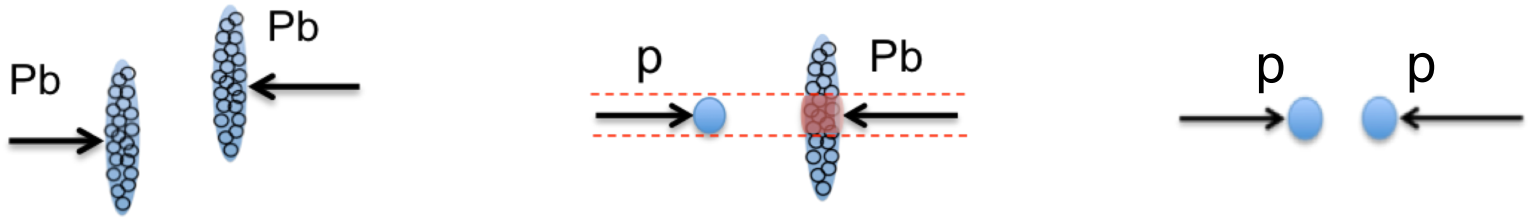
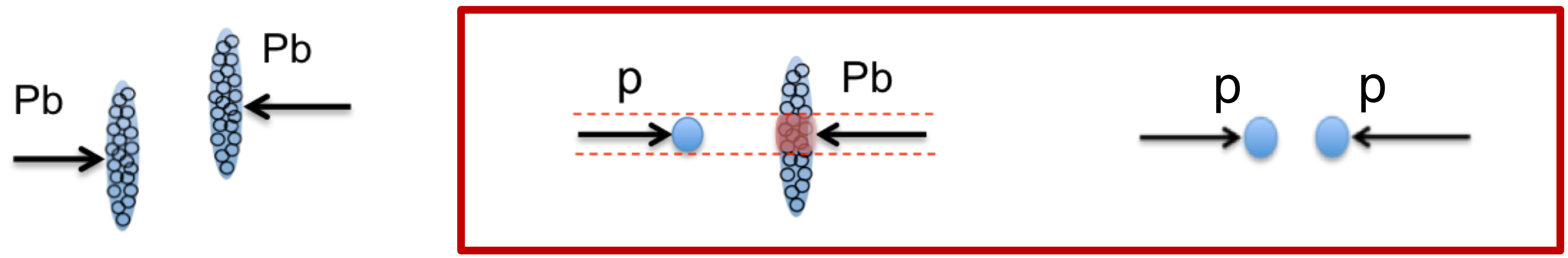


Long-range collectivity in high-energy collisions and implications to quantum entanglement

Wei Li
Rice University

Workshop on Quantum Entanglement at Collider Energies
CFNS, Stony Brook
September 10-12, 2018



Long-range collectivity in high-energy collisions and implications to quantum entanglement

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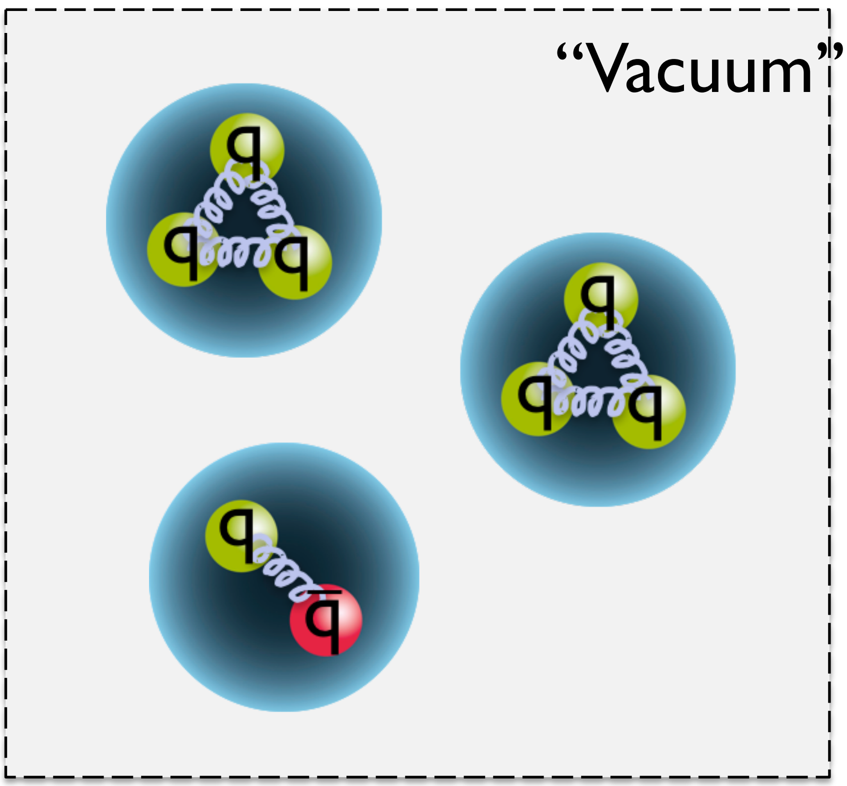
Mystery of quark confinement



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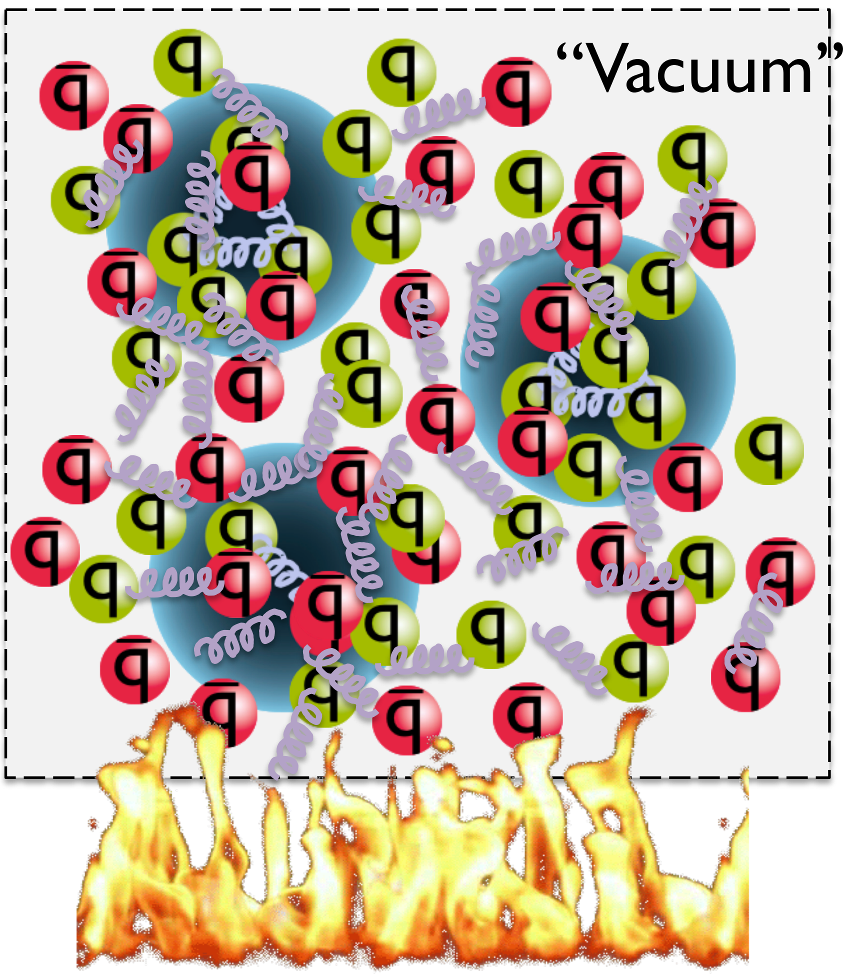

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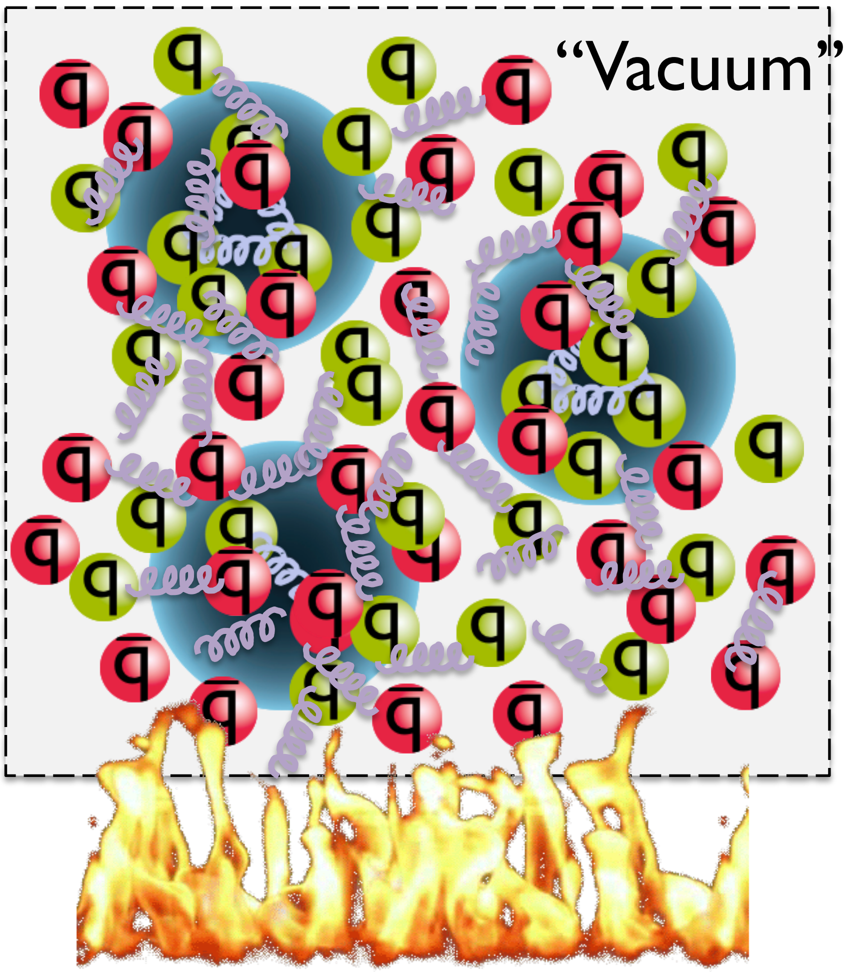
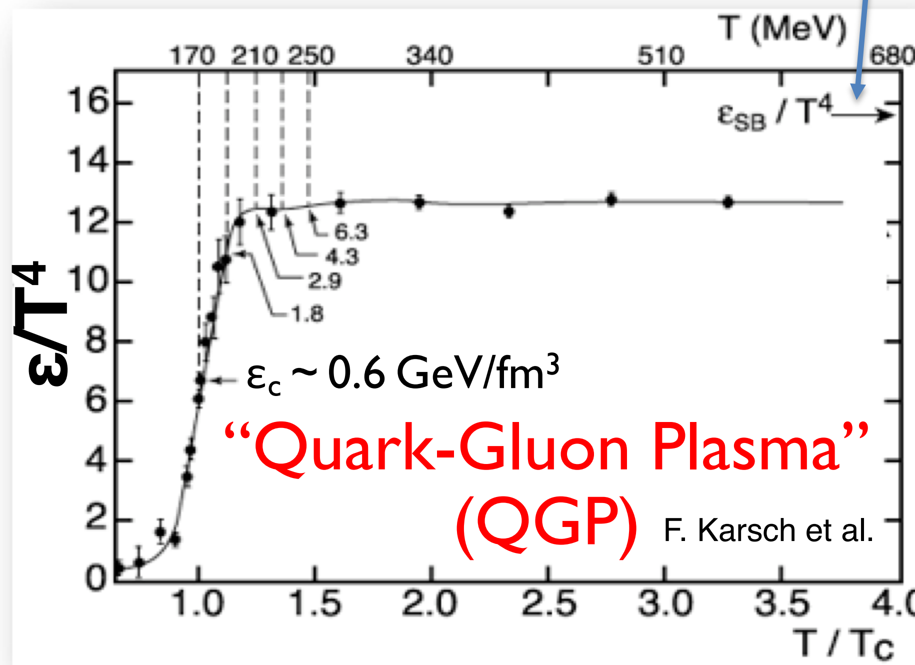


Lattice QCD

"ideal gas"

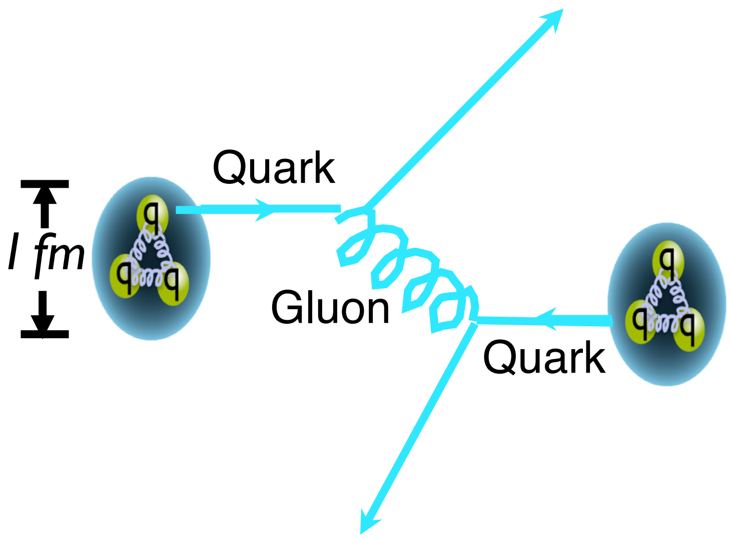


T_C ~ 154 MeV ~ **2x10^{12} K**

Liberated quarks/gluons at high T (weakly coupled)?

Creating the QGP

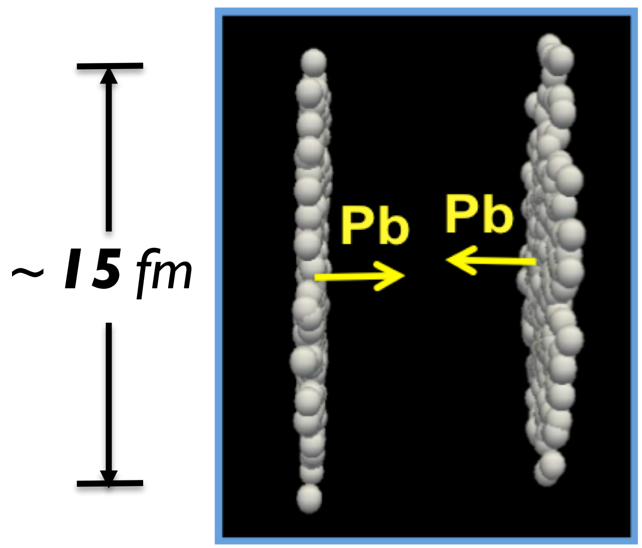
Proton-proton



Too small, dilute!

Colliding large *nuclei* instead

T.D. Lee, RMP *47*, 267(1975)

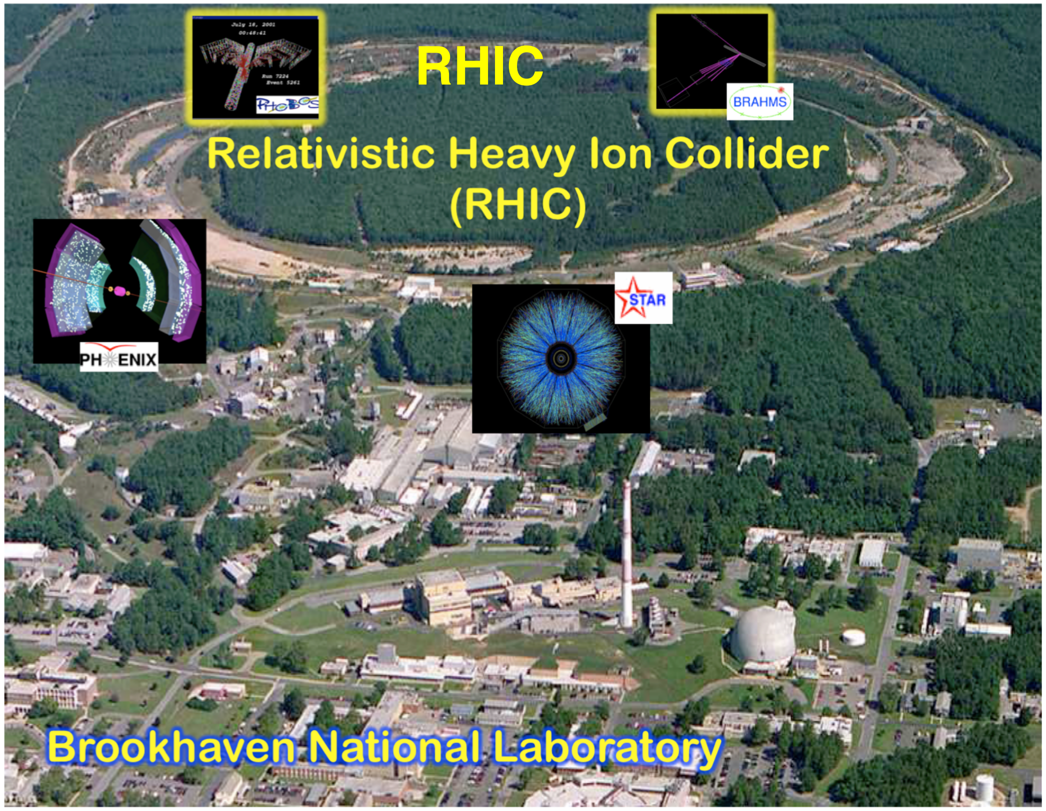


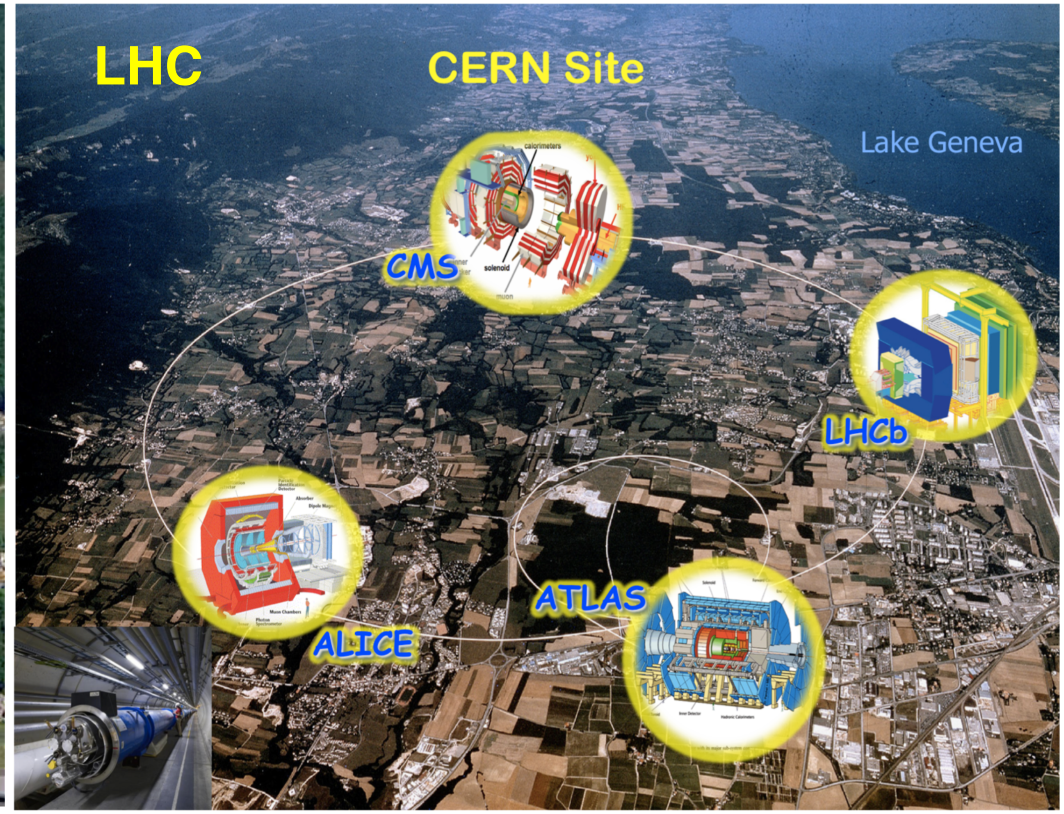
$\gamma \sim 100 - 2000$

Total colliding energy:

$\sim 10^6$ GeV

High-energy heavy ion colliders





Long Island, NY

Geneva, Switzerland

x25

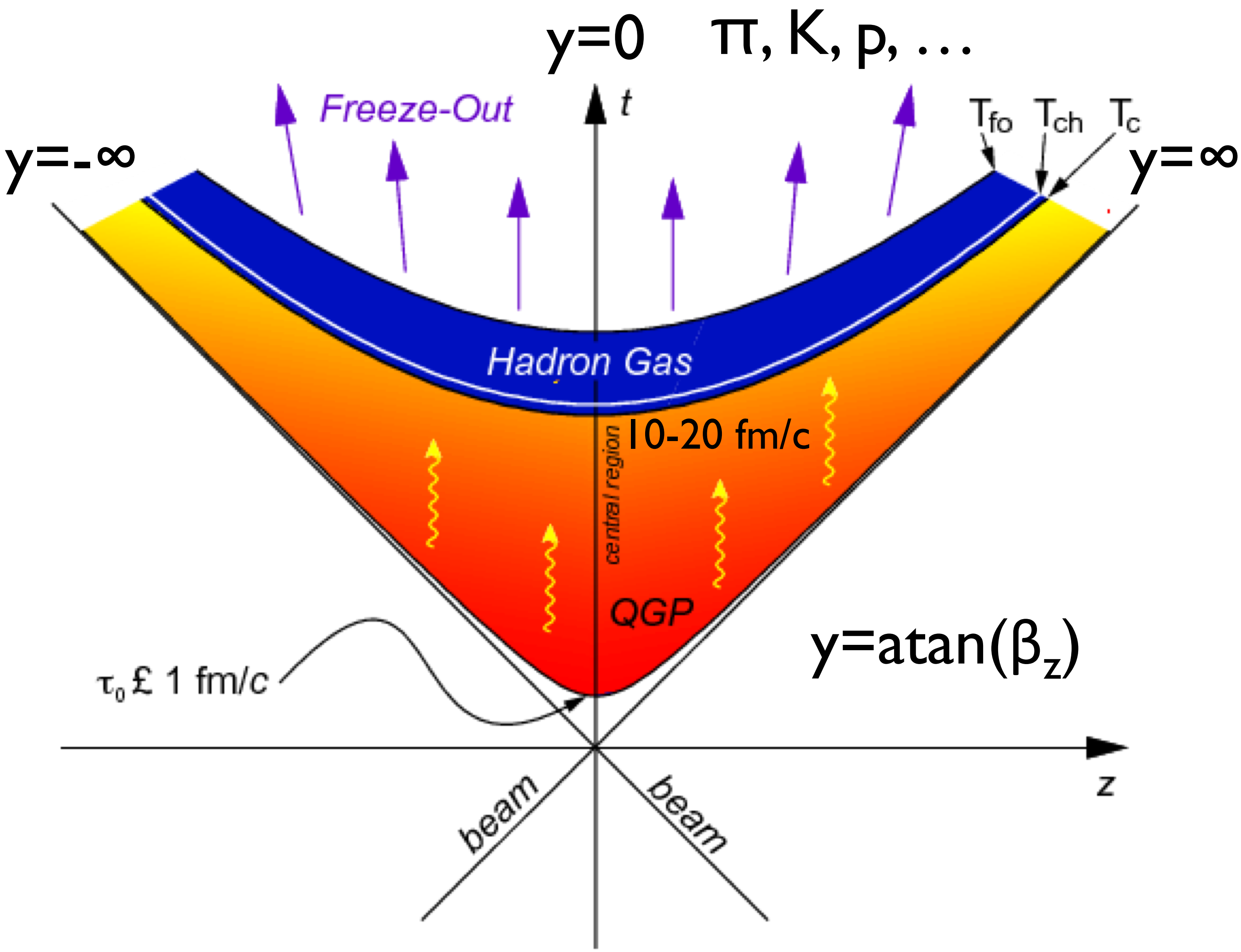
2000 -

- pp, pAu, dAu, He^3Au, CuCu, CuAu, AuAu, UU, ...
- $\sqrt{s_{NN}}$ ~ 0.007 – 0.2 TeV

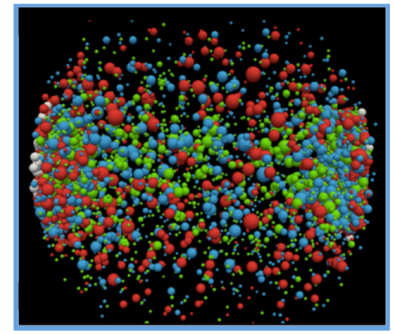
2010 -

- pp, PbPb, pPb, XeXe, …
- $\sqrt{s_{NN}}$ ~ 5 – 8 TeV

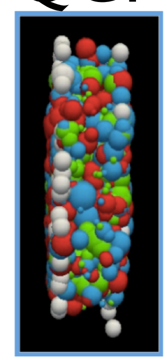
Space-time evolution of a heavy ion collision



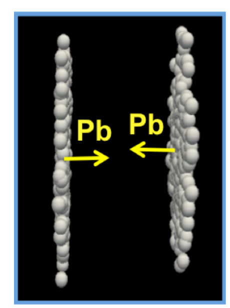
Freeze-out

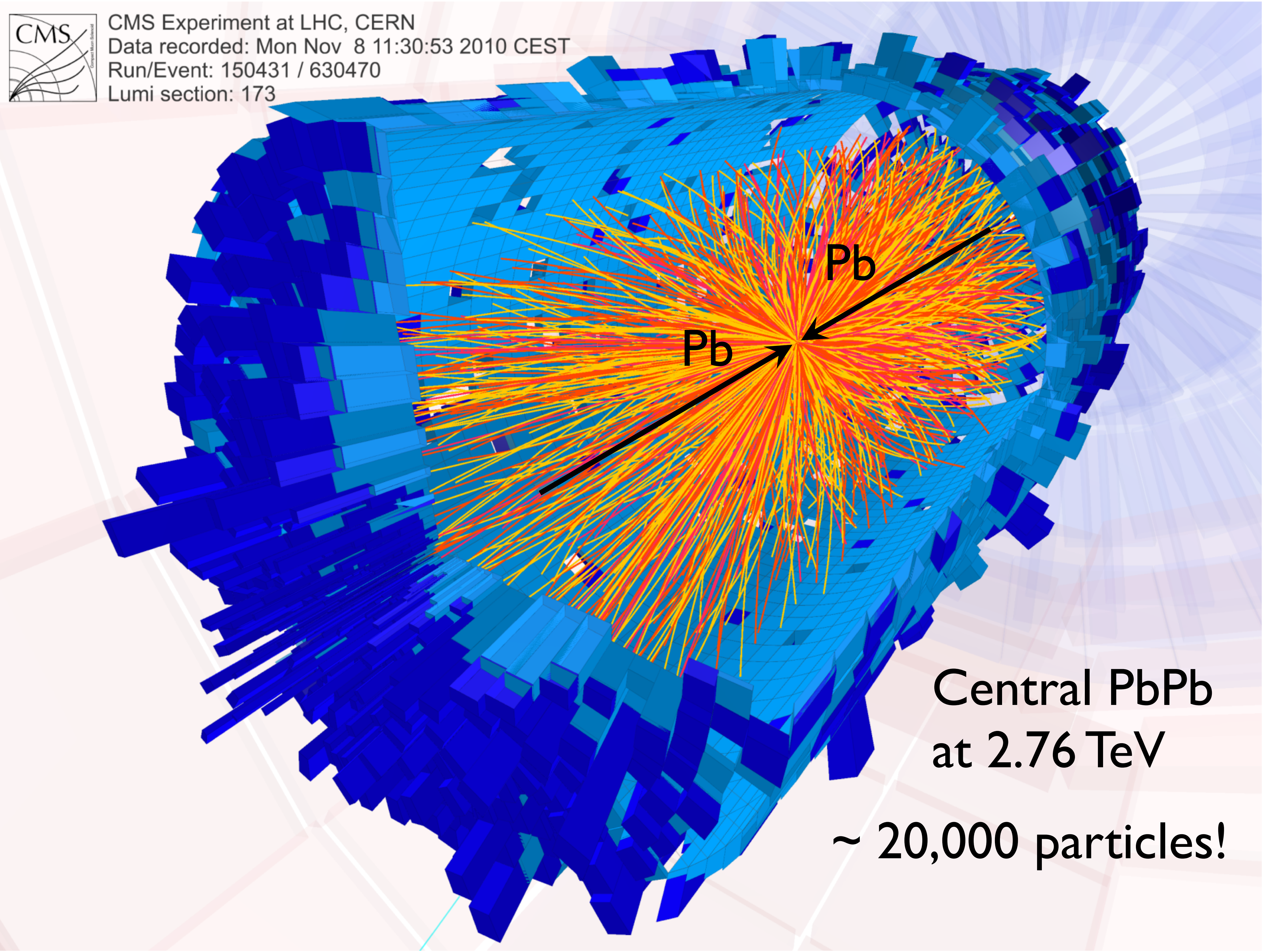


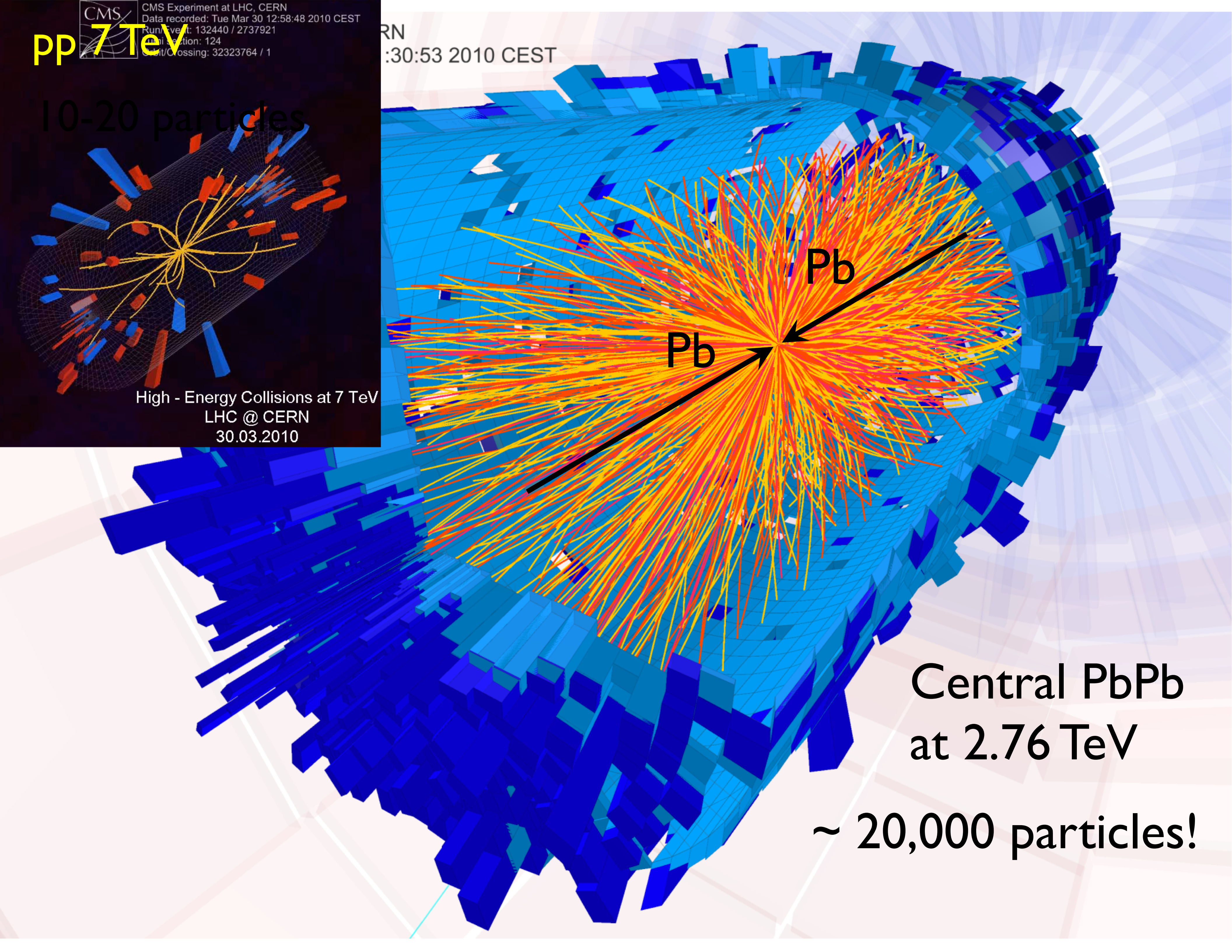
QGP



Pre-reaction




CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173
Pb
Pb
Central PbPb
at 2.76 TeV
~ 20,000 particles!


CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 12:58:48 2010 CEST
pp 7 TeV
10-20 particles
High - Energy Collisions at 7 TeV
LHC @ CERN
30.03.2010
:30:53 2010 CEST
Pb
Pb
Central PbPb
at 2.76 TeV
~ 20,000 particles!

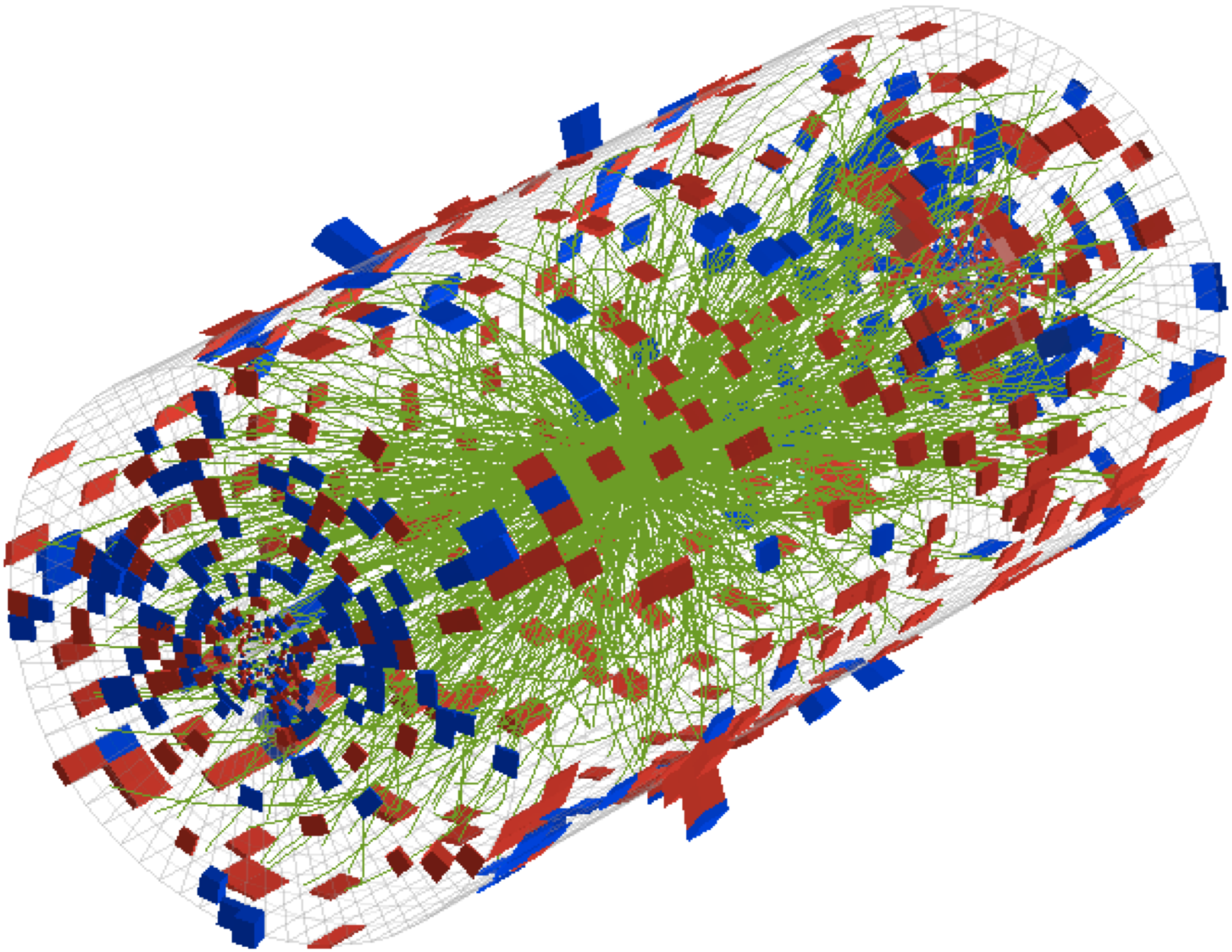
RHIC Scientists Serve Up 'Perfect' Liquid instead of a gas!?

New state of matter more remarkable than predicted — raising many new questions

Monday, April 18, 2005

Reaffirmed later by LHC experiments

Particle correlations and QGP fluidity



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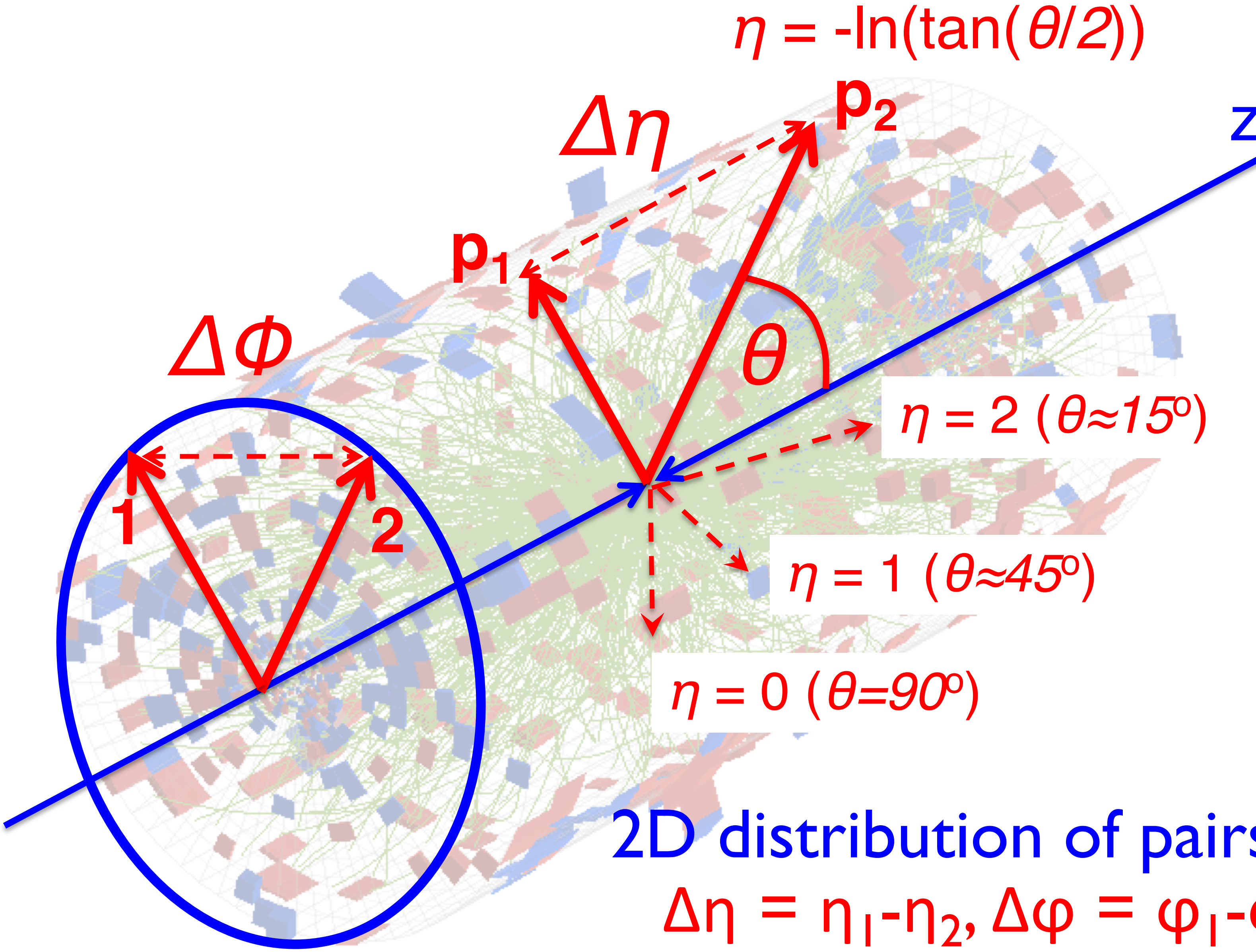
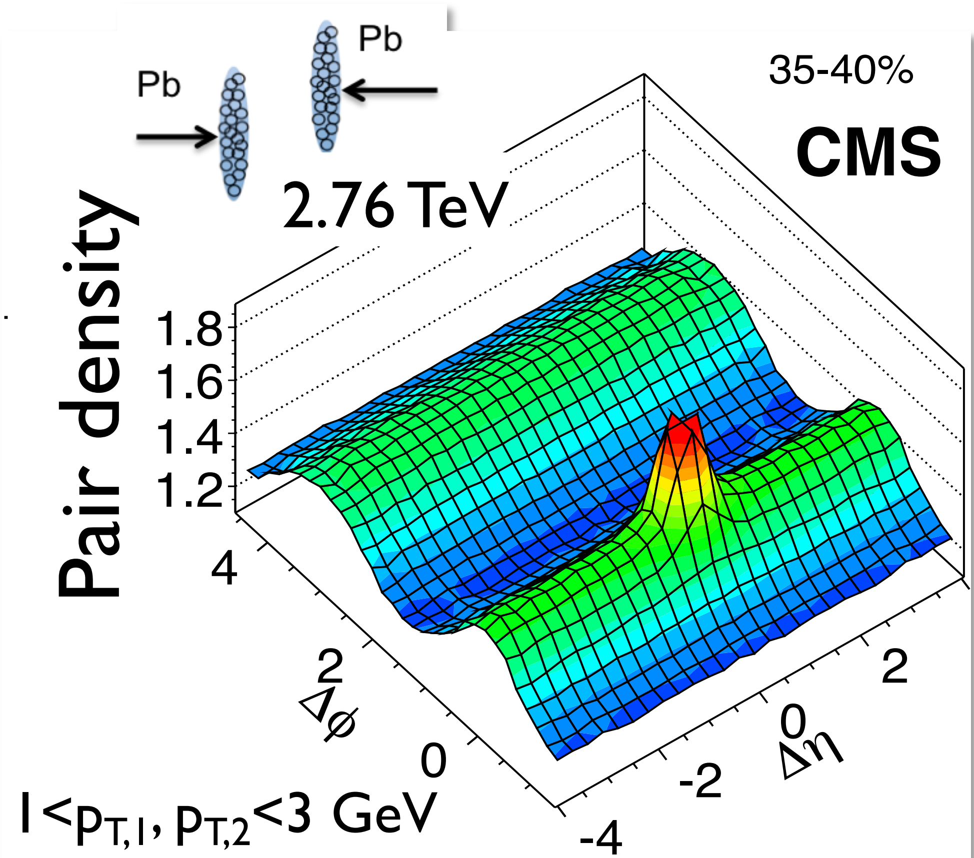


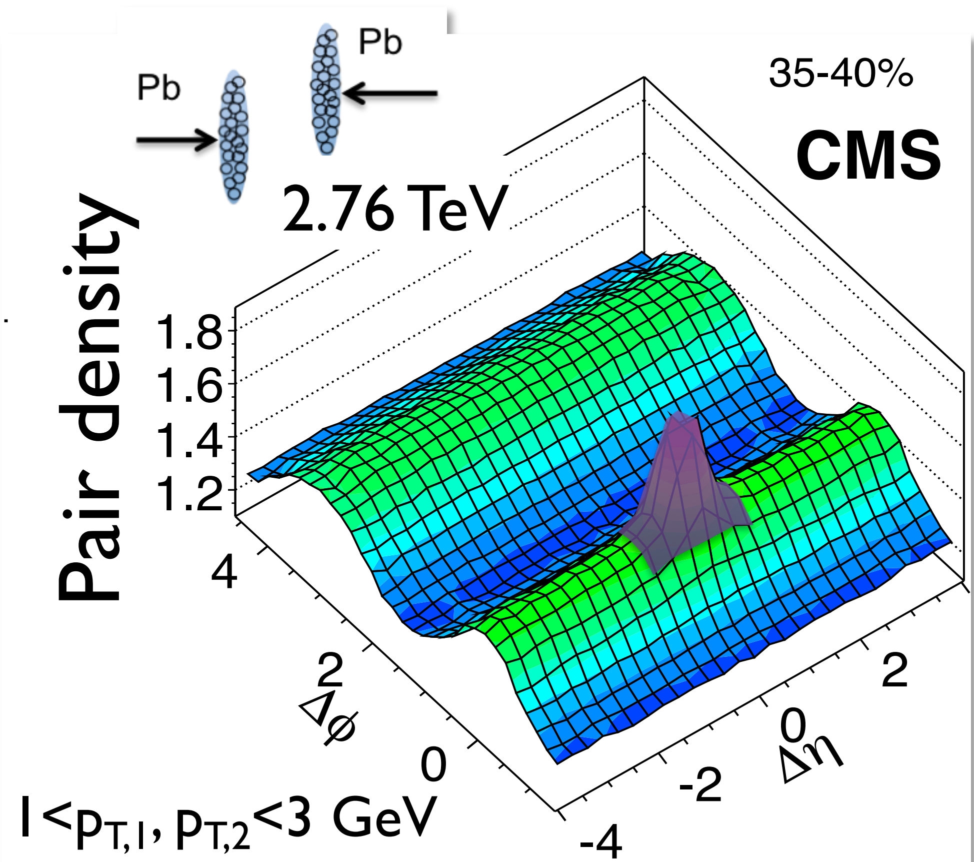
2D distribution of pairs in
$\Delta\eta = \eta_1 - \eta_2$, $\Delta\varphi = \varphi_1 - \varphi_2$

QGP fluid paradigm in AA collisions



Azimuthal correlations over wide rapidities (>4-5 units)

QGP fluid paradigm in AA collisions



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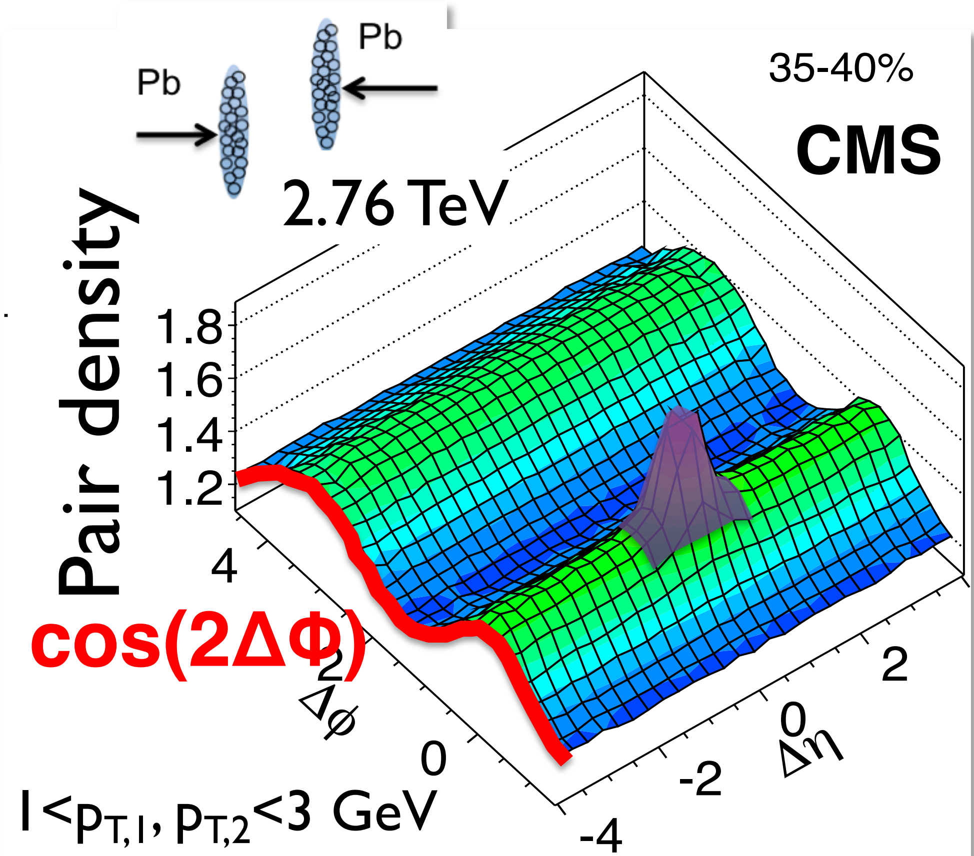

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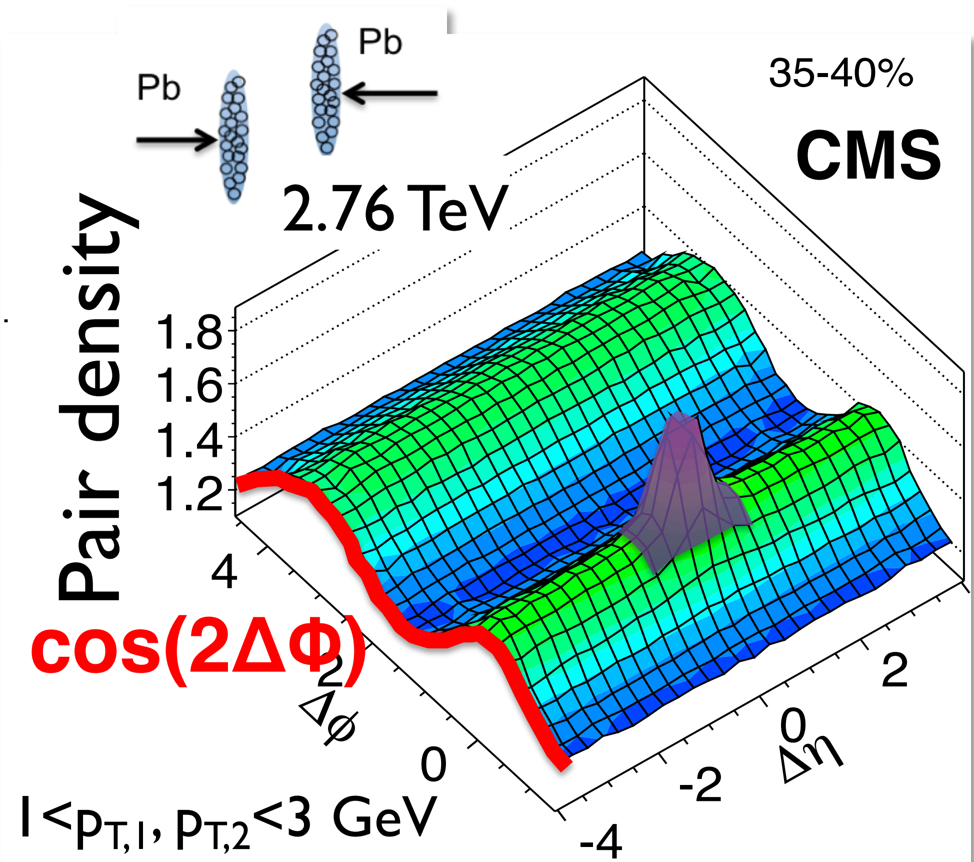
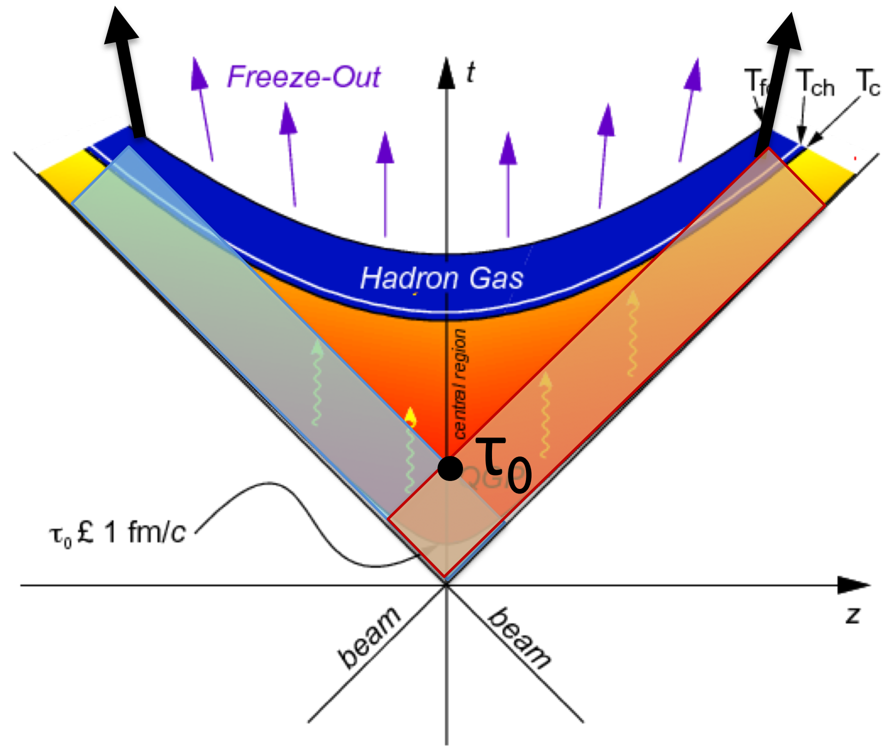


Azimuthal correlations over wide rapidities (>4-5 units)

At large rapidity gap, particles causally disconnected

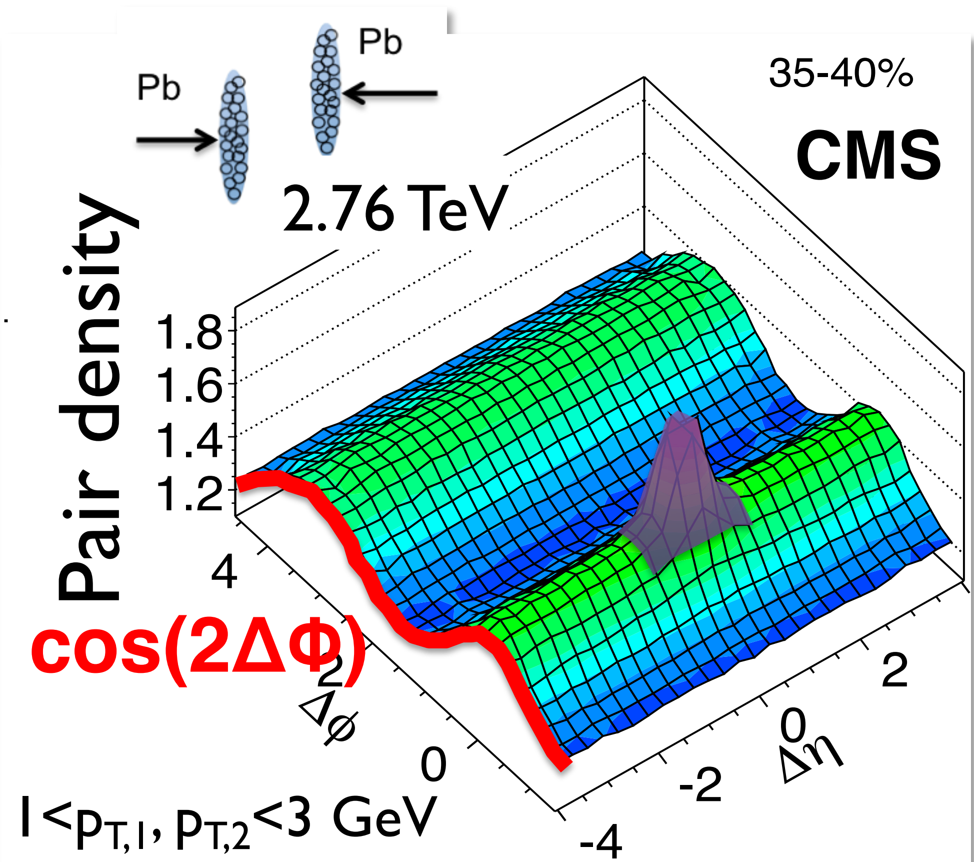


Correlation at very early time

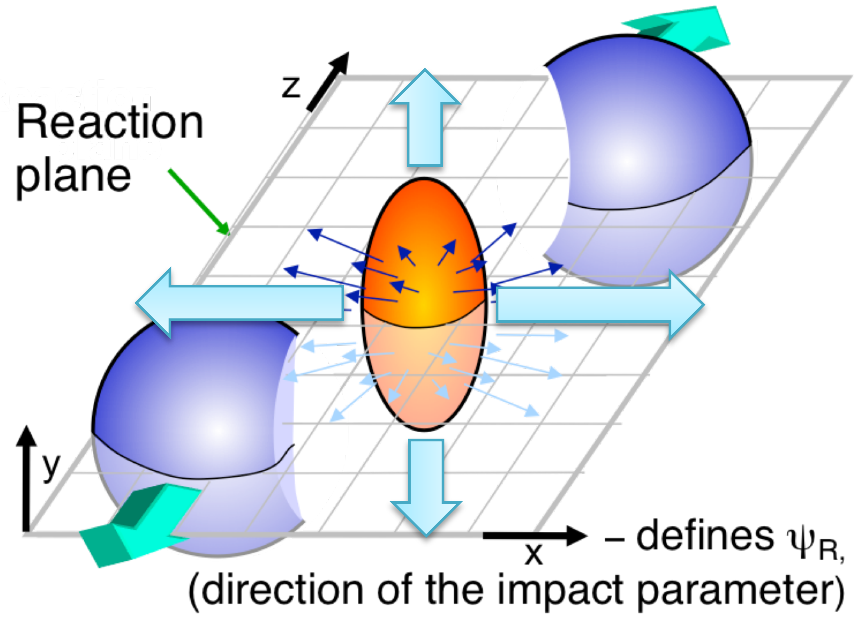
$$\tau_O \le \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1 \text{ fm}$$

A. Dumitru et. al., Nucl. Phys. A 810 (2008) 91

QGP fluid paradigm in AA collisions



Pressure-driven expansion

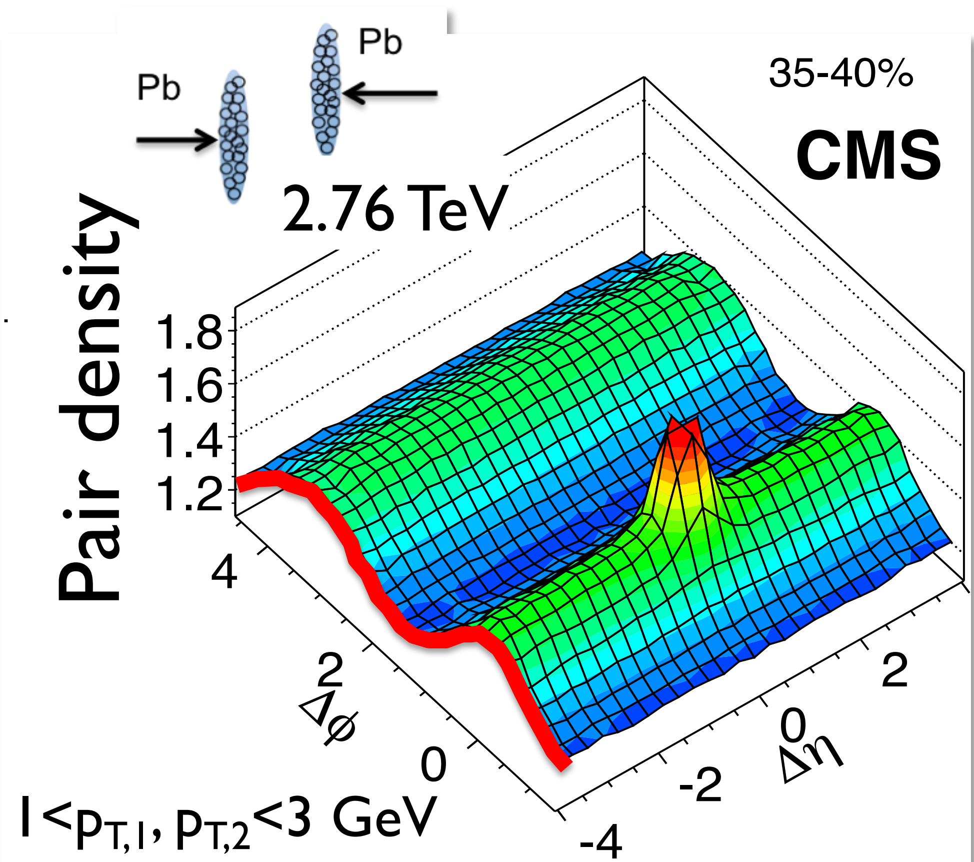


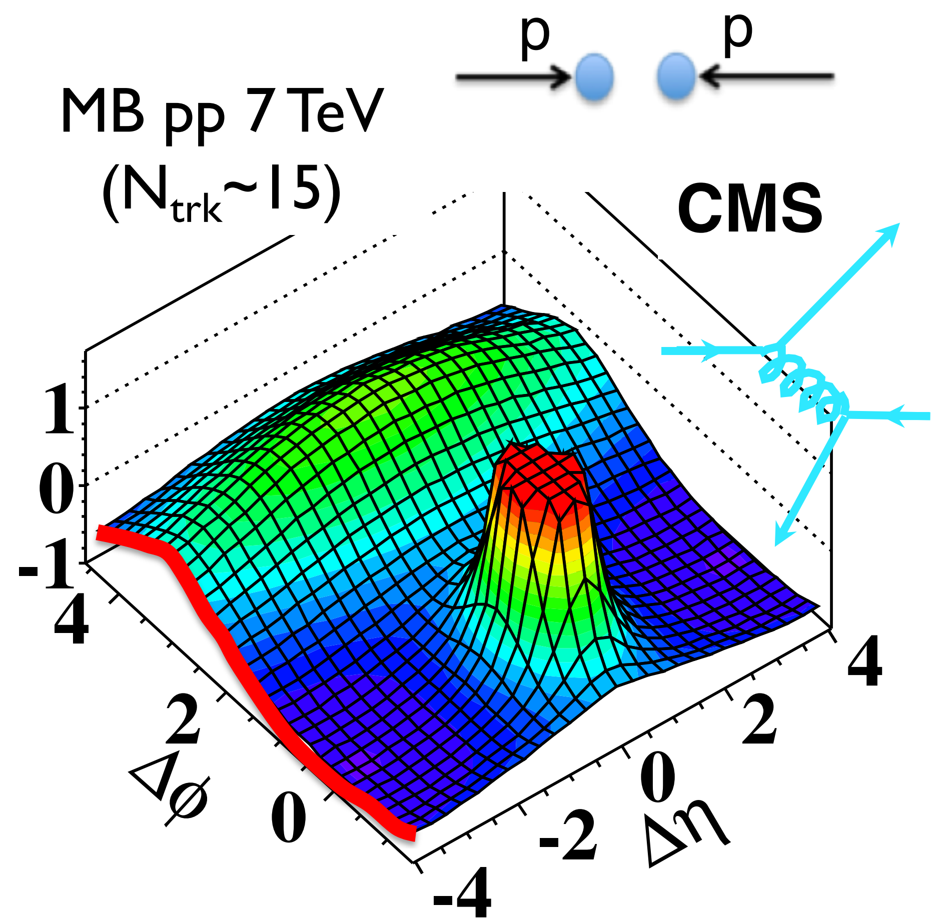
Azimuthal correlations over wide rapidities (>4-5 units)

"Elliptic flow"

$$1 + 2(v_2)^2 \cos 2\Delta\phi$$

QGP fluid paradigm in AA collisions

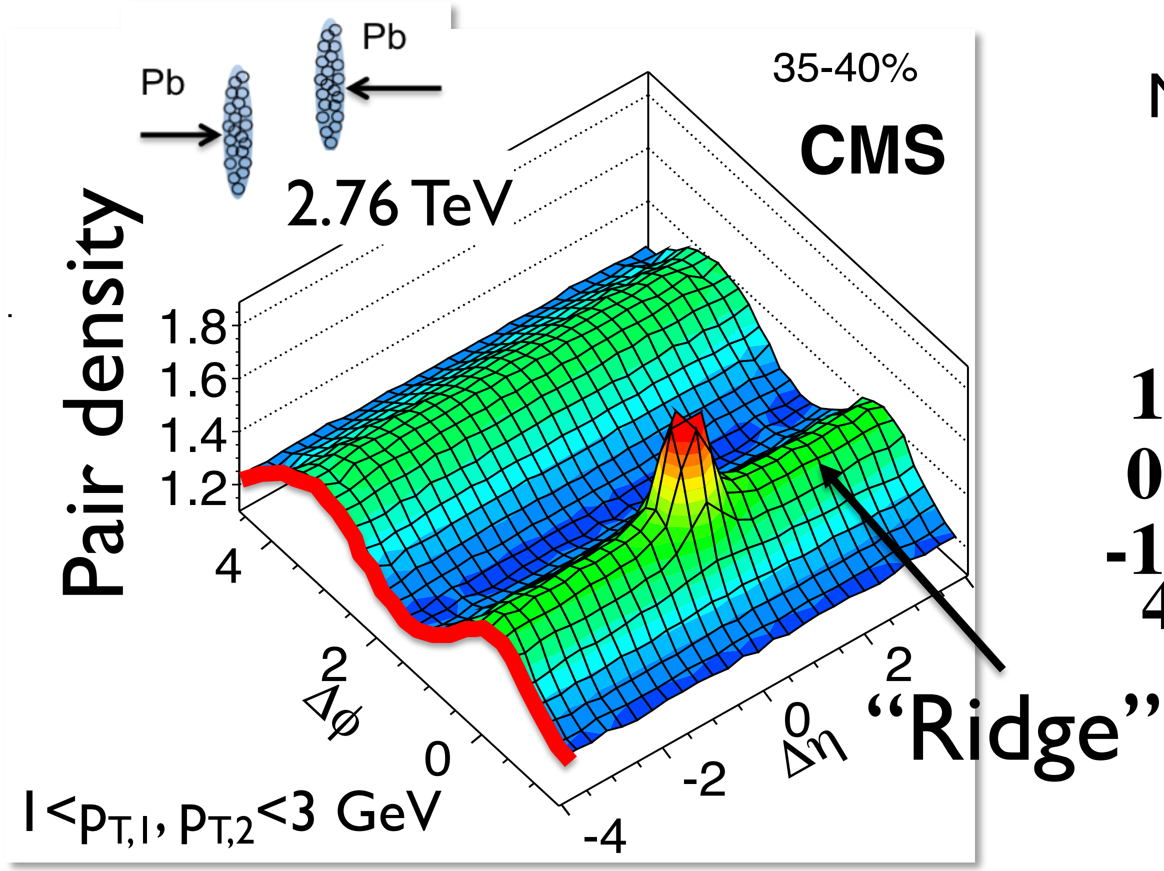


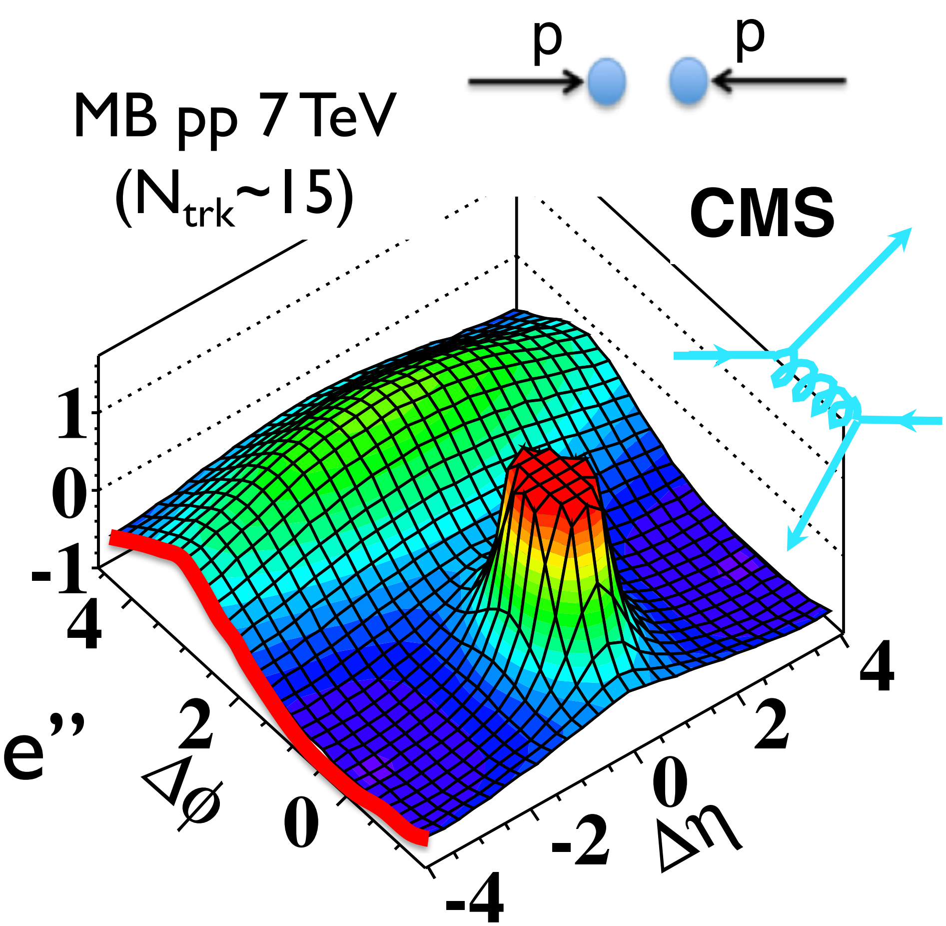


"Hot" QCD matter

"Cold" QCD matter
– no QGP in pp/pA

QGP fluid paradigm in AA collisions





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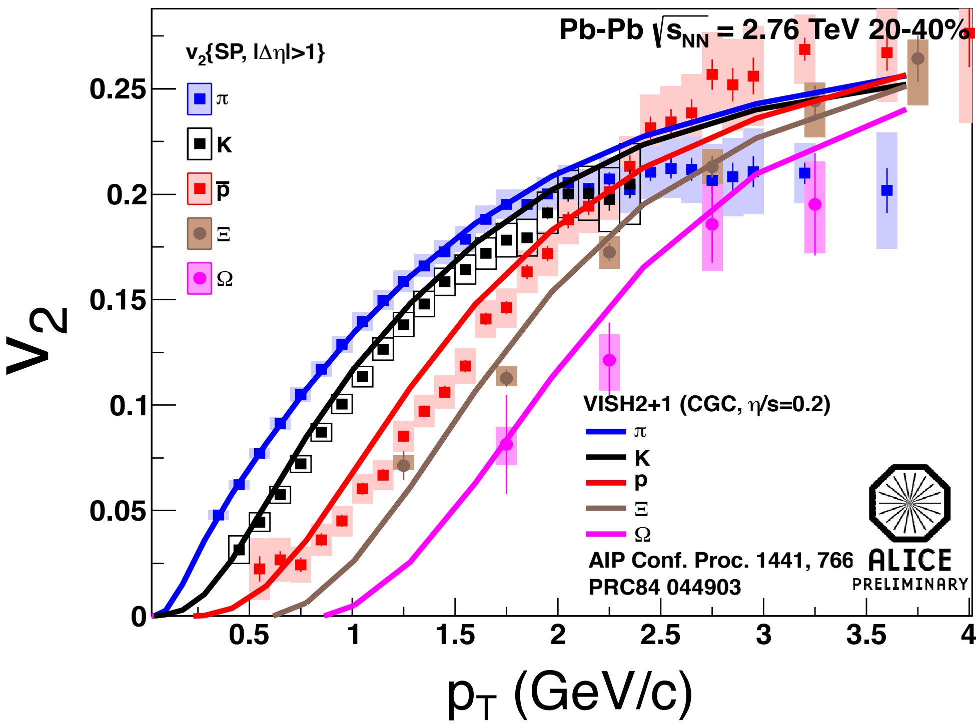
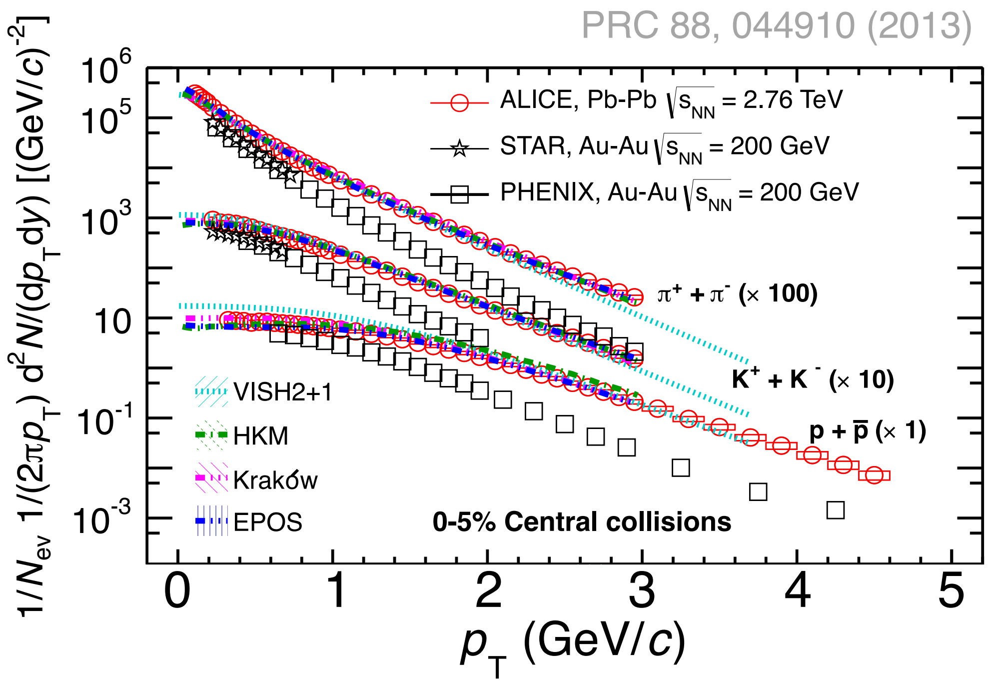


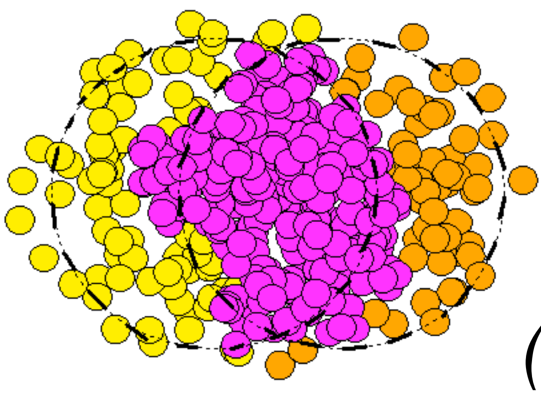
Thermal-like p_T spectra



Data well described by nearly ideal hydrodynamics

QGP fluid paradigm in AA collisions

Initial energy density
("Geometry")



$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi\rangle + \langle r^2 \sin n\varphi\rangle}}{\langle r^2\rangle}$$

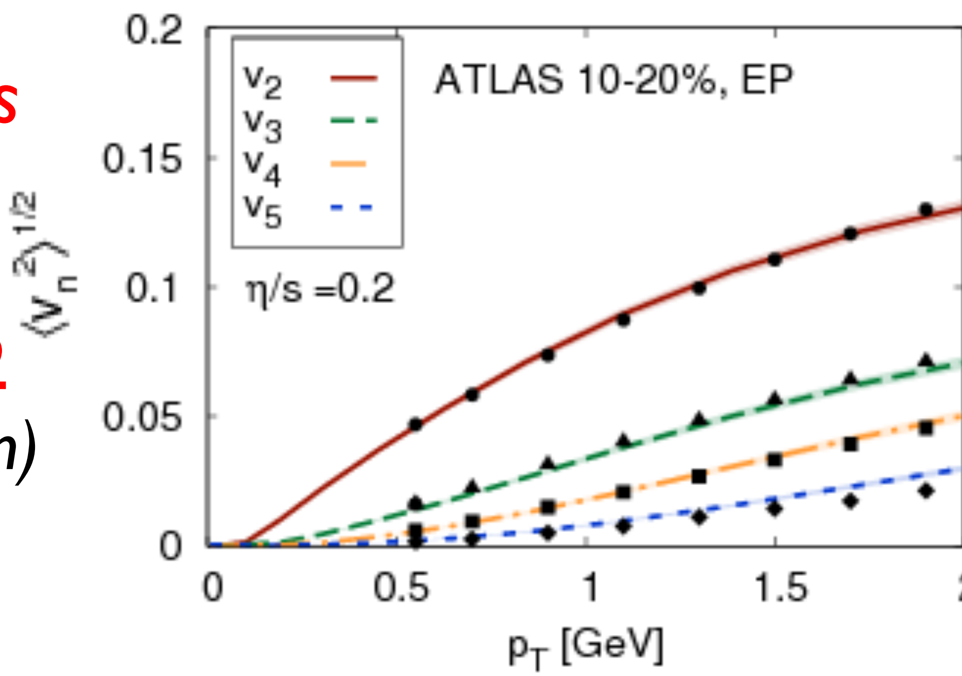
Hydrodynamics

$(\partial_\mu T^{\mu\nu}=0)$

η/s ~ 0.08-0.2

(viscous correction)

Final-state correlations



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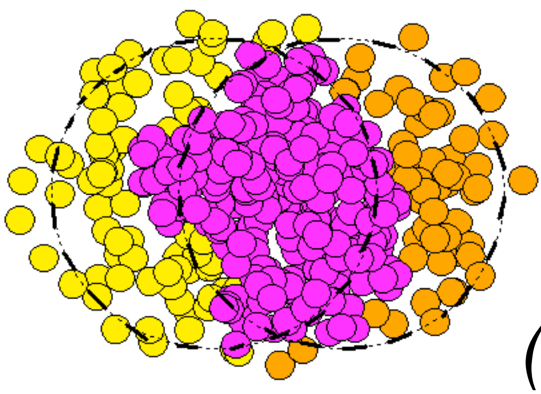

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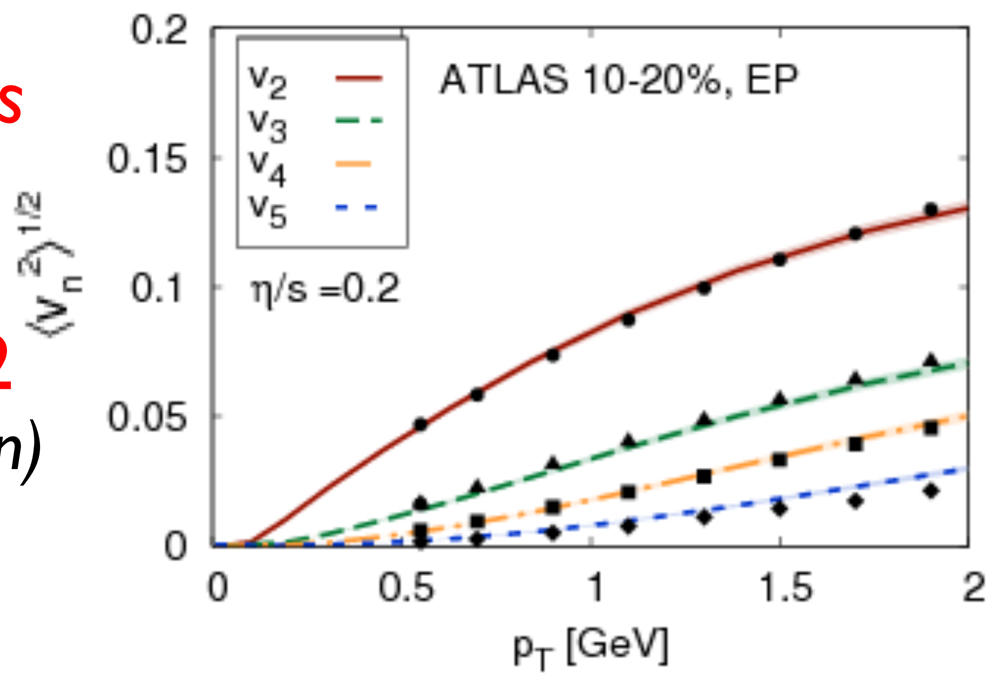

Correlations mostly seeded by fluctuations of *nucleons*

QGP fluid paradigm in AA collisions

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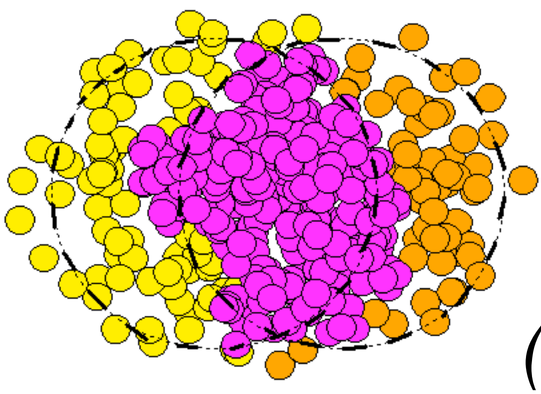

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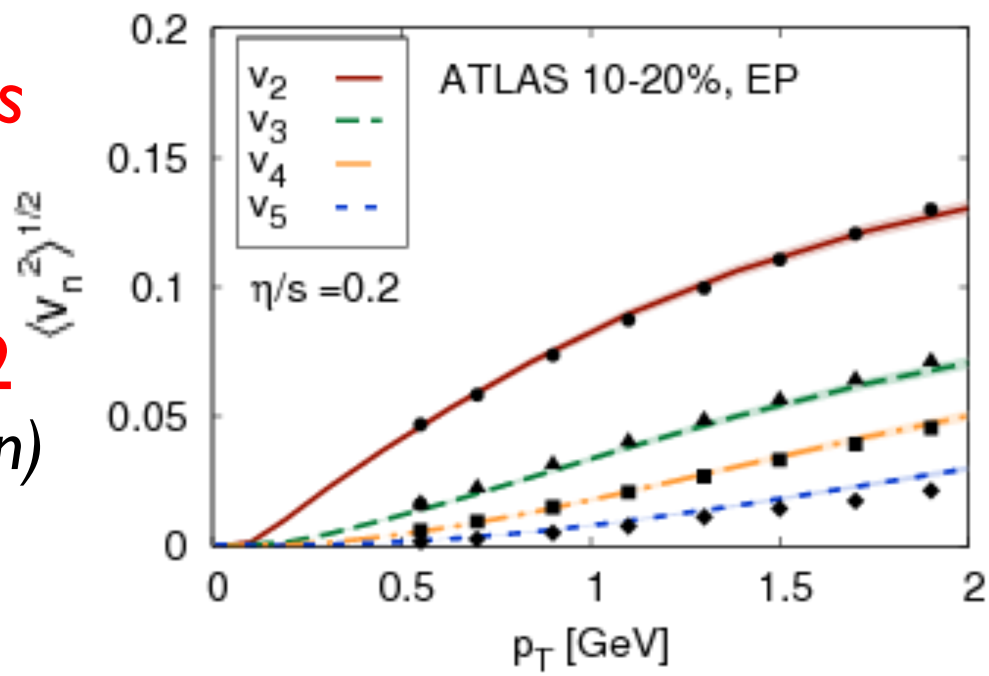


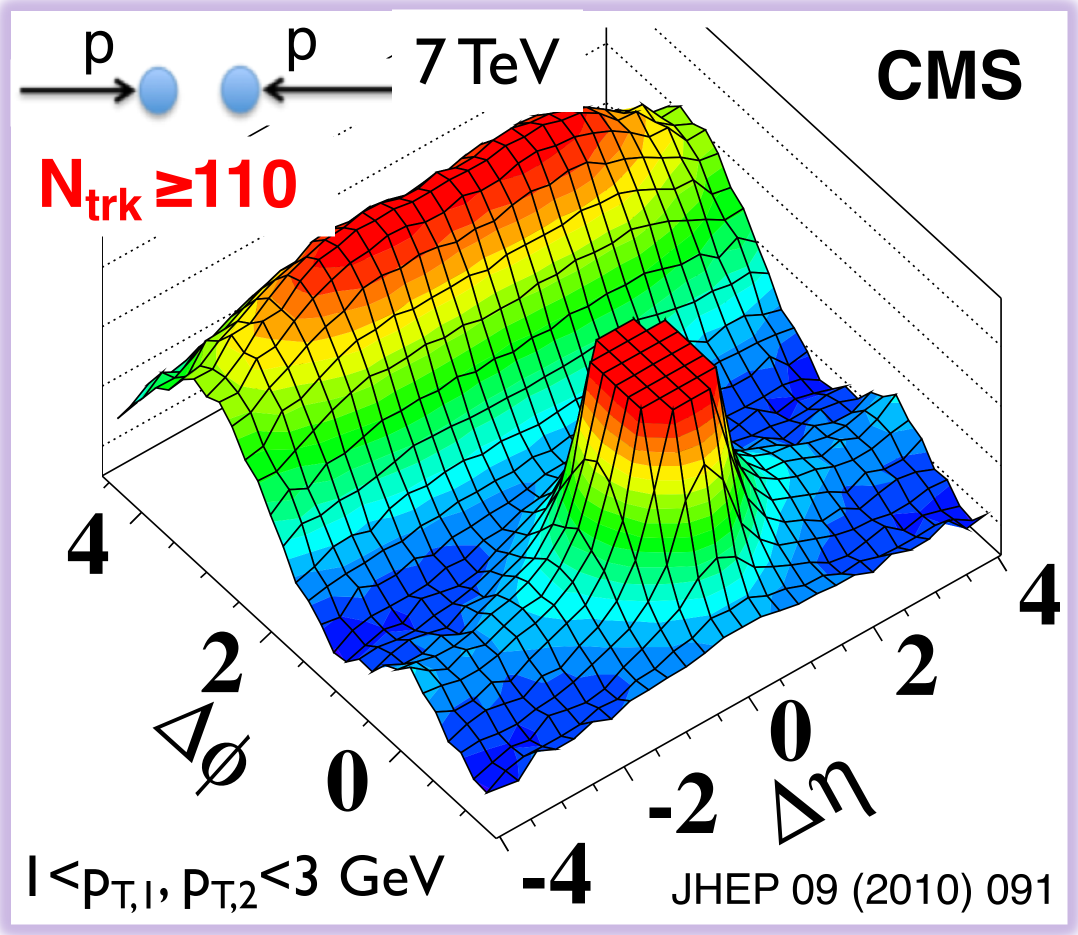
Correlations mostly seeded by fluctuations of *nucleons*

η/s approaches conjected quantum lower limit

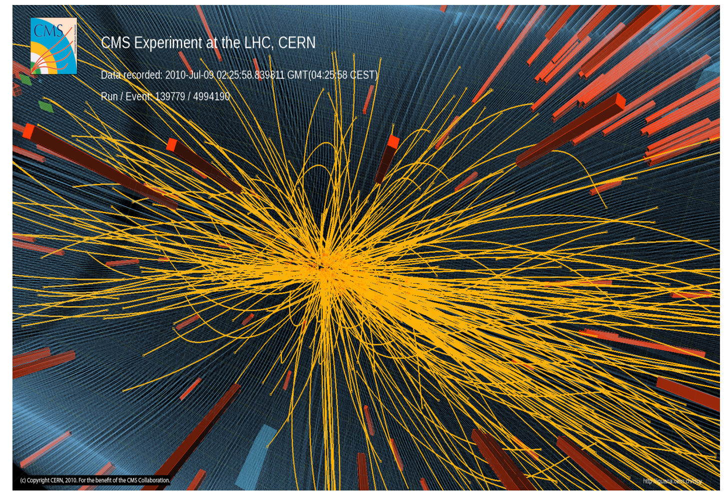
$\eta/s \gtrsim 1/(4\pi) \sim$ **0.08**

Kovtun, Son, Starinets
PRL 94 (2005) 111601

Discovery Phase II: *"Ridge" in pp (2010)*



High-multiplicity pp ($N_{trk} \geq 110$)



$O(10^{-6})$ most violent events

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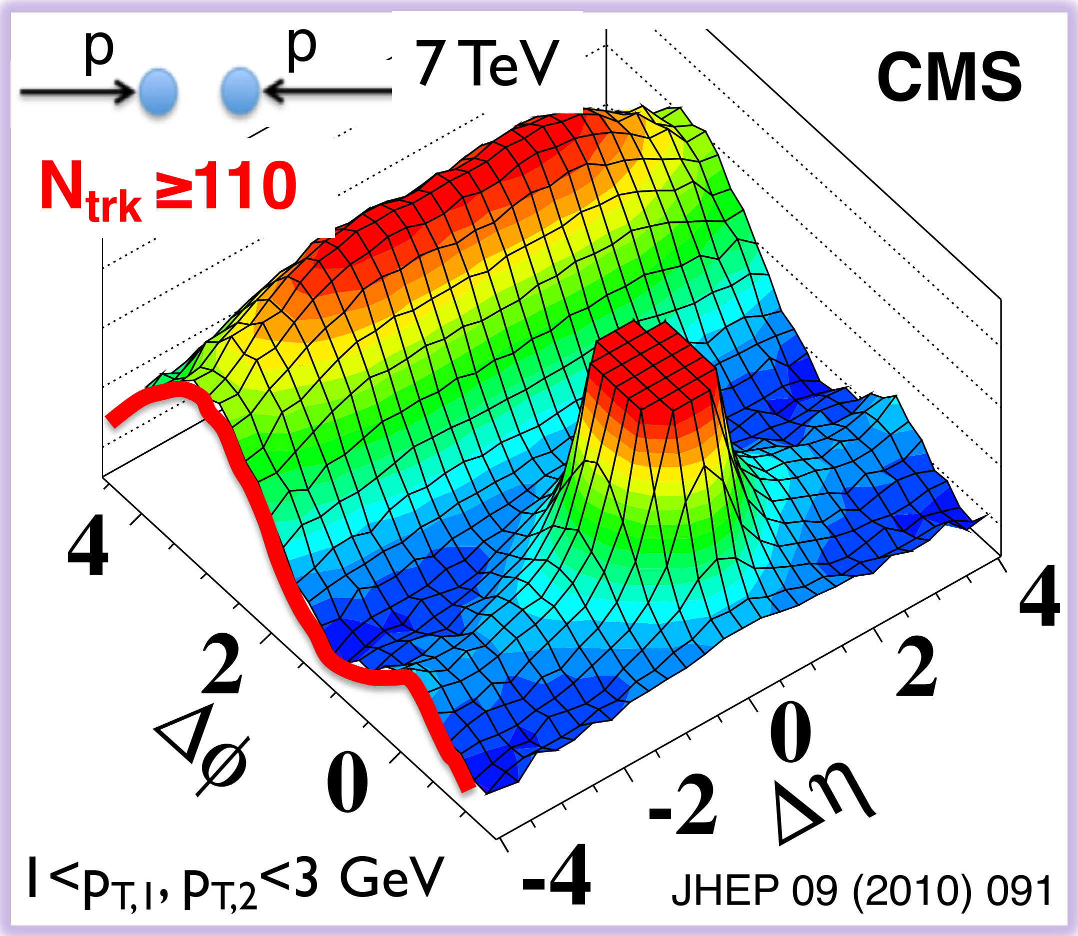

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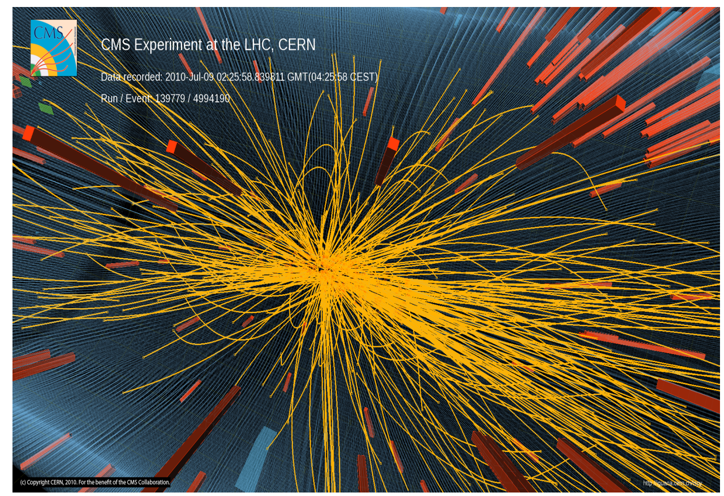

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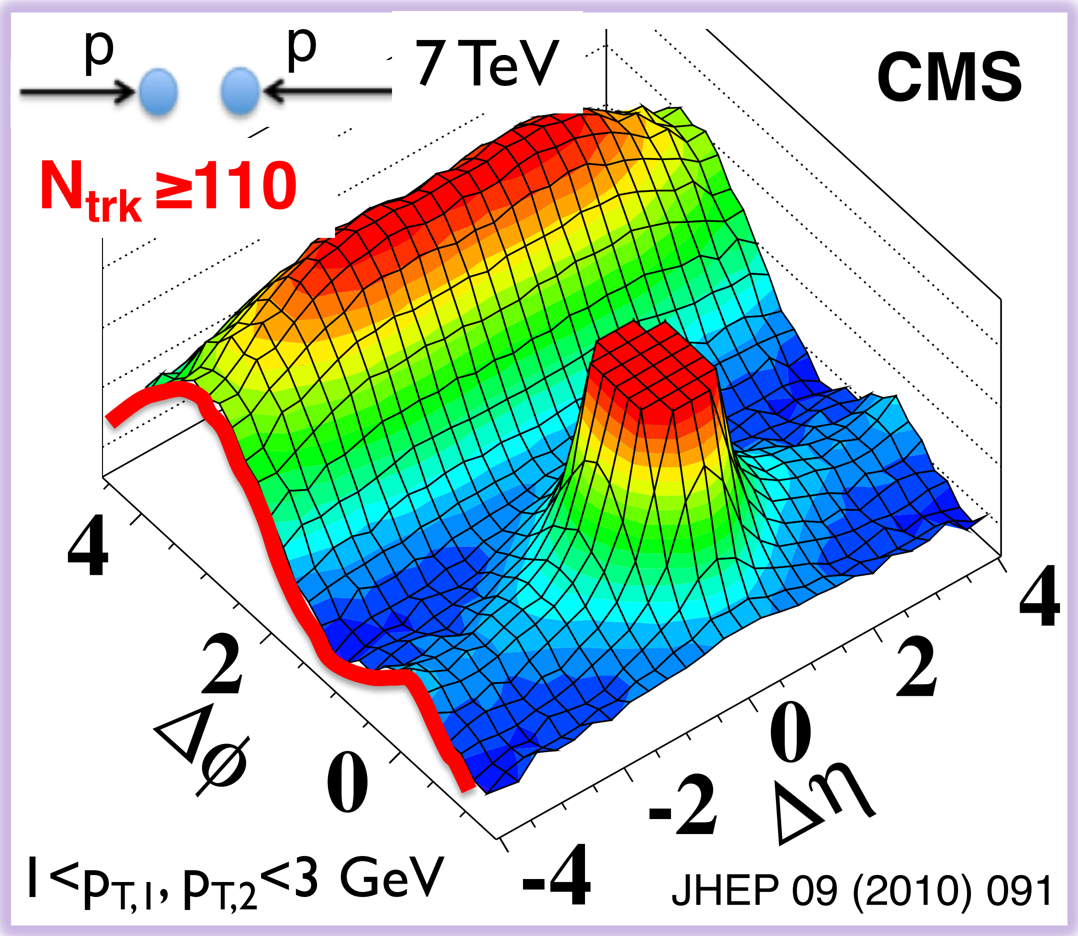

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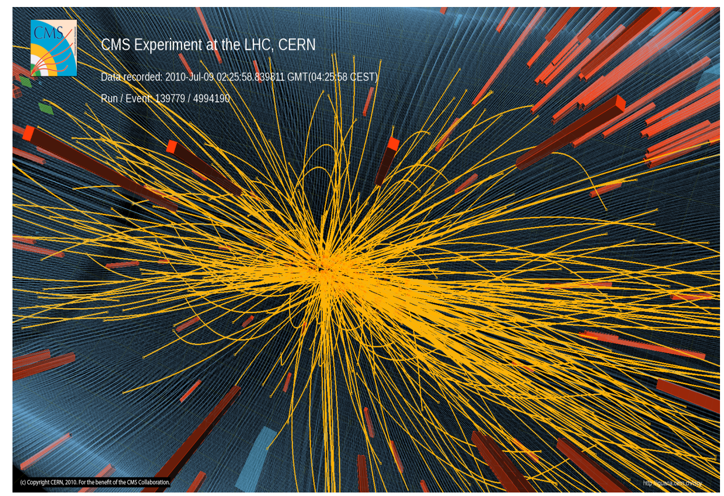
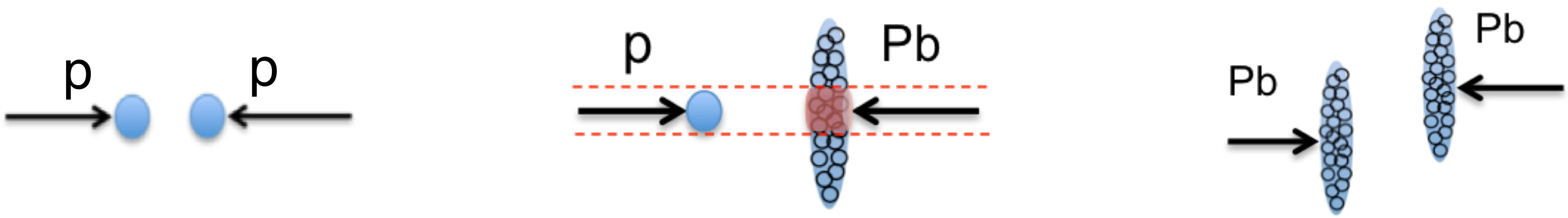


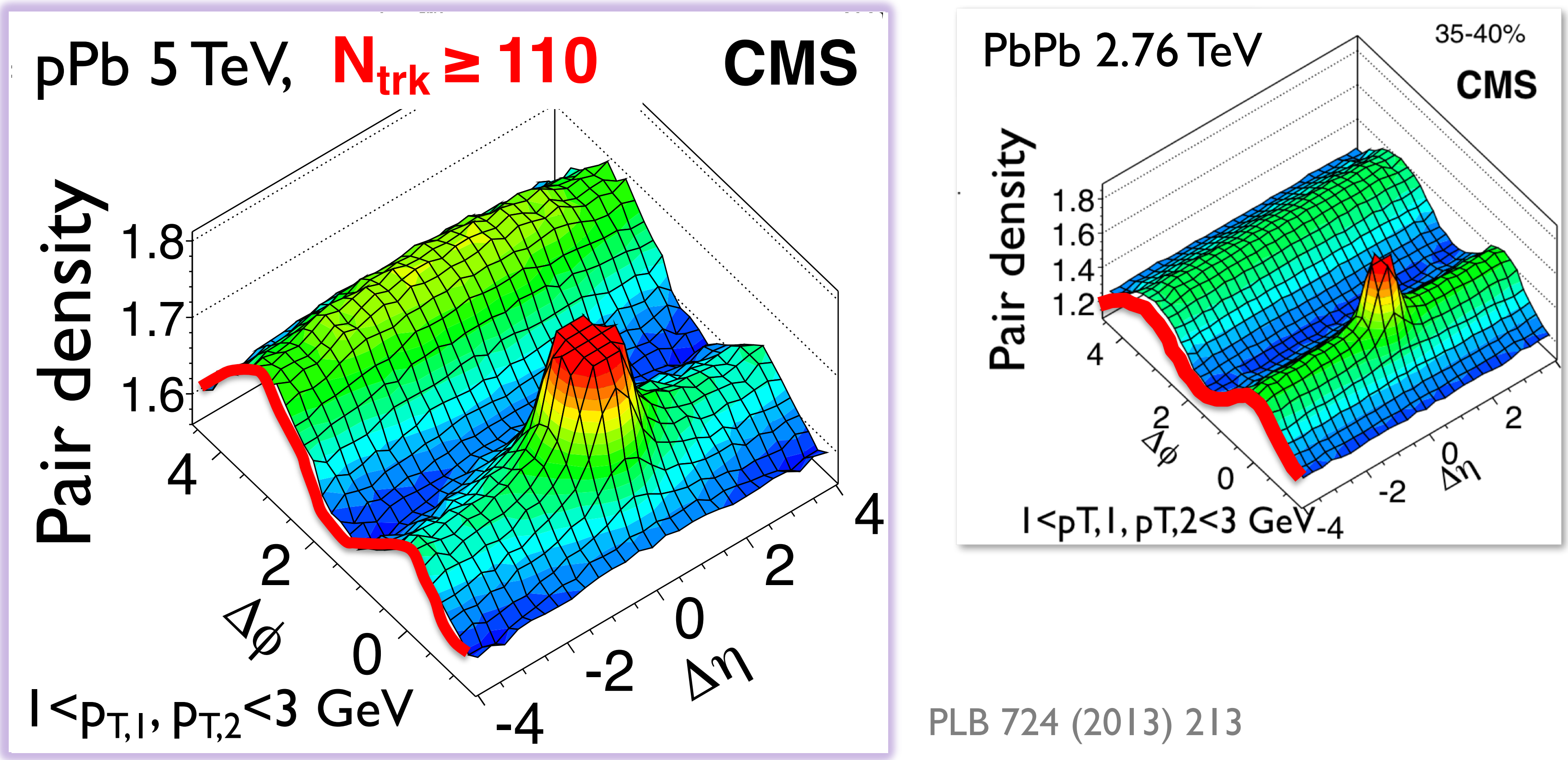
$O(10^{-6})$ most violent events

QGP droplet at sub-fermi scales? Or NO QGP after all?

– *Beginning of a new paradigm!*

Proton-lead collisions at the LHC

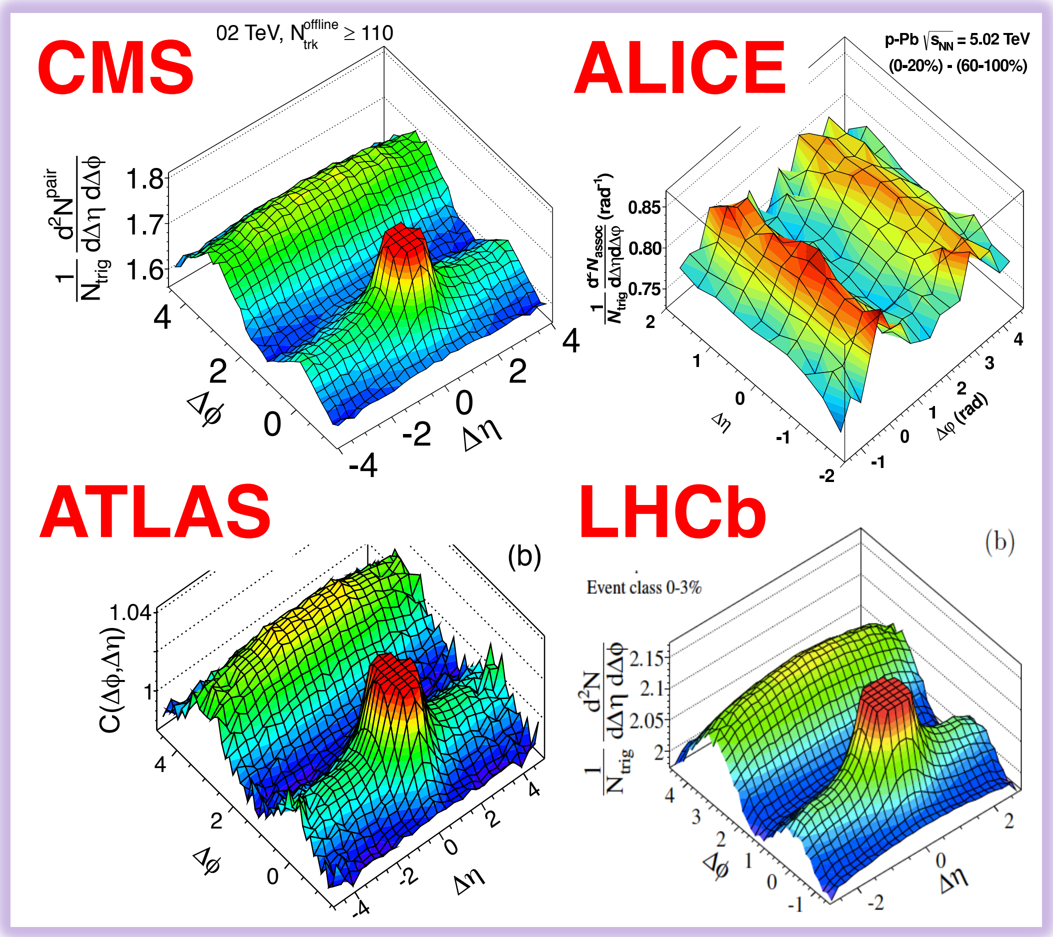




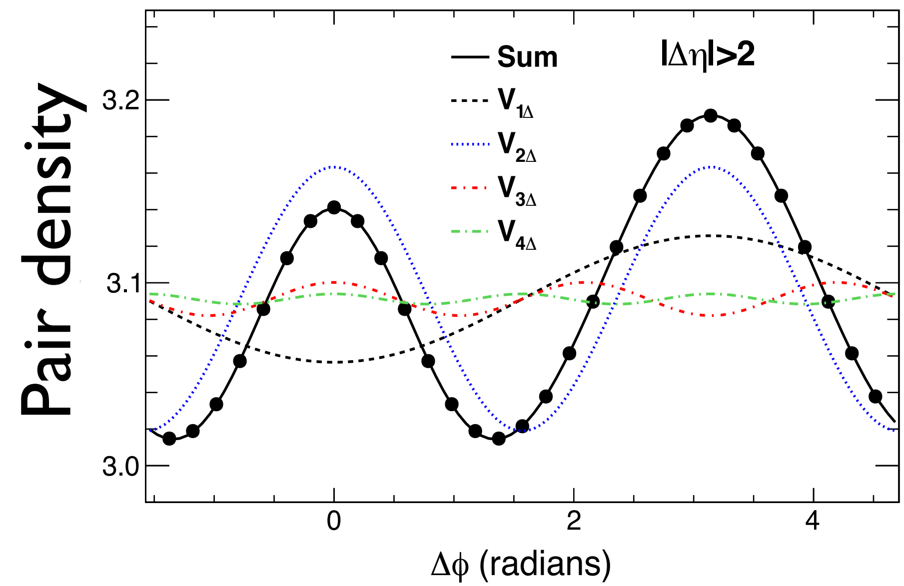
PLB 724 (2013) 213

Striking "Ridge" signal in pPb!

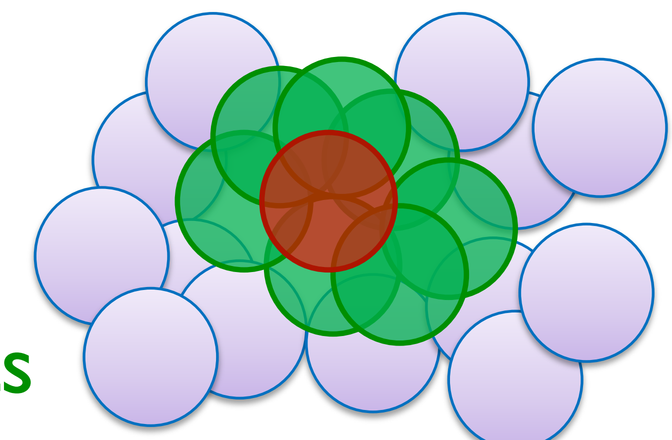
The "Ridge" tsunami in pPb collisions



"Flow" analysis



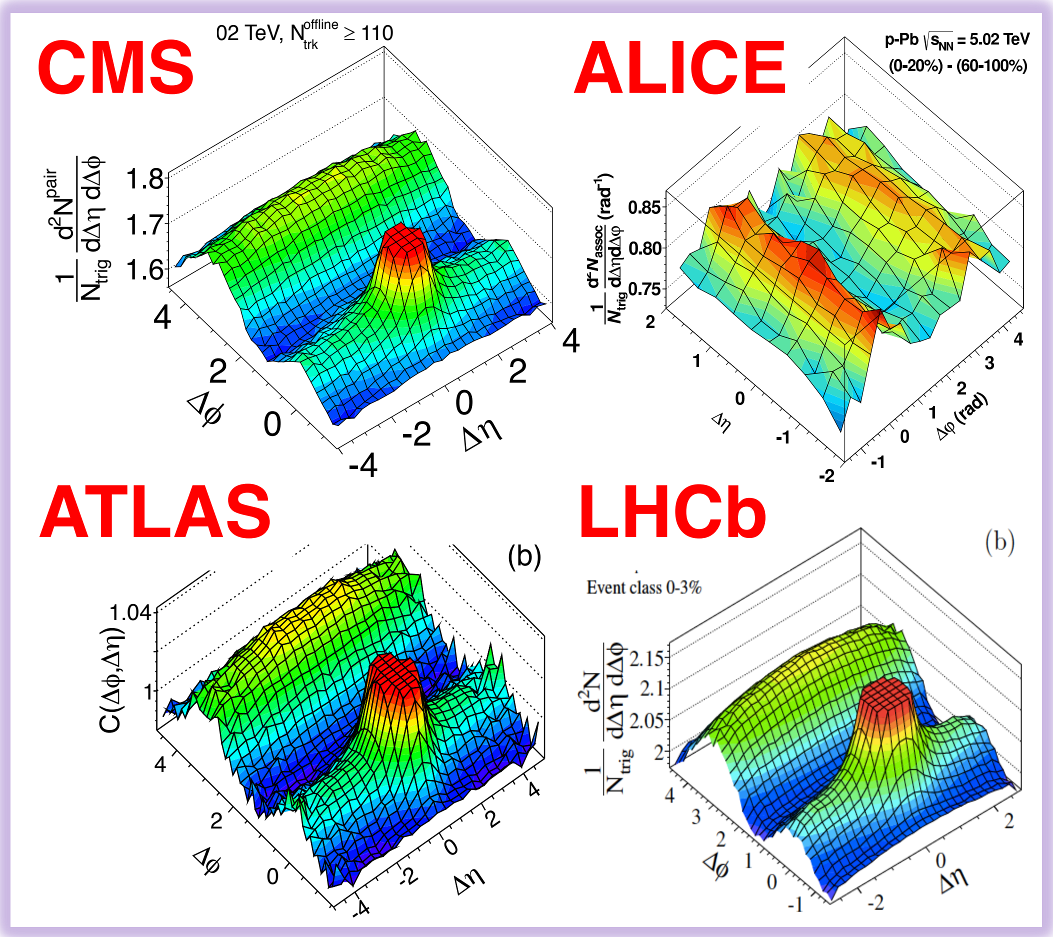
Geometry in pA



Proton projectile

Nucleus Participants

The “Ridge” tsunami in pPb collisions



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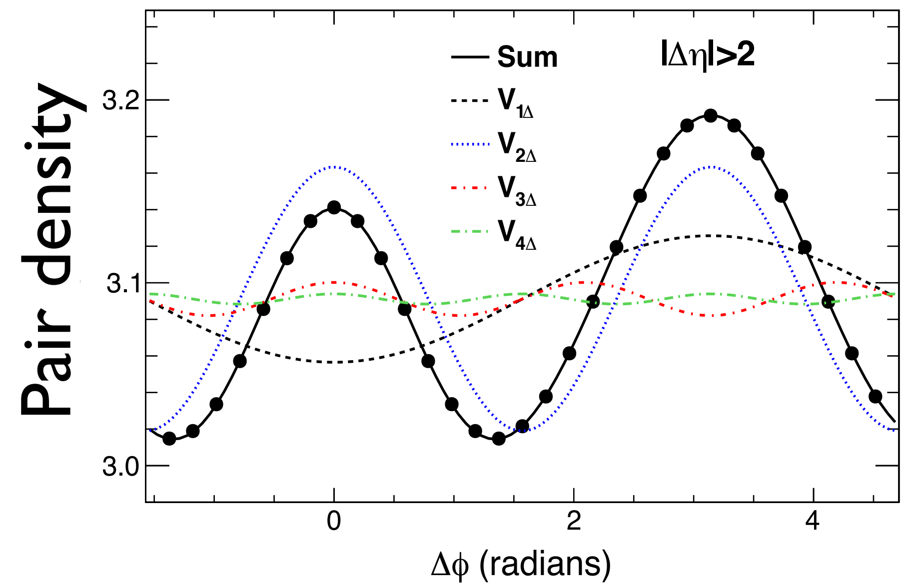

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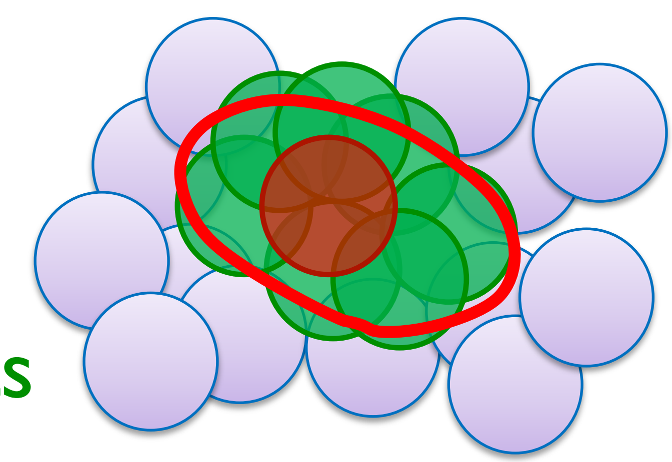

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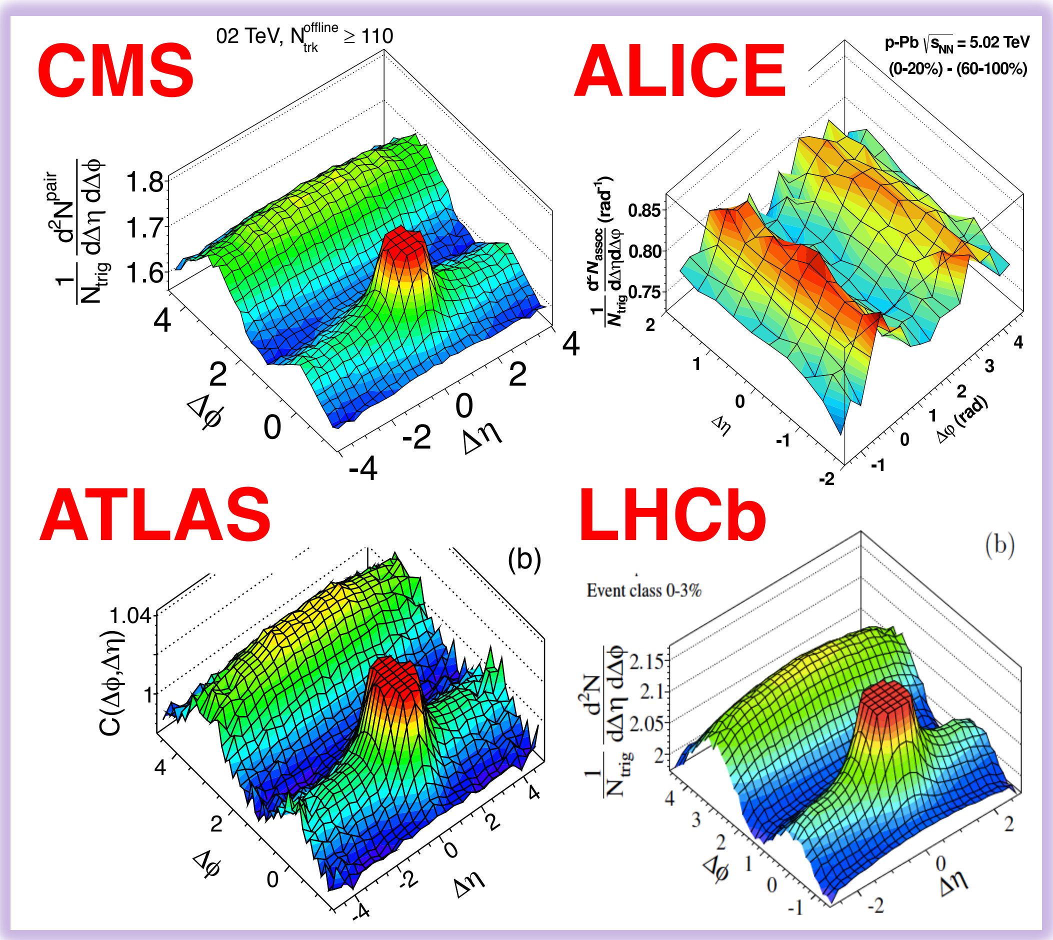

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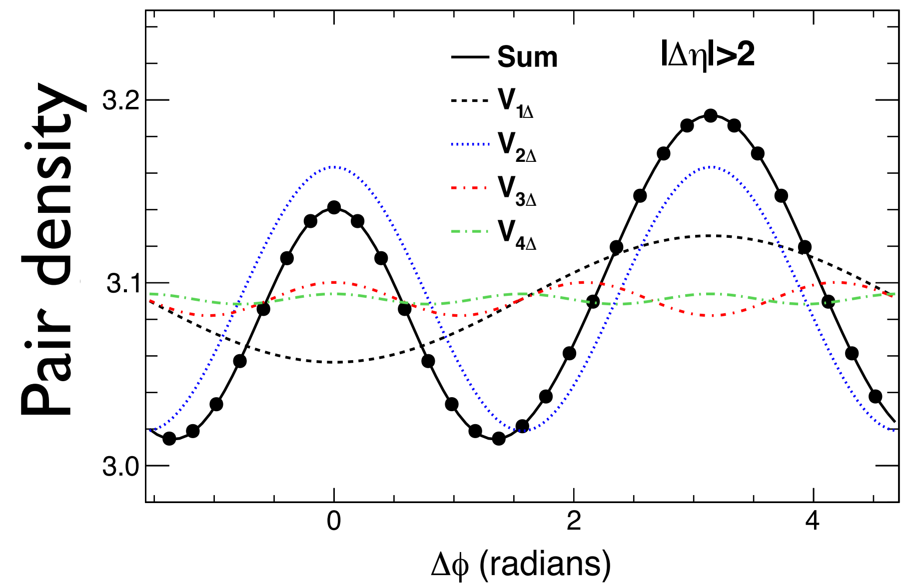

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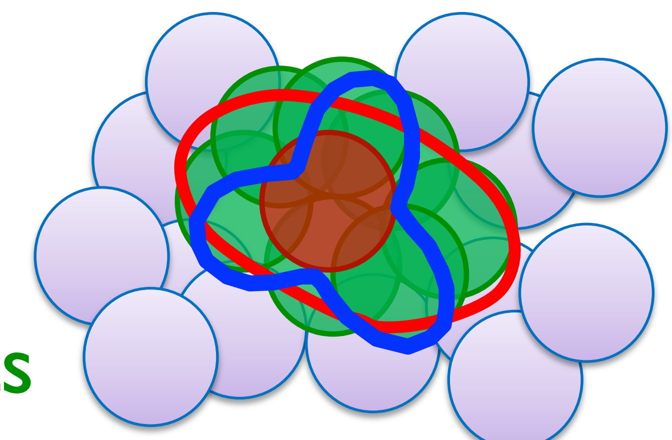

Proton projectile

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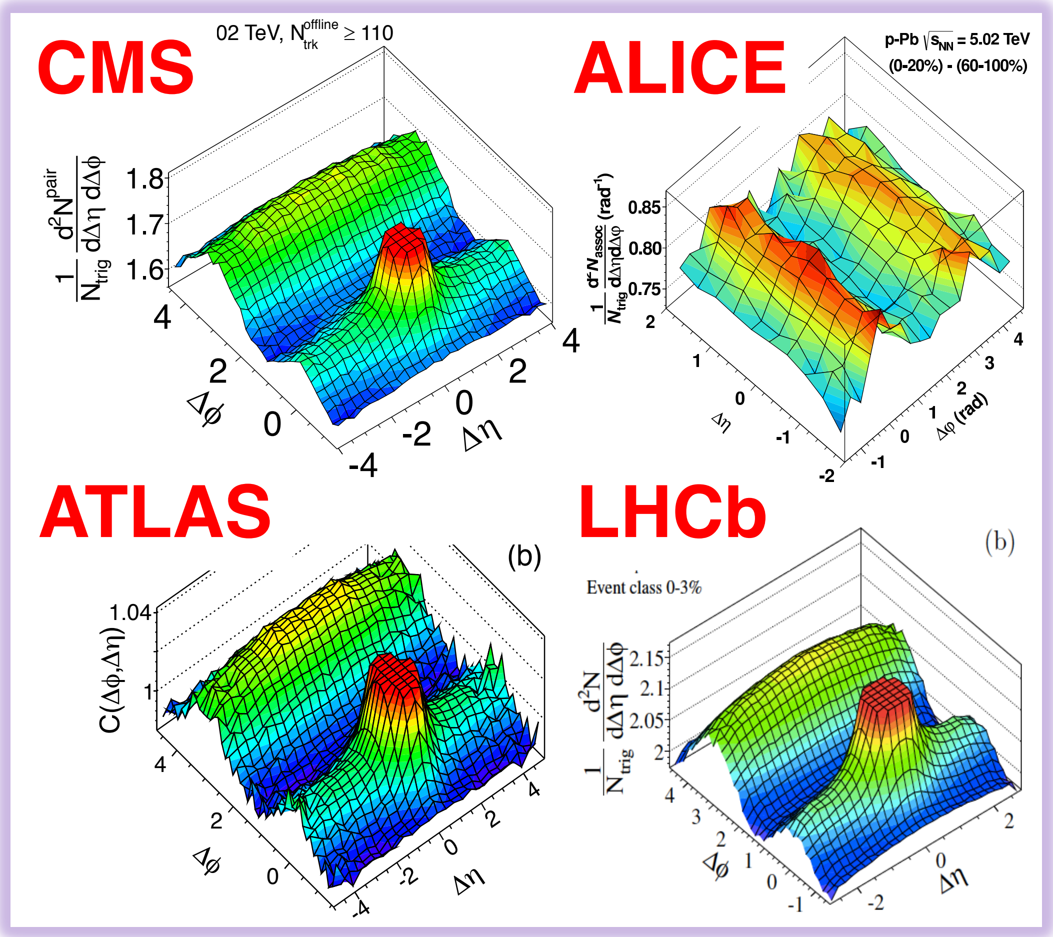

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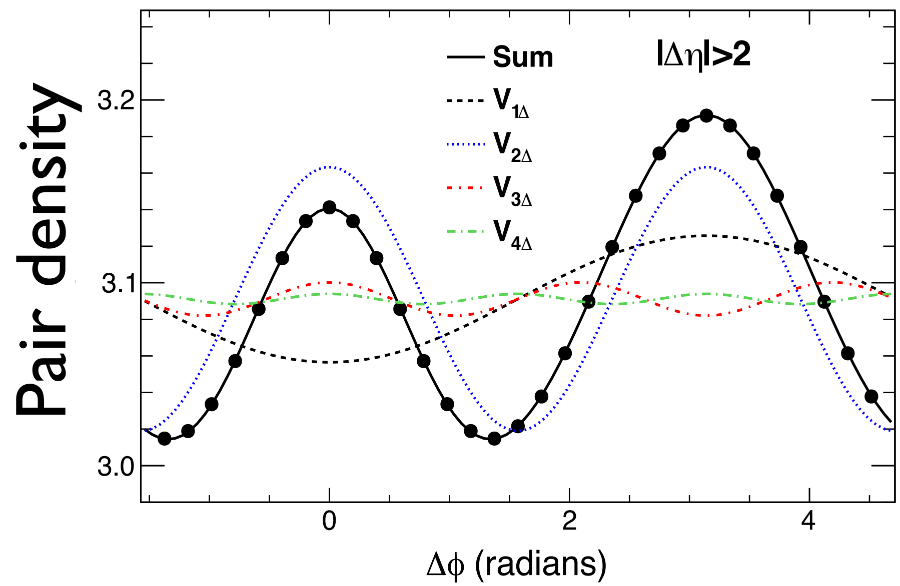
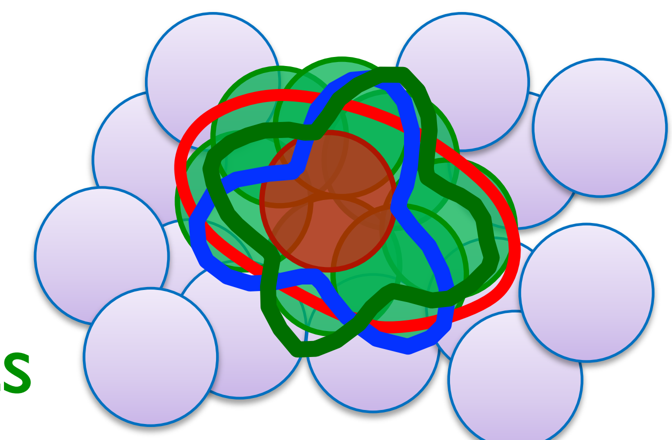


Geometry in pA

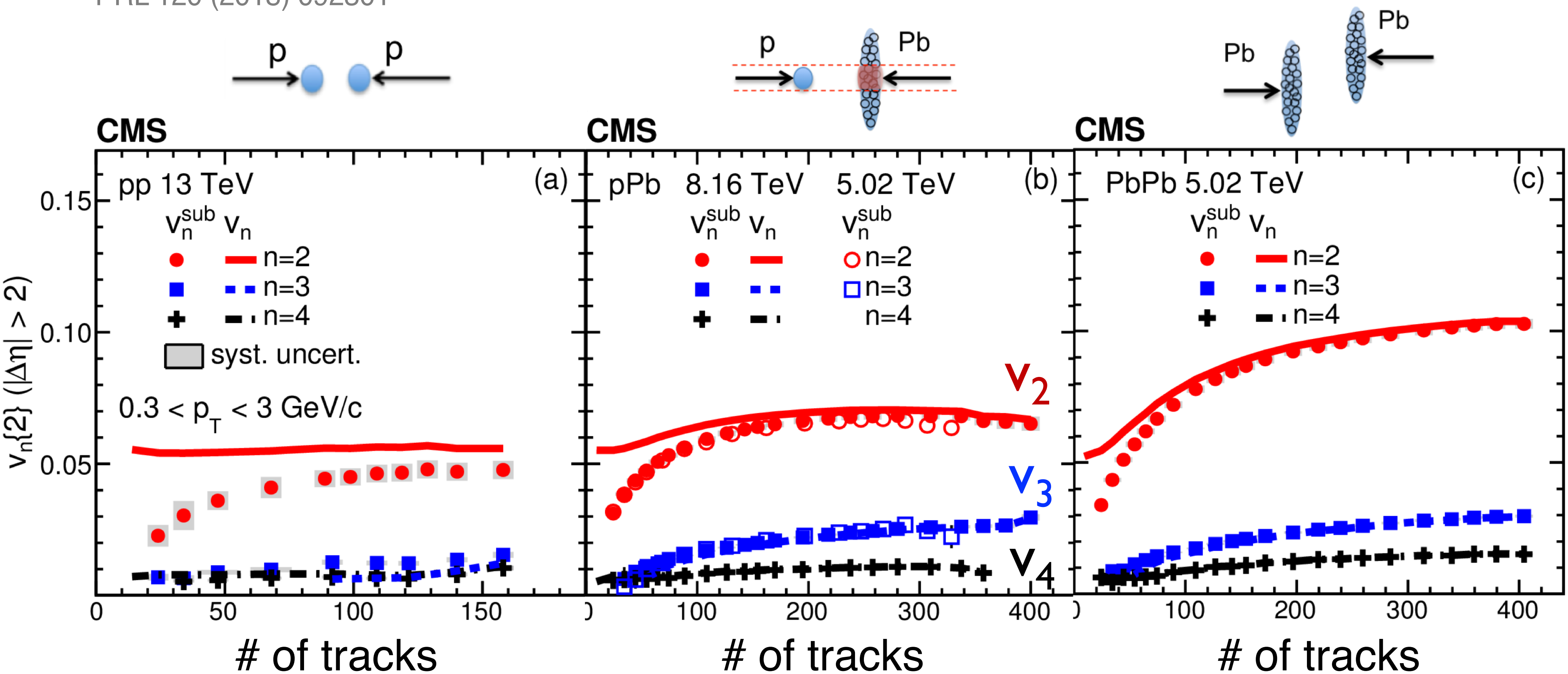


Proton projectile

Nucleus Participants

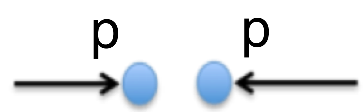
"Flow" in small systems

PRL 120 (2018) 092301



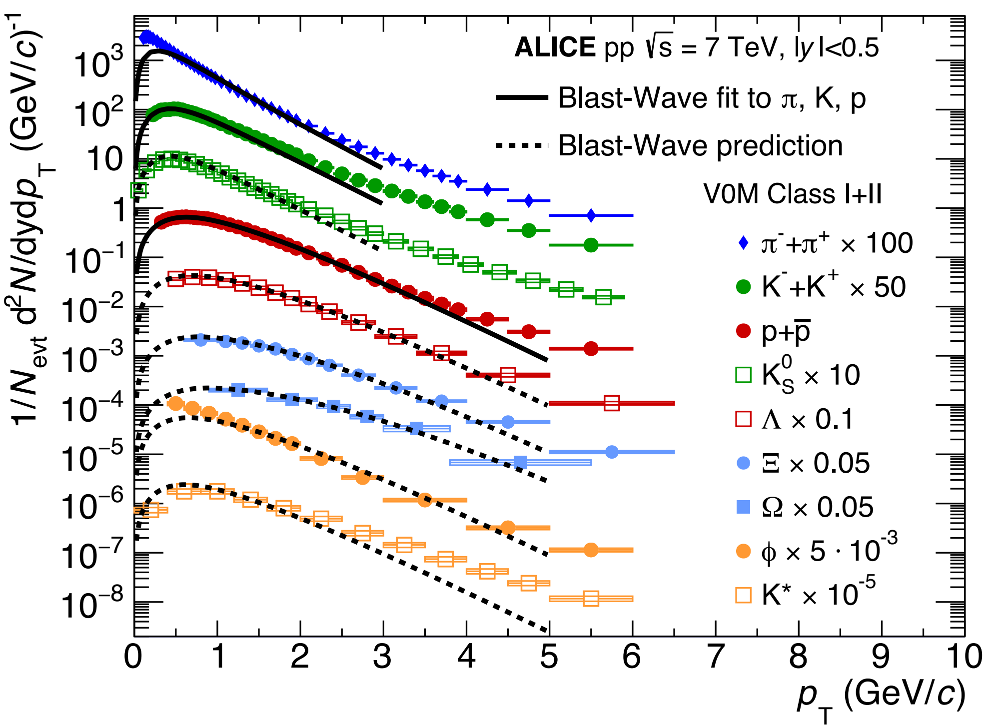
Flow-like behavior similar across all systems

“Flow” in small systems



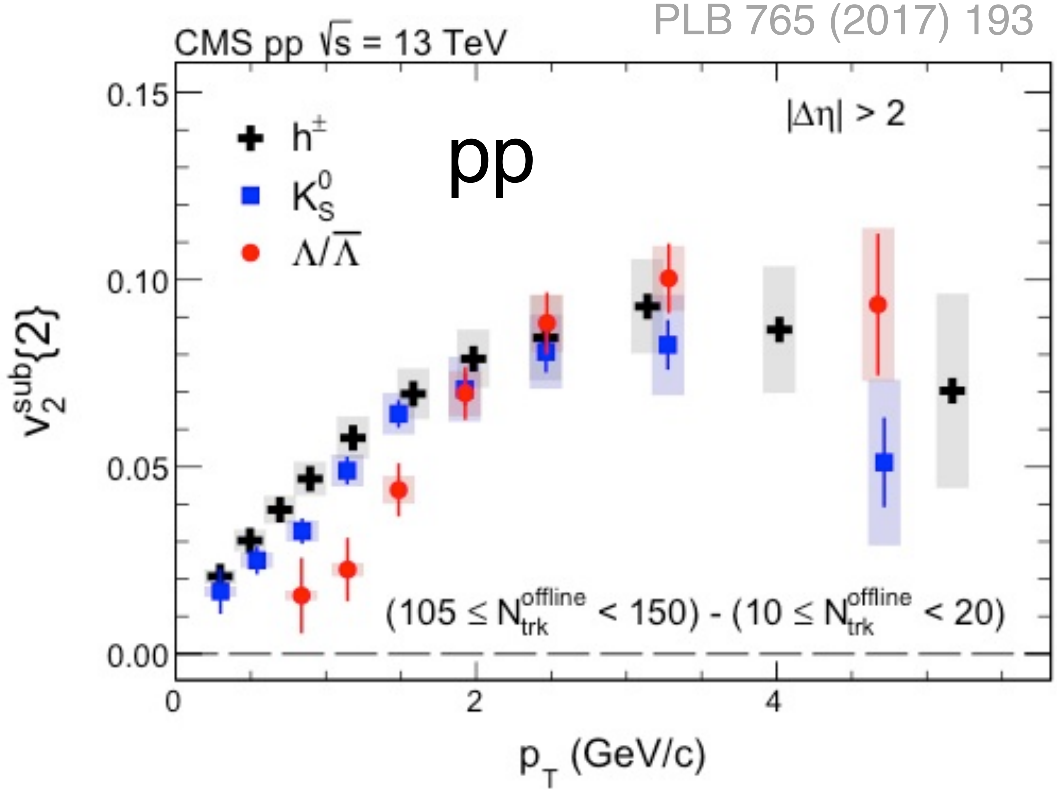
“Thermal/hydro” spectra

arXiv:1807.11321



Particle species dep. of v_2

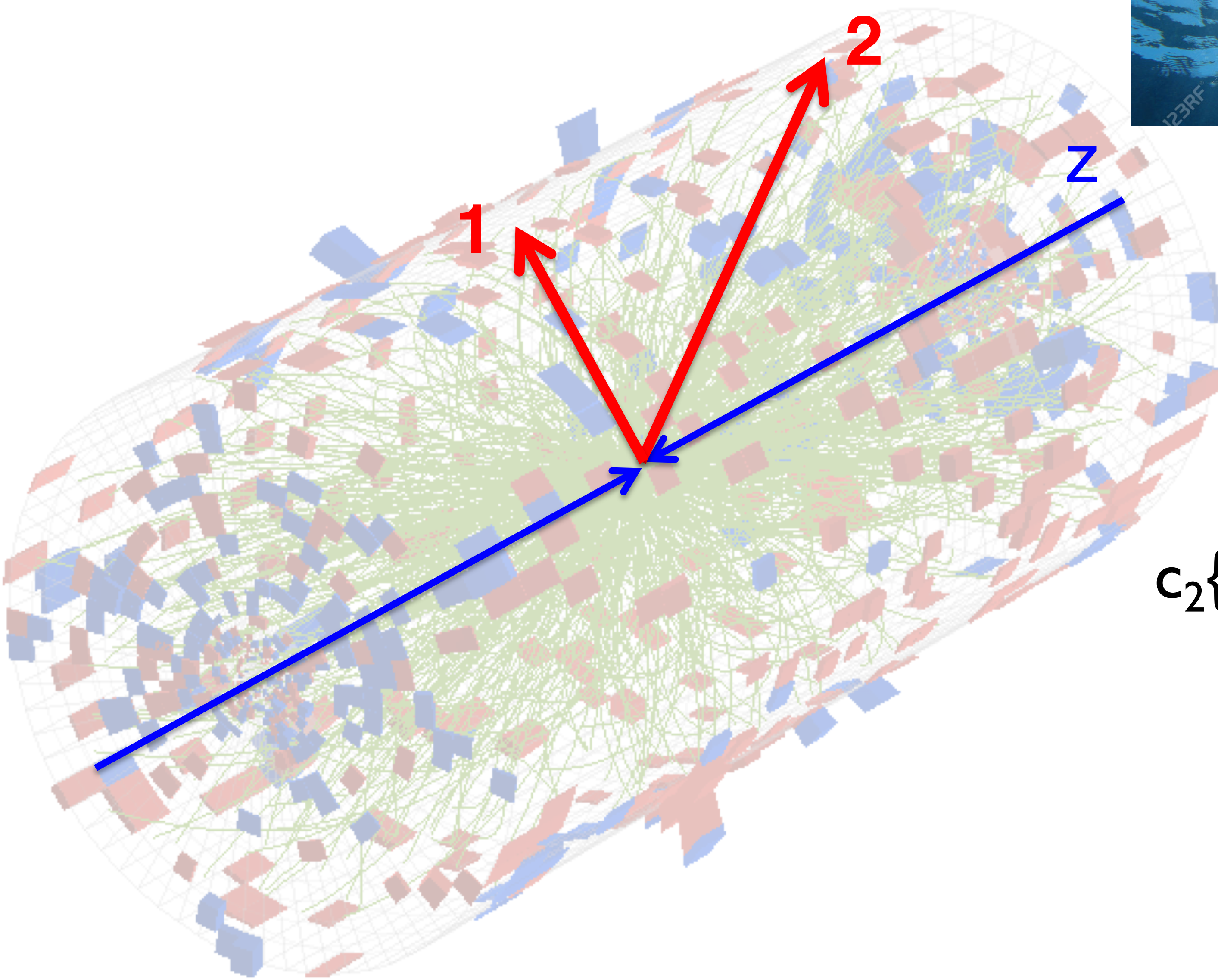
PLB 765 (2017) 193



Similar features for pPb and PbPb

Collective or NOT?

(all entities follow a common behavior)

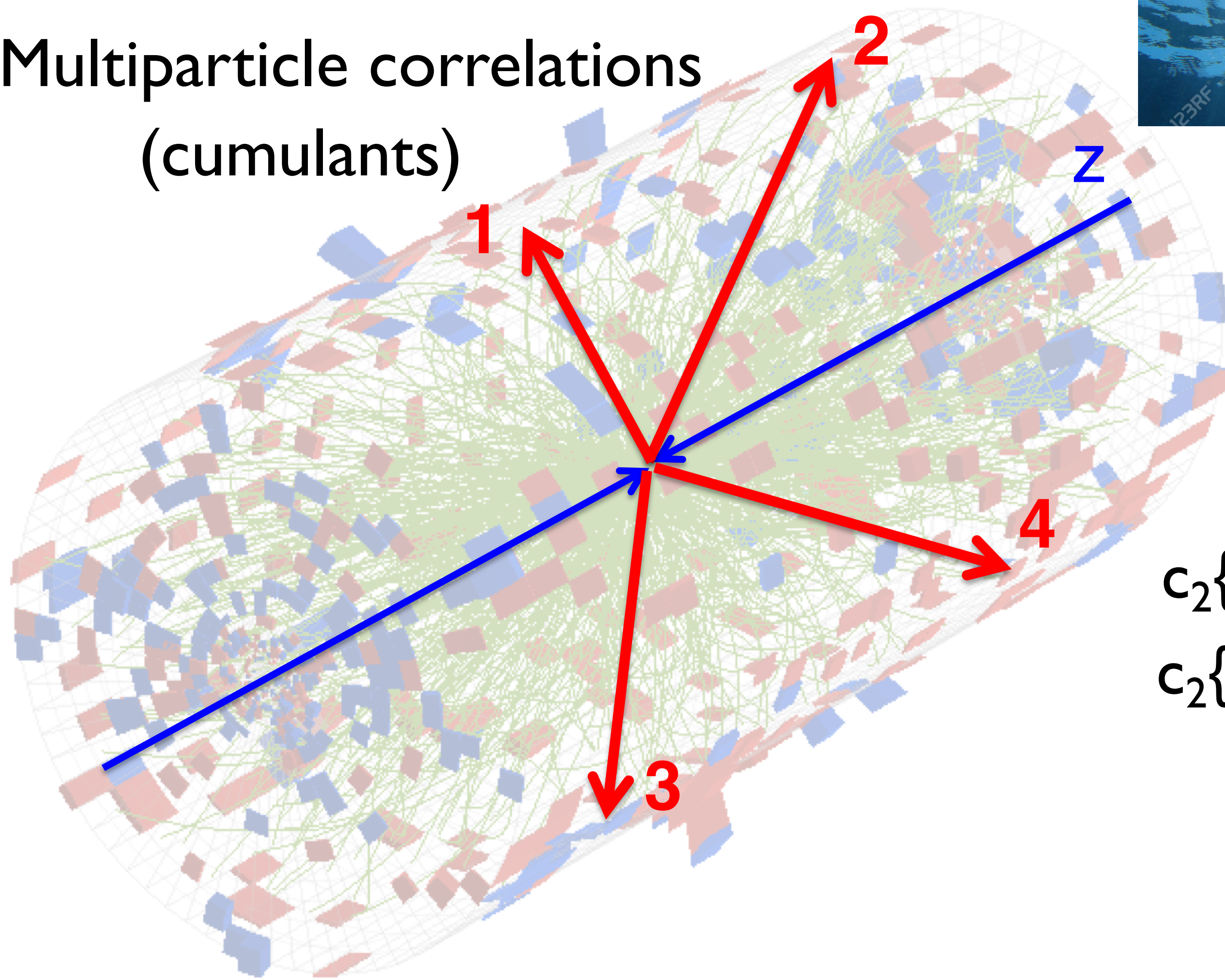


$c_2\{2\} \sim (v_2\{2\})^2$

Collective or NOT?

(all entities follow a common behavior)

Multiparticle correlations
(cumulants)



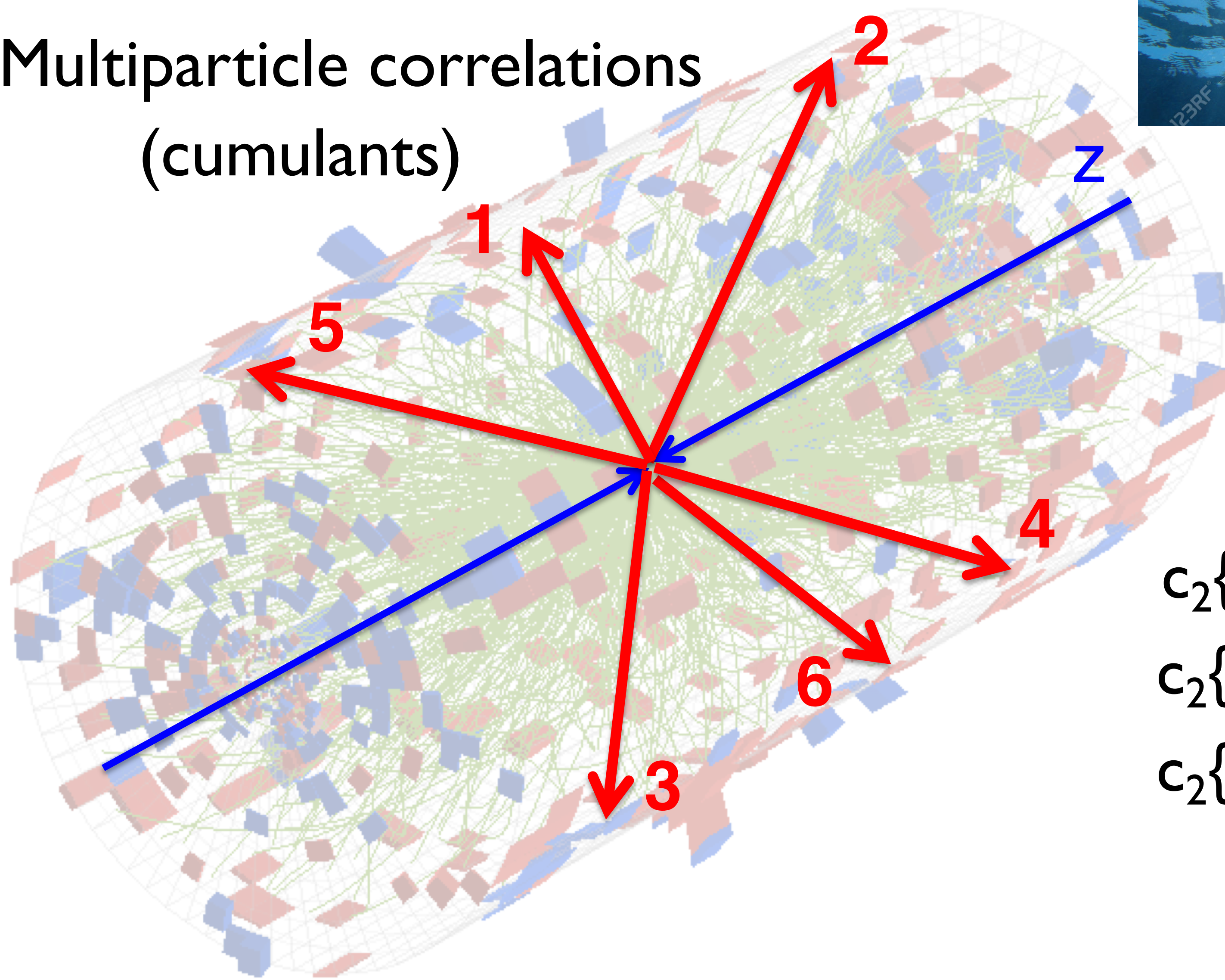
$c_2\{2\} \sim (v_2\{2\})^2$

$c_2\{4\} \sim (v_2\{4\})^4$

Collective or NOT?

(all entities follow a common behavior)

Multiparticle correlations
(cumulants)



$c_2\{2\} \sim (v_2\{2\})^2$

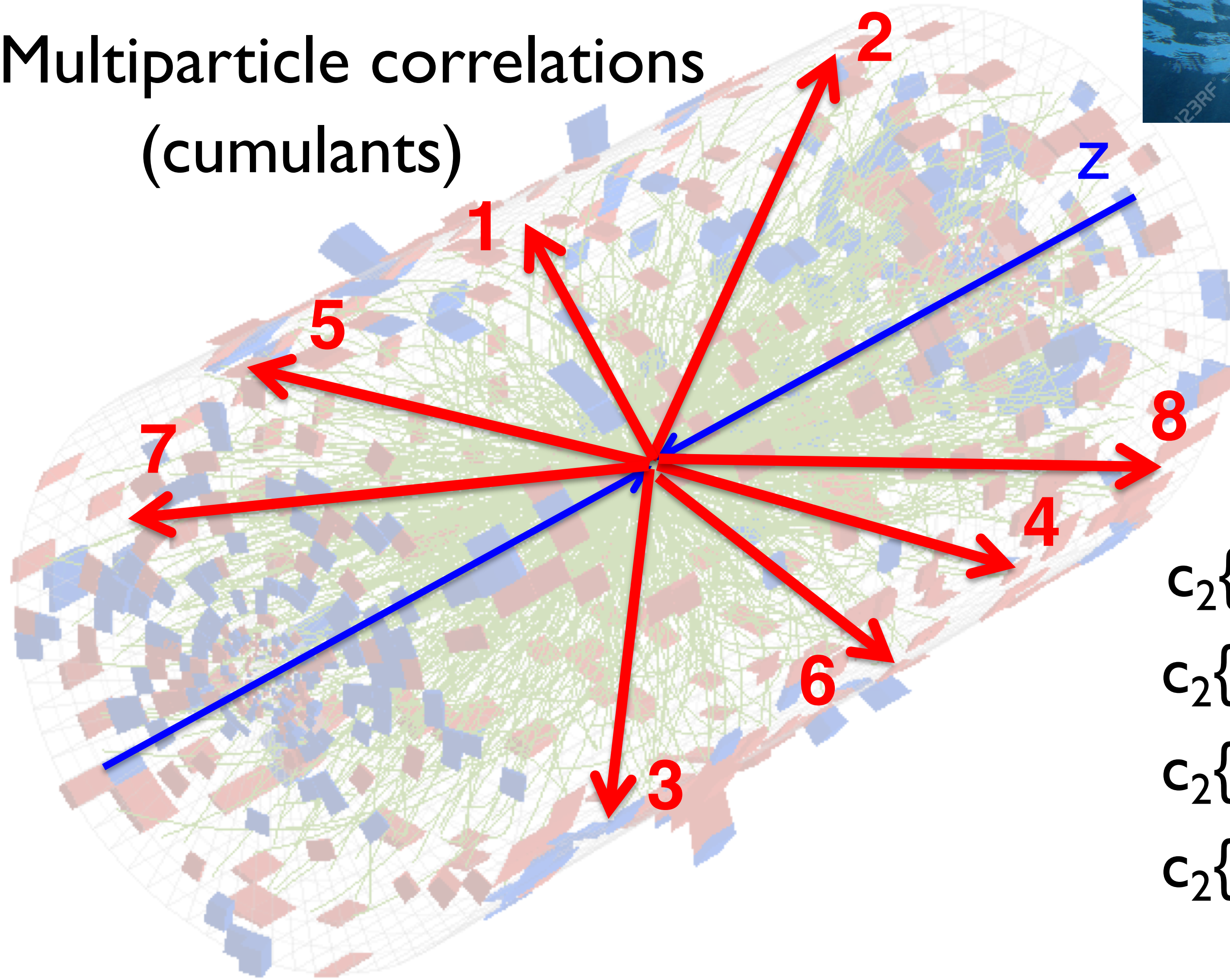
$c_2\{4\} \sim (v_2\{4\})^4$

$c_2\{6\} \sim (v_2\{6\})^6$

Collective or NOT?

(all entities follow a common behavior)

Multiparticle correlations
(cumulants)



$c_2\{2\} \sim (v_2\{2\})^2$

$c_2\{4\} \sim (v_2\{4\})^4$

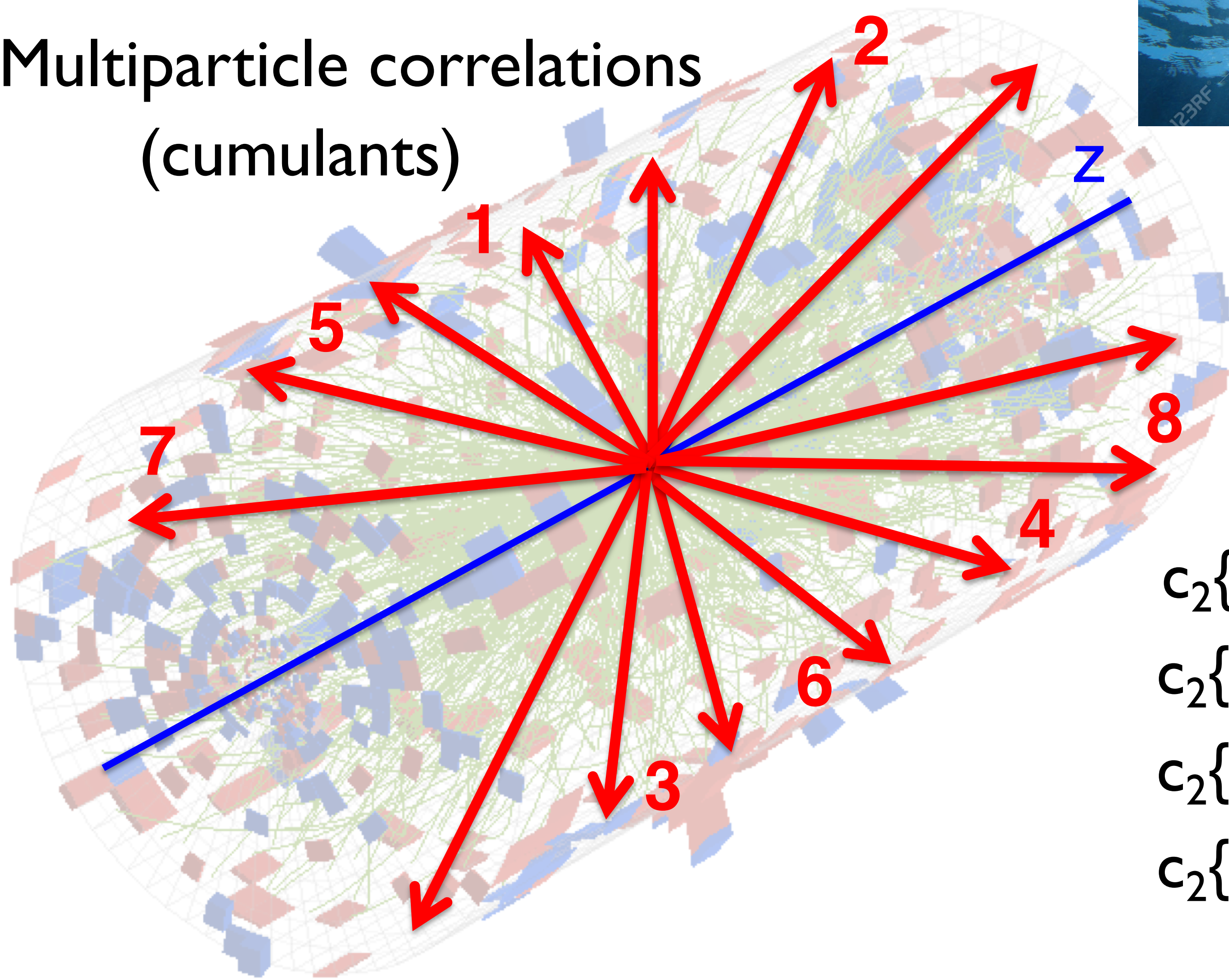
$c_2\{6\} \sim (v_2\{6\})^6$

$c_2\{8\} \sim (v_2\{8\})^8$

Collective or NOT?

(all entities follow a common behavior)

Multiparticle correlations (cumulants)



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$c_2\{4\} \sim (v_2\{4\})^4$

$c_2\{6\} \sim (v_2\{6\})^6$

$c_2\{8\} \sim (v_2\{8\})^8$

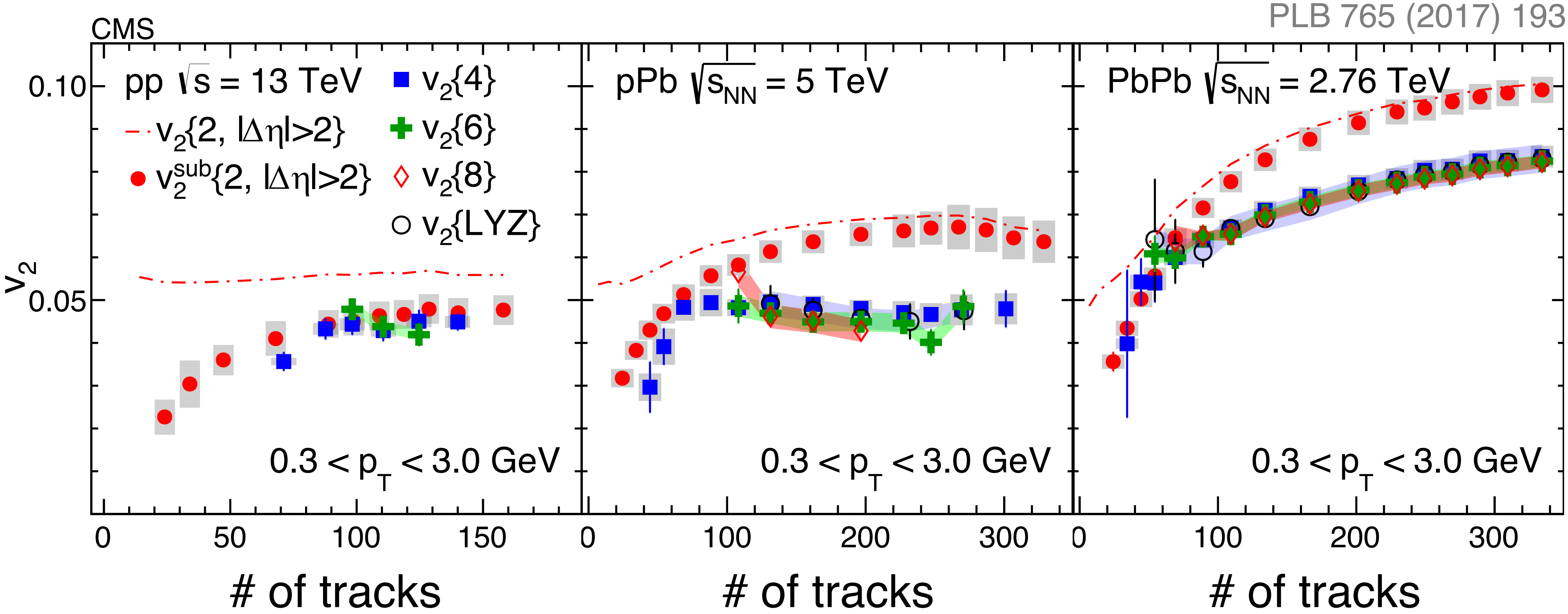
……

Collectivity: $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \ldots \approx v_2\{\infty\}$

Collectivity

Multiparticle correlations

PLB 765 (2017) 193

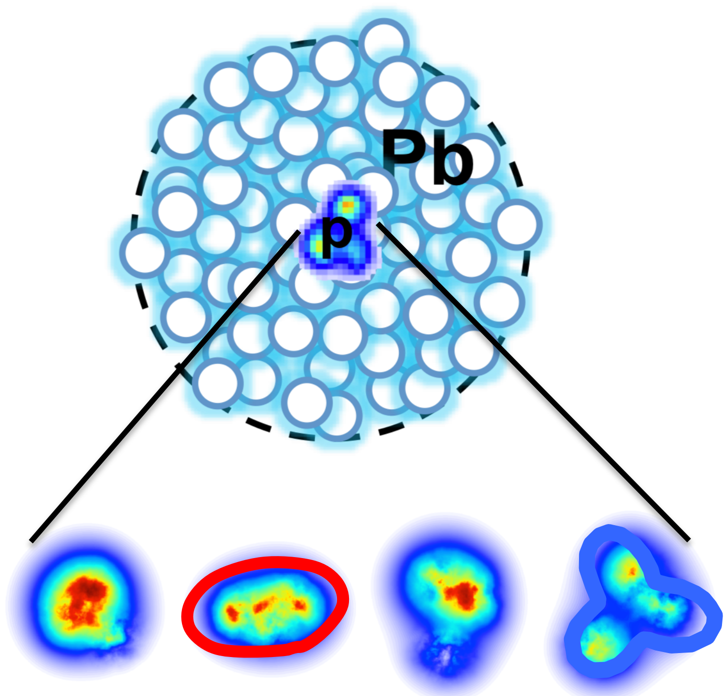


Direct evidence for

Long-range collective particle correlations

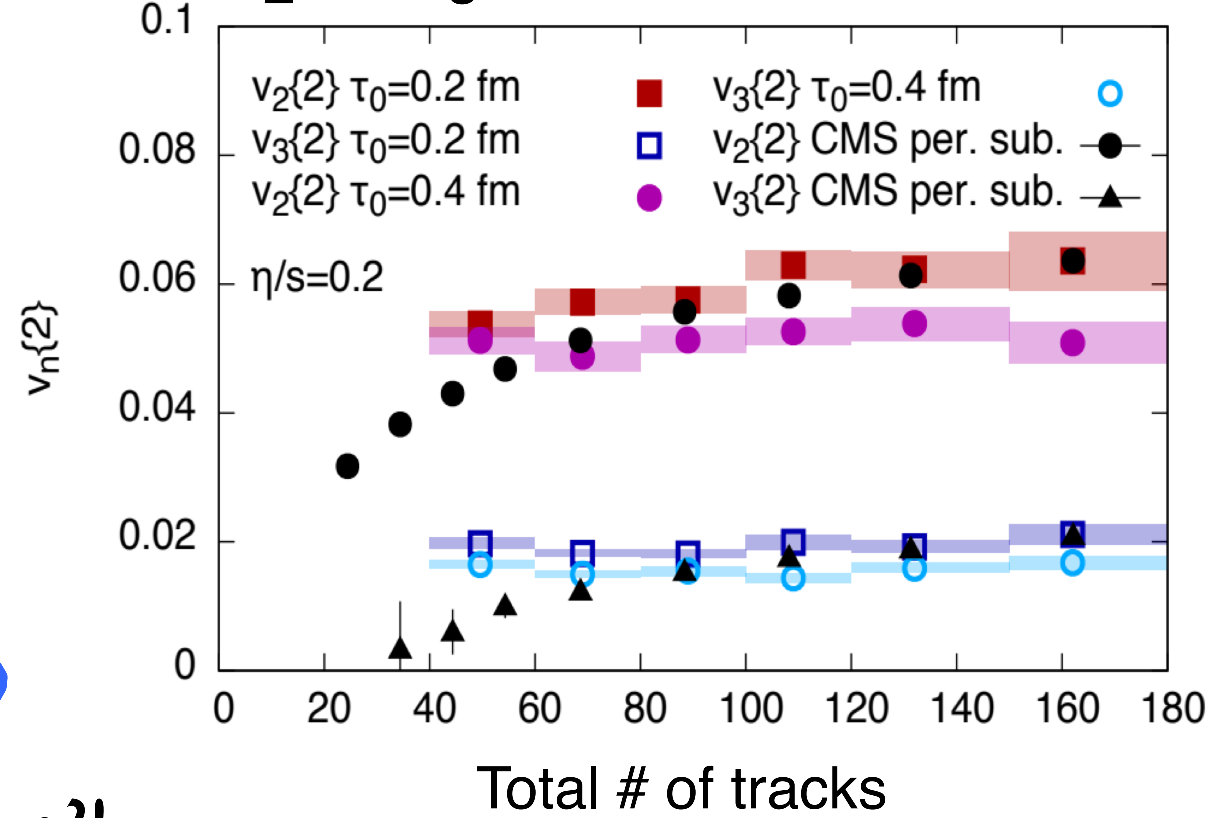
Hydrodynamics in pA and ***pp***!

Eccentric proton



"Proton shape" fluctuation?!

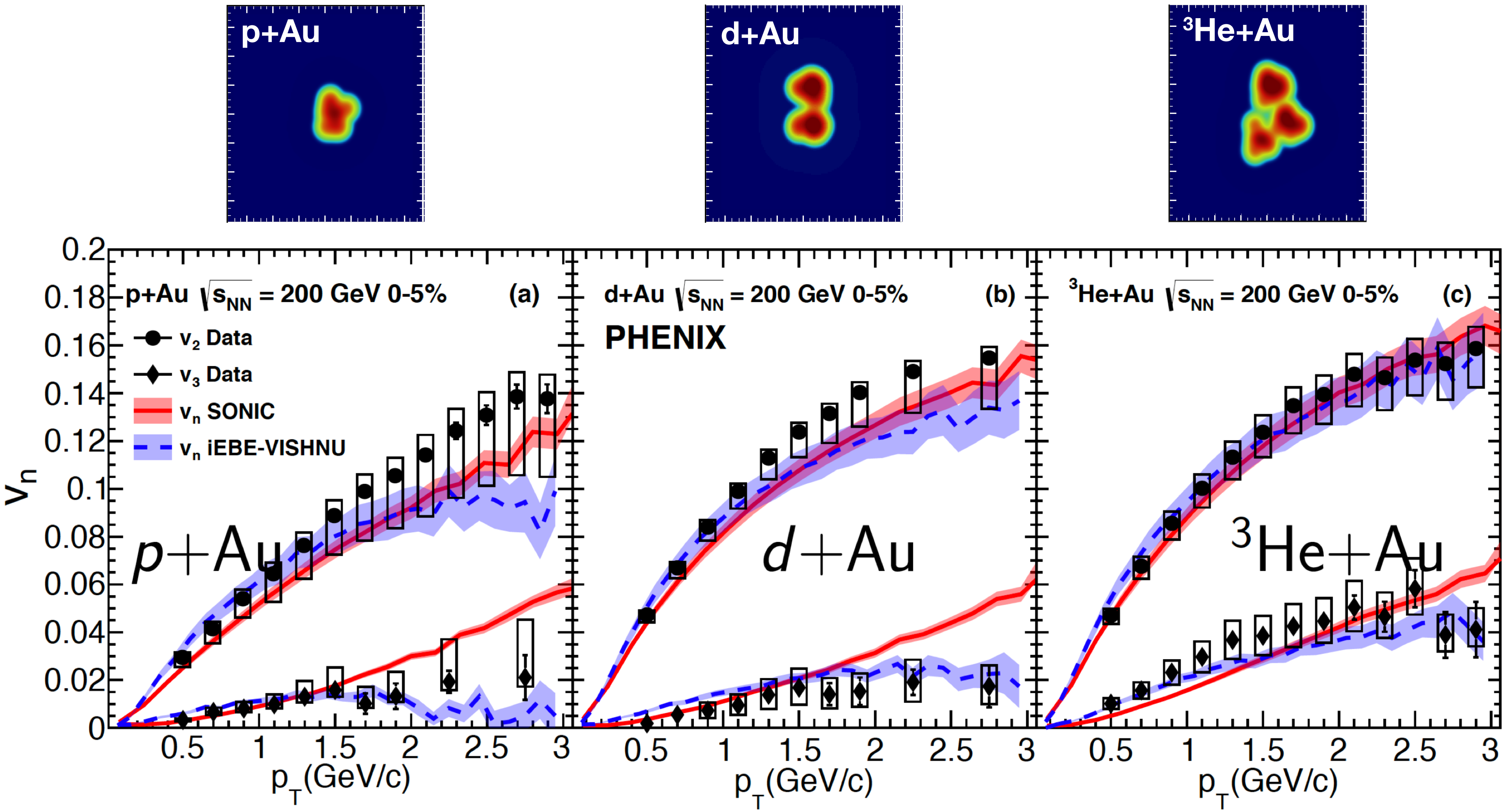
v_2 & v_3



Mäntysaari, Schenke, PLB 772 (2017) 681

Opportunity of probing quantum fluctuations at sub-fermi and yoctosec scales!

Small System Scans at RHIC



Consistent with hydrodynamics driven by initial geometry

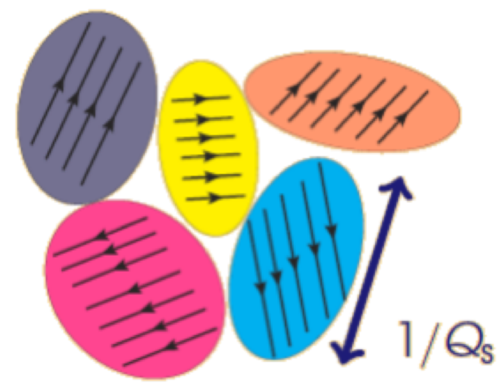
Maybe an alternative origin of the "Ridge"

Before the collision,

Gluon interference

(a.k.a., CGC)

"Momentum Domains"
Or Color Electric Fields



Lappi, Schenke, Schlichting, Venugopalan
JHEP 01 (2016) 061

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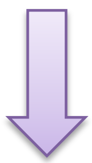
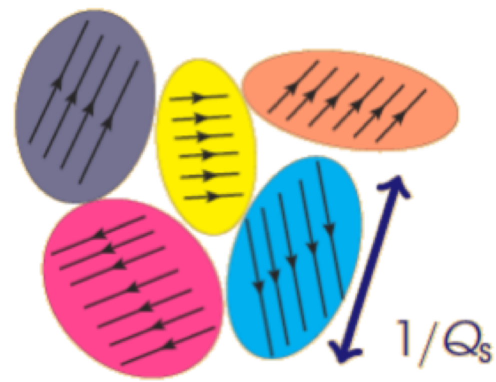




Lappi, Schenke, Schlichting, Venugopalan
JHEP 01 (2016) 061

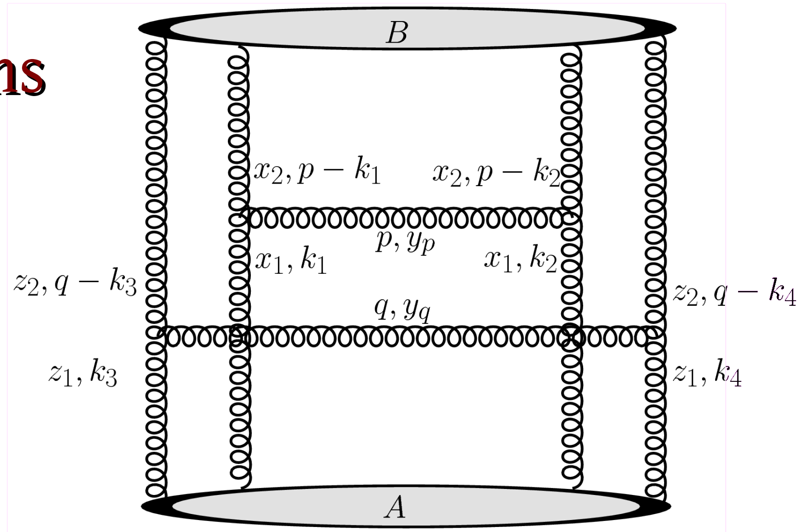
"Born to flow" (at t=0)

- Non-*Geometry* related
- No *final-stage* interactions as for Hydro.

Subdominant in large (than domain size) systems but highly relevant in small systems (pp, pA, etc.)

- Ridge pure final-state effect or is it there in pp @ LHC ?

genuine B-JIMWLK terms from THIS diagram:



B-JIMWLK four-point function (in Gaussian approximation), incl. "Nc corrections":

$$\langle \rho^a \rho^b \rho^c \rho^d \rangle = \delta^{ab}\delta^{cd}\left\langle \rho^2 \right\rangle^2 + \frac{1}{N_c} f^{abe} f^{cde} \mathcal{F}(k_i) \left\langle \rho^2 \right\rangle^2 + \cdots$$

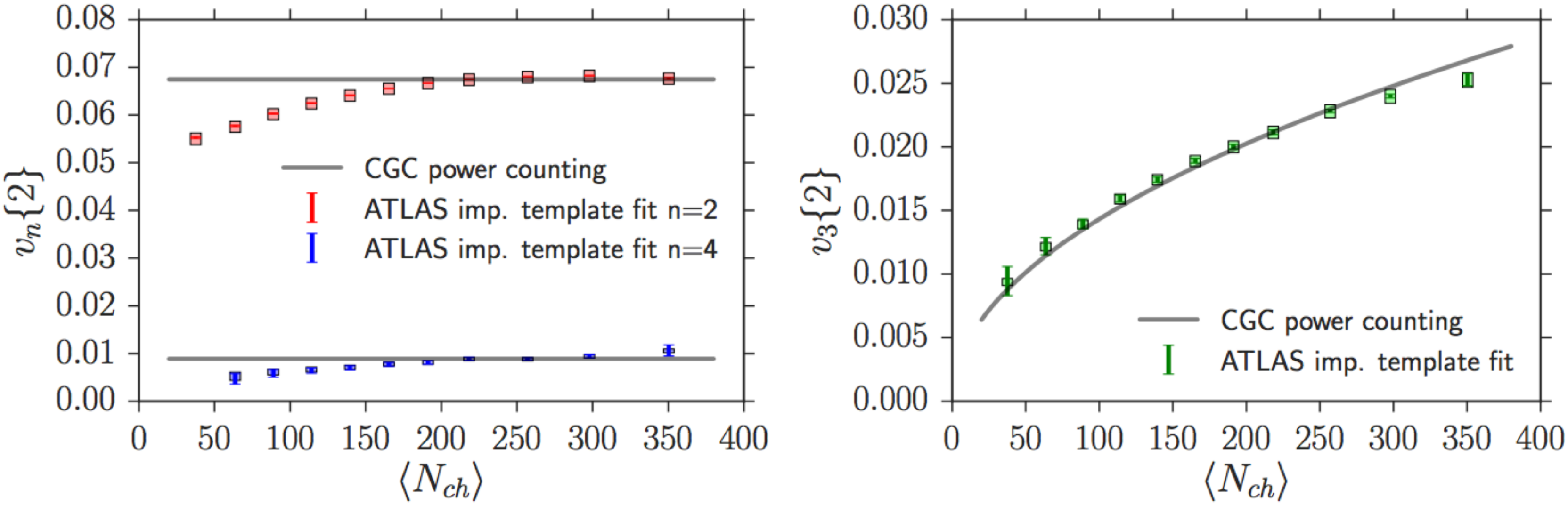
A.D., J. Jalilian-Marian, arXiv:1001.4820

☆ **ridge in pp @ LHC ?!**

Maybe an alternative origin of the "Ridge"

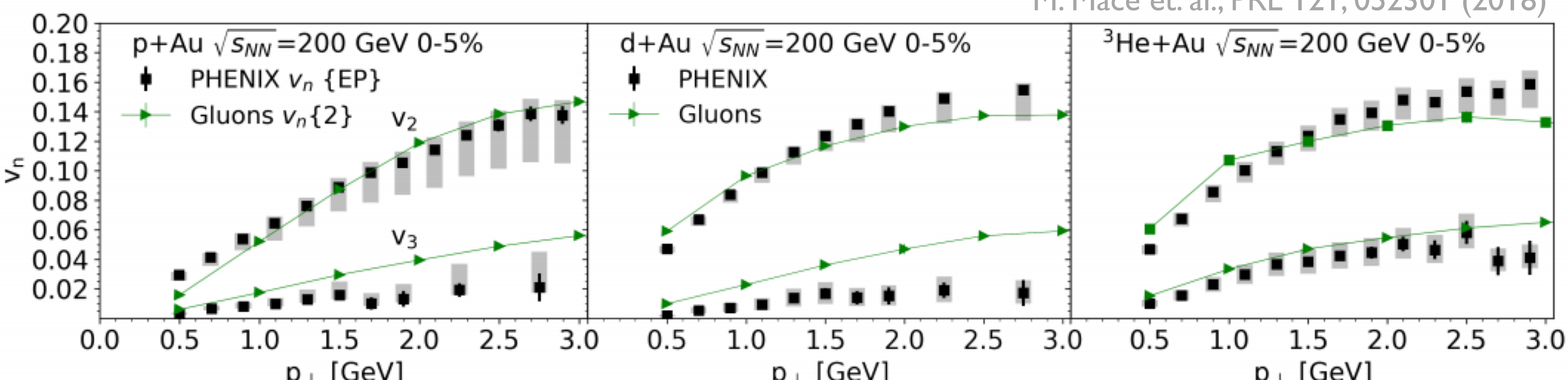
v_2, v_3, v_4 in pPb at LHC from CGC

M. Mace et. al., arXiv:1807.00825



v_2, v_3 in pAu, dAu, He^{3}Au at RHIC from CGC

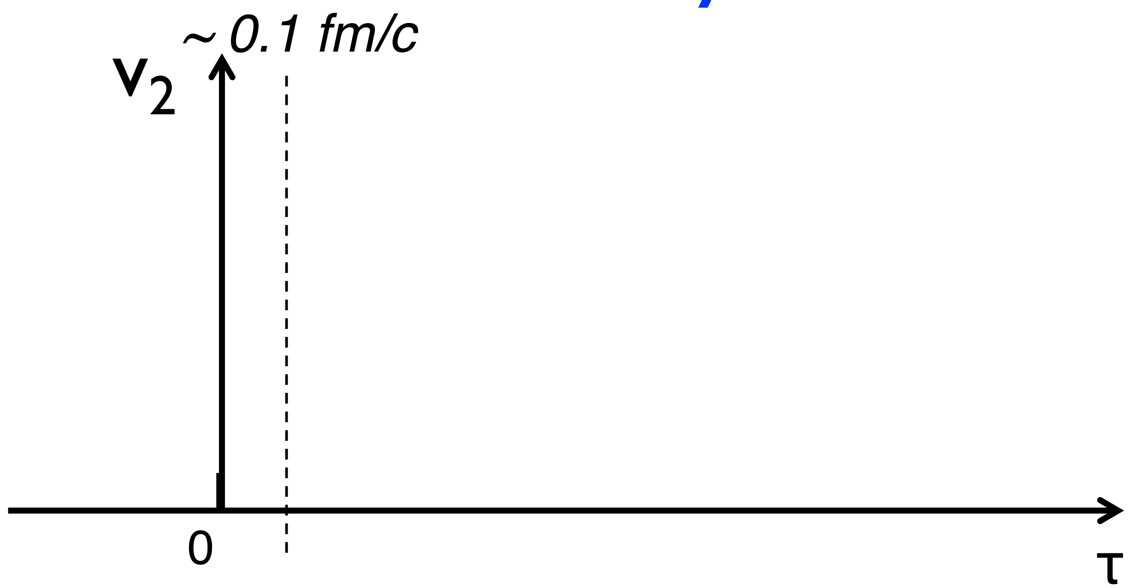
M. Mace et. al., PRL 121, 052301 (2018)



Where do we stand?

Experimental observation of <u>long-range</u> collectivity in all hadronic, HM events (pp, pA, AA)

CGC vs. "Hydro"



Where do we stand?

Early-time origin(s)

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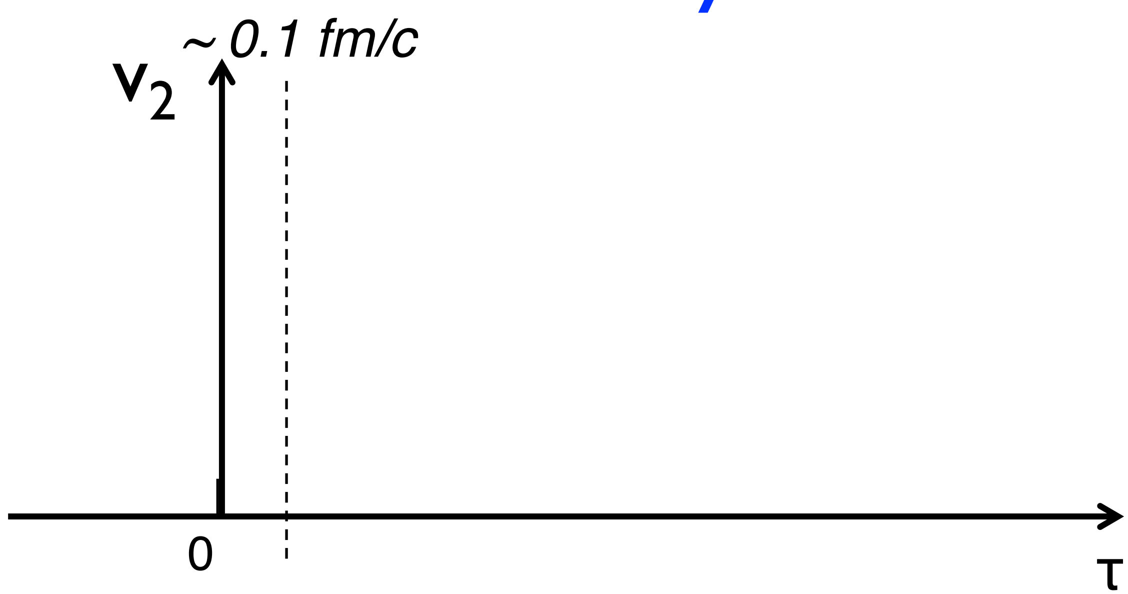

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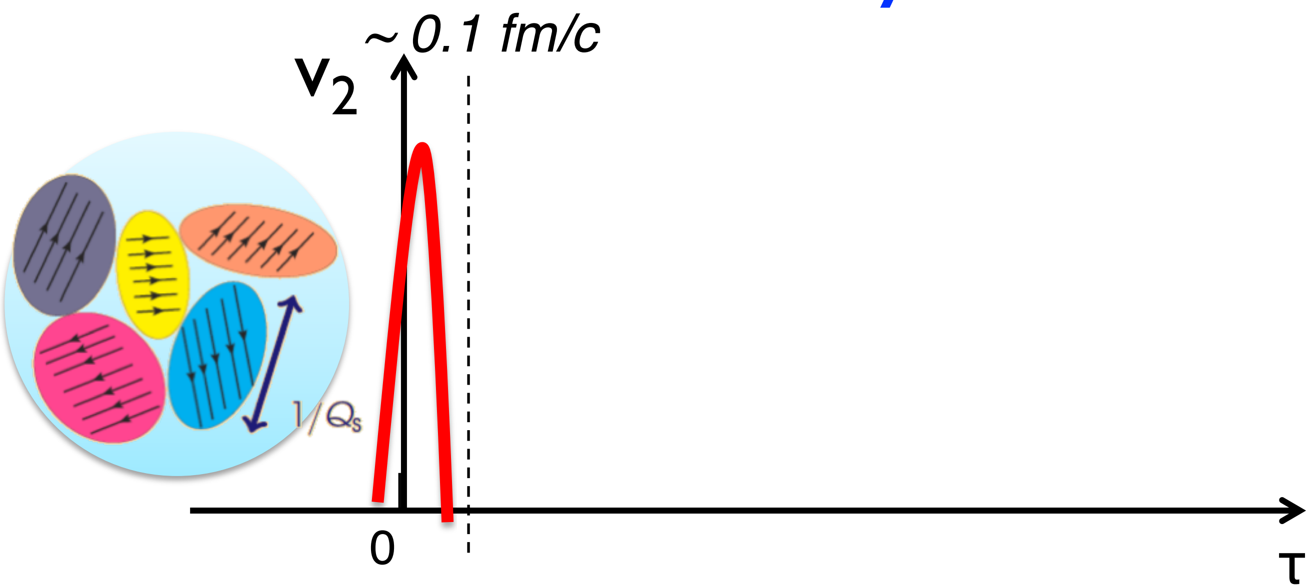

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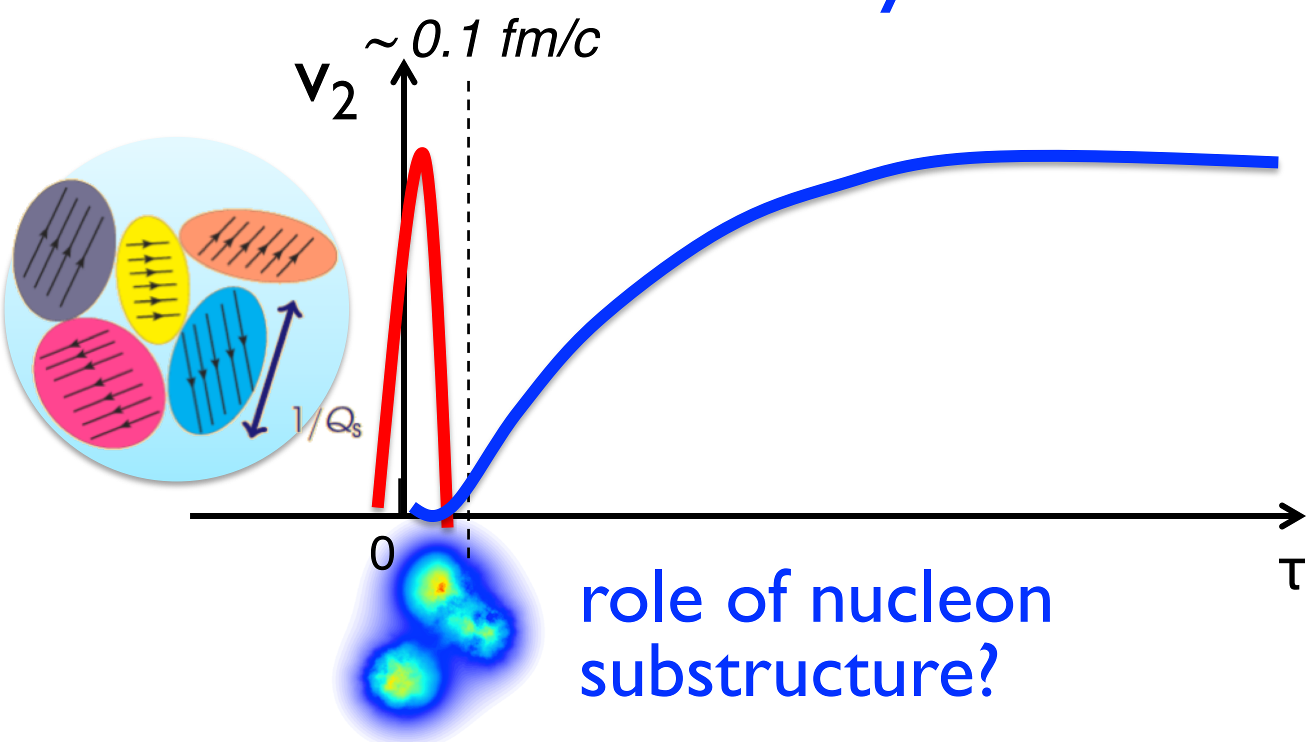

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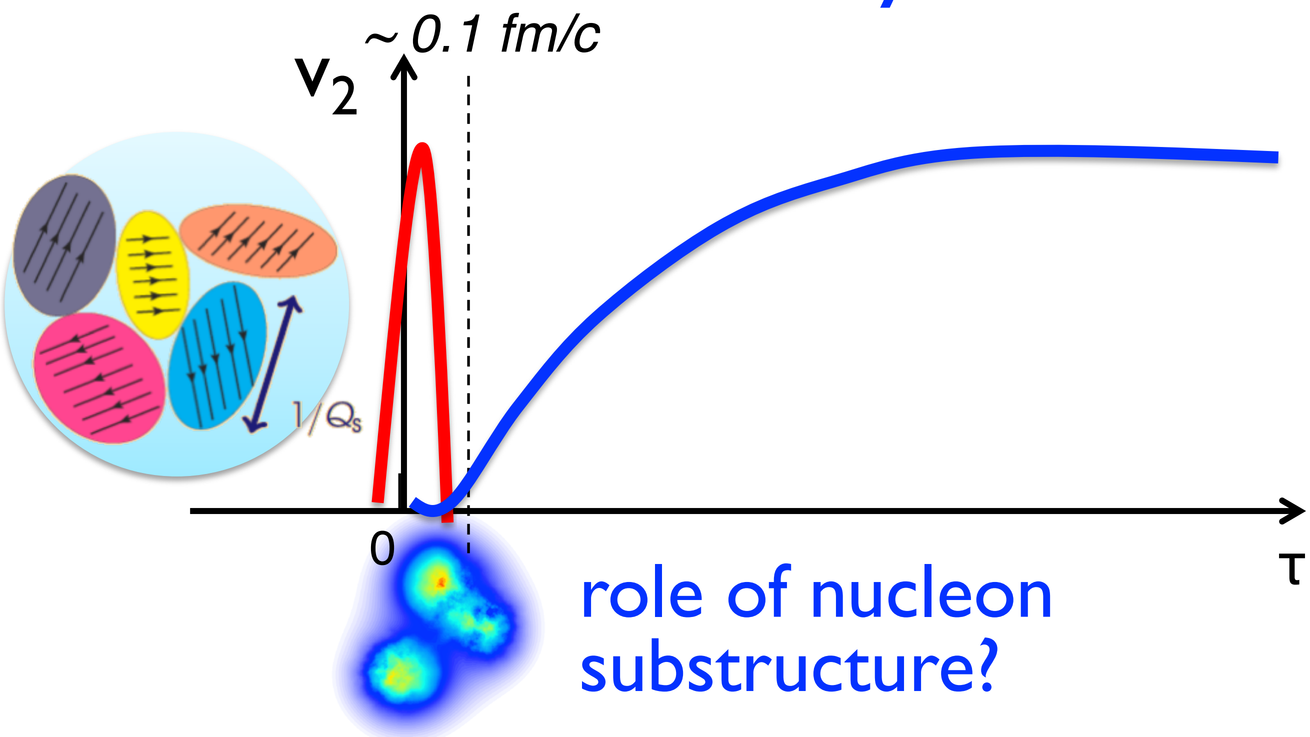
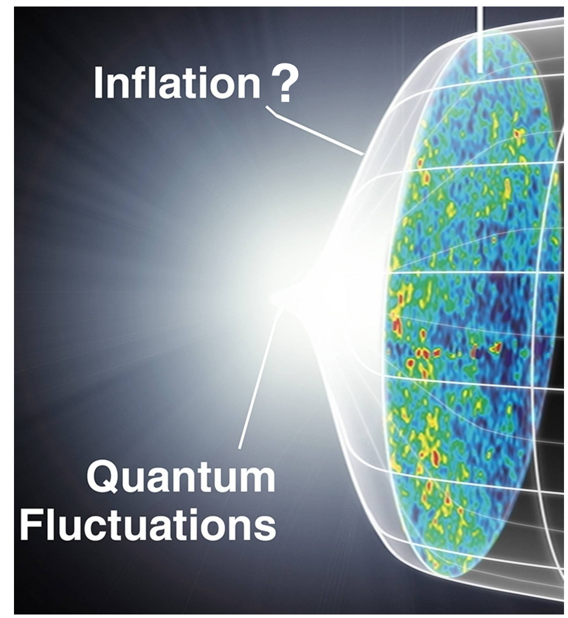


role of nucleon substructure?

Cosmic debate



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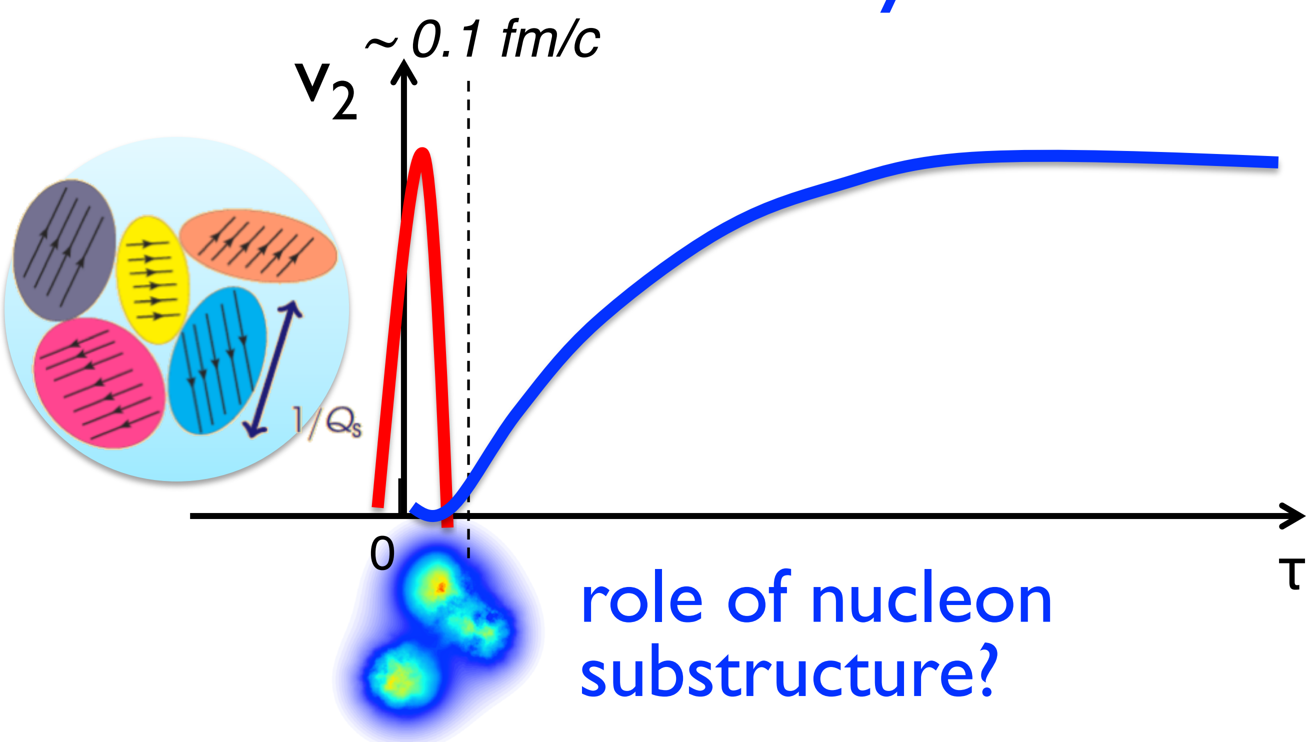
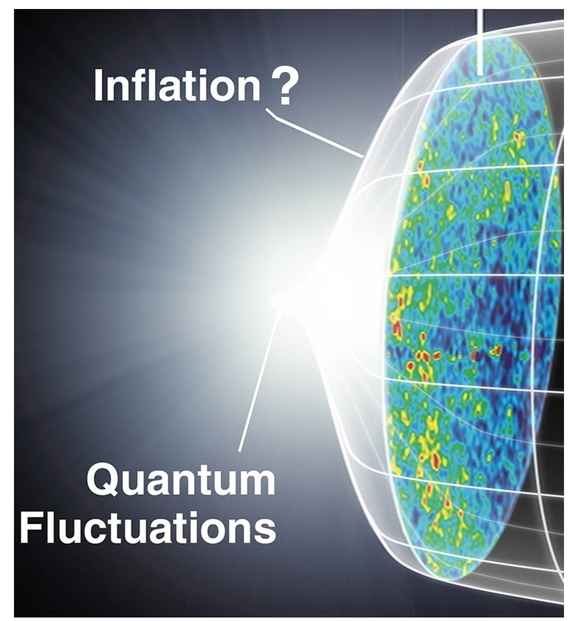
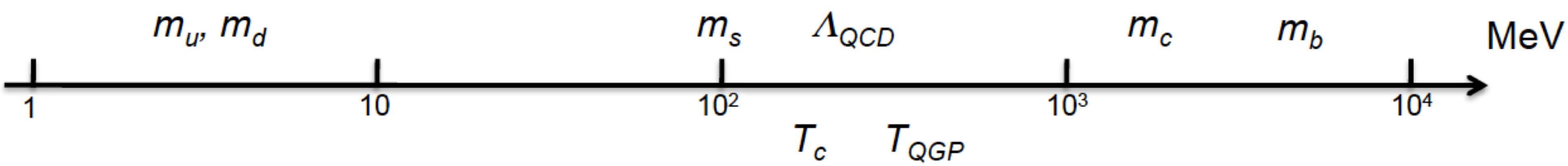


Cosmic debate



- ➢ Sensitivity to time history?
- ➢ Importance to understand the ***proton***

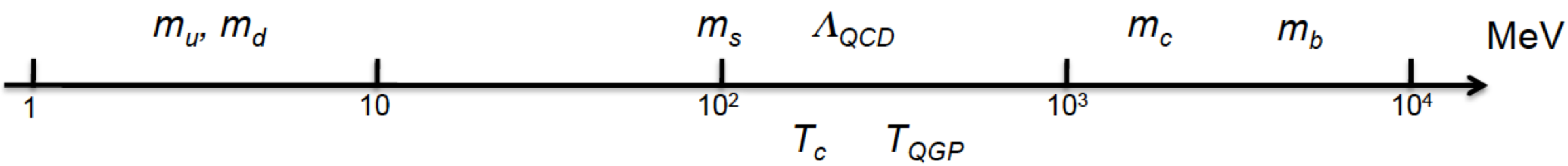
Heavy quarks as massive probes



$m_{c,b} >> T_{QGP}$: mainly from initial scattering, decoupled from the QGP medium

Do heavy quarks flow?
(charm, bottom)

Heavy quarks as massive probes



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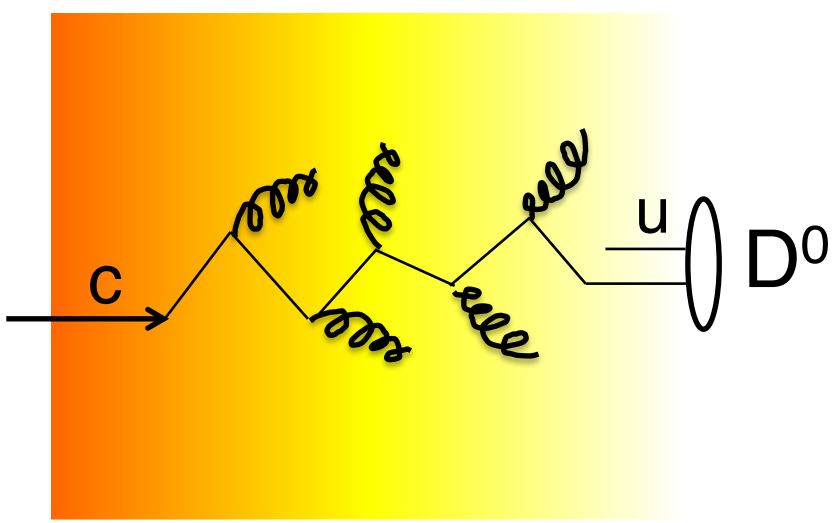
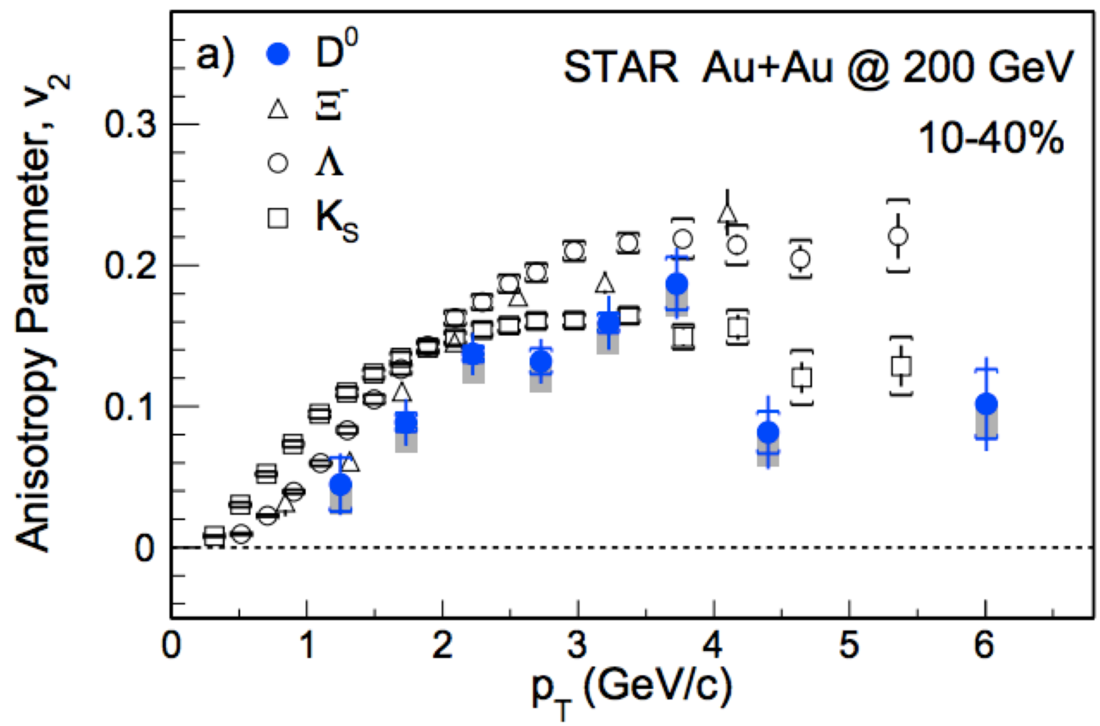
PRL 118 (2017) 212301

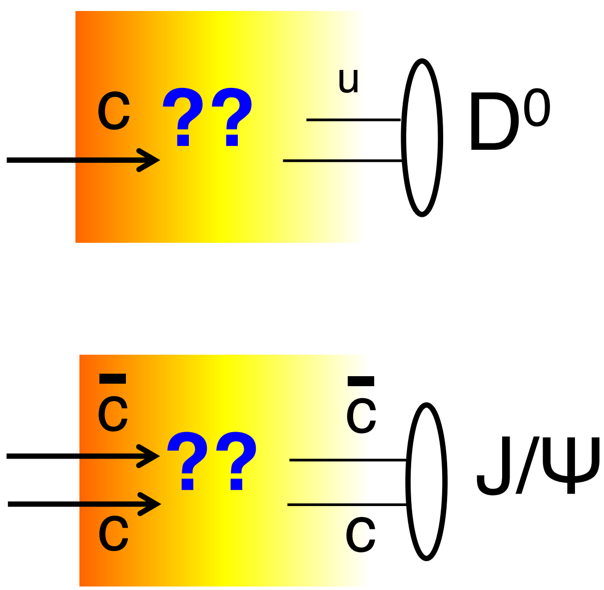


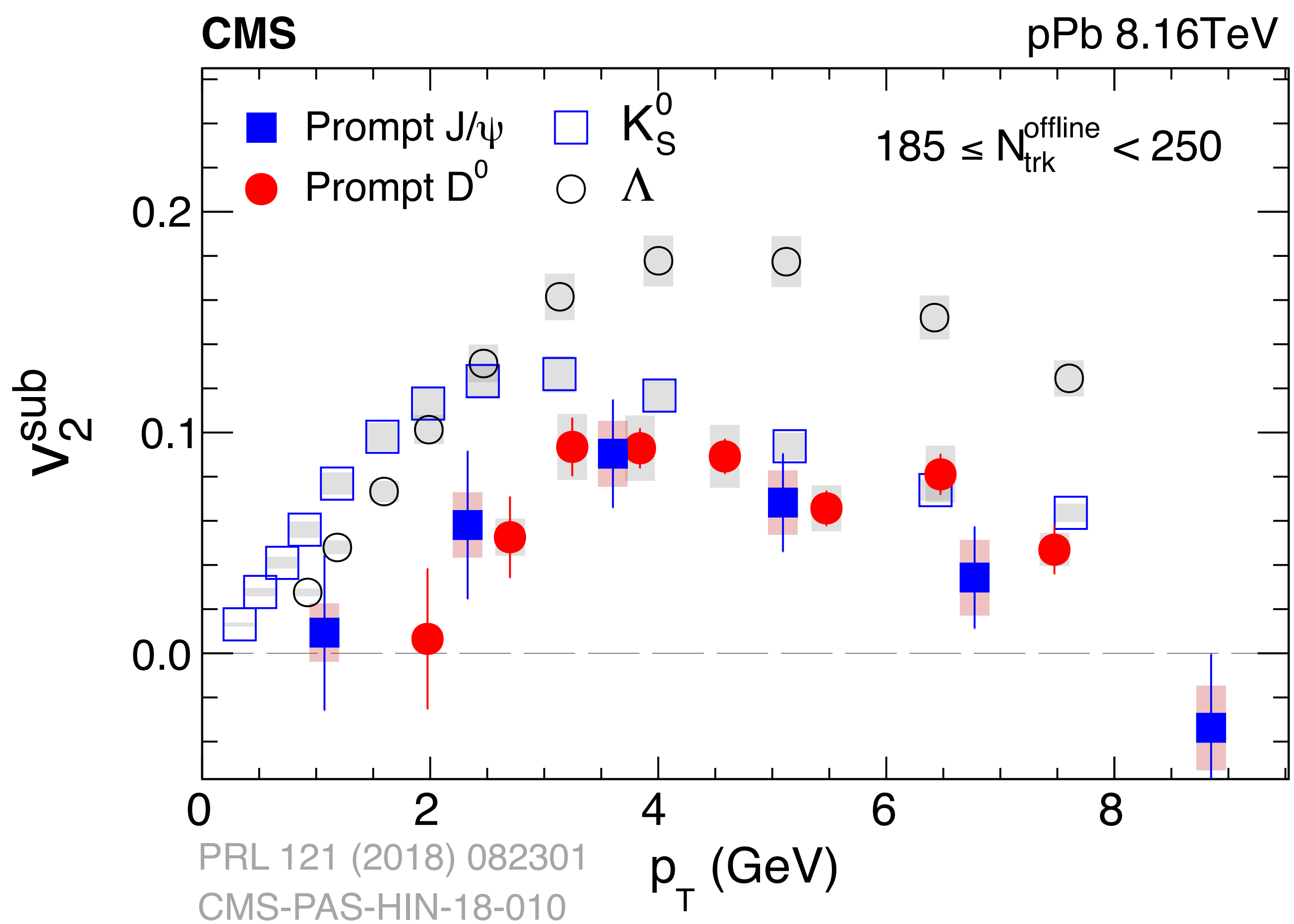


Strong charm flow in AA

Heavy quarks as massive probes

In small systems?





(Surprisingly!?) strong collective signal for ***charm***

Future: detailed studies of ***c*** and ***b*** in pp and pPb (e.g., B→D)

Theoretical inputs needed!

An alternative view of the proton

Features of "thermalization" seen in *pp*, e+e-, *etc* from quantum entanglement?

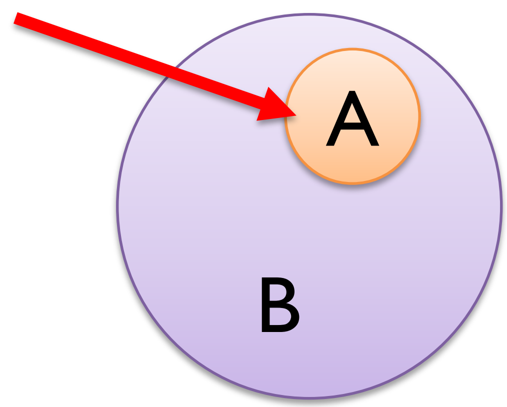
D. Kharzeev, E. Levin, PRD 95 (2017) 114008

Proton (or any hadron):

a color singlet, pure quantum state

$$|\Psi_{AB}\rangle = \sum_n \alpha_n |\Psi_n^A\rangle |\Psi_n^B\rangle$$

– *entangled!*



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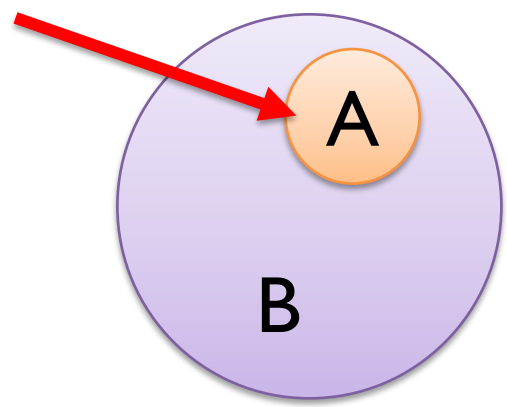

"Thermal" distributions after quench (collision)

"Born to thermalize" (at t~0) – same physics as CGC?

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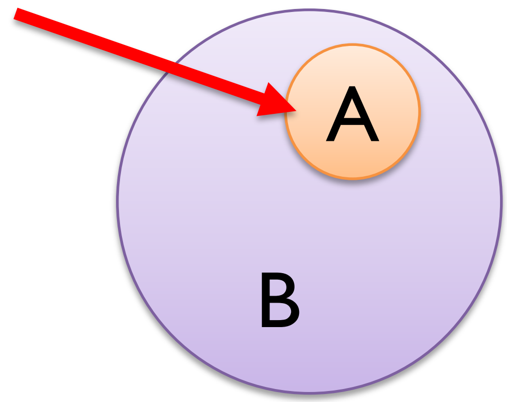

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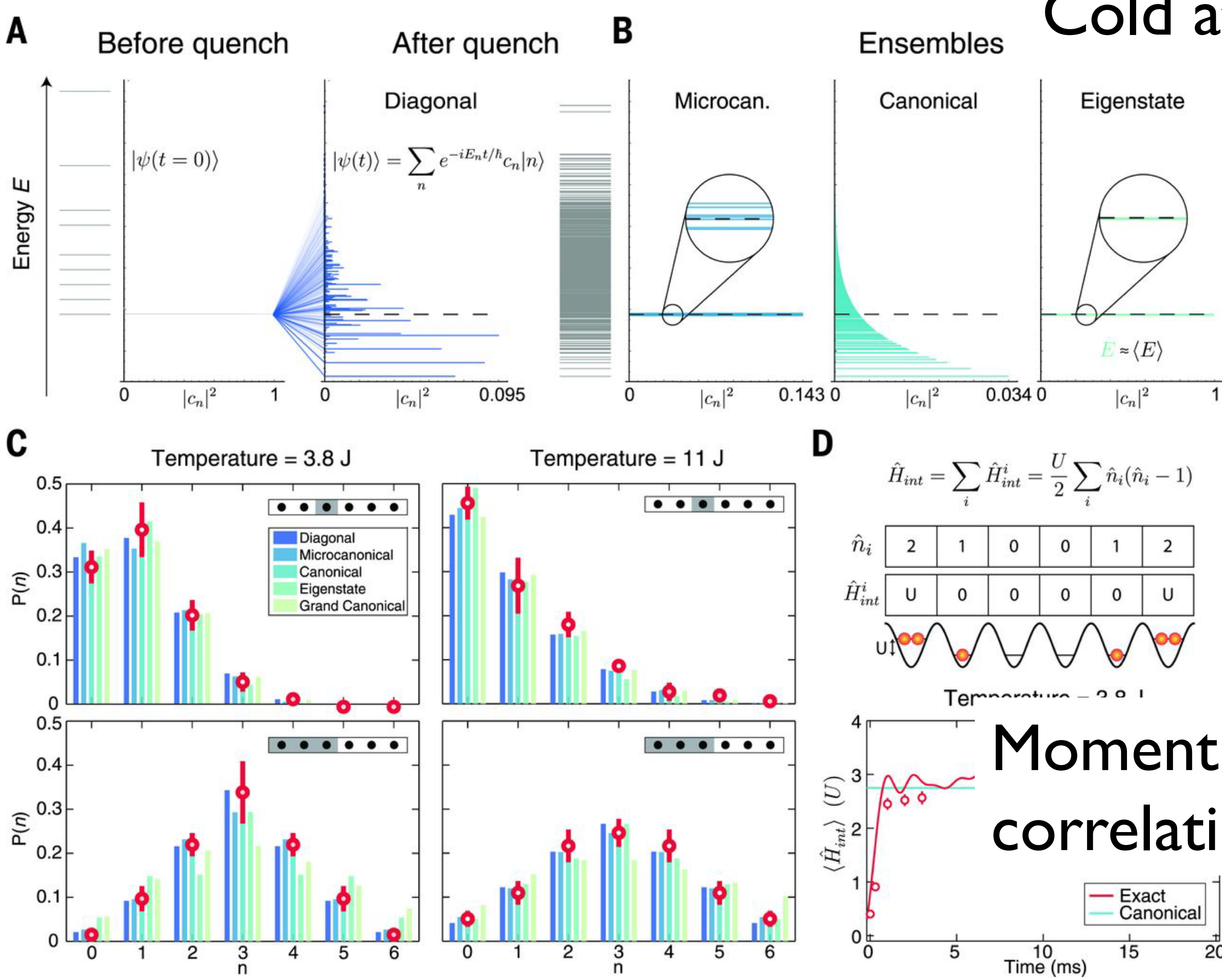
Azimuthal correlations from n-parton states?

Quantum thermalization through entanglement in an isolated many-body system

A. M. Kaufman et al, Science 353 (2016) 794

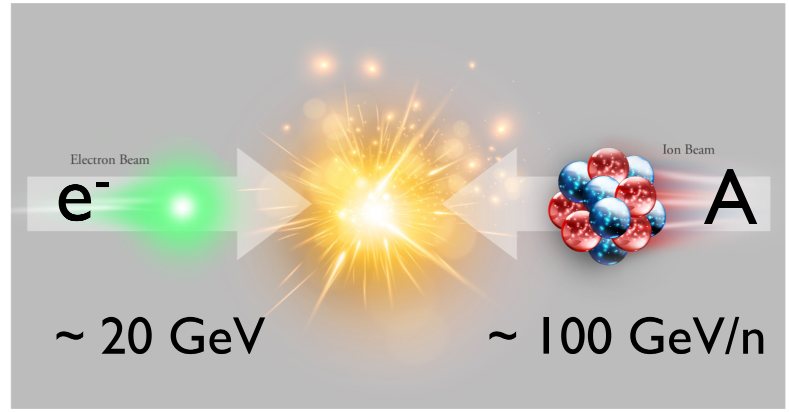
Cold atom system



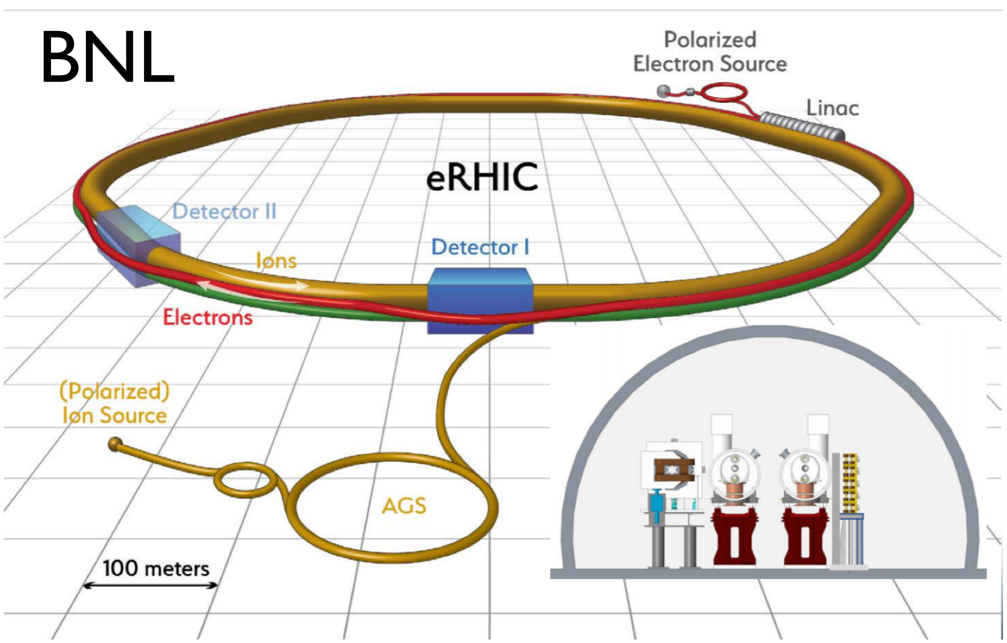
Momentum space correlations?

Electron-Ion Collider (EIC)

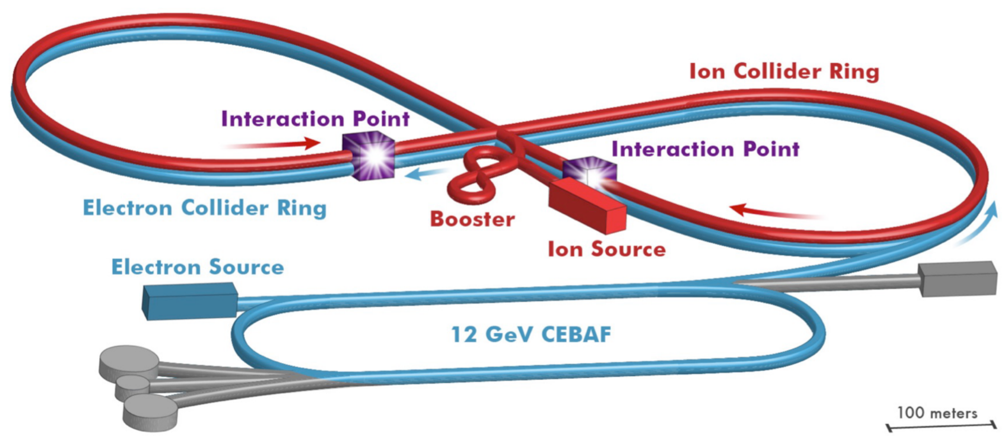
- ✓ Detailed imaging of *p*/*A* (cold QCD matter)
- ✓ *"Hot QCD matter" in e+A?*



BNL

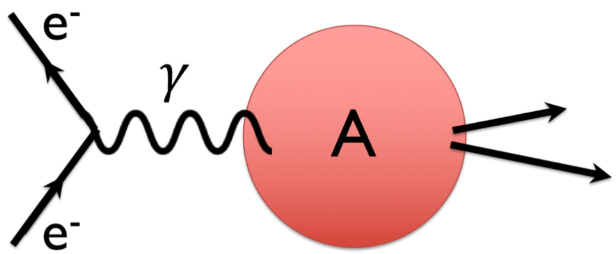


JLab

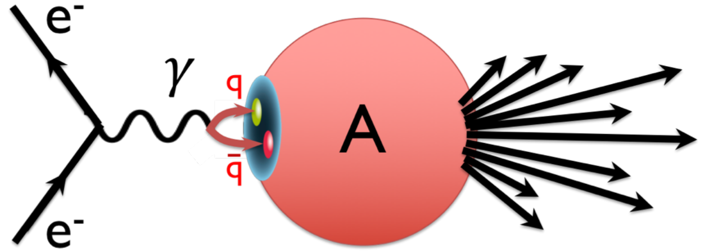


“Hot QCD matter” at EIC?

Typical e+A

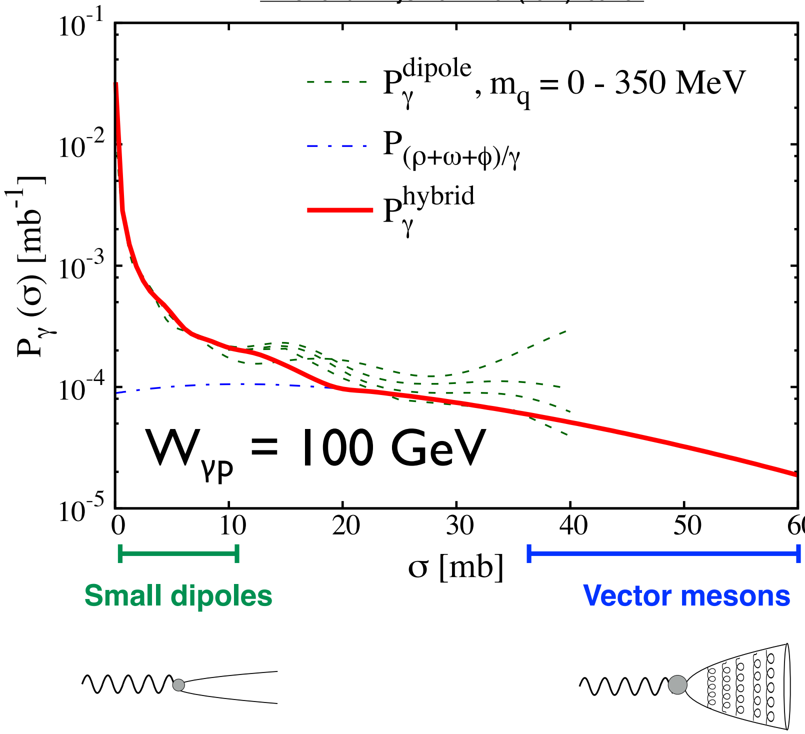


High-multiplicity e+A = ($q\bar{q}$)+A?

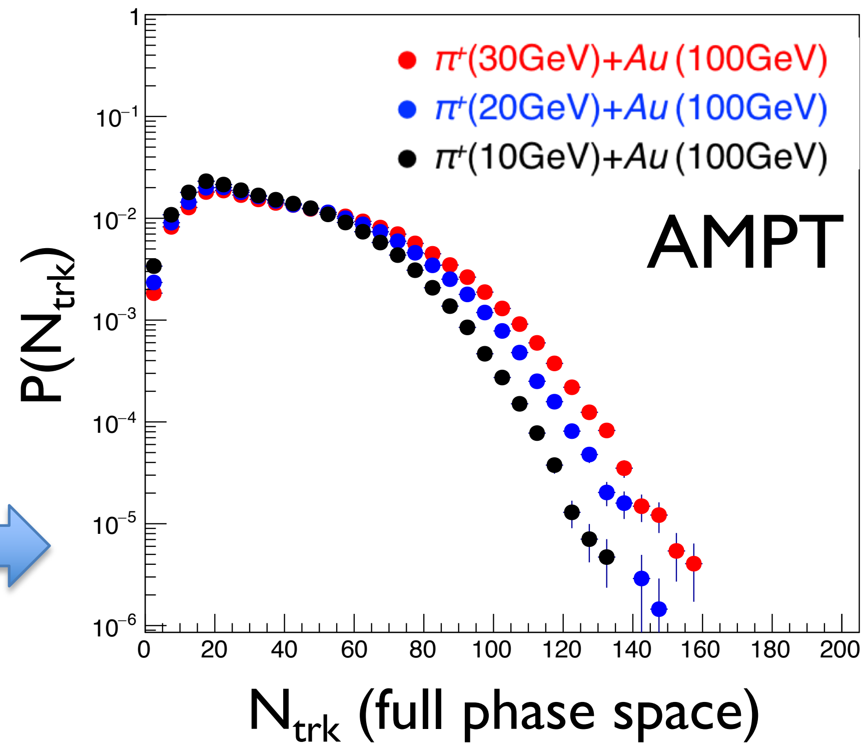


Fluctuations of “photon size”

Alvioli et. al. Phys. Lett. B767 (2017) 450-457



Multiplicity fluctuation



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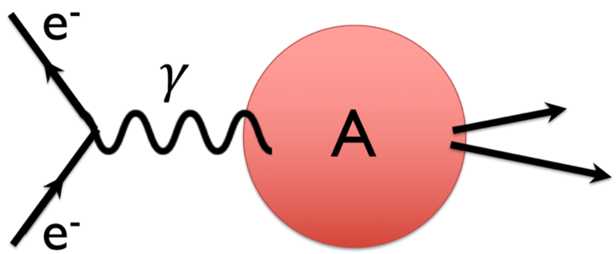

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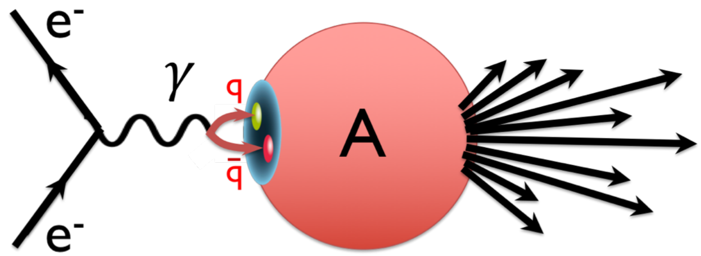

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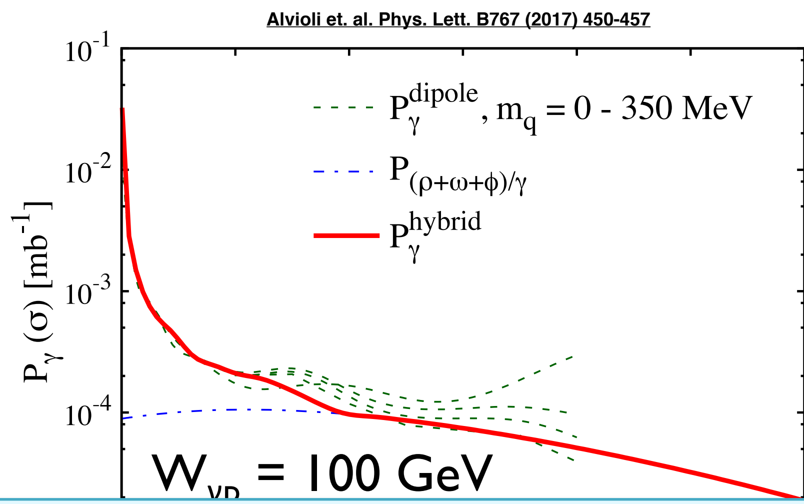

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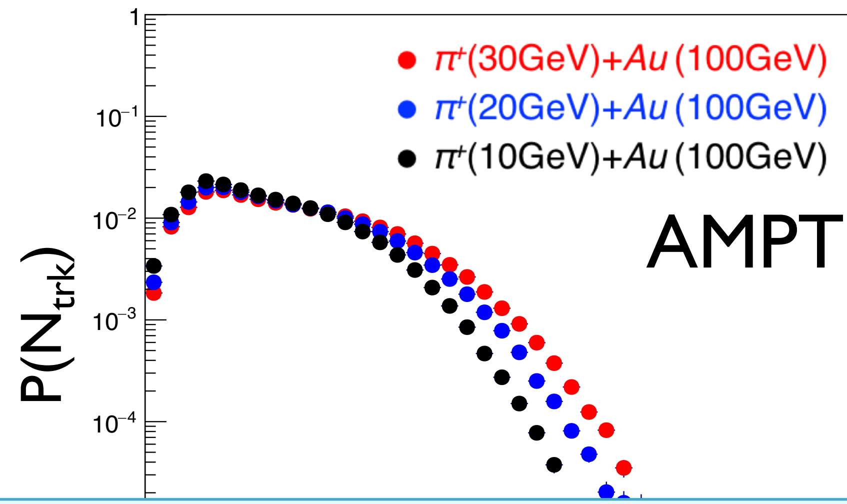


"Ridge" and "thermal" features should be observable at EIC in high-multiplicity e+Au events!

Summary

Remarkable long-range collectivity observed across all hadronic collision systems (pp/pA/AA)

Physics origin in small systems still under intense debate (CGC vs Hydro.) but a lot of progress made

Understanding the proton is the key

- role of quantum interference or entanglement?

e+A has a $(q\bar{q})$+A component

- A "ridge" should be observable at high multiplicities
- New insights to our understanding of the "ridge"

Acknowledgement

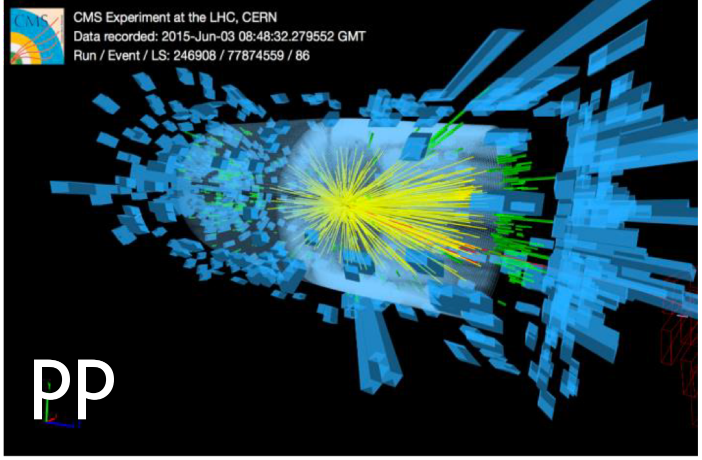
U.S. DEPARTMENT OF ENERGY

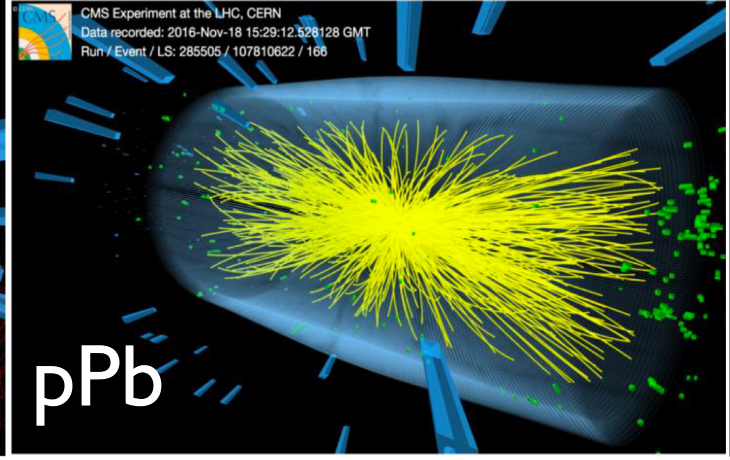
Office of Science

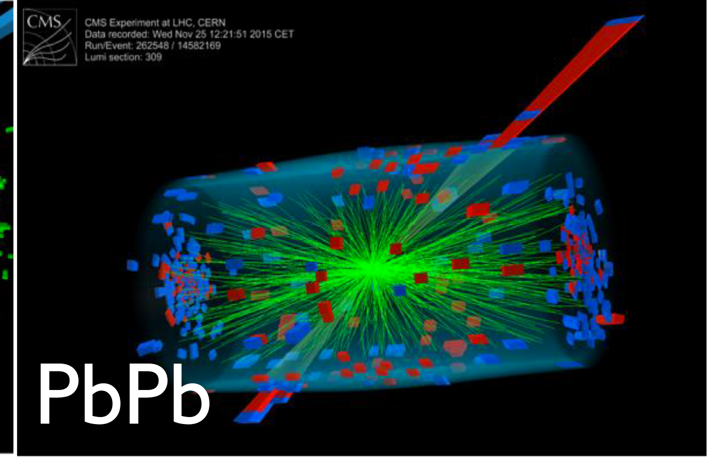
Alfred P. Sloan FOUNDATION

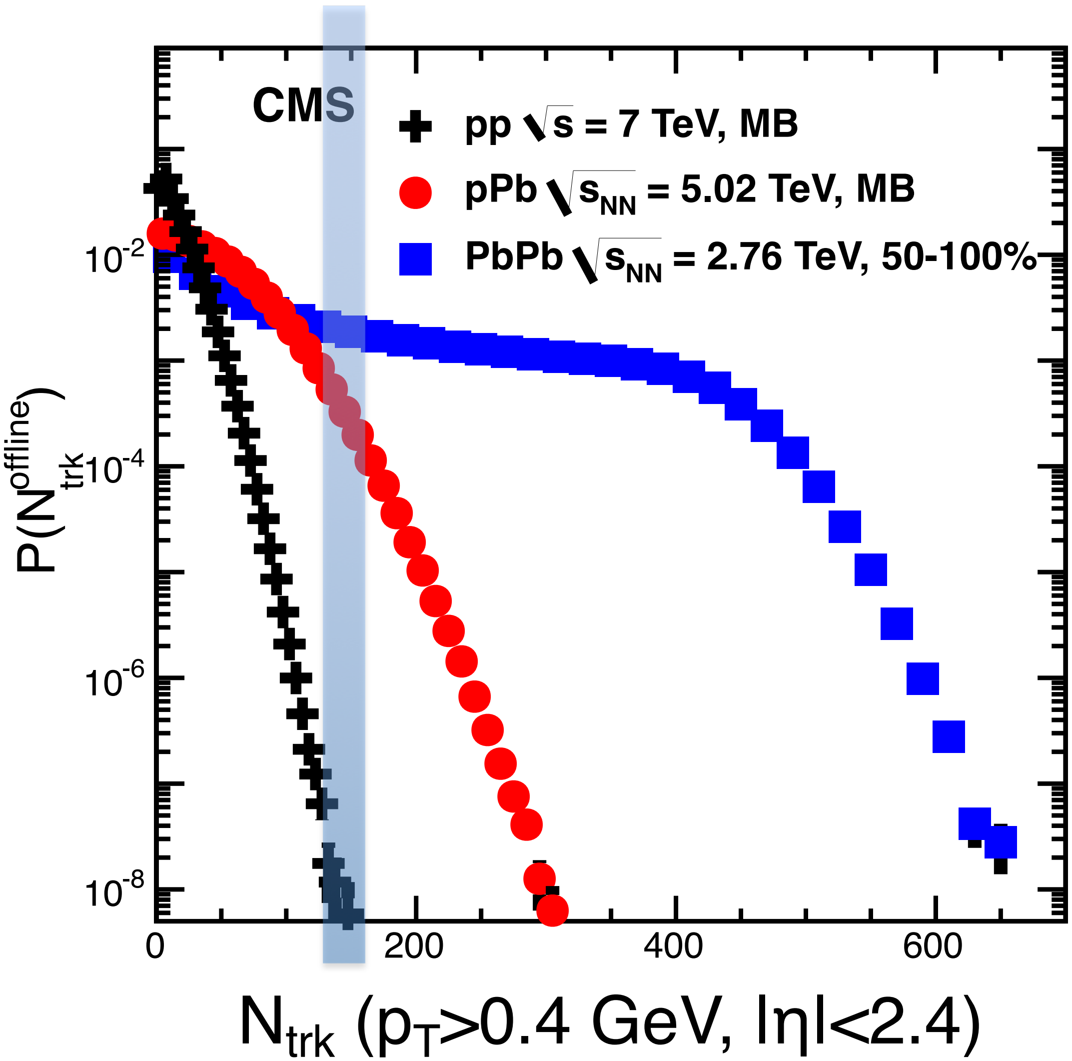
THE Welch FOUNDATION

Backups







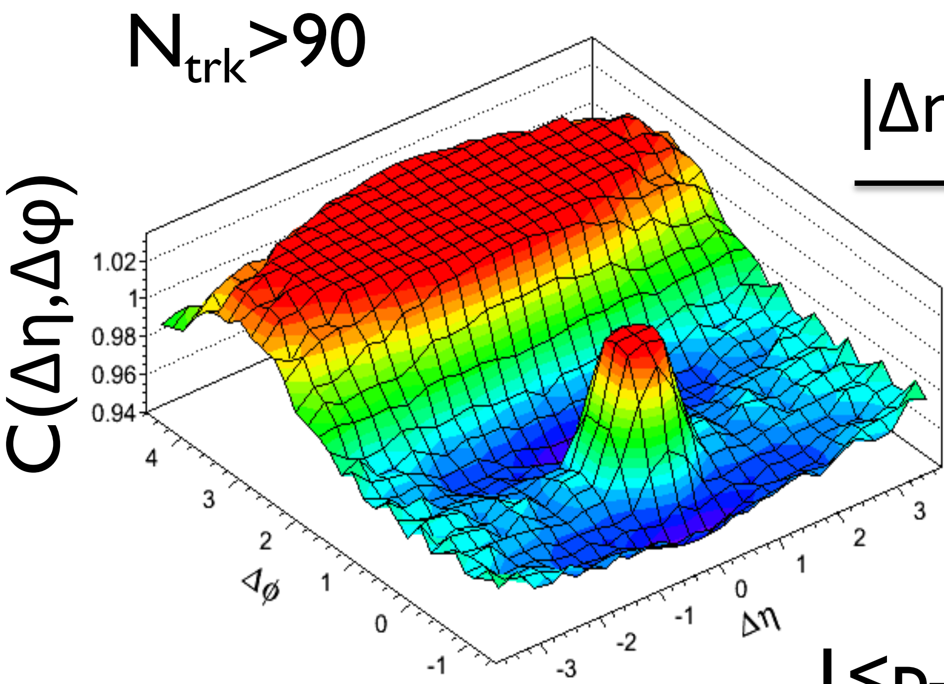


N_{trk}(minimum bias)

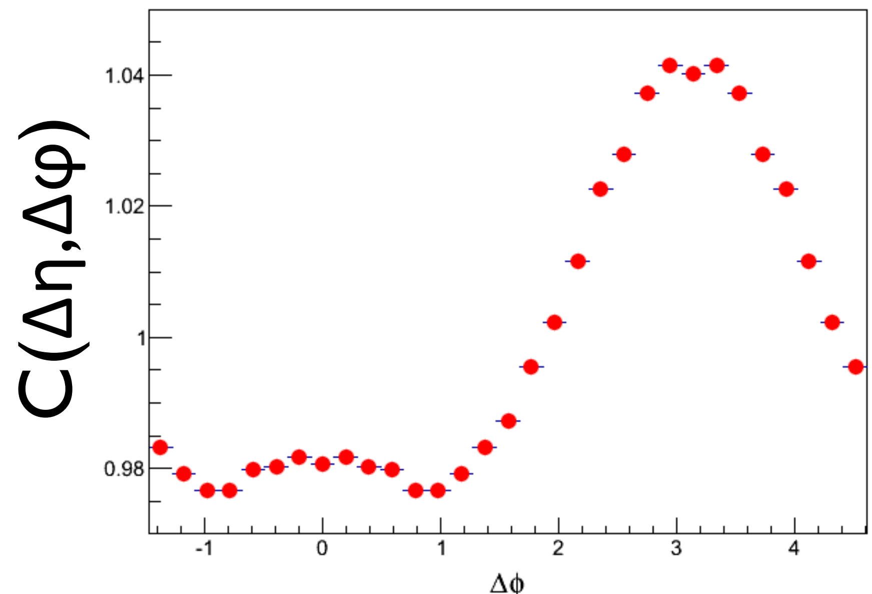
- pp: ~ 15
- pPb: ~ 40

“Hot QCD matter” at EIC?

π[+](30GeV)+***Au***(100GeV) from AMPT



|Δη|>2

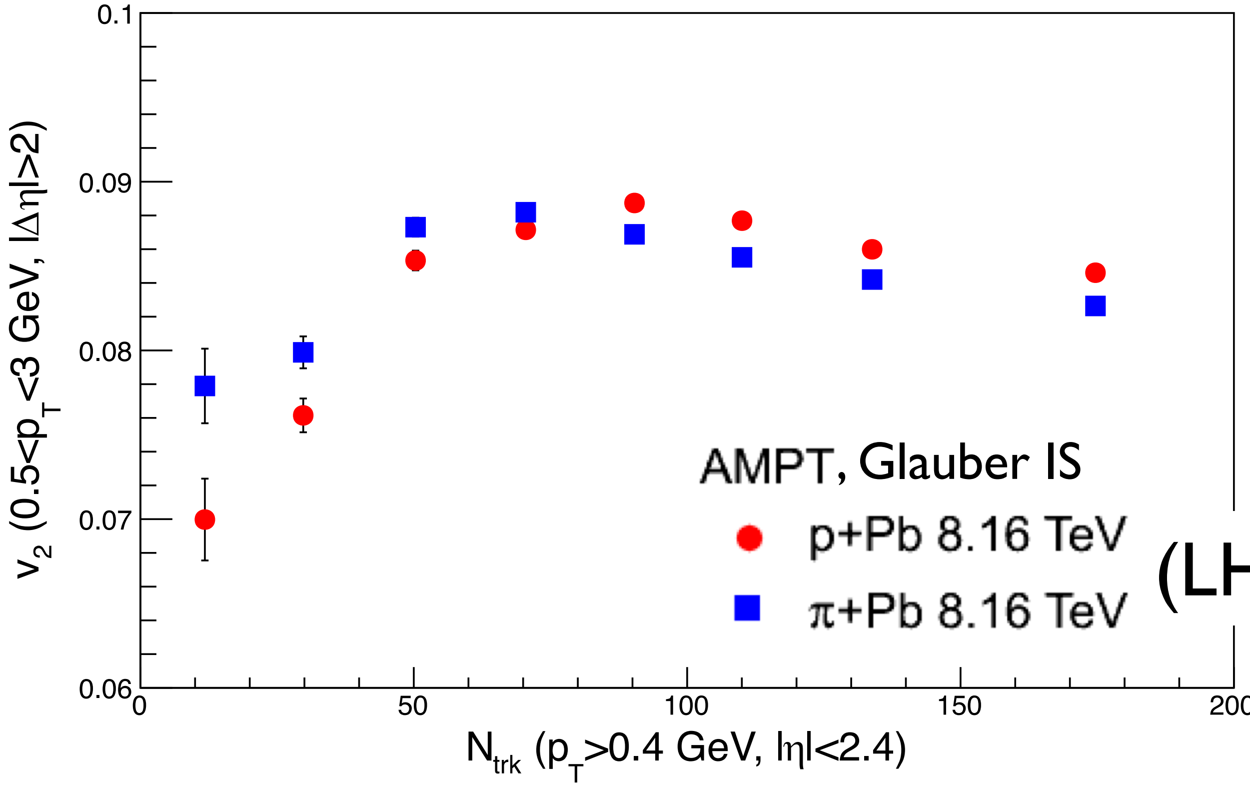


$1<p_T<3$ GeV

A long-range ridge can be observed at EIC in high-multiplicity e+Au events!

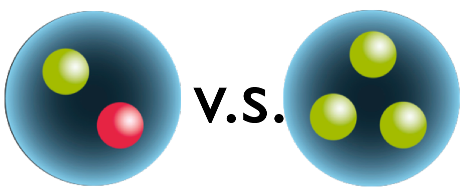
"Hot QCD matter" at EIC?

Comparing v_n in (qqq)+A vs ($q\bar{q}$)+A



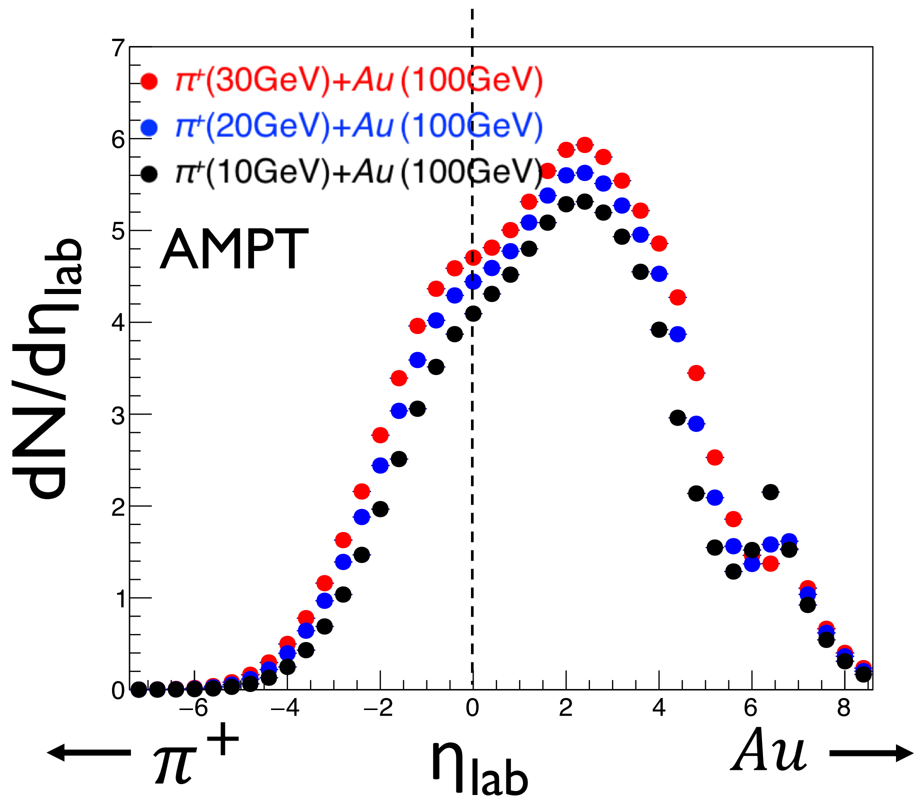
(LHC energies)

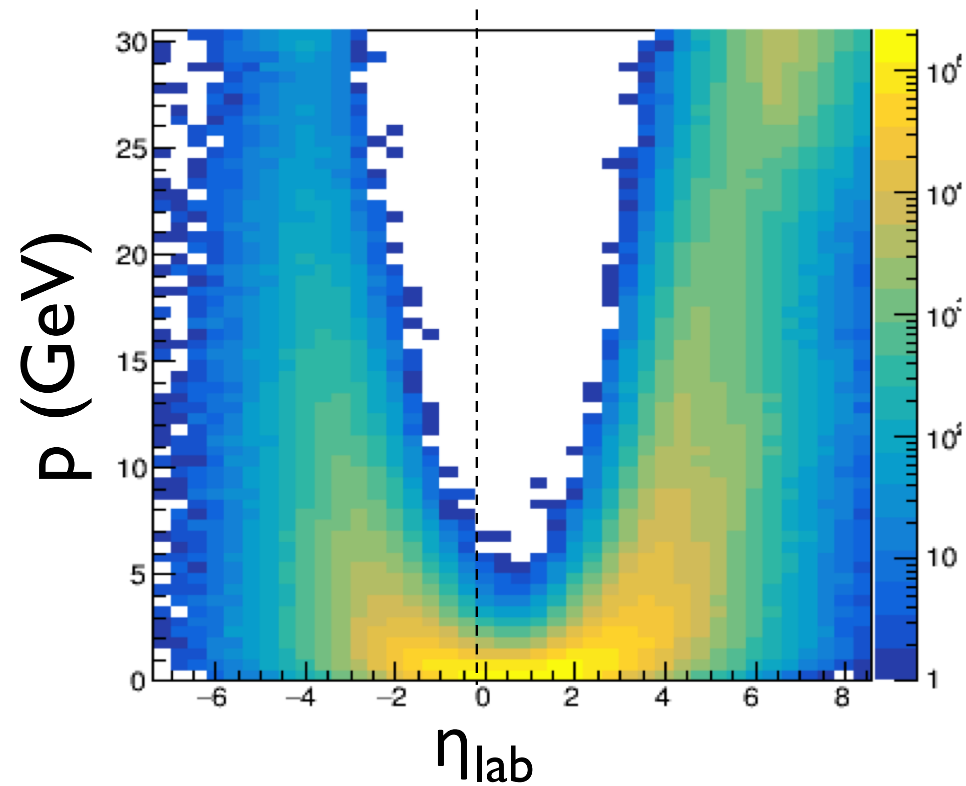
- Disentangle "hydro" vs CGC?
- Insight on subnucleonic fluctuations?



“Hot QCD matter” at EIC?

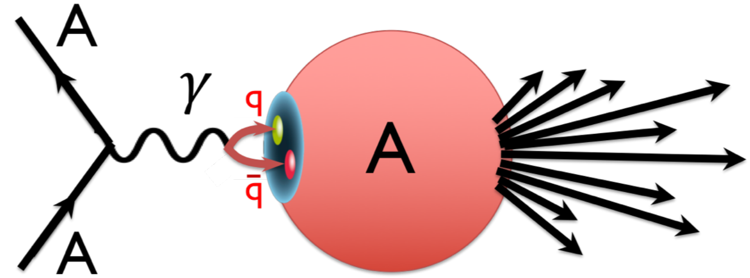
Experimental requirements

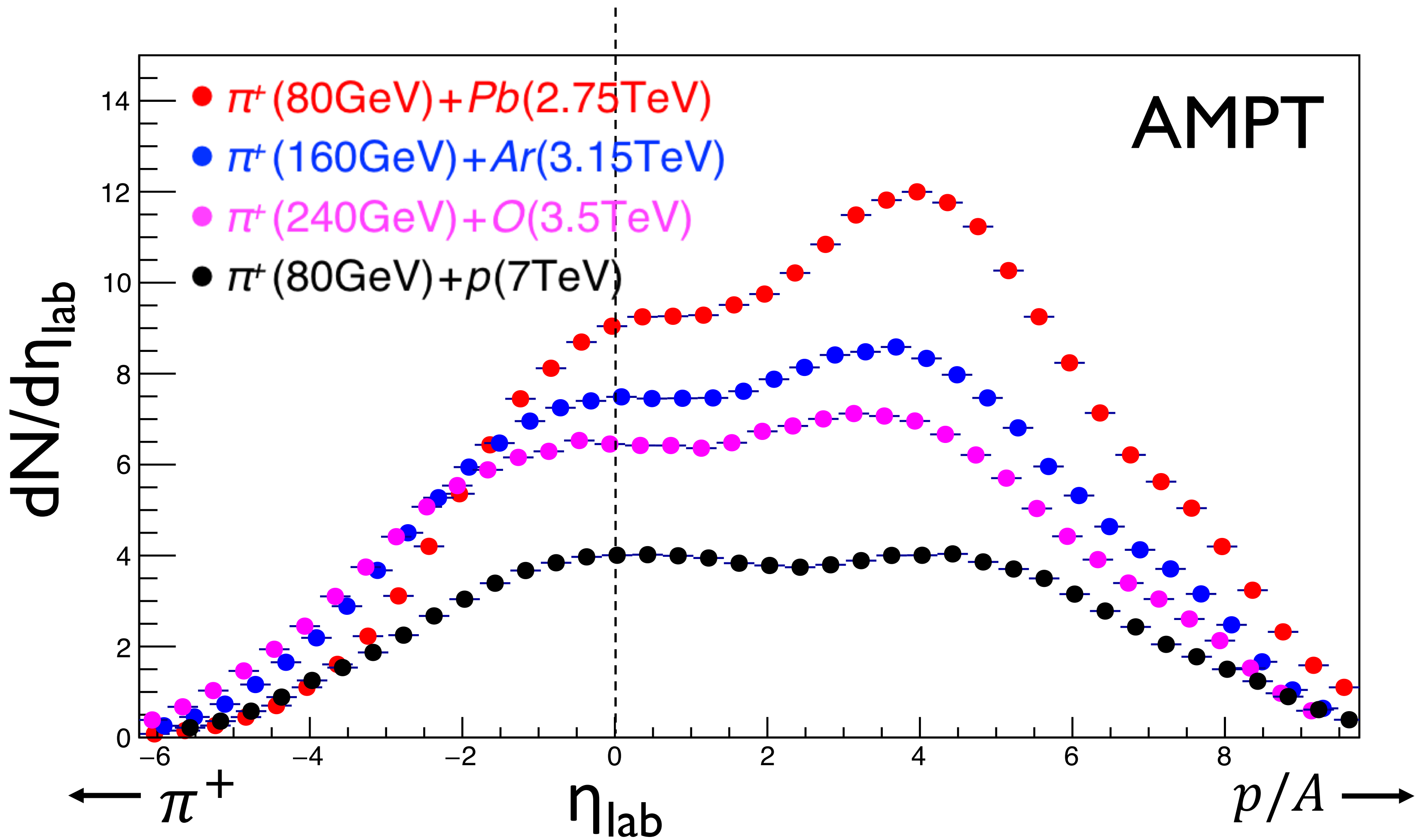


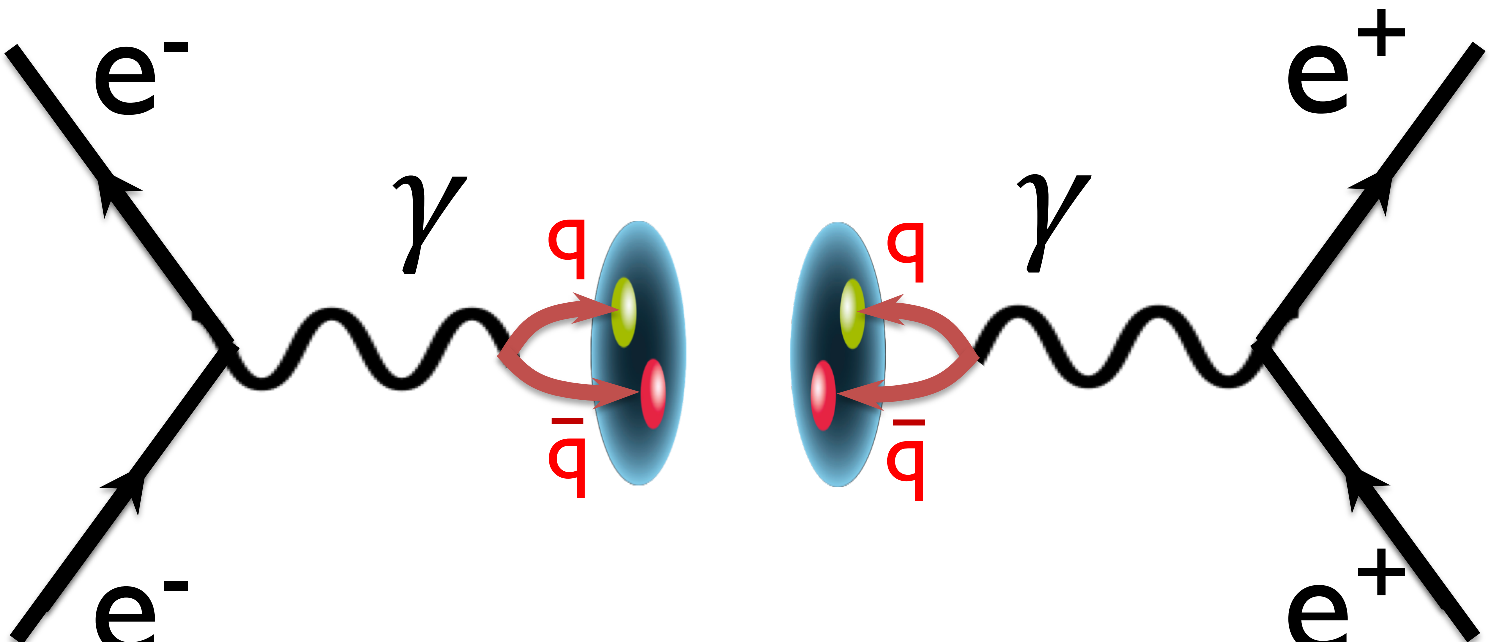


“Hot QCD matter” in UPC AA

Ridge in high-multiplicity UPC?







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