Entangled glue or collective flow: a QCD puzzle at the LHC & RHIC

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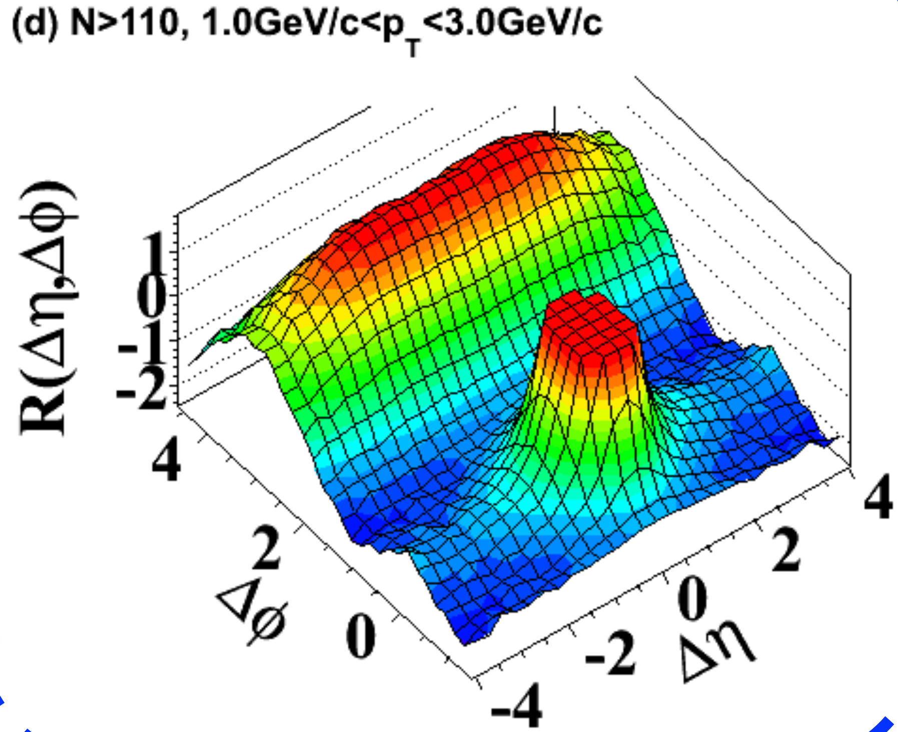
Brookhaven National Laboratory

MIT p+A workshop, May 17-18, 2013

Near side ridge in high multiplicity p+p collisions

"Discovery"

CMS: JHEP 1009, 091 (2010)



Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

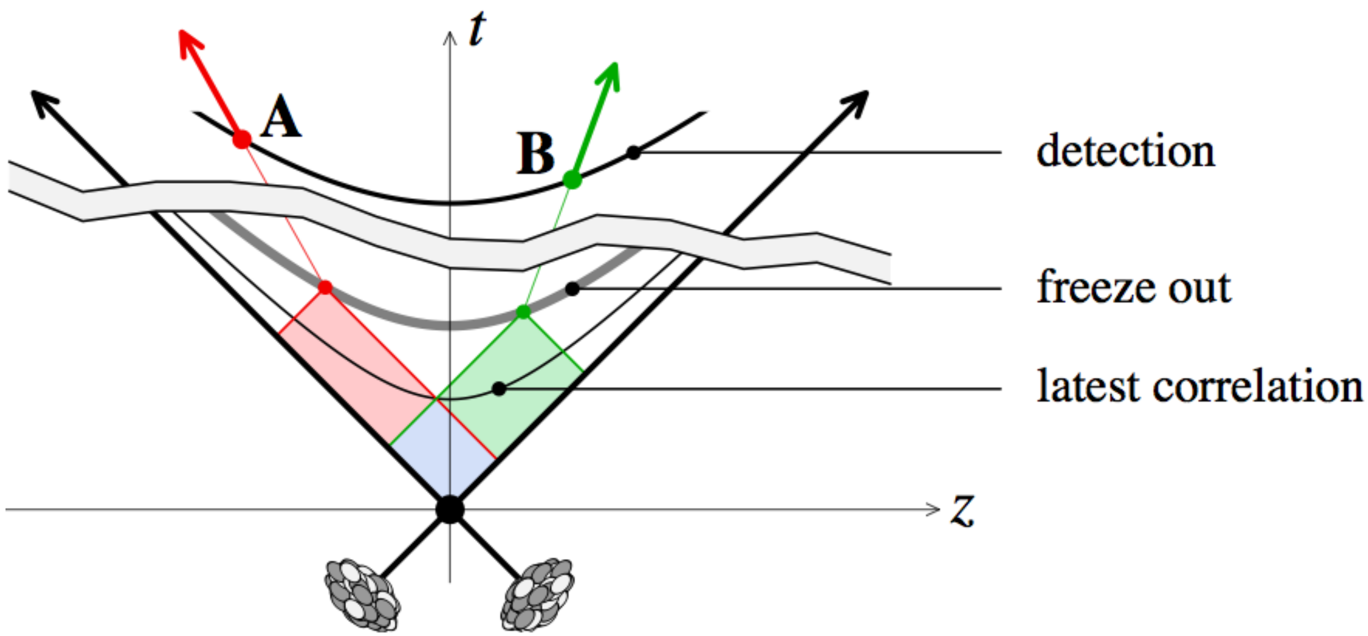
Scientific American, February (2011)

Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

The high-energy collisions of protons in the LHC may be uncovering "a new deep internal structure of the initial protons," says Frank Wilczek of the Massachusetts Institute of Technology, winner of a Nobel Prize

"At these higher energies [of the LHC], one is taking a snapshot of the proton with higher spatial and time resolution than ever before"

Long range rapidity correlations as a chronometer

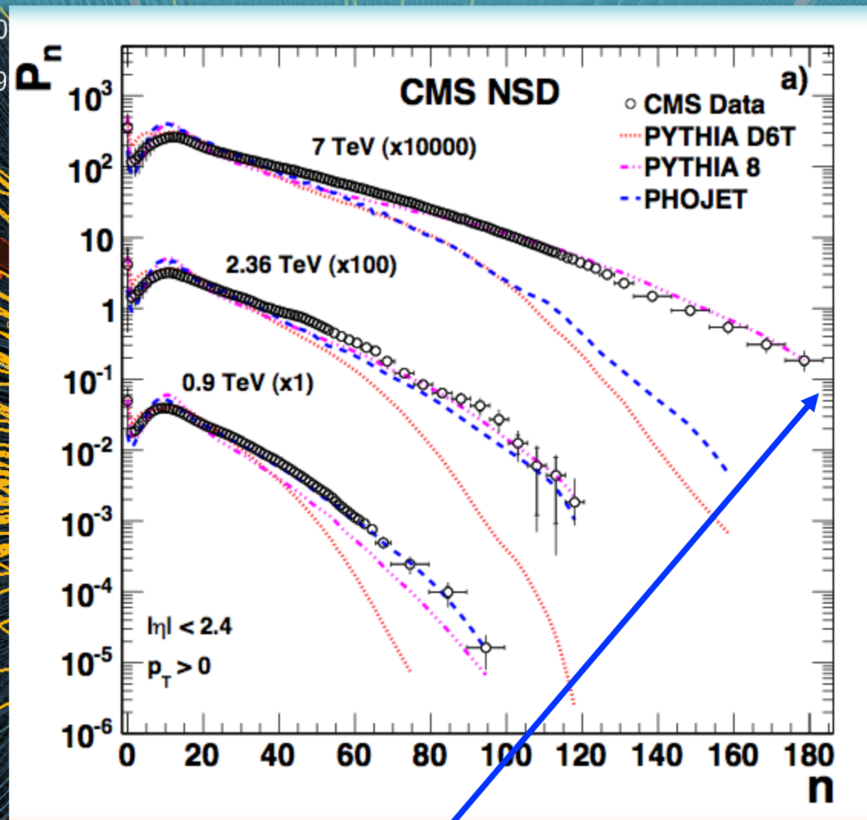


$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

- **Long range correlations sensitive to very early time (fractions of a femtometer ~ 10^{-24} seconds) dynamics in collisions**

High Multiplicity pp collisions

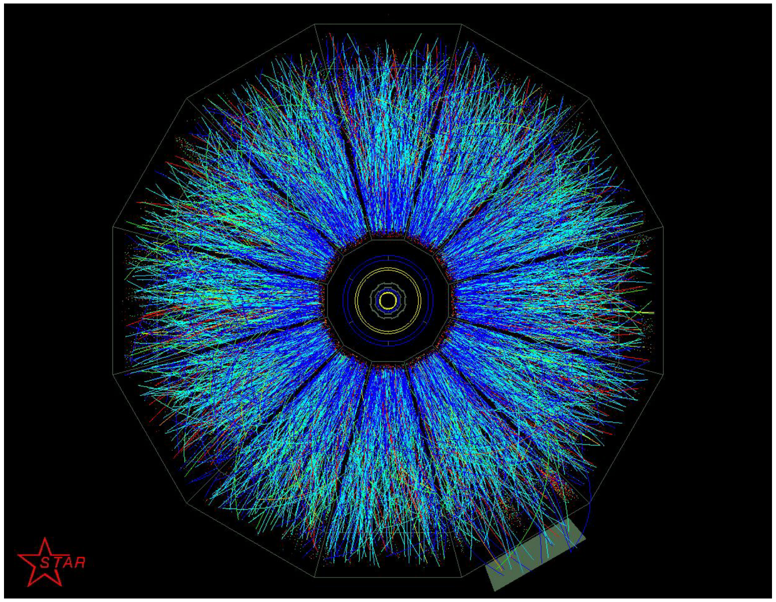
High Multiplicity events are rare in nature



Very high particle density regime

Is there anything peculiar happening there?

How can we compute bulk multiparticle production *ab initio* in QCD ?



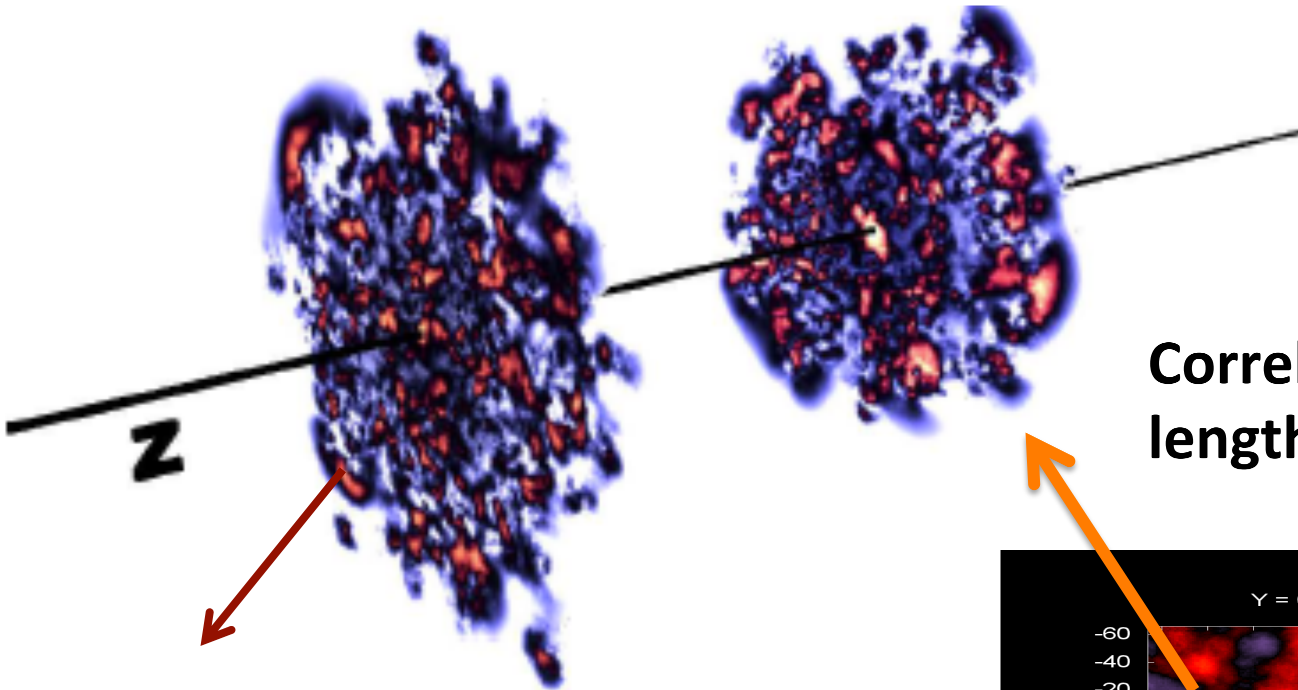
Interesting question:

-~~***perturbative VS non-perturbative,***~~

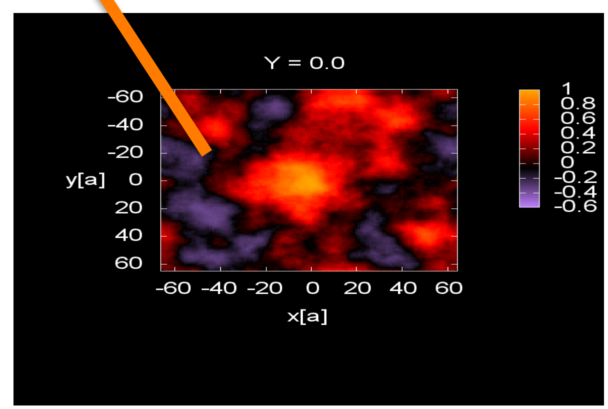
strong coupling VS weak coupling

Always non-perturbative – QFT in strong time dependent fields

Multiparticle production: high multiplicity events



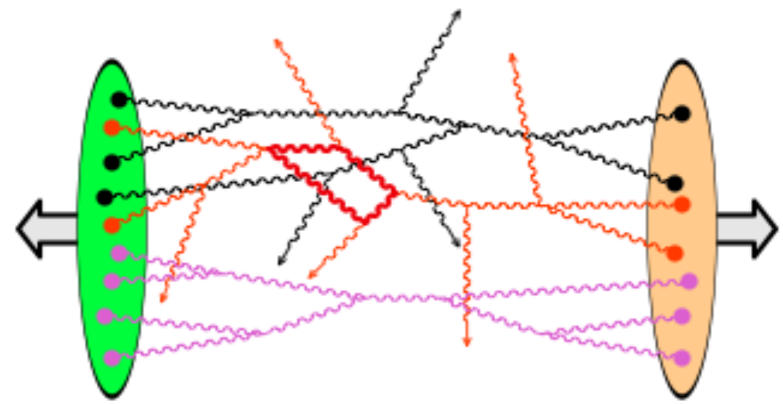
Correlation length is $1/Q_S^2$



Weak coupling EFT approach: Color Glass Condensate

Highly occupied gluon states of maximal occupancy allowed in QCD

Non-perturbative weak coupling QCD in strong time dependent fields



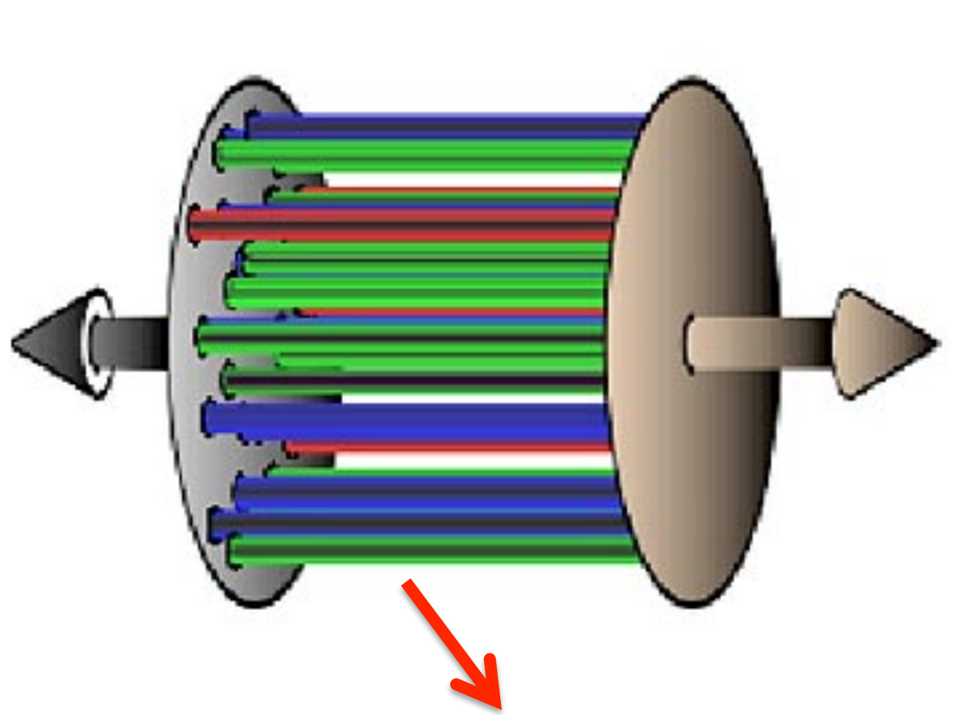
Interesting question:

-*~~CGC versus hydro~~*

-*Initial state dynamics versus final state dynamics*

The Glasma: shattering CGCs

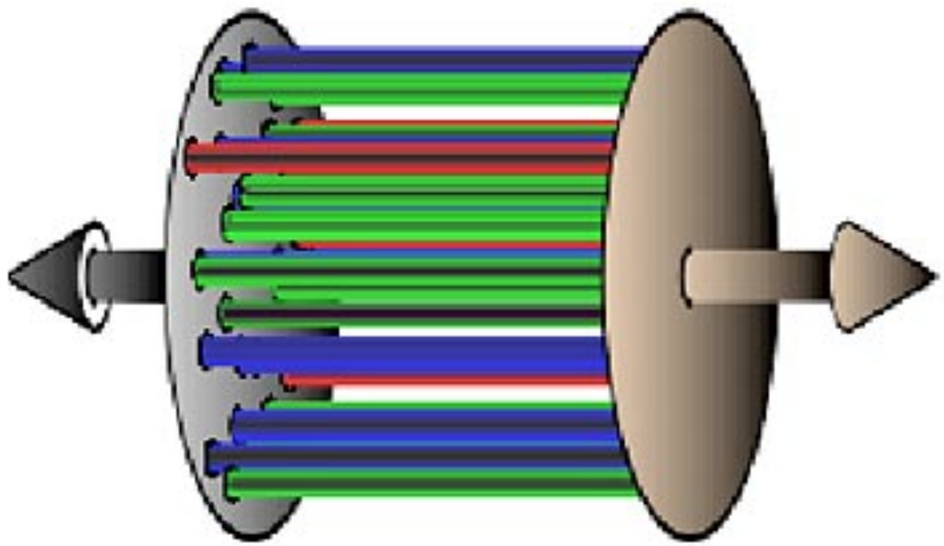
High occupancy=dominance of classical fields



Classical QCD Yang-Mills eqns. demonstrate that each of these color "flux tubes" stretching out in rapidity is of transverse size $1/Q_S << 1$ fm

The Glasma: shattering CGCs

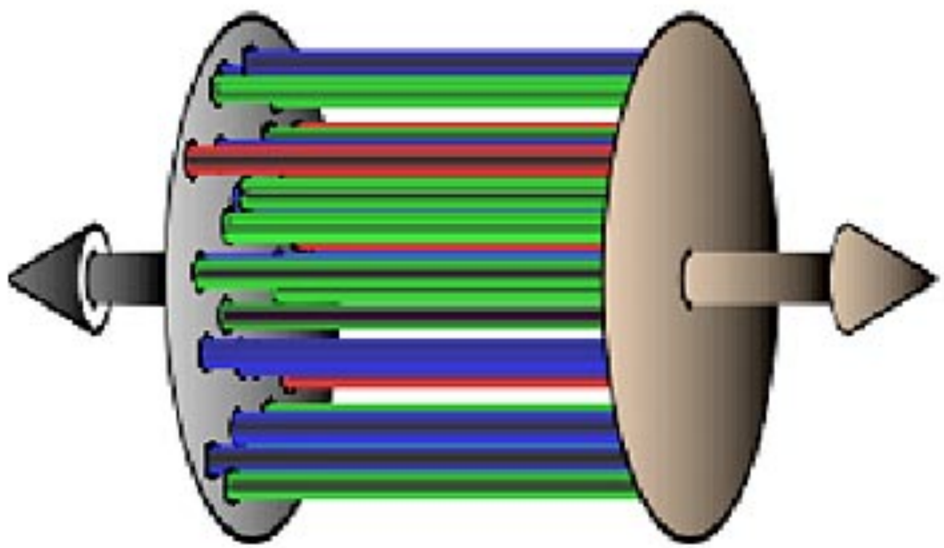
High occupancy=dominance of classical fields



Decay of fields on t ~ $1/Q_S$ leads to multiparticle dynamics
-- controlled by sub-nucleon QCD scales

The Glasma: shattering CGCs

High occupancy=dominance of classical fields



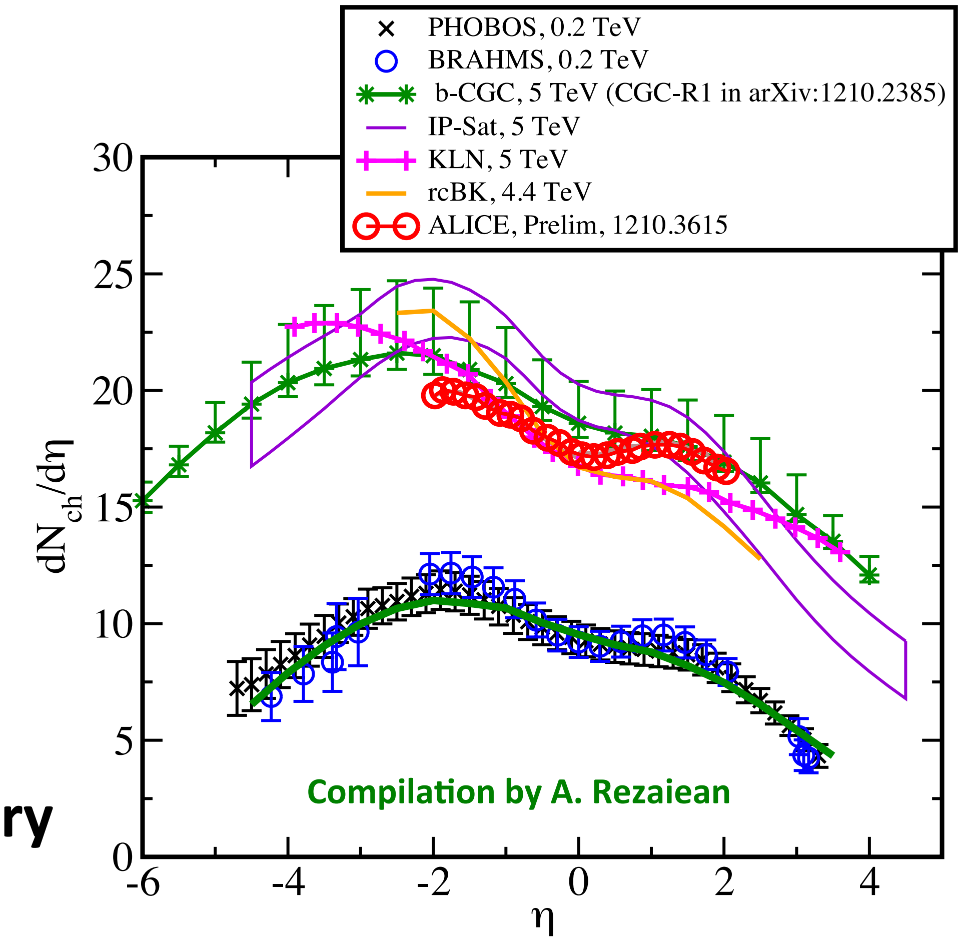
There are ~ $\pi R^2 Q_S^2$ flux tubes – $dn/d\eta \approx \pi R^2 Q_S^2/\alpha_S$

How do these models do with p+A at the LHC ?

In saturation models

$$\frac{dN}{d\eta} \propto \frac{Q_S^2\, S_\perp}{\alpha_S(Q_S)}$$

Multiplicities have some sensitivity to "infrared" non-pert. physics/geometry



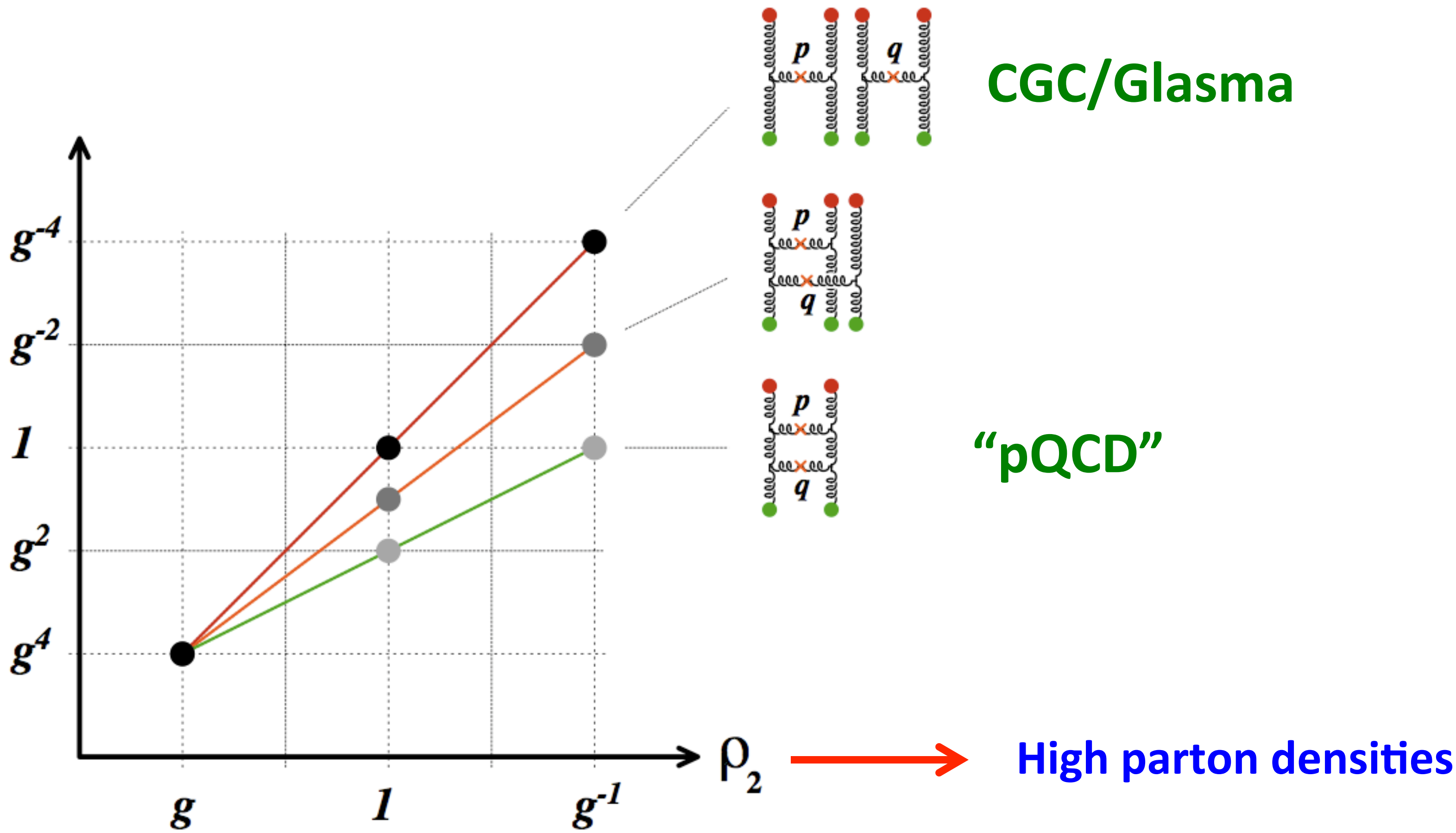
Also describes centrality dependence of multiplicities in A+A

Multi-part. production: systematic power counting

Counting powers of "effective" color charge density $\rho = g\, n_{occ}$

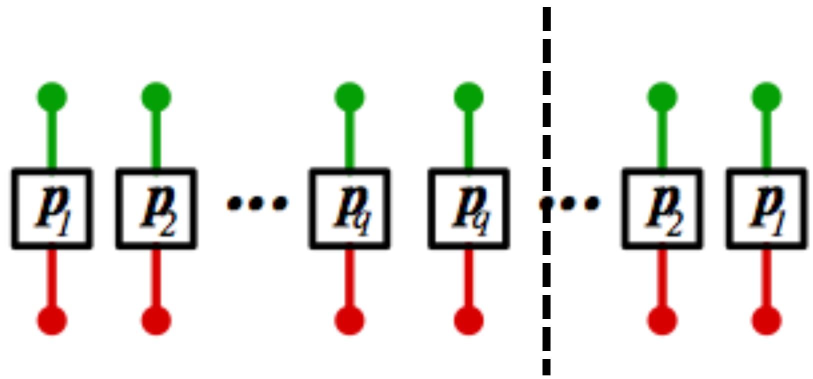
$k_T \leq Q_S$, $n_{occ} = 1/g^2 \Rightarrow \rho \approx 1/g$

$k_T \gg Q_S$, $n_{occ} = 1 \Rightarrow \rho \approx 1$

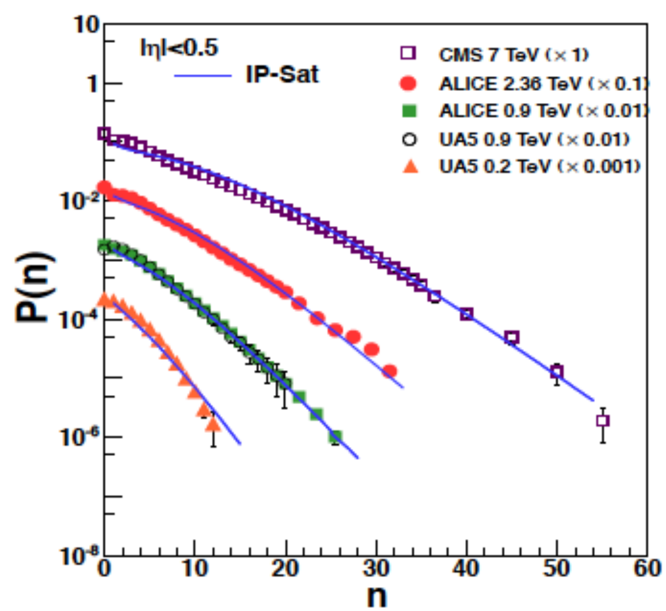


N-particle correlations

Dusling,Fernandez-Fraile,RV
Gelis, Lappi,McLerran



Leading combinatorics gives a negative binomial distribution

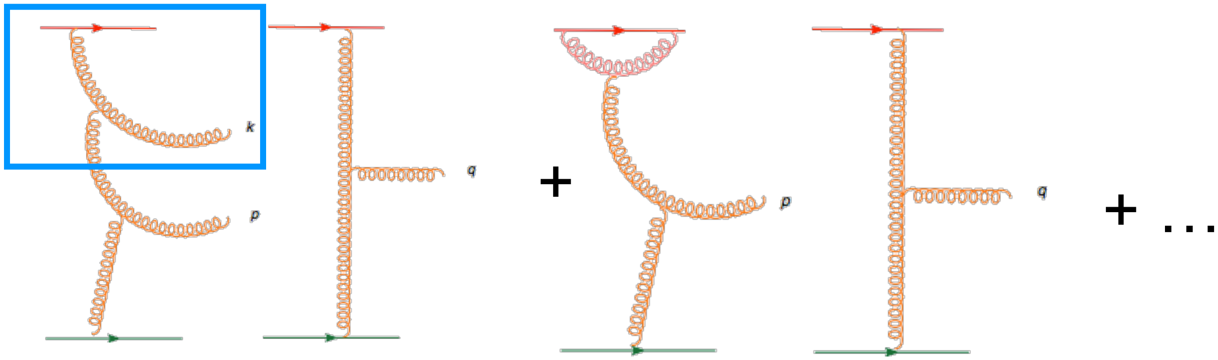


Tribedy, RV
1112.2445

The saturated hadron: Glasma graphs -I

RG evolution:

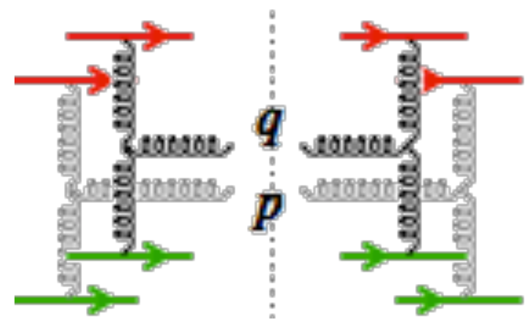
Dumitru,Gelis,McLerran,RV: 0804.3858
Gelis, Lappi, RV, arXiv: 0807.1306



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



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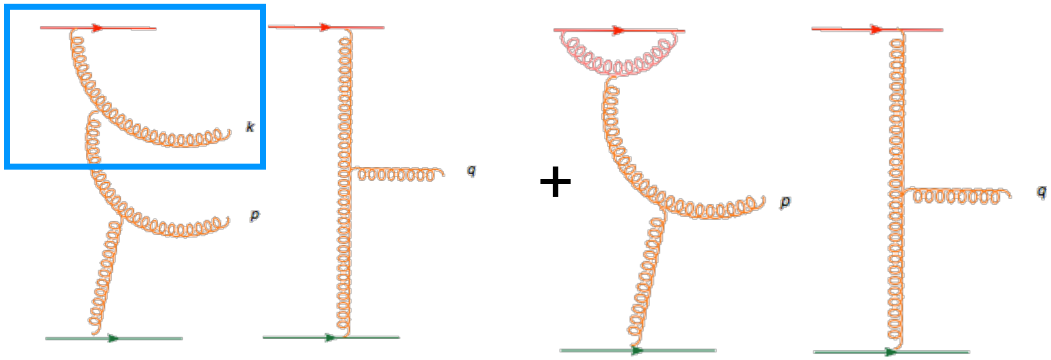

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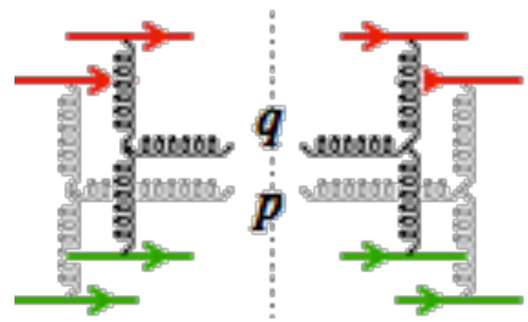
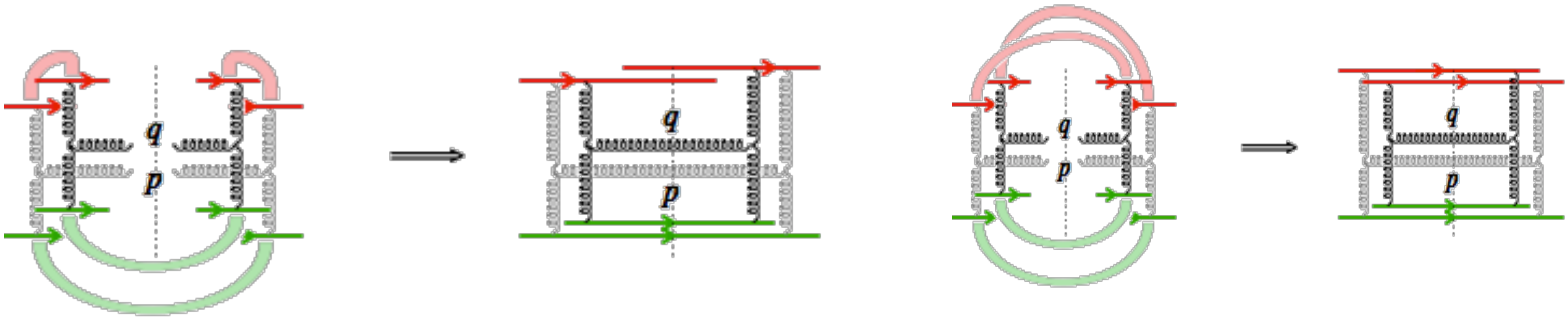


$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

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

The saturated hadron: Glasma graphs-II

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



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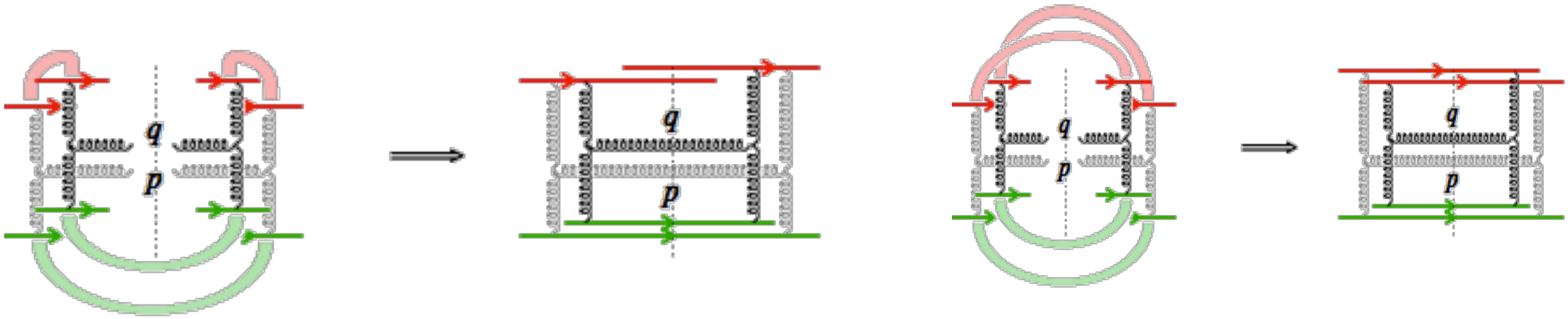

Glasma graphs generate long range rapidity correlations…

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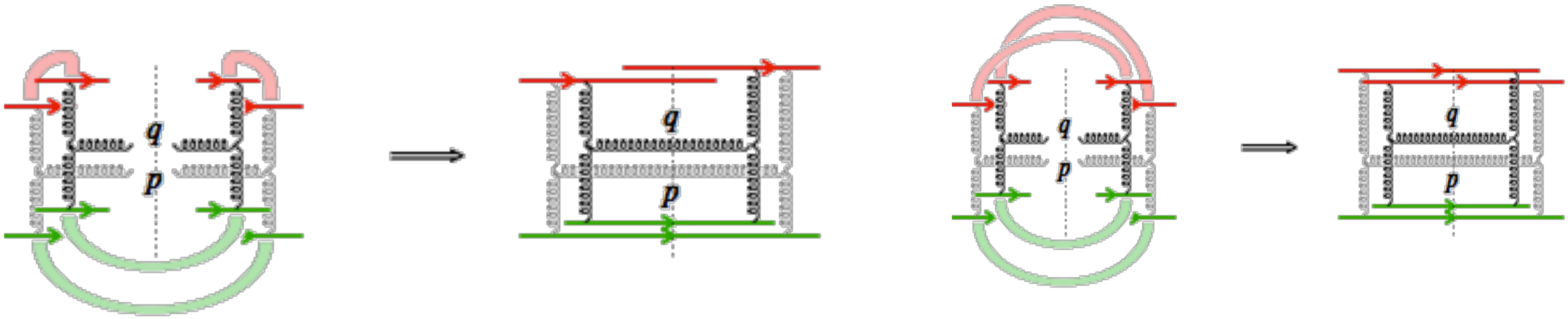

Glasma graphs generate long range rapidity correlations…

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)

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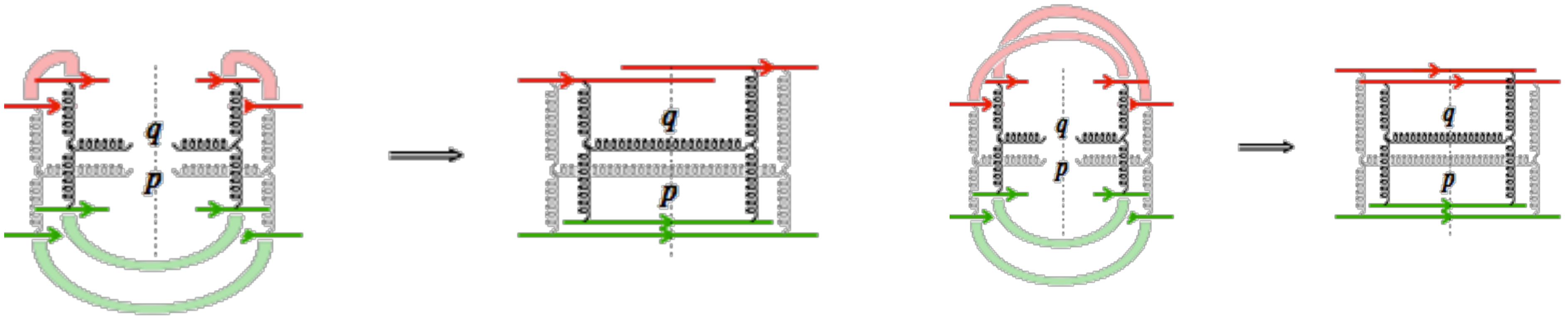


Glasma graphs generate long range rapidity correlations…

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

Nearside collimation: quantum interference of glue

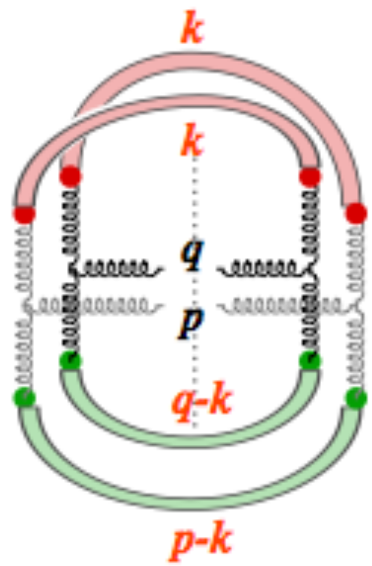
Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV, arXiv:1009.5295

RG evolution of two particle correlations C(p,q) expressed in terms of "unintegrated gluon distributions" in the proton

$$C(\mathbf{p},\mathbf{q}) \quad \propto \quad \frac{g^4}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int \mathrm{d}^2\mathbf{k}_{1\perp}\ \Phi_{A_1}^2(y_p, \mathbf{k}_{1\perp}) \Phi_{A_2}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q, \mathbf{q}_\perp - \mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$

Proton 1

Proton 2



k_T factorized approximation to full RG simulation

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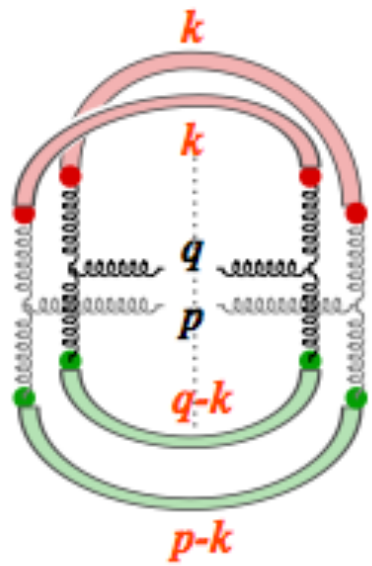

These contributions are of order α_S^6/N_c^2 in min. bias events-
in high multiplicity events power counting changes to $1/\alpha_S^2\,N_c^2$

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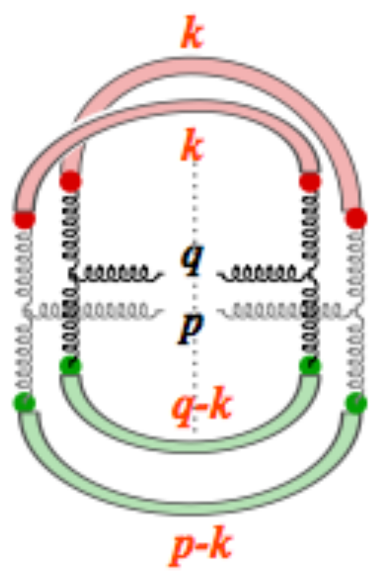

Enhancement of ~ 10^5 for $\alpha_S = 0.2$!

Nearside collimation: quantum interference of glue

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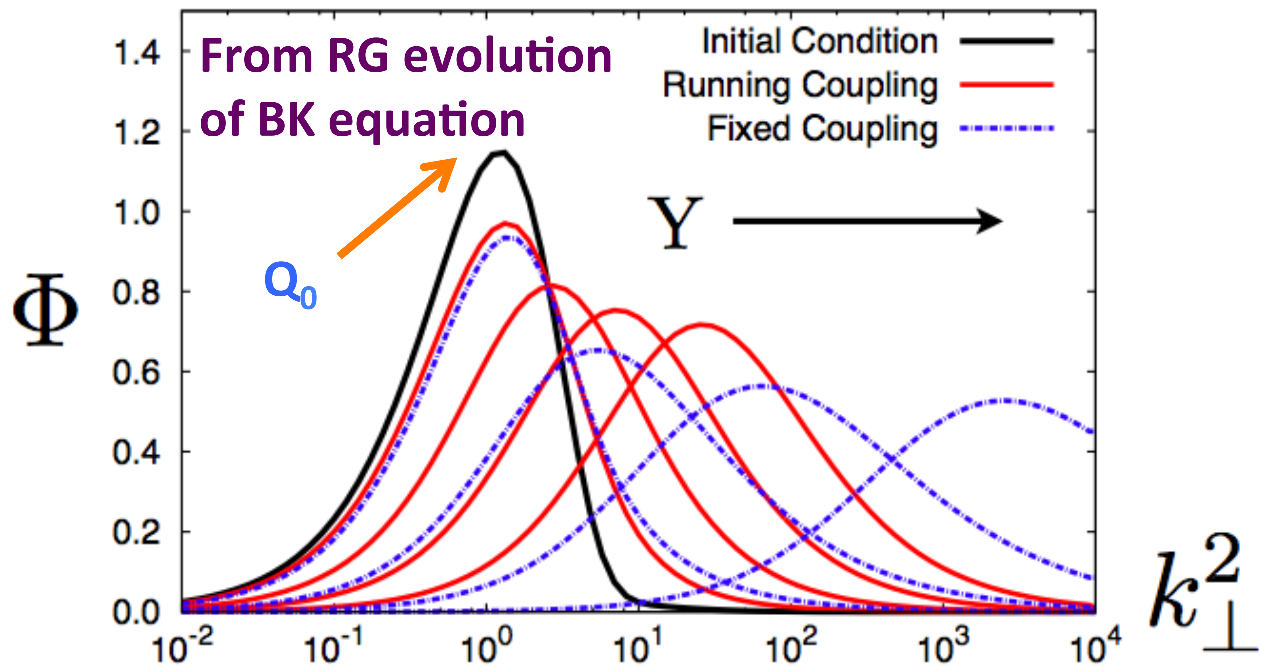

Collimated yield ?

$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}\int d^2\mathbf{k}_{1\perp}\,\Phi_{A_1}^2(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$
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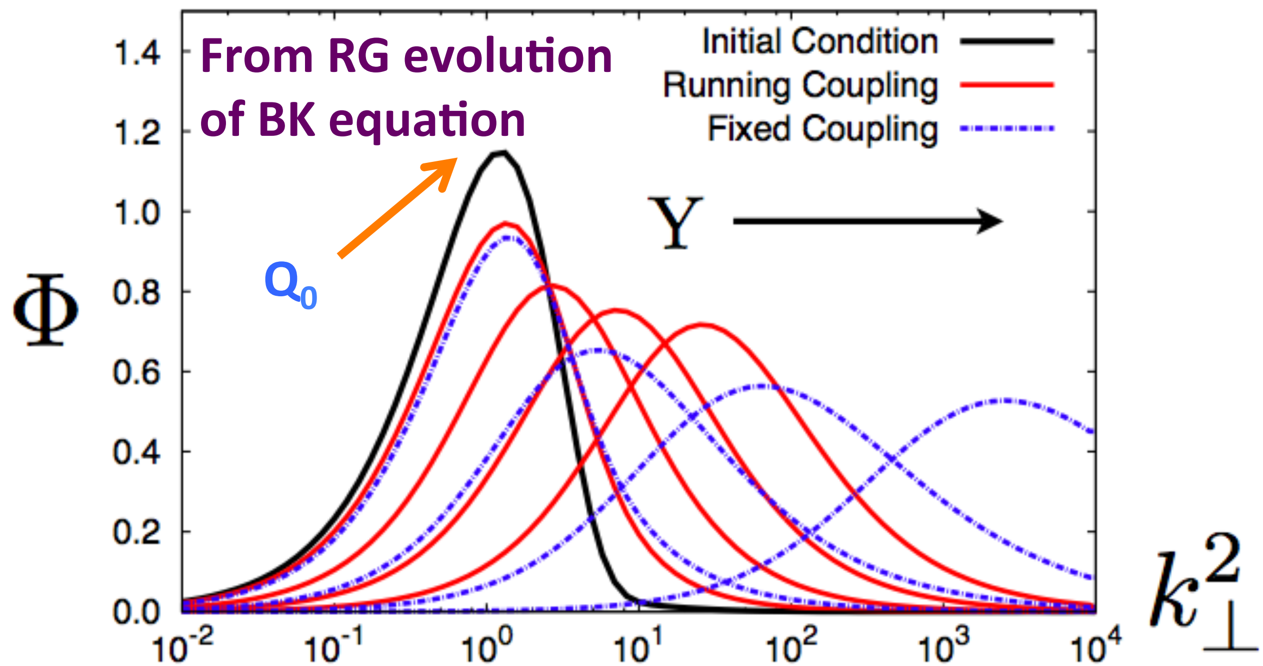
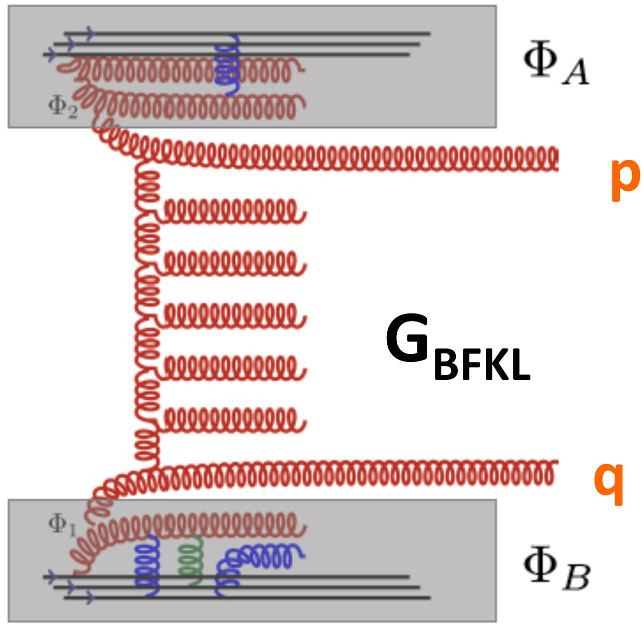


Dominant contribution from $|p_T\text{-}k_T| \sim |q_T\text{-}k_T| \sim |k_T| \sim Q_S$

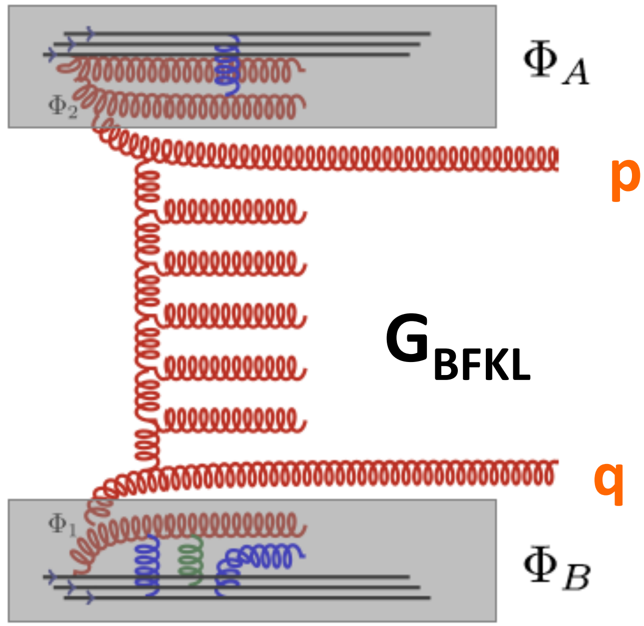
This gives a collimation for $\Delta\Phi \approx 0$ and π

Angular structure from (mini-) Jet radiation



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

Angular structure from (mini-) Jet radiation

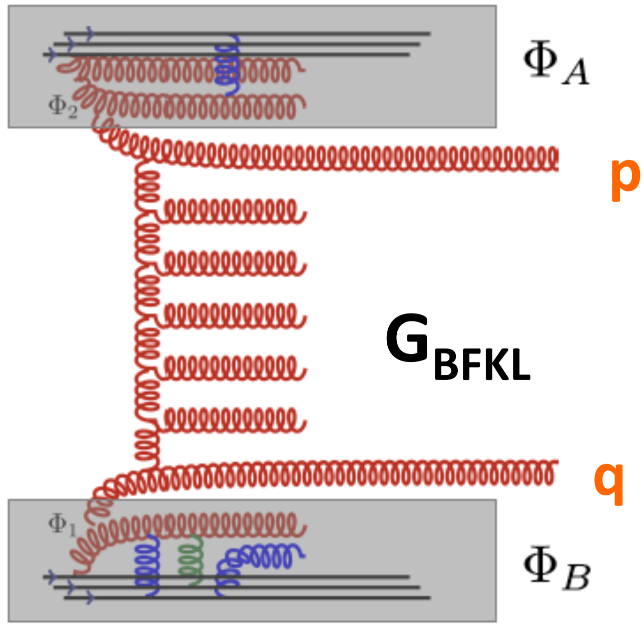


$$C_{\text{dijet}}(\mathbf{p}, \mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\text{BFKL}}$$

Mini-jets: O (1) in high multiplicity events

- give an angular collimation, albeit only at ΔΦ≅π

Angular structure from (mini-) Jet radiation

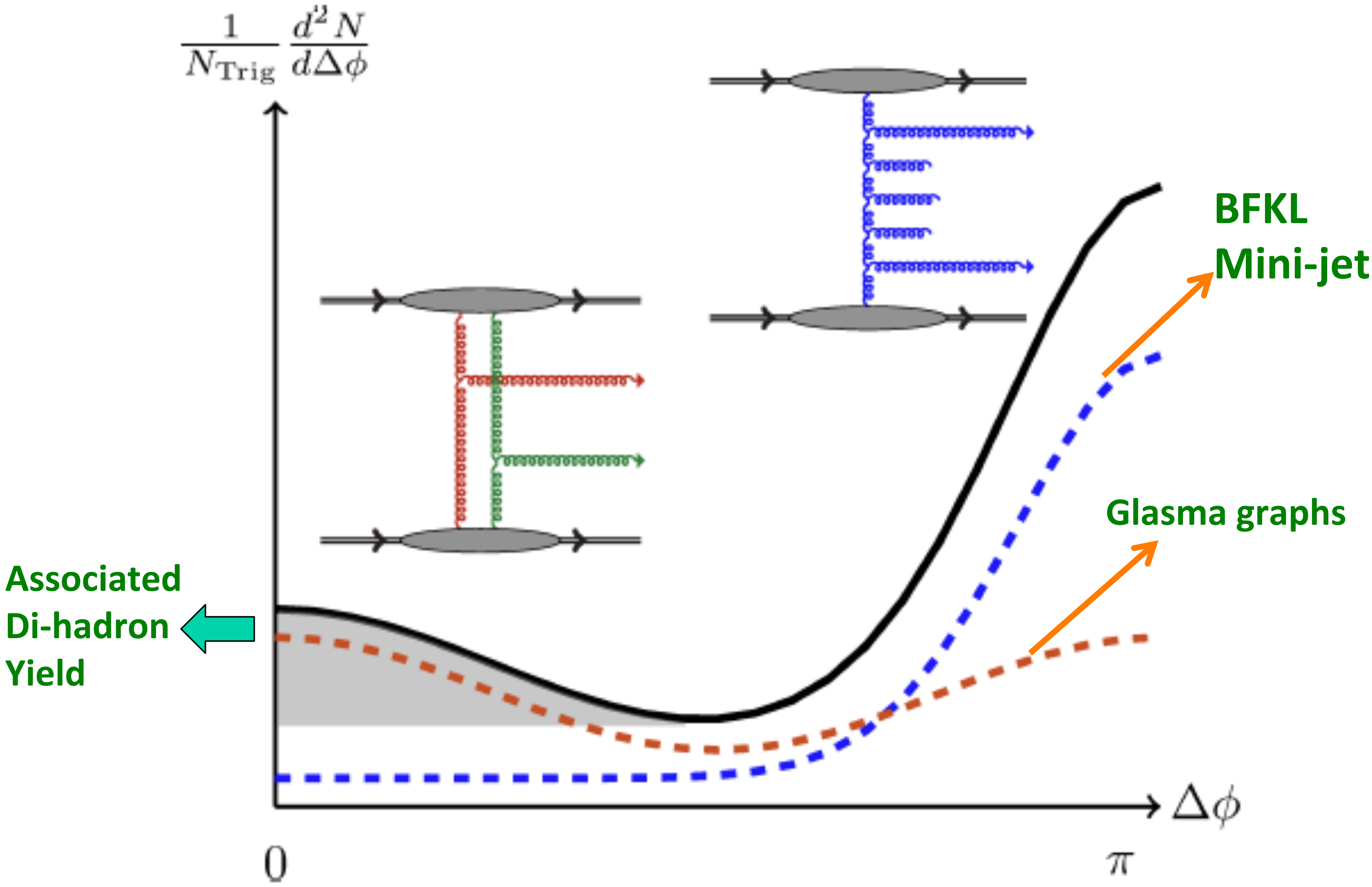


$$C_{\mathrm{dijet}}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\mathrm{BFKL}}$$

Mini-jets: O (1) in high multiplicity events
- give an angular collimation, albeit only at $\Delta\Phi \cong \pi$

LHC p+p & p+A "ridge" results also test the structure of bremsstrahlung radiation between jets

Anatomy of long range collimation yields



Quantitative description of pp ridge

Dusling,RV:PRL108 (2012)262001

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

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

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

(6

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

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

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

Dependence on transverse area cancels in ratio…

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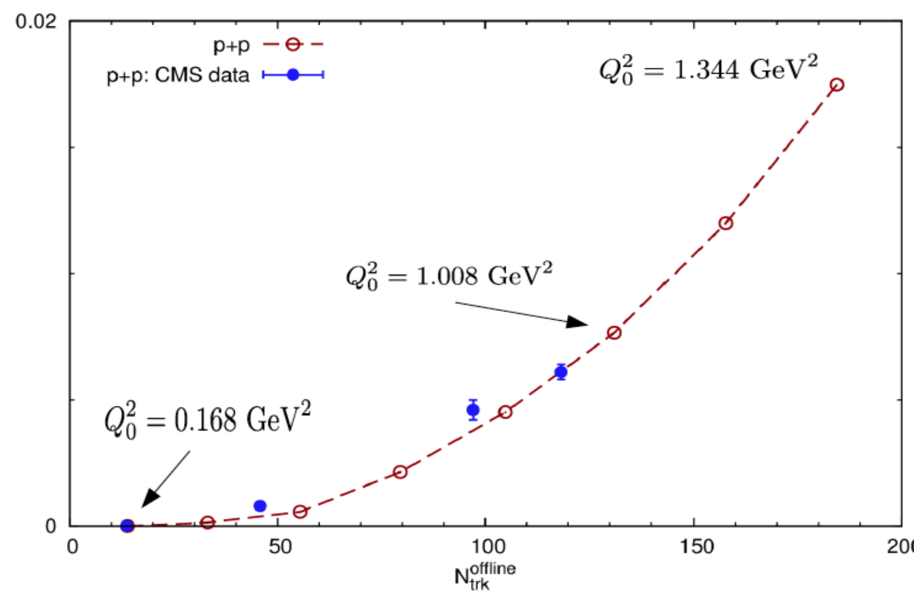
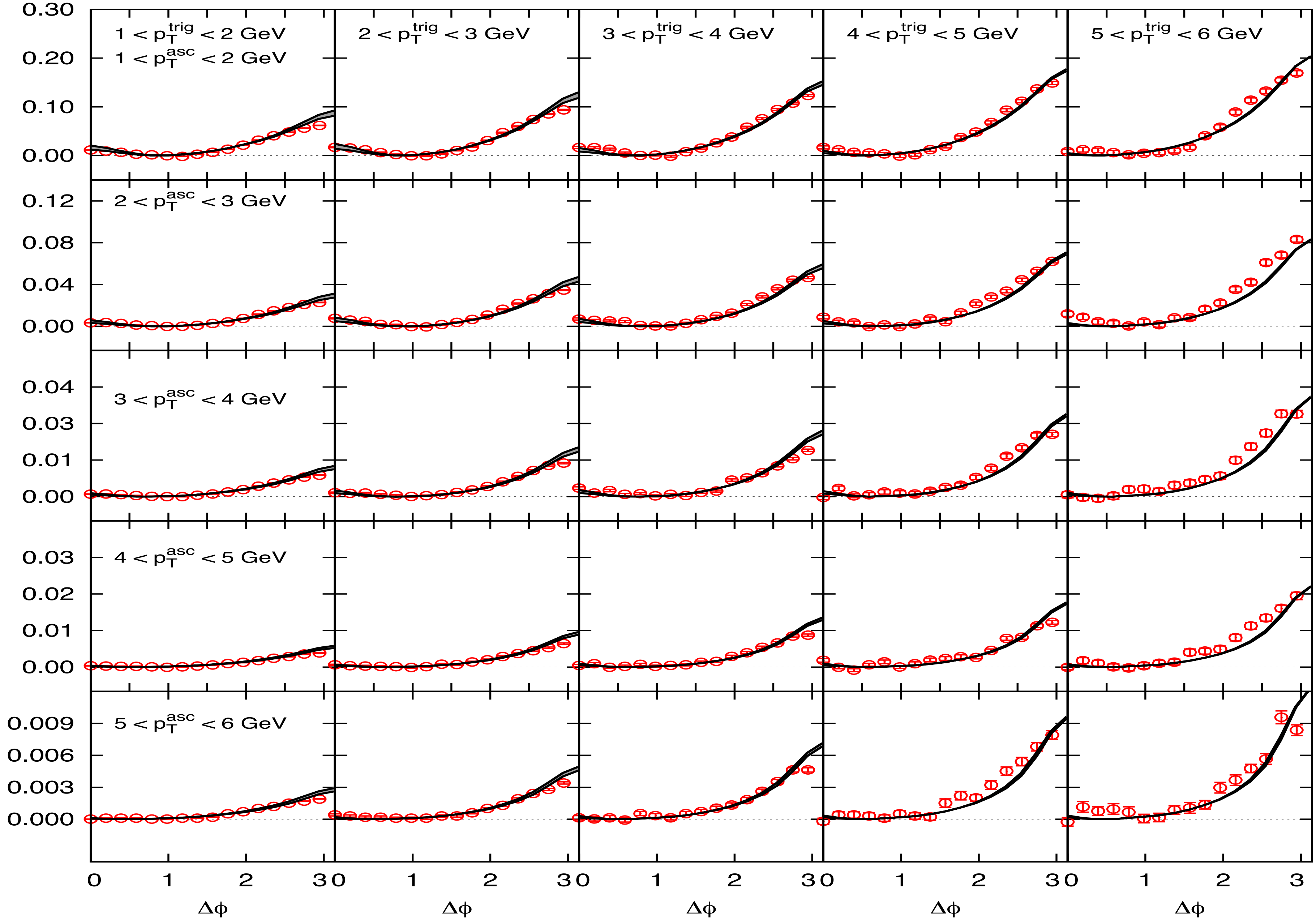
Dependence on transverse area cancels in ratio…

Rarer and rarer gluon configurations probed in the proton

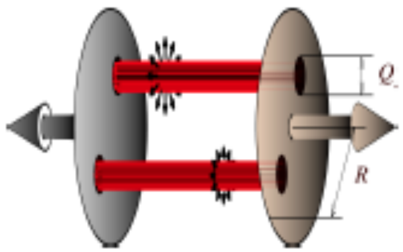


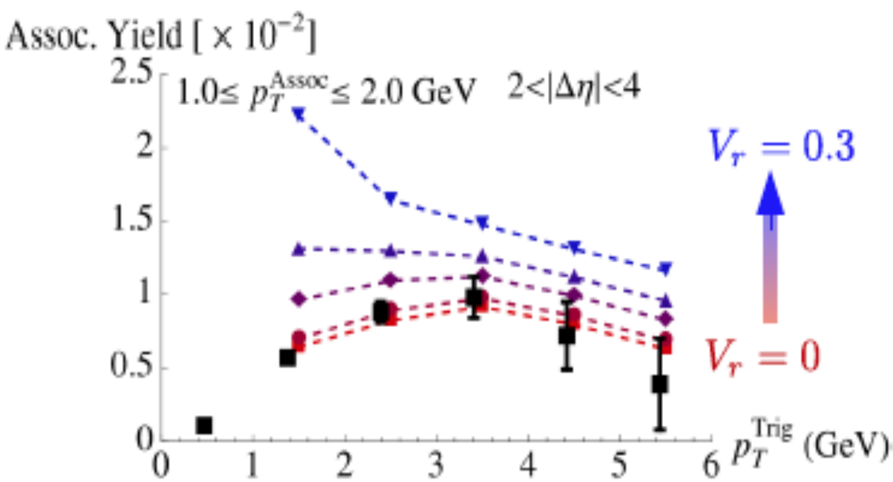
Dusling,RV, PRD 87, 051502 (R) (2013); arXiv:1302.7018



p+p vs A+A

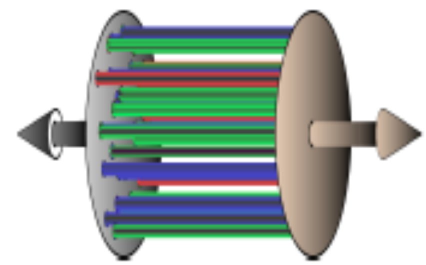
In p+p we are seeing the intrinsic collimation from a single flux tube

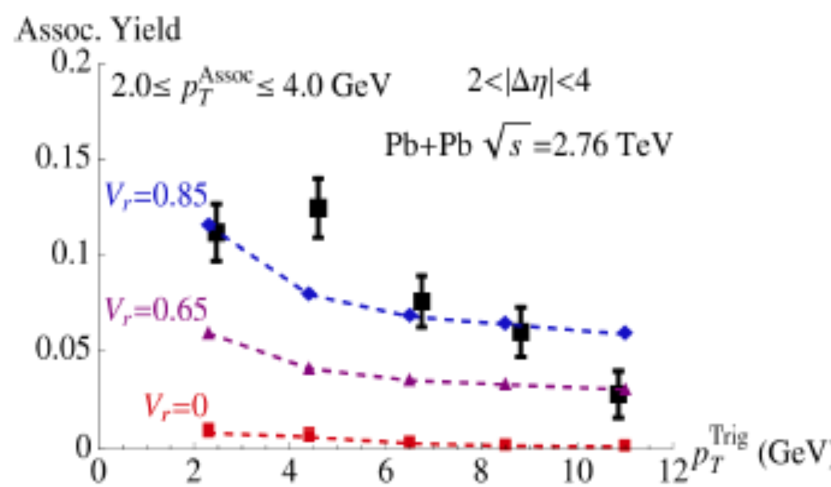




Increasing transverse flow in p+p creates a discrepancy with data.

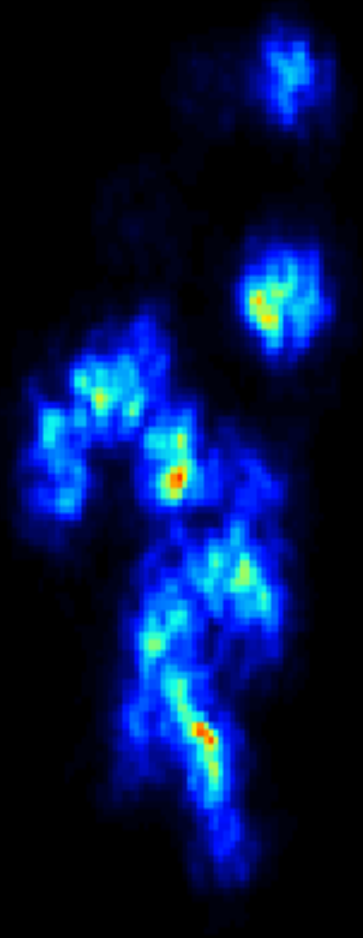
In A+A there are many such tubes each with an intrinsic correlation enhanced by flow



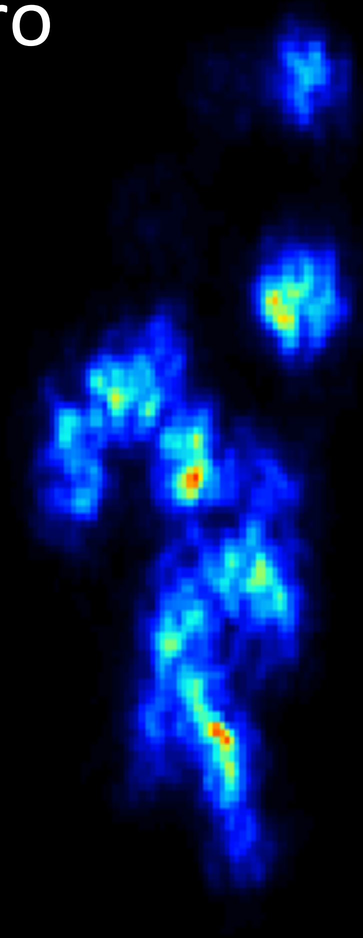


Yet, transverse flow is needed to explain identical measurements in Pb+Pb

IP-Glasma model: match event-by-event Yang-Mills to viscous hydro



2+1-D Yang-Mills



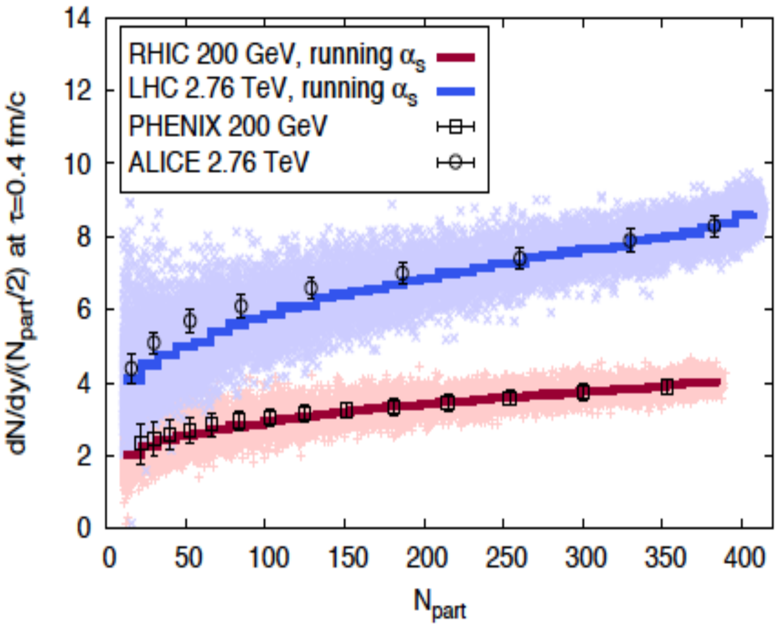
2+1-D Yang-Mills +
2+1-D Viscous hydro

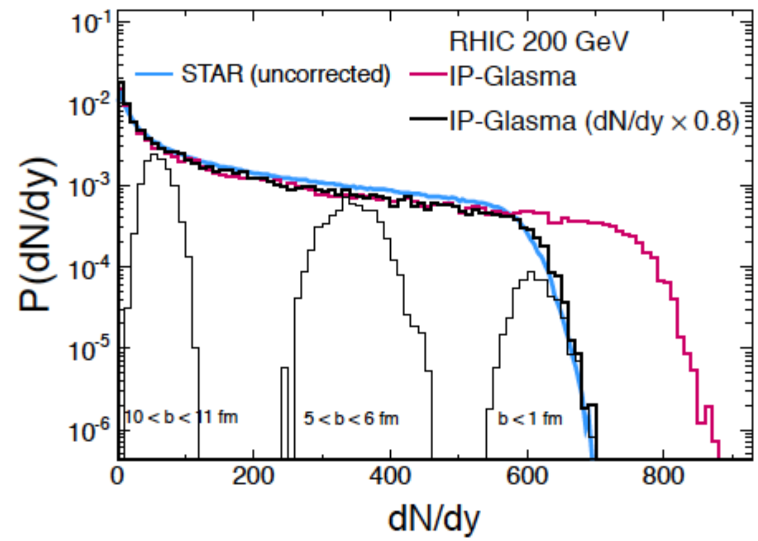
t = 0.0 fm/c

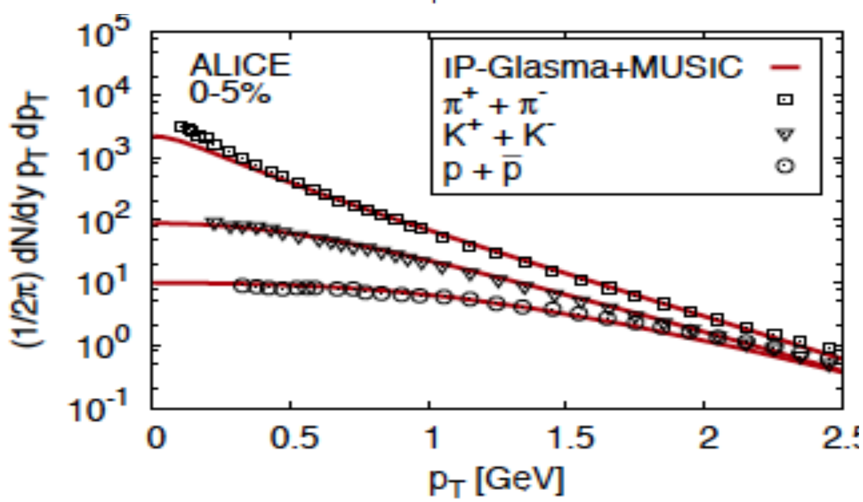
Heavy Ion phenomenology: IP-Glasma model

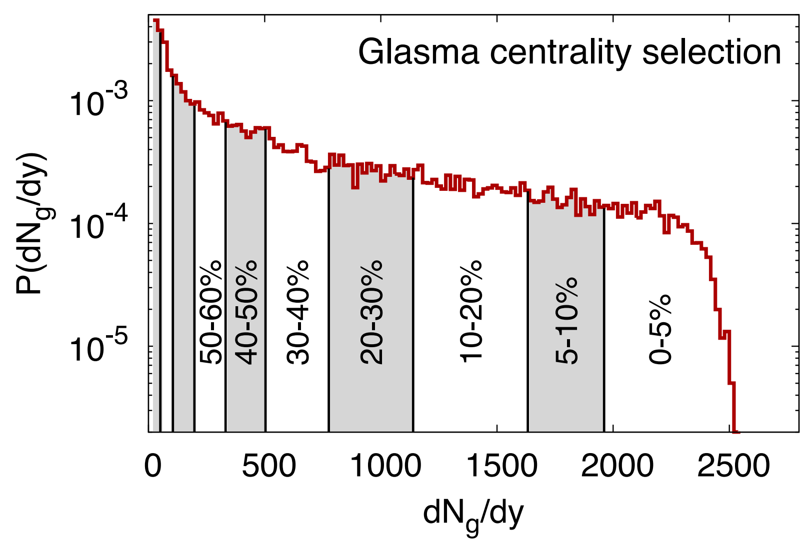
I) Multiplicity distributions

Schenke,Tribedy,RV: PRL108 (2012), 252301; arXiv:1206.6805



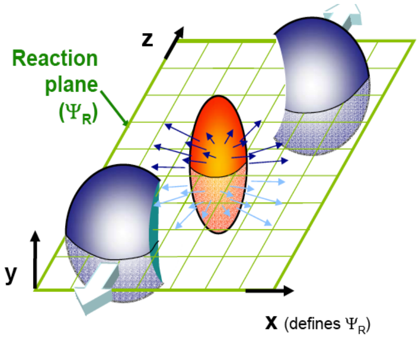






IP-Glasma model for A+A

II) Harmonic flow moments (event-by-event 2+1-D CYM + viscous hydro a la MUSIC)

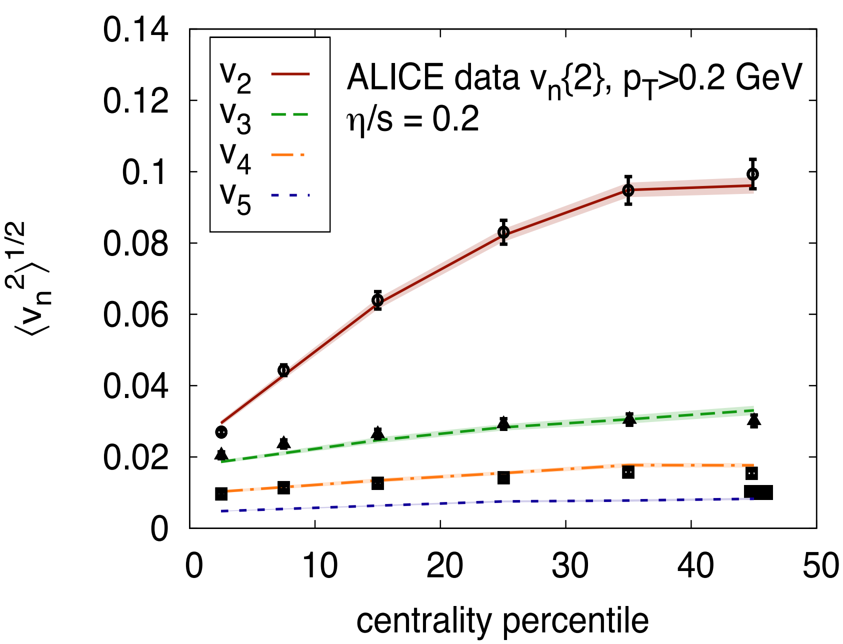


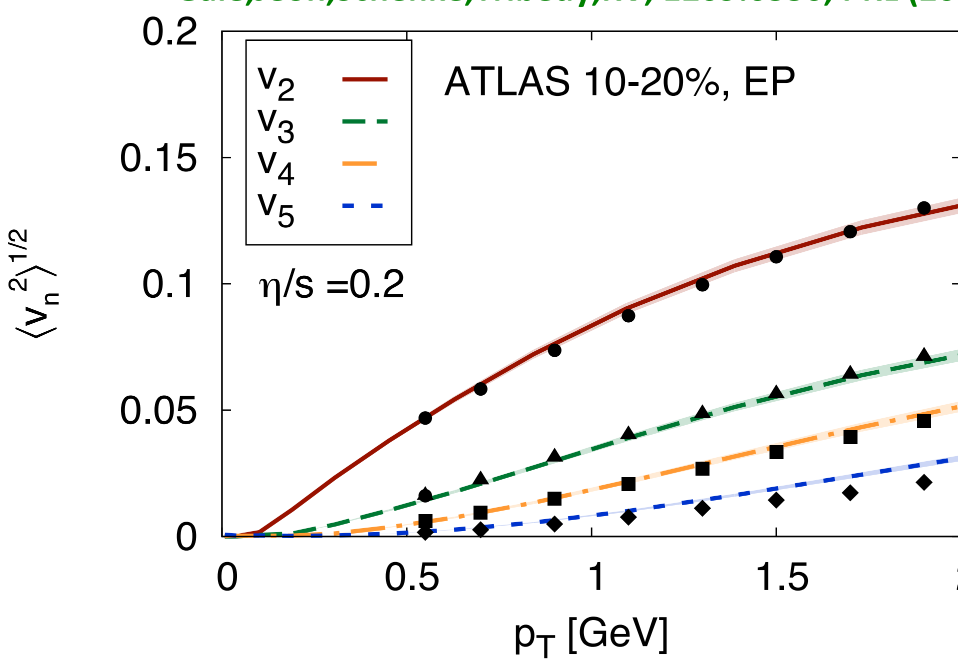
$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle$$

$$\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$$

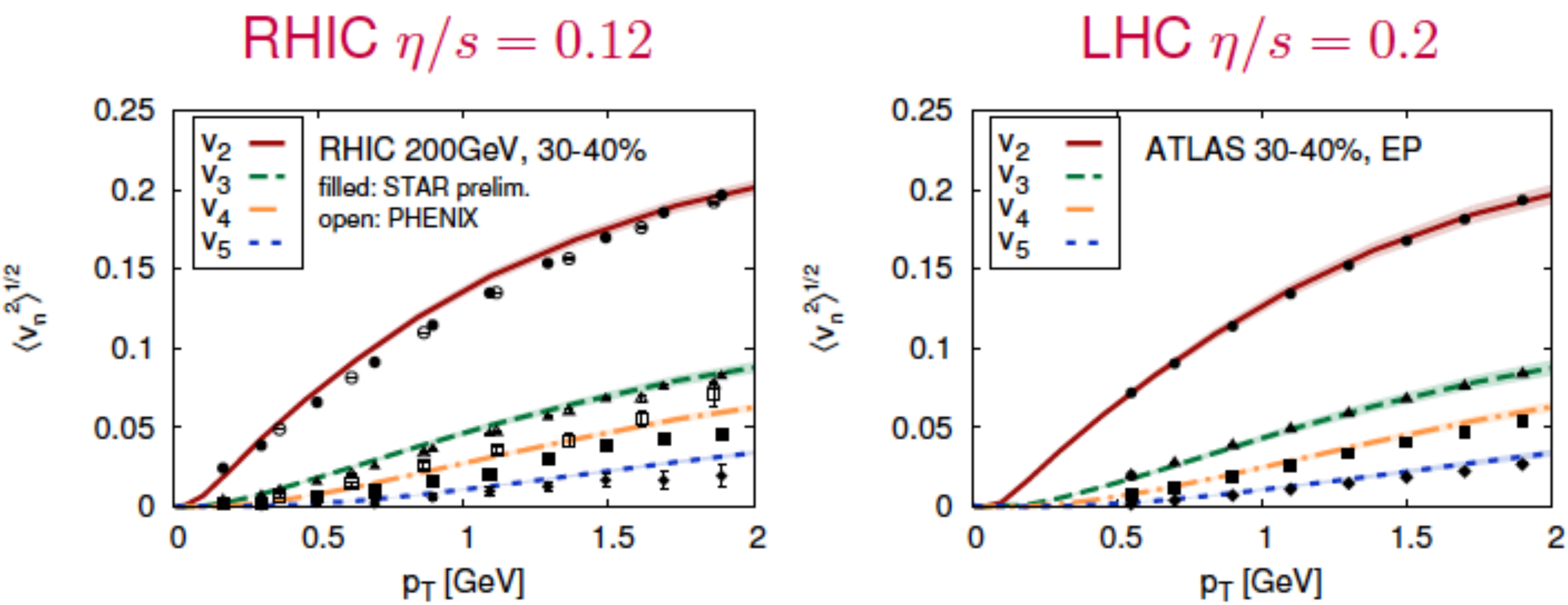
MUSIC:Schenke,Jeon,Gale (2011)

Gale,Jeon,Schenke,Tribedy,RV, 1209.6330, PRL (2013)



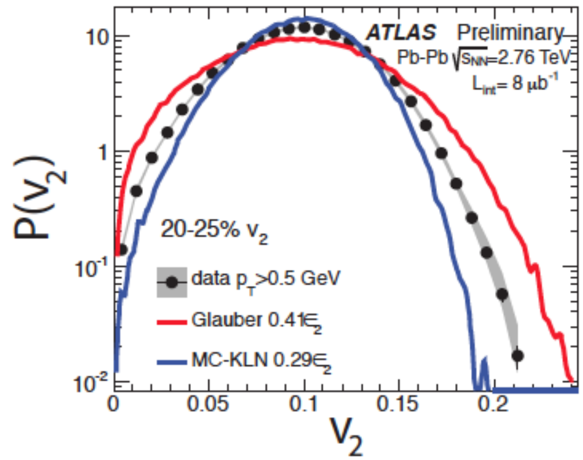


IP-Glasma model for A+A



Initial state Glasma fluctuations + flow describe v_n data for wide range of centrality classes in A+A

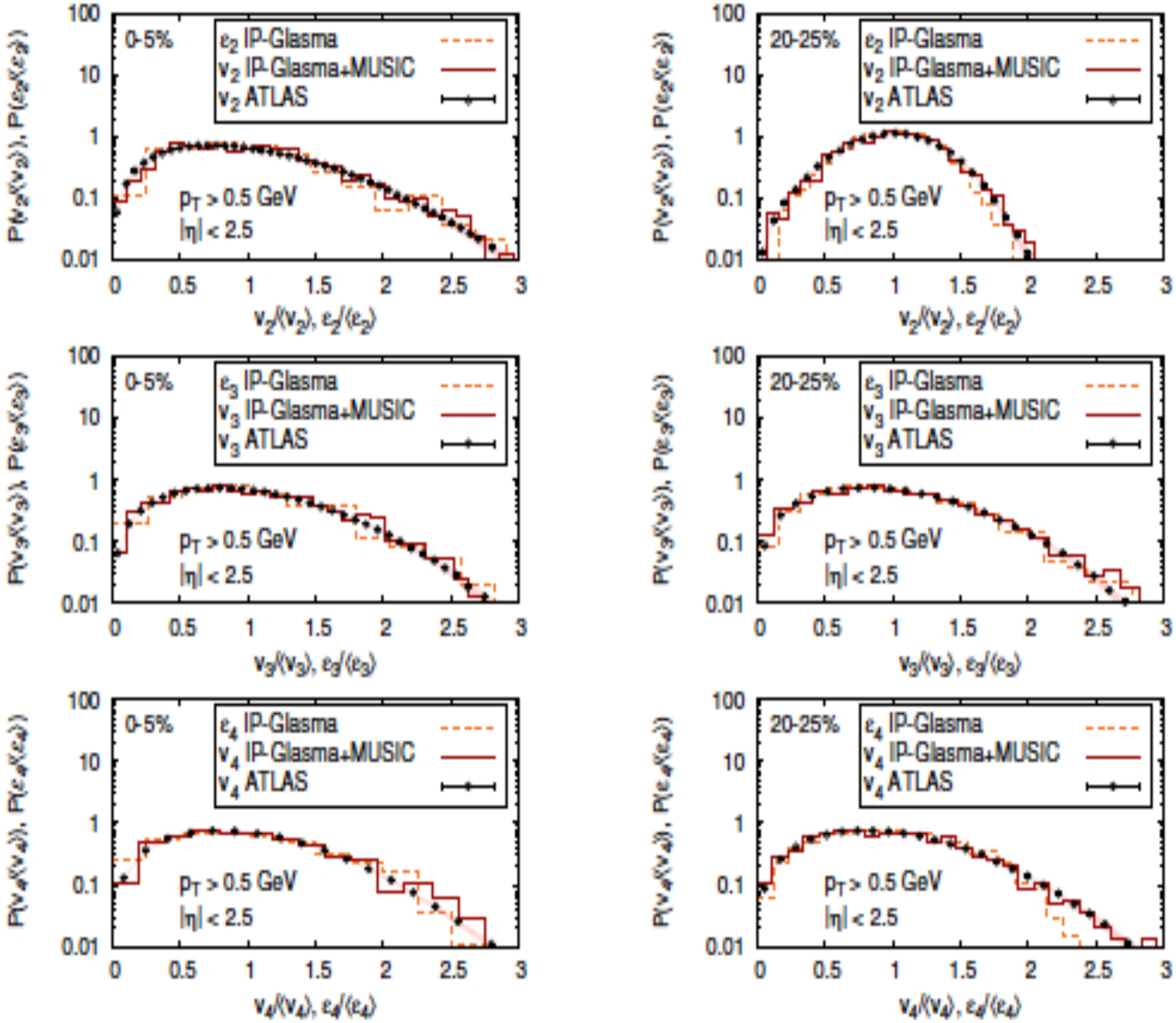
IP-Glasma model for A+A



Event-by-event flow fluctuations of v_2,v_3,v_4

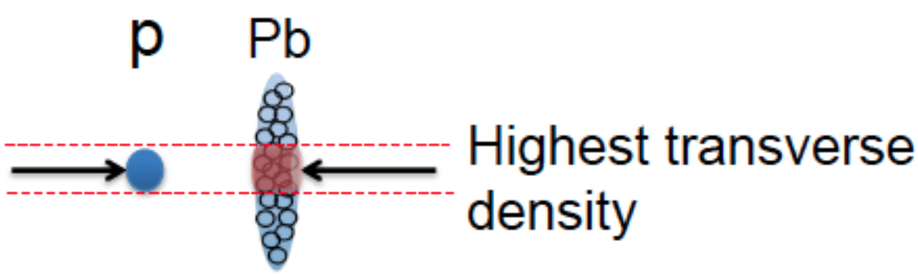
0-5%

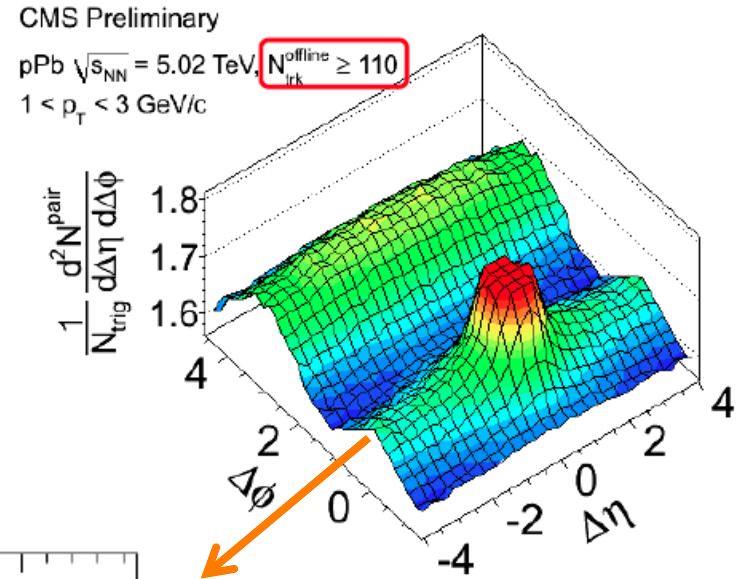
20-25%

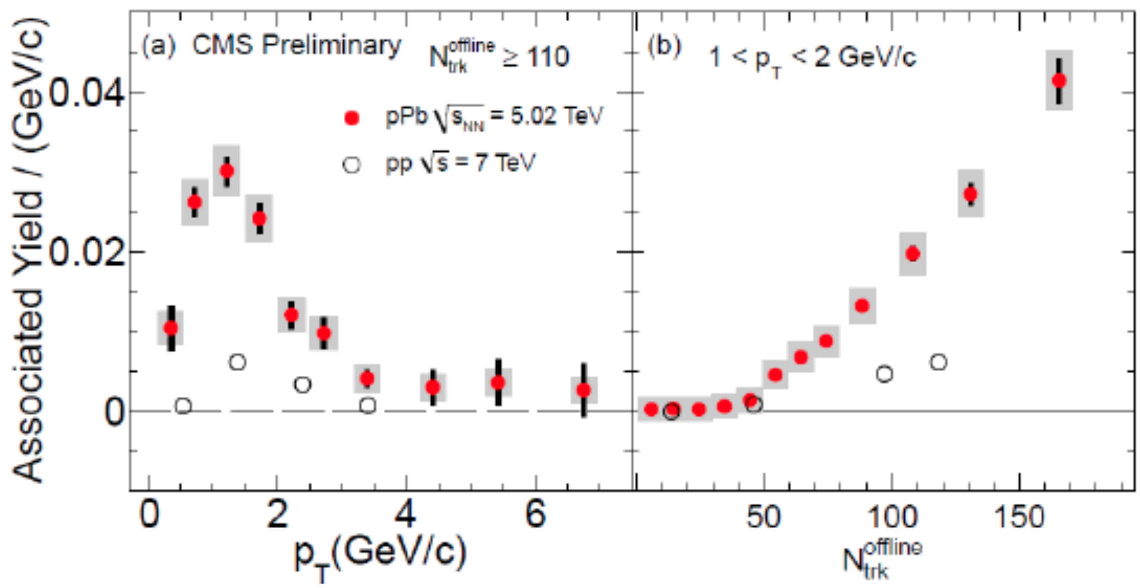


What about p+A ? LHC "pilot" run data

CMS coll. arXiv:1210.5482, Phys. Lett. B







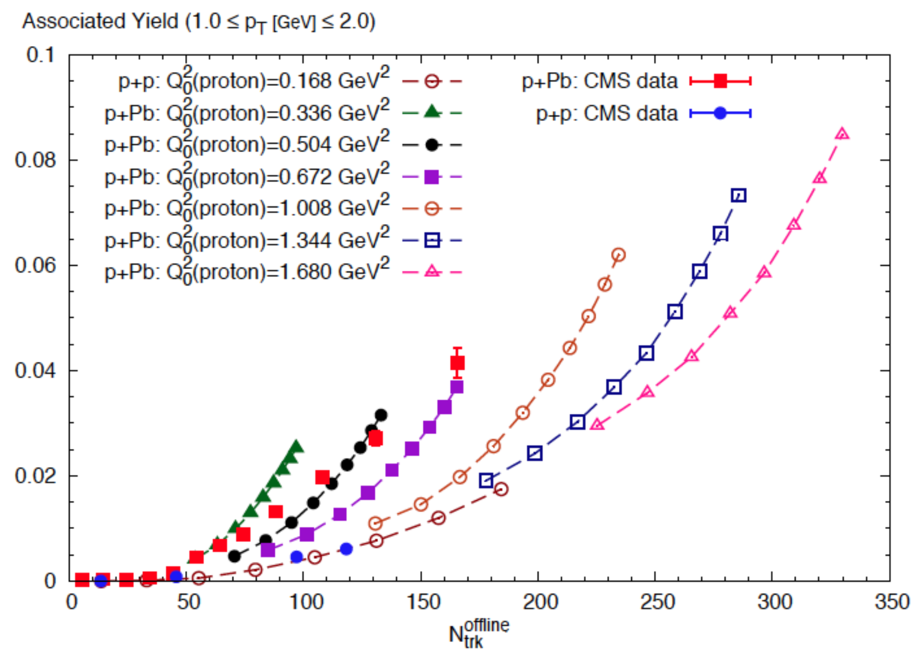
Ridge much bigger than p+p for the same multiplicity !

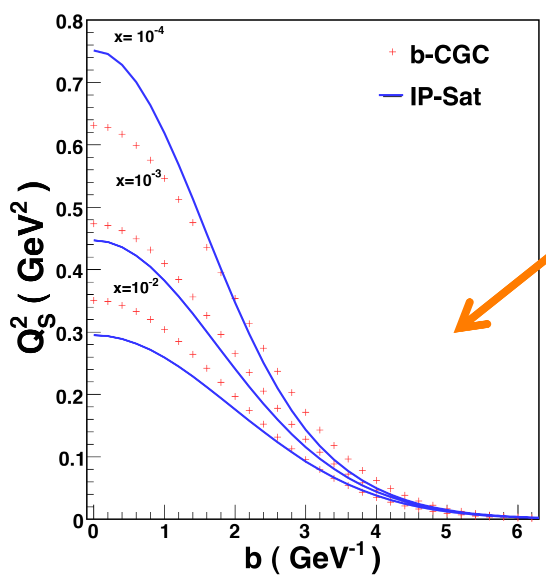
CMS p+Pb pilot run data explained

Dusling, RV: 1302.7018

$Q_0^2(\text{lead}) = N_{Part}^{Pb} * Q_0^2(\text{proton})$

of "wounded" nucleons in Lead nucleus





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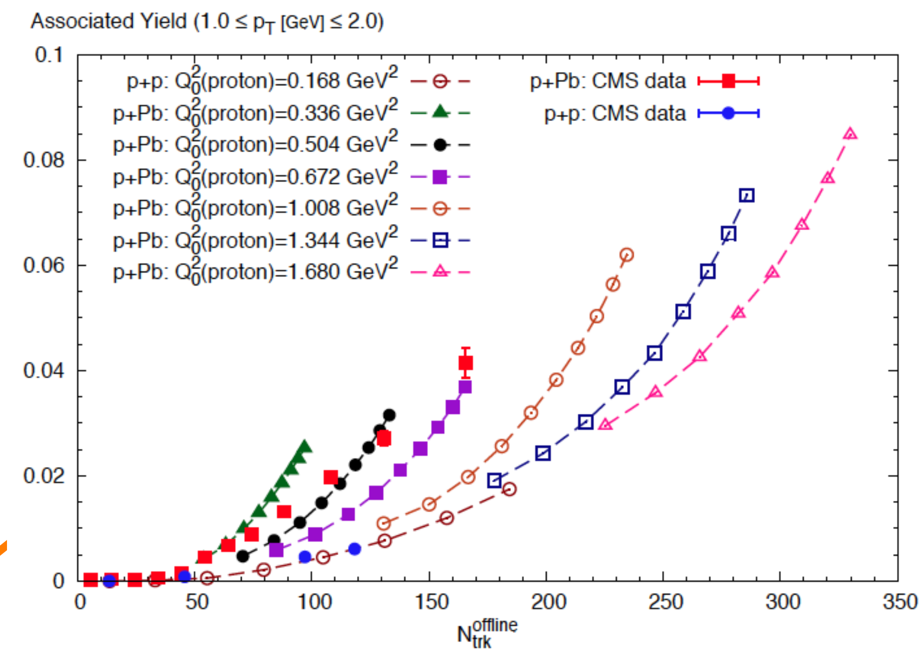
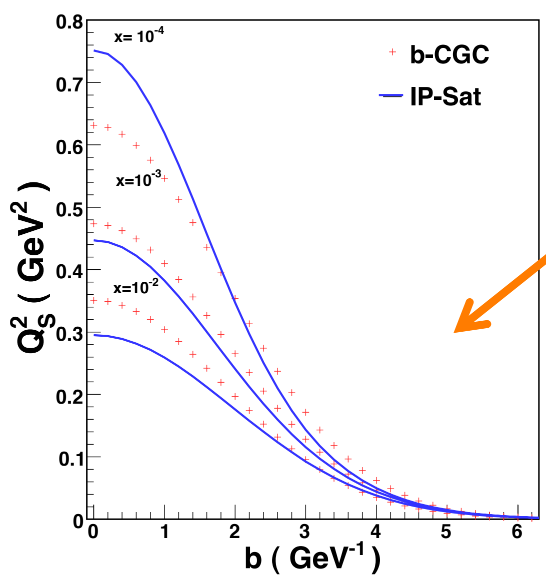


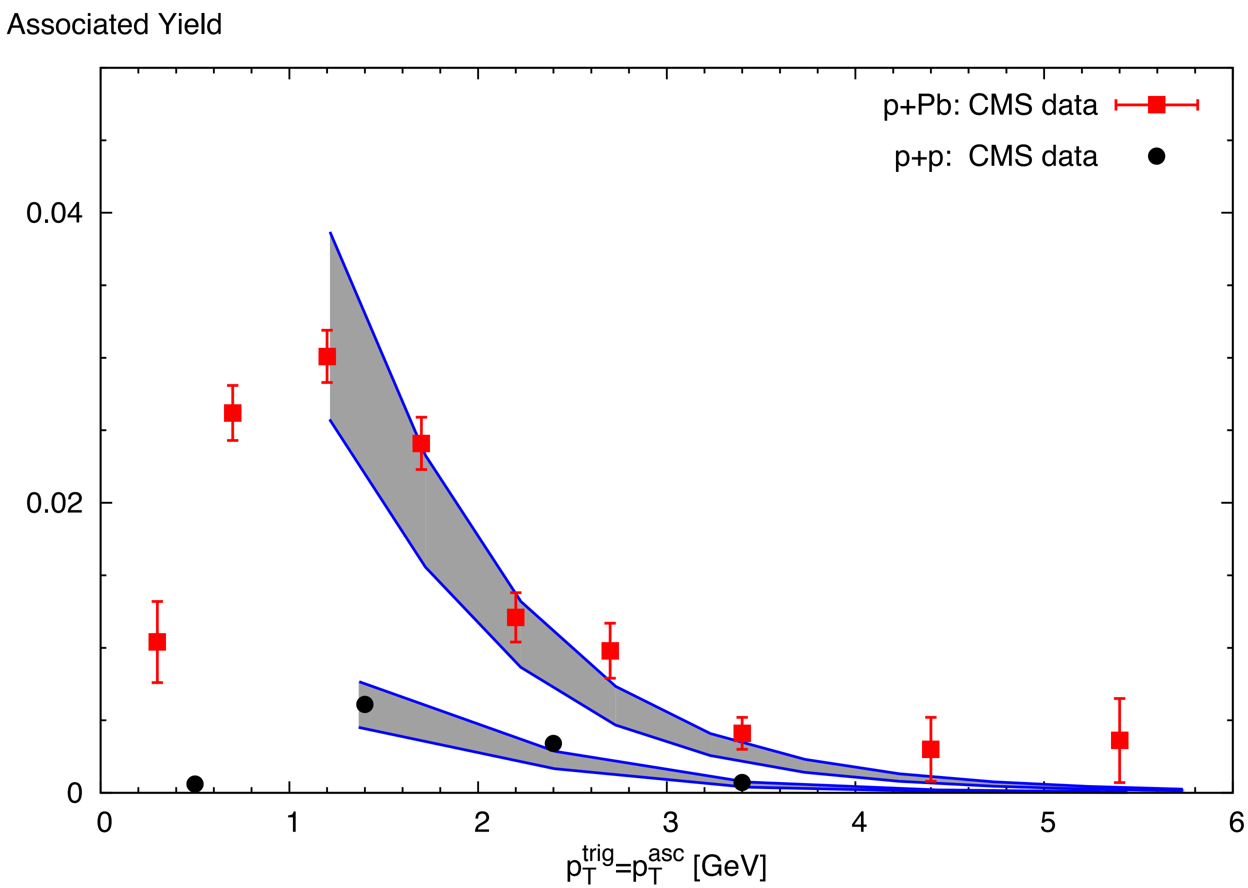


Large "ridge" seen by varying saturation scale in proton and # of wounded nucleons

--rarer and rarer Fock configurations probed in both proton and nucleus

CMS p+Pb pilot data explained

Dusling, RV: 1211.3701
1302.7018



CMS pilot p+Pb data explained

Dusling, RV: 1211.3701
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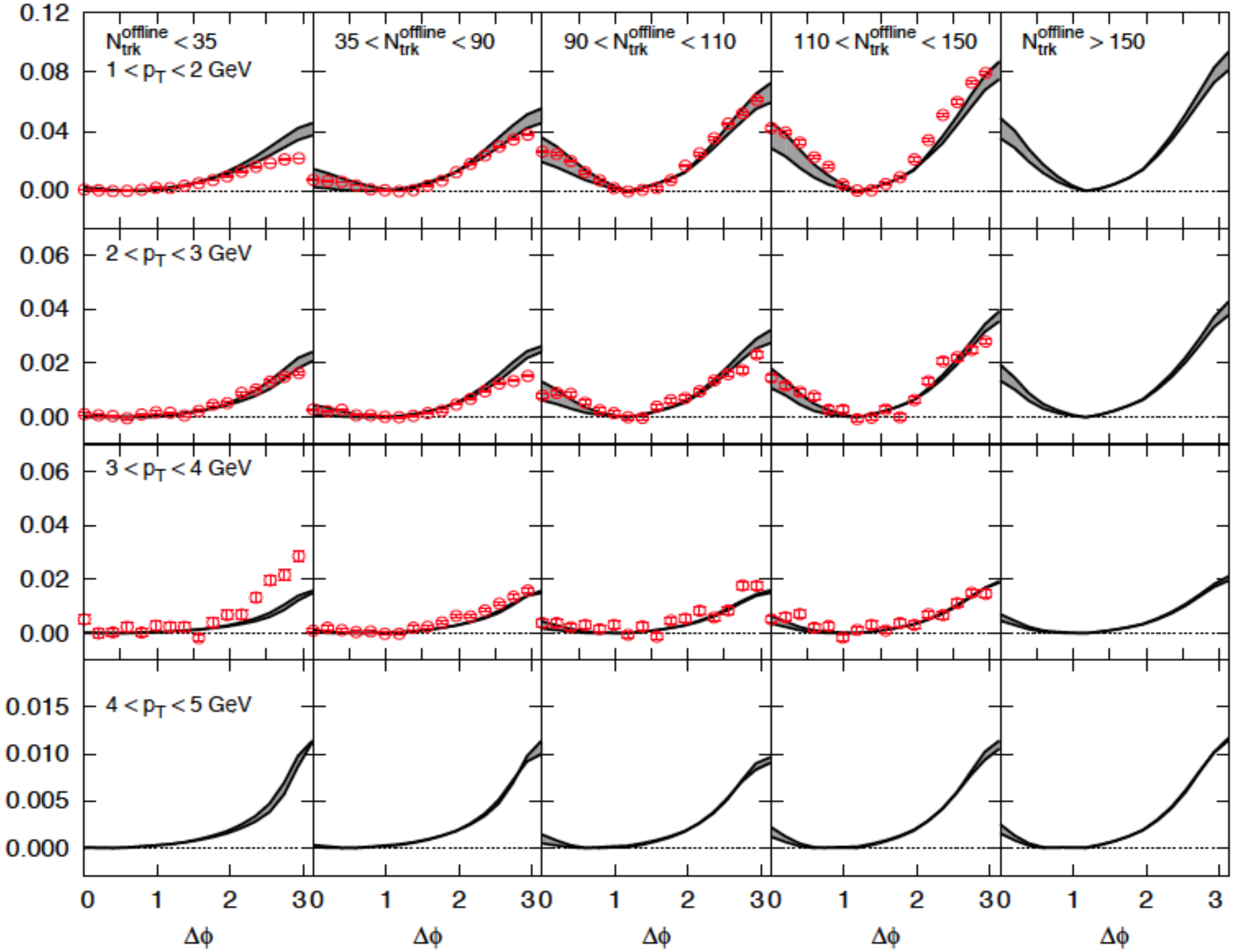
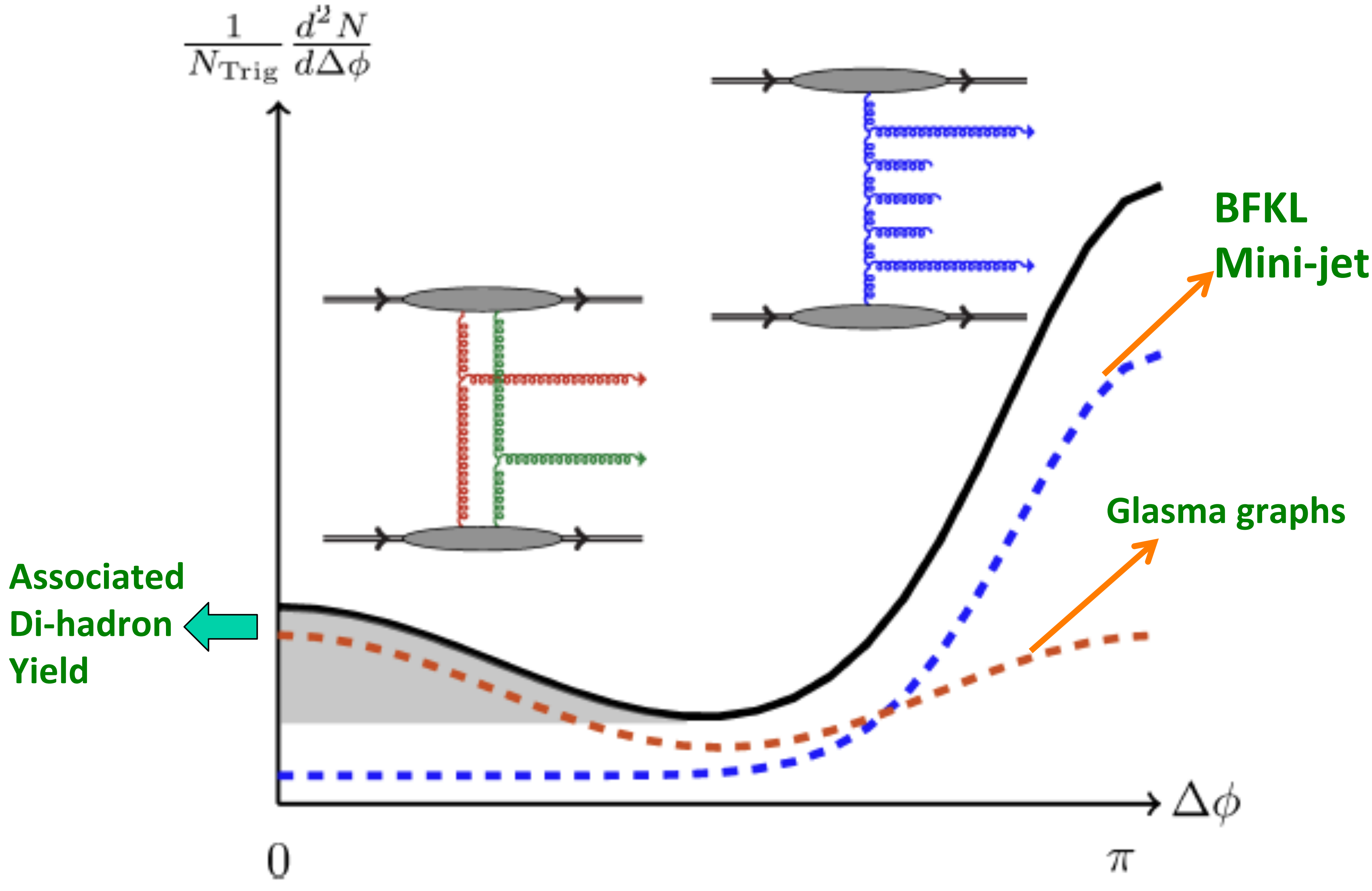


Anatomy of long range di-hadron collimation



ALICE data on the p+Pb ridge

ALICE coll. arXiv:1212.2001

Different acceptance ($|\Delta\eta| < 1.8$) than CMS ($2 < |\eta| < 4$) and ATLAS ($2 < |\eta| < 5$).

ALICE subtracts away-side “jet” contribution at 60-100%
centrality from most central events

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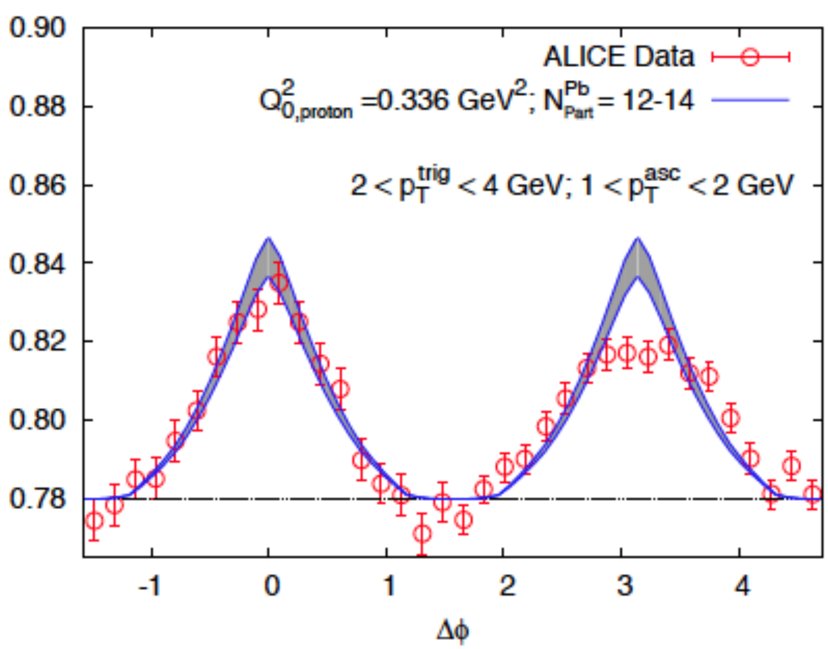
–this gives dipole shape of correlation



Different analysis technique from CMS/ATLAS

-- same normalization as for CMS/ATLAS

Curves for $Q_{0,proton}^2$ =0.336 GeV^2 & N_{part}^{Pb} = 12 - 14

ALICE data on the p+Pb ridge

ALICE coll. arXiv:1212.2001

Different acceptance ($|\Delta\eta| < 1.8$) than CMS ($2 < |\eta| < 4$) and ATLAS ($2 < |\eta| < 5$).

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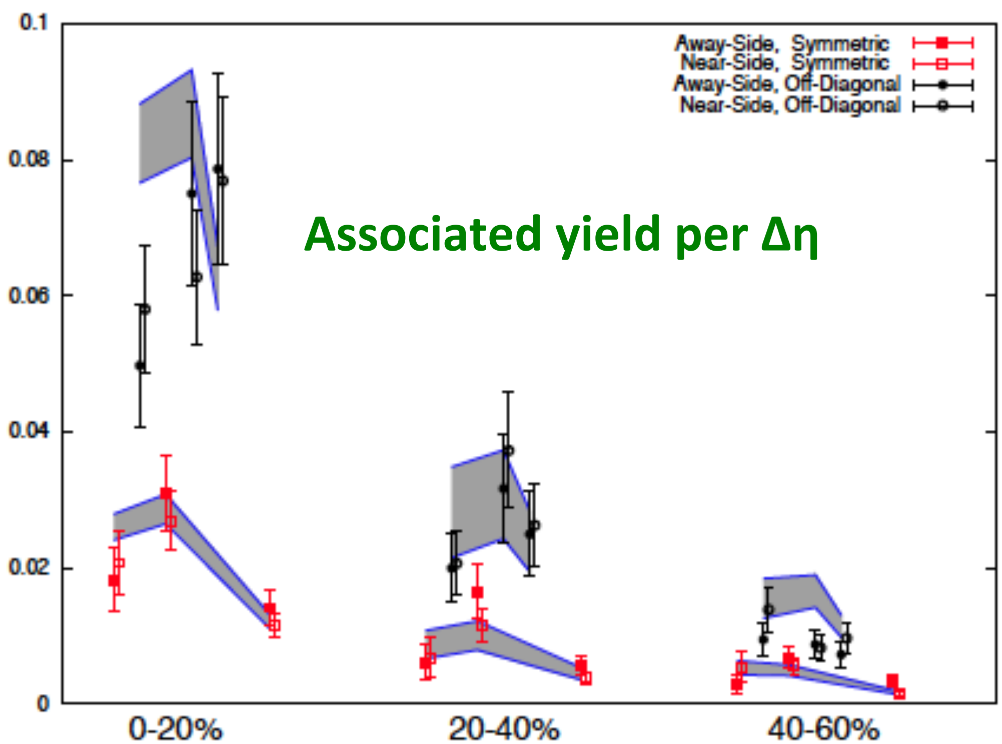


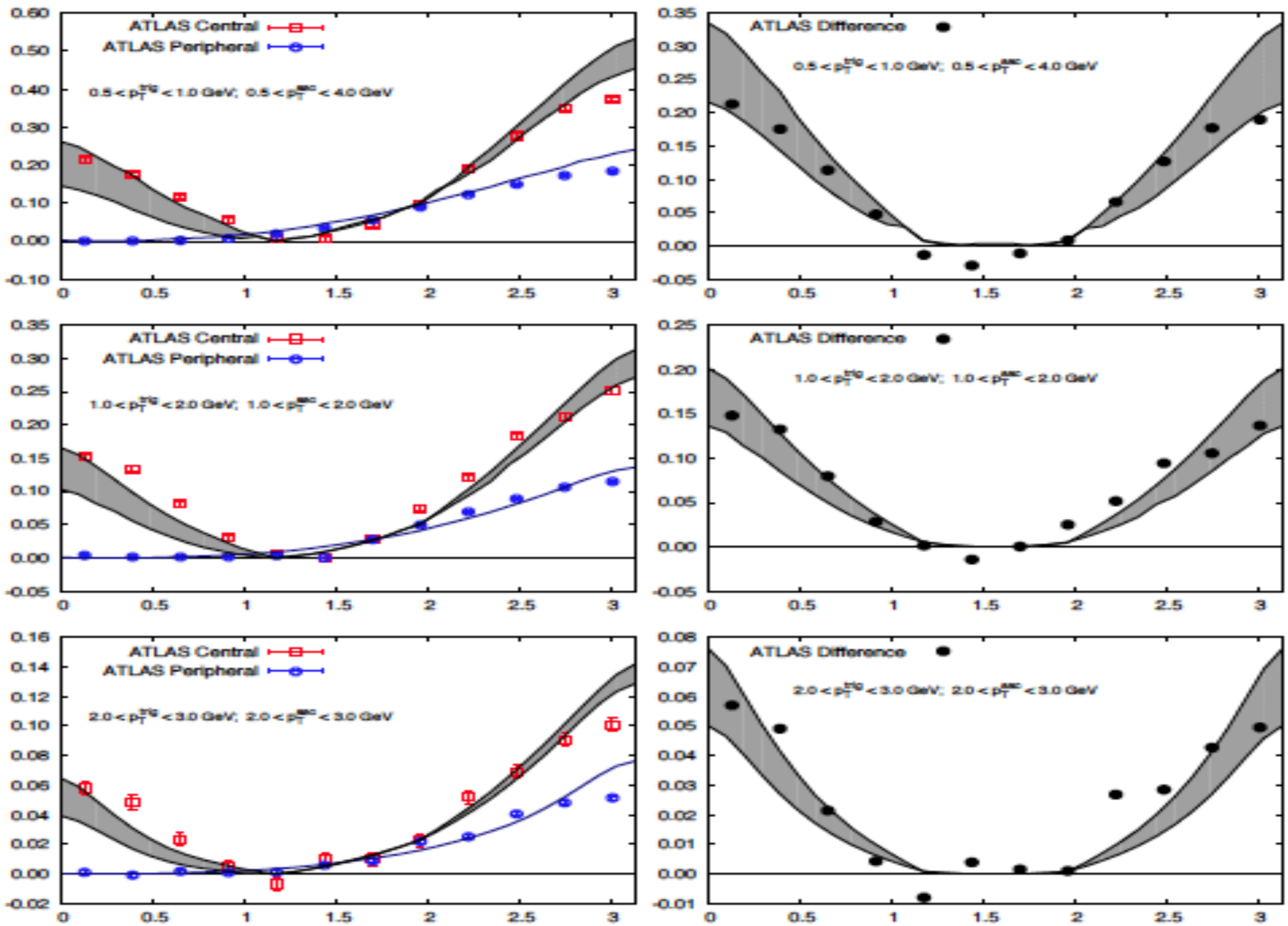
0-20% : $Q_{0,proton}^{\ 2}$ =0.336 GeV^2 & N_{part}^{Pb} = 12 – 14

20-40% : $Q_{0,proton}^{\ 2}$ =0.336 GeV^2 & N_{part}^{Pb} = 4 – 6

40-60%: $Q_{0,proton}^{\ 2}$ =0.168 GeV^2 & N_{part}^{Pb} = 3-4

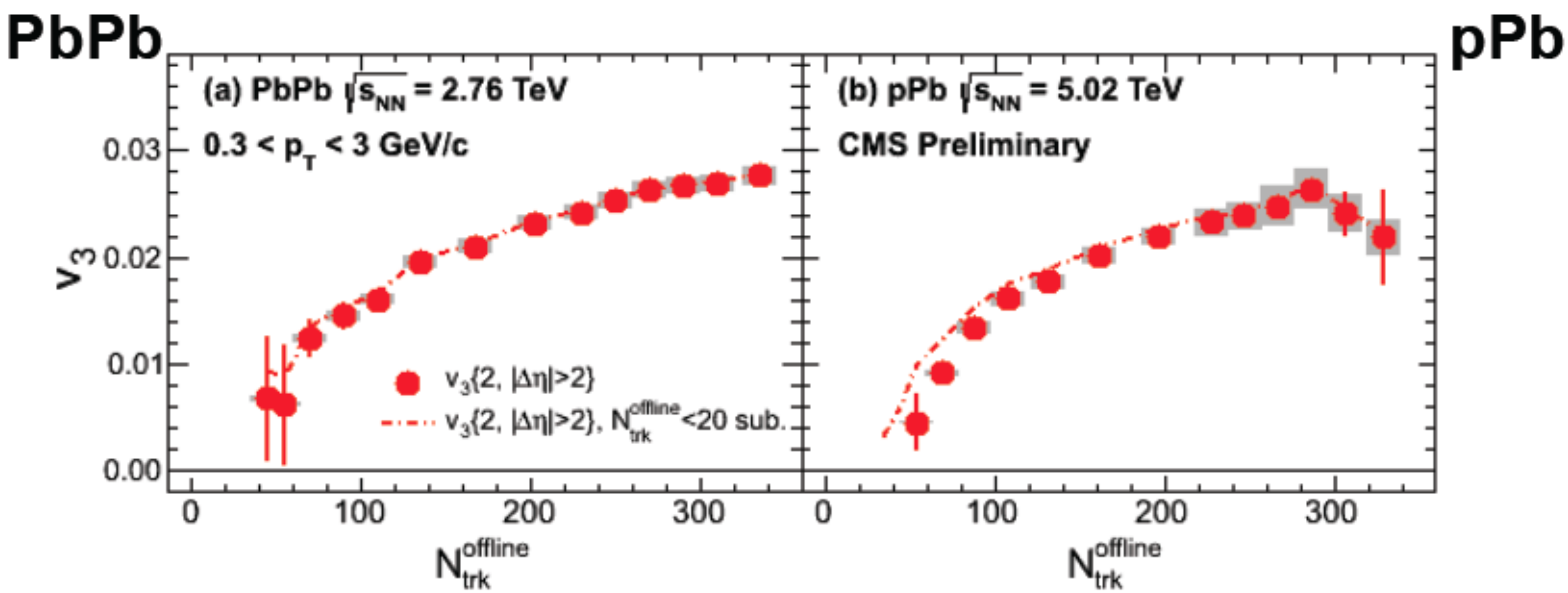
Comparison to ATLAS p+Pb ridge

ATLAS coll. arXiv: 1212.5198



Striking new data presented by CMS

G. Roland, talk at RBRC worshop, BNL, April 16, 2013
CMS 1305.0609



A non-zero v_3 is not obviously obtained from the Glasma graphs, which gives only even moments.

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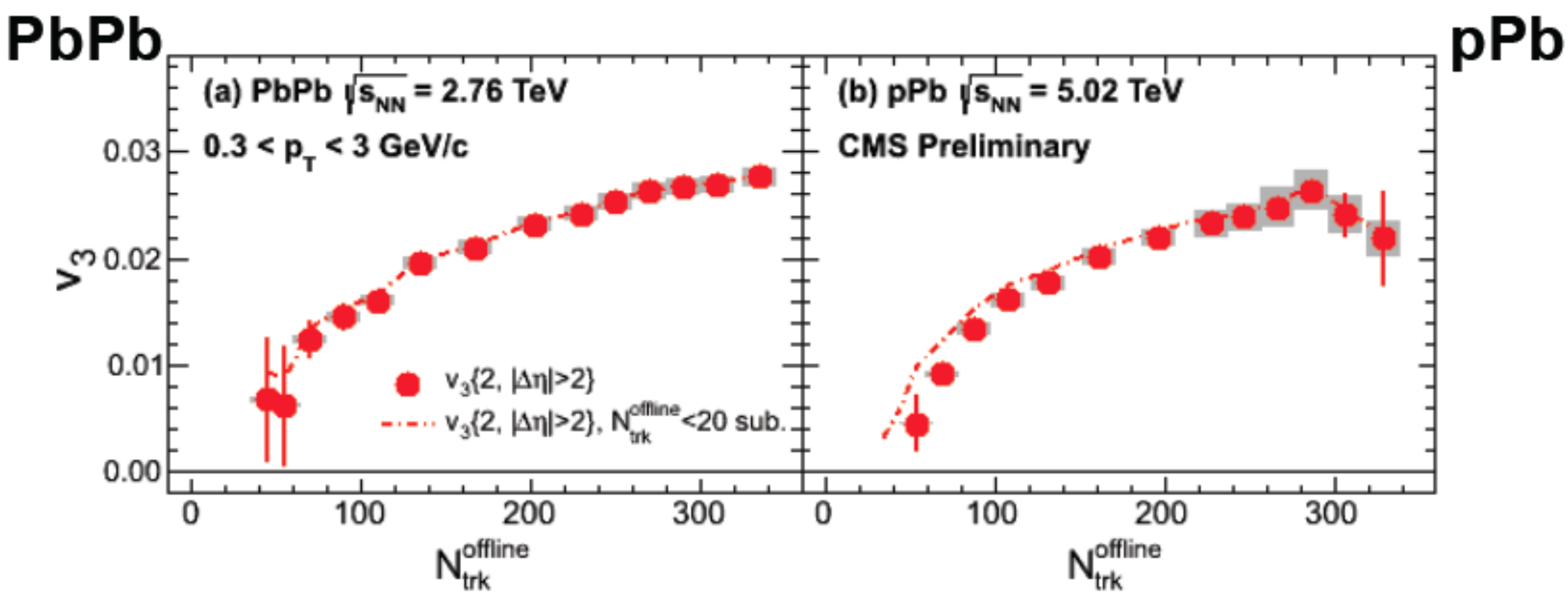
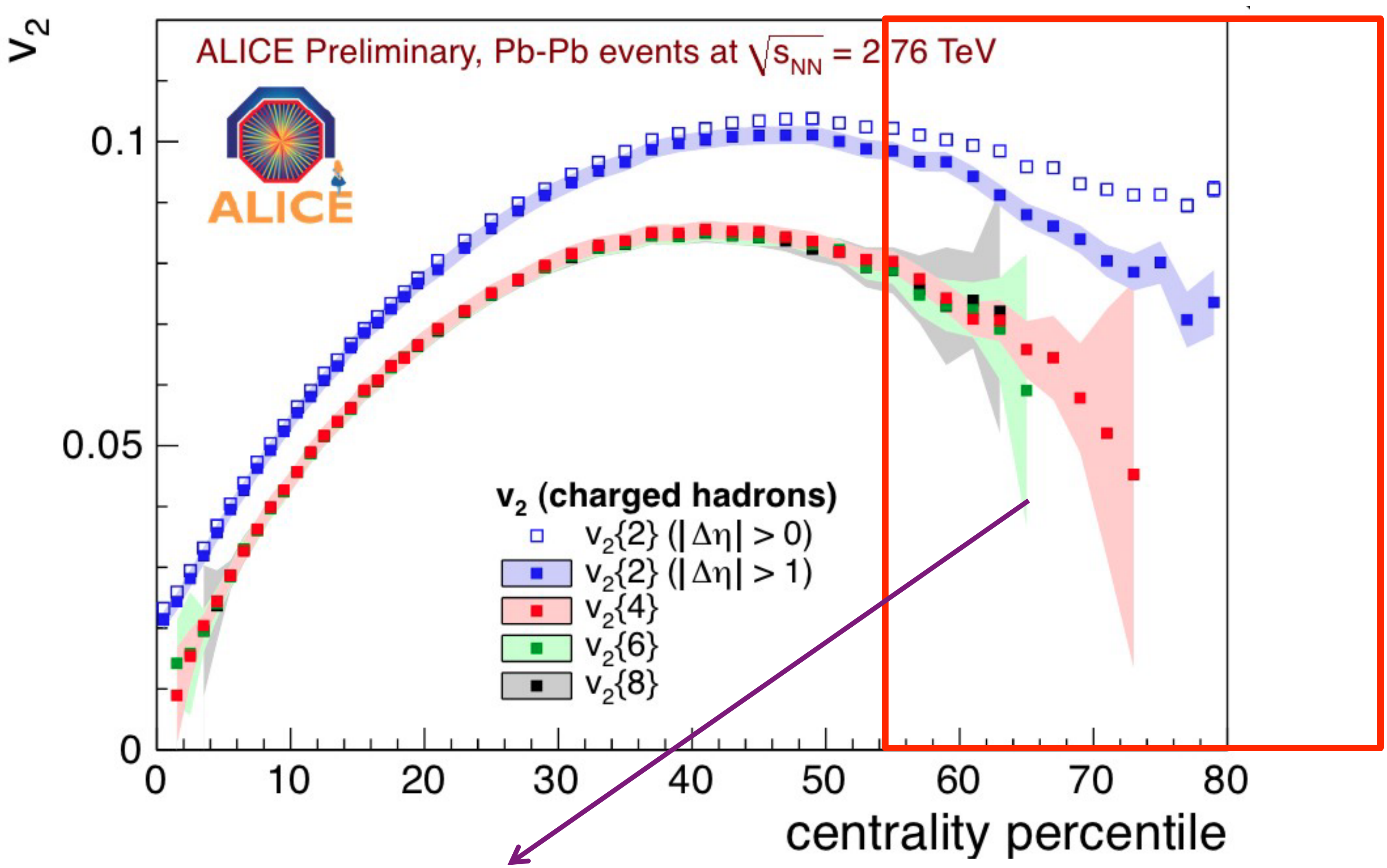


A non-zero v_3 is not obviously obtained from the Glasma graphs, which gives only even moments.

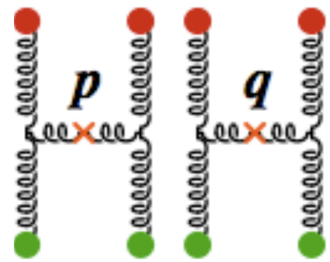
Is it an indication of flow ?

p+Pb versus Pb+Pb

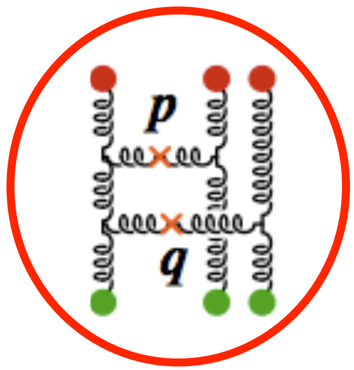


CMS Pb+Pb data comparison is
In 55%-92% centrality range

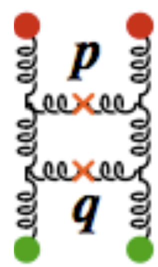
Multi-part. production: systematic power counting



CGC/Glasma yield



Jet/Glasma interference



"pQCD" jet

Maybe flow …

but jet/Glasma interference term not computed previously--assumed small. Check if one gets v_3…

IP-Glasma+MUSIC model for p+A

Bzdak,Schenke,Tribedy,RV:1304.3403

Initial conditions from IP-Glasma model

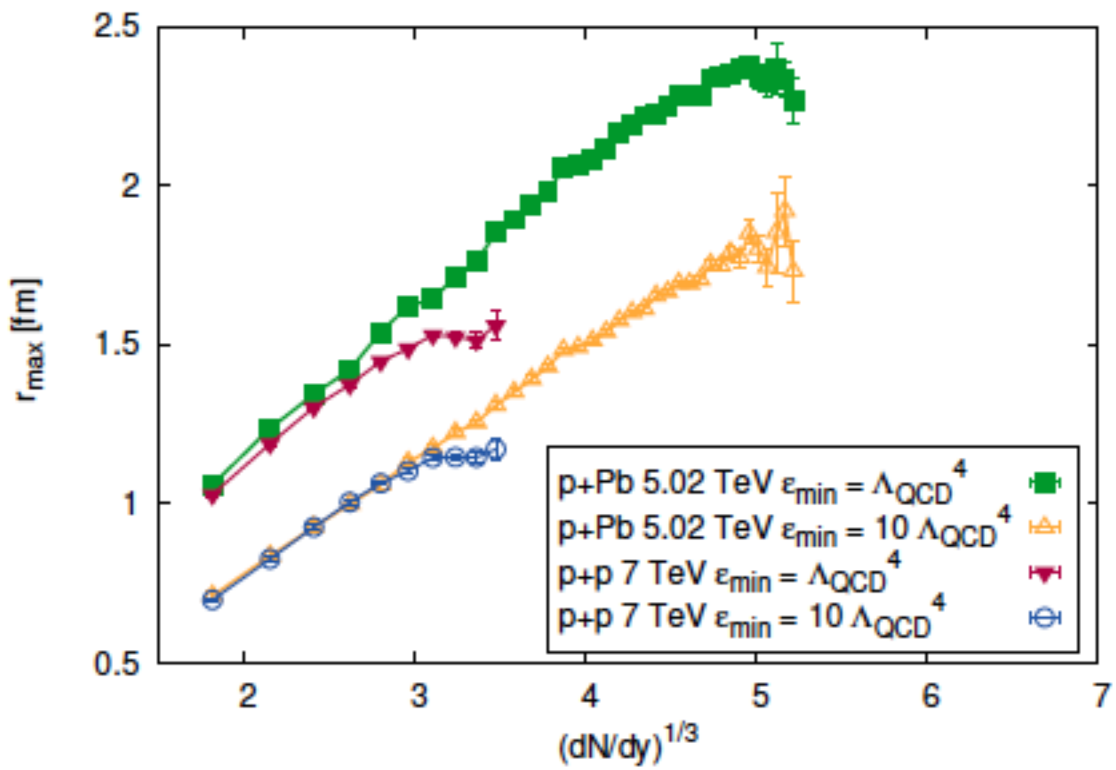
Event-by-event viscous hydro with MUSIC

Flow in p+A: IP-Glasma+MUSIC model

Bzdak,Schenke,Tribedy,RV:1304.3403

CGC initial conditions from IP-Glasma model

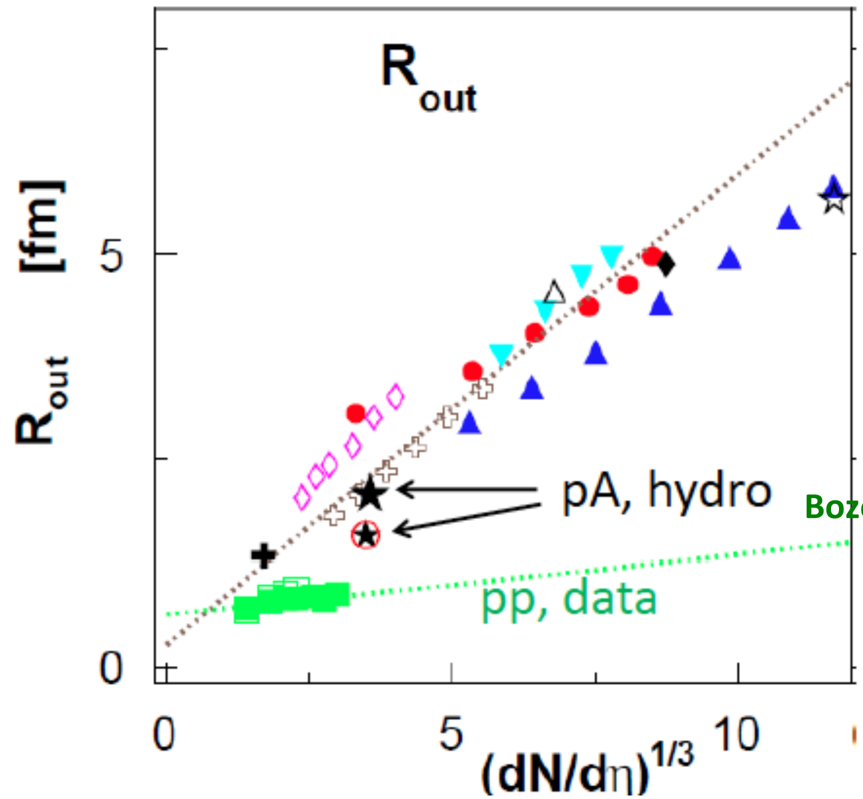
Event-by-event viscous hydro with MUSIC



Initial radii are nearly identical in p+p and p+A

IP-Glasma+MUSIC model for p+A

Bzdak,Schenke,Tribedy,RV:1304.3403

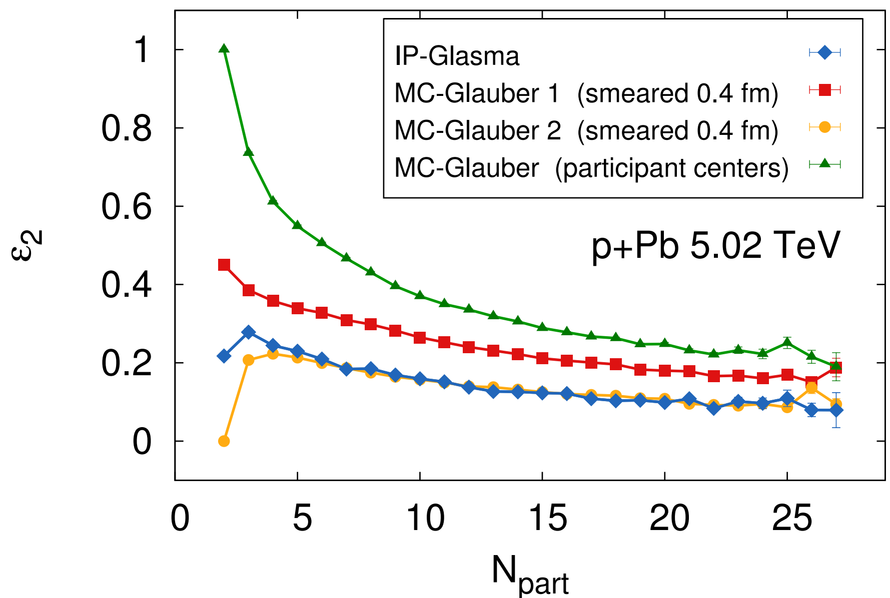


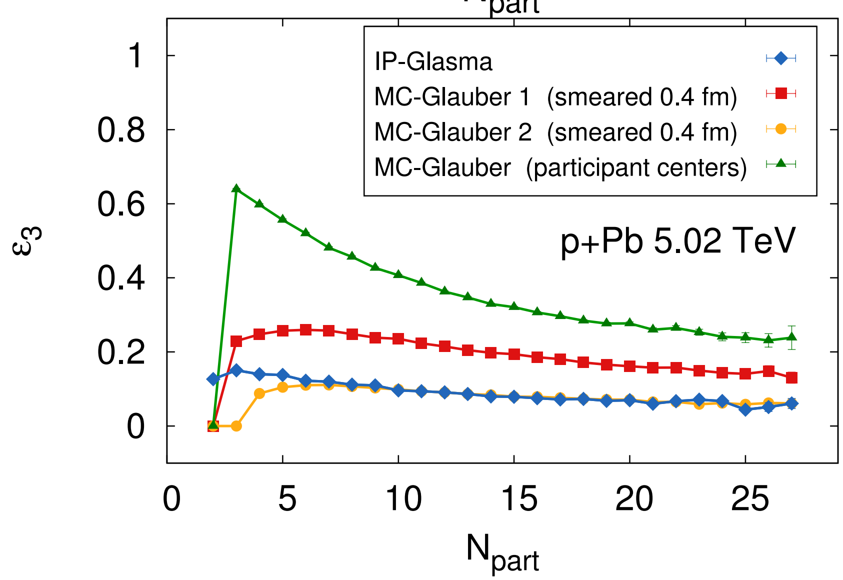
Bozek+Broniowski

Without flow, HBT radii in p+p and p+A will be similar in IP-Glasma

Initial conditions in p+A: IP-Glasma vs “Glauber”

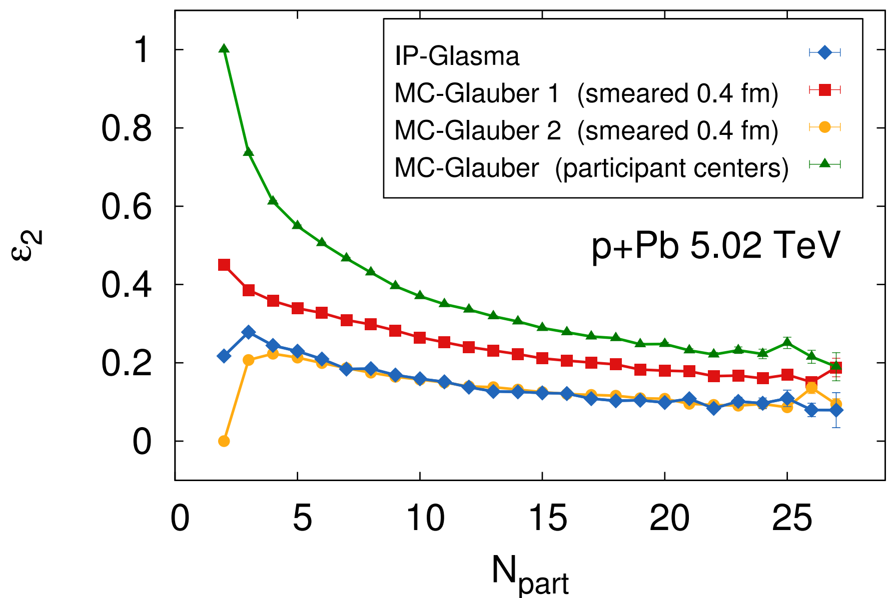
Bzdak,Schenke,Tribedy,RV:1304.3403

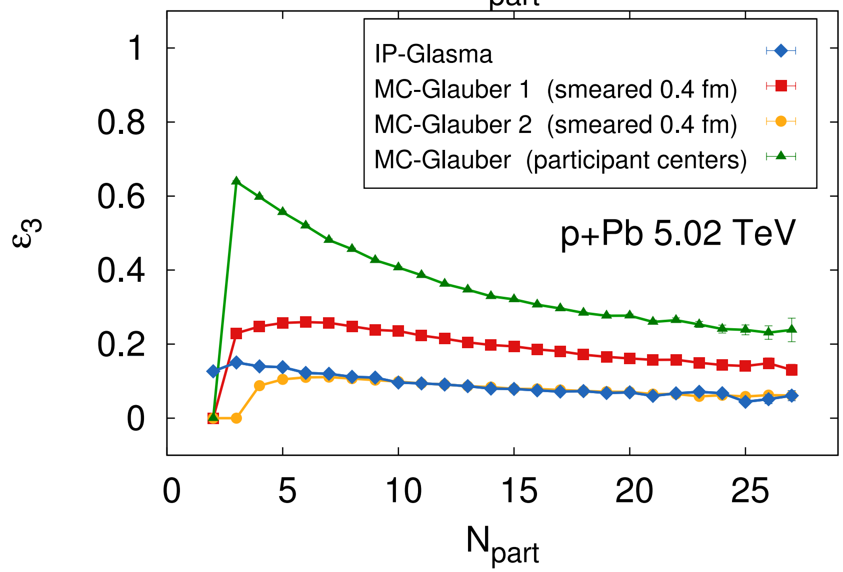


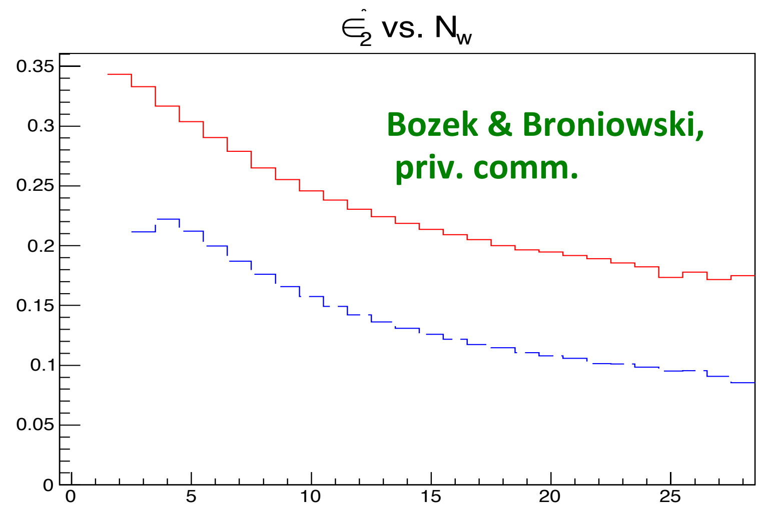


Initial conditions in p+A: IP-Glasma vs "Glauber"

Bzdak,Schenke,Tribedy,RV:1304.3403



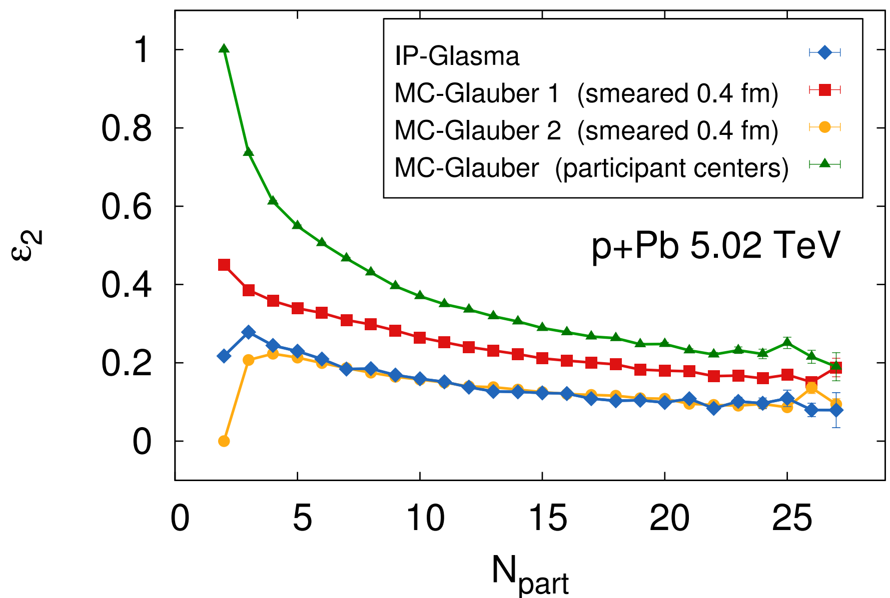


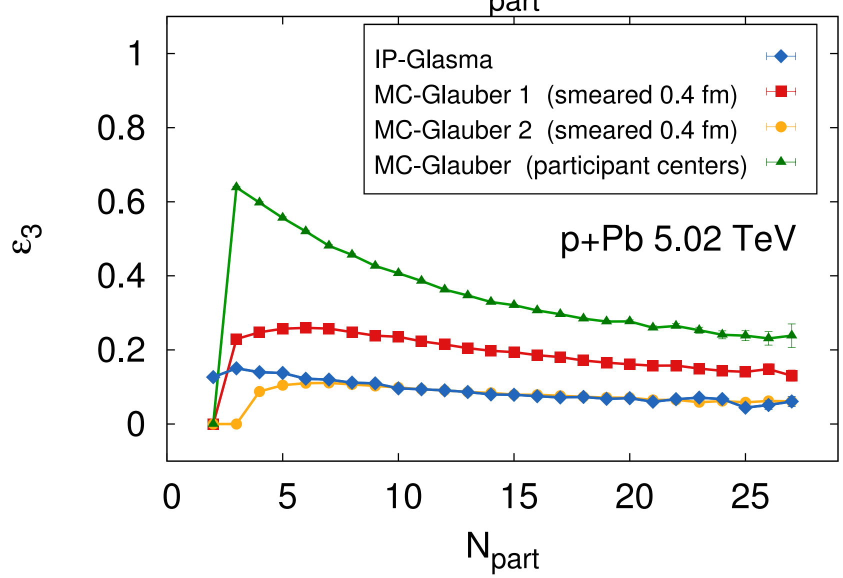


In MC Glauber 1, big differences in hard sphere & Gaussian smearing

Initial conditions in p+A: IP-Glasma vs “Glauber”

Bzdak,Schenke,Tribedy,RV:1304.3403



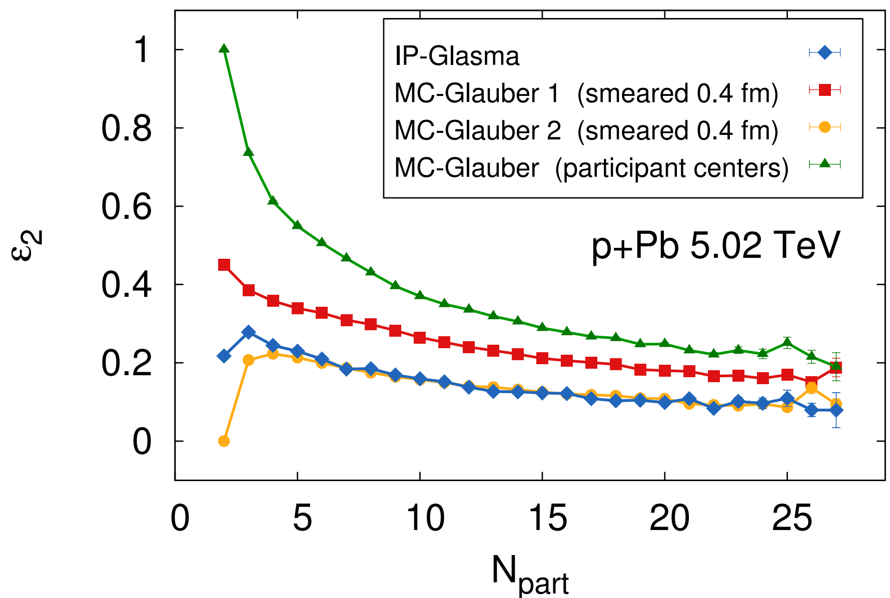


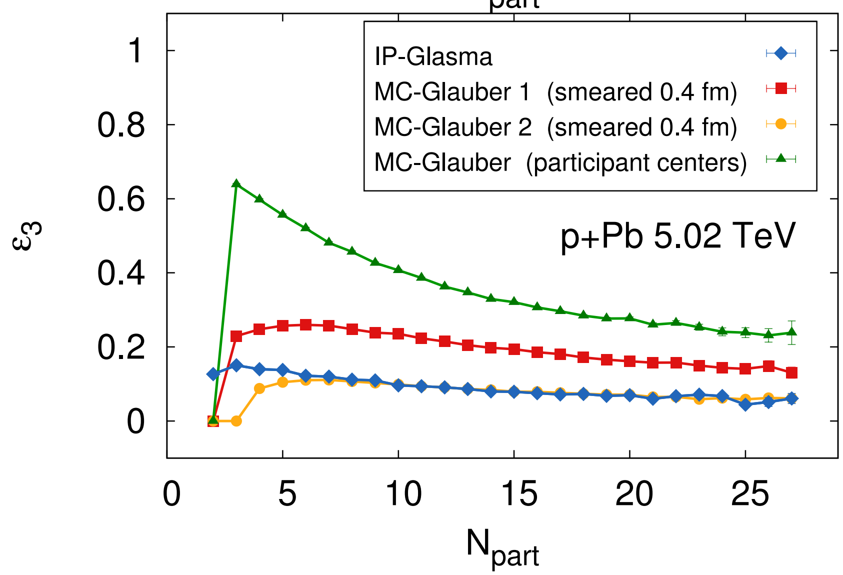
Lesson: dividing v_2 by ε_2 is perilous for small size systems

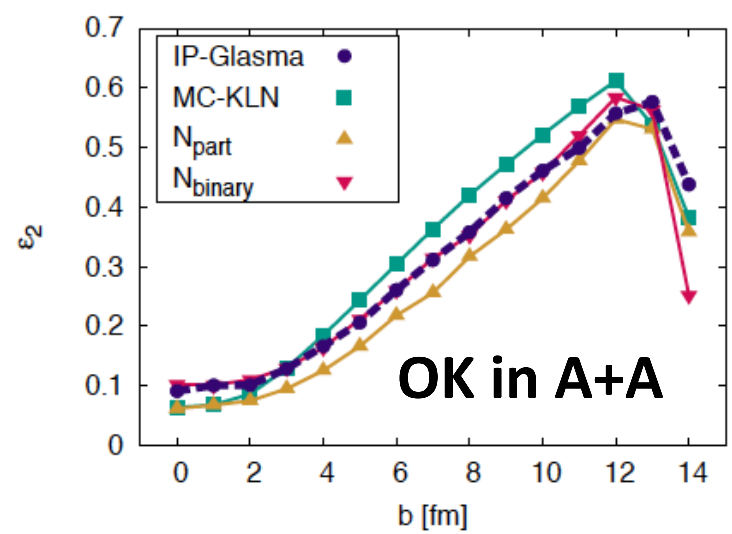
Initial state dynamics matters!

Initial conditions in p+A: IP-Glasma vs "Glauber"

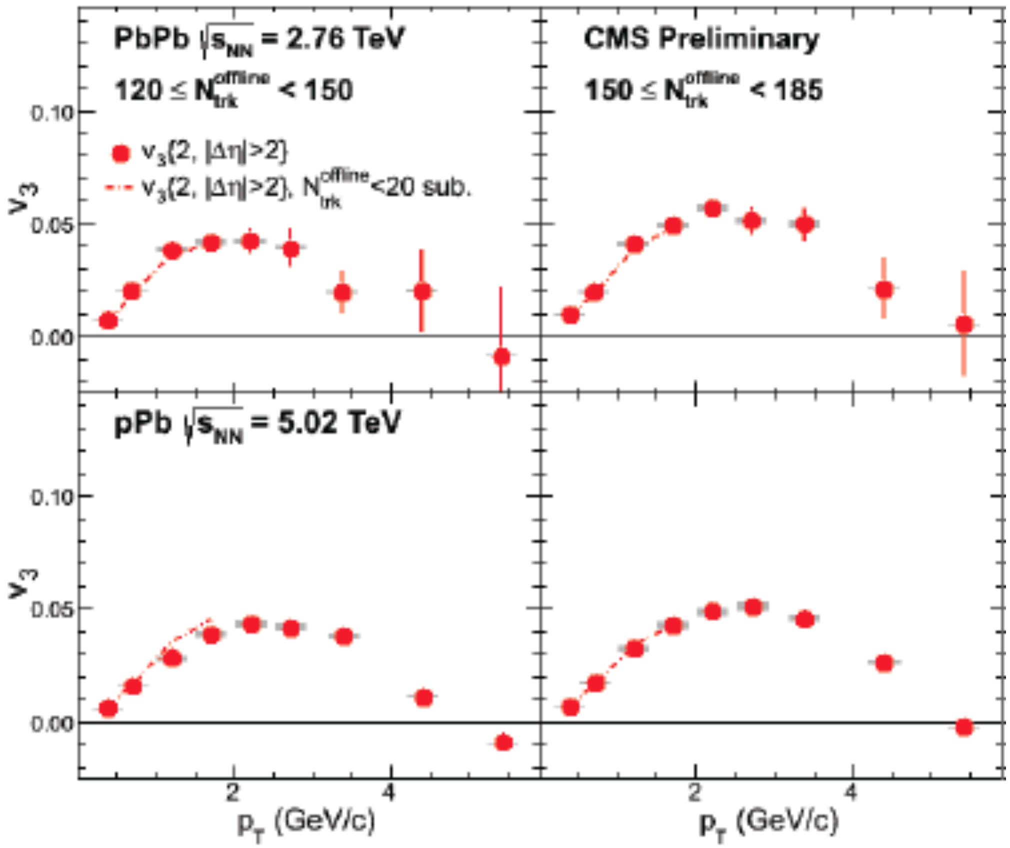
Bzdak,Schenke,Tribedy,RV:1304.3403

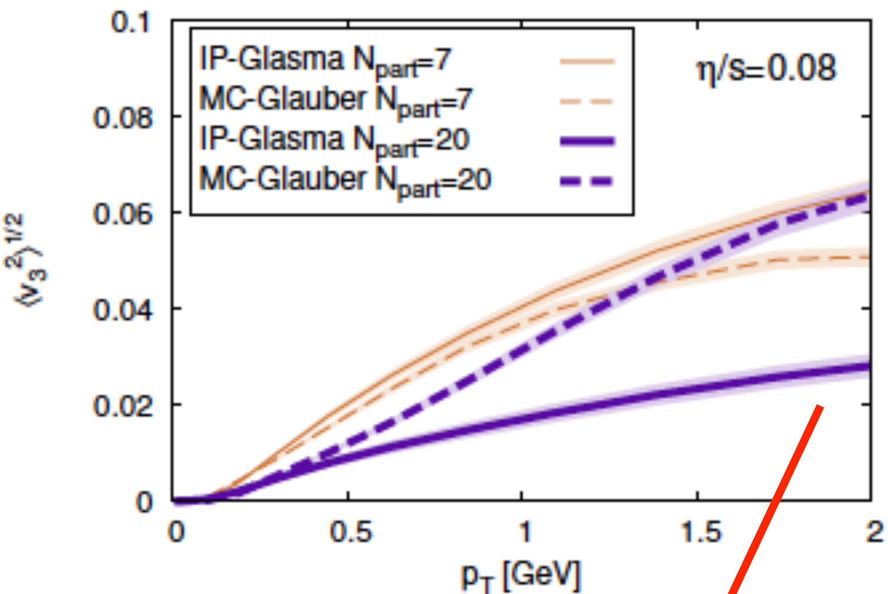






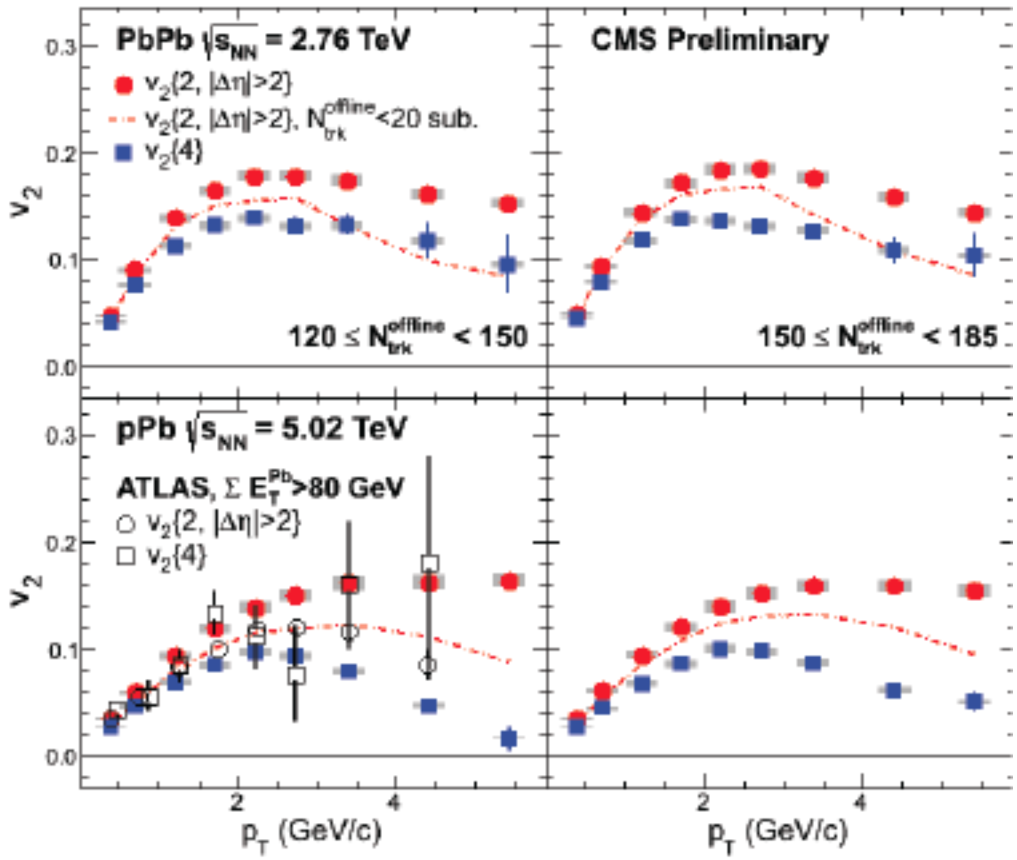
Flow in p+A

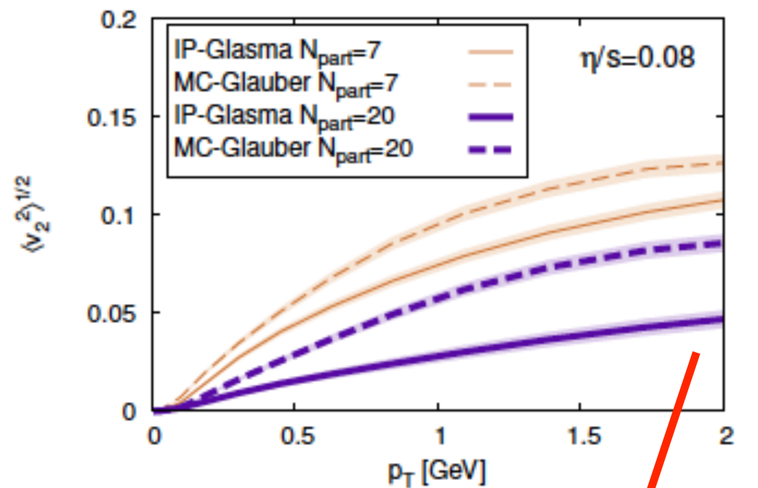




IP-Glasma result
2 times smaller than
data for η/s=0.08

Flow in p+A





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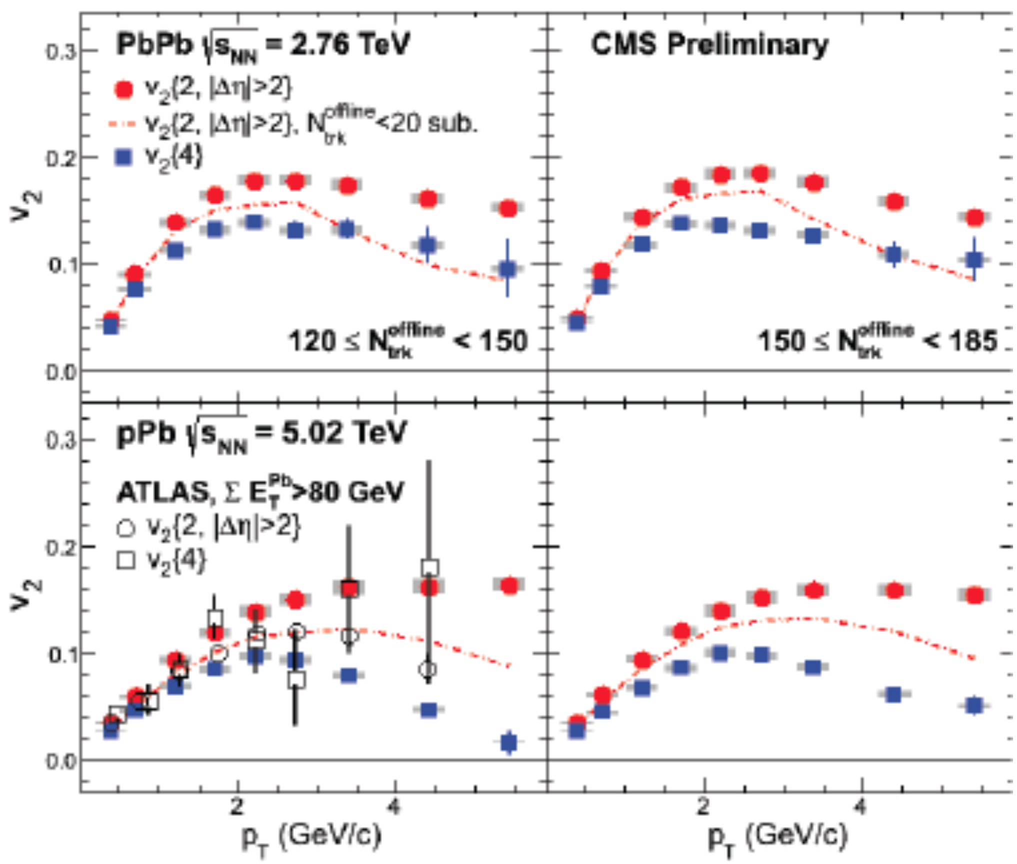
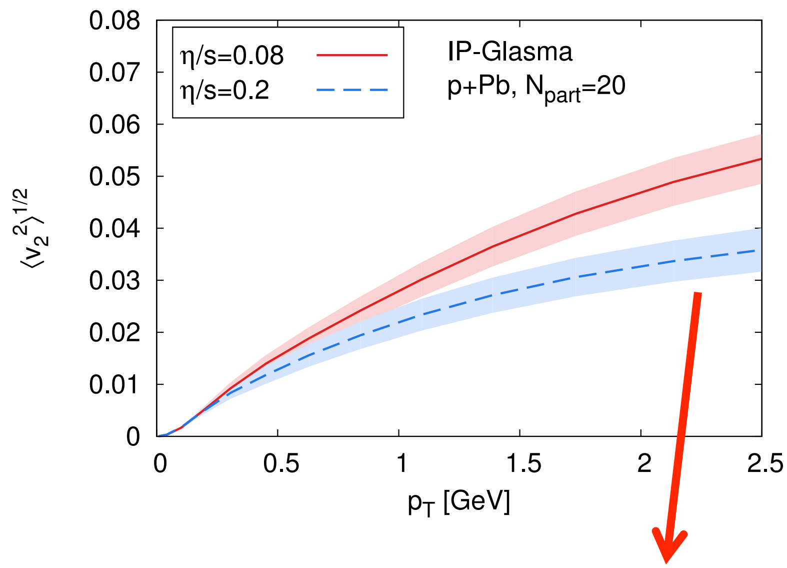
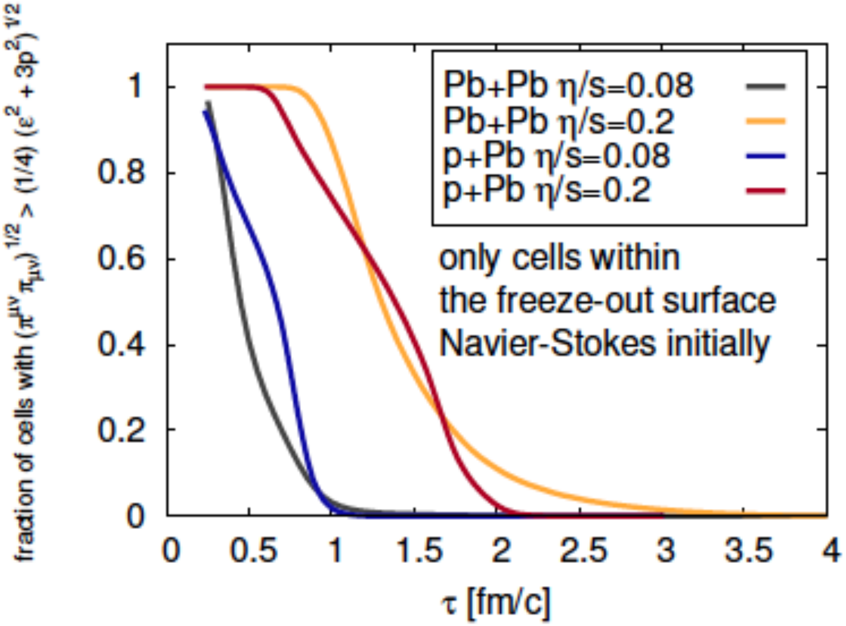
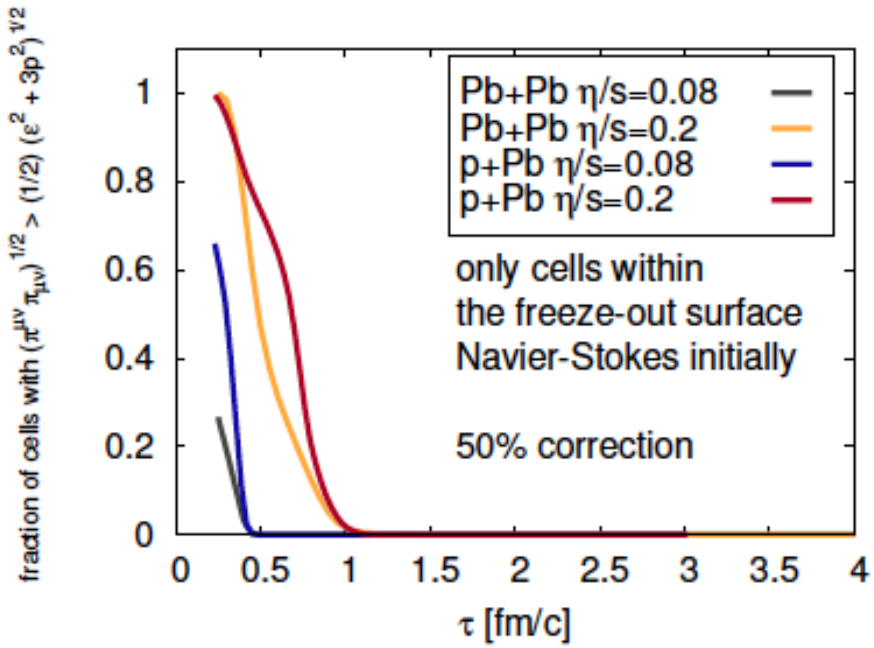




IP-Glasma result nearly 3 times smaller than data for η/s=0.2

Validity of hydrodynamics for small size systems

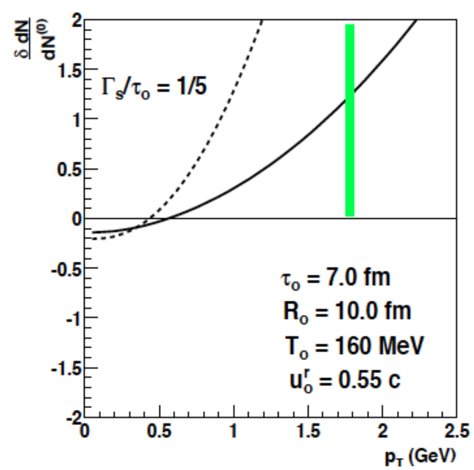




◆ **Significant viscous corrections at early times for both p+Pb and Pb+Pb but lifetime of Pb+Pb is 5-6 times longer**

◆ **δf viscous corrections are large in small size systems**

$$\frac{\delta N}{N} \propto \frac{\eta}{s}\frac{1}{T\tau_0}\left(\frac{p_T}{T}\right)^2$$



Teaney, nucl-th/0310099

Conclusions

- The Glasma framework allows for systematic study of multi-particle production in p+p, p+A and A+A collisions

- The p+p ridge can be quantitatively understood from gluon saturation enhanced quantum interference

  Glasma graphs + BFKL graphs

- The A+A ridge and v_n moments are quantitatively described in the same framework by

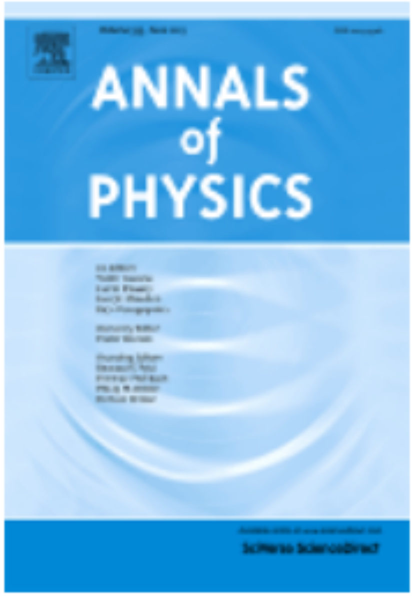
  IP-Glasma initial conditions + flow

Conclusions

- The p/d+A ridge situation is not completely clear yet
  - but will be clarified soon

- 2-part corr. data presented thus far
  are described by Glasma+BFKL dynamics within
  large systematic uncertainties.
  Whether v_3 and $v_2\{4\}$ can be generated is under investigation

- Flow in p+A is very sensitive to initial conditions.
  In the IP-Glasma framework, v_2 and v_3 are 2-3 times
  smaller than data.
  A consistent combination of initial and final state dynamics
  may be necessary



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View full aims and scope

Editors: V. Gurarie, J. Khoury, J.A. Minahan, R. Venugopalan

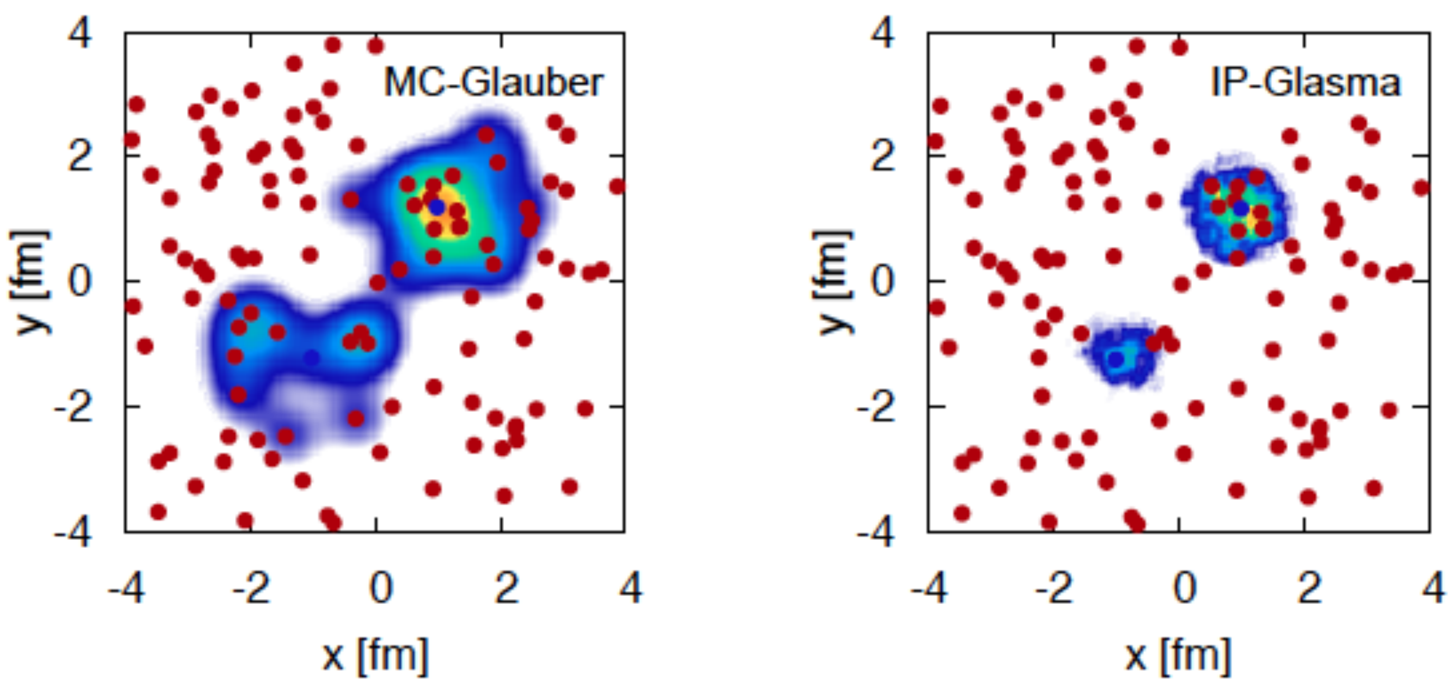
Workshop proceedings will be published as a

Special Issue of Annals of Physics

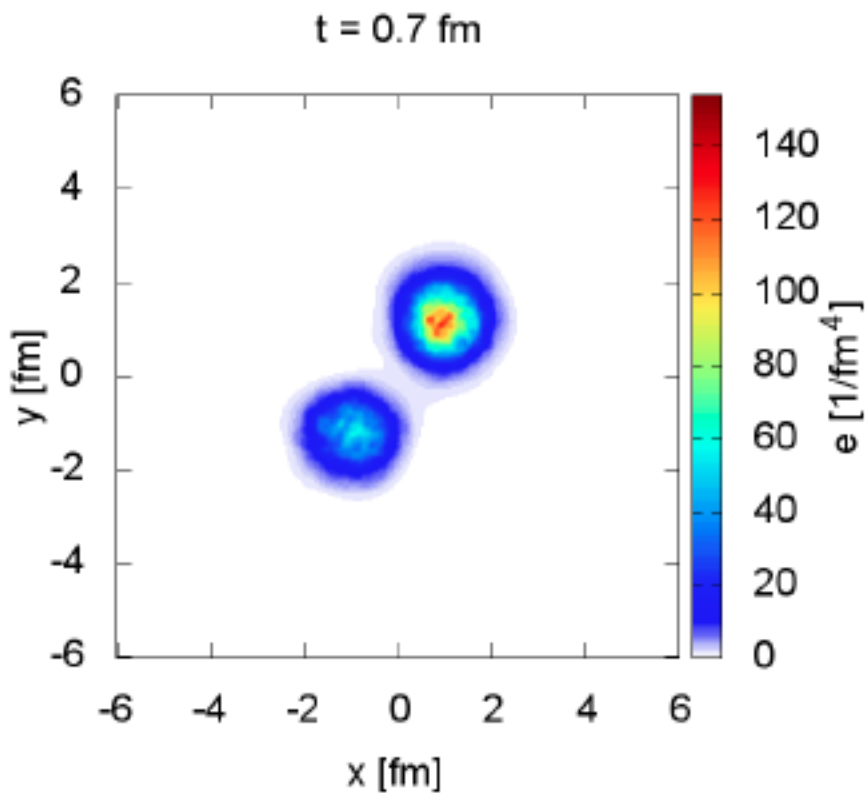
In honor of Prof. Wit Busza's contributions to QCD studies

Guest Editors: the organizers

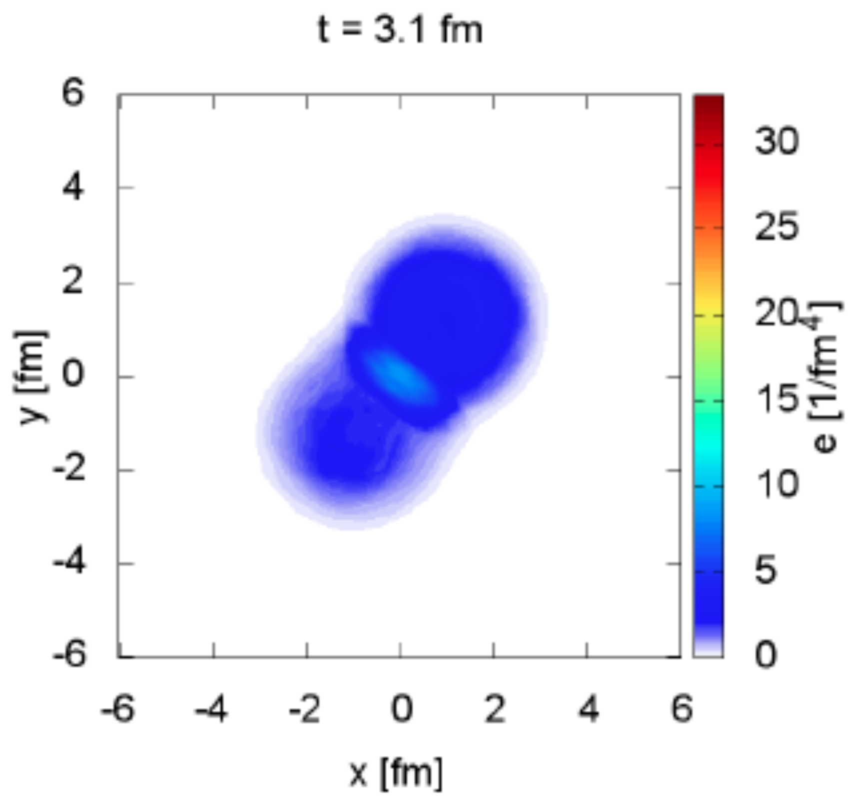
d+Au ridge at RHIC



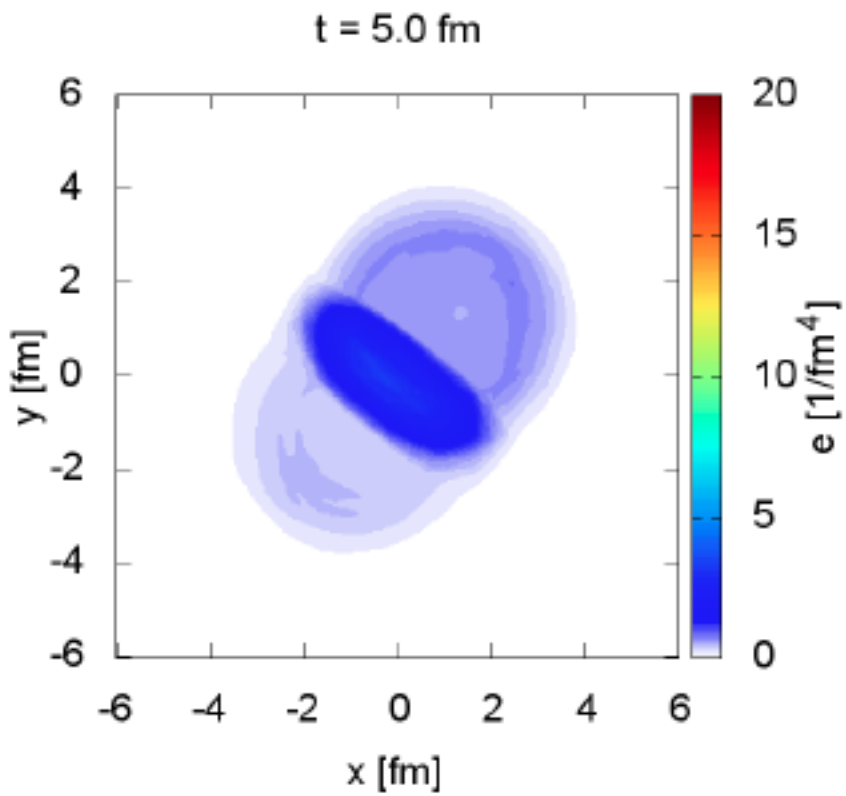
d+Au ridge at RHIC



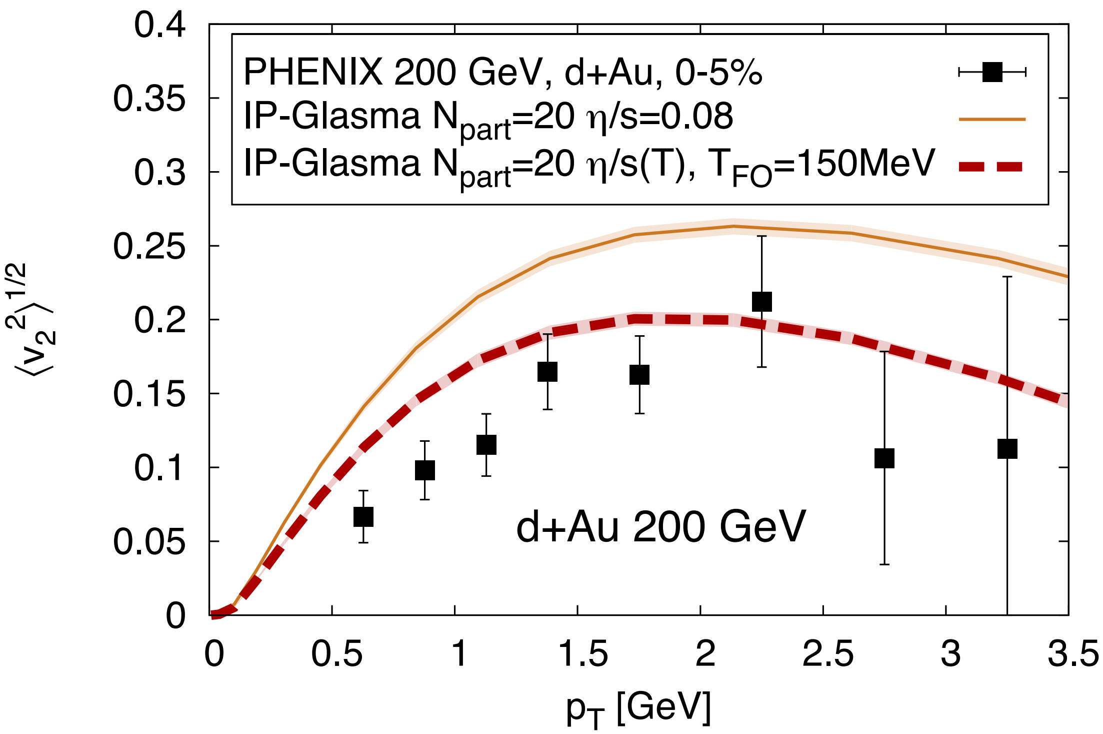
d+Au ridge at RHIC



d+Au ridge at RHIC



d+Au ridge at RHIC

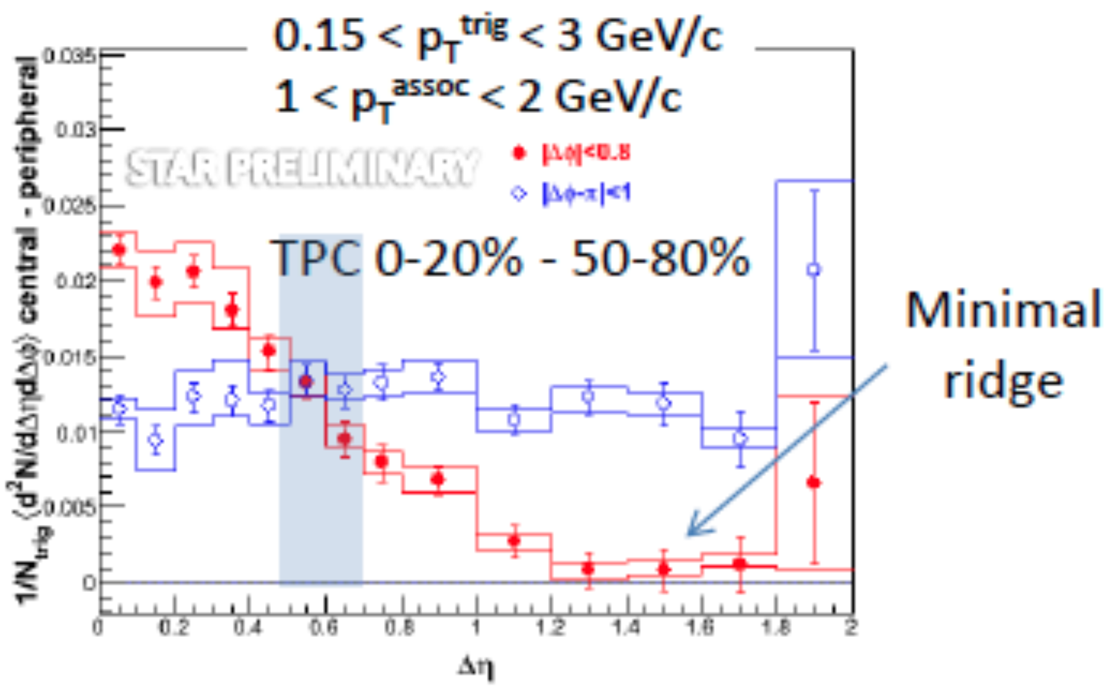


PHENIX, 1303.1794

d+Au ridge at RHIC

But: does a d+Au ridge exist at RHIC ?

Talk by Fuqiang Wang, RBRC workshop, April 15, 2013

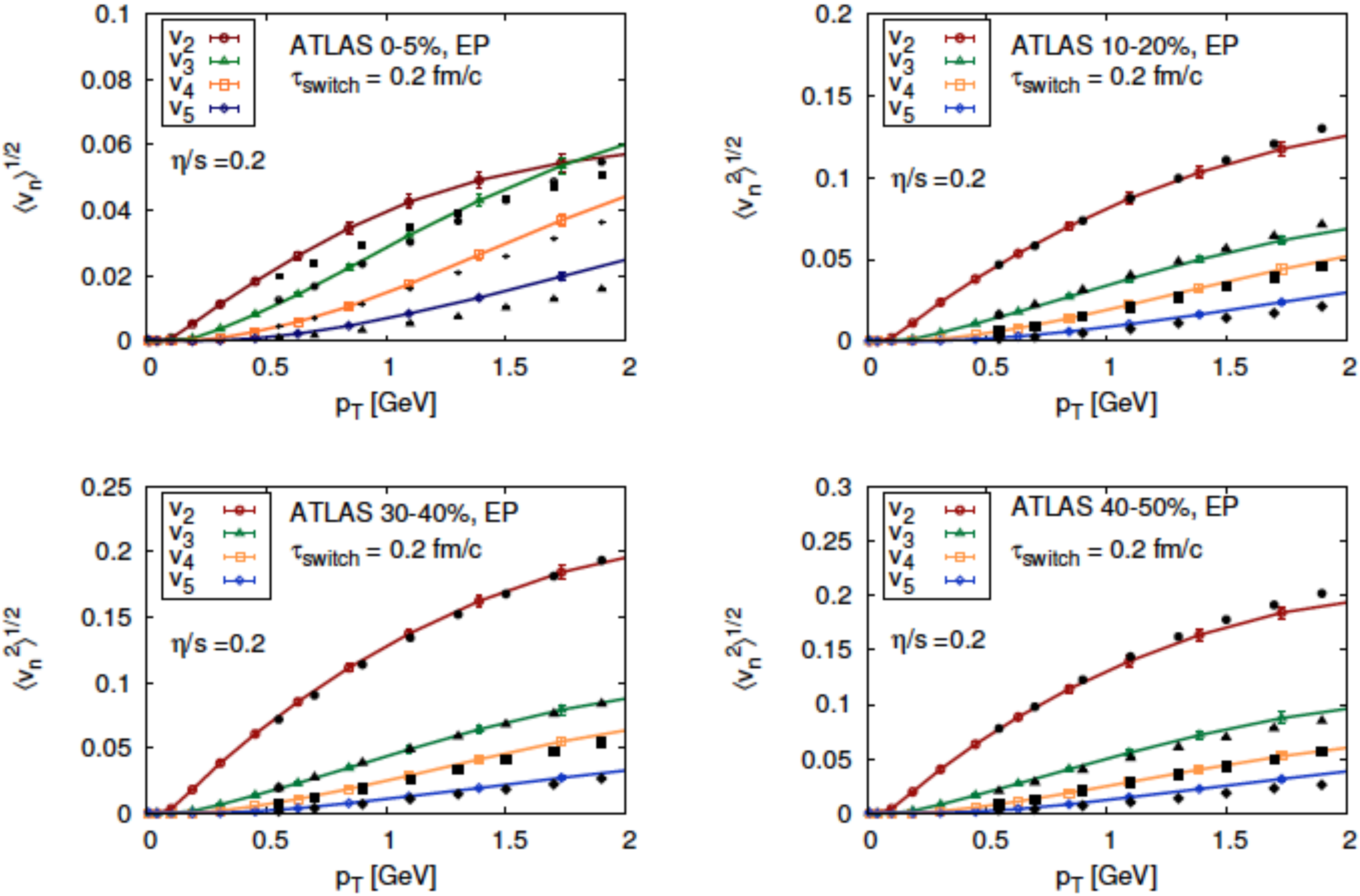


STAR argues nearside ridge goes away with increasing Δη …

Where does this leave the hydro explanation ?

Centrality dependence will be important…

More centrality classes: IP-Glasma + MUSIC



Physics underlying systematics of the ridge

For Glasma graphs

$$d^2N \propto \int d^2k_T \; \Phi_A^2(k_T) \; \Phi_B(|p_T - k_T|) \; \Phi_B(|q_T - k_T|)$$

For $|p_T| = |q_T|$, from the Cauchy-Schwarz inequality:

$$\int d^2k_T \; \Phi_A^2(k_T) \; \Phi_B(|p_T - k_T|) \; \Phi_B(|q_T - k_T|) \leq \int d^2k_T \; \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|)$$

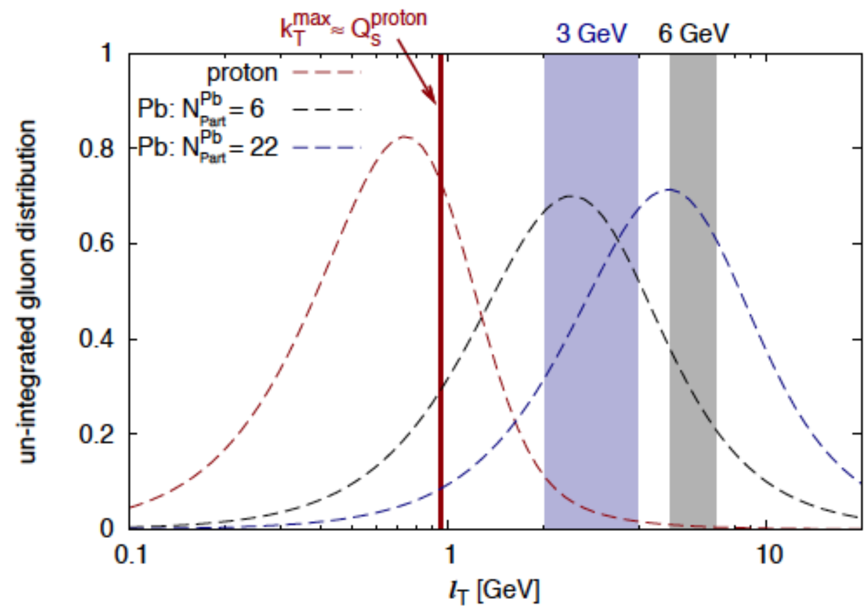
Equality implies no collimation; satisfied only iff $\Phi_B(|p_T - k_T|) \propto \Phi_B(|q_T - k_T|)$

True only if Φ is flat in k_T - for above fns. Else, there must be a collimation

Physics underlying the ridge

Look at ratio of yield at $\Delta\phi_{pq} = 0$ to $\Delta\phi_{pq}=\pi$ for $|p_T|=|q_T|$

$$\mathrm{CY} \propto \frac{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B^2(|p_T - k_T)}{\int d^2k_T\ \Phi_A^2(k_T)\ \Phi_B(|p_T - k_T|)\Phi_B(|p_T + k_T|)}$$

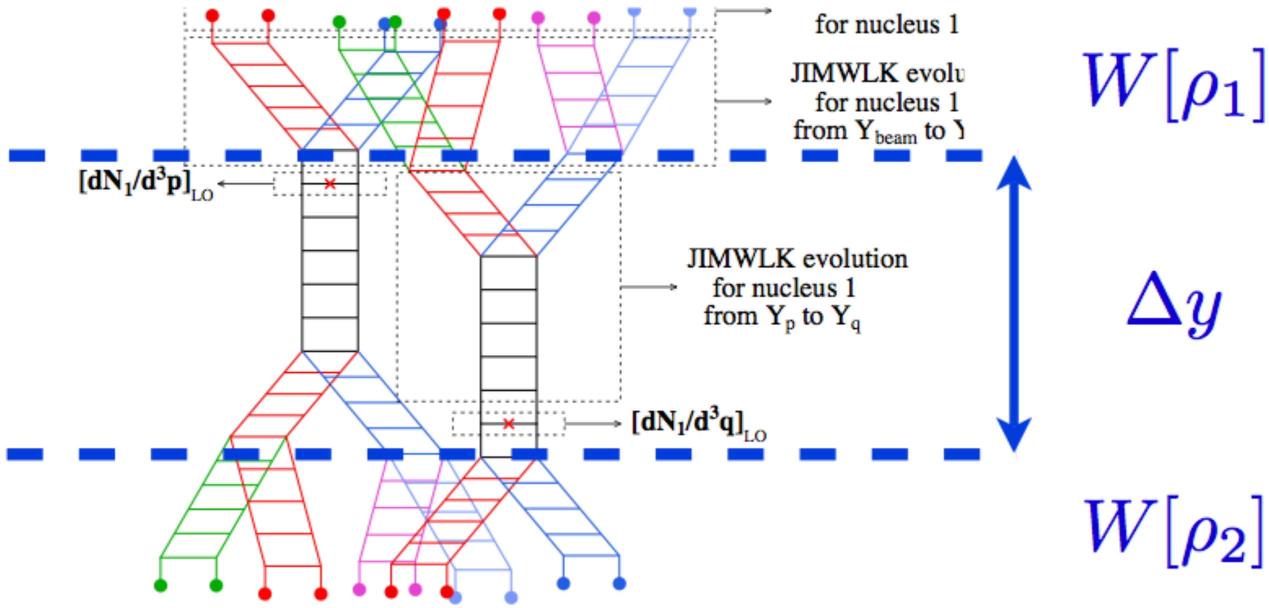


$$\mathrm{CY} \propto \frac{\Phi_B(Q_B)}{\Phi_B(\sqrt{2p_T^2 + 2Q_A^2 - Q_B^2})} \propto 1 + \frac{(Q_B - Q_A)^2}{Q_A^2} \sim N_{\mathrm{part}}$$

As seen in the LHC p+Pb data…

Long range di-hadron correlations

Gelis,Lappi,RV (2009)

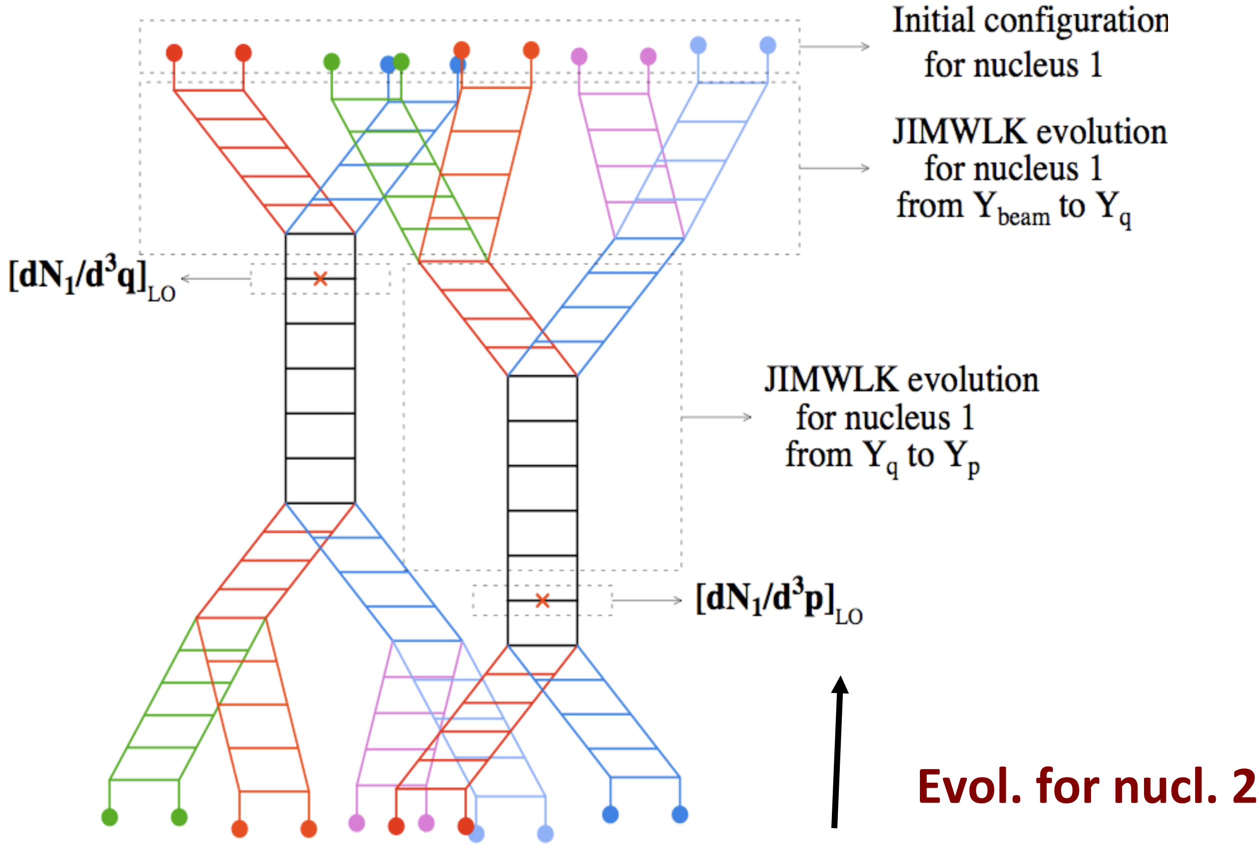


$$\left\langle \frac{dN_2}{d^2\mathbf{p}_\perp dy_p d^2\mathbf{q}_\perp dy_q} \right\rangle_{\text{LLog}} = \int [D\rho_1^p(\mathbf{x}_\perp) D\rho_2^p(\mathbf{x}_\perp) D\rho_1^q(\mathbf{x}_\perp) D\rho_2^q(\mathbf{x}_\perp)]$$
$$\times Z_{y_p}[\rho_1^p]\, G_{y_p,y_q}[\rho_1^p,\rho_1^q]\, Z_{y_q}[\rho_2^q]\, G_{y_q,y_p}[\rho_2^q,\rho_2^p]$$
$$\times \left.\frac{dN_1\,[\rho_1^p,\rho_2^p]}{d^2\mathbf{p}_\perp dy_p}\right|_{\text{LO}} \left.\frac{dN_1\,[\rho_1^q,\rho_2^q]}{d^2\mathbf{q}_\perp dy_q}\right|_{\text{LO}} .$$

Simplify using "Gaussian truncation" approximation to JIMWLK

Dusling,Gelis,Lappi,RV:0911.2720

High multiplicity events: two particle correlations

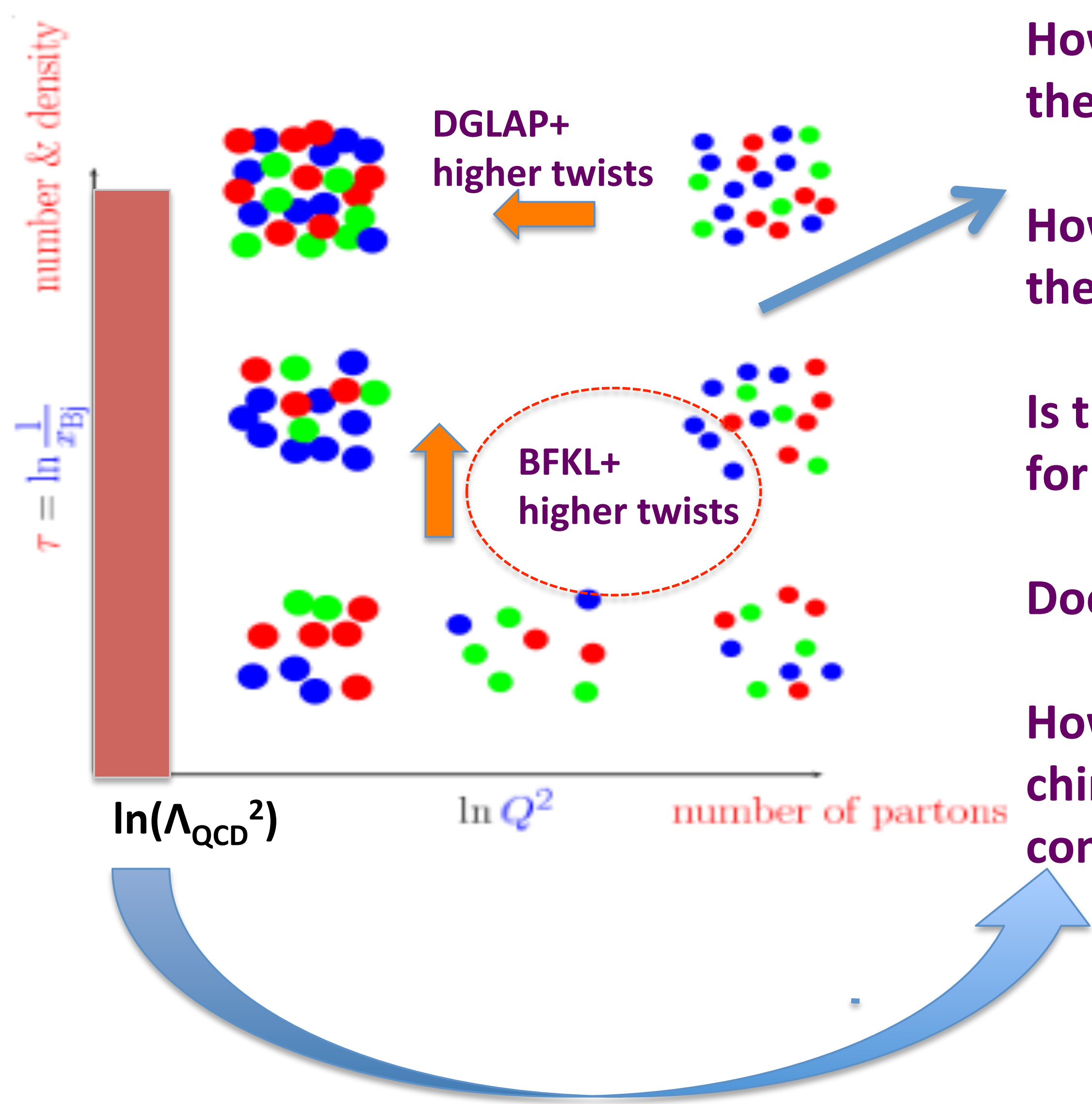


Gelis,Lappi,RV
arXiv:0804.2630 [hep-ph];
arXiv:0807.1306 [hep-ph]
arXiv:0810.4829 [hep-ph]

- Full YM+JIMWLK evolution – not available yet   Lappi,Schenke,RV in progress
- Approximations: BK Gaussian truncation approximation for $k_T \geq Q_S$; YM results for MV model available for all k_T

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

Many-body dynamics of universal gluonic matter



How does this happen ? What are the right degrees of freedom ?

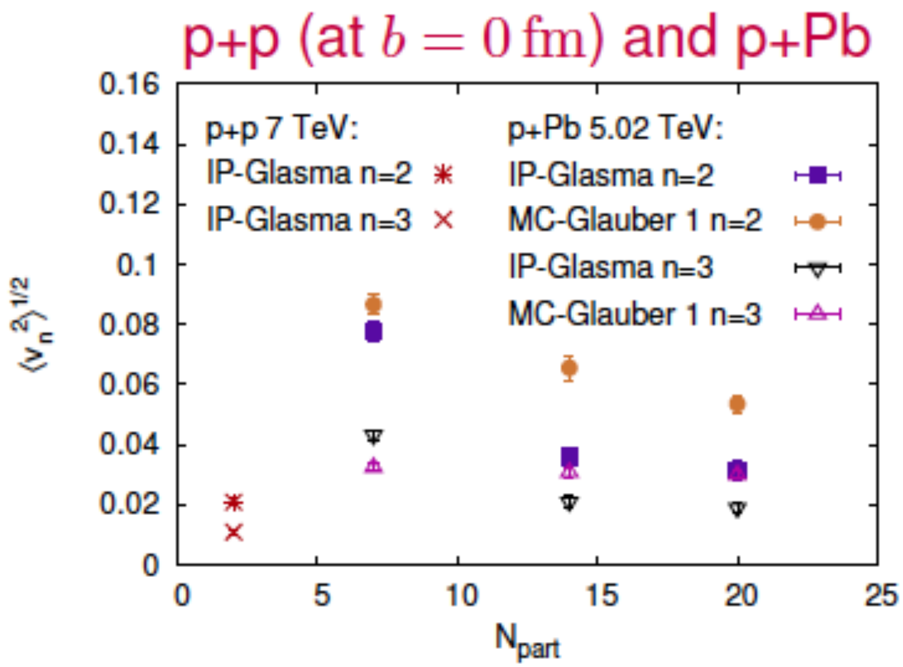
How do correlation functions of these evolve ?

Is there a universal fixed point for the RG evolution of d.o.f

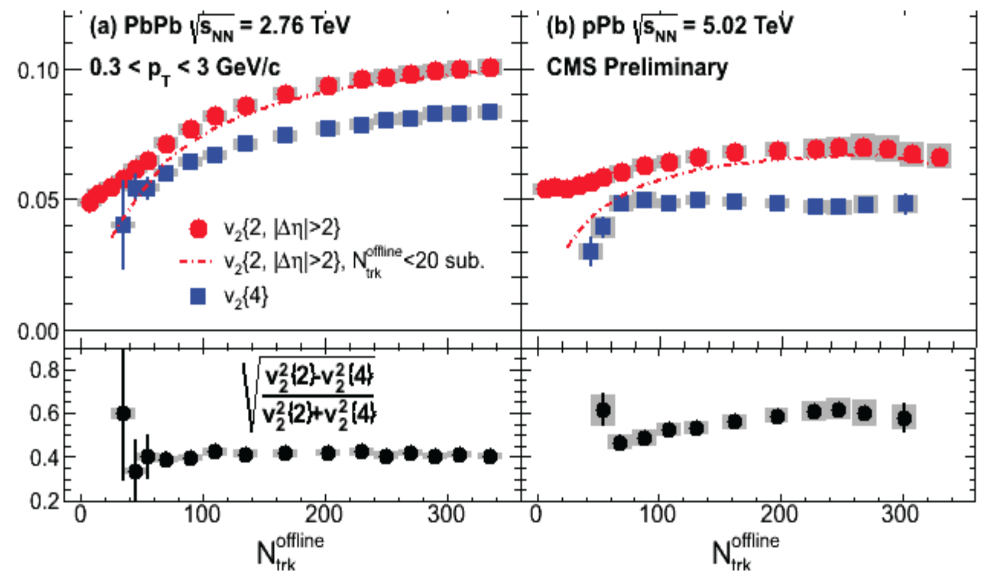
Does the coupling run with Q_s^2 ?

How does saturation transition to chiral symmetry breaking and confinement

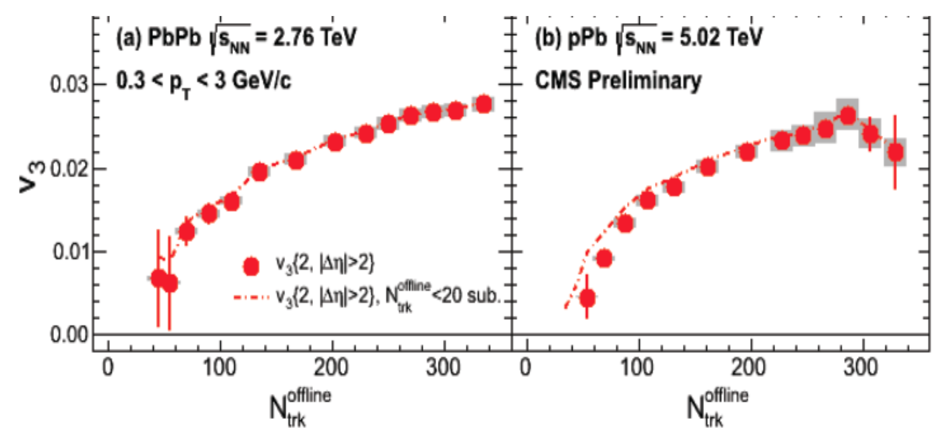
Flow in p+A



p+p (at b = 0 fm) and p+Pb
p+p 7 TeV:
IP-Glasma n=2
IP-Glasma n=3
p+Pb 5.02 TeV:
IP-Glasma n=2
MC-Glauber 1 n=2
IP-Glasma n=3
MC-Glauber 1 n=3
⟨v_n^2⟩^1/2
N_part

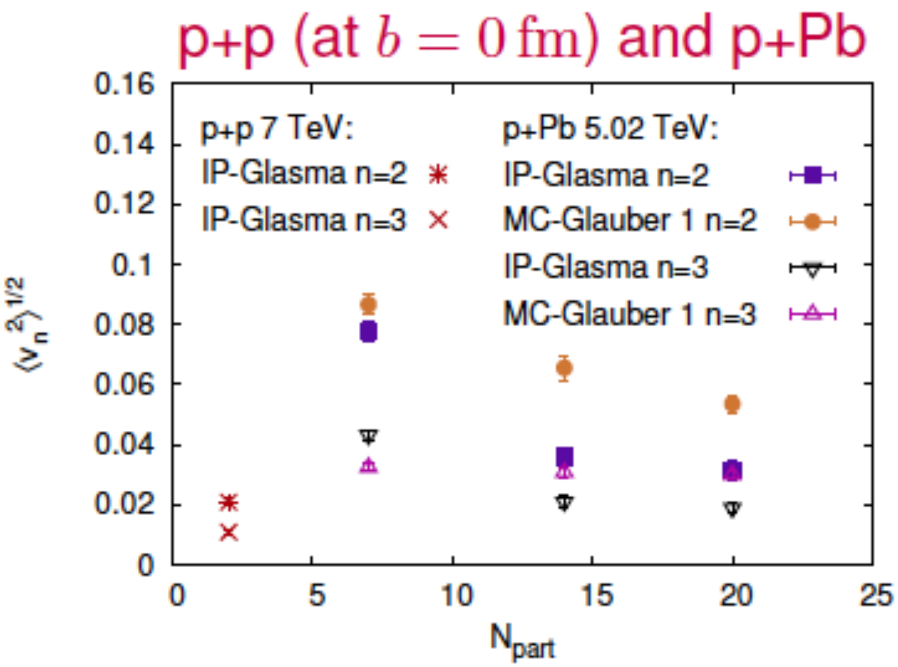


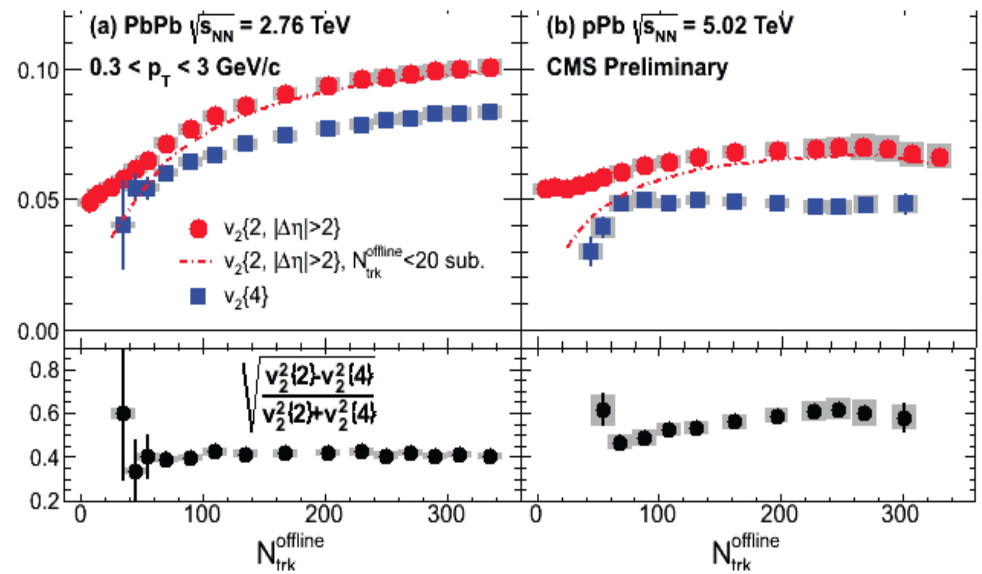
(a) PbPb √s_NN = 2.76 TeV
0.3 < p_T < 3 GeV/c
(b) pPb √s_NN = 5.02 TeV
CMS Preliminary
v2{2, |Δη|>2}
v2{2, |Δη|>2}, N_trk^offline<20 sub.
v2{4}
N_trk^offline



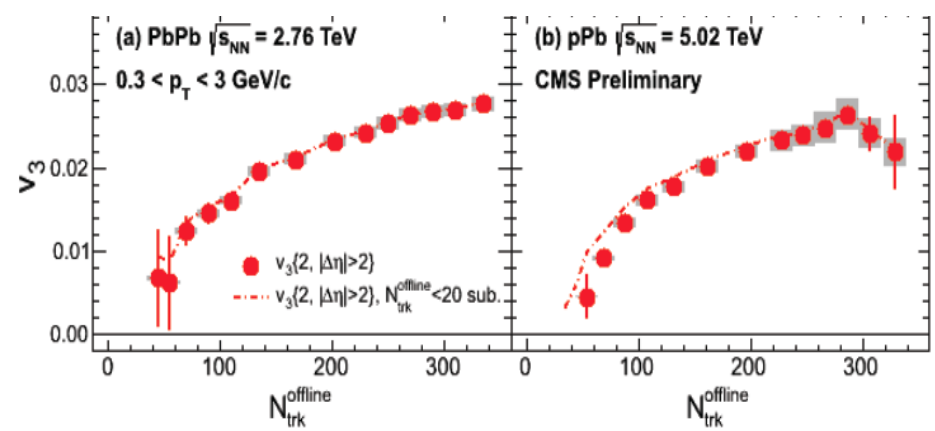
(a) PbPb √s_NN = 2.76 TeV
0.3 < p_T < 3 GeV/c
(b) pPb √s_NN = 5.02 TeV
CMS Preliminary
v3
v3{2, |Δη|>2}
v3{2, |Δη|>2}, N_trk^offline<20 sub.
N_trk^offline

Flow in p+A





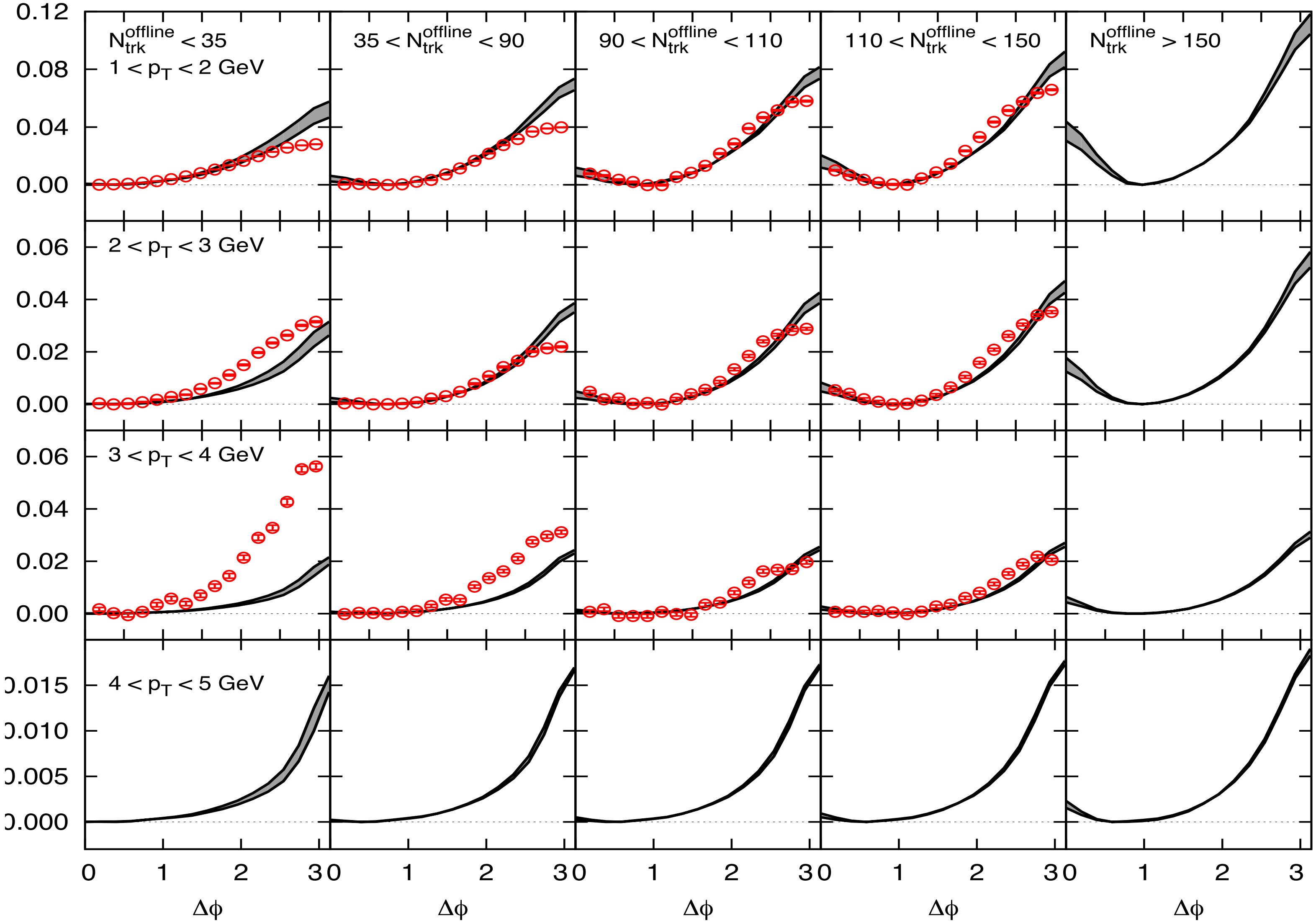
Convert IP-Glasma result to N_{trk} to make direct comparison



Note: result is for η/s=0.08

CMS data: JHEP 1009, 091 (2010); PLB 718, 795 (2013)

Assoc. yield per. trig.



K_{BFKL}=K_{Glasma}= 1

KKP fragmentation

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