Aspetti Dinamici e Termodinamici del Quark-Gluon Plasma

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in collaborazione con

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Outline

- **Aim (not a review on results and theorethical models):**
  - Provide basic introduction to QGP & next talks
  - Underline aspects and tools shared with other nuclear physics fields

QCD and QGP at high temperature :

- Thermodynamics, lattice QCD: EoS of QGP
- Initial state: gluon saturation
- Nearly perfect fluid
- QGP in the heavy quark sector
- Hadronization in a hot QCD medium

Finanziamenti e Attività Teorica in Italia

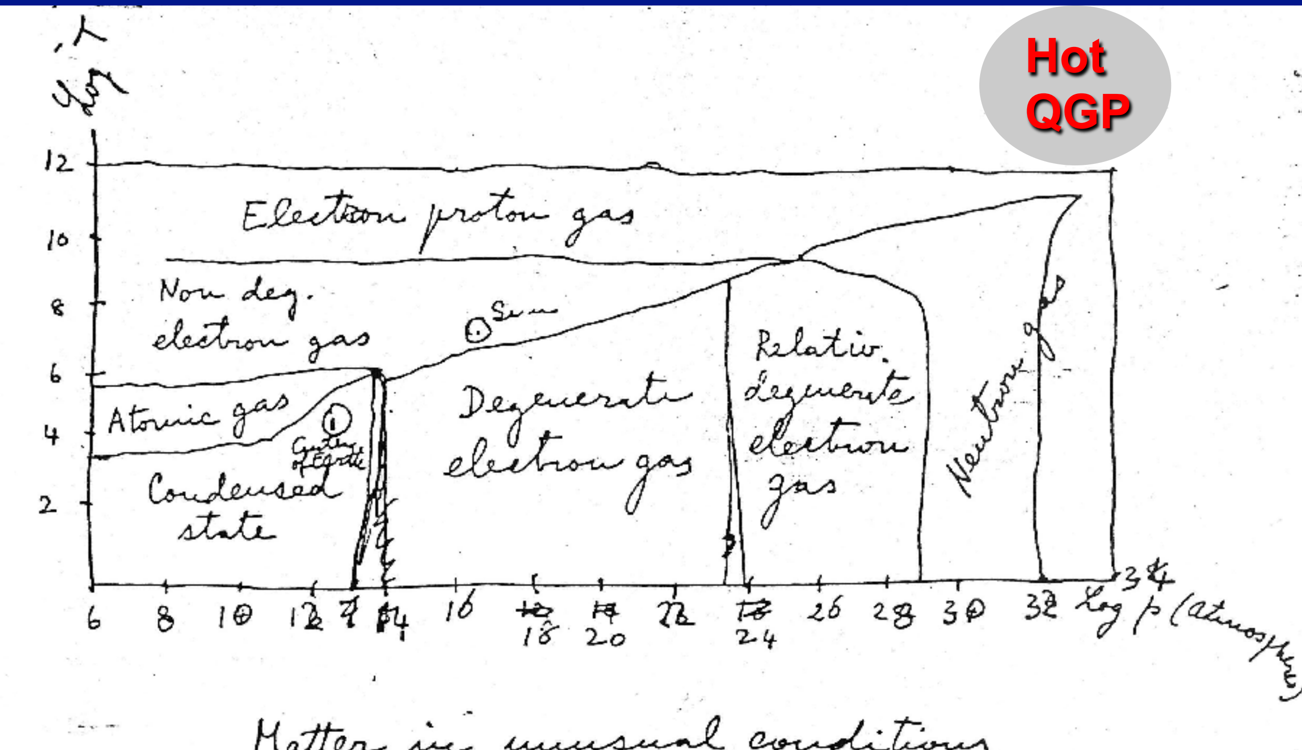
Progetti-Fondi:

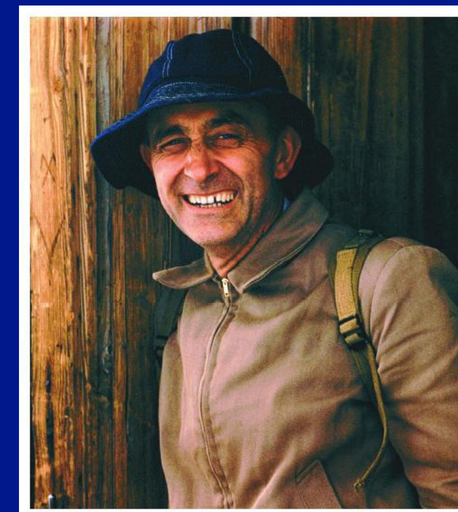
- ✧ RM31 (coord. Naz. F. Becattini) : FI, BA, CT, FE, LNS, PV, TO, TS, RM1
- ✧ FIRB 2008 (coord. Naz. V.G. + C.Ratti): CT, TO
- ✧ PRIN 2009 (coord. Naz. F. Becattini): FI,CT,TO
- ✧ ERC-StG2010 (coord. V.G.): CT
- ✧ HadronPhysics3- WP2 (coord. Naz. F. Becattini): FI,CT

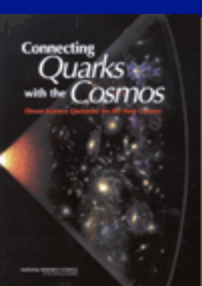
+ QGP International School (W. Alberico & M. Nardi) – Villa Gualino
joint activity with ALICE (L.Ramello, E. Vercellin & F. Antinori)

Matter under extreme conditions…

Fermi Notes on Thermodynamics







Eleven Science Questions for the New Century

RESEARCH COUNCIL OF THE NATIONAL ACADEMIES…

No. 7 - What Are the New States of Matter at Exceedingly High Density and Temperature? ***QGP is at $T>10^{12}$K and $\rho > 10^{40}$ cm^{-3}***

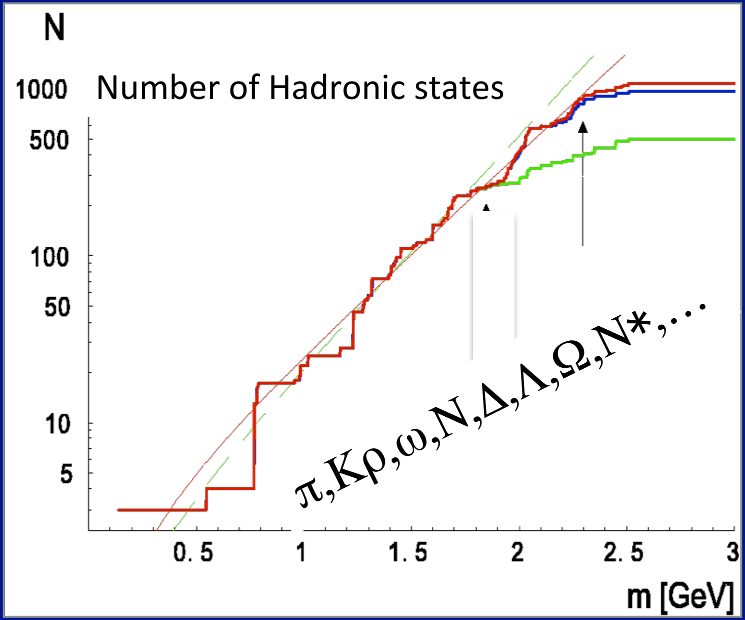
Phase Transition: from the hadronic side

- Hagedorn: density of hadronic states $\rho(m)$ grows exponentially

$$\rho(m) = C m^{\alpha} e^{m/T_0}$$

fit to exp. data T_0=160 MeV

T_0 is called Hagedorn *limiting temperature (1965) for an hadronic system* (no quarks at that time)



Perche'?

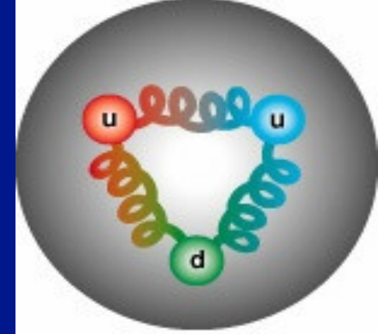
Partition function for a gas of hadrons, m>>T

$$\log Z(T,V) \propto \int_{m_0}^{\infty} dm\, m^{3/2} \rho(m) e^{-\frac{m}{T}} \propto \int_{m_0}^{\infty} dm\, m^{\alpha+3/2} e^{-m\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Integral diverges for T->T_0:
hadronic matter cannot have a T>T_0

Cabibbo-Parisi, PLB59(1975) – the year after the Gross –Wilczek paper:
Divergency of the partition function has to be associated with
a phase transition of hadronic matter to quark-gluon matter
+ asymptotic freedom at large T -> weakly quark gluon gas

Theory of Strong Interaction: QCD



$$L_{QCD} = \sum_{i=1}^{n_f} \overline{\Psi}_i \gamma_\mu \left(i\partial^\mu - g A_a^\mu \frac{\lambda_a}{2} \right) \Psi_i - m_i \overline{\Psi}_i \Psi_i - \frac{1}{4} \sum_a F_a^{\mu\nu} F_a^{\mu\nu}$$

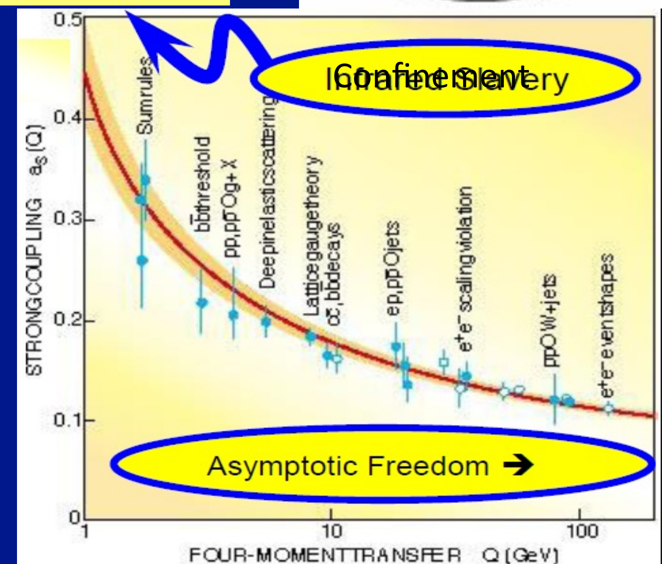
$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + i f_{abc} A_b^\mu A_c^\mu$$

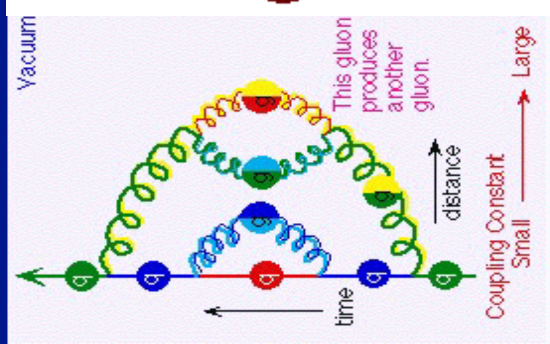
Similar to QED, but gluons self-interact!

- **Asymptotic freedom**
- **Confinement**

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log\left(\frac{Q^2}{\Lambda^2}\right)}$$

$$\Lambda \sim 200 \text{ MeV} \simeq 1 \text{ fm}^{-1} \simeq (\text{hadron size})^{-1}$$





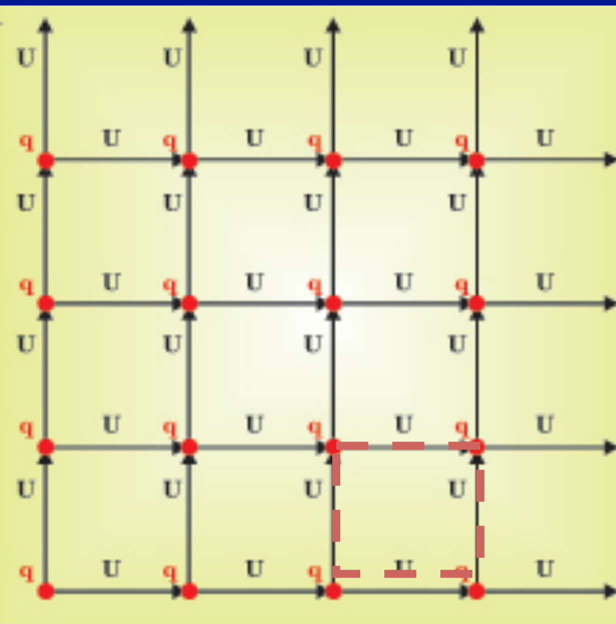
Two regimes:

- Q>>>Λ_{QCD} one can use perturbative QCD **(pQCD)**
- Q ~Λ_{QCD} , Q >Λ_{QCD} non perturbative methods :

lattice QCD ***(lQCD)*** and effective lagrangian approach

Lattice QCD : a huge computational effort

Solving QCD on a grid of points in space and time with size $(N_s)^3 x N_t$



From the partition function knowledge of all thermodynamics

$$Z = \int DA_\mu^a(x) D\overline{\psi}(x) D\psi(x) e^{i\int_0^\beta d\tau \int d^3x L[A,\overline{\psi},\psi]}$$

$$i\tau \rightarrow 1/T = \beta$$ Dynamics -> Statistics

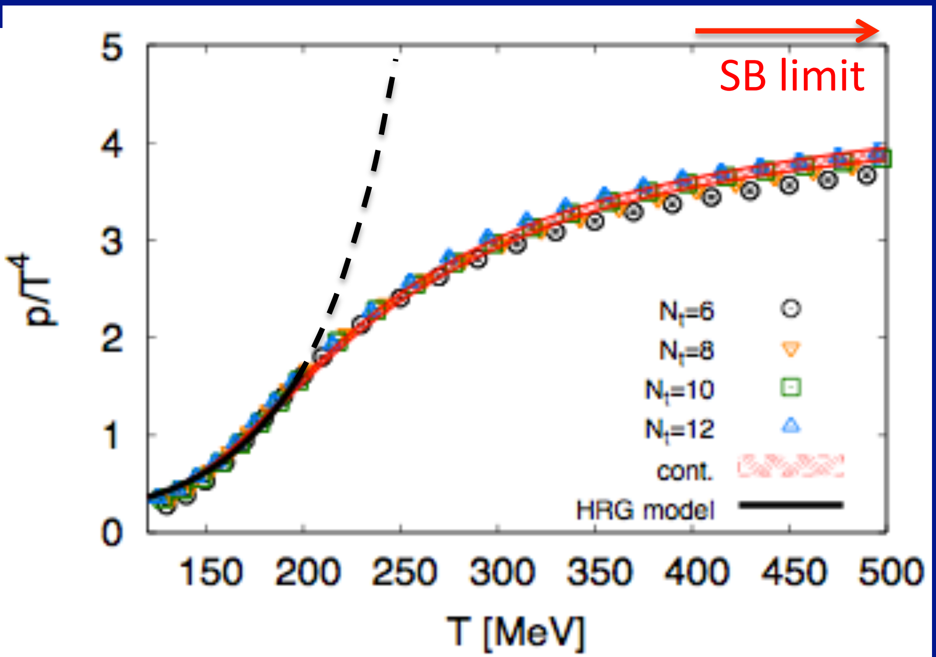
Physical size : $L = N_S a$, Time ->Temperature: $T = 1/(N_t a)$

$$U(n, n+\hat{\mu}) = \exp\left(igt^a A_\mu^a(n)\right)$$

- ✓ Only thermodynamical observables (EoS, susceptibility, ...) or correlators
  No formulation for dynamical processes!
- ✓ Cannot be directly used at finite baryon density (no neutron star aargh!!)
- ✓ Only very recently, calculations for physical quark masses became feasible!

It is a fundamental guidance, but it is not sufficient !

EoS from lattice QCD

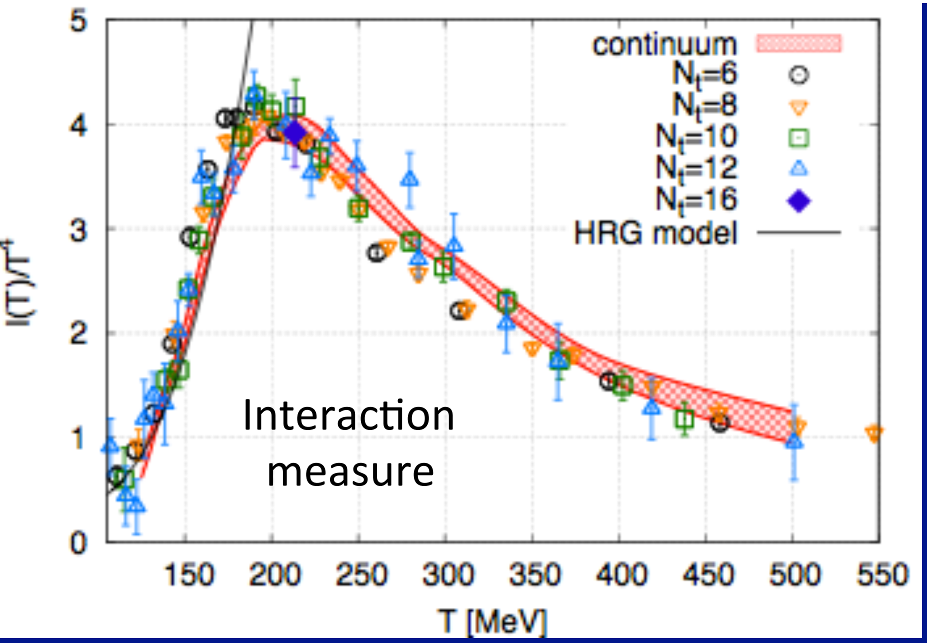


Reference a gas of non-interacting massless particle … Stefan-Boltzmann

$$\frac{\varepsilon_{SB}}{T^4} = \frac{\pi^2}{30}\left[\frac{7}{8}d_{q+\bar{q}} + d_g\right]$$

Stefan-Boltzmann limit not reached by 20 % : QGP as a weak interacting gas?

$$\varepsilon_c \approx 0.7\, GeV/fm^3$$
$$T_c \cong 160\, MeV$$

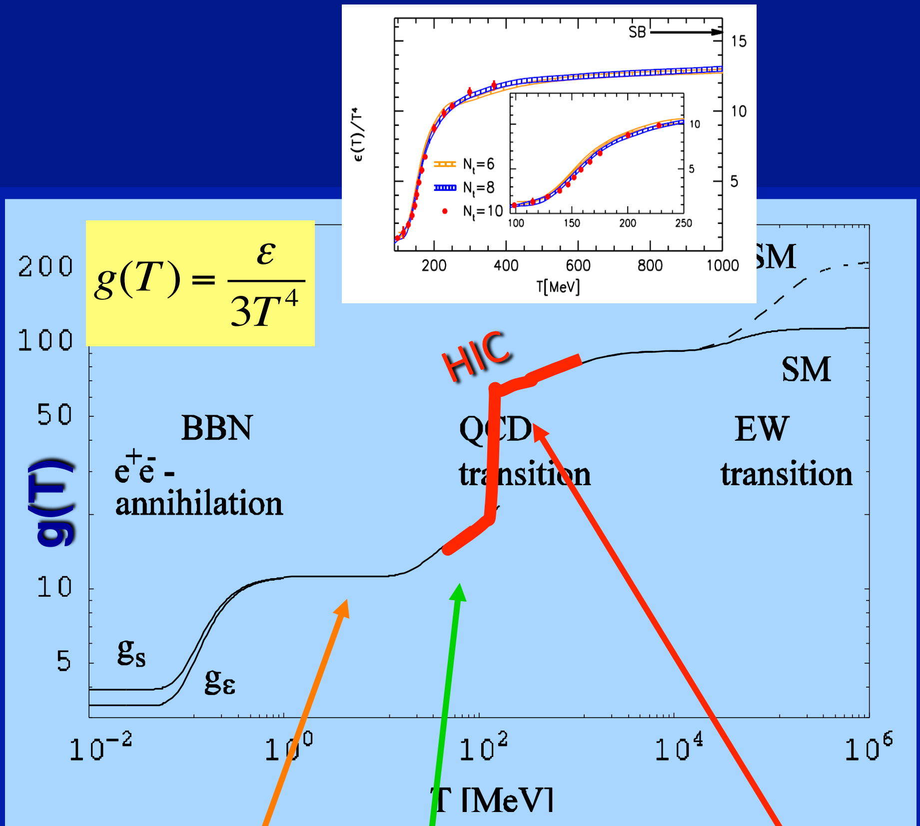


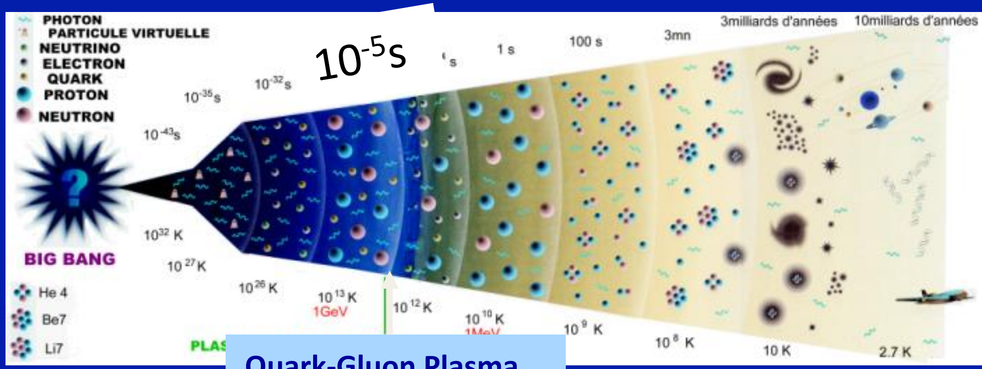
T > T_c not a hadron gas
but not
a massless quark-gluon gas

No interaction means also
I = ε-3p= 0
(for a massless gas)

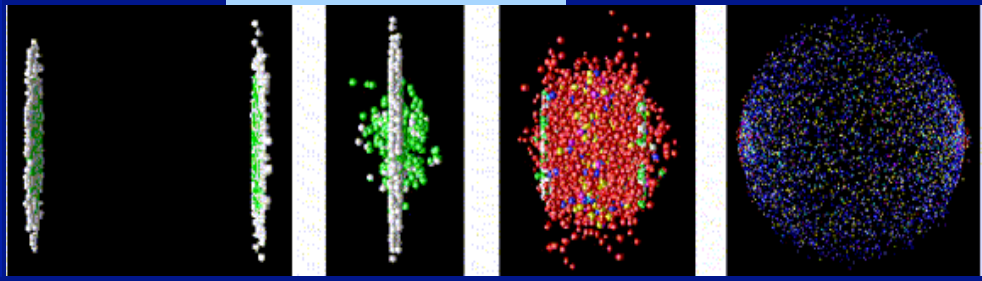
C. Ratti for the Wuppertal-Budapest collaboration, QM2012 talk

Degrees of freedom in the Universe





Quark-Gluon Plasma

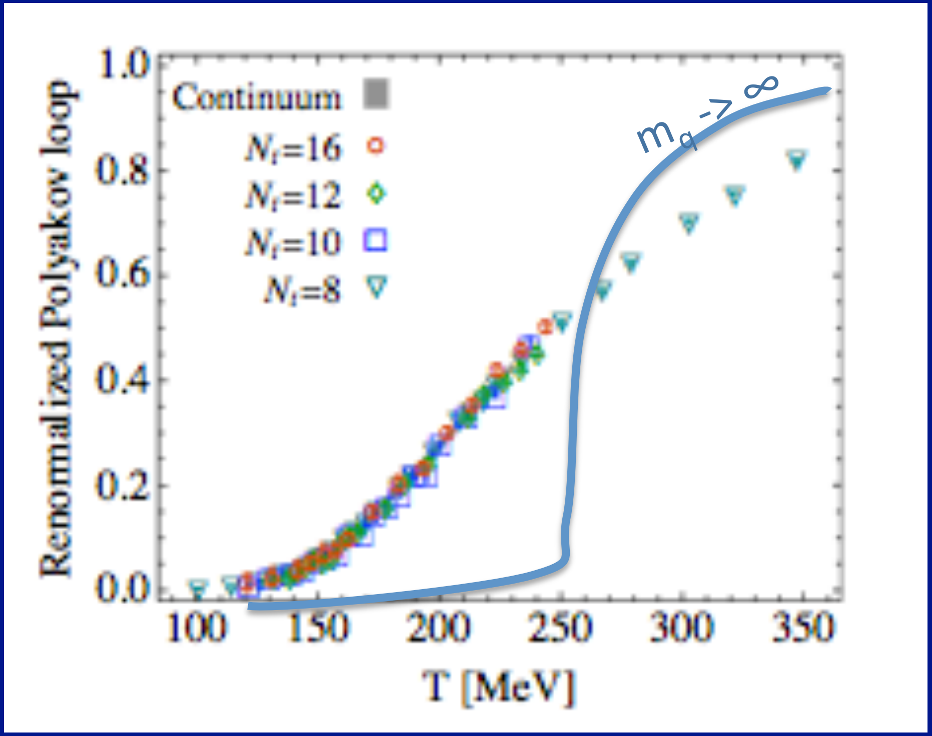


$$g(T) = 2_\gamma + 4_e + 4_\nu + 3_\mu + 3_\pi + \ldots + 16_g + 31.5_{uds} + 21_{cb} + \ldots$$

D.J.Schwartz, Ann. Phys. 2004

Order Parameters of the Phase Transition

Polyakov Loop - Confinement



$$L \propto Tr\, e^{ig\int_0^\beta A_0(\vec{x},t)\,d\tau} \approx e^{-H_{int}/T}$$

Order parameter for m_q -> ∞

Confinamento

H_{int} = ∞ -> L=0

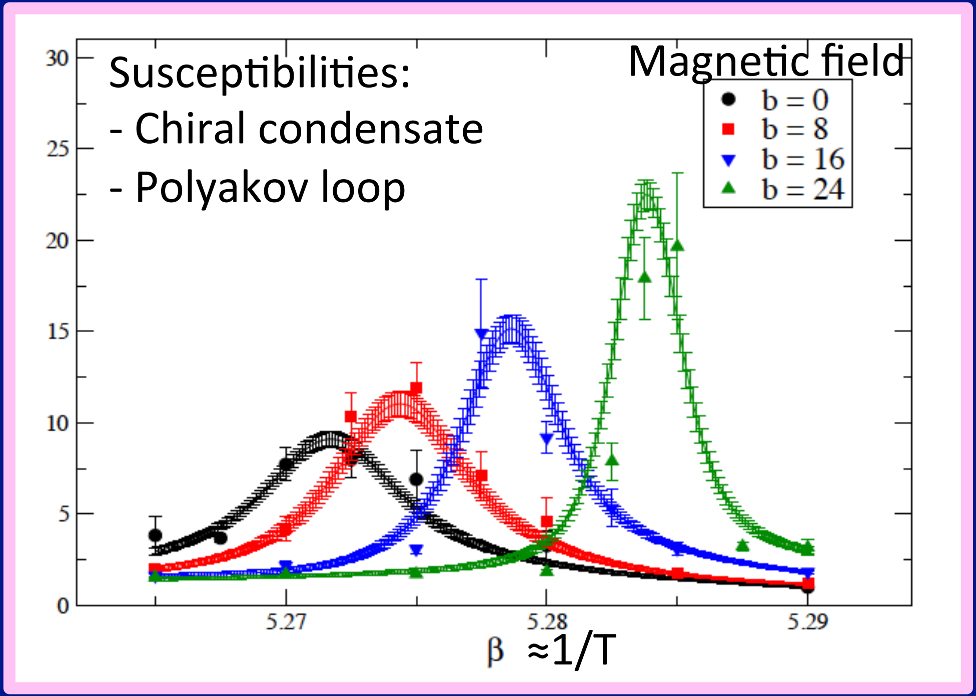
- Crossover nature of the transition
  - no real order parameter
  - very smooth behavior with temperature
  - still exhibit a rapid change in the vicinity of the phase transition

WB collaboration, JHEP (2010)

Yaoki et al., Nature **443**, 675-678 (2006)

ATTIVITA' IN ITALIA su lQCD legata al QGP:

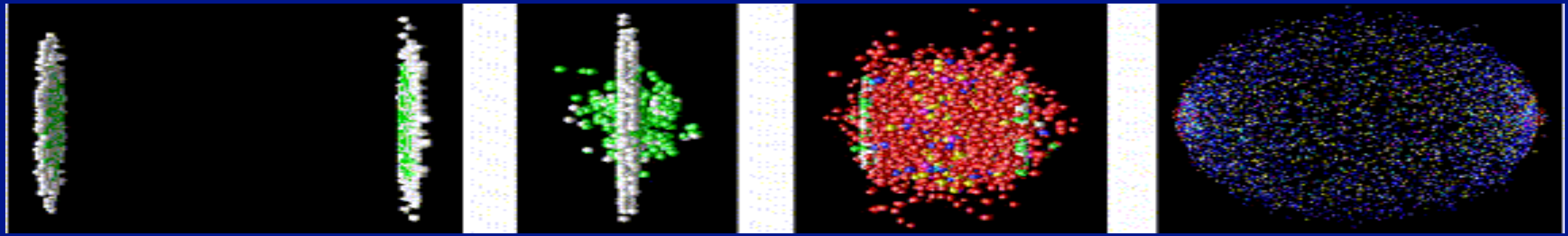
- C.Ratti (TO) – collaboration with Wuppertal Budapest
- M. D'Elia (PI) – phase diagram under large magnetic field,
- M. Lombardo (LNF) – phase diagram at finite μ_B
- P. Cea and Cosmai (BA) – Confinamento…



- ✓ T_c decrease with B
- ✓ Transiton becomes stronger towards a I order?

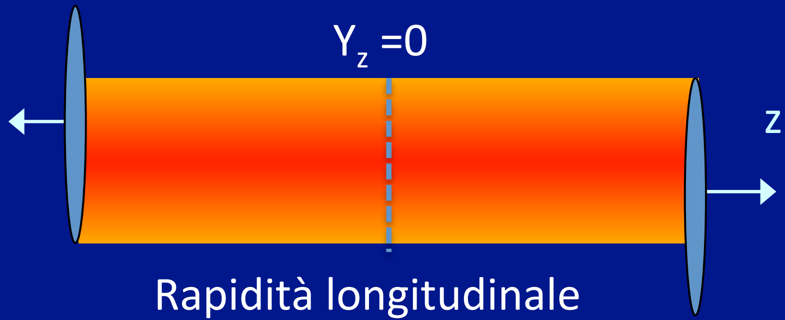
M. D'Elia

How to produce a matter with ε >>1 GeV/fm^3 lasting for τ > 1 fm/c in a volume much larger than a hadron?



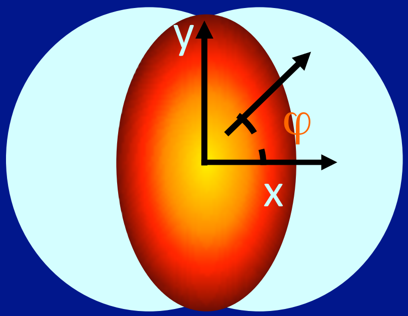
Accelerator	Lab.	Max. E_{beam} [AGeV]	$\sqrt{s}$[AGeV]	Contraction
RHIC (00-…)	BNL	100 +100	9-200	100
LHC (09-…)	CERN	2750+2750	2750-5500	2750

Some typical definitions



Rapidità longitudinale

$$y_z = \tanh^{-1}\beta = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \approx v_z$$



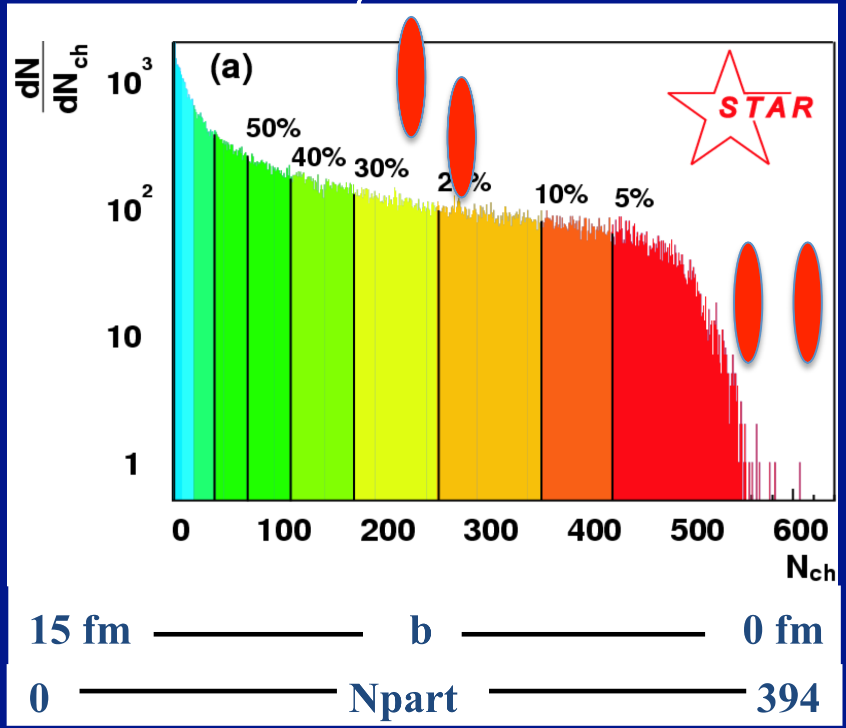
Transverse mass, energy …

$$p^\mu = \left(m_T \cosh y, \vec{p}_T, m_T \sinh y\right)$$

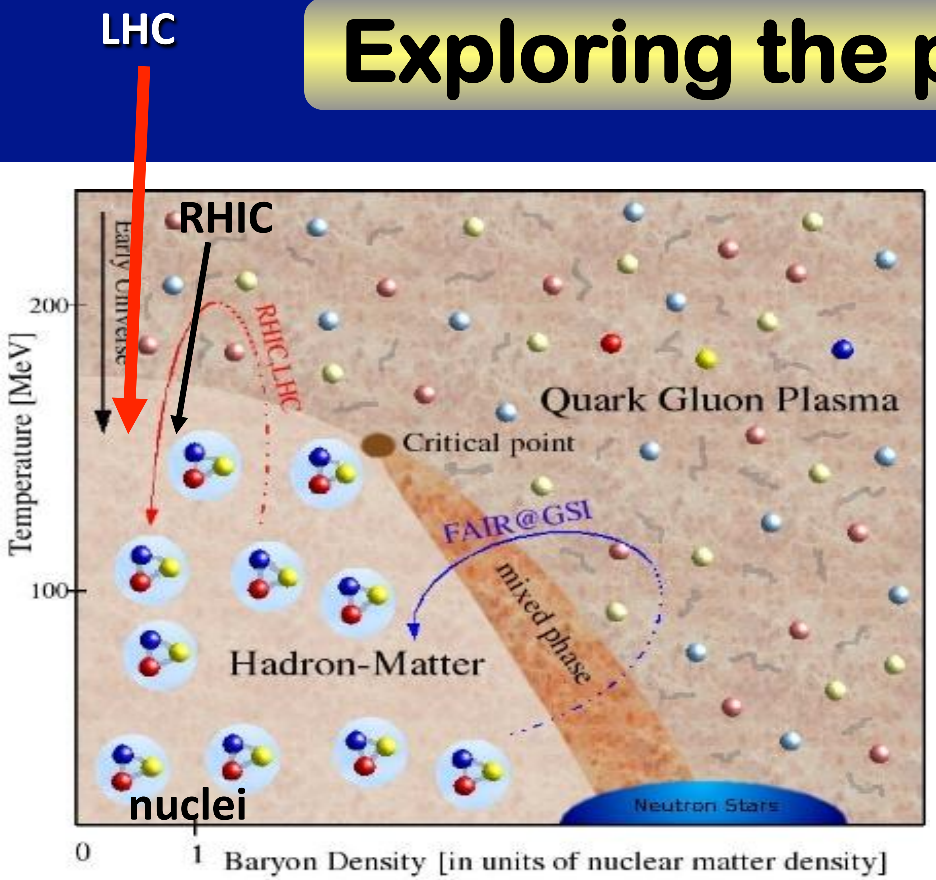
In terms of p_T and y_z

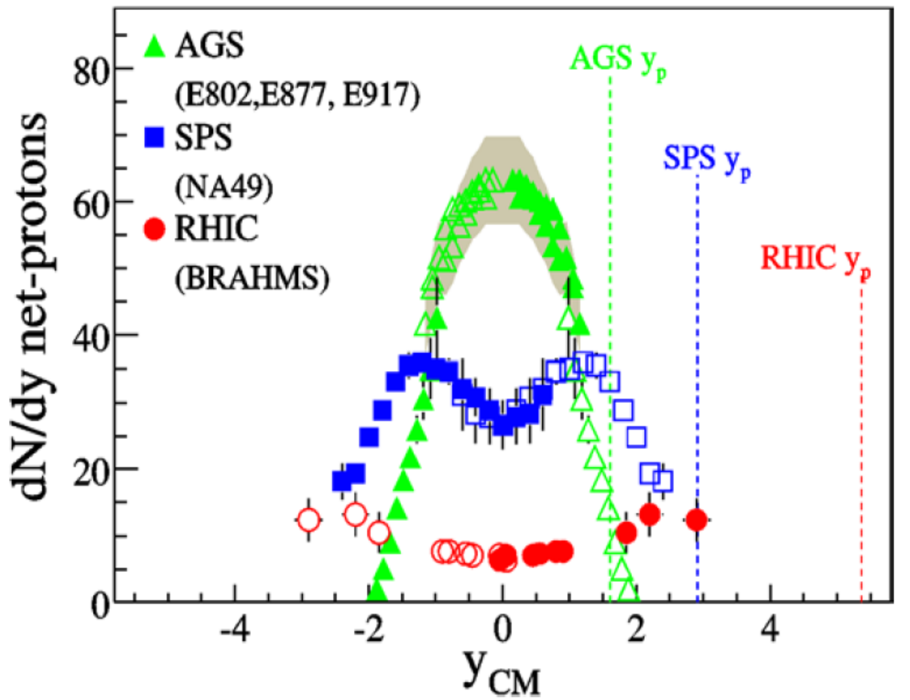
$$m_T = \left(m^2 + \vec{p}_T^{\,2}\right)^{1/2}, \; E = m_T \cosh y_z$$

Centrality of the collisions



Exploring the phase diagram

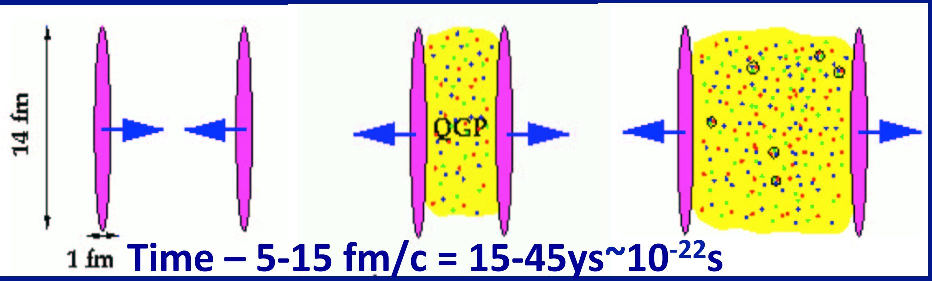




new medium created from the energy deposited

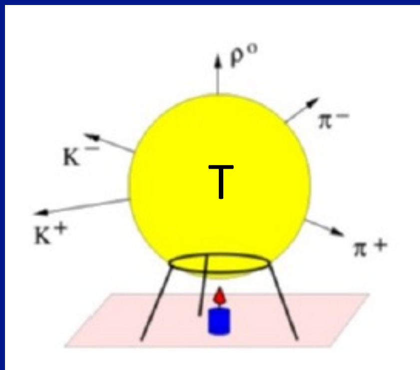
μ_B=0 (quark=antiquarks)

Hotter-denser-longer increasing E_{beam}



Increasing beam energy -> transparency
Energy distributed in a larger volume

Statistical Model analysis



Temperature

Chemical Potential

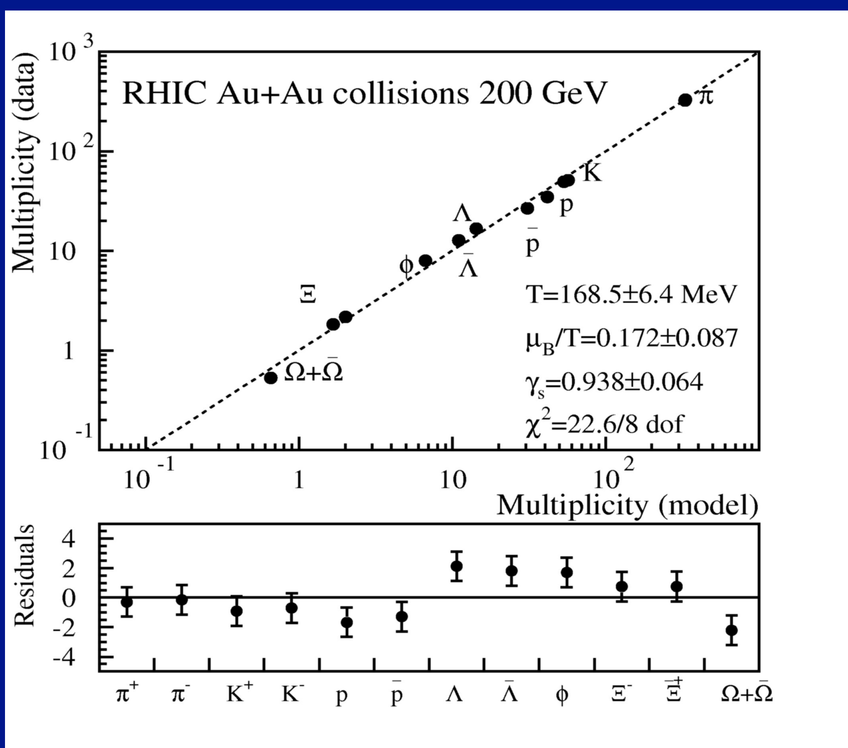
$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}$$

Yield

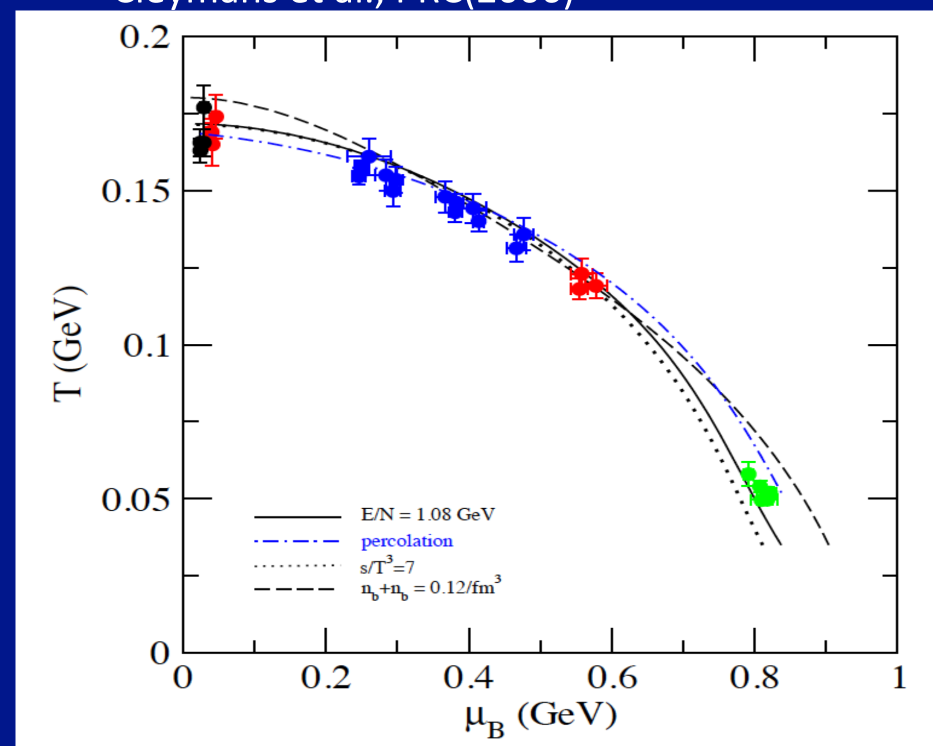
Mass

Quantum Numbers

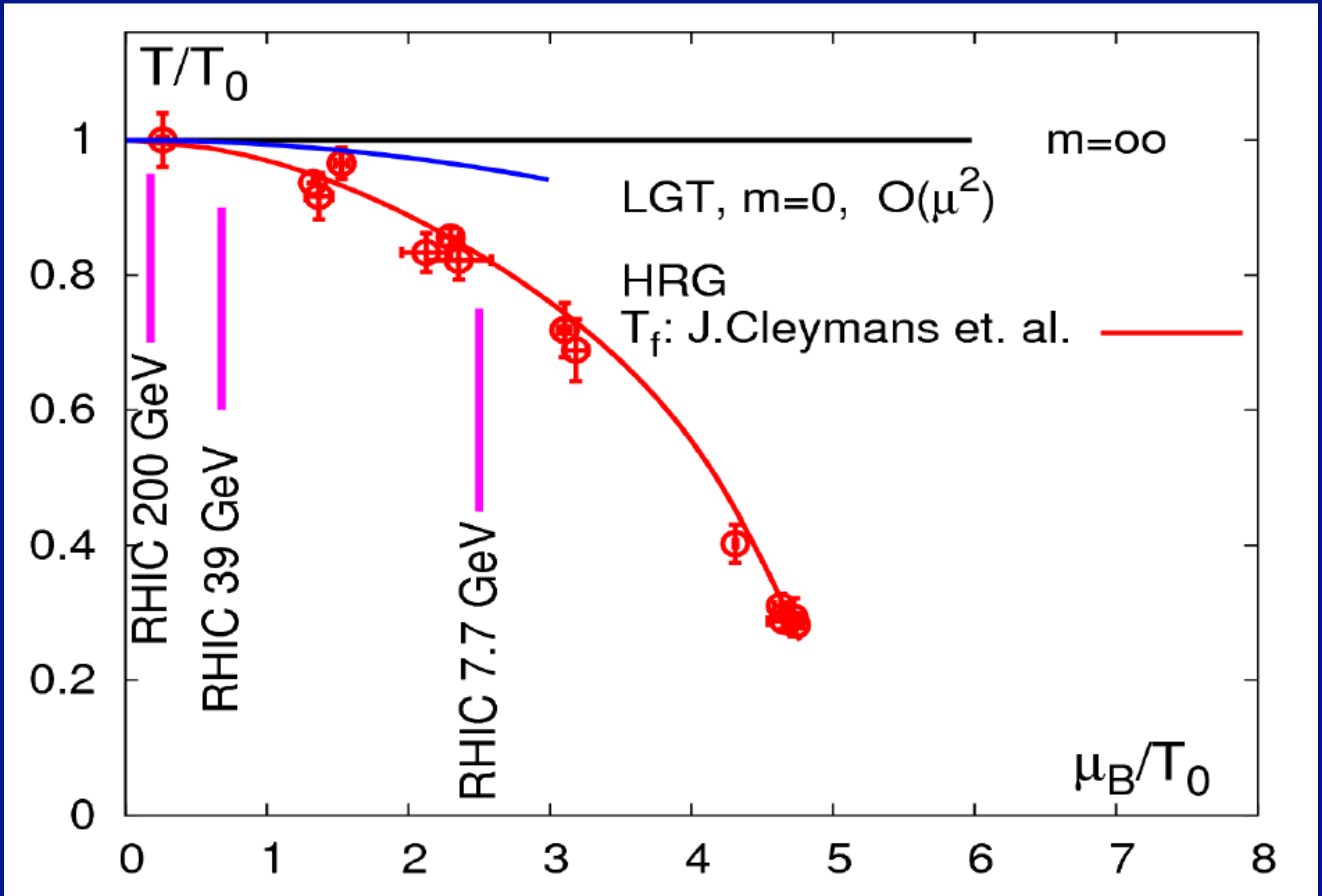
F. Becattini



Cleymans et al., PRC(2006)



Freeze-out vs lattice QCD



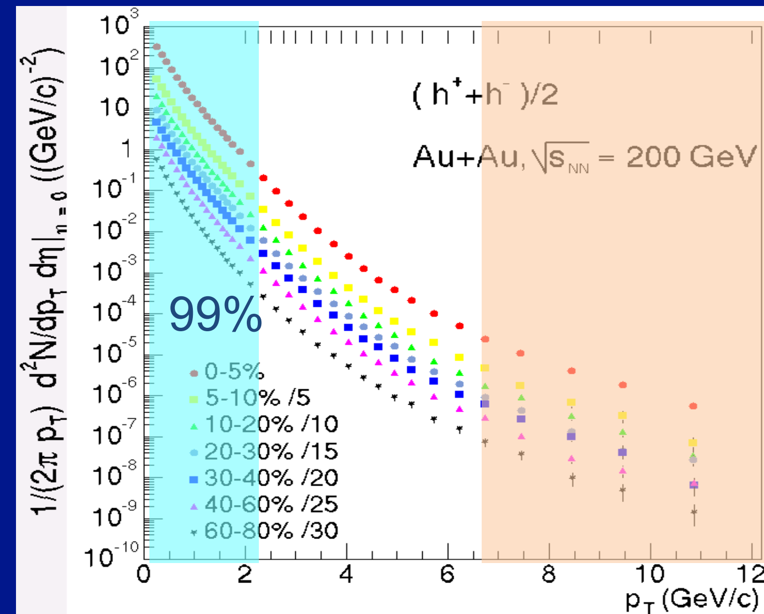
Interesting the relative location between the freeze-out in HIC and critical line of the phase diagram

Soft and Hard probes

SOFT ($p_T \sim \Lambda_{QCD}$, T)

DRIVEN BY *NON PERTURBATIVE QCD*

Hadron yields, collective modes of the bulk, strangeness enhancement, fluctuations, thermal radiation, dilepton enhancement



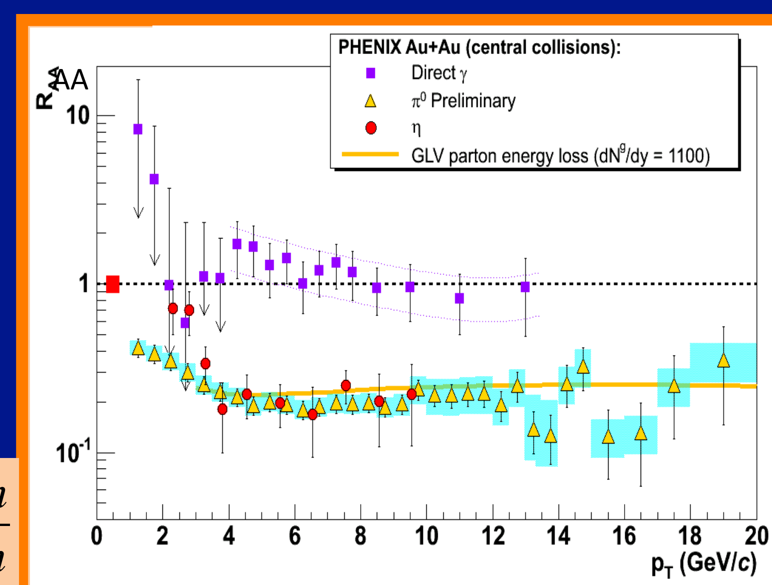
HARD ($p_T >>> \Lambda_{QCD}$)

EARLY PRODUCTION, PQCD APPLICABLE, BASELINE PP, PA

jet quenching, heavy quarks, quarkonia, hard photons (W,Z)

Nuclear modification factor

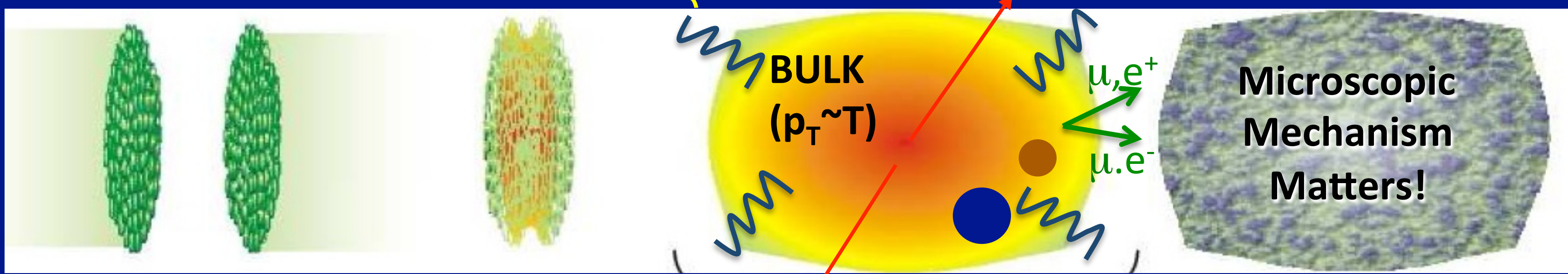
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T}{N_{coll}d^2N^{NN}/dp_T} = \frac{medium}{vacuum}$$



The various Probes

Going from $p_T \approx 1$ a $500\ \Lambda_{QCD}$ and $m_q \approx 1/20$ a $20\ \Lambda_{QCD}$

Initial Conditions — Quark-Gluon Plasma — Hadronization



ColorGlassCondensate
(x<<1)
Gluon saturation?

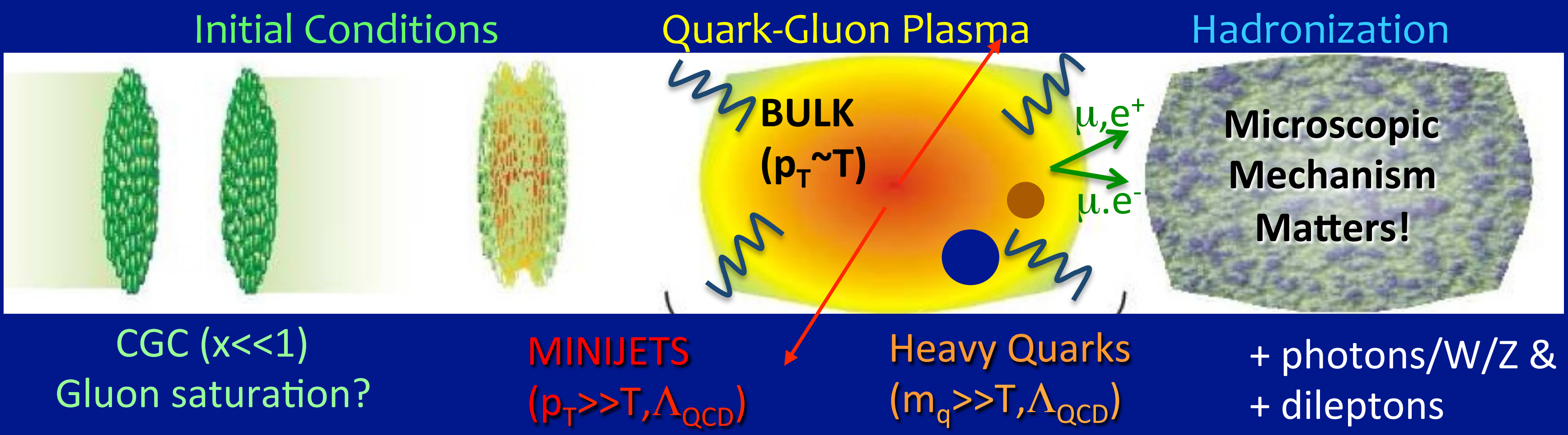
MINIJETS
(p_T>>T,Λ_{QCD})

Heavy Quarks
(m_q>>T,Λ_{QCD})

+ photons/W/Z &
+ dileptons

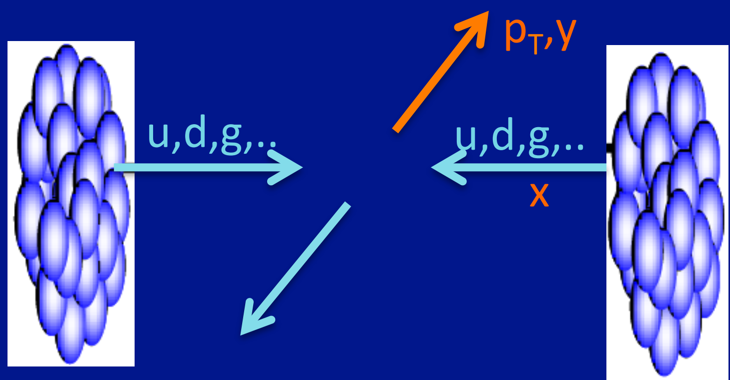
The various Probes

Going from $p_T \approx 1$ ***a 500*** Λ_{QCD} **and** $m_q \approx 1/20$ **a 20** Λ_{QCD}

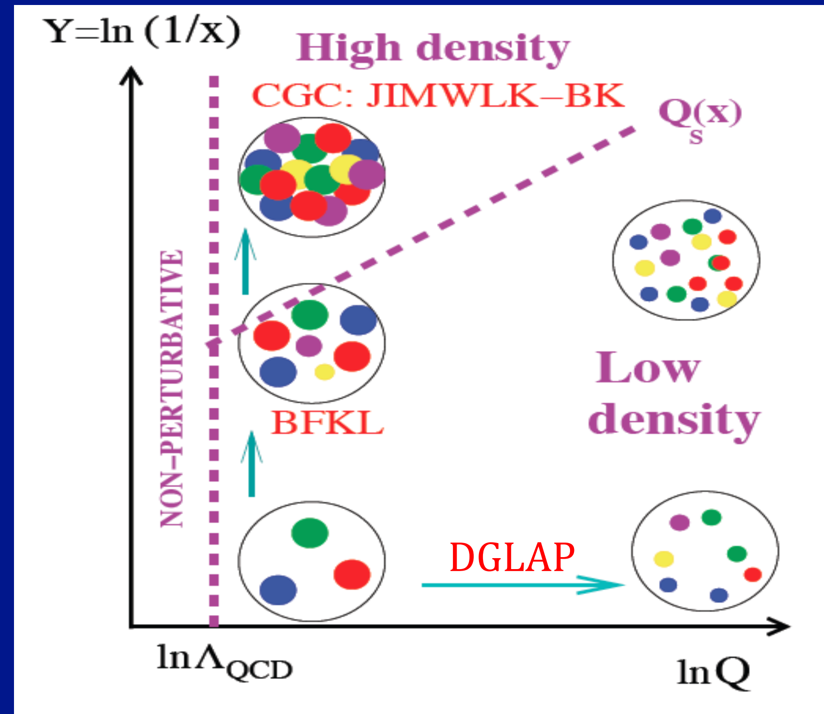


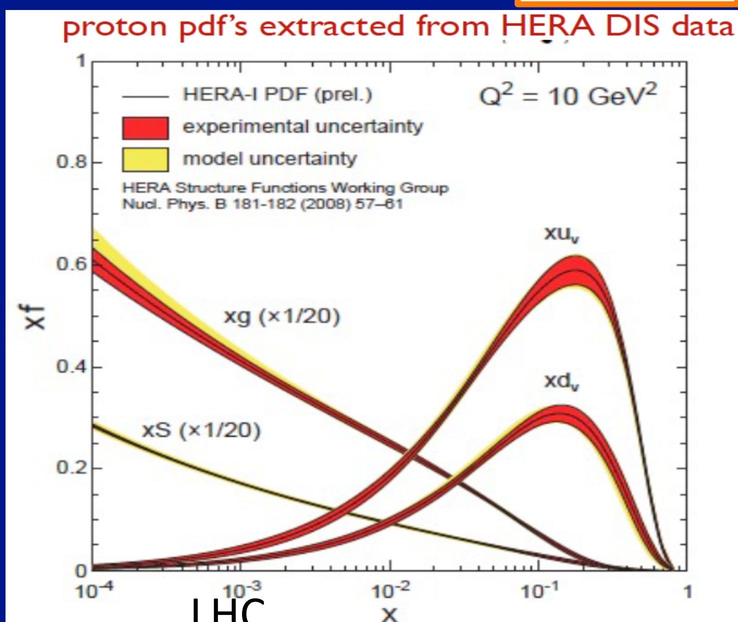
- **Initial Condition** – "exotic" non equilibrium CGC: gluon saturation

Initial conditions: CGC?



x= parton momentum fraction
from kinematic a particle at p_T and y
comes from parton with $x = \frac{p_T}{\sqrt{s}} e^{\pm y}$





We know the evolution of pdf at smaller x and fixed Q^2 is given by BFKL (-> linear evolution)

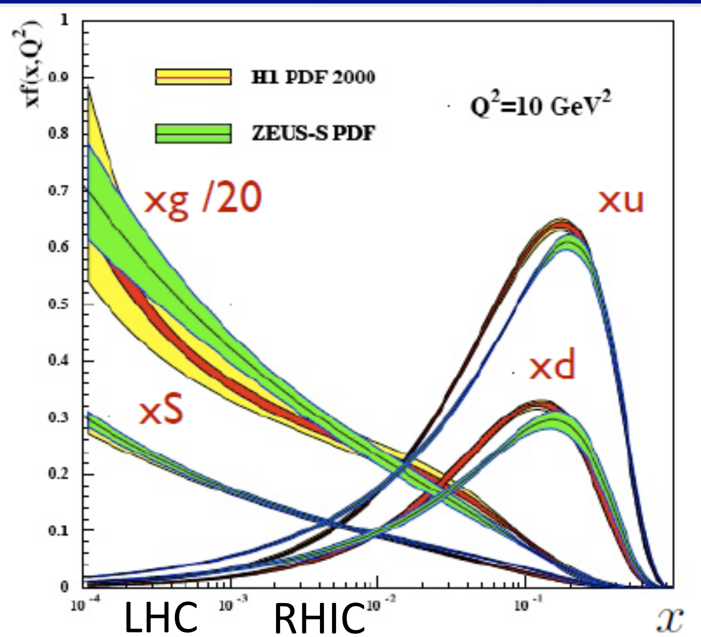
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k}_\perp)}{\partial \ln(\mathbf{x}_0/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k}_\perp) \longrightarrow \phi_{\mathrm{BFKL}} \sim \mathbf{x}^{-\alpha_s \omega}$$

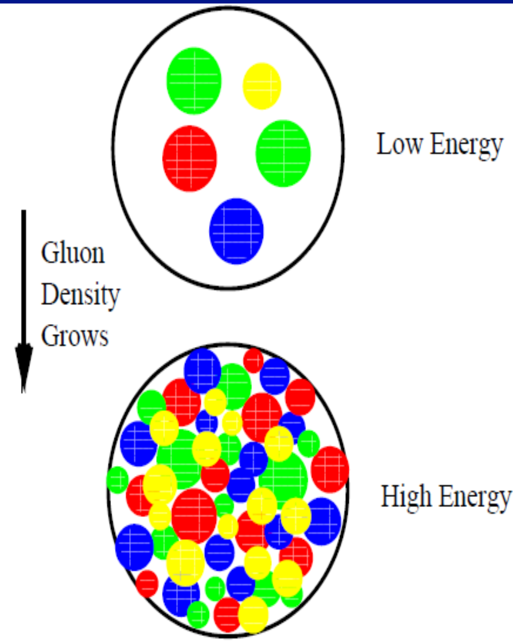
At very high gluon density there are non linear effects:
-> gluon saturation?!
or violation of Unitariety

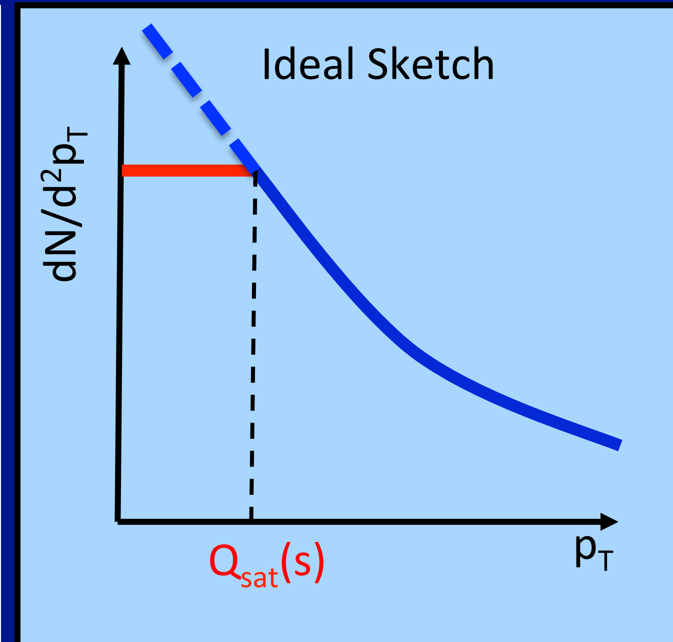
At both RHIC & LHC protons are gluon clouds

Color Glass Condensate initial conditions?

Parton distribution function







At small x (small p_T) dense gluon matter

Gluons of small x (small p_T) -> larger size > $1/Q_s$ overlap

and the gluon distribution stops growing

At RHIC Q^2 ~ 2 GeV2

At LHC Q2 ~ 5-8 GeV^2 ?

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2 \qquad \mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$$

radiation recombination

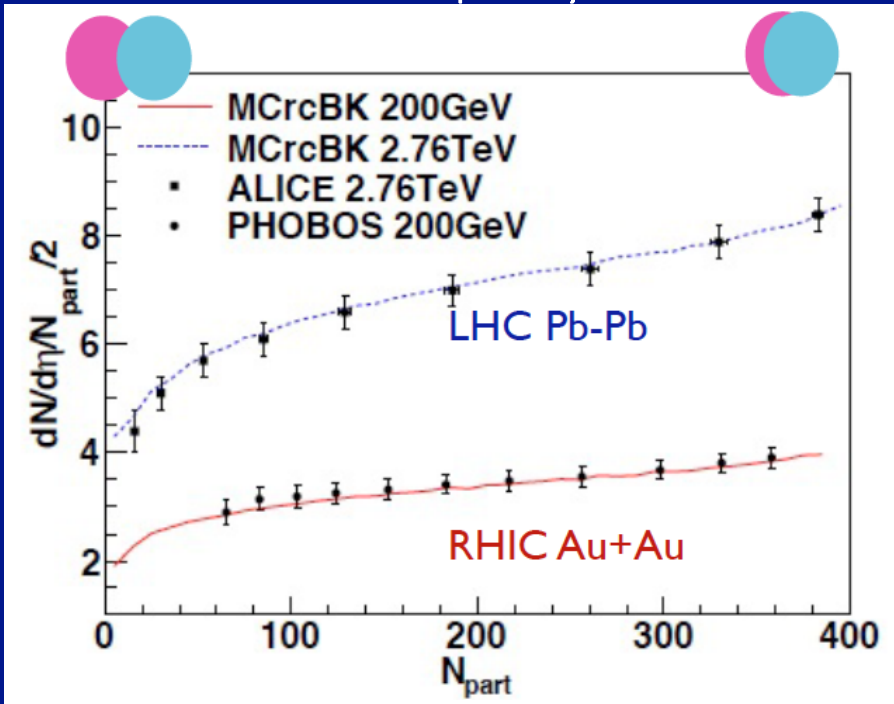
$$x = \frac{p_T}{\sqrt{s}} e^y$$

$$Q^2_{sat}(s) \propto \alpha_s(Q^2) \frac{xg(x,Q^2)}{\pi R^2} \propto A^{1/3}$$

What is the impact
of a different intial condition?

Some prediction for the phenomenology

Multiplicitty

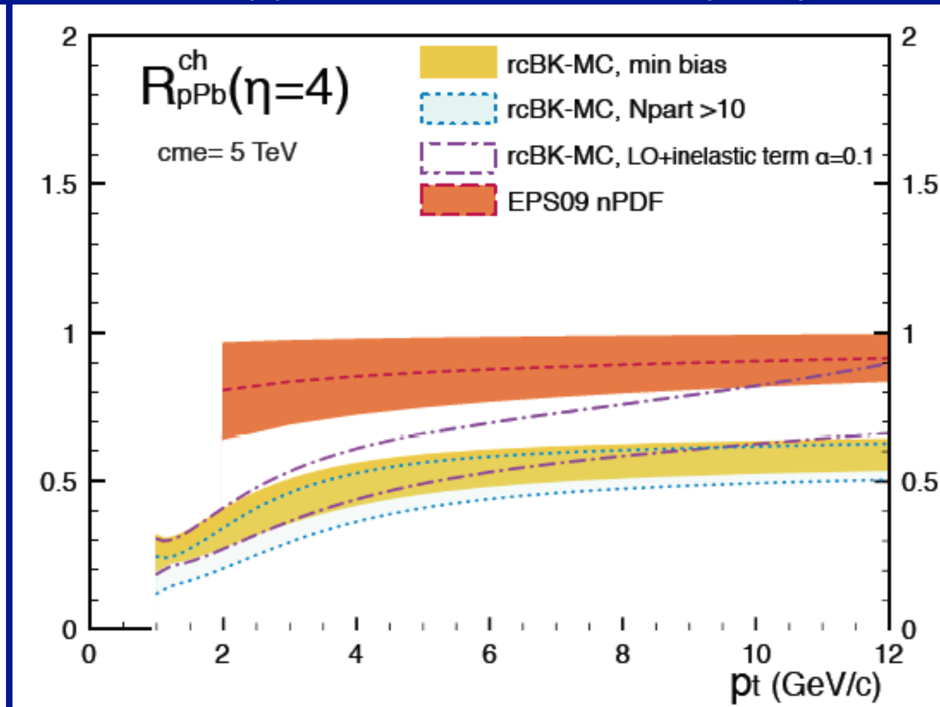


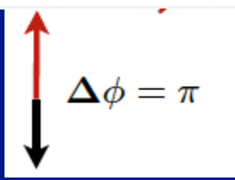
$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s},b) \sim \sqrt{s}^{0.3} N_{part}$$

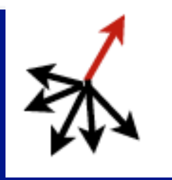
Correct description of the multiplicity

Evolution with energy (also in pp)

Suppression at forward rapidity / back-to-back correlation







At LHC (low x, denser system) :

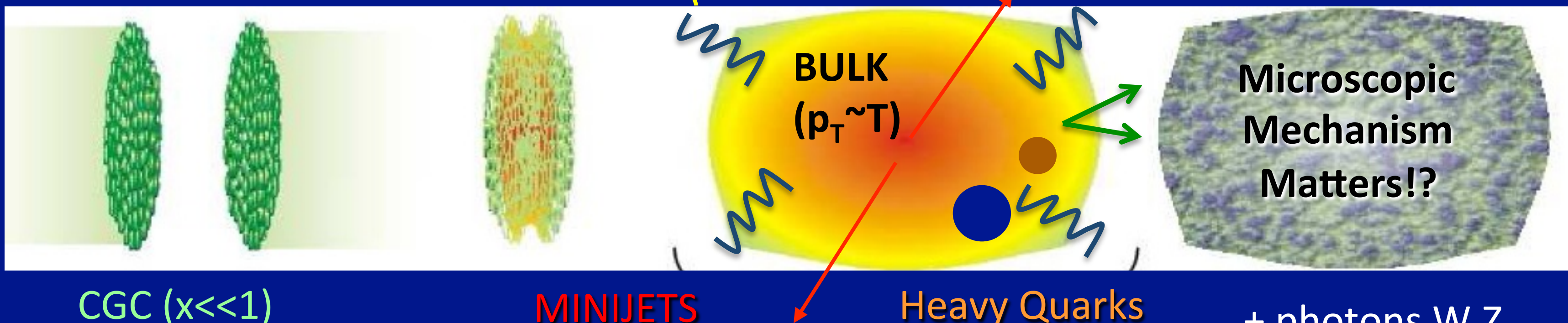
- effects on correlation
- forward minijet suppression

Should allow a much better insight!

The various Probes

Going from $p_T \approx$ *1 a 500* Λ_{QCD} and $m_q \approx 1/20$ a 20 Λ_{QCD}

Initial Conditions | Quark-Gluon Plasma | Hadronization



CGC (x<<1)
Gluon saturation?

MINIJETS
(p_T>>T,Λ_{QCD})

Heavy Quarks
(m_q>>T,Λ_{QCD})

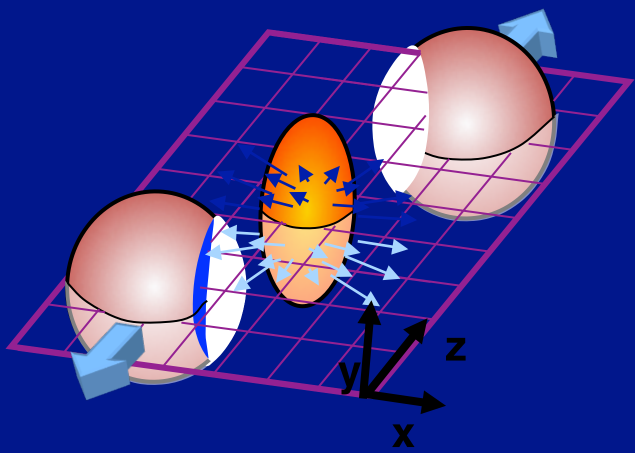
+ photons W,Z
+ dileptons

- **Bulk QGP** – Hydrodynamics *BUT* finite viscosities (η,ζ)

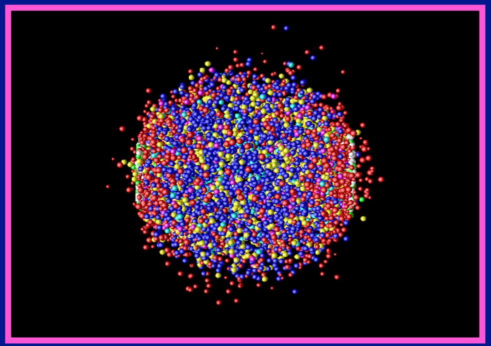
  Does we have a gas of quark and gluons?

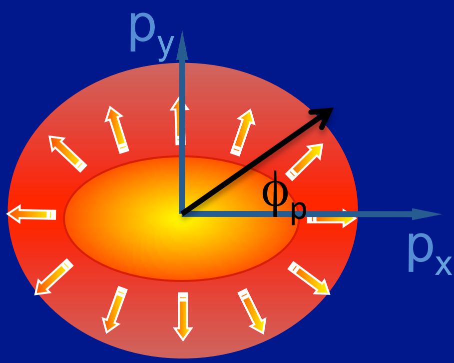
  What is the pressure of the created system?

Collective Expansion – information from non-equilibrium



Radial Flow expansion
expected to be anisotropic





v_2/ε measures efficiency
in converting the eccentricity
from Coordinate to Momentum space

$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

η/s viscosity

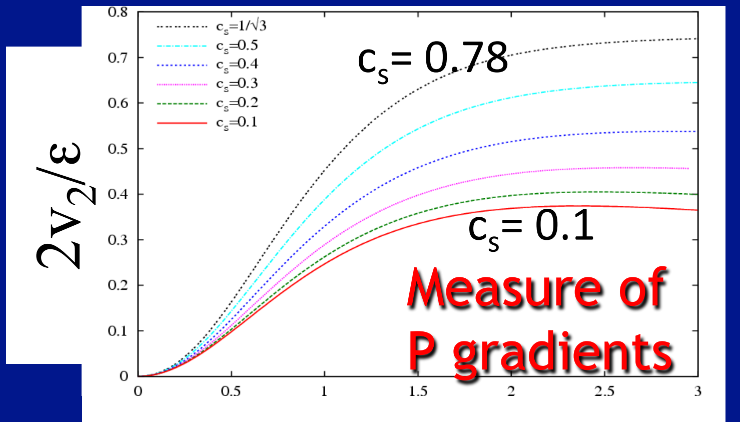
$c^2_s = dP/d\varepsilon$ – EoS

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \left\langle \cos(2\phi_p) \right\rangle$$

Can be seen also as Fourier expansion

$$\frac{dN}{dp_T d\phi} = \frac{dN}{dp_T}\left[1 + 2\,v_2 \cos(2\phi) + 2 v_4 \cos(4\phi) + \ldots\right]$$

by symmetry v_n odd expected to be zero …



Ideal Hydrodynamics: a perfect fluid?

$$\begin{cases} \partial_\mu T^{\mu\nu}(x) = 0 \\ \partial_\mu j^\mu_B(x) = 0 \end{cases}$$

$$T^{\mu\nu}(x) = [\varepsilon + p] u^\mu u^\nu - p g^{\mu\nu}$$

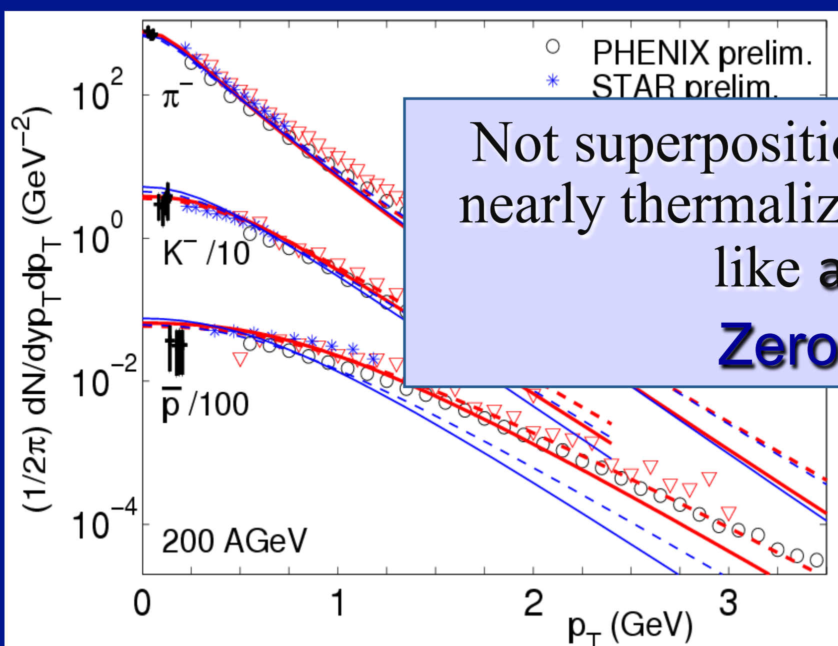
$$T^* \approx T_f + \frac{1}{2} m \langle \beta_T^2 \rangle$$

$T_f \sim 120$ MeV
$\langle\beta_T\rangle \sim 0.5$

No microscopic description (λ ->0), no dissipation,...only conservation laws!

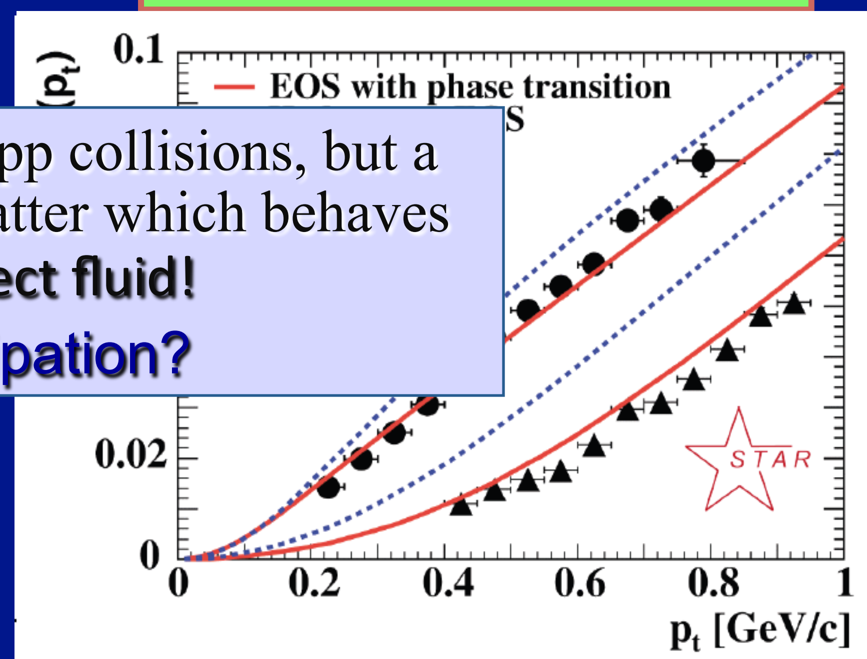
- Blue shift of dN/dp_T hadron spectra
- Large v_2/ε
- Mass ordering of $v_2(p_T)$

For the first time very close to ideal Hydrodynamics



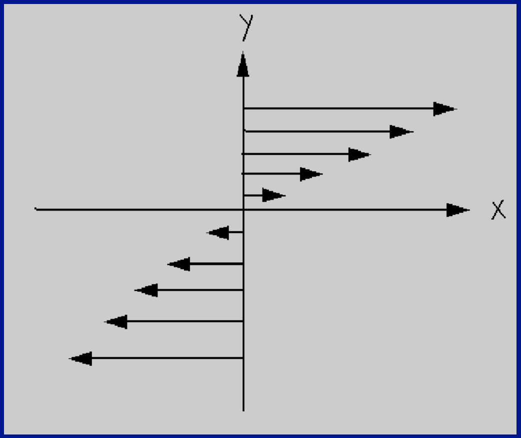
Not superposition of pp collisions, but a nearly thermalized matter which behaves like **a perfect fluid!**

Zero dissipation?



Finite Shear Viscosity

Simple case of a motion only along x



$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial v_x}{\partial y}$$

Text book

$$\frac{\eta}{s} = \frac{1}{15} < p > \cdot \lambda$$

Quantum mechanism and AdS/CFT suggest a lower bound η/s = 0.08:

$$\Delta E \cdot \Delta t \geq 1 \quad \rightarrow \eta / s > 1/15$$

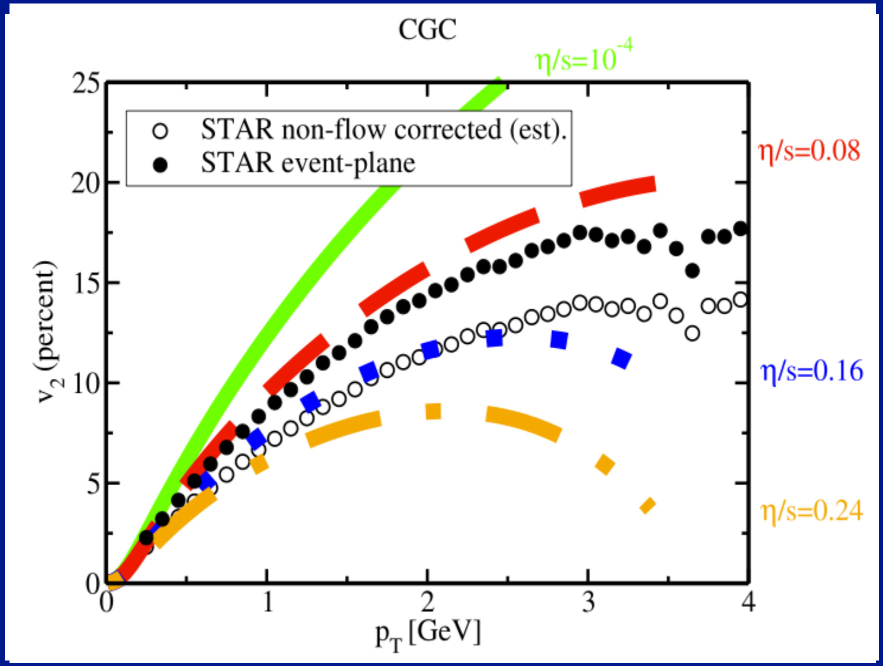
Shear Motion generates a finite dissipation

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \Pi^{\mu\nu}_{dissip}$$

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha)$$

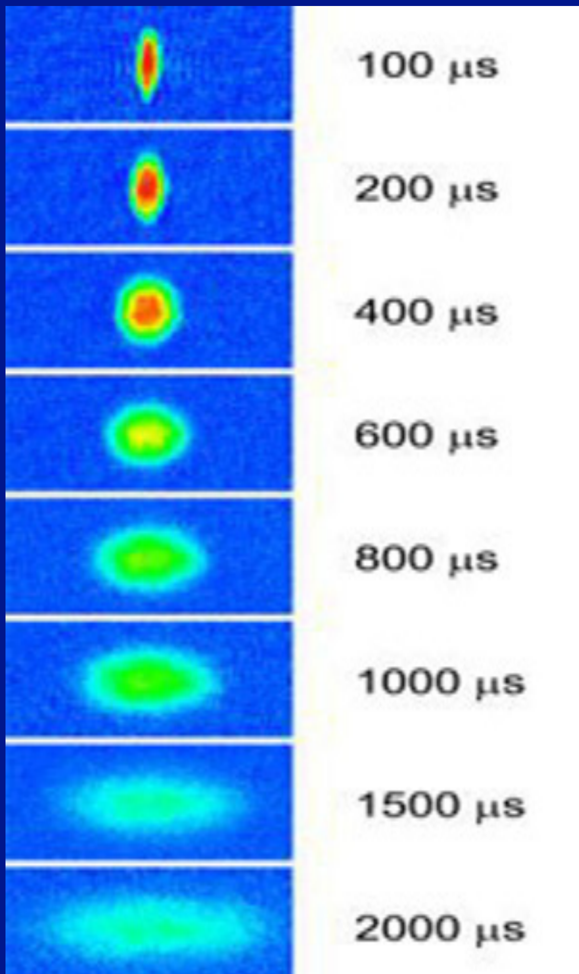
First order gradient expansion
(Hooke-like law – Navier Stokes)

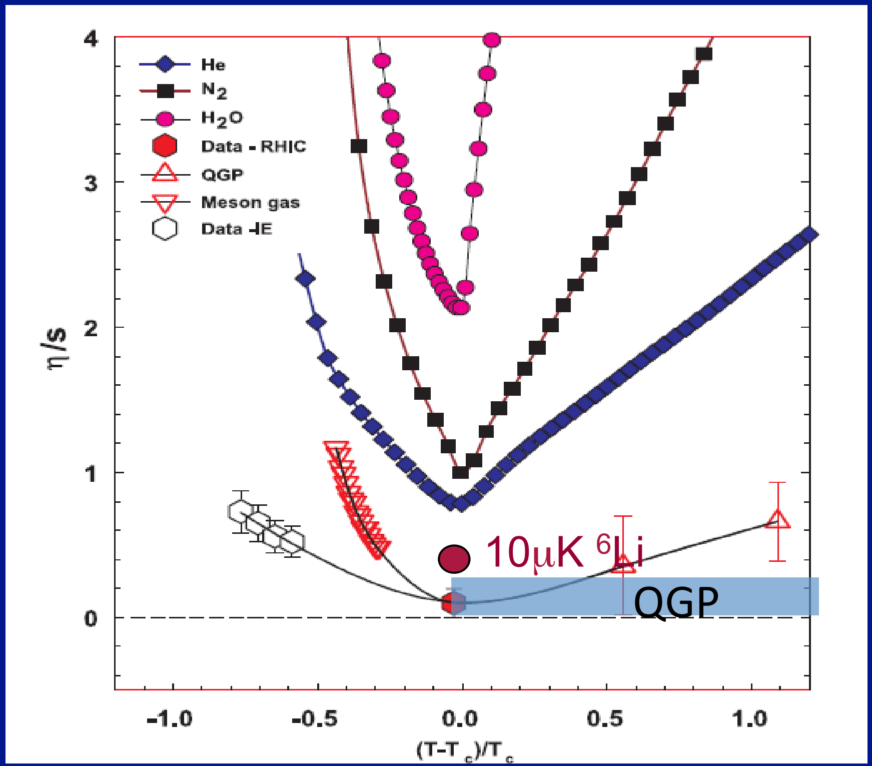
Uncertain initial condition <-> η/s



Similarly in the same years for a very cold system

Strongly interacting ^{6}Li cold atoms
In a magnetic trap: Fermi degenerate gas





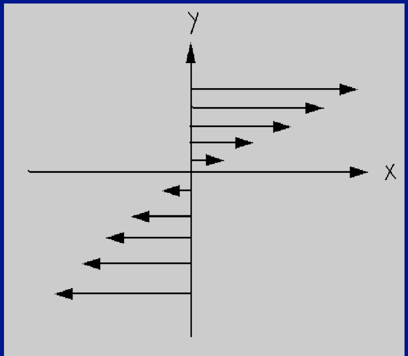
O'Hara et al., Science 298(2002)

$\eta/s \approx 0.24$

Viscous Hydrodynamics

Relativistic Navier-Stokes

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha)$$



$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial u_x}{\partial y}$$

but it violates causality,

II^0 order expansion needed -> Israel-Stewart

$$\pi^{\mu\nu} = \eta \nabla^{<\mu} u^{\nu>} + \tau_\pi \left[\Delta^\mu_\alpha \Delta^\nu_\beta D\pi^{\alpha\beta} \dots\right]$$

τ_η,τ_ζ two parameters appears +

δf ~ f_{eq} reduce the p_T validity range

A problem:

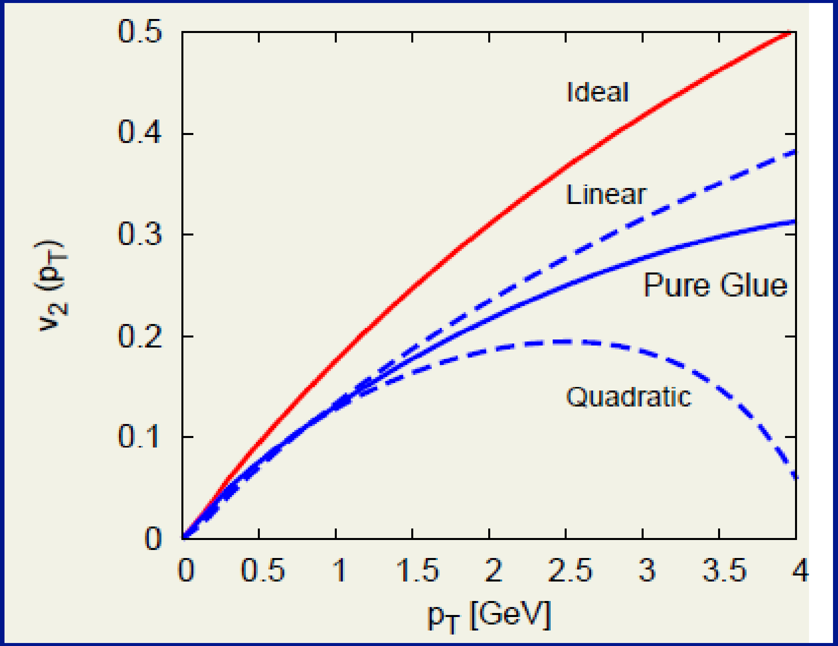
Dissipative correction to f -> $f_{eq}+\delta f_{neq}$

There is no one to one correspondence!

$$T^{\mu\nu}_{eq} + \delta T^{\mu\nu} \Leftarrow f_{eq} + \delta f$$

An Asantz (Grad) -> arbitrarietà p_T> 1.5 GeV

$$\delta f = \frac{\pi^{\mu\nu}}{\varepsilon + P} \frac{p_\mu p_\nu}{T^2} f_{eq} \approx \frac{\eta}{3s} \frac{p_T^2}{\tau T^2} f_{eq}$$



Toward a transport approach as at lower energy (see talk di ieri…)

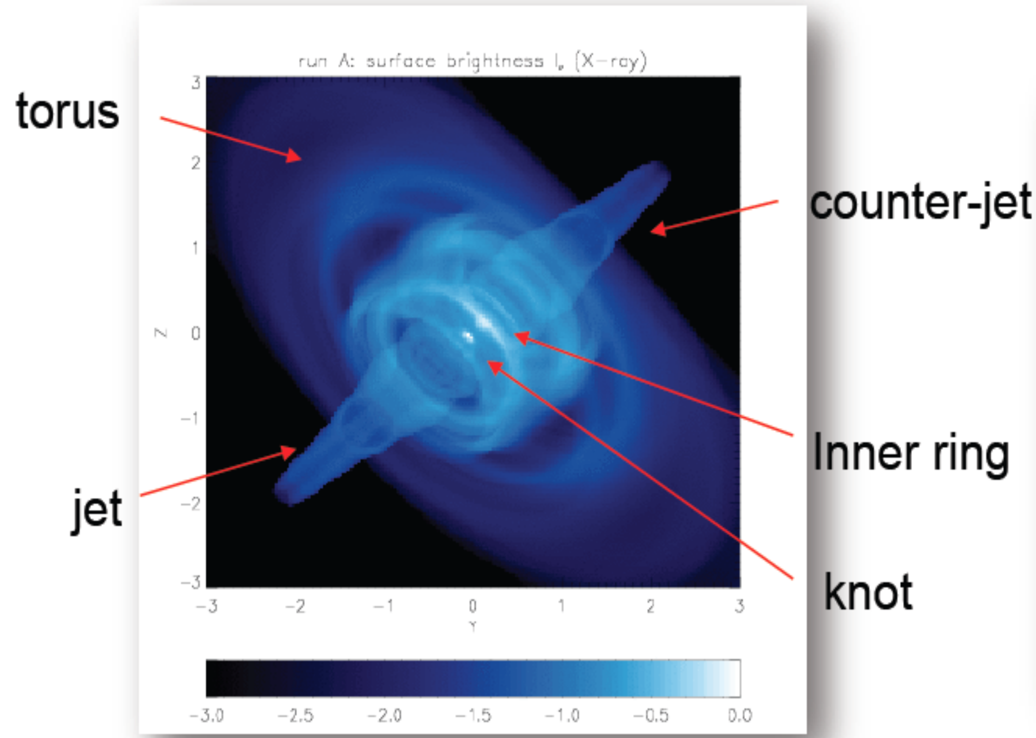
Attivita' in Italia: sviluppo codice 3+1D ECHOQGP

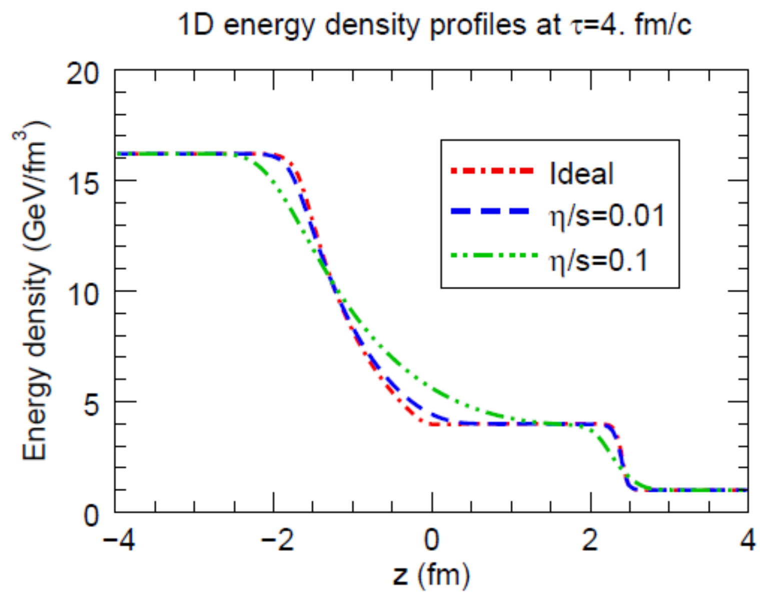
Nell'ambito delle inziative RM31 e PRIN2009

Collaborazione Firenze (F. Becattini, V. Chandra, L. Del Zanna G. Inghirami), Ferrara (A. Drago, G. Pagliara, V. Rolando), Torino (A. Beraudo, A. De Pace)

Sviluppato a partire da codice idro ideale per Plasmi astrofisici (autore L. Del Zanna)

Primi test sulla parte viscosa: positivi





Transport approach

$$\left\{p^{*\mu}\partial_\mu + \left[p^*_\nu F^{\mu\nu} + m^*\partial^\mu m^*\right]\partial^{p^*}_\mu\right\} f(x,p^*) = C_{2\leftrightarrow 2} + C_{2\leftrightarrow 3} + \ldots$$

Free streaming Field Interaction -> $\varepsilon \neq 3P$ (EoS) Collisions -> $\eta \neq 0$

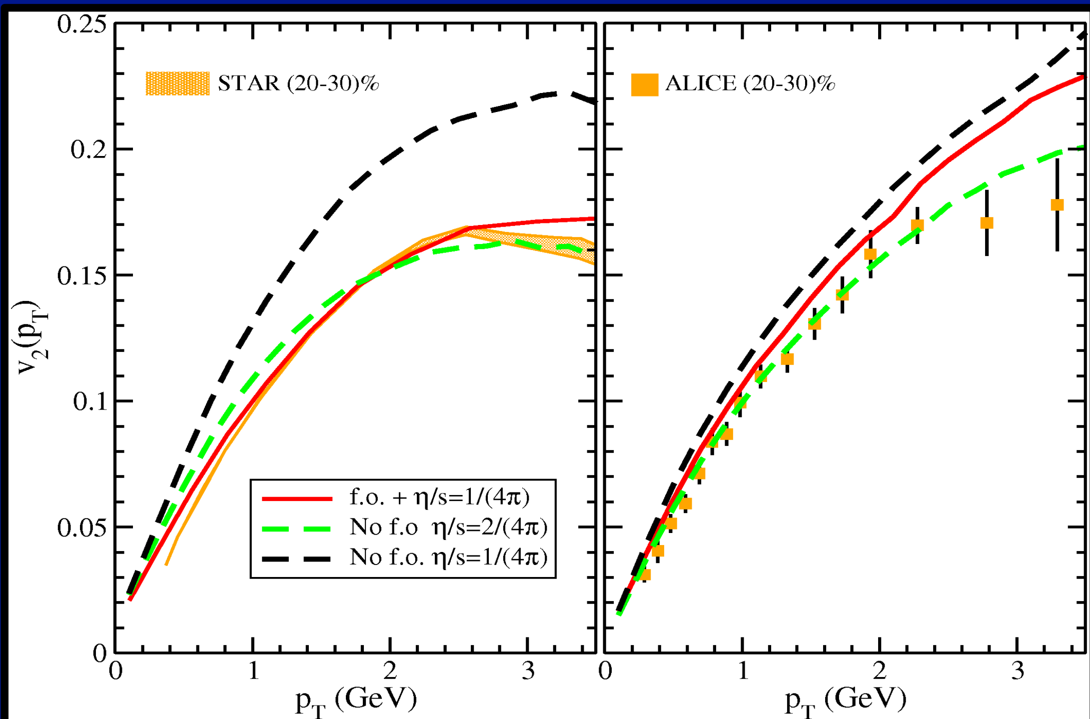
- Microscopic scale has some relevance? Know more about QGP?
- Can we link the effective $\mathcal{L}$ <-> transport dynamics in HIC
  Thermodynamics <-> phenomenology of HIC
- valid also at intermediate & high p_T out of equilibrium:
- valid also at high η/s -> LHC - $\eta/s(T)$, cross-over region
- Appropriate for heavy quark dynamics

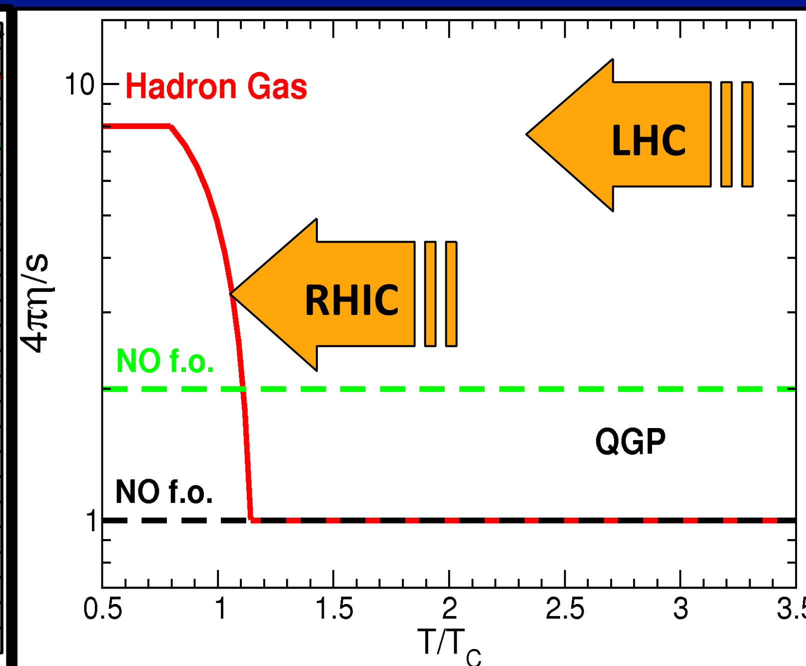
A unified framework against a separate modelling with a wide range of validity in η, ζ, p_T + microscopic level

First application: f.o. at RHIC & LHC

Nell'ambito dei progetti FIRB2008 e ERC-StG

Collaborazione: CT-LNS (VG, A. Plumari, A. Puglisi, F. Scardina, M. Ruggieri); TO (C. Ratti, M. Bluhm)



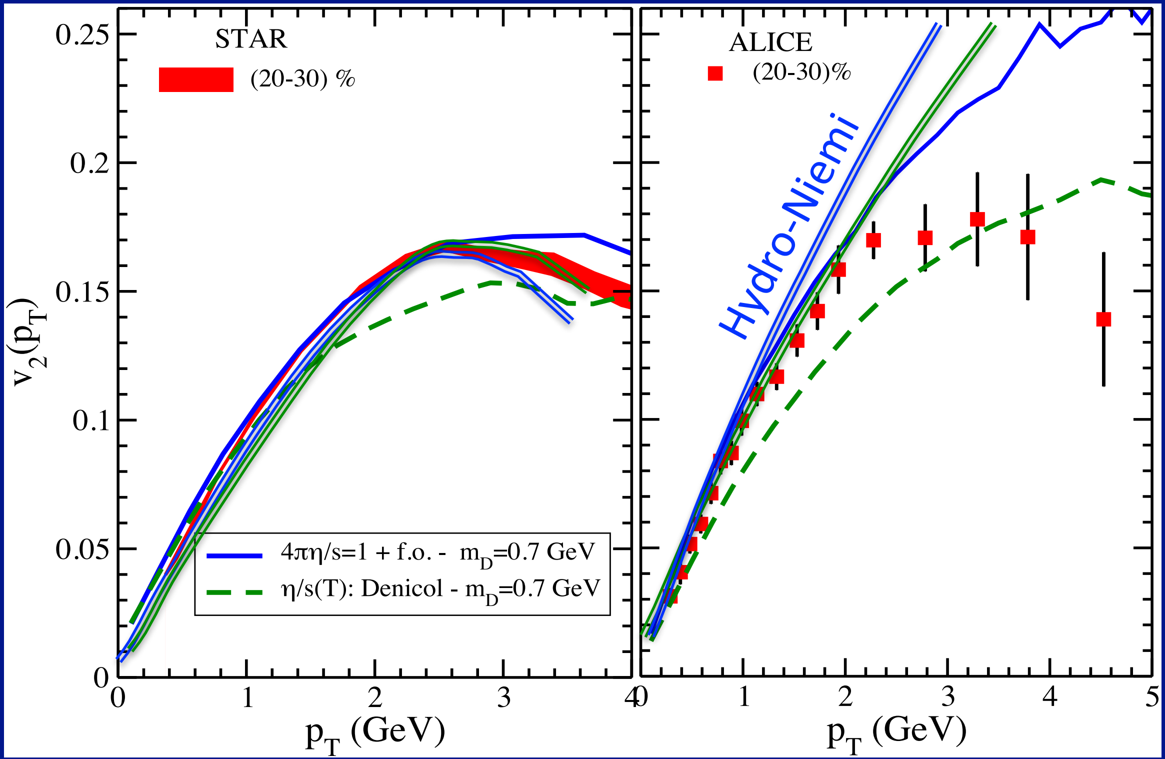


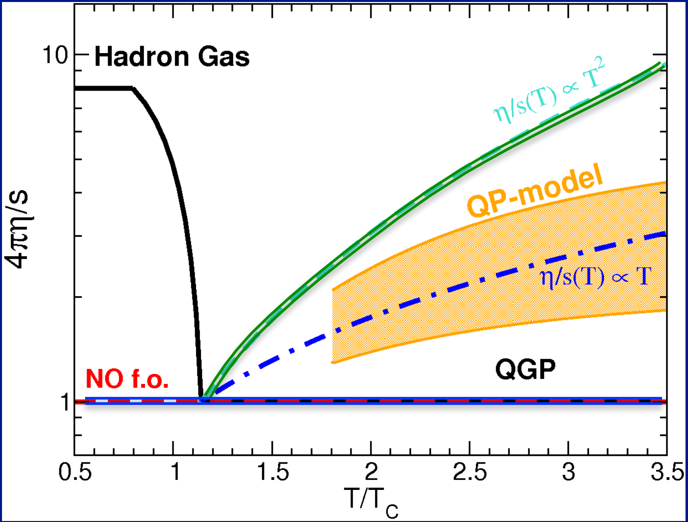
- RHIC: η/s increase in the cross-over region equivalent to double η/s in the QGP
- LHC: almost insensitivity to cross-over (≈ 5%) : v_2 from pure QGP!

Without η/s(T) increase T≤Tc we would have had v_2(LHC) < v_2(RHIC)

Statements in ALICE PRL 105(2010) should be revisited

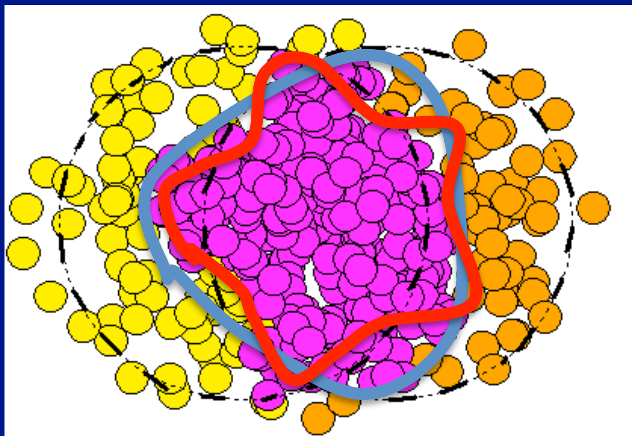
Sensitivity in transport using same η /s(T)



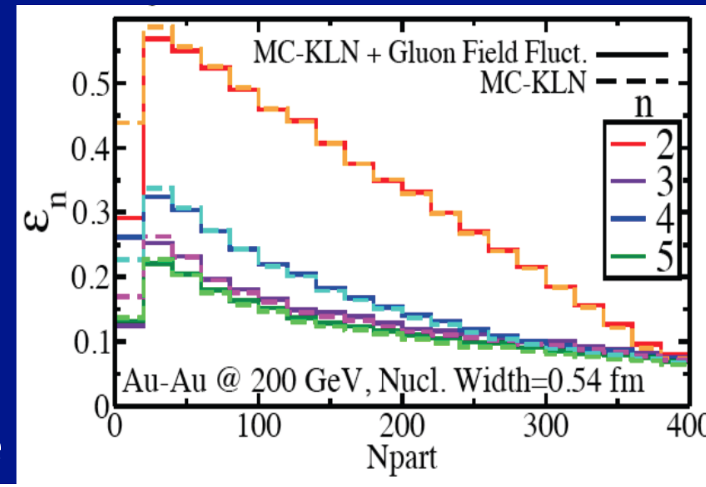


- ✓ Larger sensitivity on η/s (T) at LHC
- ✓ Effect larger respect to viscous hydro, but this depends also on δf
- ✓ An estimate of $\eta/s(T)$ is more meaningful with transport approach

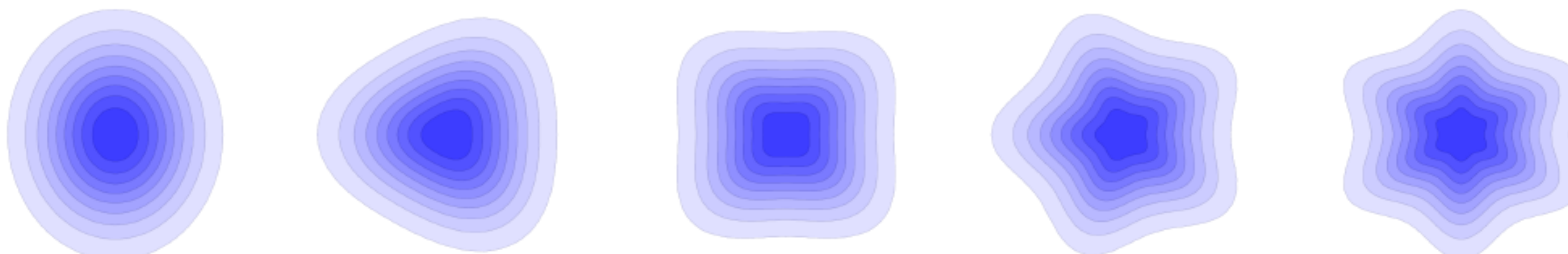
Recent development: from averages to event-by-event



εn for n>2 of similar size



When including fluctuations, all moments appear:

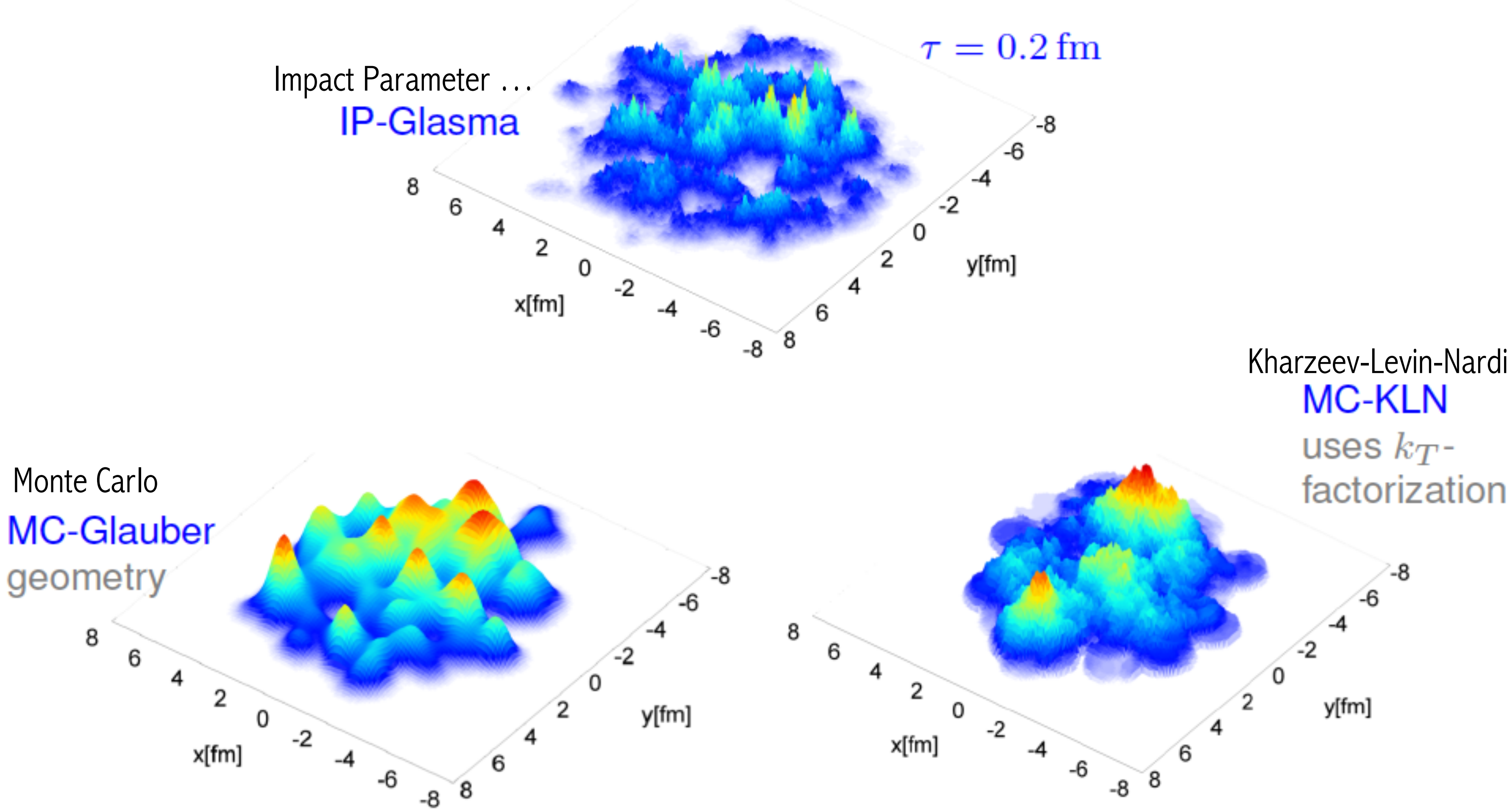


$n=2$ $n=3$ $n=4$ $n=5$ $n=6$

also v_1 and $n>6$

Compute $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$

What are really the fluctuations and/or the Initial Conditions?

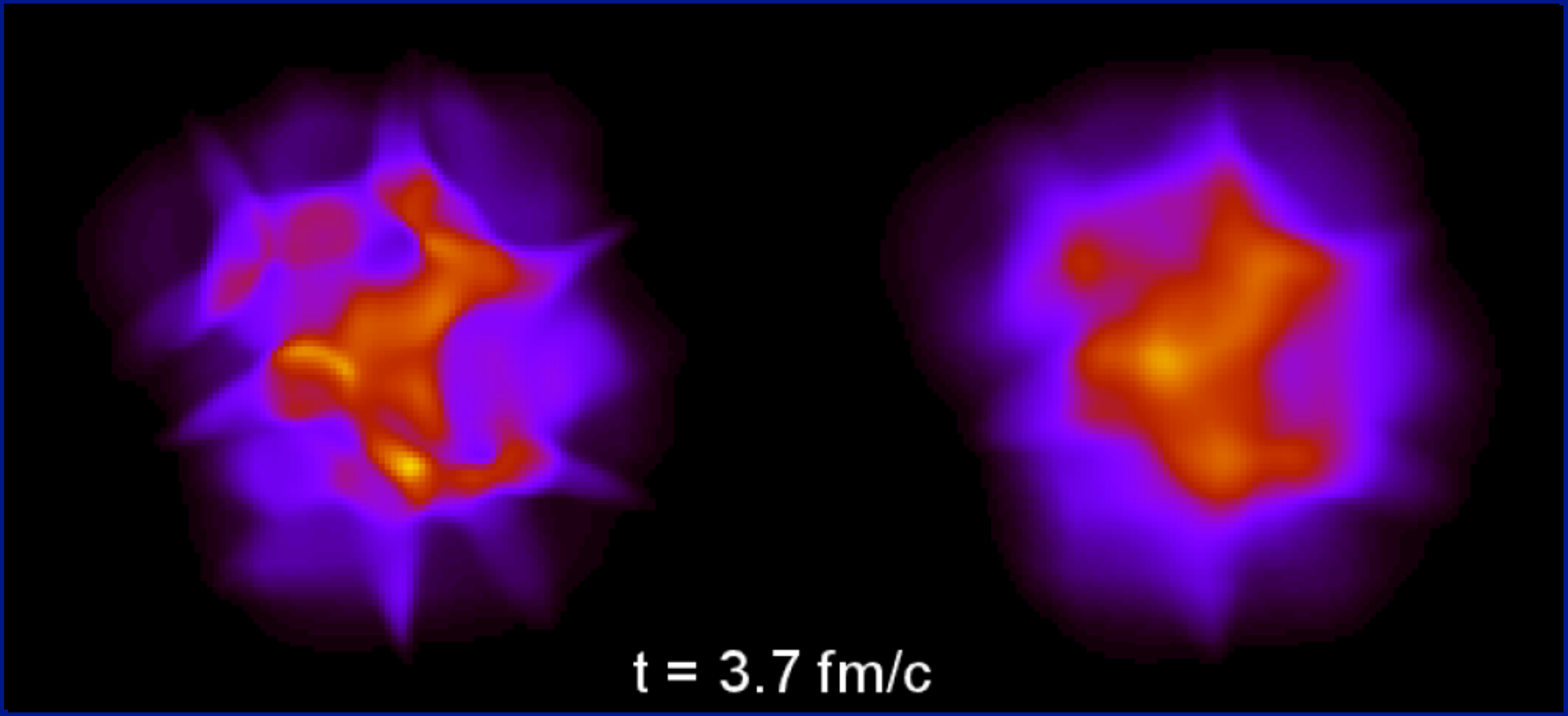


Models predict quite different “spikes”:

- This means to go to microscopic details & local large gradients -> the field of transport

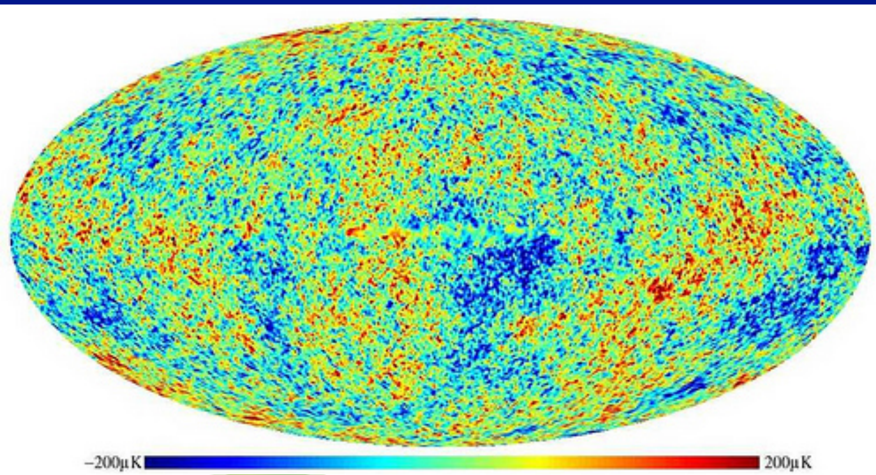
η/s smoothen fluctuations and affect more higher harmonics

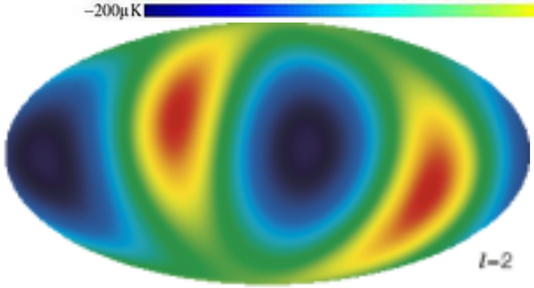
Ideal | Viscous



$\eta/s=0$ | $\eta/s=0.16$

High harmonics fluctuations reminds the CMB fluctuation and WMAP

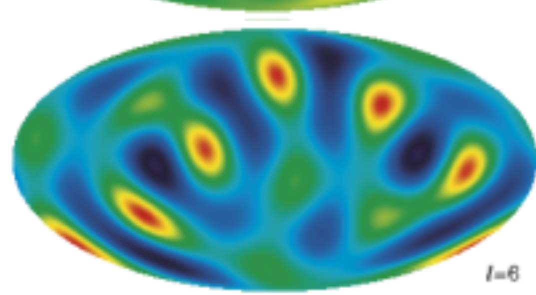


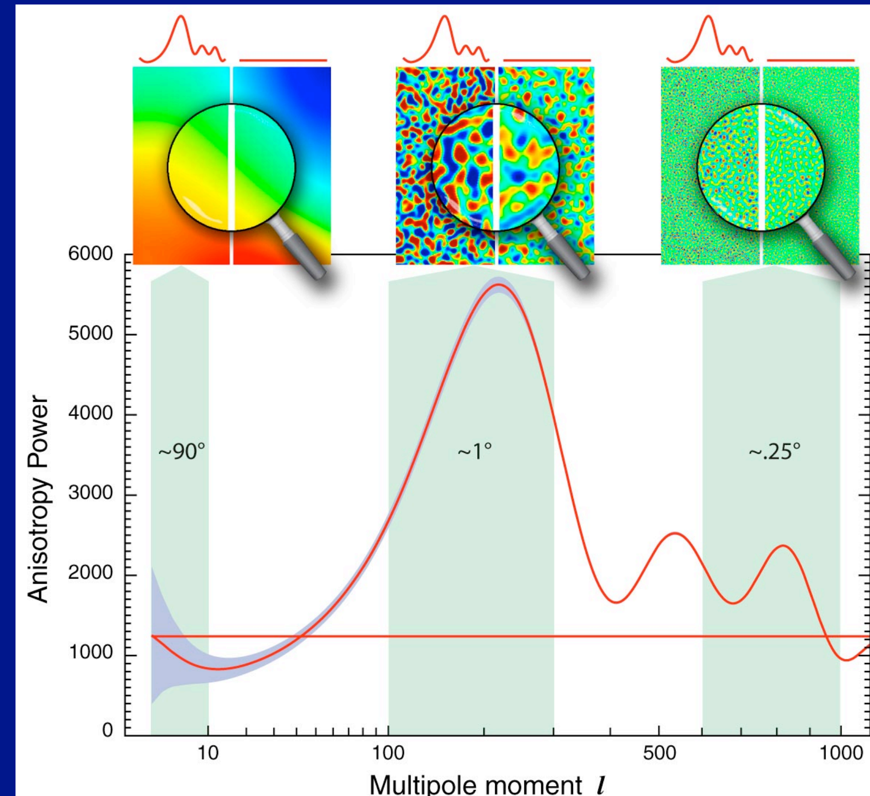


$$\frac{\Delta T}{T} \sim 10^{-5}$$

$$l_{maximum} \approx 210$$

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

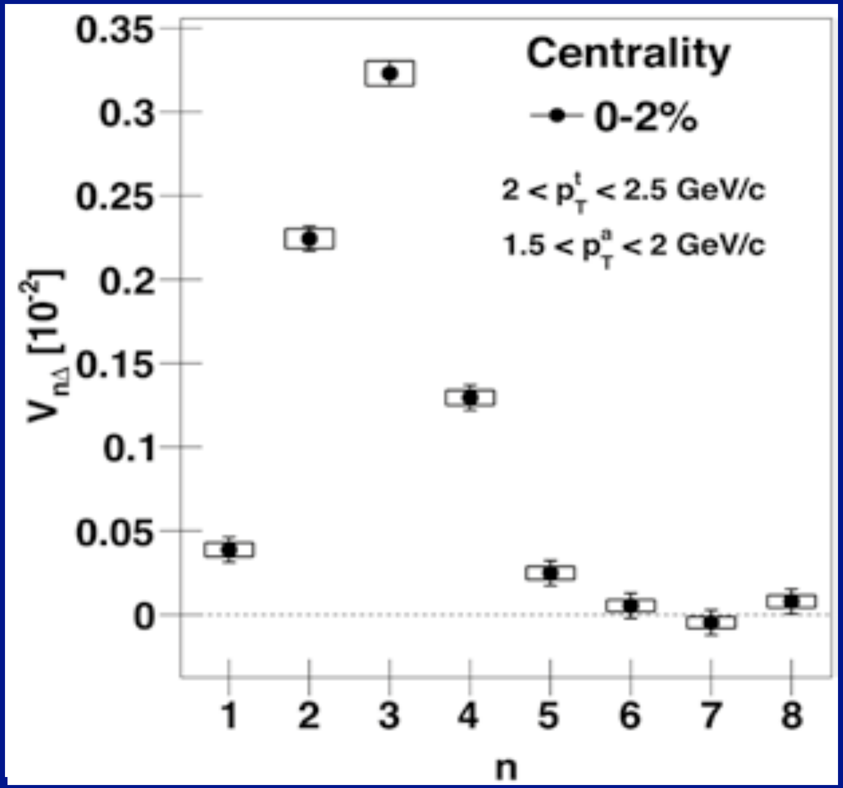




Freeze-out τ ≈ 380.000 y's (QGP ≈10^{-22} s)
Sound horizon R ≈ Mps (QGP ≈ 6 fm)

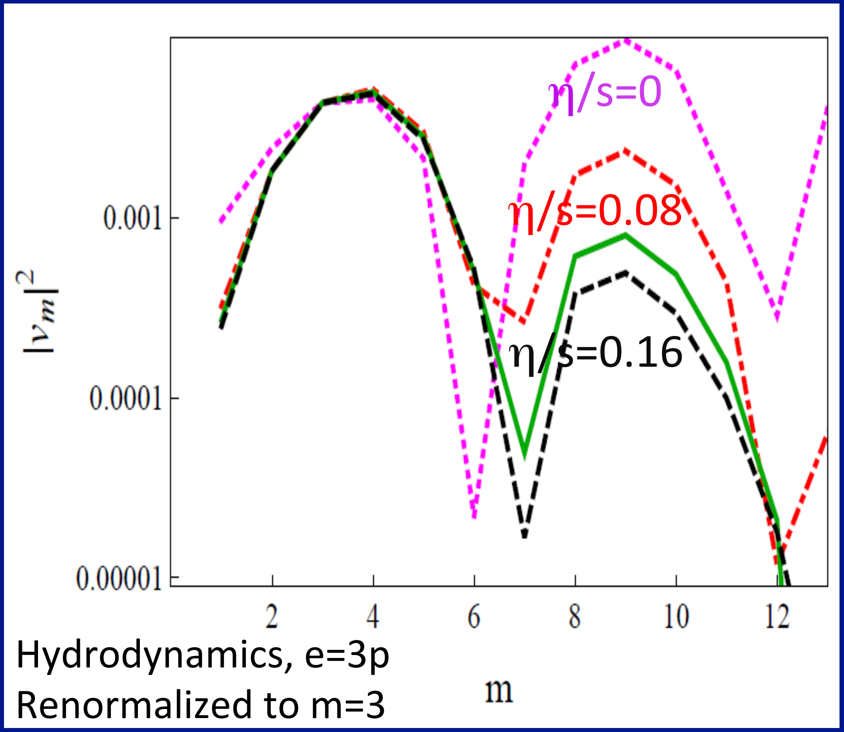
Of course n=200 is not possible to be seen for a hadron system with R ≈ 10 fm

The last impressive measurement ….



Cifarelli, Csernai, Stocker, Europhysicsnews 43 (2012)

A first schematic calculation

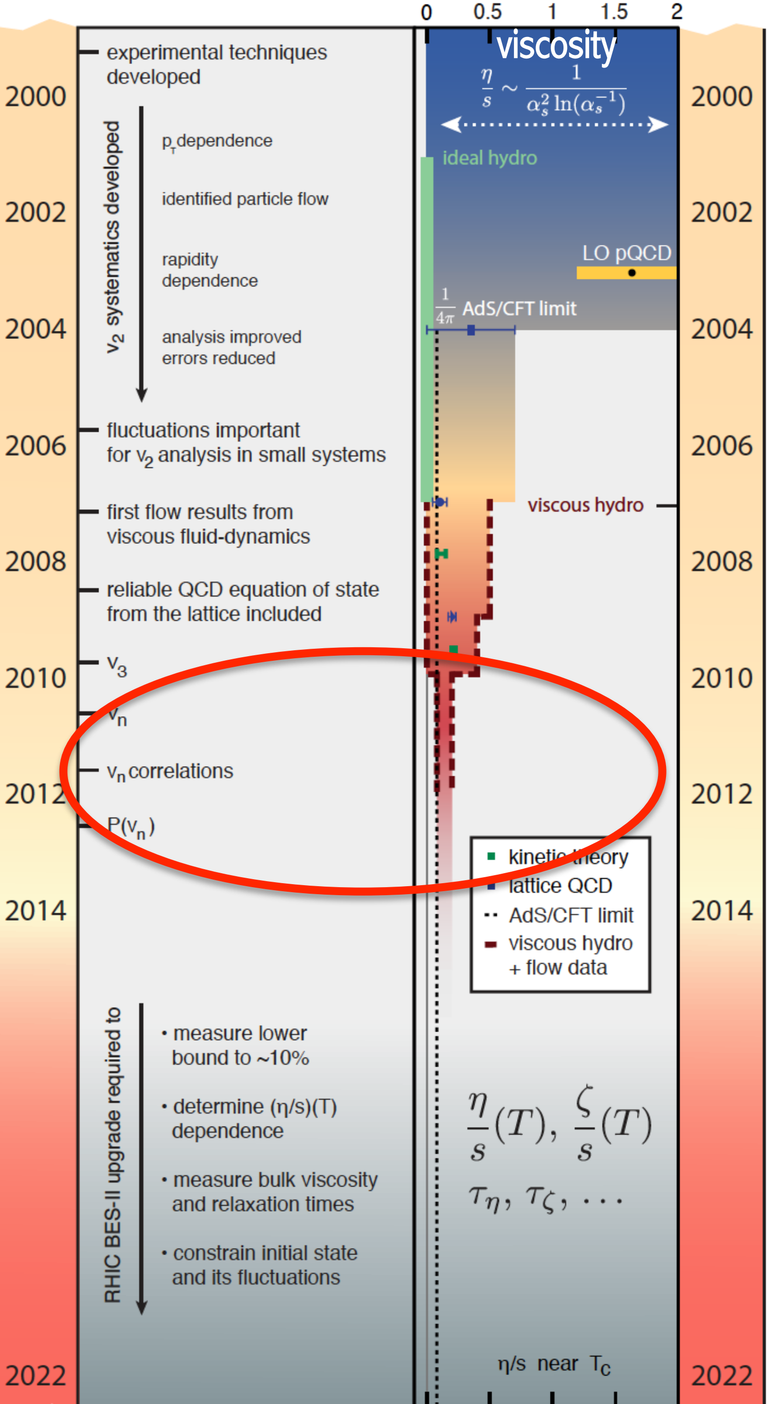


Staig & Shuryak, PRC (2011)

None of the models reproduce the correct shapes:

- No peak at n=3
- Too large for n> 6

A very promising new challenge -> new findings and knoweledge



From NSAC White Paper

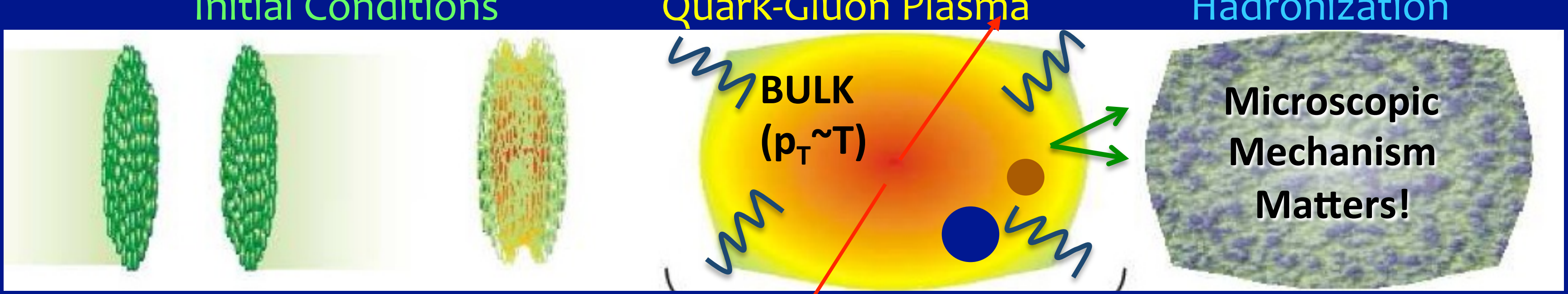
<u>KEY QUESTIONS</u>

- $\eta/s(T)$
- V_n, $P(v_n)$ revealing miroscopic details?
- we see the QGP of the lQCD? EoS and η,ζ
- Is there a bulk viscosity?
- We will costraint the initial state: CGC, Glauber, Quantum YG?

The various Probes

Going from $p_T \approx$ 1 a 500 Λ_{QCD} and $m_q \approx$ 1/20 a 20 Λ_{QCD}

Initial Conditions — Quark-Gluon Plasma — Hadronization



CGC (x<<1)
Gluon saturation?

MINIJETS
(p_T>>T,Λ_{QCD})

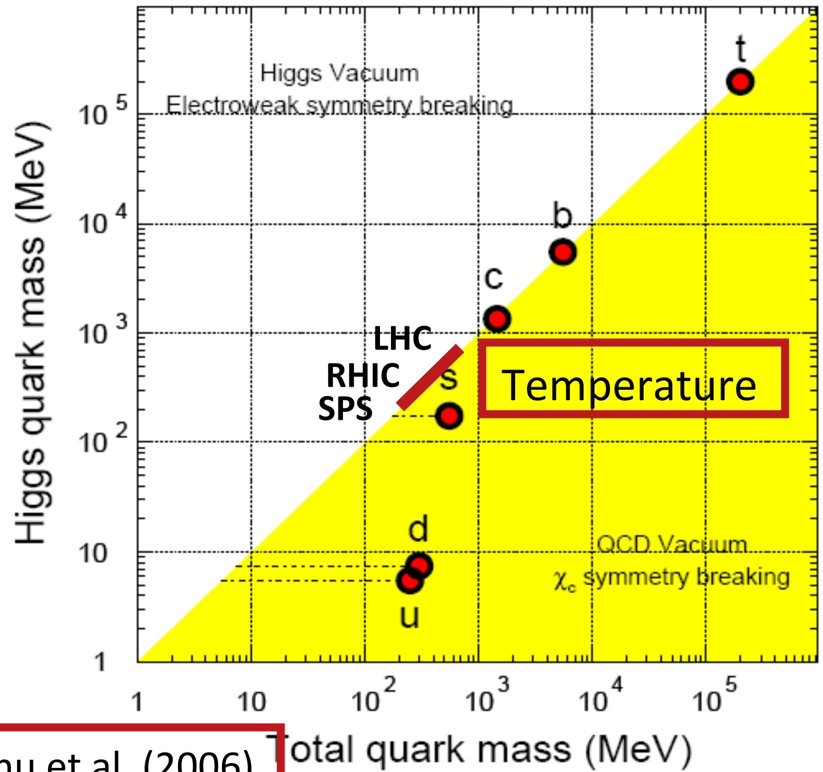
Heavy Quarks
(m_q>>T,Λ_{QCD})

+ photons &
+ dileptons

Hard Particle Production: studies in particle and hadronic physics are the baseline

- **Minijets** – perturbative QCD ***BUT*** strong Jet-Bulk "talk"
- **Heavy Quarks** – Brownian motion (?) ***BUT*** strongly dragged by the Bulk
- **Quarkonia** – Are suppressed or regenerated

Heavy Quark



Zhu et al. (2006)

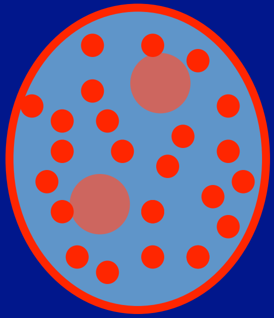
What does it mean Heavy?

Specific of Heavy Quark

- $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD processes (out of equil.)
- $m_{c,b} >> T_0$ no thermal production
- $\tau_{eq} > \tau_{QGP} >> \tau_{q,g}$ carry more information
- $m >> T \rightarrow q^2 << m^2$ transport reduced to Brownian motion
- $q_0 << |\vec{q}|$ Concept of potential V(r) <-> lQCD

Ideas about Heavy Quarks before RHIC

1) $m_Q >> m_q$ HQ not dragged by the expanding medium:

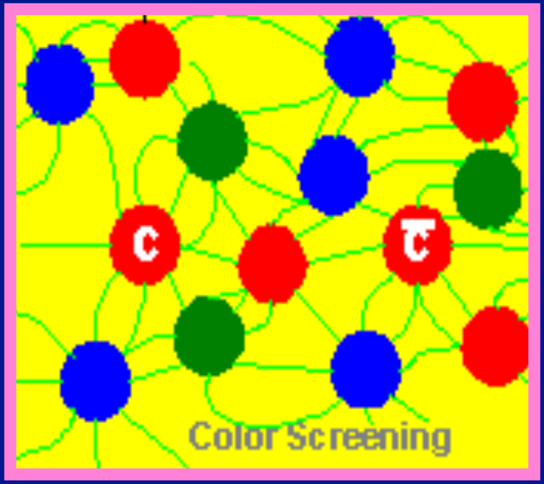


- *spectra close to the pp one*
- *small elliptic flow v_2*

2) $m_Q >> \Lambda_{QCD}$ provide a better test of jet quenching:

- *Color dependence: $R_{AA}(B/D/h)$ - q/g=4/9 Casimir factor*
- *Mass dependence: $R_{AA}(B/D/h)$ - "dead"cone*

3) $\bar{Q}Q$ Quarkonium dissoved by charge screening: Thermometer



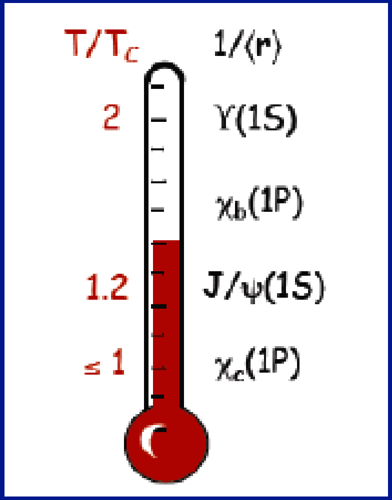
$$V \approx -\alpha_{eff} \frac{e^{-m_D r}}{r}$$

dissociation

$$r_{Q\bar{Q}} \geq \frac{1}{m_D} \approx \frac{1}{gT}$$

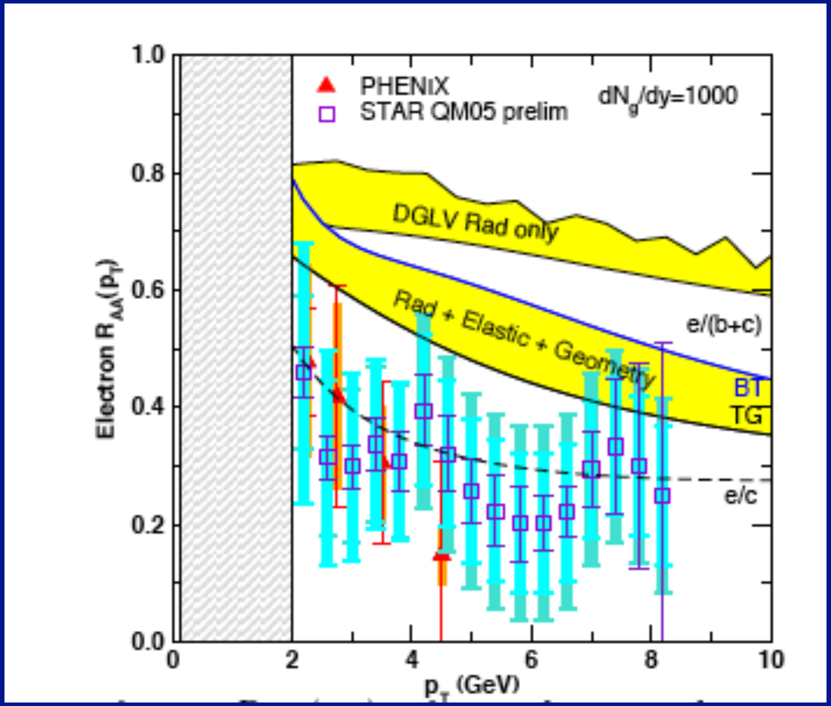
χ_c, J/Ψ, χ_b, Υ, ...

More binding -> smaller radius
-> higher temperature of suppression



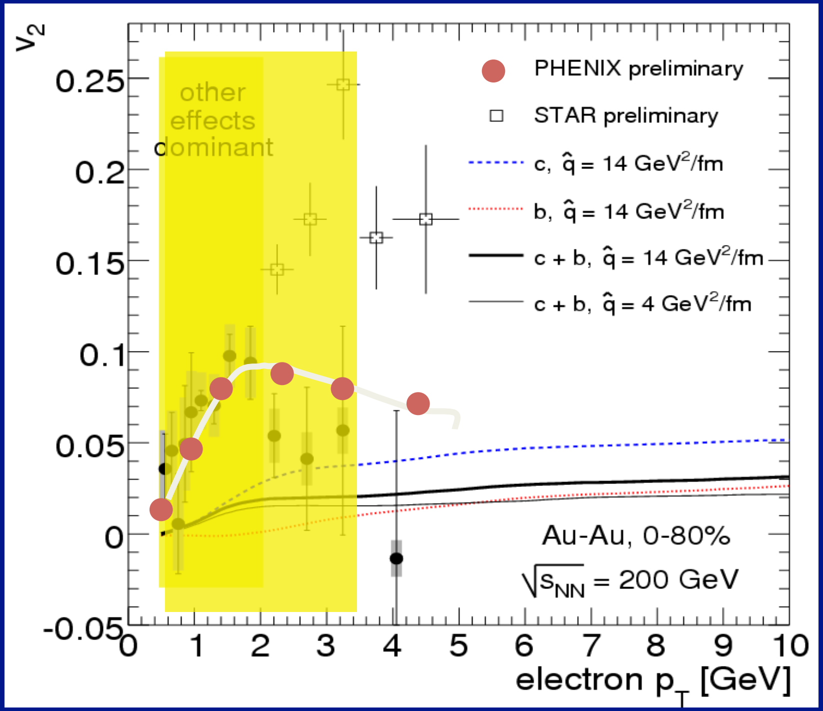
Problems with ideas 1 & 2

Strong suppression



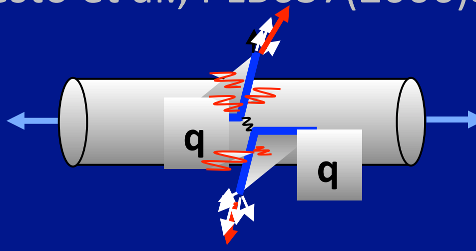
S. Wicks et al. (QM06)

Large elliptic Flow



N. Armesto et al., PLB637(2006)362

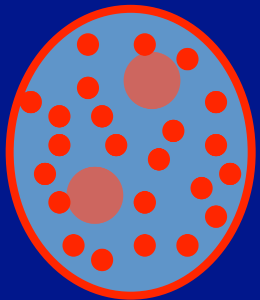
- Radiative energy loss not sufficient
- Charm seems to flow like light quarks



<u>Heavy Quark strongly dragged by interaction with light quarks</u>

pQCD does not work may be the real cross section is a K factor larger

Charm dynamics with upscaled pQCD cross section

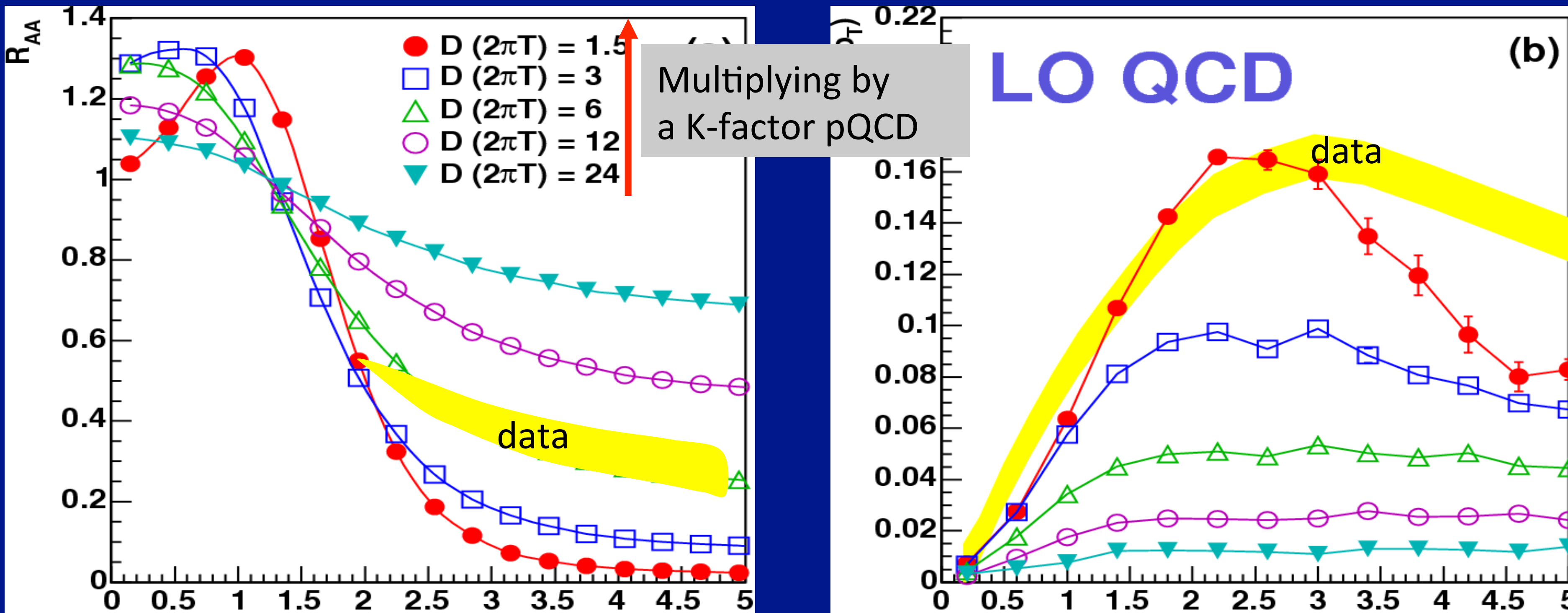


Fokker-Plank for charm interaction in a hydro bulk

Diffusion coefficient

$$D \propto \int d^3k \left| M_{g(q)c}(k,p) \right|^2 k^2$$

Scattering matrix

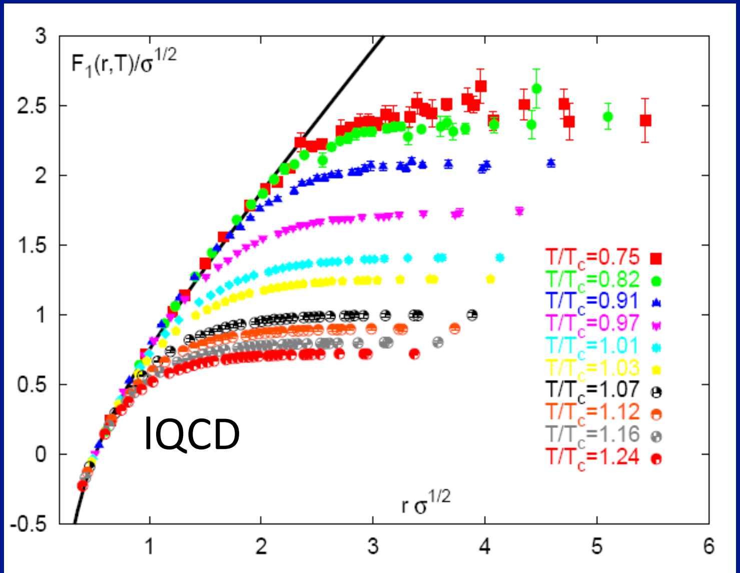


Moore & Teaney, PRC71 (2005)

It's not just a matter of pumping up pQCD cross section: too low R_{AA} or too low v_2

Solution typical of Many-Body Nuclear Theory

scattering with V_{lQCD} gives resonance states!



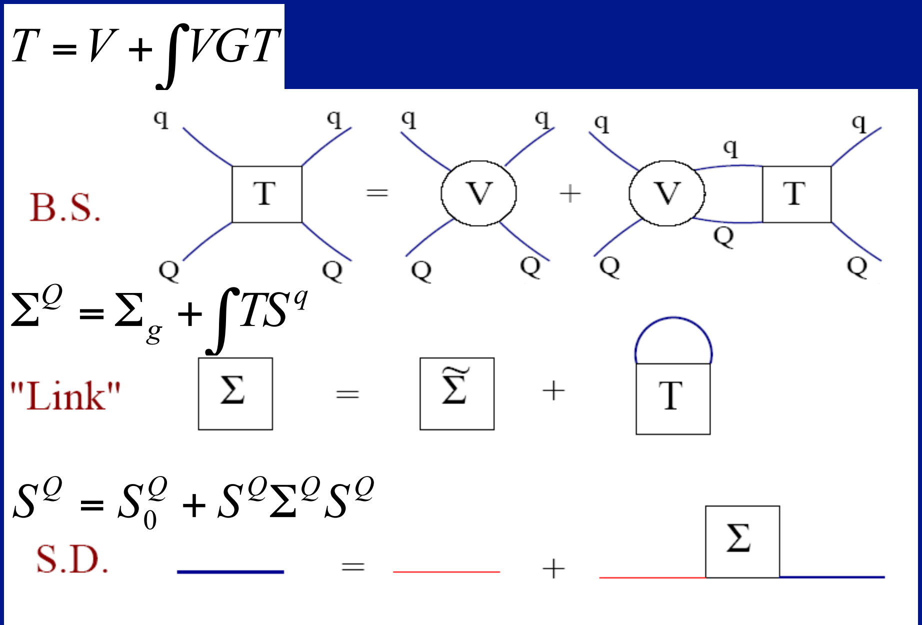
$$U_1 = F_1 - T\frac{dF_1}{dT}$$

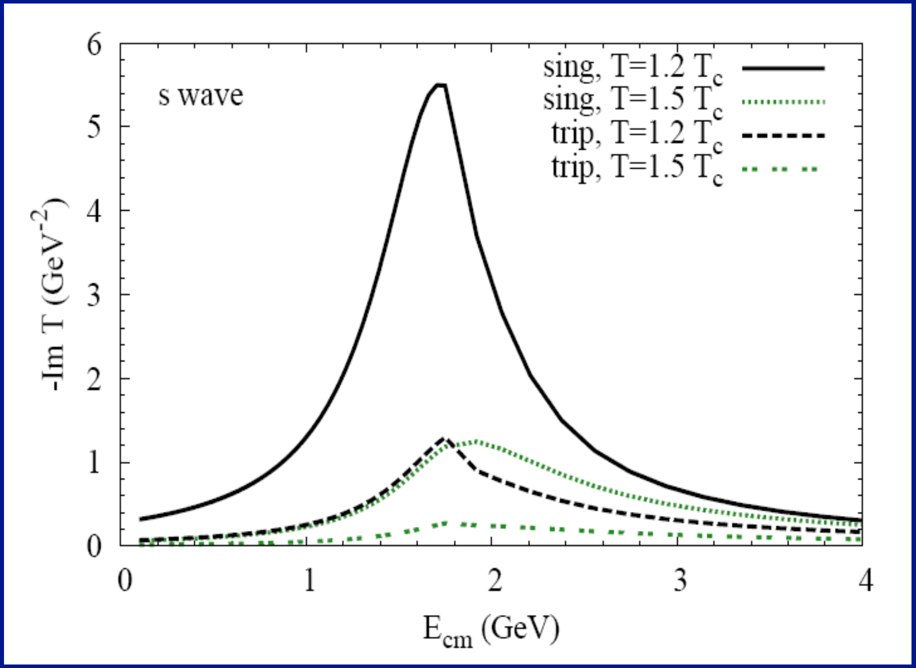
$$V_1(r,T) = U_1(r,T) - U_1(\infty,T)$$

Scattering states included:

Singlet + Octet -triplet -sextet

"Im T" dominated by meson and diquark channel



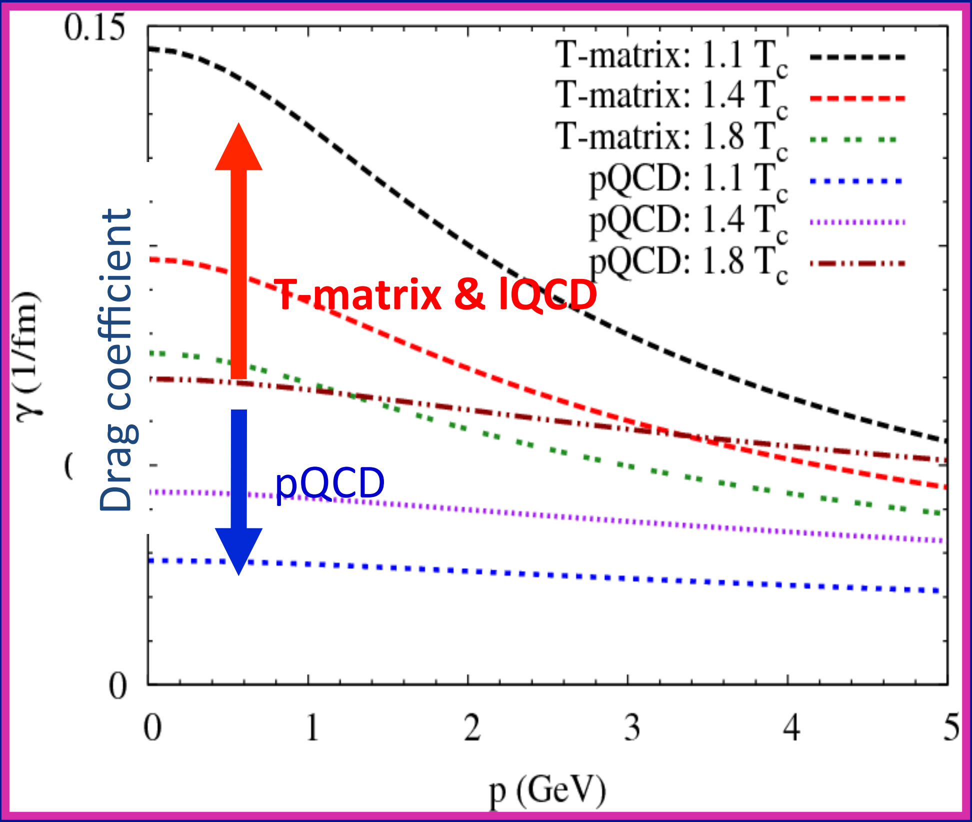


Drag Coefficient from lQCD-V(r) scattering

Opposite T-dependence of γ not a K-factor difference

$$\gamma p = \int d^3k \, |M(k,p)|^2 \, p$$

Drag coefficient
γ= D/mT



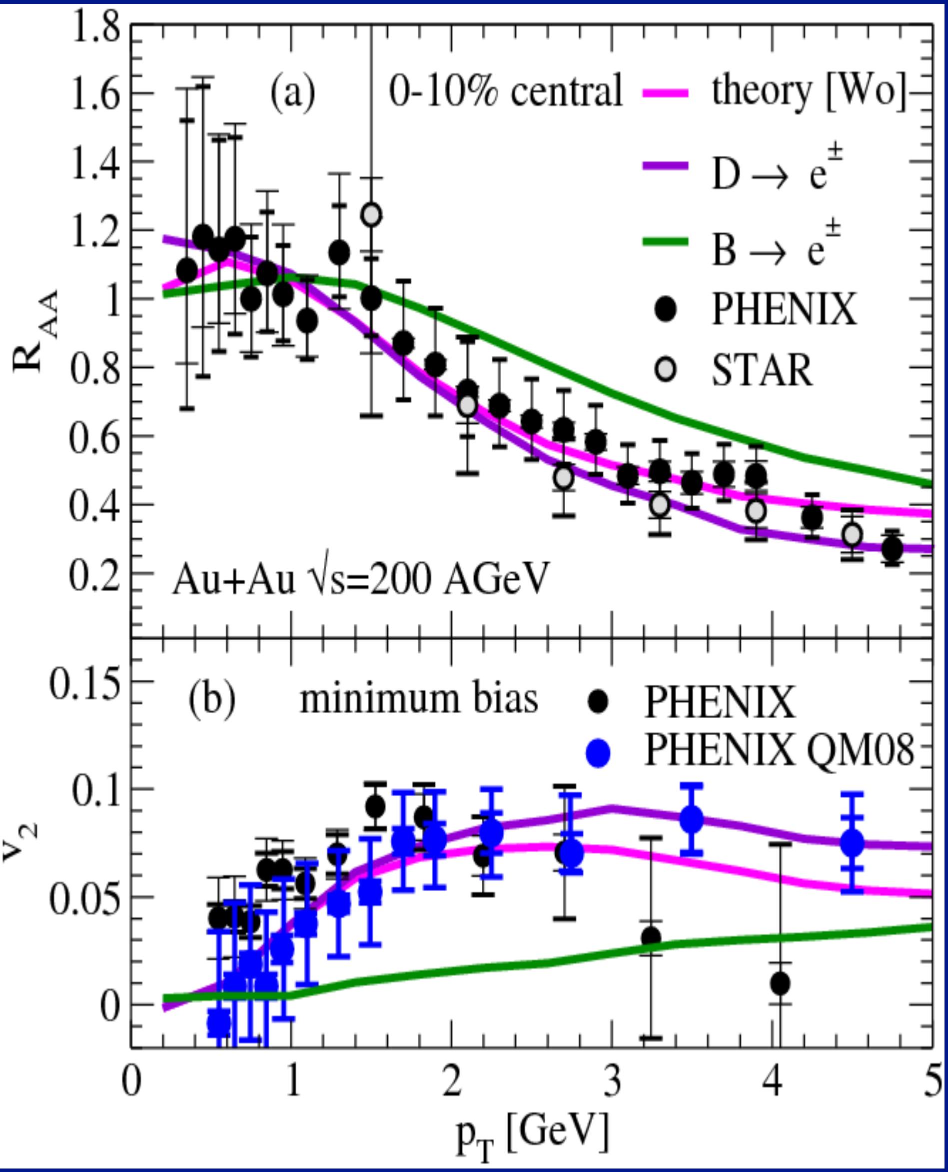
With lQCD- V(r):

-> one can expect more V_2 with the same R_{AA} because there is a stronger interaction just when v_2 is formed.

ImT increase with temperature compensates
for decreasing scatterer density

Does it solve the problem of "too low R_{AA} or too low v_2" ?

T-matrix calculation vs PHENIX data



Hees-Rapp-Greco, PRL100 (2008)

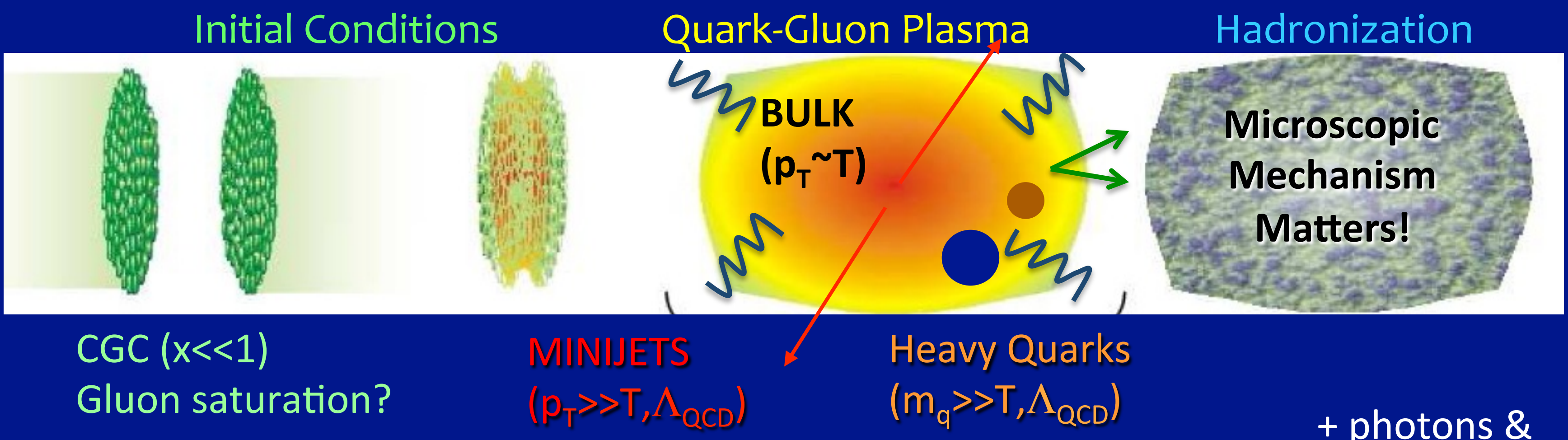
One can get both R_{AA} and v_2 with no free tunable parameters:

Essential at LHC the possibility to disentangle B and D

What happened at LHC? F. Antinori TALK

The various Probes

Going from $p_T \approx 1$ a 500 Λ_{QCD} and $m_q \approx 1/20$ a 20 Λ_{QCD}



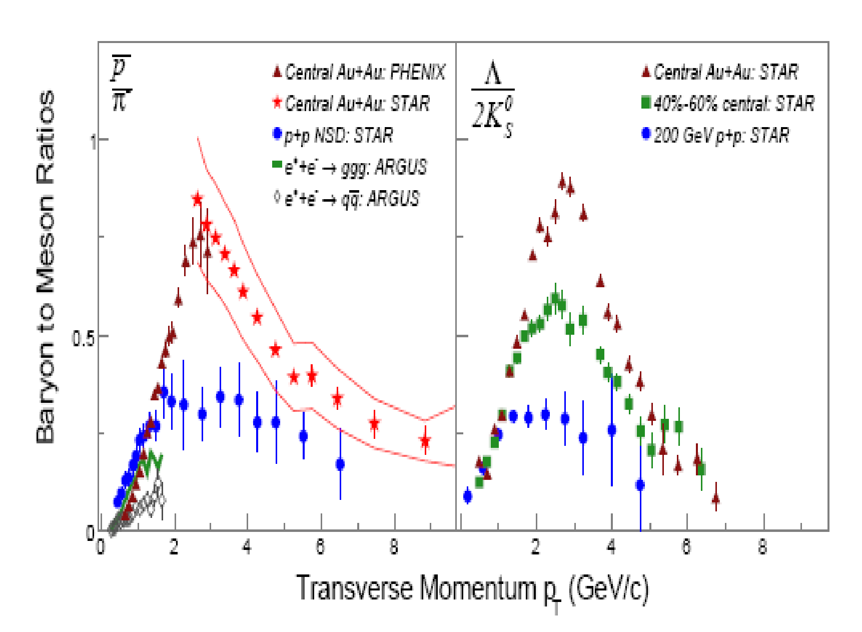
+ photons &
+ dileptons

- **Hadronization –** Can modify QGP observables?

  Is it the same as in pp?

A surprise@RHIC

Barvon/Mesons

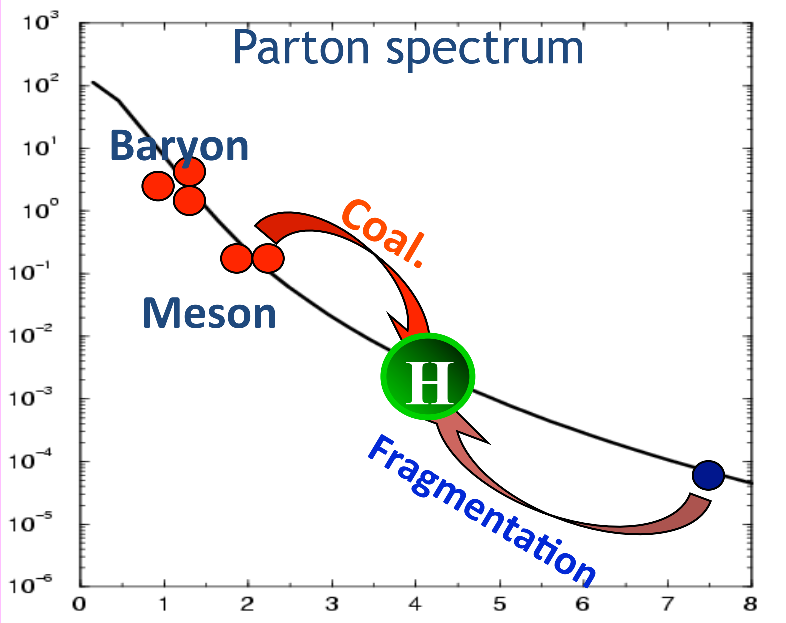


- In pp (vacuum) p/π ~ 0.3 at p_T> 2 GeV explain but Jet fragmentation

$$\frac{d^3N_H}{d^3P} = \int_\Sigma f_{q,g}(p_T) \otimes D_{q,g\to H}(z) \quad , z = P/p_T$$

- In AA Jet quenching affects anyway both baryon & meson

Coalescence/Fragm.



Greco et al., PRL 90(03)

Exploit dense quark medium

$$\frac{d^3N_H}{d^3P} = \int_\Sigma f_q(P/2) \otimes f_{\bar{q}}(P/2) \otimes \Phi_M$$

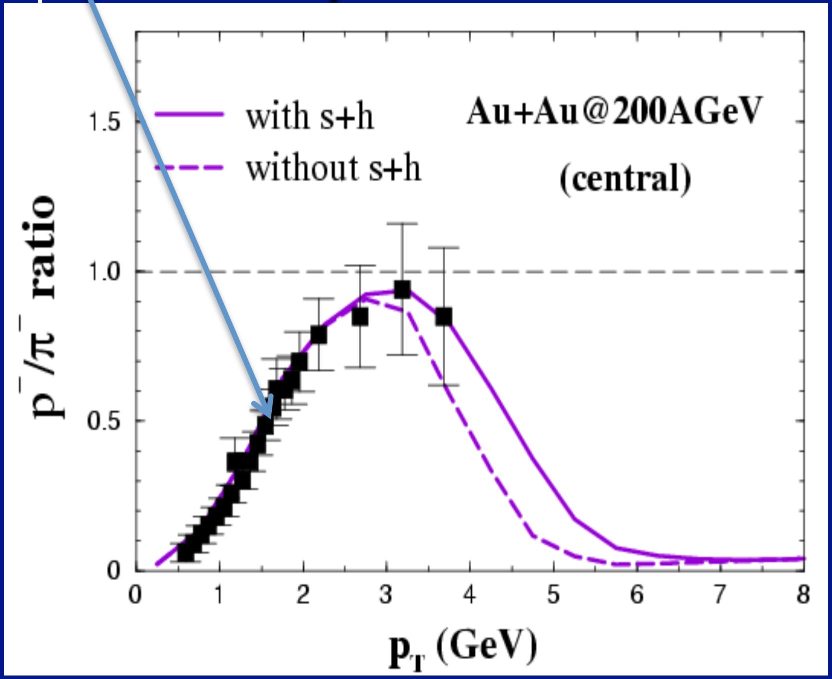
Add quark momenta

More easy to produce baryons

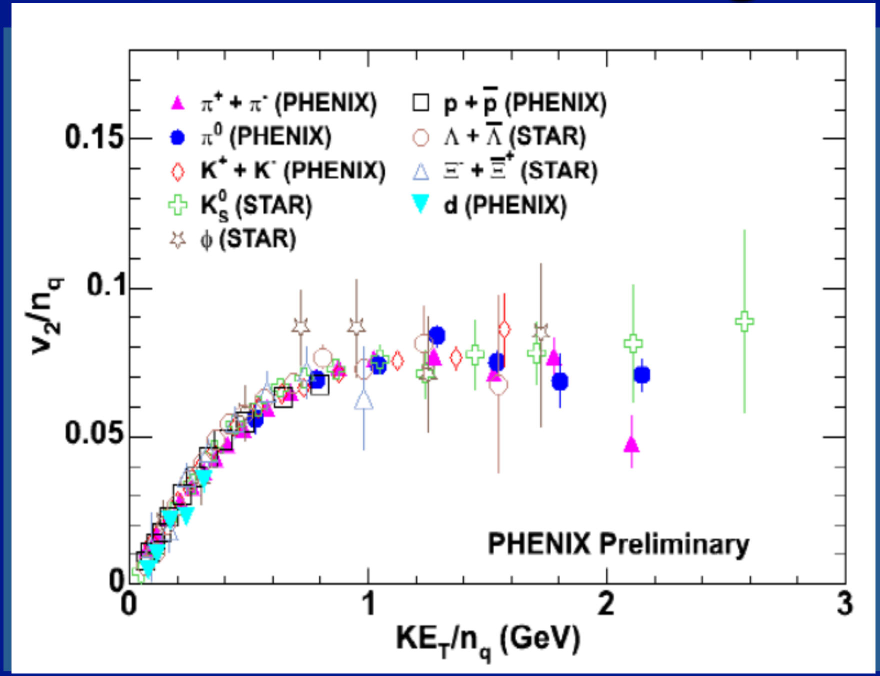
Hadronization by Coalescence

Dominance of $\rho - 2\pi$

Baryon/Mesons



Quark number scaling



Coalescence scaling

Enhancement of v_2

$$\frac{dN_q}{dp_T d\varphi} = \frac{dN_q}{dp_T}\left[1 + 2v_2\cos(2\phi)\right]$$

$$\frac{dN_H}{dp_T}(p_T) \propto \left[\frac{dN_q}{dp_T}(p_T/n)\right]^n$$

$$v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2)$$

$$v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3)$$

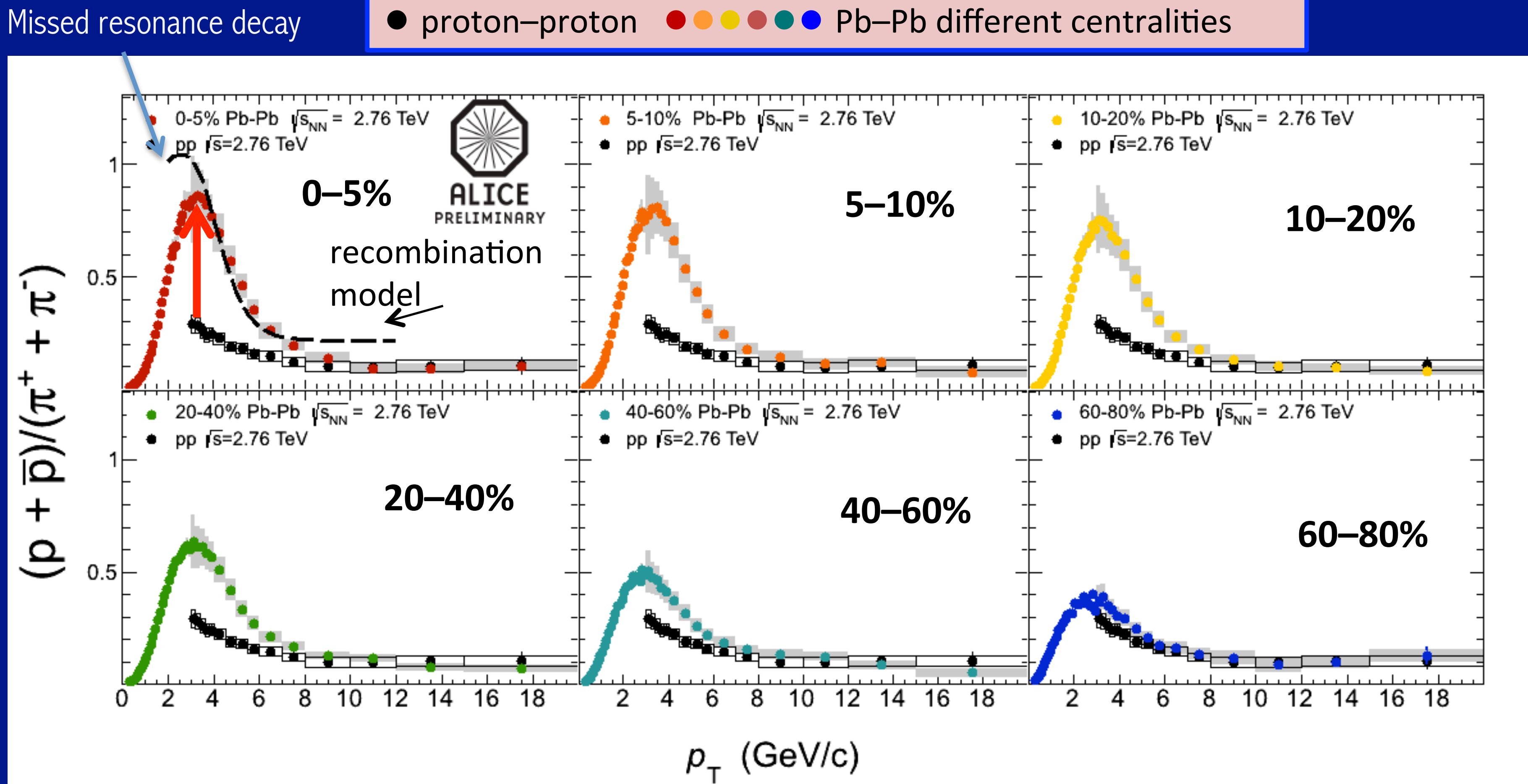
Dynamical quarks visible

Knowledge on hadronization in QCD medium

Fries-Greco-Sorensen - Ann. Rev. Part. Sci. 58, 177 (2008)

Baryon-to-meson ratio: p/π at LHC

● proton–proton ●●●●●● Pb–Pb different centralities



p/π ratio at $p_T \approx 3$ GeV/c in 0–5% central Pb–Pb collisions factor ~ 3 higher than in pp
at p_T above ~ 10 GeV/c back to the “normal” pp value

recombination – radial flow ?

R.J.Fries et al., PRL 90 202303; PR C68 044902

Summary

Ultrarelativistic HIC present a very rich physics case:

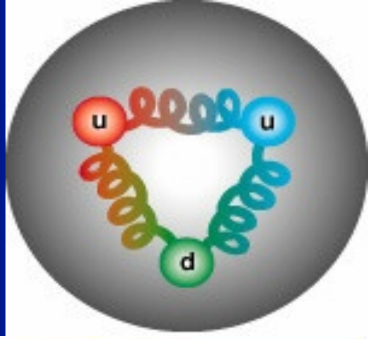
- QCD: perturbative and non-perturbative (lattice)
- Hydrodynamics and Transport Theory
- Nuclear Many-Body technicques
- Thermodynamics and Phase Transitions
- Observables shared with HIC at lower energies extended
- Information and techniques from hadronic physics
- Supersymmetric String theory at infinite coupling

Last 10 y's have seen many new results and knowledge:

➢ **perfect fluid, very opaque to jets, surprising behavior of heavy quarks, modified in medium hadronization, …**

➢ **NEXT TALKS**

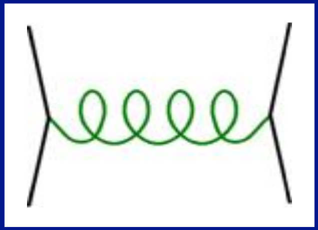
Theory of Strong Interaction: QCD

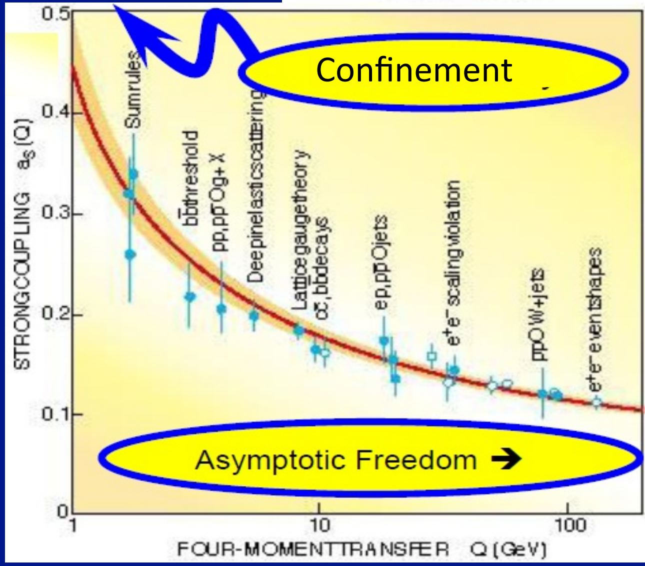


$$L_{QCD} = \sum_{i=1}^{n_f} \overline{\Psi}_i \gamma_\mu \left(i\partial^\mu - g A_a^\mu \frac{\lambda_a}{2} \right) \Psi_i - m_i \overline{\Psi}_i \Psi_i - \frac{1}{4} \sum_a F_a^{\mu\upsilon} F_a^{\mu\upsilon}$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + i f_{abc} A_b^\mu A_c^\mu$$

Similar to QED, but gluons self-interact!





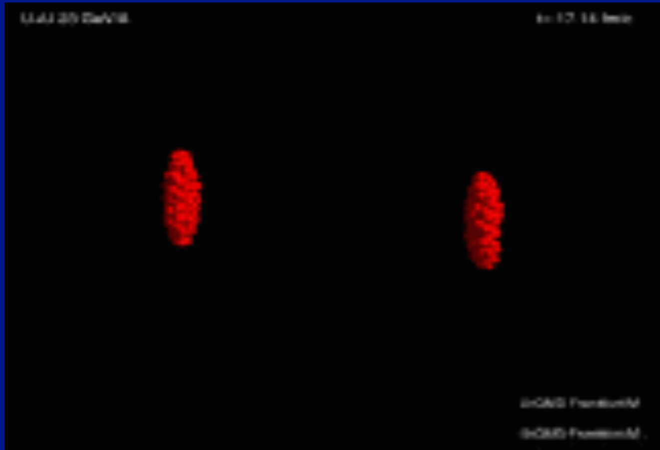
A double-fold problem studying the QGP

- QCD solvable only numerically on lattice (lQCD) and NOT for time dependent processes:

–> *Need of effective lagrangian approach*

- Information only from the transient state with non-equilibrium processes:

–> *Transport theory to simulate the HIC dynamics*



The basic relations of reference

What we should expect for a plasma of quark & gluons?
What is the EoS of the QGP?
Ideally our reference is a gas of non-interacting massless quarks and gluons!

$$n = \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T} \pm 1} = \nu \frac{\zeta(3)}{\pi^2} T^3 \qquad \nu = \begin{cases} 1 & \textit{bosons} \\ \frac{3}{4} & \textit{fermions} \end{cases}$$

where $\zeta(3) = 1.202$ (Riemann ζ function)

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{p/T} \pm 1} = \nu' \frac{\pi^2}{30} T^4 \qquad \nu' = \begin{cases} 1 & \textit{bosons} \\ \frac{7}{8} & \textit{fermions} \end{cases}$$

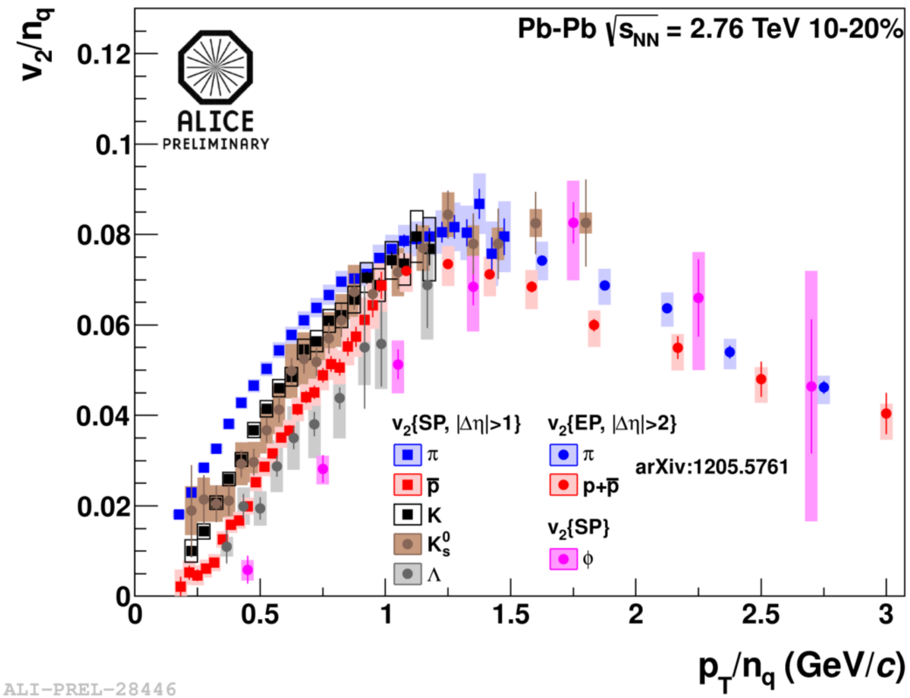
pressure: $p = \frac{\epsilon}{3}$

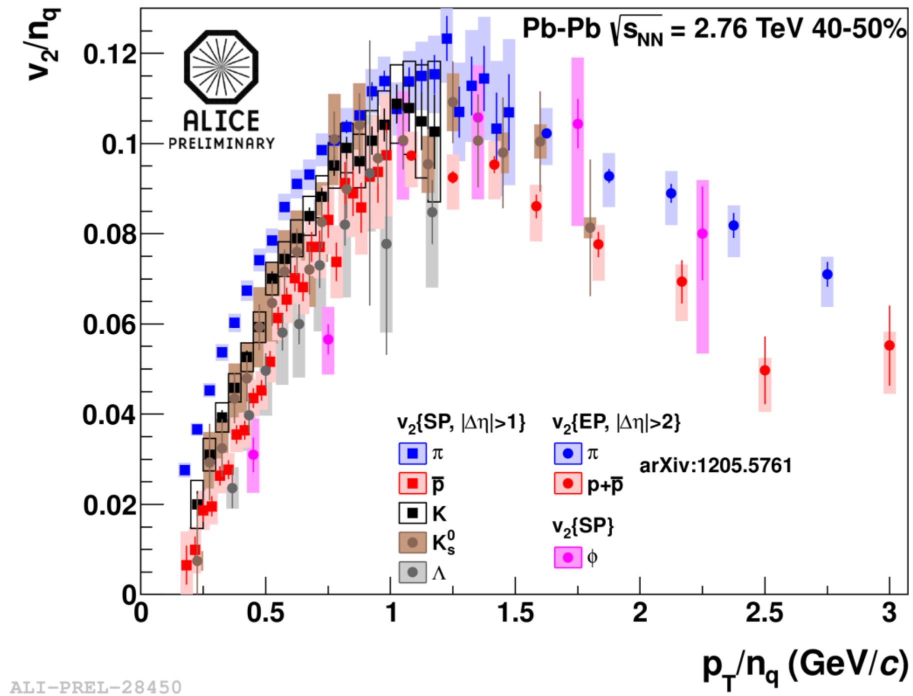
In other words the reference is the Stefan-Boltzmann law for black-body

entropy density: $Ts = \epsilon + P = \frac{4}{3}\epsilon \implies s = \frac{4}{3}\frac{\epsilon}{T} = 2\nu' \frac{\pi^2}{45} T^4$

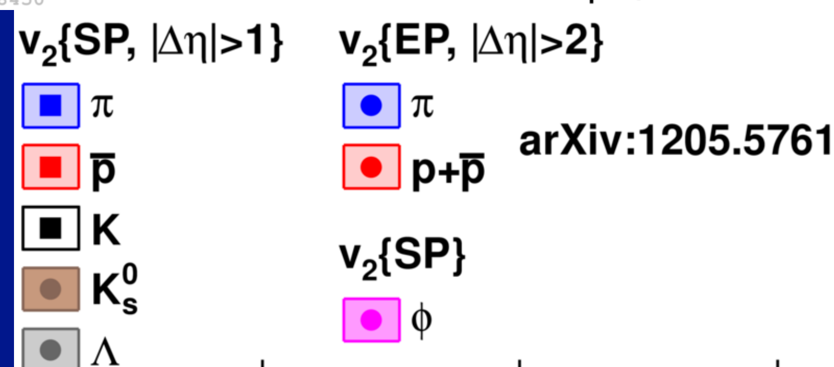
All should be multiplied by degrees of freedom
$d_{q+q} = 2*2*3*N_f = 24\text{-}30$, $d_g = 8*2$

Identified-particle v_2





v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
ϕ at low p_T (<3 GeV/c) follows mass hierarchy
– at higher p_T joins mesons
overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner

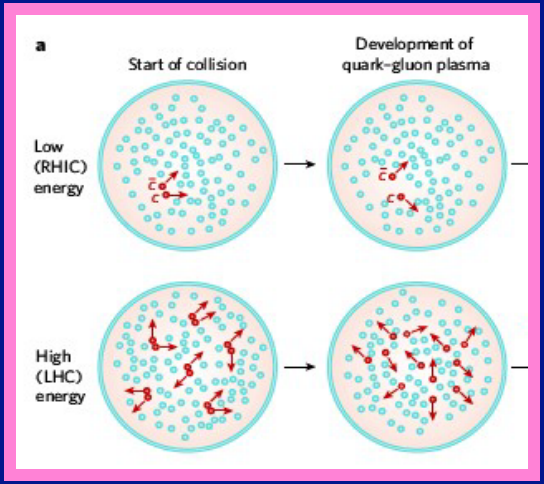


$n_q(m_T)$-scaling worse than at RHIC

$n_q(p_T)$-scaling at p_T > 1.2 GeV/c violation 10–20%

Quarkonia Suppression?

$Q\bar{Q}$ Quarkonium dissoved by charge screening: Thermometer



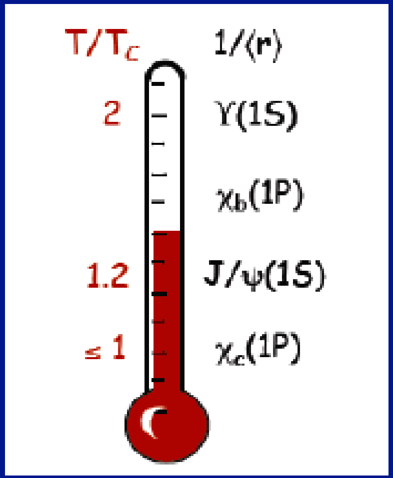
$$V \approx -\alpha_{eff} \frac{e^{-m_D r}}{r}$$

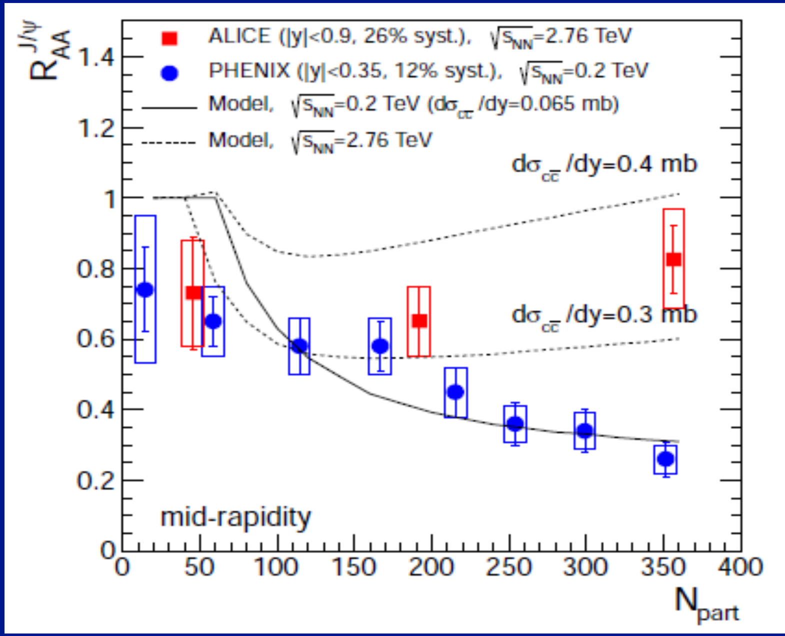
dissociation

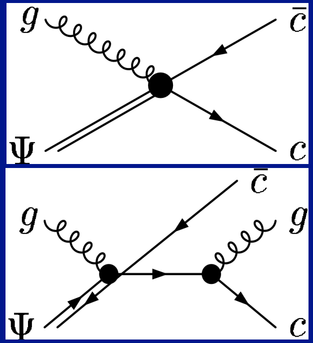
$$r_{Q\bar{Q}} \geq \frac{1}{m_D} \approx \frac{1}{gT}$$

χ_c, J/Ψ, χ_b, Υ, …

More binding -> smaller radius
-> higher temperature of suppression





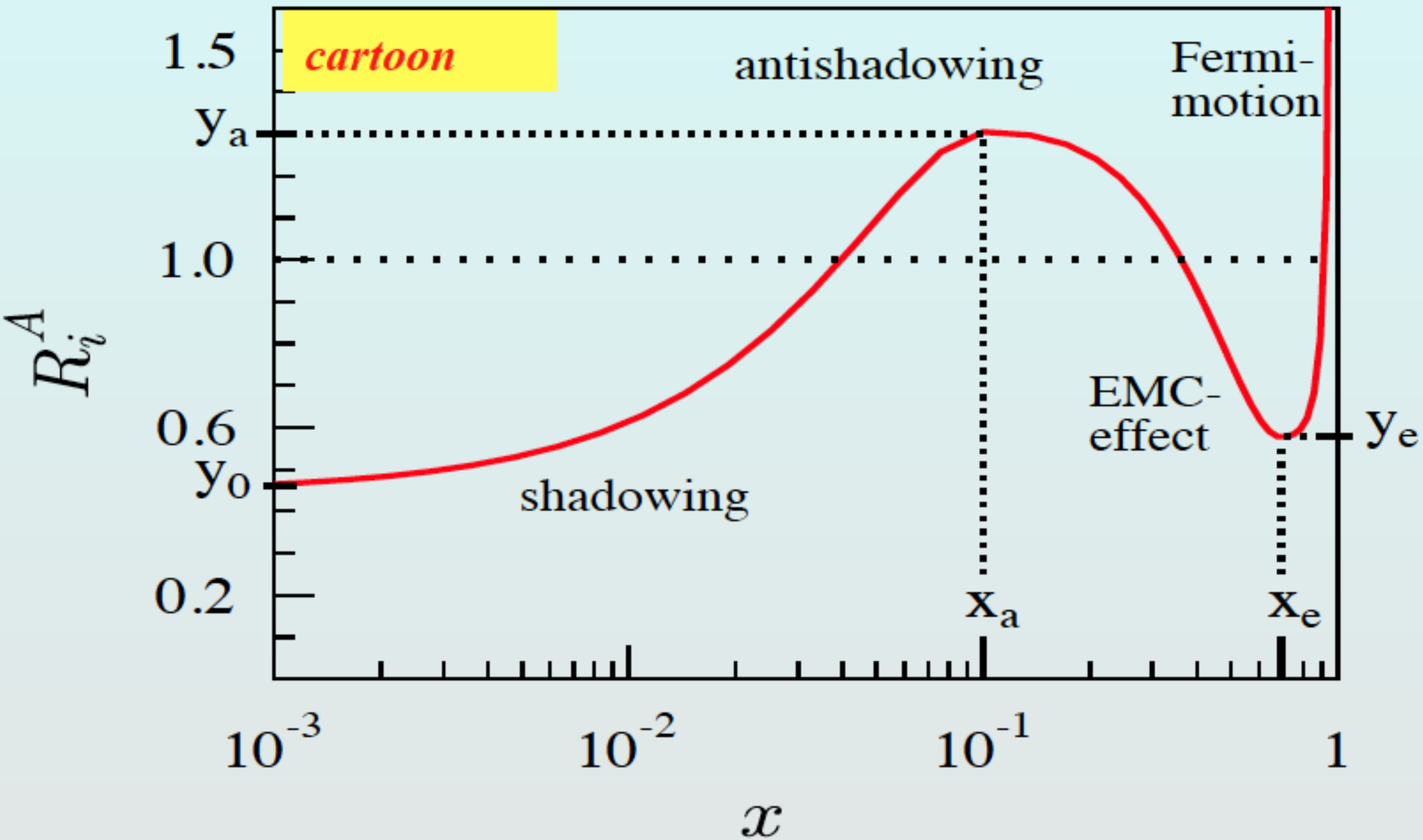


Gluon dissociation

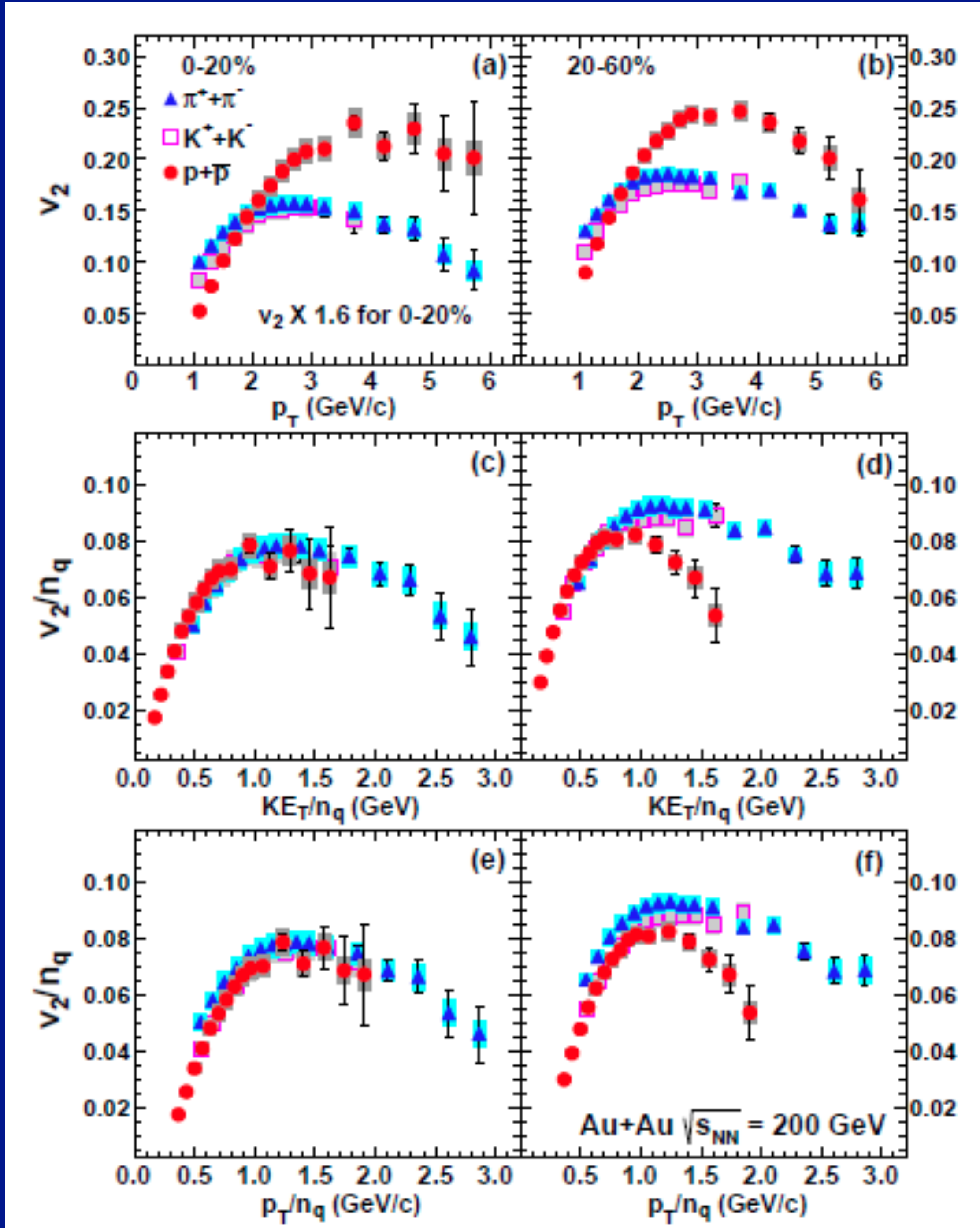
Quasi-free dissociation

$$N_{J/\psi} \propto N_{c\bar{c}}^2$$

- Scattering e Screening effects *(NuclearAstrophysics)*
- Charm shadowing in pdf *(hadronic physics)*
- Charm production cross section *(particle physics)*



cartoon
antishadowing
Fermi-
motion
EMC-
effect
shadowing
1.5
y_a
1.0
0.6
y_0
0.2
y_e
x_a
x_e
10^-3
10^-2
10^-1
1
x
R_i^A



0-20%
(a)
$\pi^+ + \pi^-$
$K^+ + K^-$
$p + \bar{p}$
v_2 X 1.6 for 0-20%
v_2
p_T (GeV/c)
20-60%
(b)
p_T (GeV/c)
(c)
v_2/n_q
KE_T/n_q (GeV)
(d)
KE_T/n_q (GeV)
(e)
v_2/n_q
p_T/n_q (GeV/c)
(f)
Au+Au $\sqrt{s_{NN}}$ = 200 GeV
p_T/n_q (GeV/c)

The modeling

HQ scattering in QGP

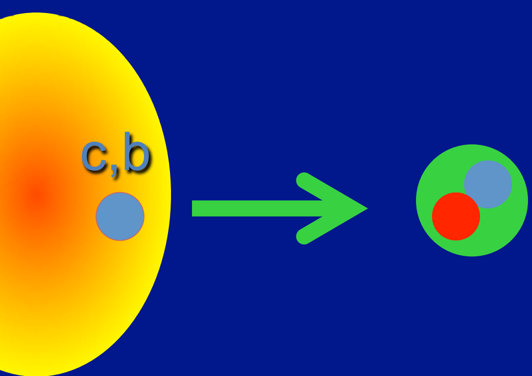
$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

T<<m_Q

From scattering matrix $|M|^2$

$$\gamma p = \int d^3k \left|M(k,p)\right|^2 p$$
$$D = \frac{1}{2}\int d^3k \left|M(k,p)\right|^2 p^2$$

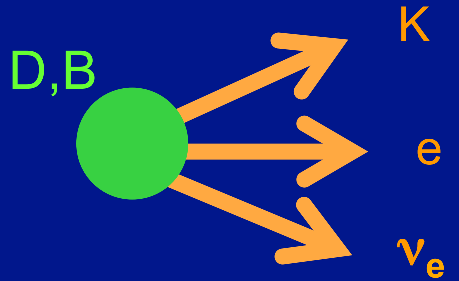
- Elastic pQCD
- **T-matrix V(r)-lQCD**



Hadronization

$$\frac{d^3 N_{D,B}}{d^3 P} = C_{D,B} \int_{\Sigma} f_{c,b} \otimes f_{\bar{q}} \otimes \Phi_M + \int_{\Sigma} f_{c,b} \otimes D_{c,b \to D,B}$$

Coalescence Fragmentation



Semileptonic decay

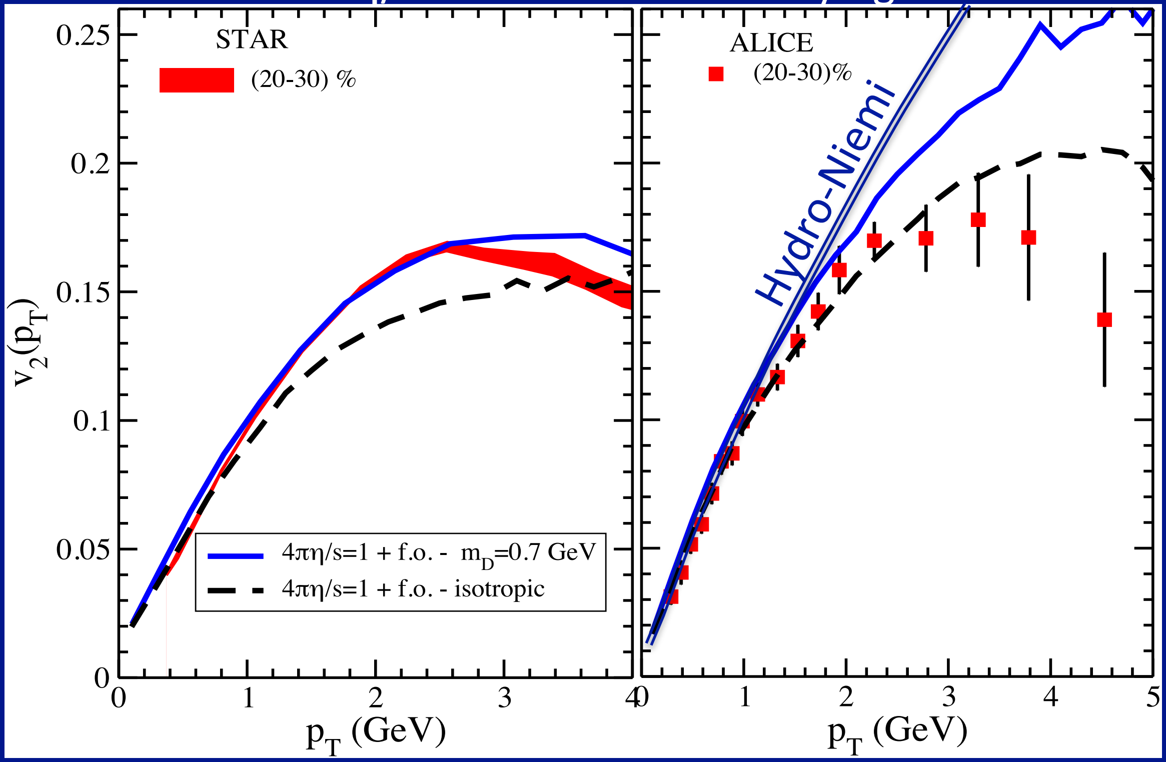
R_{AA} & v_2 of "non-photonic" e

(with B contamination ☹)

-> at LHC a new ERA started

Relevance of microscopic scale: $\sigma(\theta)$

Same η/s but different underlying σ



Out of pure hydro language!

- Microscopic details of the cross section matter at $p_T > 2$ GeV
- Larger screening mass at LHC!?
- v_n at $p_T > 2$ GeV can provide more information on the QGP micro details

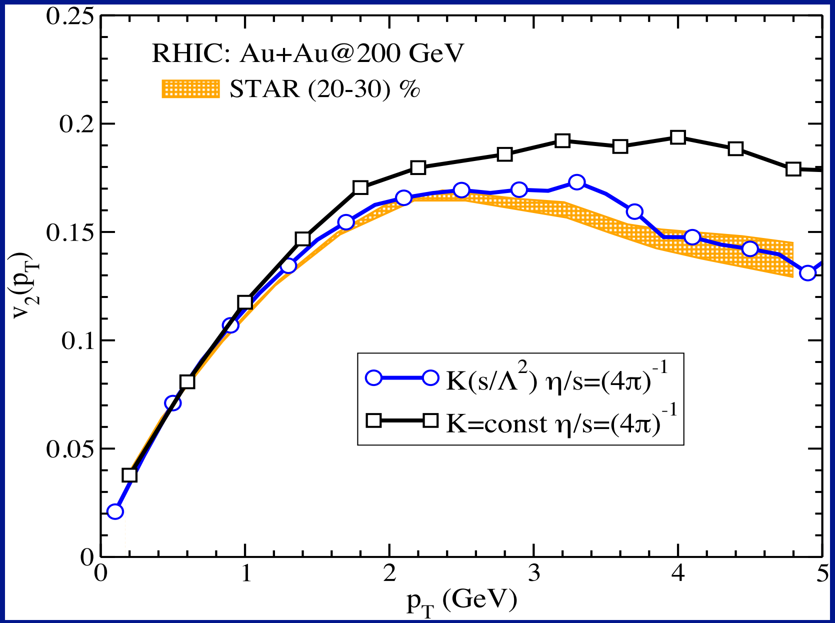
From low to high p_T

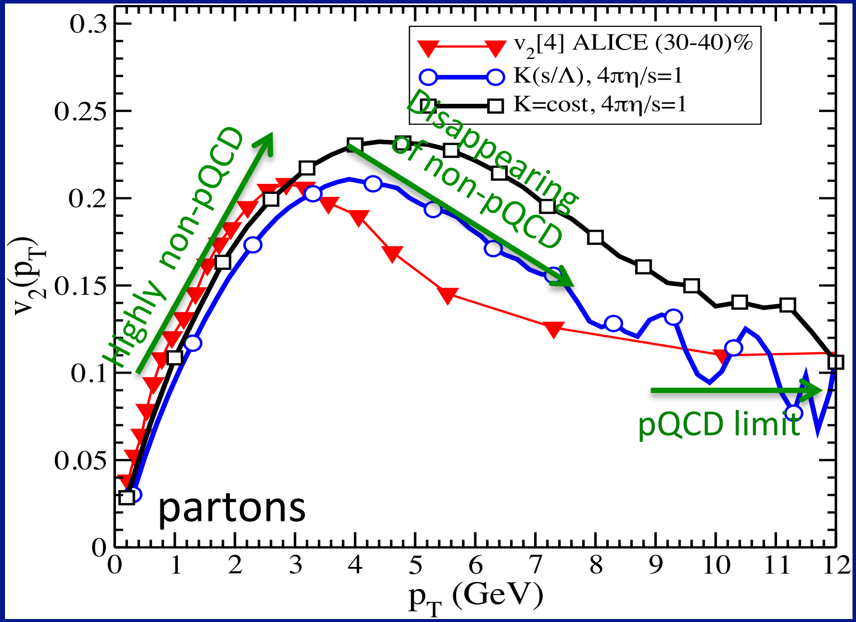
$$\sigma^*(s) = K\sigma_{pQCD}(s) >> \sigma_{pQCD}(s)$$

Takes into account the non-perturbative physics
-> $4\pi\eta/s=1$, but at all p_T !

Including the obvious: $\sigma^*(s) = K(s/\Lambda^2)\sigma_{pQCD}(s)$ $\quad K(s) = 1 + \gamma\, e^{-s/\Lambda^2}$

γ not a parameter
it is fixed by η/s)



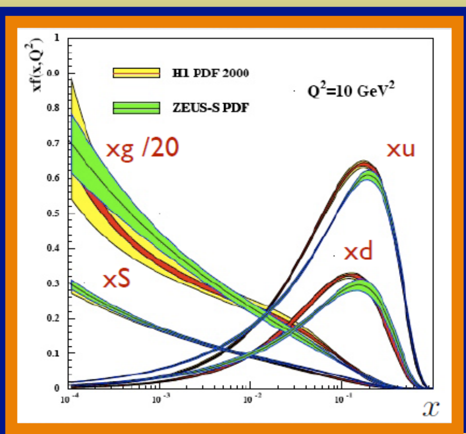


Only approach that describe $v_2(p_T)$ up to 12 GeV in a unified framework!

- Allow to extend the agreement to larger p_T, but does not affect the low p_T

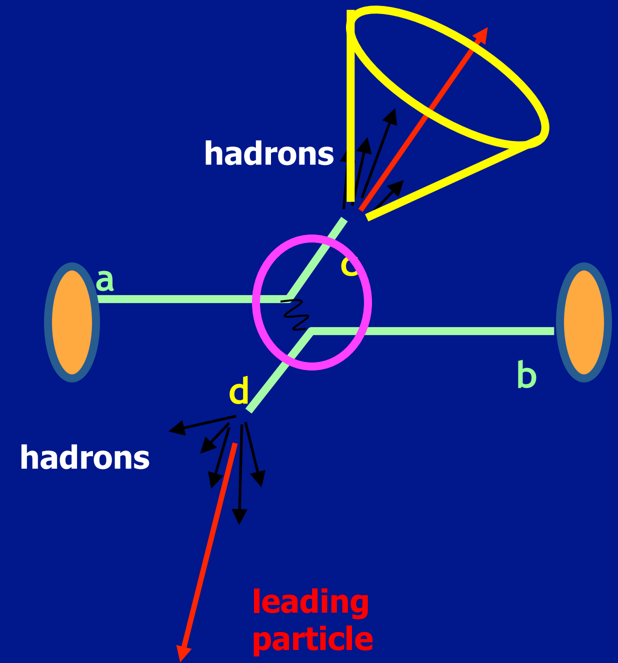
S. Plumari and VG, EPIC@LHC, AIP1422(2012)- arXiV:1110.4138 [hep-ph]

Hard Particle Production p_T,M >> Λ_{QCD} in pp



Factorization of the process in 2 steps:
- Hard collisions: pQCD
- Hadronization: npQCD

Starting point the parton distribution function



Parton Distribution Functions

Hard-scattering cross-section

Fragmentation Function

$p_{had} = z\, p_c$, $z<1$ energy needed to create quarks from vacuum

The scheme is the same for light high pt particle or for heavy quarks

$$\frac{d\sigma^h_{pp}}{dy\, d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c}$$

$\langle k^2_T \rangle$=1.8 GeV^2 is necessary

AA: Hard Particle Production $p_T, M \gg \Lambda_{QCD}$

$$\frac{dN^h_{AB}}{dy\,d^2p_T} = T_{AA}(b) K_{NLO} \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

$$p_c^* = p_c(1-\varepsilon)$$

$$z_c^* = z_c(1-\varepsilon)$$

$$\otimes f_{a/A}(x_a,Q^2) f_{b/B}(x_b,Q^2)$$ Parton Distribution Functions

$$\otimes g(\mathbf{k}_a) g(\mathbf{k}_b)$$ Intrinsic k_T, Cronin Effect

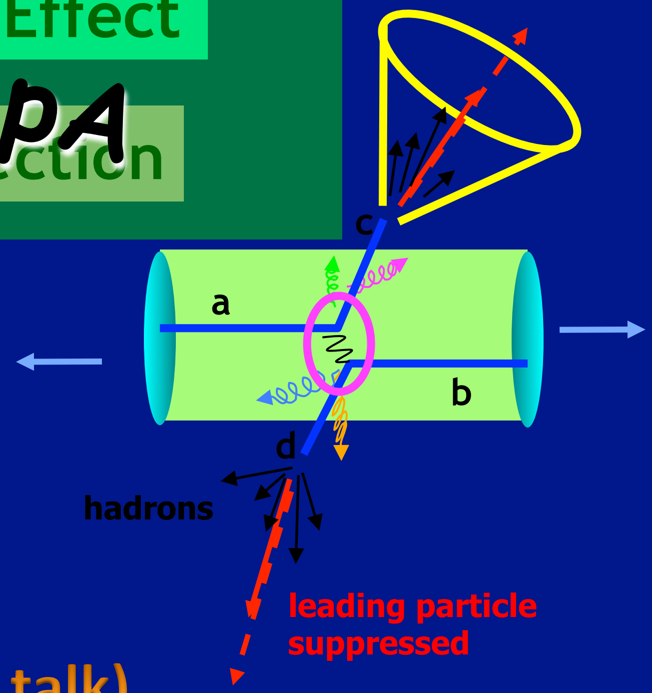
$$\otimes S_A(x_a,Q_a^2) S_B(x_b,Q_b^2)$$ Shadowing, EMC Effect

$$\otimes \frac{d\sigma}{d\hat{t}}(ab \to cd)$$ Hard-scattering cross-section

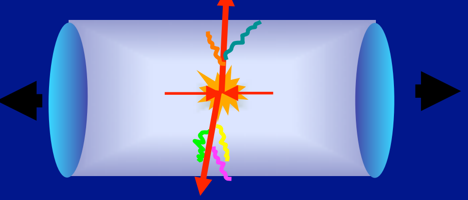
known from pp and pA

$$\otimes \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$$ Partonic Energy Loss

$$\otimes \frac{D^0_{h/c}(z_c^*, Q_c^2)}{\pi z_c}$$ Fragmentation Function



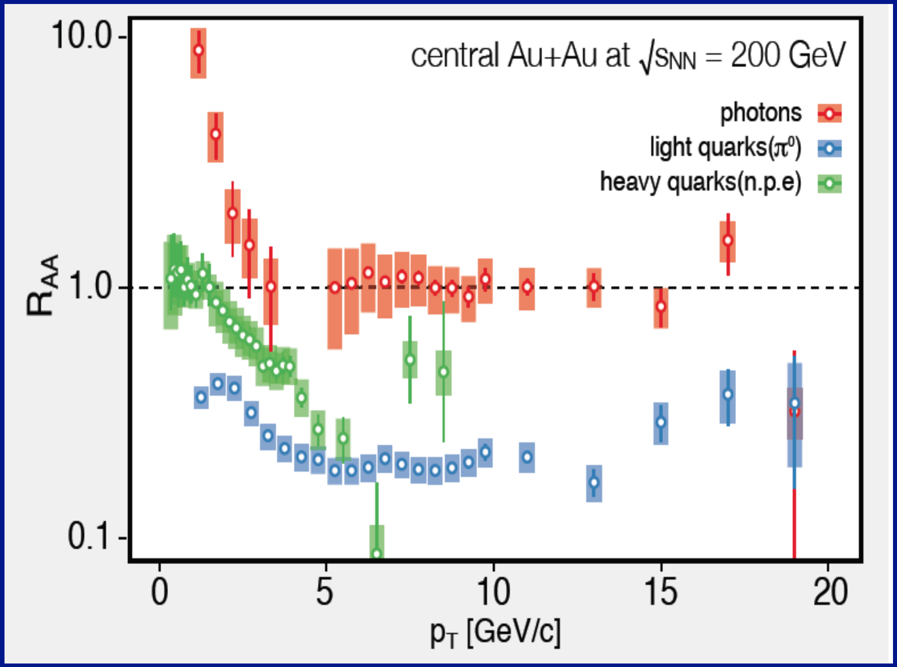
-> Strong Jet Quenching observed (Antinori's talk)

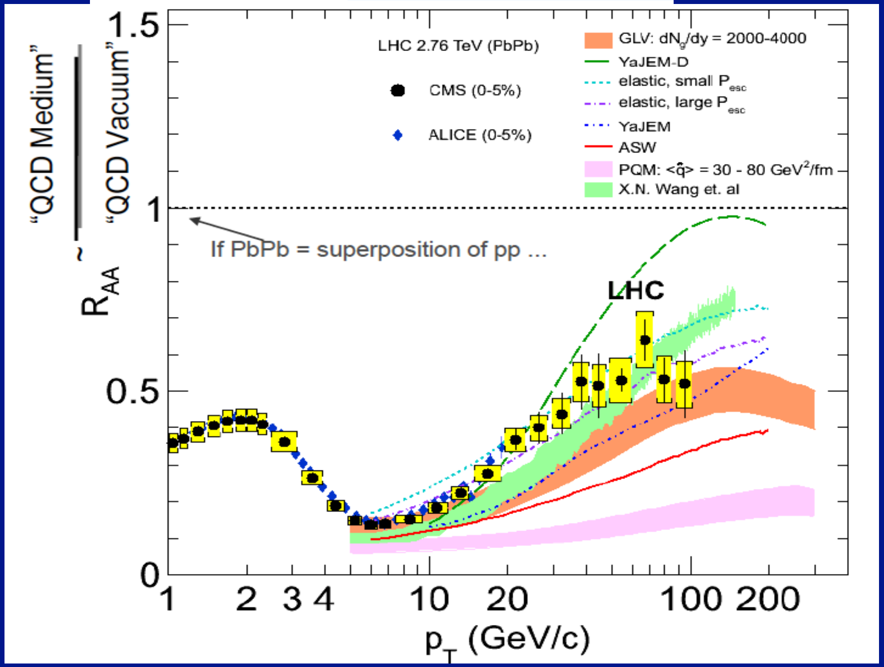


Jet Quenching

How much modification respect to pp?

$$R_{AA} = \frac{\sigma^{inel}_{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$





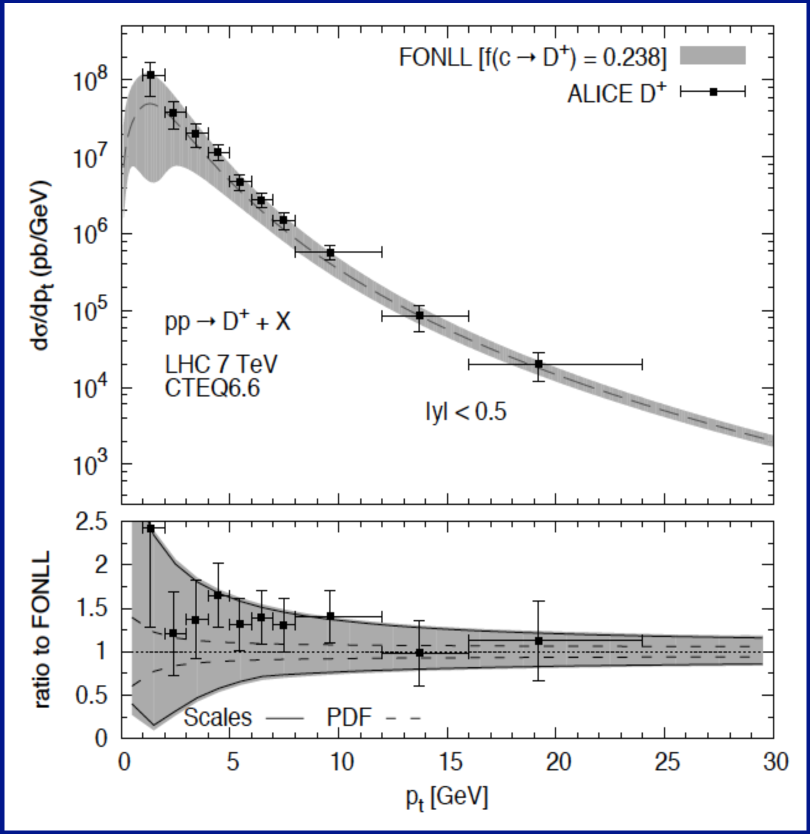
B. Jacak and B. Muller, Science 337 (2012)

❖ Jet gluon radiation observed:

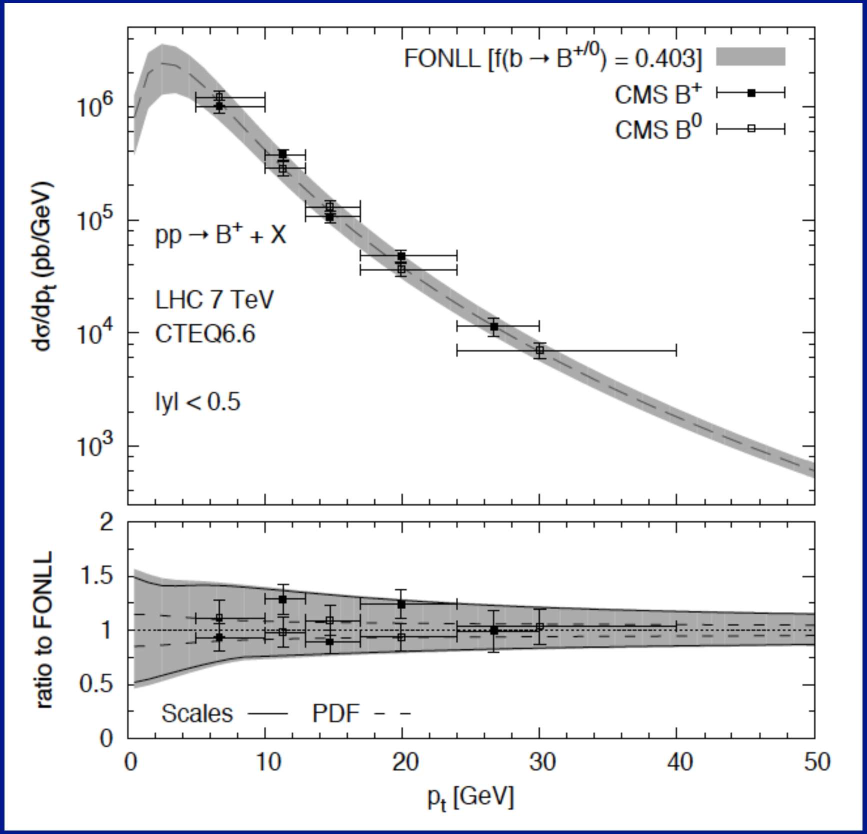
- all hadrons R_{AA} <<1 and almost flat in p_T
- photons not quenched -> suppression due to QCD
- Energy density estimated e ≈ 15 GeV/fm^3 >> ε_0 and consistent with hydro

Just an example to see how this works for heavy flavors

D meson

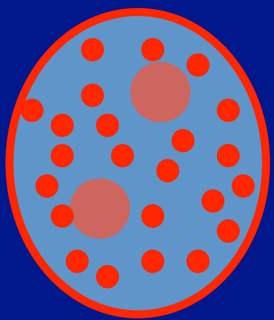


B meson



Cacciari, Frixione,Mangano, Nason, Ridolfi, JHEP (2012)

Heavy Quarks dragged by the medium?

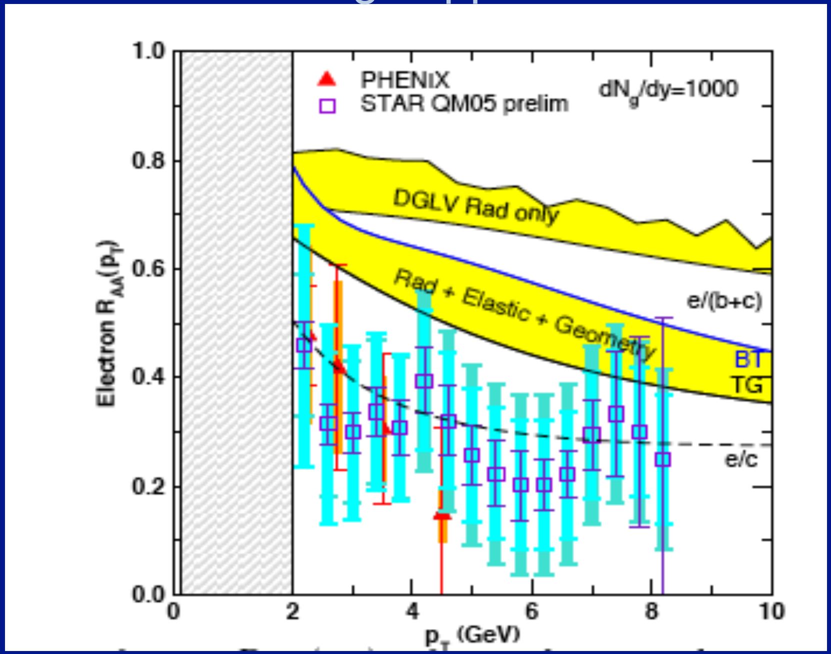


Specific of Heavy Quarks

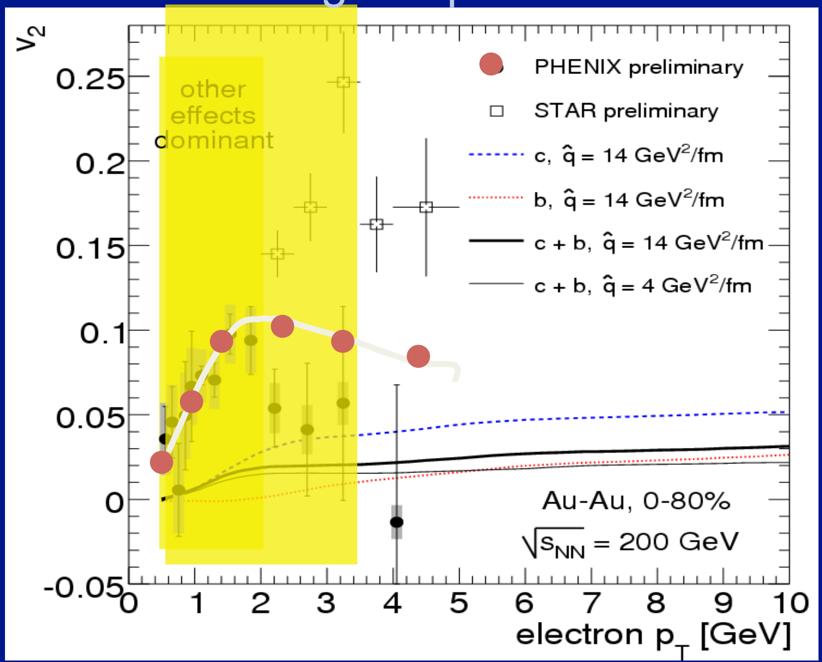
- $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD processes (out of equil.)
- $m_{c,b} >> T_0$ no thermal production
- $t_{eq} > t_{QGP} >> t_{q,g}$ non-eq. -> carry more information
- $m_{c,b} >> T$ -> $q^2 << m^2$ Brownian motion
- $q_0 << |q|$ Concept of potential V(r) <-> lQCD

Indirect measurement from semileptonic decay D(cq)->Keν came as a surprise

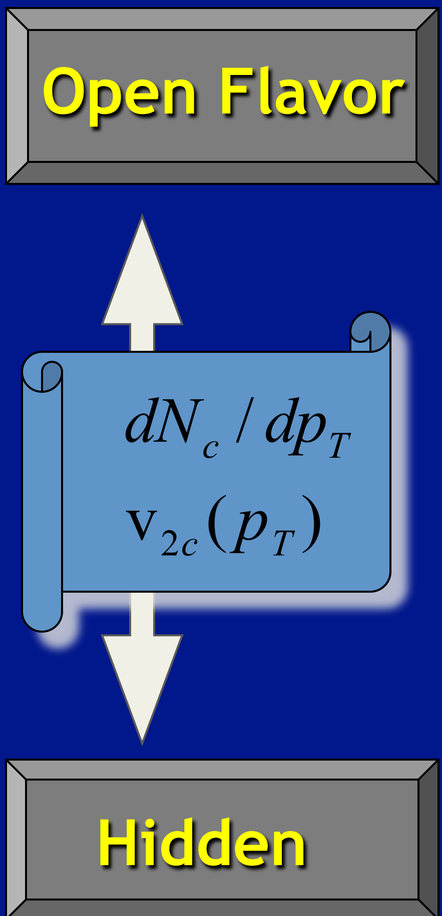
Strong suppression



Large elliptic Flow

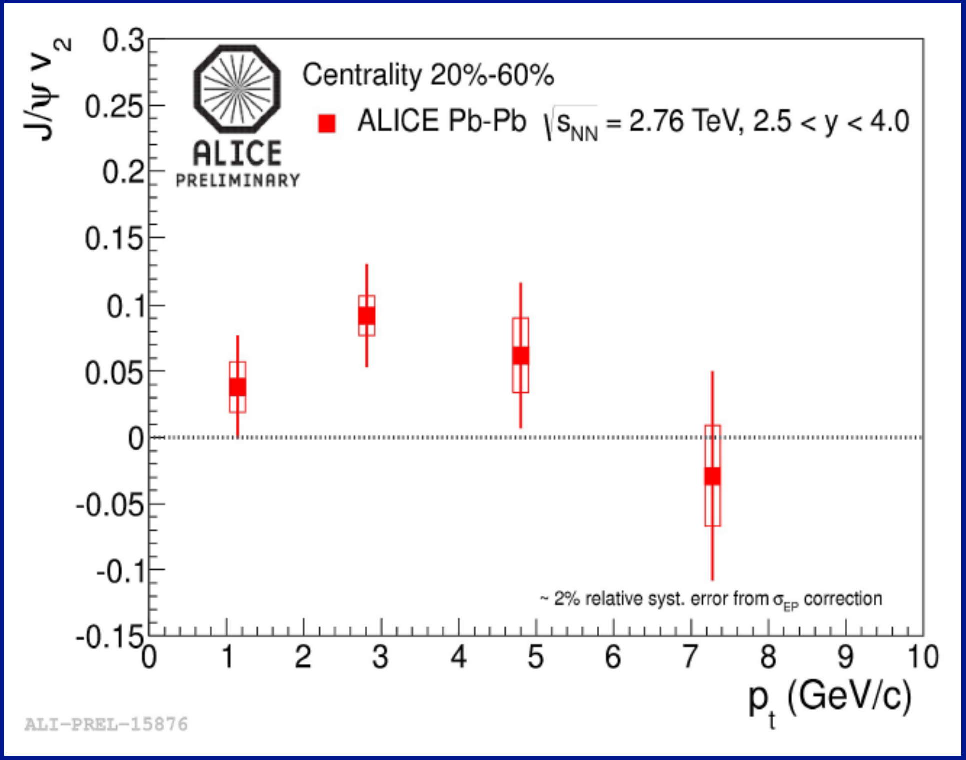


Quarkonium <–> Heavy-Quark



Greco, Ko, Rapp-PLB595(04)

❖ We can now go beyond the J/Y yield :
- the strong charm collective dynamics distinguish primordial from cc coalescence:



Leading Particle Effect

Reservoir of partons modifies hadronization

Quark-Antiquark Recombination in the Fragmentation Region

- Braaten, Jia, Mehen: Phys. Rev. Lett. 89, 122002 (2002)
- Rapp and Shuryak, Phys. Rev. D67, 074036 (2003)

$$\alpha(x) = \frac{\sigma_{D^-}(x) - \sigma_{D^+}(x)}{\sigma_{D^-}(x) + \sigma_{D^+}(x)}$$

$D^-(\bar{c}d)$

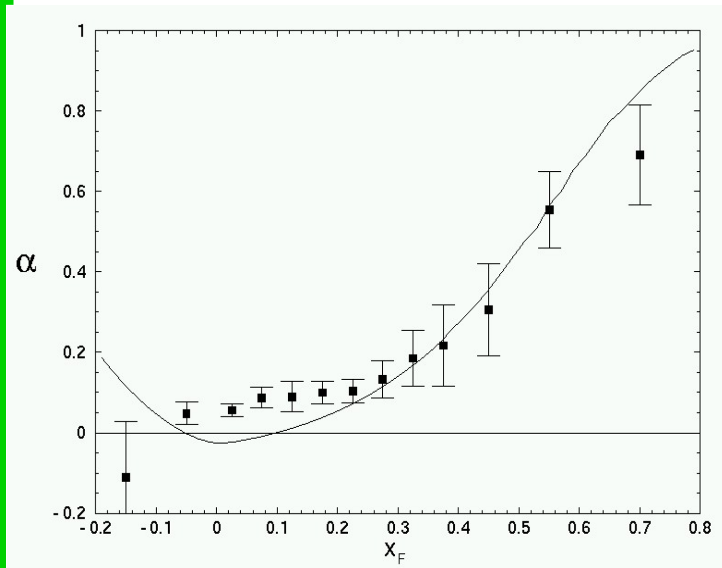
$D^+(c\bar{u})$

beam

$\pi^-(d\bar{u})$

- hard cc production;
- c recombine with d valence from π^-
–> D^- enhancement

α=0 from LO fragmentation

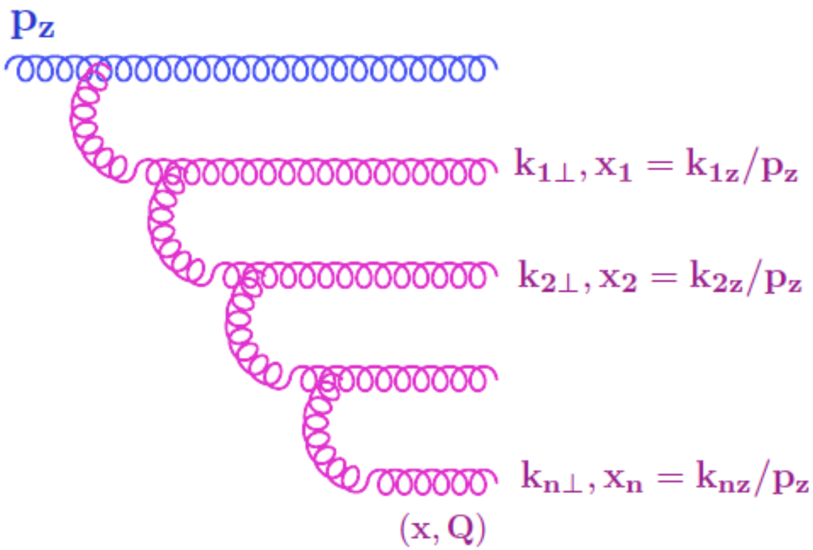


Again in the same years a similar physics to another field

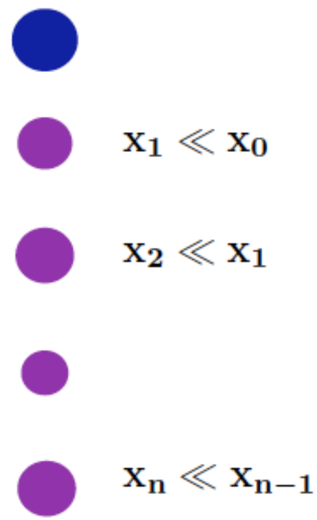
In HIC the resorvoir is the thermal bulk!

QCD evolution equations

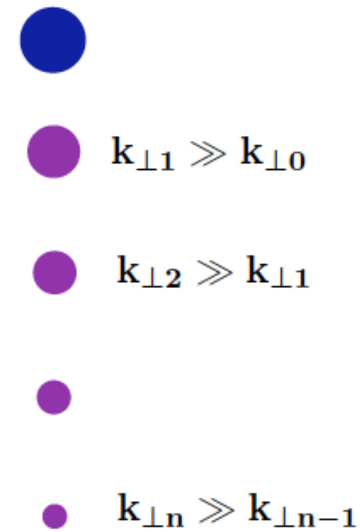
$$dP_{q/g\to g} = \frac{\alpha_s C_{F/A}}{\pi}\frac{dx}{x}\frac{d^2k_\perp}{k_\perp^2}$$



BFKL ($x \to 0$)
longitudinal momentum ordering



DGLAP ($Q^2 \to \infty$)
transverse momentum ordering



- Probability of emitting n gluons enhanced by large logarithms:

$$\mathcal{P}(n) \sim \frac{1}{n!}\left(\alpha_s \ln\left(\frac{x_0}{x}\right)\right)^n \qquad \mathcal{P}(n) \sim \frac{1}{n!}\left(\alpha_s \ln\left(\frac{Q^2}{Q_0^2}\right)\right)^n$$

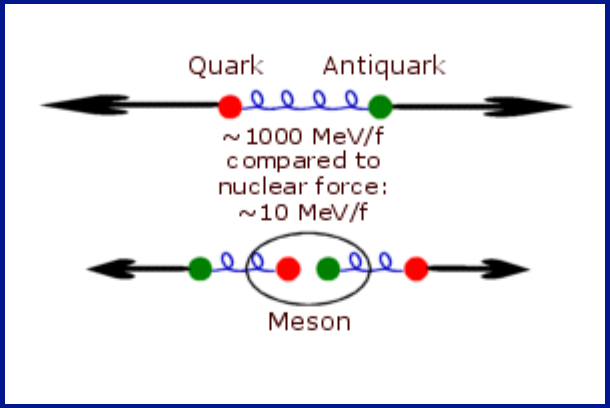
- QCD evolution equations resum large logarithmic contributions to all orders:

$$\frac{\partial \phi(x, k_\perp)}{\partial \ln(x_0/x)} \approx \mathcal{K} \otimes \phi(x, k_\perp) \qquad \frac{\partial xG(x, Q^2)}{\partial \ln(Q^2/Q_0^2)} \approx P_{gg} \otimes xG(x, Q^2)$$

"BFKL eqn" "DGLAP eqn"

Unintegrated gluon distribution: $\phi(x, k_\perp) = \dfrac{dN^g}{d\ln(x_0/x)\, d^2k_\perp}$ $\qquad xG(x, Q^2) = \int^Q d^2k_\perp \phi(x, k_\perp)$

Deconfinement from Quark-antiQuark in lQCD



Vacuum

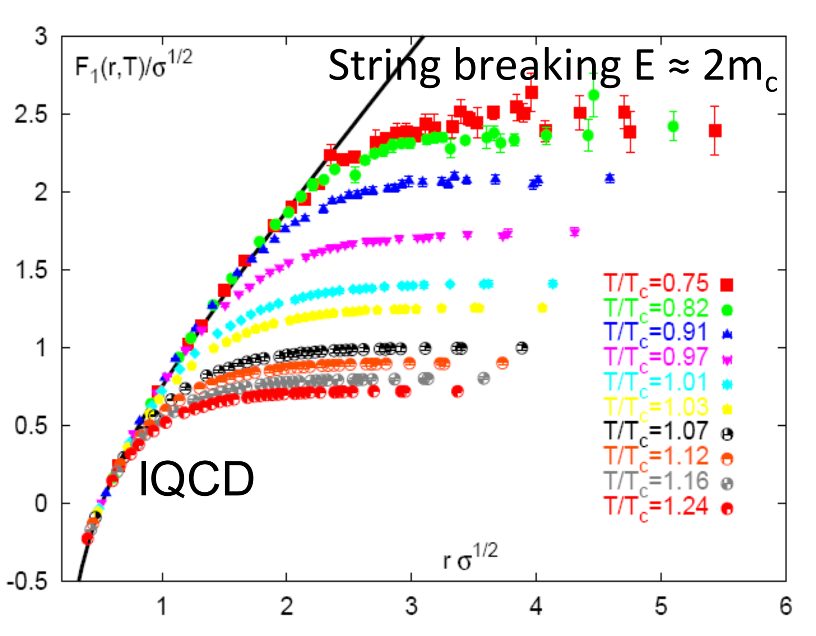
$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

We cannot observe free quarks -> qq pair creation

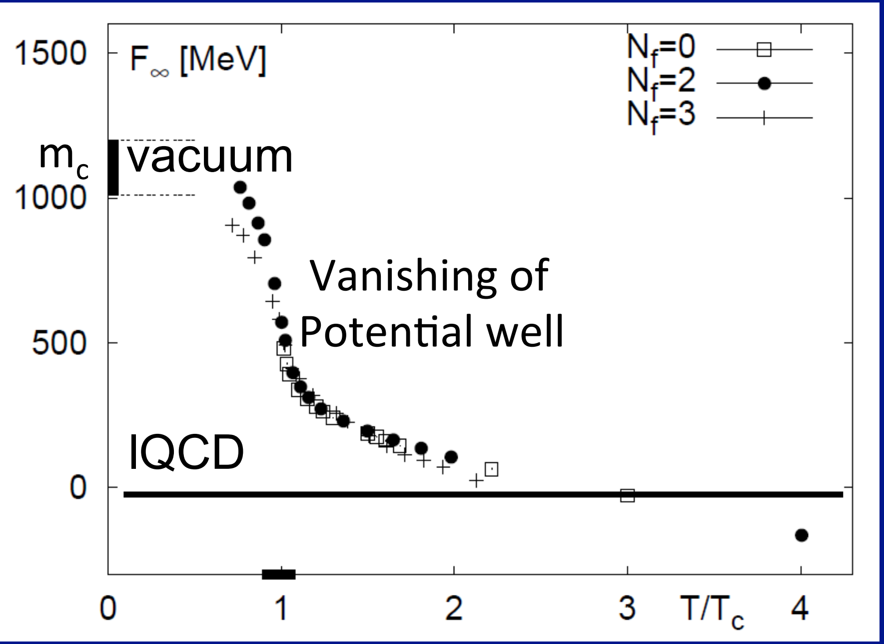
but at some Tc the drops down

-> weakly interacting gas of quarks and gluons?

Charm Quarks



Asymptotic value of V(r ->∞)



Kaczmarek et al., PoS 129,560(2004)