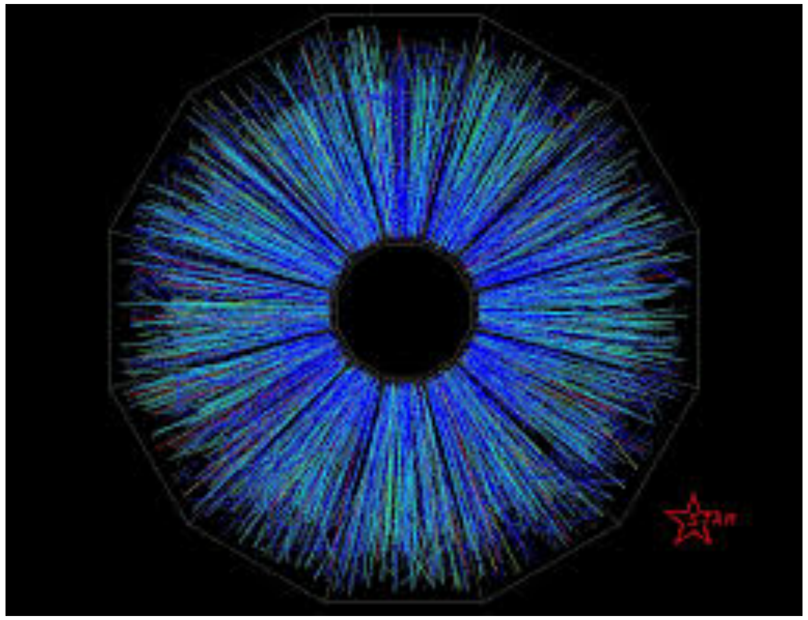
A quest for Quark-gluon plasma



Edward Shuryak
Stony Brook University

Strongly coupled quark-gluon plasma in heavy ion collisions
ES, Rev.Mod.Phys. 89 (2017) 035001

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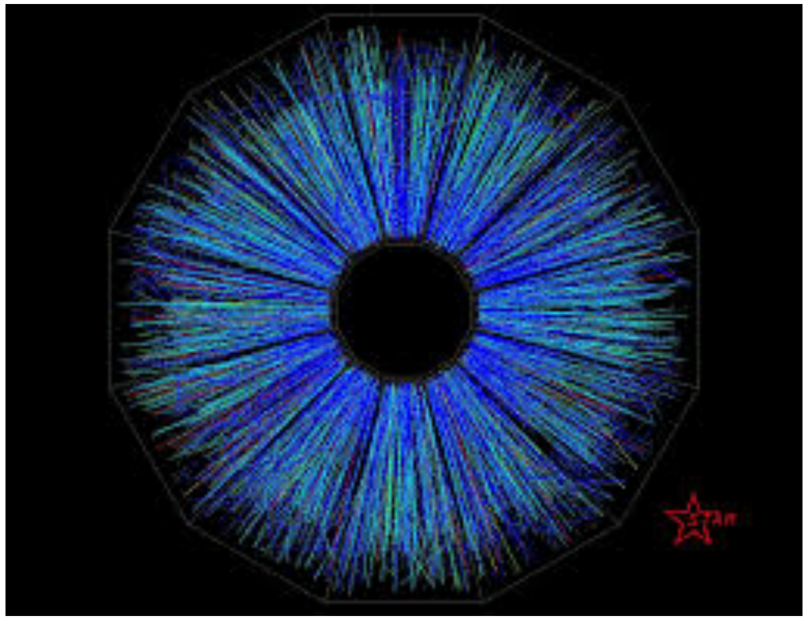

(a dream which came true)

Edward Shuryak
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outline

the story

- History: can a fm-size fireball be macroscopic?
- QCD at finite temperature
- RHIC and LHC: radial and elliptic flows
- Sounds and higher harmonics of flow
- the smallest drops of QGP are very explosive as well

the e/m duality and monopoles

- QGP kinetic properties are unusual
- classical and quantum monopole dynamics
- plasma made of electric+magnetic charges
- BEC of monopoles and confinement

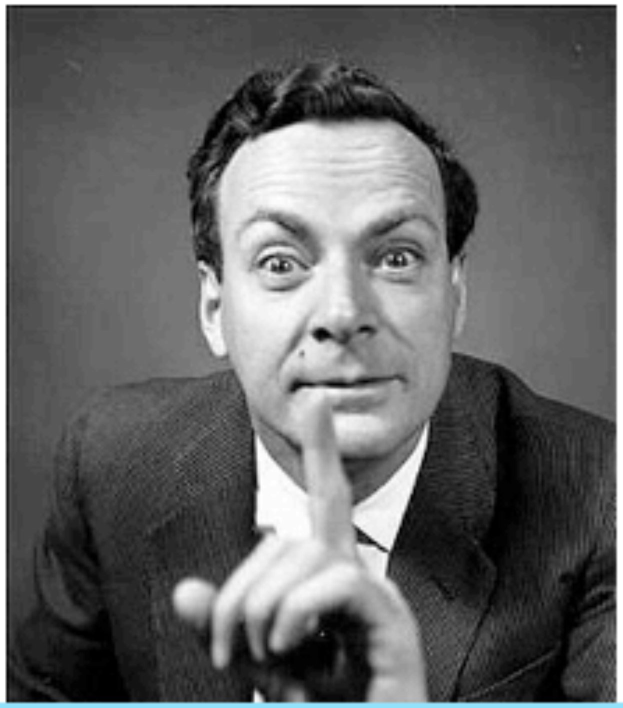
Historic remarks

my pre-history

1968. (I became a diploma student at Budker Institute)
Iosif Khriplovich found (-22/3) in charge renormalization of the SU(2) gauge theory

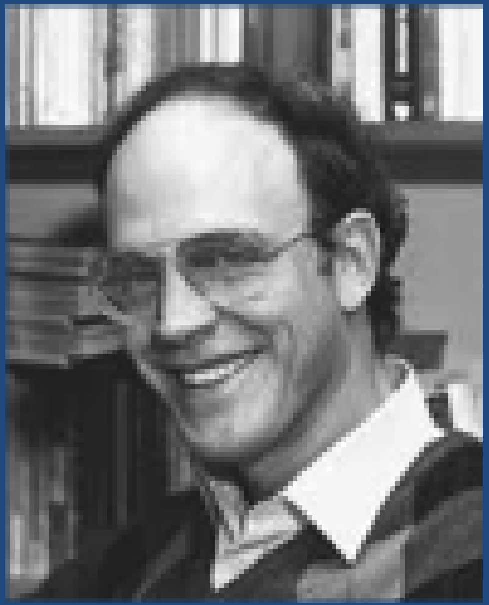
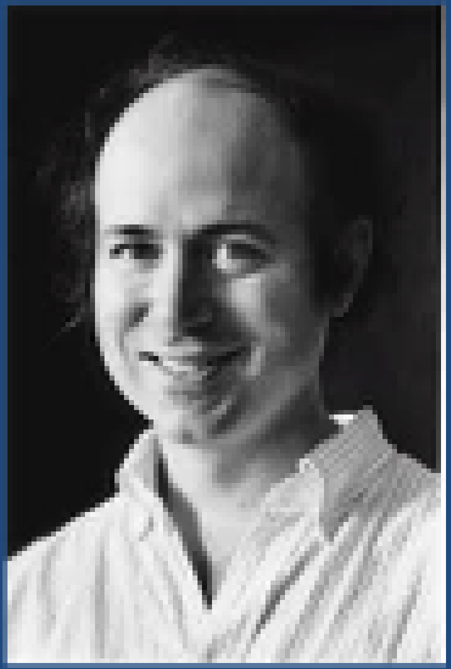
1969. SLAC exp <= Bjorken scaling for deep inelastic eN scattering

1970. Feynman announced the parton model
(deep impression on anyone: I start working on Drell-Yan pairs in 71)



Very few people knew both the Khriplovich paper and were interested in strong interactions. I had 3 years to connect the dots, but failed to do so...

1973: QCD (45 years old this year)


- D.Gross, F.Wiczek and D.Politzer connected the asymptotic freedom to SLAC-MIT experiment and suggested QCD as The theory of strong interactions
- (Nobel prize 2004)

1970's

Theory of Hadronic Plasma, ES
Sov.Phys.JETP 47 (1978) 212-219, Zh.Eksp.Teor.Fiz. 74 (1978) 408-420

QED: both in vacuum and in plasma
the charge is **screened**

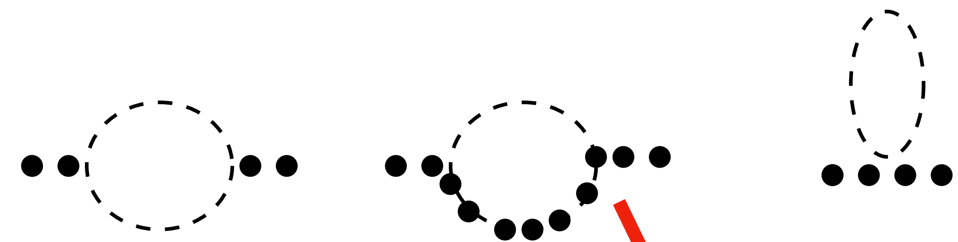
AF=**antiscreening** of the charge
in the QCD vacuum at small r.

What happens in **quark-gluon plasma?**

Screened! (ES,1976)
perturbative theory of QGP at high T
because AF at small r and screening at large r.

$$\Pi_\perp(\vec{q} \to 0, q_0 = 0, T) = 0$$

presence of matter => preferred frame
non-Lorenz-invariant gauges possible
so I followed Khriplovich and Coulomb gauge
dots are A0, dashed are transverse gluons



(a) (b) (c)

$$\Pi_{00}(\vec{q}) = \frac{g^2\vec{q}^2}{\pi^2} log(\frac{\vec{q}^2}{\Lambda^2})(+\frac{1}{2} - 6 + 0)$$

(b) can have minus because there is no physical state
of transverse and Coulomb fields
It is this diagram which gives us asymptotic freedom

$$\Pi_{00}(\vec{q} \to 0, q_0 = 0, T) = g^2T^2(\frac{1}{2} + 0 + \frac{1}{2} + \frac{N_f}{6})$$

Contribution to the screening mass
the diagram (b) gives nothing
it is positive! Thus "plasma"

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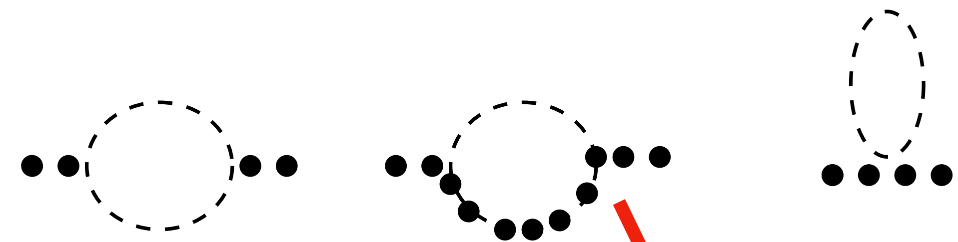

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the magnetic field is not screened
in any order of perturbation theory
but it is screened in QGP
=> monopoles

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- 1980's: **inventing the signals**

meetings attended by a dozen of theorists and few experimentalists

- **penetrating probes (photons and dileptons) (ES, 1978).**
- **Robust hydronamical explosion of the QGP (ES, 1978).**
- **jet quenching (Bjorken, 1982)**
- **subsequent melting of charmonium and bottonium states (Matsui and Satz, 1986)**

I dont have the time to speak of photon and deletion data, heroically obtained, but mention only two puzzles

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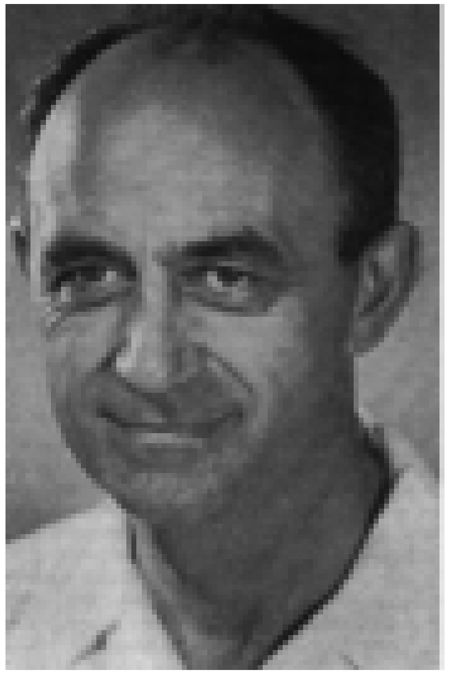
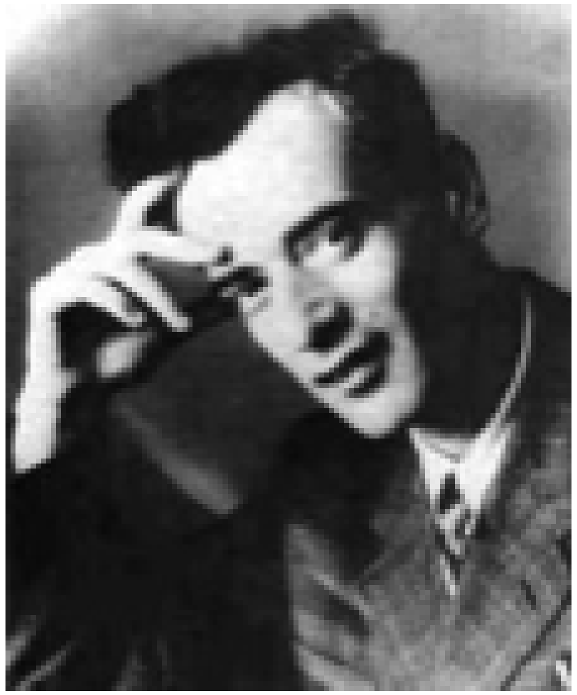
the initial chemical equilibration of qgp:
when and how quarks appear?
pQCD processes not enough
=> hot glue scenario?
most likely due to the sphaleron explosions
ES,Zahed, Venugopalan, Mace

Prehistory
1950's

Thermo and hydrodynamics: can they be used at sub-fm scale?





- Here are three people who asked this question first:
- Fermi (1951) proposed strong interaction leading to equilibration: <n>about $s^{1/4}$
- Pomeranchuck (1952) introduced freezeout
- Landau (1953) explained that one should use hydro in between, saving Fermi's prediction via entropy conservation {he also suggested it should work because coupling runs to strong at small distance! No asymptotic freedom yet in 1950's…}

1970's

Does the Landau theory describe high energy pp collisions?

velocity $v_{||} = tanh(y)$ rapidity

$$c_s^2 \equiv \frac{dp}{d\epsilon}$$

$$\frac{dN}{dy} \sim e^{\sqrt{L^2-y^2}} \approx e^{L-y^2/2L}$$

$$L = \frac{4}{3}\frac{c_s^2}{1-c_s^4} log(\frac{s}{4M^2})$$

$$N \sim s^{\frac{1-c_s^2}{2(1+c_s^2)}}$$

with my generalization (1972) to arbitrary value of the sound velocity and cs^2=0.2 it described pp data from the first hadronic collider ISR CERN very well !
(and it still does for all pp and AA data including RHIC and LHC)

But, if the Landau theory be a correct description of pp collisions it would mean the matter is the Resonance Gas and not QGP (which has cs^2=1/3)!

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Can it be really true? (a dream)

The transverse (or radial) flow

We decided to look in detail
at transverse momentum distribution
of secondaries

the idea was that particles of different
mass -pions, kaons, nucleons-
would be affected by flow
differently

the idea was correct but in ISR pp data
no traces of flow was seen

Vacuum Pressure Effects In Low P(t) Hadronic Spectra
Edward V. Shuryak, O.V. Zhirov 1979. 3 Phys.Lett. 89B (1979) 253-255

QGP is produced but fails to expand
against large vacuum pressure …

It is in a way true: QCD flux tubes are
Pressure balanced

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Yet when heavy ions were used in 1980's, RHIC (>2000) it was observed, by this very method

in the first run of LHC (2010) radial and elliptic flows were observed in rare high multiplicity events

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The lesson: sometimes your dreams may come true, but many many years later

what theorists were arguing prior to RHIC

Flow at the SPS and RHIC as a quark gluon plasma signature
D. Teaney, J. Lauret, Edward V. Shuryak Phys.Rev.Lett. 86 (2001) 4783-4786

minijet models:
in the first approximation isotropic uncorrelated emission in azimuthal angle; in the second: showers and thus more secondaries in the longer direction: v2<0

hydrodynamics:
pressure gradient is larger in the shorter direction: elliptic flow v2>0 linearly growing with pt

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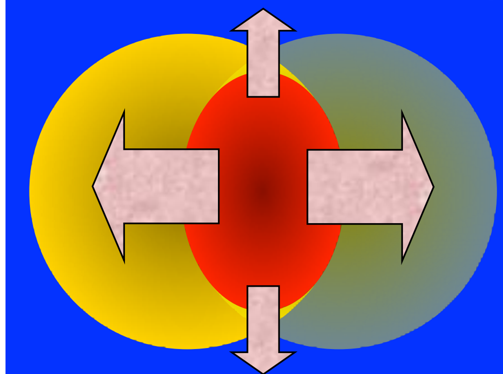
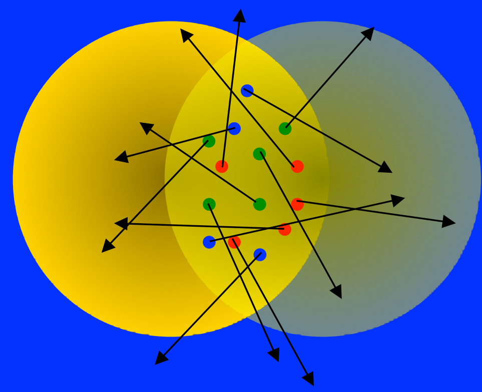
Contrary to expectations of most, hydrodynamics does work at RHIC!

Elliptic flow
How does the system respond to initial spatial anisotropy?





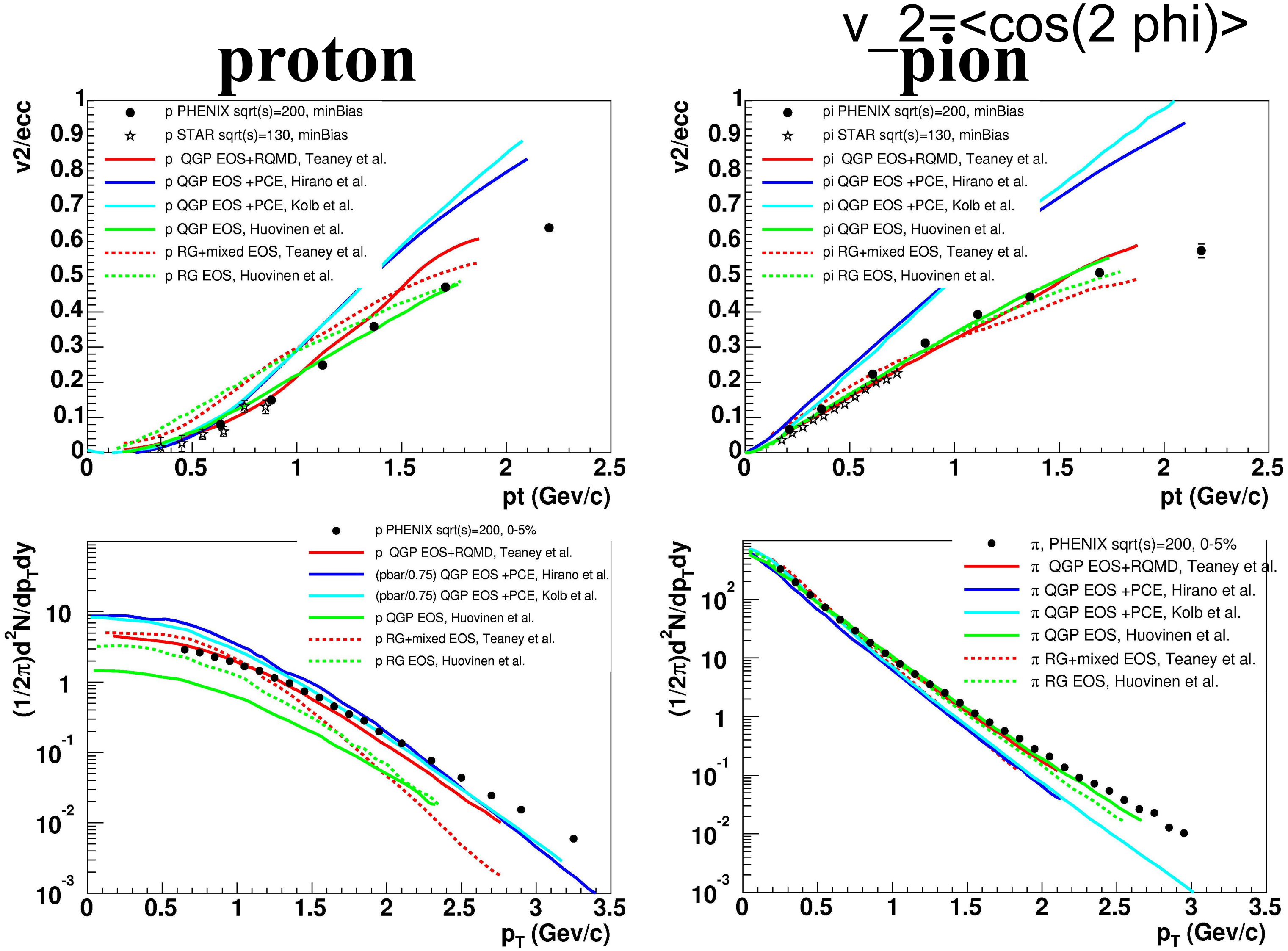
$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots\right)$$

$$v_2(p_T, y) = \frac{\int d\phi \cos(2\phi)\frac{dN}{p_T dp_T dy d\phi}}{\int d\phi \frac{dN}{p_T dp_T dy d\phi}} = \langle \cos(2\phi) \rangle$$

2001-2005: hydro describes radial and elliptic flows for all secondaries , pt<2GeV, centralities, rapidities, A (Cu,Au)…
Experimentalists were very sceptical but were convinced and ``near-perfect liquid” is now official,

=>AIP declared this to be discovery #1 of 2005 in physics

v_2=<cos(2 phi)>



PHENIX,

Nucl-ex/0410003

red lines are for ES +Lauret+Teaney done before RHIC data, never changed or fitted, describes SPS data as well! It does so because of the correct hadronic matter /freezout via (RQMD)

Note that theory lines only go to pt= 2 GeV. Can it be used further?

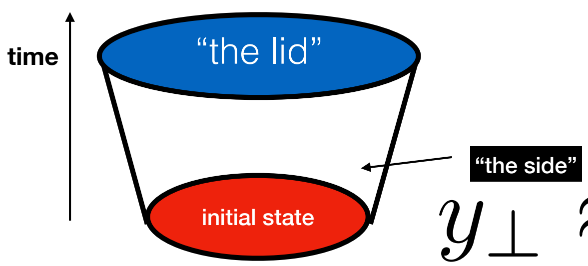
Thermal spectra describe data till masses of He4, 4 GeV

Exponential spectra turn to power-like at pt>5-6 GeV

$$y_\perp < 1.2$$

Extending the hydrodynamical description of heavy ion collisions to the outer edge of the fireball

Adith Ramamurti and Edward Shuryak



$$y_\perp \approx 1.$$

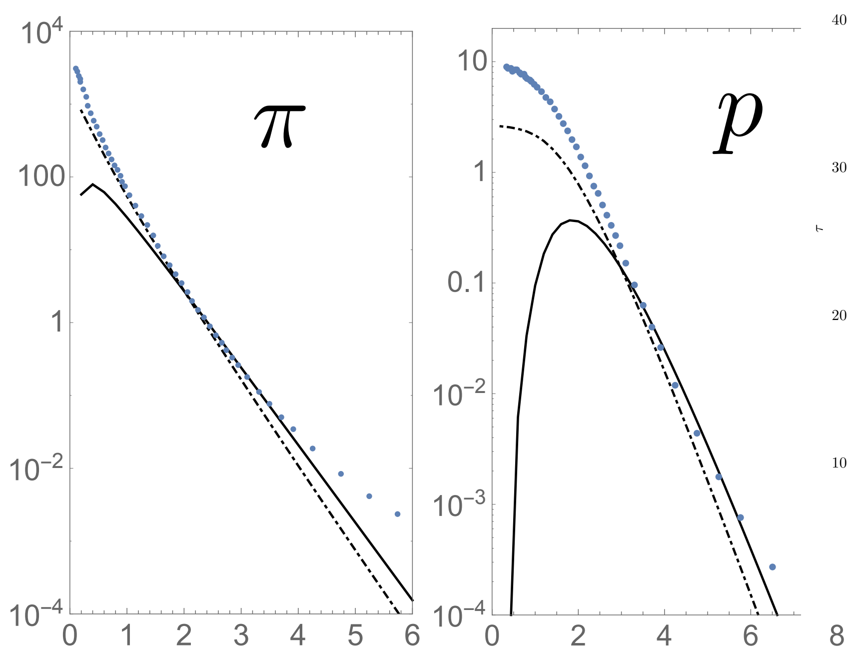
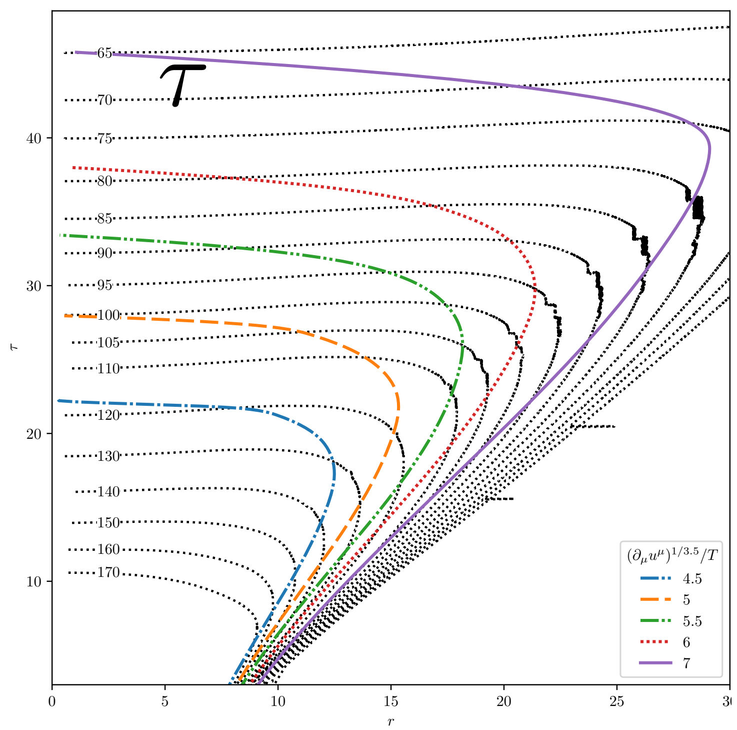
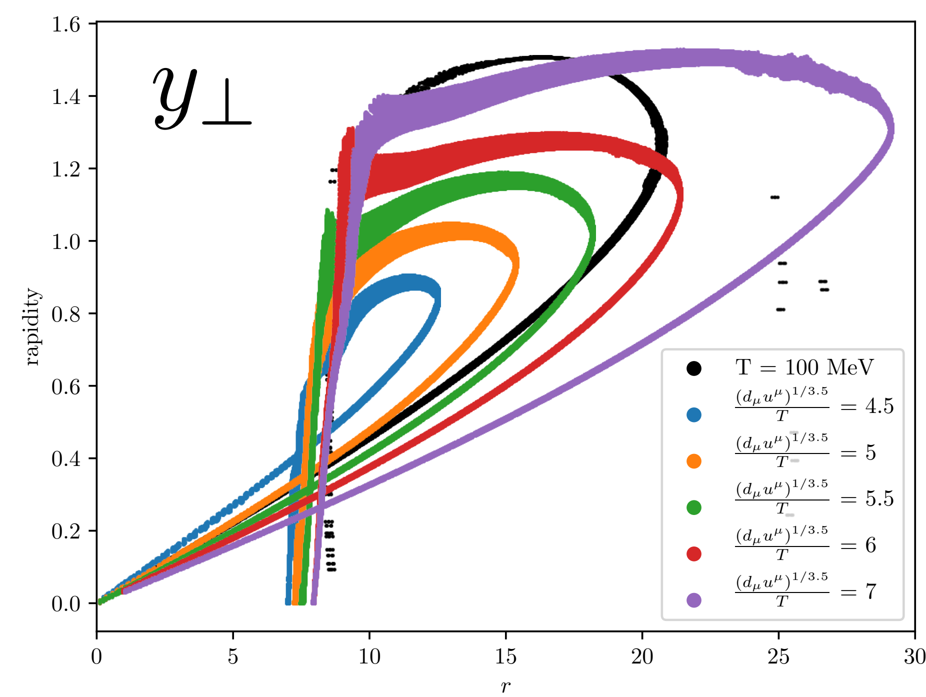


FIG. 5: The transverse momentum spectrum $dN/dydp_\perp^2$ $((GeV)^{-2})$ for pions (left plot) and protons (right plot). The points correspond to ALICE 0-5% centrality data, the dash-dotted lines show the "lid" contribution, and the solid lines show that of the "outer edge", with additional factor $P_{wall} = 1/4$.





$$T_f = 100\ MeV$$

In the outer edge there is analytic solution: The Riemann rarefaction fan

The freezeout condition is not T=const, but coll.rate=expansion rate:

Perturbations of the Big and the Little Bangs

Frozen sound (from the era long gone) is seen on the sky, both in CMB and in distribution of Galaxies

$$\frac{\Delta T}{T} \sim 10^{-5}$$

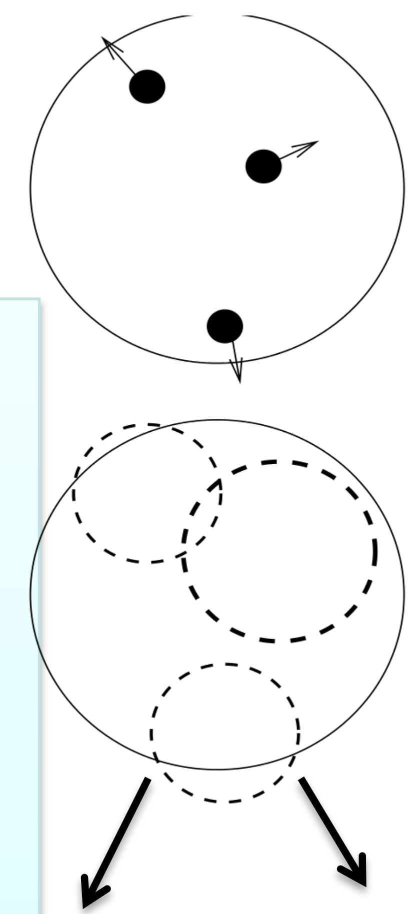
$$l_{maximum} \approx 210$$

$$\delta\phi \sim 2\pi/l_{maximum} \sim 1^o$$

They are literally circles on the sky, around primordial density perturbations

Initial state fluctuations in the positions of participant nucleons **lead to perturbations of the Little Bang also**

$$\frac{\Delta T}{T} \sim 10^{-2}$$



Cylindrical (extended in z) at FO surface tau$_f$=2R and sound velocity is ½ => radius is about R =>

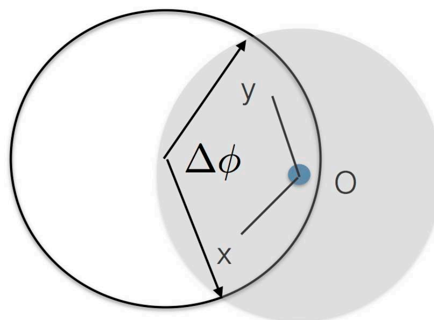
Radial flow enhances the fireball surface: move toward detection with v about 0.8 c So we should see two "horns"

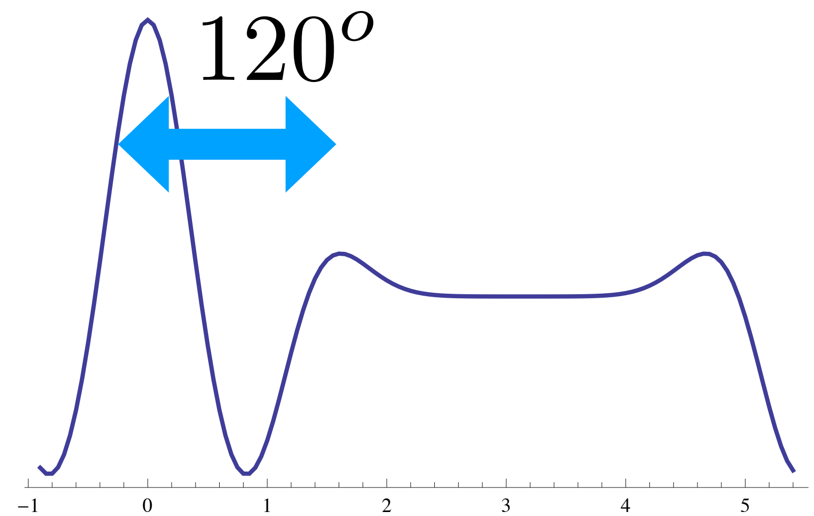
Azimutal harmonics m=O(1) Angle about 1 radian

Higher flow harmonics are just deformed sounds

The Fate of the Initial State Fluctuations in Heavy Ion Collisions. III The Second Act of Hydrodynamics

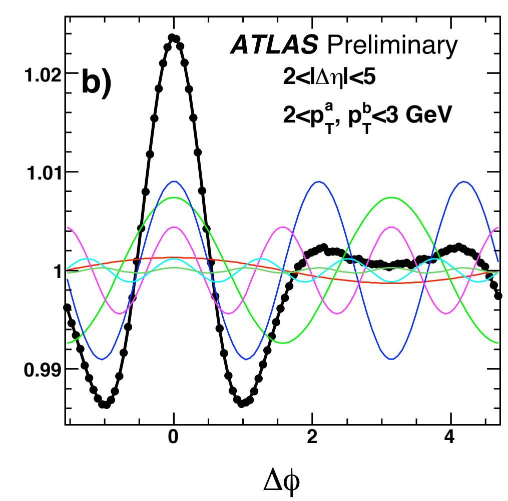
Pilar Staig, Edward Shuryak, Phys.Rev. C84 (2011) 044912 arXiv:1105.0676

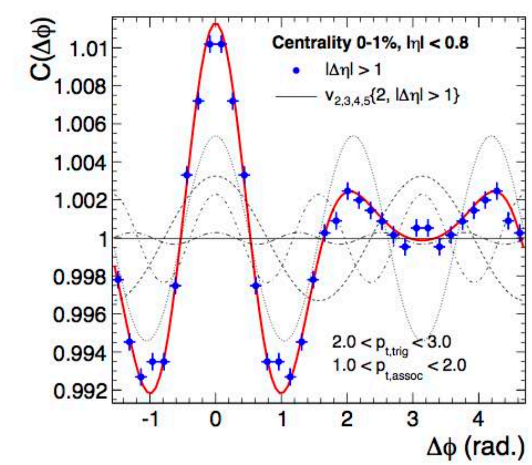




$$\int d\tau c_s(\tau) \approx R$$

so the “sound circle”
has the same size as a fireball





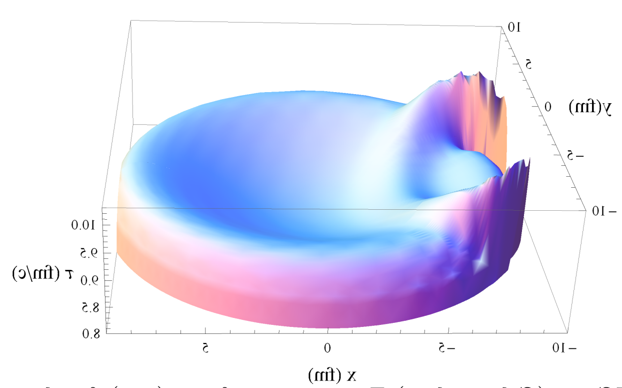


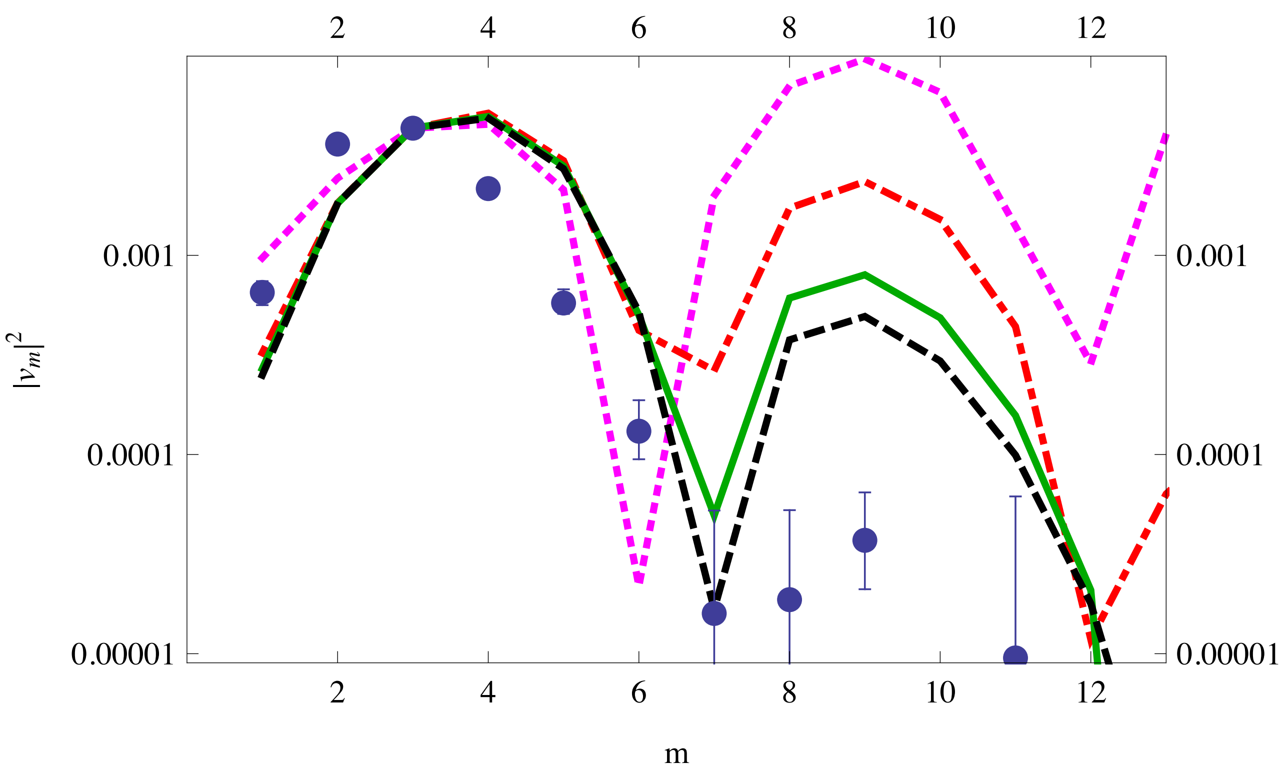
FIG. 5: (Color online) Freeze-out surface $\tau(x,y)$ for the inviscid case.

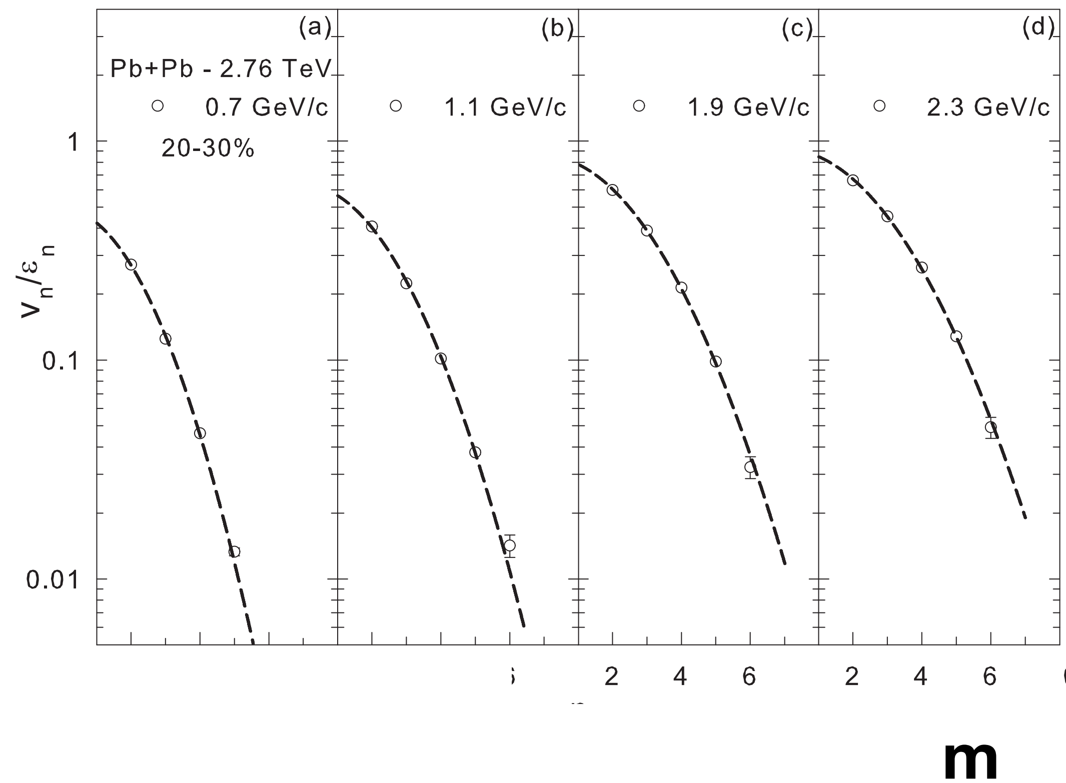
Fig. 16.3 (a) Calculated two-pion distribution as a function of azimuthal angle difference $\Delta\phi$, for viscosity-to-entropy ratios $\eta/s = 0.134$, Experimental data for ultra-central collisions from LHC collaboration ATLAS and ALICE are shown in (b) and (c)

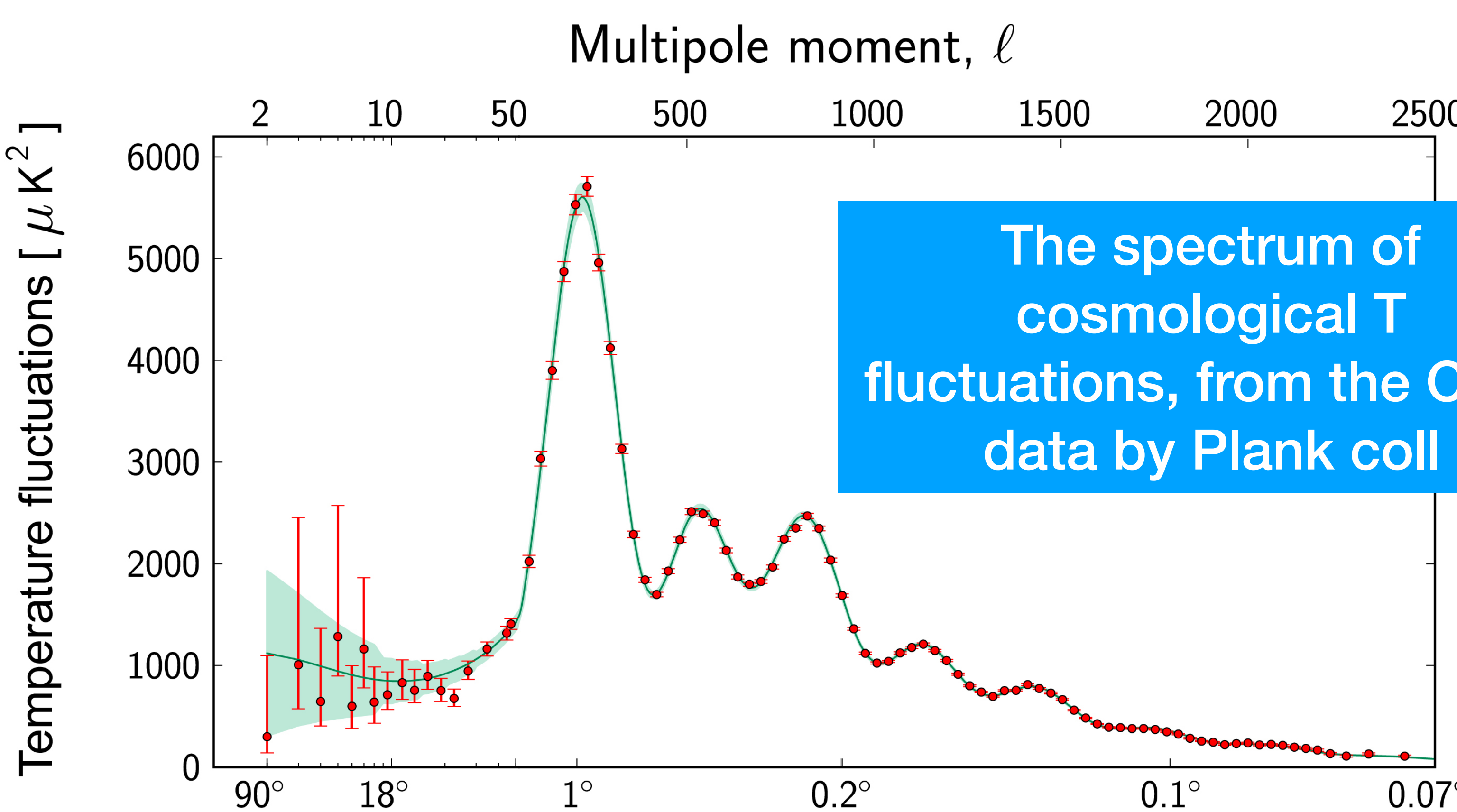
the spectrum of azimuthal harmonics show the effect of viscous damping much more clearly

data from ATLAS coll

$$P_m = \exp\left[-m^2 \frac{4}{3}\left(\frac{\eta}{s}\right)\left(\frac{1}{TR}\right)\right]$$







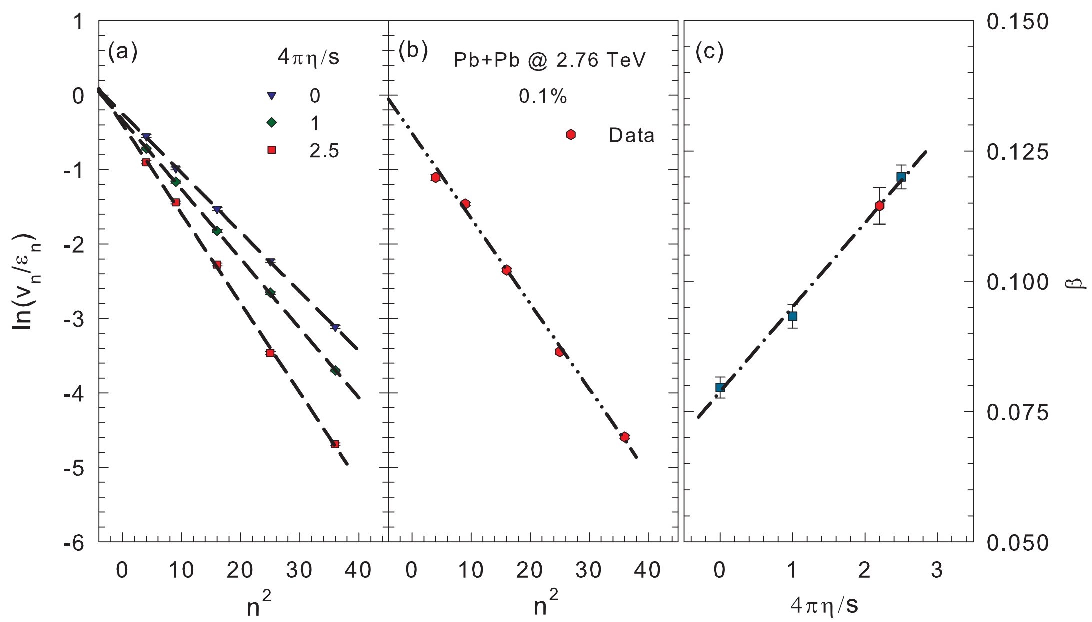
The spectrum of cosmological T fluctuations, from the CMB data by Plank coll

the sounds of the Little and Big Bang

The Fate of the Initial State Fluctuations in Heavy Ion Collisions. III The Second Act of Hydrodynamics
Pilar Staig, Edward Shuryak, Phys.Rev. C84 (2011) 044912 arXiv:1105.0676

The acoustic damping formula works well, even for nonlinear terms

$$\frac{v_n}{\epsilon_n} \sim e^{\left[-n^2 \frac{4\eta}{3s} \frac{1}{RT}\right]}$$



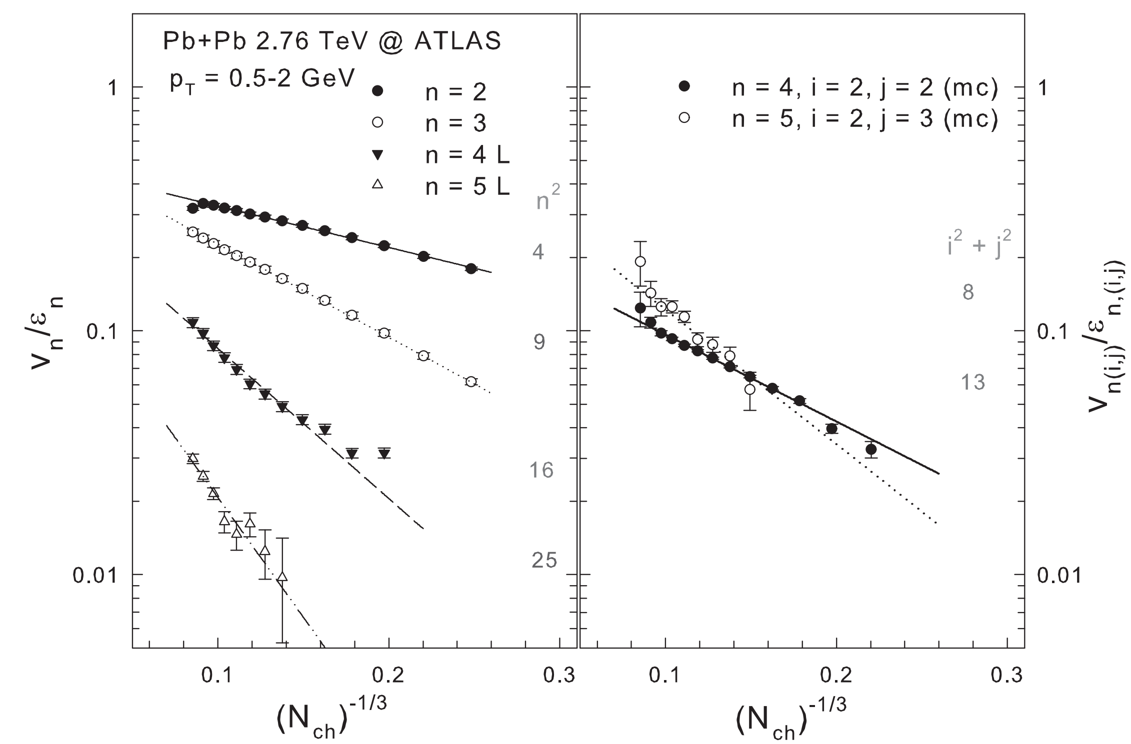


FIG. 2. Same as Fig. 1 but for ATLAS data [22]; the β-prefactors n^2 and $(\mathrm{i}^2+\mathrm{j}^2)$ are indicated in the figure.

$$\mathrm{v}^{\mathrm{mc}}_{4,(2,2)} = \frac{\langle \mathrm{v}_4 \mathrm{v}_2^2 \cos(4\Psi_4 - 4\Psi_2)\rangle}{\sqrt{\langle \mathrm{v}_2^4\rangle}} \approx \langle \mathrm{v}_4 \cos(4\Psi_4 - 4\Psi_2)\rangle,$$

$$\mathrm{v}^{\mathrm{mc}}_{5,(3,2)} = \frac{\langle \mathrm{v}_5 \mathrm{v}_3 \mathrm{v}_2 \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle}{\sqrt{\langle \mathrm{v}_3^2\, \mathrm{v}_2^2\rangle}} \approx \langle \mathrm{v}_5 \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle,$$

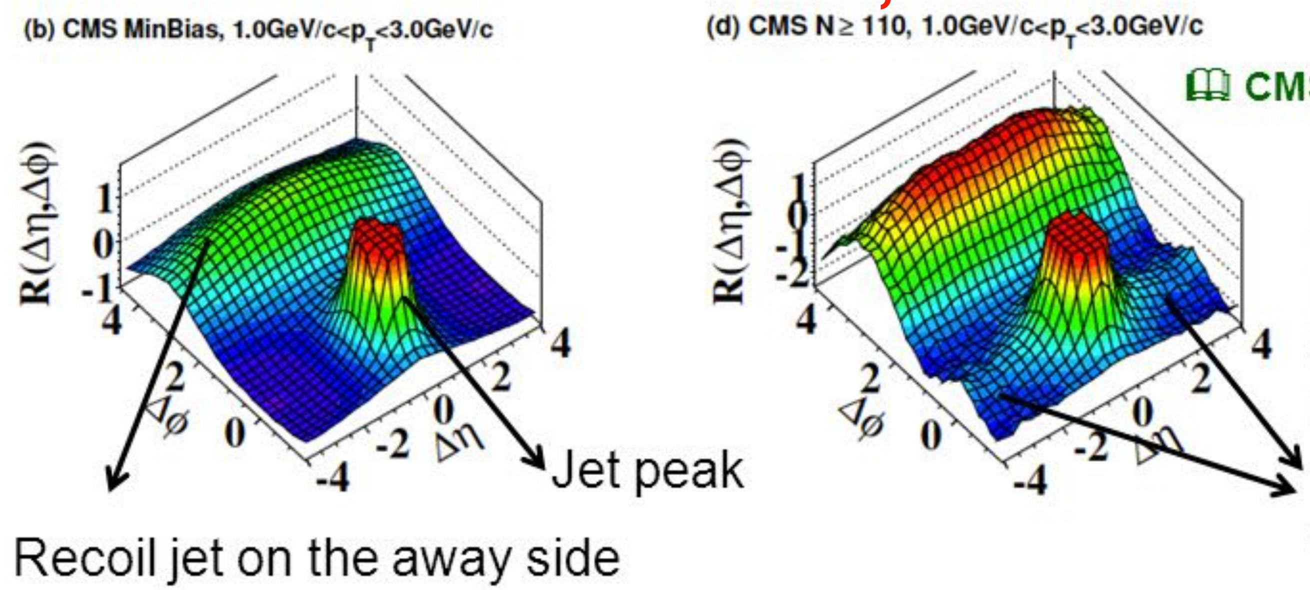
$$\frac{\mathrm{v}^{\mathrm{L}}_{\mathrm{n}}}{\varepsilon'_{\mathrm{n}}} \propto \exp\left(-\mathrm{n}^2 \beta \frac{1}{\mathrm{RT}}\right),$$

$$\frac{\mathrm{v}^{\mathrm{mc}}_{\mathrm{n},(\mathrm{i},\mathrm{j})}}{\varepsilon^{\mathrm{mc}}_{\mathrm{n},(\mathrm{i},\mathrm{j})}} \propto \exp\left(-(\mathrm{i}^2+\mathrm{j}^2)\beta \frac{1}{\mathrm{RT}}\right),$$

Acoustic scaling of linear and mode-coupled anisotropic flow; implications for precision extraction of the specific shear v
Peifeng Liu, Roy A. Lacey Phys.Rev. C98 (2018) no.2, 021902 arXiv:1802.06595

Is there a hydrodynamical explosion in pp and pA collisions?

Yes, but not in all of them!



CMS, JHEP 1009 (2010) 091

High-multiplicity pp events
8x average multiplicity
-> **near side ridge** along $\Delta\eta$: origin?

CMS managed to use high multiplicity trigger in the first pp run at LHC and discovered the "ridge"

subsequent studies showed this ridge is the elliptic flow, also higher harmonics were observed

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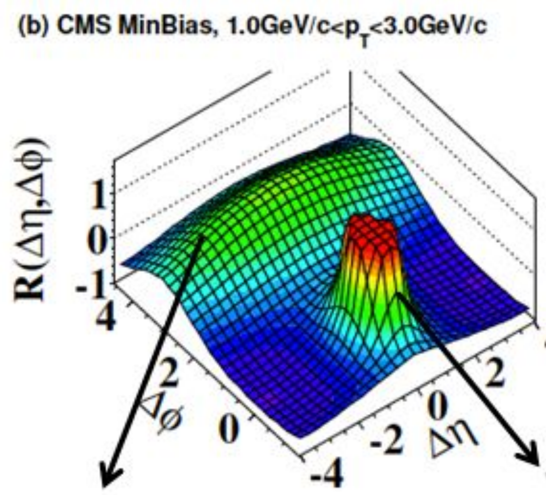
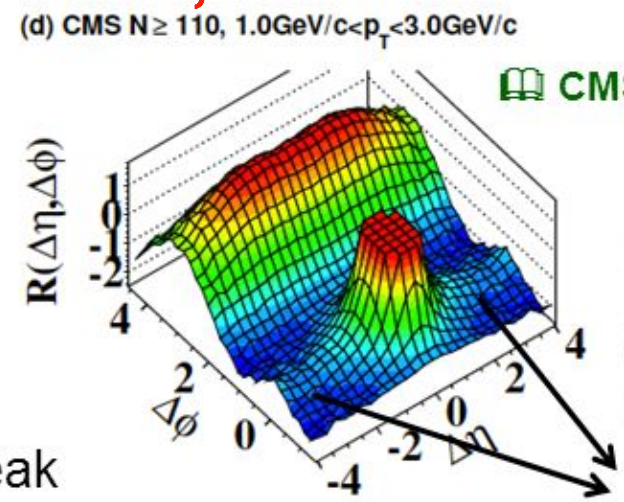


Jet peak

Recoil jet on the away side



CMS, JHEP 1009 (2010) 091

High-multiplicity pp events
8x average multiplicity
-> **near side ridge** along Δη: origin?

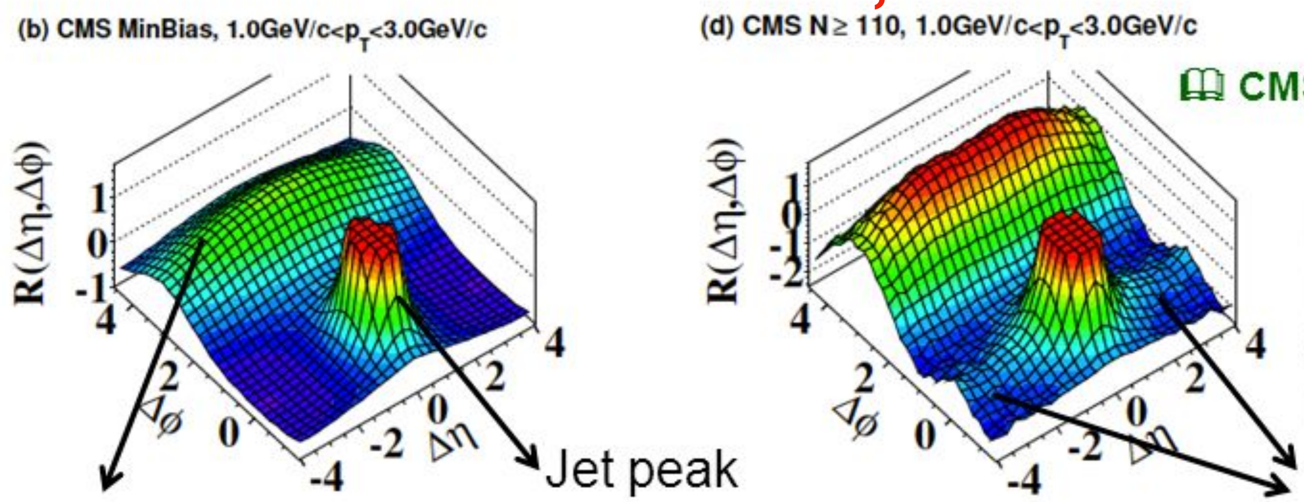
CMS managed to use high multiplicity trigger in the first pp run at LHC and discovered the “ridge”

Min.bias events cost 1$ each
high multiplicity P=10^(-6) event costs 10^6 $ each
and one needs many to make such histogram

subsequent studies showed this ridge is the elliptic flow, also higher harmonics were observed

Is there a hydrodynamical explosion in pp and pA collisions?

Yes, but not in all of them!



Jet peak

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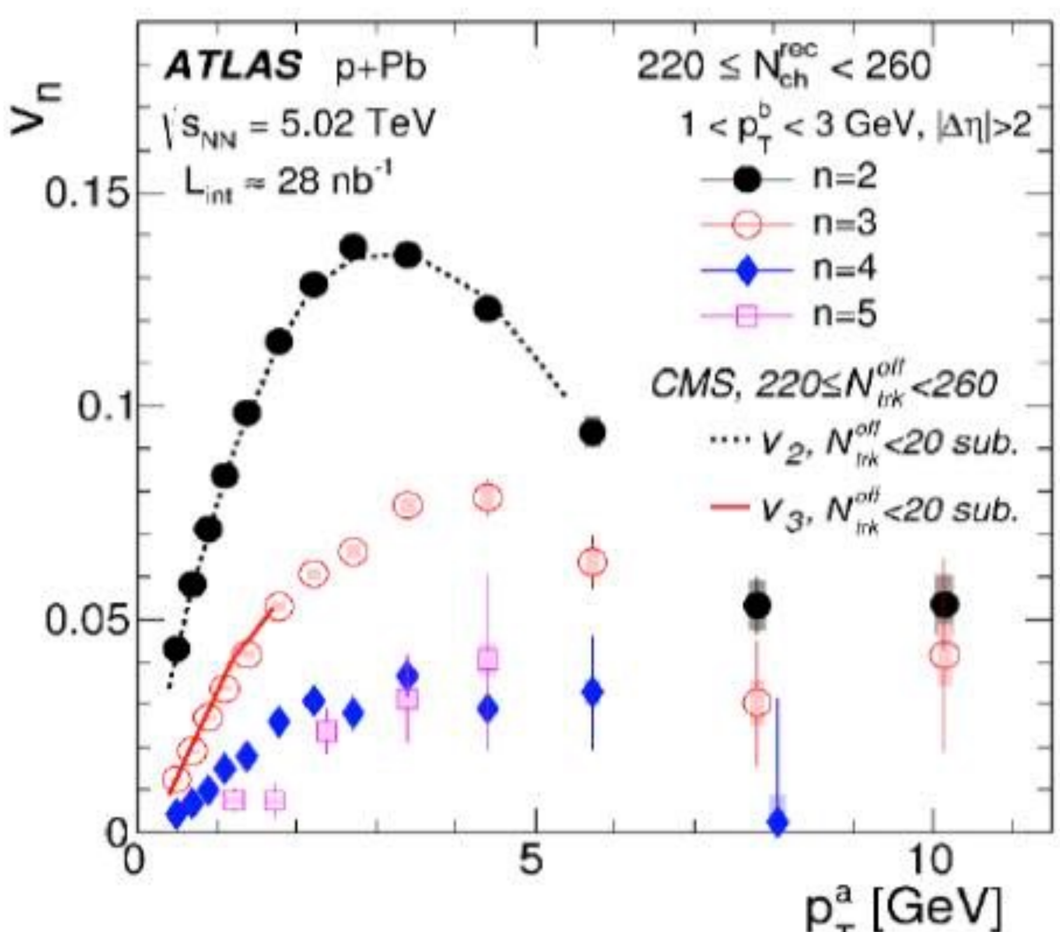

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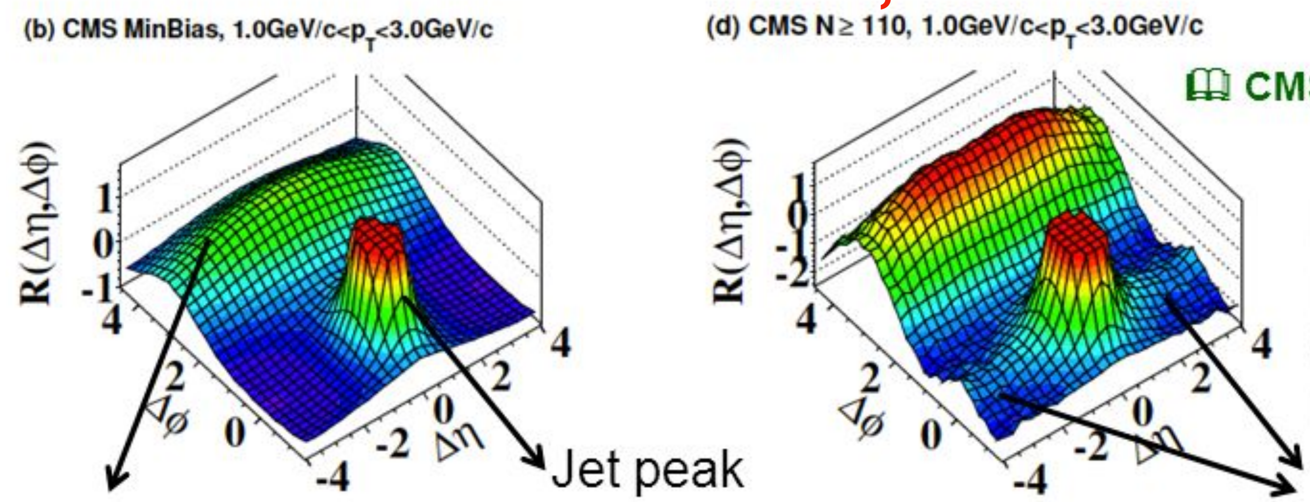

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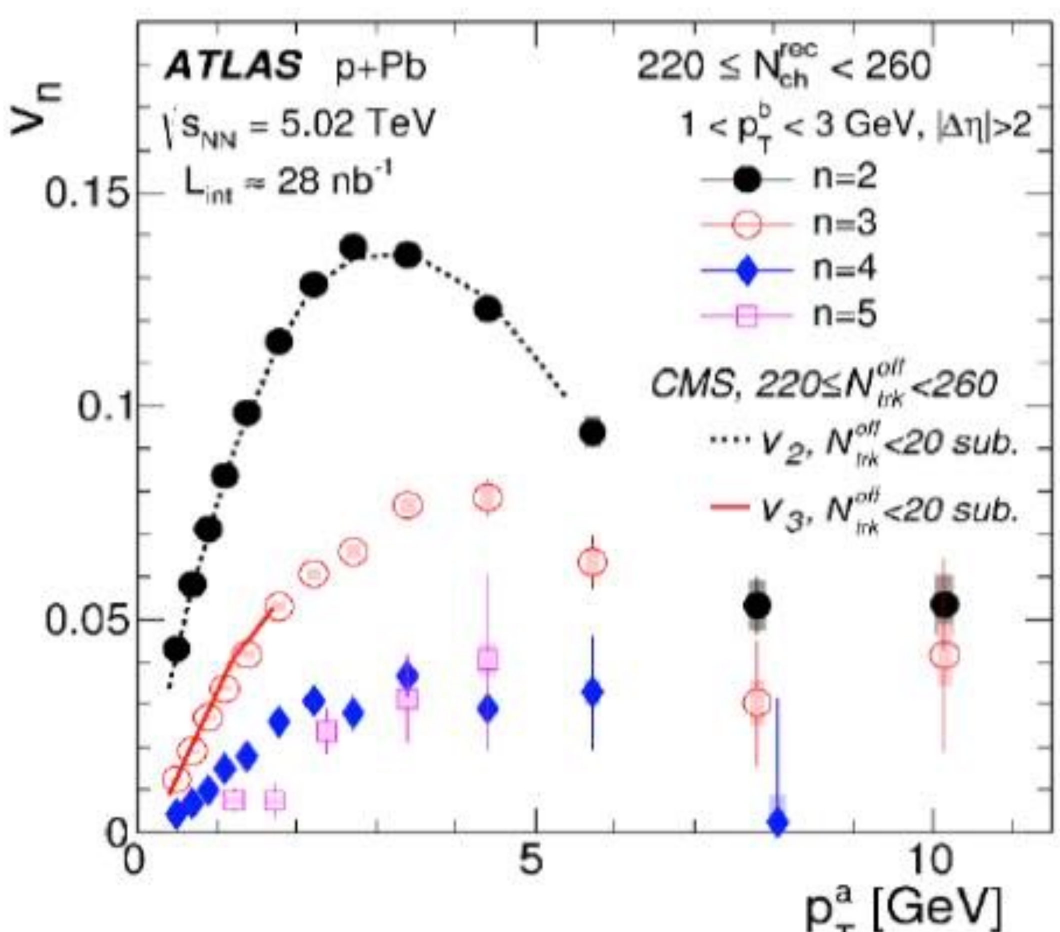

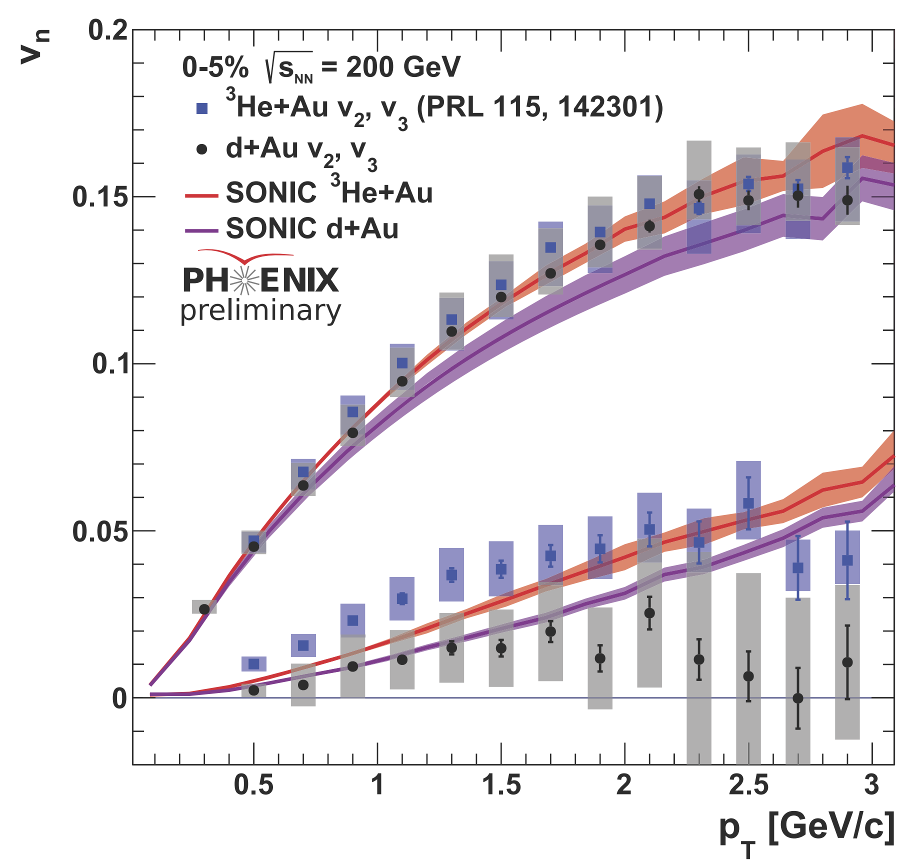

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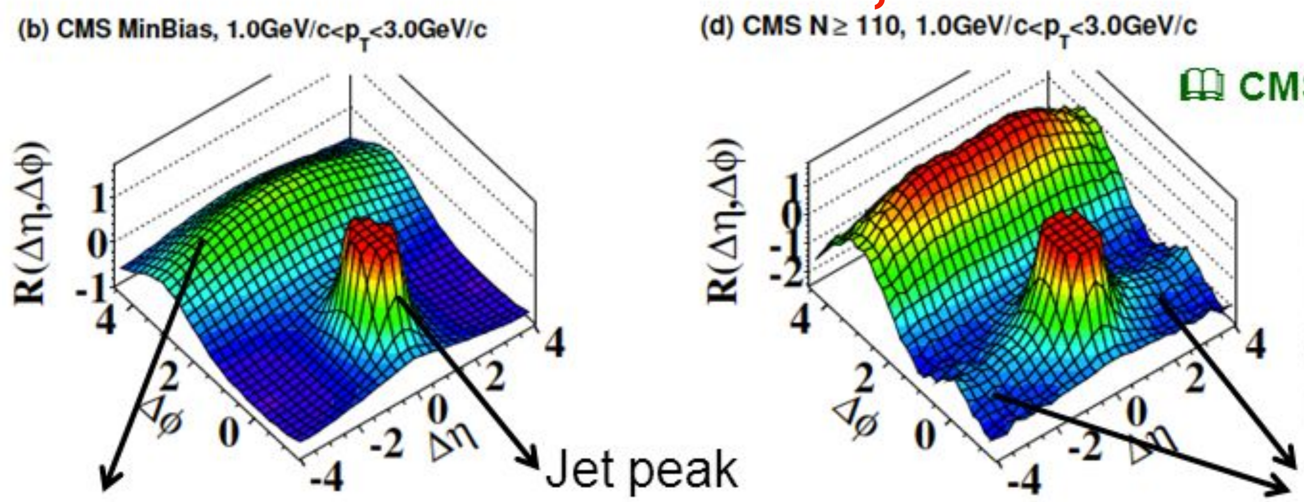

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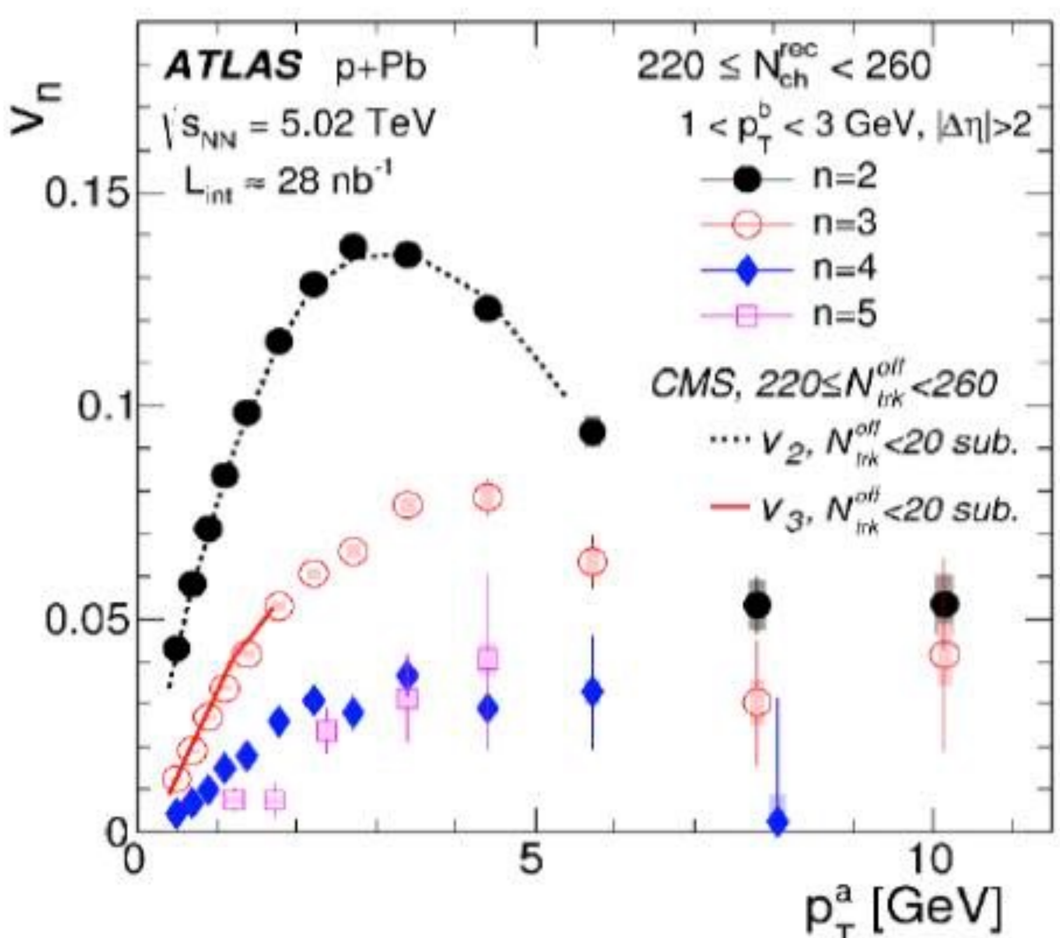

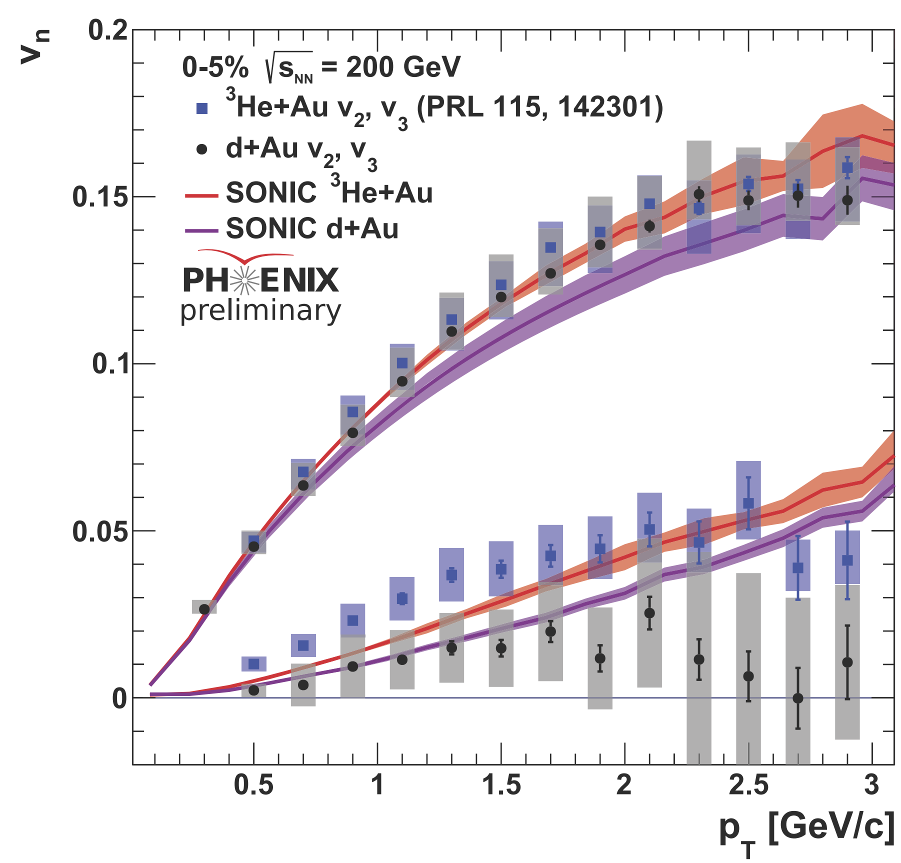

double or triple explosion centers at RHIC left no doubt it is generated by the initial state geometry

Can 1fm-size fireball in pA and pp be hydrodynamical?

If one naively estimate viscosity times the gradient, it is comparable to the local terms

But re-summation of higher gradients change it to smaller effective value Helping to explain why hydro works for small systems

$$\eta_{model\,2} = \frac{\eta_0}{1 - \eta_{2,0}\,k^2 - i\,w\,\eta_{0,1}}$$

Improved Hydrodynamics from the AdS/CFT
Michael Lublinsky, Edward Shuryak (SUNY, Stony Brook). May 2009. 25 pp.
Published in **Phys.Rev. D80 (2009) 065026** , **arXiv:0905.4069**

Using renormalization group Similar viscosity renormalization Was found by Blaizot and Li Yan

Fluid dynamics of out of equilibrium boost invariant plasmas
Jean-Paul Blaizot (IPhT, Saclay), Li Yan (McGill U.). Jul 16, 2018. 4 pp.
Conference: C18-05-14.5
e-Print: **arXiv:1807.06104**

Relation between monopoles and semiclassical theory (instantons, instanton-dyons)

Why is QGP so unusual?
Short answer: because it is in a strongly coupled regime.
(unusually small mean free path)

A gift from string theory community,
AdS/CFT correspondence

It lead to many beautiful physics
Ideas, uniting general relativity,
strings, strongly coupled
Plasmas in equilibrium and
In out-of-equilibrium settings,
All of which were “solved from first principles”
It is a true Disneyworld for theorists

Unfortunately, it would be hard on non-experts
And perhaps require a colloquium
of its own

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I will focus instead on another duality
The electric-magnetic one
Which is based on the
Renormalization group flow
And magnetic monopoles:

QGP is a dual plasma
which has both
electrically and magnetically
charged particles.
Their interactions are very curious

There is another form of the theory of nonperturbative phenomena
The semiclassical theory based on instanton-dyons
Which is very successful but will not be discussed in this talk

One can start in the theory
in which there is a complete theoretical control
on both and **compare two approaches directly**

N.Dorey and A.Parnachev
JHEP 0108, 59 (2001)
hep-th/0011202]

N=4 extended supersymmetry
with Higgled scalar
compactified on a circle

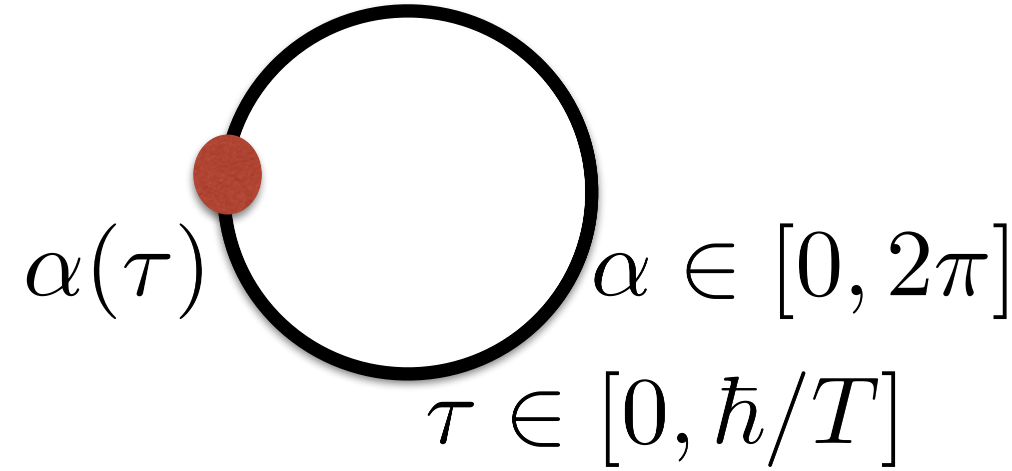
Partition function calculated in terms of monopoles

Partition function calculated in terms of instanton-dyons

Configurations are obviously very different
Zs also look different,
and yet they are related
by the Poisson summation formula
and thus are the same!!!

Is there any relation between the semiclassical instanton-dyons and QCD monopoles?

Adith Ramamurti,[*] Edward Shuryak,[†] and Ismail Zahed[‡]



The same phenomenon in much simpler setting: quantum particle on a circle at finite T

A Hamiltonian vs Lagrangian approaches

$$Z_1 = \sum_{l=-\infty}^{\infty} \exp\left(- \frac{l^2}{2\Lambda T} + il\omega \right)$$

moment of inertia

Aharonov-Bohm phase

$$Z_2 = \sum_{n=-\infty}^{\infty} \sqrt{2\pi\Lambda T}\, \exp\left(- \frac{T\Lambda}{2}(2\pi n - \omega)^2 \right).$$

Matsubara winding number

$$\alpha_n(\tau) = 2\pi n \frac{\tau}{\beta},$$

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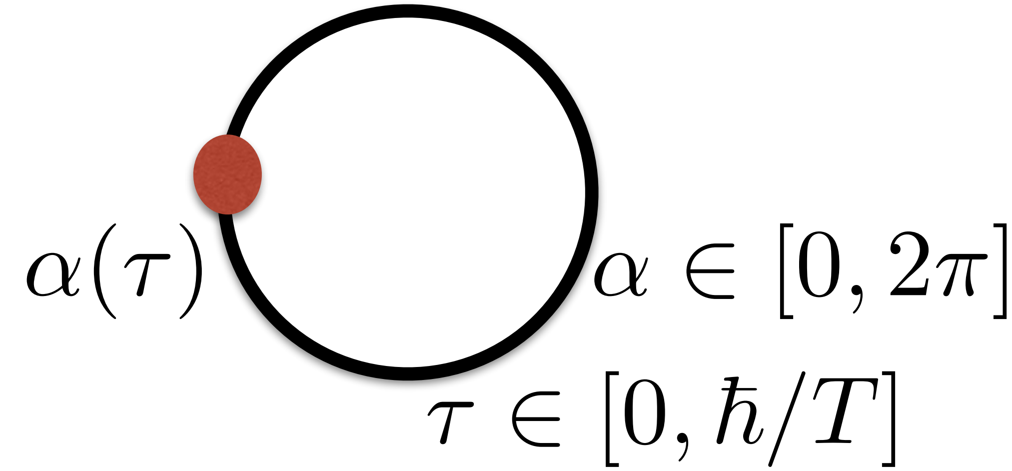

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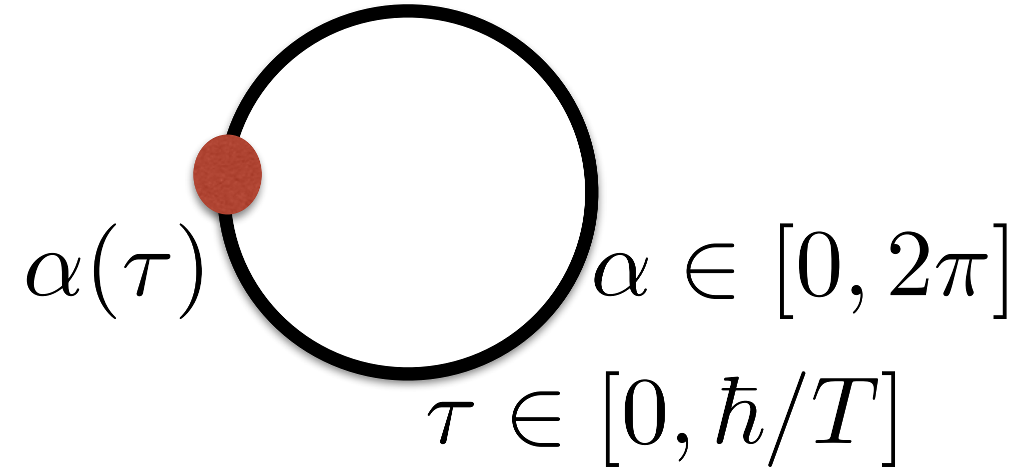

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And yet, they are the same!
(elliptic theta function of the 3 type)

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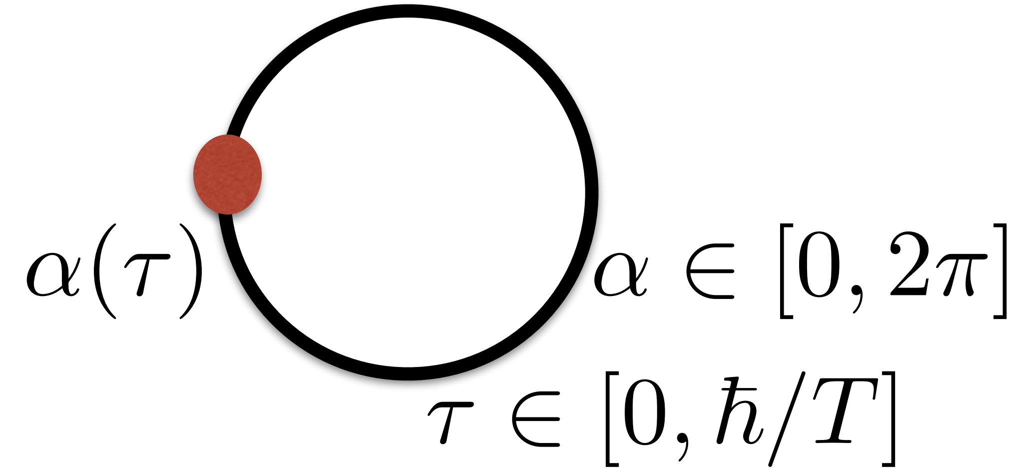

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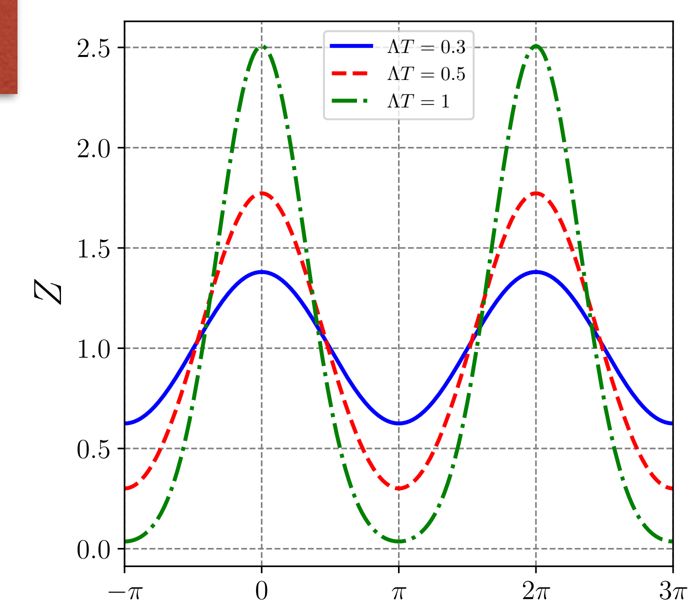

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instanton-dyons with winding number n

The twisted solution is obtained in two steps. The first is the substitution

$$v \to n(2\pi/\beta) - v\,, \tag{13}$$

and the second is the gauge transformation with the gauge matrix

$$\hat{\Omega} = \exp\left(-\frac{i}{\beta} n\pi\tau\hat{\sigma}^3 \right), \tag{14}$$

where we recall that $\tau = x^4 \in [0, \beta]$ is the Matsubara time. The derivative term in the gauge transformation adds a constant to A_4 which cancels out the unwanted $n(2\pi/\beta)$ term, leaving v, the same as for the original static monopole. After "gauge combing" of v into the same direction, this configuration – we will call L_n – can be combined with any other one. The solutions are all

$$S_n = (4\pi/g^2)|2\pi n/\beta - v|$$

$$\sum_{n=-\infty}^{\infty} f(\omega + nP) = \sum_{l=-\infty}^{\infty} \frac{1}{P} \tilde{f}\left(\frac{l}{P}\right) e^{i2\pi l\omega/P}$$

Poisson summation formula can be used to derive the monopole Z

$$Z_{\text{inst}} = \sum_n e^{-\left(\frac{4\pi}{g_0^2}\right)|2\pi n - \omega|}$$

$$Z_{\text{mono}} \sim \sum_{q=-\infty}^{\infty} e^{iq\omega - S(q)}$$

$$S(q) = \log\left(\left(\frac{4\pi}{g_0^2}\right)^2 + q^2\right)$$

$$\approx 2\log\left(\frac{4\pi}{g_0^2}\right) + q^2\left(\frac{g_0^2}{4\pi}\right)^2 + \ldots$$

q is angular momentum of rotating monopole, so it is electric charge

The density of monopoles is well fitted by an inverse power of log(T) , not power of T =>

so they are not really semiclassical objects!

$$S_{mono} \sim log(const/g^2) = log\big(log(T/Tc)\big)$$

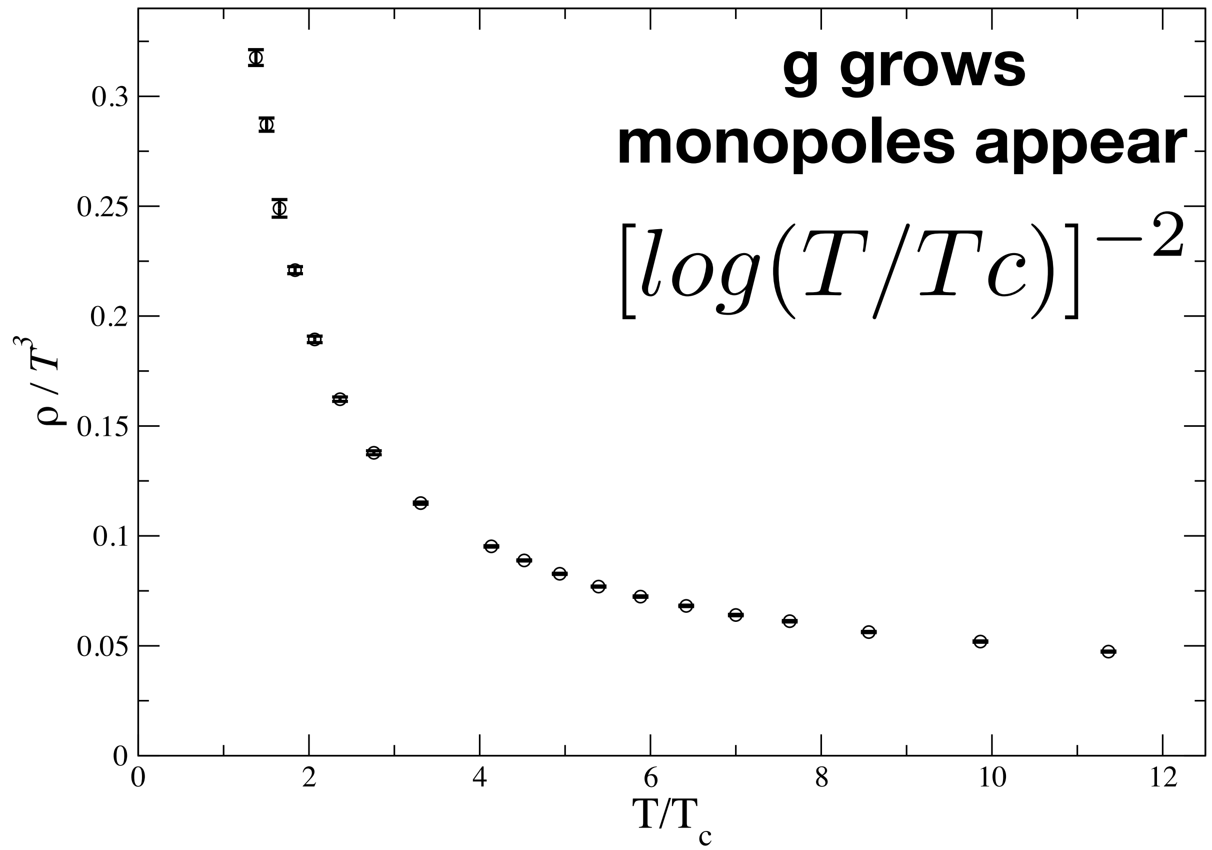

Fig. 2.6 The normalized monopole density ρ/T^3 for the $SU(2)$ pure gauge theory as a function of the temperature, in units of the critical temperature T/T_c, above the deconfinement transition.

D'Alessandro, A. and D'Elia, M. (2008). Magnetic monopoles in the high temperature phase of Yang-Mills theories. Nucl. Phys., B799:241–254. 0711.1266.

For instantons and dyons it is different

$$exp(-S) \sim exp(-const/g^2) = exp(-const' * log(T)) = 1/T^{power}$$

Monopoles
Why does QGP theory need them?

matter composition, by d.o.f.

quarks

Role of QCD monopoles in jet quenching
Adith Ramamurti, Edward Shuryak (SUNY, Stony Brook). Aug 14, 2017. 16 pp.
Published in **Phys.Rev. D97 (2018) no.1, 016010**

monopoles

gluons

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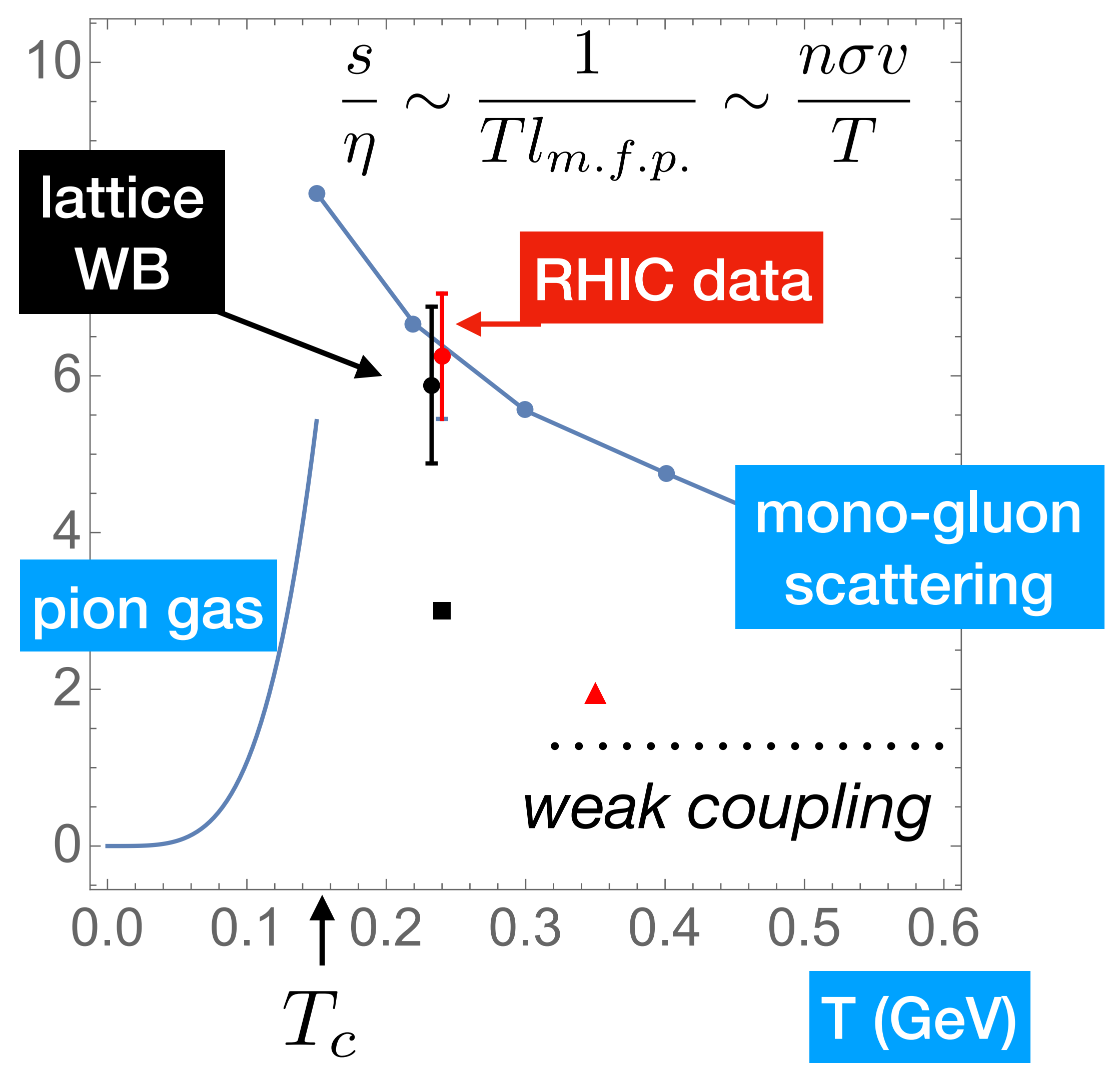
Edward Shuryak Rev.Mod.Phys. 89 (2017) 035001



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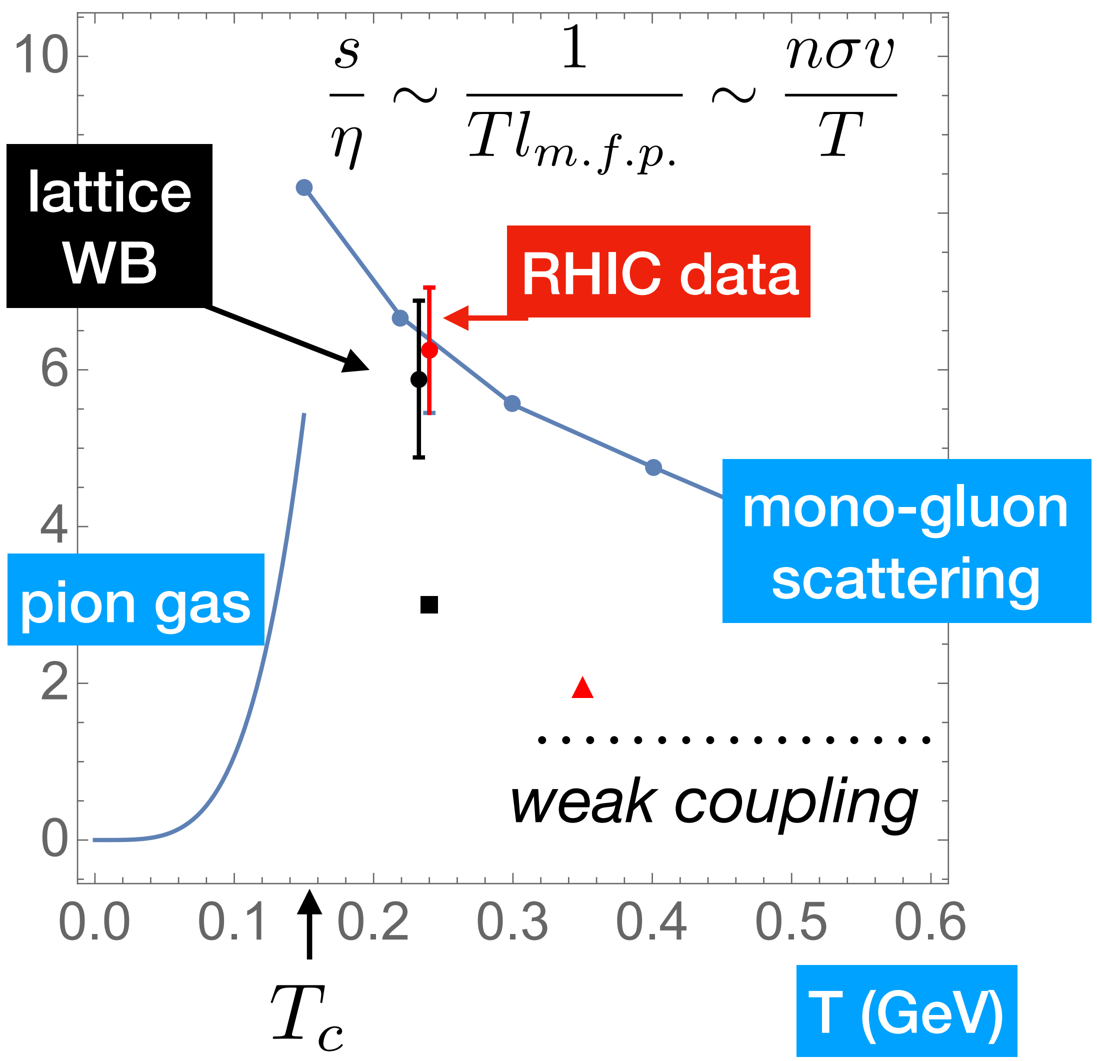

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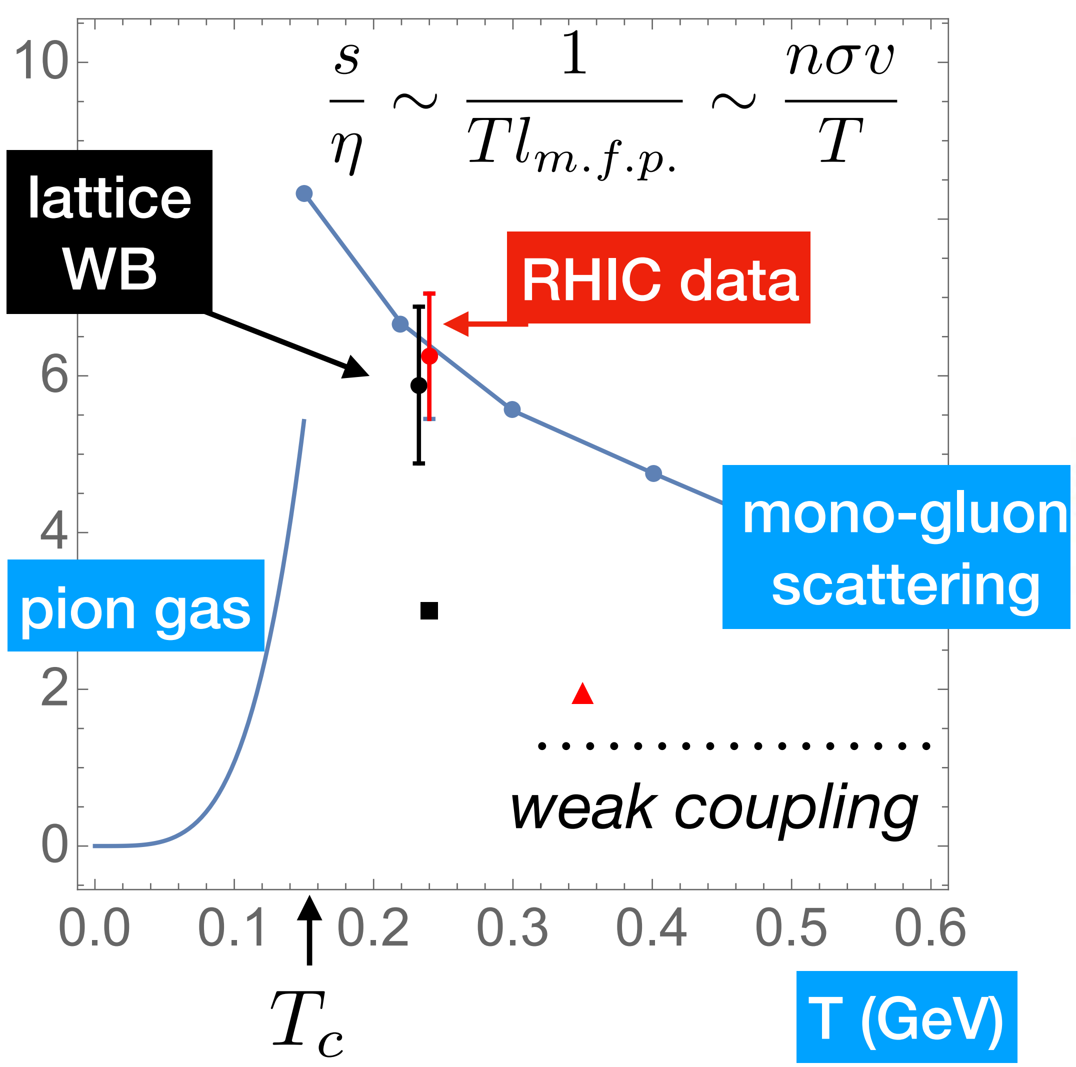

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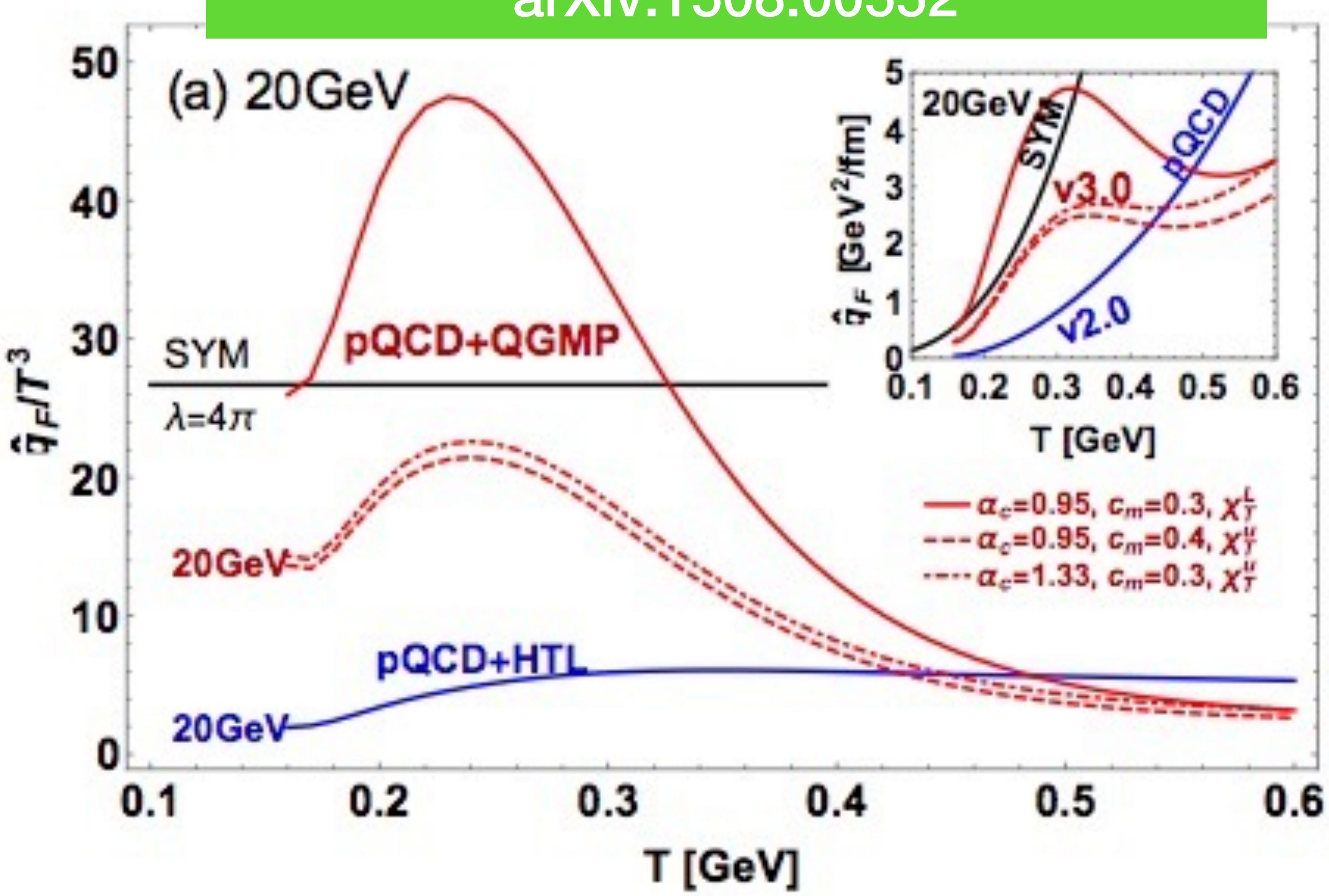

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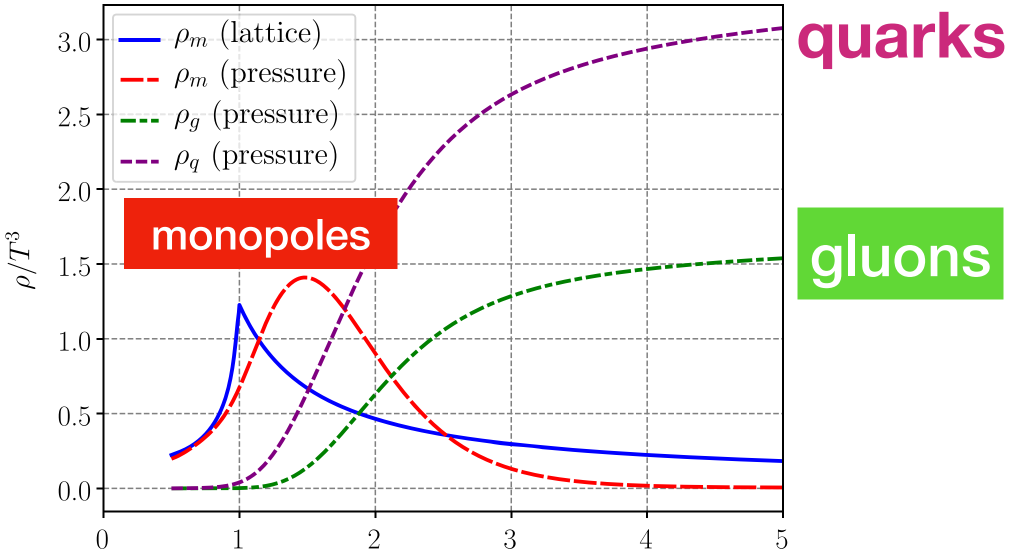

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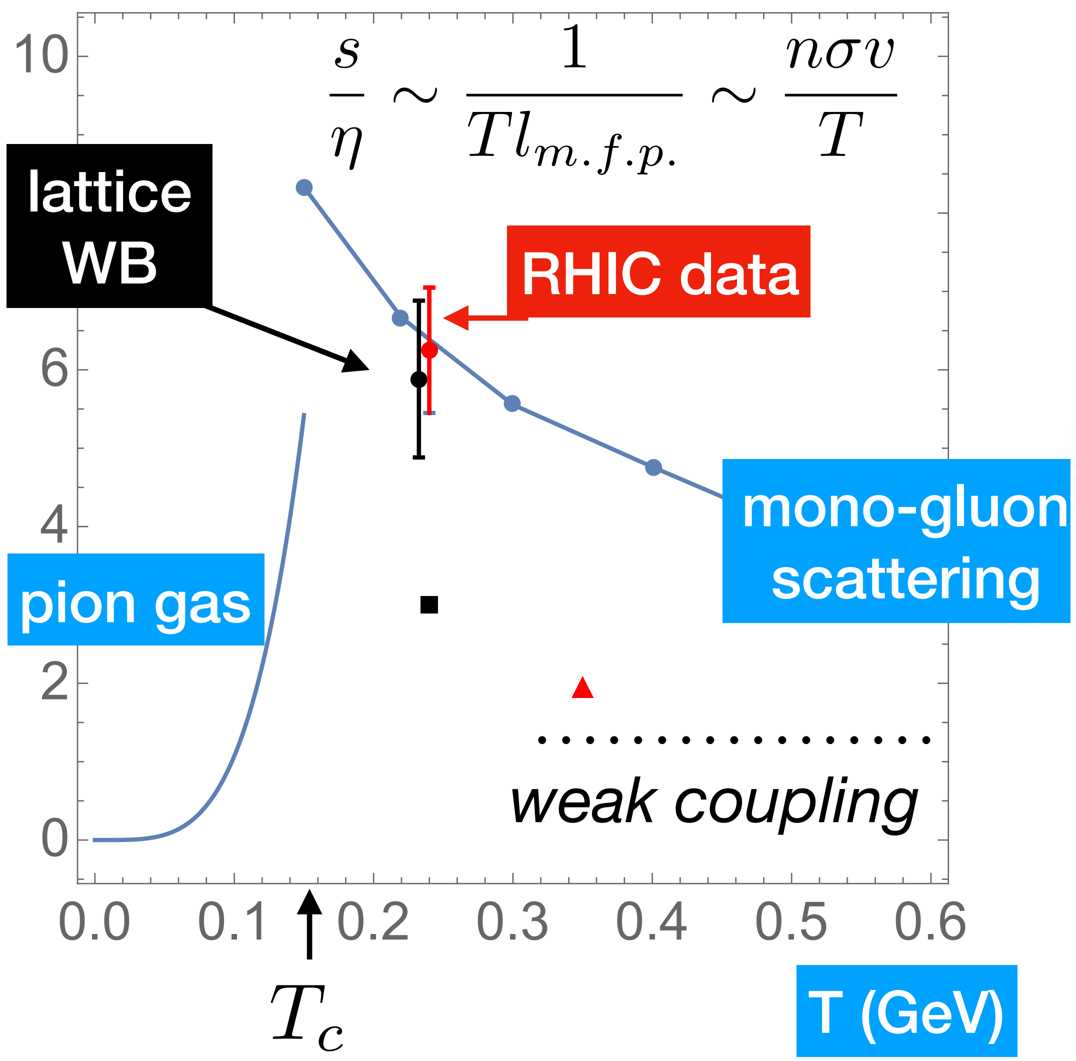

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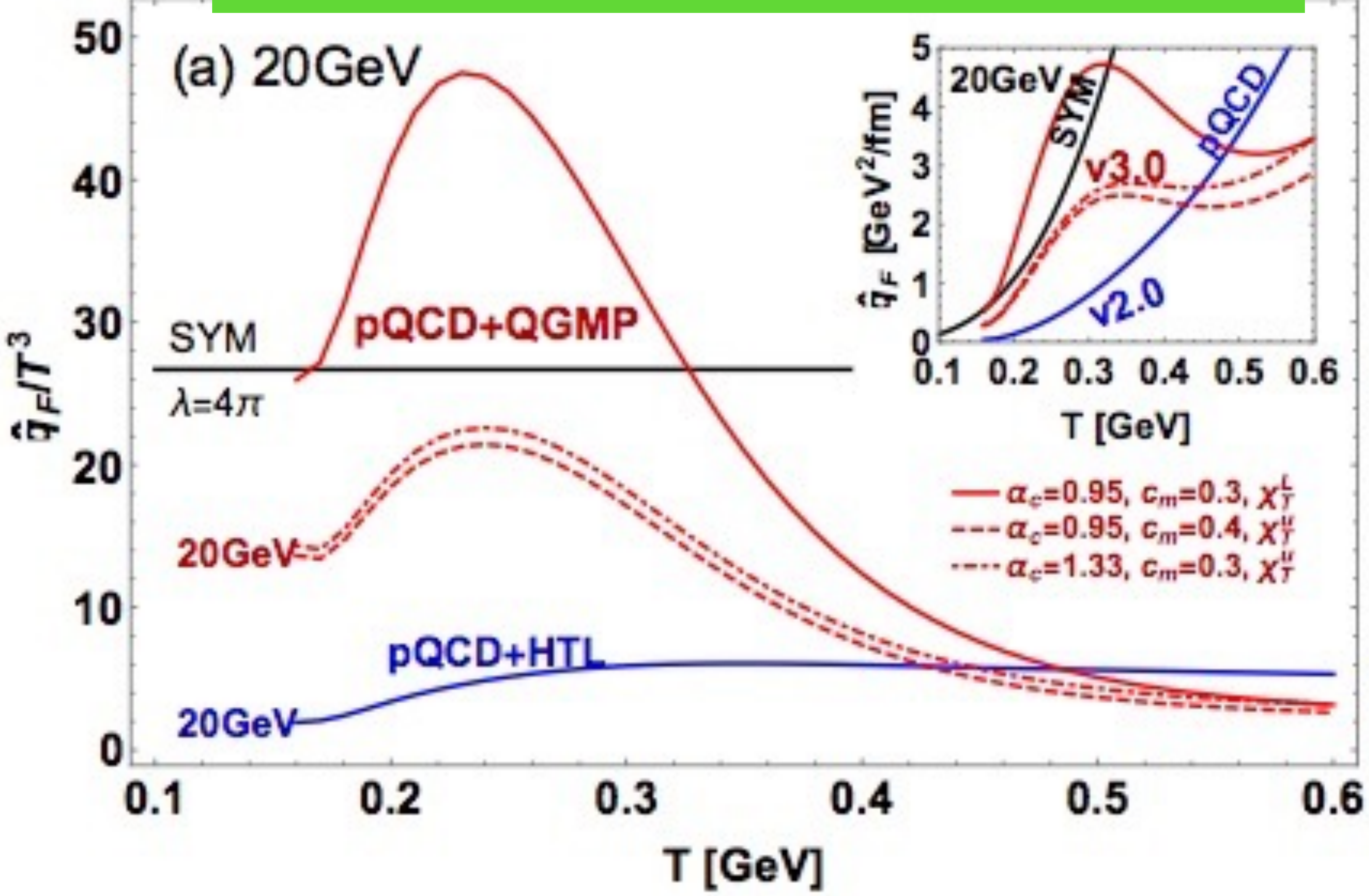

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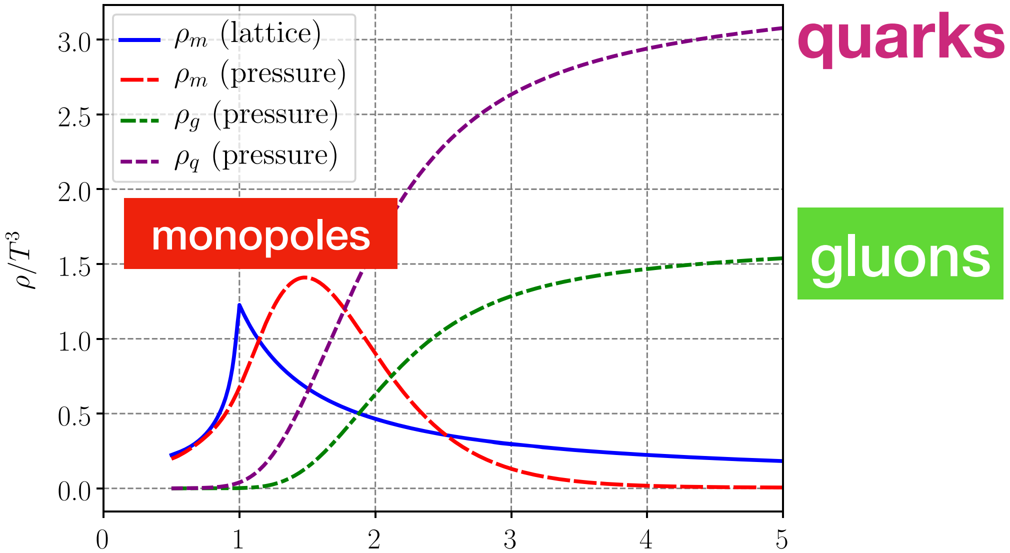

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only the monopole density peaks near Tc!

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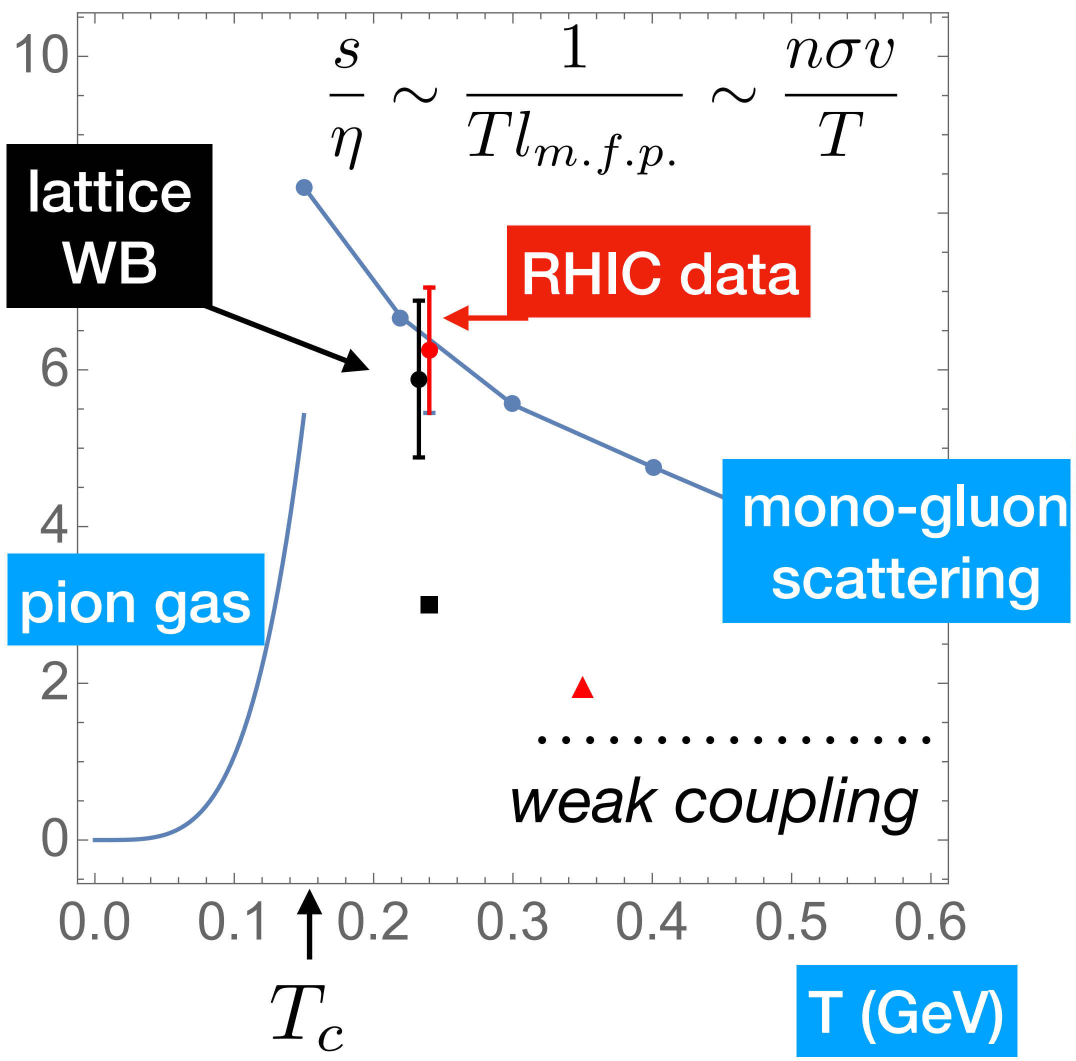

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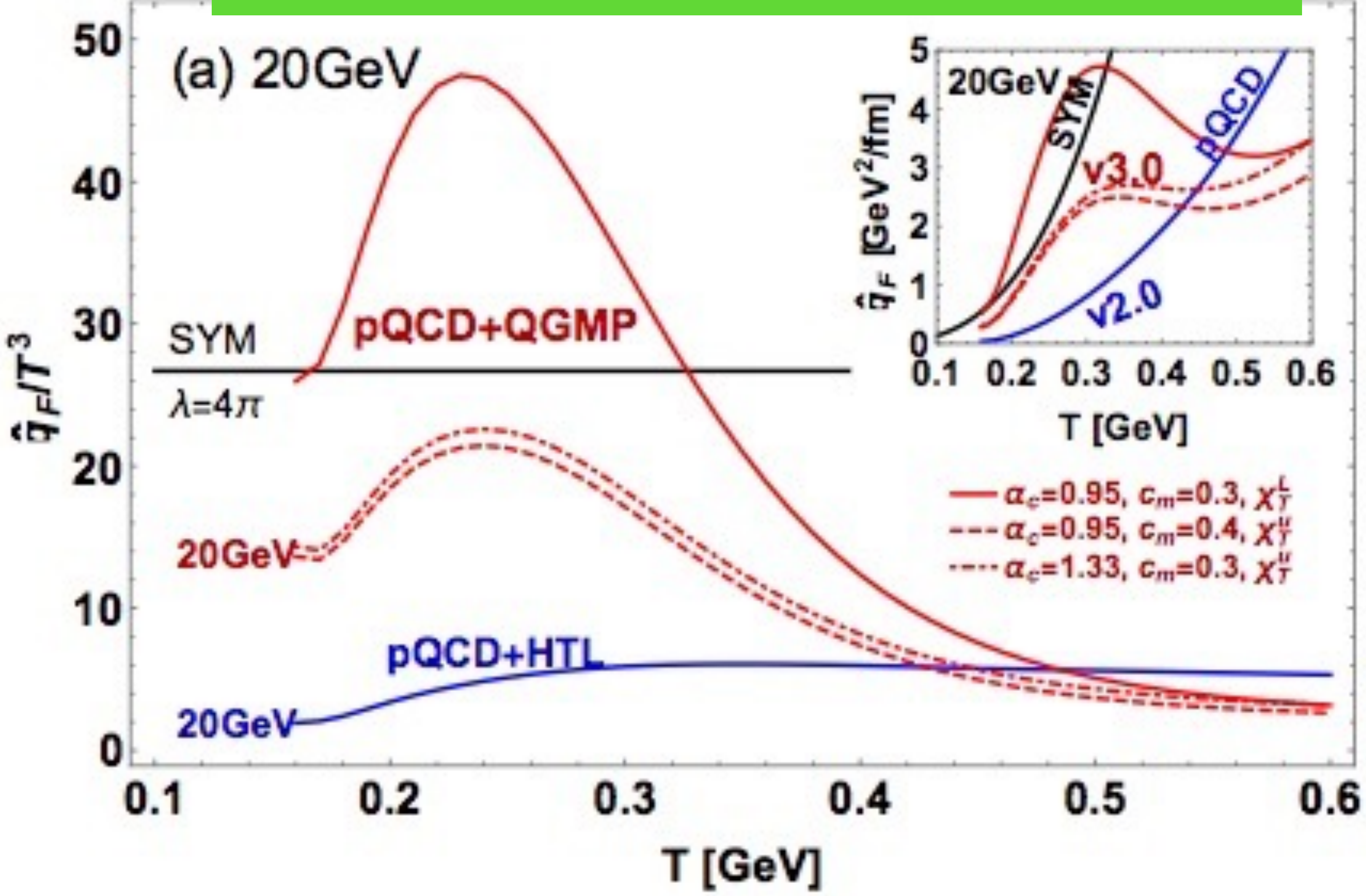
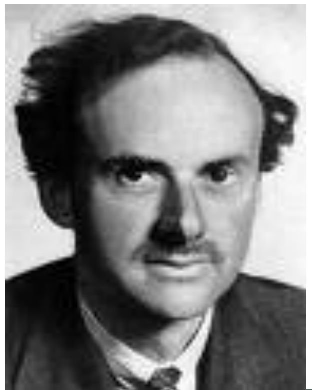
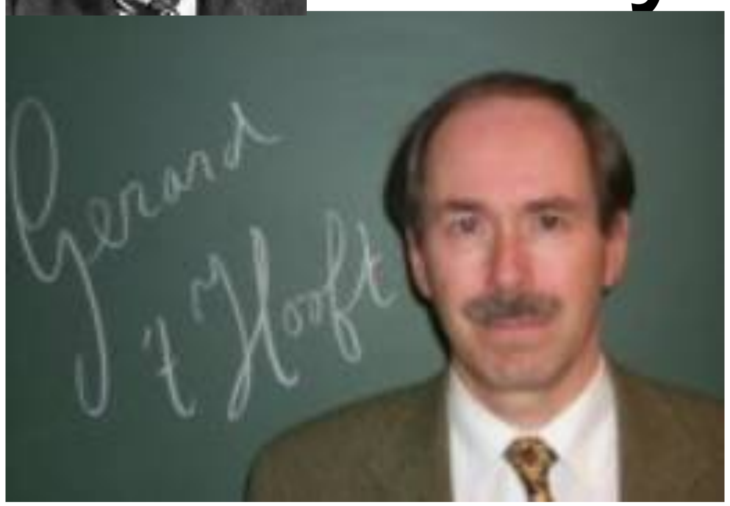


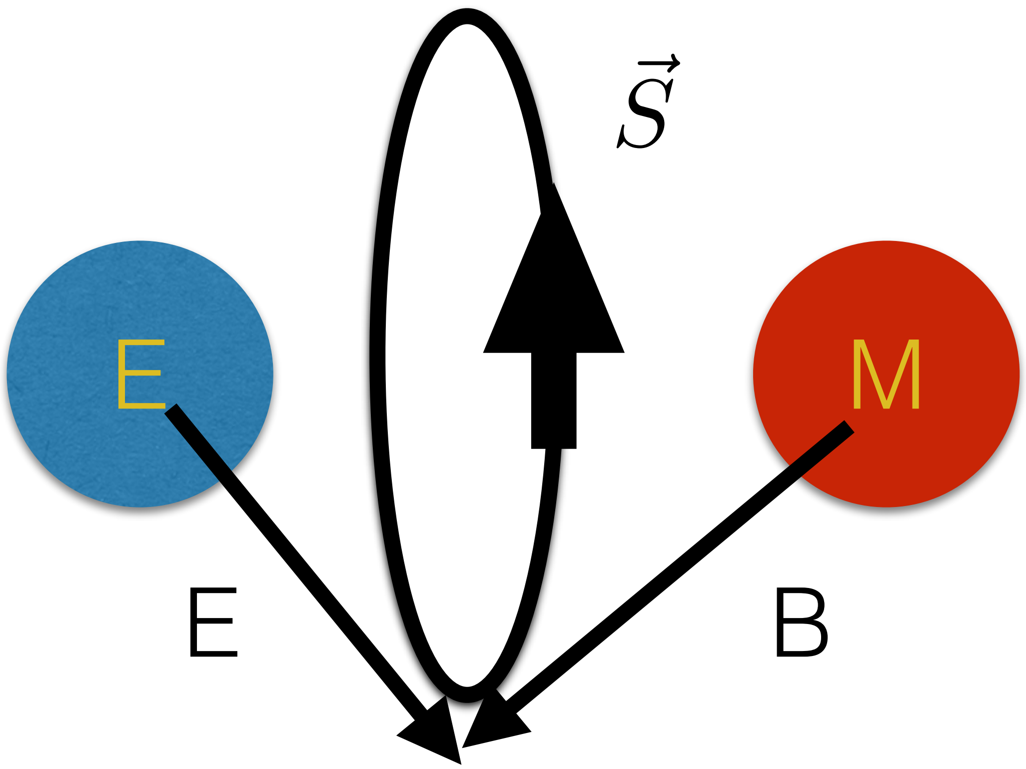


Particle - monopoles and their dynamics: classics



- Dirac explained how magnetic charges may coexists with quantum mechanics (1934)
- ‘t Hooft and Polyakov discovered **monopoles** in Non-Abelian gauge theories (1974)
- ‘t Hooft and Mandelstam suggested “dual superconductor” mechanism for confinement **(1976)**
- Seiberg and Witten shown how it works, in the **N=2 Super - Yang-Mills theory (1994)**

a monopole and a charge: classical motion



$$\vec{S} = [\vec{E} \times \vec{B}]$$

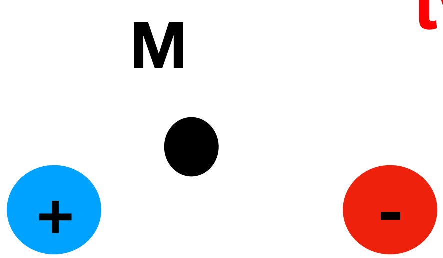
Pointing vector rotates

Observation by J.J.Thompson:

even static charge+monopole lead to rotating electromagnetic field

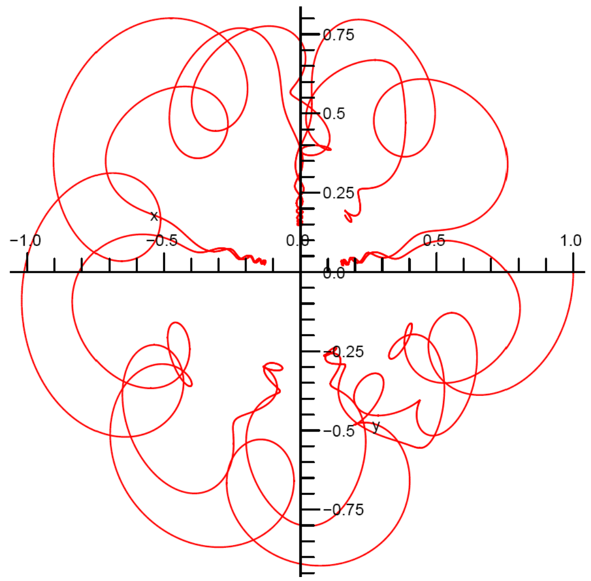
A.Poincare:
angular momentum of the particle plus that of the field is conserved => motion on a cone, not plane as usual

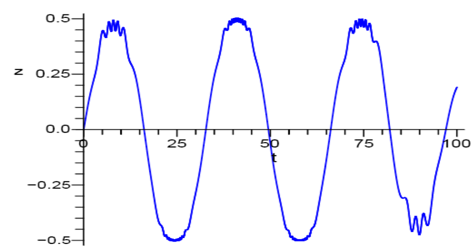
. H. Poincaré, C. R. Acad. Sci. Ser. B. 123, 530 (1896).



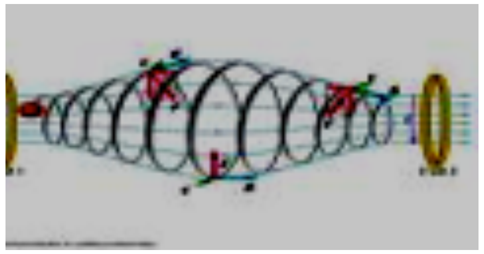
two charges play ping-pong
with a monopole without
even moving!

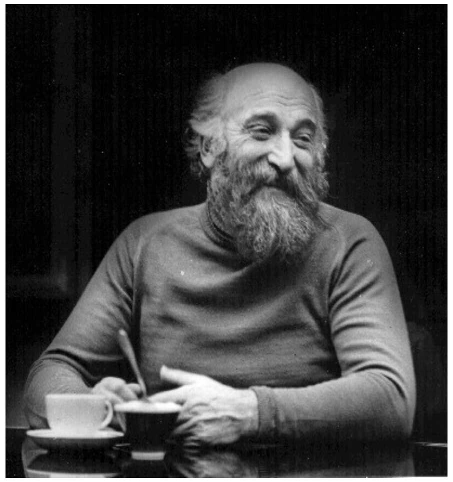
Indeed, collisions are much
more frequent than in cascades

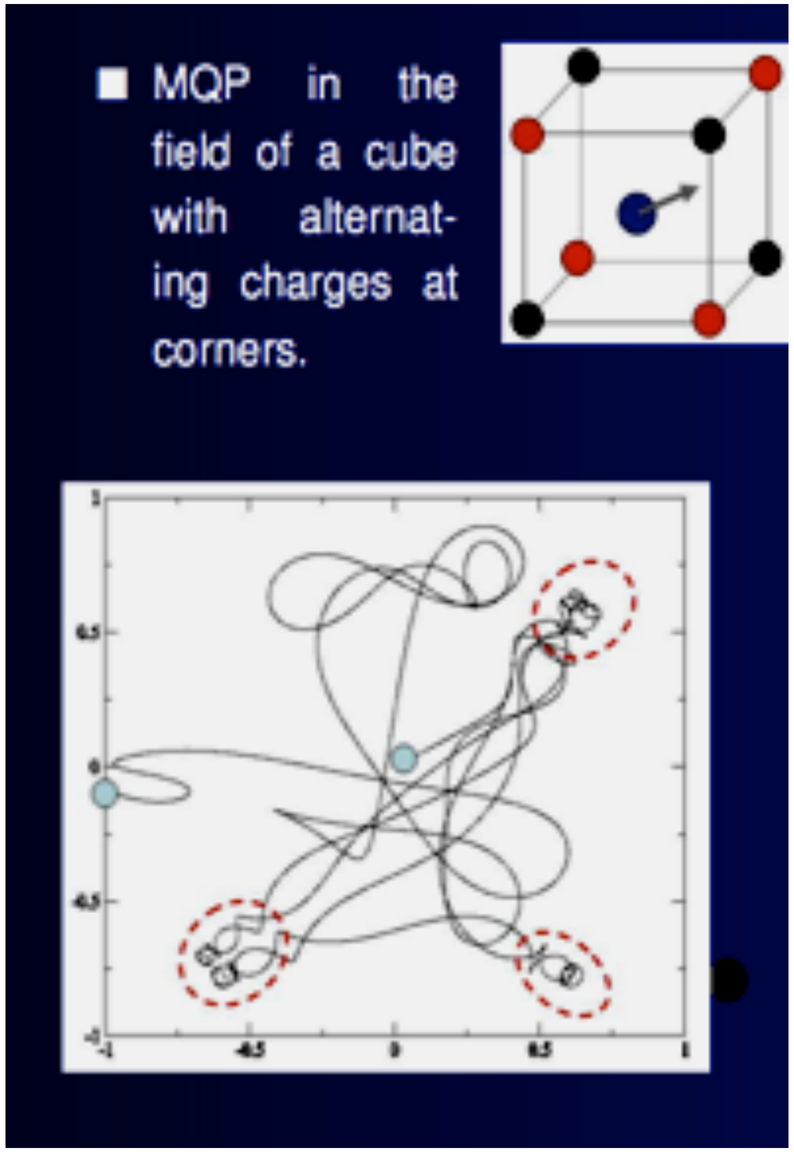


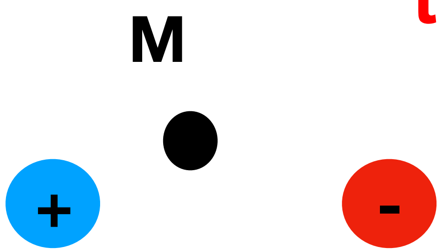


Dual to Budker's magnetic bottle









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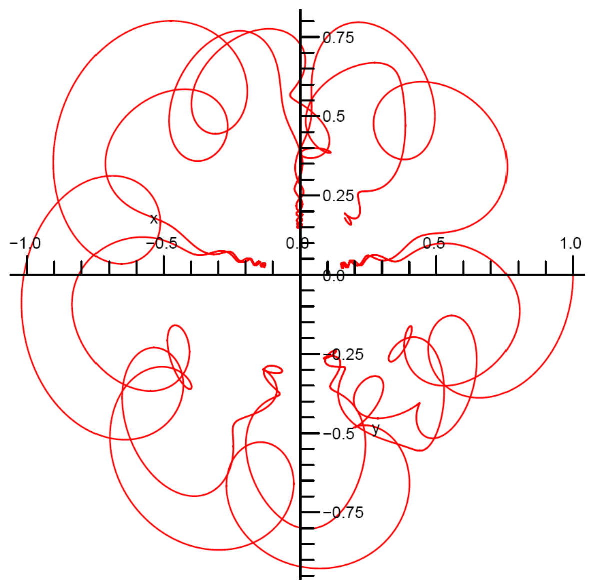
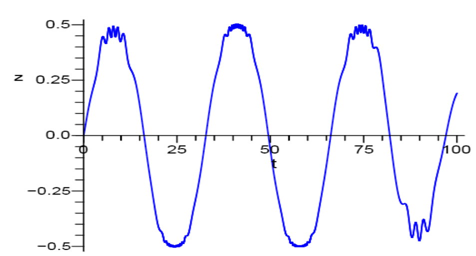
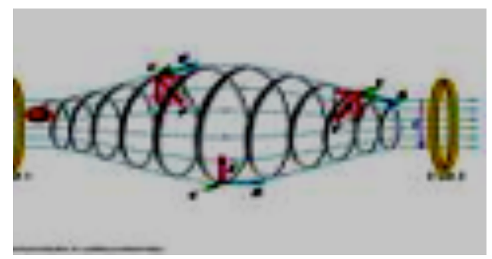
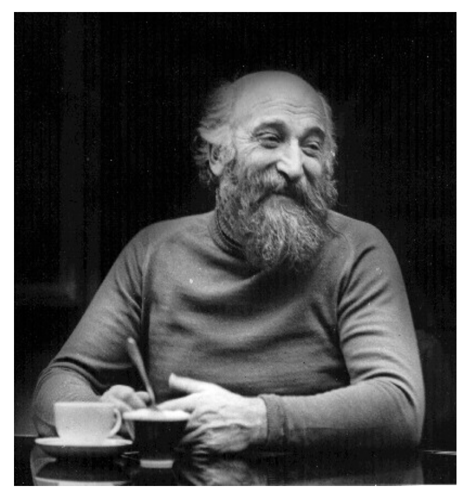
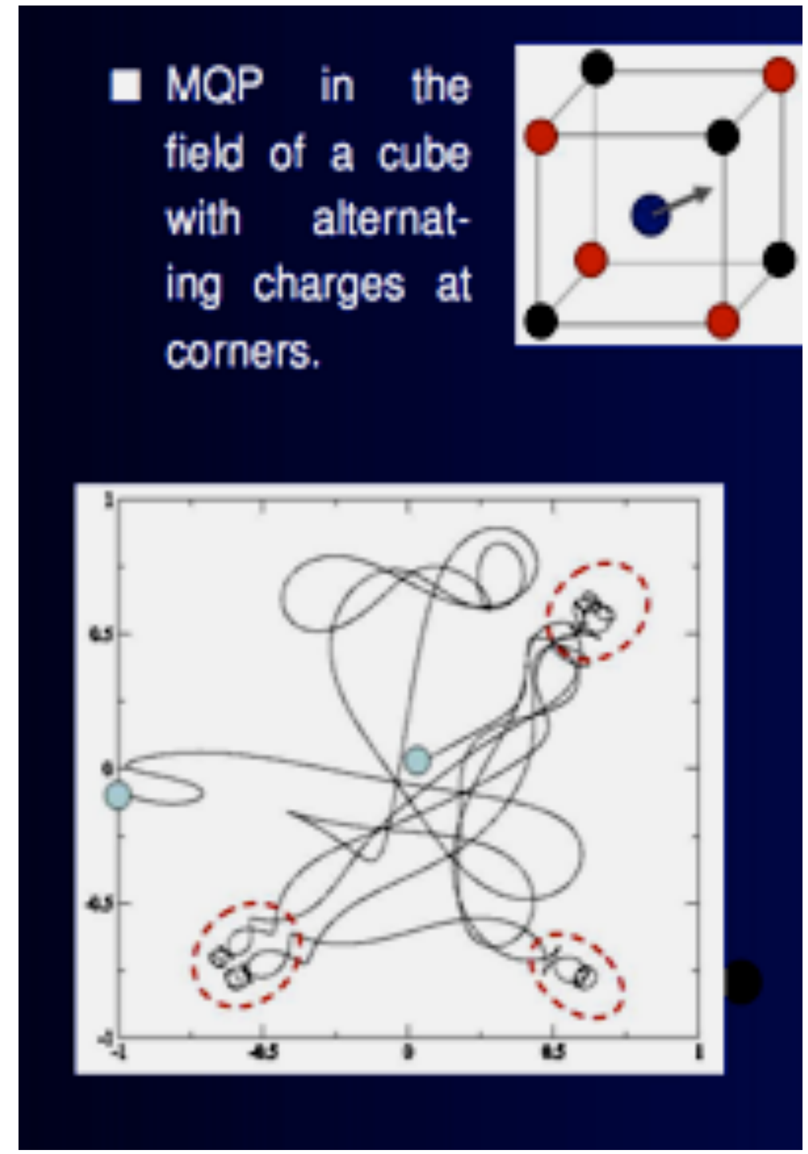




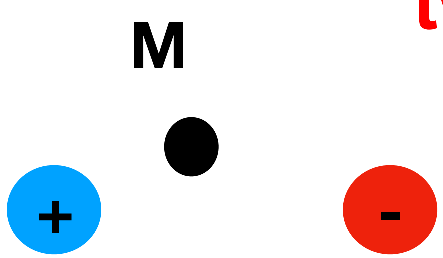
Dual to Budker's magnetic bottle





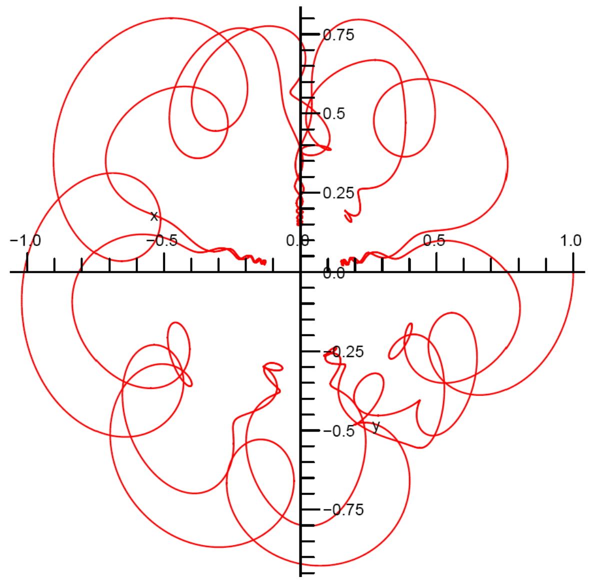


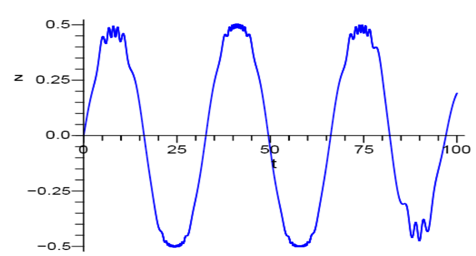
like a proverbial drunkard cannot go home colliding with few lamp posts



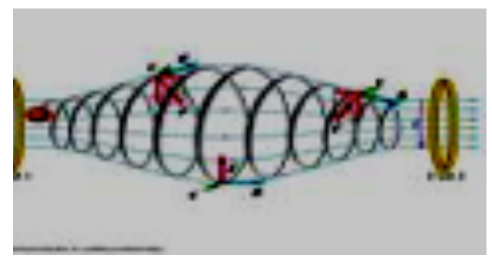
two charges play ping-pong with a monopole without even moving!

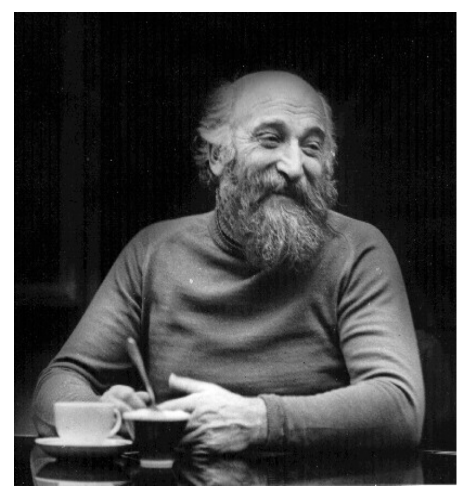
Indeed, collisions are much more frequent than in cascades

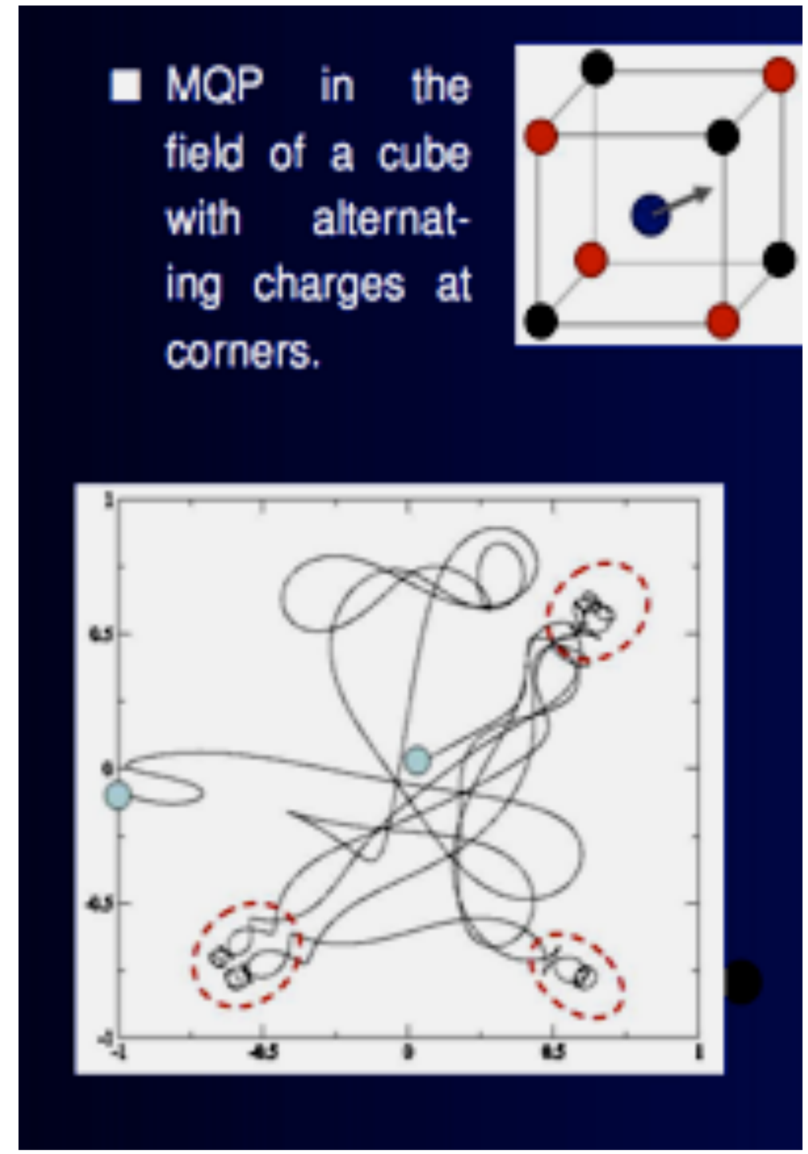




Dual to Budker's magnetic bottle







like a proverbial drunkard cannot go home colliding with few lamp posts

classical kinetics of the "dual plasma", with E and M charges was simulated by molecular dynamics, diffusion coefficient and viscosity calculated

Quantum-mechanical problem of a charge-monopole scattering (should belong to QM textbooks but is not there)

$$e \cdot g \equiv n \quad integer$$

$$\delta_j = \pi j'$$

$$j'(j'+1) = j(j+1) - n^2$$

is the only parameter
It is dimesionless
so the scattering phase
cannot depend on momenta

Both j (total orbital mom.)
and n (that of the field) are integers
but j’ is not!!!!! Thus complicated
angular distribution

Unlike in a standard scattering problem
Ylm angular functions cannot be used:
At large l,m>>1 those describe a scattering plane
But we know in classical limit it is the Poincare cone

D. G. Boulware, L. S. Brown, R. N. Cahn, S. D. Ellis, and C. k. Lee, Phys. Rev. D 14, 2708 (1976).

J. S. Schwinger, K. A. Milton, W. Y. Tsai, L. L. DeRaad, and D. C. Clark, Ann. Phys. (N.Y.) 101, 451 (1976).

quantum scattering of quarks and gluons on monopoles and viscosity of strongly coupled QGP

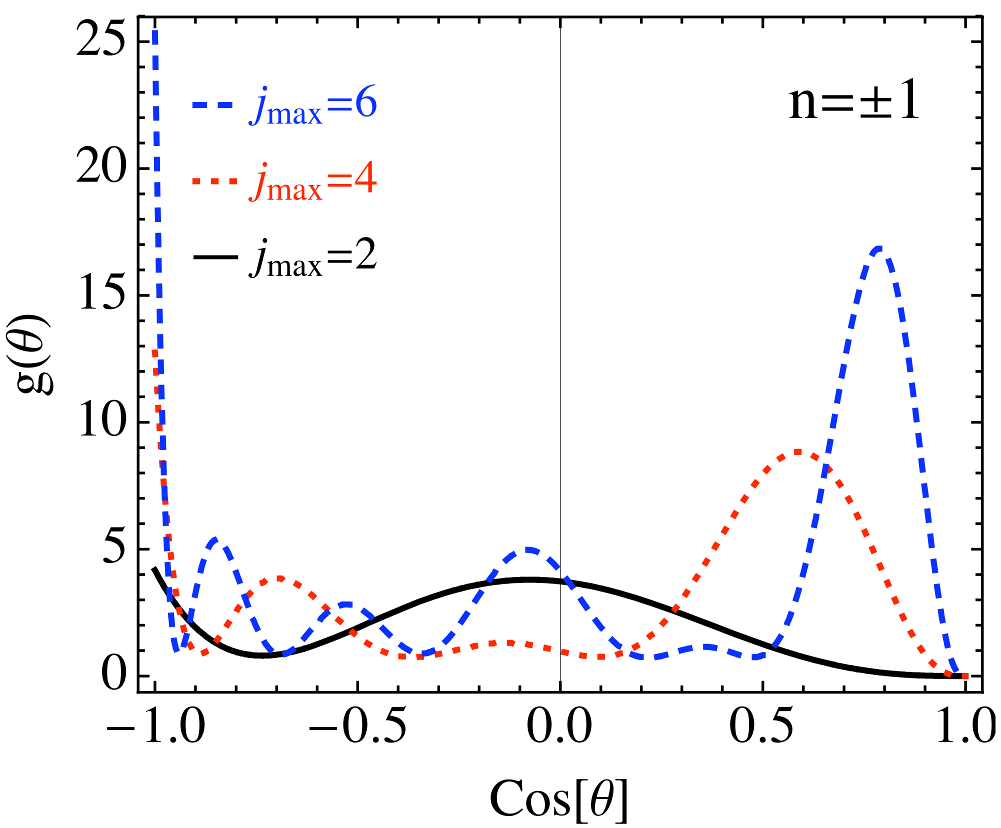
gluon-monopole scattering explains small viscosity!

PHYSICAL REVIEW D **80,** 034004 (2009)

Role of monopoles in a gluon plasma

Claudia Ratti and Edward Shuryak*

backward peak important for transport cross section



$$(1 - cos(\theta))|f(\theta)|^2$$

Not surprising, large correction to transport

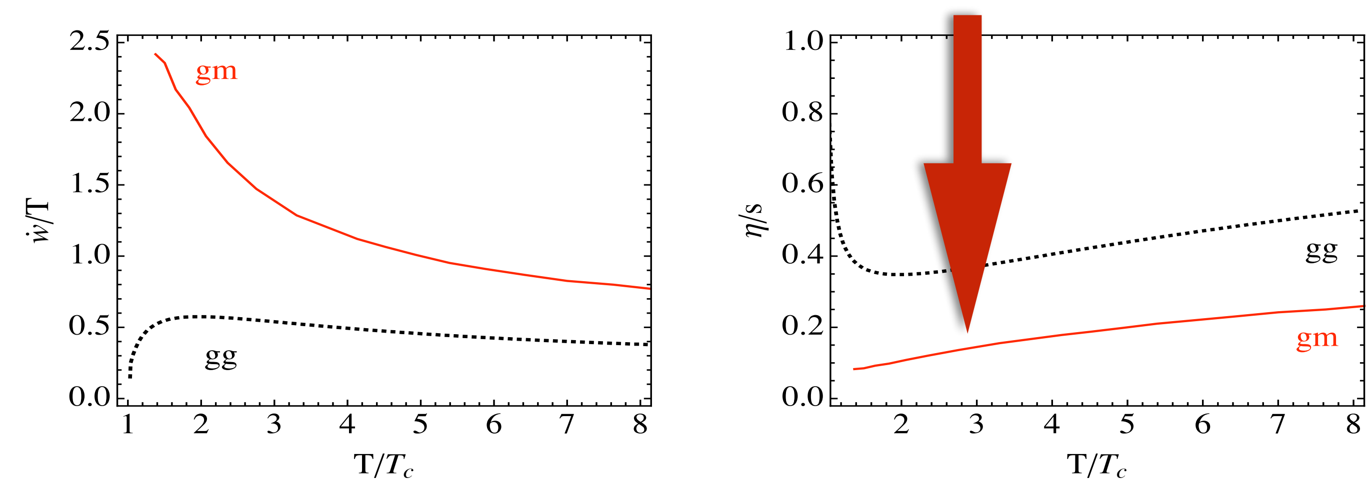


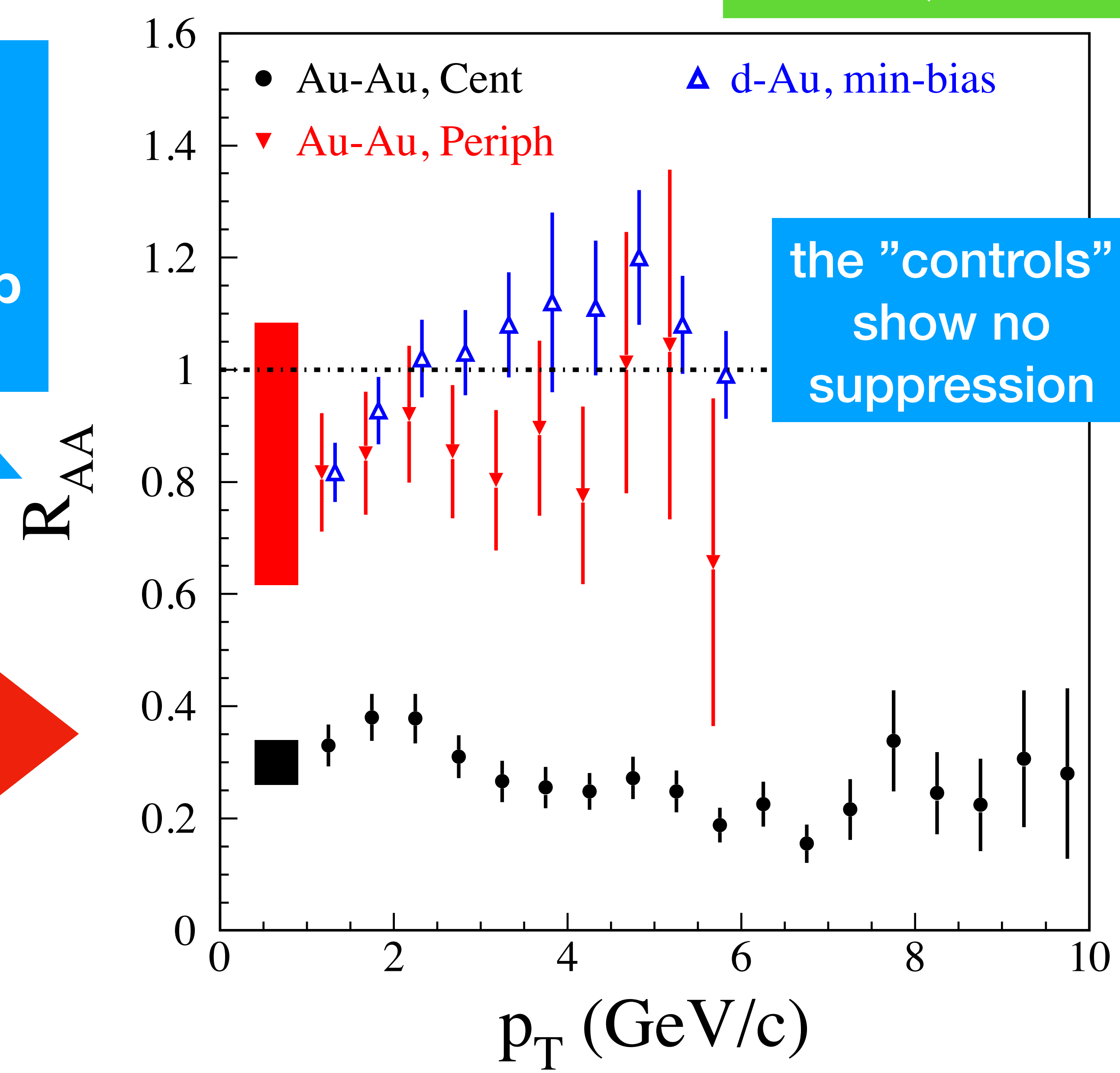
Figure 14: Left panel: gluon-monopole and gluon-gluon scattering rate. Right panel: gluon-monopole and gluon-gluon viscosity over entropy ratio, η/s.

- **RHIC: T/Tc<2, LHC T/Tc<4**: we predict hydro will still be there, with η/s about .2

Strong jet quenching was found at RHIC

historic PHENIX data from 2004 "QGP discovery" volume

the observed number of "hard" hadrons divided by the expected (as calculated from spectra in pp and number of pp collisions)



the "controls" show no suppression

large pt hadrons (and thus jets) are suppressed by a factor 3-4

Strong jet quenching was found at RHIC

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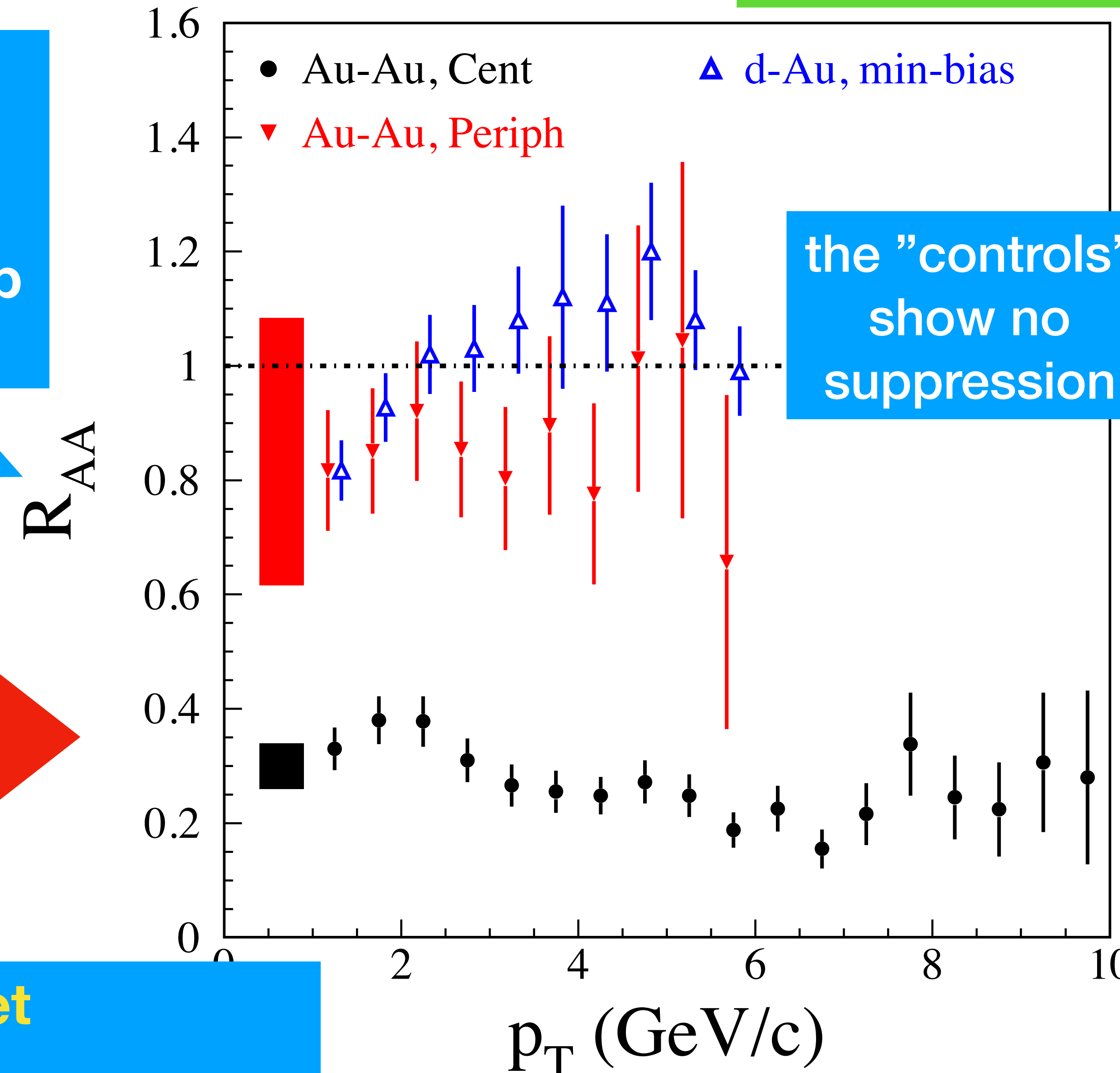

the ”controls” show no suppression

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Radiative theory of jet quenching, accounting for Landau-Pomeranchuck-Migdal effect

Strong jet quenching was found at RHIC

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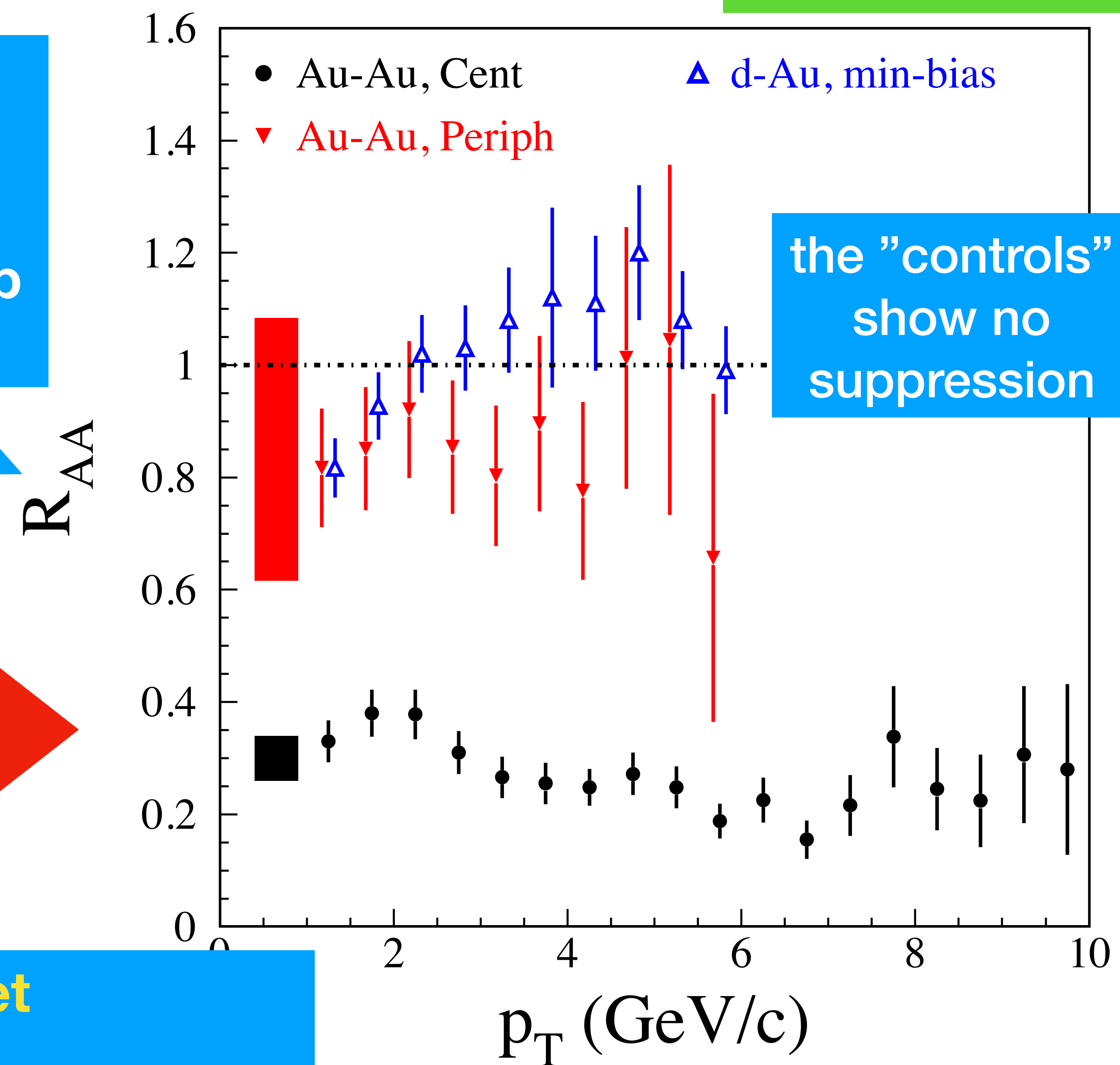
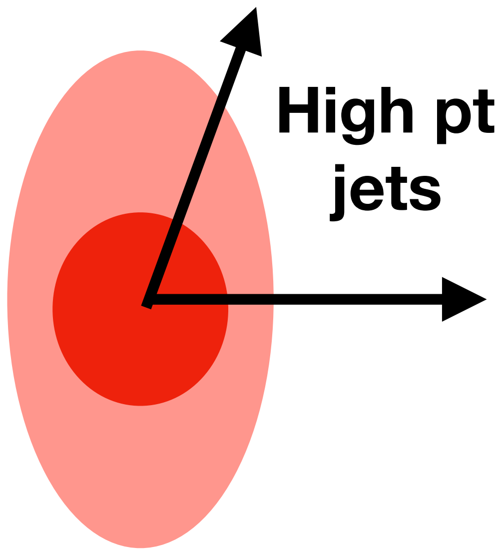


the "controls" show no suppression

Radiative theory of jet quenching,
accounting for Landau-Pomeranchuck-Migdal effect

Radiative energy loss and p(T) broadening of high-energy partons in nuclei
R. Baier, Yuri L. Dokshitzer, Alfred H. Mueller, S. Peigne,
D. Schiff Nucl.Phys. B484 (1997) 265-282

A relatively recent story: the angular distribution of jet quenching and monopoles



$$\frac{dN}{dyd^2p_\perp} \sim \left[1 + 2v_2(p_\perp)cos(2\phi)\right]$$

A jet in shorter x direction suffers less quenching by matter

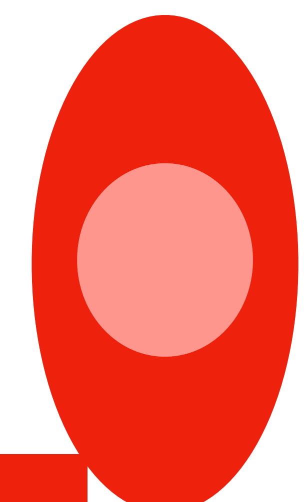
The Azimuthal asymmetry at large p(t) seem to be too large for a `jet quenching'
E.V. Shuryak (SUNY, Stony Brook). Dec 2001. 3 pp.
Published in **Phys.Rev. C66 (2002) 027902**

The theory gave reasonably good description of quenching itself
But experiment stubbornly gave v2 about twice larger than
all theories predicted

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition
Jinfeng Liao, Edward Shuryak Phys.Rev.Lett. 102 (2009) 202302

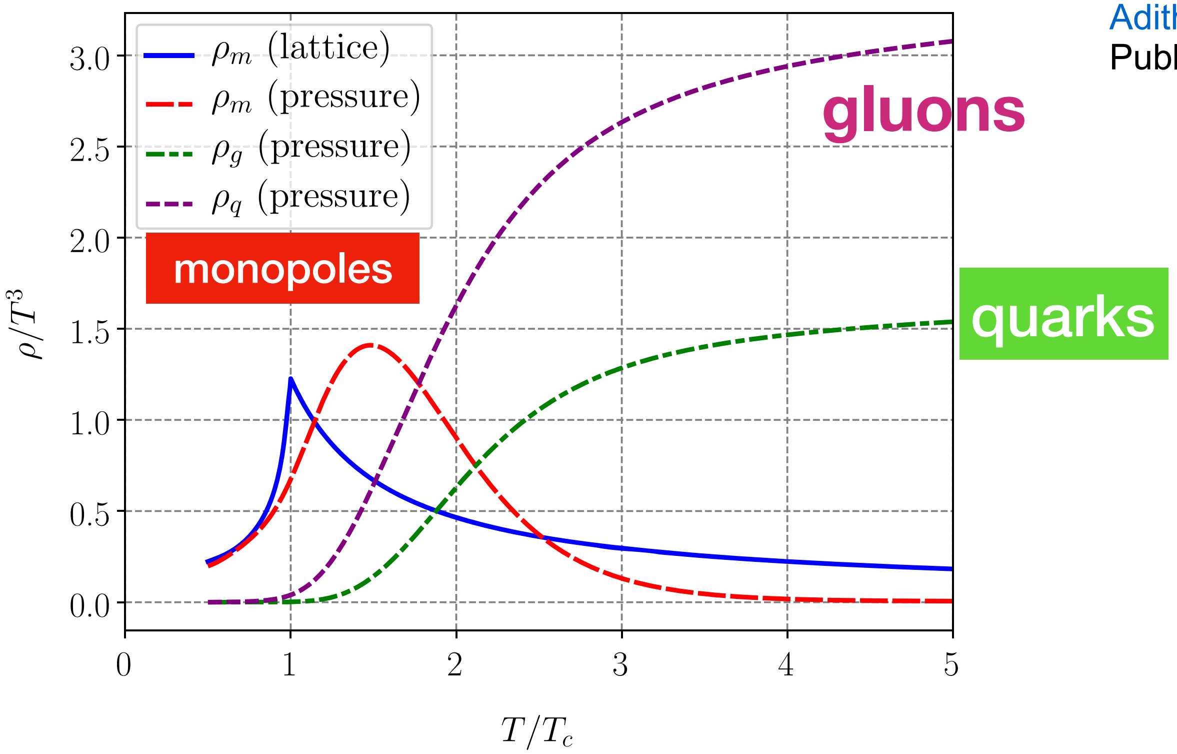
An explanation proposed: in these theories
the quenching is proportional to the density.
And the most dense region (shown by the dark red)
is much "more round" than less dense (pink) region.
Perhaps quenching peaks at intermediate density?

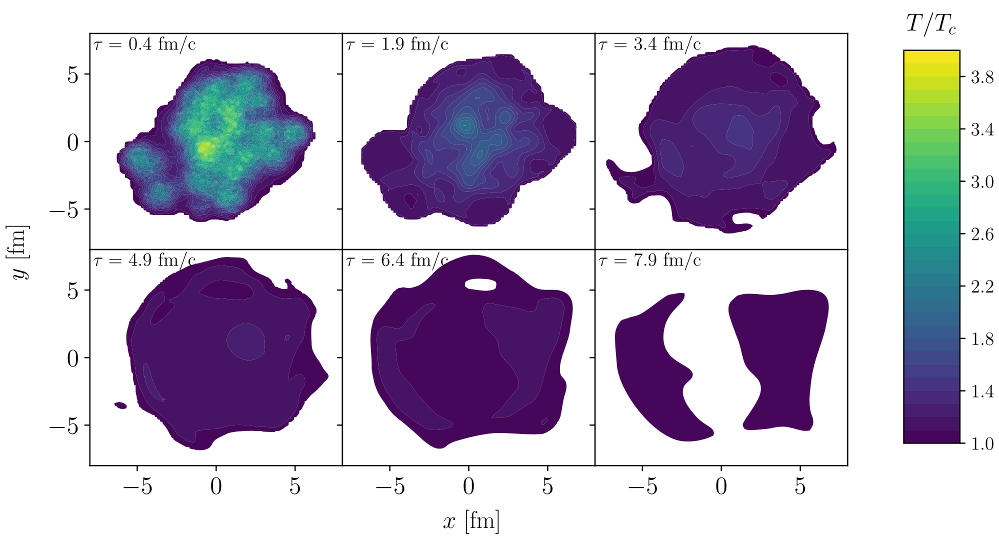
$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{length}$$



this reproduces
the azimuthal distribution of jet quenching.

matter composition, by d.o.f.



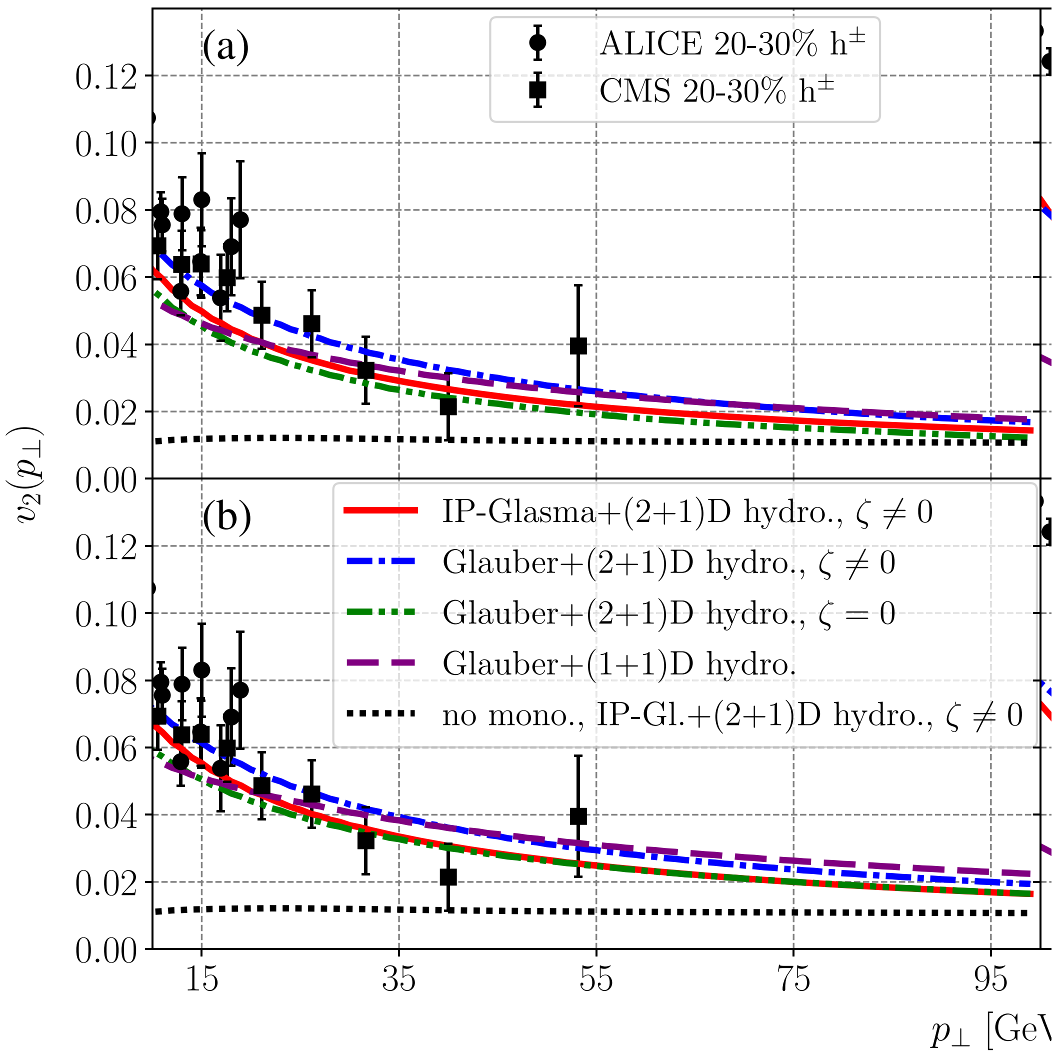


Role of QCD monopoles in jet quenching

Adith Ramamurti, Edward Shuryak (SUNY, Stony Brook). Aug 14, 2017. 16 pp.

Published in **Phys.Rev. D97 (2018) no.1, 016010**

jets=gluons(or quarks)
while passing through matter
get electric kick $\sim (e^2)^2 \sim \alpha_s^2$
monopoles give magnetic kick $\sim (ge)^2 \sim 1$

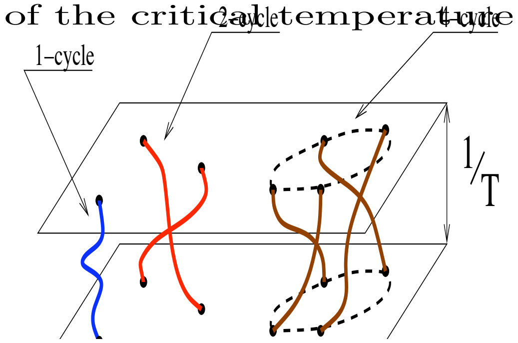


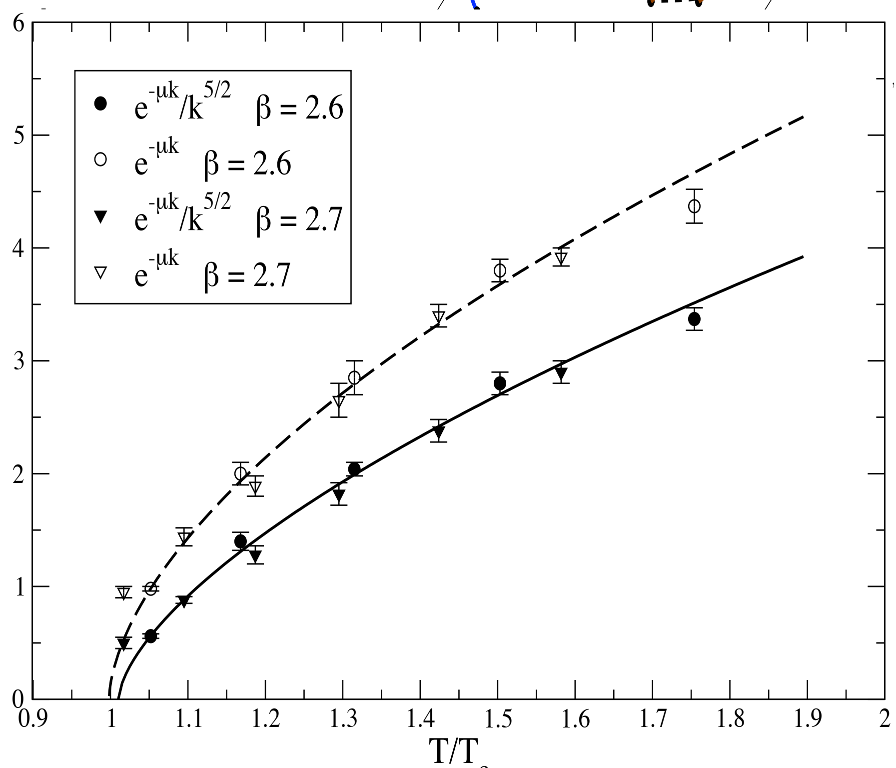
Is confinement due to BEC of monopoles?

Thermal Monopole Condensation and Confinement in finite temperature Yang-Mills Theories

Alessio D'Alessandro, Massimo D'Elia[1] and Edward V. Shuryak[2]
[1] *Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, 16146 Genova, Italy*
[2] *Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA*
(Dated: February 22, 2010)

We investigate the connection between Color Confinement and thermal Abelian monopoles populating the deconfined phase of SU(2) Yang-Mills theory, by studying how the statistical properties of the monopole ensemble change as the confinement/deconfinement temperature is approached from above. In particular we study the distribution of monopole currents with multiple wrappings in the Euclidean time direction, corresponding to two or more particle permutations, and show that multiple wrappings increase as the deconfinement temperature is approached from above, in a way compatible with a condensation of such objects happening right at the deconfining transition. We also address the question of the thermal monopole mass, showing that different definitions give consistent results only around the transition, where the monopole mass goes down and becomes of the order of the critical temperature itself.





, in which

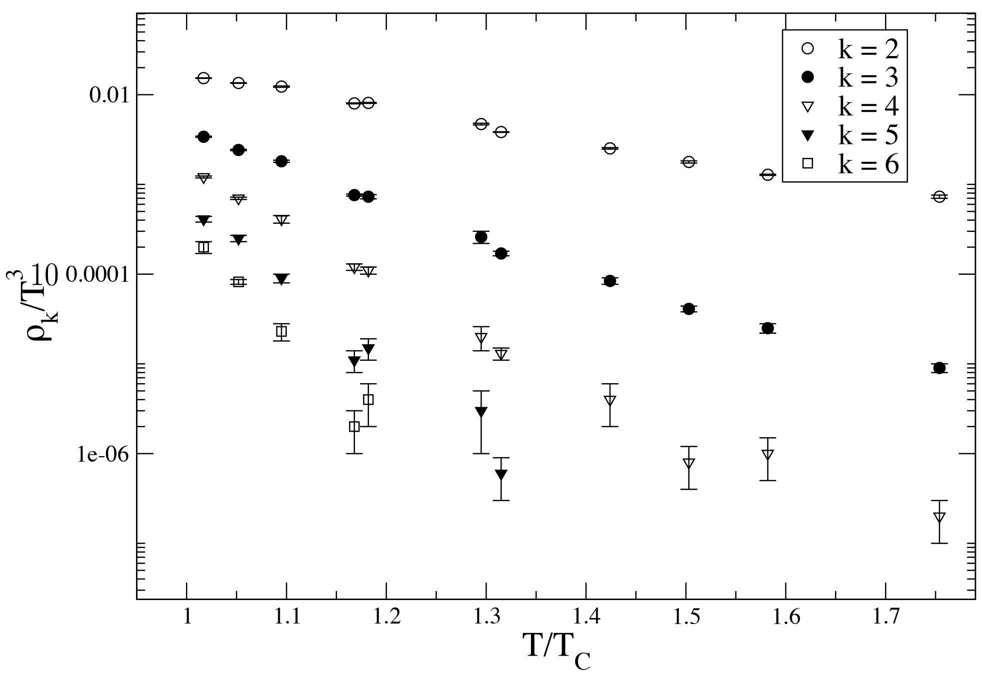


FIG. 2: Normalized densities ρ_k/T^3 as a function of T/T_c.

The lesson: monopoles at T_c, behave as He^4 =>Bose-Einstein condensation

Quantum phenomena, including BEC, in ensemble of monopoles recently studied by Path Integral Monte Carlo

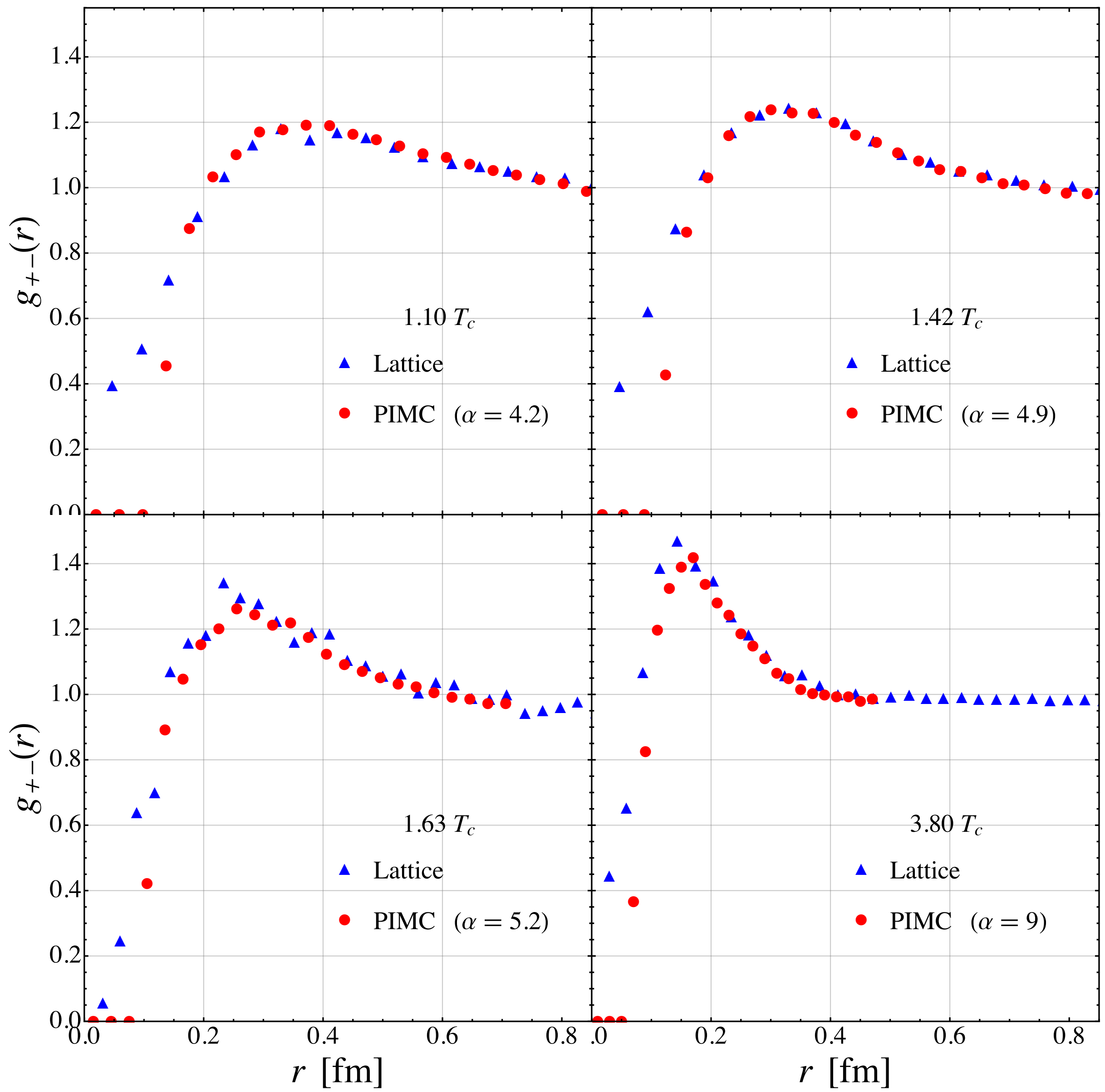


Fig. 3.19 Spatial correlations of particles in quantum Coulomb Bose gas, from PIMC simulations (red circles) compared to lattice data for monopoles.

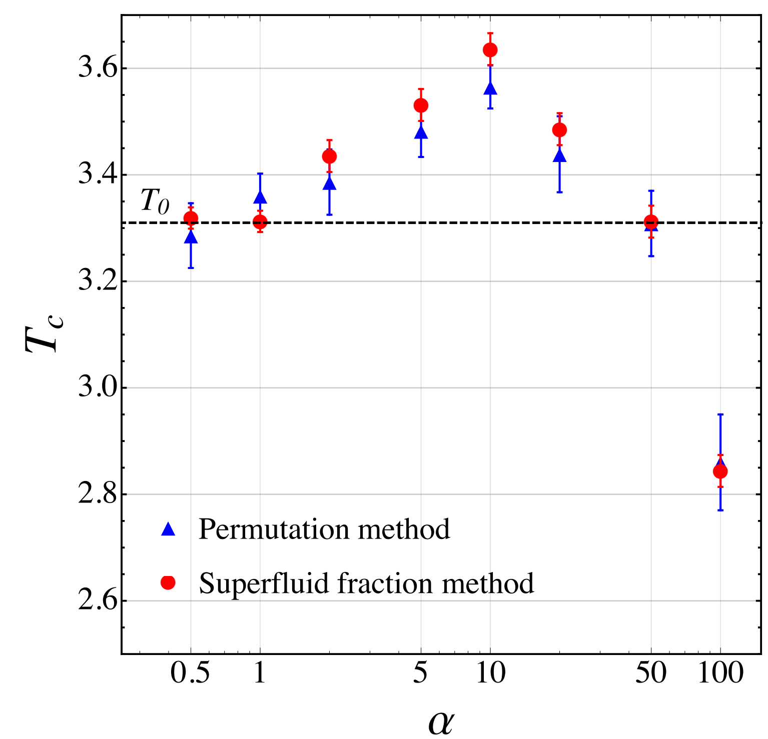


Fig. 3.18 The critical temperature for the BEC phase transiion as a function of the coupling, α. The red circles are the results of the finite-size scaling superfluid fraction calculation for systems of 8, 16, and 32 particles; the blue triangles are the results of the permutation-cycle calculation for a system with 32 particles. The black dashed line denotes the Einstein ideal Bose gas critical temperature.

Ramamurti, A. and Shuryak, E. (2017). Effective Model of QC

From Numerical Study of One- and Two-Component Couloml

Phys. Rev., D95(7):076019.

``magnetic scenario": Liao,ES hep-ph/0611131,Chernodub+Zakharov

Old good Dirac condition

α_s(electric) α_s(magnetic)=1

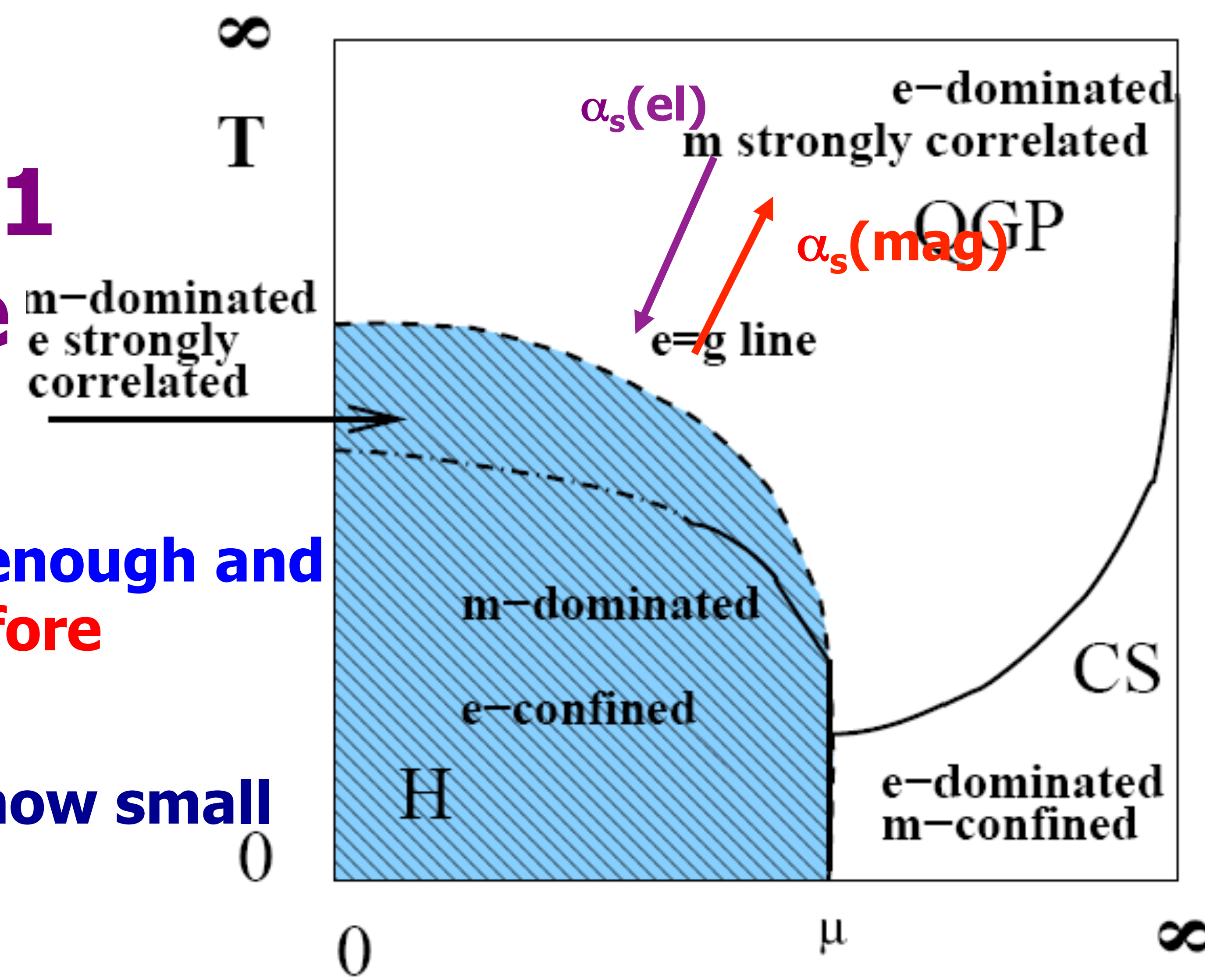
=>electric/magnetic couplings (e/g)

must run in the opposite directions!

the "equilibrium line"

α_s(el)= α_s(mag) =1

needs to be in the plasma phase



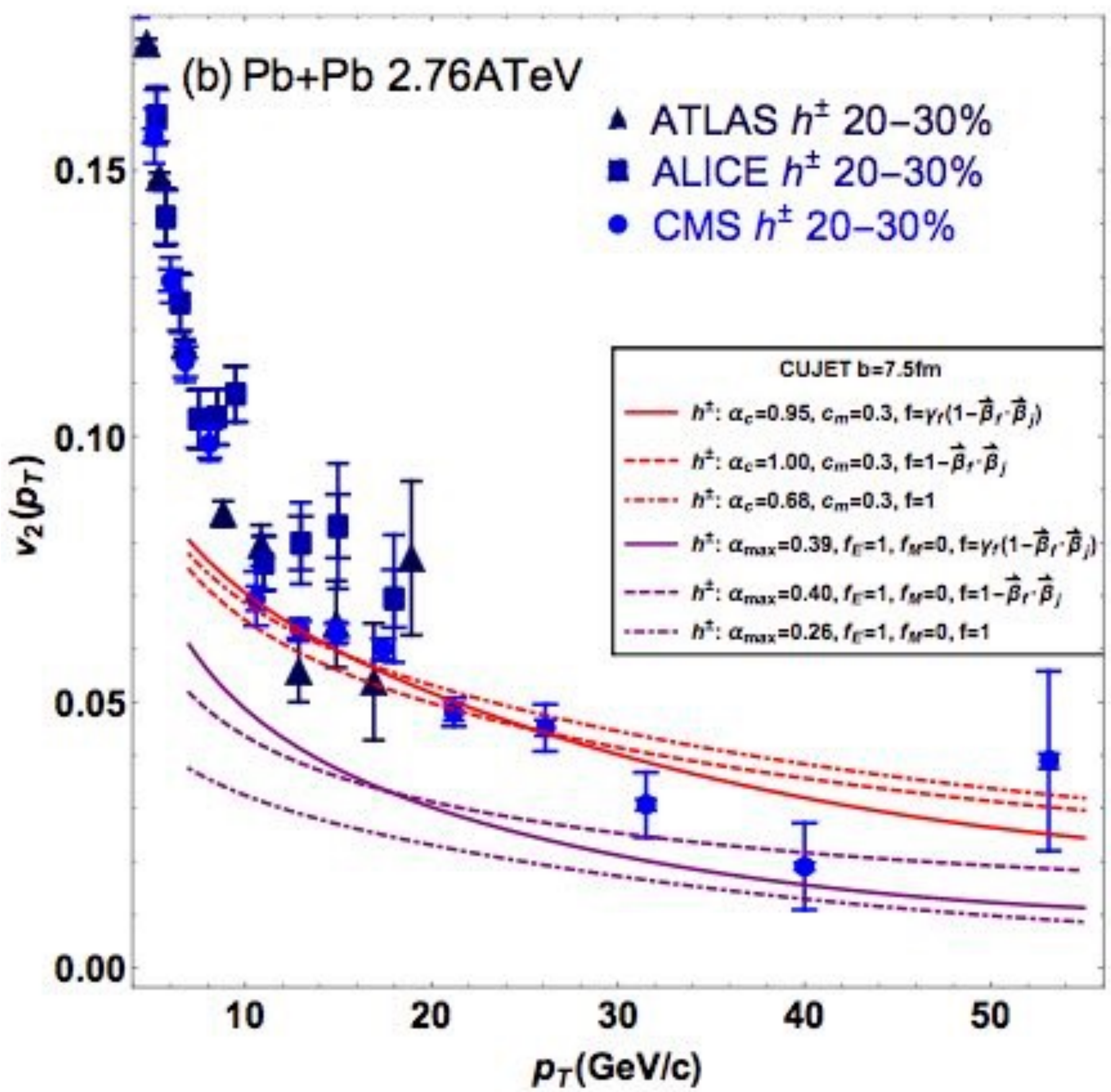
monopoles should be dense enough and sufficiently weakly coupled before deconfinement to get BEC

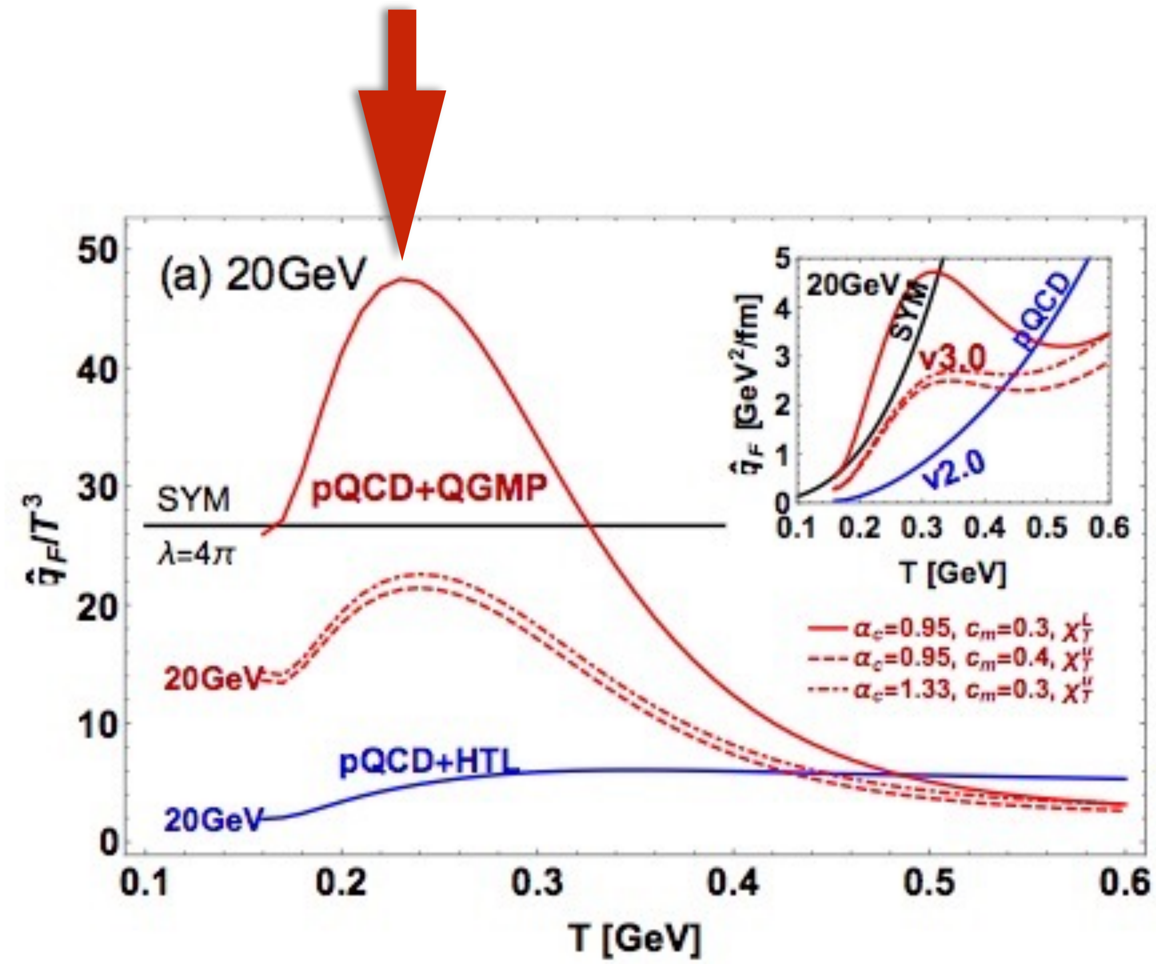
=>α_s(mag) < α_s(el): how small can α_s(mag) be?

summary

- QGP is a new form of matter at T>Tc. Near Tc it is a record holder of the smallest viscosity (mean free path) and the highest jet quenching
- **this happens because of peaking density of magnetic monopoles there**
- **at T<Tc monopoles undergo BEC**
- **In QCD. Monopoles are not semiclassical, but instanton-dyons are!**

peak of the density of monopoles at Tc
explains not only a **dip in viscosity (m.f.p.)**
but also other things such as jet quenching





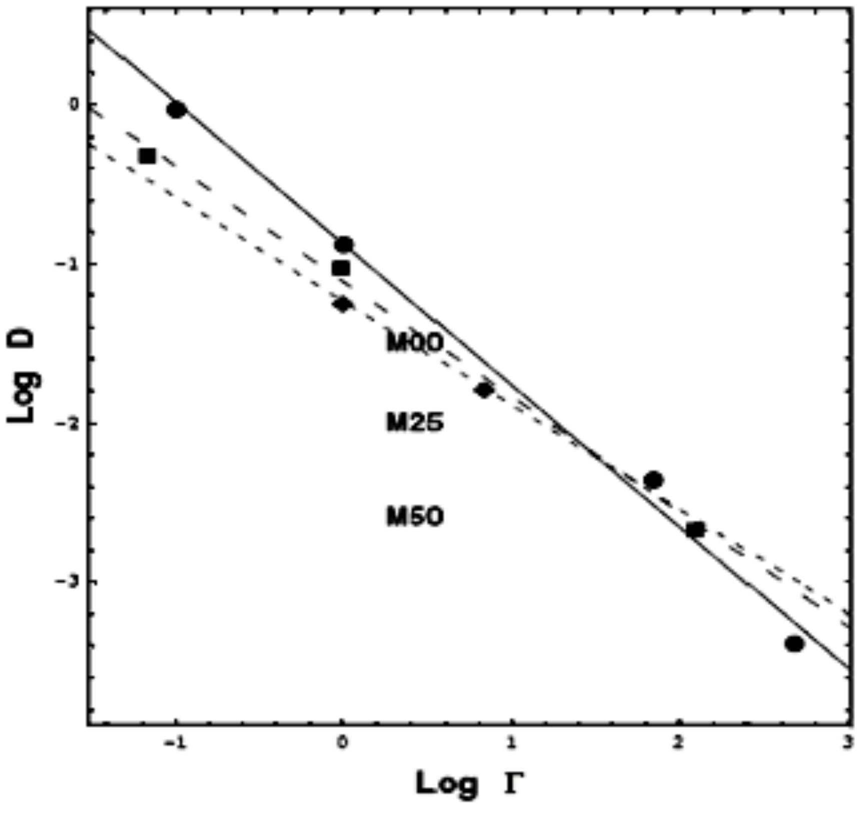
Xu, J., J. Liao, and M. Gyulassy (2015), arXiv:1508.00552

extra slides

MD simulation for novel plasma containing both charges and monopoles (Liao,ES hep-ph/ 0611131)

monopole admixture up to M50=50% , 1000 particles, numerically solved

diffusion decreases indefinitely, viscosity does not



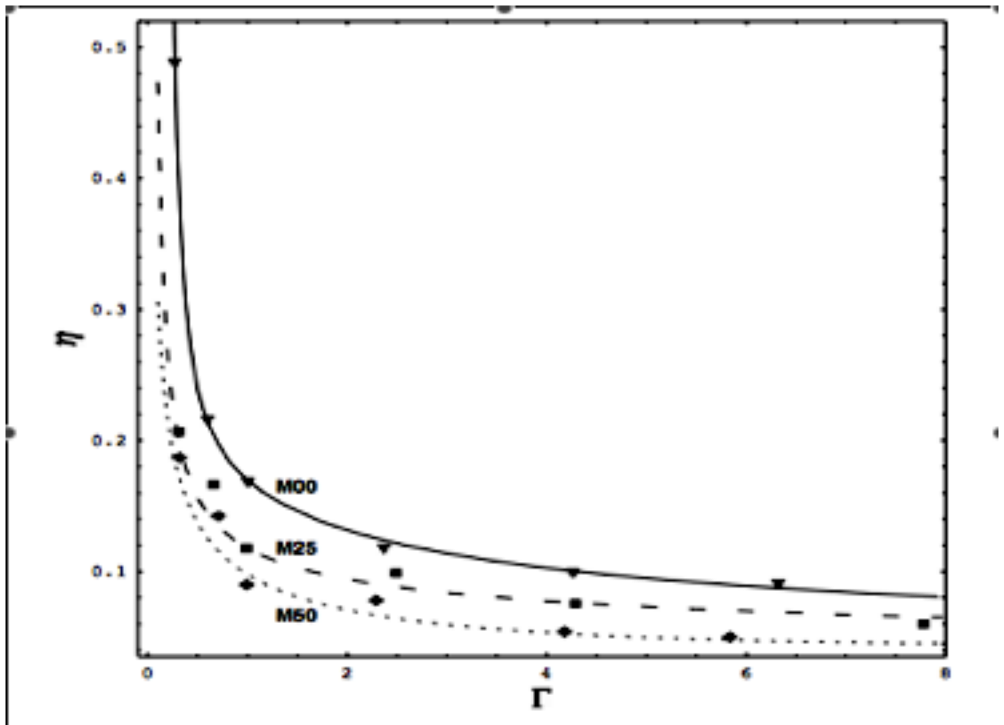


FIG. 16. Shear viscosity η calculated at different plasma parameter Γ for M00(circle), M25(square), and M50(diamond) plasma respectively.