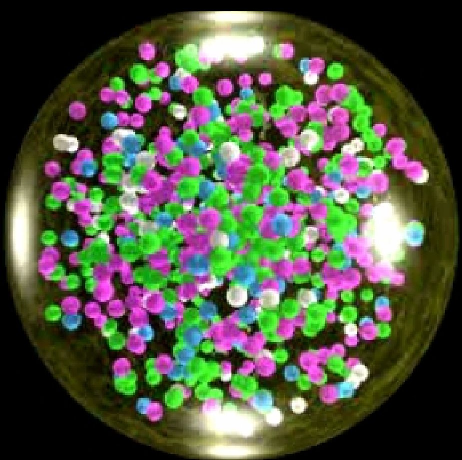
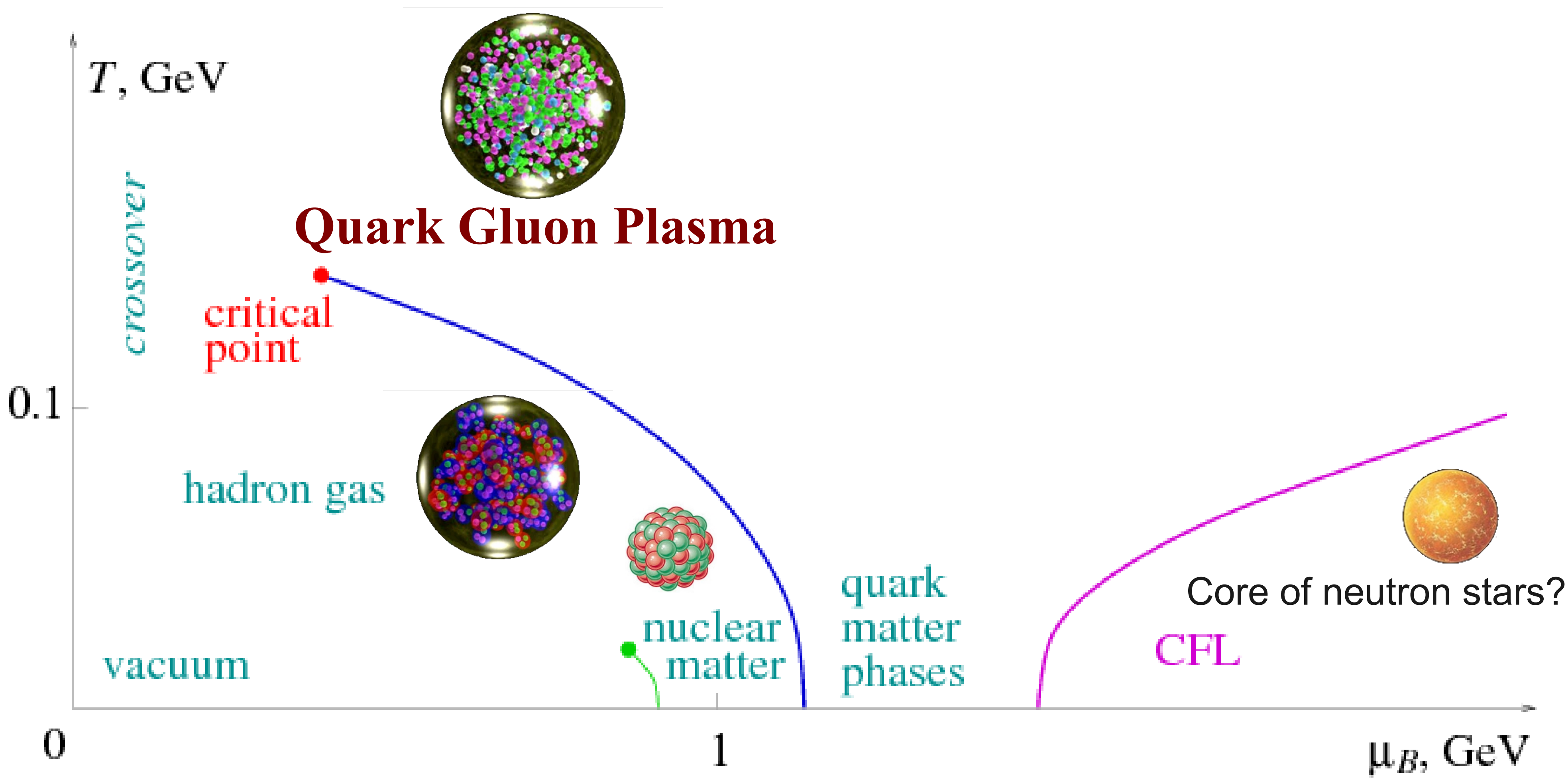
The little bang: probing the quark gluon plasma



Christine Nattrass
University of Tennessee at Knoxville

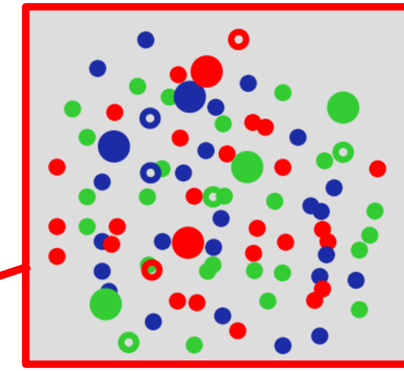
Phase diagram of nuclear matter



Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2\cdot10^{12}$K) – over a million times hotter than the core of the sun

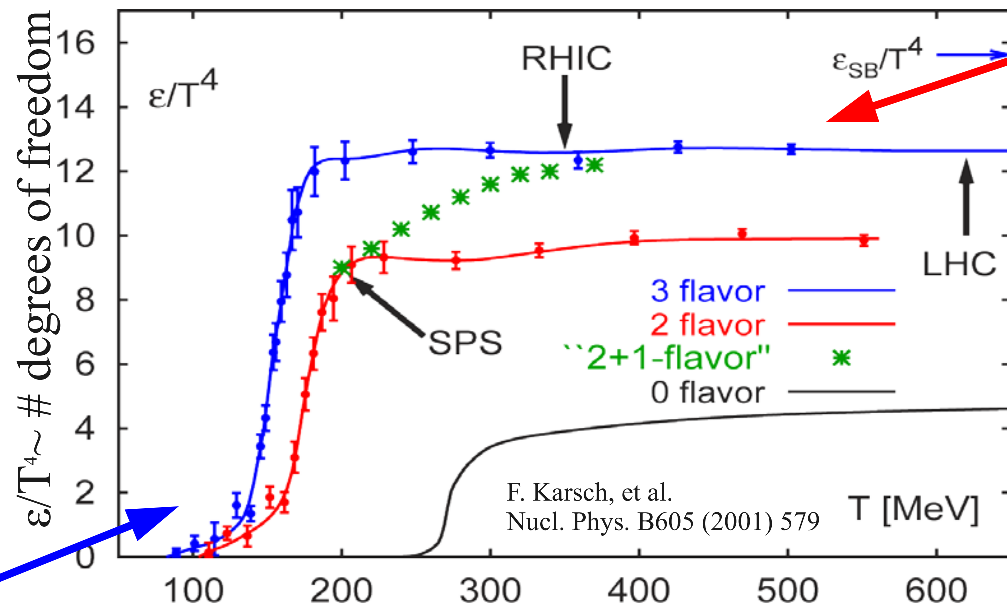
Exploring QCD at high temperatures

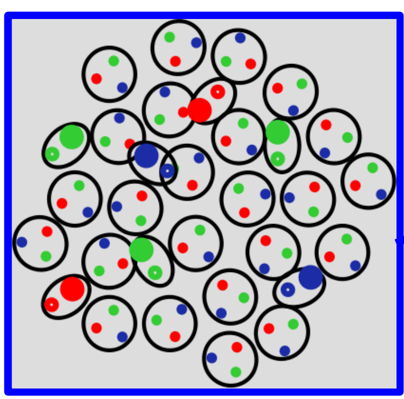
Quark-gluon plasma



Deconfined - more degrees of freedom

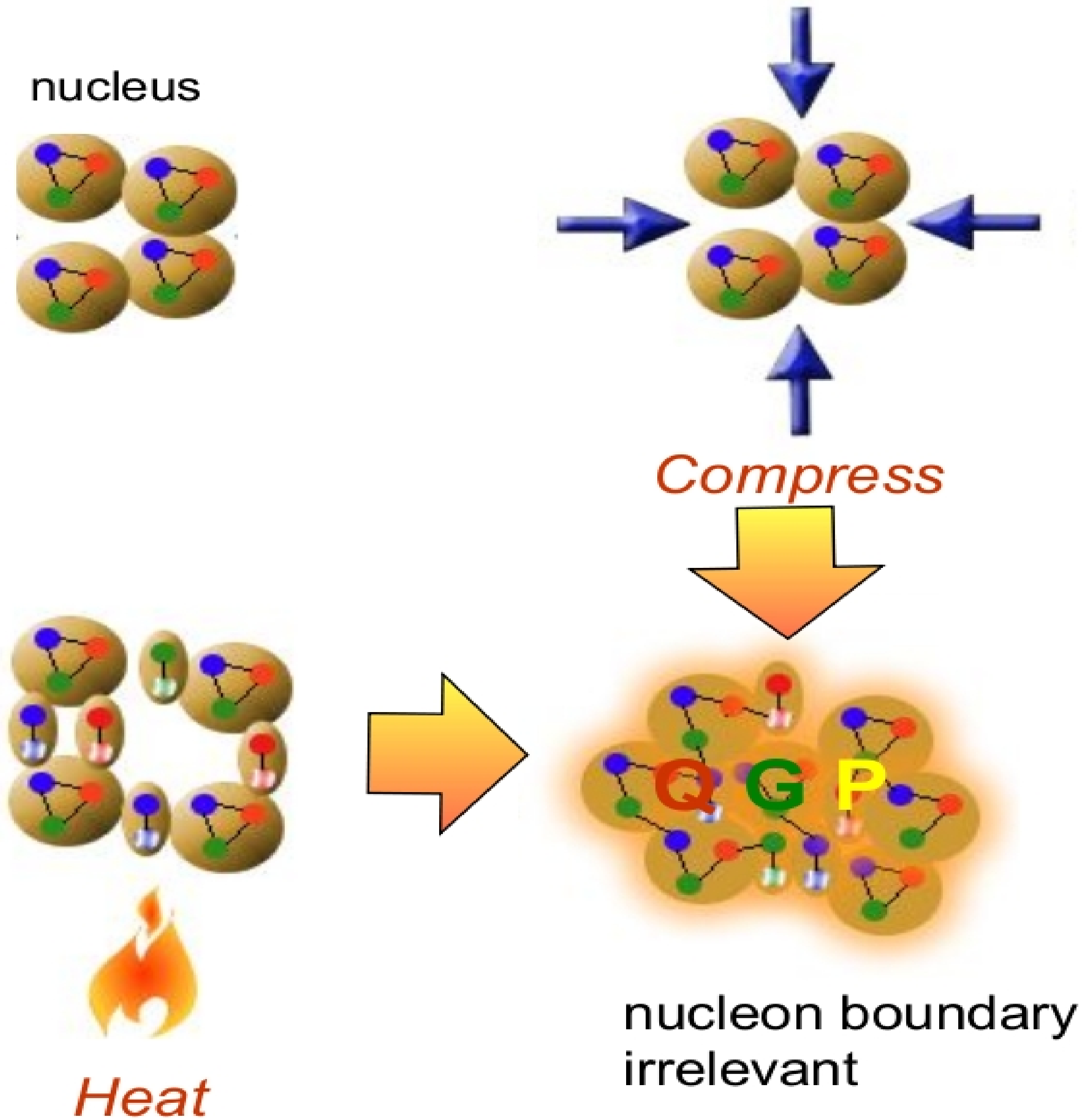
$T_C \sim 175 \pm 8$ MeV $\rightarrow \varepsilon_C \sim 0.3$ -1 GeV/fm^3



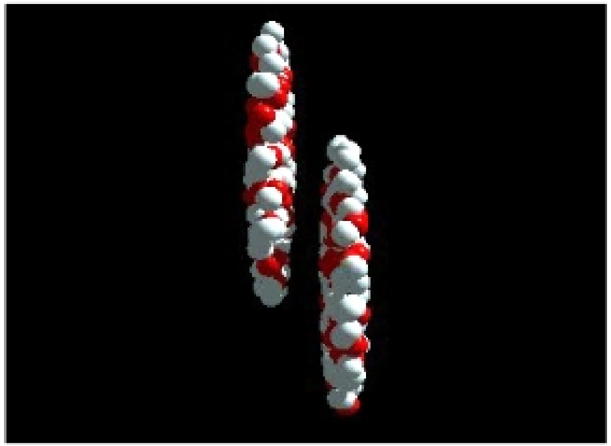


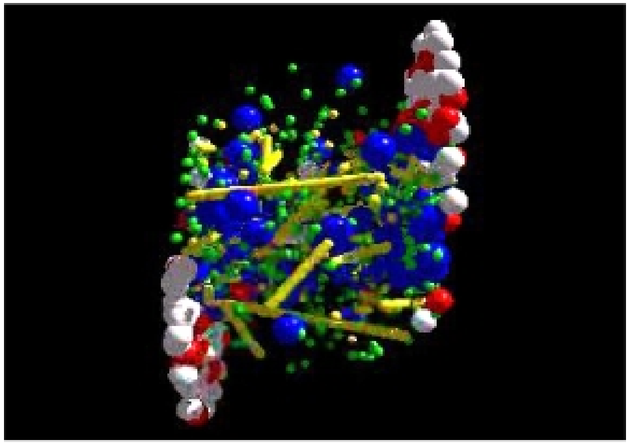
Confined - fewer degrees of freedom

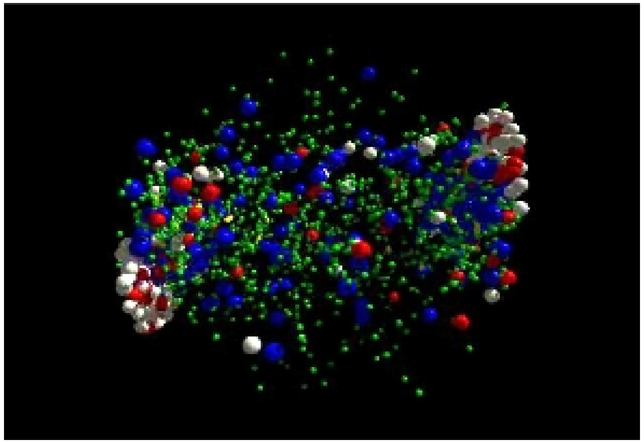
How to make a Quark Gluon Plasma

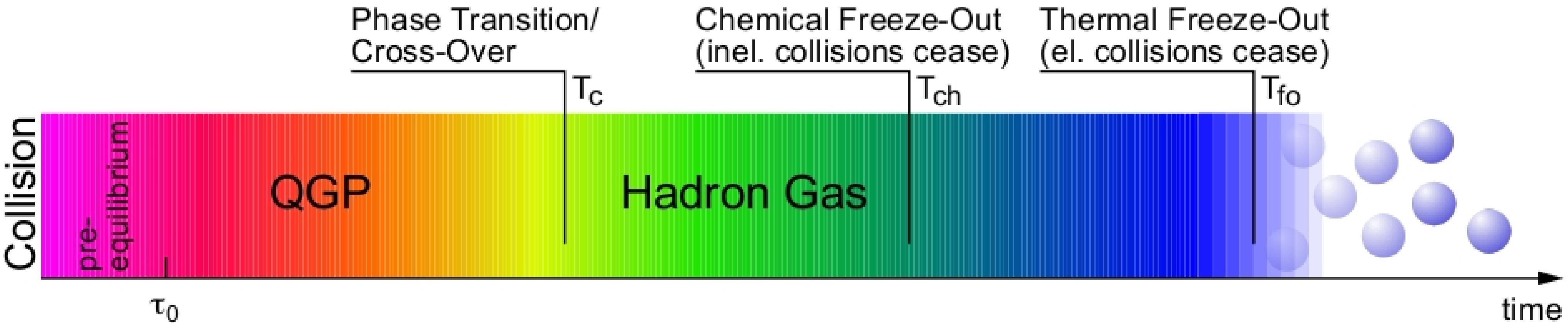


The phase transition in the laboratory

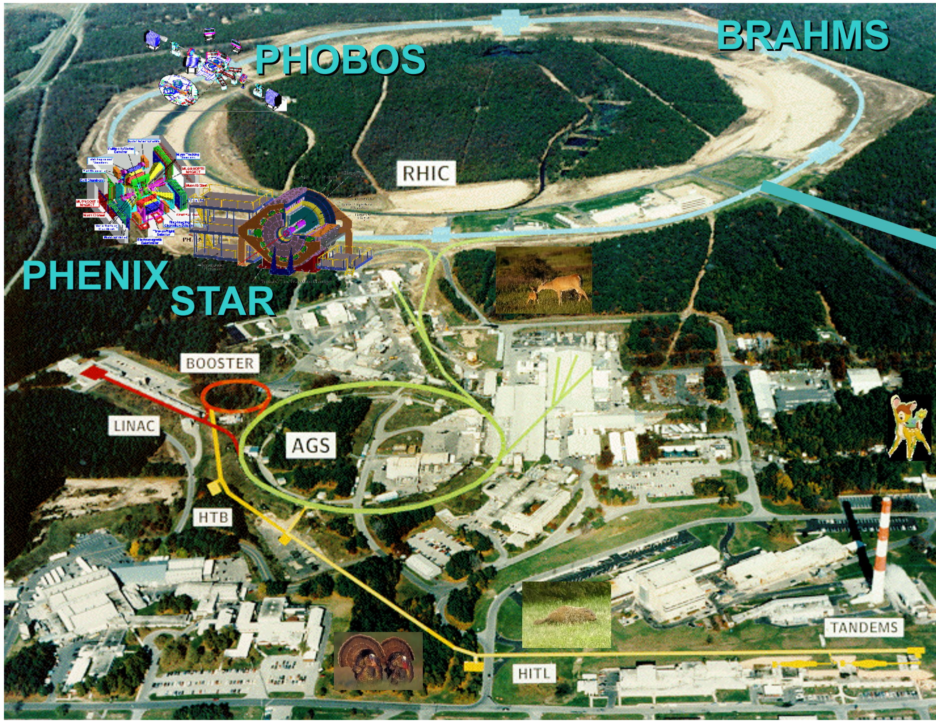






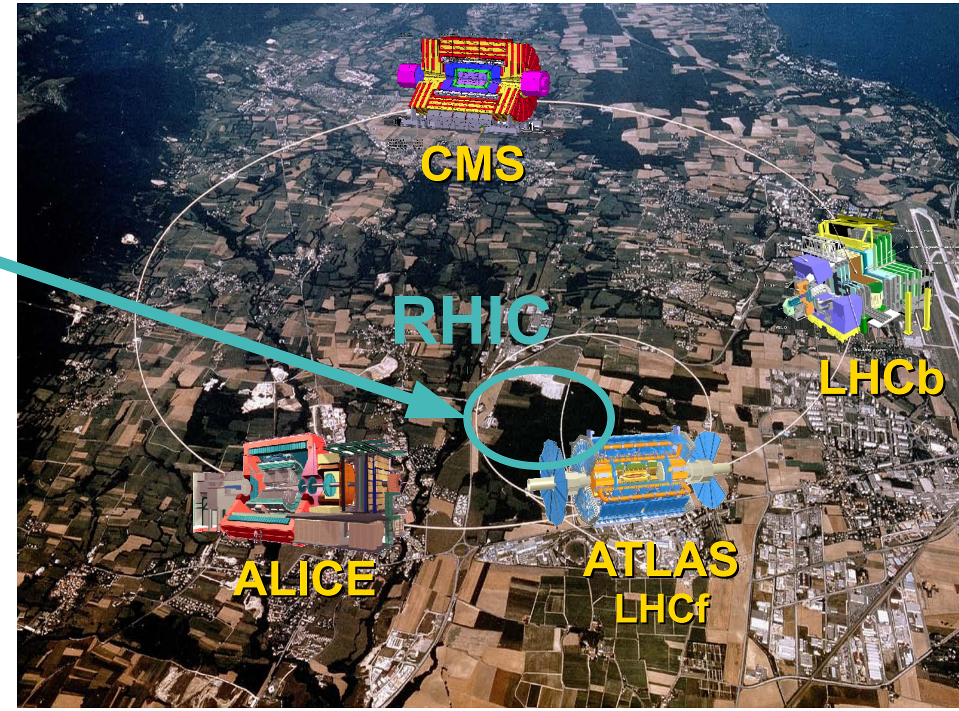


Relativistic Heavy Ion Collider

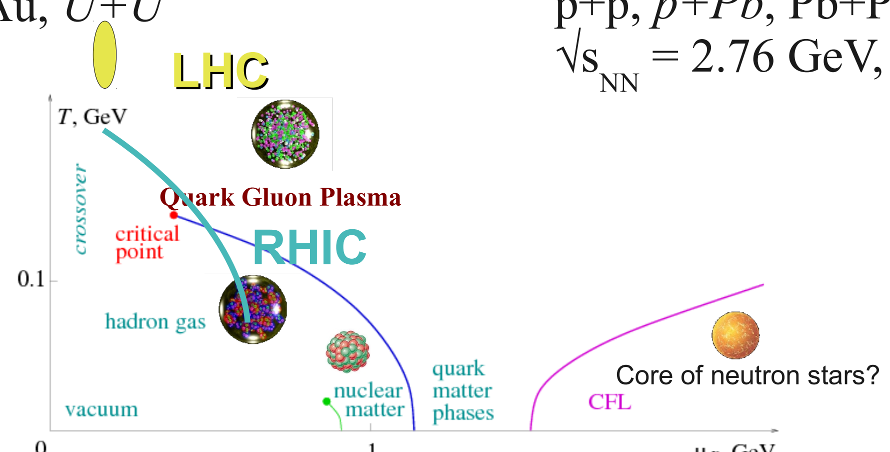


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s}_{NN}$ = 9 - 200 GeV

Large Hadron Collider



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s}_{NN}$ = 2.76 GeV, *5.5 TeV*



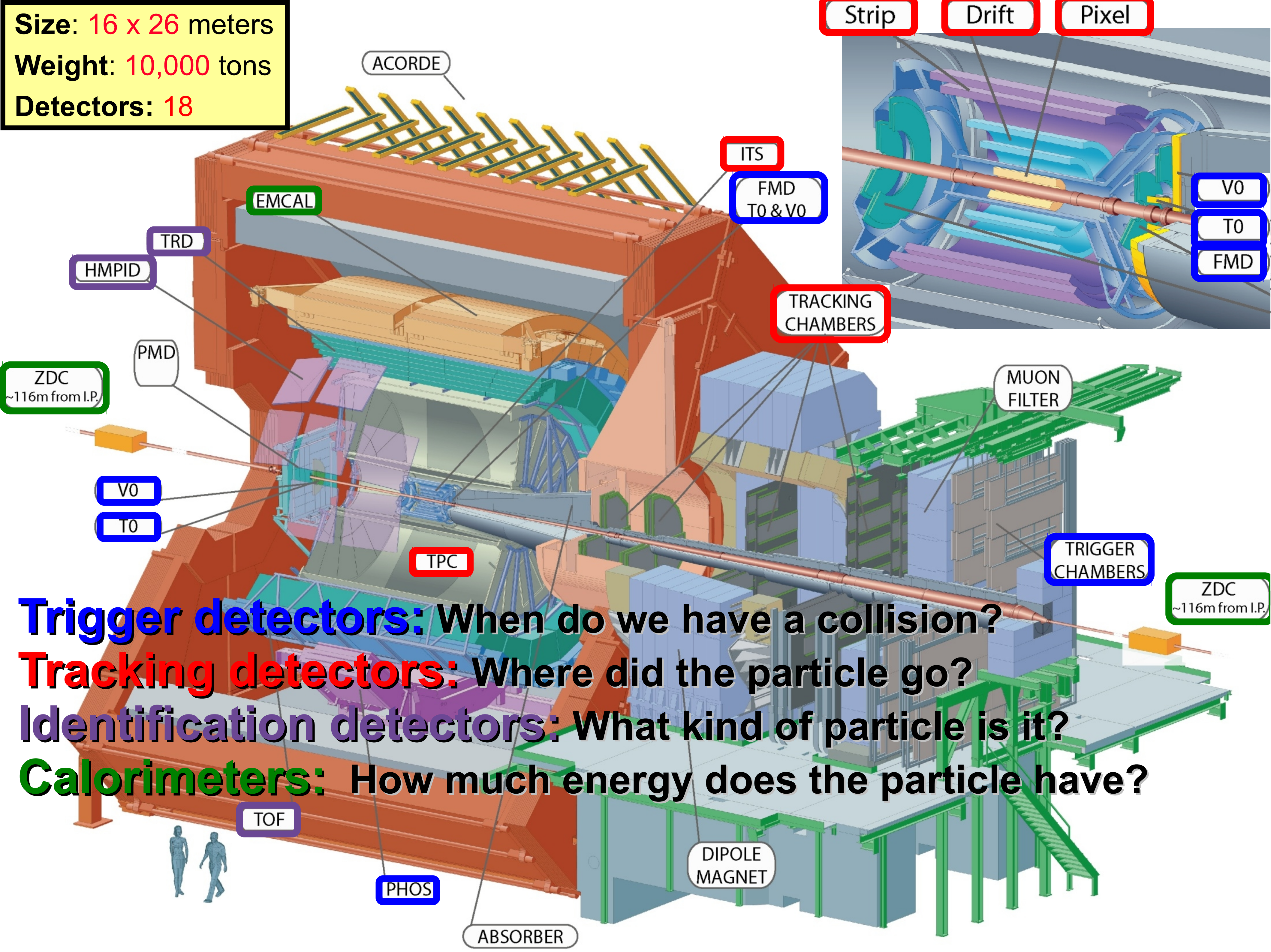
Comparison of colliders

	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600, ??	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	~15	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

RHIC and LHC:

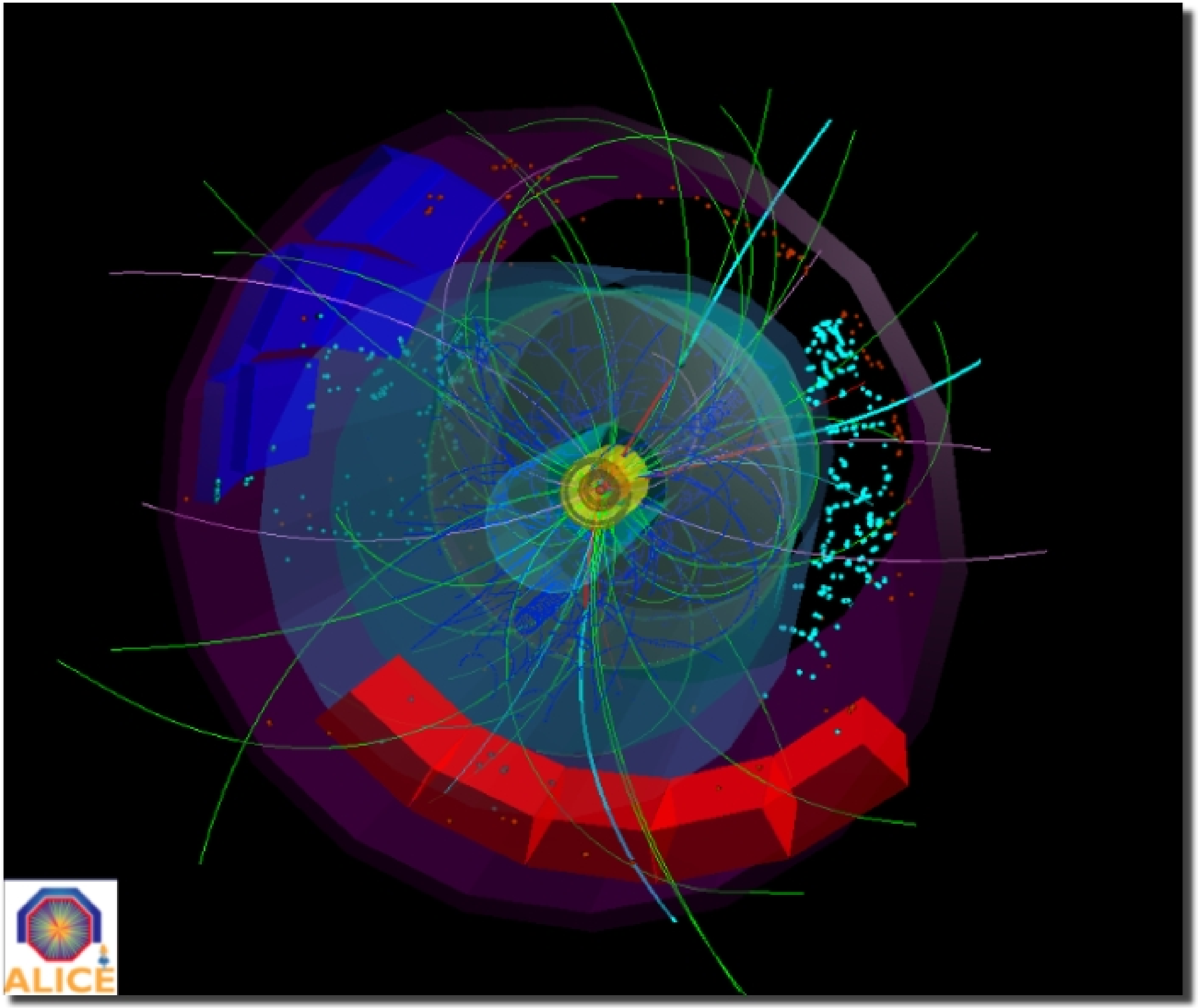
Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$ = 9 GeV –5.5 TeV)

To discover the properties of hot nuclear matter at T ~ 150 –600 MeV



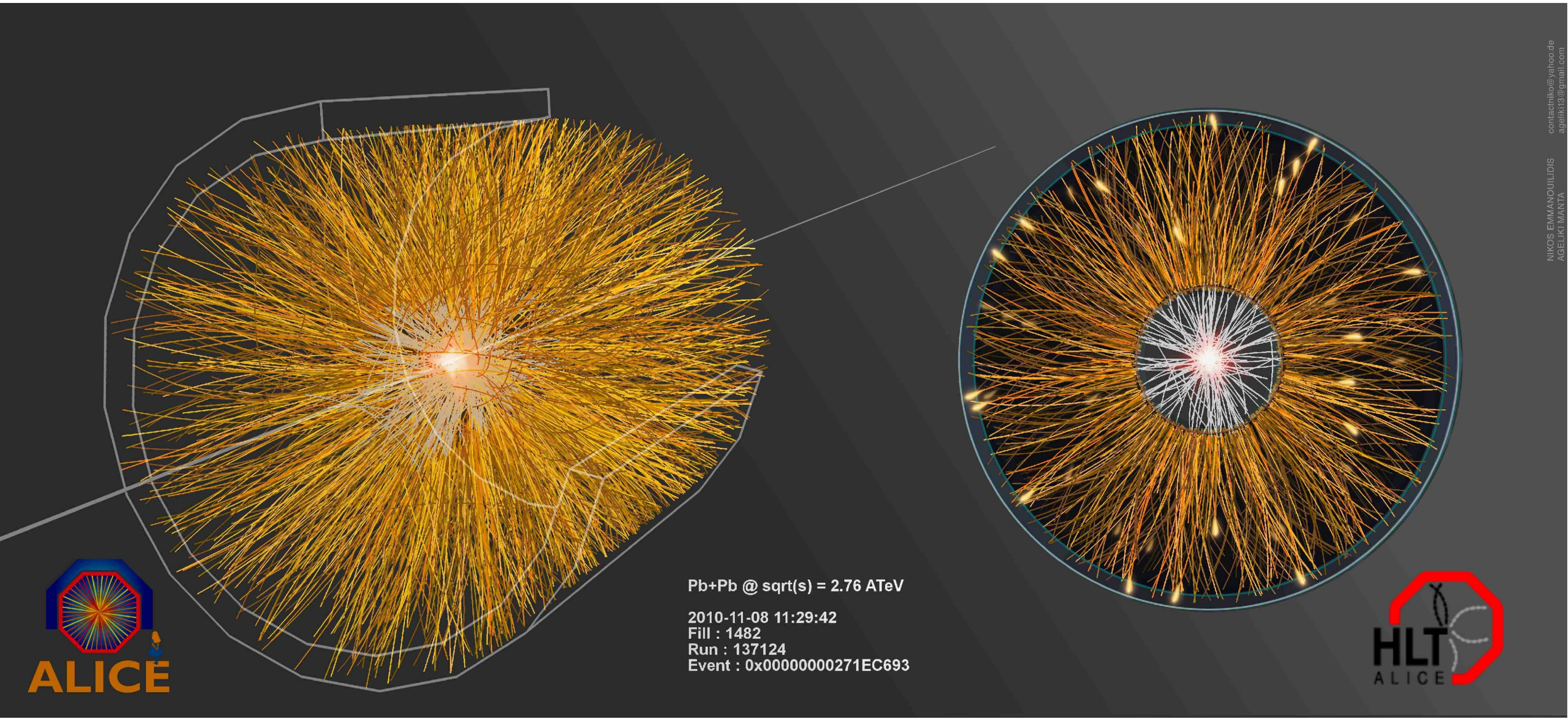
Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
V0
T0
FMD
EMCAL
TRD
HMPID
PMD
ZDC
~116m from I.P.
TRACKING
CHAMBERS
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?
TOF
PHOS
ABSORBER
DIPOLE
MAGNET

p+p collisions



3D image of each collision

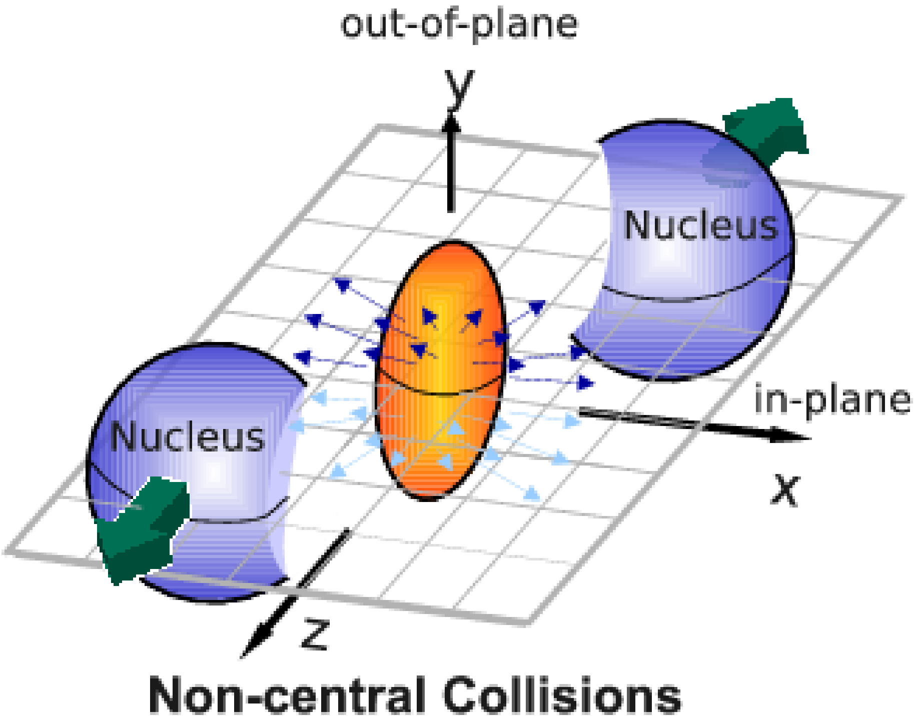
Pb+Pb collisions

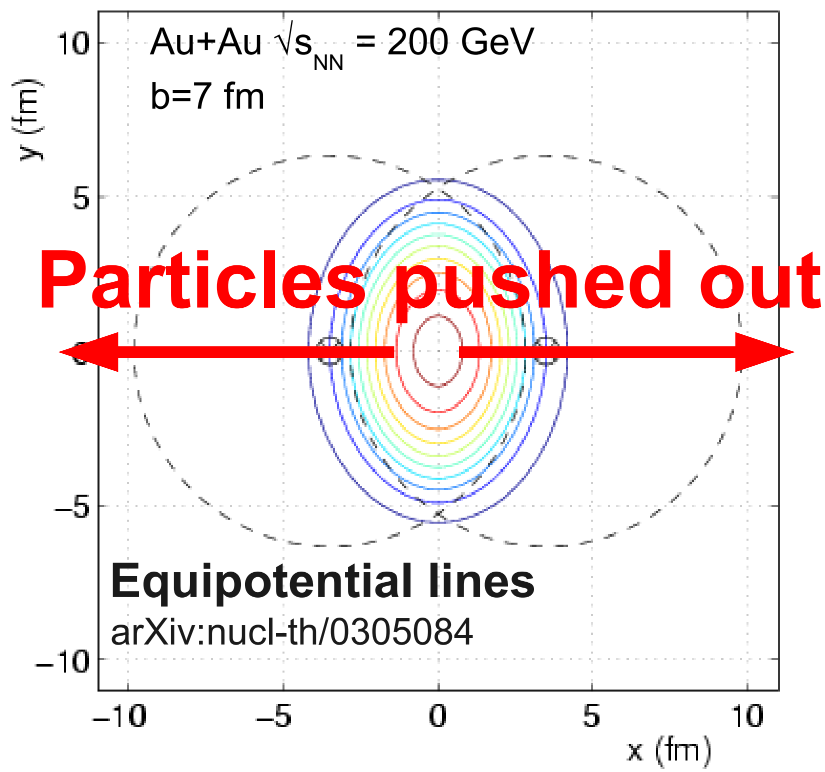


How do we study a QGP?

Tool	**Analogous to:**
Hard probes – jets, heavy flavor (charm & beauty), direct photons	Spectroscopy – probe travels through the medium, changes indicate interaction with the medium
Hydrodynamical flow	Measurements of viscosity
Particle ratios	Measuring chemical composition in a solution
Thermal photons, charmonium	Thermometer

If we have a fluid...



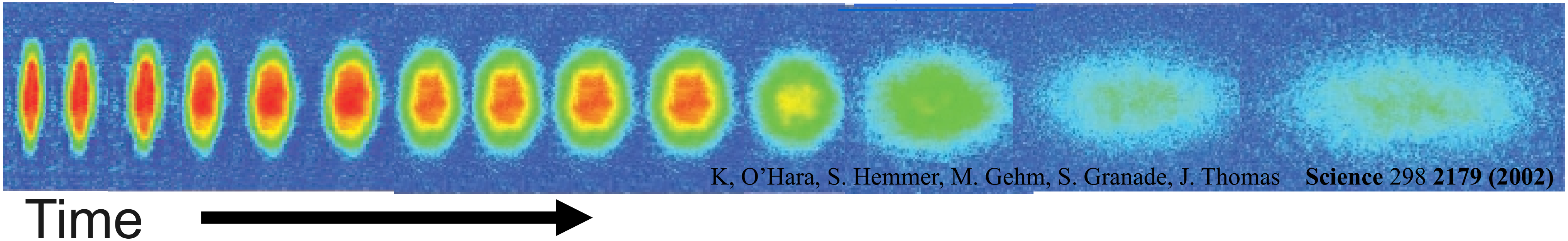


- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

$$\frac{d^2N}{dp_T\,d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$

What does it mean?

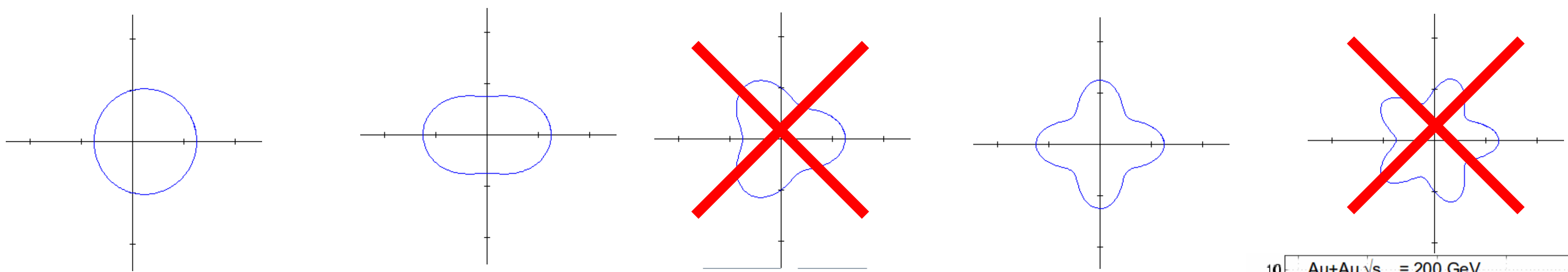
Same phenomena observed in gases of strongly interacting atoms



Initial state anisotropies converted to final state anisotropies

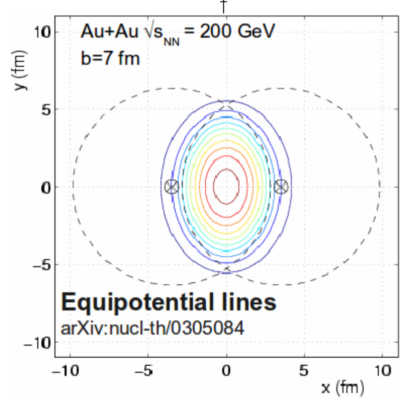
Fourier decomposition:

$$\frac{d^2 N}{dp_T\, d\phi} \approx 1 + 2 v_1 \cos(d\phi) + 2 v_2 \cos(2d\phi) + 2 v_3 \cos(3d\phi) + 2 v_4 \cos(4d\phi) + 2 v_5 \cos(5d\phi) + \ldots$$

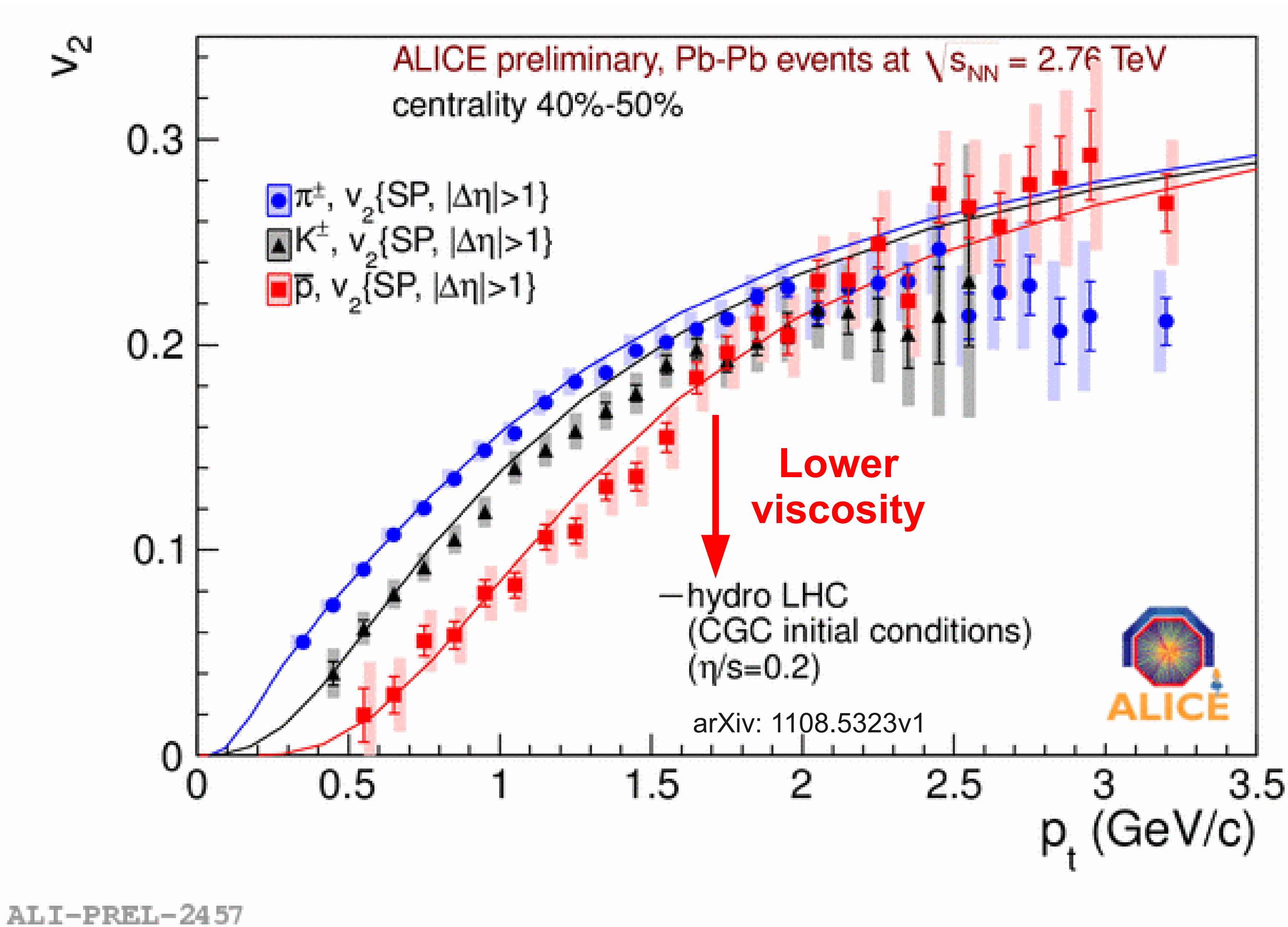


Offset measured

Nuclei are symmetric → No odd coefficients

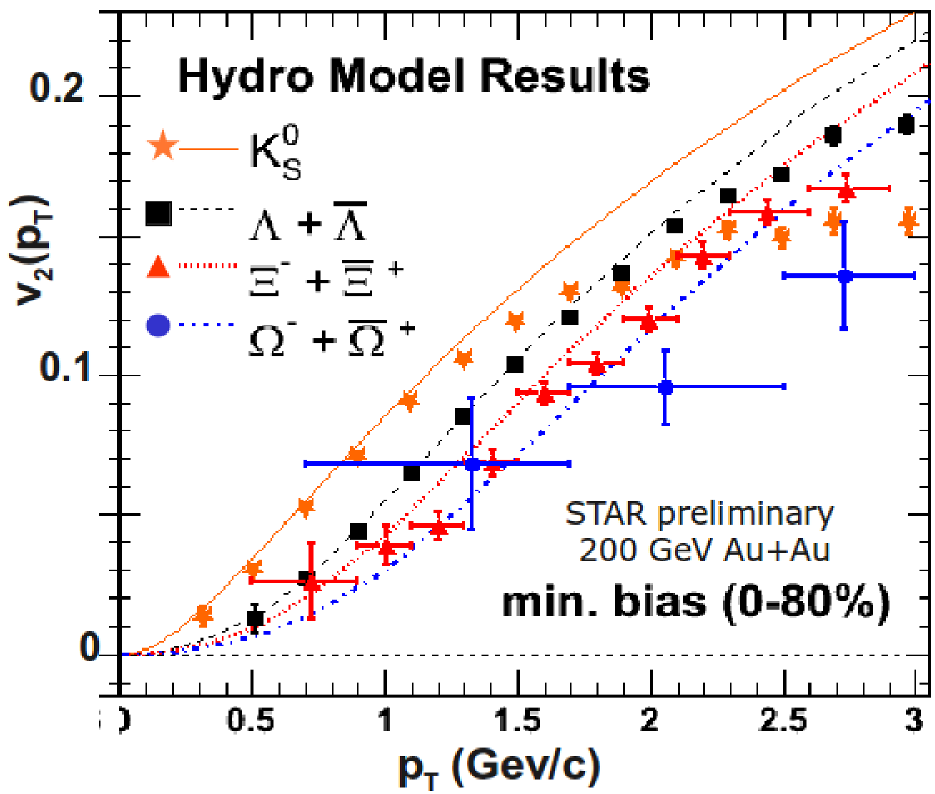


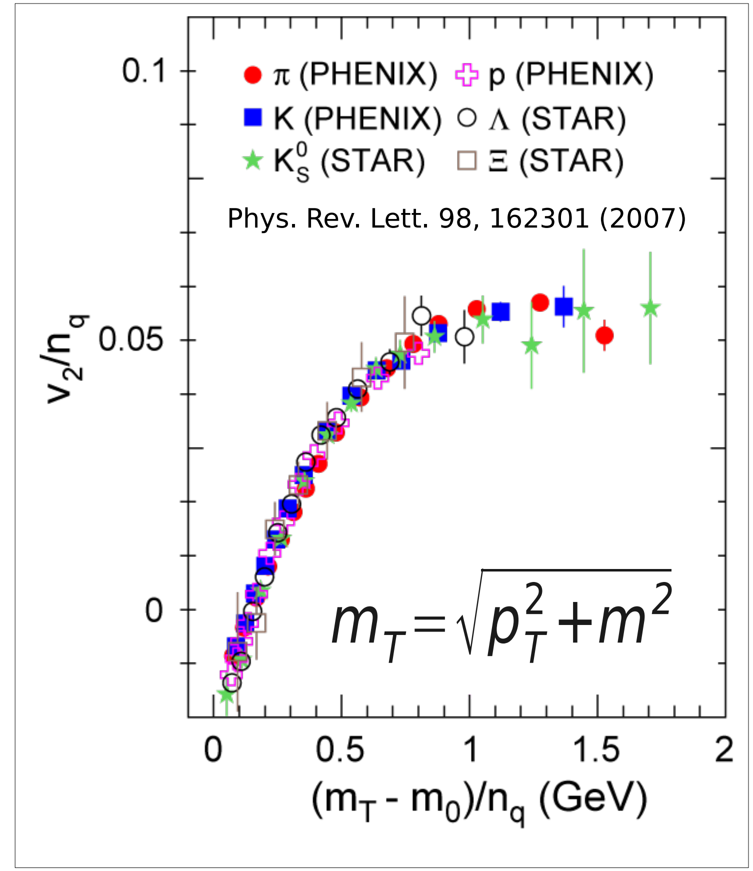
Does this describe the data?



Yes!

More data





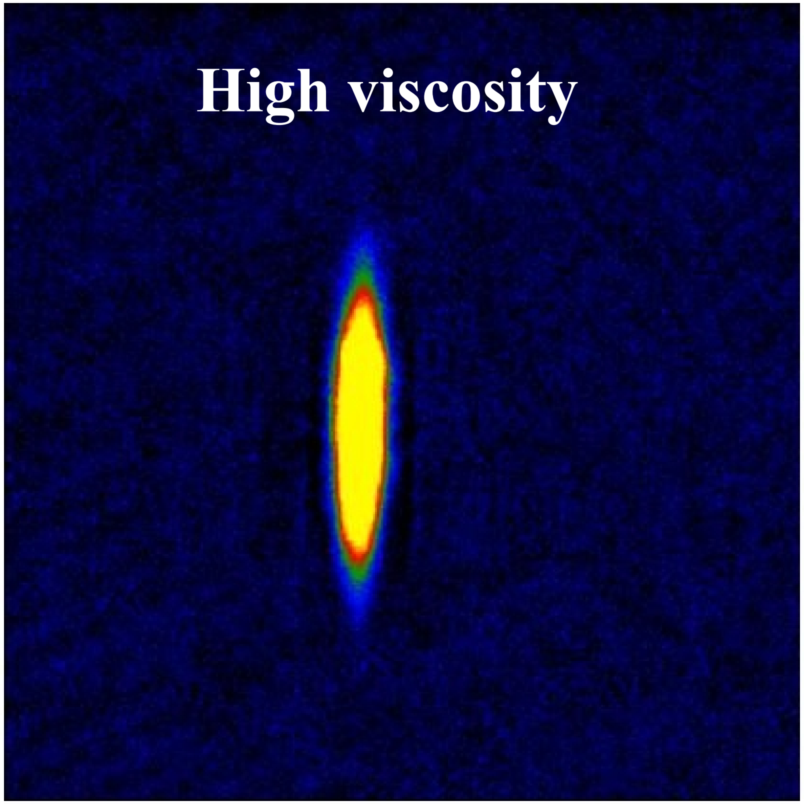
Mass ordering:
$v_2(K) > v_2(\Lambda) > v_2(\Xi)$

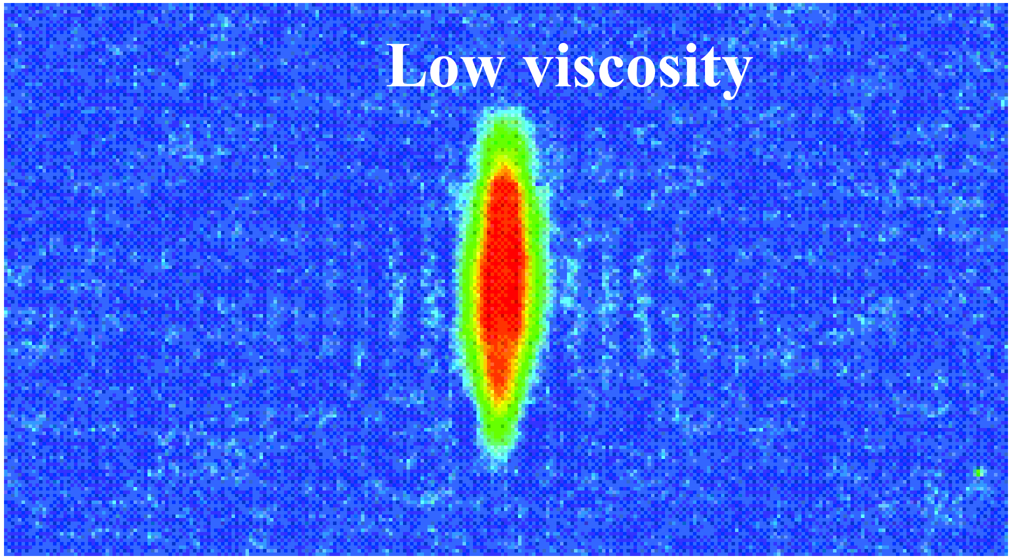
$v_2(p_T^{hadron})\ \mu\ n_{quark} v_2(p_T^{quark})$

We have a liquid of quarks and gluons!

What does this mean?

- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**





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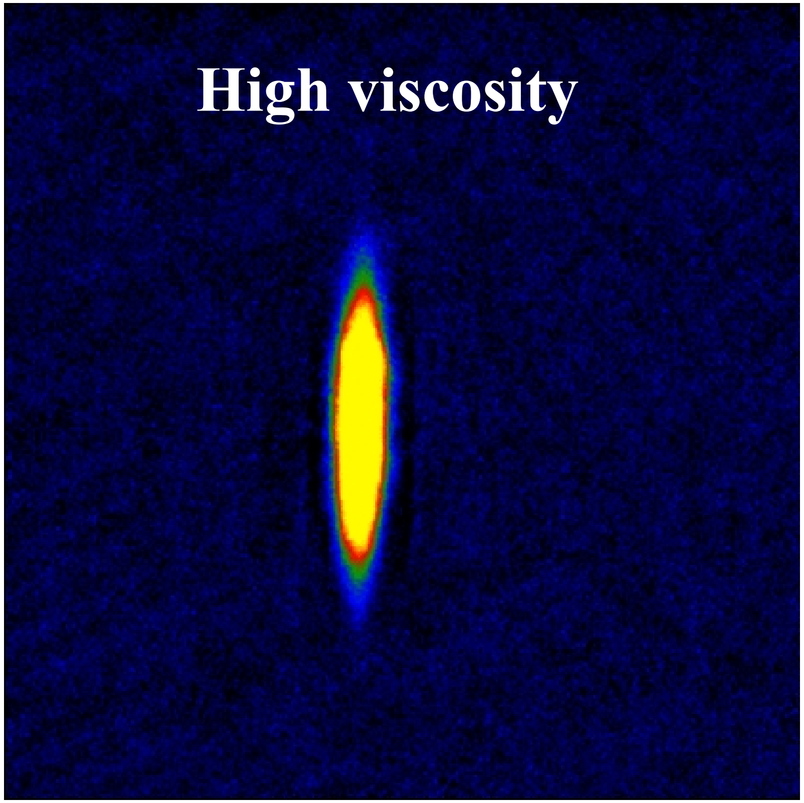
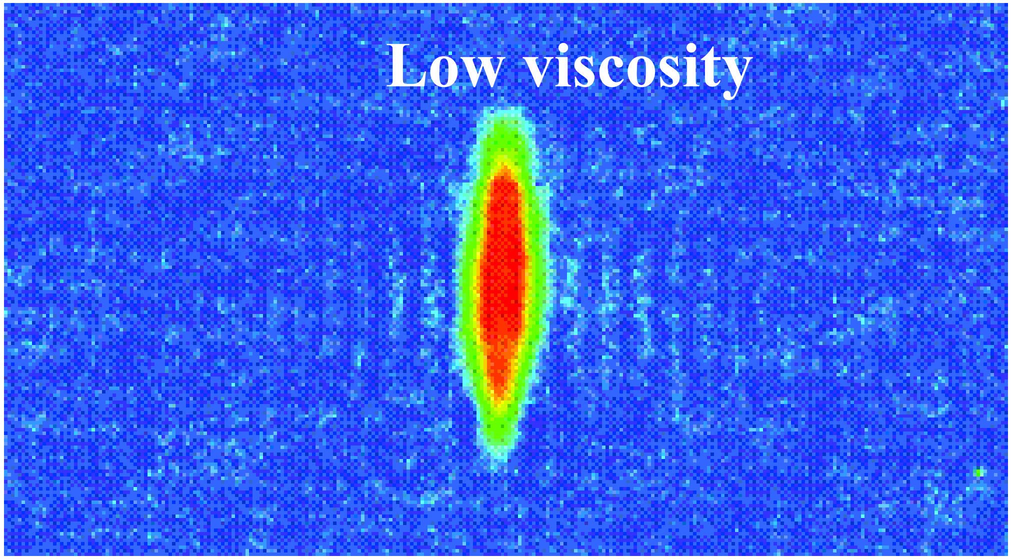




The Quark Gluon Plasma has a very low viscosity

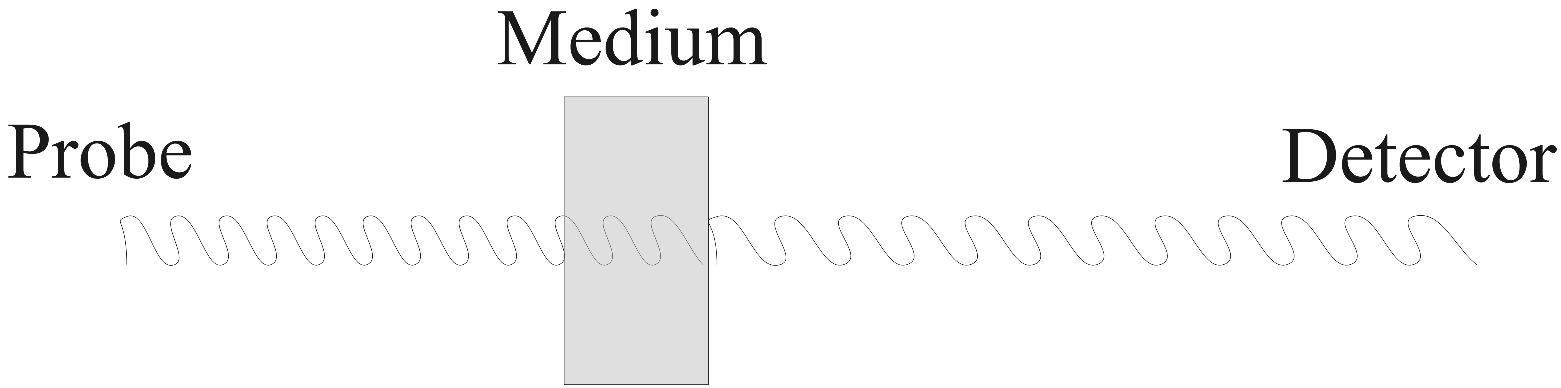
But what does this mean?

- Hydrodynamics works →
  - (local) thermalization
  - image of the initial state
- Really low viscosity
  - Near AdS/CFT bound
  - $\eta/S \sim 1/4\pi$

The QGP is the perfect liquid!

(not the gas of "free" quarks and gluons we expected)

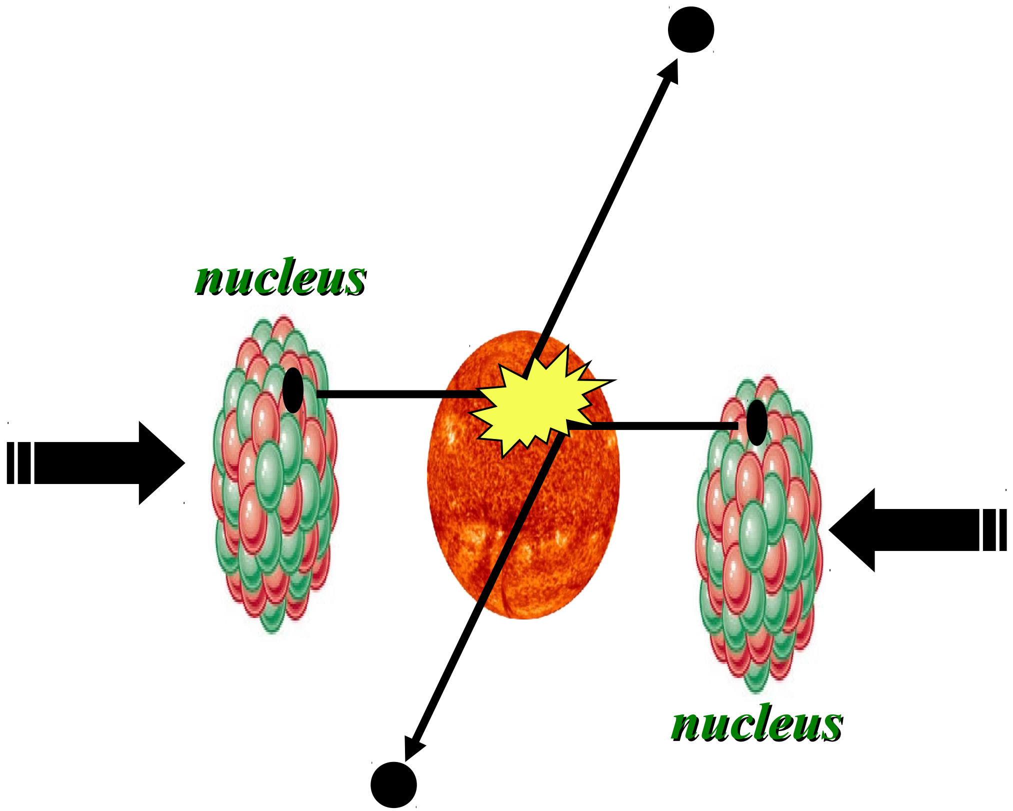
Probing the Quark Gluon Plasma



Want a probe which traveled through the collision

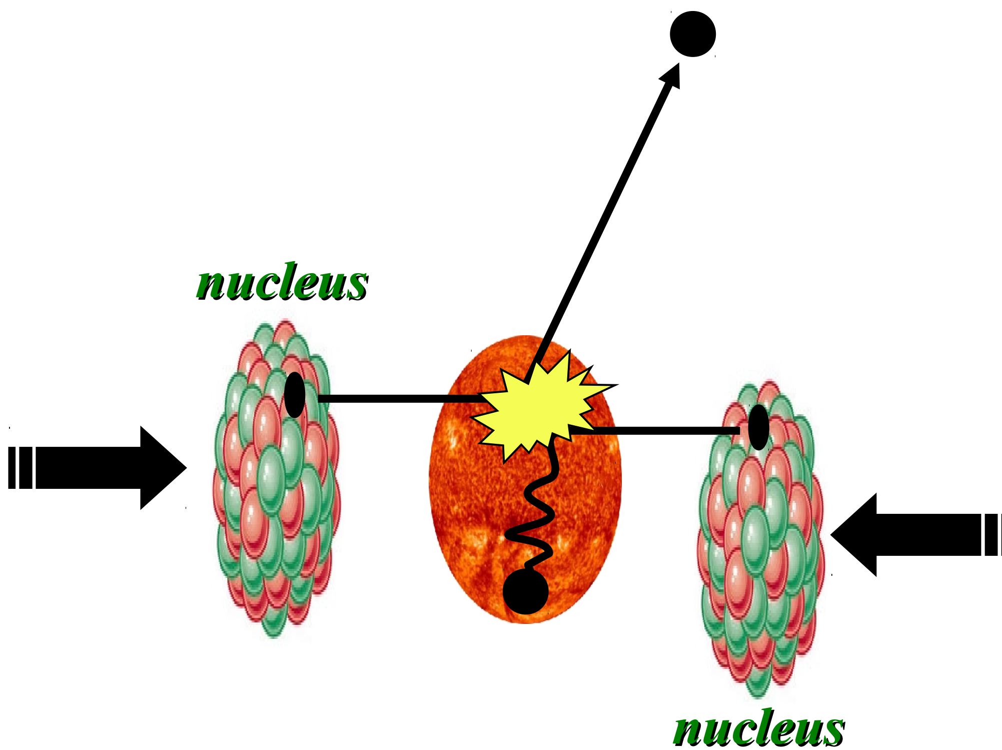
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

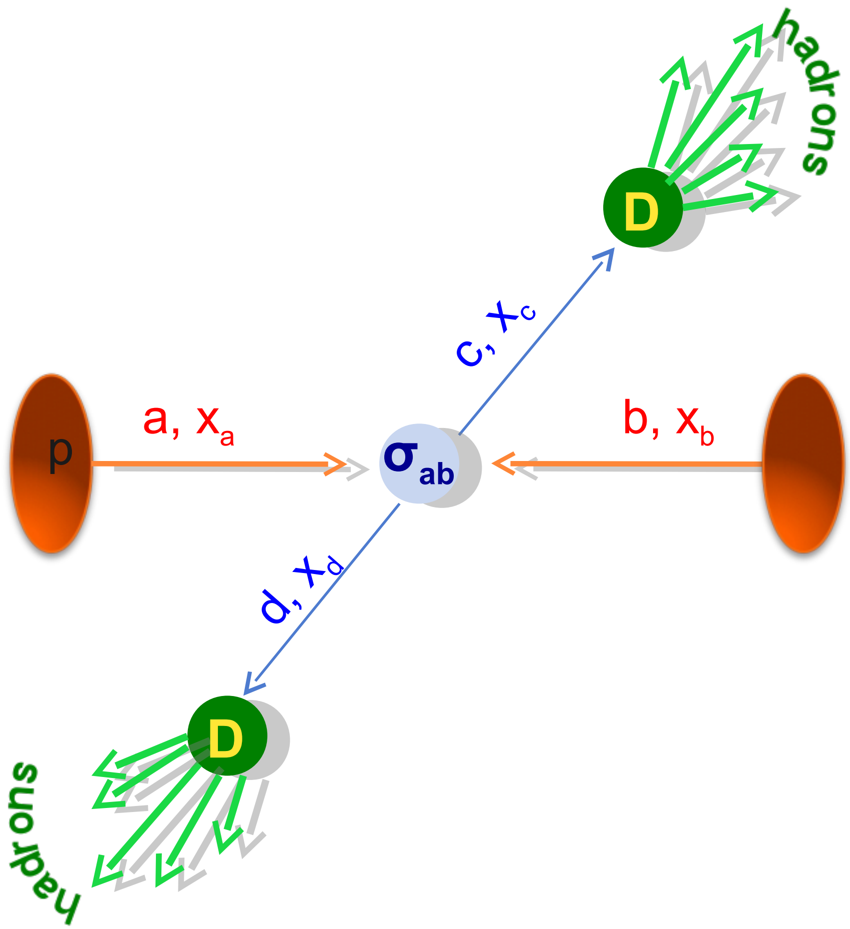


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

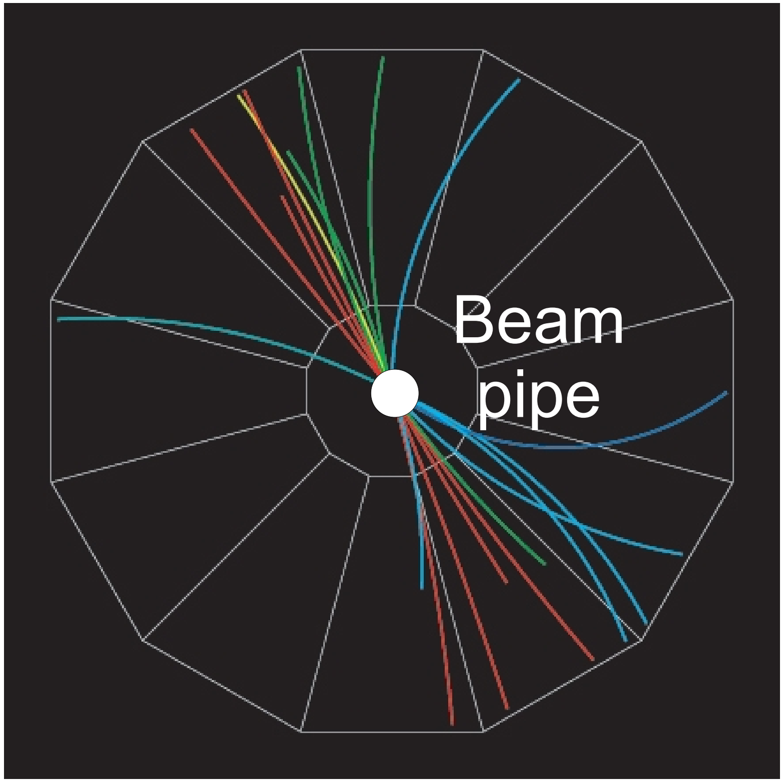
Hard probes

- Hard probes - energies involved (Q^2) are large, high confidence in theory calculations (perturbative quantum chromodynamics)
  - Jets – quarks and gluons from a hard parton scattering, most commonly occurring as di-jets
  - Heavy quarks – charm and beauty quarks
  - Direct photons – photons created in the collision, not expected to interact with the medium → control

Jets



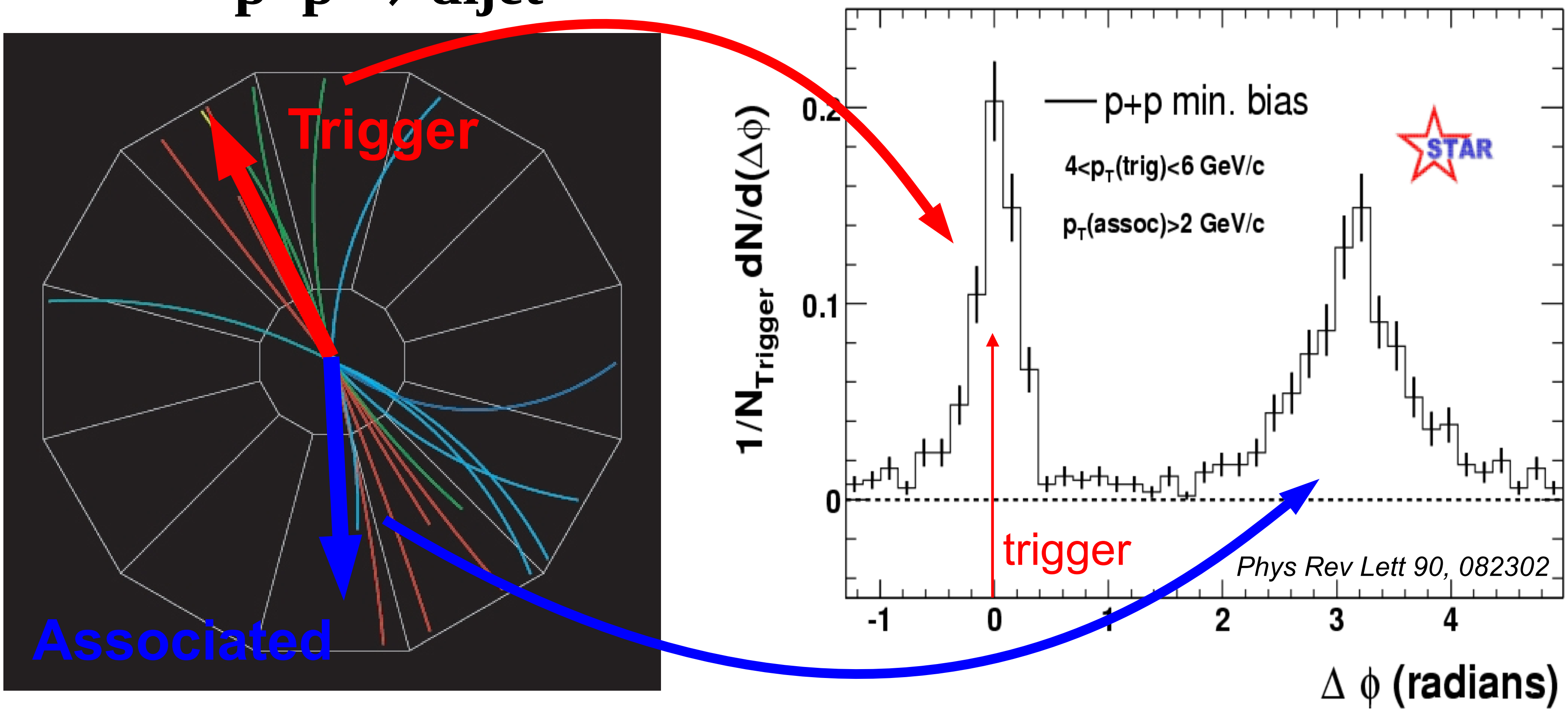
p+p → dijet



Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

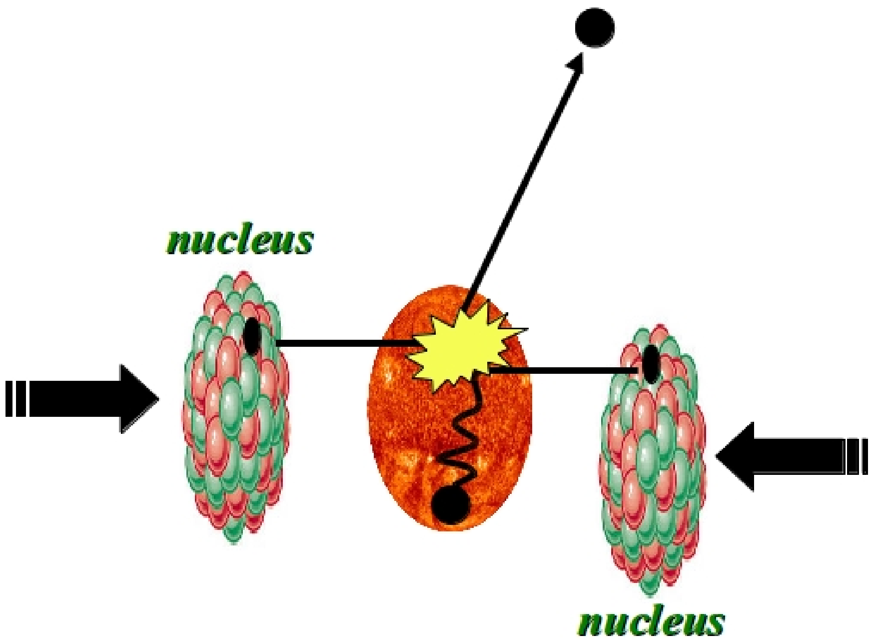
Jets – azimuthal correlations

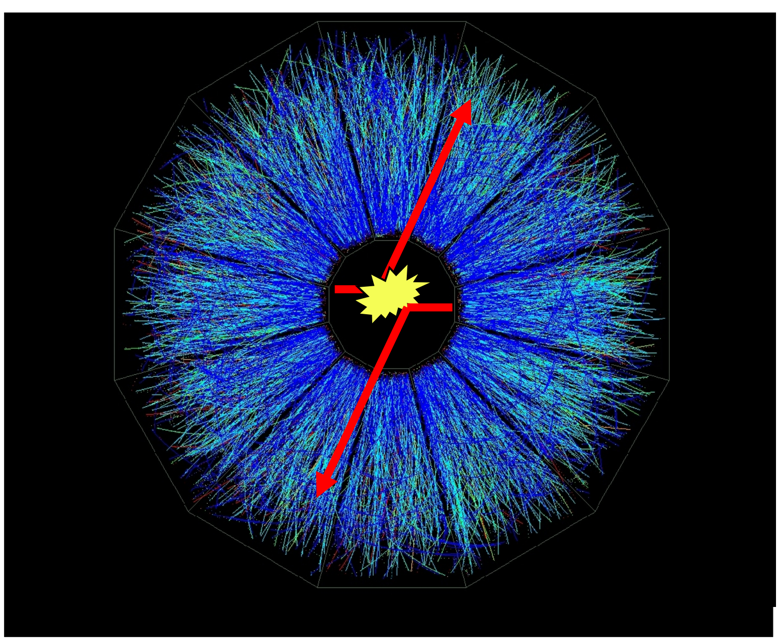
p+p → dijet

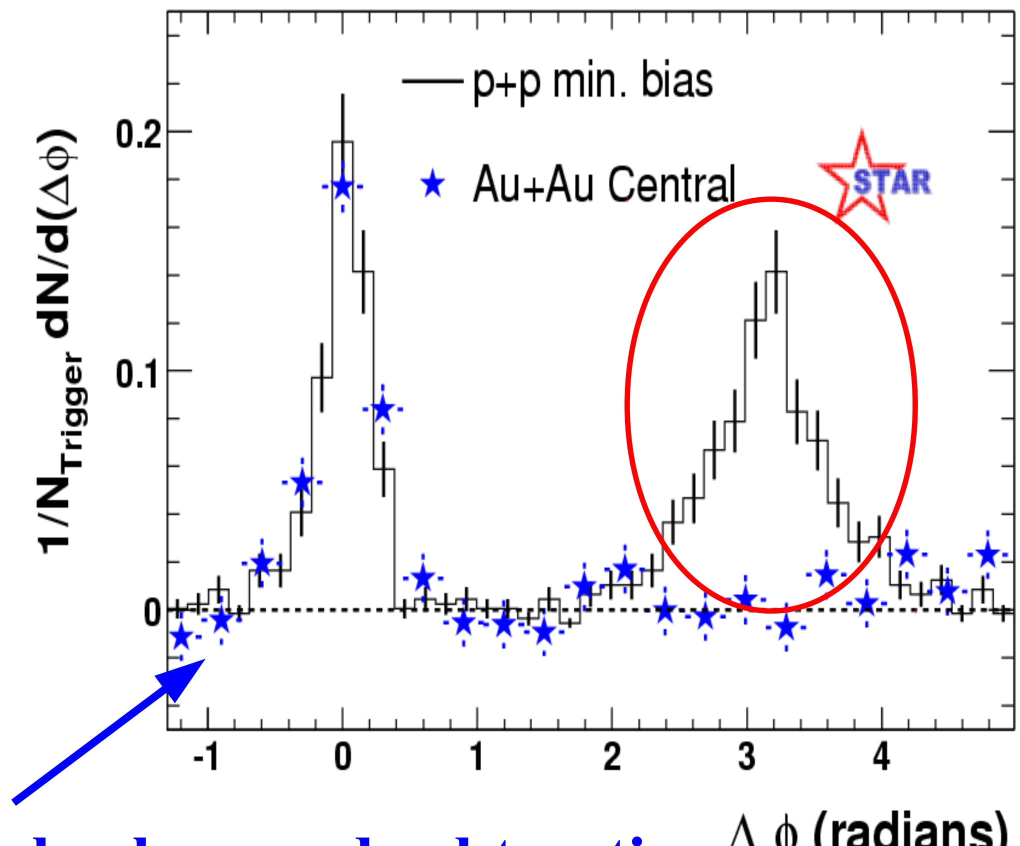


Select high momentum particles → biased towards jets

Jets – azimuthal correlations







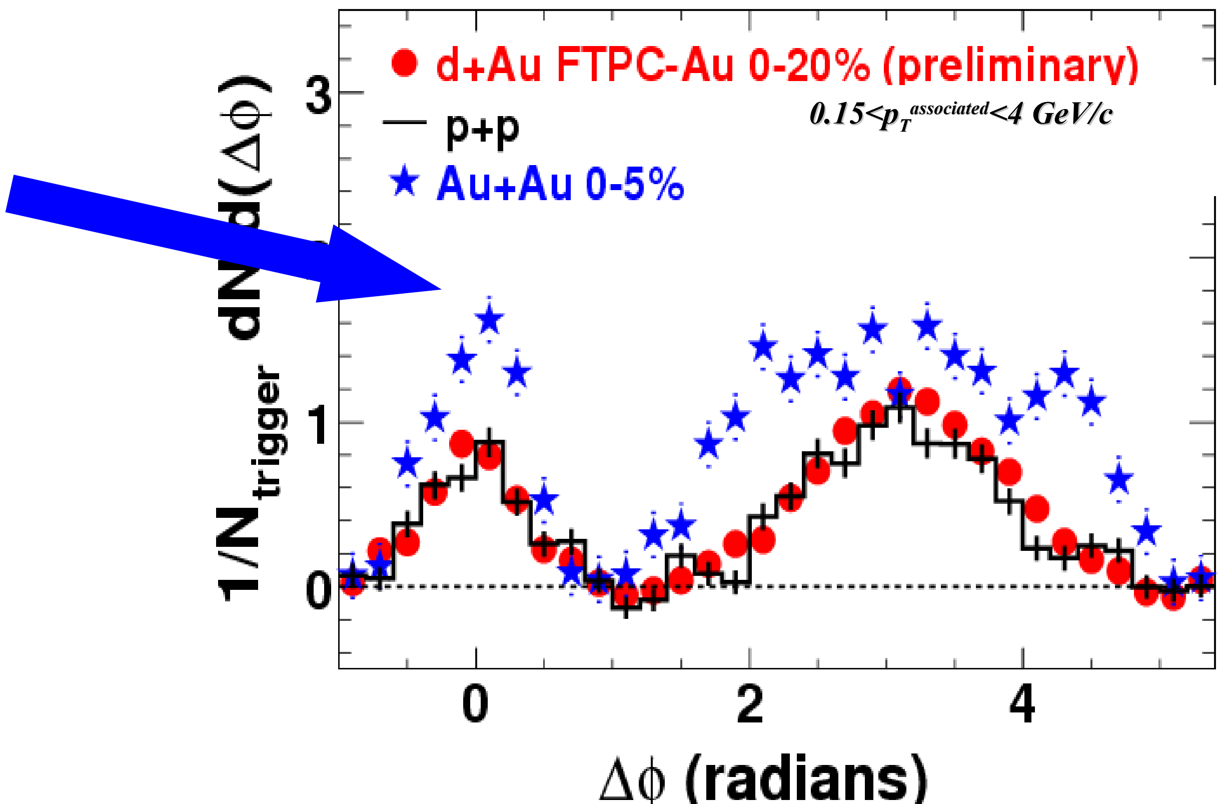
Big background subtraction

Jet quenching – absorption of jets by the medium

But at lower momenta...

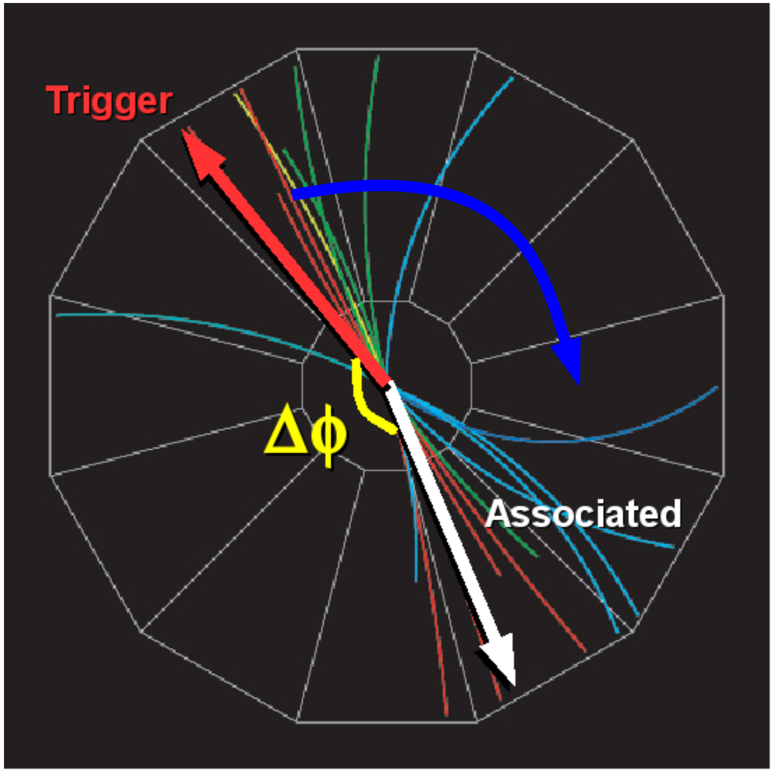
Near-side shows modification

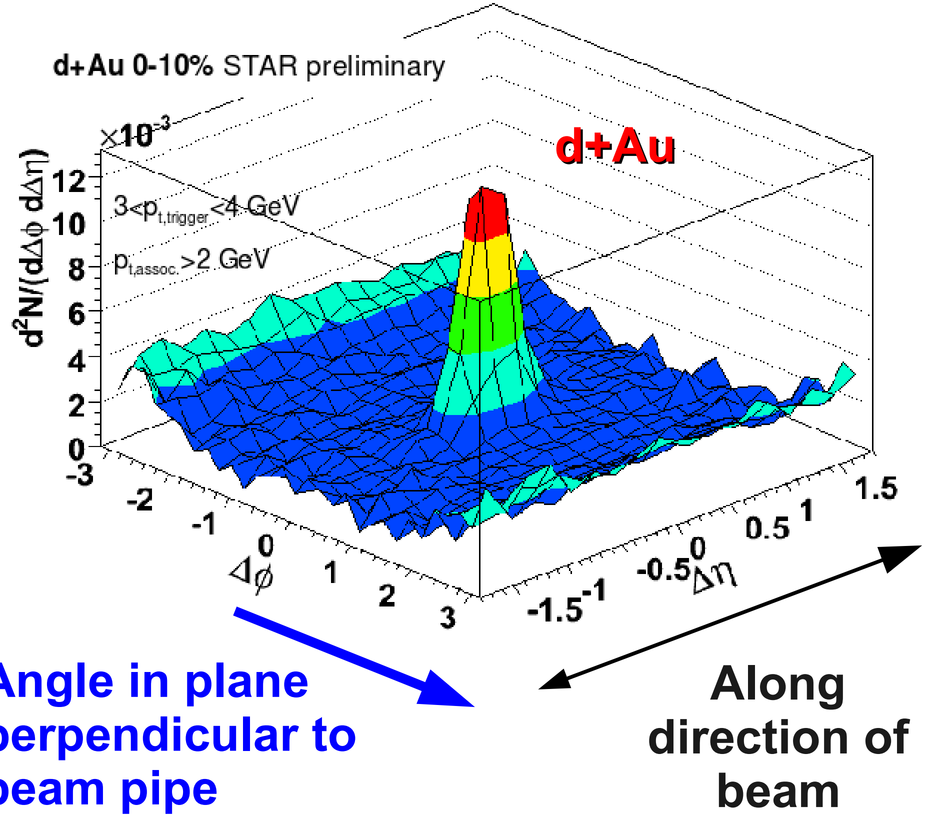
Excess yield in Au+Au relative to p+p



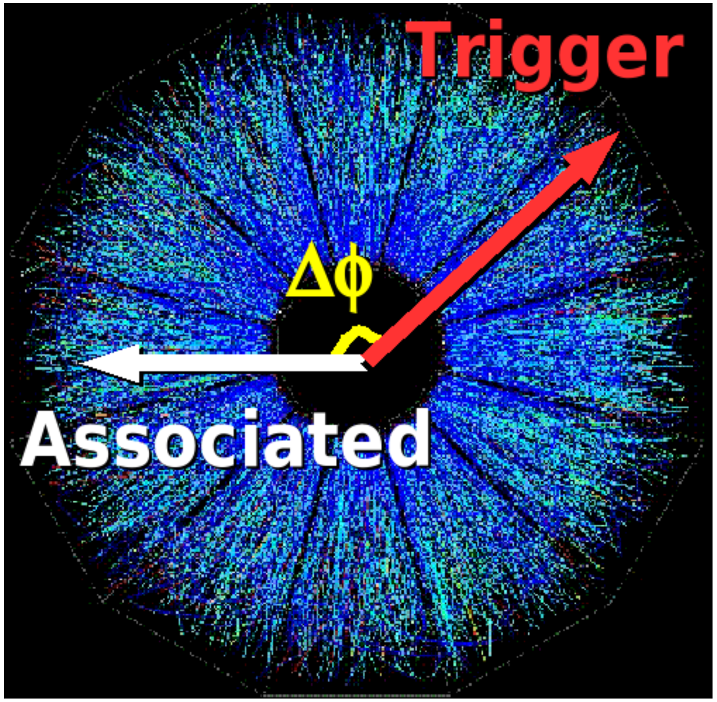
STAR PRL **95** (2005) 152301

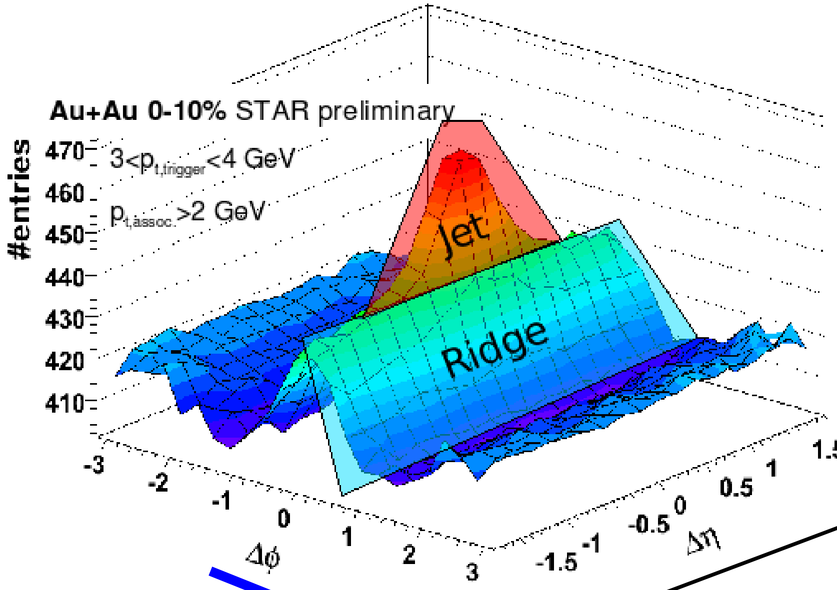
Looking in two dimensions





In two dimensions in Au+Au

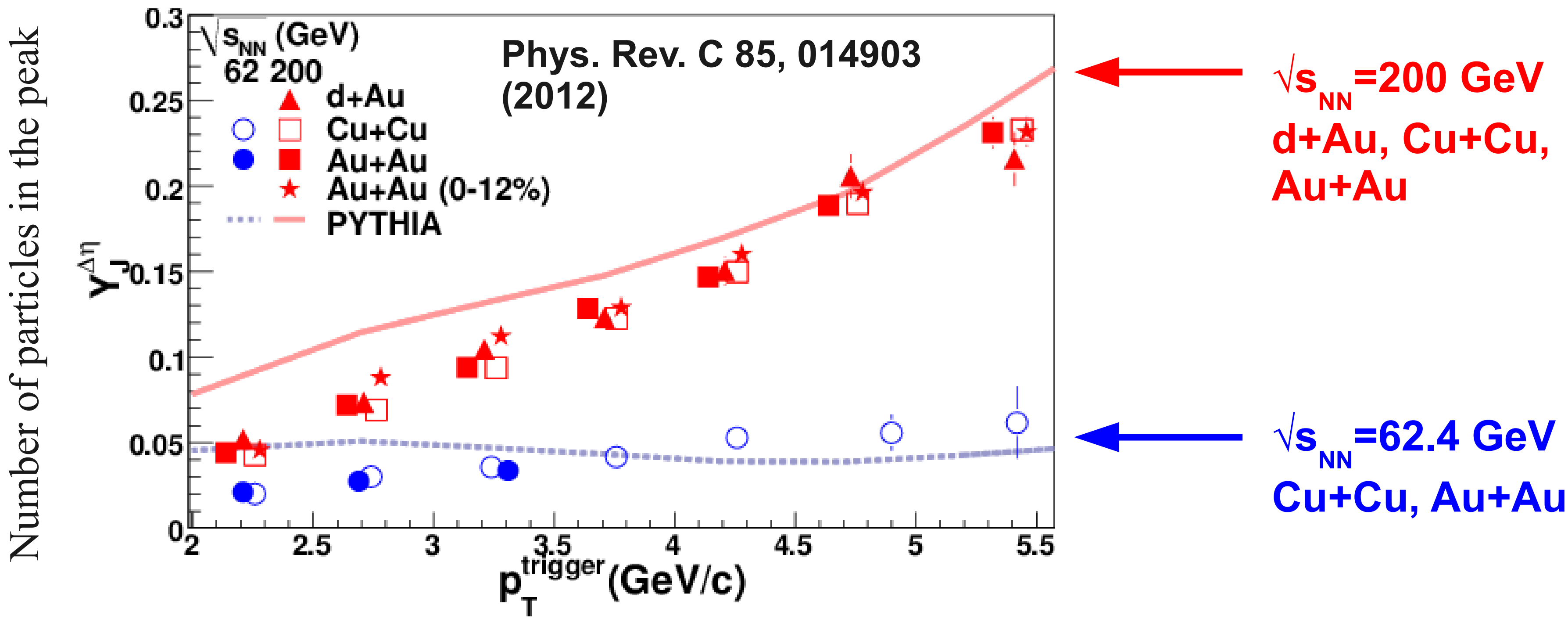




Angle in plane perpendicular to beam pipe

Along direction of beam

The jet-like correlation



- Appears to be dominantly produced by vacuum fragmentation
  - No difference between collision systems
  - Consistent with QCD-inspired Monte Carlo (PYTHIA)

Ridgeology (2006-2011)

- Hundreds of papers on the ridge, over 10 distinct production mechanisms proposed
  - Gluon brehmsstrahlung
  - QCD color fields
- Measured just about everything possible
  - Size, particle composition, collision species dependence, collision energy dependence, size relative to the reaction plane, momentum dependence

Measurements I worked on

Background subtraction

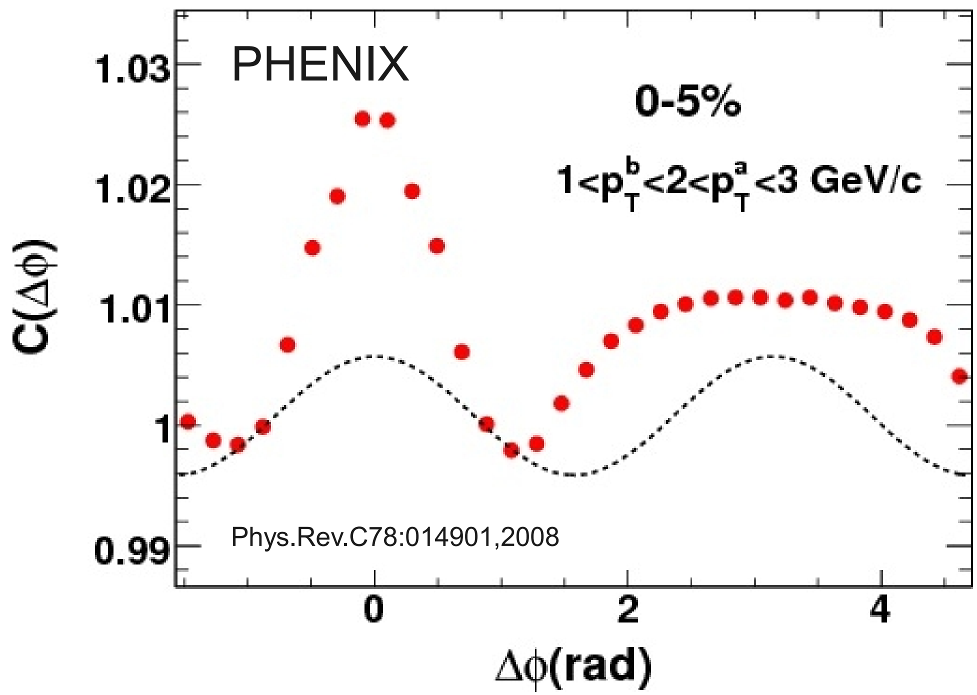
- Two component model:

  Di-hadron correlations are composed of

  - Correlations arising from jet fragmentation
  - Correlations arising from elliptic flow (v_2)

  Assume jets are not correlated with background

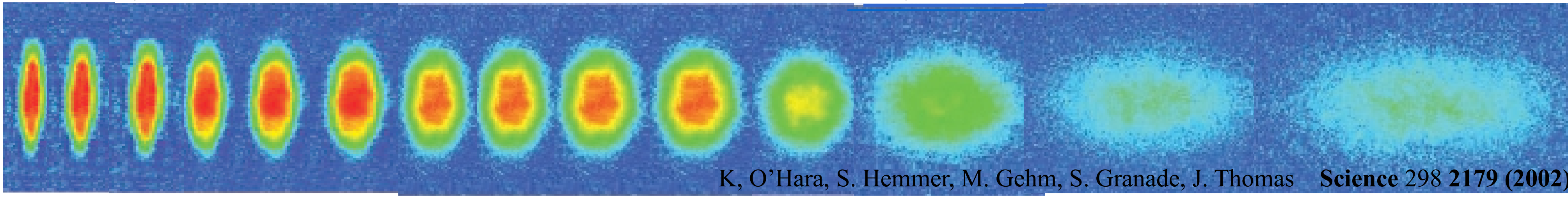
  The background is then
  $B(1+2\, v_2^{trig}\, v_2^{assoc} \cos(2\Delta\Phi))$
  Phys.Rev. C69 (2004) 021901



- Zero-Yield-At-Minimum (ZYAM)
  - Assumes there is a region where there is no signal
  - Fix B in this region assuming two component model
  - Use v_2 from independent measurements

What does it mean?

Same phenomena observed in gases of strongly interacting atoms

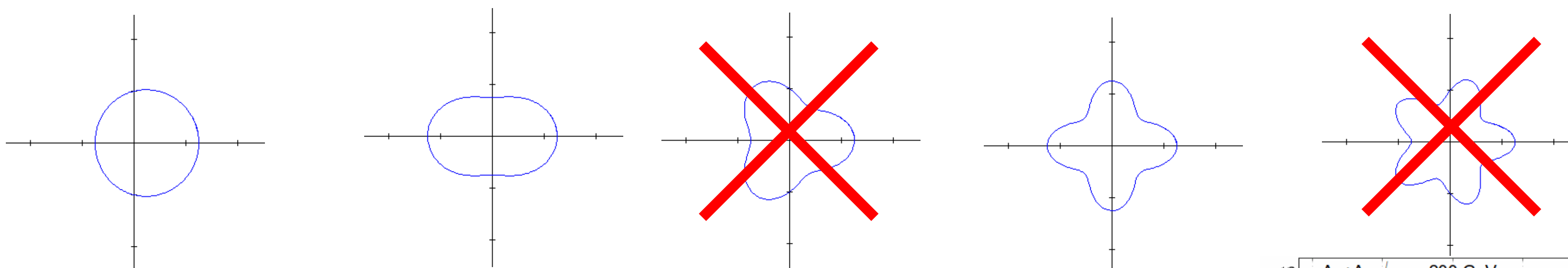


Time →

Initial state anisotropies converted to final state anisotropies

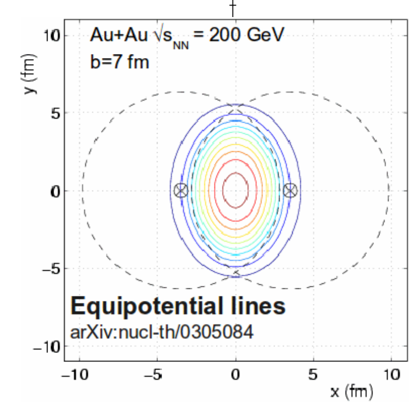
Fourier decomposition:

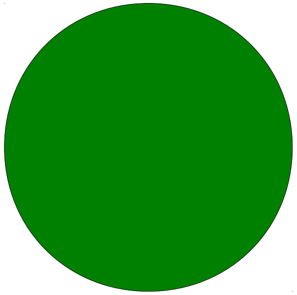
$$\frac{d^2N}{dp_T\,d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$



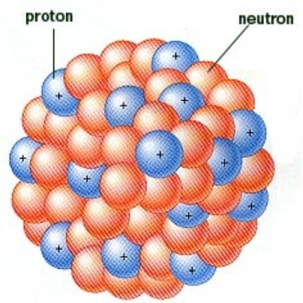
Offset measured

Nuclei are symmetric → No odd coefficients





This is not what a nucleus looks like



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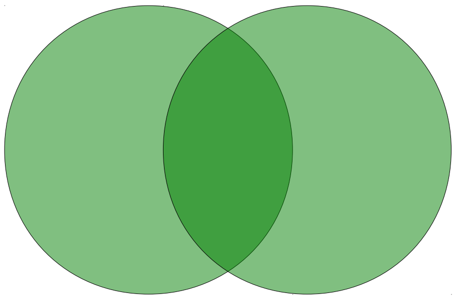
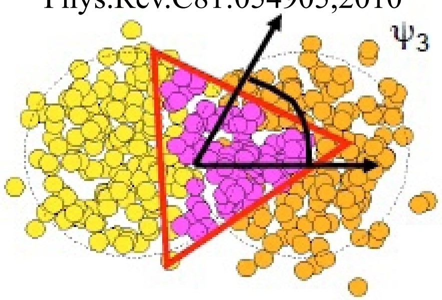


This is not what our collision looks like

Phys.Rev.C81:054905,2010



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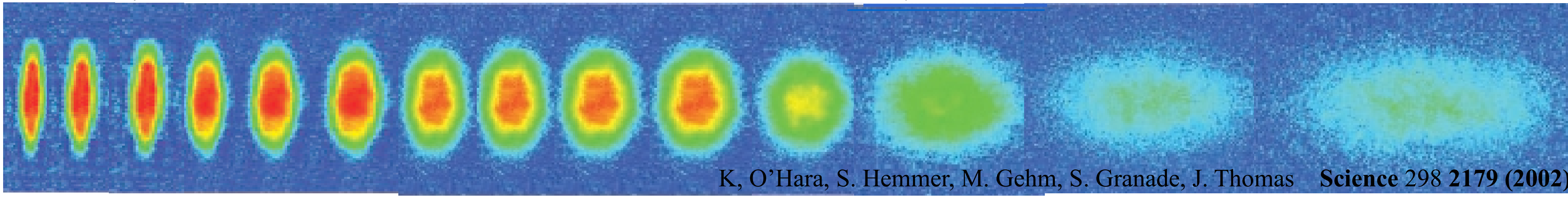

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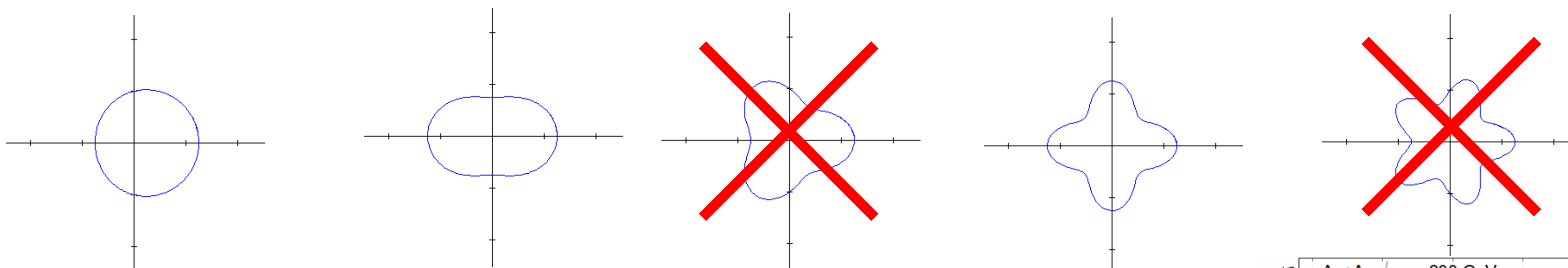

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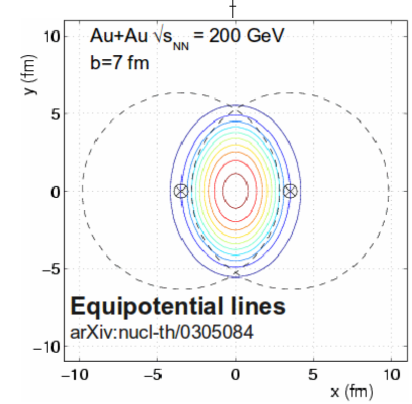

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  Phys.Rev. C69 (2004) 021901

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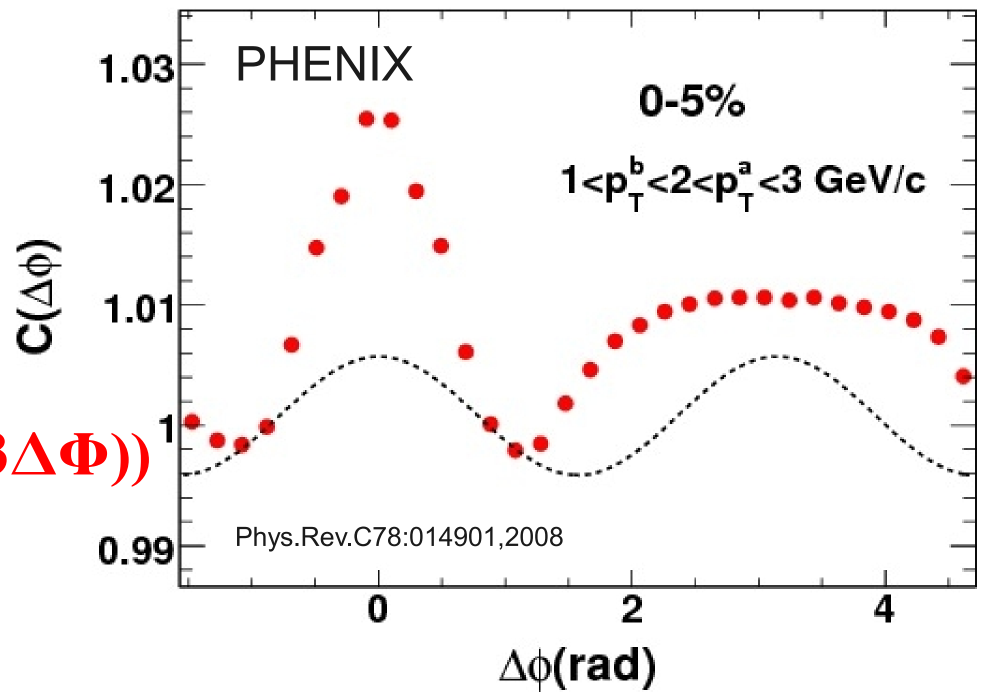
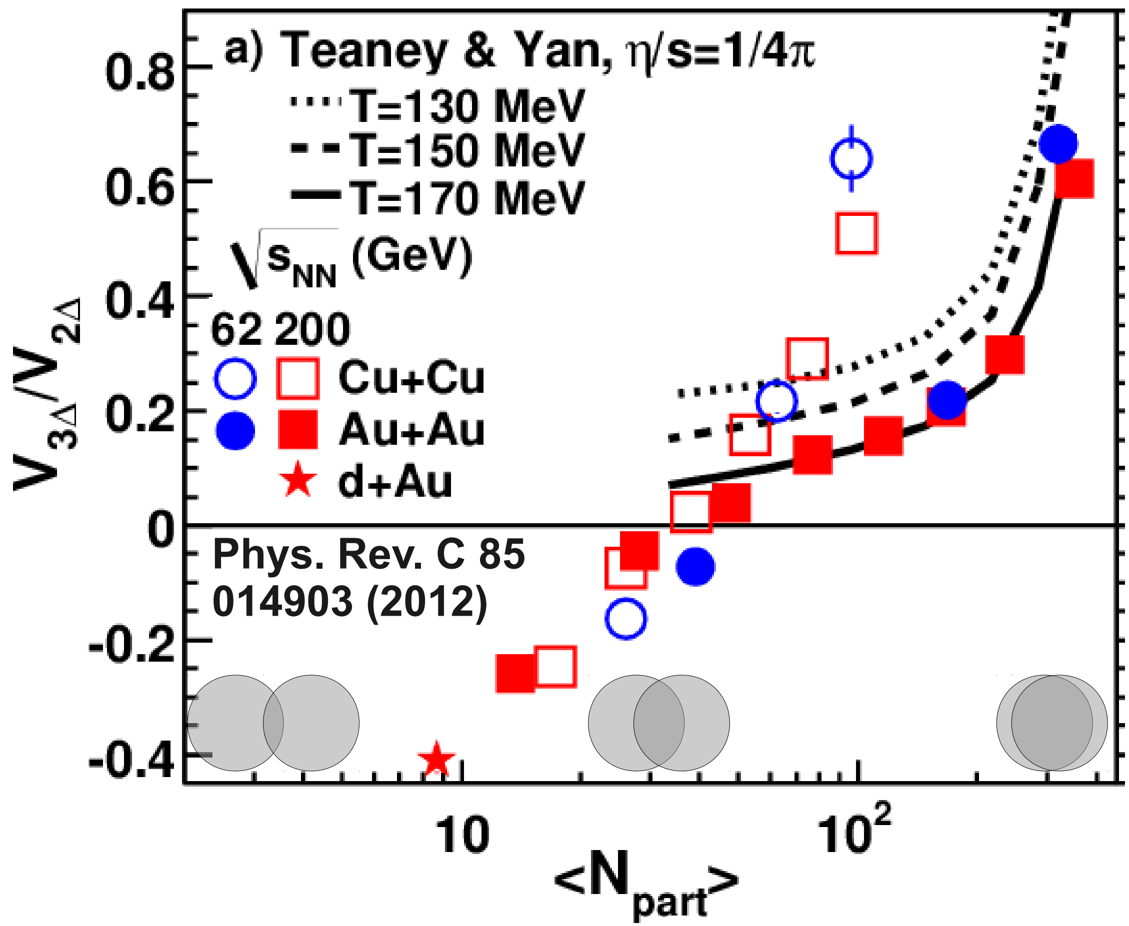
  - Fix B in this region assuming two component model
  - Use v_2 from independent measurements



What the ridge is...



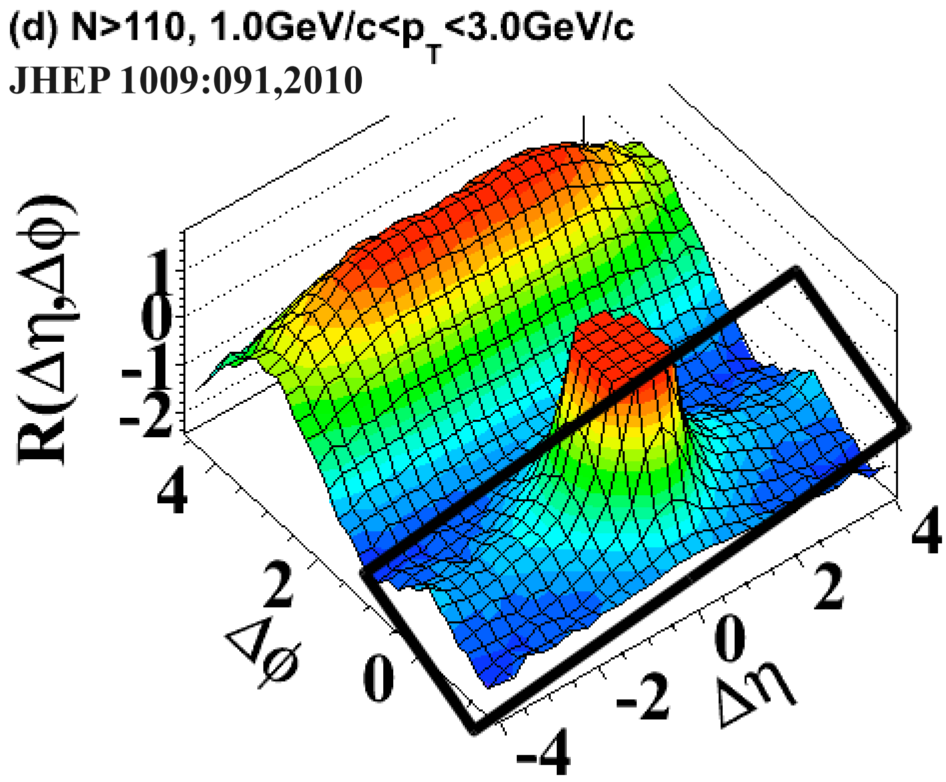
...is strong evidence that the Quark Gluon Plasma is a liquid!

This is not what we were looking for.

What have we learned from this?

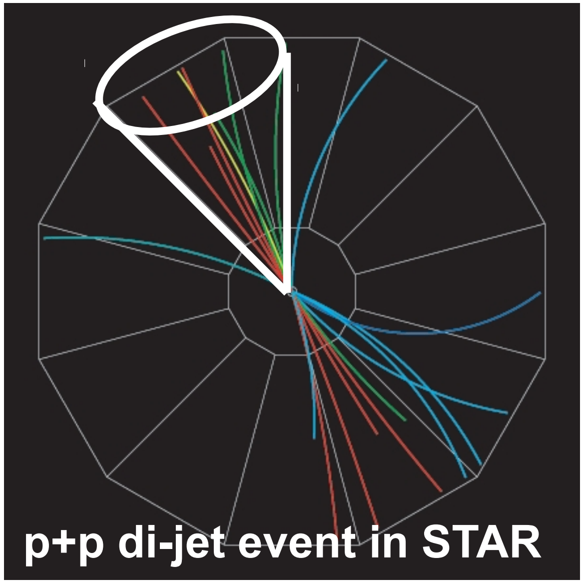
- The Quark Gluon Plasma is a liquid of quarks & gluons, the hottest matter produced in a laboratory, and the lowest viscosity fluid every observed.
- Sometimes you don't find what you're looking for, but you find something else interesting.

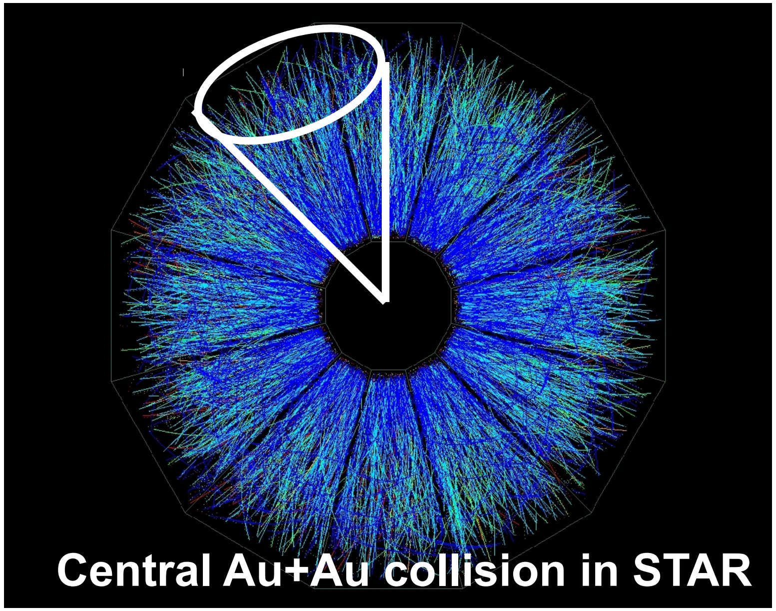
So what's this?



Seen by CMS in 7 TeV proton-proton collisions

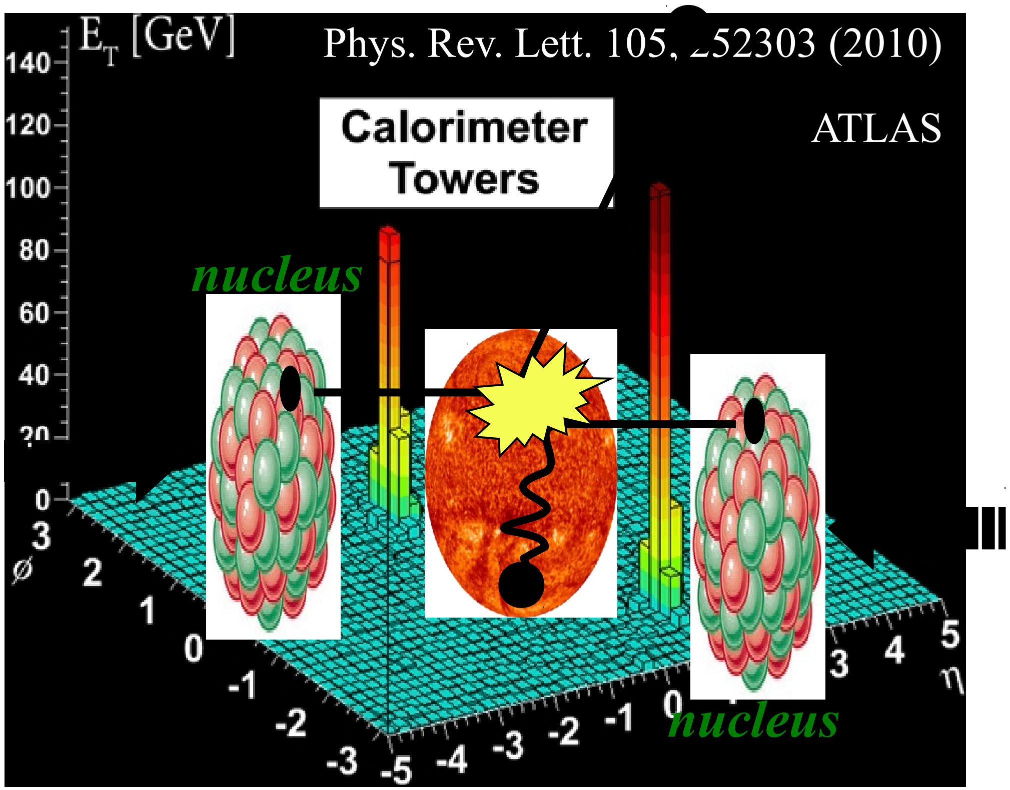
Jet reconstruction

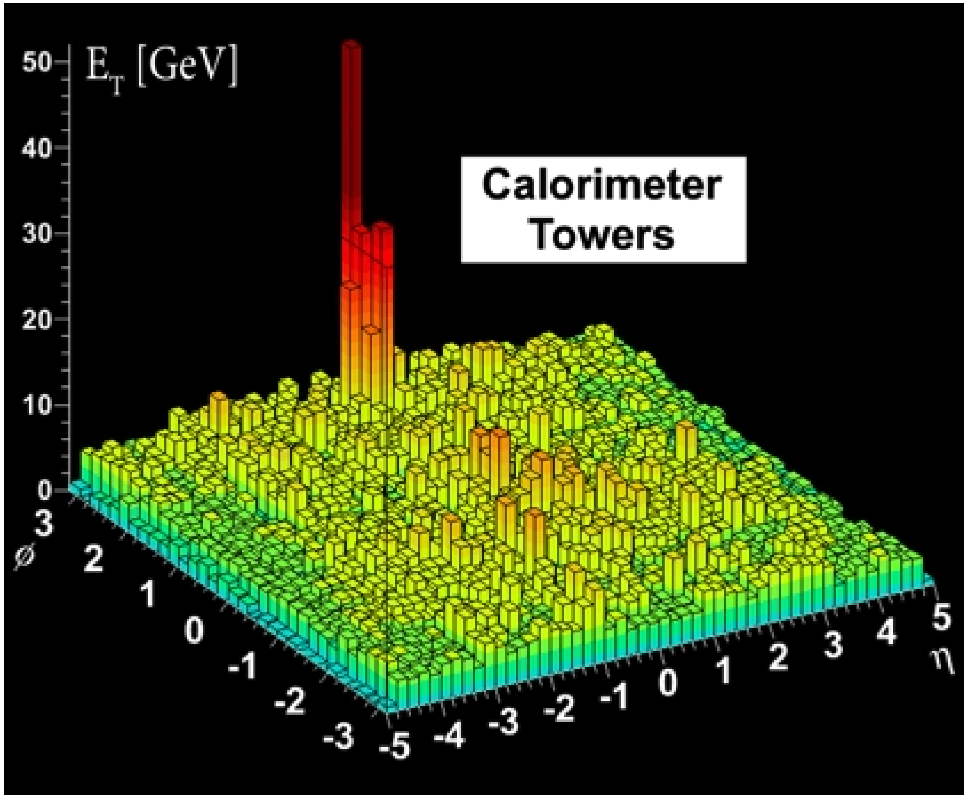




- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

Jets at the LHC



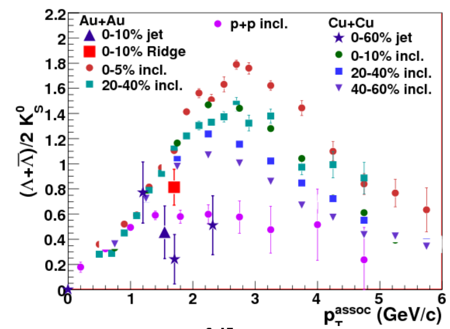


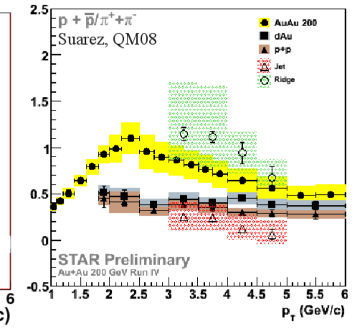

Just the beginning!
~~THE END~~

Backup slides

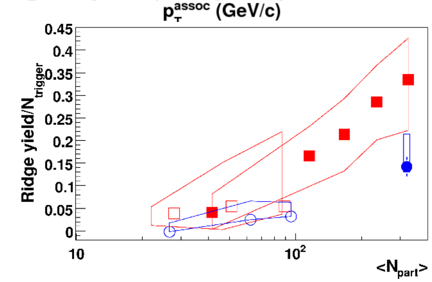
Key experimental results

Jet-like correlation is dominantly produced by fragmentation → *Ridge* production must not affect formation of jet-like correlation

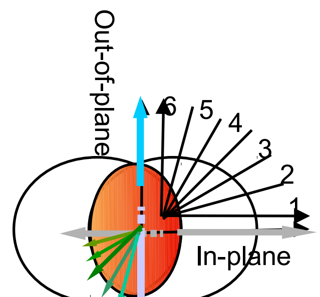




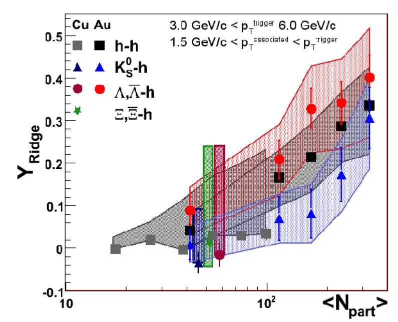
Particle ratios in *Ridge* comparable to bulk



The *Ridge* is smaller in collisions at $\sqrt{s_{NN}}$ = 62 GeV than 200 GeV



Ridge is larger in plane than out of plane

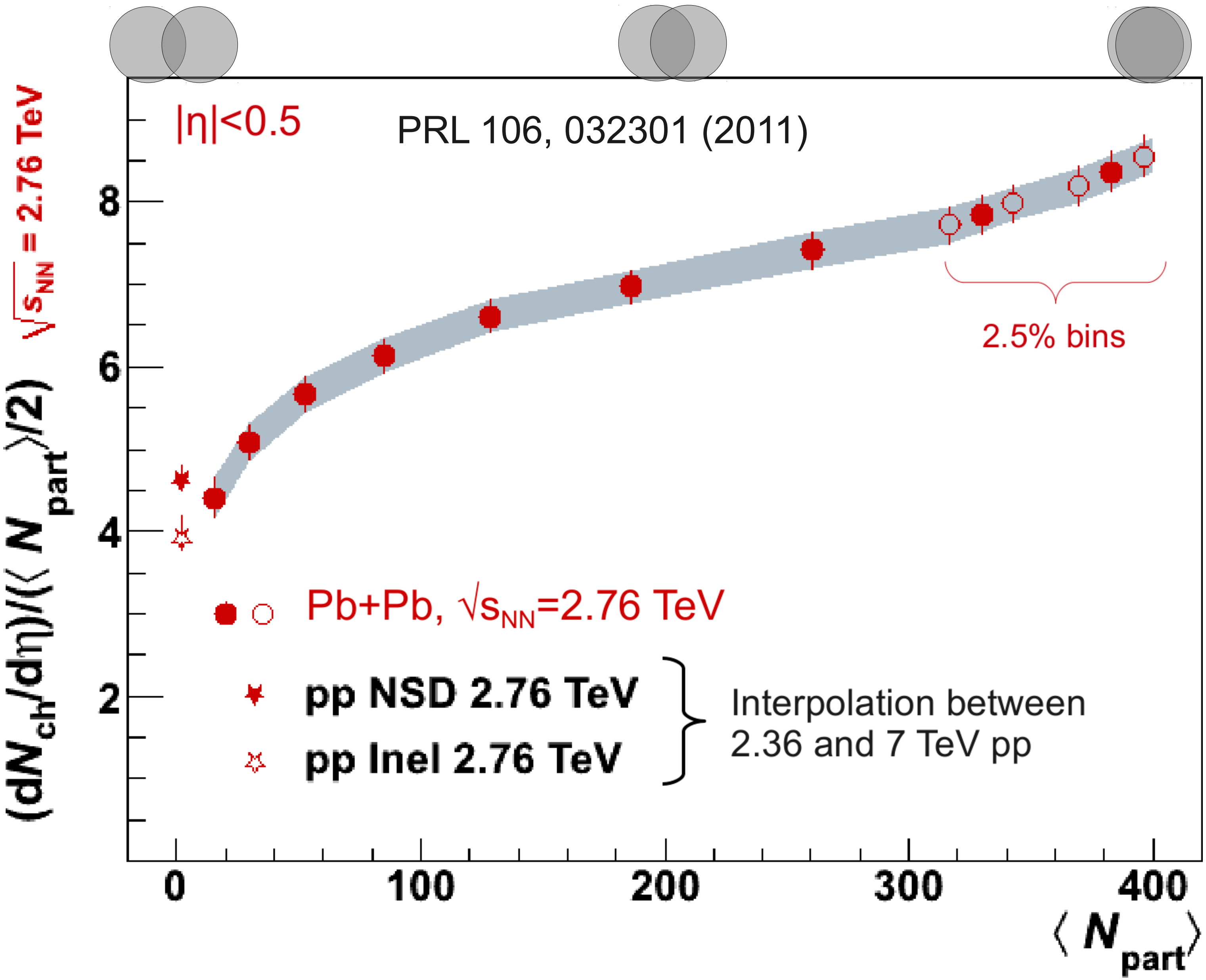


If there is a mass ordering, *Ridge* increases with increasing trigger mass

The Ridge is broad in Δη

Bulk properties

Centrality dependence of $dN_{ch}/d\eta$

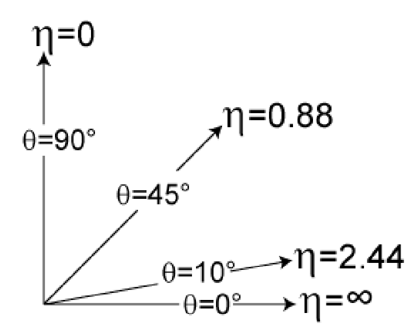


RHIC data scaled by 2.1

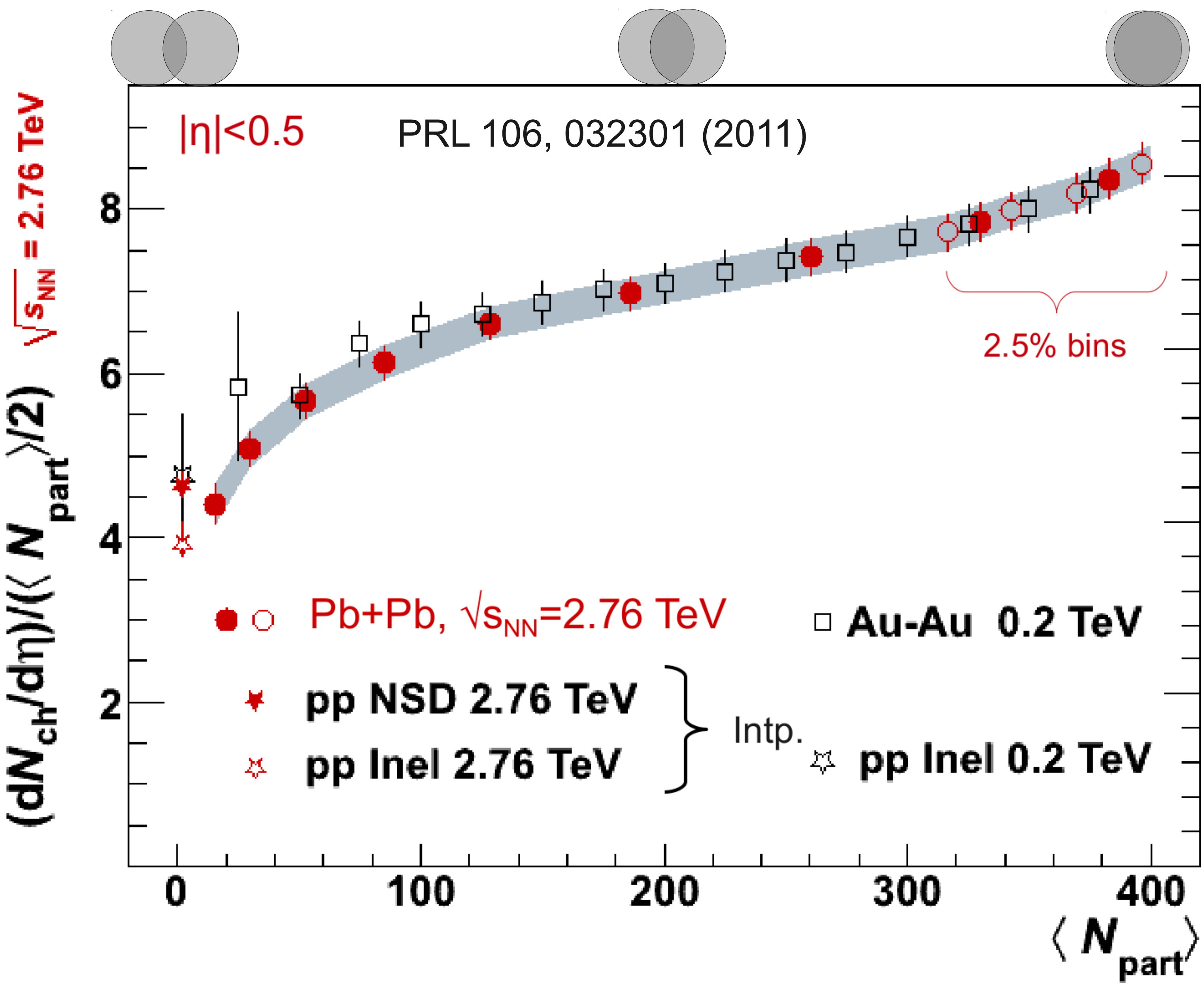
PHENIX
PRC 71, 034908 (2005)

$dN_{ch}/d\eta$ = Number of charged tracks per unit pseudorapidity

η = pseudorapidity
$= -\ln[\tan(\theta/2)]$



Centrality dependence of $dN_{ch}/d\eta$



RHIC data scaled by 2.1

PHENIX
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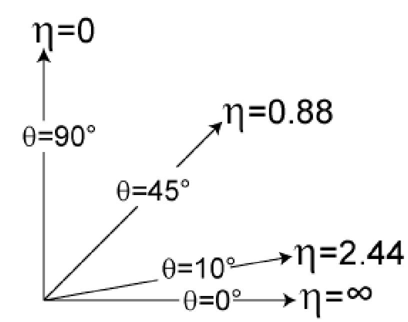
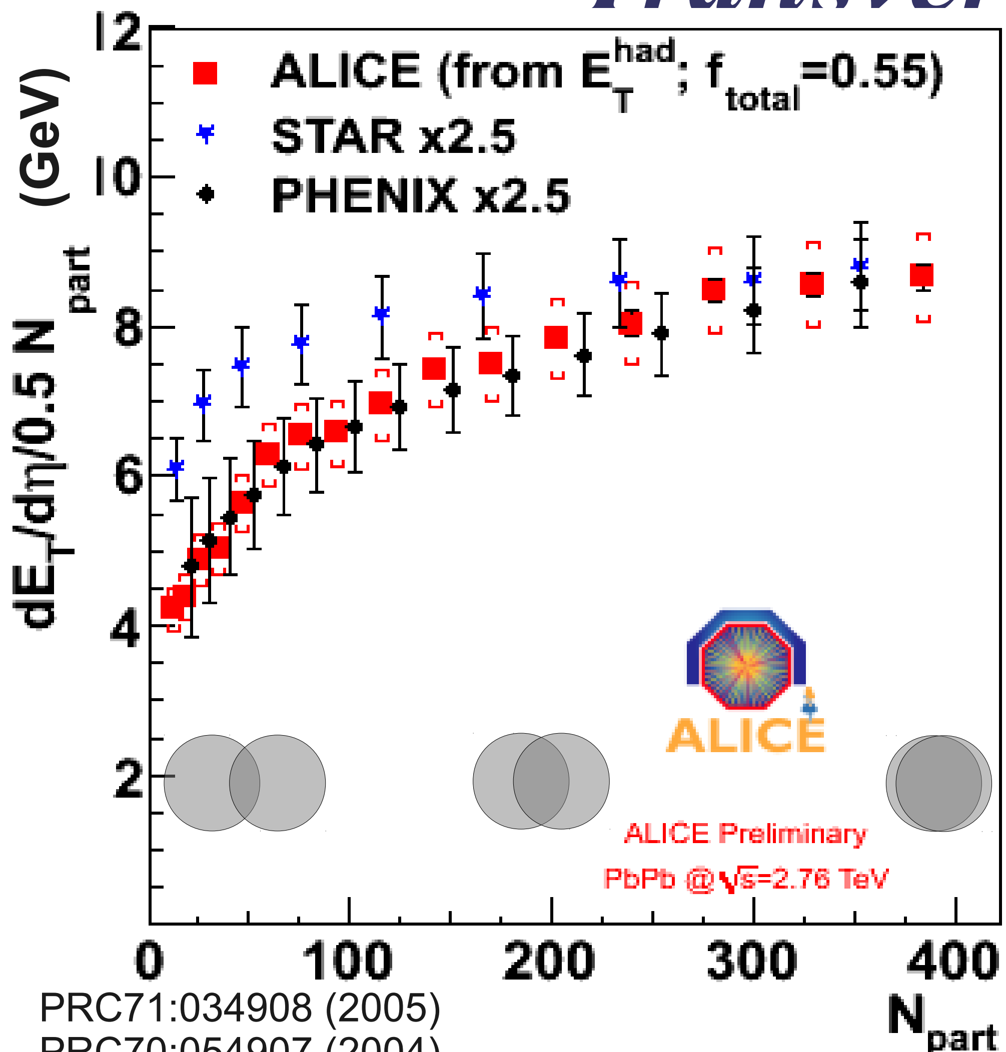


N_{part} = number of participating nucleons

Transverse Energy



PRC71:034908 (2005)
PRC70:054907 (2004)

Centrality dependence similar to RHIC (PHENIX)

- E_T^{had} from charged hadrons directly measured by the tracking detectors
- f_{total} from MC to convert into total E_T
- From RHIC to LHC
  - ~2.5 increase $dE_T/d\eta/(0.5*N_{part})$
- Energy density (Bjorken)

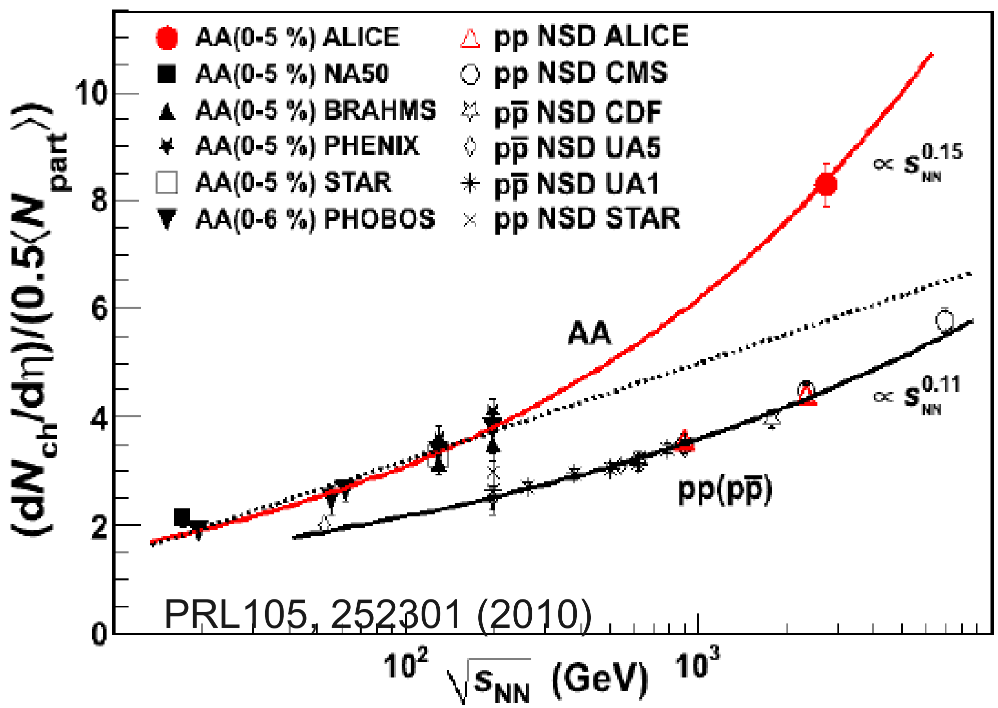
$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy} \qquad R = 1.12\, A^{1/3} fm$$

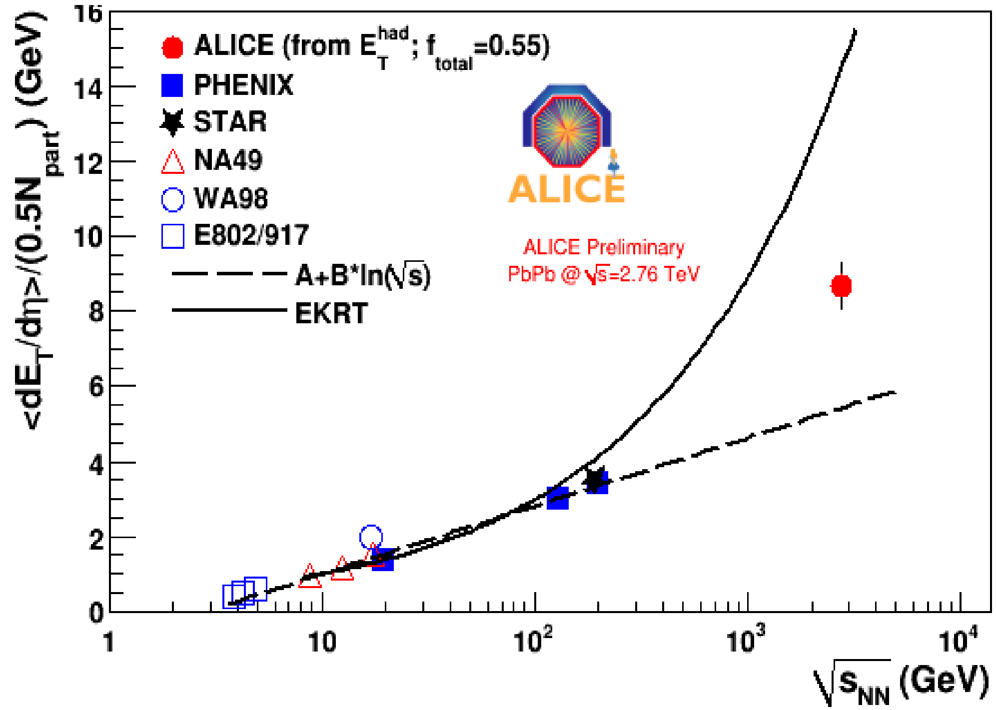
- $\varepsilon\tau \sim 16$ GeV/(fm^{2}c)
  RHIC: $\varepsilon\tau = 5.4 \pm 0.6$ GeV/(fm^{2}c)

$\sqrt{s}_{NN}$ *dependence*

- $dN_{ch}/d\eta/(0.5*N_{part}) \sim 8$
- **2.1 x RHIC**
  1.9 x pp (NSD) at 2.36 TeV
- growth with $\sqrt{s}$ faster in AA than pp
- $dE_T/d\eta/(0.5*N_{part}) \sim 9$ in 0-5%
- ~5% increase of N_{part} (353 → 383)
  → **2.7 x RHIC**
  (consistent with 20% increase of $\langle p_T \rangle$)

Grows faster than simple logarithmic scaling extrapolated from lower energy





$\sqrt{s}_{NN}$ = Center of mass energy per nucleon

Probes of the Quark Gluon Plasma

Single particles

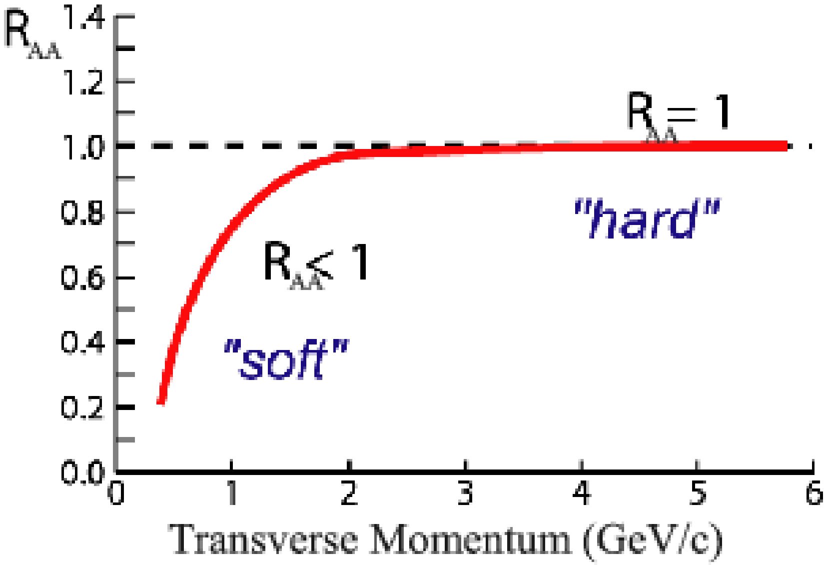
Measure spectra of hadrons and compare to those in p+p collisions or peripheral A+A collisions

If high-p_T hadrons are suppressed, this is evidence of jet quenching

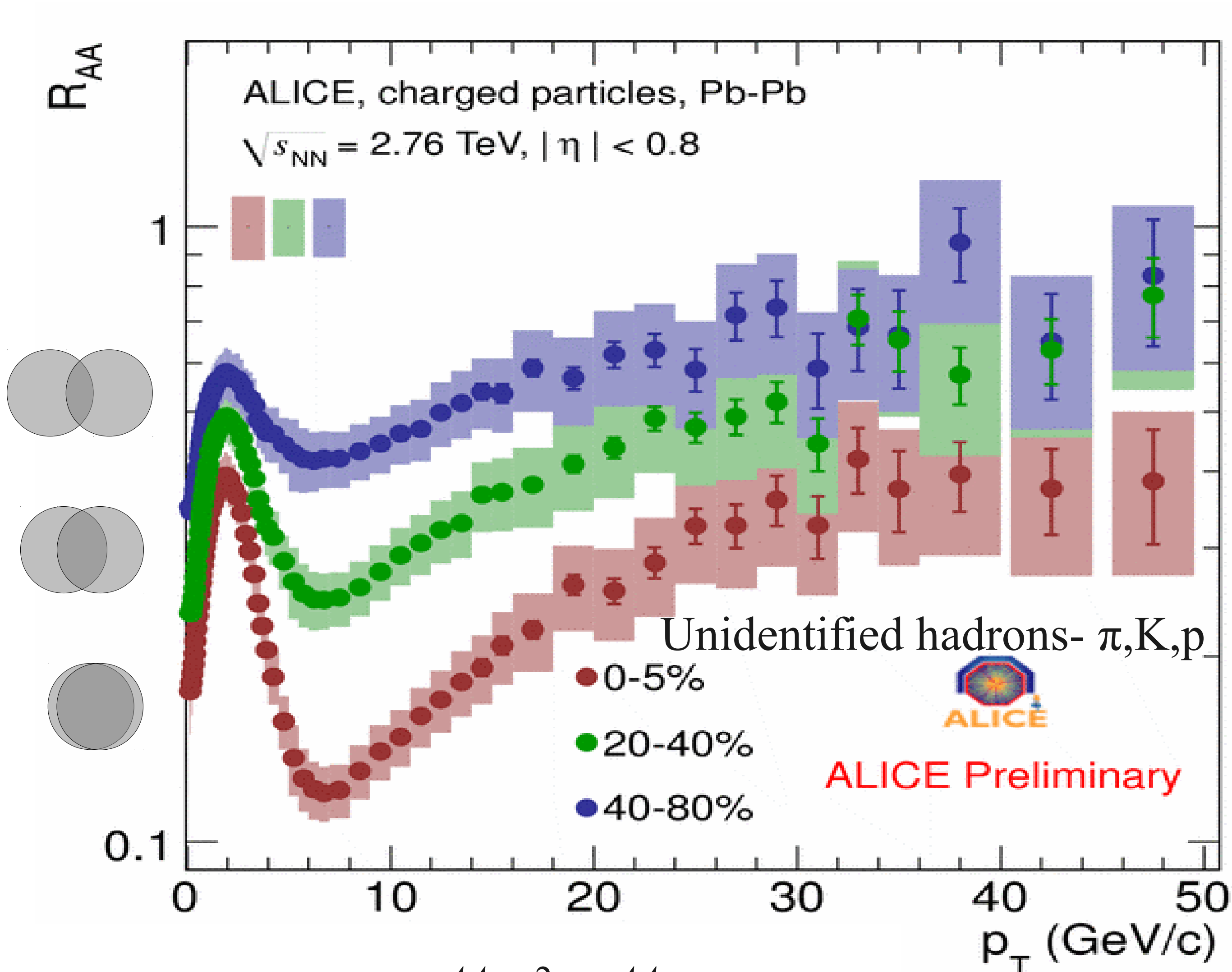
Assumption: sufficiently high-p_T hadrons mostly come from jets

Unmodified spectra:

$$R_{AA} = \frac{1/N_{evt}^{AA}\, d^2 N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2 N_{ch}^{pp}/d\eta\, dp_T}$$

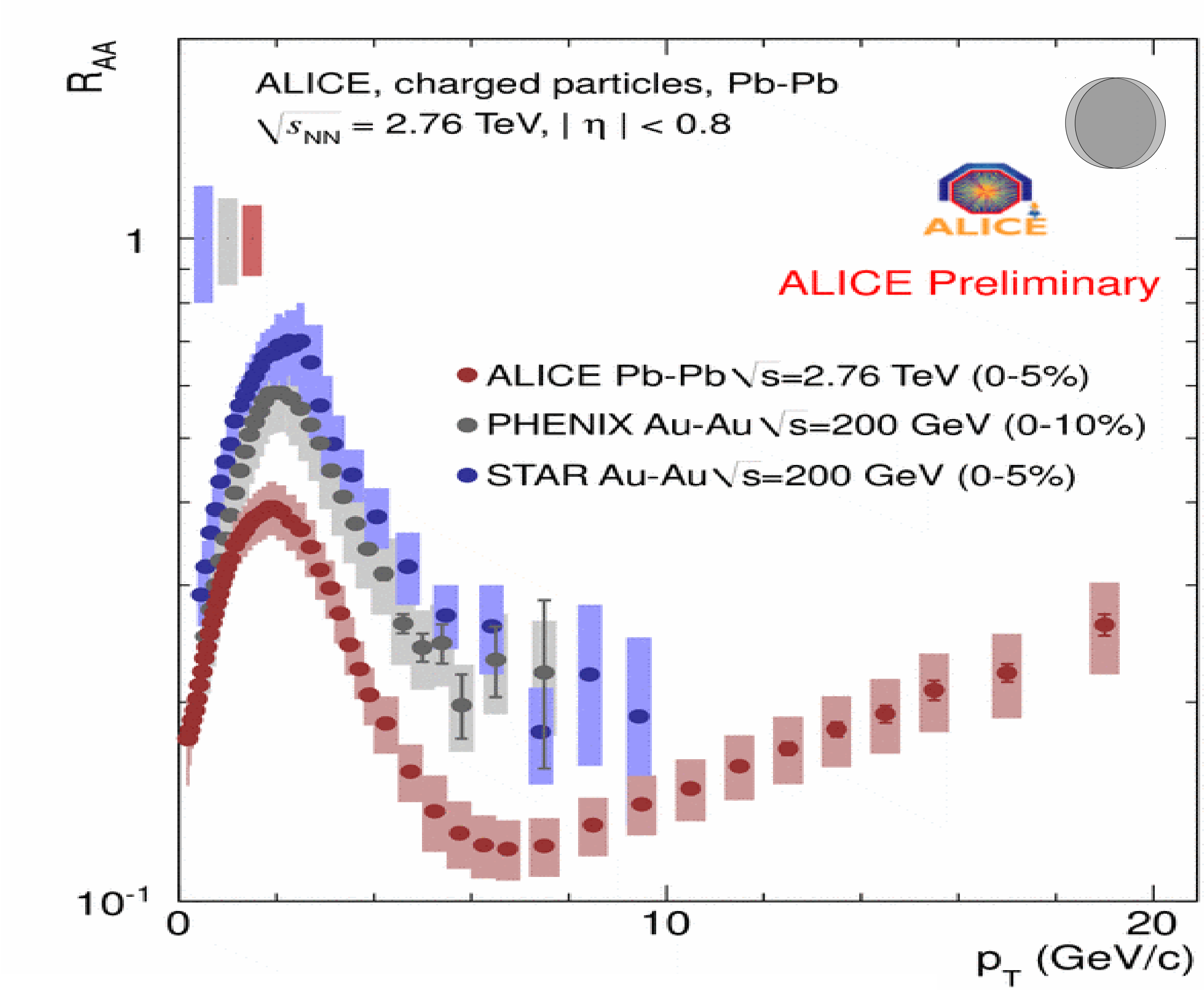


Nuclear modification factor (R_{AA})



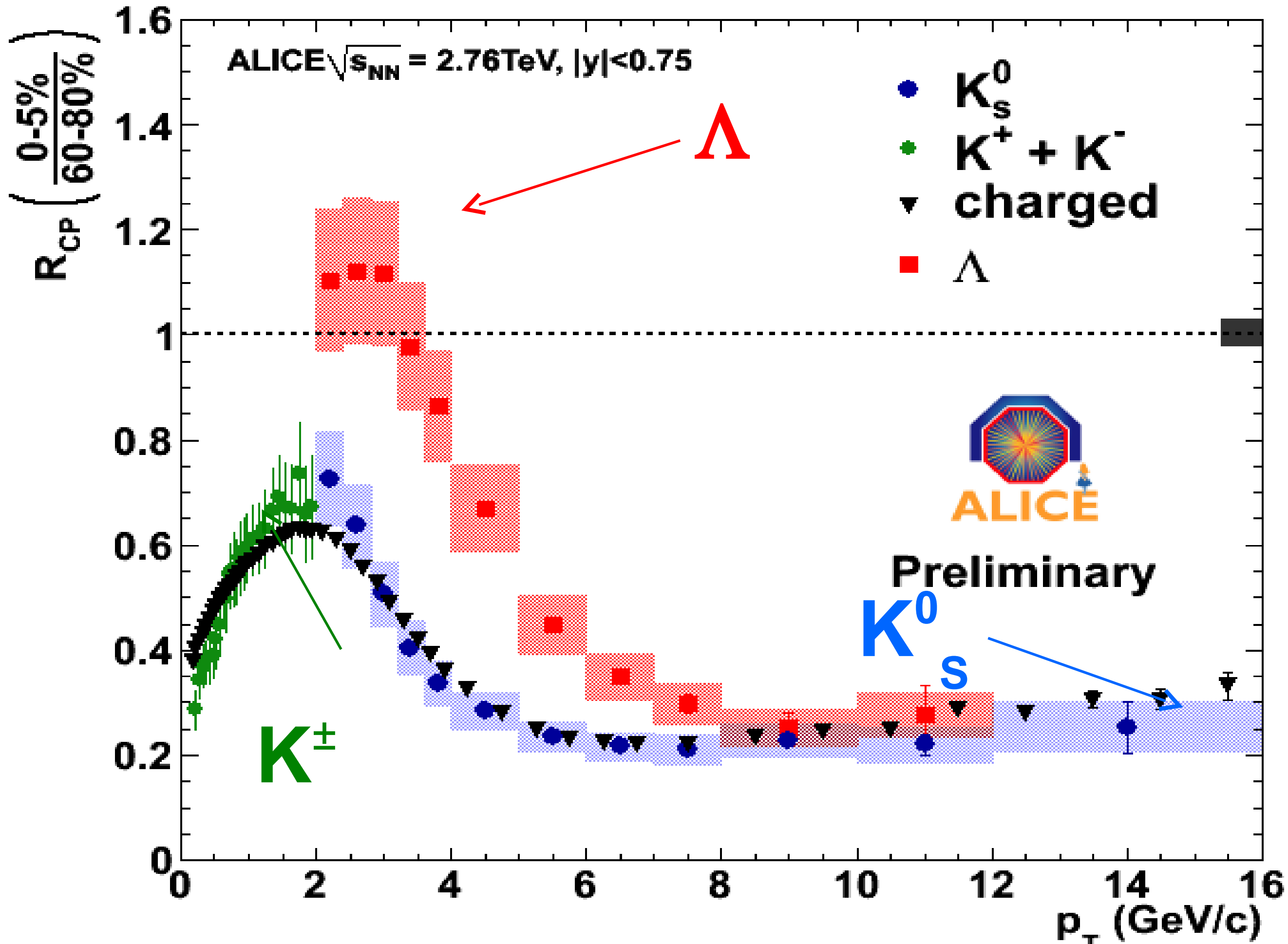
$$R_{AA} = \frac{1/N_{evt}^{AA}\, d^2 N_{ch}^{AA} / d\eta\, dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2 N_{ch}^{pp} / d\eta\, dp_T}$$

Nuclear modification factor (R_{AA})

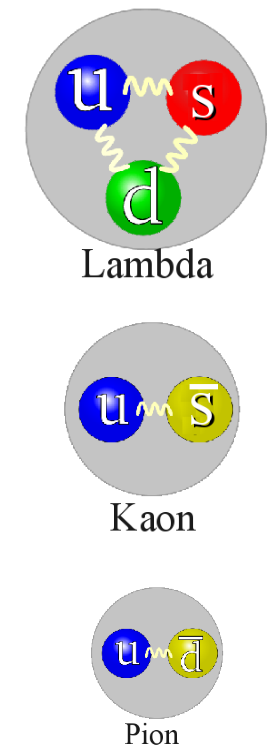


$$R_{AA} = \frac{1/N_{evt}^{AA} d^2 N_{ch}^{AA} / d\eta dp_T}{\langle N_{coll} \rangle (1/N_{evt}^{pp}) d^2 N_{ch}^{pp} / d\eta dp_T}$$

Nuclear modification factor (R_{AA})



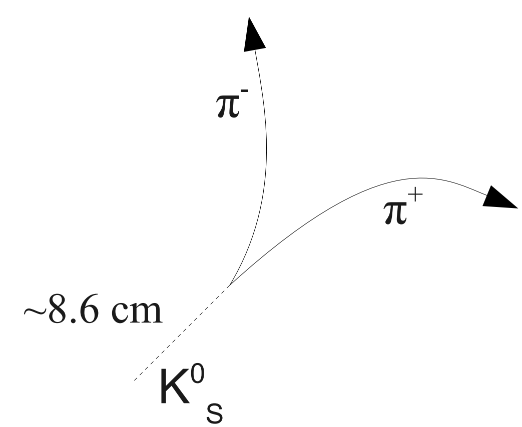
$$R_{AA}=\frac{1/N^{AA}_{evt}\,d^2N^{AA}_{ch}/d\eta\, dp_T}{\langle N_{coll}\rangle\left(1/N^{pp}_{evt}\right)d^2N^{pp}_{ch}/d\eta\, dp_T}$$



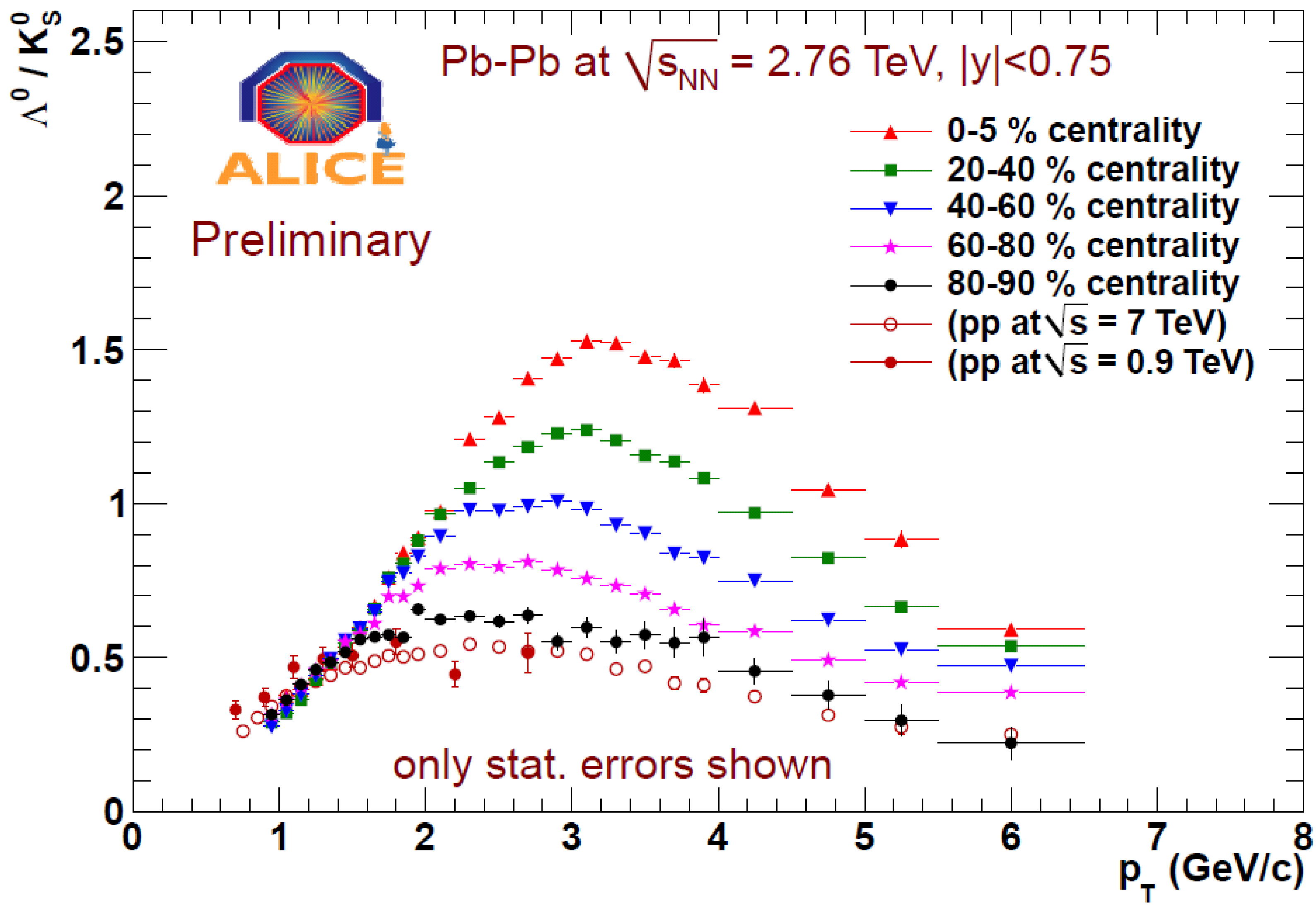
~1116 MeV/c²

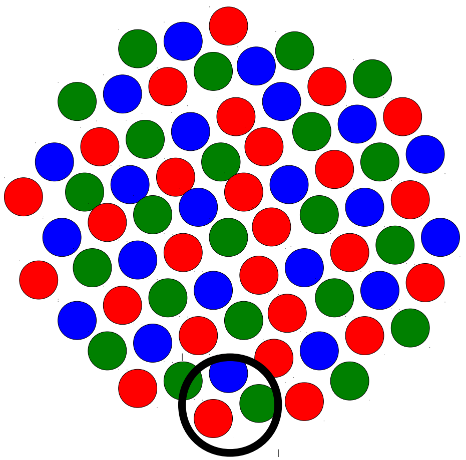
~494 MeV/c²

~140 MeV/c²



Baryon anomaly: Λ/K^0_S





Recombination
Ann.Rev.Nucl.Part.Sci.58:177-205,2008