Azimuthal quadrupole correlation from gluon interference in 200 GeV and 7 TeV p+p collisions

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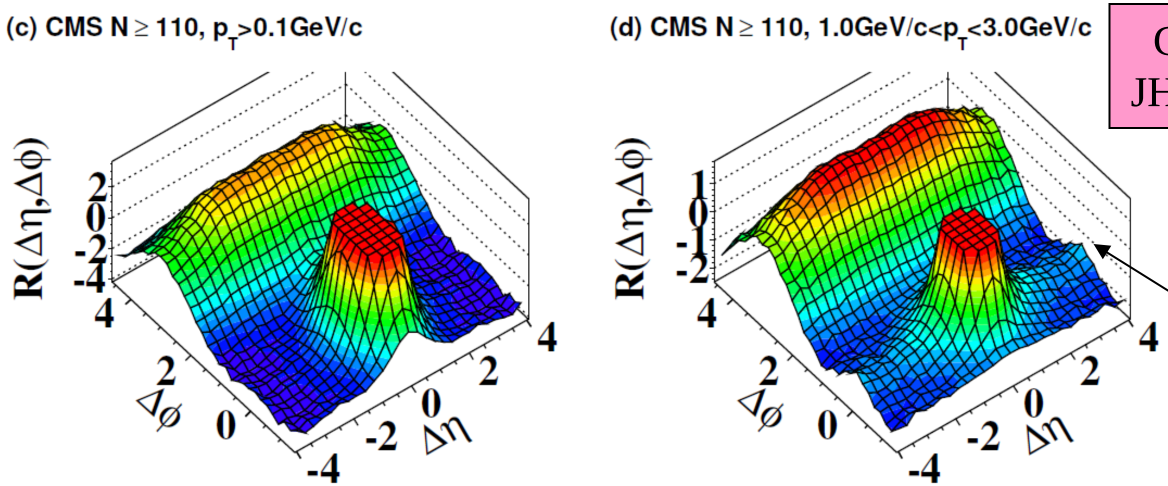
Introduction and Background

Unexpected observation of same-side, long-range η correlation
in high multiplicity p+p collisions at 7 TeV by CMS:

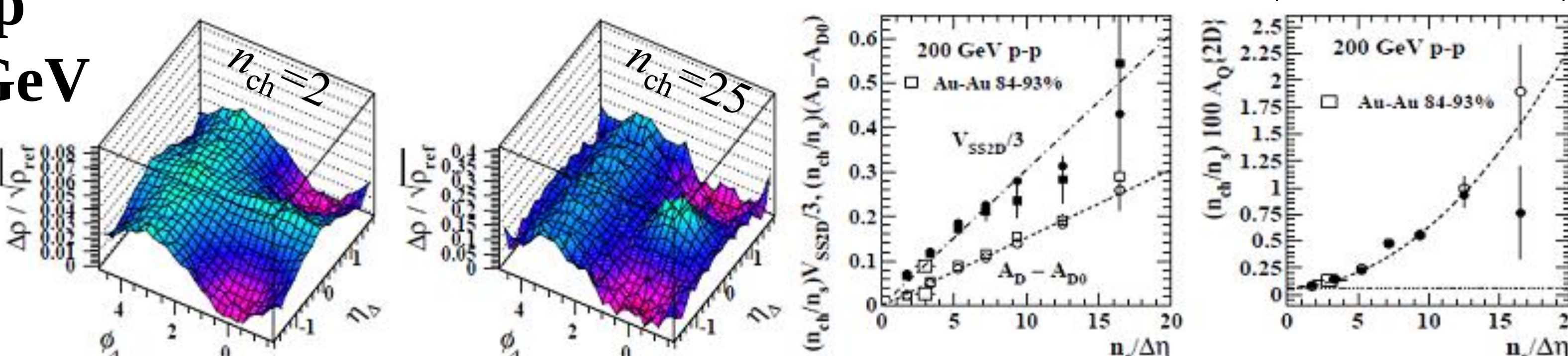
p+p
7 TeV



CMS Collaboration,
JHEP **1009**,091(2010).

Described with
$2A_Q\cos(2\Delta\phi)$
quadrupole

p+p
200 GeV



STAR Preliminary

Prindle and Trainor (STAR), Proc. XLIII Int. Symp.
Multiparticle Dynamics, p. 219 (2013); arXiv:1310.0408

Introduction and Background

- Same-side, long-range correlations (e.g. non-jet quadrupole) are ubiquitous in high energy, high multiplicity p+p and p+A (later in talk) "elementary" collision systems.

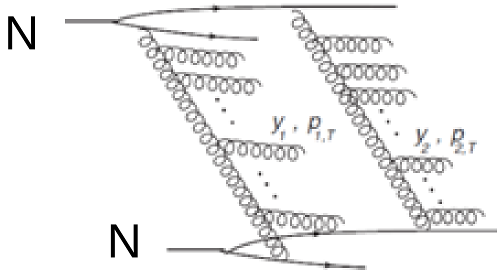
- Is this feature caused by hydro in p+p, p+A?
  e.g. Bozek, Broniowski, Eur. Phys. J C **71**, 1530 (2011); Phys. Lett. B **718**, 1557 (2013); Phys. Rev. C **85**, 014911 (2012).

- Or by initial-state process?
  e.g. **color-dipole model:** Kopeliovich, Phys. Rev. D **78**, 114009 (2008);
  CGC glasma and gluon interference: Dusling, Gelis, Lappi, McLerran, Venugopalan, Nucl. Phys. **A772**, 200 (2006); Acta. Phys. Pol. B **37**, 3253 (2006); Phys. Rev. D **87**, 051502(R) (2013); **87**, 094034 (2013);
  BFKL-Pomeron with gluon interference:
  Levin and Rezaeian, Phys. Rev. D **84**, 034031 (2011).

- Here, the Levin and Rezaeian BFKL Pomeron model with *interfering gluon* radiation is applied to the above correlation structure in p+p collisions.

Levin & Rezaeian BFKL* Pomeron model

E. Levin and A. H. Rezaeian, Phys. Rev. D **84**, 034031 (2011)



Two-BFKL Pomeron exchange with two-gluon emission & interference; parton showers

Single gluon density from two-parton showers

$$\frac{d\sigma}{dy\,dp_t^2} \approx \int d^2\vec{q}_t \left.\frac{d\sigma}{dy\,dp_t^2}\right|_{Q_t=0} \left\{1 + \frac{\vec{p}_t\cdot\vec{Q}_t}{q_t'^2} + 2\frac{\left(\vec{p}_t\cdot\vec{Q}_t\right)^2}{q_t'^4} + \cdots\right\} \quad (\vec{Q}_t \text{ expansion, momentum transfer})$$

$$\left(\vec{p}_t\cdot\vec{Q}_t\right)^2 \Rightarrow \cos 2(\phi - \hat{Q}_t) \Rightarrow \quad \boldsymbol{v_2}$$

anisotropy

Two-gluon density

$$\frac{d\sigma}{dy_1 dp_{t1}^2 dy_2 dp_{t2}^2} = \frac{1}{2}\int d^2\vec{Q}_t \underbrace{N_{Ph}^2(Q_t^2)}_{\text{probability for producing two parton showers}} \frac{d\sigma}{dy_1 dp_{t1}^2}\left(\vec{Q}_t\right)\frac{d\sigma}{dy_2 dp_{t2}^2}\left(-\vec{Q}_t\right)$$

*(Balitsky, Fadin, Kuraev, Lipatov)

Levin & Rezaeian BFKL Pomeron model

Two-gluon correlations from p + p collisions which produce two, BFKL parton showers:

$$\frac{\dfrac{d\sigma}{dy_1 dp_{t1}^2 dy_2 dp_{t2}^2}}{\dfrac{d\sigma}{dy_1 dp_{t1}^2}\dfrac{d\sigma}{dy_2 dp_{t2}^2}} \approx 1 + \frac{1}{2} p_{t1}^2 p_{t2}^2 \langle Q_t^4 \rangle \left\langle \frac{1}{q_t^4} \right\rangle^2 \left(2 + \cos 2(\phi_1 - \phi_2)\right) \equiv 1 + f \text{, for small } p_t$$

quadrupole

$$\text{where } \langle Q_t^4 \rangle \begin{cases} = \mu^4/15,\ \mu^2 = 0.8 \rightarrow 1.6\ \text{GeV}^2 \text{ (low gluon density)} \\ \rightarrow Q_S^4 \text{ (saturation limit, high gluon density)} \end{cases}$$

model uncertainty

$$\langle q_t^{-4} \rangle \approx Q_S^{-4} \text{ (integral dominated by the saturation region at RHIC and LHC)}$$

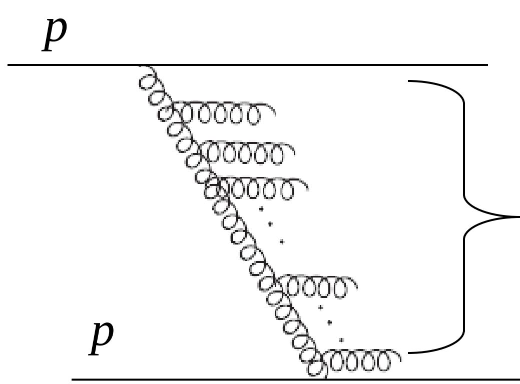
Numerical predictions require:

1) Multi-parton shower probabilities
2) Gluon saturation scale Q_S
3) Proper accounting of hard scattering

Assumptions:

1) Gluon → hadron (soft component), *local parton hadron duality*
2) # correlated pairs scale as *m(m-1)/2* for *m* parton showers
3) Two-component (Kharzeev-Nardi) soft + hard component multiplicity model

Multi-parton shower probabilities



Each shower produces a Poisson dist.

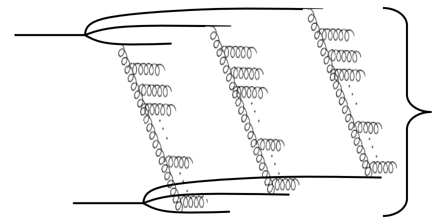
$$\mathscr{P}(n_s, \langle n_{ch} \rangle) \text{ (Poisson)}$$

$$\langle n_{ch} \rangle / \Delta\eta \text{ (minbias)}$$

$$= 2.5 \text{ at } 200 \text{ GeV}$$

$$= 5.78 \text{ at } 7 \text{ TeV}$$

For multi-parton showers:



$$\mathscr{P}(n_s, m\langle n_{ch} \rangle)$$

$$m = 1, 2, 3 \cdots$$

Event ensemble: $\sum_m P_m \mathscr{P}(n_s, m\langle n_{ch} \rangle)$

Include hard scattering component:

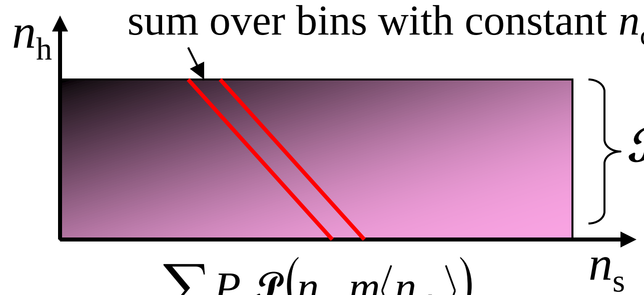
Soft+hard components in 200 GeV minbias p+p STAR, Phys. Rev. D **74**, 032006 (2006)

$$n_{ch} = n_s + n_h$$

$$\frac{n_h}{n_s} = \frac{\alpha n_{ch}}{\Delta\eta}, \ \alpha = 0.005$$

$$n_s = n_{ch} / (1 + \alpha n_{ch} / \Delta\eta)$$

Scatter plot of soft vs hard multiplicity for minimum-bias p+p collisions



$$\mathscr{P}(n_h, \bar{n}_h(n_s))$$

$$\bar{n}_h(n_s) = \frac{\alpha n_s^2 / \Delta\eta}{1 - \alpha n_s / \Delta\eta}$$

$$\sum_m P_m \mathscr{P}(n_s, m\langle n_{ch} \rangle)$$

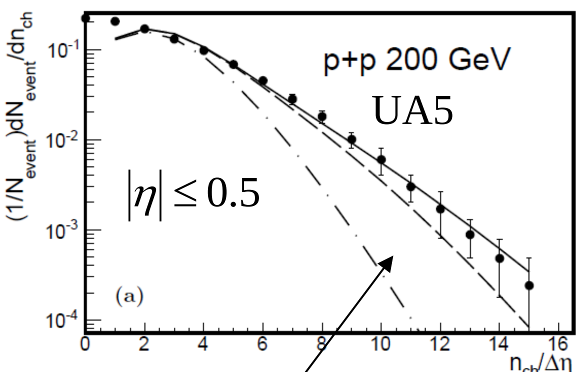
Multi-parton shower probabilities

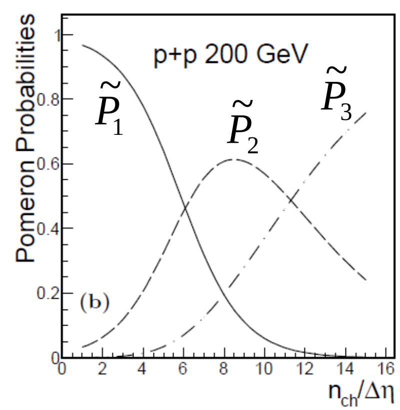
Adjust the multi-parton shower probabilities P_m to fit the frequency distribution.

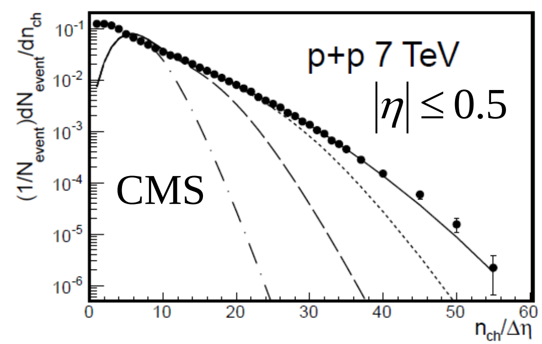
$$\frac{1}{N_{events}}\frac{dN_{events}}{dn_{ch}} = \sum_{n_s} \mathscr{P}\left(n_{ch}-n_s, \underbrace{\bar{n}_h(n_s)}_{\bar{n}_h(n_s)=\frac{\alpha n_s^2/\Delta\eta}{1-\alpha n_s/\Delta\eta}}\right) \sum_{m=1}^{M} P_m \mathscr{P}\left(n_s, m\langle n_{ch}\rangle\right), \text{ where } \sum_{m=1}^{M} P_m = 1,$$

$$\langle n_{ch}\rangle/\Delta\eta = 2.5 \text{ at } 200\,\text{GeV}$$
$$= 5.78 \text{ at } 7\,\text{TeV}$$

$\tilde{P}_m(n_{ch})$







1+2+3 Pomerons; $P_{1,2,3} = 0.802, 0.168, 0.030$

1+2+3+4 Pomerons

(These results are published in Phys. Rev. D **90**, 054013 (2014).)

Gluon saturation estimates

Basic idea:

Parton effective area $\sigma = \alpha_S(Q^2)\pi / Q^2$, Q is parton p_t

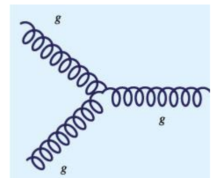
Area of nucleus in transverse plane $= \pi R_A^2$

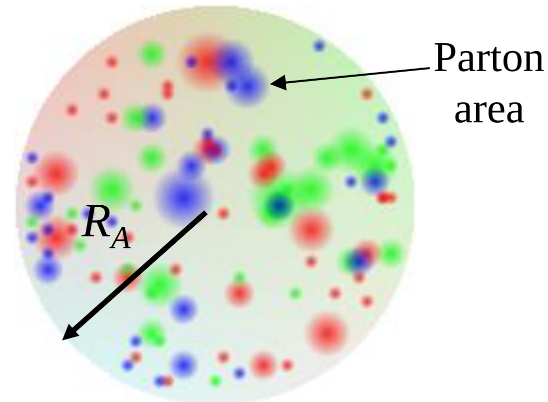
If #partons $N_A \sim \pi R_A^2 / \sigma$, then partons begin to overlap and $g + g \to g$ dominates.

Gluon density *saturates* at

$$Q_S^2 \sim \alpha_S(Q^2) N_A / R_A^2$$

$$= 1\text{-}2\ \mathrm{GeV}^2 \text{ for } 200\ \mathrm{GeV},\ 0\text{-}5\%\ \mathrm{Au+Au}$$



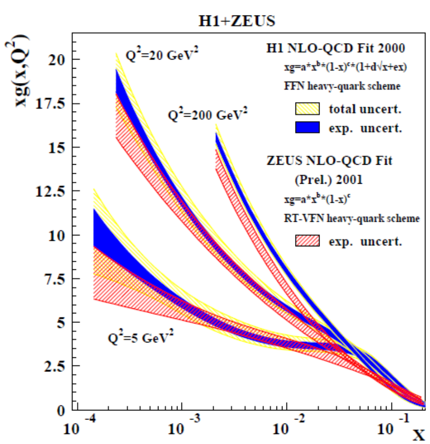


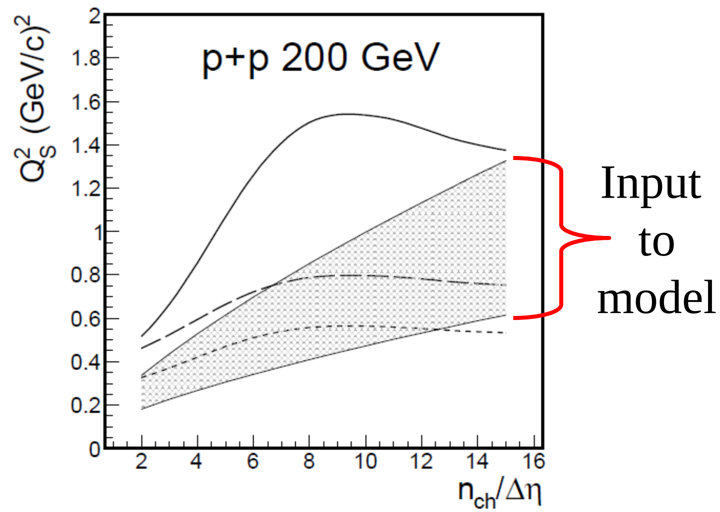
Low-x partons projected onto transverse plane

Scaling:

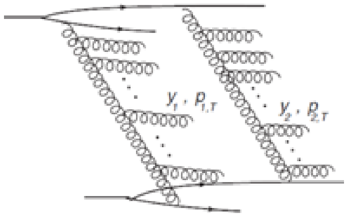
This result needs to be scaled to p + p for $\sqrt{s}$ and n_{ch} :

#partons $\propto N_{part}$ and n_{soft}, $\sqrt{s}$ from HERA





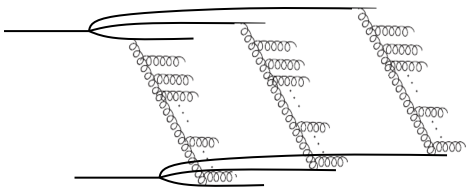
Application to p+p correlations



Two-gluon density from two parton showers (as in L & R)

$$\rho_{2Pom}(n_s';1,2)=\frac{n_s'-1}{n_s'}\rho_{2Pom}(n_s';1)\rho_{2Pom}(n_s';2)+\Delta\rho_{2Pom}(n_s';1,2)$$

$$=\frac{n_s'-1}{n_s'}\rho_{2Pom}(n_s';1)\rho_{2Pom}(n_s';2)(1+f);\ (f \text{ defined on slide 5})$$



Correlated gluon density from multi-parton showers

$$\Delta\rho_{mPom}(n_s;1,2)=\tfrac{1}{2}m(m-1)\Delta\rho_{2Pom}(\tfrac{2}{m}n_s;1,2)$$

With varying number of parton showers: $\Delta\rho(n_s;1,2)=\sum_m \tilde{P}_m(n_{ch})\Delta\rho_{mPom}(n_s;1,2)$

Single gluon density and two-gluon reference : $\sum_m \tilde{P}_m(n_{ch})\rho_{mPom}(n_s;1) \Rightarrow \rho_{ref}(n_s;1,2)$

Construct $\Delta\rho/\rho_{ref}$, integrate over p_{t1}, p_{t2}, obtain the quadrupole amplitude from

$$\frac{n_{ch}}{2\pi\Delta\eta}\frac{\Delta\rho}{\rho_{ref}}=2A_Q\cos 2(\phi_1-\phi_2)+\cdots \text{(fitting model elements)}$$

$$A_Q(n_{ch})=\frac{1}{2}\frac{n_{ch}}{2\pi\Delta\eta}\sum_{m=1}^{M}\tilde{P}_m(n_{ch})\tfrac{1}{2}m(m-1)\left(\frac{2n_s/m-1}{m(n_s-1)}\right)\langle p_t^2\rangle^2 F(Q_S^2(n_{ch}))$$

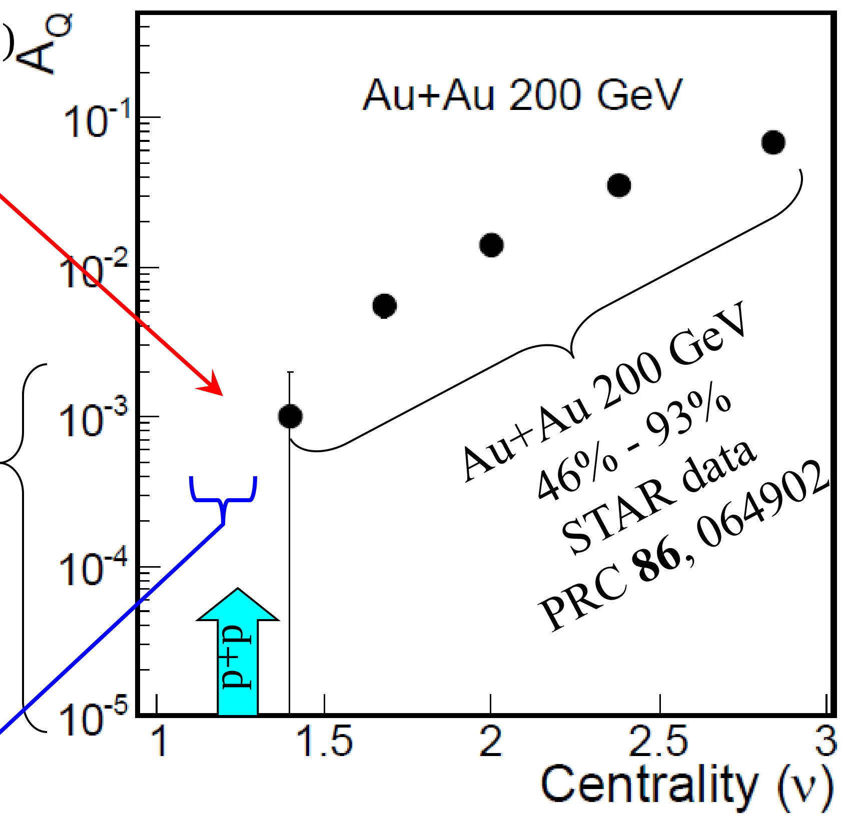
where

$$F(Q_S^2(n_{ch}))= \begin{cases} Q_S^{-4}(n_{ch}) \text{ in the dense, saturation limit} \\ (\mu^4/15)Q_S^{-8}(n_{ch}) \text{ for lower gluon densities} \end{cases}$$

Results for 200 GeV p+p minbias

Quadrupole amplitude vs centrality

STAR preliminary (arXiv:1310.0408)
$A_{Q,mb}$ = 0.00135 +/– 0.00009
using pair weighted event averaging and the UA5 $|\eta|<0.5$ multiplicity frequency dist.



Prior to STAR's measurement the only A_Q estimates for p+p were from Au+Au extrapolation, which includes any value from 0 to 0.002

The L&R model predictions with range of Q_S and $<Q_t^4>$ uncertainty for $F(Q_S^2)$

increasing magnitude

$$\left\{ \begin{aligned} F &= Q_S^{-4} \\ &= (1.6\,\mathrm{GeV}^2/15)Q_S^{-8} \\ &= (0.8\,\mathrm{GeV}^2/15)Q_S^{-8} \end{aligned} \right\}$$

peripheral → central

$$\nu \equiv \frac{N_{bin}}{N_{part}/2}$$

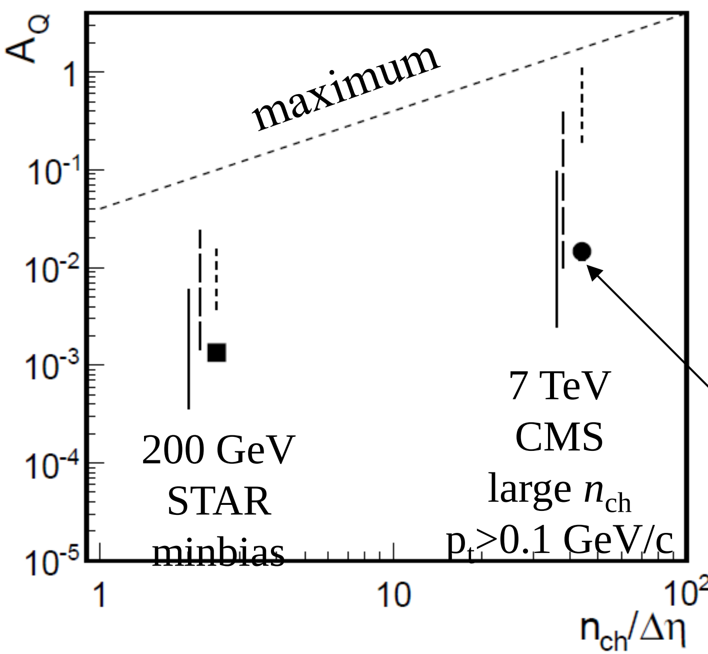
See: Phys. Rev. D ***90****, 054013 (2014).*

Results for 7 TeV p+p with large n_{ch}

The CMS "ridge" was observed in the higher n_{ch} events, specifically $N_{trk}^{offline} > 110$ for both the $p_t > 0.1$ GeV/c and $1.0 < p_t < 3.0$ GeV/c, for $|\eta| < 2.4$, corresponding to corrected $n_{ch}/\Delta\eta = 44$.

In Phys. Rev. D **84**, 034020 (2011) I showed that these data were best fit with a model including a quadrupole, which in the present definition equals:
$A_{Q,Ntrk>110,pt>0.1} = 0.0146 \pm 0.0007(\text{stat}) \pm 0.0022(\text{syst})$ ⇨ *"ridge" amplitude*

$$F = \begin{cases} Q_S^{-4} \\ (1.6\,\text{GeV}^2/15)Q_S^{-8} \\ (0.8\,\text{GeV}^2/15)Q_S^{-8} \end{cases}$$



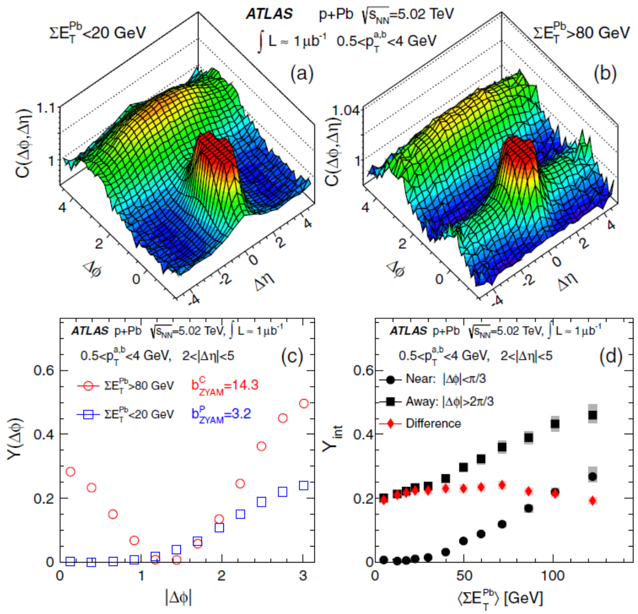
Energy/multiplicity trend correctly reproduced

(from fit model in PRD **84**, 034020)

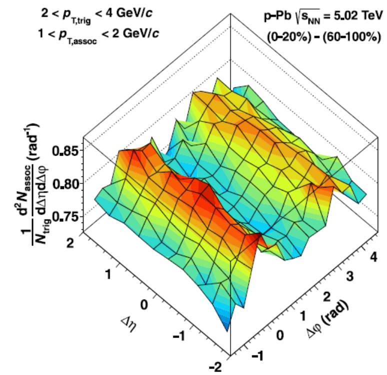
*See: Phys. Rev. D **90**, 054013 (2014).*

Extension to p+Pb, d+Au collisions

ATLAS, Phys. Rev. Lett. **110**, 182302 (2013)

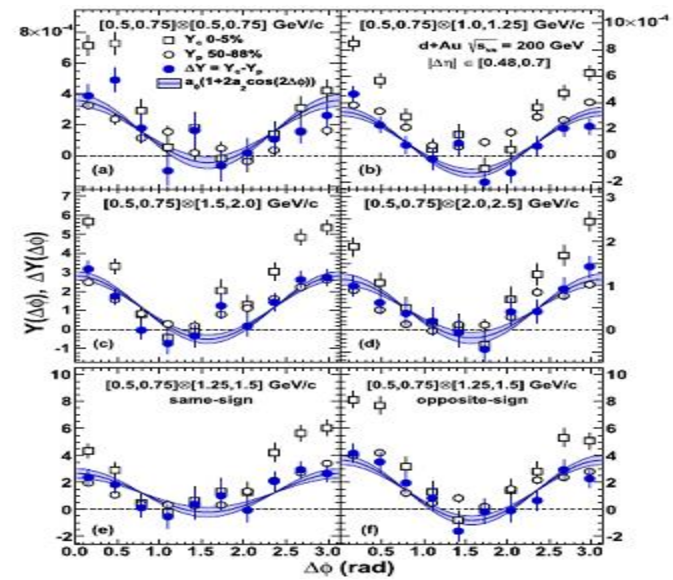


ALICE, Phys. Lett. B **719**, 29 (2013)

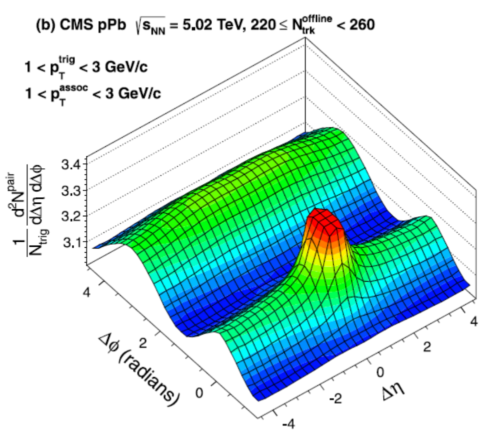


large – small N_{ch}
↓
quadrupole

PHENIX, Phys. Rev. Lett. **111**, 212301 (2013);
d+Au 200 GeV – azimuth projections & quadrupole

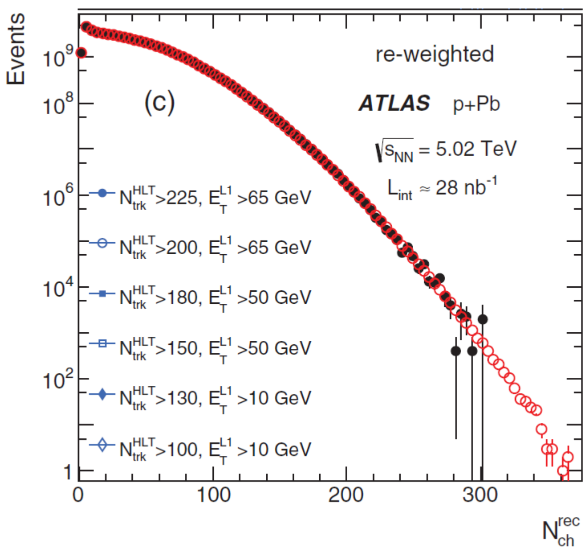


CMS, Phys. Lett. B **724**, 213 (2013)



Extension to p+Pb, d+Au collisions

ATLAS, Phys. Rev. C **90**, 044906 (2014)



Initial, *naïve* approach:

1) Analyze multiplicity frequency distribution estimating parton shower probabilities
2) Estimate Q_S via N_{part} scaling
3) Use L&R equation for $A_Q(N_{ch})$

$$A_Q(n_{ch}) = \frac{1}{2}\frac{n_{ch}}{2\pi\Delta\eta}\sum_{m=1}^{M}\tilde{P}_m(n_{ch})\,\tfrac{1}{2}\,m(m-1)\left(\frac{2n_s/m-1}{m(n_s-1)}\right)\left\langle p_t^2\right\rangle^2 F(Q_S^2(n_{ch}))$$

where

$$F(Q_S^2(n_{ch})) = \begin{array}{l} Q_S^{-4}(n_{ch}) \text{ in the dense, saturation limit} \\ \left(\mu^4/15\right)Q_S^{-8}(n_{ch}) \text{ for lower gluon densities} \end{array}$$

Comments and Conclusions

- v_2 varies between 0.05 – 0.07 for both datasets; <u>*large*</u> and similar to that in A+A. $$A_Q = \frac{n_{ch}}{2\pi\Delta\eta} v_2^2$$

- Predictions have large uncertainties; however, the L&R model can be falsified, but isn't so far.

- The correctly predicted energy,n_{ch} dependence is interesting because most factors in the model change by an order-of-magnitude or more between the two cases, *this is a significant test of the model*.

- The model with saturation limit for $\langle Q_t^4 \rangle$ is falsified.

- I hope that these apparently successful results will encourage the QCD community to continue to work on gluon radiation – interference models, and in the gluon saturation region in particular.

- The next step is to apply these ideas to the p + Pb and d + Au quadrupole correlations and to then determine if this new mechanism is relevant for v_2 in A+A.

(These results are published in Phys. Rev. D **90**, 054013 (2014).)