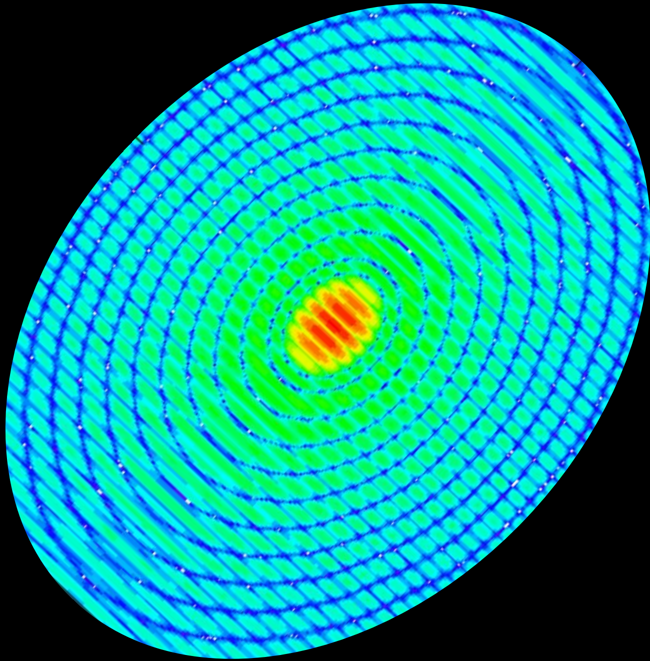
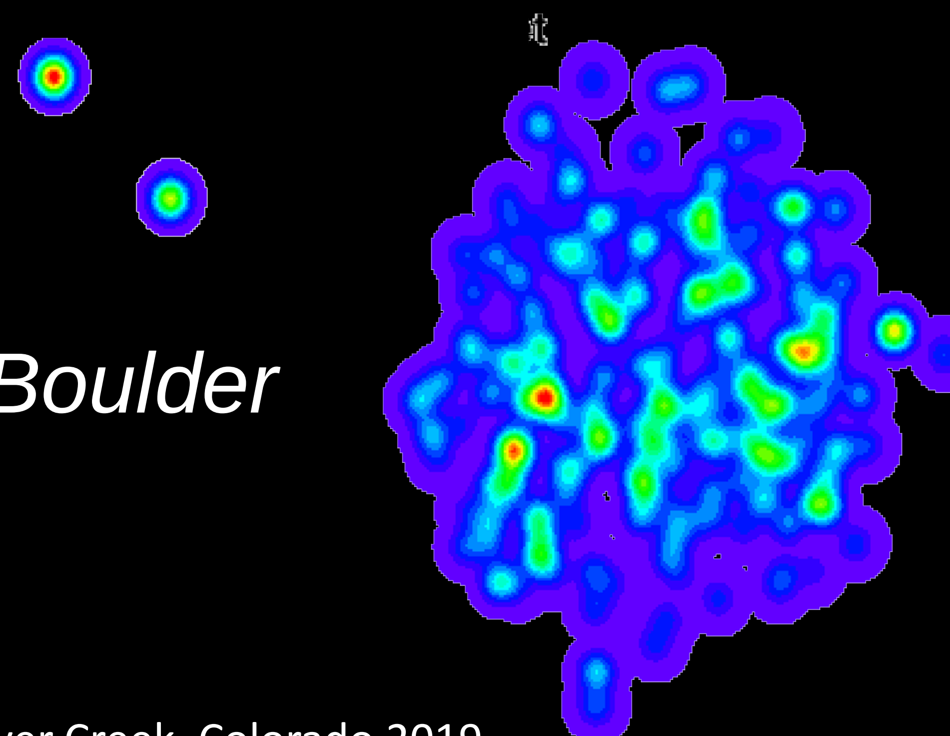


Ab Initio or *Non Pertinent*

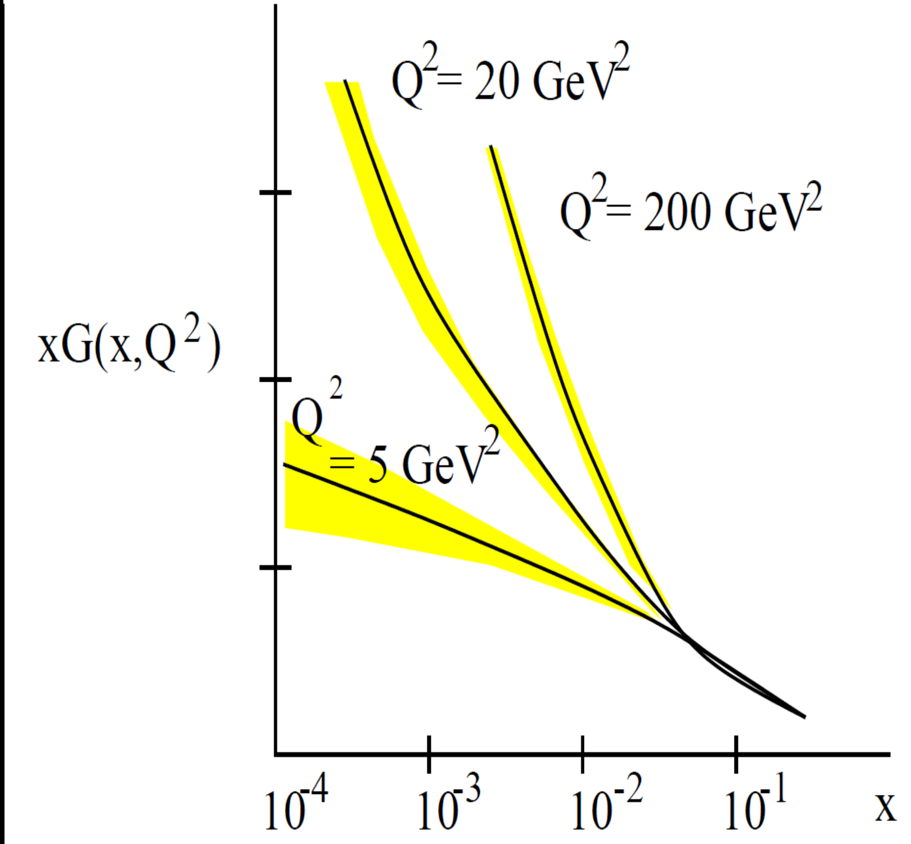


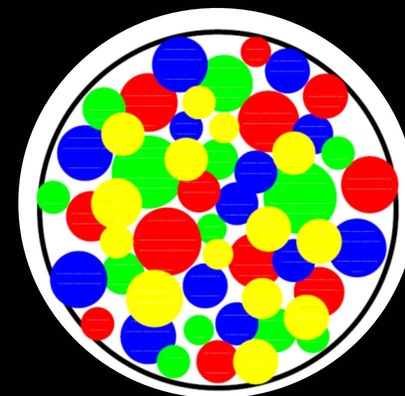
Jamie Nagle
University of Colorado Boulder

Winter Workshop on Nuclear Dynamics, Beaver Creek, Colorado 2019

Ab Initio Effective Theory

gluons, gluons, gluons





Gluon packing fraction *K* ~ 1 sets a new scale Q_s

$$\kappa = \rho^g \cdot \sigma^{gg} \sim \frac{xG(x,Q^2)}{\pi R_h^2} \cdot \frac{\alpha_s}{Q^2}\bigg|_{Q^2=Q_s^2} \sim 1$$

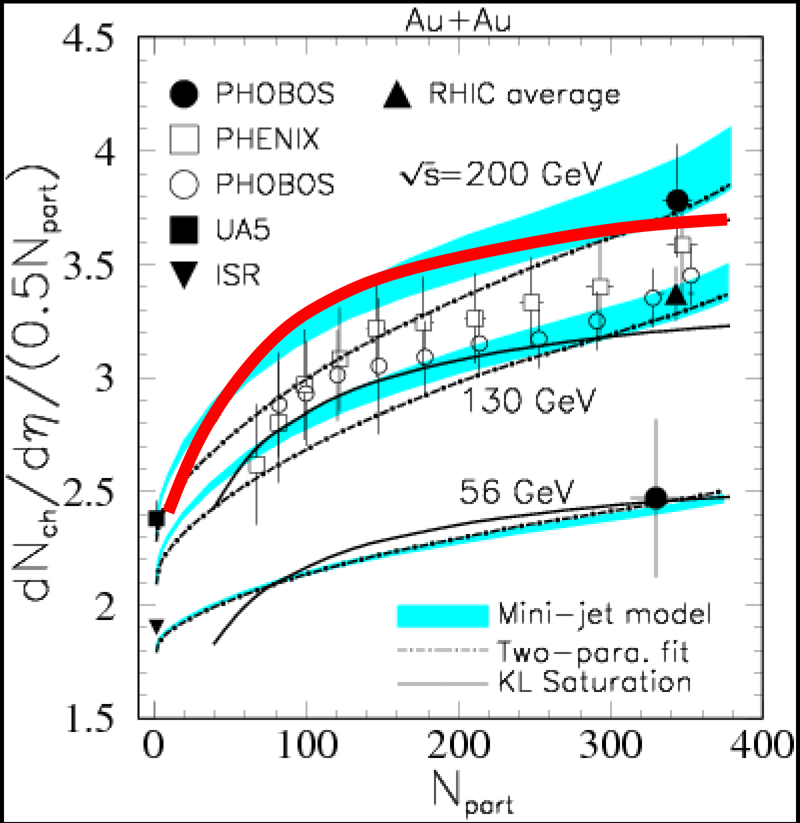
Effective theory at high gluon occupation such that α_s << 1 (weak)

Early Days at RHIC

Particle Production increases per participant pair and then levels off

Saturation physics naturally explains via

$$\frac{1}{N_{part}}\frac{dN}{dy} \sim \frac{1}{\alpha_S(Q^2_{sat})} \sim \log N_{part}$$

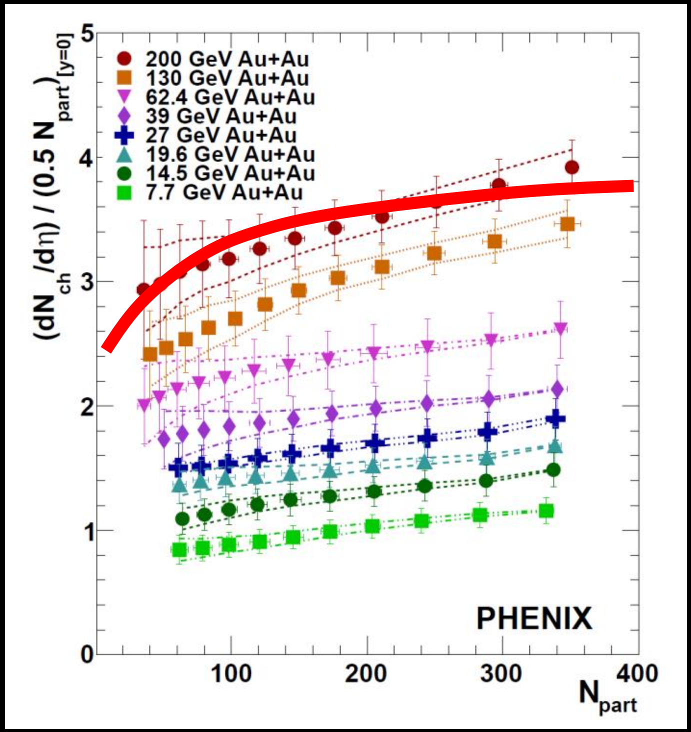


However, like many things, the obvious was right in front of us…

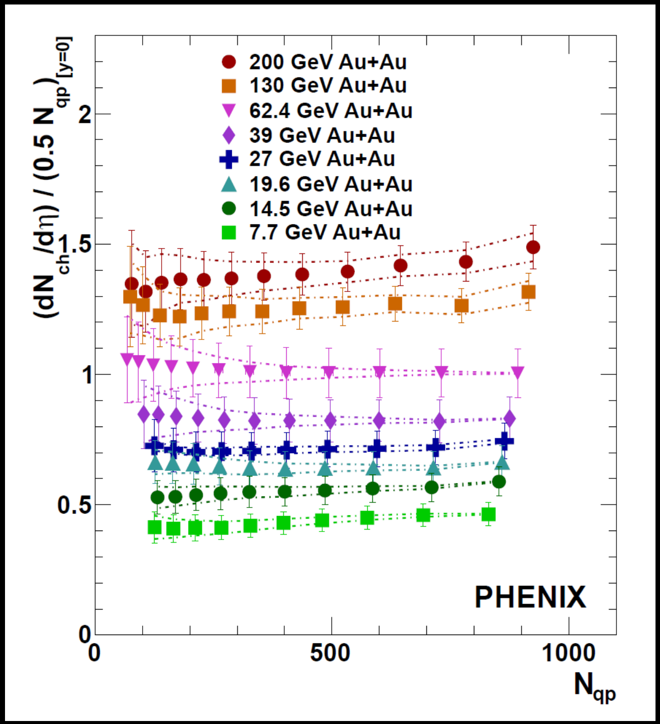
All nucleon participants are not struck the same (i.e. impact parameter)

PHENIX Scaling Results

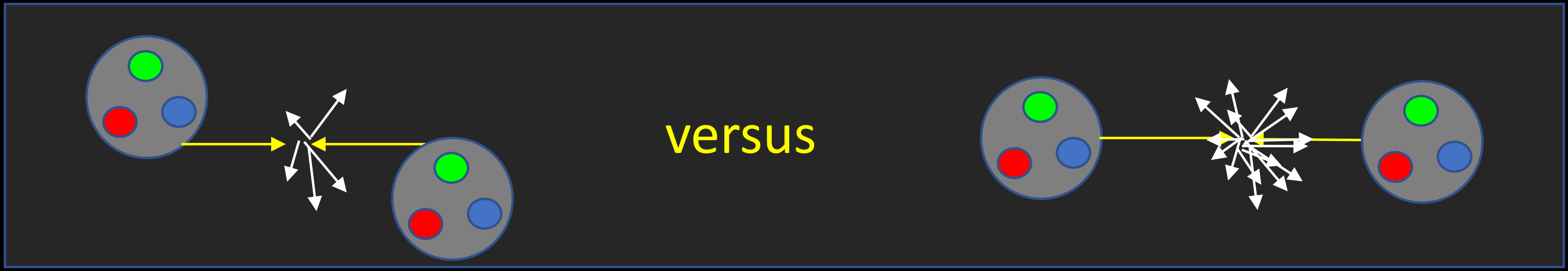
Nucleon Scaling



Quark Scaling



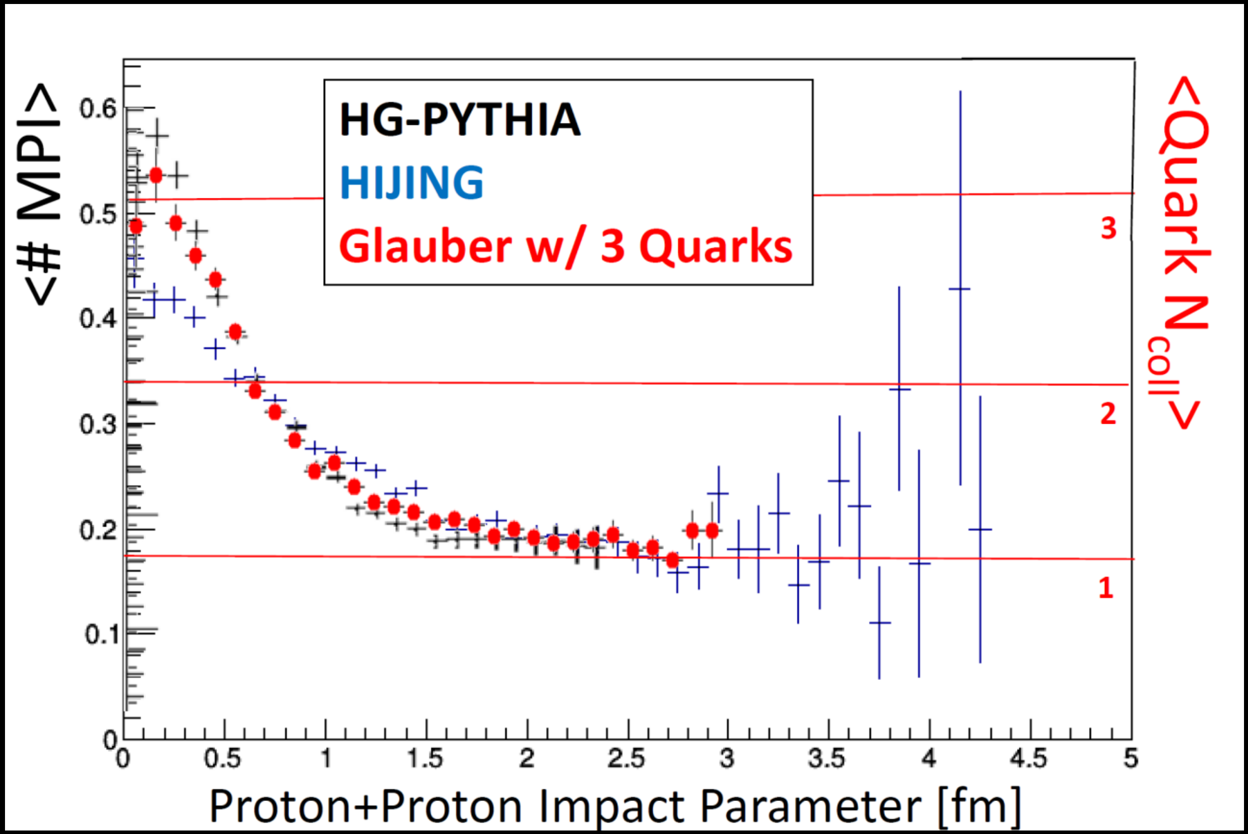
Simple geometry of nucleon overlap explains data at all energies

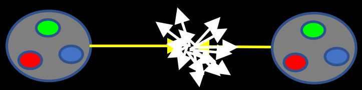


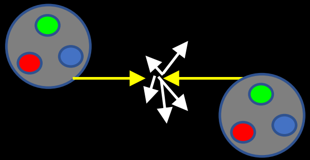
No real evidence for 3 quark cloud configuration!

Anything with an impact parameter dependence

(3,4,5 substructures; Glauber-Gribov; MPI; etc.)



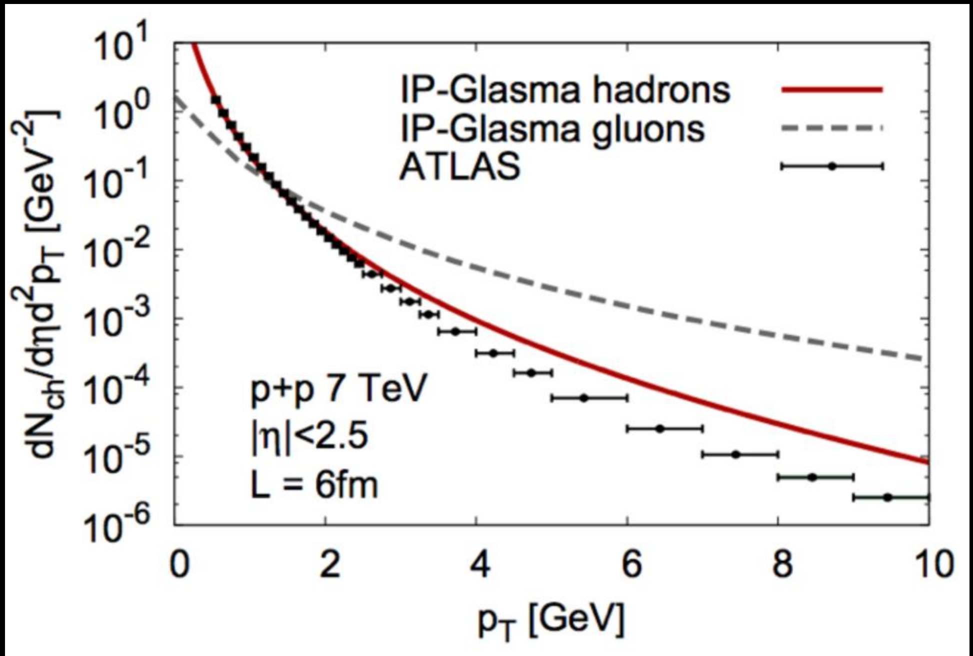




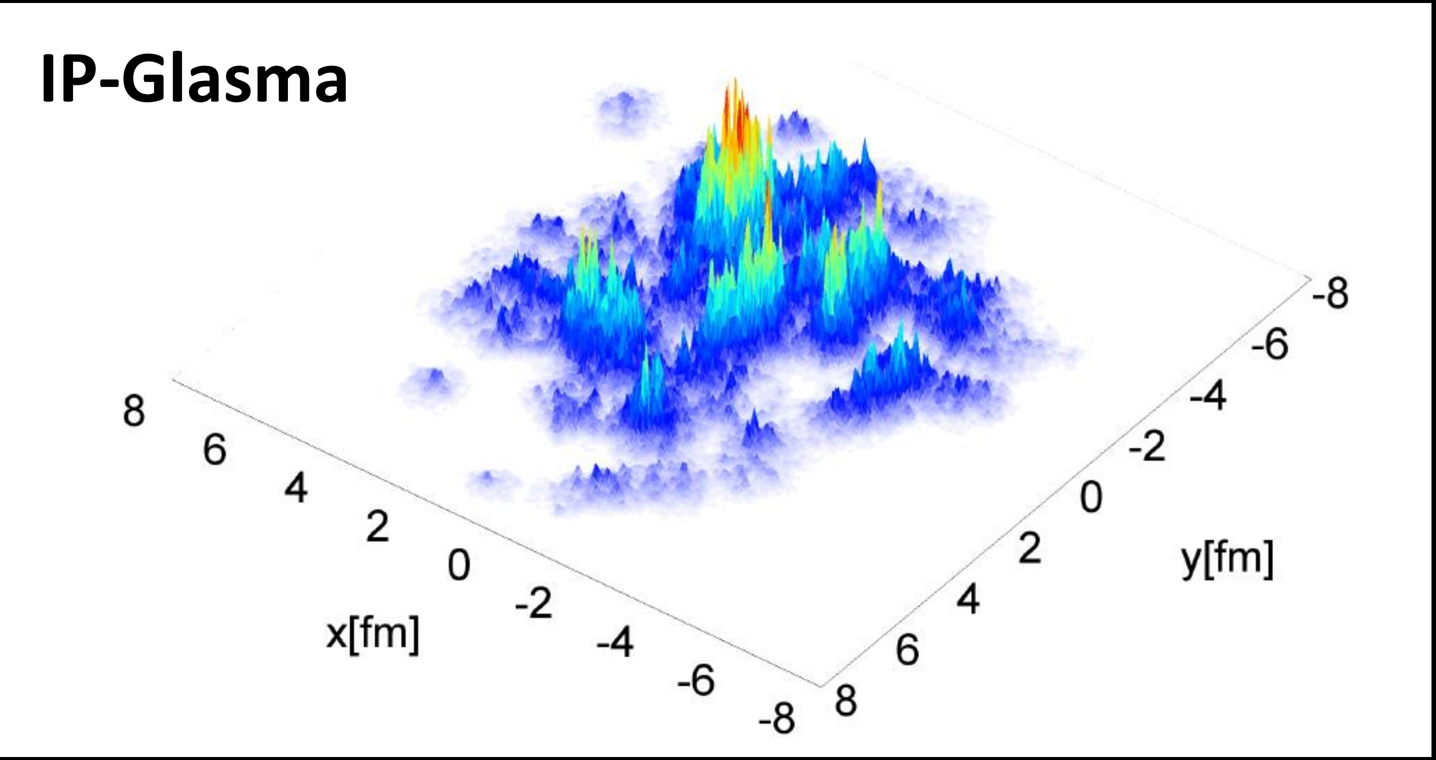
- Simple geometry provides compact explanation
- In 2019 we should not see any more two-component model results for particle production
- Saturation may still play a role, but no strong evidence
- Saturation calculations have gluon $\langle p_T \rangle \sim 1 - 1.4$ GeV/c

Thus caution about comparing gluon v_2 with hadron v_2

That really means just don't do it.



Jump forward 10 years …



How often is this shown as an indication of sub-nucleonic quantum fluctuations?

IP-Glasma

1. MC Glauber to obtain nucleon x,y positions in each event

2. Use IP-Sat (impact parameter saturation model) to calculate the Q_s^2 distribution on an x,y lattice

$$Q_s^2(x,y) = Q_{s,0}^2 \times Exp(-r_T^2/(2\sigma^2))$$

Just a uniform Gaussian with σ = 0.32 fm at RHIC and slightly narrower (0.29) at the LHC

3. Simple linear sum Q_s^2 (projectile) and Q_s^2 (target)

4. Then calculate the resulting energy density in the interaction

Romatschke & Romatschke (arXiv:1712.05815) found that IP-Glasma yields:

$T_A(x,y) = \Sigma\, Q_s^2(x,y)$ [proj] and $T_B(x,y) = \Sigma\, Q_s^2\,(x,y)$ [targ]

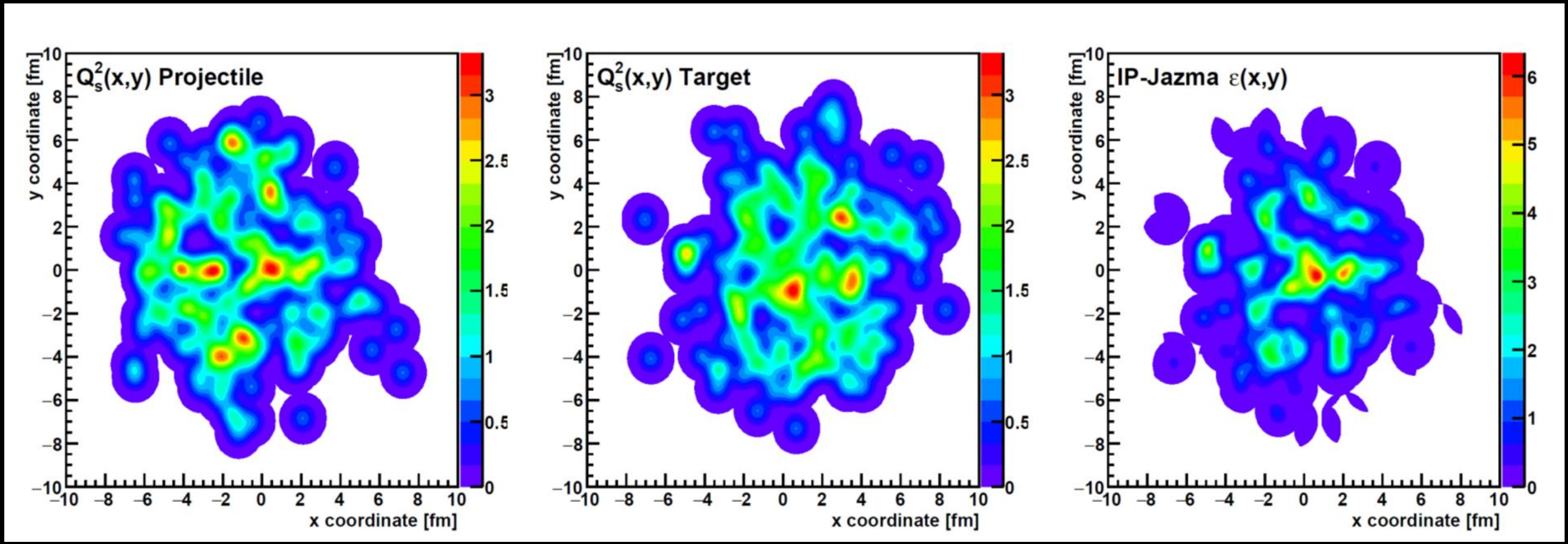
$\varepsilon \propto g^2\, T_A(x,y) \times T_B(x,y)$ (dense-dense limit)

Simply the product of thickness functions as the linear sum of Gaussian distributions (σ loosely constrained at HERA).

N.B. IP-Glasma always in the dense-dense limit, including to obtain initial conditions for p+Au, d+Au, ^{3}He+Au, p+Pb (e.g. arXiv:1407.7557v1)

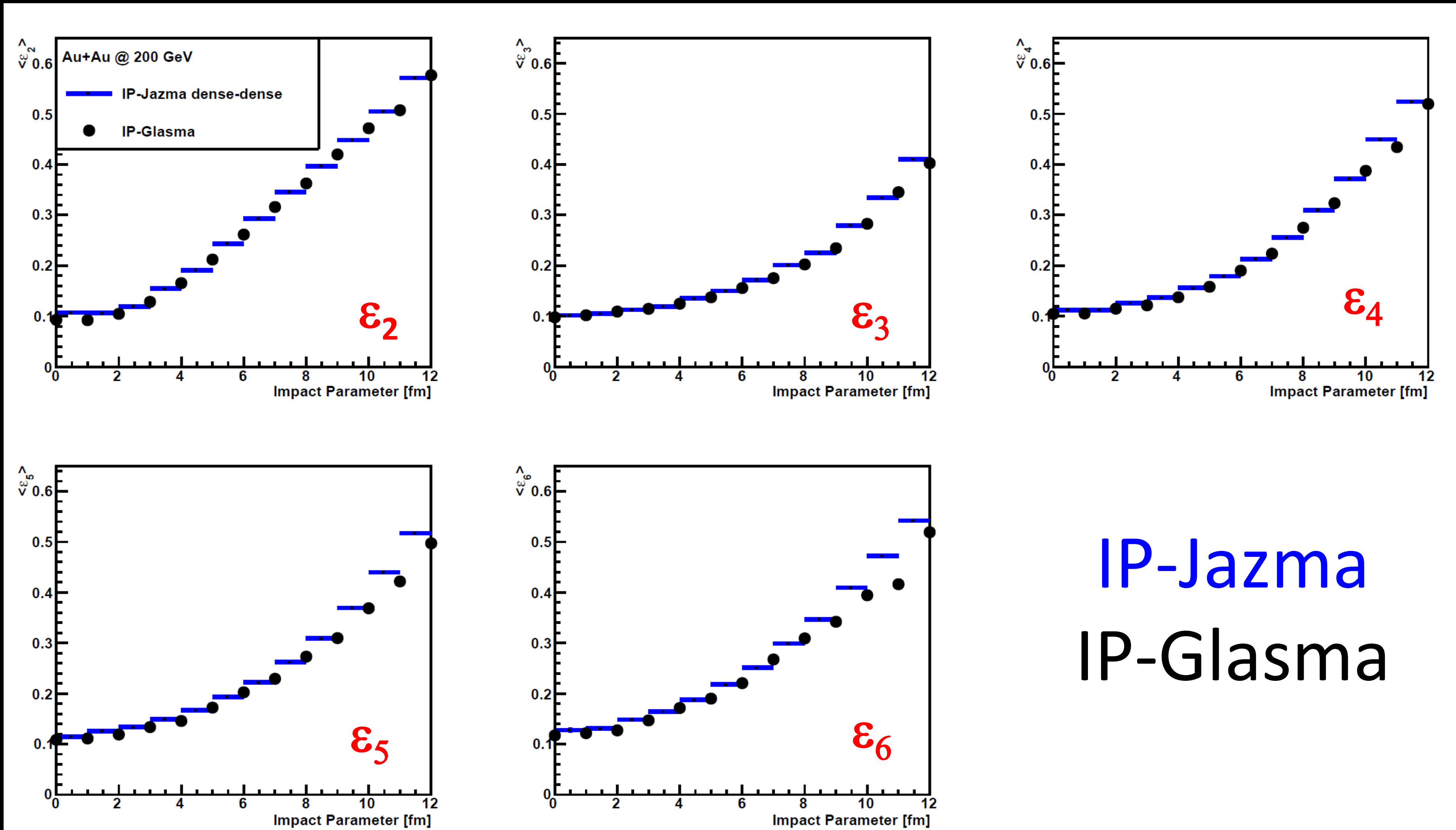
IP-Jazma Framework

https://arxiv.org/abs/1808.01276
https://github.com/jamienagle/IPJazma



$T_A(x,y) = \Sigma\, Q_s^2(x,y)$ [proj] $\quad T_B(x,y) = \Sigma\, Q_s^2\,(x,y)$ [targ] $\quad \varepsilon \propto g^2\, T_A(x,y) \times T_B(x,y)$

Au+Au @ 200 GeV Geometry



Initial geometry totally dominated by simple nucleon overlaps

No evident effect of lattice artifacts or saturation effects

Test All Claims Or → Mistaken Attribution

IP-Glasma

In Fig. 1 we show the event-by-event fluctuation in the initial energy per unit rapidity. The mean was adjusted to reproduce particle multiplicities after hydrodynamic evolution. This and all following results are for Au+Au collisions at RHIC energies ($\sqrt{s} = 200\,A\,\mathrm{GeV}$) at midrapidity. The best fit is given by a negative binomial (NBD) distribution, as predicted in the Glasma flux tube framework [37]; our result adds further confirmation to a previous non-perturbative study [38].

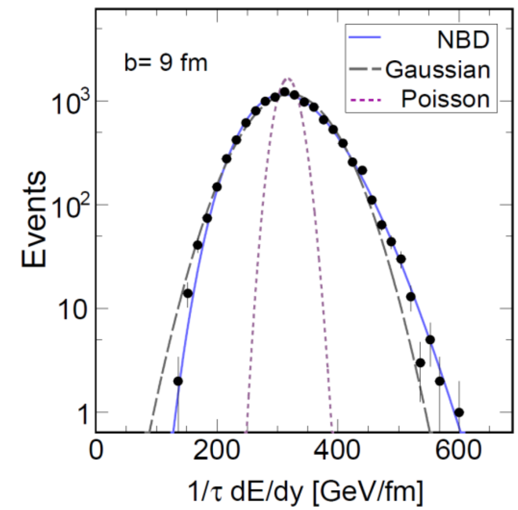
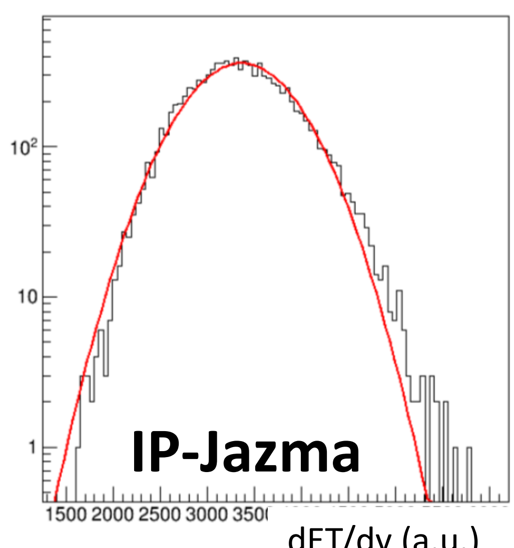


FIG. 1. The IP-Glasma event-by-event distribution in energy for $b = 9$ fm on the lattice compared to different functional forms. The negative binomial distribution (NBD) gives the best fit.

https://arxiv.org/abs/1202.6646v2

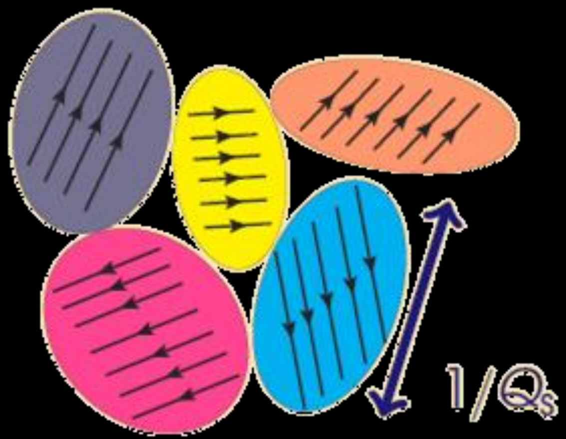


IP-Jazma distribution is also
not Gaussian (red line)
and has a high side skew (Γ distribution)

Nothing to do with Glasma flux tubes.

Jump forward a few more years …

Color Domains



Theory has color domains…
Size scale ~ 0.2-0.4 fm

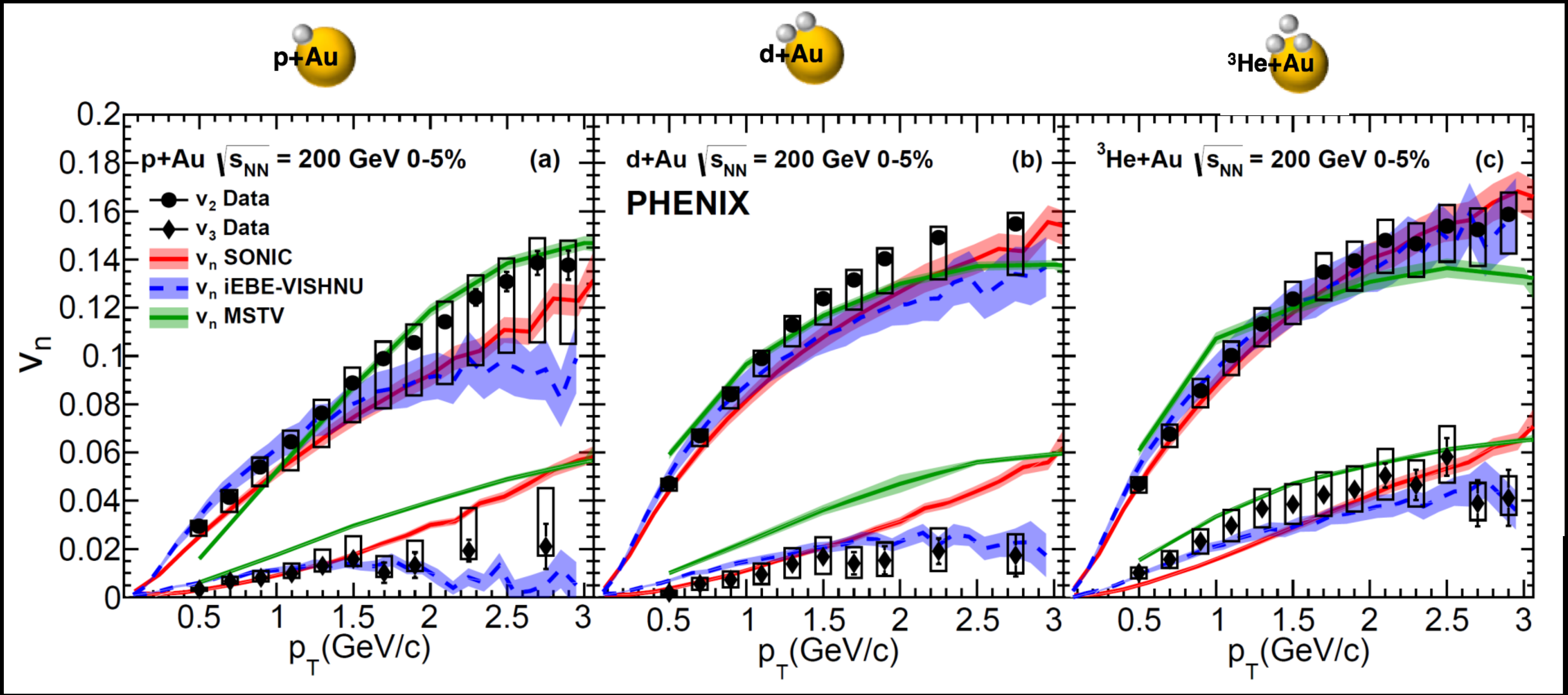
Gluons scattering from these domains if they have the right color get a kick (anti) aligned with field.

Correlation is suppressed by a factor $1 / (S_T Q_s^2 N_c^2)$

Domains = $S_T Q_s^2$

Thus predicting v_2 (dAu) < v_2(pAu) which is opposite to the data

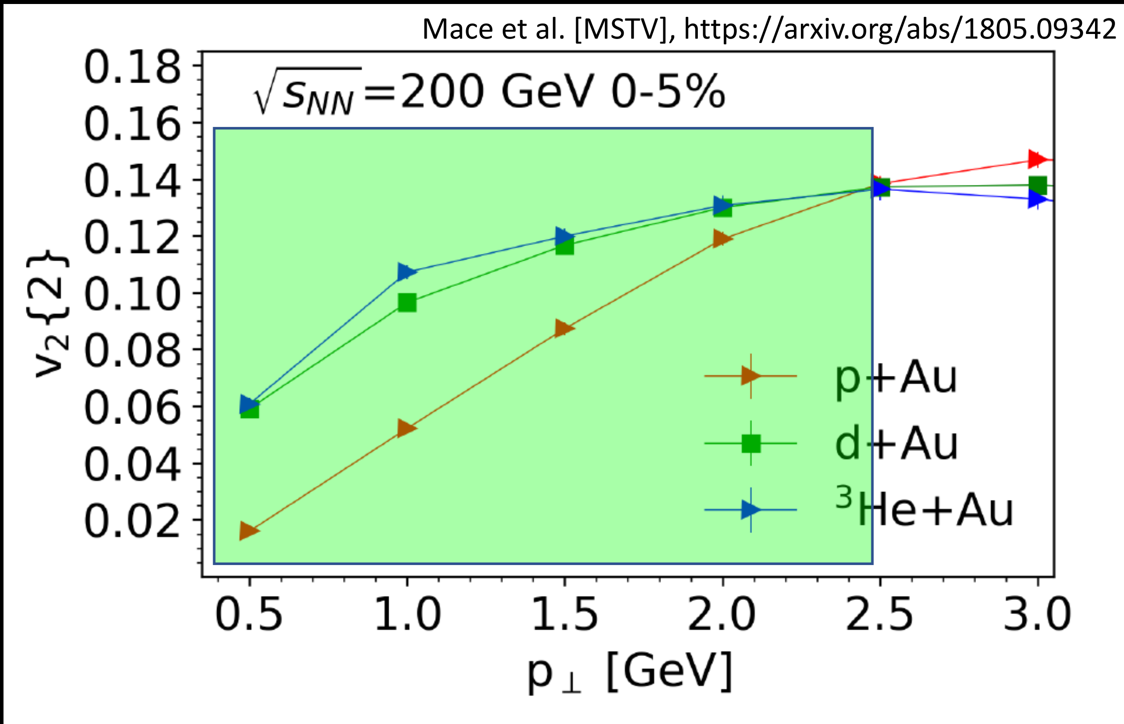
PHENIX Data Published in Nature Physics



Correlation Model Postdictions (MSTV)

Color domain result has very poor p-value.

At the same time, how does it have the right order v_2(dAu) > v_2(pAu)?



Individual domains not resolved up to pT ~ 2.5 GeV!

If 1/Q_s [projectile] > 1/k_T then individual domains are not resolved
→ Hence uncertainty principle blurs domain resolution

d+Au results are even higher because “higher color charge density” than in p+Au

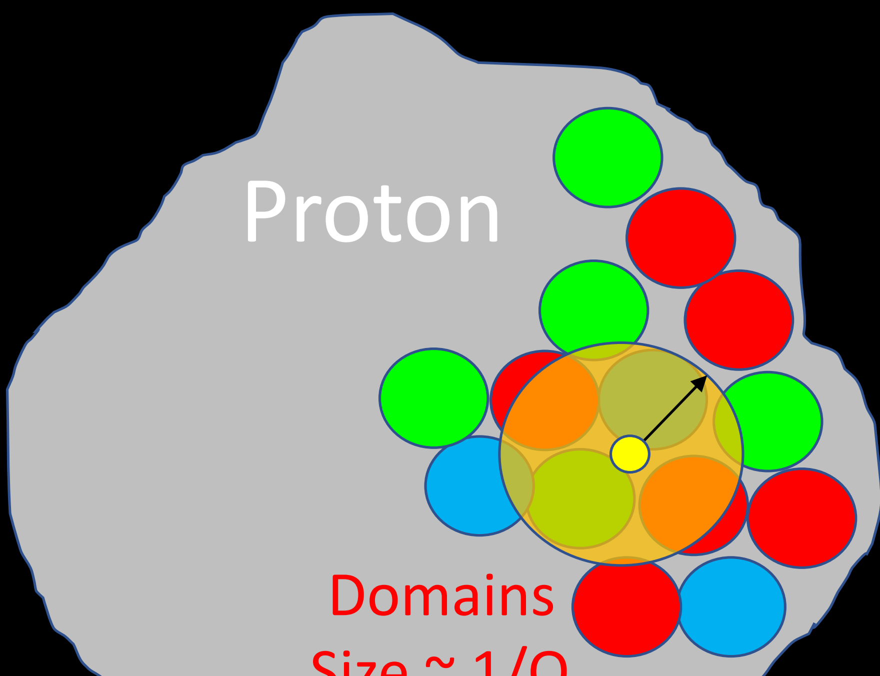
Do these explanations make sense?

Uncertainty Principle

Incoming target gluon with k_T
uncertainty principle blurs the gluon with radius

r [fm] = hbar/k_T = 0.2 / k_T[GeV]

If k_T = 1 GeV, r = 0.2 fm



Projectile (proton) radius ~ 0.9 fm

If Q_s = 2 GeV, r_{domain} = 0.1 fm.
Note that this is x5 larger than value at x = 0.01.

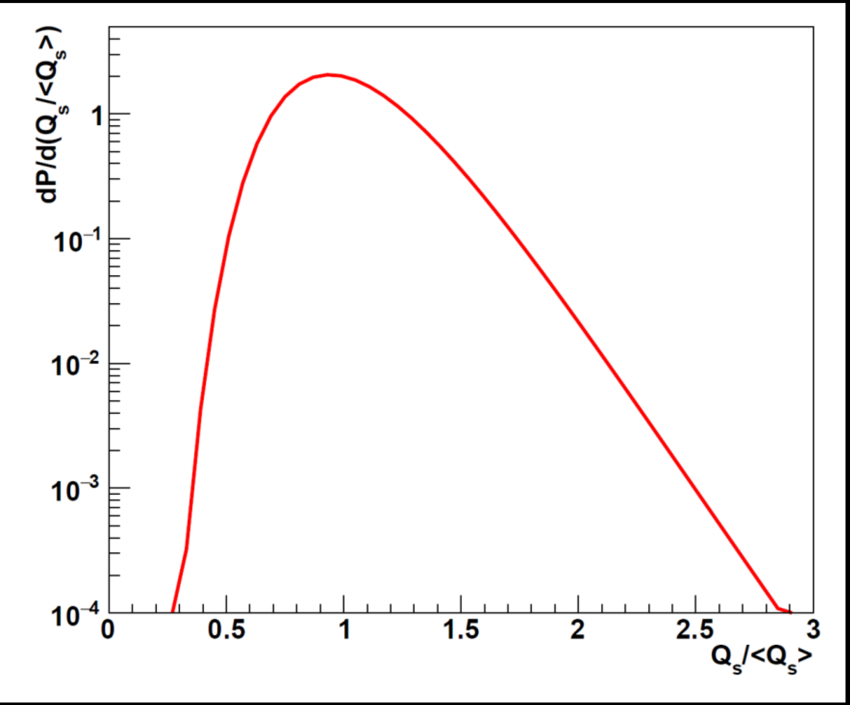
Then target gluon sees
$(Q_s/k_T)^2$ ~ 4 domains at once,
but still not the size of a deuteron!

The "finger physics" numbers seem off by a factor of 5-10

Q_s Fluctuations

MSTV includes nucleon-by-nucleon fluctuations in $Q_{s,0}{}^2$ (the amplitude of the IP-Sat Gaussian). Thus, each nucleon is still a perfect Gaussian, just different amplitudes.

Implemented with variance 0.5 on $\log(Q_s^2)$ – i.e. high side tail.



- Non-perturbative on many scales
- Not part of the standard CGC framework
- *Ad hoc* not *ab initio*

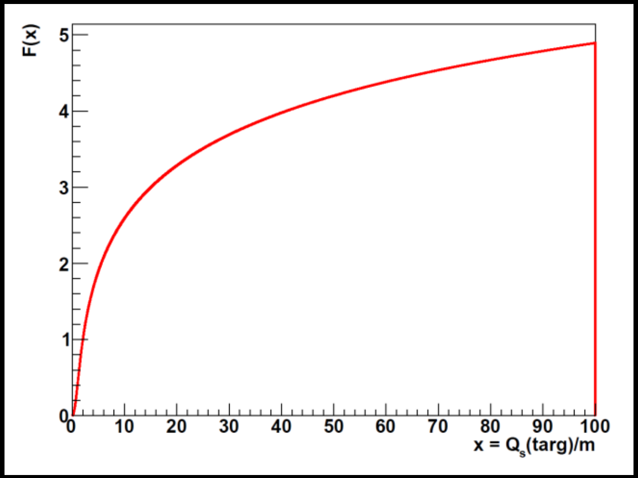
Dilute-Dense Framework

MSTV utilize the dilute-dense framework
(hep-ph/0402256, hep-ph/0402257, arXiv:0711.3039)

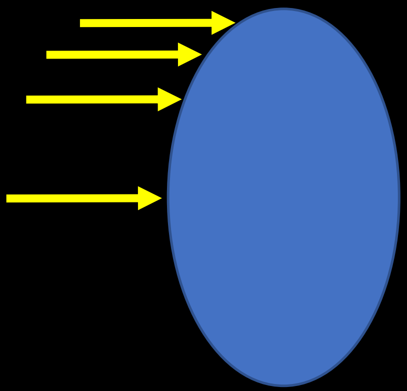
The dilute-dense limit implies that $Q_s(\text{proj}) < k_T < Q_s(\text{targ})$ and one obtains on average:

$$N_{gluon} \propto \; g^2 Q_s^{\,2}(\text{proj}) \times F(\, Q_s(\text{targ})/ m \,) \quad (\text{dilute-dense limit})$$

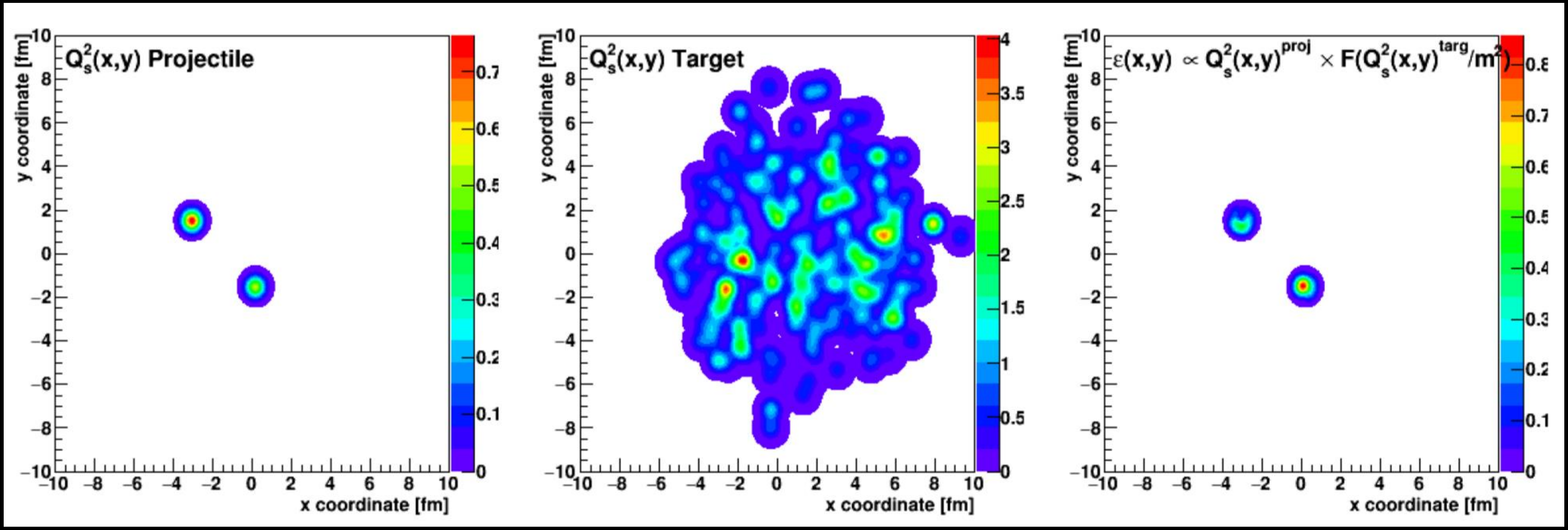
where m is the infrared cutoff (= 0.3 GeV in MSTV).



Once you hit a thick enough part of the target, you free all the projectile gluons and no more.



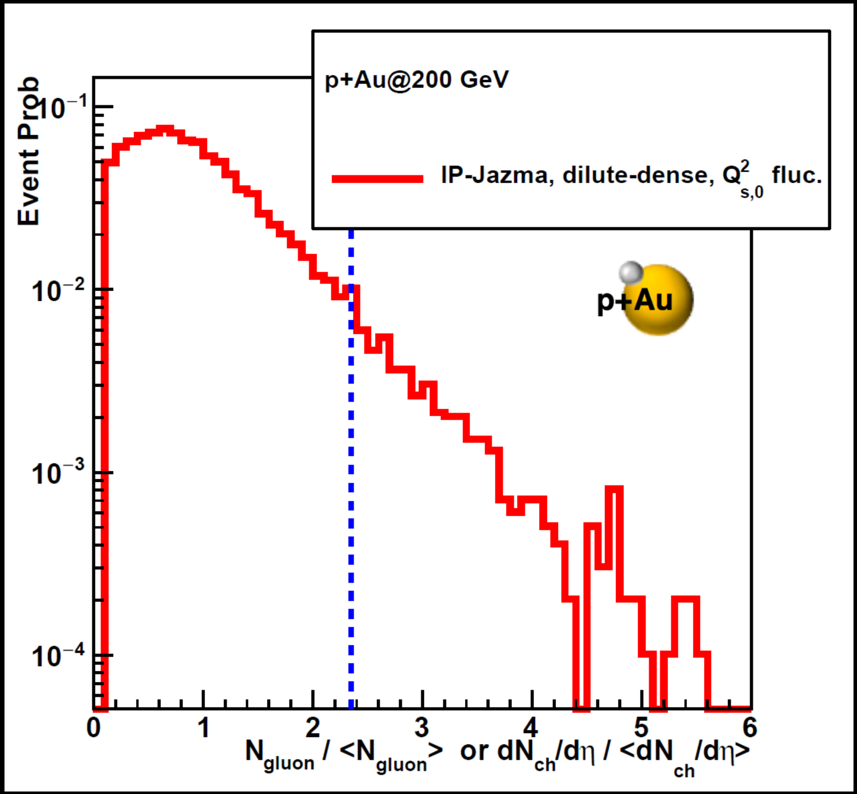
IP-Jazma Results

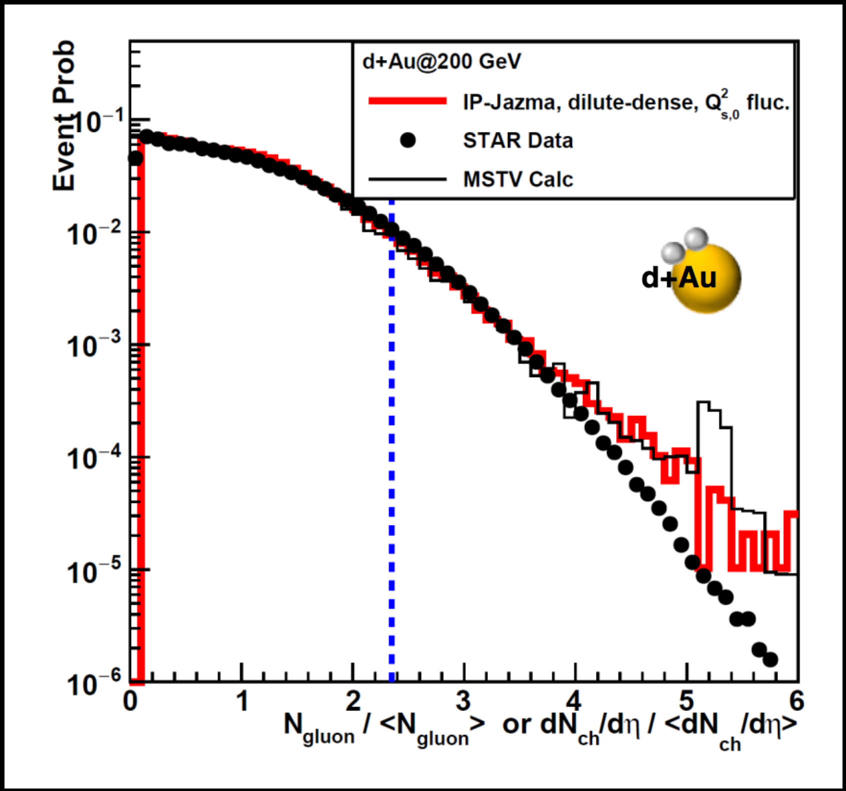


At this point, none of these fluctuations are *ab initio*.

All MC Glauber and "put-in-by-hand" $Q_{s,0}{}^2$ fluctuations.

IP-Jazma: 5% p+Au has $Q_{s,0}^2$ 2.2x larger, 5% d+Au has $Q_{s,0}^2$ 1.7x larger



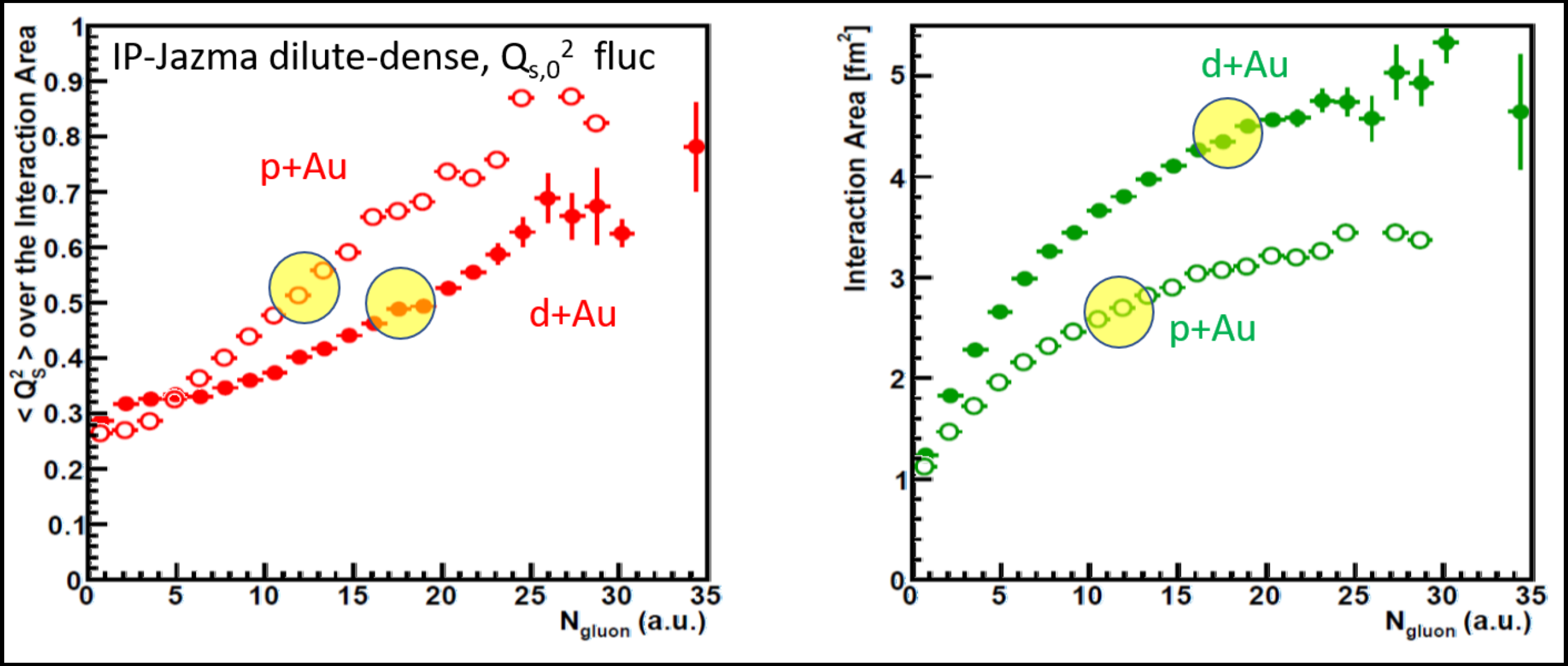


<u>Essentially perfect agreement of d+Au multiplicity with MSTV</u>

Distribution dominated by ad hoc $Q_{s,0}^2$ fluctuations;
other color fluctuations not in evidence!

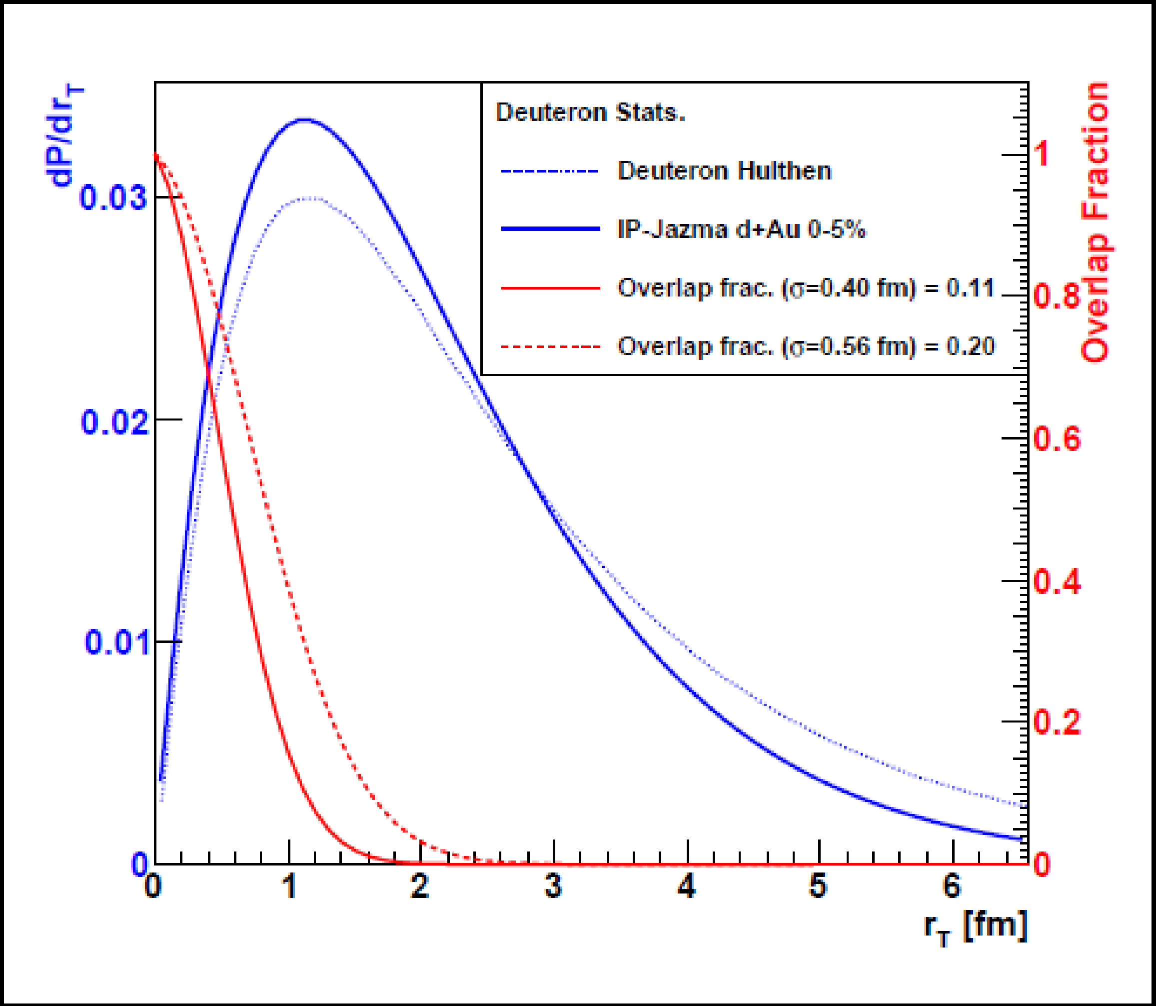
MSTV: larger correlation in d+Au because of larger color charge density

IP-Jazma: Not true.
Central d+Au collisions do not have a higher gluon density, but rather a larger overlap area.



Then why do they find $v_2(dAu) > v_2(pAu)$?

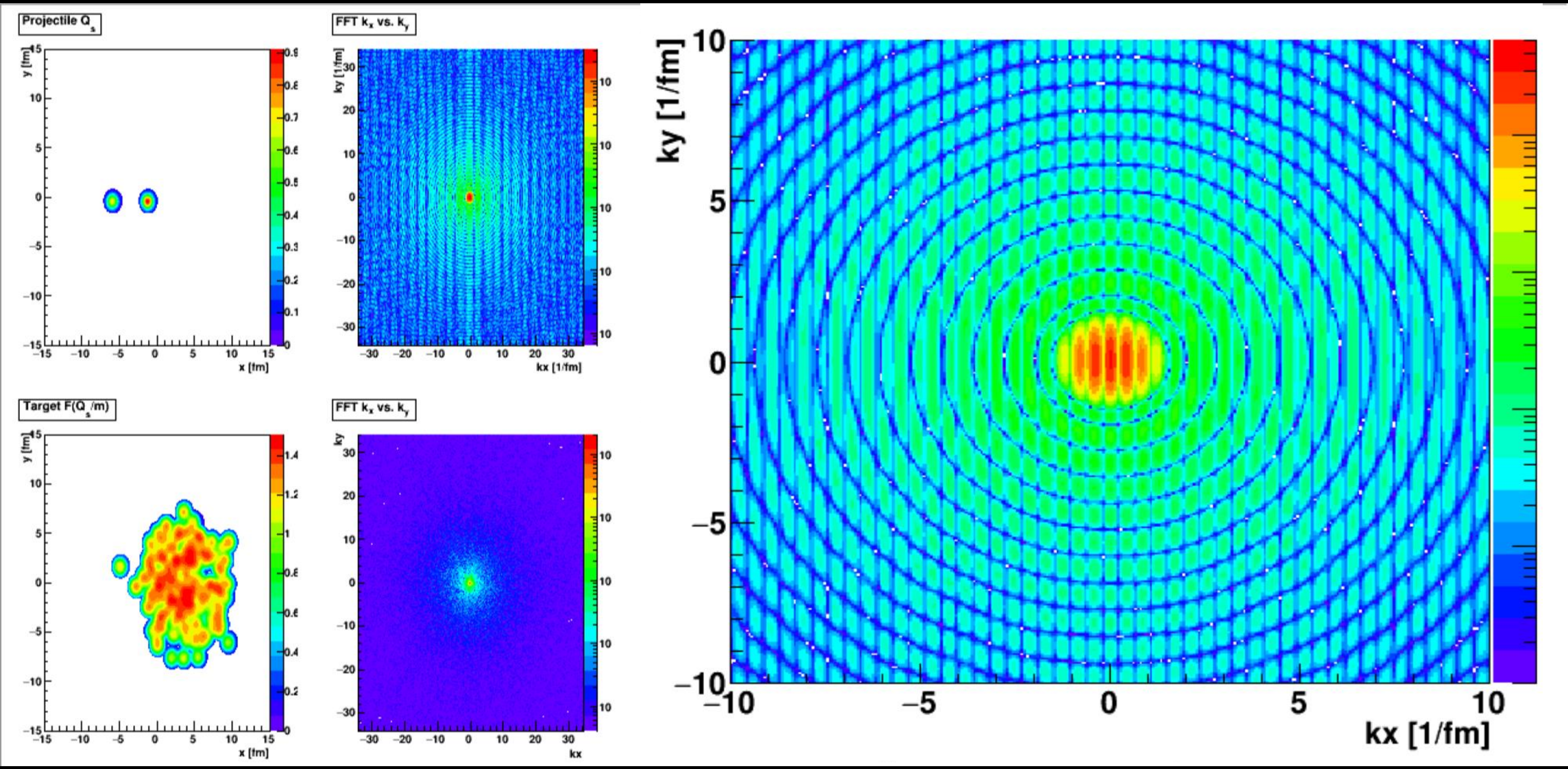
Bias to closer deuteron configurations



IP-Jazma published result for bias in overlap (rather small)

It would be great to compare with the MSTV result!

Momentum Space Calculation (FFT)



The k_T kicks from the projectile comes from the Fourier Transform.
Maybe it is just geometry after all.

Simple test – calculate v_2 with respect to the deuteron axis.

Concluding Question

One should consider whether there are any non-trivial features that can be ascribed to saturation physics in heavy ion collisions.

Does this consideration help inform a future program of saturation physics at the Electron Ion Collider?

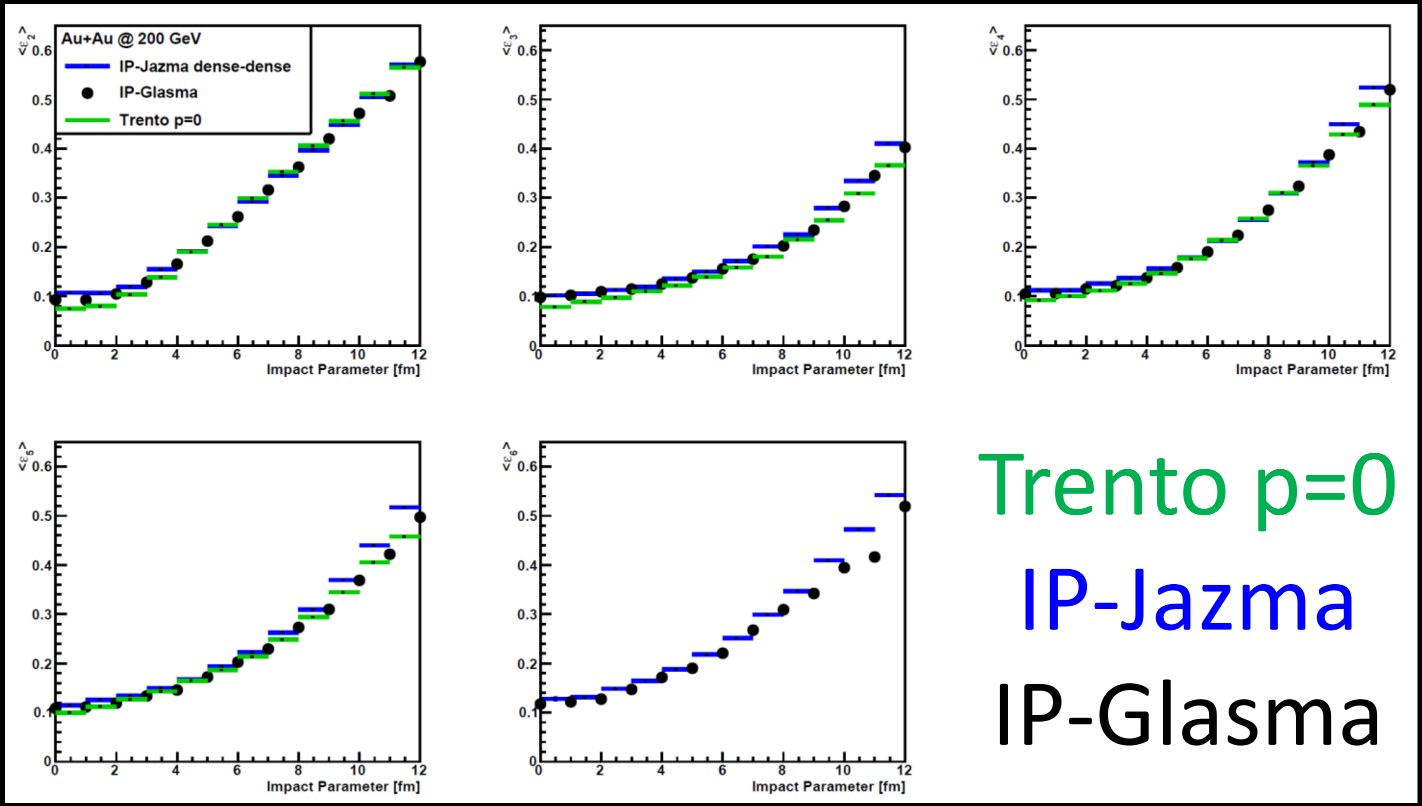
Extras

Trento Initial Condition Comment

Trento p=0 yields similar geometry to IP-Glasma

$$T_R = \sqrt{T_A T_B} \qquad p = 0, \qquad \text{(geometric)}$$

However, there is a difference of the SQRT and thus Gaussian widths cannot be compared directly.



Ab initio or *non pertinet*

$Q_{s,0}^2$ (gluon) = 0.67 GeV^2
for x = 0.01 at the very center
of the proton,
and averaged over
r = 0.67 fm the value would be
Q_s^2 (gluon) = 0.28 GeV^2

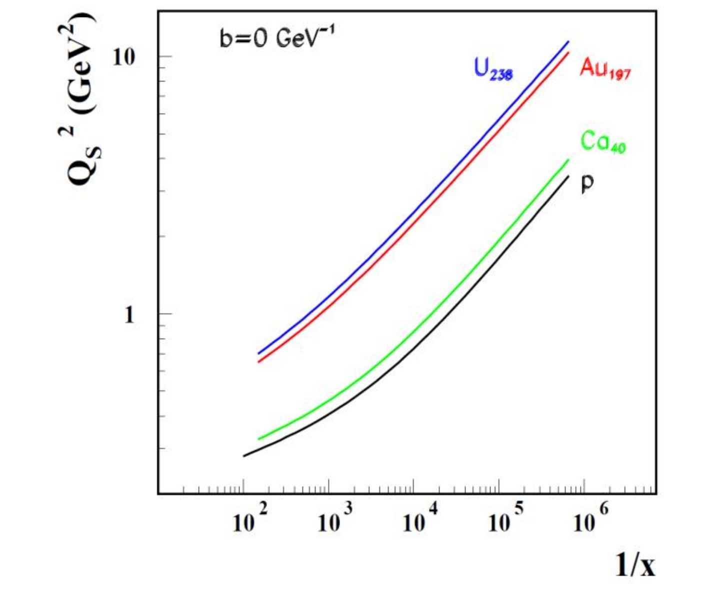
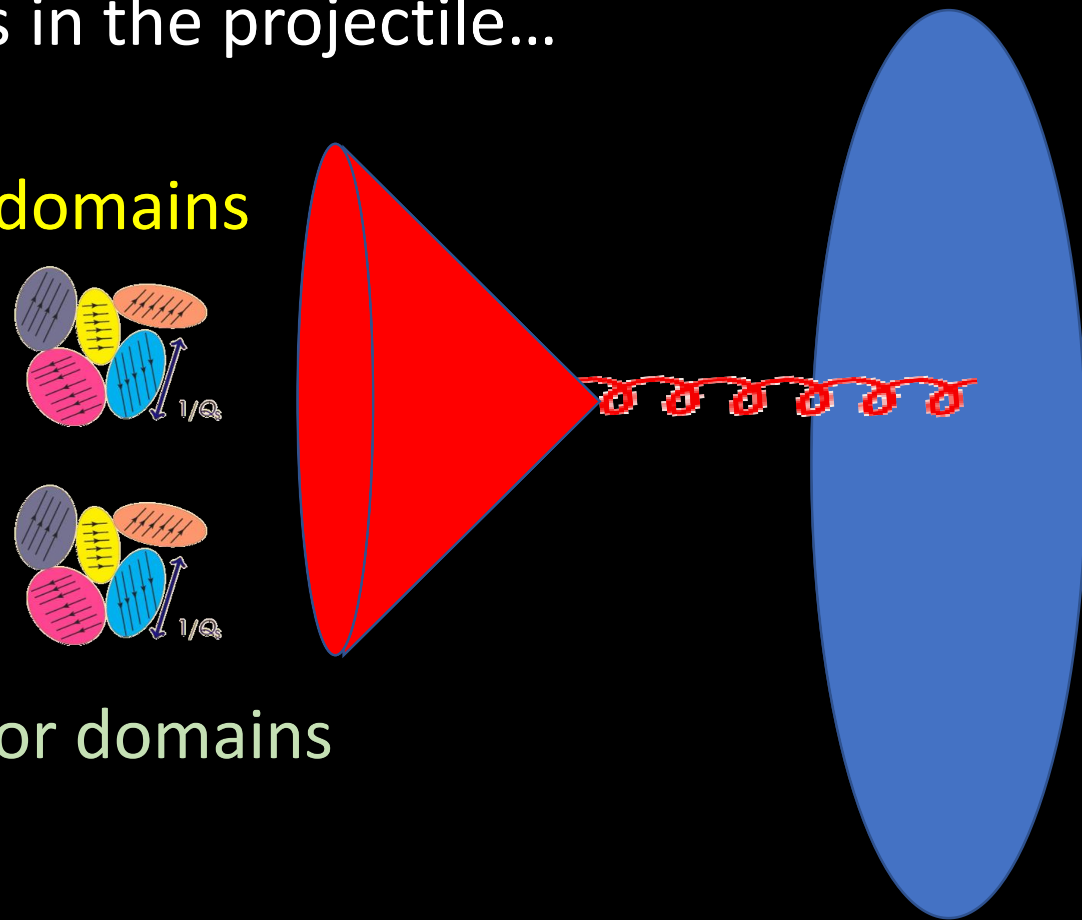


FIG. 25: The quark saturation scale $(Q_s^2)_q$ at $b = 0$ as a function of x for various nuclei . The gluon saturation scale is $(Q_s^2)_g = \frac{N_c}{C_F}(Q_s^2)_q \approx 2.25\,(Q_s^2)_q$.

Essential physics

Think of a gluon with k_T from the target and its interaction with domains in the projectile…

Proton color domains

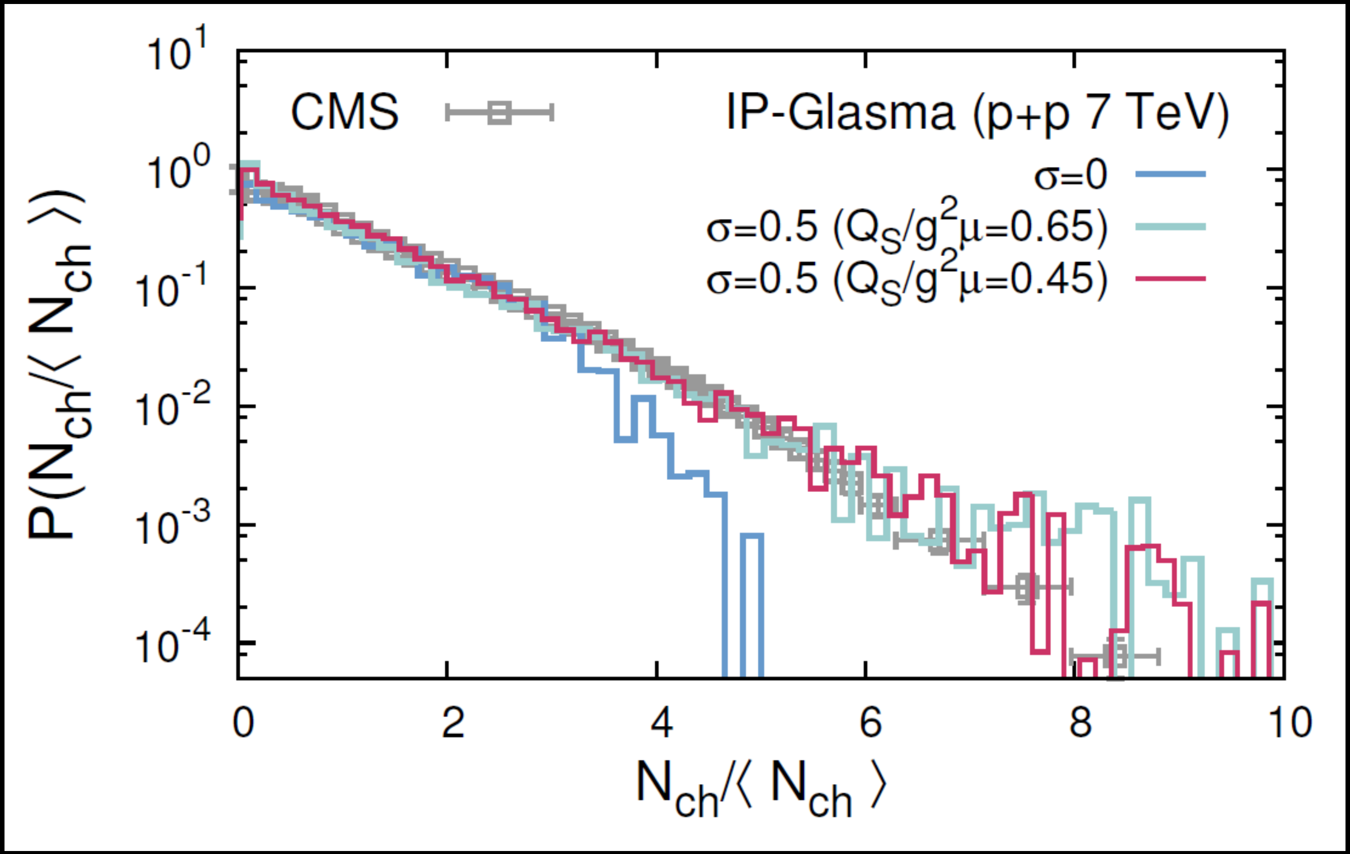


Deuteron color domains

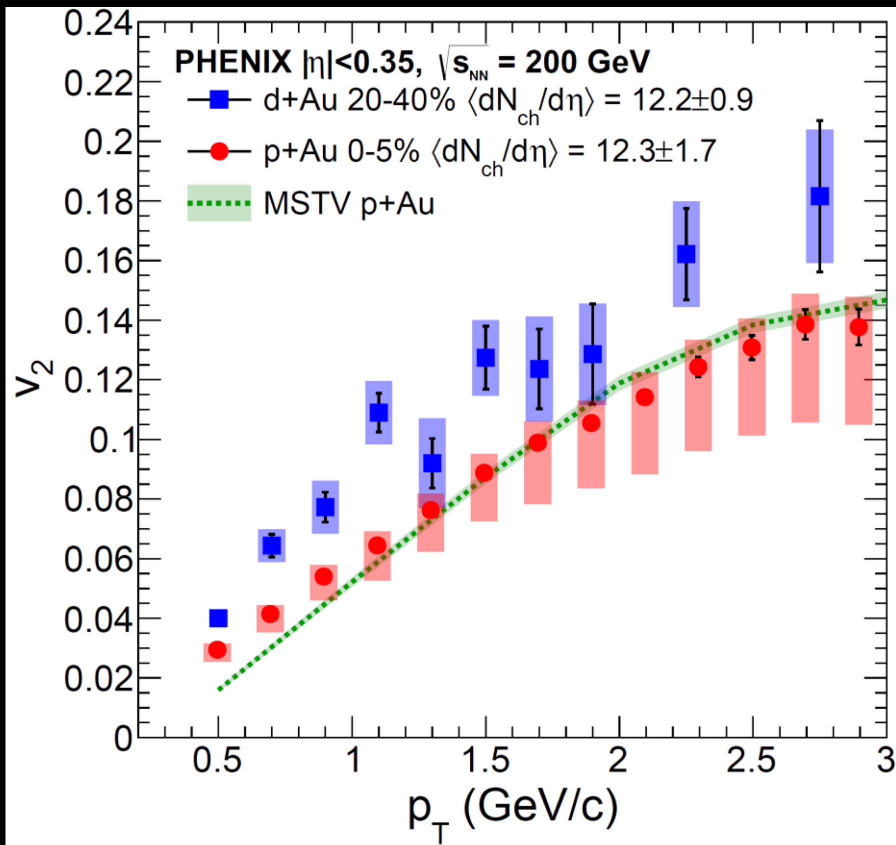
Uncertainty principle blurring of gluon allows it to interact with multiple domains.

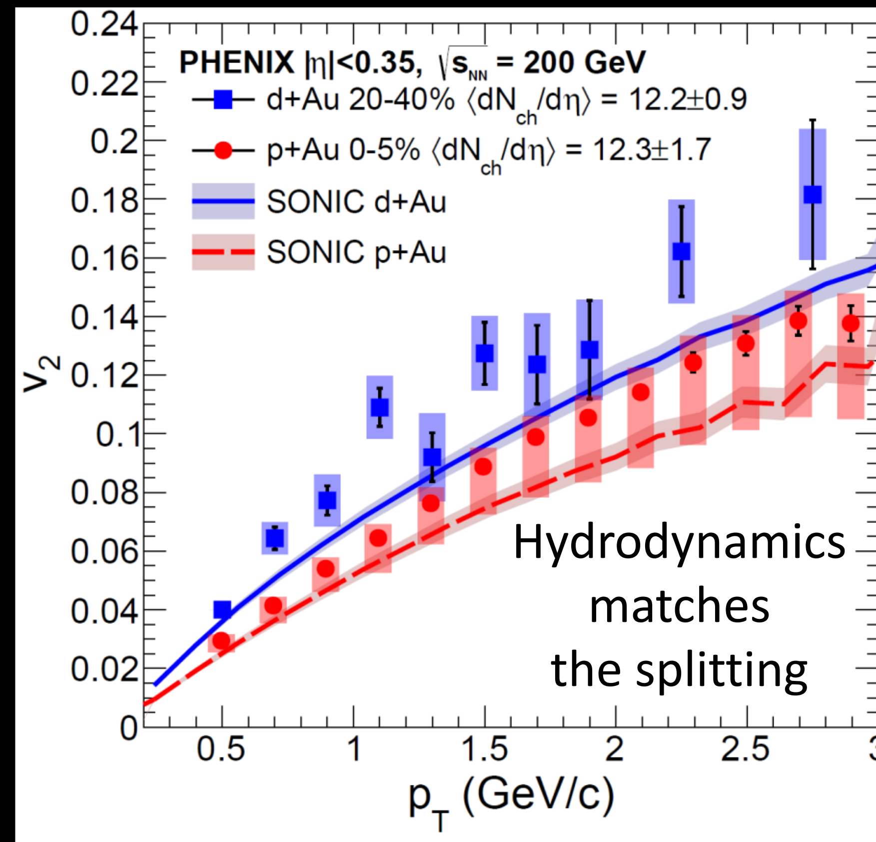
Explored by McLerran (arXiv:1508.03292v2) to explain high multiplicity tail of LHC p+p N_{ch} distributions.

$Q_{s,0}^2$ fluctuates to 5-6 times average value to explain the high N_{ch} tail.

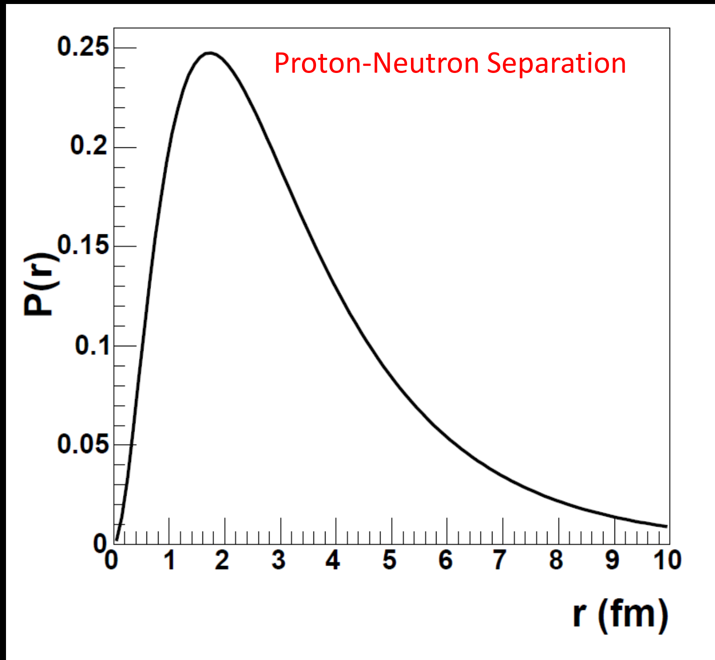


MSTV scaling of N_{ch} with Q_s^2(proj) leads them to predict "that $v_{2,3}(p_T)$ for high multiplicity events across small systems should be *identical* for the same N_{ch}."





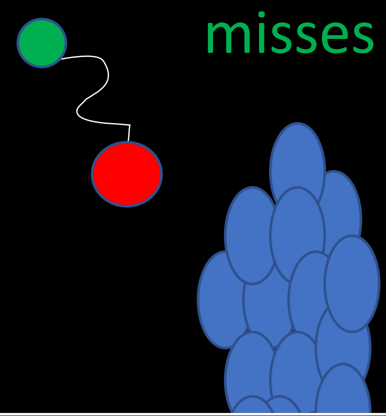
Turns out this prediction is actually yet another postdiction
Existing PHENIX measurement already rules this out!

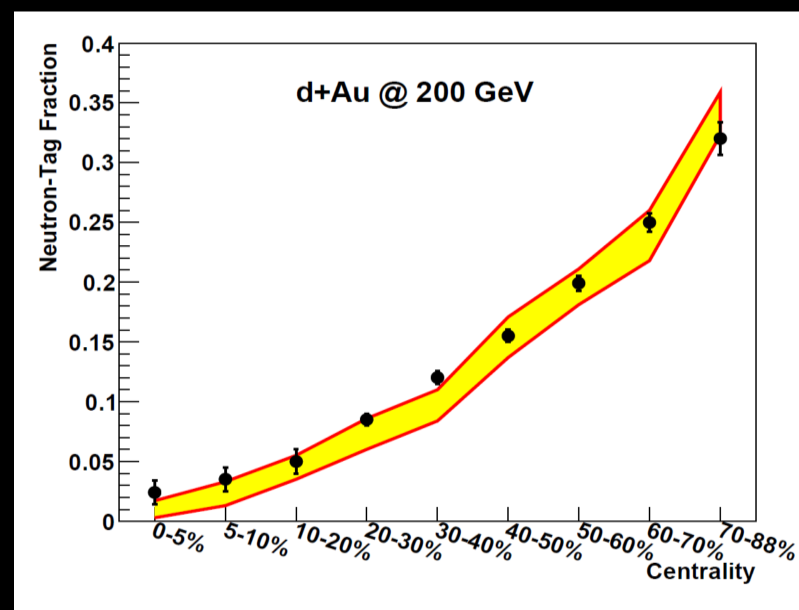


Deuteron is a loosely bound system

d+Au

Sometimes the neutron misses





http://journals.aps.org/prc/abstract/10.1103/PhysRevC.90.034902

Romatschke & Romatschke (https://arxiv.org/abs/1712.05815)

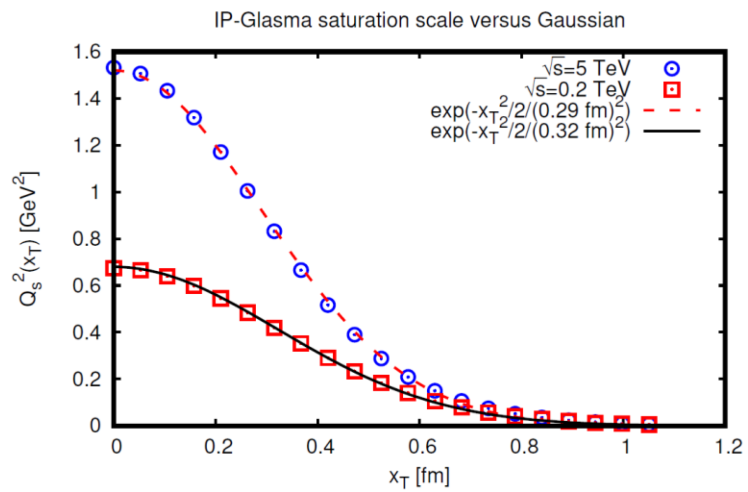


Figure 4.5: Transverse coordinate dependence of the saturation scale in the IP-Glasma model from Eq. (4.35) for two representative center-of-mass collision energies $\sqrt{s}$. For comparison, a simple Gaussian parametrization is shown.

$$Q_s^2(x, \mathbf{x}_\perp) = \frac{\pi}{3R^2}\alpha_s\left(Q_0^2 + 2Q_s^2\right) f\left(x, Q_0^2 + 2Q_s^2\right) e^{-\frac{\mathbf{x}_\perp^2}{2R^2}}, \qquad (4.35)$$

At RHIC energies, resulting Gaussian in Q_s^2 has $\sigma = 0.32$ fm. Note that this corresponds to a Gaussian in Q_s with $\sigma = 0.45$ fm.

Of course this depends on your choice of B_G, translating into R in the equation below.

$$\chi_A(\mathbf{x}_\perp) \propto \sum_{i=1}^{A} Q_s^2(x, \mathbf{x}_\perp^{(i)}),$$

In dense-dense limit, just sum Q_s^2 values for each nucleus. Then energy density proportional to T_{A1A2} scaling

as defined in (4.7). The final result for the energy density in the weak-coupling approximation then reads

$$\langle T^{\tau\tau}\rangle_{\rm cf} \propto g^2 T_{A_1}(\mathbf{x}_\perp) T_{A_2}(\mathbf{x}_\perp + \mathbf{b}_\perp) + \mathcal{O}(\tau^2). \qquad (4.44)$$