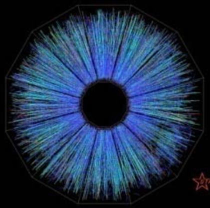
Challenges for Heavy Ions at the LHC

Quark Matter Italia, Roma, 23 July 2010

John Harris (Yale)

“Big Picture” from RHIC



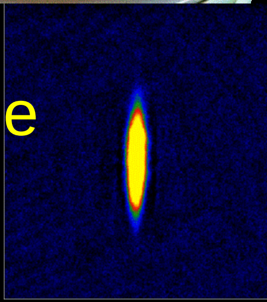
Have created the hottest matter ever on Earth

$T > 2 \times 10^{12}$ K

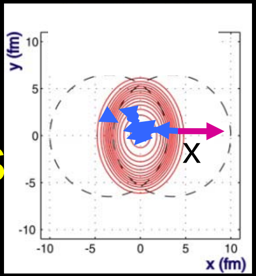
> 100,000 times hotter than the core of Sun

It has characteristics of a soup of quarks and gluons

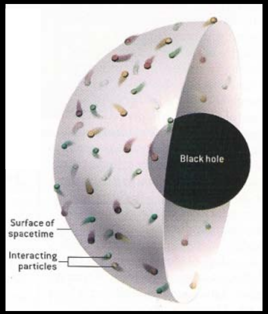
It flows like a liquid, better than any we know or have made



It is opaque to the most energetic parton probes



It has some properties predicted in strongly-coupled AdS/CFT with black hole in 5D projected onto our 4D world!

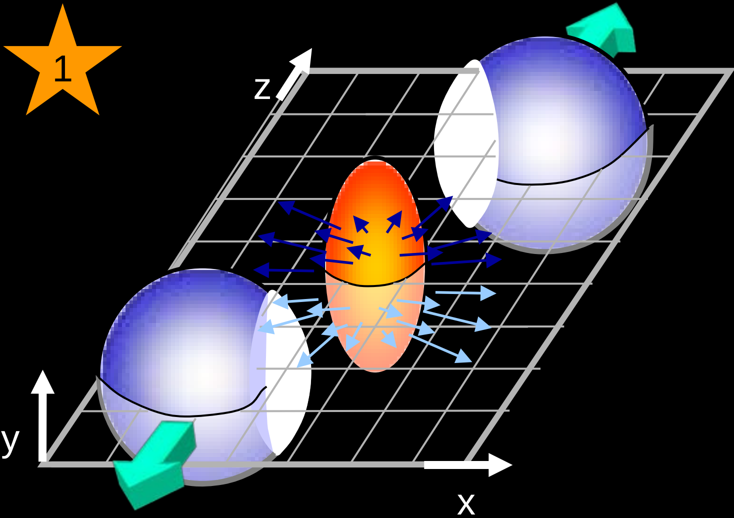


On the Horizon……..

Heavy Ions in the Large Hadron Collider!

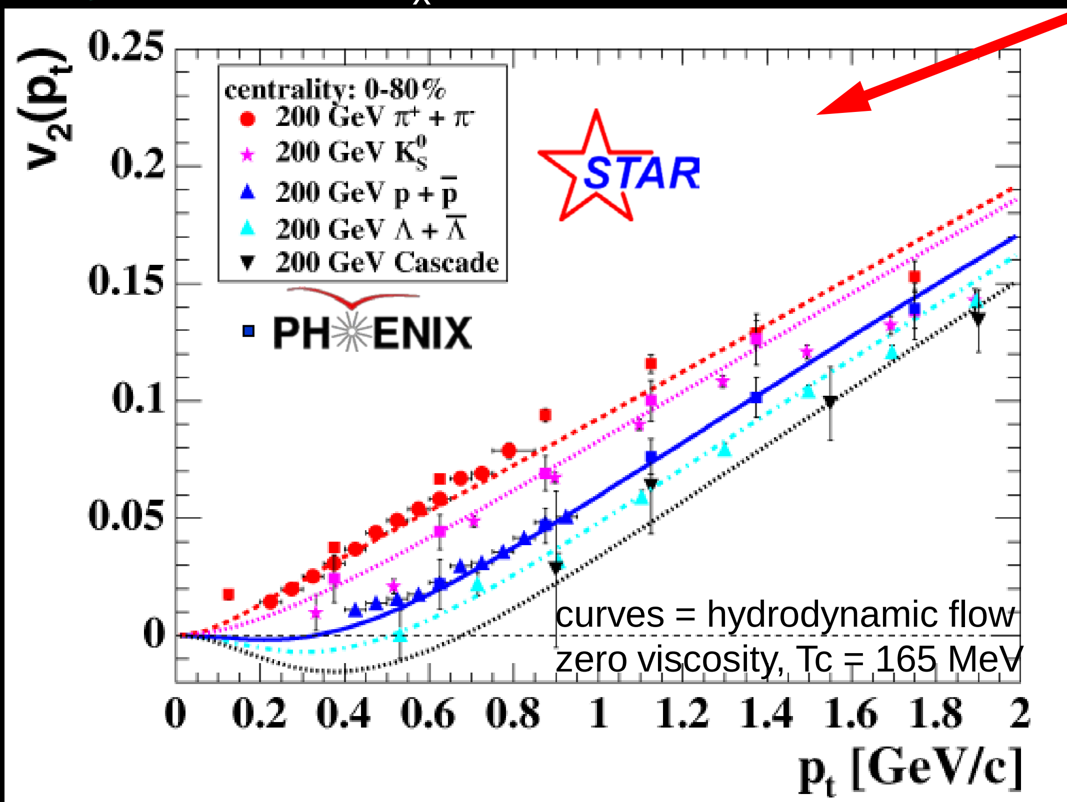
Seminal Results from RHIC in More Detail

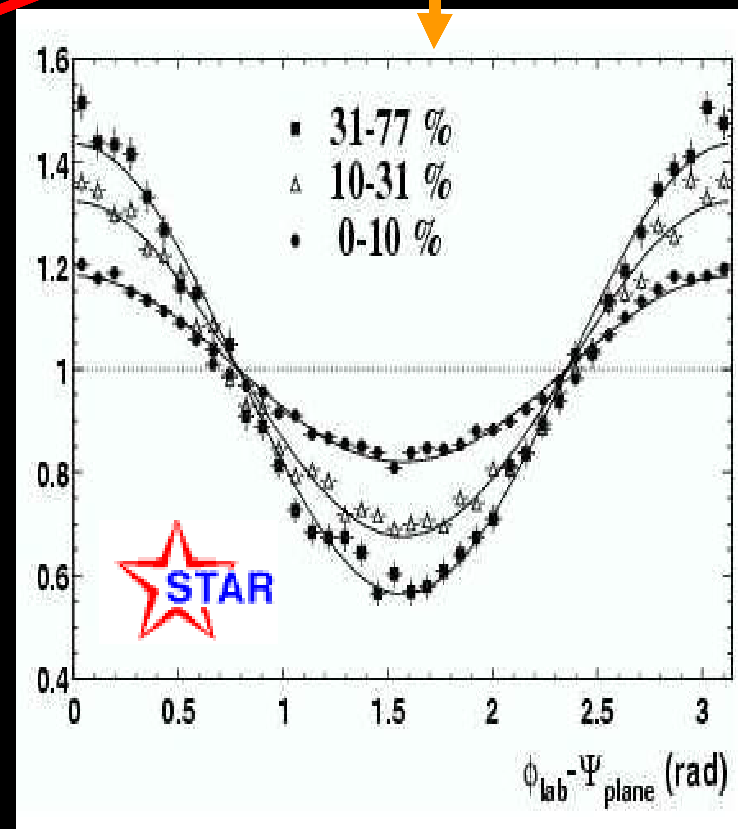
Elliptic Flow Saturates Hydrodynamic Limit

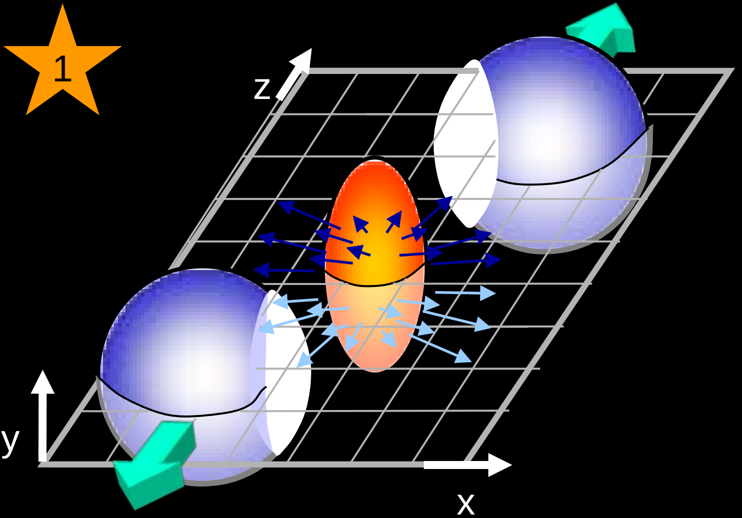


- Azimuthal asymmetry of charged particles:

  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$







Elliptic Flow Saturates Hydrodynamic Limit

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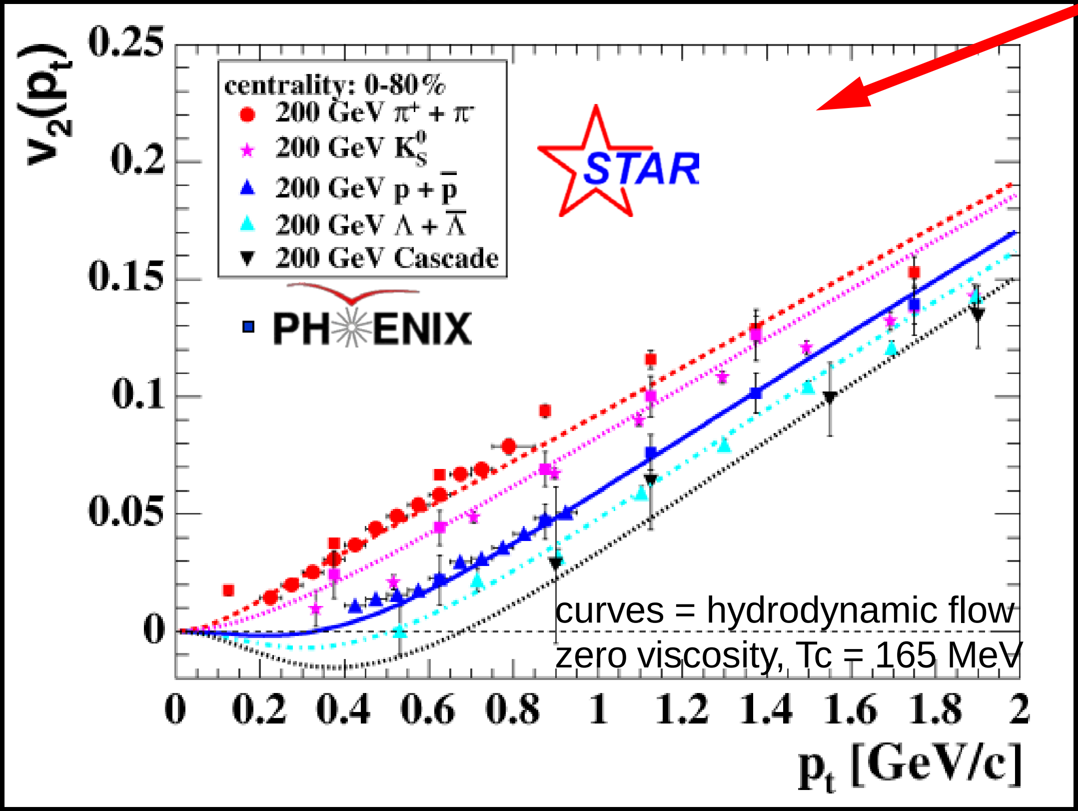


Mass dependence of v_2

Requires -

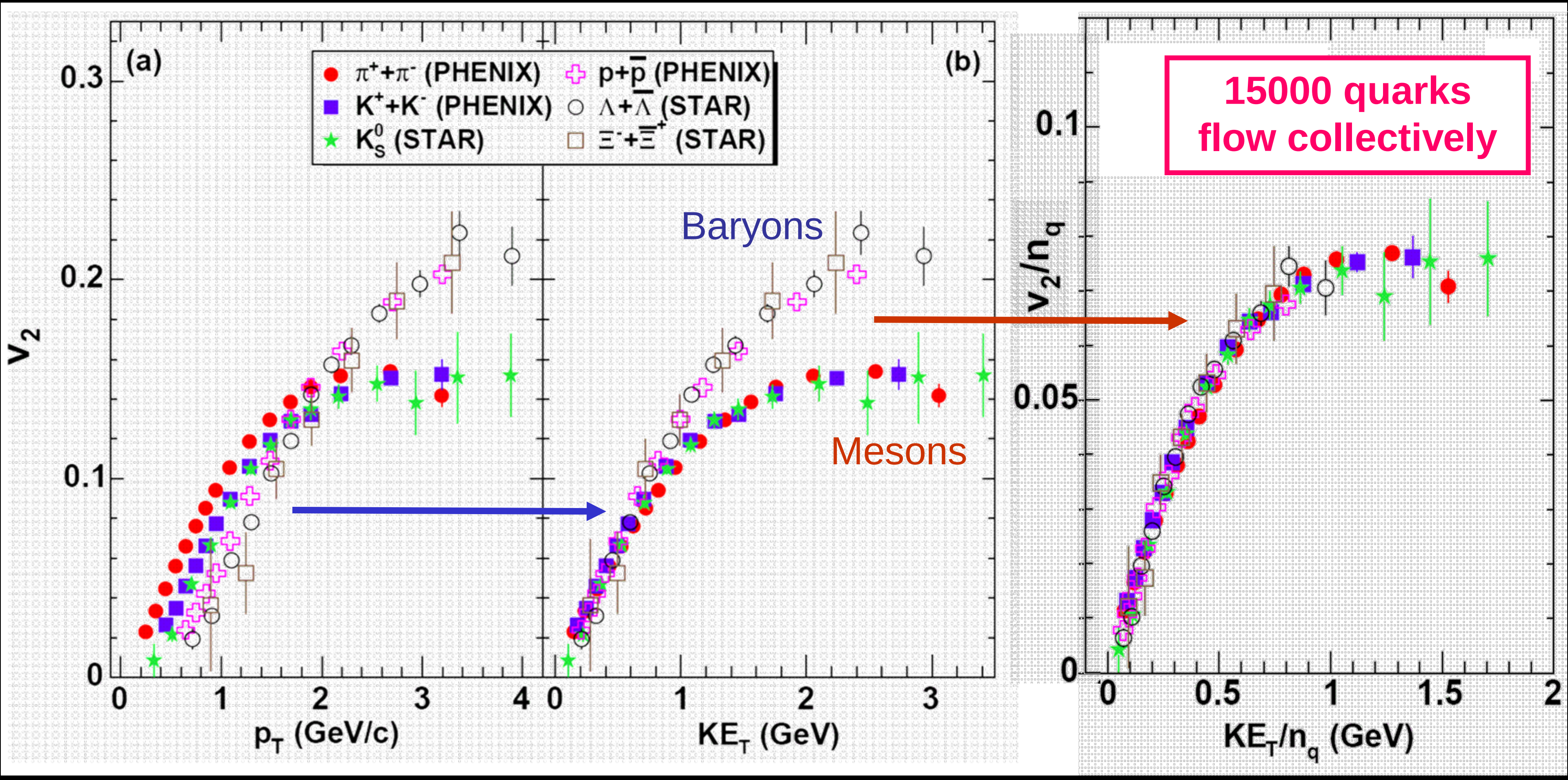
- **Early thermalization (0.6 fm/c)**
- **Ideal hydrodynamics (zero viscosity)**

  → "nearly perfect fluid"
- **$\varepsilon \sim 25$ GeV/fm^3 (>> $\varepsilon_{critical}$)**
- **Quark-Gluon Equ. of State**

Identified Hadron Elliptic Flow Complicated

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons

$$d^2n/dp_Td\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi)$$

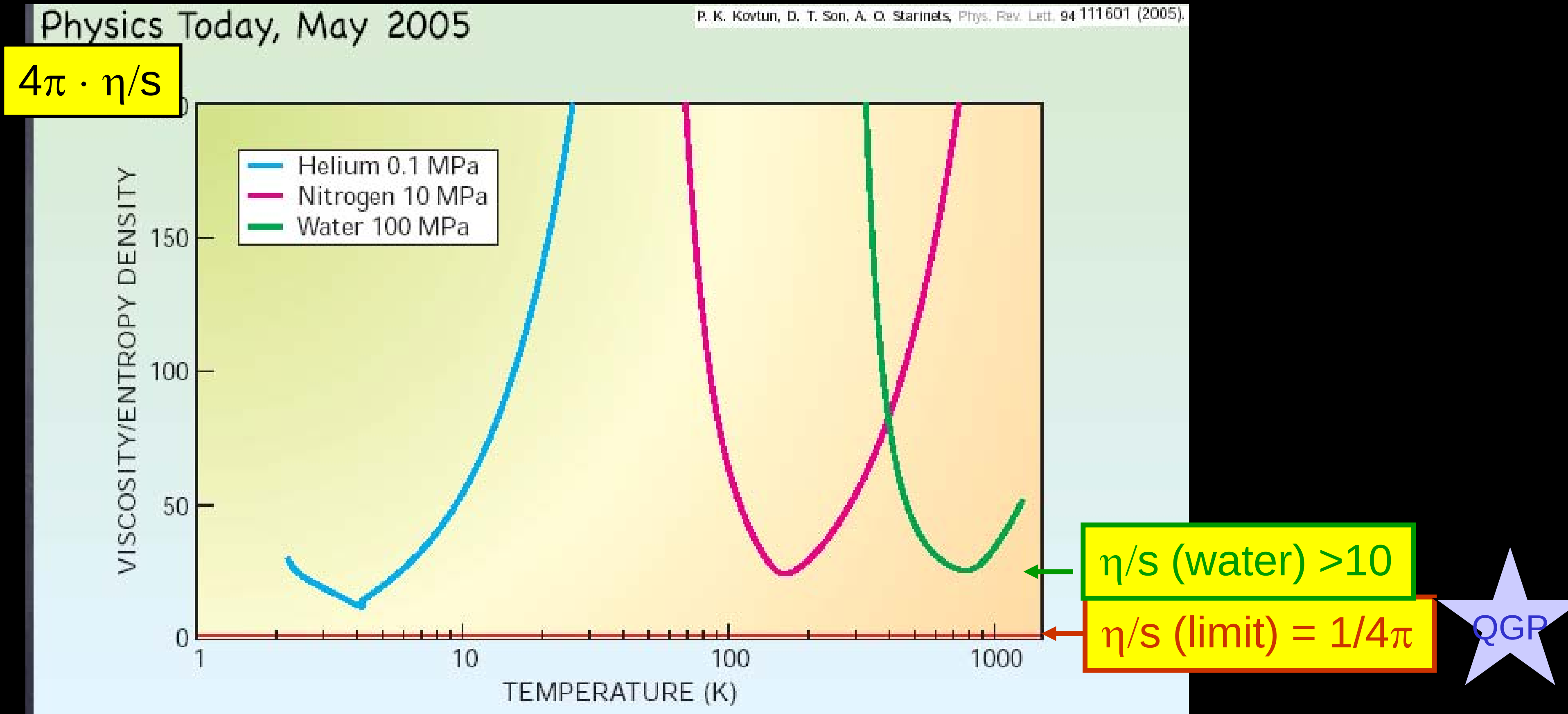


If the flow established at quark level, it is predicted to be *simple* →

$KE_T \rightarrow KE_T / n_q$, $v_2 \rightarrow v_2 / n_q$, n_q = (2, 3 quarks) for (meson, baryon)

Baryons & mesons form
from independently flowing quarks
so
quarks are deconfined
for a brief moment (~ 10^{-23} s), then hadronization!

Ultra-low (Shear)Viscosity Fluids



T = 2 x 10^{12} K

Quantum lower viscosity bound: $\eta/s > 1/4\pi$ (Kovtun, Son, Starinets)

From strongly coupled *N* = 4 SUSY YM theory.

2-d Rel Hydro describes STAR v_2 data with $\eta/s \leq 0.1$ near lower bound!

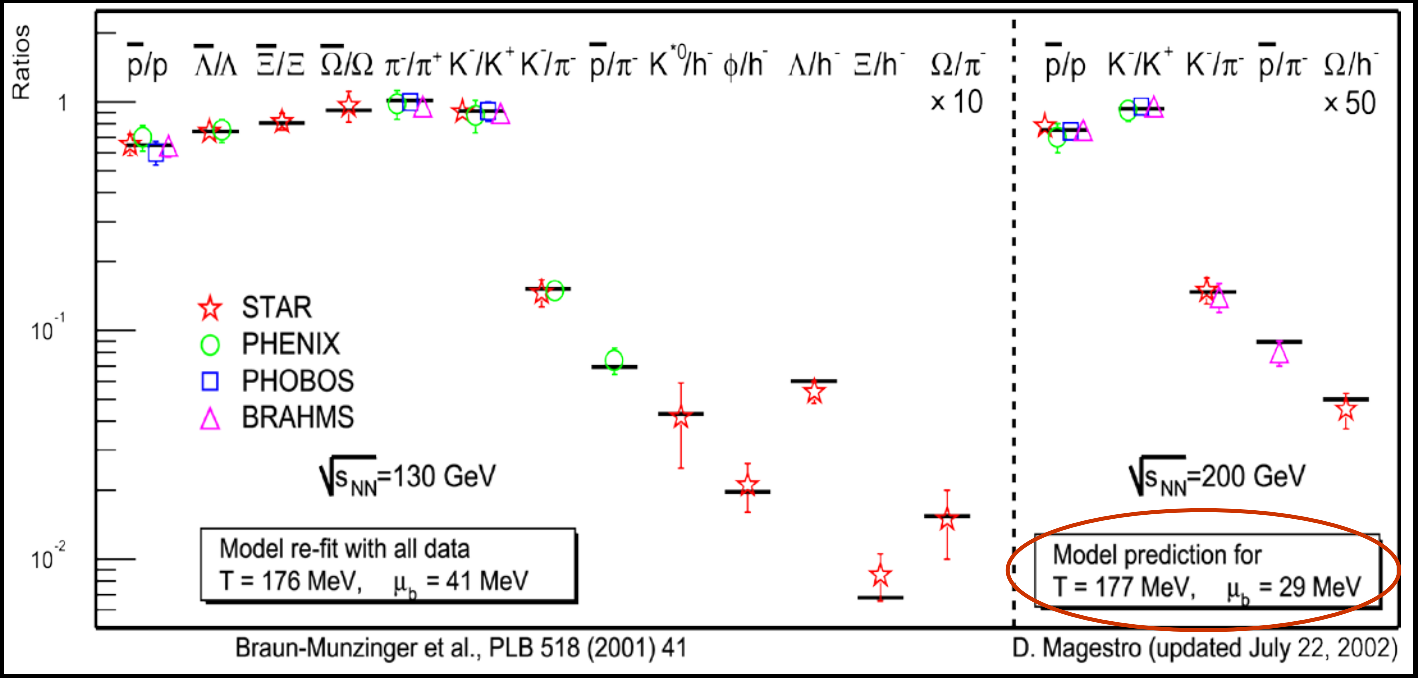
"The RHIC fluid may be the
least viscous fluid ever seen"

It Flows and Appears to Be Thermalized

"Chemical" equilibration (particle yields & ratios):

Particles yields represent equilibrium abundances

→ universal hadronization temperature

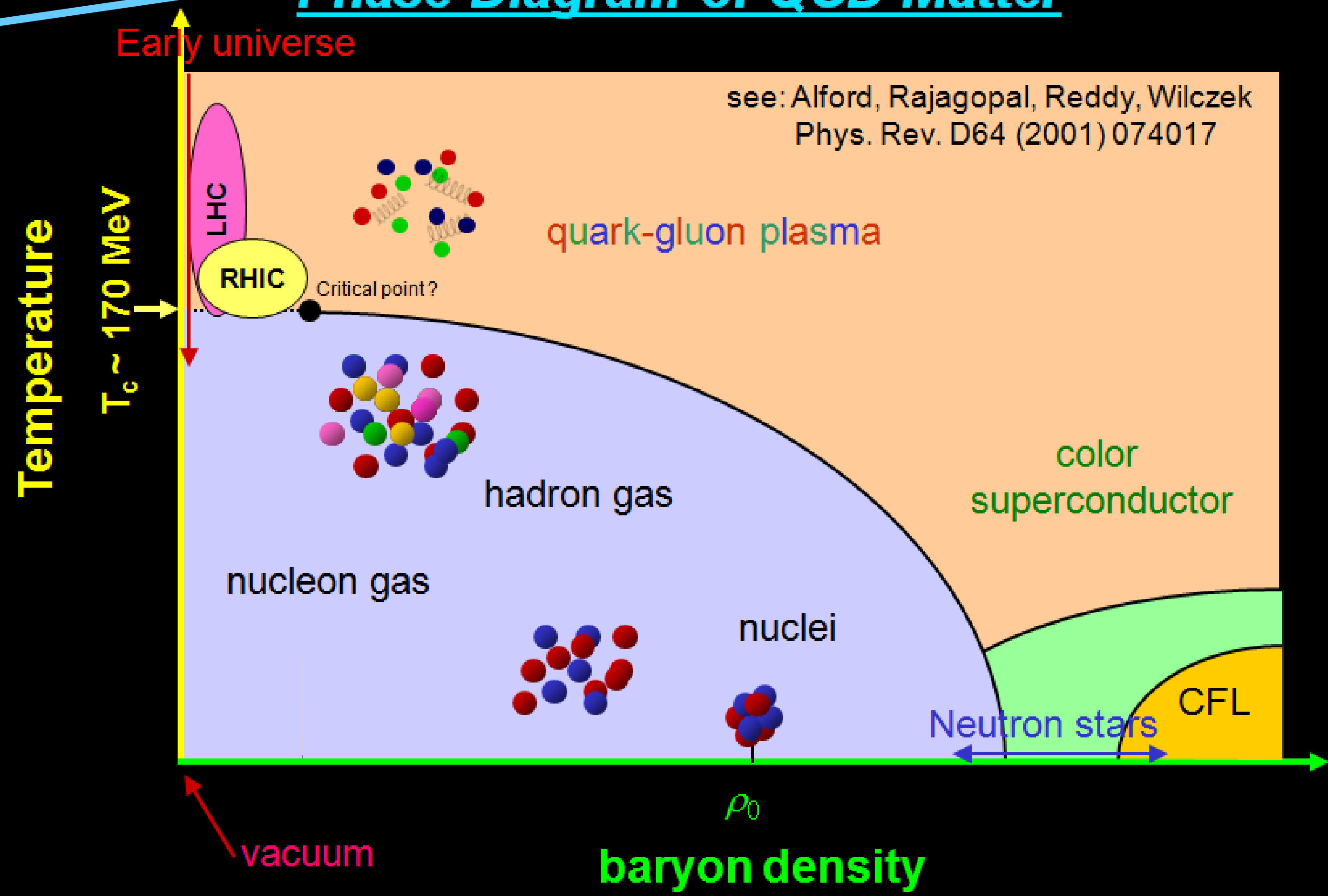


Small net baryon density (K^+/K^-, $\bar{B}/B$ ratios) → μ_B ~ 25 - 40 MeV

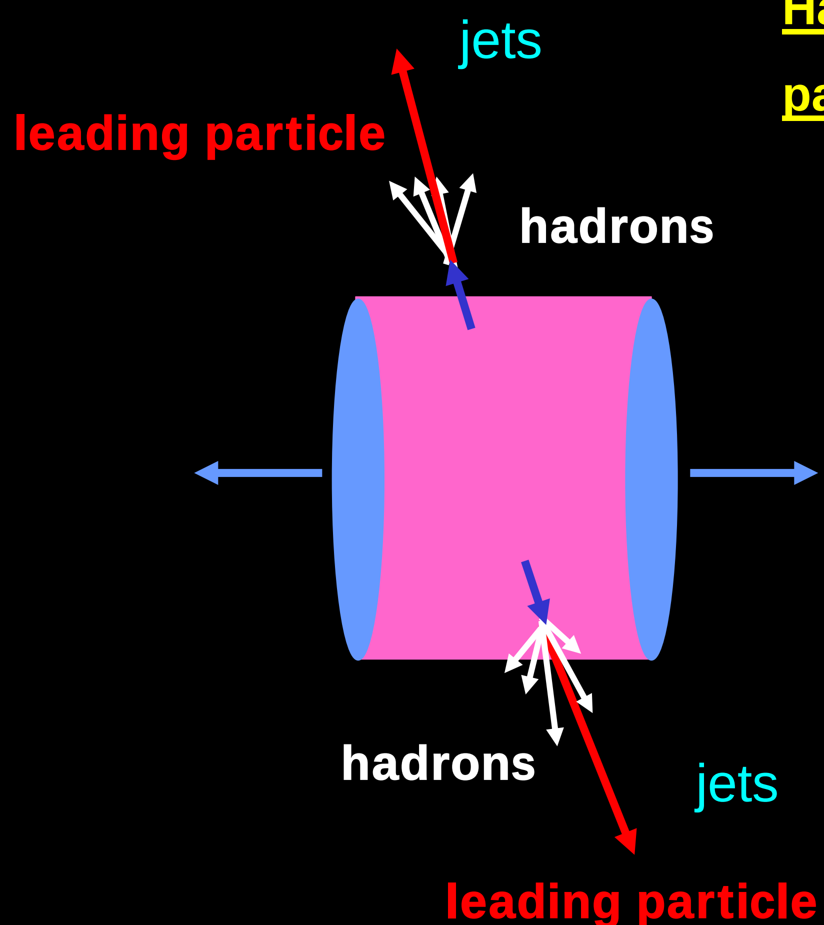
Chemical Freezeout Conditions → T = 177 MeV, μ_B = 29 MeV → T ~ $T_{critical}$ (QCD)

Particles are thermally distributed and flow collectively,
at universal hadronization temperature T = 177 MeV!

Phase Diagram of QCD Matter



Probing Hot QCD Matter with Hard Probes



Hard Probes (from initial parton scattering):

Large "p_T" partons

Heavy quark production

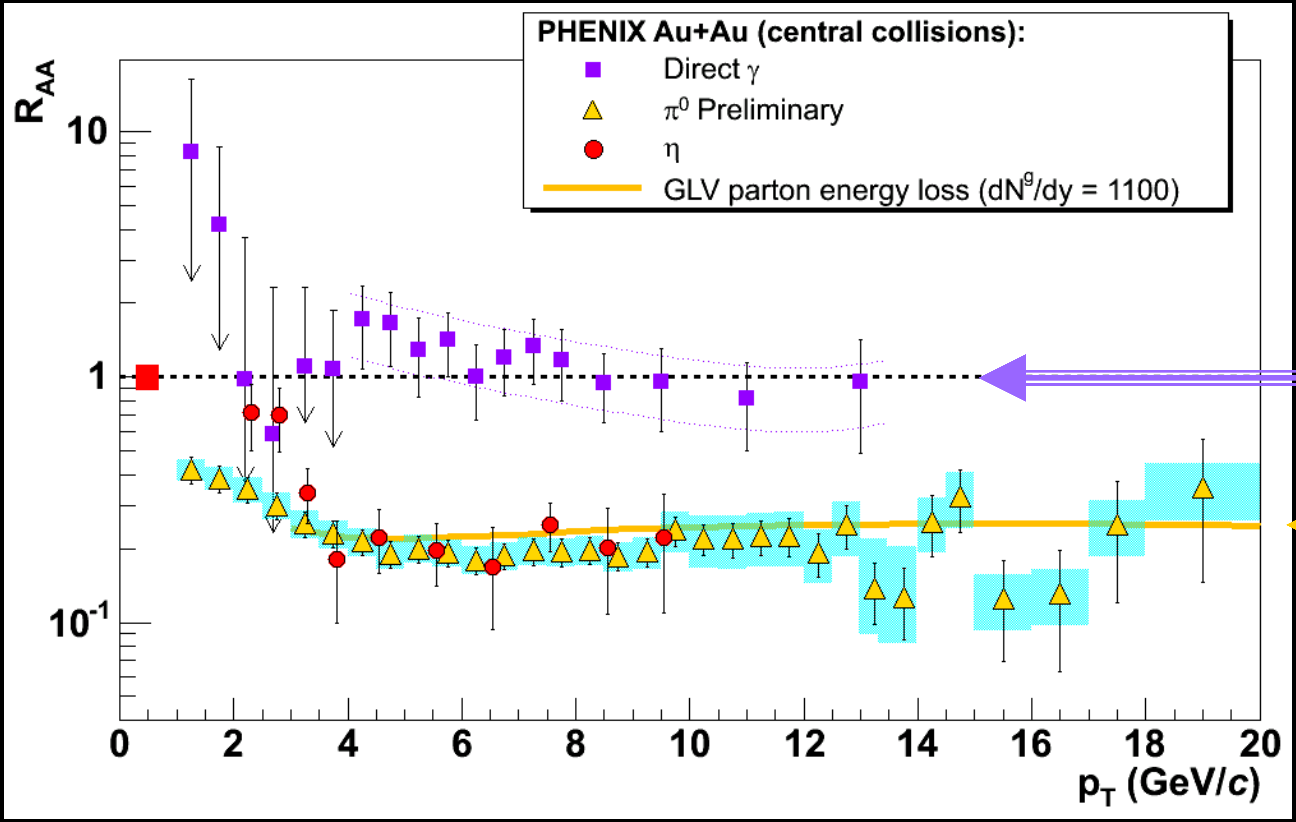
→ **parton energy loss:**

modification of jets and leading particles & jet-correlations

3

High Momentum Hadrons Suppressed, Photons Not

Deviations from binary scaling of hard collisions: $R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$



Photons

Hadrons factor 4 – 5 suppression

Heavy Quark Suppression

pQCD Calculations: Armesto, Cacciari, Dainese, Salgado, Wiedemann, PLB637:362, 2006

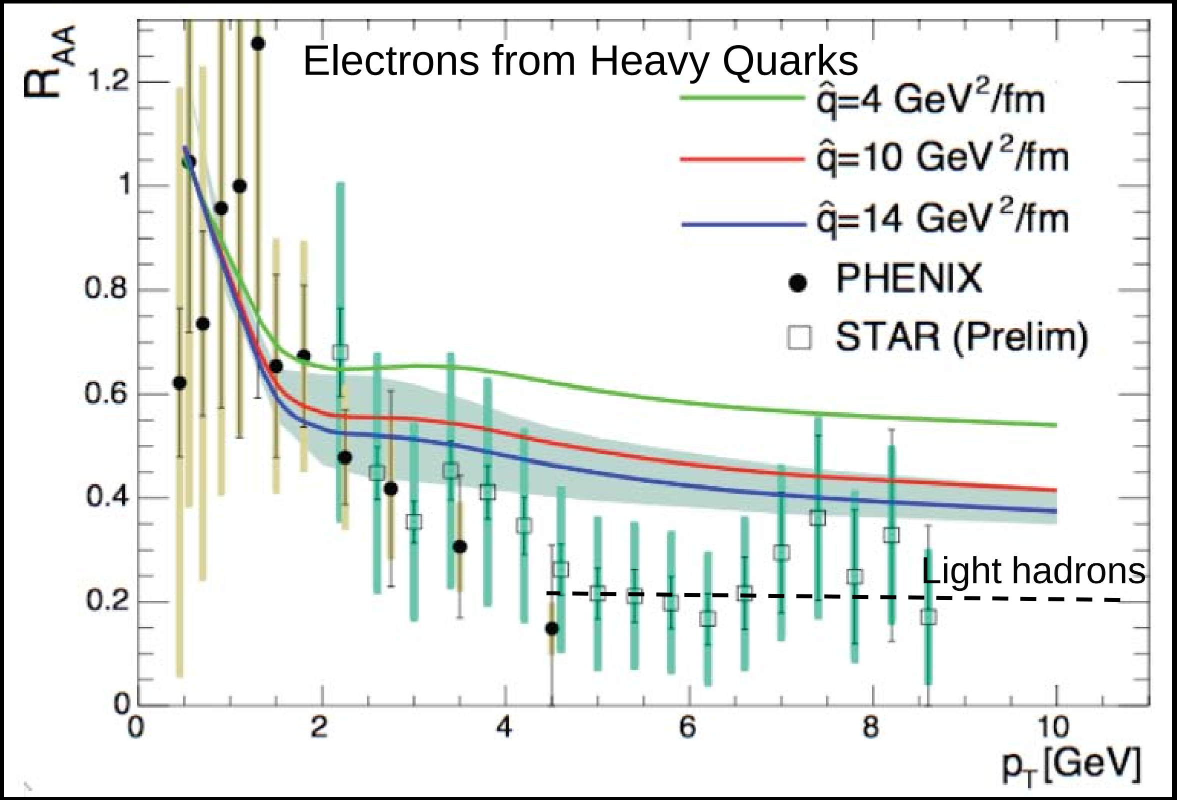
Using fixed order next-to-leading log (FONL)

cross sections for heavy quarks (charm and beauty)

PHENIX & STAR data

Heavy quarks appear to be suppressed ~ light quarks !!

Cannot be explained from theory!

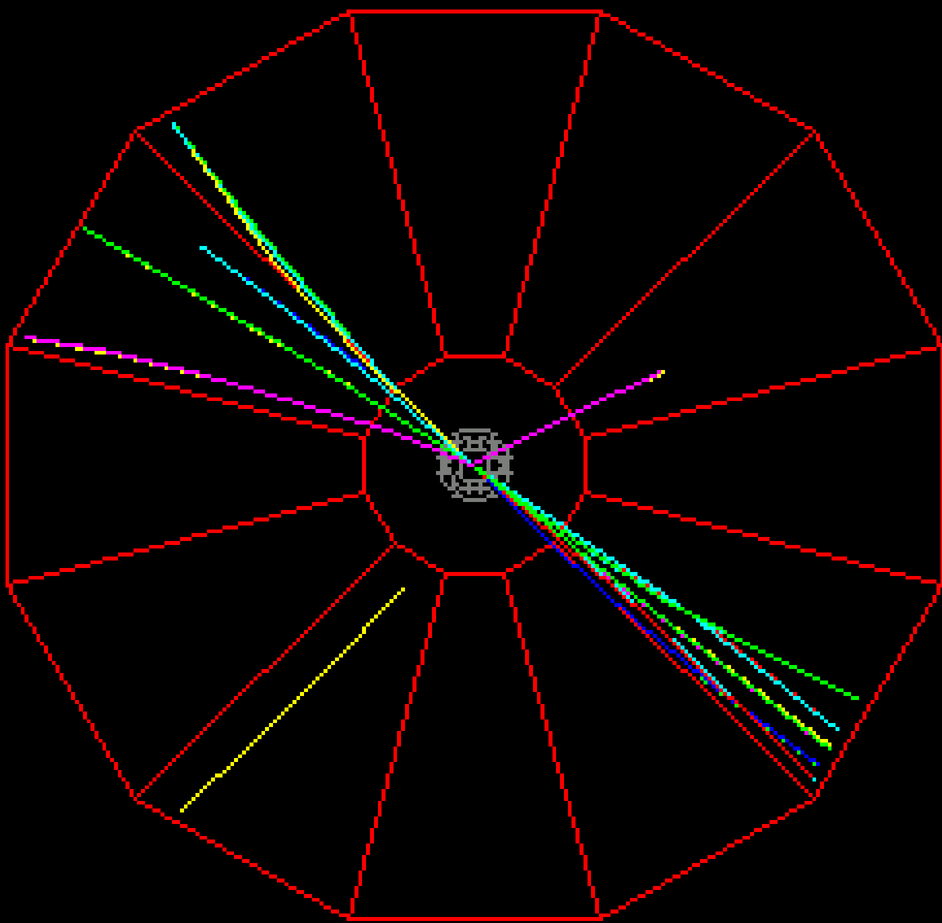


Important to measure ΔE of gluons → light → heavy quarks…

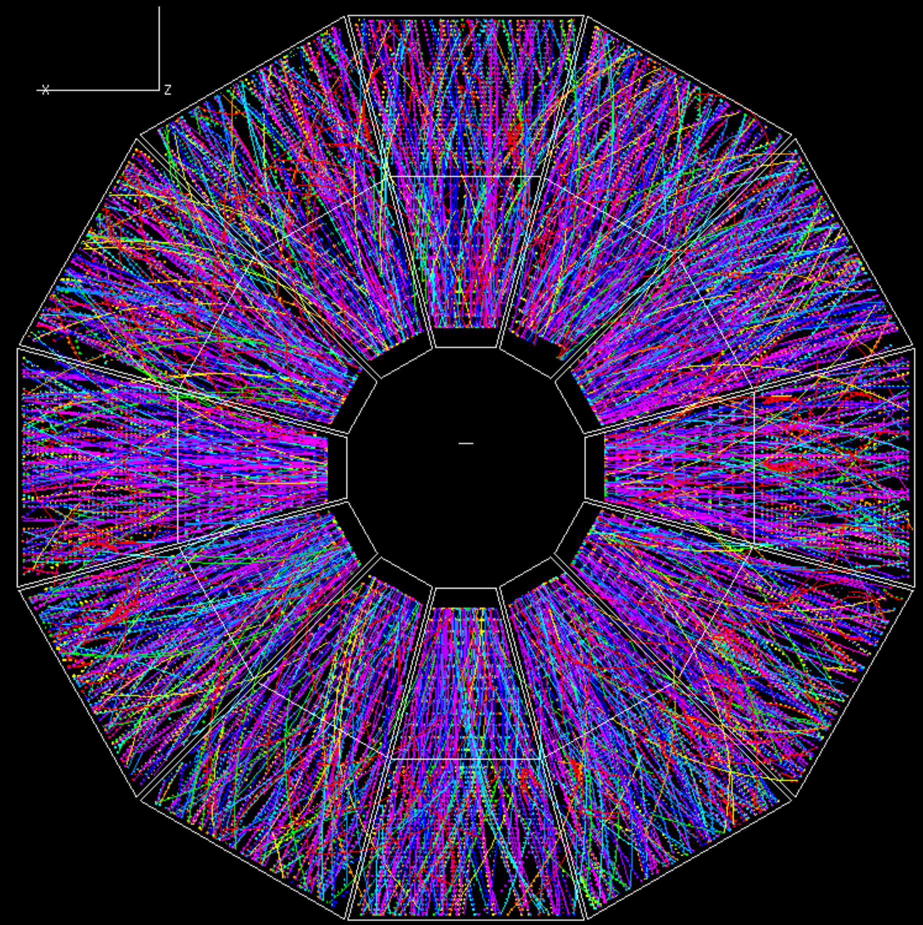
$\Delta E_{gluon} > \Delta E_{quark,\,m=0} > \Delta E_{quark,\,m>0}$

Hard Scattering (Jets) as a Probe of Dense Matter

STAR p + p $\rightarrow$ jet event

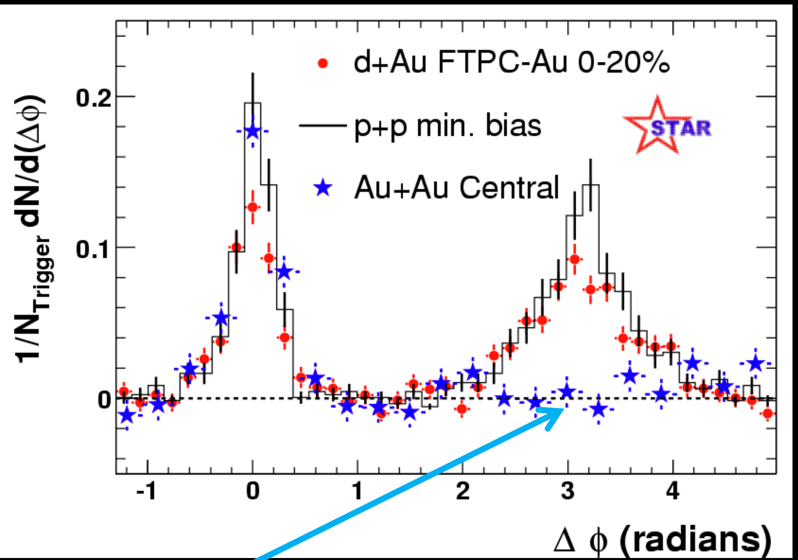


STAR Au+Au (jet?) event

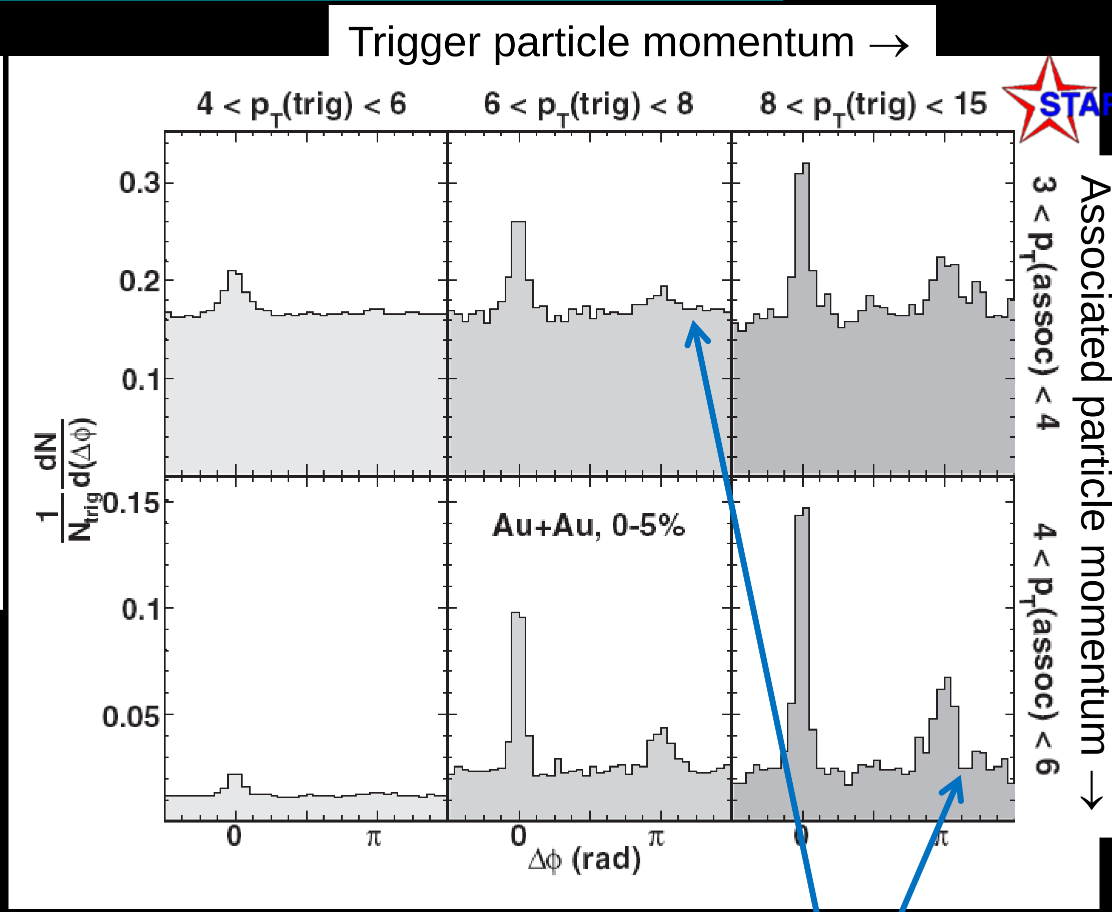


Can we see jets in high energy Au+Au?

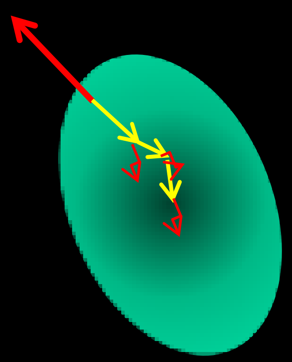
Disappearance of Away-Side "Jet"



Disappearance of away-side jet



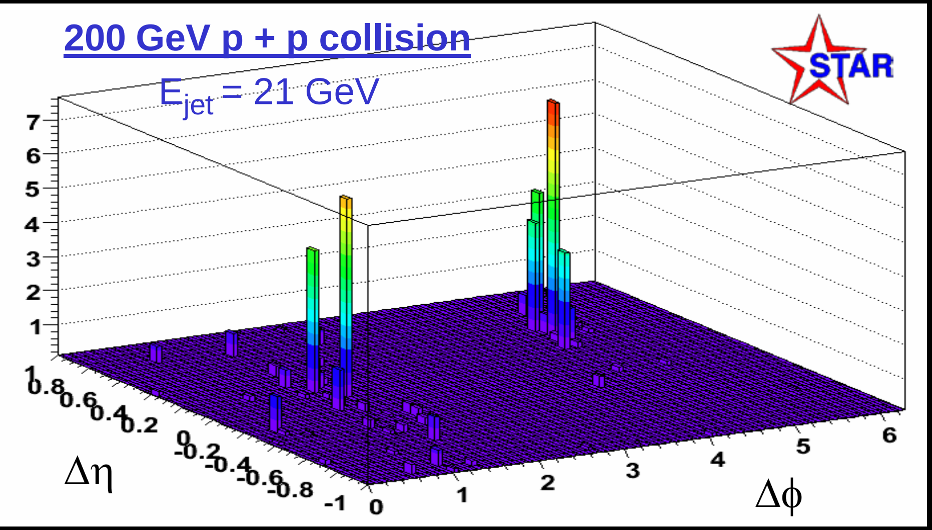
Trigger particle

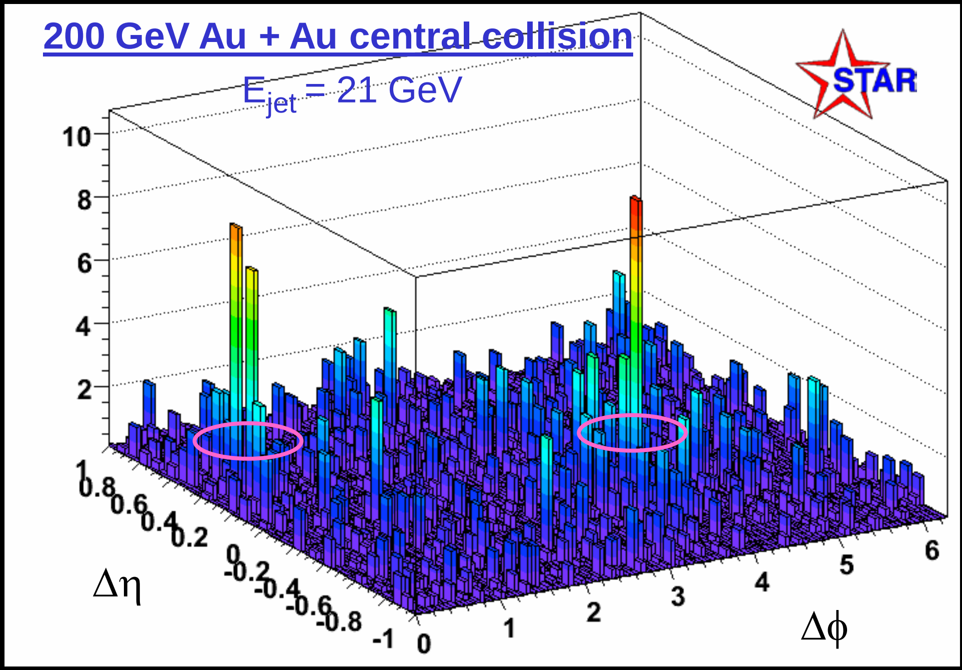


Away-side particle(s)

Re-appearance of the away-side jet

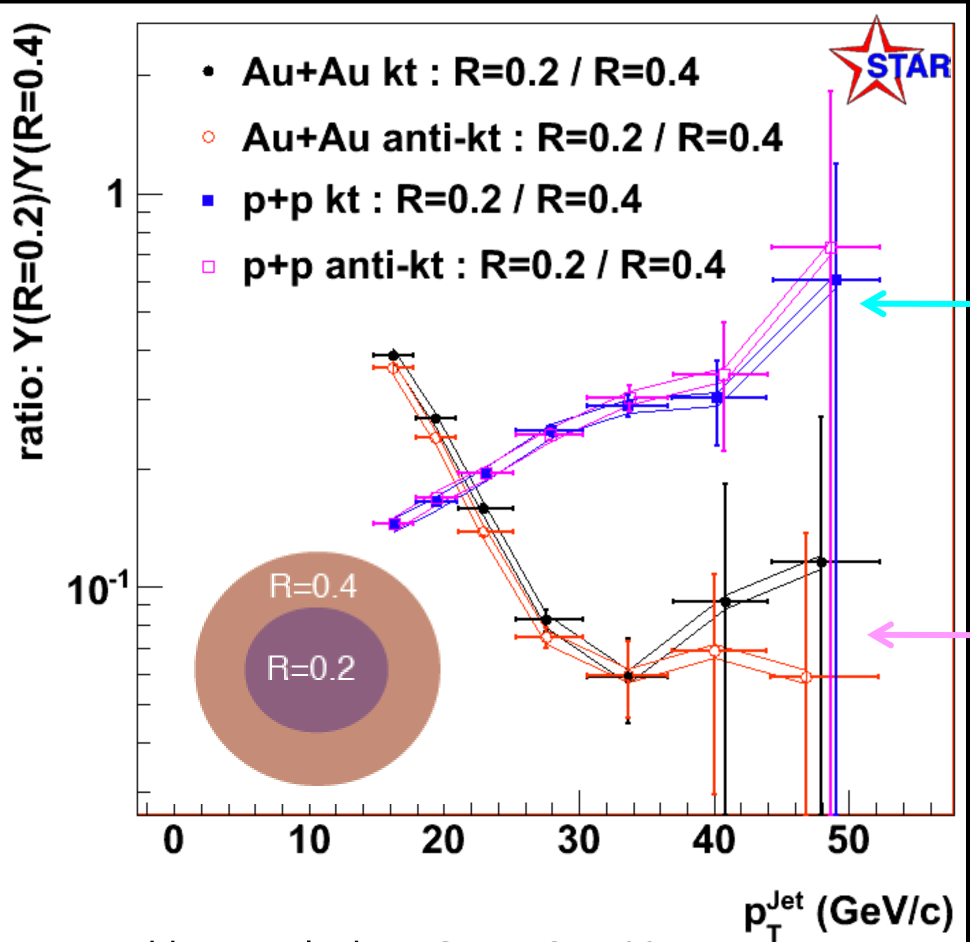
Real Jets to Probe Dense Matter!





Possible with appropriate consideration of background

Initial Results on Jet Energy Profile



J. Putschke, M. Ploskon, STAR QM ‘09

p + p: “Narrowing” of jet structure with increasing jet energy

Au + Au: “Jet Broadening” i.e. “Deficit” of jet energy within R=0.2

Strong evidence for broadening of the jet energy profile

The suppression of high p_T hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium. !

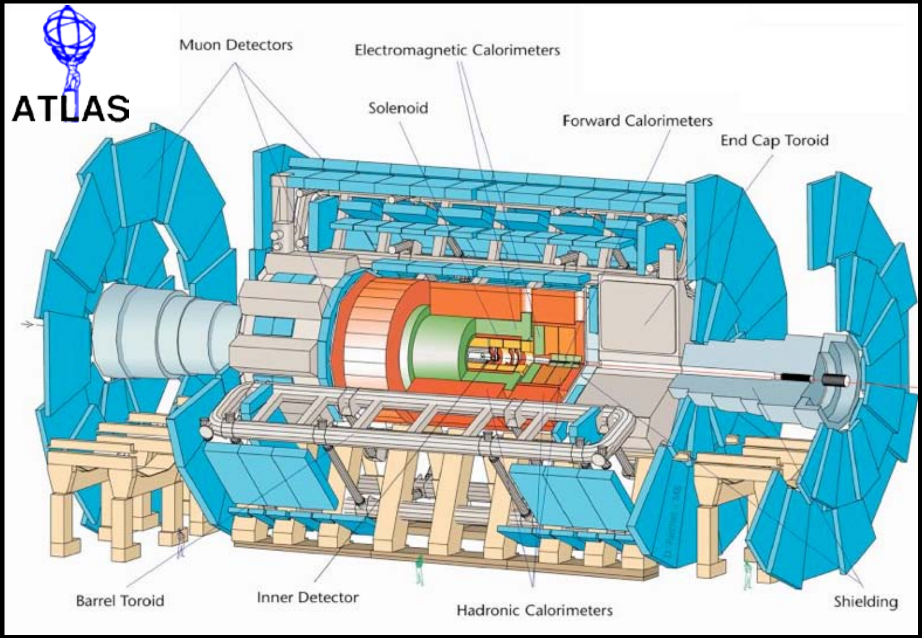
Soon in Geneva Heavy Ions in Large Hadron Collider

RHIC and LHC:

Cover 2 – 3 decades of energy ($\sqrt{s_{NN}}$ ~ 20 GeV – 5.5 TeV)

What are the properties of hot QCD in this temperature range (T ~ 150 – 600 MeV)?

LHC Heavy Ion Program

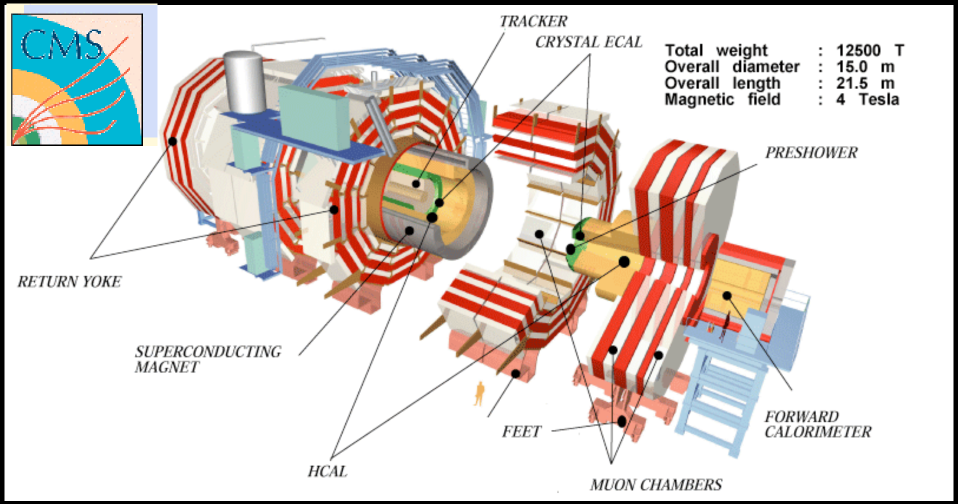


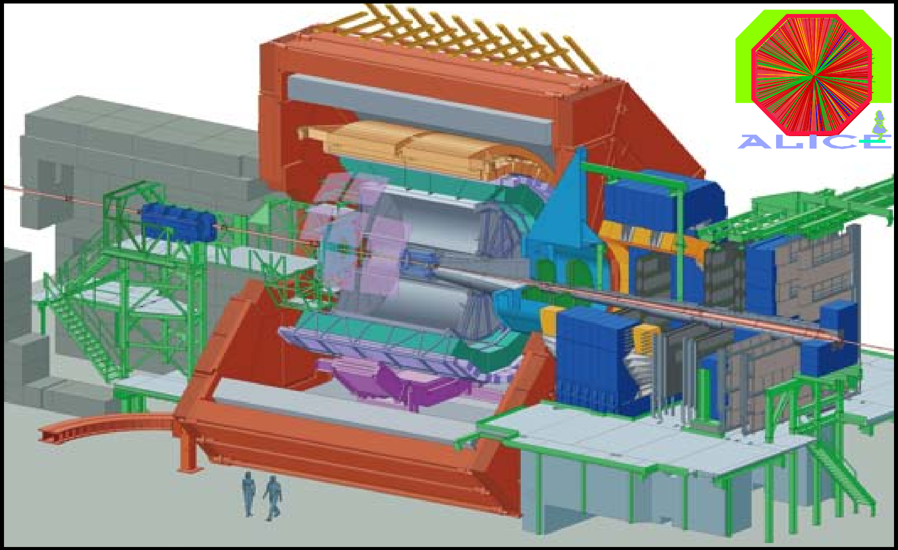
LHC Heavy Ion Data-taking

Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

(1 month per year)

- LHC Collider Detectors
  - ATLAS
  - CMS
  - ALICE





“Probable” LHC Near-term Heavy Ion Program

2010 (official)

18 – 31 Oct: Change-over from p + p to Pb + Pb

1 – 28 Nov: $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics

2011 (anticipated)

November timeframe: $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb for physics

2010 – 2011: increasing L $\rightarrow$ integral luminosity $\int L\,dt \sim 25\ \mu b^{-1}$

2012 (official)

Shutdown for maintenance, installation & repairs

2013

1 month $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics

2014

1 month $\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics to reach $\int L\,dt \sim 1\ nb^{-1}$

2015

1 month* $\sqrt{s_{NN}}$ = 5.5 TeV p + Pb and Pb + p for physics

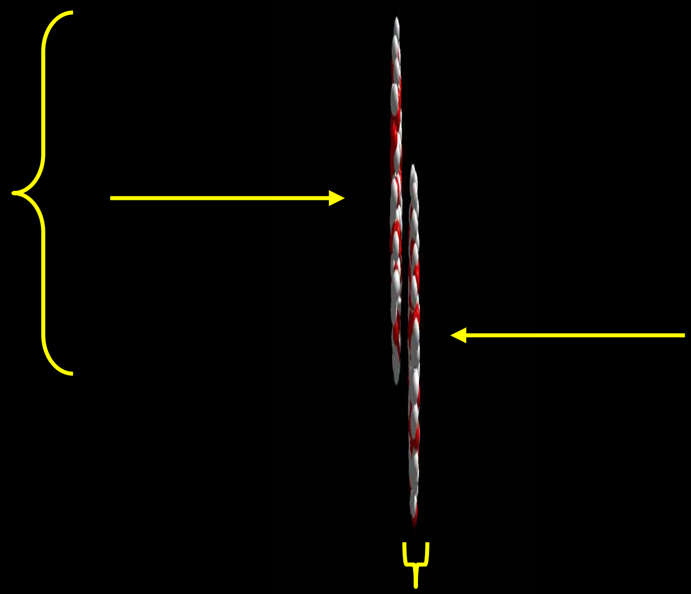
* Possibly longer than 1 month due to proton injector shutdown/upgrade

lighter A + A possible

Simple Expectations – Heavy Ion Interactions at LHC

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	factor 28
T / T_c	1.1	1.9	3.0 - 4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤ 2	2-4	> 10	longer-lived

Lead nucleus diameter ~ 14 fm



γ = 2,700 (Lorenz contracted)

$\tau \sim$ (14 fm/c) / γ < 0.01 fm/c

Challenges for Heavy Ions at the LHC

- **Determine Initial Conditions** – ***What is the extent of shadowing, saturation, CGC?***

$\rightarrow$ sets the stage for particle production / dynamics

- **Determine Dynamics** – ***What are the timescales, interactions times, temperature?***

Does system still equilibrate rapidly?

Thermal model still apply? $\rightarrow$ T still ~ T_c (lattice QCD)?

Does it flow?

Elliptic Flow change? $\rightarrow$ v_2 still saturated? More or less v_2? p_T dependence?

Is the QGP still strongly- (or weakly-) coupled?

Liquid? More like a gas? $\rightarrow$ No longer "nearly-perfect" fluid flow? viscosity?

$\rightarrow$ Impact on energy loss!!

- **Understand parton energy loss!** – ***What are the microscopic processes?***

$\rightarrow$ mass and flavor dependence?

$\rightarrow$ use high p_T jets & tag heavy quark jets

- **Understand response of the medium!**

Strongly interacting quarks and gluons $\rightarrow$ away-side response?

- **Color screening of the medium!**

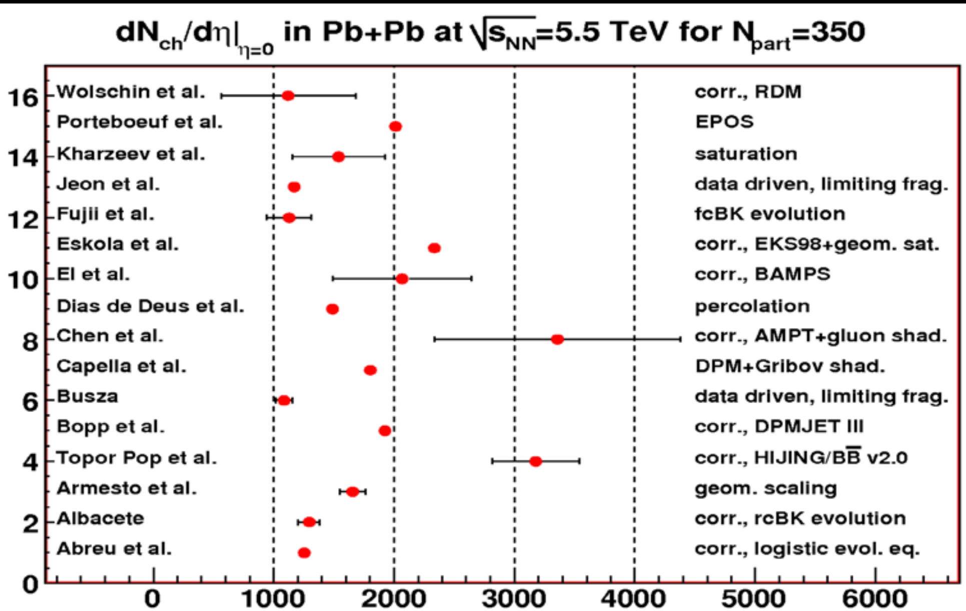
Deconfinement? (compare LQCD), initial T, other effects $\rightarrow$ J/ψ & Y states

Challenges for Heavy Ions at the LHC

• ***Determine Initial Conditions*** **–** ***What is the extent of shadowing, saturation, CGC?***

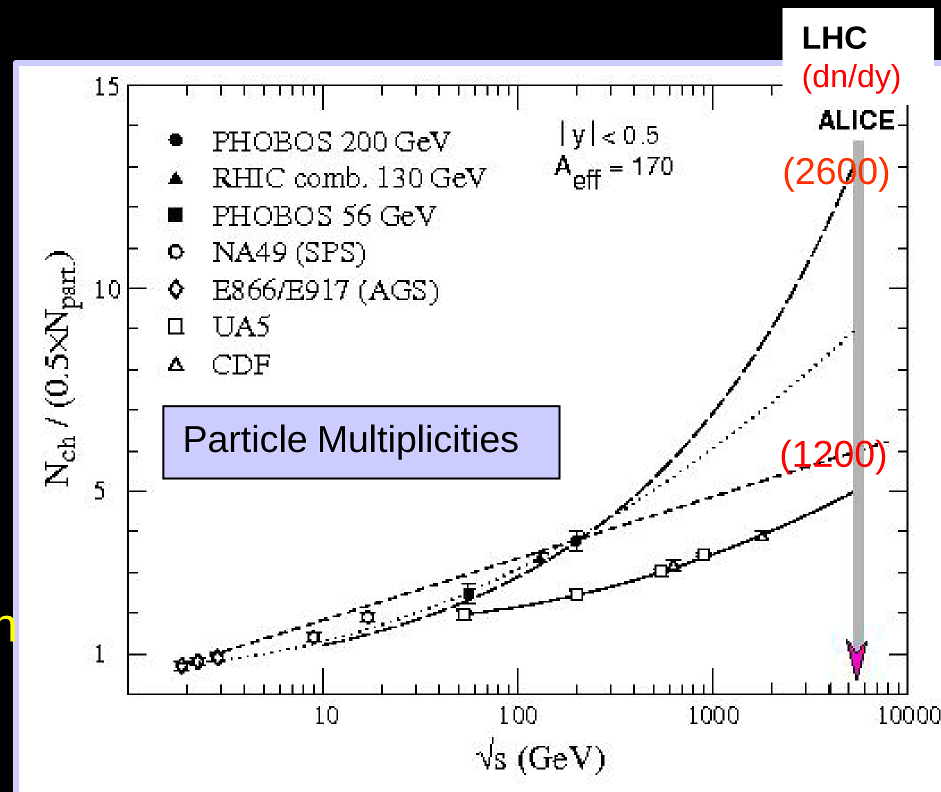
→ sets the stage for particle production / dynamics

Initial Conditions at the LHC



N. Armesto, arXiv:0804.4158

LHC predictions: An overview



Establish initial conditions at LHC

→*Measure particle multiplicities*

shadowing, gluon saturation, CGC?

establish the topology for particle production and dynamics at LHC!

Challenges for Heavy Ions at the LHC

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Does system still equilibrate rapidly?

Thermal model still apply? → T still ~ T_c (lattice QCD)?

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→ Impact on energy loss!!

Dynamics from Soft Physics at the LHC

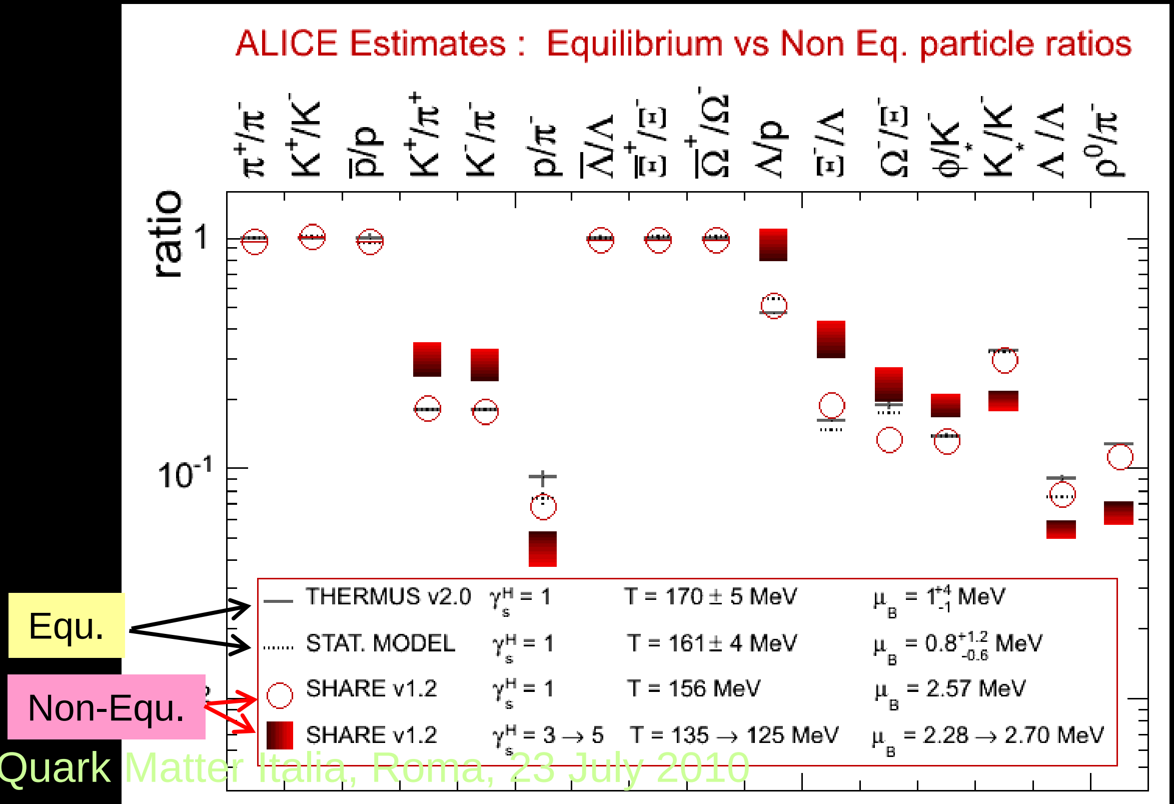
Measure particle ratios, spectra and yields with heavy ions at LHC

- Chemical freezeout temperature should be same as T_{cr} ~175 MeV?

  If not, we are completely wrong about interpretation of RHIC data!

  e.g. initial T_{LHC} ~ $2T_{RHIC}$ …. in any case T_{cr}(LHC) = T_{cr}(RHIC) = T_{cr}(QGP)!

T, μ_B &volume are only parameters – connected to QCD phase boundary



B. Hippolyte et al. (ALICE)
Eur. Phys. J. C49 (2007) 121.

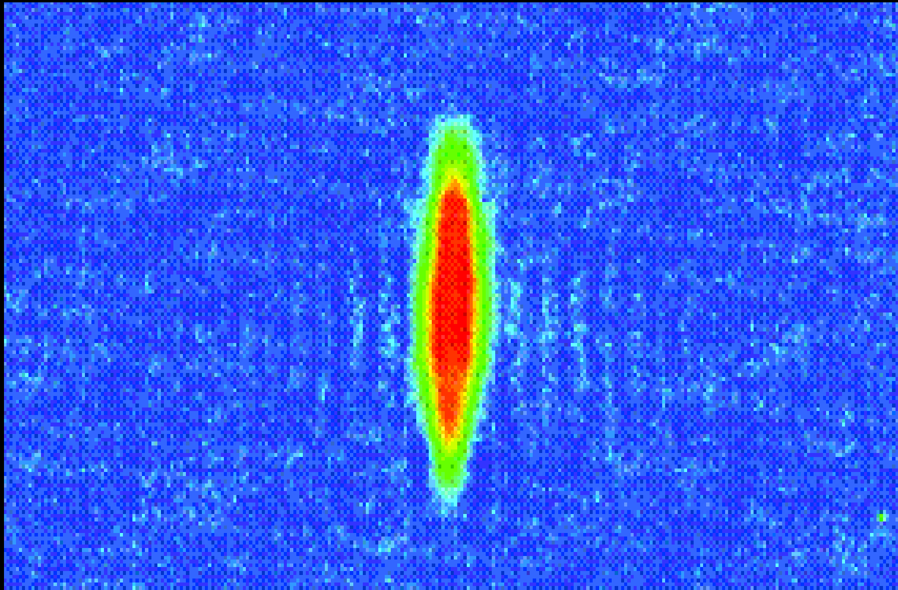
Heavy Ion Collision Dynamics at the LHC

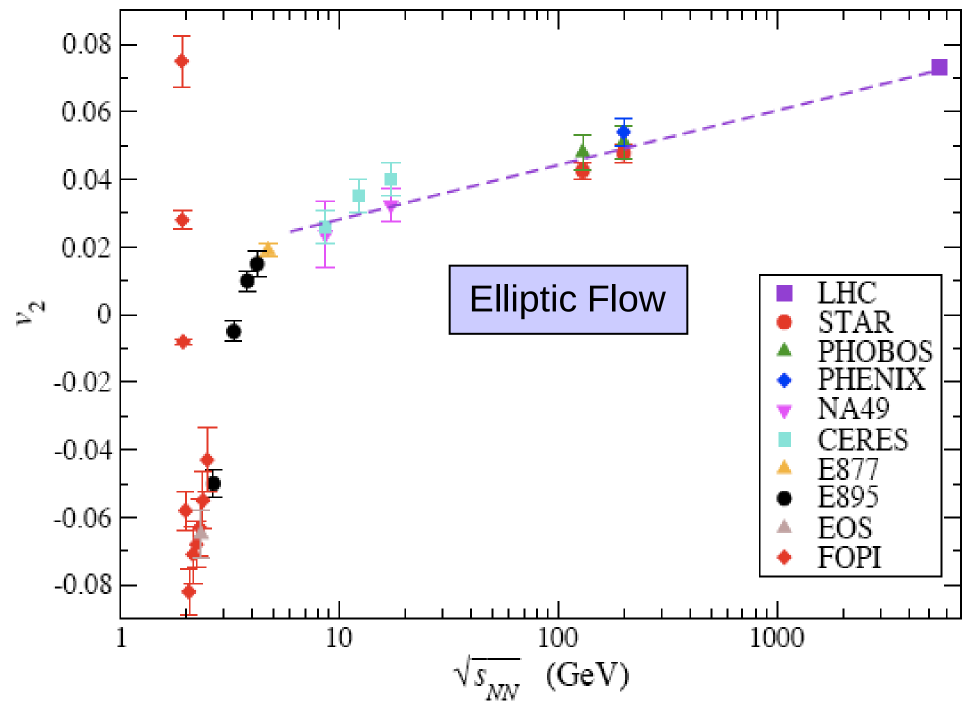
LHC Heavy Ions –

- expectations based on pQCD predictions & RHIC results
- a lesson from RHIC – guided by theory + versatility + **“expect the unexpected”**

Soft Physics ($p_T \leq 2$ GeV/c) with heavy ions at LHC –

- smooth extrapolation from **SPS → RHIC → LHC?**
- expansion dynamics different (initial state, flow, HBT, evolution of T, strange/charm/beauty)





v2 → viscosity → coupling strength

Challenges for Heavy Ions at the LHC

•***Understand parton energy loss!*** **–** ***What are the microscopic processes?***

→ mass and flavor dependence?

→ use high p_T jets & tag heavy quark jets

• ***Understand response of the medium!***

Strongly interacting quarks and gluons → away-side response?

High p_T Particles and Jet Rates at LHC

Hard probe physics measurements:

- High p_T hadron (PID) suppression (R_{AA})
- Di-hadron $\Delta\phi$ correlations to ~100 GeV/c
- Jet spectra & shapes
- γ, Z, γ-jet (Z-jet) corr's (statistics?)

Hard Probe statistics with 0.5 nb^{-1} in ALICE/ATLAS/CMS:

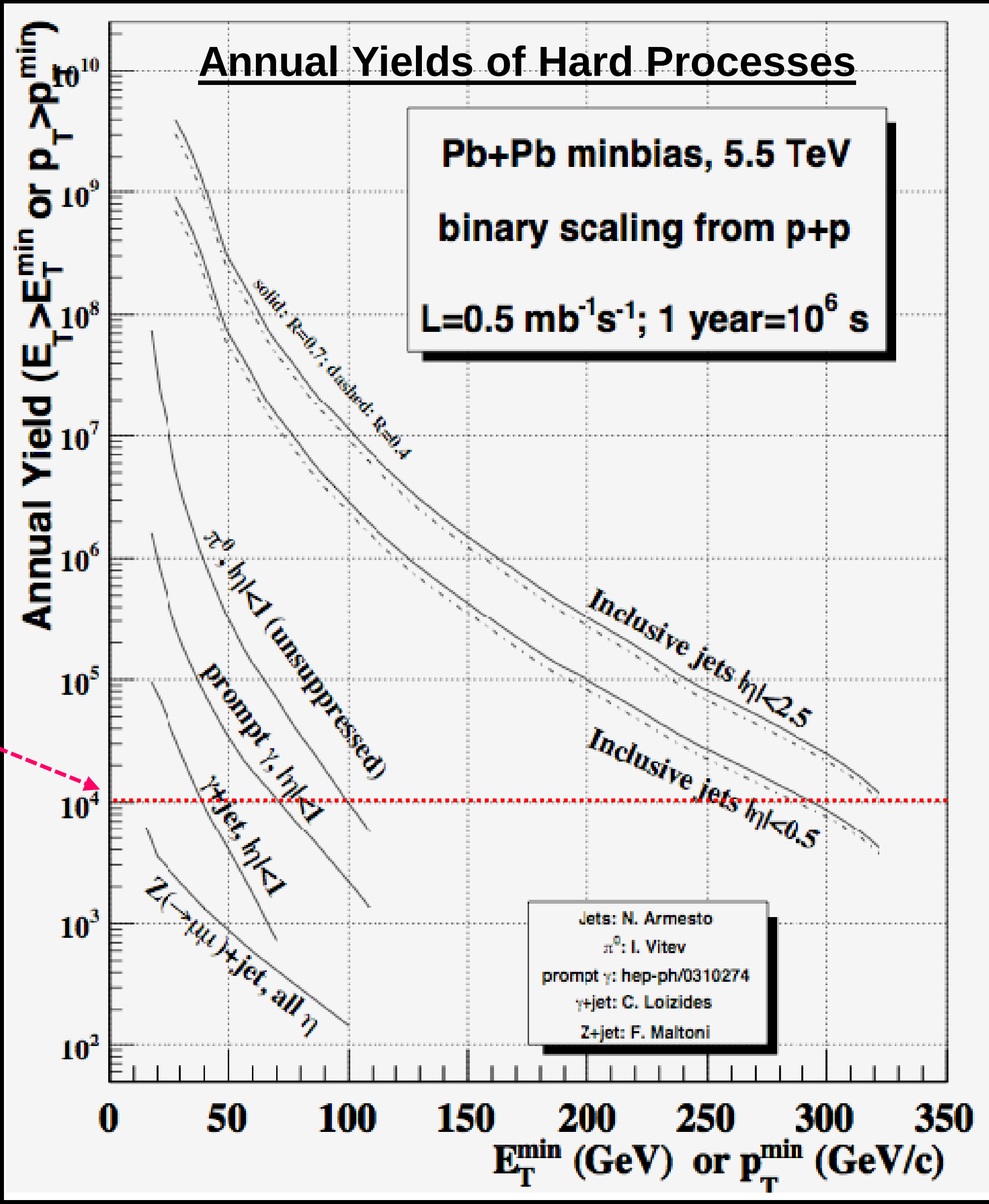
10^4/year

inclusive jets: E_T ~ 200-325 GeV

dijets: E_T ~ 170-250 GeV

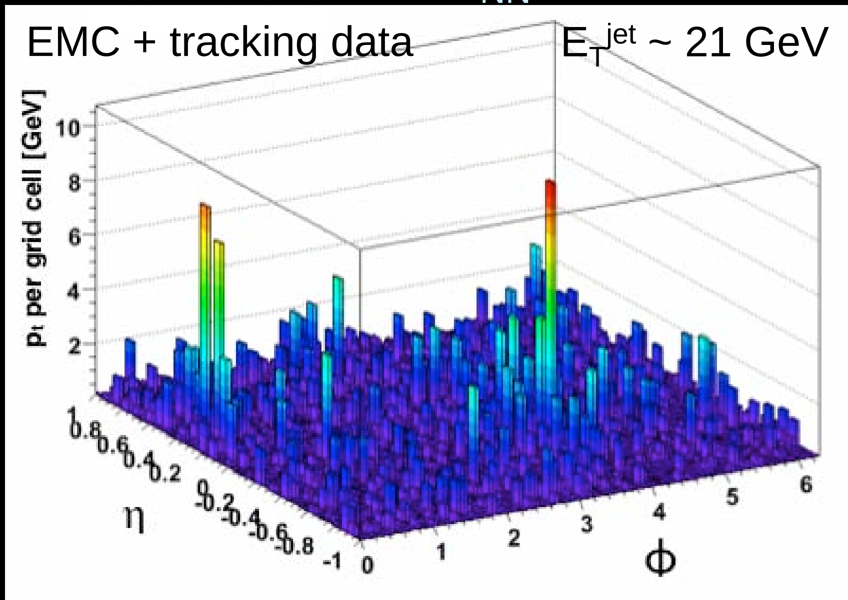
π^0: p_T ~ 75-150 GeV/c

inclusive γ: p_T ~ 45-100 GeV

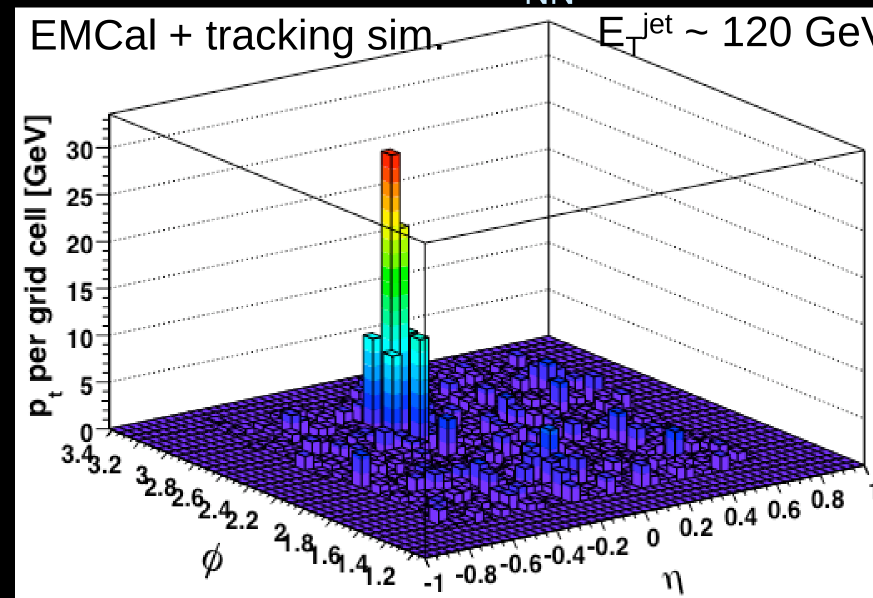


Jets in Heavy Ion Collisions at RHIC & LHC

Central Au+Au $\sqrt{s_{NN}}$=200 GeV



Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV



Jets in heavy ion collisions? [inclusive, di-jets, hadron-jet, γ-jet,..]

- Parton energy loss in QCD medium

  Requires detailed measurements for theoretical comparison / understanding

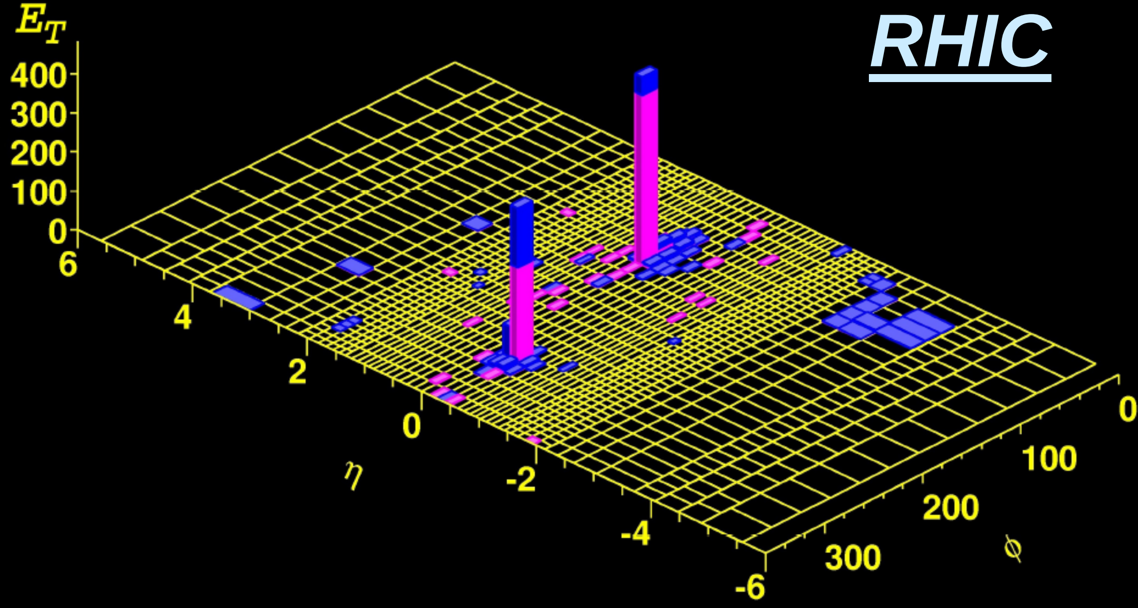
  Establish energy-loss mechanisms

  – energy flow within jets, quark vs gluon jet differences

  Flavor and mass dependence, fragmentation modification …

- Medium response to parton energy loss – establish properties of the medium

Challenge for Jet-finding - Learning from Tevatron & RHIC



p + $\bar{p}$ experience (CDF)

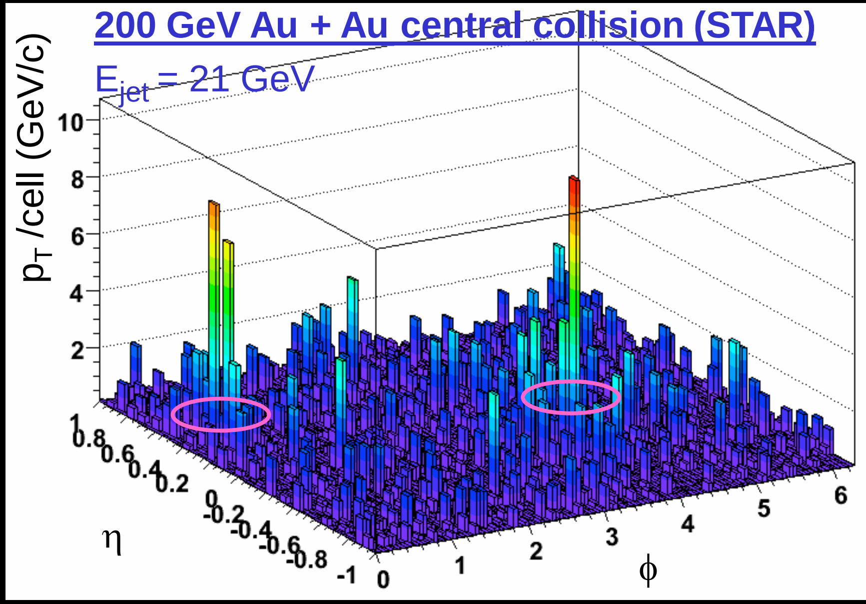
- most of energy within cone of

$$R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} < 0.3$$

Au + Au experience (STAR) - HI Background

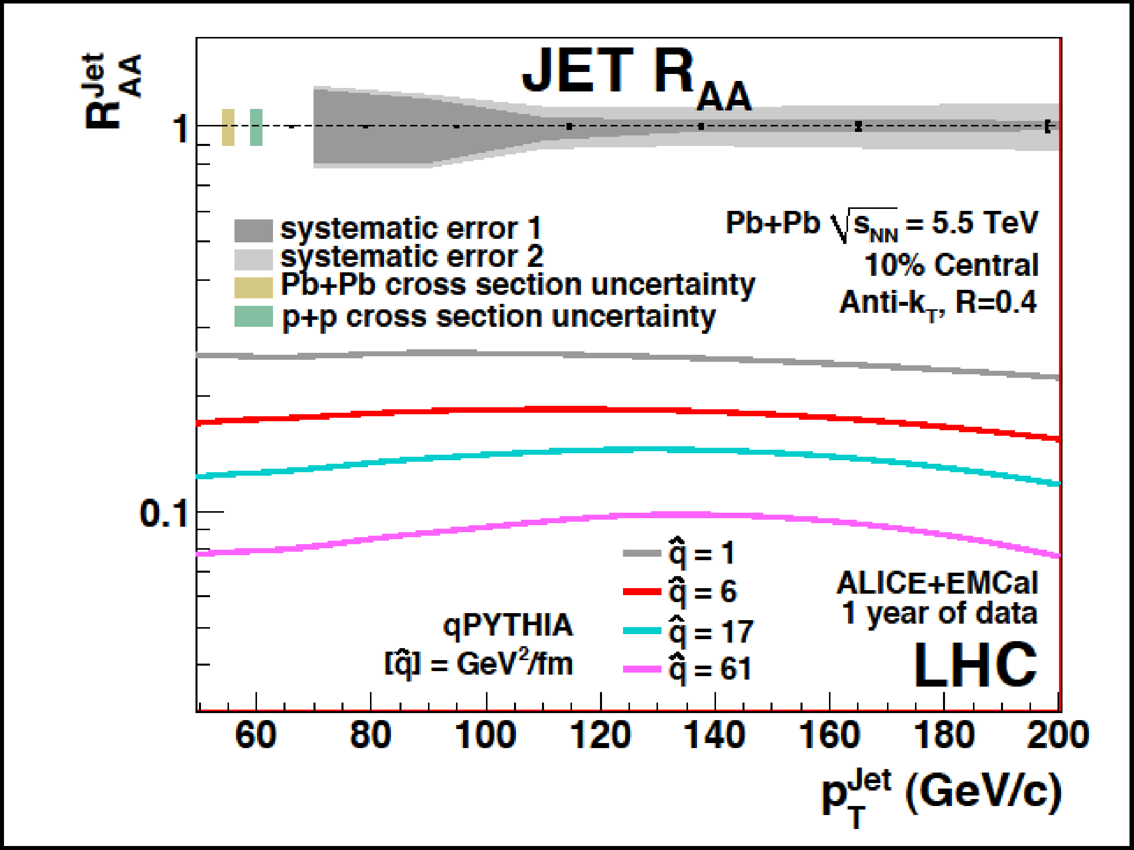
Must suppress "soft" background:

- small jet cones R = 0.3-0.4
- p_T cut: $p_T > 1 – 2$ GeV/c
- EbyE out-of-cone background energy



Example – Jets in ALICE with EMCal: R_{AA}

Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV



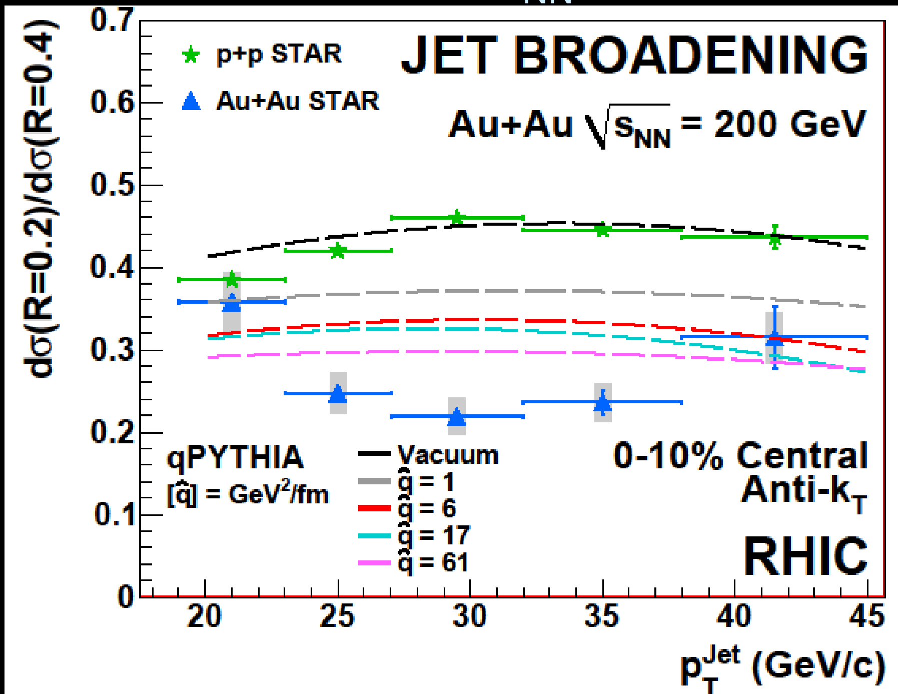
Jet systematic uncertainties small!

Measurements possible to 200 GeV – statistically and systematically

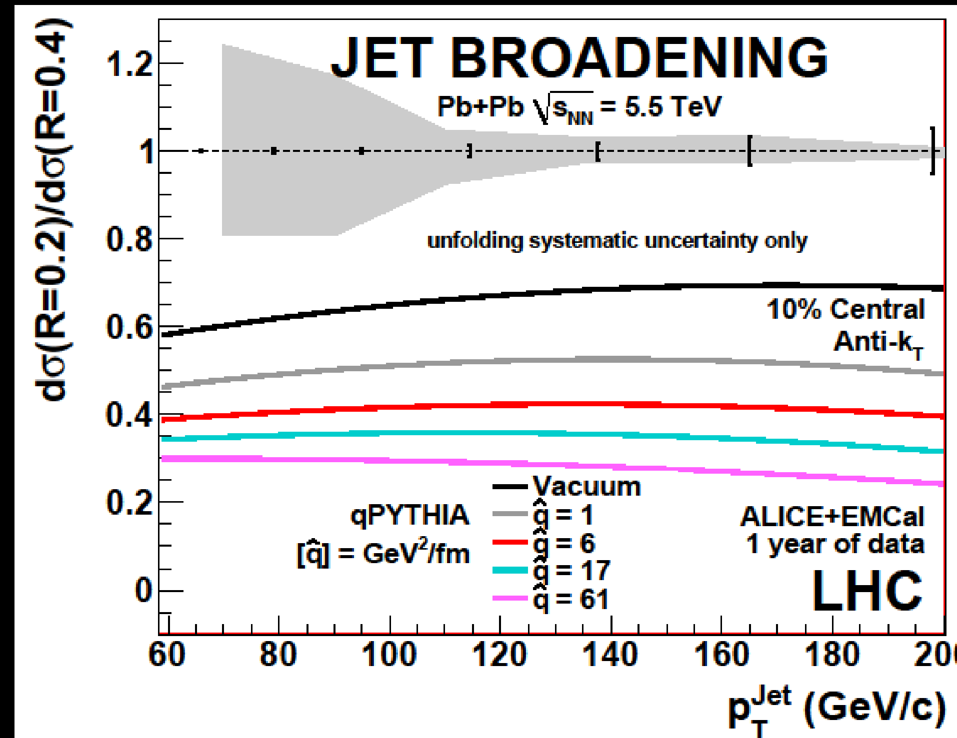
Jet Broadening at RHIC & ALICE with EMCal

Ratio of jet yields within R = 0.2 vs R = 0.4 using anti-KT algorithm

Central Au+Au $\sqrt{s_{NN}}$=200 GeV



Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV



- qPYTHIA not optimized (yet) – do not draw conclusions from shape diff's.
- Jet energy profile (AuAu data) BROADENED indicating JET QUENCHING!
- Small experimental systematic uncertainties in measurements (ratios from same exp. and data set) → a precision measurement at LHC!

Challenges for Heavy Ions at the LHC

• ***Color screening of the medium!***

Deconfinement? (compare LQCD), initial T, other effects $\rightarrow$ J/ψ & Y states

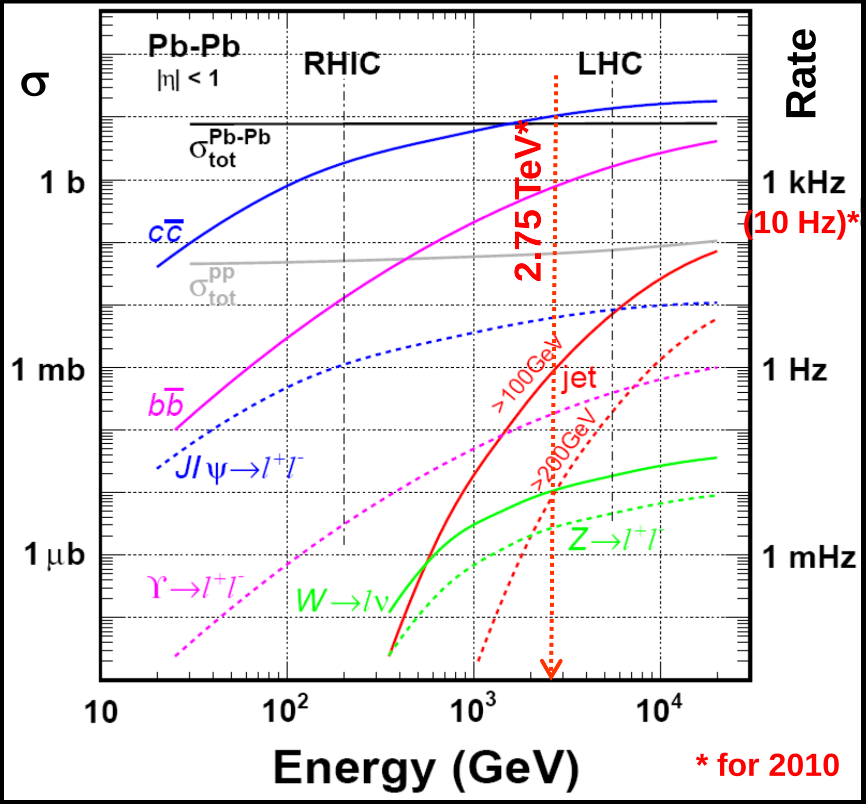
Heavy Flavor at LHC

Significant increase at LHC

- Abundance of heavy flavors
  probe early times, calculable

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)

σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)



Heavy Quarkonia

- J/ψ suppression (or enhancement?)
- Υ suppression (statistics limited)

Open Charm & Beauty

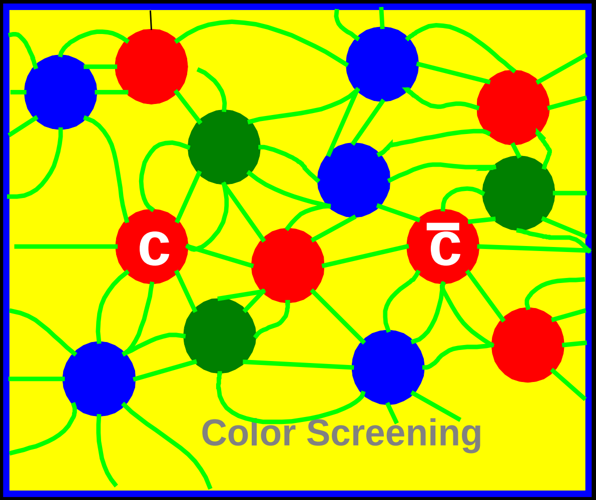
- Open charm and beauty p_T spectra
  Displaced vertices: D- & B-mesons (e.g. $D^o \rightarrow K^- \pi+$, $B \rightarrow e$ + hadrons)
- Heavy quark in-medium energy loss → Mass/color charge dependence

Quarkonia at the LHC

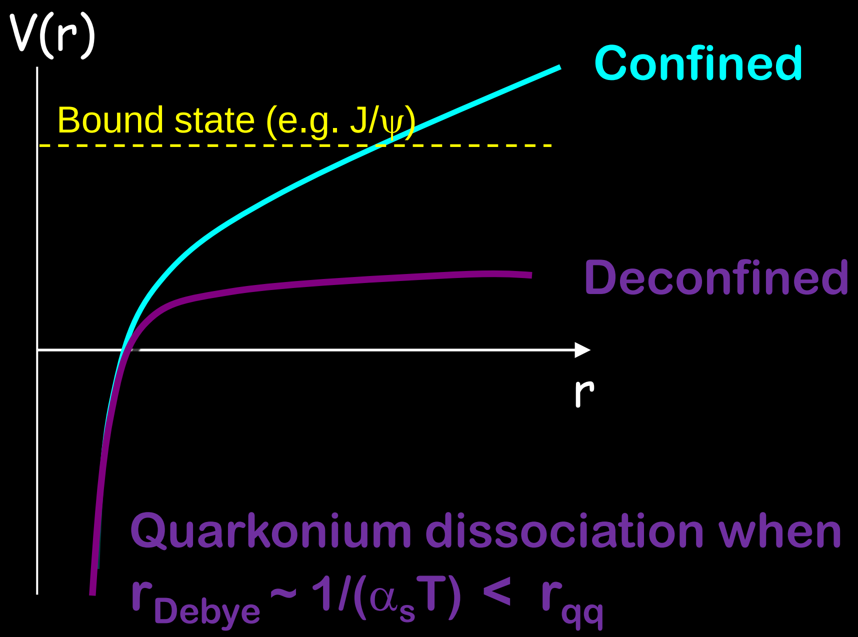
Quarkonia

(initial temperature, Debye color screening, recombination)

- J/ψ, ϒ, ϒ′ (excellent), ϒ’’(2-3 yrs), ψ’ (very difficult)



Color screening of cc pair results in J/ψ (cc) suppression!

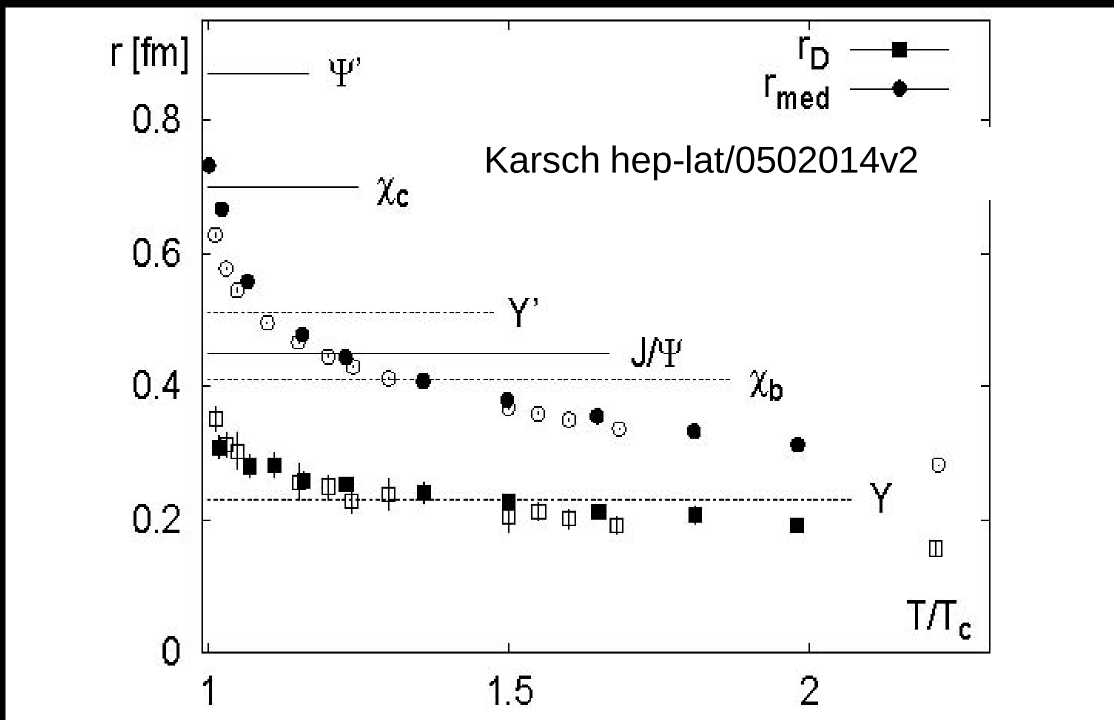


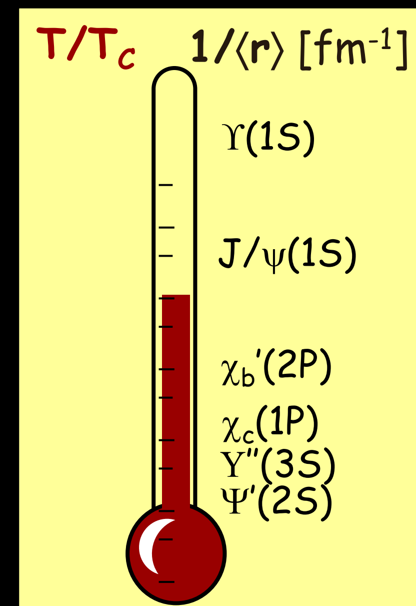
Quarkonia at the LHC

Quarkonia

(initial temperature, Debye color screening, recombination)

- J/ψ, ϒ, ϒ′ (excellent), ϒ″(2-3 yrs), ψ′ (very difficult)





Measure melting order of $c\bar{c}$: Ψ′, χ_c, J/ψ $b\bar{b}$: ϒ″, ϒ′, ϒ

Questions – Quark-Gluon Plasma at RHIC & LHC

- How does the system evolve and thermalize from its initial state?

- What are the properties & constituents (vs. T) of the QGP?

- Can we understand parton energy loss at a fundamental level?

- How does hadronization take place?

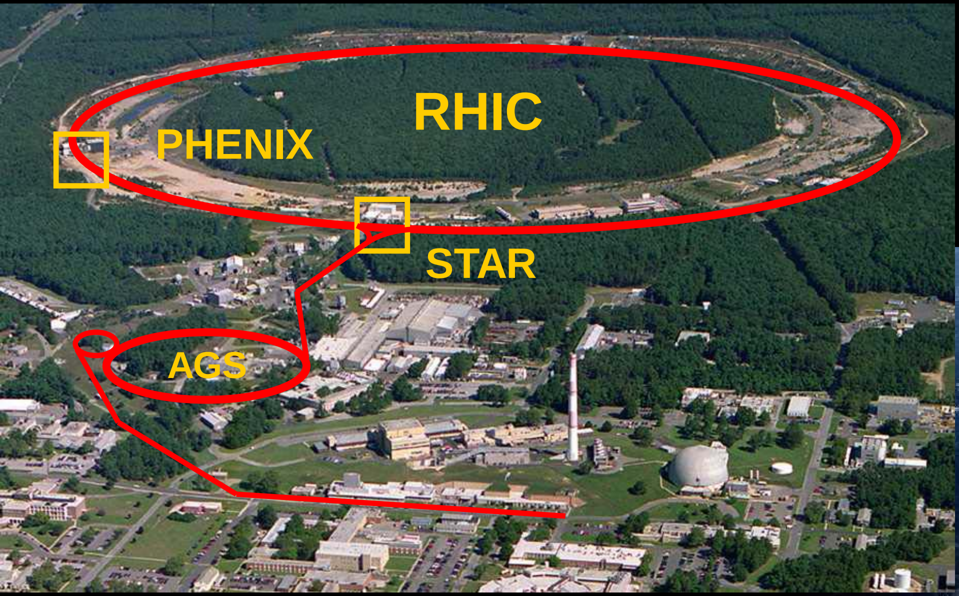
- Is the QCD Phase Diagram featureless above Tc? Coupling strength vs T….

- Are there new phenomena?

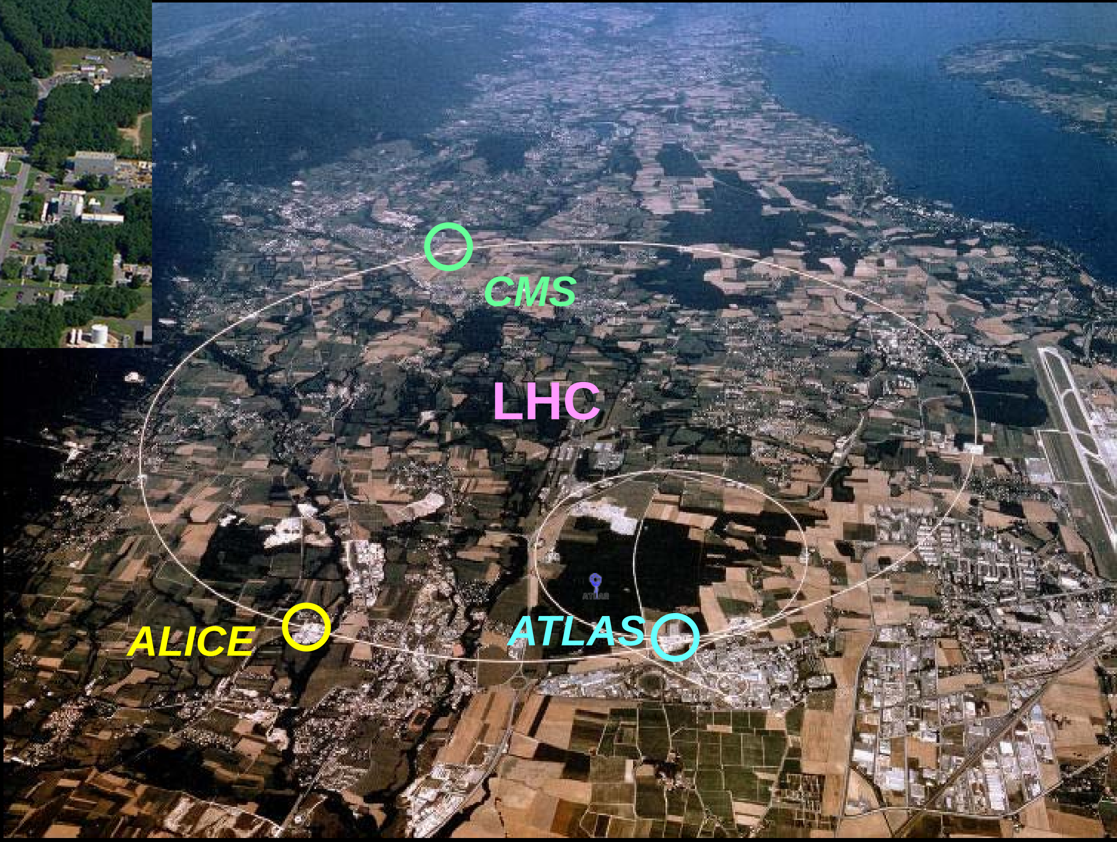
- What's the range of validity of the theories (non-pQCD, pQCD, strings)?

- Can there be new developments in theory (lattice, hydro, parton E-loss, string theory…) and understanding……across fields……?

Heavy Ion Programs at RHIC and LHC



Cover 3 decades of energy in center-of-mass



To investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

The End