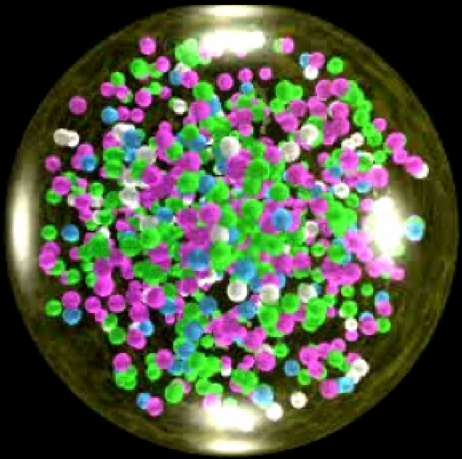
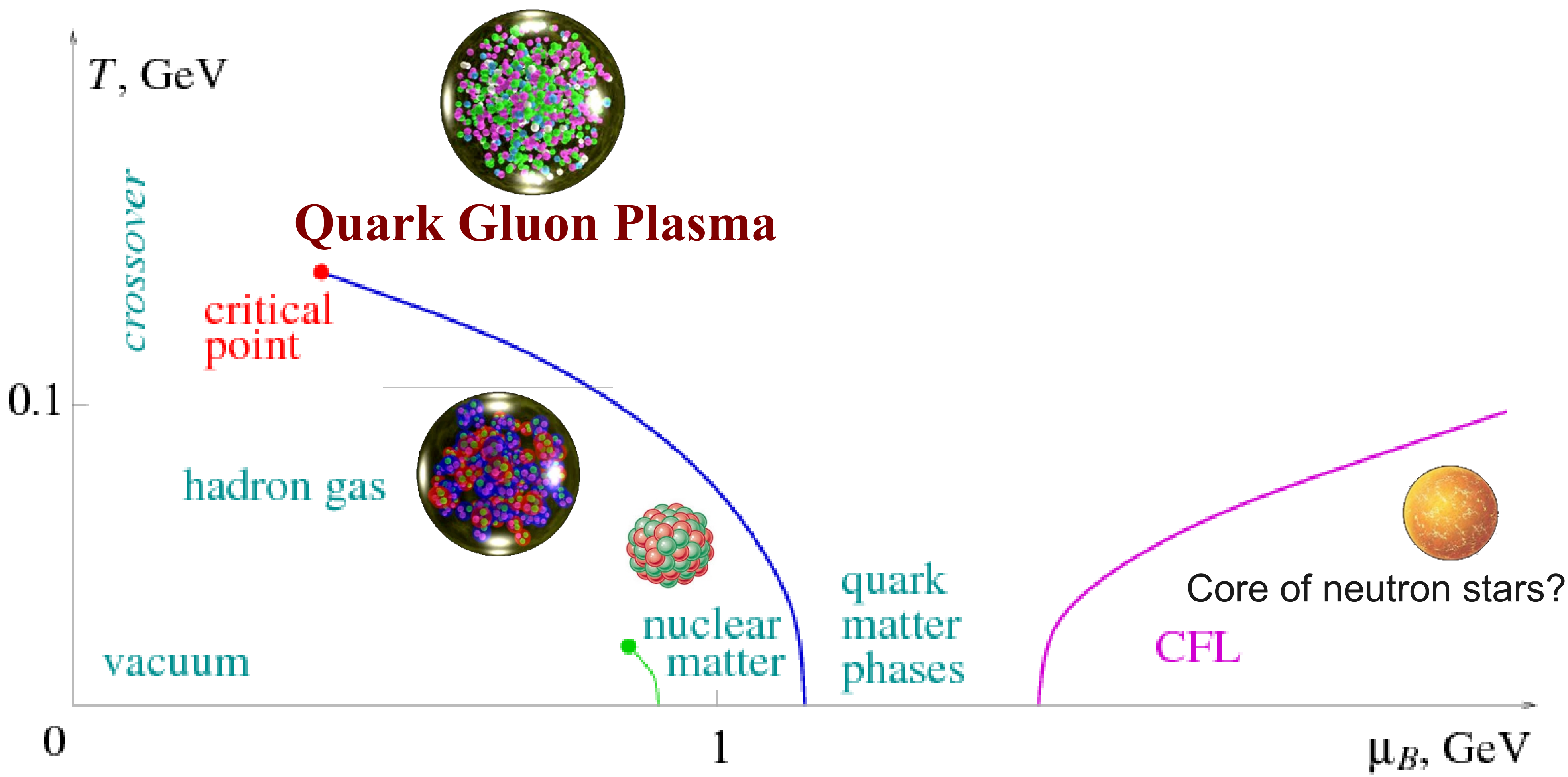
The little bang: understanding the quark gluon plasma



Christine Nattrass
University of Tennessee at Knoxville

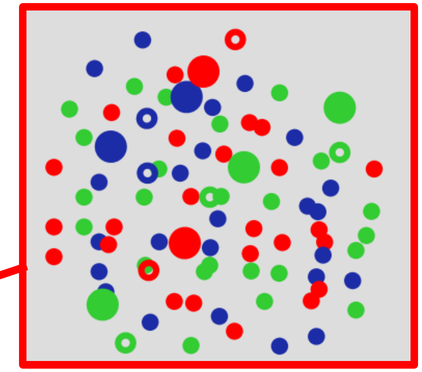
Phase diagram of nuclear matter



Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun

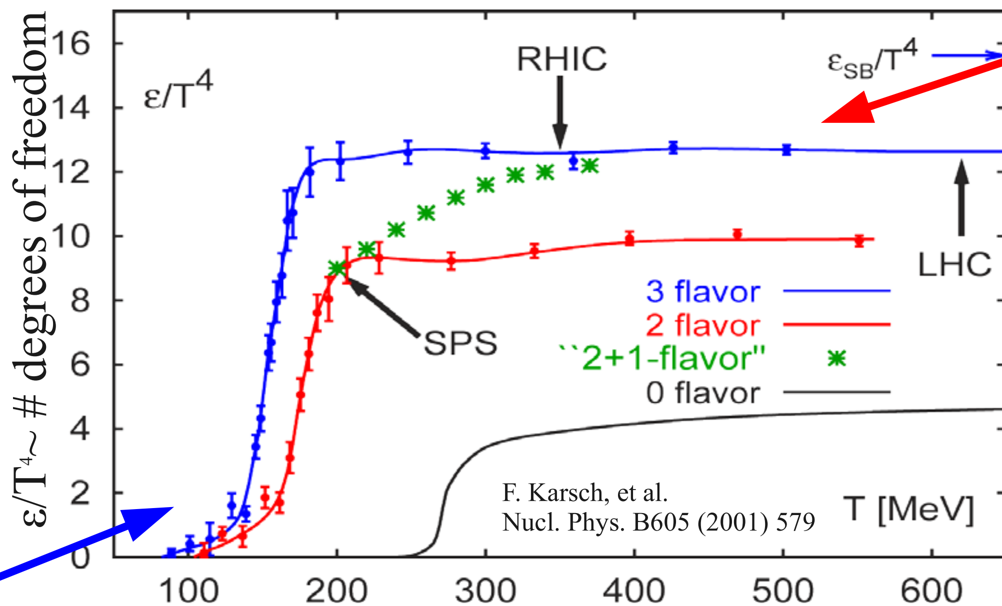
Exploring QCD at high temperatures

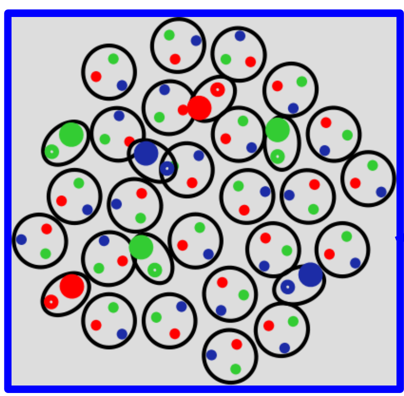
Quark-gluon plasma



Deconfined - more degrees of freedom

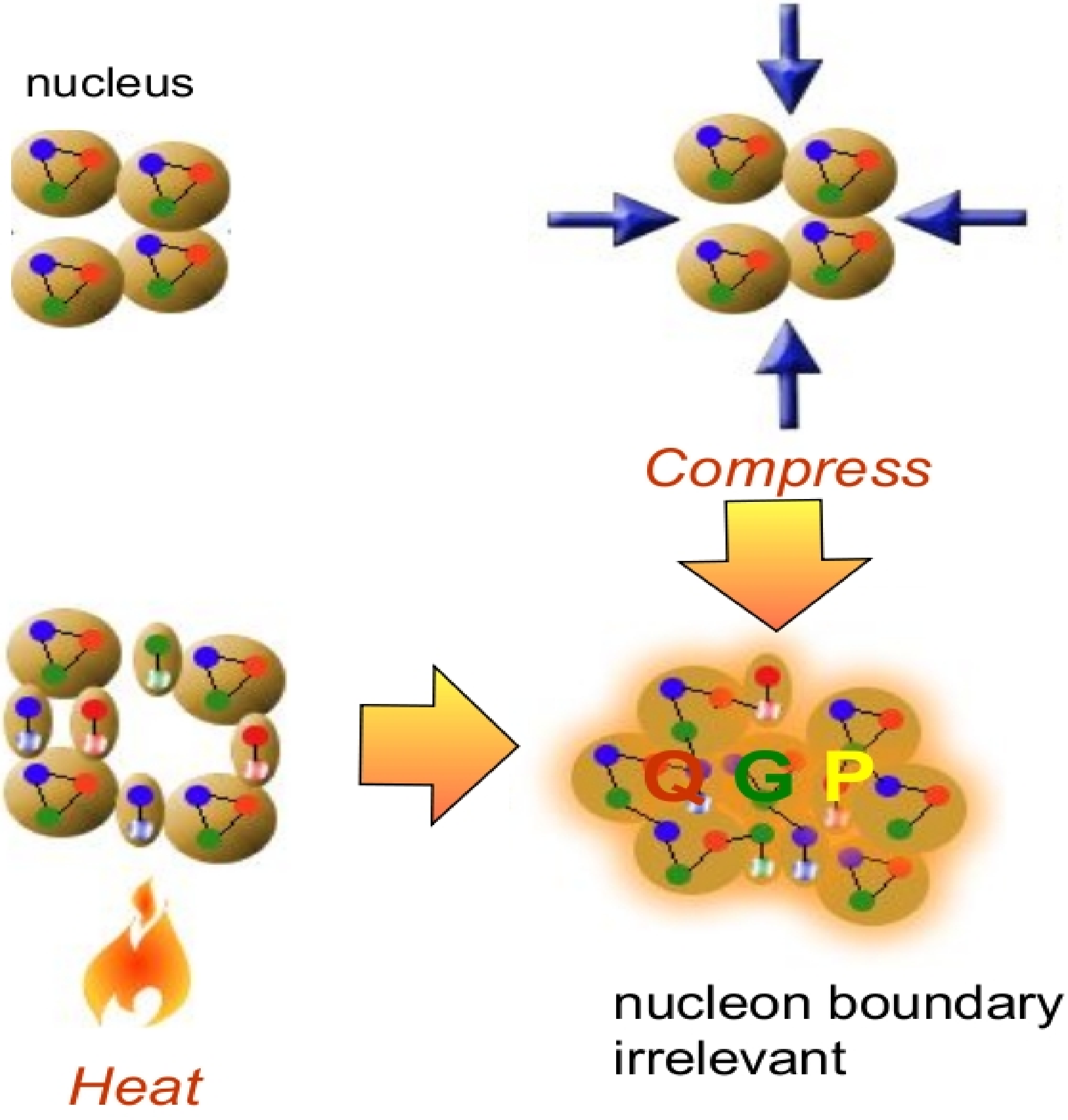
$T_c \sim 175 \pm 8$ MeV $\rightarrow \varepsilon_c \sim 0.3$ -1 GeV/fm^3



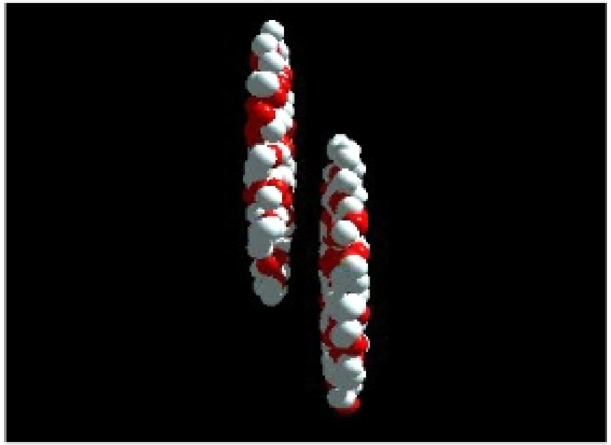


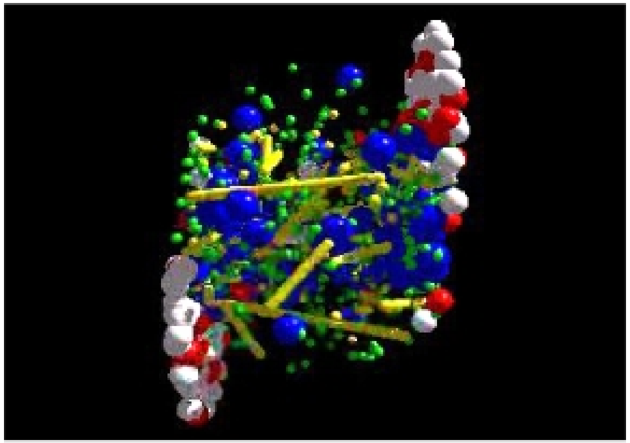
Confined - fewer degrees of freedom

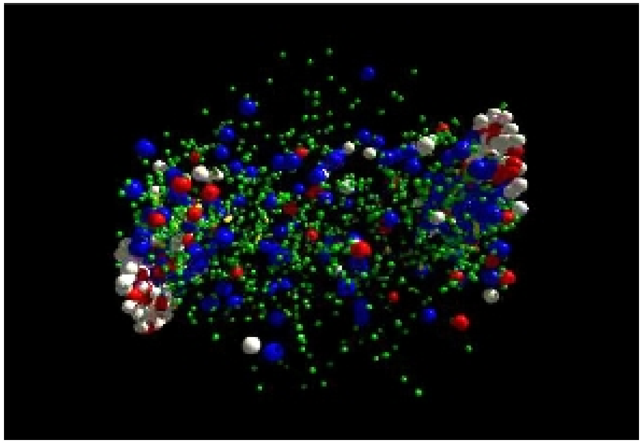
How to make a Quark Gluon Plasma

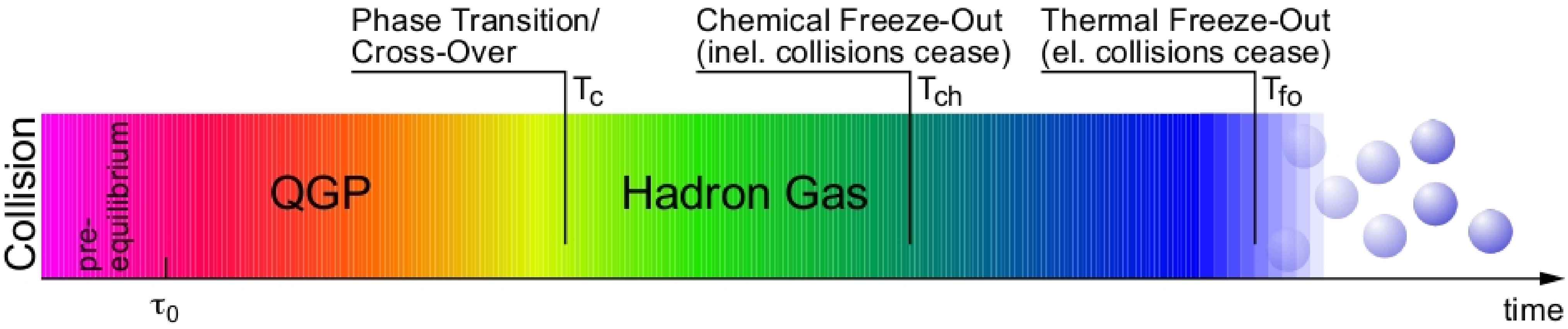


The phase transition in the laboratory

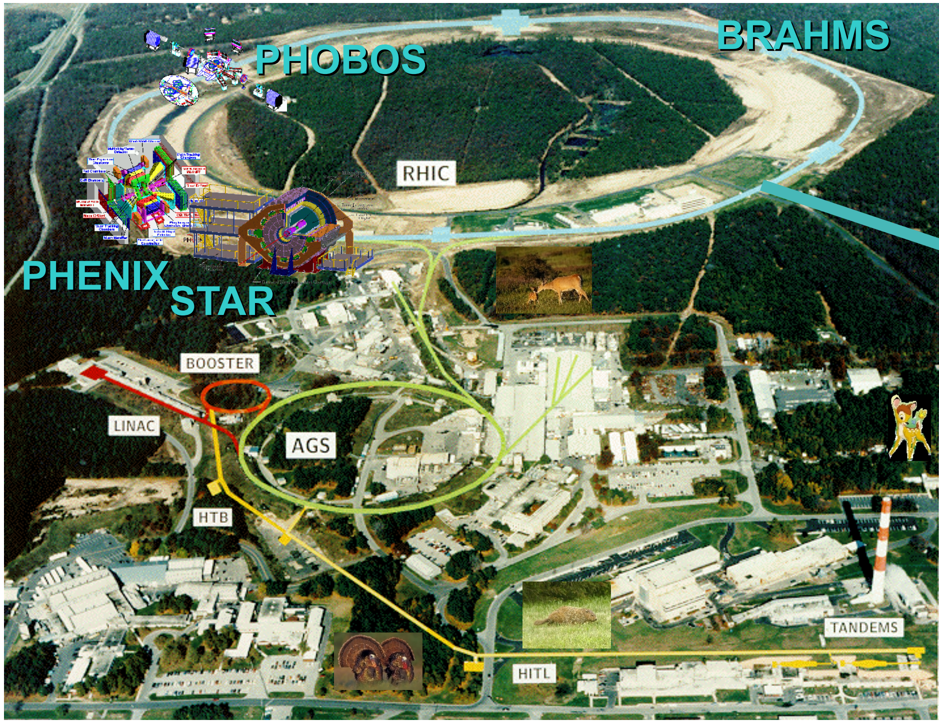






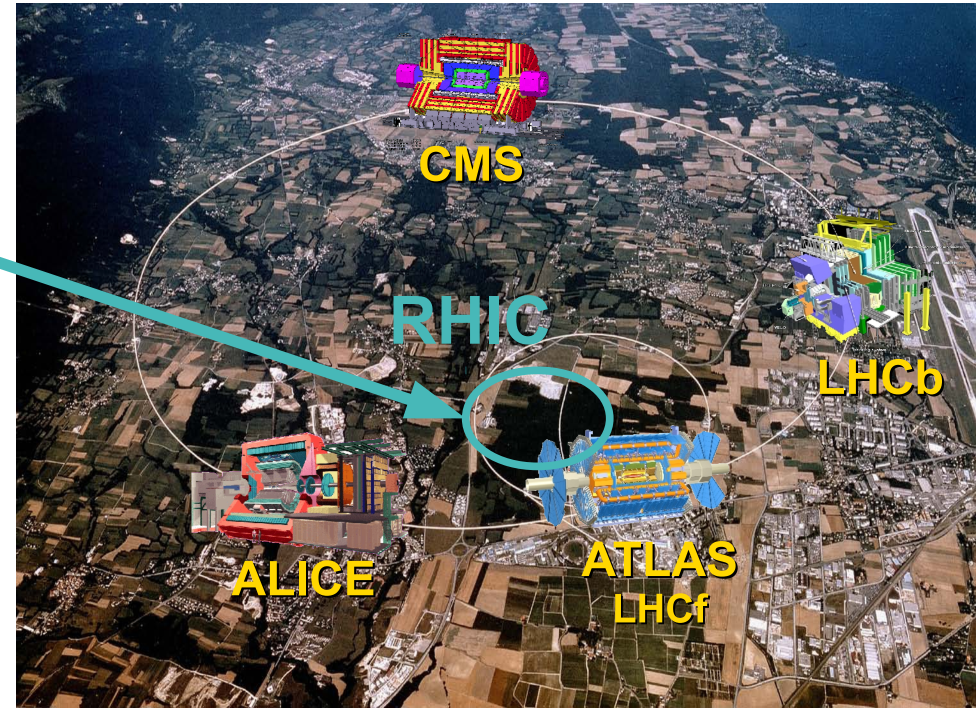


Relativistic Heavy Ion Collider

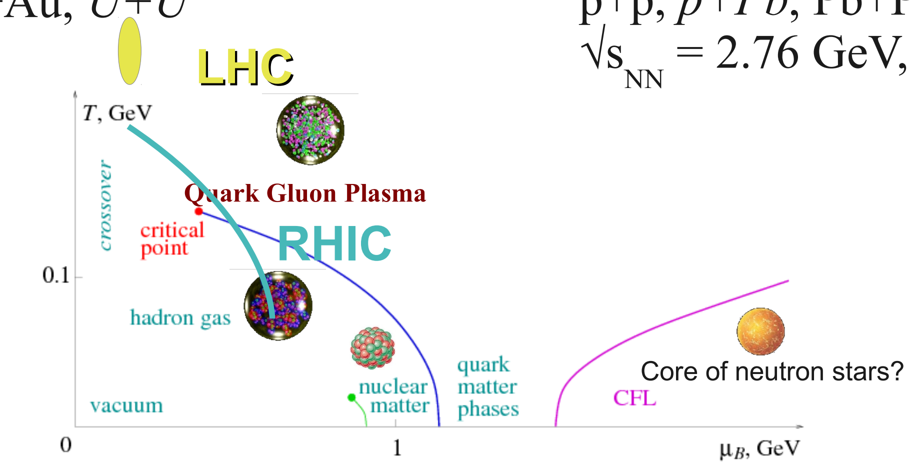


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

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*

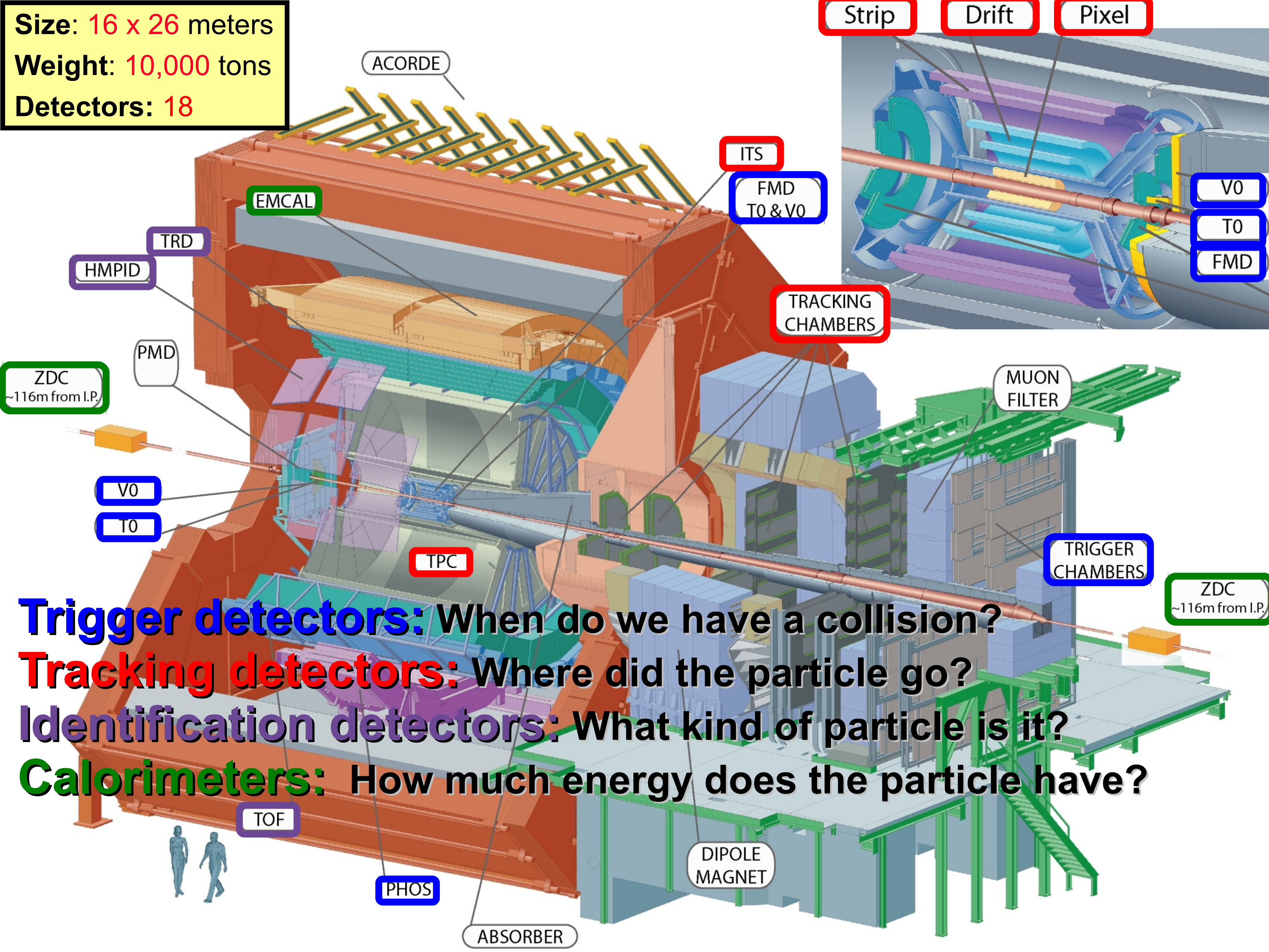
<u>RHIC and LHC:</u>

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

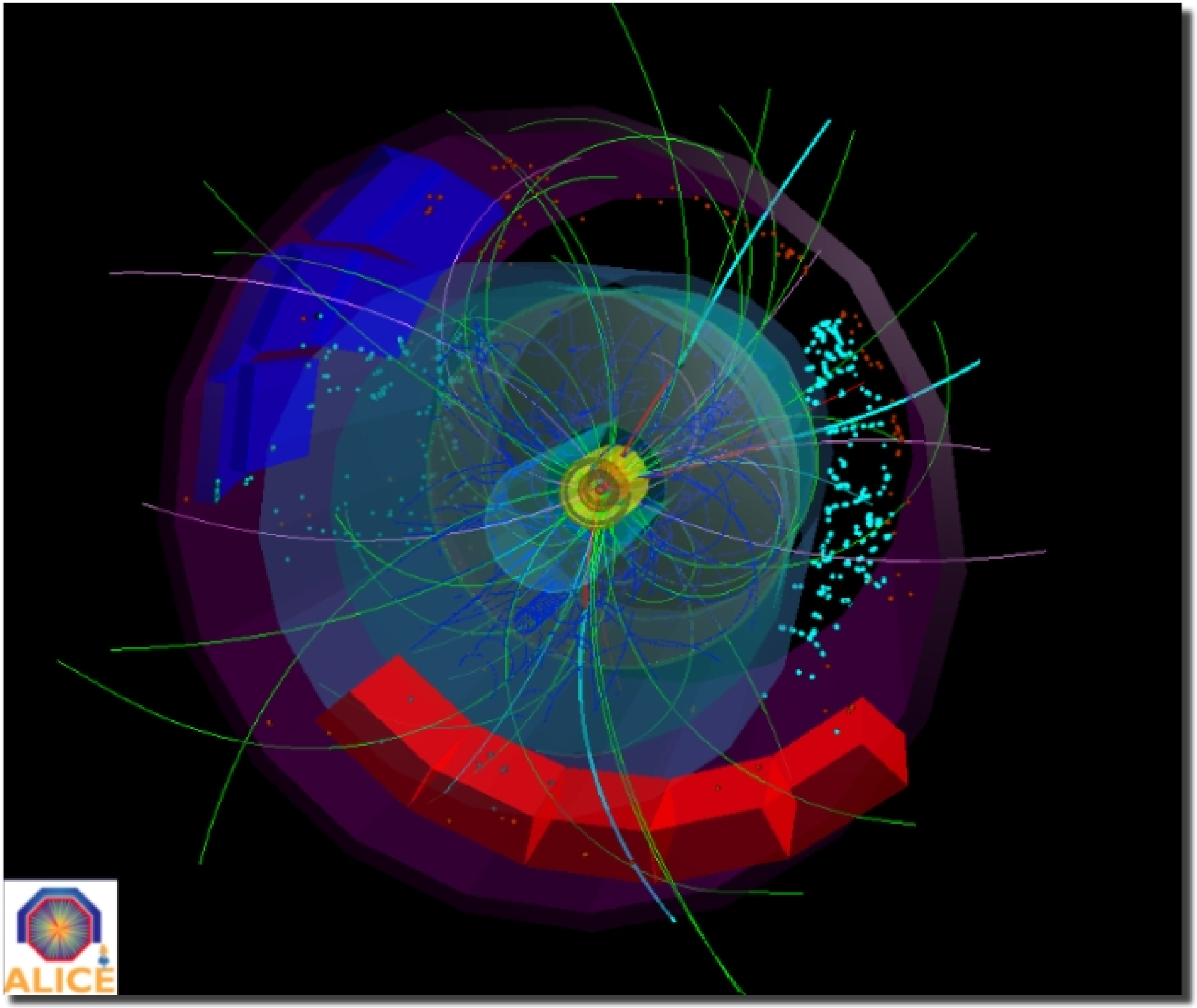
To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

Interesting observables

- Different hadronization mechanisms
  → Identify particle types
- Collective motion of particles
  → Low momentum acceptance
- Even common processes are not well understood
  → Do not need 4π acceptance or high rates

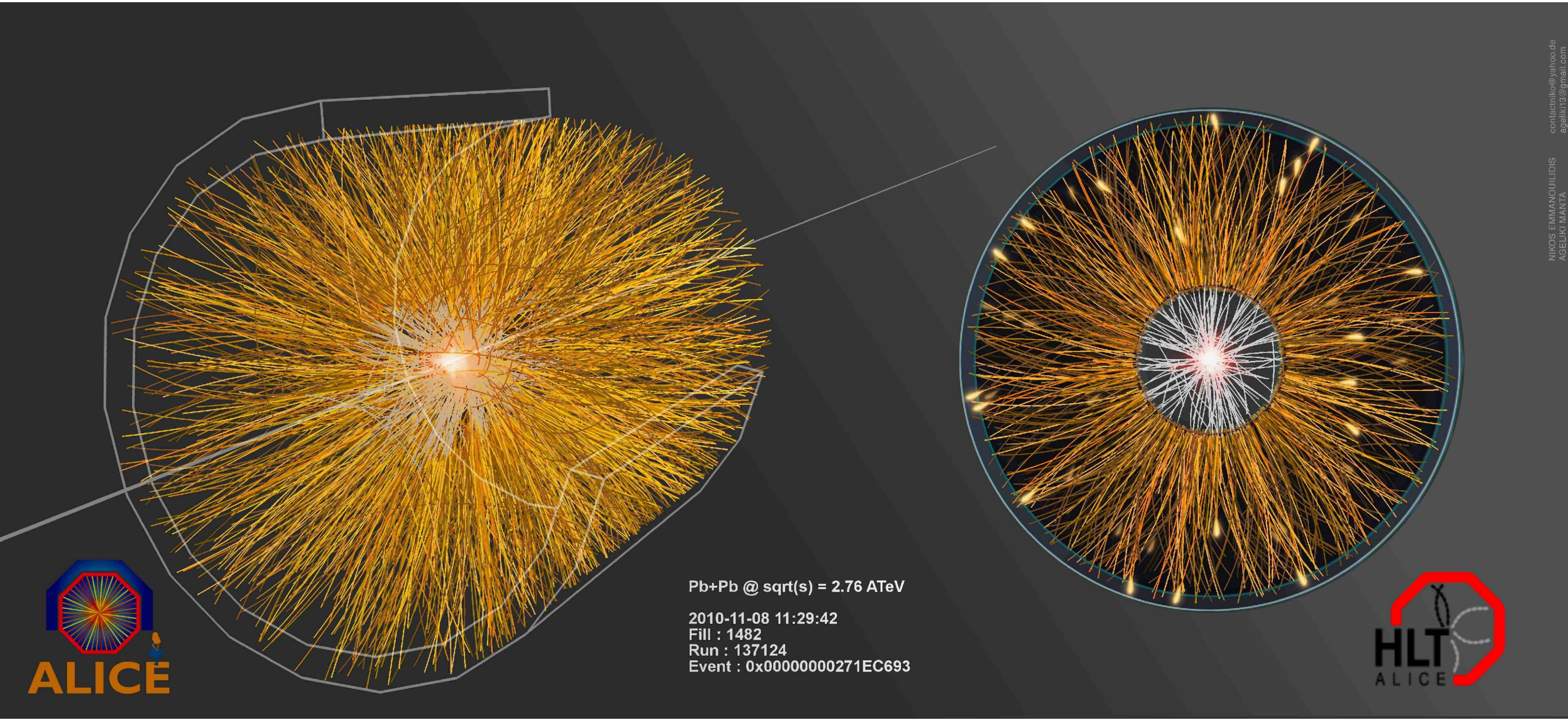

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
V0
T0
FMD
EMCAL
TRD
HMPID
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
Trigger detectors: When do we have a collision?
Tracking detectors: Where did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

p+p collisions



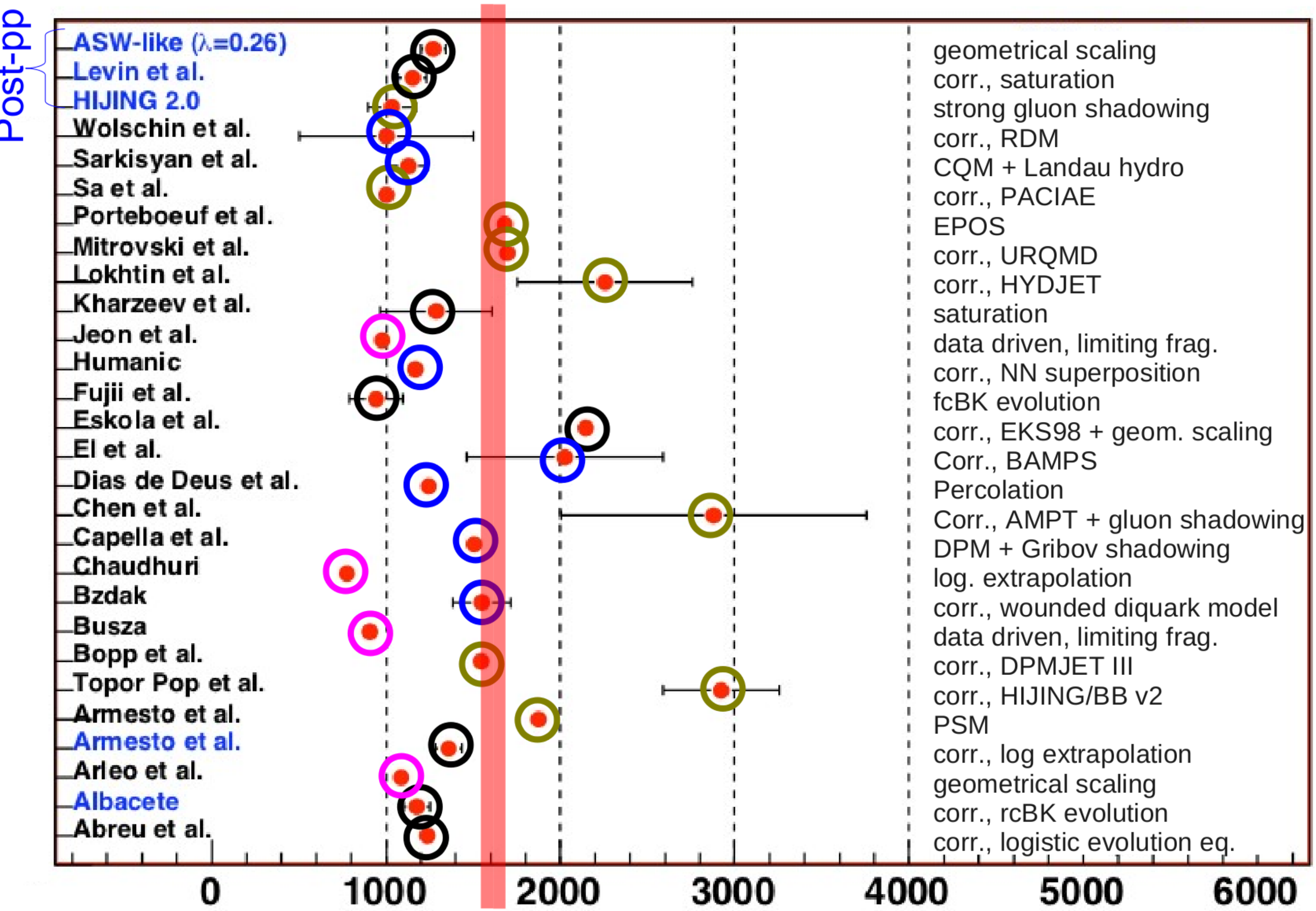
3D image of each collision

Pb+Pb collisions



Multiplicity in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

Measured dNch/dη = 1584 ± 76 (sys.)   PRL, 105, 252301 (2010)



Compilation from N. Armesto

Monte Carlo, coherence via collectivity, strong gluon saturation

Saturation ideas

Data driven, limiting frag.

Miscellaneous: superposition, WNM, diffusion eqs., DPM + shadowing/ percolation

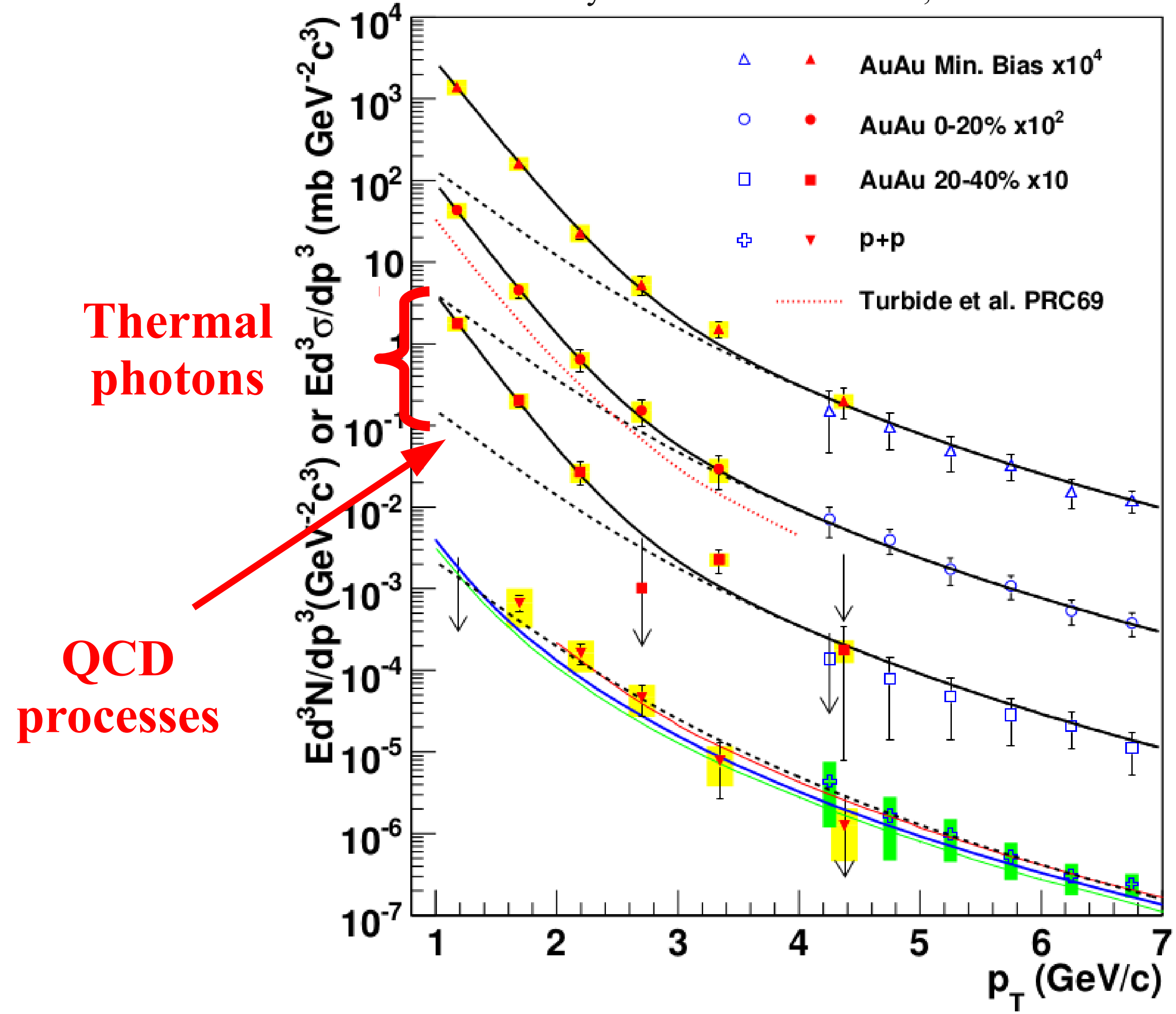
How do we study a QGP?

Tool	**Analogous to:**
Thermal photons, charmonium	Thermometer
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

Measuring temperature

Thermal photons

Phys.Rev.Lett.104:132301,2010



PHENIX collaboration
Au+Au collisions at
$\sqrt{s_{NN}}$=200 GeV

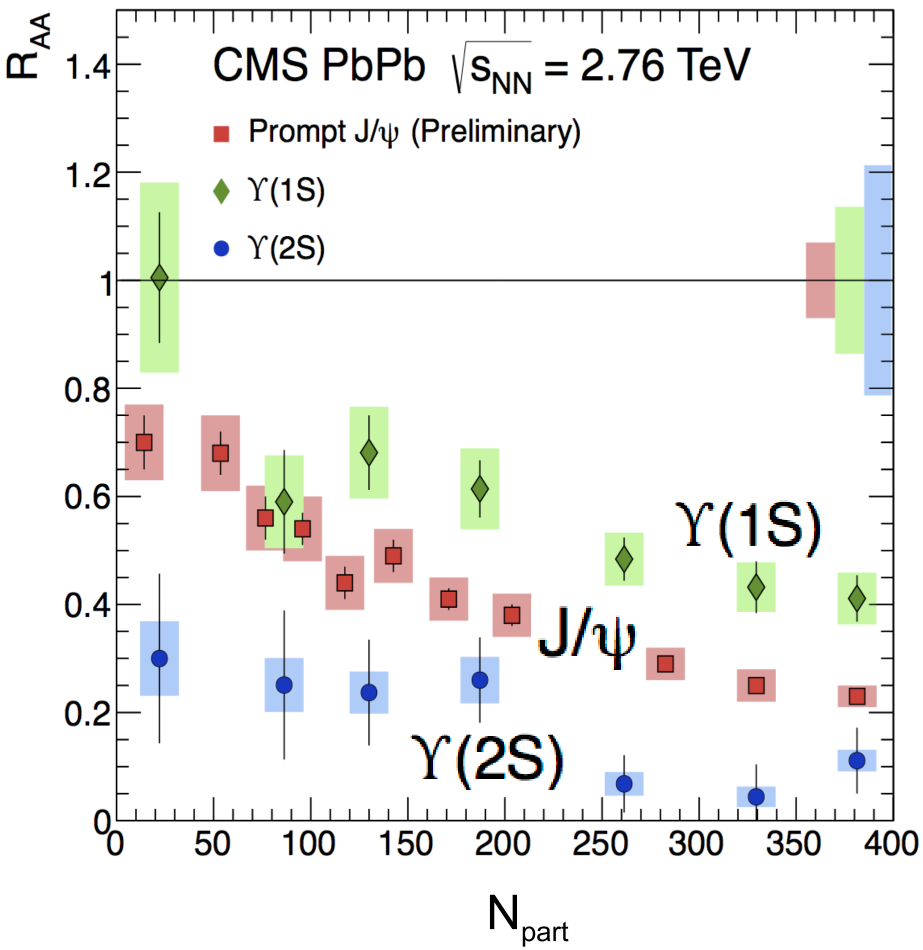
Inverse slope:
T = 221 +/- 19 (stat) +/- 19 (syst) MeV

Consistent with models with T=300-600 MeV

T_c ~ 170 MeV

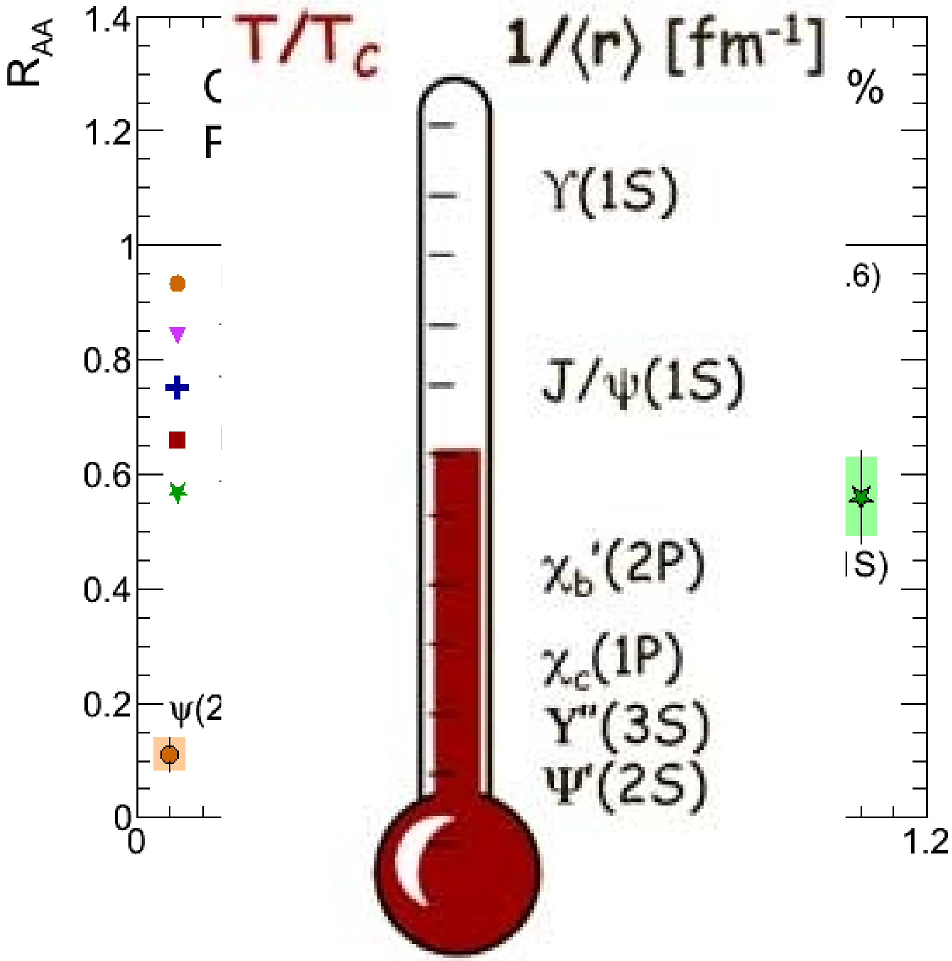
Building a quarkonium-thermometer

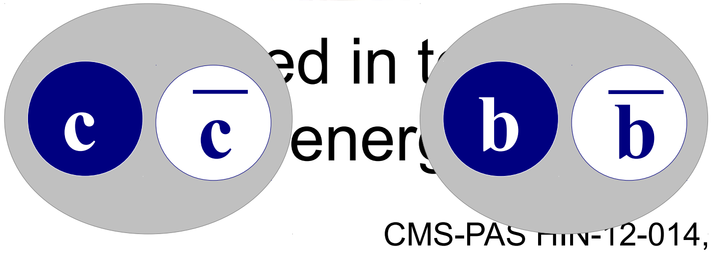
CMS-PAS HIN-11-011



Clear hierarchy in R_{AA} of different quarkonium states

Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)

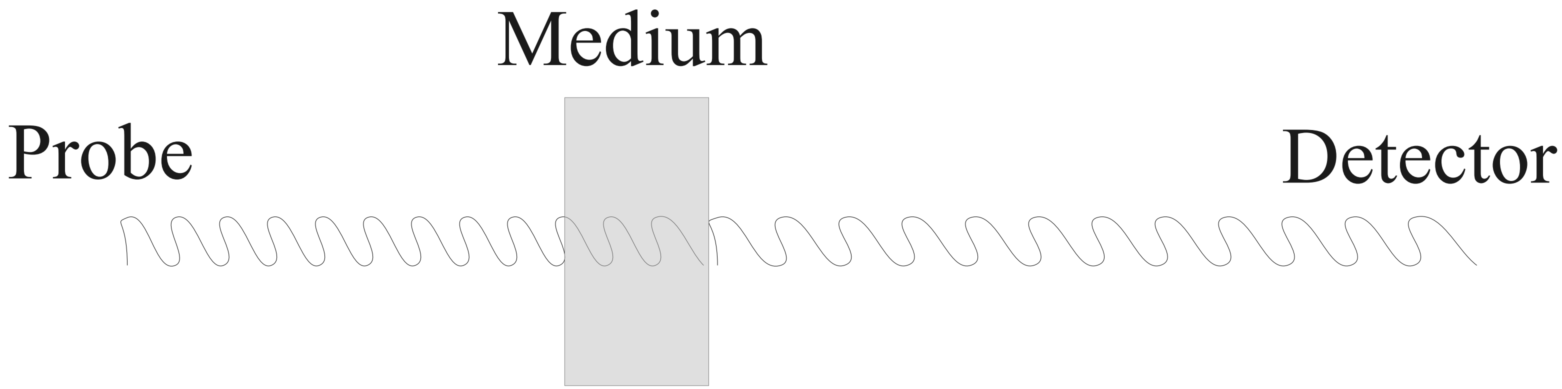




CMS-PAS HIN-12-014, HIN-12-007

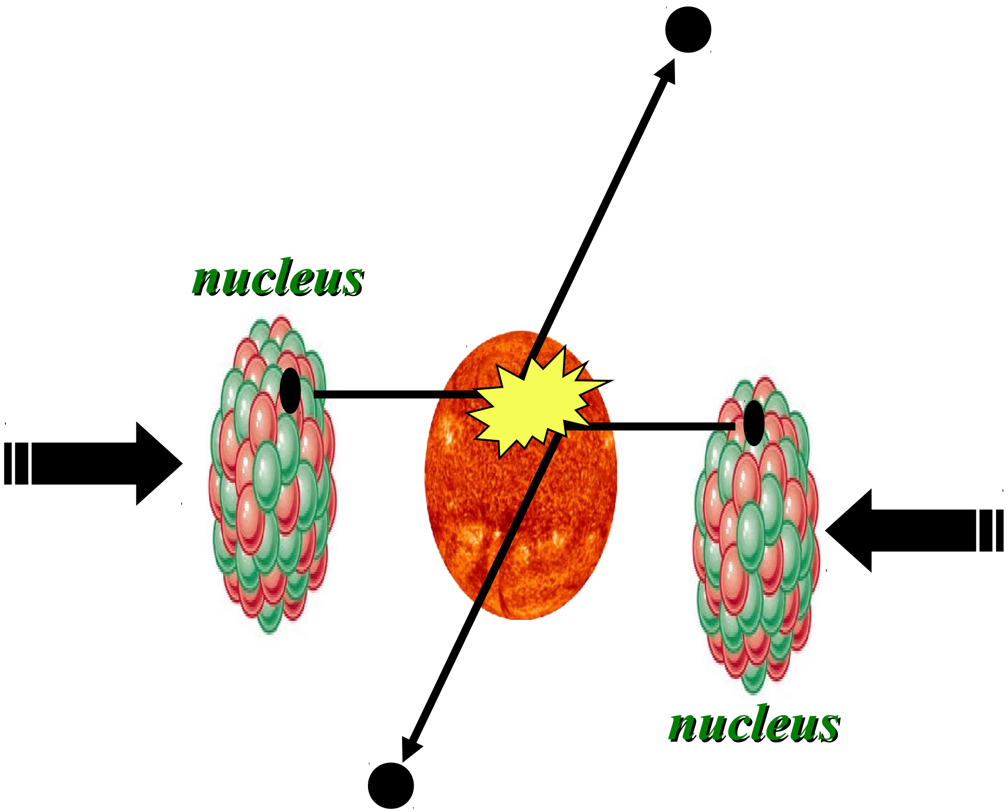
Hard probes

Probing the Quark Gluon Plasma



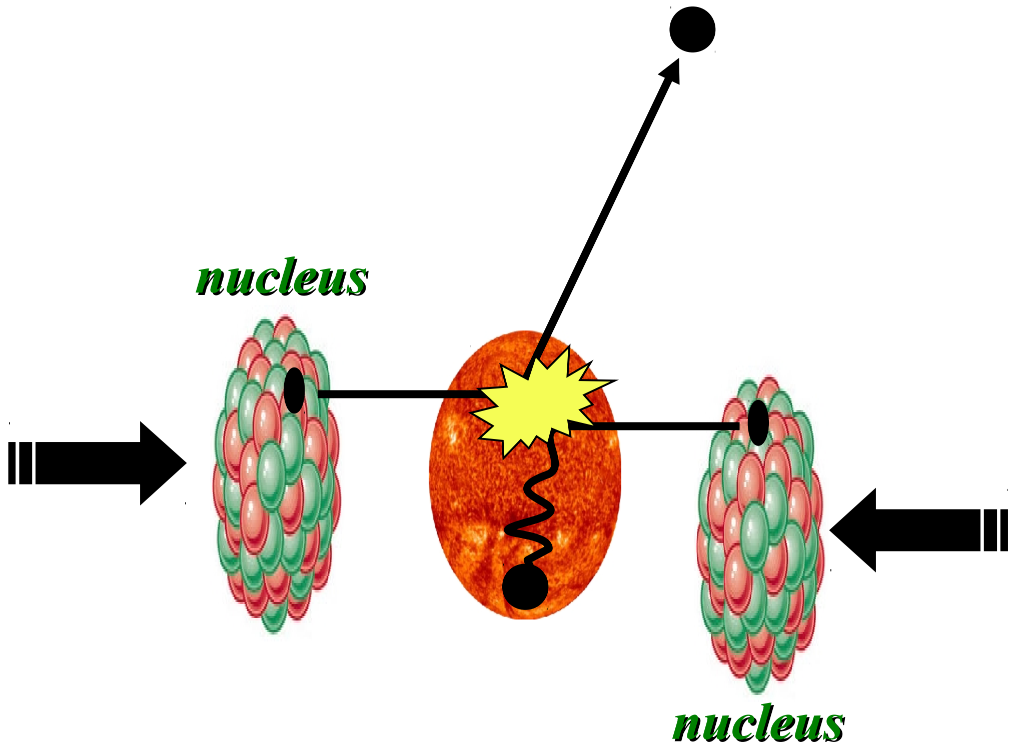
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
 cannot use an external probe

Probes of the Quark Gluon Plasma



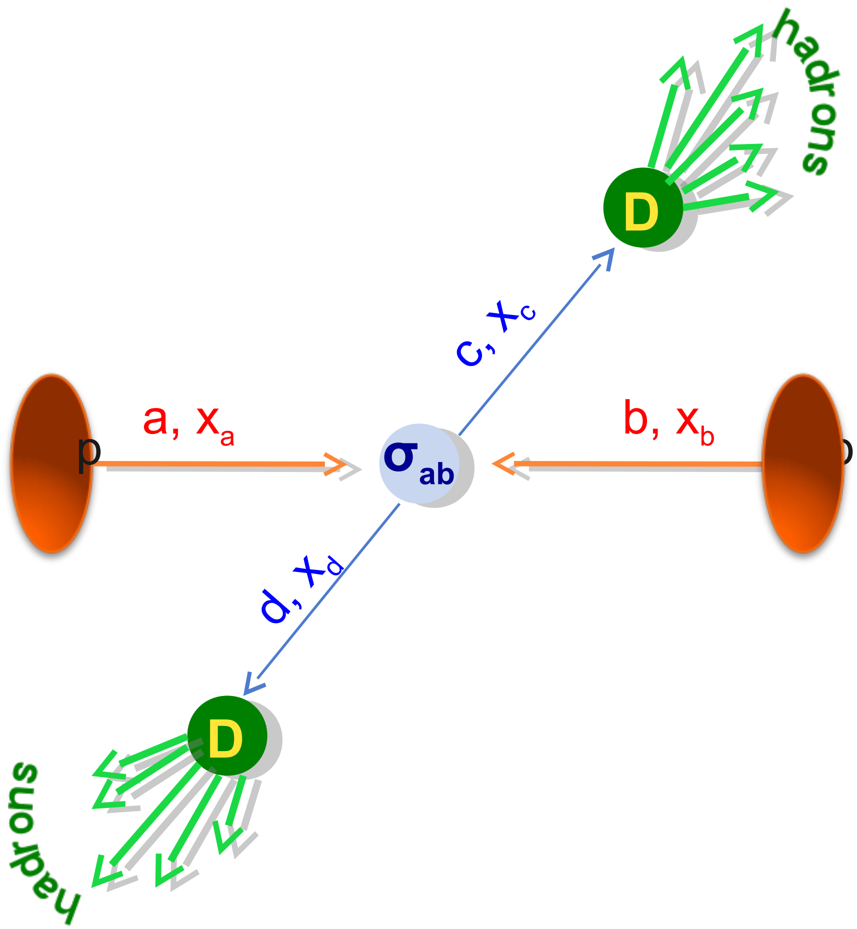
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

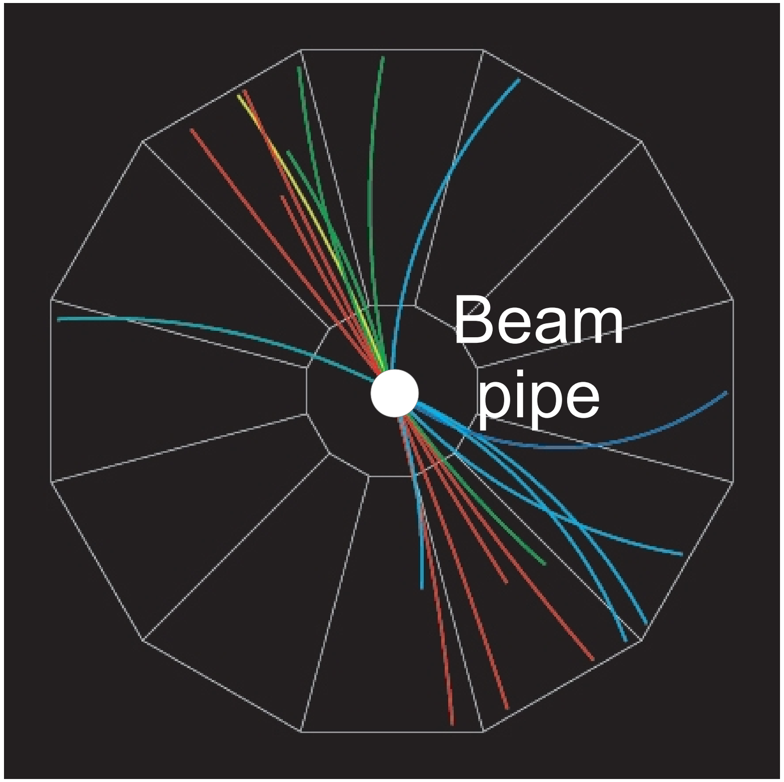


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

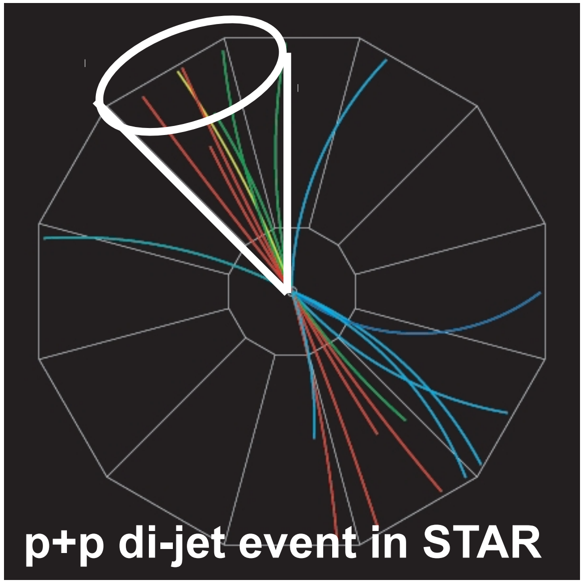


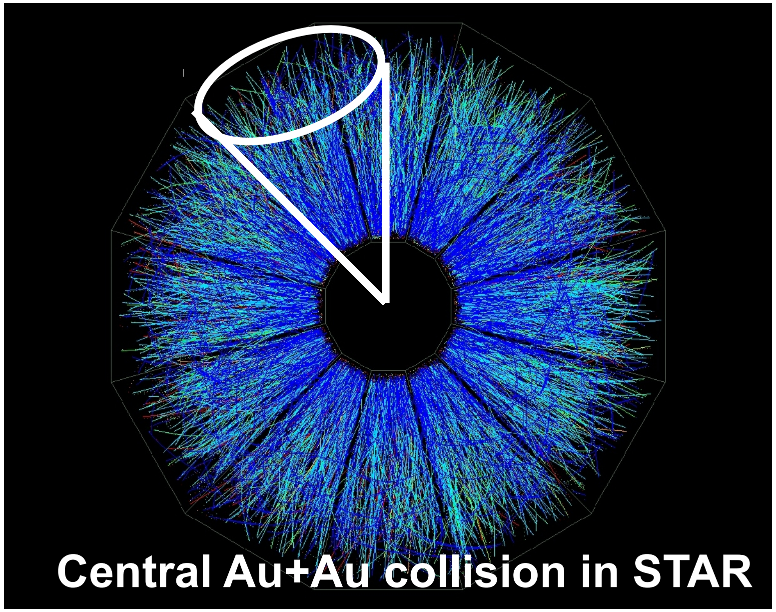
p+p → dijet



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

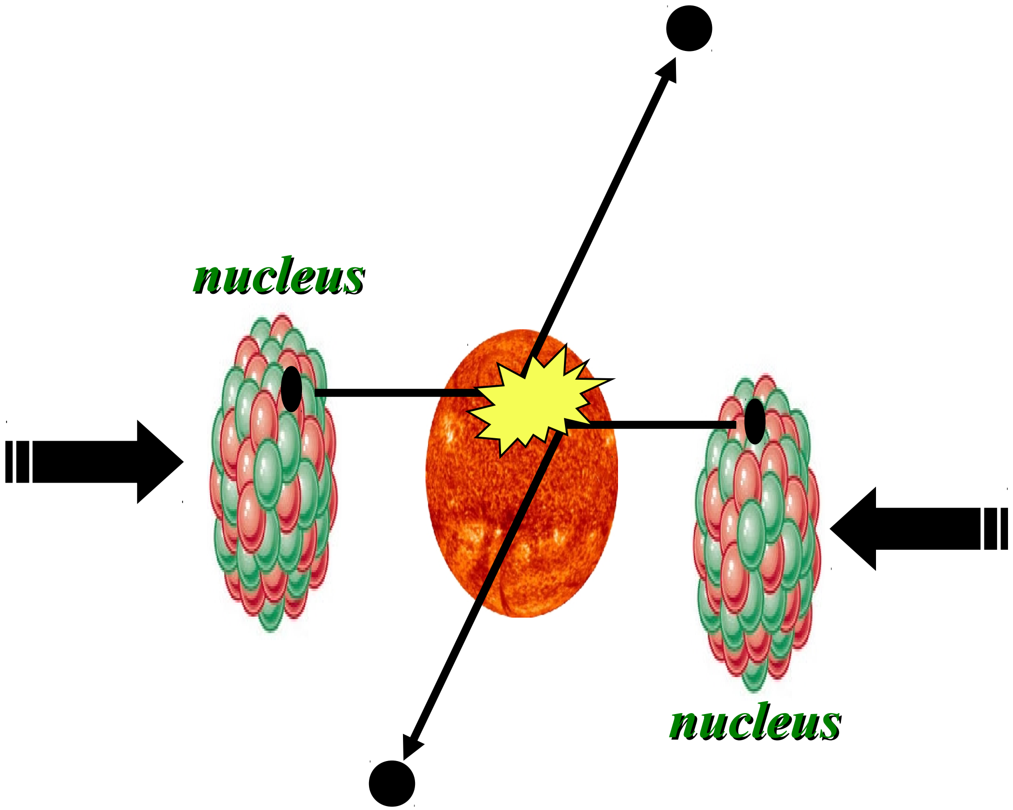
Jet reconstruction

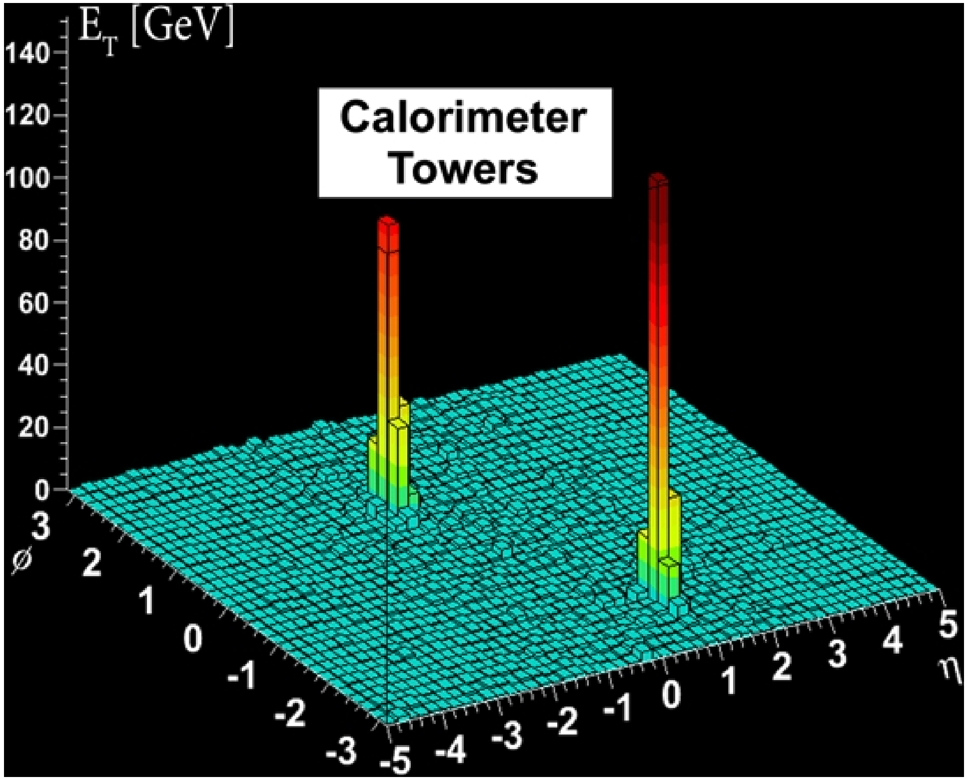




- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

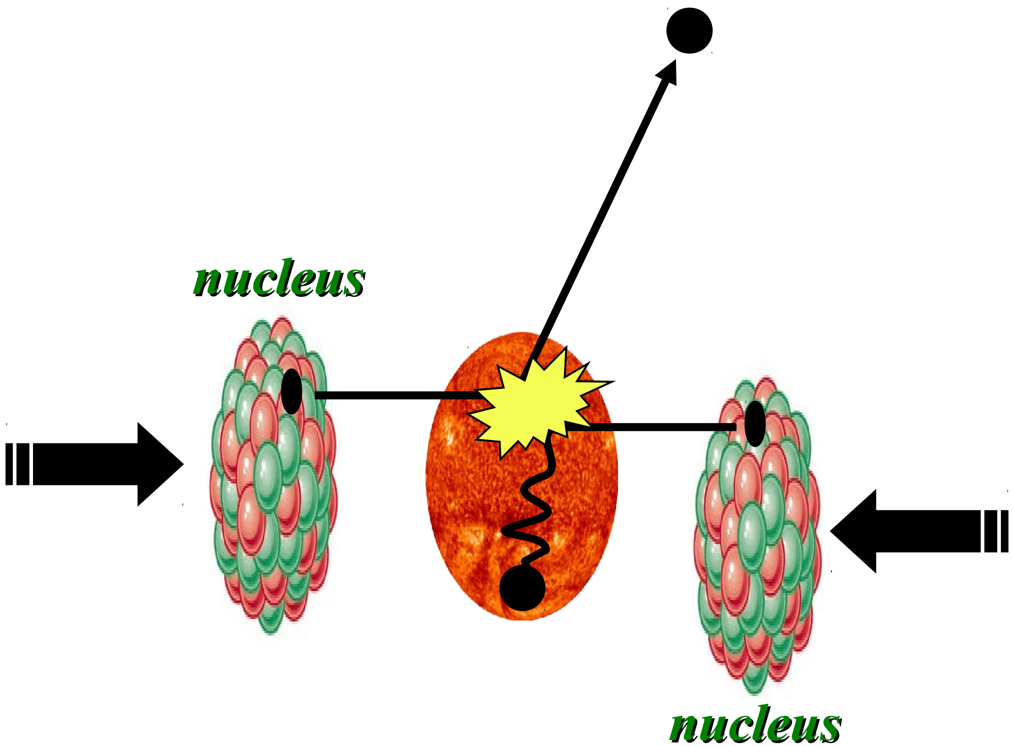
Jets

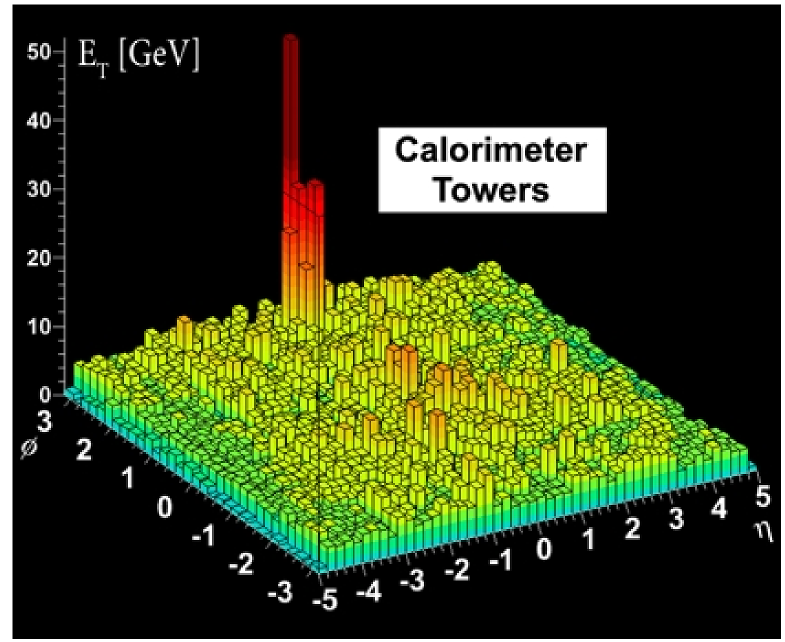




- Quarks and gluons are confined – we don't see them outside of mesons and baryons
- Instead we see a cone of particles around the outgoing quark or gluon
- Looking at jets analogous to spectroscopy

Quenched jets



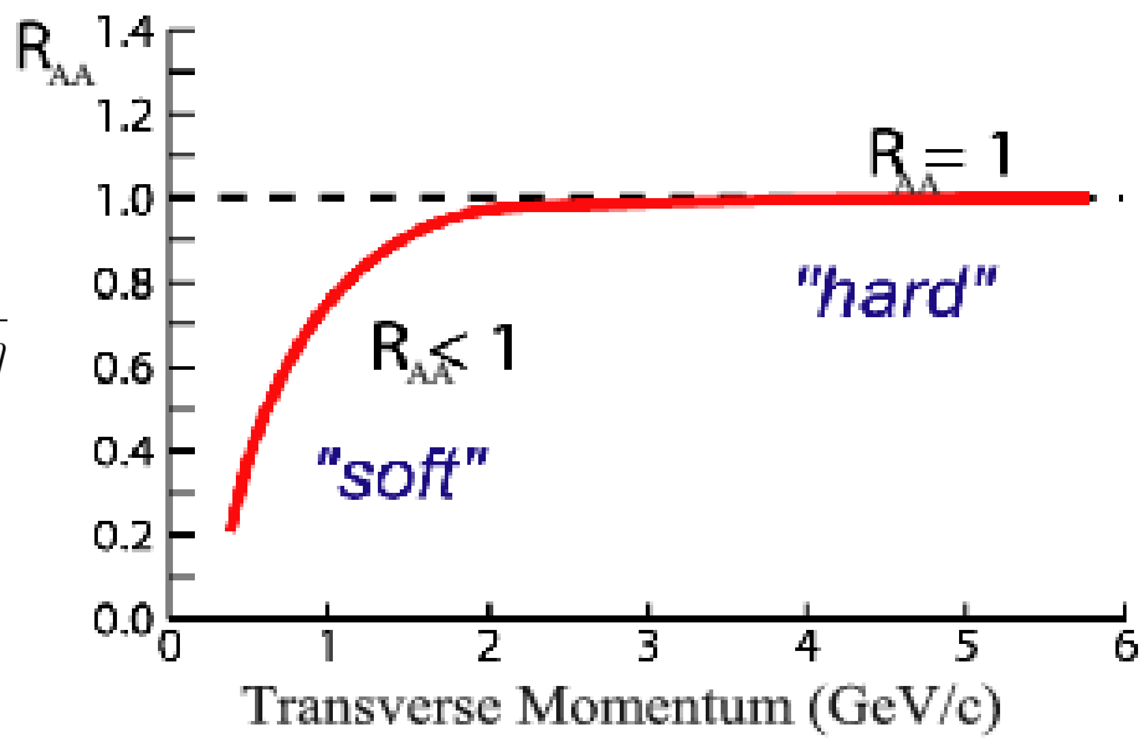


- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



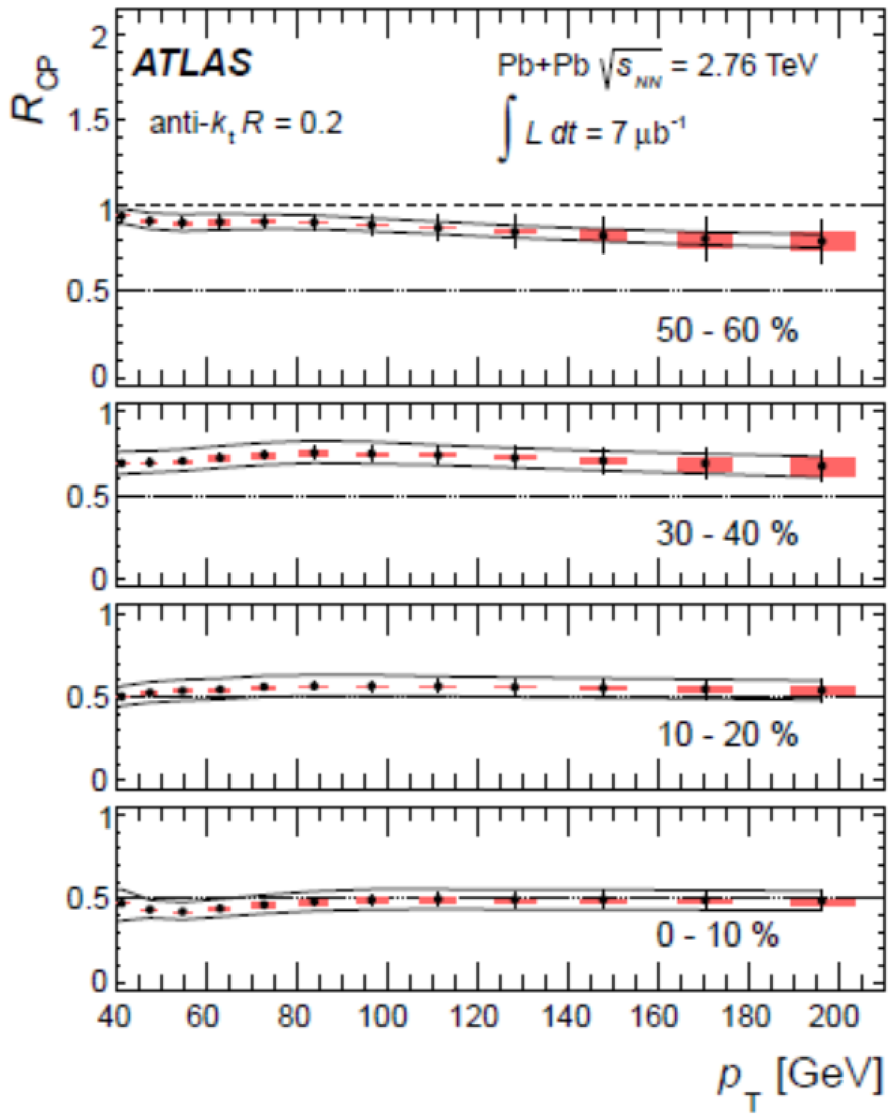
Enhancement

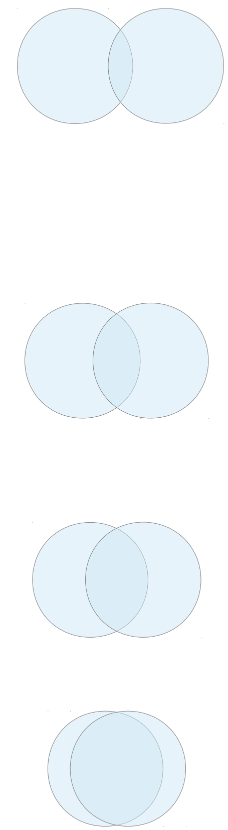
Suppression

Jet nuclear modification factor*

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

ATLAS collaboration
Anti-kT algorithm
R=0.2

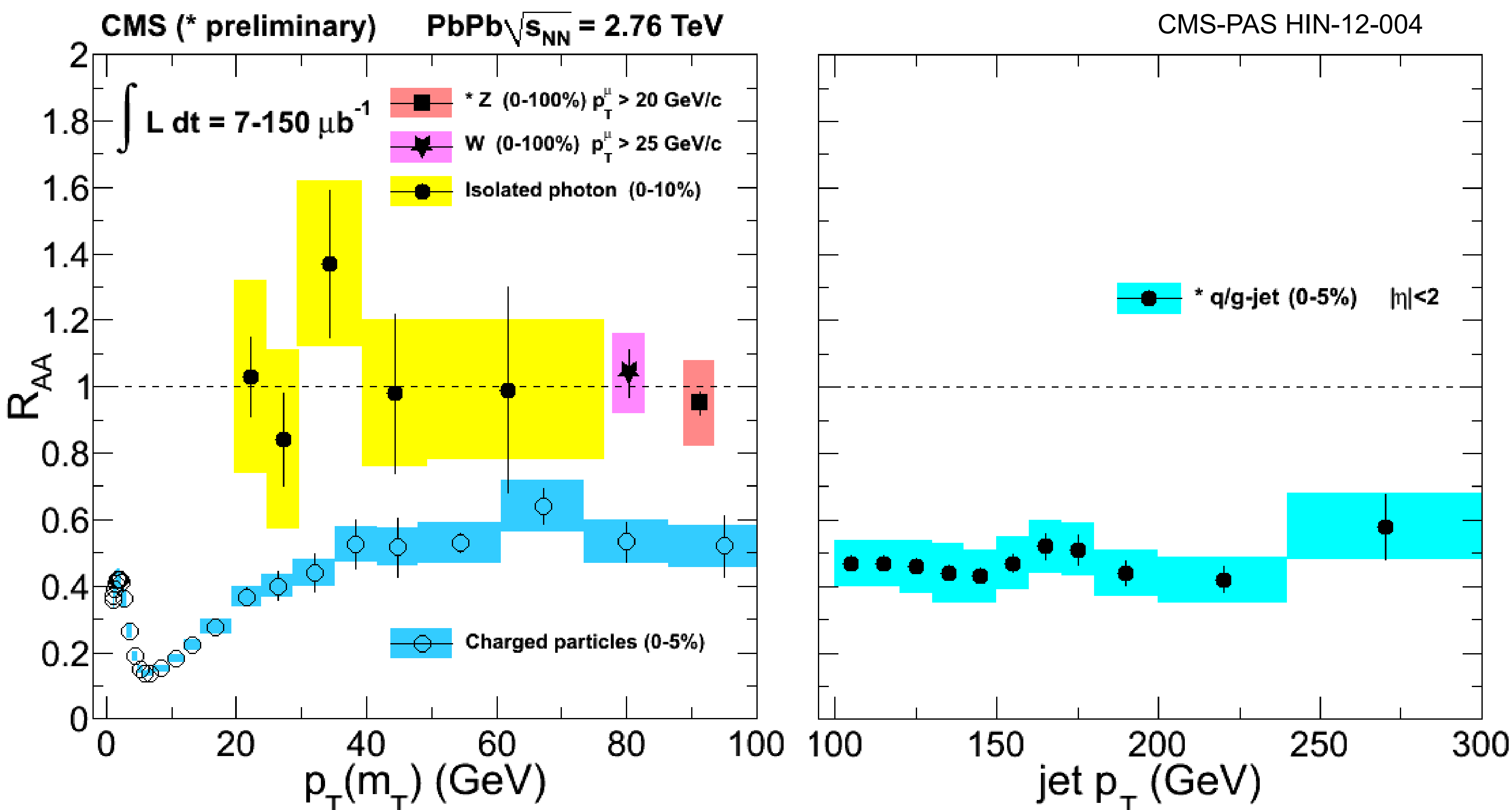




*Rcp is the ratio of central to peripheral A+A collisions instead of A+A collisions to p+p

Nuclear modification factors

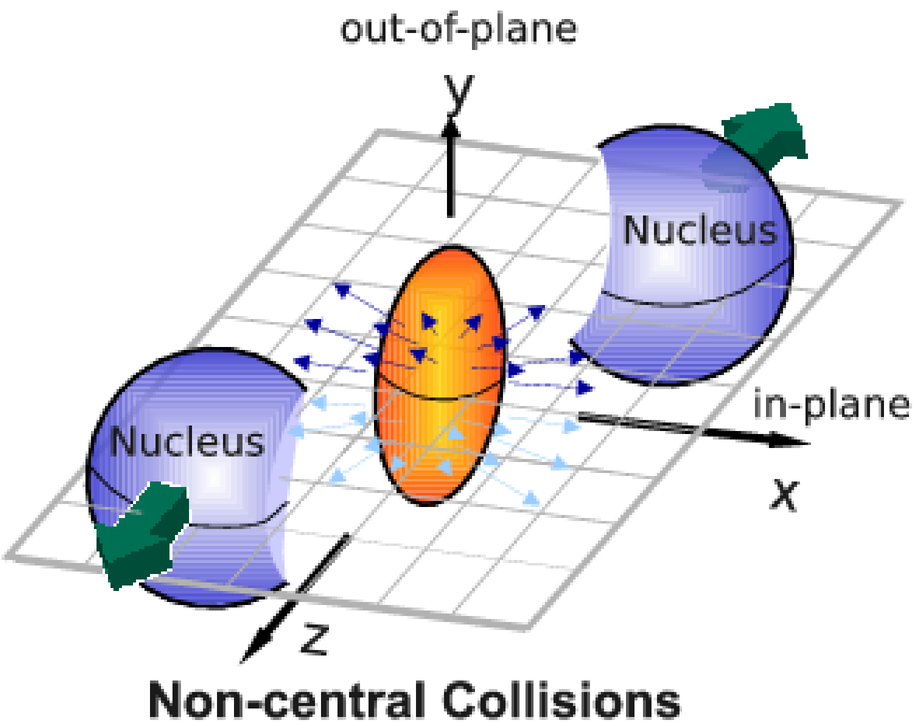
Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference

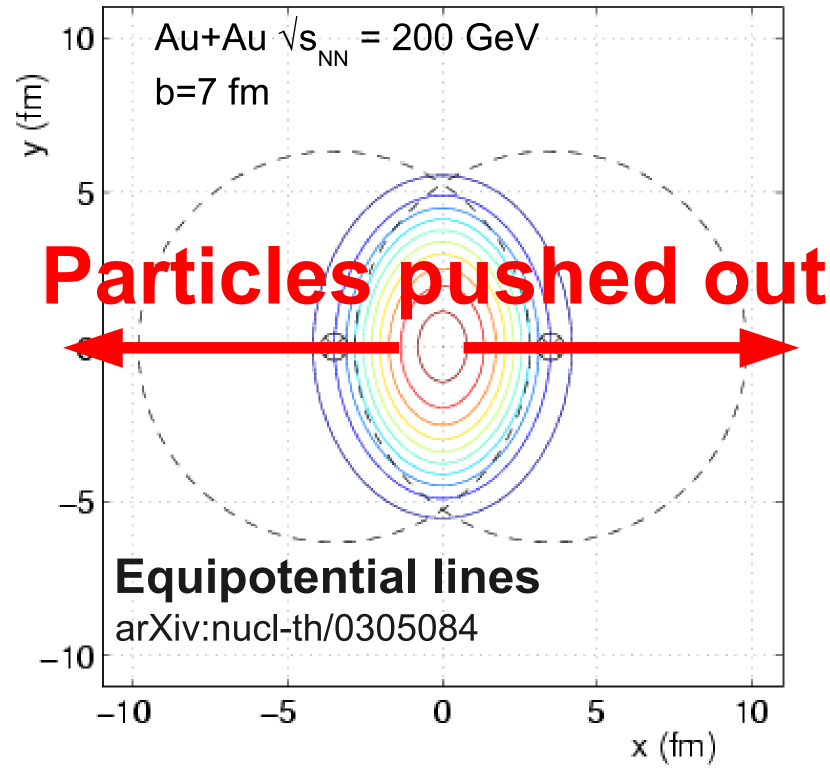


Like for charged particles,
high-p_T jet R_{AA} flat at ≈ 0.5

Hard probes

If we have a fluid...



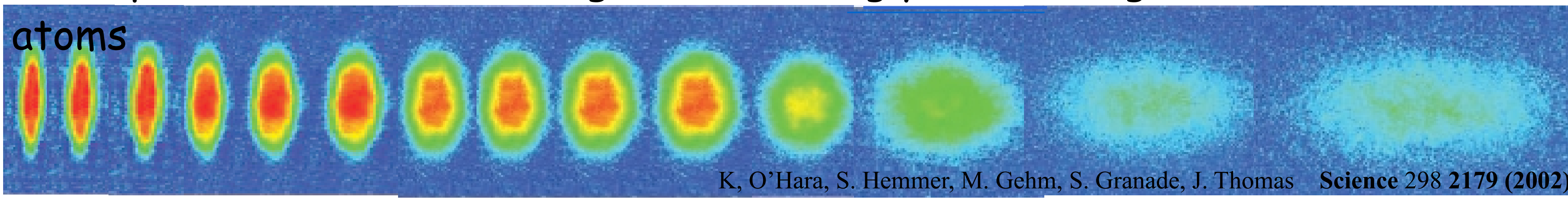


- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

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

What does it mean?

Same phenomena observed in gases of strongly interacting atoms

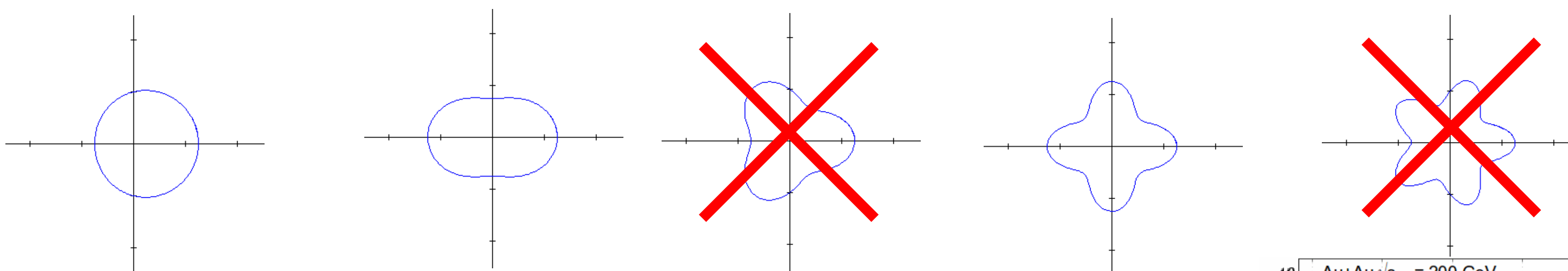


Time →

Initial state anisotropies converted to final state anisotropies

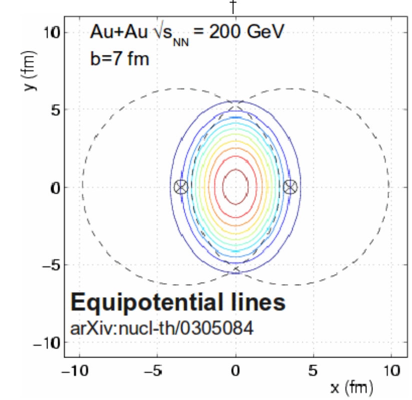
Fourier decomposition:

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

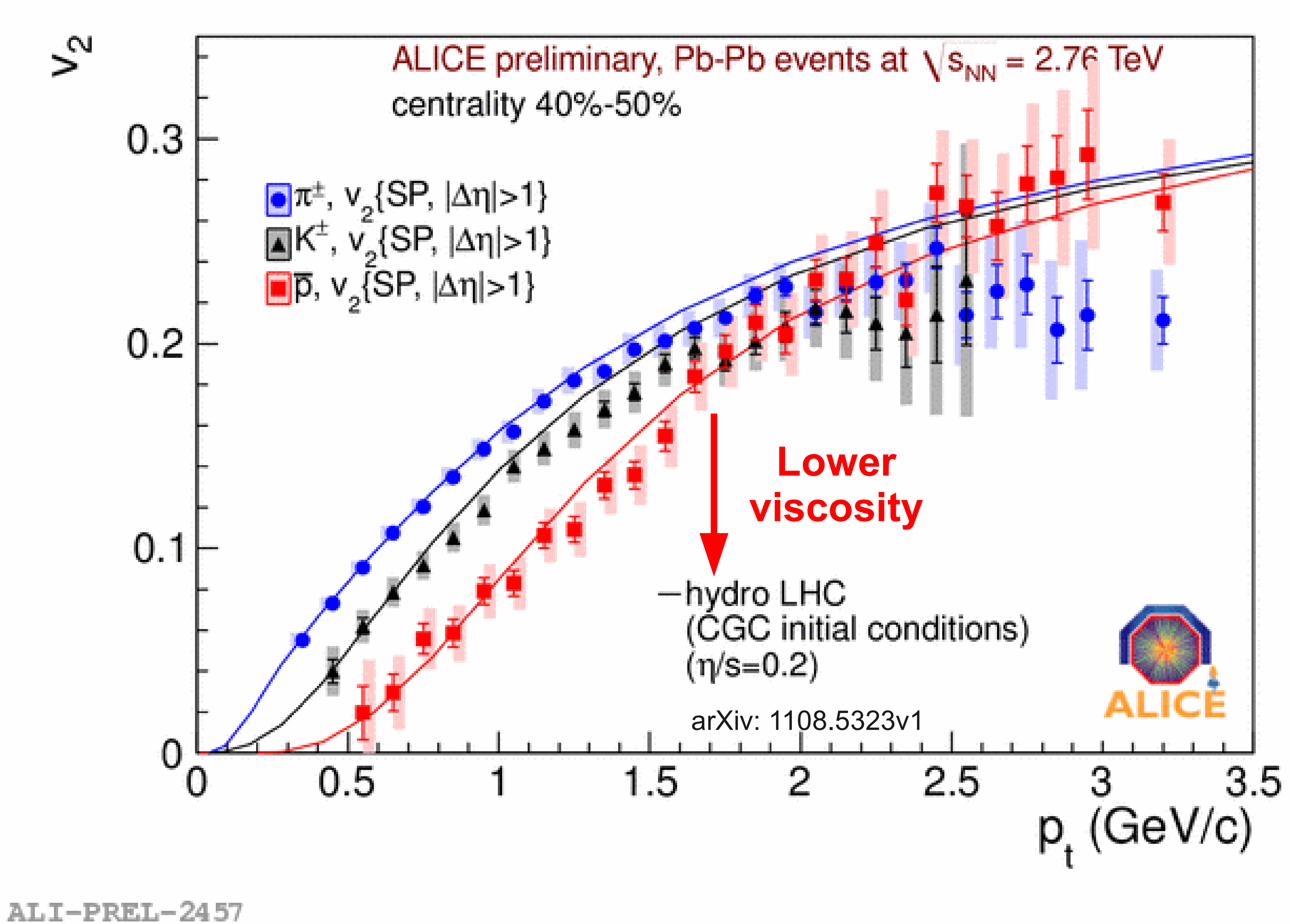


Offset measured

Nuclei are symmetric → No odd coefficients

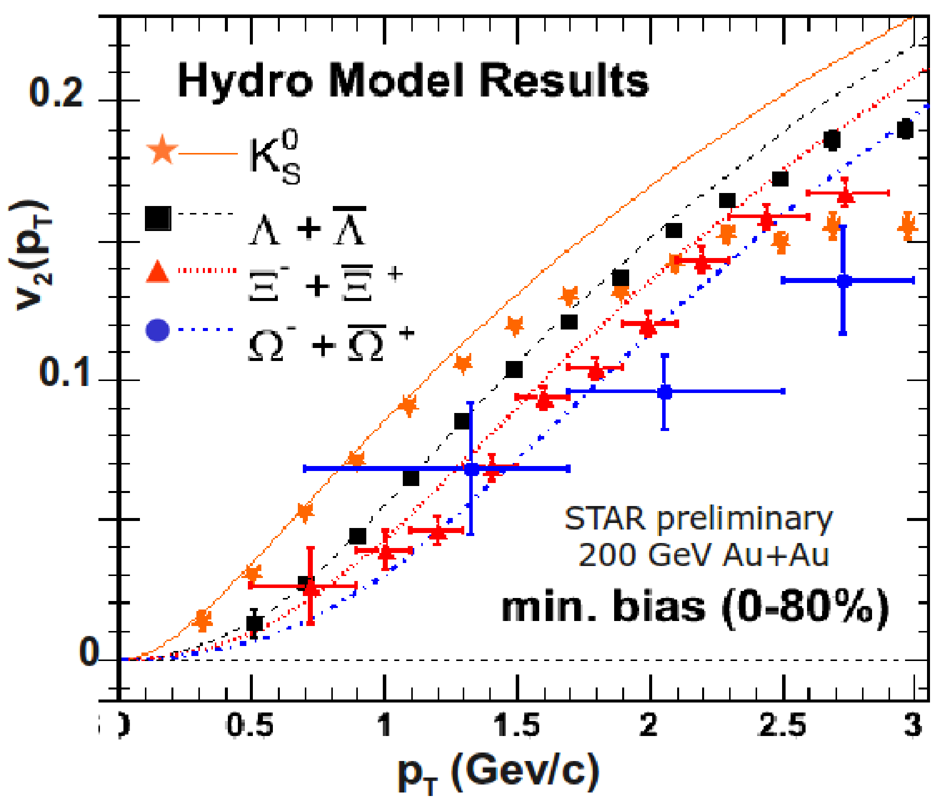


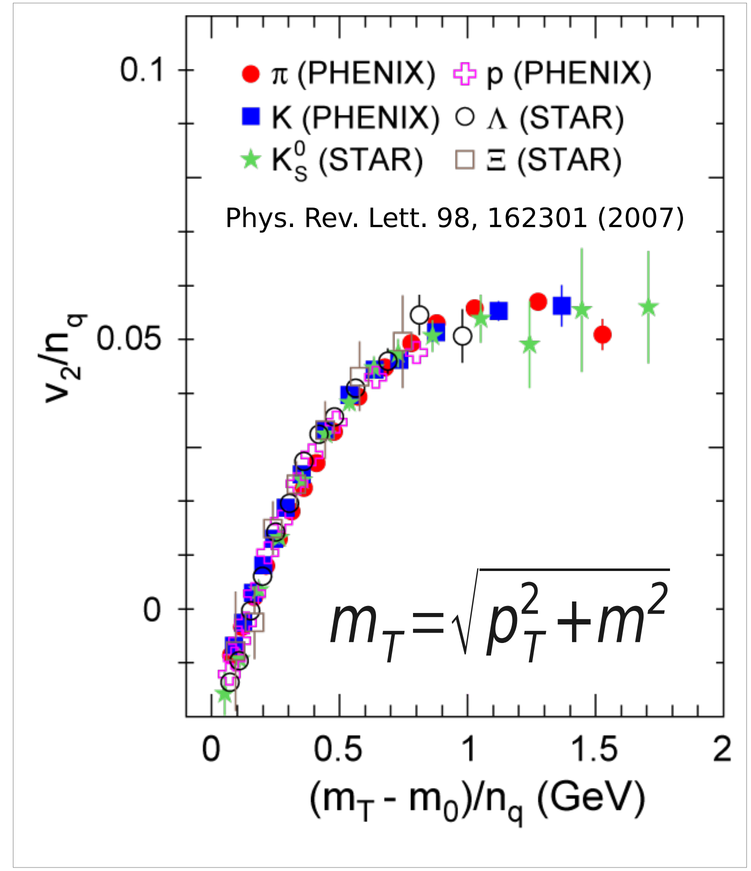
Does this describe the data?



Yes!

More data





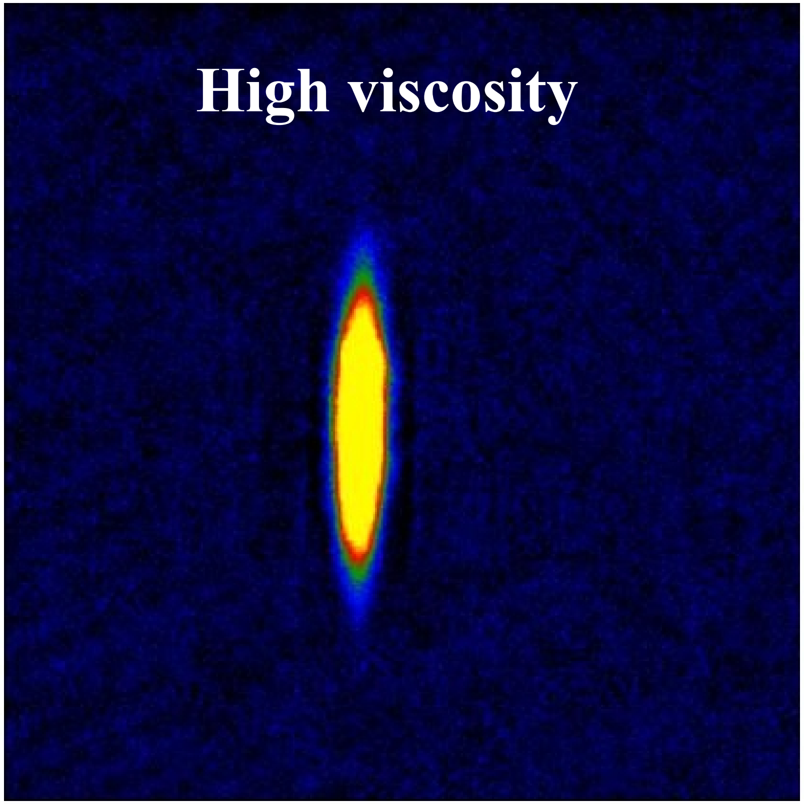
Mass ordering:
$v_2(K) > v_2(\Lambda) > v_2(\Xi)$

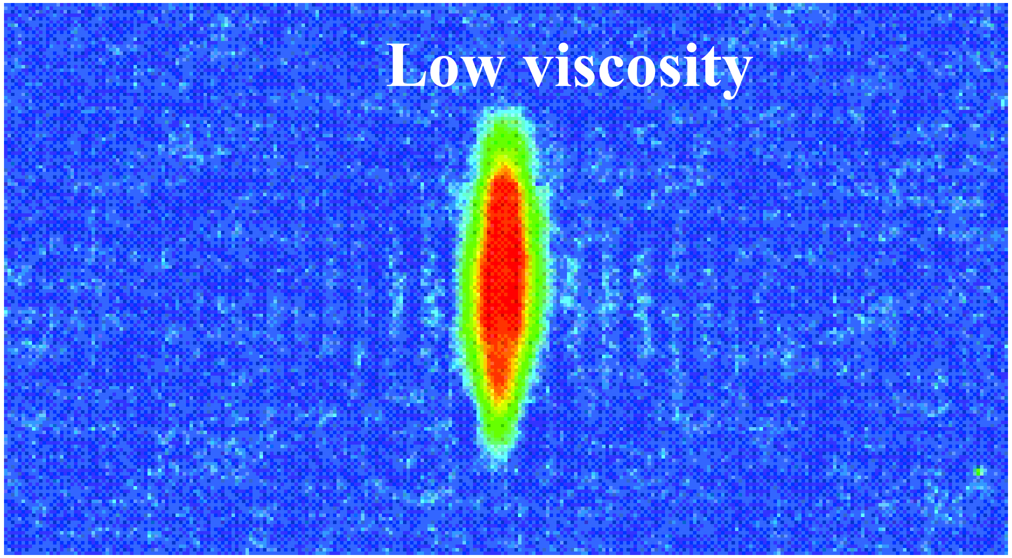
$v_2(p_T^{hadron})$ µ $n_{quark} v_2(p_T^{quark})$

We have a liquid of quarks and gluons!

What do we learn about the QGP?

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





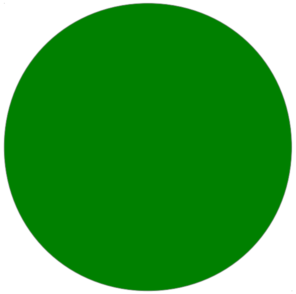
The Quark Gluon Plasma has a very low viscosity

What do we learn about the QGP?

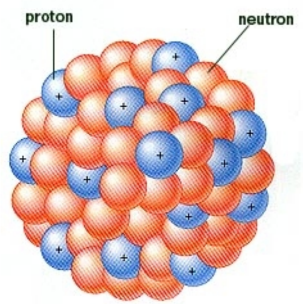
- Hydrodynamics works →
  - (local) thermalization
  - image of the initial state
- Really low viscosity
  - Near AdS/CFT bound
  - $\eta/S \sim 1/4\pi$

The QGP is the perfect liquid!

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



This is not what a nucleus looks like



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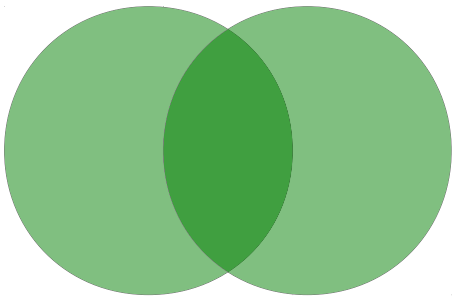
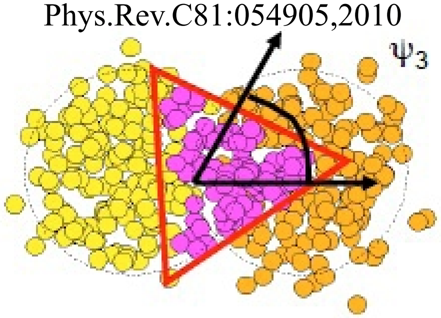


This is not what our collision looks like

Phys.Rev.C81:054905,2010



This is what our collision looks like

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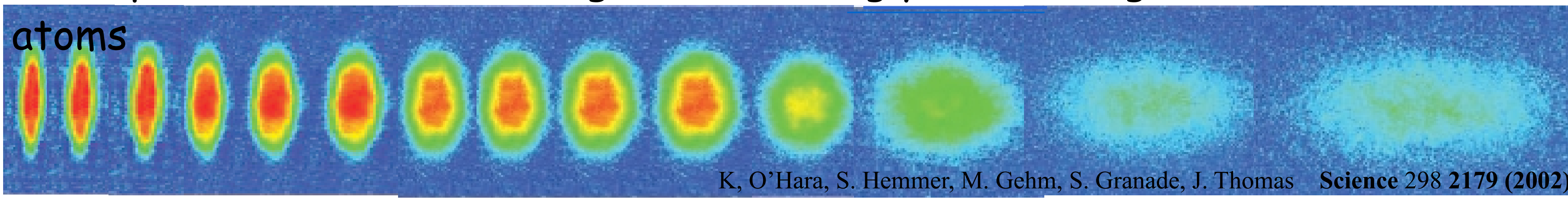

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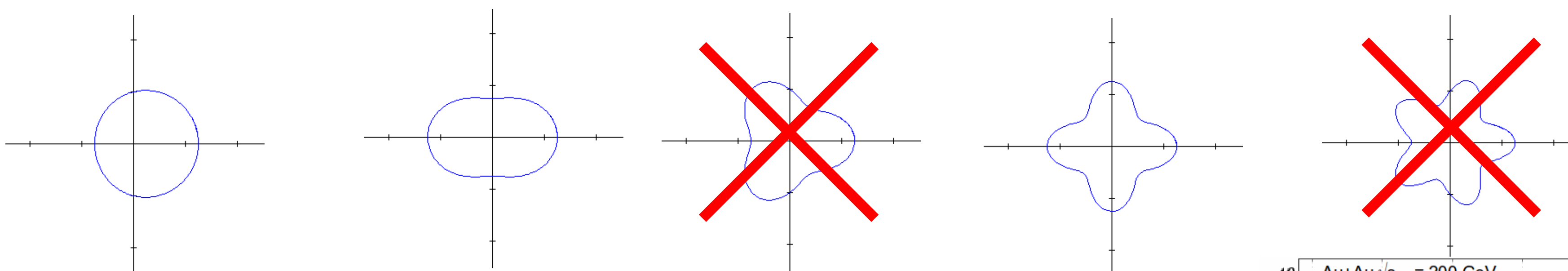

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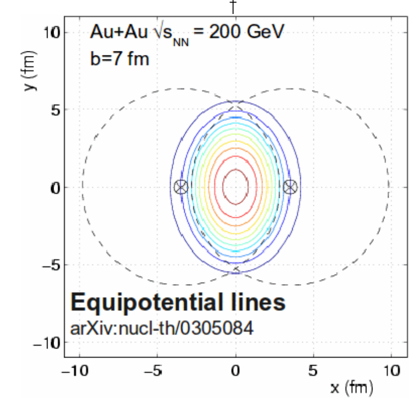
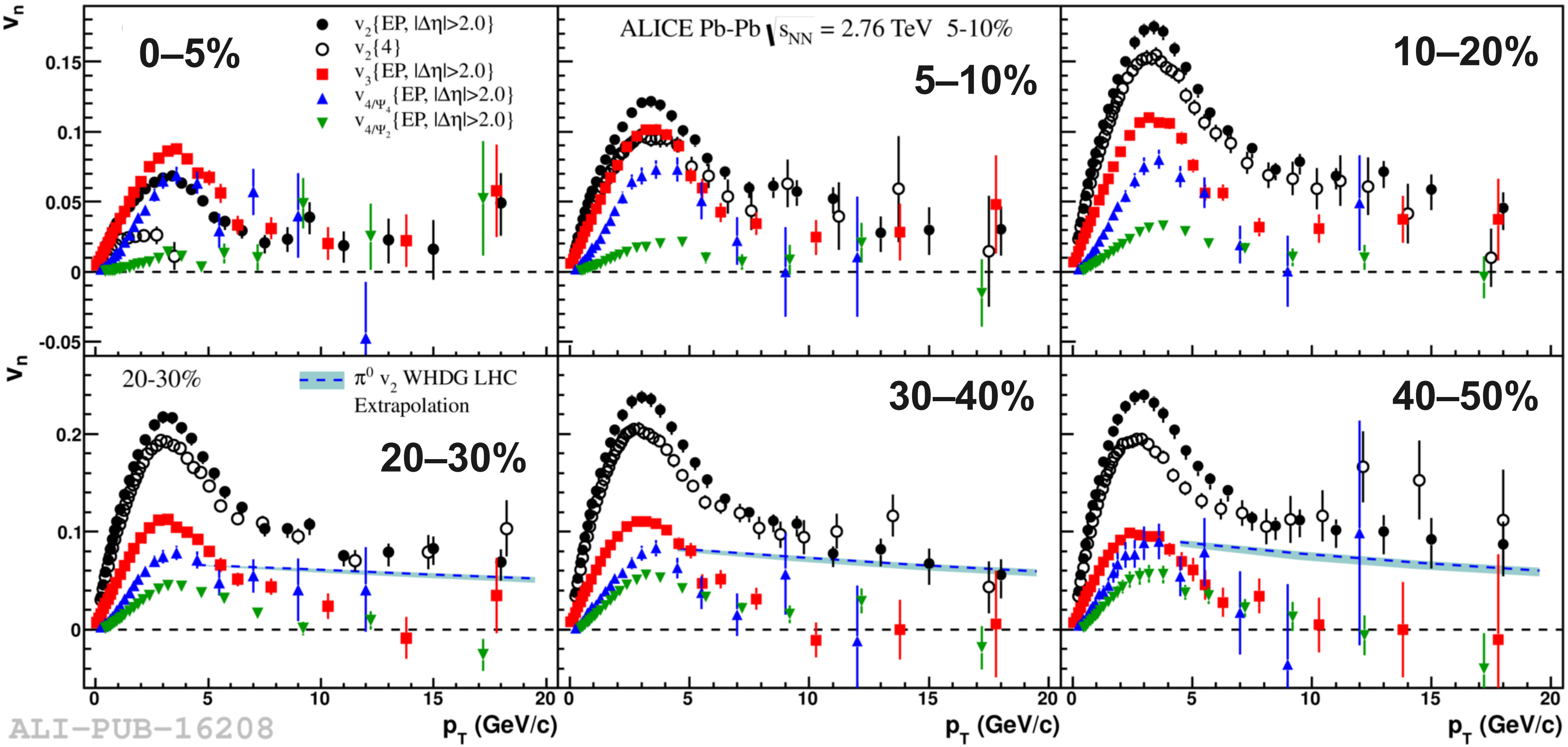


Odd and even v_n



Odd n: sensitive to fluctuations in the initial state

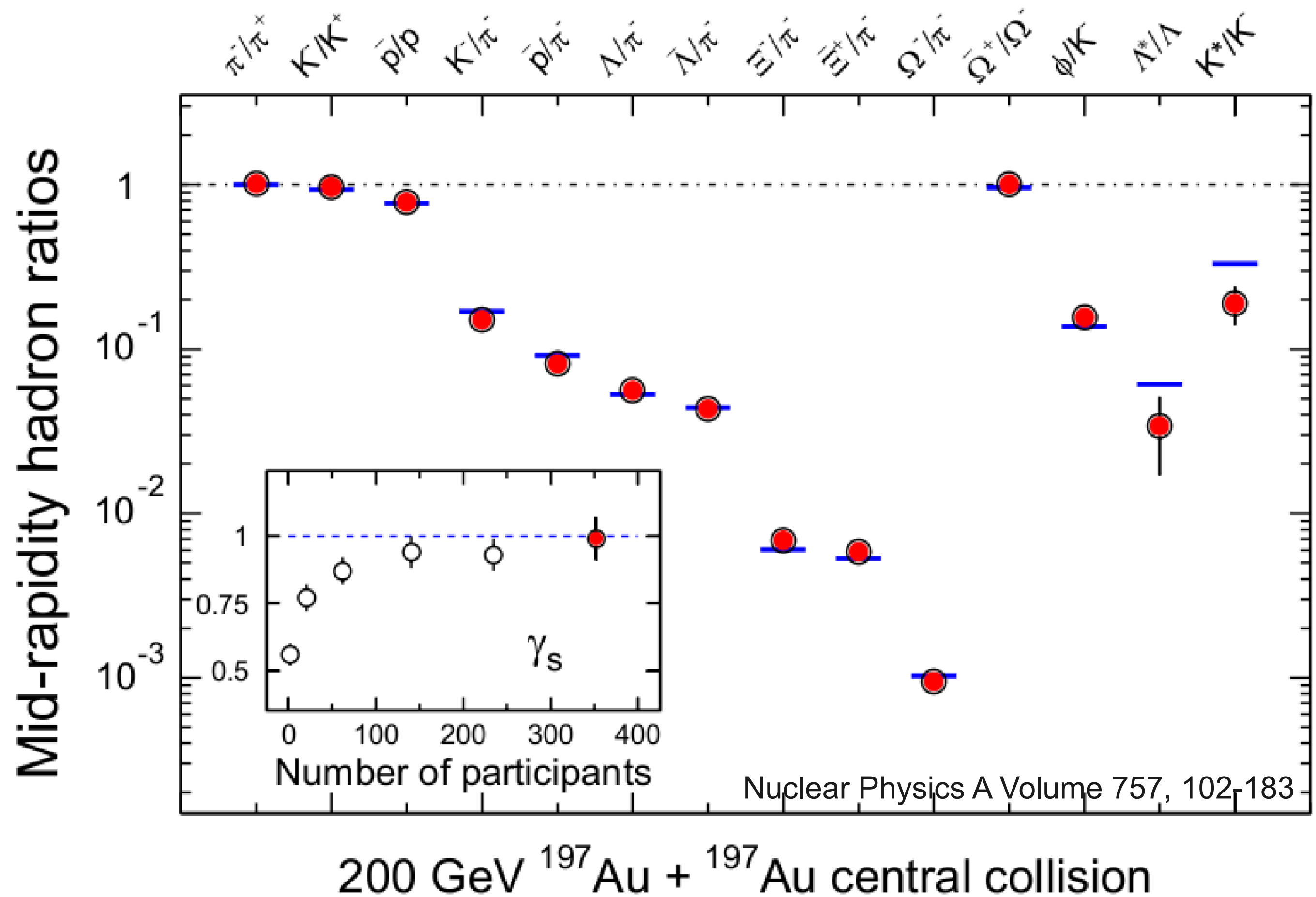
Conclusions

- Form Quark Gluon Plasma in A+A collisions
- $T>T_c$
- Jet suppression → strongly interacting medium
- Hydrodynamical flow → low η/S, perfect liquid

QGP Chemistry

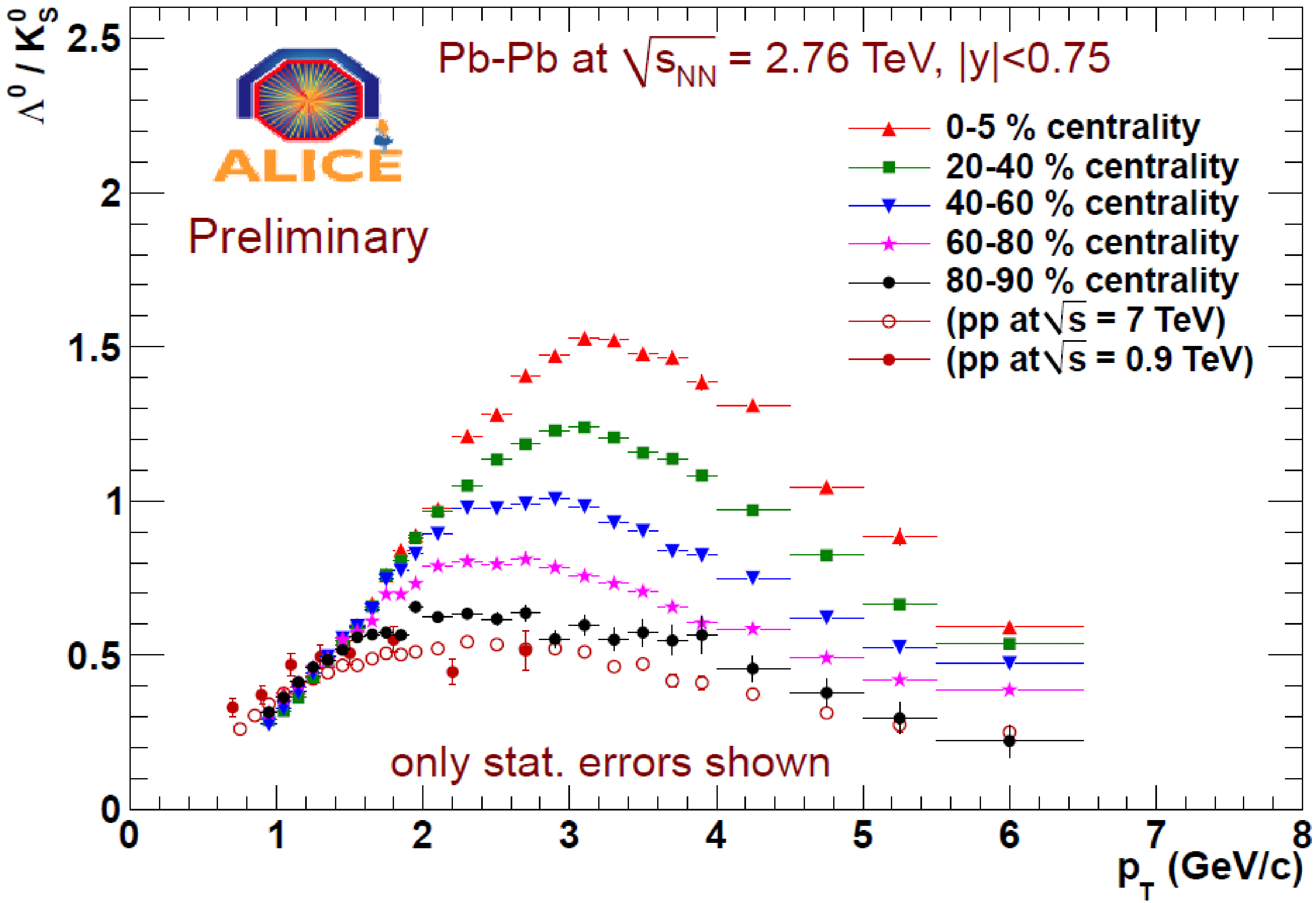
Chemistry - equilibrium

T~170 MeV



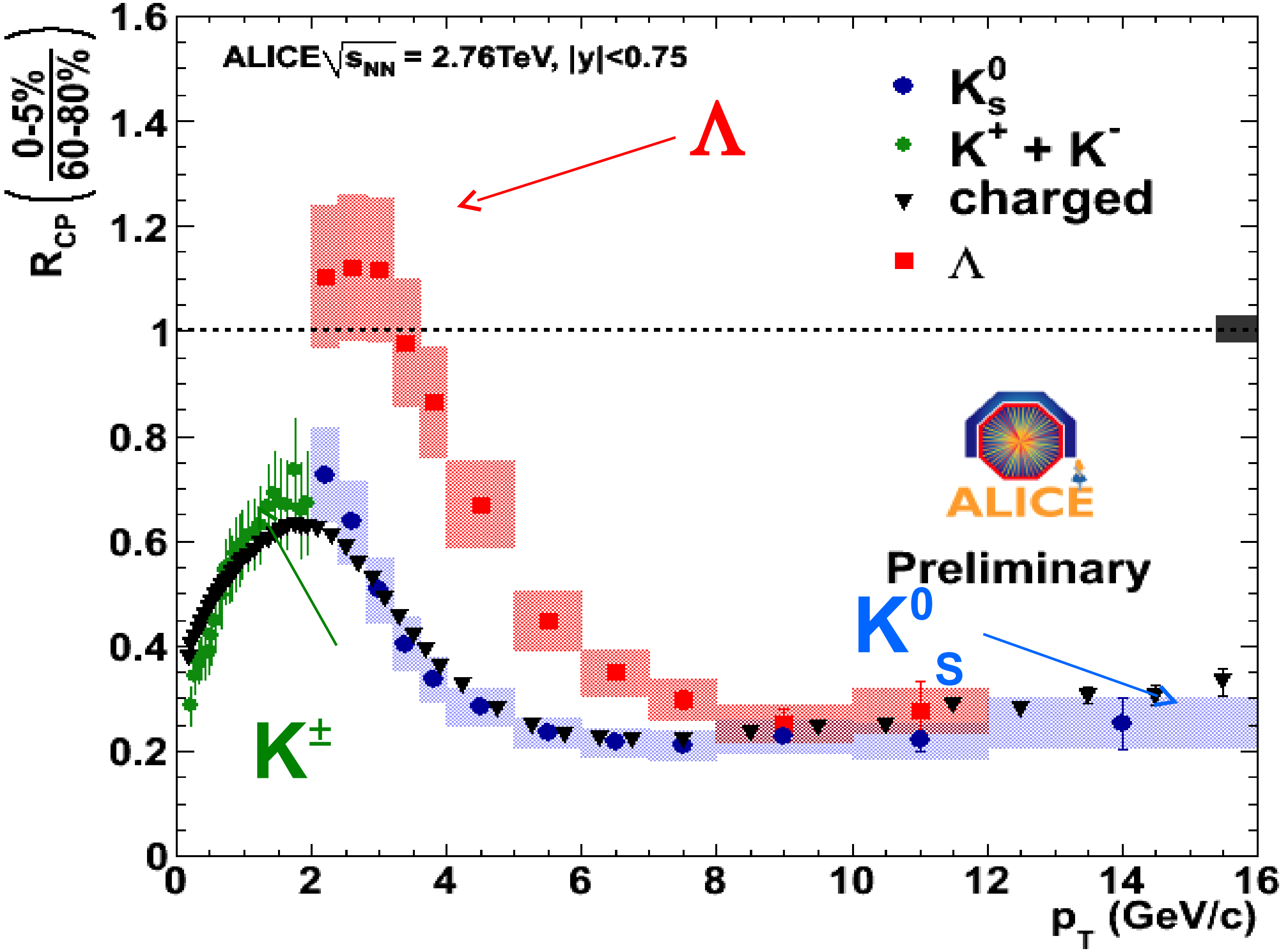
- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

Baryon anomaly: Λ/K^0_S



Pb+Pb

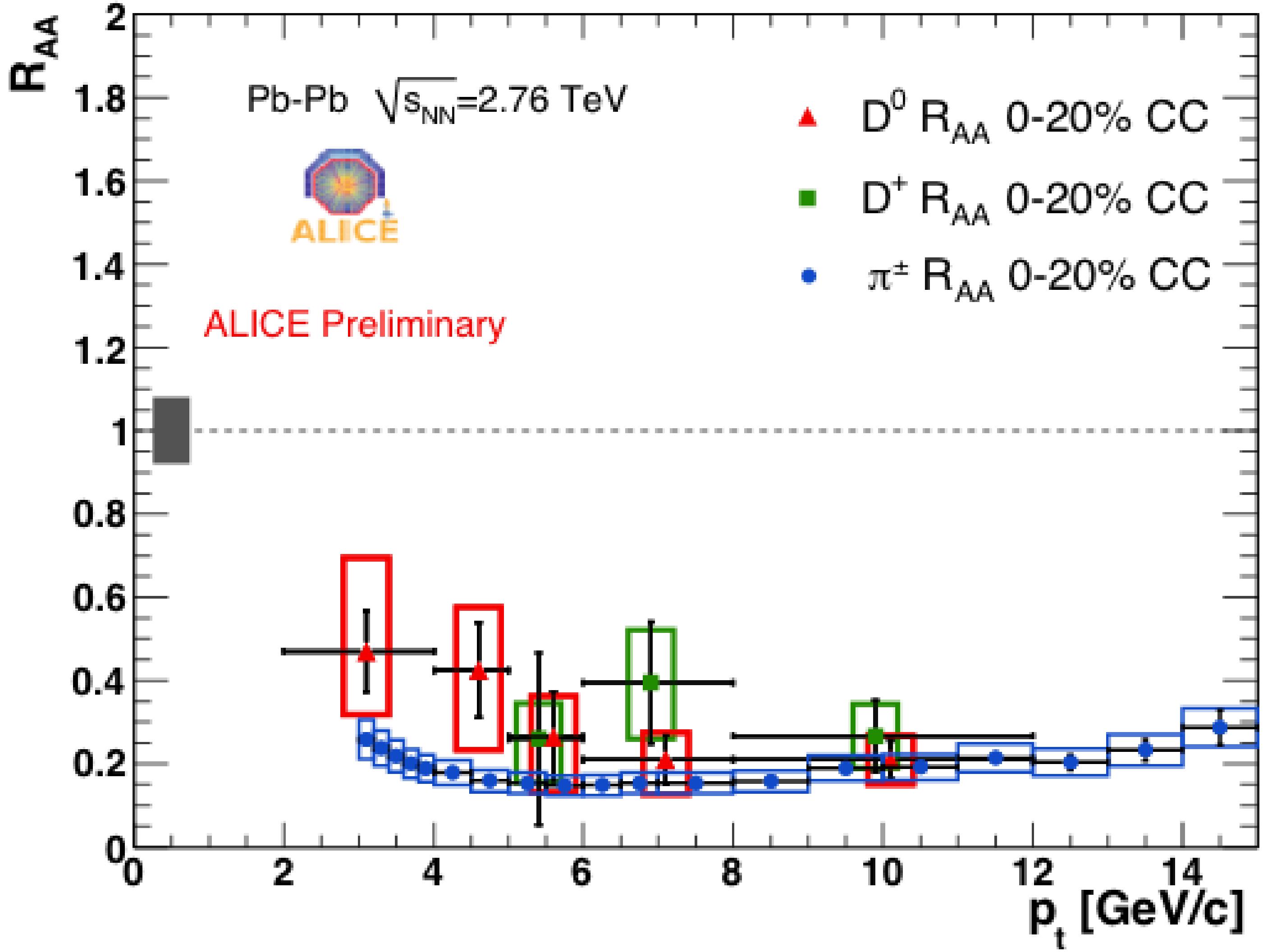
Nuclear modification factor (R_{AA})



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

Pb+Pb

Charm nuclear modification factor



Pb+Pb

Conclusions

- Form Quark Gluon Plasma in A+A collisions
- $T>T_c$
- Jet suppression → strongly interacting medium
- Hydrodynamical flow → low η/S, perfect liquid
- Quark chemistry modified in QGP