Relativistic Heavy Ion Overview

NSAC Sub-committee presentation

W.A. Zajc
Columbia University

Questions Addressed by Relativistic Heavy Ion Physics

- Overarching questions:
  - Are there new states of matter at extremely high temperature and density?
  - Can we explore the phase structure of a fundamental gauge theory via nuclear collisions?
  - Can the study of strongly-coupled QCD matter inform our understanding of other gauge theories (including gravity)?

(See back-up material for compendium)

Questions Addressed by Relativistic Heavy Ion Physics

- Discovery oriented questions:
  - Is there a critical point in the QCD phase diagram?
  - Are exotic (locally CP-violating) states of matter formed in nuclear collisions?
  - At what (energy, mass, length) scale does the perfect liquid become resolvable into the underlying quarks and gluons?

(See back-up material for compendium)

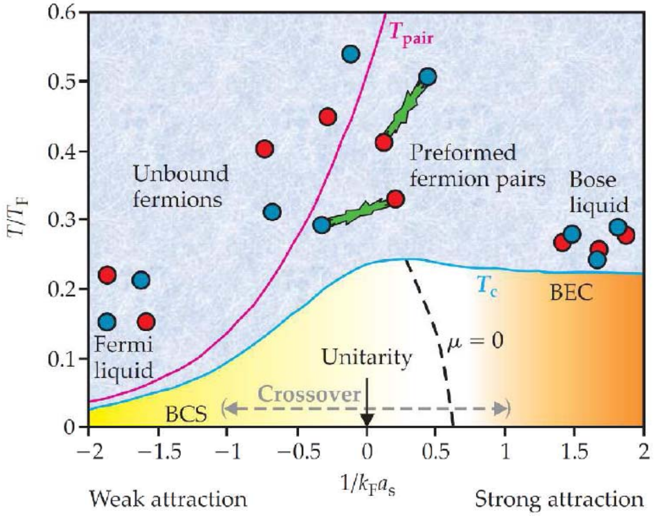
Questions Addressed by Relativistic Heavy Ion Physics

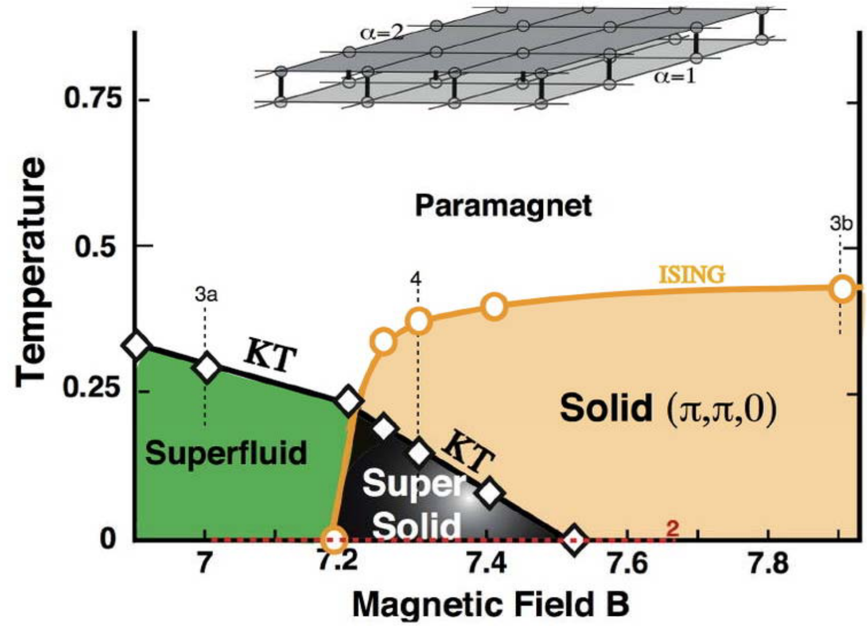
- Precision directed questions:
  - What is the value of η/s and does it respect the conjectured quantum bound?
  - What is the numerical value (and energy dependence) of the coupling constant in the quark-gluon plasma at RHIC and LHC energies?
  - What is the value of the jet energy loss parameter, and is it consistent with purely perturbative calculations?
  - What are the magnitudes of cold nuclear matter (CNM) effects as a function of probe, root-s, and momentum, and how do these impact precision measurements in hot nuclear matter?

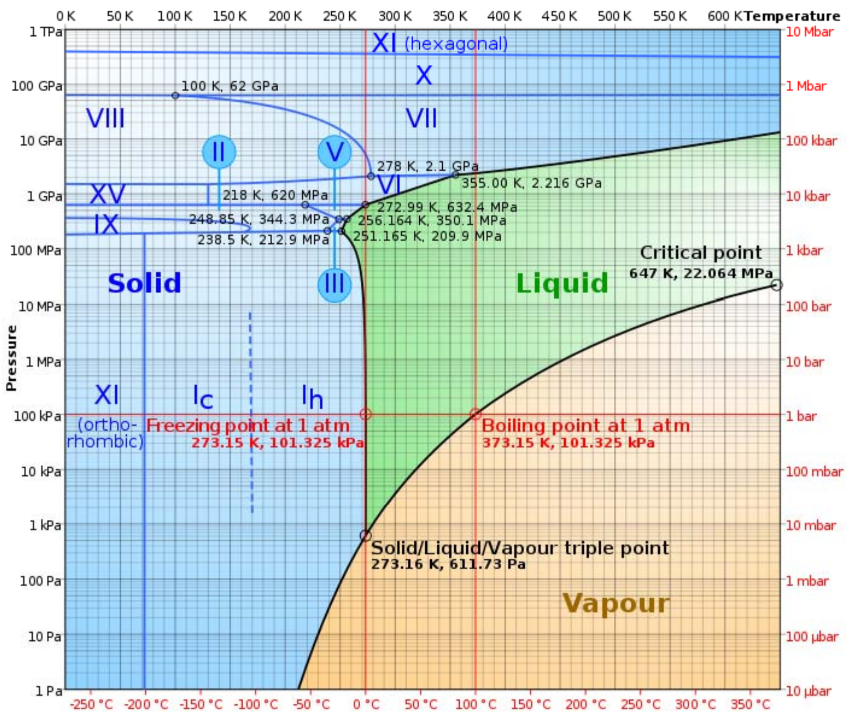
(See back-up material for compendium)

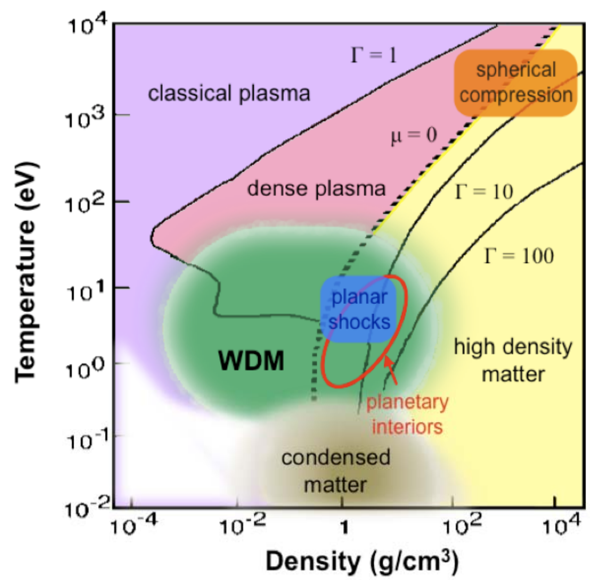
Exploring the Phase Structure of Fundamental Theories

Structure of Matter via Phase Diagrams





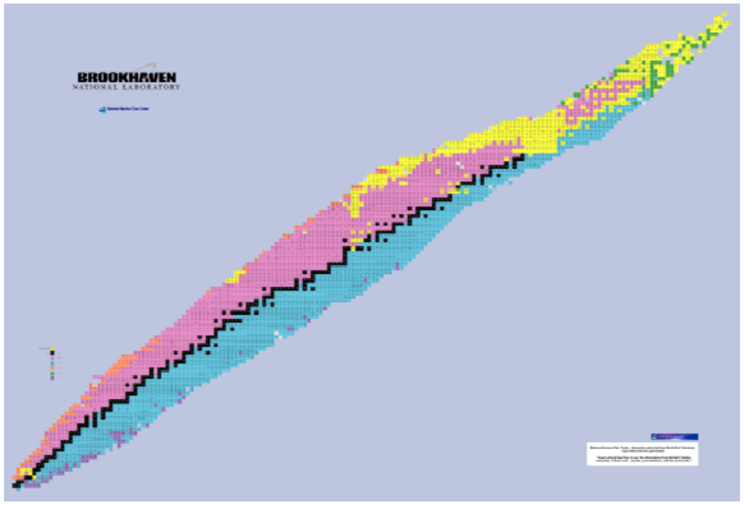




QED

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m_e)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$D_{\mu} = \partial_{\mu} + ieA_{\mu}$$

$\otimes$



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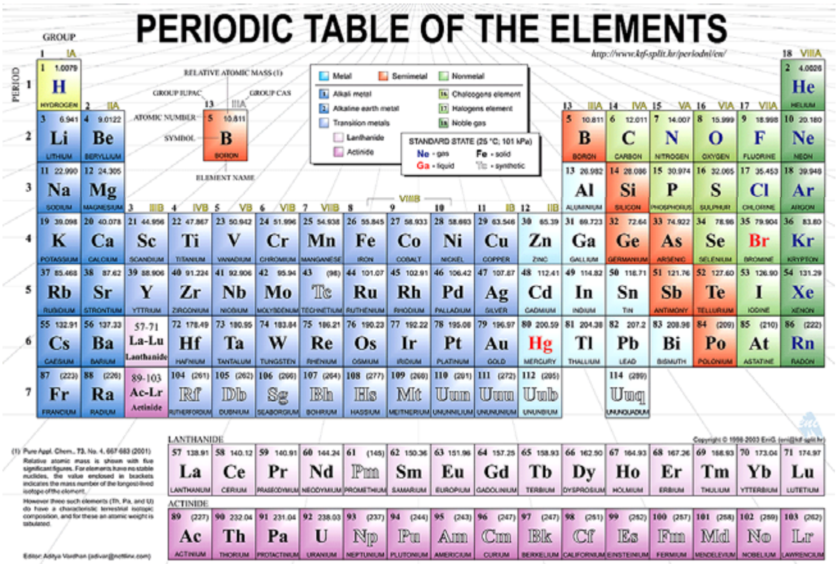

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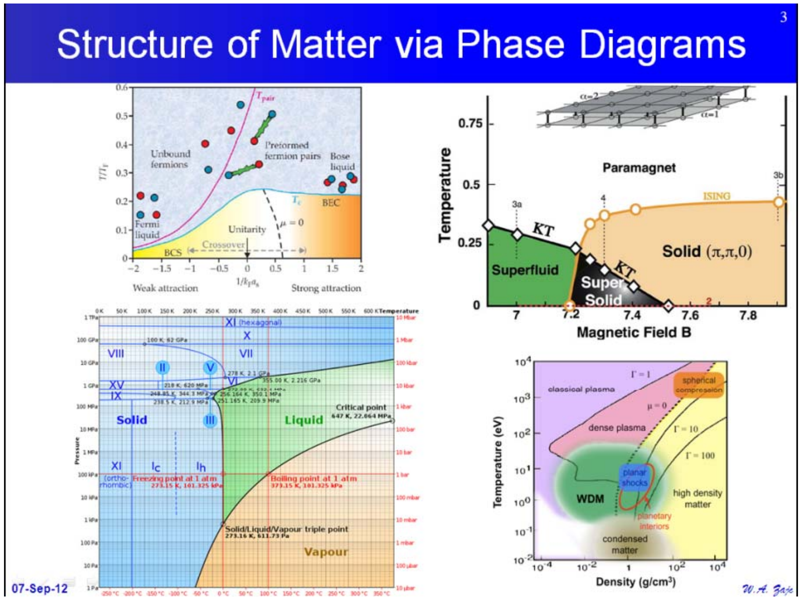
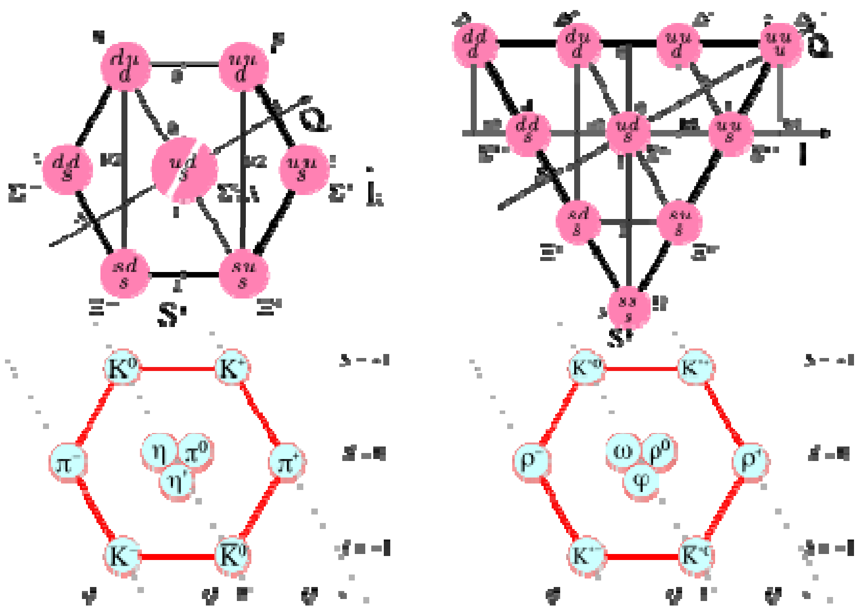


QCD

$$\boxed{\begin{aligned}\mathcal{L}_{QCD} &= \bar{\psi}(i\gamma^\mu D_\mu - \tilde{m})\psi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \\ D_\mu &= \partial_\mu + igT_aG^a_\mu\end{aligned}} \otimes \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_u & 0 \\ 0 & 0 & m_s \end{pmatrix} =$$



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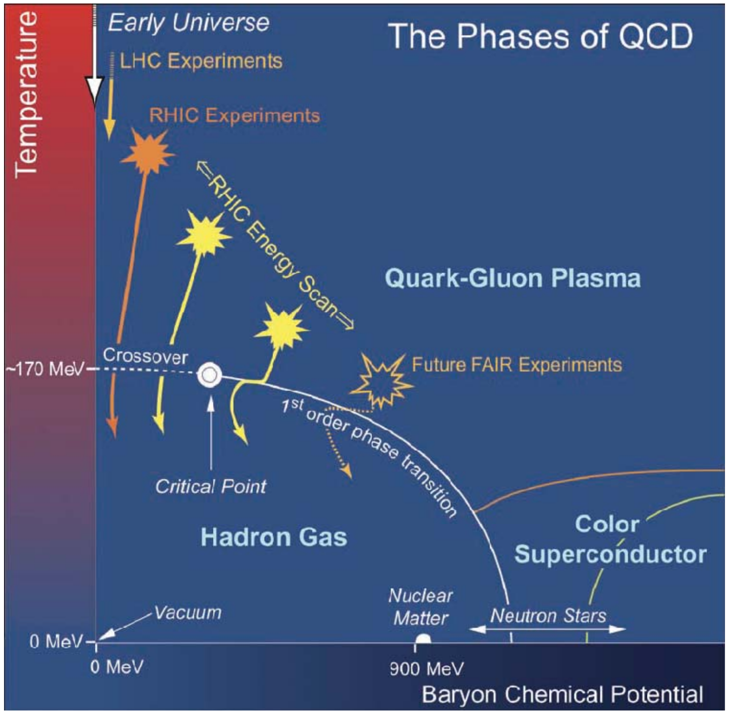
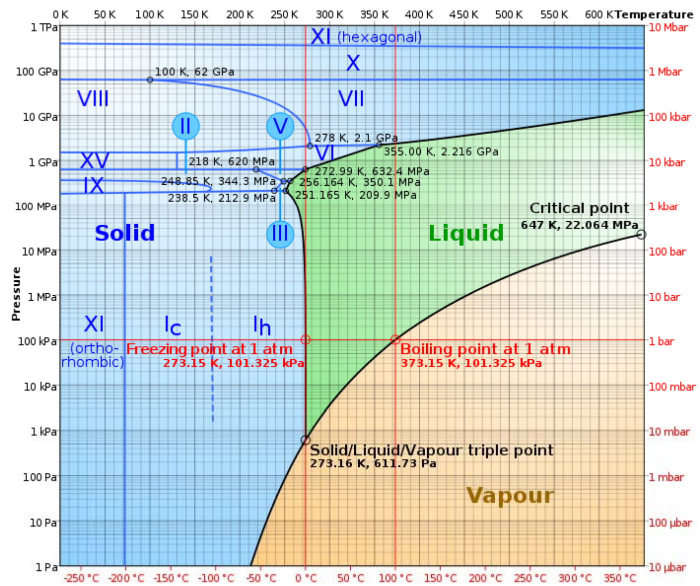


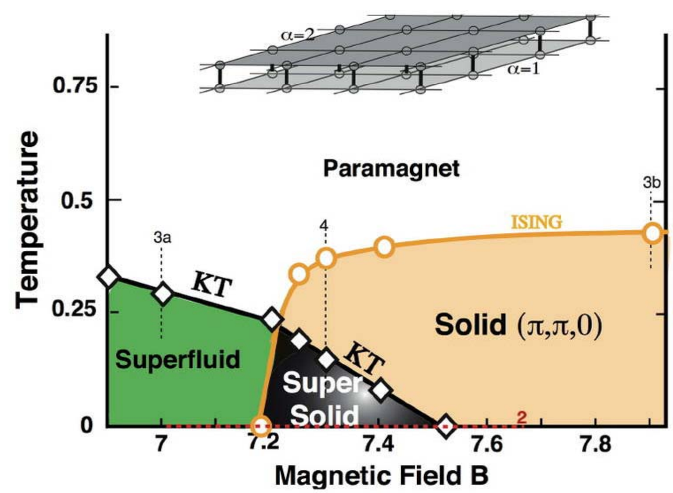
On the Meaning of *Fundamental*

- In principle, these diagrams are also "fundamental", in that they result from

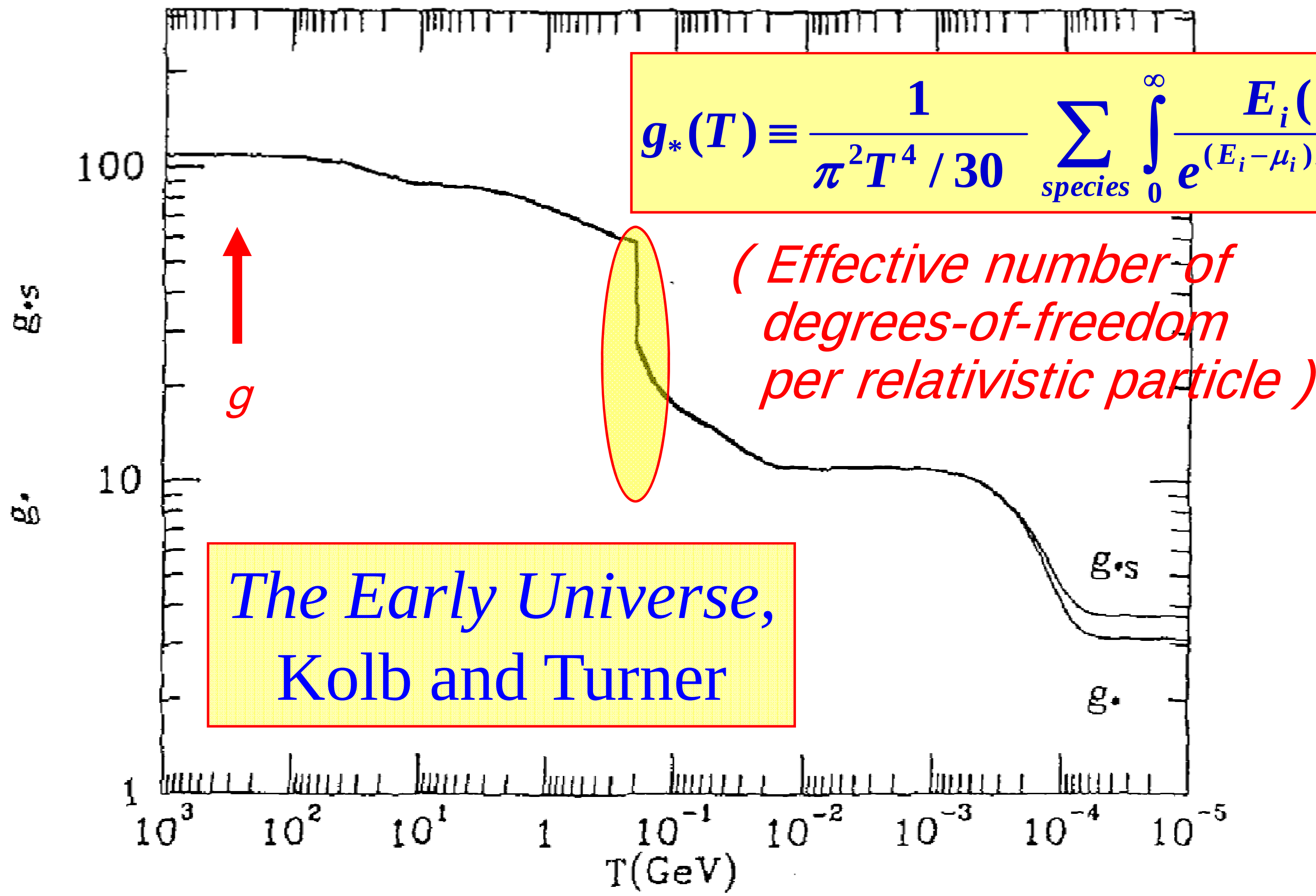
$$\boxed{\begin{aligned} \mathcal{L}_{QED} &= \bar{\psi}(i\gamma^\mu D_\mu - m_e)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ D_\mu &= \partial_\mu + ieA_\mu \end{aligned}}$$



- But in practice, they are (deeply) emergent, and depend on:
  - $m_p/m_e = 1836.15$
  - $Z(^{12}C) = 6$
  - $Z(^{16}O) = 8$
  - ….



“Natural” Appearance of the QCD Phase Transition



$$g_*(T) \equiv \frac{1}{\pi^2 T^4/30} \sum_{species} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3p}{(2\pi)^3}$$

Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

The Experimental Tools

Two Facilities

RHIC

- First collisions 2000
- p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U
- $\sqrt{s_{NN}}$ ~ 7 – 200 GeV
- Polarized protons

LHC

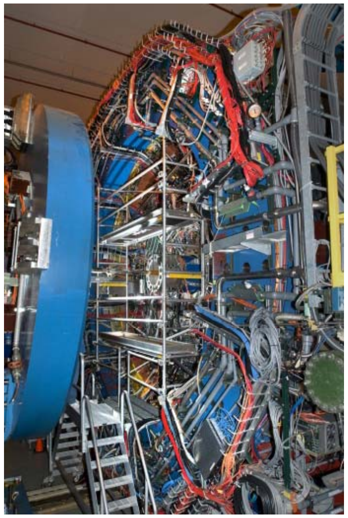
- First collisions 2010
- p+p, Pb+Pb (p+Pb in 2013)
- $\sqrt{s_{NN}}$ =2.76 TeV (5.5 TeV in 2015-16)

Five Experiments

RHIC

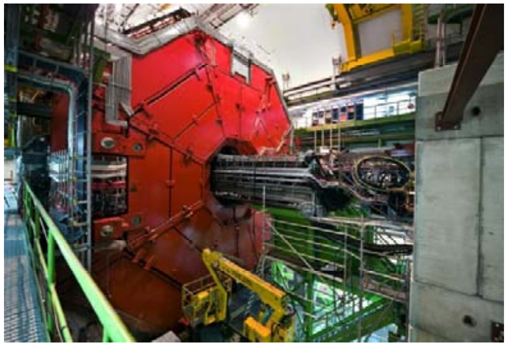
- PHENIX

- STAR

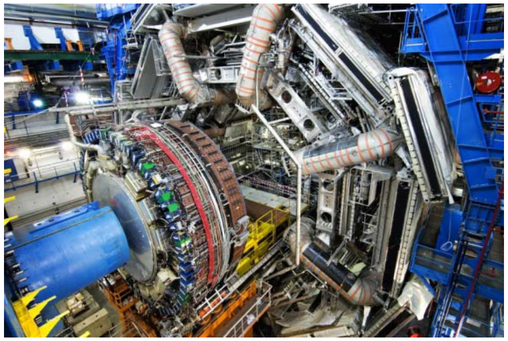


LHC

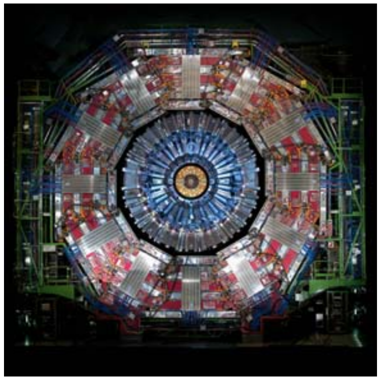
- ALICE



- ATLAS



- CMS



2007 Long Range Plan Recommendations

phenomenological modeling, and new initiatives. Strategic investments in LHC detector instrumentation and computing, which leverage the capabilities of the existing LHC detectors, are required for significant and timely U.S. participation in the LHC heavy-ion program. Collectively, these investments will result in a dramatic advance in our understanding through quantitative comparison of theory and experiment. The synergies of RHIC and the LHC will lead to a much deeper understanding of the properties and dynamics of dense QCD matter.

UNDERWAY!

2007 Long Range Plan Recommendations

RECOMMENDATION IV

The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

support. Detector upgrades at RHIC, which are part of Recommendation IV, will proceed over several years, and the accelerator modifications needed to implement beam cooling, which will significantly increase the RHIC luminosity, will be carried out between 2012 and 2015. Following this course, nuclear science in the United States will continue to have world-leading facilities into the future.

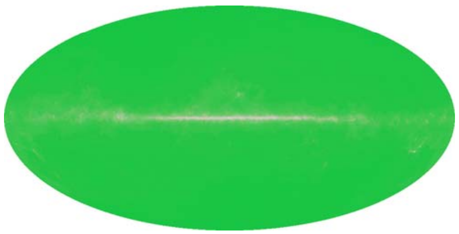
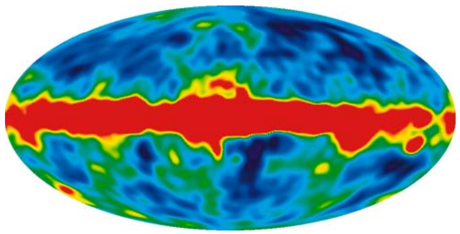
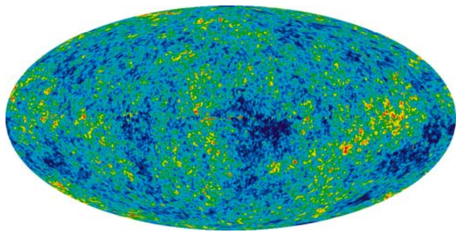
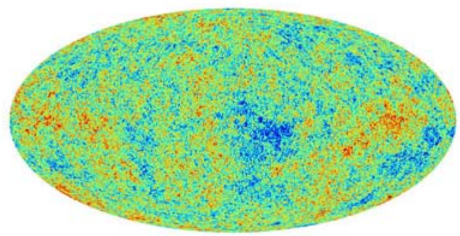
DONE!

Next Several Slides:

Discussion of the discovery of the “perfect liquid” and precision measurements of its (near)-perfection

A (Valid) Analogy

Penzias/Wilson 1965 | COBE 2003 | WMAP 2007 | Planck 2012

D I S C O V E R Y.....

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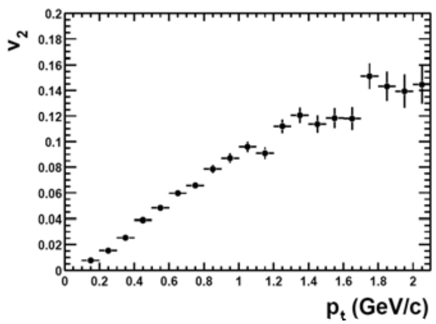
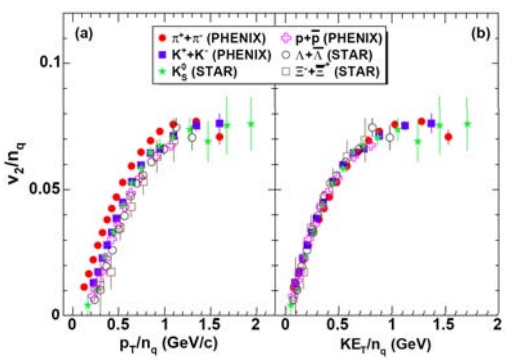
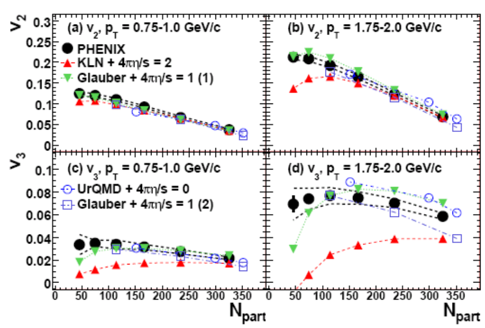
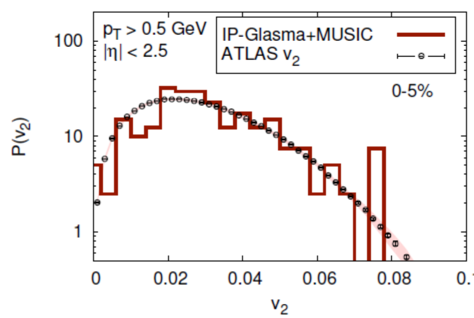








2001 | 2004 | 2008 | 2012

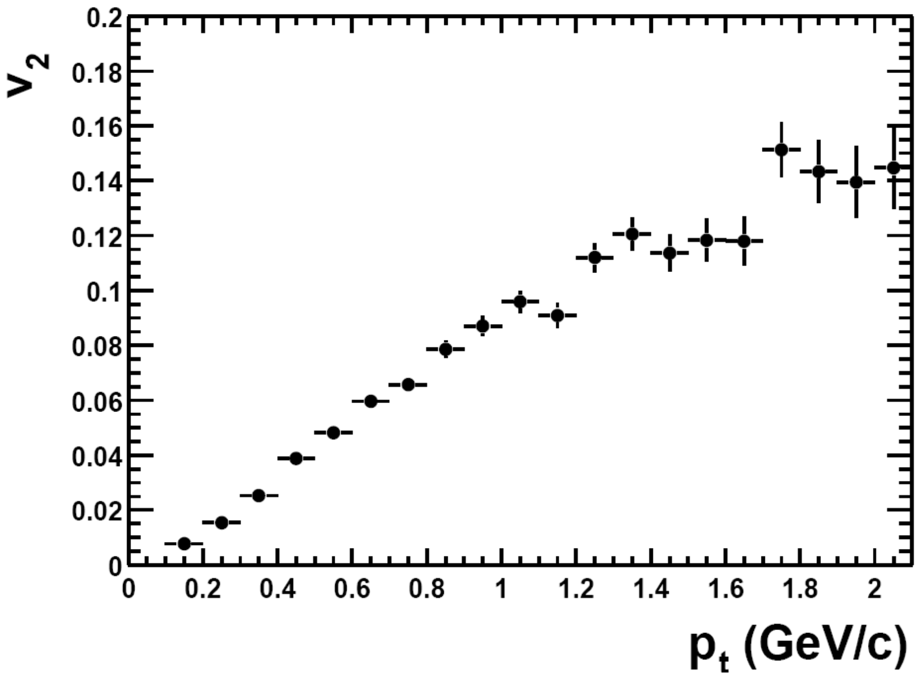
2007 Long Range Plan Highlights

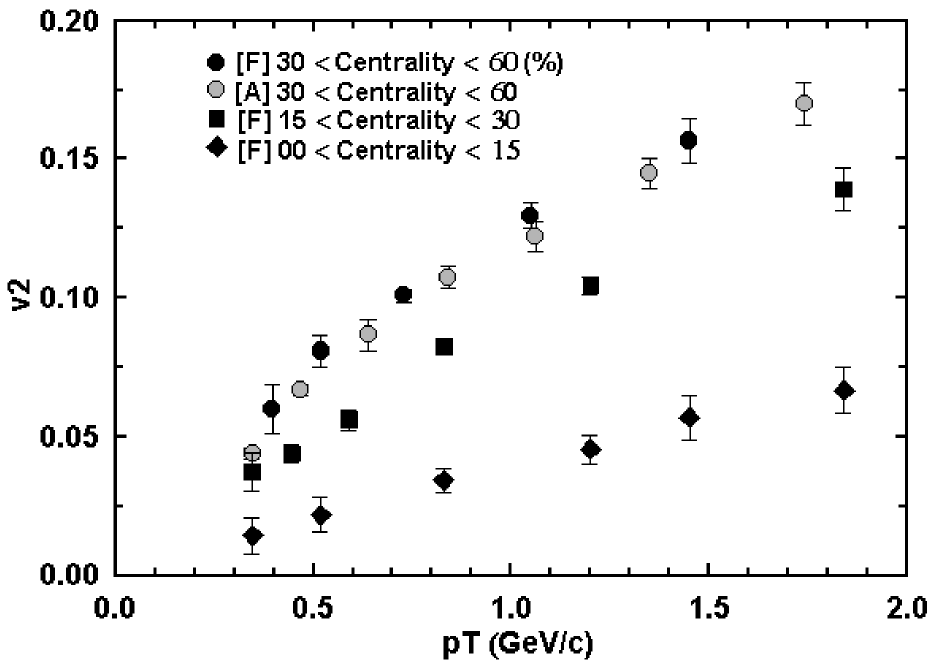
Near-Perfect Liquid

In one of the most surprising discoveries of the past few years, the hot matter that is formed when gold nuclei accelerated by the Relativistic Heavy Ion Collider (RHIC) collide seems to expand like an almost perfect liquid. A quantity used to characterize the resistance of liquids to flow—the ratio of the viscosity to entropy density—is smaller than for any other known liquid. It is so small, in fact, that it appears to be very close to a lower limit recently derived from the techniques of string theory, indicating that the quark-gluon plasma formed in the collisions at RHIC is a strongly coupled plasma and not a dilute gaseous plasma as originally expected. This finding opens a completely new area of physics—the study of extremely high-energy high-density plasmas whose microscopic and collective properties are dominated by quantum phenomena. One of the most important scientific challenges for the next decade is a quantitative exploration of this new state of matter.

Discovery - 2001

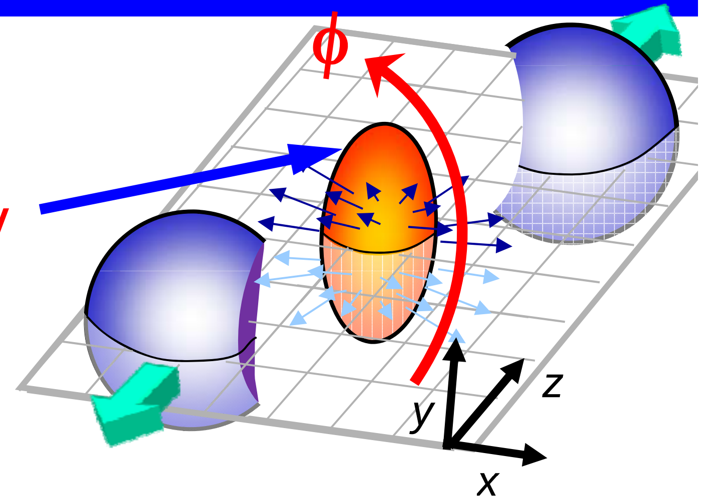
- Strong "elliptic flow" in $\sqrt{s_{NN}}$ = 130 Au+Au collisions:

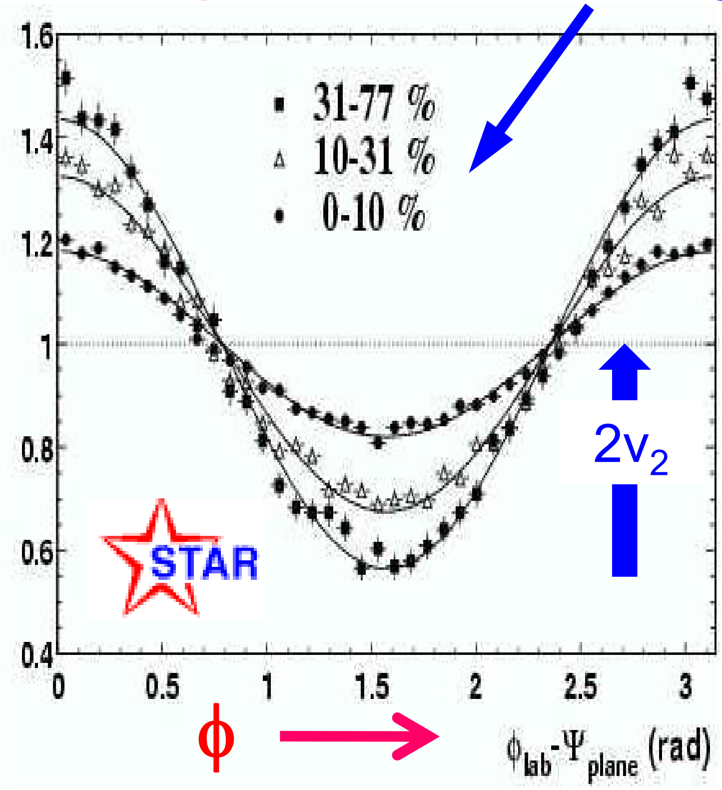


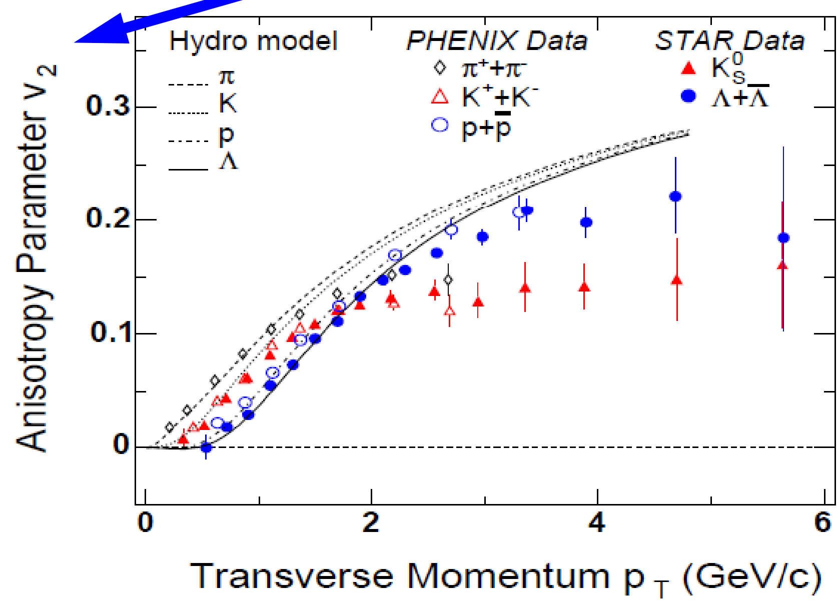


An Aside on Nomenclature

- RHIC discovery
  - The initial state azimuthal asymmetry
  - produces a ***strong*** signal in the final state particle emission pattern $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

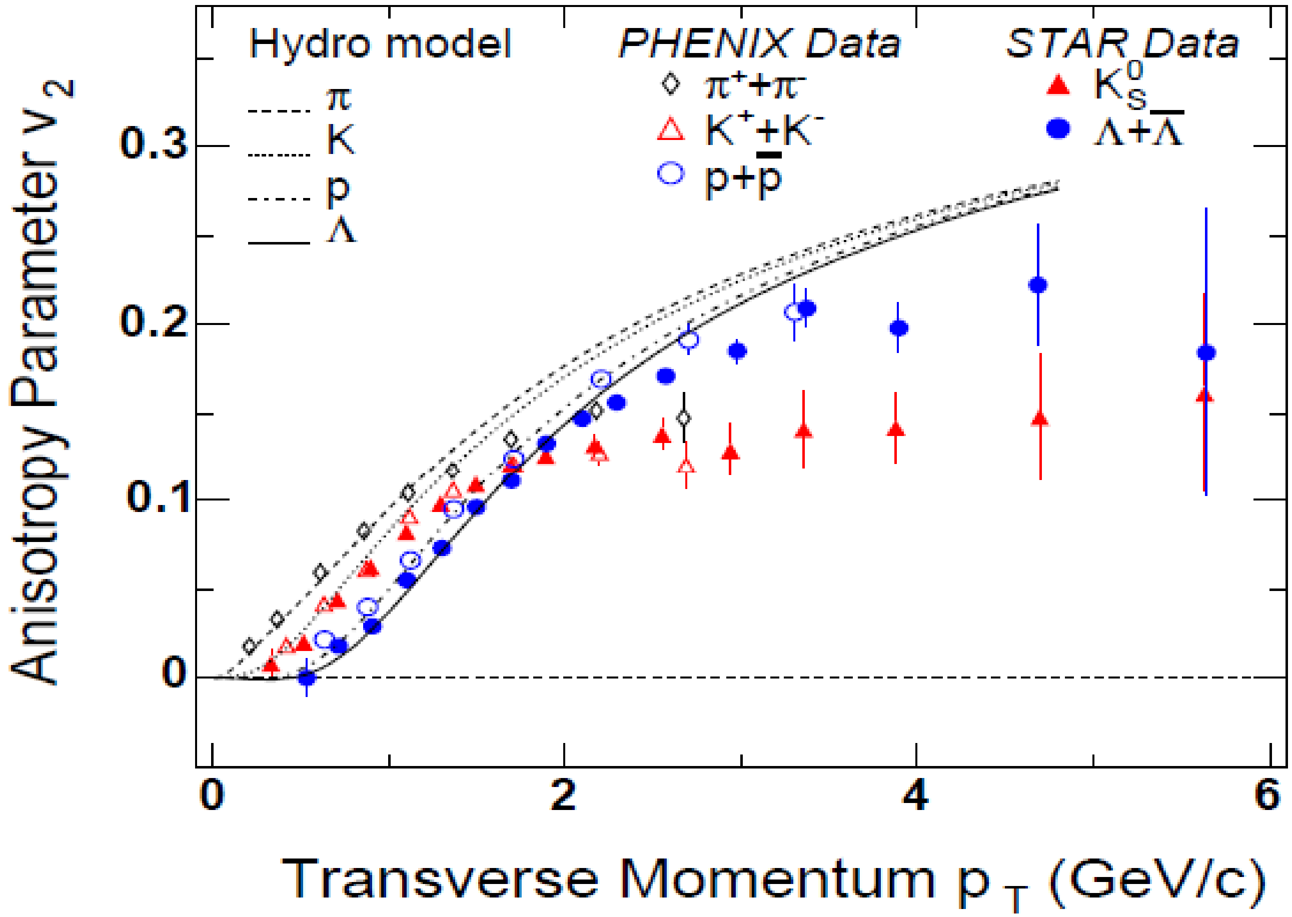






Theory State of the Art 2003-4

- Reasonable agreement using *ideal* hydrodynamics



arxiv.org/abs/nucl-th/0306046

Simultaneously in 2003-4

- An ~~estimate~~ (bound?) on visocity appeared from string theory's AdS/CFT correspondence:
  - *A Viscosity Bound Conjecture*,
  P. Kovtun, D.T. Son, A.O. Starinets,
  hep-th/0405231

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

$\Longrightarrow$ Very important to quantify *departures* from ideal hydrodynamics

2004-8: Grappling With Non-Ideal Hydrodynamics

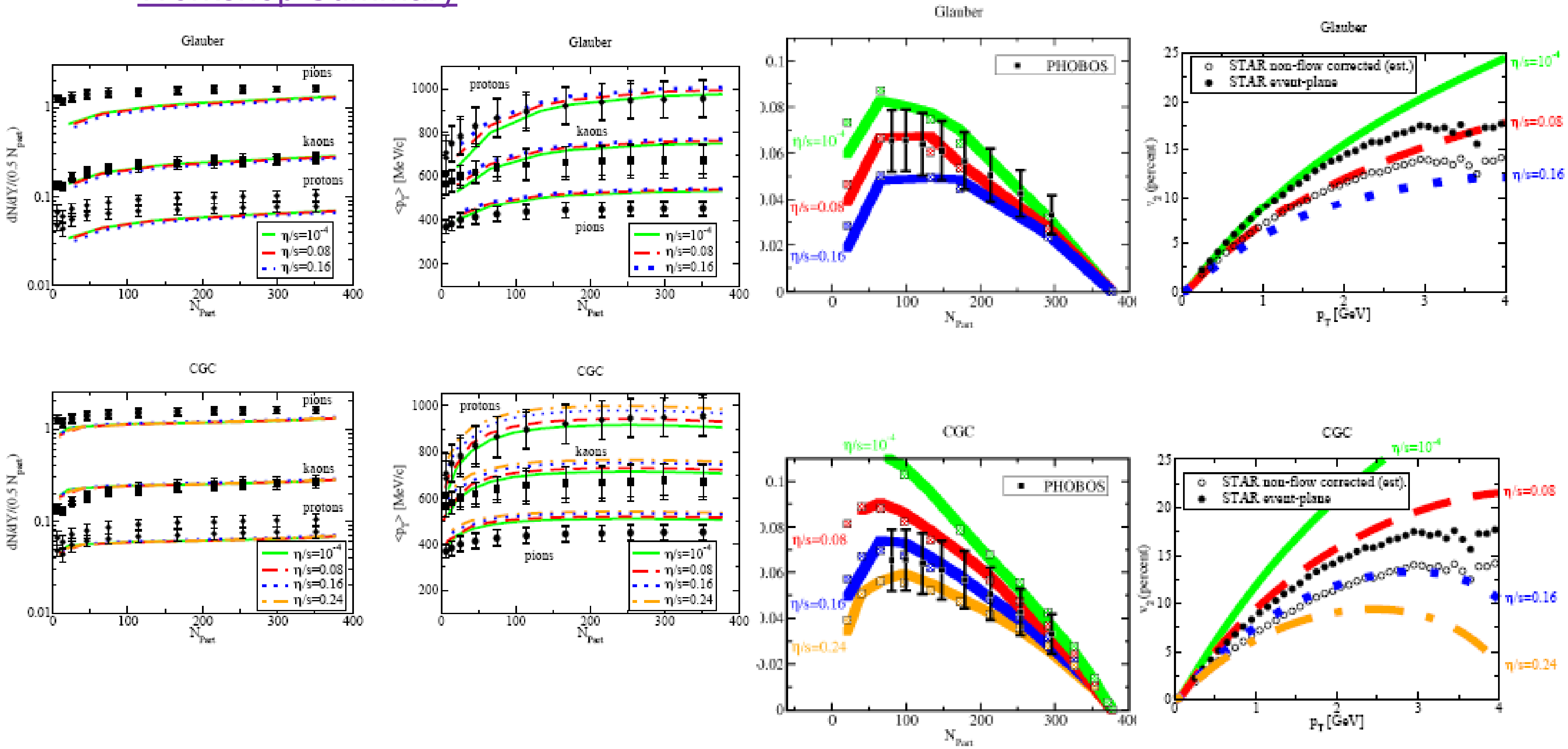
- Seemingly insurmountable:

$$
\begin{aligned}
\tau_\Pi \dot{\Pi} + \Pi &= \Pi_{\rm NS} + \tau_{\Pi q}\, q\cdot\dot{u} - \ell_{\Pi q}\,\partial\cdot q - \zeta\,\hat{\delta}_{0,1}\,\Pi\,\theta \\
&+ \lambda_{\Pi q}\, q\cdot\nabla\alpha + \lambda_{\Pi\pi}\,\pi^{\mu\nu}\sigma_{\mu\nu} + \hat{\delta}_{0,2}\,\Pi^2 + \hat{\epsilon}_0\, q\cdot q + \hat{\eta}_0\,\pi^{\mu\nu}\pi_{\mu\nu} \\
\tau_q\,\Delta^{\mu\nu}\dot{q}_\nu + q^\mu &= q^\mu_{\rm NS} - \tau_{q\Pi}\,\Pi\,\dot{u}^\mu - \tau_{q\pi}\,\pi^{\mu\nu}\,\dot{u}_\nu \\
&+ \ell_{q\Pi}\,\nabla^\mu\Pi - \ell_{q\pi}\,\Delta^{\mu\nu}\,\partial^\lambda\pi_{\nu\lambda} + \tau_q\,\omega^{\mu\nu}\,q_\nu - \frac{\kappa}{\beta}\,\hat{\delta}_{1,1}\,q^\mu\,\theta \\
&- \lambda_{qq}\,\sigma^{\mu\nu}\,q_\nu + \lambda_{q\Pi}\,\Pi\,\nabla^\mu\alpha + \lambda_{q\pi}\,\pi^{\mu\nu}\,\nabla_\nu\alpha \\
&+ \hat{\delta}_{1,2}\,\Pi\,q^\mu + \hat{\eta}_1\,\pi^{\mu\nu}\,q_\nu \\
\tau_\pi\,\dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} &= \pi^{\mu\nu}_{\rm NS} + 2\,\tau_{\pi q}\,q^{<\mu}\dot{u}^{\nu>} \\
&+ 2\,\ell_{\pi q}\,\nabla^{<\mu}q^{\nu>} + 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\omega^{\nu>\lambda} - 2\,\eta\,\hat{\delta}_{2,1}\,\pi^{\mu\nu}\,\theta \\
&- 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\sigma^{\nu>\lambda} - 2\,\lambda_{\pi q}\,q^{<\mu}\nabla^{\nu>}\alpha + 2\,\lambda_{\pi\Pi}\,\Pi\,\sigma^{\mu\nu} \\
&+ \hat{\delta}_{2,2}\,\Pi\,\pi^{\mu\nu} - \hat{\eta}_2\,\pi_\lambda{}^{<\mu}\pi^{\nu>\lambda} - \hat{\epsilon}_2\,q^{<\mu}q^{\nu>}
\end{aligned}
$$

  - Unknown Initial Conditions
  - Eccentricity fluctuations
  - Unknown equation of state
  - Instabilities, acausal effects in relativistic viscous hydrodynamics
  - Hadronic rescattering effects
  - Bulk viscosity
  - Numerical viscosity
  - Finite size, core/corona effects

2008: Concordance

- BNL, April 2008:
  - *Workshop on Viscous Hydrodynamics and Transport Models in Heavy Ion Collisions*
  - Workshop Summary



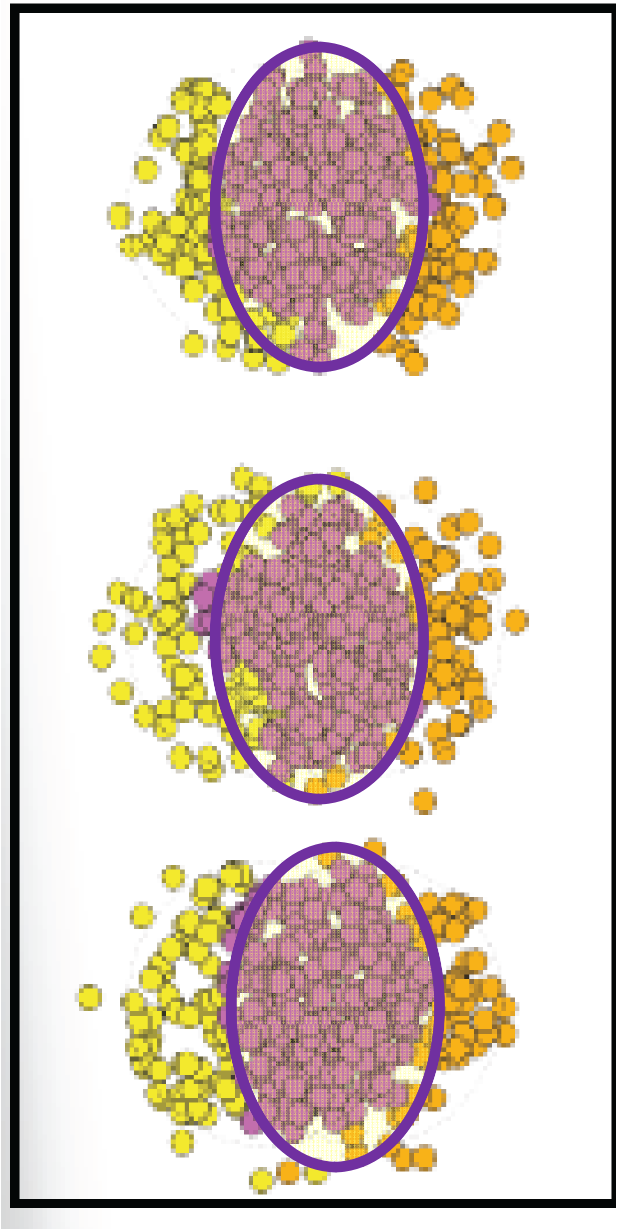
M. Luzum and P. Romatschke Phys.Rev.C78:034915,2008.

2008-10: The Important Role of Fluctuations

- B. Alver and G. Roland,
  Phys. Rev. C81, 054905 (2010)

- Importance of higher harmonics

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



2008-10: The Important Role of Fluctuations

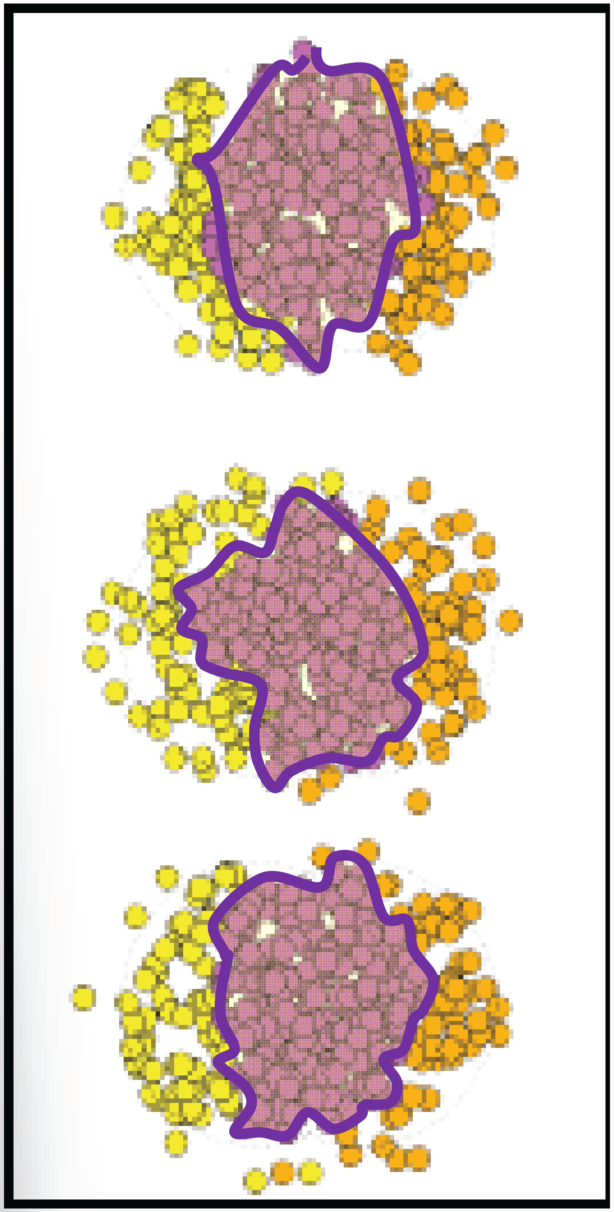
- B. Alver and G. Roland,
  Phys. Rev. C81, 054905 (2010)

- Importance of higher harmonics

☞Persistence of "bumps" ➔ small η/s !

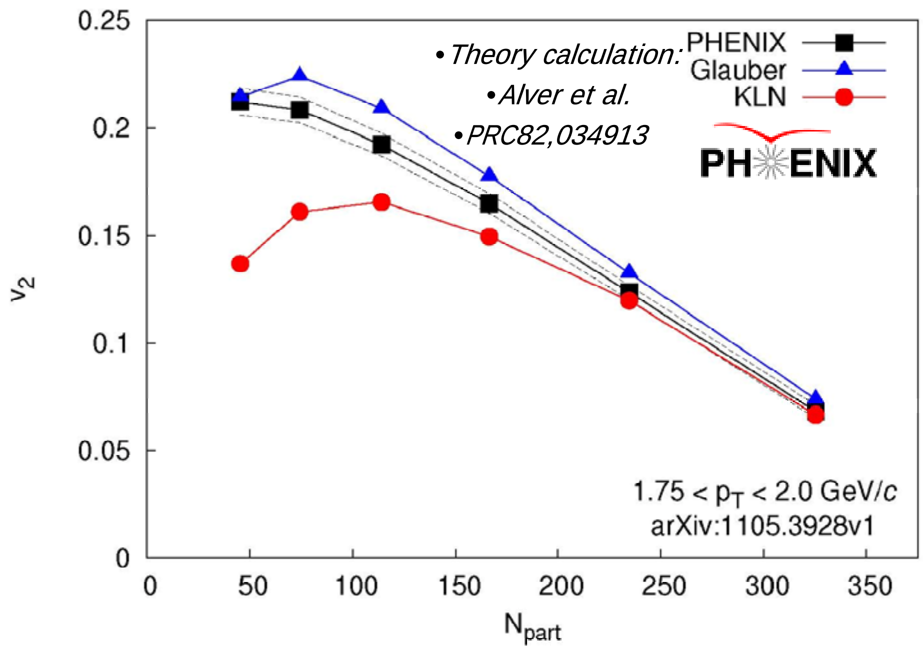
- $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$
  $+ 2\, v_3(p_T) \cos(3\phi)$
  $+ 2\, v_4(p_T) \cos(4\phi) + \ldots$

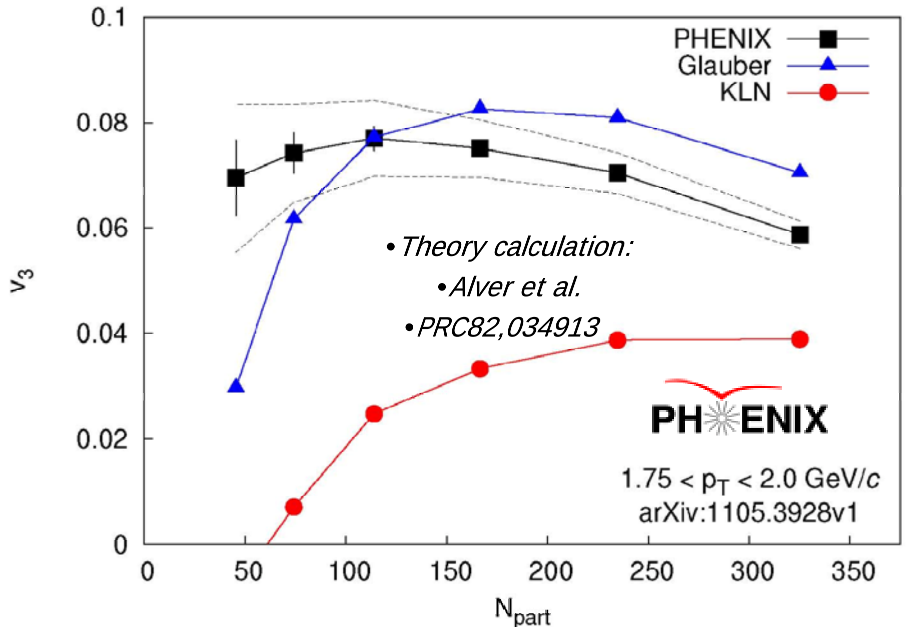
Important in restricting allowed range of η / s .



Increasing Sensitivity

- Higher harmonics help reduce uncertainty in η/s *and* initial conditions





- *Lappi, Venugopalan, PRC74, 054905*
- *Drescher, Nara, PRC76, 041903*

Glauber
Glauber initial state
$\eta/s = 1/4\pi$

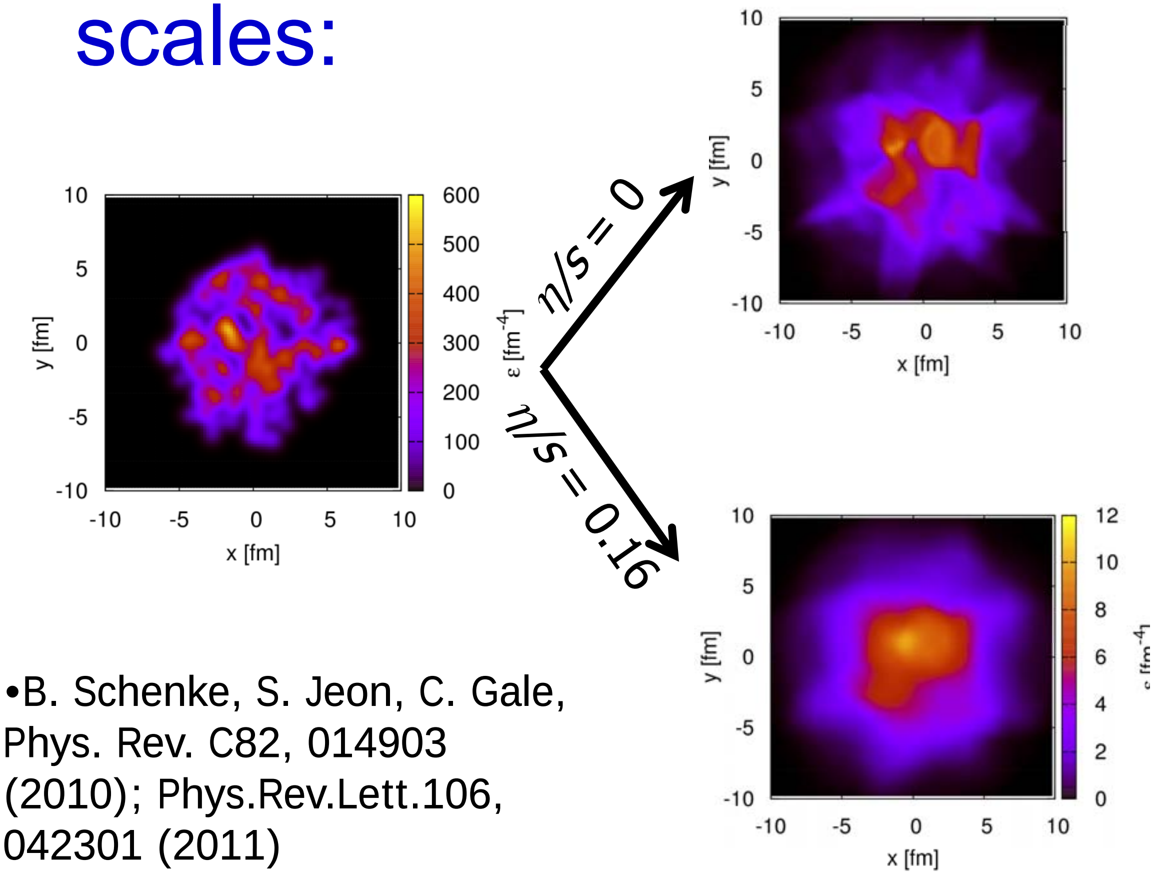
← • *Two models* →

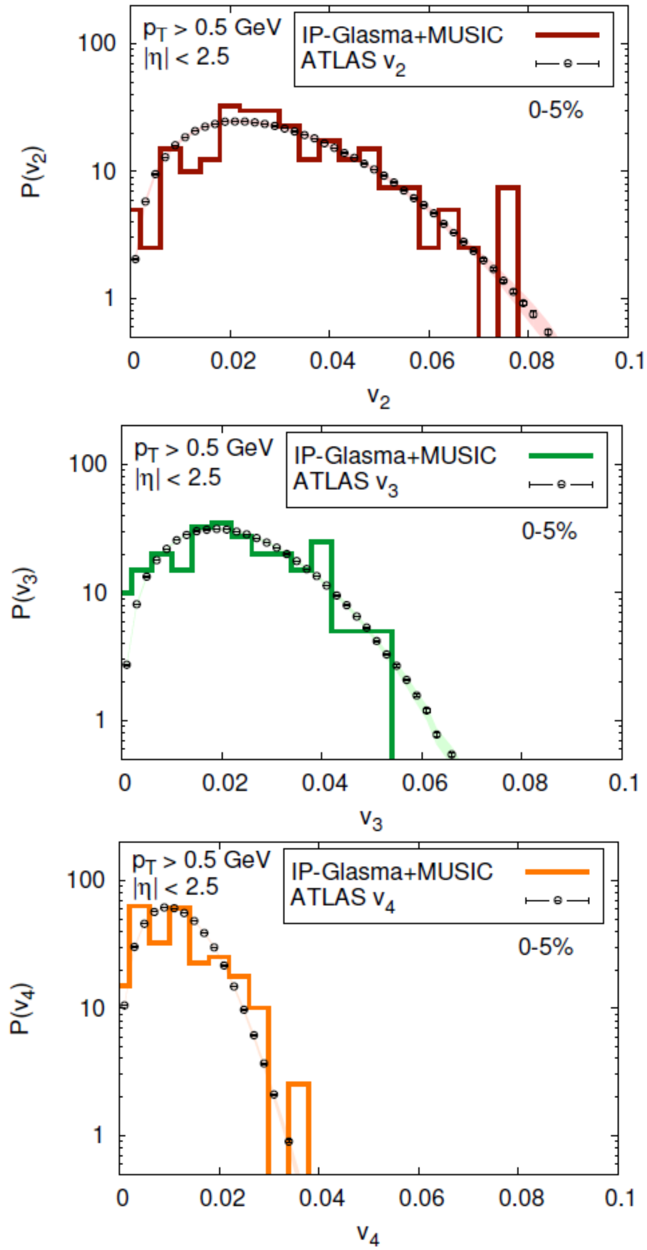
MC-KLN
CGC initial state
$\eta/s = 2/4\pi$

arxiv.org/abs/1105.3928

2012 State of the Art – *Event-by-Event* Distributions

- Treatment of gauge field fluctuations at sub-nucleon scales:

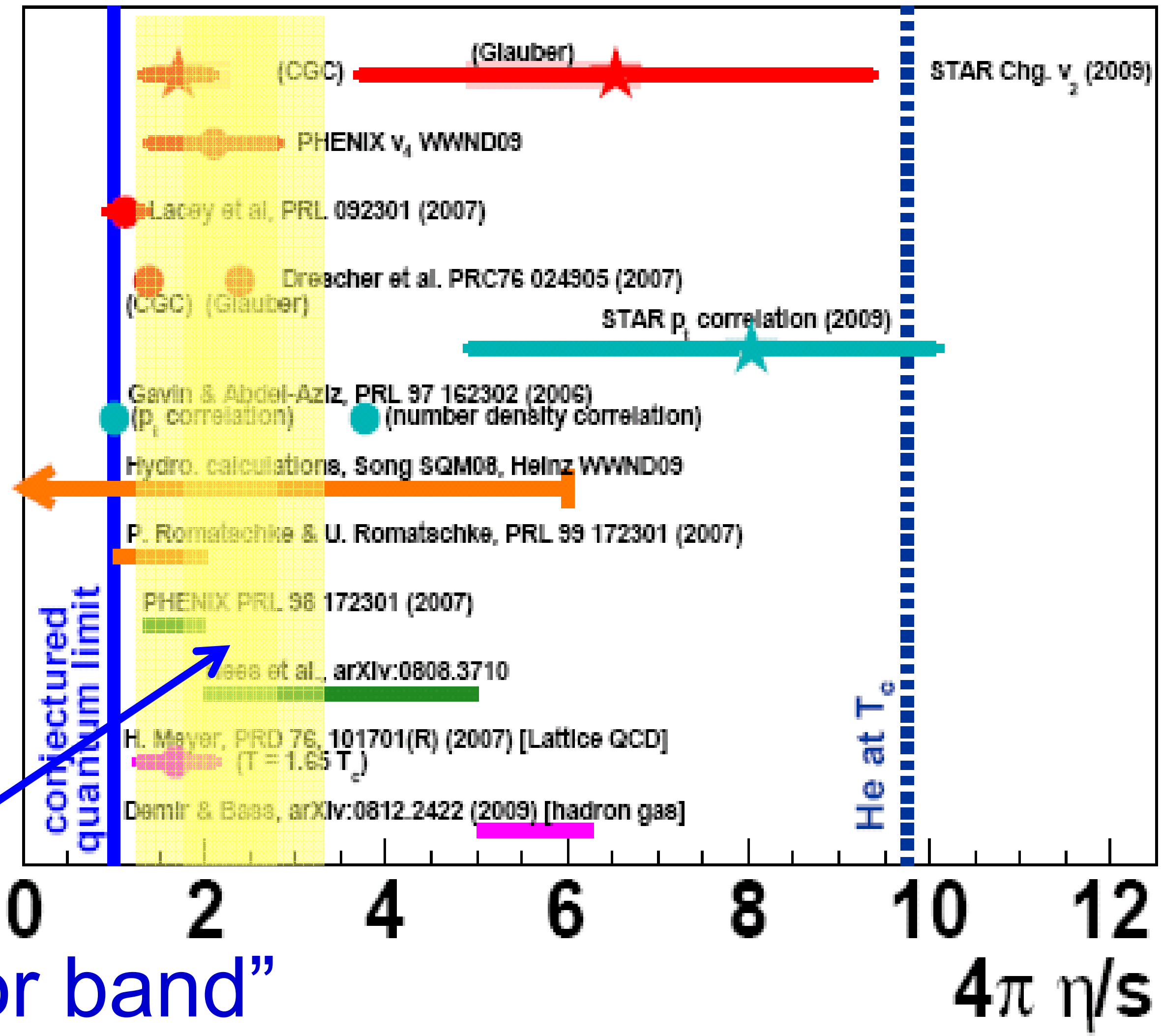




- B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)
- B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

Bounding η/s at RHIC

- Range of estimates:
  - (Compilation by A. Tang, R.J. Lacey)



- N.B. These are range estimates, *not* 1σ error bars.
- Estimated “error band”

Towards a Systematic Error Budget on η/s

- M. Luzum (Quark Matter 2012)

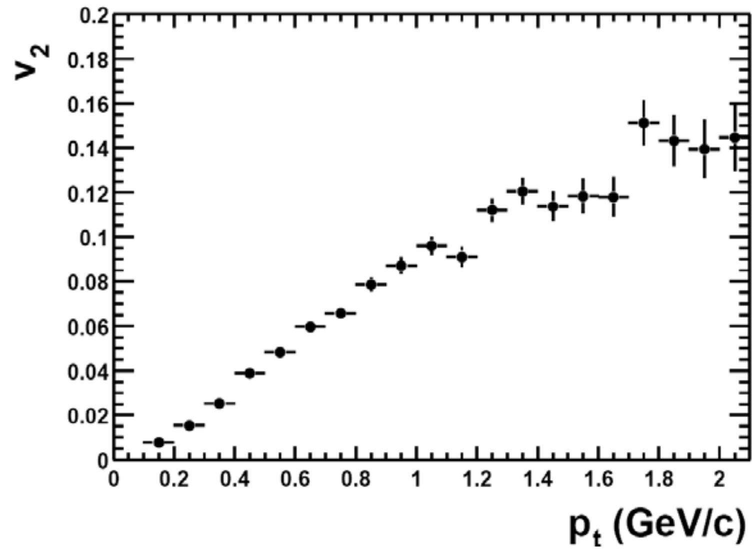
(Preliminary!)

Experimental uncertainties	± 0.020
Initial eccentricity	± 0.050
$v_n/\varepsilon_n =$ constant	$\sim \pm 0.010$
Thermalization time	± 0.030
Initialization of shear tensor	± 0.005
Initial flow	± 0.050
Equation of State	± 0.015
Second-order transport coeff.	± 0.005
Bulk Viscosity	$\sim \pm 0.010$
Deviation from boost-invariance / longitudinal fluct.	$\sim \pm 0.005$
Viscous correction to f.o. distribution	± 0.015
Other aspects of freeze out	$\sim \pm 0.025$

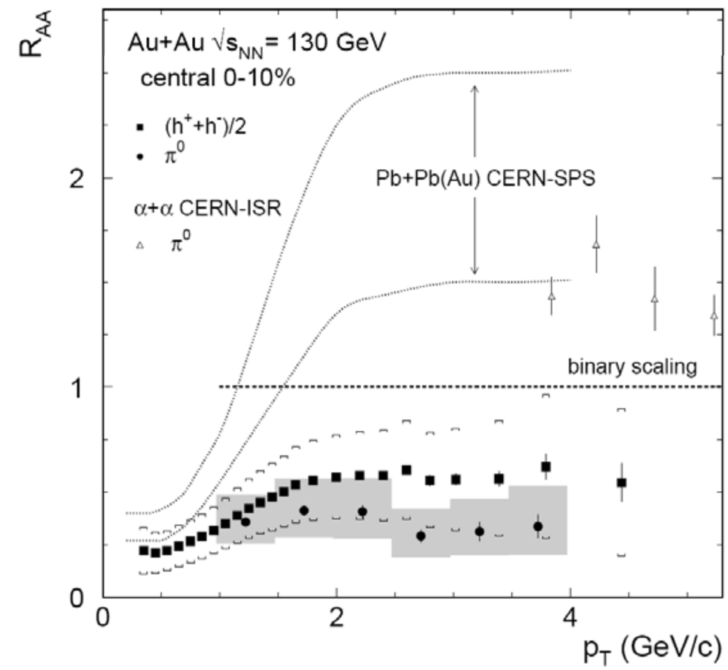
- Note: This emphasis on increased precision for η/s should not obscure the *paradigm shift* resulting from RHIC discoveries (next slide)

RHIC's Two Major Discoveries → *Paradigm Shift*

- Discovery of strong "elliptic" flow:
  - Elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, (K.H. Ackermann *et al.*). Phys.Rev.Lett.86:402-407,2001
  - *473 citations*



- Discovery of strong "jet quenching"
  - Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration (K. Adcox *et al.*), Phys.Rev.Lett.88:022301,2002
  - *664 citations*



Implications

- The bulk behavior of "strongly-coupled QGP" (sQGP) depends only on $\alpha_s(T)$ and $\hbar$.
  - A true "quantum liquid".
- The very low value of $\eta/s \Rightarrow$ no quasiparticles.
  - Urs Wiedemann, Quark Matter 2012:
    "This plasma is unique in that it does not carry quasi-particle excitations"
  - National Academy Decadal Survey:
    "Does the QGP have a particulate description at any length scale?"

2007 Long Range Plan

Jet Quenching

QCD jets occur in all kinds of very-high-energy collisions, arising from the hard scattering of incoming quarks and gluons and their subsequent breakup into a characteristic spray of particles that are measured in a detector. Jets have been observed at RHIC in proton-proton, deuteron-gold, and gold-gold collisions. But a dramatic change occurs in the jet distributions from gold-gold collisions. When collisions are nearly head-on, the typical pattern of back-to-back jets, which are clearly seen in proton-proton and deuteron-gold collisions, disappears and only one jet is observed. This jet quenching indicates that the scattered quarks and gluons that would produce the second jet undergo large energy loss—corresponding to a density that is 100 times that of normal nuclei—as they traverse the matter formed in the collision. Recent results further suggest that the energy lost by the high-energy jets may appear as a collective "sonic boom." If this suggestion proves correct, it will allow determination of the speed of sound in this new matter. The effect of jet quenching may open a new way for us to probe the gluon density distribution of the matter—the quark-gluon plasma—formed in these violent collisions.

Next Several Slides:

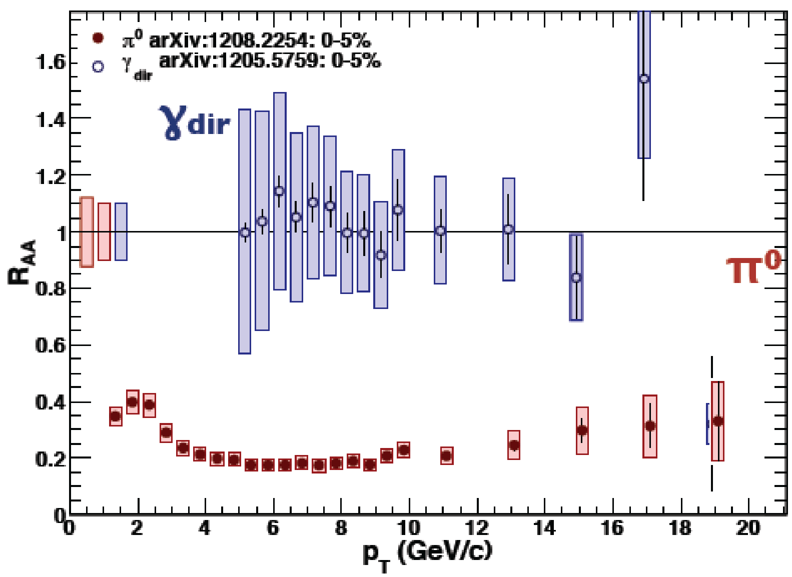
Describing the key interplay between RHIC and LHC measurements towards (ongoing) efforts to develop a concordance on "jet quenching".

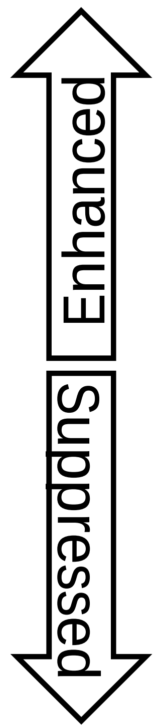
Plasma Diagnostics

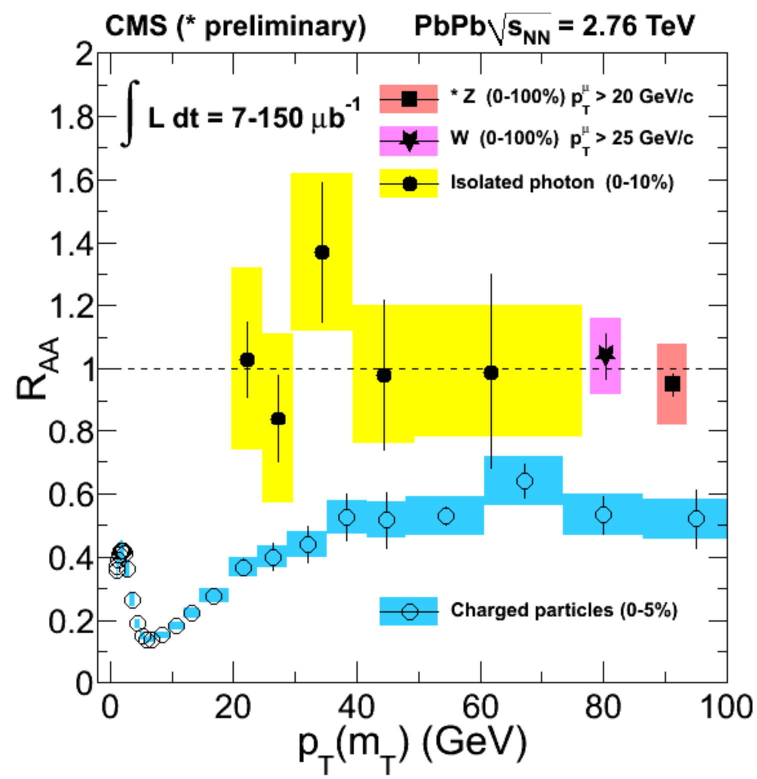
- Needed: Tools to interrogate sQGP at small distances
- Intrinsic scales of the sQGP:
  - T ~ 200 MeV
  - gT ~ 500 MeV ~ gluon effective mass
- Hard processes provide a wide variety of perturbative scales:
  - M_c ~ 1.3 GeV
  - M_b ~ 4.2 GeV
  - M_W ~ 80 GeV
  - M_Z ~ 90 GeV
  - Q ~ 10-300 GeV

Plasma Diagnostics (Cont'd)

- 0-th order: $R_{AA}(p_T) \equiv \dfrac{\text{Measured Yield in } A+A}{\text{Expected Yield from Scaled } p+p}$







- 1st, 2nd, 3rd order:
  - Differential studies versus: impact parameter, reaction plane, away-side partner; flavor tagging, tagged photons, complete jet reconstruction…

The Intellectual Challenges and Rewards

- Challenge: Solving a multi-scale, highly dynamic transport problem in an intrinsically quantum system

- Rewards:
  - *Possible resolution of quasiparticles*
  - *Measurement of transport coefficients*

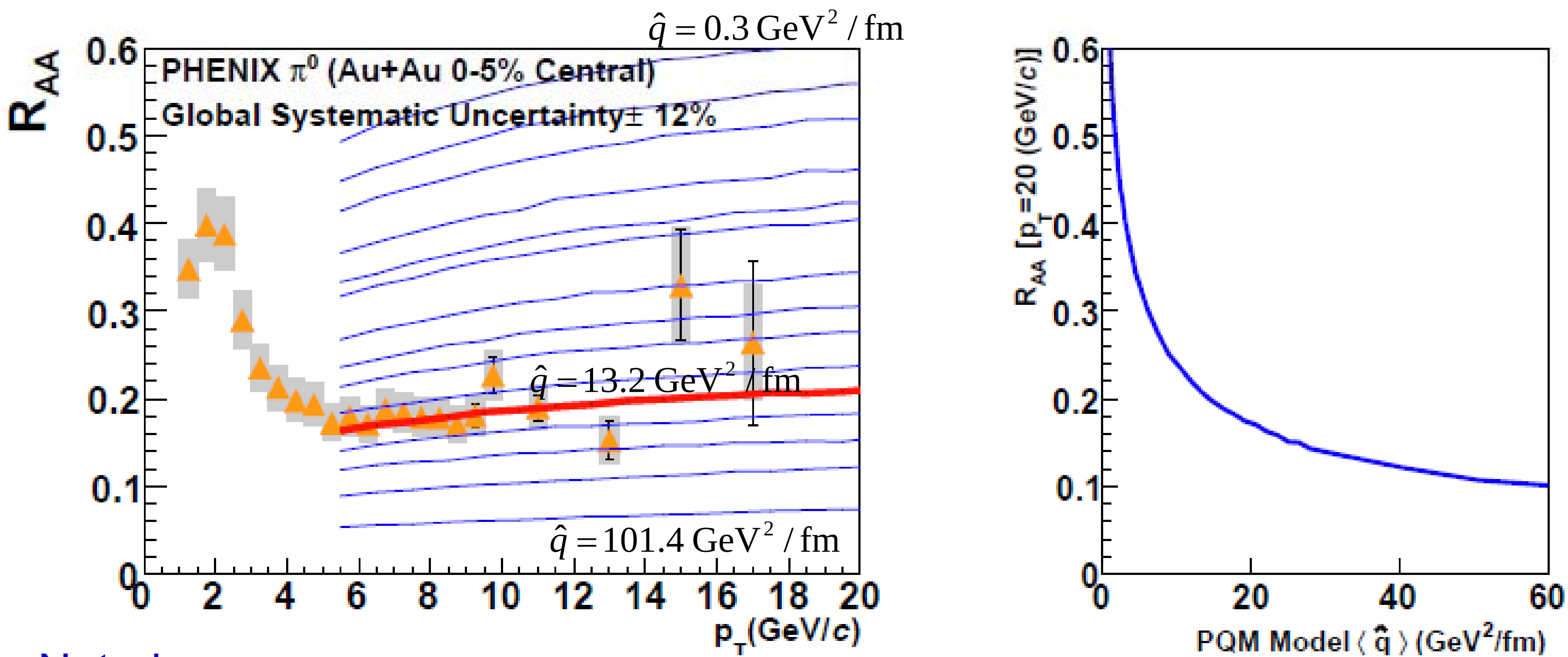
$$\hat{q} = \frac{\left\langle p_T^{\ 2} \right\rangle_L}{L} \qquad \hat{e} = \frac{\left\langle \Delta E \right\rangle_L}{L}$$

in a fundamental gauge theory

An Early Attempt

- Quantitative Constraints on the Transport Properties of Hot Partonic Matter from Semi-Inclusive Single High Transverse Momentum Pion Suppression in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV, arXiv:0801.1665 :

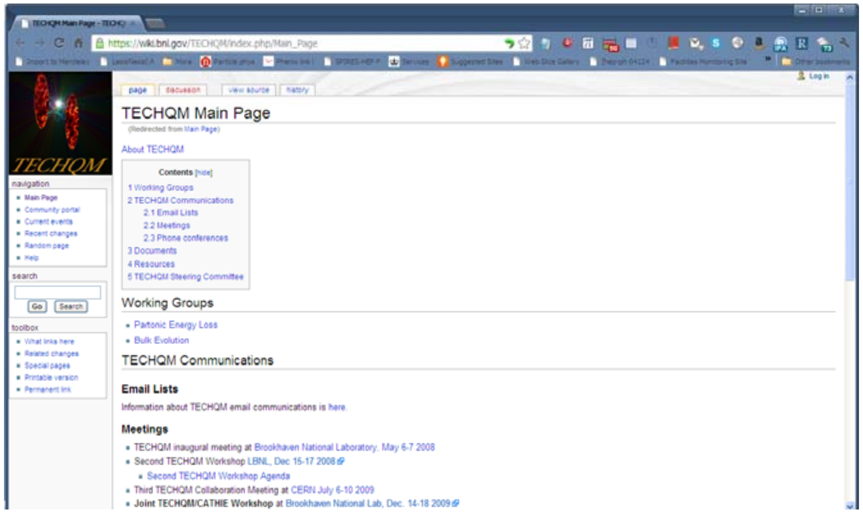
$$\hat{q} = 13.2_{-3.2}^{+2.1}\ \mathrm{GeV}^2/\mathrm{fm}$$



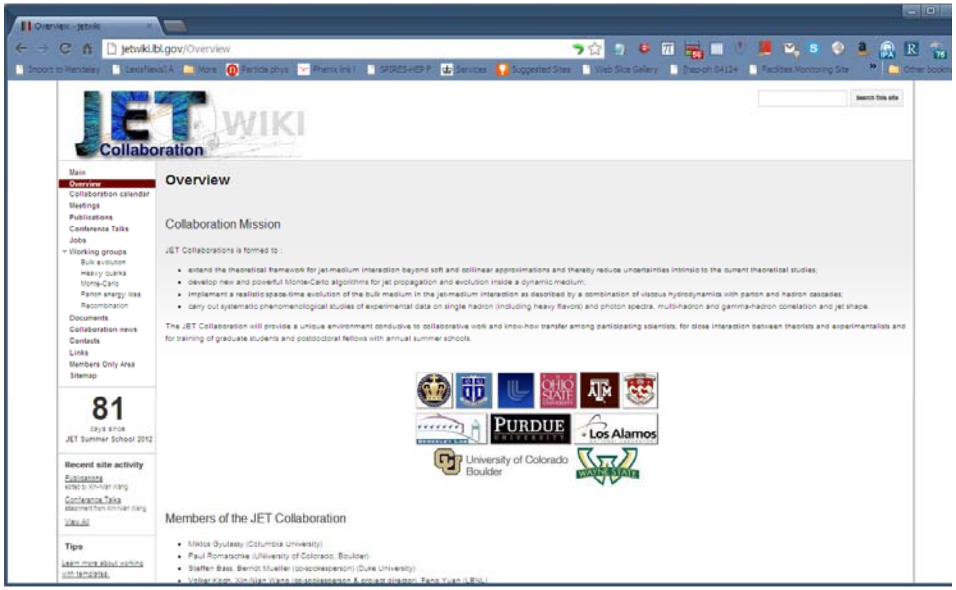
- Noted:
  "*These constraints include only the experimental uncertainties, and further studies are needed to compute the corresponding theoretical uncertainties.*"

"…To Compute the Corresponding Theoretical Uncertainties"

- Collaborative efforts between theorists and experimentalists:
- TECH-QM:
  - Initiated 2008
  - Evolved towards JET Topical Collaboration

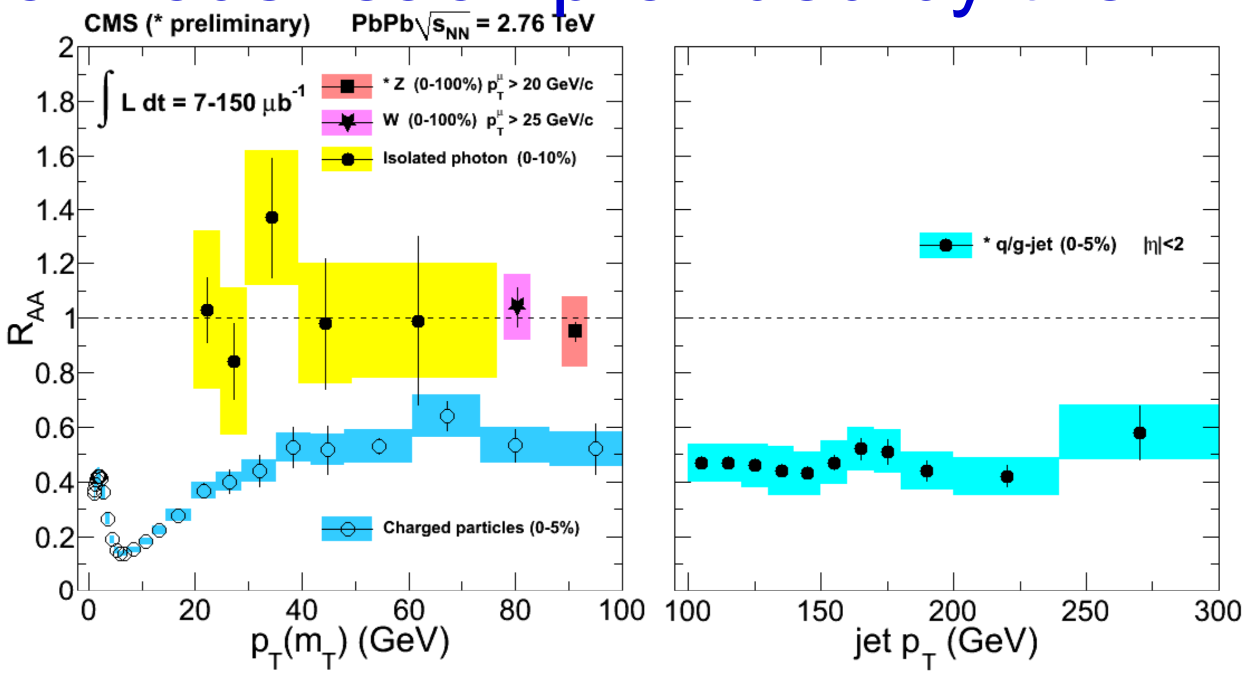


- JET
  - Sponsored workshops, meetings, schools
  - 57 publications to date

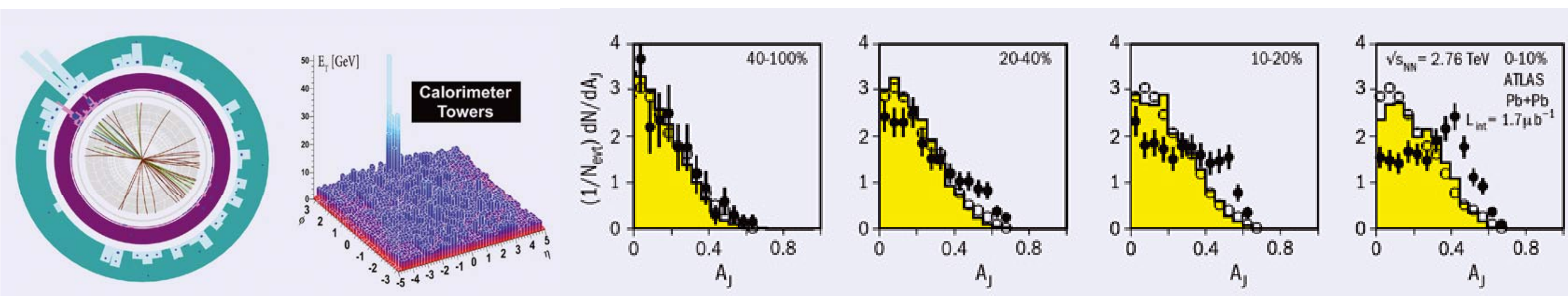


The Ultimate Lever-Arm

- The enormous reach provided by the LHC:

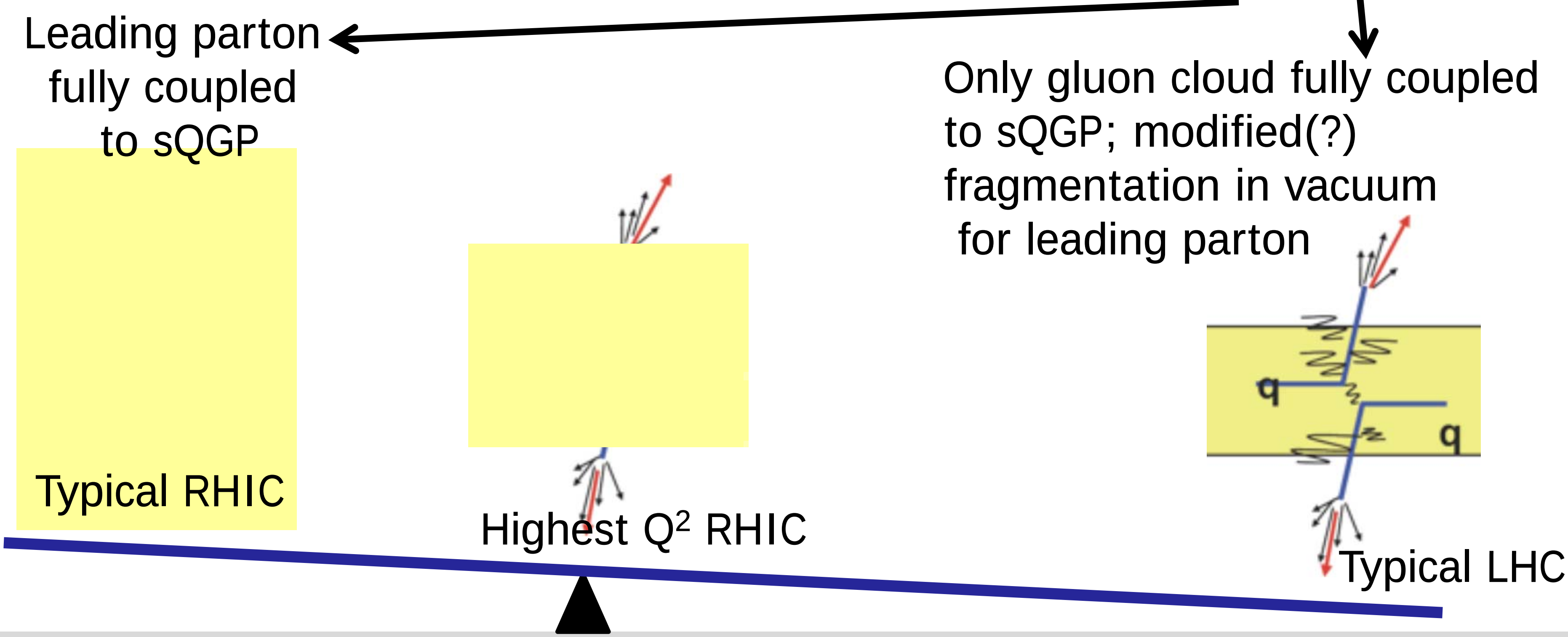


- New observables/discoveries at the LHC:



Our Evolving Understanding

- Entire lever arm needed to vary "impedance match" (virtuality) of probe to medium: $Q^2 = \max\left(\hat{q}L, E/L\right)$



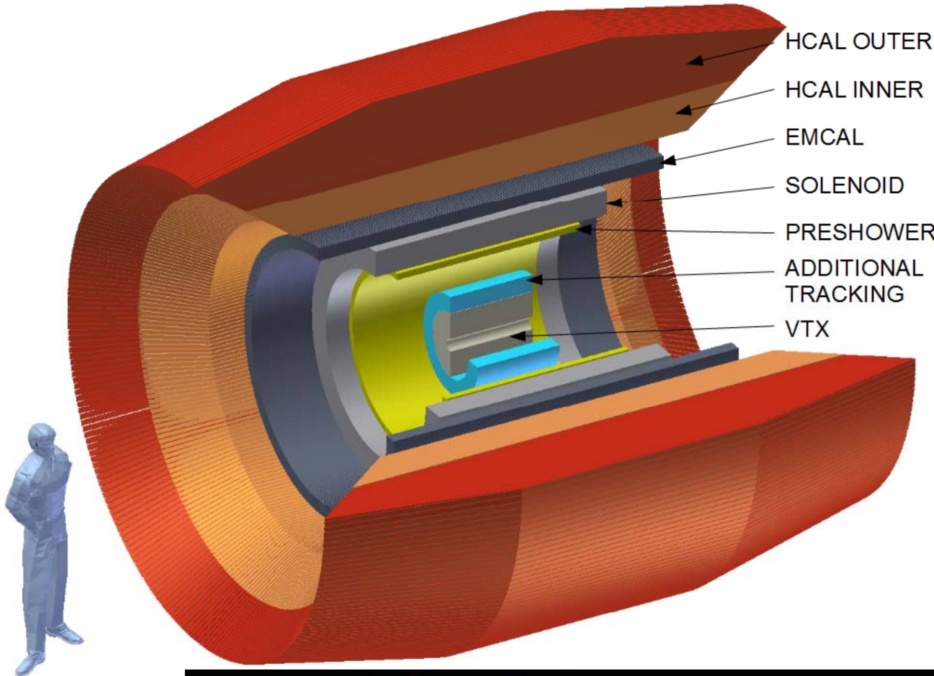
"…it seems clear that one or two advanced detectors with world-class jet measurement capabilities (acceptance, resolution, counting rate) will be needed at RHIC to realize these opportunities." (B. Müller, Hard Probes 2010)

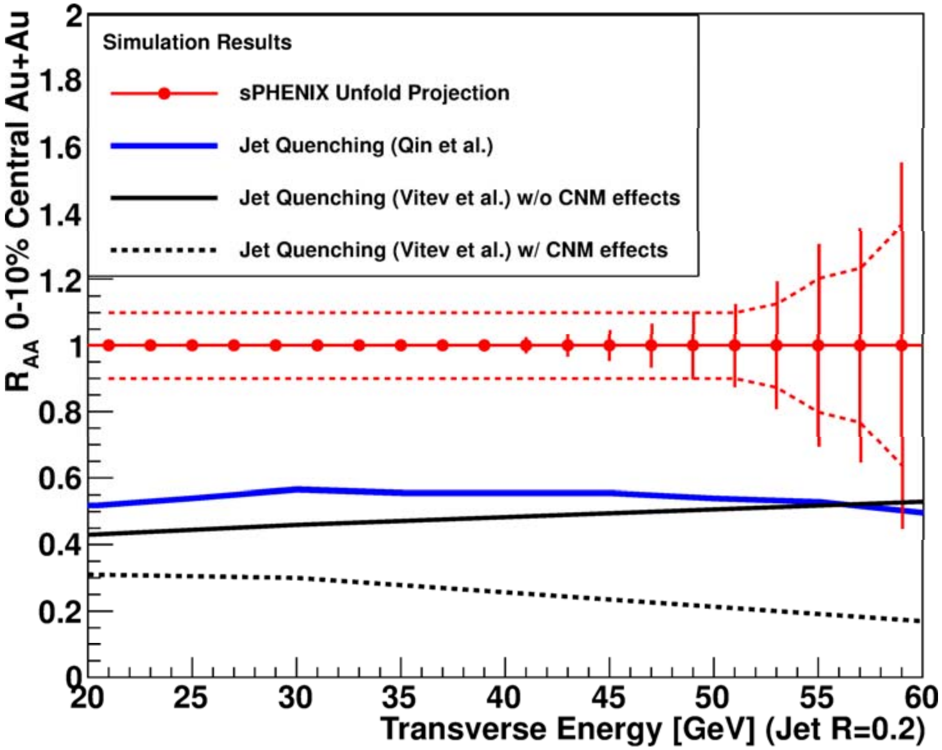
(In this context) :

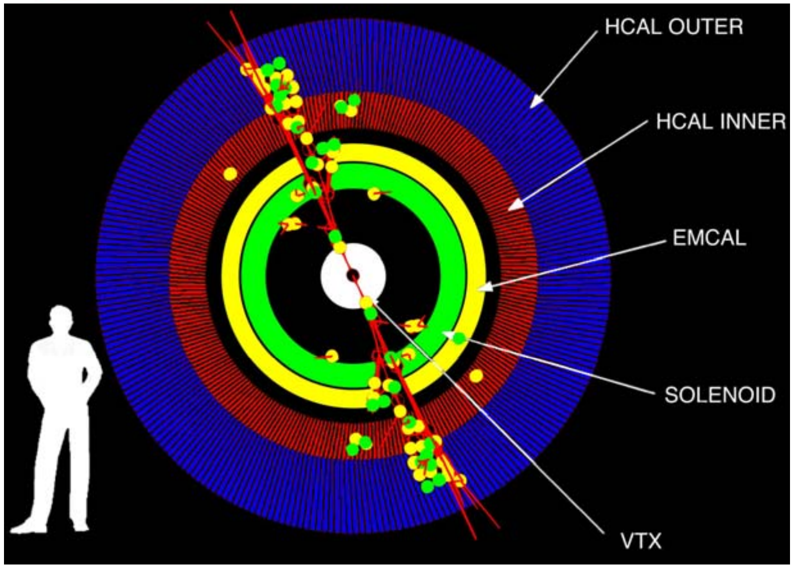
"We need RHIC, we need upgrades to RHIC" (Jose Guilherme Milhano, Quark Matter 2012)

Towards That End

- sPHENIX proposal, [arXiv:1207.6378]

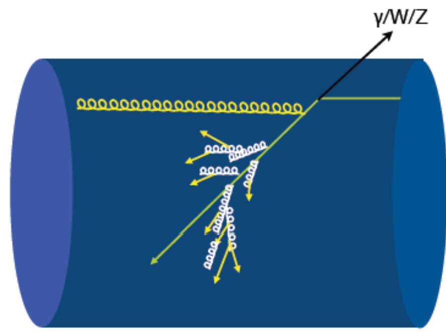




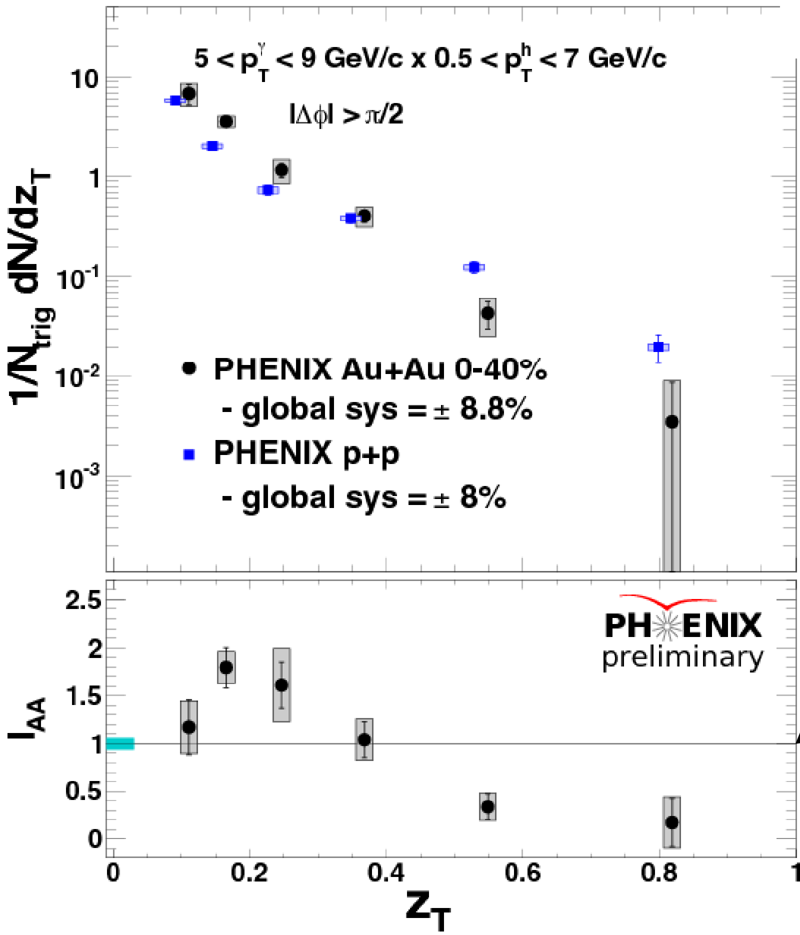


New Tools Coming Online

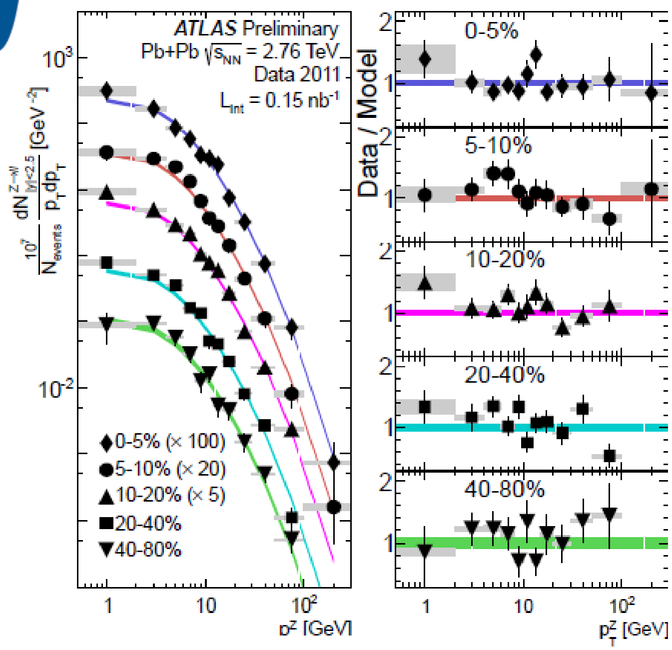
- RHIC:
  Luminosity upgrade
  ⇒ tagged-photon jets

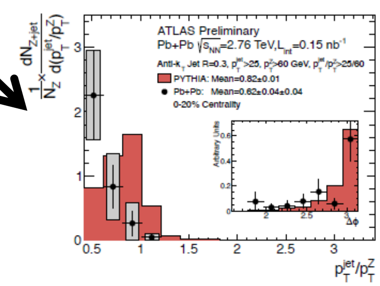


- LHC:
  Higher √s
  ⇒ tagged-Z^0 jets



Modifications from medium clearly visible



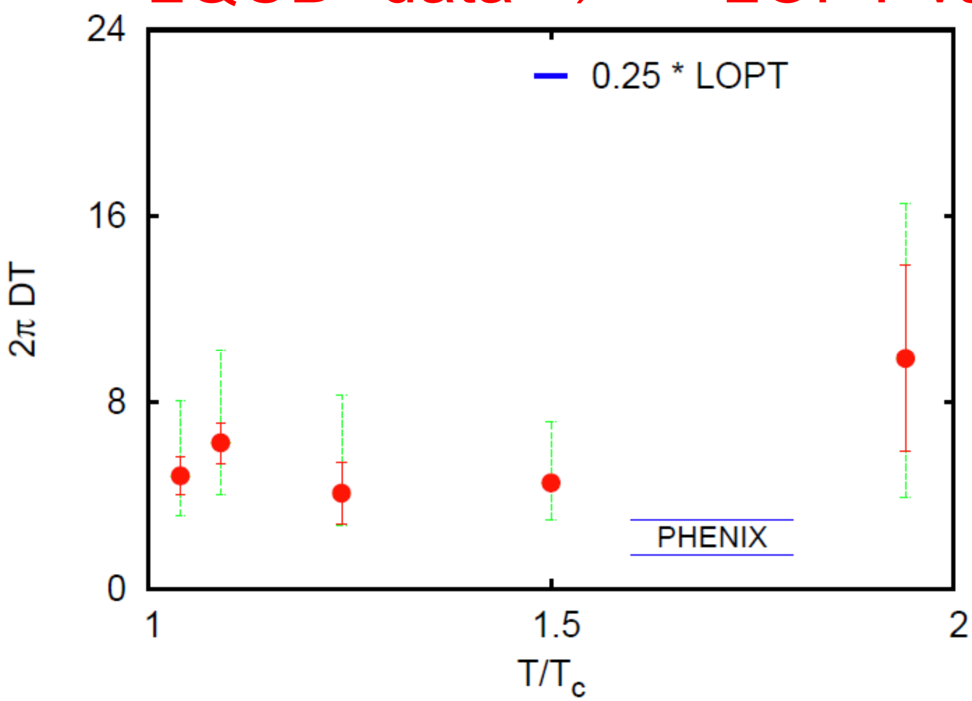


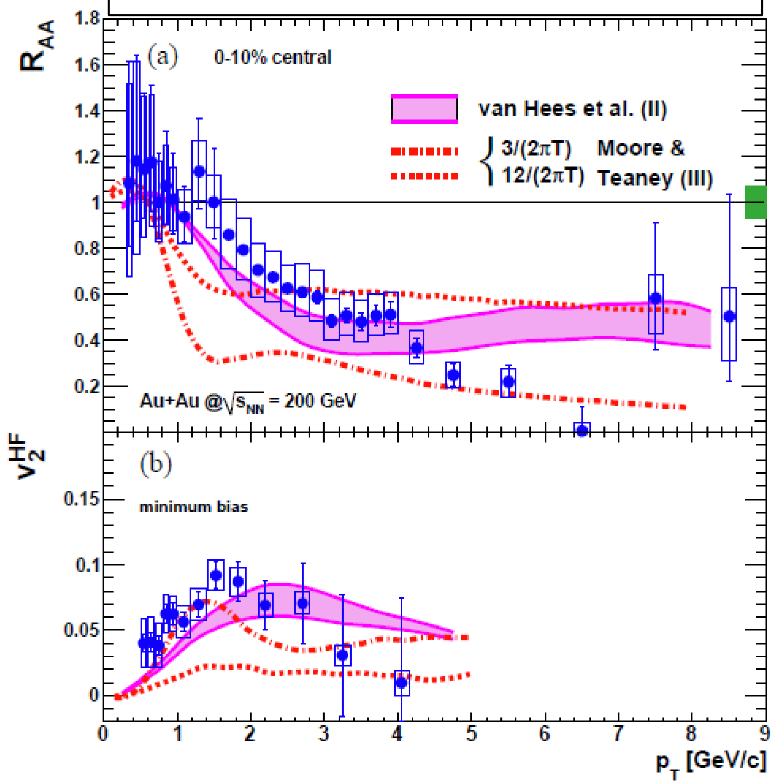
0-20% central

A Control Parameter

- Large mass of c and b quarks ⇒ new scale.
- Key parameter:
  - heavy quark diffusion constant D
  - Closely related to η/s
  - LQCD+data ⇒ << LOPT value

Heavy flavor
suppressed,
flows





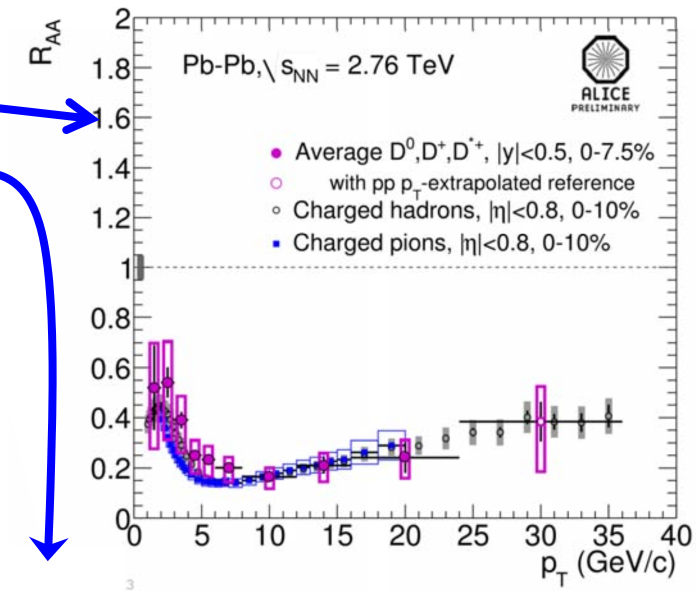
http://arxiv.org/abs/1109.5738 http://arxiv.org/abs/1005.1627

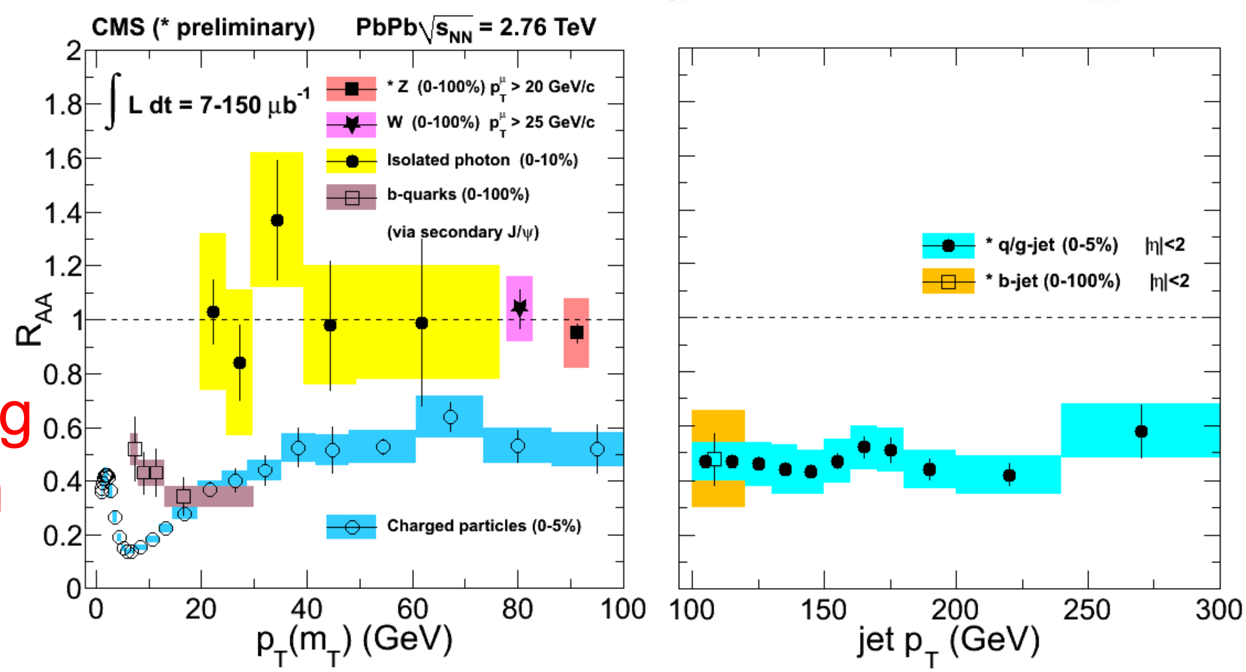
Heavy Quark *Suppression*

- c quarks highly suppressed
- b quarks significantly suppressed

⇒A key future measurement at RHIC

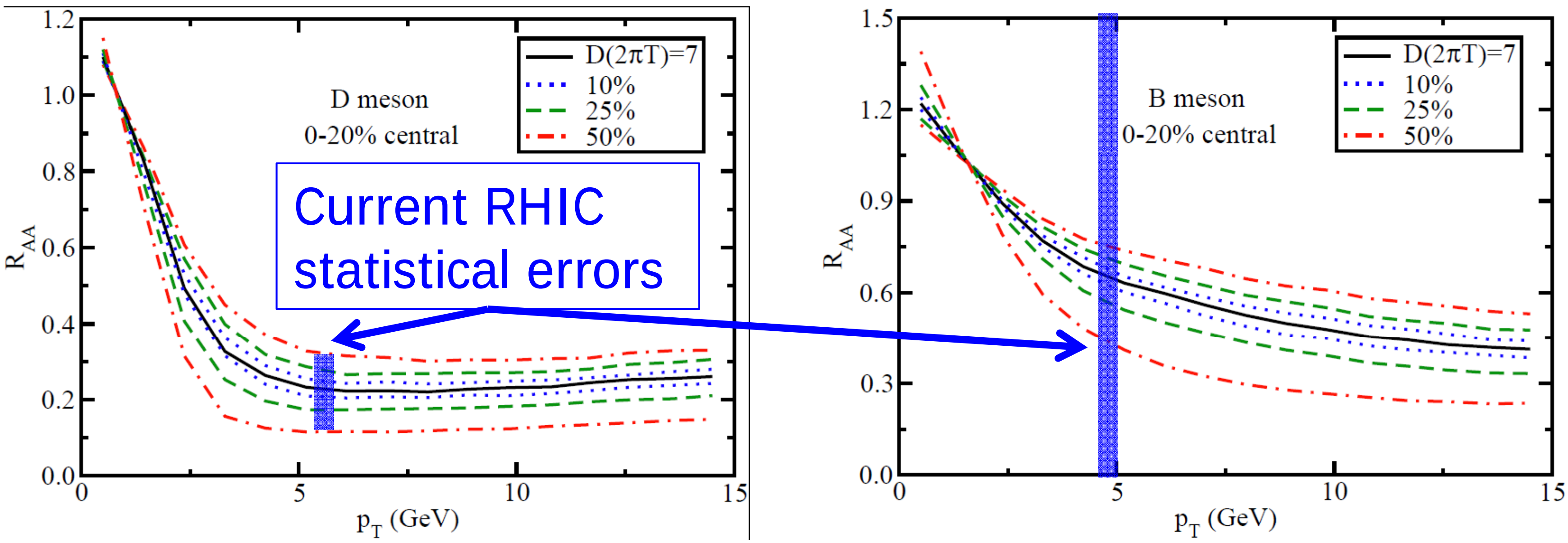
- Vertex upgrades
  - PHENIX 2010-2012
  - STAR 2013
- A critical measurement to understand *mystery* of heavy quark strong coupling to the medium





Heavy Quark Physics

- Large mass $\Rightarrow$ model by Langevin process
  - Diffusion coefficient D
  - Drag coefficient γ_D



- Fluctuation-Dissipation theorem $\Rightarrow$ D = $T/M_Q\gamma_D$
  - Fundamental test of medium parameters in fundamental system
- Similarly to test $\hat{q} \sim M_{QP}\,\hat{e}$ $\Rightarrow$ comparable precision needed in jet quenching program

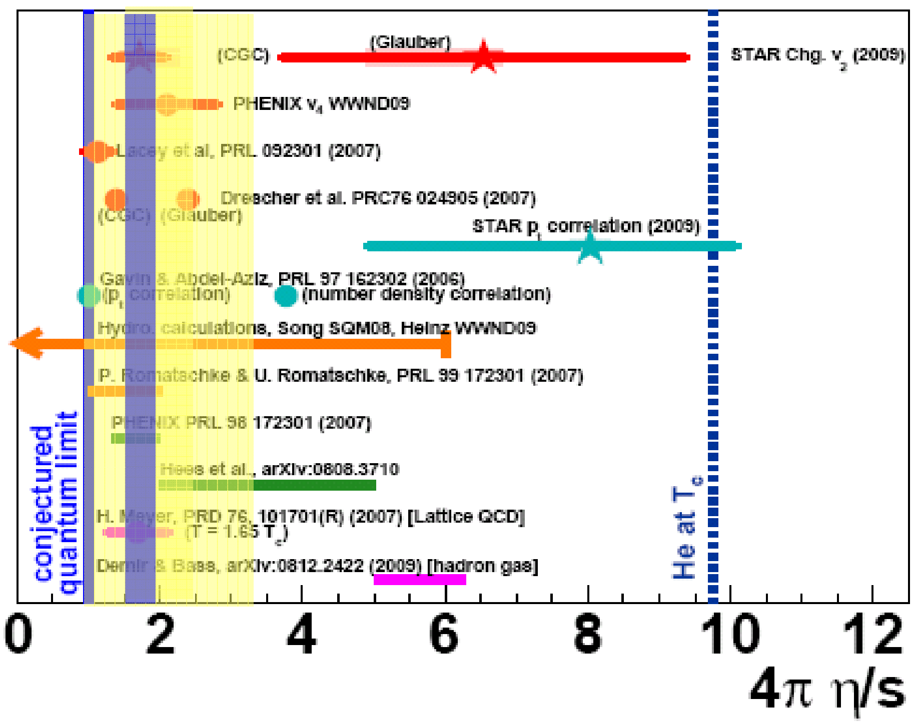
An Aspirational Goal

- To establish if η/s is
  - Truly the lowest value ever studied in the laboratory
  - Consistent with corrections from quantum gravity
- This may indeed be possible:
  - Establish range of α_S (0.25-0.33?) from jets, heavy flavor, …
  - Use *(naïve)* $\alpha_s = g_{YM}^2/4\pi$) in in result from Myers, Paulos and Sinha (http://arxiv.org/abs/0806.2156)

$$\lambda = g_{YM}{}^2 N_C \rightarrow 4\pi\alpha_S N_C$$

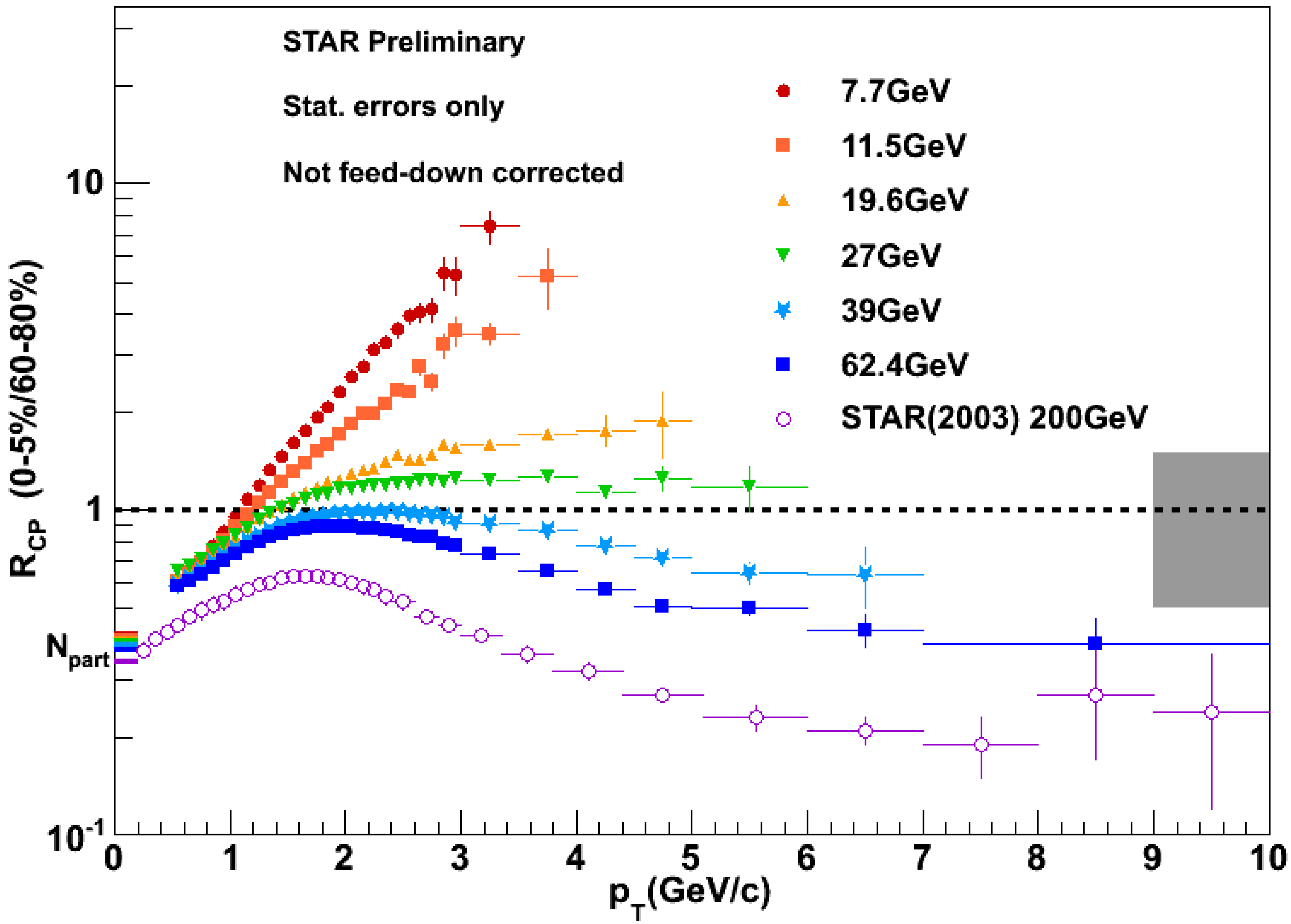
$$\frac{\eta}{s} = \frac{1}{4\pi}\left\{1 + \frac{15\zeta(3)}{\lambda^{3/2}} + \frac{5}{16}\frac{\lambda^{1/2}}{N_C{}^2} + \cdots\right\}$$

$$\Rightarrow \quad \frac{\eta}{s} \sim (1.54 - 1.73)\frac{1}{4\pi}$$



A Key Control Parameter

- Systematic investigation of all variations with √s



A Key Control Parameter

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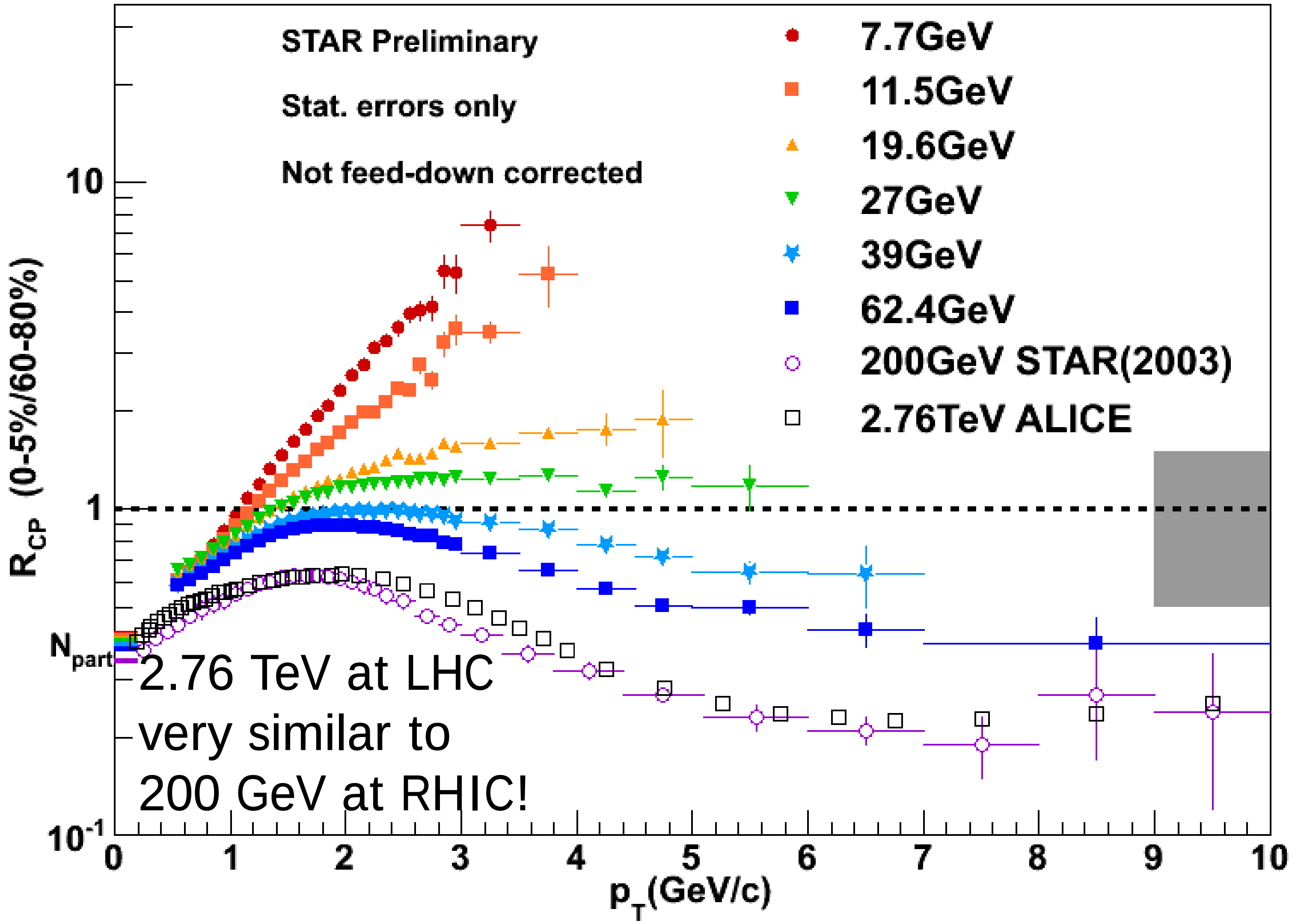


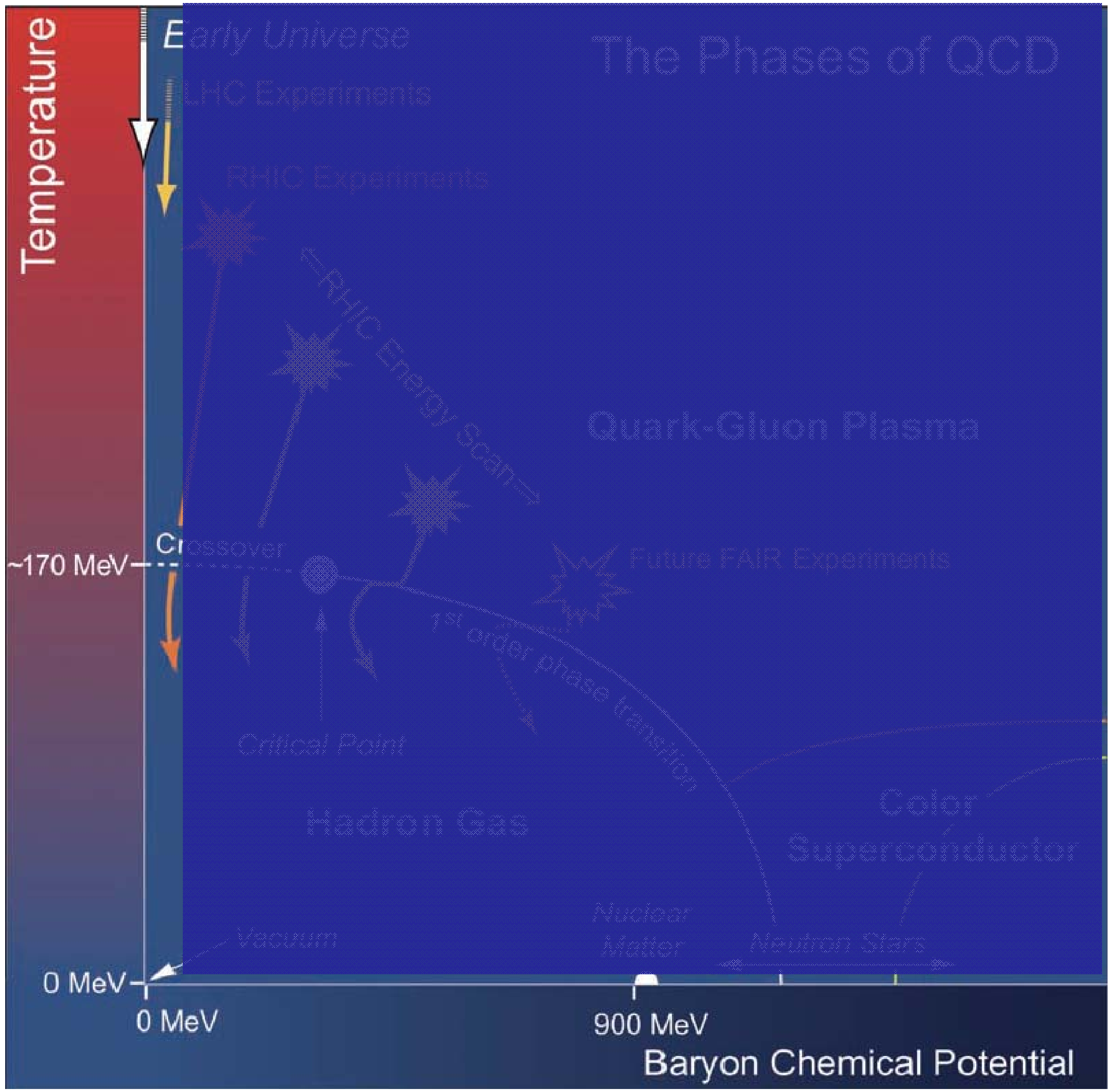
Implications

- RHIC is uniquely suited to study *the transition* from dense hadronic matter to formation of sQGP.
  - Provided by RHIC's broad dynamic range:
  - $\sqrt{s}$ = 200 GeV → 7.7 GeV demonstrated
    ~5 GeV possible

- RHIC is ideally suited for exploration of the QCD phase diagram away from ~zero baryon chemical potential μ_B.

√s Varies a True Control Parameter: μ_B

- Emphasis in first part of this talk:
  - "Recreating conditions in the early universe" with μ_b/T <<1
  - A *subset* of "exploring the QCD phase diagram"



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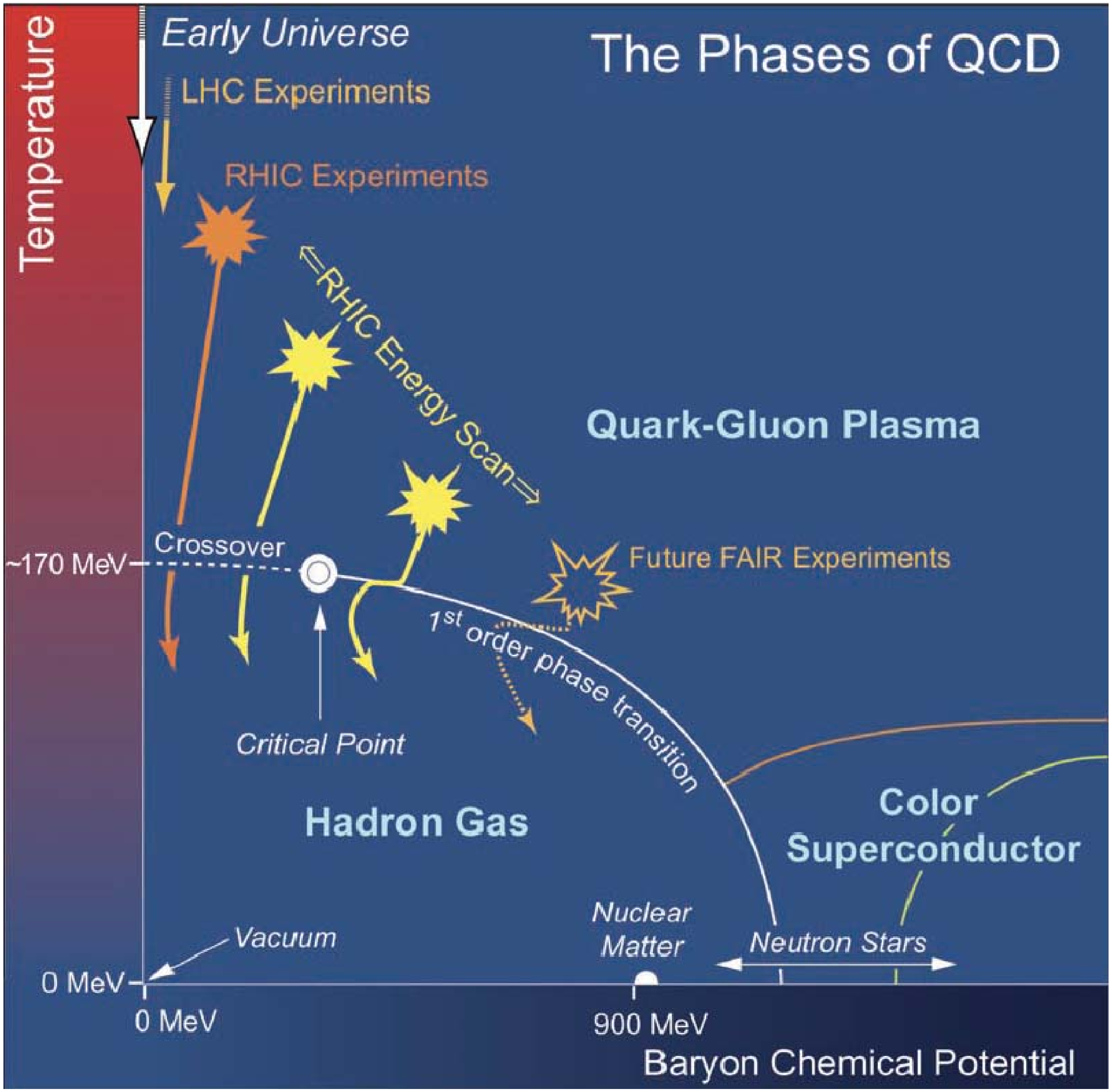
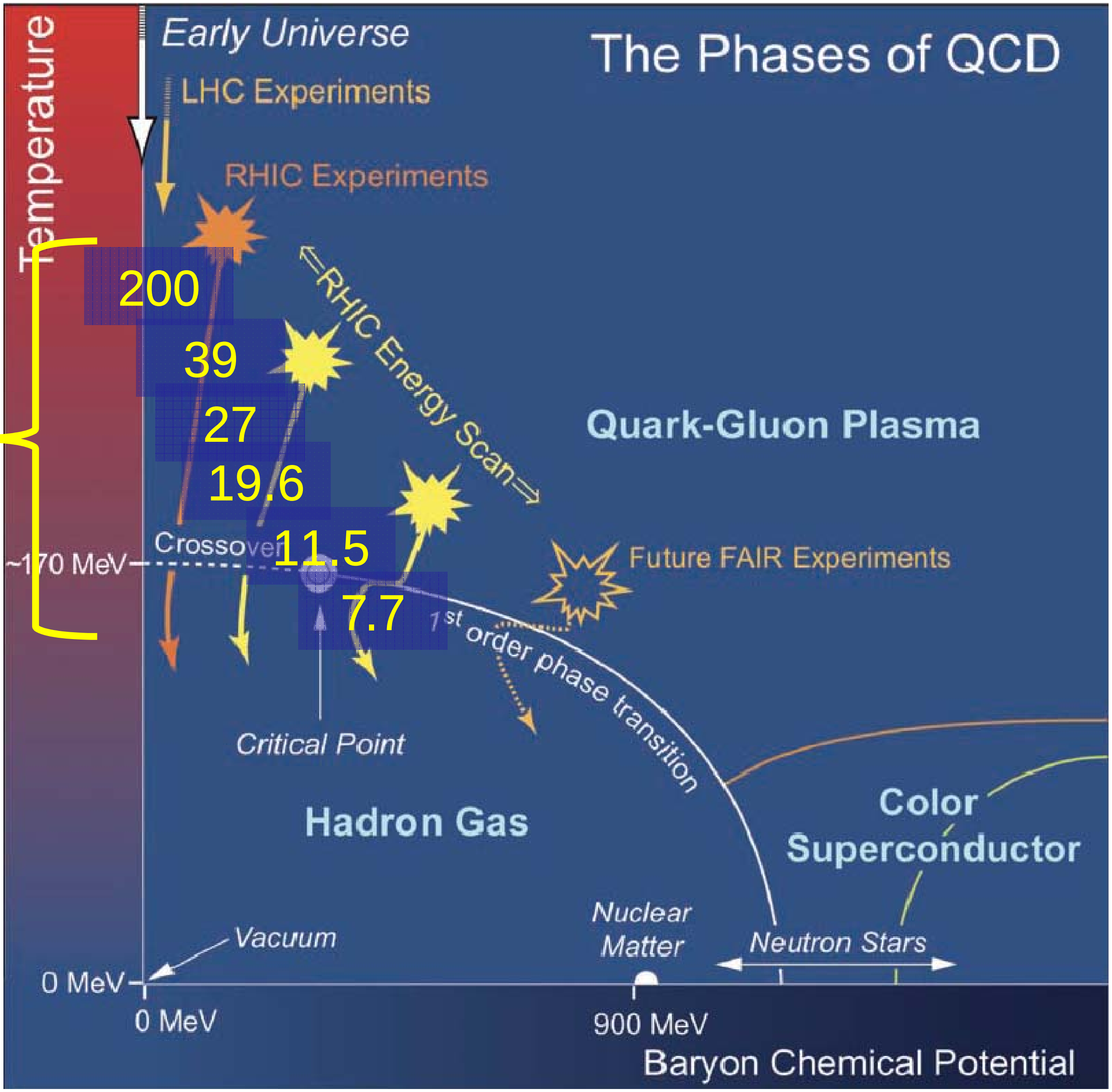


√s Varies a True Control Parameter: μ_B

- Beam Energy Scan at RHIC
  - *Only at RHIC !*
  - Range explored to date
    - ☞ **Note:** horizontal position accurate; vertical position schematic
  - "Exploring the QCD phase diagram" in search of the critical point



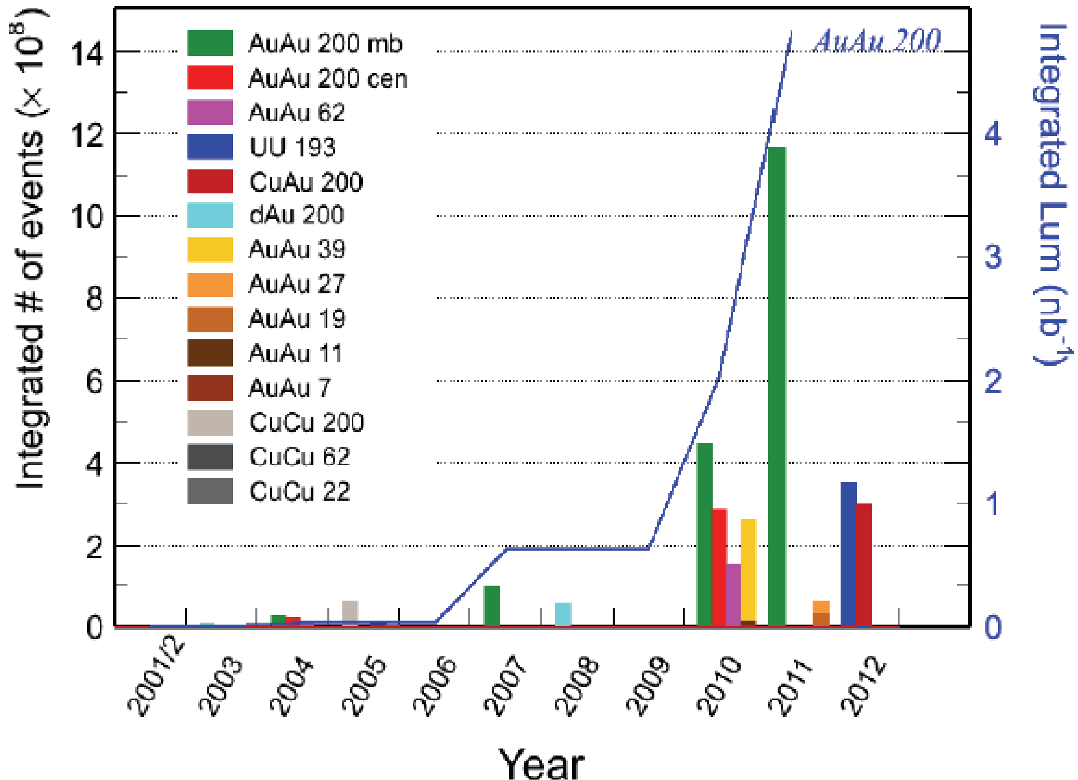
Next Several Slides:

Returning to the further quantification of the QCD phase diagram.

Applying RHIC's Versatility – Round I

- RHIC – the most versatile collider ever operated.

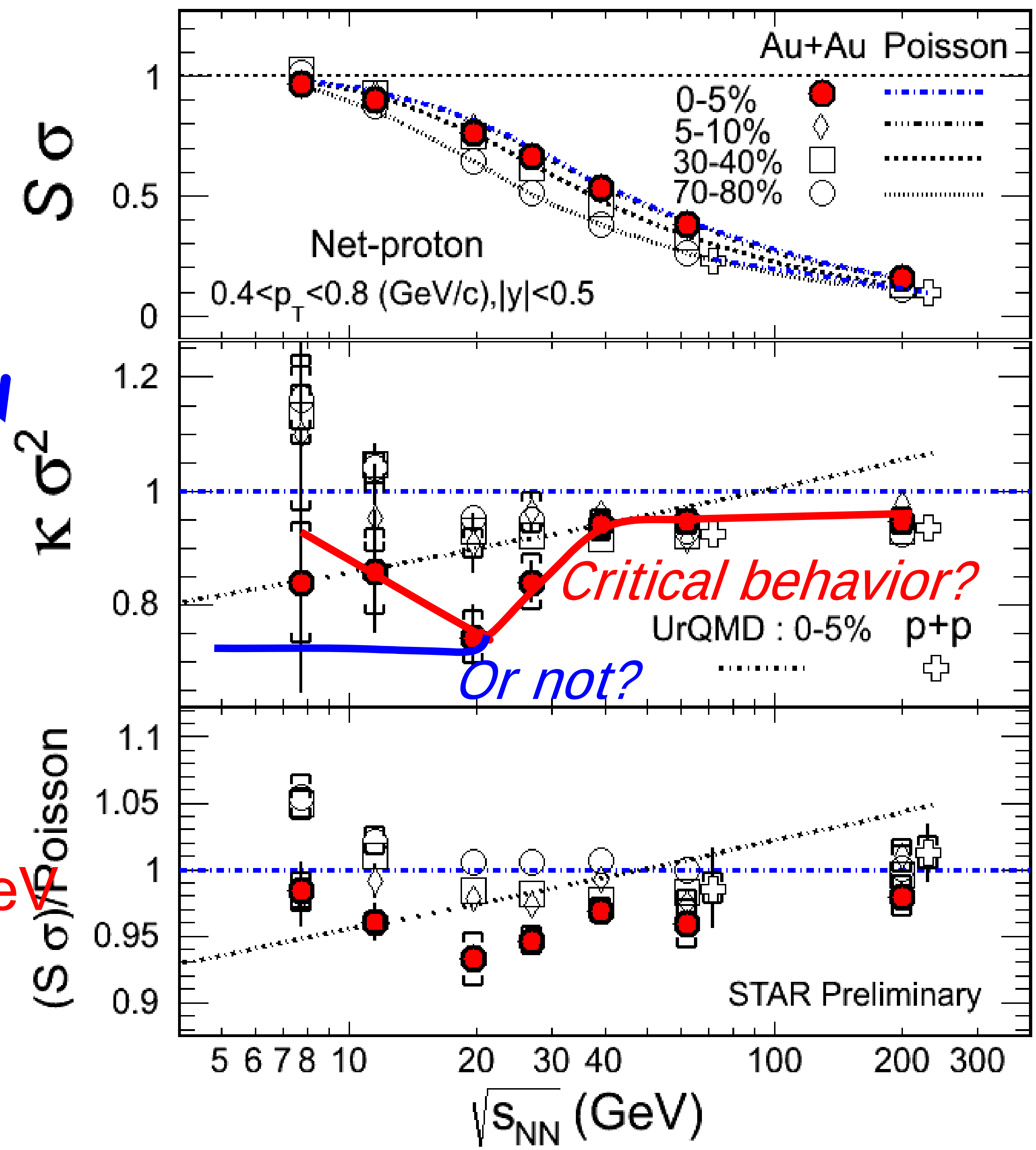
RHIC Run	Year	Species	Energy	Ldt
Run-1	2000	Au+Au	130 GeV	1 μb-1
Run-2	2001-2	Au+Au	200 GeV	24 μb-1
		Au+Au	19 GeV	
		p+p	200 Gev	150 nb-1
Run-3	2002/3	d+Au	200 GeV	2.74 nb-1
		p+p	200 GeV	0.35 nb-1
Run-4	2003/4	Au+Au	200 GeV	241 μb-1
		Au+Au	62.4 GeV	9 μb-1
Run-5	2005	Cu+Cu	200 GeV	3 nb-1
		Cu+Cu	62.4 GeV	0.19 nb-1
		Cu+Cu	22.4 GeV	2.7 μb-1
Run-6	2006	p+p	200 GeV	10.7 pb-1
		p+p	62.4 GeV	100 nb-1
Run-7	2007	Au+Au	200 GeV	813 μb-1
Run-8	2007/2008	d+Au	200 GeV	80 nb-1
		p+p	200 GeV	5.2 pb-1
		Au+Au	9.2 GeV	
Run-9	2009	p+p	200 GeV	16 pb-1
		p+p	500 GeV	14 pb-1
Run-10	2010	Au+Au	200 GeV	1.3 nb-1
		Au+Au	62.4 GeV	100 μb-1
		Au+Au	39 GeV	40 μb-1
		Au+Au	7.7 GeV	260 mb-1
Run-11	2011	p+p	500 GeV	27 pb-1
		Au+Au	200 GeV	915 μb-1
		Au+Au	27 GeV	5.2 μb-1
		Au+Au	19.6 GeV	13.7 M events
Run-12	2012	p+p	200 GeV	9.2 pb-1
		p+p	510 GeV	30 pb-1
		U+U	193 GeV	171 μb-1
		Cu+Au	200 GeV	4.96 nb-1



- A significant fraction of RHIC running to date: Systematic "beam energy scan"

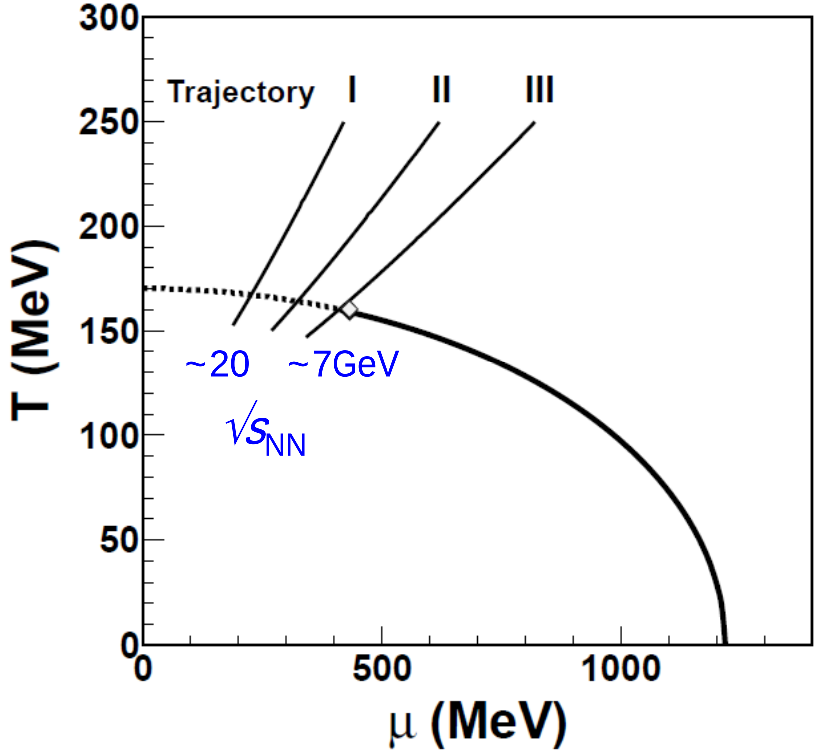
Fluctuation Observables for Critical Point

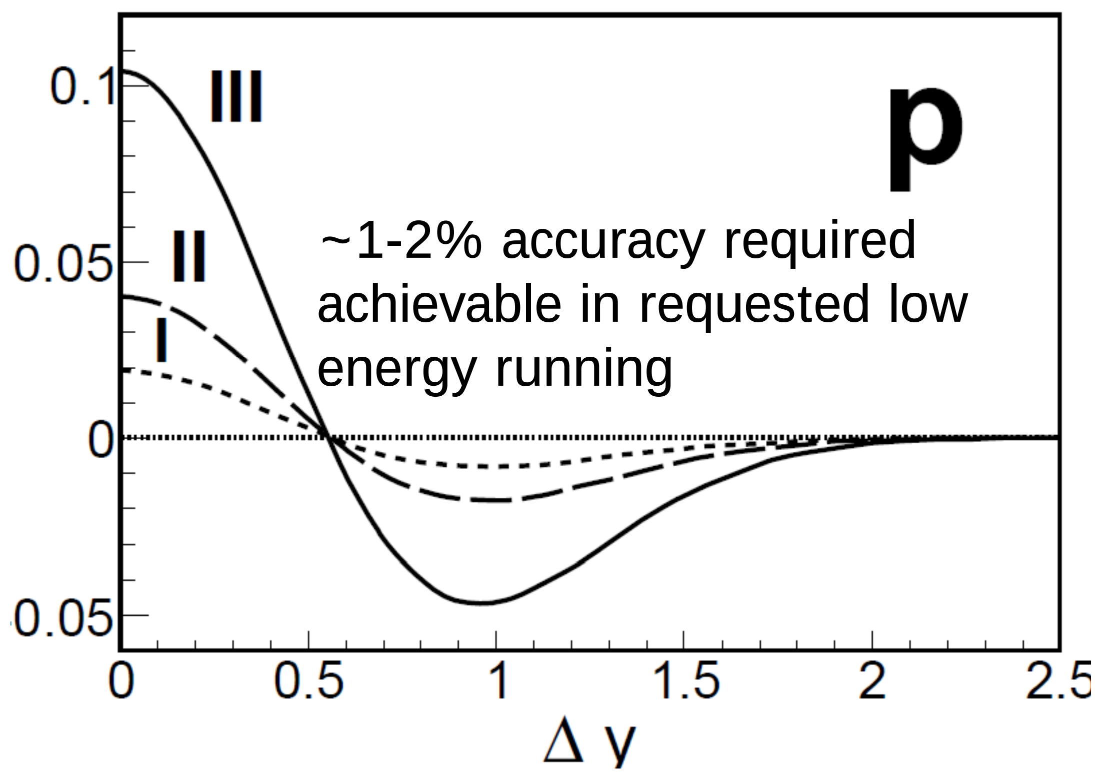
- In particular, scaled kurtosis
- Current data provide only "hints"
- Required:
  - 10-20 x larger data set at low √s
  - Additional data point at $\sqrt{s_{NN}}$ = 15 GeV
  - ~ 3 years with demonstrated RHIC performance



Another Example

- J. Kapusta, QM12:
  - Studies fluctuations in thermal conductivity
  - Calculates effect on proton correlation function for various “fly-bys” near the critical point

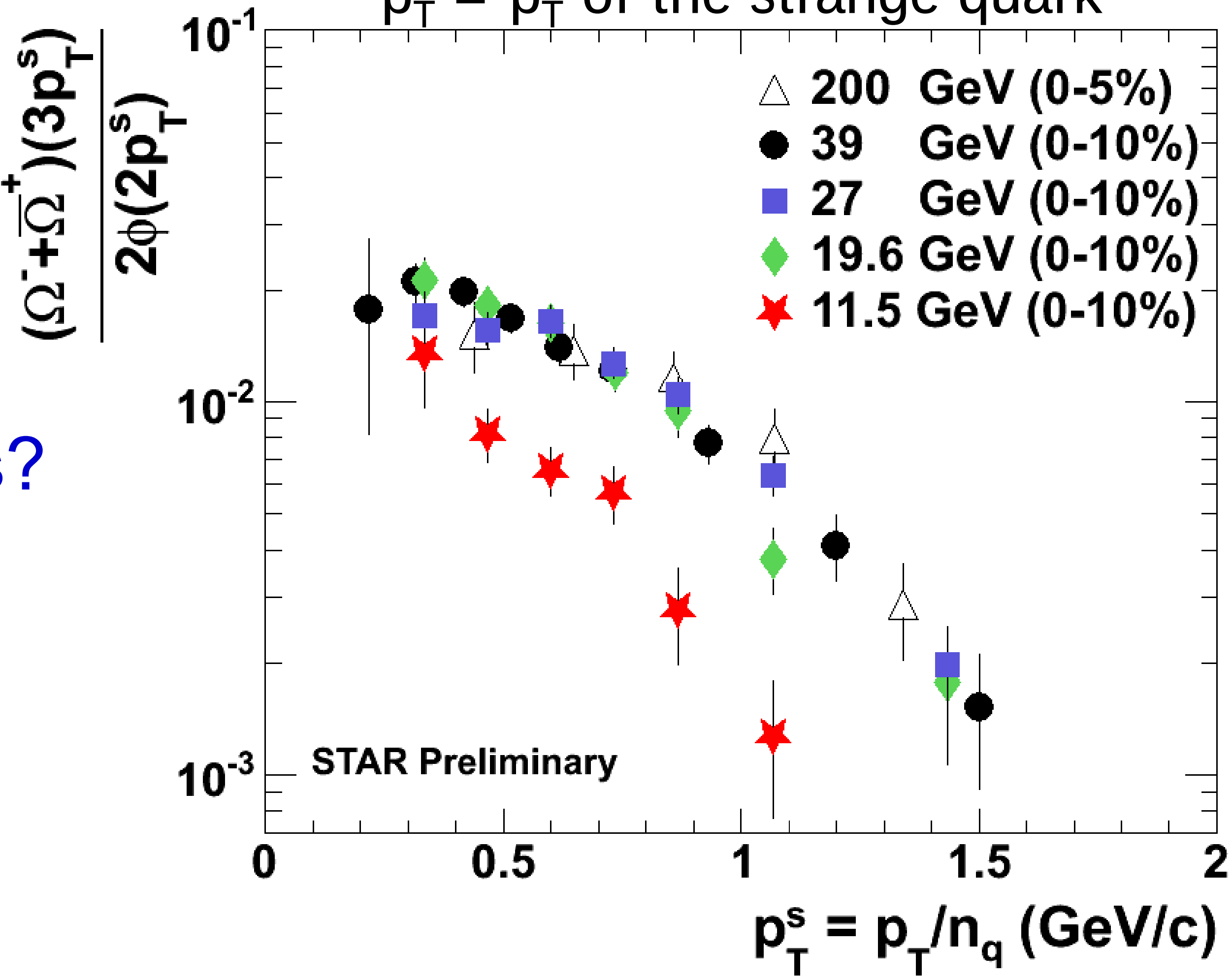




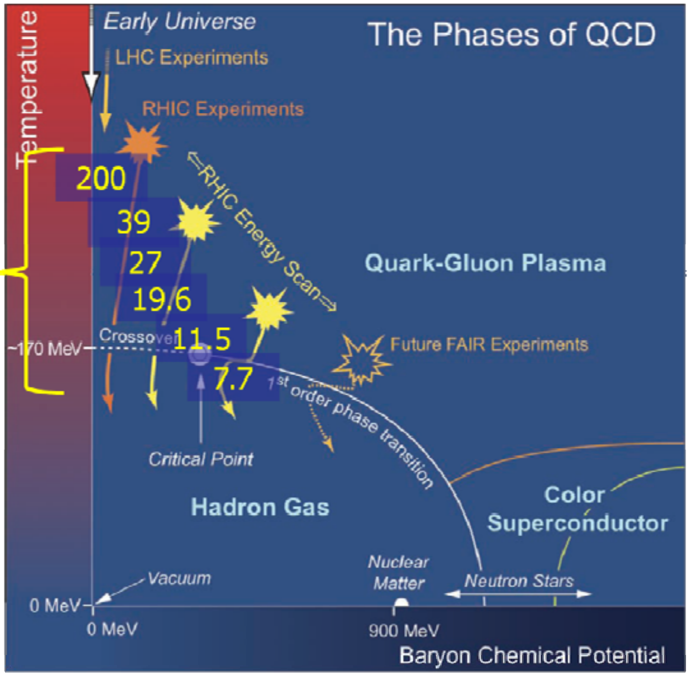
Another Example

- New STAR data suggest change in strange quark dynamics between 19.6 GeV and 11.5:
- Is this a "sharp" onset?
- Or a gradual evolution with √s?
- Or phase space?

Roughly, this ~ dn/dp_T^s,
$p_T^s = p_T$ of the strange quark



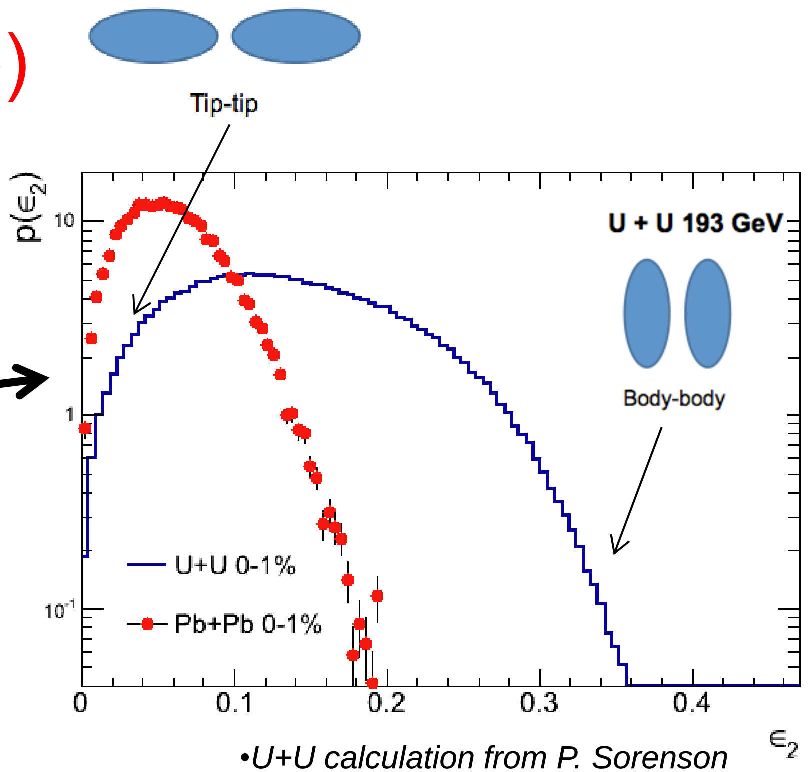
Unique Collider Capabilities



- Of course: ability to reach high $\sqrt{s}$:
  - $\sqrt{s}$=7.7 GeV $\Rightarrow E_{FIX}$ = 31 GeV
  - $\sqrt{s}$ =200 GeV $\Rightarrow E_{FIX}$ = 21 TeV
- At least as important when scanning energies:
  - The CM-frame *is* the LAB frame
  - Example: “Interesting” range on RHIC E-scan:
    - $\sqrt{s}$ = 5 GeV $\Rightarrow \theta_{CM} = 23.5^o$
    - $\sqrt{s}$ = 15 GeV $\Rightarrow \theta_{CM} = 7.7^o$
  - Much harder to control systematics at 10-20% level when acceptance changes by factors of 3…

Unique RHIC Capabilities

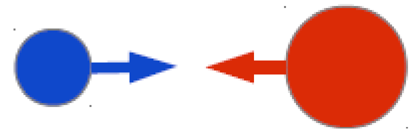
- Uranium+Uranium collisions
  - Made available by new (2012) upgrade (Electron Beam Ion Source)
  - Use large intrinsic deformation to
    - Dramatically extend distribution of initial-state eccentricities
    - Create elliptic flow even in the most central events
    - Critical control measurement for chiral magnetic effect
    - Increased energy density in subset of central events
  - First run: 2012, first results presented at QM12



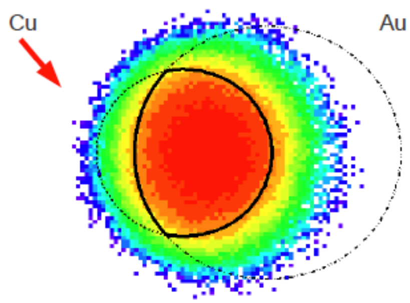
•U+U calculation from P. Sorenson

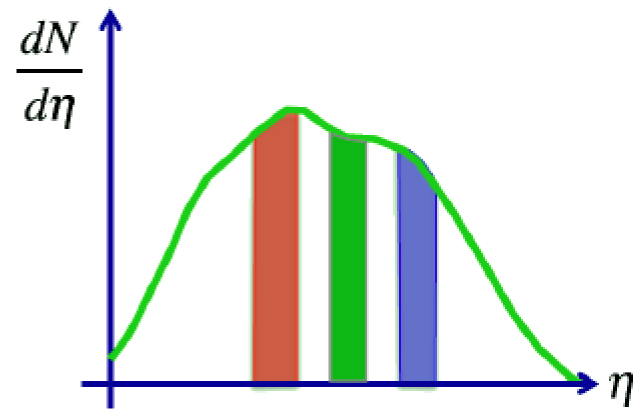
Unique RHIC Capabilities

- Asymmetric ion collisions (e.g., Cu+Au)
  - Made available by new (2012) upgrade (Electron Beam Ion Source)

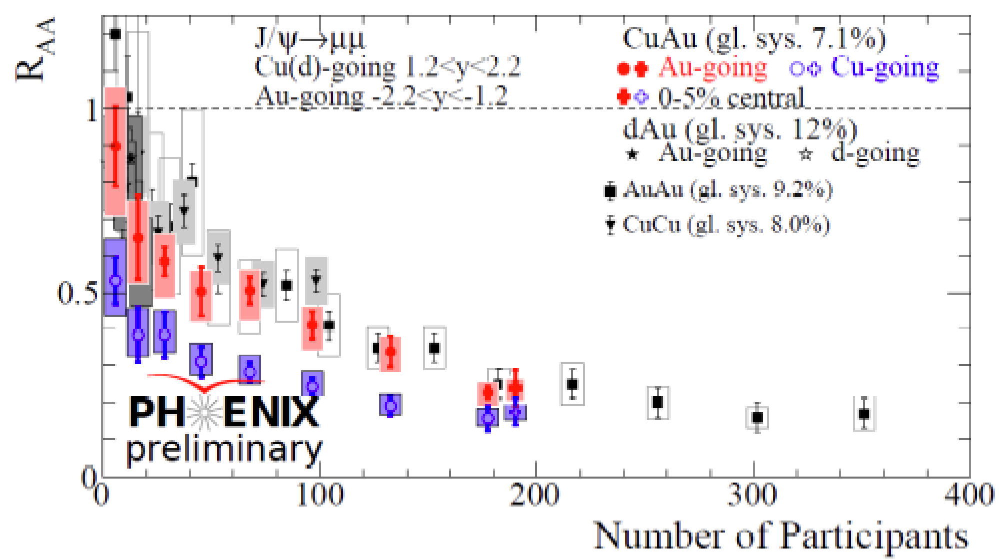


  - Use to
    - Directly excite odd v_n harmonics
    - Directly test "local energy density" effects in J/Ψ absorption
    - Reduce effect of "cold" corona present in symmetric collisions





- Results available just 6 weeks after first run in 2012



Unique RHIC Capabilities

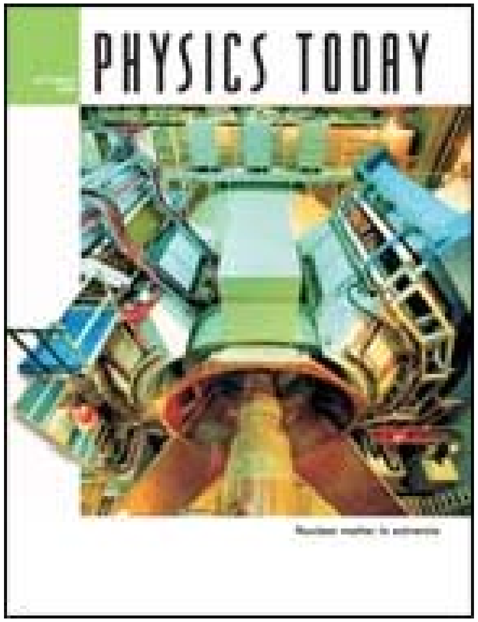
- Polarization ! (see talk by R. Holt)
- As but one example:
  - "Single Spin Asymmetry Scaling in the Forward Rapidity Region at RHIC", Z. Kang and F. Yuan, http://arxiv.org/abs/1106.1375
  - Polarized p+A collisions sensitive to gluon saturation scales:

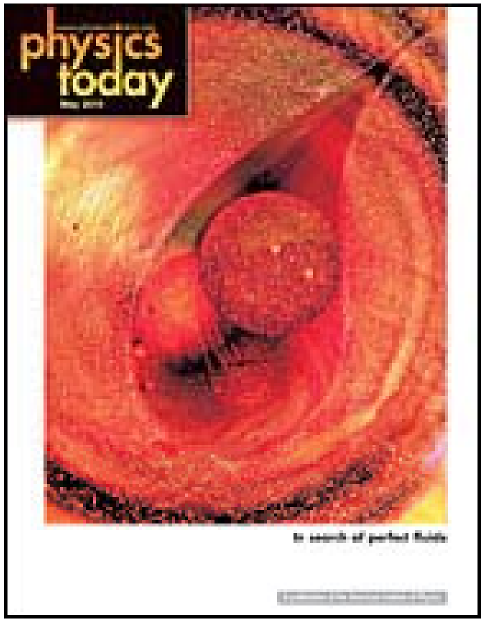
$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \to \begin{cases} \dfrac{Q_{s,p}^2}{Q_{s,A}^2} f(p_T^h) & p_T^h << Q_s^2 \\ 1 & p_T^h >> Q_s^2 \end{cases}$$

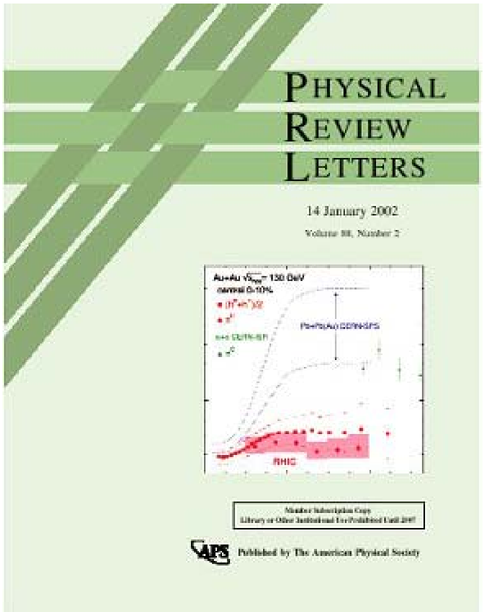
- Fascinating tie between "spin" physics, saturation physics and initial state in A+A

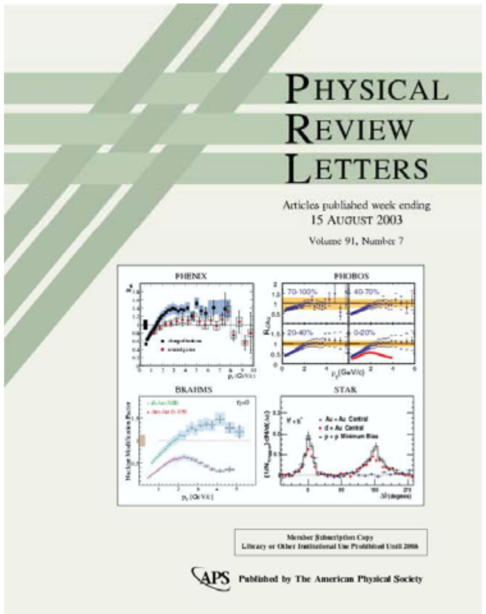
An Extended Summary

National and International Recognition

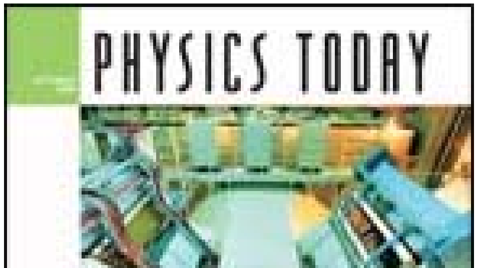


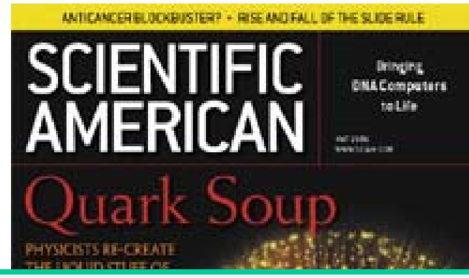


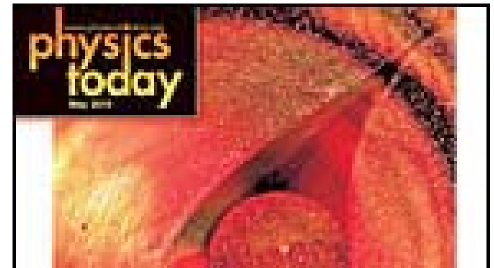




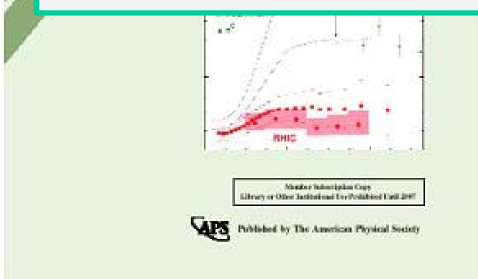
National and International Recognition

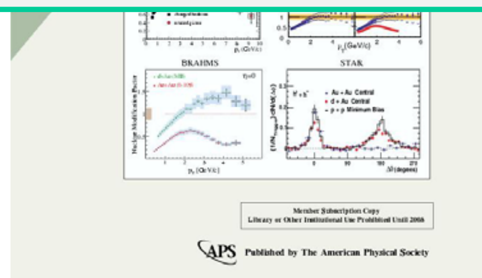


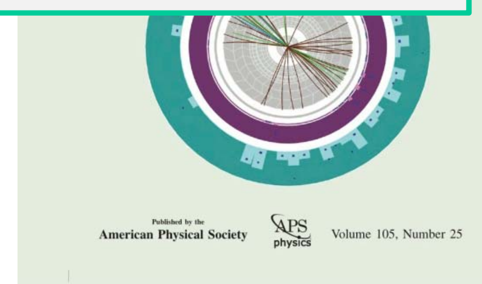




- Saskia Mioduszewski, 2003 Presidential Early Career Award
- Sean Gavin, 2004 Presidential Early Career Award
- Zhangbu Xu, 2004 Presidential Early Career Award
- Yuri Kovchegov, co-recipient 2006 Raymond and Beverly Sackler Prize
- Michael Harrison and Satoshi Ozaki, 2007 IEEE Particle Accelerator S&T Award
- Mickey Chiu, 2007 Presidential Early Career Award
- Paul Sorensen, 2008 George E. Valley Jr. Prize
- Ivan Vitev, 2008 Presidential Early Career Award
- Saskia Mioduszewski, 2009 Maria Goeppert Mayer Award
- Satoshi Ozaki, 2009 Robert R. Wilson Prize
- Yasuyuki Akiba, 2011 Nishina Prize

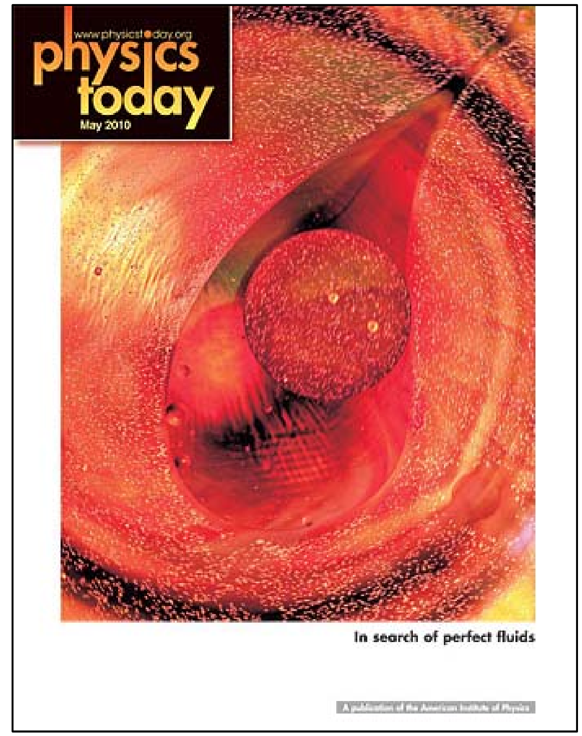






The Big Picture

- The strongly-coupled fluid at RHIC has created strong coupling to other fields:



AdS/QCD

Perfect liquid

AdS/CFT

Prediction of η/s bound

AdS/CMT

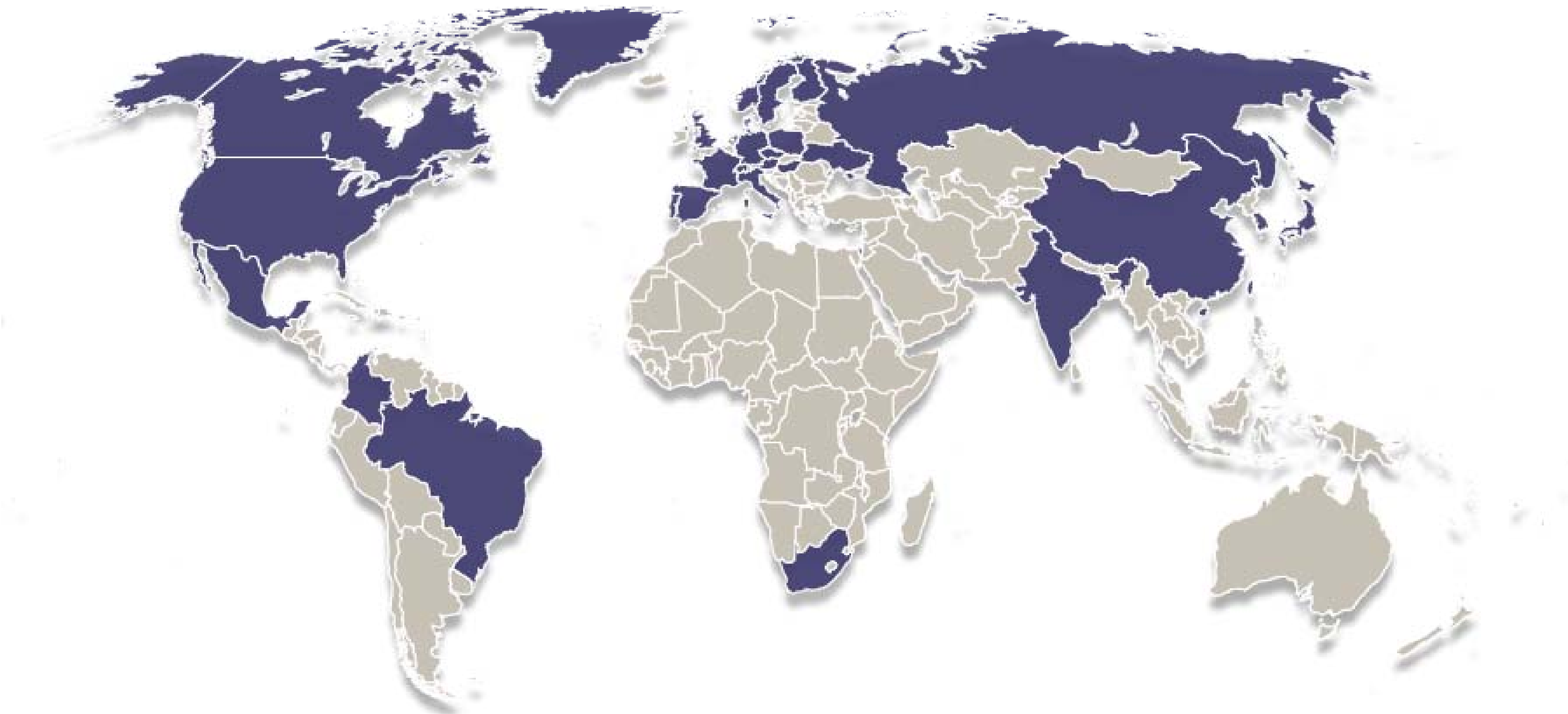
Cold atomic gases

Strongly correlated electrons

The “Quark Matter” Community

Quark Matter 2012

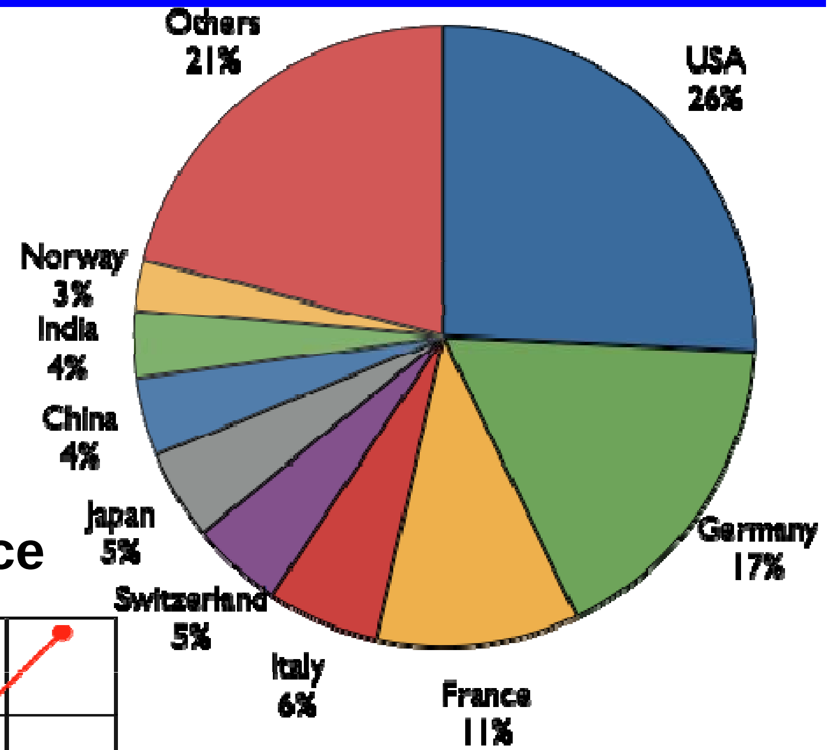
The XXIII International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
August 13-18, 2012, Washington D.C.



Community Demographics

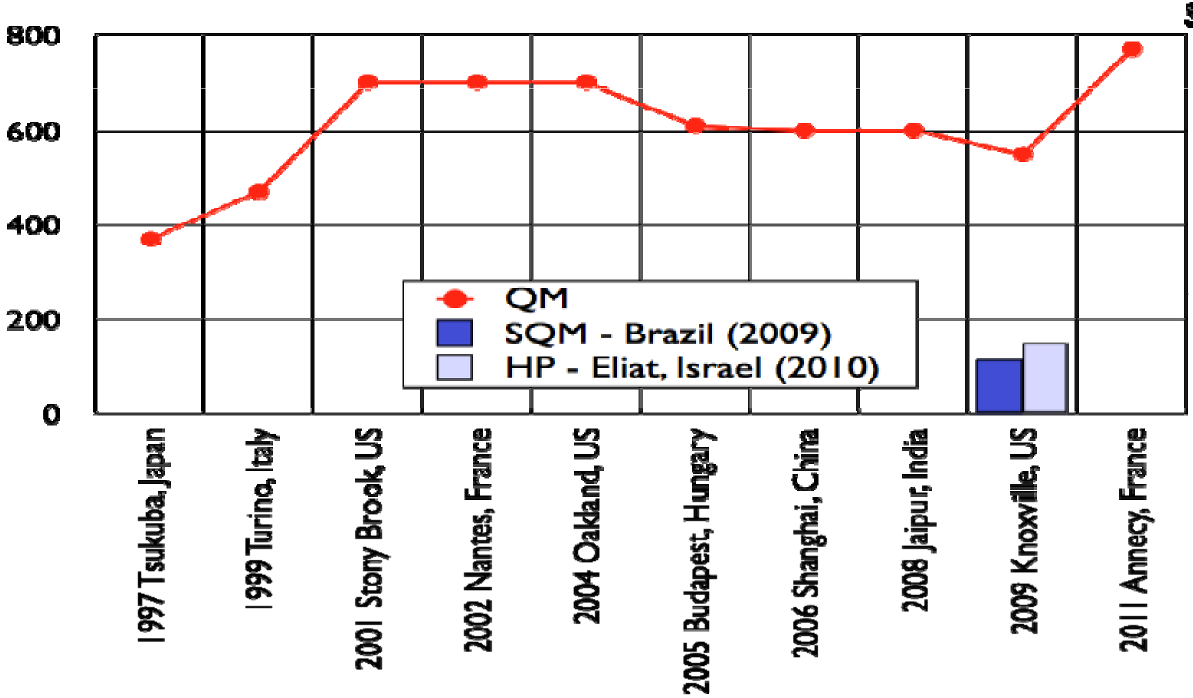
• **Others:** Brazil, Canada, Chile, Czech Republic, Denmark, Finland, Greece, Hungary, Ireland, Israel, Korea, Mexico, Netherlands, Portugal, Romania, Russia, Slovakia, South Africa, Spain, Sweden, Ukraine, United Kingdom

•**Total: 32 countries**



(Numbers from QM2011)

Quark Matter Conference Attendance



Recent Town Meeting

- “2012 D.C. Town Meeting for Heavy Ions”
  - Saturday afternoon
  - in August
  - in D.C.
  - following 5.5. day conference.

- 250+ participants!

(Worldwide) Community Observations

- CERN Council European Strategy Group June 2012 Town Meeting:
  - "The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark Gluon Plasma."
- Summary talk, J. Schukraft, Hard Probes 2012

•***Strength of RHIC: Our 'dedicated facility'***

Beam energy dependence

- vary ε, T, (maybe) the coupling, …

Nuclear size dependence

- extract core-corona effects, …

RHIC -> LHC comparison is crucial

- we need to raise the temperature

Yet another clear-cut case for 'long live the RHIC'

- National Academy Decadal Survey for Nuclear Physics (2012):
  - **Finding:** By capitalizing on strategic investments, including the ongoing upgrade of the continuous electron beam accelerator facility (CEBAF) at the Thomas Jefferson Accelerator Facility and the recently completed upgrade of the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory, as well as other upgrades to the research infrastructure, nuclear physicists will confront new opportunities to make fundamental discoveries and lay the groundwork for new applications.

Observations

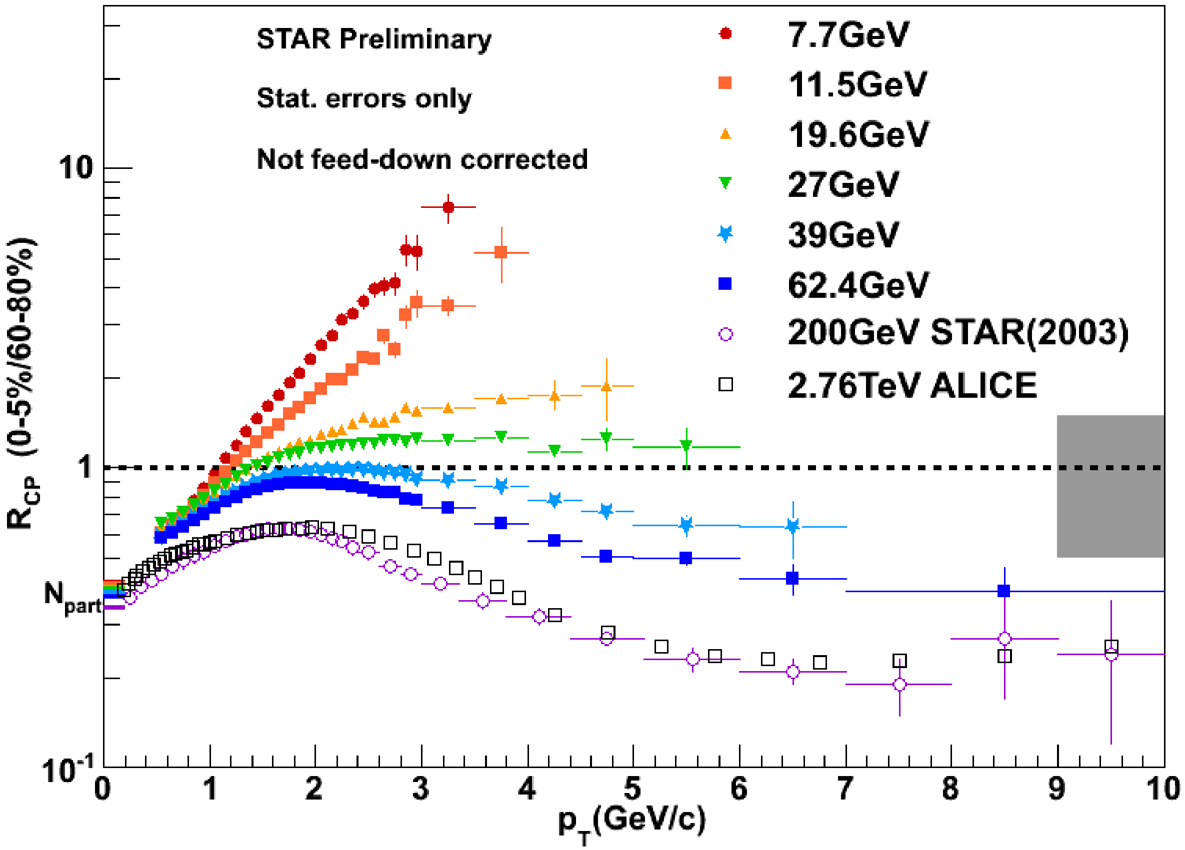
- The extraordinary success of RHIC in its first decade of operations was possible because it is a *dedicated* facility.

- The extraordinary success of the heavy ion program at the LHC is in part due to the successful import of techniques developed at RHIC.

- With the luminosity upgrade, EBIS, and detector upgrades, RHIC is perfectly positioned to quantify QGP properties and to explore the QCD phase diagram

The Program Going Forward

- A rich combination of precision and discovery:



- Exploration of the QCD phase diagram
- Quantification of the QGP medium properties

+

- Exploration of exotica
- Cold nuclear matter
- Spin
- Saturation physics

Back-Up Material

Science Questions (2007 LRP)

- What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
- What does QCD predict for the properties of strongly interacting matter?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons and gluon self-interactions in nucleons and nuclei?
- What determines the key features of QCD, and what is their relation to the nature of gravity and spacetime?

Science Questions (Decadal Survey)

- Does the QGP have a particulate description at any length scale? At any temperature scale? Is the somewhat hotter QGP produced and studied at the LHC also liquid-like, as at RHIC, or does it start to show signs of behaving like a weakly-coupled, more conventional, plasma?
- Experiments at RHIC indicate that the quark-gluon plasma liquid forms and reaches local equilibrium remarkably quickly, in about the time it takes light to travel across one proton. How does this happen? How does the system go from the strong gluon fields hypothesized to occur inside large nuclei to the flowing QGP liquid? Does this also happen in heavy ion collisions at the LHC?
- Does the quark-gluon plasma liquid produced at RHIC dissolve even the very small particles formed from heavy quarks and their anti-particles? Does the quark-gluon plasma prevent a heavy quark and antiquark from binding to each other only when they are farther apart than some "screening length"? How close together do they have to be for them to feel the same attraction that they would feel if they were in vacuum?
- How do the energetic particles produced in the earliest stages of a heavy ion collision interact with and deform the fluid? Are very high energy quarks or very heavy "bottom quarks" weakly coupled to the fluid or do they rapidly become part of the soup?
- Experiments at RHIC and lattice QCD calculations both indicate that as QGP cools, the reassembly of quarks and gluons into hadrons takes place over a broad temperature range. But, some theoretical calculations indicate that quark-gluon plasma in which there is a greater excess of quarks over antiquarks, as produced in lower energy collisions, should cool through a true phase transition, much like thecondensation of water droplets from cooling vapor. If so, there is a sharp phase transition line in the phase diagram of QCD that must end at a "critical point". Is there such a critical point in the experimentally accessible domain?

Science Questions (RHIC White Paper)

- What techniques can be used to pump and probe condensed strongly interacting matter that lives for only ~10^{-23} seconds after a collision?
- What are the unique emergent phenomena for matter governed by QCD?
- How did these emergent phenomena influence the evolution of the early universe?
- What roles do quantum fluctuations play in the evolution of the "mini-universe" created in each RHIC collision?
- Are there lessons to be learned from QCD matter that can inform our understanding of other non-Abelian matter (e.g., that at the ElectroWeak phase transition in the infant universe) that is more difficult or not possible to subject to laboratory investigation?

Science Questions (RHIC White Paper)

- How does strongly coupled liquid behavior arise from an asymptotically free theory?
- How close does η/s come to the AdS/CFT bound, and how does it vary as one goes from temperatures below to well above the deconfinement transition?
- What are the values of other transport coefficients in the QGP as a function of temperature, and how do they compare to expectations from lattice QCD?
- How does the QGP matter respond to the absorption of energy 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, and how is the rapid thermalization influenced by details of the gluon-dominated initial state in the collisions?
- Do heavy (c and b) quarks participate fully in the thermalization, the collective flow and the energy loss phenomena established so far for lighter quarks?
- How is the color force that binds quarks together screened, over distances comparable to hadron sizes, by the presence of colored QGP matter?

From June 2012 Town Meeting of European Strategy Group

Major recommendations

1. *The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.*

2. **At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.**

3. **The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.**

4. **Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.**

Long Range Plan Recommendations

RECOMMENDATION IV

The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

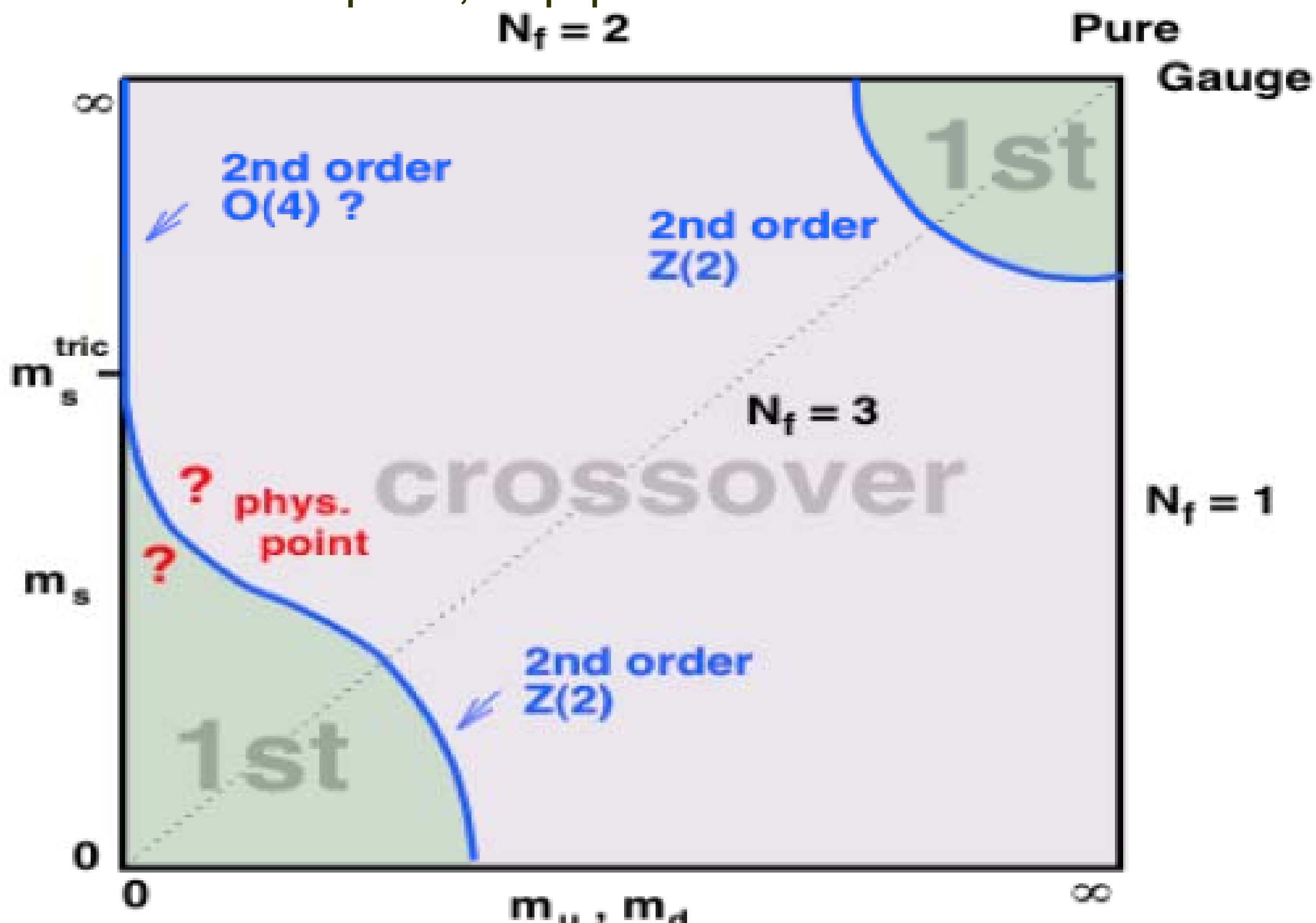
The major discoveries in the first five years at RHIC must be followed by a broad, quantitative study of the fundamental properties of the quark-gluon plasma. This can be accomplished through a 10-fold increase in collision rate, detector upgrades, and advances in theory. The RHIC II luminosity upgrade, using beam cooling, enables measurements using uniquely sensitive probes of the plasma such as energetic jets and rare bound states of heavy quarks. The detector upgrades make important new types of measurements possible while extending significantly the physics reach of the experiments. Achieving a quantitative understanding of the quark-gluon plasma also requires new investments in modeling of heavy-ion collisions, in analytic approaches, and in large-scale computing.

support. Detector upgrades at RHIC, which are part of Recommendation IV, will proceed over several years, and the accelerator modifications needed to implement beam cooling, which will significantly increase the RHIC luminosity, will be carried out between 2012 and 2015. Following this course, nuclear science in the United States will continue to have world-leading facilities into the future.

phenomenological modeling, and new initiatives. Strategic investments in LHC detector instrumentation and computing, which leverage the capabilities of the existing LHC detectors, are required for significant and timely U.S. participation in the LHC heavy-ion program. Collectively, these investments will result in a dramatic advance in our understanding through quantitative comparison of theory and experiment. The synergies of RHIC and the LHC will lead to a much deeper understanding of the properties and dynamics of dense QCD matter.

To Be Fair…

- *Order* of QCD transition sensitive to $m_s/m_{u,d}$
  - E. Laermann and O. Philipsen, hep-ph0303042

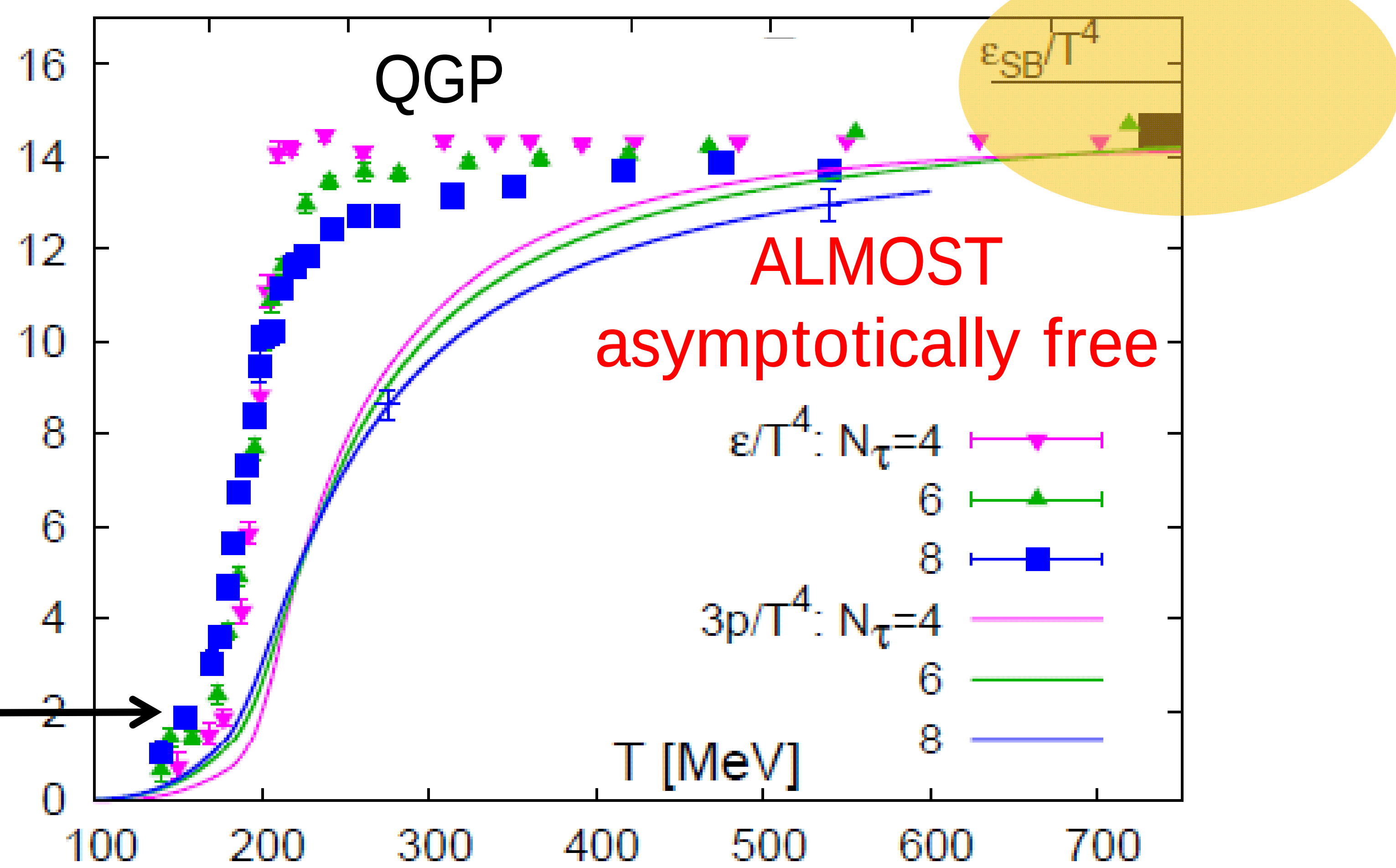


- But qualitative features persist for “all” $m_s/m_{u,d}$

The Paradigm Shift - Before

- Recall Stefan-Boltzmann → $\varepsilon = \frac{\pi^2}{30} T^4 \sim \frac{1}{3} T^4$ *per* d.o.f.

$$\frac{\varepsilon}{T^4} \sim \frac{\text{d.o.f}}{3}$$



"Pion" gas

The Paradigm Shift – After

- Recall Stefan-Boltzmann → $\varepsilon = \frac{\pi^2}{30} T^4 \sim \frac{1}{3} T^4$ *per* d.o.f.

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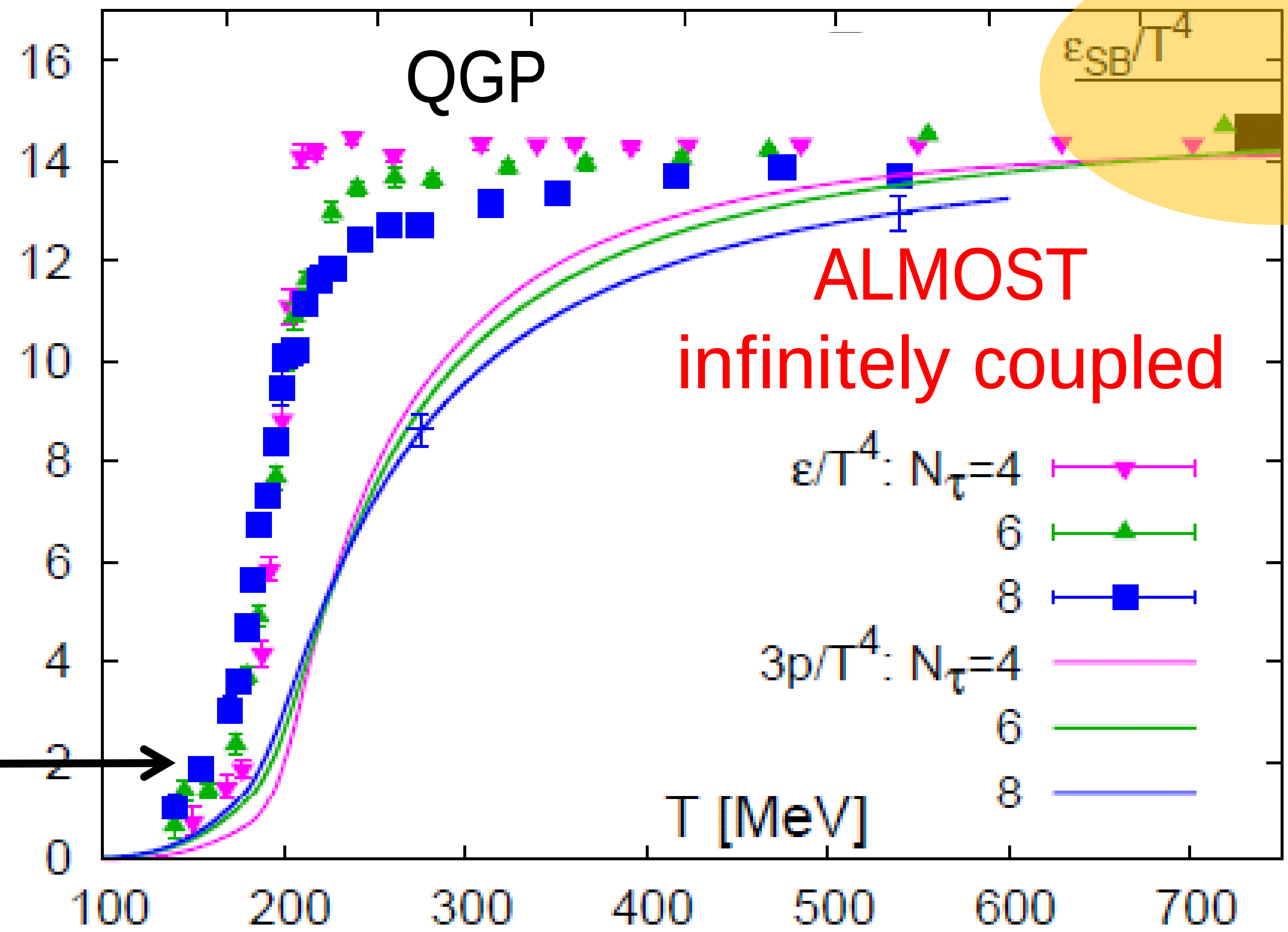
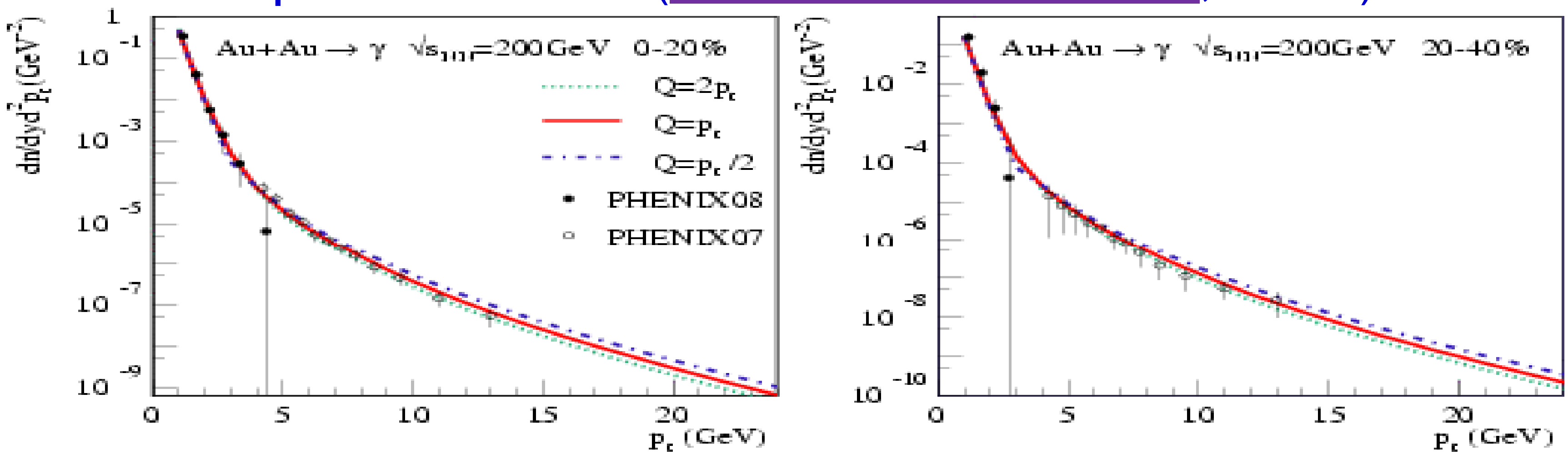


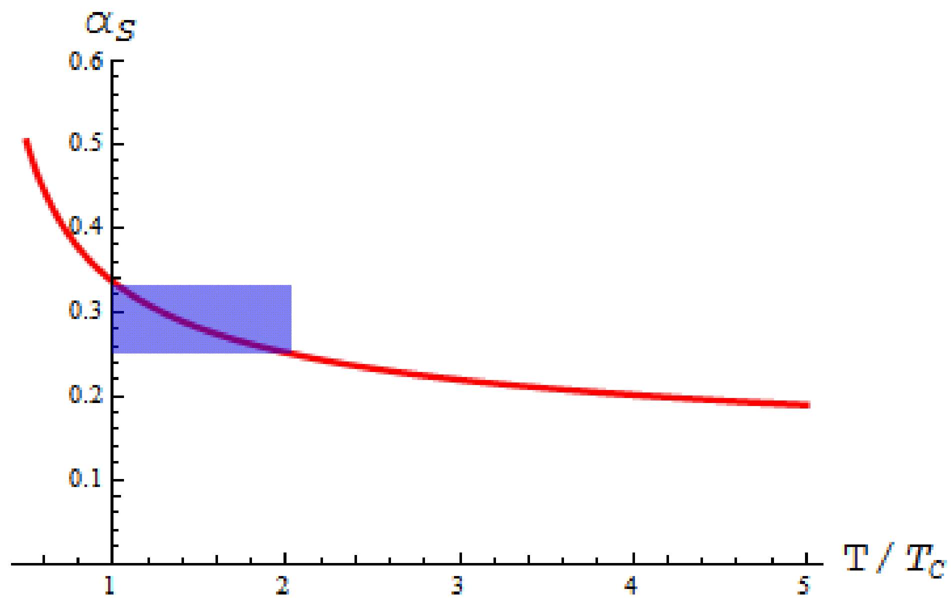
Beyond ‘t Hooft Limit ? (1)

- A foolish consistency is the hobgoblin of little minds…
- Hydro direct photon results (Liu, Hirano, Werner, Zhu; QM09)



use

$$\alpha_s(T) = \frac{6\pi}{(33-2N_f)\log\left(\frac{8T}{T_c}\right)} \sim 0.25-0.33$$



Beyond 't Hooft Limit ? (2)

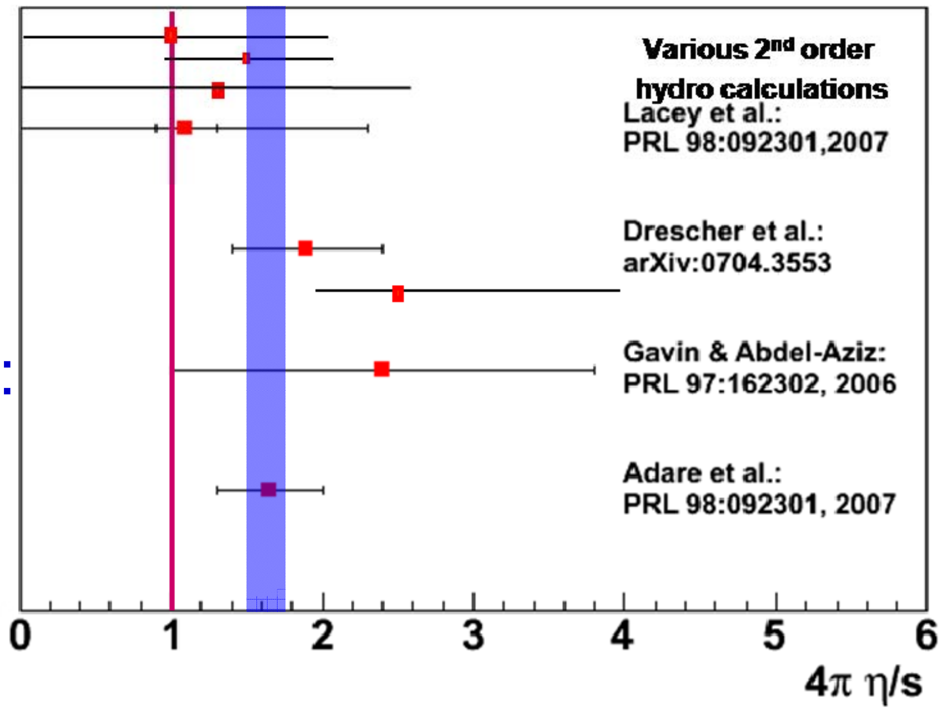
- Use this range for α_S ~0.25-0.33 in result from Myers, Paulos and Sinha (http://arxiv.org/abs/0806.2156)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left\{1 + \frac{15\zeta(3)}{\lambda^{3/2}} + \frac{5}{16}\frac{\lambda^{1/2}}{N_C{}^2} + \cdots\right\} \Rightarrow \frac{\eta}{s} \sim (1.54 - 1.73)\frac{1}{4\pi}$$

→ (Using *most naïve* $\alpha_s = g_{YM}{}^2/4\pi$)

$$\lambda = g_{YM}{}^2 N_C$$

- Compare this to compilation of η/s estimates:



!

Beyond 't Hooft Limit ? (3)

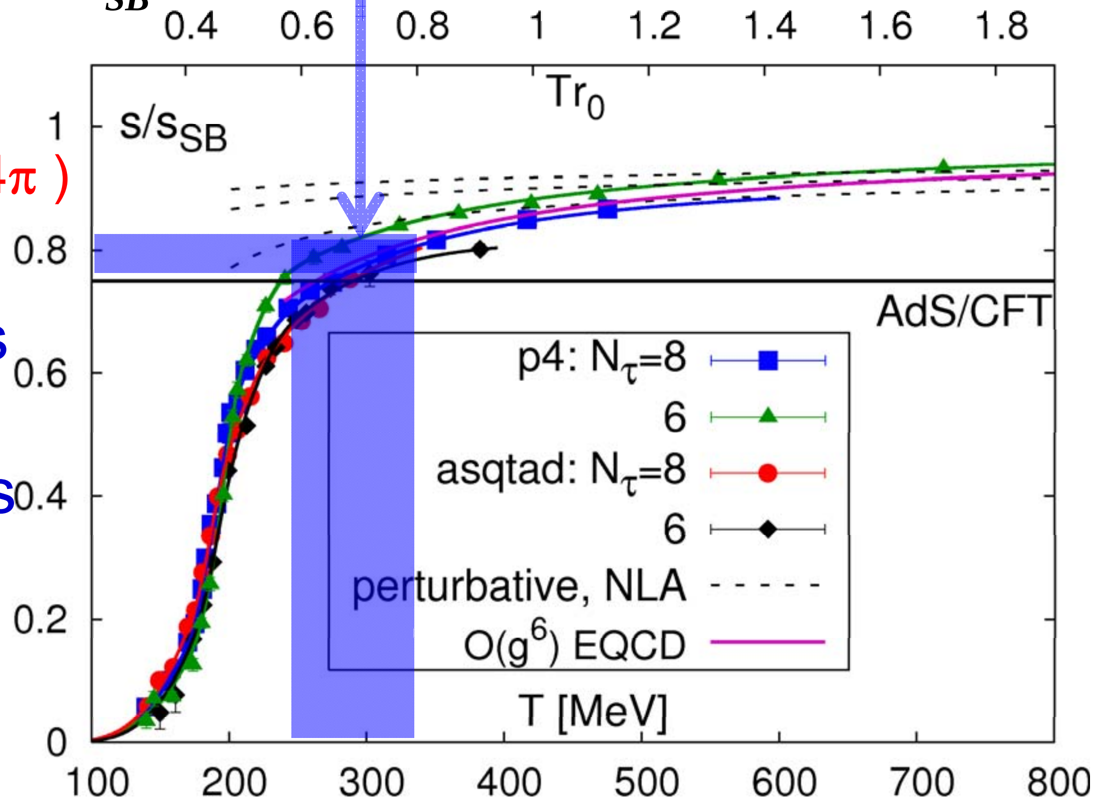
- Consistency check: Use *same* range α_S ~0.25-0.33
  In 'ancient' result from

  Gubser, Klebanov and Tseytlin (http://arxiv.org/abs/hep-th/9805156)

$$\frac{s}{s_{SB}} = \frac{3}{4} + \frac{45\zeta(3)}{32\lambda^{3/2}} + \cdots \quad \Rightarrow \quad \frac{s}{s_{SB}} \sim 0.78 - 0.81$$

→ (Using *most naïve* $\alpha_s = g_{YM}^2/4\pi$)

- Check if this corresponds to 'sensible' temperature range using lattice results for $s(T)/s_{SB}$:



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