Quark-Gluon Plasma

From RHIC to LHC

Berndt Müller

SCGT12

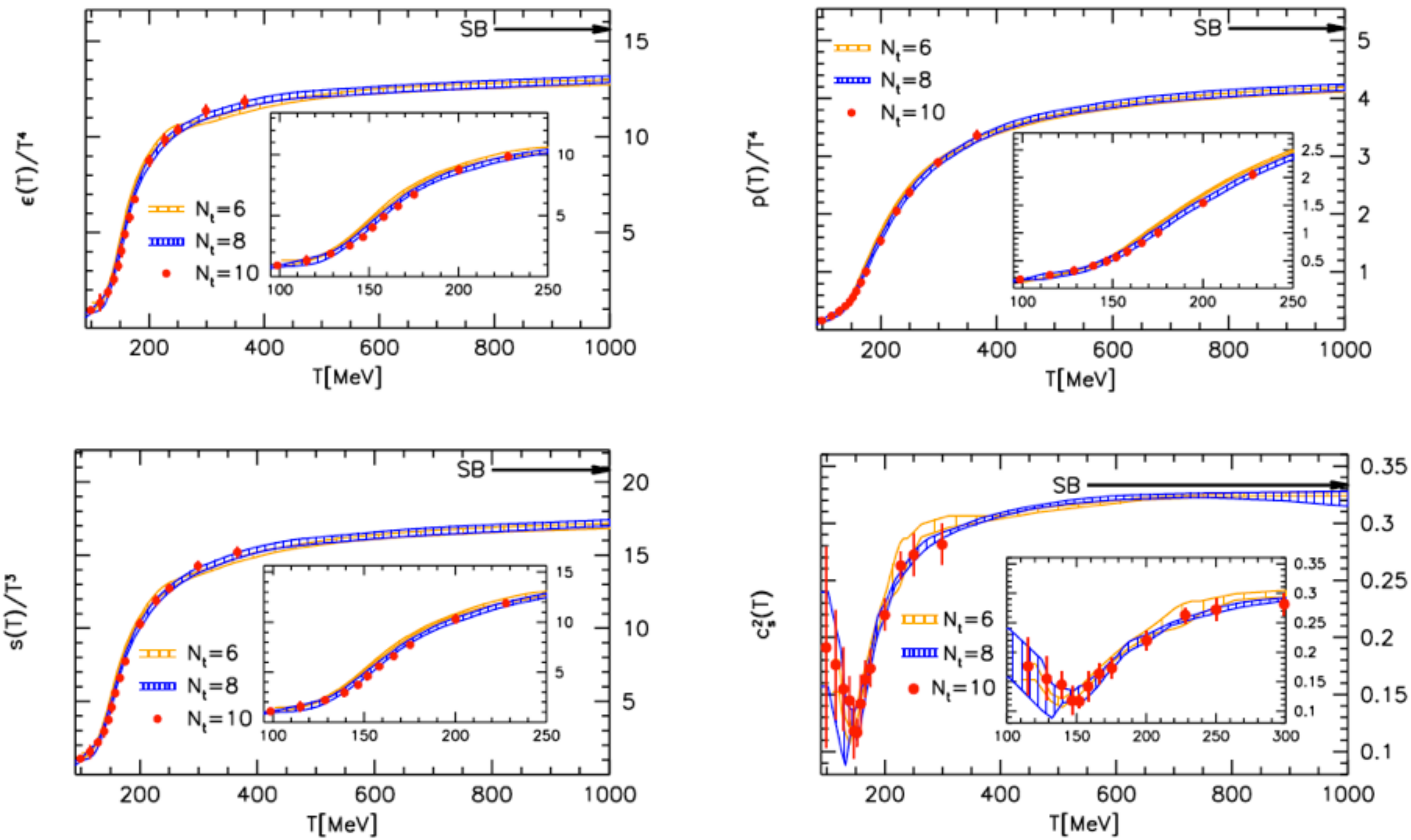
Nagoya

4-7 December 2012

See also: Barbara Jacak and B.M.
The Exploration of Hot Nuclear Matter
Science **337**, 310-314 (20 July 2012)

Introduction

QCD EOS at $\mu_B = 0$

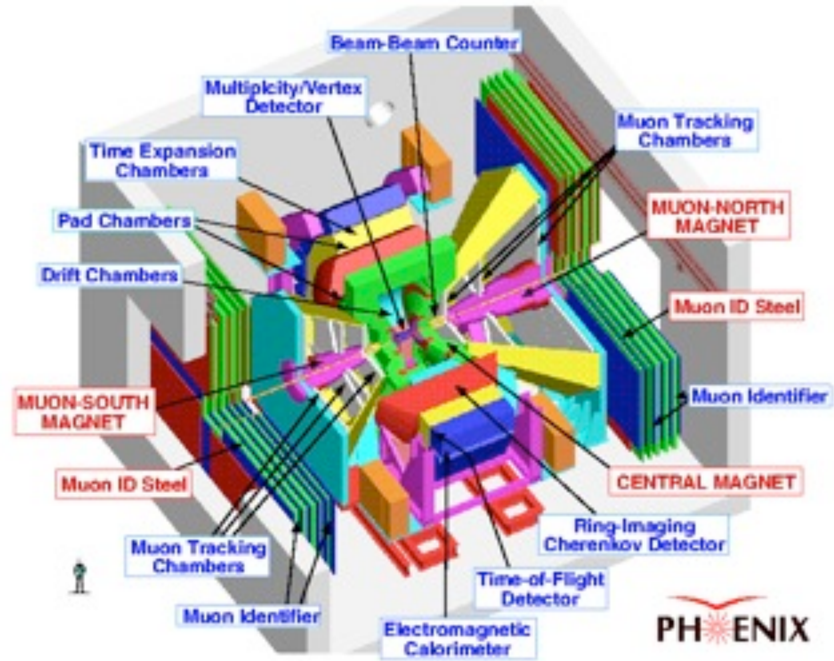


Accelerators

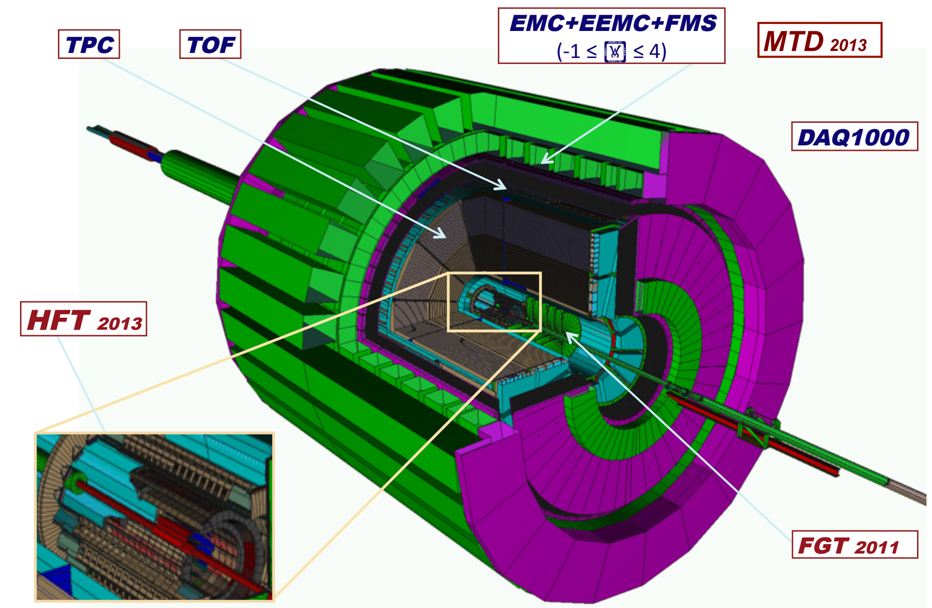
The Large Hadron Collider
27 km circumference
Energy: E_{cm} = 2.76 TeV/NN

The Relativistic Heavy Ion Collider
3.8 km circumference
Top energy: E_{cm} = 200 GeV/NN

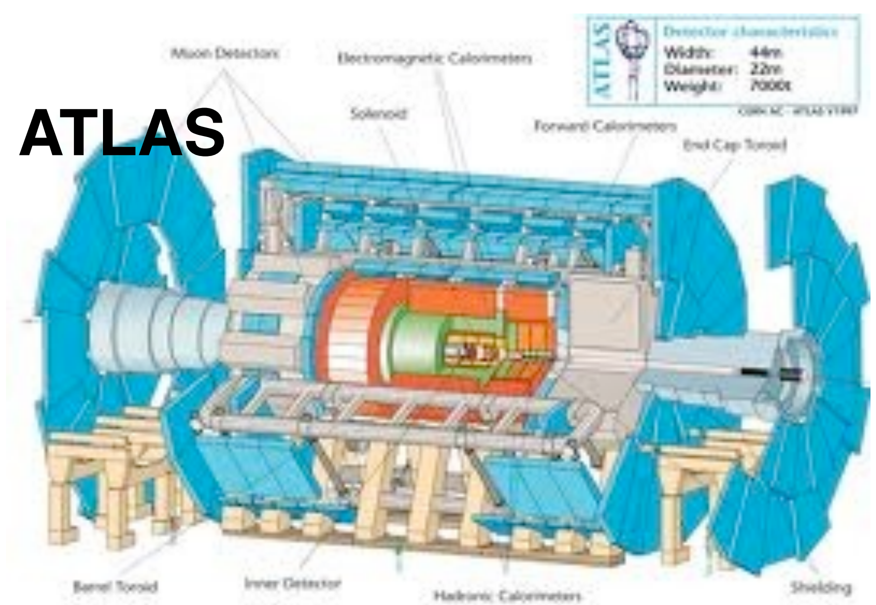
Detectors

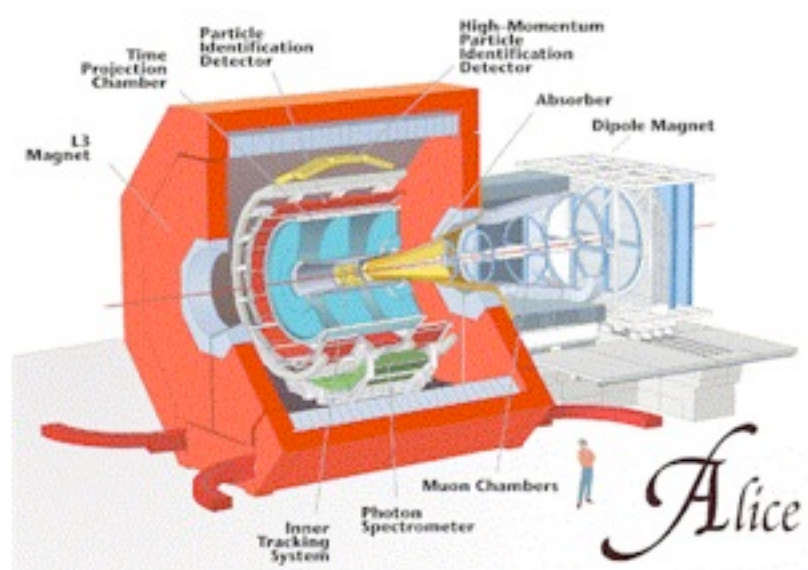


STAR Detector

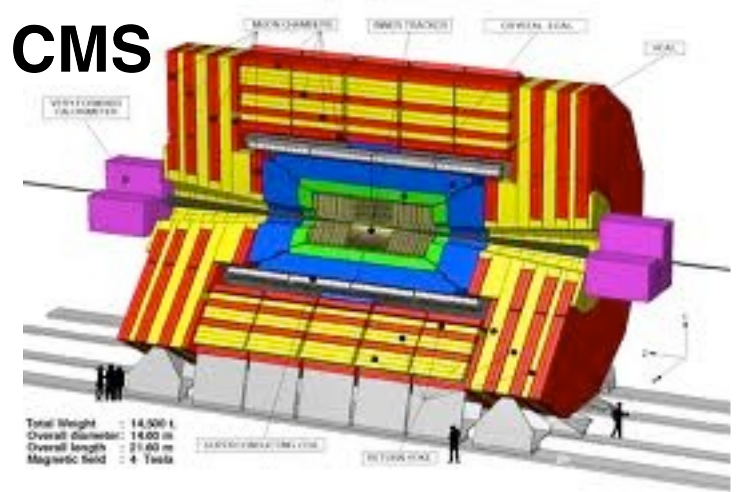


ATLAS

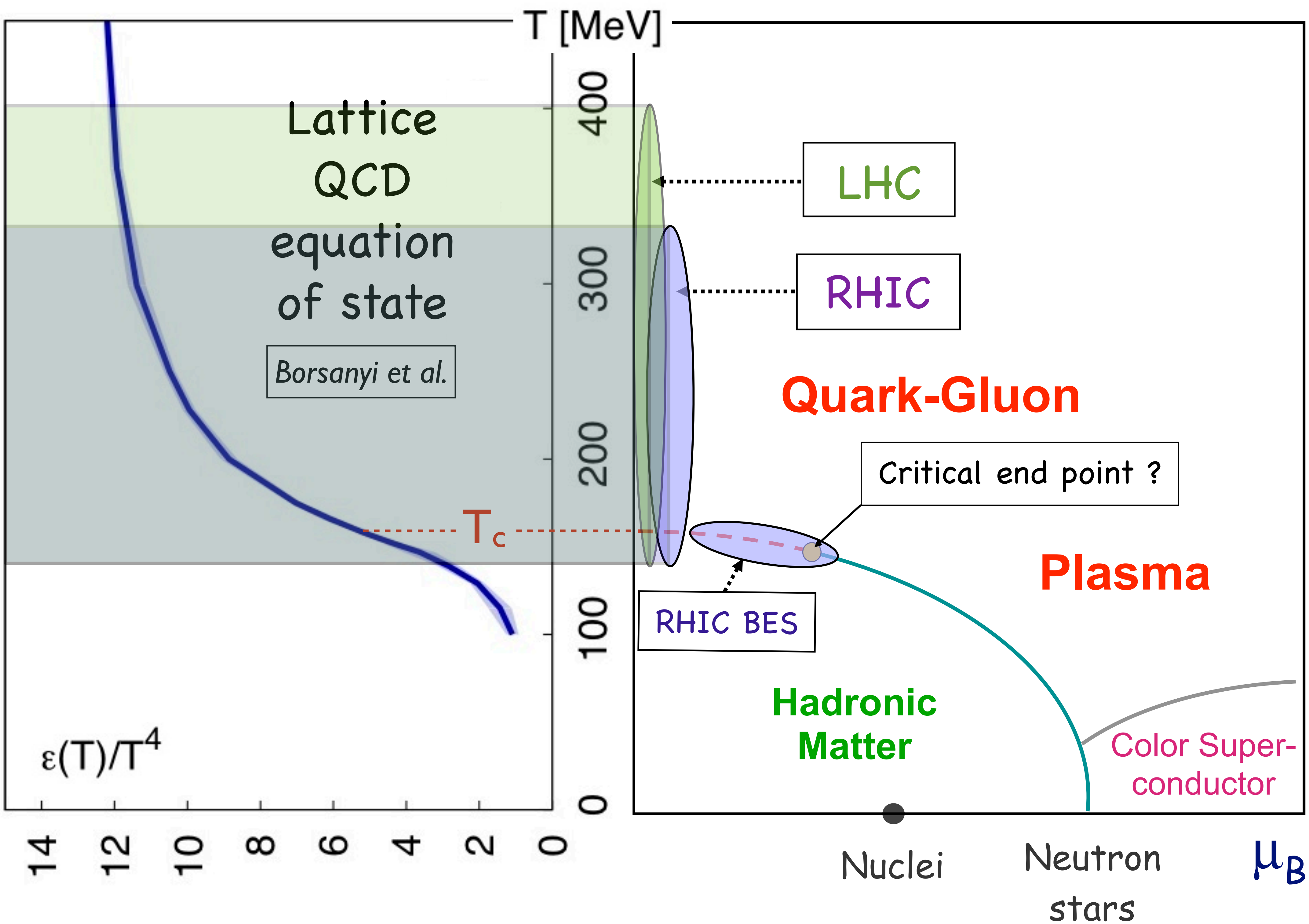




CMS



QCD Phase Diagram



Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, coll. flow, fluctuations

$c_S^2 = \partial p / \partial \varepsilon$ **Speed of sound**: correlations

$\eta = \frac{1}{T}\int d^4x \langle T_{xy}(x) T_{xy}(0) \rangle$ **Shear viscosity**: anisotropic collective flow

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \rangle \\
\hat{e} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \rangle \\
\kappa &= \frac{4\pi \alpha_s}{3N_c} \int d\tau \langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \rangle
\end{aligned}\right\}$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

$m_D = -\lim_{|x| \to \infty} \frac{1}{|x|} \ln \langle U^\dagger E^a(x) U E^a(0) \rangle$ **Color screening**: Quarkonium states

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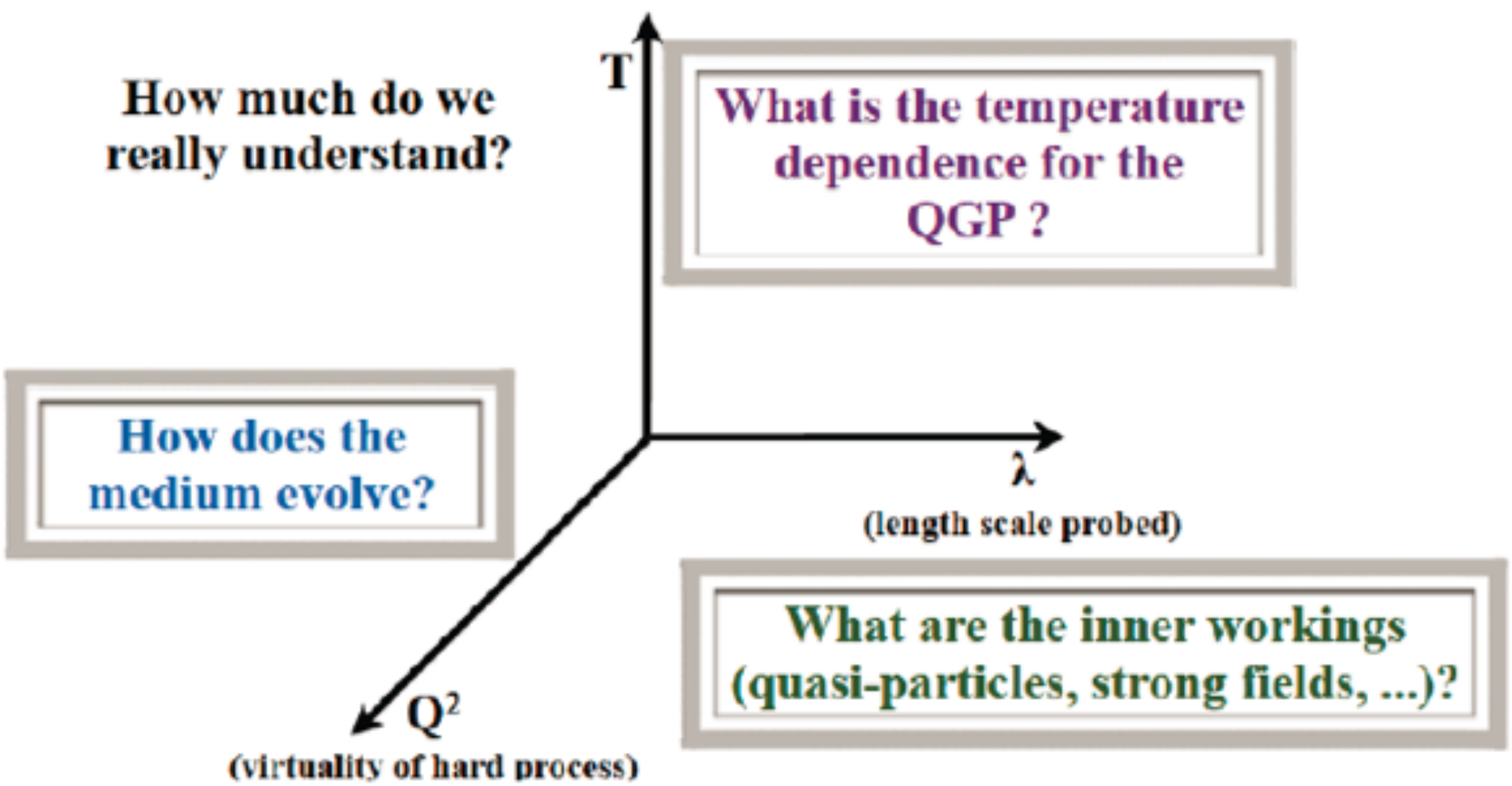
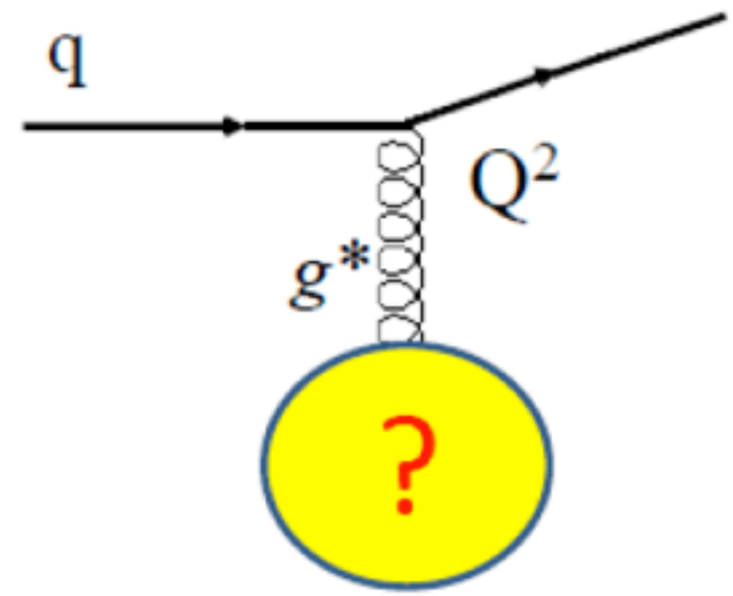
Color screening: Quarkonium states

What we hope to learn

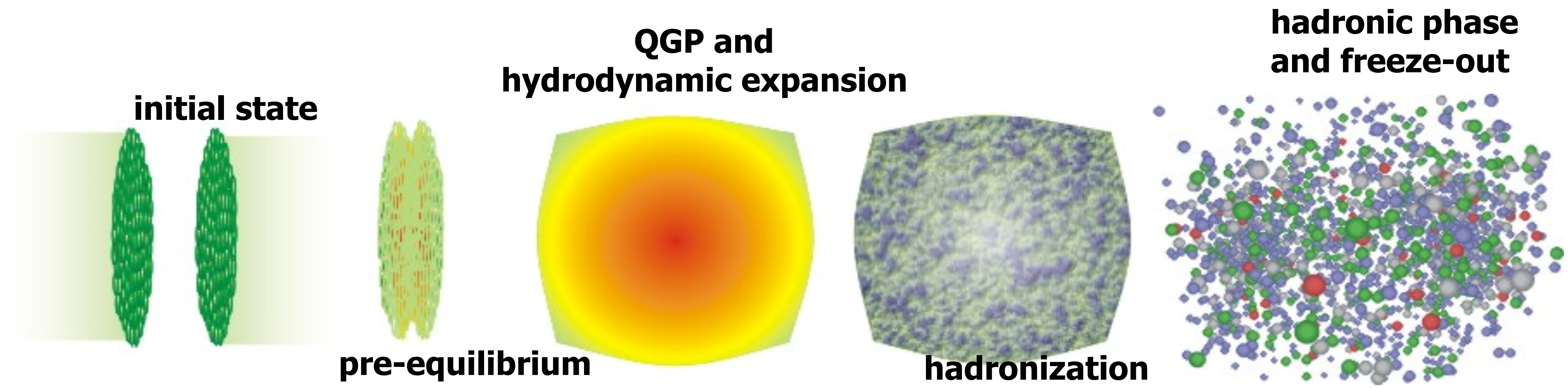
Apart from $\Pi^{\mu\nu}$ all medium properties are expressed as correlators of color gauge fields. They reflect the gluonic structure of the QGP.





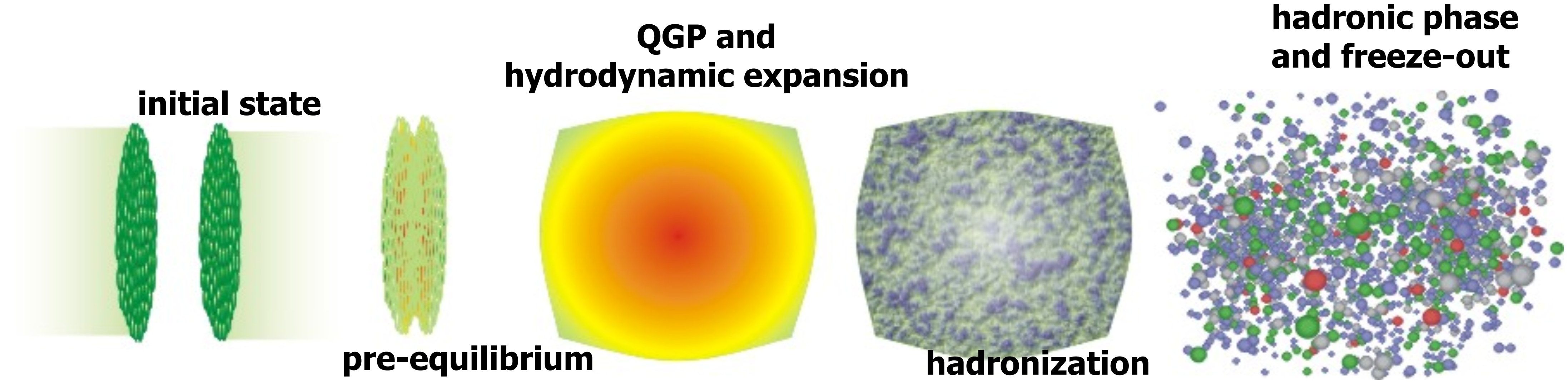
At high Q^2 and/or high T, the QGP is weakly coupled and has a quasiparticulate structure. At which Q^2 (T) does it become strongly coupled? Does it still contain quasiparticles? Can we use hard partons to locate the transition? Which quantities tell us where the transition occurs?

The “standard model”



CGC “Glasma” Hydrodynamics Hadronic gas

The “standard model”



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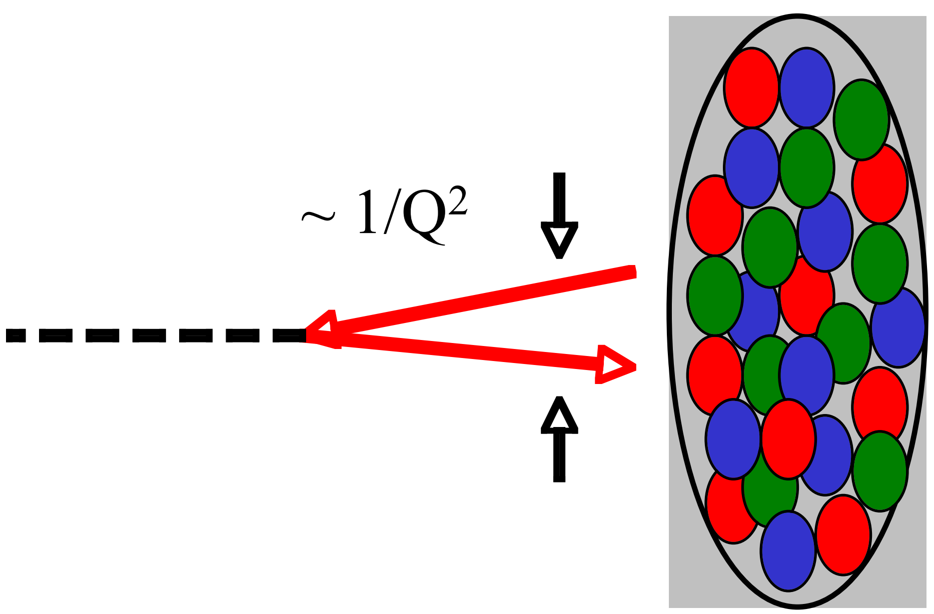
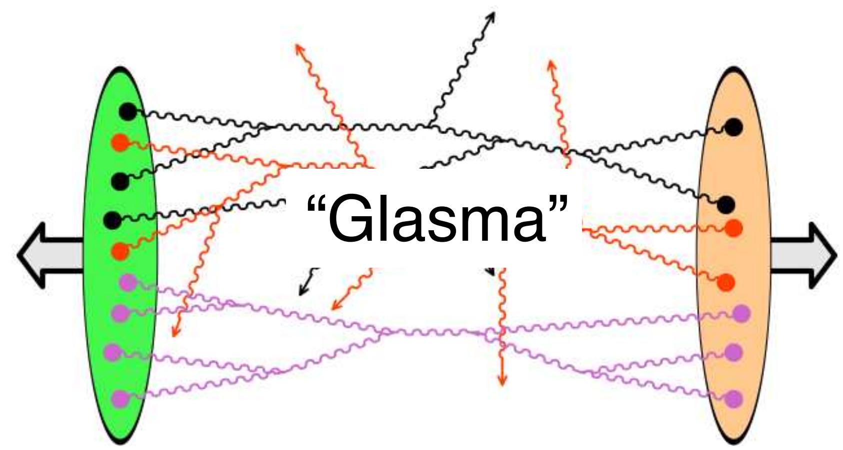


Color Glass Condensate

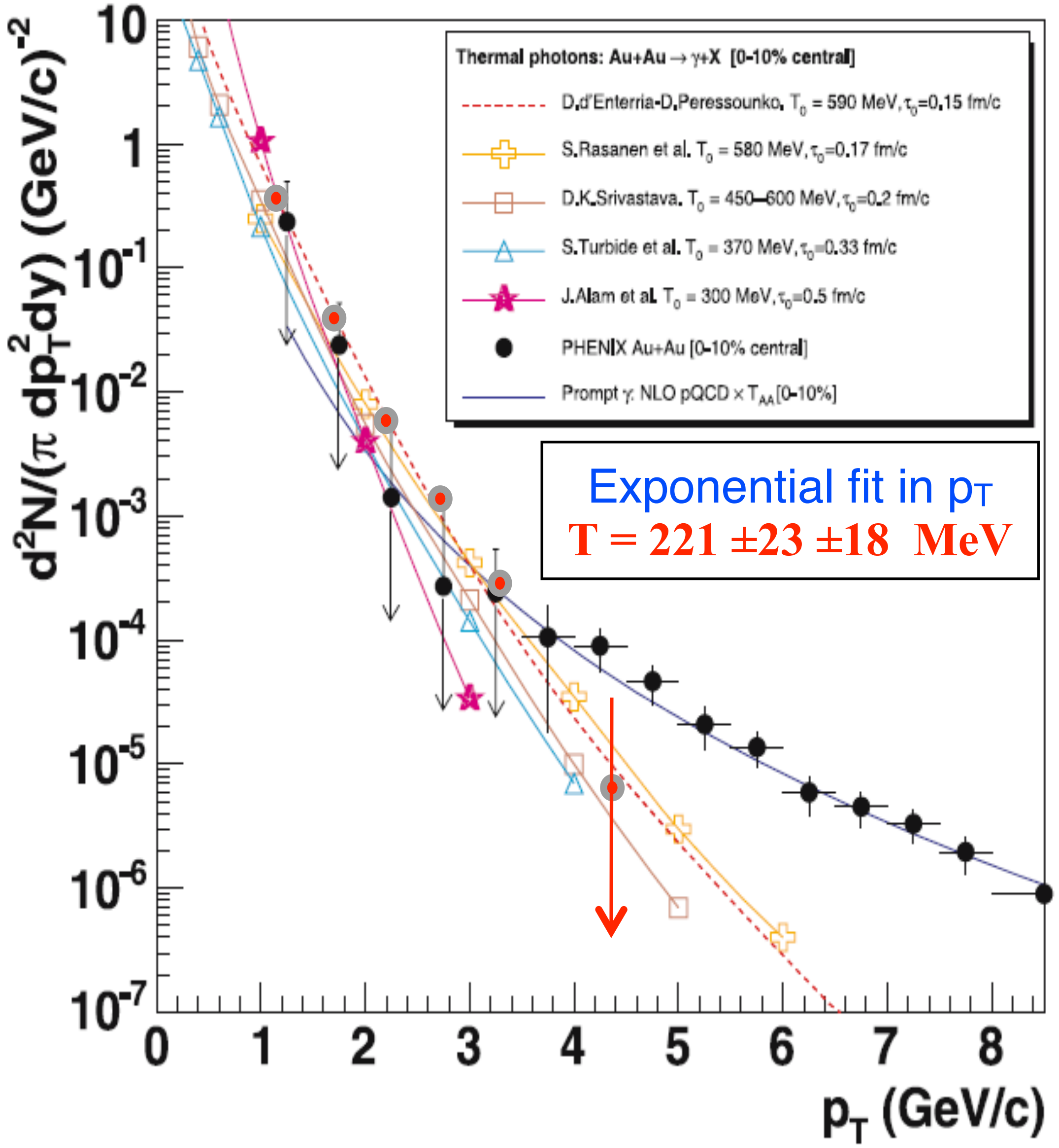
$\Rightarrow Q_s^2(x, A)$

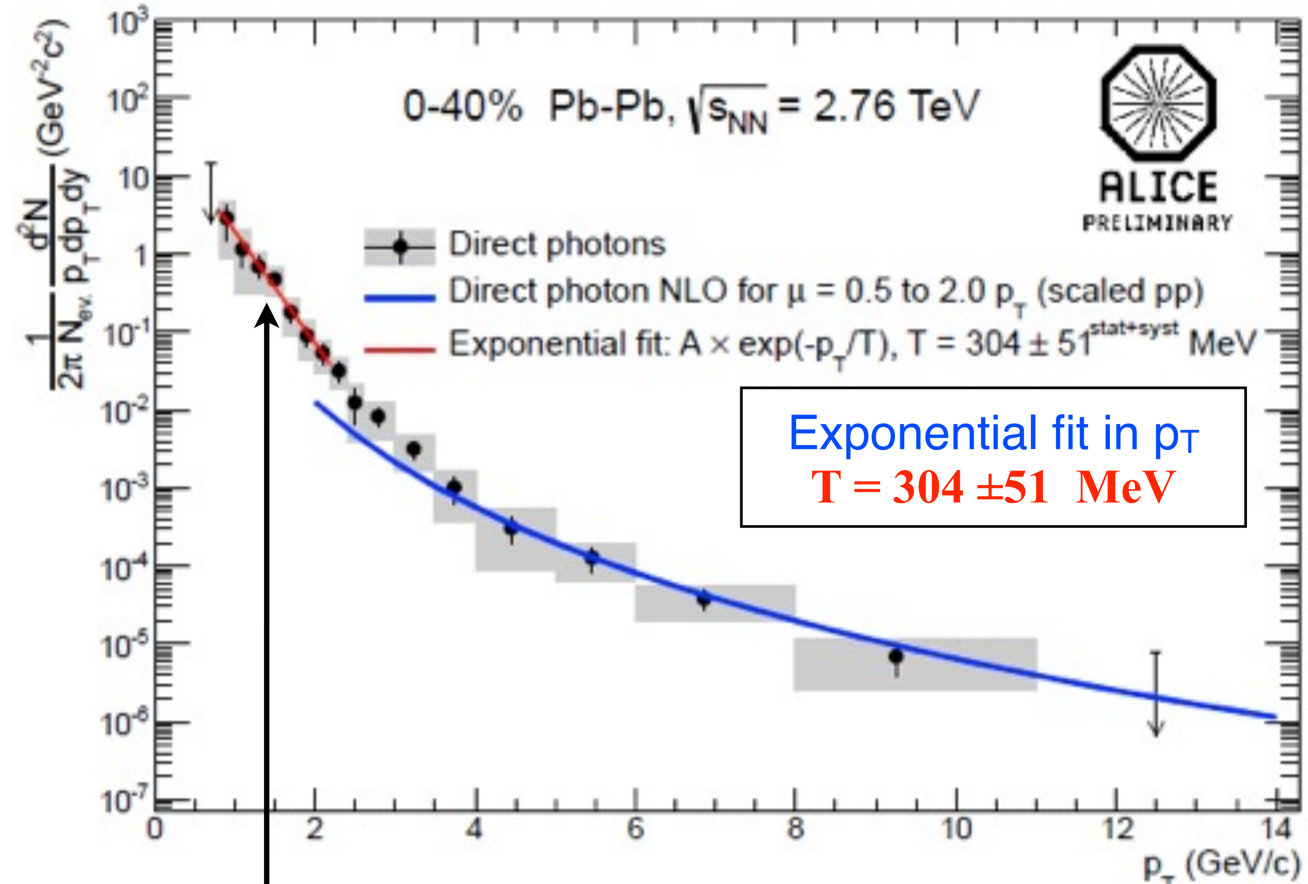


$$\text{gluon density} \times \text{area} \sim \frac{A^{1/3}x^{-0.3}}{Q_s^2} \approx 1$$

Universal saturated state at small x: $Q_s >> \Lambda_{QCD}$

A Guinness record





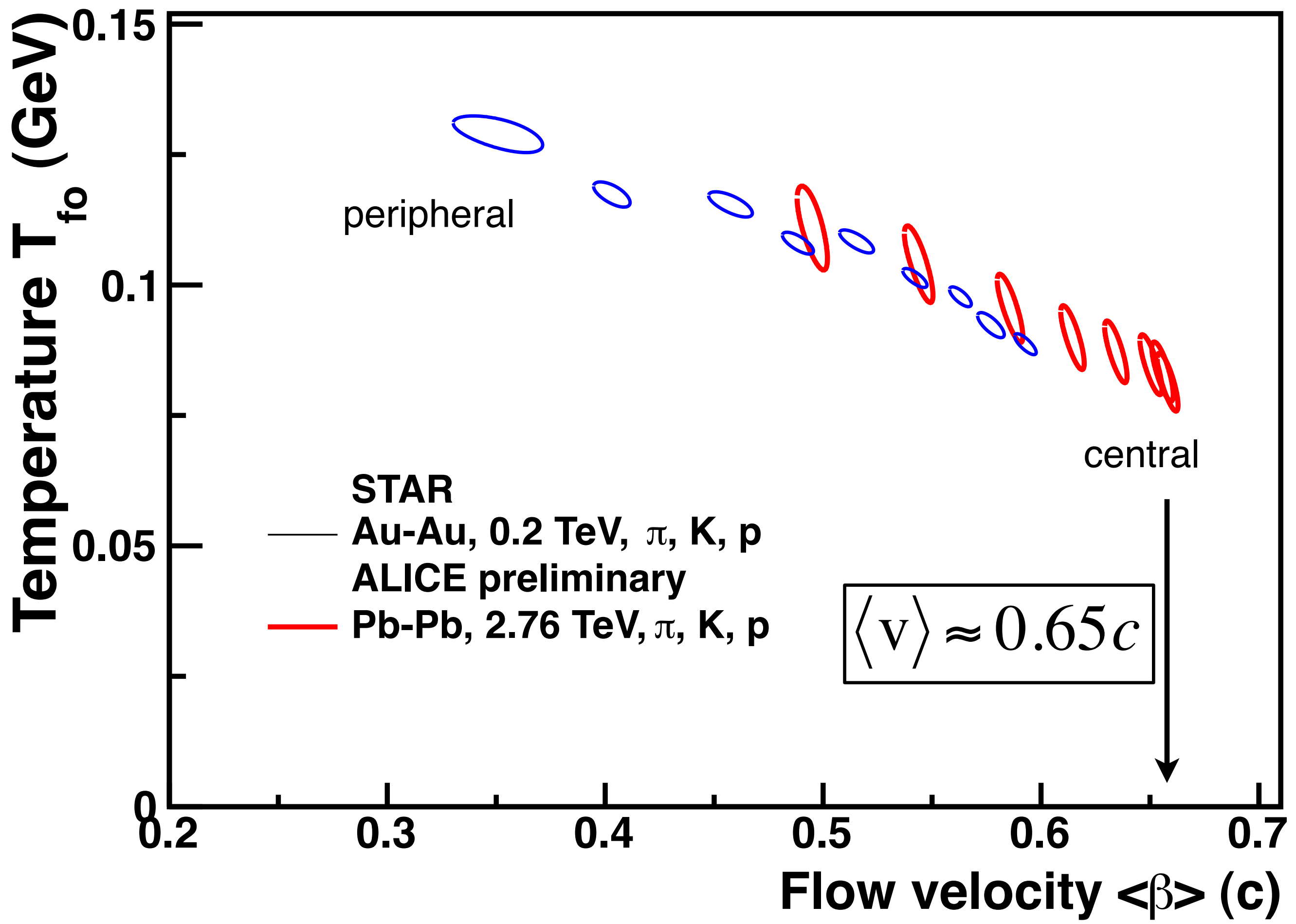
Hydro fits
$T_{init} \geq 300$ MeV

New **record "temperature"** measured in Pb+Pb at LHC:

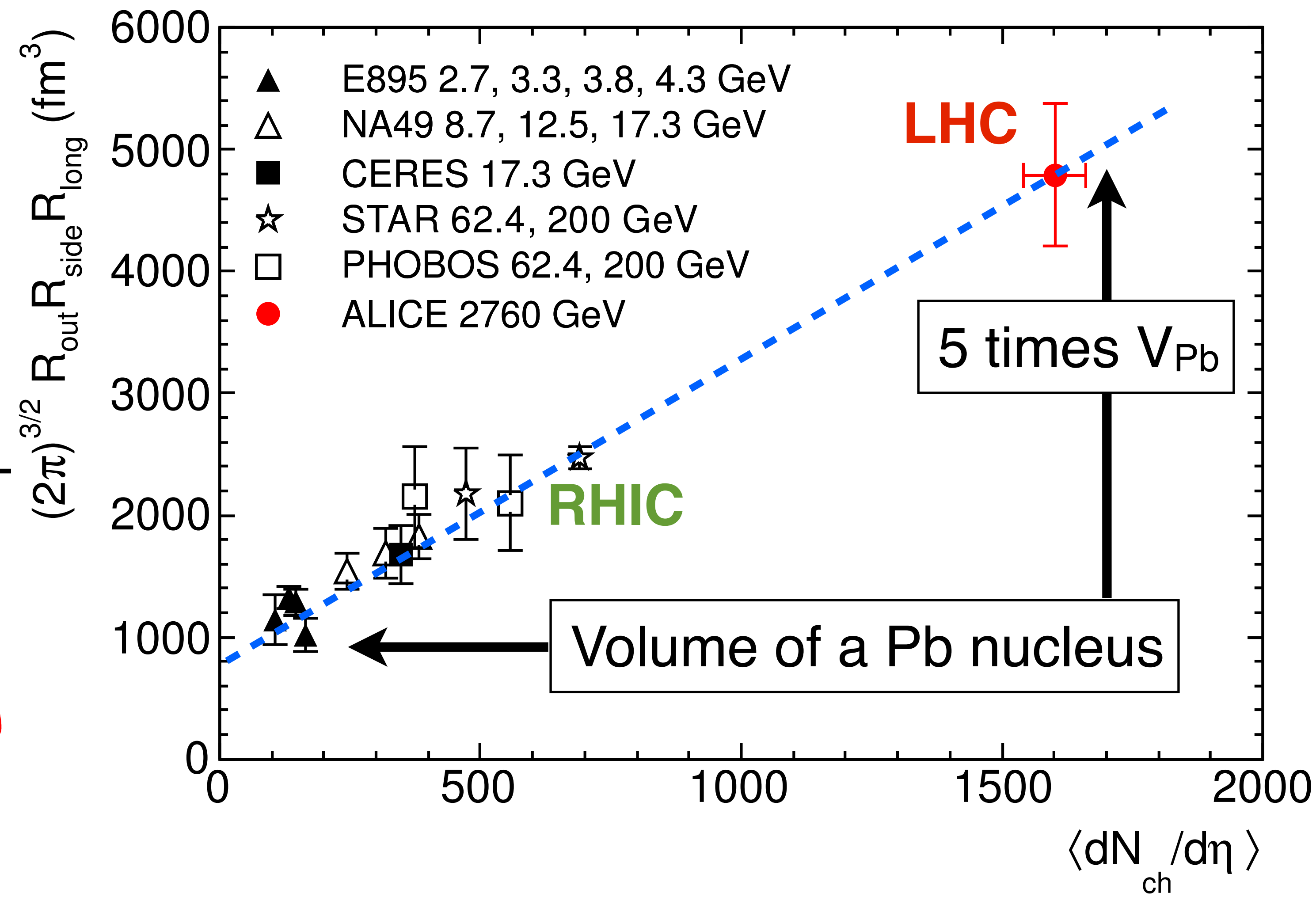
$T_{LHC} = 1.37\ T_{RHIC}$.

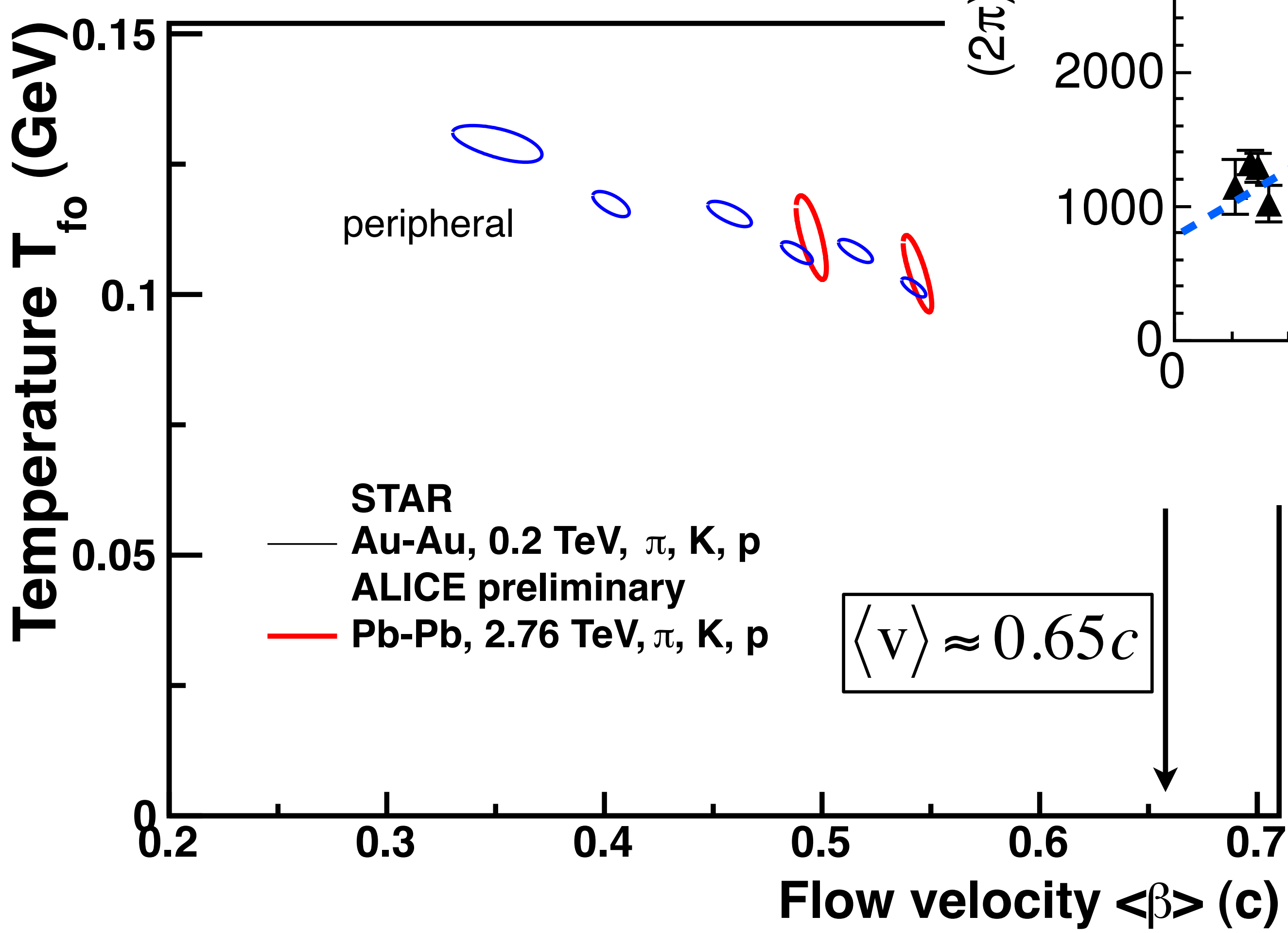
Reflects larger initial temperature T_{in}, but not to be identified with T_{in}.

Size and flow



Size and flow





The “perfect” liquid

Viscous hydrodynamics

Hydrodynamics = effective theory of energy and momentum conservation

energy-momentum tensor = **ideal fluid** + **dissipation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \qquad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

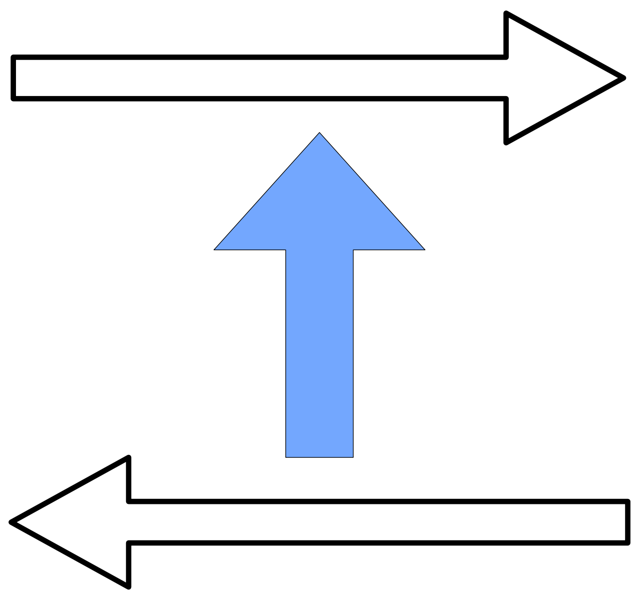
$$\tau_\Pi \left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{du^\lambda}{d\tau} \right] = \eta \left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu}$$

Input: Equation of state P(ε), shear viscosity, initial conditions ε(x,0), u^μ(x,0)

Shear viscosity is normalized by density: kinematic viscosity η/ρ.

Relativistically, the appropriate normalization factor is the entropy density s = (ε+P)/T, because the particle density is not conserved: **η/s**.

Shear viscosity



Shear viscosity describes ability to transport momentum across flow gradients! Kinetic theory:

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f \qquad \lambda_f = \frac{1}{n\sigma} \quad \rightarrow \quad \eta \approx \frac{\bar{p}}{3\sigma}$$

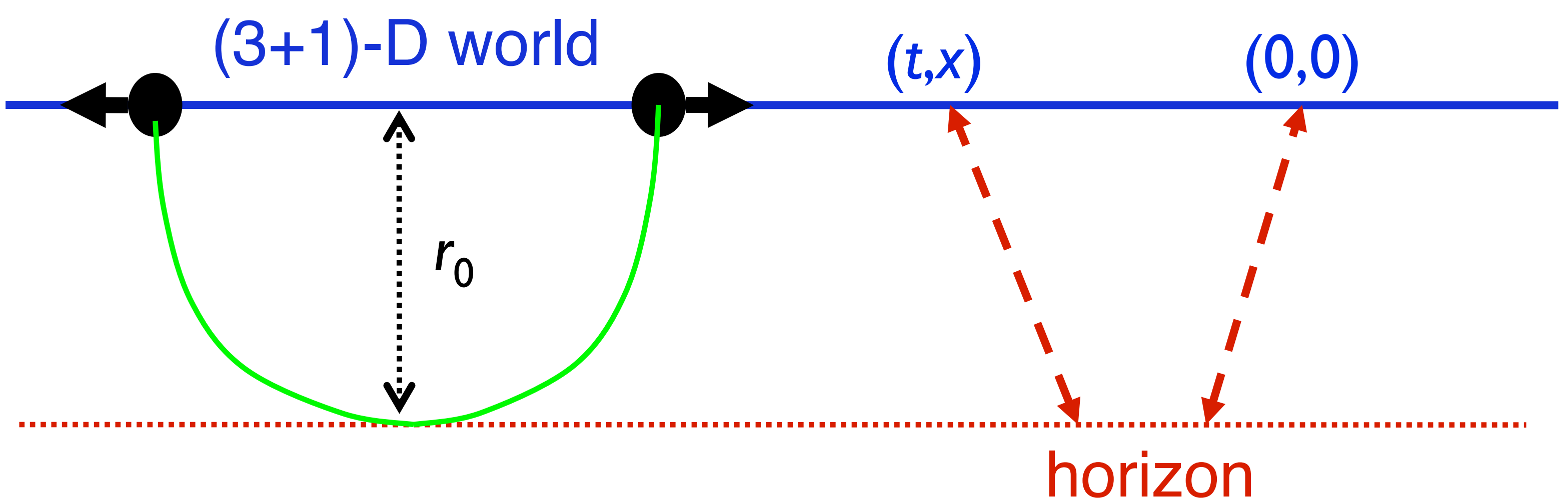
$$\sigma \leq \frac{4\pi}{\bar{p}^2} \quad \rightarrow \quad \eta \geq \frac{\bar{p}^3}{12\pi}$$

Relativistic system of massless particles: $\bar{p} \sim T \quad \rightarrow \quad \bar{p}^3 \sim T^3 \sim s$

$$\boxed{\Rightarrow \quad \frac{\eta}{s} \geq \text{some lower bound} = \# \cdot \left[\frac{\hbar}{k_B} \right]}$$

Holographic argument

General argument [Kovtun, Son & Starinets, PRL 94 (2005) 111601] based on the holographic duality (AdS/CFT) between thermal QFT and string theory in five-dimensional curved space with a "black-hole" metric.



$$r_0 = \frac{1}{\pi T}$$

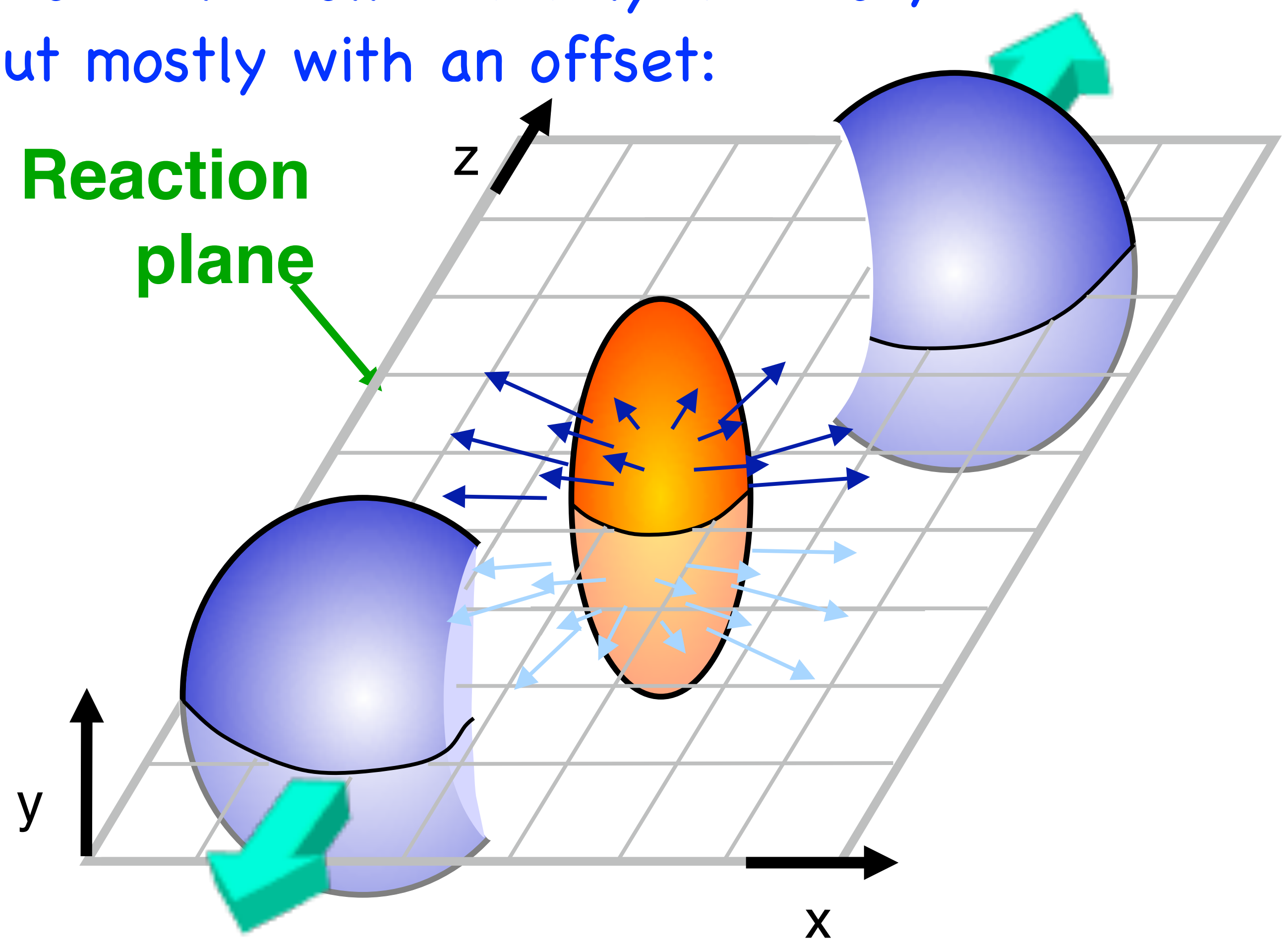
Dissipation in QFT is dual to the absorption of gravitons by the black hole:

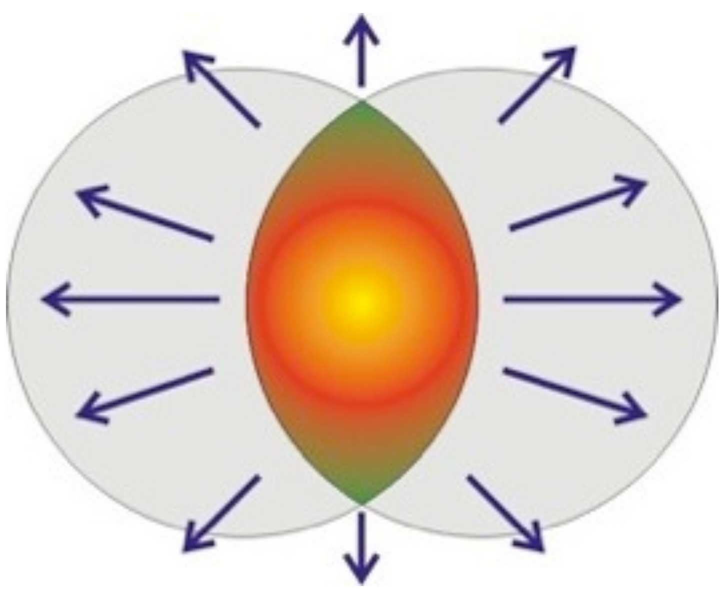
$$\sigma_{abs}(\omega) = \frac{8\pi G}{\omega} \int dt\, d^3x\, e^{i\omega t} \left\langle \left[T_{xy}(t,\vec{x}), T_{xy}(0,0) \right] \right\rangle \xrightarrow[\omega \to 0]{} a \quad \text{(horizon area)}$$

Thus: $\eta = \dfrac{\sigma_{abs}(0)}{16\pi G} = \dfrac{a}{16\pi G} = \dfrac{s}{4\pi}$ because $s = \dfrac{a}{4G}$ $\rightarrow$ $\boxed{\dfrac{\eta}{s} = \dfrac{1}{4\pi}}$

Elliptic flow

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

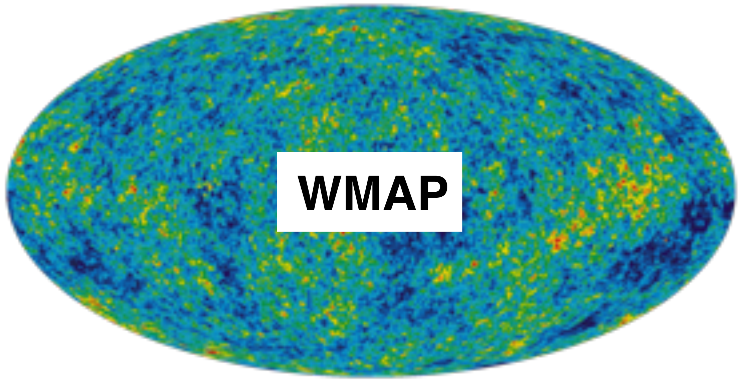
$$2\pi \frac{dN}{d\phi} = N_0\left(1 + 2\sum_n \mathrm{v}_n(p_T,\eta)\cos n\left(\phi - \psi_n(p_T,\eta)\right)\right)$$

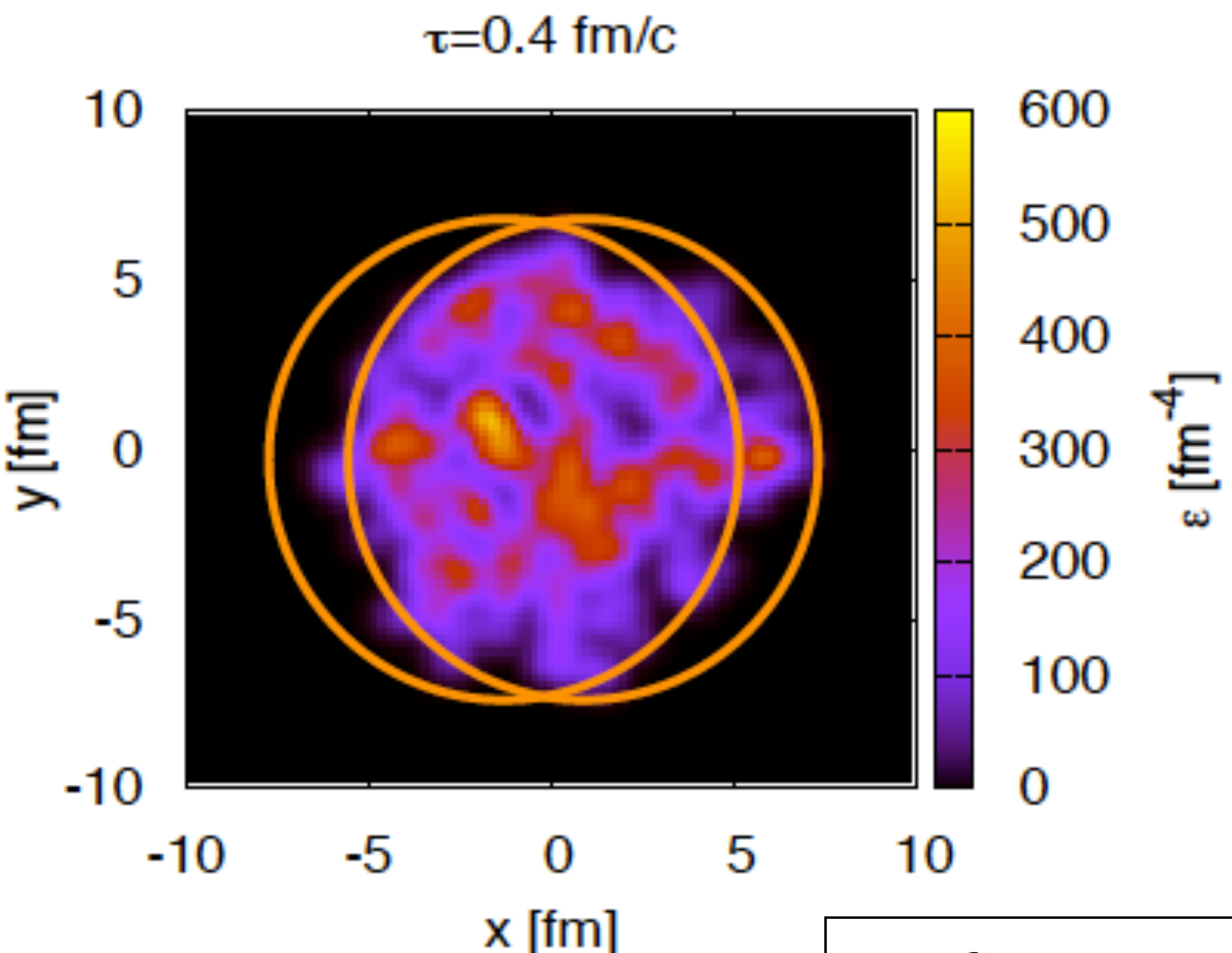
anisotropic flow coefficients

event plane angle

Event-by-event fluctuations

Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0

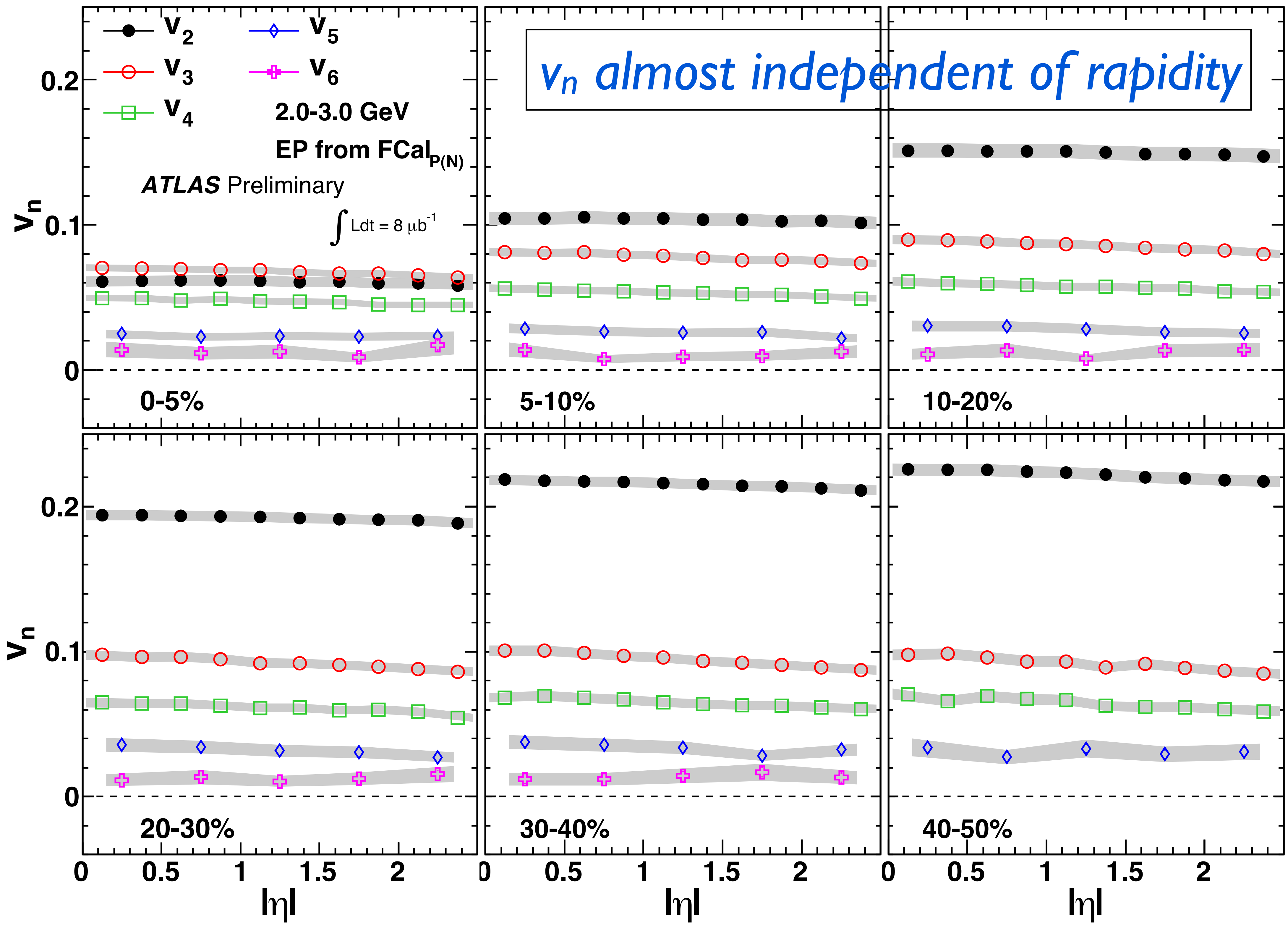




Idea: Energy density fluctuations in transverse plane from initial state quantum fluctuations. These thermalize to different temperatures locally and then propagate hydrodynamically to generate angular flow velocity fluctuations in the final state.

⇒ flows v_1, v_2, v_3, v_4,…

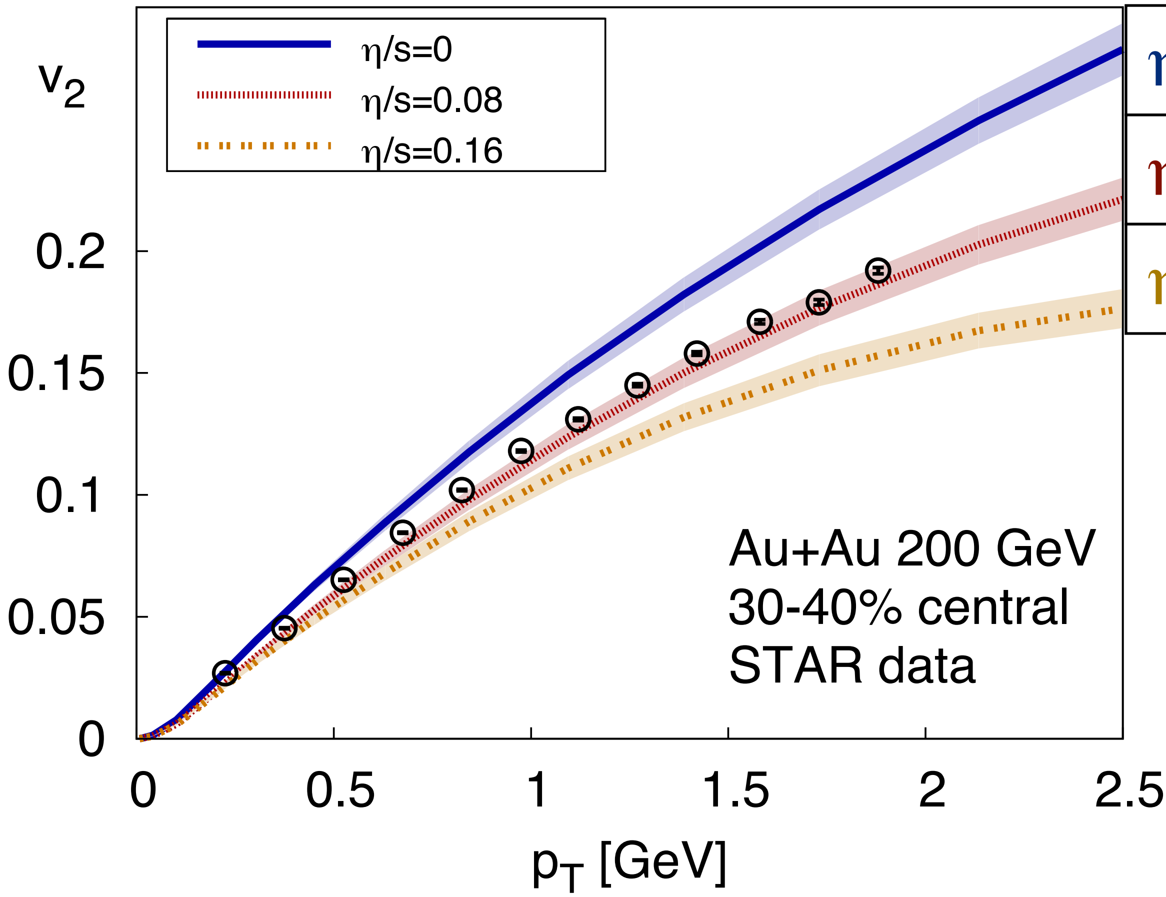
v_n (n = 2,...,6)



v_2
v_3
v_4
v_5
v_6
2.0-3.0 GeV
EP from $FCal_{P(N)}$
ATLAS Preliminary
$\int Ldt = 8\ \mu b^{-1}$
v_n almost independent of rapidity
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
v_n
$|\eta|$

Elliptic flow “measures” η_{QGP}

Schenke, Jeon, Gale, PRL 106 (2011) 042301



$\eta/s = 0$

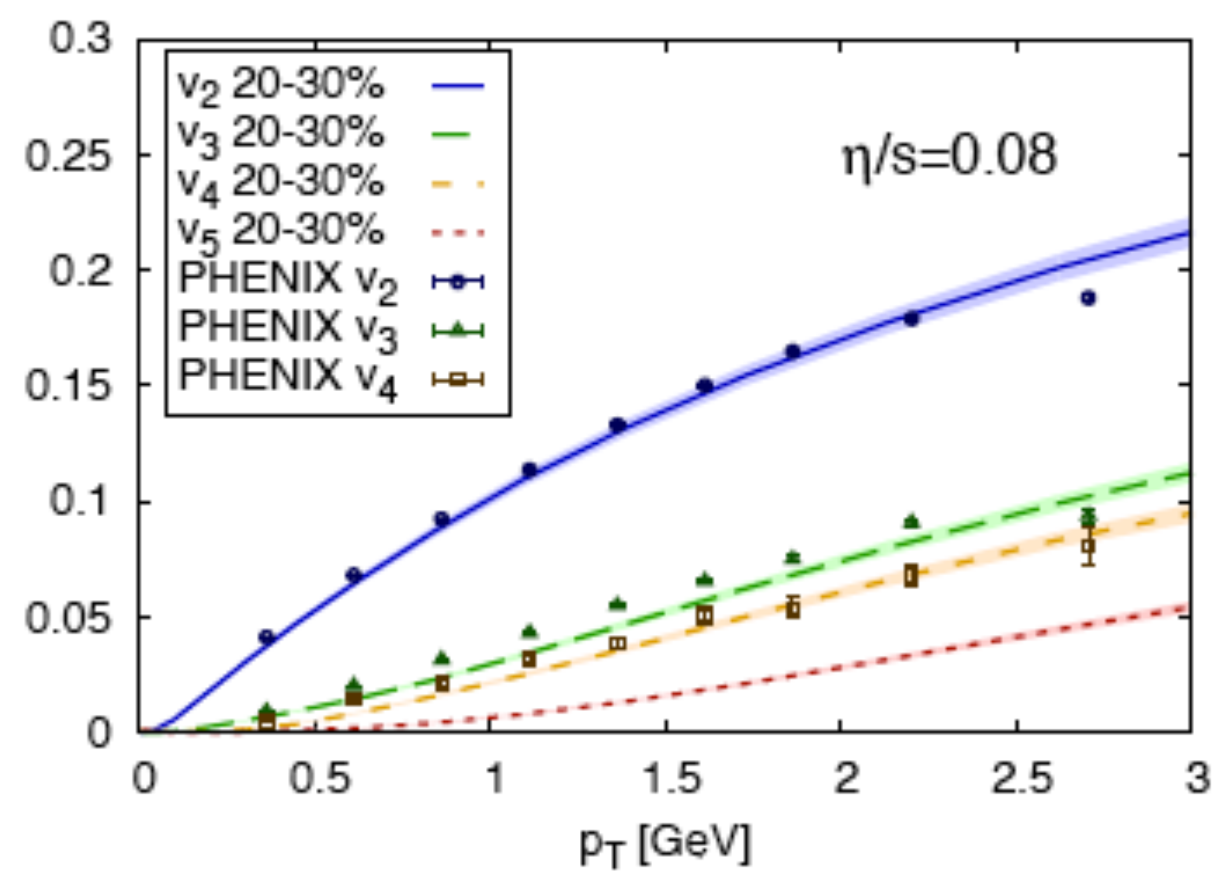
$\eta/s = 1/4\pi$

$\eta/s = 2/4\pi$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \to 1/4\pi$

aka: the “perfect” liquid

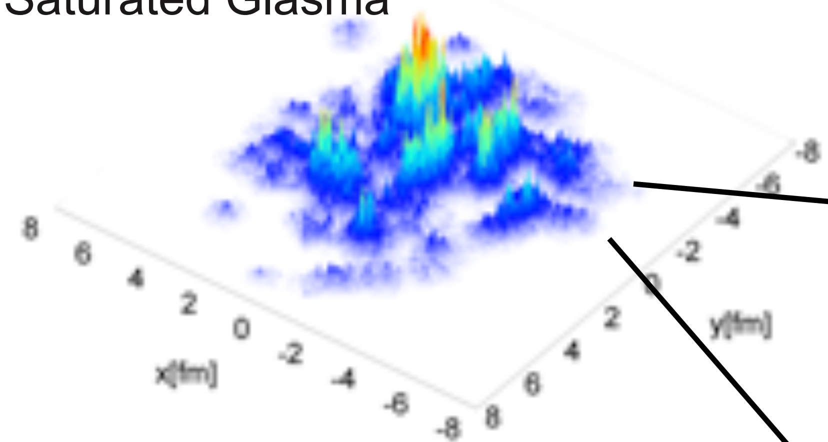


Schenke, Jeon, Gale, PRC 85 (2012) 024901

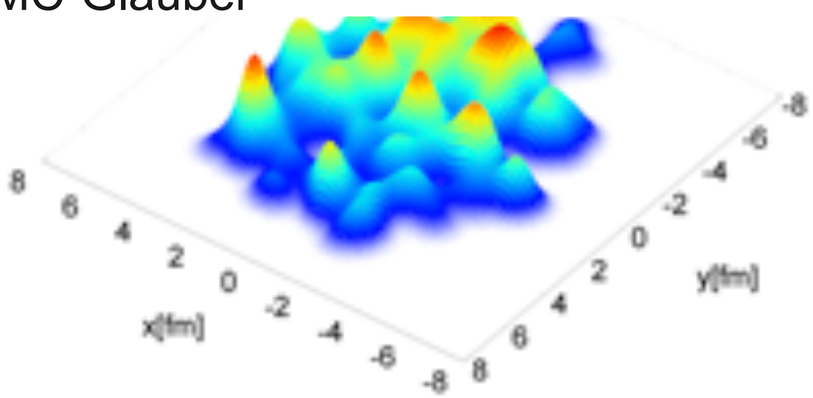
RHIC vs. LHC

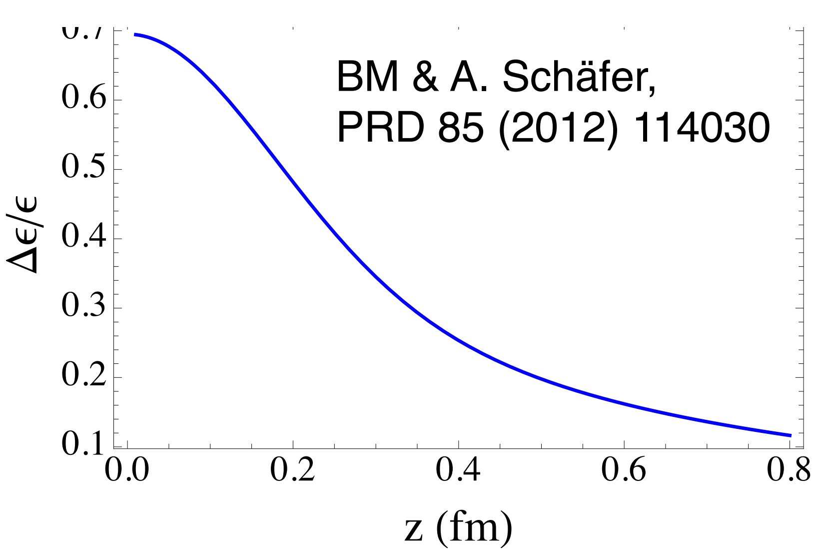
Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330

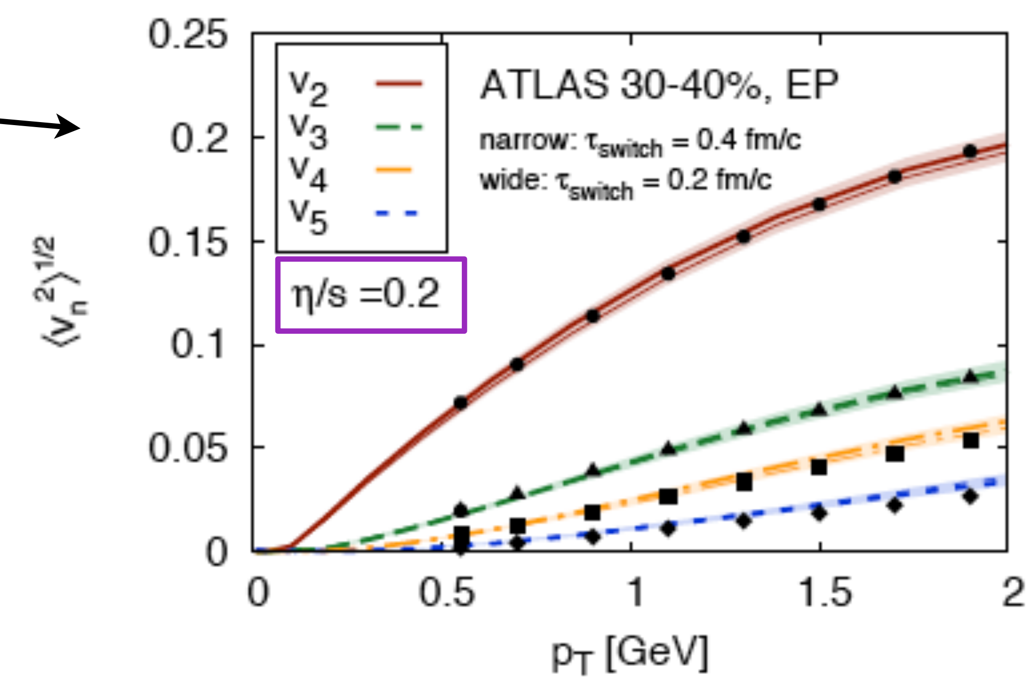
Saturated Glasma



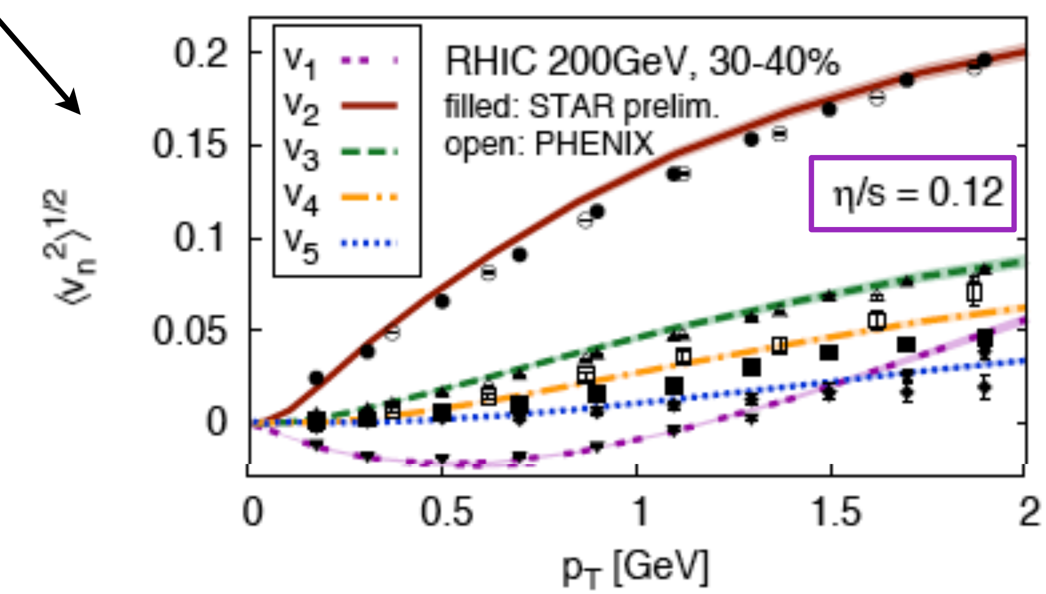
MC-Glauber







LHC

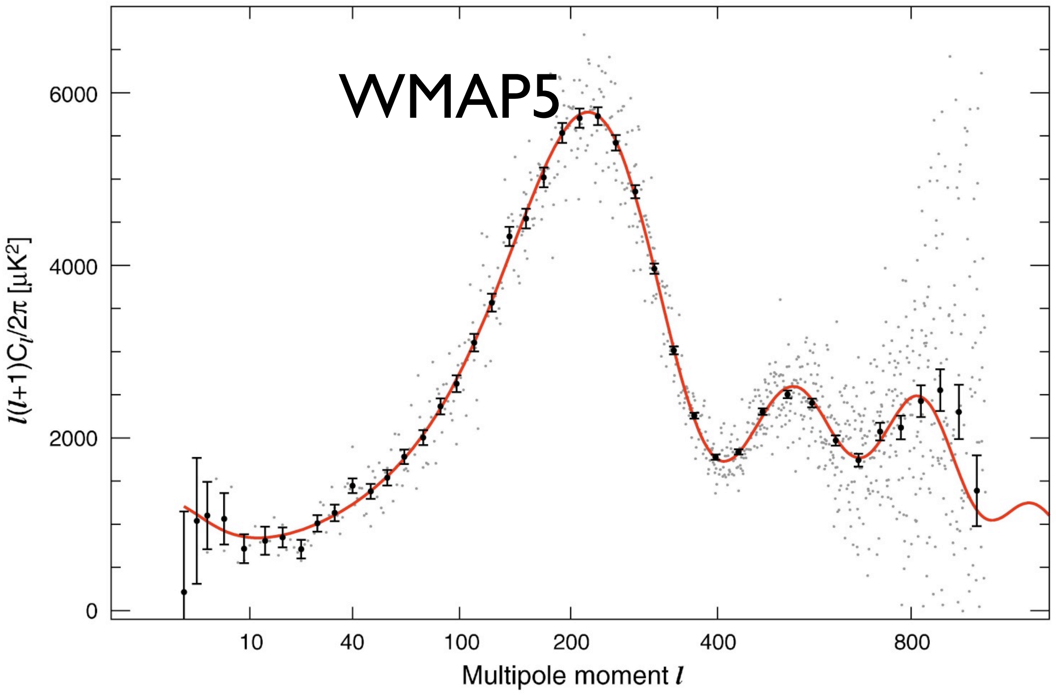


RHIC

Fluctuation spectrum

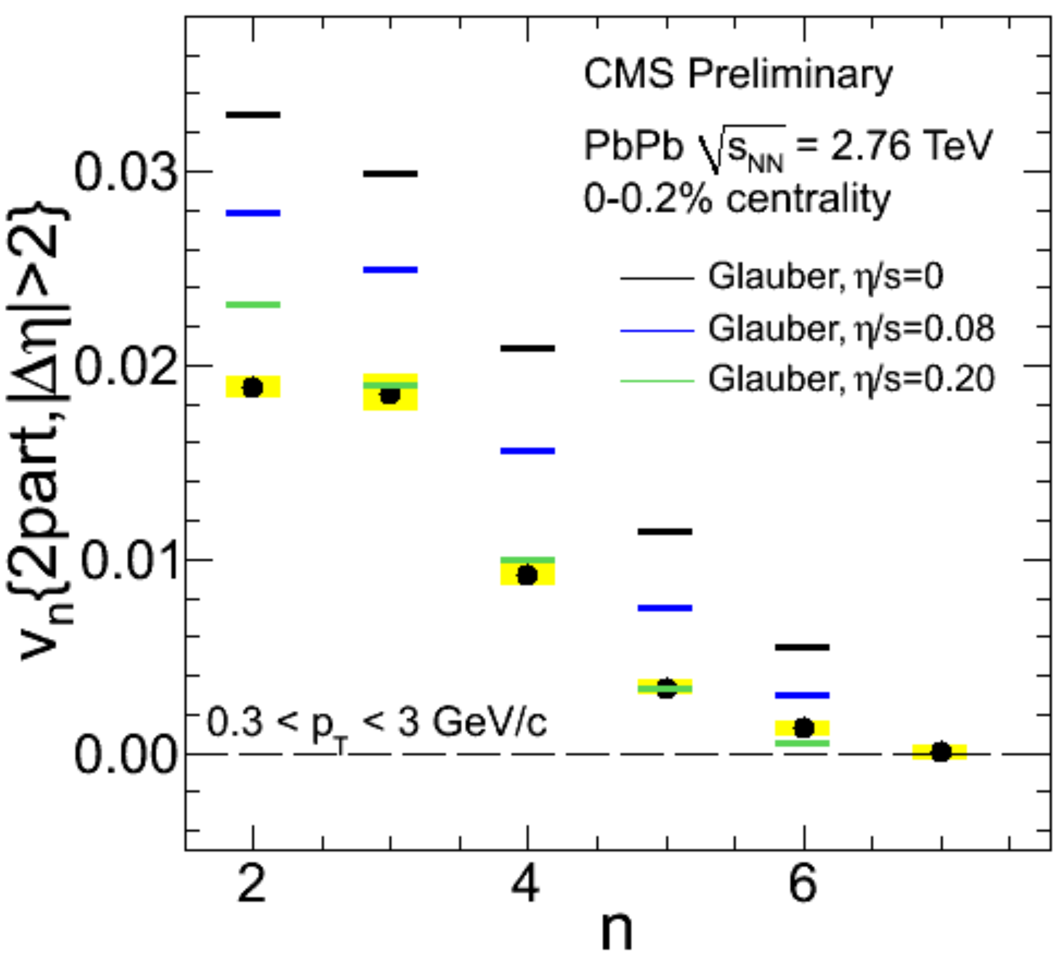
Can different distributions of various eccentricities in different collision systems be used to discriminate between energy deposition models / theories?

Can the power spectrum of v_n be used to determine η/s and v_{sound} ?



The RHIC/LHC advantage:
There are many knobs to turn, not just a single universe to observe.

M. Luzum et al.



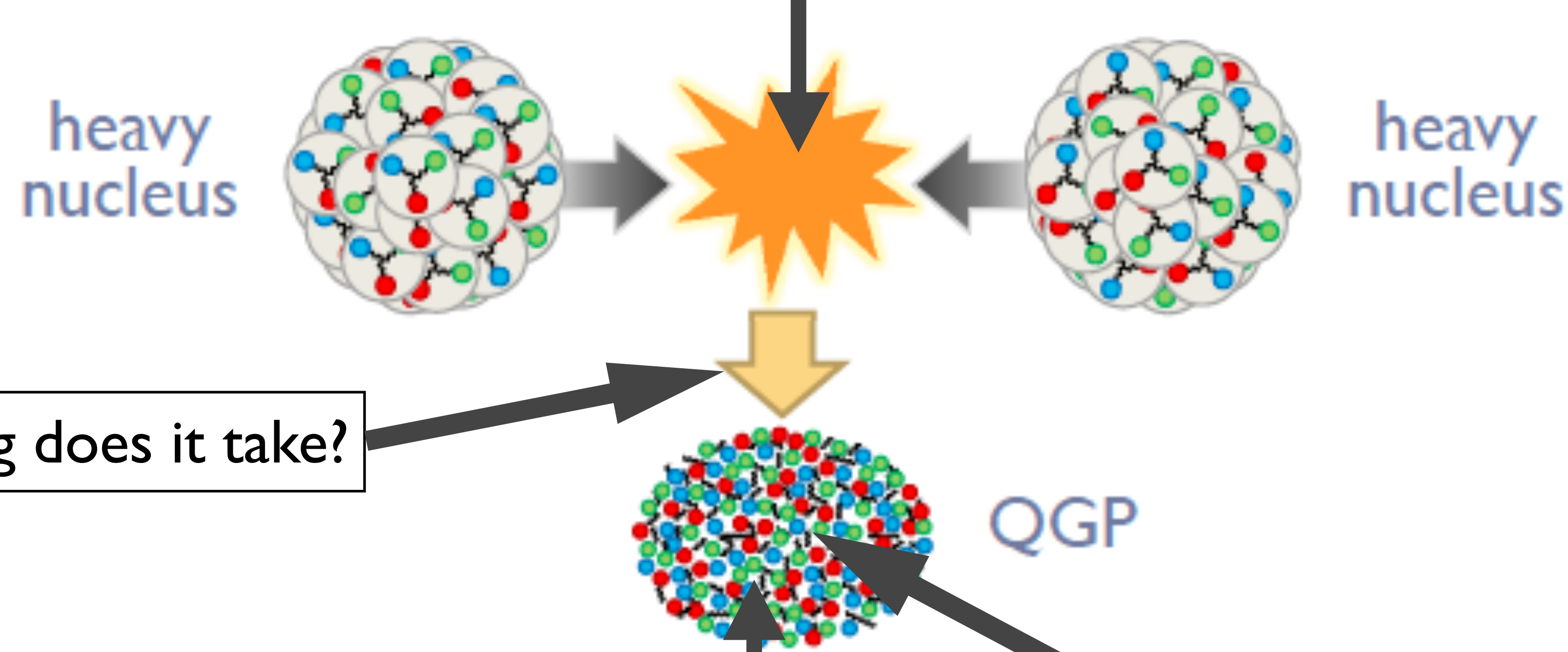
Future challenges

- Determination of transverse profile
  - Can gluon saturation provide a firm prediction?
    - Can we use d+Au (p+Pb) collisions to constrain CGC approach?
    - Are there theoretically founded alternatives?
- Check of system independence
  - Cu+Cu, Cu+Au, U+U
    - Very important to demonstrate theoretical control (RHIC!)
- Anomalous viscosity?
  - Dynamical generation of color fields during thermalization?
  - Do glasma properties survive into hydro stage?

Thermalization

Thermalization

Characteristic participant parton momentum scale: Q_s



How long does it take?

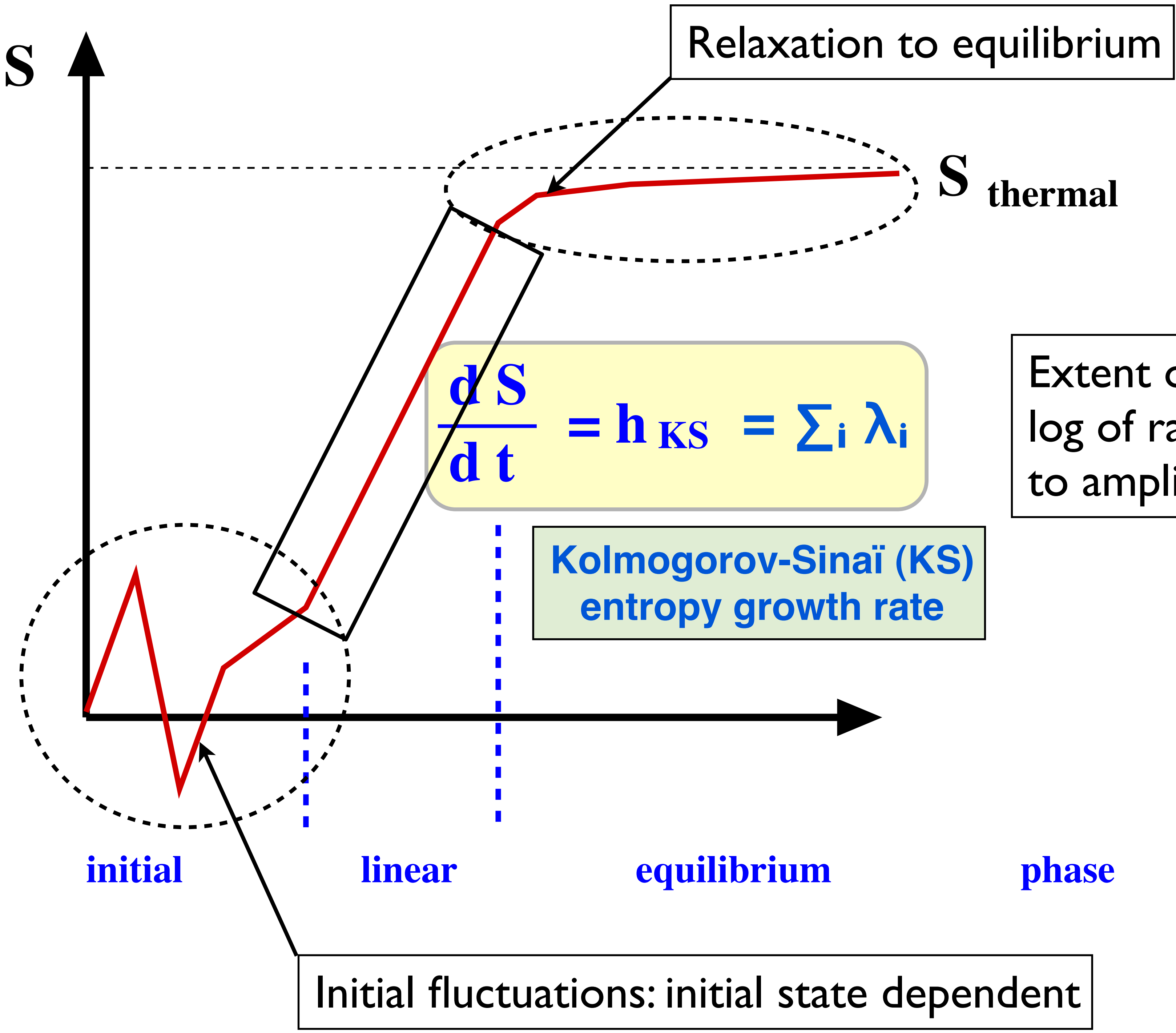
How thermal is it?

Characteristic parton momentum scale: $T << Q_s$
(at weak coupling)

How does the thermalization process work at strong coupling?

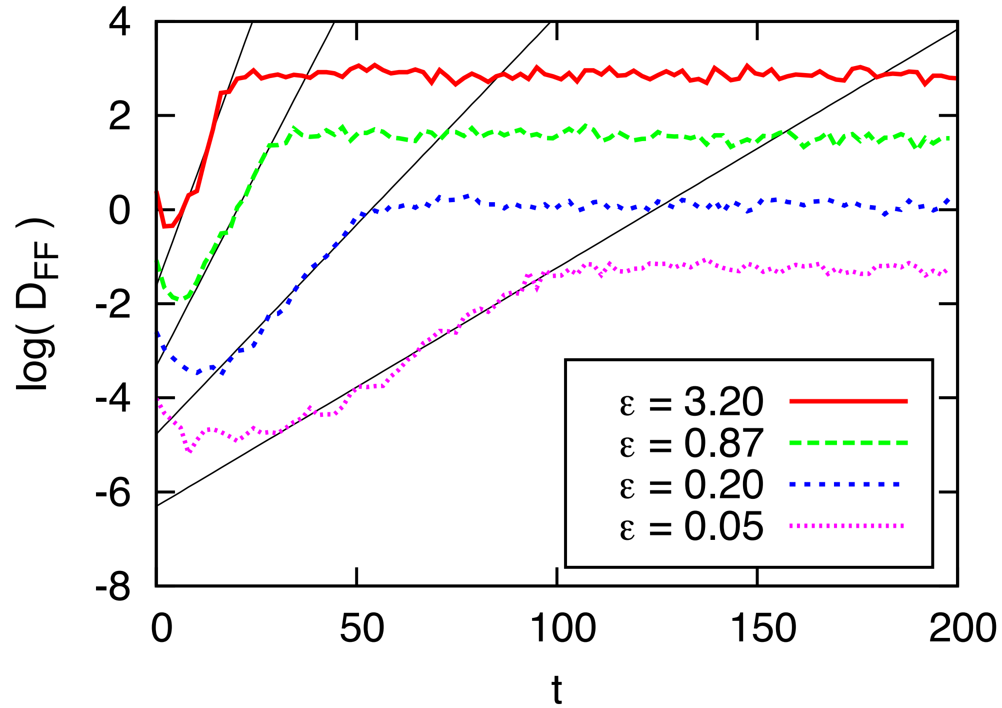
If not "bottom up", what else?

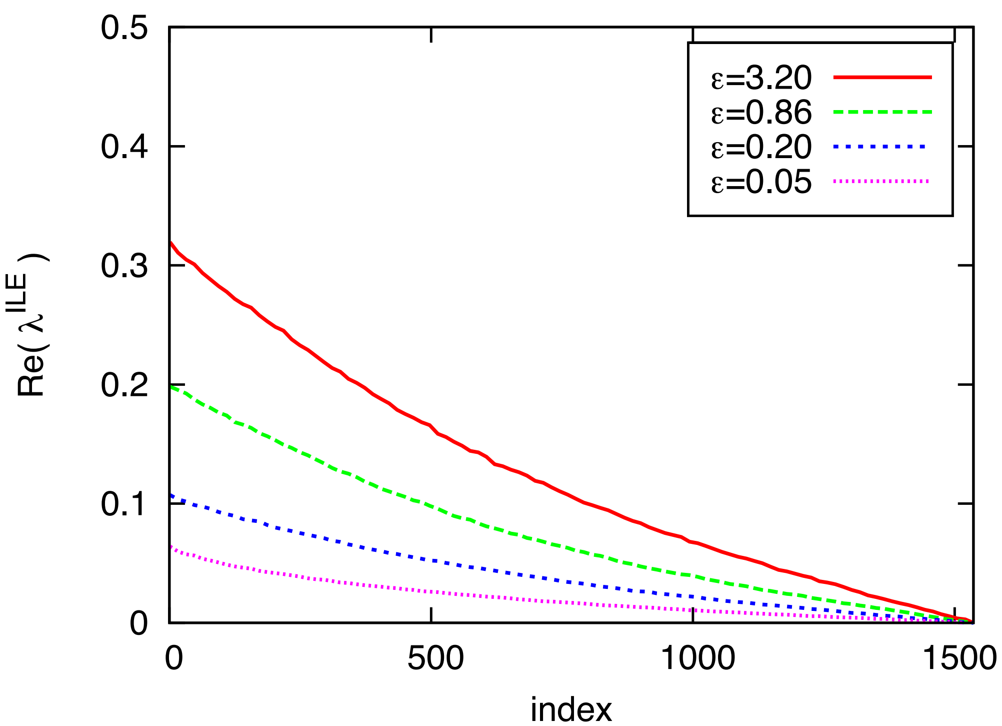
Classical picture



Extent of linear region depends on log of ratio of thermal fluctuations to amplitude of initial fluctuations.

Classical lattice SU(3)





T. Kunihiro, BM, A. Ohnishi, A. Schäfer, T. Takahashi & A. Yamamoto, PRD 82 (2010) 114015

ILE = Intermediate Lyapunov exponents:
= Growth rate of distance between neighboring gauge field config's

Lattice gauge fields exhibit extensive spectrum of positive Lyapunov exponents.

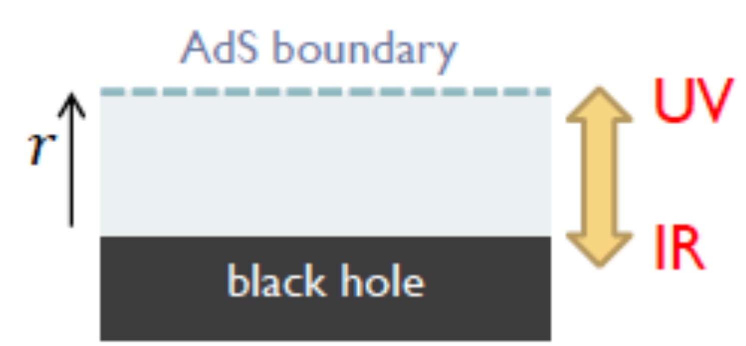
➥ Finite KS entropy density.

AdS/CFT dictionary

- Want to study strongly coupled phenomena in QCD
- Toy model: $\mathcal{N} = 4\ SU(N_c)$ SYM

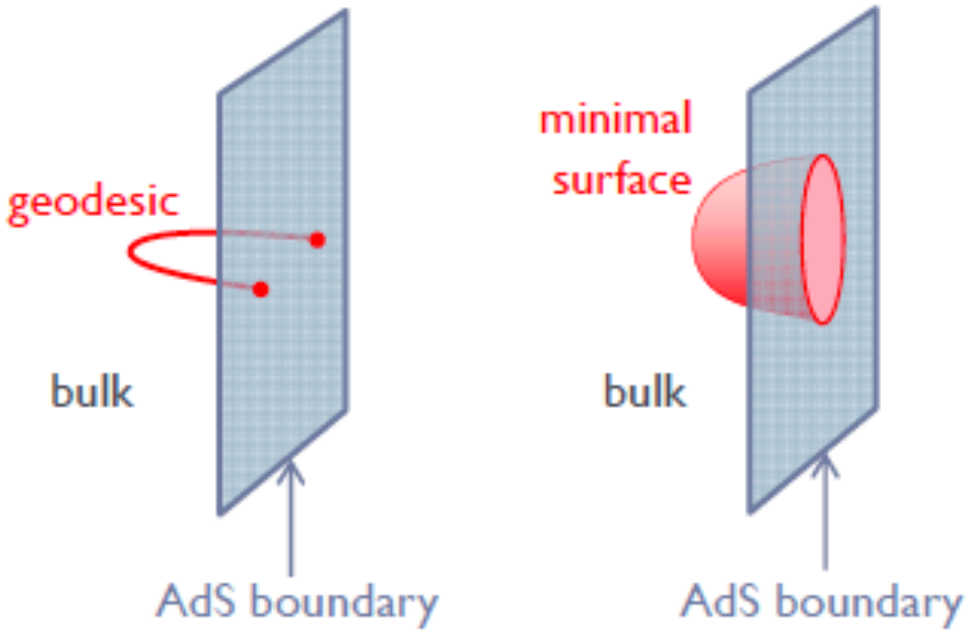
$\mathcal{N} = 4$ SYM	holo. dual $\Longleftrightarrow$ AdS/CFT	String theory in AdS_5
Strong coupling	$\longleftrightarrow$	Weak coupling
Vacuum	$\longleftrightarrow$	Empty AdS_5
Thermal state (equilibrated plasma)	$\longleftrightarrow$	AdS BH
Thermalization	$\longleftrightarrow$	BH formation
HI collision	$\longleftrightarrow$	Energy injection

$$\left(\frac{R_{AdS}}{l_s}\right)^4 = g_{YM}^2 N_c \equiv \lambda$$



Thermality probes

- 2-point function
  - $\langle \mathcal{O}(x)\mathcal{O}(x)\rangle$
  - Bulk: geodesic (1D)
- Wilson line
  - $W = P\{\exp[\int_C A_\mu(x)dx^\mu]\}$
  - Bulk: minimal surface (2D)
- Entanglement entropy
  - $S_A = -\mathrm{Tr}_A[\rho_A \log \rho_A], \quad \rho_A = \mathrm{Tr}_B[\rho_{\mathrm{tot}}]$
  - Bulk: codim-2 hypersurface (same dimension as boundary space)



Use semiclassical approximation

For details: *V. Balasubramanian, et al.*, PRL **106**, 191601 (2011); PRD 84, 026010

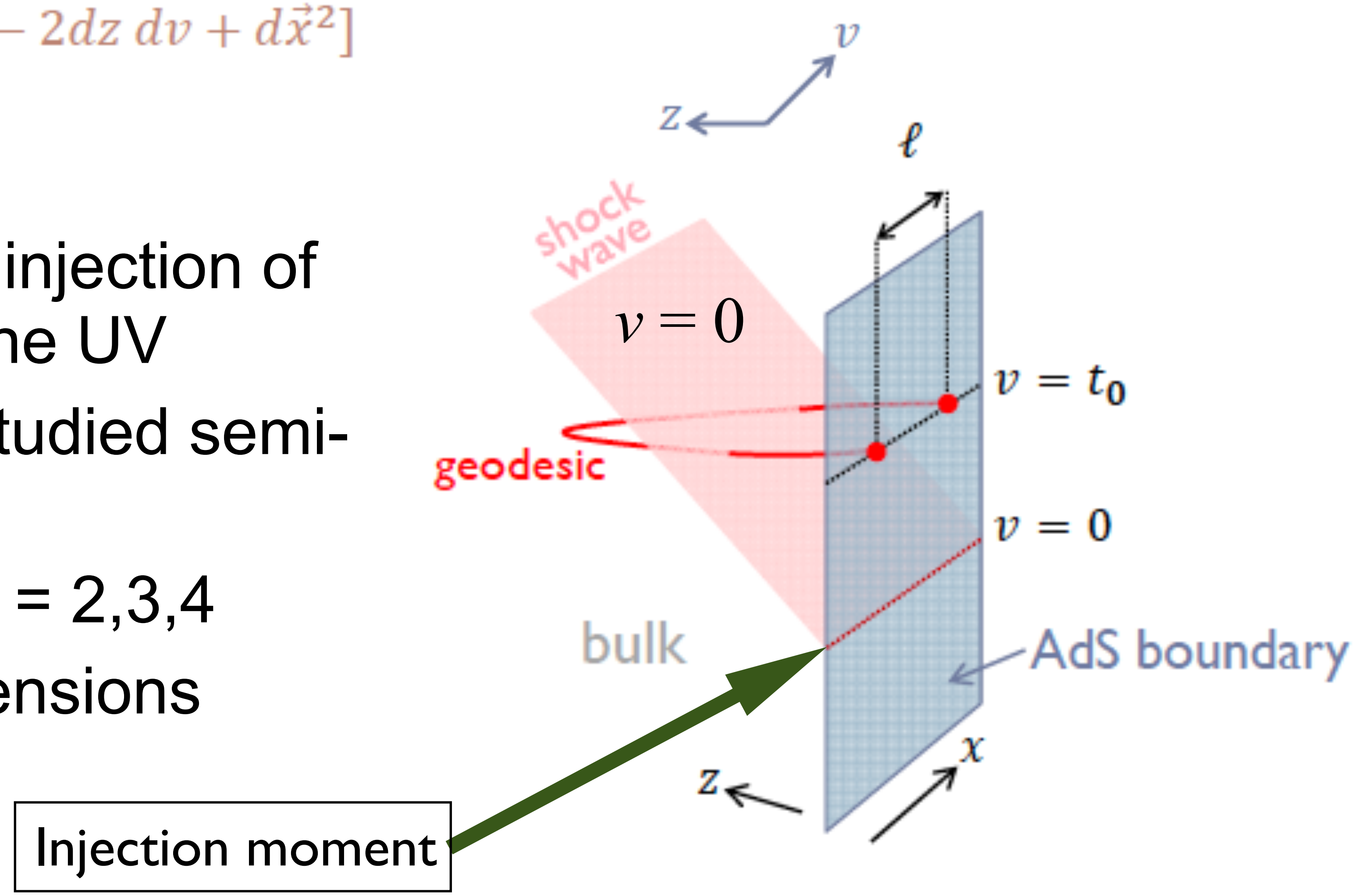
See also: S. Caron-Huot, P.M. Chesler & D. Teaney, arXiv:1102.1073

Vaidya-AdS geometry

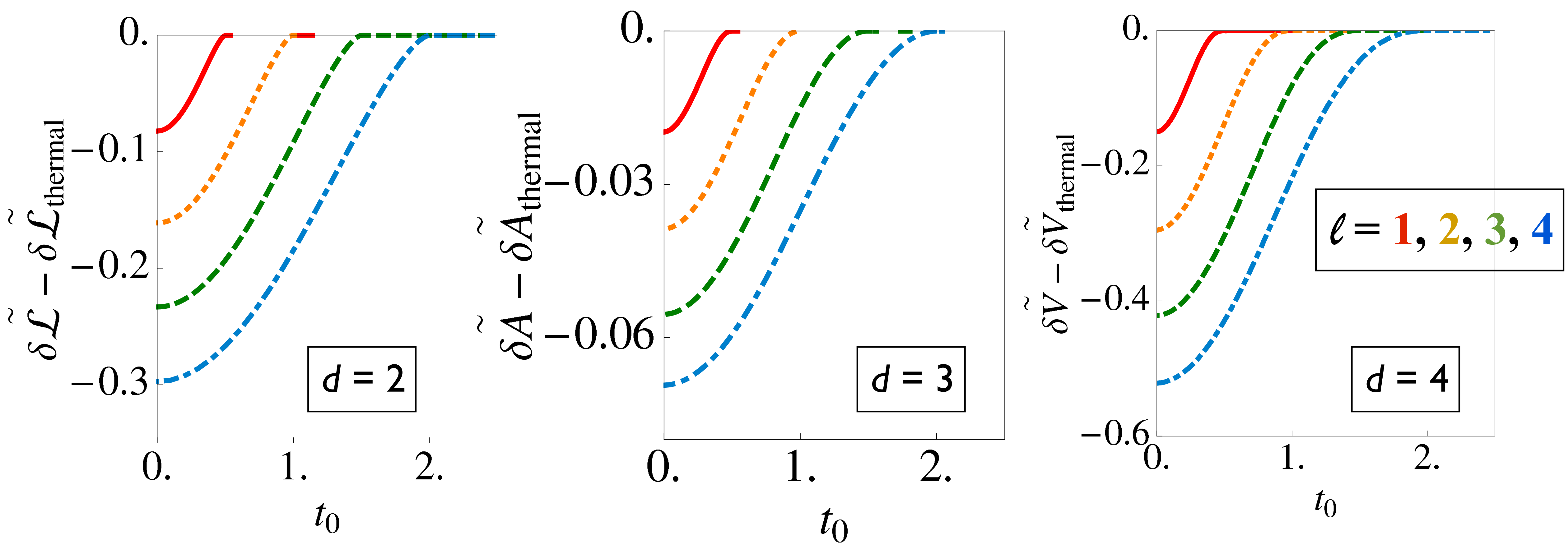
- Light-like (null) infalling energy shell in AdS (shock wave in bulk)
  - *Vaidya-AdS space-time* (analytical)

$$ds^2 = \frac{1}{z^2}\left[-\left(1 - m(v)z^d\right)dv^2 - 2dz\,dv + d\vec{x}^2\right]$$

  - $z = 0$: UV $\quad z = \infty$: IR
  - Homogeneous, sudden injection of entropy-free energy in the UV
  - Thin-shell limit can be studied semi-analytically
  - We studied AdS_{d+1} for d = 2,3,4
  - ⇔ Field theory in *d* dimensions



Entanglement entropy



Thermalization time for entanglement entropy: $\tau_{\text{th}} = \ell/2$

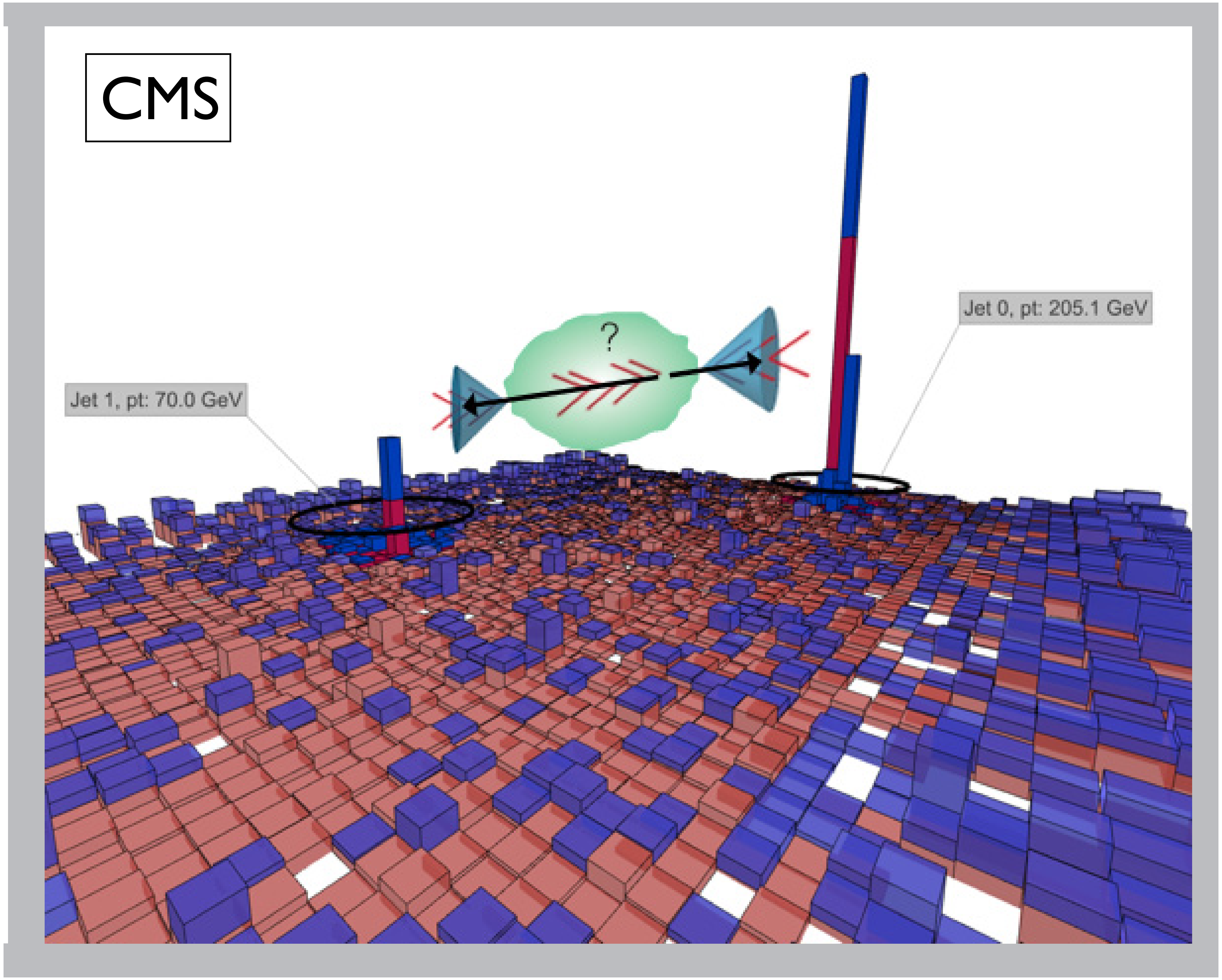
= time for light to escape from the center of the volume to the surface.

Other observables thermalize faster.

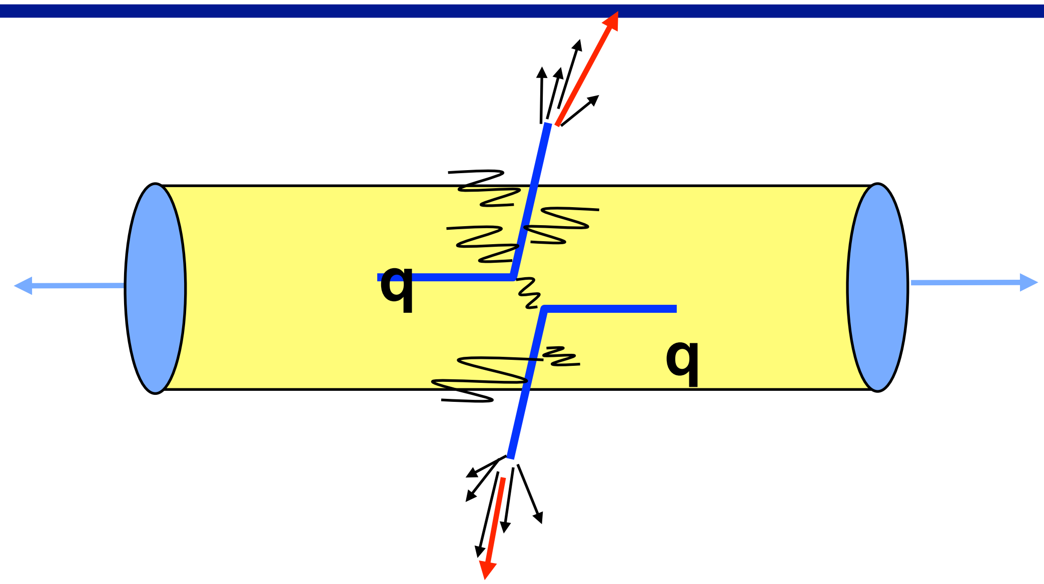
Crude estimate: **$\tau_{\text{crit}} \sim 0.5\ \hbar/T \approx 0.3$ fm/c for $T = 300 - 400$ MeV**

Jet quenching

Di-jet asymmetry

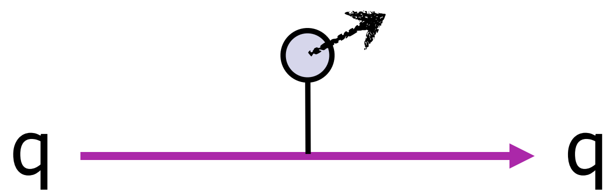


Parton energy loss

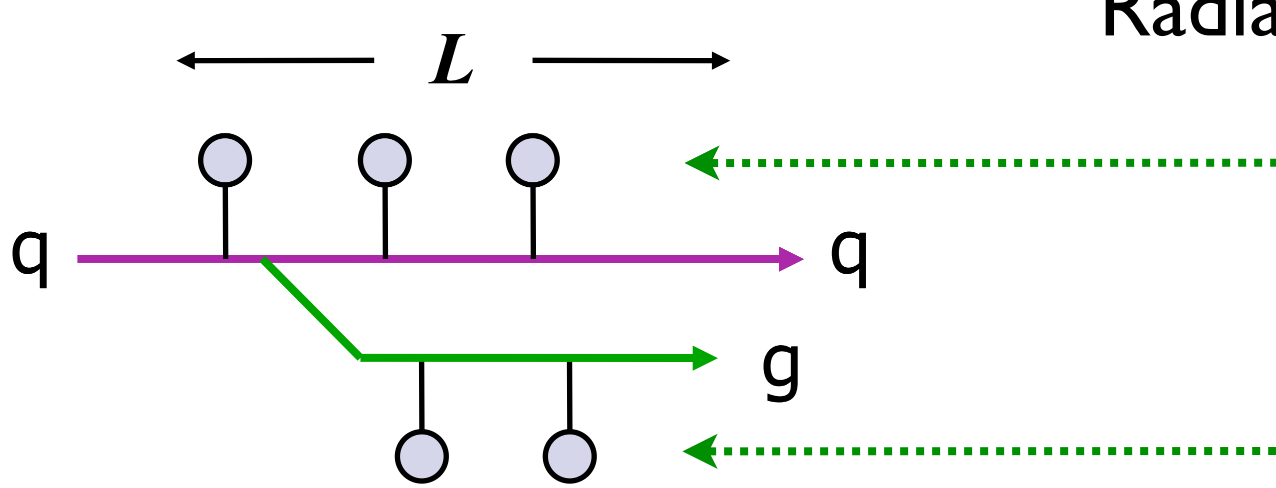


Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



Radiative energy loss:

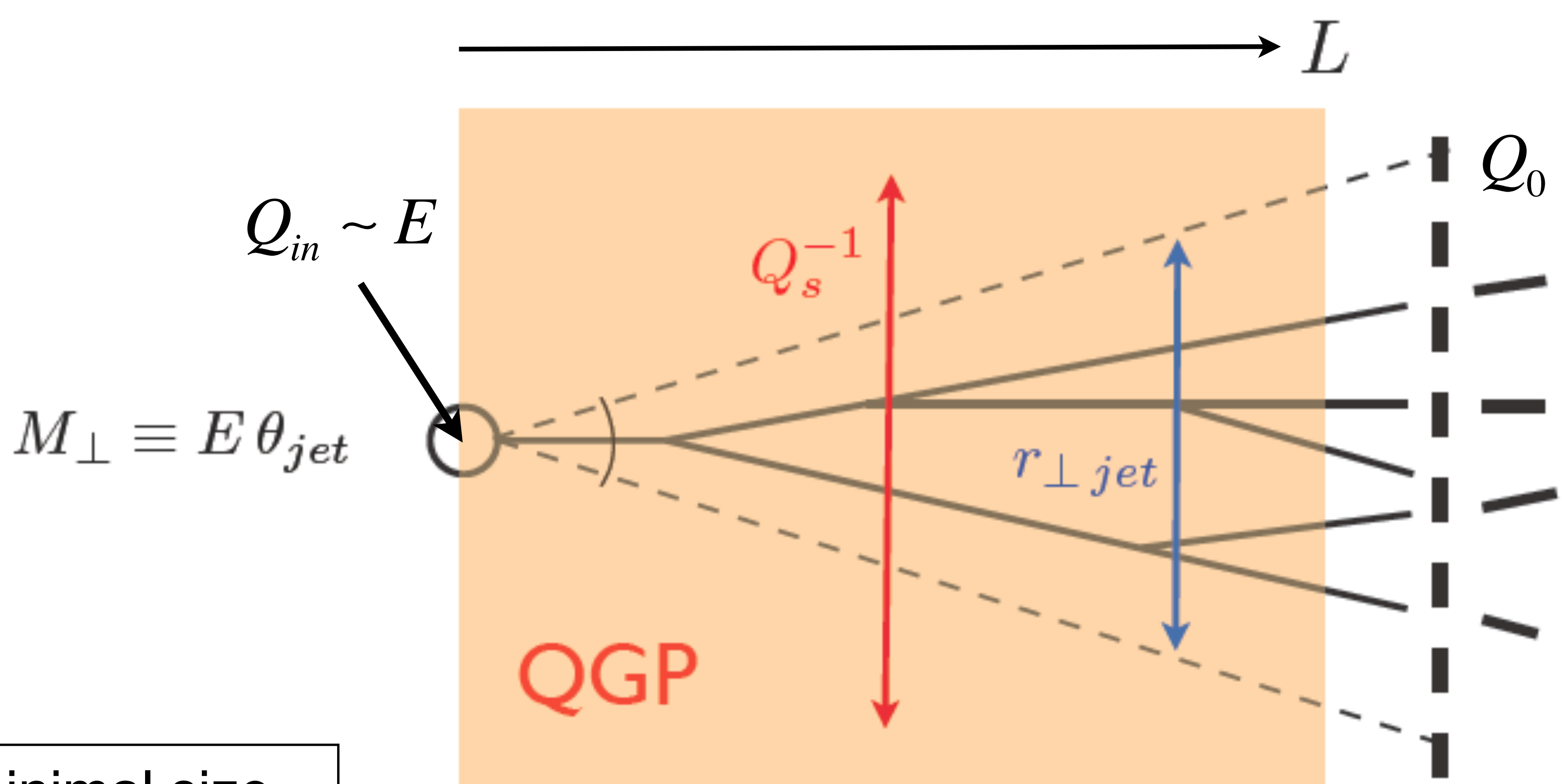


Scattering centers
⇔ color charges

$$\frac{dE}{dx} = -C_2\,\hat{q}\,L$$

$$\hat{q} = \rho\int q^2\,dq^2\,\frac{d\sigma}{dq^2} = \int dx^-\left\langle F_i^{+}(x^-)F^{+i}(0)\right\rangle$$

Jets in the medium



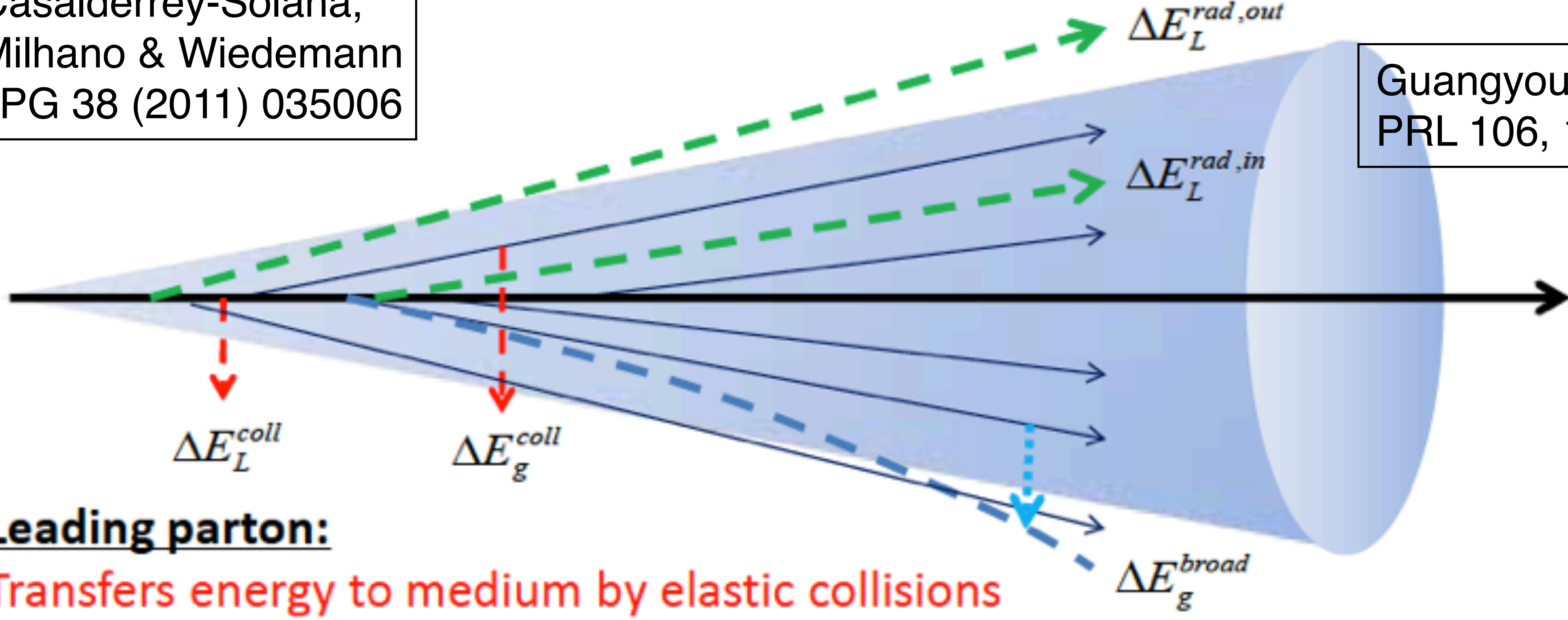
Q_s^{-1} = minimal size of probe to which the medium look opaque

Momentum scale of medium $Q_s = \sqrt{qL} \approx m_D \sqrt{N_{\text{scatt}}}$

Transverse size of jet $r_{\perp\,\text{jet}} = \theta_{\text{jet}} L$

Jet collimation

Casalderrey-Solana, Milhano & Wiedemann JPG 38 (2011) 035006



Guangyou Qin & BM PRL 106, 162302 (2011)

Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

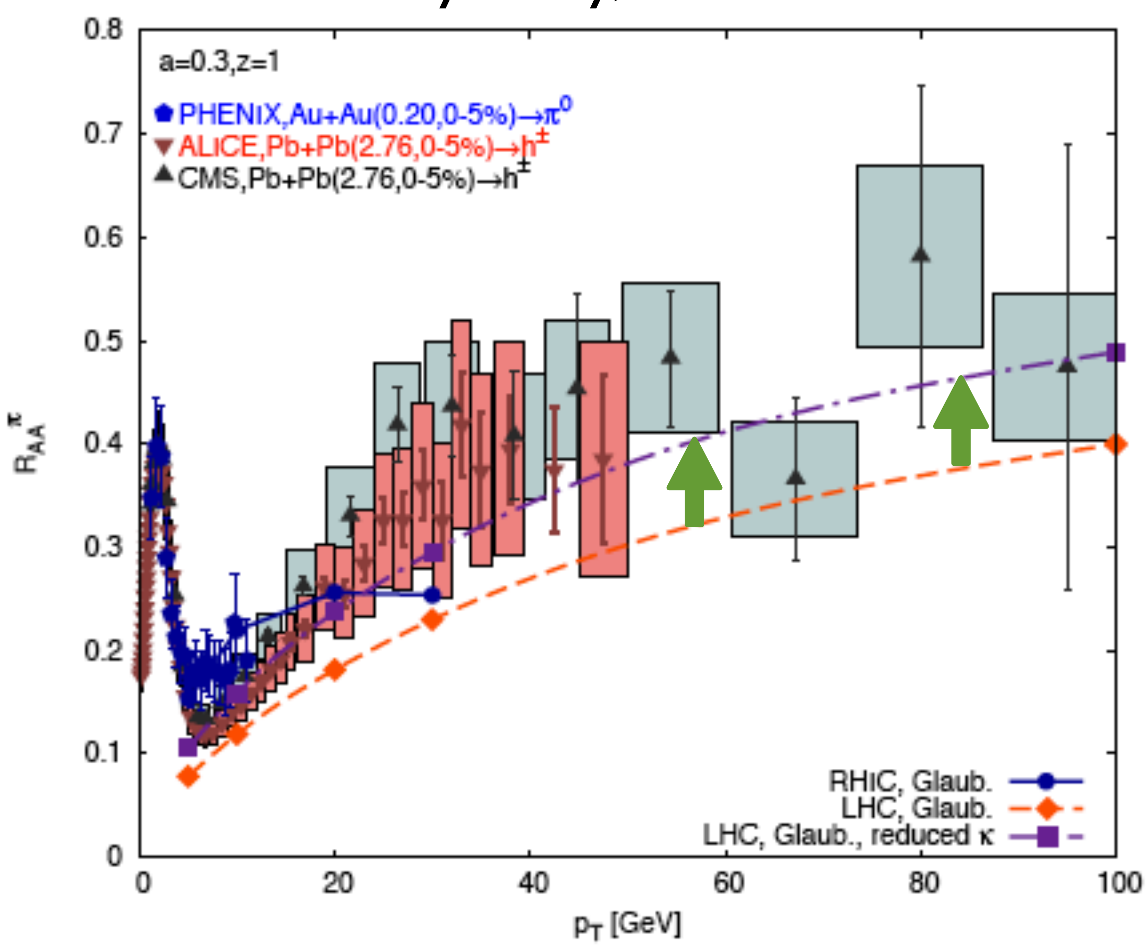
Core questions

- What is the mechanism of energy loss ?
  - “radiative” = into non-thermal gluon modes
  - “collisional” = directly into thermal plasma modes
- How are radiative and collisional energy loss affected by the structure of the medium (quasiparticles or not)?
  - Quasiparticle masses in weak coupling
  - AdS/CFT inspired models with weak-strong coupling transition?
- What happens to the lost energy and momentum ?
  - If “radiative”, how quickly does it thermalize = what is its longitudinal momentum (z) distribution ?
  - What is its angular distribution (the jet “shape”) = how much is found in a cone of angular size R ?
- How do the answers depend on the parton flavor ?

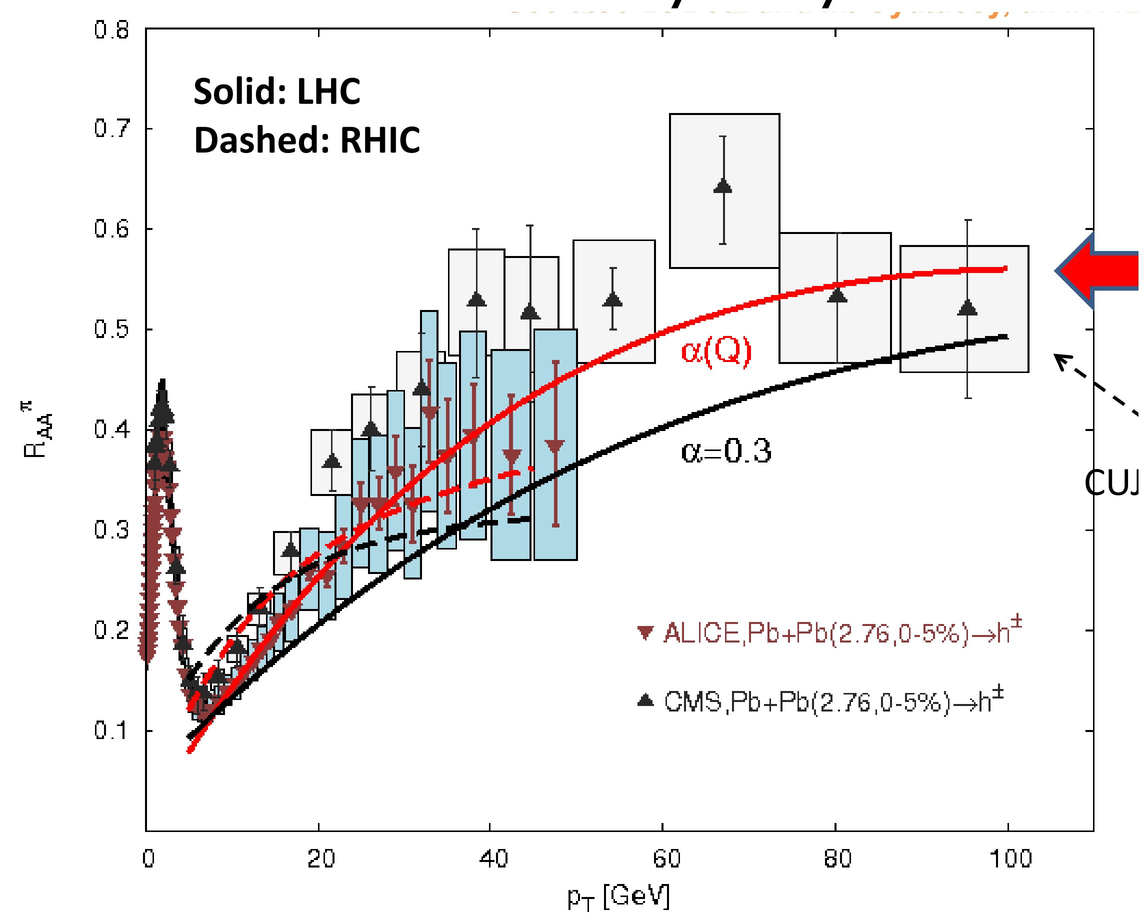
Color opacity

$\kappa \sim \alpha_s \hat{q} \sim \alpha_s^3$ $\kappa_{LHC} \approx 0.6\ \kappa_{RHIC}$ α_s runs!

Betz & Gyulassy, arXiv:1201.0281

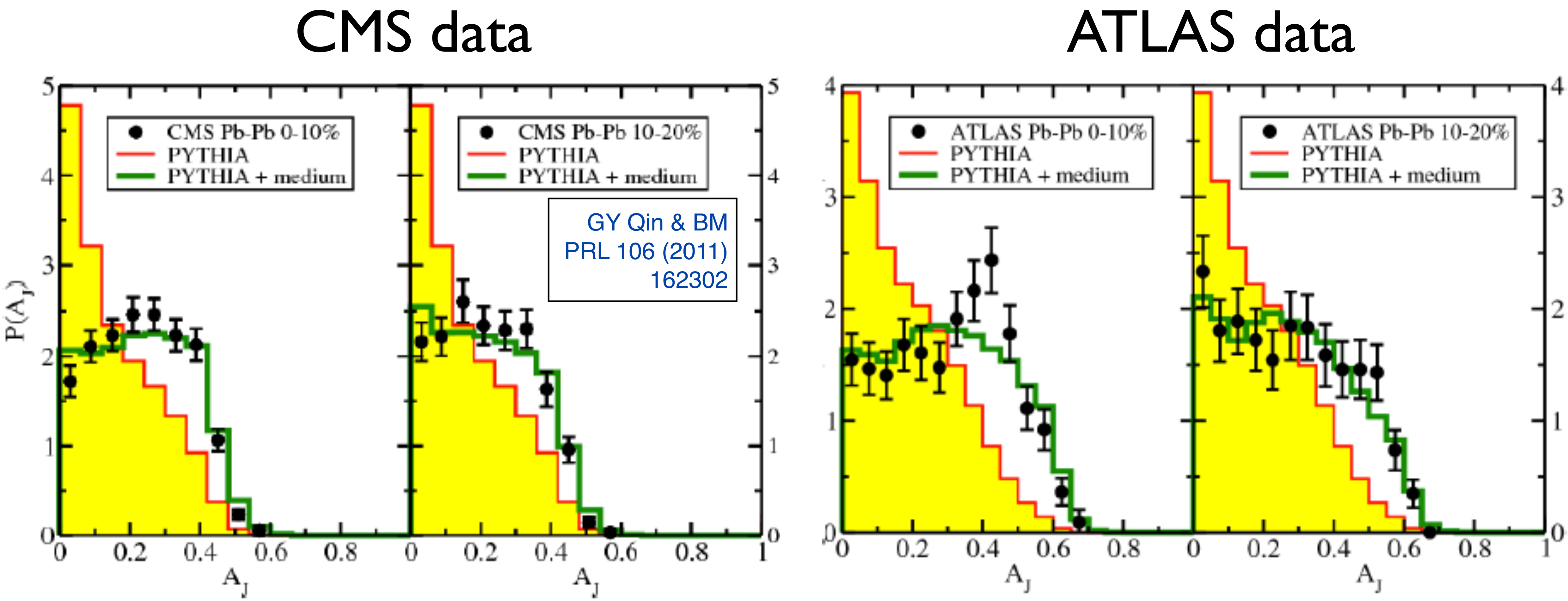


Buzzatti & Gyulassy



Is T-dependence of q^ gradual or rather a steep change for T > T_c ?

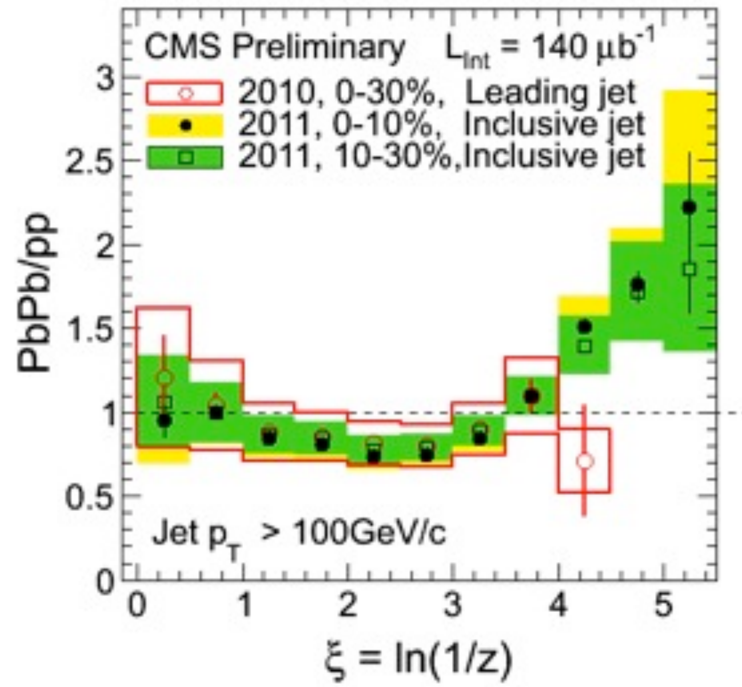
Di-jet asymmetry

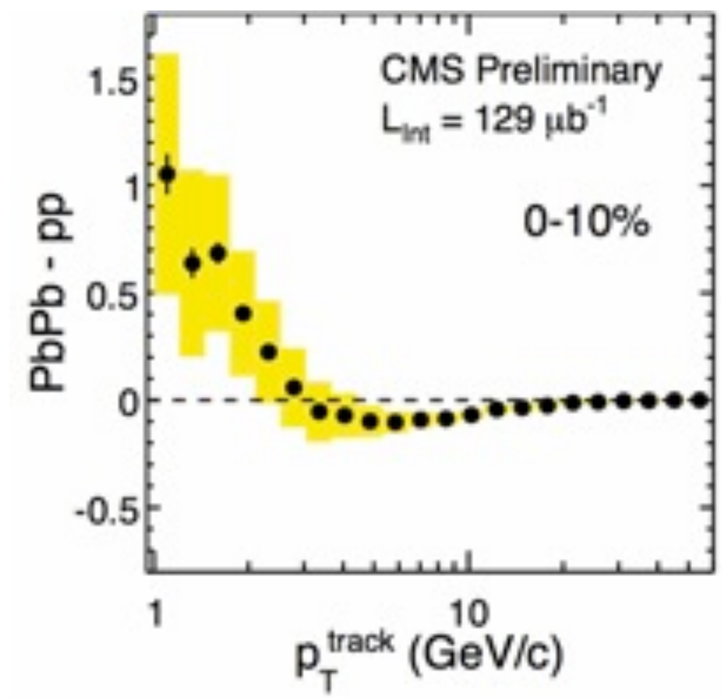


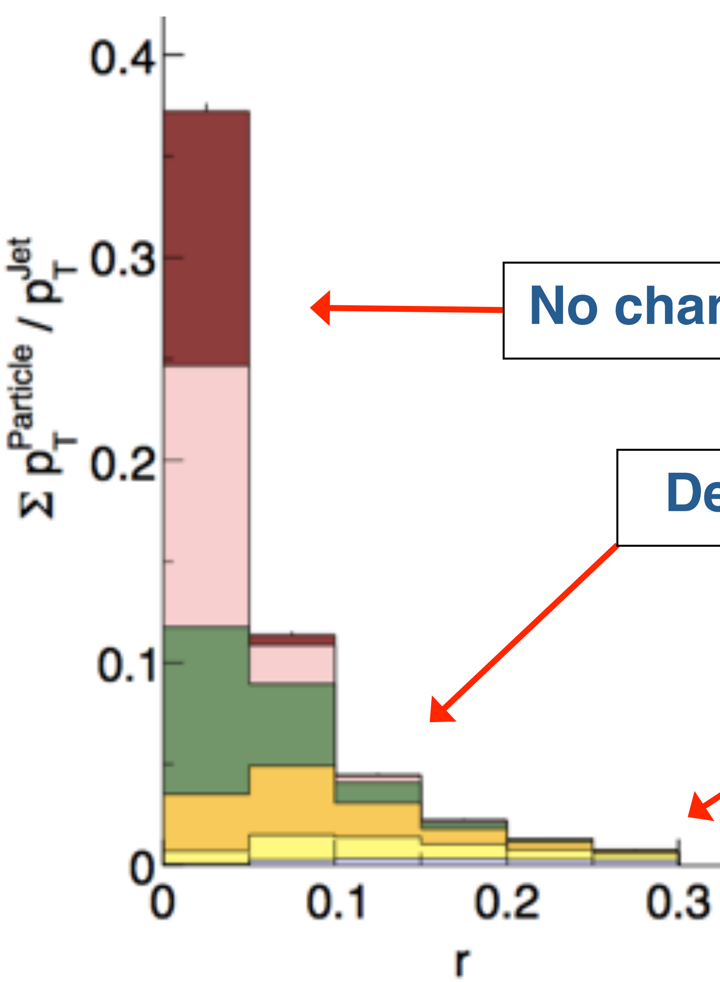
ATLAS and CMS data differ in cuts on jet energy, cone angle, etc; results depend somewhat on precise cuts and background corrections.
Several calculations using pQCD jet quenching formalism fit the data.

General conclusion: *pQCD jet quenching can explain these data.*

Jet modification synopsis



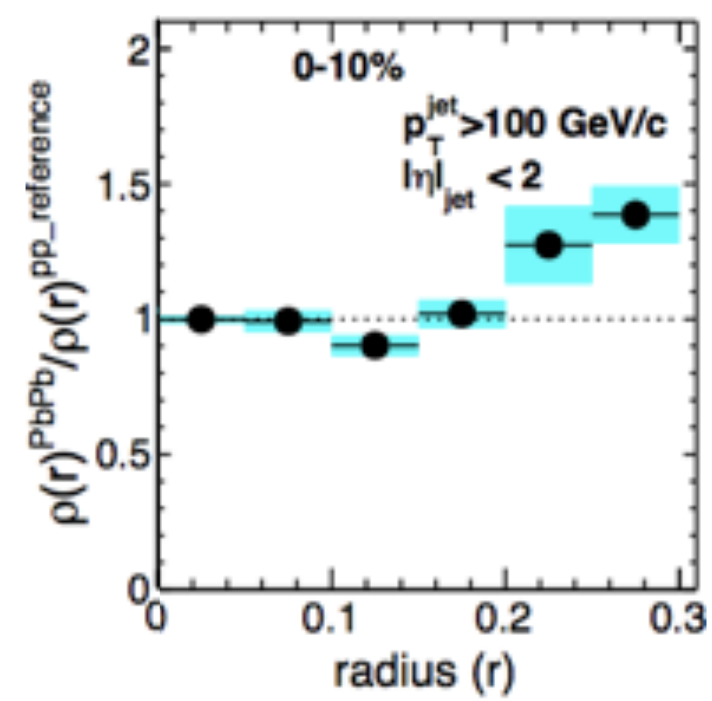




No change at small r, high p_T

Depletion at intermediate r, p_T

Excess at large r, low p_T



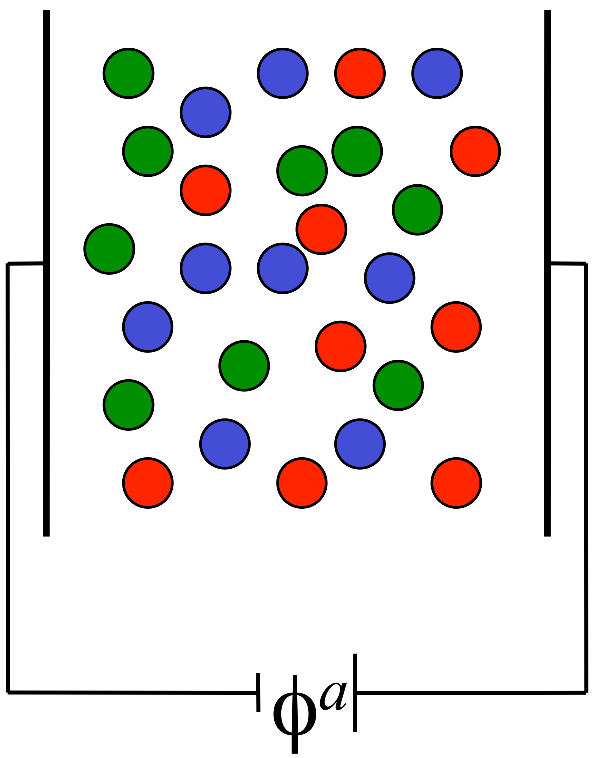
Jets summary

- Strongly coupled (AdS/CFT) jets are ruled out by LHC data:
  - Partons with $p_T > 10$ GeV/c are not strongly coupled, but behave as quasiparticles.
  - pQCD jet quenching theory works for high-p_T jets, R_{AA}.
- Jet modification is concentrated at pT < 4 GeV/c and large angles in the jet cone:
  - Gluons with $p_T \leq$ few GeV/c may be strongly coupled.
  - PHENIX data for b-quarks suggests that “slow” heavy quarks may be strongly coupled.
- Relation between medium and jet scales different at RHIC and LHC:
  - Need for a large acceptance, calorimetric jet detector at RHIC.

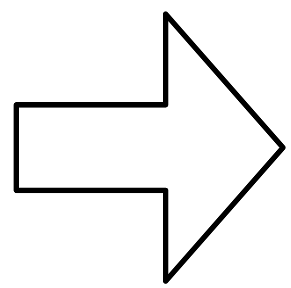
Quarkonium melting

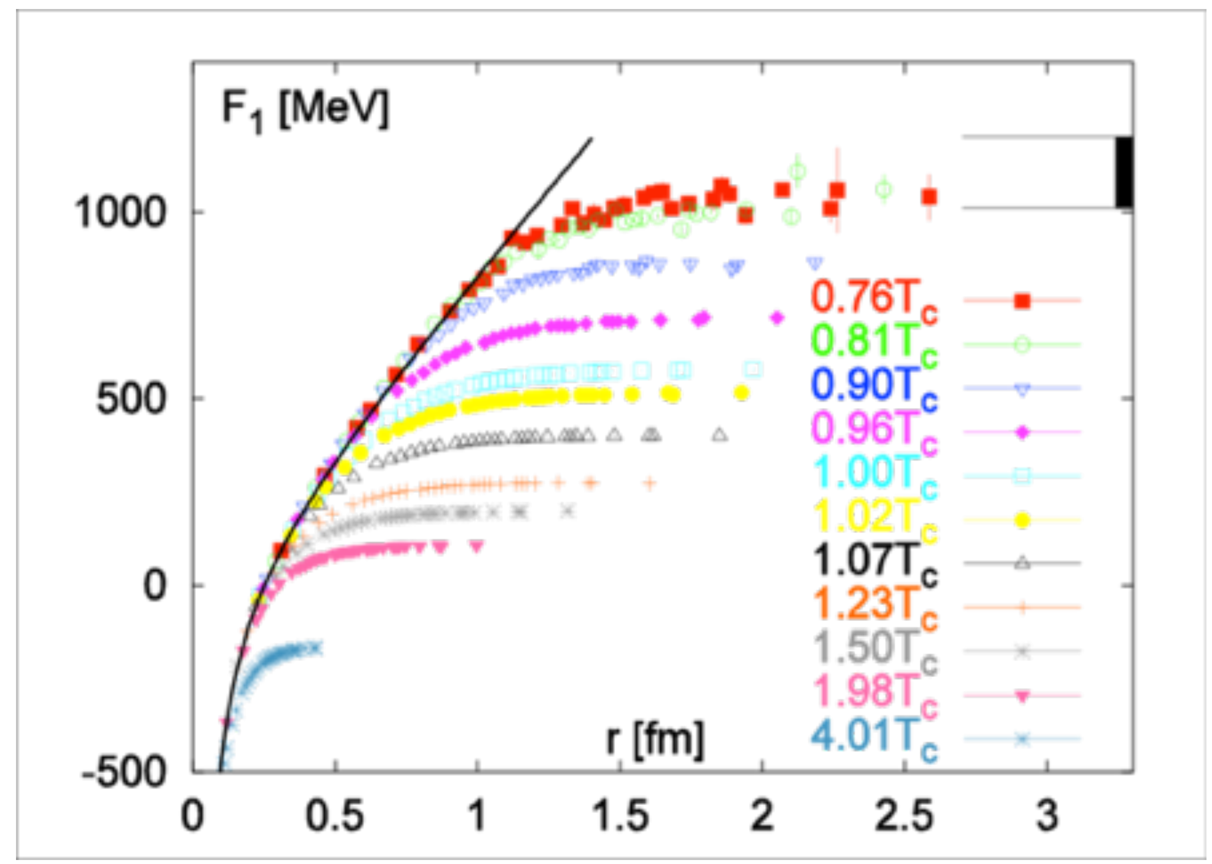
In the good old days...

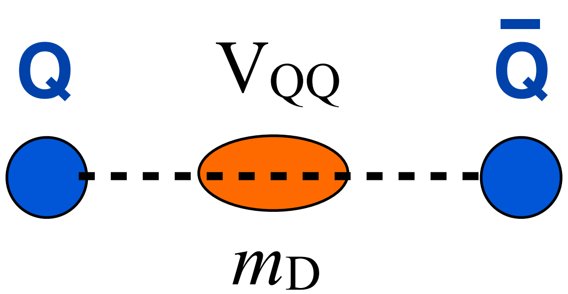
... life seemed simple: It's all color screening



Lattice QCD







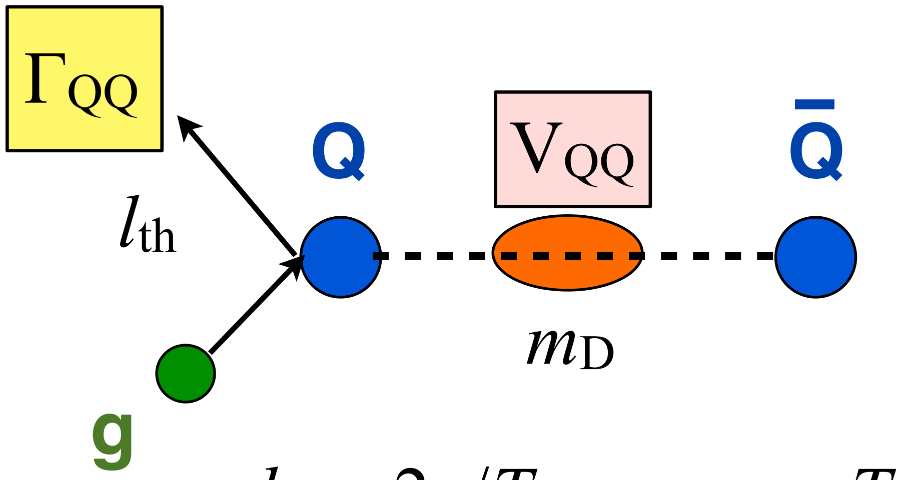
$m_D \sim gT$

Only the data did not quite fit the theory!

The real story...

...is more complicated (as usual).

Q-Qbar bound state interacts with medium elastically and inelastically!



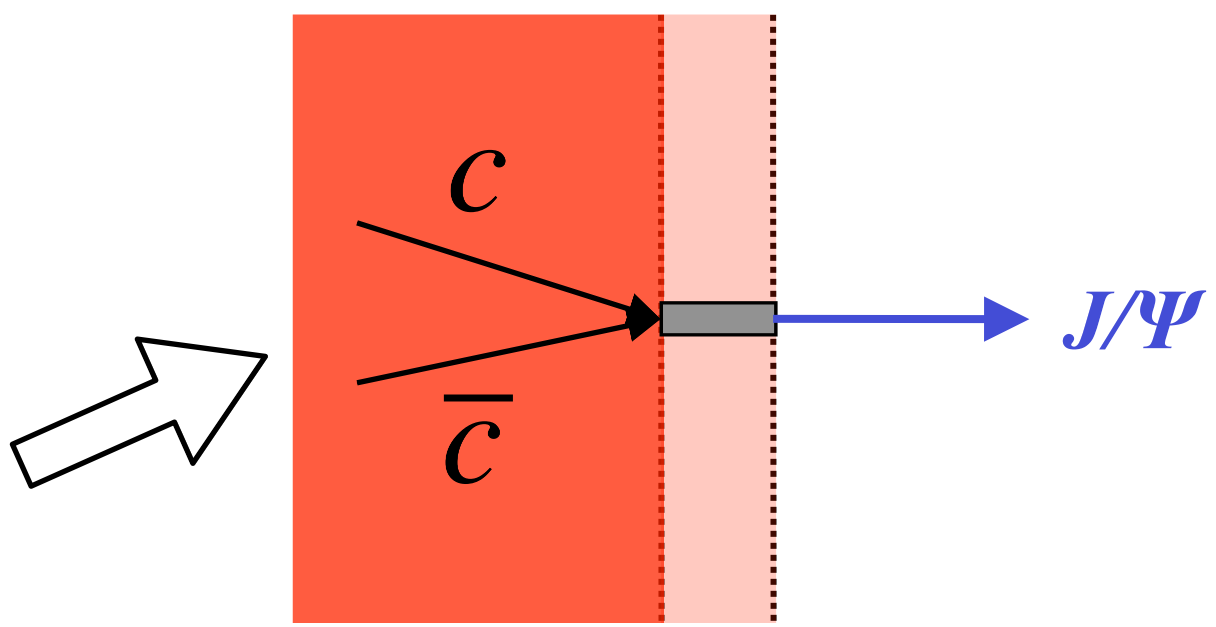
$$l_{th} \sim 2\pi/T, \qquad m_D \sim gT$$

$$i\hbar \frac{\partial}{\partial t} \Psi_{Q\bar{Q}} = \left[\frac{p_Q^2 + p_{\bar{Q}}^2}{2M} + V_{Q\bar{Q}} - \frac{i}{2}\Gamma_{Q\bar{Q}} + \eta \right] \Psi_{Q\bar{Q}}$$

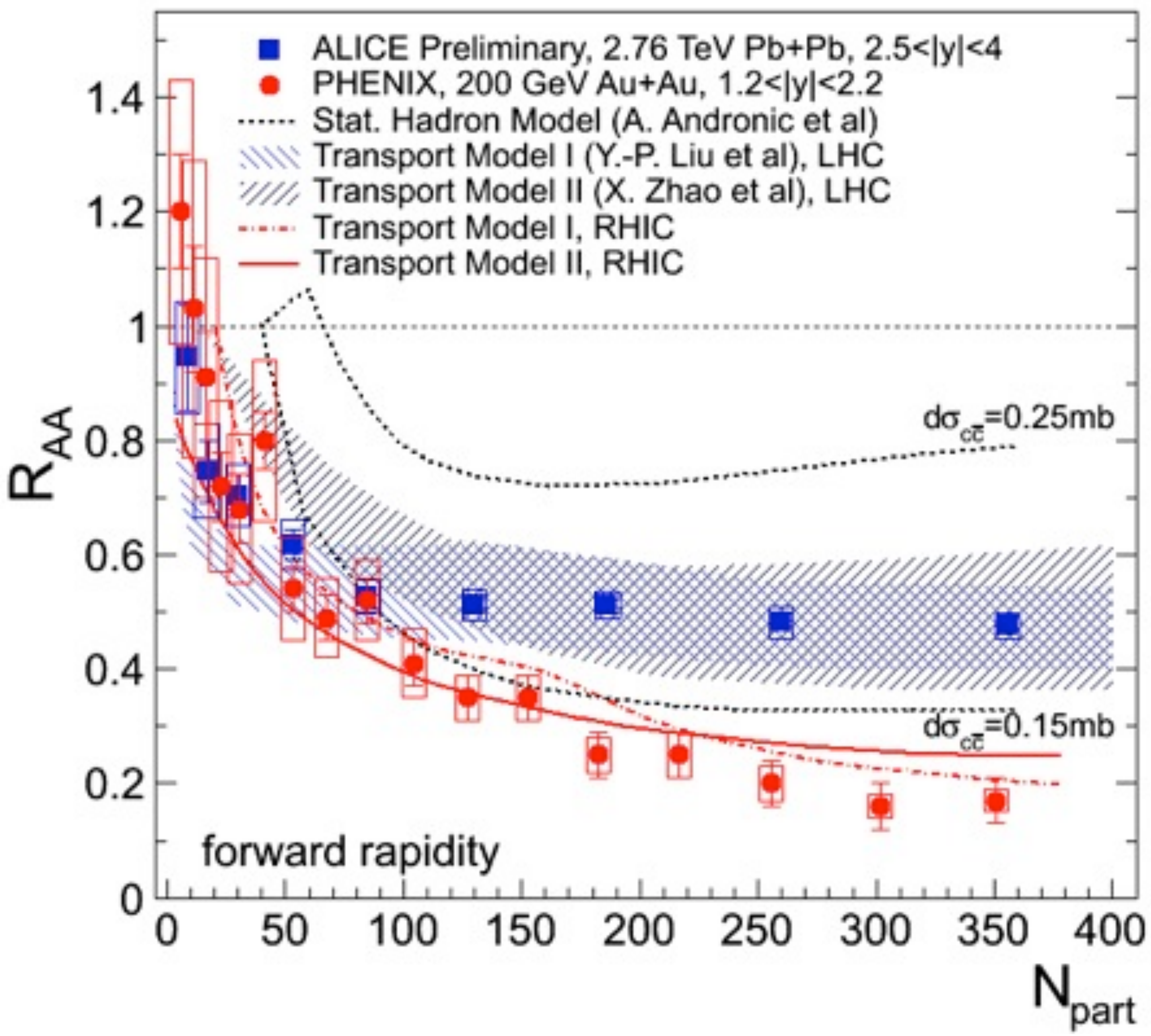
Strickland, arXiv:1106.2571, 1112.2761;
Akamatsu & Rothkopf, arXiv:1110.1203

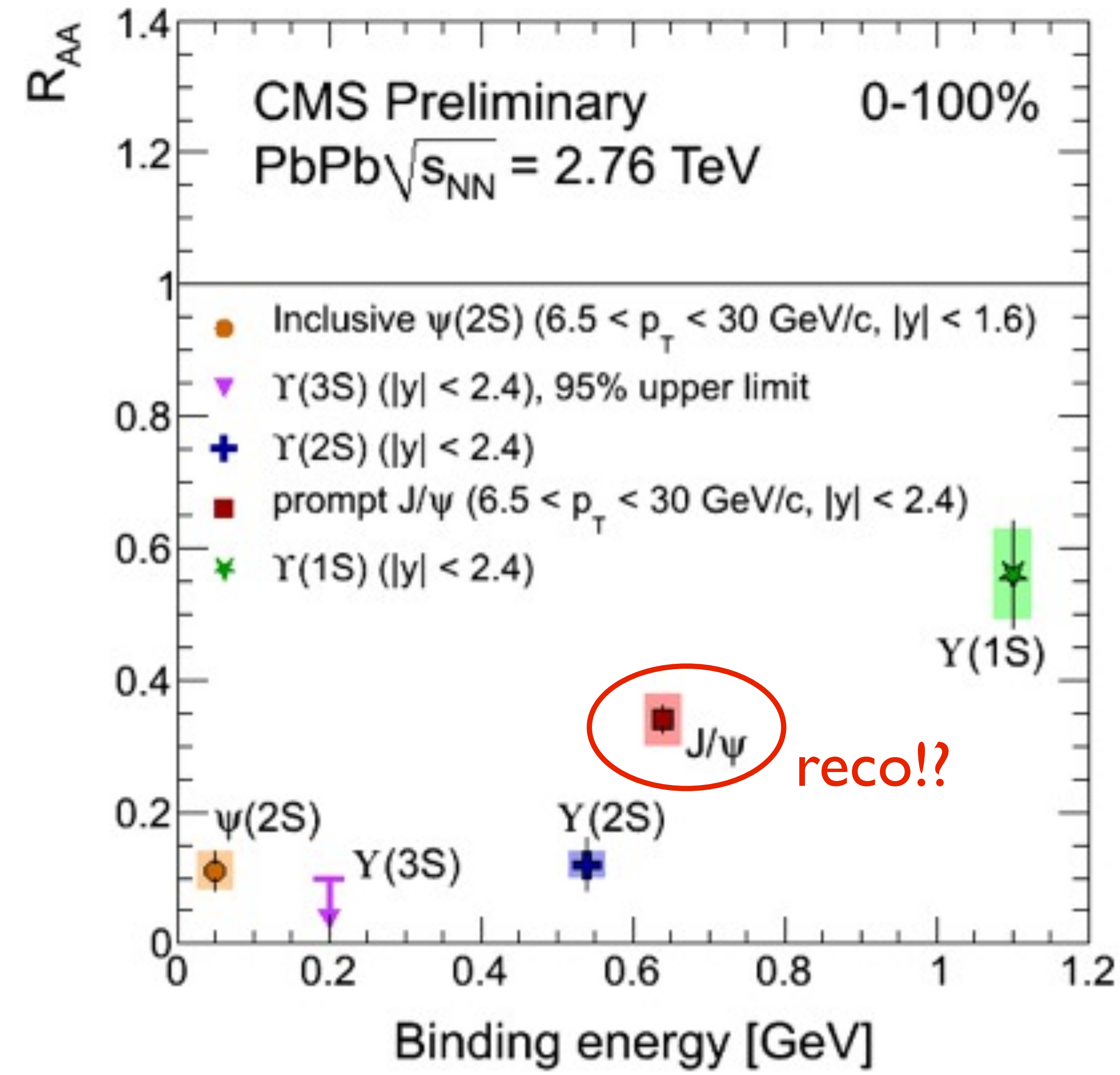
Heavy-Q energy loss and Q-Qbar suppression are closely related

Recombination can also contribute when c-quark density is high enough!



J/ψ suppression





Less J/ψ suppression at LHC than at RHIC, at mid-rapidity and mid-forward rapidities:
c-cbar recombination explains data.

Full range of quarkonium states is becoming accessible.

Summary & Outlook

Lessons and Questions

- QGP at LHC is less strongly coupled than at RHIC
  - Average η/s at LHC larger than at RHIC (?)
  - QGP at LHC appears less opaque than at RHIC
- Using E-by-E fluctuations as a versatile probe
  - Beam energy dependence varies sensitivity to E-by-E fluctuations
  - Can initial state structure and viscous effects be separated?
- Jet physics opens new avenues of probing the QGP
  - Matter effect on jet structure creates probes of scales
  - Kinematic threshold between quasiparticle and liquid domains ?
  - Structure of the sQGP reflected in energy loss mechanisms
- Quarkonium spectroscopy blossoms
  - Quarkonium melting is not just static screening
  - Recombination likely dominates at LHC for c-cbar states

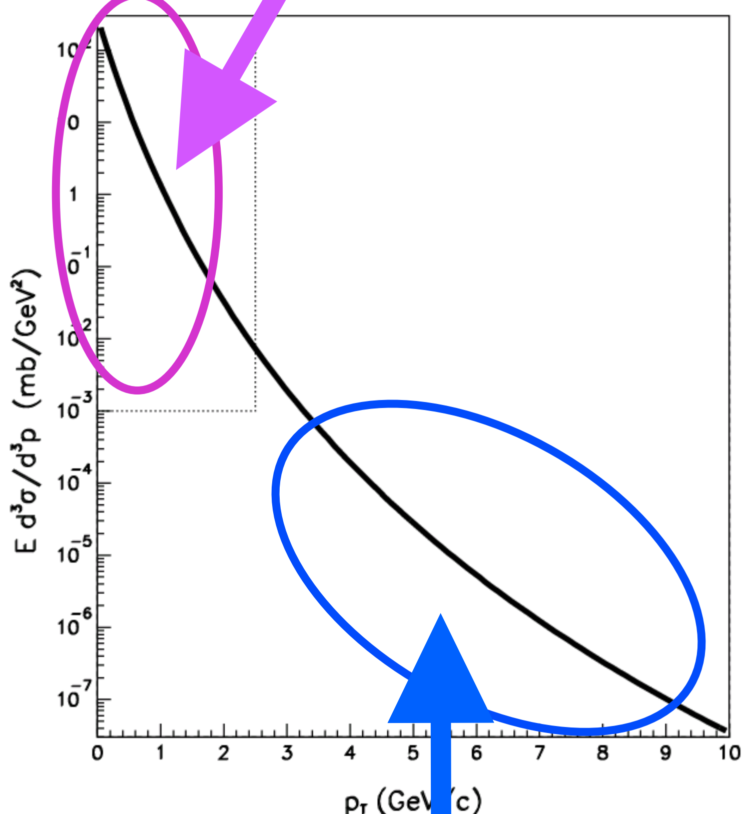
Additional slides

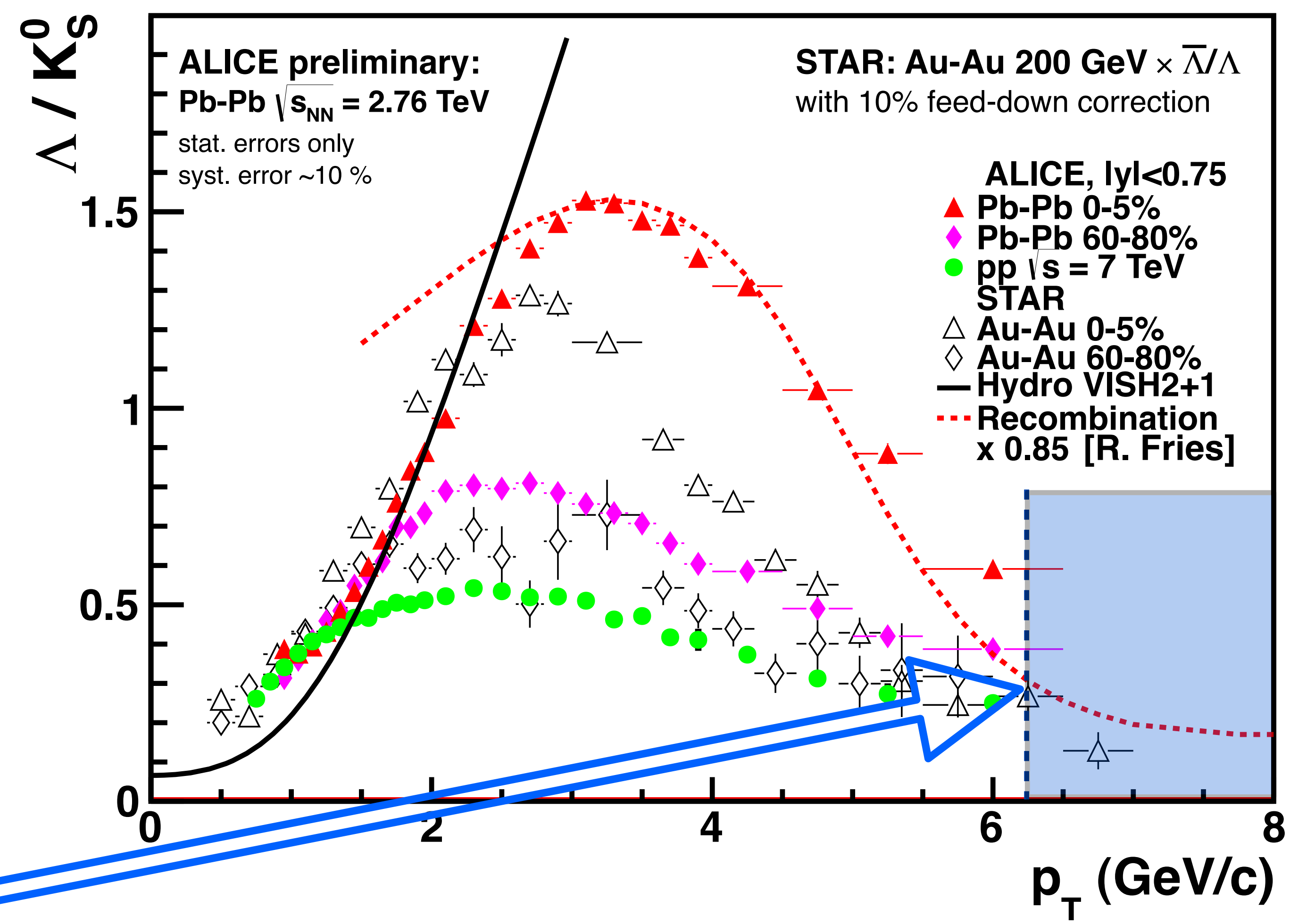
The Hadronizing QGP

Where does "hard" start?

p_T < 1.5 - 2 GeV/c
"thermal" particles
radiated from bulk medium

How do we know what "X" is ?

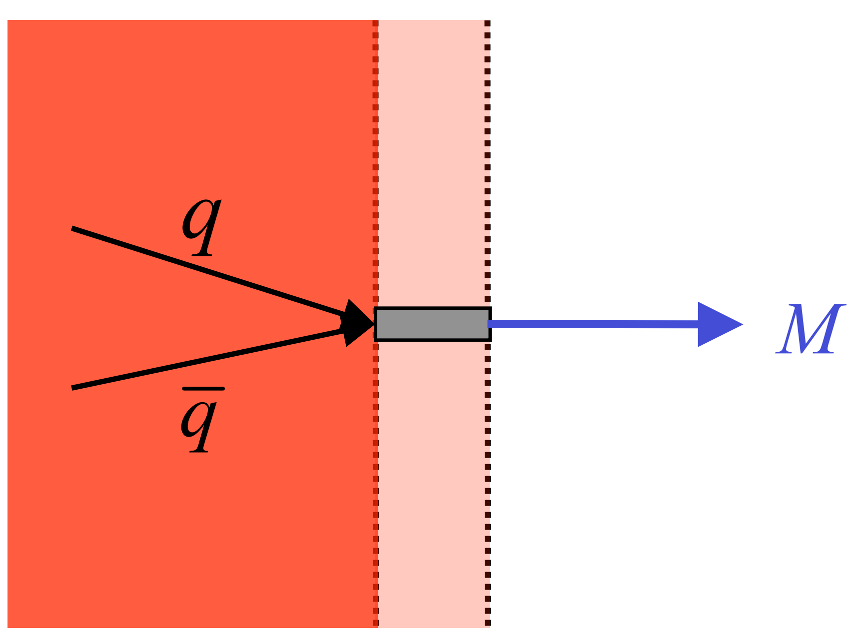




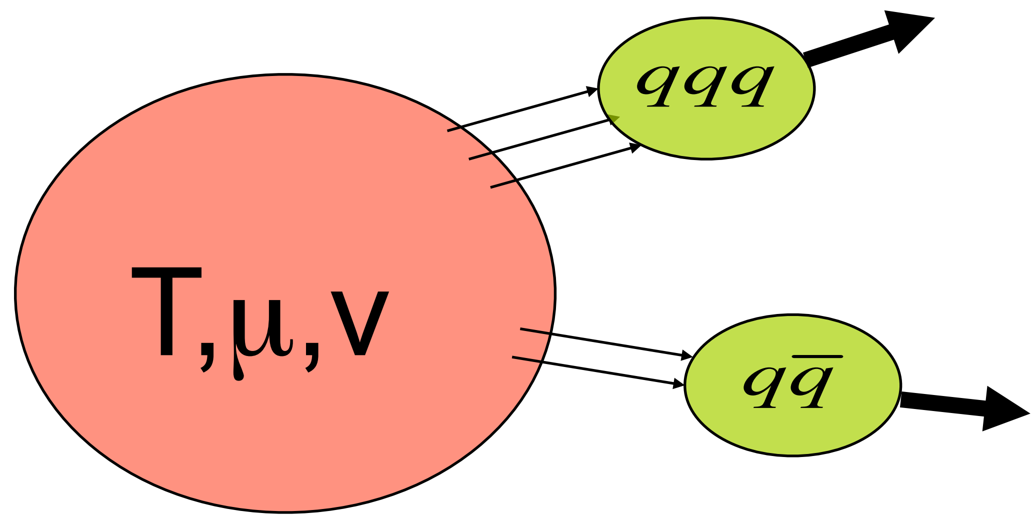
p_T > X GeV/c
autogenerated "external"
probes described by pQCD

Bulk hadronization

Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons



Sudden recombination



$$p_B \approx 3p_Q$$

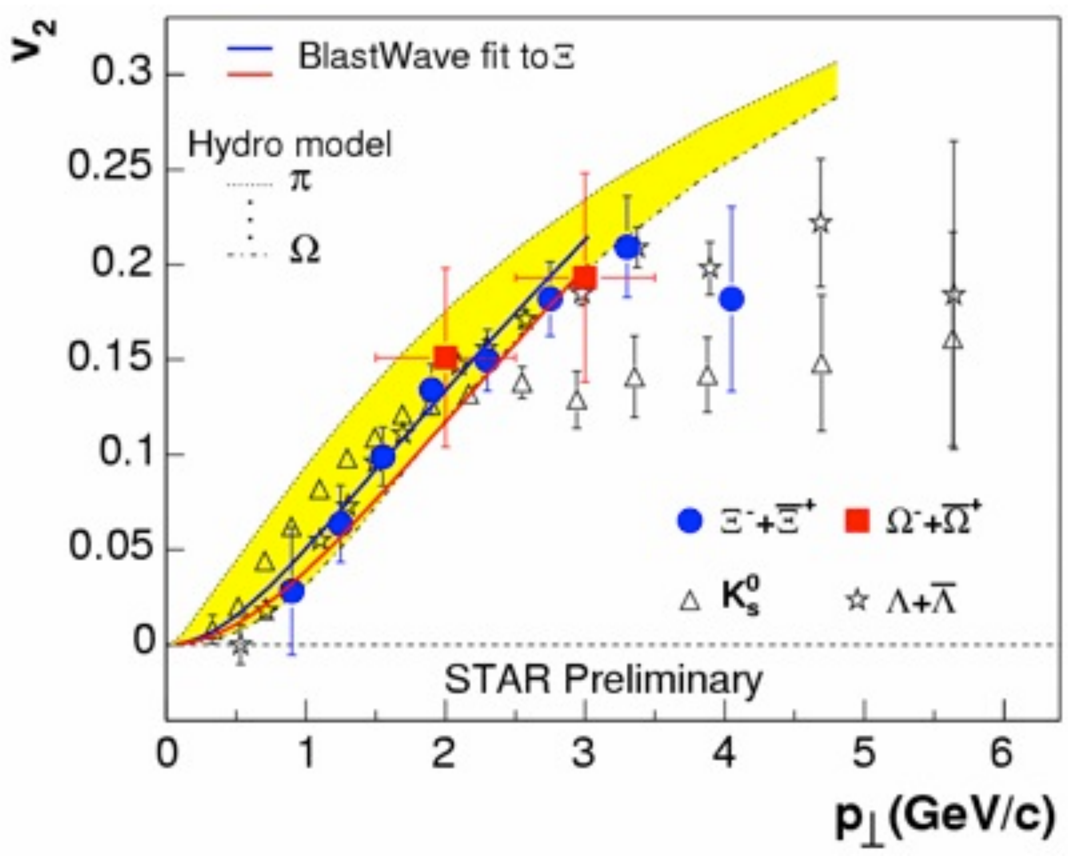
$$p_M \approx 2p_Q$$

$$v_2^M(p_t) = 2v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^Q\left(\frac{p_t}{3}\right)$$

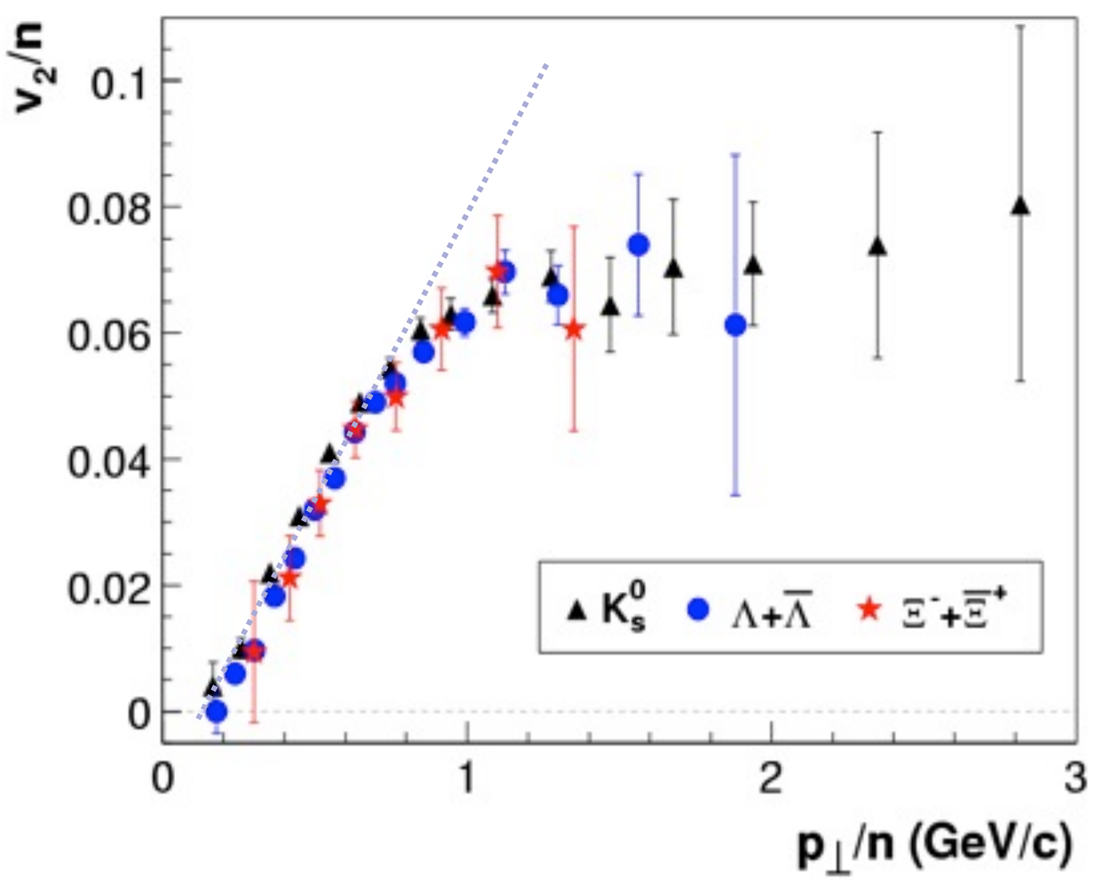
Quark number scaling of v_2

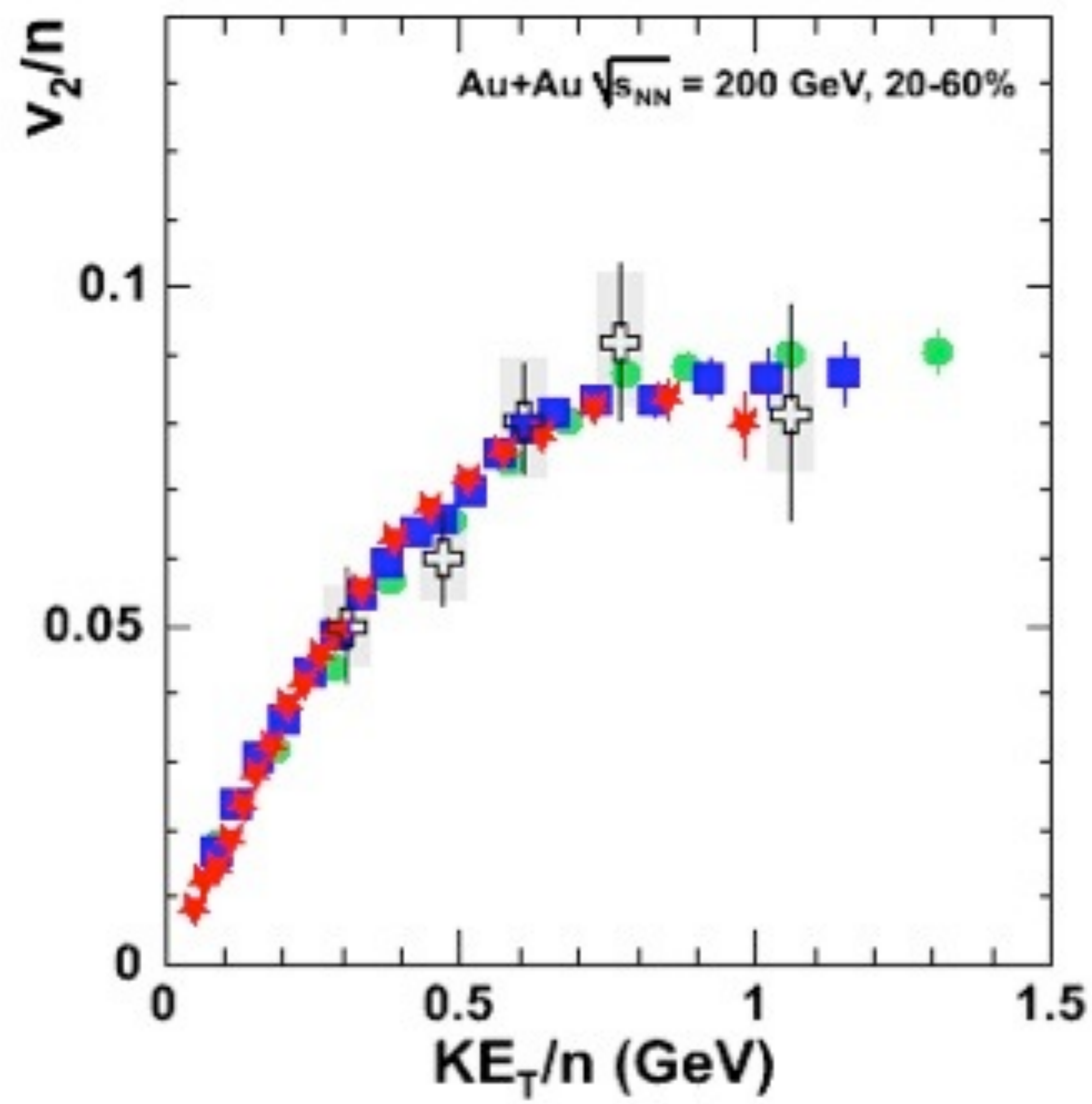
$$\frac{1}{2} v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3} v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$



Quark number scaling of v_2

$$\frac{1}{2}v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3}v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$

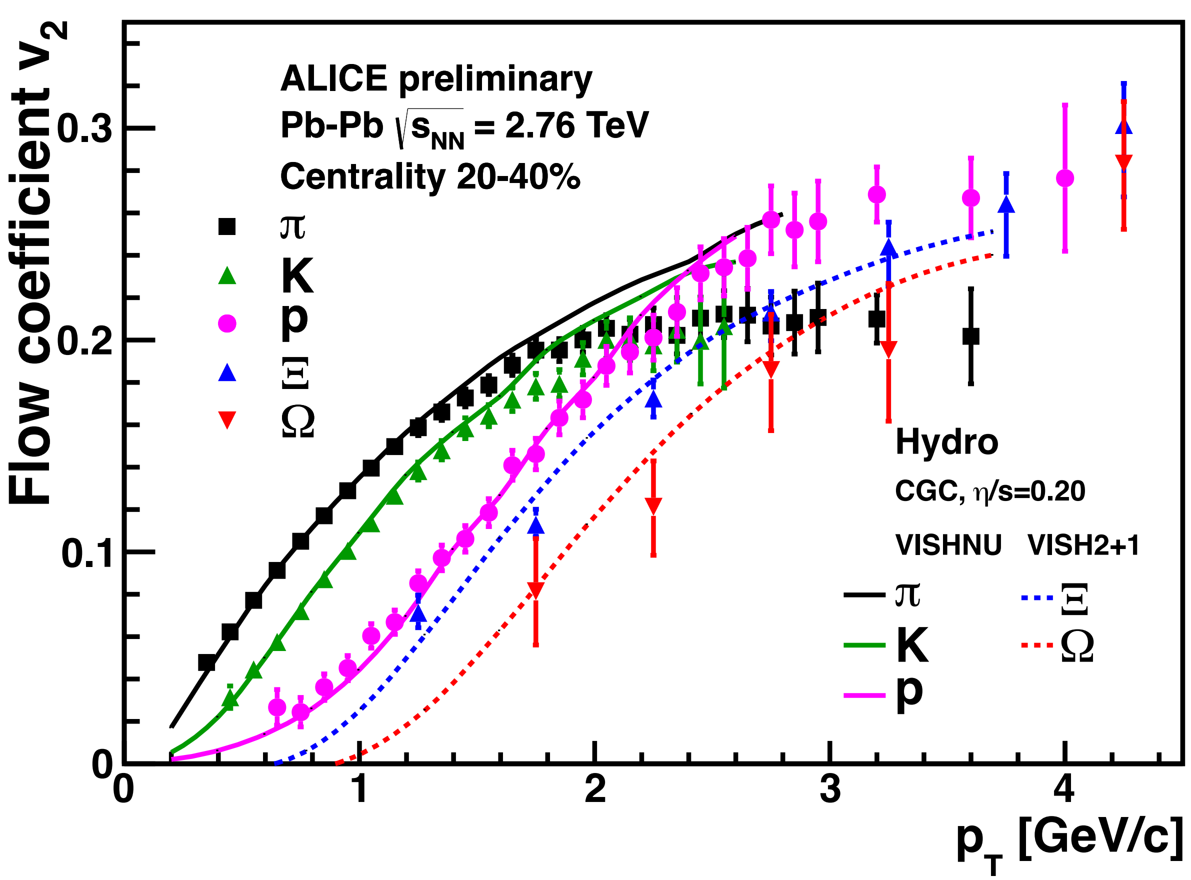




Emitting medium is composed of unconfined, flowing quarks.

Scaling at LHC?

Hydro works for mesons up to approximately 1.5 GeV/c.



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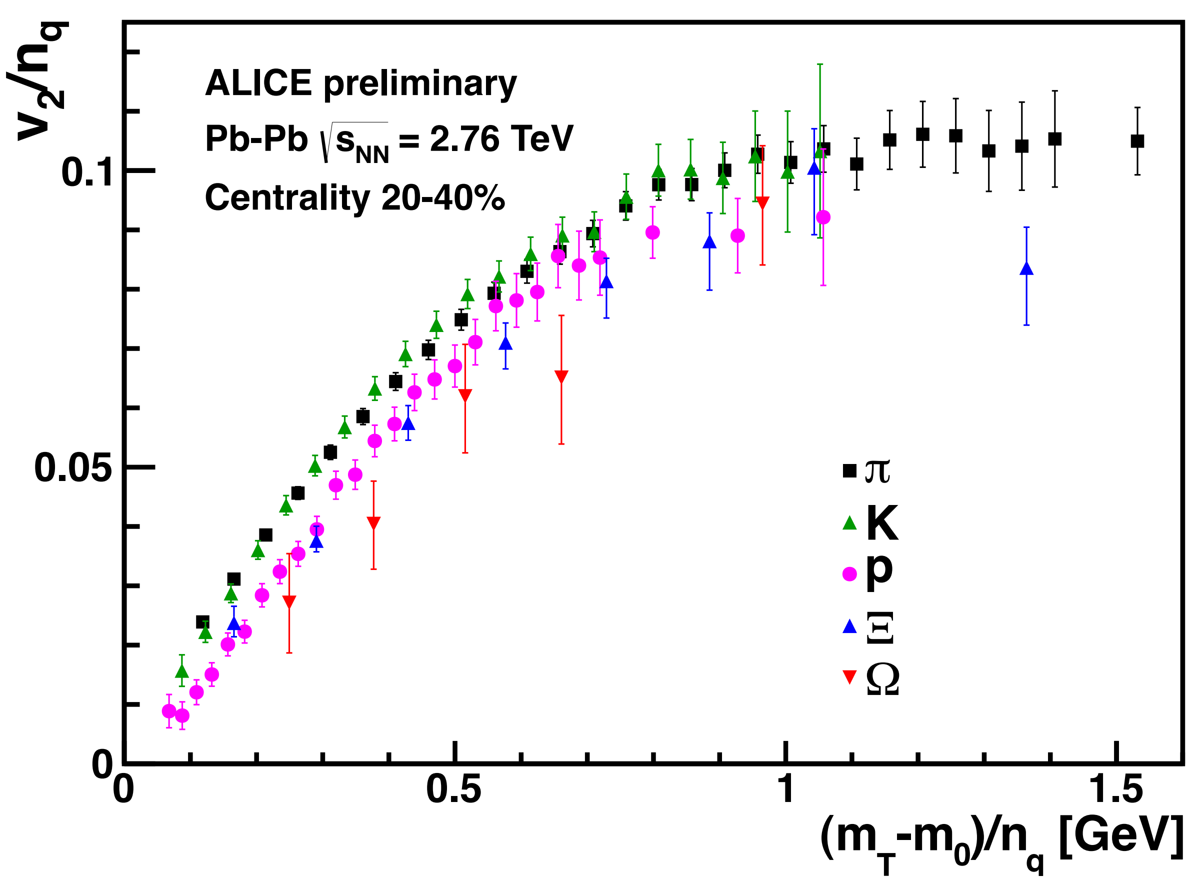
Valence quark scaling appears to fail over whole p_T range.



Scaling at LHC?

Hydro works for mesons up to approximately 1.5 GeV/c.

Valence quark scaling appears to fail over whole p_T range.

Elliptic flow must be corrected for late hadronic phase contribution to flow. Effect is larger for baryons than mesons. Valence quark scaling works after blue shift correction.