News and theoretical challenges from recent heavy ion experiments

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CERN PH-TH

XQCD, Workshop on QCD under extreme conditions
5 August 2013, Bern

Program for XQCD 2013

Workshop on QCD under extreme conditions

Bern, 5-7 August 2013

Monday, August 5

08:30	**Registration opens**		
09:30	Welcome		
09:45	Urs Wiedemann	News and theoretical challenges from recent heavy ion experiments
10.30	**Coffee Break**	
11:00	Guy Moore	NLO calculations at finite temperature and the lightcone
11:45	Kari Rummukainen	Qhat from EQCD
12:15	Seyong Kim	Lattice NRQCD study of bottomonium around the deconfinement temperature
12:45	**Lunch**	
14:00	Harvey Meyer	Non-perturbative approaches to transport properties and spectral functions in hot QCD
14:45	Bastian Brandt	QCD thermodynamics with O(a) improved Wilson fermions at $Nf = 2$
15:10	Heng-Tong Ding	QCD transition at finite temperature with domain wall fermions
15:35	**Coffee Break**	
16:10	Yu Maezawa	Meson screening masses at finite temperature with highly improved staggered quarks
16:35	Oscar Akerlund	Scale hierarchy in high-temperature QCD
	Sponsor talks	Poster session opens
17:00	Mike Clark	TBA
17:30	Edmund Preiss	Intel's HPC and Xeon Phi oriented Software development tools
18:00	**Apero**	Poster session continues

Tuesday, August 6

09:15	Heiri Leutwyler	The mass of the two lightest quarks
10:00	Christian Schmidt	The strange degrees of freedom in QCD at high temperature
10:30	**Coffee Break**	
11:00	Dean Lee	Lattice effective field theory for nuclear physics
11:45	Sourendu Gupta	The QCD critical point
12:15	Andrei Alexandru	QCD at imaginary chemical potential with Wilson fermions
12:45	**Lunch**	
14:00	Michael Endres	Unitary fermions
14:45	Simon Hands	A strongly-interacting Fermi surface? Voltage-biased bilayer graphene
15:10	Yuji Sakai	Analytic continuation in two color QCD with clover-improved Wilson fermion at finite density
15:35	**Coffee Break**	
16:10	Rajiv Gavai	Quark number susceptibility divergence can be subtracted off
16:35	Jacques Bloch	Solving the sign problem in one-dimensional QCD
17:00	Thomas Kloiber	Dual methods for lattice field theories at finite density
17:25	Kim Splittorff	The QCD sign problem as a total derivative
17:50	**Group photo**	
19:00	**Dinner**	Restaurant Rosengarten

How to learn about 'QCD under extreme conditions' via data from heavy ion experiments?

1. Flow

as the dynamic manifestation of QCD thermodynamics

2. Hard Probes

- as "DIS of the QGP" (jet quenching)
- as "QCD thermometer" (quarkonia)

3. Searches

- critical point
- chiral magnetic, chiral vortical effect
- …

Why is a fluid dynamic description of interest?

Dissipative fluid dynamics is

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

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

- sensitive *only* 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, …

The limiting case of perfect fluid dynamics

$$N_i^\mu = n_i u^\mu + \cancel{\overline{n}_i}$$ (n comp.)

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - p\Delta^{\mu\nu} + \cancel{q^\mu u^\nu} + \cancel{q^\nu u^\mu} + \cancel{\Pi^{\mu\nu}}$$ (5 comp.)

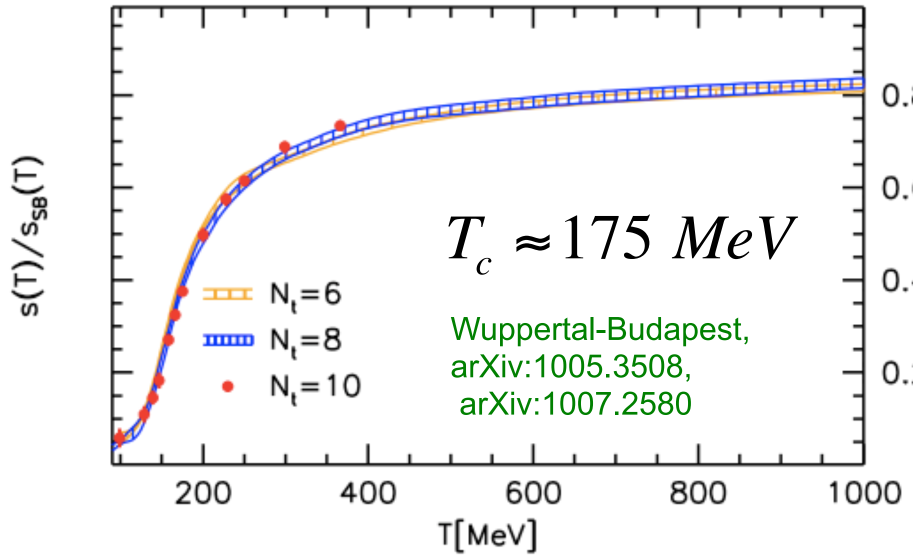
Equations of motion

$$\partial_\mu N_i^\mu \equiv 0$$ (n constraints)

$$\partial_\mu T^{\mu\nu} \equiv 0$$ (4 constraints)

closed by equation of state

$$p = p(\varepsilon, n)$$ (1 constraint)



Viscous fluid dynamics

Characterizes dissipative corrections in gradient expansion *Ideal fluid:*

$$N_i^\mu = n_i\, u^\mu + \cancel{\overline{n}_i}$$ (4n comp.) *(n comp.)*

$$T^{\mu\nu} = \varepsilon\, u^\mu u^\nu - p\Delta^{\mu\nu} + \cancel{q^\mu} u^\nu + \cancel{q^\nu} u^\mu + \cancel{\Pi^{\mu\nu}}$$ (10 comp.) *(5 comp.)*

To close equation of motion, supplement conservation laws and eos

$$\partial_\mu N_i^\mu \equiv 0$$ (n constraints)

$$\partial_\mu T^{\mu\nu} \equiv 0$$ (4 constraints)

$$p = p(\varepsilon, n)$$ (1 constraint)

by point-wise validity of 2nd law of thermodynamics

$$T\partial_\mu S^\mu(x) \geq 0 \qquad\qquad S^\mu = s\, u^\mu + \beta\, q^\mu + O\left(\nabla^2\right)$$

The resulting Israel-Stewart relativistic fluid dynamics depends in general on

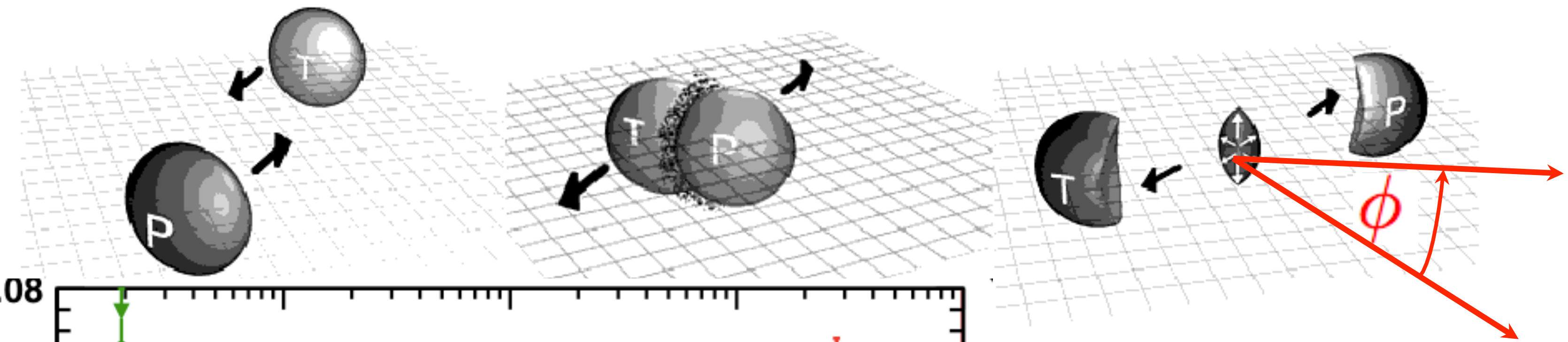
relaxation times
and
transport coefficients.

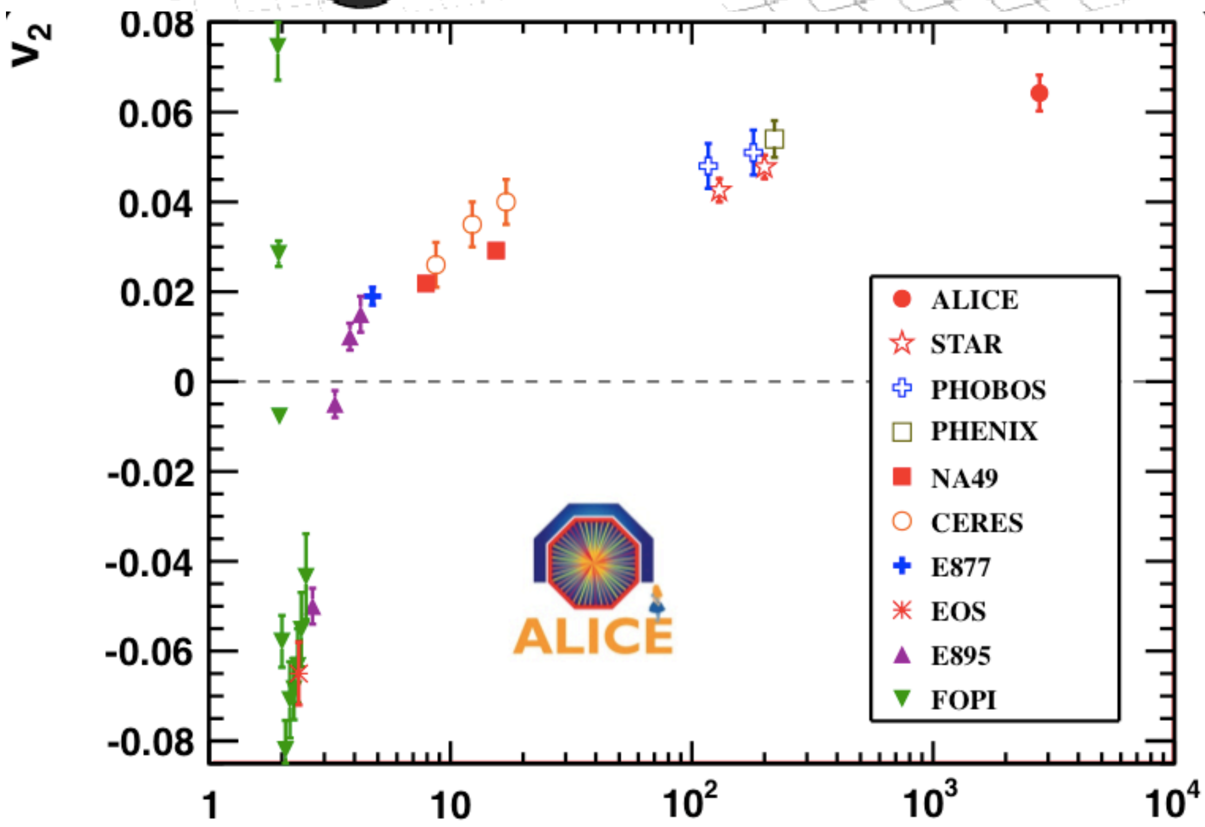
$$\left(\varepsilon + p\right) D u^\mu = \nabla^\mu p - \Delta^\mu_\nu \nabla^\sigma \Pi^{\nu\sigma} + \Pi^{\mu\nu} D u_\nu$$

$$D\varepsilon = -(\varepsilon + p)\nabla_\mu u^\mu + \tfrac{1}{2}\Pi^{\mu\nu}\left\langle \nabla_\nu u_\mu \right\rangle$$

$$\tau_\pi \Delta^\mu_\alpha \Delta^\nu_\beta D\Pi^{\alpha\beta} + \Pi^{\mu\nu} = \eta \left\langle \nabla^\mu u^\nu \right\rangle - 2\tau_\pi \Pi^{\alpha(\mu}\omega^{\nu)}_\alpha$$

Elliptic Flow: hallmark of a collective phenomenon





$$\frac{dN}{d\phi} \propto \left[1 + 2 v_2 \cos(2\phi)\right]$$

Compilation
ALICE, PRL 105, 252302 (2010)

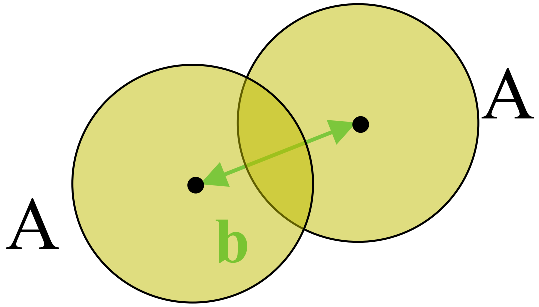
How to measure flow?

How to establish QCD hydrodynamics?

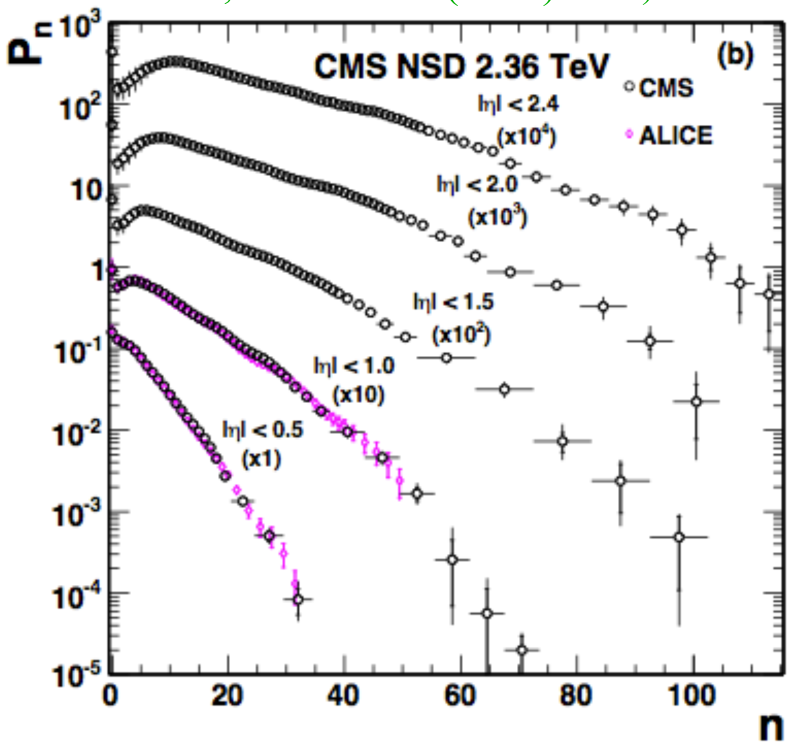
Determining Impact Parameter b

- In AA (unlike pp), multiplicity distribution is dominated by geometry (impact parameter dependence)

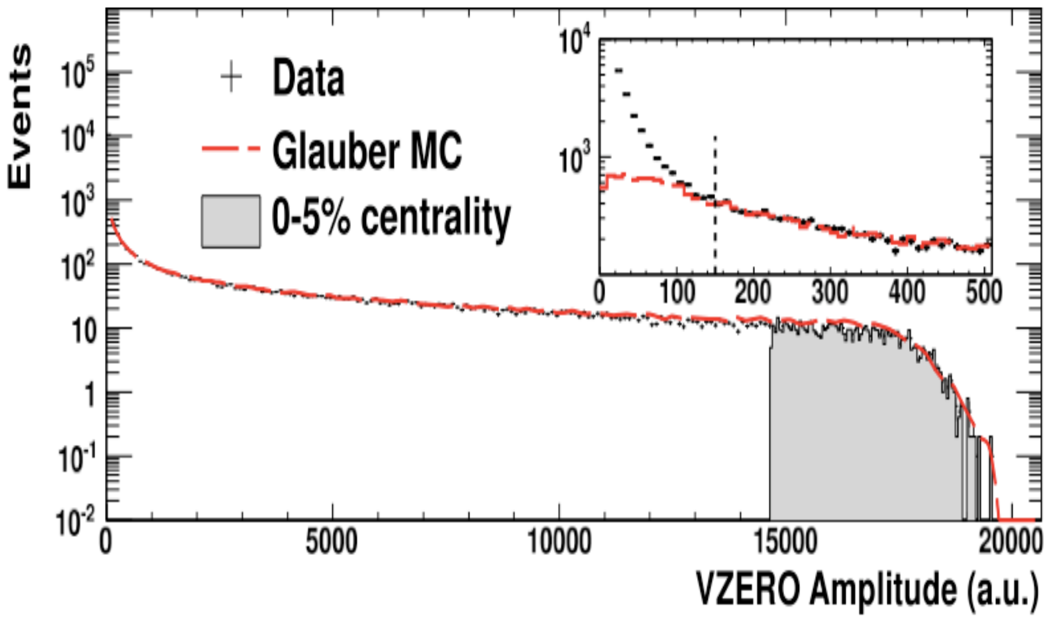
A. Bialas and W. Czyz, Nucl. Phys. B111 (1976) 461



CMS, JHEP 1101 (2011) 079)



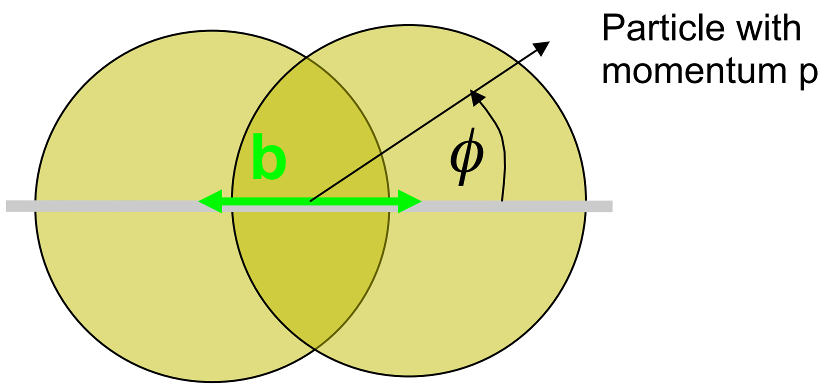
ALICE, PRL 105 (2010) 252301, arXiv:1011.3916



n_{max}~20000

Particle production w.r.t. reaction plane

Consider single inclusive particle momentum spectrum



$$f(\vec{p}) \equiv dN/E\, d\vec{p}$$

$$\vec{p} = \begin{pmatrix} p_x = p_T \cos\phi \\ p_y = p_T \sin\phi \\ p_z = \sqrt{p_T^2 + m^2}\,\sinh Y \end{pmatrix}$$

To characterize azimuthal asymmetry, measure n-th harmonic moment of f(p).

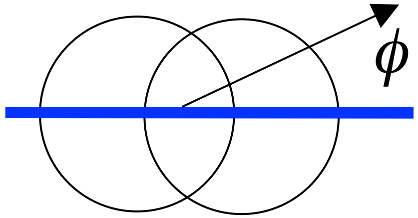
$$v_n \equiv \langle\langle e^{i\,n\,\phi} \rangle\rangle = \left\langle \frac{\int d\vec{p}\, e^{i\,n\,\phi} f(\vec{p})}{\int d\vec{p}\, f(\vec{p})} \right\rangle_{\substack{event\\average}}$$

n-th order flow

<u>Problem</u>: This expression cannot be used for data analysis, since the orientation of the reaction plane is not known a priori.

Measuring flow – one procedure

- Want to measure particle production as function of angle w.r.t. reaction plane



$$\boxed{v_n(D) = \left\langle e^{in\phi} \right\rangle_D}$$

But reaction plane is unknown ...

- Have to measure particle correlations:

$$\left\langle e^{in(\phi_1-\phi_2)} \right\rangle_{D_1 \wedge D_2} = v_n(D_1)\, v_n(D_2) + \boxed{\left\langle e^{in(\phi_1-\phi_2)} \right\rangle^{corr}_{D_1 \wedge D_2}}$$

"Non-flow effects"

$$\boxed{\sim O(1/N)}$$

But this requires signals $v_n > \dfrac{1}{\sqrt{N}}$

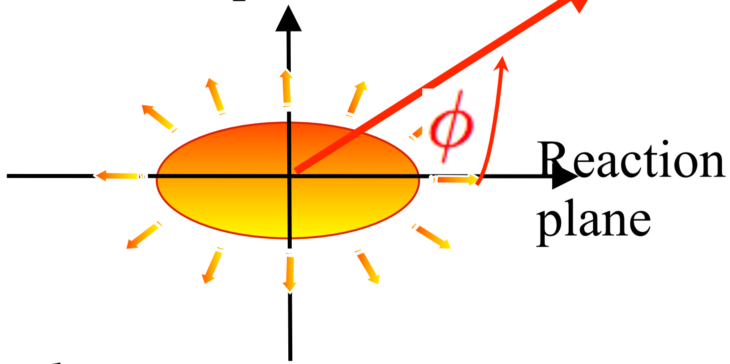
- Improve measurement with higher cumulants: Borghini, Dinh, Ollitrault, PRC (2001)

$$\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle - \left\langle e^{in(\phi_1-\phi_3)} \right\rangle \left\langle e^{in(\phi_2-\phi_4)} \right\rangle - \left\langle e^{in(\phi_1-\phi_4)} \right\rangle \left\langle e^{in(\phi_2-\phi_3)} \right\rangle = -v_n^4 + O\left(1/N^3\right)$$

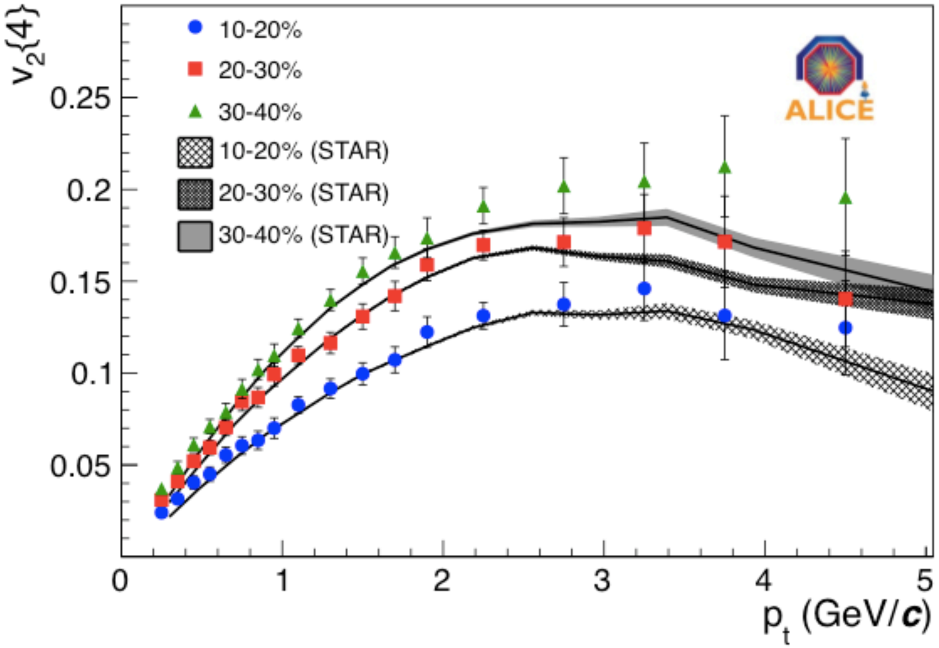
This requires signals $v_n > \dfrac{1}{N^{3/4}}$

v_2 @ LHC

- Momentum space



$$\frac{dN}{d\phi\; p_T dp_T} \propto \left[1 + 2 v_2(p_T)\cos(2\phi)\right]$$



- Signal $v_2 \approx 0.2$ implies 2-1 asymmetry of particles production w.r.t. reaction plane.

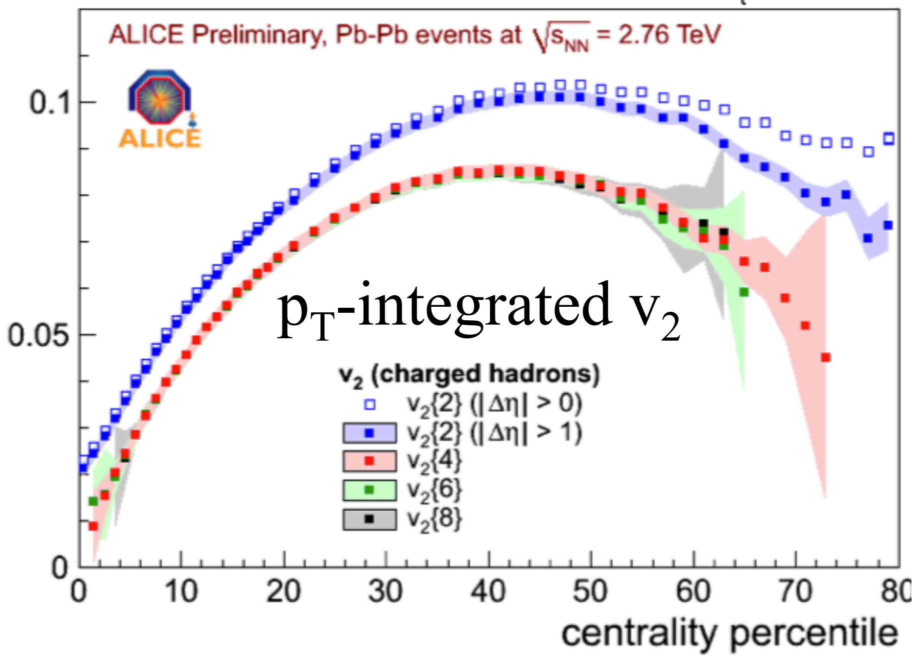
- 'Non-flow' effect for 2nd order cumulants

$$N \sim 100 - 1000 \Rightarrow 1/\sqrt{N} \sim 0.1 \sim O(v_2)\,??$$

2nd order cumulants do not characterize solely collectivity.

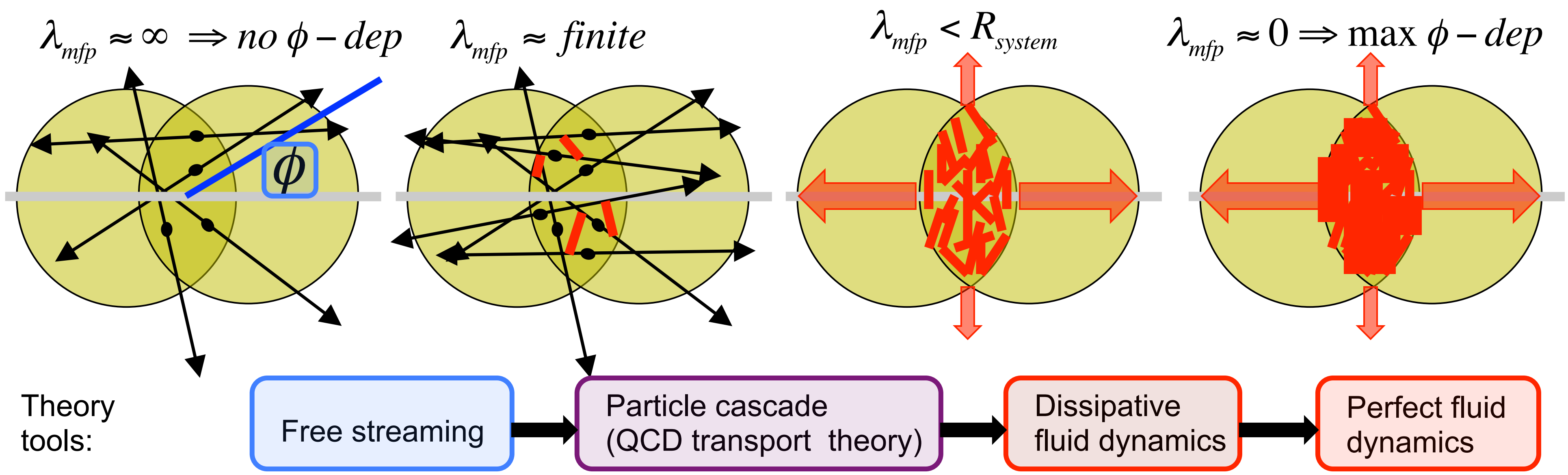
$$1/N^{3/4} \sim\leq 0.03 \ll v_2$$

Strong Collectivity !



The appropriate dynamical framework

- depends on mean free path
  (more precisely: depends on applicability of a quasi-particle picture)

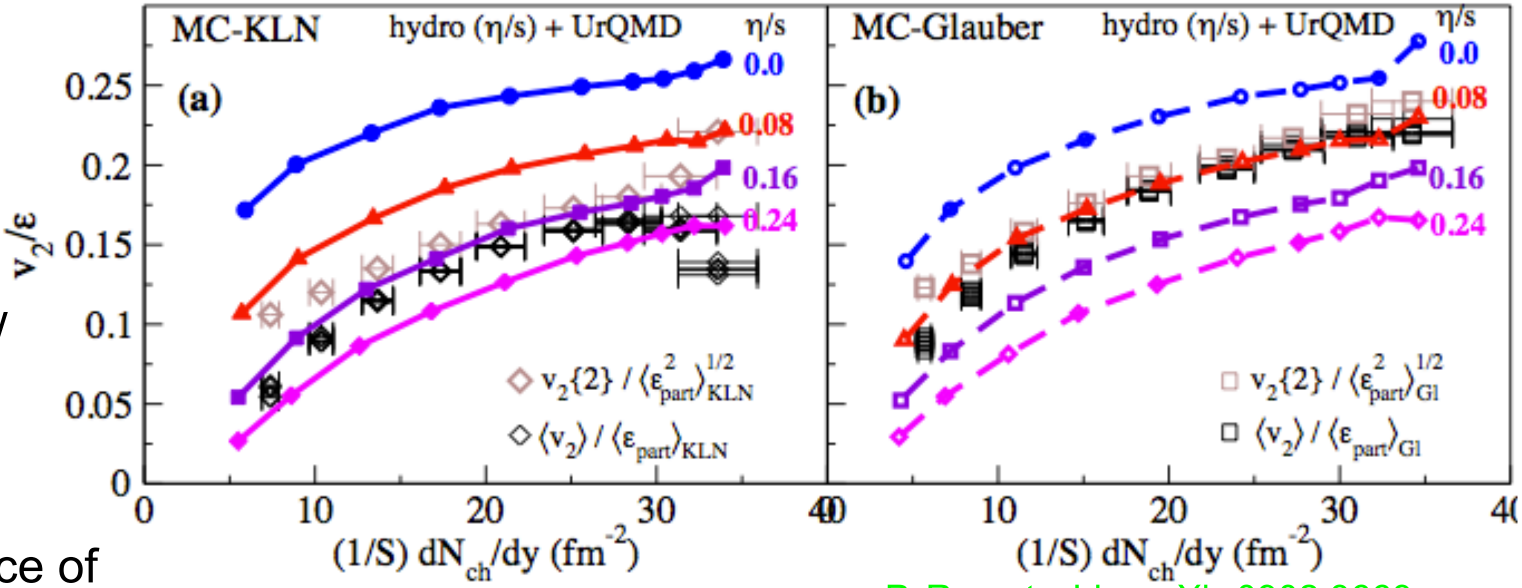


System p+p ?? … pA …?? … AA … ??

Fluid dynamic prior to LHC - results

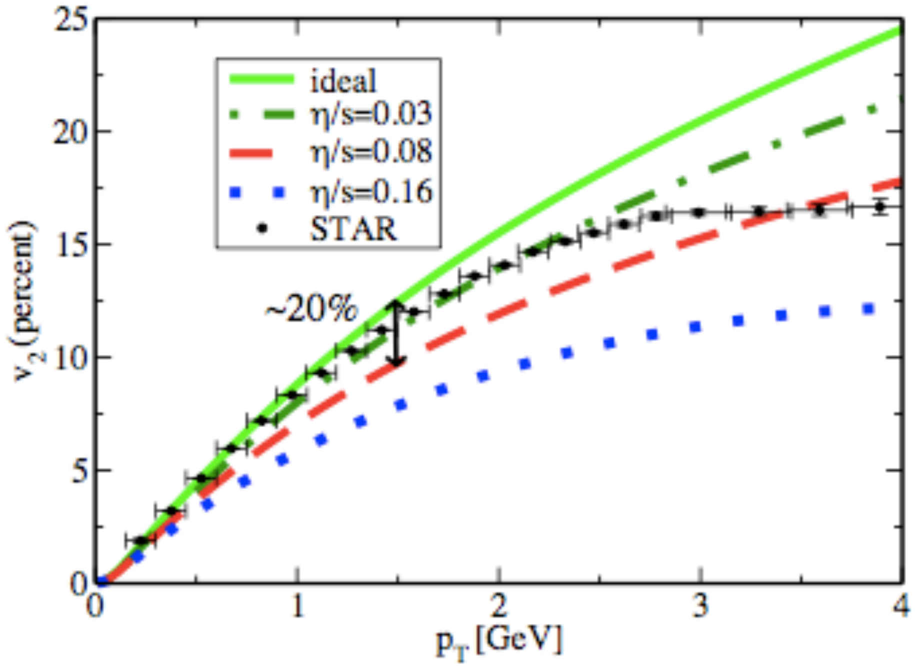
<u>Fluid dynamics accounts for:</u>

- Centrality dependence of elliptic flow



P. Romatschke arXiv.0902.3663

- pt-dependence of elliptic flow
- **Mass dependence** of elliptic flow (all particle species emerge from common flow field)
- Single inclusive transverse momentum spectra at pt (< 3 GeV)



In terms of fluid with minimal shear viscosity

$$\boxed{\frac{\eta}{s} << 1}$$

Implications of minimal viscosity

Back of envelope:

For 1-dim expanding fluid (Bjorken boost-invariant), entropy density increases like

$$\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T}$$

Isentropic "perfect liquid" applies if

$$\frac{\eta}{\tau T}\frac{1}{s} << 1$$

Put in numbers

$$\tau \sim 1\, fm/c, \quad T \sim 200\, MeV \Longrightarrow \frac{\eta}{s} << 1$$

Theory

Minimal viscosity implies strongly coupled plasma.

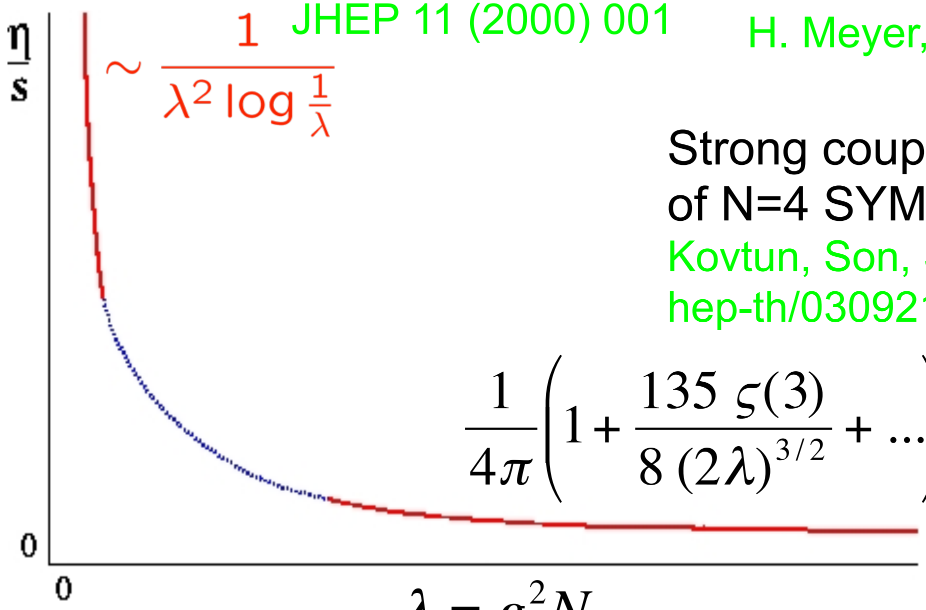
$\Rightarrow$ Importance of strong coupling techniques

Arnold, Moore, Yaffe, JHEP 11 (2000) 001

$$\sim \frac{1}{\lambda^2 \log \frac{1}{\lambda}}$$

Lattice QCD

H. Meyer, arXiv:0704.1801



Strong coupling limit of N=4 SYM

Kovtun, Son, Starinets, hep-th/0309213

$$\frac{1}{4\pi}\left(1 + \frac{135\,\varsigma(3)}{8\,(2\lambda)^{3/2}} + \ldots\right)$$

$$\frac{\eta}{s} > \frac{1}{4\pi}$$

$$\lambda \equiv g^2 N_c$$

Phenomenological implication

Minimal dissipation ⇔ Maximal Transparency to Fluctuations

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

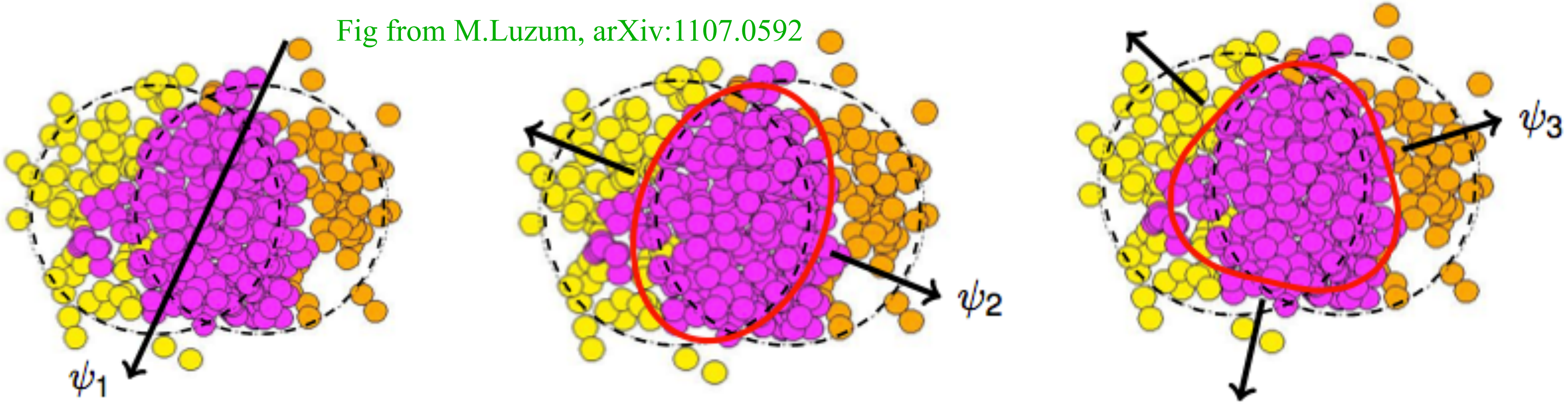
$$\tau_{1/e}(k = 1\, fm^{-1}) \approx 10 - 20\, fm$$

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

Fluctuations decay on time scale, $\tau_{1/e}(k) = \dfrac{1}{\Gamma_s k^2}$

Models of the initial density distributions in AA-collisions show generically a set of event-by-event **EbyE fluctuations**

Fig from M.Luzum, arXiv:1107.0592



Can we see how these **spatial eccentricities** propagate to asymmetries v_n in momentum distributions?

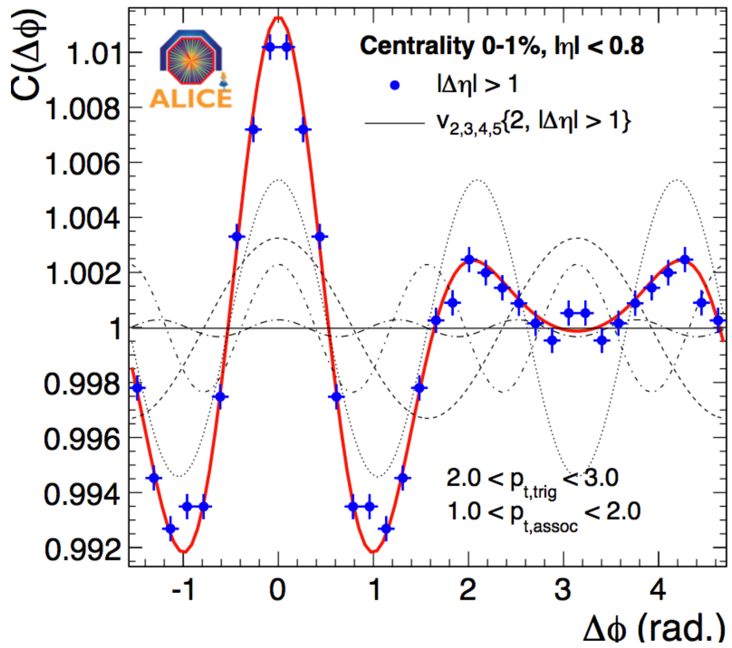
(Historically, Alver and Roland identified in 2009 this triangularity as the origin of a v3-like structure seen in data.)

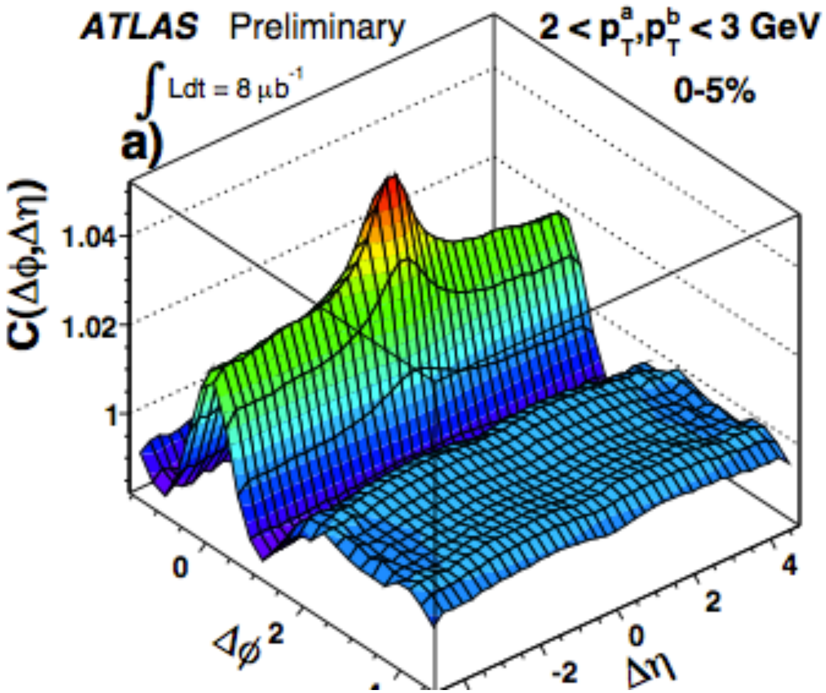
Odd harmonics dominate central collisions

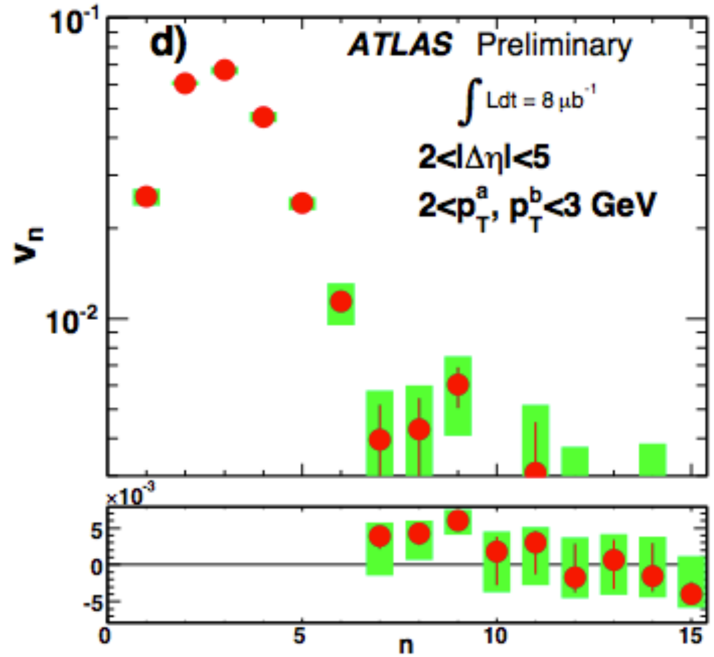
In the most central 0-5% events,

$$v_3 \geq v_2$$

Fluctuations in initial conditions dominate flow measurements







Flow as linear response to spatial asymmetries

Characterize **spatial eccentricities**, e.g., via moments of transverse density

$$\varepsilon_{m,n} e^{in\phi_{m,n}} \equiv -\frac{\{r^m e^{in\phi}\}}{\{r^m\}}, \quad \varepsilon_n \equiv \varepsilon_{n,n} \qquad \{\ldots\} \equiv \frac{\int d^2x\, \rho(x) \ldots}{\int d^2x\, \rho(x)}$$

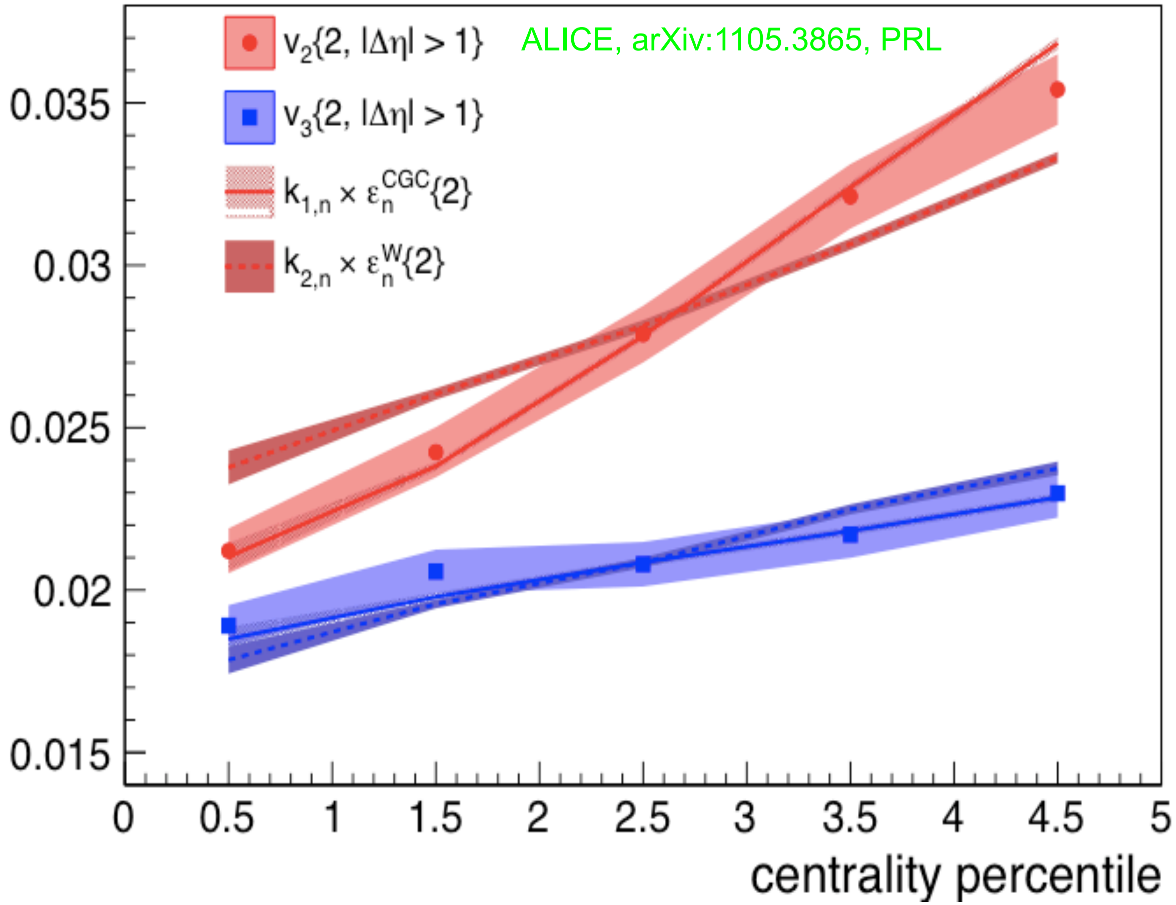
LHC data indicate:

Spatial eccentricity

is related approx. linearly to

(**momentum**) **flow**

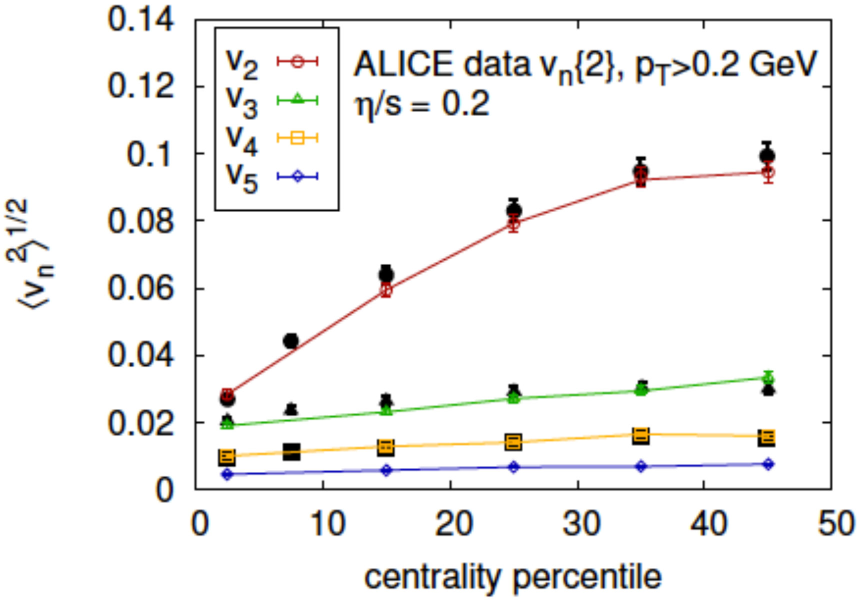
$$\boxed{v_n \propto \varepsilon_n}$$

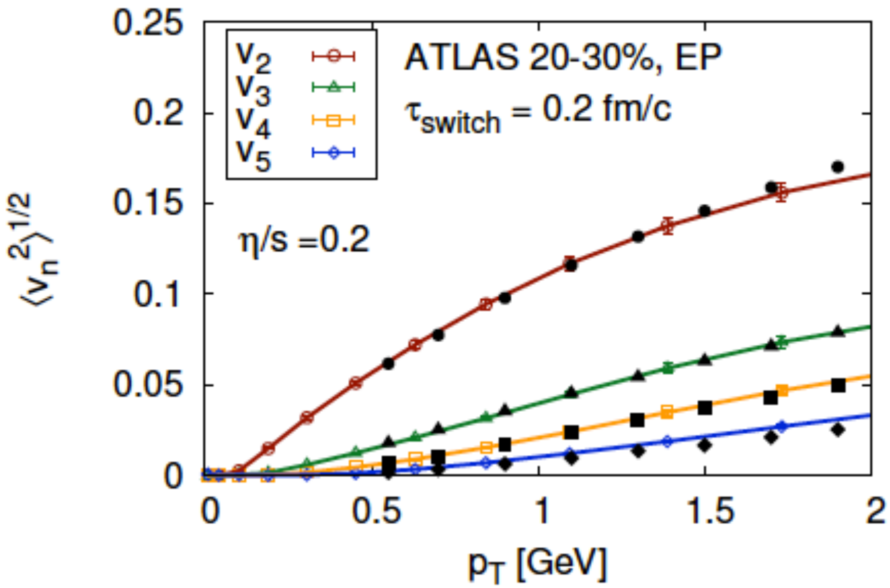


Hydrodynamics propagates EbyE fluctuations

- Fluid dynamics maps initial spatial eccentricities onto measured v_n
- 3+1 D viscous hydrodynamics
  with suitably chosen initial conditions
  reproduces v_2, v_3, v_4, v_5 in p_T and centrality

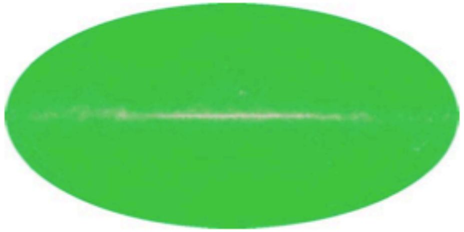
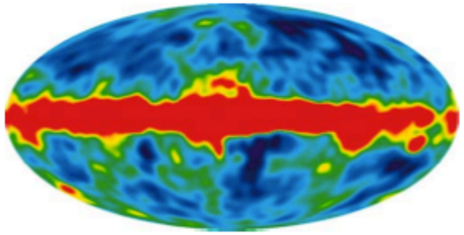
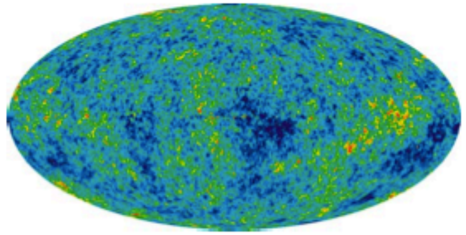
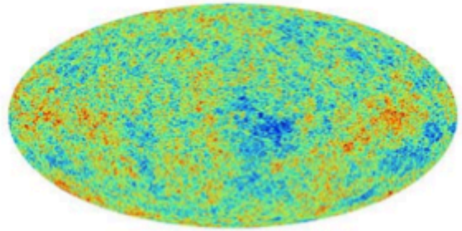
B. Schenke, MUSIC, .QM2012





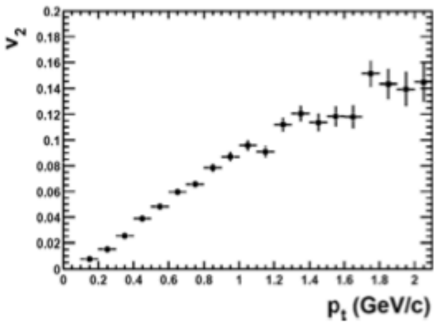
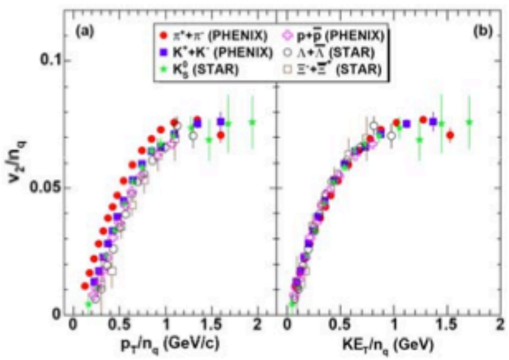
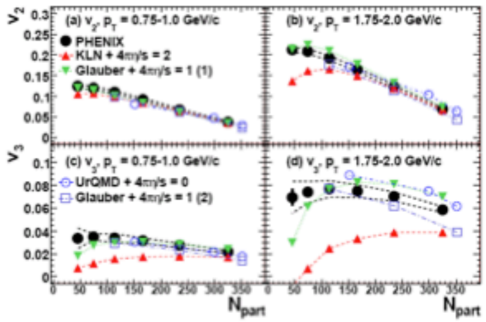
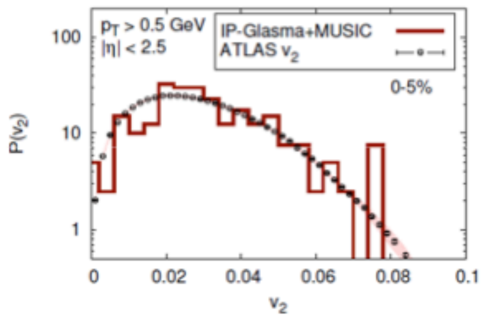
Theoretical challenges
‘Flow’

A (valid) analogy – how far can it be pushed?

Penzias/Wilson 1965	COBE 2003	WMAP 2007	Planck 2012
			

From a signal … via fluctuations ….

…. to properties of matter

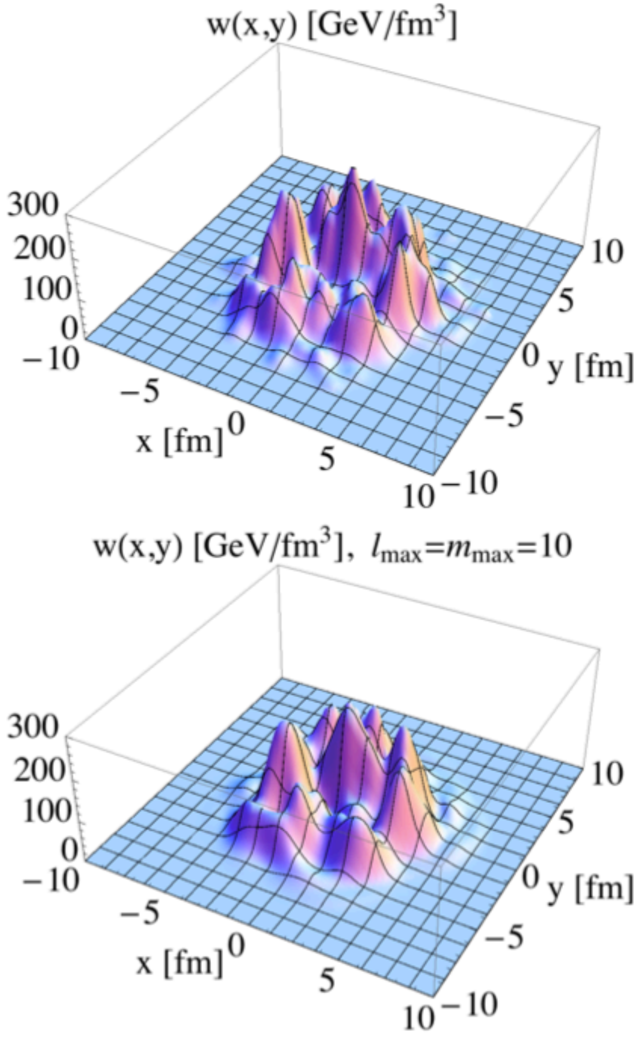
			
2001	2004	2008	2012

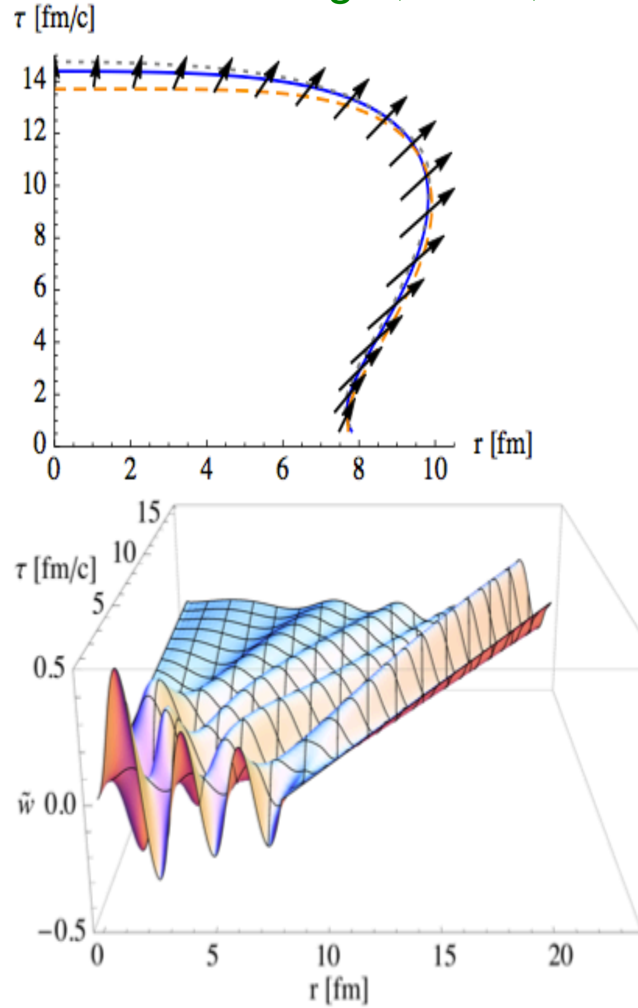
Slide adapted from W. Zajc

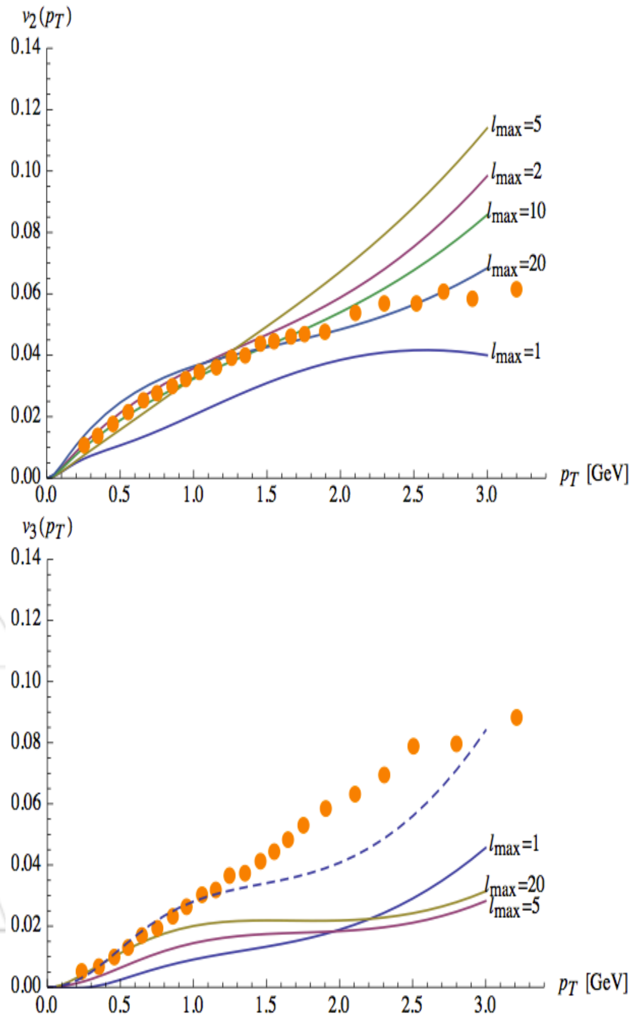
One Example: Mode-by-mode fluid dynamics

Decomposing initial conditions in modes → Propagating each mode individually → Understanding the signal composition mode-by-mode

S. Flörchinger, UAW, 1307.3453; 1307.7611

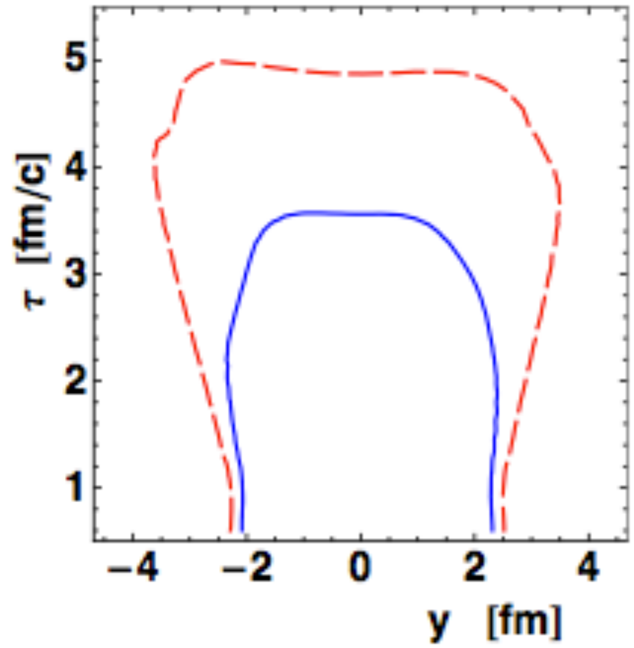


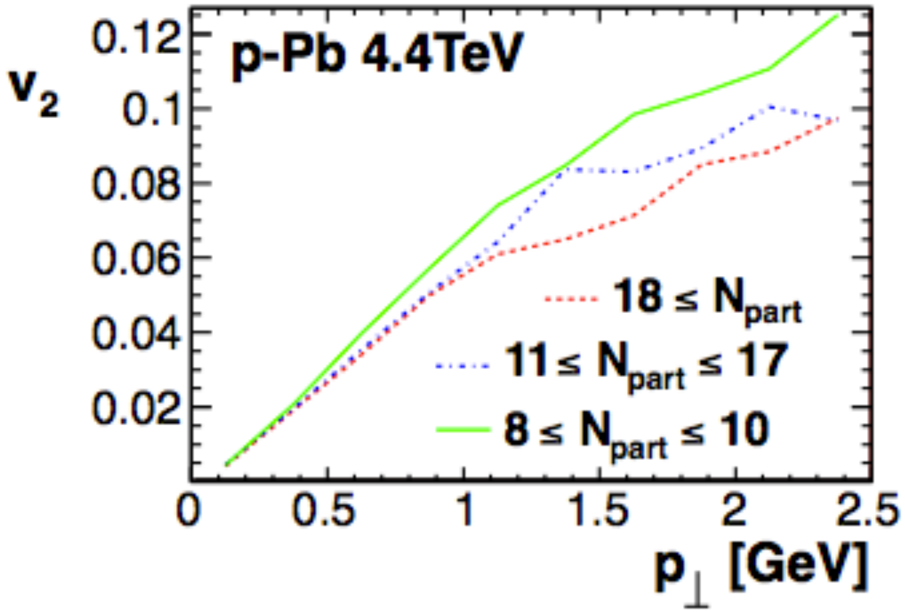




Do smaller systems show flow: pPb?

A fluid dynamical simulation of pPb@LHC yields P. Bozek, 1112.0915



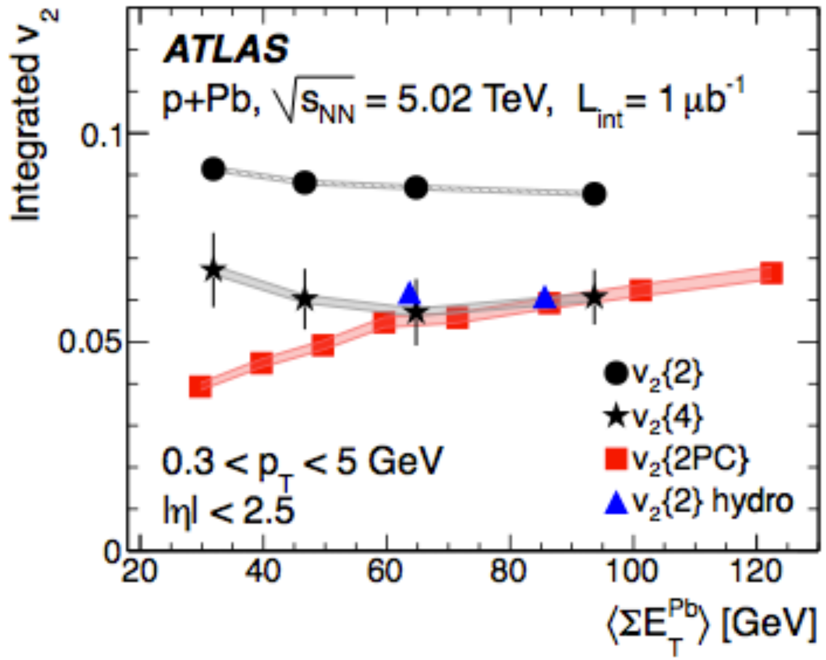


Fluid dynamics compares surprisingly well with

$$v_2\{2\}, v_2\{4\}, v_3\{2\}$$

in pPb@LHC.

ATLAS, 1303.2084
CMS, 1305.0609

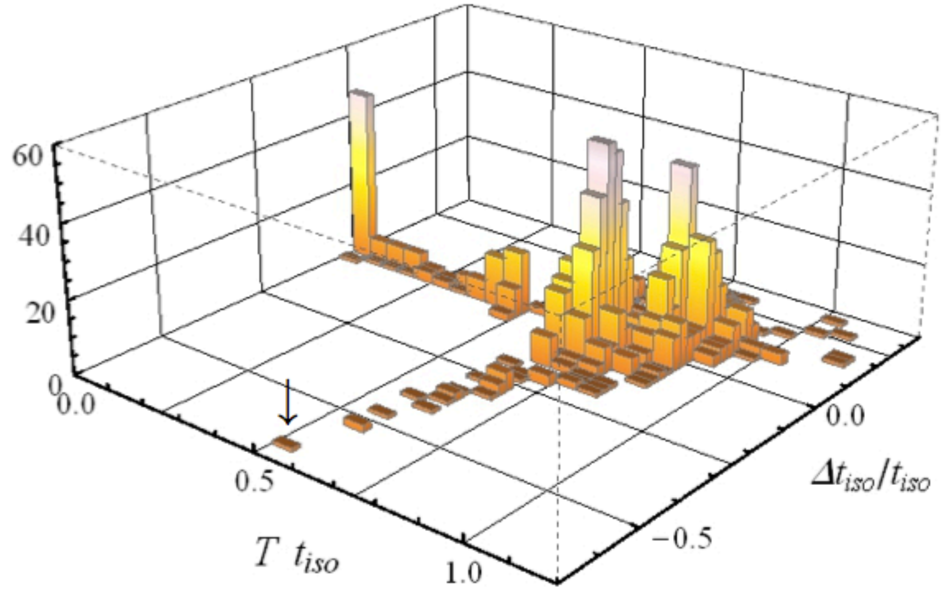


How can non-abelian plasmas thermalize quickly?

- Model-dependent in QCD but a rigorously calculable problem of numerical gravity in AdS/CFT
- **Very fast non-perturbative isotropization**

$$\boxed{\tau_{iso} < \frac{1}{T}}$$

M. Heller, R. Janik et al, PRL, 1202.0981



- The first rigorous field theoretic set-up in which fluid dynamics applies at very short time scales

$$\alpha_s >> 1 \quad \Rightarrow \boxed{0.65 \leq \tau_0\, T_0}$$

Chesler, Yaffe, PRL 102 (2009) 211601

- These non-abelian plasma are unique in that they do not carry quasi-particle excitations:

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

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

…and another theoretical challenge within the focus of XQCD:

What are the prospects of improved lattice QCD calculations of

transport coefficients?
relaxation times?

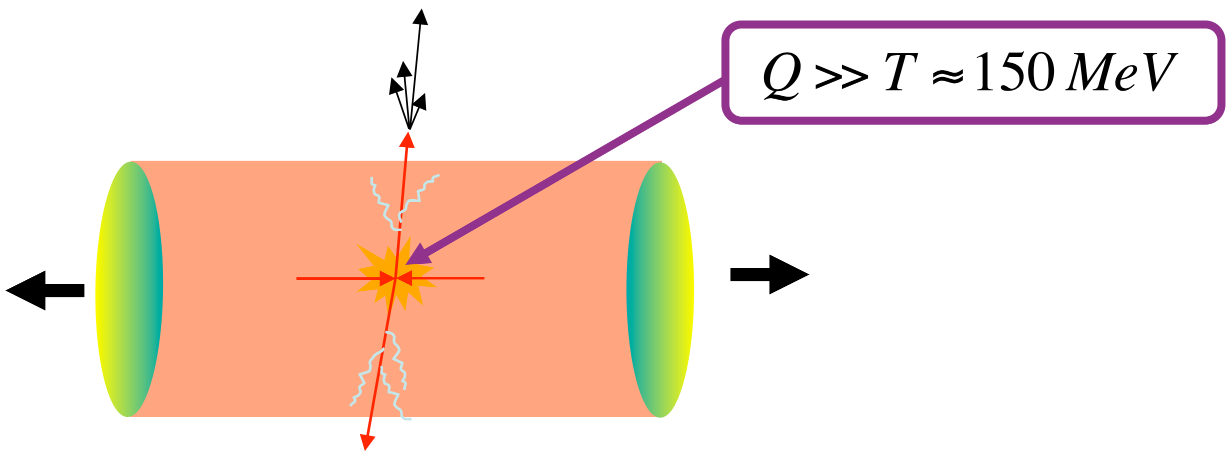
(strong coupling results exist for the plasmas of QFTs with gravity dual)

Hard Probes

Hard Probes of Dense Matter

To test properties of QCD matter, large- Q^2 processes provide well-controlled tools (example: DIS).

Heavy Ion Collisions produce auto-generated probes at high $\sqrt{s_{NN}}$



Q: How sensitive are such 'hard probes'?

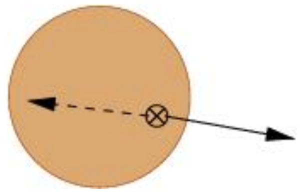
Bjorken's original estimate and its correction

Bjorken 1982: consider jet in p+p collision, hard parton interacts with underlying event ⇨ collisional energy loss

$$dE_{coll}/dL \approx 10\, GeV/fm$$

(error in estimate!)

Bjorken conjectured monojet phenomenon in proton-proton



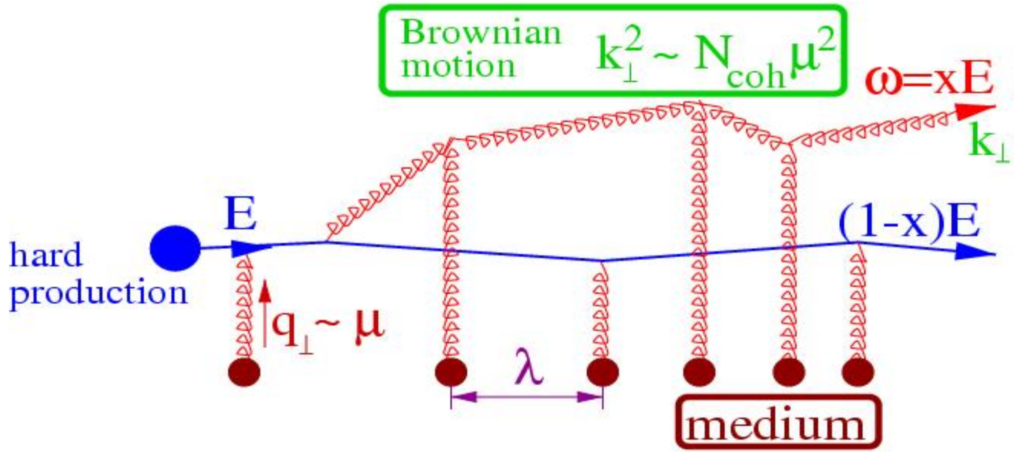
But: radiative energy loss expected to dominate

$$\Delta E_{rad} \approx \alpha_s \hat{q} L^2$$

Baier Dokshitzer Mueller Peigne Schiff 1995

- p+p: $L \approx 0.5\ fm, \quad \Delta E_{rad} \approx 100\ MeV$ Negligible !
- A+A: $L \approx 5\ fm, \quad \Delta E_{rad} \approx 10\, GeV$ Monojet phenomenon! Observed at RHIC

Parton energy loss - a simple estimate



Medium characterized by transport coefficient:

$$\hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{density}$$

- How much energy is lost ?

Phase accumulated in medium: $\left\langle k_T^2 \Delta z \big/ 2\omega \right\rangle \approx \frac{\hat{q}L^2}{2\omega} = \frac{\omega_c}{\omega}$ Characteristic gluon energy

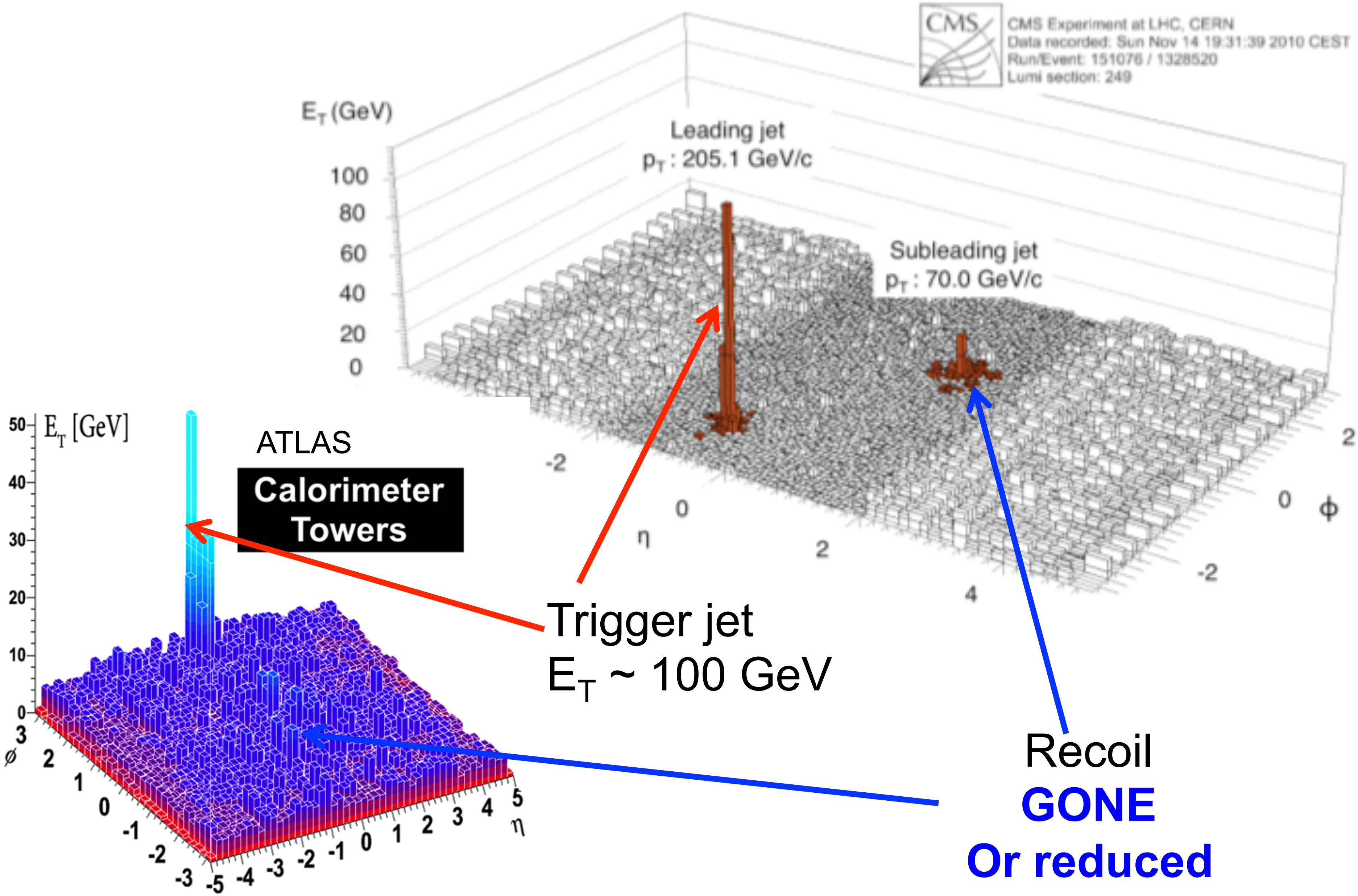
Number of coherent scatterings: $N_{coh} \approx \frac{t_{coh}}{\lambda}$, where $t_{coh} \approx \frac{2\omega}{k_T^2} \approx \sqrt{\omega/\hat{q}}$

$k_T^2 \approx \hat{q}\, t_{coh}$

Gluon energy distribution: $\omega \frac{dI_{med}}{d\omega\, dz} \approx \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega\, dz} \approx \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$

Average energy loss $\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega\, dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$

Dijet asymmetries at LHC



Jet Finding at high event multiplicity (exp)

CMS, Phys.Rev. C84 (2011) 024906

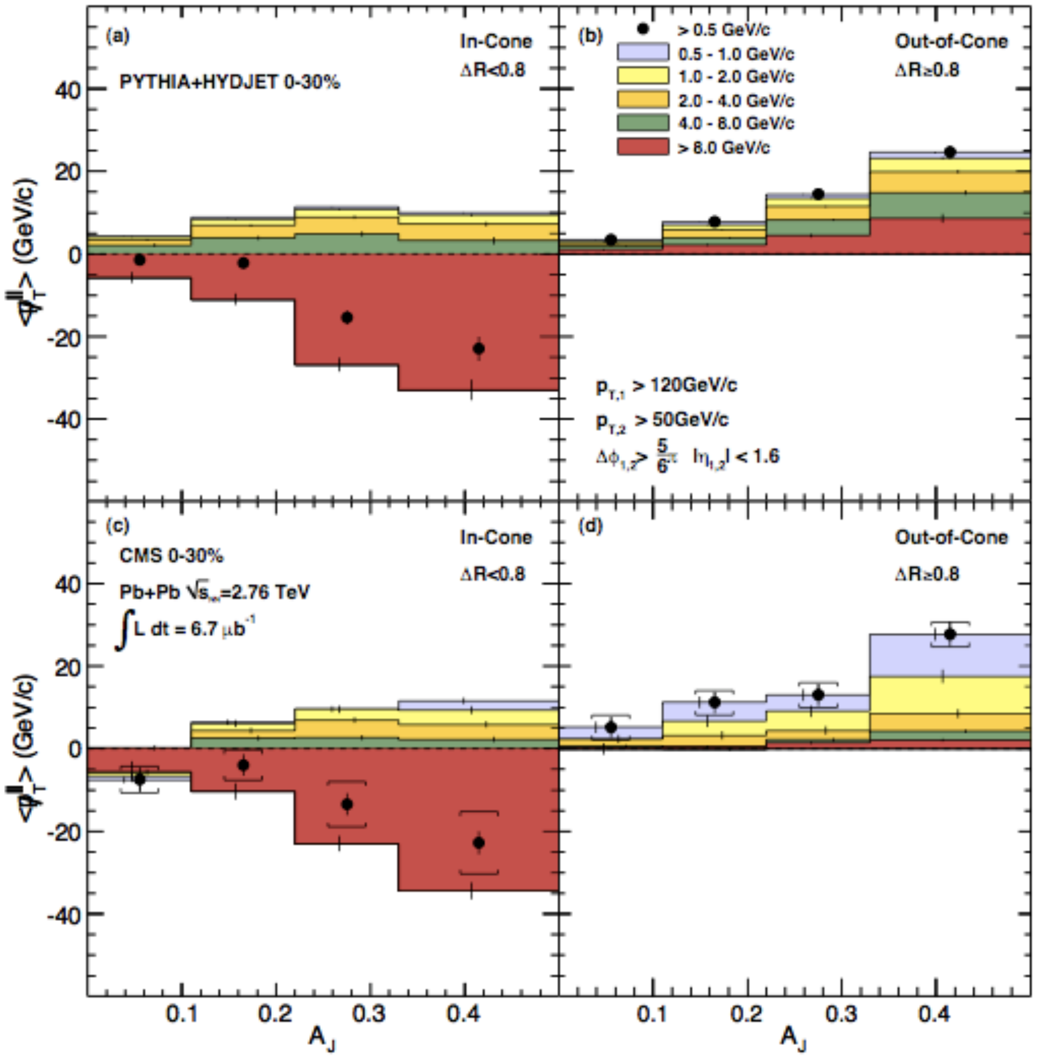
- Impressive experimental checks

  energy ‘lost’ from jet cone

  - found completely out-of-cone

  - found in soft components at very large angles

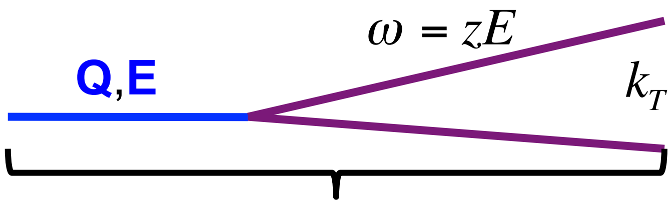
- Angular distribution of dijets almost unchanged



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?

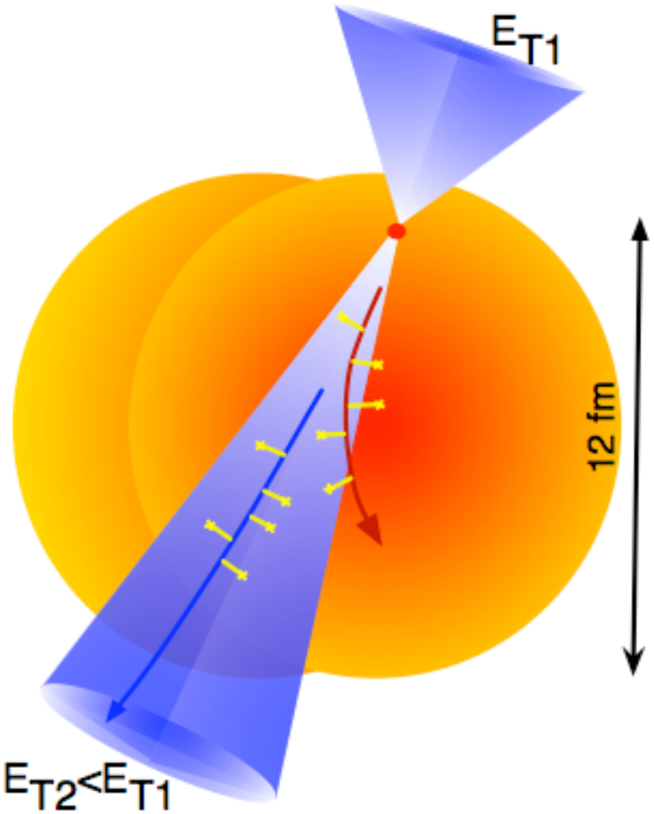
In vacuum, soft modes form **late**



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

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

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

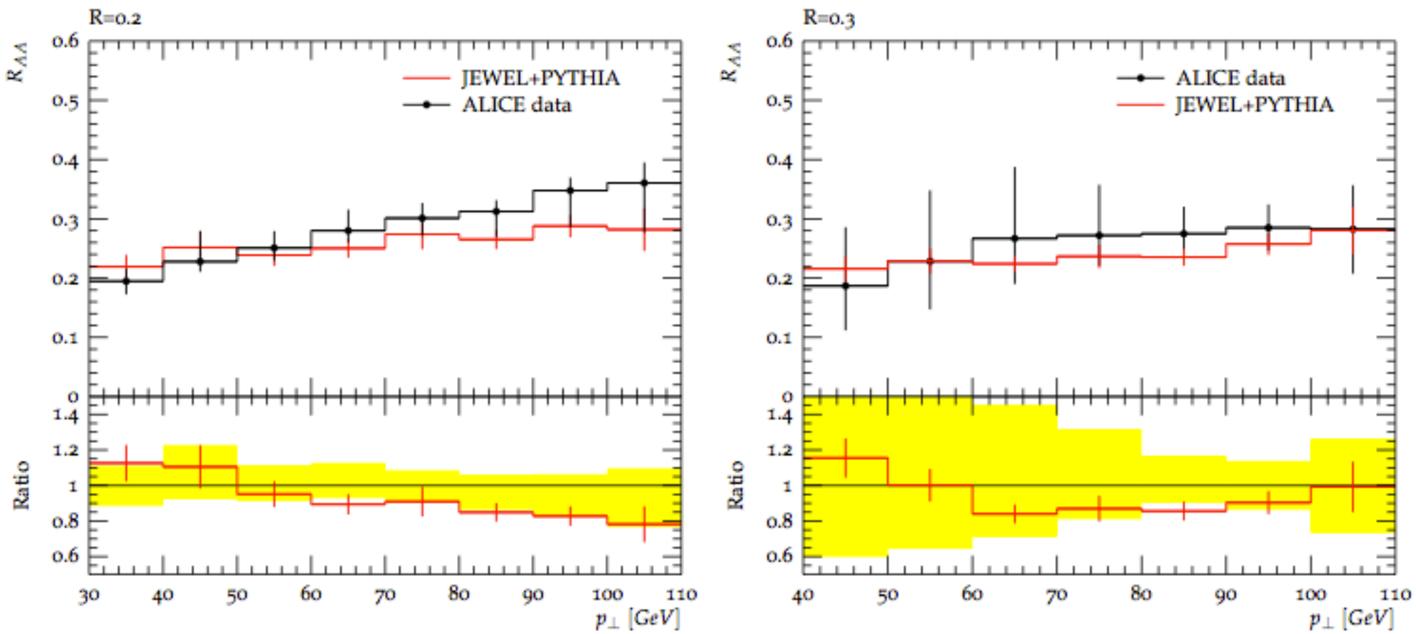


J. Casalderrey-Solana, G. Milhano, U.A. Wiedemann, arXiv:1012.0745

How far can we push a perturbative description?

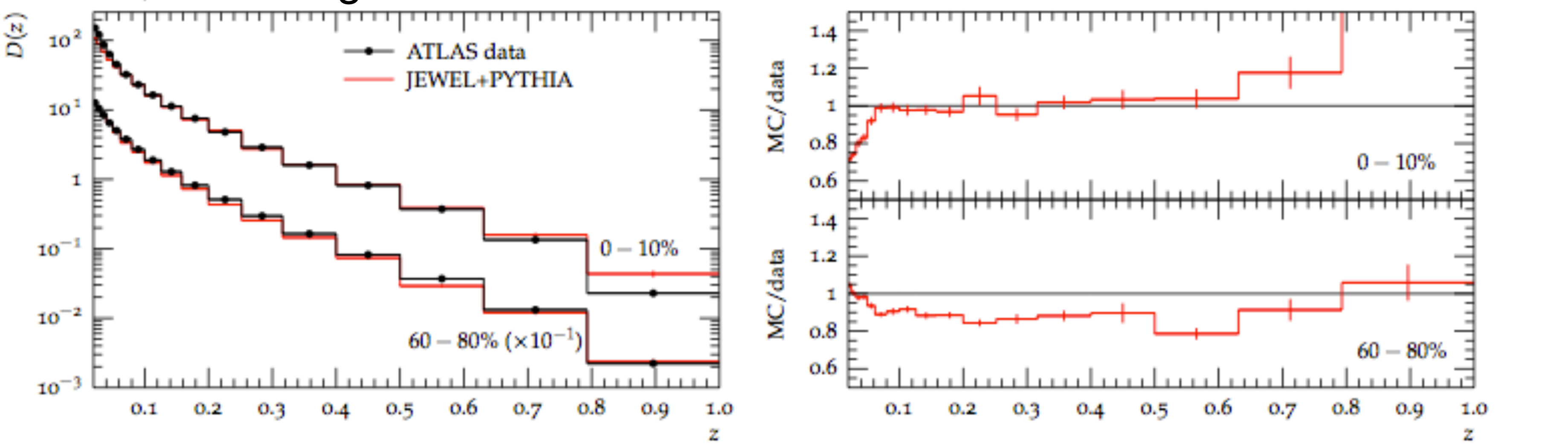
Perturbative description of ‘high-pt’ jet quenching fairs well

Nuclear Modification factor



- MC code JEWEL -
K. Zapp, F. Krauss, UAW, JHEP 1303 (2013) 080

Jet fragmentation function



Theoretical challenges 'Hard Probes'

- How can perturbative jet evolution be reconciled with non-perturbative collective dynamics?
- "*<u>Jet quenching MCs</u>*": How to formulate a medium-modified parton shower?
- "*<u>Jet finding</u>*": Which jet measurements can be performed reliably within a high multiplicity background?
- "*<u>Medium response</u>*": How to establish it, since it must exist?
- "*<u>Quarkonia</u>*": How to calculate suppression within a strongly expanding medium?
- …

End