Two-particle correlations in high energy collisions.

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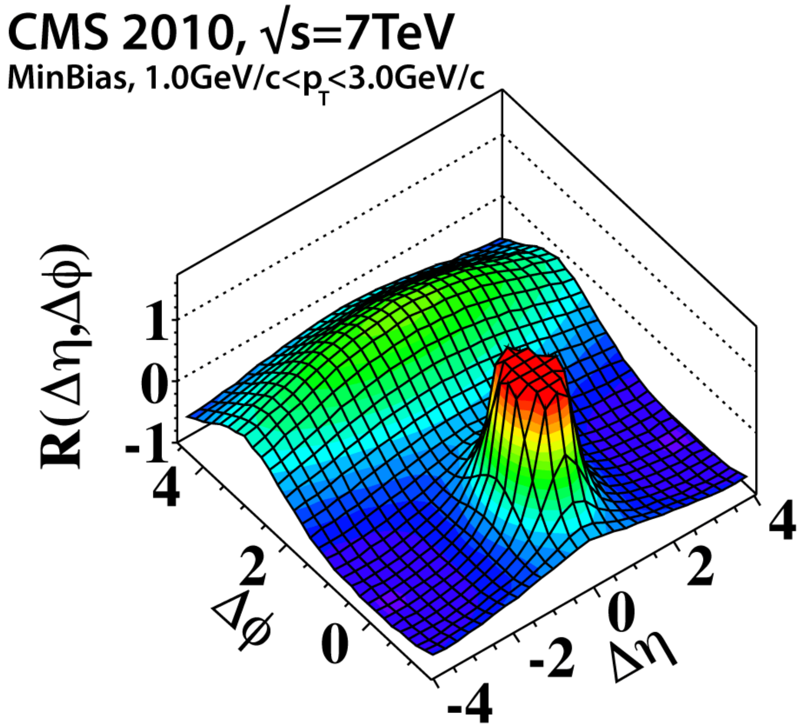
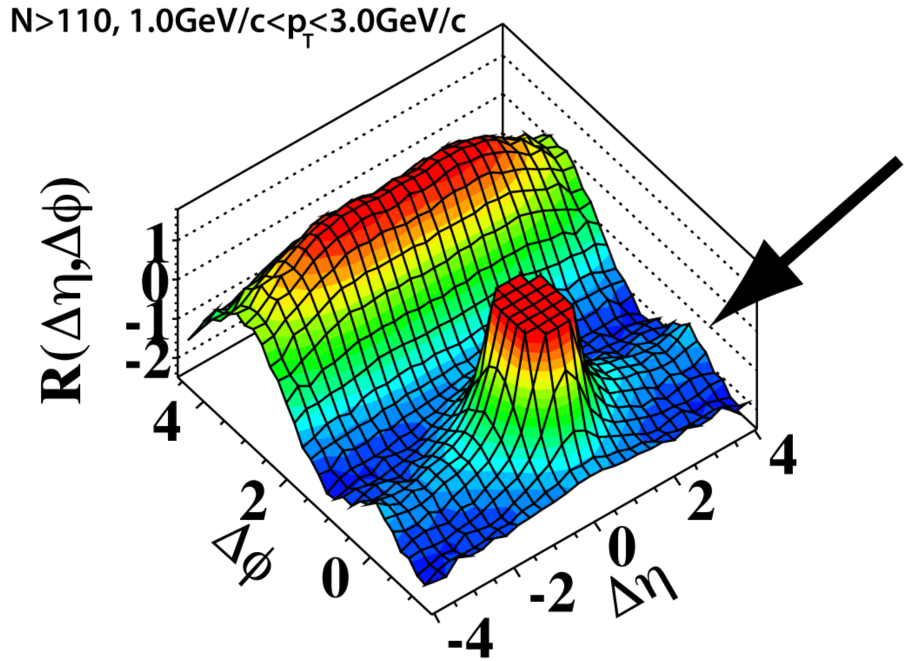
with Alex Kovner; arXiv:1012.3398 [hep-ph]

"RIDGE" - ANGULAR CORRELATIONS

Two particle correlations in $p-p$: long range in rapidity, near-side angular correlatons





"High multiplicity" collisions with over a hundred charged particles produced

Forward pick. Backward ridge at the angle π – back-to-back correlation.

Same-side ridge is a new "correlation" effect   PYTHIA and friends fail

a very similar phenomenon in heavy ion collisions at RHIC

Open questions

- **Origin of angular collimation?**
  Could be many. For sure explosive "wind" from hydro would lead to some.

- **Origin of long range rapidity correlations?**
  Causality: correlations exist in early stage of the collision (like in cosmology)

- **Do we see a sign of universality between $p-p$ and heavy ion collisions?**
  Hopefully Yes! High energy QCD implies this universality. In both experiments the effect emerges only when high densities are involved.

- **Do we see a collective phenomenon (QGP?) in $p-p$?**
  We don't know yet ...

Our Goal

To discuss some general features of gluon production at high energy.

We need to compute correlations in two-gluon inclusive production rate

$$\left[\frac{d^2N}{d^2p\, d\eta\, d^2k\, d\xi} - \frac{dN}{d^2k\, d\xi}\,\frac{dN}{d^2p\, d\eta}\right] / \frac{dN}{d^2k\, d\xi}\,\frac{dN}{d^2p\, d\eta}$$

Bad news: Nobody knows how to compute dense on dense, but we keep working on that

Good news: We do know quite a lot about dilute on dense (DIS)
For DIS, we do have QCD-derived formulae for multi-gluon production, including high energy evolution between produced gluons.

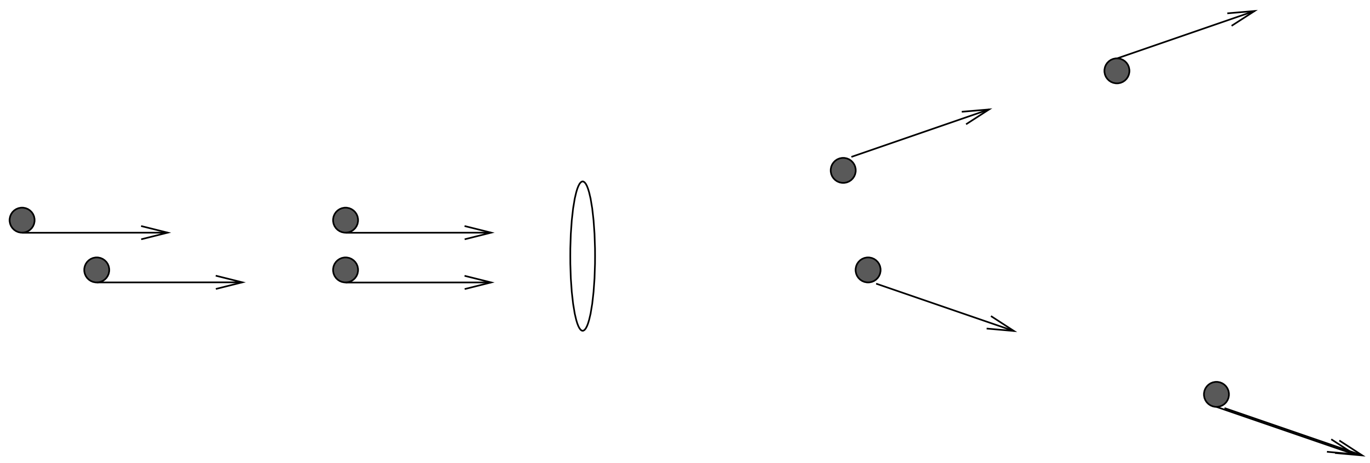
Here I talk about only one source for the observed phenomena, INITIAL CONDITIONS, as follows from quite general QCD-based considerations, but I have no quantitative results.

NAIVE PICTURE OF EIKONAL GLUON PRODUCTION

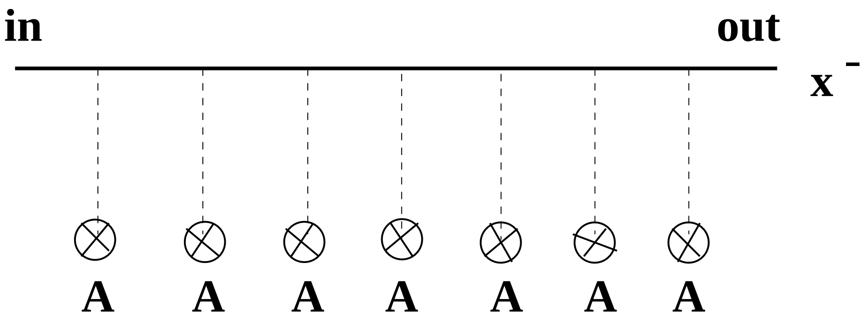
Long range rapidity correlations come for free with boost invariance

Incoming $|P\rangle$ is boost invariant: exactly the same gluon distribution at Y_1 and Y_2.
What happens at Y_1, happens also at Y_2: If it is probable to produce a gluon at Y_1, it is also probable to produce a gluon at Y_2.

But exactly by the same logic there must be angular correlations:
Gluons scatter on exactly the same target
If the first gluon is most likely to be scattered to the right, the second gluon at the same impact parameter will be also scattered to the right



Eikonal approximation



Eikonal scattering for all $k^+ \geq \Lambda$
Eikonal factor does not depend on k^+

$$|\mathbf{in}\rangle = |\mathbf{z}, \mathbf{b}\rangle \, ; \qquad |\mathbf{out}\rangle = |\mathbf{z}, \mathbf{a}\rangle \, ; \qquad |\mathbf{out}\rangle = \mathbf{S}\, |\mathbf{in}\rangle$$

For a composite projectile which has some distribution ρ_p of gluons in its wave function

$$\hat{\mathbf{S}} = \exp\left\{ \mathrm{i} \int_{\mathbf{x}} \rho_{\mathrm{p}} \, \alpha_{\mathrm{t}} \right\}$$

Eikonal scattering is a color rotation: for two gluons to scatter with the same S-matrix they have to be initially in the same color state and scatter from the same target field α_t

Eikonal scattering is rapidity independent!

TWO GLUON INCLUSIVE PRODUCTION

Using dilute projectile formulae, but thinking of it as being dense

$$\frac{\mathbf{dN}}{\mathbf{d^2pd^2kd}\eta\mathbf{d}\xi} = \langle\ \sigma(\mathbf{k})\ \sigma(\mathbf{p})\ \rangle_{\mathbf{P,T}}\ +\ \text{terms subleading in } \rho$$

for fixed configuration of projectile charges ρ and fixed target fields S

$$\sigma(\mathbf{k}) = \int_{\mathbf{z},\bar{\mathbf{z}},\mathbf{x_1},\bar{\mathbf{x}}_1} \mathbf{e}^{\mathbf{ik(z-\bar{z})}}\vec{\mathbf{f}}(\bar{\mathbf{z}}-\bar{\mathbf{x}}_1)\cdot\vec{\mathbf{f}}(\mathbf{x_1}-\mathbf{z})\ \Big\{\rho(\mathbf{x_1})[\mathbf{S}^\dagger(\mathbf{x_1})-\mathbf{S}^\dagger(\mathbf{z})][\mathbf{S}(\bar{\mathbf{x}}_1)-\mathbf{S}(\mathbf{z})]\rho(\bar{\mathbf{x}}_1)\Big\}$$

$$f_i(x-y) = \frac{(x-y)_i}{(x-y)^2}$$

$\sigma(k)$ as a unction of k has a maximum at some value $k = q_0$. Clearly then the two gluon production probability configuration by configuration has a maximum at $\mathbf{k} = \mathbf{p} = \mathbf{q_0}$.

This is the near side correlation!

The value of $\mathrm{q_0}$ depends on configuration, but the fact that $\mathbf{k} \simeq \mathbf{p}$ does not.

We expect $\mathbf{q_0} \simeq \mathbf{Q_s}$

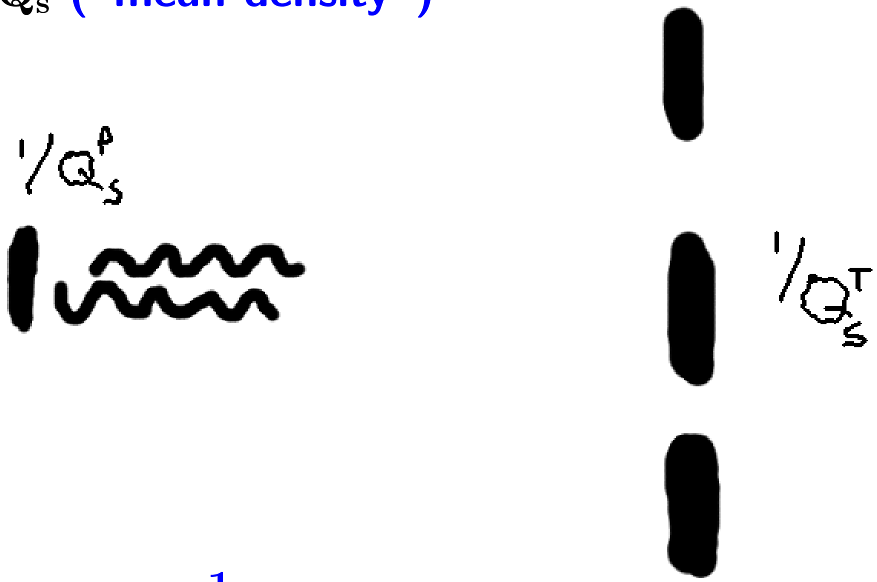
How big is the effect?

To be correlated two gluons have to be in the same incoming color state and have to scatter of the same target field

Transverse correlation length in the hadron $\mathrm{L} = 1/\mathrm{Q_s}$ ("mean density")

The correlated production $\propto 1/(\mathrm{Q_s^{max}})^2$,

while the total multiplicity $\propto \mathrm{S_A^{min}}$



$$\left[\frac{\mathrm{d^2N}}{\mathrm{d^2pd^2k}} - \frac{\mathrm{dN}}{\mathrm{d^2k}}\frac{\mathrm{dN}}{\mathrm{d^2p}}\right] \Big/ \frac{\mathrm{dN}}{\mathrm{d^2k}}\frac{\mathrm{dN}}{\mathrm{d^2p}} \propto \frac{1}{(\mathrm{Q_s^{max}})^2\,\mathrm{S_A^{min}}}\,.$$

Q_s grows with energy. Hence correlations should disappear with increasing energy. Less correlations at the LHC than at RHIC? Not obvious, because we fully ignored the flow.

Can we understand the large multiplicity and p_t window?

Qualitatively we probably can:

The energy of the collision is not high enough so that the "average" configurations of the proton wave function do not contain enough gluons at different rapidities and the same impact parameter for correlations to be observable. The high multiplicity events are presumably due to rare fluctuations in the proton wave function which create "hot spots"

The ridge appears at transverse momenta of hadrons in the range $1 \text{ GeV} < p_t < 3 \text{ GeV}$ the transverse momentum of the gluons emitted initially must have been in the range $3 - 5 \text{ GeV}$, much higher than expected $Q_s \leq 2\, GeV$.

Again hot spot fluctuation of $Q_s^{hot\, spot} \gg Q_s$

CONCLUSIONS

- Gluon production at high energy leads naturally to rapidity correlations and angular correlations. There just have to be many gluons so that more than one is produced at fixed impact parameter (within $\Delta \mathrm{b} \sim 1/\mathrm{Q_s}$)

- "Classical" term leads to the strongest correlations – thus the correlations should be largest for nucleus projectile where it dominates. On the other hand effect becomes weaker with increasing Q_s. So, maybe actually the other way around – it is strongest for $p - p$ in a limited range in energy?

- None of these qualitative features depends on what averaging procedure we use to average over the projectile and target fields, but quantitative of course it will.

Many sources of uncertainty:

– large N_c

– target/projectile averaging

– target/projectile evolution

– rapidity evolution between produced gluons

– the role of trigger

– QGP hydro explosion