# *Dissipation in quantum gauge theories - interesting open questions*

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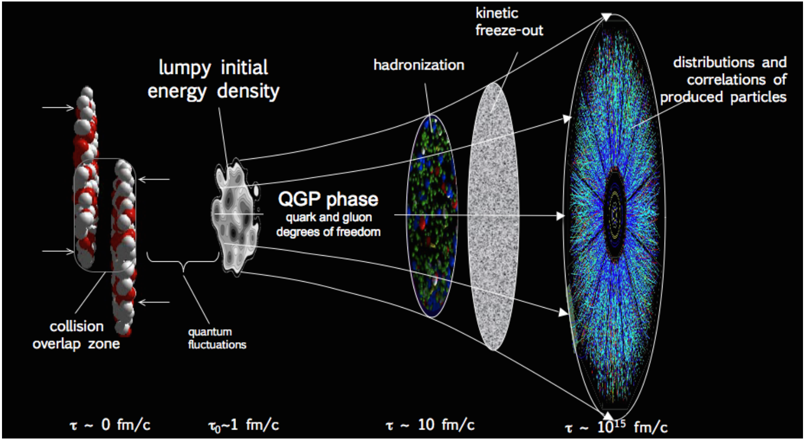
## *Why heavy ion collisions ?*

- Study quantum gauge theories at non-zero temperature and density
- Microscopic physics of QCD quite well understood - but challenging to understand more macroscopic aspects
- Chance to improve general understanding of quantum field theory - important also for cosmology and condensed matter physics
- Quark gluon plasma has filled the universe from about $10^{-12}$ s to $10^{-6}$ s after the big bang. Study it in laboratory experiments !
- Ongoing large experimental programs at at RHIC (BNL) and the LHC (CERN).

# *Little bangs in laboratory*



# *Evolution in time*

- Non-equilibrium evolution at early times
  - initial state from QCD? Color Glass Condensate? ...
  - thermalization via strong interactions, plasma instabilities, particle production, ...
- Local thermal and chemical equilibrium
  - strong interactions lead to short thermalization times
  - evolution from relativistic fluid dynamics
  - expansion, dilution, cool-down
- Chemical freeze-out
  - for small temperatures one has mesons and baryons
  - inelastic collision rates become small
  - particle species do not change any more
- Thermal freeze-out
  - elastic collision rates become small
  - particles stop interacting
  - particle momenta do not change any more

# *Microscopic description*

Lagrangian

$$\mathscr{L} = -\frac{1}{2}\text{tr}\,\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \sum_f \bar{\psi}_f \left(i\gamma^\mu \mathbf{D}_\mu - m_f\right)\psi_f$$

with

$$\mathbf{F}_{\mu\nu} = \partial_\mu \mathbf{A}_\nu - \partial_\nu \mathbf{A}_\mu - ig[\mathbf{A}_\mu, \mathbf{A}_\nu], \qquad \mathbf{D}_\mu = \partial_\mu - ig\mathbf{A}_\mu$$

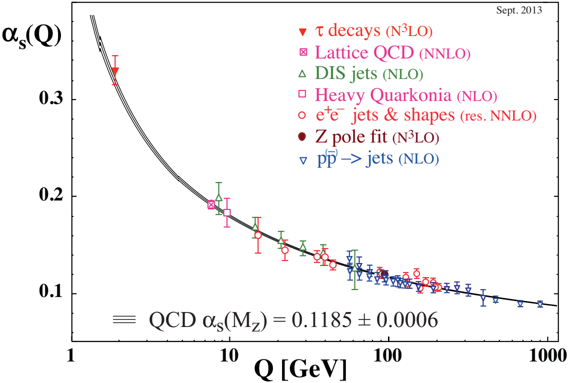
Particle content

- $N_c^2 - 1 = 8$ real massless vector bosons: gluons
- $N_c \times N_f$ massive Dirac fermions: quarks

Quark masses

| | | | | | |
|---|---|---|---|---|---|
| Up | 2.3 MeV | Charm | 1275 MeV | Top | 173 GeV |
| Down | 4.8 MeV | Strange | 95 MeV | Bottom | 4180 MeV |

# *Asymptotic freedom*




[Particle Data Group (2013)]

- Coupling constant small at high momentum transfer / energy scale
- High-temperature QCD should be weakly coupled
- Low-temperature QCD should be strongly coupled

## *Collision energies*

- Large Hadron Collider (LHC), run 1
  - total collision energy for Pb-Pb

$$\sqrt{s} = 2 \times 574\,\text{TeV}$$

  - $^{208}$Pb has $82 + 126 = 208$ nucleons
  - collision energy per nucleon

$$\sqrt{s_{\text{NN}}} = \frac{574}{208}\,\text{TeV} = 2.76\,\text{TeV}$$

  - also proton-ion collisions (pA) at $\sqrt{s_{\text{NN}}} = 5.02\,\text{GeV}$
- Relativistic Heavy Ion Collider (RHIC) at BNL (since 2000)

$$\sqrt{s_{\text{NN}}} \leq 200\,\text{GeV}$$

- Lower energy experiments
  - Alternating Gradient Synchrotron (AGS) at BNL (since mid 1980's)

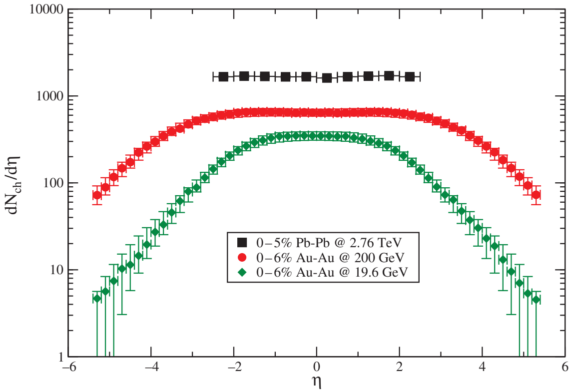
$$\sqrt{s_{\text{NN}}} \approx 2 - 5\,\text{GeV}$$

  - CERN SPS fixed target experiments (since 1994)

$$\sqrt{s_{\text{NN}}} \leq 17\,\text{GeV}$$

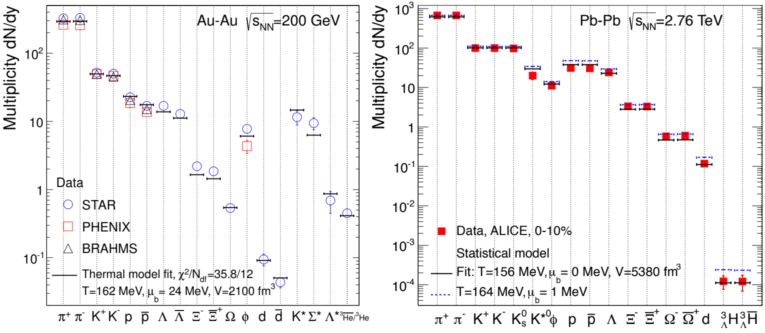
## *Multiplicity*

Number of charged particles found in the detector




- as function of pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$
- integration gives $N_{\text{ch}} = 5060 \pm 250$ at upper RHIC energy
- not all particles are charged, about $1.6 \times 5060 \approx 8000$ hadrons in total
- $N_{\text{ch}}$ grows with collision energy
- estimate for LHC: $N_{\text{ch}} = 25\,000$ or about $40\,000$ hadrons in total

# *Identified particle multiplicities*




[Andronic, Braun-Munzinger, Redlich, Stachel (2012/2013)]

Multiplicities of identified particles well described by statistical model:

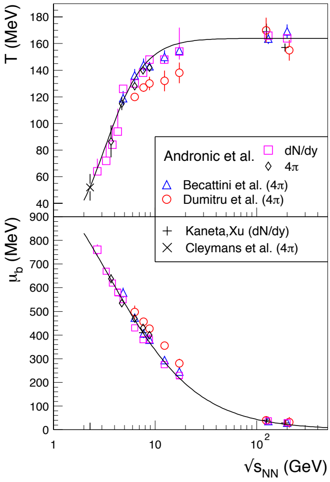
- non-interacting hadron resonance gas in thermal and chemical equilibrium.
- includes all hadronic resonances known to the particle data group.
- fit parameters are temperature $T$, volume $V$ and chemical potentials for baryon number $\mu_b$, isospin, strangeness and charm.

# *Chemical freeze-out interpretation*

- Why does statistical model work that well?
- Hadronization is governed by non-perturbative QCD processes. Not completely understood yet.
- Interpretation in terms of chemical freeze-out:
  - Close-to-equilibrium evolution with expansion and cool-down
  - Number changing processes are first fast and keep up equilibrium
  - At low temperature they become too slow to keep up with the expansion
  - Particle numbers get frozen in
- Interpretation seems reasonable for heavy ion collisions.
- Puzzle: Statistical model works also for electron-positron or proton-proton collisions with similar temperatures.

## *Statistical model fits and collision energy*

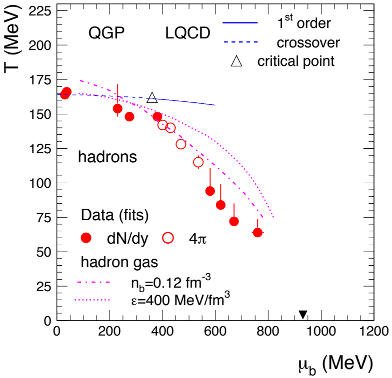
Statistical model fits have been made at different collision energies




[Andronic, Braun-Munzinger, Stachel (2009)]

# *A phase diagram from chemical freeze-out ?*

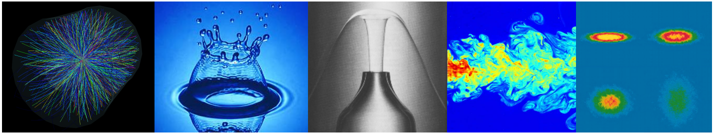
- The fit parameters $(T, \mu)$ from different collision energies lead to a suggestive diagram. What is the physical significance ?




[Andronic, Braun-Munzinger, Stachel (2009), LQCD from Fodor, Katz (2004)]

- At large $\mu_b$ / small $T$ no phase transition at the chemical freeze-out line [Floerchinger, Wetterich (2012)]

# *Fluid dynamics*



- Long distances, long times or strong enough interactions
- matter or quantum fields form a fluid!
- Needs **macroscopic** fluid properties
  - equation of state $p(T, \mu)$
  - shear viscosity $\eta(T, \mu)$
  - bulk viscosity $\zeta(T, \mu)$
  - heat conductivity $\kappa(T, \mu)$
  - relaxation times, ...
- For QCD no full *ab initio* calculation of transport properties possible yet but in principle fixed by **microscopic** properties encoded in $\mathscr{L}_{\mathrm{QCD}}$
- Ongoing experimental and theoretical effort to understand this in detail

## *Relativistic fluid dynamics*

**Energy-momentum tensor** and conserved current

$$T^{\mu\nu} = (\epsilon + p + \pi_{\text{bulk}})u^\mu u^\nu + (p + \pi_{\text{bulk}})g^{\mu\nu} + \pi^{\mu\nu}$$
$$N^\mu = n\, u^\mu + \nu^\mu$$

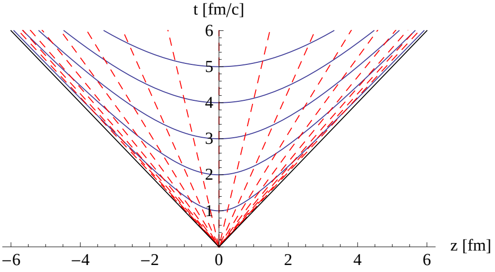
- tensor decomposition w. r. t. fluid velocity $u^\mu$
- pressure $p = p(\epsilon, n)$
- **close-to-equilibrium**: constitutive relations from derivative expansion
  - bulk viscous pressure $\pi_{\text{bulk}} = -\zeta\, \nabla_\mu u^\mu + \ldots$
  - shear stress $\pi^{\mu\nu} = -\eta \left[\Delta^{\mu\alpha}\nabla_\alpha u^\nu + \Delta^{\nu\alpha}\nabla_\alpha u^\mu - \frac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha\right] + \ldots$
  - diffusion current $\nu^\alpha = -\kappa \left[\frac{nT}{\epsilon+p}\right]^2 \Delta^{\alpha\beta}\partial_\beta \left(\frac{\mu}{T}\right) + \ldots$
- more general: **dynamical equations** for $\pi_{\text{bulk}}$, $\pi^{\mu\nu}$ and $\nu^\mu$

$$\tau_{\text{bulk}}\, u^\mu \partial_\mu \pi_{\text{bulk}} + \pi_{\text{bulk}} = -\zeta\, \nabla_\mu u^\mu + \ldots$$

Fluid dynamic equations for $\epsilon, n$ and $u^\mu$ from covariant **conservation laws**

$$\nabla_\mu T^{\mu\nu} = 0, \qquad \nabla_\mu N^\mu = 0.$$

# *Bjorken boost invariance*




How does the fluid velocity look like?

- Bjorkens guess: $v_z(t, x, y, z) = z/t$
- leads to an invariance under Lorentz-boosts in the $z$-direction
- use coordinates $\tau = \sqrt{t^2 - z^2}$ $x$, $y$, $\eta =$ arctanh$(z/t)$
- fluid velocity $u^\mu = (u^\tau, u^x, u^y, 0)$
- thermodynamic scalars like energy density $\epsilon = \epsilon(\tau, x, y)$
- remaining problem is 2+1 dimensional
- Bjorken boost symmetry is an idealization but it is reasonably accurate close to mid-rapidity $\eta \approx 0$.

# *The Bjorken model*

[coordinates: $\tau = \sqrt{t^2 - z^2}$, $x$, $y$, $\eta = \text{arctanh}(z/t)$]

- Consider initial conditions at $\tau = \tau_0$ of the form

$$\epsilon = \epsilon(\tau_0), \qquad u^\mu = (1, 0, 0, 0)$$

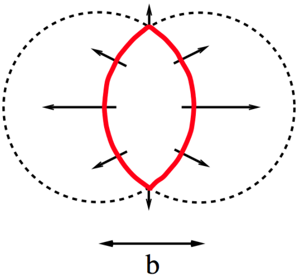
- Simplified model for inner region at early times after central collision.
- Symmetries
  - Bjorken boost invariance $\eta \to \eta + \Delta\eta$
  - Translations and rotations in the transverse plane $(x, y)$

  imply
  - $u^\mu = (1, 0, 0, 0)$ for all times $\tau$
  - $\epsilon = \epsilon(\tau)$ independent of $x, y, \eta$
- Equation for energy density in first order formalism

$$\partial_\tau \epsilon + (\epsilon + p)\frac{1}{\tau} - \left(\tfrac{4}{3}\eta + \zeta\right)\frac{1}{\tau^2} = 0$$

- Solution depends on equation of state $p(\epsilon)$ and viscosities $\eta(\epsilon)$, $\zeta(\epsilon)$

# *Non-central collisions*



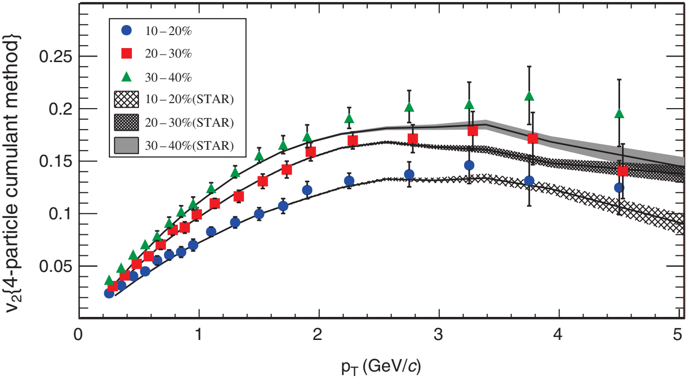

- pressure gradients larger in reaction plane
- leads to larger fluid velocity in this direction
- more particles fly in this direction
- can be quantified in terms of elliptic flow $v_2$
- particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_m v_m \cos\left(m\left(\phi - \psi_R\right)\right)\right]$$

- symmetry $\phi \to \phi + \pi$ would imply $v_1 = v_3 = v_5 = \ldots = 0$.

# *Elliptic flow*

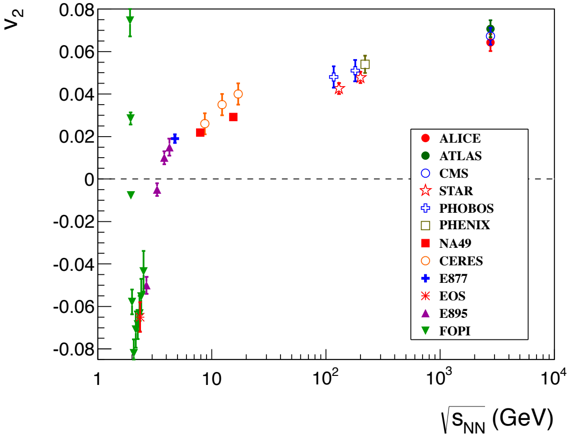
Elliptic flow coefficient $v_2$ as a function of $p_T$ for different centrality classes




[ALICE (2010)]

# *Elliptic flow at different collision energies*

Elliptic flow coefficient $v_2$ for centrality class 20-30% as a function of $\sqrt{s_{NN}}$




[ALICE (2010)]

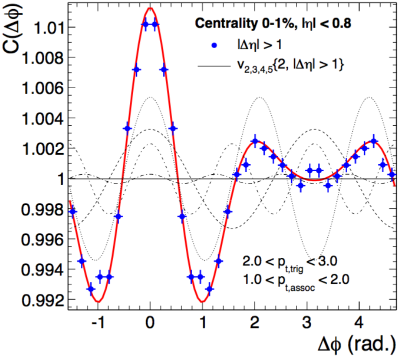
- Elliptic flow in fixed centrality class increases with collision energy.
- At very small energy not enough time to develop flow.

# *Two-particle correlation function*

- normalized two-particle correlation function

$$C(\phi_1, \phi_2) = \frac{\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \rangle_{\text{events}}}{\langle \frac{dN}{d\phi_1} \rangle_{\text{events}} \langle \frac{dN}{d\phi_2} \rangle_{\text{events}}} = 1 + 2 \sum_m v_m^2 \cos(m(\phi_1 - \phi_2))$$

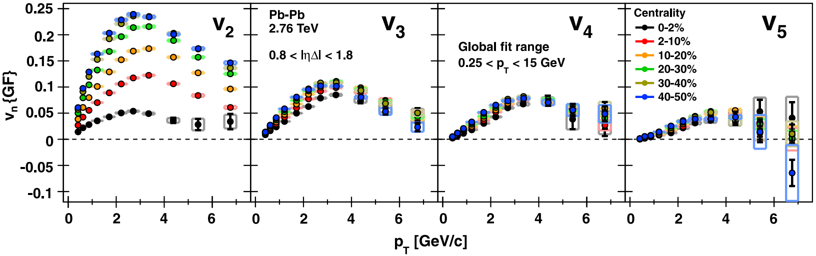
- Surprisingly $v_2$, $v_3$, $v_4$, $v_5$ and $v_6$ are all non-zero!




[ALICE 2011, similar results from CMS, ATLAS, Phenix]

# *Harmonic flow coefficients*

Flow coefficients $v_2$, $v_3$, $v_4$ and $v_5$ for charged particles as a function of transverse momentum for different centrality classes.

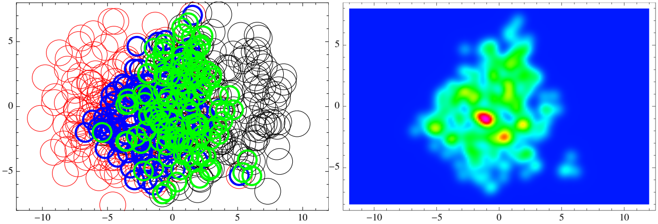



[ALICE (2012)]

- Elliptic flow $v_2$ has strongest centrality dependence.
- Triangular flow $v_3$ as well as $v_4$ and $v_5$ are all non-zero.
- $v_n(p_T)$ at fixed $p_T$ decreases for increasing $n$

# *Event-by-event fluctuations*

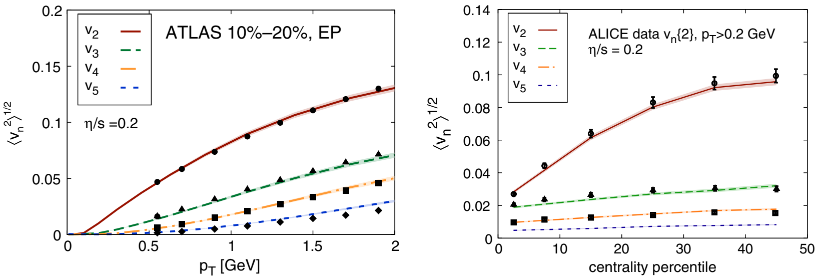
- argument for $v_3 = v_5 = 0$ is based on event-averaged geometric distribution
- deviations from this can come from event-by-event fluctuations.
- one example is Glauber model




- initial transverse density distribution fluctuates event-by-event and this leads to sizeable $v_3$ and $v_5$
- more generally also other initial hydro fields may fluctuate: fluid velocity, shear stress, baryon number density etc

# *Fluid dynamic simulations*

- Second order relativistic fluid dynamics is solved numerically for given initial conditions.
- Codes use thermodynamic equation of state from lattice QCD.
- Initial conditions fluctuate from event-to-event and different models are employed and compared.
- $\eta/s$ is varied in order to find experimentally favored value.

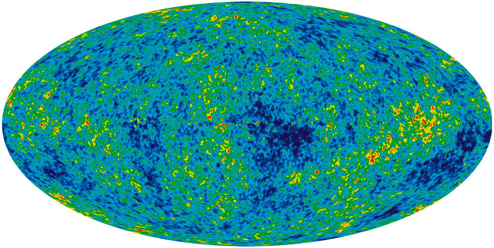


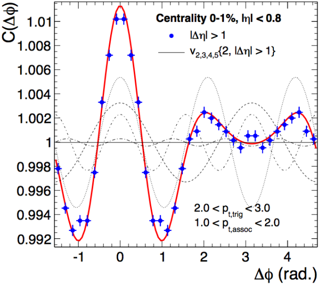

[Gale, Jeon, Schenke, Tribedy, Venugopalan (2013)]

## *What perturbations are interesting and why?*

- **Initial fluid perturbations**: Event-by-event fluctuations around a background or average of fluid fields at time $\tau_0$:
  - energy density $\epsilon$
  - fluid velocity $u^\mu$
  - shear stress $\pi^{\mu\nu}$
  - more general also: baryon number density $n_B$, electric charge density, electromagnetic fields, ...
- governed by universal evolution equations
- can be used to constrain thermodynamic and transport properties
- contain interesting information from early times
- measure for deviations from equilibrium

# *Similarities to cosmic microwave background*





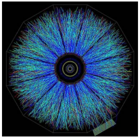

- fluctuation spectrum contains info from early times
- many numbers can be measured and compared to theory
- can lead to detailed understanding of evolution and properties
- could trigger precision era in heavy ion physics

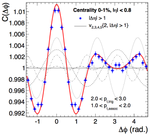
# *A program to understand fluid perturbations*

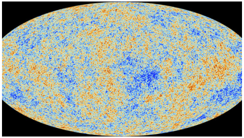
1. Characterize initial perturbations.
2. Propagated them through fluid dynamic regime.
3. Determine influence on particle spectra and harmonic flow coefficients.
4. Take also perturbations from non-hydro sources (e.g. jets) into account.

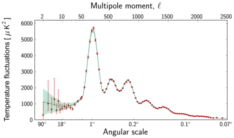
# *Fluid dynamic perturbation theory for heavy ions*

proposed in: [Floerchinger & Wiedemann, PLB 728, 407 (2014)]



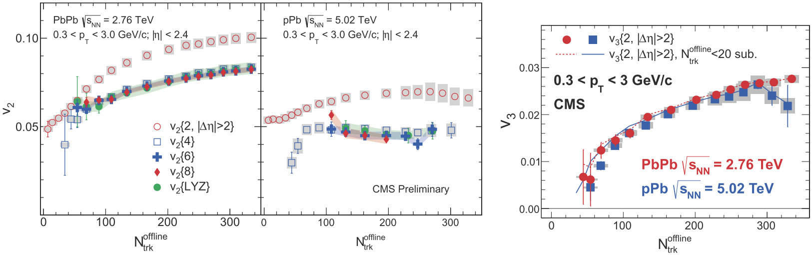





- goal: determine transport properties experimentally
- so far: numerical fluid simulations e.g. [Heinz & Snellings (2013)]
- new: solve fluid equations for smooth and symmetric background and order-by-order in perturbations
- less numerical effort
- good convergence properties [Floerchinger *et al.*, PLB 735, 305 (2014)]
- similar technique used in cosmology since many years

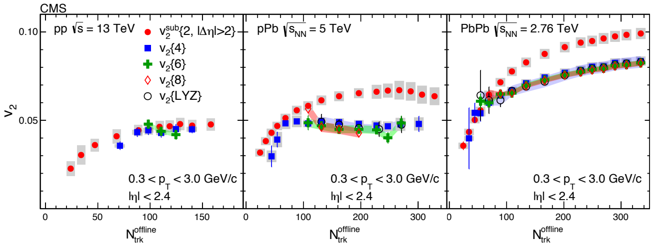
# *Collective behavior in proton - ion collisions*




[CMS (2014), similar from ALICE, ATLAS]

- Signatures for fluid dynamic behavior were found also in proton-ion collisions.
- Triangular flow very similar for comparable multiplicity.
- Theoretical understanding: Collision geometry smaller but higher initial energy density.

# *Collective flow signals in proton - proton collisions (?)*




[CMS (2016), 1606.06198]

- Collective flow signals are also visible in data from proton-proton collisions with large collision energy and large particle multiplicity
- Are there alternative explanations in terms of field theory concepts? Initial state physics?

# *Theoretical puzzles*

- Traditional description of proton-proton collision physics is in terms of factorization
  - Parton distribution function
  - Cross section for elementary processes
  - Fragmentation into hadrons
- Harmonic flow coefficients need physics beyond this !
- Working theoretical model is based on fluid dynamics
  - assumes local thermalization
  - uses fluid velocity and thermal variables
- Unitary time evolution *versus* dissipative dynamics (entropy generation)
- Where does fluid dynamics become applicable / break down ?

## *Entropy*

- Unitary time evolution conserves entropy
- Thermal fluid is produced from dissipative dynamics
- Information loss by restriction of observation
- Entropy as entanglement entropy

$$S_A = -\mathrm{Tr}\left\{\rho_A \ln \rho_A\right\} \qquad \text{with} \qquad \rho_A = \mathrm{Tr}\big|_{\bar{A}}\rho,$$

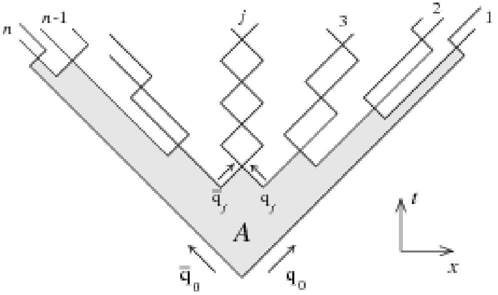
# *Thermalization, dissipation and entanglement*

- Kinetic theory: One-particle spectrum can thermalize
  - One-particle spectrum from tracing over other excitations
  - Entropy from entanglement between particles / excitations
- Local apparent thermalization
  - no quasi-particle description needed
  - local observables from tracing over other regions
  - Entropy from entanglement between regions

## *Hadronization*

- QCD in terms of quarks and gluons is weakly coupled at high energies
- QCD in therms of mesons and baryons is weakly coupled at low energies
- QCD is strongly coupled at intermediate energies
- Dissipation / thermalization is particularly efficient at large coupling
- Hadronization is not very well understood, but could actually be very important stage for apparent thermalization

# *The Lund model*

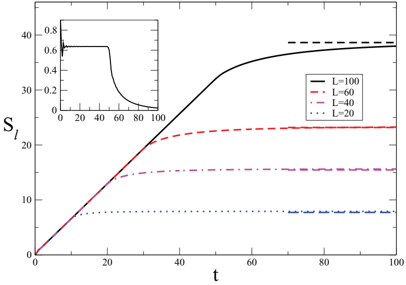



- basic model for hadronization
- underlies many Monte-Carlo codes (e.g. PYTHIA)
- model for classical gauge fields in $d = 1$ and classical massless particles
- mesons as jo-jo states
- probability for pair production as in static Schwinger model
- formulated as a (classical) probabilistic cascade model along light cone

# *Entanglement entropy in one dimension*

- Conformal field theories in $d = 1$ are well studied
- Entanglement entropy of interval with length $l$ can be followed in time

$$S_l(t) = -\mathrm{Tr}\big|_{\bar{l}}\,\rho(t)\ln\rho(t)$$




[Calabrese, Cardy (2005)]

- Entanglement entropy becomes extensive: thermalization
- Moreover, all local observables show thermalization !

# *Entanglement dynamics in string model of hadronization*

- Consider QCD string dynamics as $d = 1$ model
- What is the dynamics of entanglement between different intervals of the string?
- String breakup and hadron production should be local processes. Does meson spectrum generated from entangled string show a thermal spectrum?
- More general: are transverse degrees of freedom thermal-like?
- How would the Lund model have to be modified to take this into account?

# *Conclusions*

- Many features of high energy nuclear collisions are described by relativistic fluid dynamics.
- Evolution of fluid perturbations analogous to cosmological perturbations.
- Flow signals also found in proton-nucleus and nucleus-nucleus collisions.
- Range of applicability / point of breakdown of fluid dynamics and thermodynamics in high energy collisions not entirely clear.
- Hadronization / soft QCD physics still not totally understood.
- Entanglement dynamics in high energy nuclear collisions could be quite interesting.