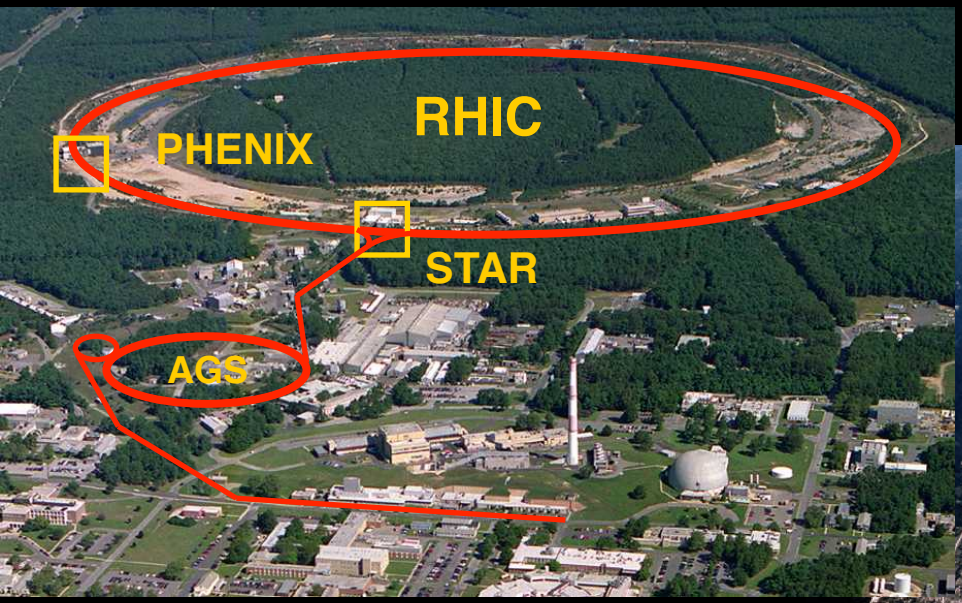
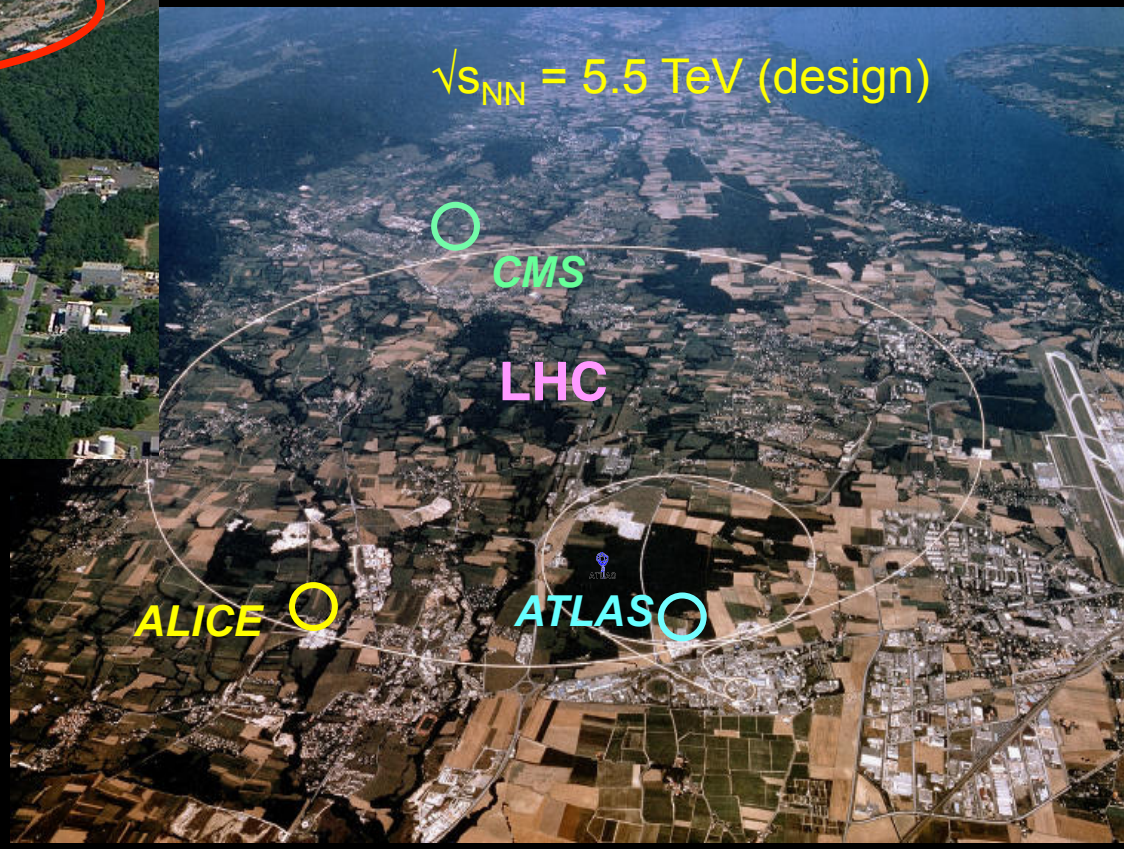
Future Perspectives for Heavy Ions with RHIC & LHC

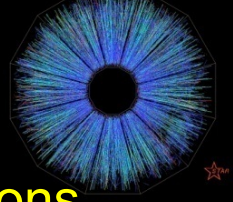


$\sqrt{s_{NN}}$ = 5 - 200 GeV

Cover 3 decades of energy in center-of-mass



"What Do We Know" from RHIC & LHC

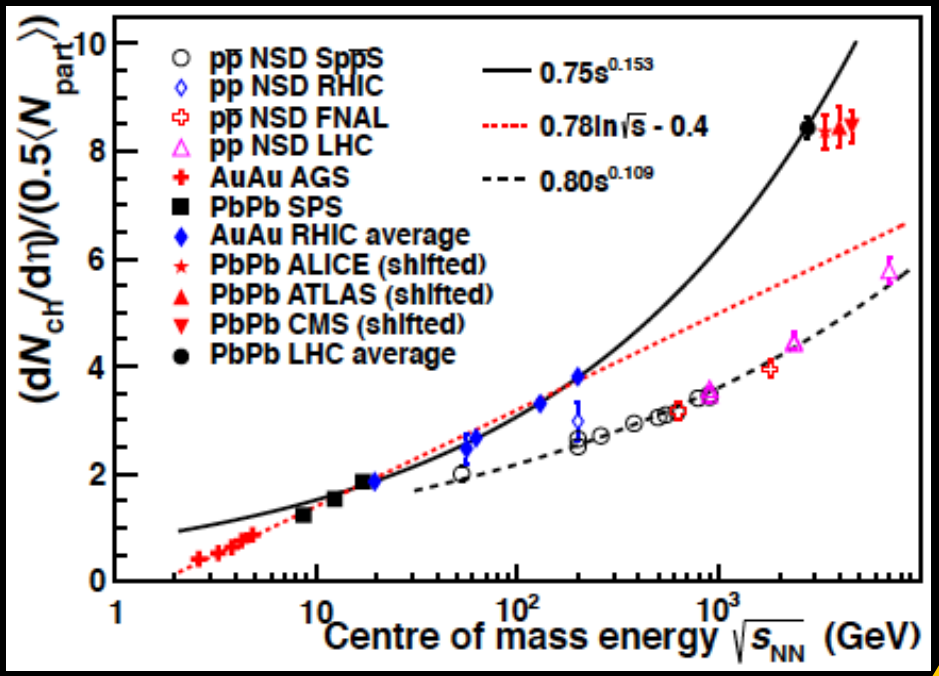


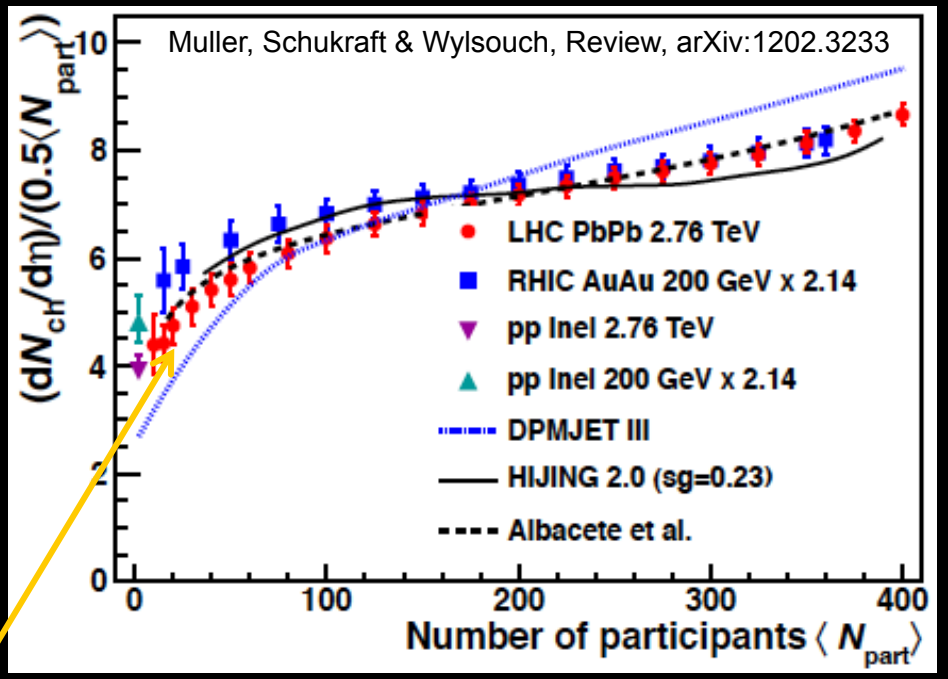
Consistent Picture of Geometry, Dynamics and Evolution of RHI Collisions

Dynamics & Evolution of RHI Collisions

"LHC & RHIC provide consistent picture" of dynamics & evolution of collisions

→ multiplicities, system size & lifetimes from RHIC to LHC



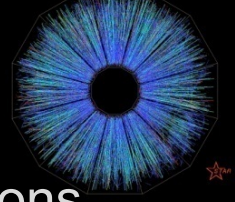


Small differences due to initial conditions (PDF shadowing vs geometry, hard processes ~ # binary collisions at LHC vs RHIC)?

Glauber vs CGC, Initial state fluctuations, Extent of shadowing

LHC pPb data later this year!

"What Do We Know" from RHIC & LHC



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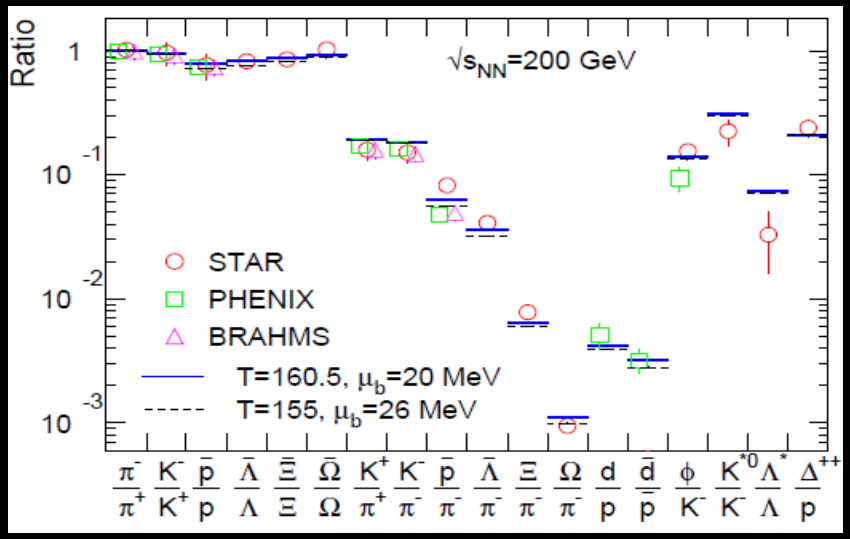
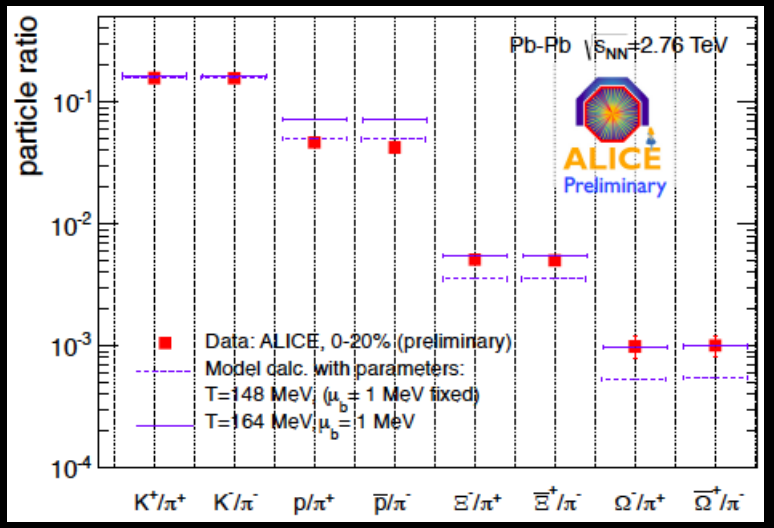
Particle ratios → equilibrium abundances → universal hadronization $T_{critical}$

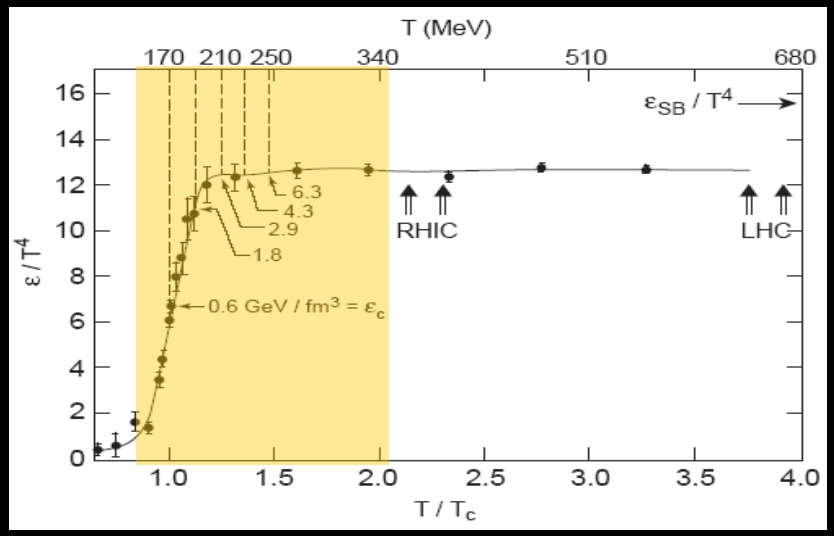
Confirm lattice predictions for $T_{critical}$, μ_B

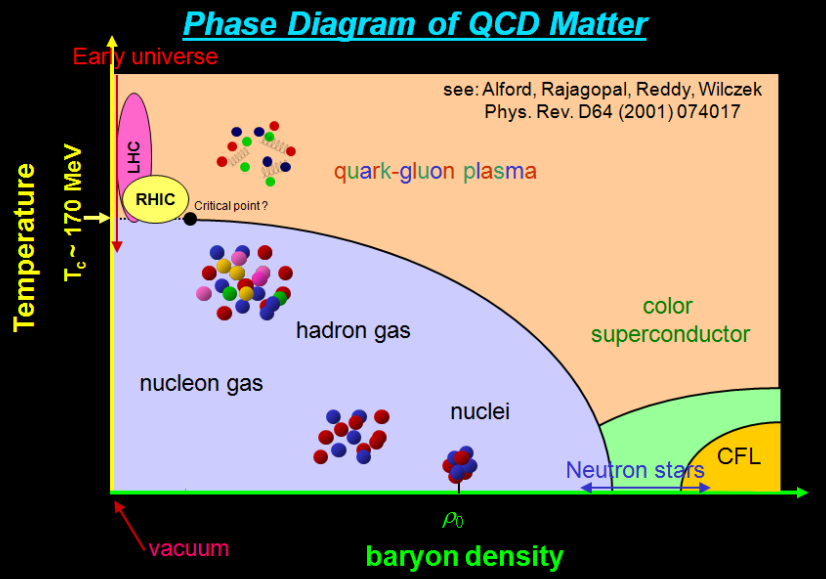
Particles Formed at Universal Hadronization T





Particles yields → equilibrium abundances → universal hadronization $T_{critical}$





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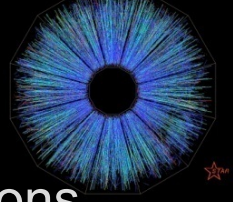

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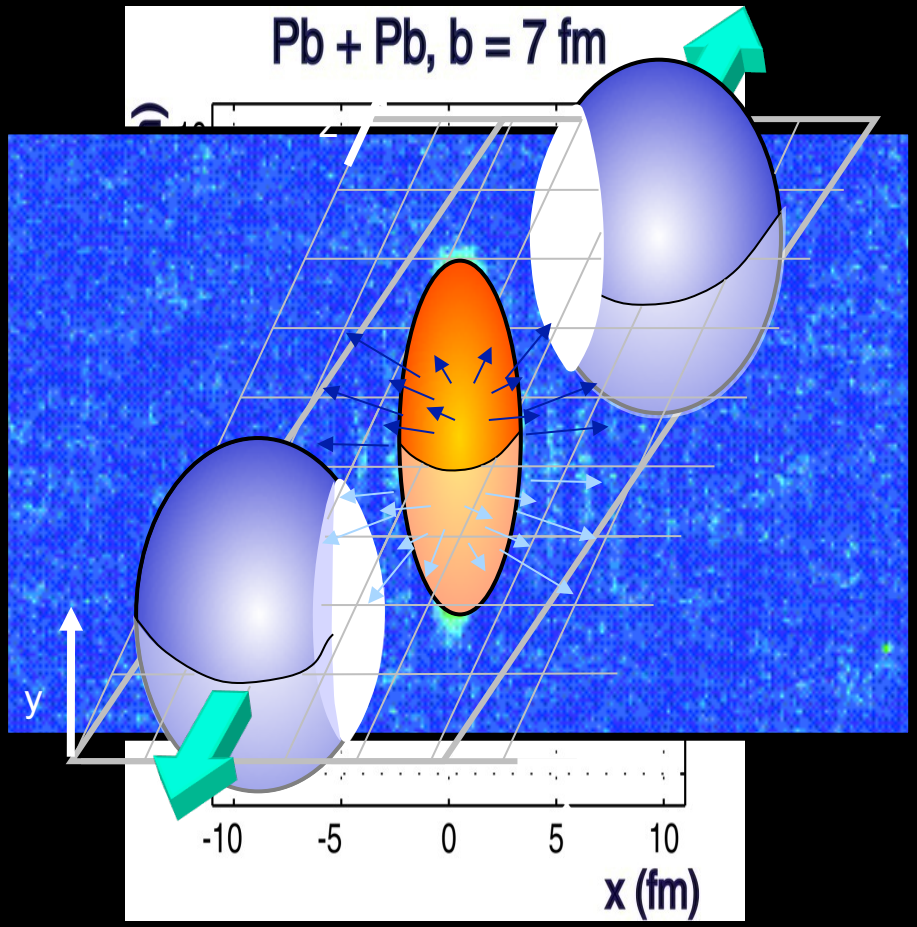
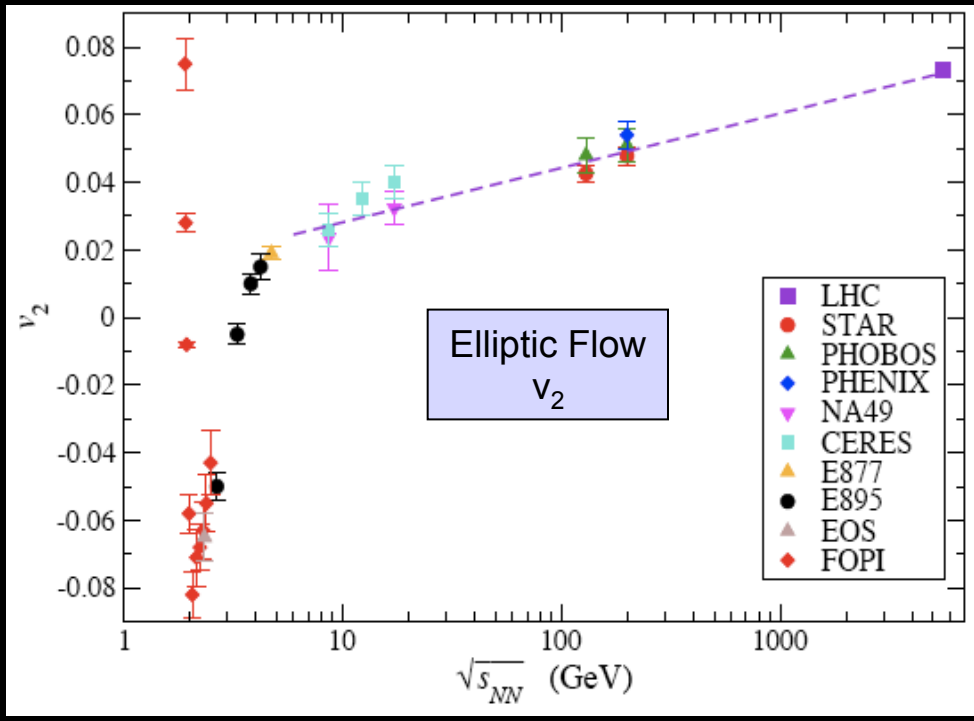
Strongly-coupled liquid

Flows with ultra-low shear viscosity

Large Elliptic Flow Observed – Implications?



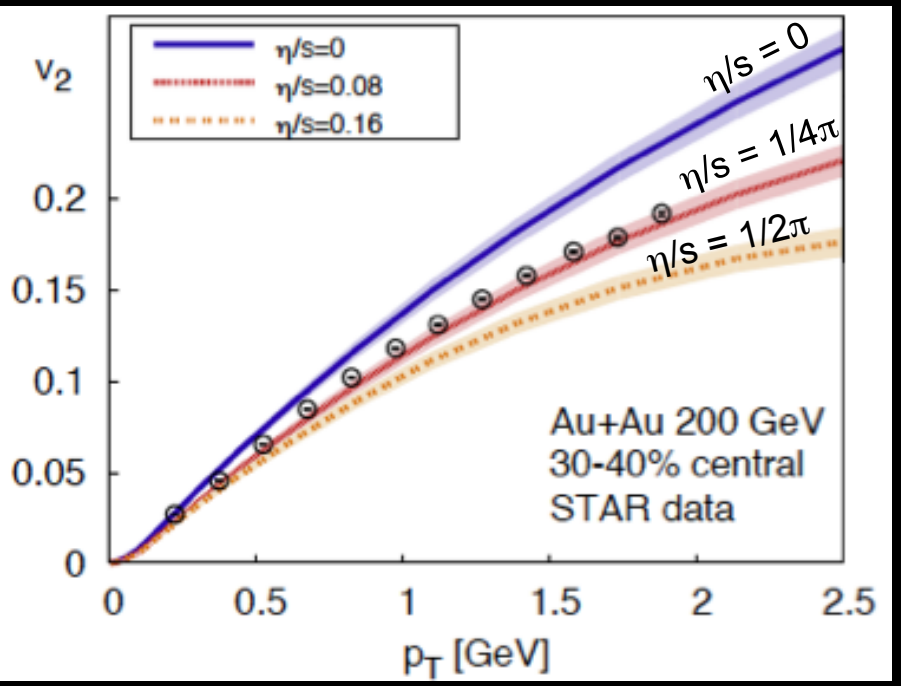
Azimuthal asymmetry of particles:
$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

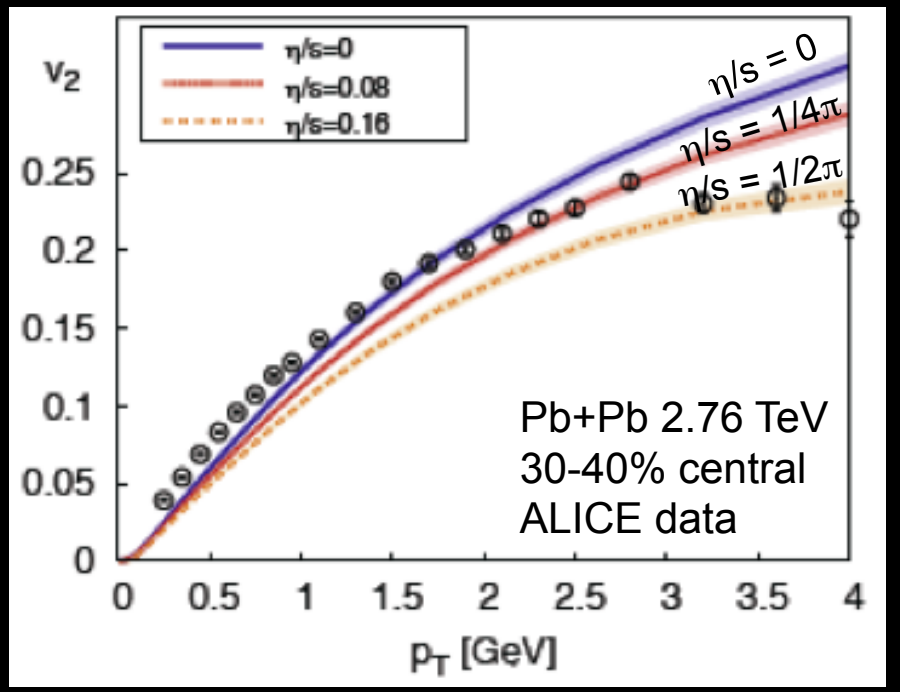


Predicted by hydrodynamics with very low shear viscosity

Increase in v_2 from RHIC to LHC

It's a Strongly-Coupled Medium with Ultra-Low Shear Viscosity





Viscous hydrodynamics calculations from Schenke, Jeon, Gale, PRL 106 (2011) 042301.

$\rightarrow 1/4\pi < \eta/s < 1/2\pi$

There exists a universal lower bound on shear viscosity / entropy ratio (η/s):

The strong-coupling limit of non-Abelian gauge theories with a gravity dual:

$\rightarrow \eta/s = 1 / 4\pi$ for the "perfect liquid"

Power Spectrum for Heavy Ions ↔ Analog WMAP!

An acoustic horizon in fluid dynamics (A Mocsy, P. Sorensen, arXiv:1101.1926)

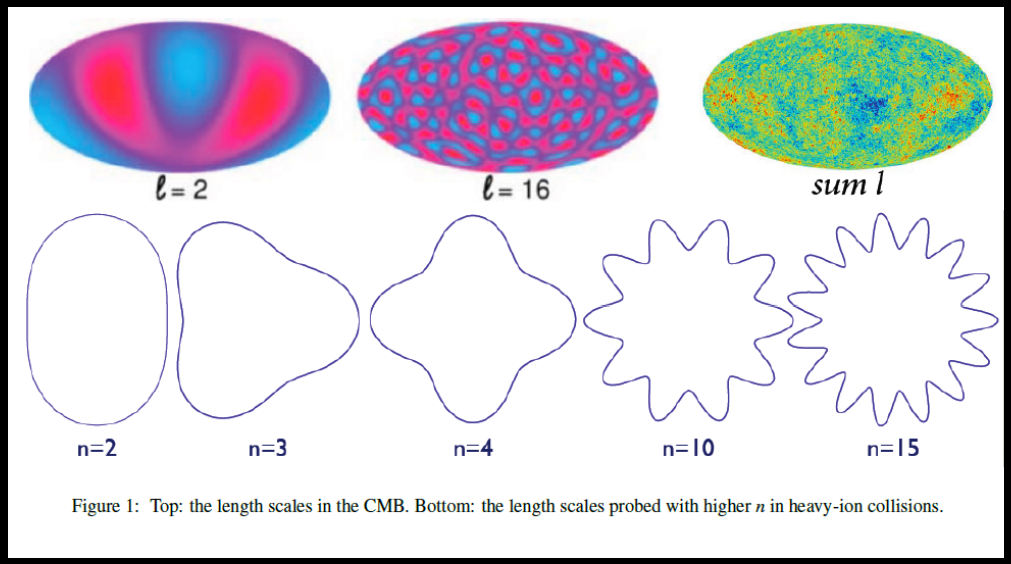
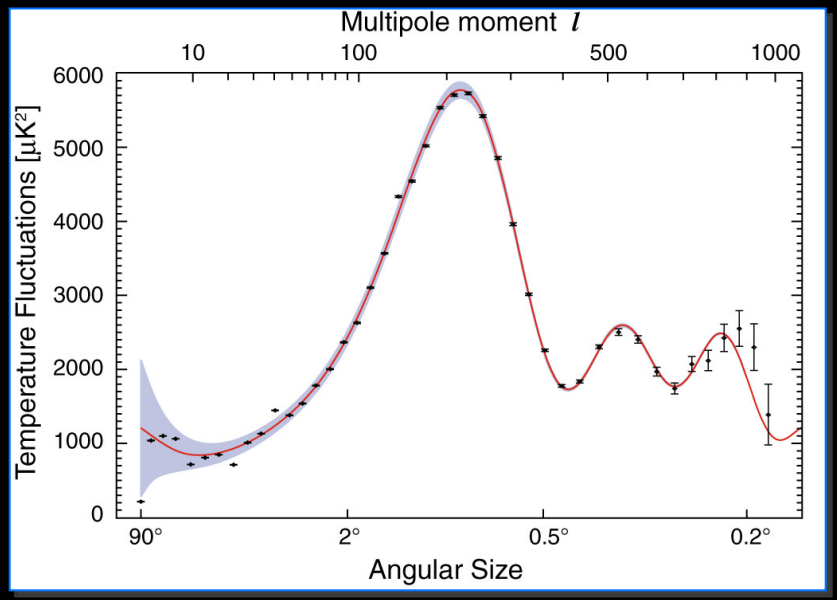
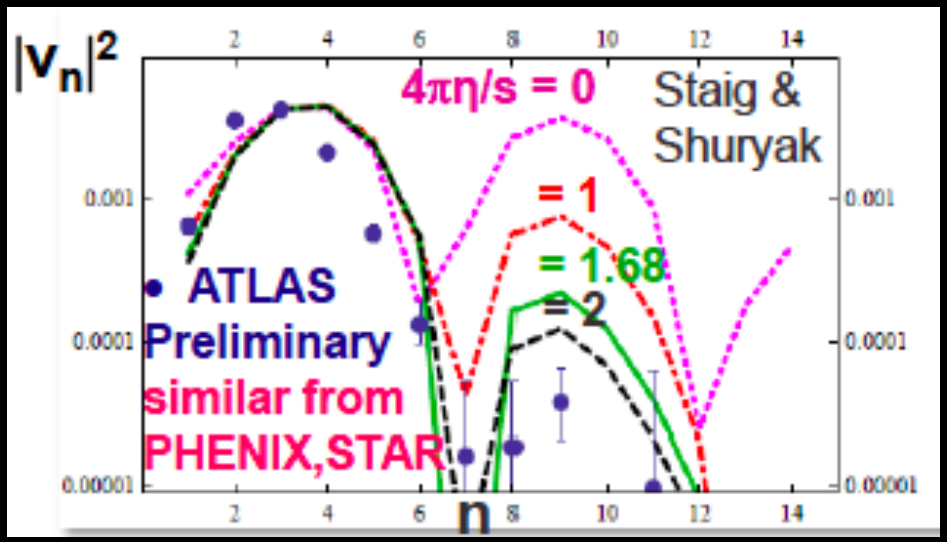


Figure 1: Top: the length scales in the CMB. Bottom: the length scales probed with higher n in heavy-ion collisions.





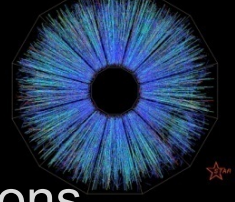
Gaussian width related to length scales

such as mean free path, acoustic horizon.

Like measurements of early universe sound harmonics…

Heavy Ion harmonics give key constraints on viscous damping & spatial correlations

"What Do We Know" from RHIC & LHC



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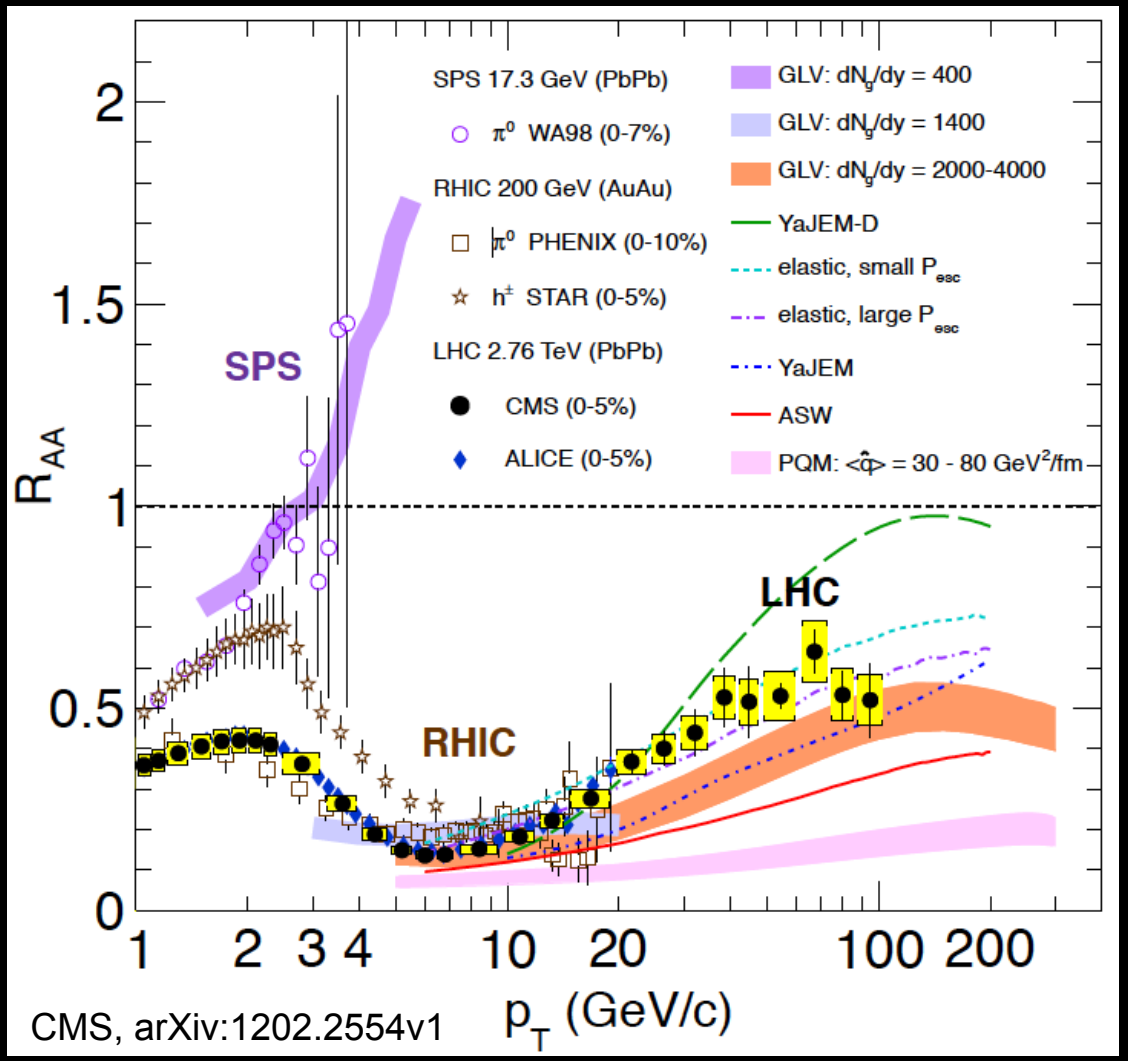
Light & heavy quarks are suppressed at large p_T

Jets quenched and away-side jet energy imbalance

Large Transverse Momentum (p_T) Particles Are Suppressed



$$R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$$

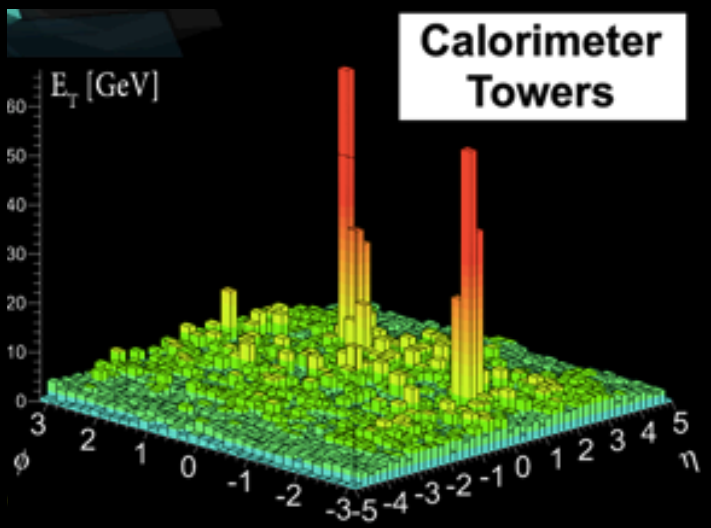
$R_{AA} = 1$

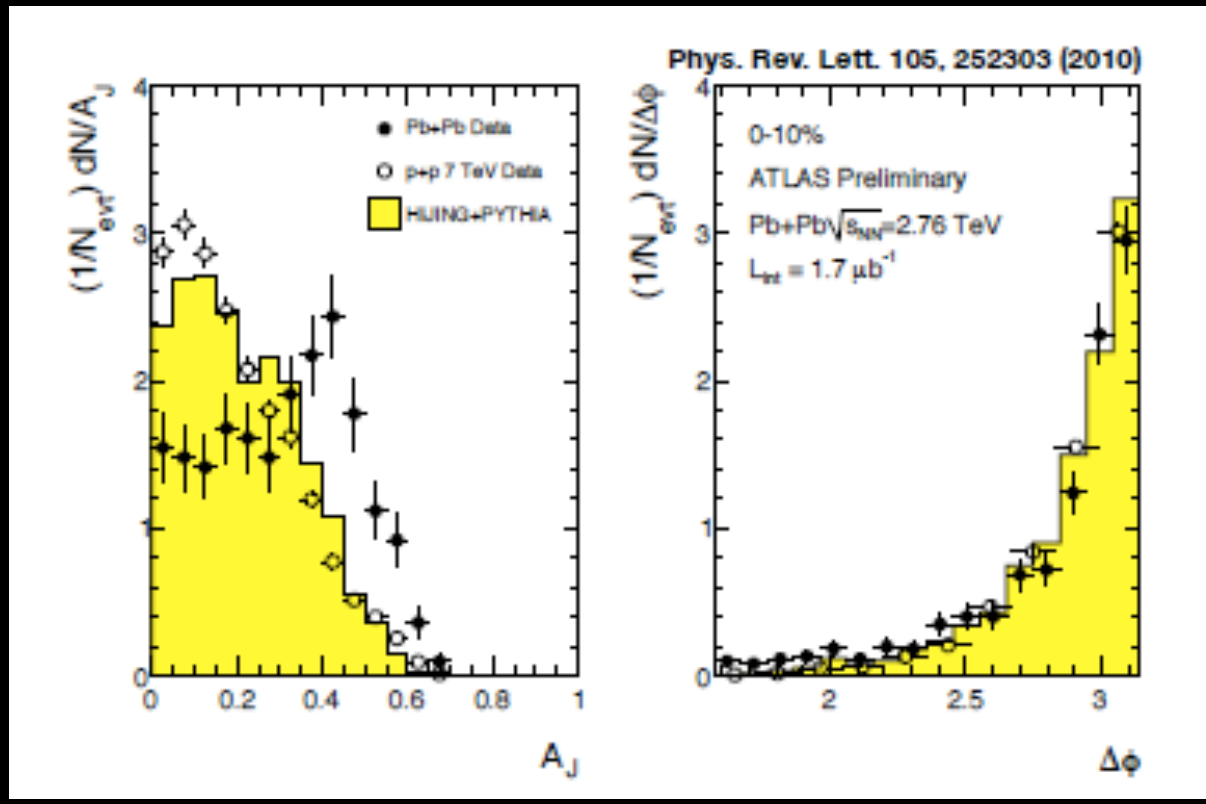
Suppression

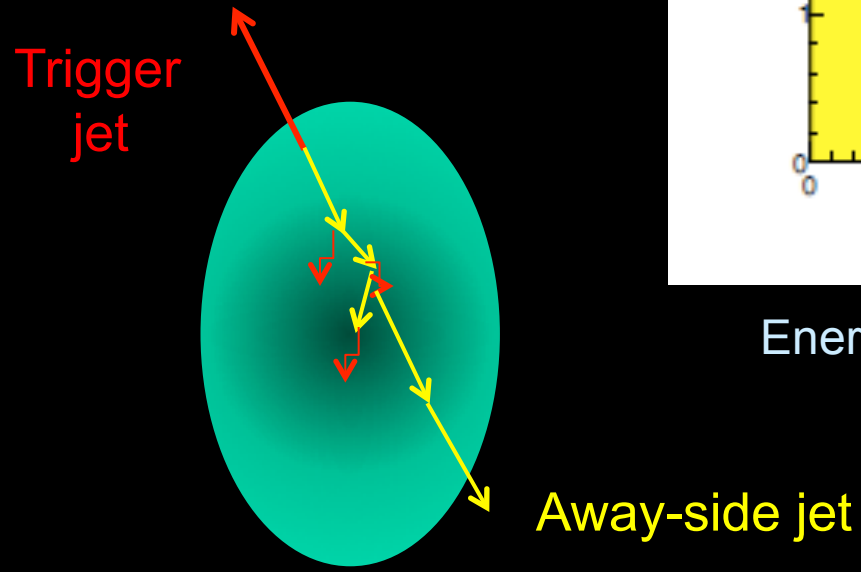
ALICE

CMS

Jets at the LHC – Di-Jet Energy Imbalance!







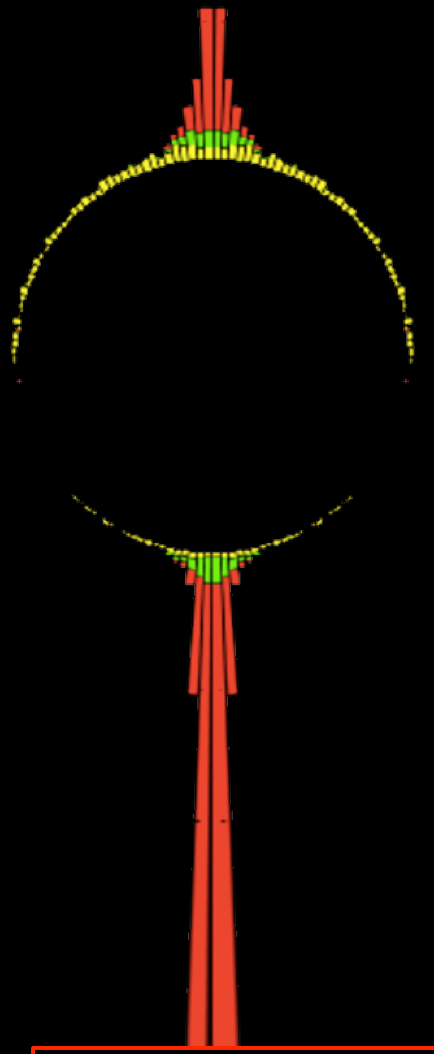
Energy Asymmetry: $A_J = E_{T1} - E_{T2} \ / \ E_{T1} + E_{T2}$

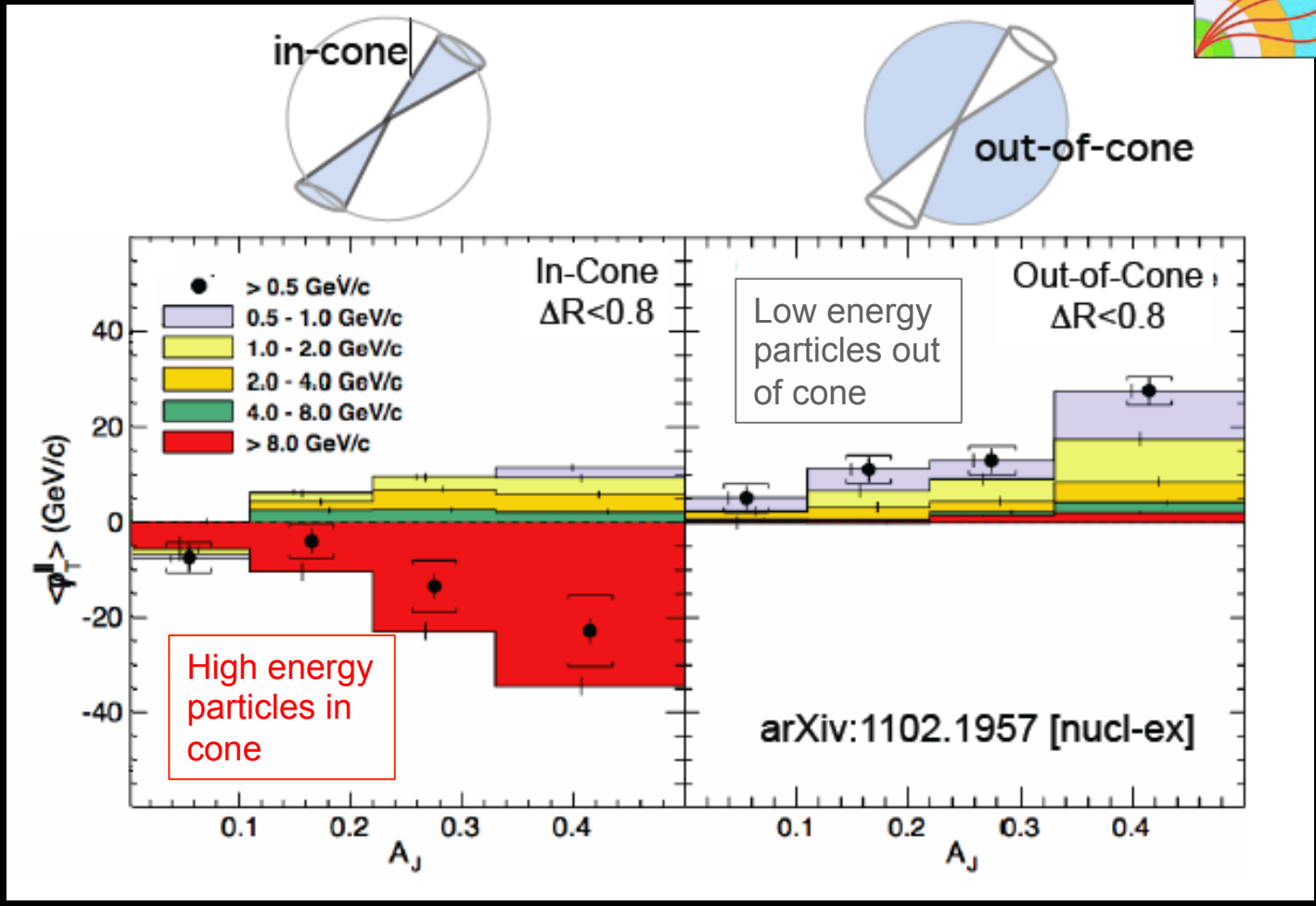
for $\Delta\phi > \pi/2$

$E_{T1} > 100$ GeV $\quad E_{T2} > 25$ GeV

Where does the Energy Go? – CMS

PRC 84 (2011) 024906

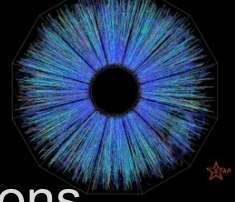




Energy/momentum balance in event is carried by low momentum particles at large angles to jets!

pQCD, vacuum fragmentation, thermalization of lost energy?

"What Do We Know" from RHIC & LHC



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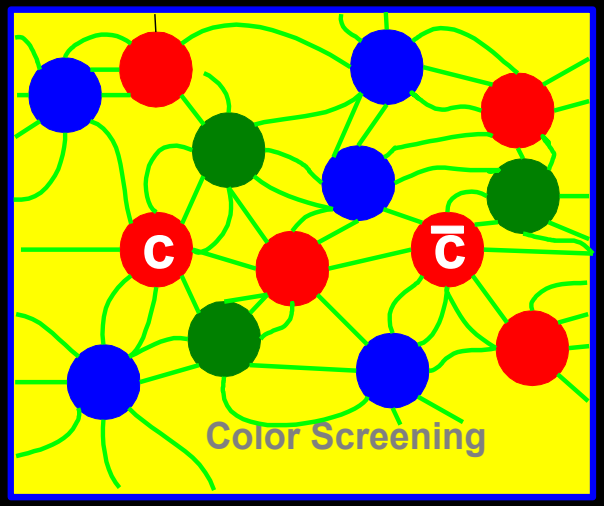
It has properties of color-screening

Suppression of quarkonia (J/ψ and Υ states)

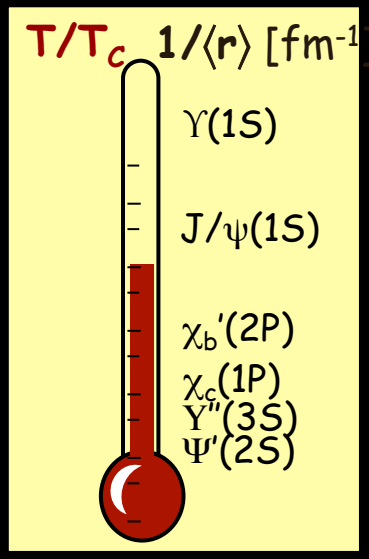
Quarkonium "Melting" at LHC and RHIC

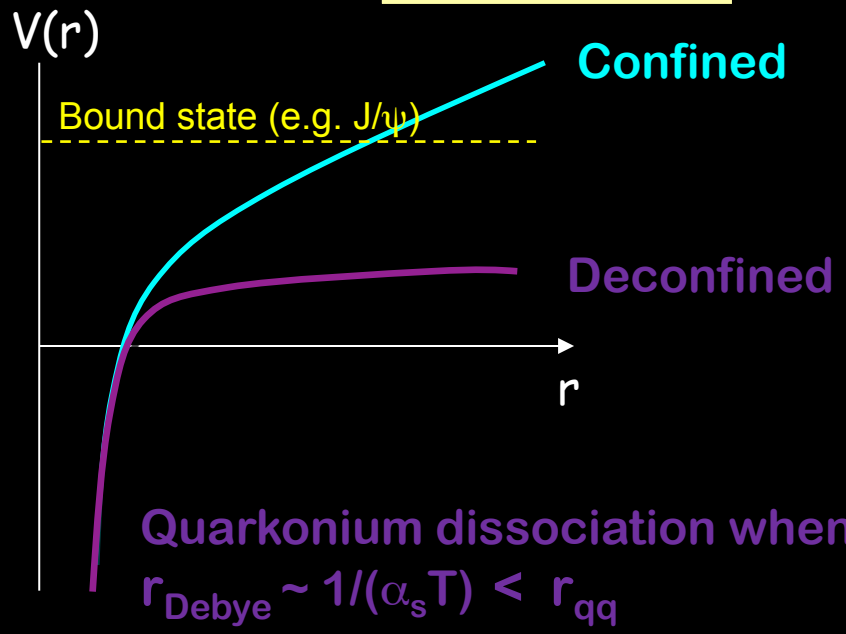
Quarkonia: $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Υ'', Υ', Υ

(Debye color screening, recombination)



Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!

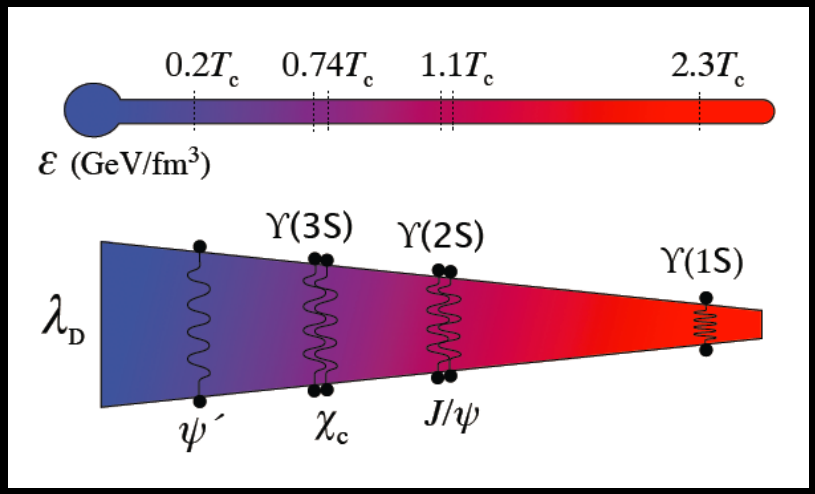


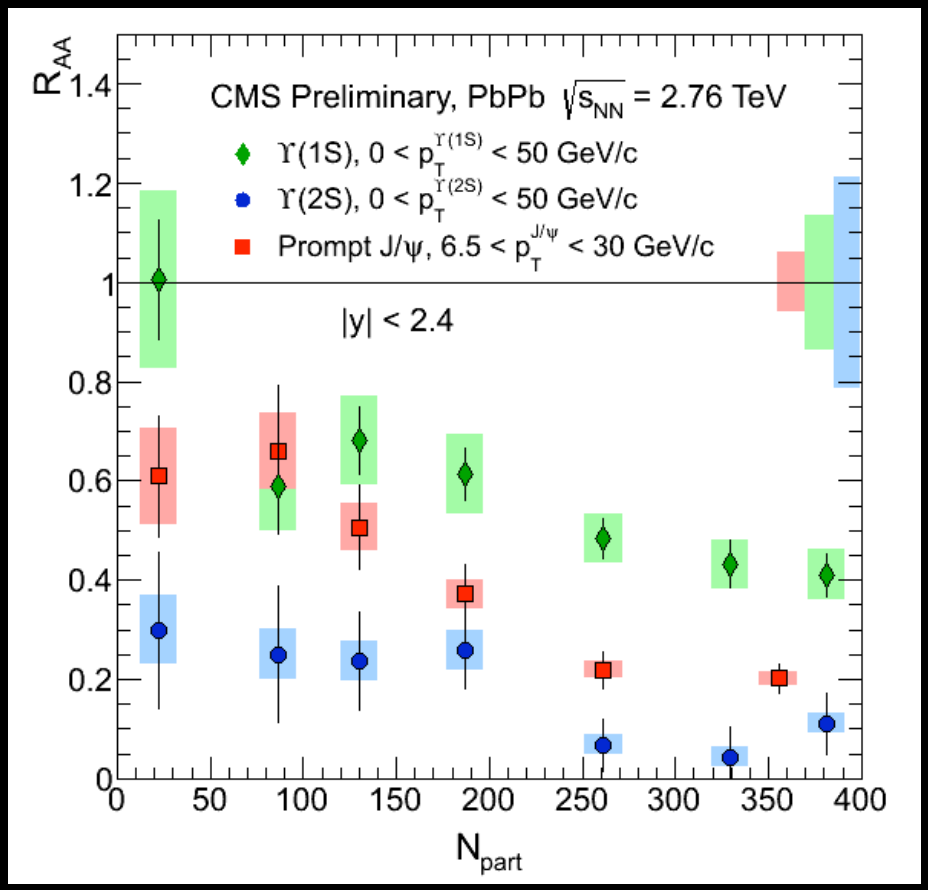


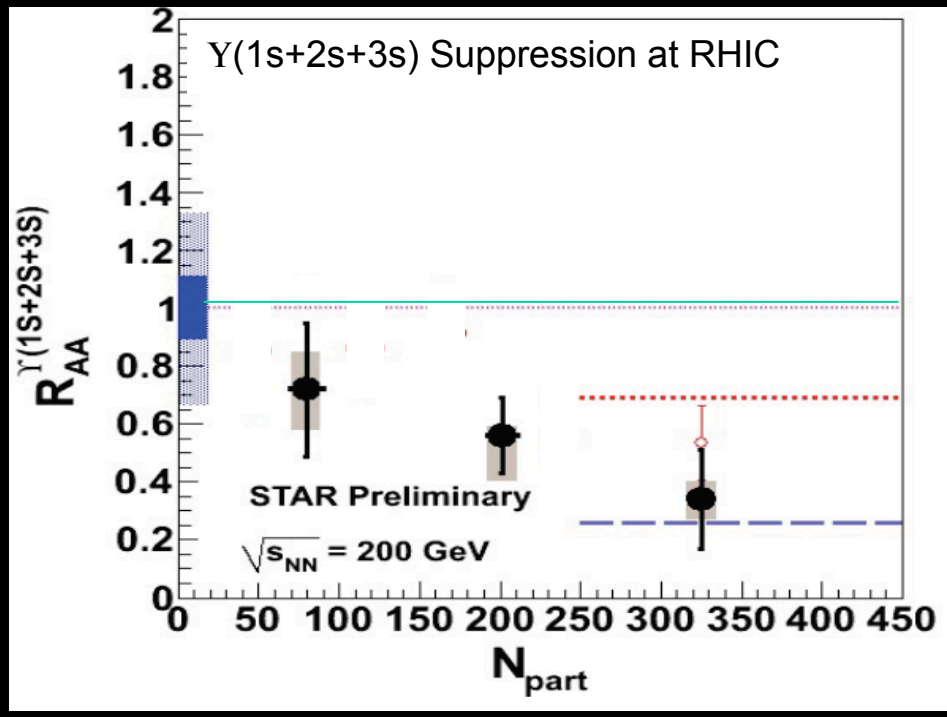
Quarkonium dissociation when $r_{Debye} \sim 1/(\alpha_s T) < r_{qq}$

Quarkonium "Melting" at LHC and RHIC

Y (b-bbar) cleaner, less recombination than J/ψ
- (heavier) and less thermal
- melting sequence vs temperature!







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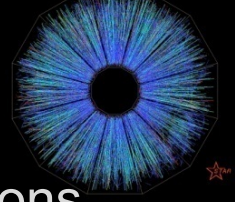

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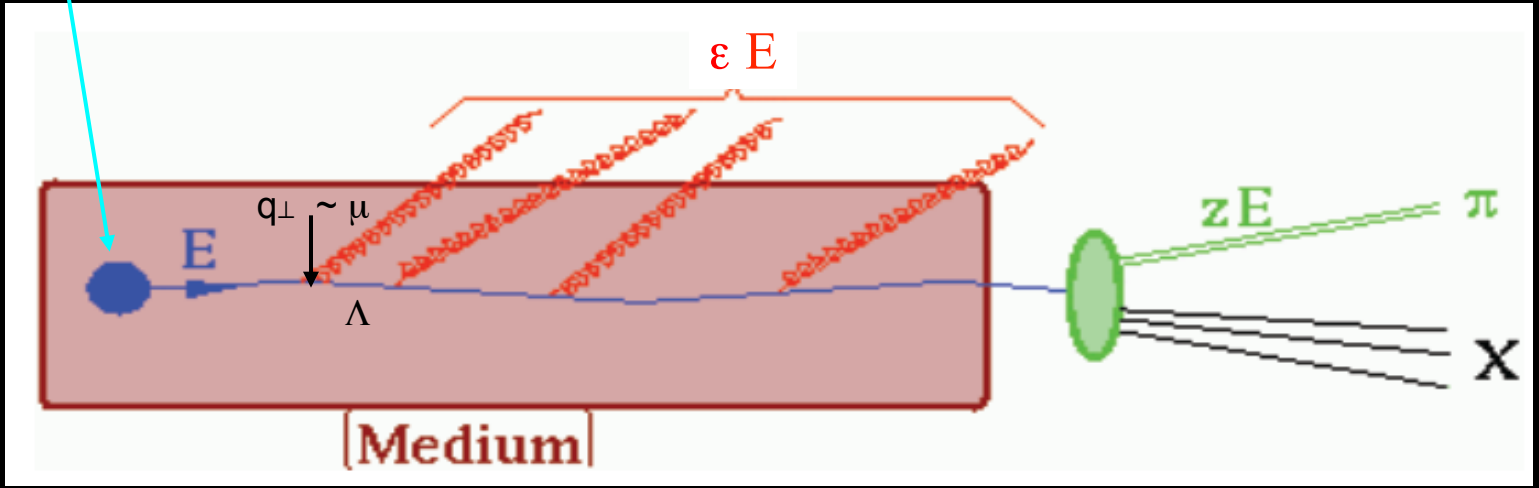
Suppression of quarkonia (J/ψ and Υ states)

Still much to be done experimentally and theoretically……

Parton Energy Loss in QCD and QGP

How does parton lose energy?

Measure radiation products/energy!



What is the dependence on the type of parton?

Measure energy loss of parton!

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

thus:

$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

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

Fundamental Questions about Parton Energy Loss and Implications for the QGP Medium

What are the energy loss mechanisms?

- "radiative" = into non-thermal gluon modes
- "collisional" = directly into thermal plasma modes

How are these affected by the structure of the QGP (quasiparticles or not)?

- What is QCD at high T?
- Are AdS/CFT inspired models applicable?
- What is the weak-strong coupling transition?

What happens to the parton energy and momentum lost (medium response?)?

- If "radiative", how quickly does it thermalize
  - i.e., what is its longitudinal momentum (z) distribution?
- What is its angular distribution (the jet "shape")
  - i.e., how much is found in a cone of jet angular size R ?

How do the answers depend on flavor of the parton?

How to Address Parton Energy Loss

Measurements to Determine Parton Energy Loss (Disentangle effects!)

- Mass and color effects $\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$

  b-quark vs c-quark vs light-quark suppression/propagation!

  (ALICE, ATLAS & CMS Upgrades)

  Better secondary vertex discrimination & background suppression

  Smarter triggering capabilities at lower levels allowing

  Better statistics on specific signals (vs background!)

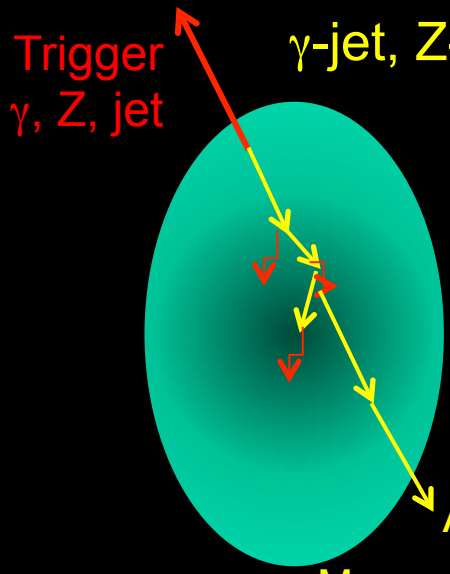
- Establish initial parton kinematics for jets (before parton energy loss!)

  γ-jet, Z-jet, di-jets – γ and Z non-interacting in QGP!

  Gluon vs quark suppression (color factor), use of jets

  Measure dE/dx (color charge in QCD ala QED!)

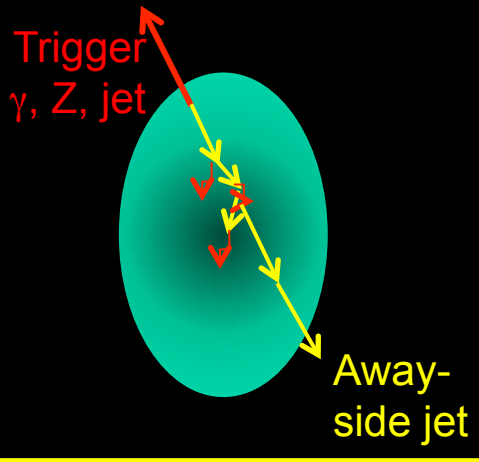
  Virtuality of partons different at RHIC & LHC



Measure pathlength L dependence

Virtuality at RHIC and LHC in pQCD

Virtuality Q^2 of parton in the medium controls physics of radiative energy loss:



$$Q^2(L) \approx \max\left(\hat{q}\,L, \frac{E}{L}\right)$$

medium vacuum

Measure pathlength L & E or p_T dependence of jets and "radiated" particles

RHIC: 20 GeV parton, L = 3 fm

$\hat{q}\,L \approx 4.5\ \mathrm{GeV}^2 >> E/L \approx 1.5\mathrm{GeV}^2$

Virtuality of primary parton is medium dominated and small enough to "experience" the strongly coupled medium

LHC: 200 GeV parton, L = 3 fm

$\hat{q}\,L \approx 9\ \mathrm{GeV}^2 < E/L \approx 13\ \mathrm{GeV}^2$

Virtuality of primary parton is vacuum dominated and only its gluon cloud "experiences" the strongly coupled medium

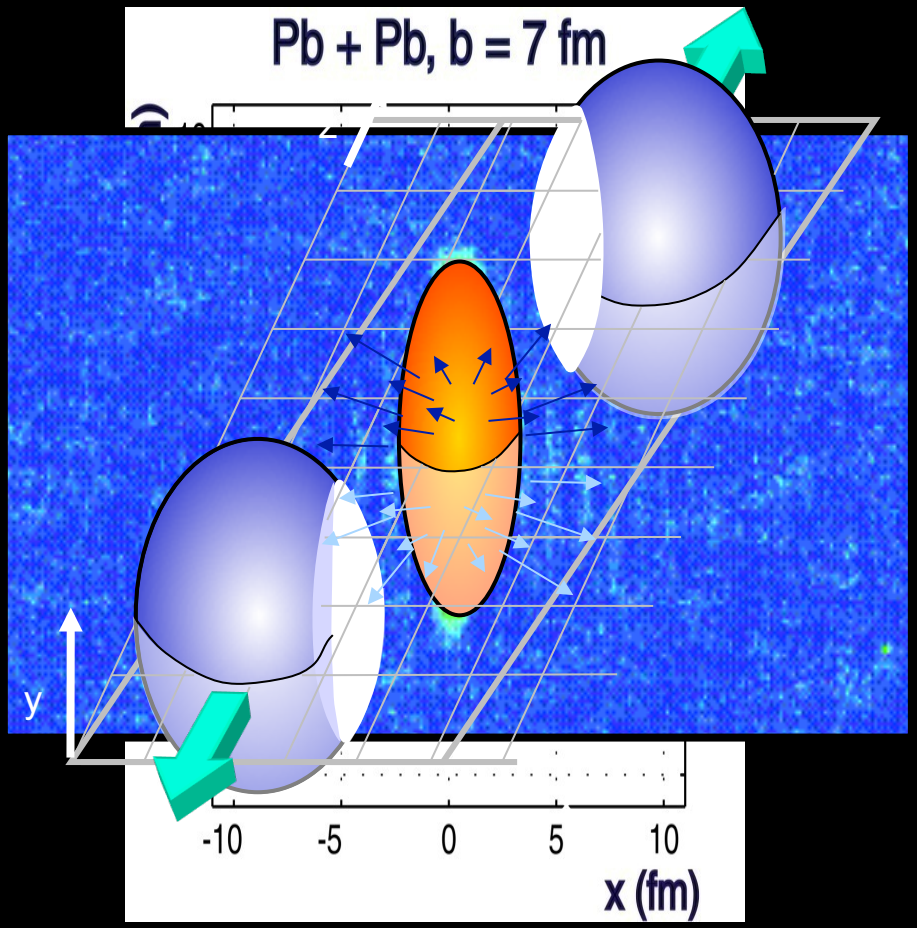
B. Mueller, Hard Probes 2012

Why Differential Quantities?

Detailed investigation of variables (parton attenuation & QGP transport properties) as function of:

- Centrality (impact parameter/shape) & Event Plane (Directionality)

(Pressure gradients and pathlength dependence)



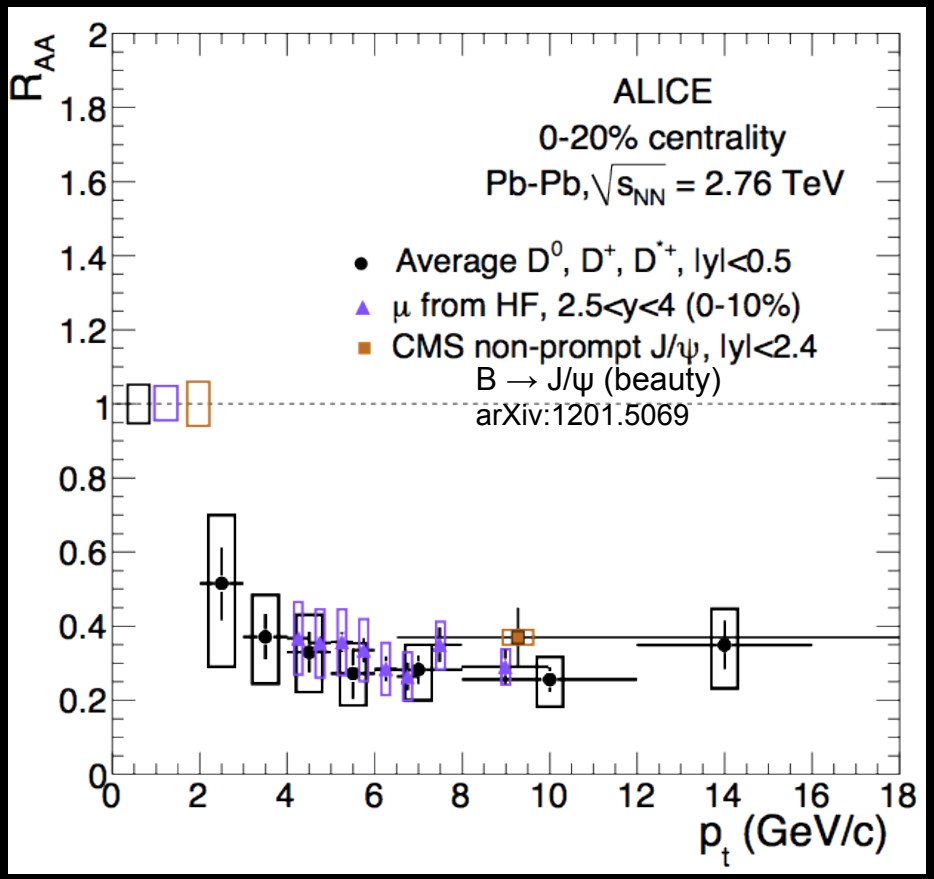
Measure & correlate differences in:

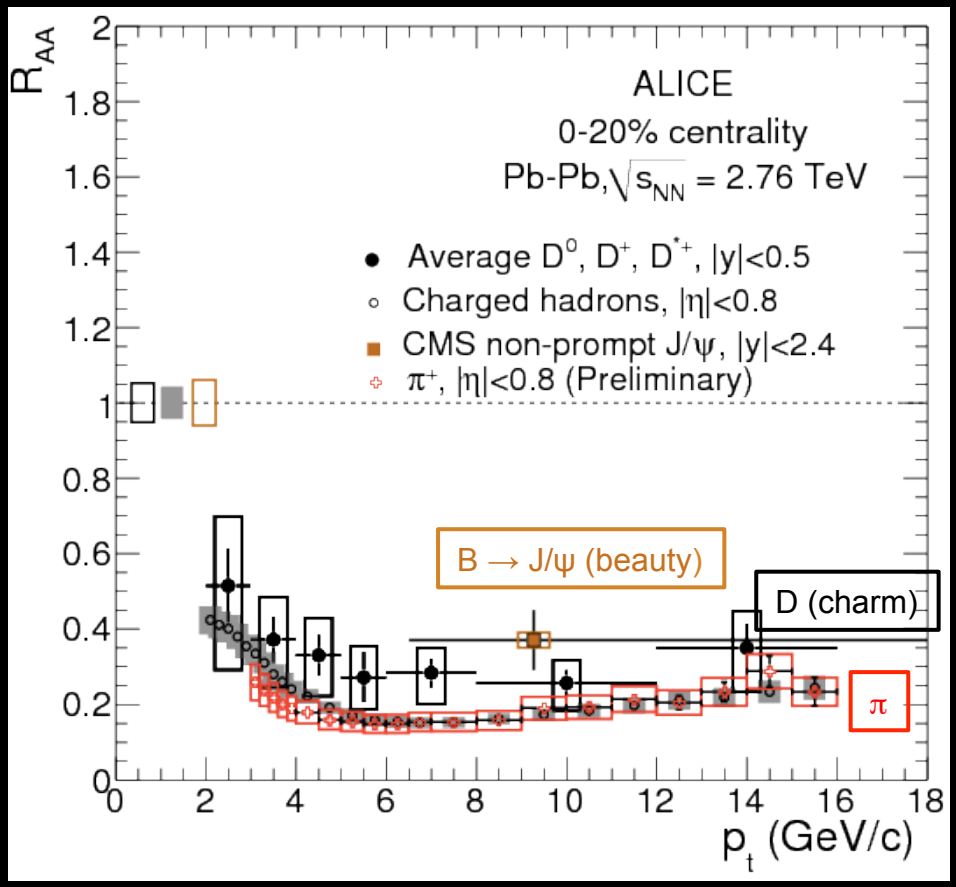
Parton propagation
Transport properties

Also dependence on:

Momentum
Flavor

Suppression of Heavy Flavors



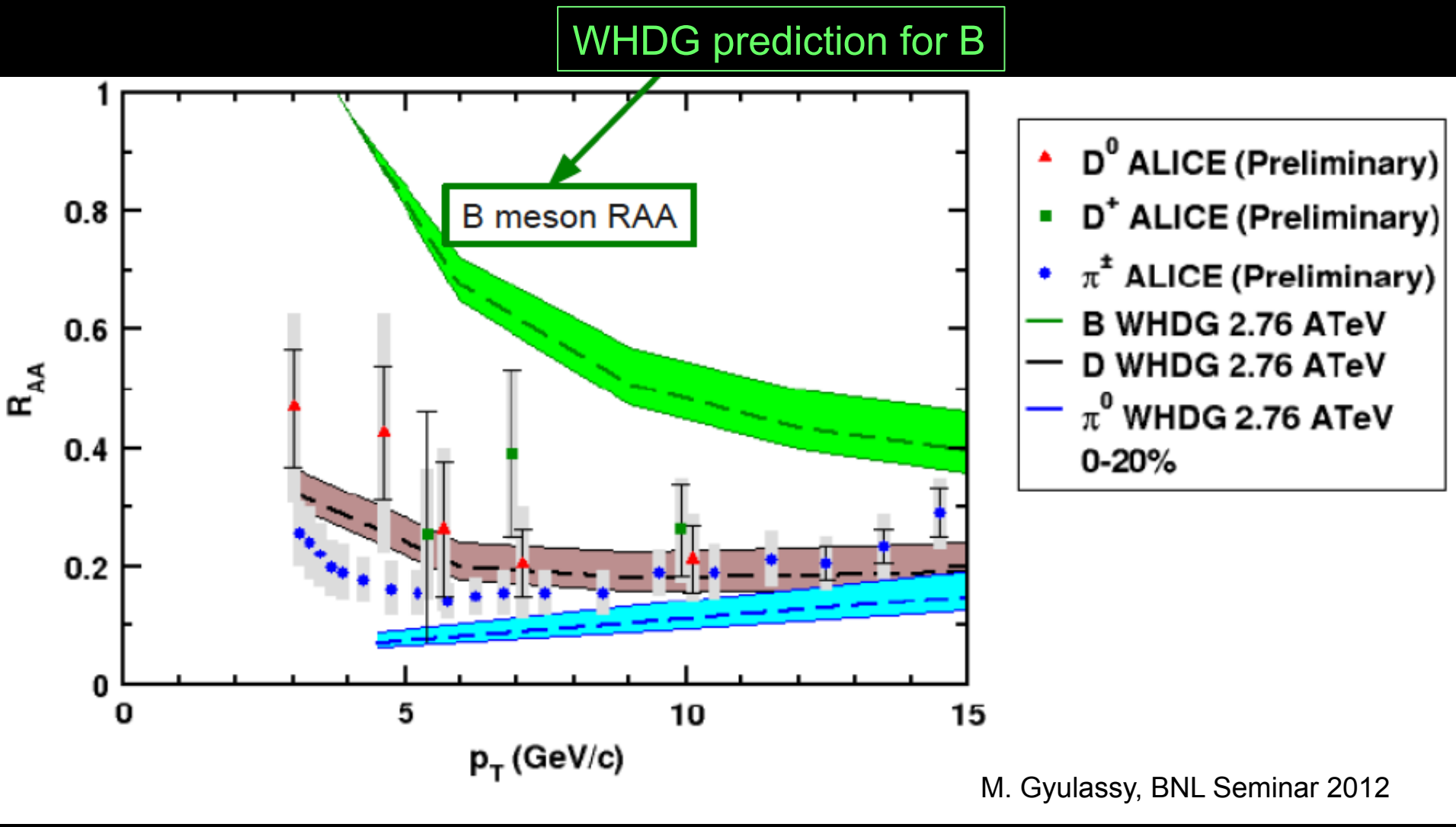


Charm and beauty:
No evidence of mass effects yet!

Pions, charm and beauty:
Suggestion of a hierarchy!

Requires better statistics, esp. for beauty and path-length dependence!

Heavy Quark Energy Loss in the Medium



M. Gyulassy, BNL Seminar 2012

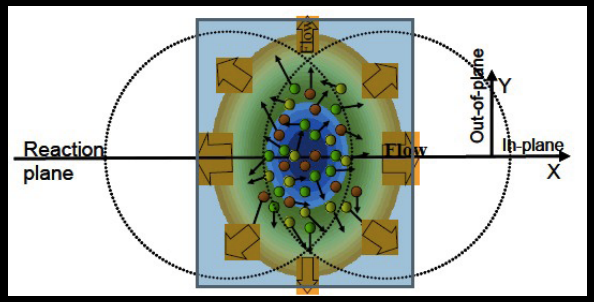
Will b-quarks behave as pQCD predicts (Dead-cone Effect→less suppressed)?

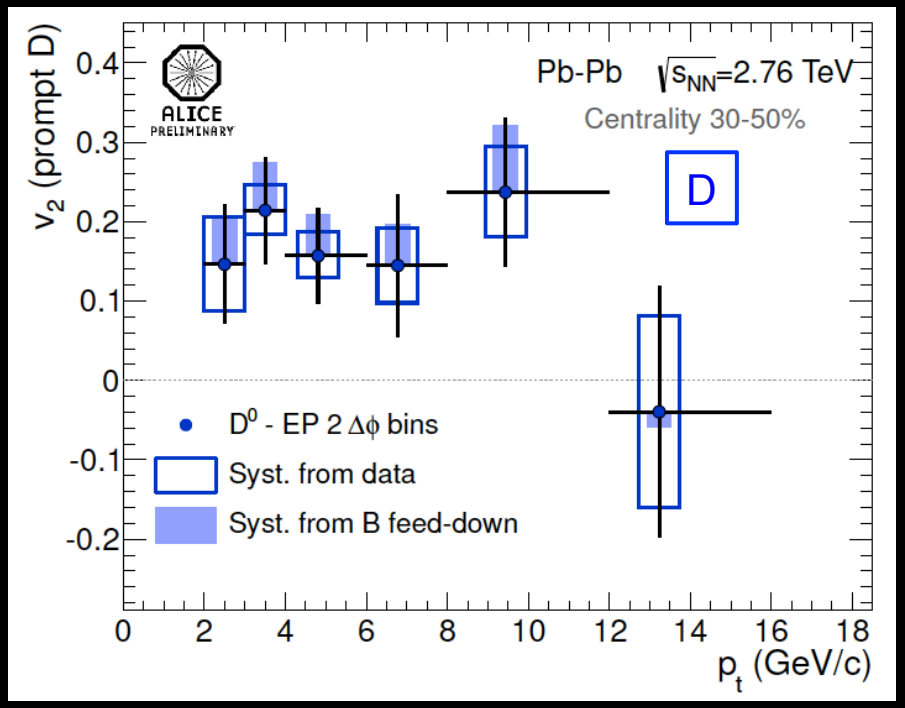
Flow of Heavy Flavors

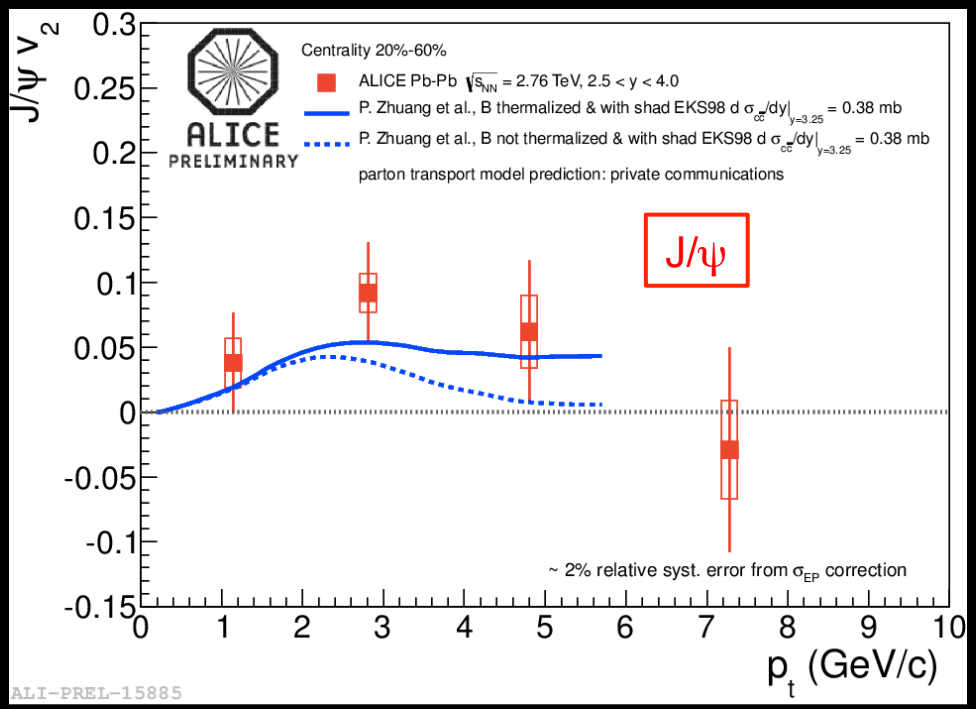
Detailed investigation of flow as function of:

- Particle type (quark content):
- Centrality (impact parameter/shape)
- Event Plane (Directionality)

(Pressure gradients and pathlength dependence)







Requires much better statistics, esp. for path-length dependence!

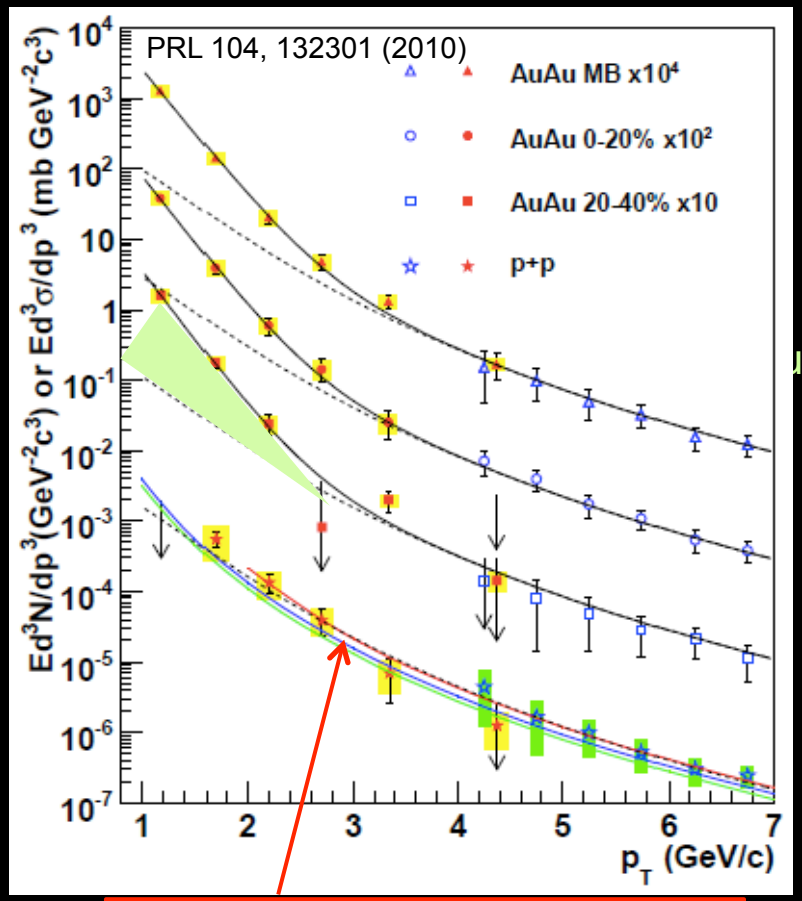
Real and Virtual Photons at RHIC

In progress at LHC…?

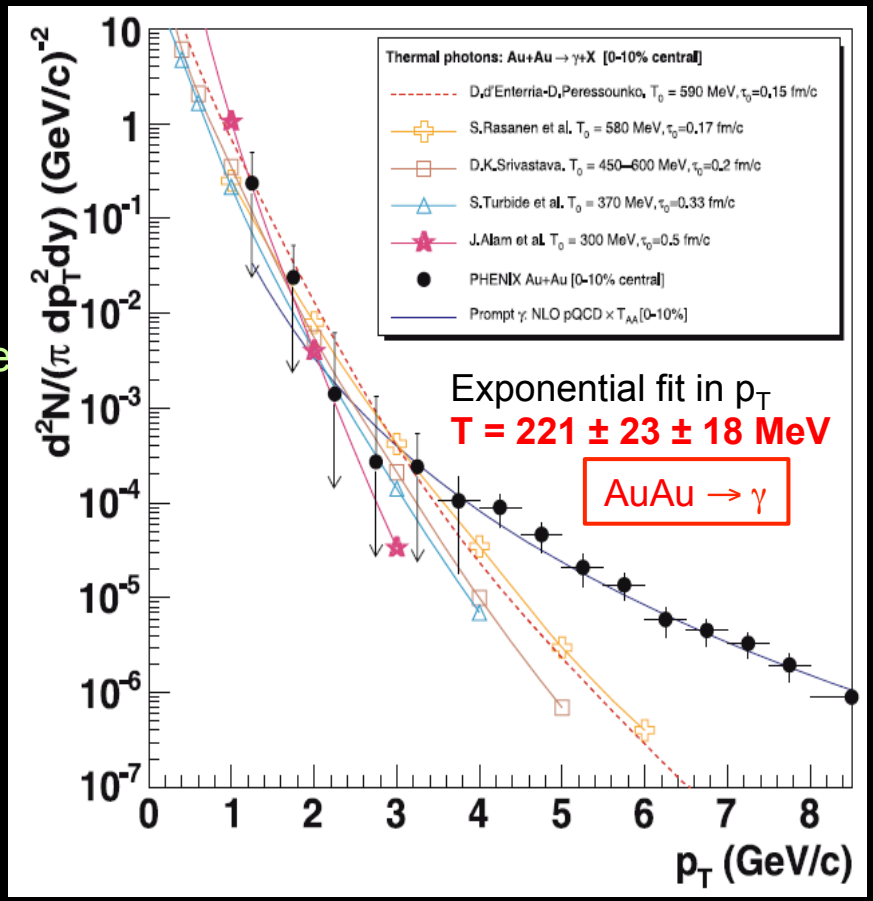
Thermal photons – shining of the QGP (at RHIC)

Must understand the other contributions

Spectrum integrates over space-time evolution



pp→ γ, good agreement with pQCD



Real and Virtual Photons

In progress at LHC…?

Virtual photons – Di-leptons

Medium modification of resonance & hadron masses

Chiral symmetry restoration?

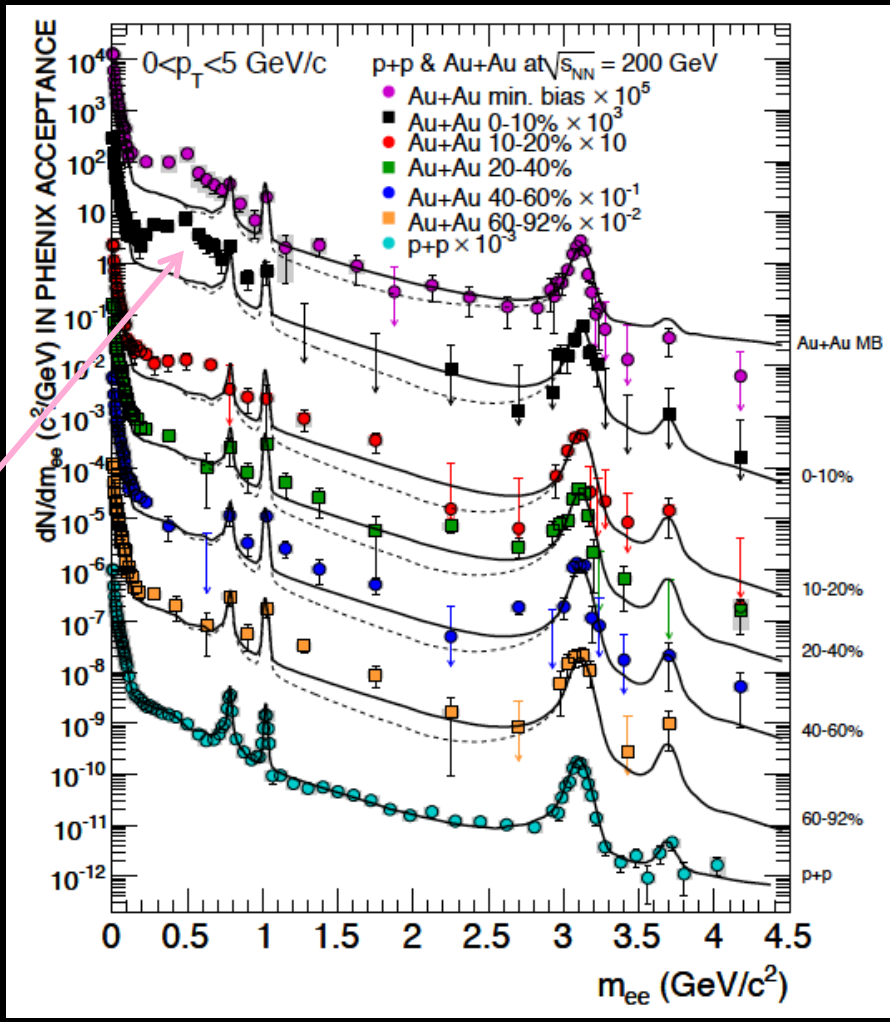
Centrality dependence:
PHENIX, PRC81, 034911(2010), arXiv:0912.0244

Virtual photons from decays in QGP

Must subtract all hadronic decays outside medium (scale pp data)

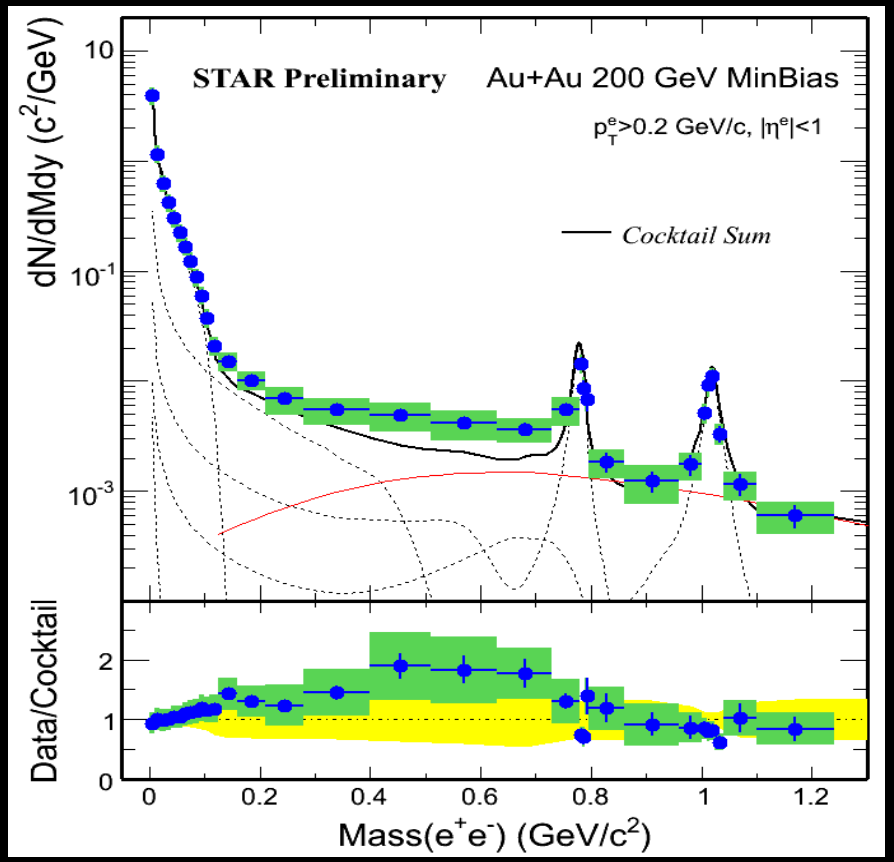
Low mass di-lepton Enhancement!

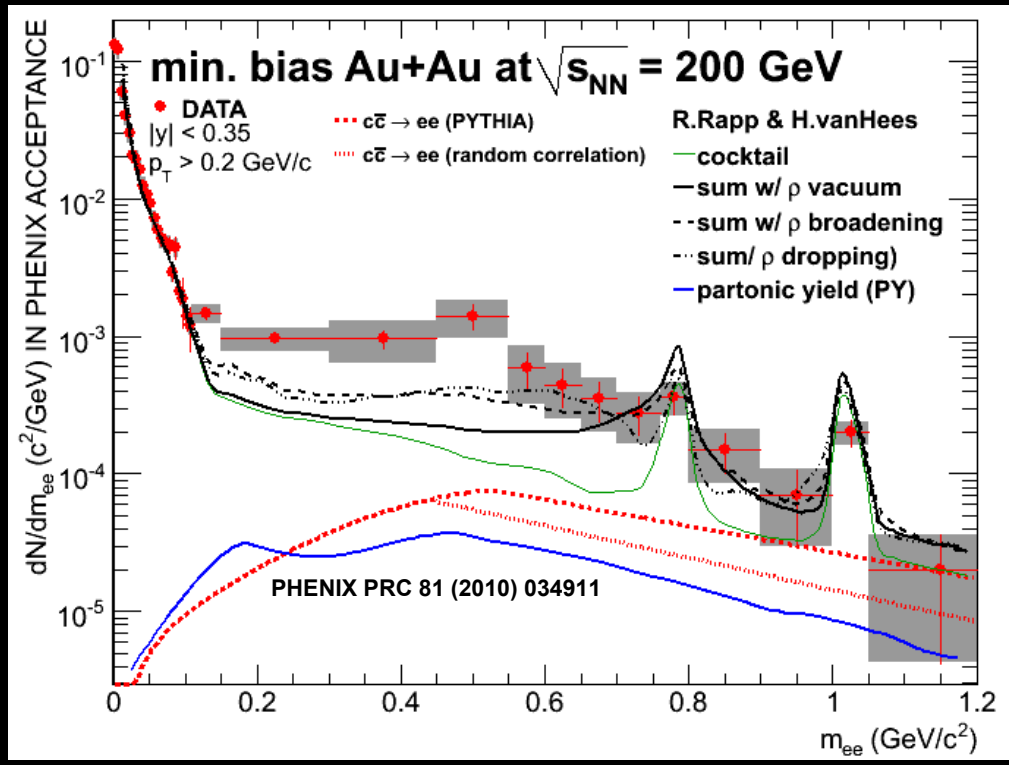
Increases with centrality.



Low Mass Di-Leptons at RHIC

In progress at LHC…?





Enhancement factor in 0.15<M_{ee}<0.75 Gev/c2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Note: Acceptance differences etc.

Disagreement & very difficult “task”!

Future LHC Heavy Ion Operating Schedule

Adapted from:
J.M. Jowett, Chamonix Meeting 2012

Year	Beams	Program
2013 2014	none	Long Shutdown 1
2015	Pb-Pb	Design luminosity ($\approx$250 μb^{-1})
2016	Pb-Pb	Design luminosity ($\approx$250 μb^{-1})
2017	Pb-Pb p-Pb	If int. lumi. still insufficient, else at highest possible energy
2018	none	Long Shutdown 2, ALICE upgrade installation, DS collimators to protect magnets
2019	Pb-Pb	Operation beyond design luminosity
2020-21	p-Pb Ar-Ar	If still priority, else intensity to be seen from injector commissioning for SPS fixed target
2022	none	Long Shutdown 3, stochastic cooling?
>2022	ions	Lumi. production, other ions (U?)

CMS Future with Heavy Ions

- 2011: PbPb (150 μb^{-1} at 2.76 TeV) on tape…
- 2012: pPb (30 nb^{-1} at 5 TeV) run to check for cold effects
- 2013: Long LHC shutdown/maintenance
  - CMS upgrades: 4 pixels, muon system, HF PMTs, CASTOR, trigger system will also benefit to heavy-ion program
- 2014–2018:
  - PbPb run at 5.5 TeV, higher luminosity
  - Another pA run with a corresponding (5.5 or 8.8 TeV?) higher energy and with higher luminosity
  - Run with smaller ion species at high luminosity at 5.5 TeV(?)
- After ~2018: depends on many new experimental and theoretical developments
- Aims: new probes (jets, Z, γ-jet…) and precision measurements of
  - Elliptic flow (viscosity), correlations, particle spectra, R_{AA}, jet quenching, jet fragmentation functions, γ-jet and Z-jet events, Υ family, J/Ψ, ultra-peripheral collisions and exotic phenomena…
- Higher luminosity is still desirable for most of the hard probes listed above

ALICE Upgrade Plans

2010 and 2011 Pb–Pb: $\int Ldt$ = 10 μb^{-1} and 100 μb^{-1}
2012 p-Pb
2015-2017: Pb–Pb runs at full energy few 100 μb^{-1} each → By 2017 ~ 1 nb^{-1}

Upgrade tracking to 50 kHz Pb-Pb collision rates → several nb^{-1} per run
(& 2 MHz proton-proton rate).

Improve vertex resolution

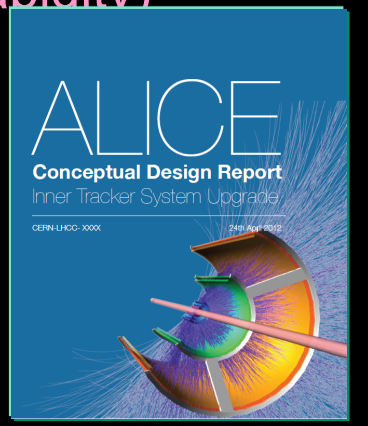
- New Inner Tracking System (ITS):
  - B/D separation, heavy baryons, low-mass di-electrons (mid-rapidity)
- New forward tracking:
  - b-tagging for low p_t J/ψ, low-mass di-muons (forward rapidity)

VHMPID: New Very High Momentum Particle ID

- Extend PID capabilities (mid-rapidity)

FOCAL: Forward calorimeter

- Low-x physics with identified γ/π^0



ALICE Upgrade Physics Focus

New physics explored (centrality, event plane, p_T, flavor dependence):

- Energy loss of partons in the QGP via γ-jet & jet-jet
- Dynamics & propagation of heavy quarks in the QGP

  Precision measurements of spectra, correlations and flow of hadrons with open charm and open beauty down to very low transverse momenta.
- Study of deconfined heavy quarks in the QGP: charmonium spectrum.
- Precision measurements: thermal photons & low-mass lepton pairs from QGP
- Search for (or stringent limits on) existence of exotic objects such as H dibaryon or Λ-neutron bound states

This requires high precision measurements and statistics

The upgrade strategy is based on the following expectations/assumption:

Accumulate 10 nb^{-1} in Pb-Pb collisions in the period 2019 – 2023.

ALICE will run at high rates: 50kHz Pb-Pb, 2MHz p-p & requires:

New Inner Tracking, major TPC mods, forward tracking, VHMPID, FOCAL

ATLAS Upgrade Plans*

Phase I (~ 2014)

Tracker upgrade – Insertable B-Layer

present tracker inner layer reaches rad limit after 1 year of design *L*

insertable inner layer with smaller radius beam pipe

Fast Track Trigger (proposal being developed)

add Level 1.5 tracking hardware trigger for B-tagging

Forward Physics Upgrade (proposal)

far forward – 420 and 220 m distance from IP

using 3D silicon sensors with < 10 ps timing

diffractive production of Higgs

forward physics

Phase II (~ 2019 to utilize sLHC L ~ 10^{35} cm^{-2} s^{-1})

Tracker upgrade – replace entire tracking system

very rad hard silicon pixel (3D?) upgrade

Trigger/DAQ upgrade – continuing upgrades to L1 & L2, introduce L1.5 triggers

sLHC goal at L1 – 100KHz rate (~400 interactions per crossing)

* http://www.slac.stanford.edu/exp/atlas/upgrade/

Improved Heavy Ion Capabilities from ATLAS Upgrades

Key improved measurements:

- γ + jet and Z + jet improved by trigger performance for photons

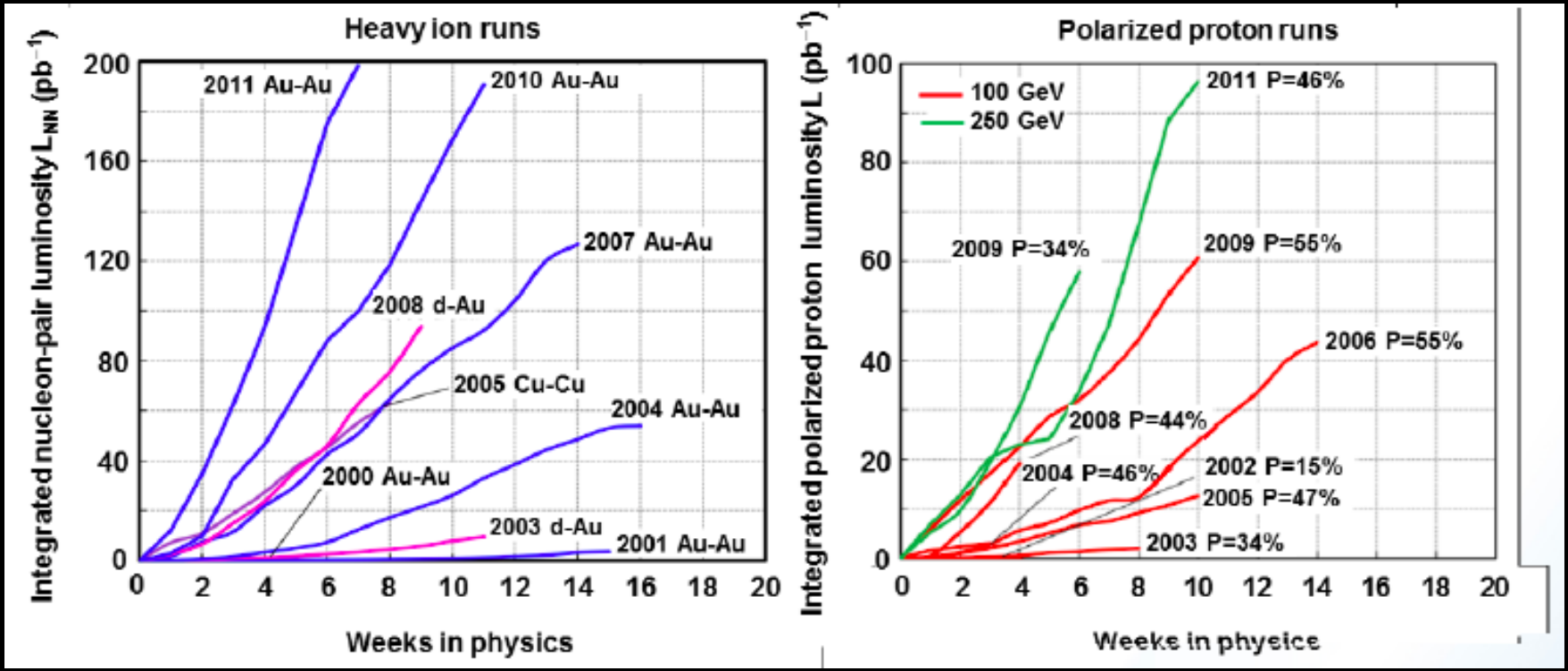
- Electrons (calorimeter triggering improvements) and muons (muon improvements).

- Heavy flavor and quarkonia triggering improved by fast track trigger and muon triggering.

- Dijets improved by the overall HLT efficiency upgrades.

These are all major priorities for the ATLAS HI program now & in the future. Photons and Z's are especially rate limited and will only become precision tools with large increases of statistics.

RHIC's Versatility & Future Plans



- 2013-2018 – RHIC research
  - Exploit RHIC's unique machine capabilities (above, critical point energy scan with Au+Au down to 7 GeV, U+U & Cu+Au this yr) & physics
  - Exploit recent and ongoing upgrades (PHENIX VTX, STAR HFT, …)
  - Continue proton-proton and deuteron-ion collisions aimed at the cold QCD matter studies.

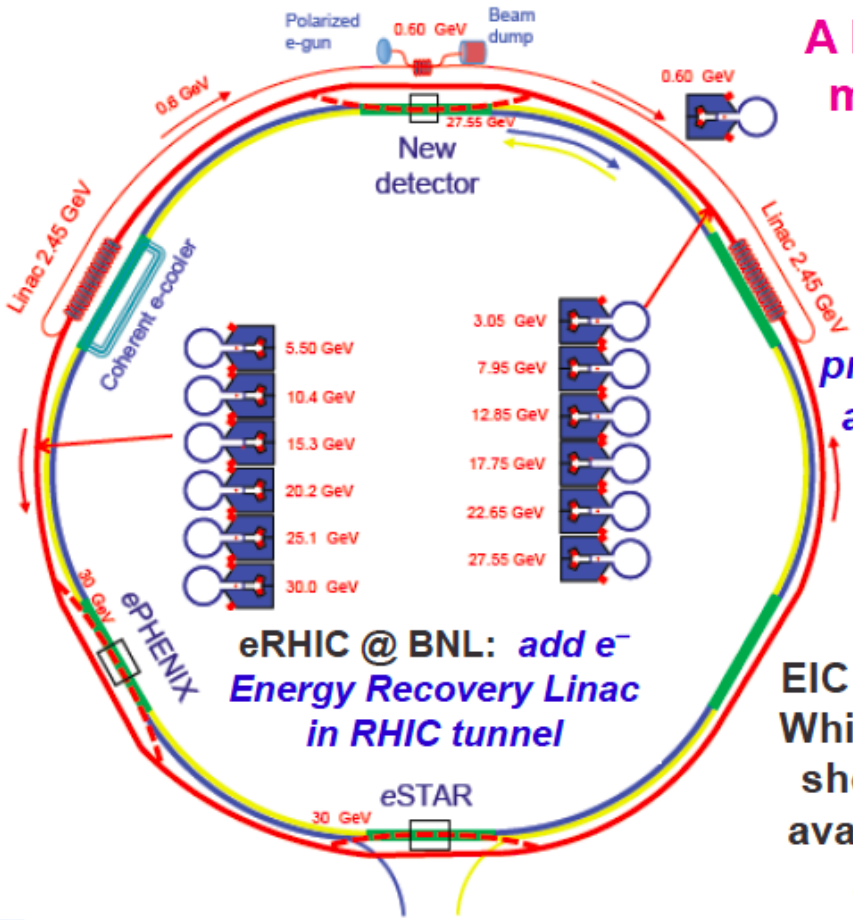
Compelling RHIC Physics Questions

- How does strongly coupled liquid behavior arise from an asymptotically free theory?
- How close is η/s to the AdS/CFT bound (limit of strong coupling)?
  - How does it vary from lower temperatures to well above Tc?
- What are the values of the transport coefficients (v_s, momentum diffusion length, relaxation time, …) in the QGP as a function of T?
  - How do they compare to expectations from lattice QCD?
- How does QGP matter respond to energy deposition from traversing partons?
  - Can we learn about the transition from weak to strong coupling by studying jet quenching and QGP response as a function of jet and collision energy?
- How does the matter thermalize so rapidly?
  - How is the rapid thermalization influenced by details of the gluon-dominated initial state in the collisions?
- To what extent do heavy (c and b) quarks participate in the thermalization, the collective flow & the energy loss phenomena established thus far for light quarks?

Not so different from LHC, except different regimes of T, virtuality and p_T!

RHIC Future Plans

Beyond 2018 at RHIC → Upgrade PHENIX & STAR detectors → Electron-Ion Collider



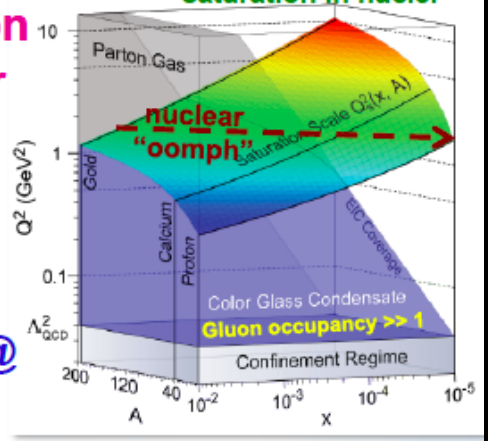
eRHIC @ BNL: *add e⁻ Energy Recovery Linac in RHIC tunnel*

Design allows easy staging of machine in energy. Technical & cost reviews in 2011-12.

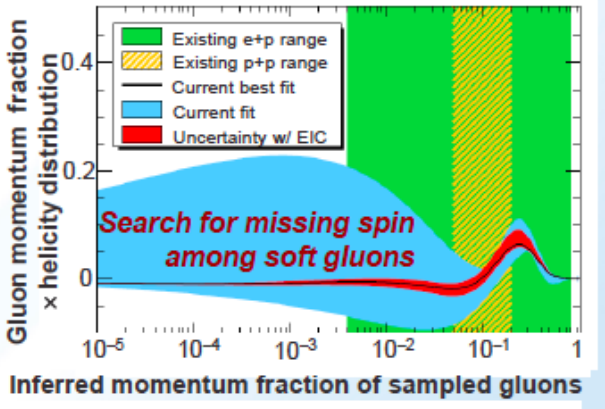
A high-resolution microscope for cold gluon-dominated matter:

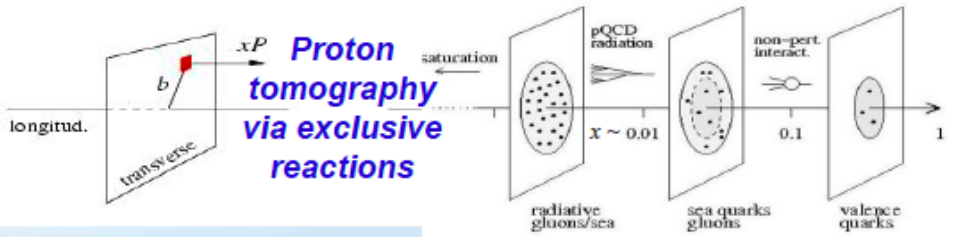
2010 INT program report @ arXiv:1108.1713

Probe onset of gluon saturation in nuclei



EIC Science White Paper should be available in 2012



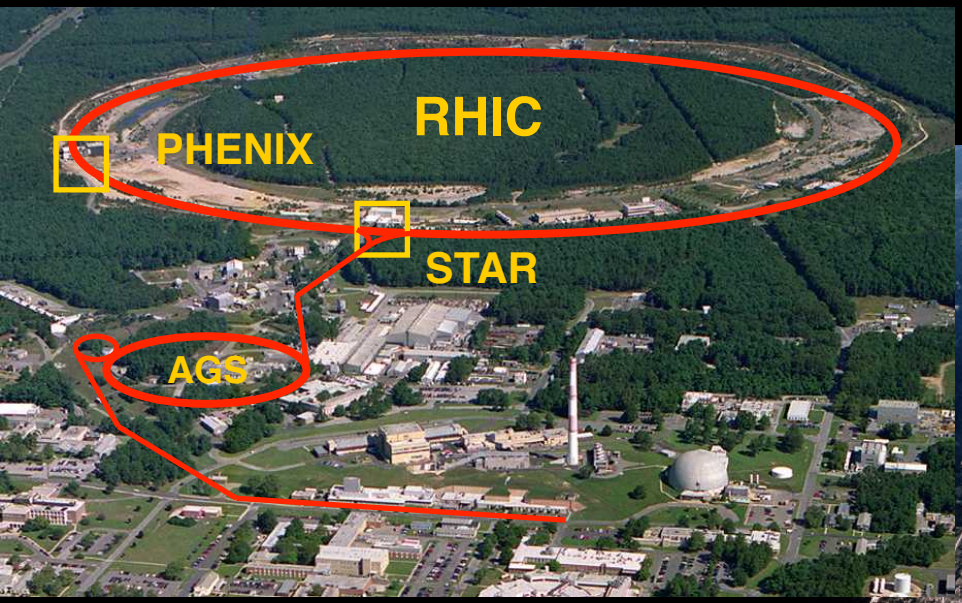


Brookhaven Science Associates

What Are the Remaining Exciting Questions for the Field at RHIC & LHC?

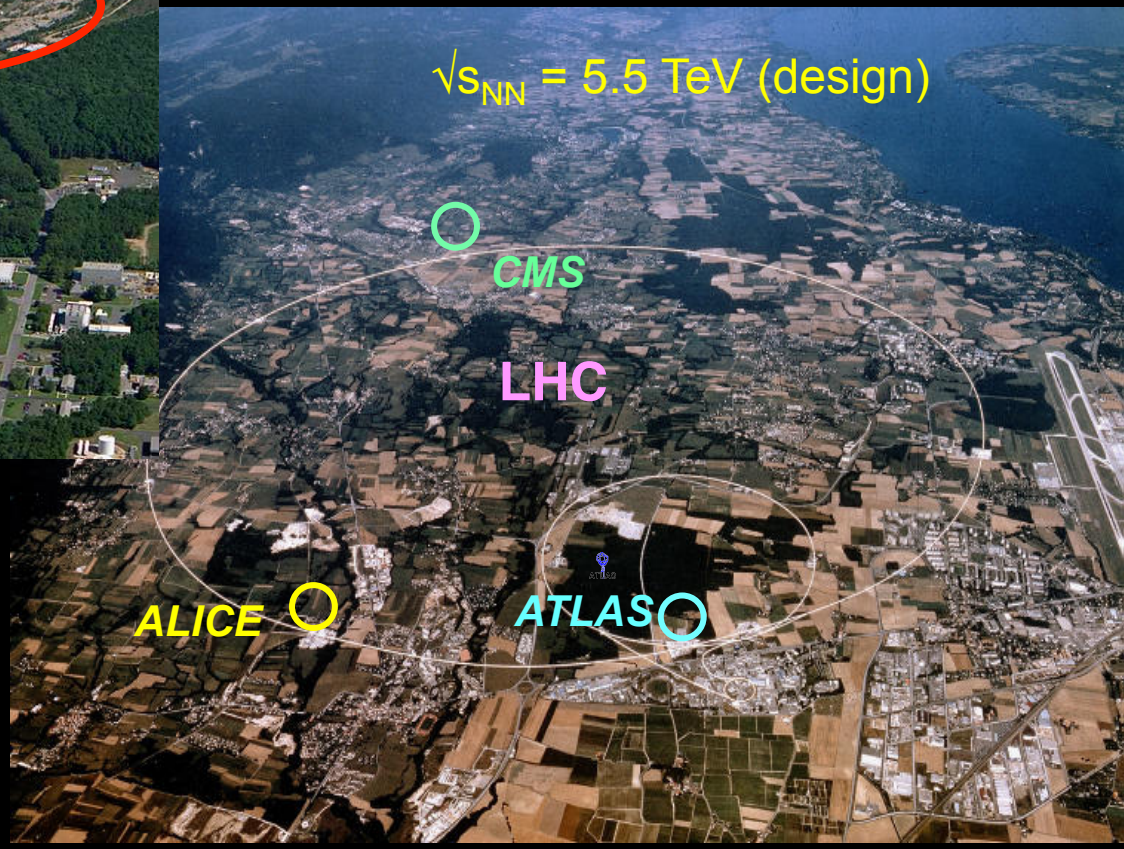
- How does the system evolve and thermalize from its initial state?
  What is the initial state (Color-Glass Condensate?)→ pPb run in November 2012
- What are the properties & constituents (vs. T) of the QGP?
- Can we understand parton propagation & energy loss at a fundamental level?
  What can we learn about the response of the QGP?
  How does hadronization take place as the parton propagates?
- Can we understand quarkonium melting (suppression) at the basic level?
  What does it tell us? Is the melting vs T consistent with LQCD?
- Is the QCD Phase Diagram featureless above Tc?
  What is the coupling strength vs T….
- Are there new phenomena? Can we say something about χ-symmetry restoration?....
- Can there be new developments in theory (lattice, hydro, parton E-loss, string theory…) and understanding……across fields……?

Future Perspectives for Heavy Ions with RHIC & LHC



$\sqrt{s_{NN}}$ = 5 - 200 GeV

Cover 3 decades of energy in center-of-mass



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

Thanks for contributions &

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Miklos Gyulassy

Jamie Nagle

Berndt Mueller

Raphael Granier de Cassagnac

Peter Steinberg

Steve Vigdor