Extreme QCD and the ridge phenomenon

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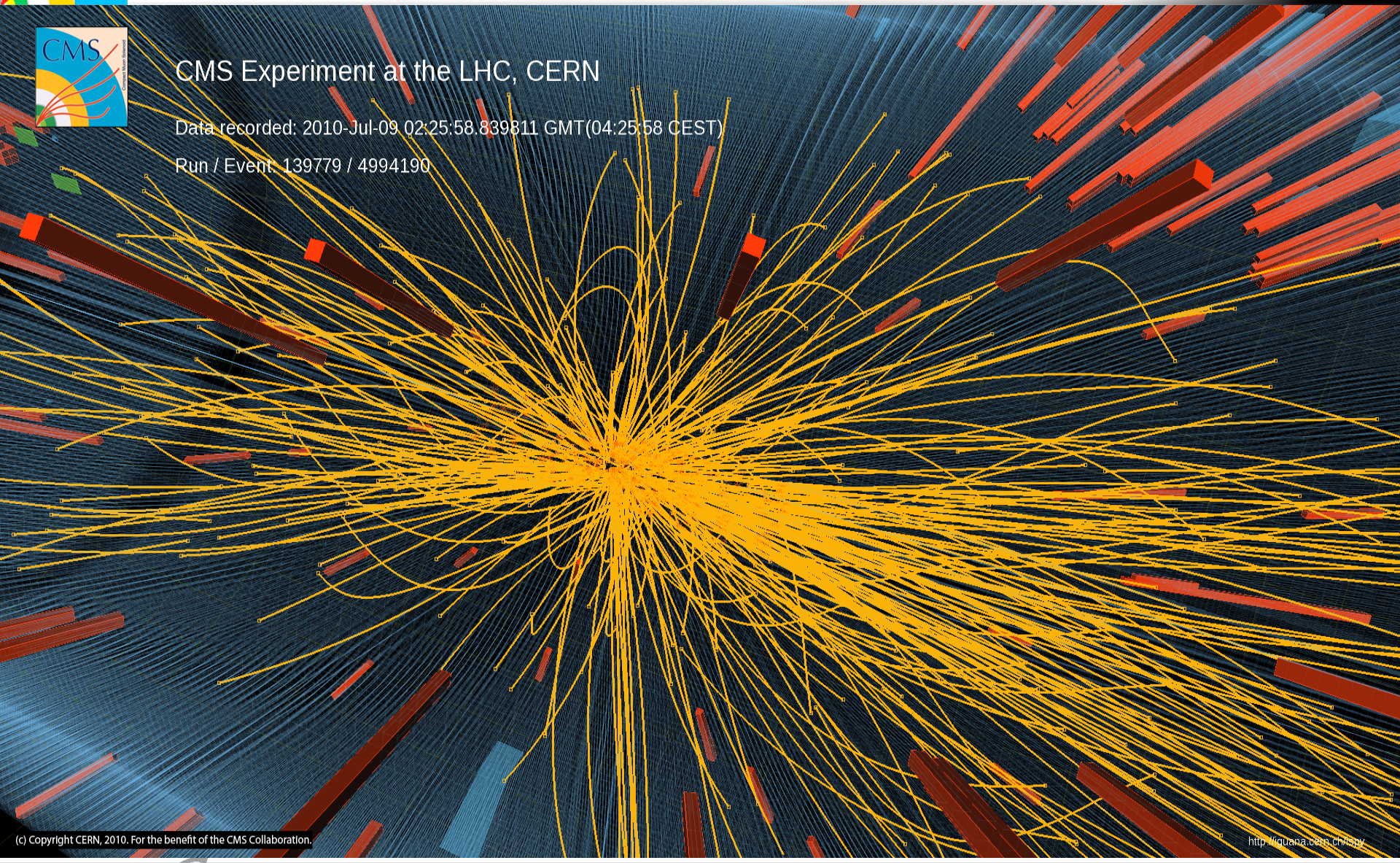
Orsay Summer School, July 4 2014

High Multiplicity pp collisions



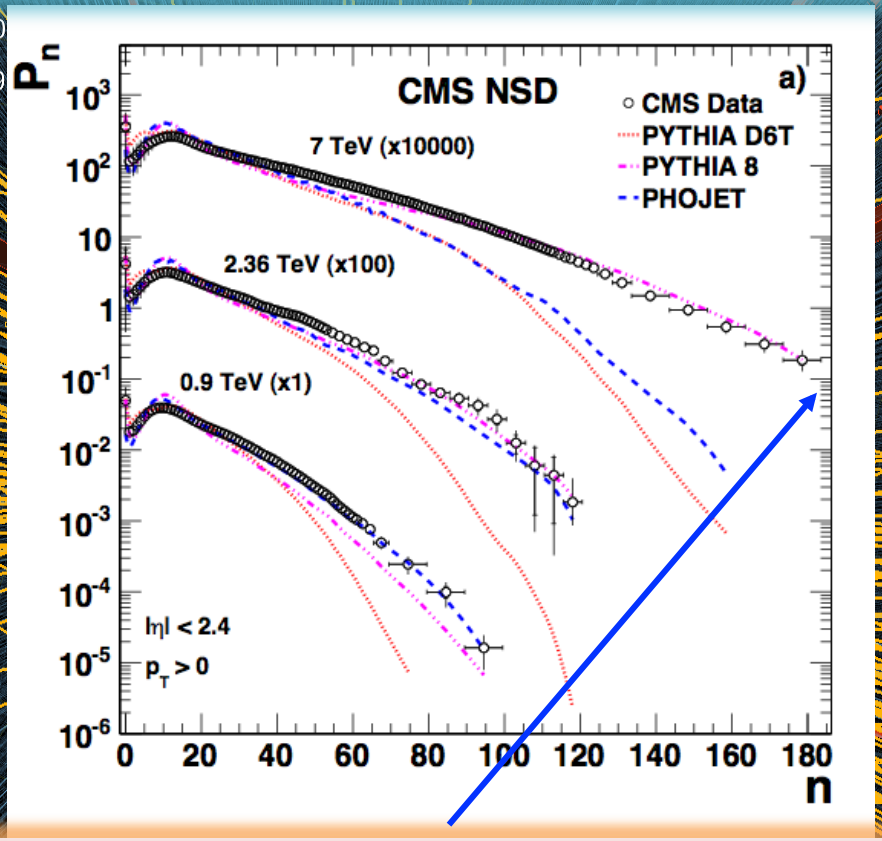
High Multiplicity pp collisions

CMS Experiment

Data recorded: 2010-Jul-0

Run / Event: 139779 / 499

High Multiplicity events are rare in nature



Very high particle density regime

Is there anything peculiar happening there?

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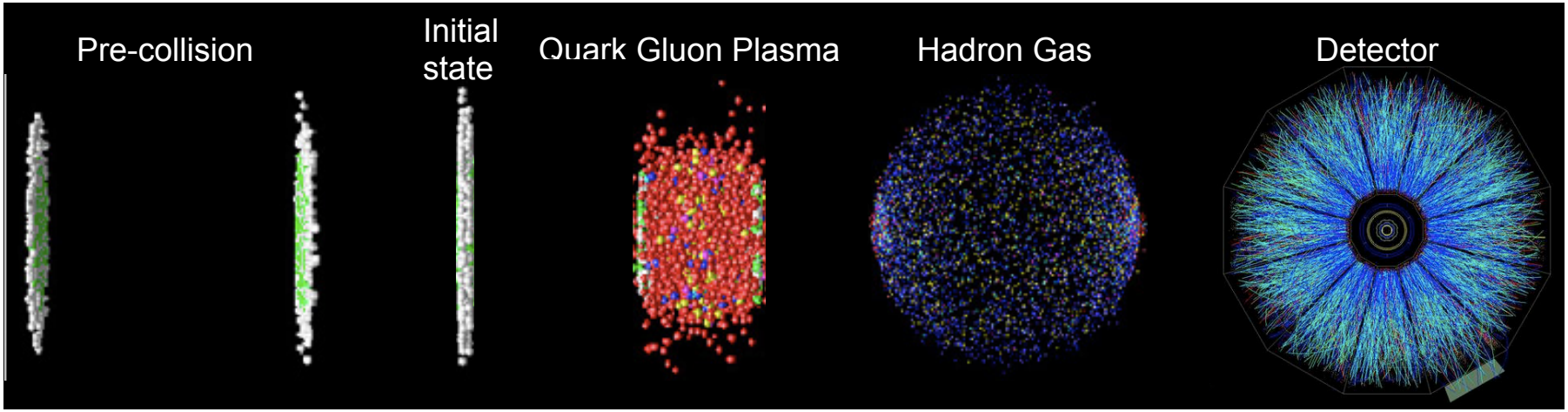
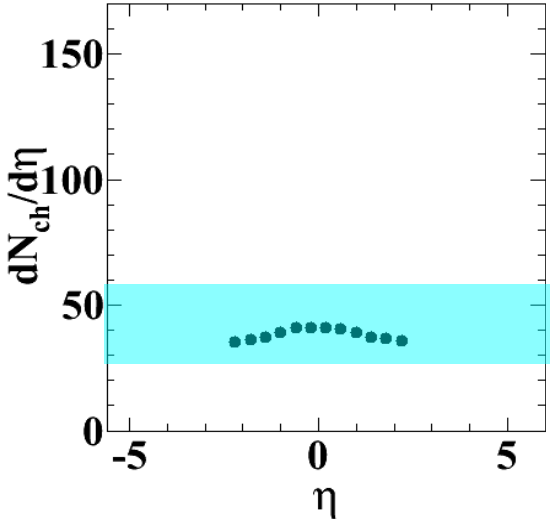
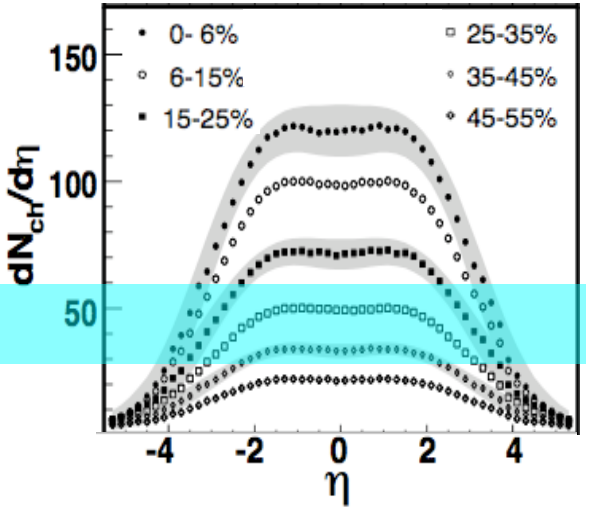
Relativistic Heavy Ion Collisions



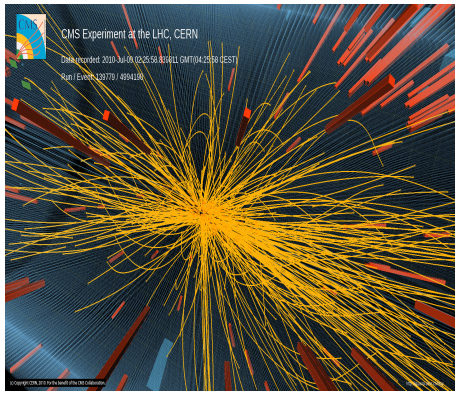
CMS pp 7TeV, N>110



PHOBOS CuCu 62.4GeV



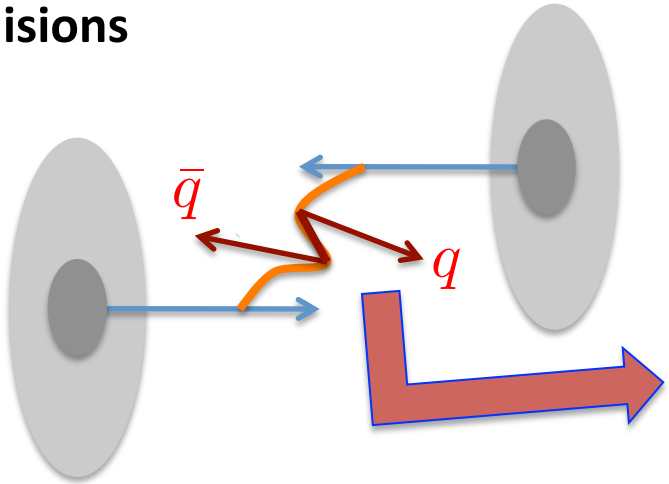
?



The p+p ridge

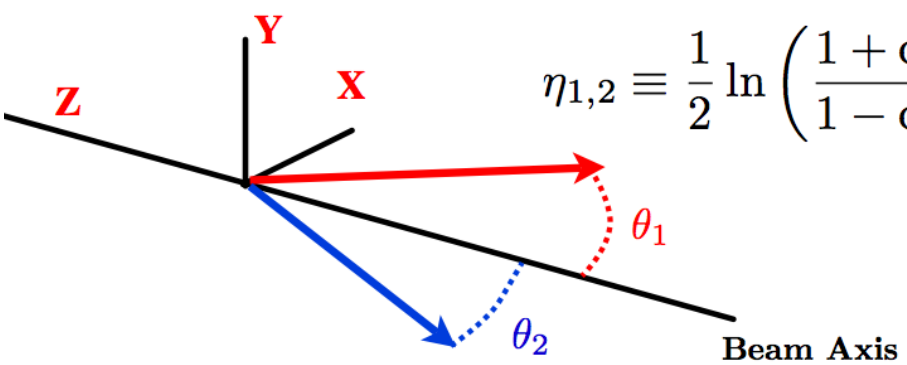
CMS reported a remarkable structure seen in two particle correlation spectrum as a function of angular variables Δη, ΔΦ in very high multiplicity p+p collisions

CMS, arXiv:1009.4122

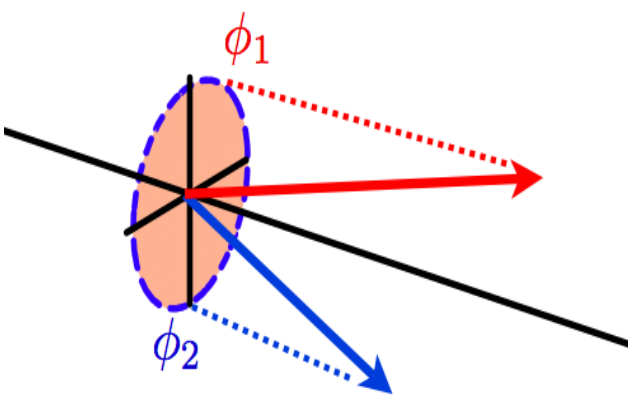


Back to back jet correlation in p+p

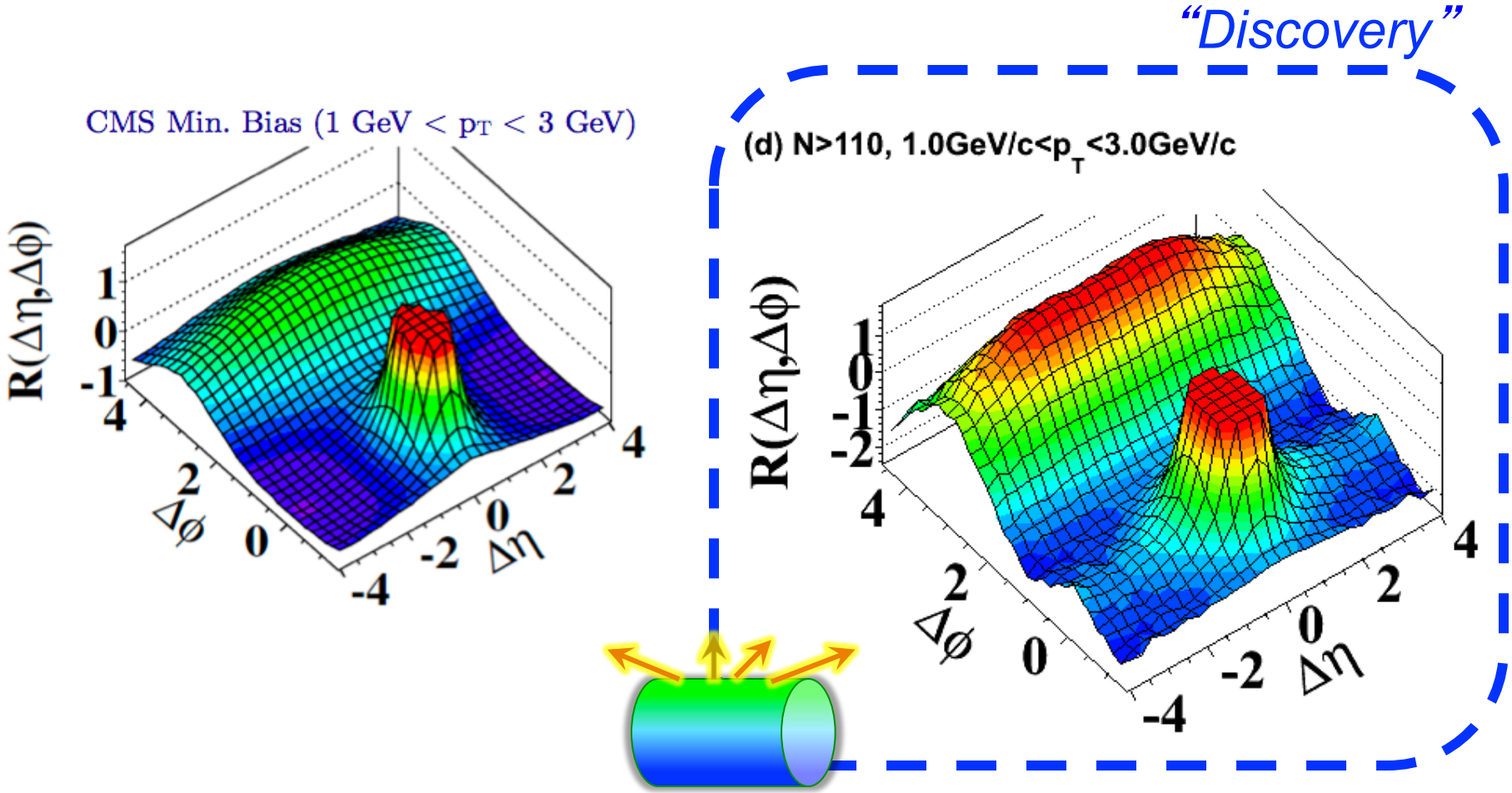
Collision Geometry:



$$\eta_{1,2} \equiv \frac{1}{2} \ln \left(\frac{1 + \cos\theta_{1,2}}{1 - \cos\theta_{1,2}} \right)$$

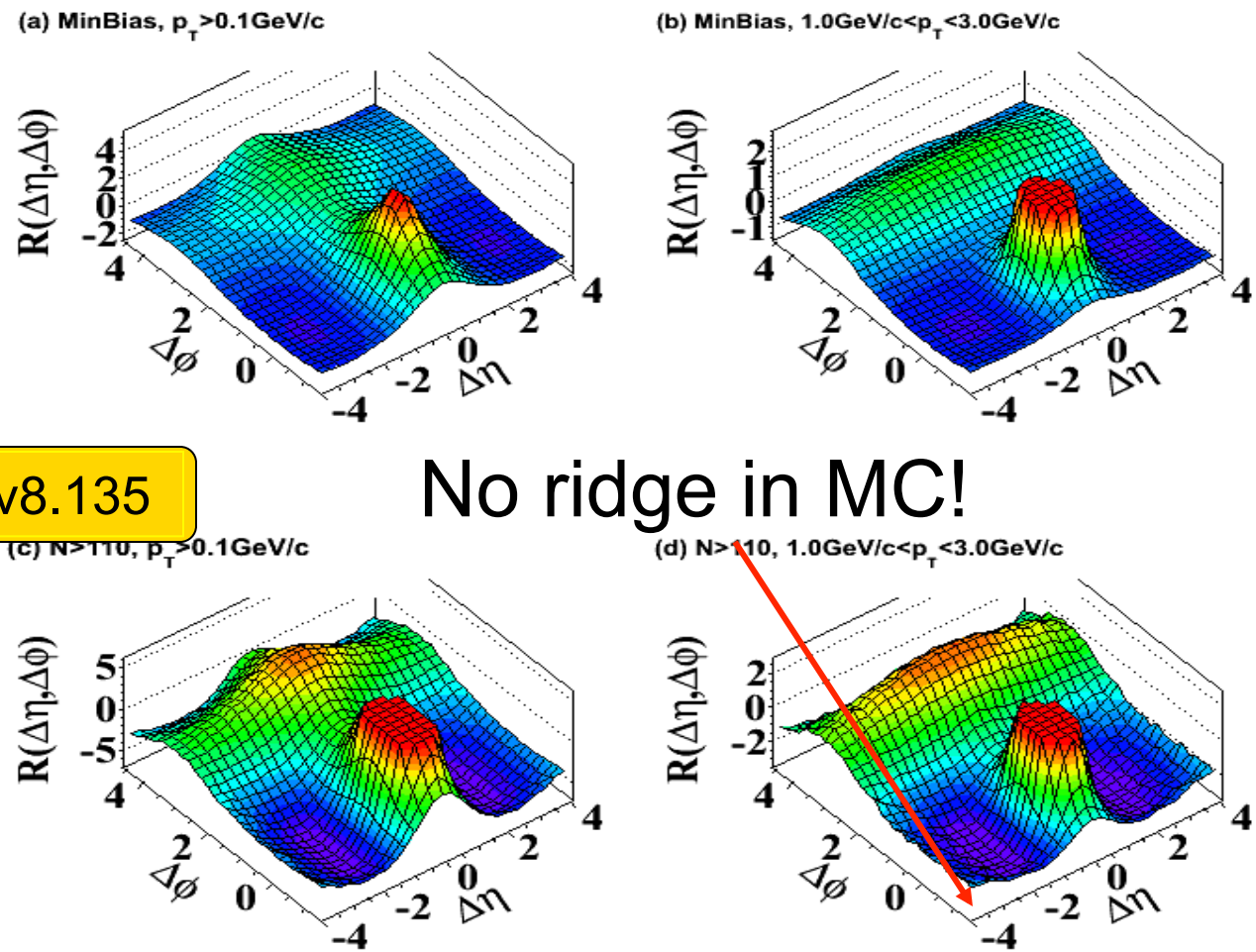


Two particle correlations: CMS results



- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

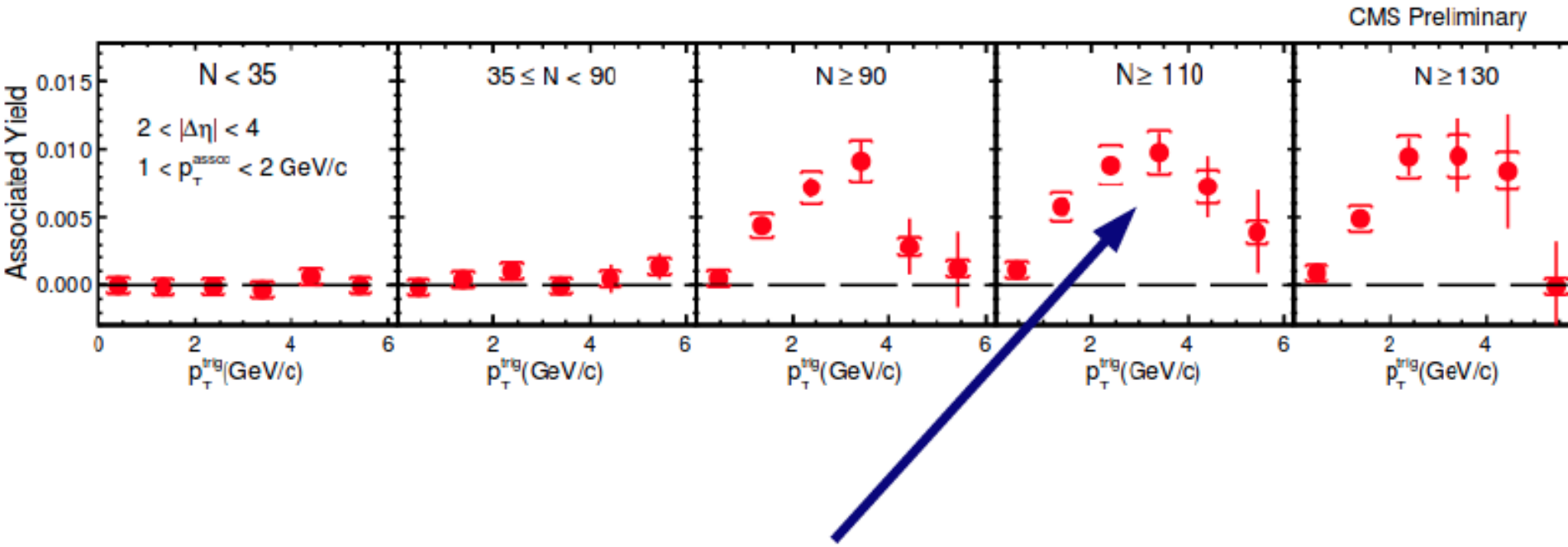
Comparing to MC models



PYTHIA8, v8.135

No ridge in MC!

The ridge



Evidence of a semi-hard scale in the data ?

See Inside

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

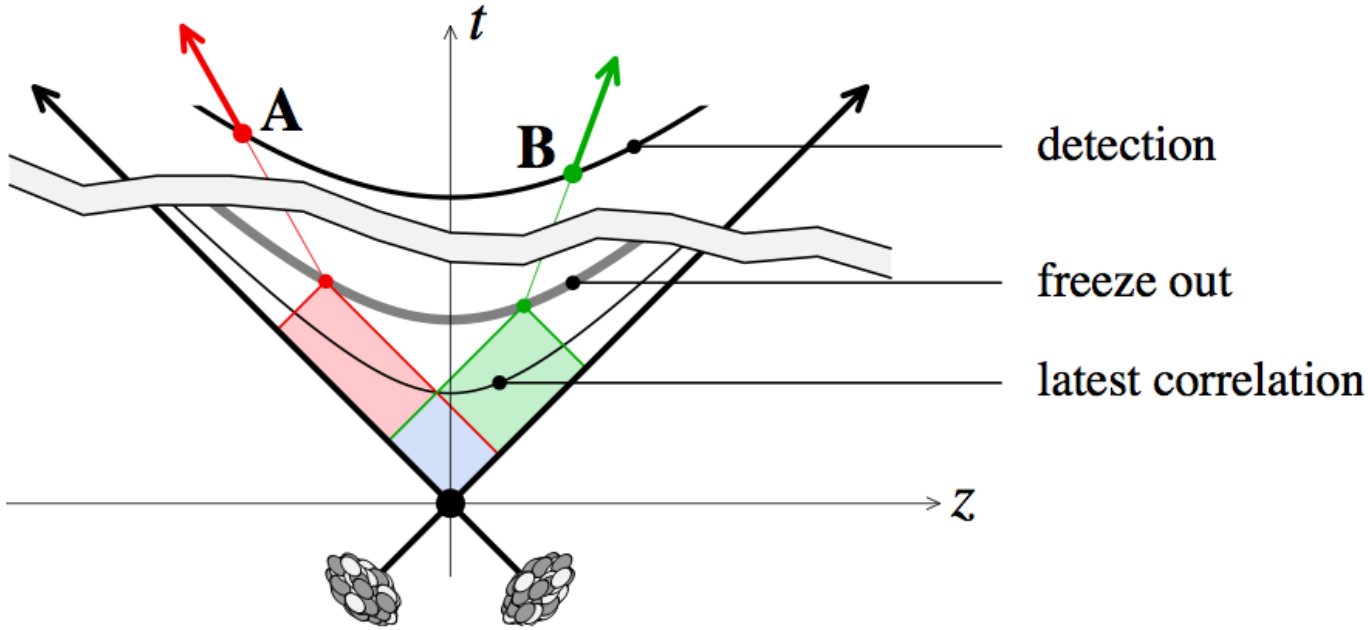
Scientific American, February (2011)

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"

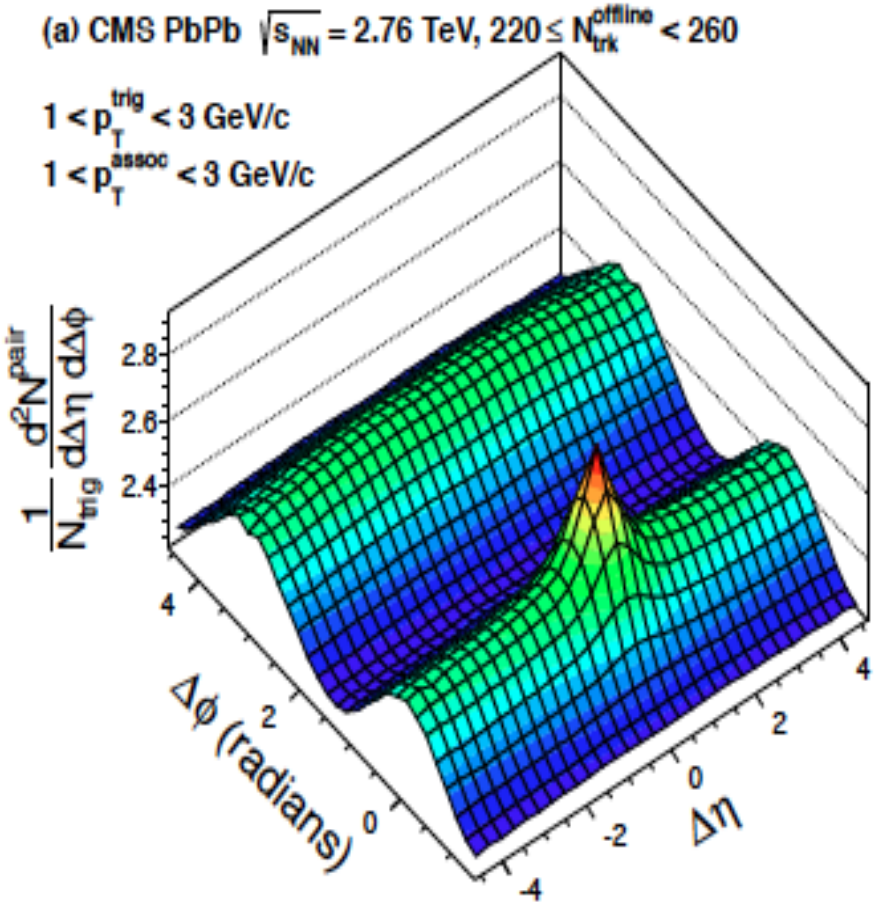
Long range rapidity correlations as a chronometer

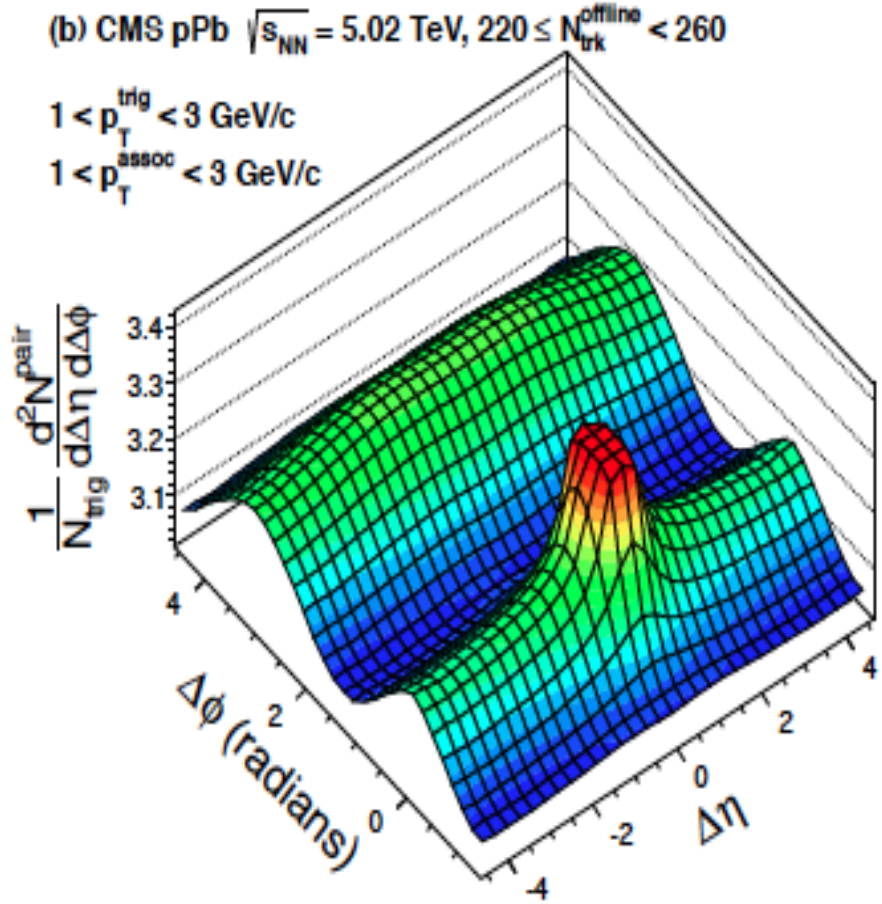


$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

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

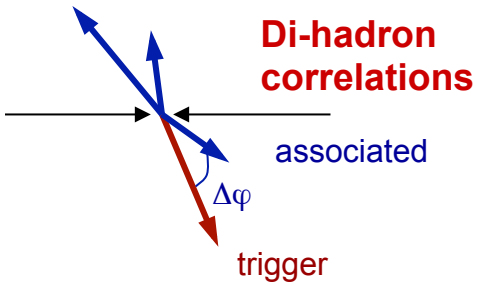
Striking results from LHC p+A collisions

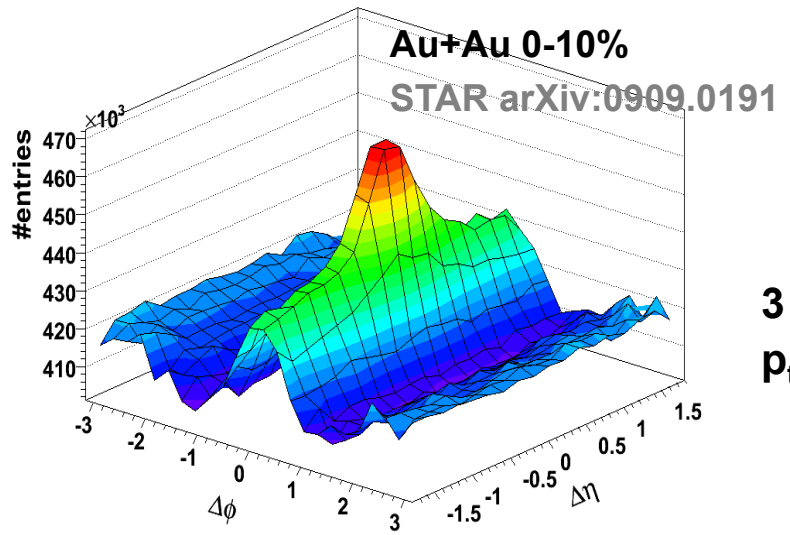


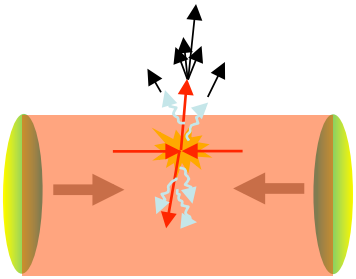


p+A ridge much large than p+p at same multiplicity and nearly as large as that in peripheral Pb+Pb collisions

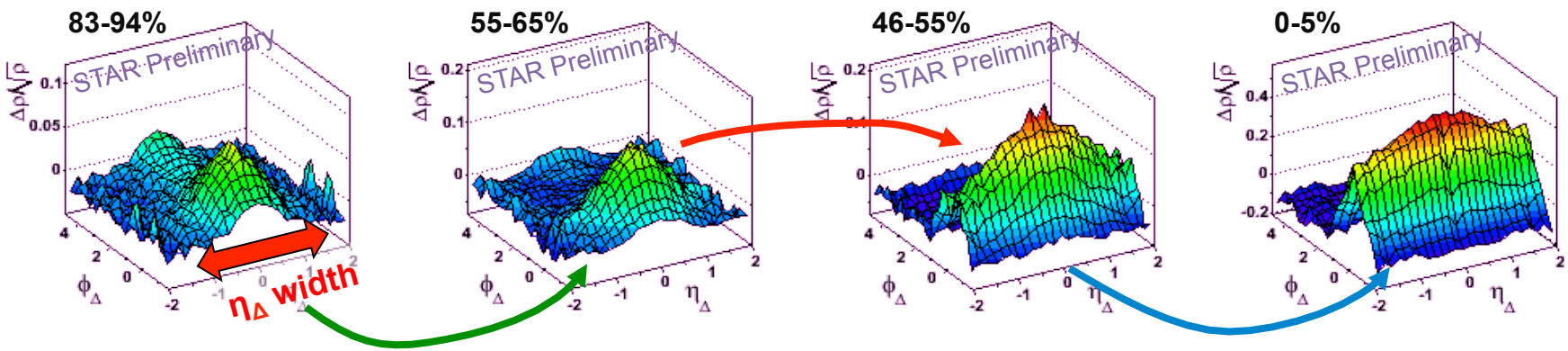
The ridge in A+A collisions







$3 < p_{t,trigger} < 4$ GeV
$p_{t,assoc.} > 2$ GeV

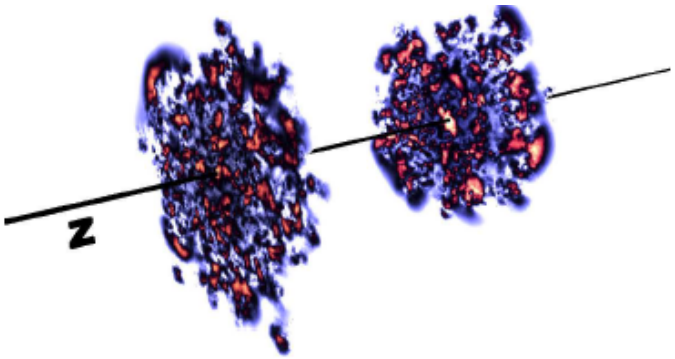


In (central) A+A, the ridge is commonly interpreted as hydrodynamic "hubble" flow of initial "stringy" structures in rapidity

- the structures in the Δϕ direction decomposed into the V_n Fourier "Flow moments"
(recall the recent talk by my colleague Bjoern Schenke)

Multiparticle production

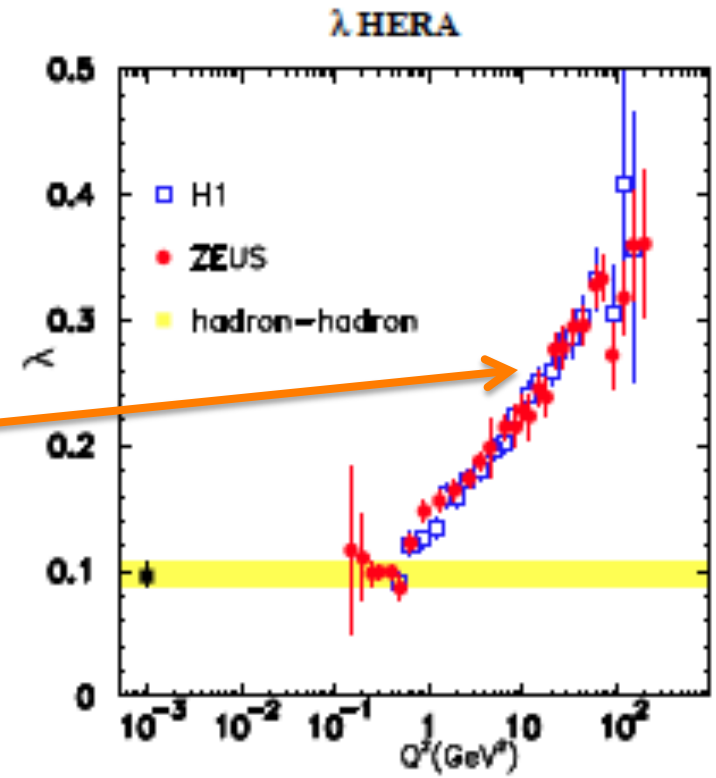
What does it take to produce
~ 150 hadrons per 5 units of rapidity
in a single p+p event ?



What's the guidance from HERA?

$$N_{\text{glue}}^{\text{proton}}(Q^2) = \int_{\text{xmin}}^{\text{xmax}} dx \, \frac{dN}{dx}(x, Q^2)$$
$$\sim \int_{\text{xmin}}^{\text{xmax}} dx \, \frac{1}{x^{1+\lambda(Q^2)}}$$
$$= \frac{1}{\lambda(Q^2)} \left(\frac{1}{x_{\text{min}}^{\lambda(Q^2)}} - \frac{1}{x_{\text{max}}^{\lambda(Q^2)}} \right)$$

$$\text{xmin}(Q^2 = 2, y = 0) = 2 \cdot 10^{-4}$$
$$\text{xmax}(Q^2 = 2, y = 2.4) = 2.2 \cdot 10^{-3}$$



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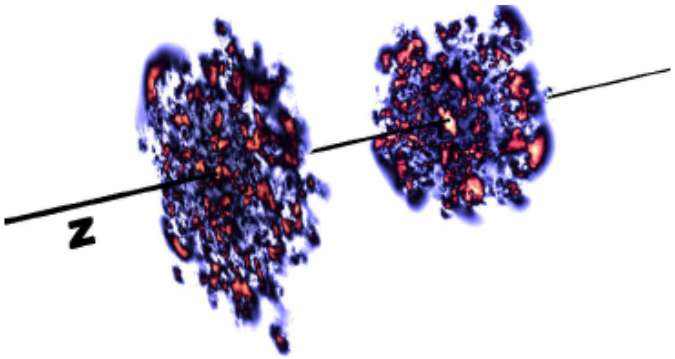
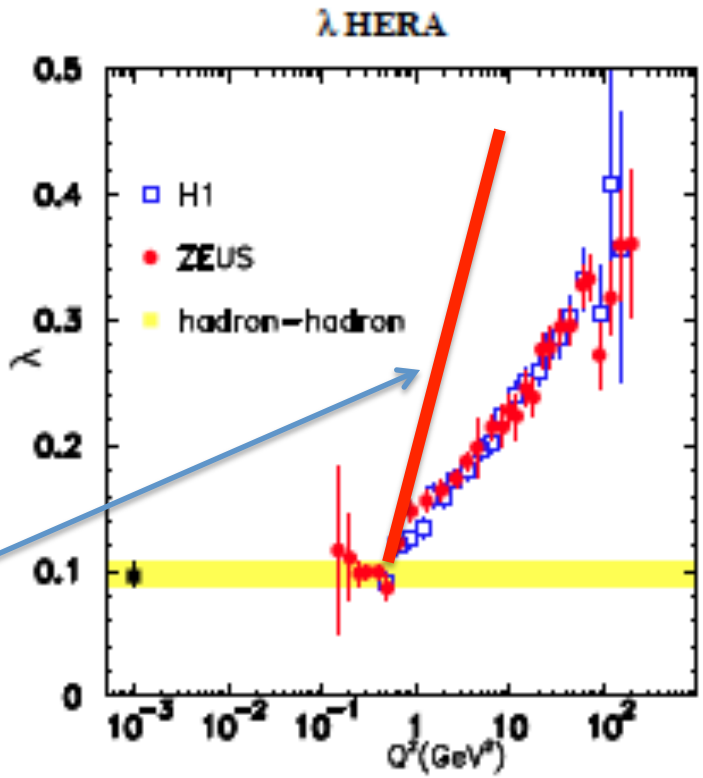


For λ=0.14, get about 13 gluons produced in 5 units ~ min.bias hadron multiplicity

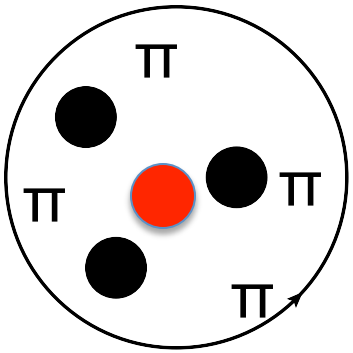
λ=0.3: ~45 gluons in 5 units,
λ=0.4: ~90 gluons in 5 units, in ball park…

Very rapid growth of gluon dist. in such events…

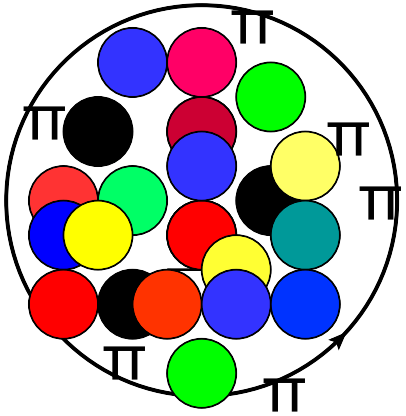


The proton in a high multiplicity event

$Y=y_{beam}$



$Y=0$



For Q^2= 2 $GeV^{2,}$, what's the proton's gluon radius?

The proton in a high multiplicity event

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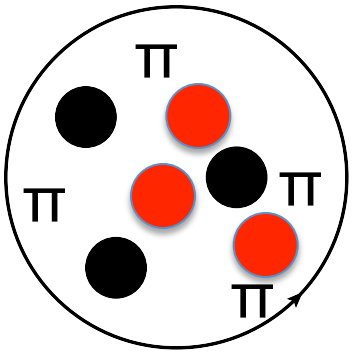

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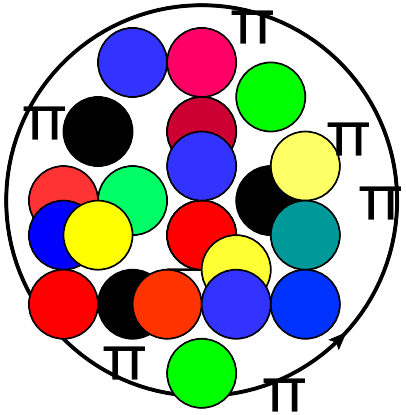
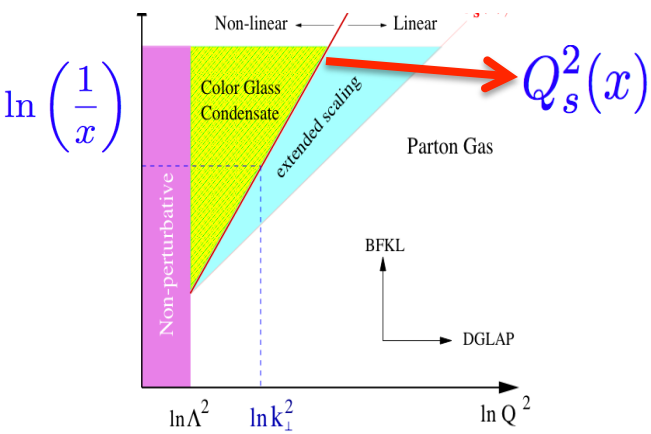


For Q^2= 2 GeV^2, what's the proton's gluon radius?

$$\frac{4\pi}{Q^2} * N_g(Q^2) = \pi R^2_{\text{glue}}$$

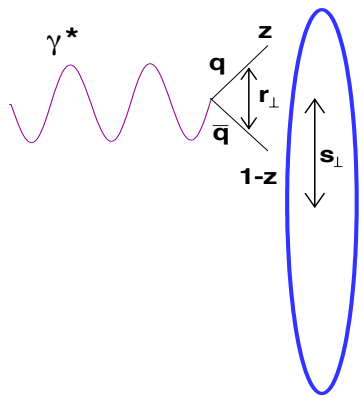
Gribov diffusion => R^2 ~ ln(s)
R_g grows much faster depending on N_g rate
--will violate unitarity

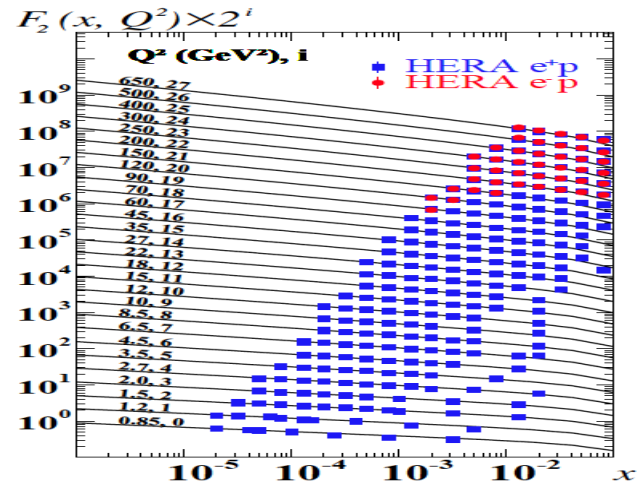


Saturation regulates this by adding increasingly "smaller" gluons of size $1/Q_s(x)$ with decreasing x

Extracting lumpy glue in the proton: IPSat model

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



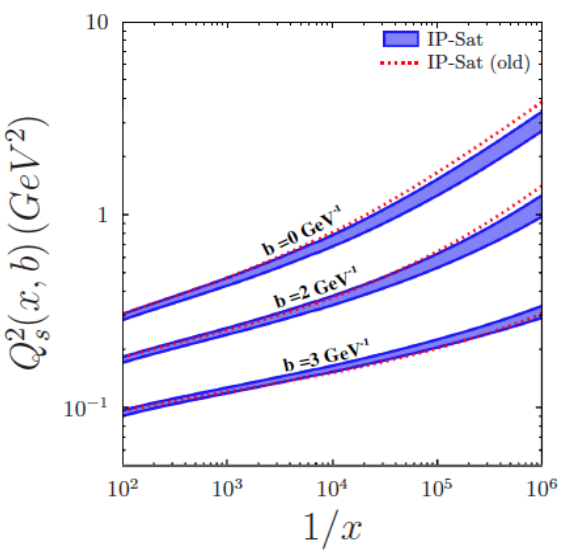


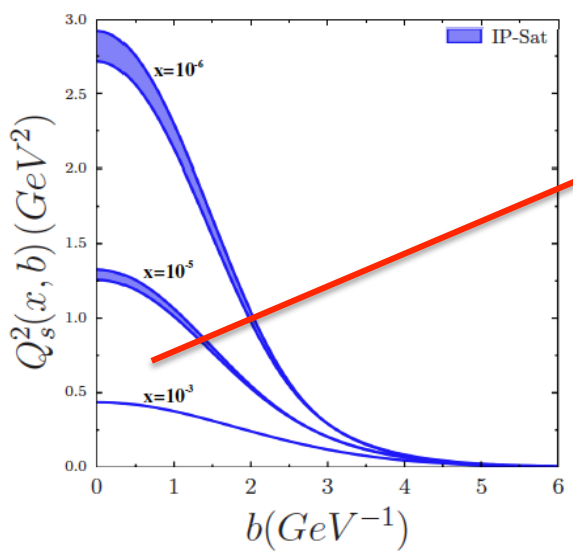
$$\frac{d\sigma^{p}_{dip}}{d^2\mathbf{b}_\perp}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\mathcal{N}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_\perp{}^2\alpha_s(\tilde{\mu}^2)xg(x,\tilde{\mu}^2)T_p(\mathbf{b}_\perp)\right)\right]$$

$$T_p(b_\perp) = e^{-\frac{b_\perp^2}{2B_G}}$$

Average gluon radius of the proton extracted from HERA diffractive data

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





Q_s^2 in the rare p+p events nearly a factor of 5 > than typical HERA events

What's the underlying dynamics?

- **Large number of models with a range of speculations**

- **Similar ridges was seen in heavy ion collisions @ RHIC (and now in HI collisions @ LHC) - *are we seeing hydrodynamic flow in p+p and p+A collisions ?***

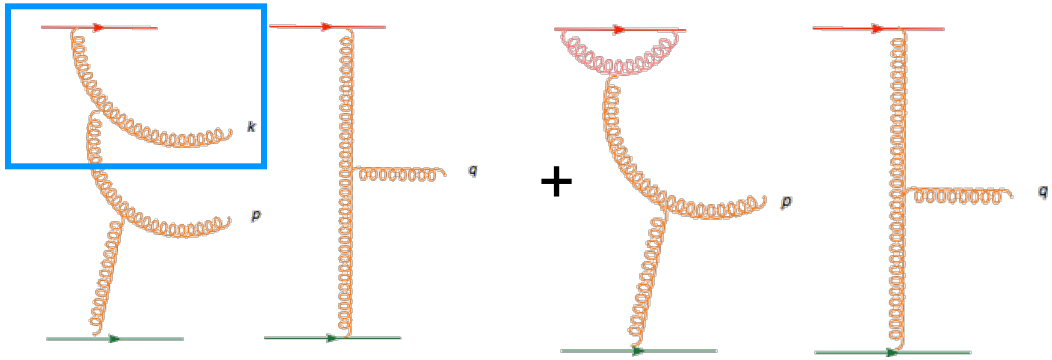
- **I will show that key features of these structures can arise due to initial state correlations enhanced in high multiplicity collisions.**

- **Interesting interplay between initial state correlations and final state rescattering of glue. The latter can overwhelm the former. Both are a consequence of gluon saturation—is it exclusively so ?**

The saturated hadron: Glasma graphs -I

RG evolution:

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

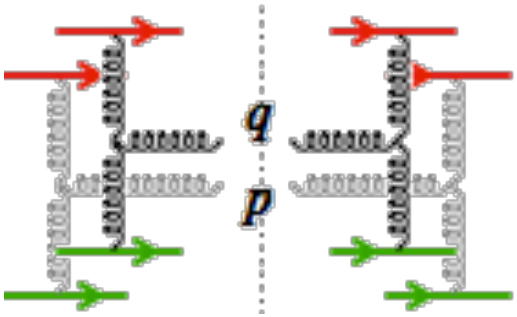


+ . . .

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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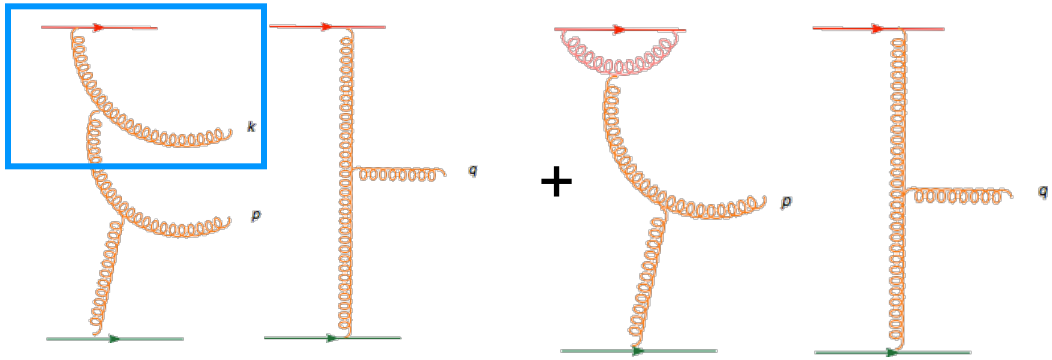

+ . . . Keeping leading logs in x to all orders (NLO+NNLO+...)

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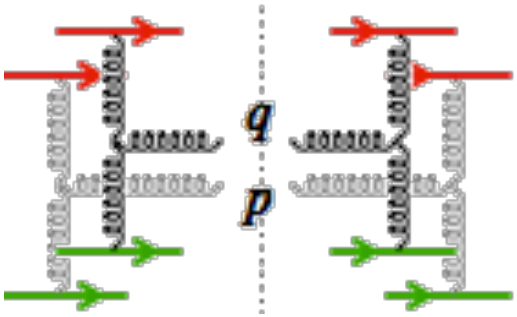
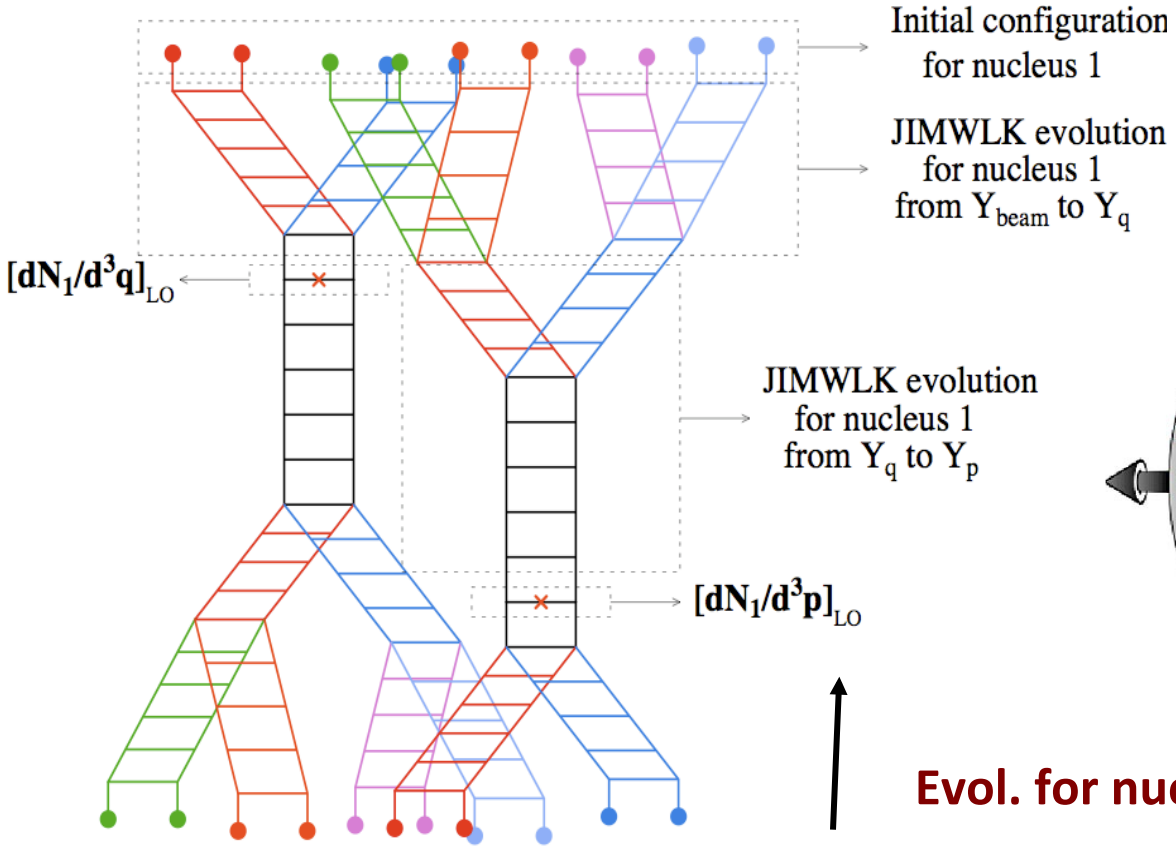


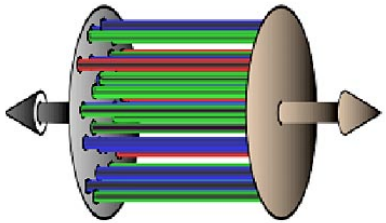
$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}|_{\rm LO}\, \frac{dN}{d^3q}|_{\rm LO}$$

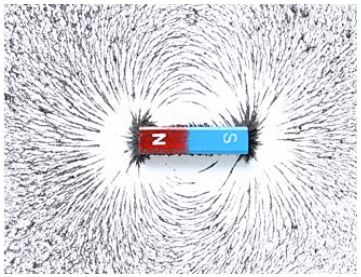
From solns. of Yang-Mills eqns.with two light cone sources
Includes all mult. scat. contributions $(g\rho_1)^n$ and $(g\rho_2)^n$

High multiplicity events: two particle correlations



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



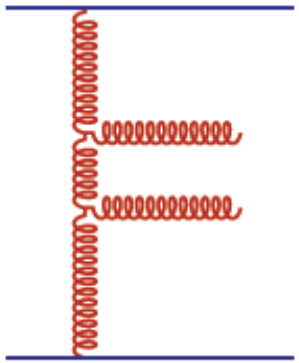
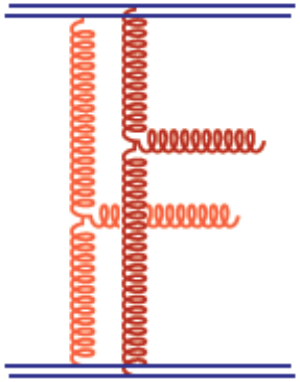
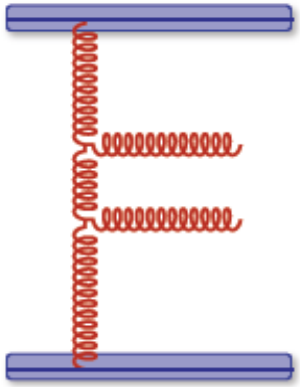
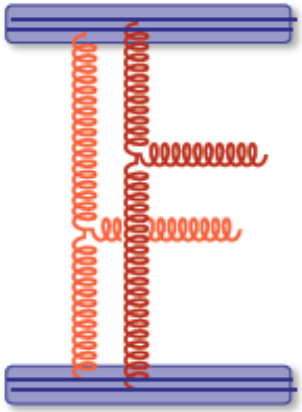


Evol. for nucl. 2

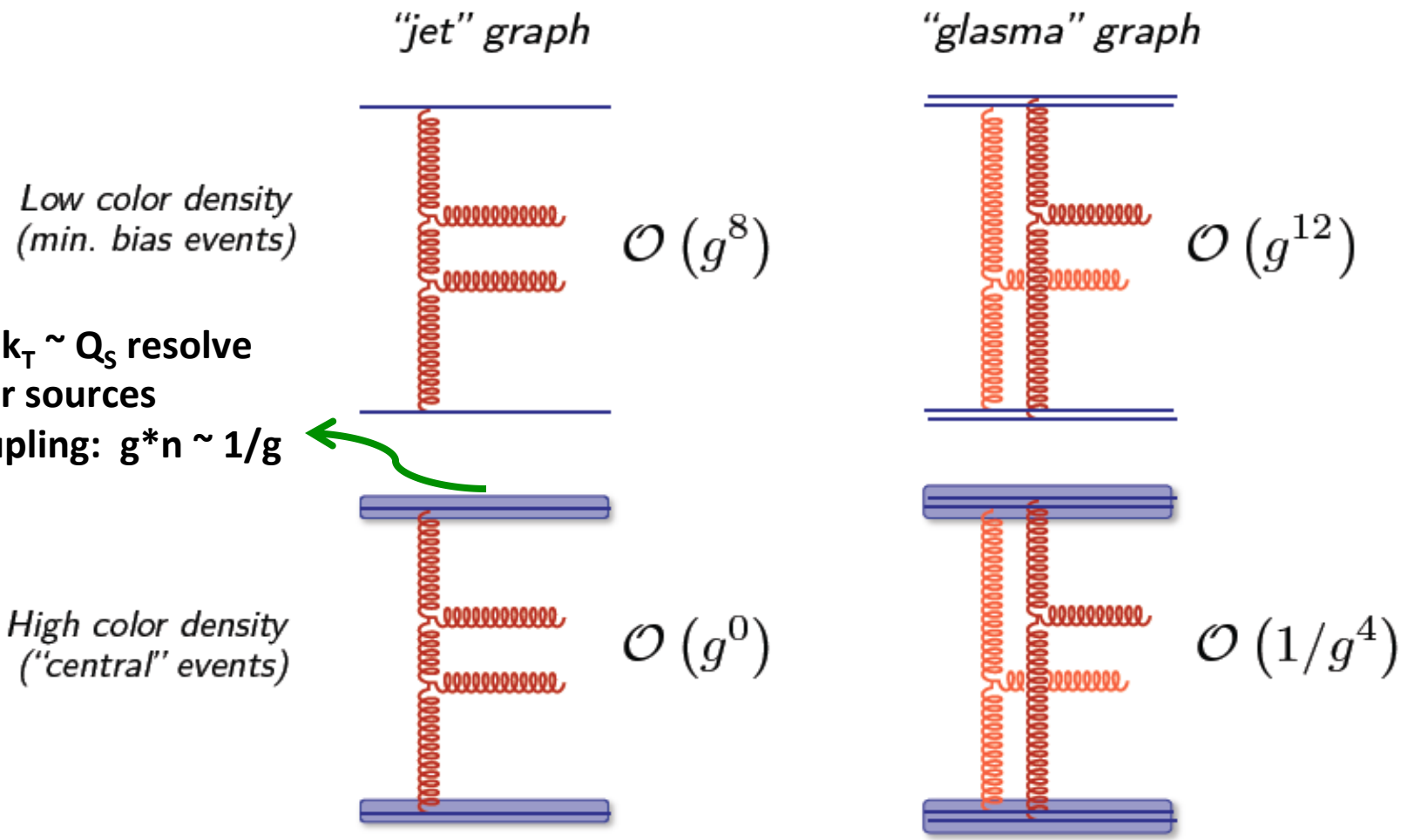
- Full YM+JIMWLK evolution – not available yet
- Approximations: BK Gaussian truncation approximation for $k_T \geq Q_S$; YM results for MV model available for all k_T

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

2 particle correlations in pQCD: counting powers

	"jet" graph	*"glasma" graph*
Low color density (min. bias events)	 $\mathcal{O}\left(g^8\right)$	 $\mathcal{O}\left(g^{12}\right)$
High color density ("central" events)	 $\mathcal{O}\left(g^0\right)$	 $\mathcal{O}\left(1/g^4\right)$

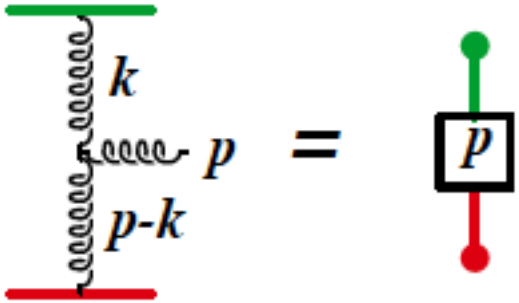
2 particle correlations in pQCD: counting powers

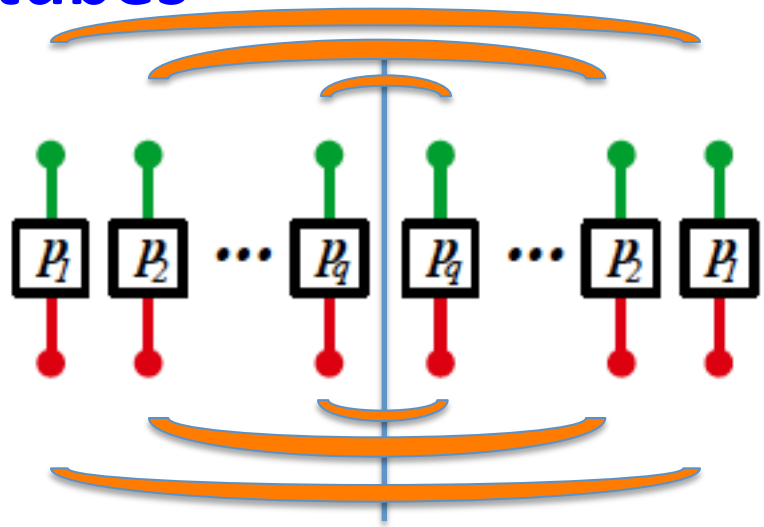


Gluons with $k_T \sim Q_S$ resolve
$n \sim 1/g^2$ color sources
Effective coupling: $g*n \sim 1/g$

Glasma graphs enhanced in high mult. events by α_S^{-8}

Lasing gluons: Stimulated emission from Glasma flux tubes

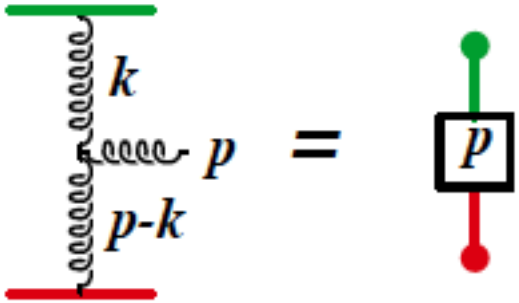


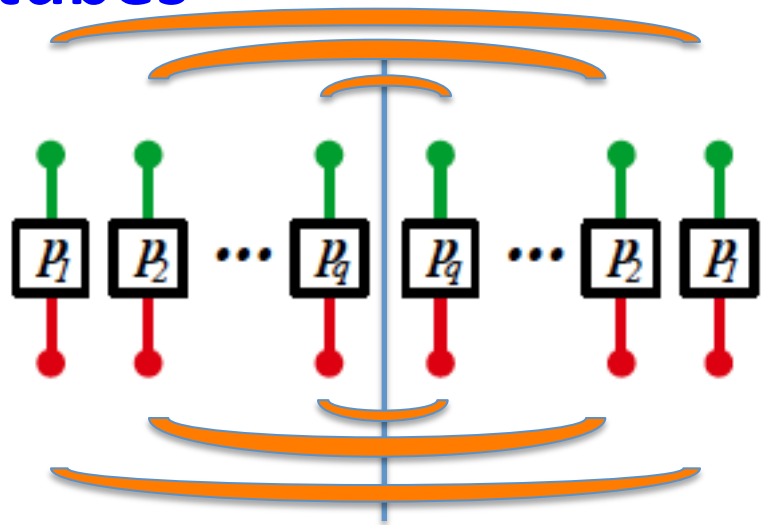


Dumitru,Gelis,McLerran,RV (2008)
Dusling,Fernandez-Fraile,RV (2009)
Gelis,Lappi,McLerran (2009)

Color combinatorics of cut graphs: a negative binomial distribution

Lasing gluons: Stimulated emission from Glasma flux tubes





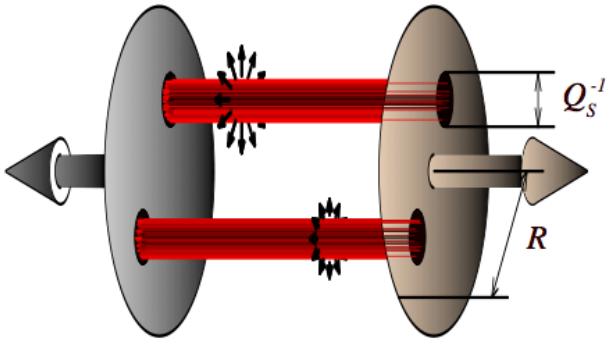
Dumitru,Gelis,McLerran,RV (2008)
Dusling,Fernandez-Fraile,RV (2009)
Gelis,Lappi,McLerran (2009)

Color combinatorics of cut graphs: a negative binomial distribution

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

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

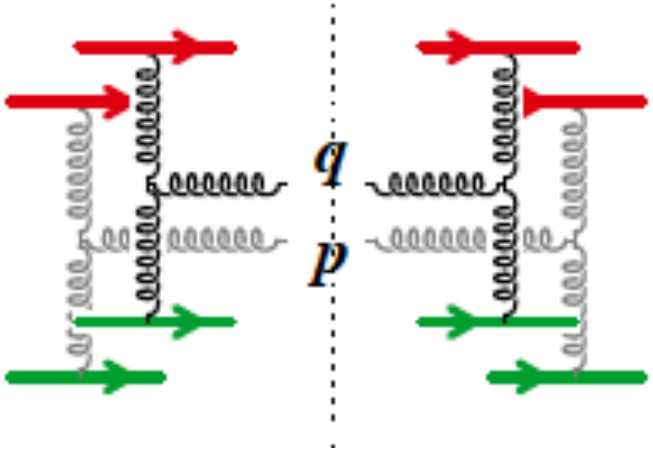
$$k = \kappa \frac{(N_c{}^2 - 1) Q_s^2 S_\perp}{2\pi}$$



For $Q_S{}^2 \approx 1/S_T$
close to a Bose-dist!

The saturated hadron: Glasma graphs

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

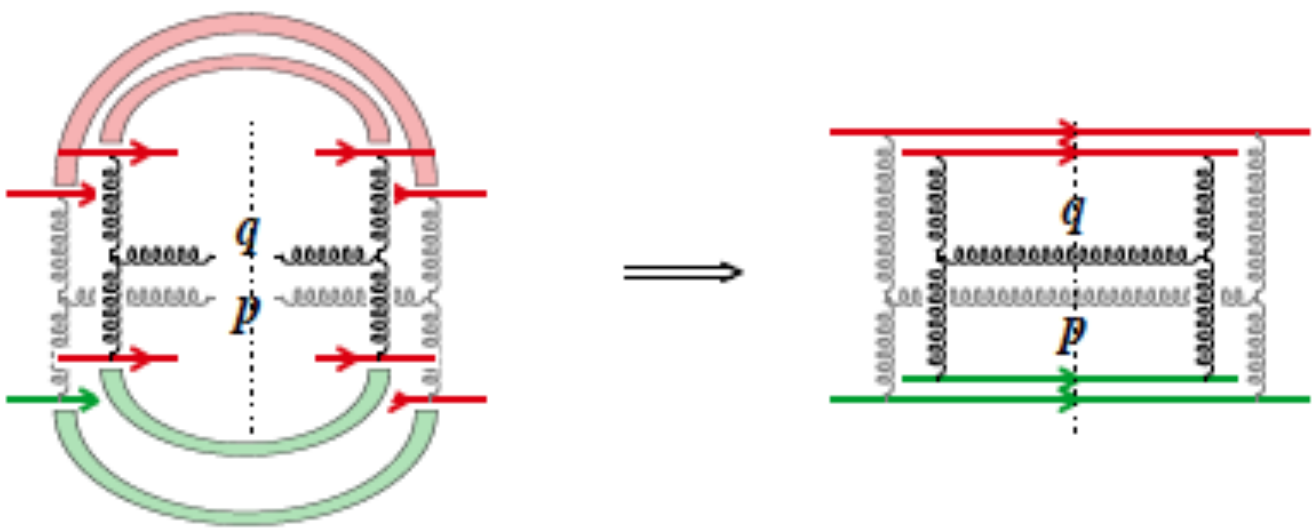


Correlations between the gluons are independent of Δy
-- good approximation for $\Delta y < 1/\alpha_S$

Evolution between sources, see,
Gelis,Lappi,RV,arXiv:0810.4829
Iancu,Triantafyllopolous, arXiv:1307.1559

Color correlations: Glasma graphs-II

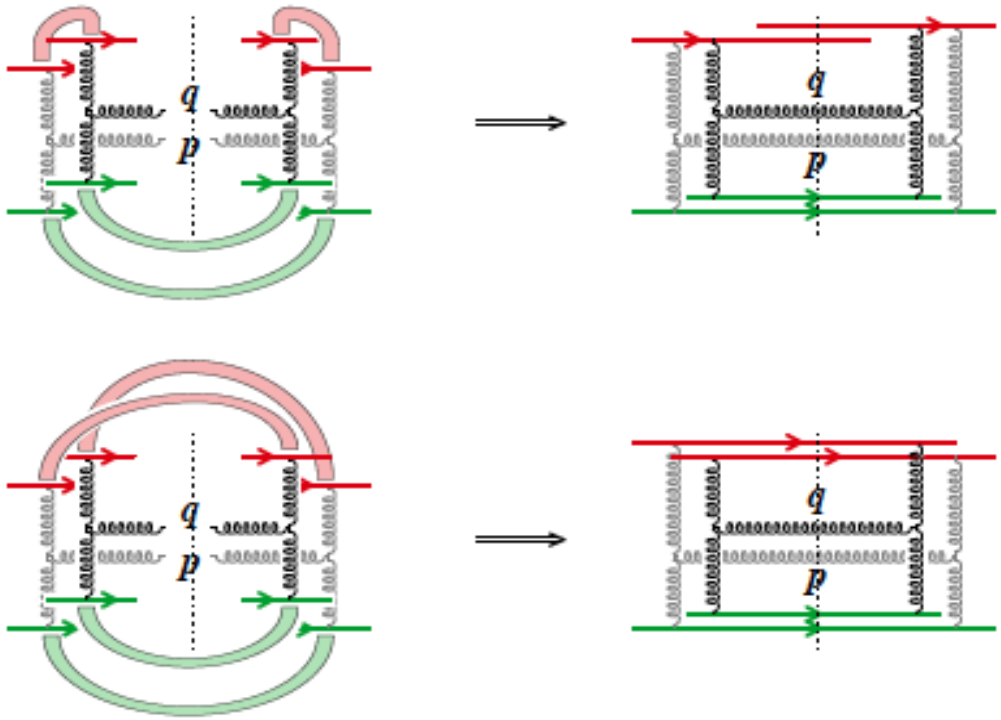
Correlations induced by color fluctuations -- vary event to event – for Gaussian weight functionals in ρ, color screening radius ~ $1/Q_S$



"Uncorrelated graph" ~ N^2 ~ $1/\alpha_S^2$

This produces the "uncollimated" background

Color correlations: Glasma graphs-II

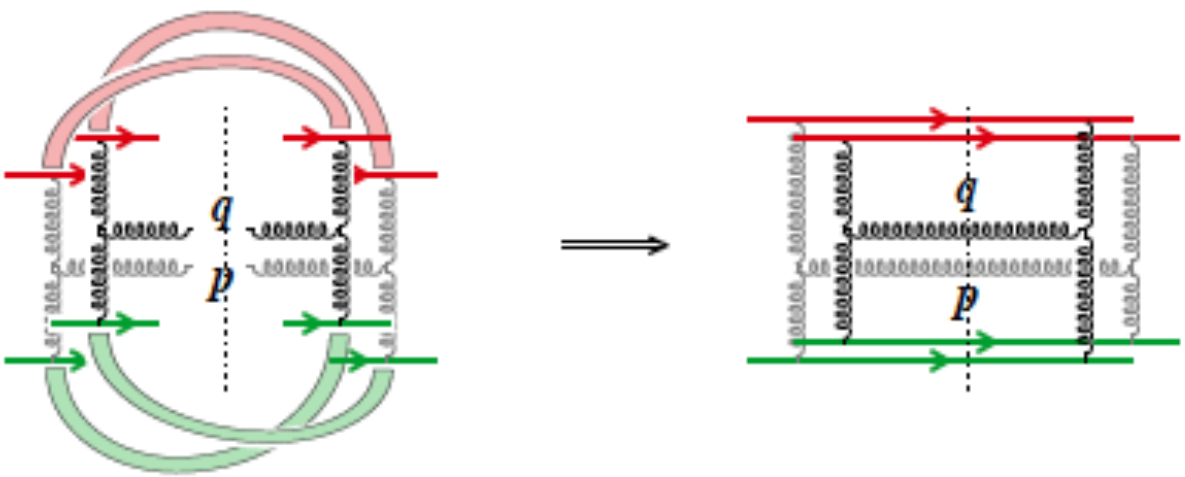


Leading correlated graph $\sim 1 / \alpha_s^2 N_c^2$

Color correlations: Glasma graphs-II

"Sub-leading" graphs (also ~ $1 / \alpha_s^2 N_c^2$)

$$\propto \delta^{(2)}(\vec{p}+\vec{q})$$



$$\propto \delta^{(2)}(\vec{p}-\vec{q})$$

Nearside collimation: quantum interference of glue

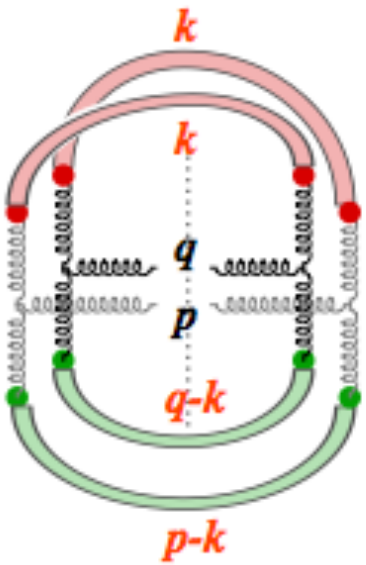
Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,RV, arXiv:1009.5295

RG evolved leading Glasma contribution expressed in terms of "unintegrated gluon distributions" in the proton

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

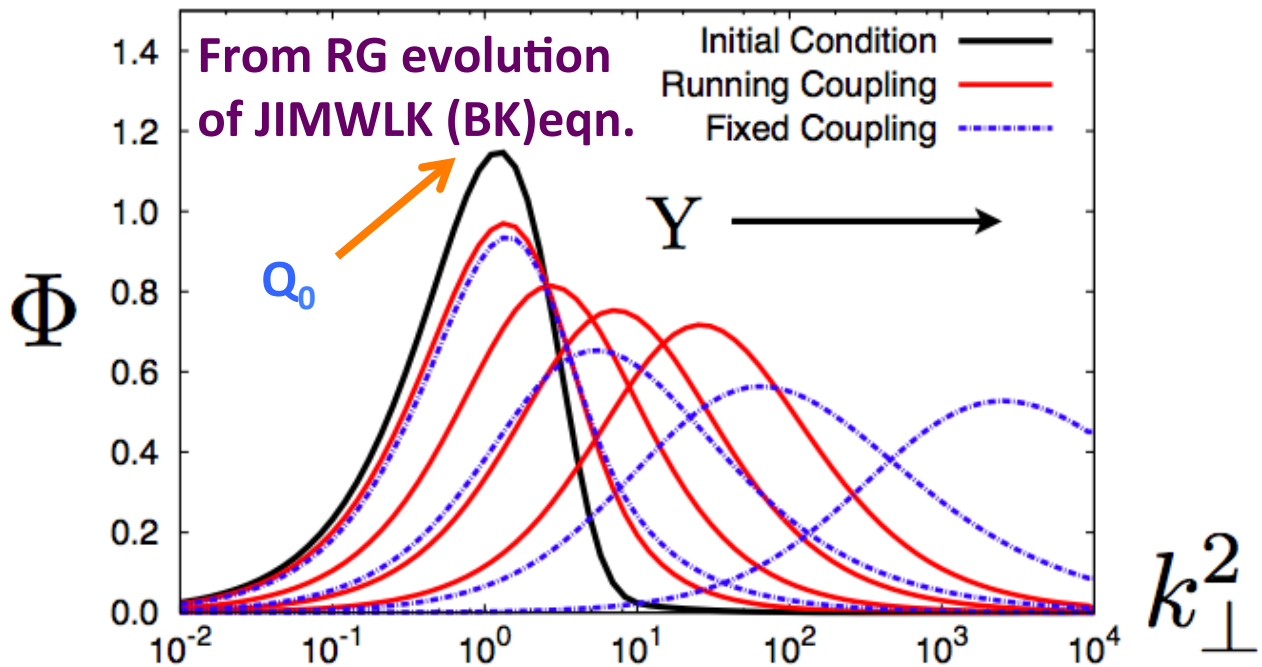
Proton 1

Proton 2



Collimated yield ?

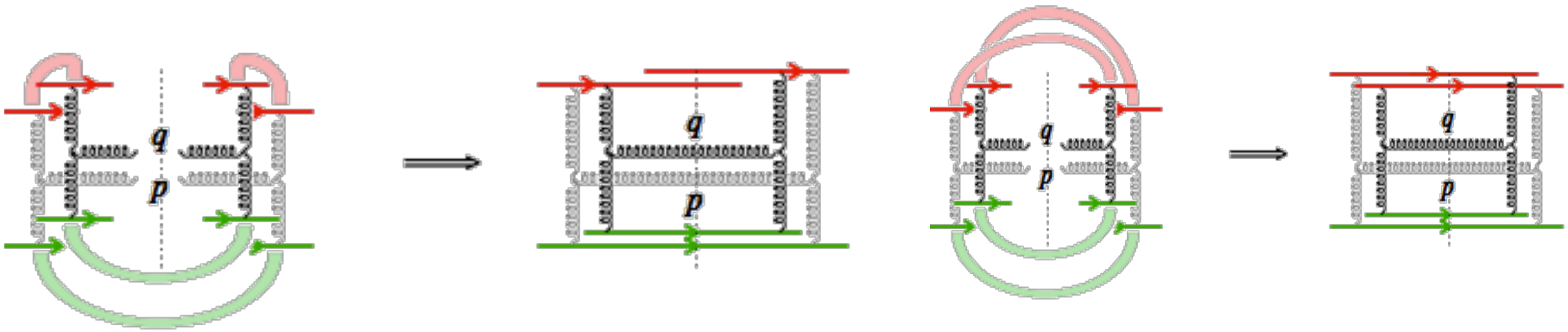
$$C(\mathbf{p},\mathbf{q}) \propto \frac{g^4}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int \mathrm{d}^2\mathbf{k}_{1\perp}\, \Phi^2_{A_1}(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$



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

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

Glasma graphs-key features



Glasma graphs generate long range rapidity correlations

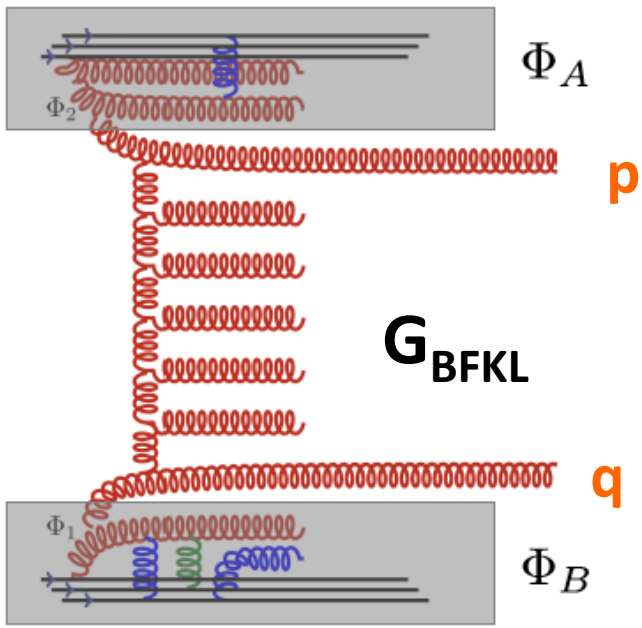
Suppressed for $Q_S << p_T$ by powers of α_S AND N_C

(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 for typical α_S !

(central impact parameters, small x, low p_T, large nuclei)

Angular structure from (mini-) Jet radiation

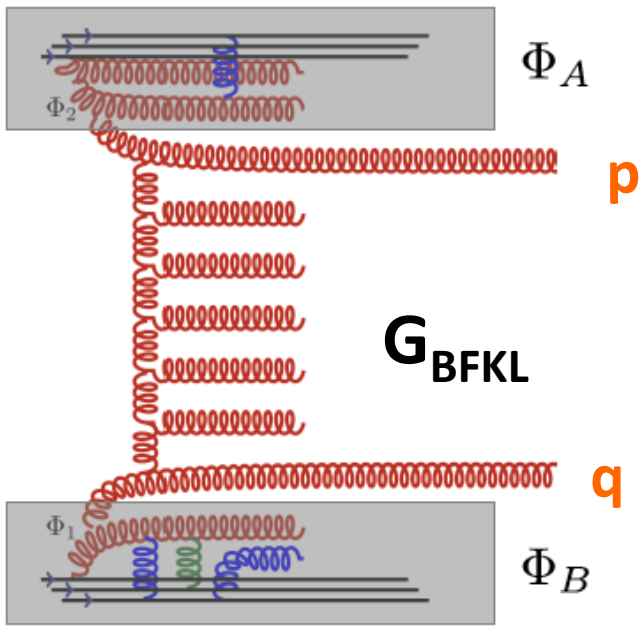


$$C_{\rm dijet}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\rm BFKL}$$

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

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

Angular structure from (mini-) jet radiation

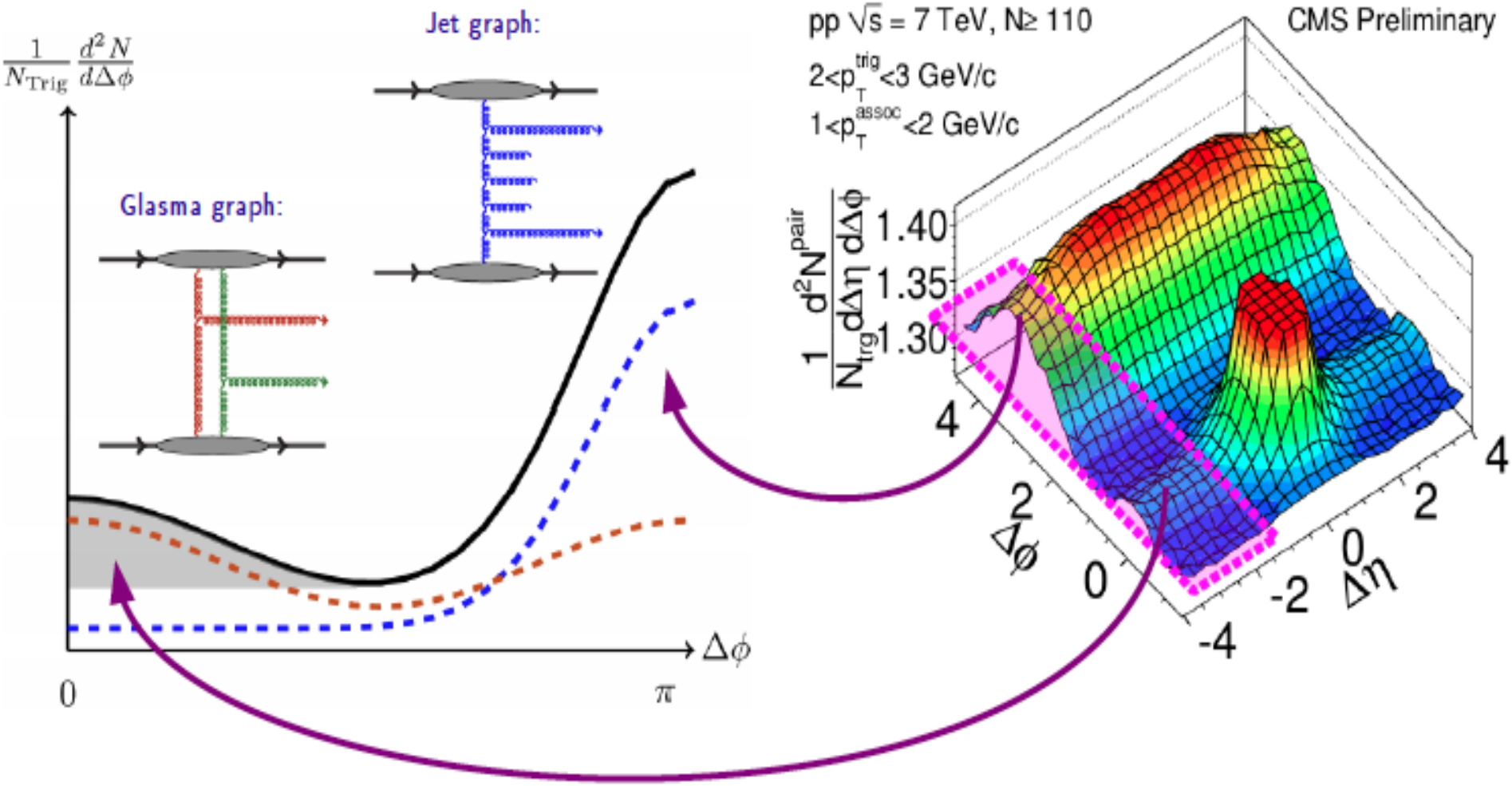


$$C_{\rm dijet}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\rm BFKL}$$

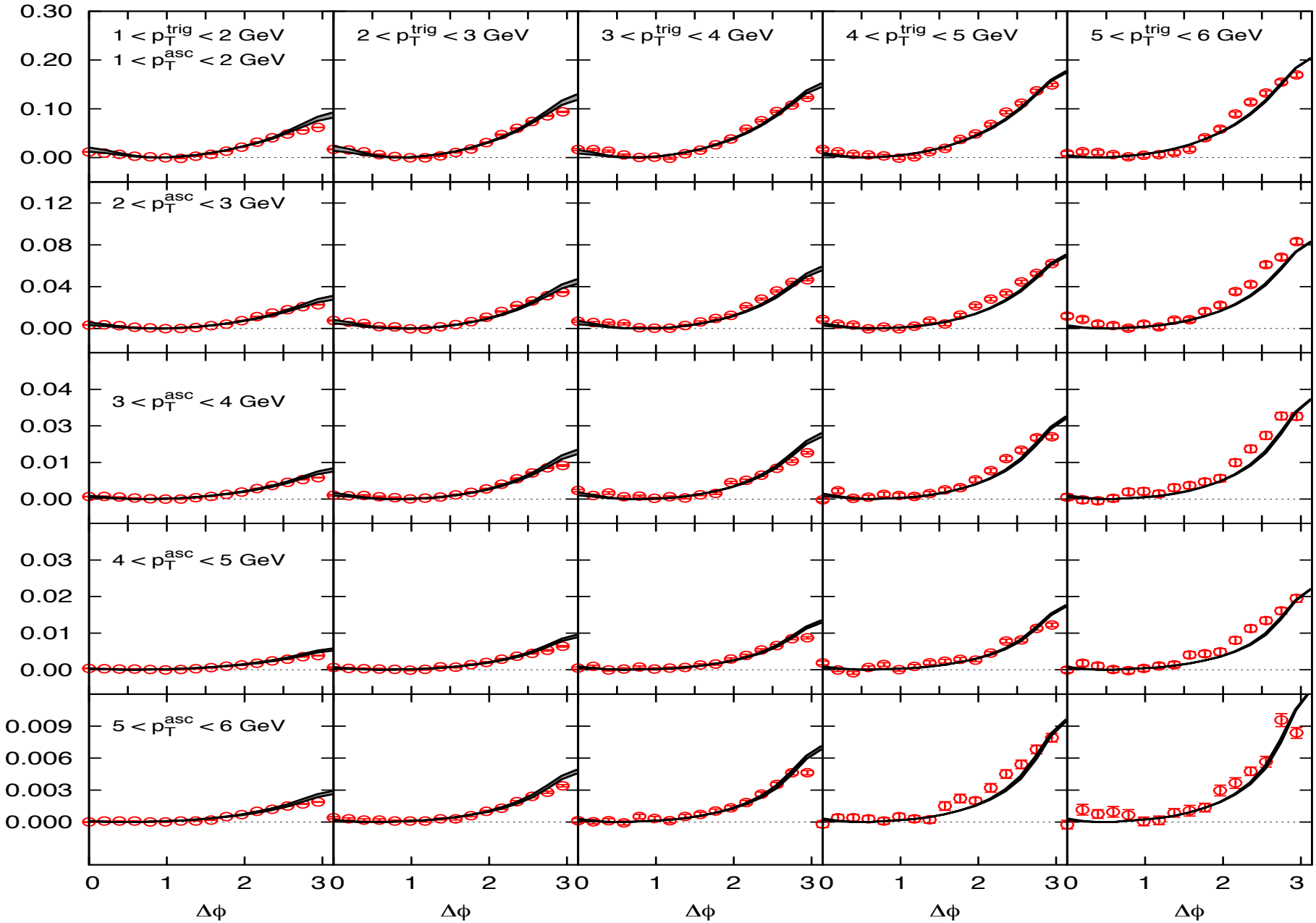
Mini-jets: give a ΔΦ ≅ π collimation

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

Anatomy of long range collimation

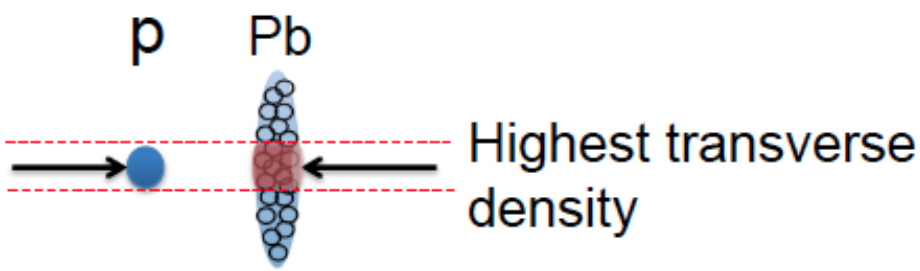


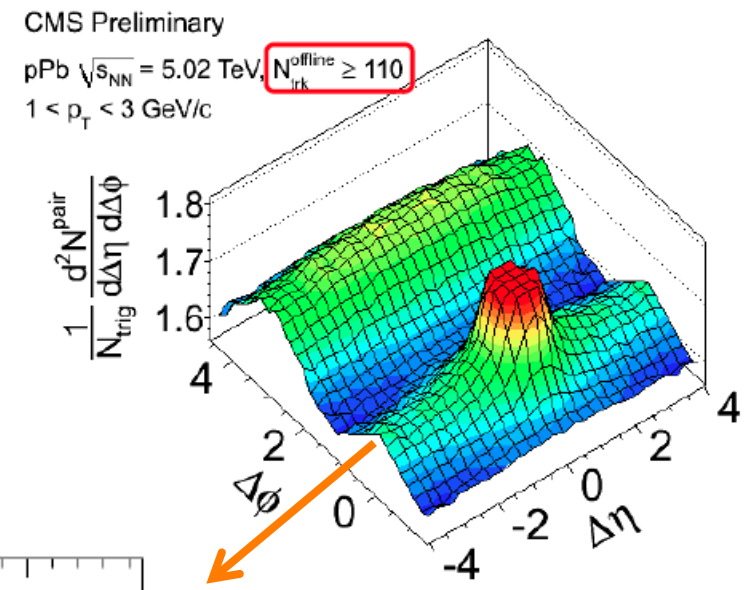
Dusling,RV, PRD 87, 051502 (R) (2013); arXiv:1302.7018

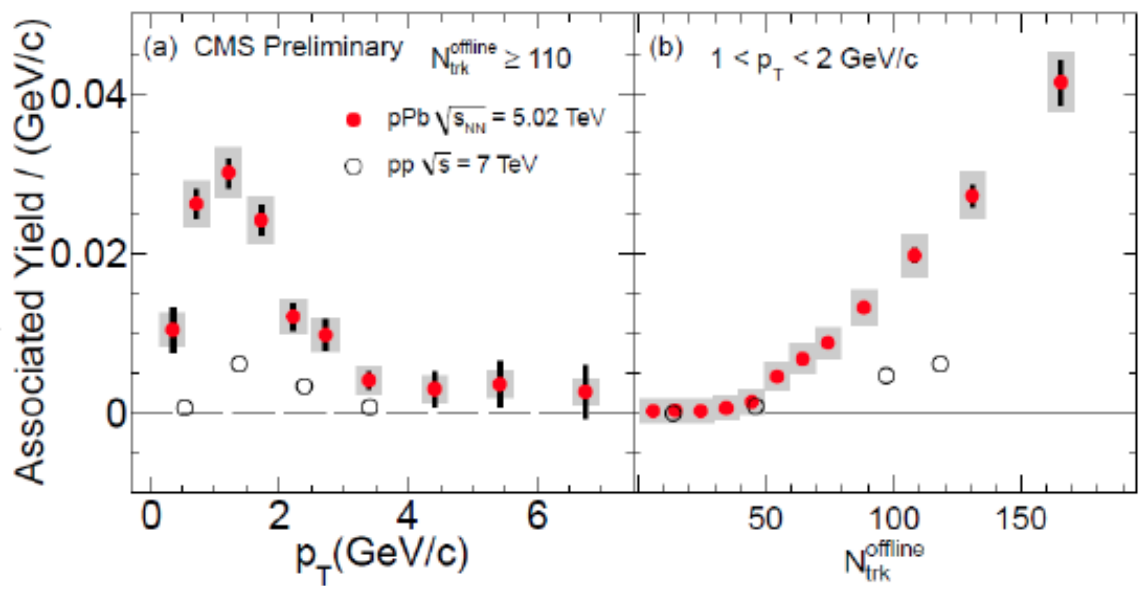


What about p+A ?

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



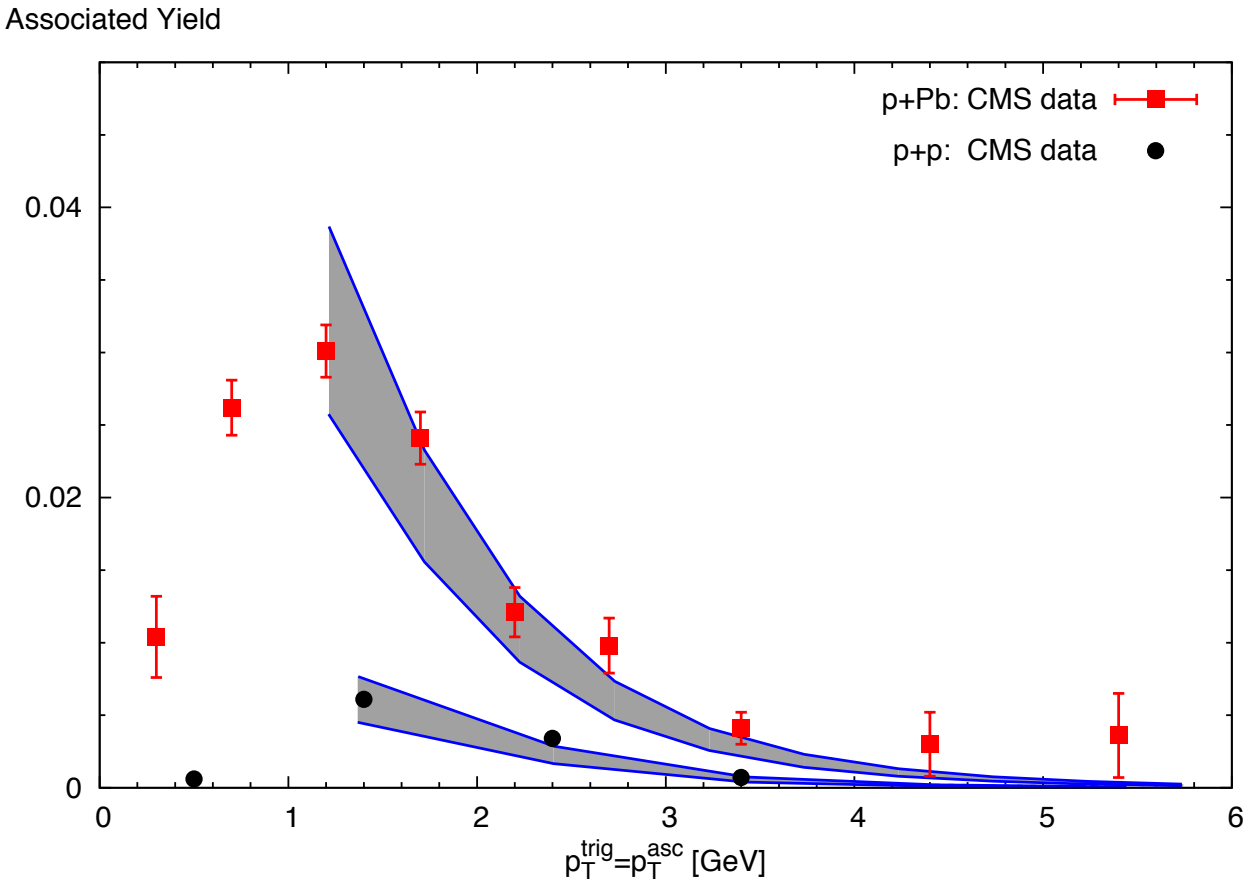




Ridge much bigger than p+p for the same multiplicity !

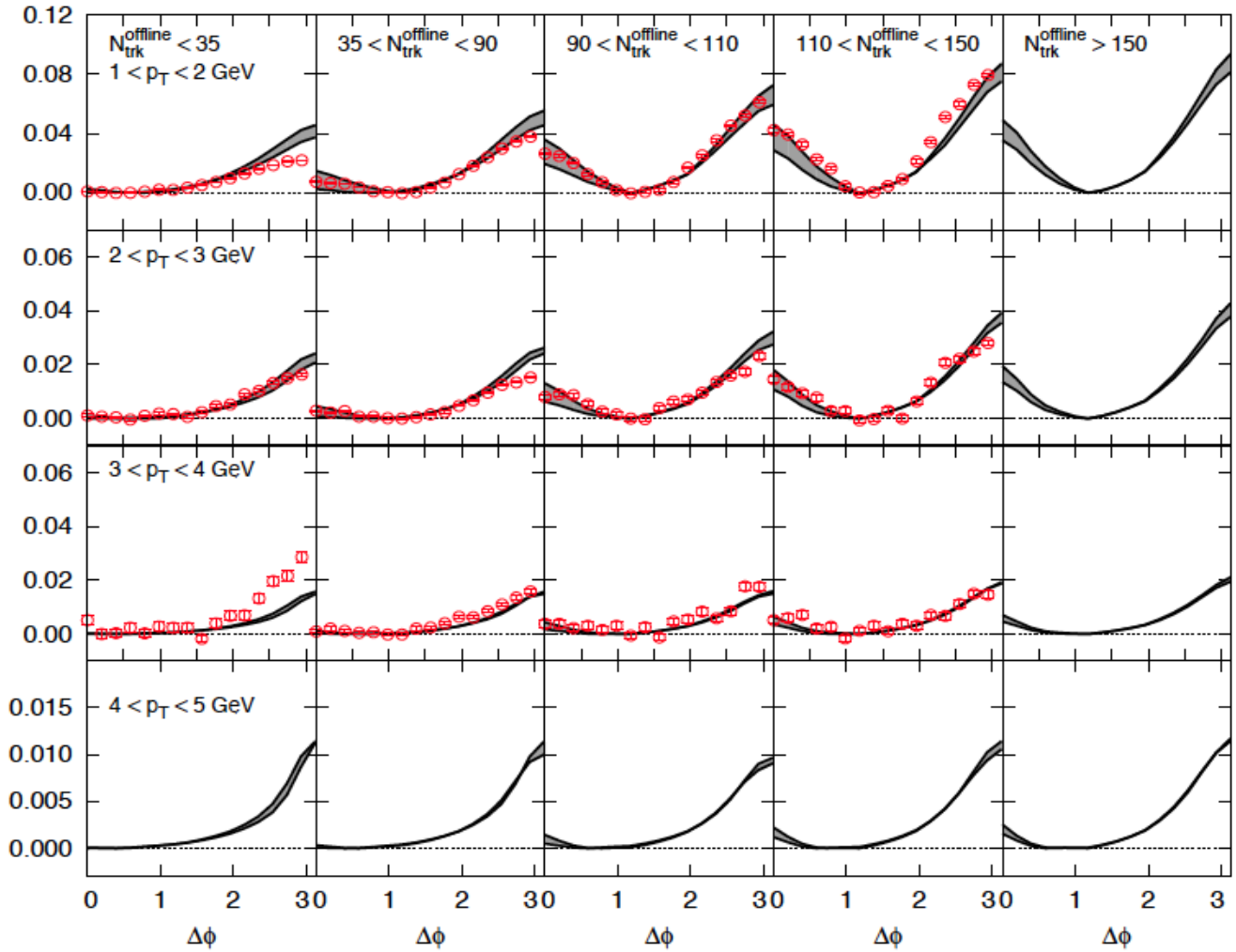
CMS p+Pb data

Dusling, RV: 1211.3701
1302.7018



CMS p+Pb data

Dusling, RV: 1211.3701
1302.7018



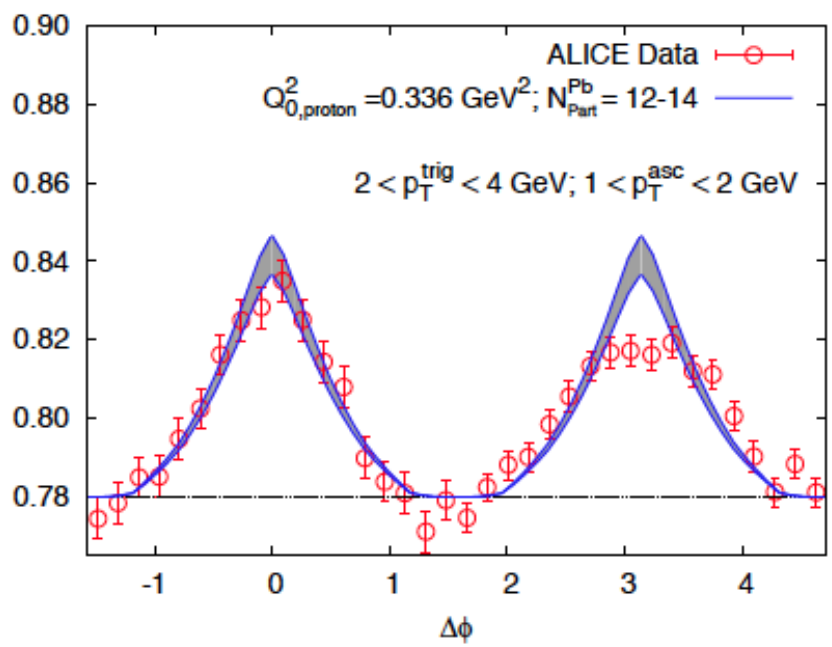
ALICE data on the p+Pb ridge

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 40-60% centrality from most central events

–this gives dipole shape of correlation



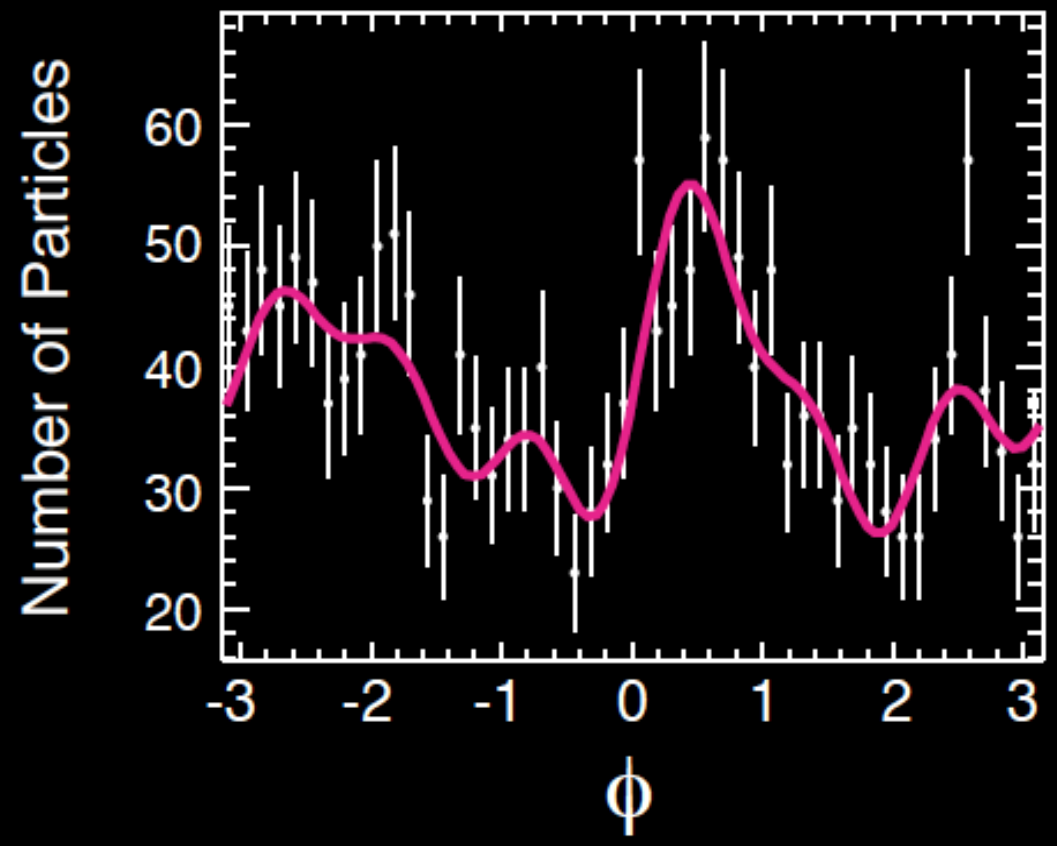
Different analysis technique from CMS/ATLAS

-- same normalization as for CMS/ATLAS

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

ANGULAR PARTICLE DISTRIBUTION

EXPERIMENTAL DATA: ATLAS COLLABORATION

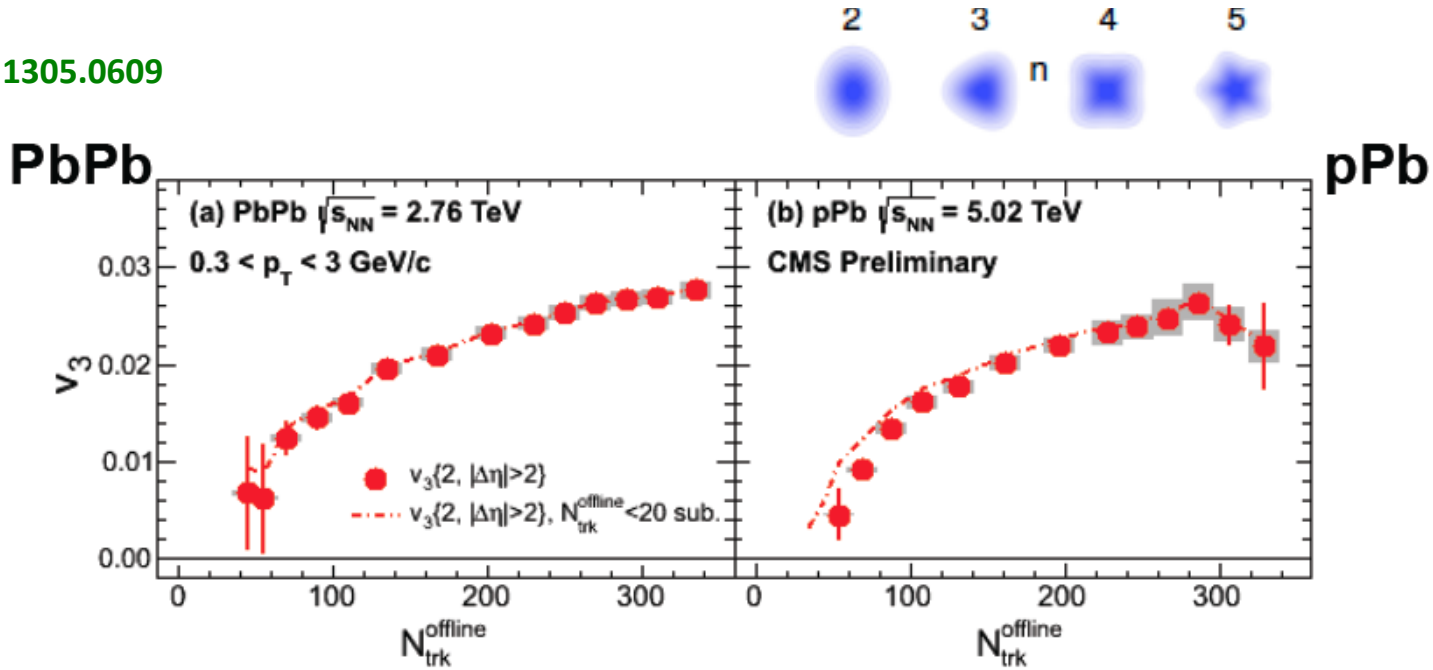


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots\right)\right)$$

Likewise,decompose two particle correlations in a Fourier series Cos(nΔΦ)…

Striking data presented by CMS

CMS arXiv:1305.0609

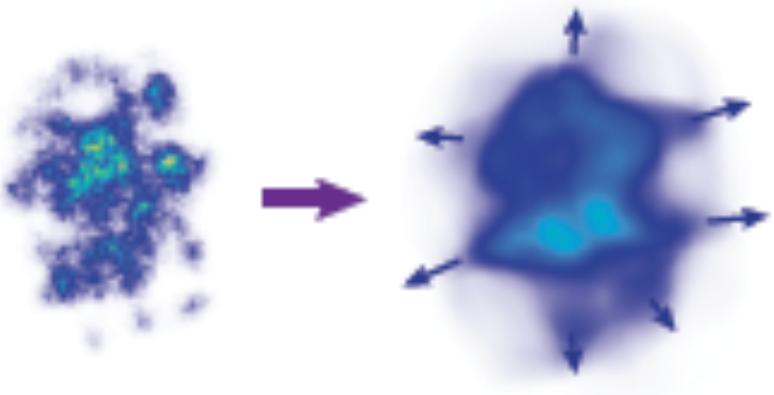


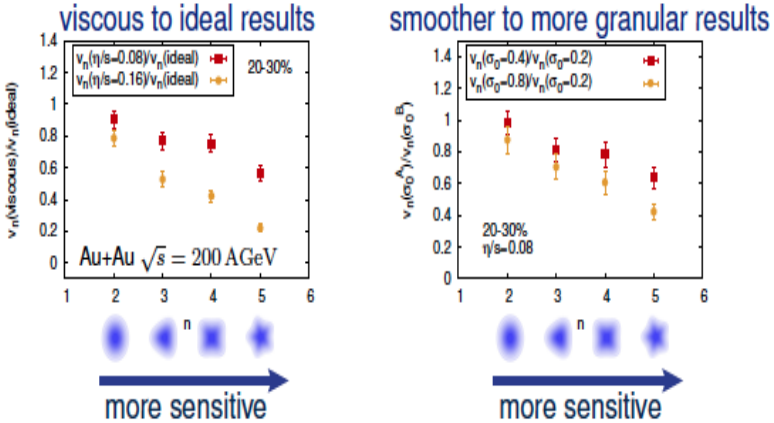
A non-zero (odd moment) v_3 is not obviously obtained from the Glasma graphs, which give only even moments.

Identical to those in A+A *peripheral* collisions

Is it an indication of flow ?

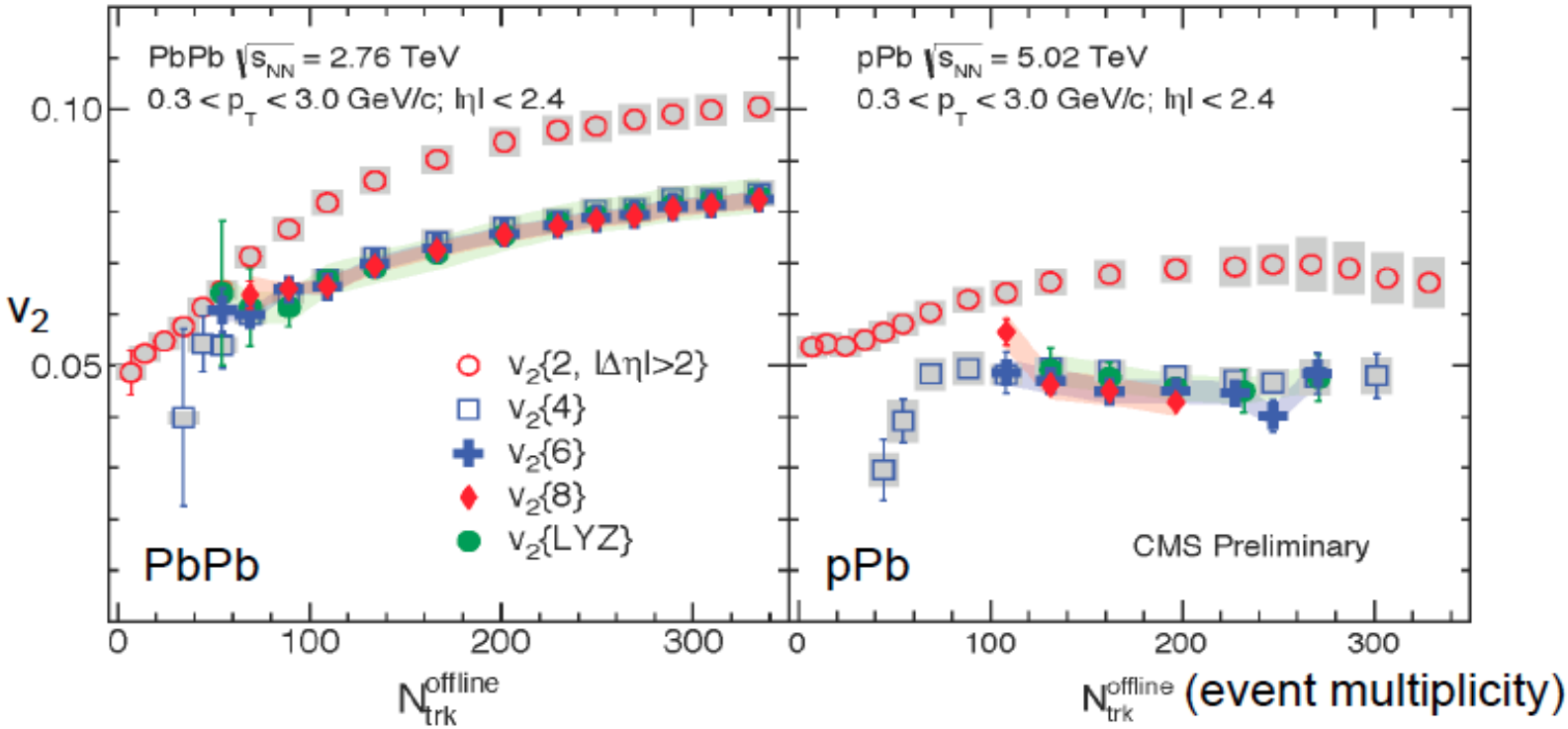
Hydrodynamics in p+A collisions?





Hydrodynamics efficiently converts spatial anisotropy into momentum anisotropy

A striking result at Quark Matter 2014



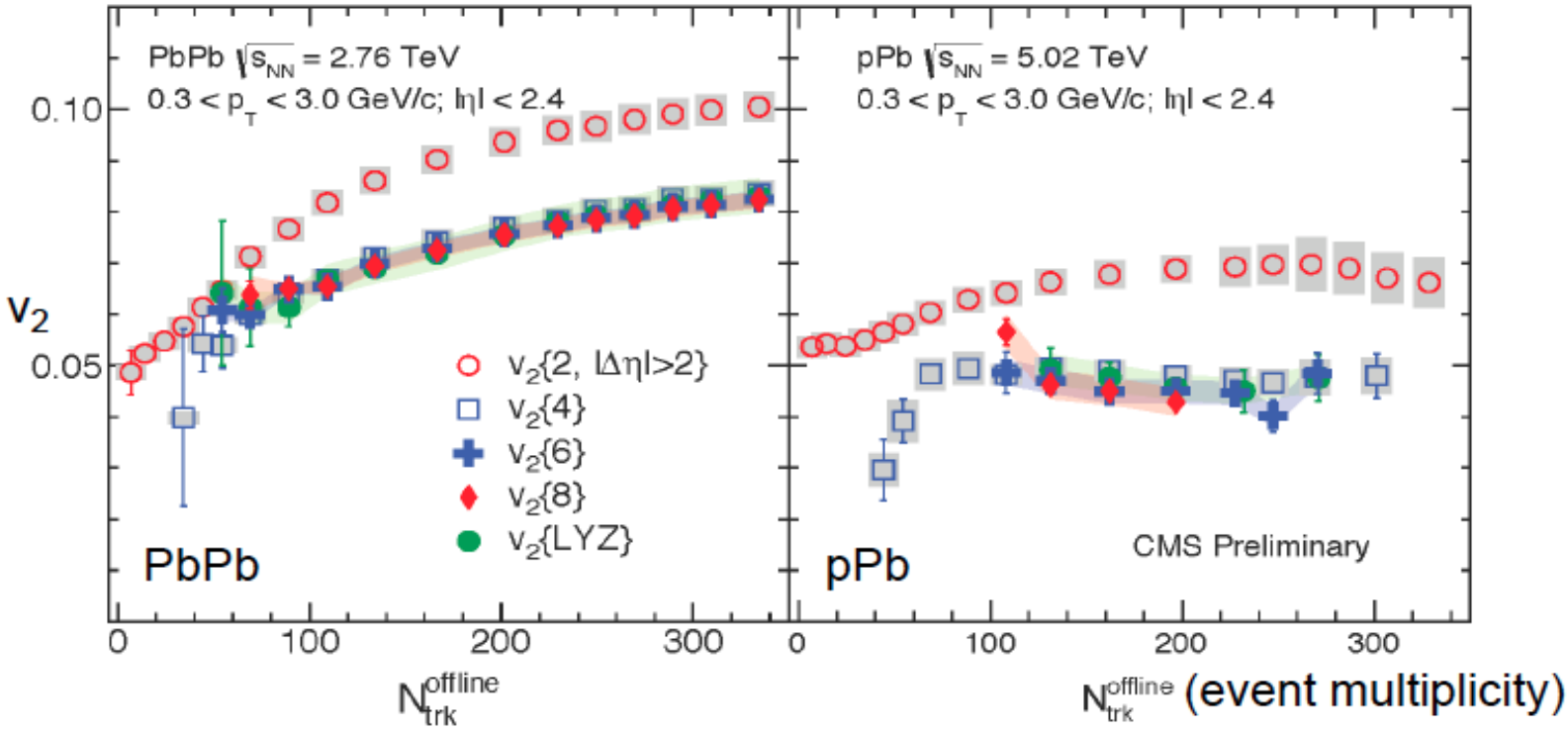
A number of simple models of eccentricities give $\varepsilon\{4\} \approx \varepsilon\{6\} \approx \varepsilon\{8\}$

"Linear response" $v_n\{m\} \approx c_n \varepsilon_n\{m\}$ **possible explanation of effect?**

Natural in ideal hydro—is it more generic ?

Bzdak,Bozek,McLerran, arXiv:1311.7325
Bzdak, Skokov, arXiv: 1312.7349
Li, Ollitrault, arXiv:1312.6555,
Basar,Teaney, arXiv:1312.6770

A striking result at Quark Matter 2014



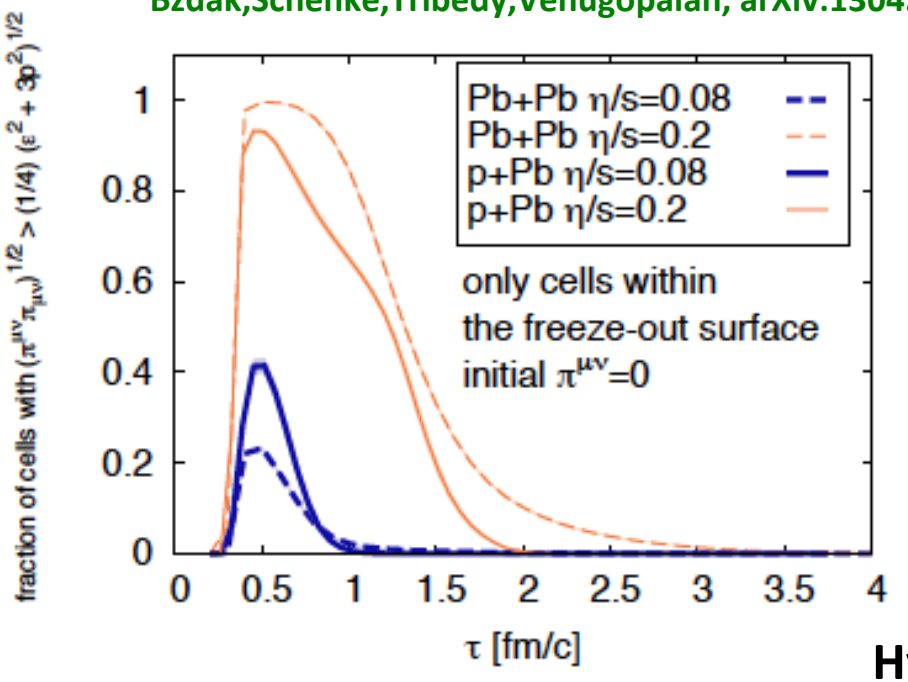
We may be comparing apples and oranges. The integrated v2 shown is sensitive to low momenta –

Some sort of hydro may be a good effective theory of low momenta

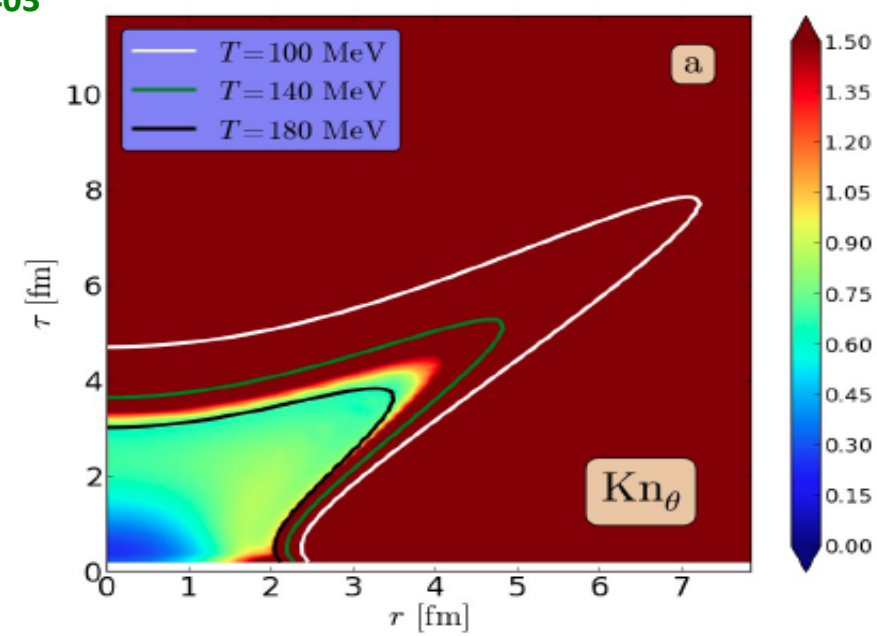
Hydro in small size systems: sensible or not ?

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

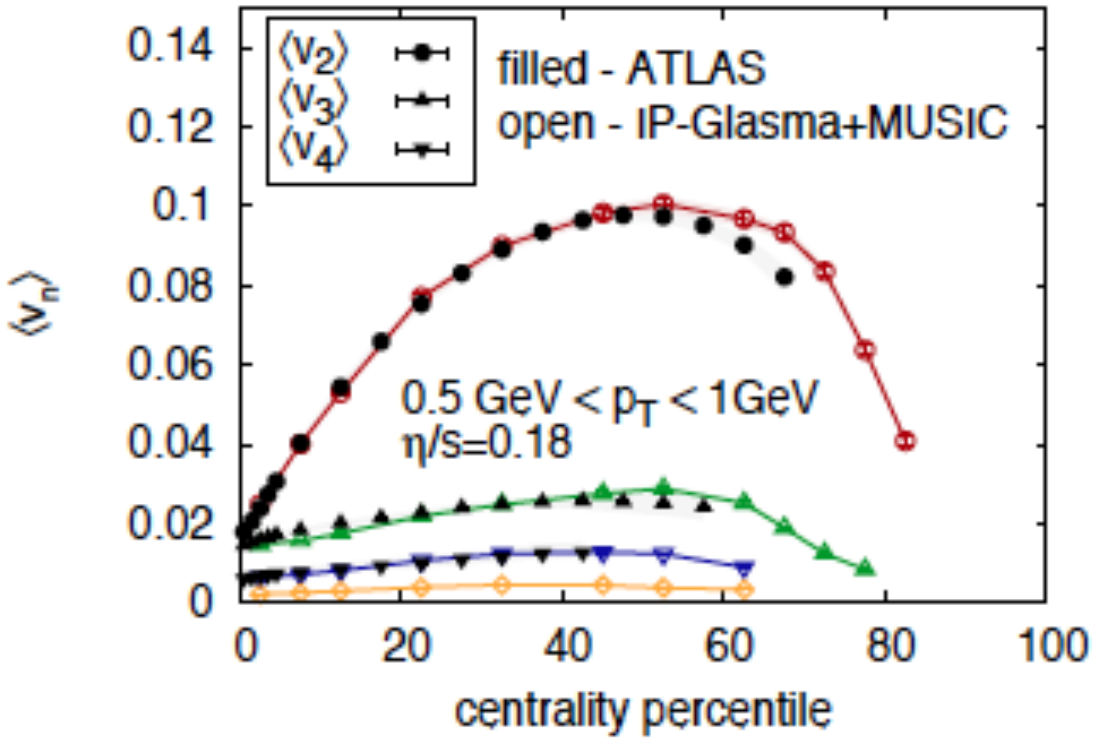
$$R^{-1} \propto (\Pi^{\mu\nu}\Pi_{\mu\nu})^{1/2}/(\epsilon^2 + 3P^2)^{1/2}$$

$$\mathrm{Kn} = \frac{\tau_\pi}{L} \quad ; \quad \tau_\pi \propto \frac{\eta}{sT}$$

IP-Glasma+MUSIC model in A+A

IP-Glasma= initial state
MUSIC=event.by.event. hydro

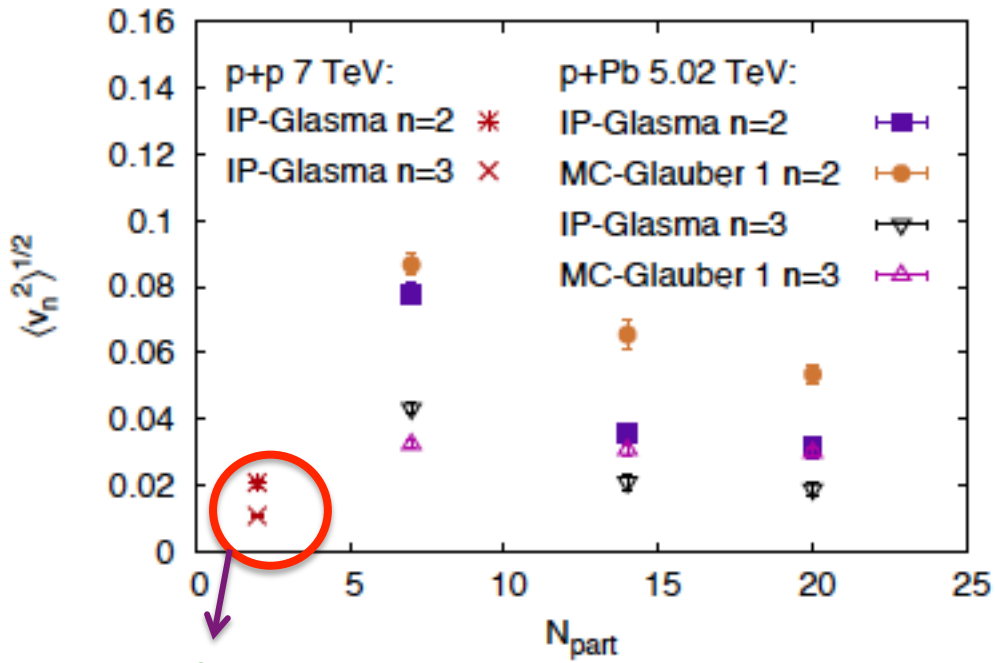
Schenke,Venugopalan, arXiv:1405.3605



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

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

Bzdak,Schenke,Tribedy,Venugopalan: 1304.3403



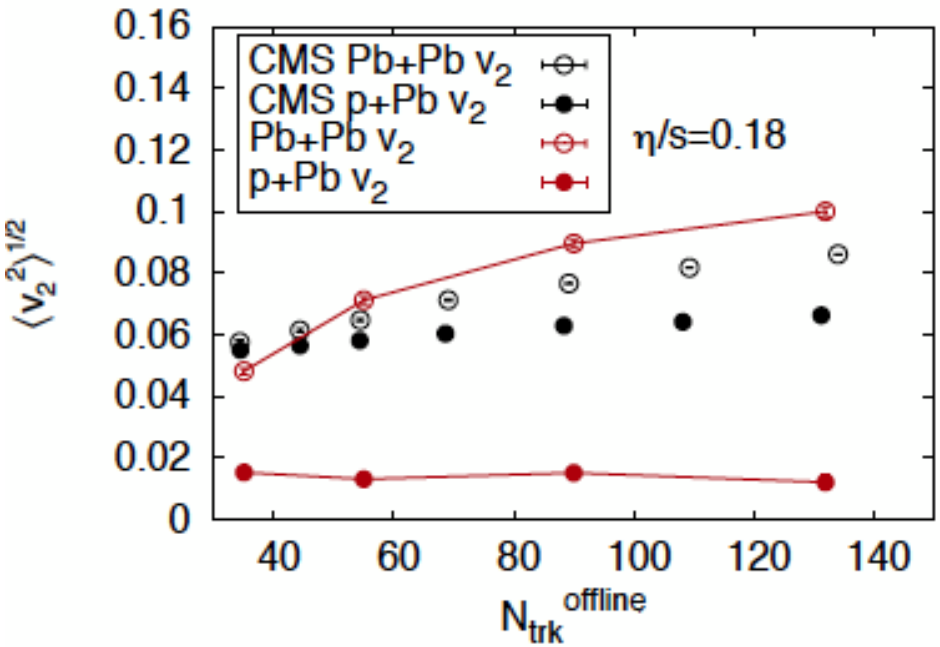
p+p at b=0

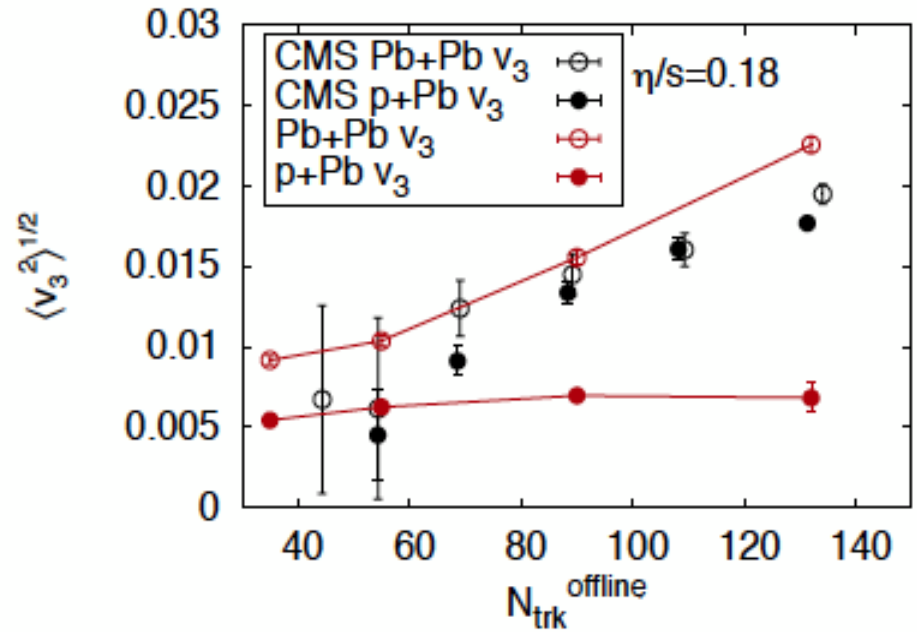
IP-Glasma+ MUSIC (hydro) gives much less v_2 than Glauber models that have significantly larger spatial sizes and shapes

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

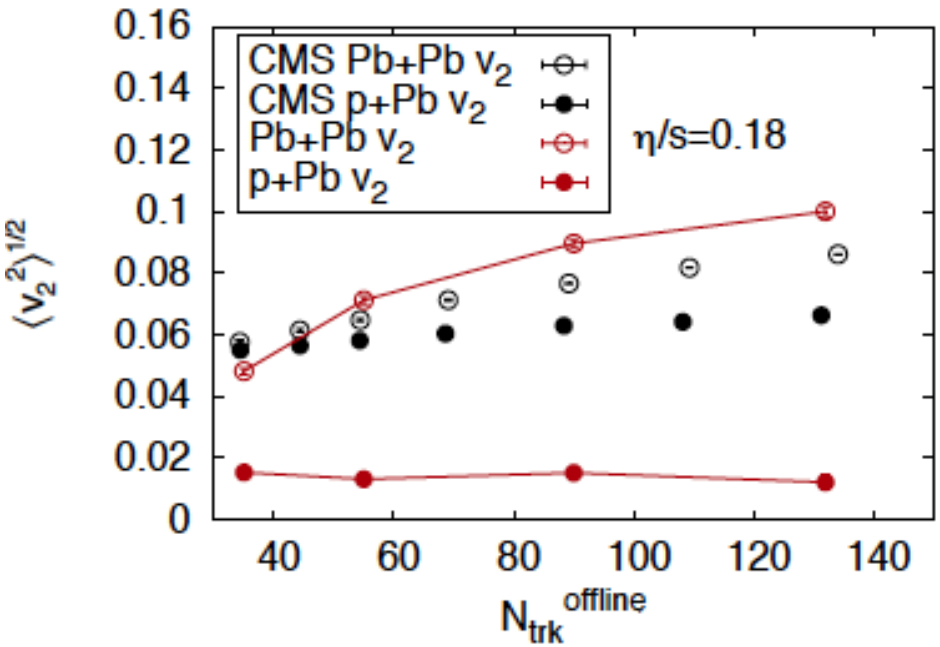


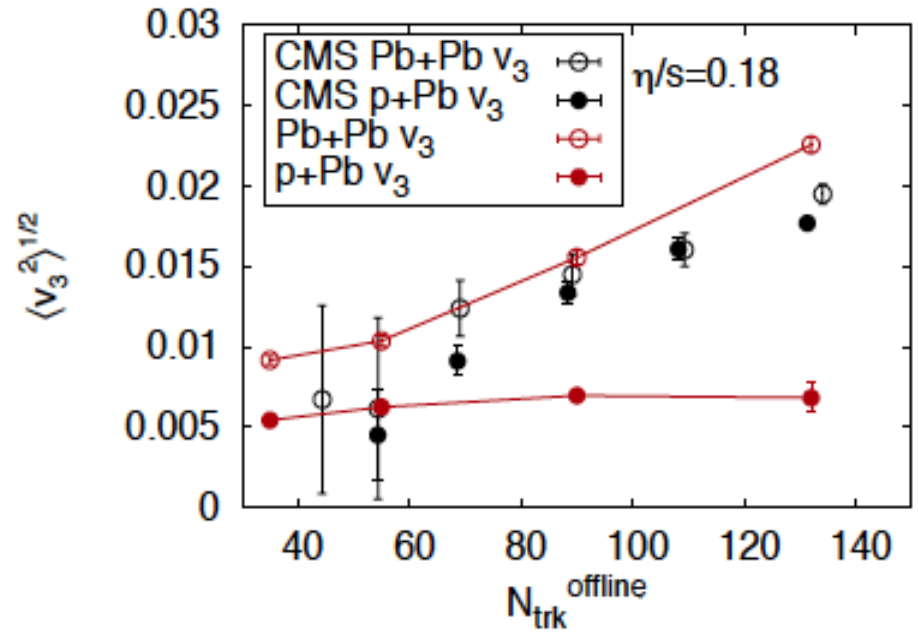


In contrast to A+A, both shape and magnitude of
IP-Glasma+MUSIC p+Pb results completely off from data

The ridge: flow in p+Pb?

Schenke and Venugopalan, arXiv:1405.3605





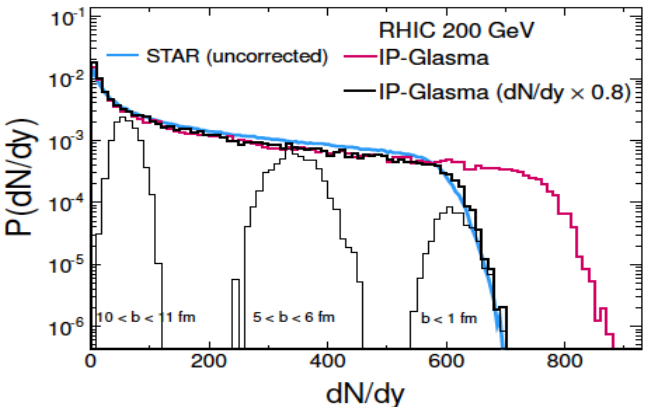
In contrast to A+A, both shape and magnitude of IP-Glasma+MUSIC p+Pb results completely off from data

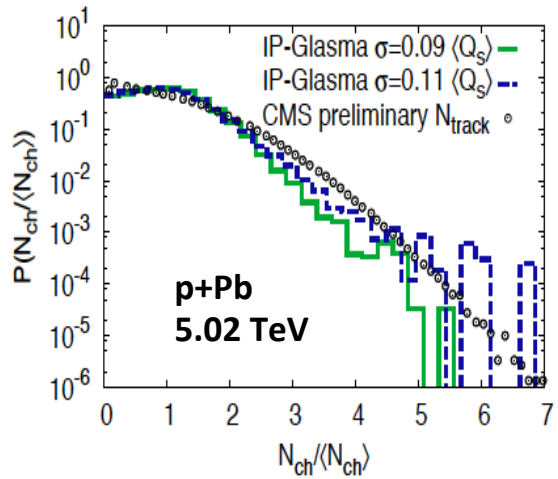
Maybe shapes are treated incorrectly in IP-Glasma ? Note they seem off even for multiplicites where the IP-Glasma multiplicity distribution agrees with the data…

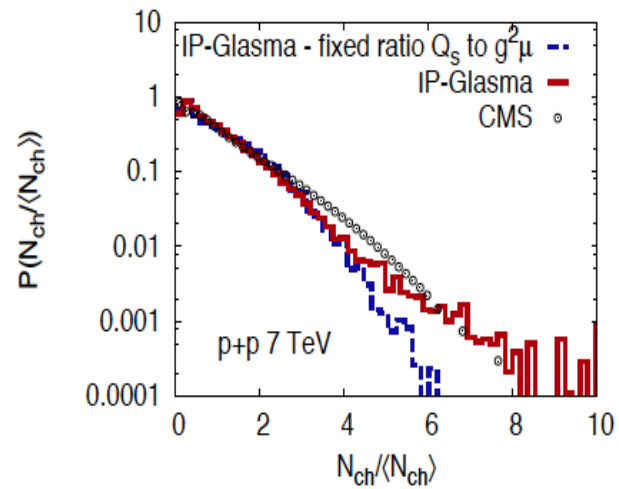
Alternative: hydro shouldn't work for small size systems?

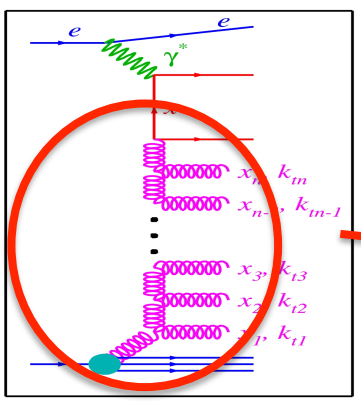
IP-Glasma model: multiplicity distributions

Schenke,Tribedy,Venugopalan, arXiv 1311.3636



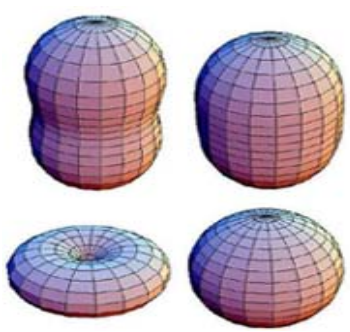






Color charge fluctuations: different color configurations for same gluon number

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…?

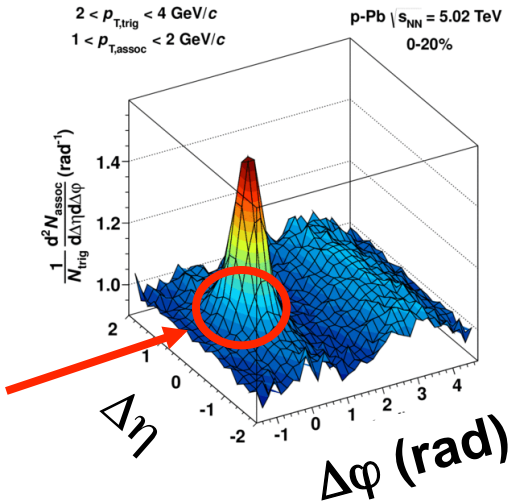
Additional puzzles for the collectivity picture in p+A

- **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 $\langle p_T \rangle$ seen even at $N_{ch} = 6$?**

Lots of data, theory speculations, and confusion…stay tuned !!

p-Pb

And the Jet at low p_T?



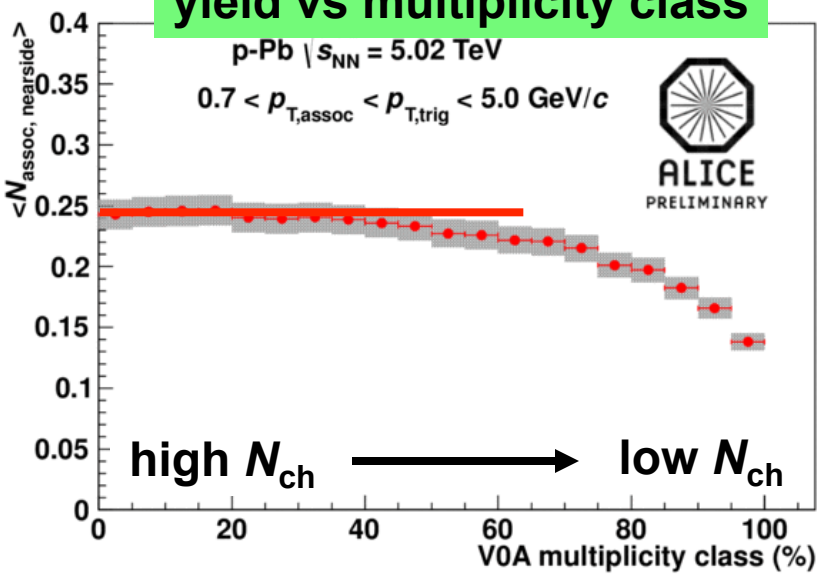
- No modification at high p_T
- Double ridge at low p_T
- Spectra modified at low p_T?

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

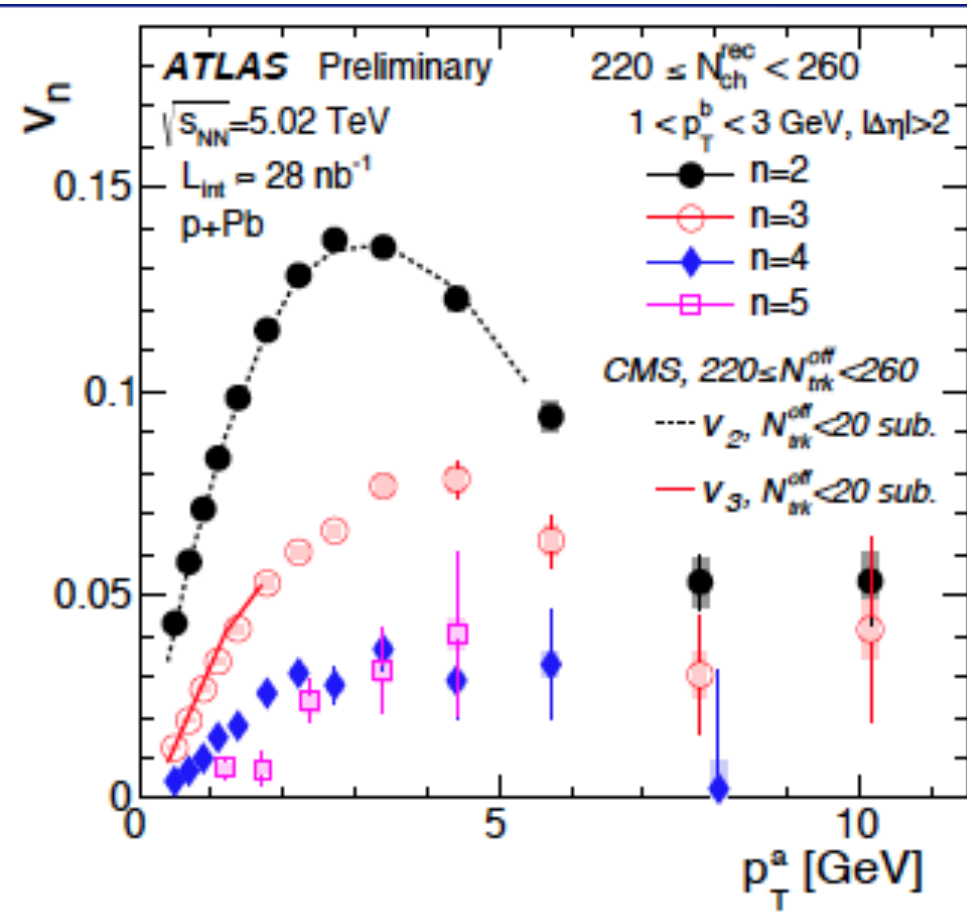
- Consistent with a picture of minijets in p-Pb collisions from superposition of NN collisions with incoherent fragmentation

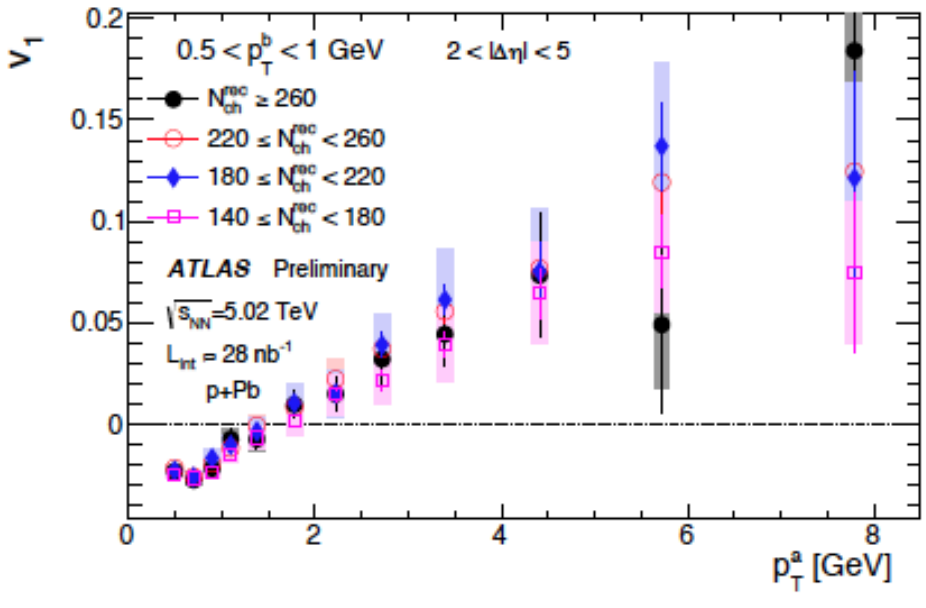
yield vs multiplicity class



→ L. Milano (Tue PM)

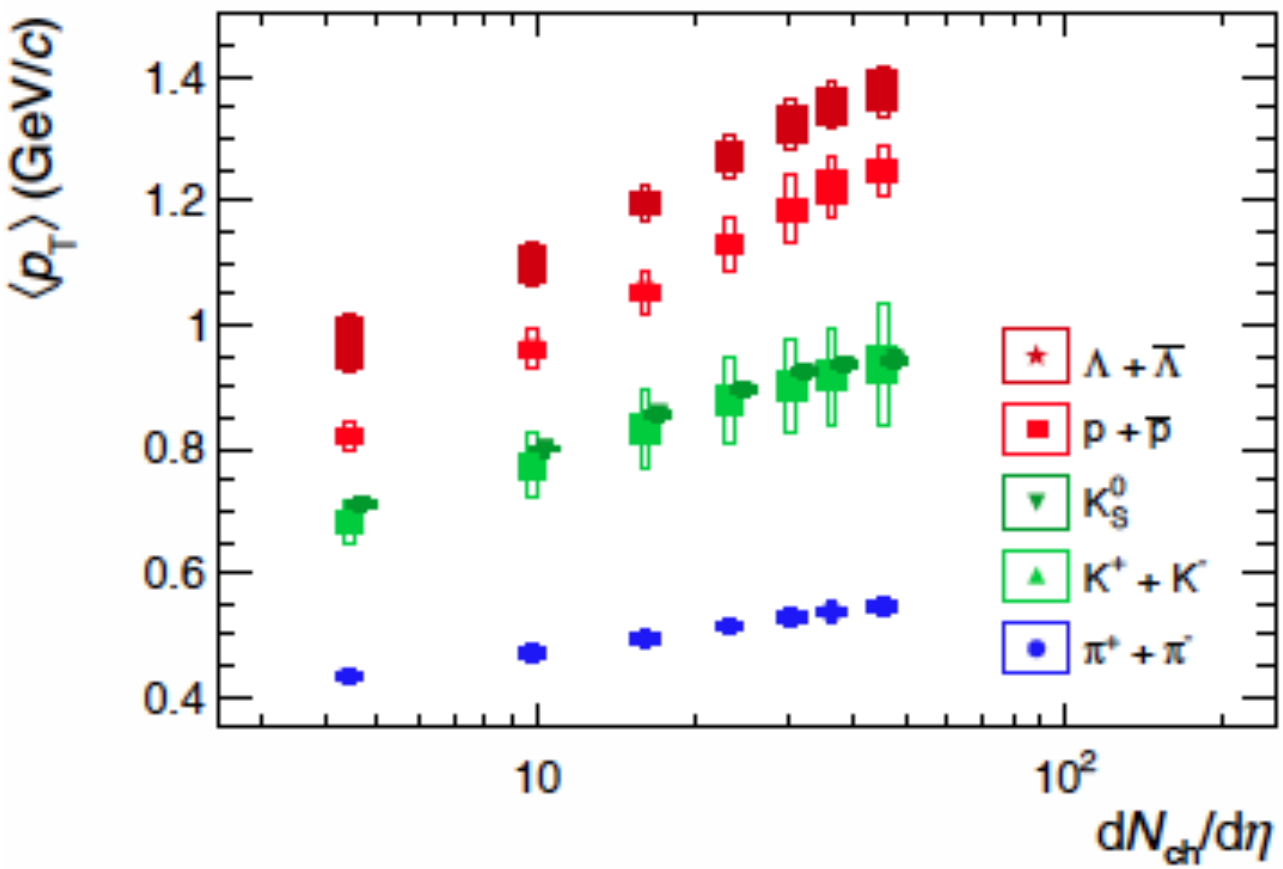
Significant v_n moments in p+Pb out to large p_T





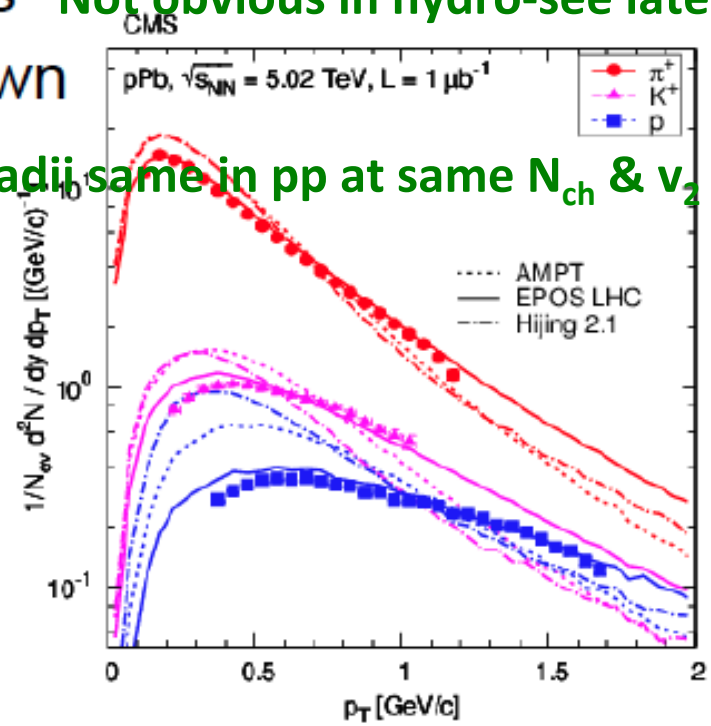
Mass ordering seen down to low N_{ch}

ALICE, 1307.6796



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!