Collectivity in small systems

- The **deconfined** quark-gluon plasma formed in nucleus-nucleus collisions at RHIC and the LHC is best described as a fluid.
- But the phenomena leading to this conclusion have then been observed, to some extent, in proton-nucleus, and even high-multiplicity proton-proton collisions.
- *Are the underlying mechanisms identical in all systems?*
- *Can we describe small systems as fluids?*

Collectivity in small systems

- Roberta Arnaldi (Torino, Italy), ALICE experiment
- Wei Li (Rice University, USA), CMS experiment
- Piotr Bożek (Cracow, Poland), hydrodynamics
- Dénes Molnár (Purdue University, USA), kinetic theory
- Wilke van der Schee (MIT, USA), strong coupling&holography
- Sören Schlichting (Brookhaven, USA), Yang-Mills dynamics
- Jean-Yves Ollitrault (Saclay, France).

Round table: Collectivity in Small Systems

Experimental Overview

Wei Li (Rice University)

XII Quark Confinement and the Hadron Spectrum
Aug. 29 – Sep. 3, 2016

Why colliding ultra-relativistic heavy ions?

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some 'bulk' phenomena by distributing high energy over a relatively large volume."

Prof. T.D. Lee, Rev. Mod. Phys. *47*, 267(1975).

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(AA)

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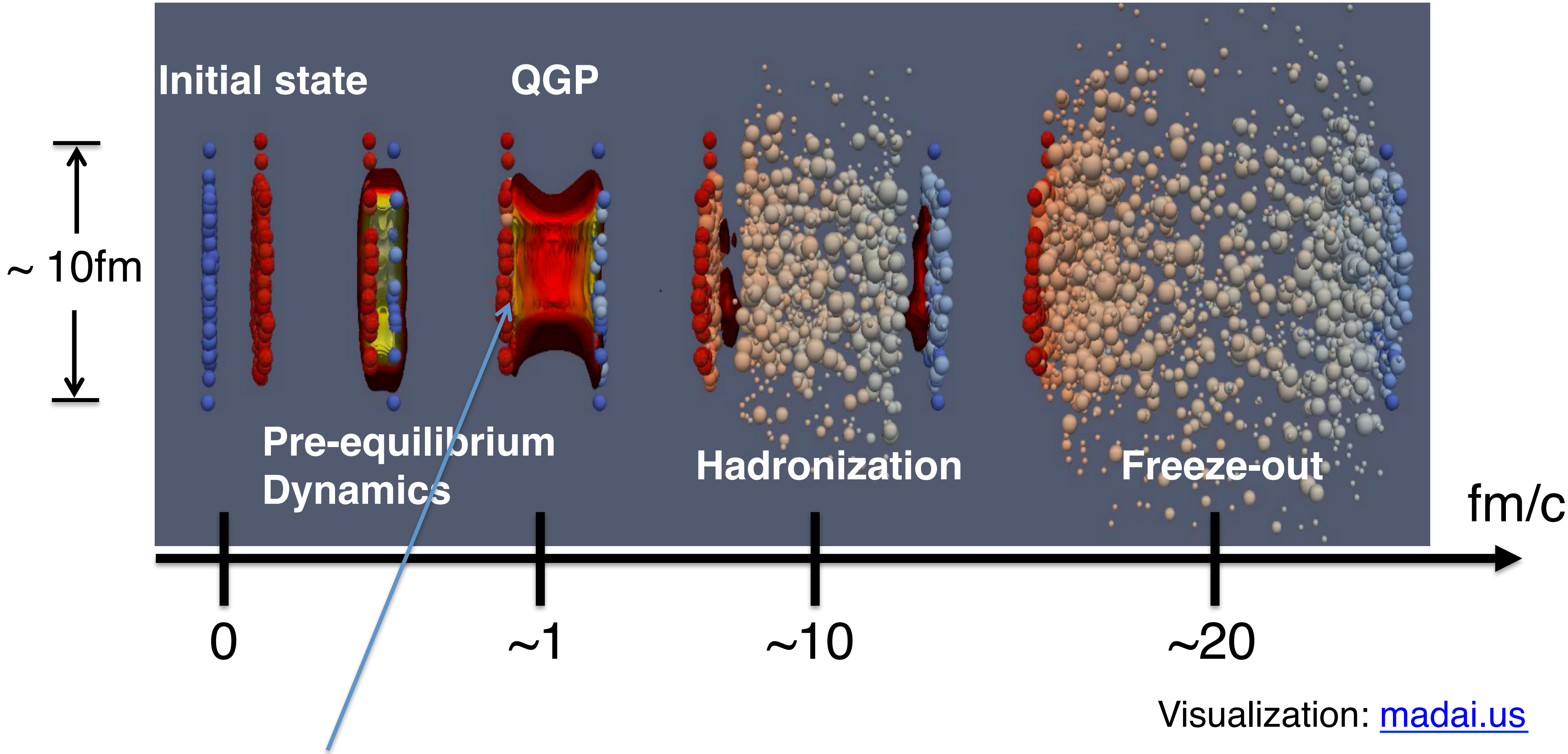
Standard paradigm of a heavy-ion collision

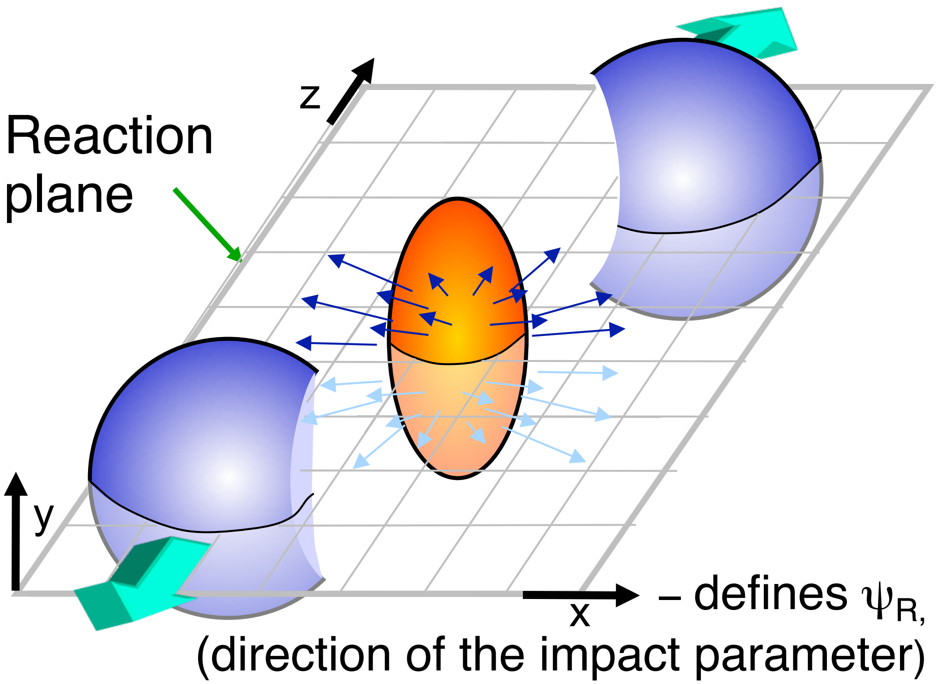


Visualization: madai.us

Discovery of a high temperature, thermalized medium with quark and gluon degree of freedom

Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction)

Initial-state asymmetry:



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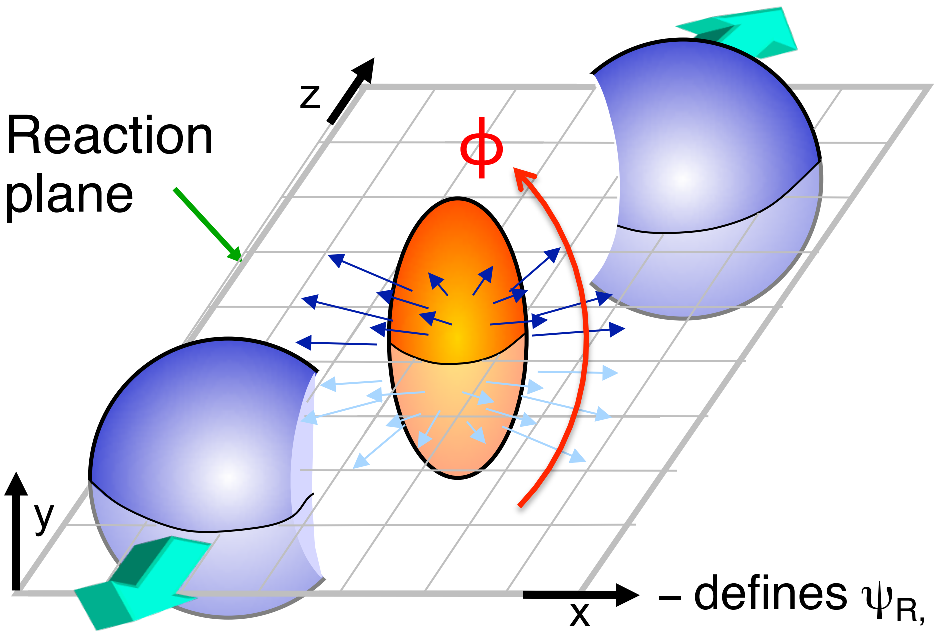
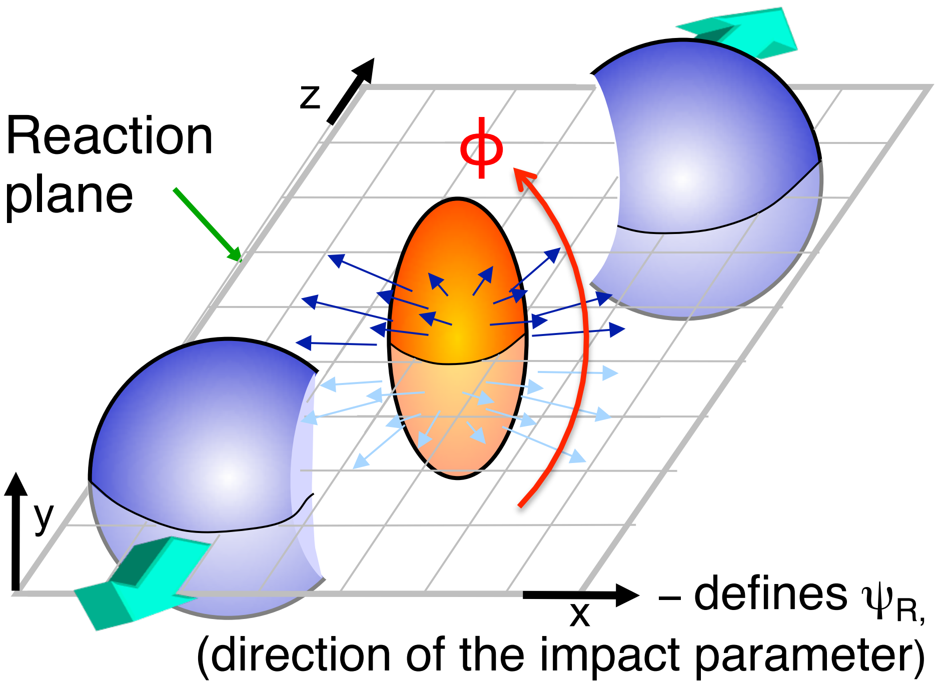


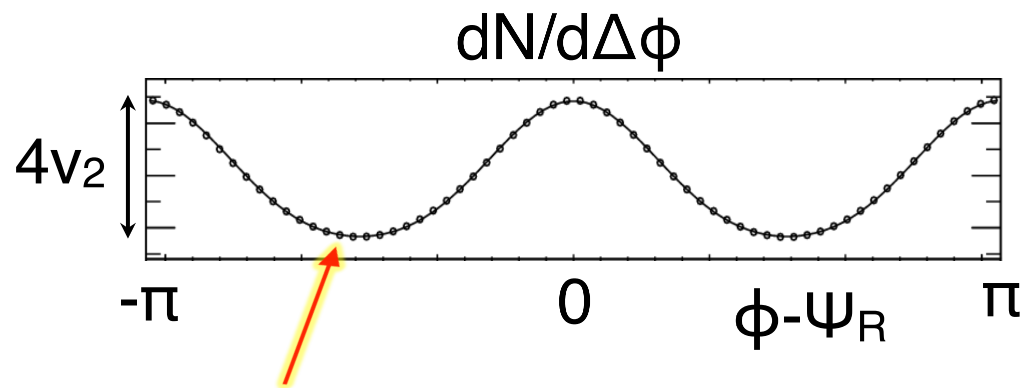
– defines ψ_R,
(direction of the impact parameter)

Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction)

Final-state anisotropy:

Initial-state asymmetry:



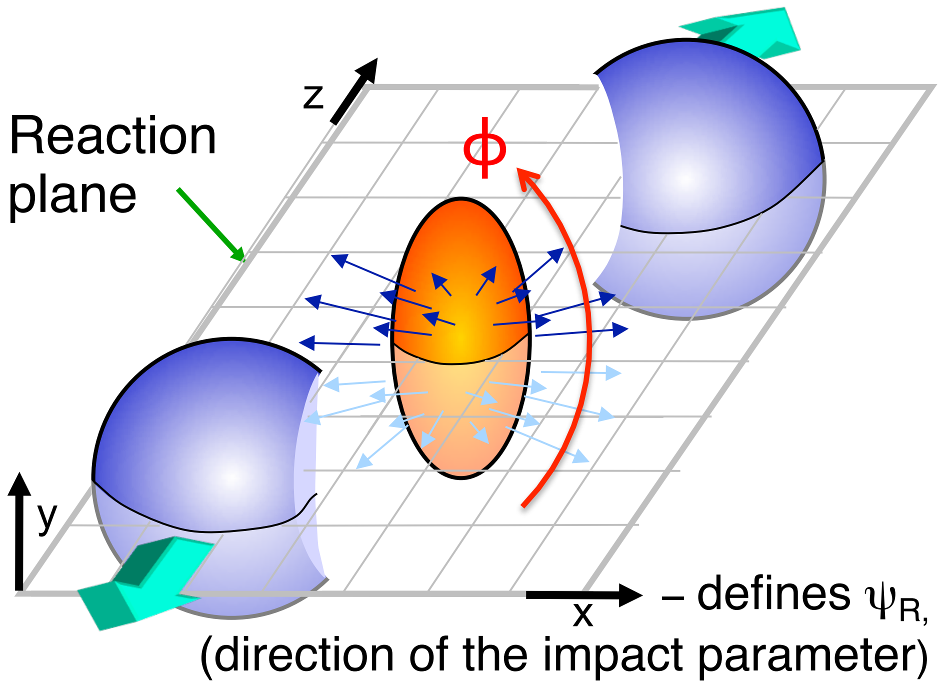


$\sim 1 + 2\,v_2 \cos[2(\phi - \Psi_R)]$

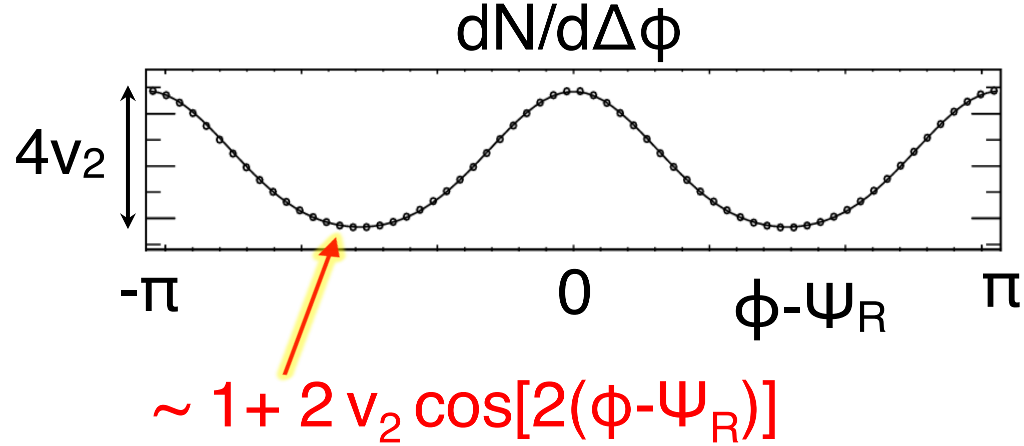
"elliptic flow"

Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction)

Initial-state asymmetry:

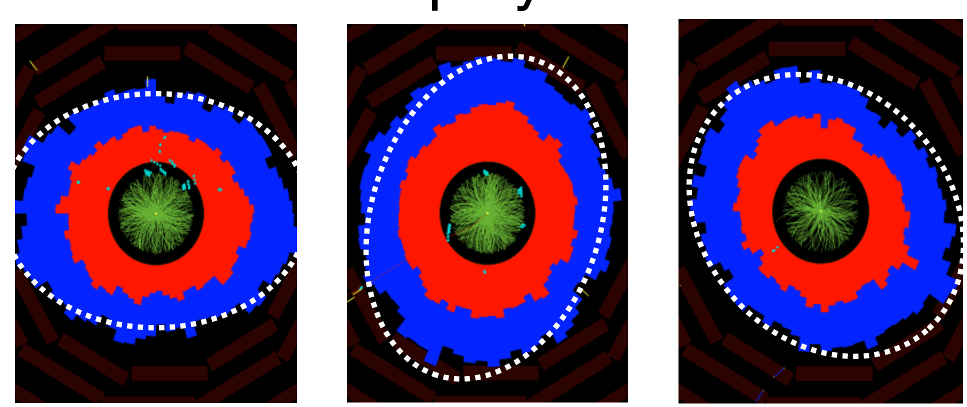


Final-state anisotropy:

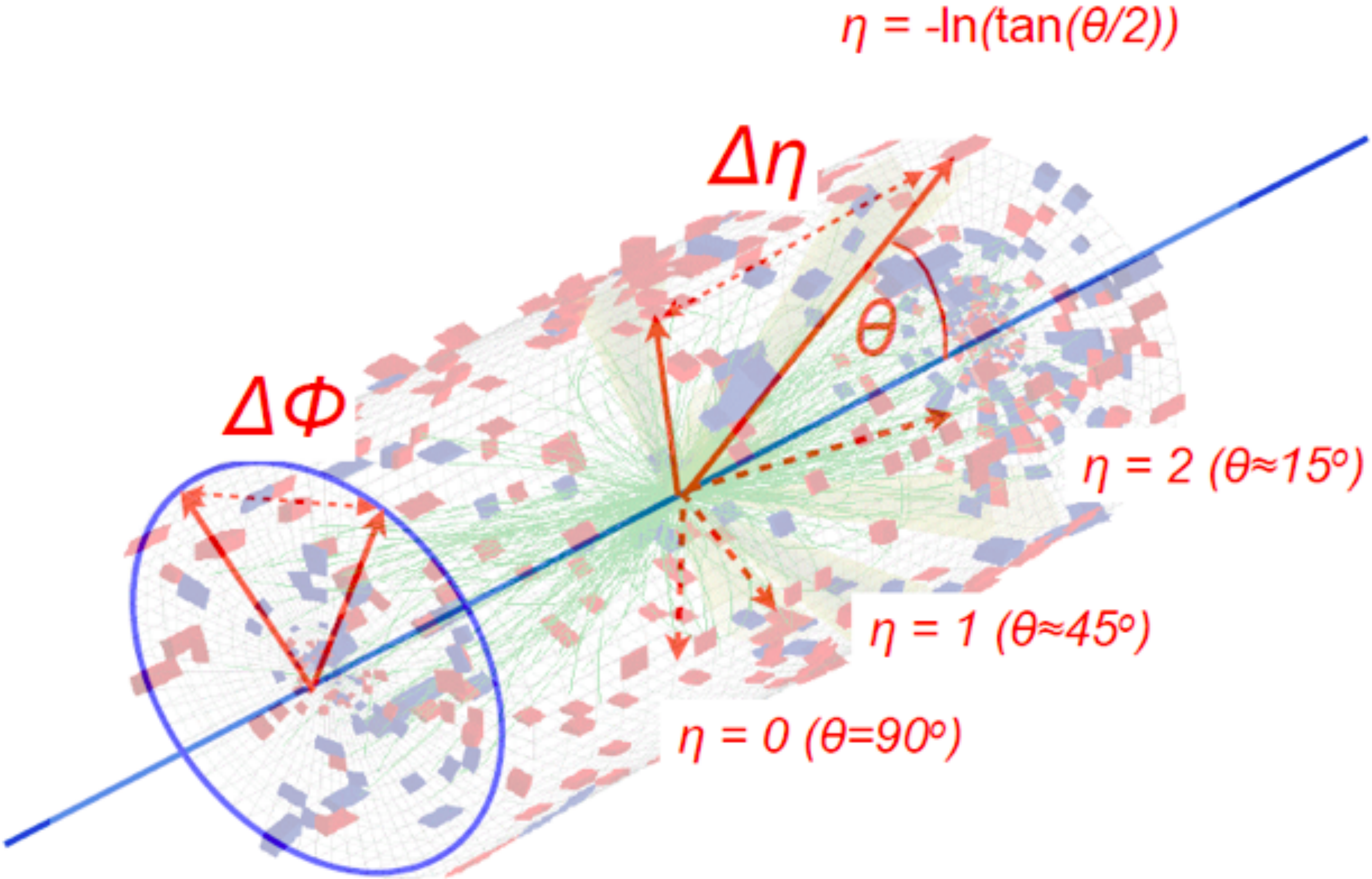


"elliptic flow"

CMS event displays



Flow, two-particle correlations, ridge …



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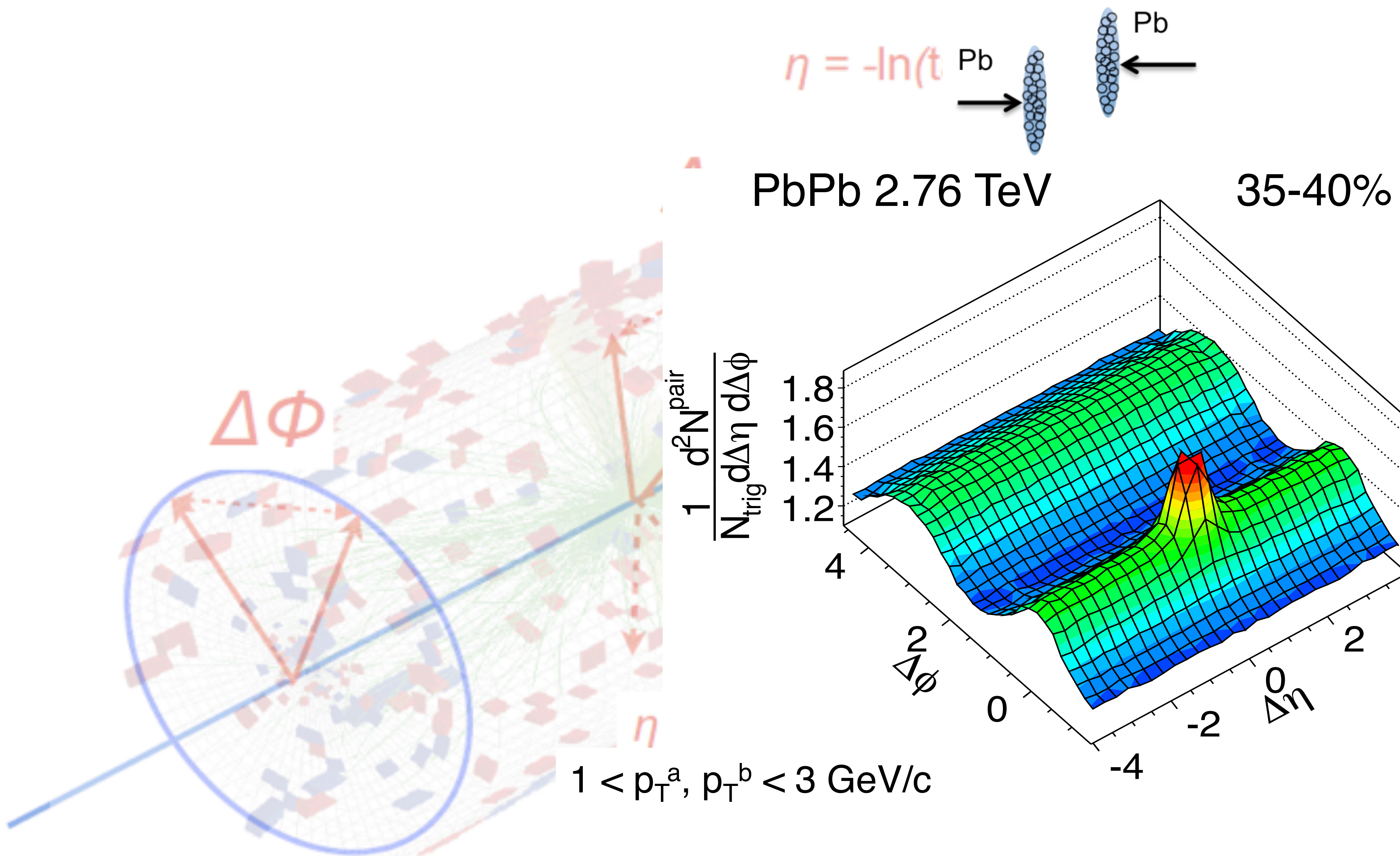

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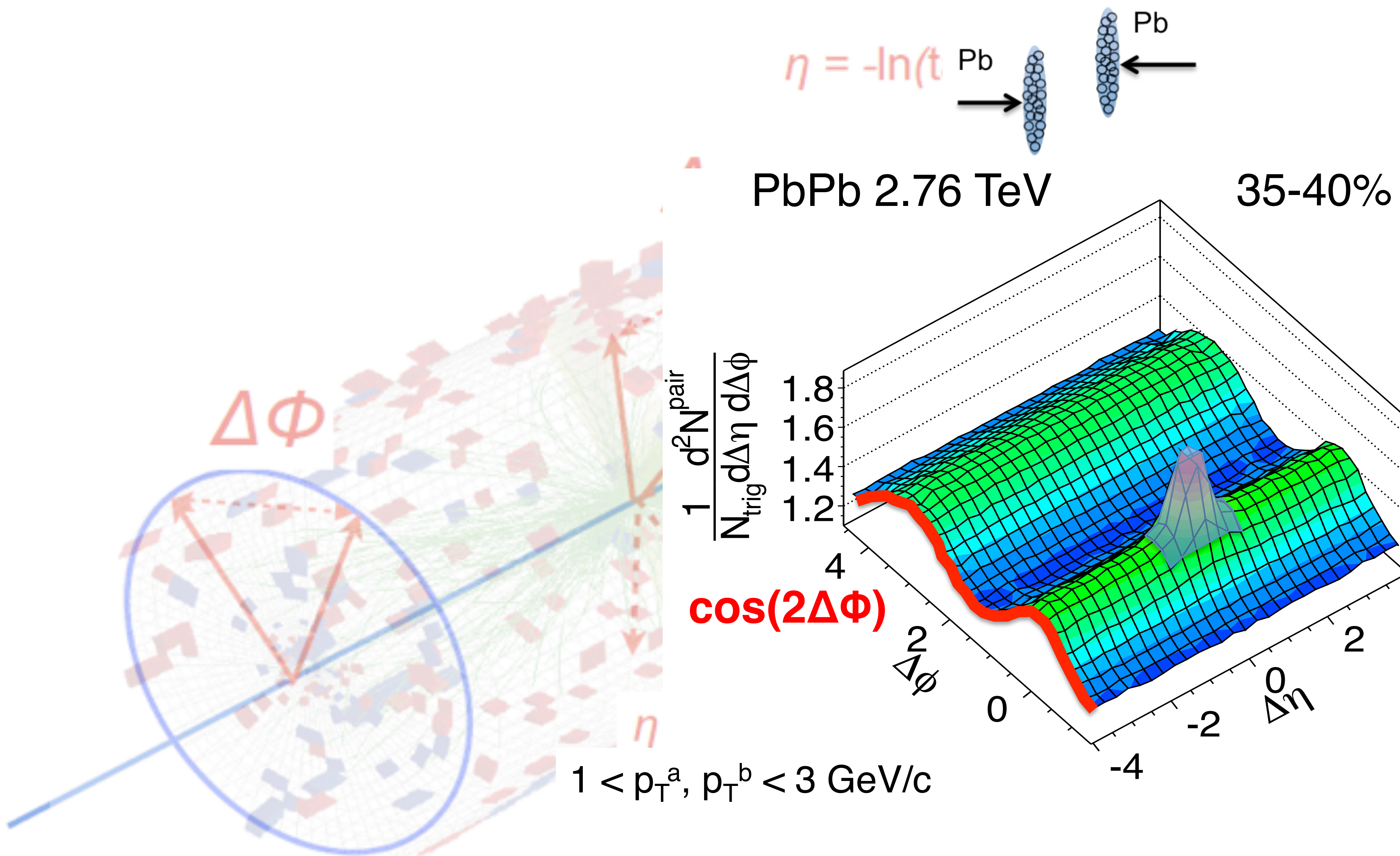

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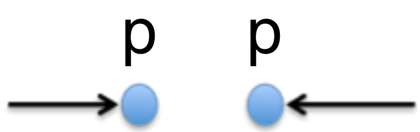
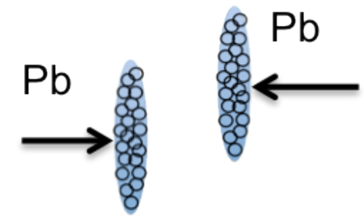
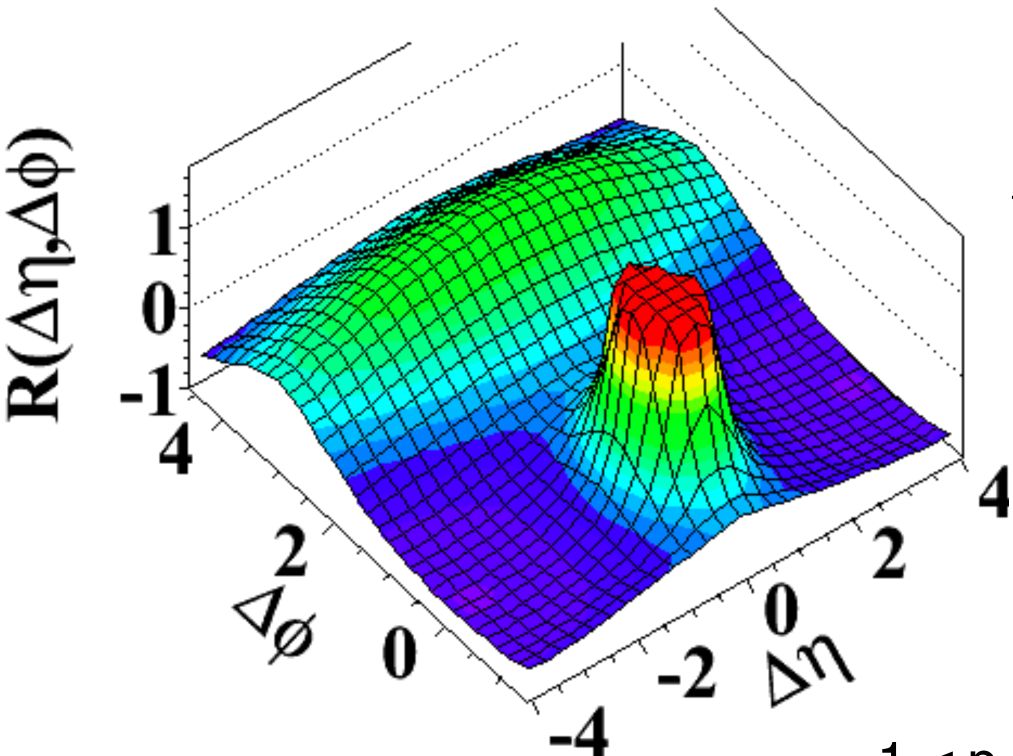


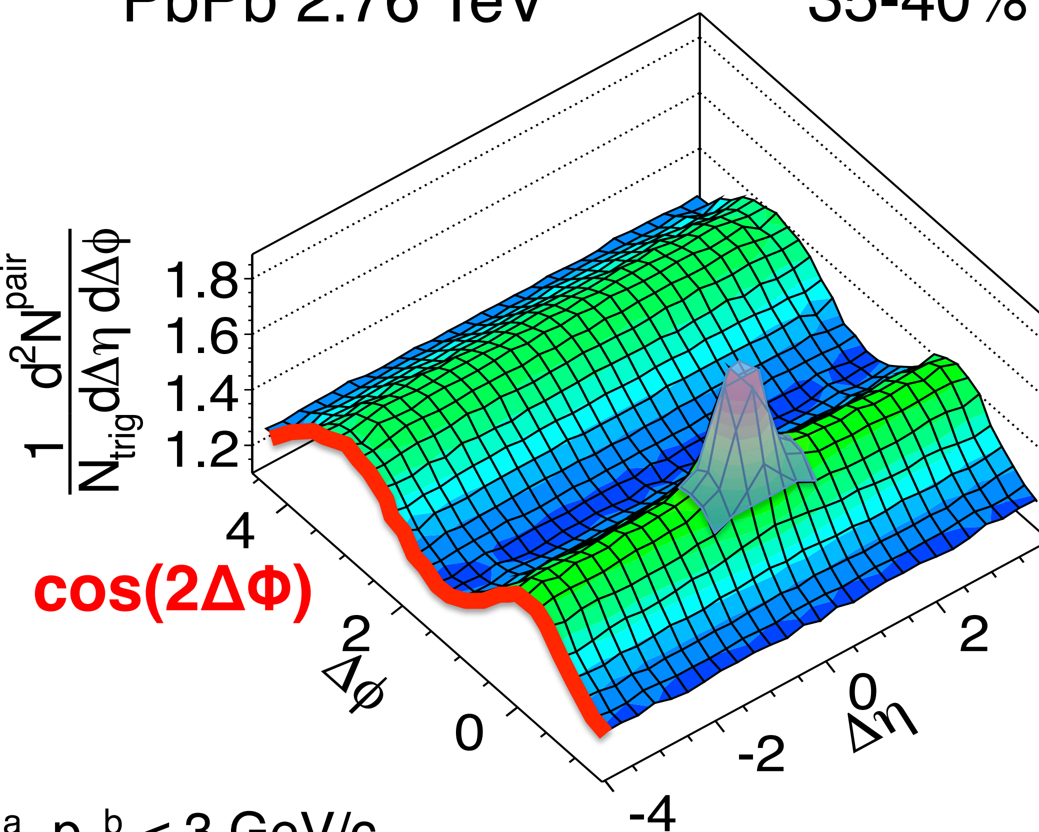


pp 7 TeV, MinBias

PbPb 2.76 TeV

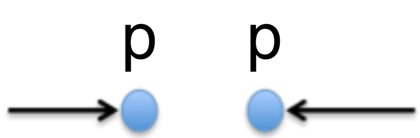
35-40%

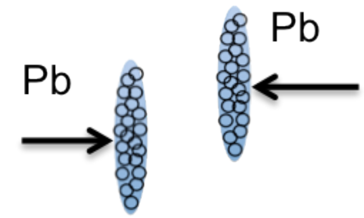




$1 < p_T^a, p_T^b < 3$ GeV/c

Flow, two-particle correlations, ridge …





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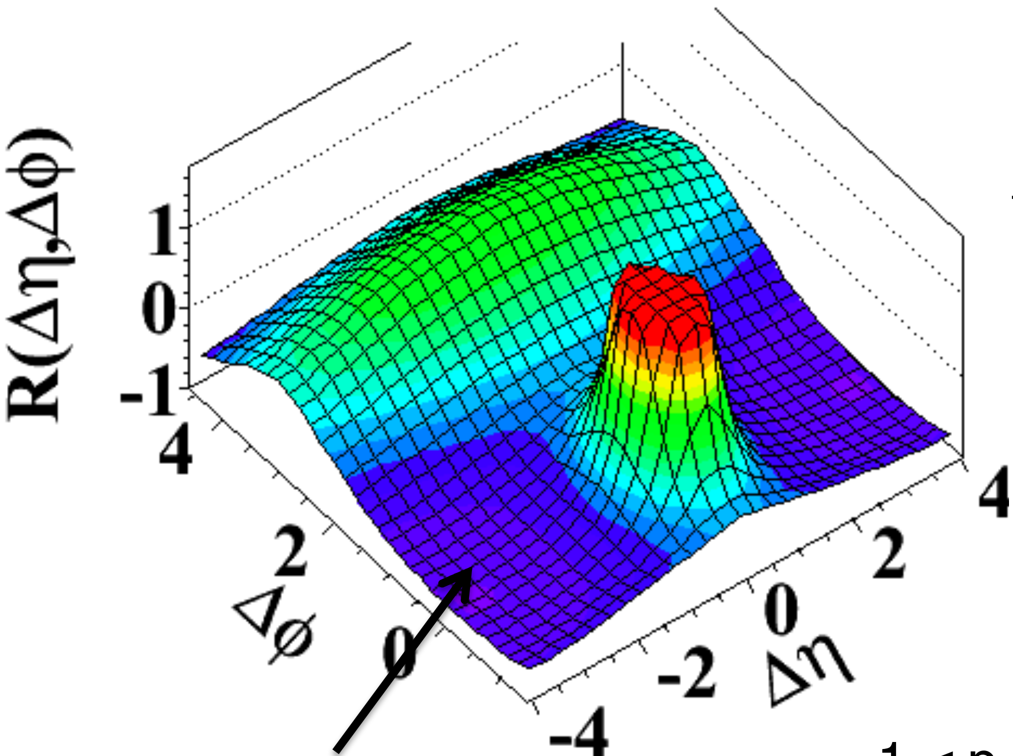
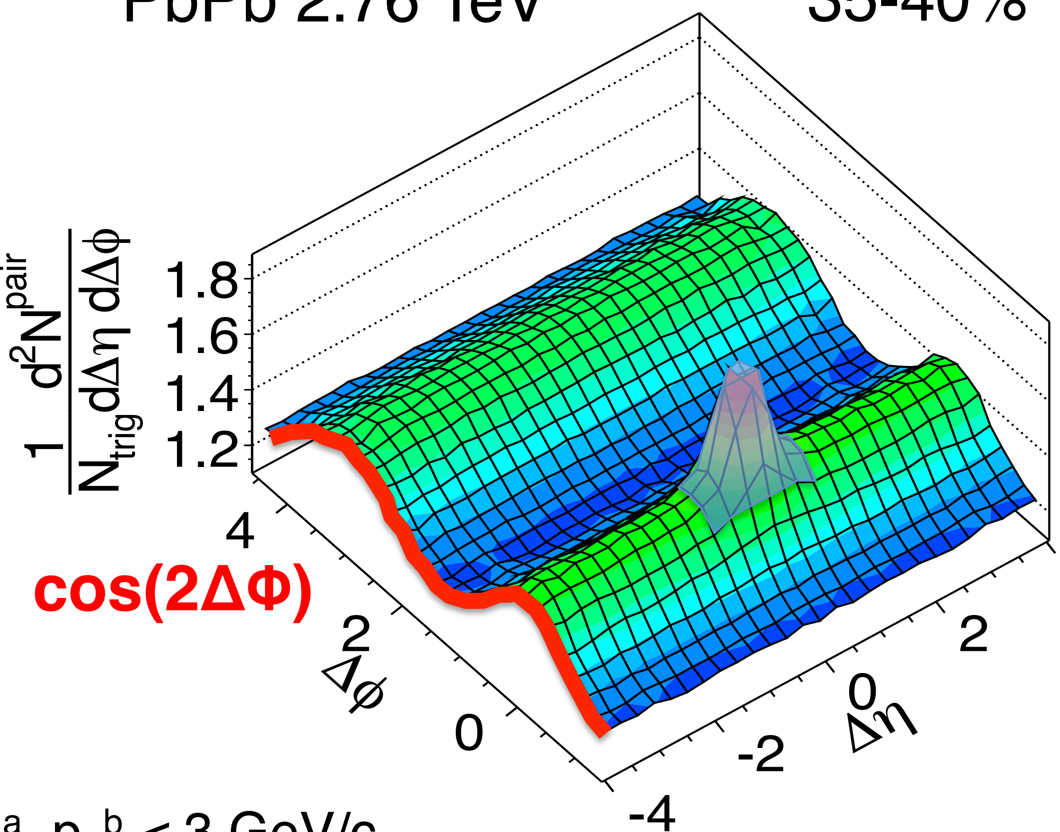
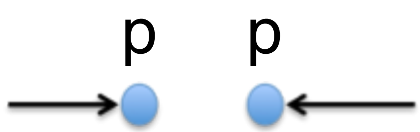




$1 < p_T^a, p_T^b < 3$ GeV/c

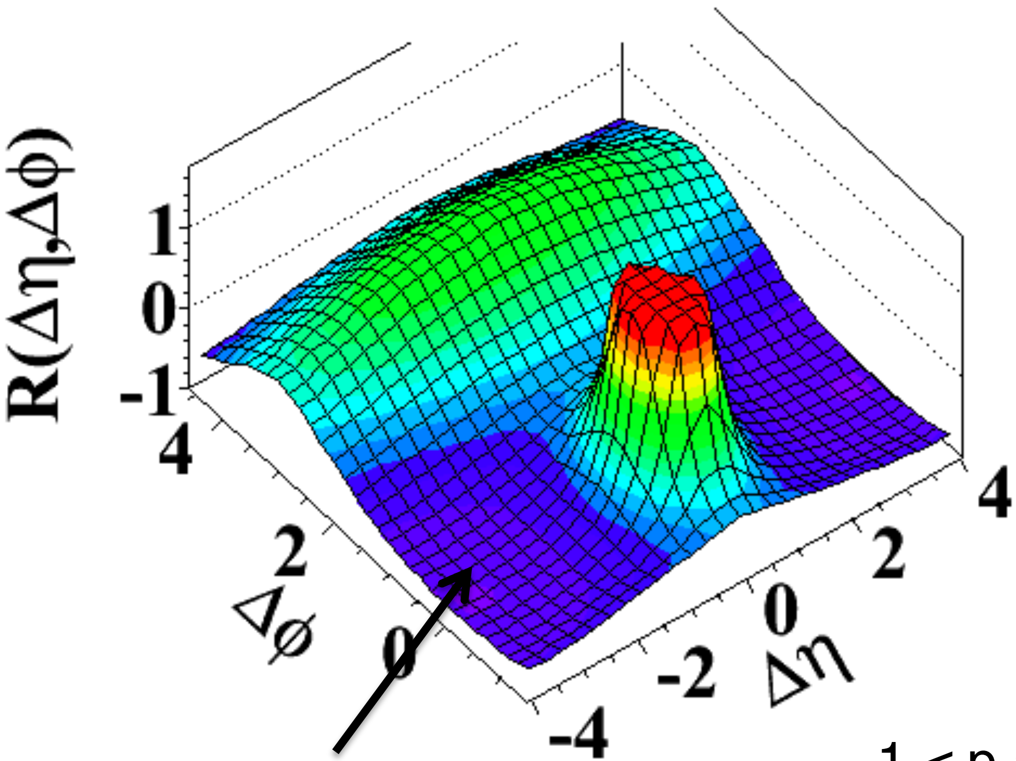
Nothing at ΔΦ ~ 0, |Δη|>2
(Near-side)

Breaking news in 2010!

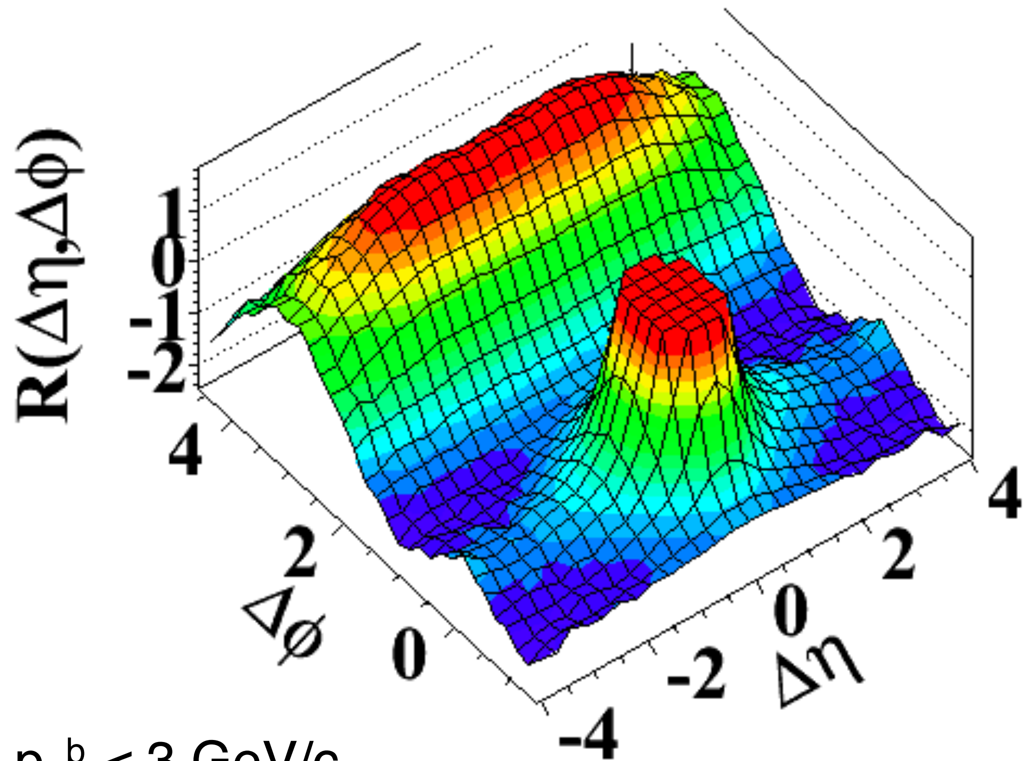


High-multiplicity pp events

pp 7 TeV, MinBias $\langle N_{trk} \sim 15 \rangle$



pp 7 TeV, $N_{trk} > 110$



Nothing at ΔΦ ~ 0, |Δη|>2
(Near-side)

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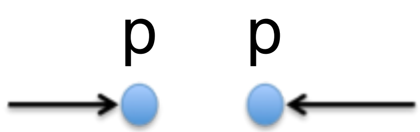
CMS, JHEP 09 (2010) 091

Breaking news in 2010!



High-multiplicity pp events

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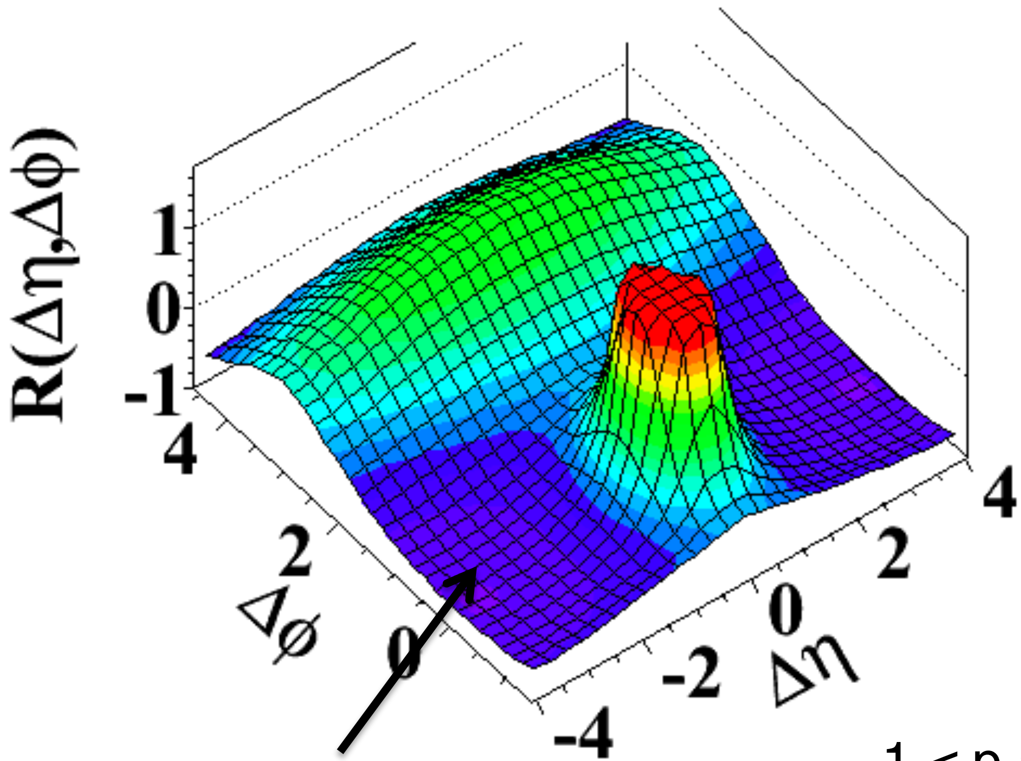

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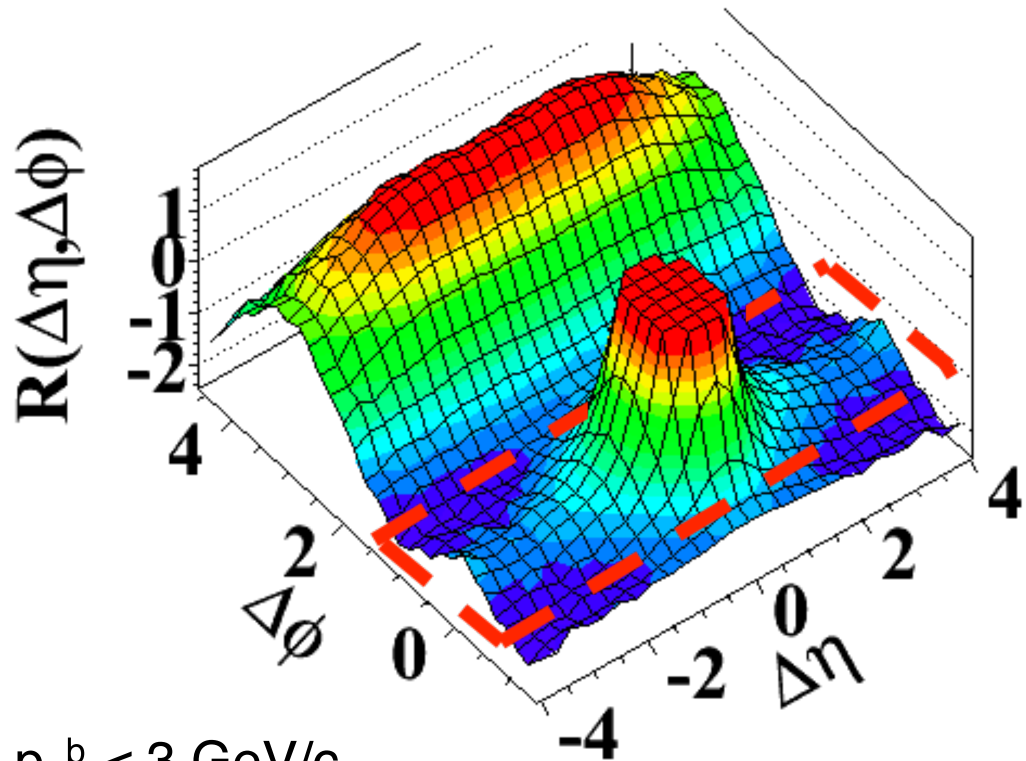

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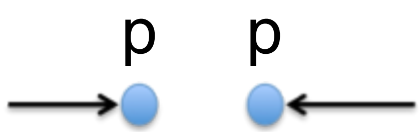
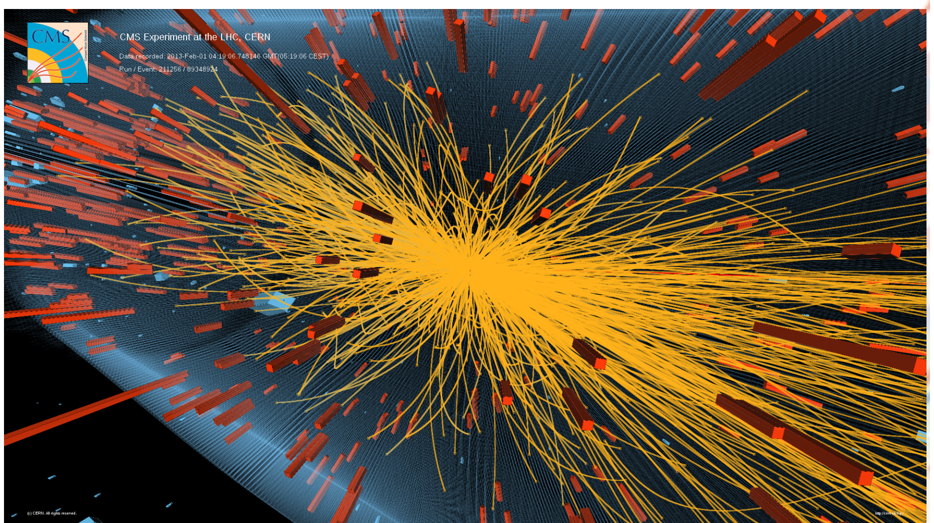
CMS, JHEP 09 (2010) 091

Near-side ridge

Breaking news in 2010!



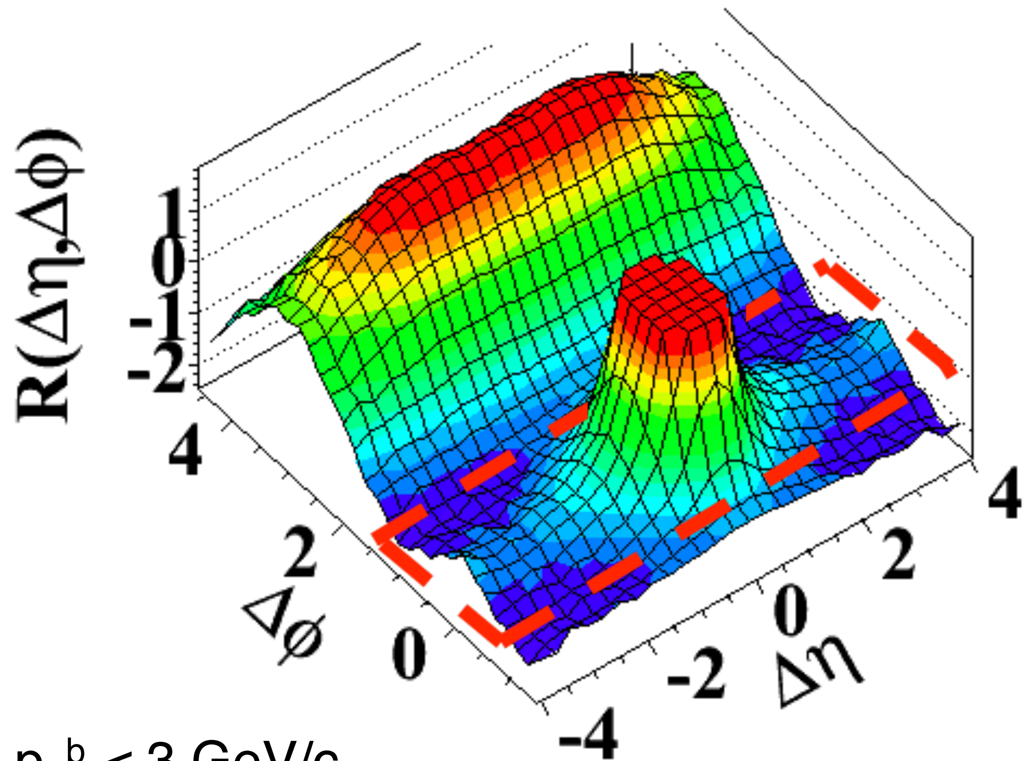
High-multiplicity pp events



Not a pileup!

10^{-6} – 10^{-5} prob.

pp 7 TeV, **N_{trk}>110**



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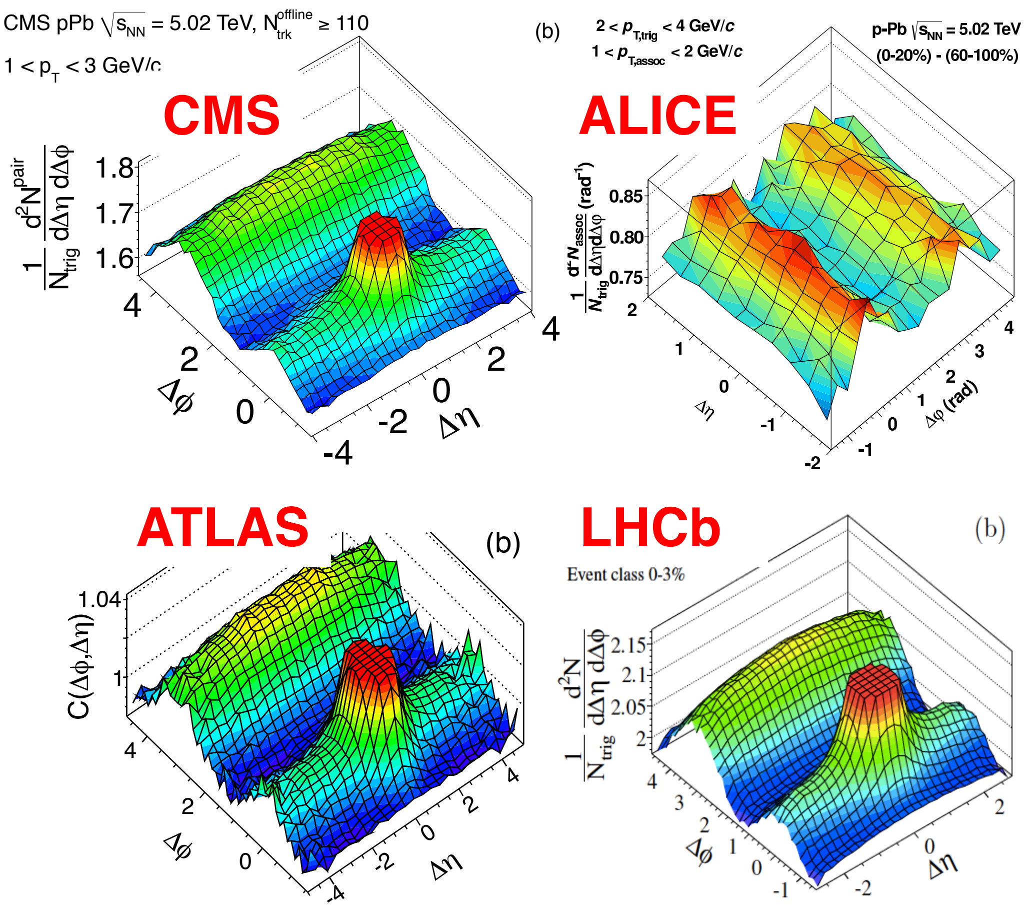
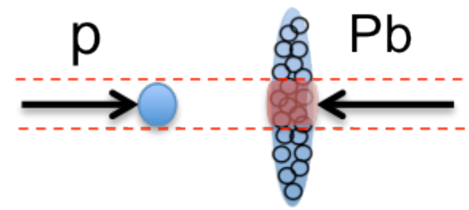
CMS, JHEP 09 (2010) 091

Near-side ridge

“Ridge” tsunami in pPb at the LHC

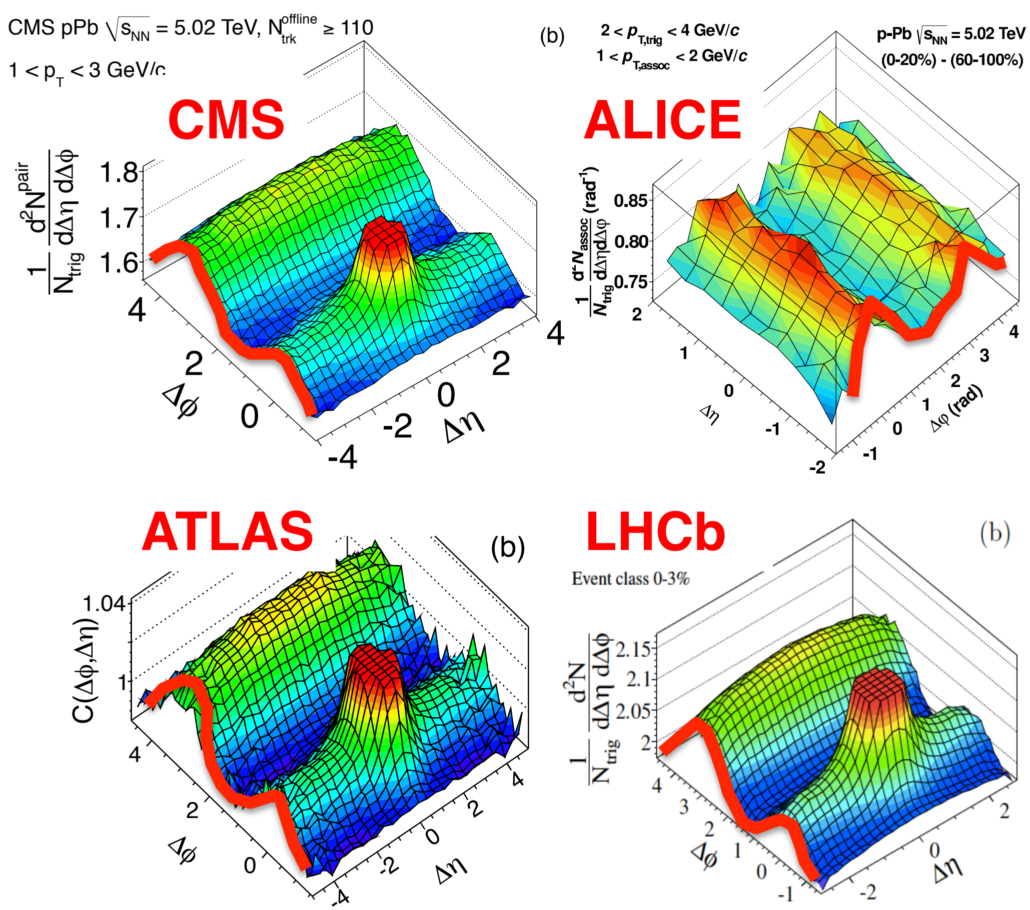


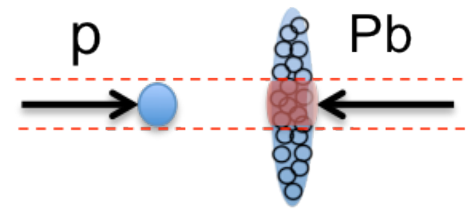


in 2012

Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!

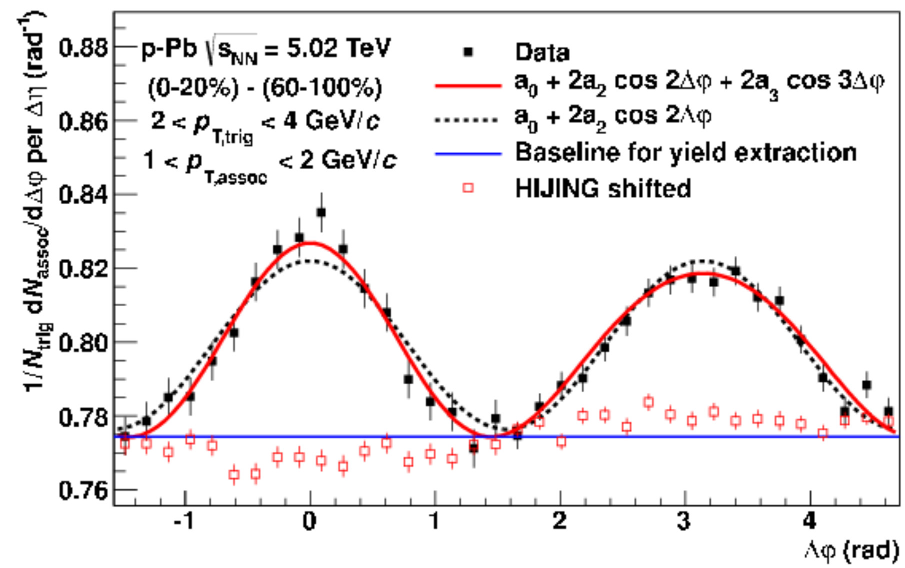
“Ridge” tsunami in pPb at the LHC





in 2012

“Flow” analysis

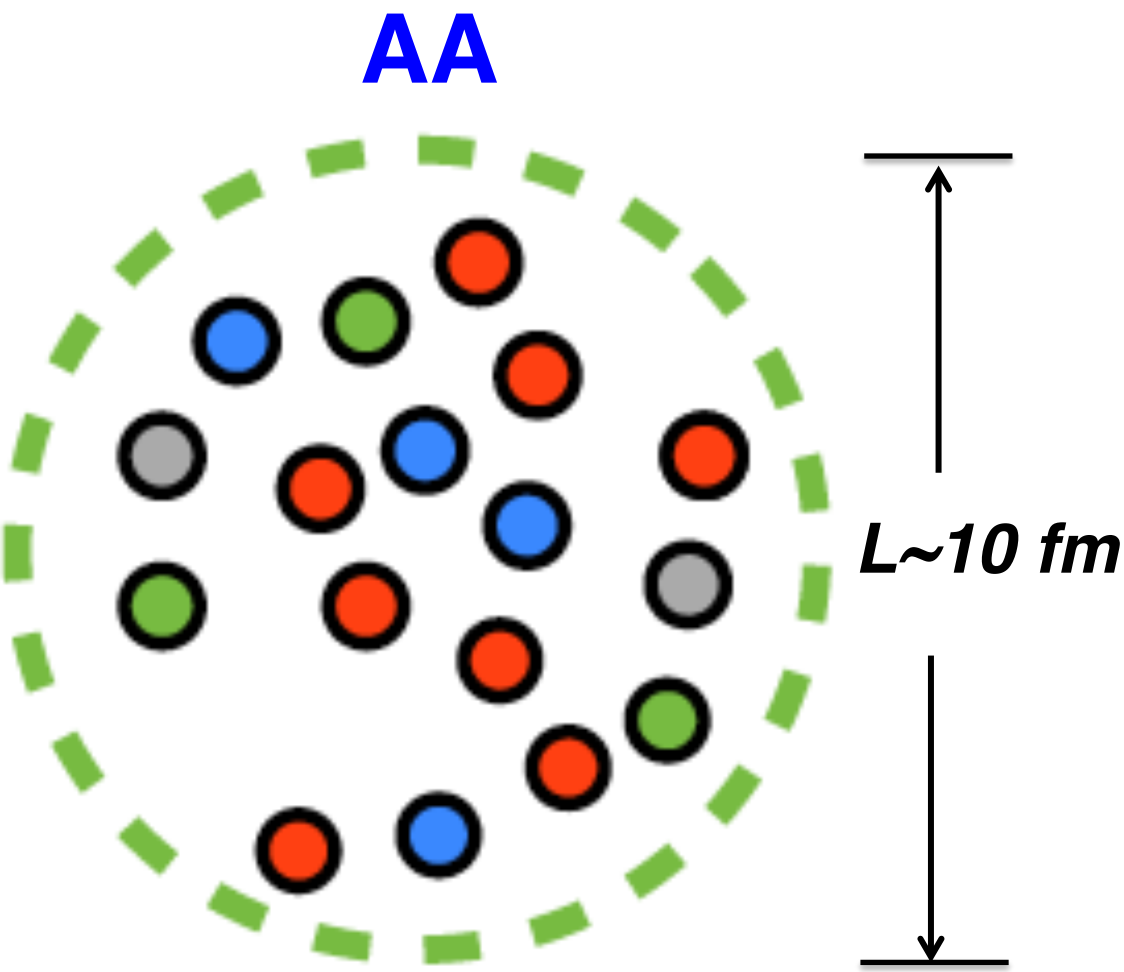


Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!

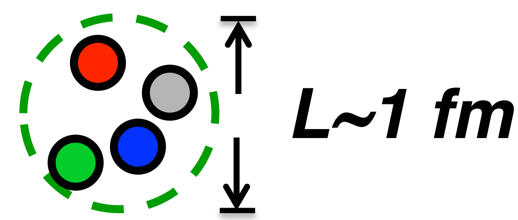
How small a QGP fluid can be?

Hydrodynamic applies when:

$$L >> \lambda_{m.f.p.}$$



Too small and dilute?



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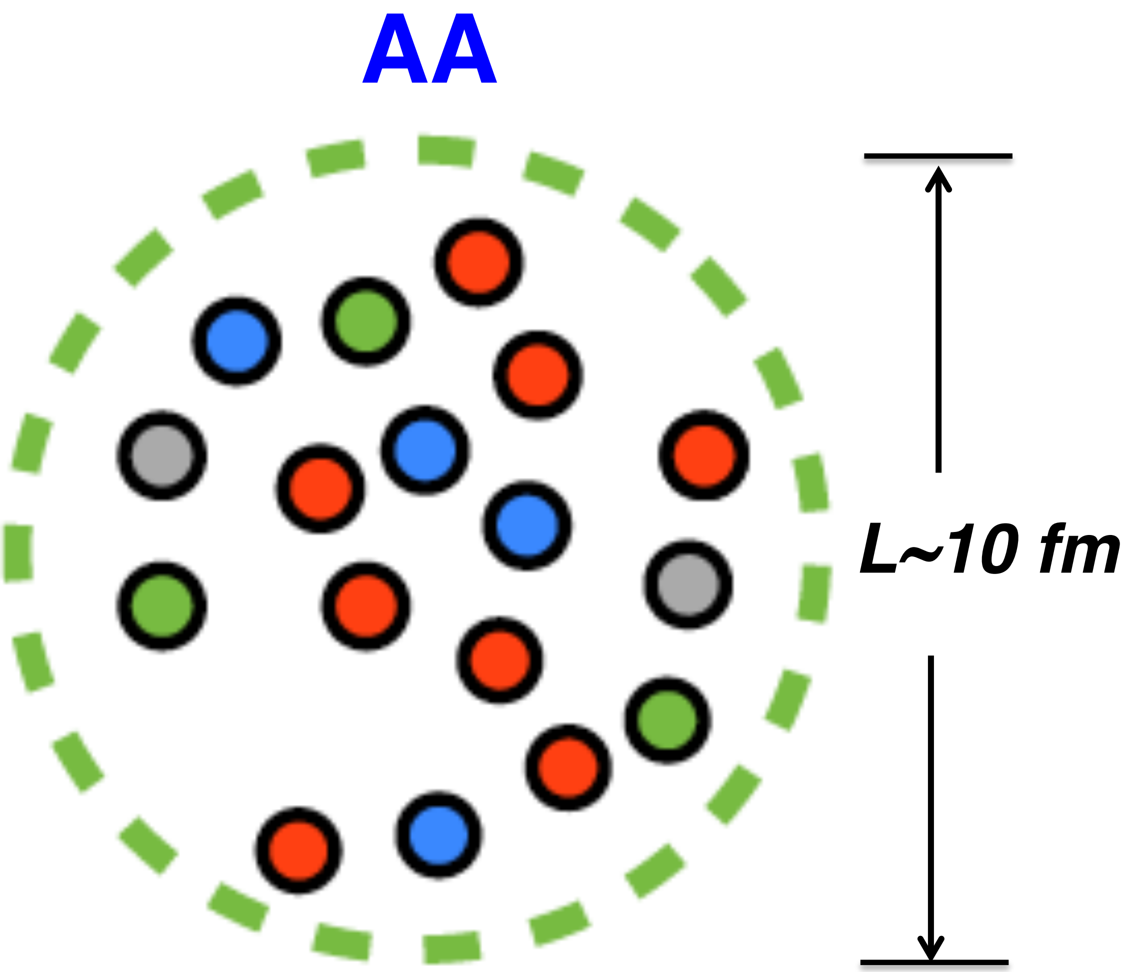
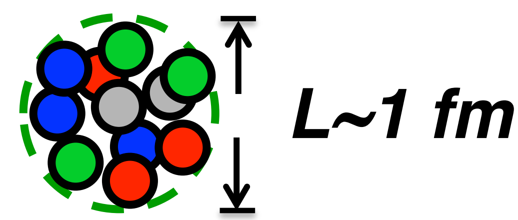


What if making it denser by increasing N_{trk}?



Summary of current status

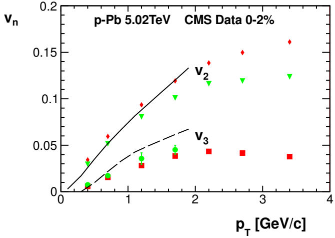
Almost all signatures of “flow” phenomena now commonly observed in all hadronic systems (pp, pA, AA), at sufficiently high multiplicities.

Some questions:

- ✧ Is QGP fluid created in small systems like pp?
- ✧ Is there a smallest scale of QCD fluid-like system?
- ✧ What’s still needed (experimentally) to reach a definitive conclusion?
- ✧ If everything flows, do we learn anything new about QGP from small systems?

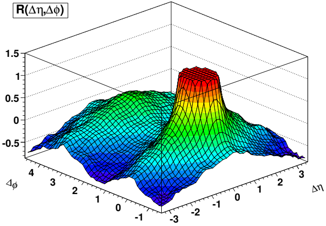
Elliptic and triangular flow in p-Pb

Hydro consistent with data



PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, . . .

Hydro generates the ridge



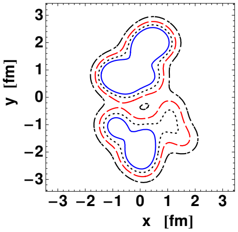
Werner, Karpenko, Pierog, 1011.0375

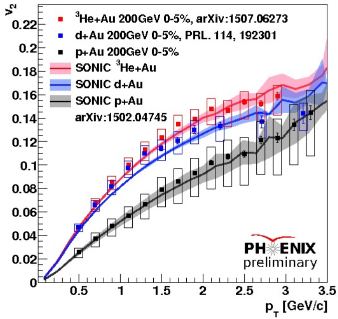
- v_2, v_3 consistent with hydro (Glauber MC, EPOS3)

$v_{2,3}$ - hydro response to initial deformation !

Elliptic and triangular flow in p-AU, d-Au, ^{3}He-Au

(small) deformed projectile





deuteron projectile(PB 1112.091

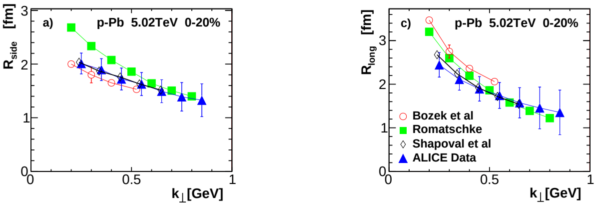
intrinsic deformation dominates over fluctuations

- hierarchy of v_2 and v_3 consistent with fireball geometry

large eccentricity - large flow component

collective response to geometry

1. **Elliptic and triangular flow**
2. **Hierarchy of v_2 and v_3 in p-A, d-A, He-A**
   collective response to geometry (final state effect)
3. **Flow from higher cumulants**
4. **Interferometry radii**

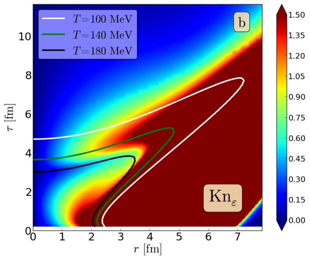


right magnitude and $k_\perp$ dependence of HBT radii
indication of space-momentum correlations

5. **Factorization at intermediate $p_\perp$ and large $\Delta\eta$**
   particles at intermediate $p_\perp$, large η, correlated to geometry
6. **Mass splitting of v_2**
7. Mass hierarchy of spectra $(< p_\perp >)$

Validy of hydrodynamics?

$K < 1$

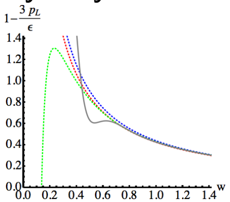


H. Niemi, G. Denicol 1404.7327

large gradients in the evolution

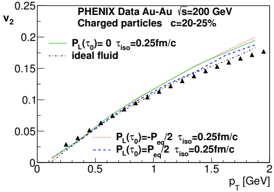
pressure asymmetry

1. **Hydrodynamics works with $P_L \ll P_\perp$**



Heller, Janik, Witaszczyk 1103.3452, solution converges to hydro

2. **Pressure asymmetry $P_L \ll P_\perp$ irrelevant**



PB, I. Wyskiel-Piekarska 1011.6210; J. Vredevoogt, S. Pratt 0810.4325, pressure asymmetry irrelevant for flow

Collective expansion observed in pA

- Is it hydrodynamics ?

Requires dominance of hydrodynamic modes

- estimate for a system size R (Spalinski 1607.06381)

$$RT > 2\pi\sqrt{2T\tau_\pi \, \eta/s} \simeq 1-3$$

in numerical AdS/CFT: $RT > 1$, (Chesler 1601.01583)

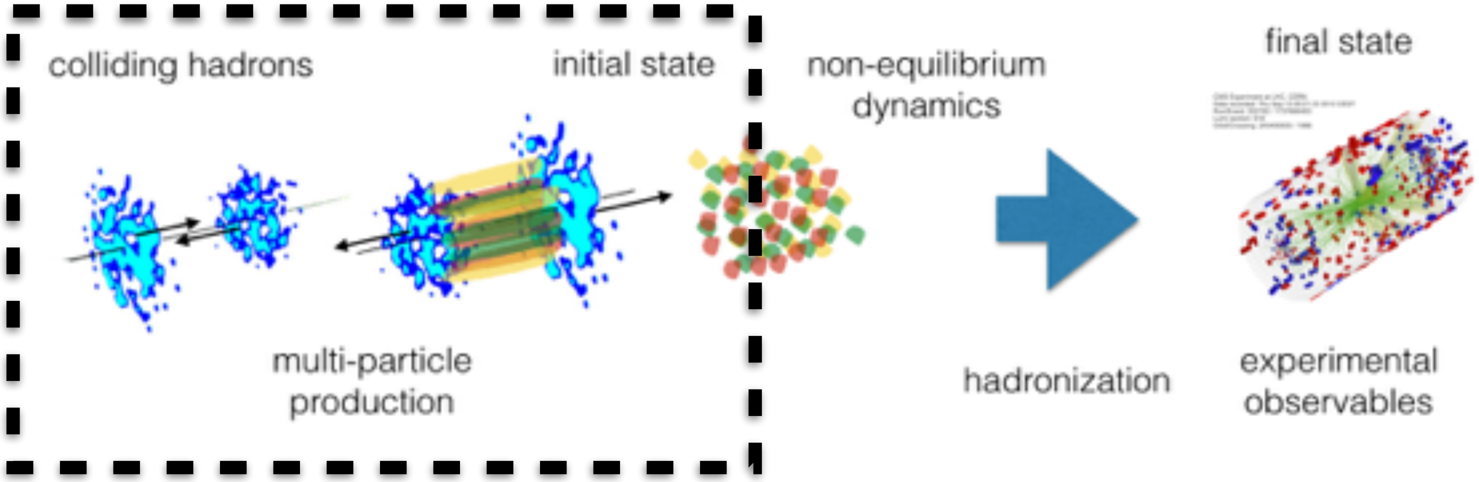
Hydrodynamics works down to $N_{ch} = 10 - 30$ (ATLAS, CMS)

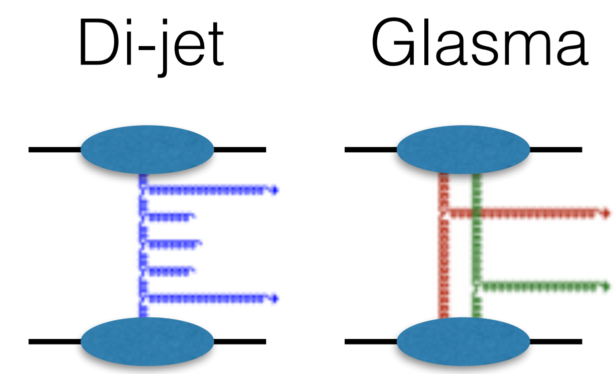
Success of hydrodynamics not accidental!

Break down of hydrodynamics difficult to observe (non-flow, jets . . .)

Initial state effects

Soeren Schlichting (BNL)





Multi-particle production in QCD naturally leads to momentum space correlations

-> multi-parton correlations in hadronic wave functions

Effects are sizable in small systems (p+p/A)

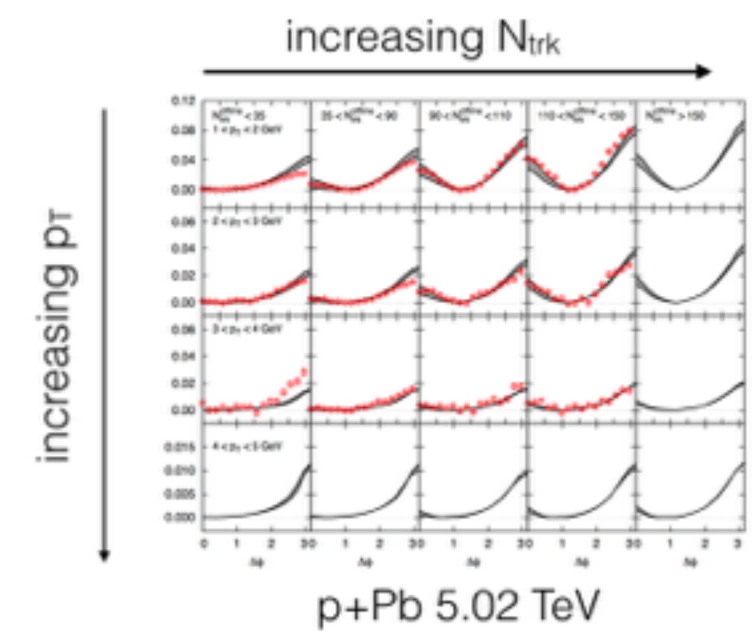
Calculations based on initial state correlations can describe two-particle correlations in wide range of semi-hard p_T and N_{trk}

-> $d^2N/d\Delta\Phi$, $<p_T>$ & $v_2(p_T)$ mass ordering, …

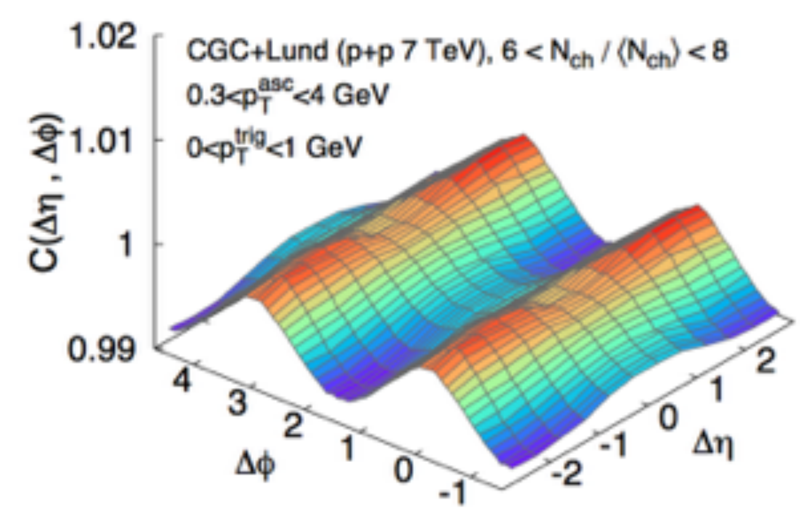
(c.f. talk by Schlichting on Tuesday)

Challenges: Extend calculations to lower p_T (di-jet,hadronization, …)

Compute multi-particle correlations (n>2)



Dusling, Venugopalan PRD 87 (2013) 9, 094034



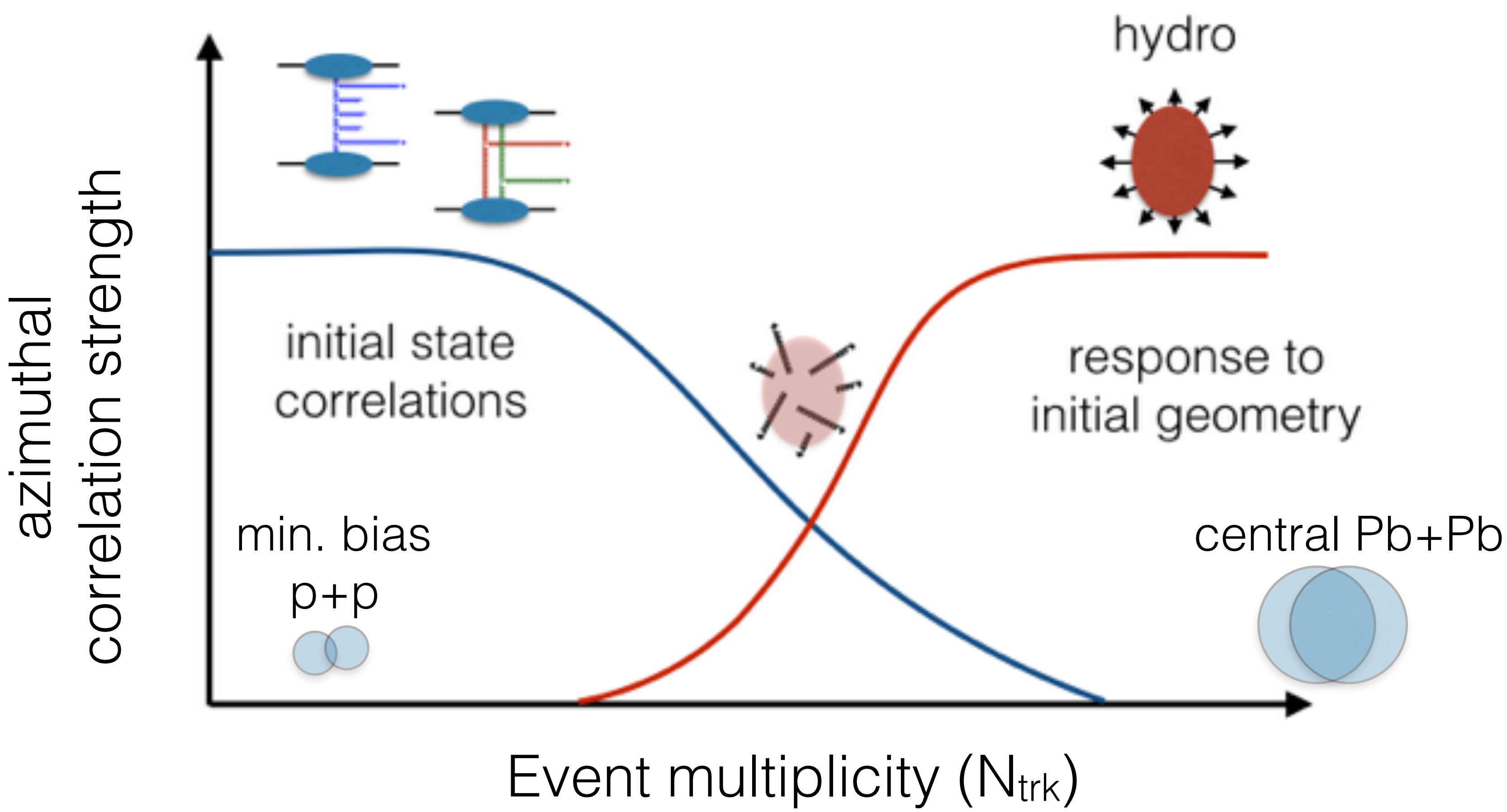
Schenke,SS,Tribedy,Venugopalan arXiv:1607.02496

Initial state vs. final state effects

Sizable correlations exist between particles produced in the initial state of hadronic collisions (p+p/A; p/d/He3+A)

How much they contribute to final state observables depends to what extent they are modified by final state effects

Qualitative picture:



Challenges:

Develop theoretical framework including initial state & final state effects

Identify observables to distinguish different regimes? (mini-) jet-quenching?

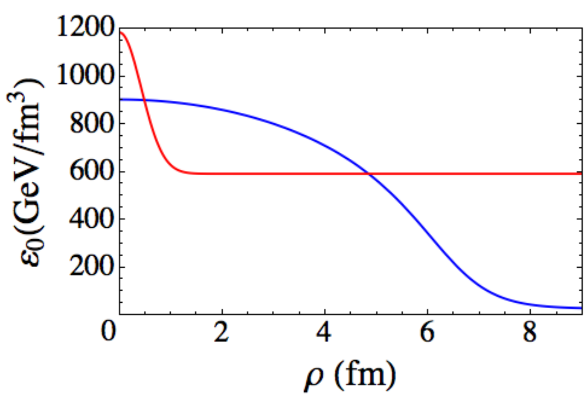
HYDRO IN SMALL SYSTEMS?

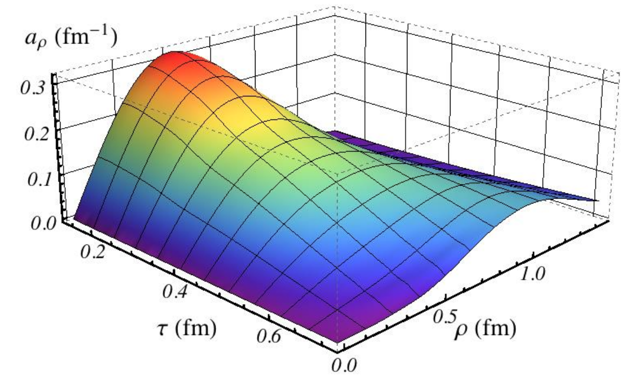
When is hydro applicable?

- Not far-from-equilibrium (shock)
- Not when pressure is negative (unstable)
    - But **viscous/anisotropic hydro** can apply if pressure ~ 0 (!!)
- Not in small system: $L \gg 1/T$ (perhaps $L \gg 1/\pi T$?): $VT^3 \gg 1$
- Shocks: **hydro applies within** *0.3/T*

TWO COMPUTATIONS FOR SMALL SYSTEMS

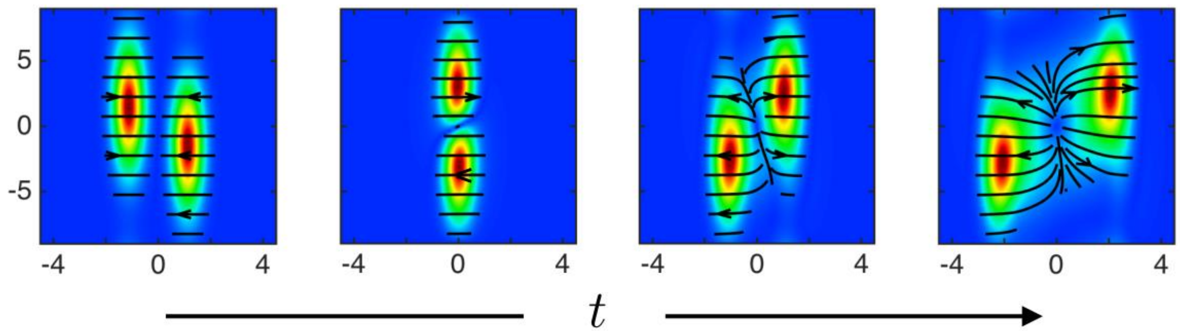
A fluctuation in a thermal bath:





- Hydro works within 0.2 fm/c, for system of size 0.5 fm.

A full-blown off-center `p-p collision':



- Hydro found to work in a system with R ~ 1/T

WS, Holographic thermalization with radial flow (2012)
Paul Chesler, How big are the smallest drops of quark-gluon plasma? (2016)

AN ESTIMATE

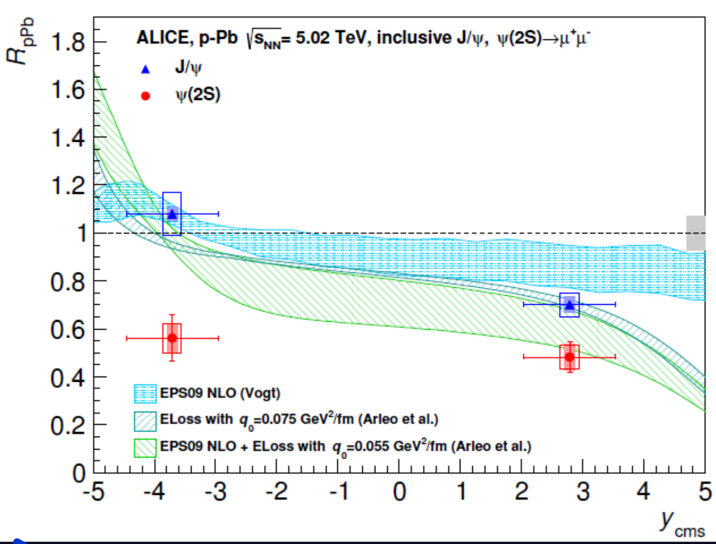
For p-Pb and p-p collisions only few particles produced

- Naïve estimate: $s \approx 16T^3$ gives $N_{ch} \approx Vs/7.5 \approx 2.1VT^3$
- When $R > 1/T$ (or $1/\pi T$??) then dN_{ch}/dy > 2.1 (0.7??)
- Note that R increases faster than $1/T$ (τ versus $\tau^{1/3}$)
  - Hydro works better at later times
  - Flow requires time to develop, i.e. 2.1 is `optimistic' estimate

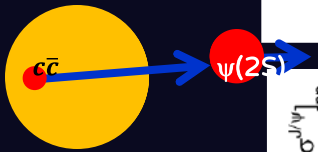
a different perspective...

- Can we learn something on the medium produced in p-A collisions looking at a different (and hard) probe?

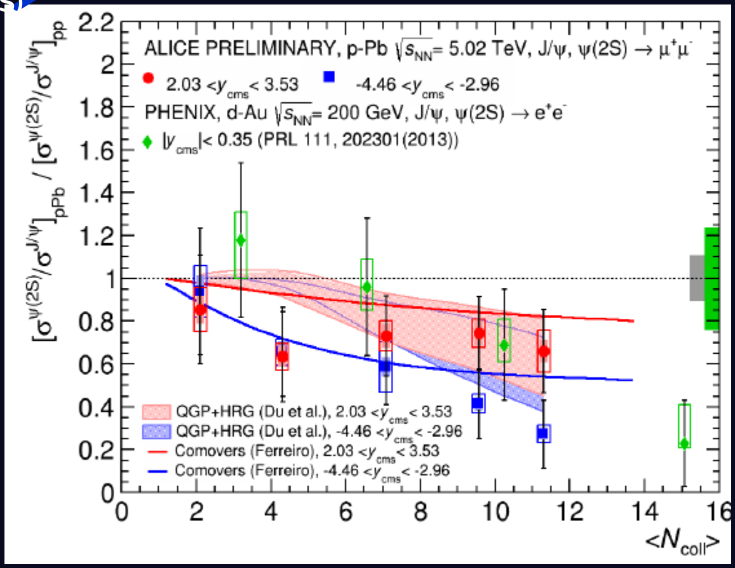
- suppression of loosely bound ψ(2S) is stronger than the J/ψ one, both at RHIC and LHC in dA, pA



→ unexpected since time spent by cc in the nucleus is shorter than charmonium formation time



→ CNM as shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression



- only models including already in pA QGP + hadron resonance gas or comovers describe the stronger ψ(2S) suppression

Re: hydro/kinetic theory applied to systems of $\mathcal{O}(1\ \mathrm{fm})$ size with sub-fermi structures...

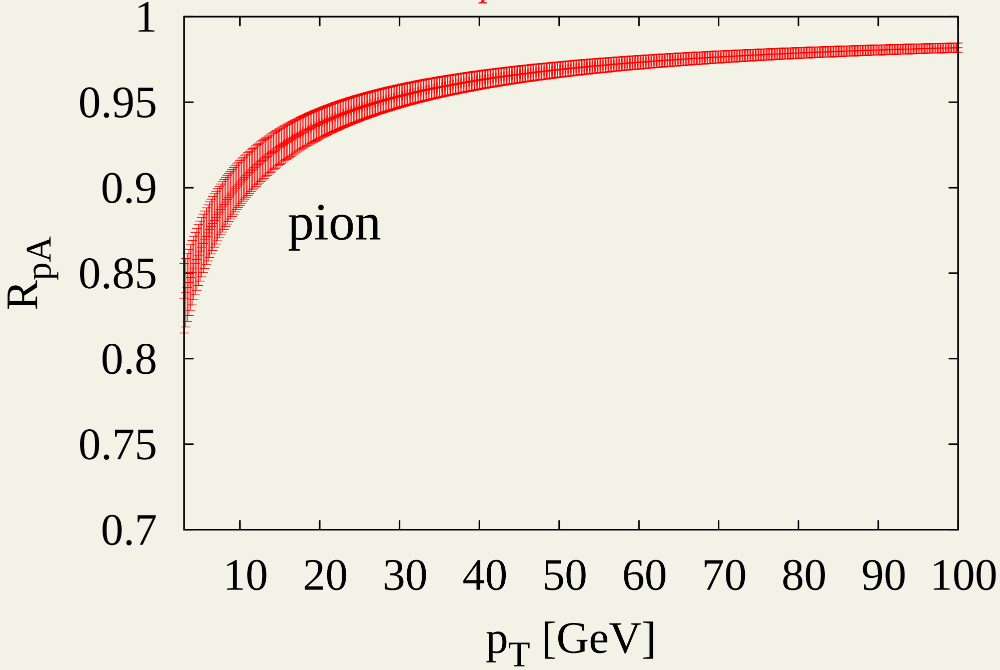
one intriguing question: how/when quantum mechanics (wave physics) enters - e.g., cannot localize both in x and p

$\Rightarrow$ **inherent momentum anisotropies** e.g. DM, Wang & Greene 1404.4119

Also, if these systems are opaque enough for hydro, there should be energy loss (jet quenching) signatures. E.g., p+Pb @ 5.02 TeV (top 3.4% cent):

DM & Sun at QM2015

$\pi^0\ R_{pA}$



$\pi^0\ v_2, v_3, v_4$