Predicting higher-dimensional ridges in p-p and p-A collisions from gluon saturation

(based on arxiv:1409.6347)

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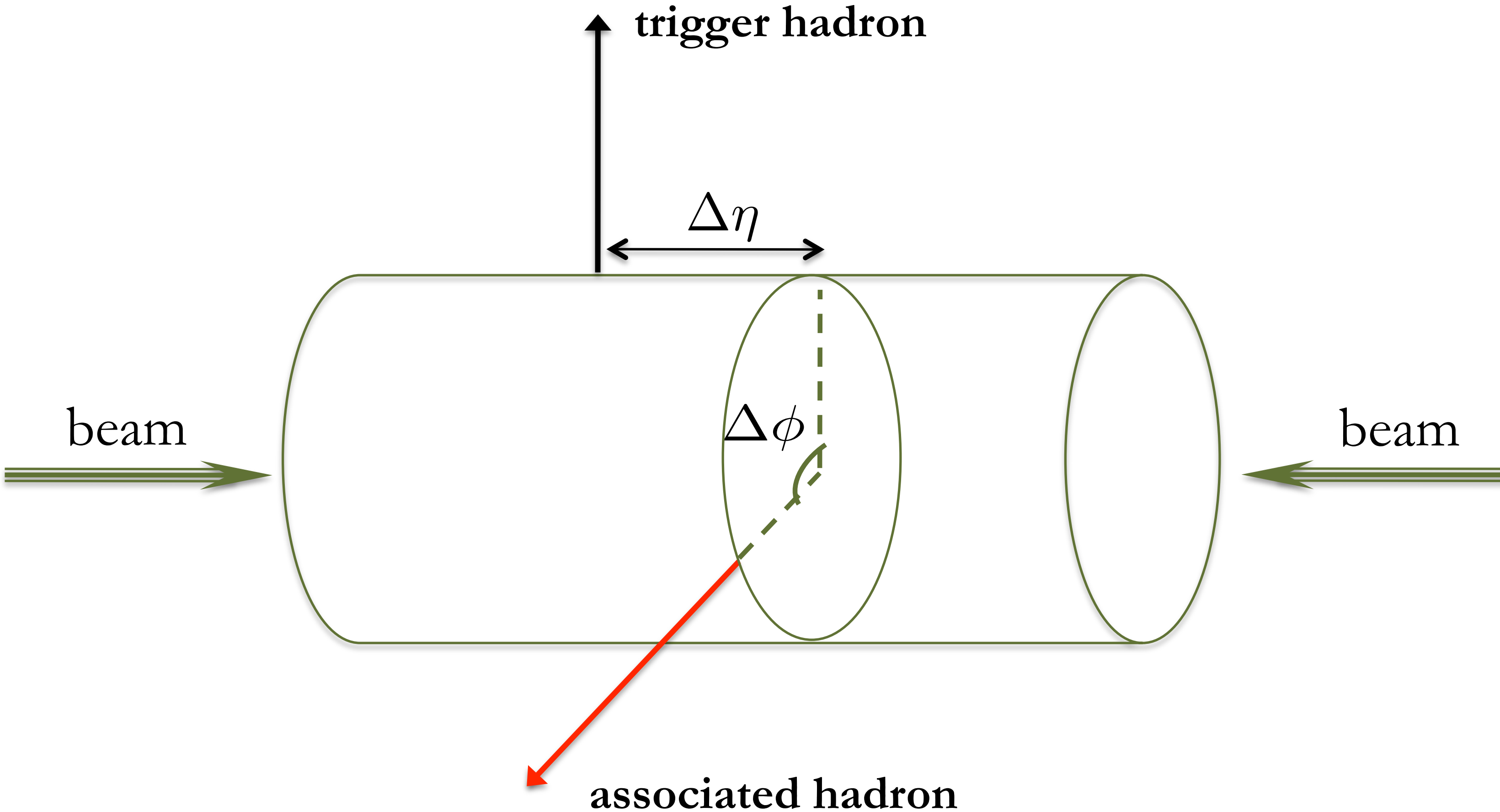
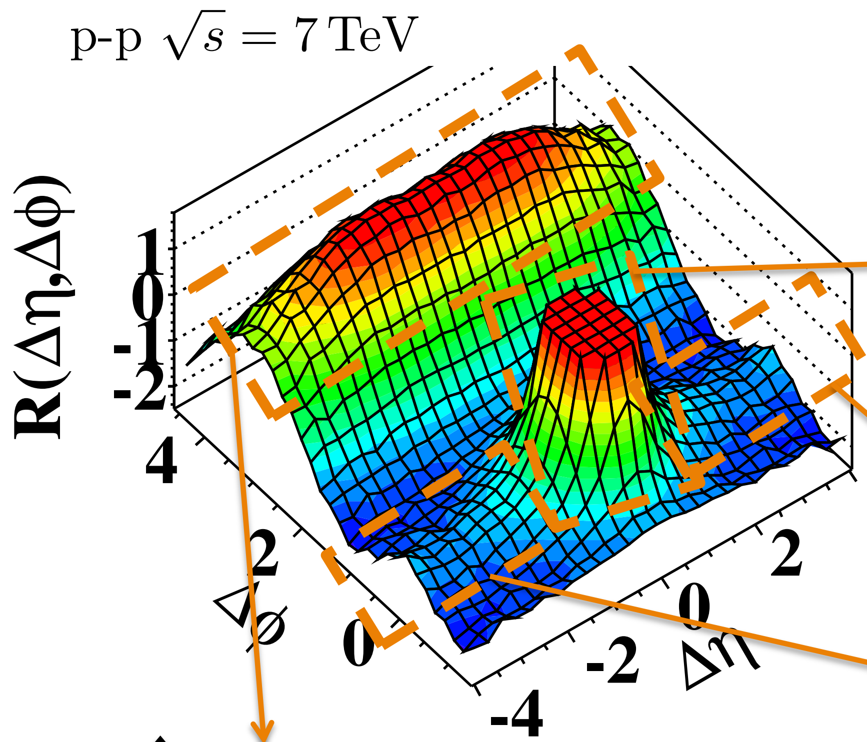
Detector Angles

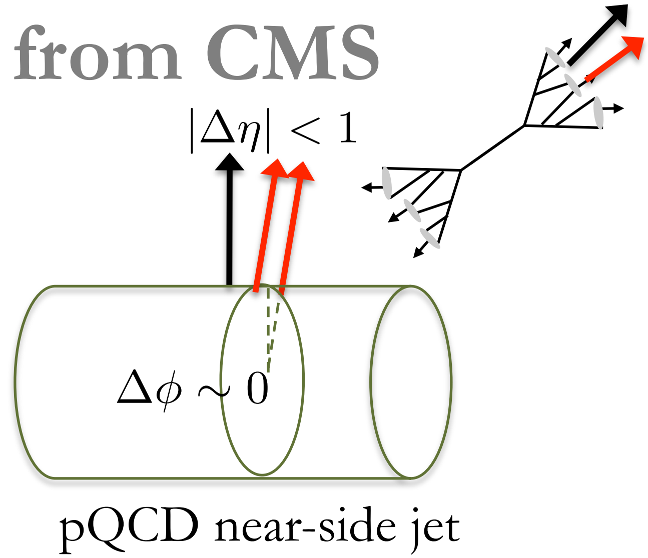
Pseudo-rapidity: η

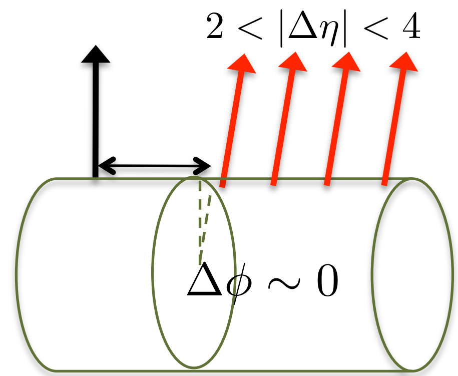
Azimuthal angle: ϕ

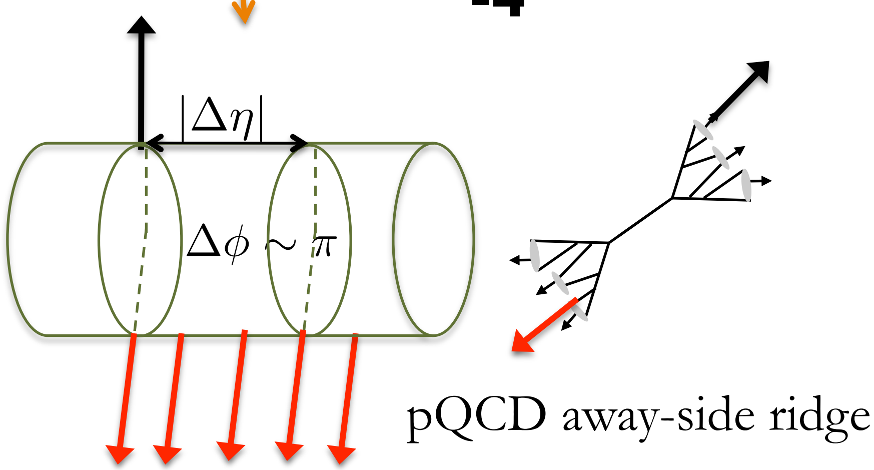


Two-Hadron Correlations from CMS







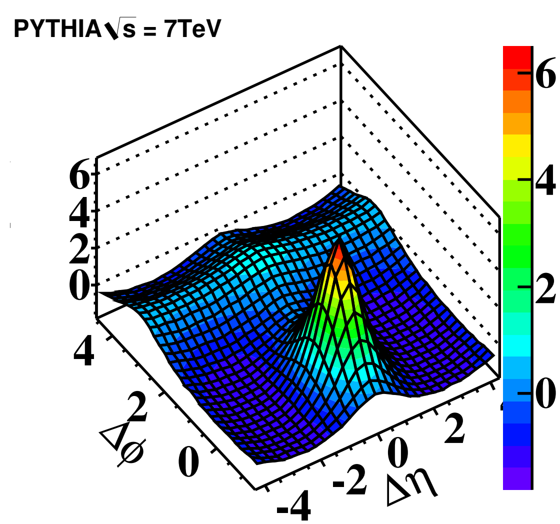


The (near-side) *ridge.*

- Never seen in the experiments or simulations (PYTHIA etc) in p-p.
- Never anticipated. Origin???

Two-Hadron Correlations from CMS

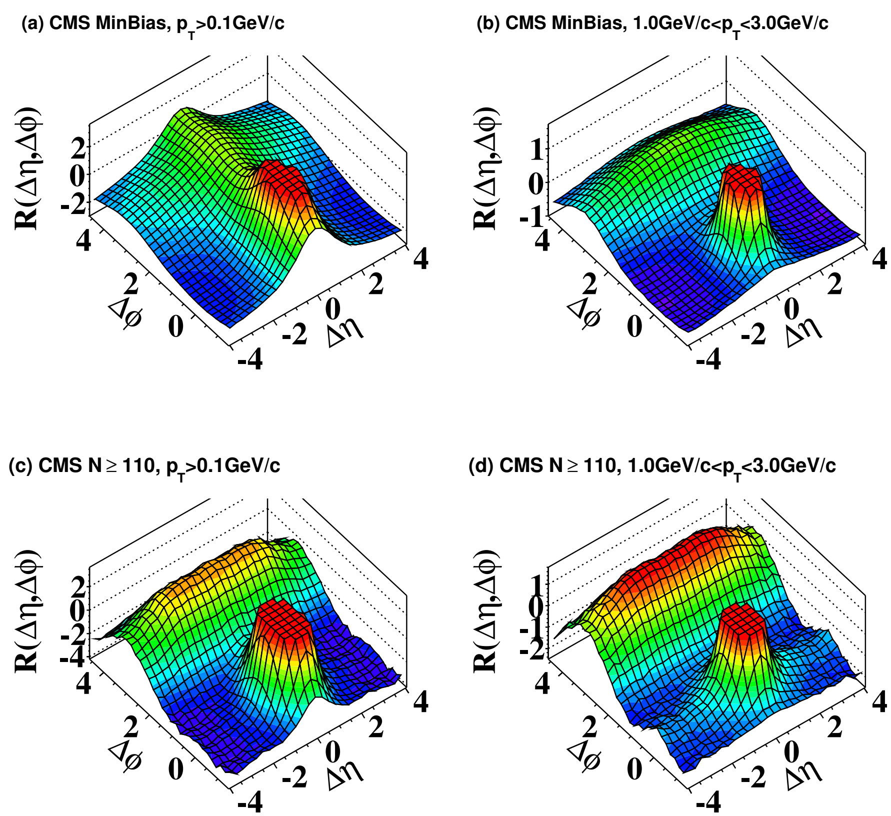
"This [the near-side ridge] is a novel feature of the data which has never been seen in two-particle correlation functions in pp and $p\bar{p}$ collisions. Simulations using MC models do not predict such an effect. An identical analysis of high multiplicity events in PYTHIA8 results in correlation functions which do not exhibit the extended ridge at $\Delta\phi \approx 0$ while all other structures of the correlation function are qualitatively reproduced. (...) Several other PYTHIA tunes, as well as HERWIG++ and Madgraph events were also investigated. No evidence for near-side correlations corresponding to those seen in data was found." (CMS collaboration - JHEP 09 (2010) 091)



•The ridge appears at high multiplicity events, at low/intermediate p_T.

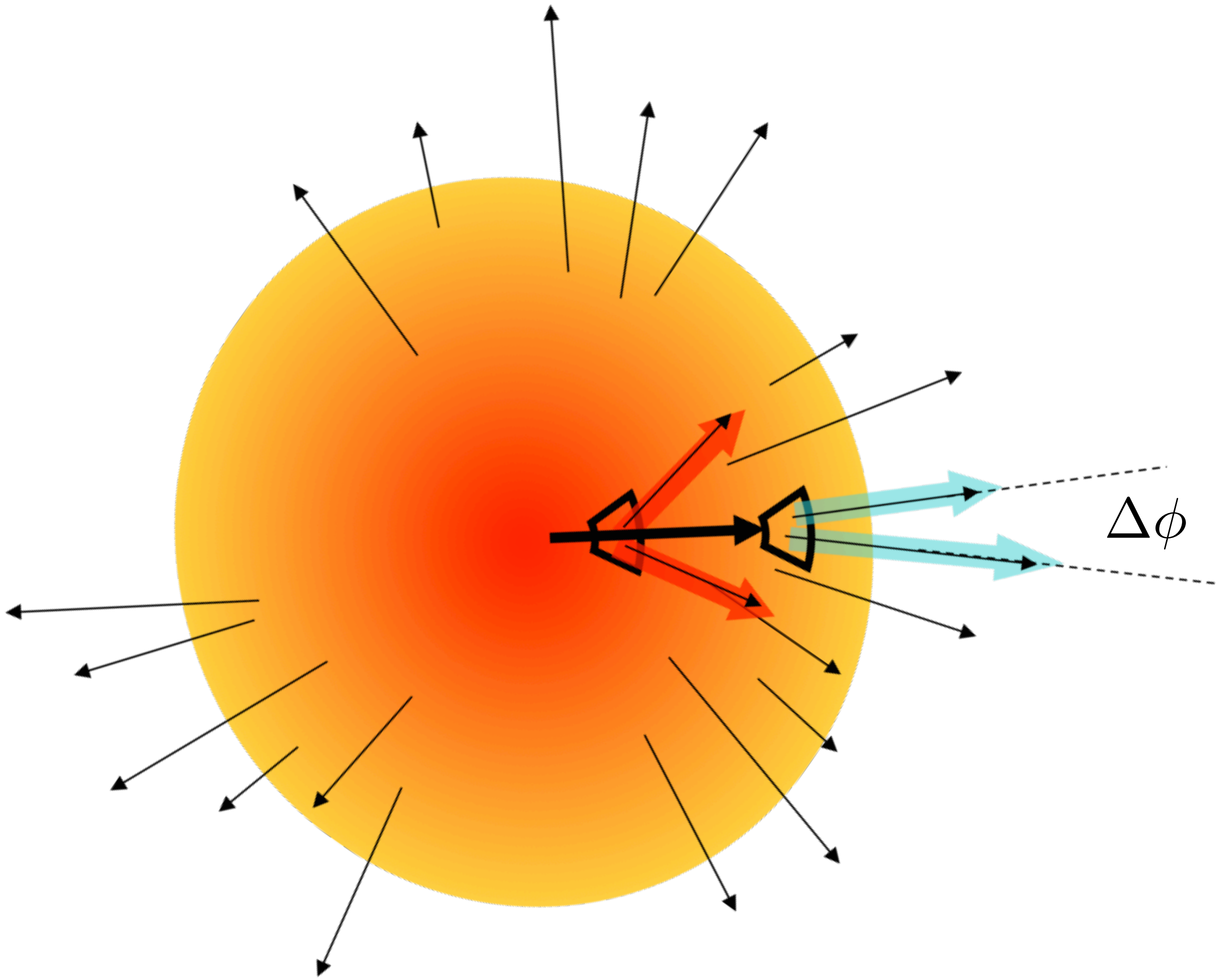
•**Visible in p-p when N_{track} >90 and p-Pb when N_{track} >35.**

•Using p-A data for R_{AA} of charmonium? In p-A, there is not only cold nuclear matter effects, but also 'collectivity.'

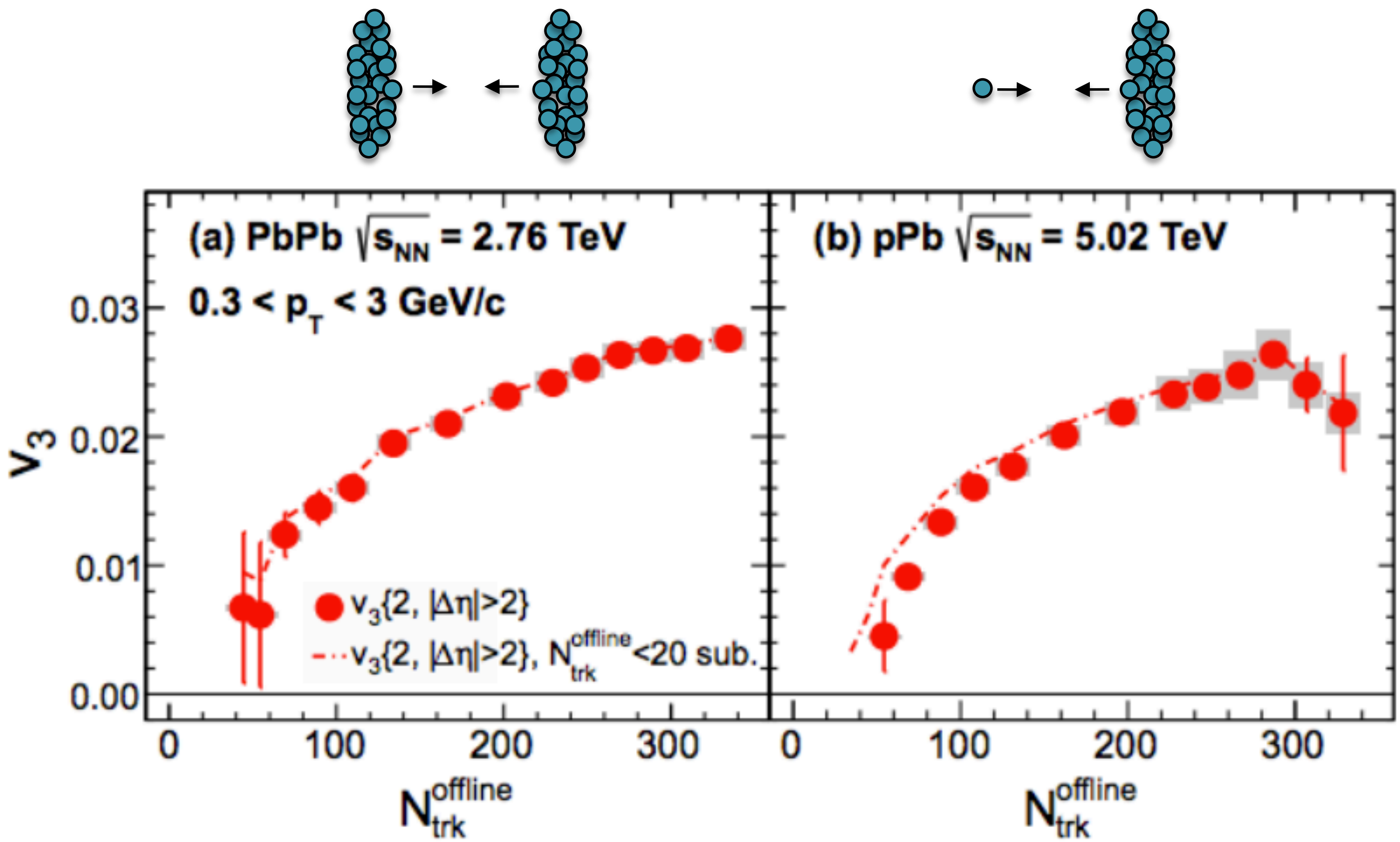


- **How the flow of QGP produces ridges.**
- How pQCD does NOT produce ridges.
- How gluon saturation produces ridges

Azimuthal Correlations due to Collective Flow

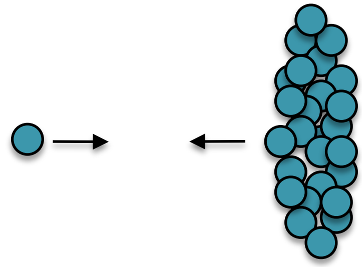


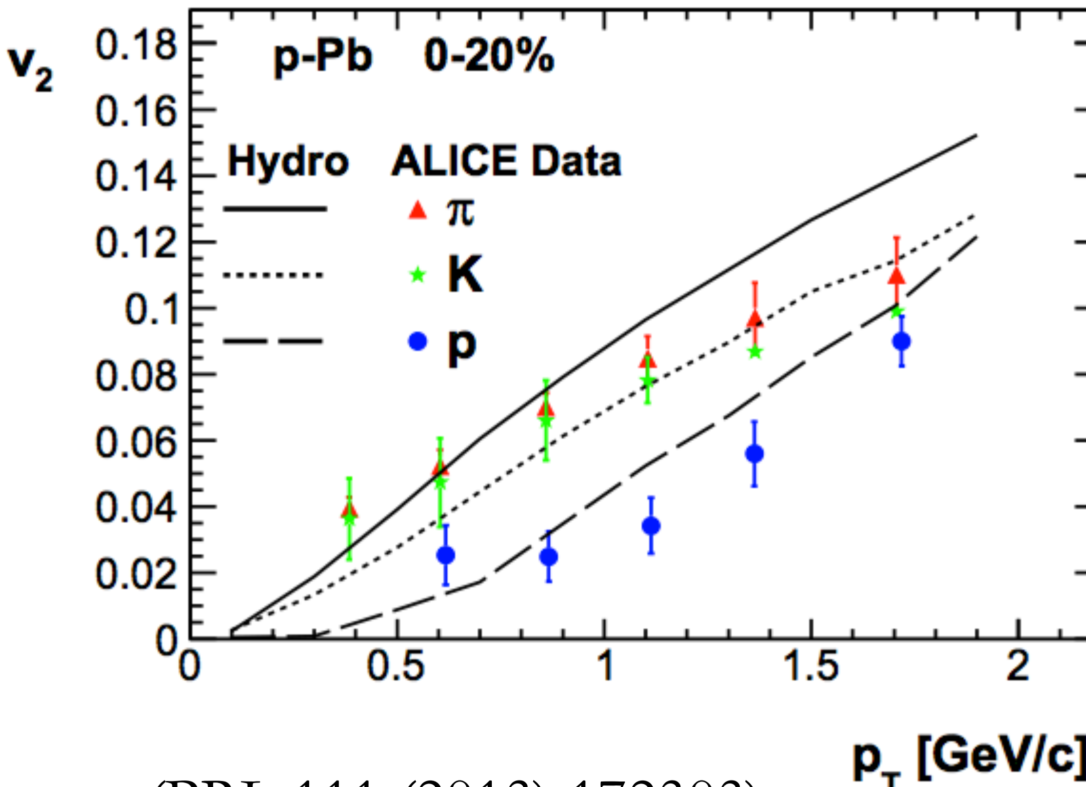
Striking similarities between v_3's of Pb-Pb and p-Pb.



• QGP in p-Pb? Or maybe just 'collectivity' (many-body effects) but not necessarily (thermalized) 'liquid?'

Hydrodynamics vs. Data





(PRL 111 (2013) 172303)

- How the flow of QGP produces ridges.
- **How pQCD does NOT produce ridges.**
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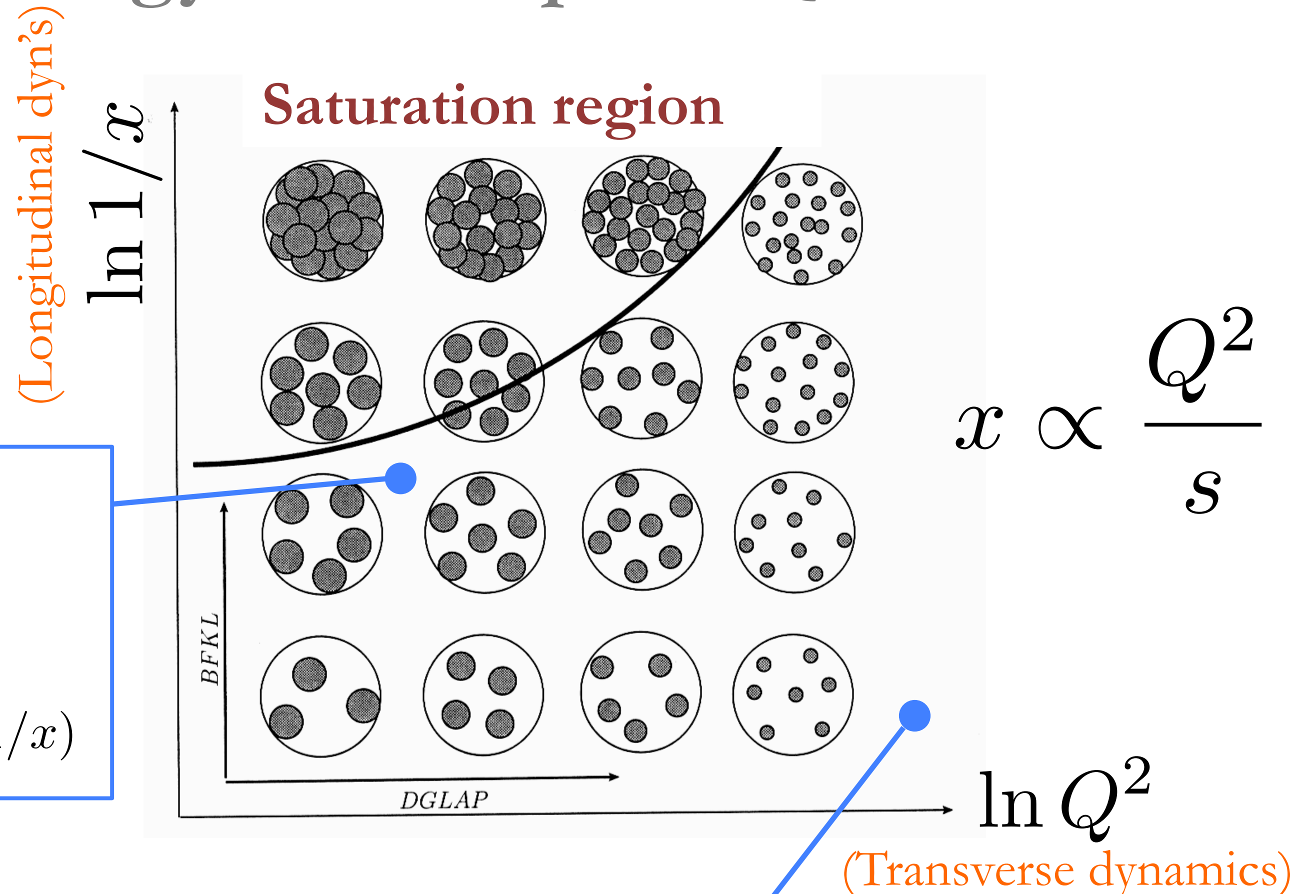
Energy Landscape of QCD



$$x \propto \frac{Q^2}{s}$$

Regge limit:

$Q^2 \sim$ constant

$x \to 0$

evolution in $\alpha_s \ln(1/x)$

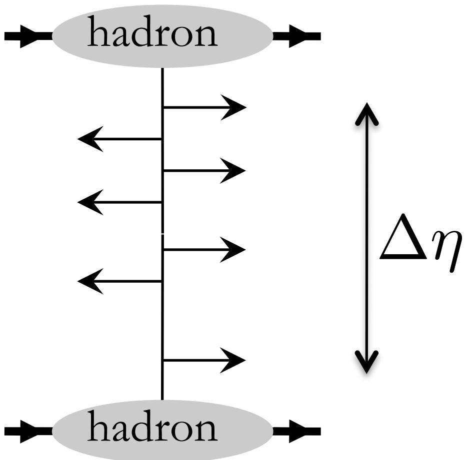
Bjorken limit:

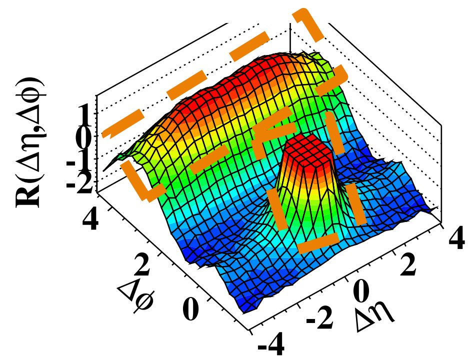
$x \sim$ constant

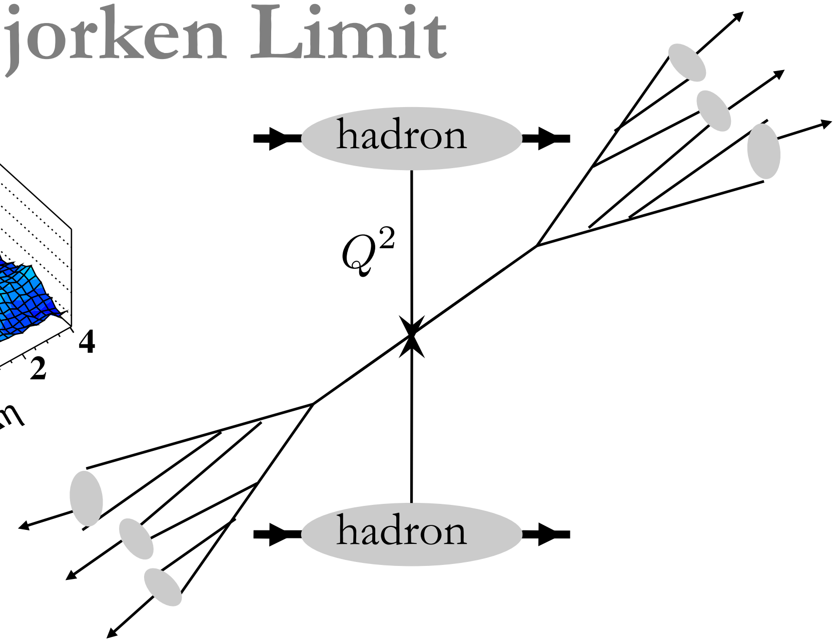
$Q^2 \to \infty$

evolution in $\alpha_s \ln(Q^2)$

Regge Limit vs. Bjorken Limit







Regge limit of QCD

• Partons are ordered in x (or η) by being local in Q^2. Important when particles are produced with large rapidity gap $\Delta\eta$ (at small-x).

• Multi-Regge Kinematics or BFKL give correlations between back-to-back jets that are separated in rapidity, but cannot produce the azimuthal collimation. .

Bjorken limit of QCD

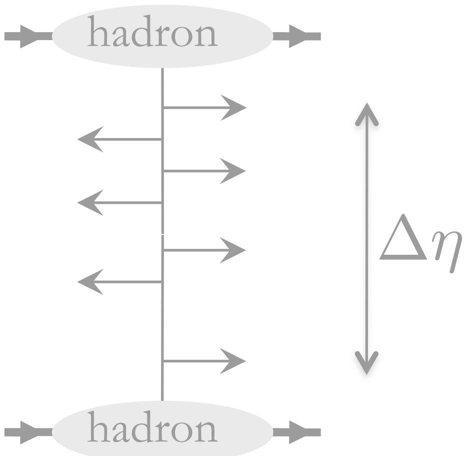
• Partons are ordered in k_T whereas being local in rapidity η. Hence, the correlations in rapidity are short-ranged.

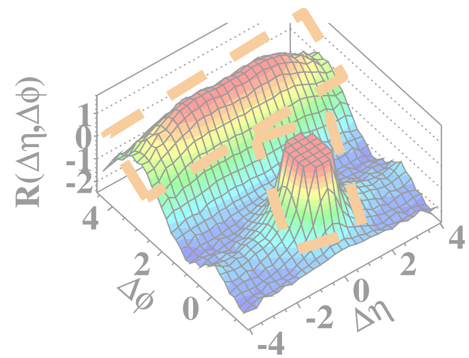
$$C(\eta_1, \eta_2) \propto e^{-\gamma|\Delta\eta|}$$

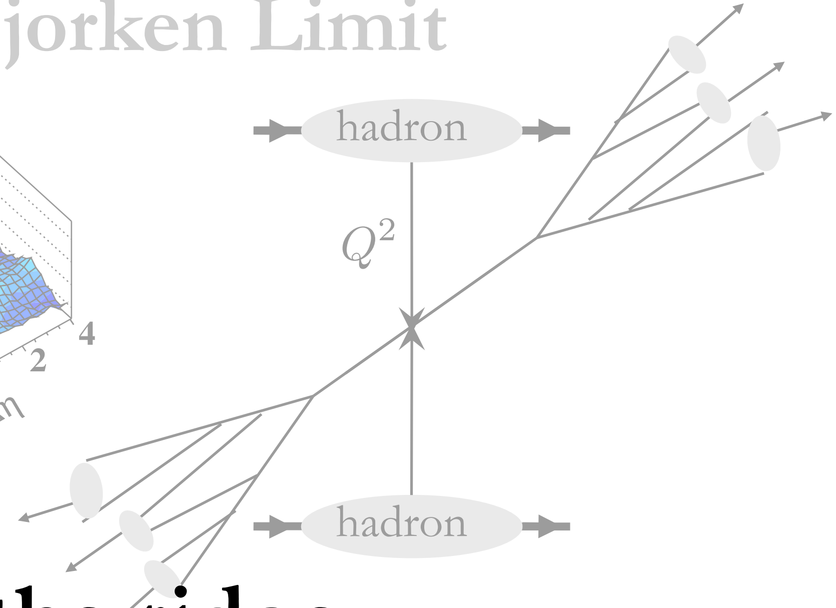
• pQCD jets from hard scattering at large Q^2 and not so small x.

• Event generators (e.g. PYTHIA) successfully describe the pQCD jet peak and the away-side ridge (momentum conservation of the back-to-back jets).

Regge Limit vs. Bjorken Limit







- **Neither can explain the ridge.**
- **Also neither has gluon saturation built-in.**

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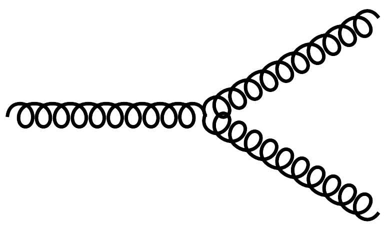
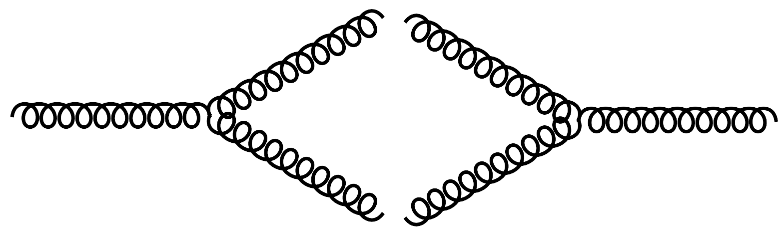
- How the flow of QGP produces ridges.
- How pQCD does NOT produce ridges.
- **How gluon saturation produces ridges**

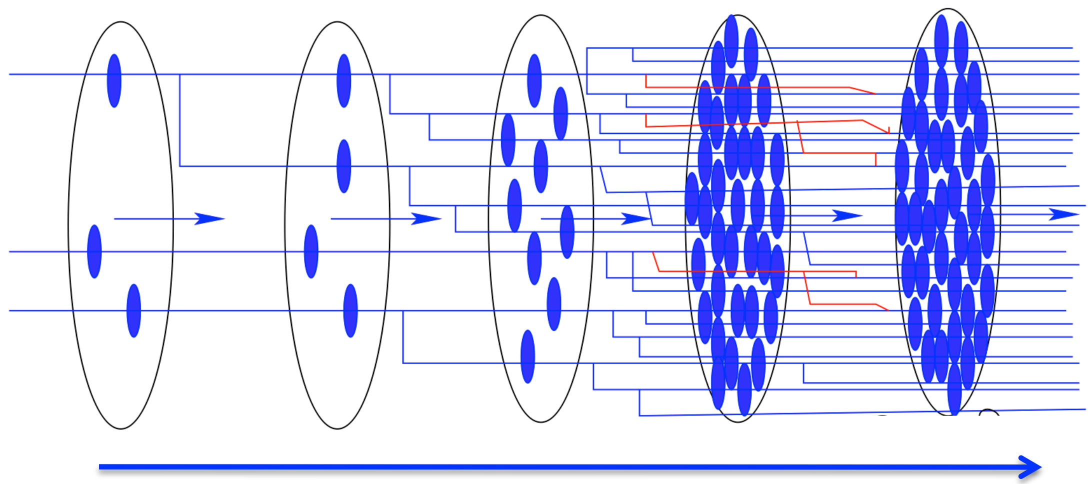
Interlude: Gluon Saturation



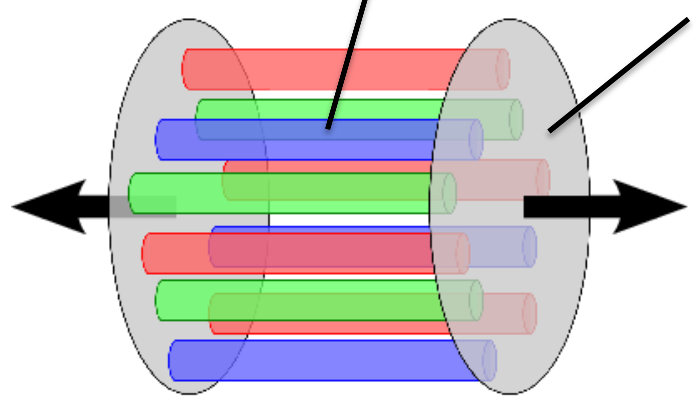
Only splitting (DGLAP, BFKL etc.)



Splitting and merging balancing each other when $Q_{\text{sat}} \gg \Lambda_{\text{QCD}}$ (rcBK, JIMWLK etc.)



Larger $\sqrt{s}$ (i.e. small $x \propto \frac{Q^2}{s}$)



Glasma ('glassy plasma'): Classical, strong chromo-electric and –magnetic color flux tubes between the target and projectile.

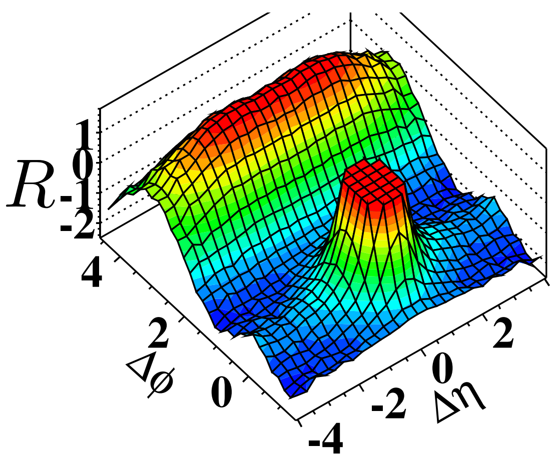
They are created by the target and projectile which are highly populated by gluons at small-x ('color glass condensate').

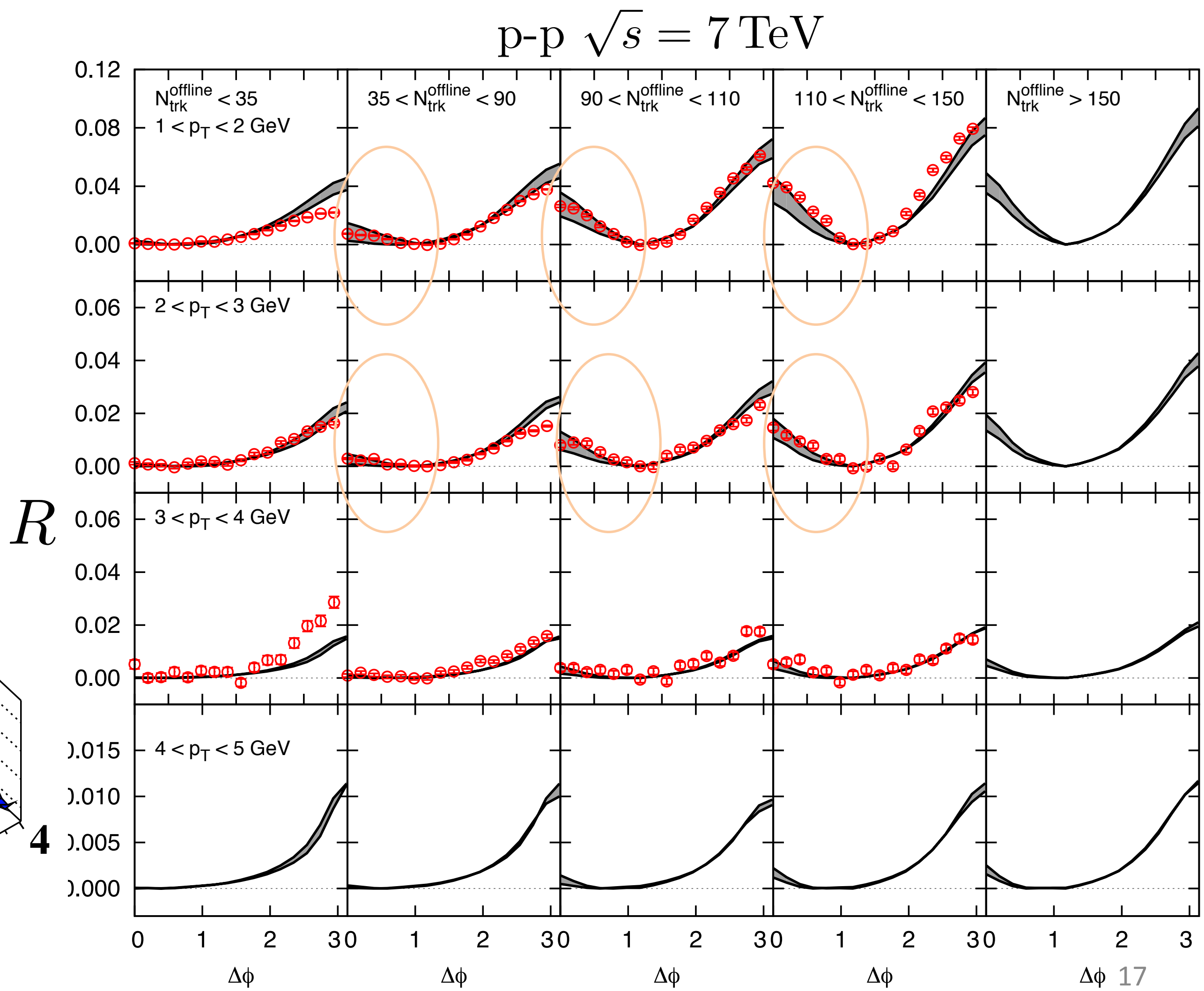
Experiment vs. Glasma

• Glasma diagrams (flux tubes) with gluon saturation reproduce the ridge and explains the systematics of the p-p and p-Pb data well.

gray band: data

red circles: glasma model



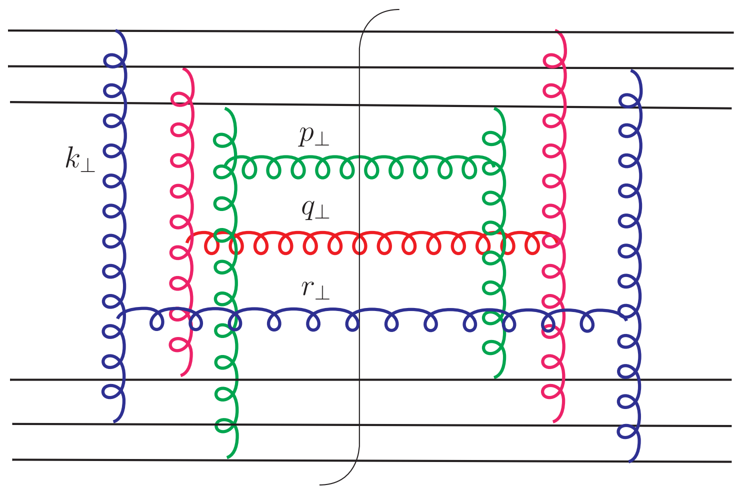


•A **hydro** person can argue: High multiplicity leads to equilibrated medium (fluid).

•A **glasma** person can argue: High multiplicity due to higher gluon saturation scale, hence glasma diagrams becomes enhanced and as important as the jet graph.

•You can argue both ways. **To settle this issue, we need to look at the triple- and quadruple-hadron correlations.**

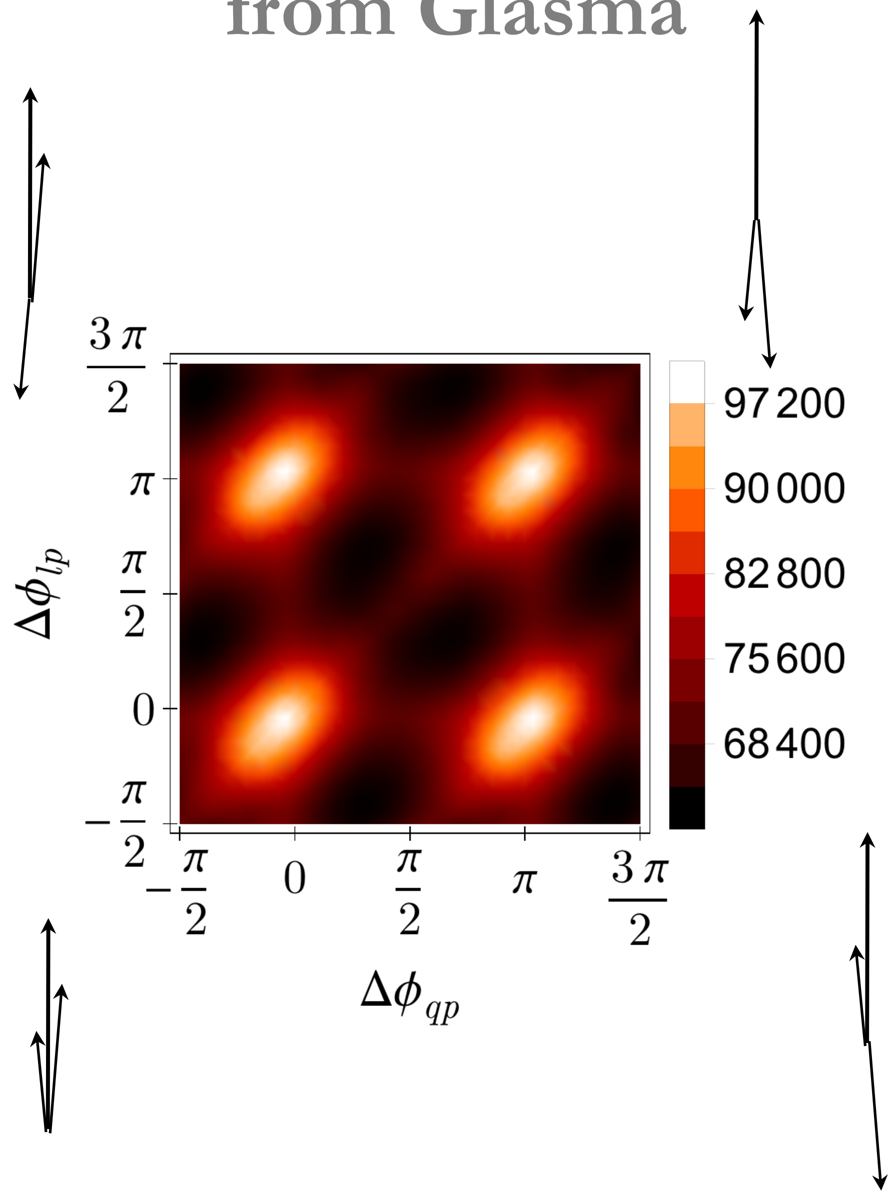
Gluon production from glasma diagrams



$$\frac{dN_3^{\text{glasma}}}{d\Delta\phi_{pq}d\Delta\phi_{pr}d\Delta\eta_{pq}d\Delta\eta_{pr}} \propto \frac{\alpha_s^3}{\boldsymbol{p}_\perp^2\boldsymbol{q}_\perp^2\boldsymbol{r}_\perp^2}\int d^2\boldsymbol{k}_\perp \underbrace{\Phi(y_p,\boldsymbol{k}_\perp)\times\ldots\times\Phi(y_q,\boldsymbol{q}_\perp+\boldsymbol{k}_\perp)}$$

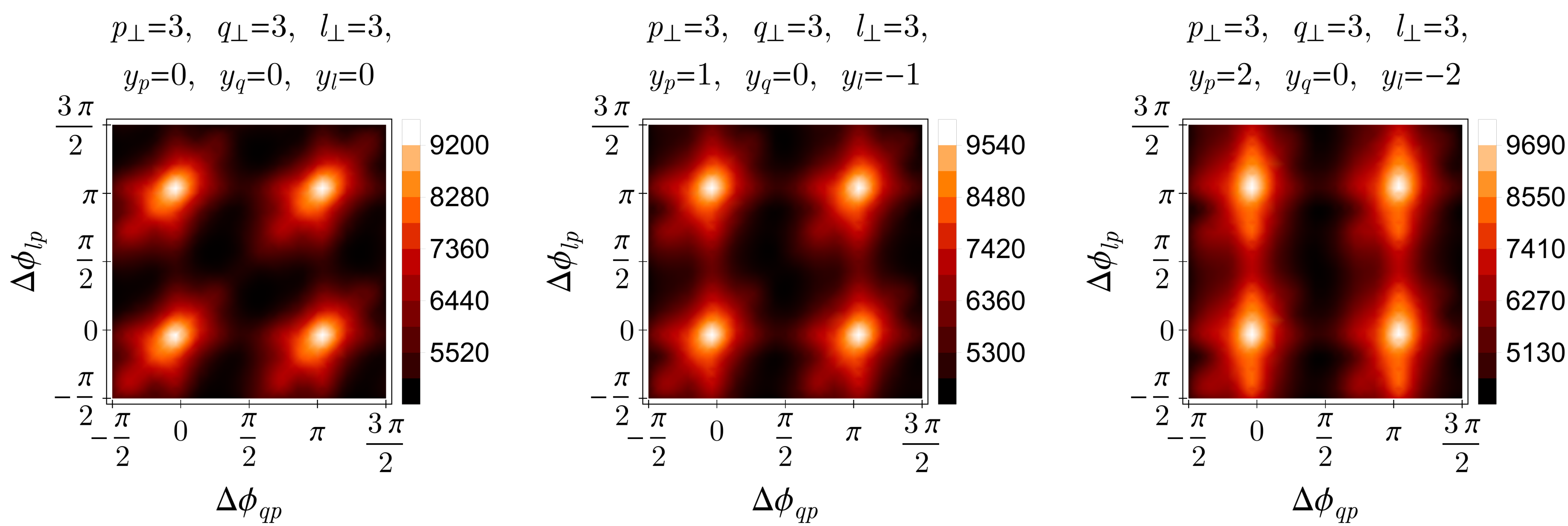
12 unintegrated
distribution functions

Triple-gluon Azimuthal Correlations from Glasma



Triple-gluon Azimuthal Correlations from Glasma

p-Pb $\sqrt{s} = 5.02$ TeV

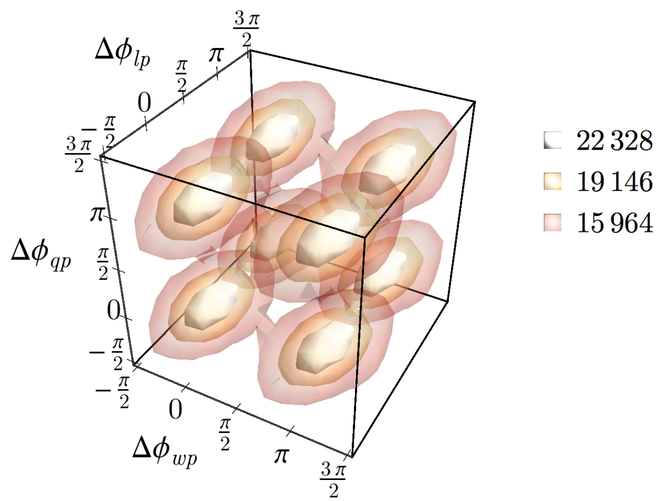


(For triple-hadron correlations, these results should be convolved with fragmentation functions)

Quadruple-gluon Azimuthal Correlations from Glasma

p-p $\sqrt{s} = 7$ TeV

$p_\perp$=3, $q_\perp$=3, $l_\perp$=3, $w_\perp$=3,
y_p=0, y_q=0, y_l=0, y_w=0



(For quadruple-hadron correlations, these results should be convolved with fragmentation functions)

flow in pA systems?

- the soft sector of pA shares a lot of features with AA
- that doesn't necessarily mean we have created mini-QGPs in pA systems
  - and if we have that doesn't necessarily mean that hydrodynamics is the only relevant physics
- however, if flow-like signals are so generic, how does that feed back into our understanding of AA collisions?

(Anne M. Sickles (BNL) at Quark Matter 2014)

Van der Waals forces for water.

Summary and Outlook

• I predict higher dimensional ridges in triple and quadruple hadron correlations.

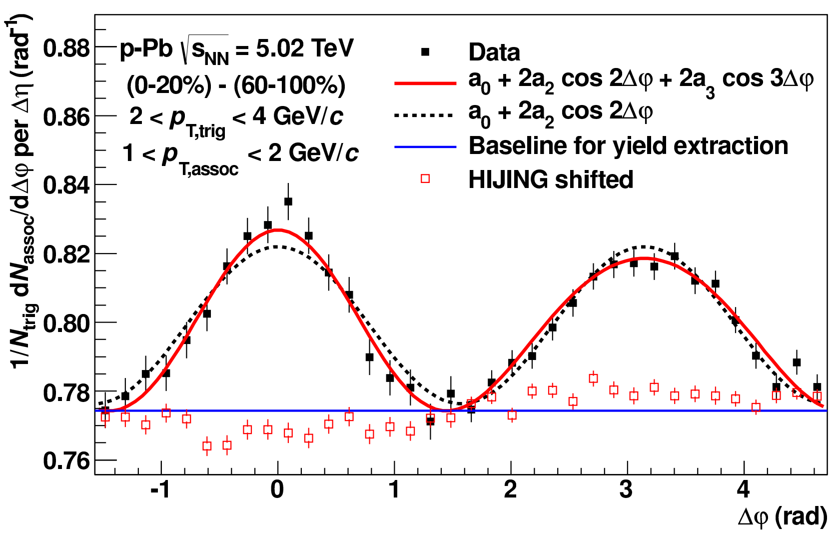
• The near-side ridge is interesting: It tells us about '**collectivity**' due to

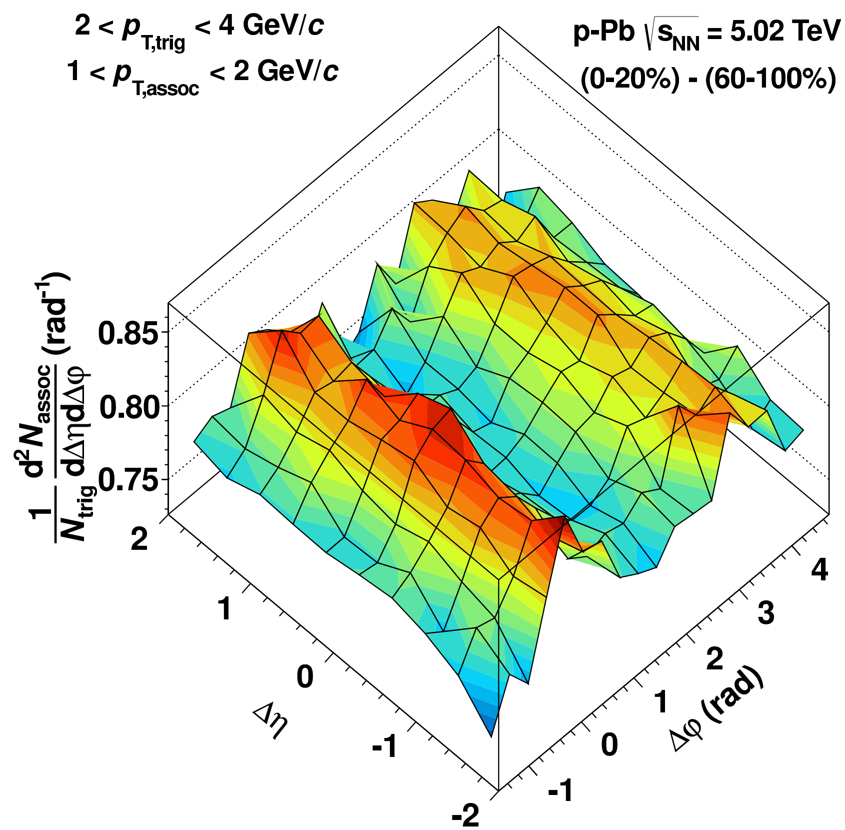
1) Possible gluon saturation effects in the colliding hadrons/nuclei,
2) Possible formation of expanding Quark Gluon Plasma and collective flow.

•Triple and quadruple-hadron correlations have not been extracted in high multiplicity p-p or p-Pb events yet. They can possibly distinguish between the two scenarios of the ridge: **Gluon saturation** or **hydrodynamics**.

Backups

p-Pb ridge at LHC after subtraction of jet and resonance decay contributions





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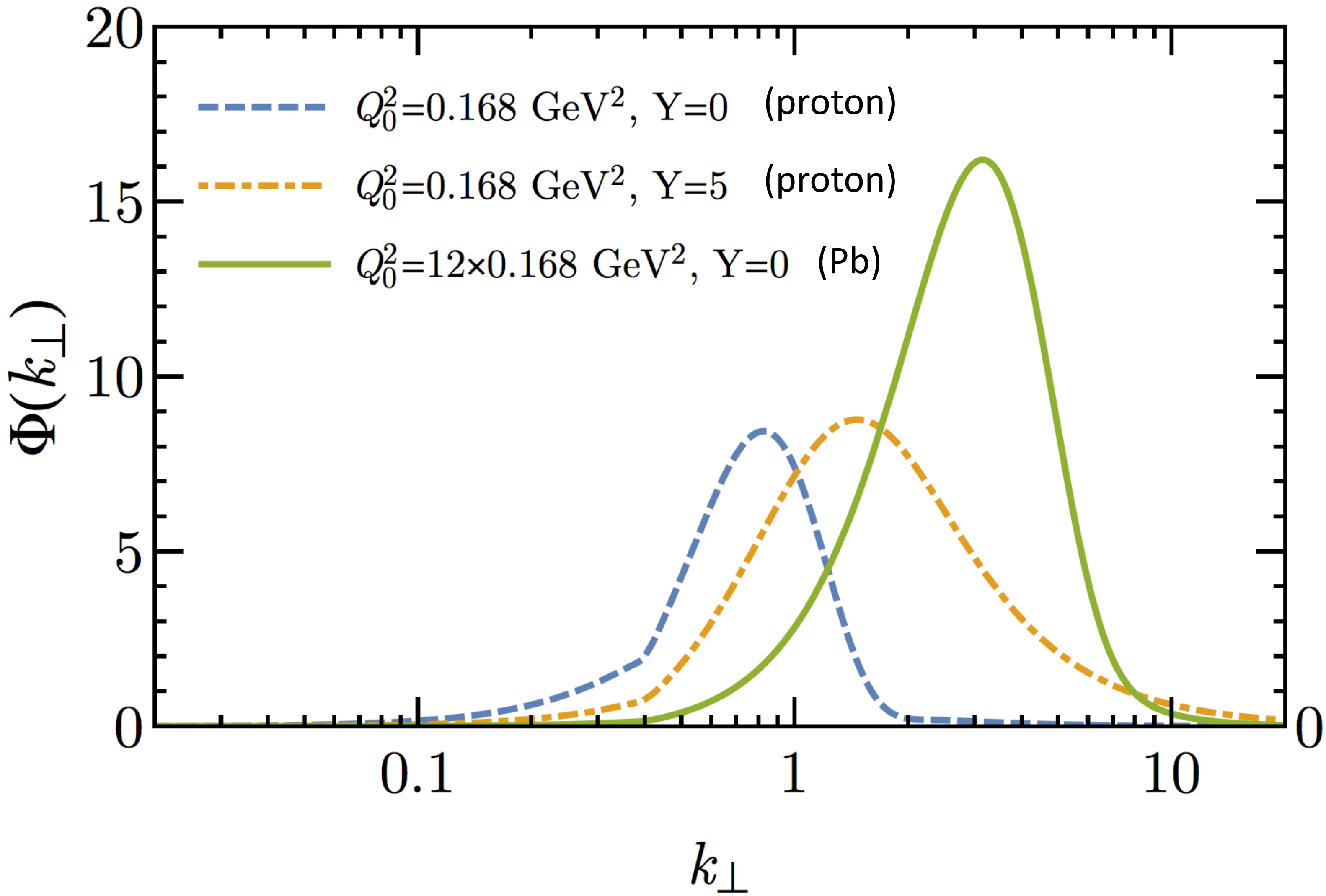
rcBK UGDs



Q_0^2=0.168 GeV^2, Y=0 (proton)
Q_0^2=0.168 GeV^2, Y=5 (proton)
Q_0^2=12×0.168 GeV^2, Y=0 (Pb)
20
15
10
5
0
0
0.1
1
10
$\Phi(k_\perp)$
$k_\perp$