Quark Gluon Plasma

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T. I. F. R., Mumbai

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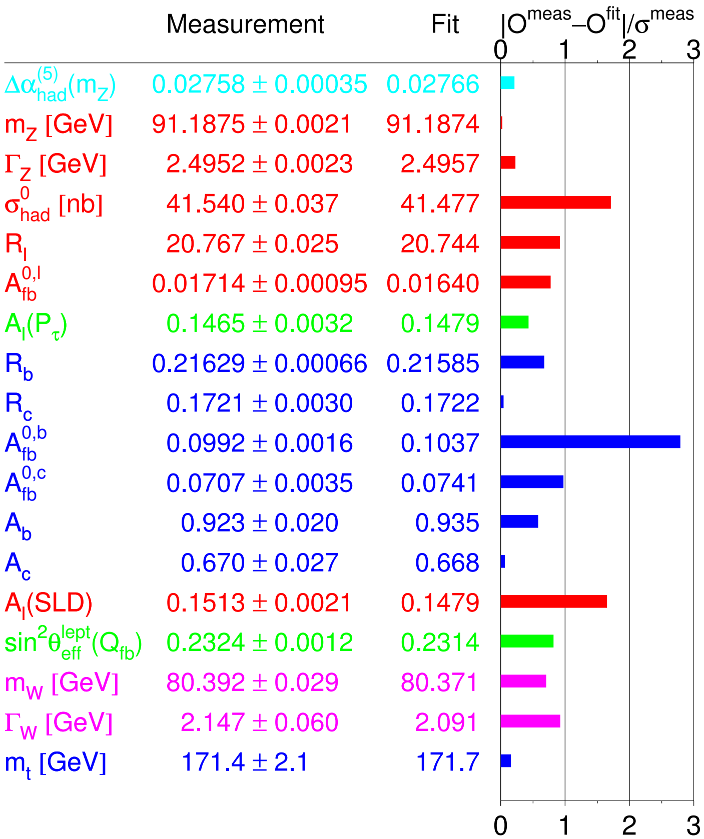
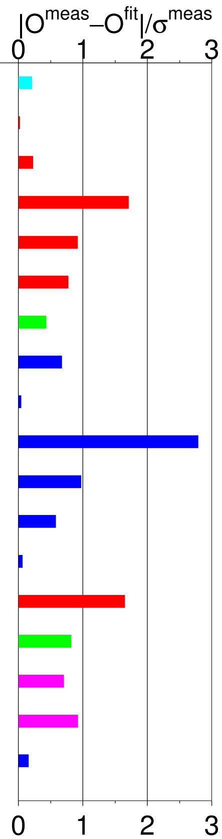
Introduction



Introduction

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



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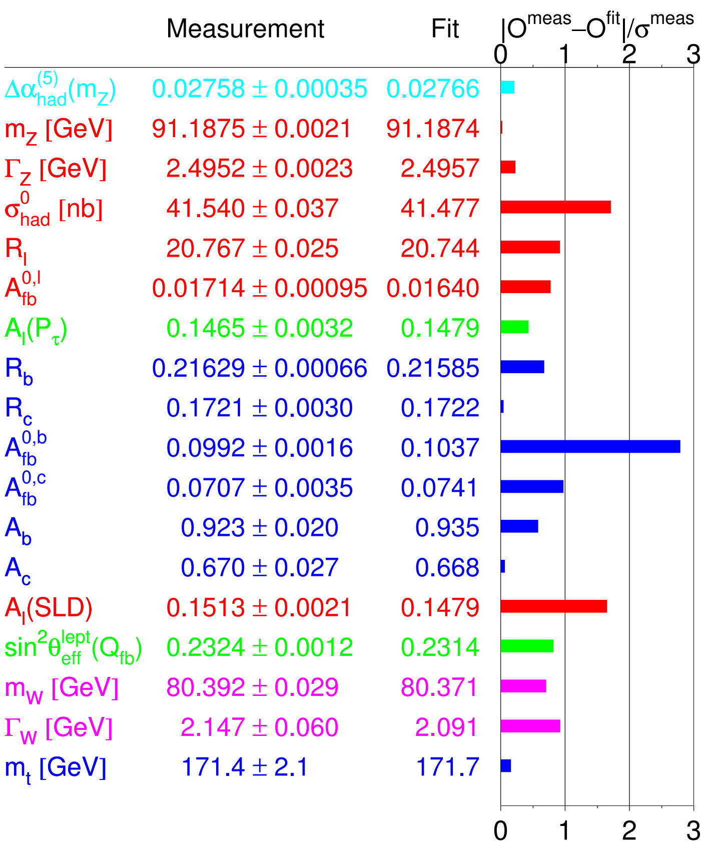

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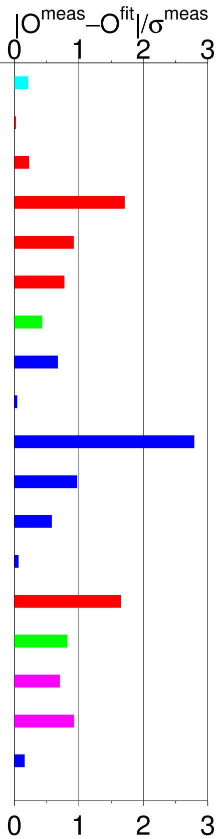

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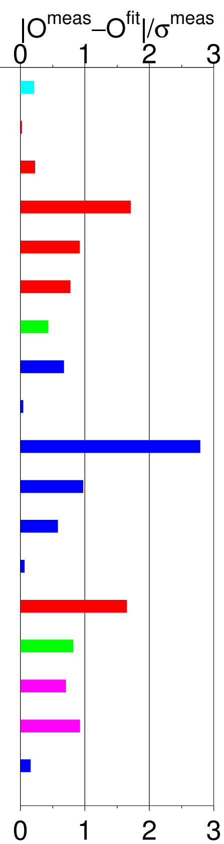

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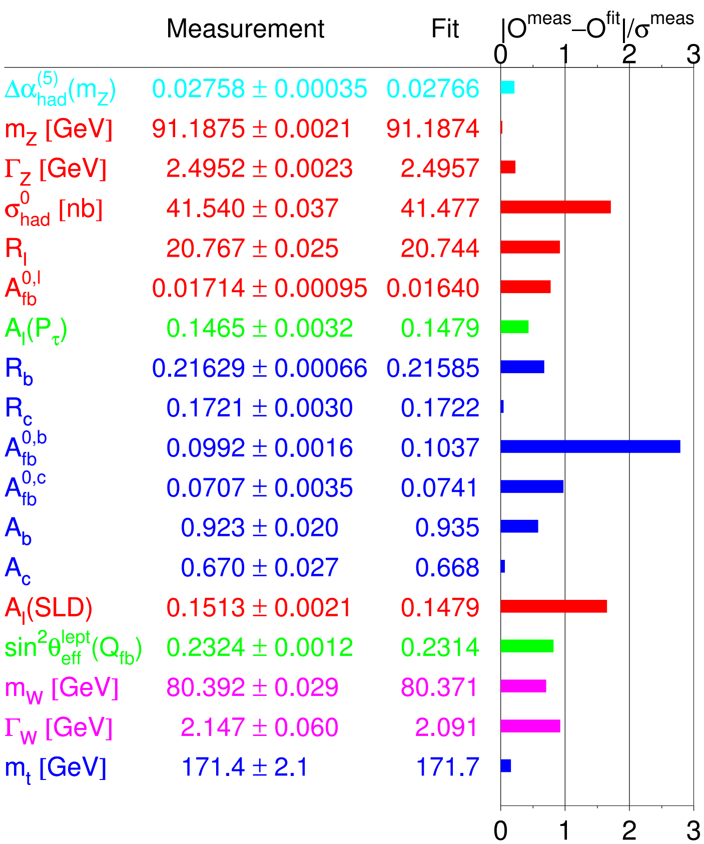

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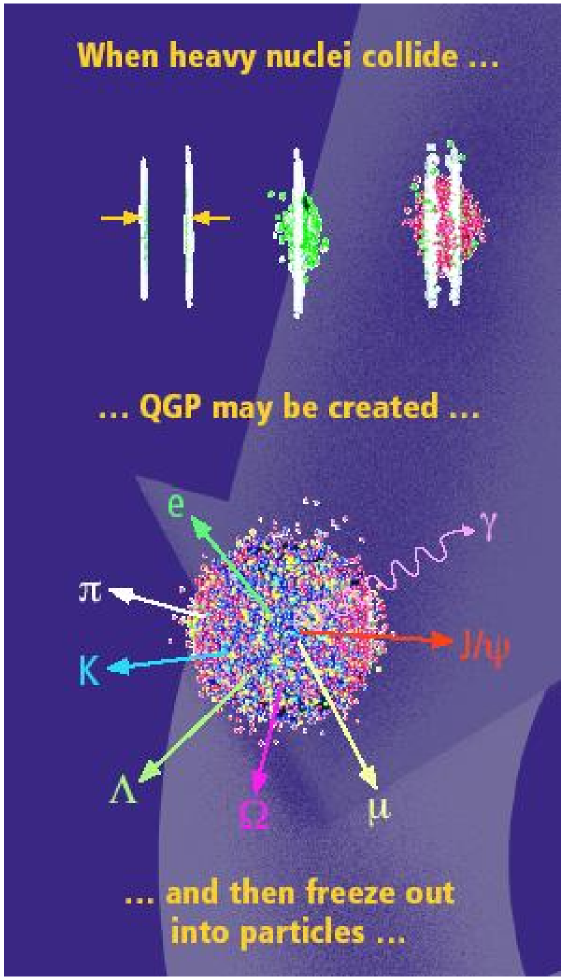
- It predicts a transition to Quark-Gluon Plasma (QGP), and QGP properties.

♠ Quest for Quark-Gluon Plasma : Heavy Ion Collisions at SPS, RHIC and LHC.



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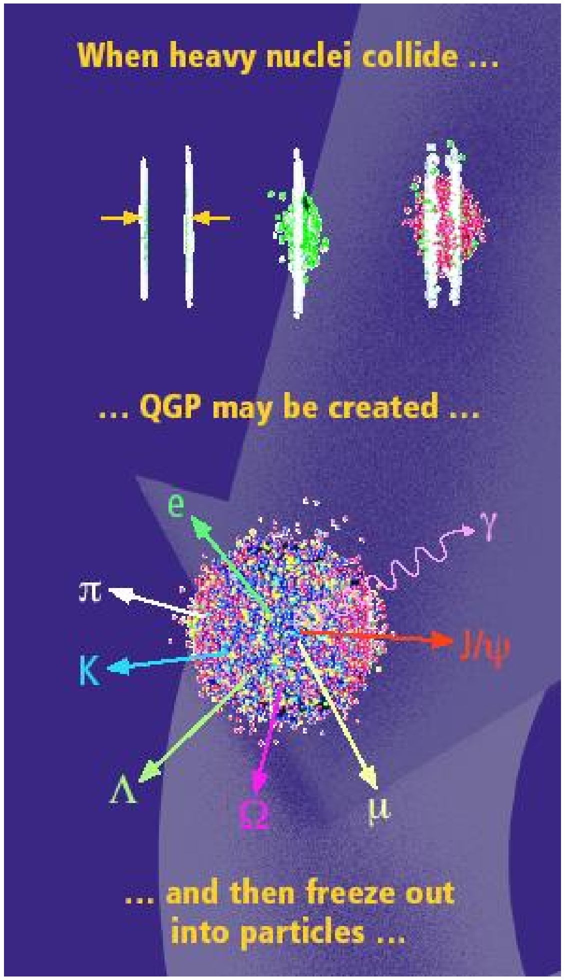

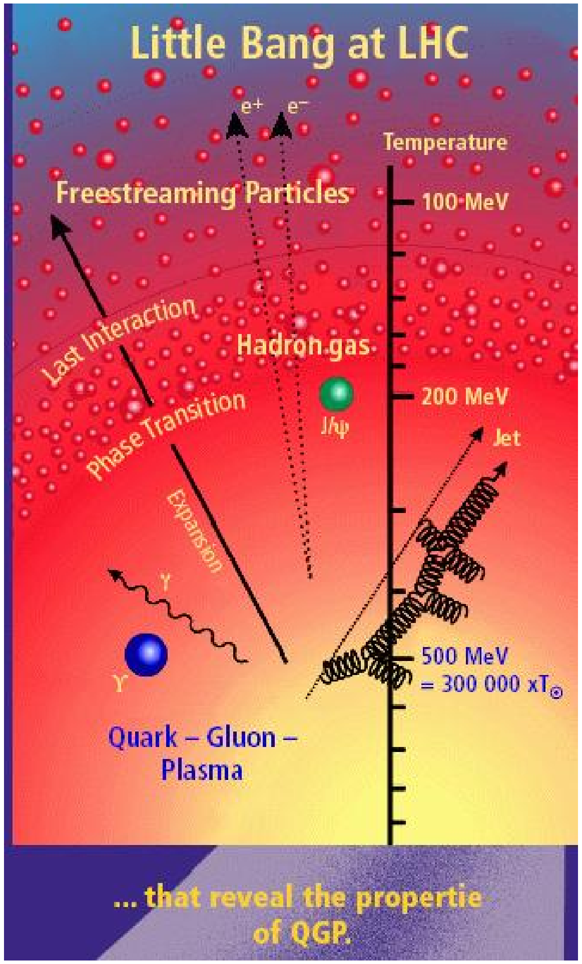

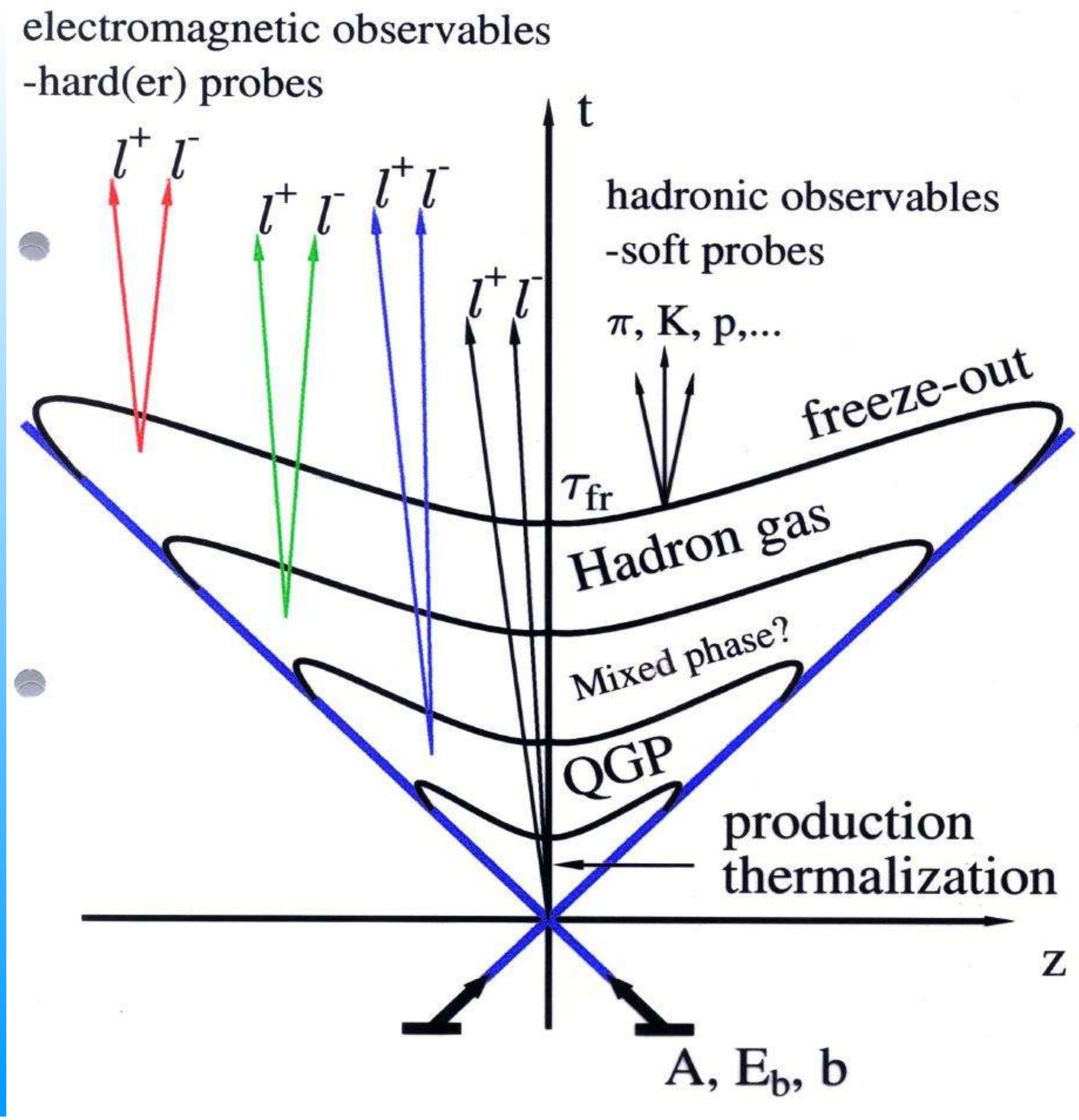

electromagnetic observables
-hard(er) probes
t
$l^+ l^-$
$l^+ l^-$
$l^+ l^-$
$l^+ l^-$
hadronic observables
-soft probes
π, K, p,...
freeze-out
τ_{fr}
Hadron gas
Mixed phase?
QGP
production
thermalization
z
A, E_b, b

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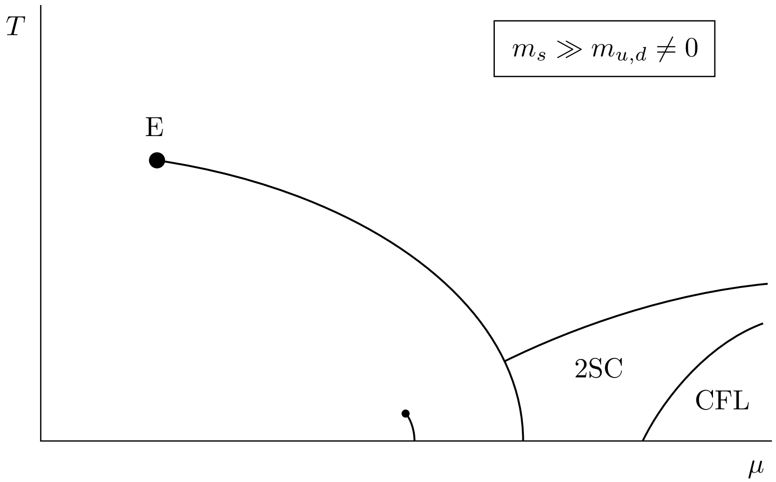
Expected QCD Phase Diagram



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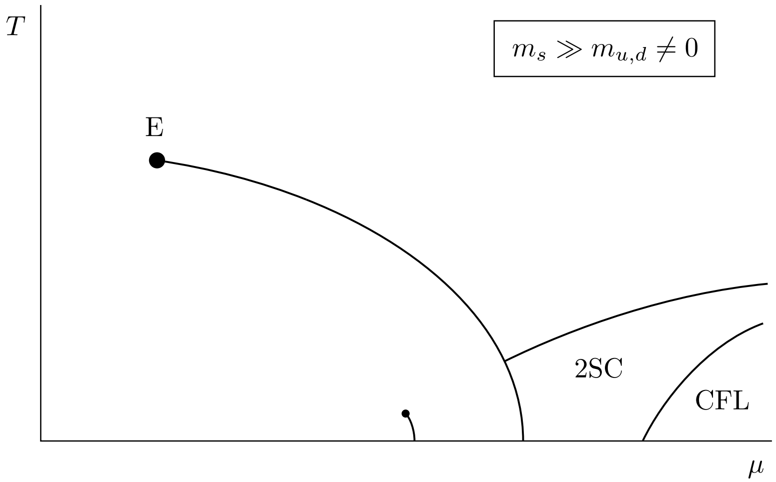

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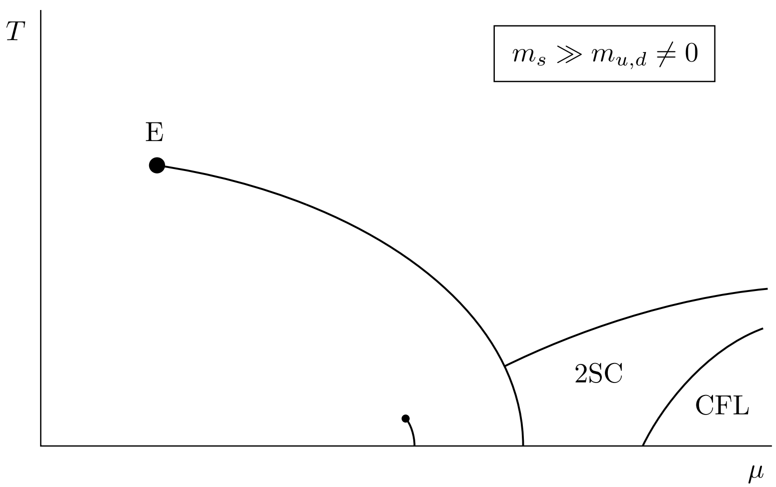

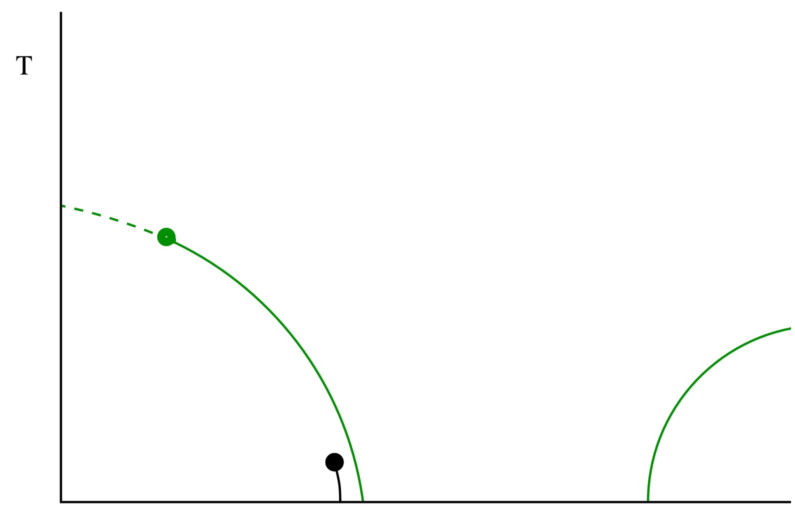

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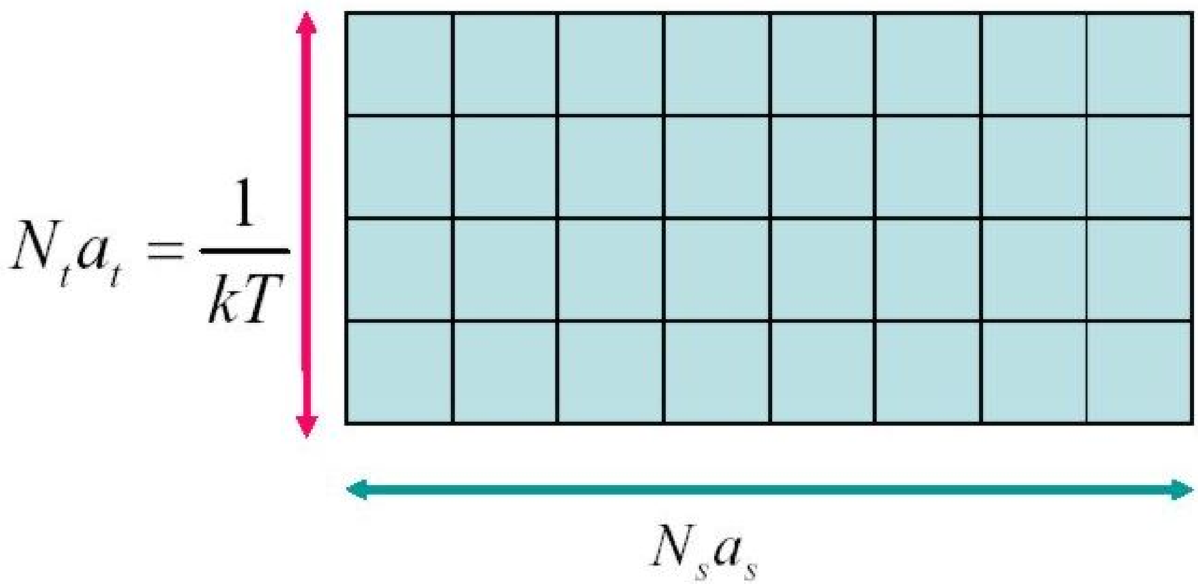

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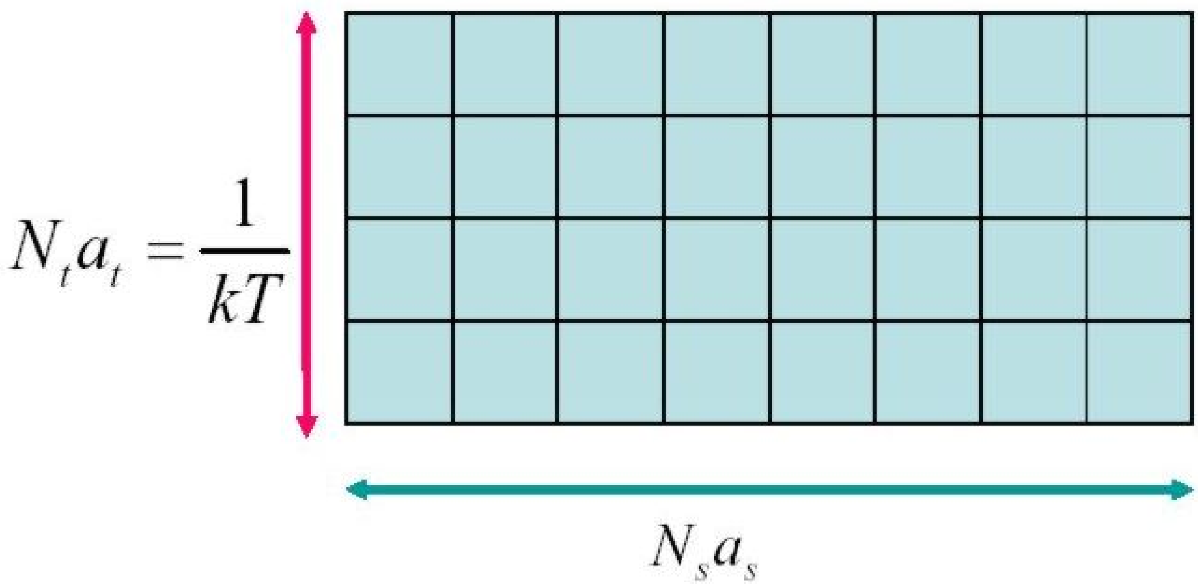

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- Completely parameter-free : Λ_{QCD} and quark masses from hadron spectrum.

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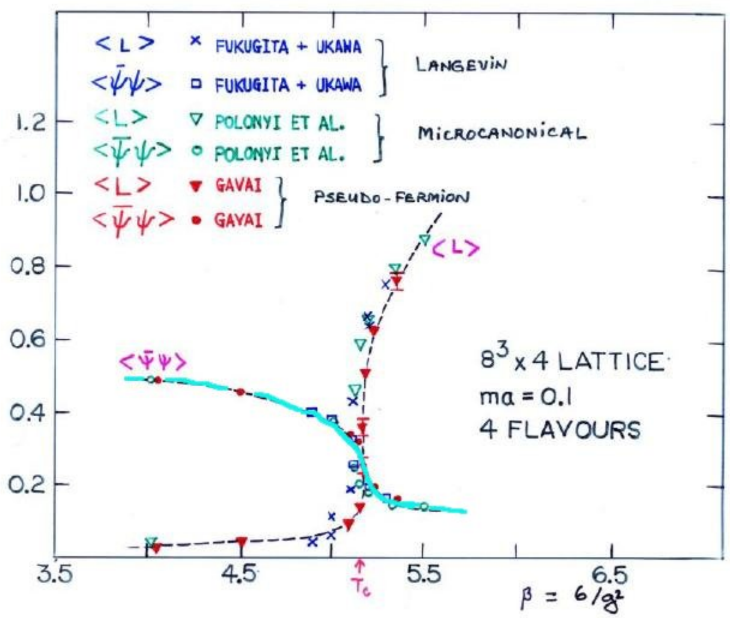

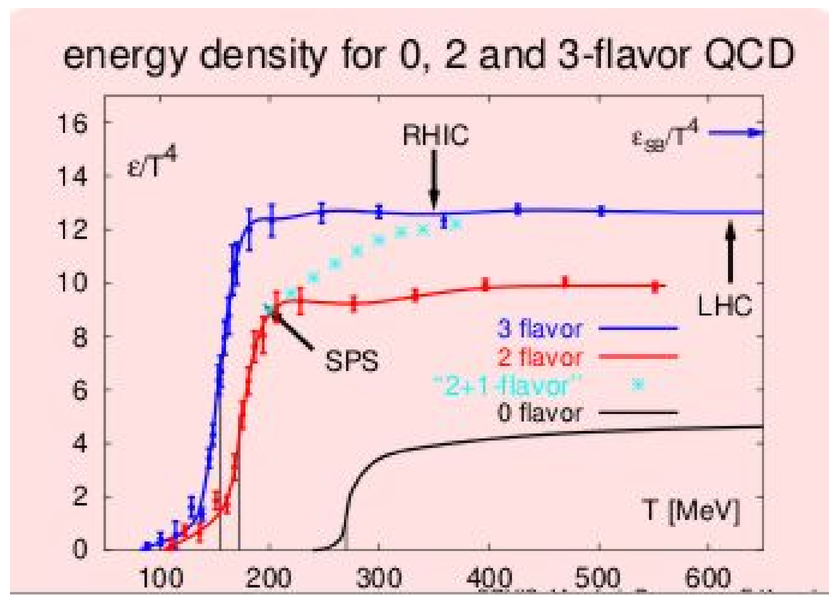

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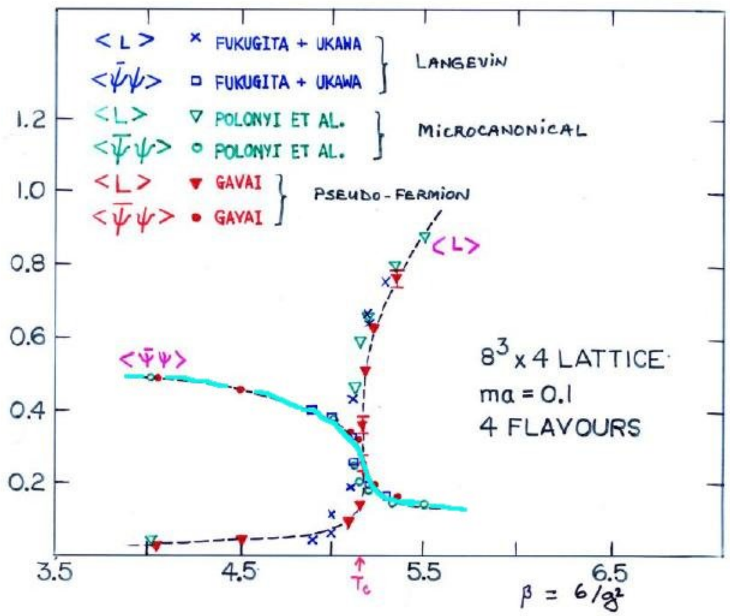

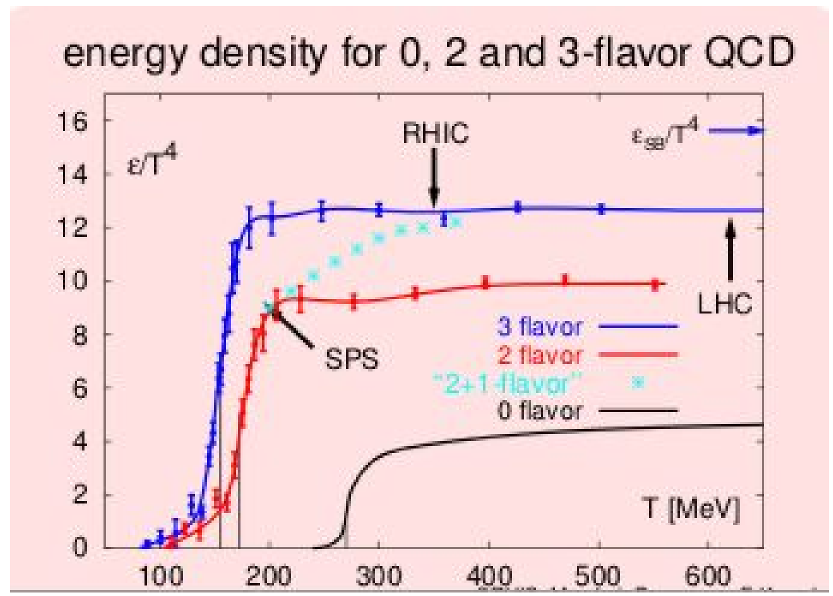

- Other quantities, notably strangeness enhancement in Heavy Ion Physics, the Wróblewski Parameter λ_s (RVG & Sourendu Gupta PR D 2002) have also been predicted by lattice QCD.

- Thrust of new results now on
  - continuum limit, lighter quarks, 2+1 flavours

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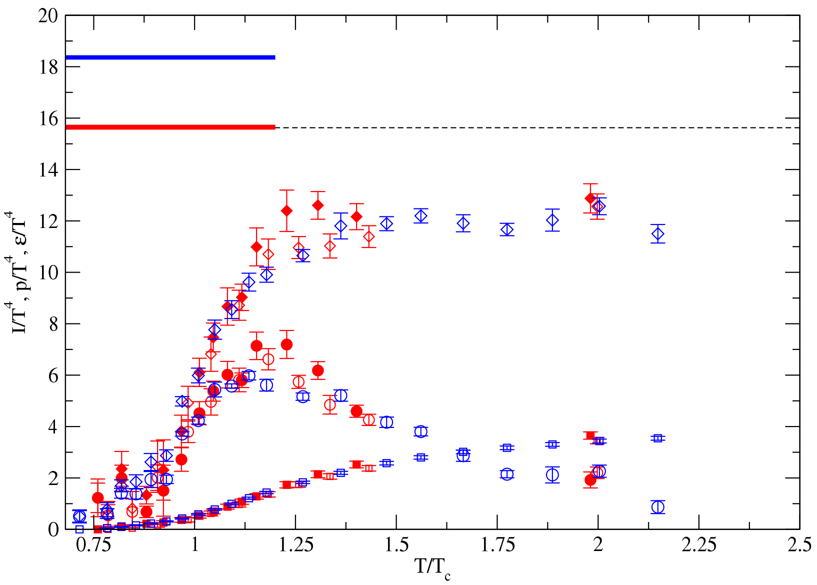
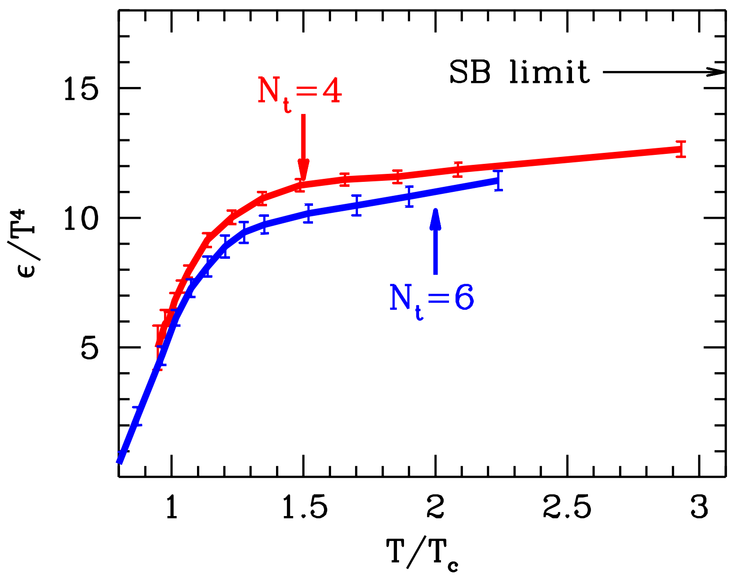
- Lot of activity in Model Building to explain Lattice QCD results: Quasi-particle models, Hadron Resonance Gas, Quarkonia from Lattice $Q\bar{Q}$ potential, sQGP and coloured states...

QGP in Bulk : EoS, Speed of Sound...

- Recent results for EoS : N_t=6, Smaller quark masses.





Bernard et al., MILC hep-lat/0509053;

Aoki et al., hep-lat/0510084.

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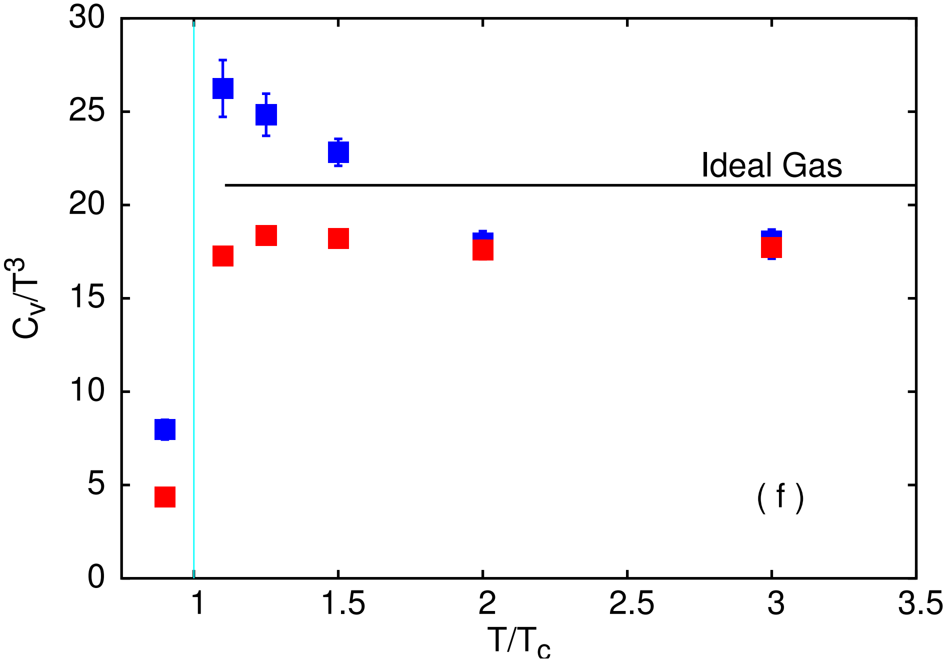
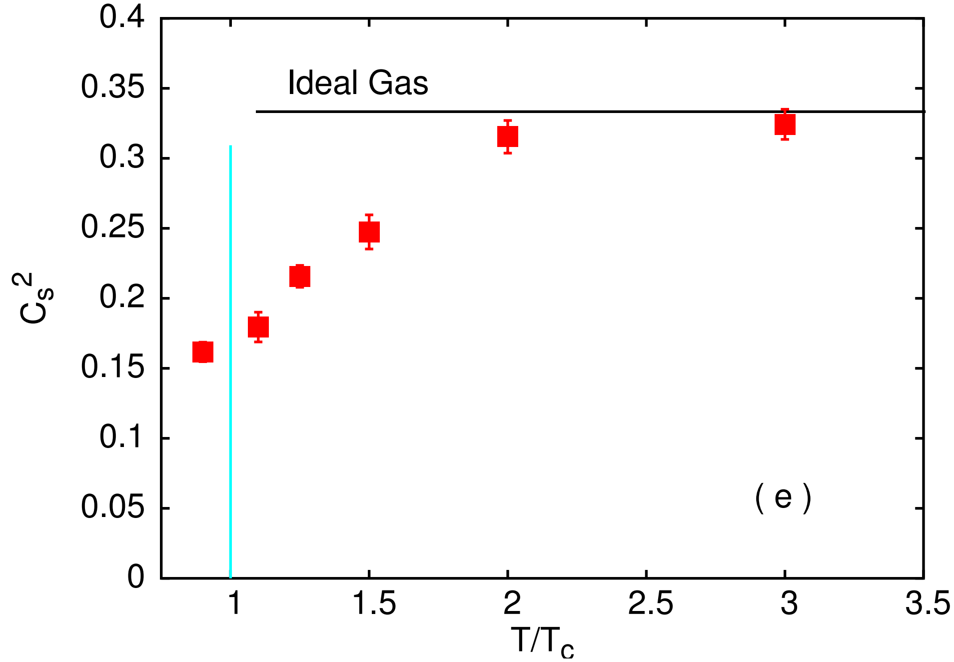
- Using lattices with 8, 10, and 12 temporal sites ($38^3 \times 12$ and 38^4 lattices) and with statistics of 0.5-1 million iterations, ϵ, P, s, C_s^2 and C_v obtained in continuum.





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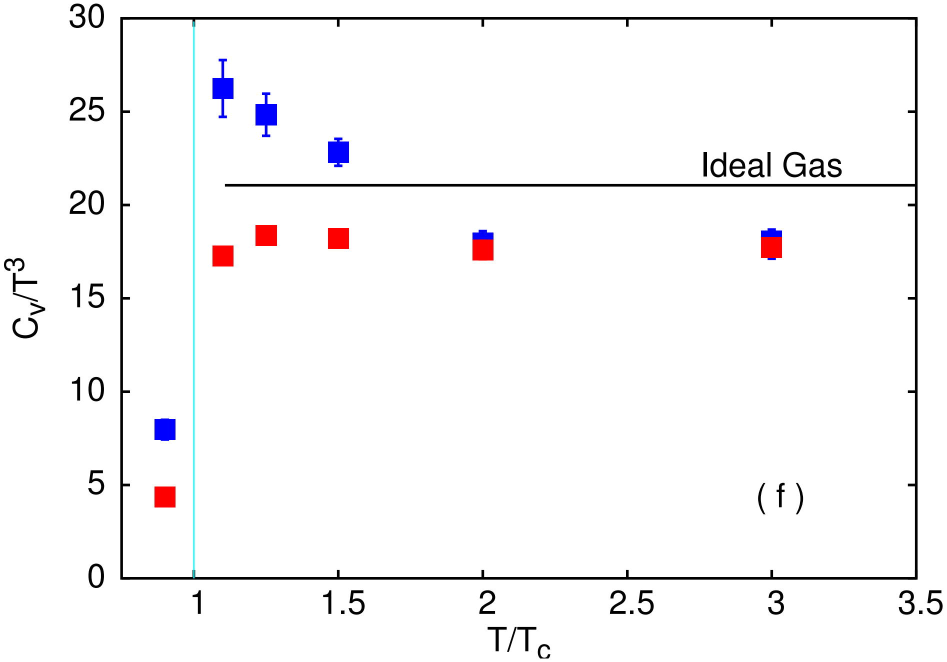

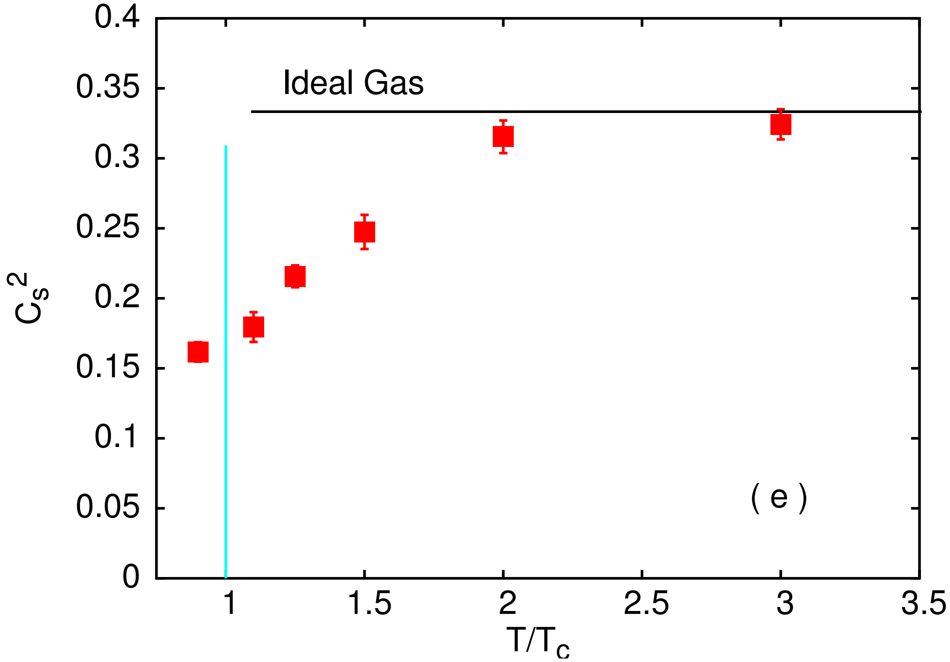

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♠ $C_v \sim 4\epsilon$ for $2T_c$ but No Ideal Gas limit.

♠ Specific heat $\Longleftrightarrow$ fluctuations in p_T ?

♠ C_s^2 closer to Ideal Gas limit; Any structure near T_c ??

- Entropy agrees with strong coupling SYM prediction (Gubser, Klebanov & Tseytlin, NPB '98, 202) for $T = 2 - 3T_c$ but fails at lower T, as do various weak coupling schemes : $\frac{s}{s_0} = f(g^2 N_c)$, where $f(x) = \frac{3}{4} + \frac{45}{32}\zeta(3)x^{-3/2} + \cdots$ and $s_0 = \frac{2}{3}\pi^2 N_c^2 T^3$.

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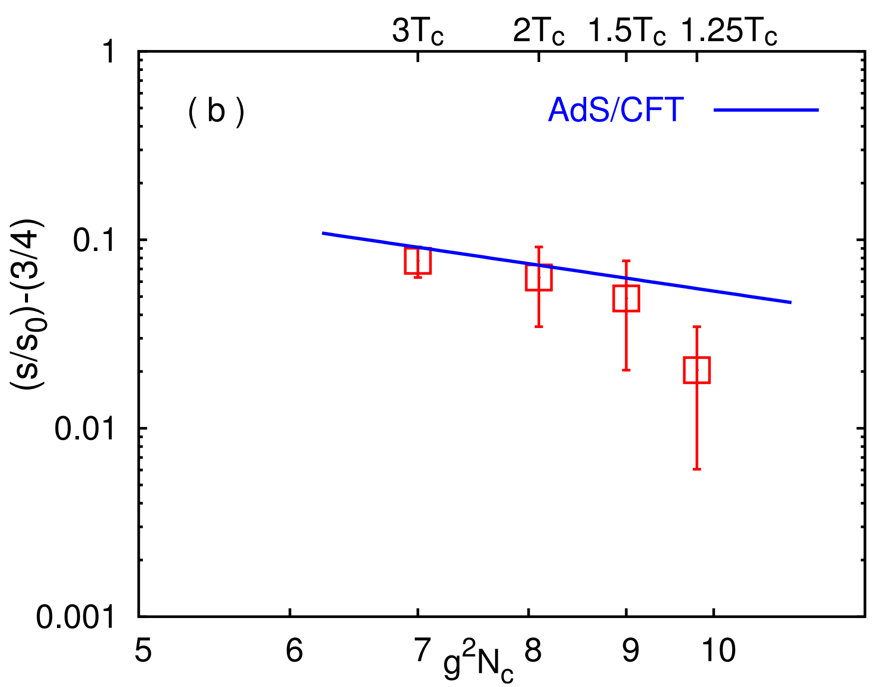

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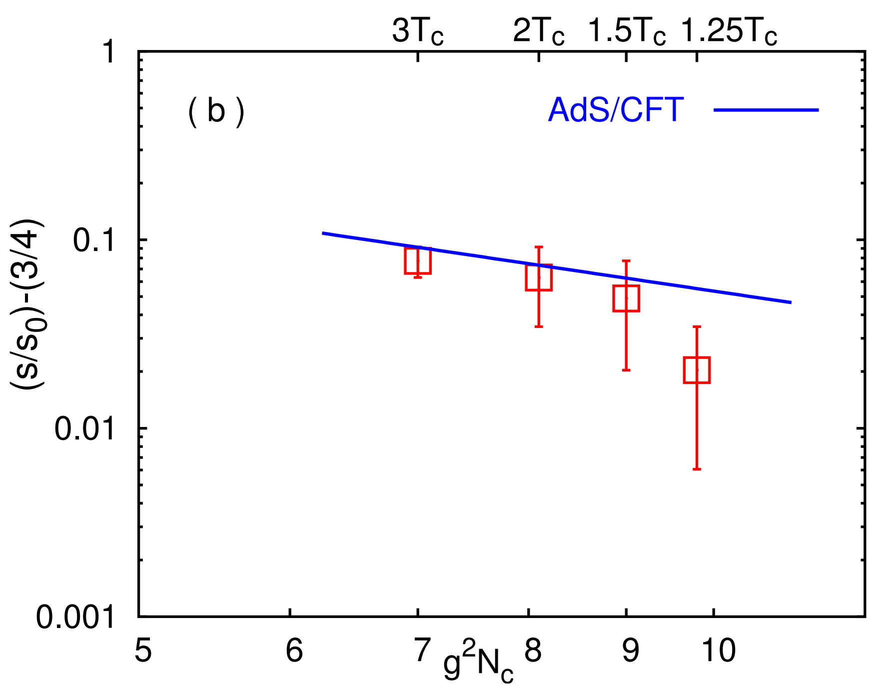
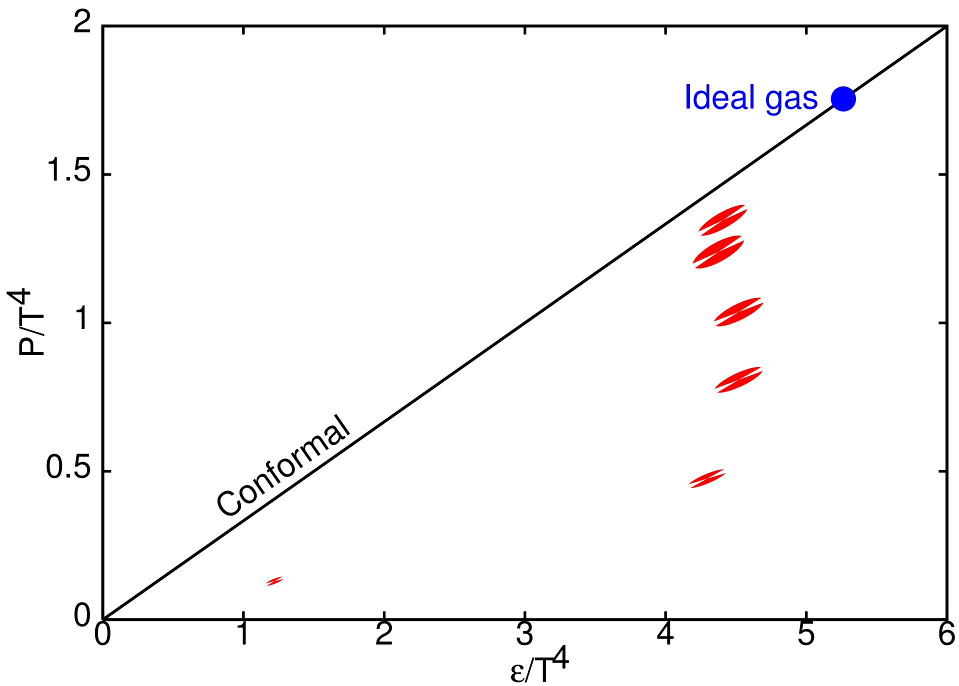
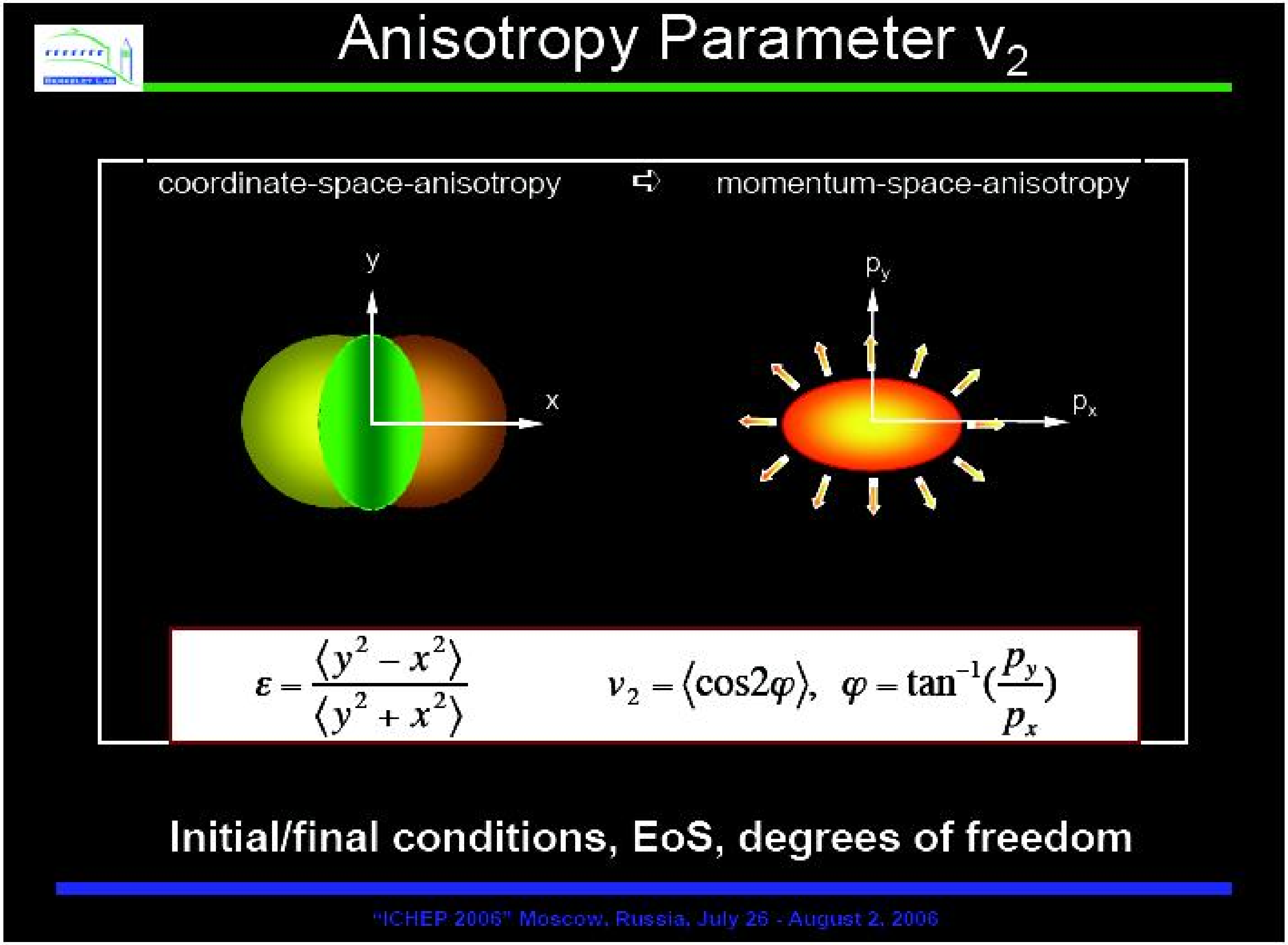
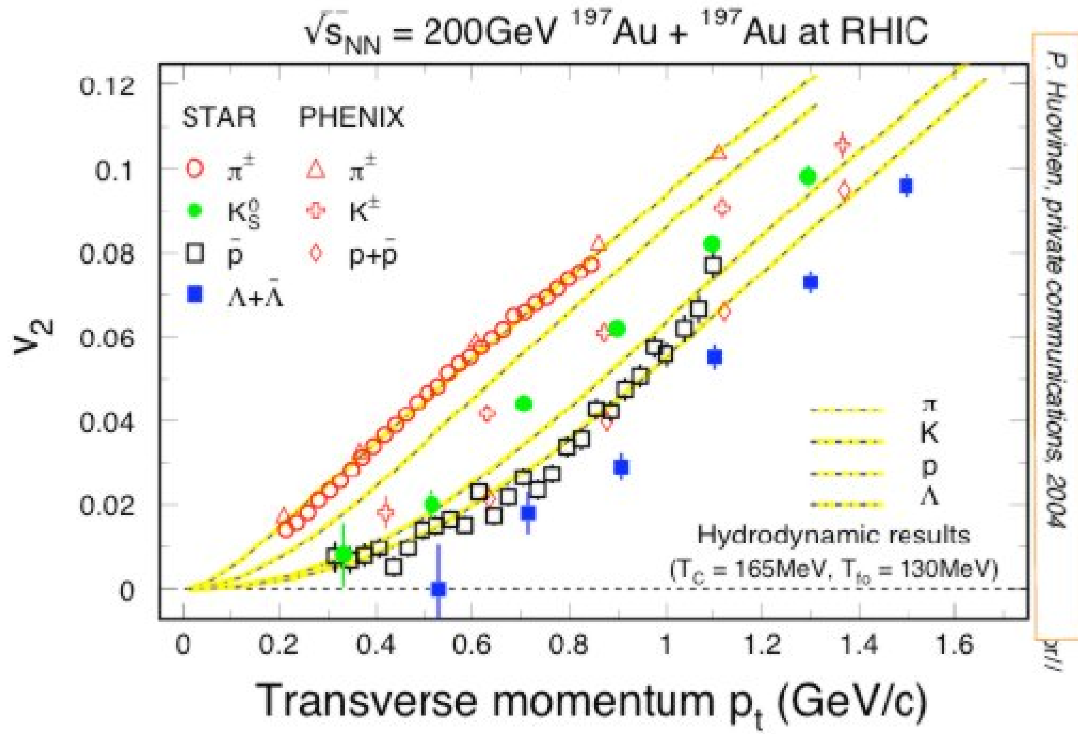




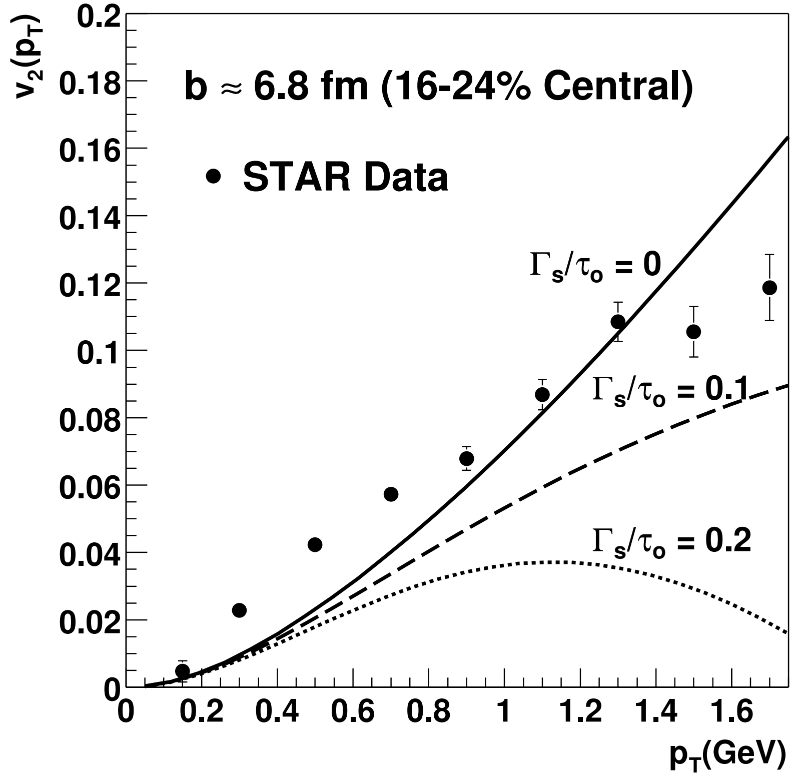

Anisotropy Parameter v_2
coordinate-space-anisotropy
momentum-space-anisotropy
y
x
p_y
p_x
$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$
$v_2 = \langle \cos 2\varphi \rangle, \ \ \varphi = \tan^{-1}(\frac{p_y}{p_x})$
Initial/final conditions, EoS, degrees of freedom
"ICHEP 2006" Moscow, Russia, July 26 - August 2, 2006

v_2 at Low p_T Region



- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details do not work, need more flow in the model!

QGP - (Almost) Perfect Liquid



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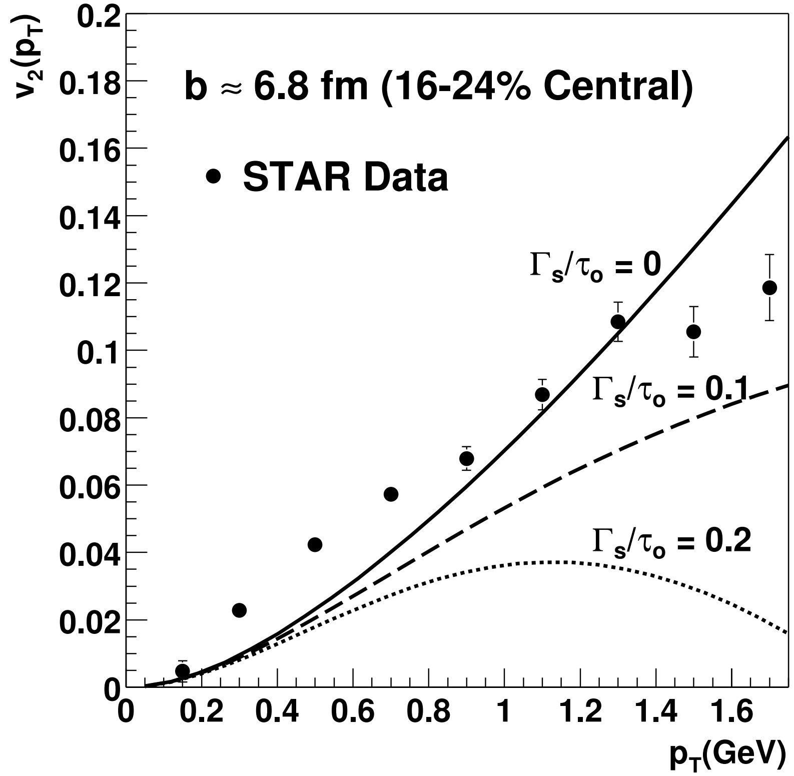

Elliptic flow consistent with Ideal Hydrodynamics $\rightsquigarrow$ bound on Shear viscosity. (D. Teaney, nucl-th/03010099; PRC 2003)

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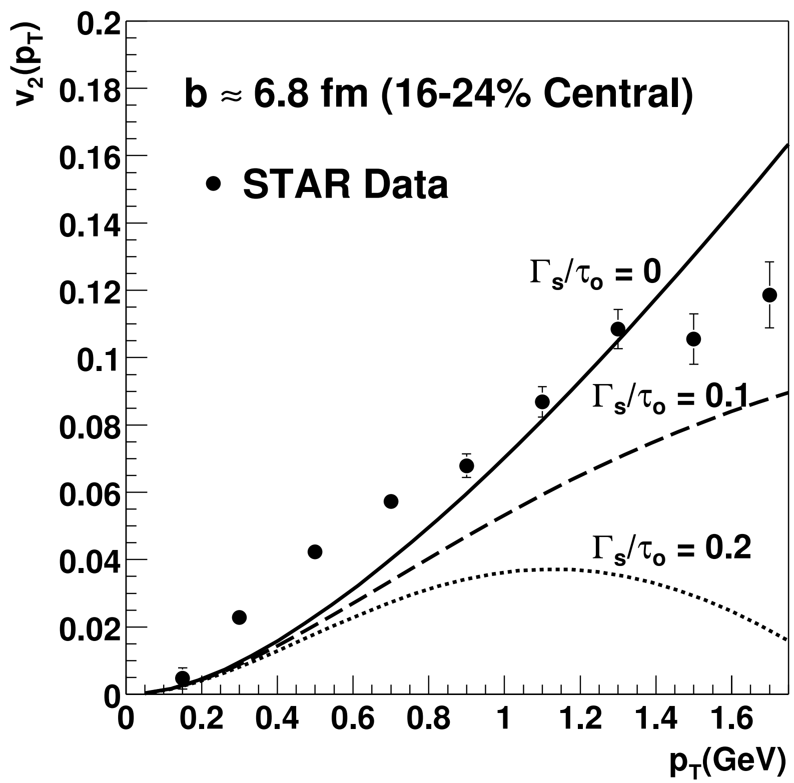

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$$\Gamma_s = \frac{\frac{4}{3}\eta}{sT} \,, \qquad (1)$$

where η is Shear Viscosity and s is entropy density; $\tau = \sqrt{t^2 - z^2}$ is the time scale of expansion.

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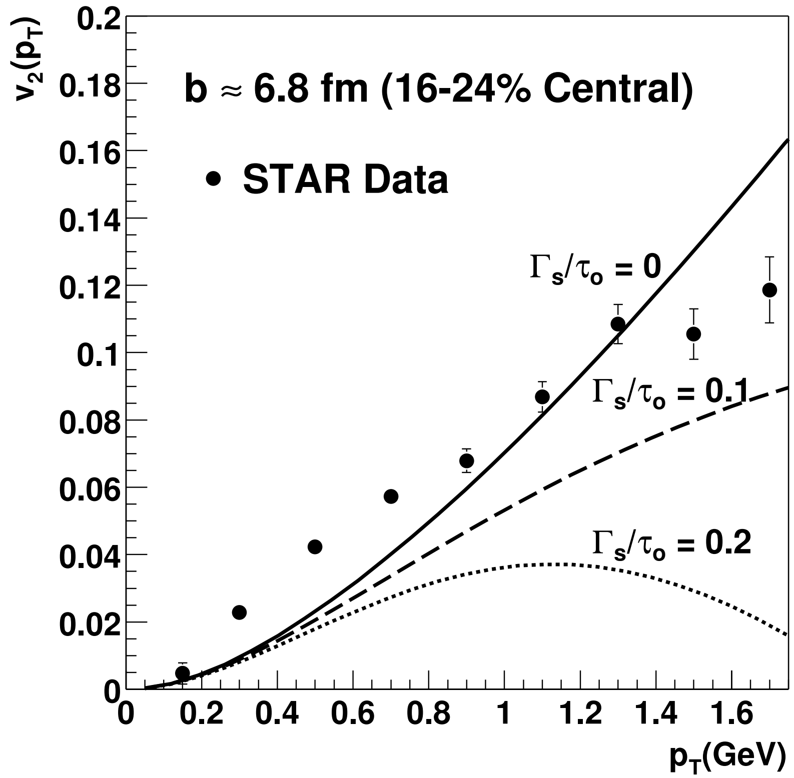

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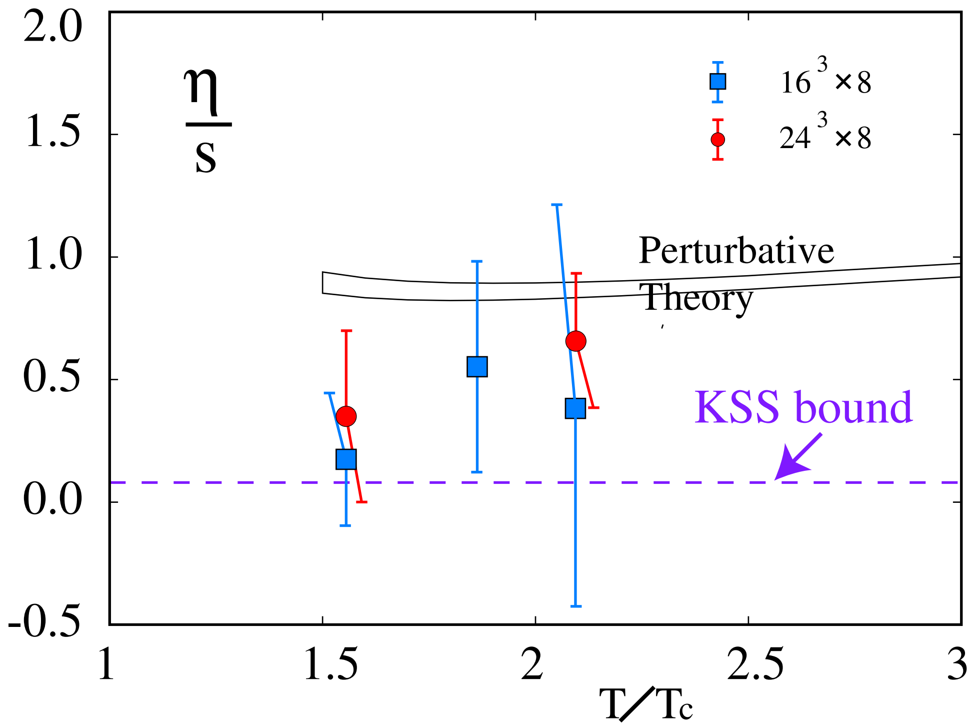
where η is Shear Viscosity and s is entropy density; $\tau = \sqrt{t^2 - z^2}$ is the time scale of expansion.

Perturbation theory $\Rightarrow$ Large η/s
Small $\eta/s \longrightarrow$ Strongly Coupled Liquid.



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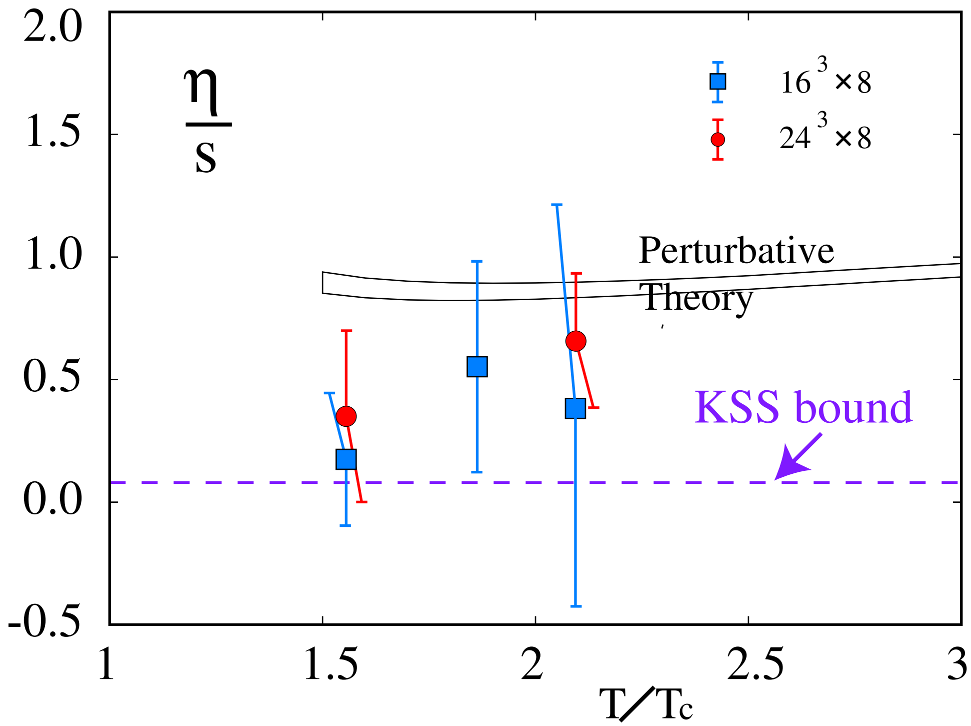

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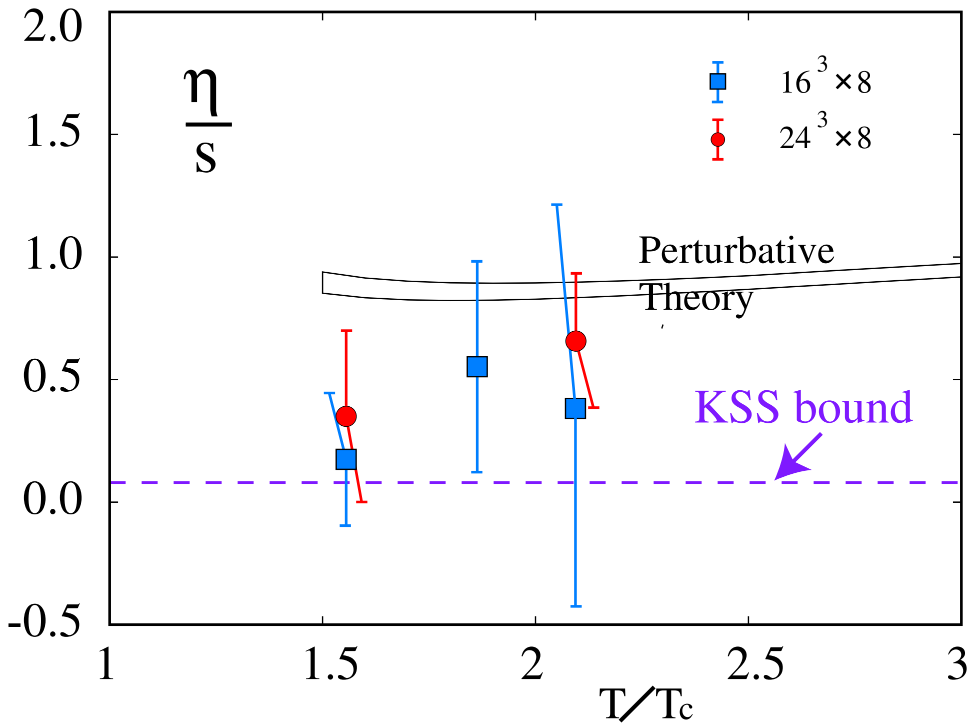

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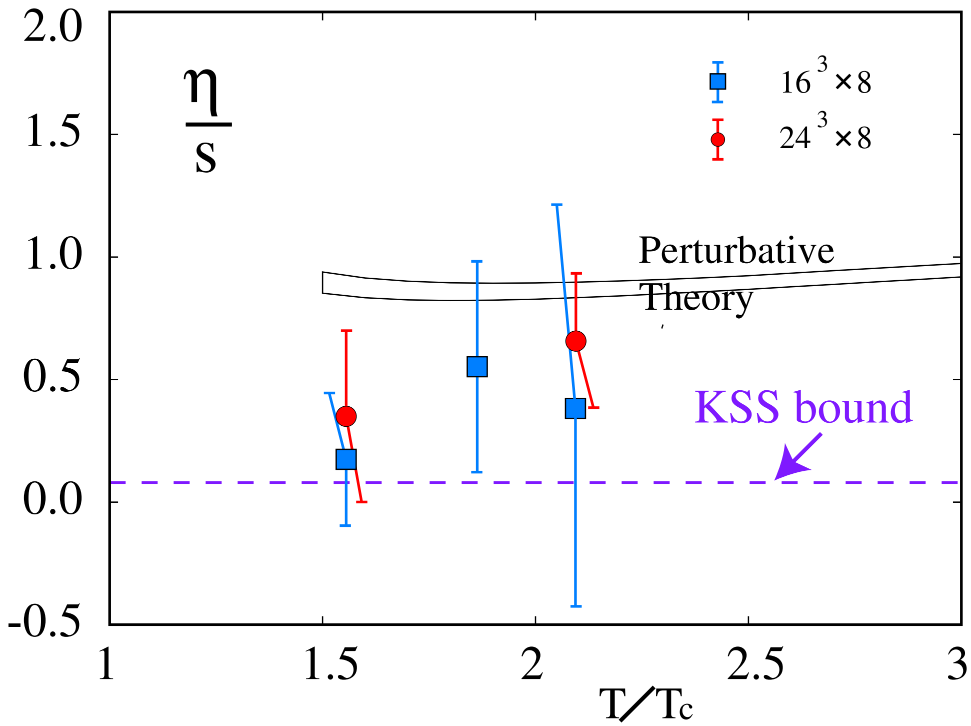

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- Continue them to get Retarded ones $\rightsquigarrow$ Shear, Bulk Viscosities.
- Larger lattices and inclusion of dynamical quarks in future.

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- Measure of Strangeness produced. Quark number susceptibilities, $\chi_{ij} \sim \partial \ln Z / \partial \mu_i \partial \mu_j$, can provide a handle; QNS also useful theoretical check on models.

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- Finally, make a relaxation time approximation ($\omega\tau \gg 1$) $\rightsquigarrow$ ratio of real parts is the same as the ratio of imaginary parts.

We use $m/T_c = 0.03$ for u, d and $m/T_c = 1$ for s quark;
At each T, ratio of χ_s and χ_{ud} $\quad \rightarrow \quad \lambda_s(T)$.

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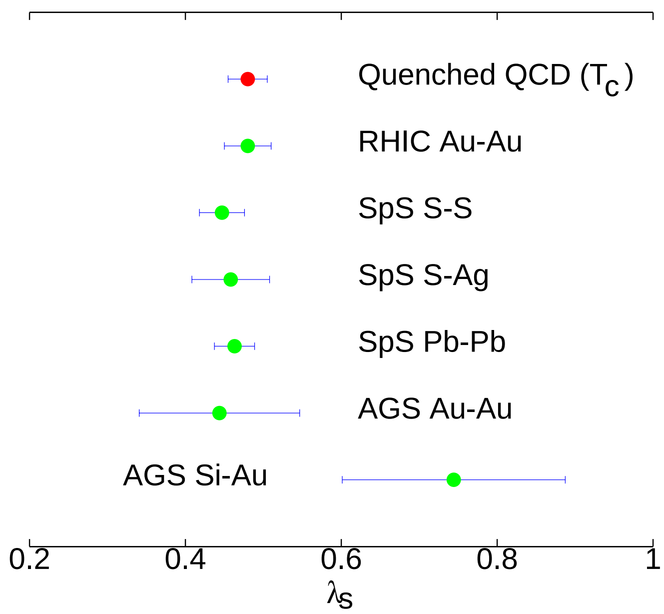

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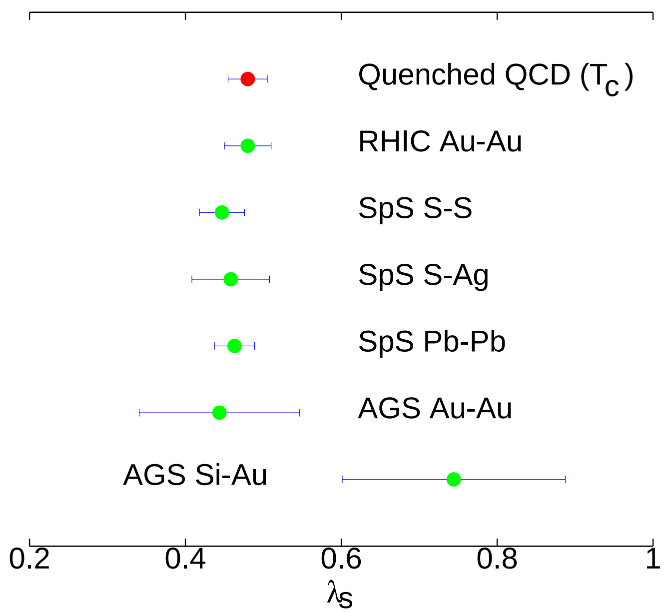

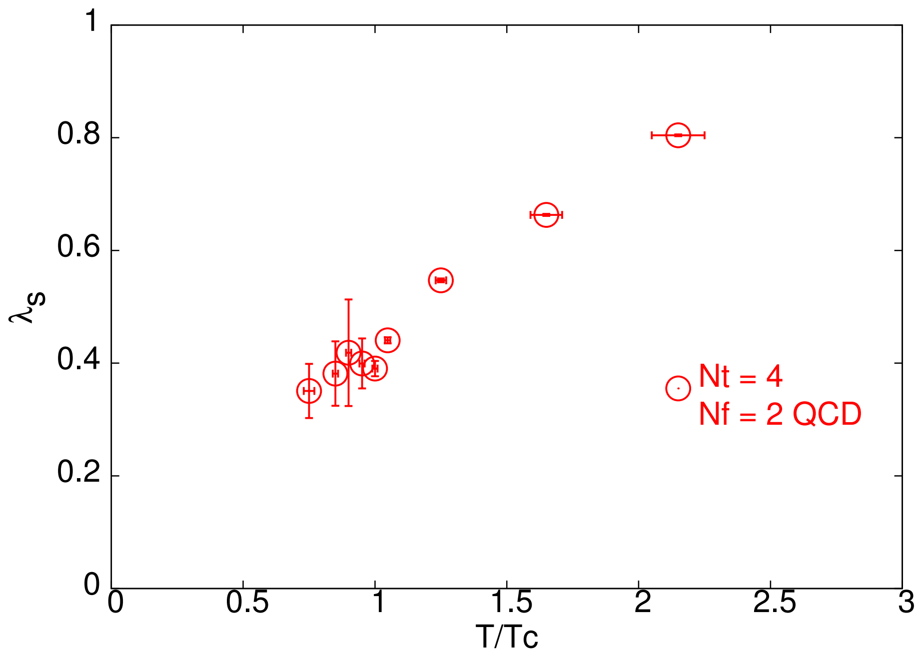

Baryon-Strangeness Correlation

♣Correlation between quantum numbers K and L can be studied through the ratio $C_{(KL)/L} = \frac{\langle KL \rangle - \langle K \rangle \langle L \rangle}{\langle L^2 \rangle - \langle L \rangle^2}$.

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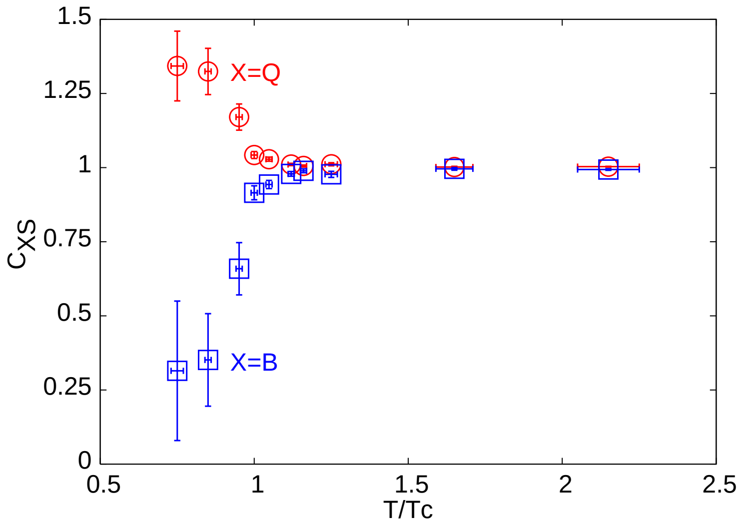

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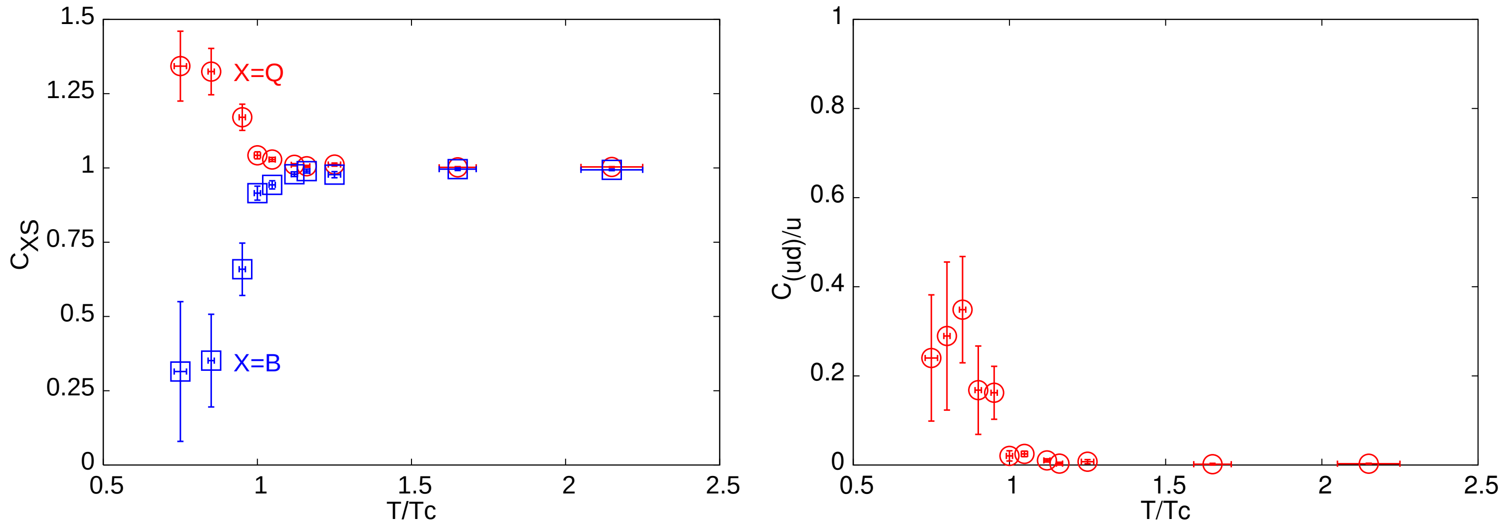


Anomalous J/ψ Suppression : CERN NA50 results

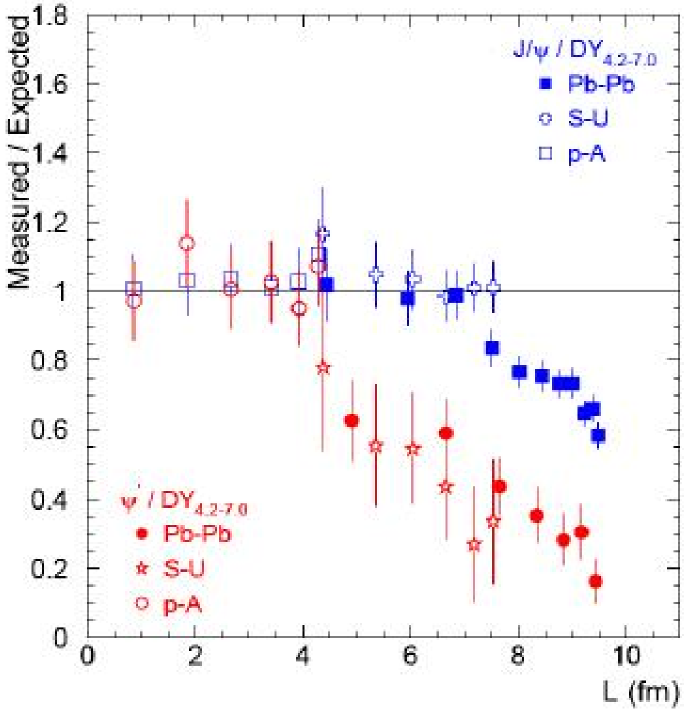
♠ Matsui-Satz idea — J/ψ suppression as a signal of QGP.
♠ Deconfinement $\rightsquigarrow$ Screening of coloured quarks,
which cannot bind.

Anomalous J/ψ Suppression : CERN NA50 results

Expected = Glauber absorption model

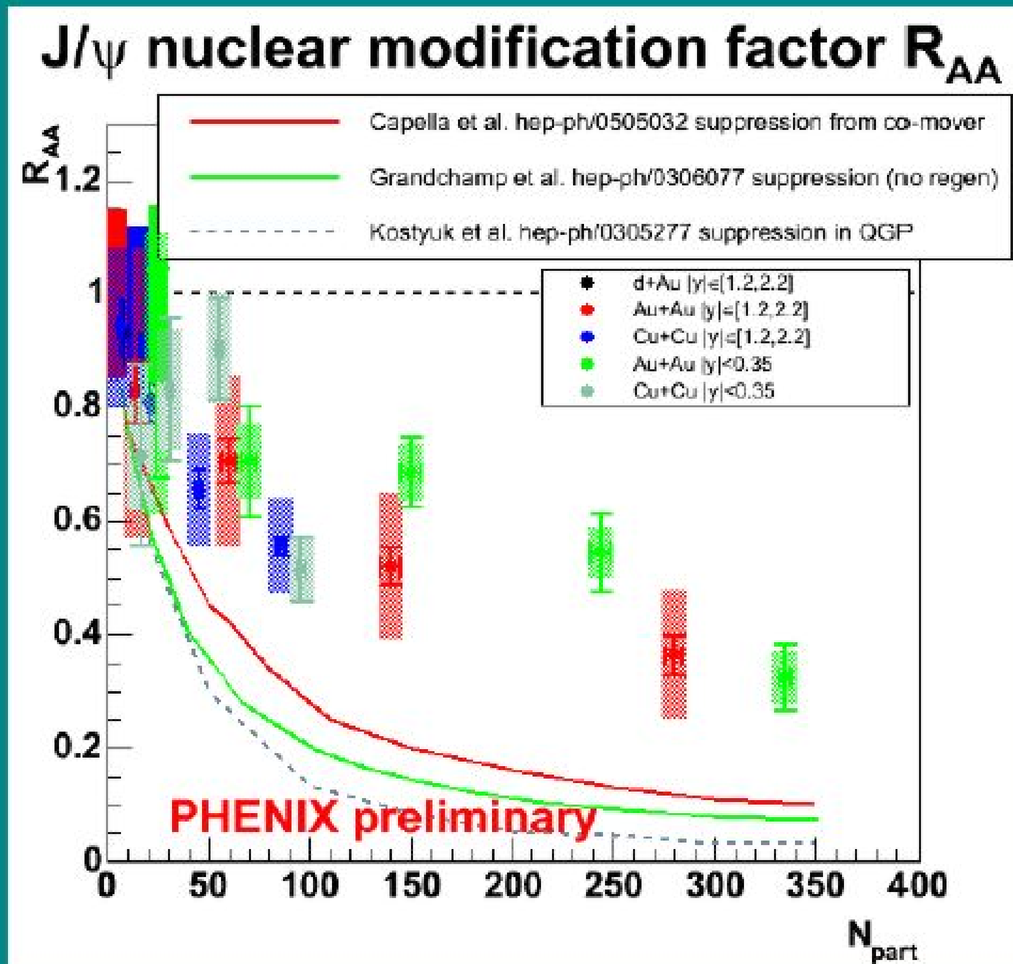
$\sigma_{abs}(J/\psi) = 4.18 \pm 0.35$ mb

$\sigma_{abs}(\psi') = 7.60 \pm 1.12$ mb



- **S-U** and **peripheral Pb-Pb (J/ψ)/DY** results follow the absorption curve extrapolated from p-A measurements.
- **Pb-Pb central** collisions show an **anomalous (J/ψ)/DY suppression** with respect to p-A behaviour.
- **ψ'/DY** behaviour is the same in **S-U** and **Pb-Pb** interactions and not compatible with the one observed in p-A collisions.
- **ψ' anomalous suppression** sets in earlier than the J/ψ one.

System-Size Dependence



Models that were successful in describing SPS data fail to describe data at RHIC
- too much suppression -

J/ψ Suppression

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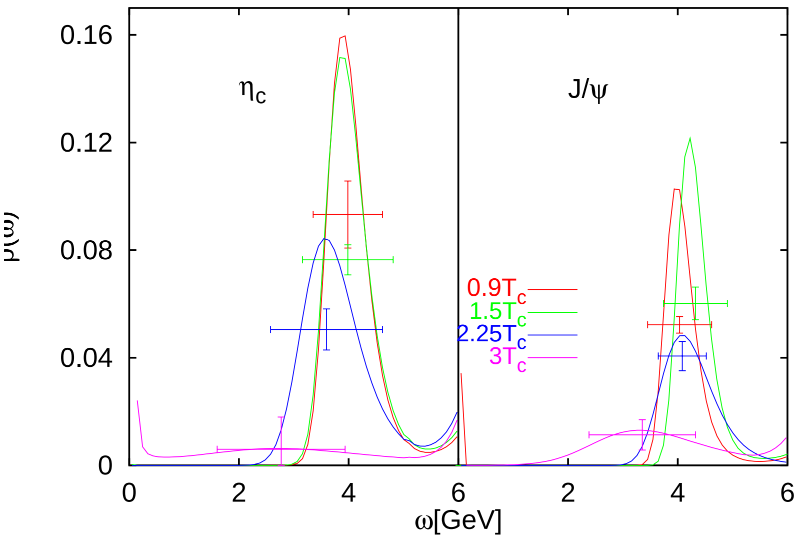
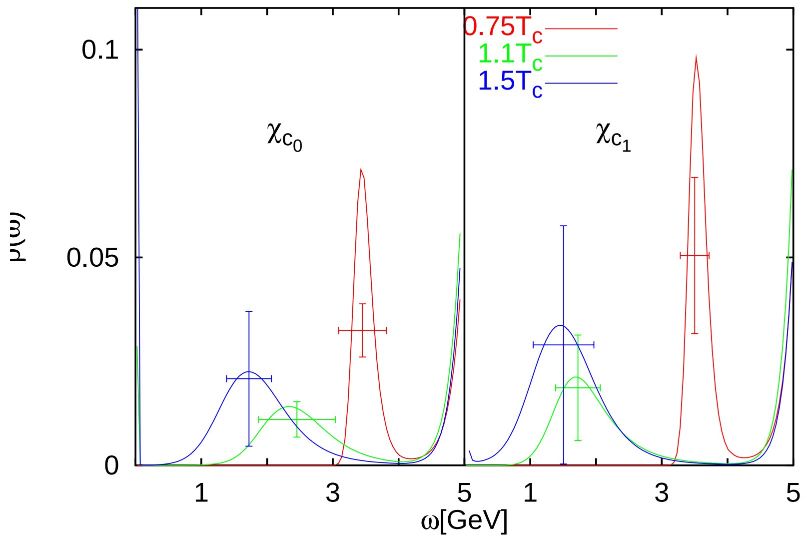
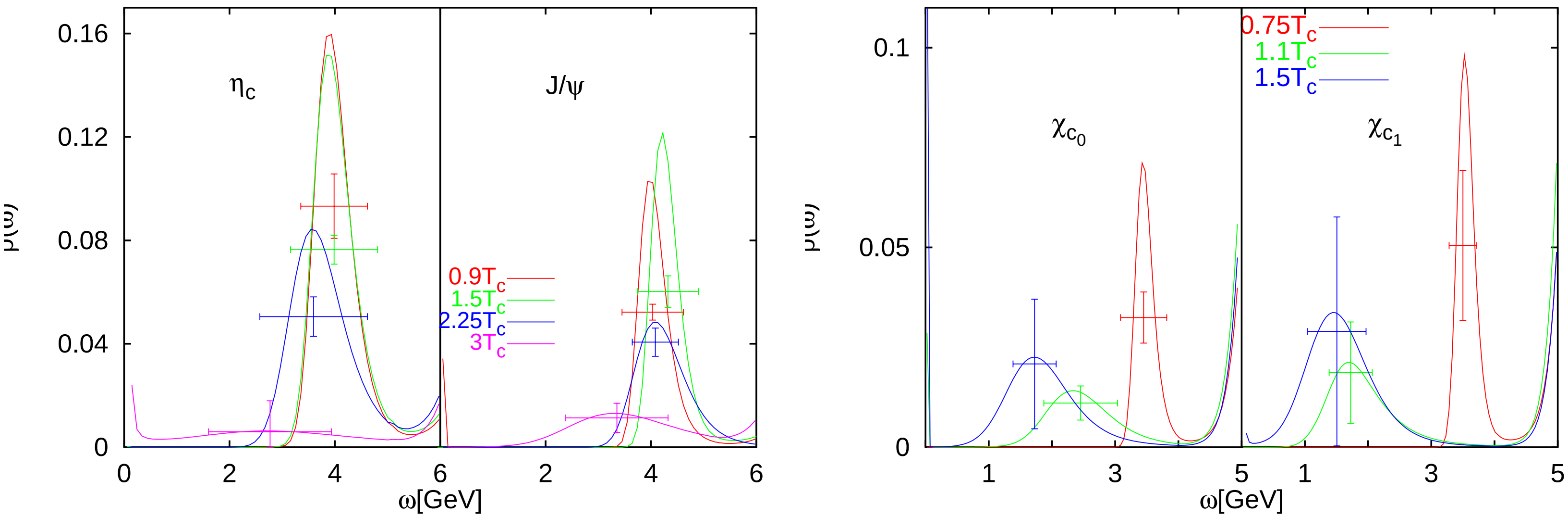
- Caution : nonzero temperature obtained by making temporal lattices shorter : $48^3 \times 12$ to $64^3 \times 24$ Lattices used. (S. Datta et al., Phys. Rev. D 69, 094507 (2004).)





♠ χ_c seems to indeed dissolve by 1.1T_c, however, J/ψ and η_c persist up to 2.25 T_c and are gone at $3T_c$; Similar results by Asakawa-Hatsuda and Matsufuru.



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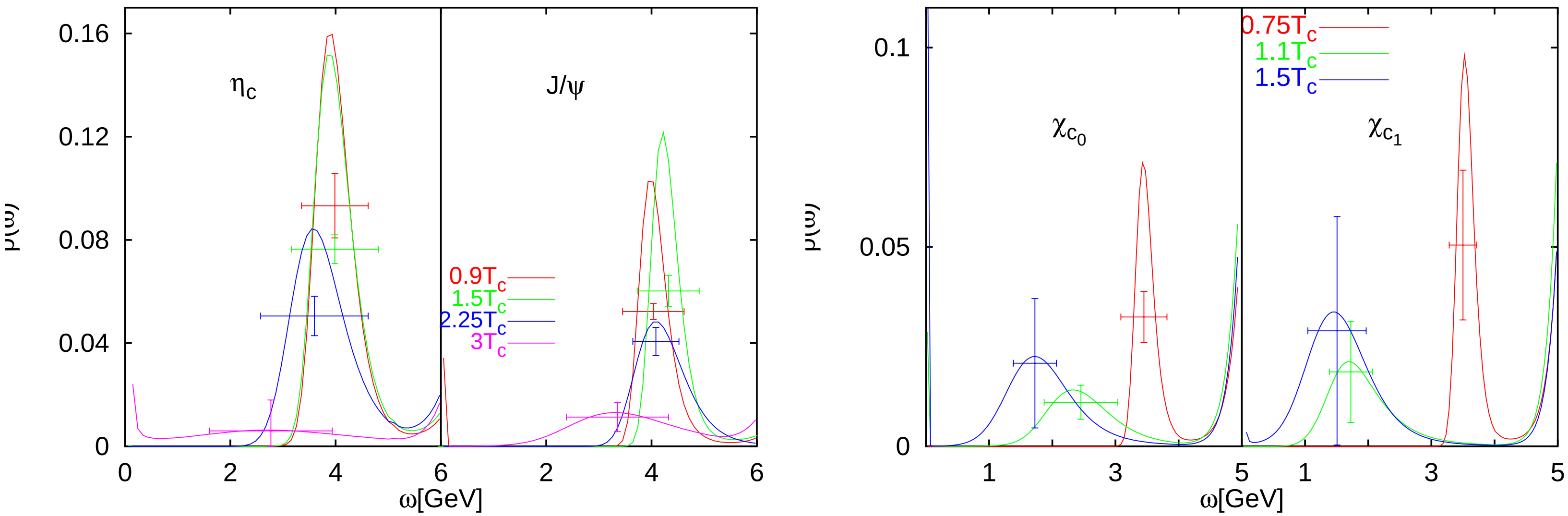

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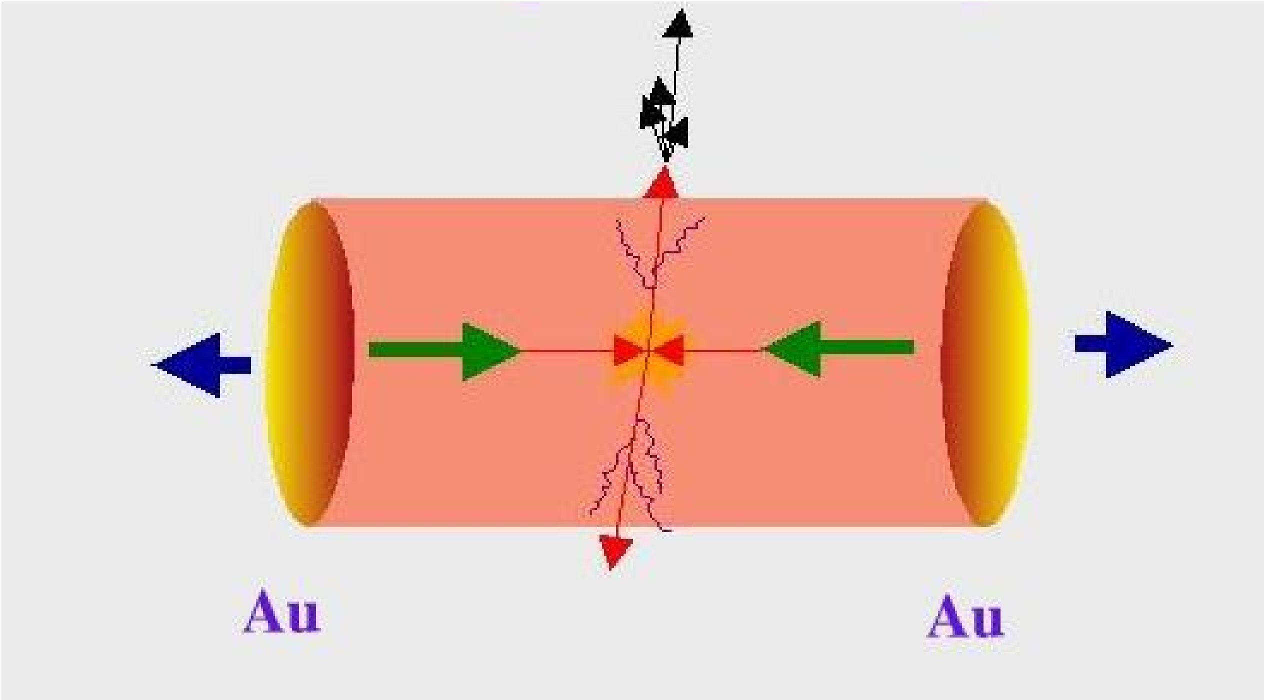
♠ No Significant Effect of inclusion of dynamical fermions ?

Jet Quenching



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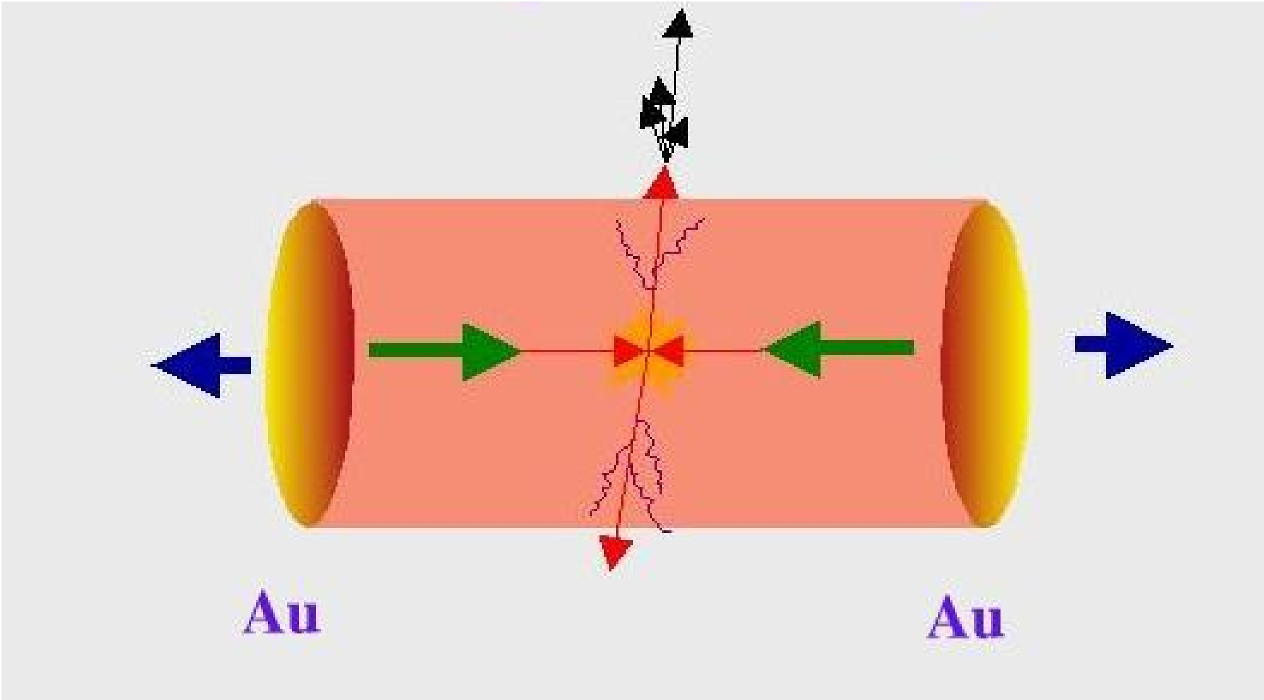

- Rare, Highly Energetic Scatterings produce jets of particles : $g + g \rightarrow g + g$.

- Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

- On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

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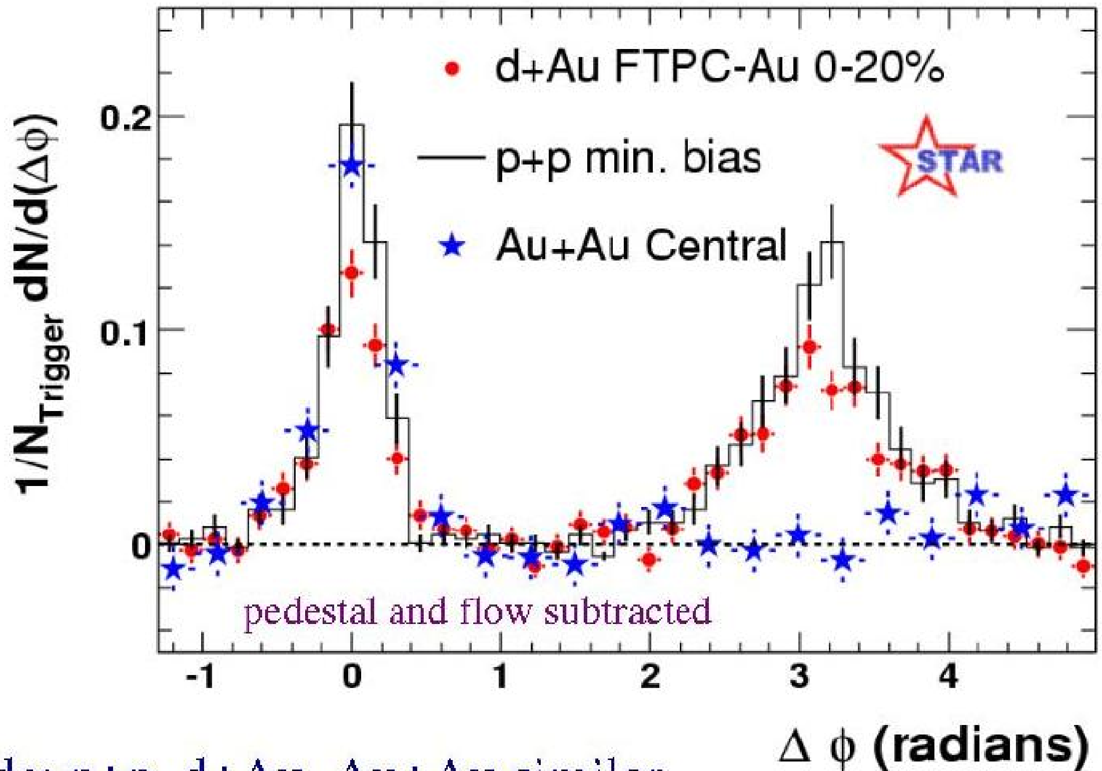
Azimuthal distributions

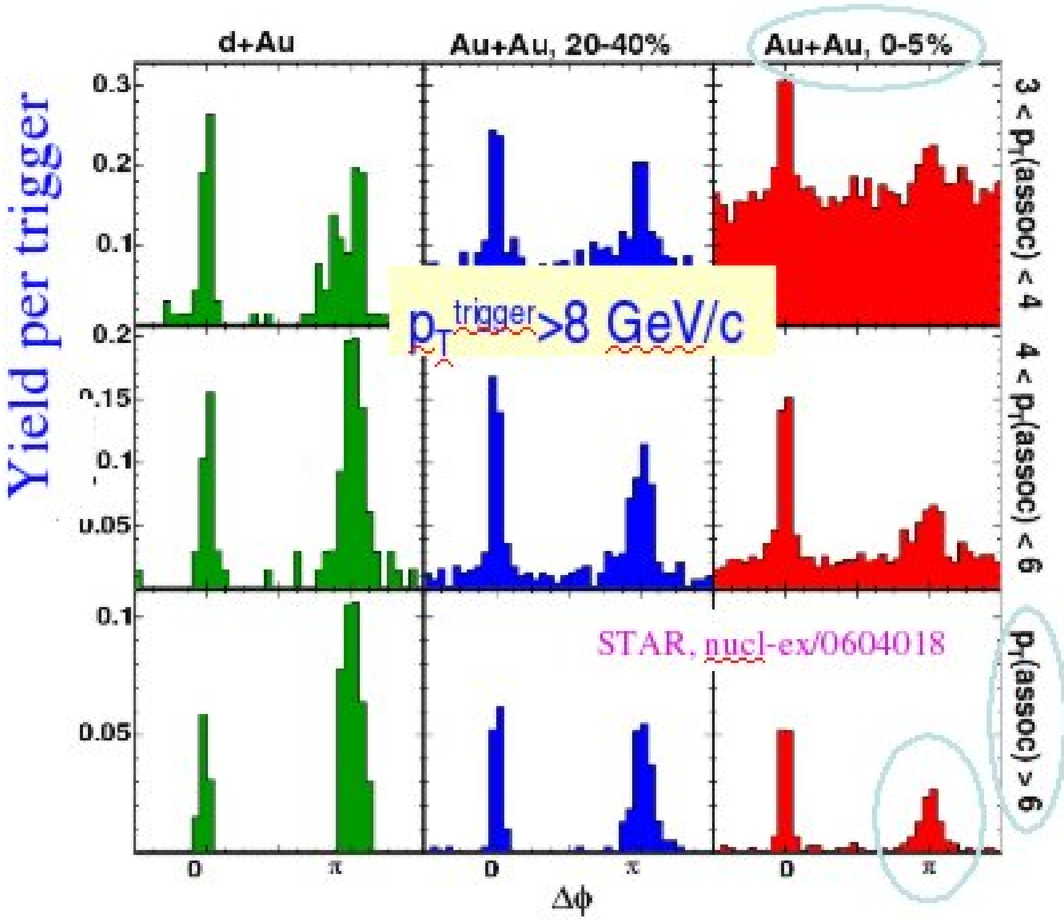


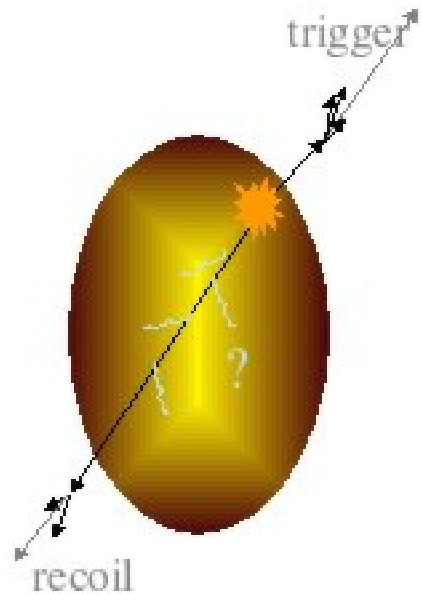
Near- side: p+p, d+Au, Au+Au similar

Back- to- back: Au+Au strongly suppressed relative to p+p and d+Au

What is new: di-hadron correlations at higher p_T

Hallman: ICHEP06



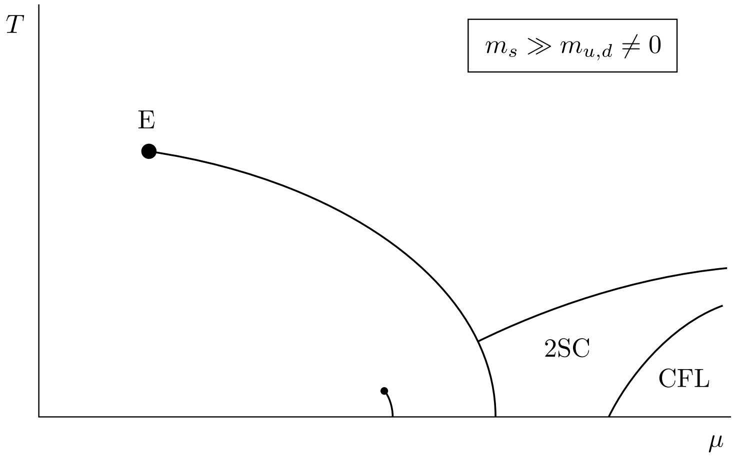


Armesto: ICHEP06

Recoil jet clearly seen above background but at suppressed rate

QCD Phase Diagram

Expected QCD Phase Diagram and Lattice Approaches to unravel it.



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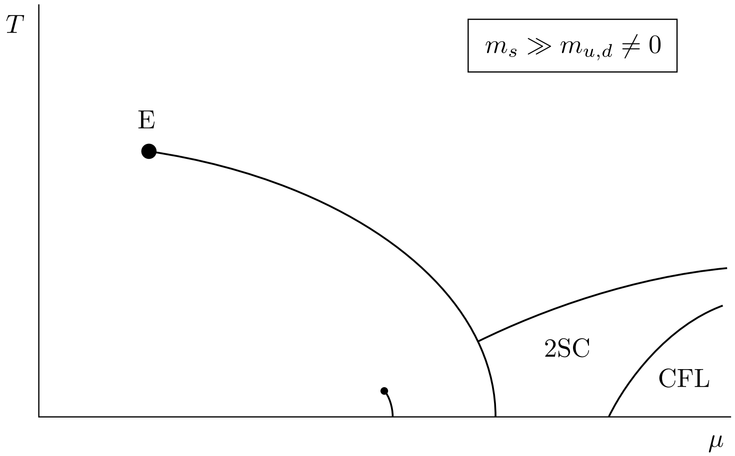

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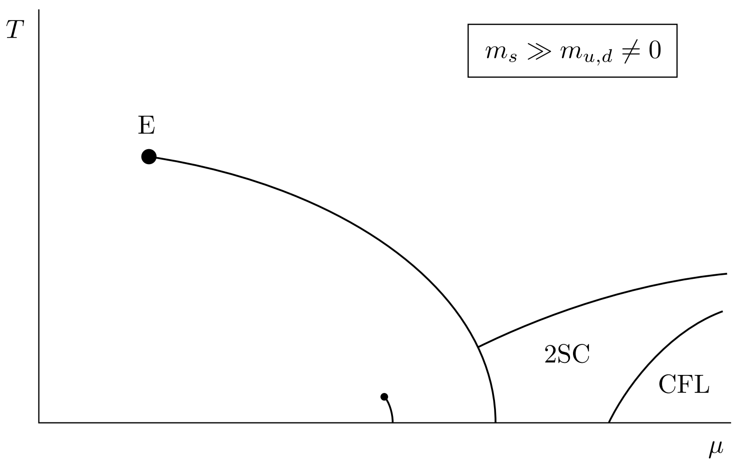

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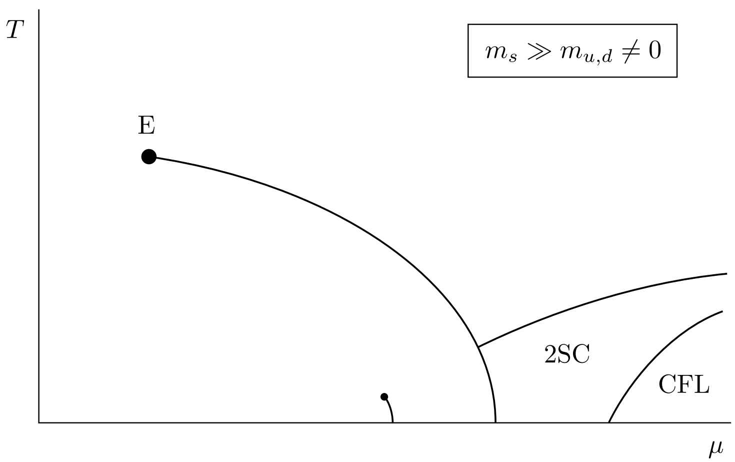

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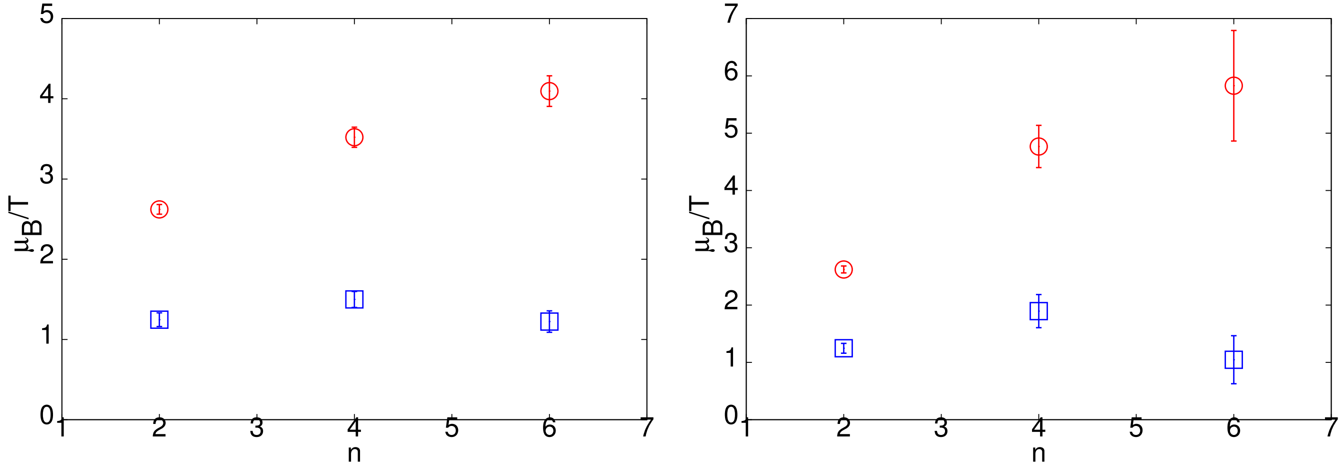
Critical Point Estimate

RVG & S. Gupta, PR D 71 2005.



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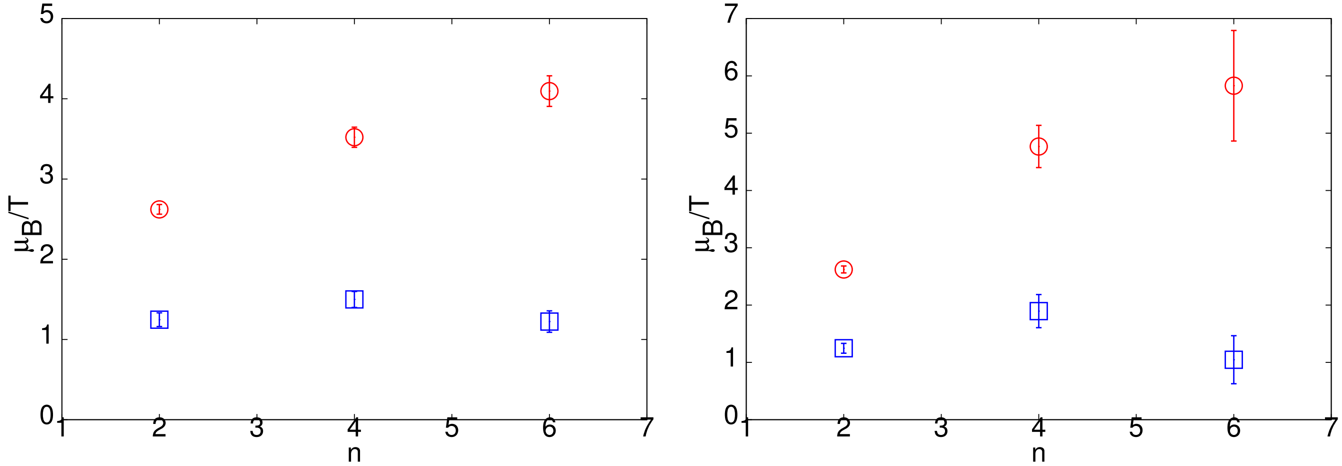

♠ Radii of convergence as a function of the order of expansion at $T = 0.95T_c$ on $N_s = 8$ (circles) and 24 (boxes). Left panel for ρ_n and right one for r_n.

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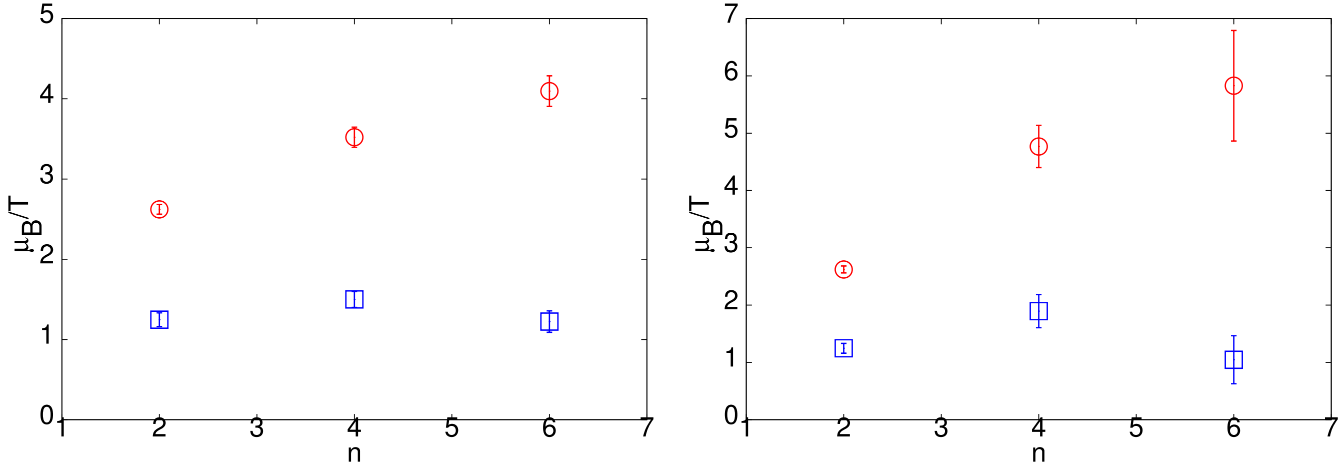

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♠ Extrapolation in $n \rightsquigarrow \mu^E/T^E = 1.1 \pm 0.2$ at $T^E = 0.95T_c$. Finite volume shift consistent with Ising Universality class.

Summary

- Lattice QCD **predicts** transition to Quark-Gluon Plasma and several of its properties, T_c, EoS, λ_s, η ...

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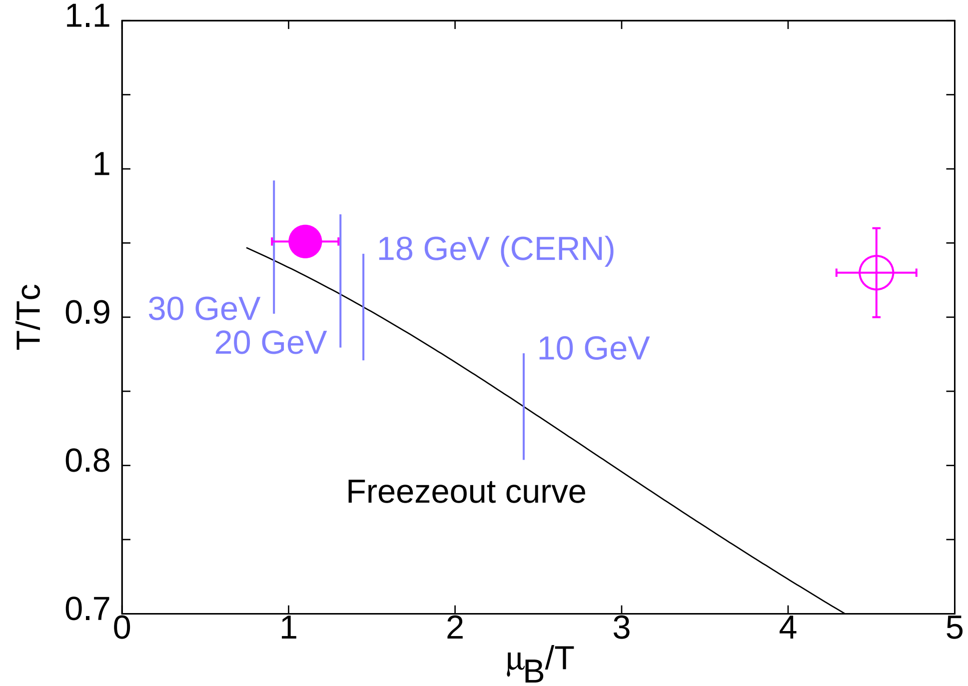

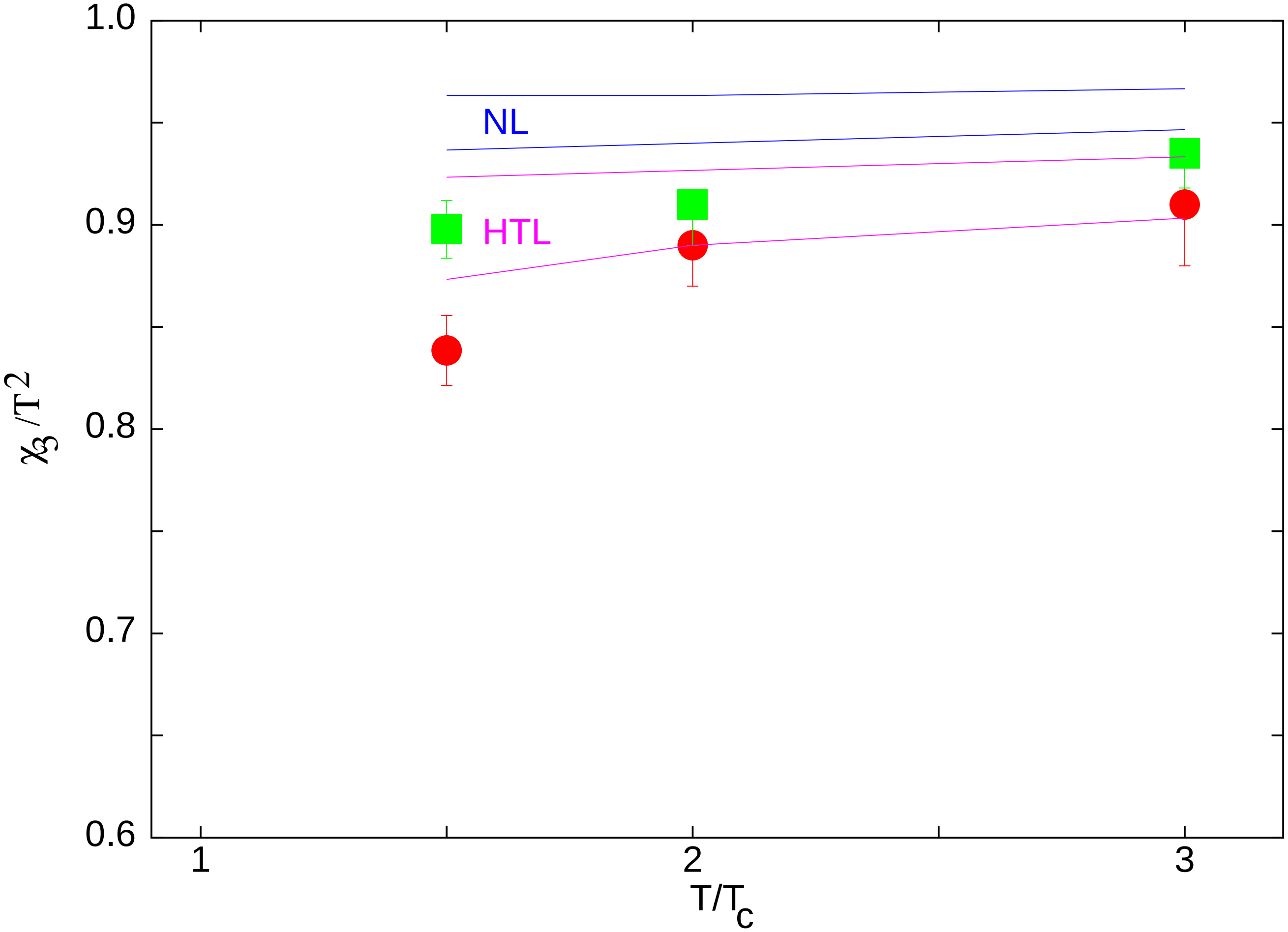
1.0
0.9
0.8
0.7
0.6
1
2
3
T/Tc
χ3/T2
NL
HTL

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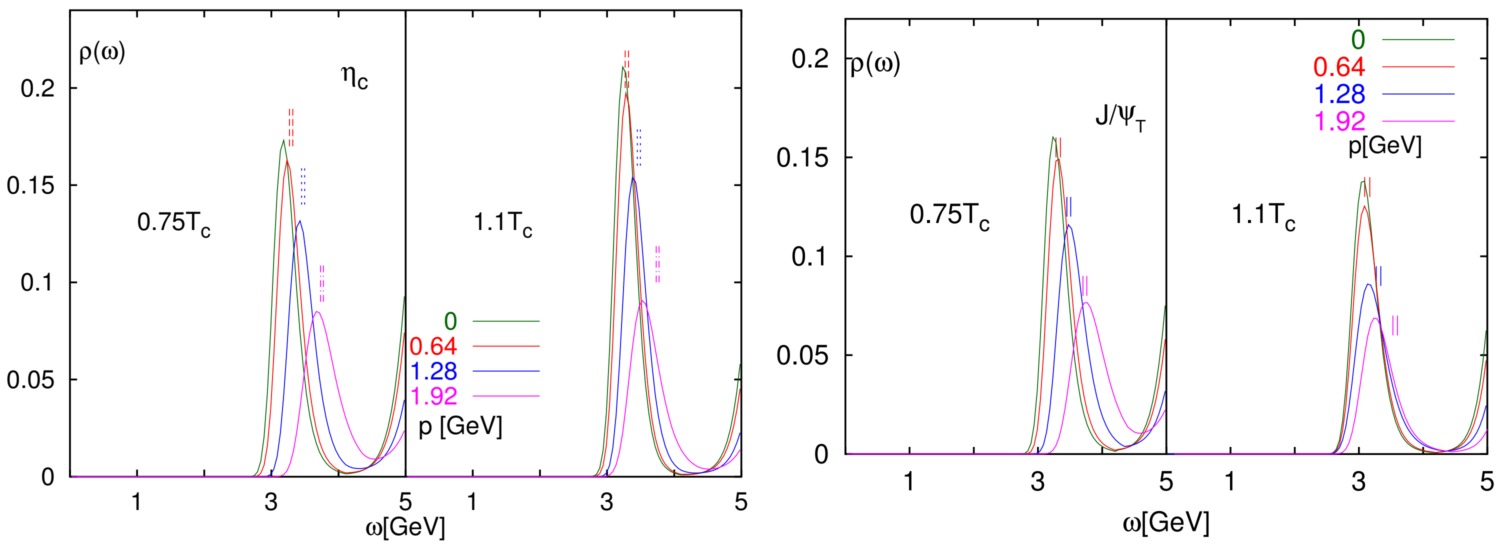

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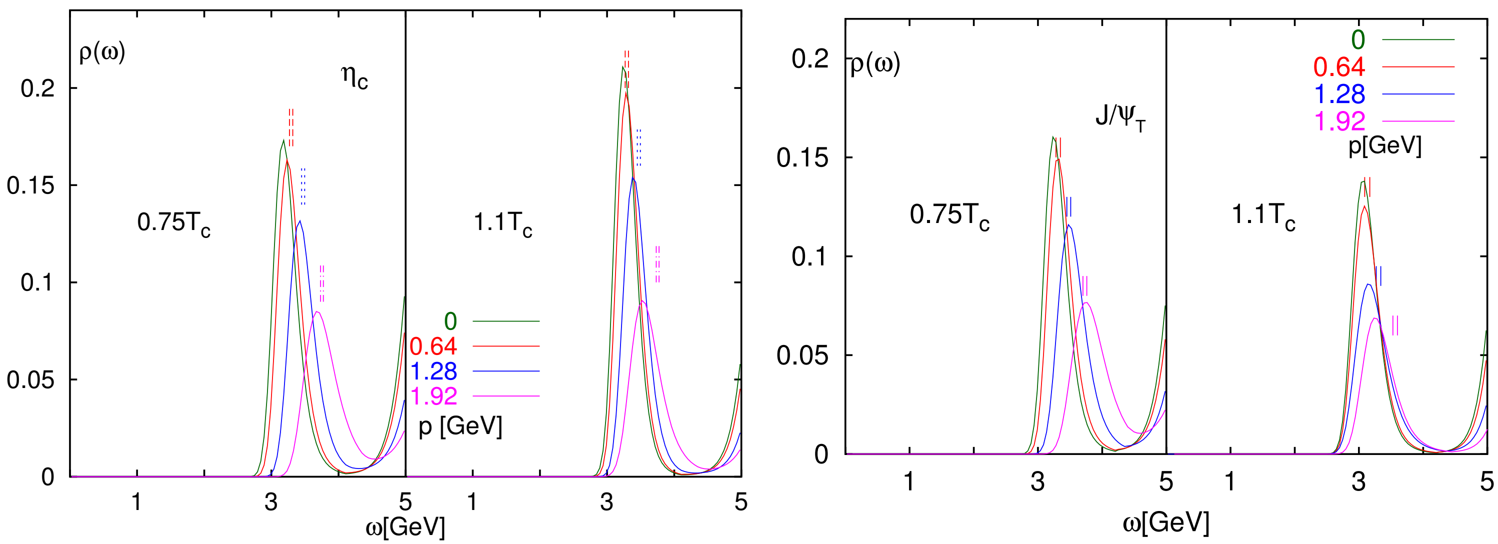

♠ Both J/ψ and η_c do show this trend.

♠ The effect is significant at both 0.75 and $1.1T_c$.

m_ρ/T_c	m_π/m_ρ	m_N/m_ρ	$N_s m_\pi$	flavours	T^E/T_c	μ_B^E/T^E
5.372 (5)	0.185 (2)	—	1.9–3.0	2+1	0.99 (2)	2.2 (2)
5.12 (8)	0.307 (6)	—	3.1–3.9	2+1	0.93 (3)	4.5 (2)
5.4 (2)	0.31 (1)	1.8 (2)	3.3–10.0	2	0.95 (2)	1.1 (2)
5.4 (2)	0.31 (1)	1.8 (2)	3.3	2	—	—
5.5 (1)	0.70 (1)	—	15.4	2	—	—

Table 1: Summary of critical end point estimates— the lattice spacing is $a = 1/4T$. N_s is the spatial size of the lattice and $N_s m_\pi$ is the size in units of the pion Compton wavelength, evaluated for $T = \mu = 0$. The ratio m_π/m_K sets the scale of the strange quark mass.

Results are sequentially from Fodor-Katz '04, Fodor-Katz '02, Gavai-Gupta, de Forcrand- Philipsen and Bielefeld-Swansea.