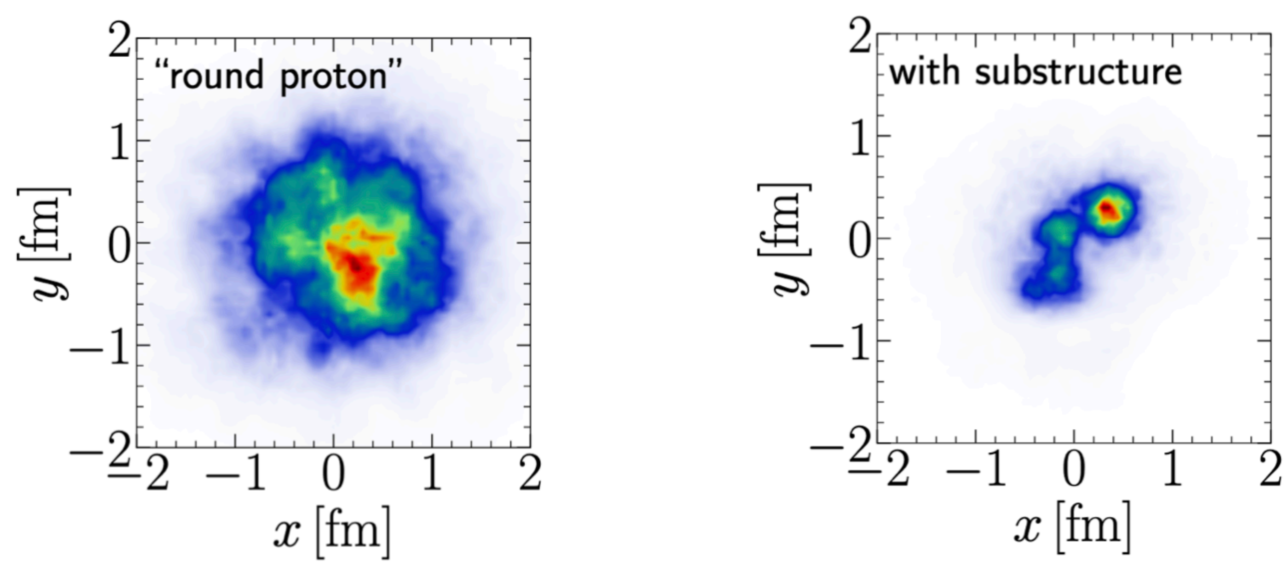
The Color Glass Condensate Picture

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, arXiv:2202.01998



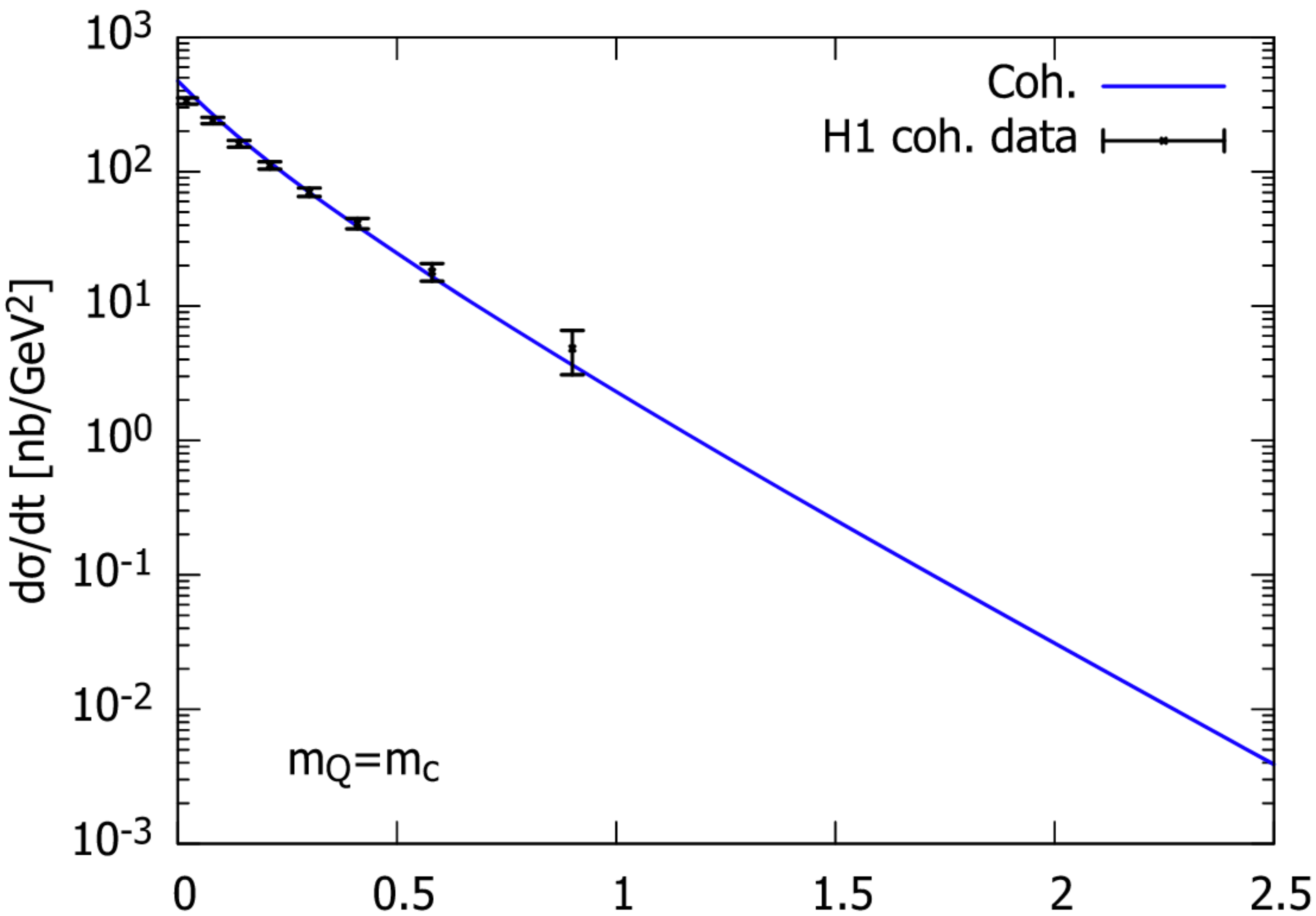
H. Mäntysaari, F. Salazar, B. Schenke, 2207.03712

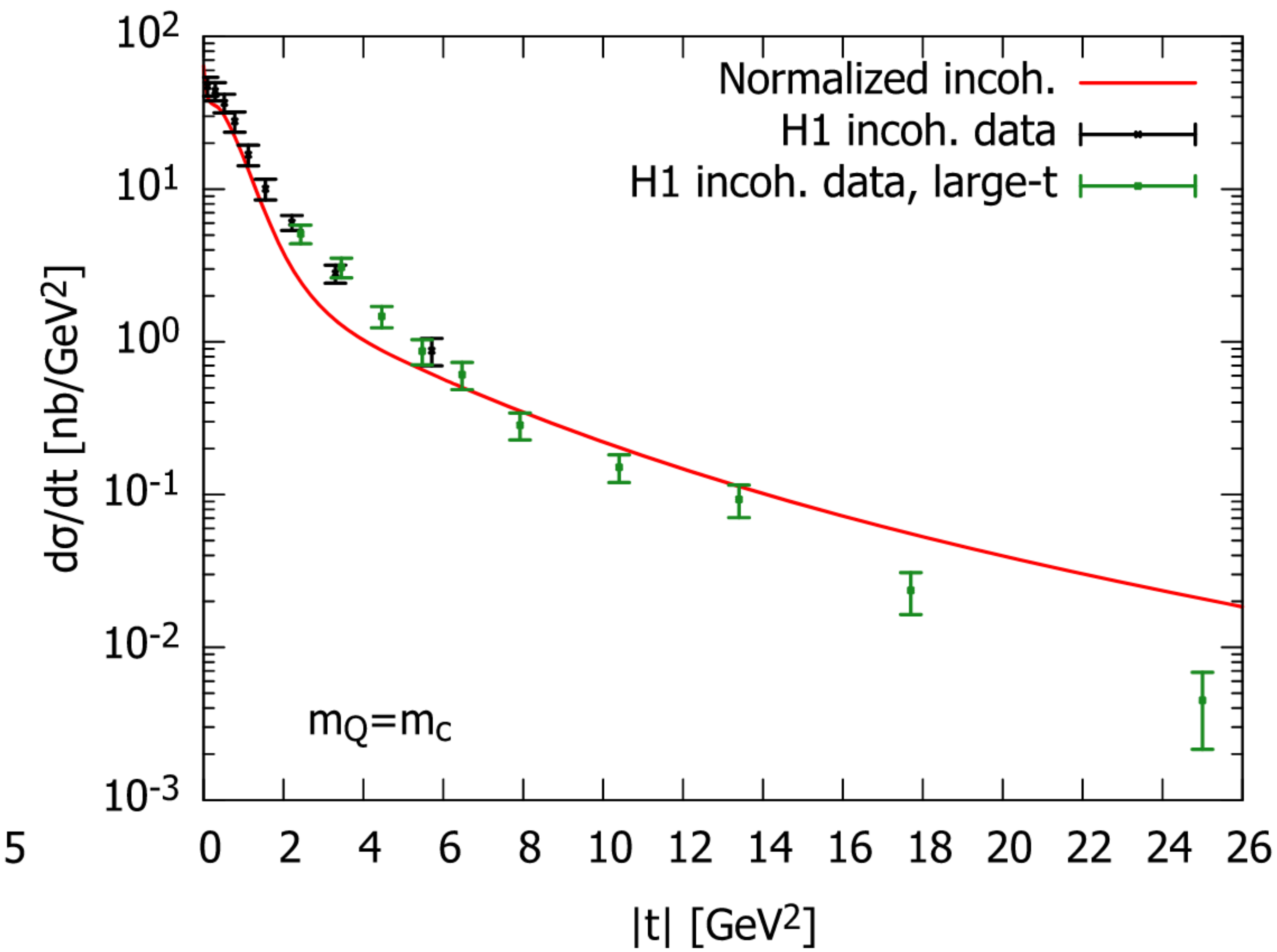


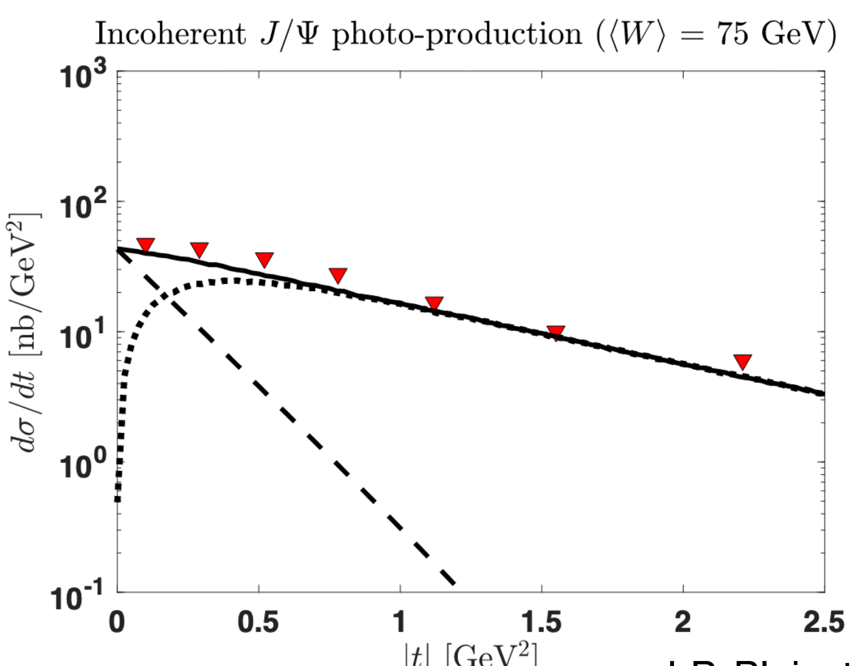


The Color Glass Condensate Picture

S. Demirci, T. Lappi, S. Schlichting 2206.05207



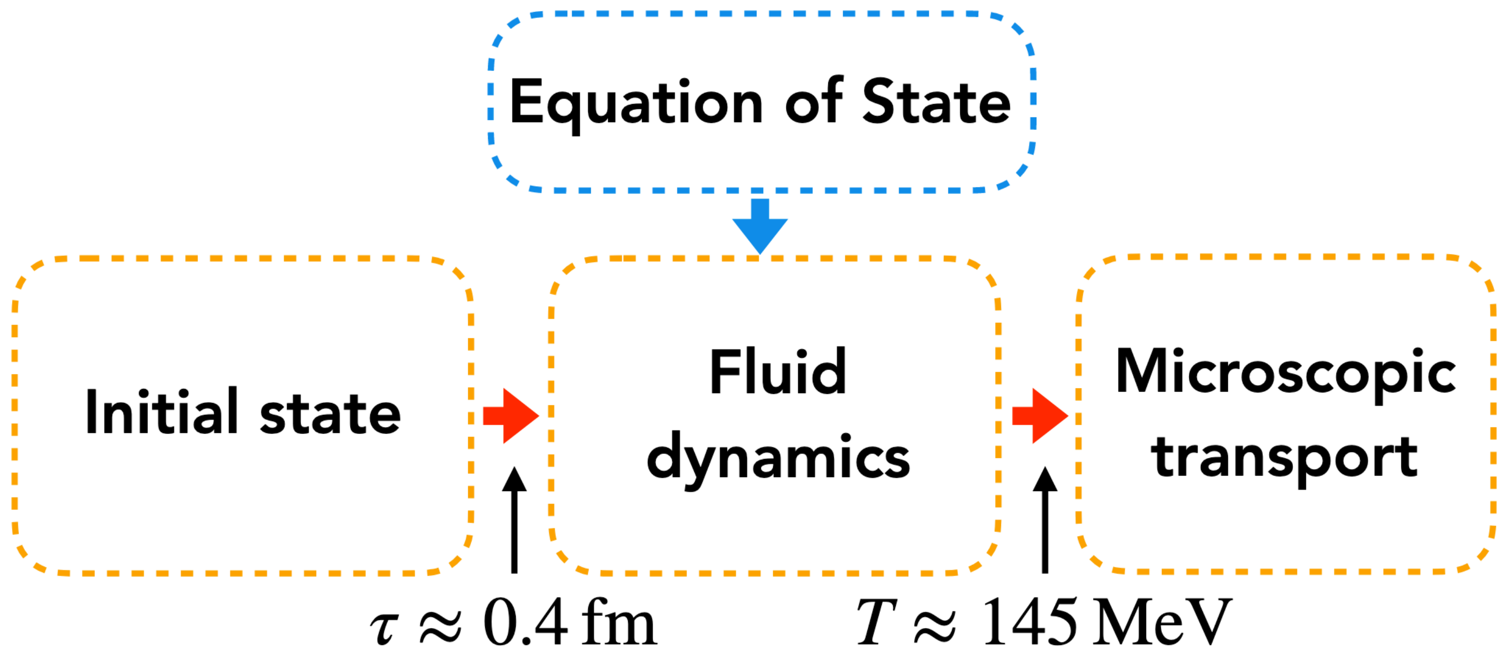


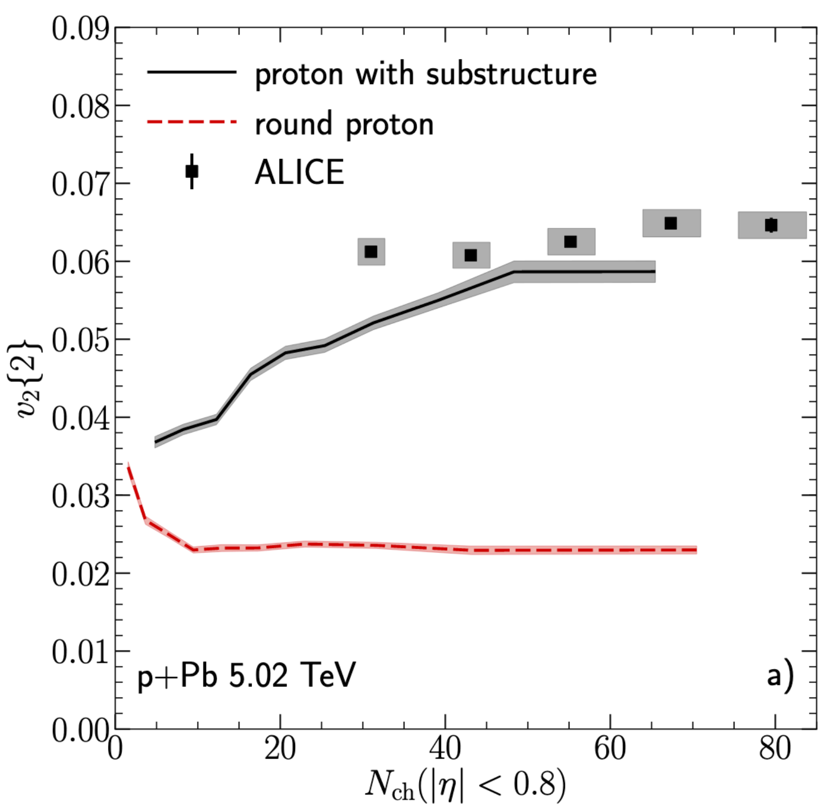


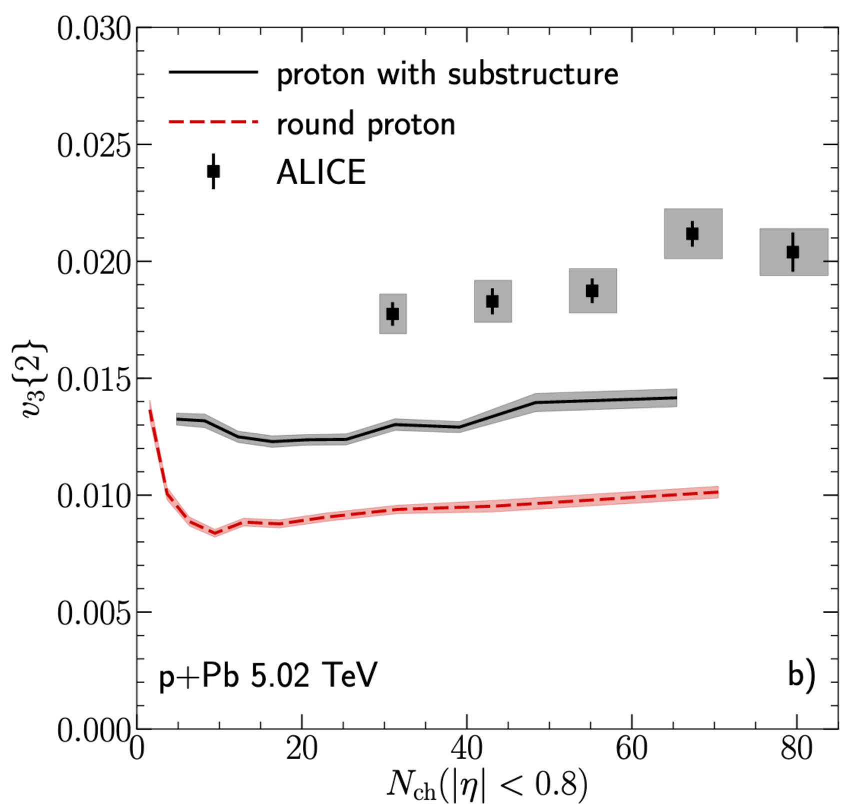
J-P. Blaizot, M.C. Traini 2209.15545

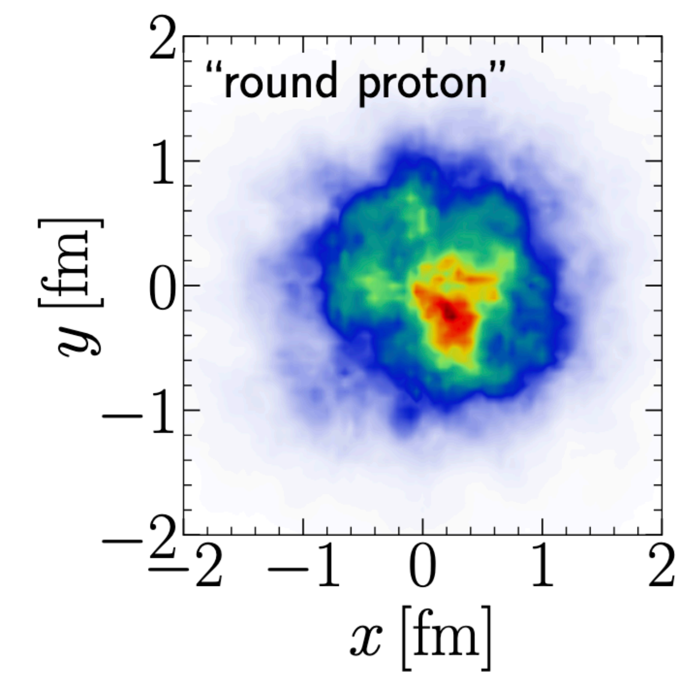
Analytical calculation in the dilute and non-relativistic limit. Incoherent normalised by 2.5.
They found that at small $|t|$ major contribution comes from fluctuations in the dipole.

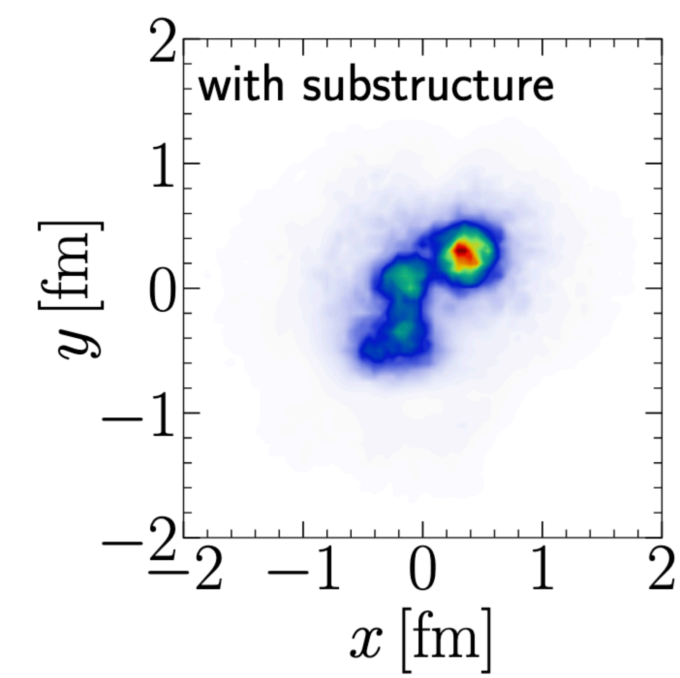
The Color Glass Condensate Picture









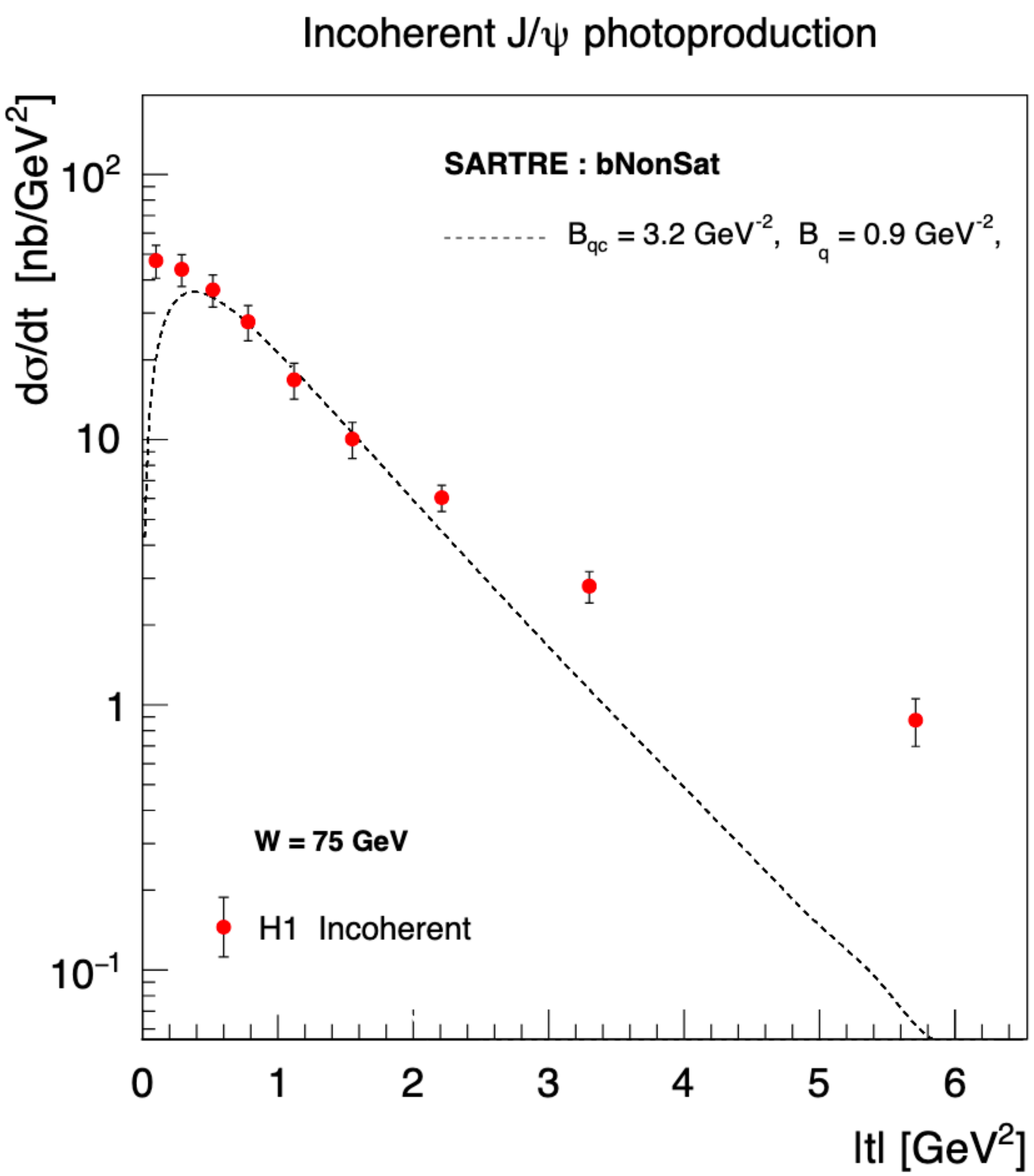


B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

Part IV:
Two pictures of the transverse gluon

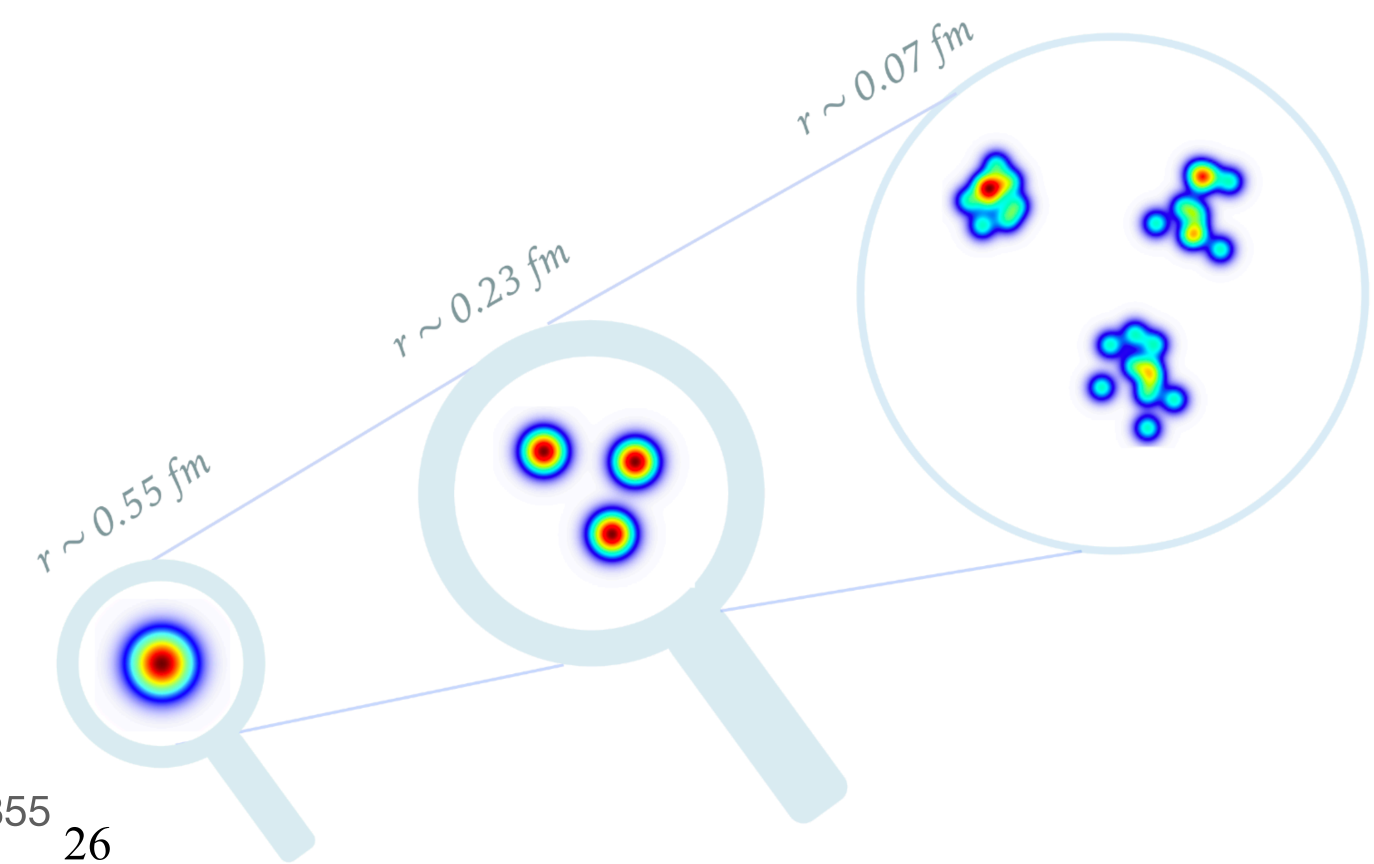
2: Hotspot Evolution

Larger $|t|$?



Appears to be two slopes in the data:
One for $0.5 \leq |t| \leq 2$ GeV^2
Another for $|t| > 2$ GeV^2

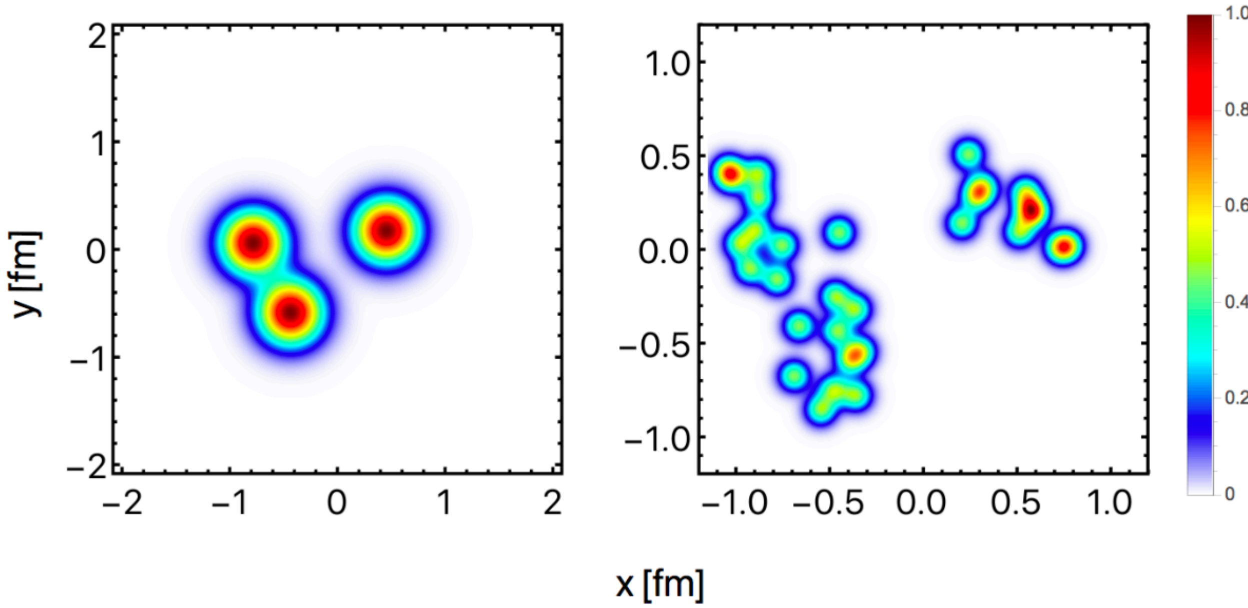
Hotspots within hotspots!

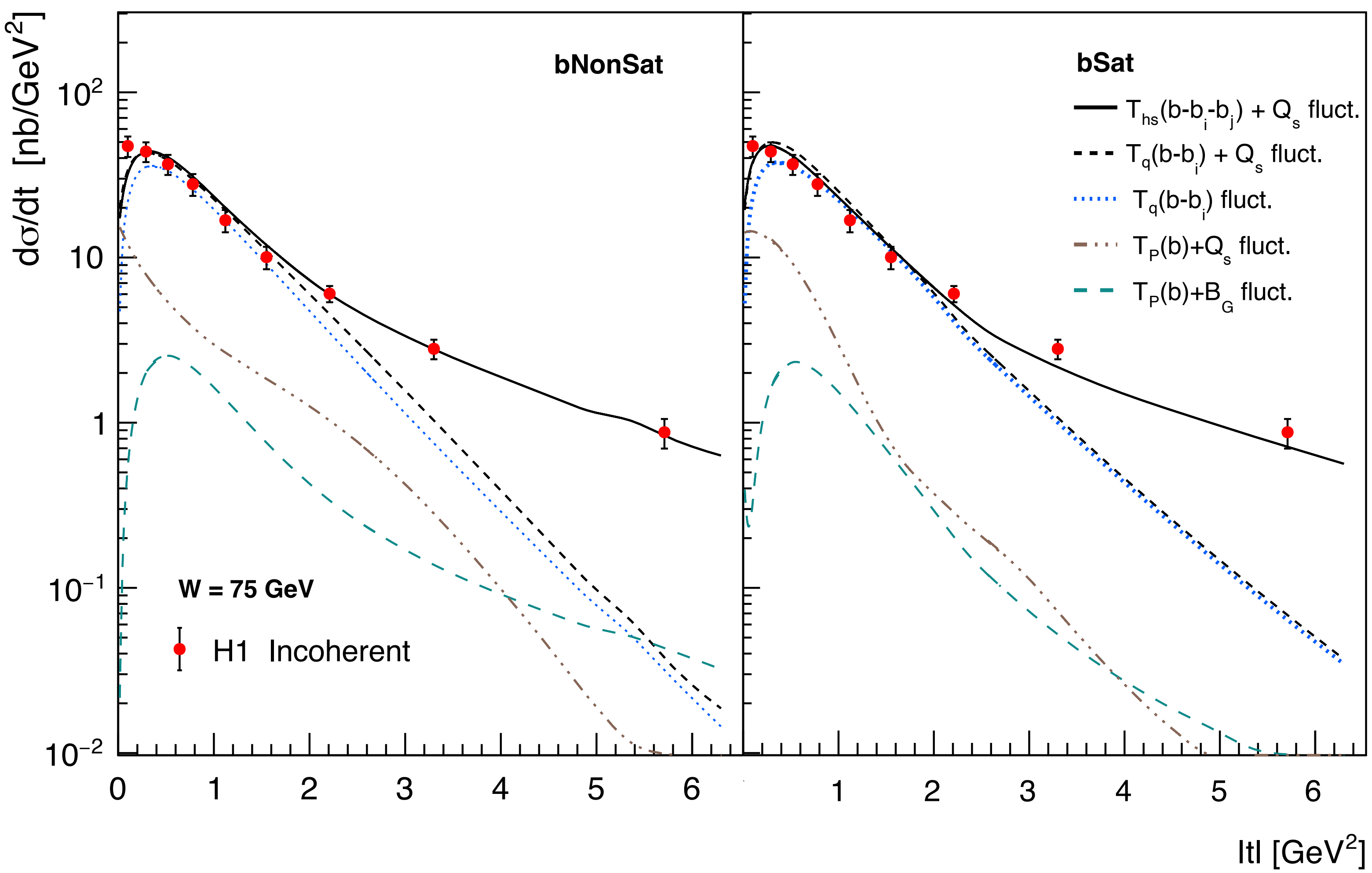


Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

Hotspots within Hotspots

Model	B_{qc}	B_q	B_{hs}	S_g	N_{hs}	σ
bNonSat hotspot	3.2	0.9	–	–	–	0.4
bSat hotspot	3.3	0.7	–	–	–	0.5
modified bSat hotspot	3.3	0.9	–	0.3	–	0.4
bNonSat refined hotspot	**3.2**	**1.15**	**0.05**	–	**10**	**0.4**
bSat refined hotspot	**3.3**	**1.08**	**0.09**	**0.4**	**10**	**0.5**





$$T_p(b) = \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(\vec{b} - \vec{b}_i)$$

$$T_q(b) = \frac{1}{N_{hs}}\sum_{i=1}^{N_{hs}} T_{hs}(\vec{b} - \vec{b}_i)$$

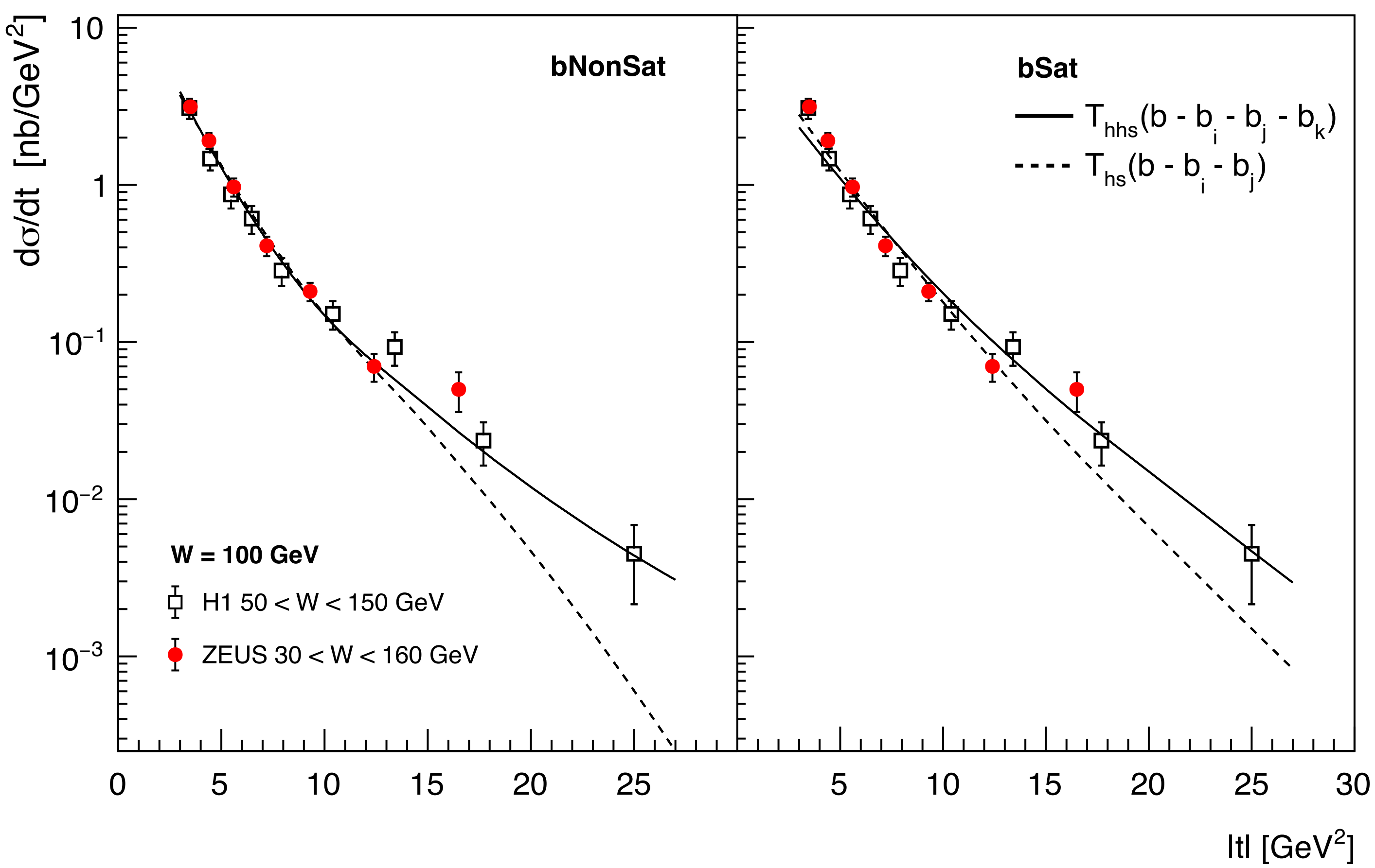
$$T_{hs}(b) = \frac{1}{2\pi B_{hs}} e^{-\frac{b^2}{2B_{hs}}}$$

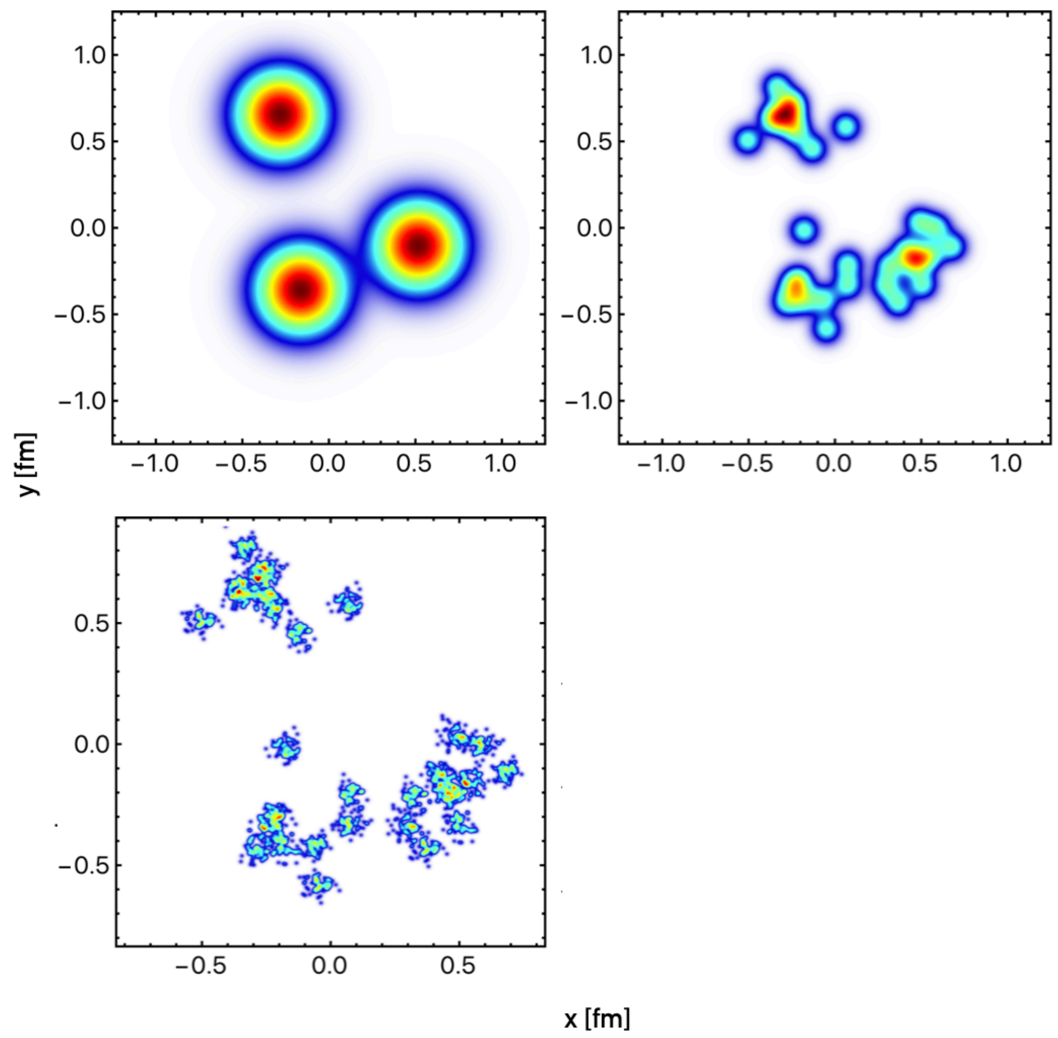
Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

Even larger $|t|$

Hotspots withing hotspots within hotspots

Model	B_{qc}	B_q	N_q	B_{hs}	N_{hs}	B_{hhs}	N_{hhs}	S_g	σ
bNonSat further refined hotspot	3.2	1.15	3	0.05	10	0.0006	65	–	0.4
bSat further refined hotspot	3.3	1.08	3	0.09	10	0.0006	60	0.4	0.5





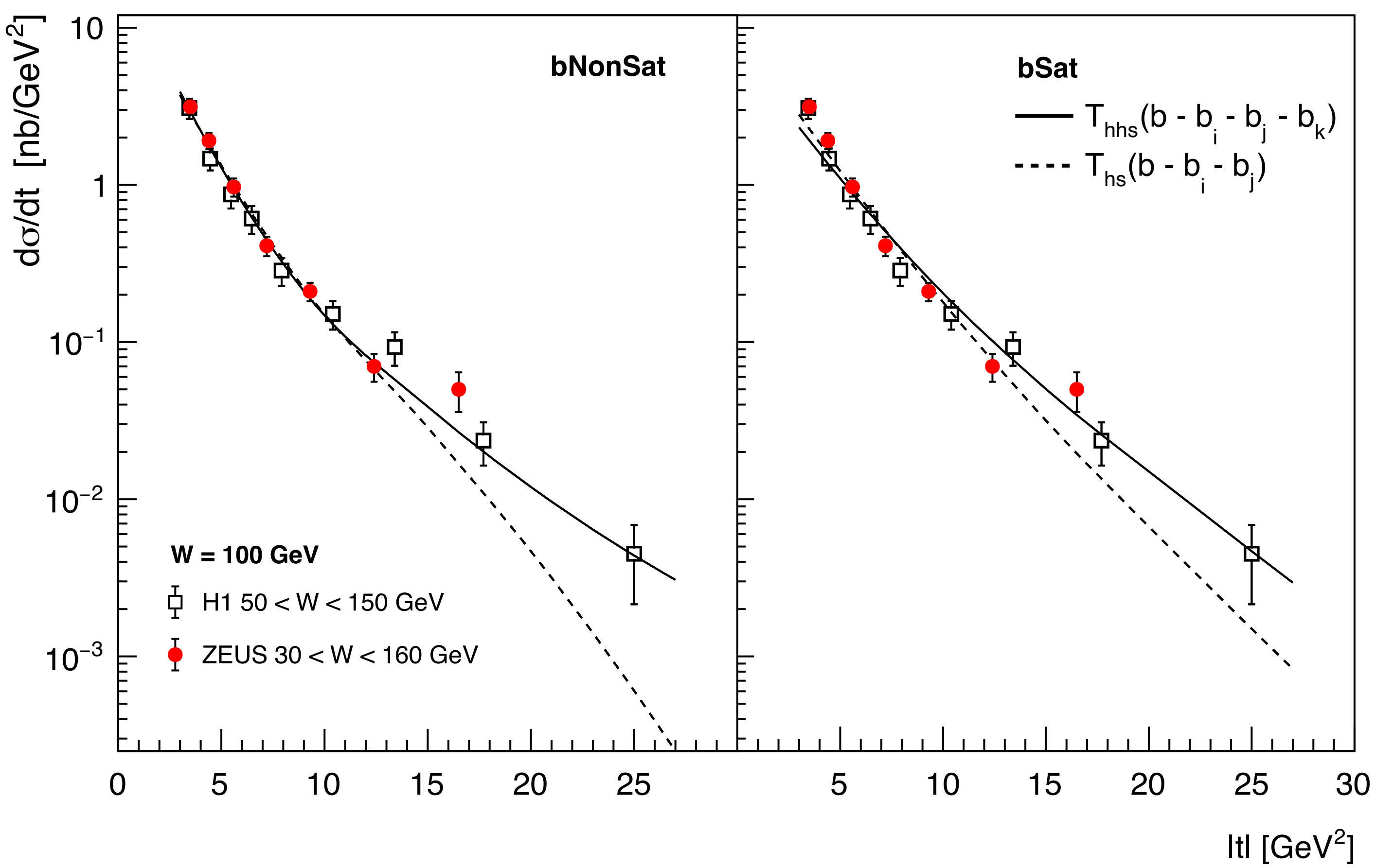
$$T_P(\vec{b}) = \frac{1}{2\pi N_q N_{hs} N_{hhs} B_{hhs}} \sum_i^{N_q} \sum_j^{N_{hs}} \sum_k^{N_{hhs}} e^{-\frac{(\vec{b} - \vec{b}_i - \vec{b}_j - \vec{b}_k)^2}{2B_{hhs}}}$$

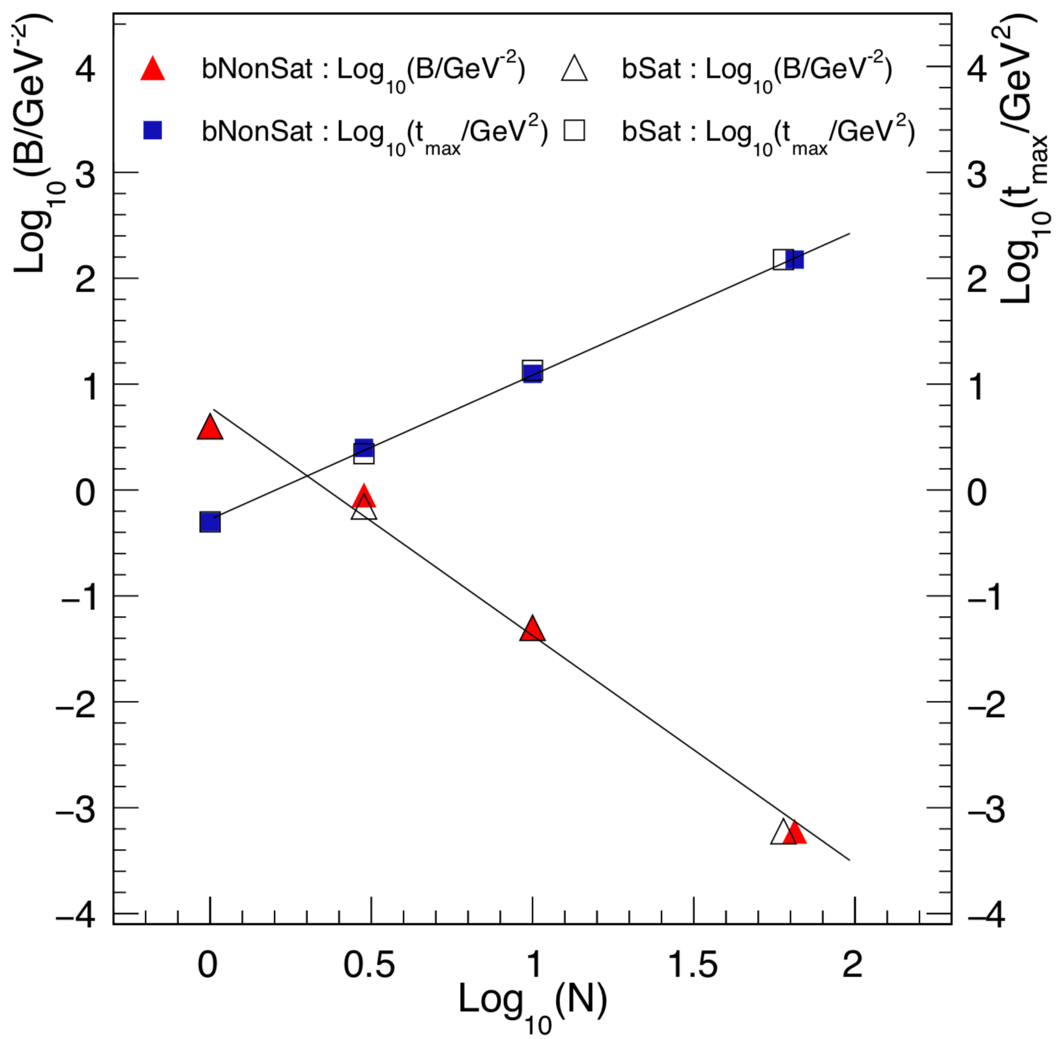
Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

Even larger $|t|$

Hotspots withing hotspots within hotspots

Model	B_{qc}	B_q	N_q	B_{hs}	N_{hs}	B_{hhs}	N_{hhs}	S_g	σ
bNonSat further refined hotspot	3.2	1.15	3	0.05	10	0.0006	65	–	0.4
bSat further refined hotspot	3.3	1.08	3	0.09	10	0.0006	60	0.4	0.5

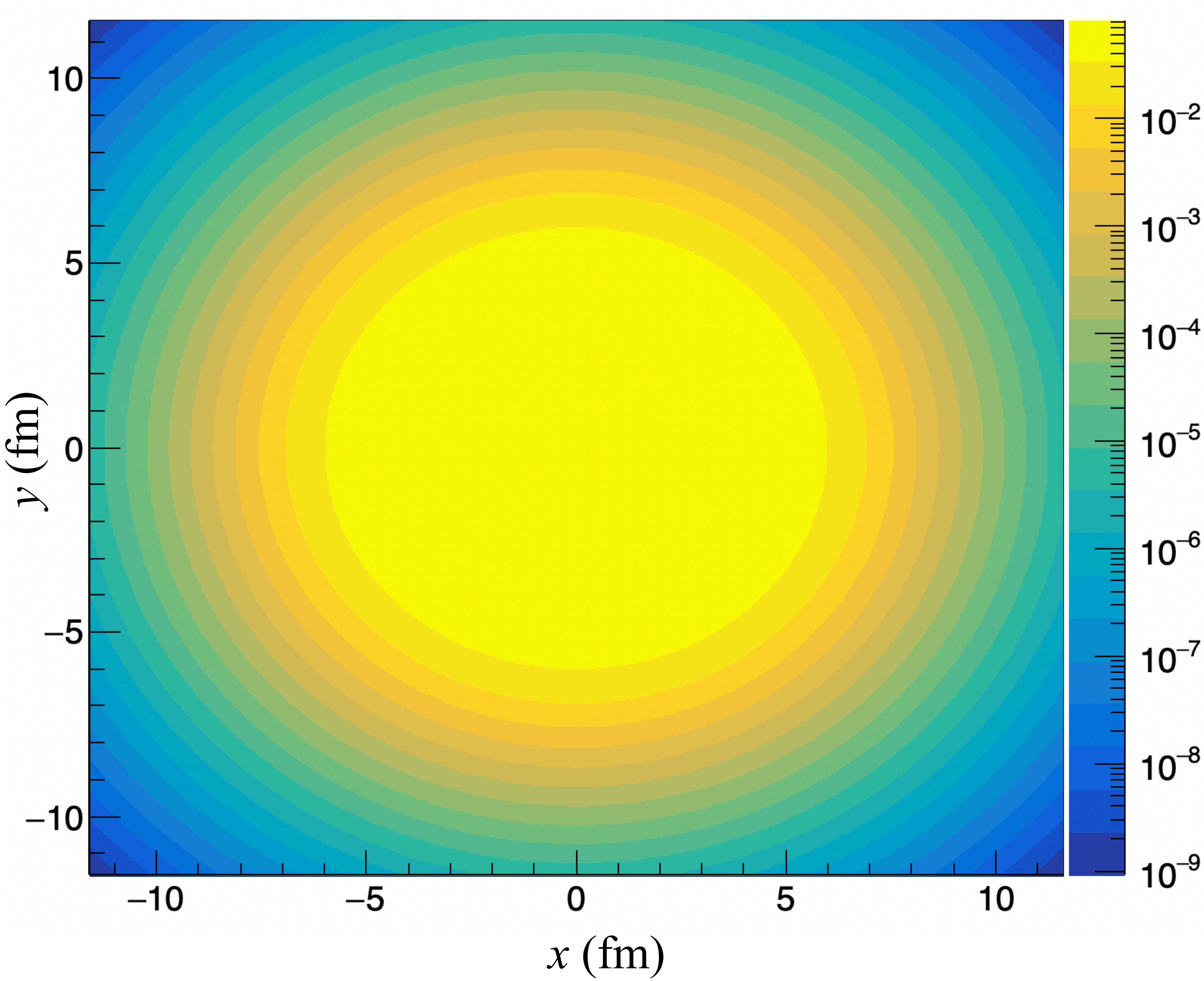




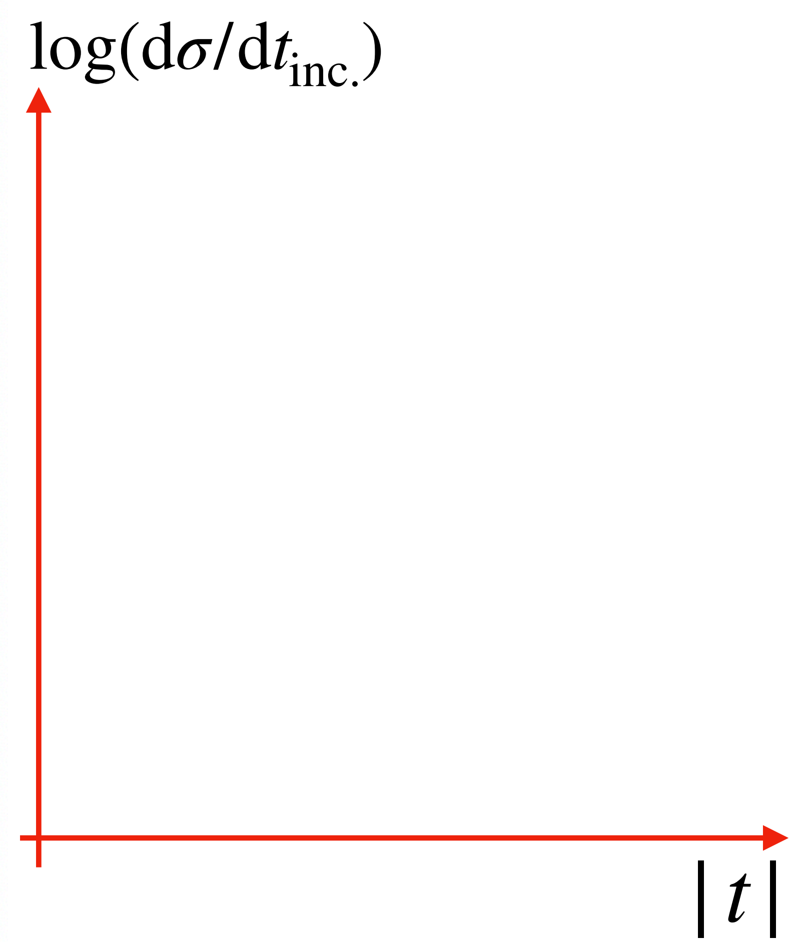
$$T_P(\vec{b}) = \frac{1}{2\pi N_q N_{hs} N_{hhs} B_{hhs}} \sum_i^{N_q} \sum_j^{N_{hs}} \sum_k^{N_{hhs}} e^{-\frac{(\vec{b}-\vec{b}_i-\vec{b}_j-\vec{b}_k)^2}{2B_{hhs}}}$$

Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

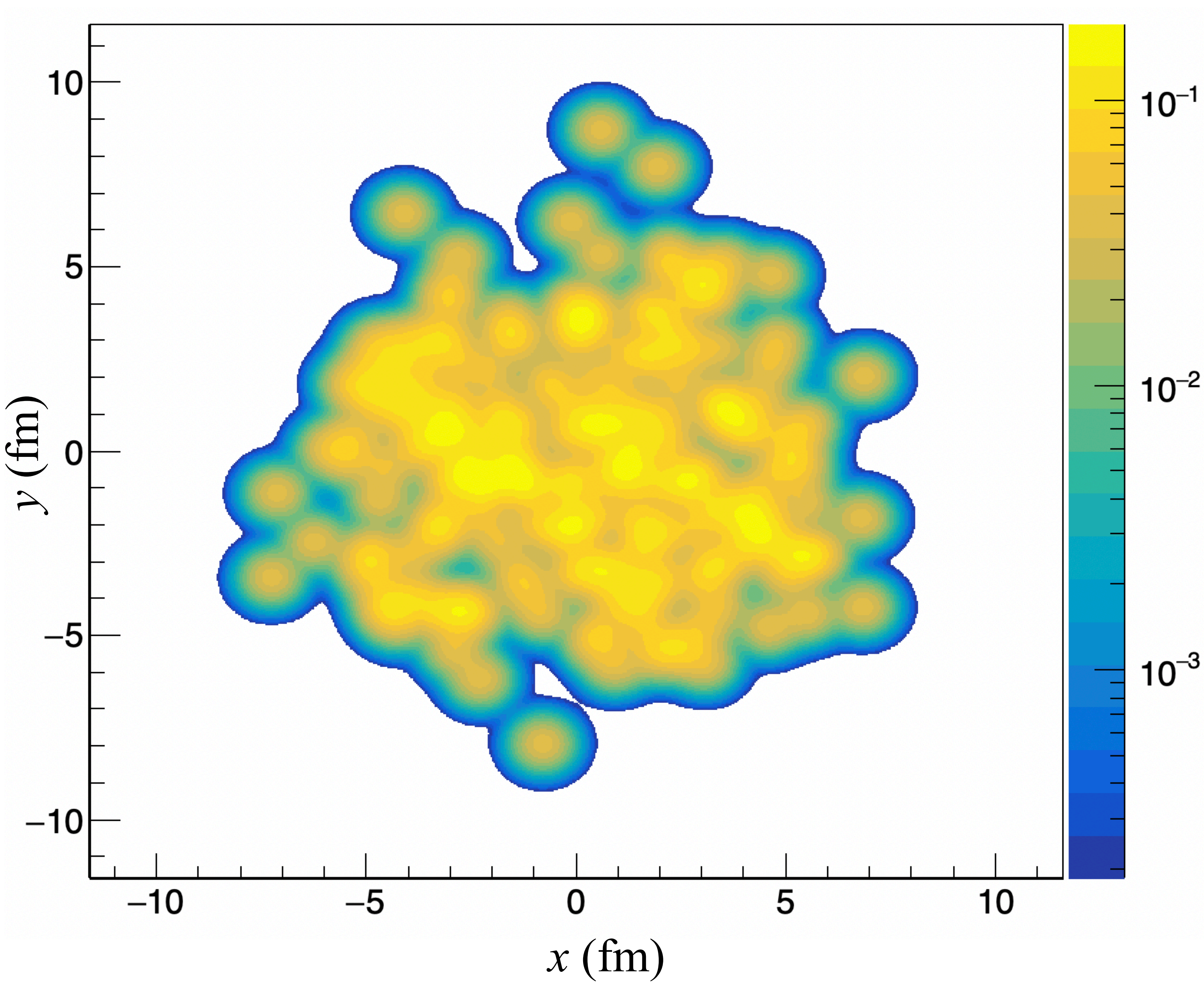
Into the heavy nucleus



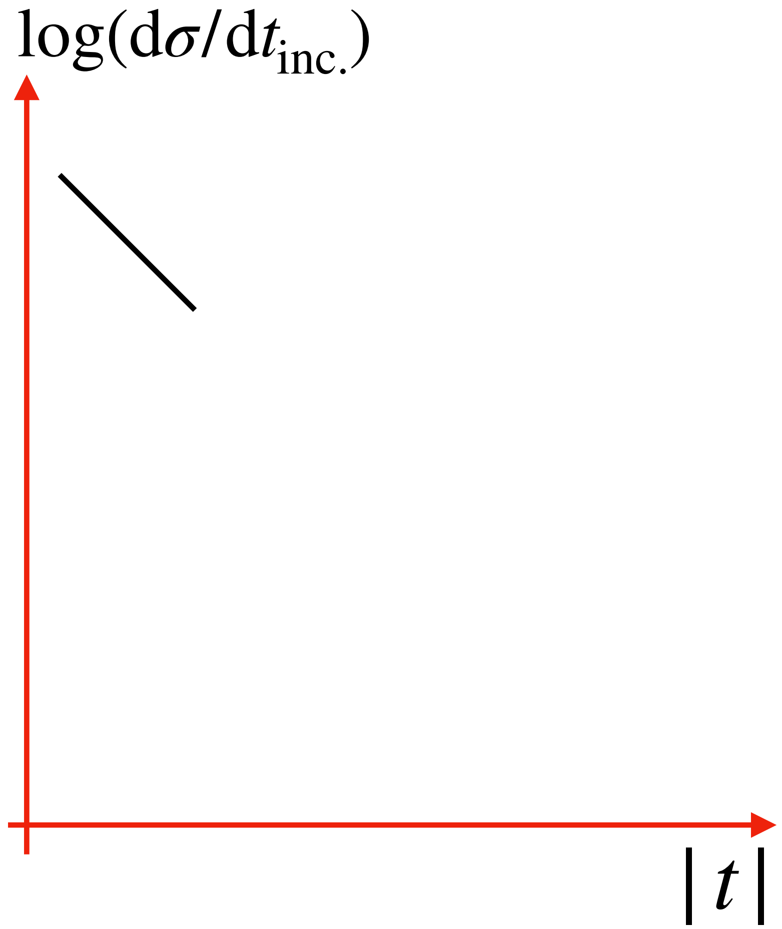
$|t| = 0$



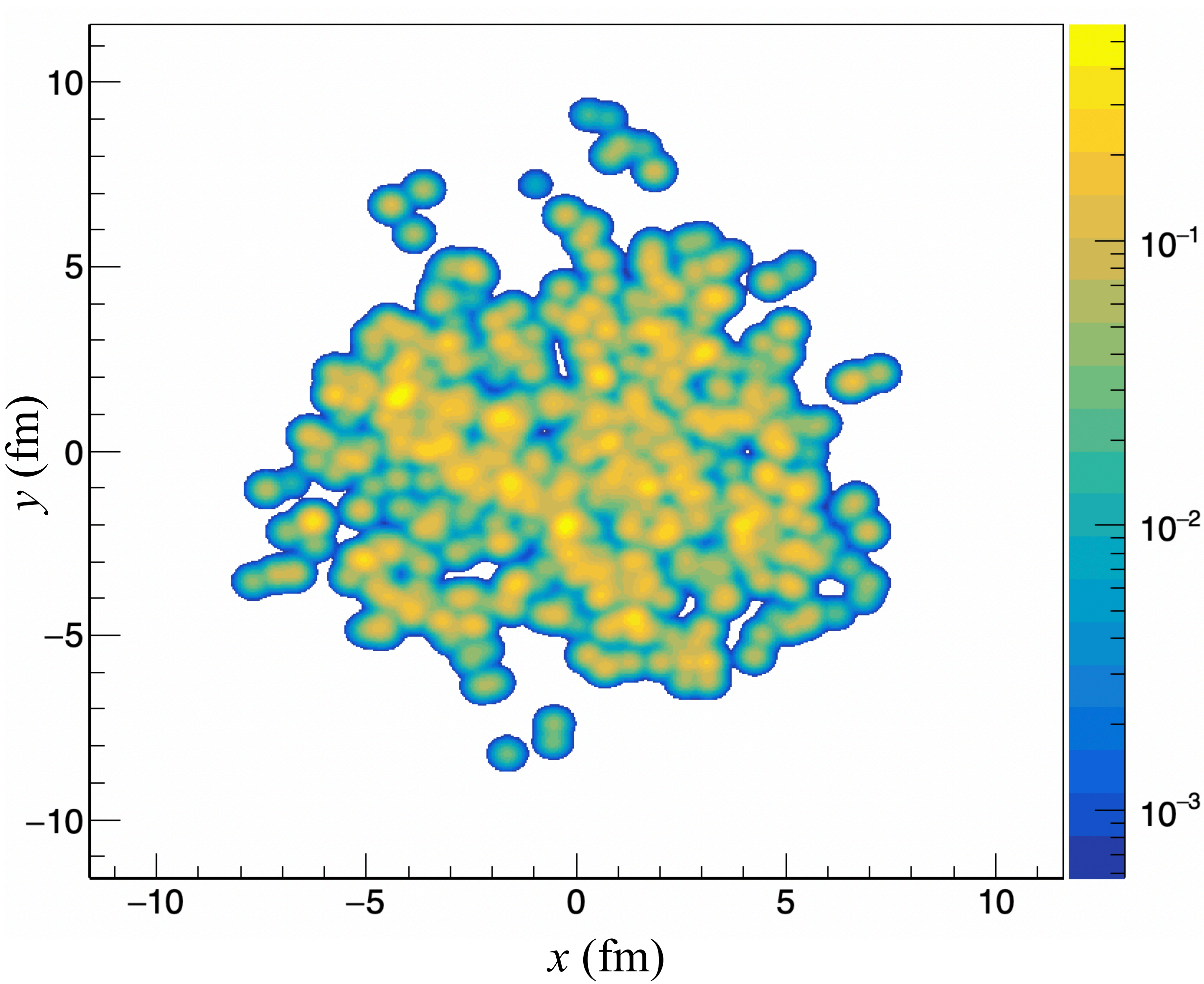
Into the heavy nucleus



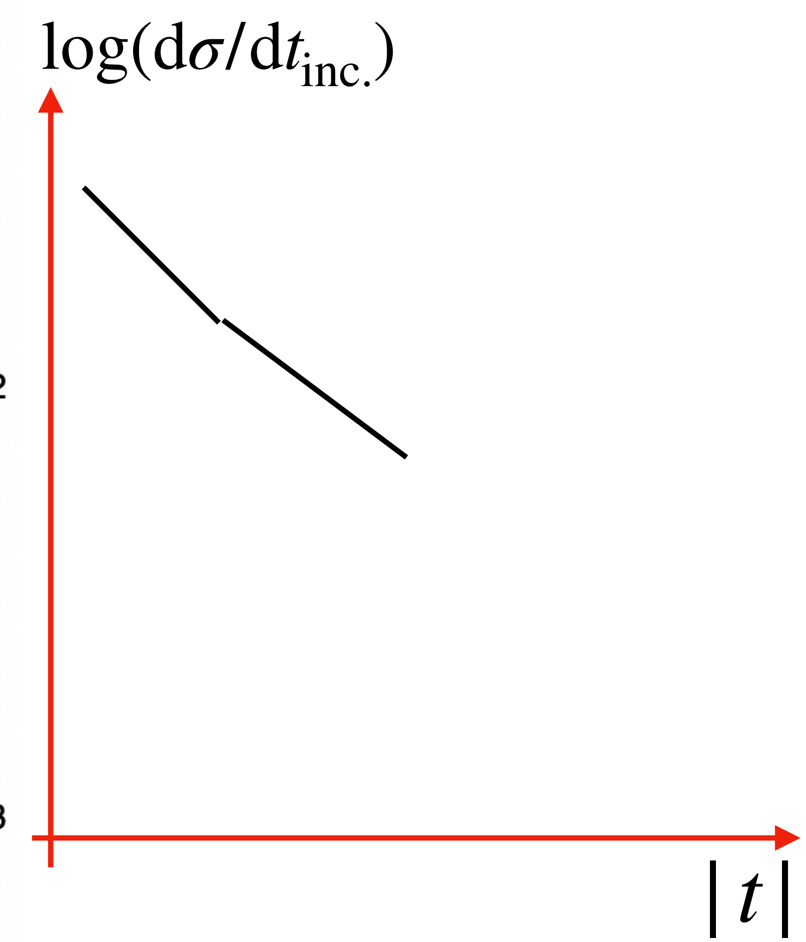
$|t| \lesssim 0.2\ \mathrm{GeV}^2$



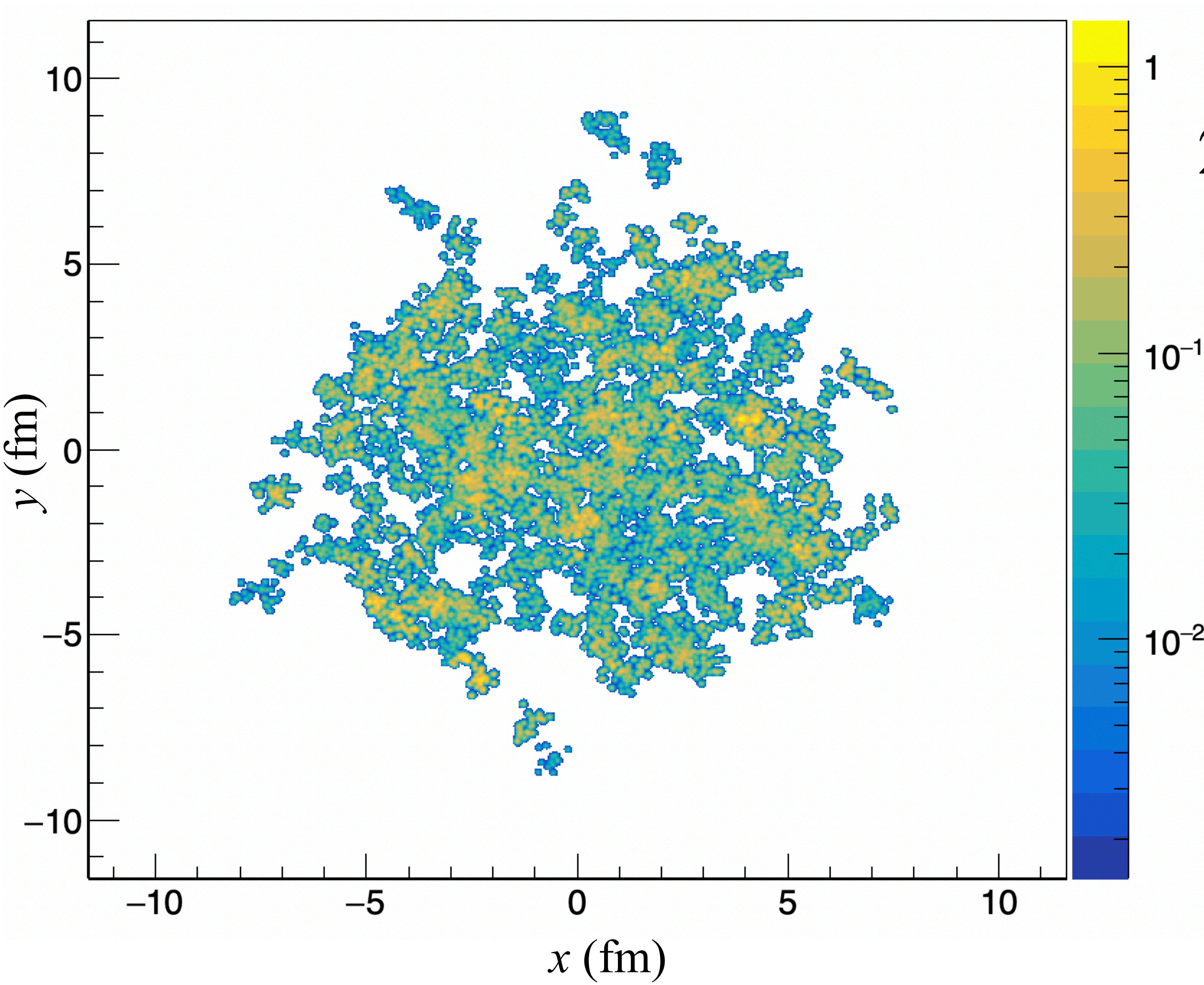
Into the heavy nucleus



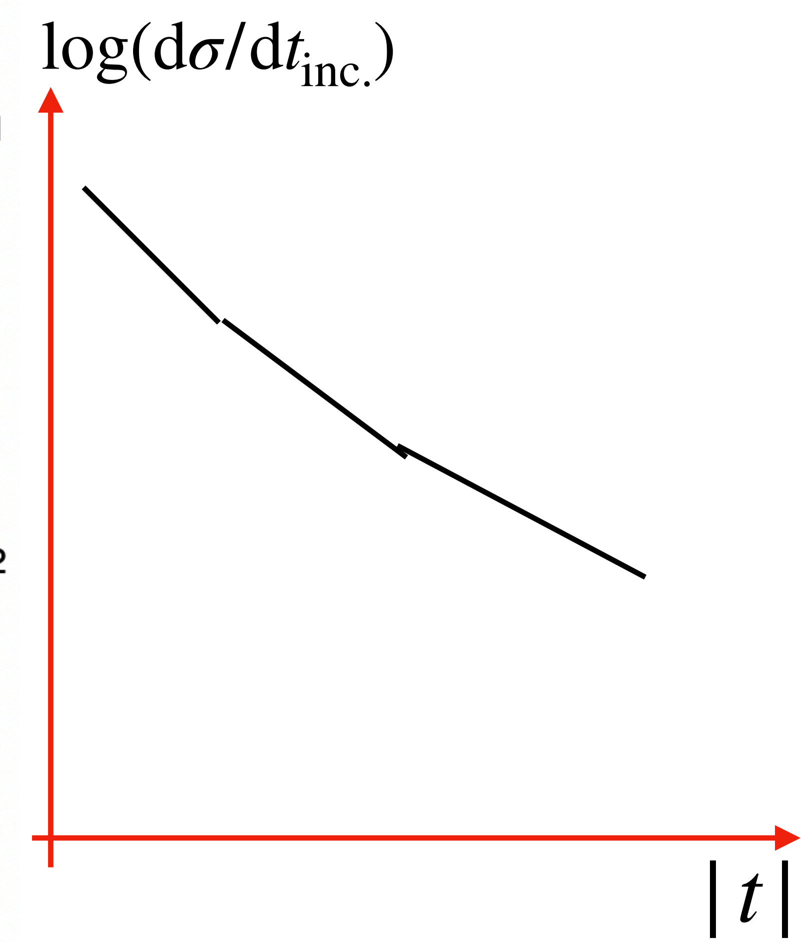
$0.2 \lesssim |t| \lesssim 2\ \mathrm{GeV}^2$



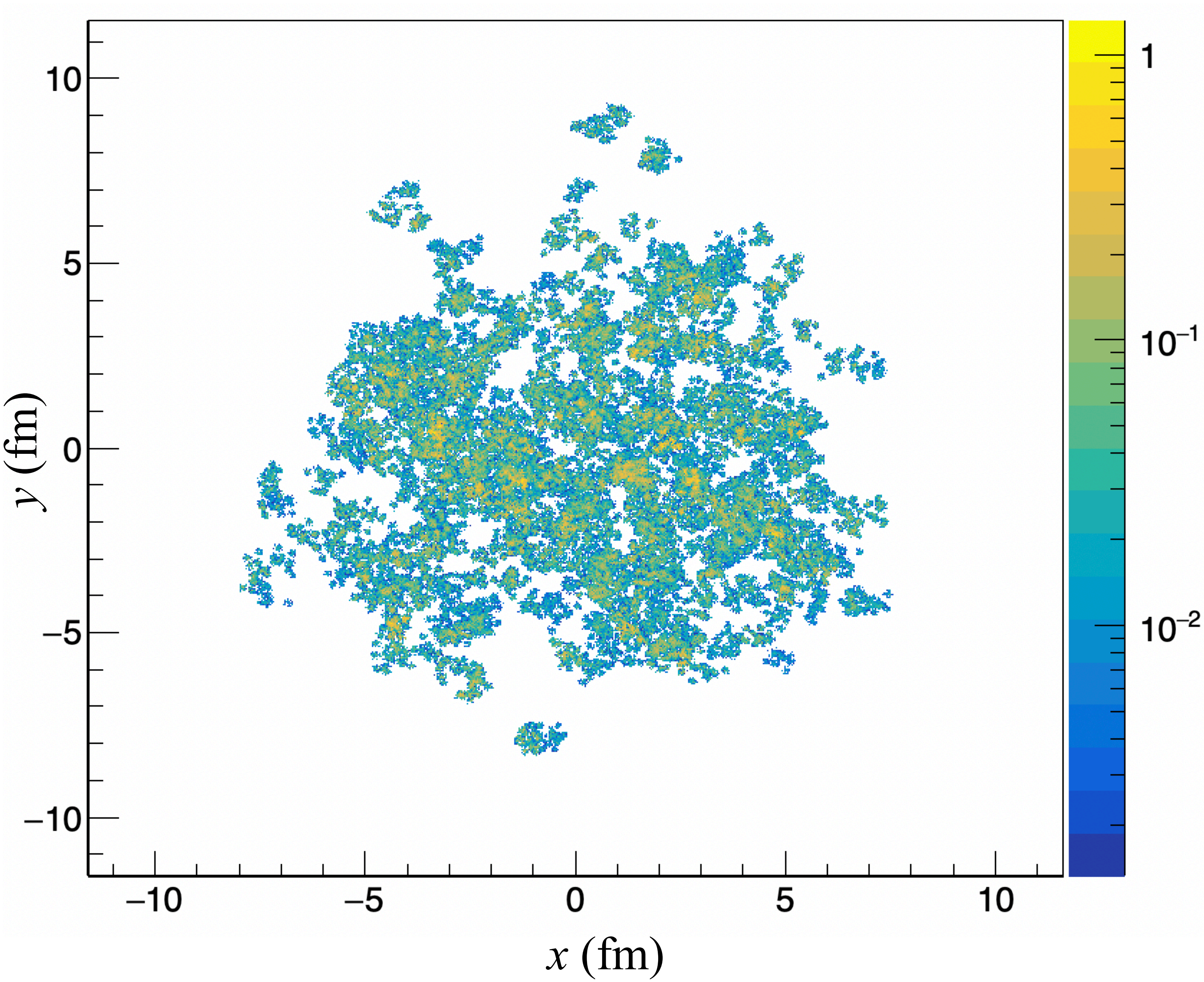
Into the heavy nucleus



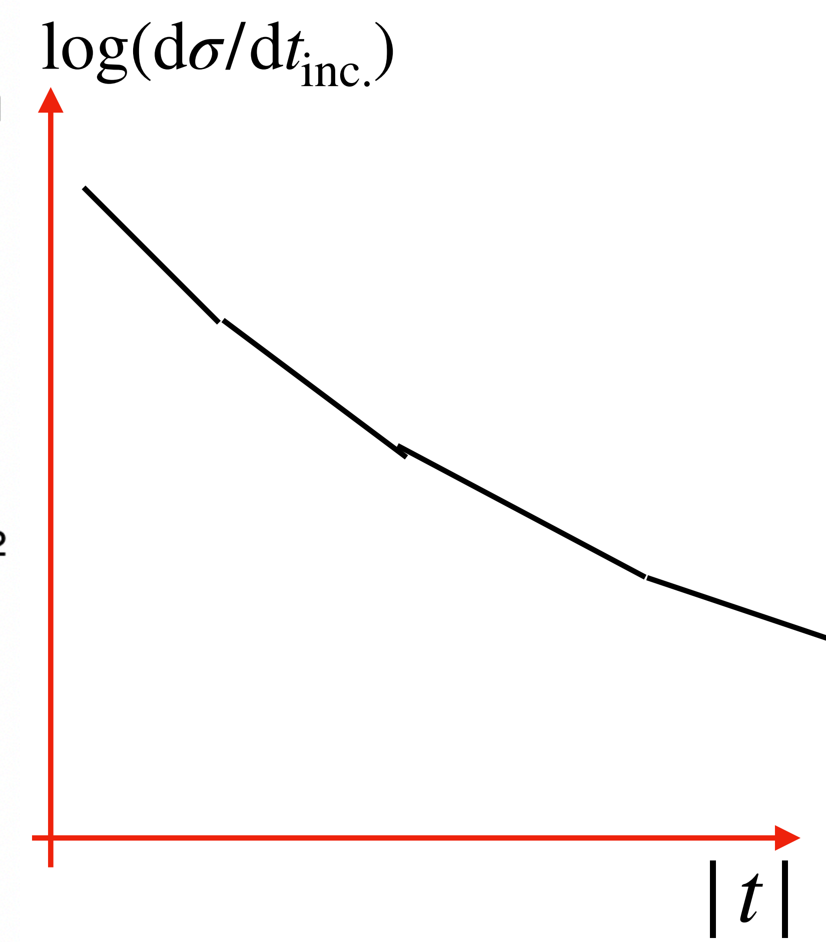
$$2 \lesssim |t| \lesssim 12 \text{ GeV}^2$$



Into the heavy nucleus



$$12 \lesssim |t| \ \mathrm{GeV}^2$$



Insights

The transverse gluon structure:

1. Appears to become dilute at large $|t|$

2. Become fractal (scaling behaviour)

This suggests that we can describe the hotspot t-spectrum with a linear, scale-independent (in $\log|t|$) evolution

Gluon number fixed by longitudinal structure $xg(x)$ (no gluon splittings as in DGLAP).

Picture: Transverse part of gluon wavefunction probed with areal resolution

$$\delta b^2 \sim \frac{1}{|t|}$$

Increased resolution appears as hotspots splitting.

The simplest Model-1

We consider a "DGLAP parton shower-like" approach based on resolution, where a hotspot may split into two as the resolution increases.

Initial State at $t = t_0$:

$$T_p(\vec{b}) = \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(|\vec{b} - \vec{b}_i|)$$

$$T_q(\vec{b}) = \frac{1}{2\pi B_q} e^{-\frac{b^2}{2B_q}}$$

Inital State Parameters:

$B_{qc} = 3.1 \text{ GeV}^{-2}$

$B_q = 1.25 \text{ GeV}^{-2}$

$N_q = 3$

Probability of a hotspot created at t_0 splitting at $t > t_0$

$$\frac{dP_{\text{split}}}{dt} = \frac{\alpha}{|t|}$$

$$\frac{dP_{\text{nosplit}}}{dt} = \exp\left(-\int_{t_0}^{t} dt' \frac{dP_{\text{split}}}{dt'}\right) = \left(\frac{t_0}{t}\right)^{\alpha}$$

$$\frac{dP}{dt} = \frac{\alpha}{|t|}\left(\frac{t_0}{t}\right)^{\alpha}$$

The simplest Model-1

We consider a "DGLAP parton shower-like" approach based on resolution, where a hotspot may split into two as the resolution increases.

Initial State at $t = t_0$:

$$T_p(\vec{b}) = \frac{1}{N_q} \sum_{i=1}^{N_q} T_q(|\vec{b} - \vec{b}_i|)$$

$$T_q(\vec{b}) = \frac{1}{2\pi B_q} e^{-\frac{b^2}{2B_q}}$$

Inital State Parameters:

$B_{qc} = 3.1 \text{ GeV}^{-2}$

$B_q = 1.25 \text{ GeV}^{-2}$

$N_q = 3$

Probability of a hotspot created at t_0 splitting at $t > t_0$

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{\alpha}{|t|} \left(\frac{t_0}{t}\right)^{\alpha}$$

Two offspring hotspots i, j created at distance $d_{ij} = |\vec{b}_i - \vec{b}_j|$,

with widths $B_{i,j} = \frac{1}{|t|}$

Conditions for resolution:

Probe resolution: $d_{ij} > \frac{2}{|\vec{\Delta}|}$ Geometry: $d_{ij} > 2\sqrt{B_{i,j}}$

Generate offspring $\vec{b}_{i,j}$ from parent $T_{\text{parent}}(\vec{b}_{i,j})$.

Reject if not resolved.

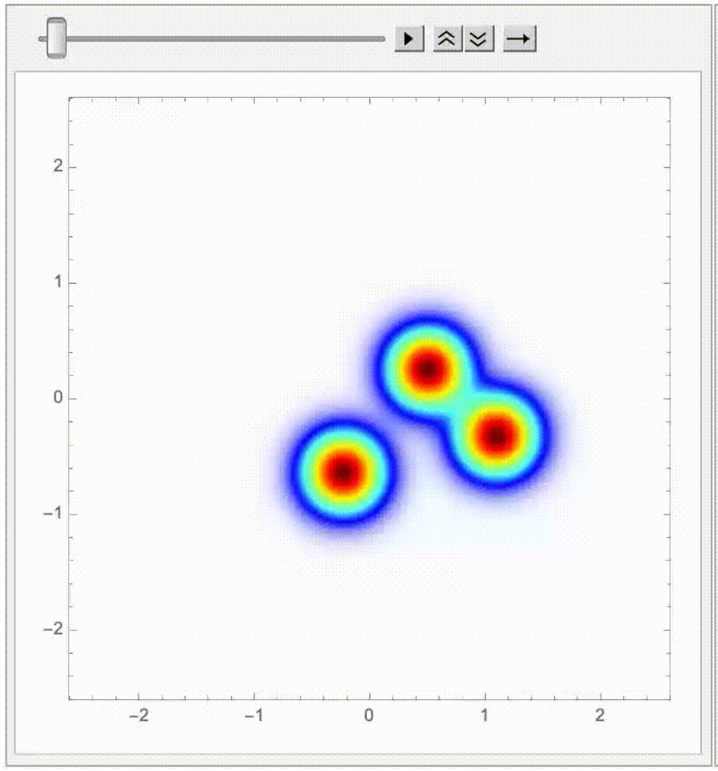
This becomes an effective hotspot repulsion.

Hotspot Evolution Model-1

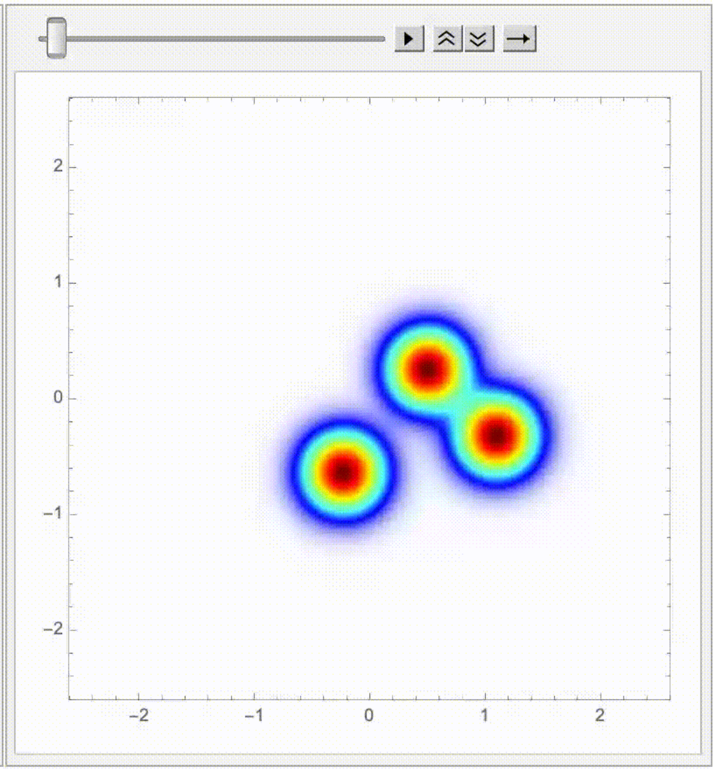
Different sources of fluctuations:
Position
Number
Width
Normalisation
Repulsion

$$\frac{dP}{dt} = \frac{\alpha}{|t|}\left(\frac{t_0}{t}\right)^{\alpha}$$

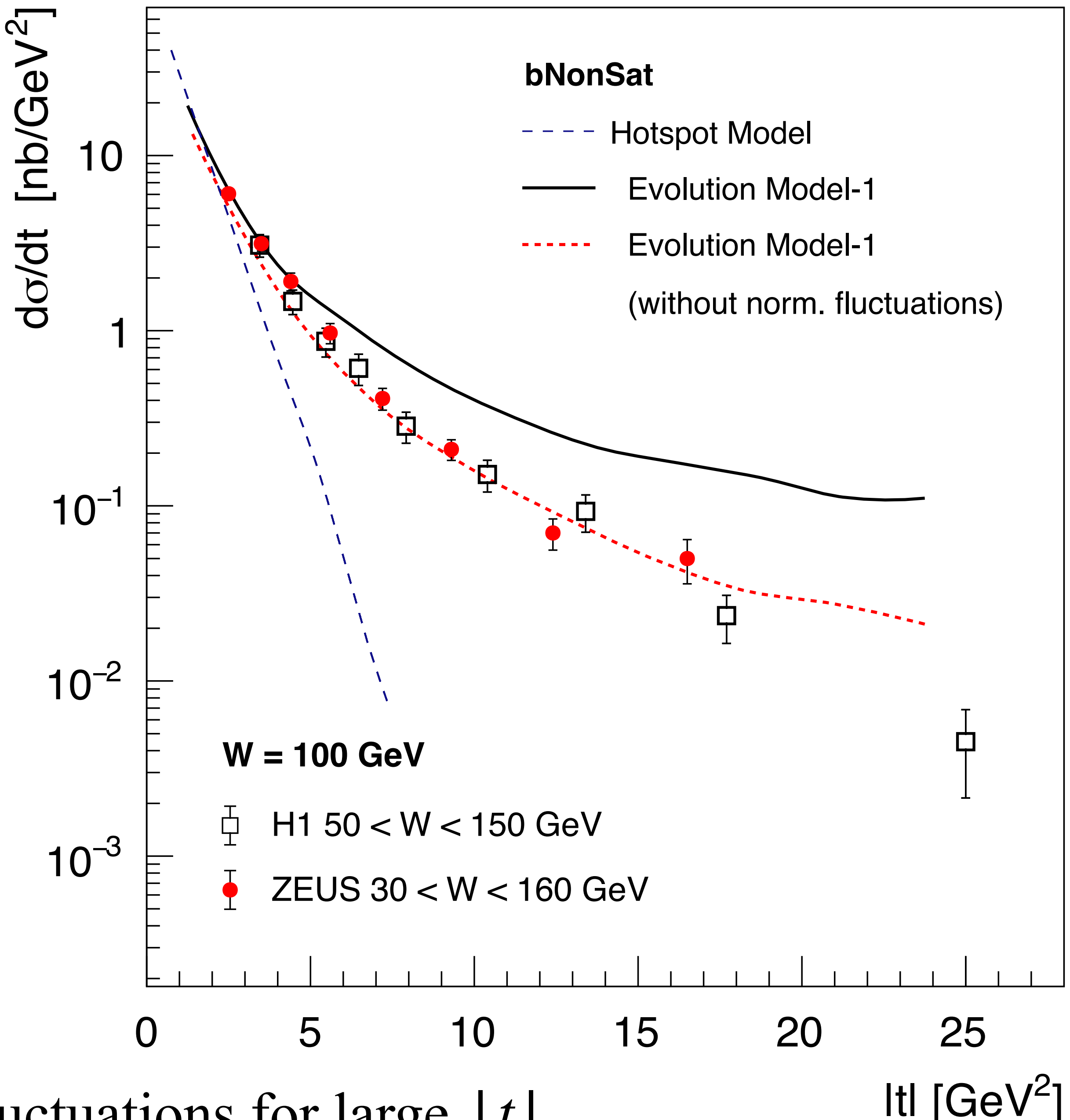
$\alpha = 2$
$t_0 = 1\ \mathrm{GeV}^2$



With Norm. Fluctations



Wihout Norm. Fluctations



Some hotspots live too long, leading to too much fluctuations for large $|t|$

The more realistic Model-2

We consider a "DGLAP parton shower-like" approach based on resolution, where a hotspot may split into two as the resolution increases.

Initial State at $t = t_0$:

$$T_p(\vec{b}) = \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(|\vec{b} - \vec{b}_i|)$$

$$T_q(\vec{b}) = \frac{1}{2\pi B_q} e^{-\frac{b^2}{2B_q}}$$

Probability of a hotspot created at t_0 splitting at $t > t_0$

$$\frac{dP_{\text{split}}}{dt} = \frac{\alpha}{|t|}\frac{t-t_0}{t}$$

$$\frac{dP}{dt} = \frac{\alpha}{|t|}\frac{t-t_0}{t}\exp\left[-\alpha\left(\frac{t_0}{t} - \ln\frac{t_0}{t} - 1\right)\right]$$

Inital State Parameters:

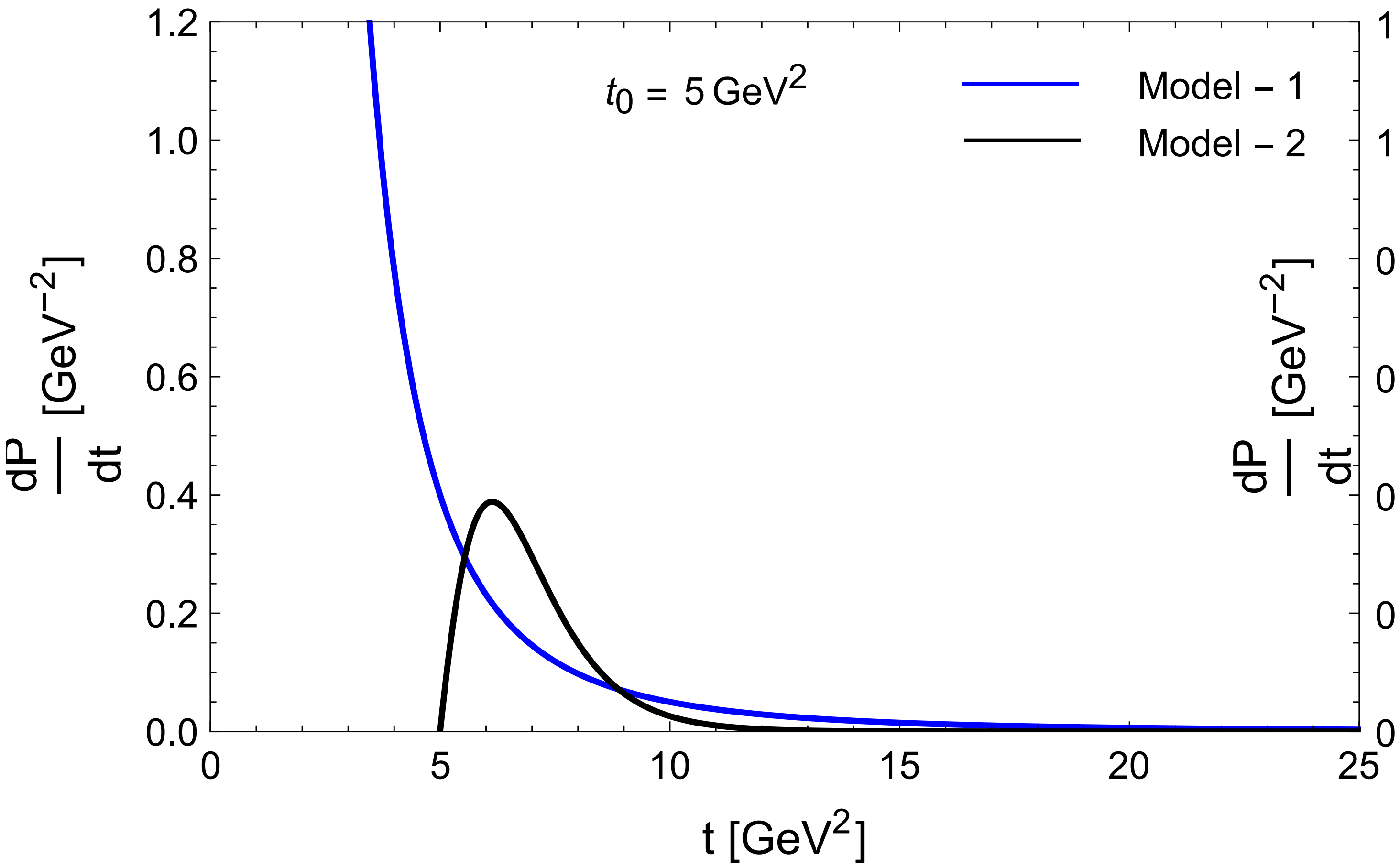
$B_{qc} = 3.1\ \text{GeV}^{-2}$

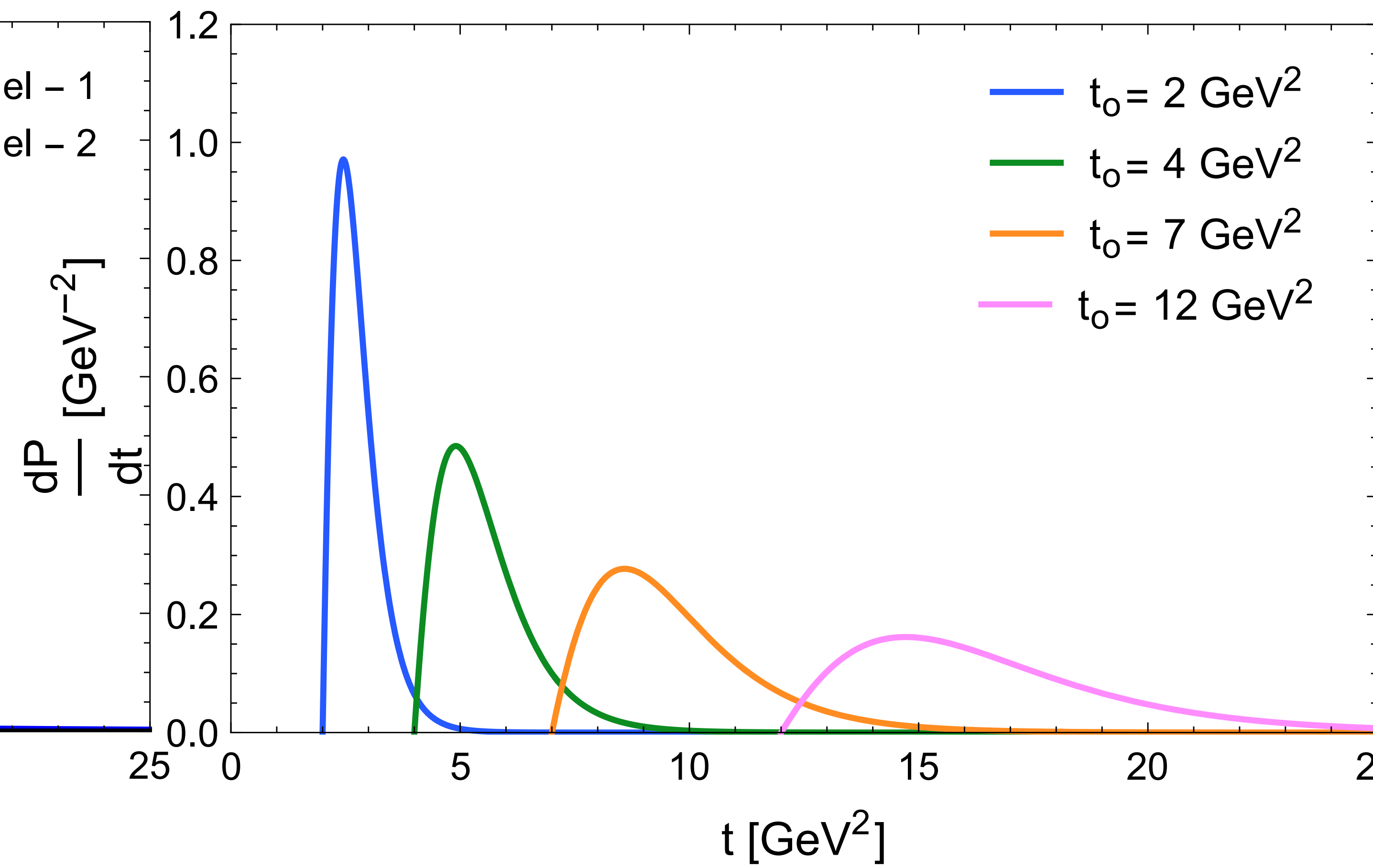
$B_q = 1.25\ \text{GeV}^{-2}$

$N_q = 3$

The more realistic Model-2

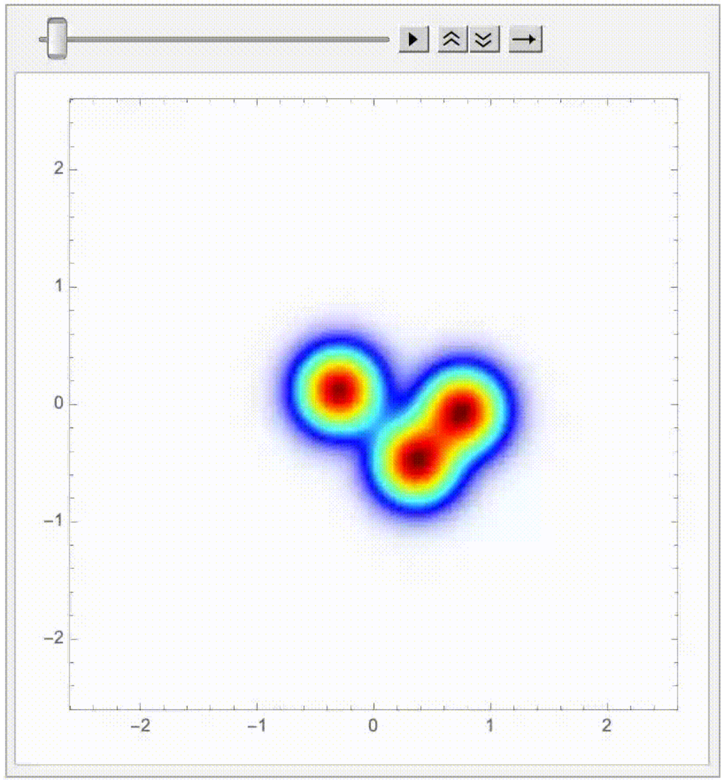
$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{\alpha}{|t|}\frac{t-t_0}{t}\exp\left[-\alpha\left(\frac{t_0}{t} - \ln\frac{t_0}{t} - 1\right)\right]$$





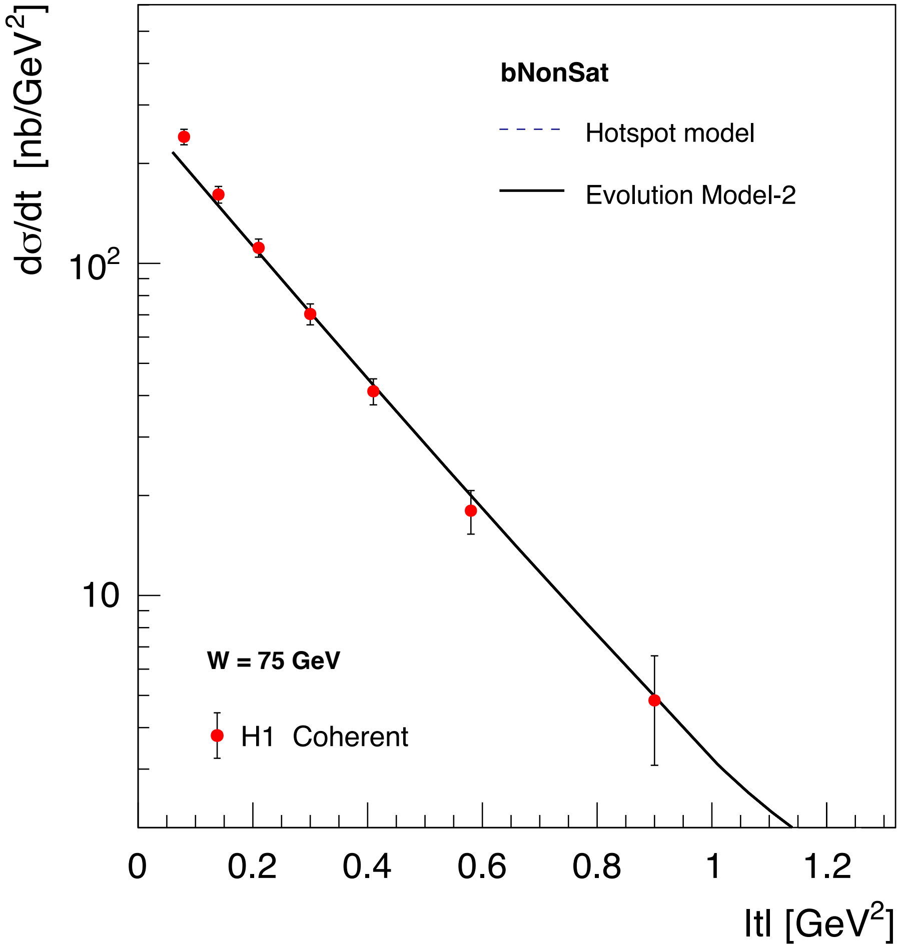
Hotspot Evolution Model-2

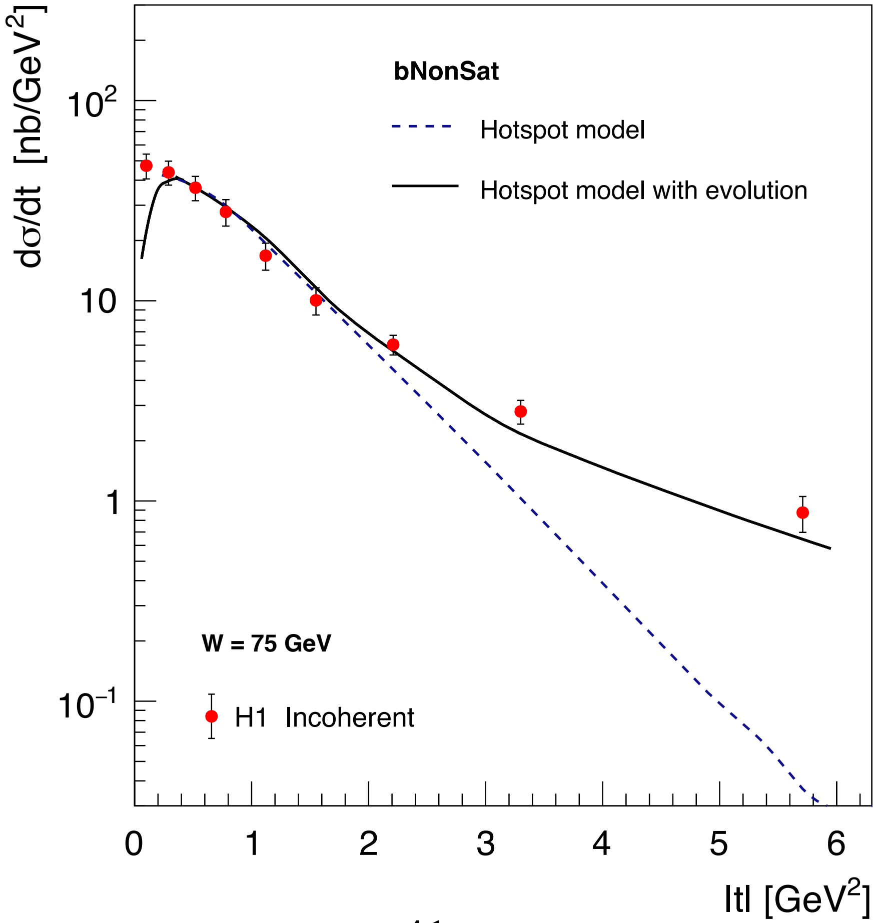
$$\frac{dP}{dt} = \frac{\alpha}{|t|}\frac{t - t_0}{t}\exp\left[-\alpha\left(\frac{t_0}{t} - \ln\frac{t_0}{t} - 1\right)\right]$$

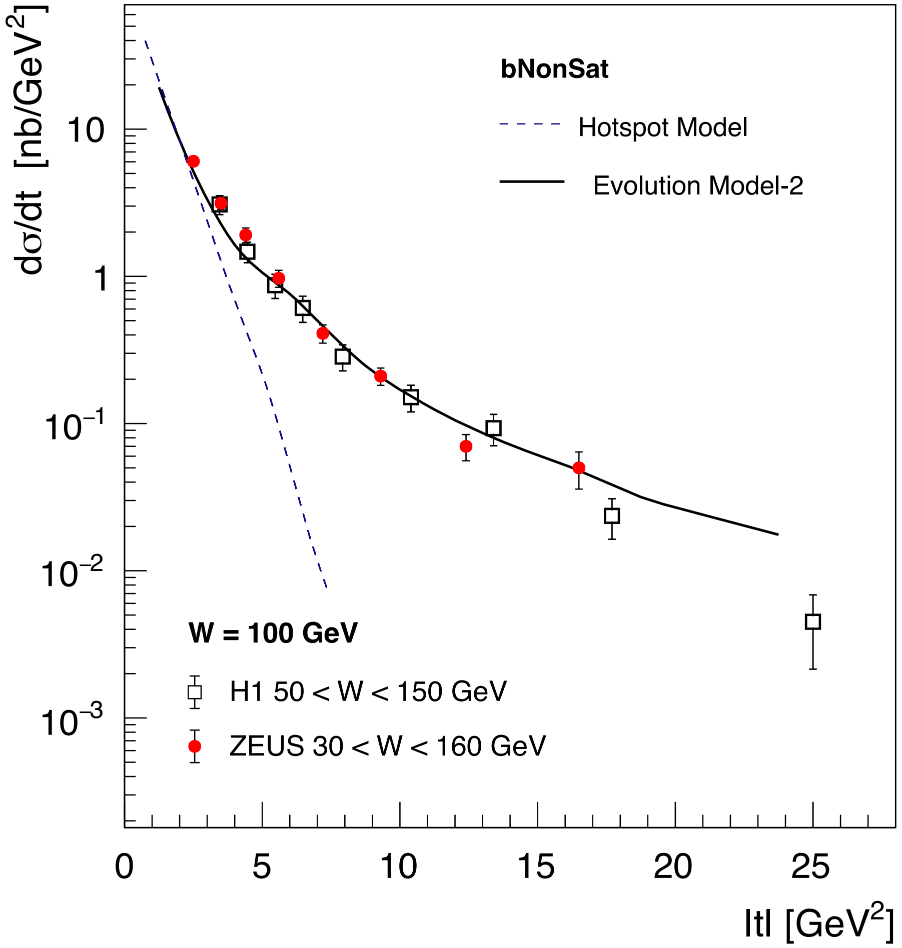


$\alpha = 18.5$

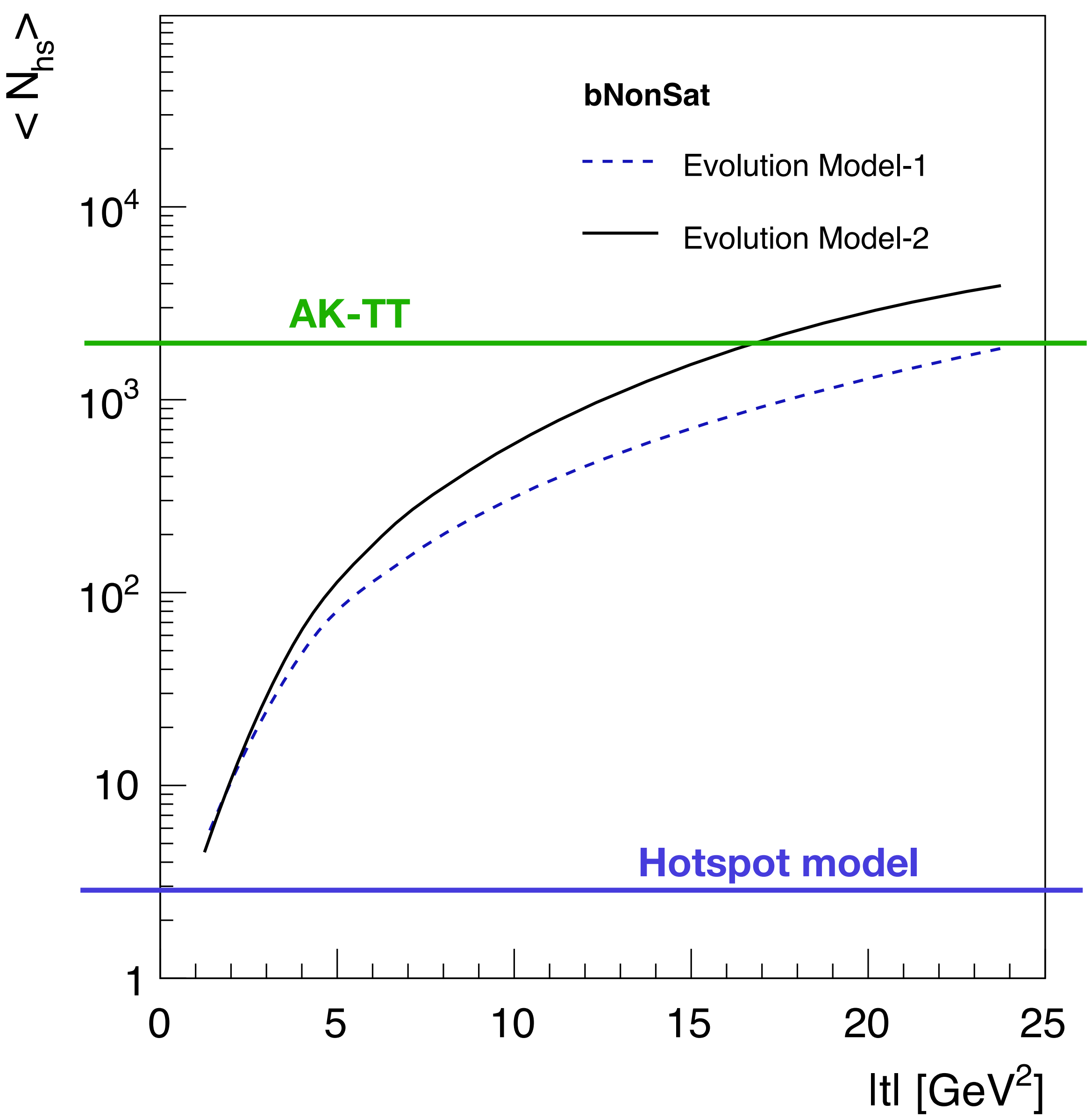
$t_0 = 1\ \mathrm{GeV}^2$

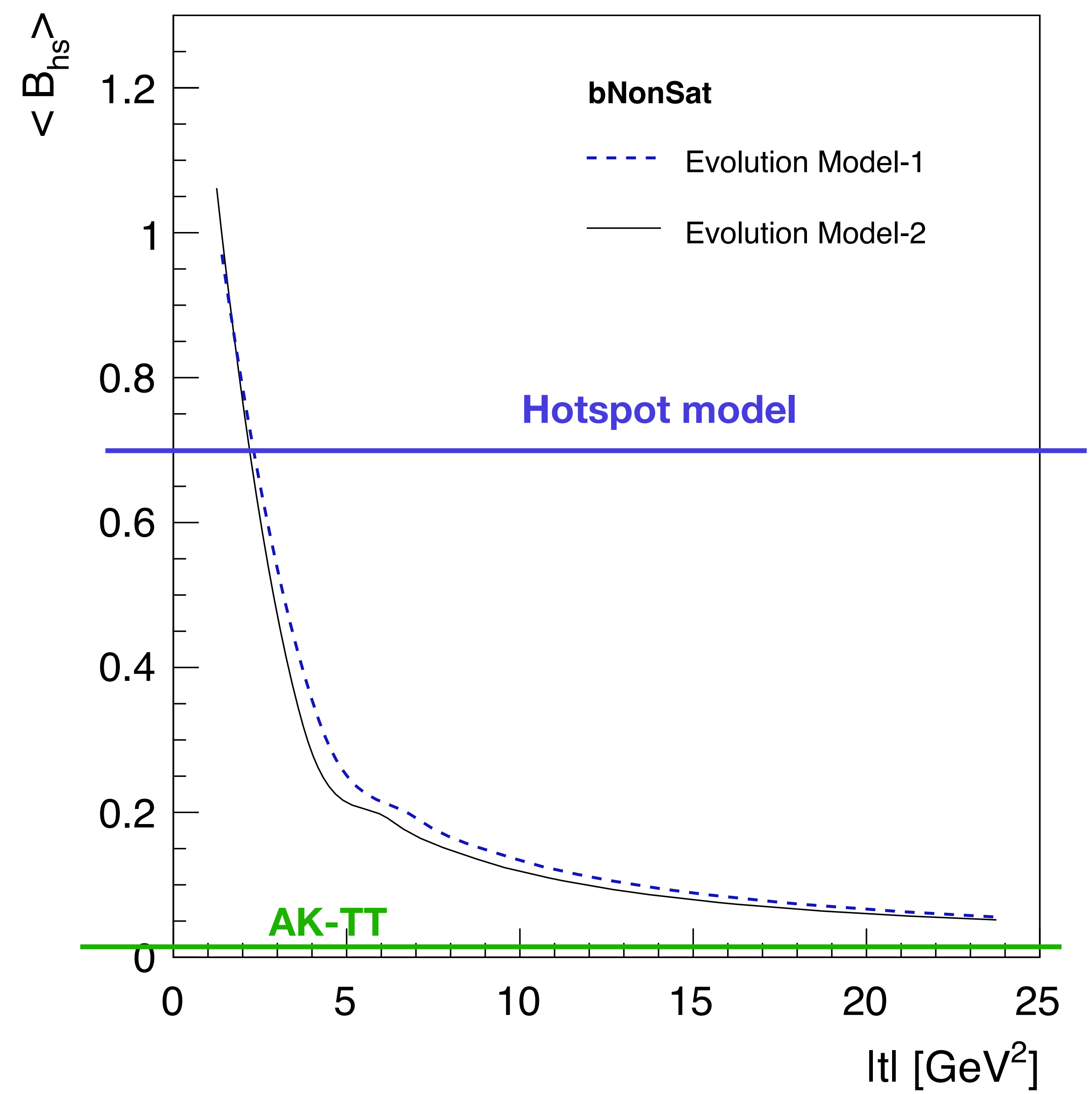






Hotspot Evolution Models

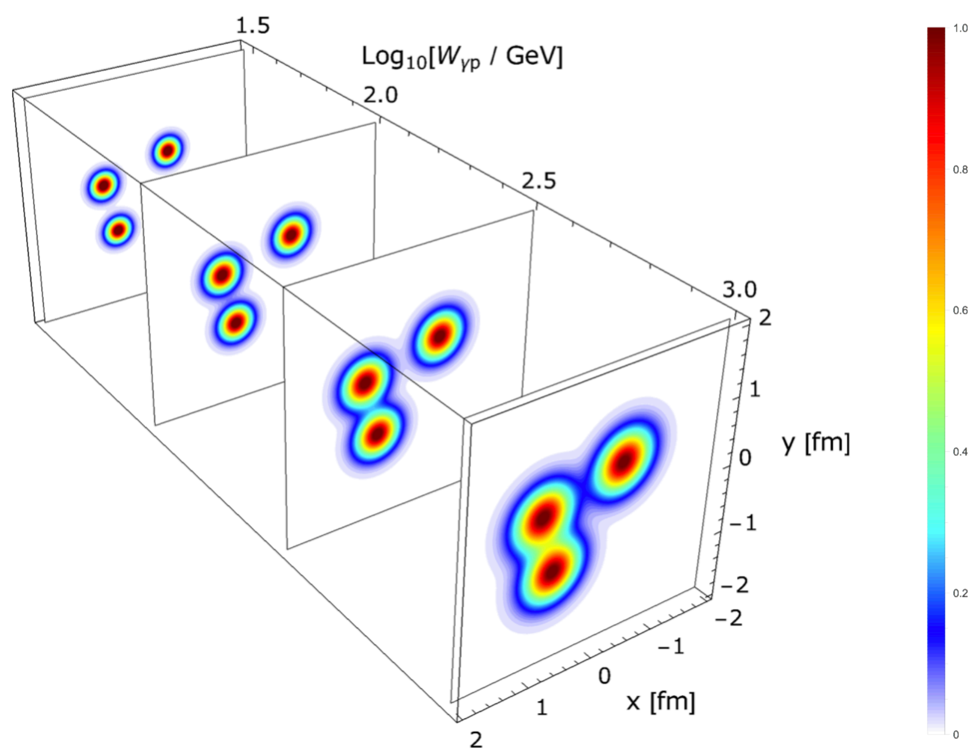




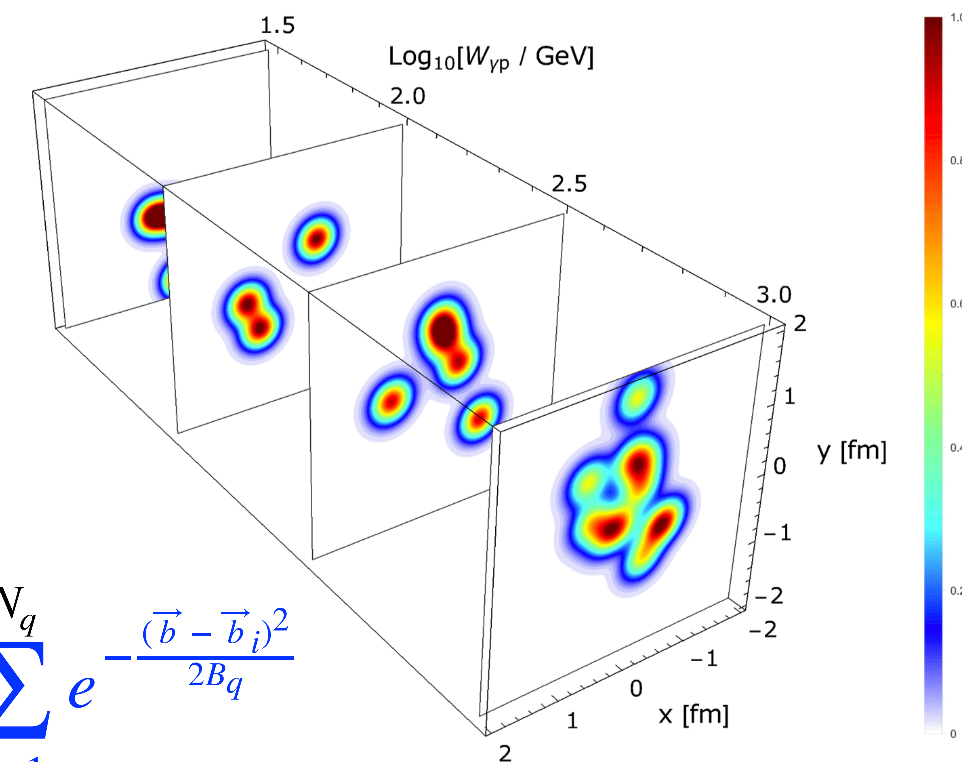
Part V:
Energy Dependence

Inital distribution energy dependence

Arjun Kumar, TT, Phys.Rev.D 105 (2022) 11, 114011 arXiv: 2202.06631



$$T_p(b) = \frac{1}{2\pi N_q B_q} \sum_{i=1}^{N_q} e^{-\frac{(\vec{b}-\vec{b}_i)^2}{2B_q}}$$



$$B_q(x_{I\!P}) = b_0 \ln^2 \frac{x_0}{x_{I\!P}}$$

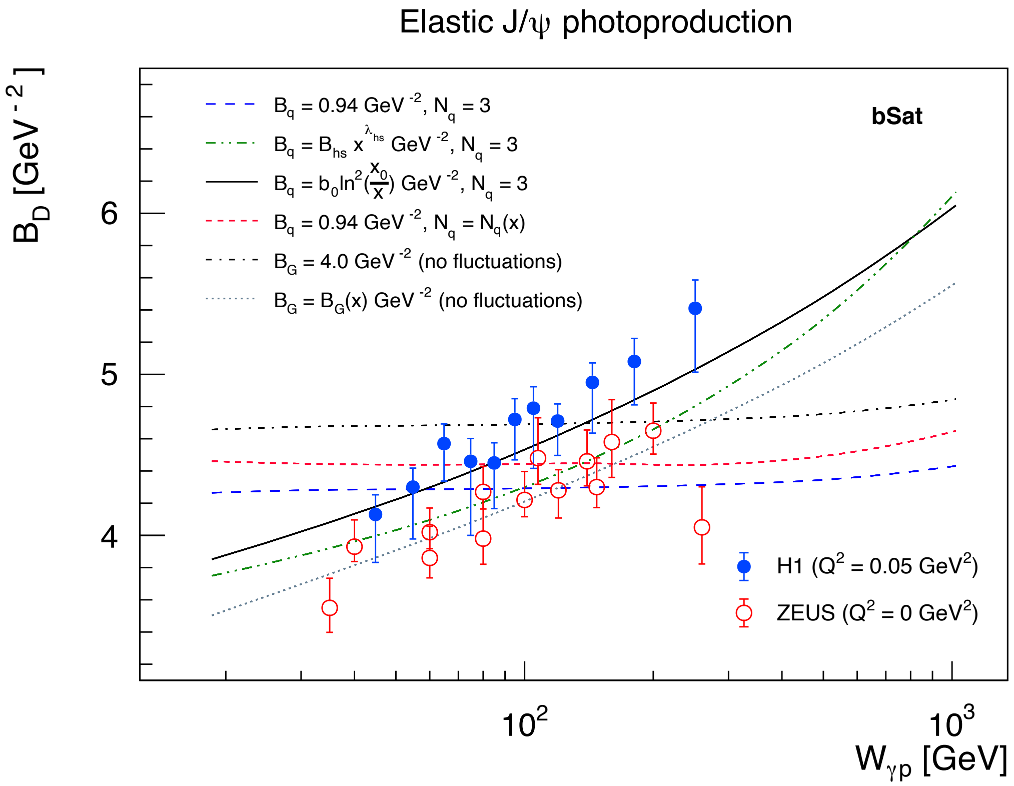
$$r_{\text{rms}} = \sqrt{2(B_{qc} + B_q(x_{I\!P}))}$$

$$N_q \to N_q(x_P) = p_0\ x_{I\!P}^{p_1}(1+p_2\sqrt{x_{I\!P}})$$

$$p_0 = 0.011,\ p_1 = -0.56,\ p_2 = 165$$

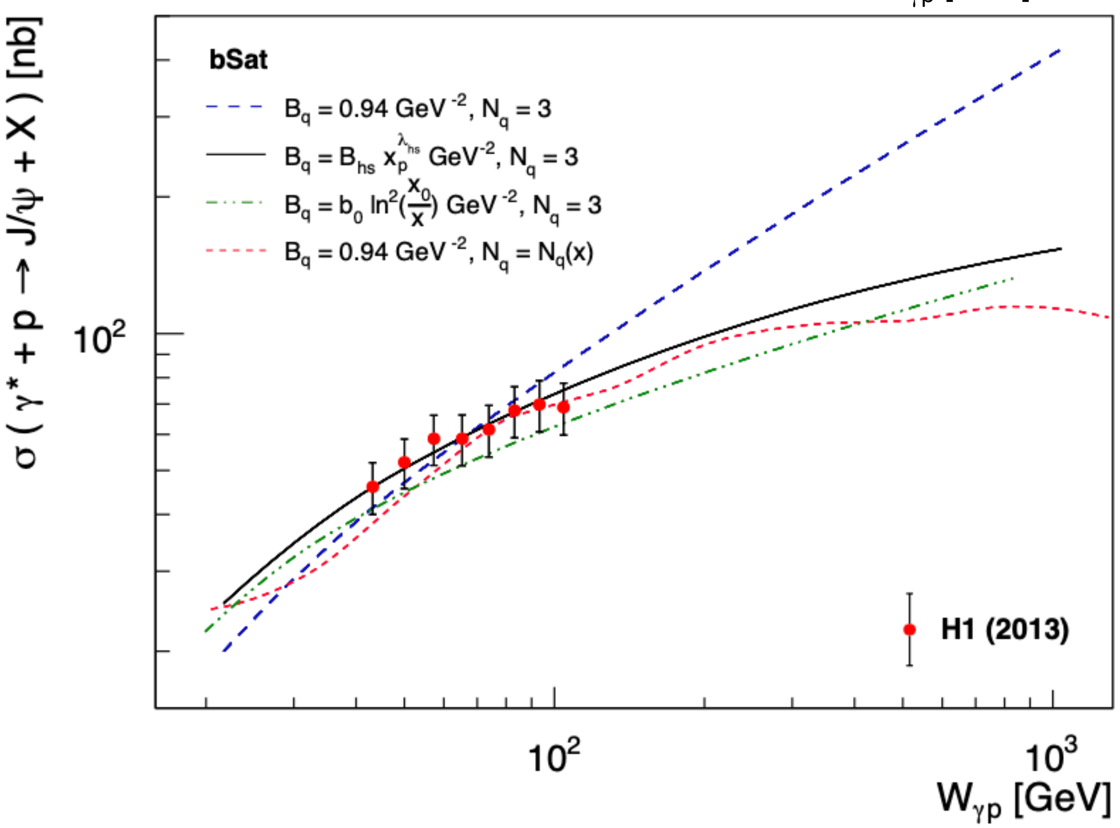
J. Cepila, J. G. Contreras, J. D. Tapia Takaki,
Energy dependence of dissociative J/ψ photoproduction as a signature of gluon saturation at the LHC,
Phys. Lett. B 766 (2017) 186–191.

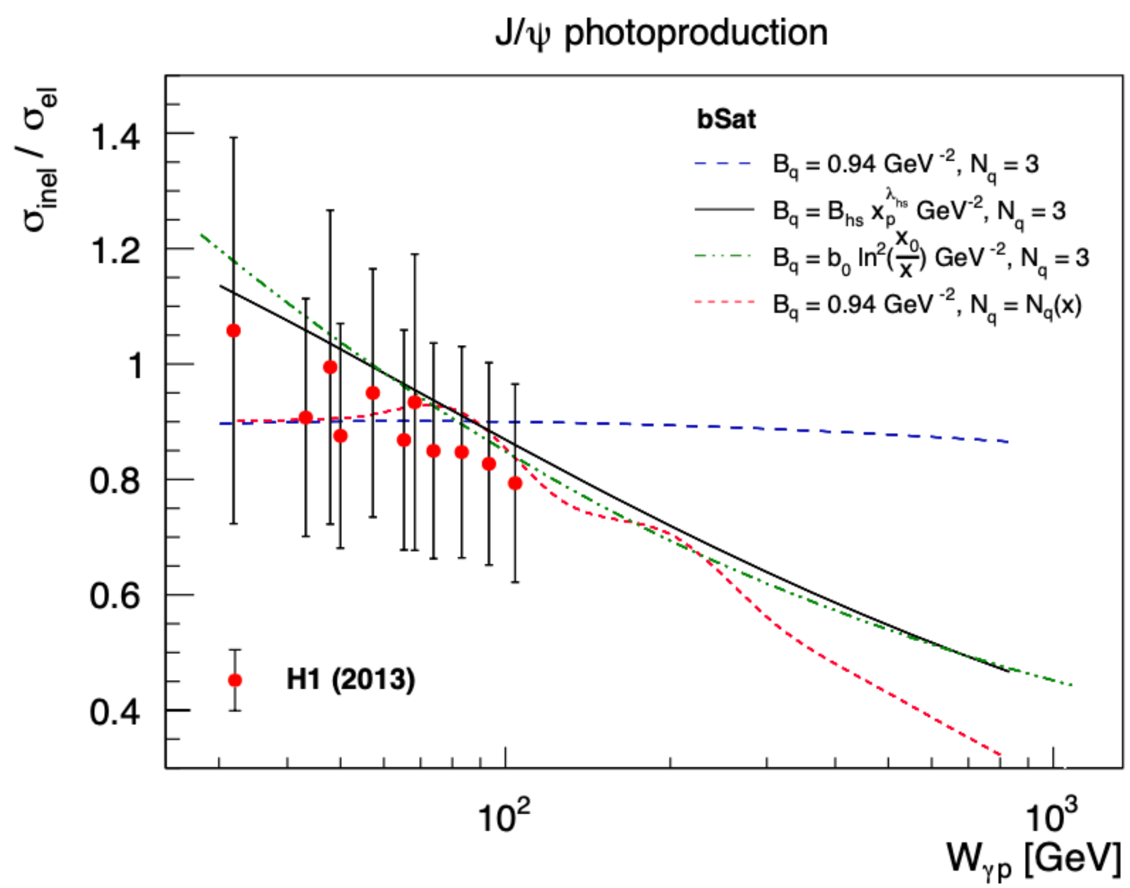
Inital distribution energy dependence



Our models indicate that the incoherent cross section will saturate at small x, while the coherent cross section will grow.

Arjun Kumar, TT, Phys.Rev.D 105 (2022) 11, 114011 arXiv: 2202.06631





For similar predictions in the IP-Glasma framework, see:
H. Mäntysaari, B. Schenke, Phys.Rev.D 98 (2018) 3, 034013; B. Schenke, Rept. Prog. Phys. 84 (2021) 8, 082301

Conclusions and Outlook

The HERA data provides much information on the small-x gluon initial state in nucleons.

To get a full handle of the intial state, we would need measured t-spectra at a range of W and Q^2

We would also want direct measurements of the *Nuclear* initial state

Two main avenues for this:

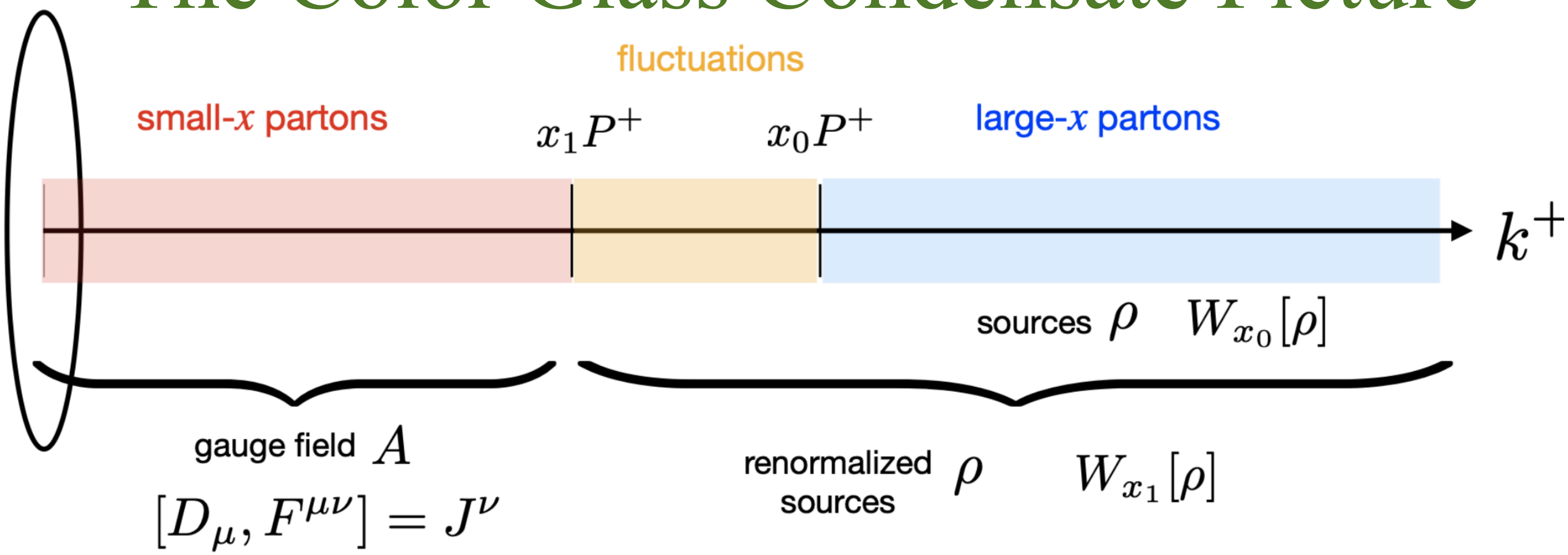
1. UPC at LHC and RHIC (only $Q^2 = 0$)
This programme has gained a lot of attention lately from all experiments which complement each other beutifully

2. The Electron-Ion collider starts taking data in 2030. High-luminosity $(10^{33} - 10^{34})/\mathrm{cm}^2\mathrm{s}$
(see plenary talk by A. Deshpande)
All Q^2, smaller energy

LHC and EIC will complement each other

Back Up

The Color Glass Condensate Picture



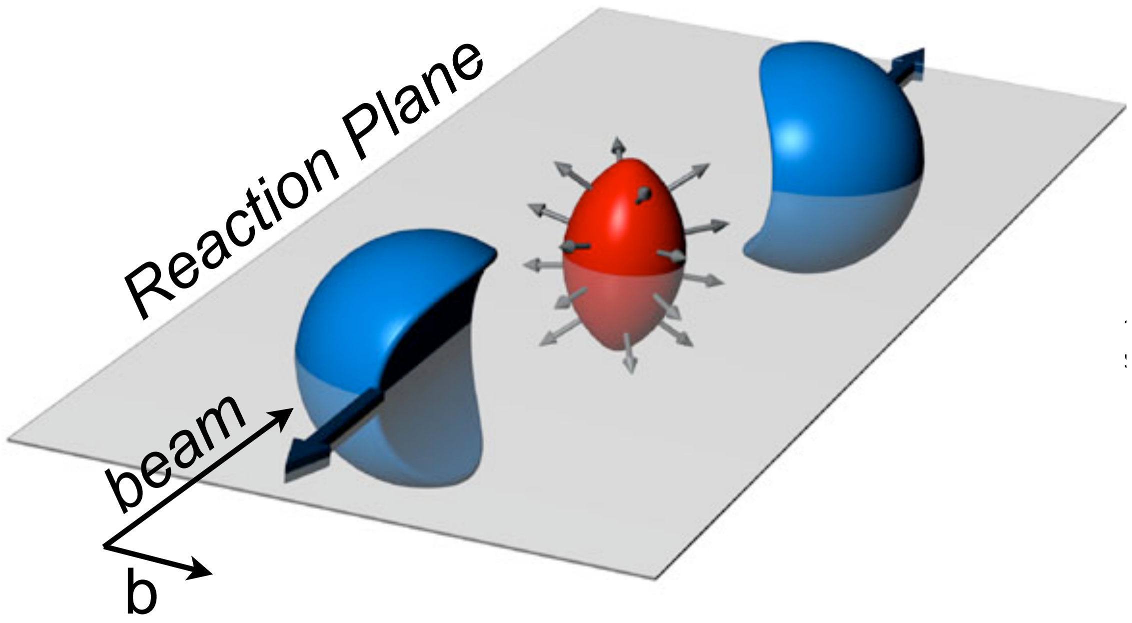
Supplement with JIMWLK evolution $\frac{dW_x[\rho]}{d\ln(1/x)} = -\mathscr{H}_{\mathrm{JIMWLK}} W_x[\rho]$

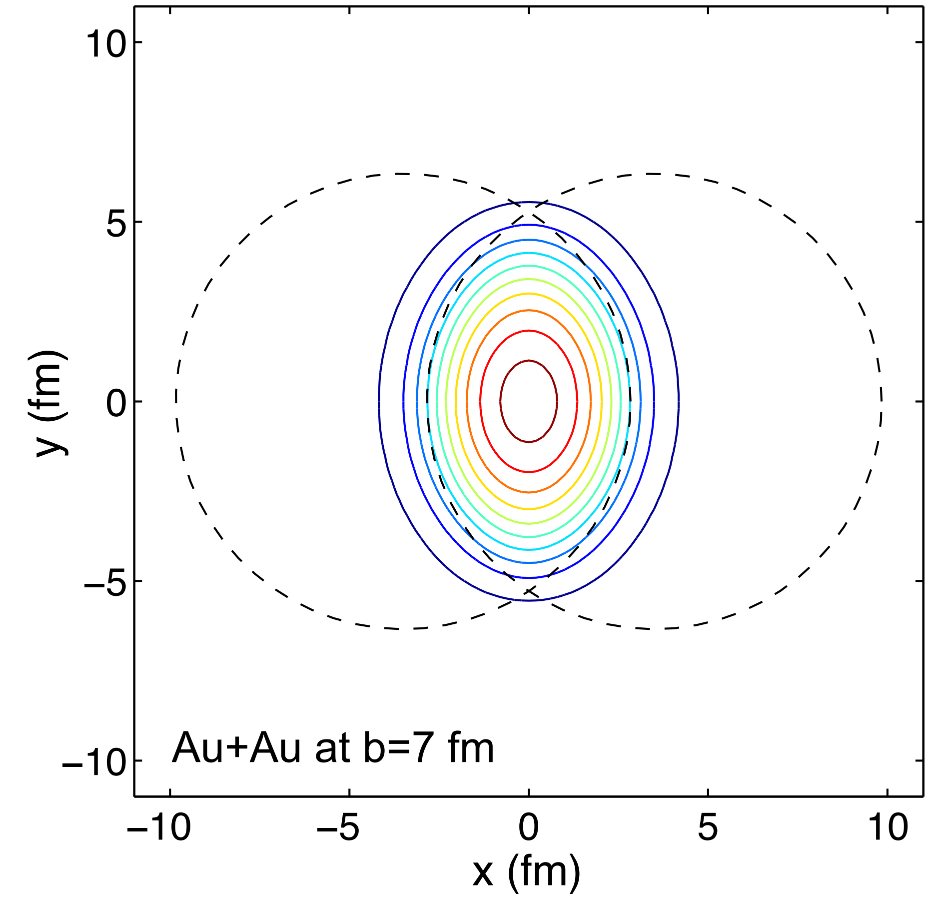
$$\left\langle \rho^a(\vec{x}) \right\rangle_{\mathrm{CGC}} = 0, \qquad \left\langle \rho^a(\vec{x})\rho^b(\vec{y}) \right\rangle_{\mathrm{CGC}} = \sum_{i=1}^{3} \mu^2\left(\frac{x + y}{2} - b_i\right)\delta^{(2)}(\vec{x} - \vec{y})\delta^{ab}$$

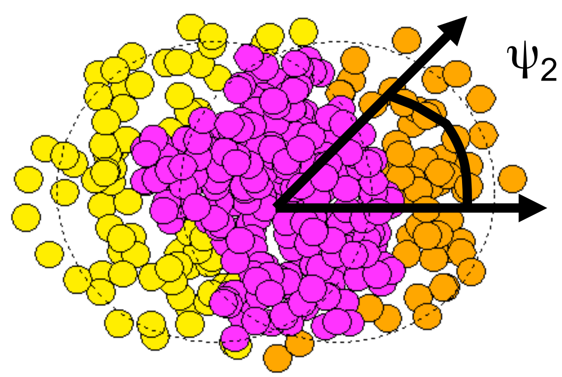
$$\mu^2(\vec{x}) = \frac{\mu_0^2}{2\pi r_H^2} e^{-\frac{\vec{x}^2}{2r_H^2}}$$

Small $|t|$ hotspot model acts as a starting distribution for the CGC nucleon.

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
H. Mäntysaari, B. Schenke, Phys.Rev. D94 (2016) 034042







$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

Sensitive to early interactions and pressure gradients

In ideal hydrodynamics $v_2 \propto$ spatial eccentricity ε_2: $\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

v_2/ε versus particle density is sensitive test of ideal hydrodynamic:

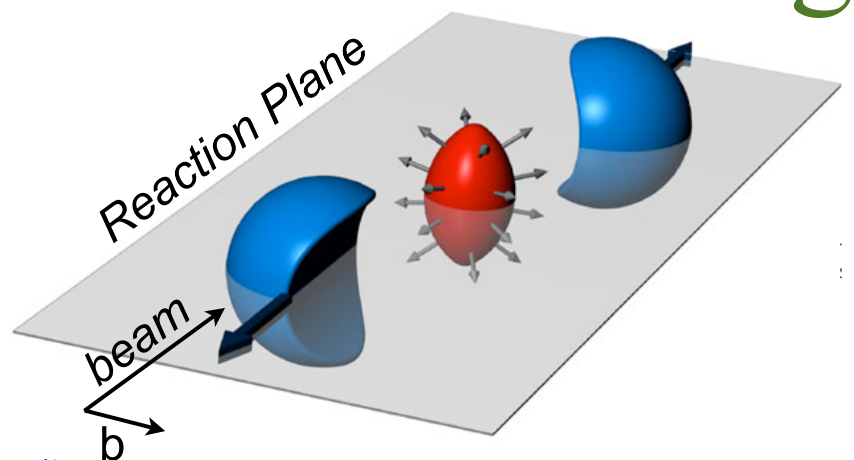
$$\frac{v_2}{\epsilon_2} = \frac{h}{1 + B/\left(\frac{1}{S}\frac{\mathrm{d}N}{\mathrm{d}y}\right)}$$

S= transverse area,

h = hydro limit of v_2/ε and B $\propto$ η/s

Different initial distributions gives different flows!

$$\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



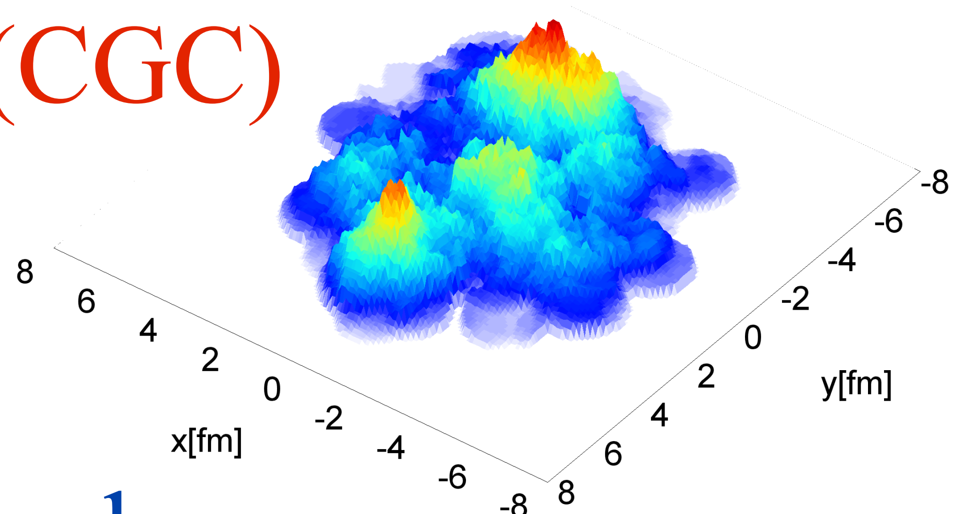
The question is what is ε?

RHIC & LHC: low-p_T realm driven almost entirely by glue ⇒ spatial distribution of glue in nuclei?

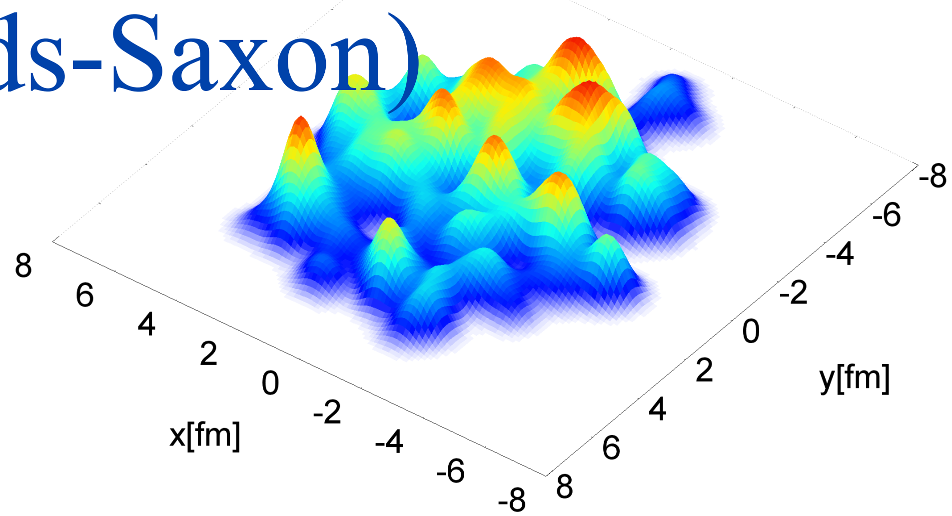
Two methods for ε:

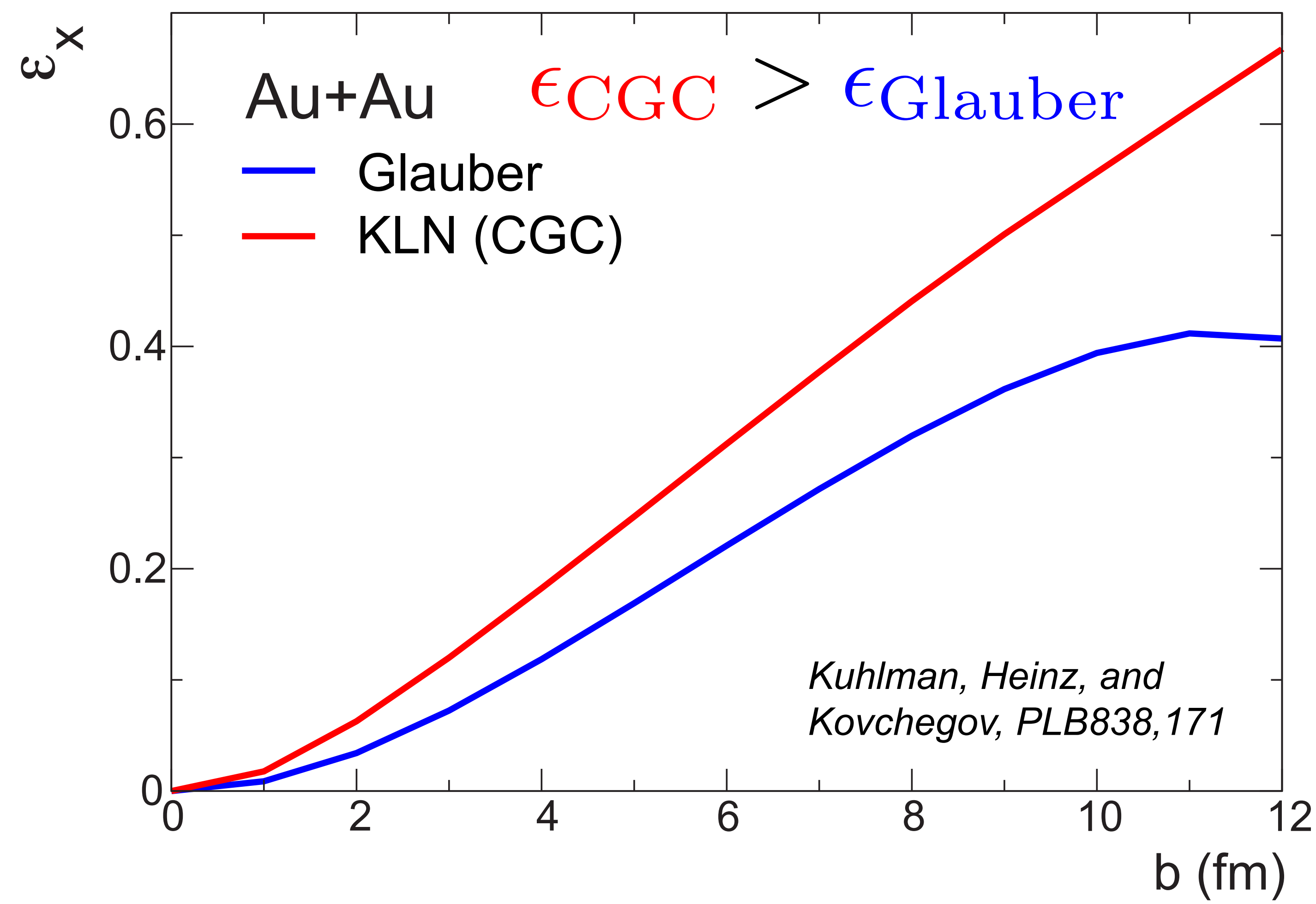
- Glauber (non-saturated)?
- CGC (saturated)?

KLN(CGC)



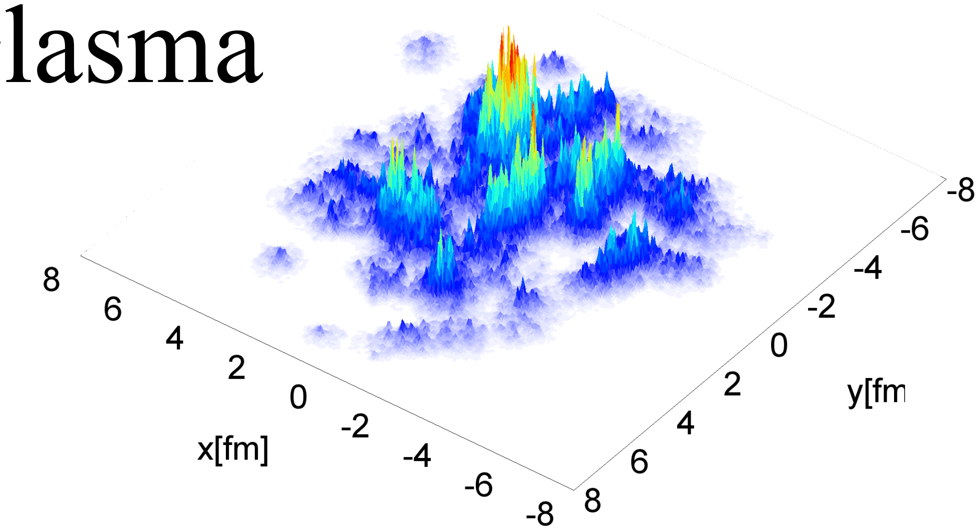
Glauber (Woods-Saxon)



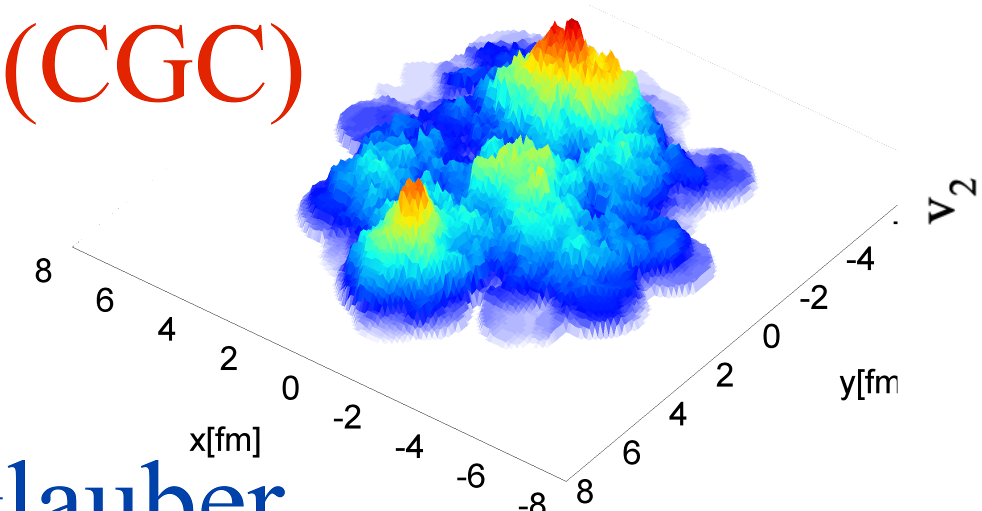


What is η/s?

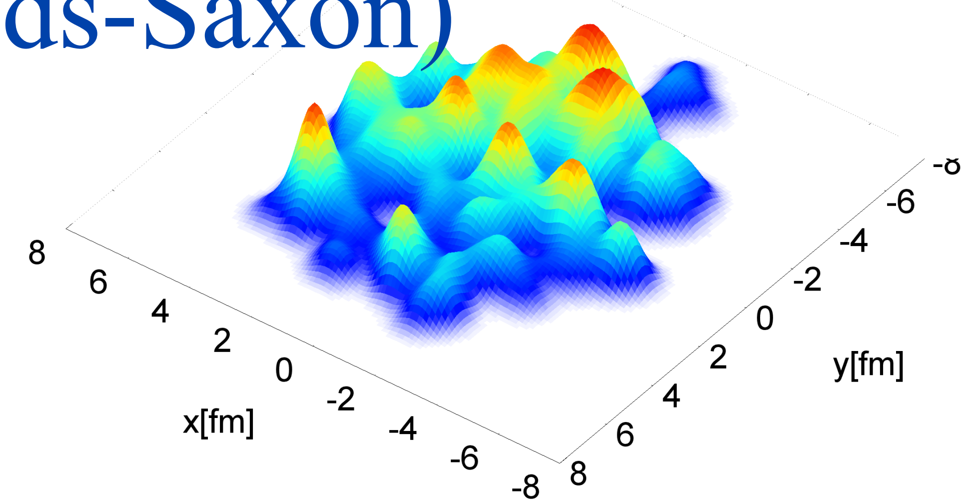
IP-Glasma



KLN(CGC)

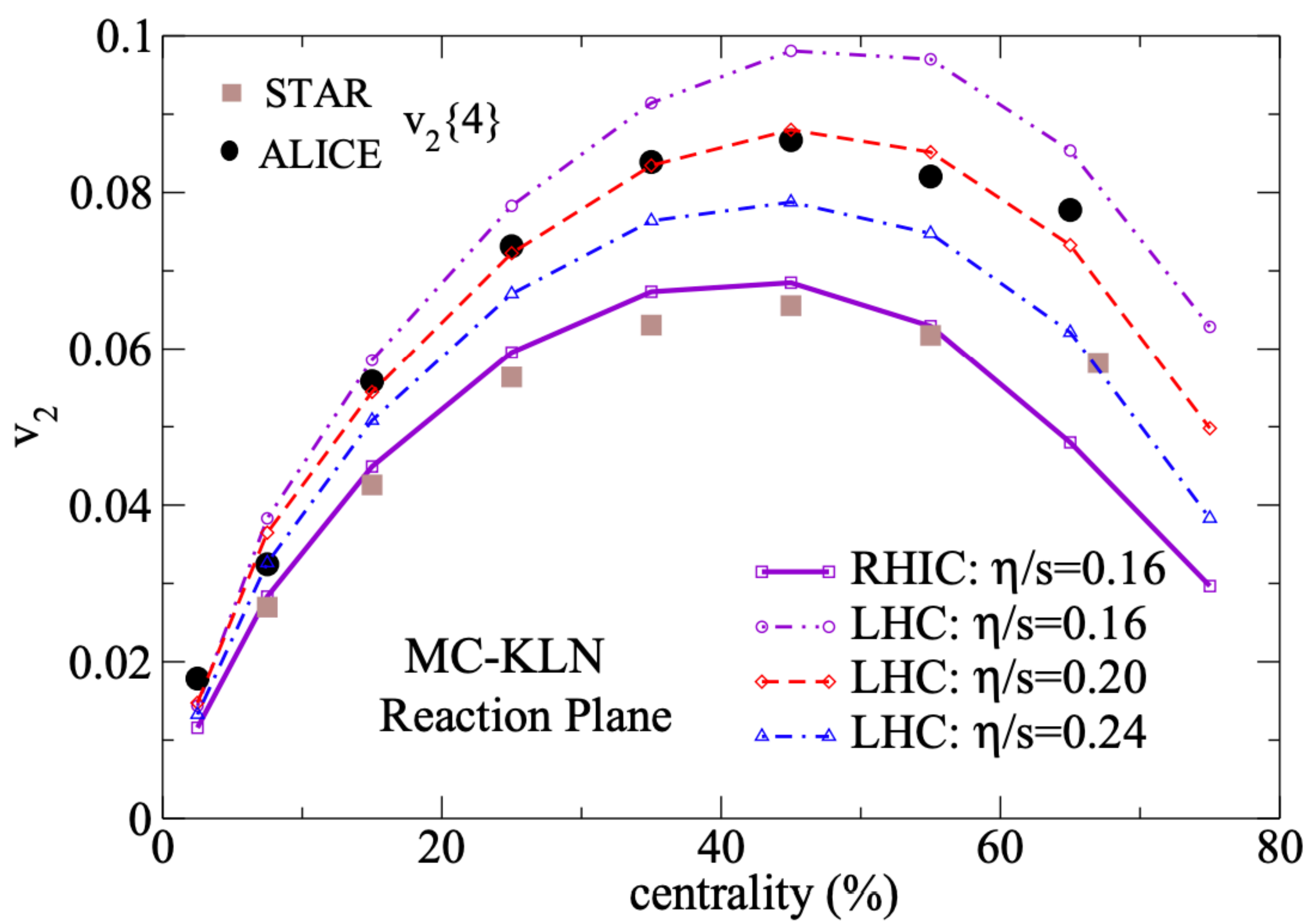


Glauber
(Woods-Saxon)

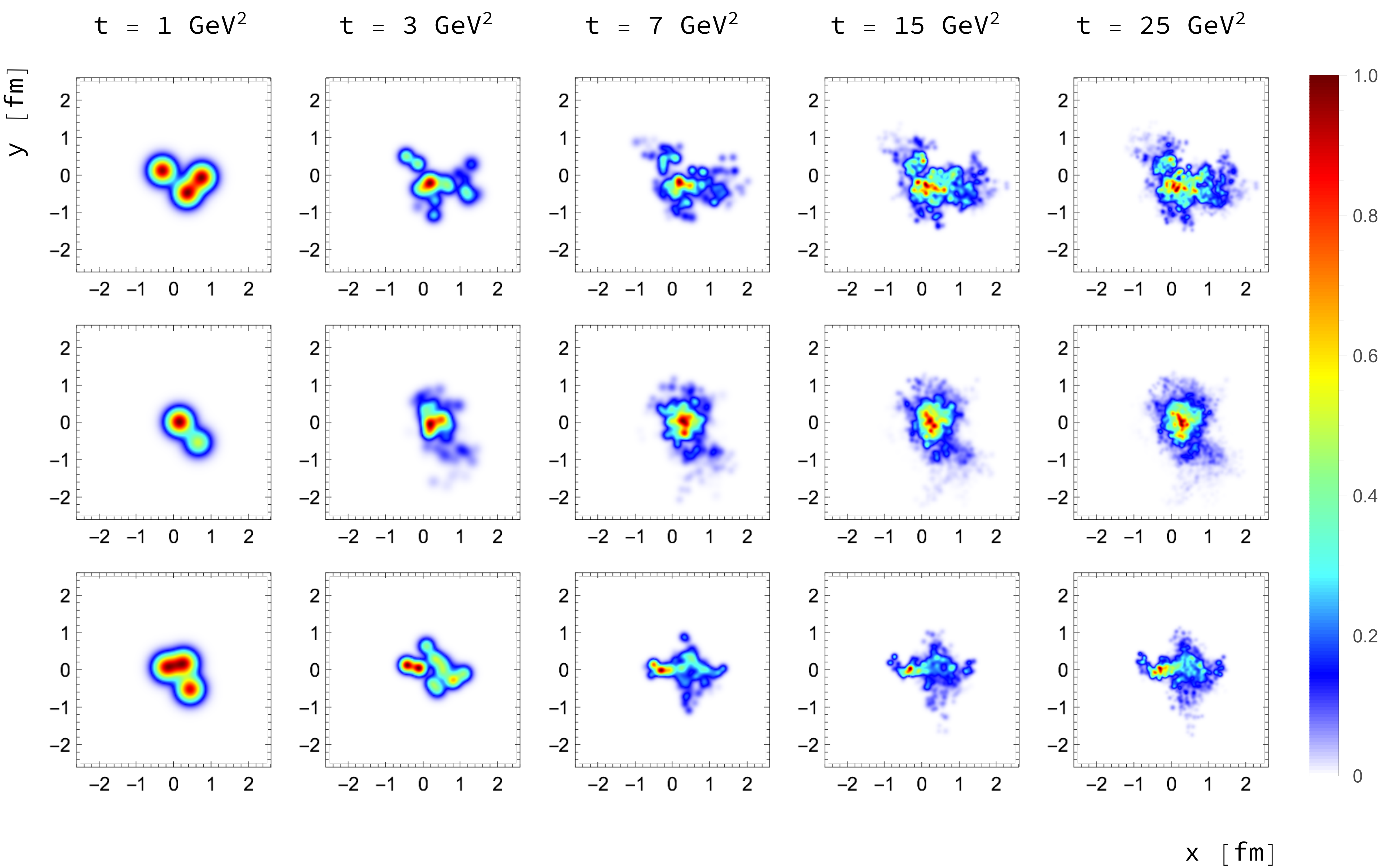


$1/(4\pi) \sim 0.08$

U. Heinz, C. Shen, H. Song, AIP Conf.Proc. 1441 (2012) no.1, 766-770



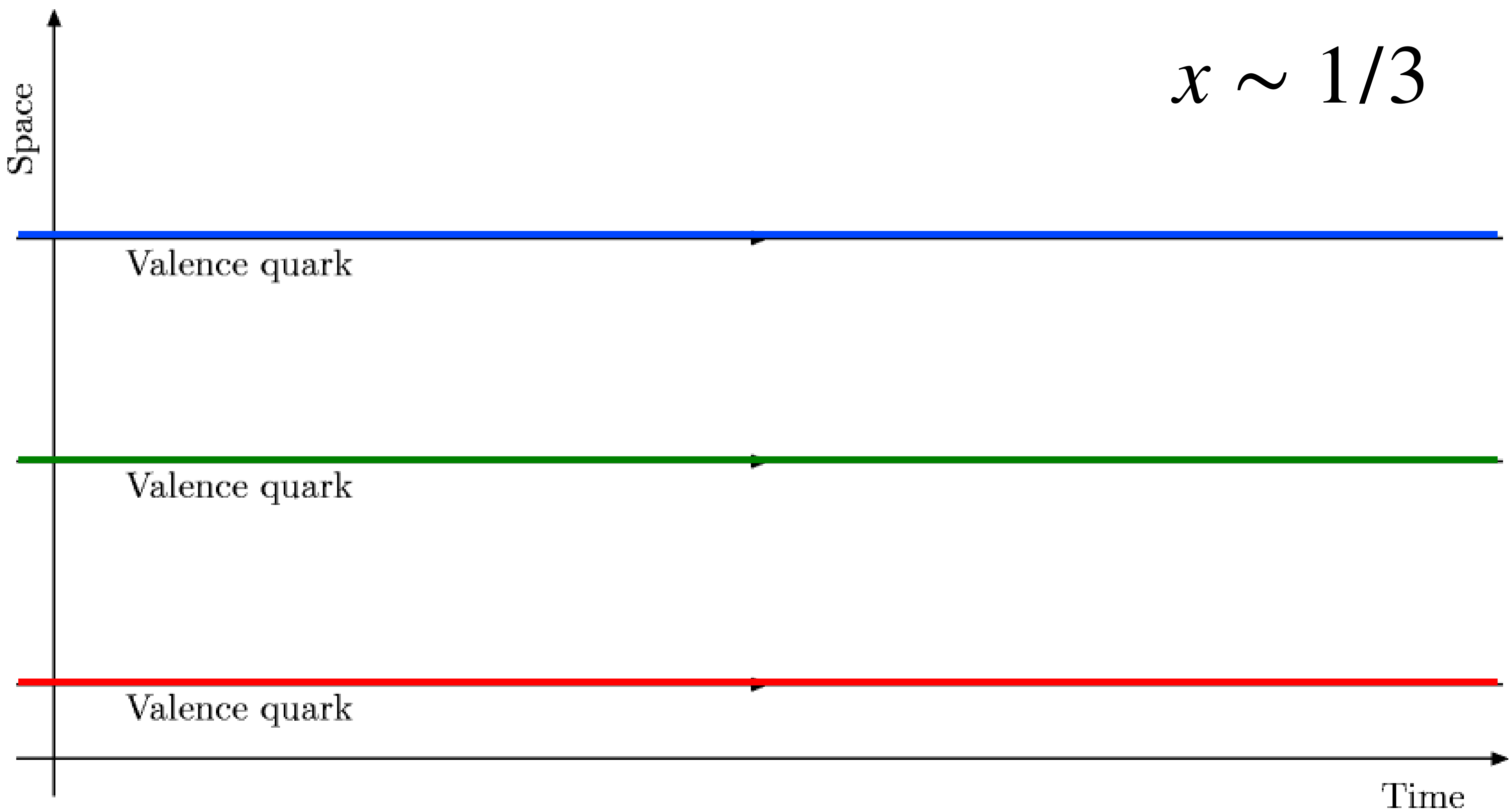
Different initial states=
different fluctuation scales



t = 1 GeV2
t = 3 GeV2
t = 7 GeV2
t = 15 GeV2
t = 25 GeV2
y [fm]
x [fm]
1.0
0.8
0.6
0.4
0.2
0

Part II:
Our understanding of the longitundial initial state

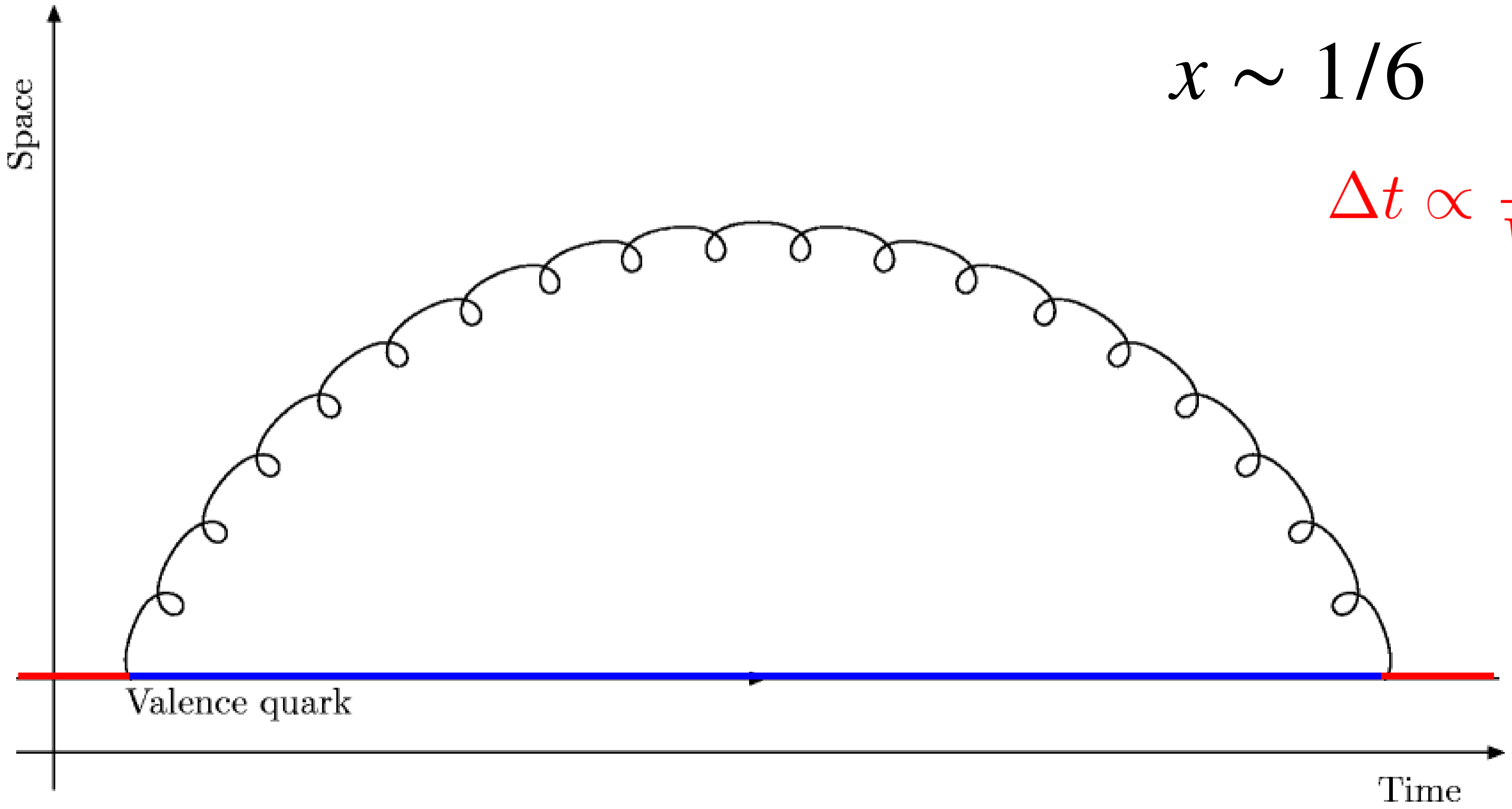
The longitudinal inital state



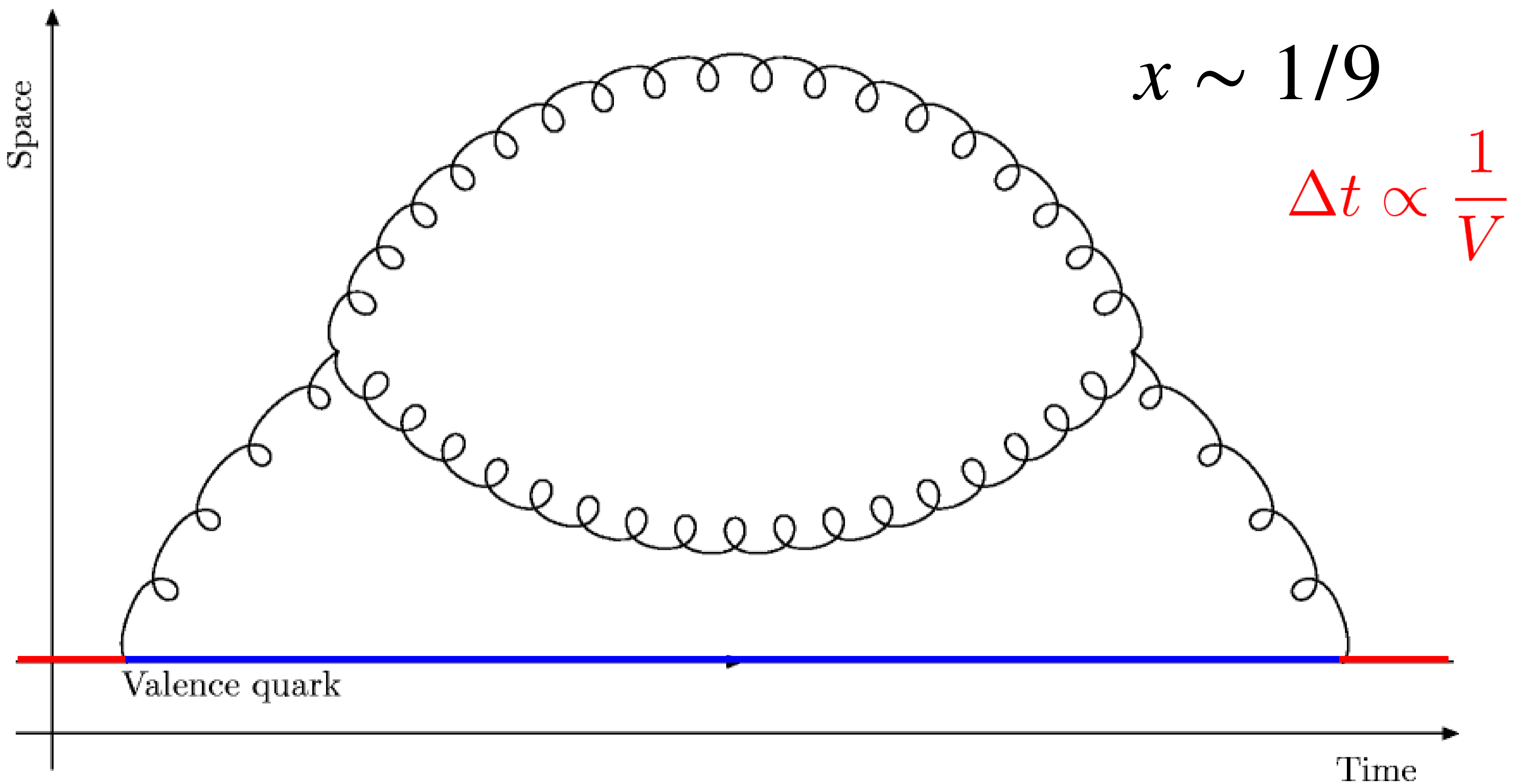
The longitudinal inital state

$x \sim 1/6$

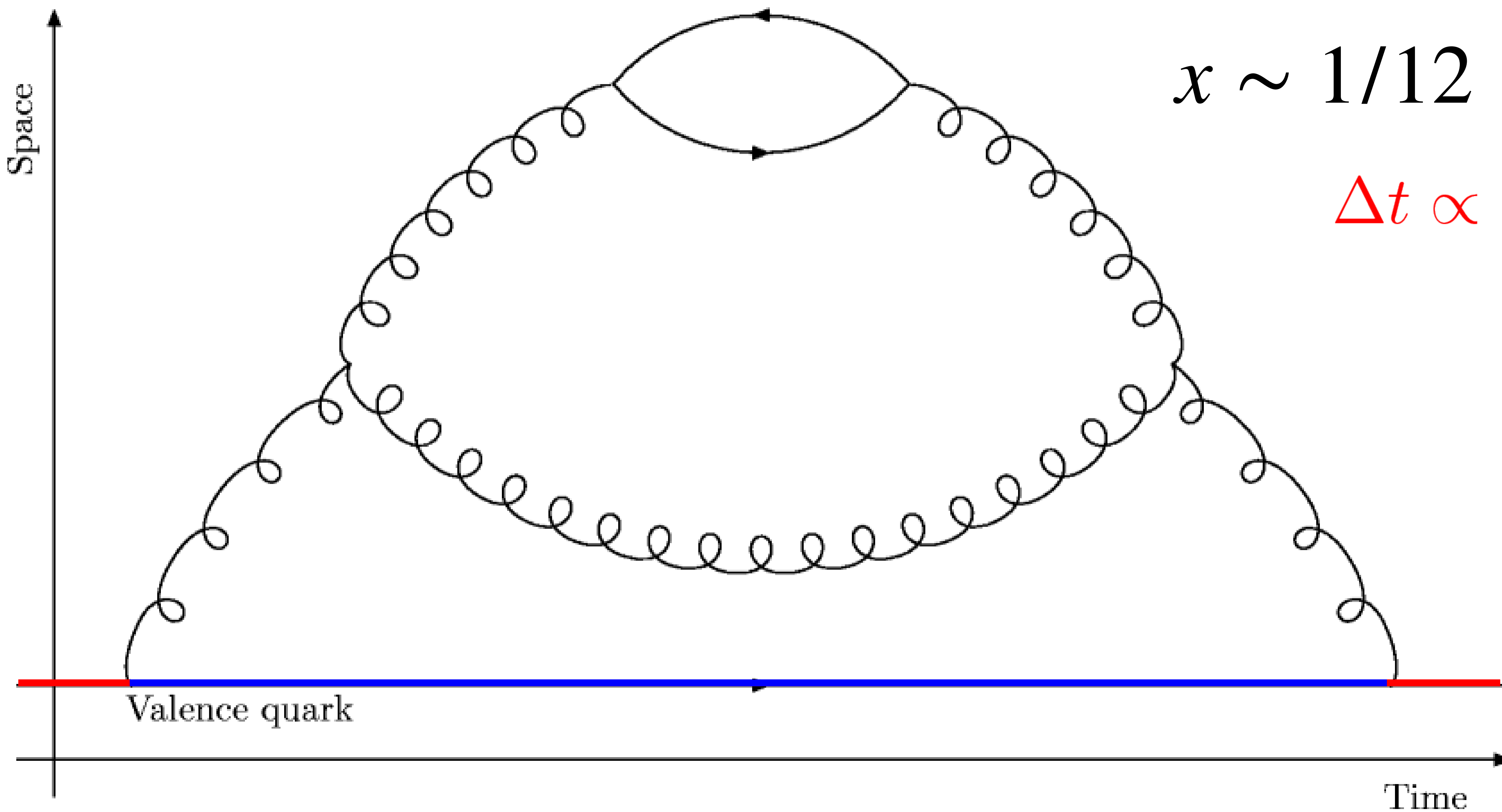
$\Delta t \propto \frac{1}{V}$



Our Understanding of Gluons



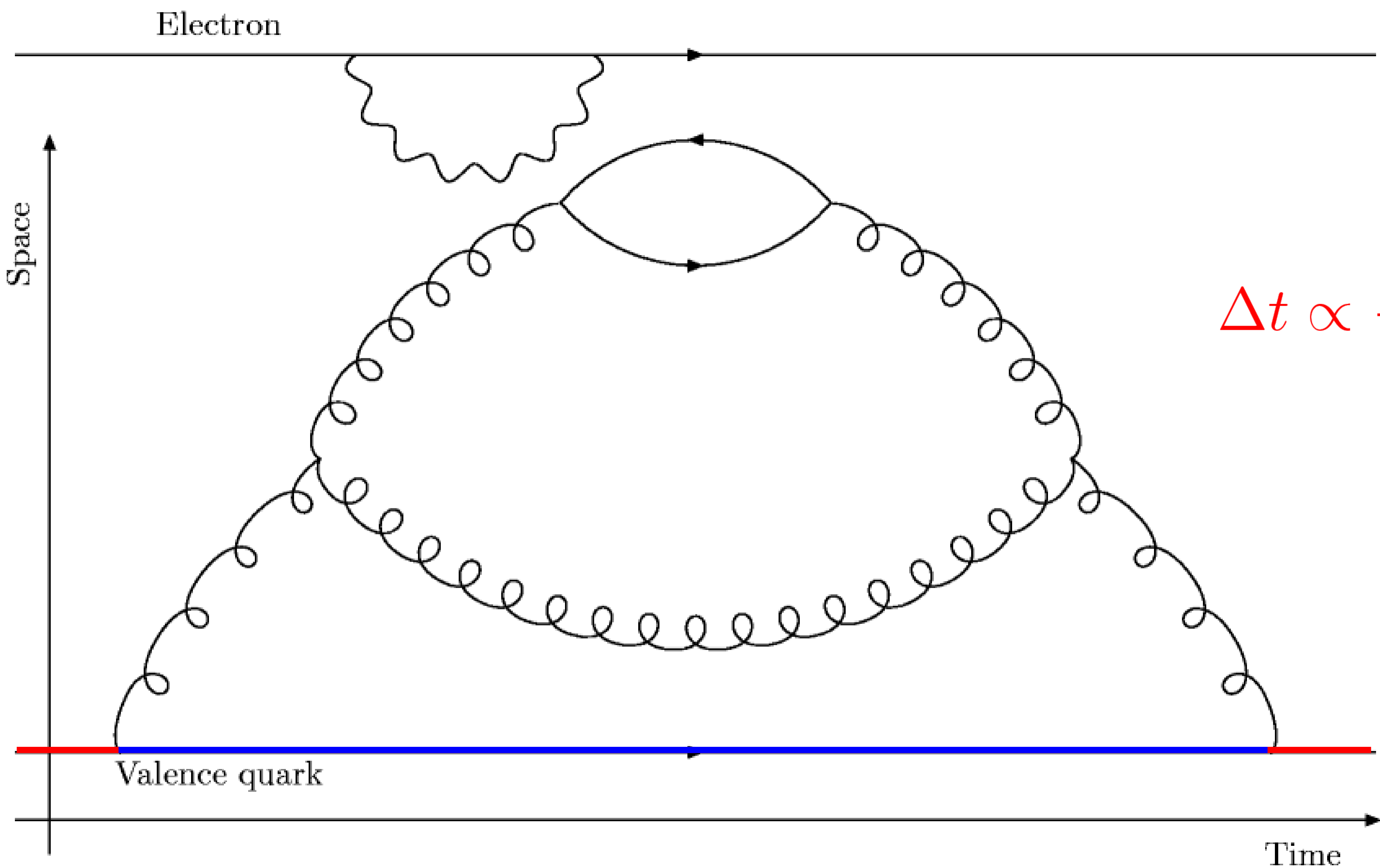
The longitudinal inital state



$x \sim 1/12$

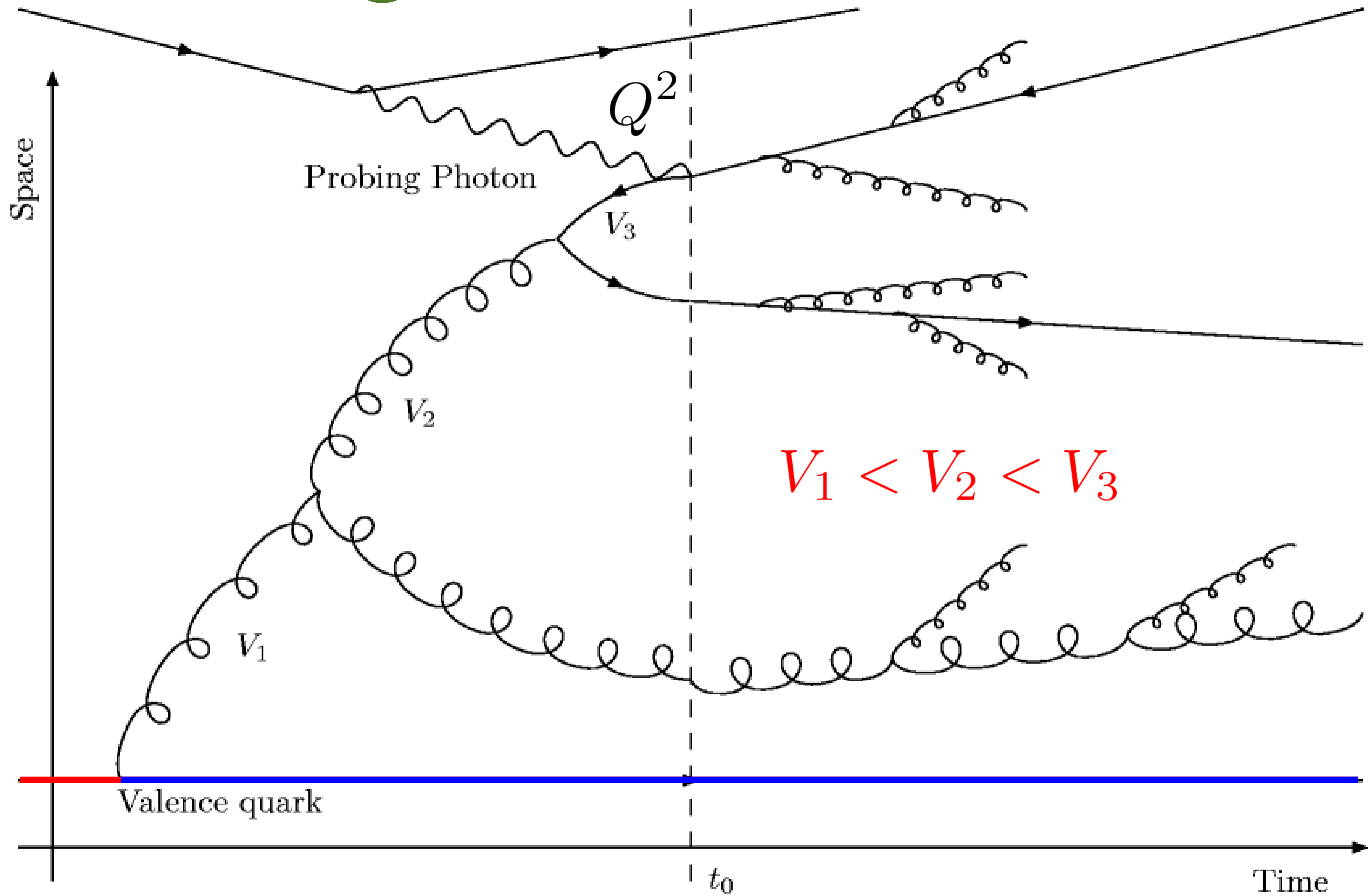
$\Delta t \propto \frac{1}{V}$

The longitudinal inital state



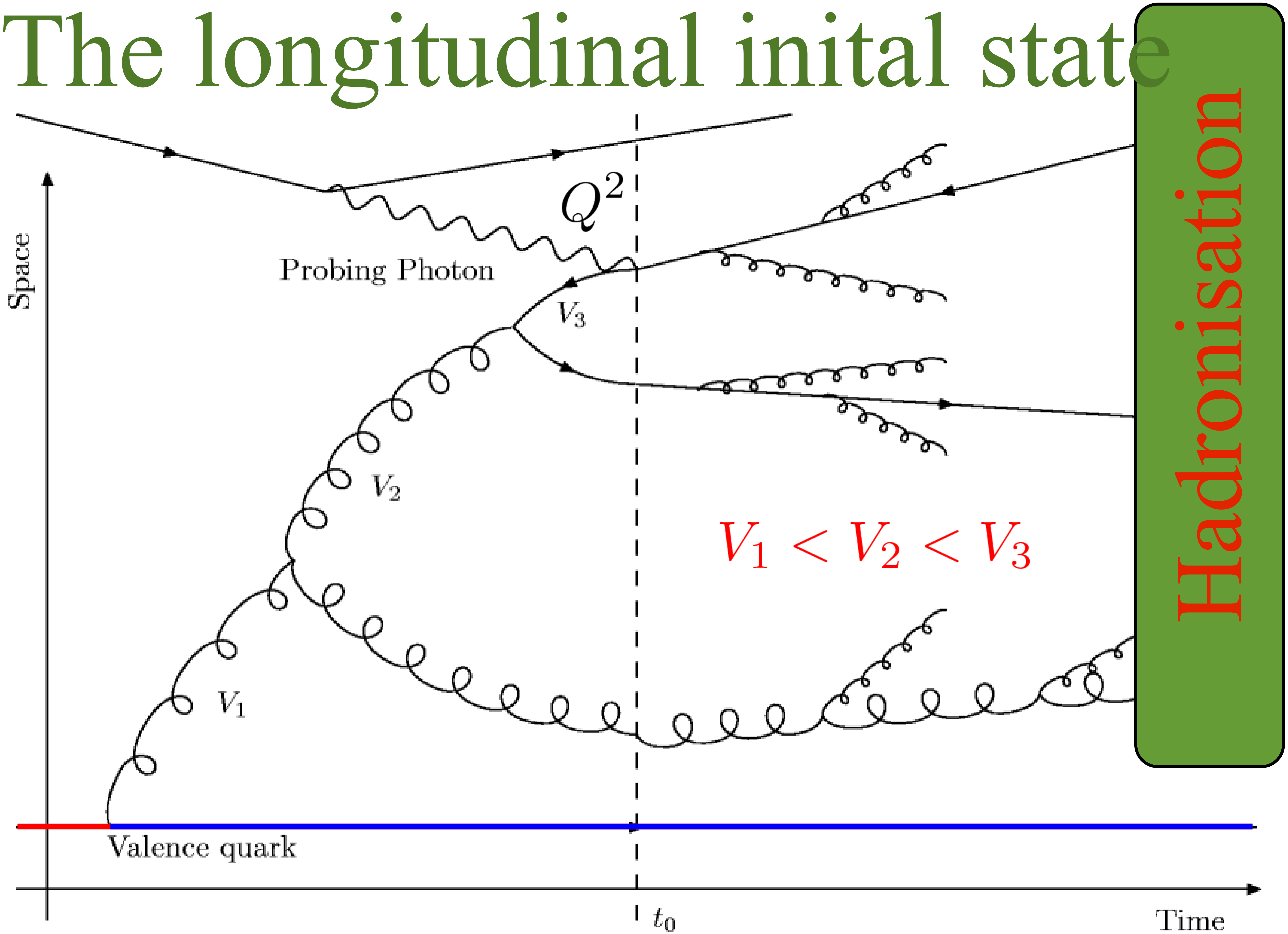
$$\Delta t \propto \frac{1}{V}$$

The longitudinal inital state



***D**okshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi* **DGLAP**

The longitudinal inital state



***D**okshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi* **DGLAP**

The longitudinal inital state