Soft Physics – Opportunities for LHCb

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Within the soft physics sector, I focus on:

a. The central open questions in heavy ion physics
- simplified overview of current understanding (slides 2-7)
- more info on current state of theory (slides 8-12)
These are included for completeness but not discussed.

b. How can LHCb contribute to these central questions in the near future? (slides 13-18)

c. A possible long-term perspective

LHCb-workshop
10 January 2017
CERN

Abstract

This document summarizes thoughts on opportunities in the soft–QCD sector from high-energy nuclear collisions at high luminosities.

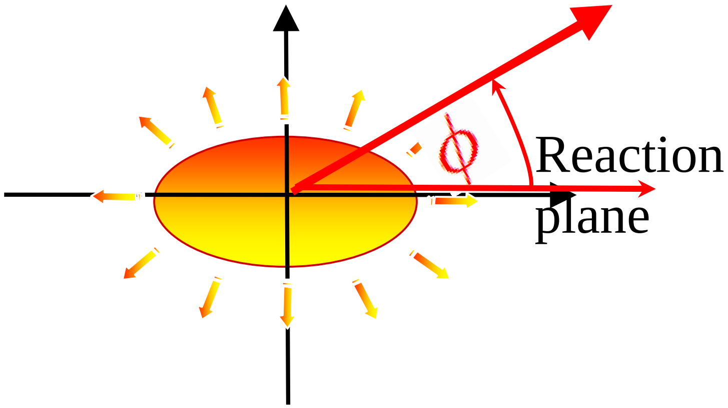
Thoughts on heavy-ion physics in the high luminosity era: the soft sector, arXiv:1604.03310

Introduction

For an accelerator-based program with nuclear beams, the main avenues for making further progress include increasing the integrated luminosity, scanning the center of mass energy, varying the beam species, as well as making suitable upgrades to detectors and software. How to combine these tools of experimental exploration depends on the physics challenges. At the LHC and at RHIC, the recent discoveries related most directly to the collective properties of hot and dense matter are arguably in the soft physics sector, and so are some of the main outstanding challenges of the field. In particular, the comparison of recent data on nucleus-nucleus, proton-nucleus d+Au, ^{3}He+A, and proton-proton collisions raise fundamental questions about the origin of apparent collectivity in smaller systems, the nature of QCD equilibration processes and – in the long term – the question of how experimental access may be gained to the physical degrees of freedom mediating collectivity.

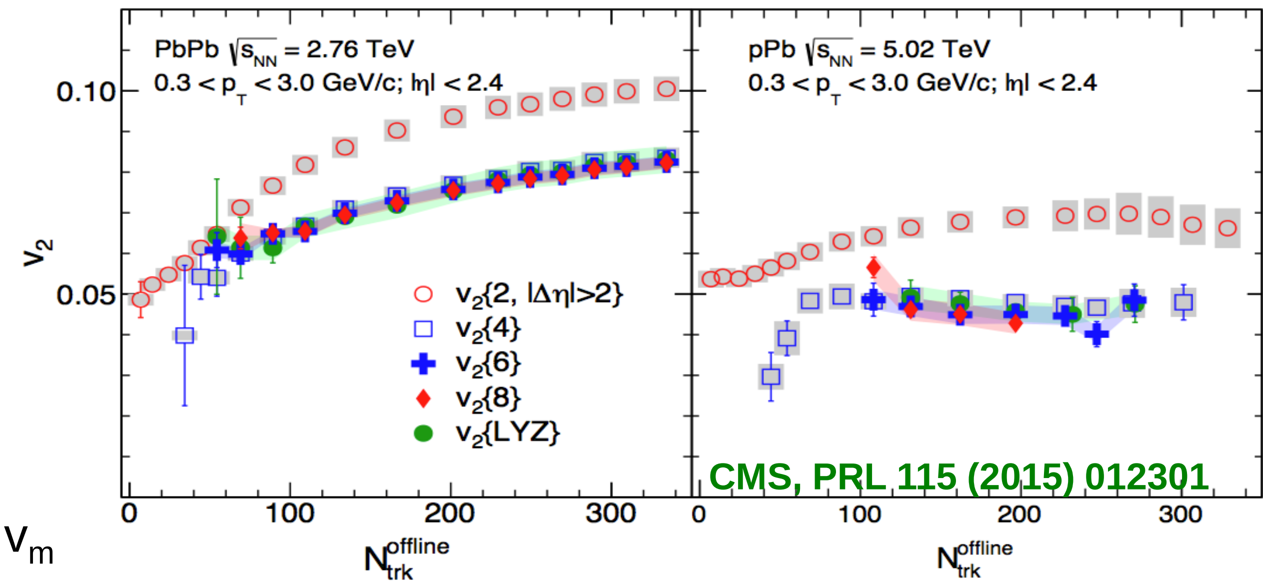
Experimental Fact 1: Flow in PbPb and pPb (pp)

$$\frac{dN}{df} \propto \left[1 + 2\sum_m v_m \cos(mf)\right]$$



- Azimuthal asymmetries v_m persist unattenuated in many-particle correlations

➡ **collectivity**

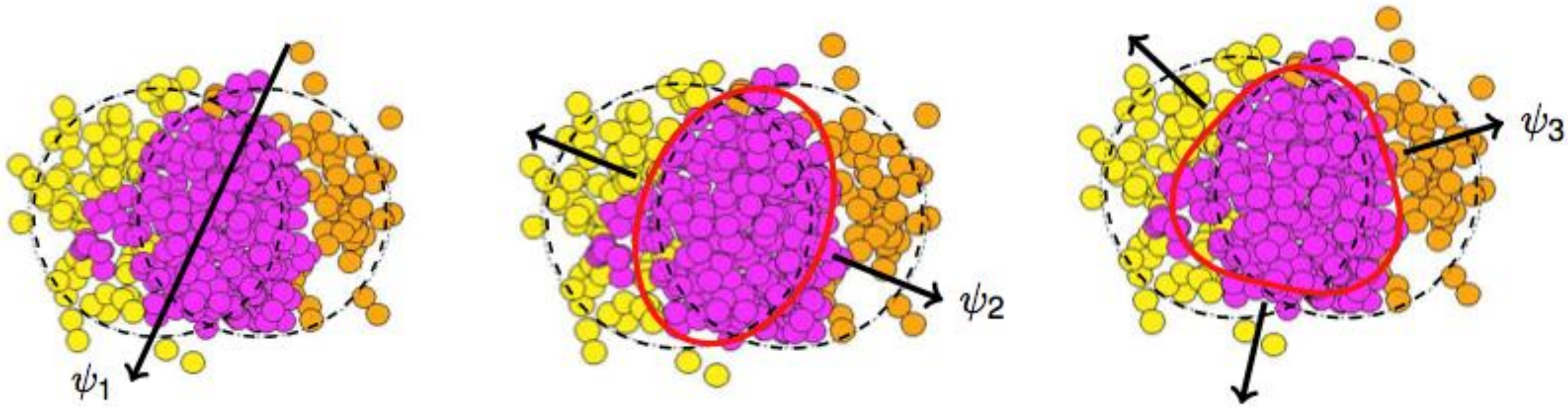


- p_T-dependence of v_m
- PID-dependence of v_m
- rapidity (in)dependence of v_m
- centrality dependence
- correlations of reaction plane orientations

➡ **support fluid dynamic picture of heavy ion collisions**

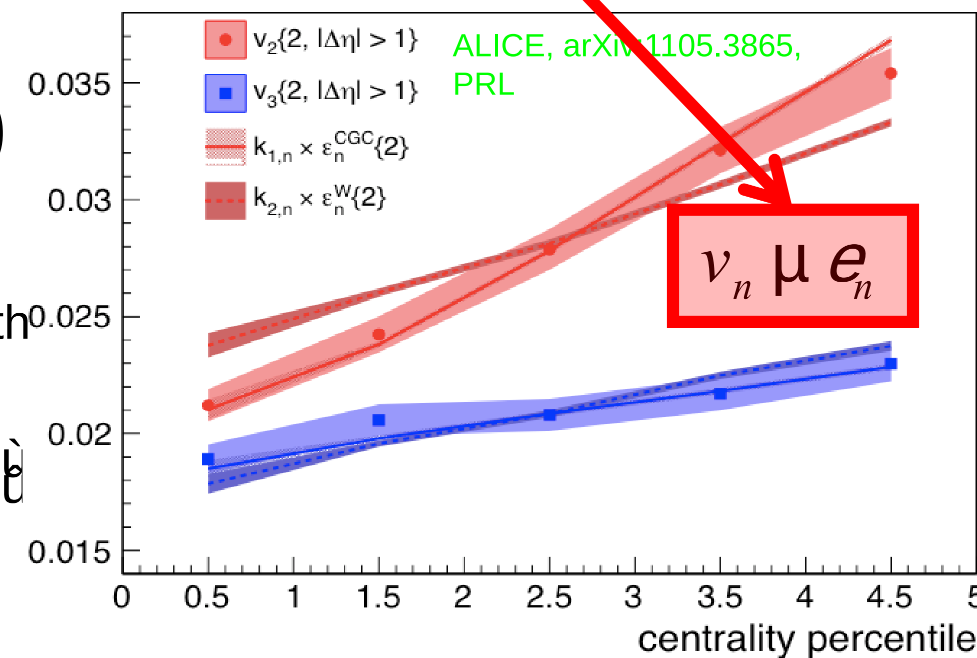
Fact 2: Flow reflects initial transverse geometry

- **Models of initial conditions:** In heavy ion collisions, initial transverse spatial densities expected to show fluctuations in the **event-by-event distribution**.



- Measured flow v_n in momentum space is **(almost) linear response** to **spatial eccentricities,**

$$\varepsilon_{m,n} e^{in\phi_{m,n}} = \frac{1}{Norm}\int r\,dr\,d\phi\, r^m e^{in\phi}\,\rho(r,\phi)$$



$$v_n \propto \varepsilon_n$$

- For fluid dynamics, only long wavelength properties of initial conditions matter

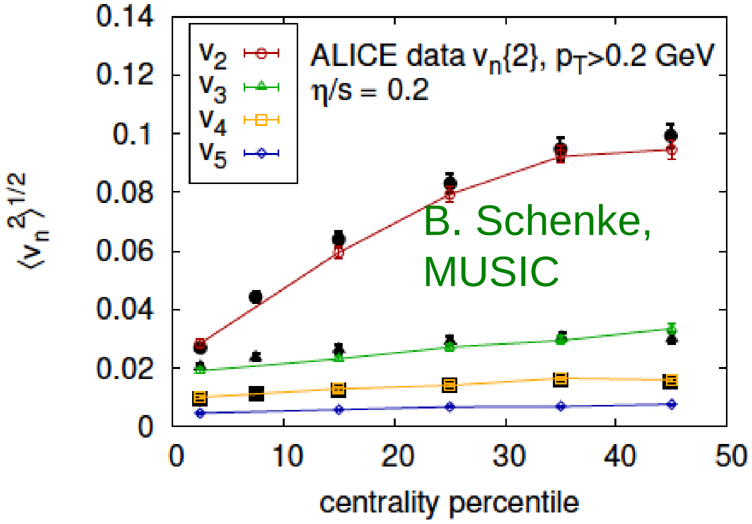
$$\delta v(\tau,k) = \delta v(\tau_0,k)\left(\frac{\tau_0}{\tau}\right)^{*} \exp\left[-\Gamma_s k^2(\tau_0-\tau)\right]$$

Heavy Ion “Hydro” Phenomenology - sketch

Fundamental QCD Lagrangian → **QCD thermodynamics**

↓

QCD hydrodynamics predicts long wavelength behavior of hot QCD → Comparing hydro predictions to flow measurements

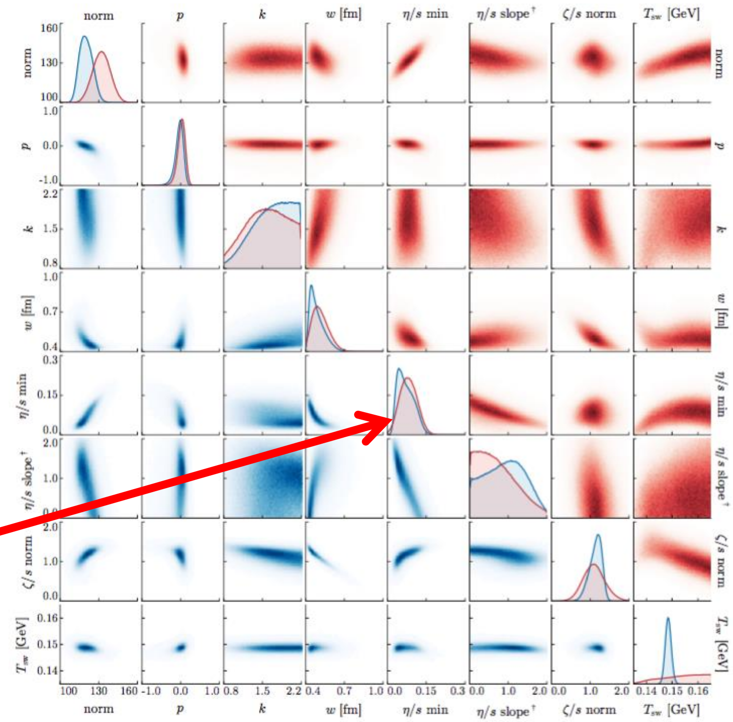


→ Determine fundamental properties of hot QCD

(equation of state, velocity of sound, transport coefficients, …)

Fluid dynamic modeling of heavy ion collsions

- Few model parameters characterize
  - ◆ Initial conditions
  - ◆ Hydro evolution
  - ◆ Particlization

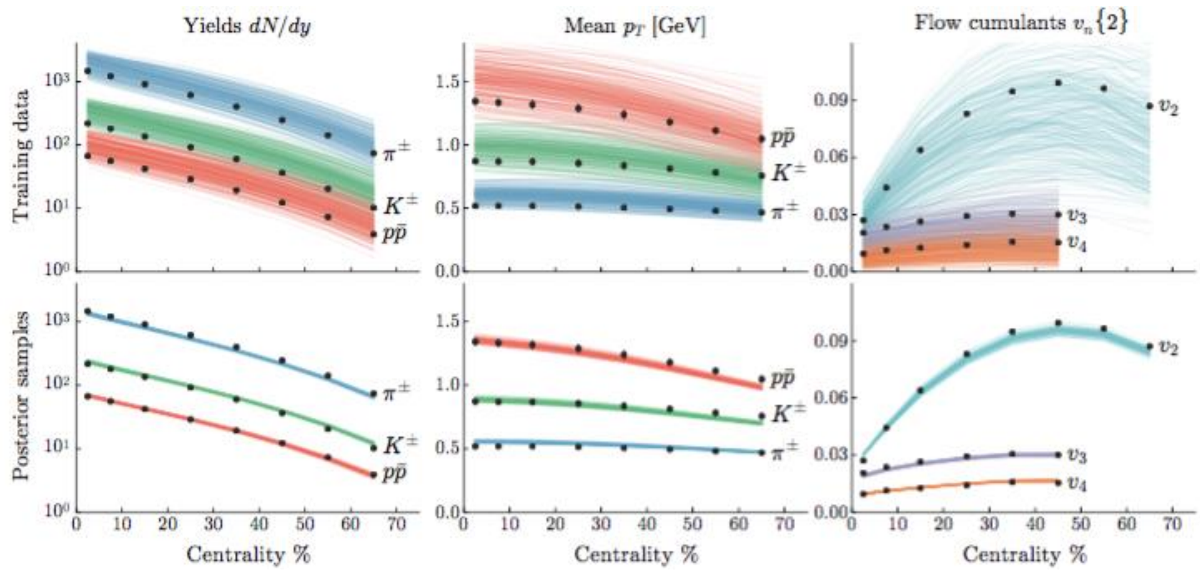


- Bayesian analysis
  - ◆ Leads to very good **posteriors**
  - ◆ Best parameters indicate a **minimally dissipative fluid**

prior

J.E. Bernhard et al. , arXiv:1605.03954v2

posterior



How can hydrodynamic behavior arise?

1. **Initial conditions**

   - non-equilibrated
   - **over-saturated** $f_{gluon}(x,p) \sim 1/\alpha_s$
   - **anisotropic** $p_T > p_L$

1. **Pre-equilibrium stage**

   - determined by effective kinetic theory
     (if dynamics is perturbative)
   - qualitatively understood in models of gauge-gravity duality
     (if dynamics is non-perturbative)

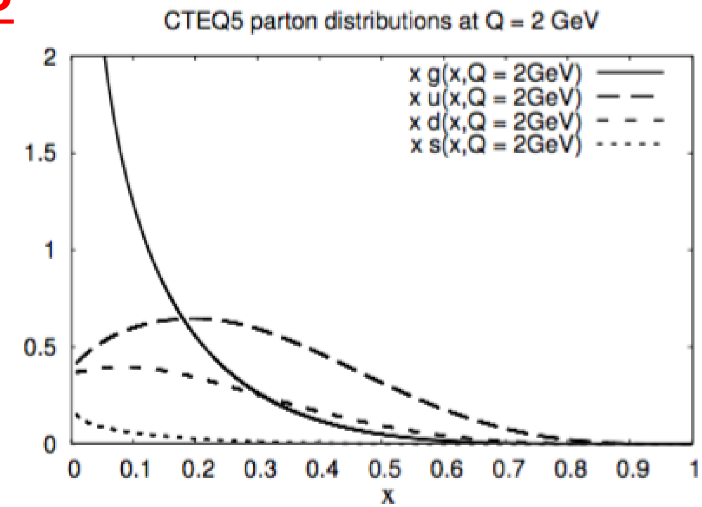
   ➡ **leads to rapid hydrodynamization**

1. **Hydrodynamic expansion**

   - controlled matching on pre-equilibrium stage
   - determined by very few thermal equilibrium properties
     (calculable from 1st principles in QCD)

➡ **in more detail …**

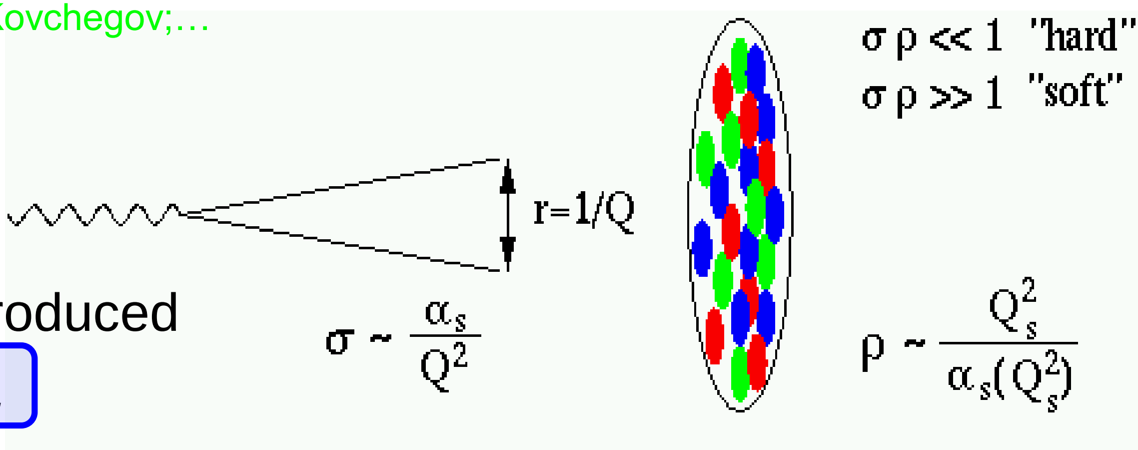
1. Initial conditions



- Gluon distributions grow rapidly at small x.
- Small-x growth in incoming nuclei can reach **maximal parton densities**

$$r \sim 1/a_s$$

Venugopalan McLerran; Jalilian-Marian, Kovner, Leonidov, Weigert; Balitsky; Kovchegov;…



- Phase space density of produced partons $f_{gluon}(x,p) \sim 1/a_s$ is over-occupied (thermal distribution $f_{gluon} \sim 1$)
- Initial momentum distribution of $f_{gluon}(x,p)$ is **anisotropic**

2a. Pre-equilibrium evolution (perturbative)

Under longitudinal expansion, initially overoccupied systems become underoccupied before reaching local thermal equilibrium.

R.Baier, A.H. Mueller, D. Schiff, D.T. Son, 2001

- QCD effective kinetic theory: $\lambda = 4\pi N_c \alpha_s$
  to order $O(\lambda f)$ and for $\lambda f \xrightarrow{\lambda\to 0} 0$
  modes with $p^2 > m^2 \equiv 2\lambda \int_p f_p / |p|$

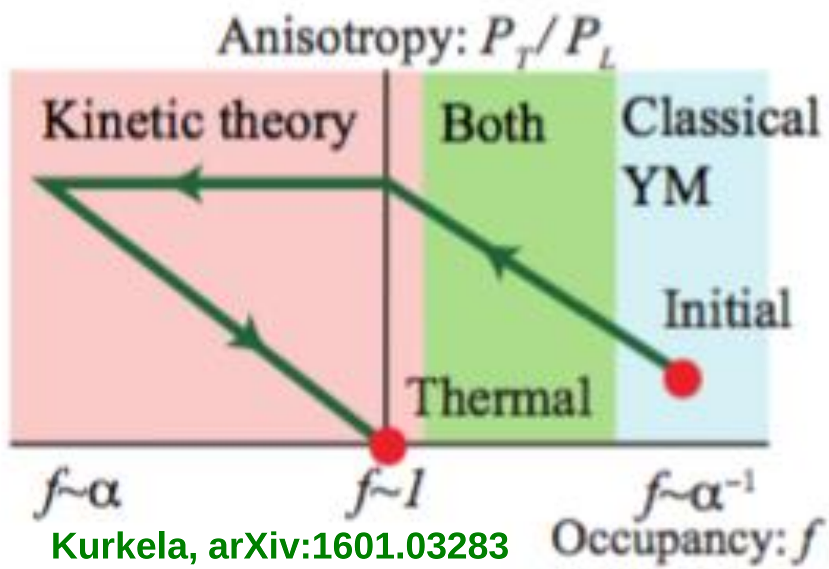
  satisfy **Boltzmann equation**

  Berges, Eppelbaum, Kurkela, Moore, Schlichting, Venugopalan, …

$$\partial_t f(p,t) = -C_{2\leftrightarrow 2}[f](p) - C_{1\leftrightarrow 2}[f](p)$$

2->2 collision kernel

LPM splitting term

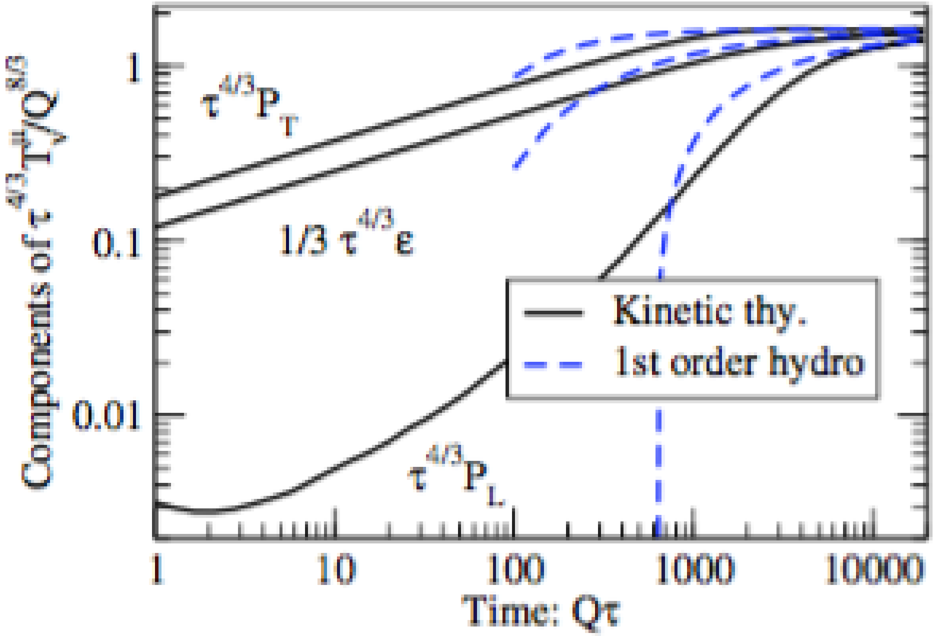


Kurkela, arXiv:1601.03283

2a. Hydrodynamization of kinetic evolution

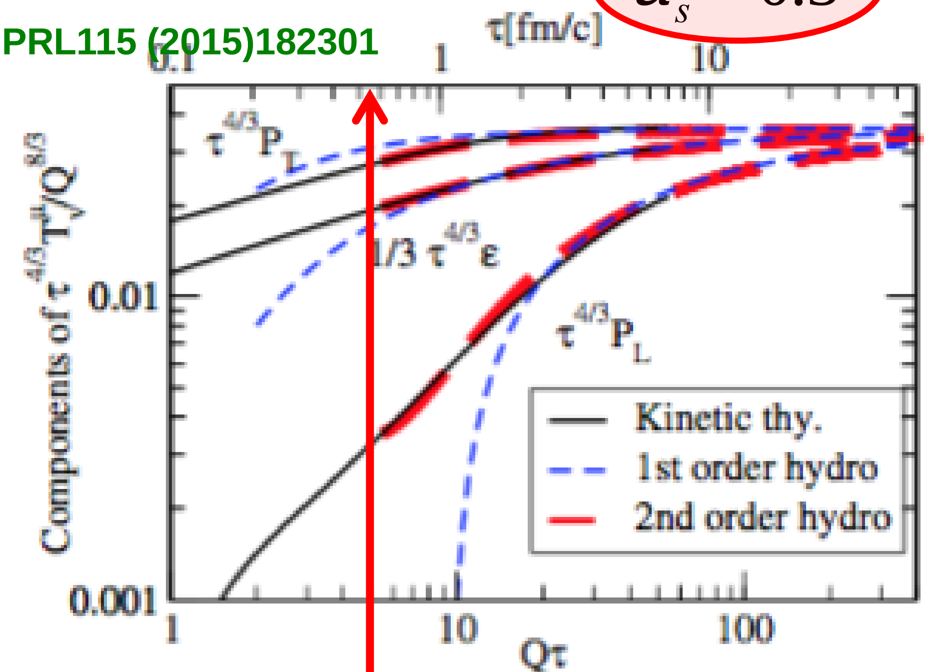
- Dissipative hydrodynamics describes long-time behavior of QCD effective kinetic theory

$a_s = 0.03$



$a_s = 0.3$

Kurkela&Zhu, PRL115 (2015)182301



Sub-fermi hydrodynamization time scale

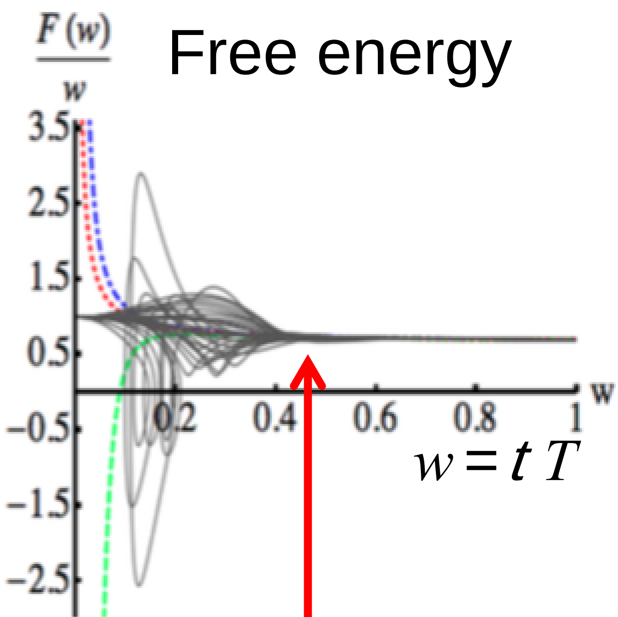
2b. Pre-equilibrium evolution (non-perturbative)

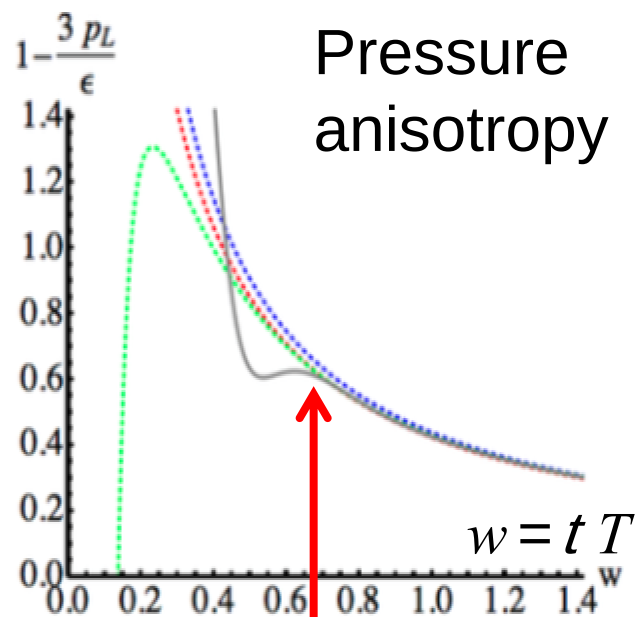
Gauge-gravity duality gives access to pre-equilibrium dynamics of a class of non-abelian plasmas in the strong coupling limit $/ = 4pN_c a_s >> 1$

- Strongly coupled non-abelian plasmas equilibrate fast
  $a_s >> 1 \;\; Þ \;\; 0.65 £ t_{eq} T$

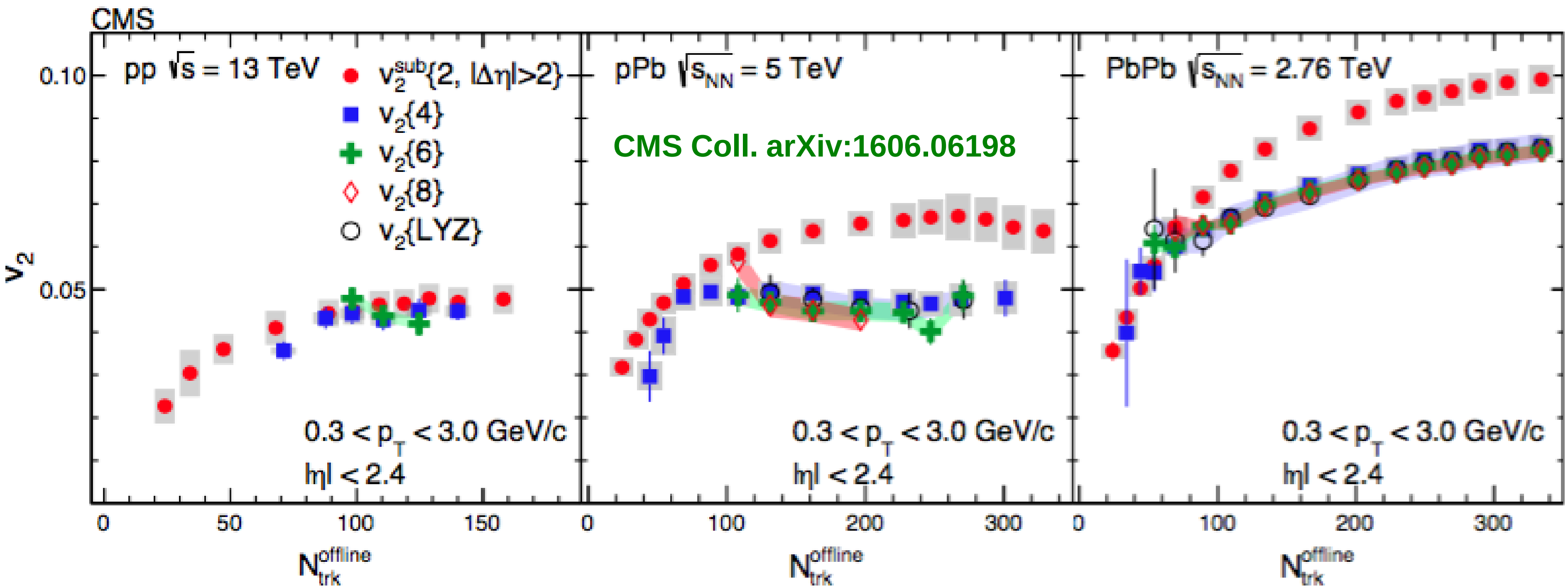
Chesler, Yaffe, PRL 102 (2009) 211601

Heller, Janik Witaszczyk, PRL 108 (2012) 201602





Sub-fermi hydrodynamization time scale



- Flow is also seen in pp@LHC. Are there alternatives to fluid dynamics that account for collectivity in small systems?

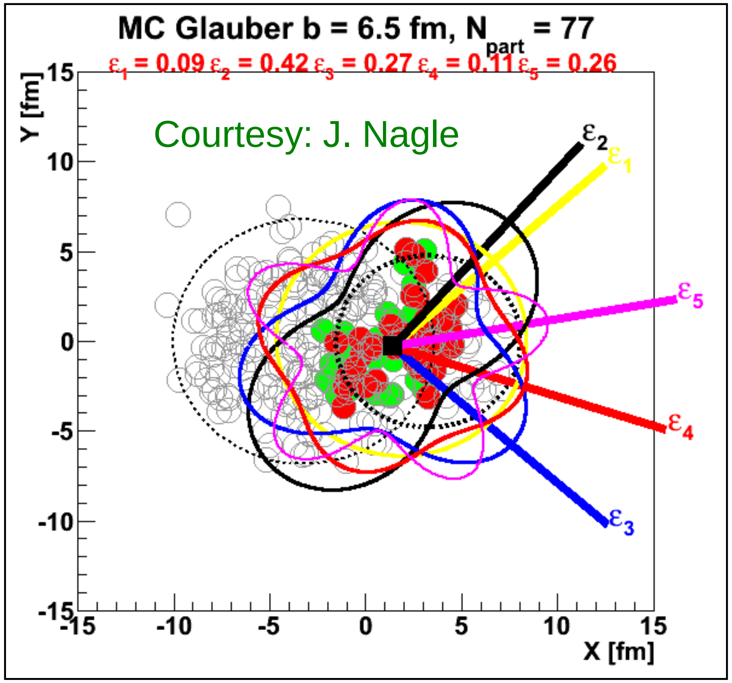
Experimental opportunities (1)

- According to fluid paradigm, varying geometry of initial geometrical overlap in A+B amounts to seeding hydro evolution with different sets of initial eccentricity fluctuations.

  This motivated U+U and Au+Cu runs at RHIC.

  To date, the LHCb SMOG system provides a unique opportunity for testing A+B collisions at the LHC.

  Primary deliverable:
  measure harmonic flow coefficients $v_m(p_T)$ in PbNe and PbAr collisions.



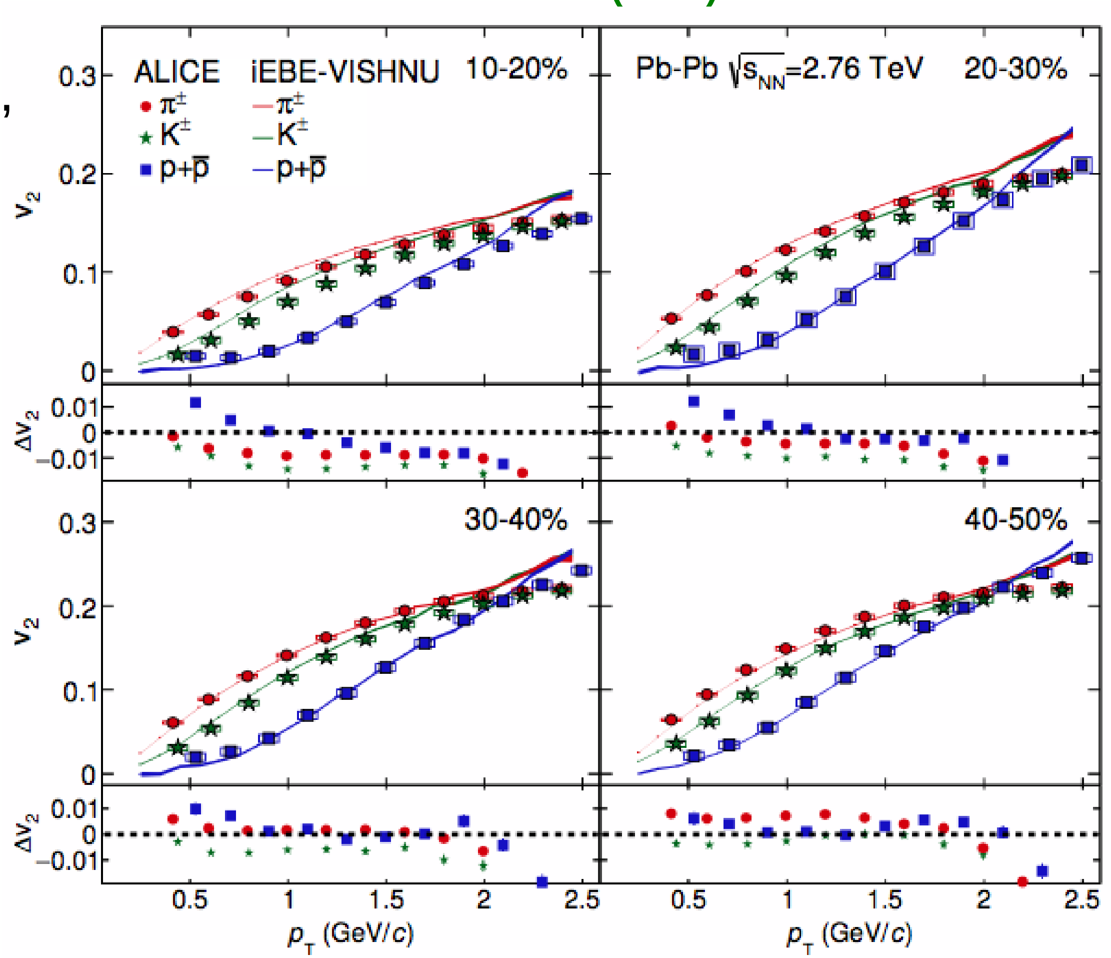
Experimental opportunities (2)

- The particle species dependence of flow measurements is a hallmark of fluid collectivity (Spectra of all particle species seem to emerge from one common flow field).

ALICE Coll. JHEP09 (2016) 164

- With superbe PID capabilities, LHCb is well-positioned to

  - extend PID-dependent v_n to forward rapidity
  - this is of interest also for pp, p+Pb and semi-peripheral Pb+Pb.



Experimental opportunities (3)

- Does heavy flavor flow? At low pt, Langevin dynamics determines how charm & beauty quarks move: The “fluid” is source of **random forces** determined by transport coefficients calculable from 1st principles in QFT

$$\frac{dp_L}{dt} = \xi_L(t) - \eta(p_L)\, p_L, \qquad \langle \xi_L(t)\xi_L(t') \rangle \equiv \kappa_L(p_L)\, \delta(t - t')$$

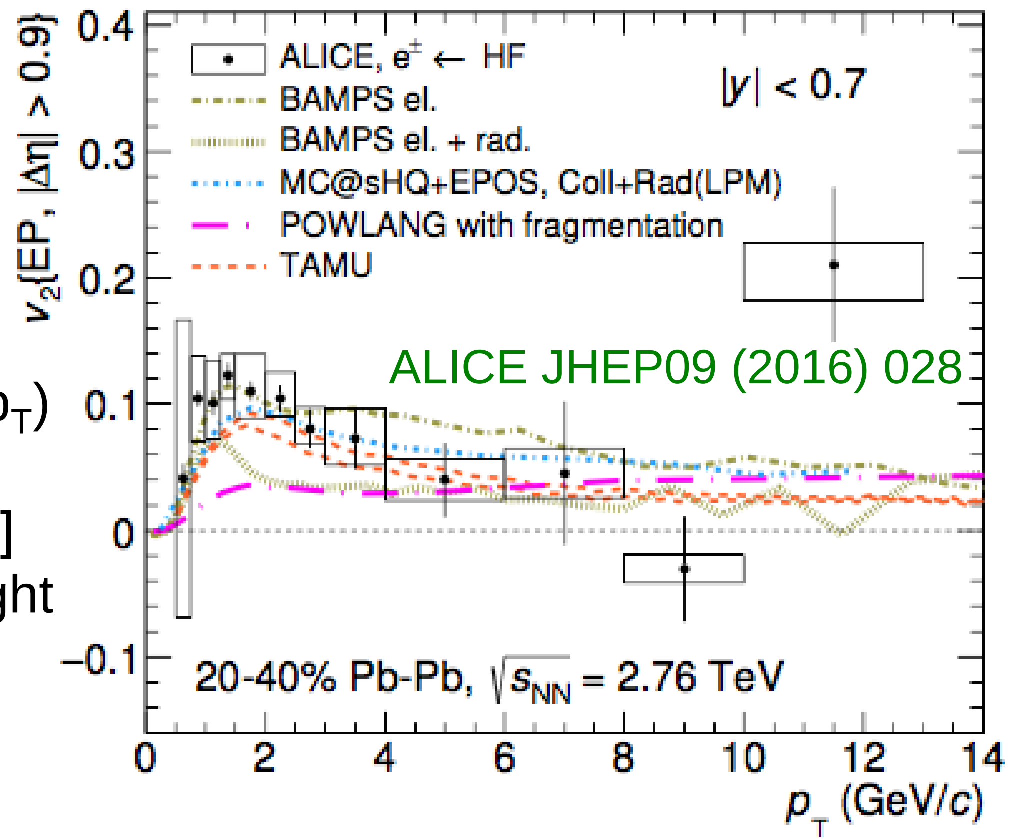
$$\frac{dp_T}{dt} = \xi_L(t) \qquad \langle \xi_{Ti}(t)\xi_{Tj}(t') \rangle \equiv \kappa_T(p_L)\, \delta_{ij}\delta(t - t')$$

- LHCb is well-positioned to

  - determine flow of heavy flavor at forward rapidity, in pPb and semi-peripheral PbPb

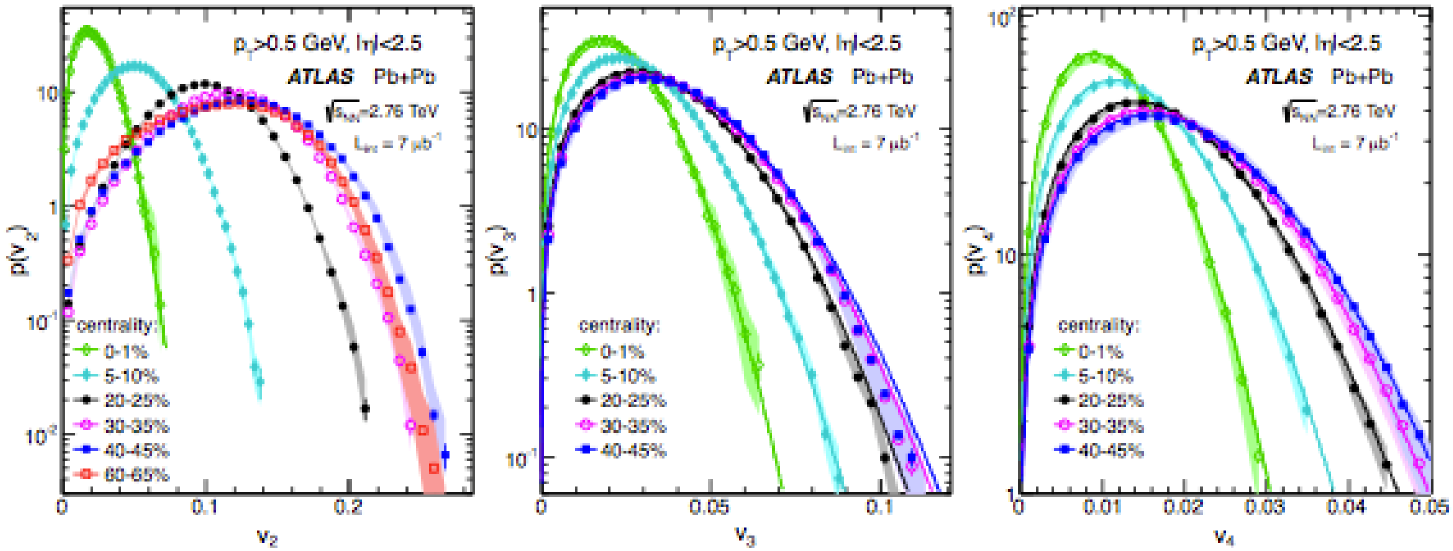
  - aim should be to determine $v_n(p_T)$ [not only v_2] for heavy flavored mesons [not only HF decay e’s] and accuracy comparable to light hadron spectra

  - flow of J/Psi, photons …?



Experimental opportunities (4)

- IMHO: the ultimate textbook plot convincing people of flow:
  1. We know EbyE probability distributions of light-flavored flows v_n:



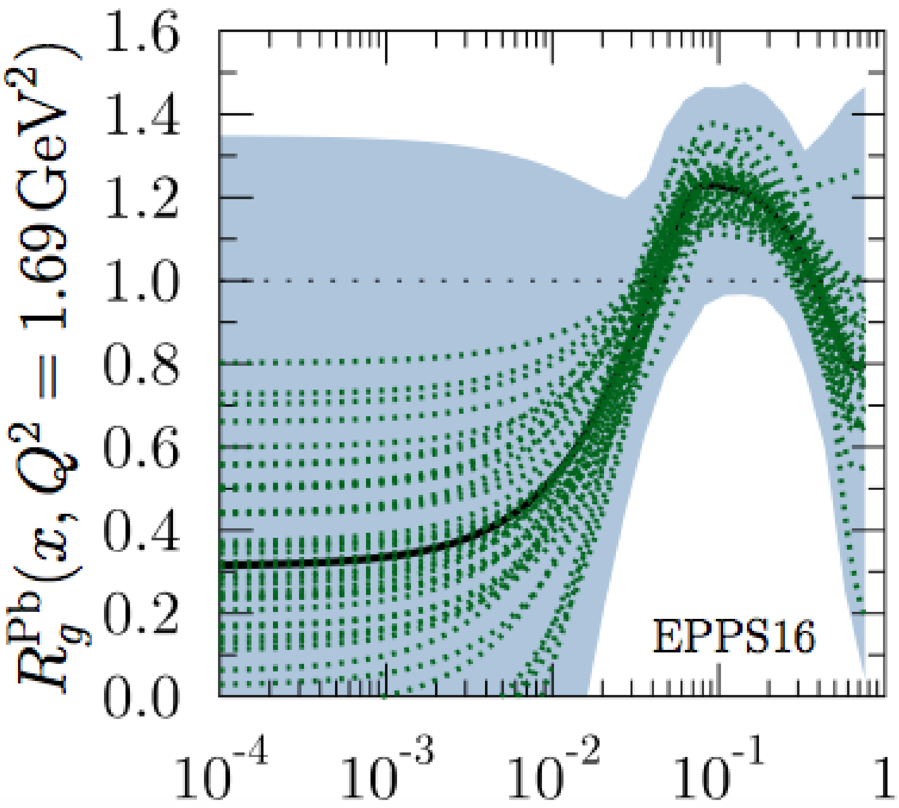
ATLAS JHEP 1311 (2013) 183

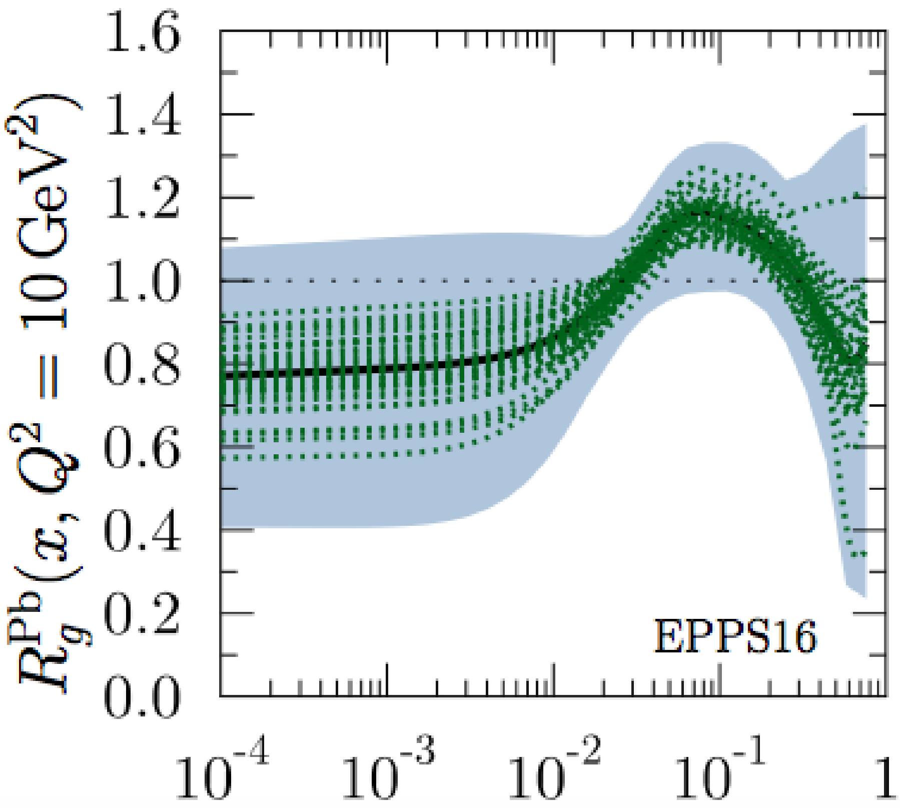
  2. Assume that the same distributions could be determined for heavy flavored mesons. This would allow one to determine cross-correlations:

  If heavy flavor “dragged along” with the common flow field (i.e. charged hadrons), then on an event-by-event level $v_m^{p} \propto v_m^{D's}$

Experimental opportunities ?

- In principle, good coverage at forward rapidity should put constraints on gluon distribution @ small-x?





LHCb should ask global npdf-fitters (EPPS16, nCTEQ, DSSZ) which measurements are most needed.

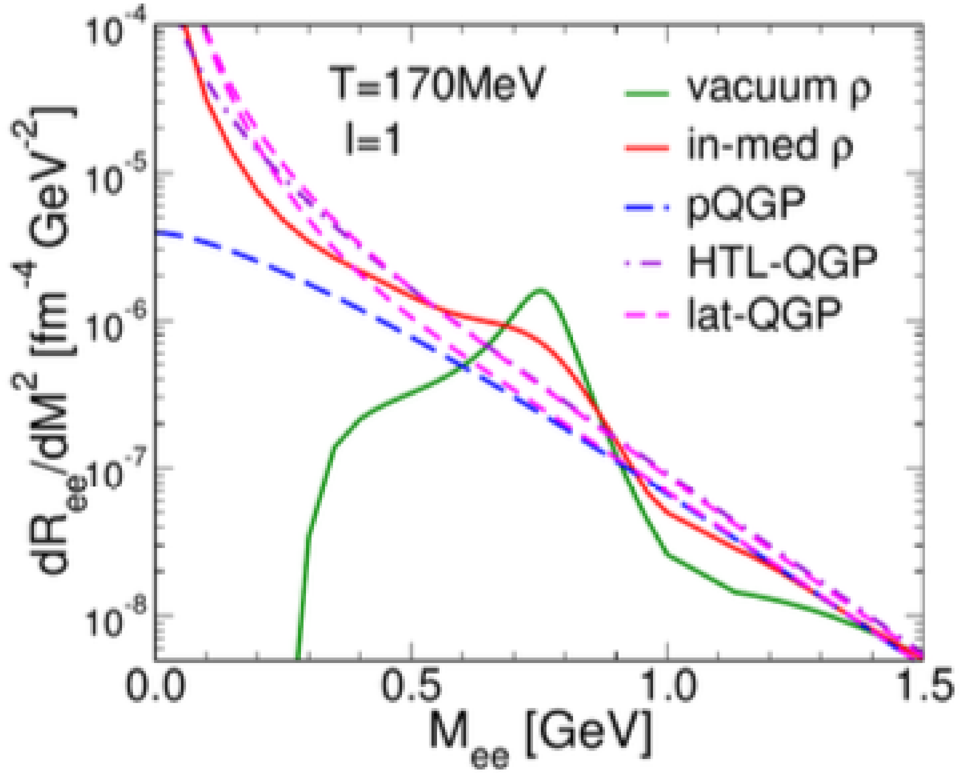
A first conclusion:

Even on relatively short timescale (before LS2)
and even if reality puts reality constraints in terms of luminosity, manpower, etc

LHCb is well-positioned to make unique contributions to key open issues about the origin of collectivity in small (pp, pPb and semi-peripheral PbPb) systems.

A unique physics programme for LHCb in the long term: Dilepton Spectra

At stake: “watch” how chiral symmetry is restored
(see talks of H. v.Hees and R. Rapp at this meeting)



Dilepton Spectra and Chiral symmetry restoration

- A central textbook topic in QCD / heavy ion physics
- Dedicated experiments at CERN SPS
- Only successful 3rd generation experiment at SPS (NA60) is still providing the world best data on dimuons (In-In data)
- RHIC had dedicated runs with “hadron blind detector”: main challenge: low pt pion / electron rejection at collider.

Perspective for an LHCb experimental flagship programme:

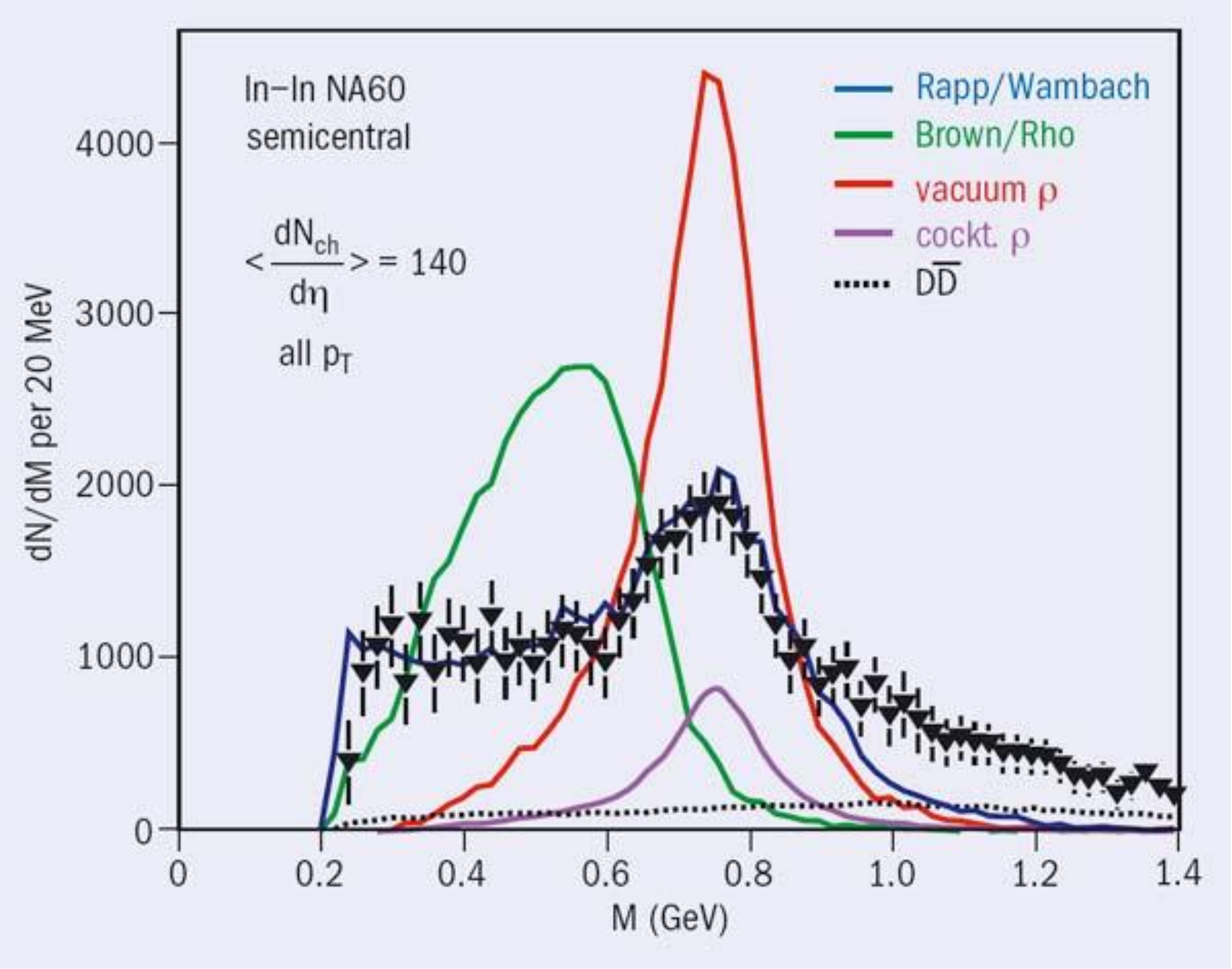
- builds on unique fixed-target option of LHCb
- provides strong physics motivation for a decade long project
- requires significant improvements over existing SMOG
- provides a platform for developing a versatile fixed target programme (polarised targets etc could be much wanted by-products)

Needs: dedicated study, dedicated experts, manpower, time, resources …

My recommendation: LHCb should assess asap what is needed, possibly by making a call to the intl. community rather than to LHCb-members only.

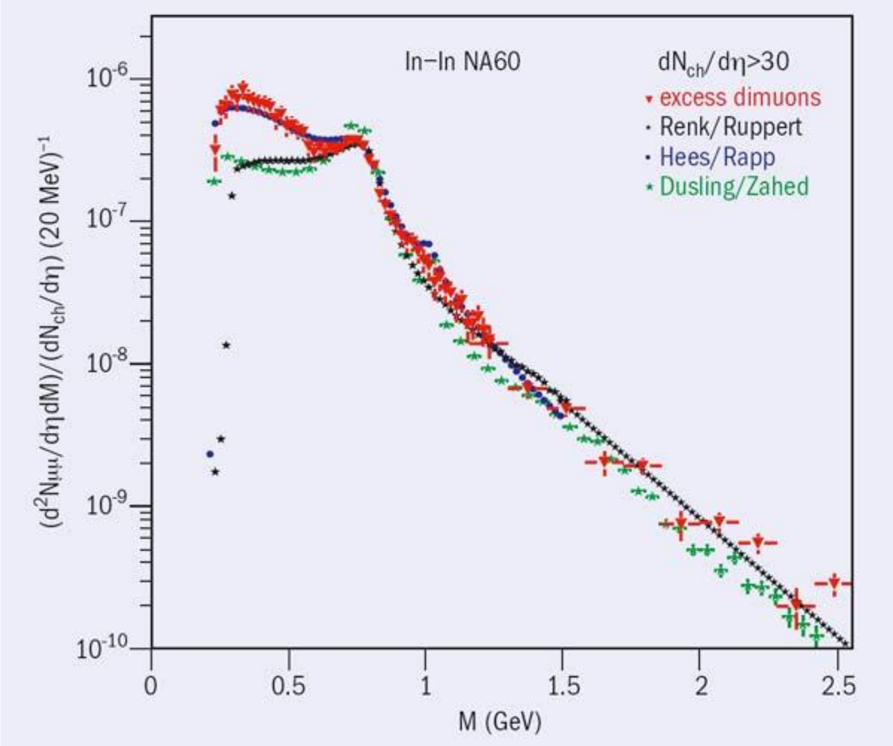
End

Dileptons …

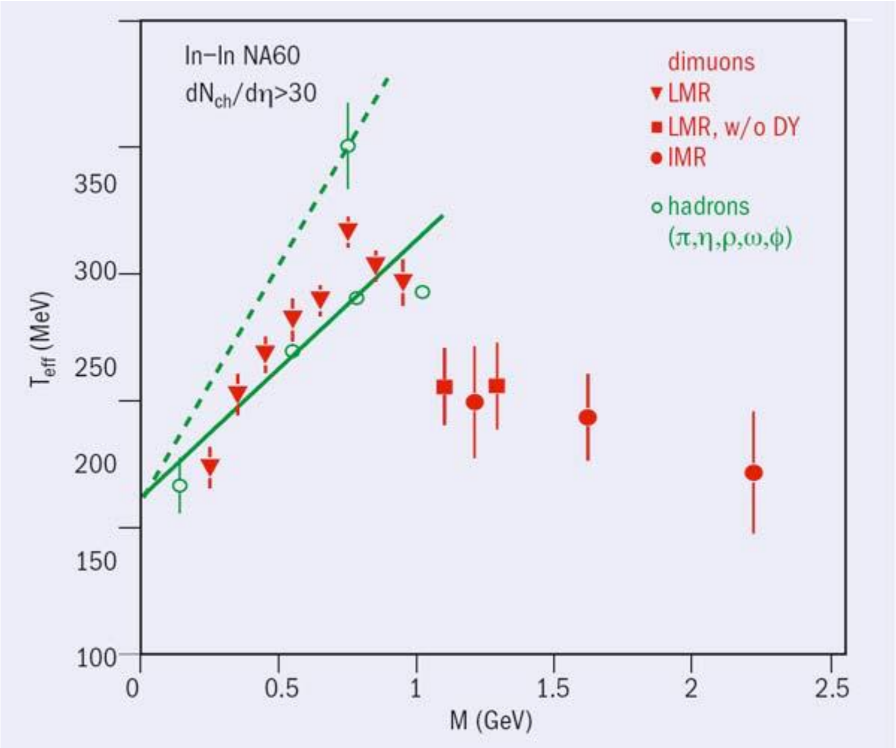


In−In NA60
semicentral
$< \frac{dN_{ch}}{d\eta} > = 140$
all p_T
Rapp/Wambach
Brown/Rho
vacuum ρ
cockt. ρ
$D\overline{D}$
dN/dM per 20 MeV
4000
3000
2000
1000
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
M (GeV)

Dileptons …



In−In NA60
dN$_{ch}$/dη>30
excess dimuons
Renk/Ruppert
Hees/Rapp
Dusling/Zahed
(d^{2}N$_{\mu\mu}$/dηdM)/(dN$_{ch}$/dη) (20 MeV)$^{-1}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
0.5
1
1.5
2
2.5
M (GeV)



In−In NA60
dN$_{ch}$/dη>30
dimuons
LMR
LMR, w/o DY
IMR
hadrons
(π,η,ρ,ω,φ)
T$_{eff}$ (MeV)
350
300
250
200
150
100
0
0.5
1
1.5
2
2.5
M (GeV)