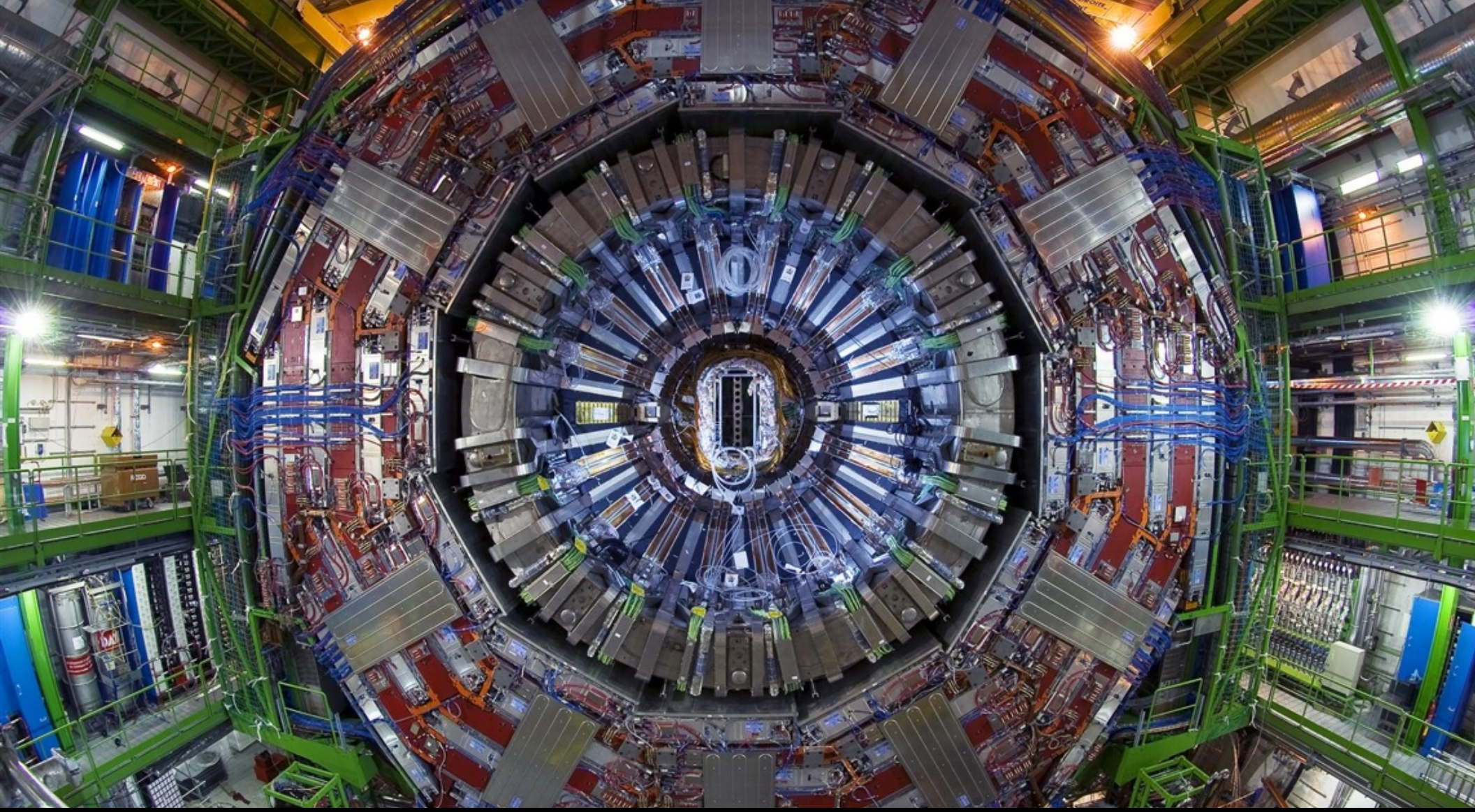


Unveiling the mystery of the hottest QCD matter with the CMS experiment at the LHC

Wei Li, Rice University

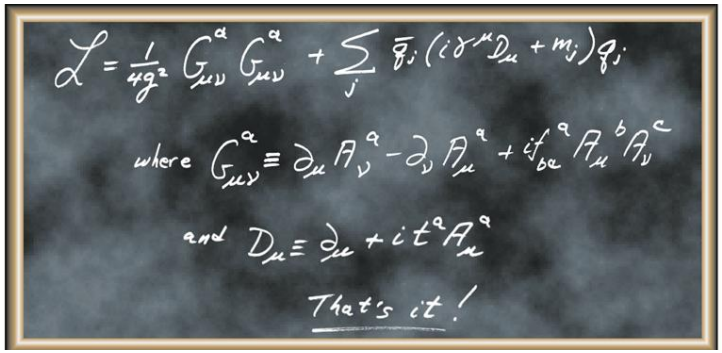
FNAL Wine & Cheese Seminar, October 31, 2014

QCD: a fundamental theory of strong force

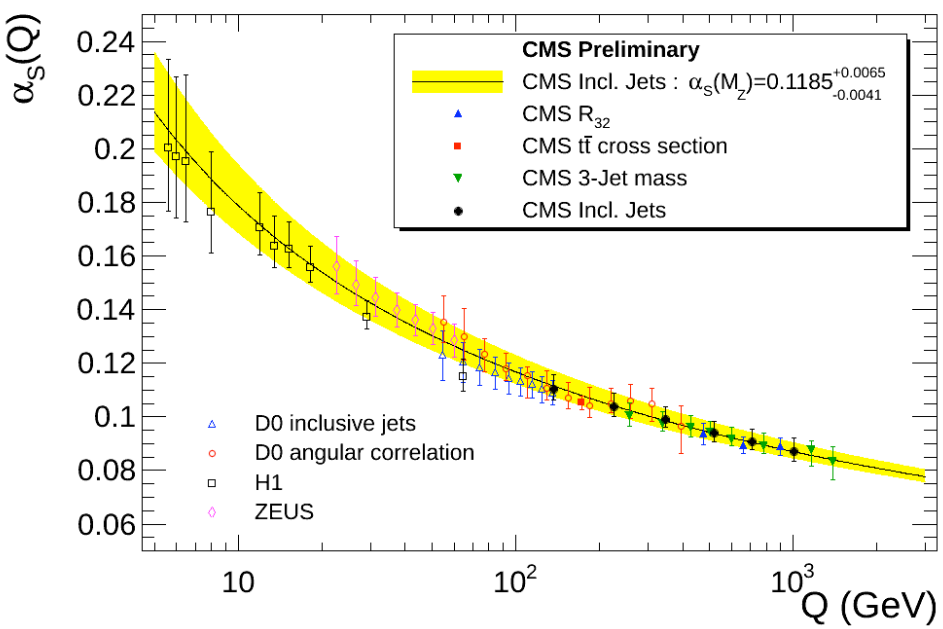
Quarks (and Glue) at the Frontiers of Knowledge

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

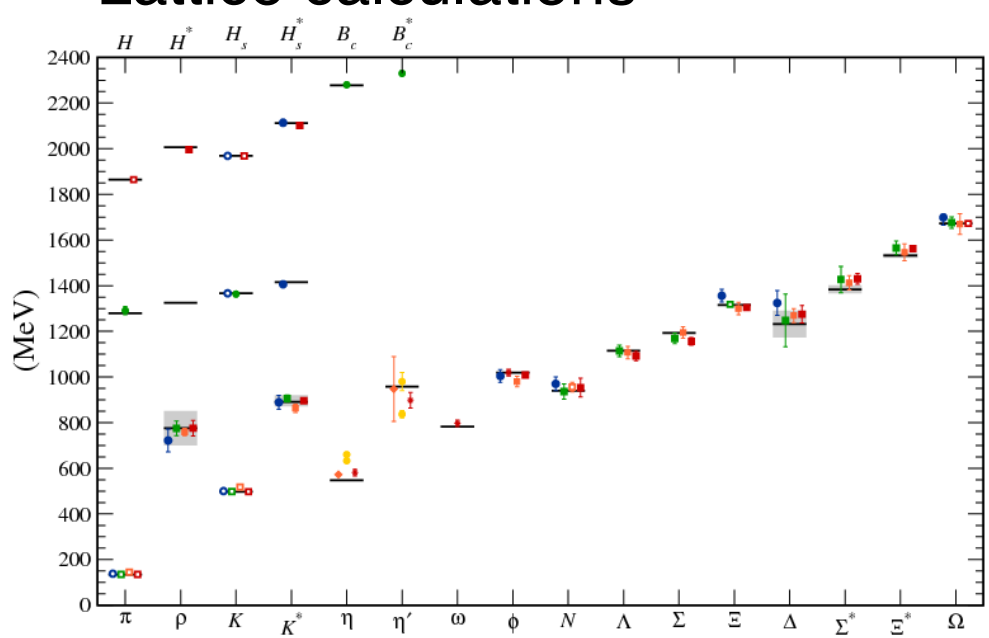
– Frank Wilczek, 2014



Perturbative

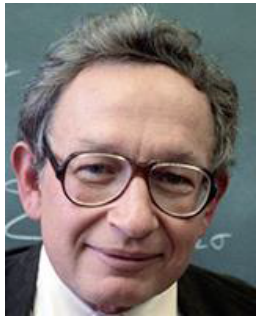


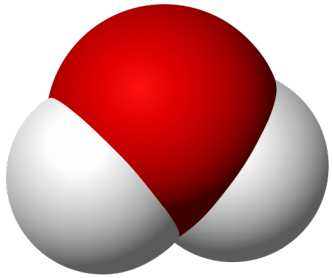
Lattice calculations



Emergent phenomena

"More is different" – P. W. Anderson



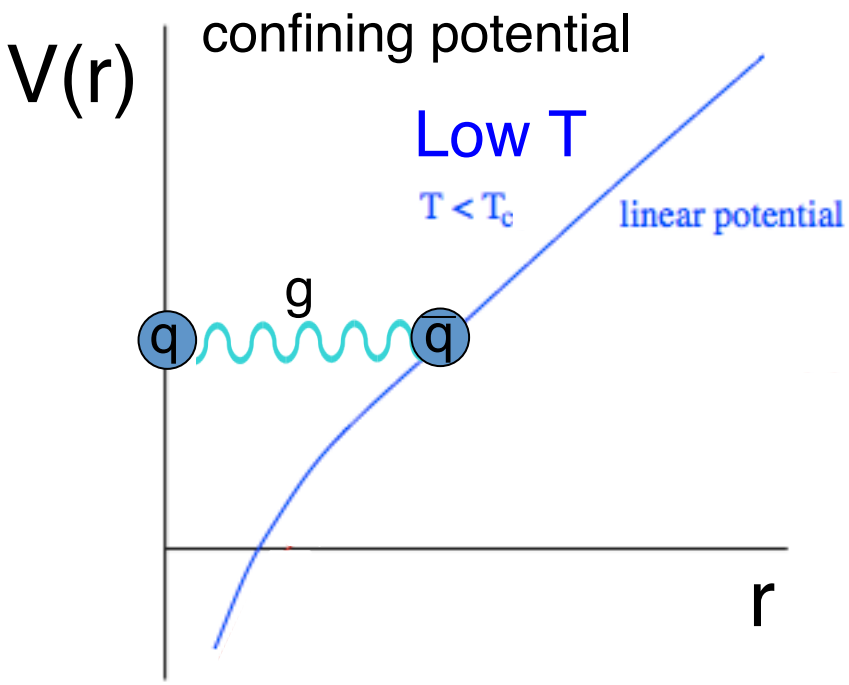


x
1,000,000,000,000,
000,000,000,000 =

Search for and study new emergent phenomena of many-body QCD system are just as fundamental!

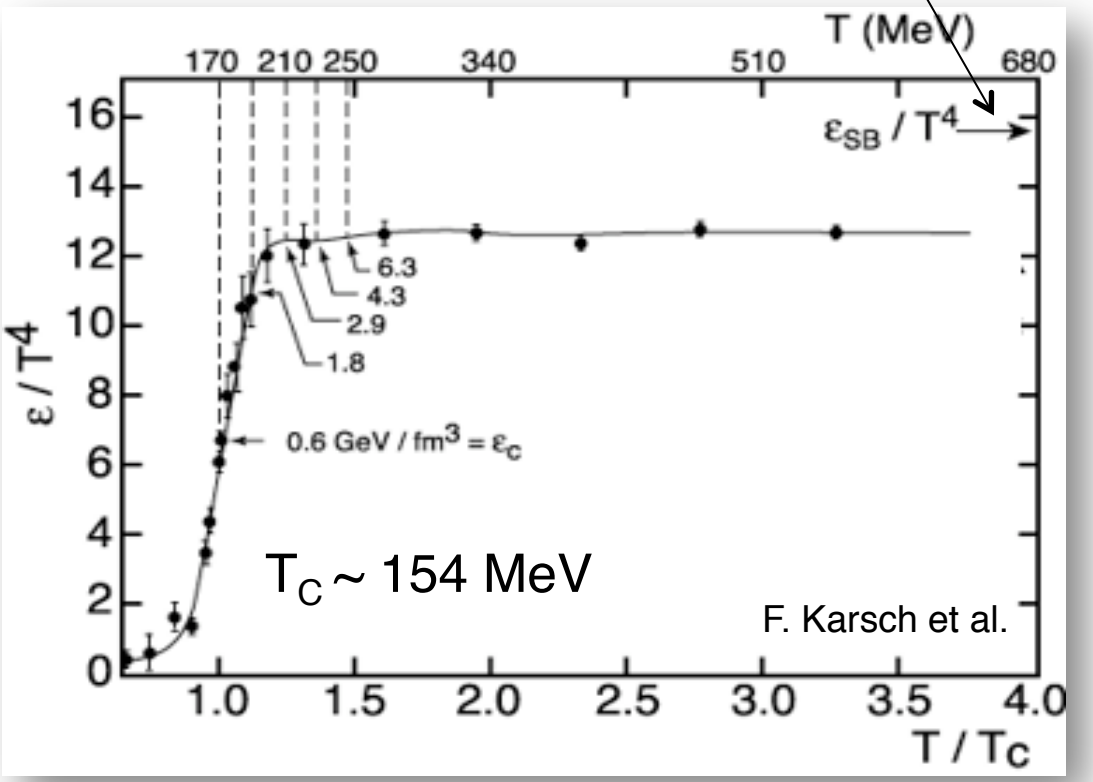
Emergent phenomena of QCD

Lattice QCD calculation



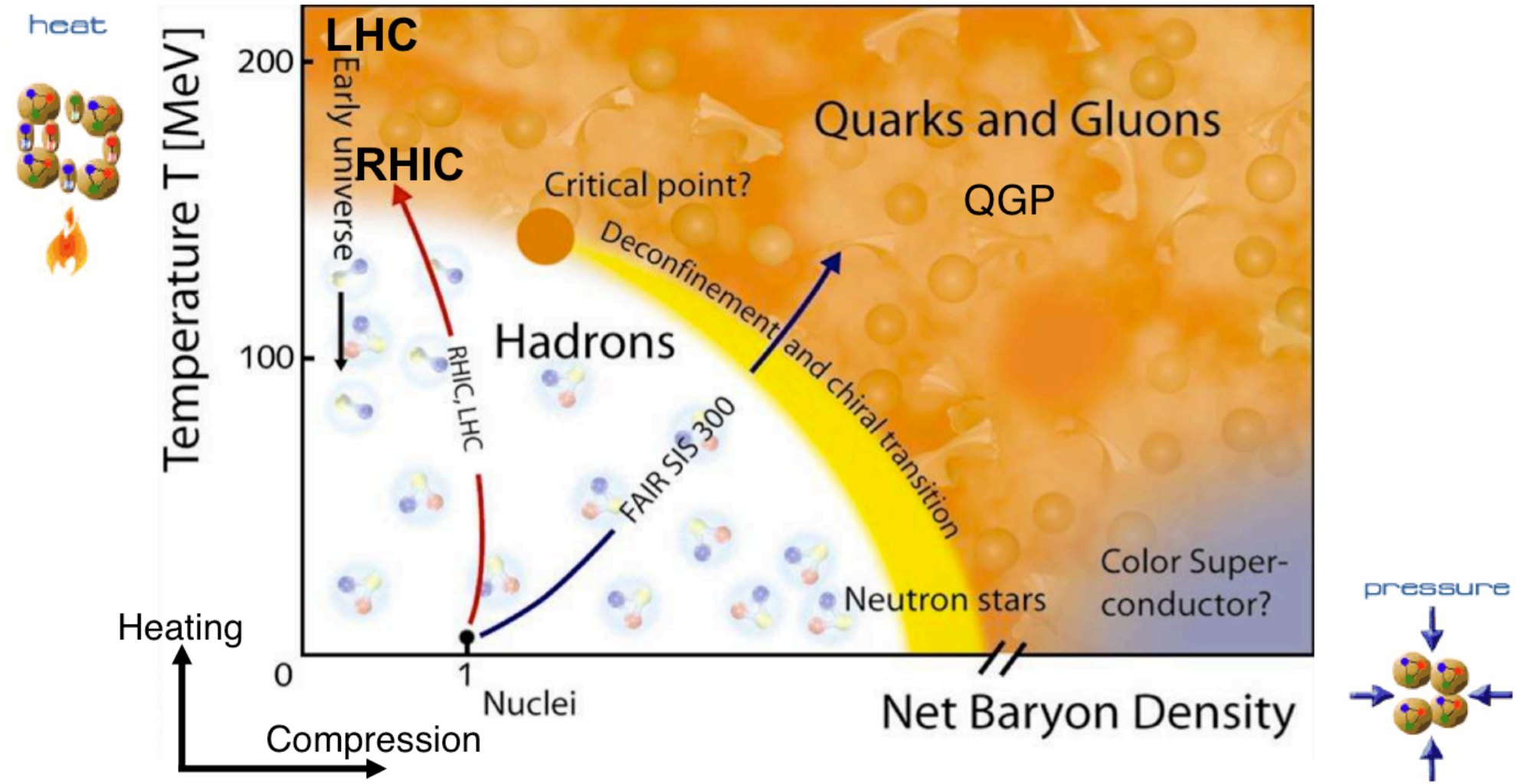
QCD equation of state

"ideal gas" limit



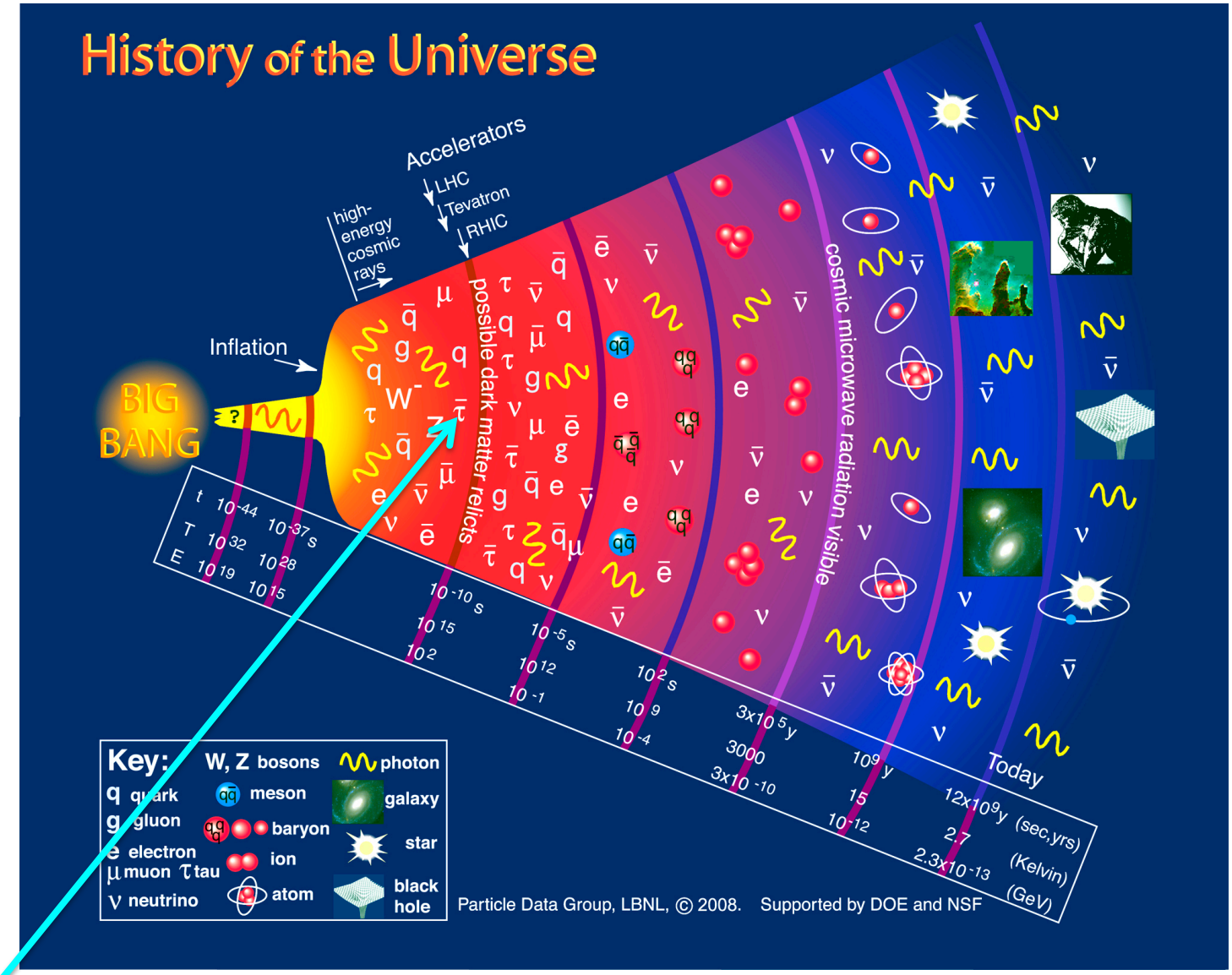
Liberated quarks/gluons at high T (weakly coupled)?

Emergent phenomena of QCD



Identify novel phases of QCD matter (i.e., QGP) and explore their novel properties

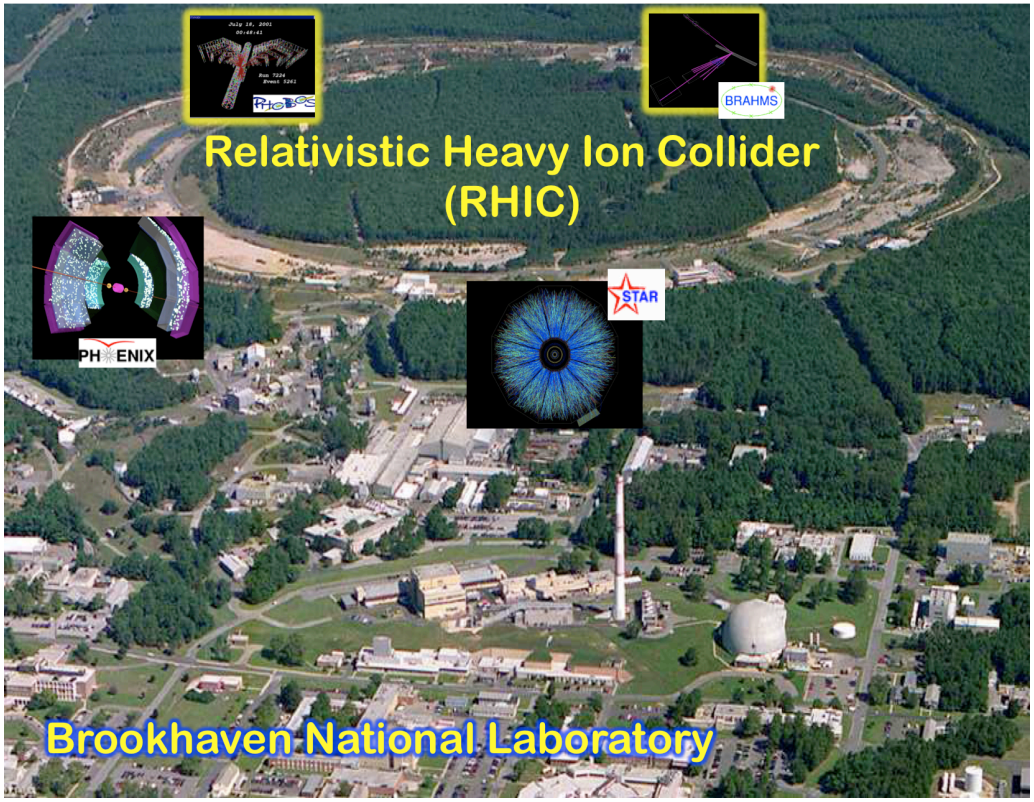
The first moment of the Big Bang



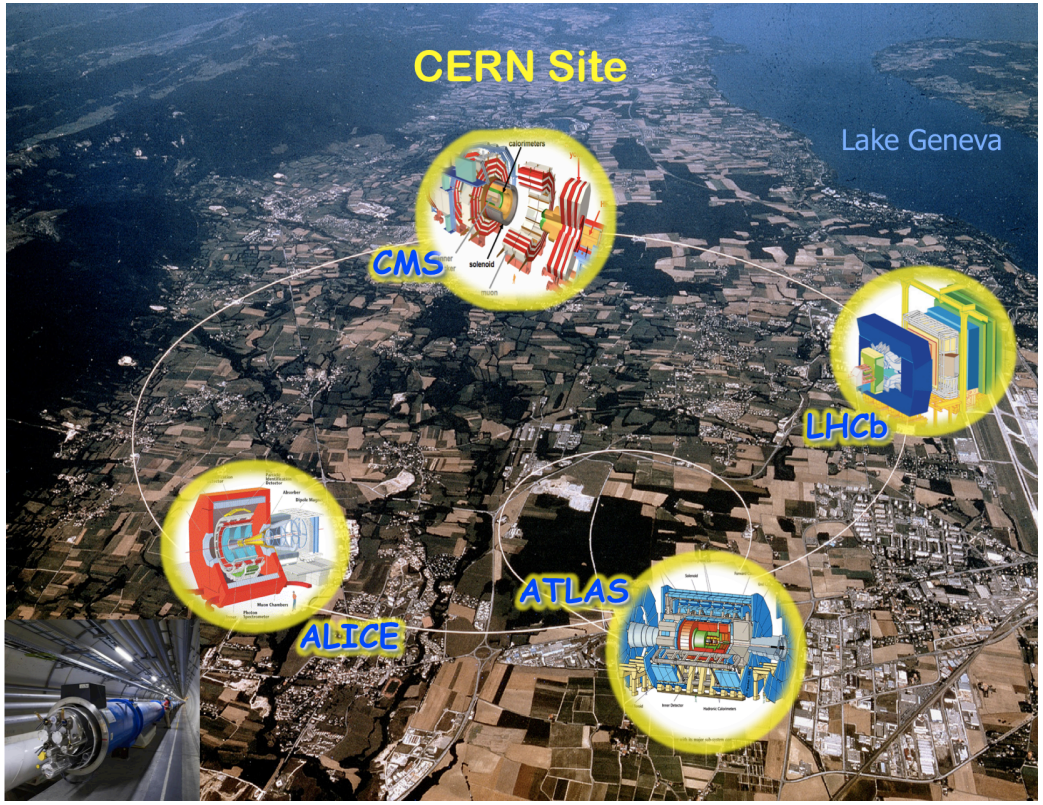
QGP once prevailed a few μs after the Big Bang

Heavy Ion Colliders

RHIC



LHC



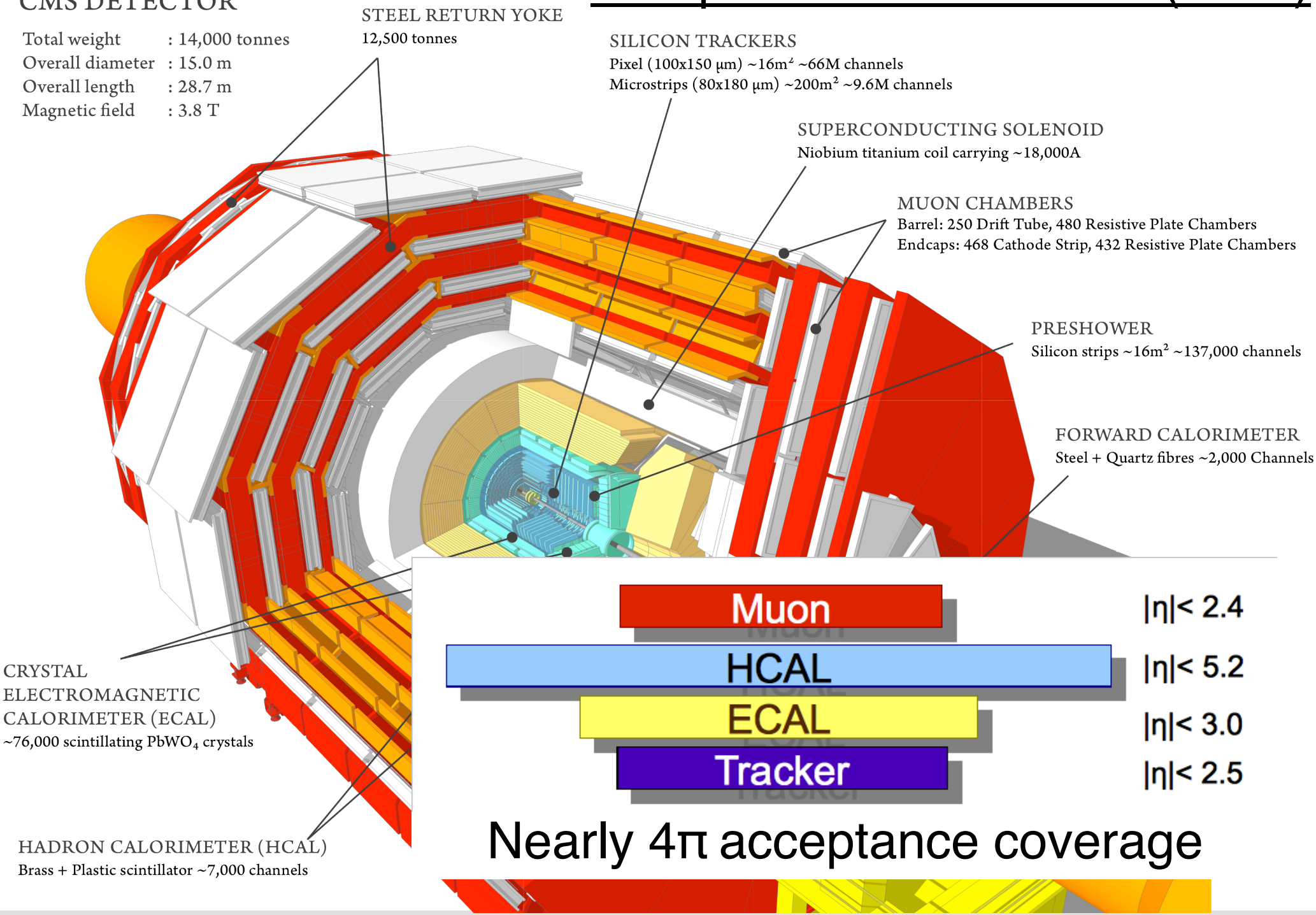
First collisions in 2000

- pp, dAu, CuCu, CuAu, AuAu, UU
- $\sqrt{s_{NN}}$ ~ **7 – 200 GeV**

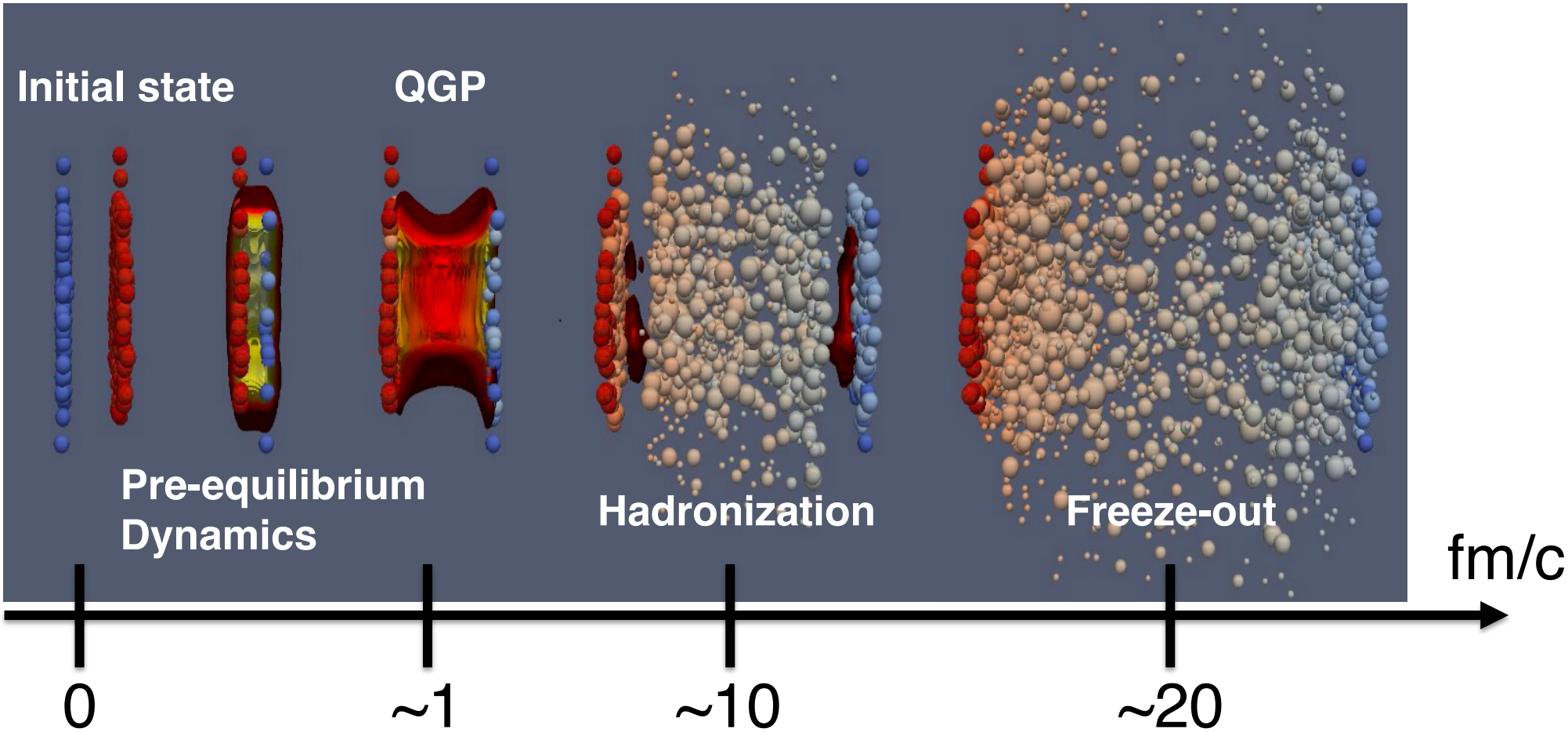
First collisions in 2010

- pp, PbPb, pPb
- $\sqrt{s_{NN}}$ ~ **2.76 TeV** (**5.5 TeV** in 2015-2016)

Compact Muon Solenoid (CMS)

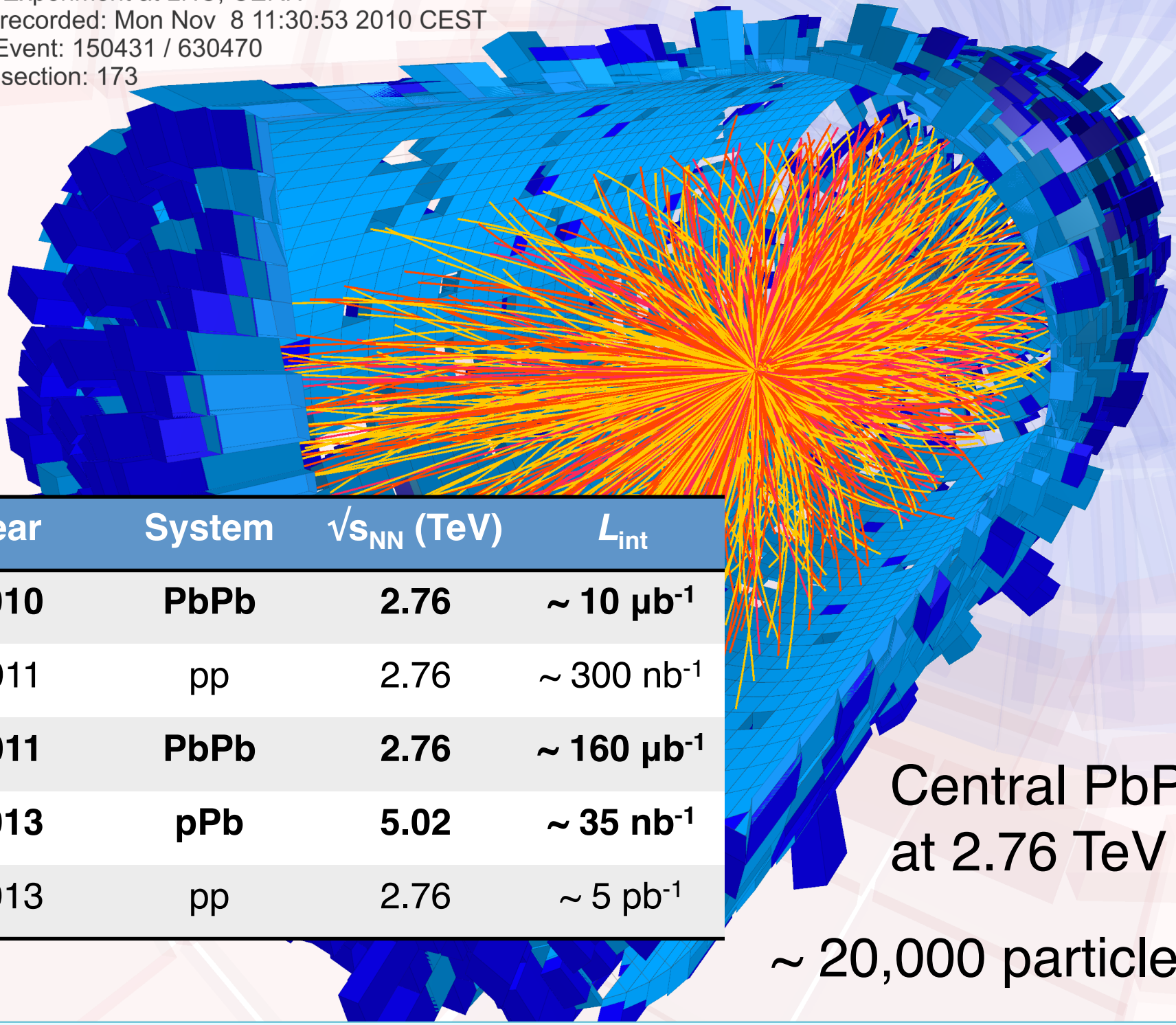


Evolution of a Heavy Ion Collision



Visualization: madai.us

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173



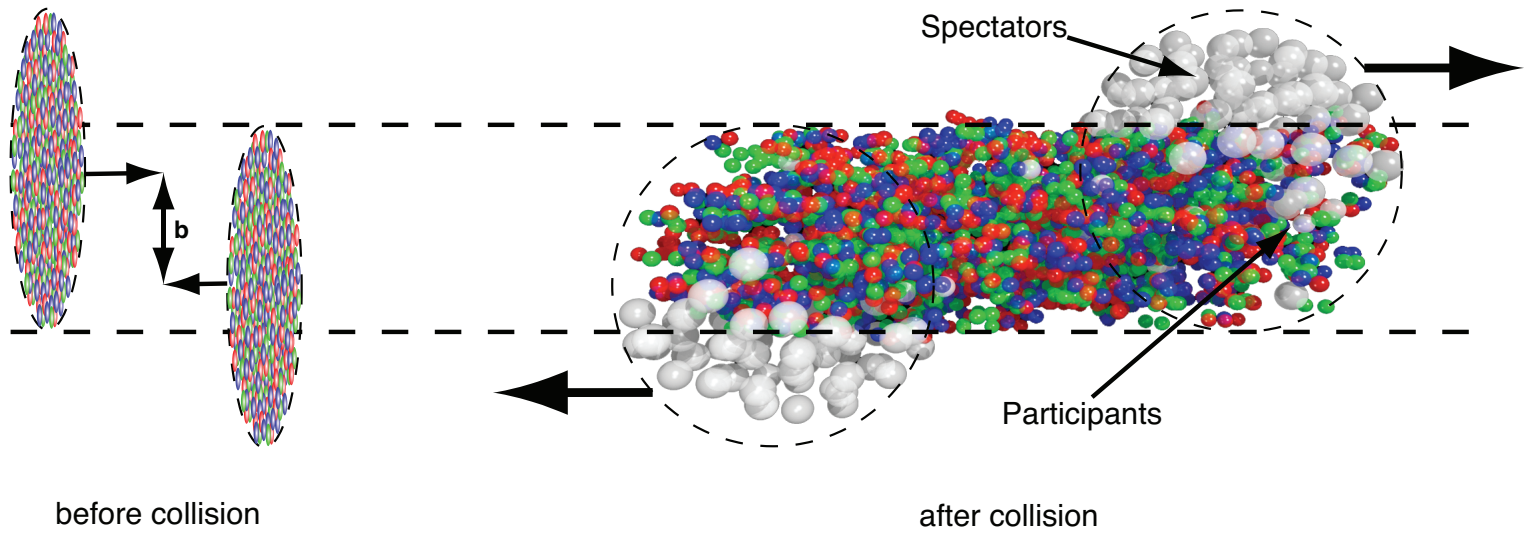
Year	System	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**PbPb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 300 nb^{-1}
2011	**PbPb**	**2.76**	**~ 160 μb^{-1}**
2013	**pPb**	**5.02**	**~ 35 nb^{-1}**
2013	pp	2.76	~ 5 pb^{-1}

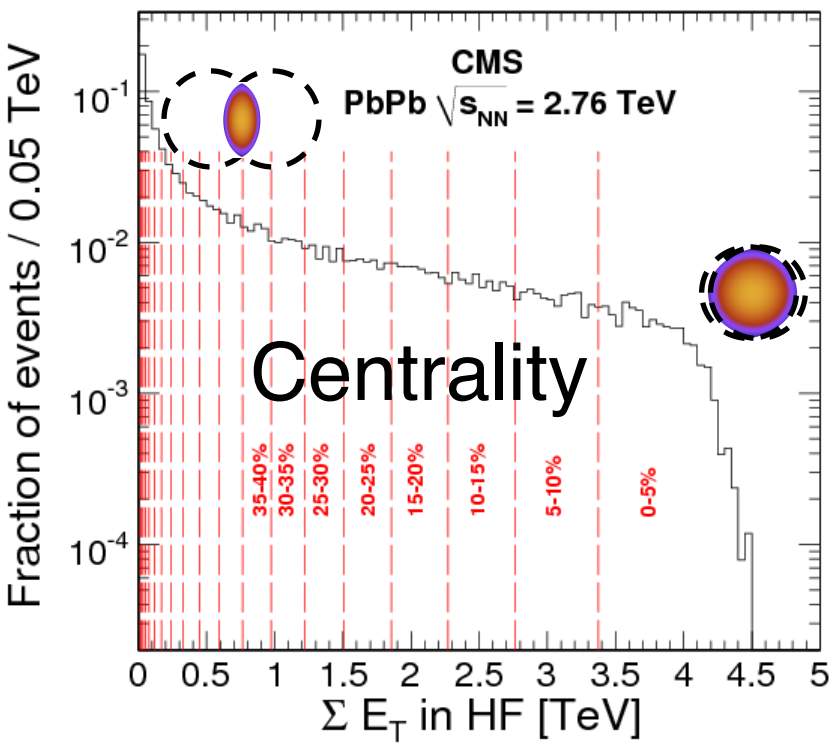
Central PbPb at 2.76 TeV

~ 20,000 particles!

see our webpage at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

QGP nomenclatures





From Glauber model:

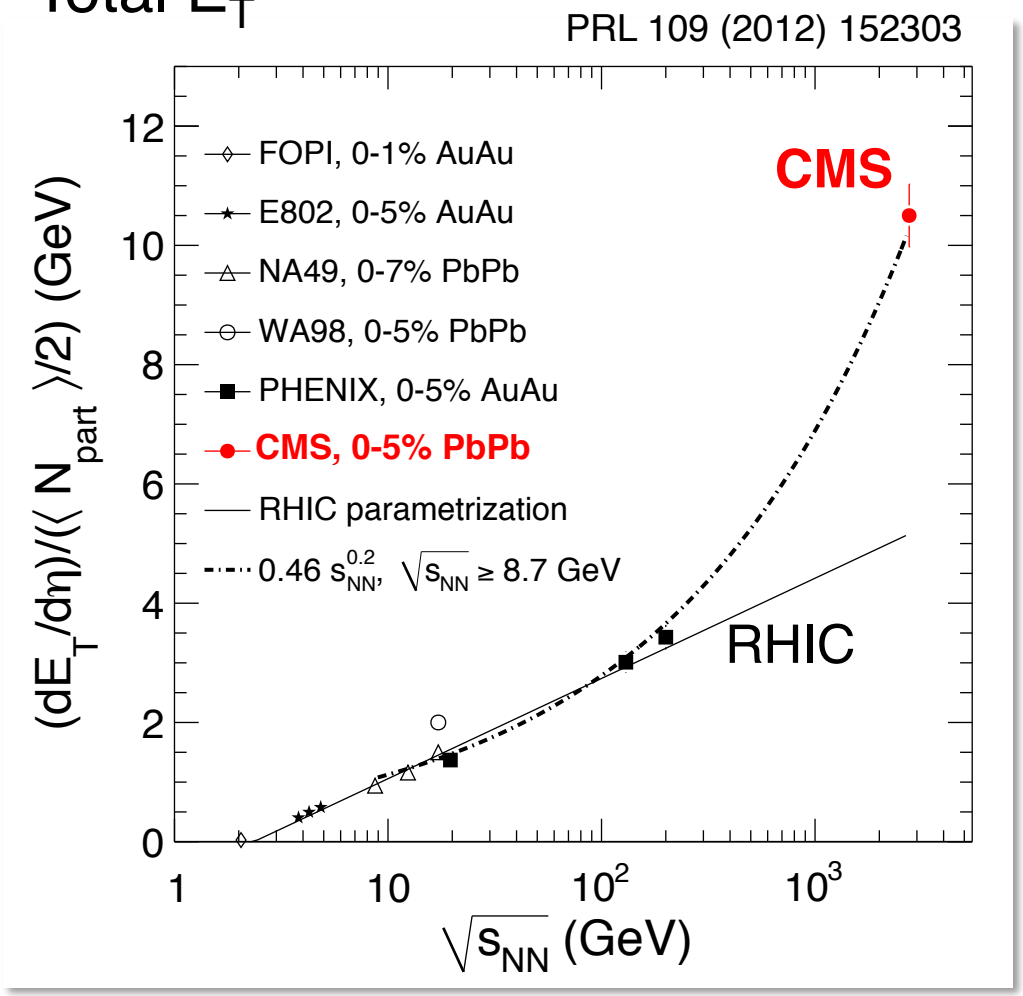
– N_{part}: # of wounded nucleons

(2×208 for exact head-on)

0% means most central collisions

Have we found the QGP yet?

Total E_T



Very likely!

$$\varepsilon(\mathrm{LHC}) = \frac{E_T}{\mathrm{volume}}$$

$$\approx \frac{2\ \mathrm{TeV}}{\pi \times (7\mathrm{fm})^2 \times 1\mathrm{fm}} \approx 13\ \mathrm{GeV/fm}^3$$

$$\sim 3 \times \varepsilon(\mathrm{RHIC})$$

$$>> \varepsilon_c \sim 0.6\ \mathrm{GeV/fm}^3$$

More strikingly: how the QGP behaves

BROOKHAVEN NATIONAL LABORATORY Newsroom Media & Communications Office

RHIC Scientists Serve Up "Perfect" Liquid

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

Monday, April 18, 2005

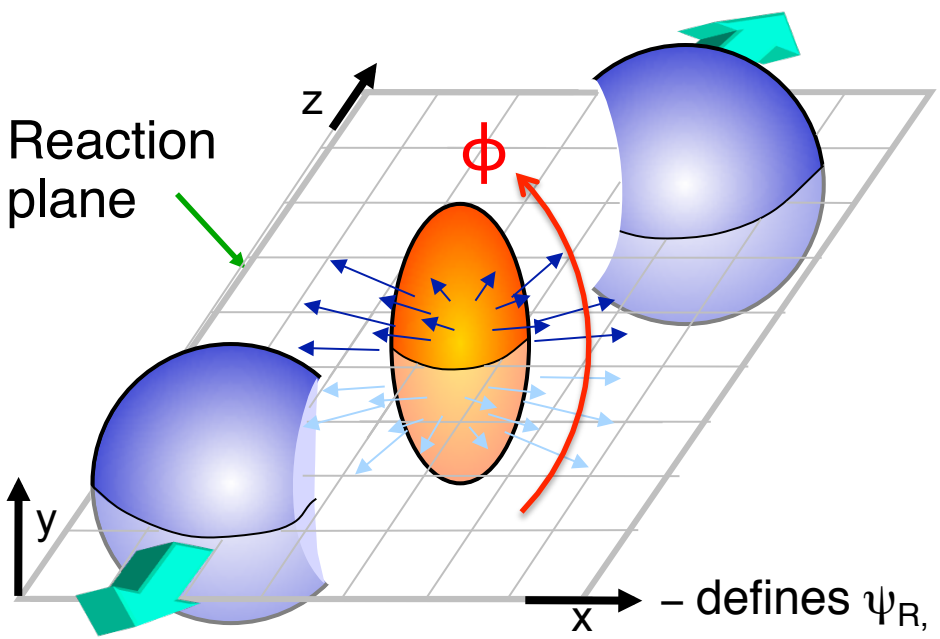
TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Paradigm of a nearly "perfect" fluid:

The QGP behaves like a liquid with almost zero frictional dissipation (viscosity) that flows better than any known matter.

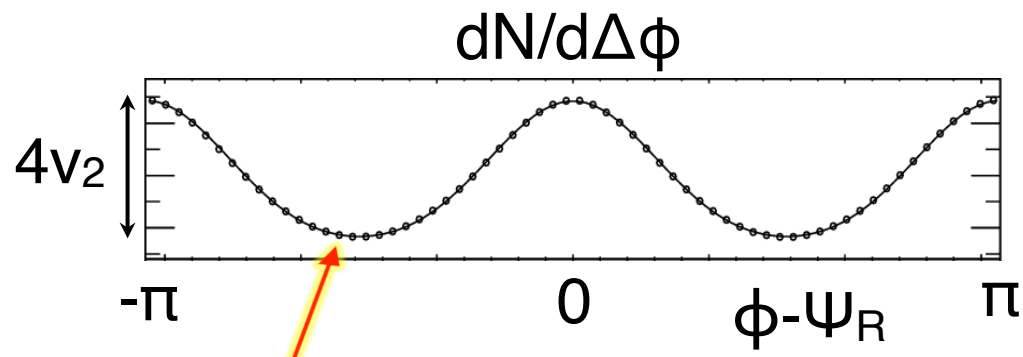
Elliptic flow

Initial-state asymmetry:



– defines ψ_R,
(direction of the impact parameter)

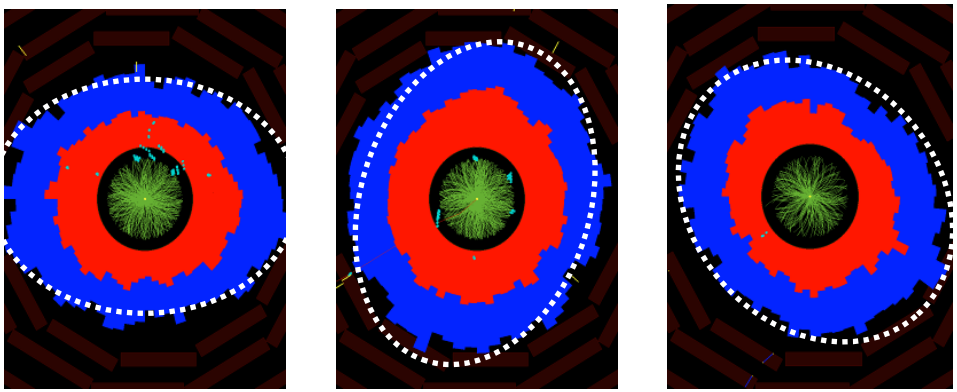
Final-state anisotropy:



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

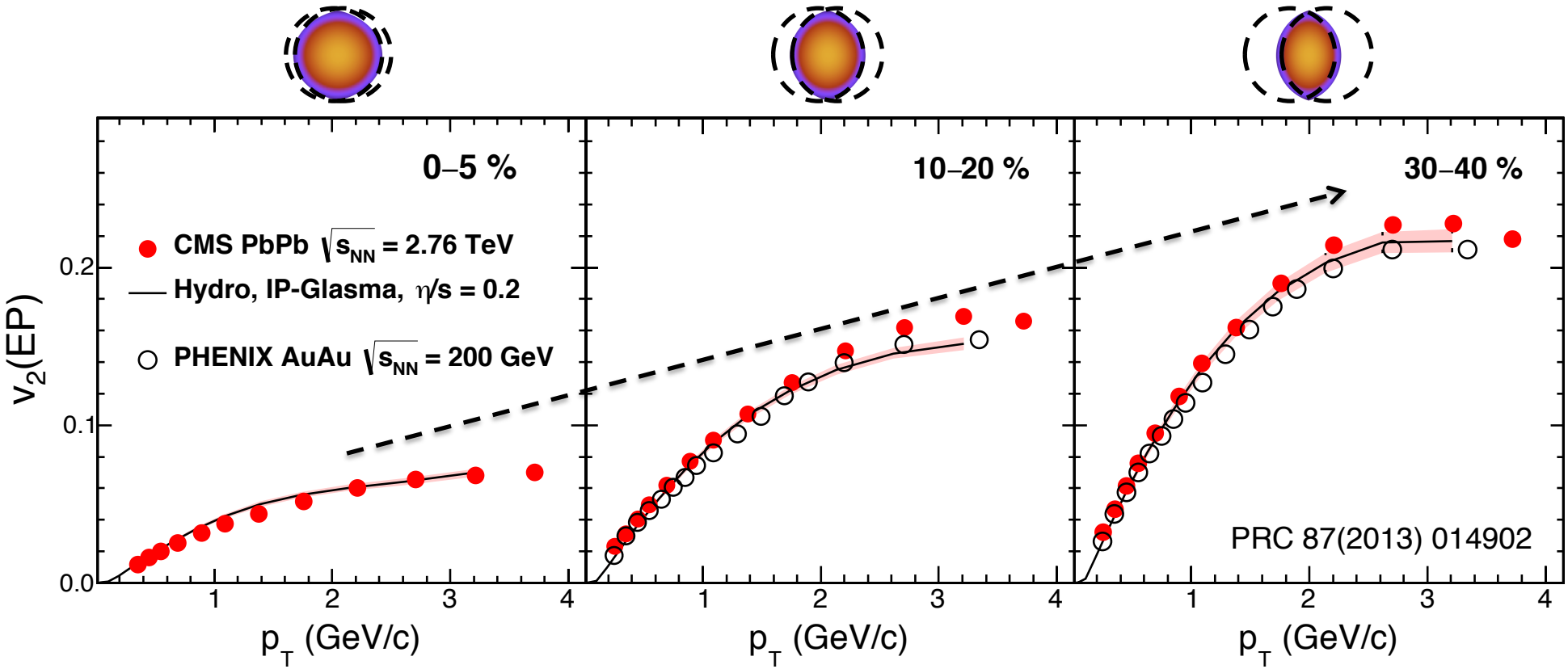
"elliptic flow"

CMS event displays



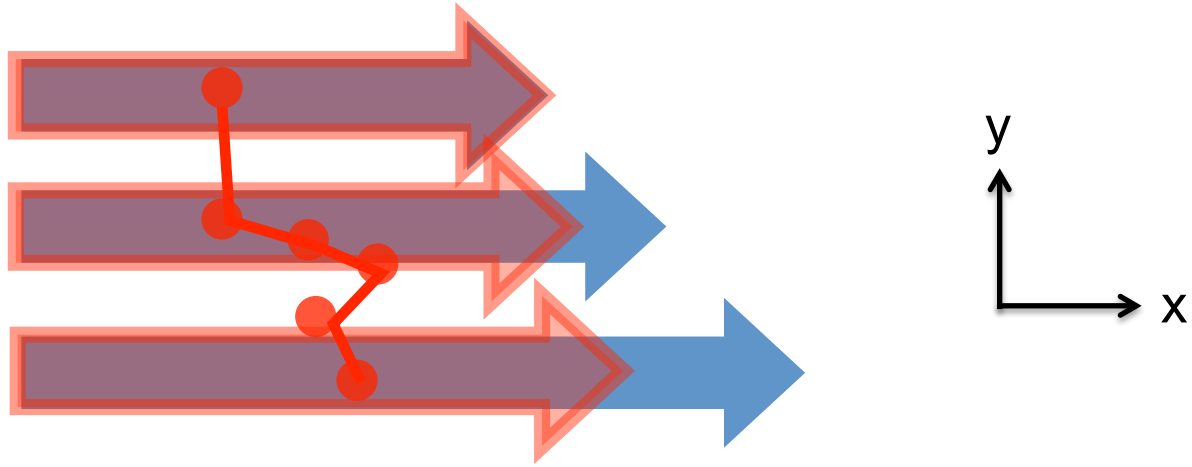
Elliptic flow

Charged particle v_2



- v_2 driven by initial lenticular geometry
- Described by hydrodynamic with ***small η/s ~ 0.2 (shear viscosity)***

A quick review of viscosity …



Shear viscosity: momentum dissipation
→ less elliptic flow

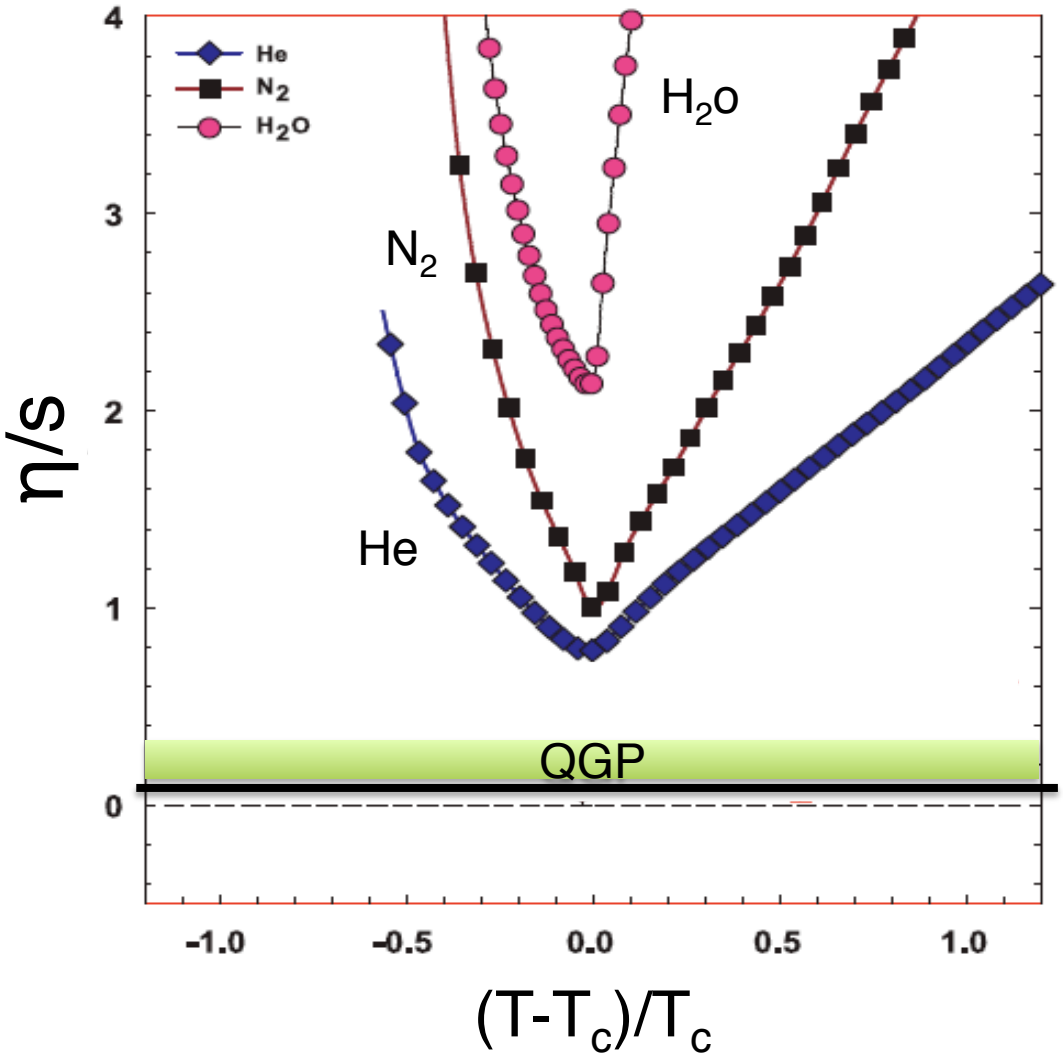
Kinetic theory:

$$\eta/s \sim \lambda_{mfp} \text{ (mean free path)}$$

Ideal gas: $\lambda_{mfp} \to \infty$, $\eta/s \to \infty$

Perfect liquid: $\lambda_{mfp} \to 0$, $\eta/s \to 0$

How “perfect” is the QGP liquid?



Conjectured viscosity bound from AdS/CFT

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$

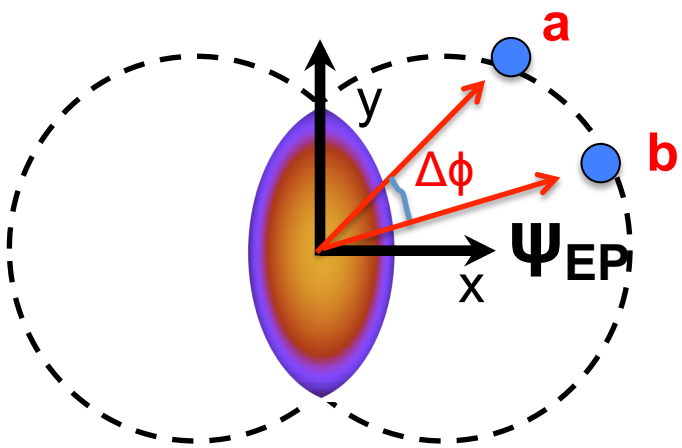
Kovtun-Son-Starinets (KSS) bound

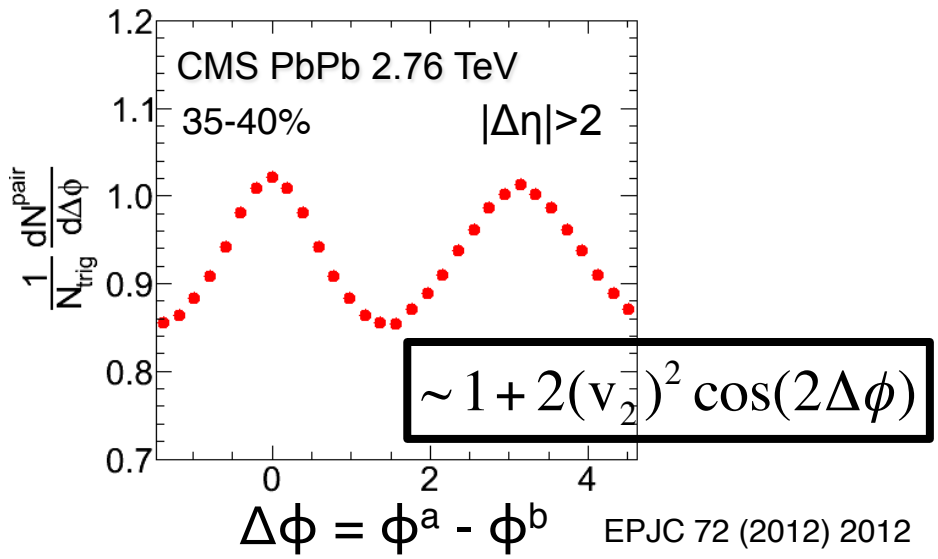
PRL 94 (2005) 111601

string theory at work!

Next: precisely measure η/s of QGP liquid

Flow, two-particle correlations, ridge …



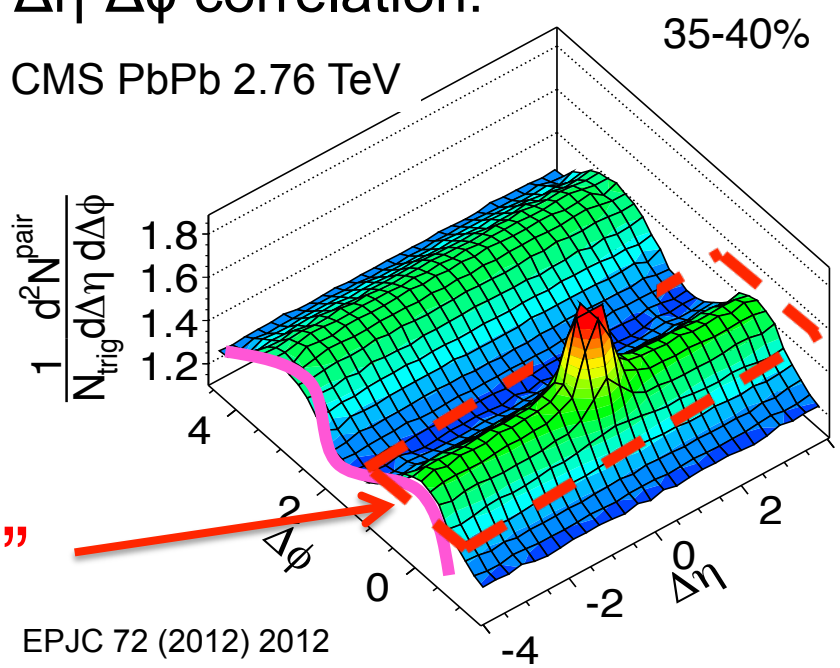


EPJC 72 (2012) 2012

Elliptic flow is long-range in pseudorapidity (η)

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

Δη-Δϕ correlation:



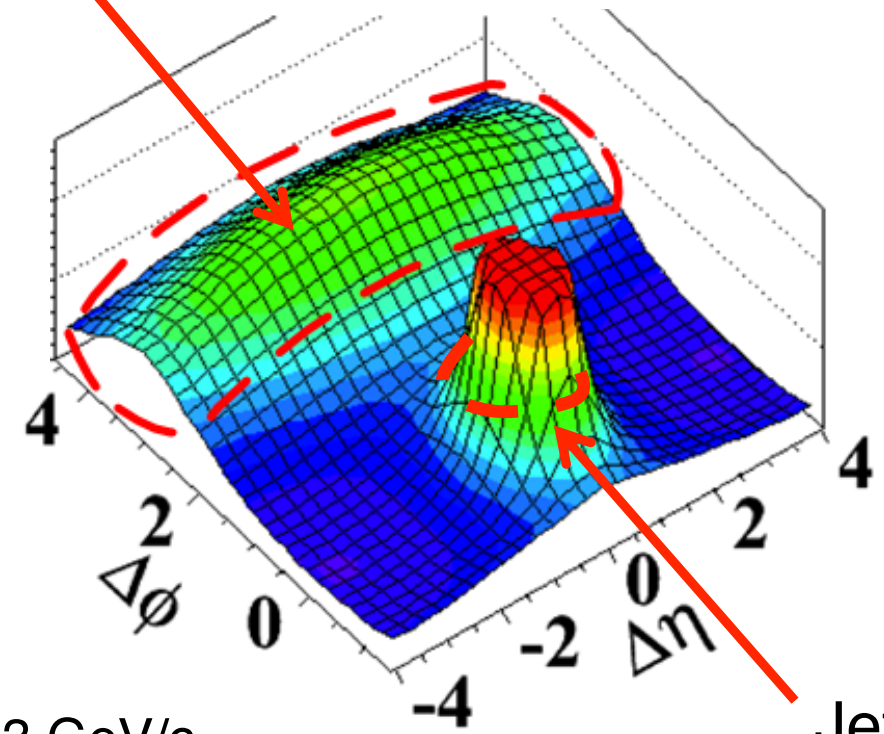
Near-side "ridge"

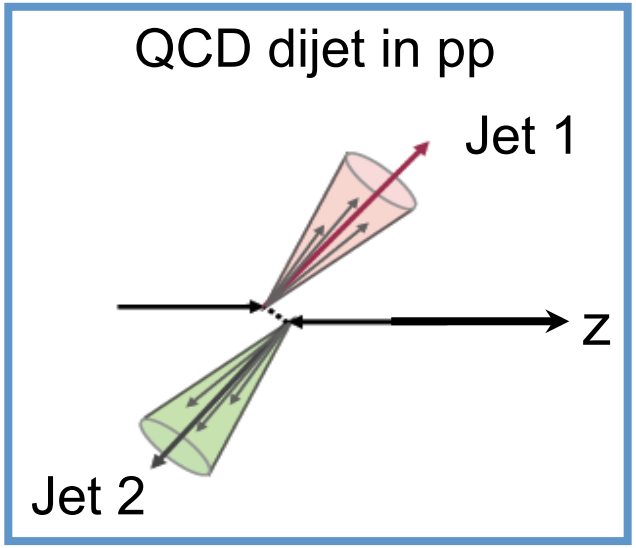
EPJC 72 (2012) 2012

Two-particle $\Delta\eta$-$\Delta\phi$ correlations

Away-side "ridge" ($\Delta\phi \sim \pi$)

CMS Minimum Bias pp 7TeV



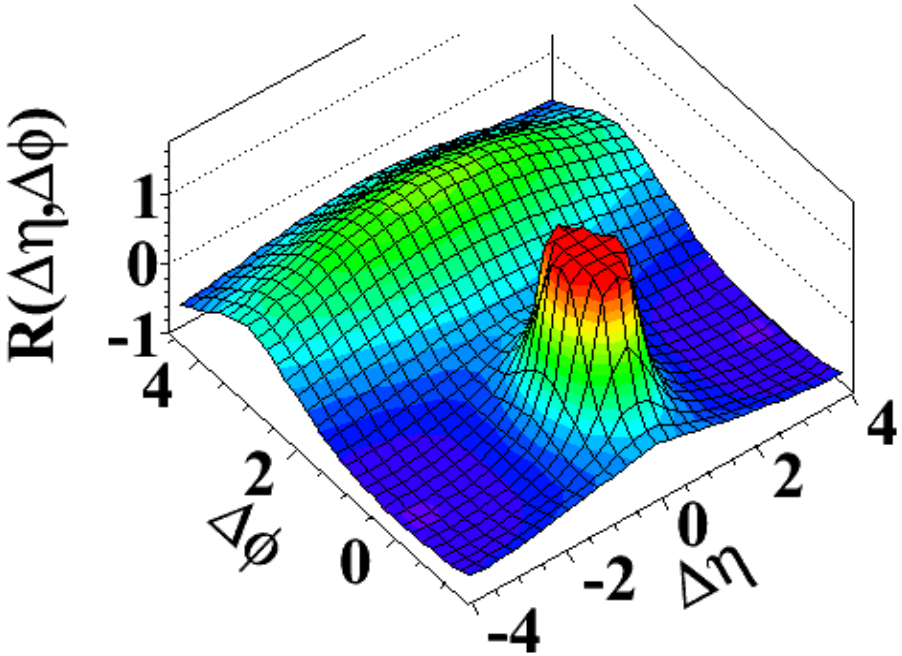


Jet peak ($\Delta\phi \sim 0$)

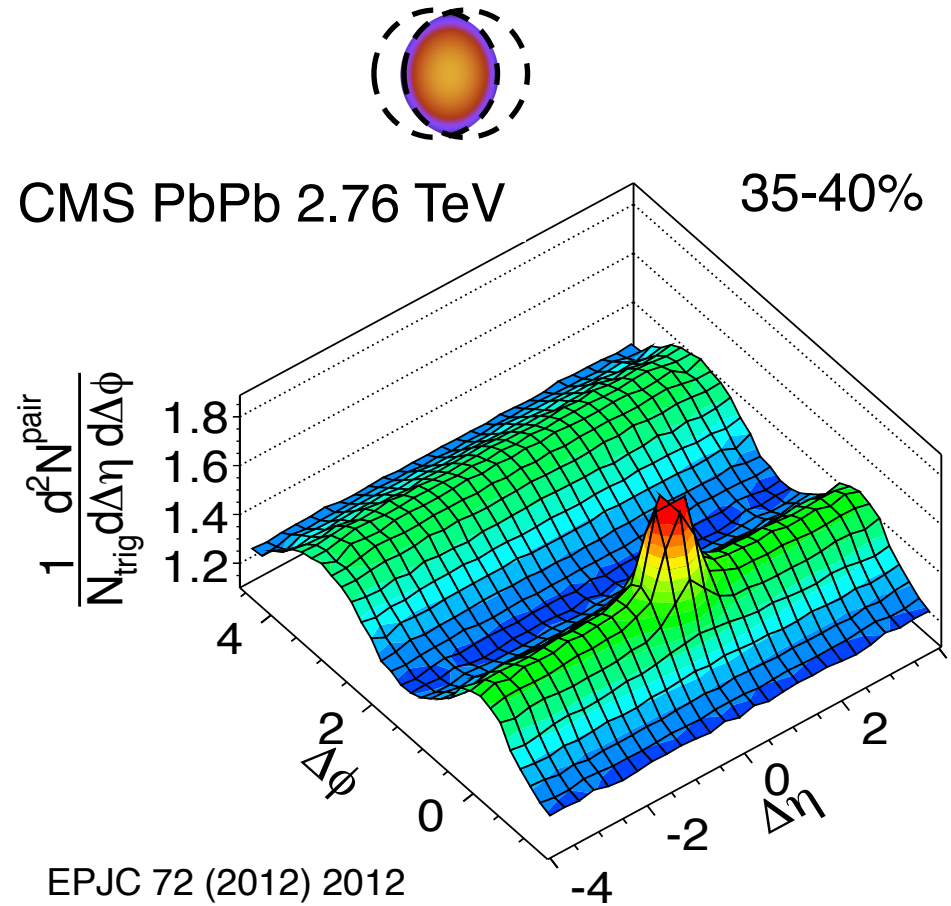
$1 < p_T^a, p_T^b < 3$ GeV/c

$$\Delta\eta = \eta^a - \eta^b$$
$$\Delta\phi = \phi^a - \phi^b$$

Two-particle Δη-Δφ correlations



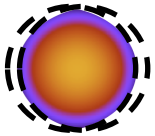
No near-side "ridge" in pp!

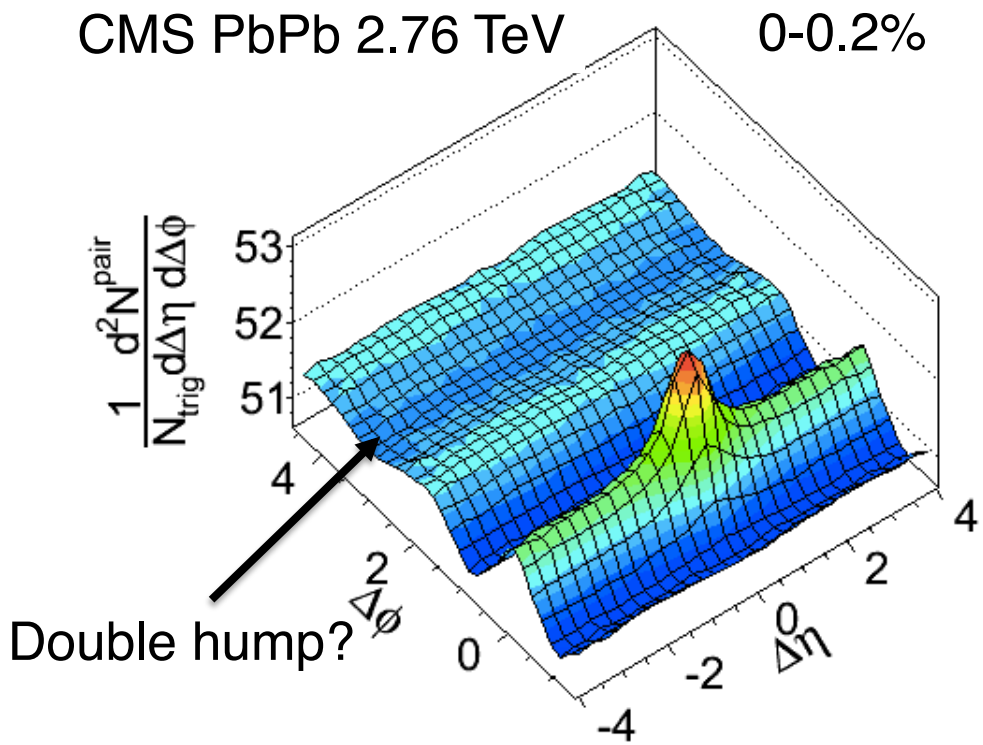


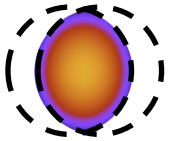
EPJC 72 (2012) 2012

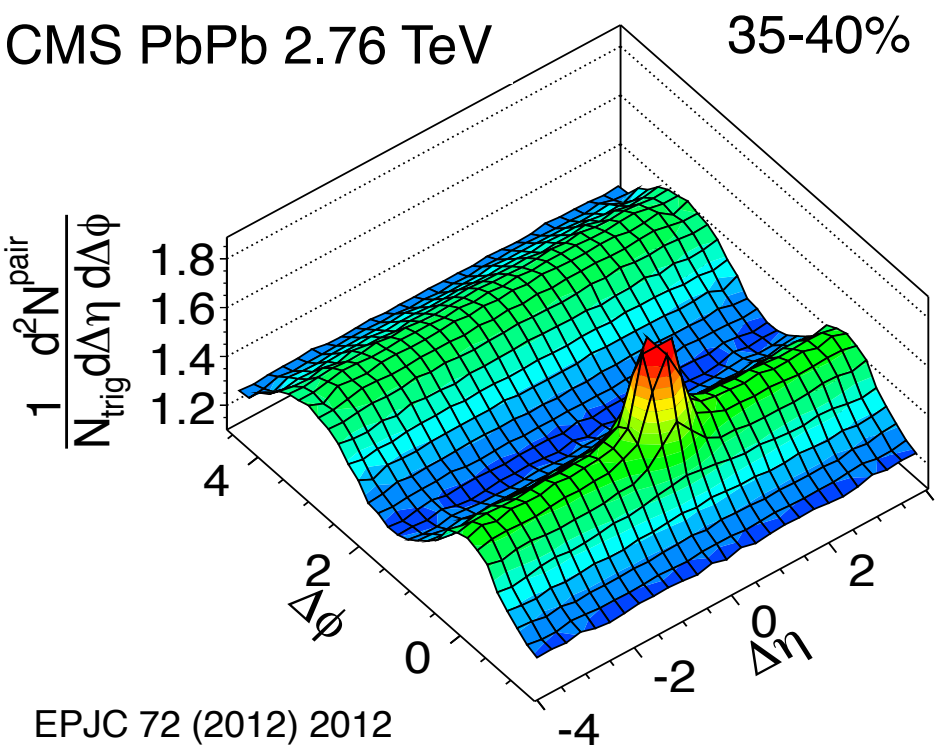
Near-side "ridge" is a new phenomenon in AA!

Two-particle Δη-Δφ correlations

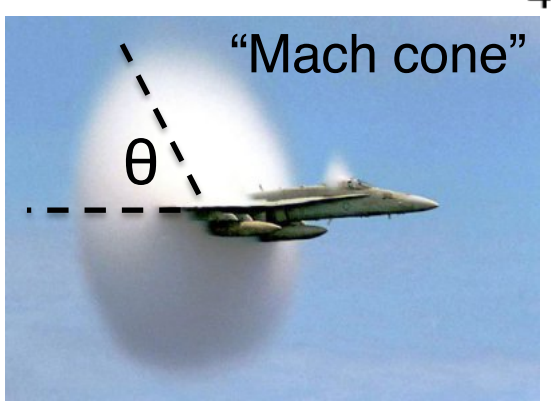








EPJC 72 (2012) 2012



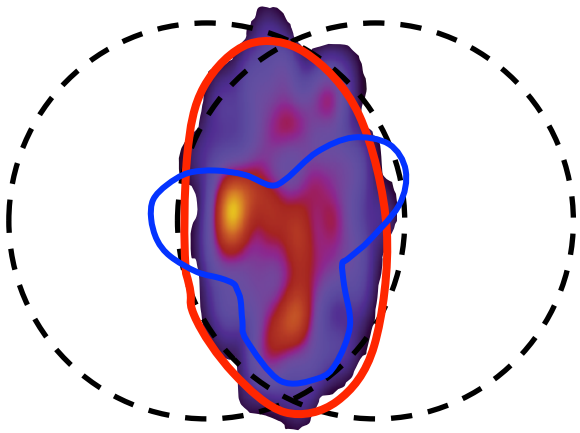
Velocity of sound

$c_s = \sin\theta \bullet c$

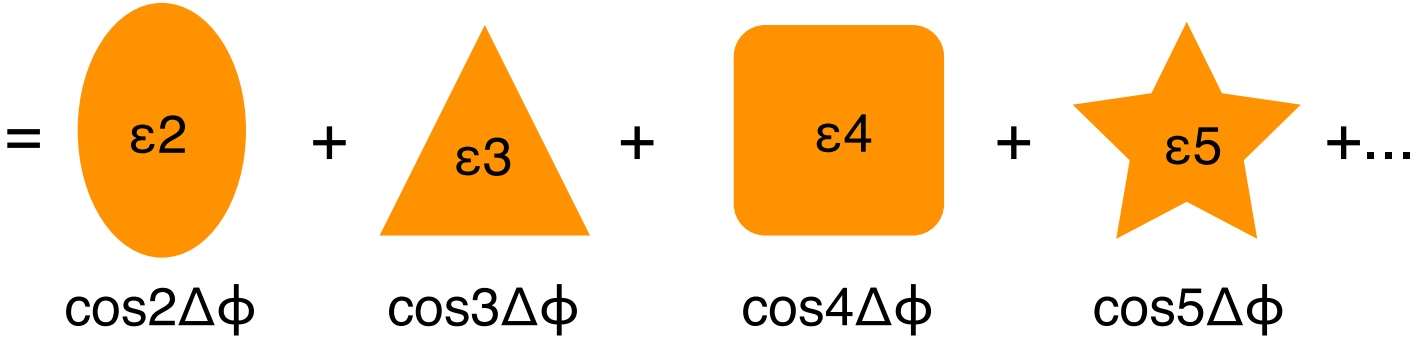
Shock wave?!

But maybe too good to be true …

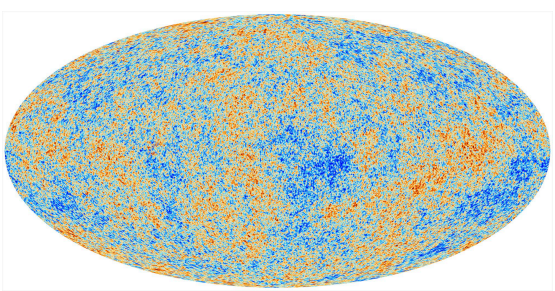
“Noise” of initial QGP shape

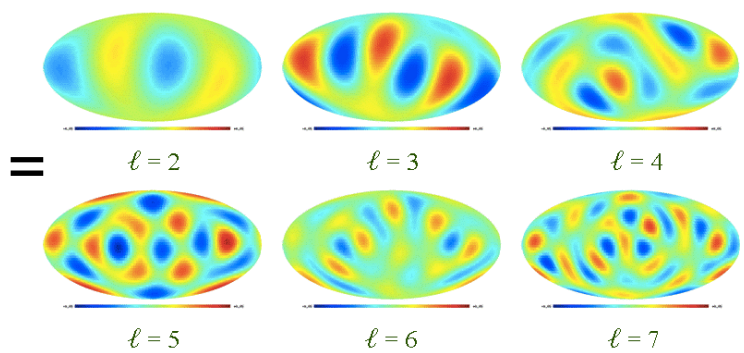


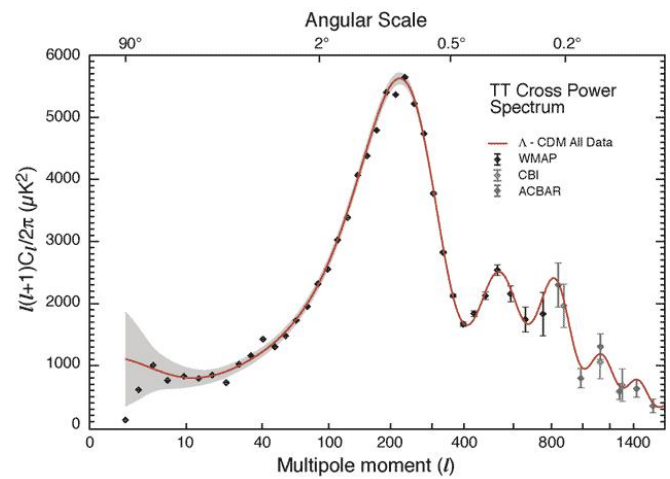
Higher multipoles in initial “QGP shape”



In analogy to CMB power spectrum

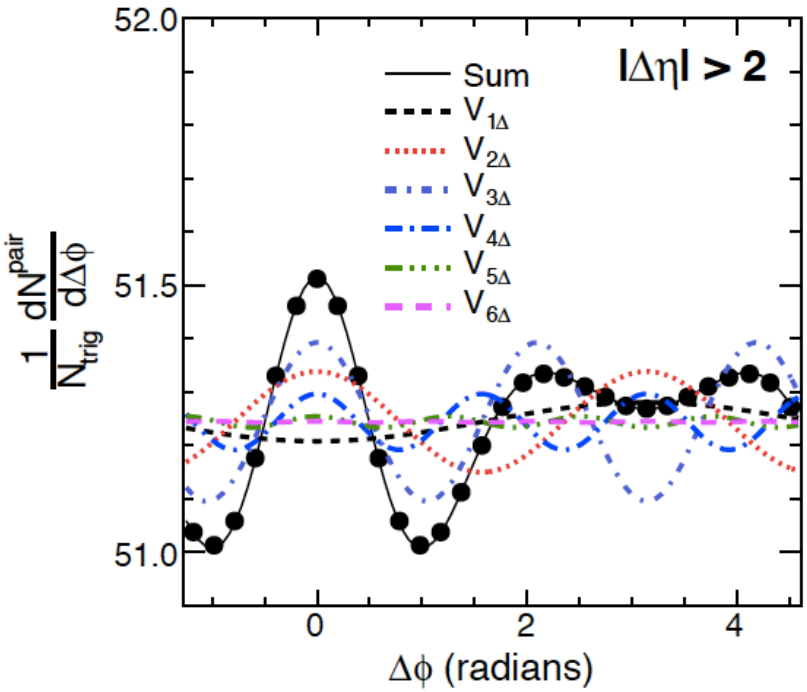






“Noise” of initial QGP shape

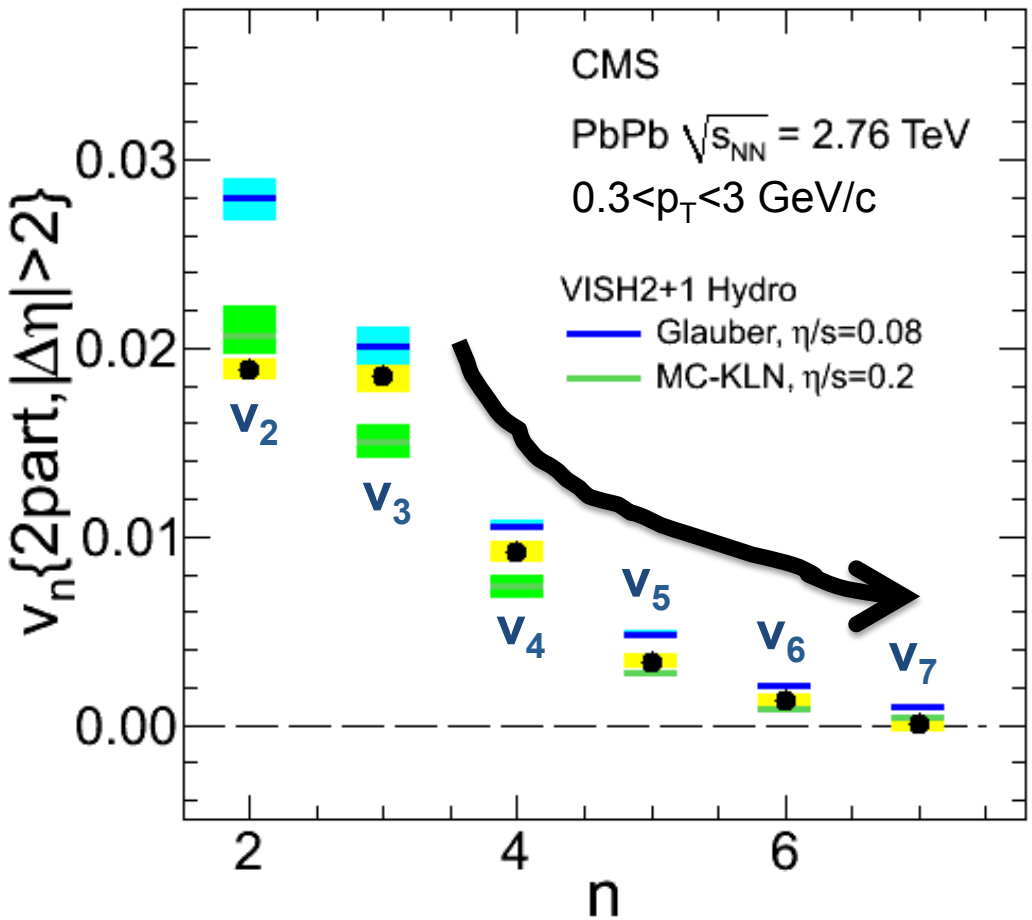
QGP inhomogeneity



“mini-bang” power spectrum

Top 0.2% central

JHEP 02 (2014) 088

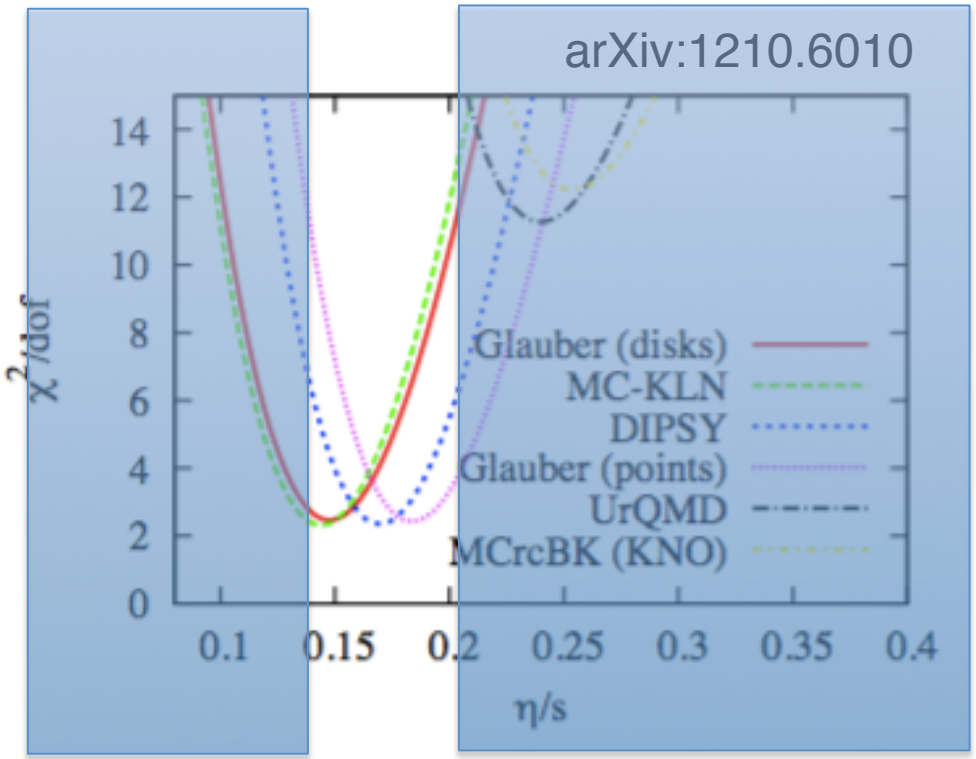


Fourier analysis:

$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2V_{1\Delta}\cos(\Delta\phi) + 2V_{2\Delta}\cos(2\Delta\phi)$$

$$+ 2V_{3\Delta}\cos(3\Delta\phi) + 2V_{4\Delta}\cos(4\Delta\phi) + \ldots$$

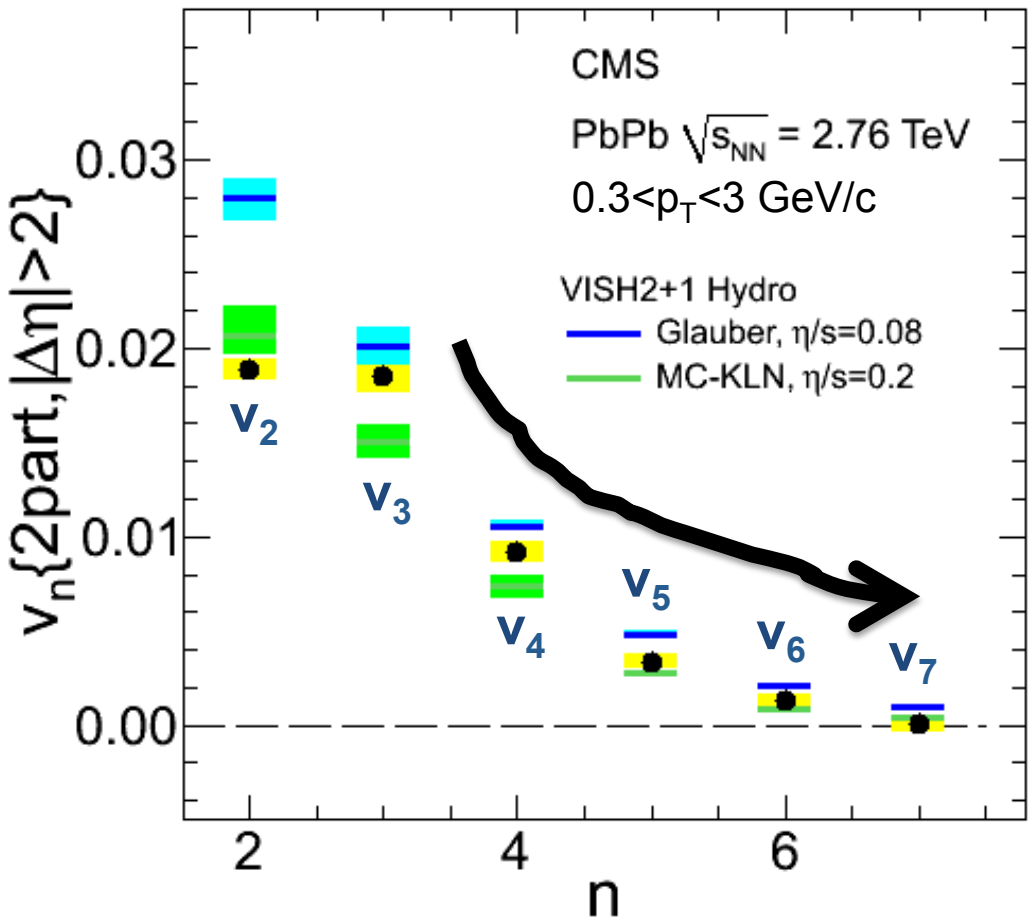
“Noise” of initial QGP shape



“mini-bang” power spectrum

Top 0.2% central

JHEP 02 (2014) 088



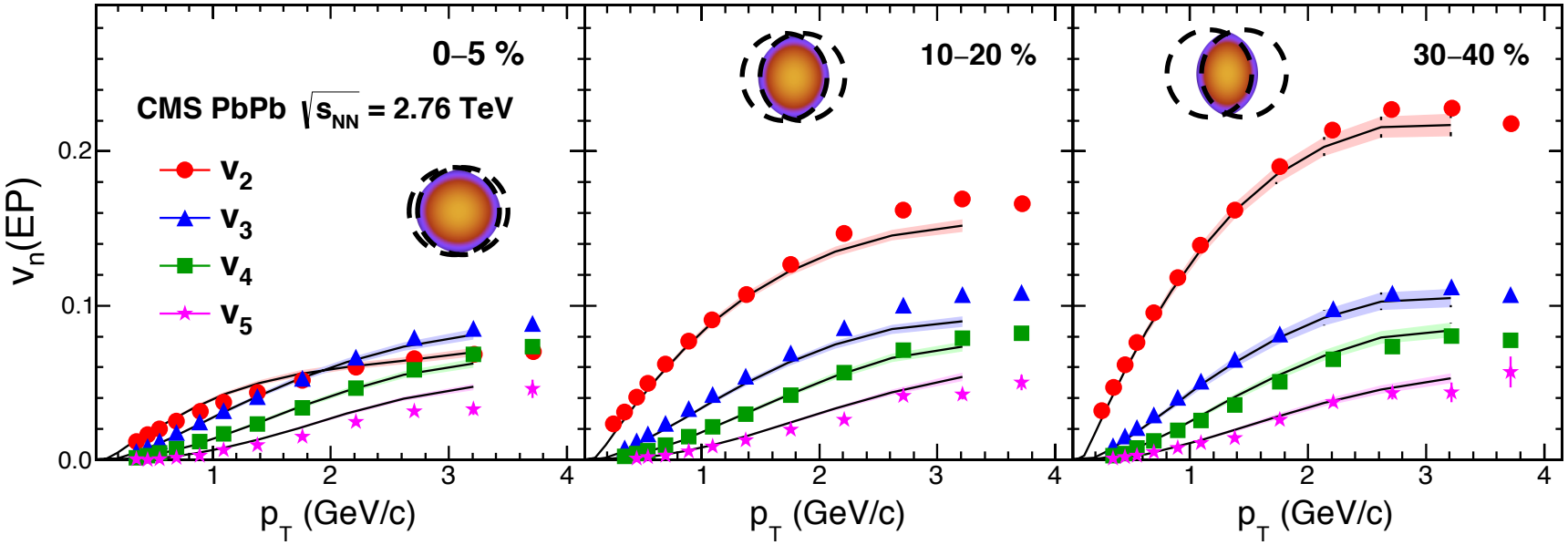
Stringent constraints on η/s:

η/s (LHC) ~ 0.14 – 0.2

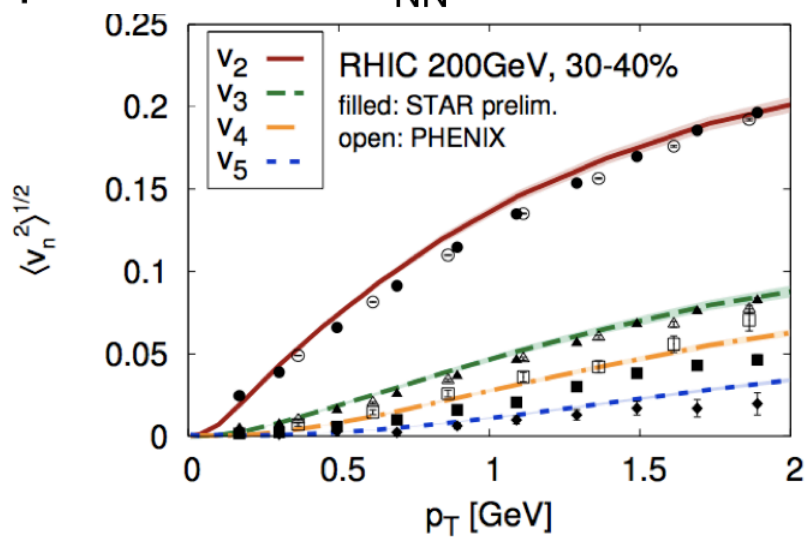
Hydrodynamic paradigm of QGP

$\eta/s \approx 0.2$ at $\sqrt{s_{NN}}$=2.76 TeV

PRC 89 (2014) 044906



$\eta/s \approx 0.12$ at $\sqrt{s_{NN}}$=200 GeV

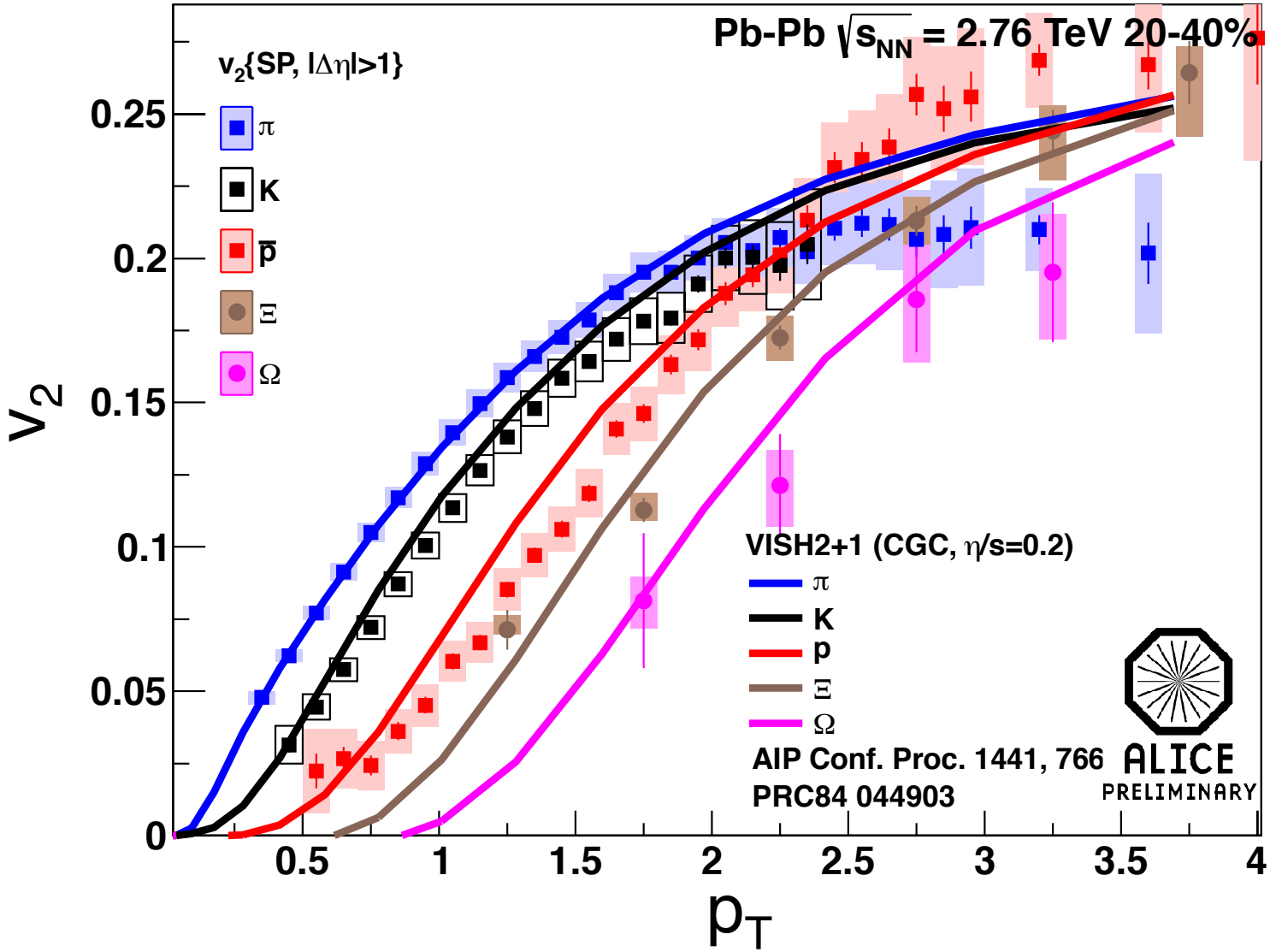


Hydro. faithfully transpose the initial "noise" into final-state momentum distributions

"Noise" is our signal!

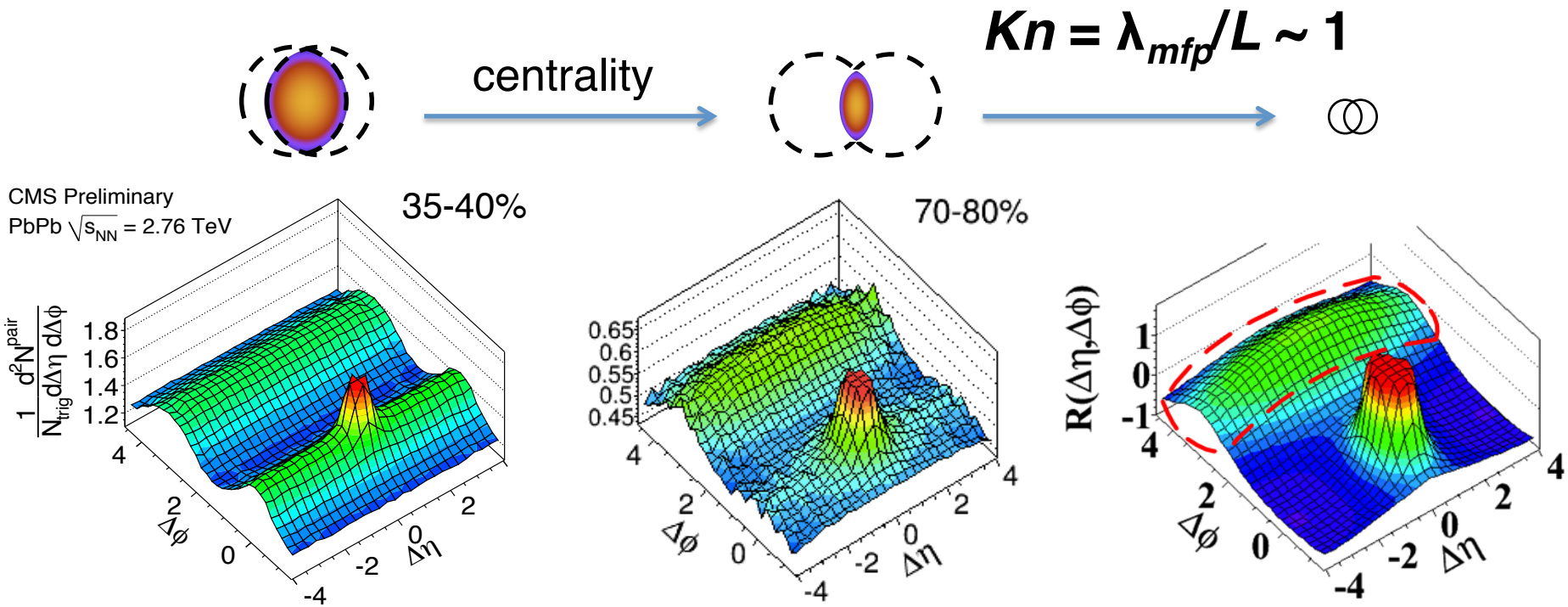
Hydrodynamic paradigm of QGP

"Mass ordering" predicted by hydrodynamics



How small a QGP can be?

Collectivity diminishing as ***L*** decreases:



No QGP fluid in pp and pPb expected!

But what if making it denser (reducing λ_{mfp})?

➔ a smaller but hotter QGP fluid?!

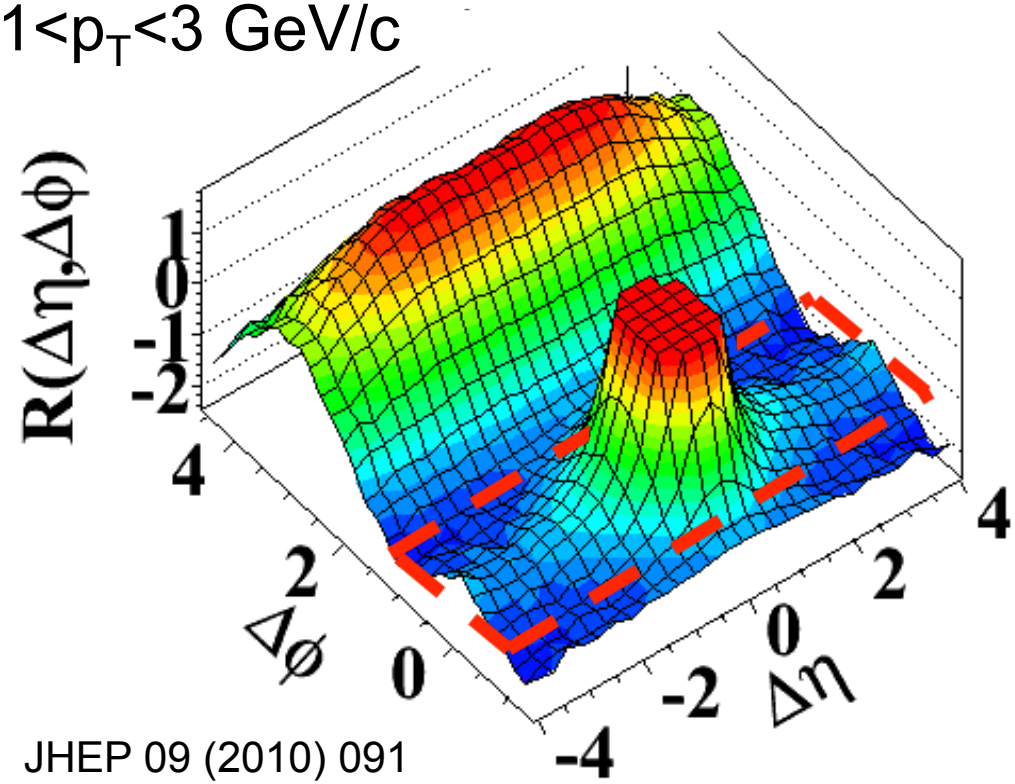
The “ridge” in **pp** at the LHC

Breaking news in 2010:

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

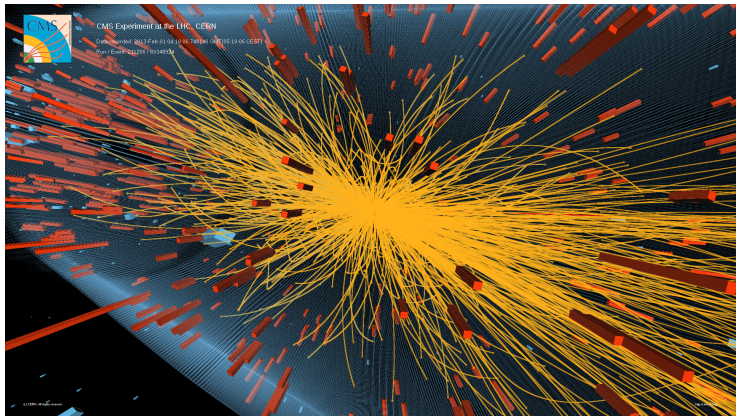
0-0.0007% central

$1<p_T<3$ GeV/c



JHEP 09 (2010) 091

High-multiplicity pp (N^{ch}_{trk}>200)



Not a pileup!

Mini-QGP fluid (L ~ 1 fm) in pp?

Beginning of a second “discovery” phase

Search for QGP in pp at FNAL

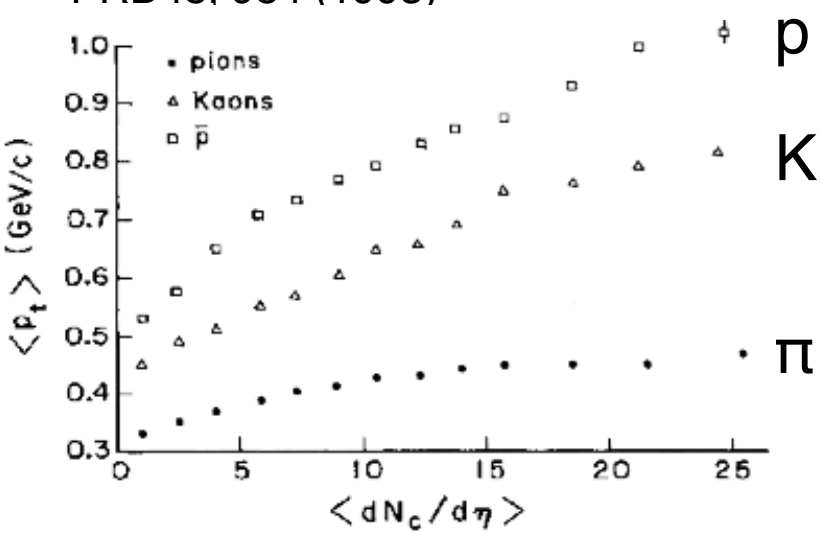
Fermi National Accelerator Laboratory

FERMILAB-Conf-90/205-E
[E-735]

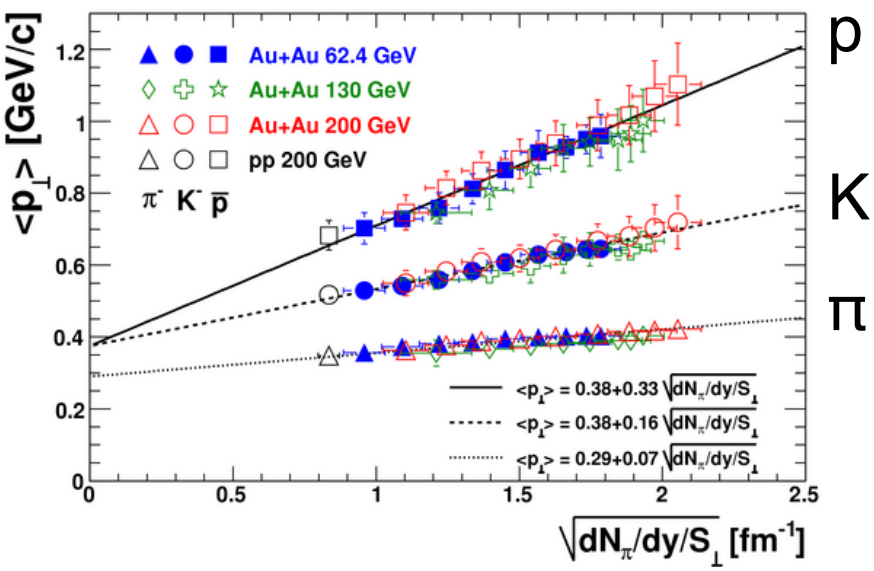
A Quark-Gluon Plasma Search in $\bar{p}$–p at $\sqrt{s}$=1.8 TeV

The E-735 Collaboration
October 8, 1990

PRD48, 984 (1993)

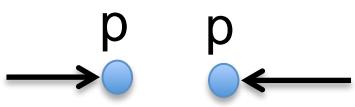


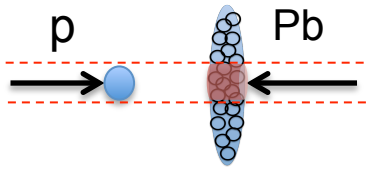
RHIC



indicative but not conclusive …

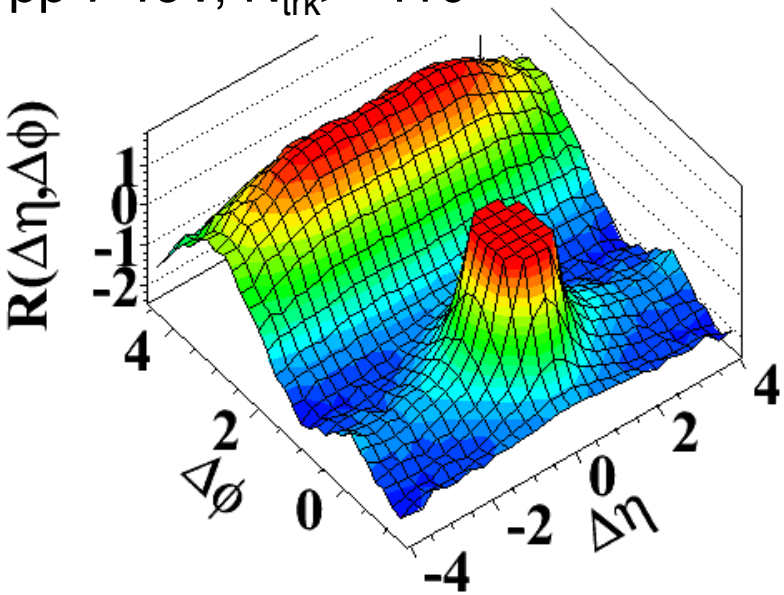
The “ridge” tsunami at the LHC





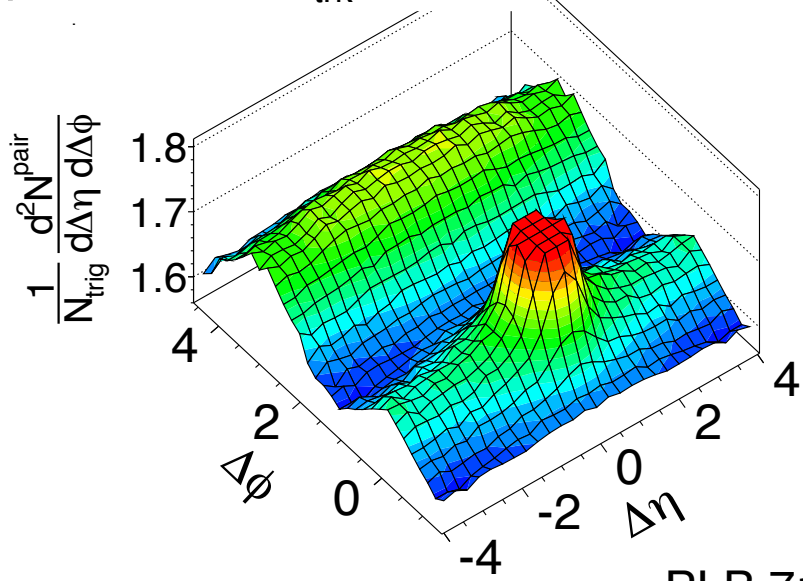
~ 4 hours of pPb beam on Sep. 21, 2012

pp 7 TeV, N_{trk}>=110



JHEP 09 (2010) 091

pPb 5 TeV, N_{trk}>=110



PLB 718 (2013) 795
(submitted Oct. 19)

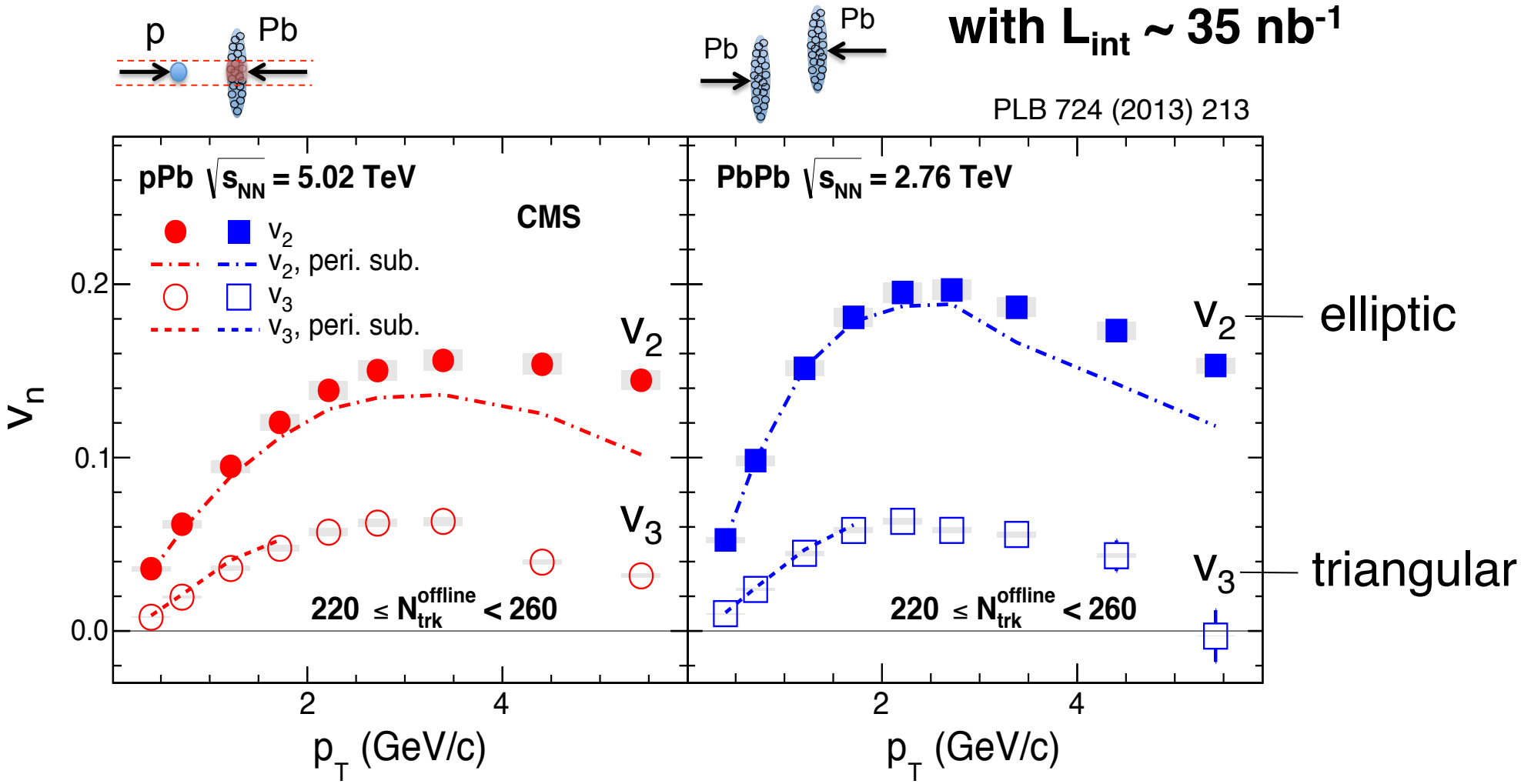
The “ridge” seen in all systems at the LHC!

➔ Everything flows?

"Flow" (v_n) in pPb

A longer pPb run in 2013 with L_{int} ~ 35 nb^{-1}

PLB 724 (2013) 213

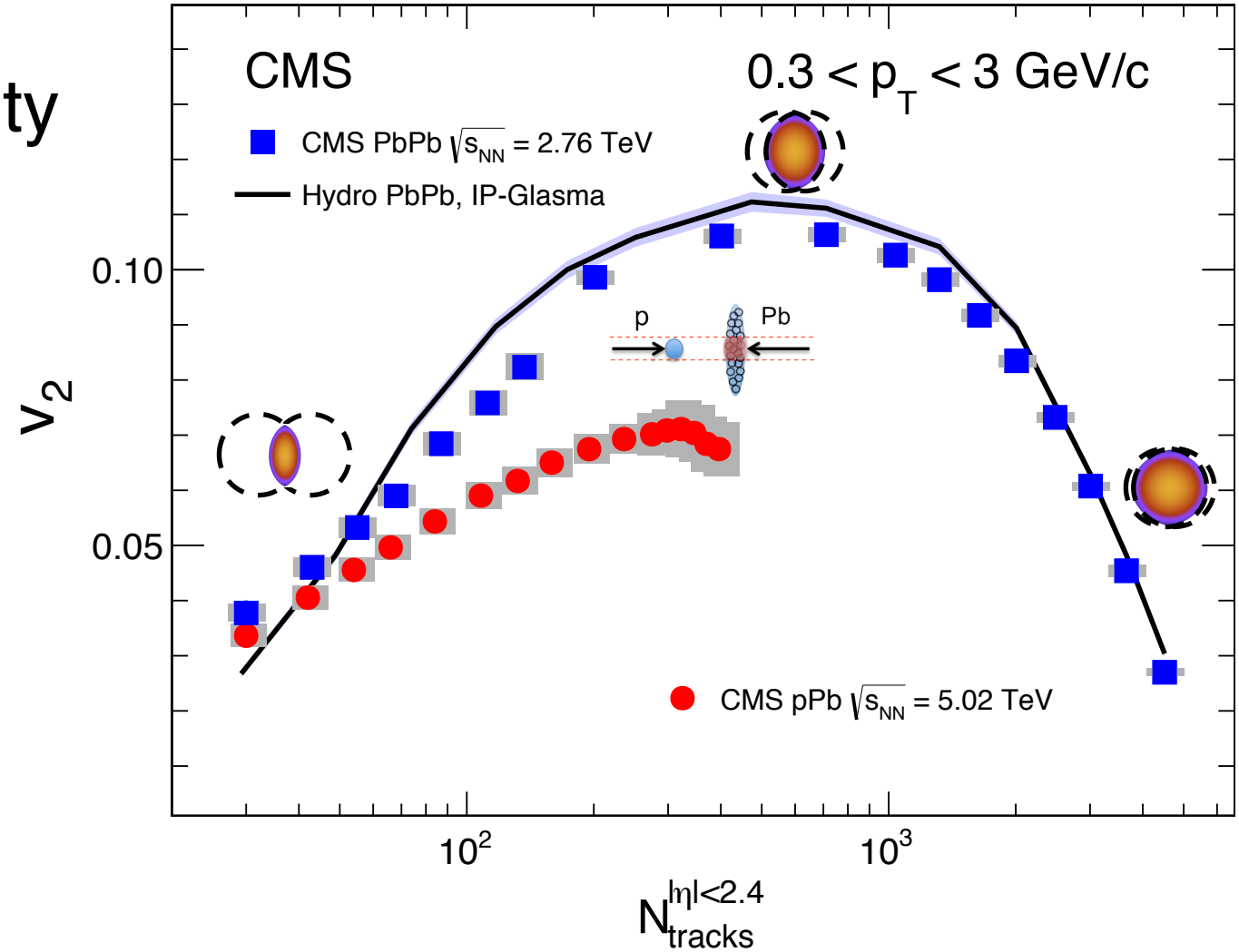


First LHC paper on 2013 pPb data!

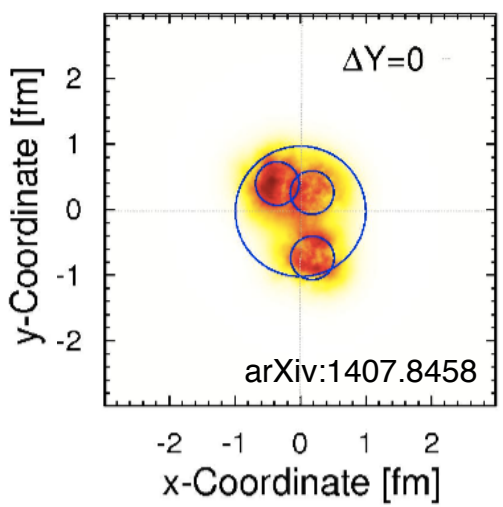
Quantitatively similar ridge effect in pPb and PbPb

“Flow” (v_n) in pPb and PbPb

v_2 vs multiplicity



“shape” of a single proton



Initial state not understood, esp. subnucleonic structure

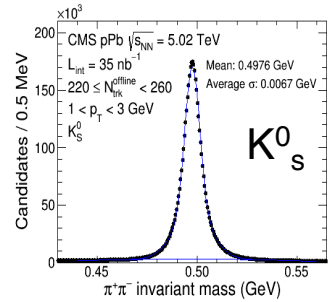
or

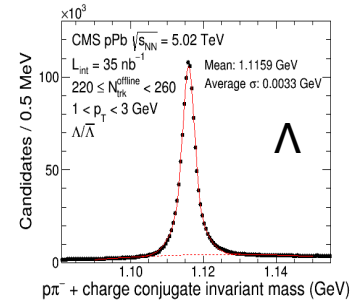
Non-hydro correlations

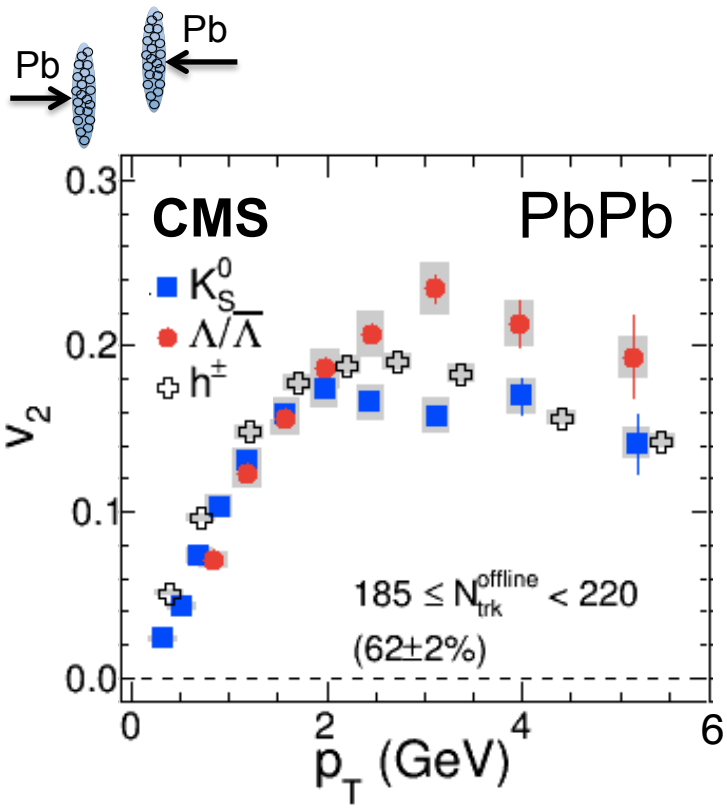
(e.g., quantum entanglement of initial gluons, PRD 87 (2013) 094034)

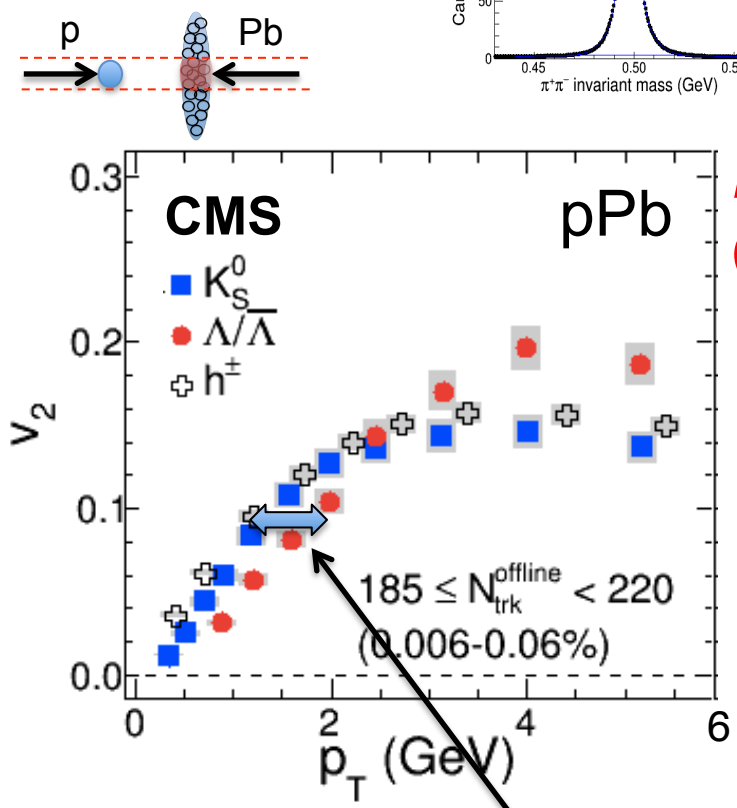
Particle identification at CMS

Excellent ID of K^0_s and Λ









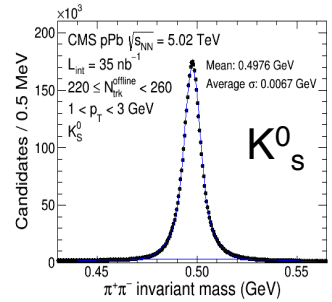
First 2014 HI paper (arxiv:1409.3392)

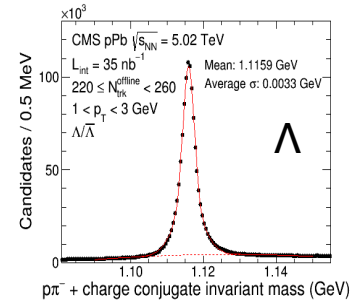
"mass ordering": $\mathbf{v_2(h^\pm \text{ or } \pi^\pm)} > \mathbf{v_2(K^0_s)} > \mathbf{v_2(\Lambda)}$ at a given p_T

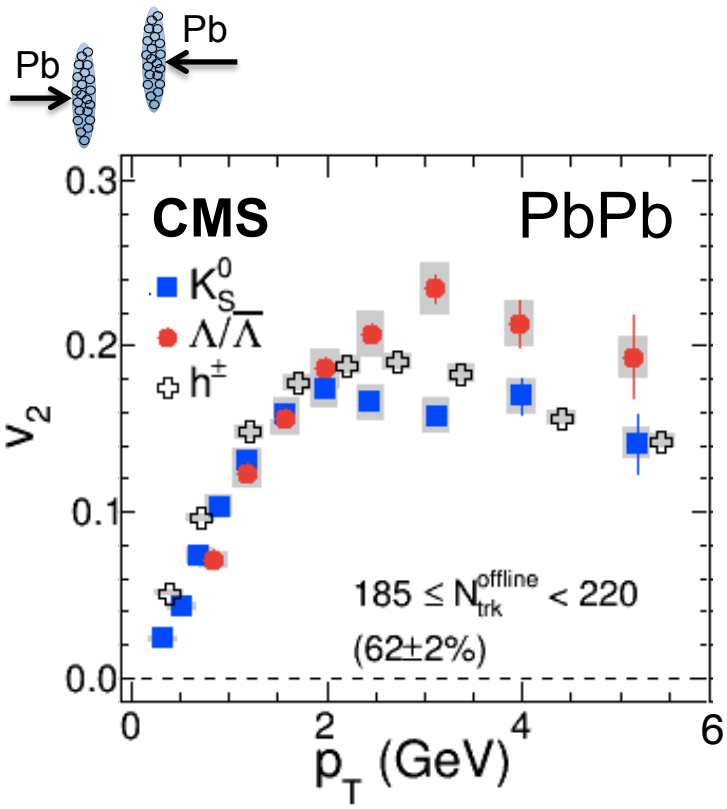
Boosted by a common velocity field: $\Delta p_T \approx \mathbf{m}\langle\beta_T\rangle$

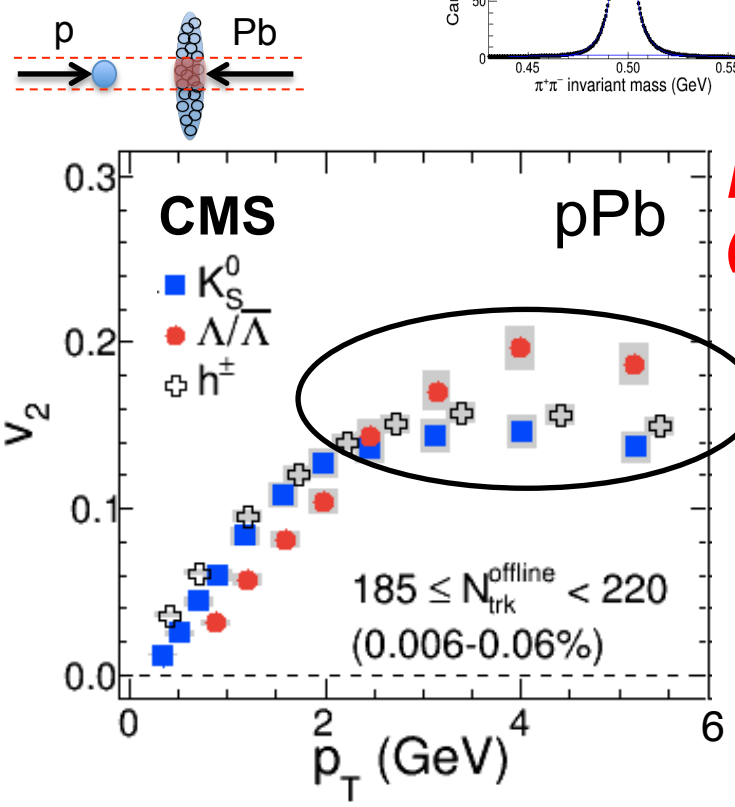
Particle identification at CMS

Excellent ID of K^0_s and Λ









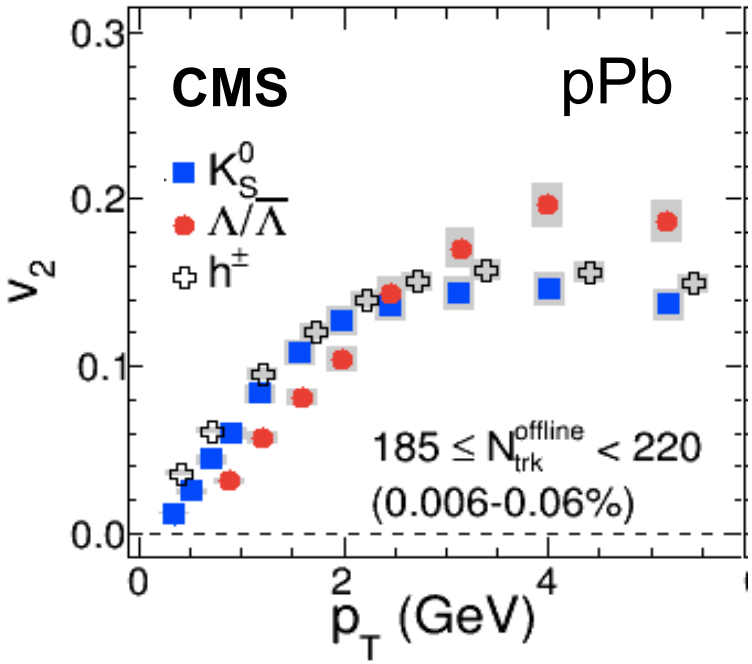
First 2014 HI paper (arxiv:1409.3392)

crossing at higher p_T?

"mass ordering": **$v_2(h^\pm$ or $\pi^\pm)$** > **$v_2(K^0_s)$** > **$v_2(\Lambda)$** at a given p_T

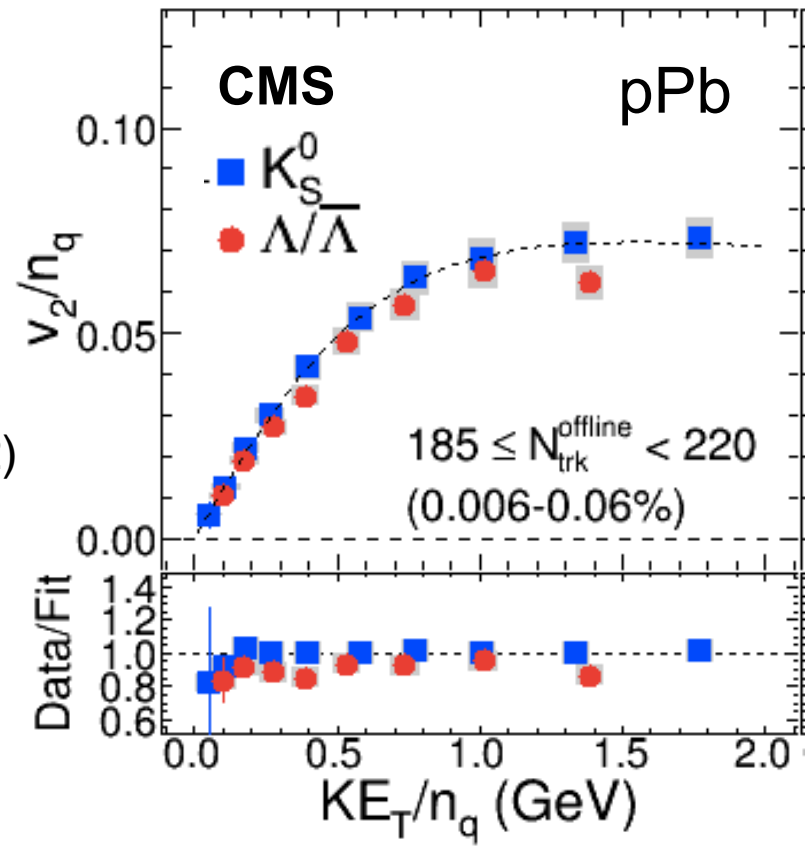
Stronger radial flow boost in smaller pPb system!

Partonic degree of freedom?

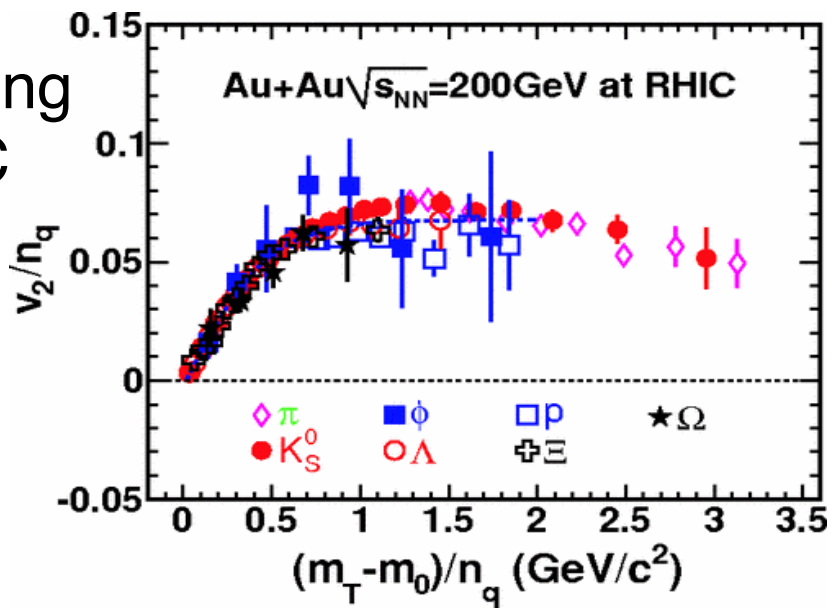


scaled by n_q

K^0_s (n_q=2)
Λ (n_q=3)



N_q-scaling at RHIC

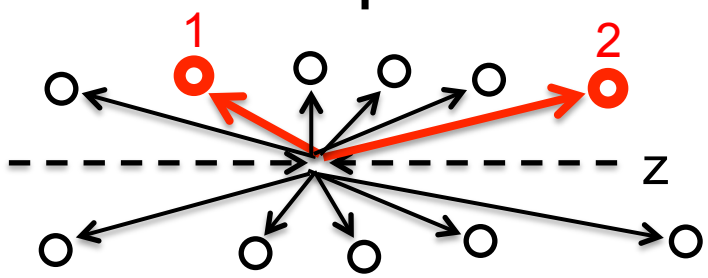


Kinetic energy: $KE_T = \sqrt{p_T^2 + m^2} - m$

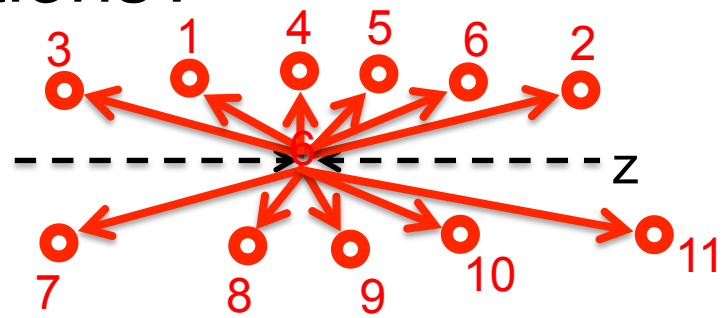
Flow developed at partonic level!?

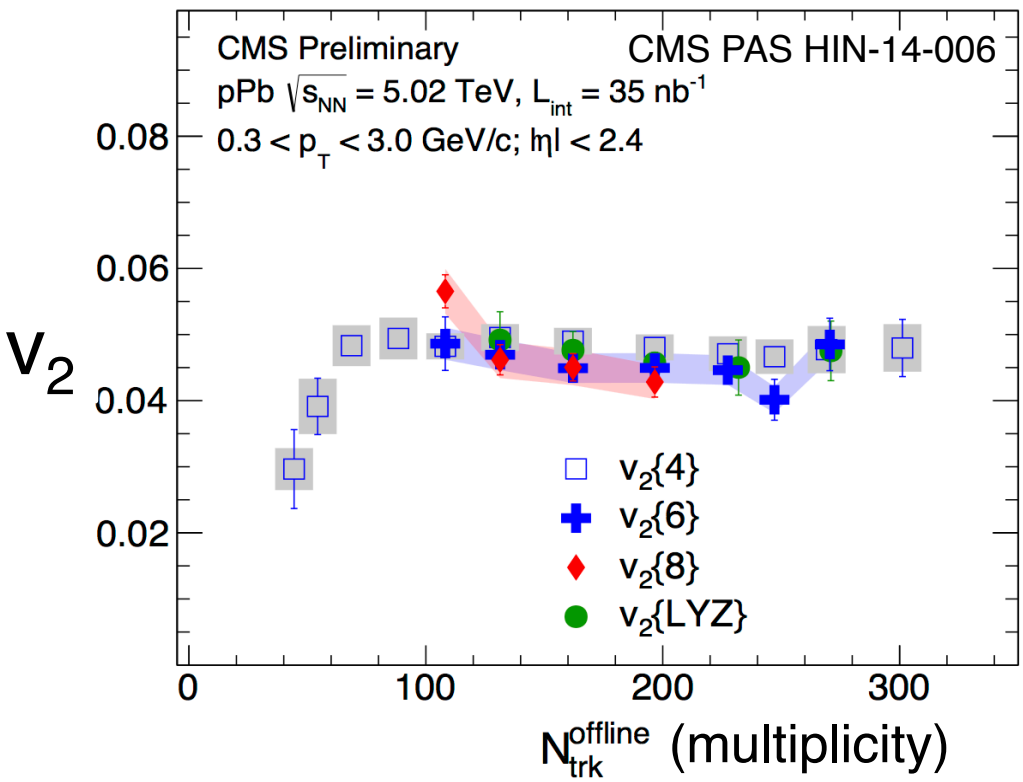
True collectivity in pPb (and pp)?

Two- or more particle correlations?



OR





$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

Direct evidence of collectivity in pPb!

(not necessarily hydro.)

Highlight of QM2014!

Comment from an PRL editor on twitter

Kevin Dusling @KevinDusling · May 20

This is the most surprising result (to me at least) of #QM2014 so far. Beautiful measurement by the @CMSexperiment

Paradigm of a "perfect" QGP fluid

By now, we know very well *what QGP does*:

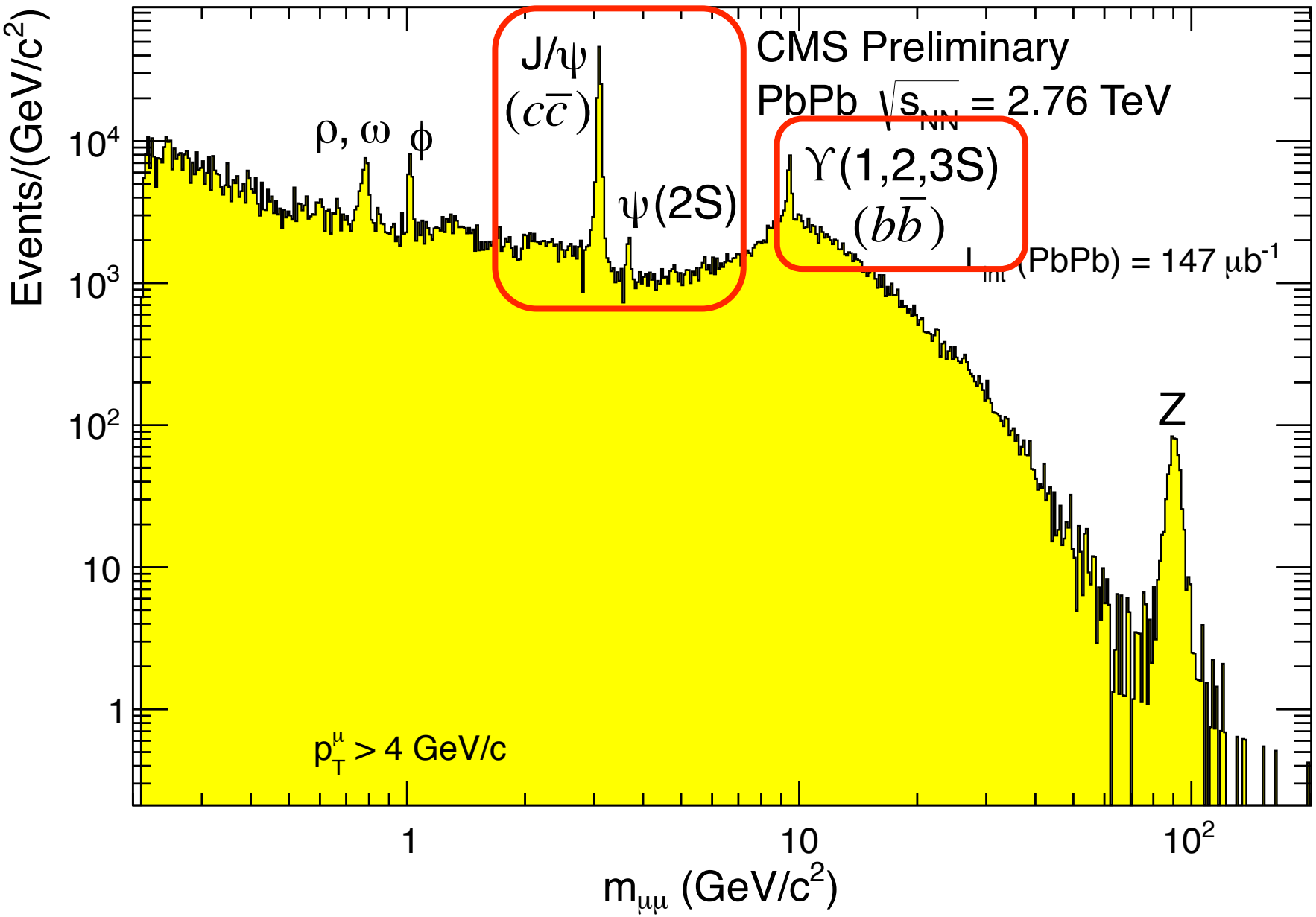
- *Flows with little frictional dissipation: $\eta/s \rightarrow 1/4\pi$*
- *Fluidity persists in smallest system ($r \sim 1$fm)*

But, we don't know *why QGP behaves like a fluid:*

- *How does this emerges from microscopic first-principle QCD?*
- *Is string theory the "holy grail" to the strongly coupled, many-body QCD system?*

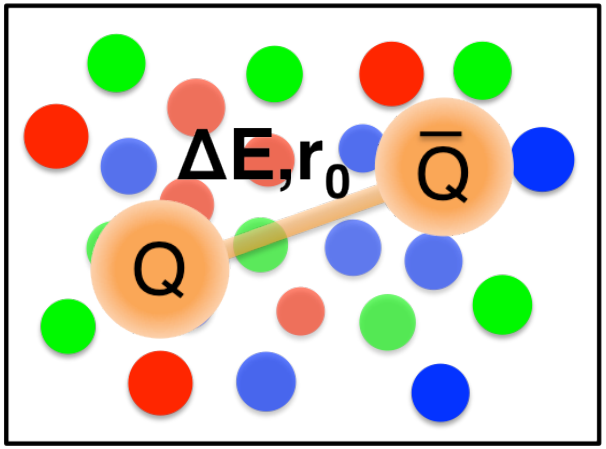
Probe QGP's finer structure (beyond its natural length scale ~ $1/T_{QGP}$) to see what is "flowing"

Compact *Muon* Solenoid

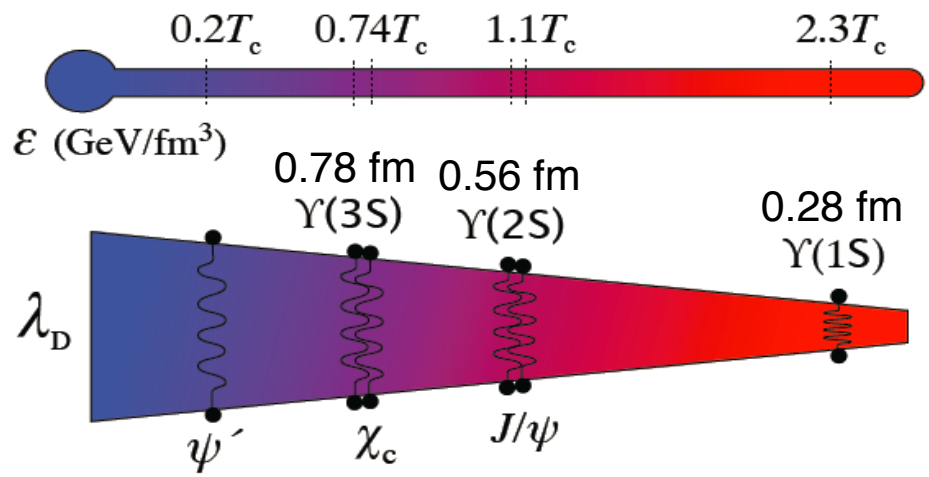


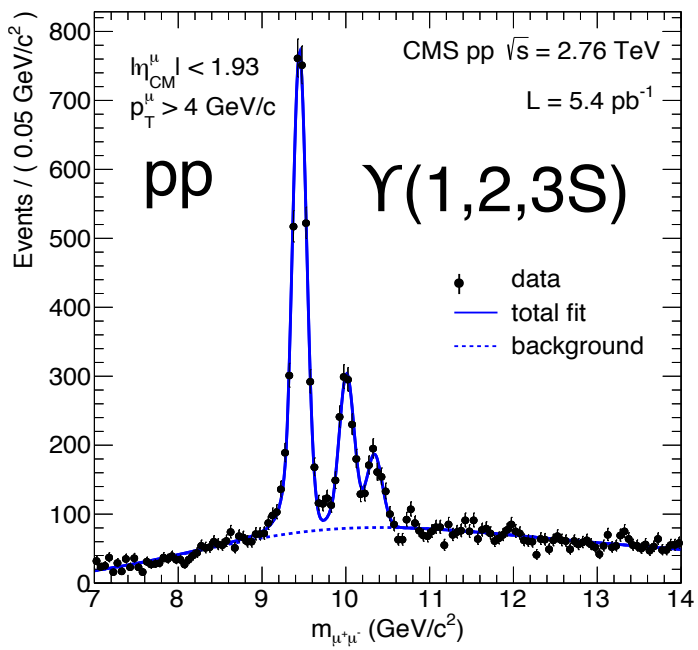
Color Debye screening of Quarkonia

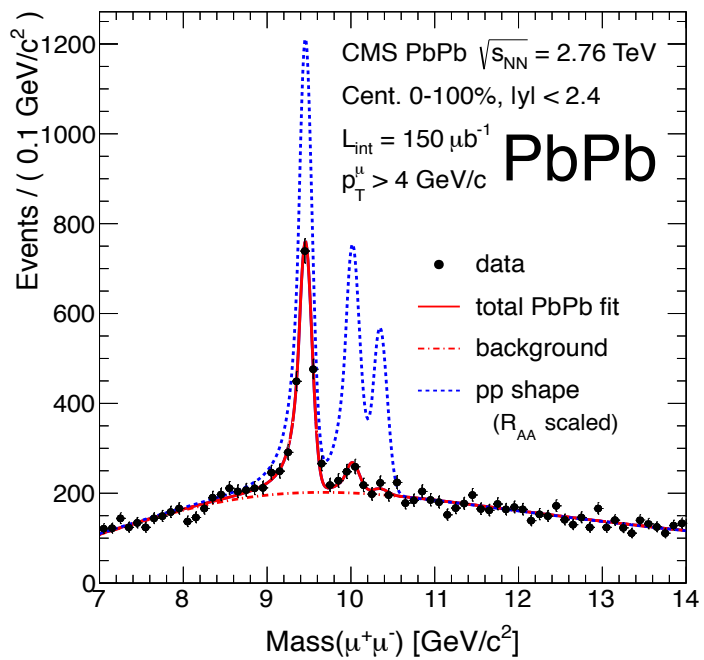
In QGP: $V(r) \sim -\frac{\exp(-r/\lambda_D)}{r}$



If $r_0 > \lambda_D(T) \rightarrow Q\bar{Q}$ dissociated



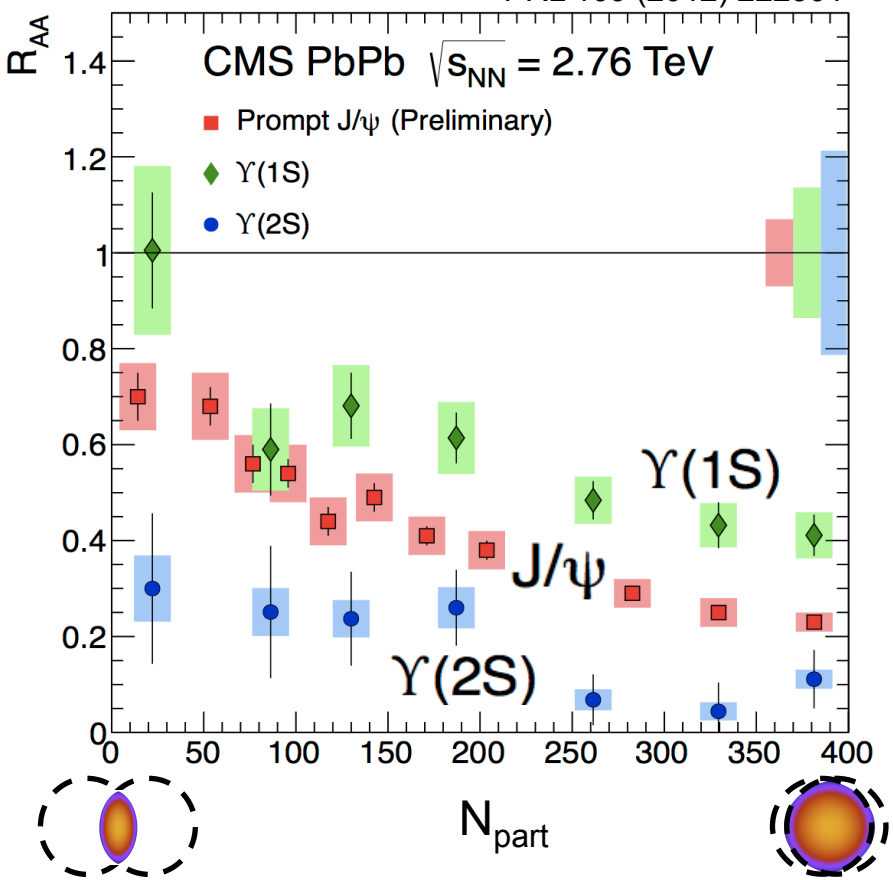




Color Debye screening of Quarkonia

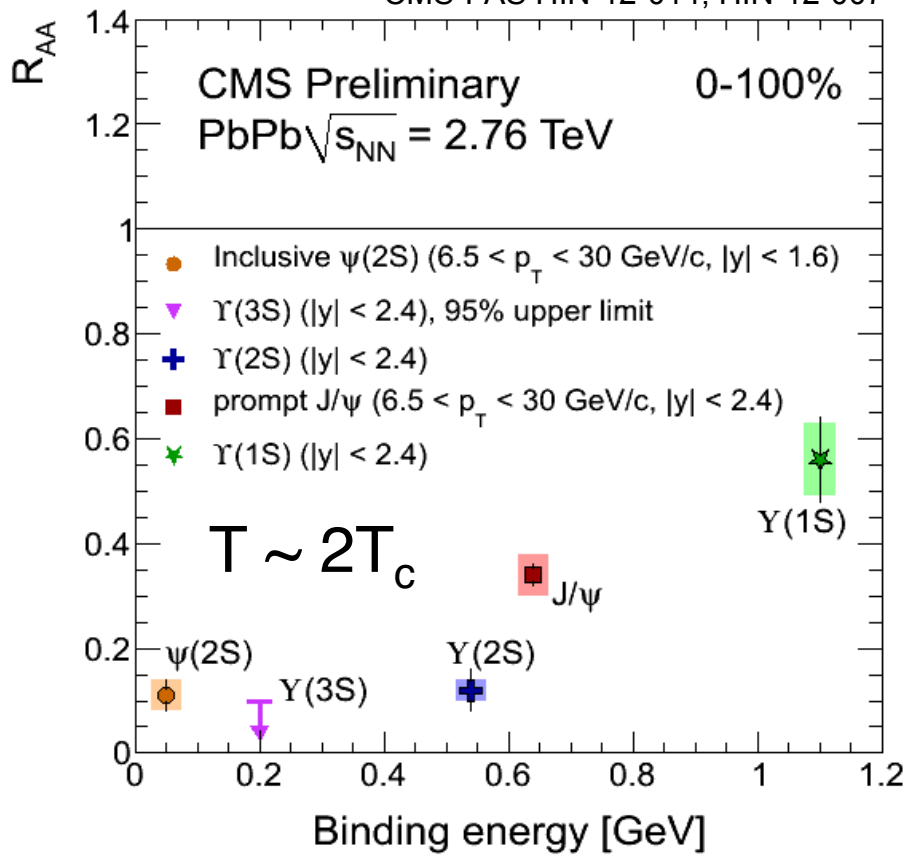
$$R_{AA} = \frac{\text{Yield in PbPb}}{\text{Yield from scaled pp}}, \quad =1 \text{ if no modification}$$

PRL 109 (2012) 222301



Clear hierarchy for different quarkonia

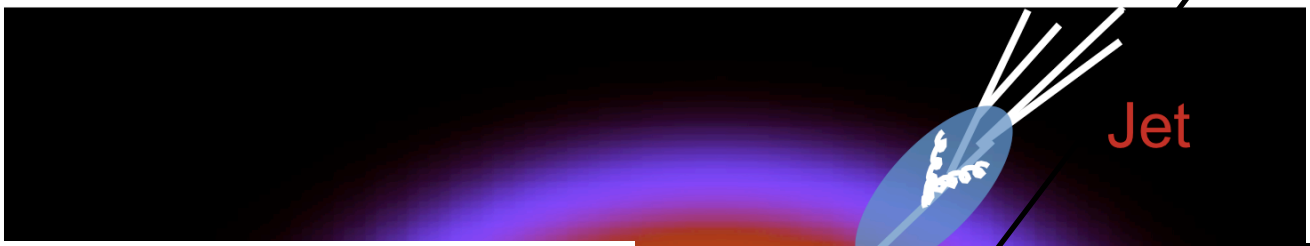
CMS-PAS HIN-12-014, HIN-12-007

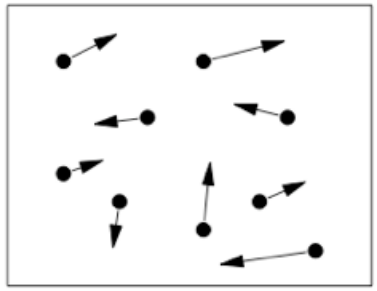


Expected in terms of binding energy

QGP tomography with jets

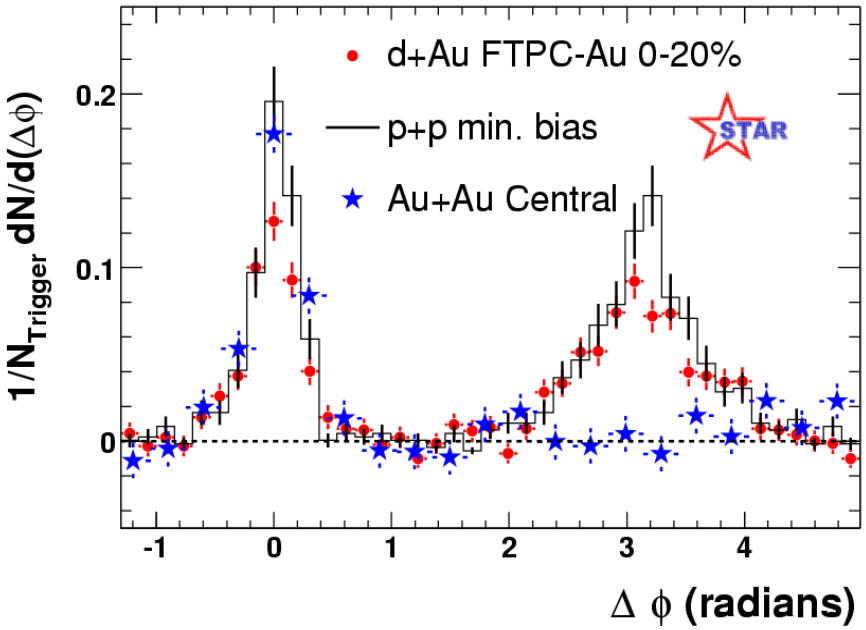
Jets as the QGP microscope

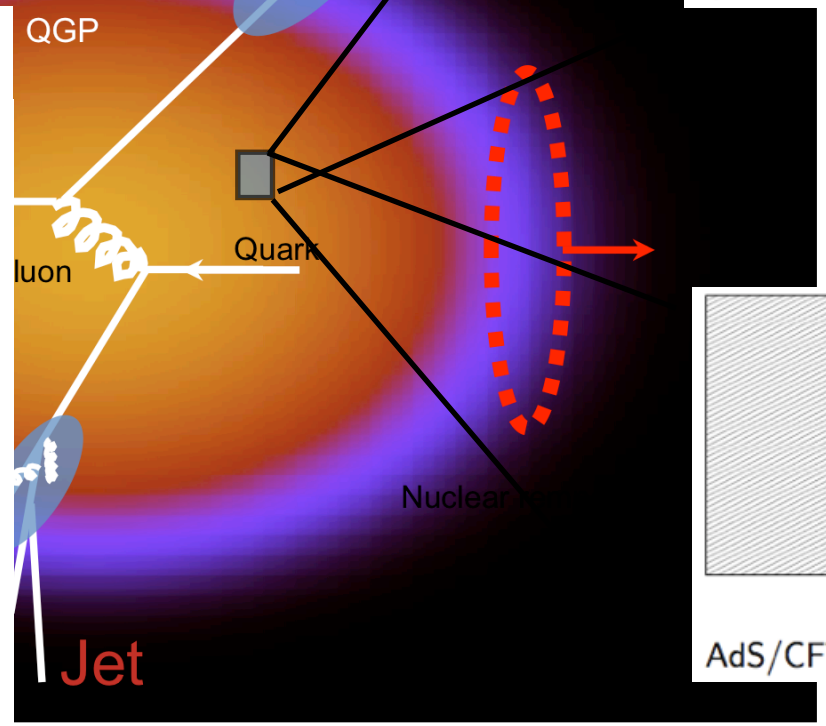




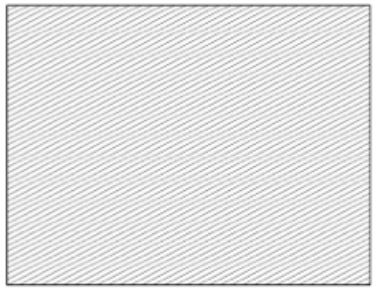
pQCD kinetic plasma

Jet quenching at RHIC





or?

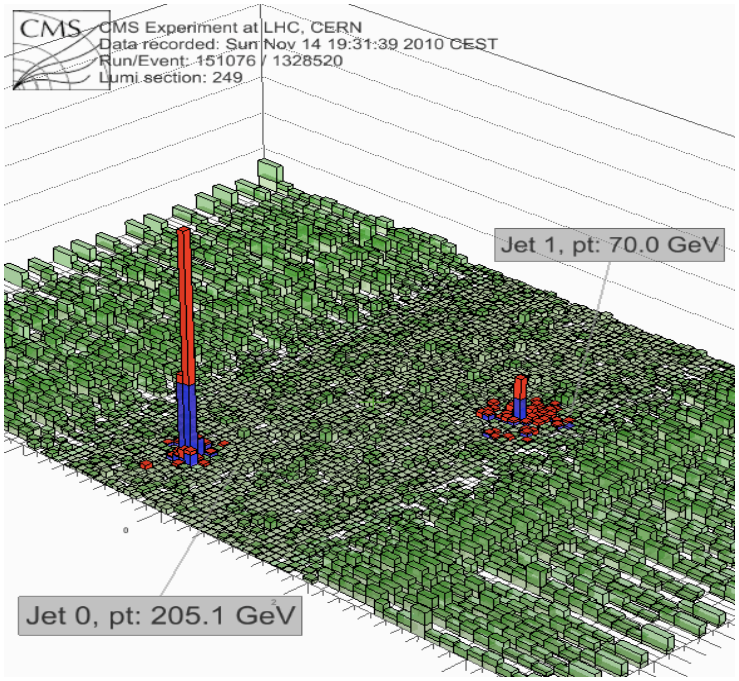


AdS/CFT low viscosity goo

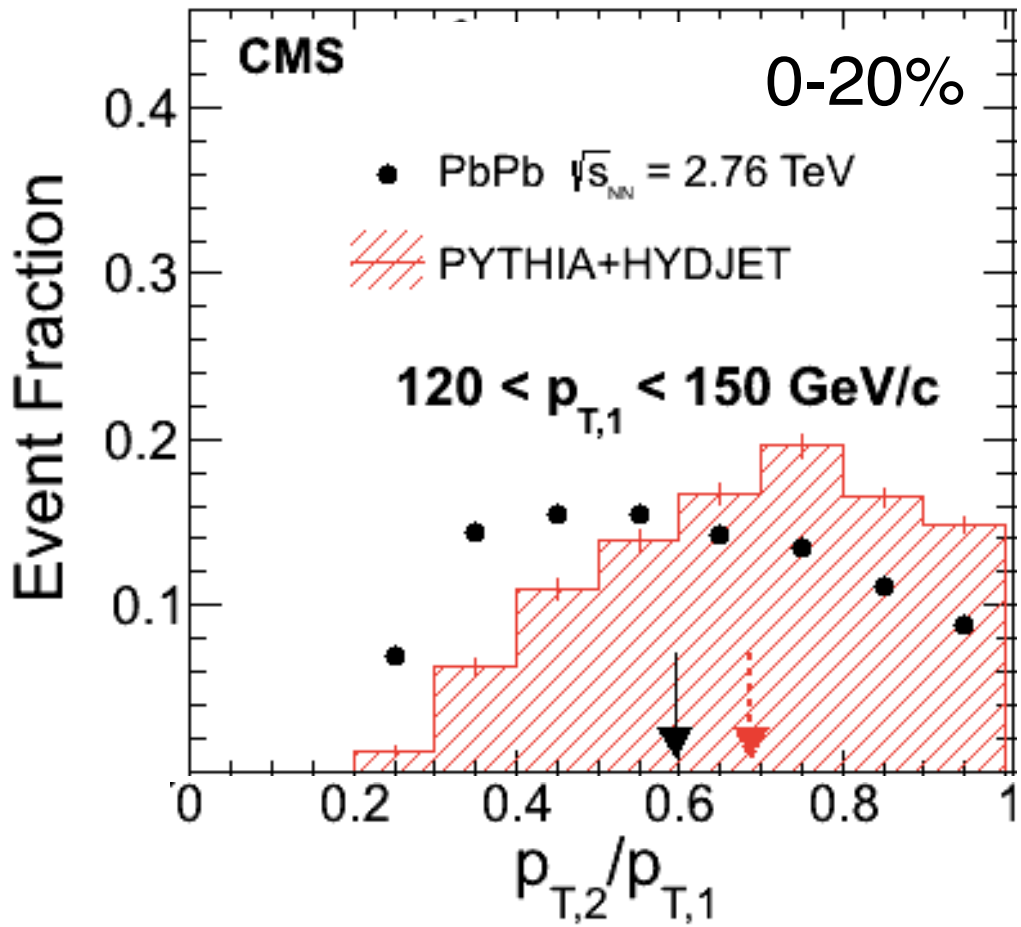
20-50 GeV (0.01-0.004 fm), 1-5 GeV (0.2-0.05 fm)

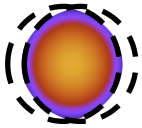
Jet quenching at the LHC

Direct observation of jet quenching



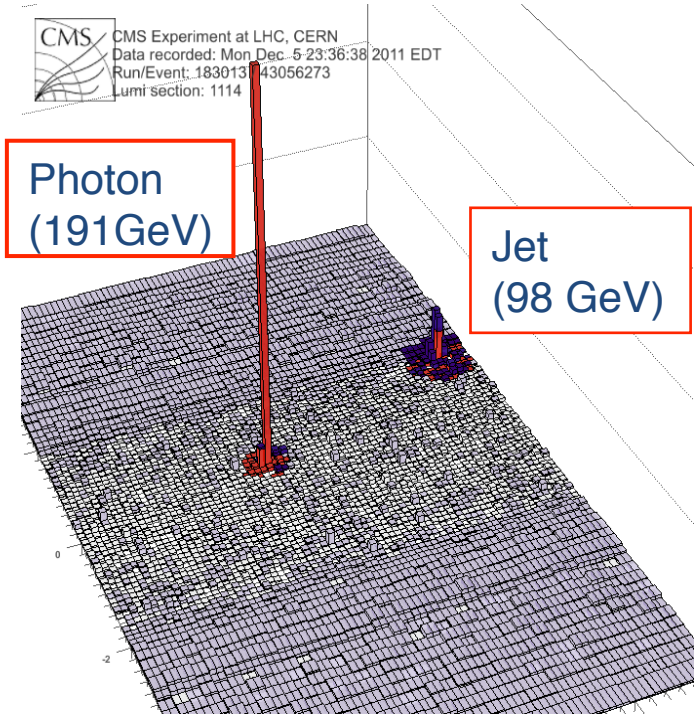
Dijet momentum imbalance

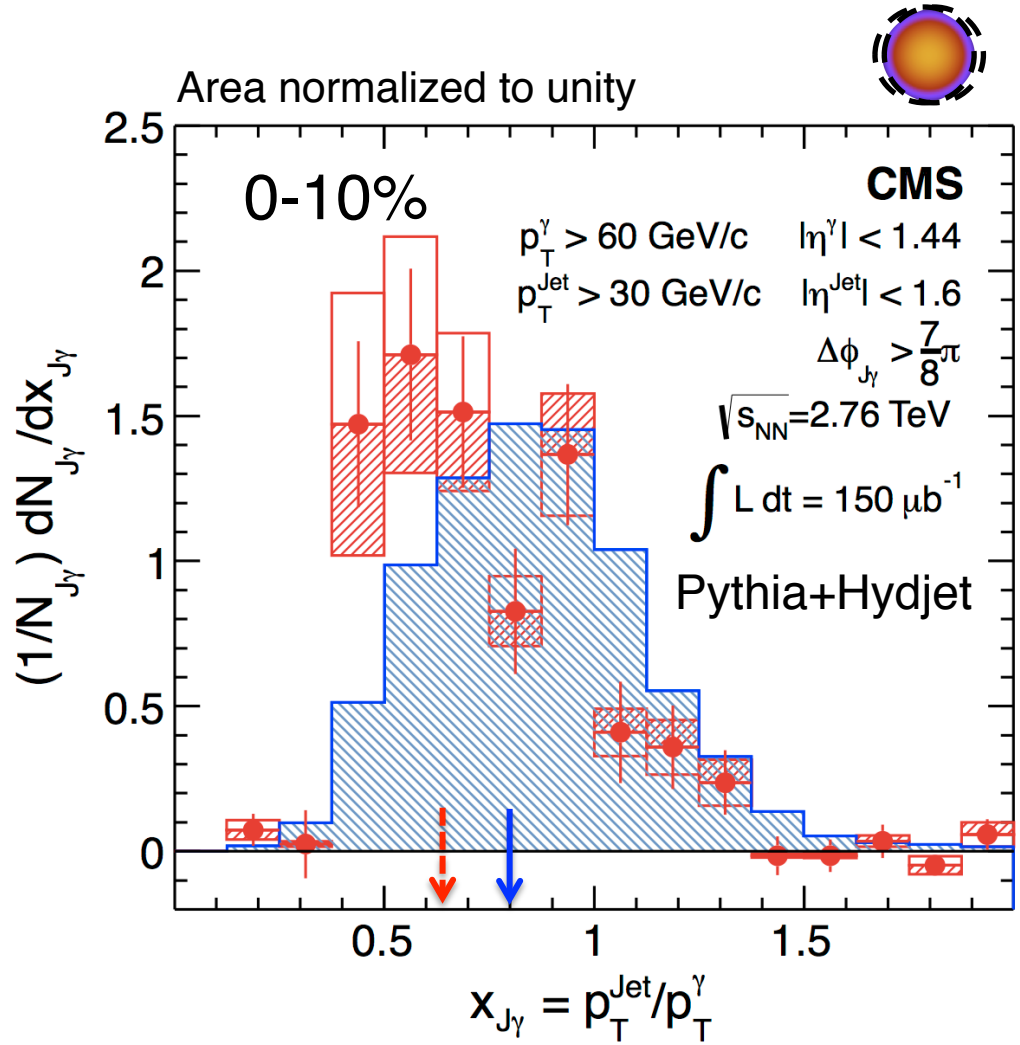




~ 10% shift in away-side jet p_T

“Golden” probes: γ+jets





Photon tag:

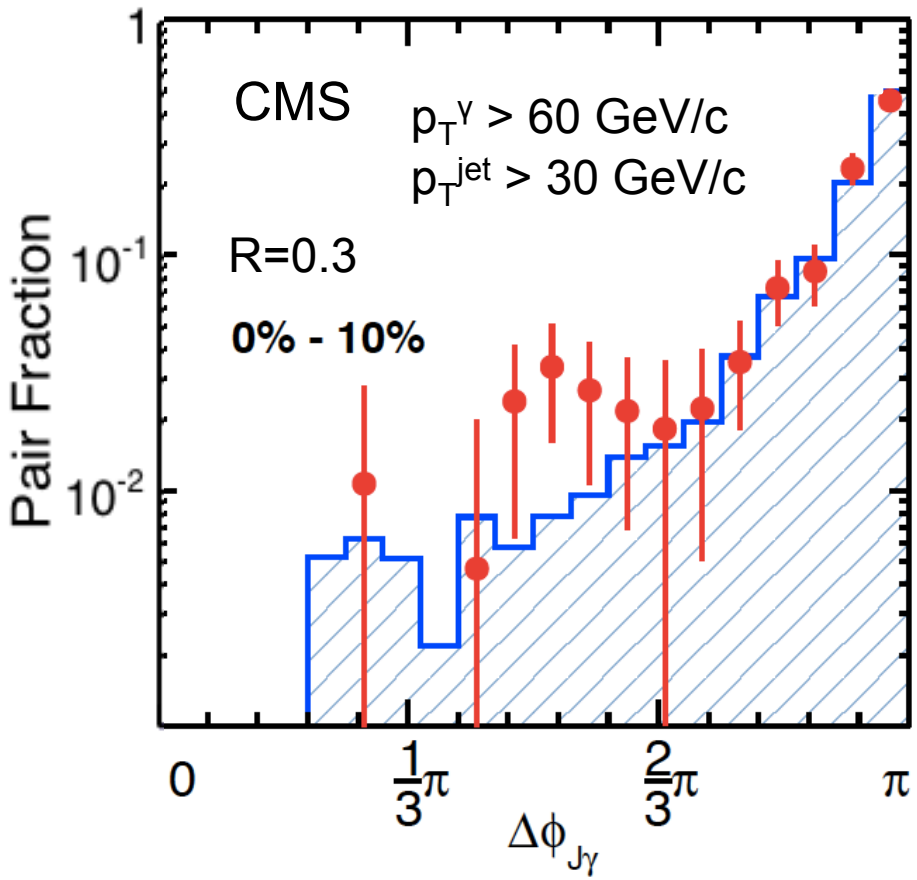
- u,d quark jet
- Initial quark direction
- Initial quark p_T

~ 14% shift in away-side jet p_T

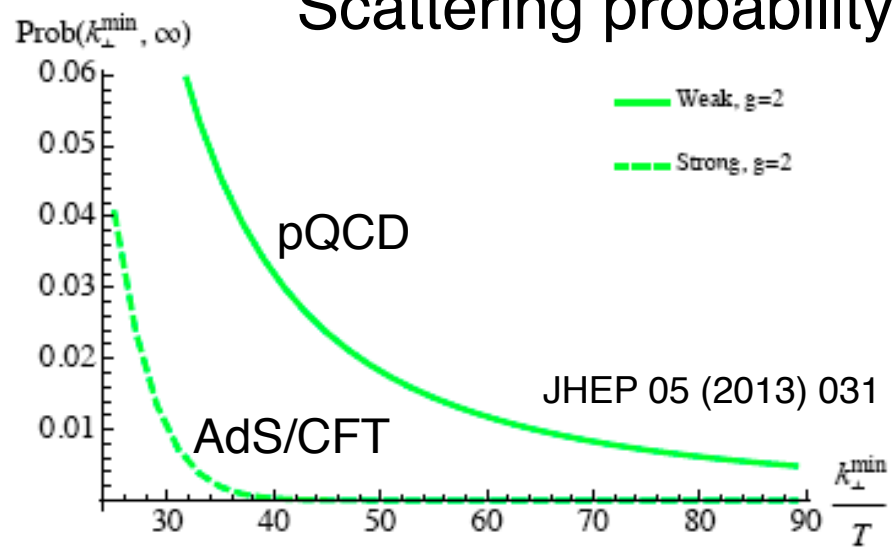
“Golden” probes: γ+jets

No deflection of away-side jets

γ+jets angular correlations



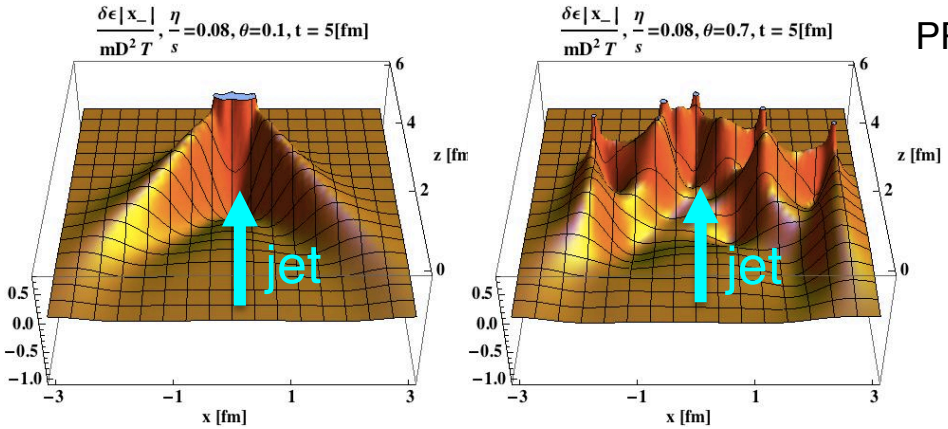
Scattering probability



More statistics (x200) are awaited!

momentum “kick”

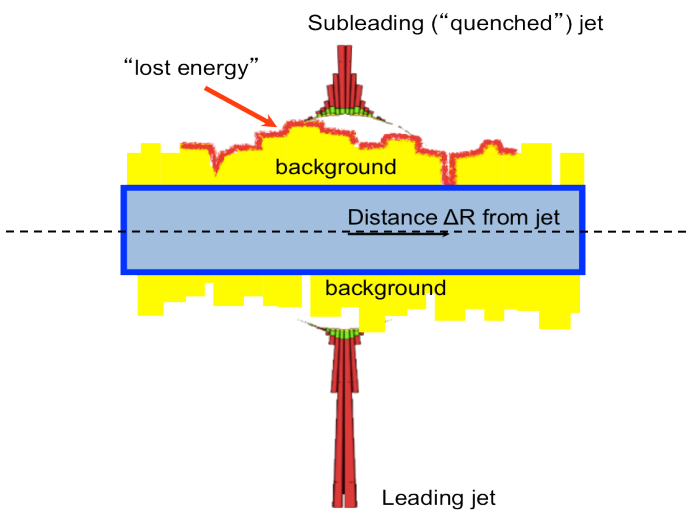
Where does the energy go?



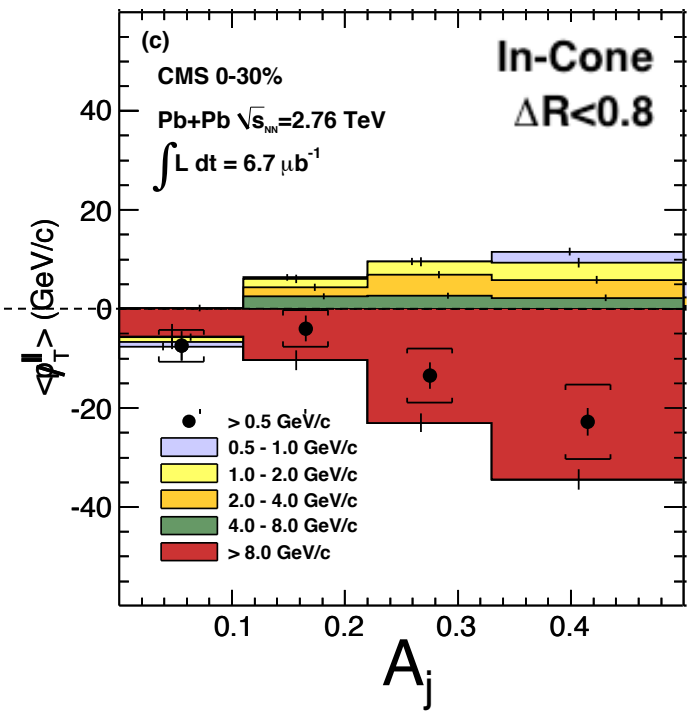
PRC 86 (2012) 024905

Shock wave?

Looking for missing p_T

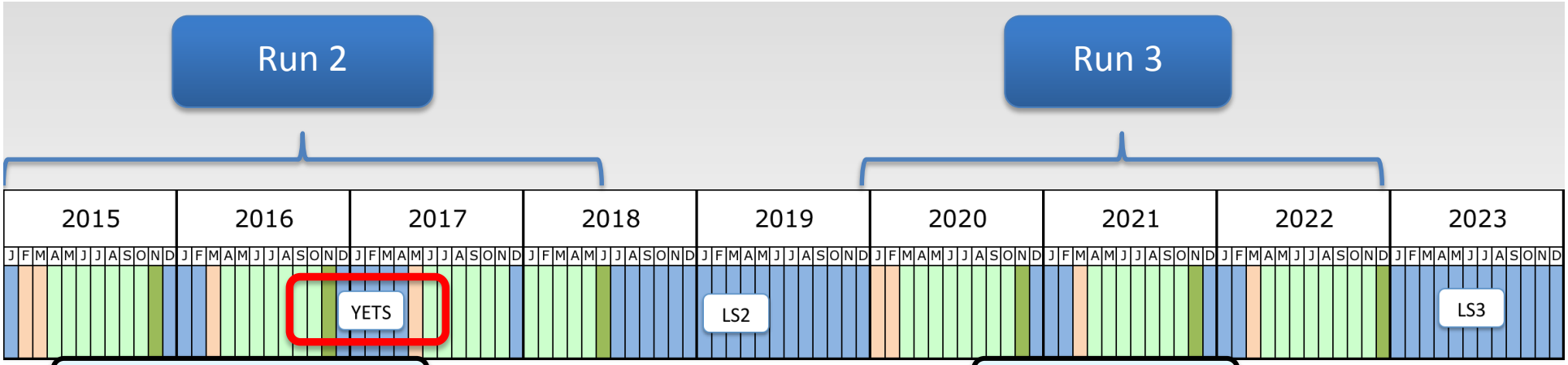


$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



Excess of low p_T particles at large angle

Future HI program at the LHC



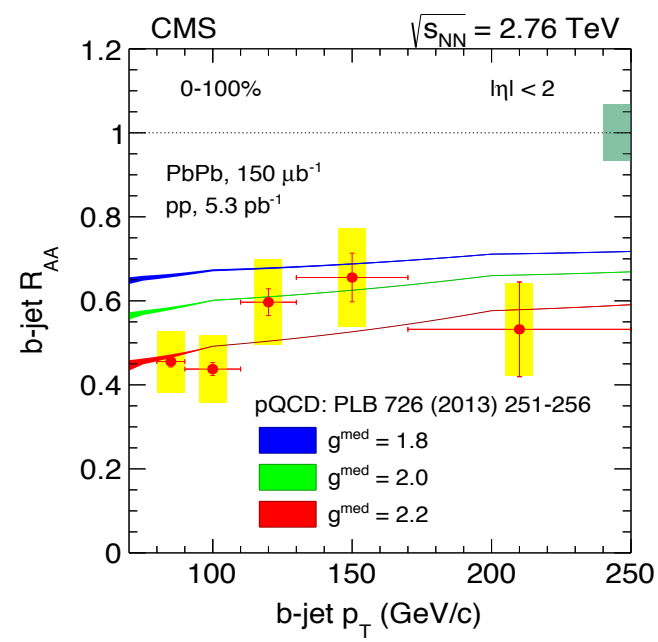
PbPb PbPb **pPb** **PbPb, ArAr, pPb, pAr**

(5 TeV, L_{int} ~ 3 nb^{-1}) **(5.5 TeV, L_{int} ~ 10 nb^{-1})**

x200

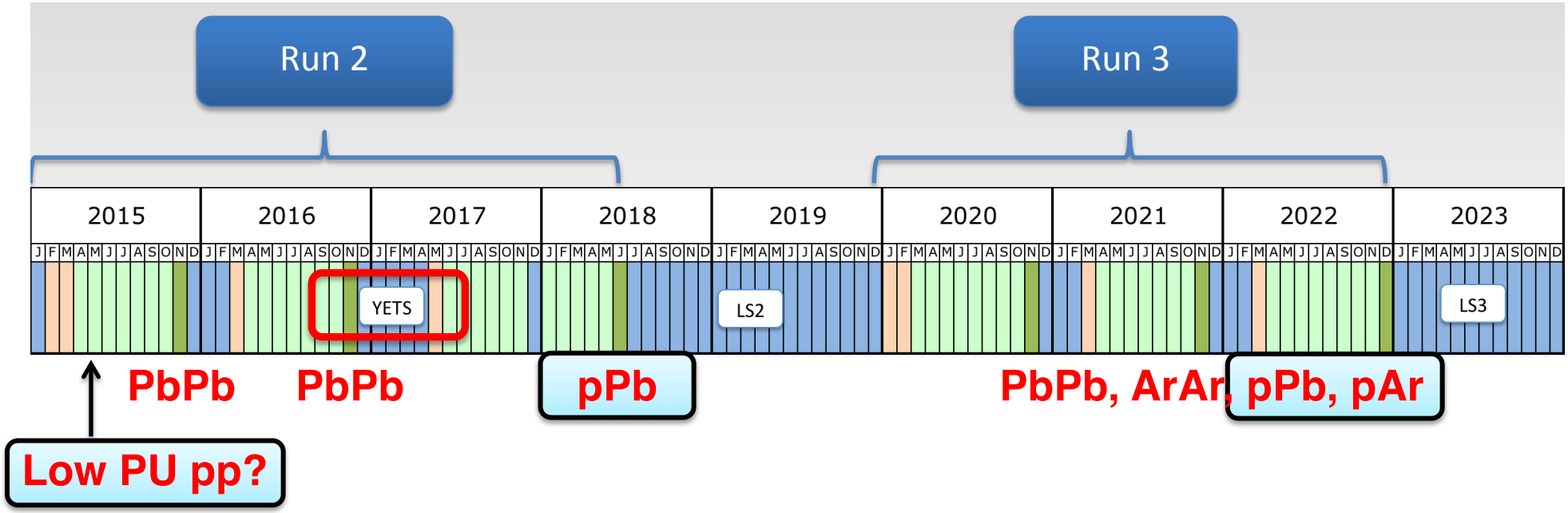
	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet (p_{T1} > 120 GeV/c)	50k	~ 10M
b-jet (p_T > 120 GeV/c)	~ 500	~ 140k
Isolated γ (p_T^γ > 60 GeV/c)	~ 1.5k	~ 300k
Isolated γ (p_T^γ > 120 GeV/c)	–	~ 10k
W (p_T^W > 50 GeV/c)	~ 350	~ 70k
Z (p_T^Z > 50 GeV/c)	~ 35	~ 7k

b-jet R_{AA} PRL 113 (2014) 132301

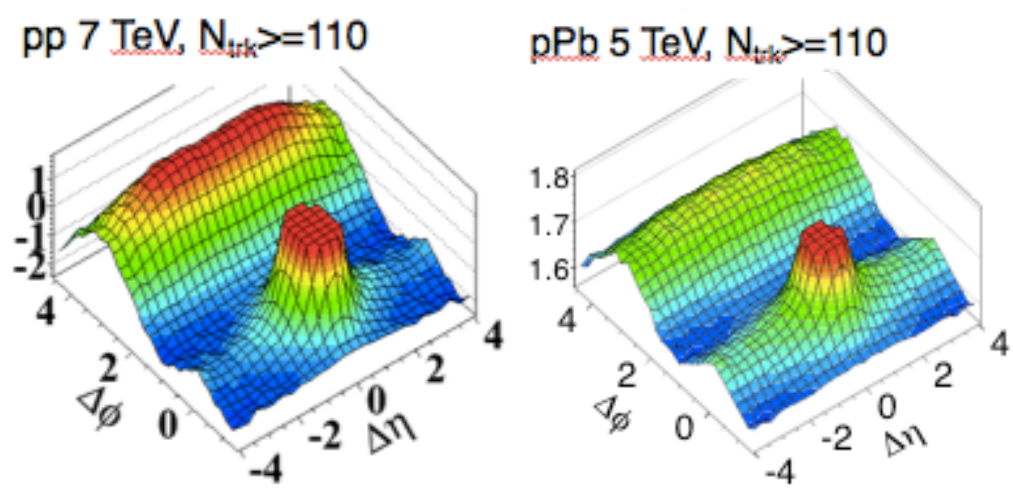


x60 from more luminosity; x3 from higher √s

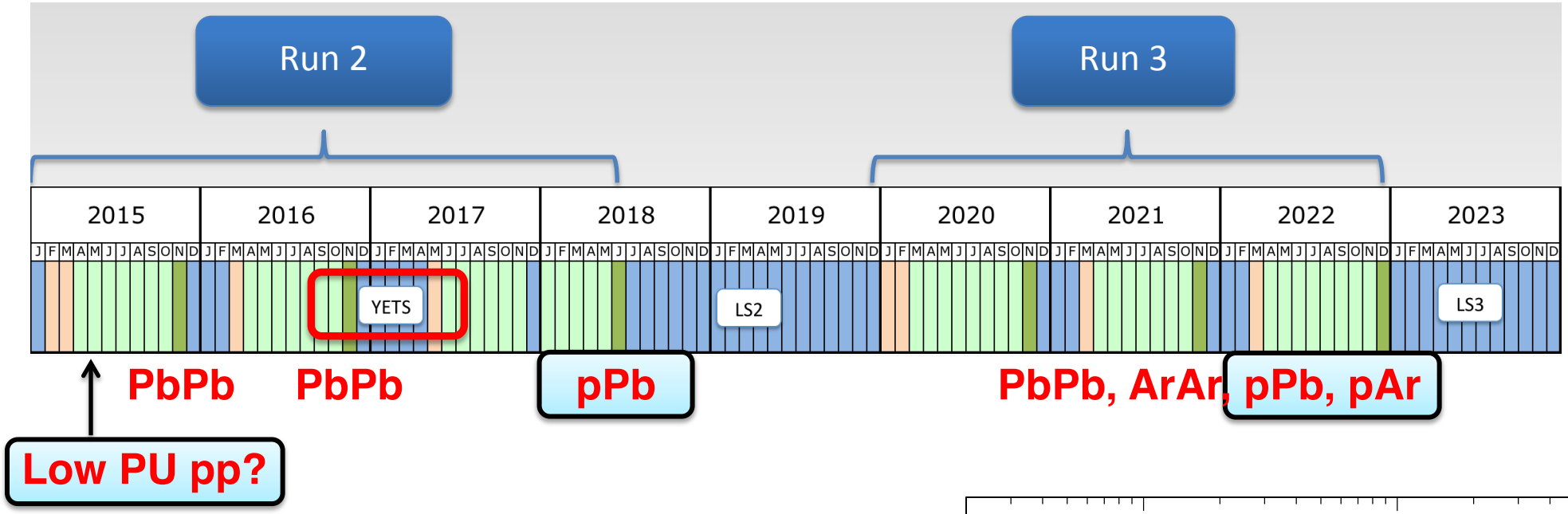
Future HI program at the LHC



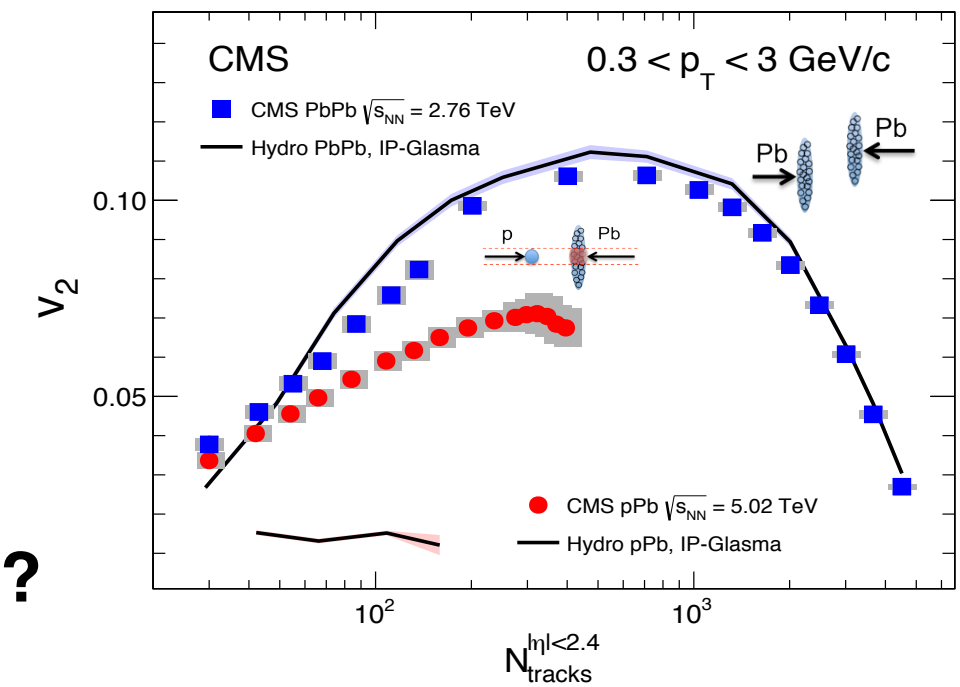
- **What is the nature of the "ridge" in pp and pPb?**



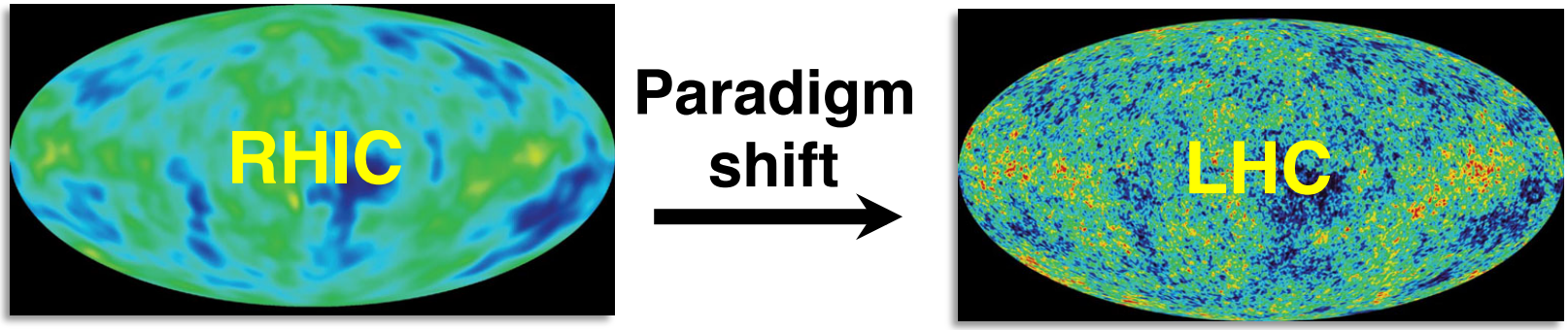
Future HI program at the LHC



- **What is the nature of the "ridge" in pp and pPb?**
- **How big is "elliptic flow (v_2)" in pp?**
- **Jet quenching in pp and pPb?**



Summary



Paradigm shift of studying strongly-couple QCD system from RHIC to the LHC

- Strong constraints on the fluid properties (η/s) of QGP
- Precision tomography with hard probes
- Discovery of smallest QGP fluid in pp and pA

CMS has demonstrated excellent and unique capability of studying heavy-ion collisions

Exciting future program is awaited to address the question “why a perfect fluid?”