HEAVY IONS

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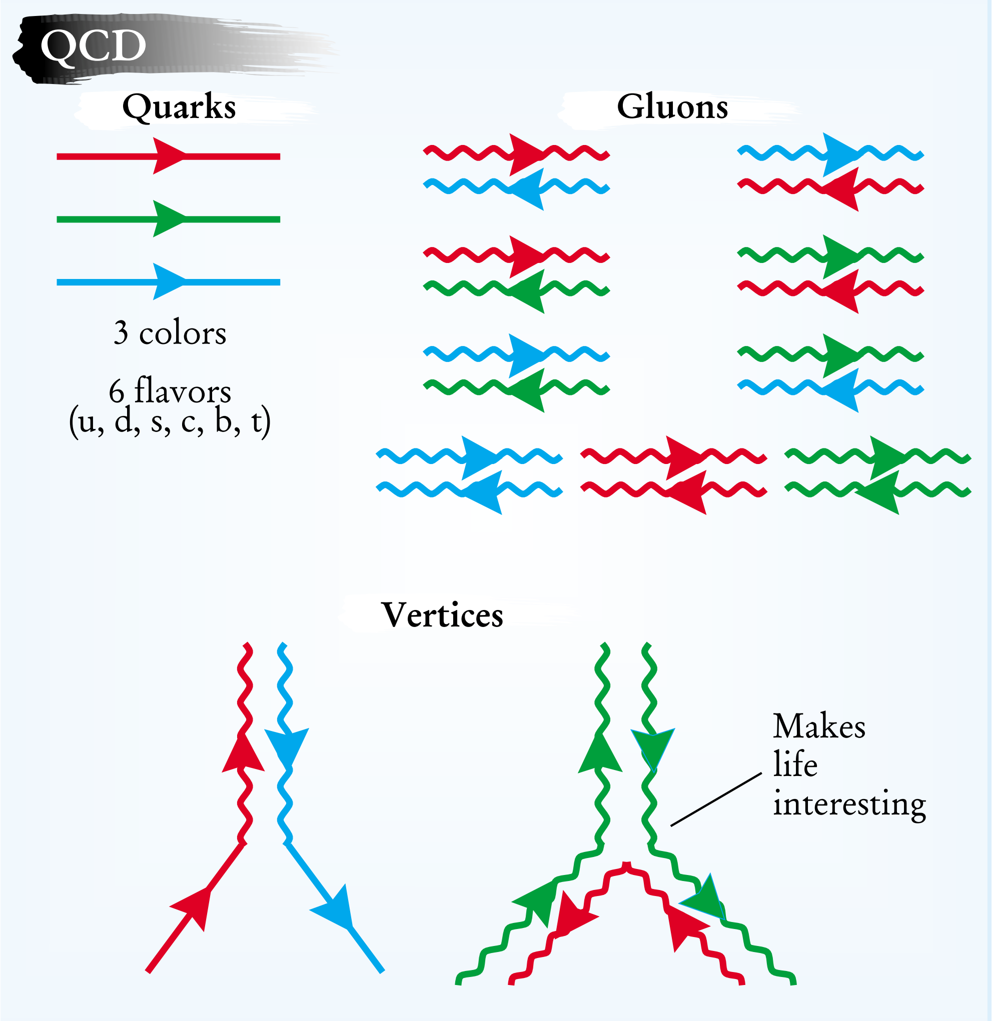
The strong nuclear interaction

- a theory of strongly interaction quarks & gluons
  - never observed directly
  - indirect measurements in experiments
- non-Abelian: gluons interact amongst themselves

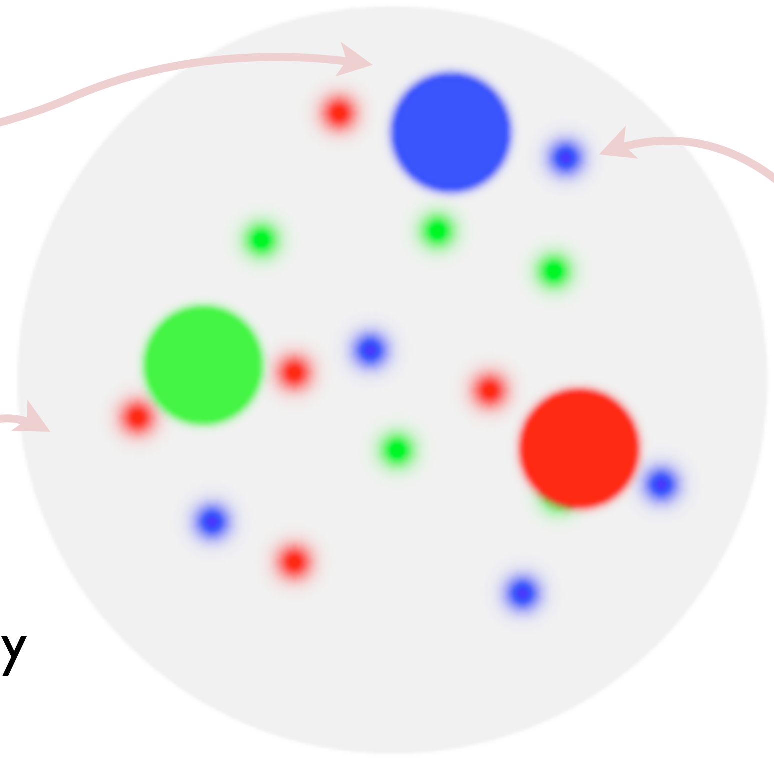


A snapshot of a proton

A conundrum: how can QCD particles be aware of the fact that "physical" (long-distance) particles only interact with **integer** electric charge?

"fractional charge"

2/3 e: up, charm and top
1/3 e: down, strange and bottom



"fuzziness"

QCD is a **quantum field theory** (creation & annihilation of particles)

$$\Delta x \Delta p \gtrsim h$$

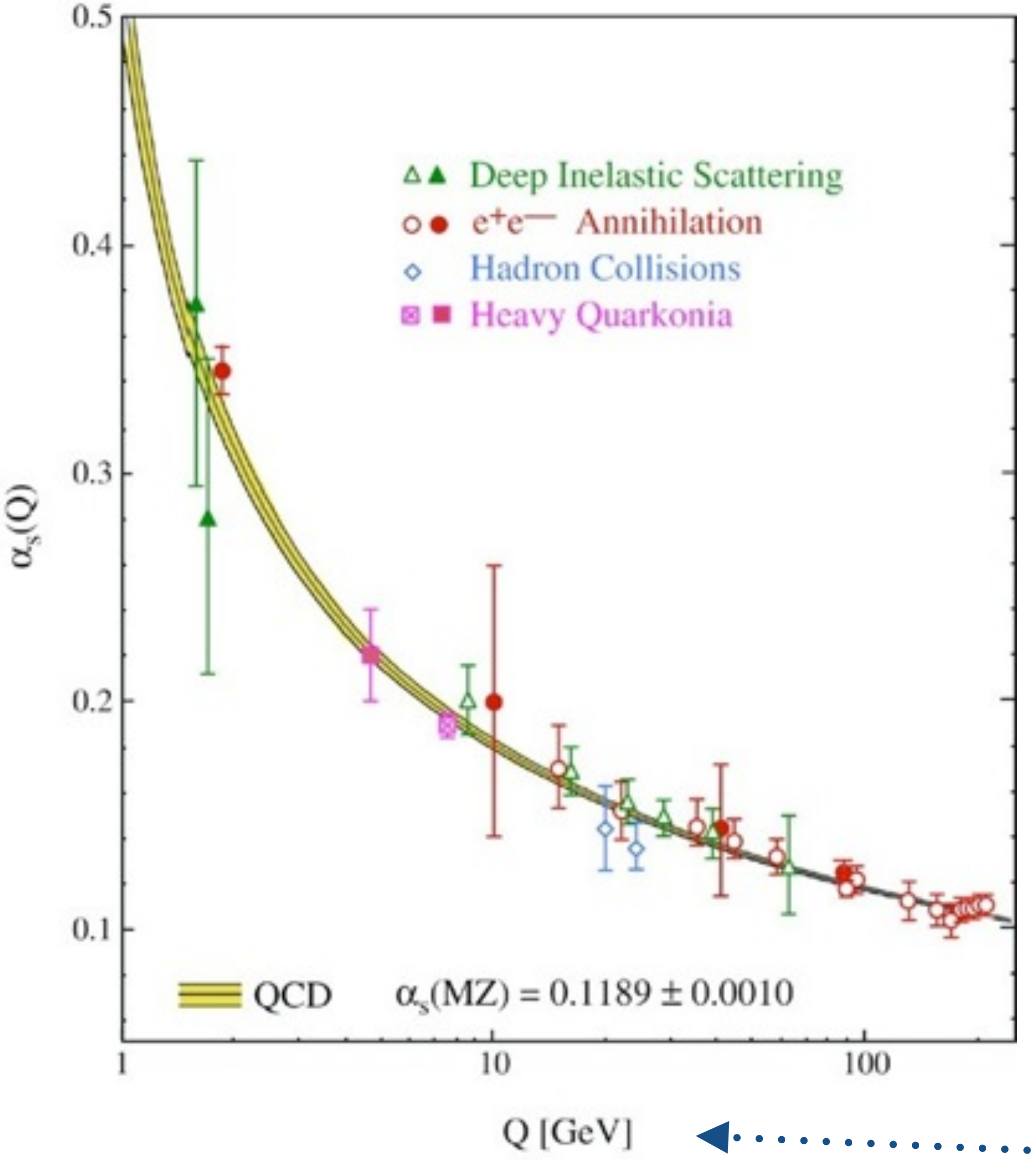
confinement

the quarks are tightly bound by the gluons inside "colorless" objects, so called **hadrons**

Millennium Prize Problem #7

Yang–Mills Existence and Mass Gap. Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in [45, 35].

Asymptotic freedom

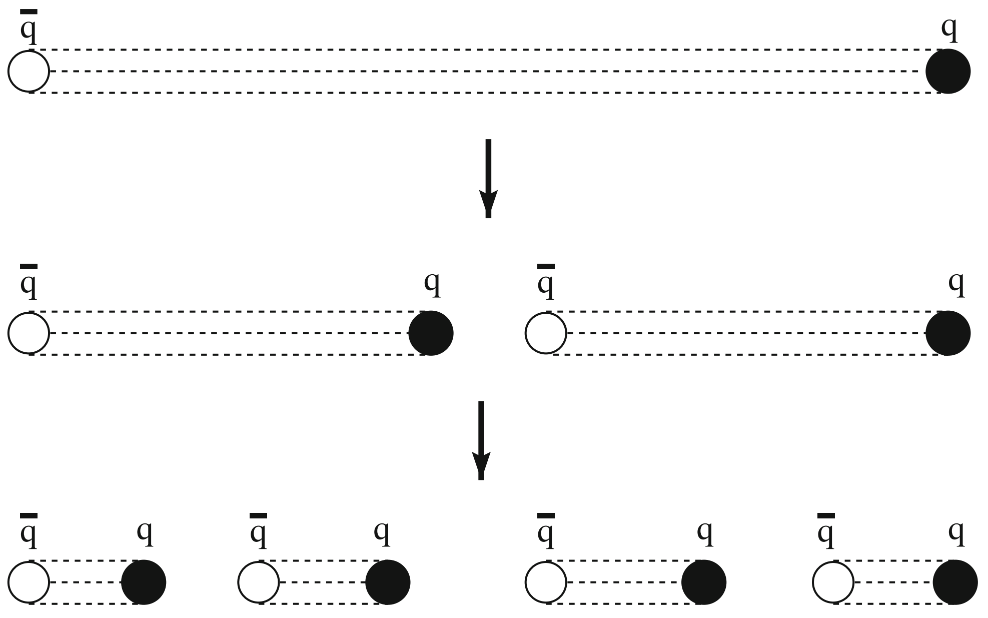


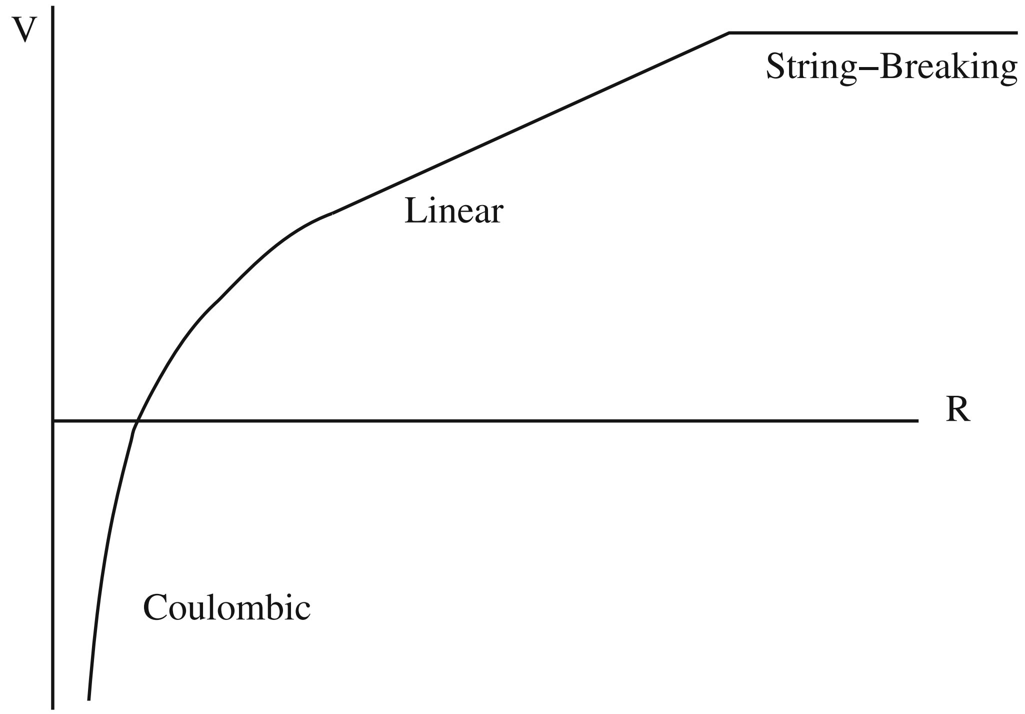
- QCD is weakly coupled at small distances — strongly coupled at large distances
- can use perturbation theory when there is a large scale in the problem
- unfortunately, in many interesting situations this is not the case…

In heavy-ions you also have to consider medium scales, such as T, geometry (1/L)…

multi-scale problem!

String breaking mechanism



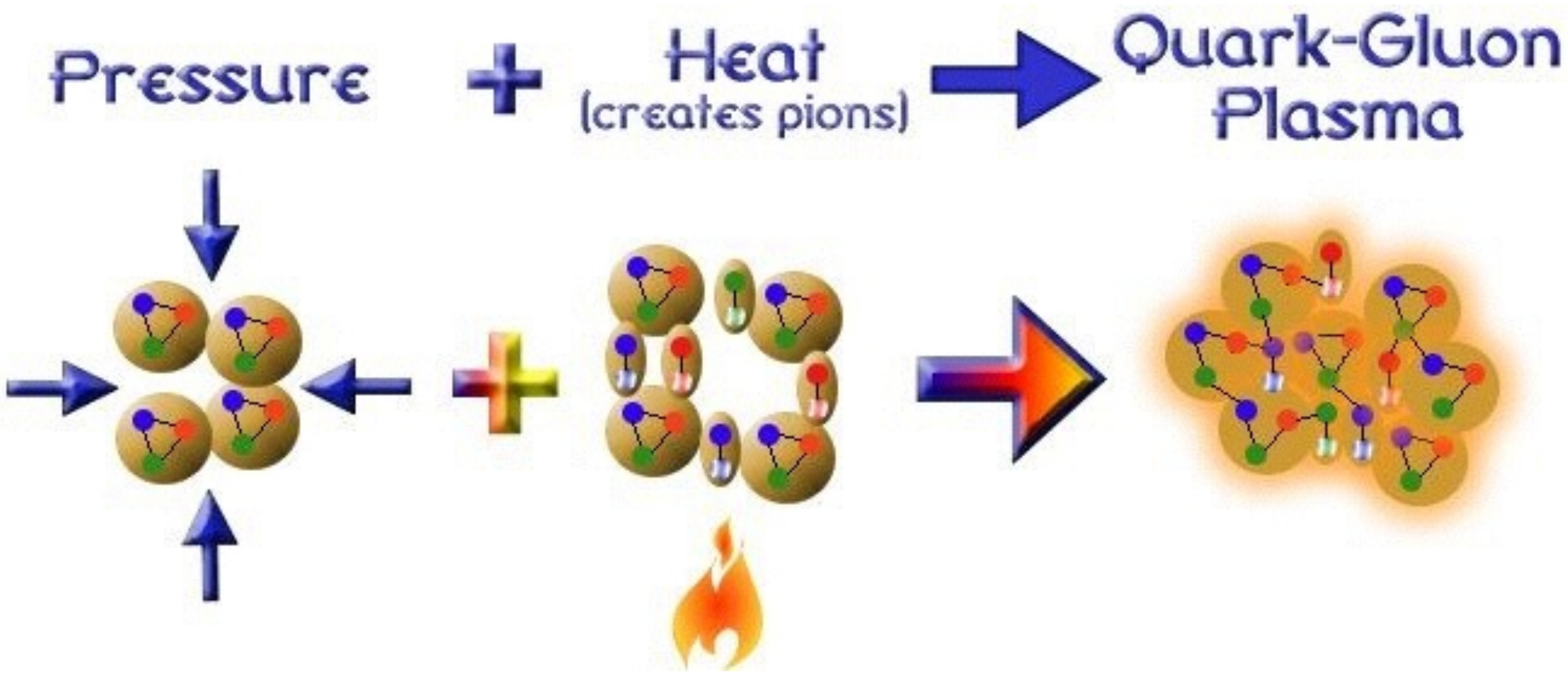


Energy stored in the tube is **σ**L with $\sigma = \int d^2x_\perp \frac{1}{2} E_k^a(x) E_k^a(x)$

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

- short-distance regime: Coulomb interaction
- $E_k = F_{0k}$ is the (color) electrical flux
- $\sqrt{\sigma}$ = 420 MeV is the so-called string tension
- string breaks due to light quarks!

Changing the dynamics

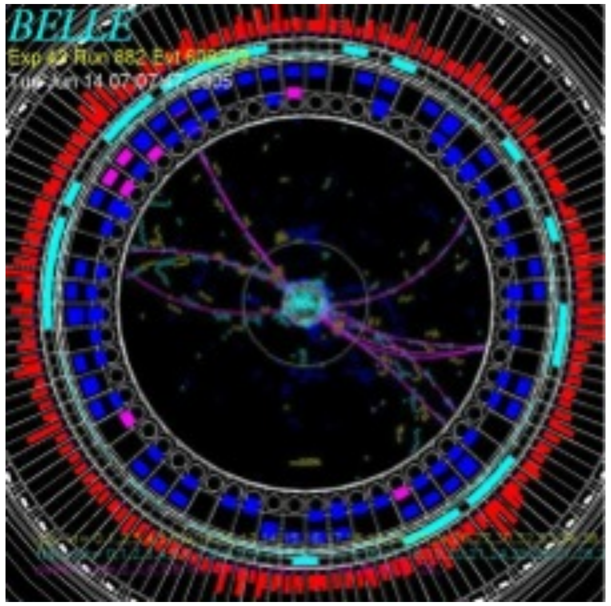


Lecture I

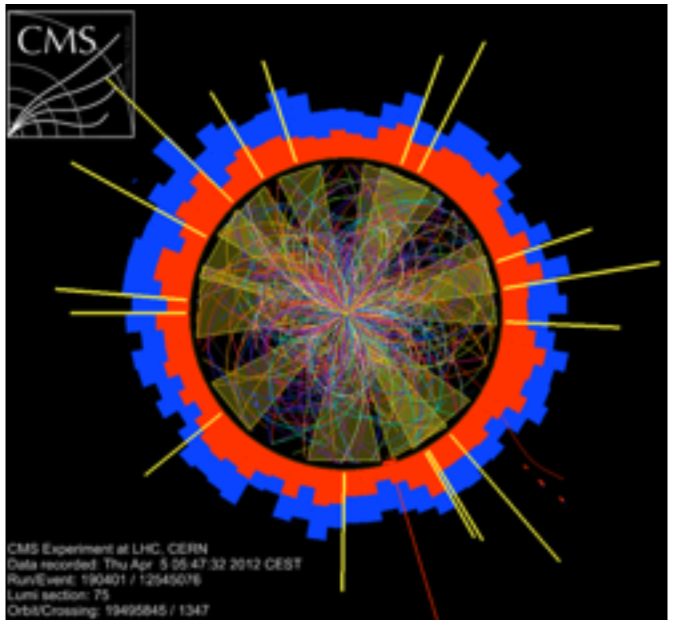
- thermal properties of QCD
- two paradigms: gas or fluid
- do we measure nucleons or gluons?

Heavy-ion collisions probe the strong interaction
in highly dynamical and complex conditions.

Collisions & colliders



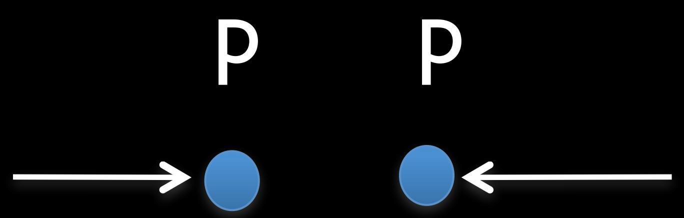
$e^+ + e^-$

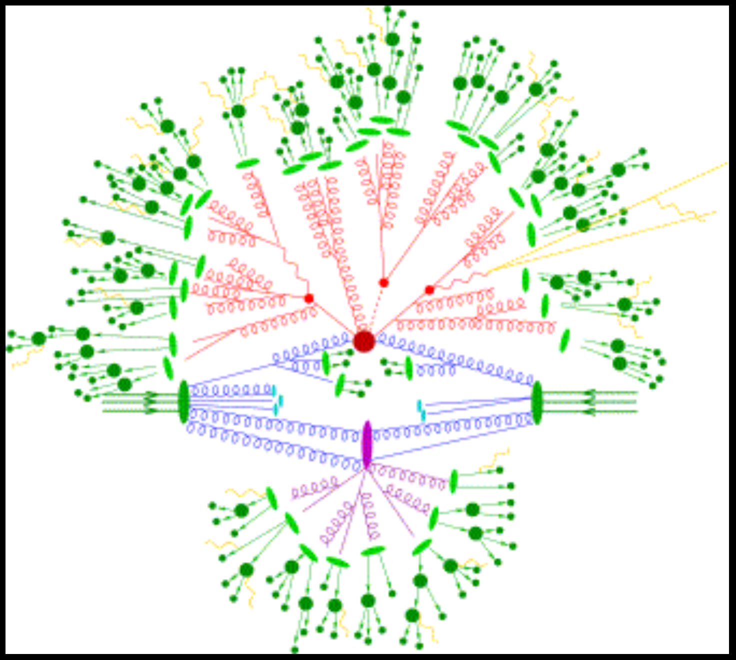


p+p

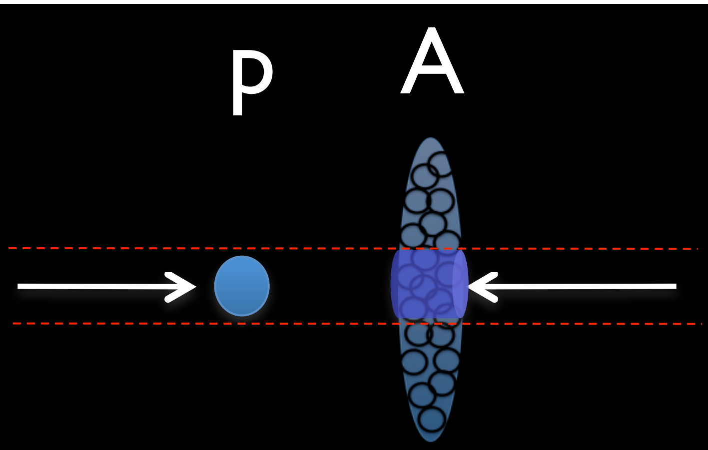
A+A

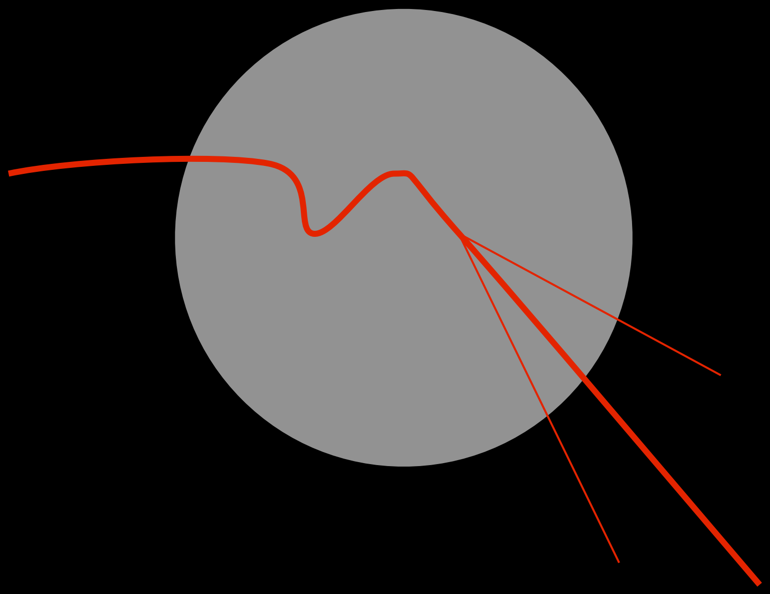
Names	Start-up	Energy ($\sqrt{s_{NN}}$)	Colliding system
Alternating Gradient Synchrotron (AGS)	mid 1980's	2-5 GeV	variety of beams
CERN Super Proton Synchrotron (SPS)	Pb since 1994	≤ 17 GeV	variety of beams
BNL Relativistic Heavy-Ion Collider (RHIC)	2000	≤ 200 GeV	p+p, d+Au, Au+Au, Cu+Cu, ...
CERN Large Hadron Collider (LHC)	2010	2.75 TeV, 4 TeV (?)	p+p, Pb+Pb, p+Pb



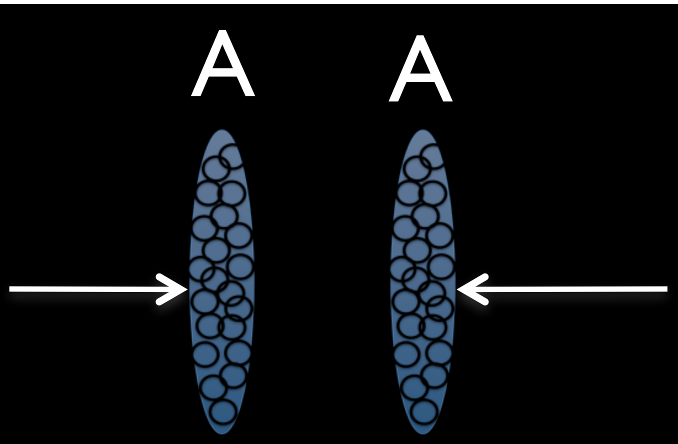


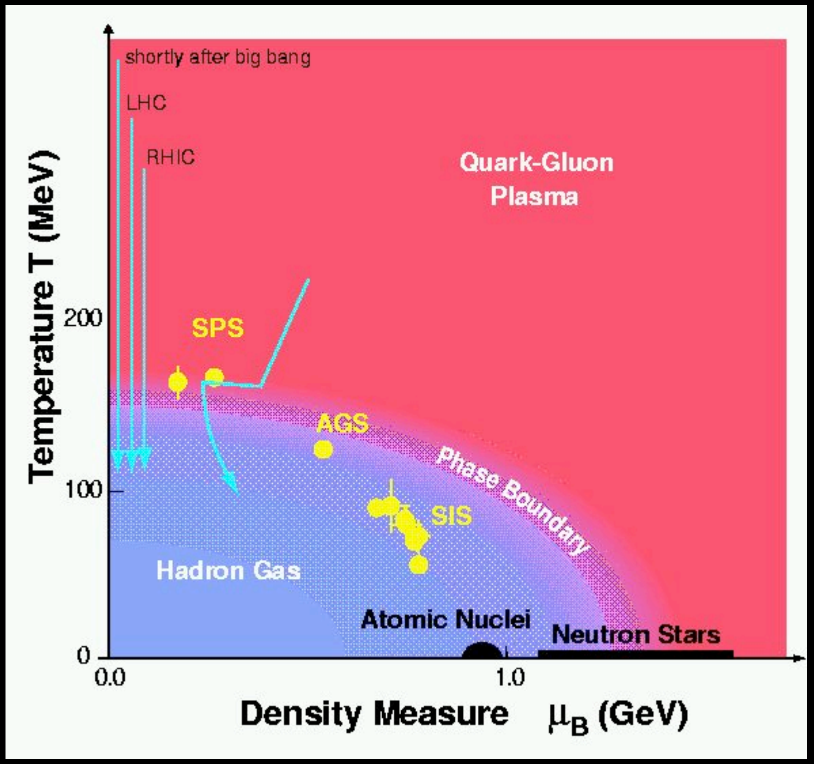
Local structure of QCD vacuum





Local QCD
+
initial state/cold nuclear matter

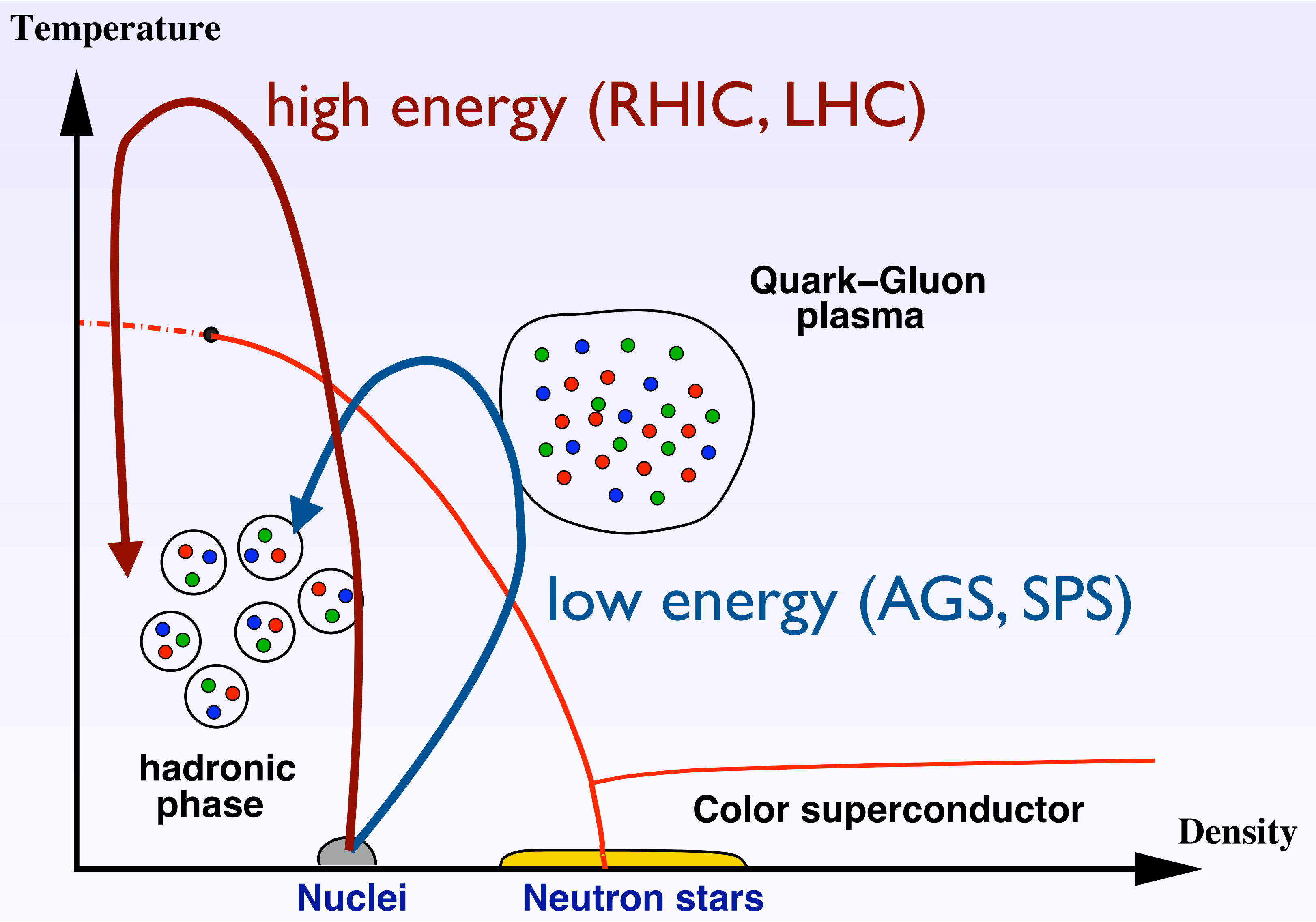




Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

Turning on the temperature

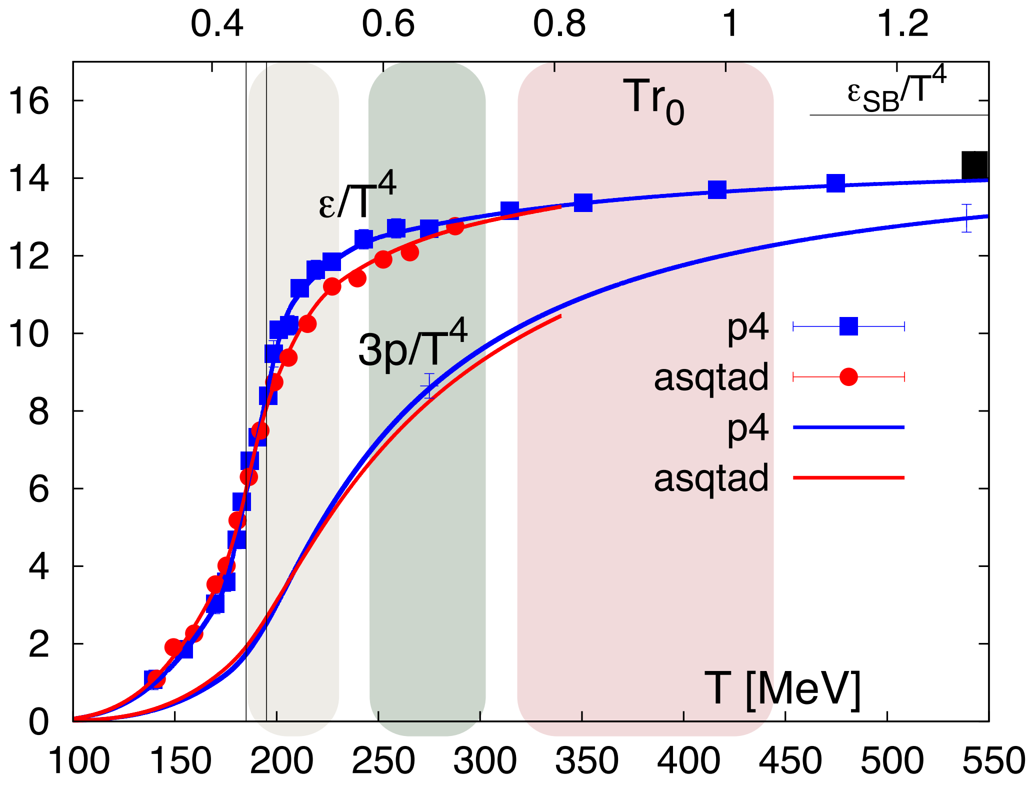
The phase diagram of QCD



μ_B = net baryon density

QCD thermodynamics

A rapid rise of energy density (pressure, entropy etc) is observed (μ_B=0).



Bazavov et al., PRD 80 (2009) 014504

Energy regimes: SPS, RHIC & LHC

Number of pions (d_π=3):
$$n_\pi = d_\pi \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{1}{e^{E_\mathbf{p}/T}-1}$$

Free parton gas:

$$e_{SB} = e_{\text{glue}} + e_{\text{quark}}$$

$$e_{\text{glue}} = d_{\text{glue}} \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{E_\mathbf{p}}{e^{E_\mathbf{p}/T}-1}$$

$$e_{\text{quark}} = d_{\text{quark}} \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{E_\mathbf{p}}{e^{E_\mathbf{p}/T}+1}$$

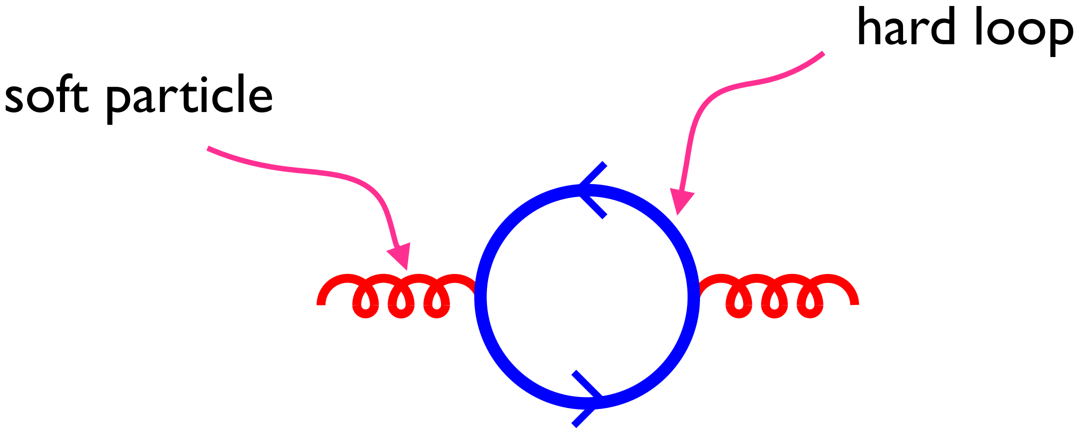
$$d_{\text{glue}} = 2\times 8$$ spin, color

$$d_{\text{quark}} = 2\times 2\times 3\times 3$$ spin, quark/antiquark, color, flavor

Do not reach Stefan-Boltzman limit — interactions survive!

Debye screening

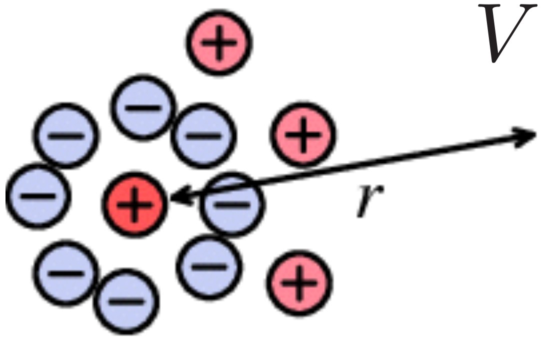
At asymptotically high T ($g \ll 1$): plasma particles with soft momenta (~gT) are dressed by fluctuations (~T).



hard loop

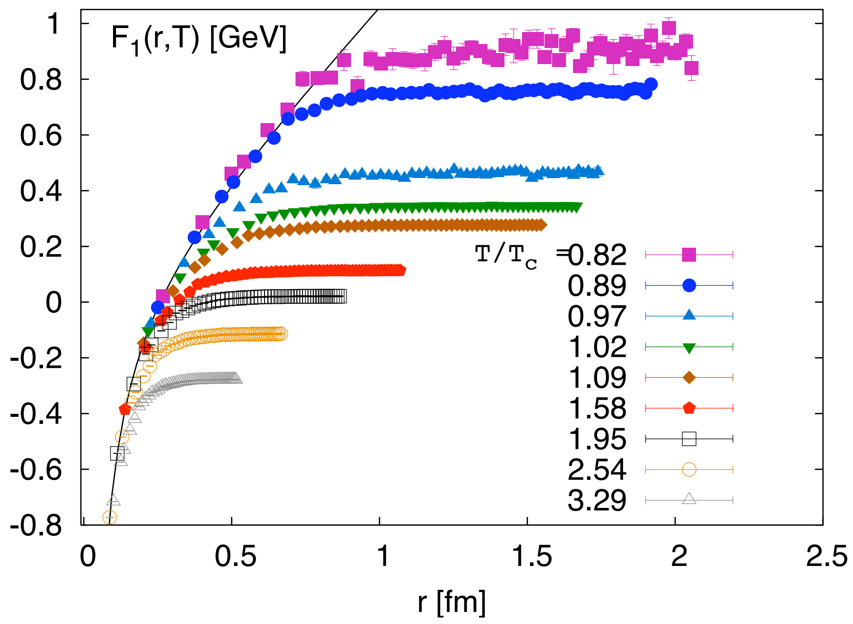
soft particle

$$m_D = \#\, gT$$



$$V(r) = \frac{\alpha'}{r} e^{-m_D r}$$

Kaczmarek 0710.0498[hep-lat]

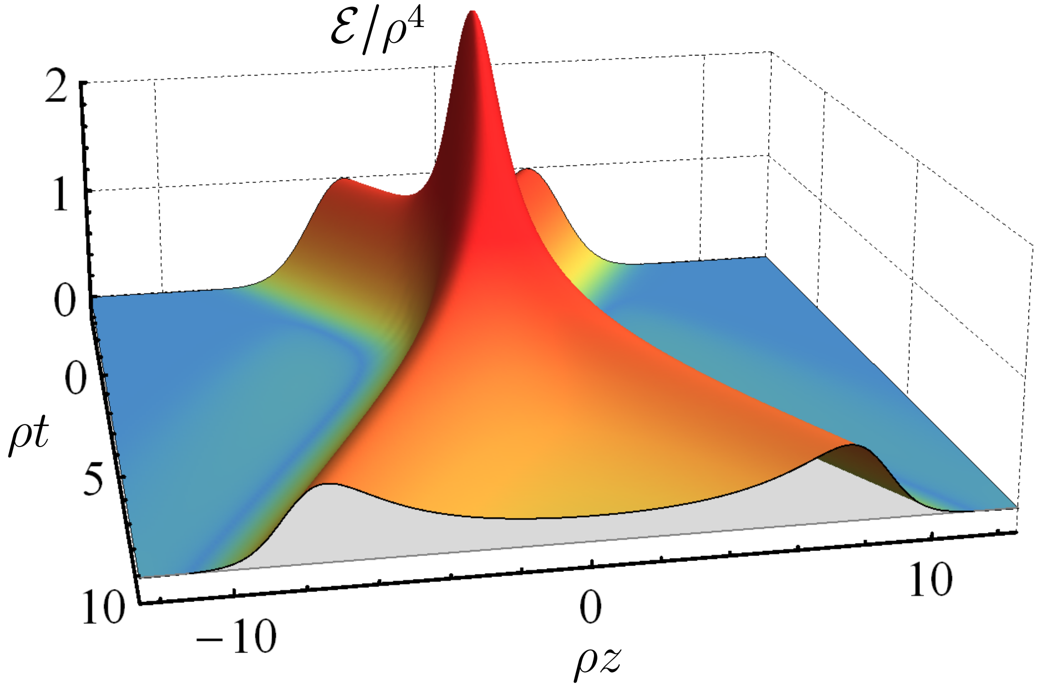


- color interactions have limited range
- gauge bosons get dressed :: longitudinal gluons
- Hard-Thermal-Loop effective field theory

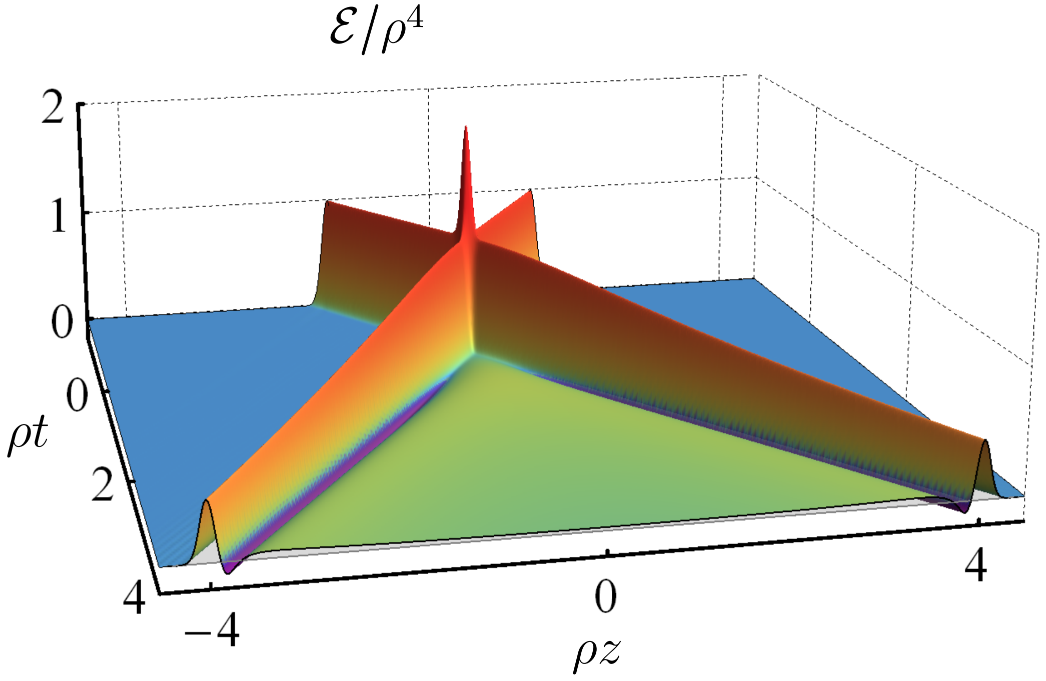
Strong-coupling approach

Gauge-gravity (AdS/CFT) duality: the strong-coupling limit of the gauge theory (N=4 SYM) is described by a weakly-coupled gravitational system in 4D AdS space.

System becomes "hydro-like" (no quasi-particles) on very short timescales and is characterized by the universal $\boldsymbol{\eta}/s = 1/4\boldsymbol{\pi}$.



Thick shock (low energy)



Thin shock (high energy)

QCD transport properties

Real-time dynamics ⇔ thermodynamics

Euclidean space and thermal fields:

$$t \to i\tau$$

$$0 \le \tau \le \beta$$

$$\beta = 1/(k_B T)$$

Schematically:

Spectral function ρ connects to the Euclidean correlator

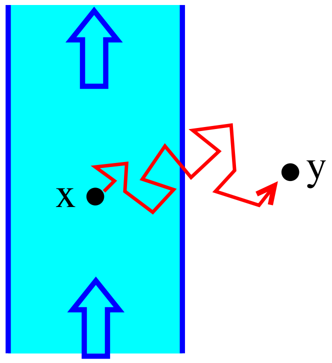
$$G_E(t) = \int_0^\infty \mathrm{d}\omega \, \rho(\omega) \, \frac{\cosh \omega(\beta/2 - t)}{\sinh \omega\beta/2}$$

Kubo formula:

$$\eta = \pi \lim_{\omega \to 0} \lim_{\boldsymbol{k} \to 0} \frac{\rho(\omega, \boldsymbol{k})}{\omega}$$

Transport properties encode the long-wave length, long-time features of the underlying theory.
This probes the E-correlator in the infrared sector — hard to control on the lattice!

The shear viscosity

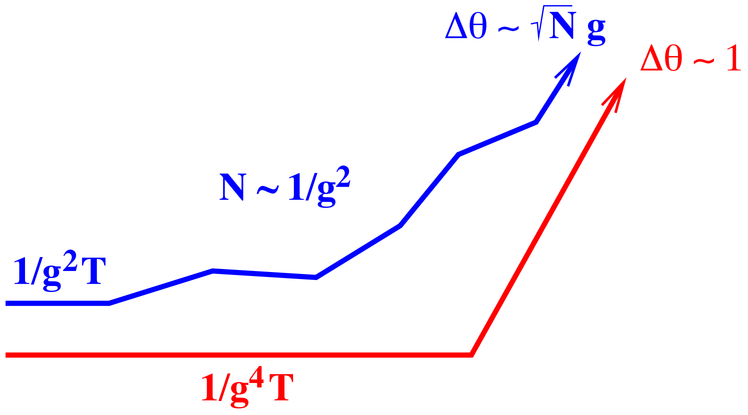


Dissipation

$$\text{rate} \quad \propto \quad \eta \quad \sim \quad (\text{mean free path}) \times (\text{energy-momentum density})$$

$$\frac{\eta}{s} \sim \tau_R T \sim \frac{\hbar}{k_B} \frac{\tau_R}{\tau_{\text{quant}}}$$

what is the relaxation time?



$$\sigma \sim \frac{g^4}{p^2}$$

$$\tau \sim (n\sigma v)^{-1} \sim (T^3\sigma)^{-1}$$

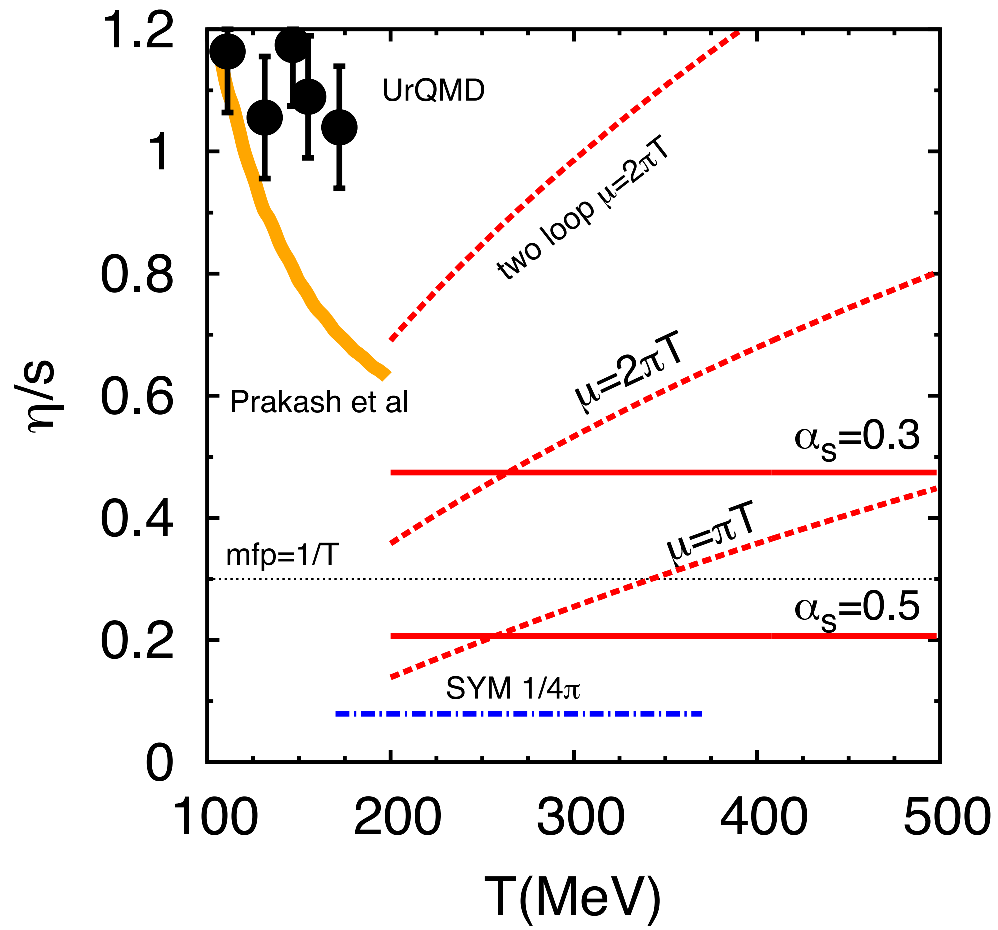
1. typical collisions p~m$_D$~gT with small deflection **Δθ**~p/E~g
    - need to wait for a long time so to experience N kicks!
2. rare collisions p~T with large deflection

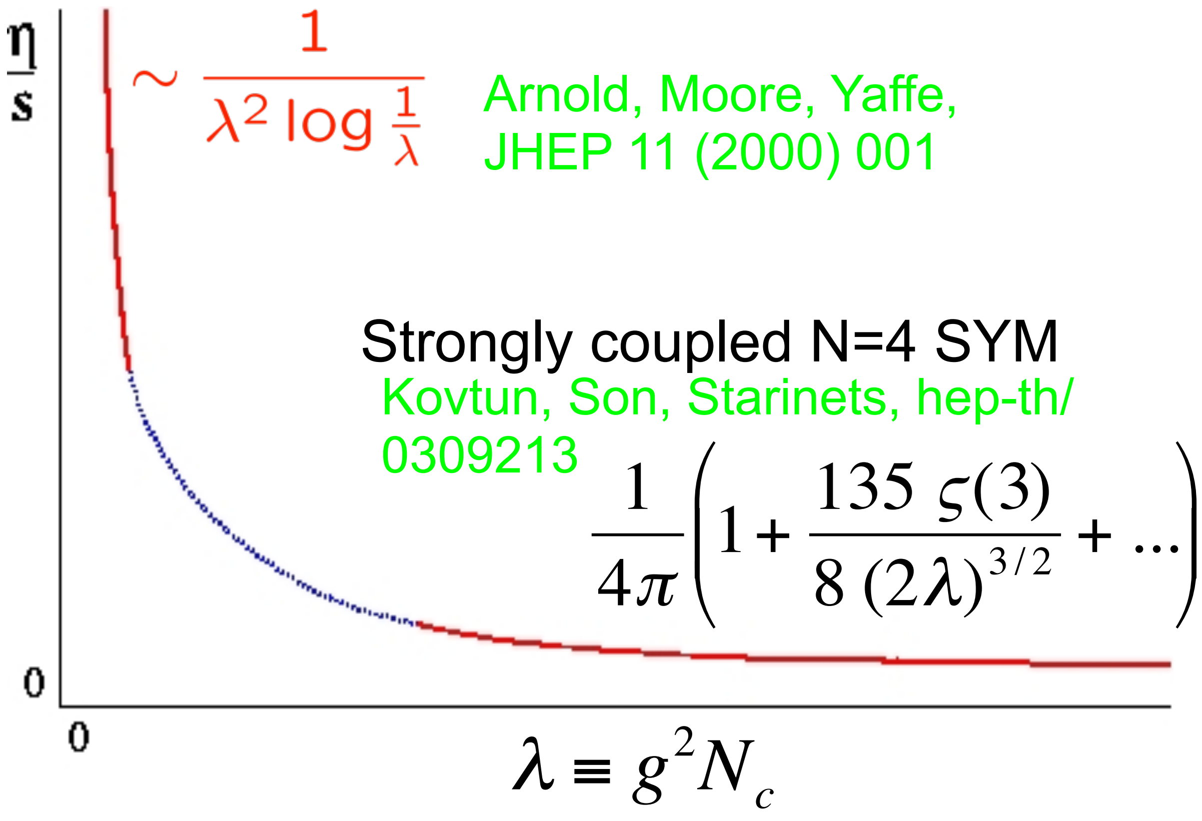
In both cases: $\tau_{\text{rand}} \sim \dfrac{1}{g^4 T \ln(1/g)}$

Measure of "fluidity"

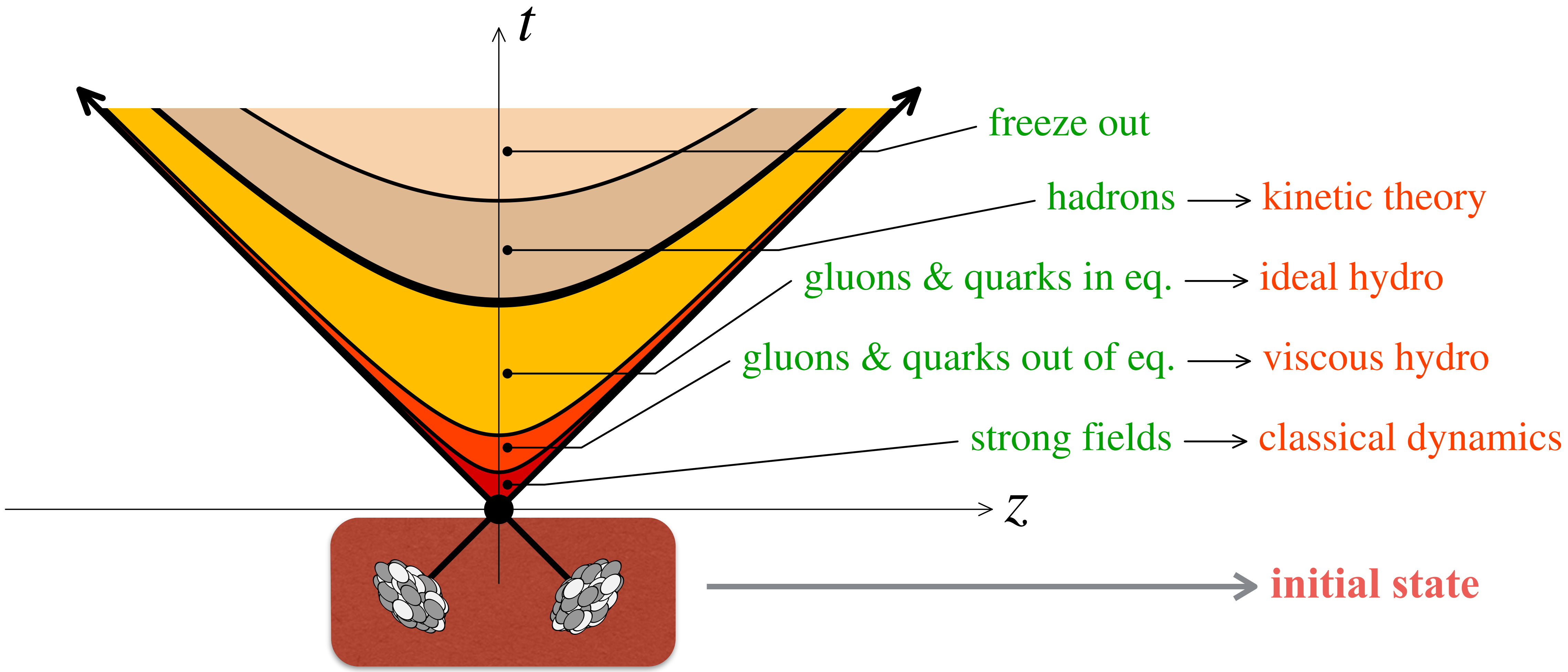
Leading log result from pert theory: $$\eta \simeq \frac{T^3}{g^4 \ln(1/g)} f\big(\ln(1/g)\big)$$

getting this log piece is difficulty an involves the LPM effect (next lecture)!





Collision evolution



freeze out

hadrons → kinetic theory

gluons & quarks in eq. → ideal hydro

gluons & quarks out of eq. → viscous hydro

strong fields → classical dynamics

initial state

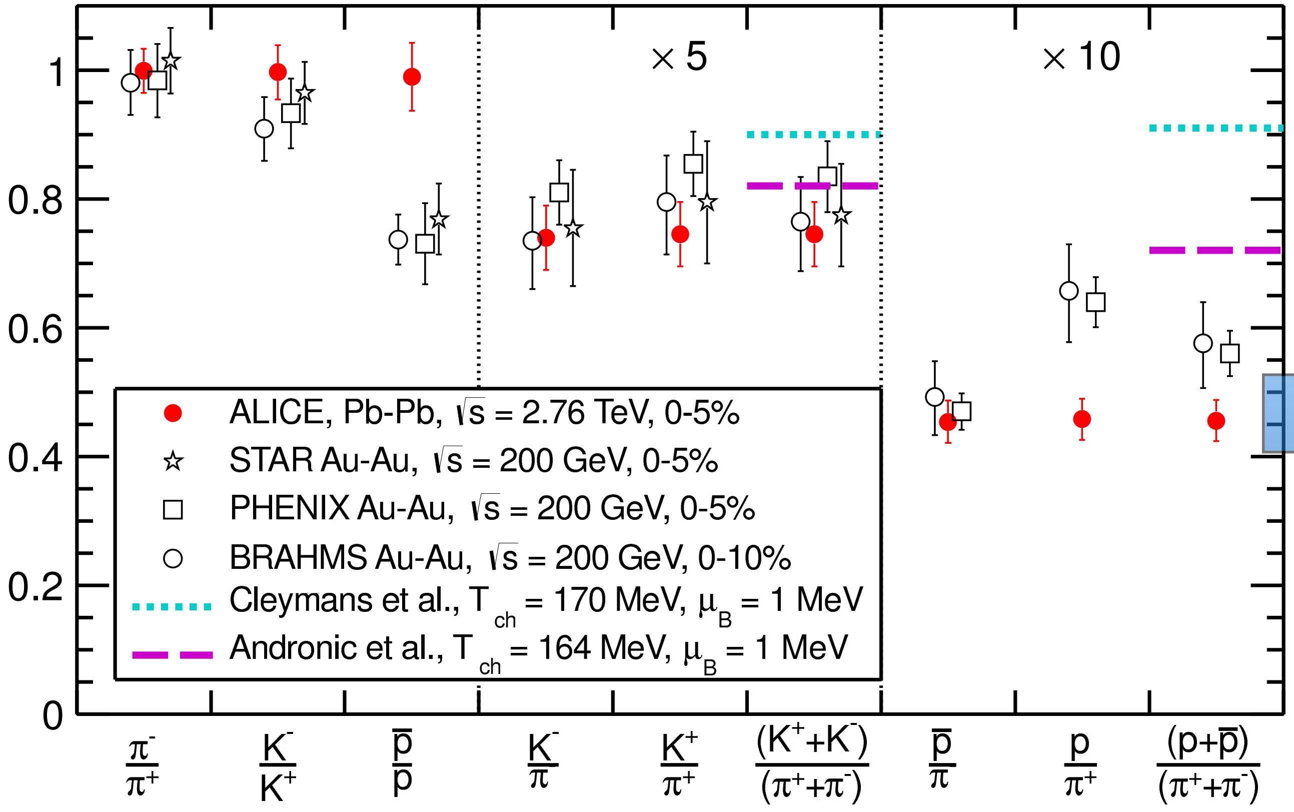
Formation time: 1 fm/c ($3 \cdot 10^{-24}$ s)
Lifetime of QGP: 10 fm/c

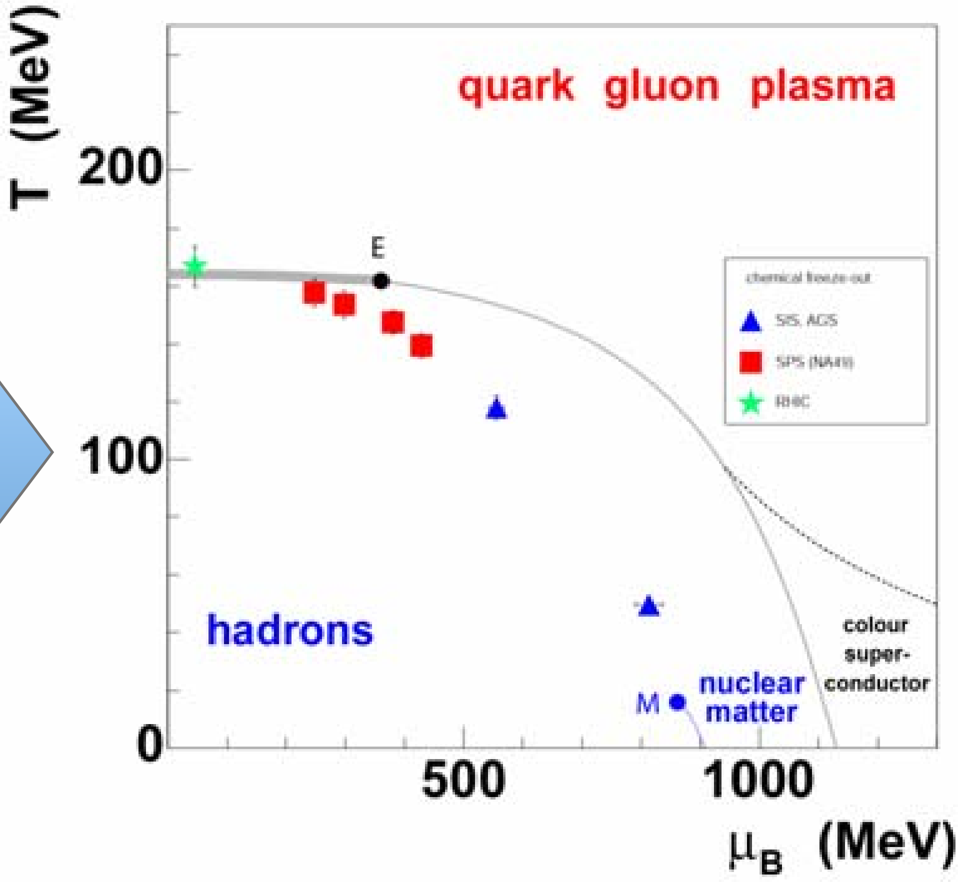
How does thermalization arise??

Statistical model

Grand canonical partition function $$\ln Z_i(V,T,\mu_Q,\mu_B,\mu_S) = \pm(2s_i+1)\frac{V}{2\pi^2}\int_0^\infty dp\,p^2 \ln\left[1\pm\lambda_i \exp(-\beta\omega_i)\right]$$

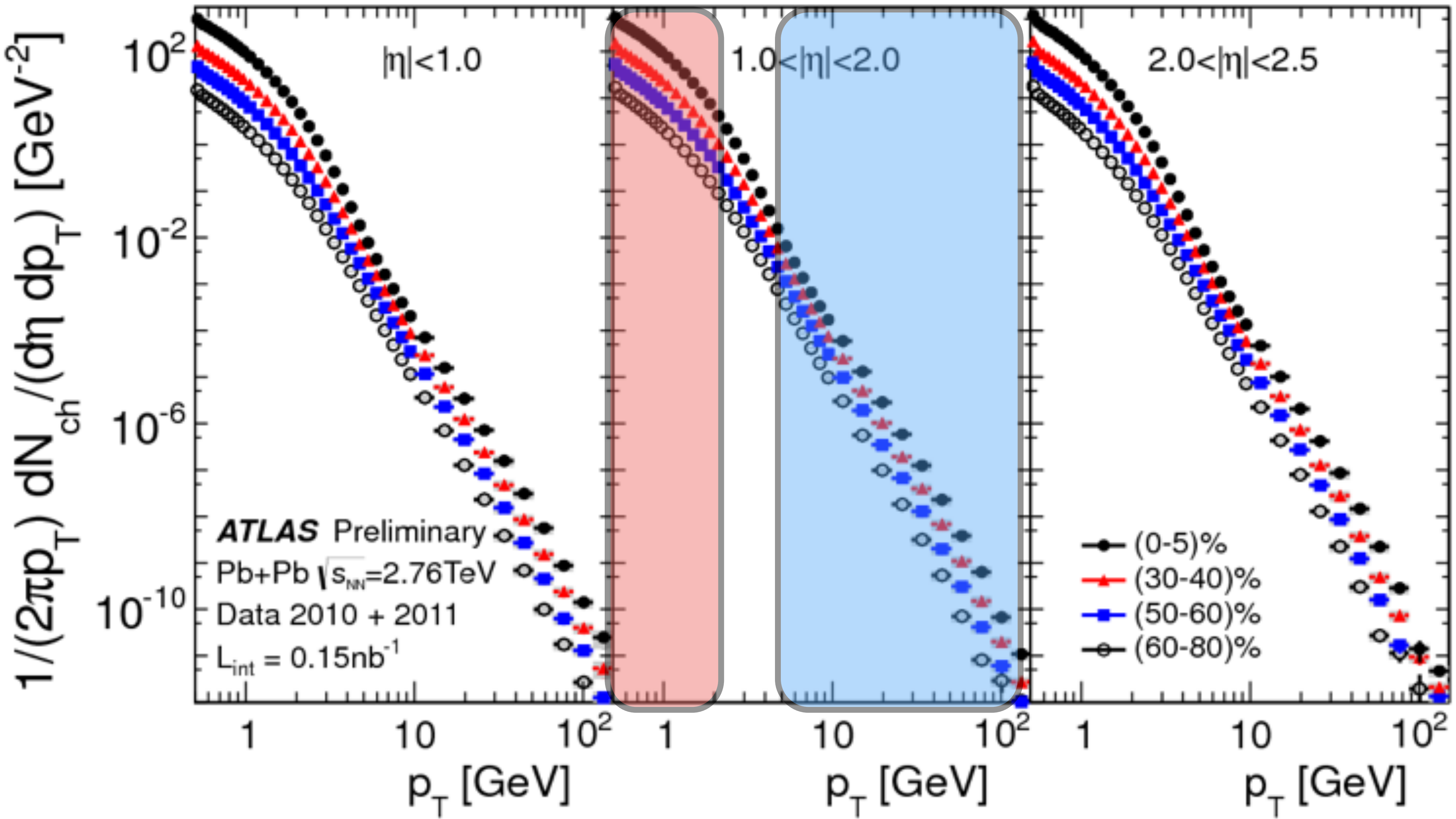
Fugacities: $$\lambda_i(T,\mu_Q,\mu_B,\mu_S) = \exp\left[\beta(\mu_Q Q_i + \mu_B B_i + \mu_S S_i)\right]$$

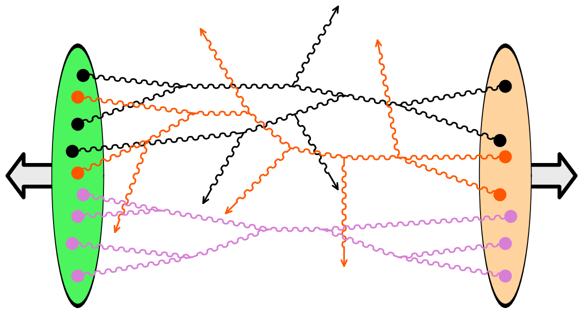




Thermal properties at the freeze-out surface.
Hadron yields are in chemical equilibrium.

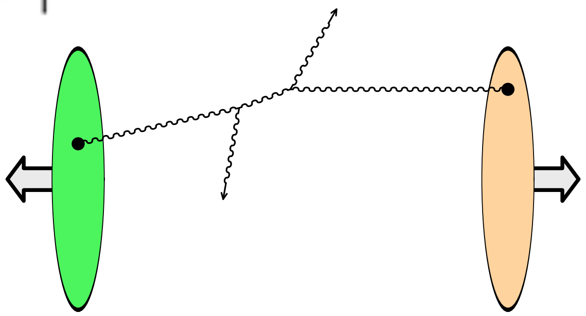
Charged particle spectrum



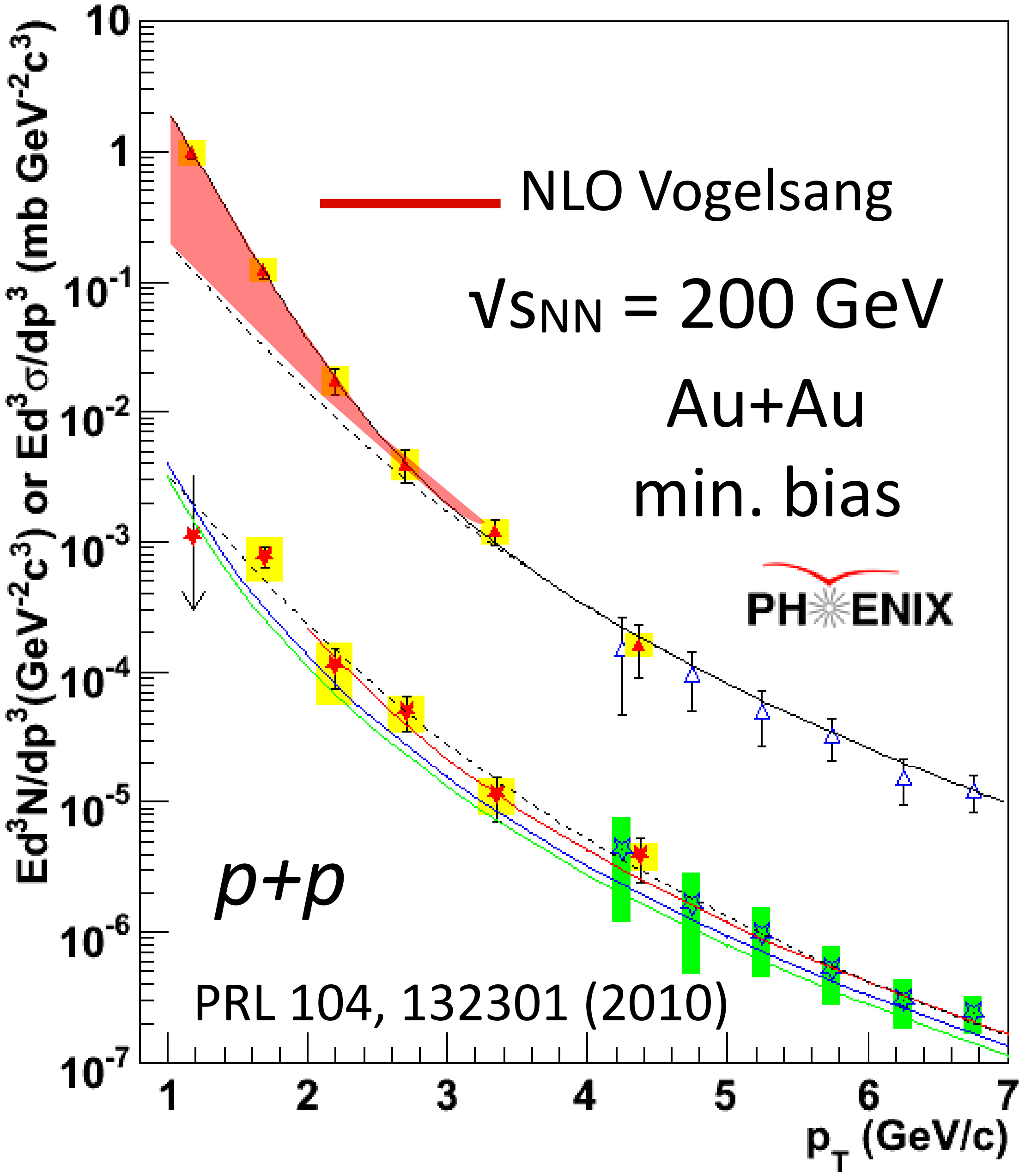


soft probes
dense regime
exponential

hard probes
dilute regime
power-like



Photon spectra

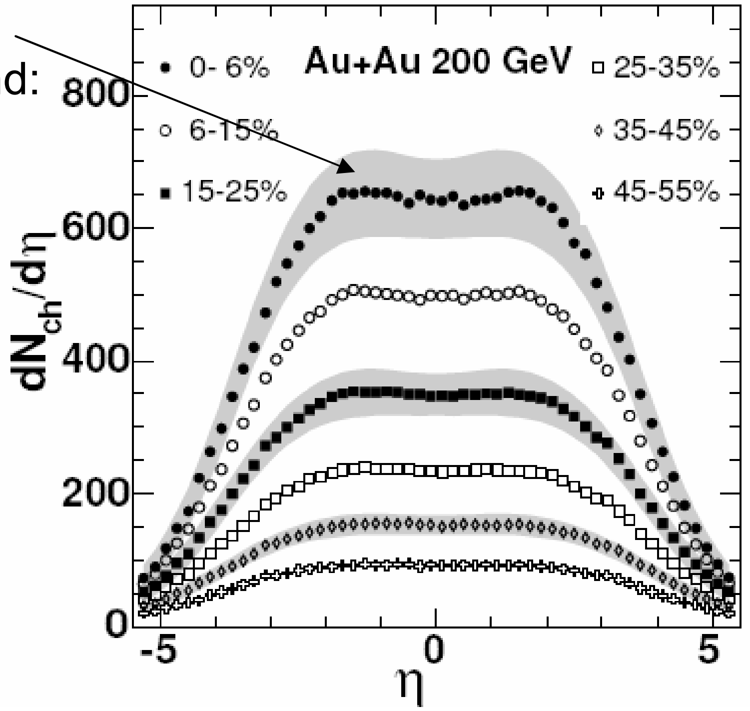


$$E\frac{dN}{d^3p} = C(y)\exp\left(-\frac{m_\perp}{T_{\mathrm{eff}}(y)}\right)$$

$$m_\perp = \sqrt{p_\perp^2 + m^2}$$

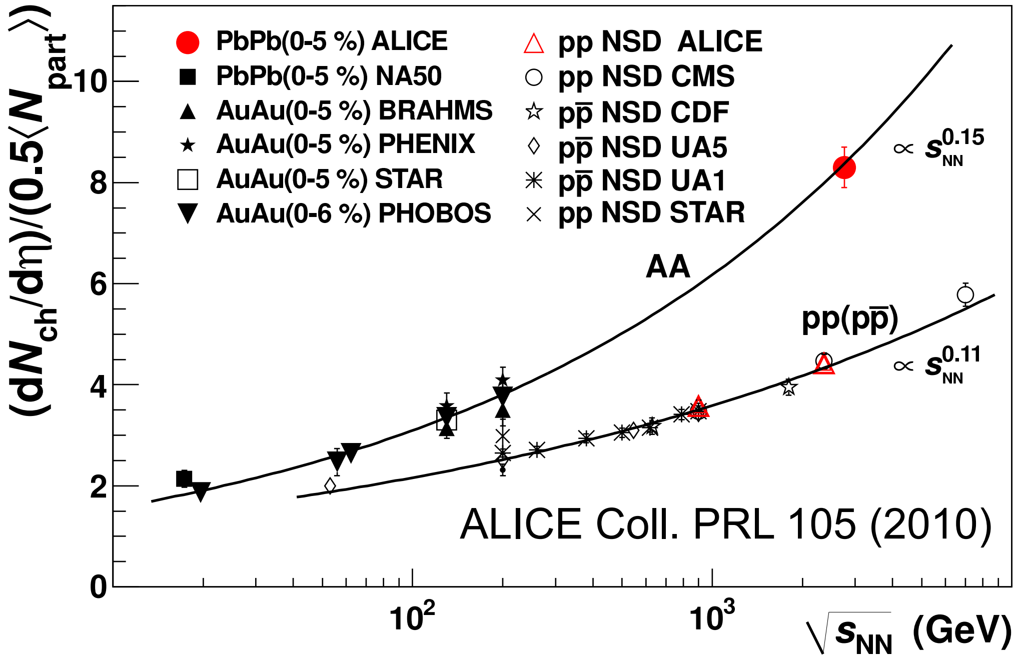
- exponential thermal photon spectrum
- inverse slope T_{eff} = 220 MeV
- T_i from hydrodynamics 300-600 MeV
- photons produced at early times
- sensitive to early-time coupling & evolution

Deposited energy



6% most central collisions (grey band: syst. error)

At mid rapidity particles have $\langle p_T \rangle \sim 500$ MeV



ALICE Coll. PRL 105 (2010)

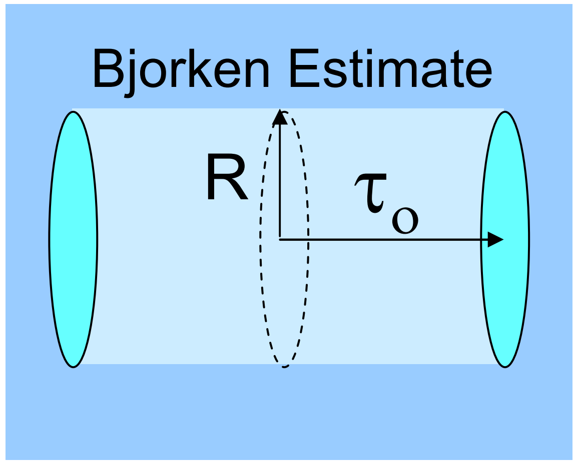
- particle density is a measure of energy density
- almost flat distribution in pseudo-rapidity
- factor of 2 from SPS to RHIC and another from RHIC to LHC

$$\frac{\mathrm{d}E}{\mathrm{d}\eta} \simeq \langle E \rangle \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} \times \frac{3}{2} \simeq 6-12 \times 0.5\,\mathrm{GeV} \times \frac{N_{\mathrm{part}}}{2}$$

$$\frac{N_{\mathrm{part}}}{2} \sim 170$$

Bjorken energy density estimate

At high energies most the matter is mostly transparent; QGP is formed in the wake.



$$\eta_s = \frac{1}{2}\log\frac{t+z}{t-z} \simeq \frac{1}{2}\log\frac{p+p_z}{p-p_z} = \eta$$

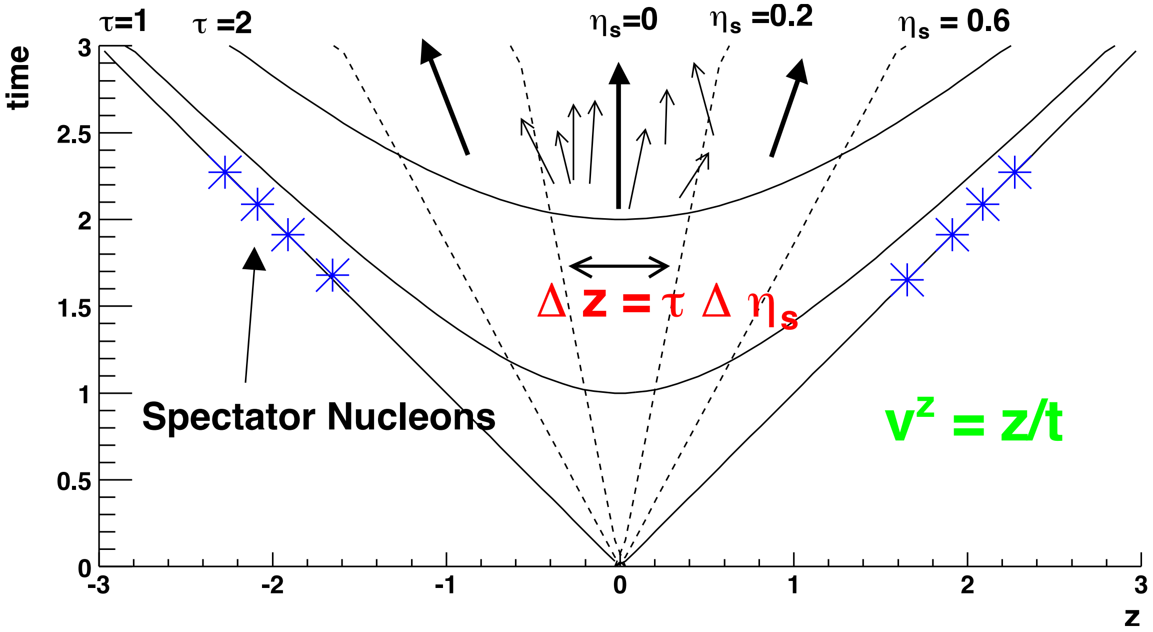
Matter at certain rapidity are created in the same space-time slice.

$$\epsilon_{\rm Bj} \simeq \frac{1}{\pi R^2}\frac{\Delta E}{\Delta z} \simeq \frac{1}{\pi R^2 \tau_0}\frac{\Delta E}{\Delta \eta}$$

- using τ_0=1 fm and R=6 fm

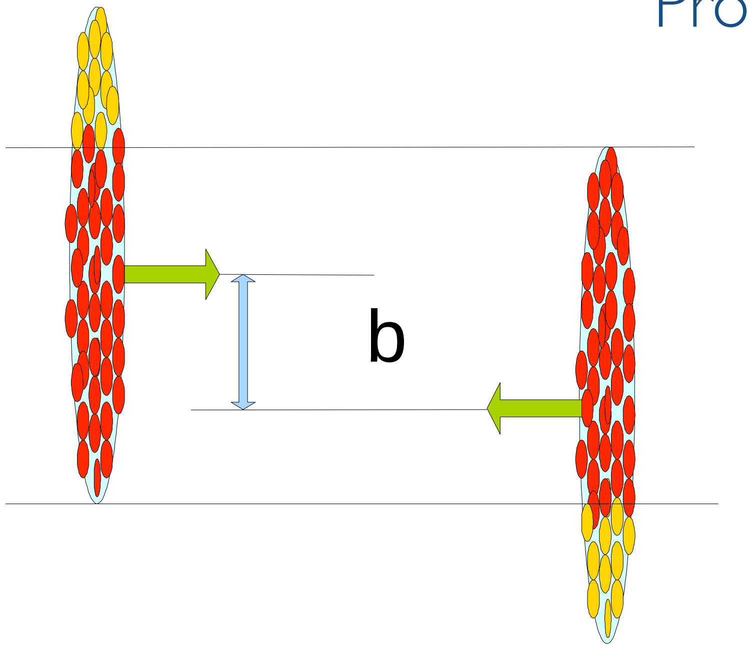
$$\epsilon_{\rm Bj} \sim 5-10\,\frac{\rm GeV}{\rm fm^3}$$

$$\rho_{\rm cold} = 0.15\frac{\rm GeV}{\rm fm^3}$$



Enough energy density to melt the nucleons!

The Glauber model



Probabilistic model of the collision.

Nuclear thickness: $T_A(\boldsymbol{b}) = \int_{-\infty}^{\infty} dz \rho(z, \boldsymbol{b})$

Optical approximation:

$$\int d\boldsymbol{s}\, T_A(\boldsymbol{b}) T_B(\boldsymbol{b}-\boldsymbol{s}) \sigma_{NN}^{\text{inel}} \equiv T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}$$

Probability of n scatterings at impact parameter b:

$$P(n, \boldsymbol{b}) = \binom{AB}{n} \left[1 - T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}\right]^{AB-n} \left[T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\text{inel}}\right]^{n}$$

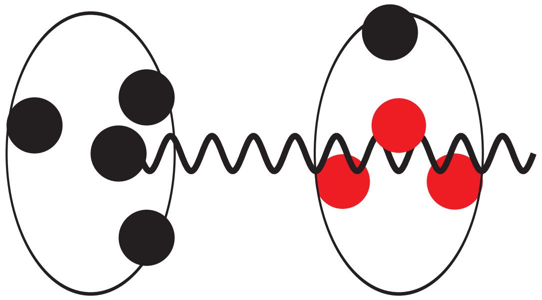
Sum over probabilities = cross section:

$$\begin{aligned} \sigma_{AB}^{\text{inel}} &= \int d^2b \left[1 - \left(1 - T_{AB}(\mathbf{b}) \sigma_{NN}^{\text{inel}}\right)^{AB}\right] \\ &\simeq \int d^2b \left\{1 - \exp\left[-AB T_{AB}(\mathbf{b}) \sigma_{NN}^{\text{inel}}\right]\right\} \end{aligned}$$

Centrality determination

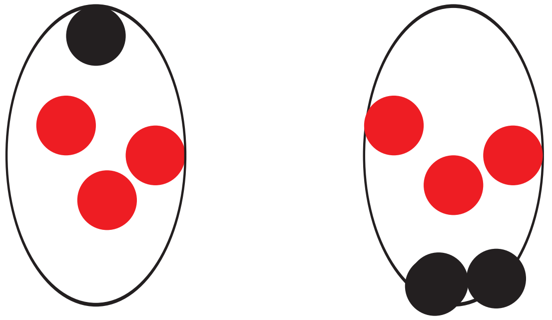
Number of collisions:

$$N_{\mathrm{coll}}^{AB}(\boldsymbol{b}) = \sum_{n=0}^{A} n P(n,\boldsymbol{b}) = AB T_{AB}(\boldsymbol{b}) \sigma_{NN}^{\mathrm{inel}}$$

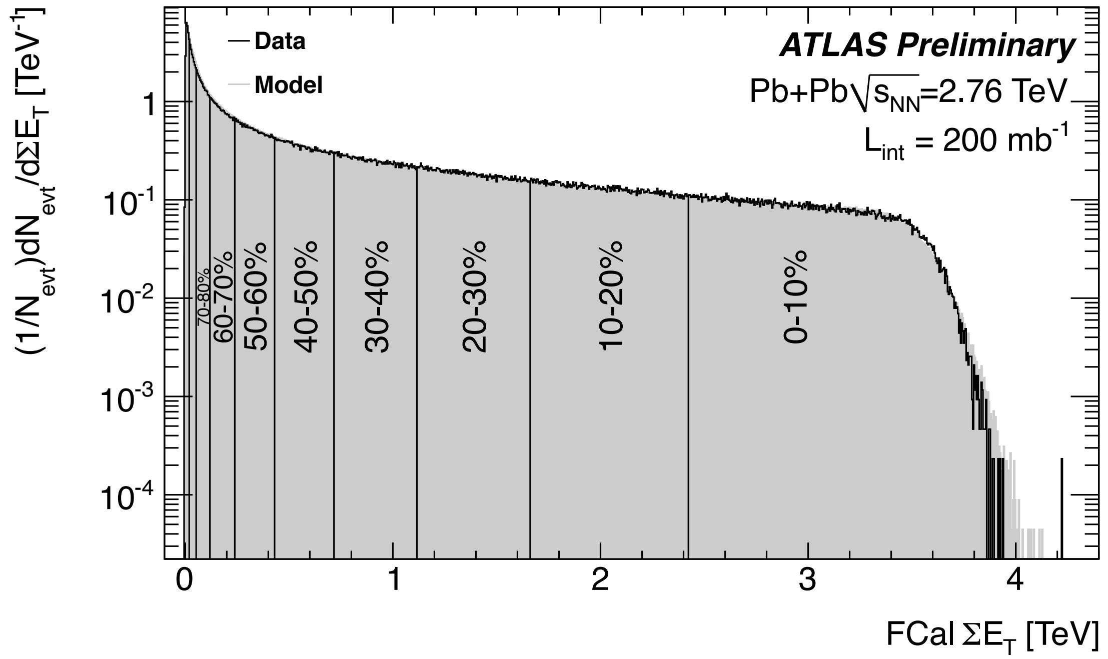


Number of participants:

$$\begin{aligned} N_{\mathrm{part}}^{A}(\boldsymbol{b}) &= \int d\boldsymbol{s}\, B\, T_B(\boldsymbol{s}) \sigma_{pA}^{\mathrm{inel}}(\boldsymbol{b}-\boldsymbol{s}) \\ &= \int d\boldsymbol{s}\, B\, T_B(\boldsymbol{s}) \exp\left[-A T_A(\boldsymbol{b}-\boldsymbol{s}) \sigma_{NN}^{\mathrm{inel}}\right] \end{aligned}$$



- events are (typically) categorized
  - soft :: N_{part}
  - hard :: N_{coll}
- how does energy or entropy scale with N_{part} & N_{coll} — not clear



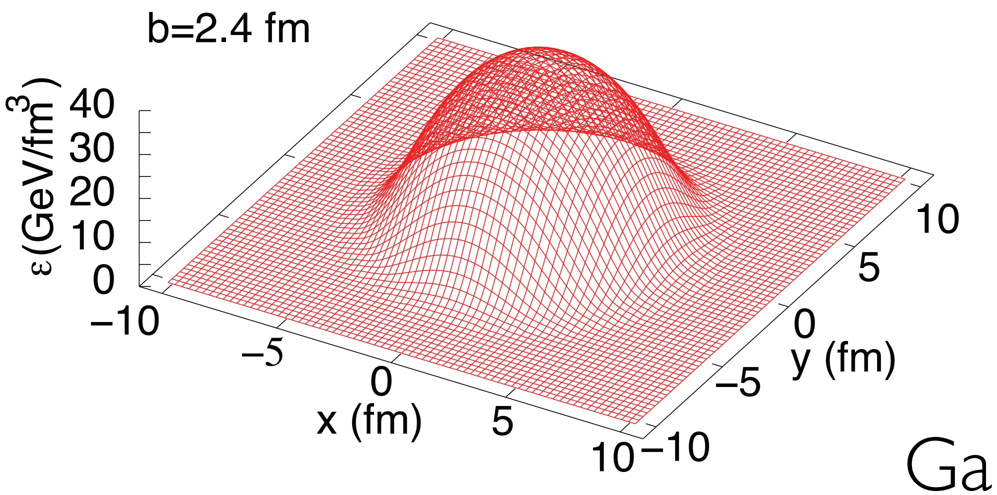
Initial conditions

Smooth distribution of wounded nucleons (participants)

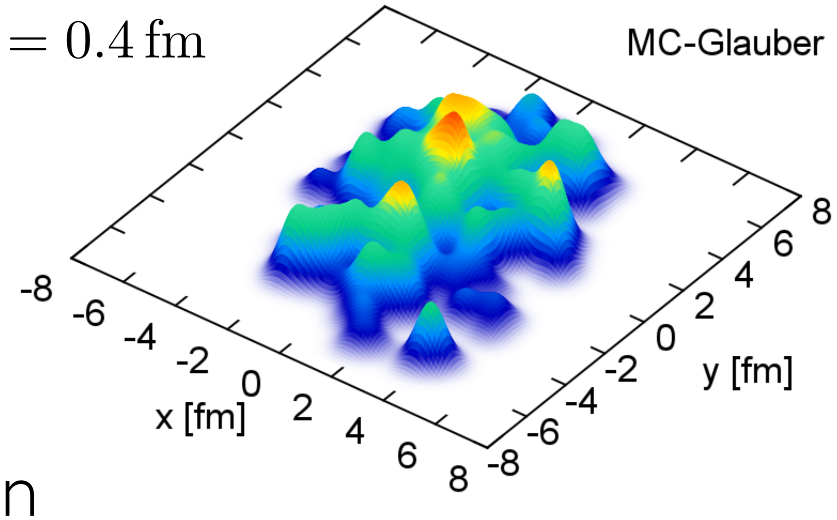
$$N_{\rm part}(x,y,b) = T_A(x+b/2,y)\left[1-\left(1-\sigma_{\rm inel}^{NN}T_B(x-b/2,y)\right)^B\right] \\ + T_B(x-b/2,y)\left[1-\left(1-\sigma_{\rm inel}^{NN}T_A(x+b/2,y)\right)^A\right]$$

Binary collisions per area: $N_{\rm coll}(x,y,b) = \sigma_{\rm inel}^{NN}T_A(x+b/2,y)T_B(x-b/2,y)$

$$\epsilon \propto \frac{dN_{\rm ch}}{d\eta} = \alpha N_{\rm part} + \beta N_{\rm coll}$$



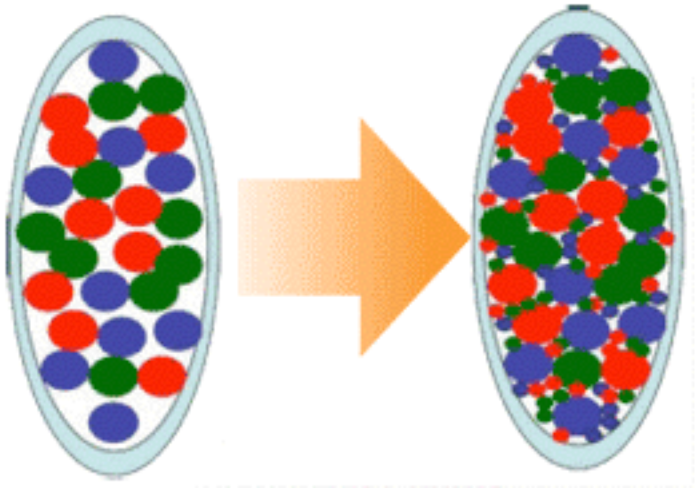
$\sigma_0 = 0.4\,{\rm fm}$



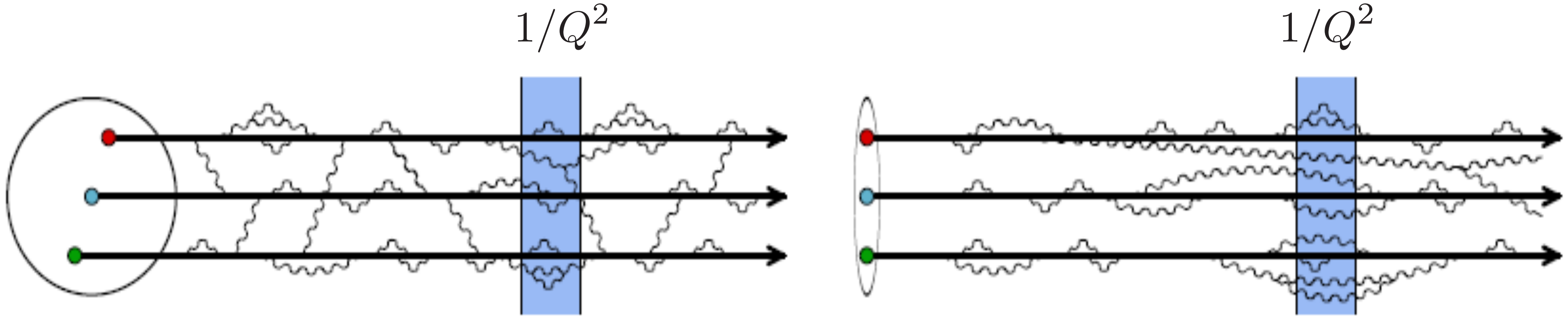
Gaussian randomization

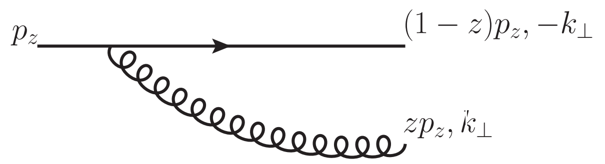
Inner life of nucleons

- the structure of the hadrons changes with energy
- partonic degrees of freedom starts taking over
- space-time picture changes
- related to the physics of infrared & collinear divergences



Digging out gluons

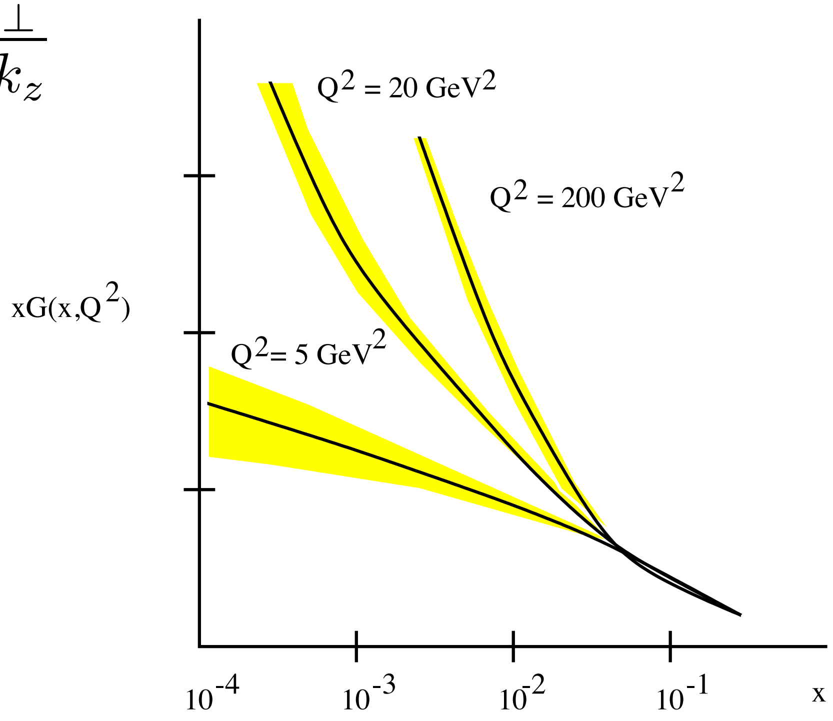




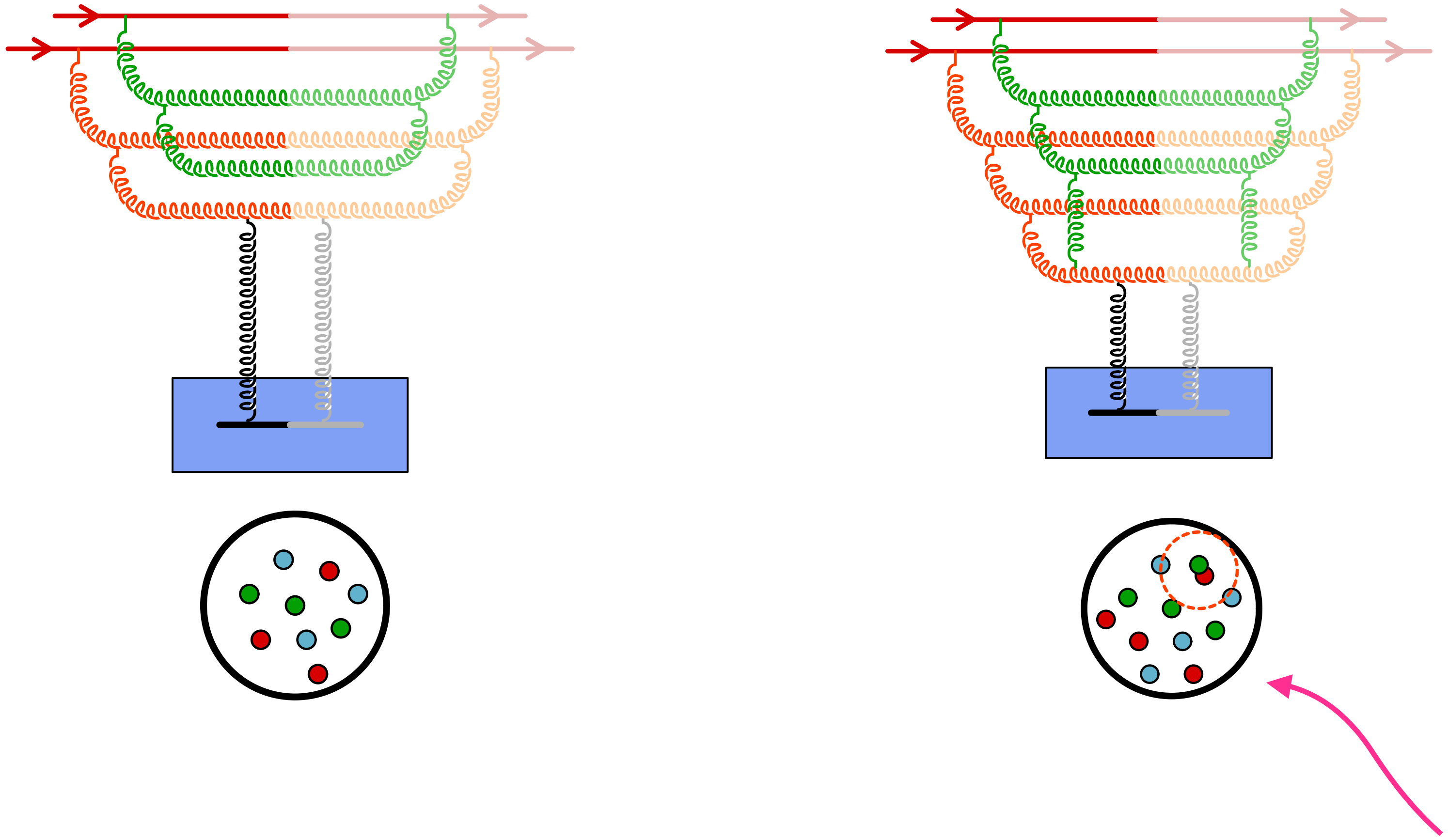
$$
\begin{aligned}
\Delta E &= -p_z + \sqrt{x^2p_z^2+k_\perp^2} + \sqrt{(1-x)^2p_z^2+k_\perp^2} \\
&\approx \frac{k_\perp^2}{2x(1-x)p_z} \approx \frac{k_\perp^2}{2k_z}
\end{aligned}
$$

Lorentz time dilation: soft fluctuations can live over long timescales.

Lifetime vs. interaction time.



Dense environment



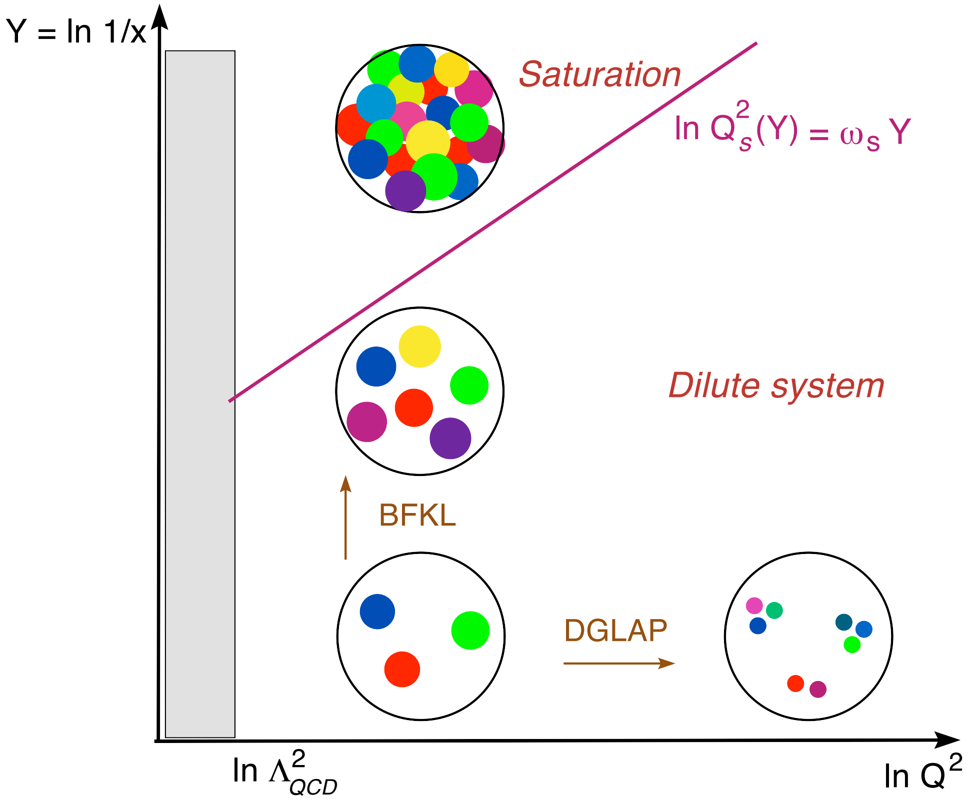
Number of gluons: $N(x, k_\perp) \sim \dfrac{xg(x, k_\perp)}{\pi R^2}$

$N\sigma_{\rm rec} \geq 1 \;\Rightarrow\; k_\perp \leq Q_s(x)$

Interaction cross-section: $\sigma_{\rm rec} \sim \dfrac{\alpha_s}{k_\perp^2}$

Saturation scale: $Q_s^2(x) \sim \dfrac{\alpha_s\, xg(x, Q_s)}{\pi R^2}$

One scale to rule them all



State-of-the-art: Gluon distribution found from solving the Balitsky-Kovchegov equation with running coupling effects.

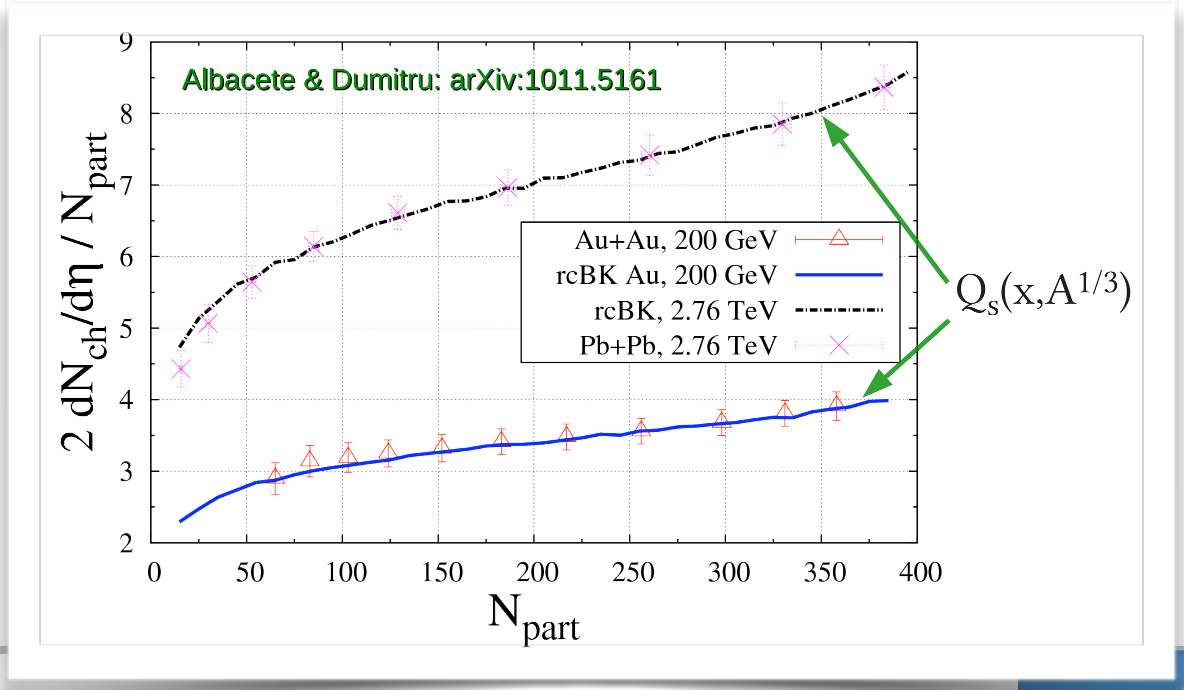
Hard scale of the problem ($Q_s \gg \Lambda_{QCD}$), governs particle production:

$$Q_s^2(x) \sim A^{1/3}\, x^{-\lambda}$$

Kinematics: $$x_{1,2} = \frac{M_\perp}{\sqrt{s}} e^{\pm Y}$$

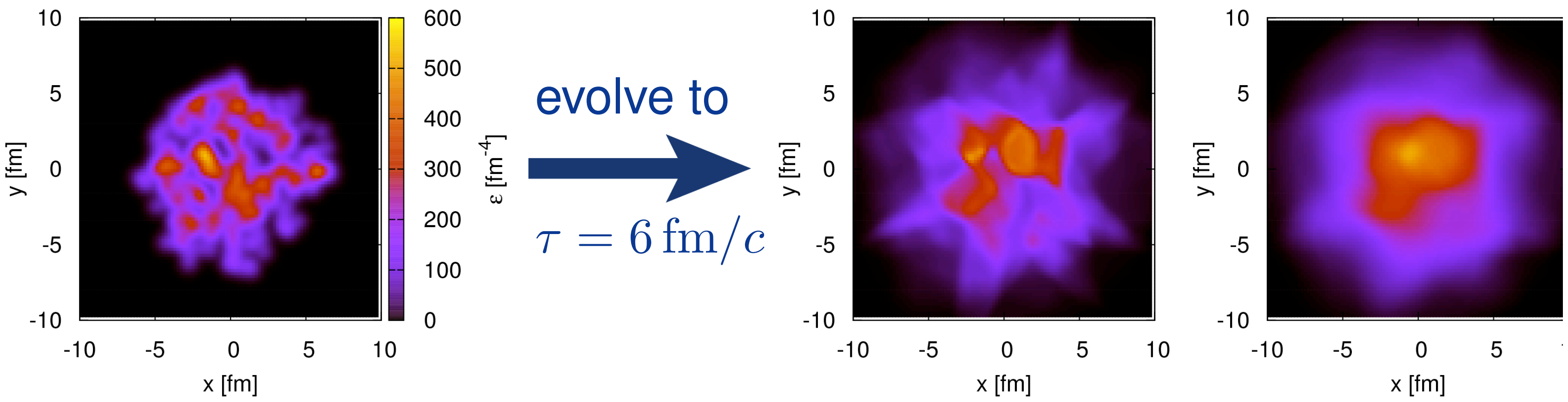
$$x \sim 10^{-2} \qquad \text{at RHIC } (\sqrt{s} = 200 \text{ GeV})$$

$$x \sim 4 \times 10^{-4} \qquad \text{at LHC } (\sqrt{s} = 5.5 \text{ TeV})$$


Albacete & Dumitru: arXiv:1011.5161

Evolving the state

- initial color charge & energy density: sensitivity to size of initial-state fluctuations
- provides initial conditions for hydrodynamics
- can pin down the shear viscosity from observables



initial

evolve to

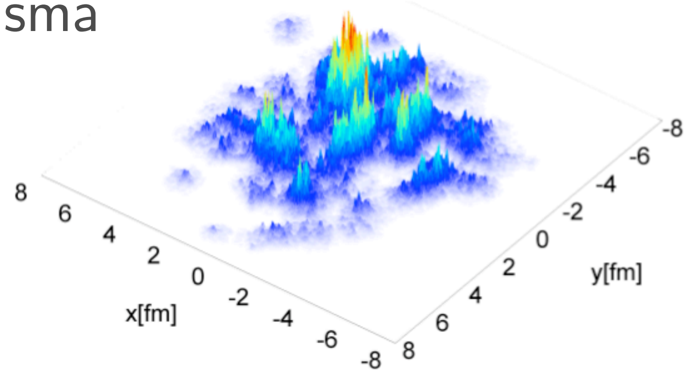
$\tau = 6\,\mathrm{fm}/c$

ideal

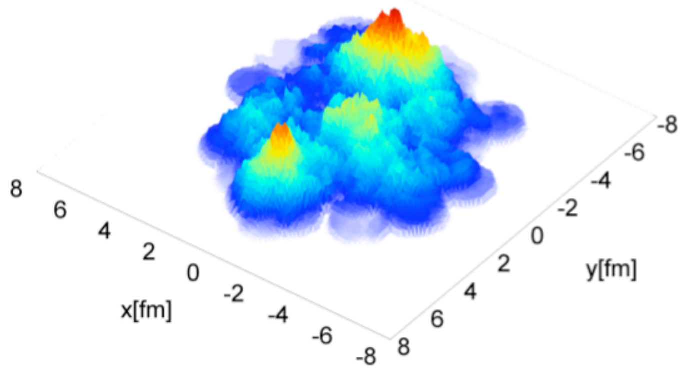
$\eta/s = 0.16$

MUSIC B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)

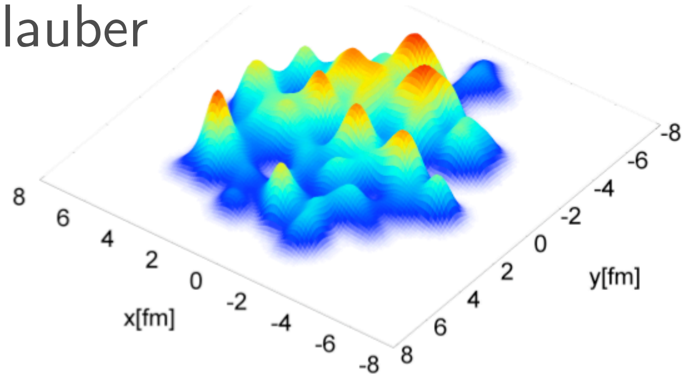
IP-Glasma



MC-KLN



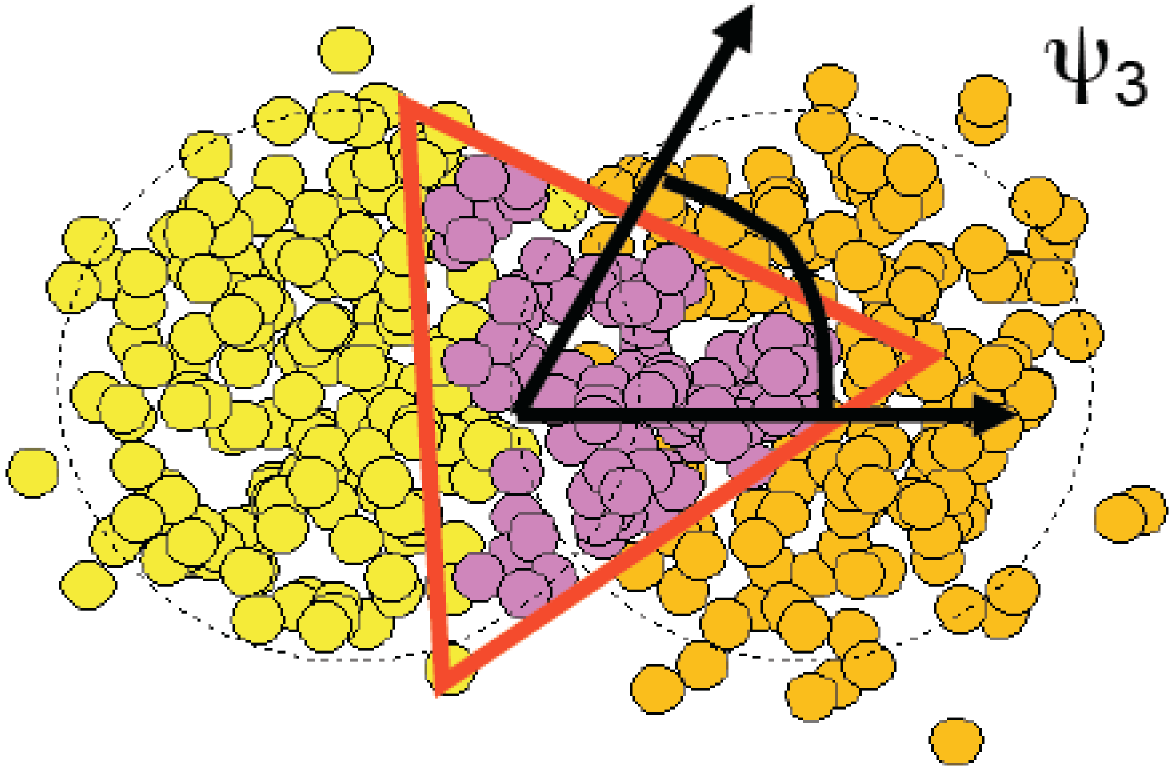
MC-Glauber



Schenke, Tribedy, Venugopalan
1206.6805. PRL 108 (2012)

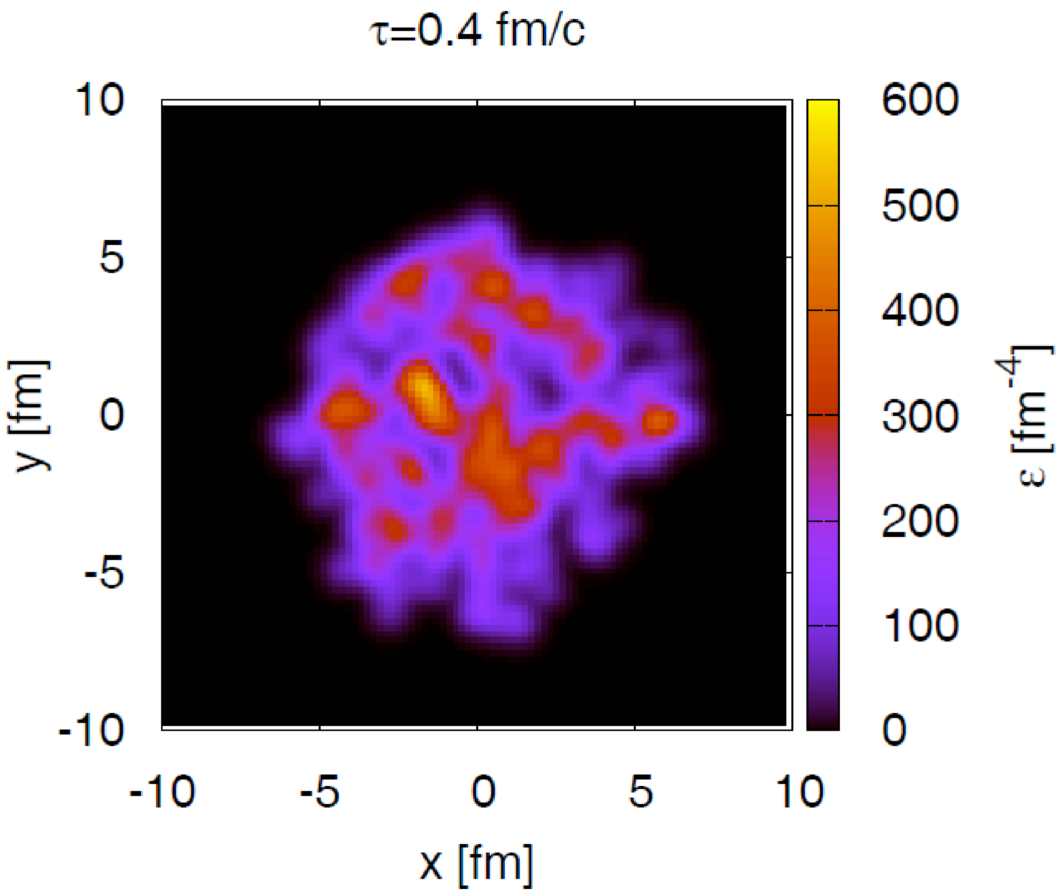
Non-central collisions

Glauber Model



B. Alver, G. Roland, PRC81 (2010) 054905

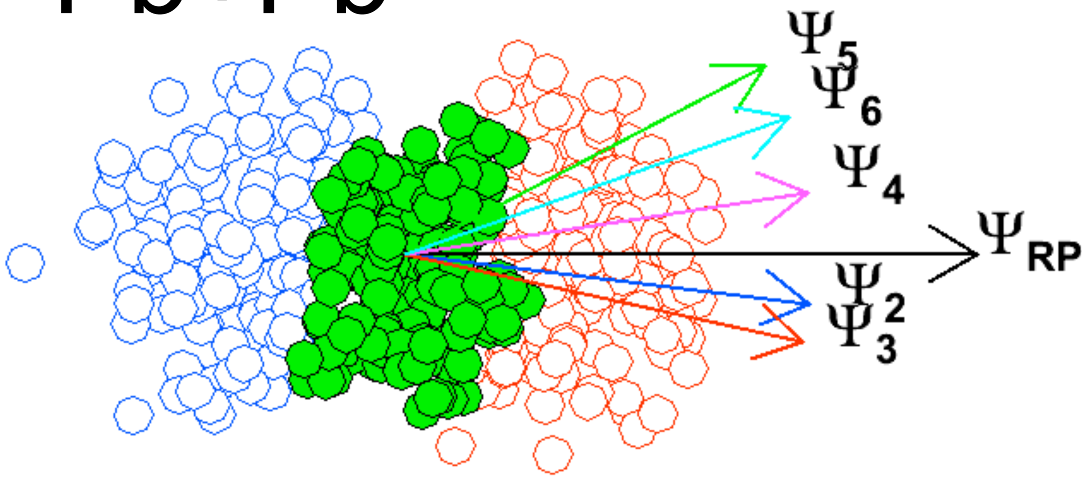
Viscous Hydro.



B. Schenke, S. Jeon, C. Gale PRL 106, 042301

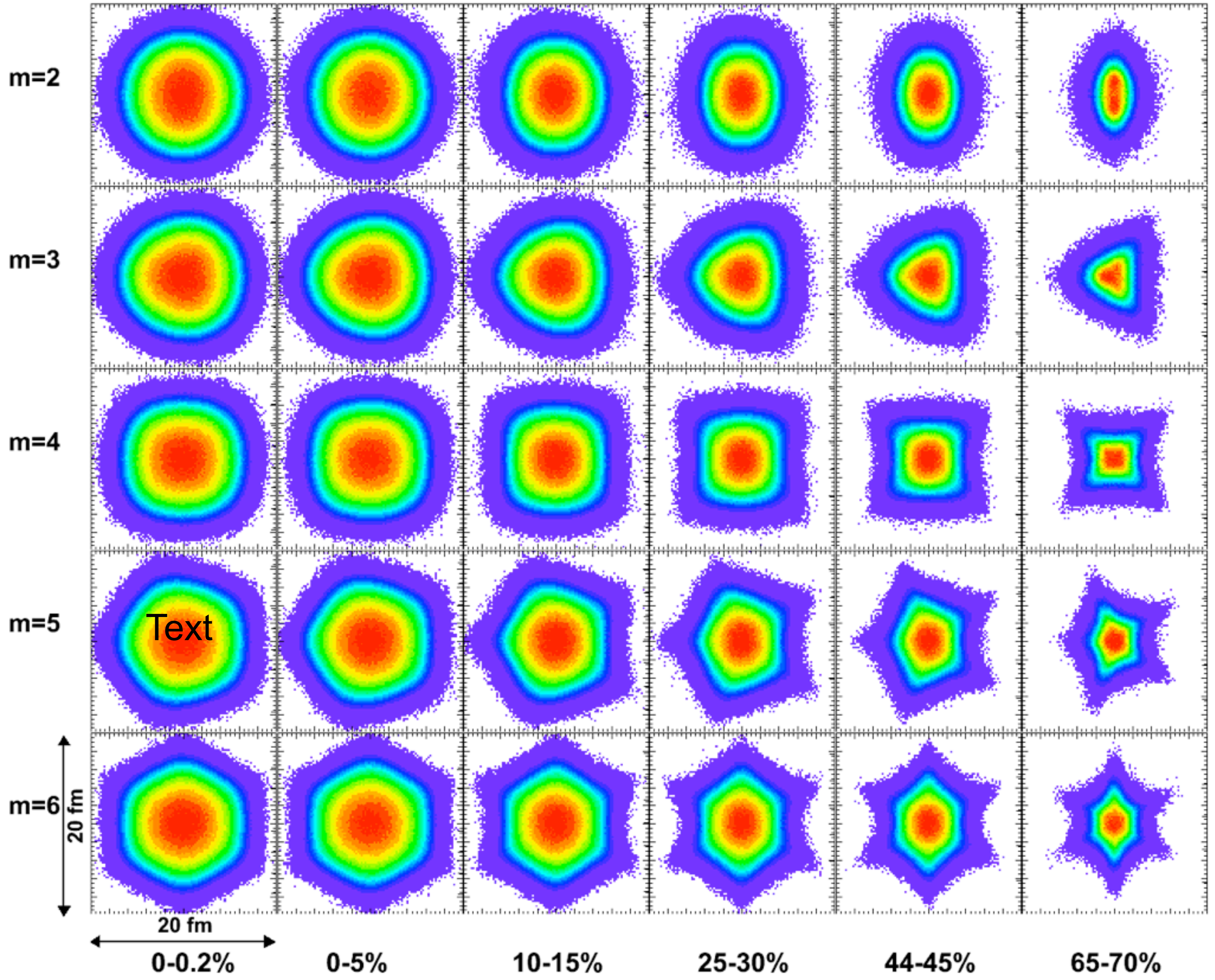
Participant densities with respect to participant plane:

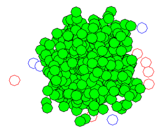
Pb+Pb

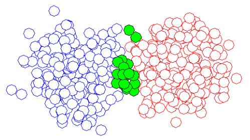


Centrality ∝35%

$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} \left(r_i'\right)^m \sin\left(m\phi_i'\right)}{\sum_{i=1}^{N_{part}} \left(r_i'\right)^m \cos\left(m\phi_i'\right)}\right\} - \frac{\pi}{m}$$







Measure:

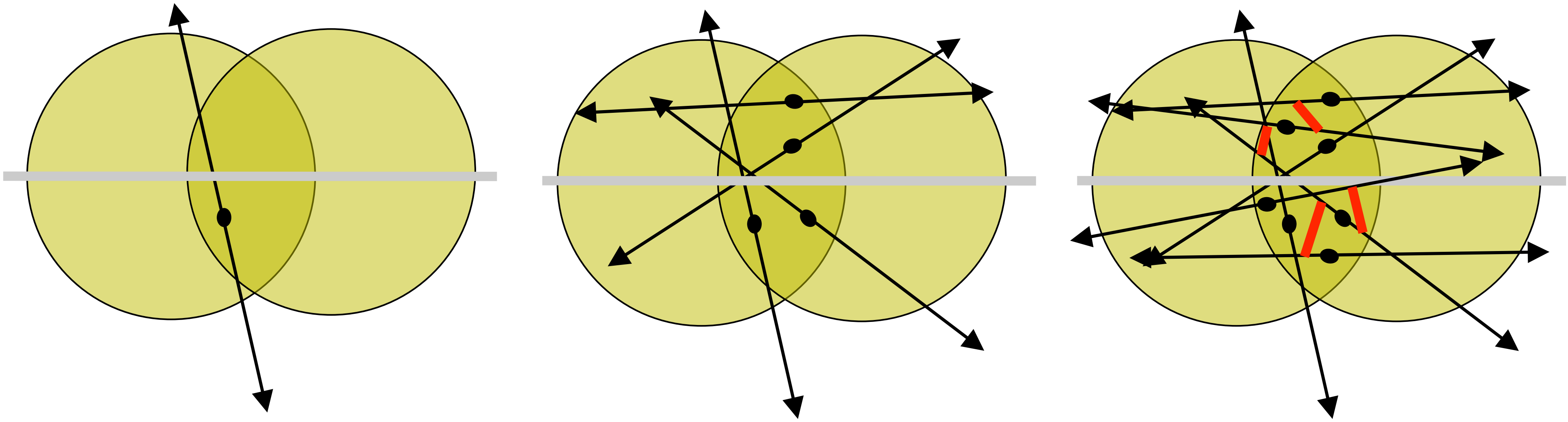
$$\frac{dN}{d\left(\phi-\Psi_m\right)} \propto 1+\sum_{n\geq m}^{\infty} 2v_n^{\mathrm{obs}}\left\{\Psi_m\right\}\cos\left[n\left(\phi-\Psi_m\right)\right]$$

Expectation:

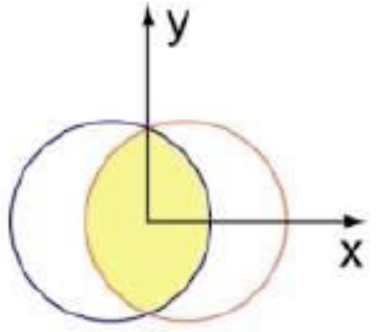
v_n=(medium evolution)×ε_n

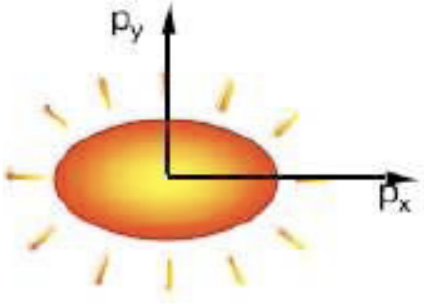
$$\Psi_m \approx \Psi_m^{pp}$$

Azimuthal asymmetries



courtesy: U.A. Wiedemann (Spåtind 2012)





dilute case	free streaming	final-state interactions
YES	YES (smaller ~1/√N)	YES
NO	NO	YES (collective component)

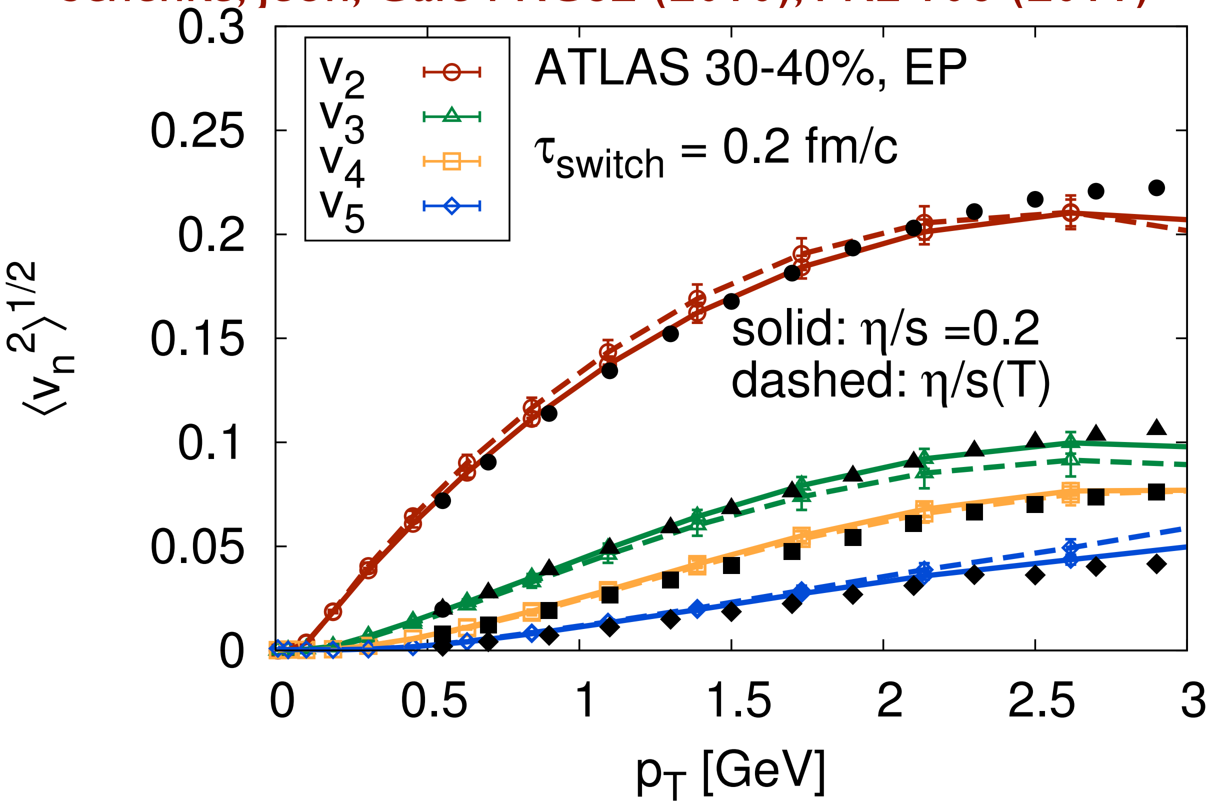
- degree of final state interactions determine the how effectively spatial asymmetries transform to momentum asymmetries
- limit σ→∞: hydrodynamical limit

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

reaction plane

The QGP flows

Schenke, Jeon, Gale PRC82 (2010), PRL 106 (2011)



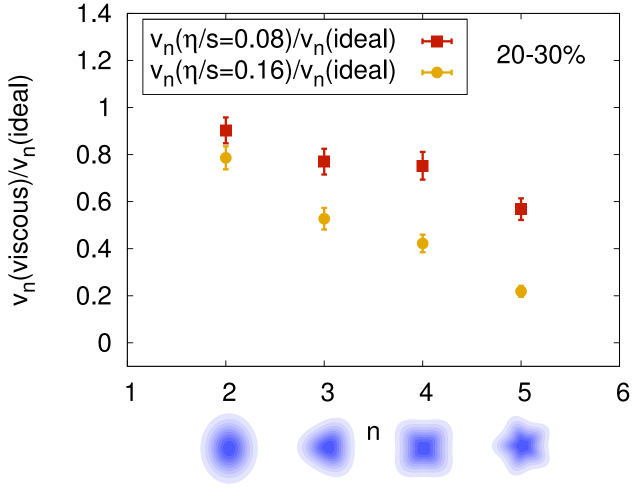
- transport coefficients can be found
- hierarchy of v_n coefficients consistent with almost perfect liquid

$$0.07 \leq \eta/s \leq 0.43$$

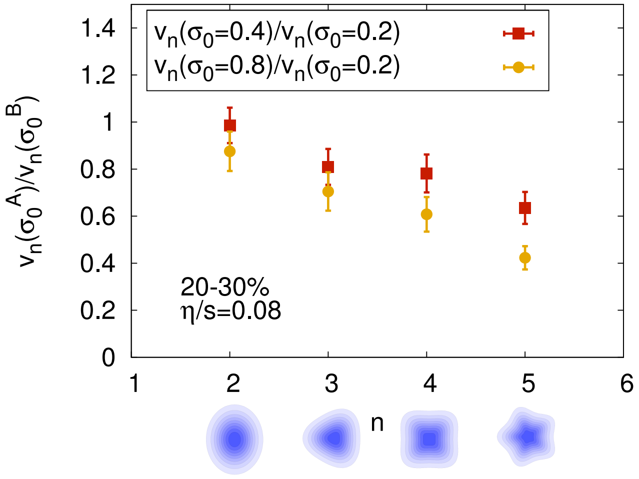
Luzum, Ollitrault et al.

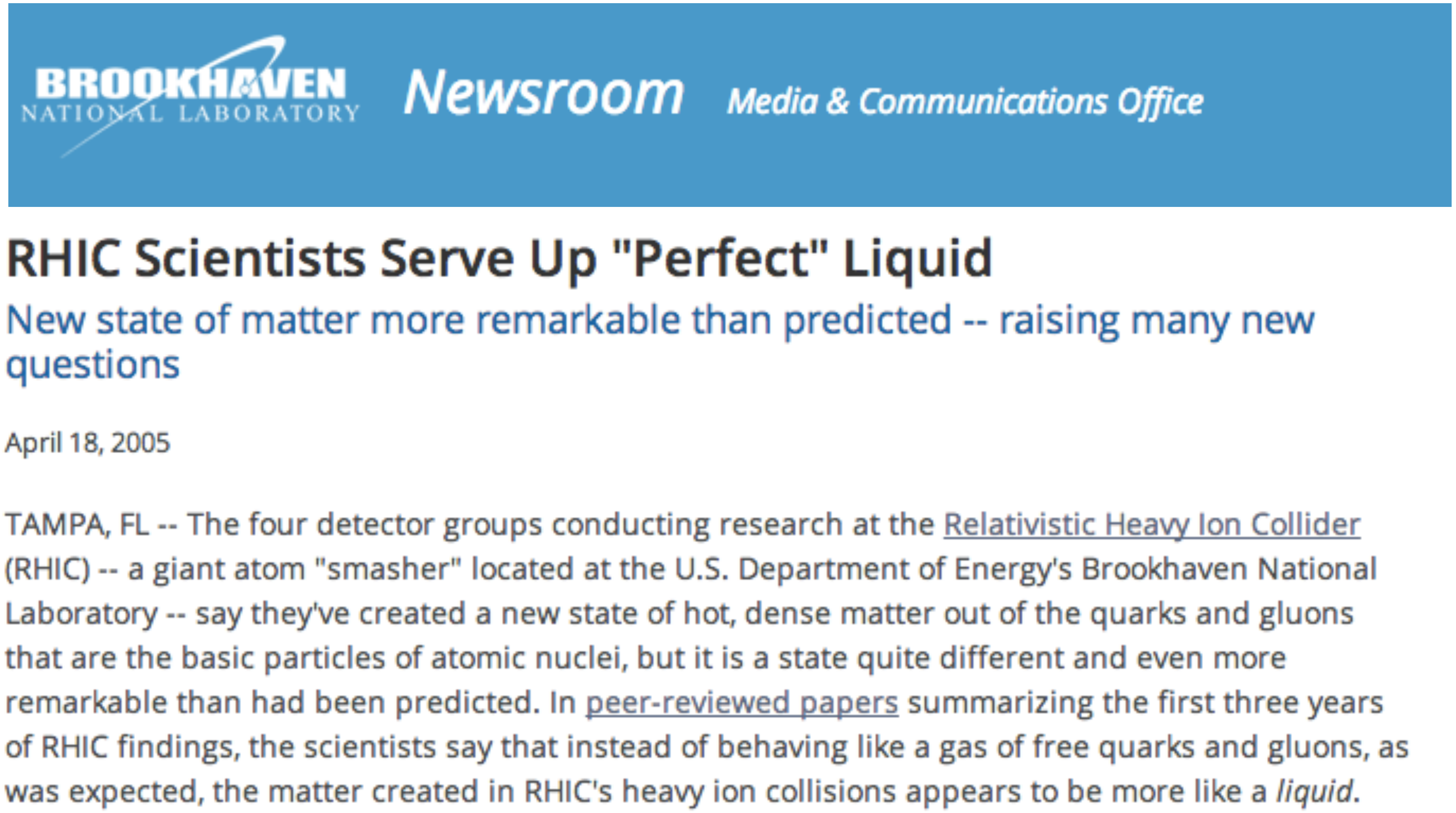
- higher harmonics are more sensitive to viscosity and granularity

viscosity



initial state granularity





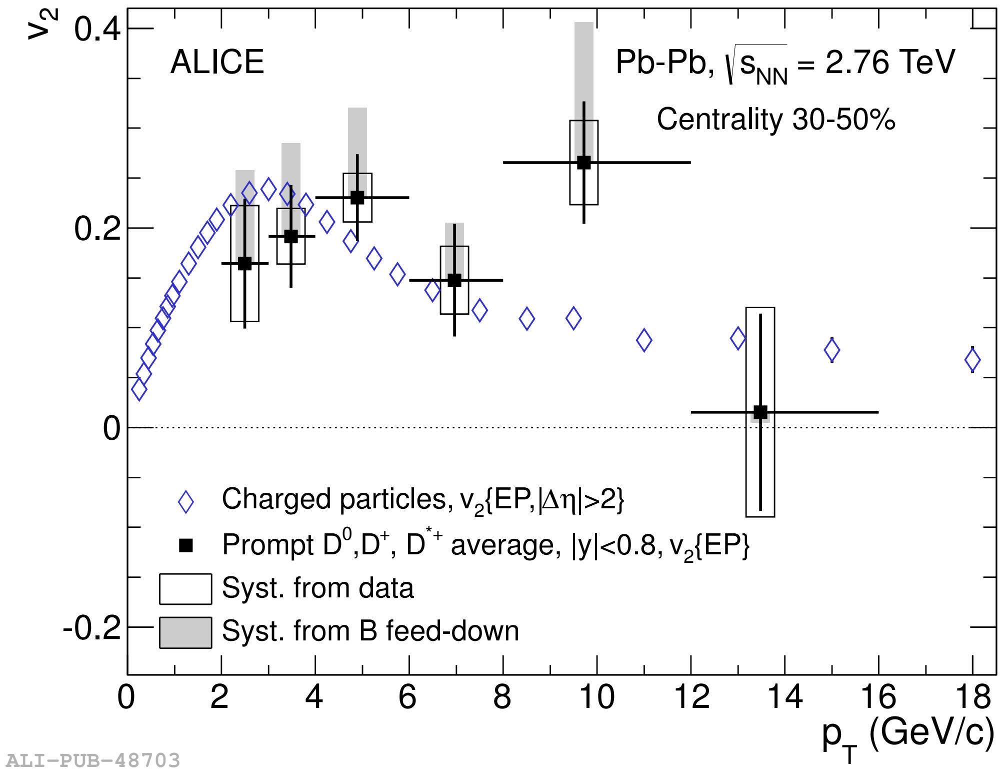
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

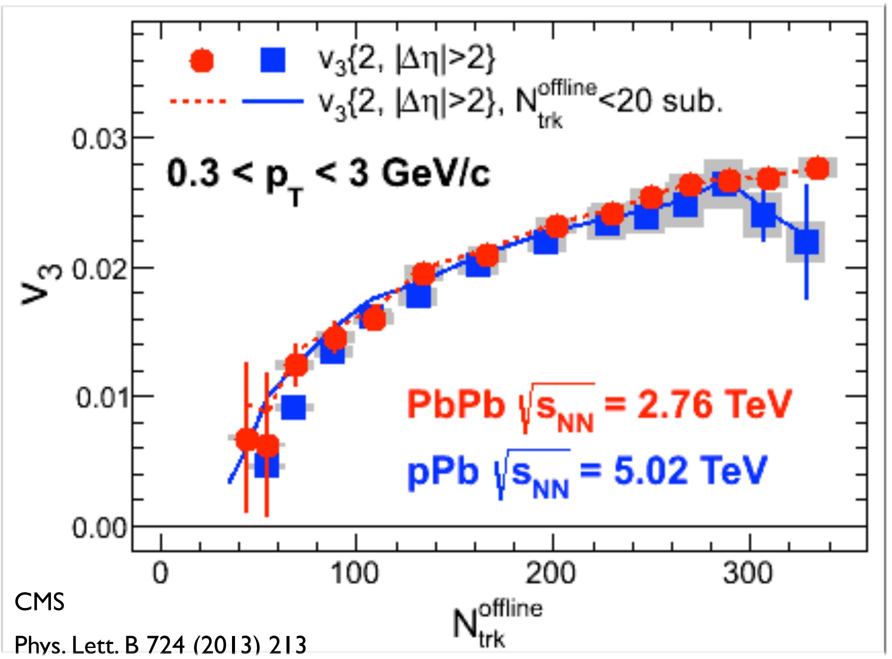
TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Further puzzles



- D meson (= u,d + c)
- mass hierarchy follows from perturbation theory
- in HIC, heavy-quarks behave (flow etc) very similarly to the light quarks
- $T_{eff} \sim m_Q$? strong-coupling dynamics?

Small system (p+Pb) shows very smiliar features — are we completely dominated by fluctuations?



Phys. Lett. B 724 (2013) 213

Summary: QCD fluid in HIC

- perturbative techniques give fundamental insight
- experimental features point to fluid-like features of the formed plasma — good description of data!
- solutions of AdS/CFT shares many of the same features (thermalization, small viscosity)
- what is the gravity dual of "real" QCD? how can we access the strong-coupling regime of QCD otherwise?