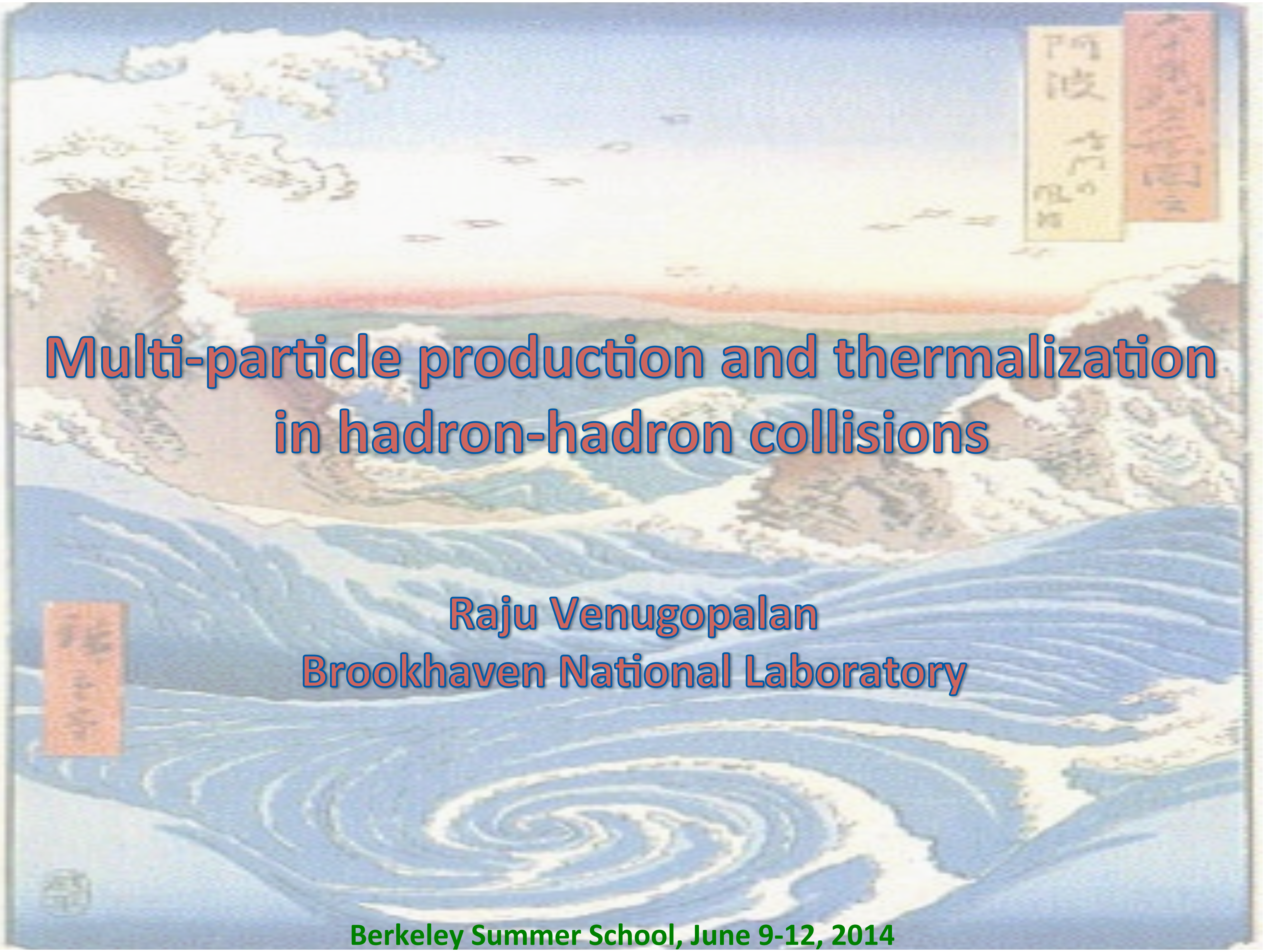


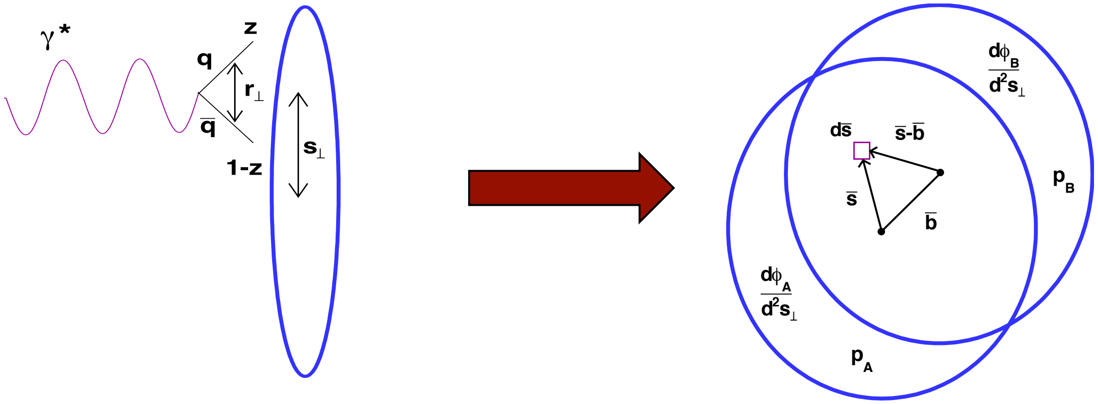
Multi-particle production and thermalization in hadron-hadron collisions

Raju Venugopalan
Brookhaven National Laboratory

Berkeley Summer School, June 9-12, 2014

Extracting lumpy glue in the proton-IPSat model

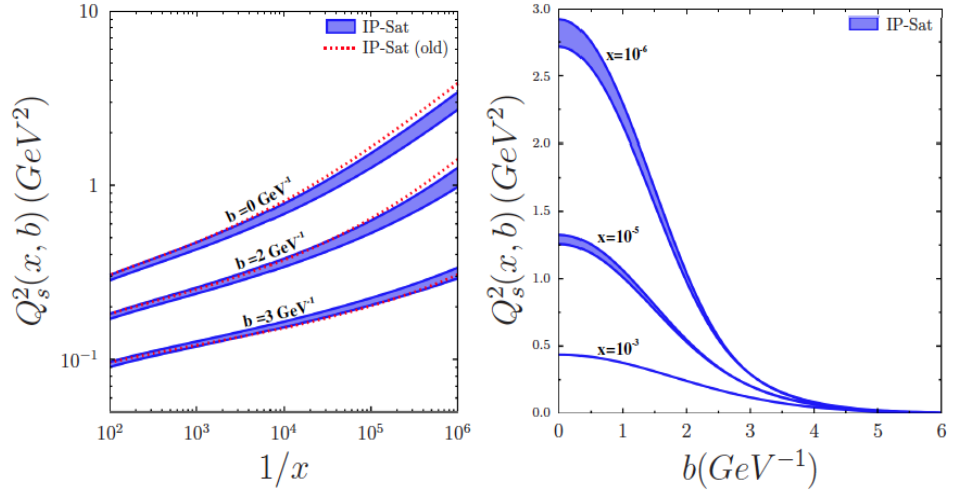
Bartels,Golec-Biernat,Kowalski
Kowalski,Teaney
Kowalski,Motyka,Watt



$$\frac{d\sigma^p_{dip}}{d^2 b_\perp}(r_\perp, x, b_\perp) = 2\mathcal{N}(r_\perp, x, b_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r_\perp{}^2 \alpha_s(\tilde{\mu}^2) x g(x, \tilde{\mu}^2) T_p(b_\perp)\right)\right]$$

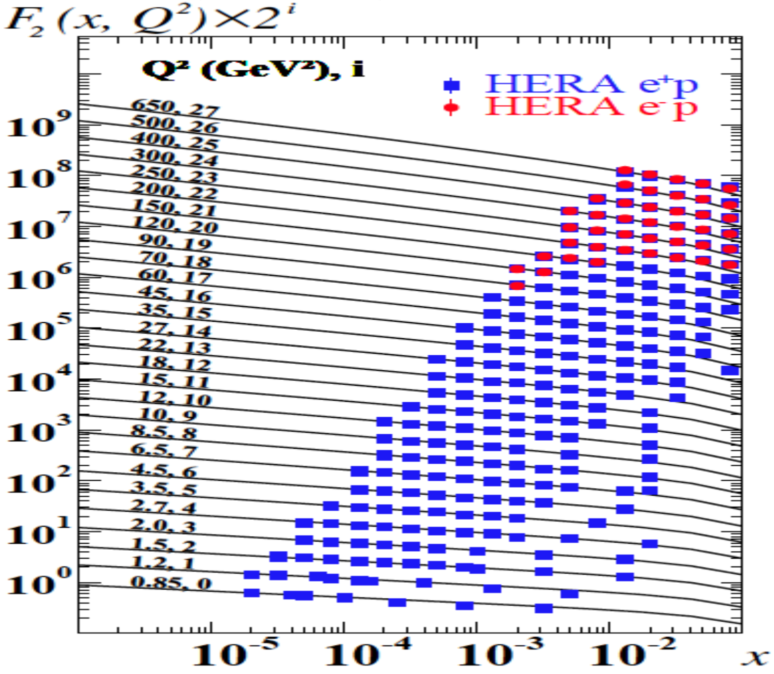
$T_p(b_\perp) = e^{-\frac{b_\perp^2}{2B_G}}$ → **Average gluon radius of the proton extracted from HERA diffractive data**

$$\tilde{\mu}^2 = \mu_0^2 + \frac{4}{r_\perp}^{2}$$



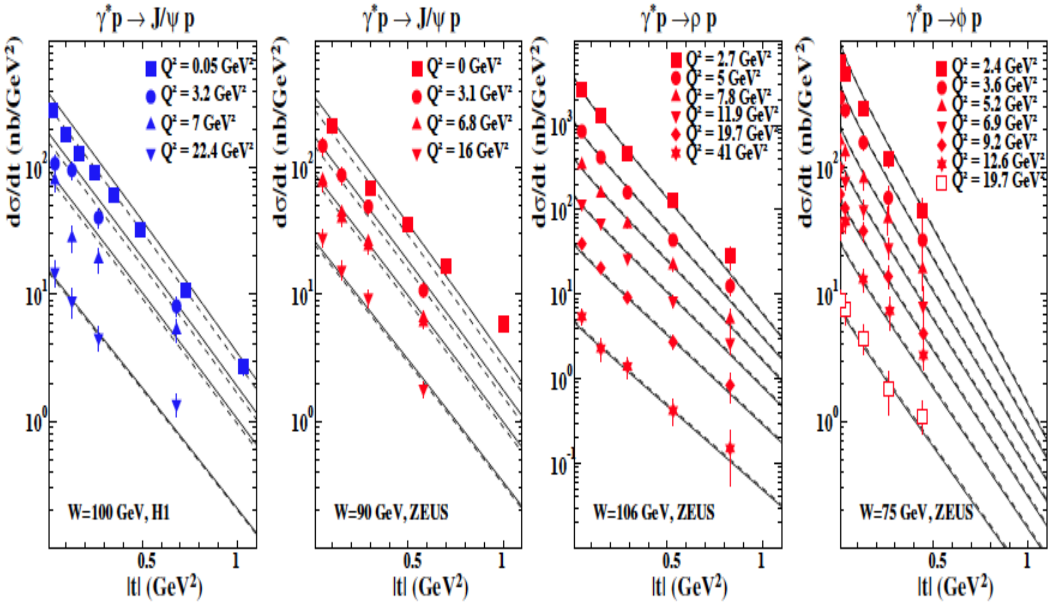
Extracting lumpy glue in the proton-IPSat model

Very good agreement of IPSat model with combined HERA data



Inclusive DIS off proton

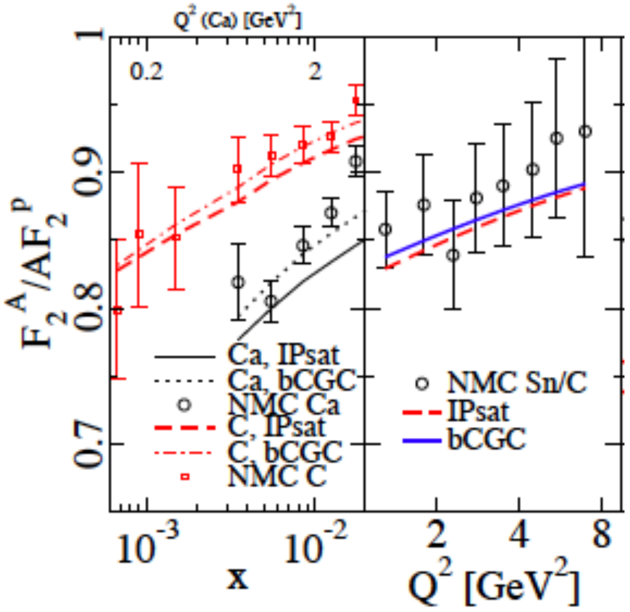
Rezaiean,Siddikov,Van der Klundert,RV:1212.2974

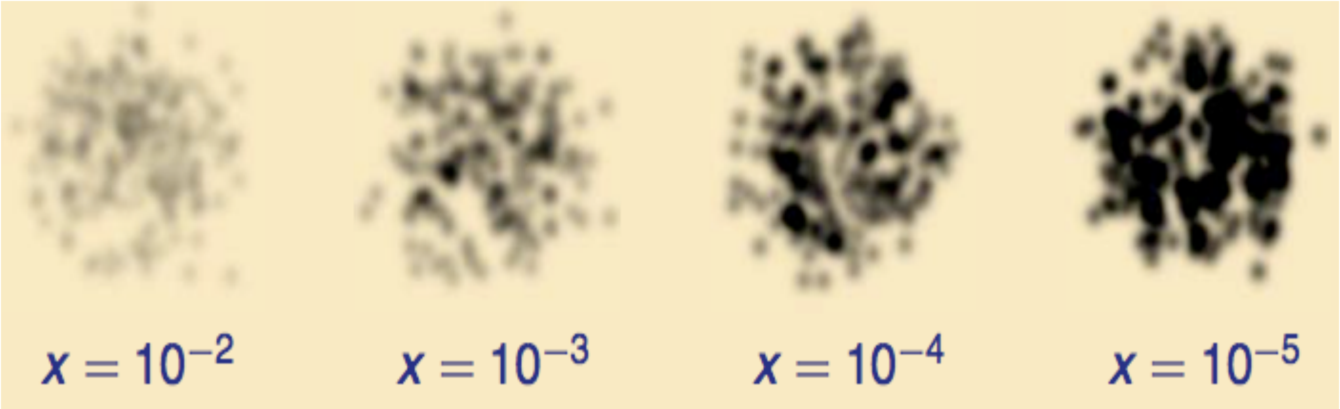


Exclusive DIS off proton

Lumpy nuclei: constrained by (limited) DIS data

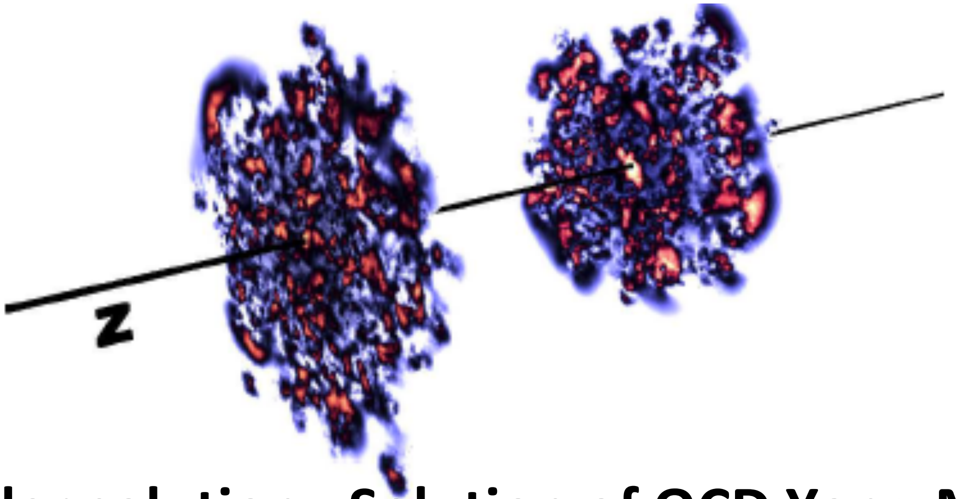
Kowalski, Lappi, RV, PRL (2008)





Heavy ion phenomenology in weak coupling

Collisions of lumpy gluon ``shock" waves



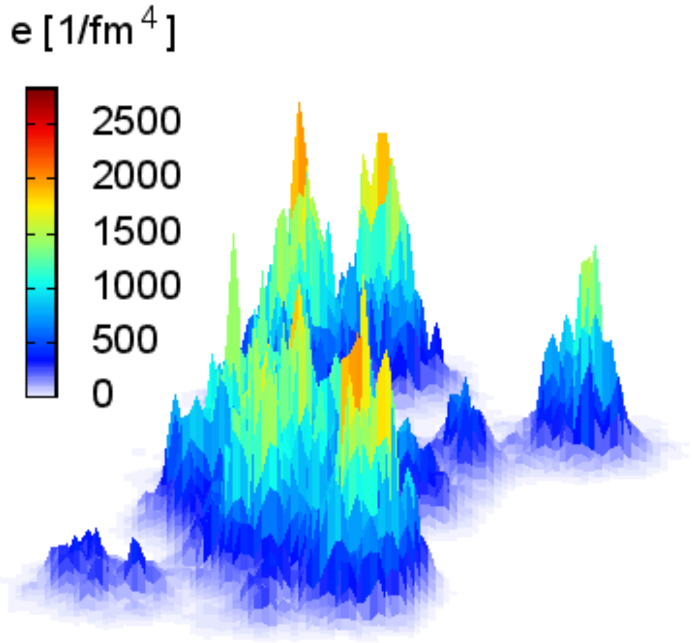
Leading order solution: Solution of QCD Yang-Mills eqns

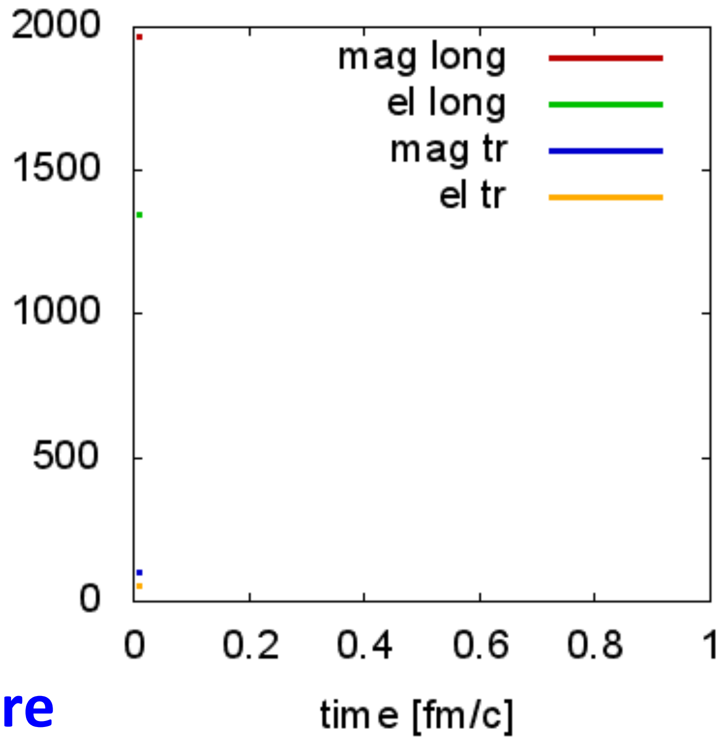
$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho_A^a(x_\perp)\delta(x^-) + \delta^{\nu-}\rho_B^a(x_\perp)\delta(x^+)$$

$$x^\pm = t \pm z$$

$$F^{\mu\nu,a} = \partial_\mu A^{\nu,a} - \partial_\nu A^{\nu,a} + g f^{abc} A^{\mu,b} A^{\nu,c}$$

$T^{\mu\nu}$ from Yang-Mills dynamics



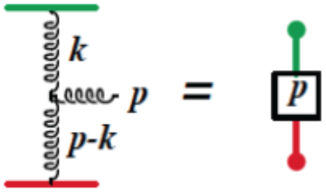


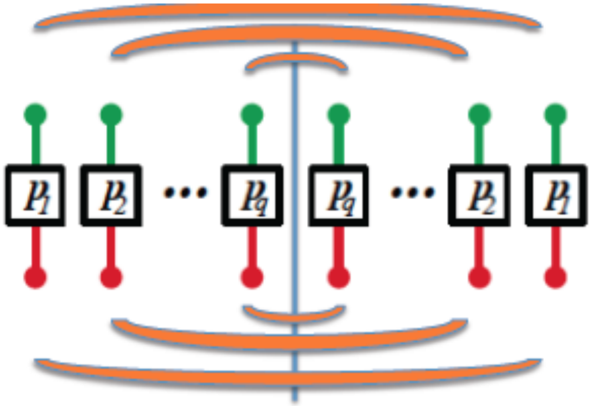
Glasma energy density and pressure

$$T_{\mu\nu}(\tau = 0) = \frac{1}{2}(B_z^2 + E_z^2) \times \mathrm{diag}(1, 1, 1, -1)$$

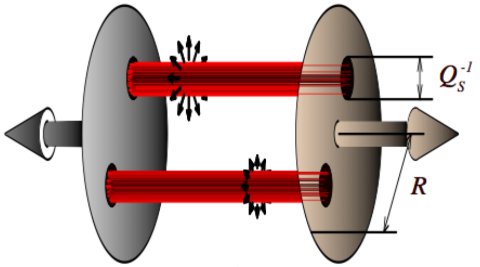
Initial longitudinal pressure is negative:
Goes to P_L =0 from below with time evolution

Multiparticle production: lasing gluons





Gelis,Lappi,McLerran,
arXiv:0905.3234



Multiparticle production in the Glasma naturally gives:

Long range rapidity correlations – key input into hydro

Negative Binomial Distributions (NBDs):

Output of model – no additional parameter unlike ``Glauber”
Fluctuations related to shapes – also unlike Glauber.

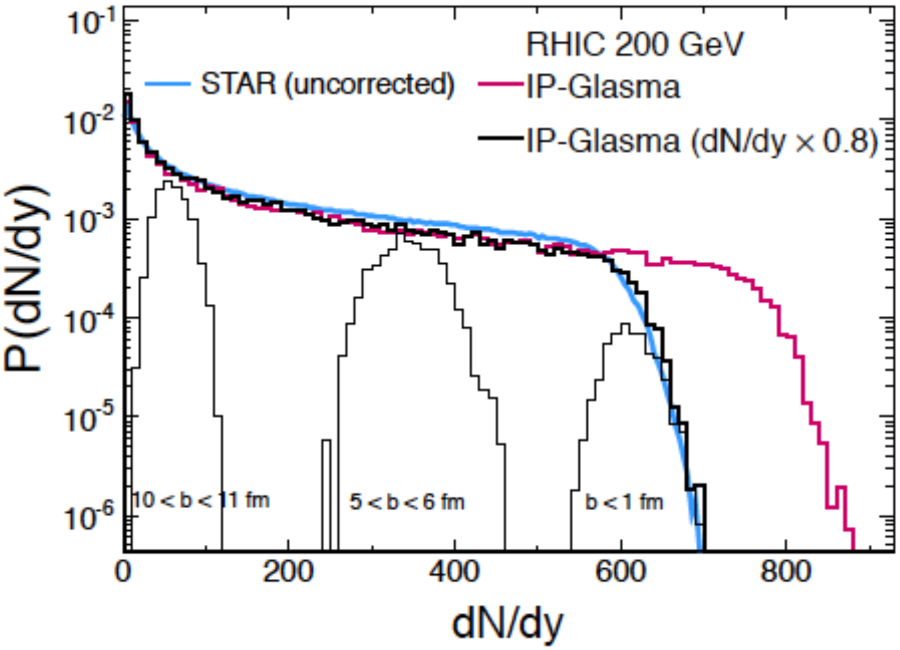
$$P_n^{\rm NB} = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

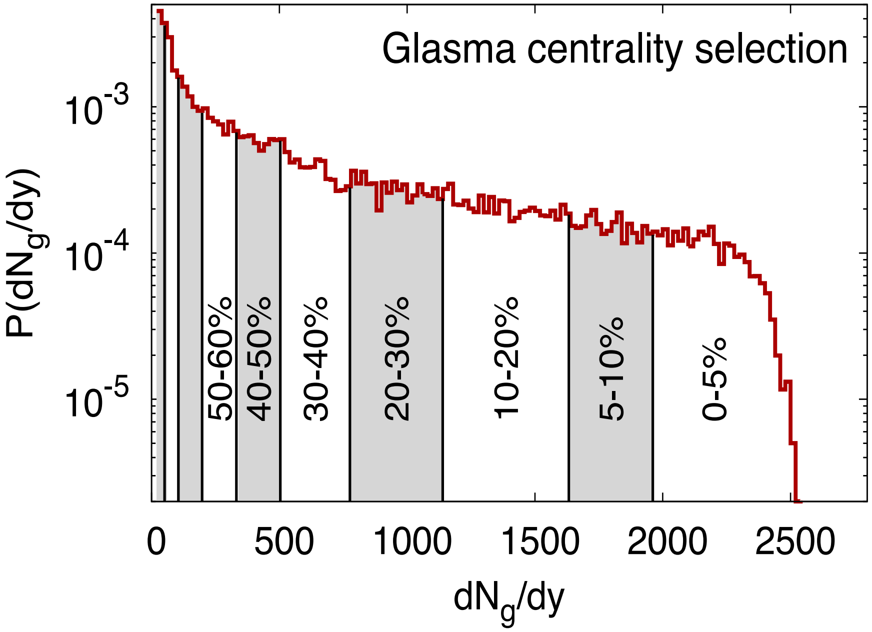
$$k = \kappa \frac{(N_c{}^2 - 1) Q_s^2 S_\perp}{2\pi}$$

k=1: Bose-Einstein dist.; k=∞: Poisson distribution

NBDs in heavy ion collisions

Schenke,Tribedy,RV: arXiv:1206.6805

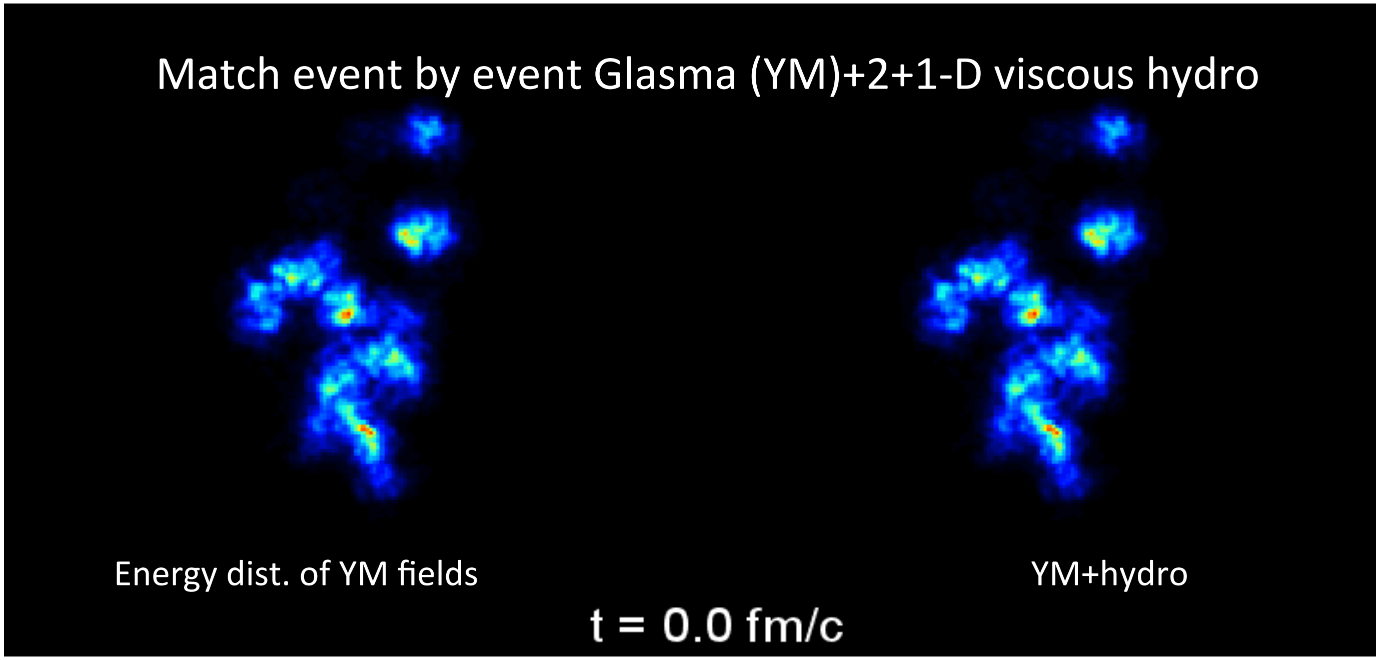




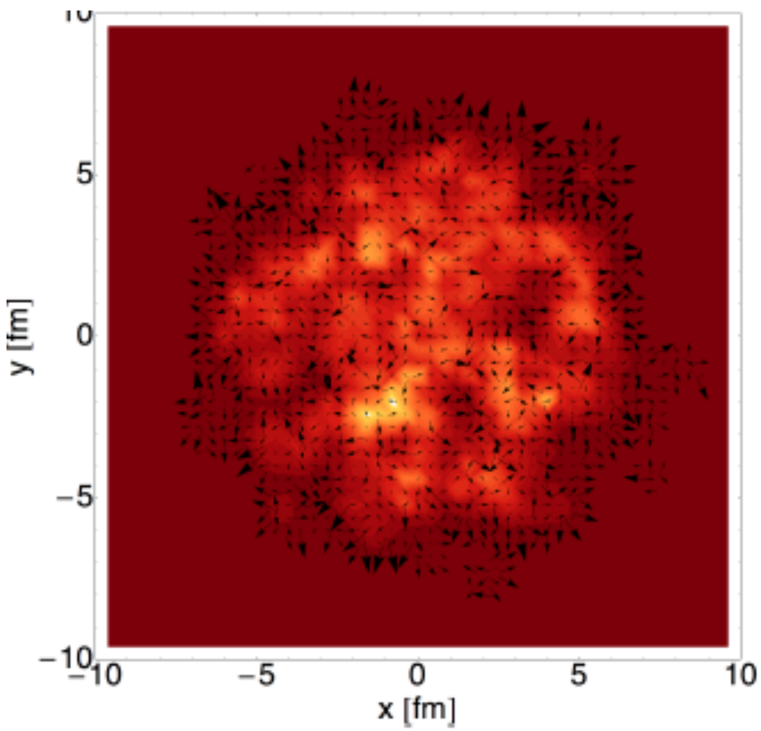
Only model of heavy ion collisions where multiplicity dist./centrality selection Is not an external input

Matching boost invariant Yang-Mills to hydrodynamics

State of the art phenomenology: Solve relativistic viscous hydrodynamic equations with Glasma (Yang-Mills) initial conditions



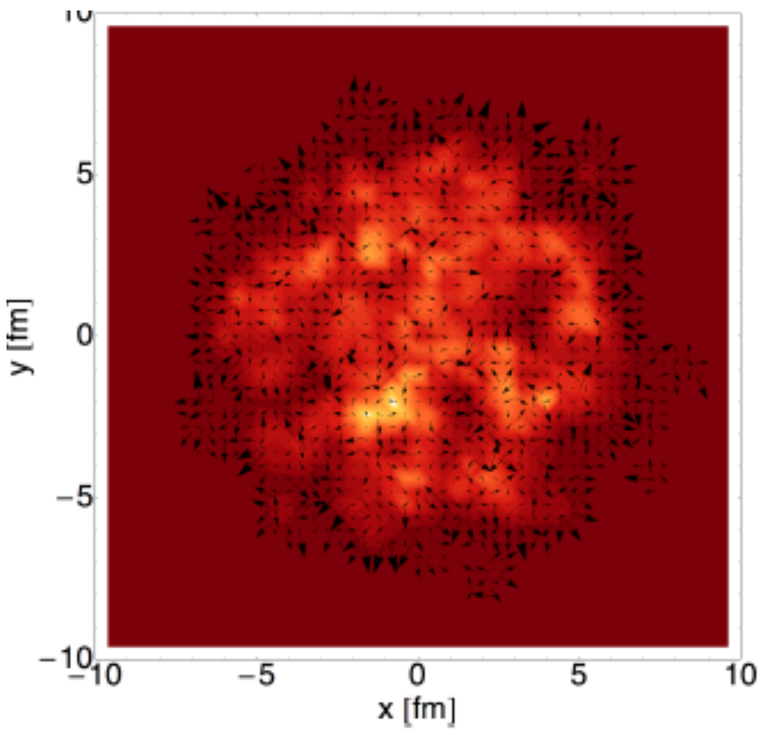
Matching boost invariant Yang-Mills to hydrodynamics



Energy density
and (u_x, u_y)
at $\tau = 0.4\,\mathrm{fm}/c$

Energy density and (u_x,u_y) from $u_\mu T^{\mu\nu} = \varepsilon u^\nu$

Matching boost invariant Yang-Mills to hydrodynamics



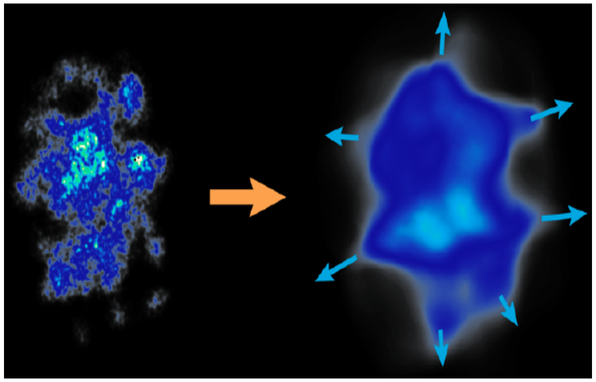
Energy density
and (u_x, u_y)
at $\tau = 0.4\,\mathrm{fm}/c$

Matching to viscous hydro is "brutal" :
assume very rapid isotropization at initial hydro time

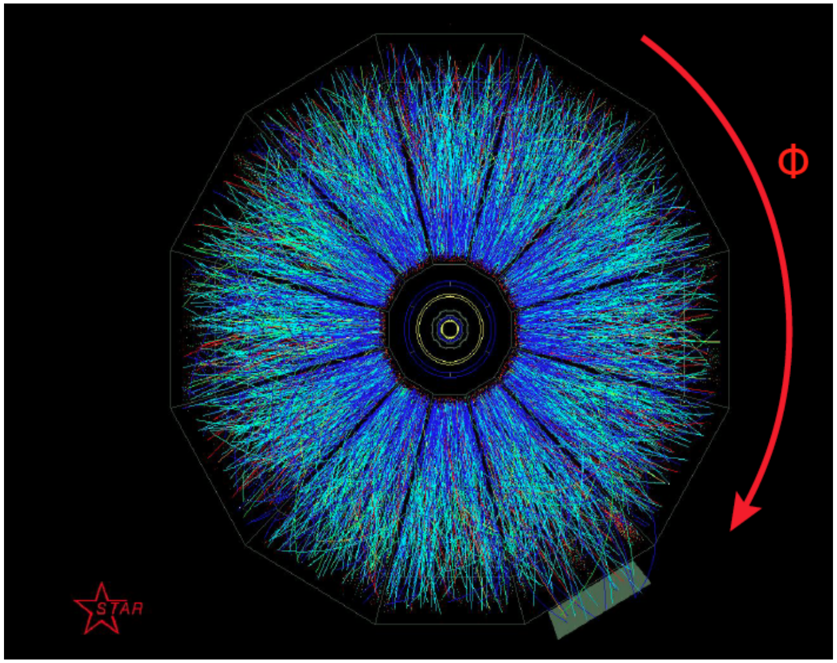
Large systematic uncertainty: how does isotropization/ thermalization occur on times < 1 fm/c ?

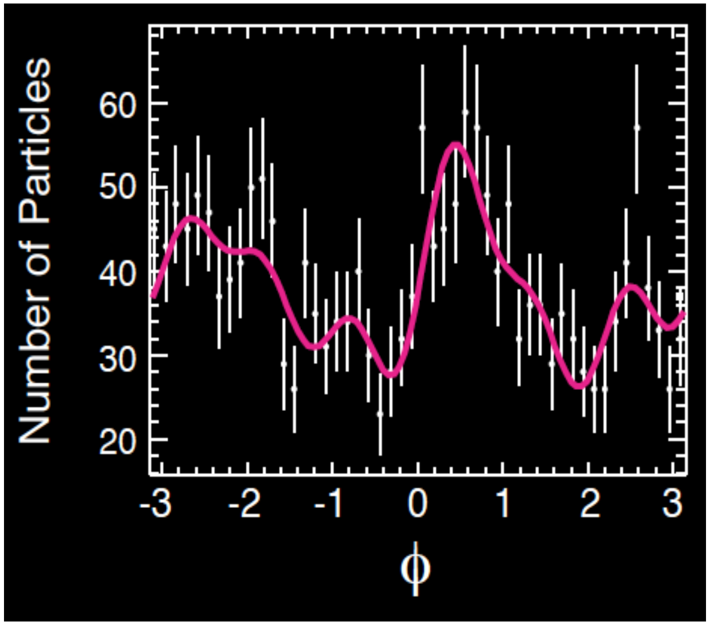
Heavy ion phenomenology in weak coupling

Hydrodynamics: efficient translation of spatial anisotropy into momentum anisotropy



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + 2v_4\cos(4\phi) + \cdots\right)$$





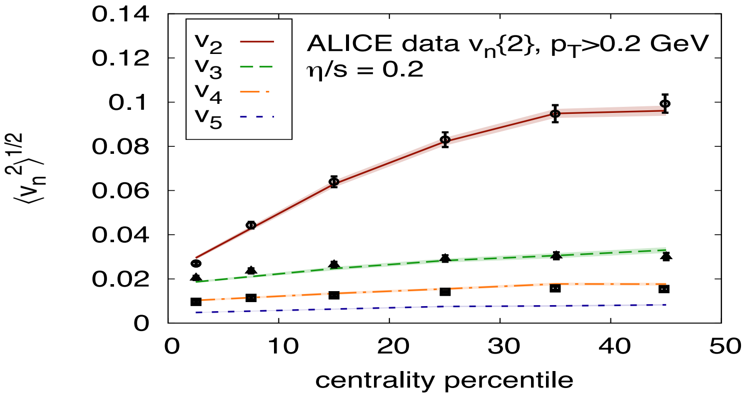
MUSIC: 3+1-D event-by-event viscous relativistic hydro model

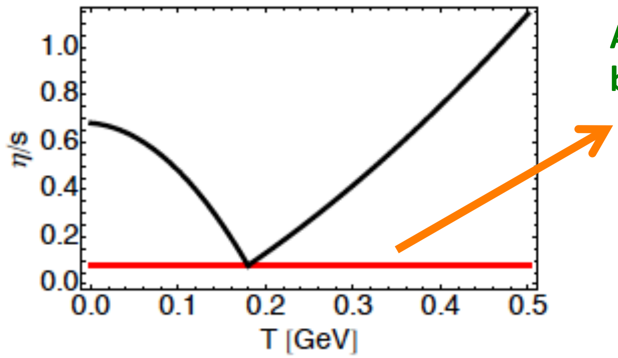
Schenke,Jeon, Gale

Heavy ion phenomenology in weak coupling

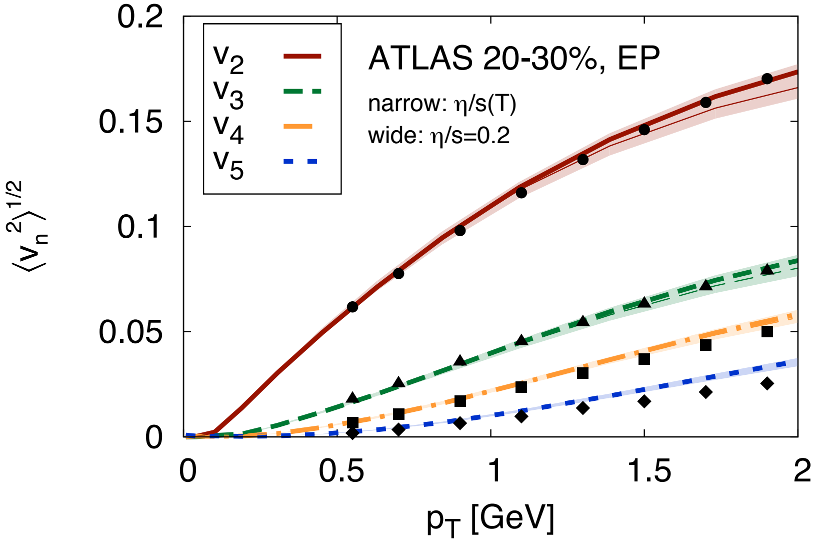
Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL (2013) 012302

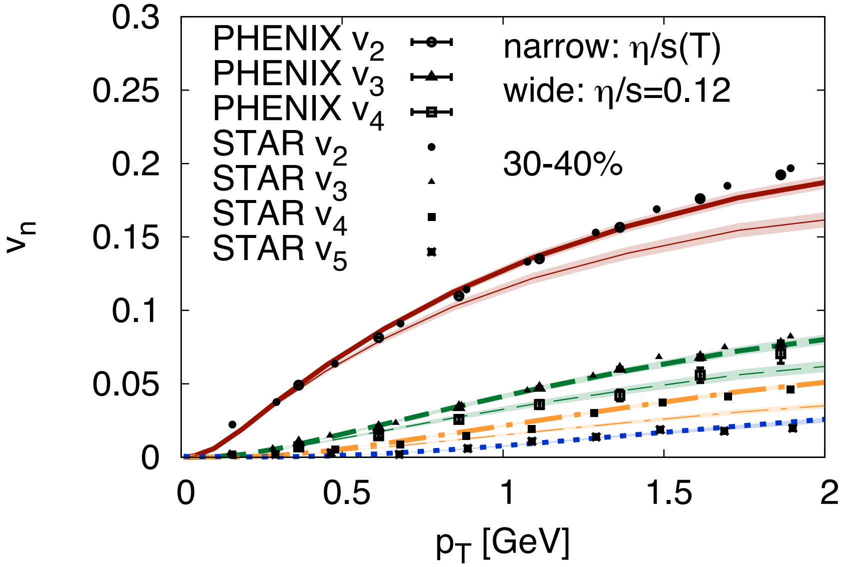
Results from the IP-Glasma +MUSIC model:





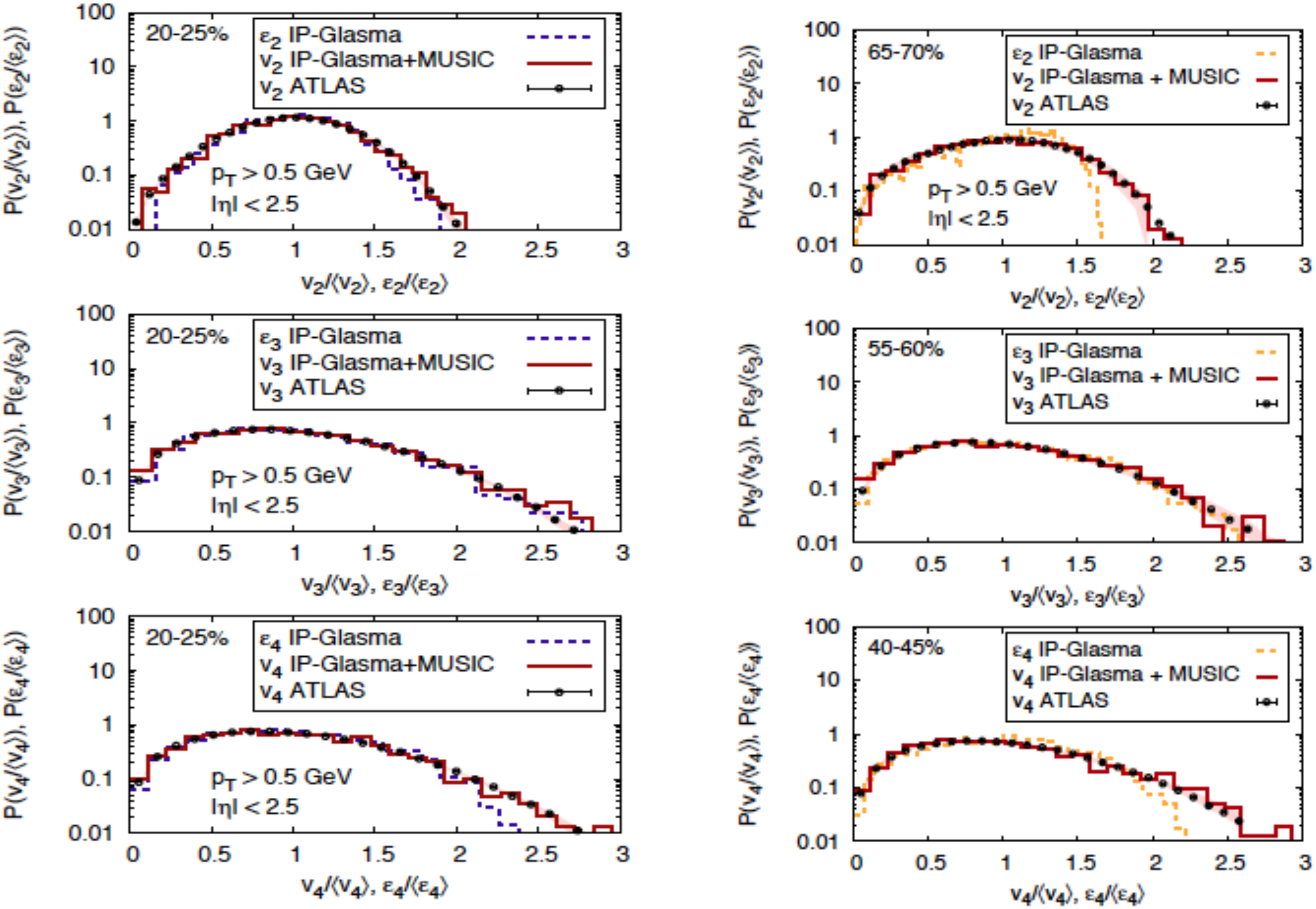
AdS/CFT
bound = 0.08





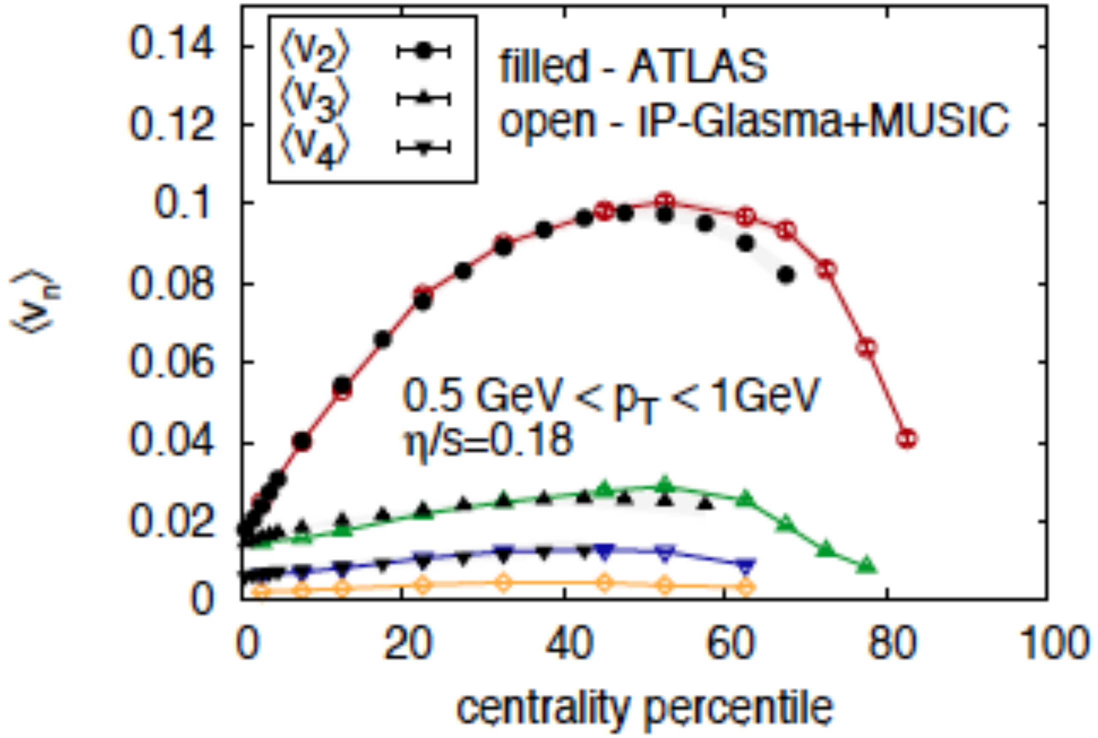
RHIC data require lower average value of η/s relative to LHC

Heavy ion phenomenology in weak coupling



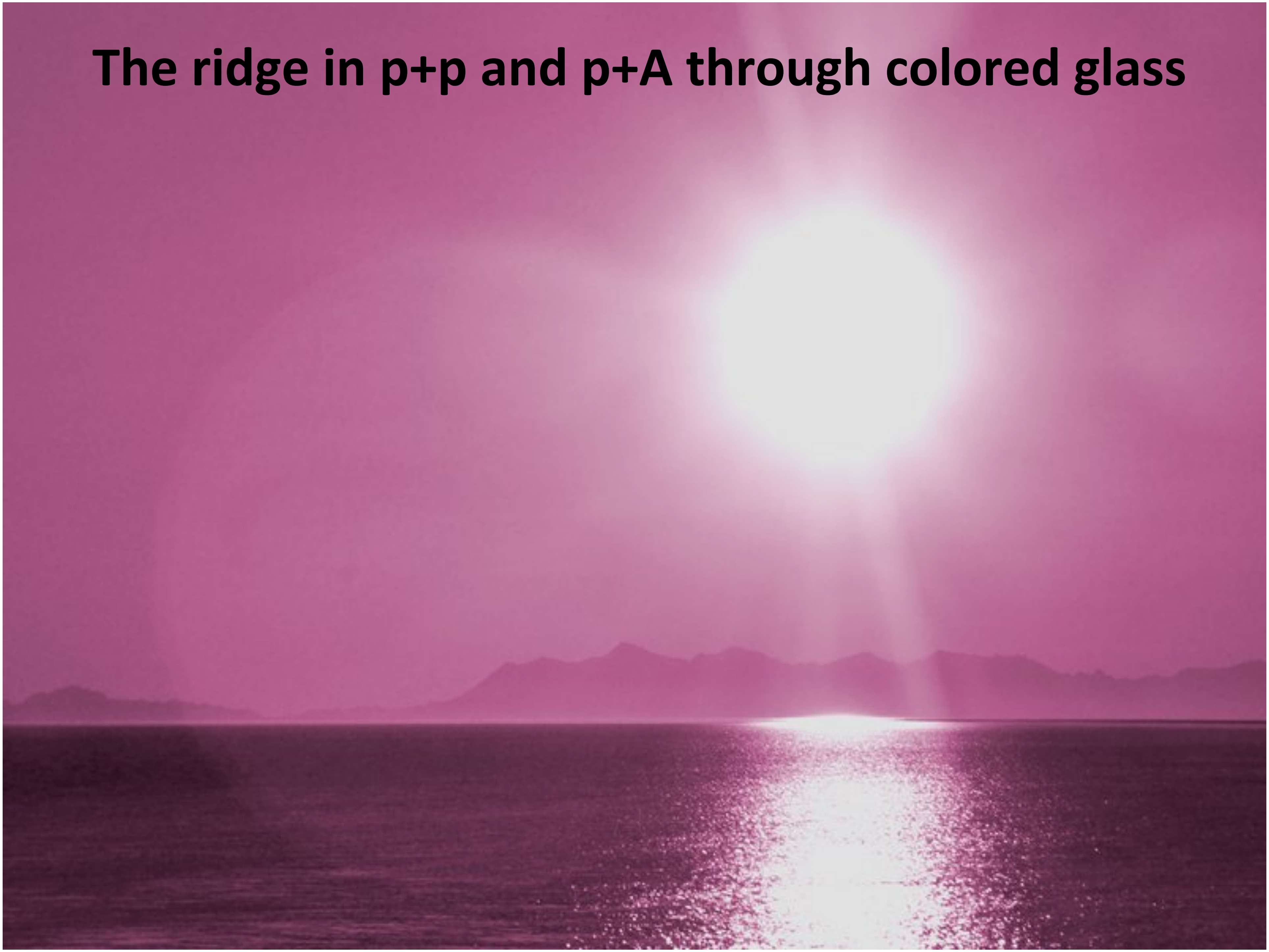
Heavy ion phenomenology in weak coupling

Schenke,Venugopalan, arXiv:1405.3605

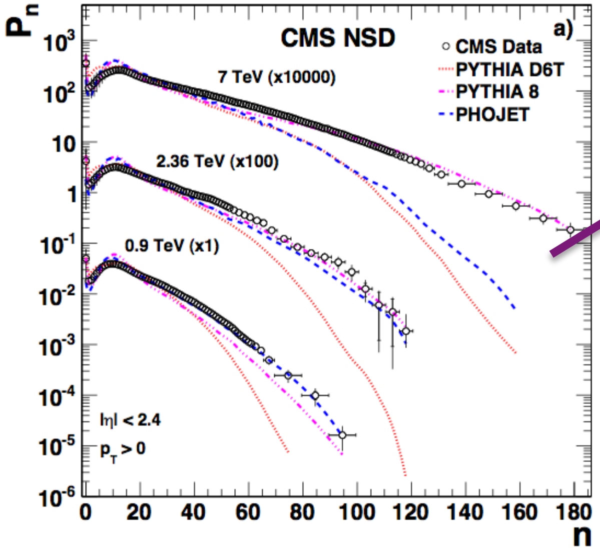


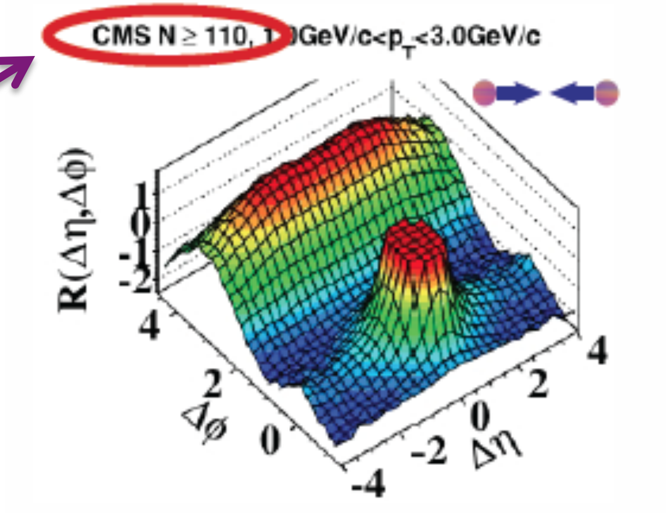
Remarkable agreement of IP-Glasma+MUSIC with data out to fairly peripheral overlap geometries…

The ridge in p+p and p+A through colored glass



The ridge Tsunami



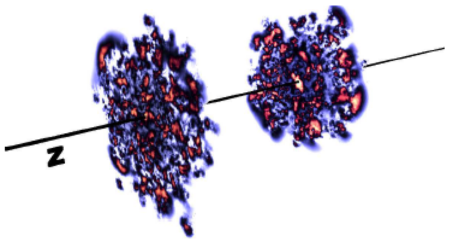


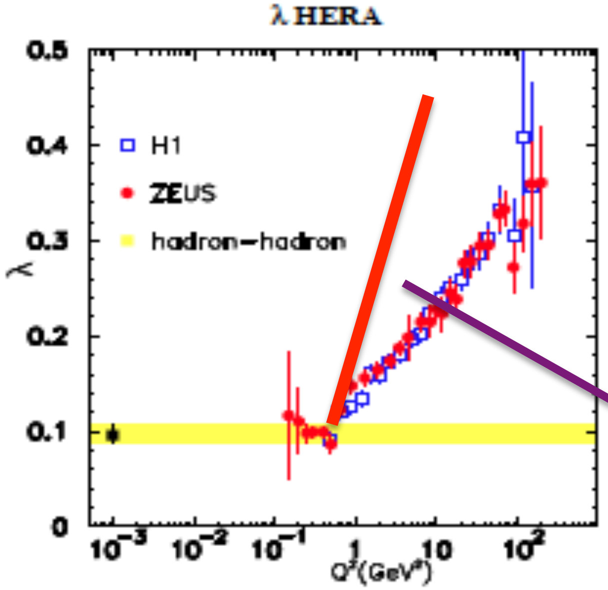
CMS Collaboration (Khachatryan, Vardan et al.)
JHEP 1009 (2010) 091 arXiv:1009.4122 [hep-ex]

- What is the underlying QCD mechanism of the ridge?
- How far can can we extend the collective flow paradigm to small size systems – and do we see systematic deviations?
- Is there "spooky quantum mechanics" at work a la photon or spin entanglement ?
- Are hadronization patterns universal QCD physics or do they reflect thermal abundances ?

High multiplicities + small systems = gluon saturation

What does it take to produce~ 150 hadrons per 5 units of rapidity in a single p+p event ?





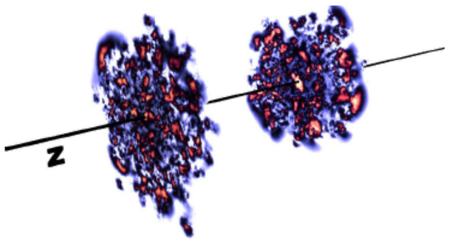
For λ=0.14, get about 13 gluons produced in 5 units ~ min.bias hadron multiplicity

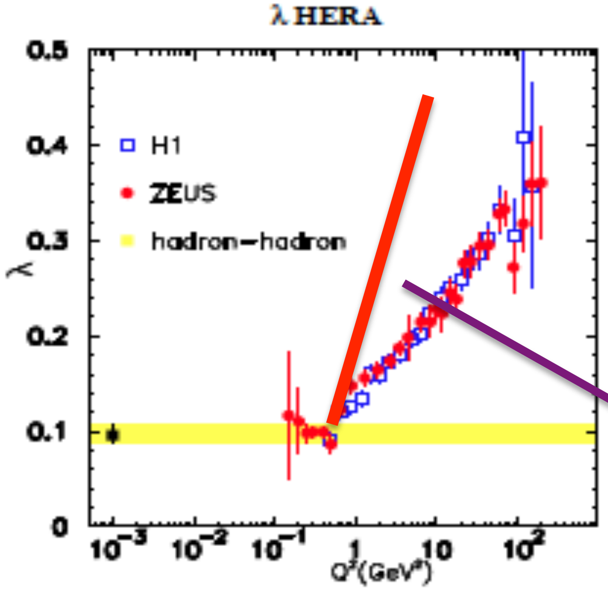
λ=0.3: ~45 gluons in 5 units,
λ=0.4: ~90 gluons in 5 units, in ball park…

Very rapid growth of gluon dist. in such events…

High multiplicities + small systems = gluon saturation

What does it take to produce~ 150 hadrons per 5 units of rapidity in a single p+p event ?





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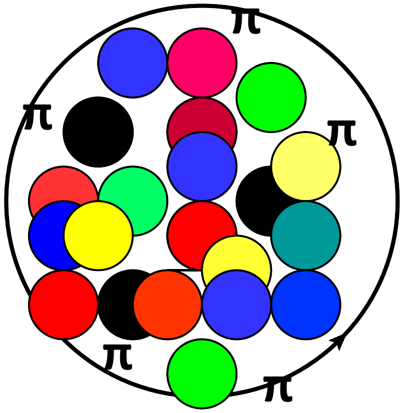
Very rapid growth of gluon dist. In such events…

Saturation regulates this by adding increasingly "smaller" gluons of size $1/Q_s(x)$ with decreasing x (increasing energy)

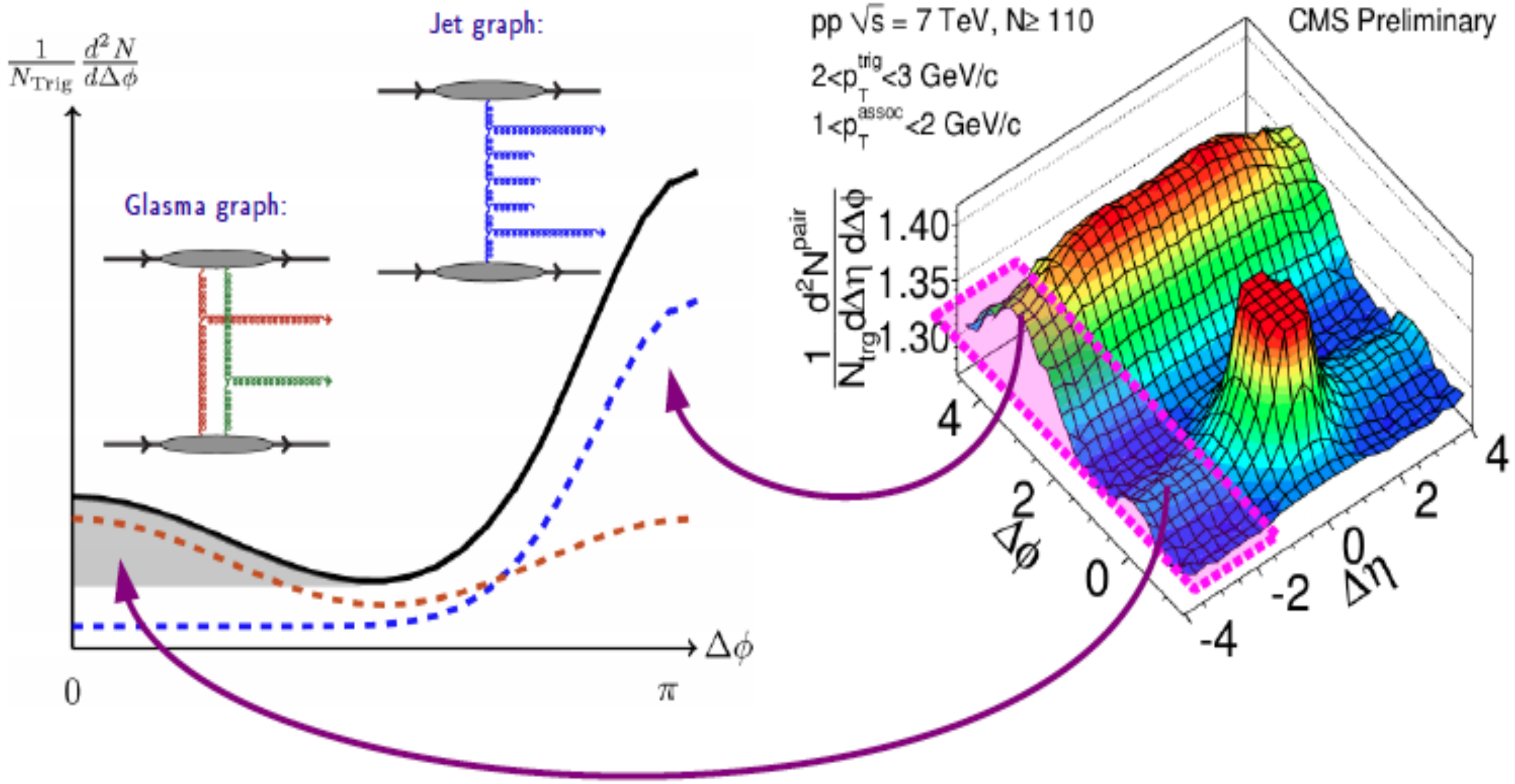


$$\boxed{\frac{dN_g^{\text{prot.}}}{d\eta} \approx \frac{1.1\, C_F}{2\pi^2}\, \frac{S_\perp Q^2_{S,\text{prot.}}}{\alpha_S}}$$

Lappi:
arXiv 0711.3039

N_g ~ 100 in 5 units for Q_S^2 ~ 2 GeV^2 : a semi-hard scale !

Initial state collimation from jet+Glasma

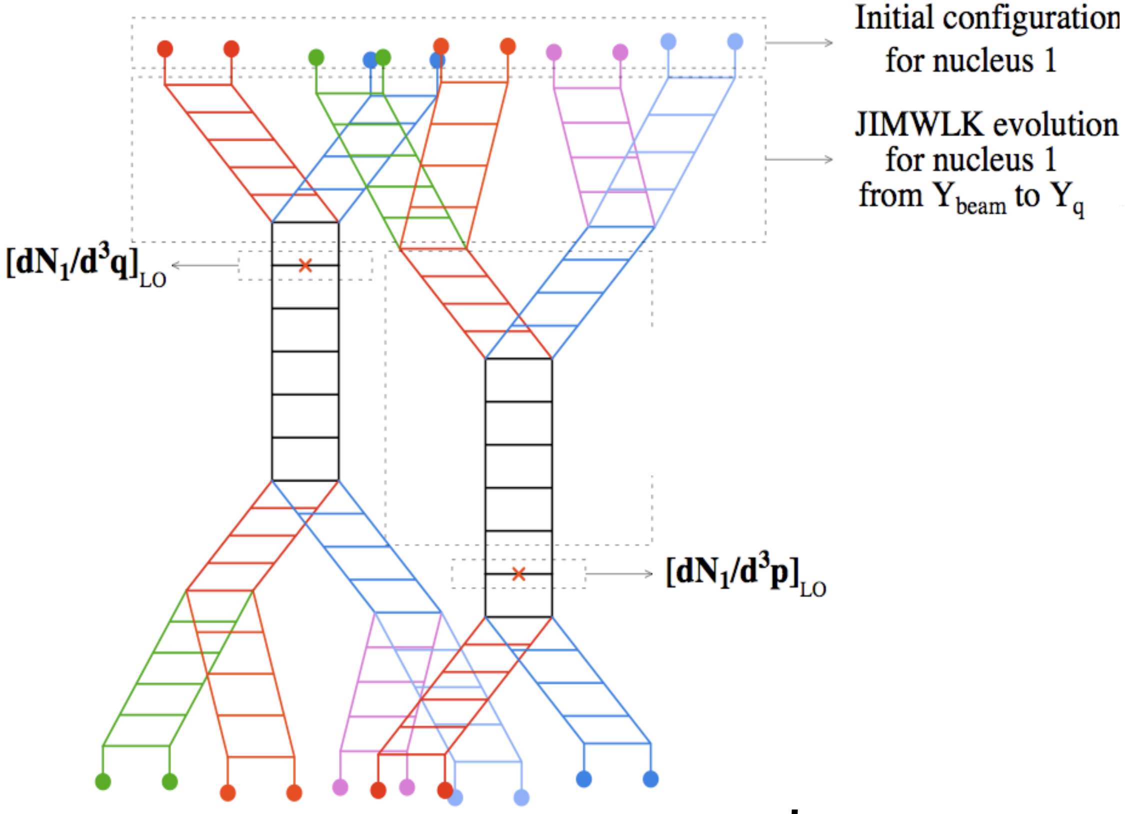


Quantitative modeling of these initial state correlations gives good description of p+p high multiplicity correlation data and features of p+A correlation data

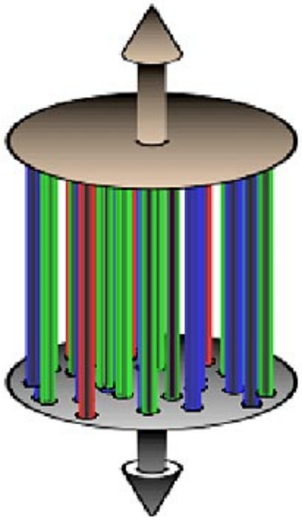
Dusling, Venugopalan, arXiv:1210.3701, arXiv:1211.3701, arXiv:1302.7018

(**Next talk by Kevin Dusling**)

High multiplicity events: two particle correlations



Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]



◆ Full YM+JIMWLK evolution – not available yet

◆ Approximations:

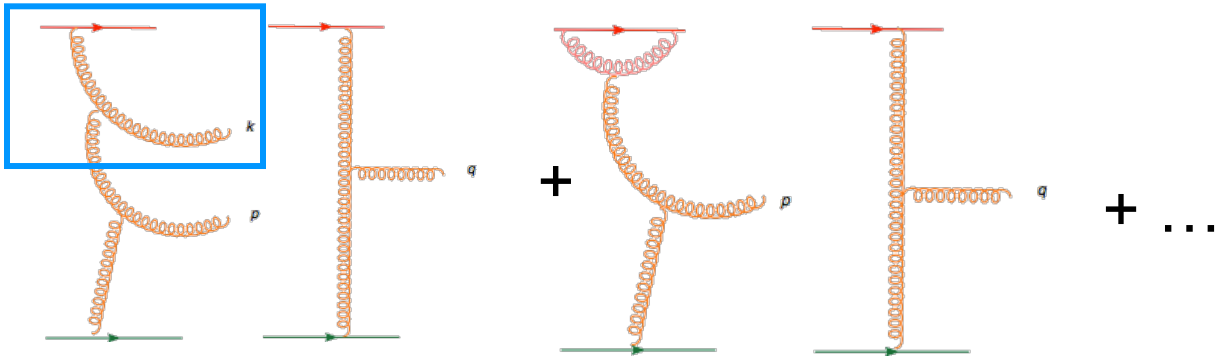
I) BK Gaussian truncation approximation -evolution but no rescattering
II) YM results for MV model: rescattering but no evolution

Dusling,Gelis,Lappi,RV:0911.2720; Lappi,Srednyak,RV:0911.2068;
Kovchegov,Wertepny: 1212.1195

Glasma graphs

RG evolution:

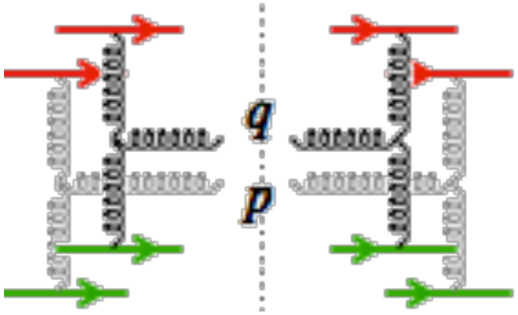
Dumitru,Gelis,McLerran,RV: 0804.3858
Gelis, Lappi, RV, arXiv: 0807.1306



Keeping leading logs to all orders (NLO+NNLO+…)

= LO graph with evolved sources

avg. over sources in each event
and over all events gives correlation



Glasma graphs

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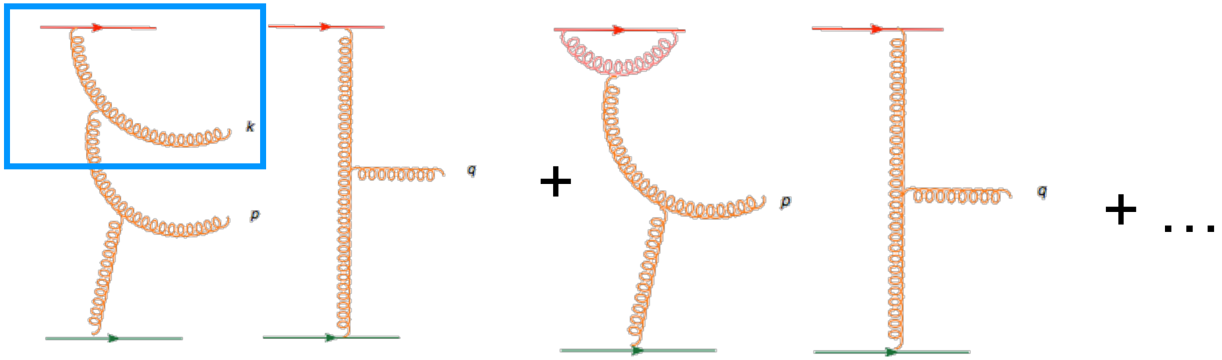

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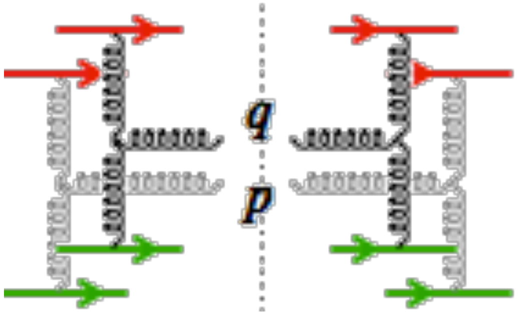
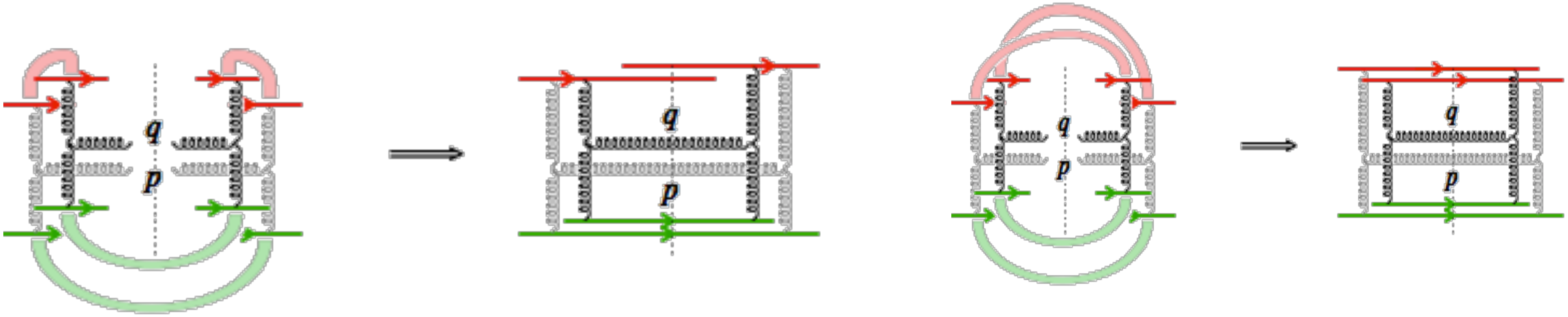


$$\langle \frac{dN_2}{d^3p\, d^3q}\rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

From solns. of Yang-Mills eqns.with two light cone sources
Includes all mult. scat. contributions $(g\rho_1)^n$ and $(g\rho_2)^n$

Glasma graphs

Correlations are induced by color fluctuations that vary event to event – for Gaussian weight functionals in ρ, have color screening radius ~ $1/Q_S$



Glasma graphs

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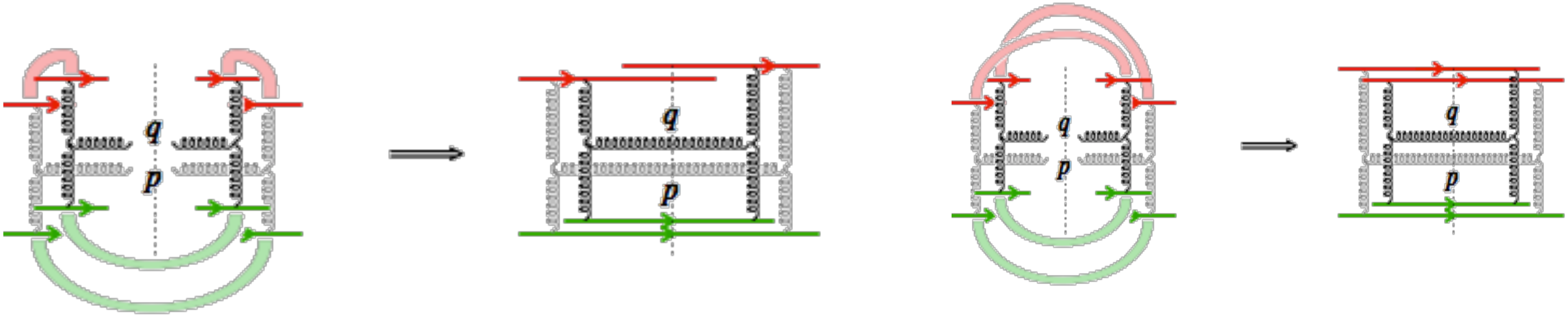
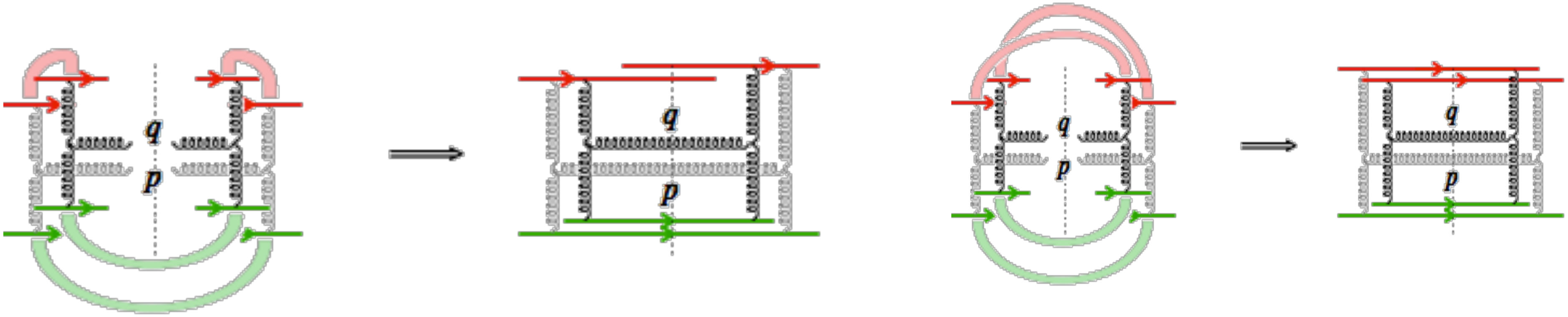


Glasma graphs generate long range rapidity correlations…

Glasma graphs

Correlations are induced by color fluctuations that vary event to event – for Gaussian weight functionals in ρ, have color screening radius ~ $1/Q_S$

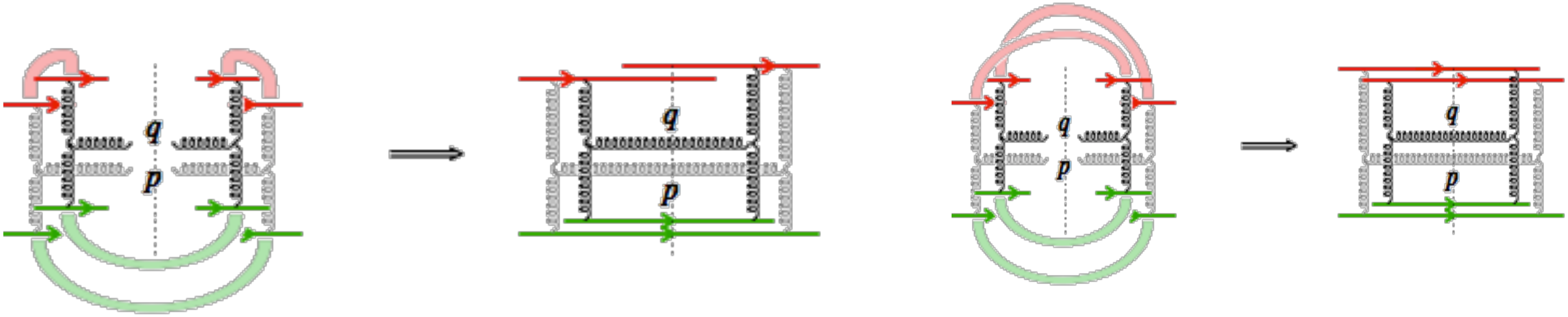


Glasma graphs generate long range rapidity correlations…

Glasma graphs are suppressed relative to “jet” graphs for $Q_S << p_T$ by powers of α_S AND N_C (At high p_T, large x or large impact parameters)

Glasma graphs

Correlations are induced by color fluctuations that vary event to event –
for Gaussian weight functionals in ρ, have color screening radius ~ $1/Q_S$

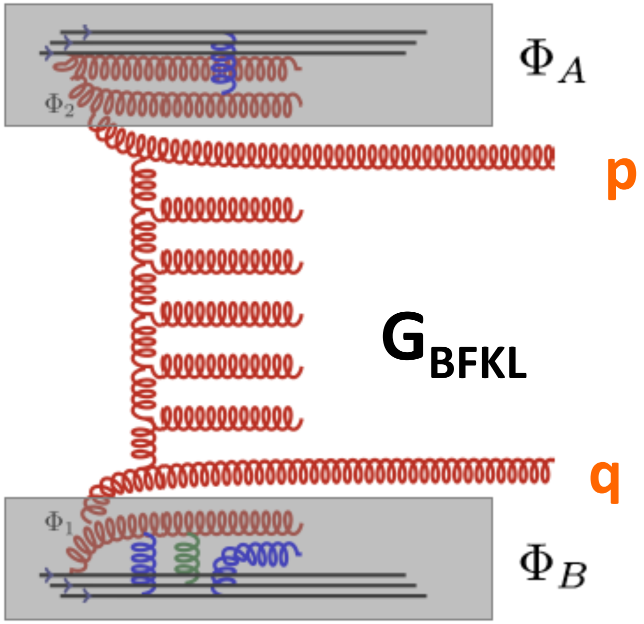


Glasma graphs generate long range rapidity correlations…

Suppressed for $Q_S \ll p_T$ by powers of α_S AND N_C
(At high p_T, large x or large impact parameters)

Glasma graphs enhanced by $1/\alpha_S^8$ for high occupancy fields (factor of 10^5 !)
(central impact parameters, small x, low p_T, large nuclei)

Angular structure from (mini-) Jet radiation



$$C_{\mathrm{dijet}}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\mathrm{BFKL}}$$

NLO in the dense-dense framework but… unsuppressed in N_C

Caveat: does not include multiple scattering contributions which may be significant for $k_T < Q_S$

Quantitative description of pp ridge

Dusling,RV:PRL108 (2012)262001

$$\frac{d^2N}{d\Delta\phi} = K\int_{-2.4}^{+2.4} d\eta_p\, d\eta_q\; \mathcal{A}(\eta_p,\eta_q)$$

$$\times \int_{p_T^{\rm min}}^{p_T^{\rm max}} \frac{dp_T^2}{2}\int_{q_T^{\rm min}}^{q_T^{\rm max}}\frac{dq_T^2}{2}\int d\phi_p \int d\phi_q\; \delta(\phi_p-\phi_q-\Delta\phi)$$

$$\times\int_0^1 dz_1 dz_2 \frac{D(z_1)}{z_1^2}\frac{D(z_2)}{z_2^2}\frac{d^2N^{\rm corr.}_{\rm Glasma}}{d^2\mathbf{p}_T\, d^2\mathbf{q}_T\, d\eta_p\, d\eta_q}\left(\frac{p_T}{z_1},\frac{q_T}{z_2},\Delta\phi\right)$$

(6

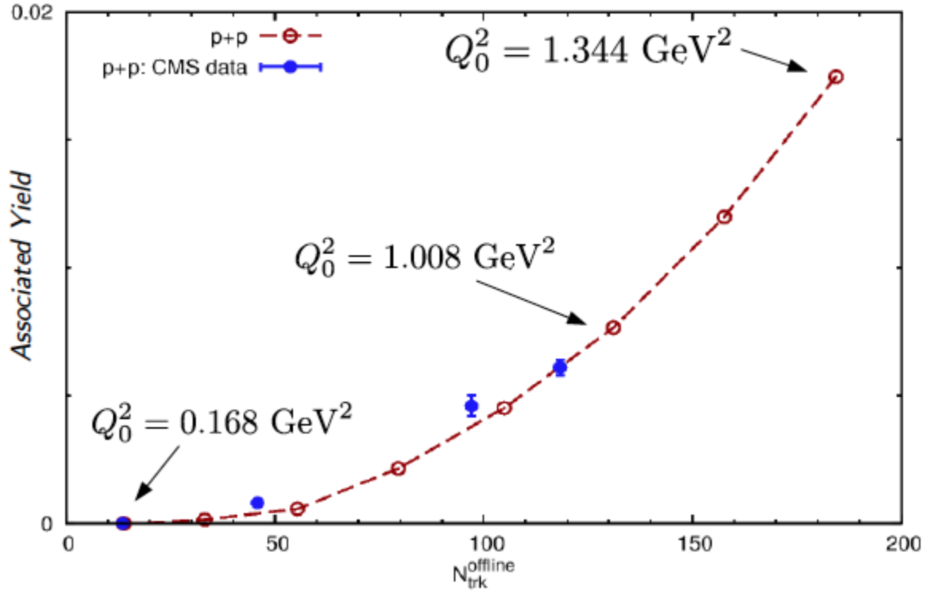
$$\mathcal{A}(\eta_p,\eta_q) = \theta(|\eta_p-\eta_q|-\Delta\eta_{\rm min})\,\theta(\Delta\eta_{\rm max}-|\eta_p-\eta_q|)$$

$$N_{\rm trig} = \int_{-2.4}^{+2.4} d\eta \int_{p_T^{\rm min}}^{p_T^{\rm max}} d^2\mathbf{p}_T\int_0^1 dz\, \frac{D(z)}{z^2}\,\frac{dN}{d\eta\, d^2\mathbf{p}_T}\left(\frac{p_T}{z}\right)$$

$$\boxed{\text{Assoc. Yield} = \frac{1}{N_{\rm trig}}\int_0^{\Delta\phi_{\rm min.}} d\Delta\phi\,\frac{d^2N}{d\Delta\phi} - \left.\frac{d^2N}{d\Delta\phi}\right|_{\Delta\phi_{\rm min.}}}$$

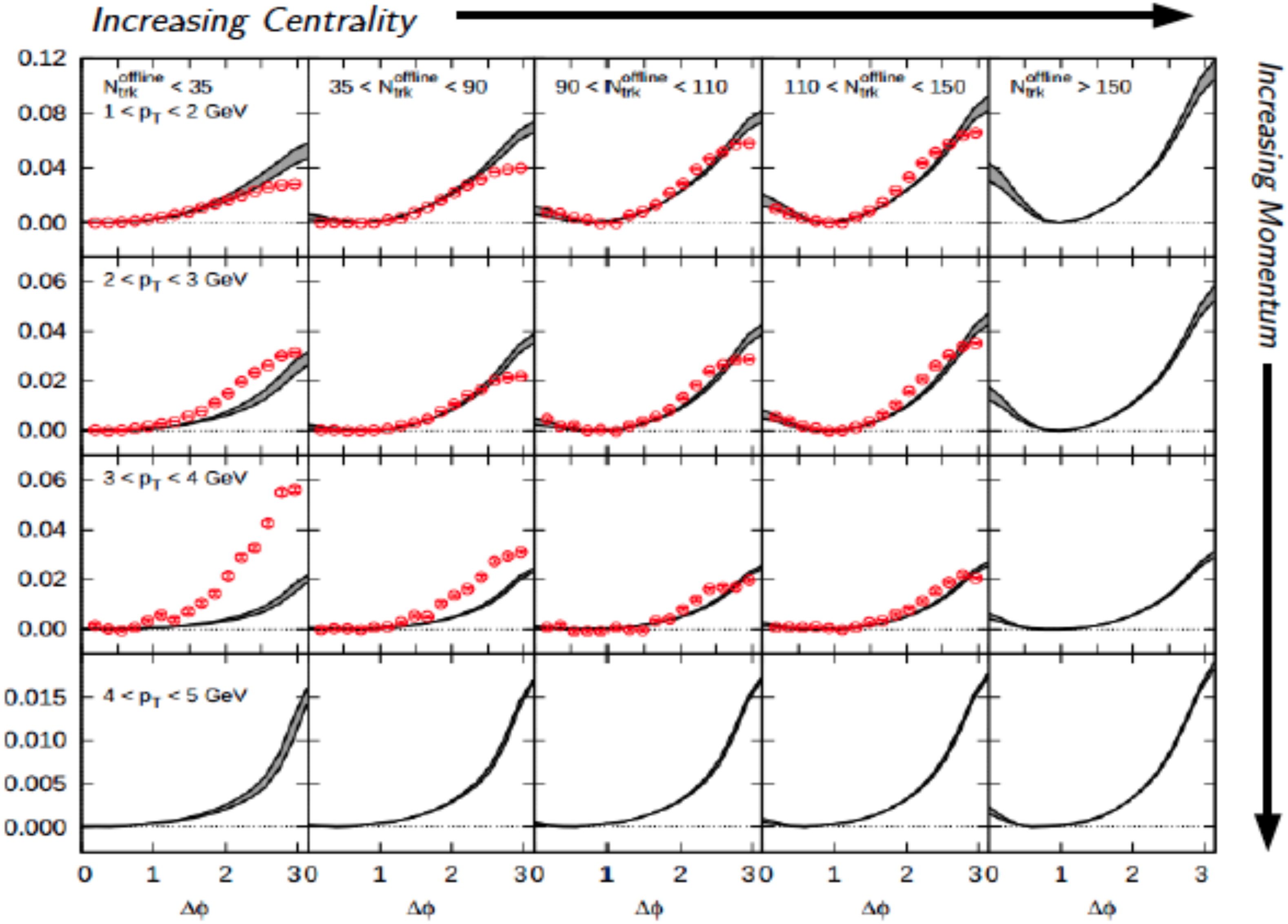
Dependence on transverse area cancels in ratio…

Rarer and rarer gluon configurations probed in the proton

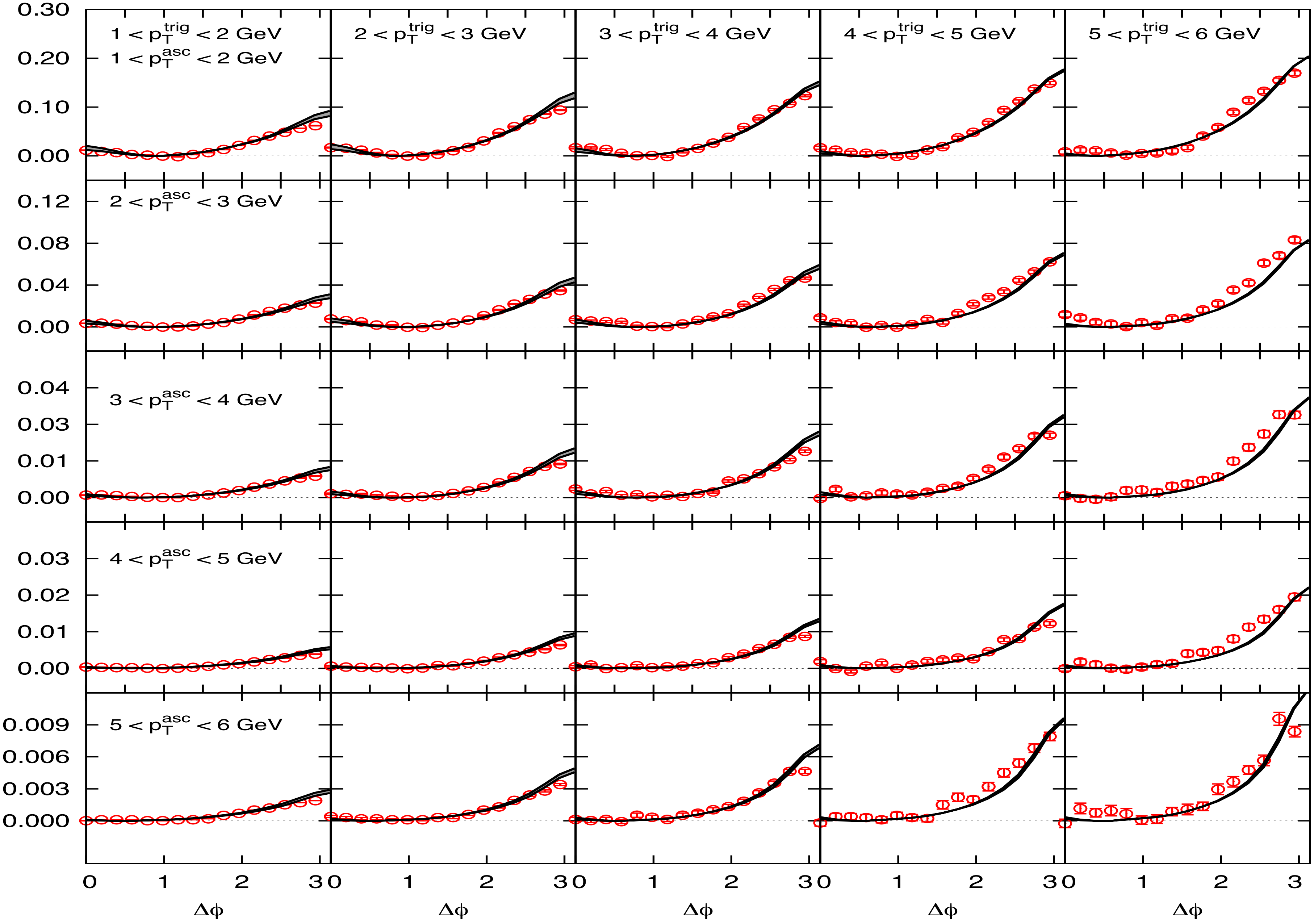


Systematics of p+p correlated yield

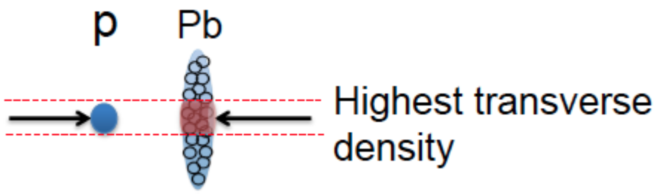
Data from CMS collaboration
Fits: Dusling,RV, arXiv:1302.7018

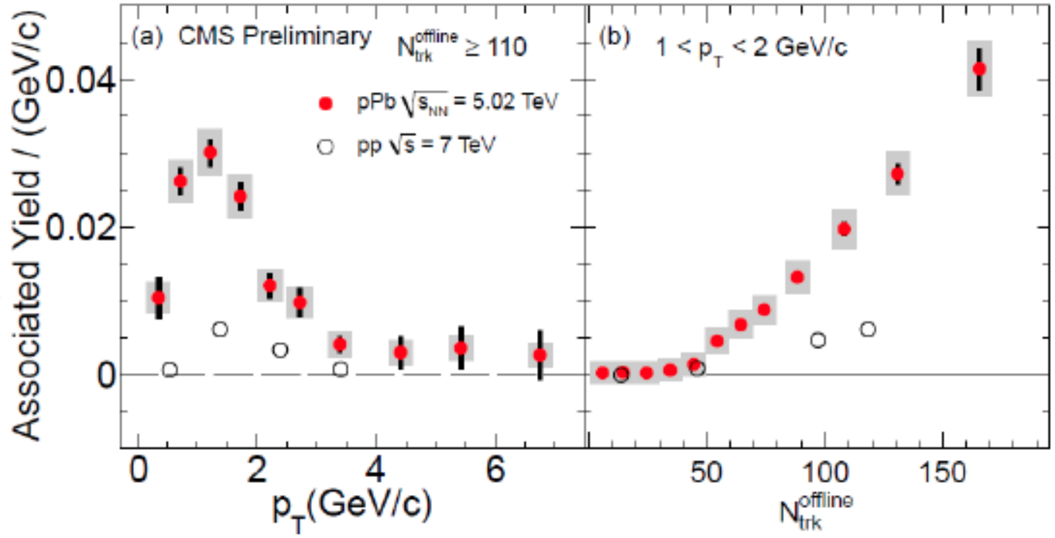


Dusling,RV, PRD 87, 051502 (R) (2013); arXiv:1302.7018

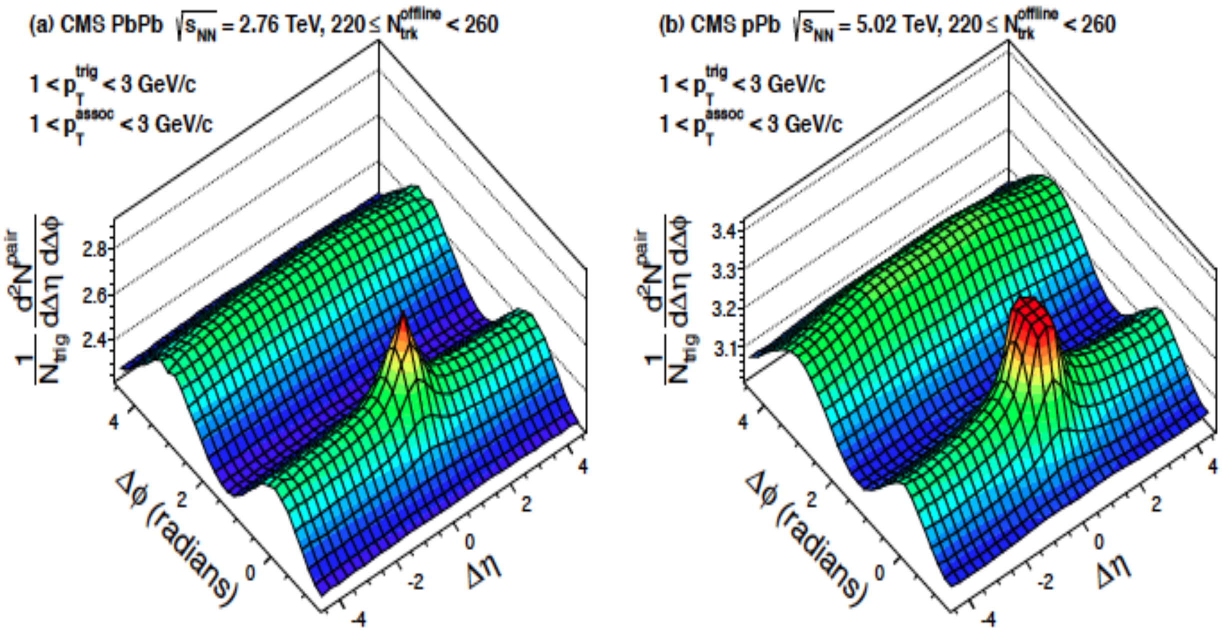


What about p+A ?





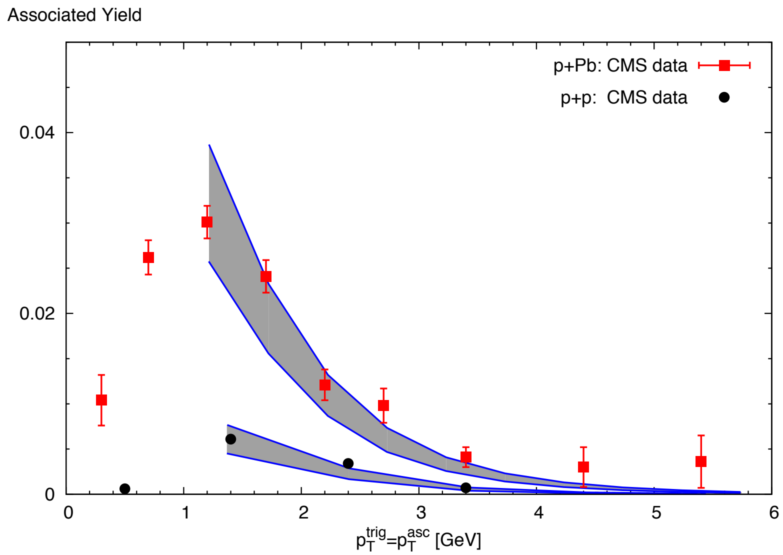
Ridge much bigger than p+p for the same multiplicity

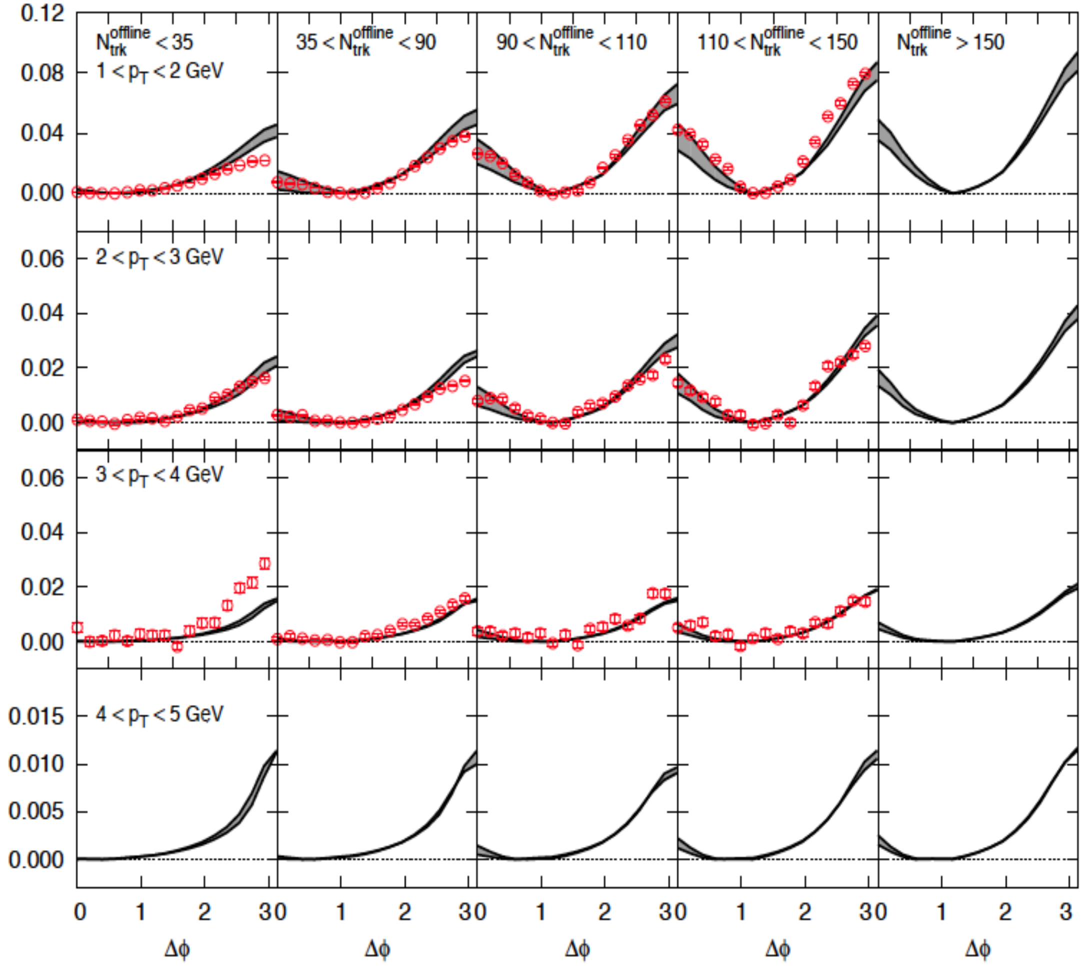


p+A ridge nearly as large as peripheral Pb+Pb

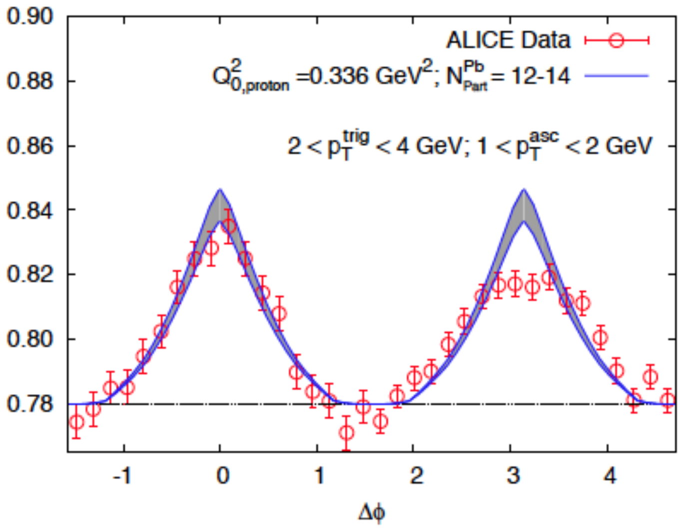
Systematics of p+Pb associated yield

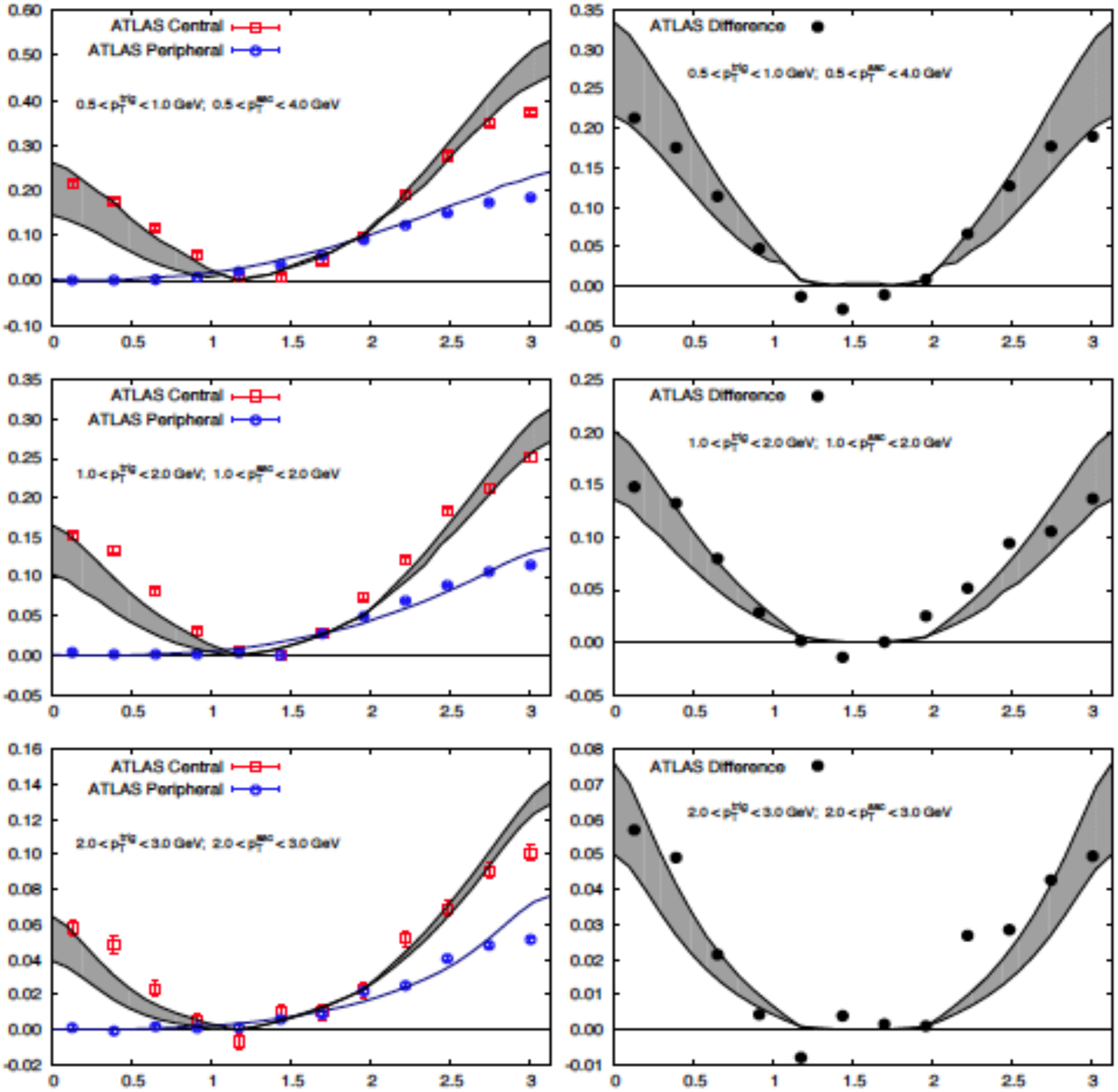
Dusling, RV: 1211.3701
1302.7018





“Jet subtracted” p+Pb ridge

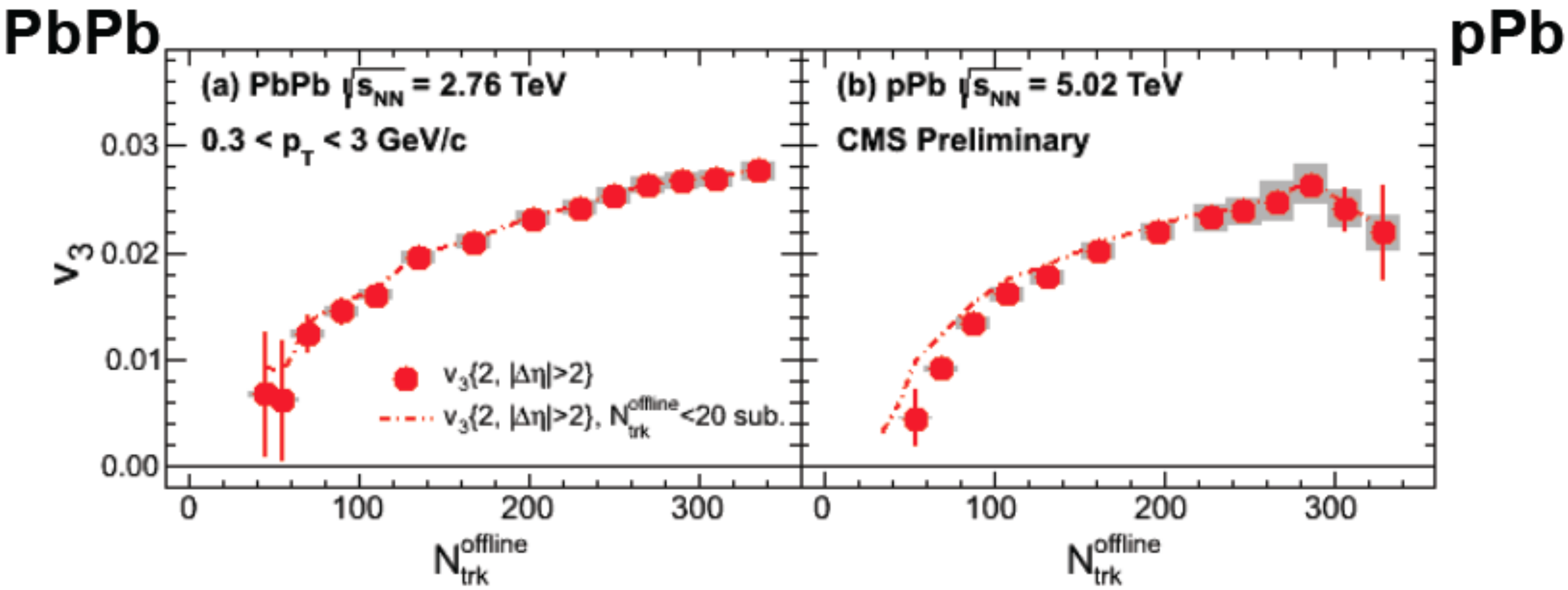




Similar subtraction in RHIC d+Au to extract ridge

The v_3 surprise in LHC pA collisions

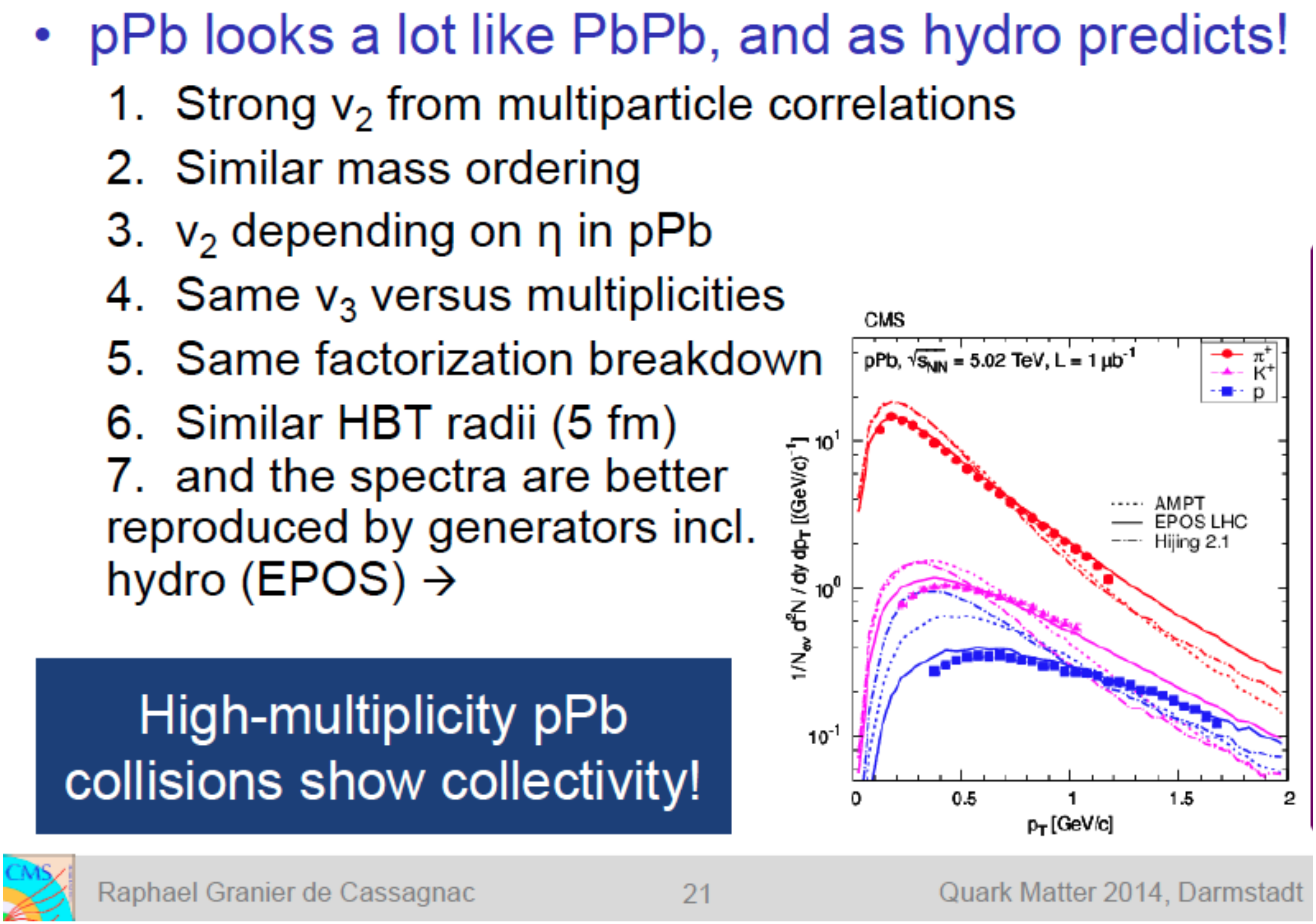
CMS 1305.0609



$v_3 > 0$ not obviously obtained from Glasma graphs in k_T factorization approximation

Only even moments obtained…

CMS summary talk at Quark Matter

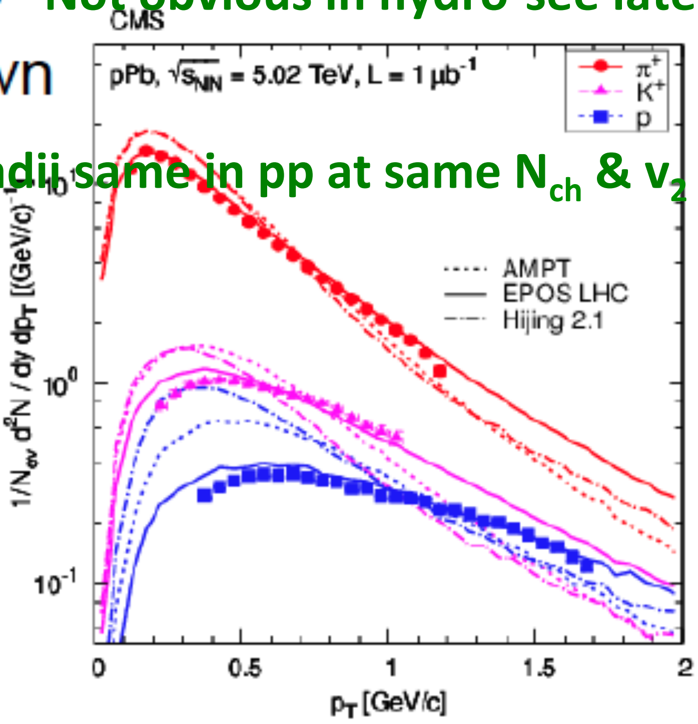


- pPb looks a lot like PbPb, and as hydro predicts!
  1. Strong v_2 from multiparticle correlations
  2. Similar mass ordering
  3. v_2 depending on η in pPb
  4. Same v_3 versus multiplicities
  5. Same factorization breakdown
  6. Similar HBT radii (5 fm)
  7. and the spectra are better reproduced by generators incl. hydro (EPOS) →

High-multiplicity pPb collisions show collectivity!

CMS summary talk at Quark Matter

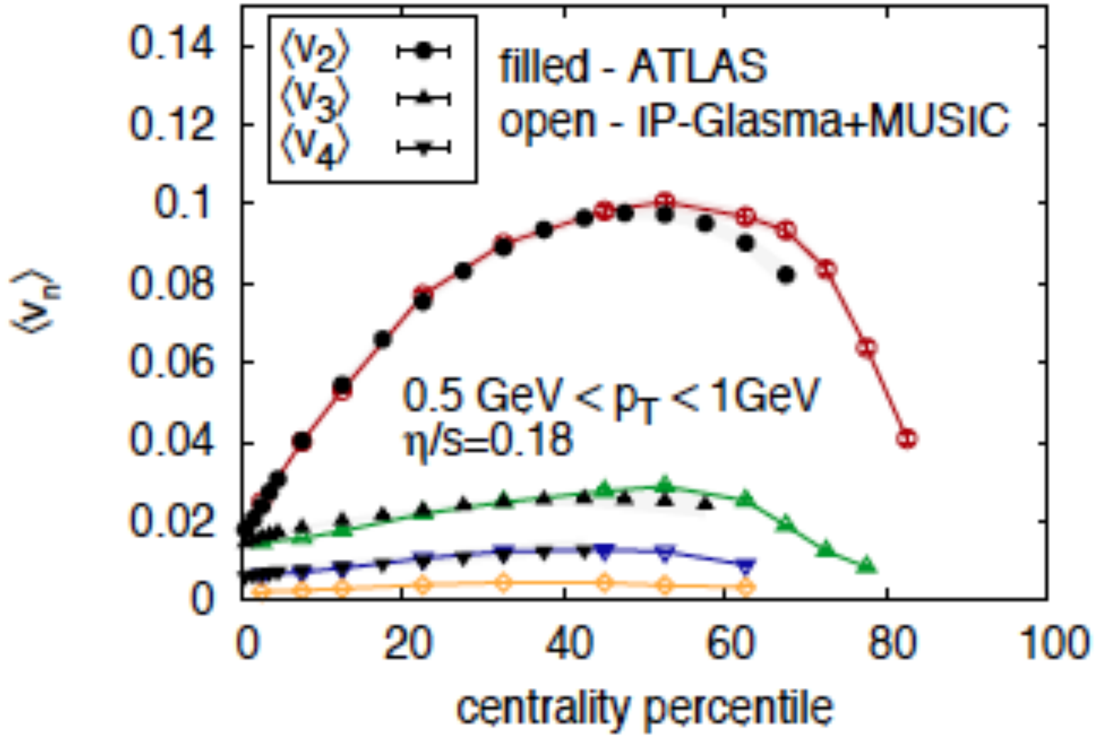
- pPb looks a lot like PbPb, and as hydro predicts!
  1. Strong v_2 from multiparticle correlations **Also from initial state**
  2. Similar mass ordering **Universal hadronization pattern?**
  3. v_2 depending on η in pPb **Reflects more underlying stringy picture**
  4. Same v_3 versus multiplicities **Not obvious in hydro-see later slides**
  5. Same factorization breakdown
  6. Similar HBT radii (5 fm) **HBT radii same in pp at same N_{ch} & v_2 smaller**
  7. and the spectra are better reproduced by generators incl. hydro (EPOS) → ??



High-multiplicity pPb collisions show collectivity!

Recall IP-Glasma+MUSIC model in A+A

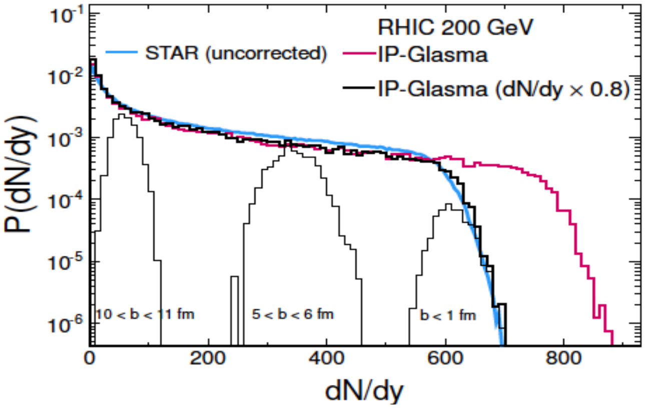
Schenke,Venugopalan, arXiv:1405.3605

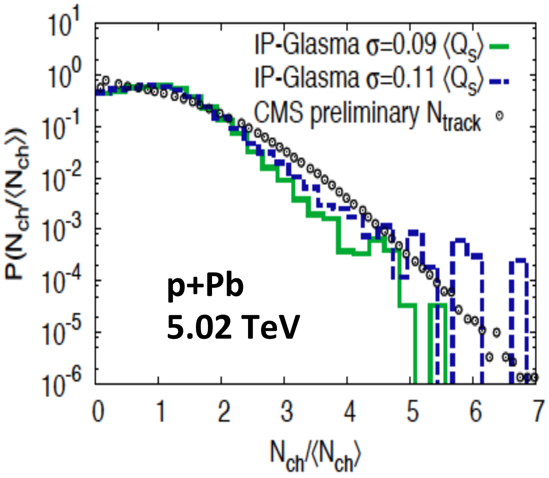


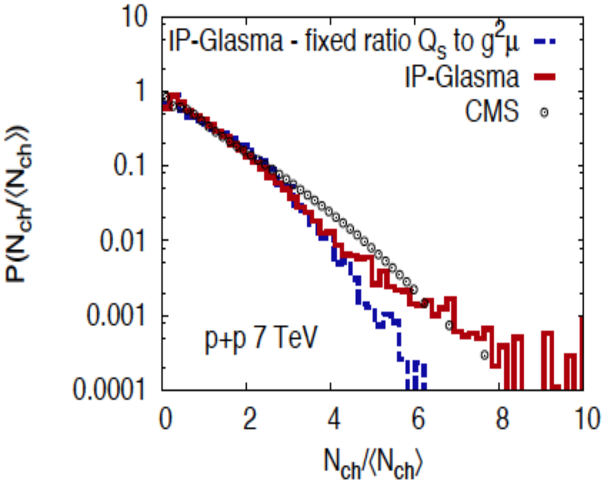
Remarkable agreement of IP-Glasma+MUSIC with data out to fairly peripheral overlap geometries…

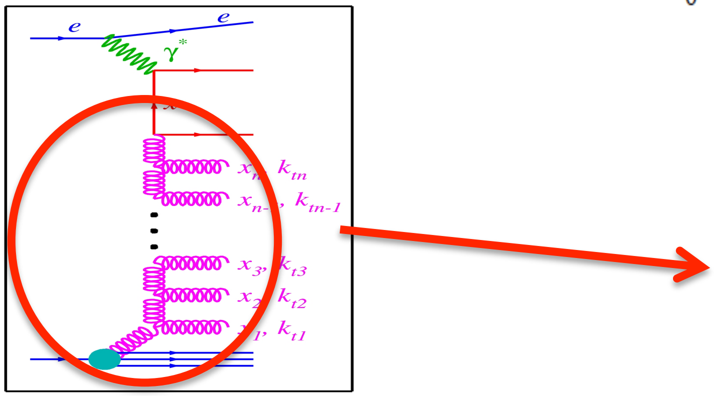
IP-Glasma model: multiplicity distributions

Schenke,Tribedy,Venugopalan, arXiv 1311.3636







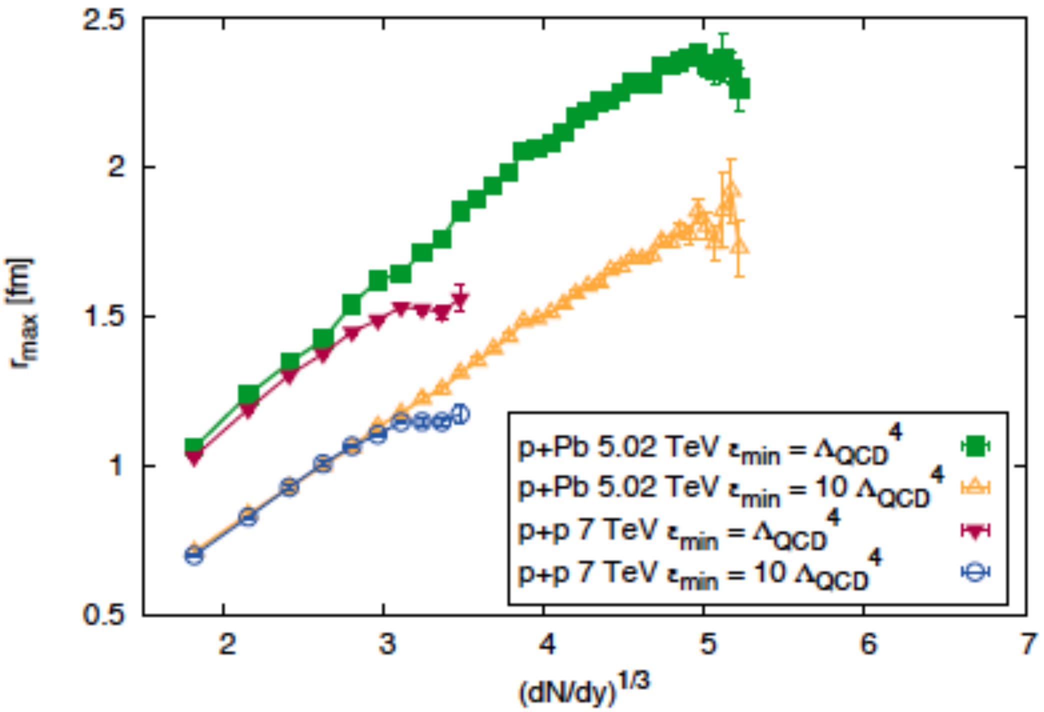


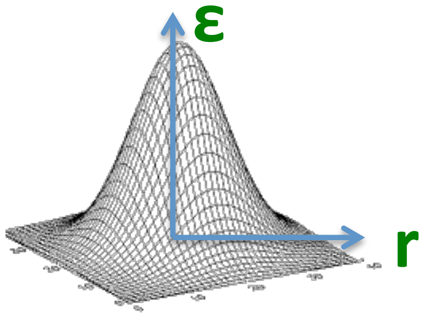
Color charge fluctuations: different color configurations for same gluon number

But gluon # in wave functions can fluctuate too. Required to explain tails of multiplicity distributions.

IP-Glasma model: system size

Bzdak, Schenke,Tribedy,Venugopalan, arXiv 1304.3403

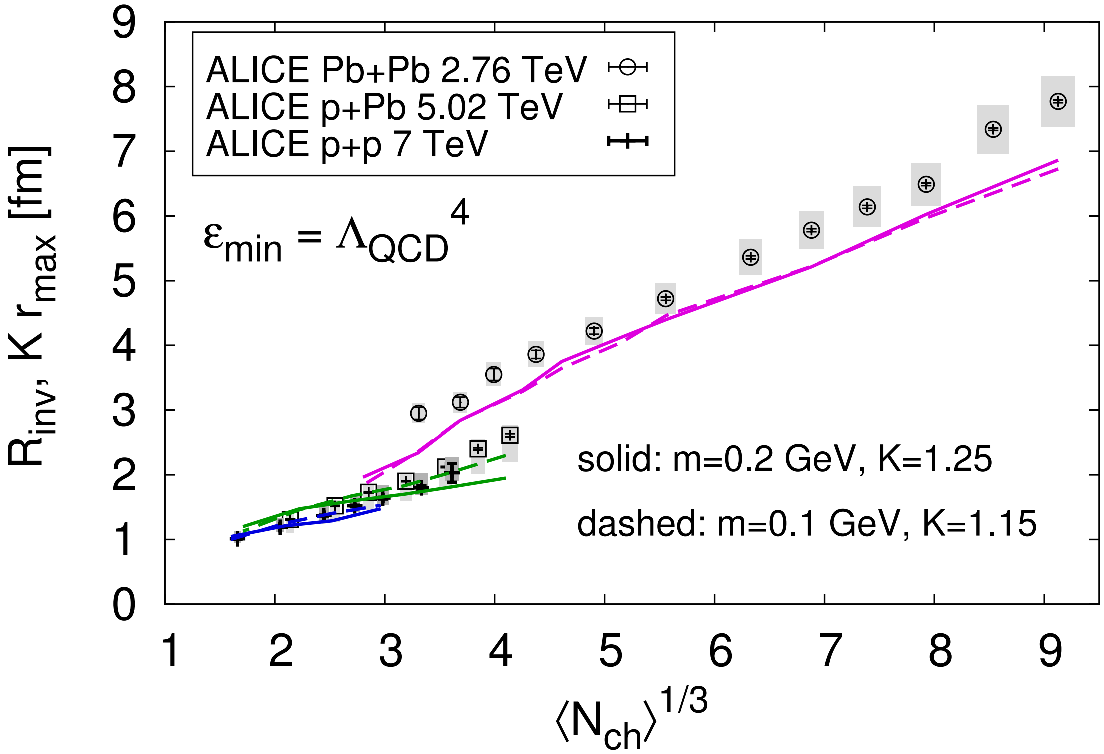


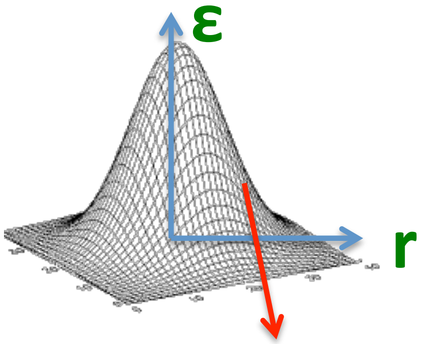


System size in IP-Glasma nearly the same in p+p and p+Pb

IP-Glasma model: system size

Schenke, Venugopalan: 1405.3605



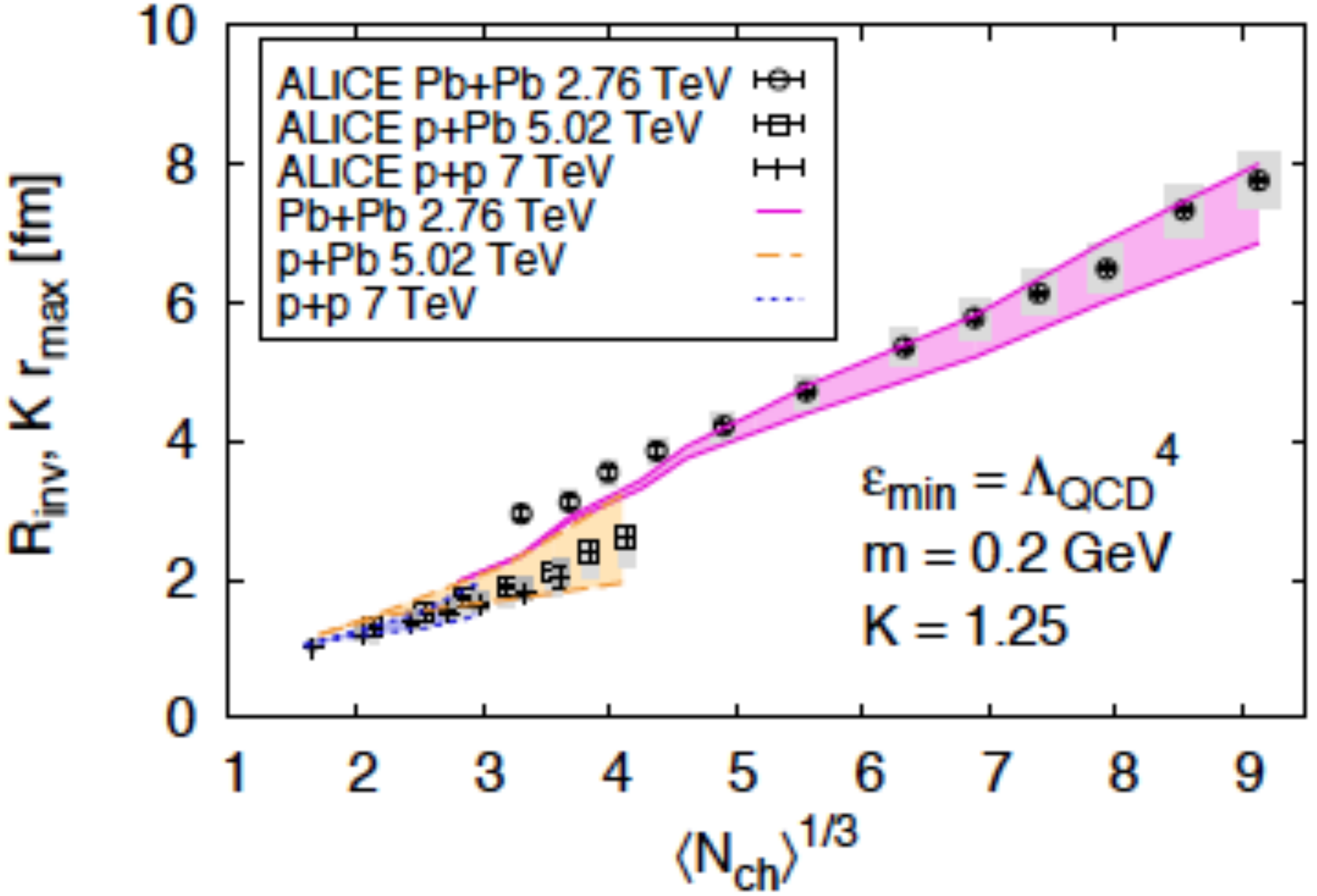


m regulates the tail of gluon distributions

Results for system size in the Glasma clearly leaves room for flow in Pb+Pb

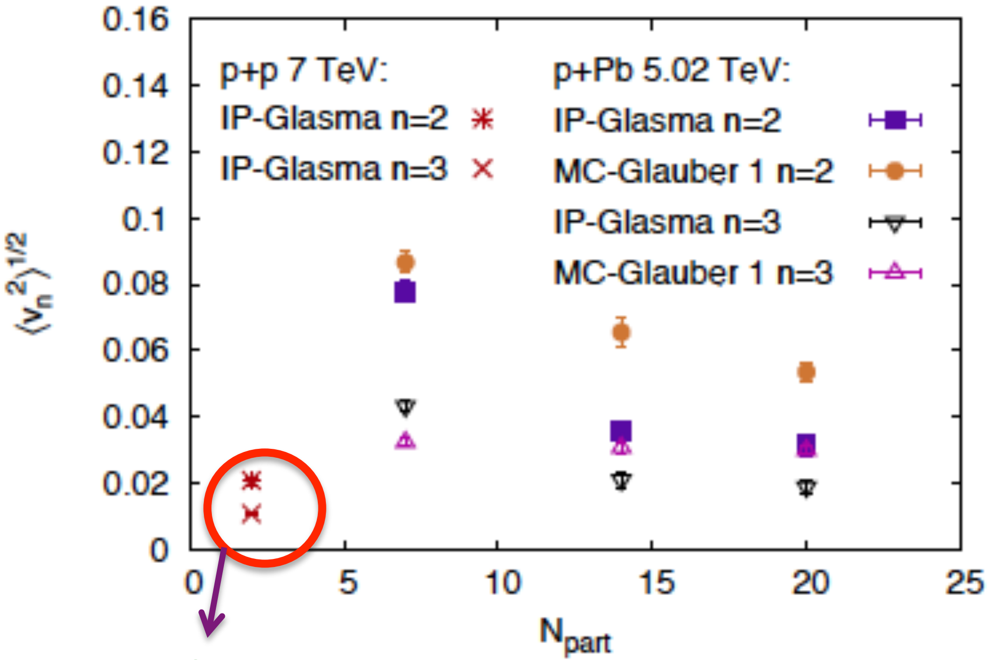
Flow not necessary in p+p to explain data up to quite rare N_{ch} = 27.
In p+Pb, whether there is room for flow in rare events
is sensitive to how the tail of the gluon distribution is regulated…

Schenke, Venugopalan, arXiv:1405.3605



The ridge: flow in p+p and p+Pb ?

Bzdak,Schenke,Tribedy,Venugopalan: 1304.3403



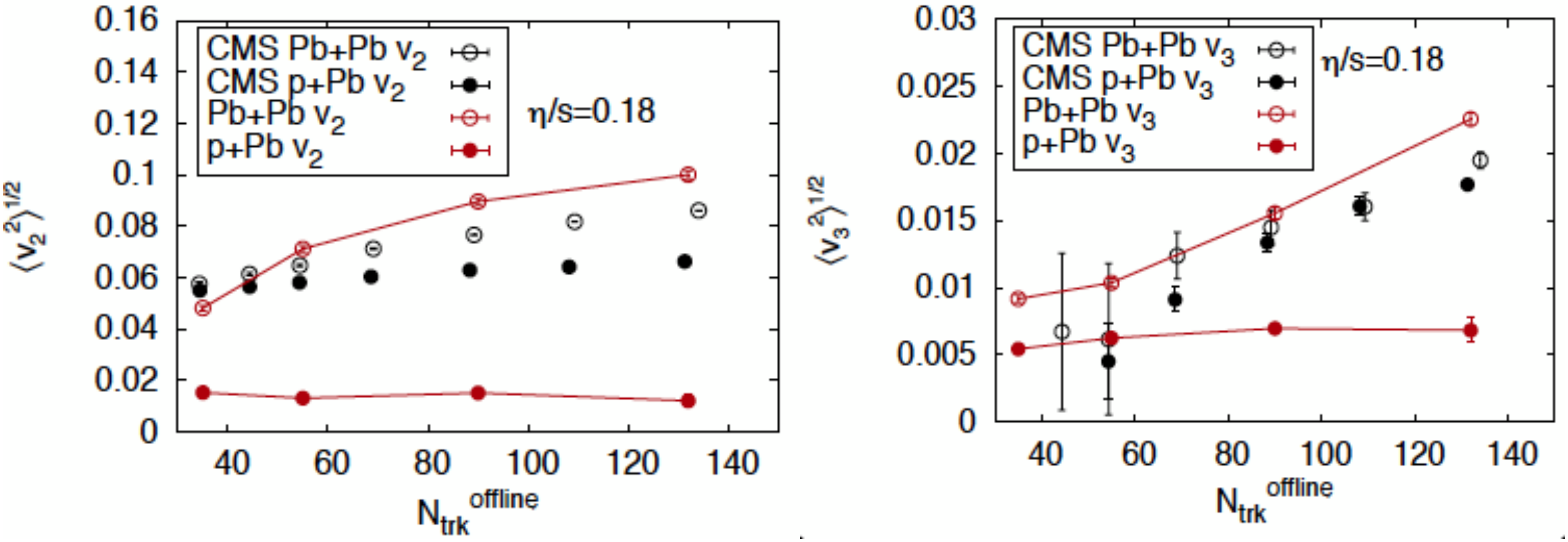
p+p at b=0

IP-Glasma+ MUSIC (hydro) gives much less v_2 than Glauber models that have significantly larger spatial sizes and shapes

Bozek,Torrieri,Broniowski, arXiv: 1307.5060
Kozlov,Luzum,Denicol,Jeon,Gale, arXiv:1405.3976

The ridge: flow in p+Pb?

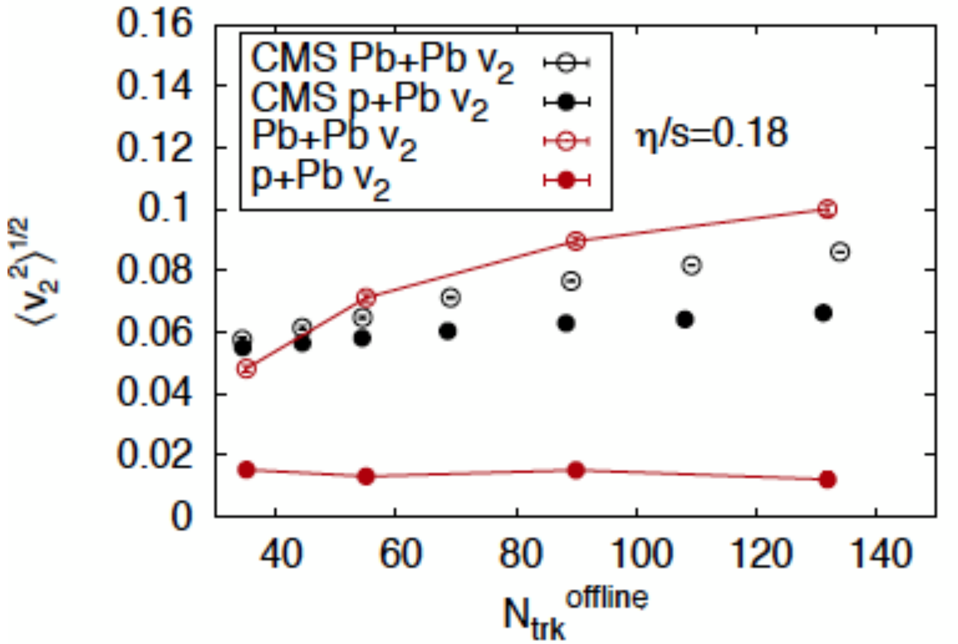
Schenke and Venugopalan, arXiv:1405.3605

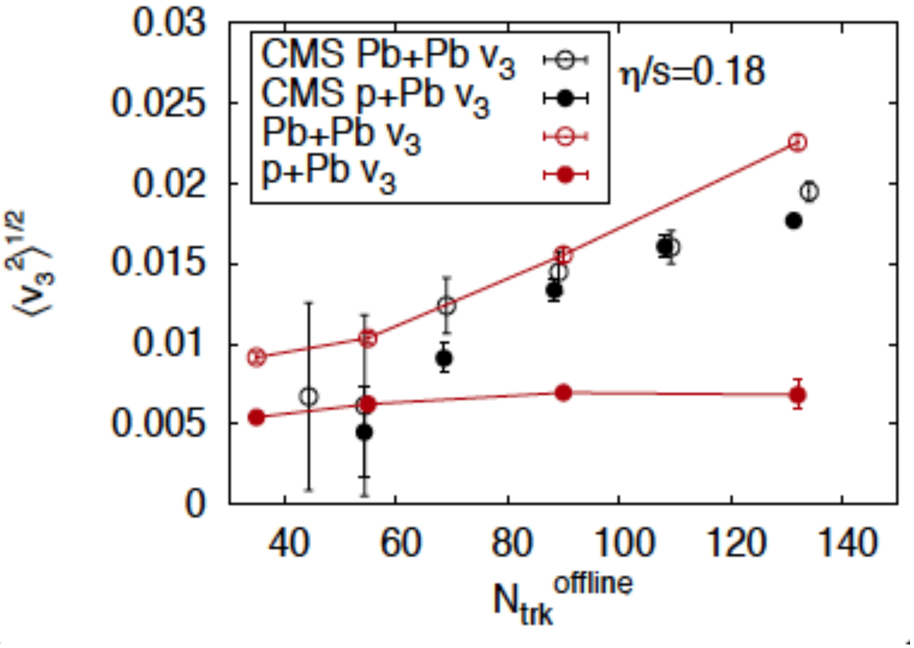


In contrast to A+A, both shape and magnitude of
IP-Glasma+MUSIC p+Pb results completely off from data

The ridge: flow in p+Pb?

Schenke and Venugopalan, arXiv:1405.3605





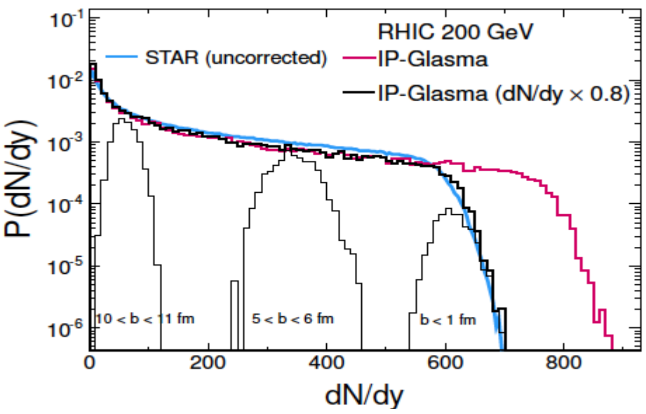
In contrast to A+A, both shape and magnitude of
IP-Glasma+MUSIC p+Pb results completely off from data

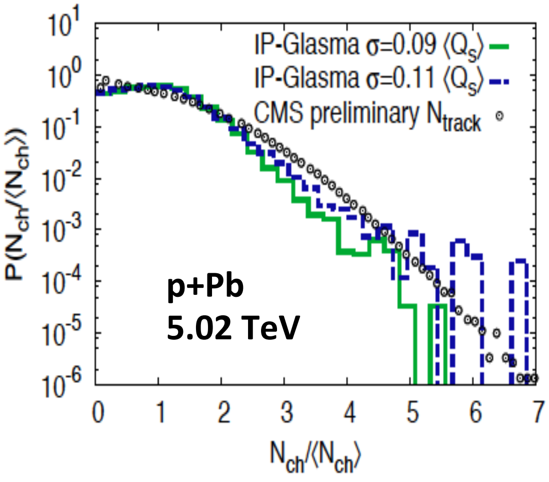
Maybe shapes are treated incorrectly in IP-Glasma ? Note they seem off even for multiplicites where the IP-Glasma multiplicity distribution agrees with the data…

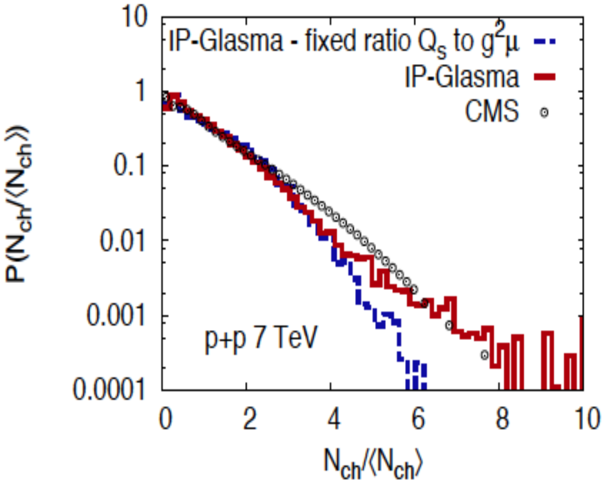
Alternative: hydro shouldn't work for small size systems?

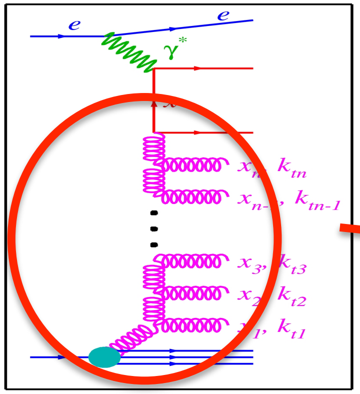
IP-Glasma model: multiplicity distributions

Schenke,Tribedy,Venugopalan, arXiv 1311.3636



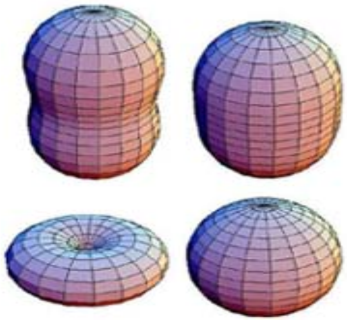






Color charge fluctuations: different color configurations for same gluon number

But gluon # in wave functions can fluctuate too. Required to explain tails of multiplicity distributions.



Large x quarks in proton can have "eccentric" shapes.

G. A. Miller, arXiv:0802.3731

Is this feasible for radiated gluons that pack the proton within constraints from confinement, causality & unitarity…?

Additional puzzles for the collectivity picture in p+A

- **Why is there no sign of "mini-jet" quenching in p+A ?**

- **Why is v_2 unchanged up to p_T of 9 GeV**

- **Why is v_2 much smaller in p+p than p+A for the same N_{ch} and HBT radius ?**

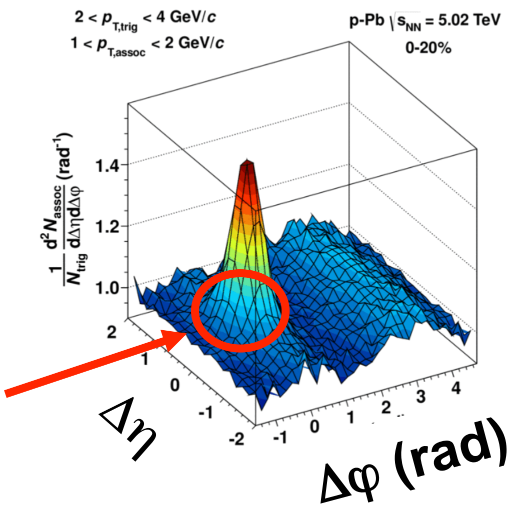
- **Why is mass ordering in $<p_T>$ seen even at $N_{ch} = 6$?**

p-Pb

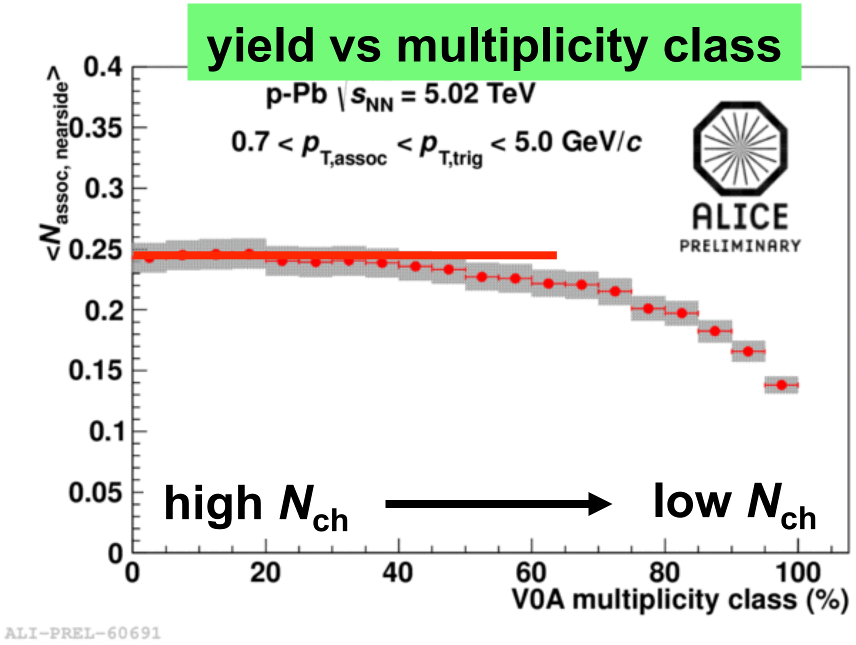
And the Jet at low p_T?

- No modification at high p_T
- Double ridge at low p_T
- Spectra modified at low p_T?

What happens to the "jet" at low p_T?



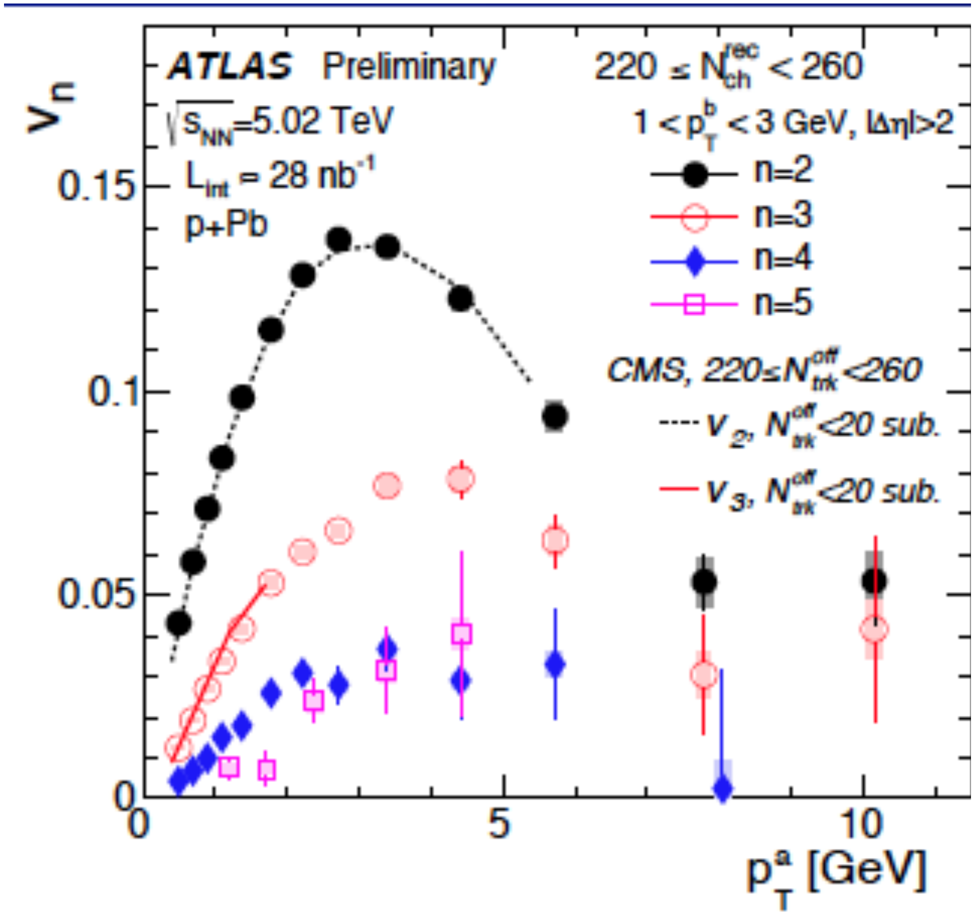
- Ridge-subtracted jet-like yields
- Ridge and jet seem additive in 2PC
- Constant jet yields for ~60% of p-Pb cross-section
  → no modification even at low p_T

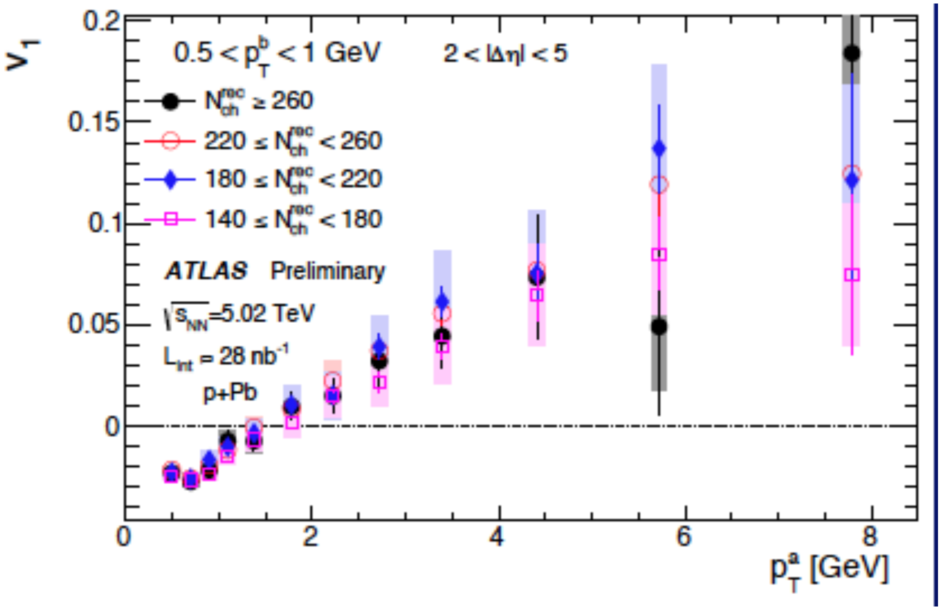

yield vs multiplicity class

- Consistent with a picture of minijets in p-Pb collisions from superposition of NN collisions with incoherent fragmentation

→ L. Milano (Tue PM)

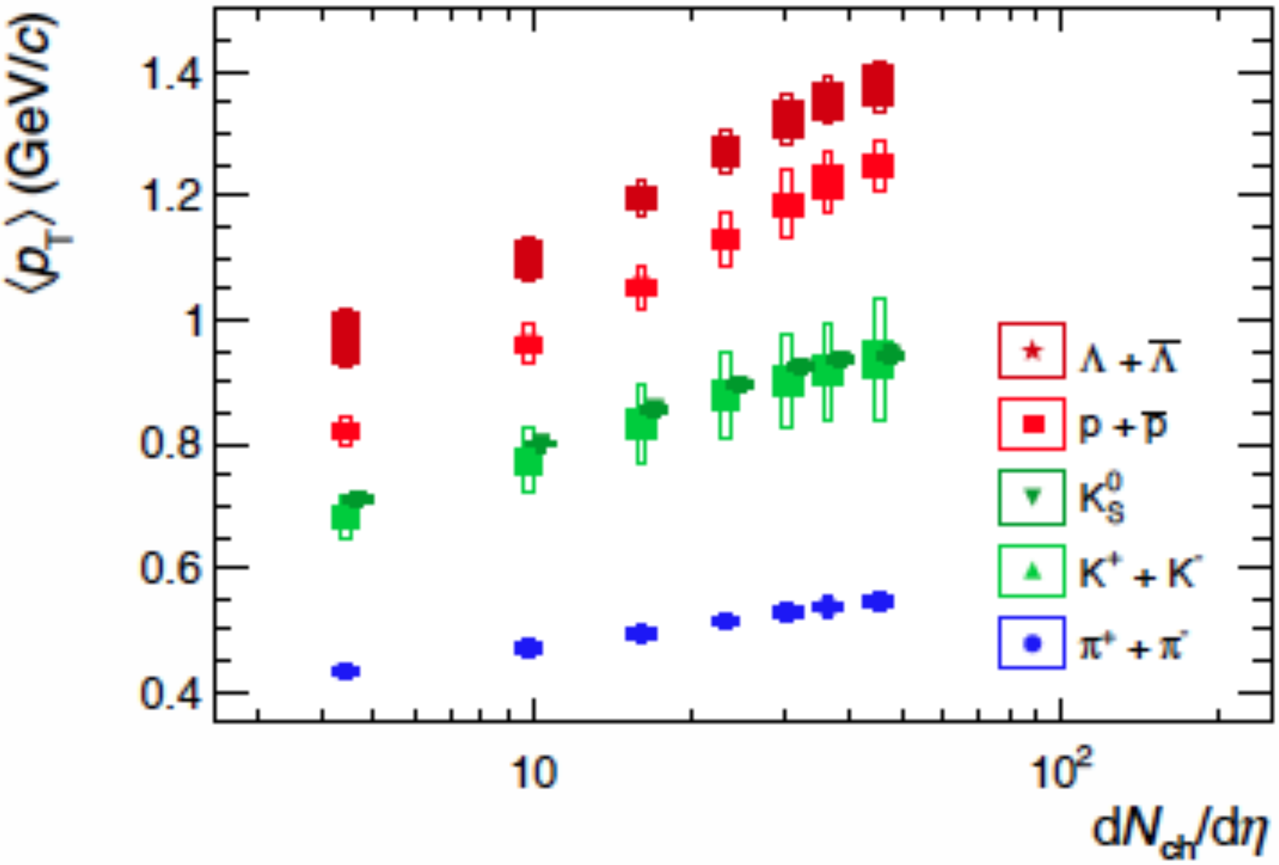
Significant v_n moments in p+Pb out to large p_T





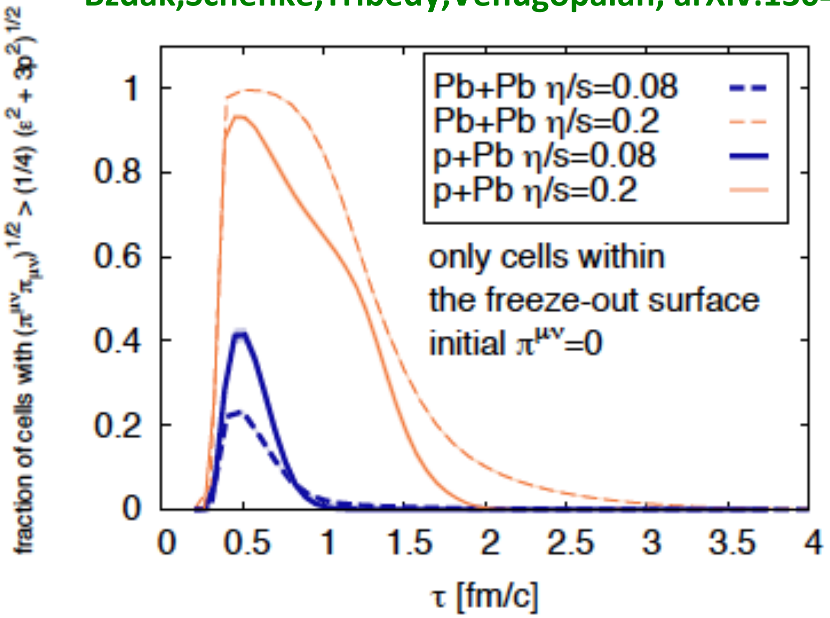
Mass ordering seen down to low N_{ch}

ALICE, 1307.6796

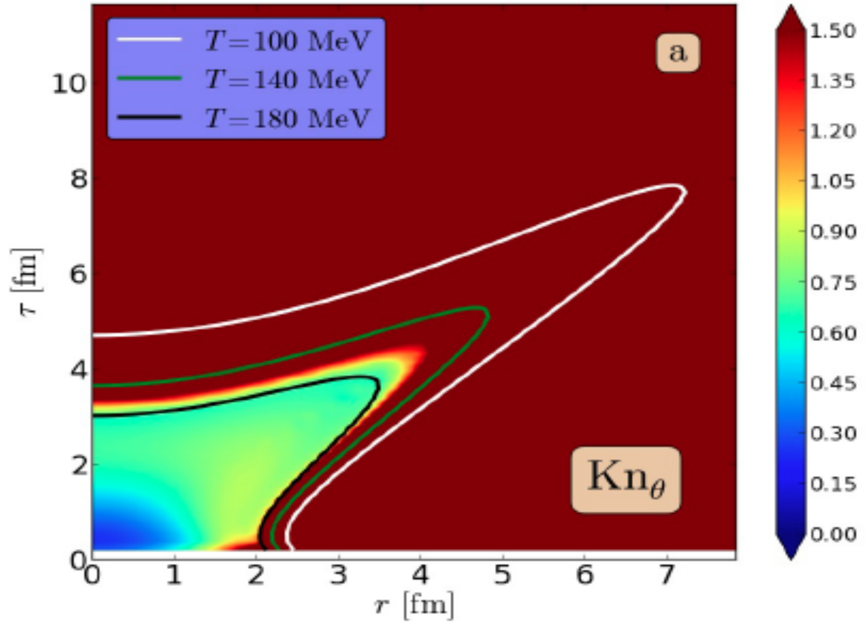


Hydro in small size systems: sensible or not ?

Two frequently used measures: Reynolds # and Knudsen #



Bzdak,Schenke,Tribedy,Venugopalan, arXiv:1304.3403



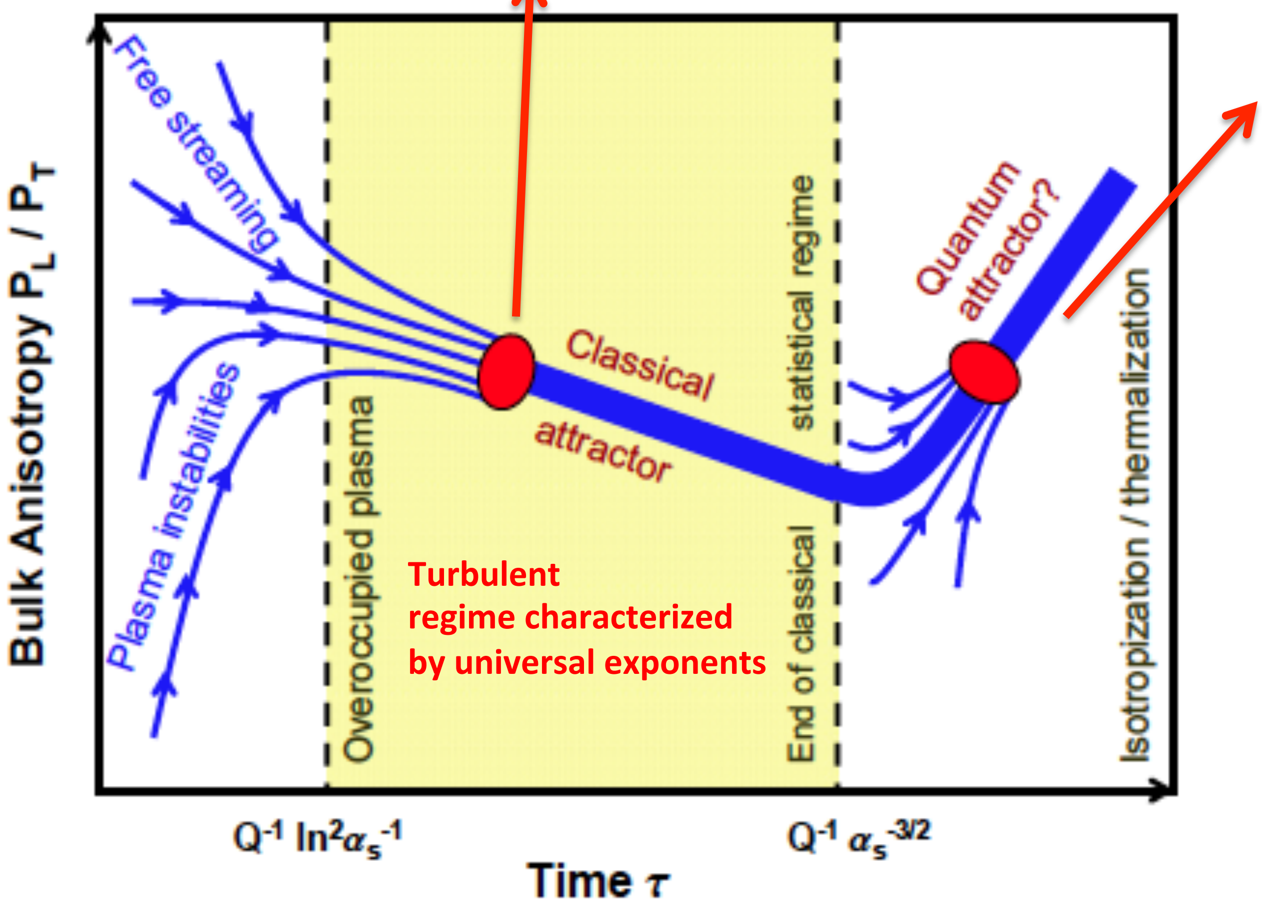
Denicol, Niemi, arXiv:1404.7327

Hydro good for Kn < 0.5, marginal for
K < 1 transient regime; K > 1 free streaming

The “bottom-up” thermalization process

Berges,Boguslavskii,Schlichting,Venugopalan

Blaizot,Dominguez,
Iancu,Mehtar-Tani



Turbulent
regime characterized
by universal exponents

A recent estimate in this picture gives $t_{\text{equilibrium}}$ < 1 fm

Kurkela,Lu, arXiv:1405.6318

BACKUP SLIDES