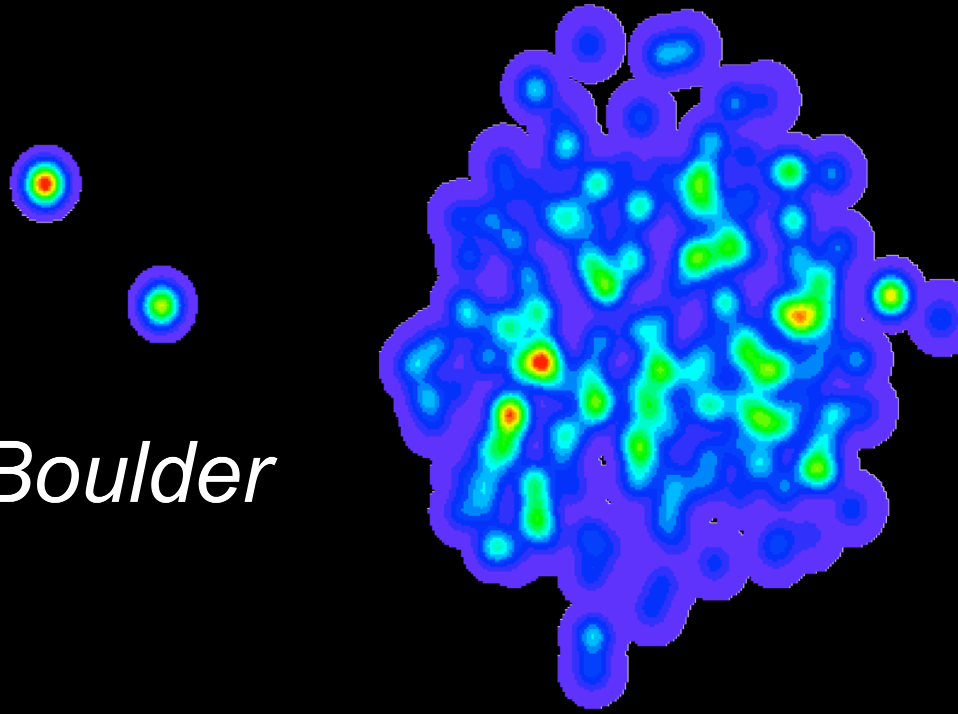
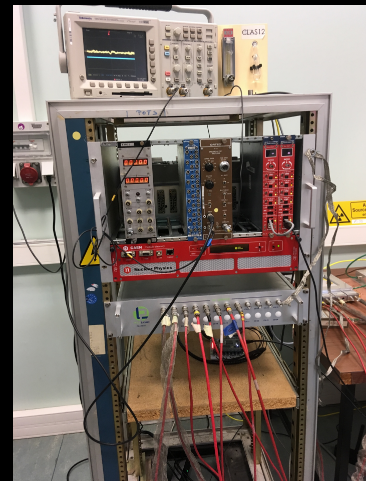
Creating circular, elliptical, and triangular droplets of quark-gluon plasma

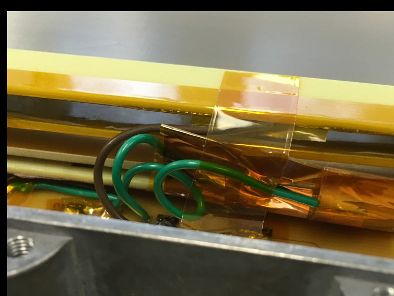


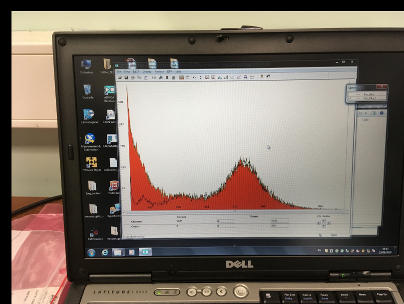
Jamie Nagle
University of Colorado Boulder
and CEA/IPhT/Saclay

CEA/Saclay Seminar – August 24, 2018

sPHENIX work on MicroMegas during 4 months in Saclay…





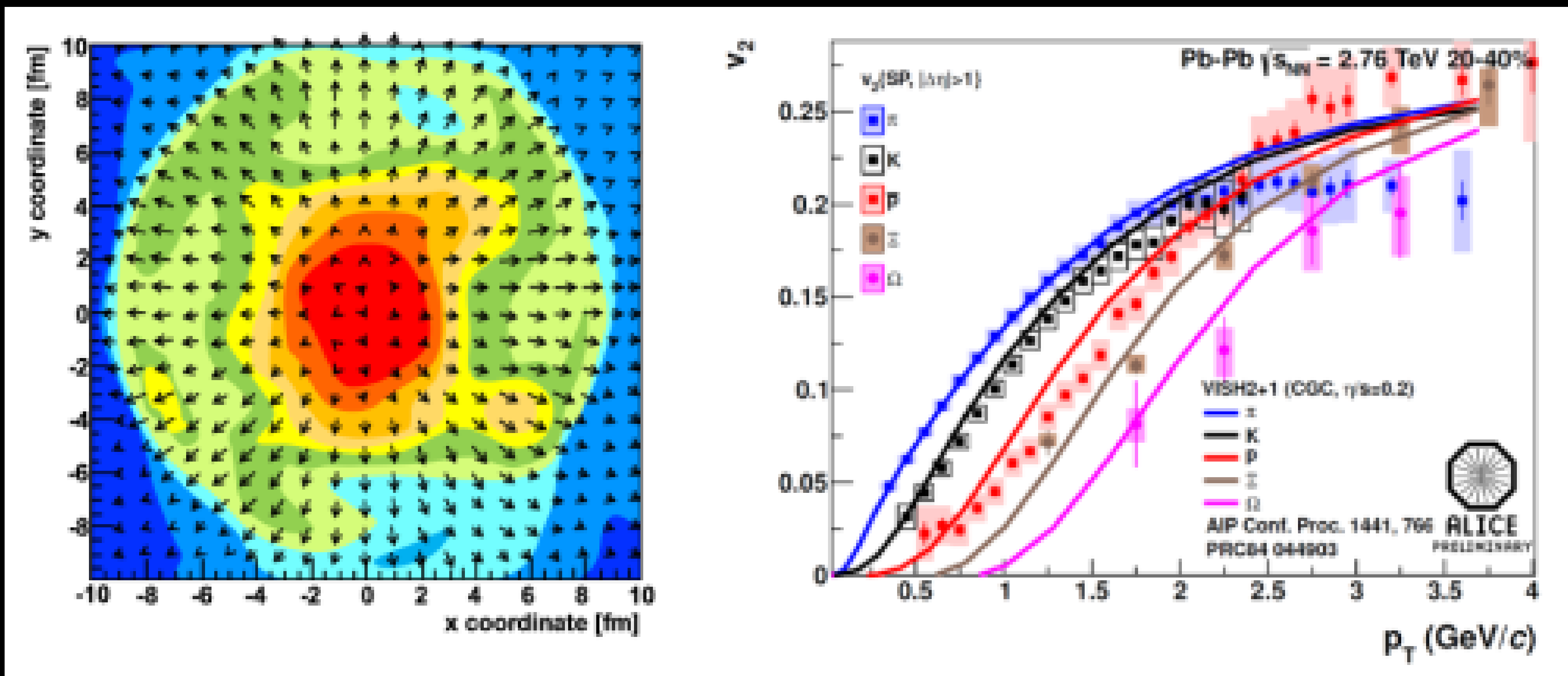


Department of Energy CD-1 and CD-3A approval!

Hopefully an exciting sPHENIX seminar in 4-5 years
with new physics!

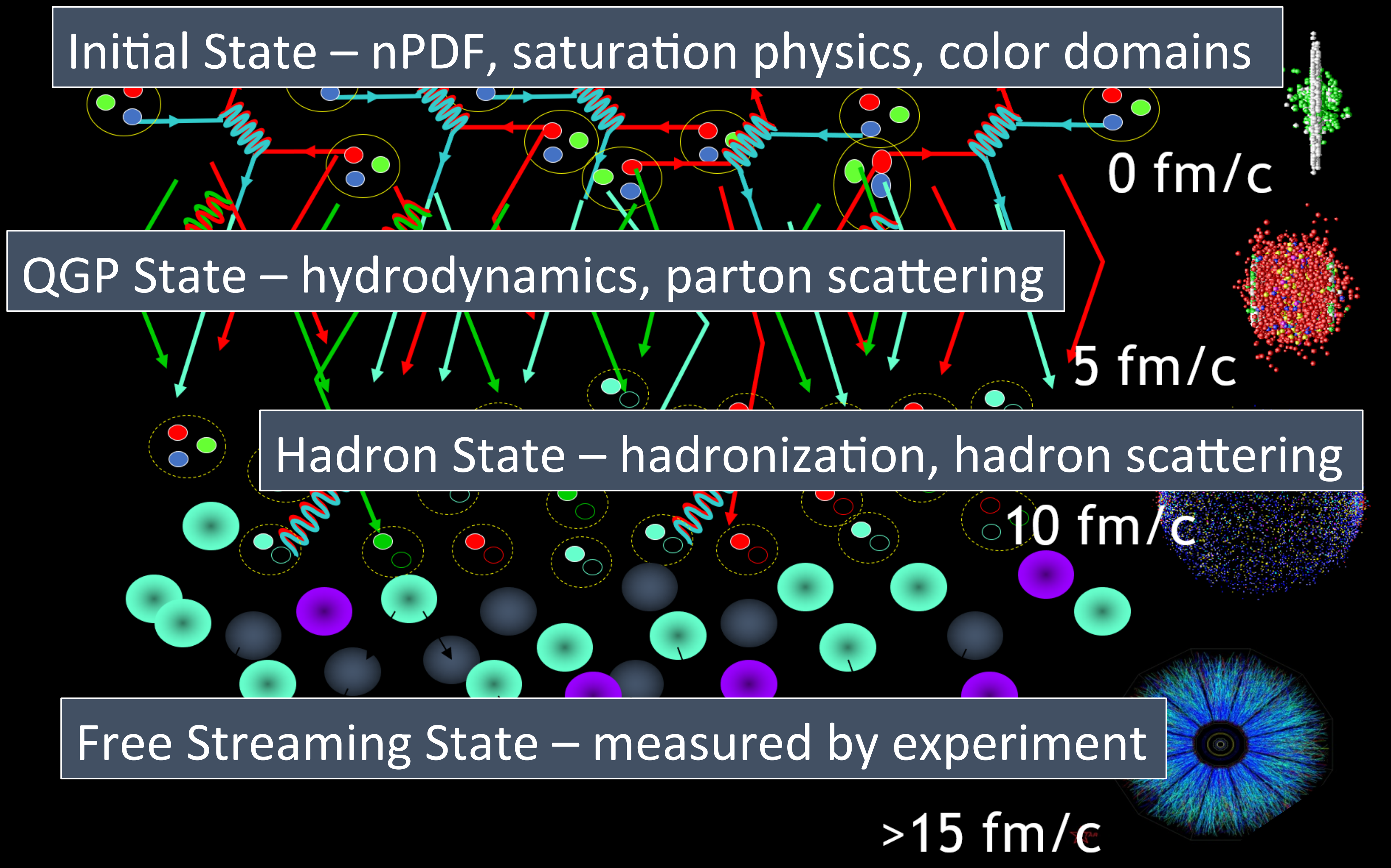
Standard Model of Heavy Ion Collisions

At RHIC and LHC, energy deposit over system R >> λ_{mfp},
hydrodynamic evolution of quark-gluon plasma
followed by hadronization and scattering



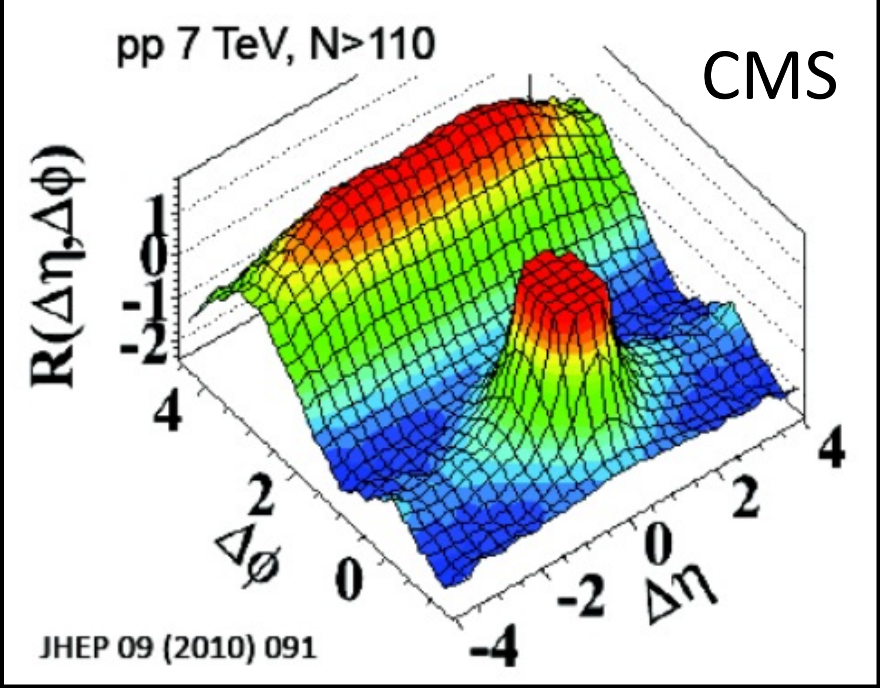
Standard Model tested in great detail and with precision

Nagle and Zajc, Annual Review, https://arxiv.org/abs/1801.03477
Snellings and Heinz, Annual Review, https://arxiv.org/abs/1301.2826


Initial State – nPDF, saturation physics, color domains
0 fm/c
QGP State – hydrodynamics, parton scattering
5 fm/c
Hadron State – hadronization, hadron scattering
10 fm/c
Free Streaming State – measured by experiment
>15 fm/c

Mini Quark-Gluon Plasma?

In 2010, hints of similar phenomena in super high-multiplicity p+p collisions (1/100,000)



Long ago Bjorken postulated QGP formation in p+pbar via the creation of a modified vacuum state and was not concerned about the small number of final state hadrons

Nagle and Zajc, Annual Review, https://arxiv.org/abs/1801.03477

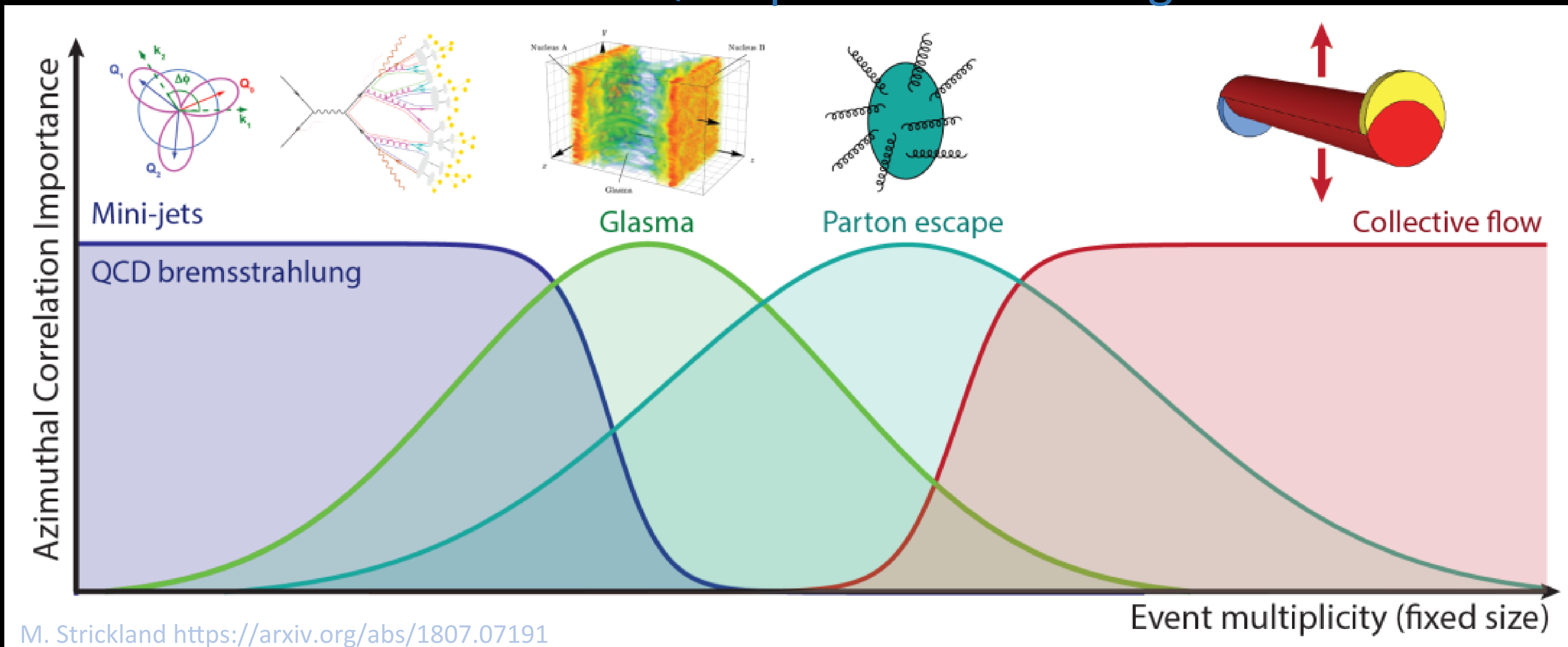
Alternative Menu of Options

Non-Flow

Initial-State

Quasiparticle Scattering

QGP Hydrodynamics

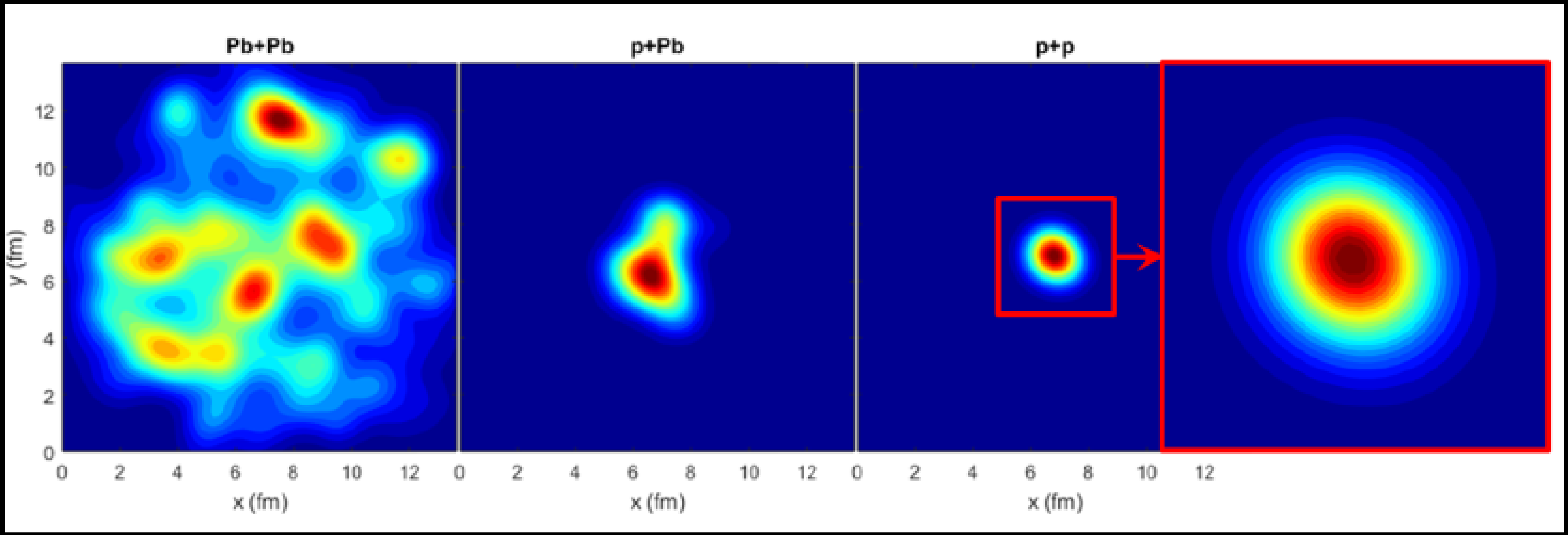


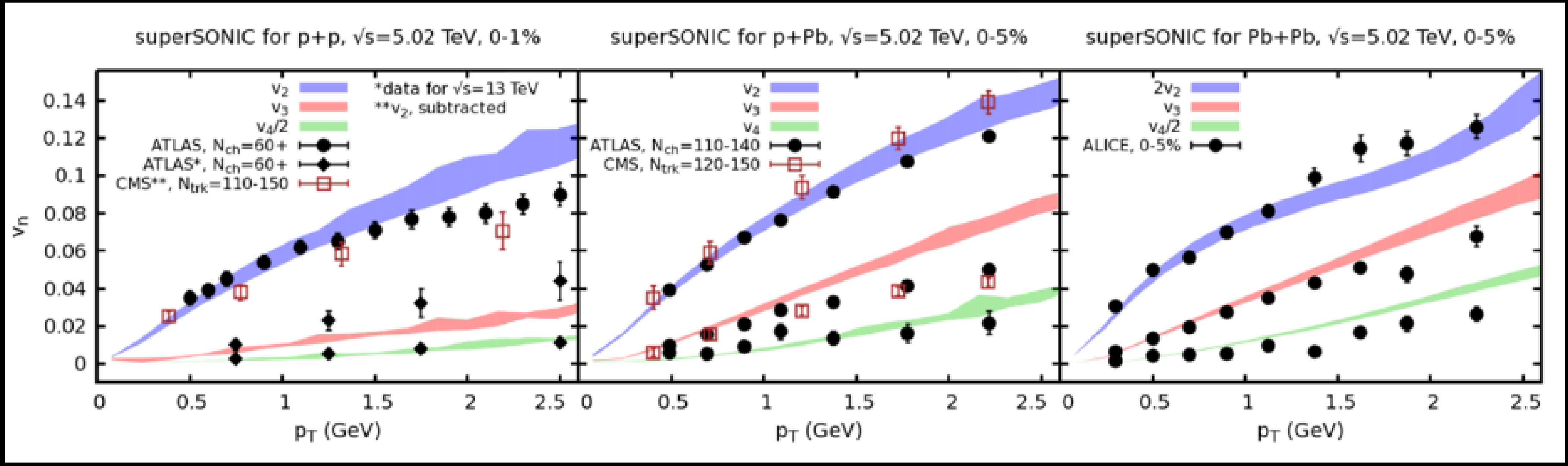
Cartoon does not make physics. What is the x-axis really?

Consider different geometries, system size, different energies, etc.

Also, each needs to mimic all the signals

"One fluid to rule them all"





Weller and Romatschke, https://arxiv.org/abs/1701.07145

Code is all publicly available and documented.
Multiple groups cross checking and producing consistent results (for example iEBE-VISHNU).

What are the systematic uncertainties, open items?

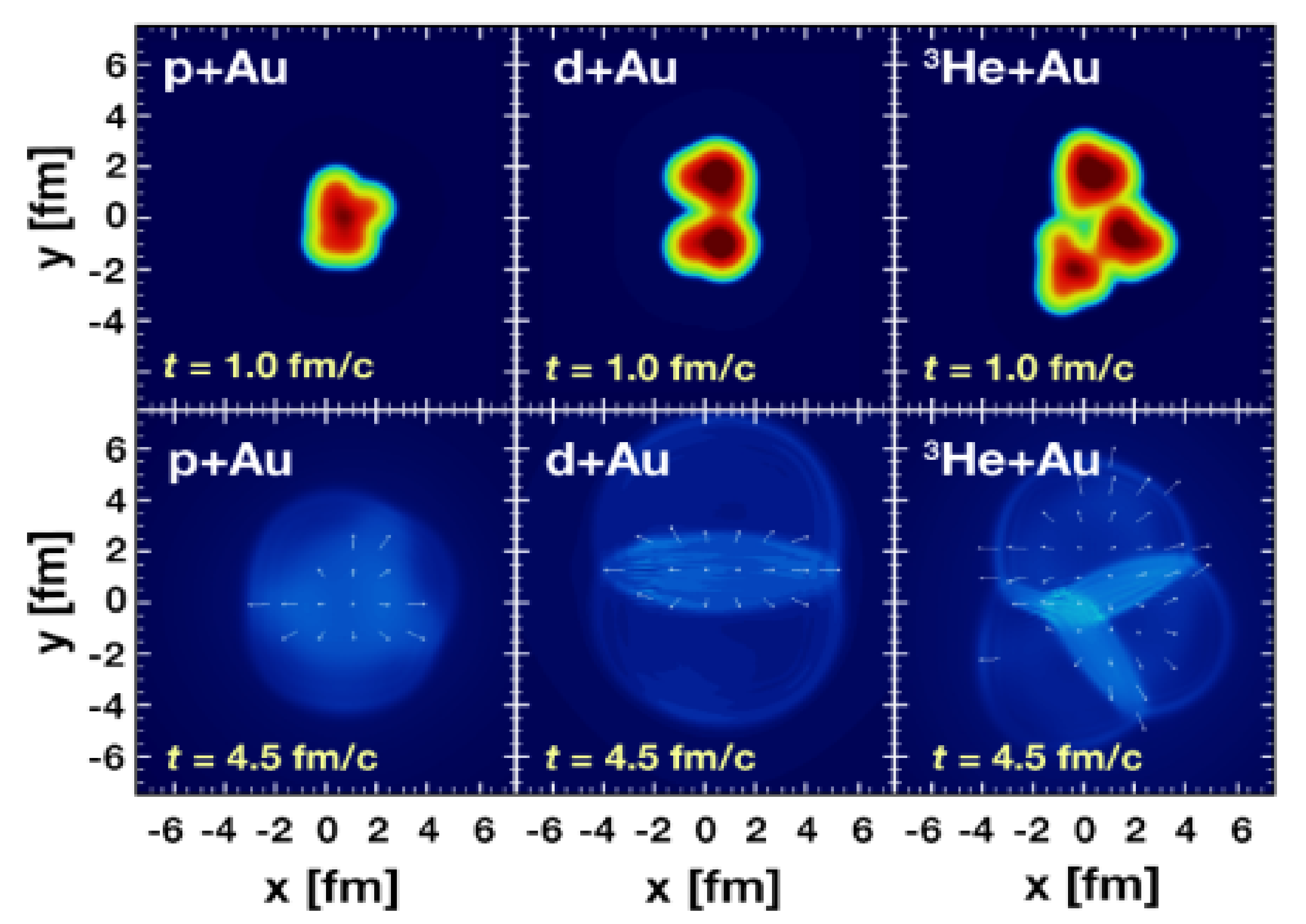
- MC Glauber + Constituent Quarks needed for p+p and includes some Gaussian σ value for local "gluon cloud"
- Bulk viscosity important to temper large radial expansion in p+p, but not as critical in A+A
- Pre-equilibrium (superSONIC) or not (SONIC)
- Unknown $\eta/s(T)$ value.
  superSONIC results with $\eta/s = 1/4\pi$ for all systems.
- Hadronic cascade model (B3D in superSONIC)
- Important questions about hydro far from equilibrium which is an entire other talk (!)

RHIC Geometry Scan

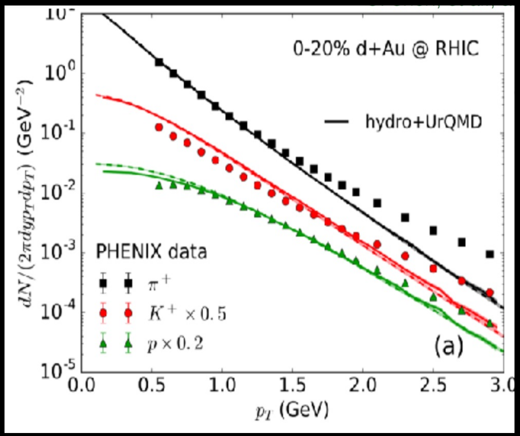
PRL 113, 112301 (2014) PHYSICAL REVIEW LETTERS week ending 12 SEPTEMBER 2014

Exploiting Intrinsic Triangular Geometry in Relativistic ^{3}He + Au Collisions to Disentangle Medium Properties

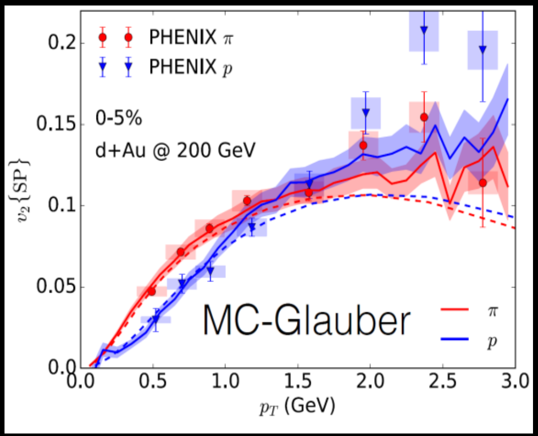
J. L. Nagle,[1,*] A. Adare,[1] S. Beckman,[1] T. Koblesky,[1] J. Orjuela Koop,[1] D. McGlinchey,[1] P. Romatschke,[1] J. Carlson,[2] J. E. Lynn,[2] and M. McCumber[2]



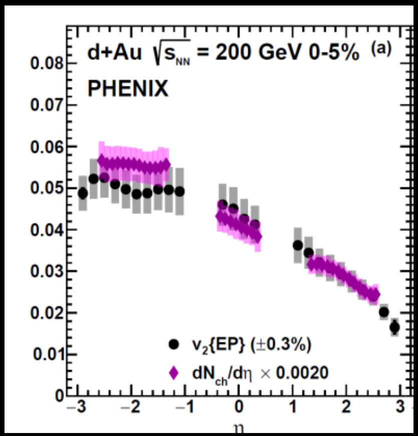
Cornucopia of d+Au Data



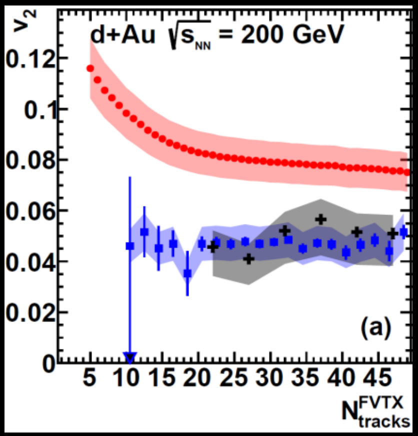
PID Spectra



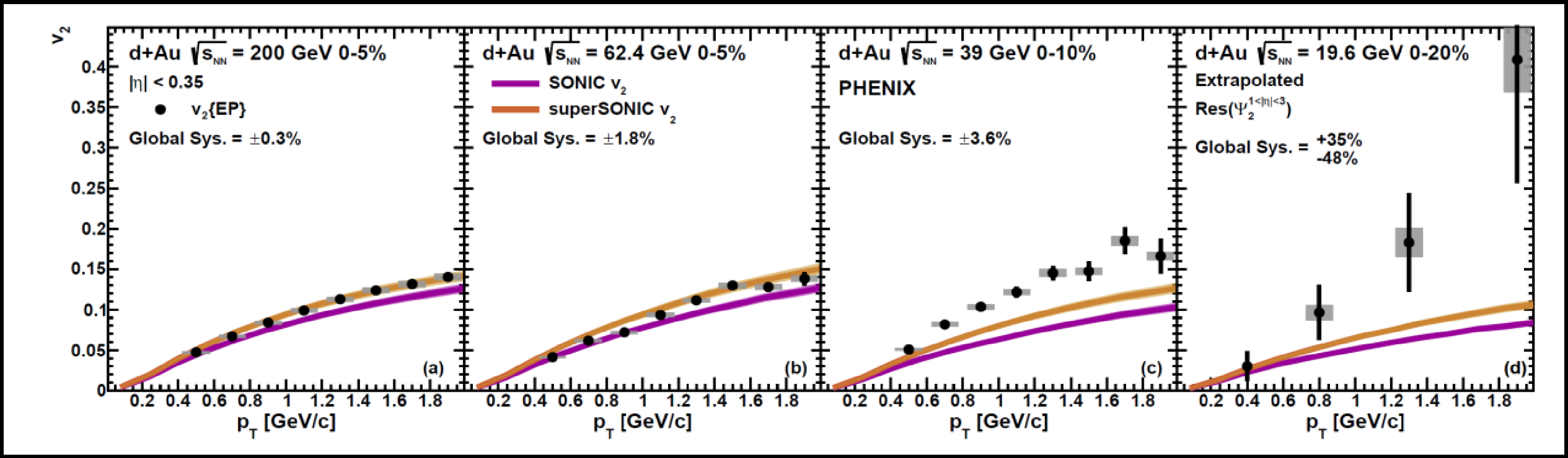
$v_2(p_T)$ PID



$v_2(\eta)$

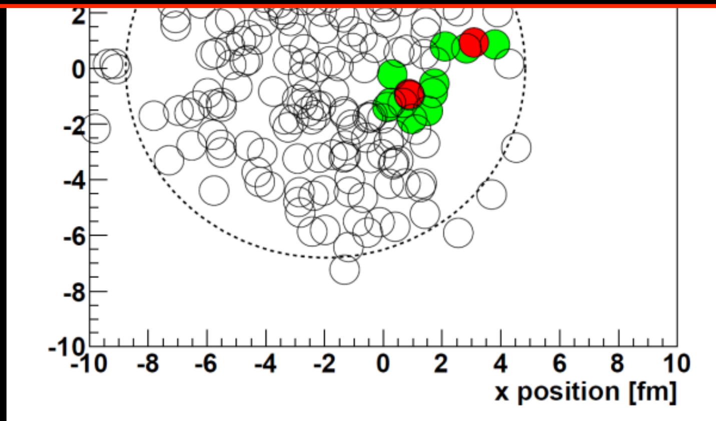


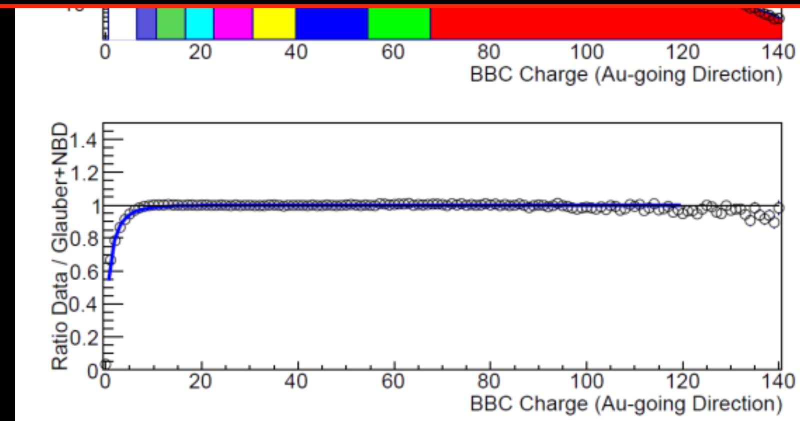
$v_2\{2\}$, {4}, {6}

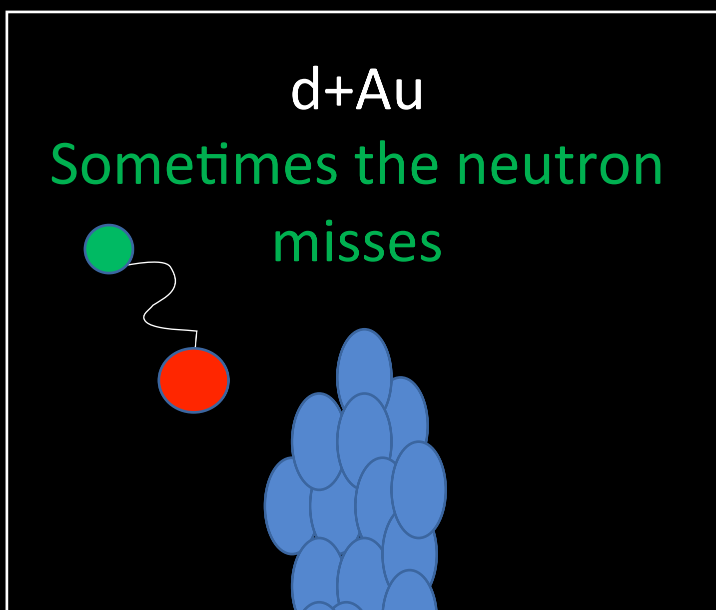


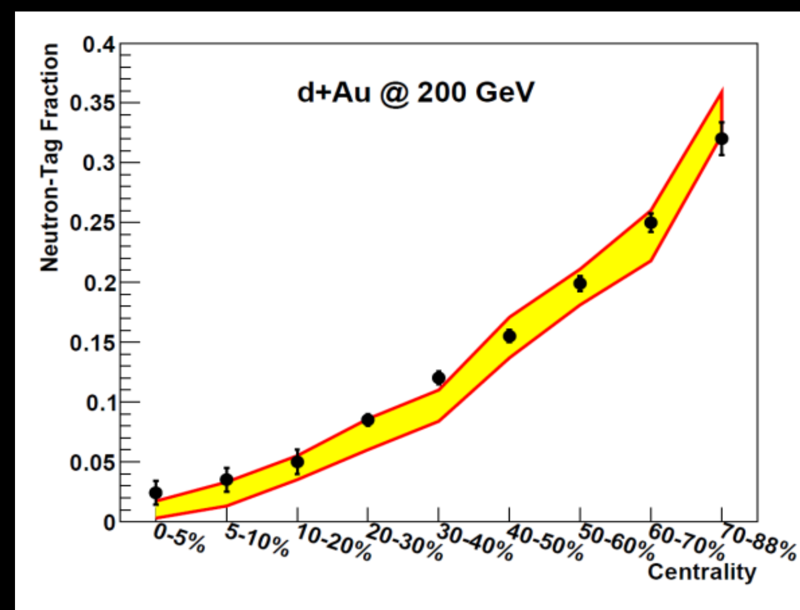
d+Au beam energy scan → 200 GeV, 62.4, GeV, 39 GeV, 19.6 GeV →

Deuteron wavefunction is well known and the geometry validated by experiment



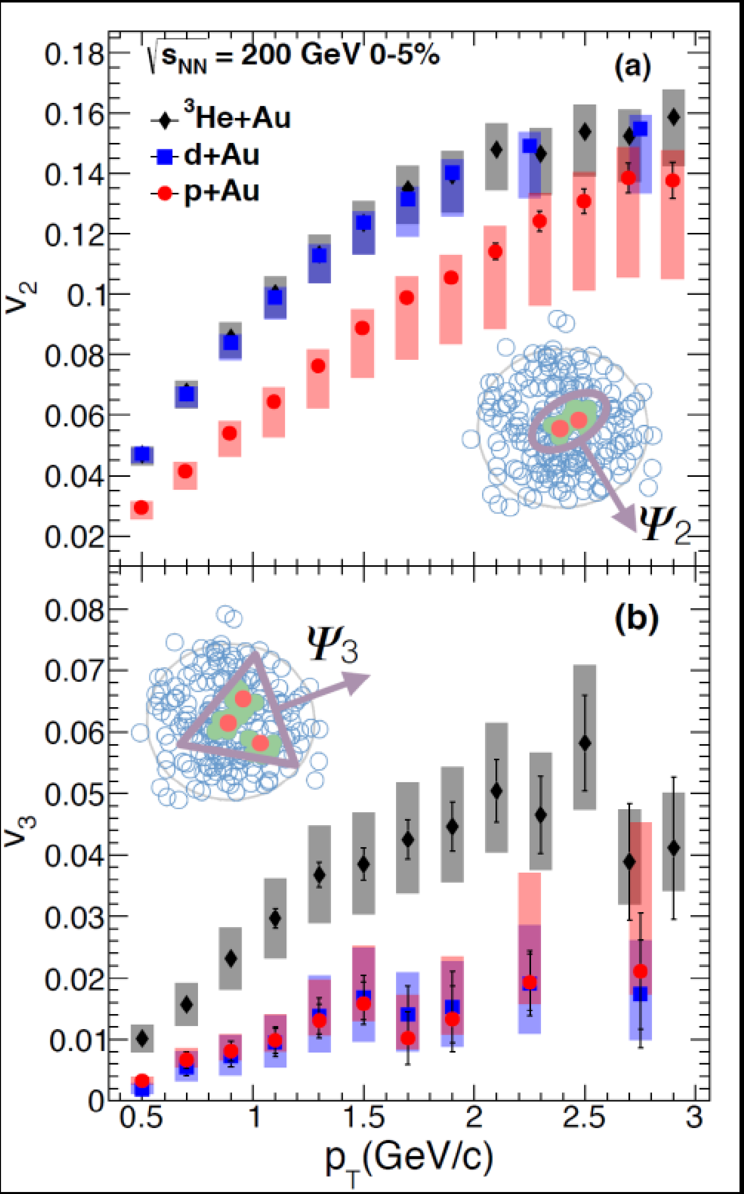




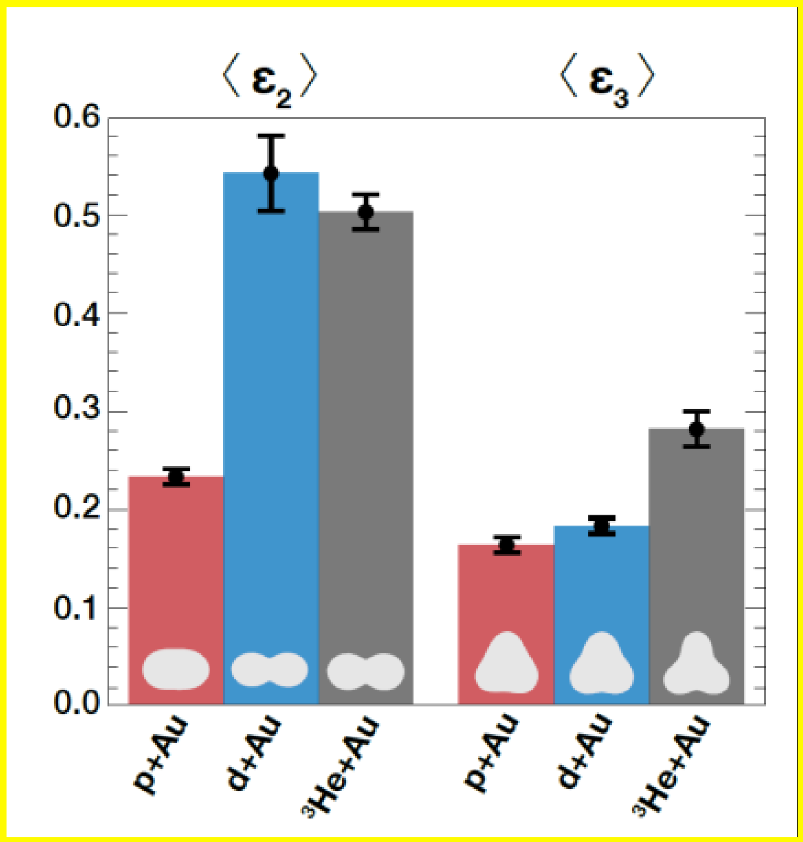


http://journals.aps.org/prc/abstract/10.1103/PhysRevC.90.034902

Experimental Data



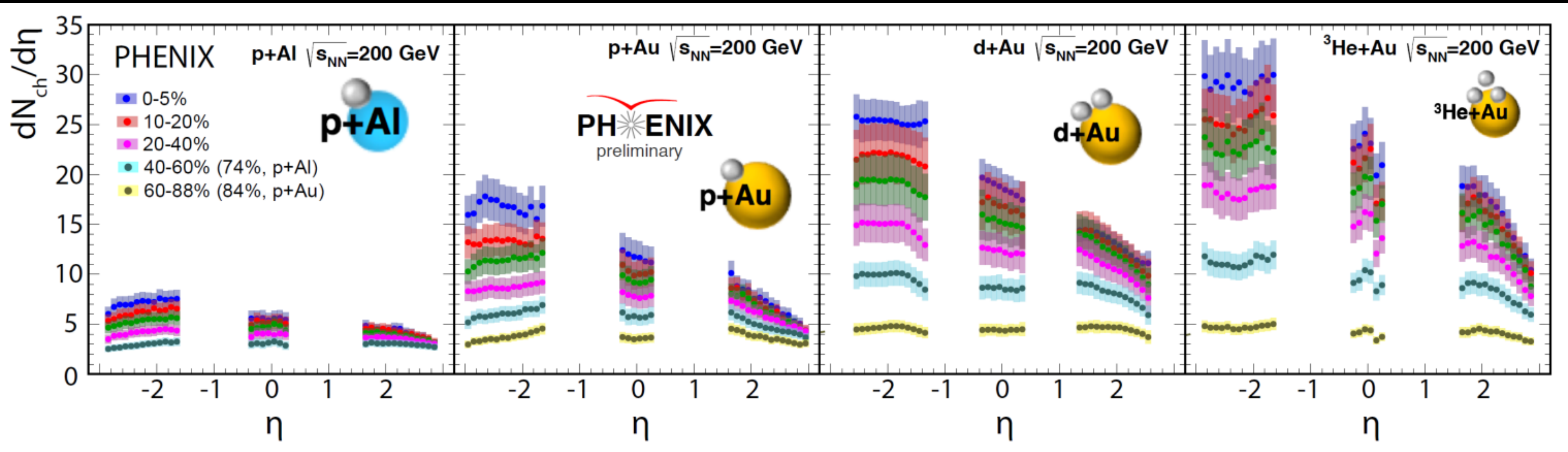
Follows ordering of eccentricities



However, multiplicity also plays a role

PHENIX, https://arxiv.org/abs/1805.02973

Particle Multiplicities



https://arxiv.org/abs/1807.11928

Midrapidity Values

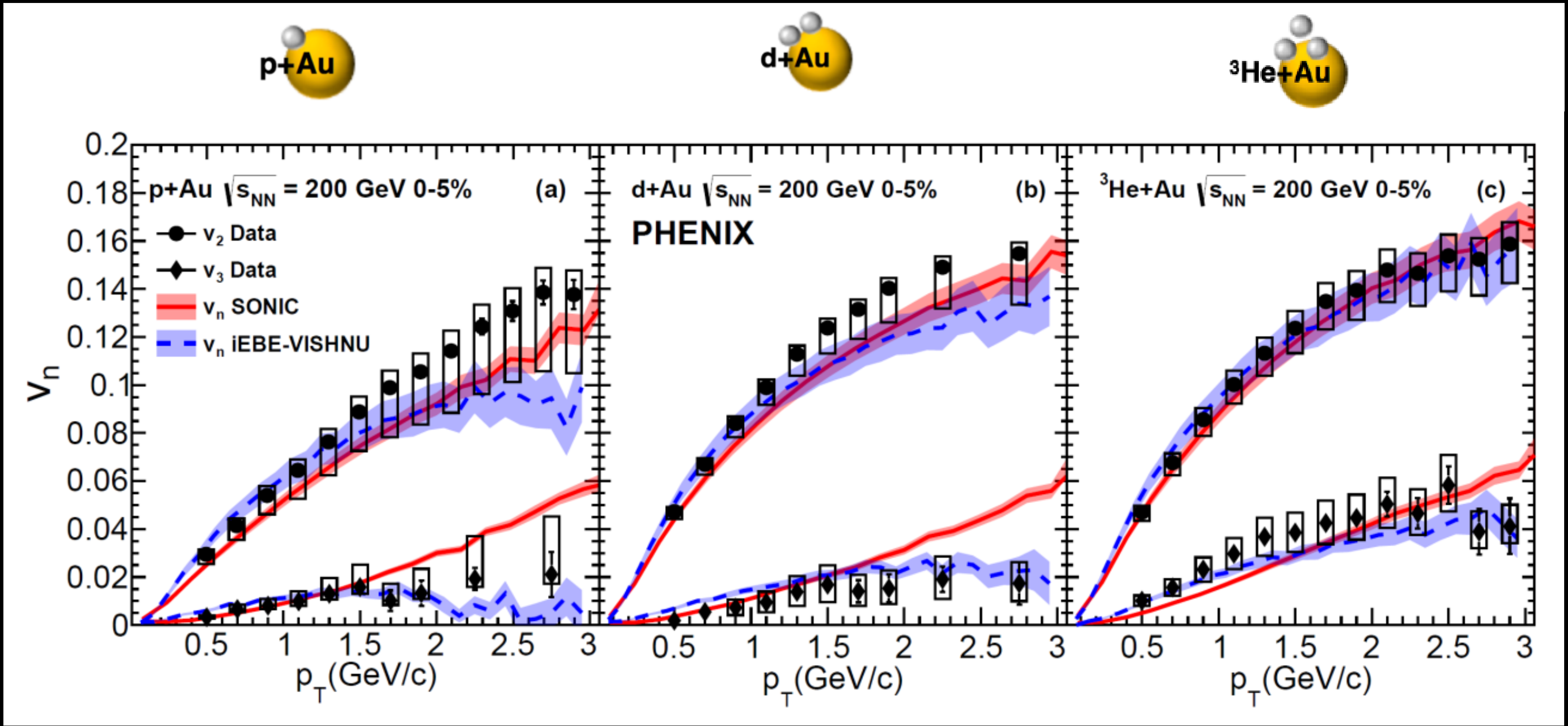
$dN_{ch}/d\eta$ ~ 12 p+Au 0-5%

$dN_{ch}/d\eta$ ~ 18 d+Au 0-5%

$dN_{ch}/d\eta$ ~ 22 ^{3}He+Au 0-5%

Hydrodynamic calculations include the initial geometry differences and match the particle multiplicity for each system

Hydrodynamic Comparison



Good agreement with v_2, v_3 (p_T) for all three systems

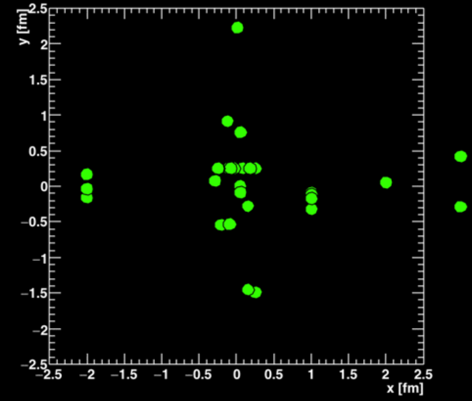
SONIC is a published prediction

No tuning of parameters or options for different systems

Parton Transport Explanation

In limit of many scatters per parton (> 4-5), this might be a dual picture to hydrodynamics

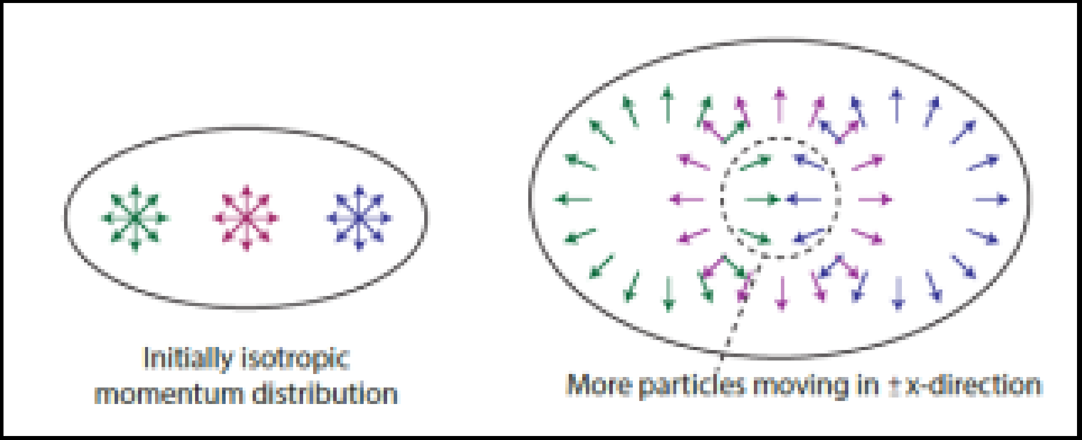
However, if most partons have zero scatters and others have just one, that seems different



AMPT Escape Mechanism paper finds very few scatterings
He *et al.*, https://arxiv.org/abs/1601.00878

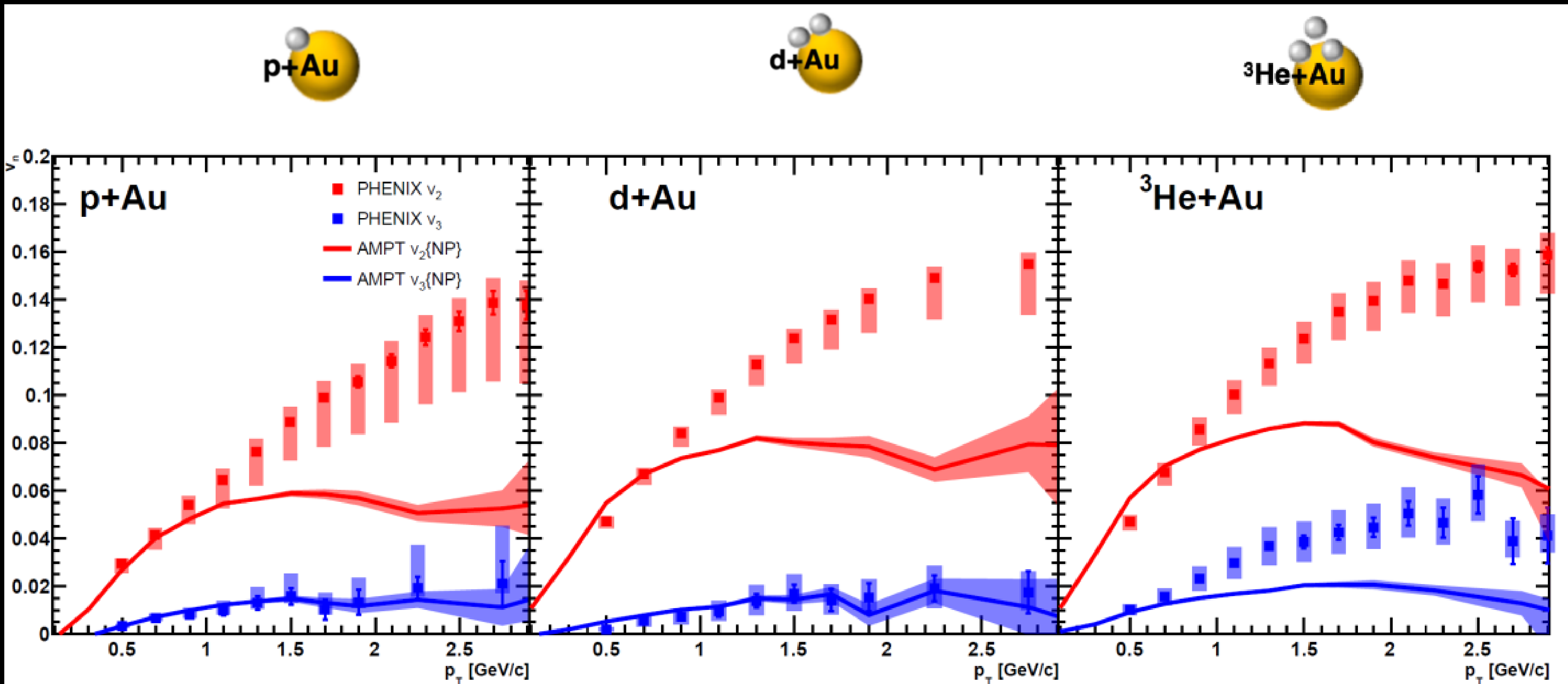
Recent analytic approach generates significant v_2 with single scatter

Kurkela, Wiedemann, Wu
arXiv:1805.04081
arXiv: 1803.02072



Small system studies with AMPT (publicly available code)

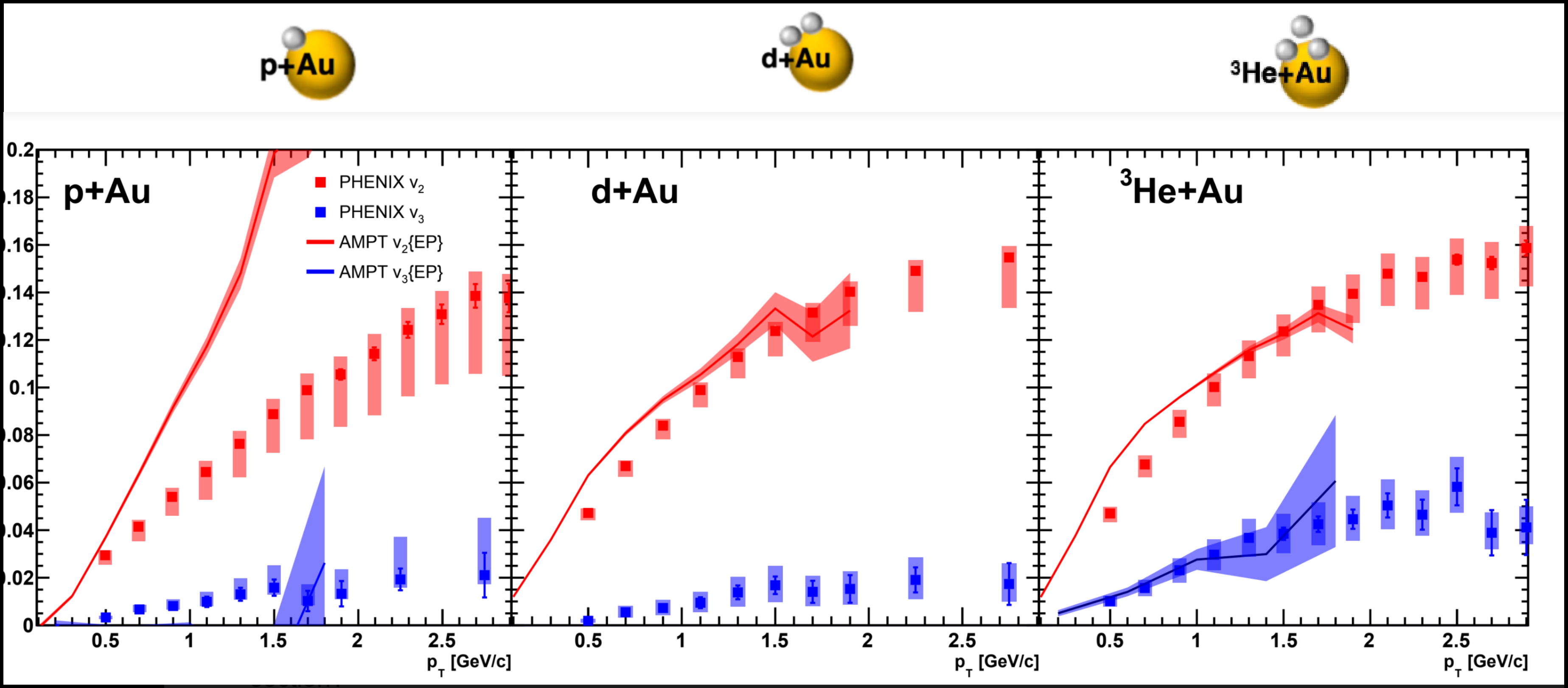
Nagle et al., arXiv:1707.02307, Orjuela Koop et al., arXiv:1512.06949, arXiv:1501.06880
Bozek, Bzdak, Ma, arXiv:1503.03655



AMPT v2.25t5 relative to true geometry defined by initial nucleons
string melting mode, σ_{parton} = 0.75 mb

Poor quantitative agreement with data,
but rough agreement with system v_n ordering

Apples-to-Apples Comparison



AMPT fully modeling the Event Plane method in PHENIX

Better agreement in ^{3}He+Au, but much worse in p+Au (non-flow), insufficient statistics for v_3 in the smaller systems (working on it)

Thoughts on AMPT and parton transport calculations:

Quasiparticle picture only useful if one can correctly identify quasiparticles and their properties (think Condensed Matter Physics)

→ which in AMPT are nearly massless < 20 MeV quarks, no gluons

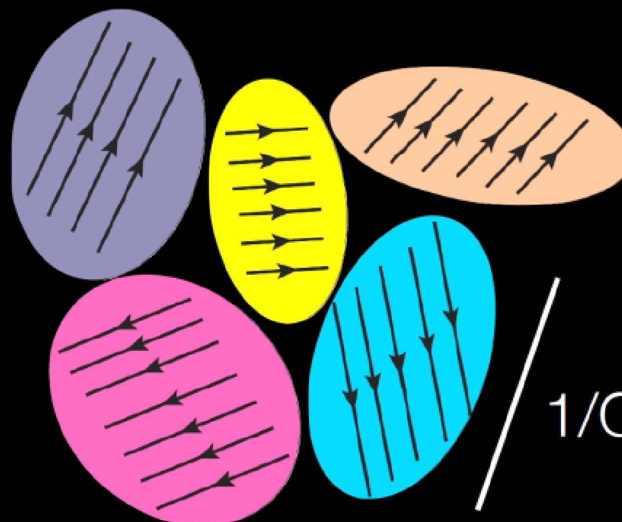
Also, one then needs to describe the “cornucopia” of other observables. For example, AMPT achieves the v2 PID dependence roughly via hadron rescattering.

Very important for the field to have multiple tools (beyond AMPT) to assess how this picture works…

Initial State Explanations

INITIAL STATE PICTURE

Intuitive picture:
Quarks or gluons are produced from color field domains in the Pb or p target



Particles that come from the same domain are correlated

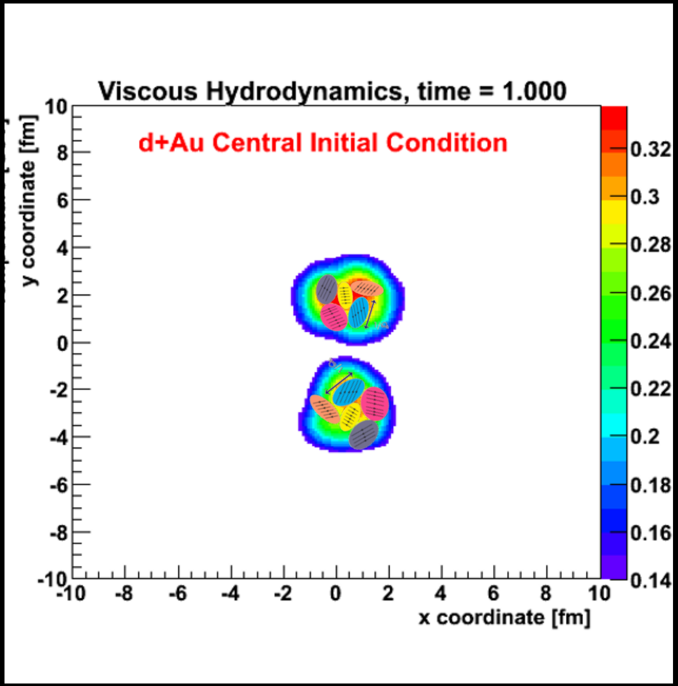
Effect is suppressed by the number of colors and the number of domains (it is small for heavy ions)

FIGURE: T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN JHEP 1601 (2016) 061; SEE ALSO: A. DUMITRU, A.V. GIANNINI, NUCL.PHYS.A933 (2014) 212; A. DUMITRU, V. SKOKOV, PHYS.REV.D91 (2015) 074006; A. DUMITRU L. MCLERRAN, V. SKOKOV, PHYS.LETT.B743 (2015), 134; V. SKOKOV. PHYS.REV.D91 (2015) 054014

Björn Schenke, BNL

More domains that are
not aligned,
correlation effect is washed out.

Nice separation of scales
Deuteron size >> Domain Size

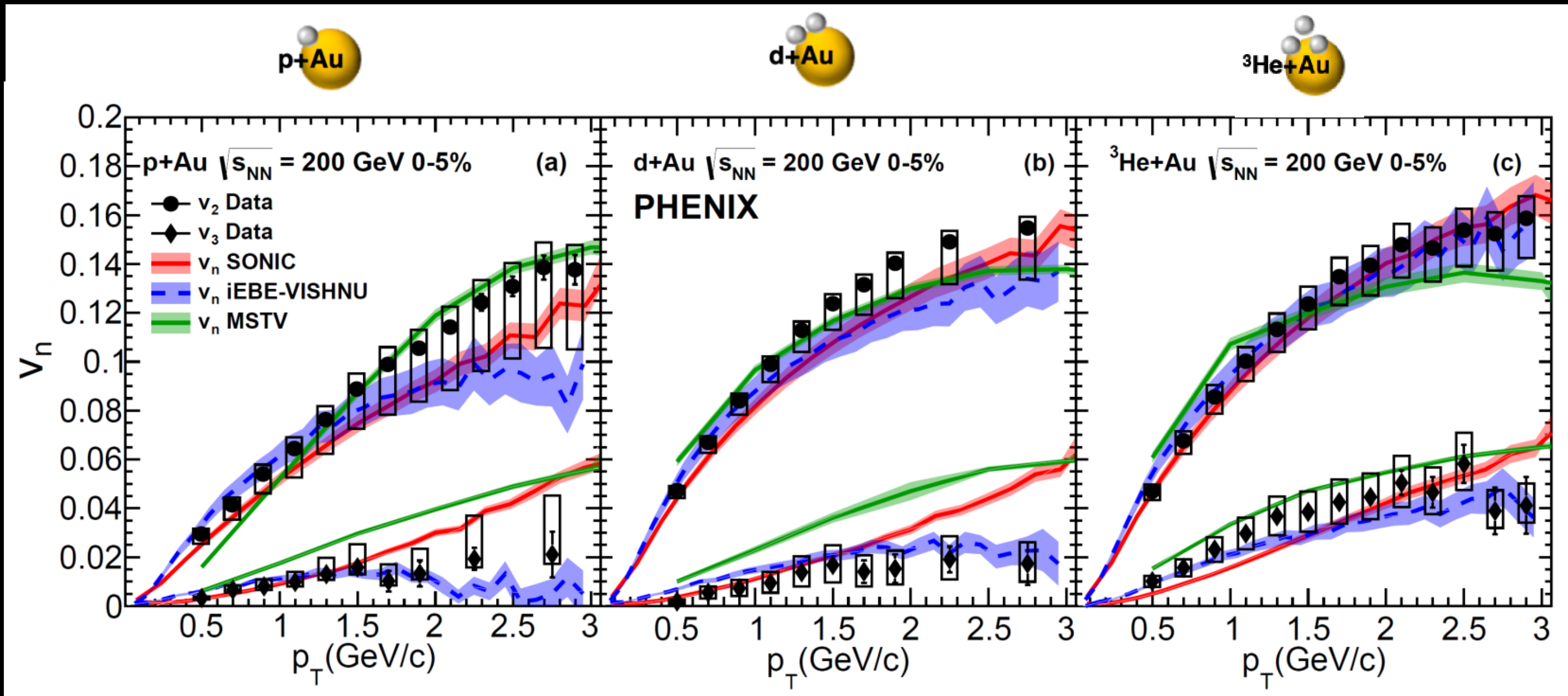


$$v_n^{p+\mathrm{Au}} > v_n^{d+\mathrm{Au}} > v_n^{^3\mathrm{He}+\mathrm{Au}}$$

Exactly the opposite of what is observed in data !

Definitively rule out scenario where initial state correlations dominate via *resolved domains of size* $1/Q_s$

15 days after the PHENIX paper was posted, postdictions appeared



Mace et al. [MSTV], https://arxiv.org/abs/1805.09342

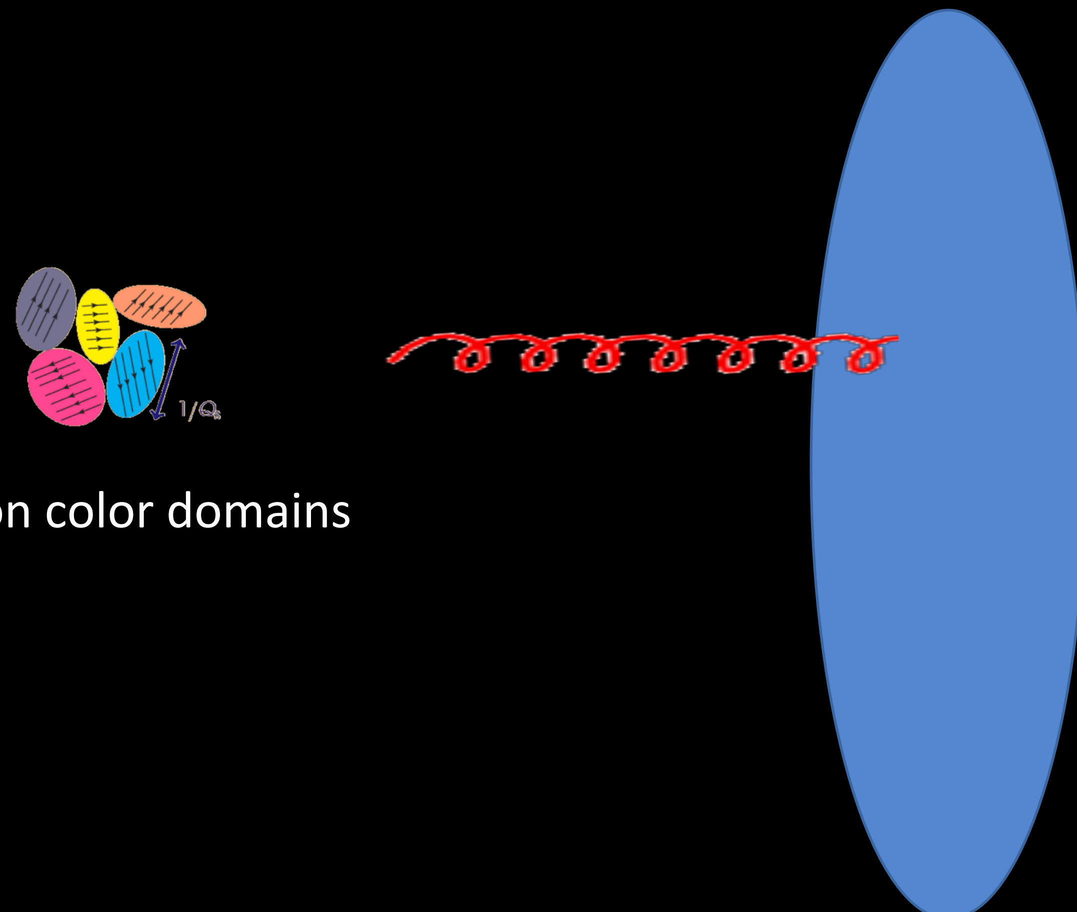
Remarkable results are counterintuitive

Code is not publicly available, many details missing so not possible to reproduce results yet

There are a number of steps — all of which are “essential”

Essential physics

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

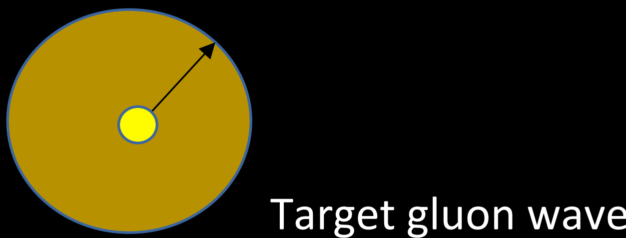


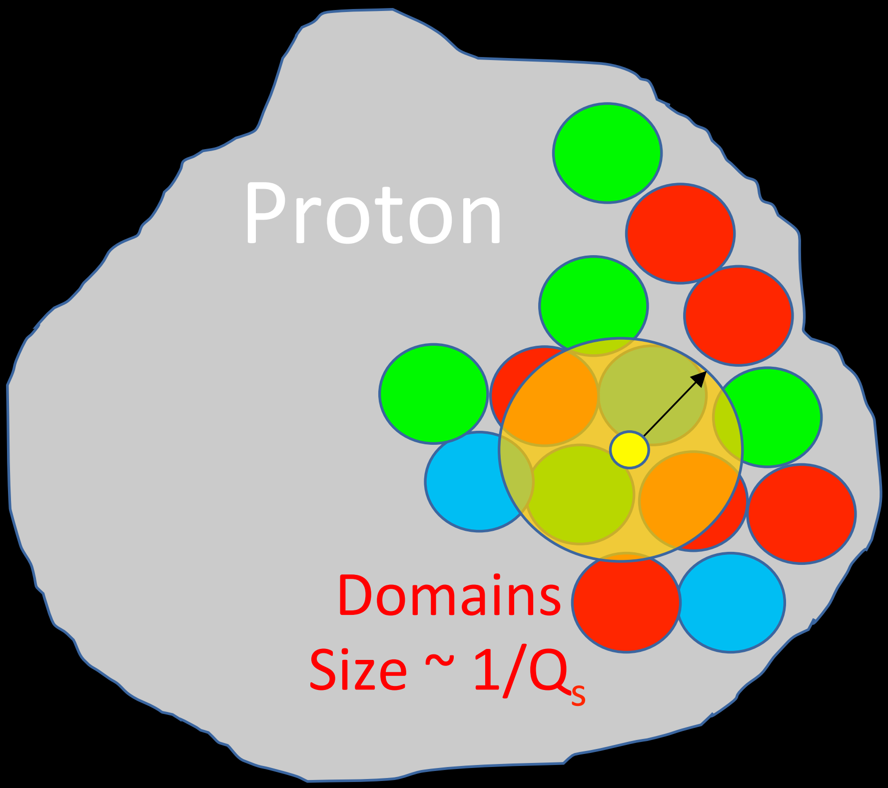
If the $k_T < Q_s$ (proj) then the target cannot resolve individual domains and interacts with many of them "coherently" or "simultaneously"

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



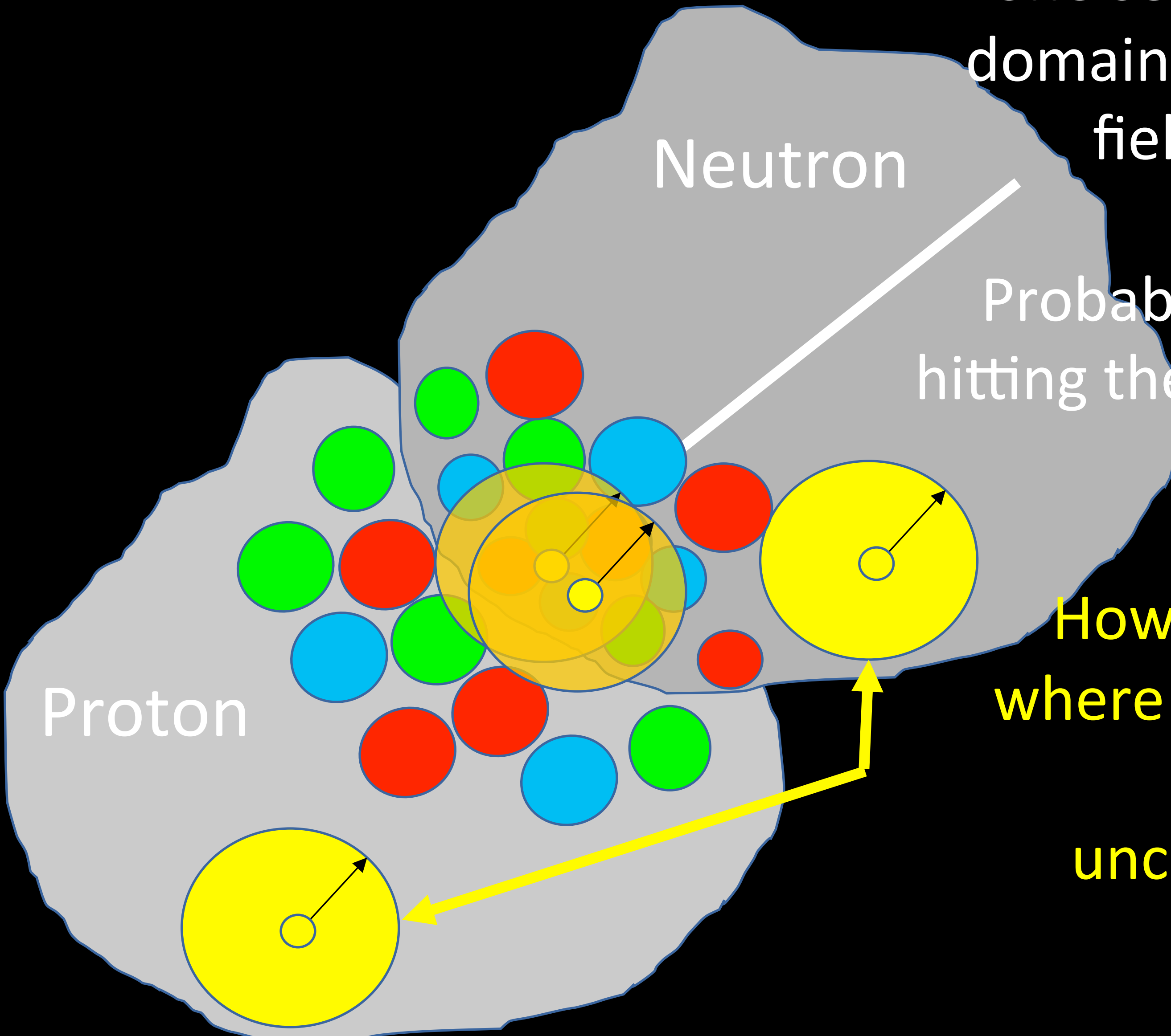


Projectile (proton) radius ~ 0.9 fm

If Q_s = 2 GeV, r_{domain} = 0.1 fm.
Of course this is an absurdly large
Q_s^2 = 4 GeV^2 for the proton x>0.01

Then target gluon sees
$(Q_s/k_T)^2$ ~ 4 domains at once.

d+Au case



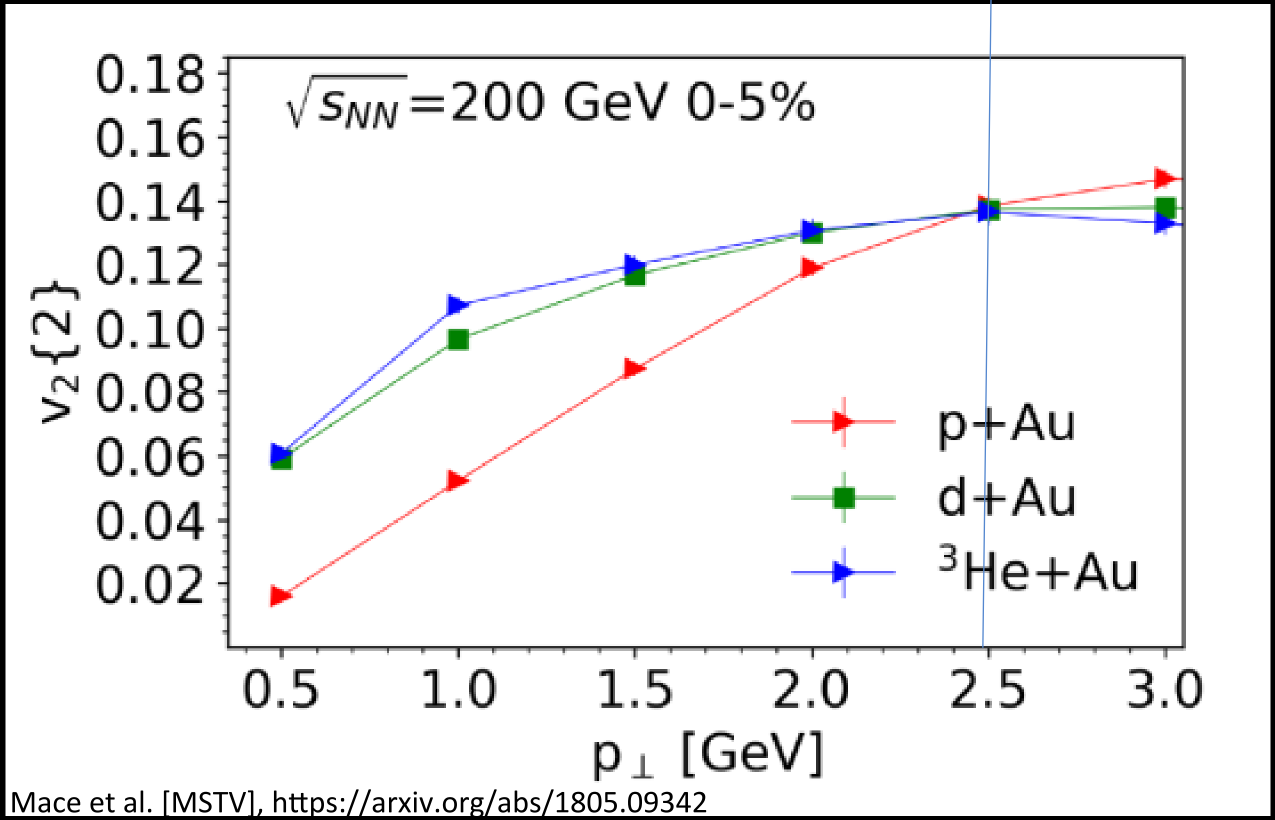
In the overlap region, one sees more "smaller" domains with larger color fields since larger Q_s.

Probability of two gluons hitting the overlap region is very small.

However, lots of cases where two target gluons see completely uncorrelated regions!

← Domains not resolved

Domains just starting to be resolved →



v_2 (d+Au) > v_2(p+Au) for p_T < 2.5 GeV

MSTV: Q_s (deut) > Q_s (prot) since N_{ch} (0-5% d+Au) > N_{ch} (0-5% p+Au) and v_2 scales with Q_s(proj)

k_T < Q_s (proj) → does that mean Q_s(proj) = 1.5-2.5 GeV?

Need exact definitions and numbers for k_T distributions

IP-Jazma

J.N. and W.A. Zajc
https://arxiv.org/abs/1808.01276

Open source code:

http://www.phenix.bnl.gov/WWW/publish/nagle/IPJAZMA

Just like jazz music, some people will not appreciate it.

IP-Jazma Details

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

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

Note that this is just a uniform Gaussian with σ = 0.32 fm at RHIC

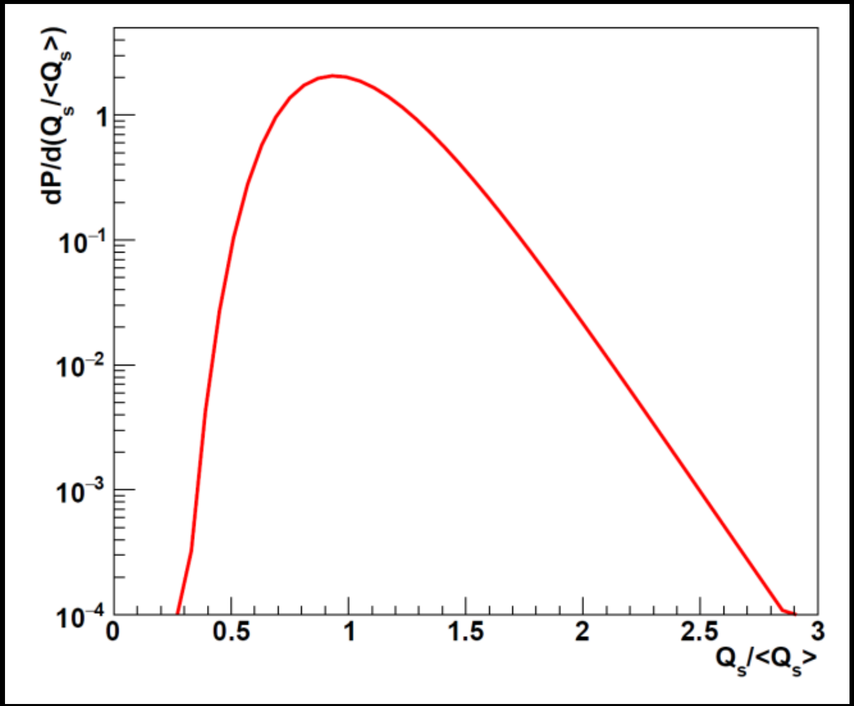
Q_s^2 is proportional to $g^4\mu^2$, where μ^2 is the number density of color charge per unit transverse area

Q_s is proportional to $g^2\mu$ and is Gaussian with σ = 0.45 fm

MSTV (private comm.) says that "our choice of B_G" corresponds to slightly larger σ = 0.56 fm, so I will match that in IP-Jazma

3. 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.

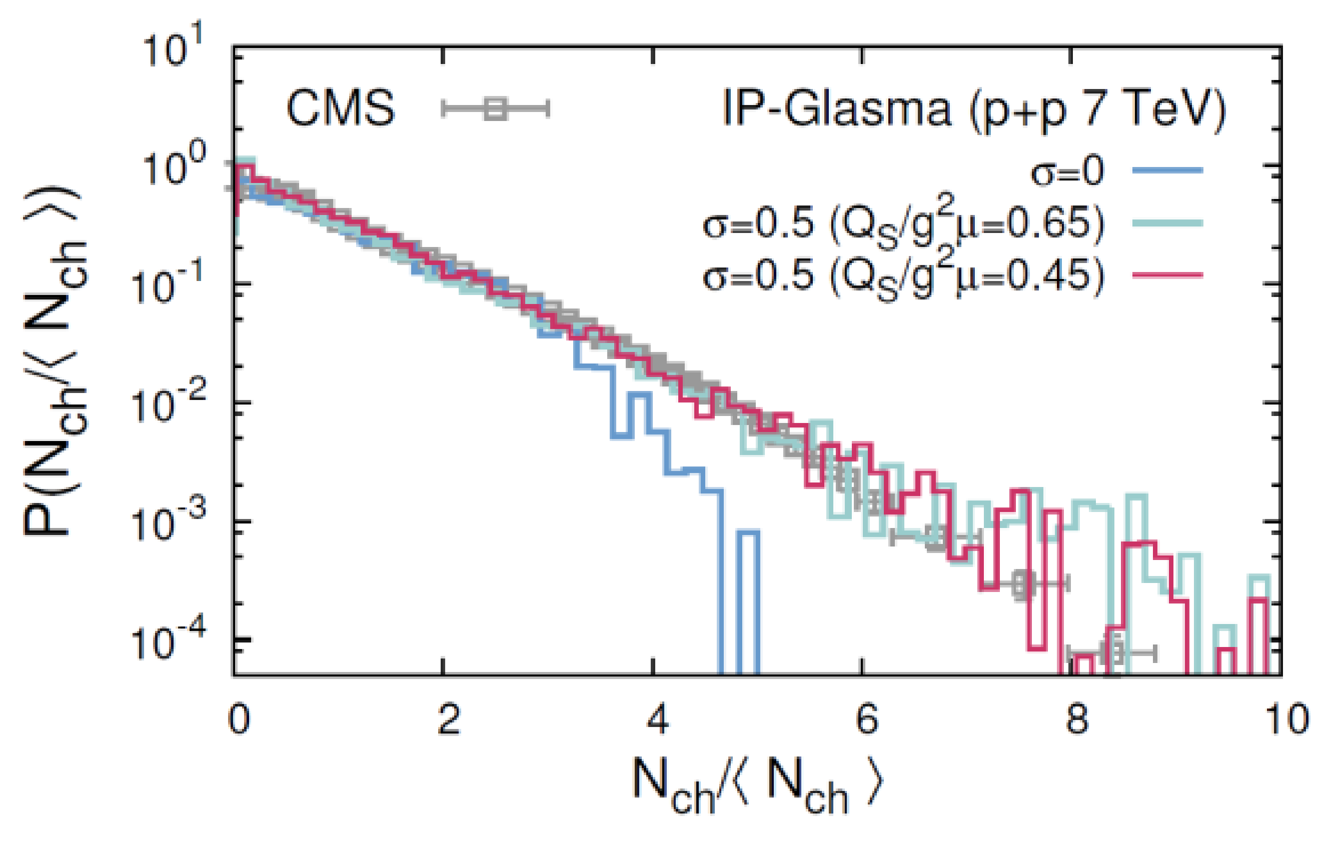
Implemented with variance 0.5 on $\log(Q_s{}^2)$ – i.e. high side tail.



- Non-perturbative on many scales
- Not part of the standard CGC framework
- Questions regarding the constraints on the functional form

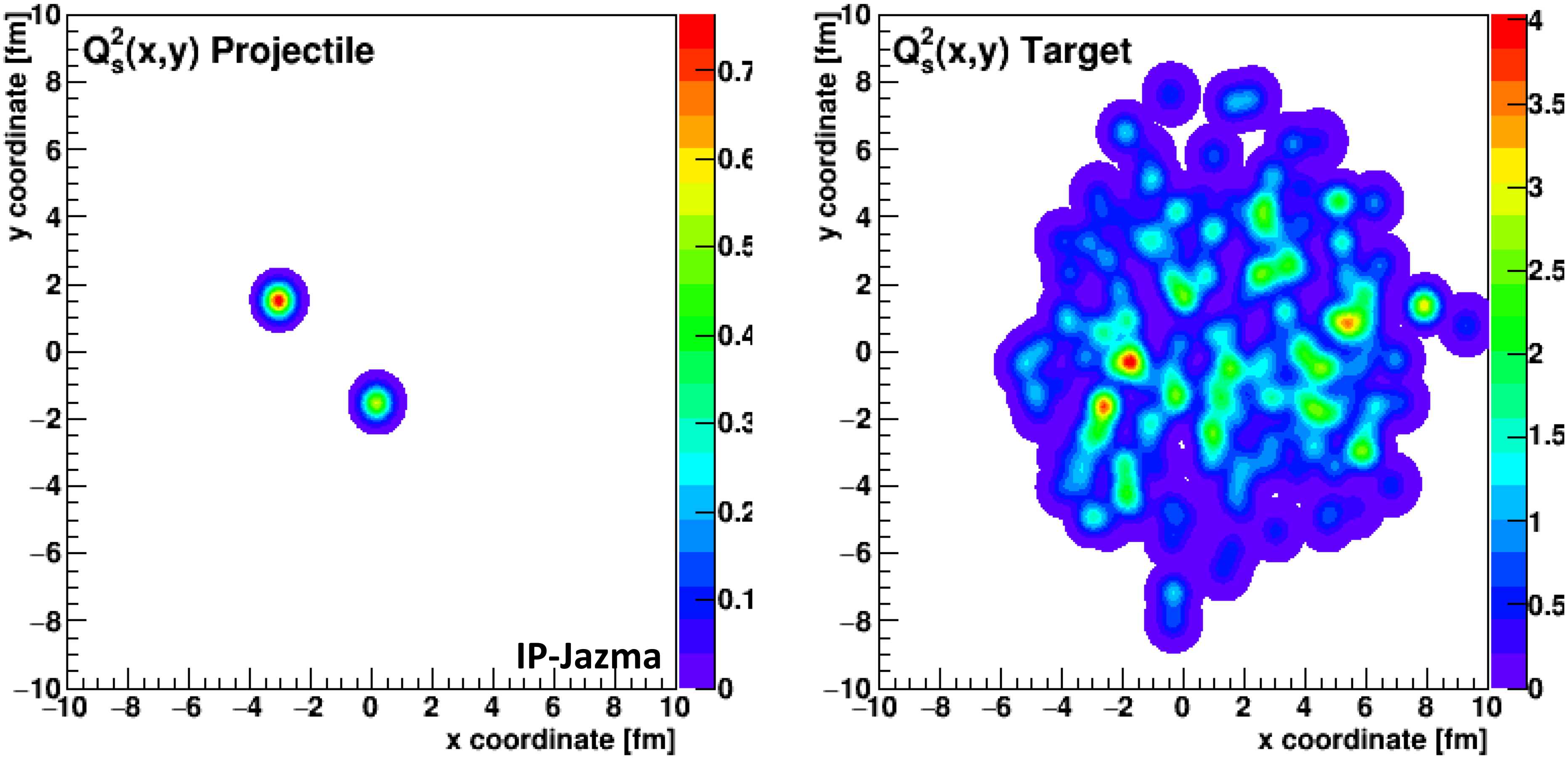
Originally proposed by McLerran (arXiv:1508.03292v2) to explain high multiplicity tail of LHC p+p N_{ch} distributions.

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



* It is a mistake to assume such matching confirms dynamical fluctuations, instead of from hadronization effects, finite rapidity window, experiment acceptance, etc.

deuteron + gold



Sum all the Q_s^2 contributions for each nucleus.
Example - nucleons from deuteron as perfect Gaussians from IP-Sat just with different amplitudes from $Q_{s,0}^2$ fluctuations.

At this point, none of these fluctuations are *ab initio*.
All MC Glauber and put-in-by-hand $Q_{s,0}^2$ fluctuations.

Dilute-Dense Framework

In the MSTV paper, they 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).

What justifies some small system papers (many) using the dense-dense limit and others (many) using the dilute-dense limit?

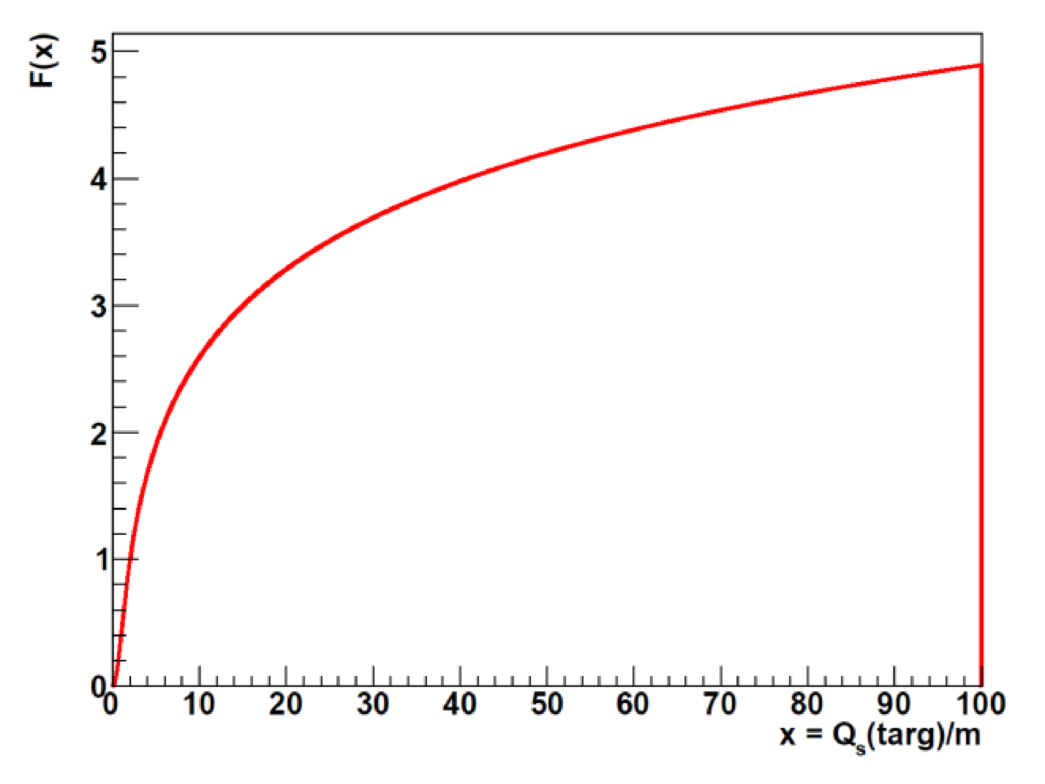
Also coherence condition $k_T < Q_s(\text{proj})$ seems in conflict with both!

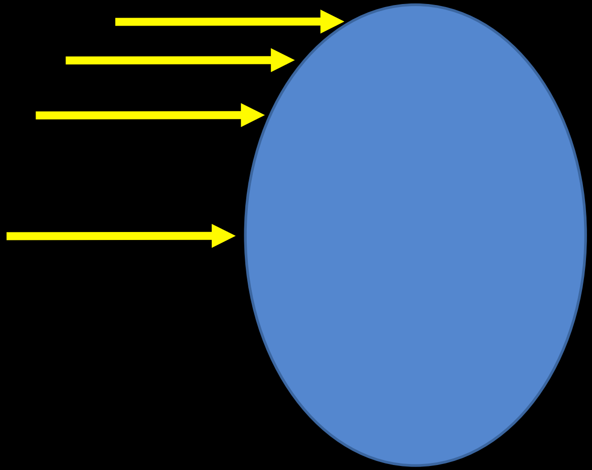
IP-Jazma Dilute-Dense

$N_g \propto g^2 Q_s^2(\text{proj}) \times F(Q_s(\text{targ})/m)$ (dilute-dense limit)

Cyrille Marquet (thanks) sent me this function F.

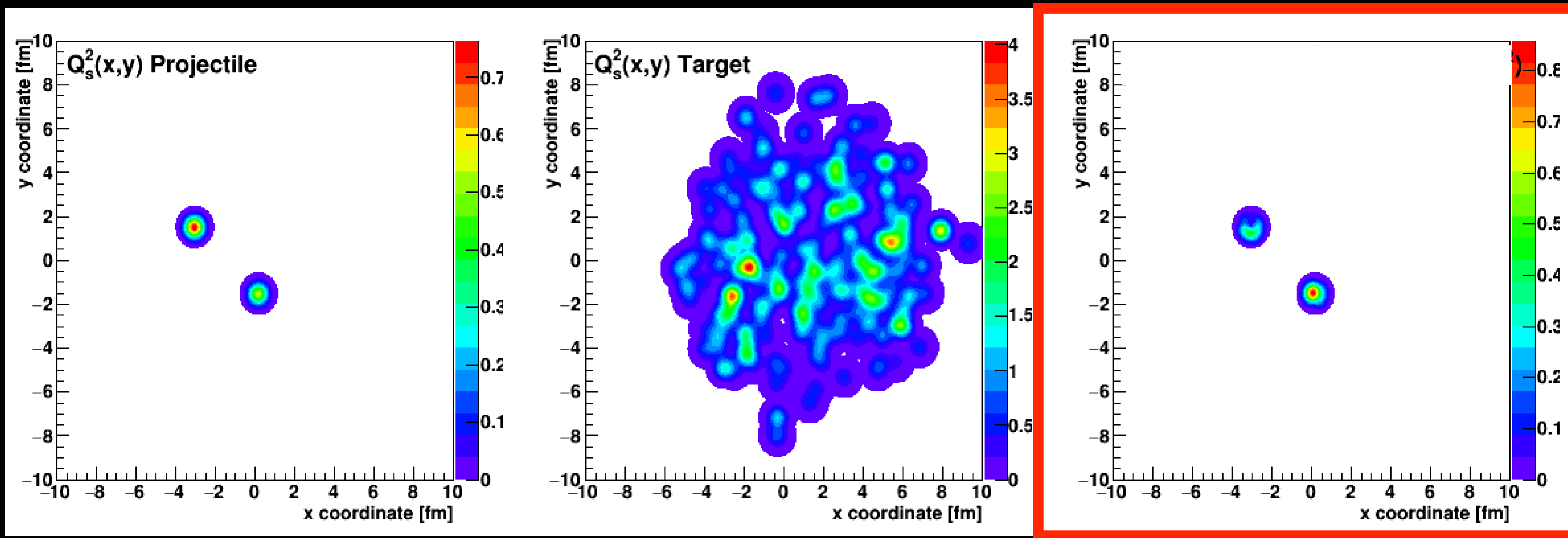
In the limit of large $Q_s(\text{targ})/m$, it scales as $\log(Q_s(\text{targ})/m)$.





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

IP-Jazma Results



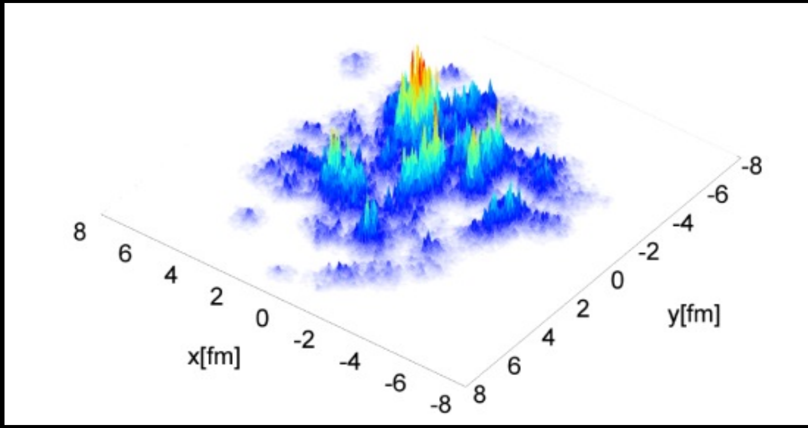
Right panel shows the density distribution for this event in the dilute-dense limit.

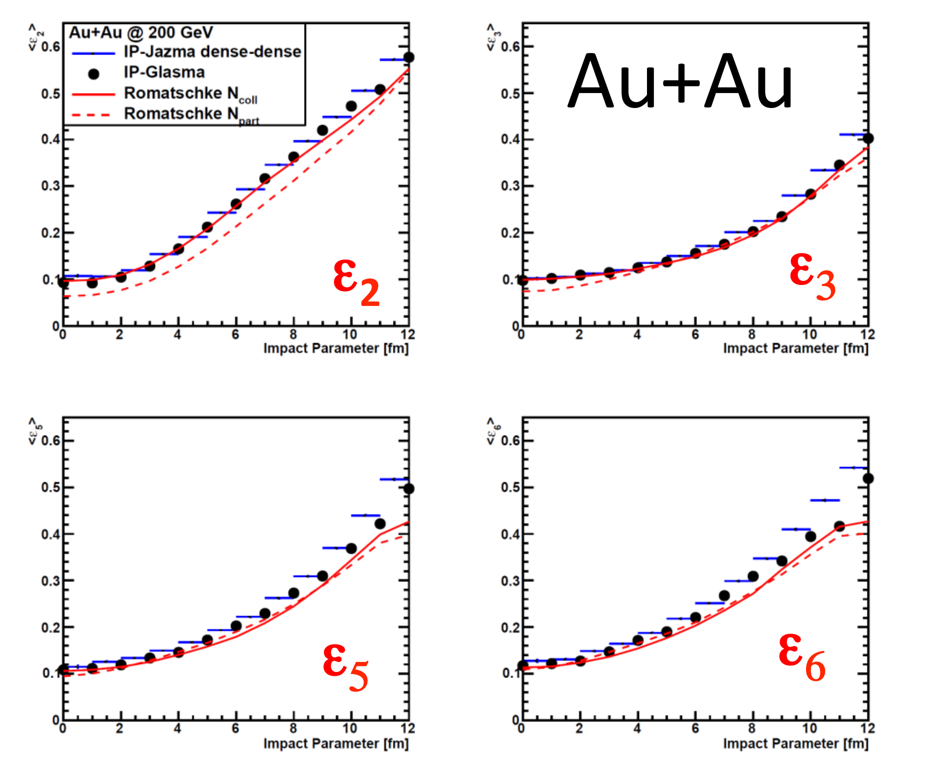
There are no sharp spikes in the energy density as often highlighted with IP-Glasma because there are no lattice site color fluctuations – though these are in part artifacts in IP-Glasma.

Aside on Spiky IP-Glasma

Success of IP-Glasma Au+Au initial conditions often highlighted by these very spikey displays

However, IP-Jazma (dense-dense) matches eccentricities ε_2-ε_6



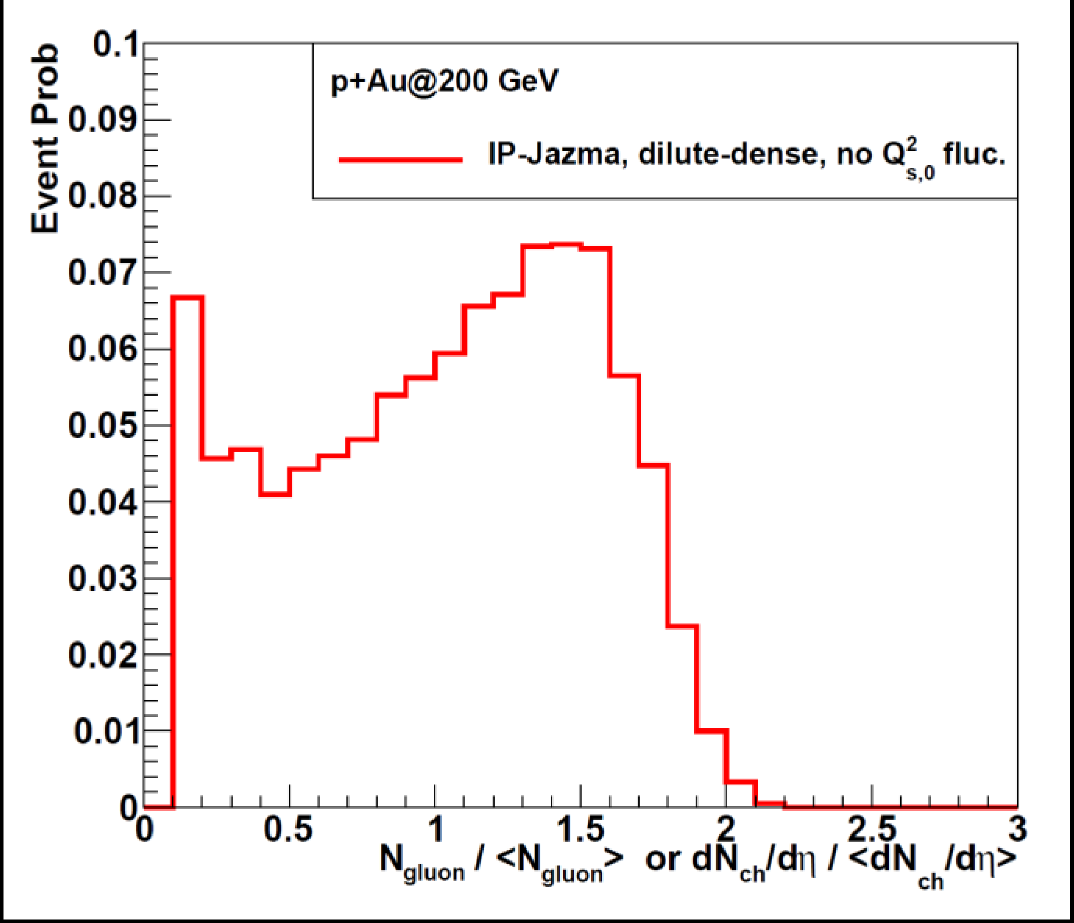


Totally dominated by $T_A \times T_B$ scaling, not color fluctuation spikes.

p+Au @ 200 GeV

Settings: Dilute-Dense, no $Q_{s,0}{}^2$ fluctuations,

no running α_s, r_{max} = 3.0 σ [leave these last two the same]

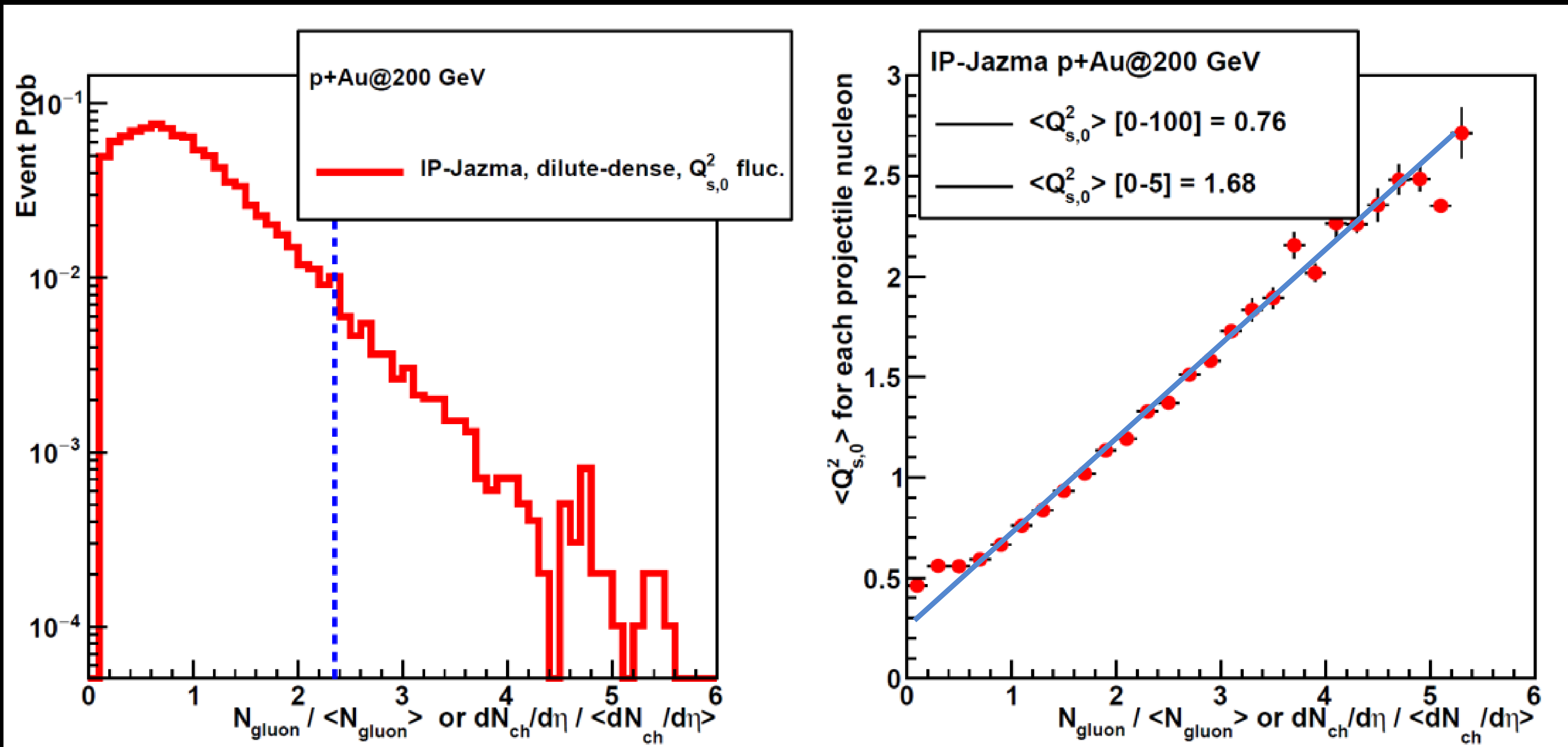


Distribution of number of gluons (N_g/<N_g>)

Once the proton is hitting the mid-region of the target the gluon production reaches a limit
i.e. one has freed all the gluons from the projectile proton

p+Au @ 200 GeV

Settings: Dilute-Dense, yes $Q_{s,0}^{\ 2}$ fluctuations

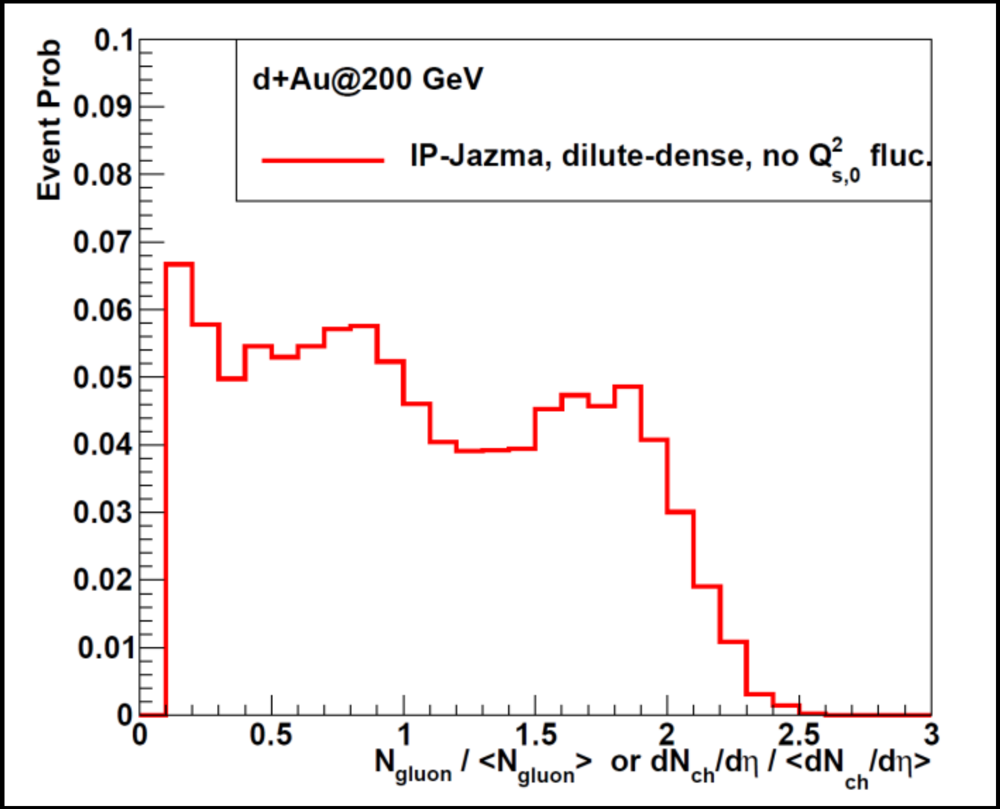


In the Monte Carlo, keep track of the $Q_{s,0}^{\ 2}$ thrown for each projectile nucleon.

As expected, there is an almost linear increase in gluon number with $Q_{s,0}^{\ 2}$ in the projectile once one is hitting a thick enough part of the nucleus.
For 0-5% high-multiplicity, the value is 2.2 times higher than average.

d+Au @ 200 GeV

Settings: Dilute-Dense, no $Q_{s,0}{}^2$ fluctuations

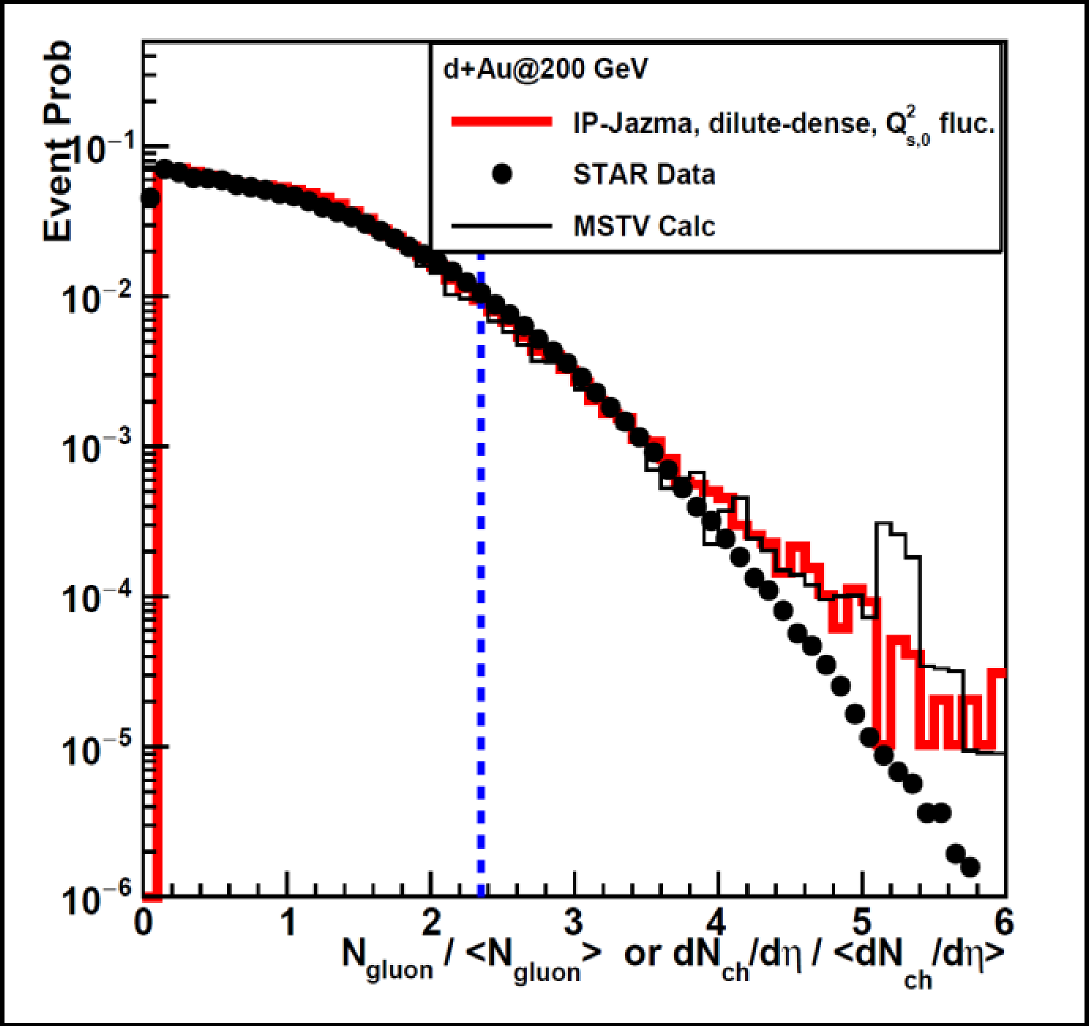


Some collisions where only proton (or neutron) hits, some collisions where both hit the target)

One reaches the limit of freeing gluons from the projectile, proton and neutron in the deuteron.

d+Au @ 200 GeV

Settings: Dilute-Dense, yes $Q_{s,0}^{\ 2}$ fluctuations



Essentially perfect agreement IP-Jazma and MSTV.

Common with MSTV we have MCGlauber fluctuations, IP-Sat $Q_{s,0}^{\ 2}$ fluctuations.

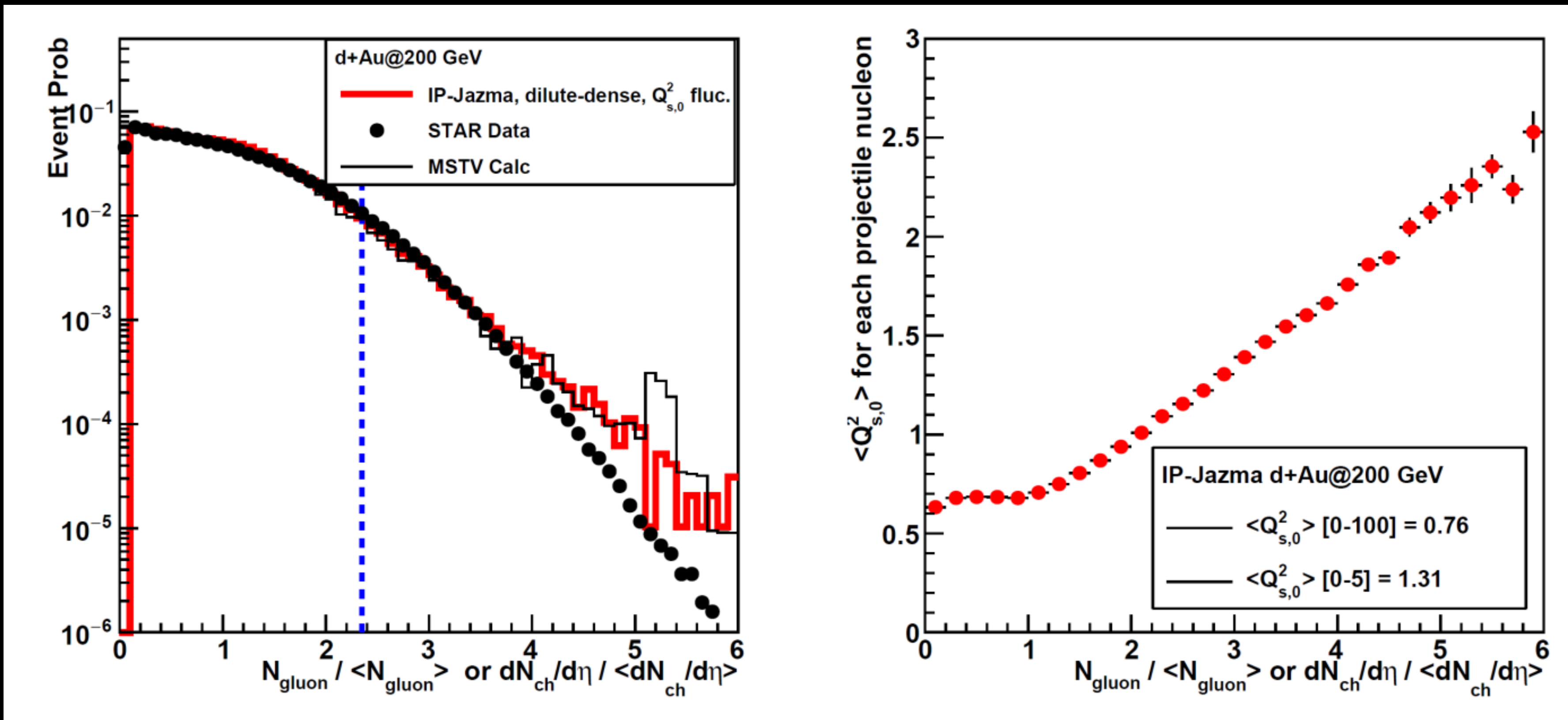
The additional color fluctuations in MSTV do not appear to be evident

Reasonable agreement with STAR up to 0.5%.

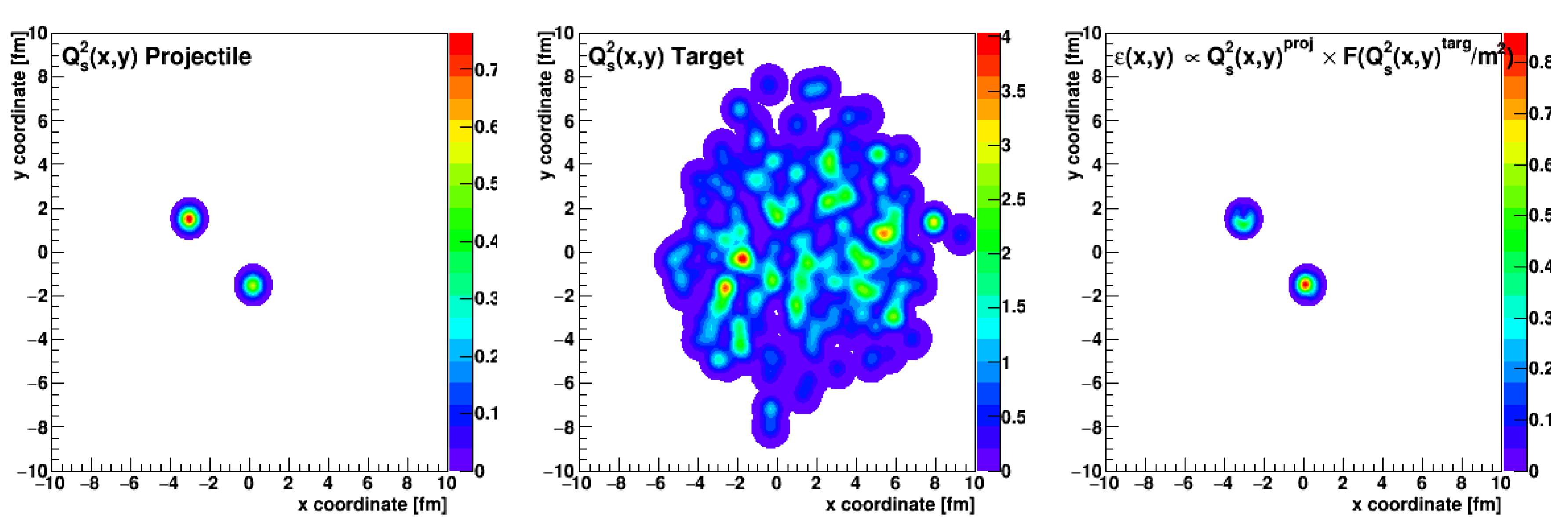
Blue line at 5% central.

d+Au @ 200 GeV

Settings: Dilute-Dense, yes $Q_{s,0}{}^2$ fluctuations



As expected there is a correlation of higher multiplicity events with larger $Q_{s,0}{}^2$ fluctuations.
Smaller than in p+Au because the deuteron nucleons fluctuate separately.

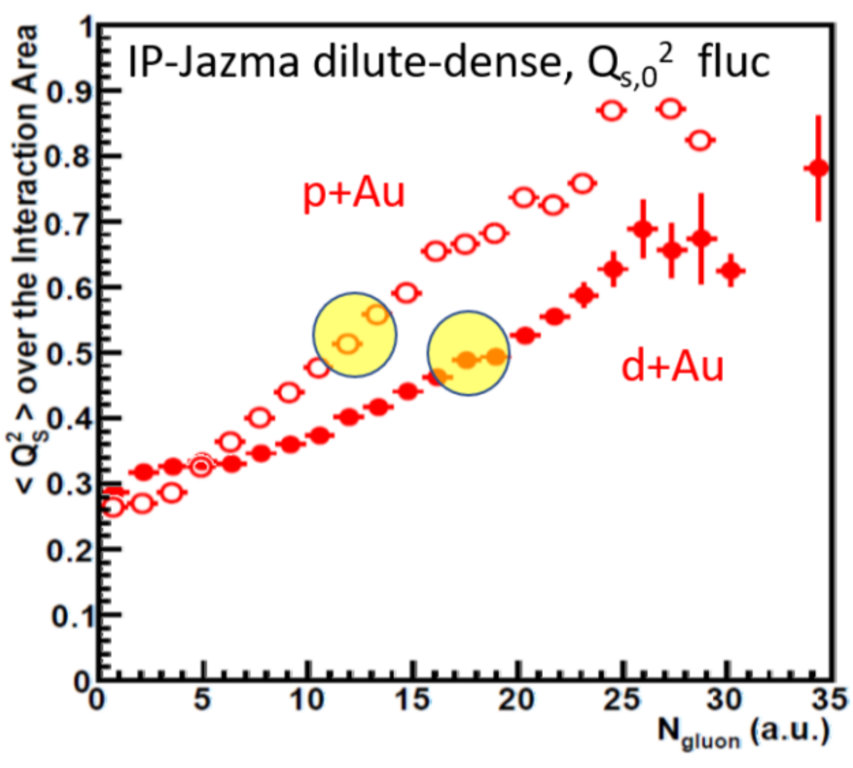


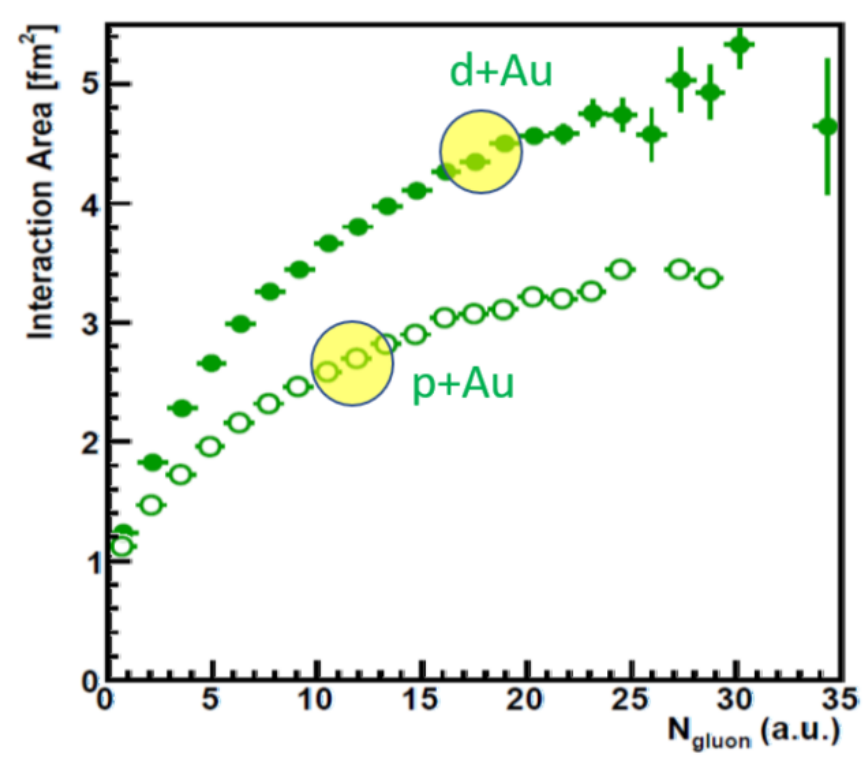
Define an "overlap area" and then calculate $\langle Q_s^2 \rangle$ within that area

For 0-5% selection in IP-Jazma, here are the results…

	p+Au	d+Au
Area [fm^2]	2.81	4.52
$\langle Q_s^2 \rangle$ [GeV^2]	0.56	0.53

d+Au has larger area, but the saturation scale is the same



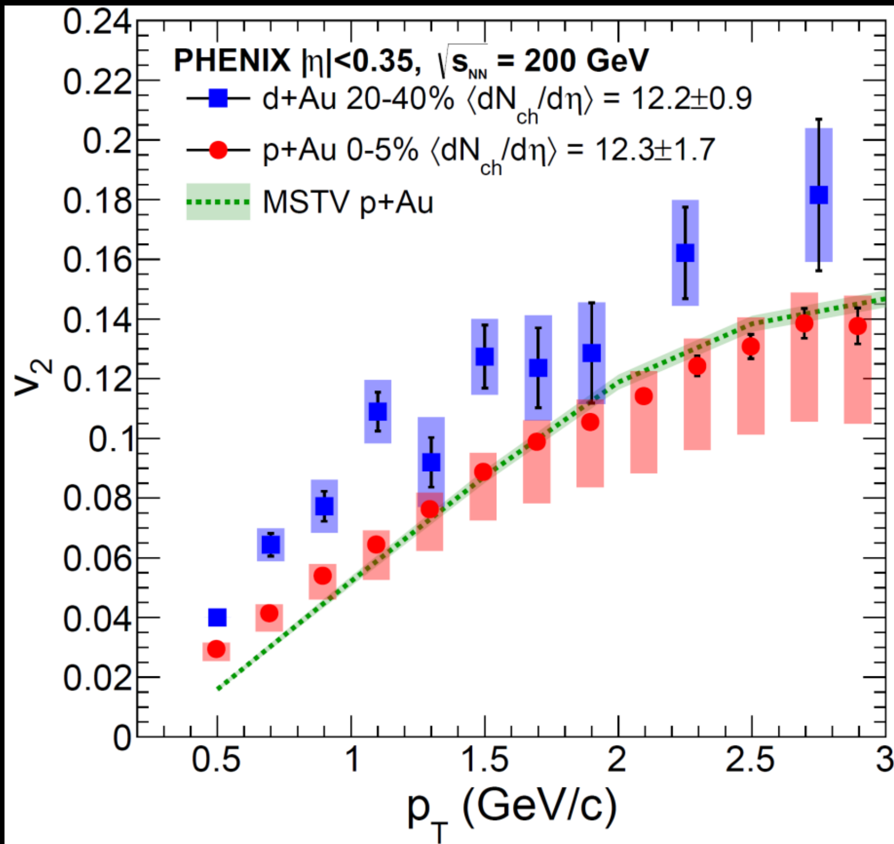


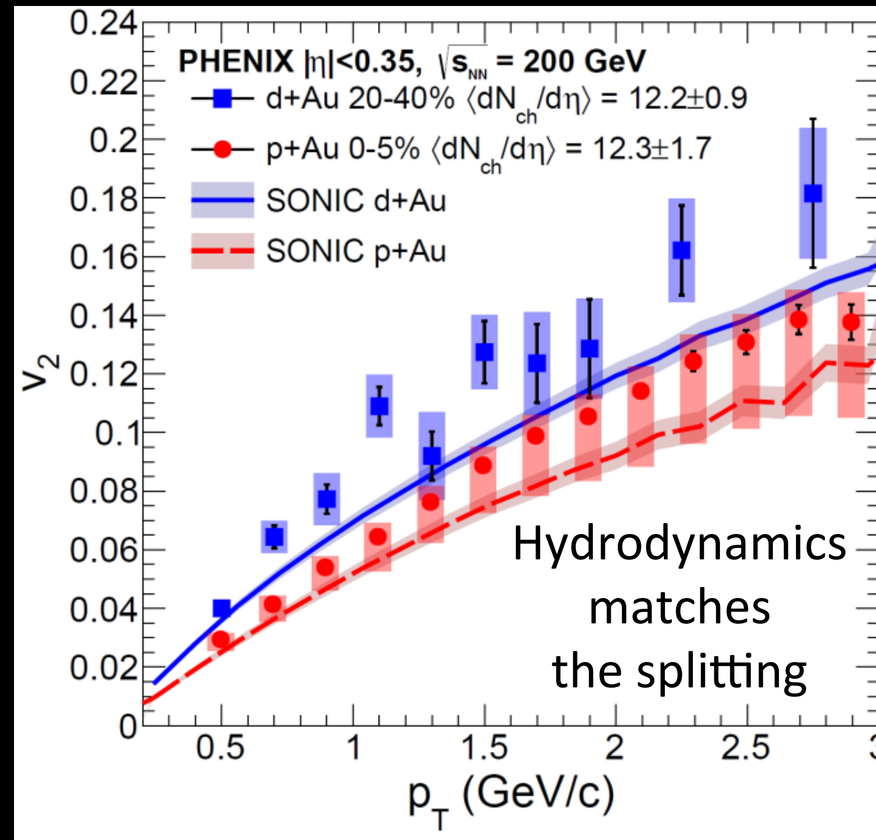
In the dilute-dense framework, multiplicity scales with Q_s^2 projectile. Thus for 0-5% centralities, Q_s^2 (deuteron) > Q_s^2 (proton). [MSTV]

We find this MSTV statement is not reproduced. The area is larger, not the saturation scale!

The MSTV statement is essential since v_2 is directly related to Q_s and this is what they say gives them v_2(dAu) > v_2(pAu)

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!

Summary (So Far)

Exciting times for studying small system collectivity

Experimental geometry scan at RHIC complete

Best agreement via hydrodynamics with QGP stage

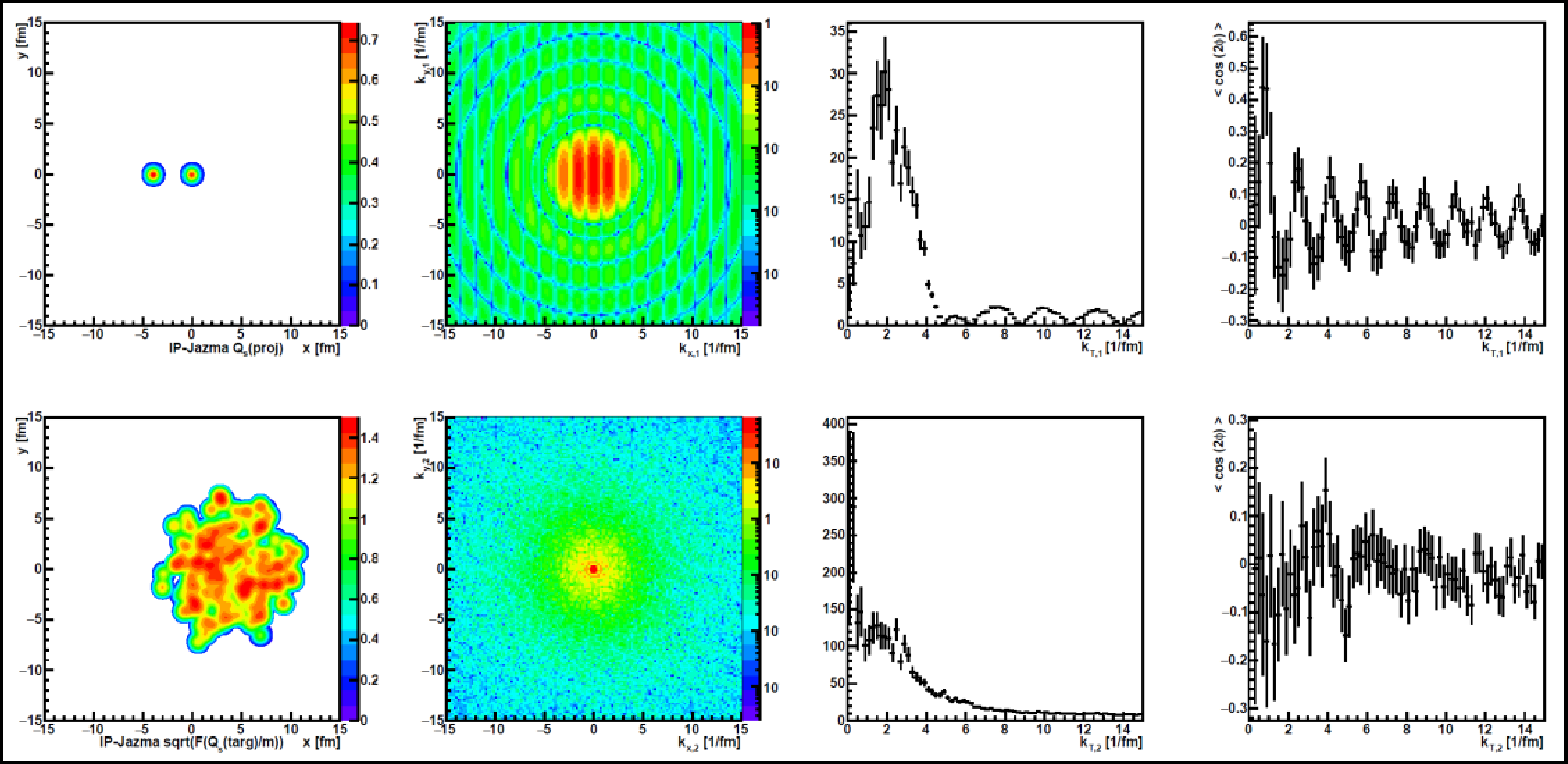
All theory approaches deserve full scrutiny

IP-Jazma new, open source tool for identifying the dominant source of fluctuations in the saturation physics framework

Further work to resolve differences in explanations with MSTV result

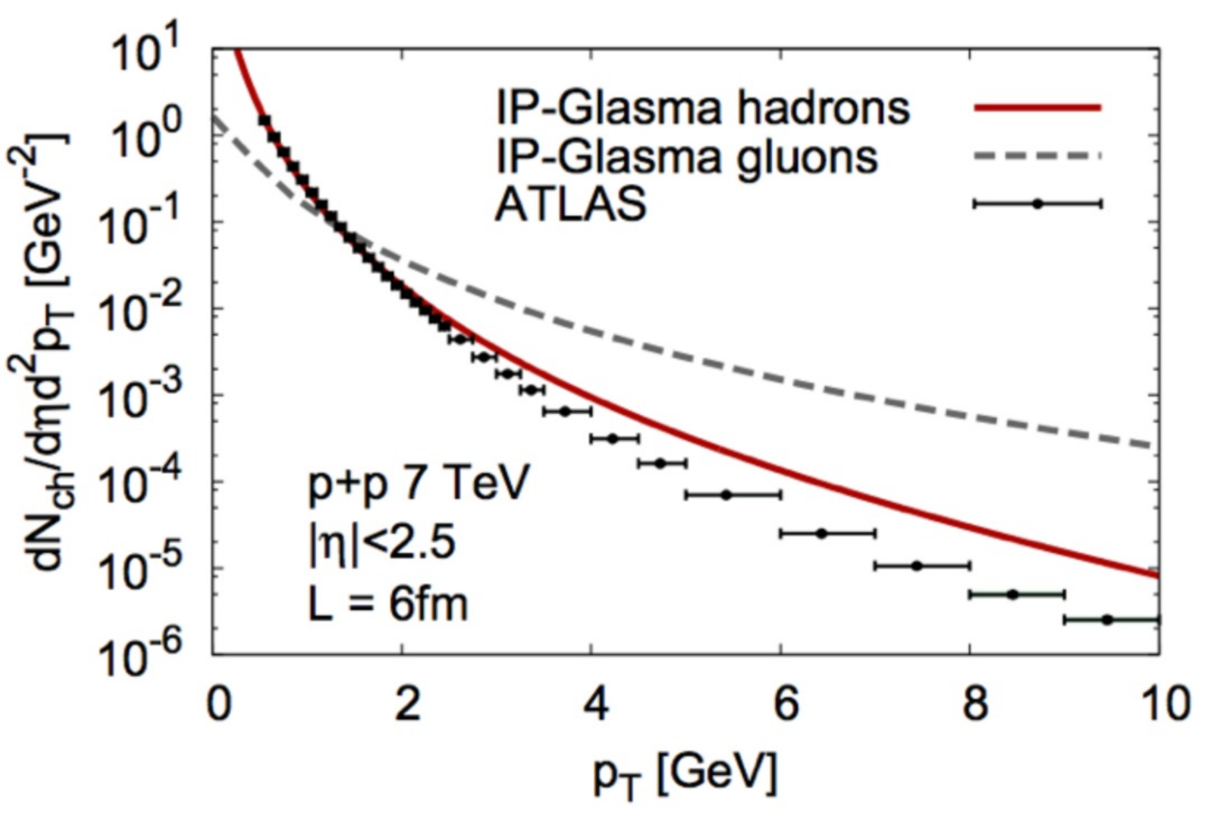
Episode V – IP-Jazma strikes back

MSTV do all calculations in momentum space, and so first Fourier Transform geometry



Extras

In previous IP-Glasma papers (e.g. arXiv:1311.3636) they point out the huge difference between gluons and hadrons.



Why is this effect ignored in the MSTV paper?

It would be good to compare the MSTV gluon p_T distribution with the published hadron p_T distribution.

Let the Buyer Beware

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 ($\sqrt{s} = 200\,A\,\text{GeV}$) 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].

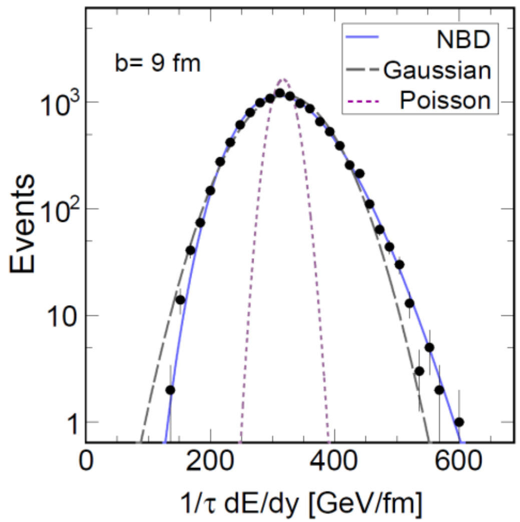
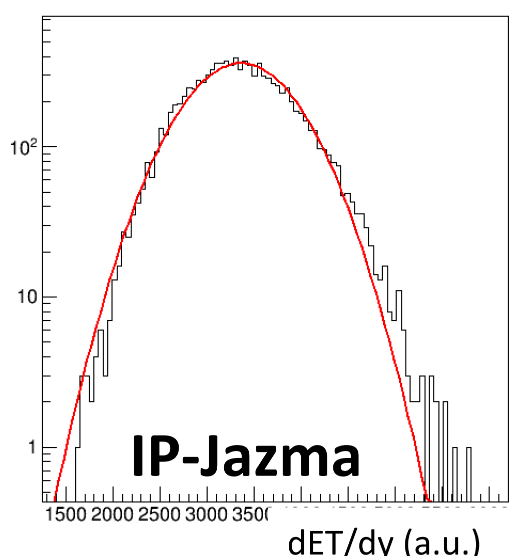


FIG. 1. The IP-Glasma event-by-event distribution in energy for $b = 9$ fm on the lattice compared to different functional forms. The negative binomial distribution (NBD) gives the best fit.

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



IP-Jazma calculation for Au+Au b=9 fm events in dense-dense limit, no $Q_{s,0}^2$ fluctuation,.

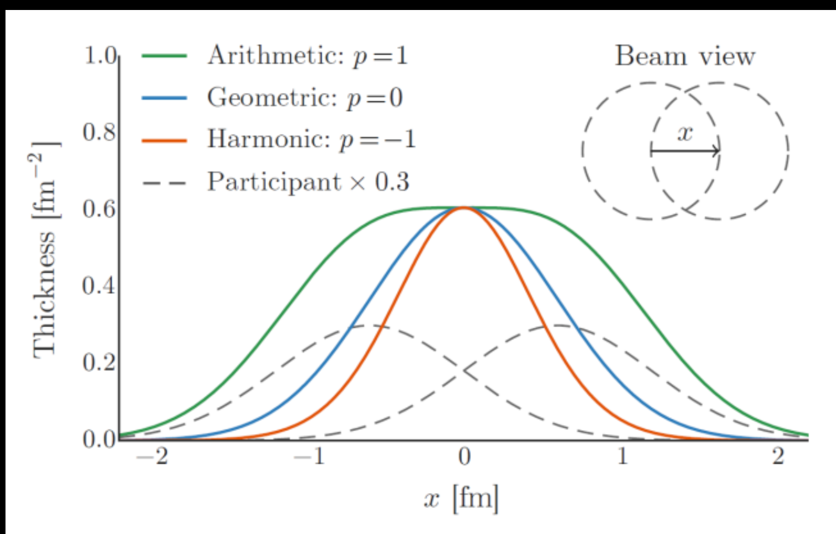
Note the gluon distribution is not Gaussian (red line) and has a high side skew (Γ dist.). Nothing to do with Glasma flux tubes.

Trento Comment… arXiv:1412.4708v2

Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions

J. Scott Moreland, Jonah E. Bernhard, and Steffen A. Bass
Department of Physics, Duke University, Durham, NC 27708-0305
(Dated: June 9, 2015)

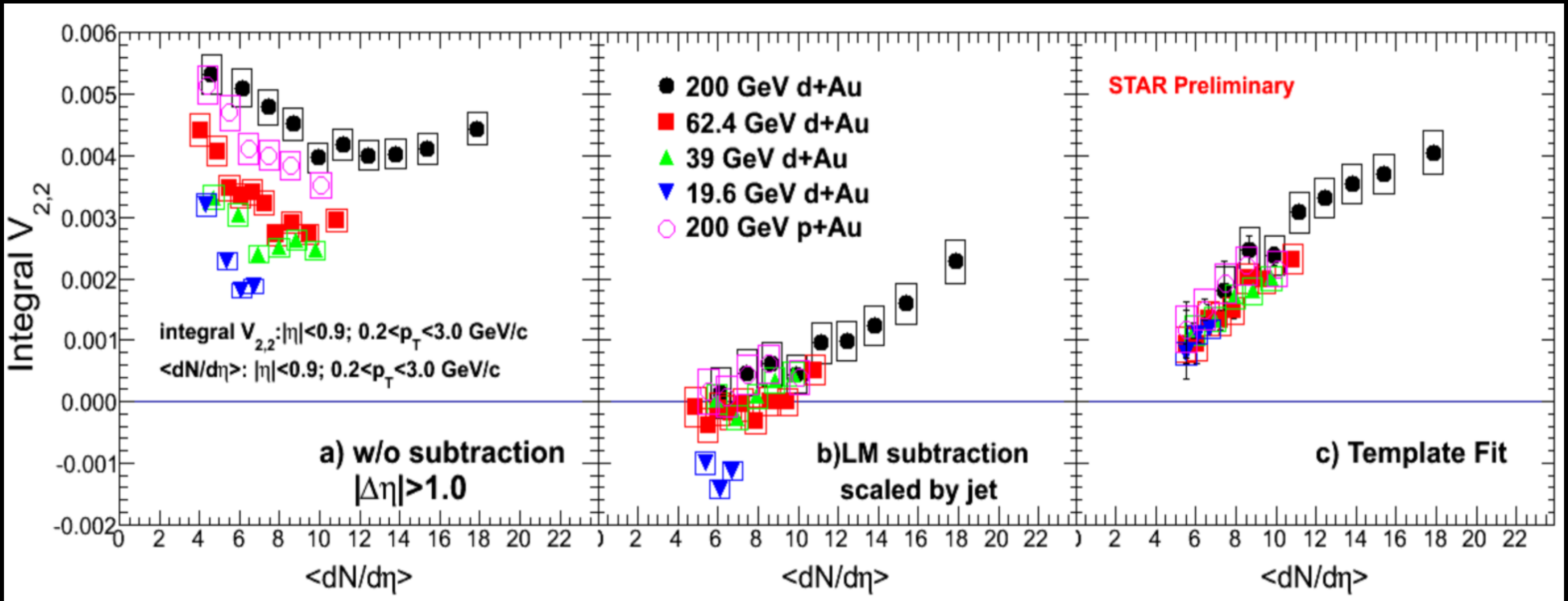
We introduce TRENTo, a new parametric initial condition model for high-energy nuclear collisions based on eikonal entropy deposition via a "reduced thickness" function. The model simultaneously describes experimental proton-proton, proton-nucleus, and nucleus-nucleus multiplicity distributions, and generates nucleus-nucleus eccentricity harmonics consistent with experimental flow constraints. In addition, the model is compatible with ultra-central uranium-uranium data unlike existing models that include binary collision terms.



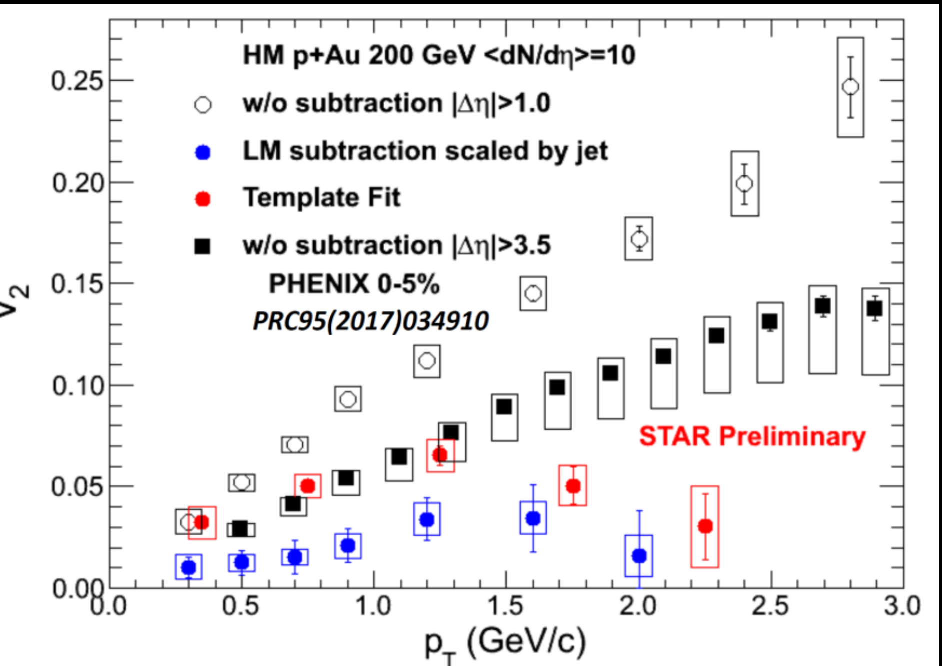
$$T_R = \begin{cases} \max(T_A, T_B) & p \to +\infty, \\ (T_A + T_B)/2 & p = +1, \ \text{(arithmetic)} \\ \sqrt{T_A T_B} & p = 0, \quad \text{(geometric)} \\ 2\,T_A T_B/(T_A + T_B) & p = -1, \ \text{(harmonic)} \\ \min(T_A, T_B) & p \to -\infty. \end{cases}$$

Trento p=0 is similar to Ncoll scaling (with extra sqrt) with an impact parameter dependence for N-N collisions. Thus, with the right parameters, quite comparable to IP-Glasma, IP-Jazma (dense-dense)

STAR Preliminary results shown at QM 2018



https://indico.cern.ch/event/656452/contributions/2869833/attachments/1649479/2637419/QM18-smallsystem-shengli-10.pdf



Due to a small Δη gap, they have a huge non-flow contribution (even at low p_T).

That is why they are so sensitive to the non-flow subtraction.

PHENIX results checked with Δη gap of 3 units and in systematic uncertainties.

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

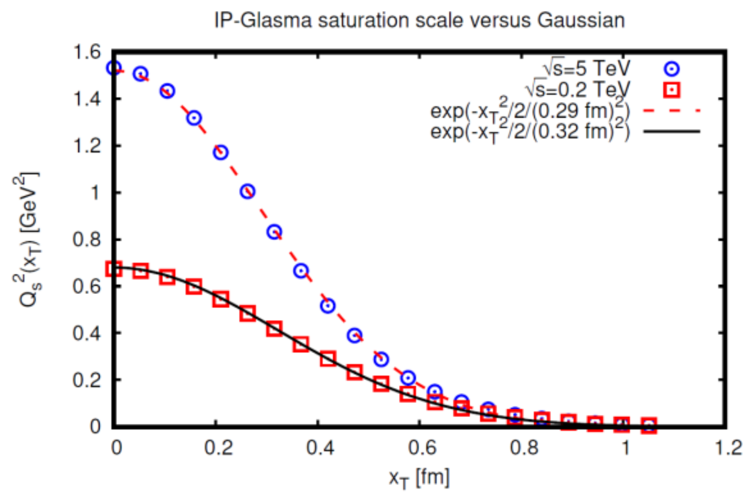


Figure 4.5: Transverse coordinate dependence of the saturation scale in the IP-Glasma model from Eq. (4.35) for two representative center-of-mass collision energies $\sqrt{s}$. For comparison, a simple Gaussian parametrization is shown.

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

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

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

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

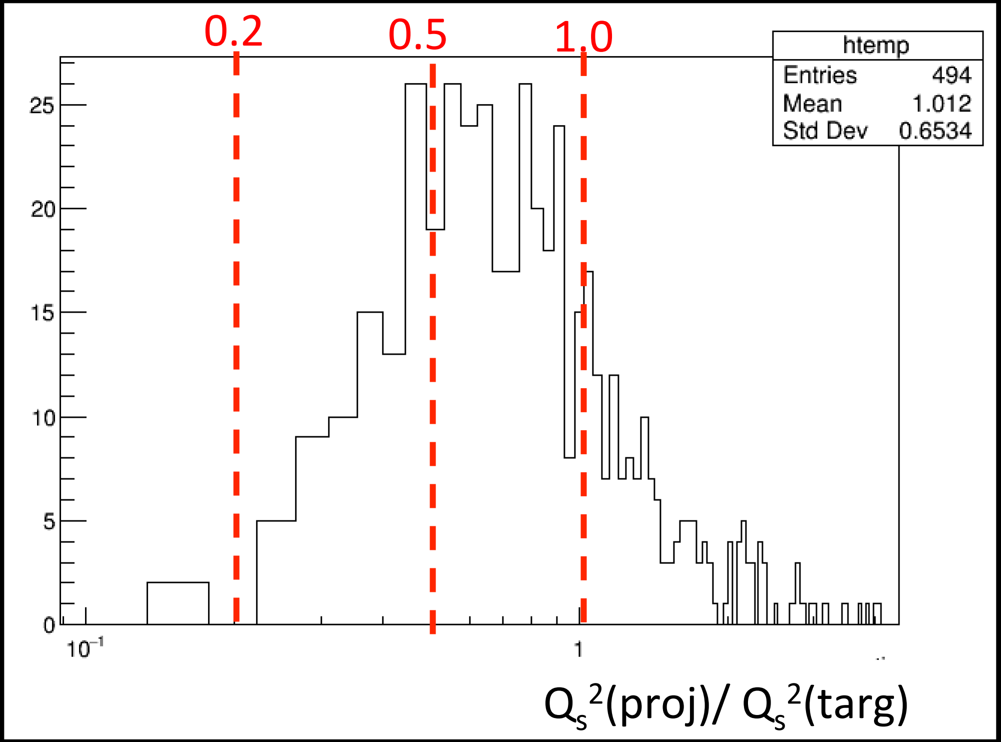
In dense-dense limit, just sum Q_s^2 values for each nucleus. Then energy density proportional to T_{A1A2} scaling

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

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

Dilute-Dense?

How valid is the dilute-dense limit when we effectively select on events that are larger fluctuations in the projectile saturation scale?

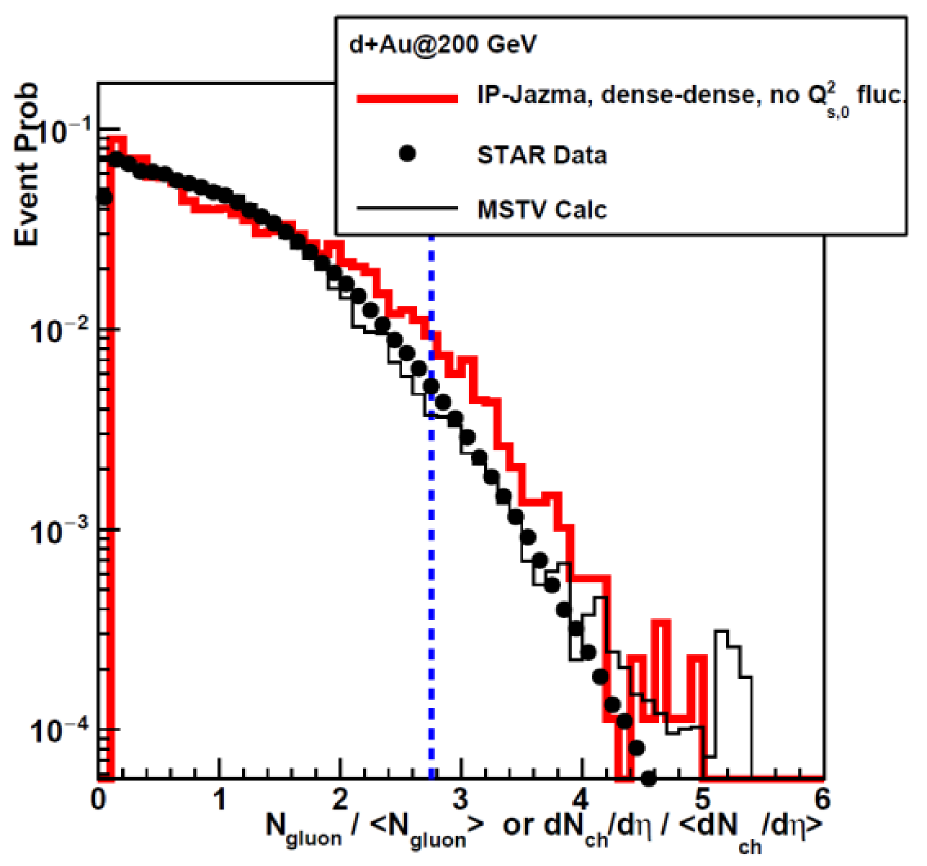


d+Au 0-5% high mult. events

Ratio Q_s^2 (proj) / Q_s^2(targ) weighted by the gluon contribution in that lattice cell (dilute-dense)

Naively might have thought ratio ~ 1 / $A^{1/3}$ ~ 0.2, but here we are selecting out fluctuations and cells with highest Q_s^2 (projectile).

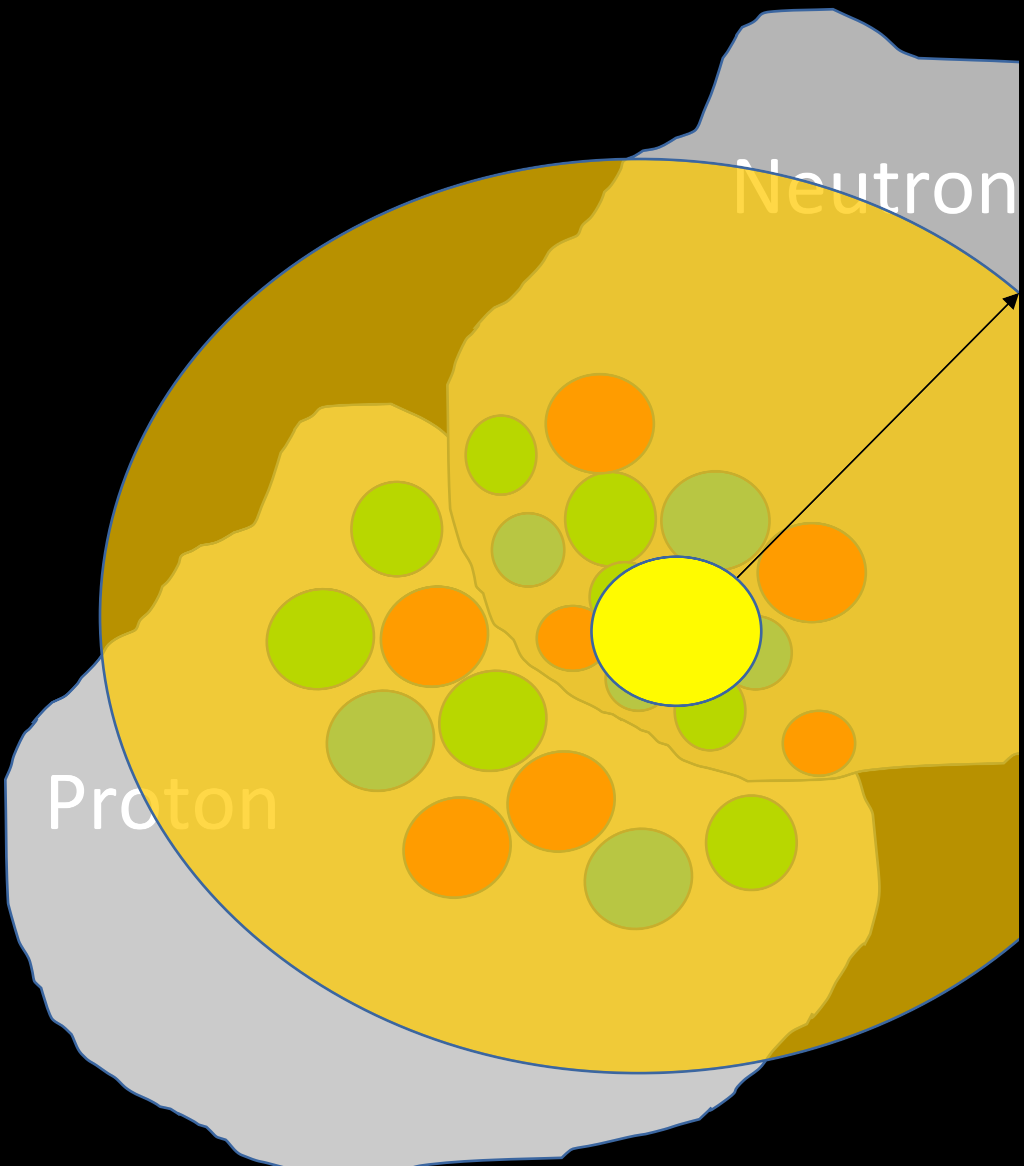
d+Au @ 200 GeV
Settings: Dense-Dense, no $Q_{s,0}^2$ fluctuations



We also obtain a reasonable (slightly worse) description of the data.
Modest adjustment of IP-Sat σ would allow better tuning.

N.B. No correlation between $Q_{s,0}^2$ projectile and gluon multiplicity.

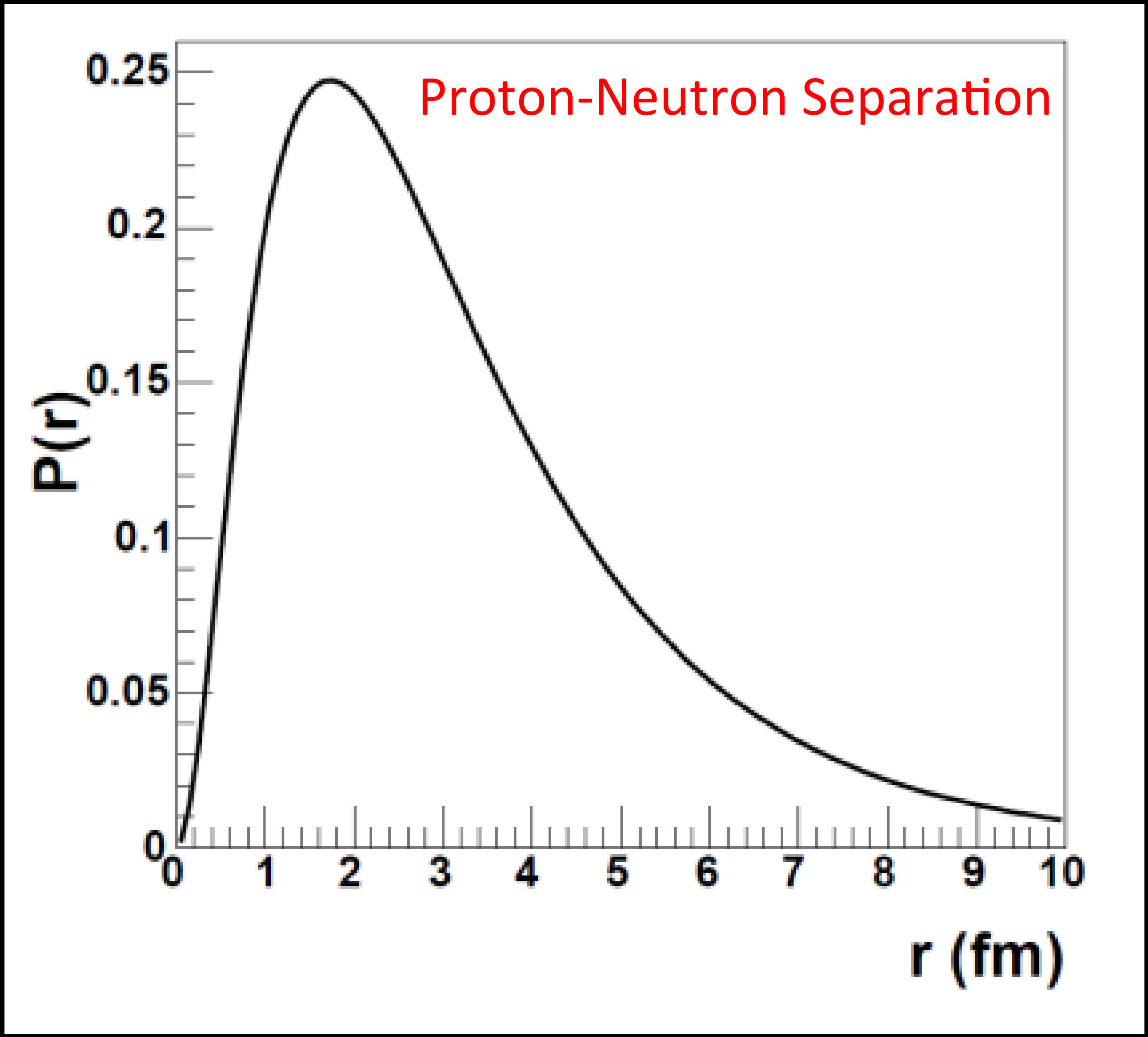
d+Au case



If the target gluon was
HUGE,
then all target gluons would "see" the same domains (all of them)
and
$v_2(dAu) \sim v_2(pAu)$
modulo the small overlap

But still need
$v_2(dAu) > v_2(pAu)$
See later…

Reminder: The Deuteron is Big!



Integrating over Lattice Fluctuations

Romatschke & Romatschke (arXiv:1712.05815) found that integrating over these color fluctuations in IP-Glasma (some are lattice artifacts anyway) one obtains the energy density:

$\varepsilon \propto g^2 Q_s^2(\text{proj}) \times Q_s^2(\text{targ})$ (dense-dense limit)

IP-Jazma is thus averaging over these lattice site fluctuations, and then assumes N_{gluon} proportional to energy density.

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).

Ab initio or *non pertinet*

Many have stated that these color domains effects are calculated *ab initio*

However, saturation physics in the proton at $x > 0.01$ challenges the whole picture of the formalism

One estimate has
$Q_{s,0}^2$ (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

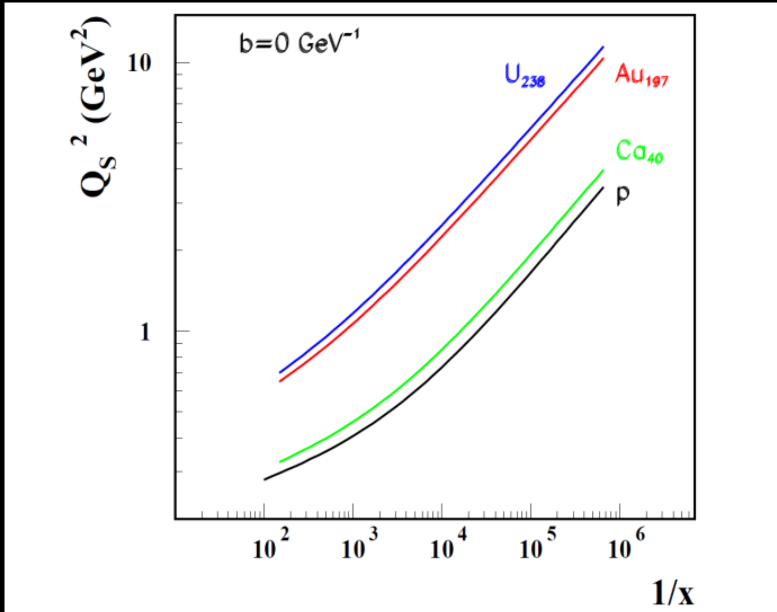


FIG. 25: The quark saturation scale $(Q_s^2)_q$ at $b = 0$ as a function of x for various nuclei . The gluon saturation scale is $(Q_s^2)_g = \frac{N_c}{C_F}(Q_s^2)_q \approx 2.25\,(Q_s^2)_q$.