Broad Overview

Urs Achim Wiedemann
CERN PH-TH

Washington, 13 August 2012

The ‘Standard Model’ of Heavy Ion Collisions

- **Flow**
  Panta rhei: all soft particles emerge from common flow field
  [v_1,…,v_6,.. ,radial flow, HBT,Ψ_n -correlations ….]

- **Quenching**
  All hard hadronic processes are strongly quenched
  [R_{AA}(pt, phi), I_{AA}, A_j, jet fragmentation, quarkonia …]

What can we learn about
fundamental properties of hot and dense matter
from this *generic* and *robust* phenomenology?

Dissipative fluid dynamic description

- Based on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- Sensitive to properties of matter that are

calculable from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

AdS/CFT =>

EOS: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

transport coefficients: shear η, bulk ξ viscosity, conductivities …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

relaxation times: τ_π, τ_Π, …

Transport properties – current status

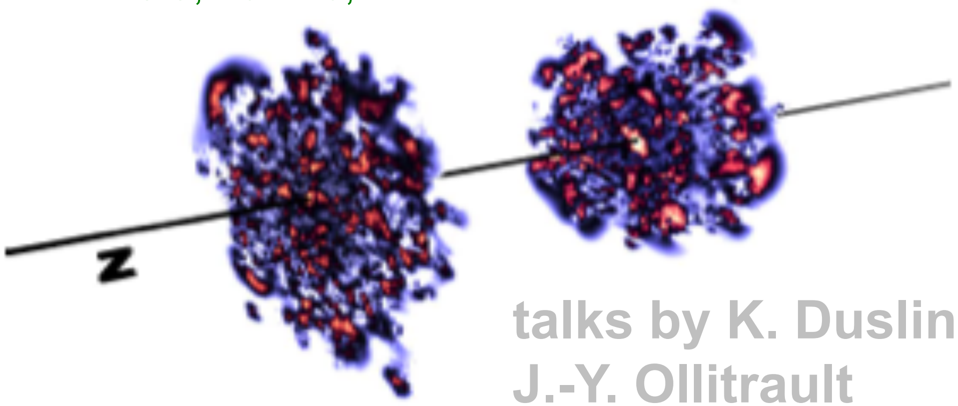
- Tight upper and lower bounds from combined analysis of v_2 and v_3

$$1 \leq 4\pi\left(\eta/s\right) \leq 2$$

talk by Huichao Song

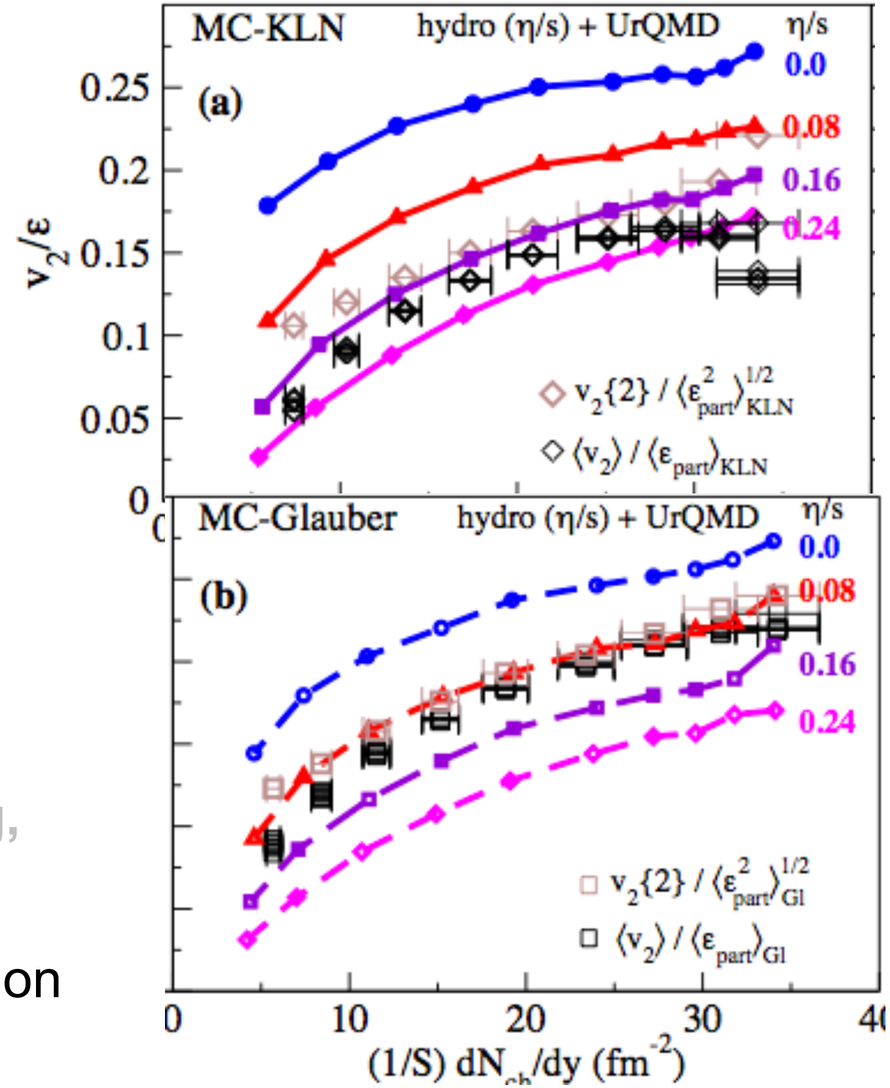
- Caveat: uncertainties in scale of initial fluctuations affects viscosity bounds

Schenke, Tribedy, Venugopalan, arXiv:1206.6805,
Nara, Dumitru, …



talks by K. Dusling,
J.-Y. Ollitrault

H. Song et al. PRL 106 (2011) 192301



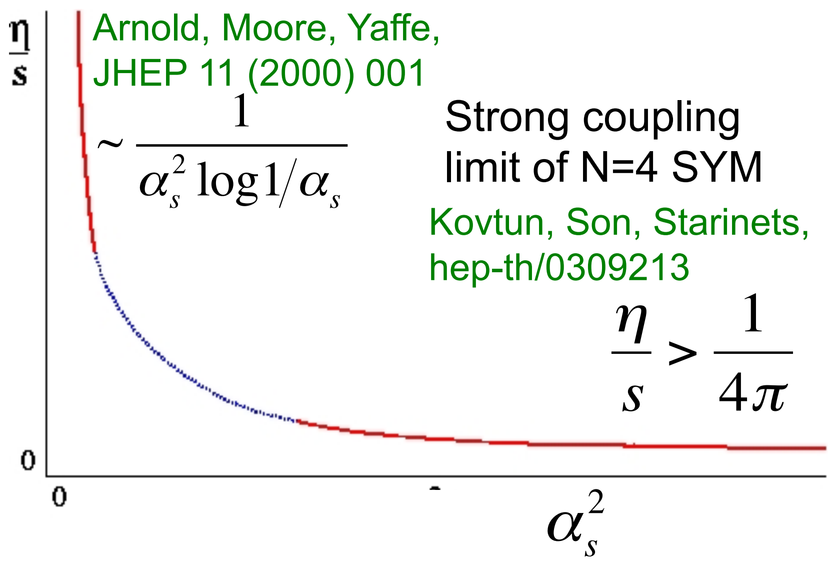
- Correlations amongst n-th order reaction planes are of fluid dynamic origin.

Z. Qiu, U. Heinz, arXiv:1208.1200
D. Teaney, L. Yan, arXiv:1207.1905

Main conclusions from current analysis

- Value of shear viscosity minimal,
  => perfect liquid,
  strongly coupled plasma

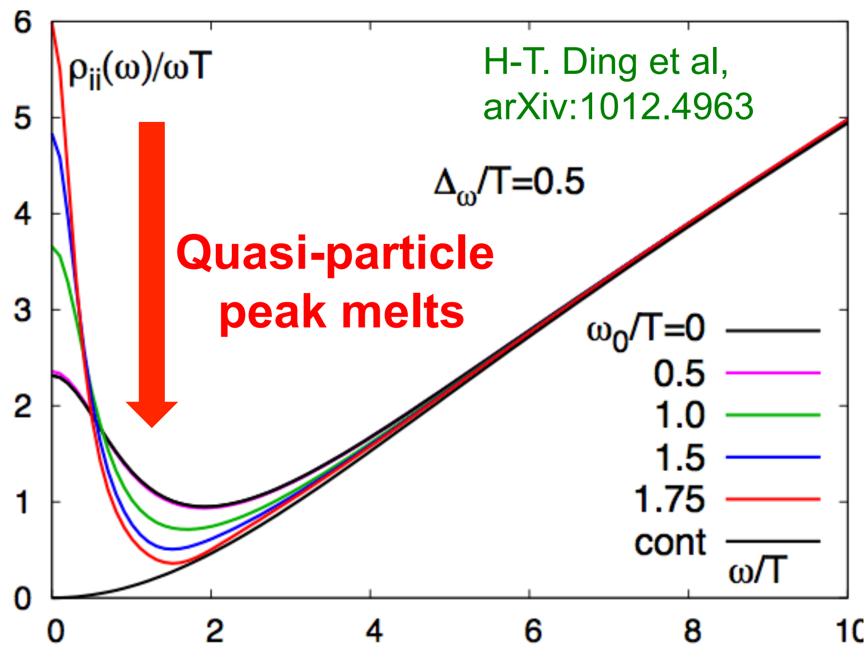
- Fluid dynamics applies at $\tau_0 < 1\,fm$
  In perturbative scenario: hydro valid if
  $$\underbrace{\alpha_s^2 T_0}_{collision\ rate} >> \underbrace{1/\tau_0}_{espansion\ rate}$$
  but
  $$\alpha_s >> 1 \quad \Rightarrow 0.65 \le \tau_0 T_0$$
  => non-perturbative thermalization
  Heller, Janik Witaszczyk, PRL 108 (2012) 201602
  Chesler, Yaffe, PRL 102 (2009) 211601



- This plasma is unique in that it does not carry quasi-particle excitations

perturbatively require $\tau_{quasi} \sim \frac{1}{\alpha_s^2 T} >> \frac{1}{T}$

but
$$\tau_{quasi} \approx \frac{const}{T}\frac{\eta}{s}$$



Expected improvements from fluctuations

- Linear fluctuations governed by **sound attenuation length** $\Gamma_s = \frac{\eta}{sT}$

$$\delta v(\tau,k) = \delta v(\tau_0,k)\left(\frac{\tau_0}{\tau}\right)^* \exp\left[-\Gamma_s k^2(\tau_0-\tau)\right]$$

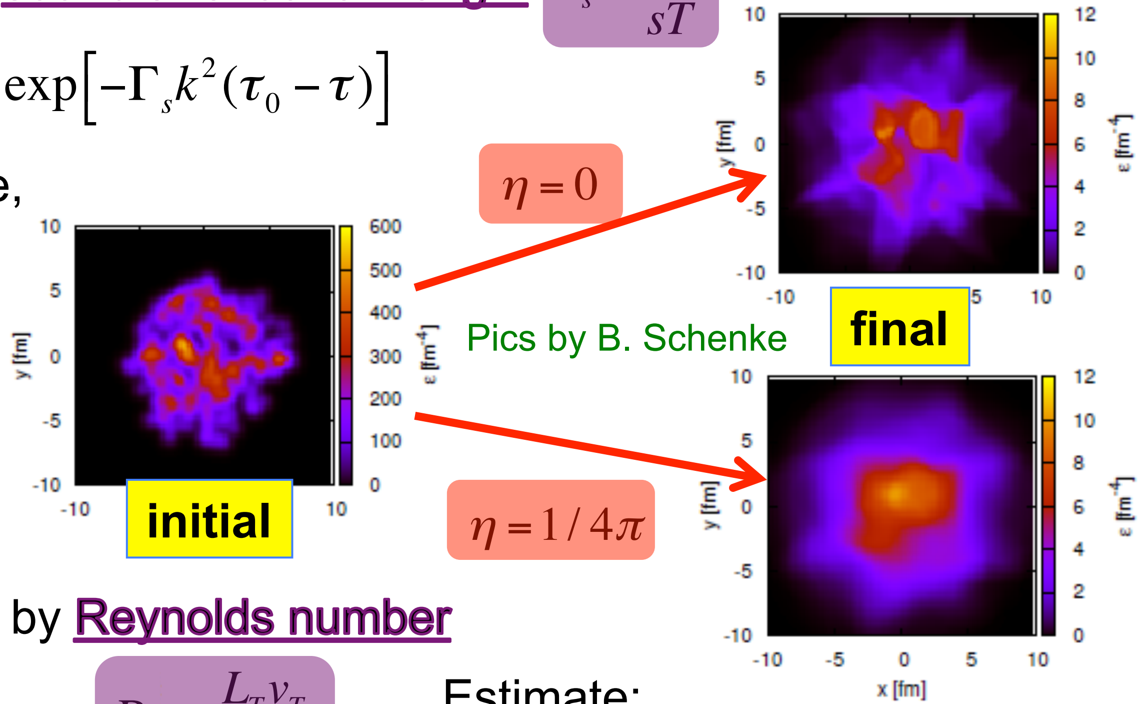
Fluctuations decay on time scale,

$$\tau_{1/e}(k) = \frac{1}{\Gamma_s k^2}$$

e.g.

$$\tau_{1/e}(k = 1\,fm^{-1}) \approx 10 - 20\,fm$$

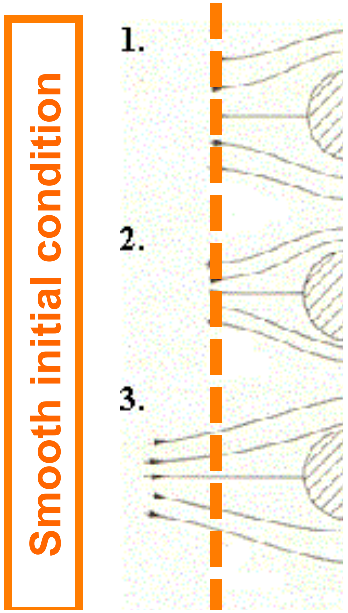
$$\tau_{1/e}\left(k = (0.5\,fm)^{-1}\right) \approx 2.5 - 5\,fm$$



- Nonlinear fluctuations governed by **Reynolds number**

$$\mathrm{Re} = \frac{L_T v_T}{\Gamma_s}$$

Estimate:
1 < Re < 100



$\mathrm{Re} \approx 1.0$

$\mathrm{Re} \approx 10.0$

$\mathrm{Re} \approx 100.0$

Improvements

- Linear fluctuations governed by **sound attenuation length** $\Gamma_s = \frac{\eta}{sT}$

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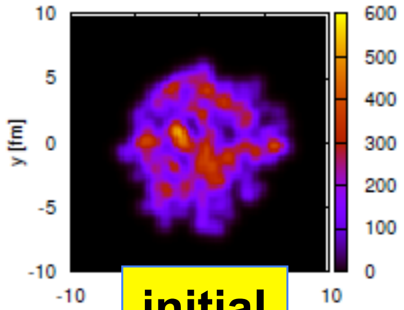
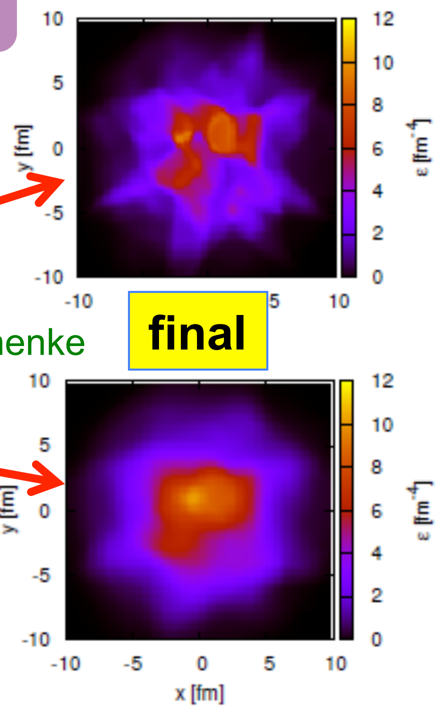


initial

$\eta = 0$

$\eta = 1/4\pi$



final

Pics by B. Schenke

- Nonlinear fluctuations governed by **Reynolds number** $\mathrm{Re} = \frac{L_T v_T}{\Gamma_s}$

Estimate:
1 < Re < 100

$\mathrm{Re} \approx 1.0$

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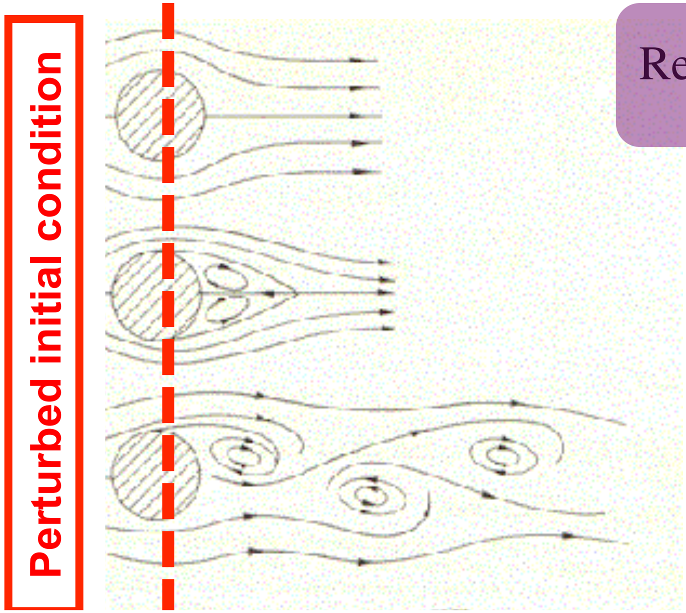


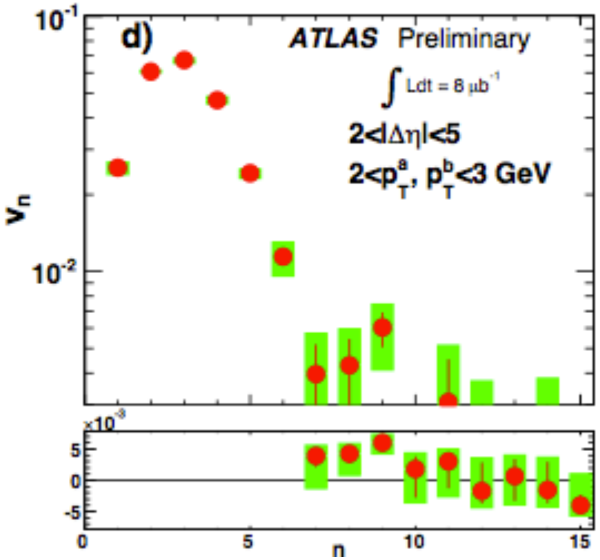
Control of perturbations and their scale k enhances sensitivity to transport properties of QCD matter.

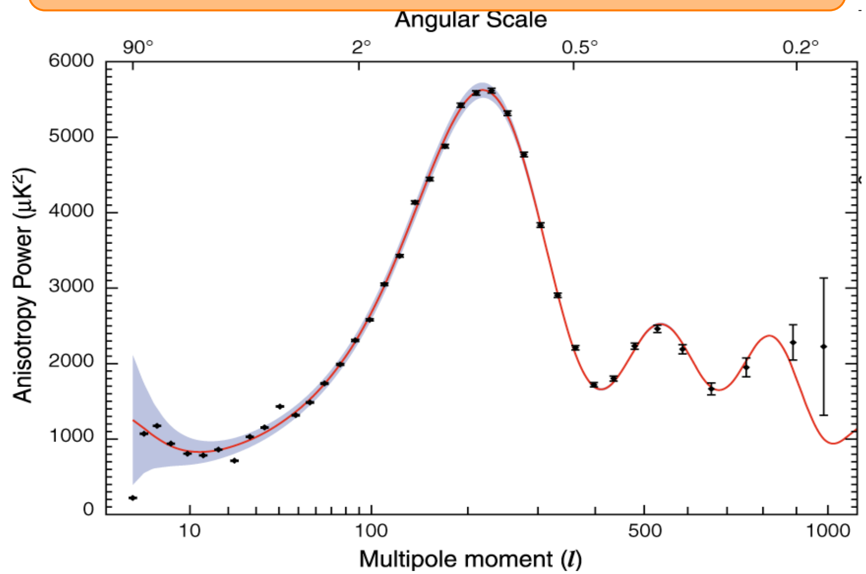
Little Bangs versus Big Bang

Hydro evolution of fluctuating initial condition reveals matter properties

$\eta/s = 0.08^{+\ldots}_{-\ldots}$

$\Omega_b = 0.044^{+0.04}_{-0.04} \quad \Omega_\Lambda = 0.73^{+0.04}_{-0.04} \ldots$





- Uncertainties in initial condition**s**
- Many observables

$$v_n(p_T),\ n = 1,\ldots,10$$

- Many small events

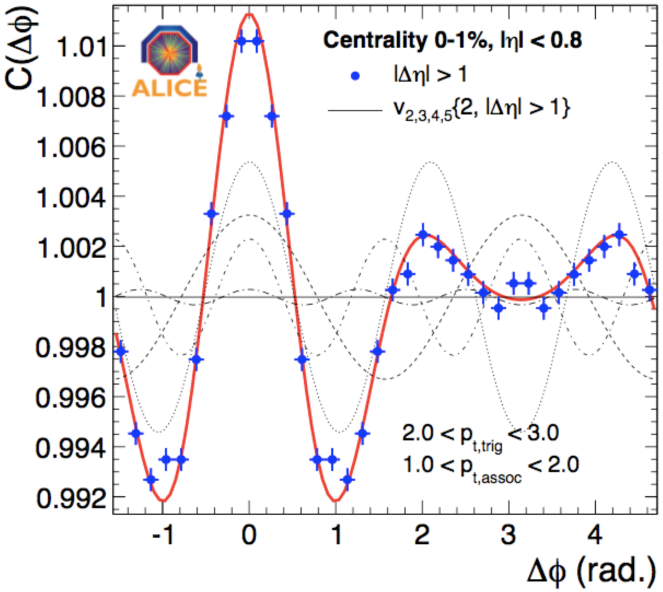
- Uncertainties in initial condition
- Many observables

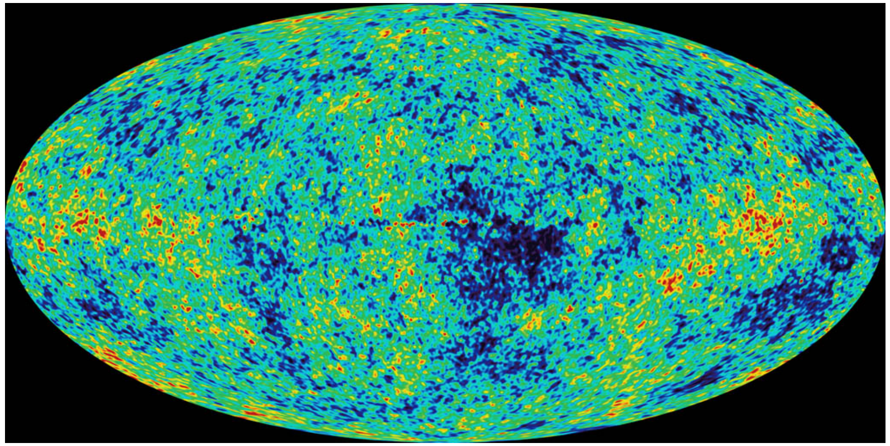
$$c_l,\ l = 1,\ldots,1000$$

- One big event

(additional uncertainty: cosmic variance)

Little Bangs versus Big Bang





- Fluctuation analyzed since 2009
  ~ 100 % uncertainty on η/s
- Improved measurements upcoming
  (future RHIC & LHC running)
- Parameter not yet listed in PDG

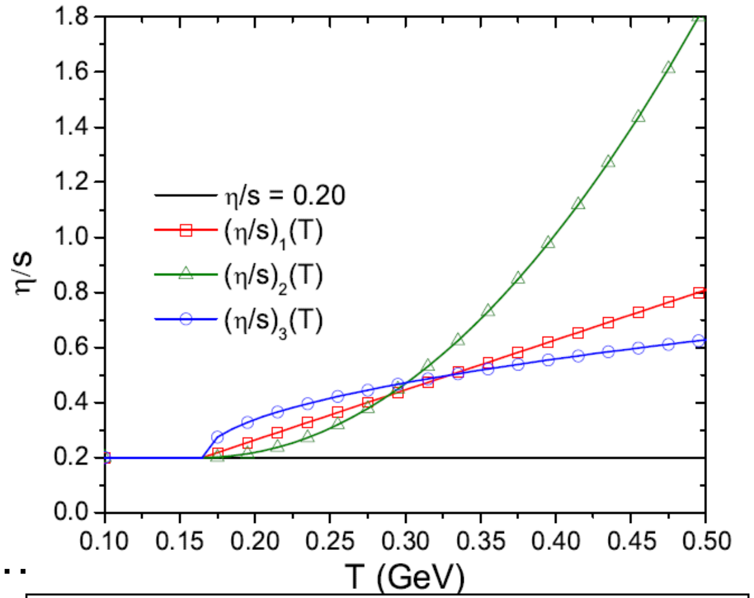
(Note: feasibility of analysis method
fully established, see rhs …)

- After more than a decade of analysis
  and measurements,
  ~1 % accuracy on key parameter
- Improved measurements upcoming
  (PLANCK, …)
- Parameter listed in PDG

Why improving accuracy of shear viscosity?

- Factor ~10 improvement needed to become sensitive to
  - bulk viscosity
  - T-dependence of shear viscosity
  - relaxation times

  …



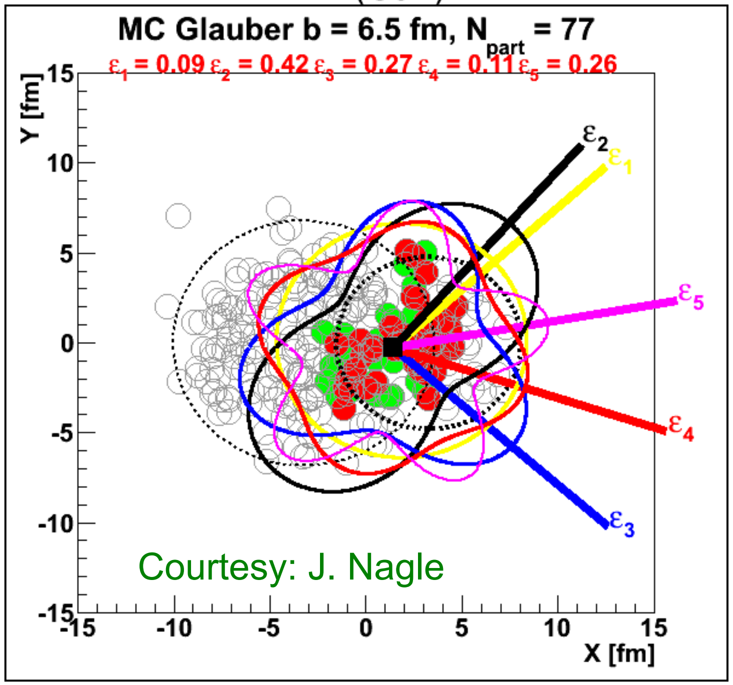
- Vary fluctuations by colliding different beam species (1st data on U+U and Cu+Au at this conference), centrality measurements …

- Any statement about T-dependence will require data from RHIC & LHC

- Aim: understand transfer matrix

S. Flörchinger

$$\begin{pmatrix} \delta\varepsilon \\ \delta v_{sound} \\ \delta v_{vorticity} \end{pmatrix}(\tau_{final}) = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{pmatrix} \delta\varepsilon(\tau_i) \\ \delta v_{sound}(\tau_i) \\ \delta v_{vorticity}(\tau_i) \end{pmatrix}$$



Quenchings & Suppressions

• Light hadrons $\pi, K, p, \Lambda, \ldots$	**fast**, propagation close to eikonal	fragile	formed late $\tau_{had} \approx \frac{1}{Q_{had}} \frac{p_T}{Q_{had}}$
• Heavy flavors $D^0, D^+, D^{*+}, \ldots$	**slow** up to medium p_T random walk?	Carry robust tag	formed earlier $\tau_{D/B} \approx \frac{1}{M_{D/B}} \frac{p_T}{M_{D/B}}$
• Quarkonia $J/\psi, \psi', \Upsilon(1s), \Upsilon(2s)\ldots$	**slow** but not static	Robust up to T_{diss}	formed early (endogamously) or late (exogamously)
• Jets	**fast**, propagation close to eikonal	from fragile to robust	Forms throughout medium evolution

Hard probes: - initiated at $\tau_{init} \approx 1/Q_{hard} << 1\,fm$

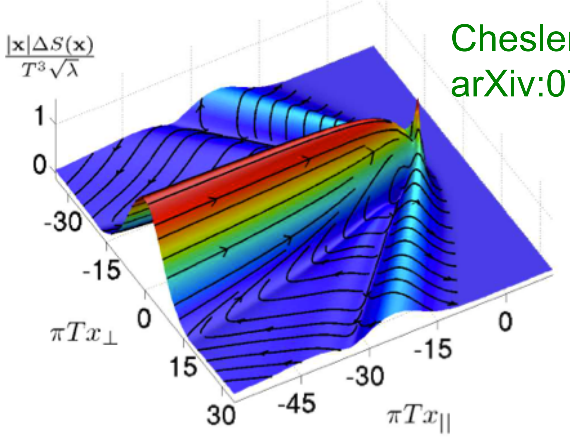
- propagate up to $\tau_{final} \approx 10\,fm$

⇨ Hard probes challenge picture of a plasma that does not carry quasi-particle excitations.

Probes propagating in a perfect liquid

Do hard probes have a finite mean free path?

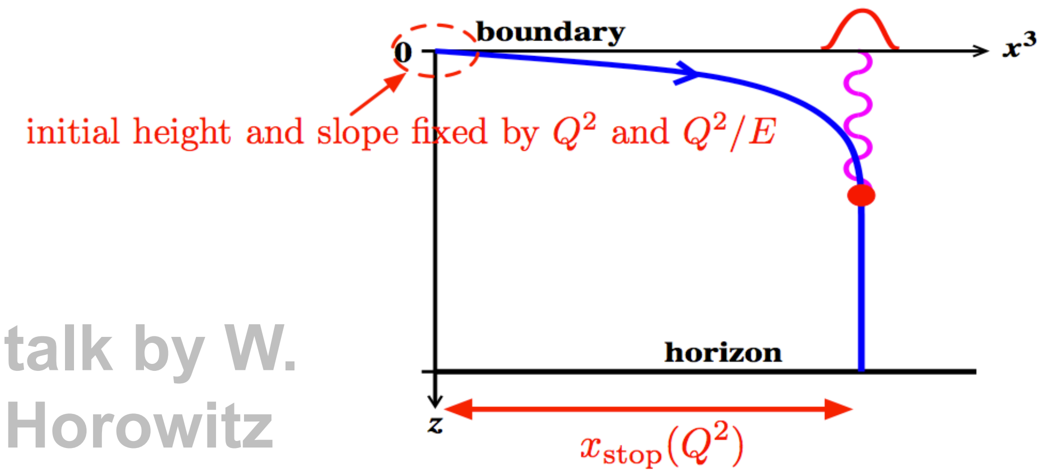
AdS/CFT view



Chesler, Yaffe
arXiv:0712.0050

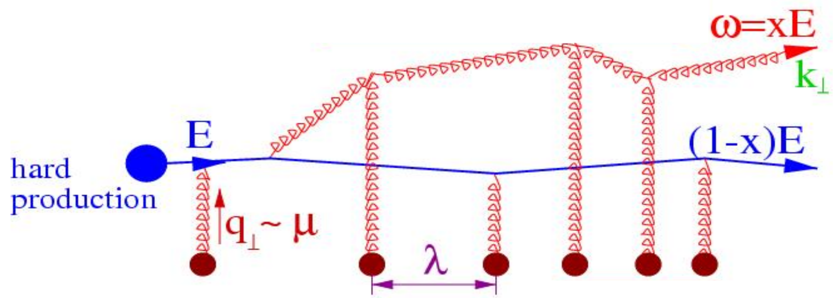
Heavy quarks propagate without mean free path
-> Lost momentum goes into Mach cone and wake

Light partons/jets propagate towards thermalization
(no collinear structure emerges, jet=hedgehog)



talk by W. Horowitz

If λ_{mfp} is finite



Energy moved to softer scales via
elastic (aka collisional) and
inelastic (aka radiative) mechanisms

Fragmentation broader but
collinear dynamics present.

talk by G. Milhano

Collinear structure can also result from
evolution outside the medium
=> Need to understand formation times

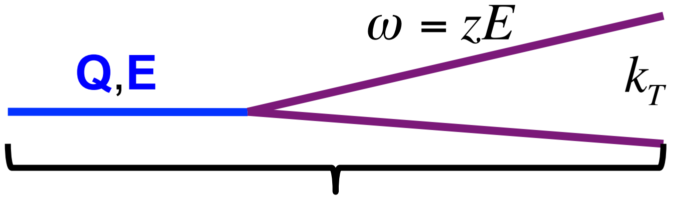
Jet quenching – formation times

- Energy transported from hard to soft scale
- Energy at soft scales transported away from jet within finite time

$$\tau_{transport} \approx 5 - 10\, fm/c$$

- Which modes ω can form in this time?

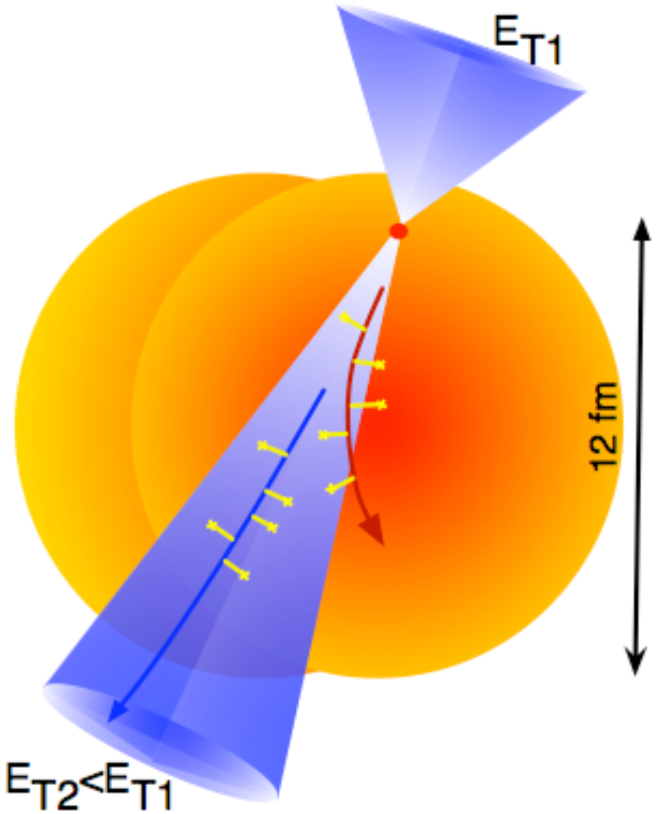
In vacuum, soft modes form **late**



$$\tau_f^{vac} \equiv \frac{E}{Q^2} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

In medium, with perturbative BDMPS-Z quenching they form **early**

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \frac{\omega}{\hat{q}\tau_f^{med}} = \sqrt{\frac{\omega}{\hat{q}}}$$

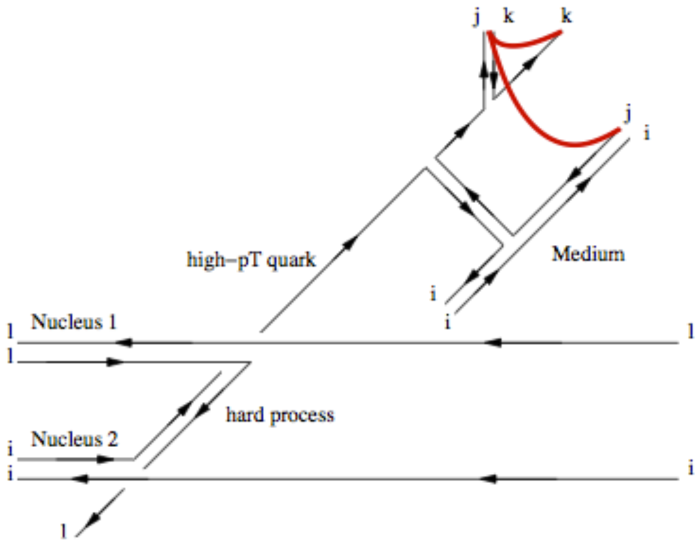


How far can we push a perturbative description?

Color correlations versus kinematics

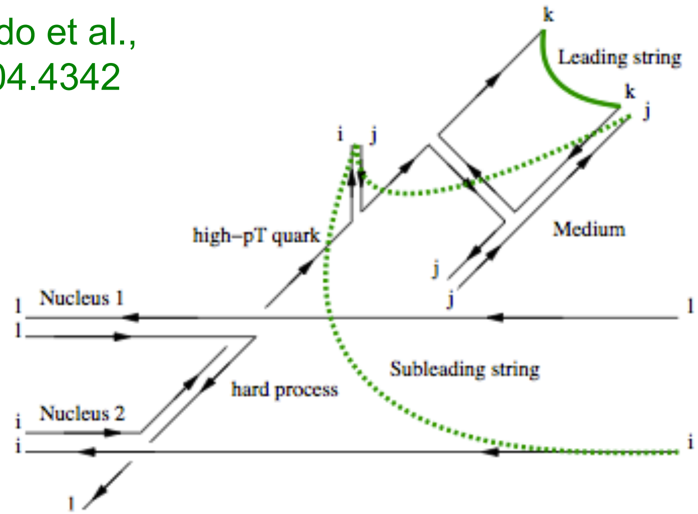
Even if hadron forms outside medium, it may form from modified color connection

- Vacuum-like hadronization
  (q & g contribute to leading hadron)



- Medium-modified hadronization
  (glue cannot contribute to leading hadron)

A. Beraudo et al.,
arXiv:1204.4342



- Subleading string hadronizes separately
  -> enhanced soft multiplicity
- Leading string hadronizes vacuum-like
  but with reduced E_T

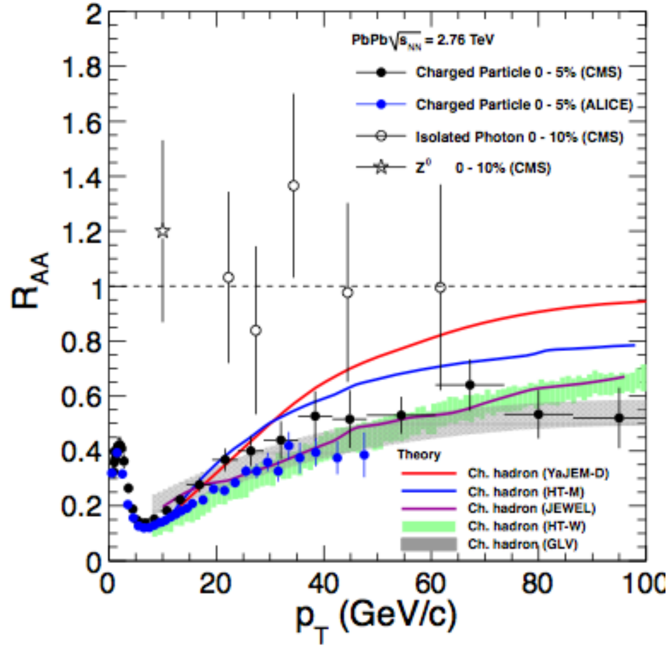
- Color connection between medium and probe
  also relevant for Quarkonium suppression

Jet quenching - Models

- Ultimate TH challenge: combine

Parton dynamics + Fluid dynamics + Hadronization

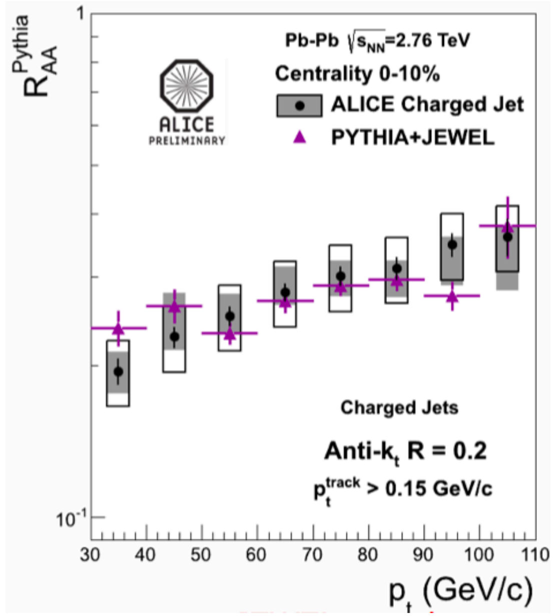
- Current priority (my view):
  Formulate perturbative baseline model of jet quenching to see where $\lambda_{mfp} = finite$ breaks down.



- Problems at interface between TH and EXP

reconstructed jets = generator level jets $\cap$ exp. jet resolution

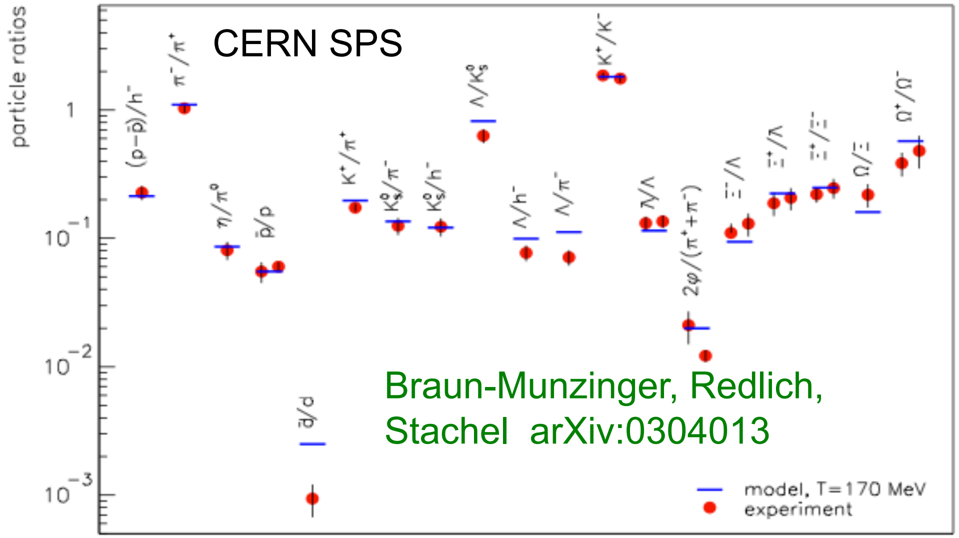
Snowmass accord for jet quenching needed?

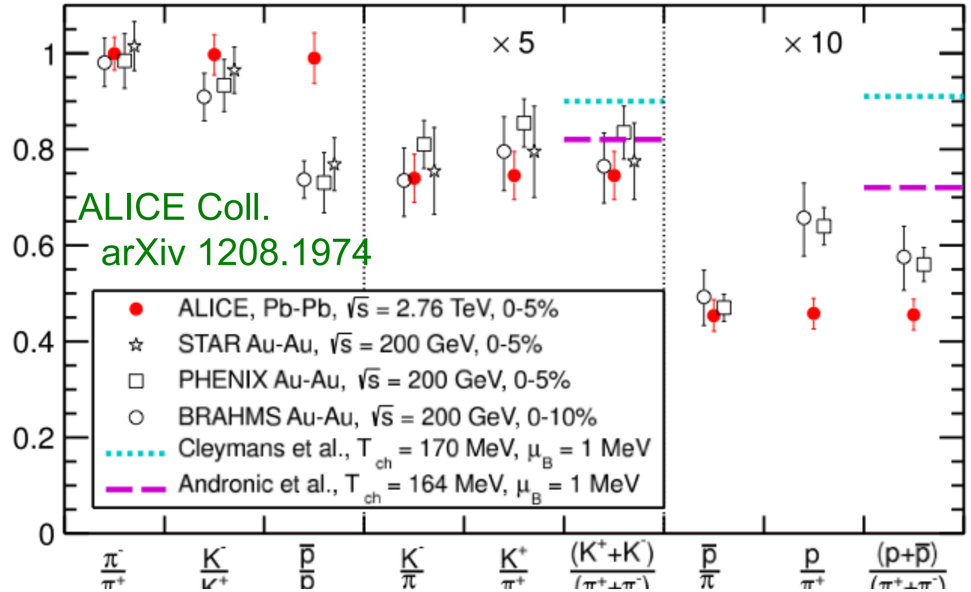


talk by G. Milhano

Hadrochemistry

- Hadronic yields and ratios fitted by statistical model in terms of (μ, T).
- Generic feature over wide energy range, e.g. Ω 15xenhanced @ SPS.
- Which microscopic dynamics turns quarks and gluons into hadrons?
- Insights from charm where initial partonic production is non-thermal?
- Insights from deviations from thermal model: proton and anti-proton yields!



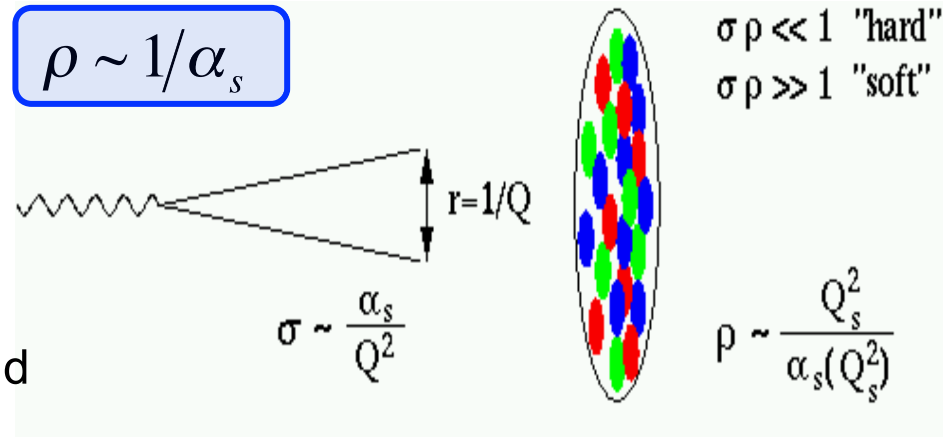


Saturation physics

- At small-x, parton densities are maximal up to large scales $Q^2 < Q^2_{sat} \sim (2-3GeV)^2$ but coupling stays small

$$\boxed{\alpha_s(Q^2_{sat}(x) >> \Lambda_{QCD})}$$

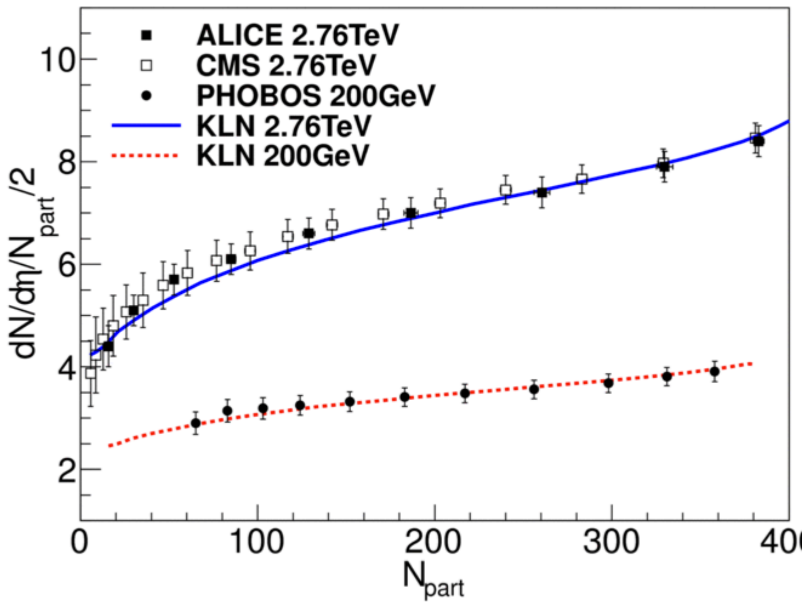
$$\boxed{\rho \sim 1/\alpha_s}$$



→ Saturation is an unavoidable and fundamental consequence of QCD dynamics.

- Saturation models account successfully for bulk observables at RHIC and LHC. Are there more direct probes? (intermediate p_T, forward physics)

  talk by A. Dumitru



- Progress towards BK @ NLO & particle production in factorized formalism

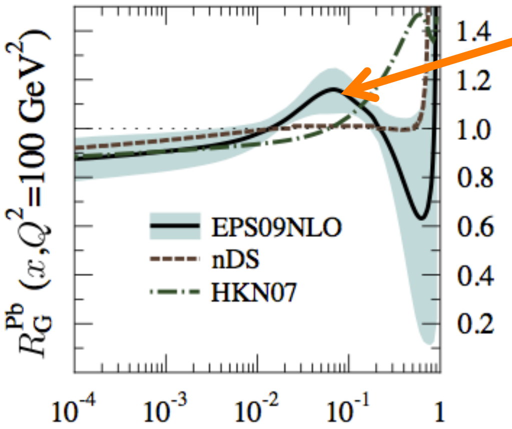
  talk by C. Marquet

- Phenomenological limitations of TH
  - transition to high x, Q2 not accounted for

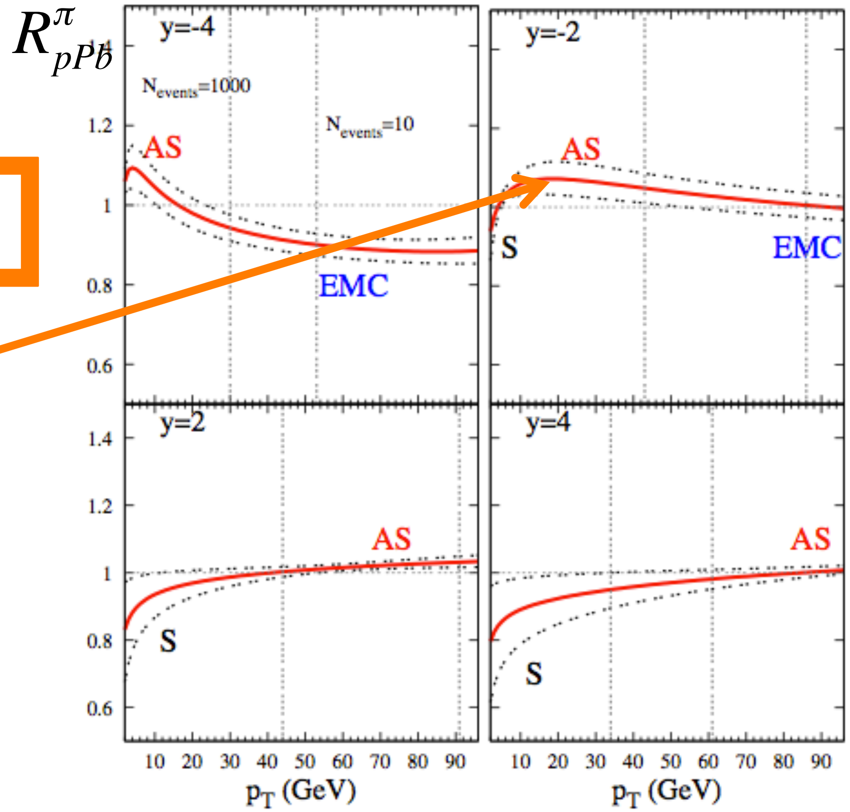
d-Au/p-Pb benchmarks for A-A

- What are the cold nuclear matter effects? Crucial baseline for interpreting A-A
- In collinear formalism:

Cronin peak $\Leftrightarrow$ Anti-shadowing (**AS**) peak

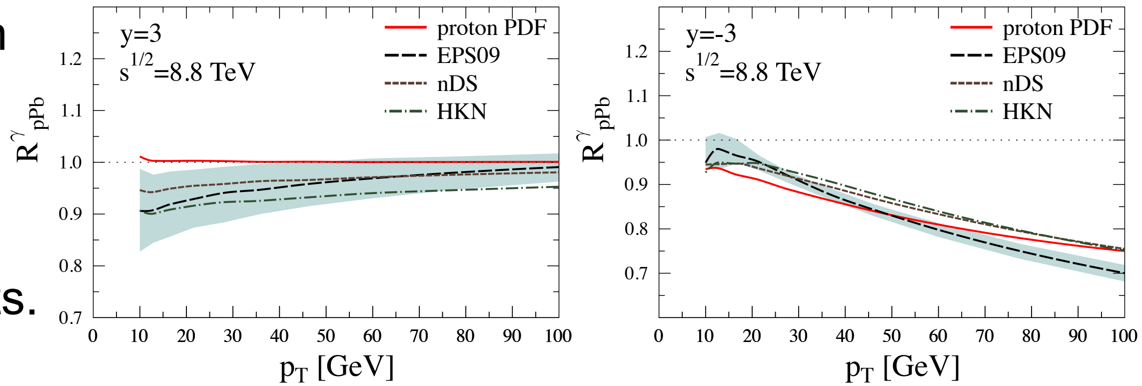


Quiroga et al, arXiv1002.2537



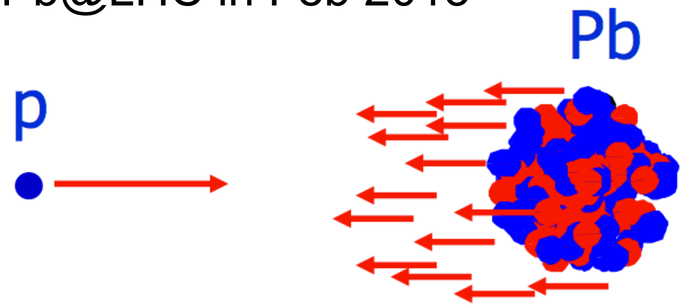
- Cleanest tests involve 2-> 1 processes at forward rapidity (Drell-Yan, photons)
- 'Ideal' signature of saturation physics would be deviation from collinear factorized baseline at intermediate p_T.
- Collinear baseline for R^{γ}_{pPb} shows very small nuclear effects.

Arleo et al, arXiv1103.1471



p-A as test of saturation

- pPb@LHC in Feb 2013

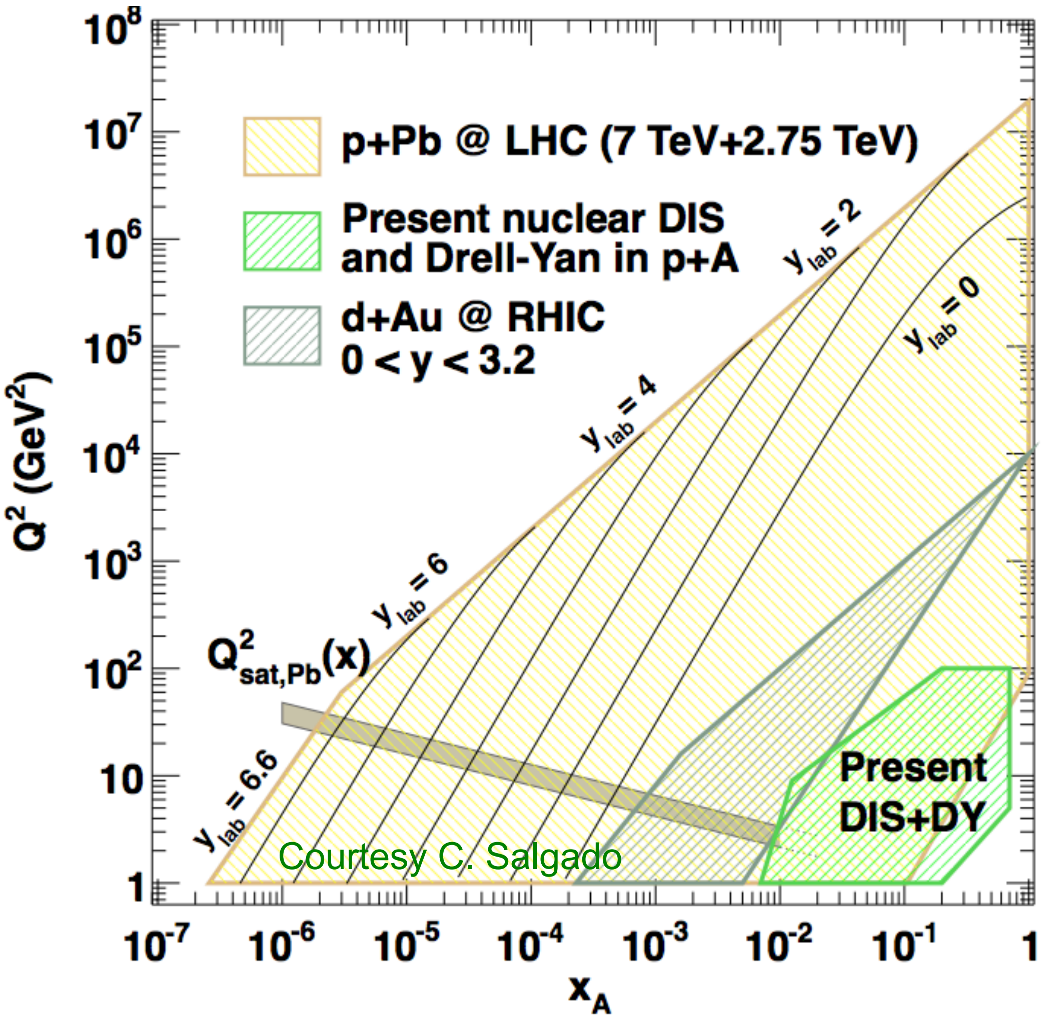


- $y^{RHIC}_{forward} \Leftrightarrow y^{LHC}_{mid-rapidity}$

- pPb@LHC accesses entire kinematic range of future e-A colliders (EIC, LHeC)

- Make full use of existing investments into hadron colliders (including pA specific upgrades) to movtivate future e-A

talk by A. Despande



We enter rapidly an era of **detailed investigation**
of the properties of dense QCD matter

Yesterday's discovery	$\Longrightarrow$	Baseline for tomorrow's investigation and understanding

Our field is on the journey
from wow-effects to numbers and to
final 'textbook' conclusions.

End