Studying the QGP in ultrarelativistic heavy-ion collisions

Carsten Greiner

PANIC, Hamburg, August 25th , 2014

- **Observables** at RHIC and **LHC** (elliptic flow, jets, heavy quarks)
- Dynamical description: “macro” or **fluid dynamics**
- Dynamical description: “micro” or **transport dynamics**
- **Transport properties** of the QGP

Sketch of heavy ion collision

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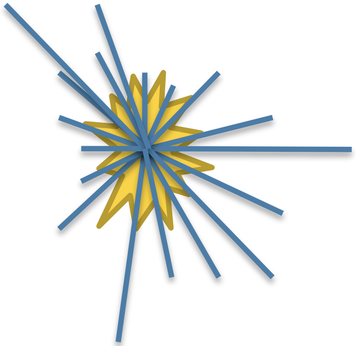
Initial pp scattering



Sketch of heavy ion collision

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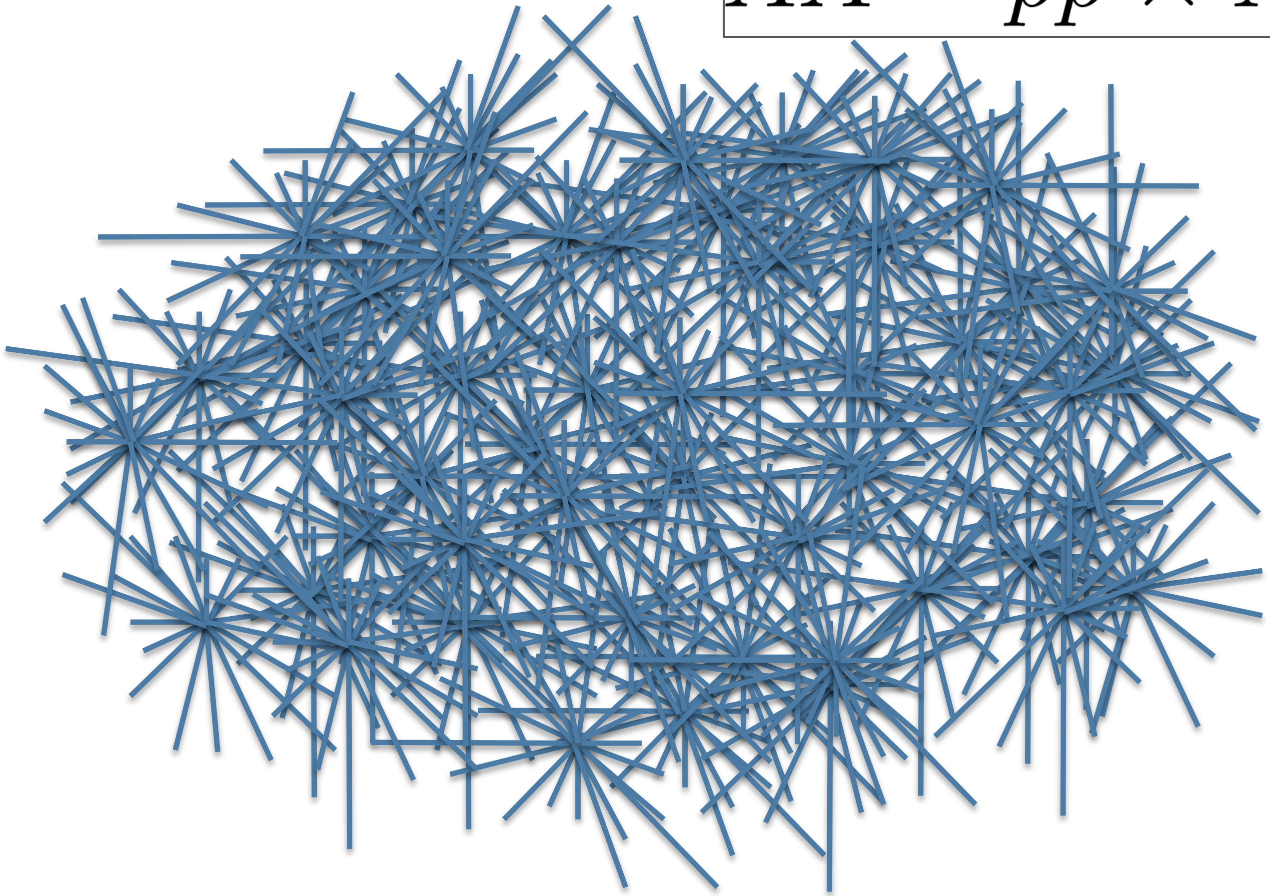
$$AA = pp \times N_{\mathrm{binary}}$$



Sketch of heavy ion collision

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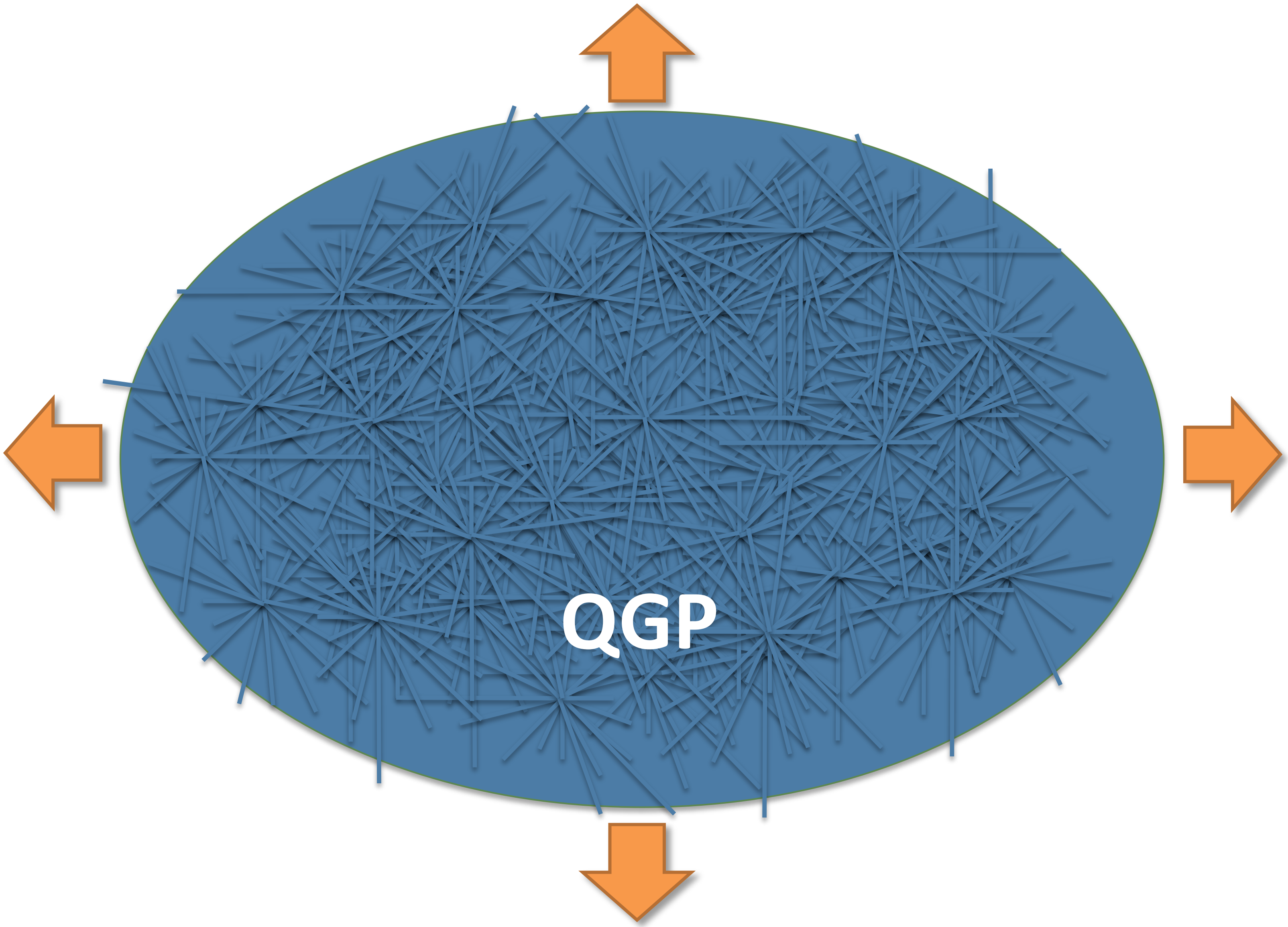
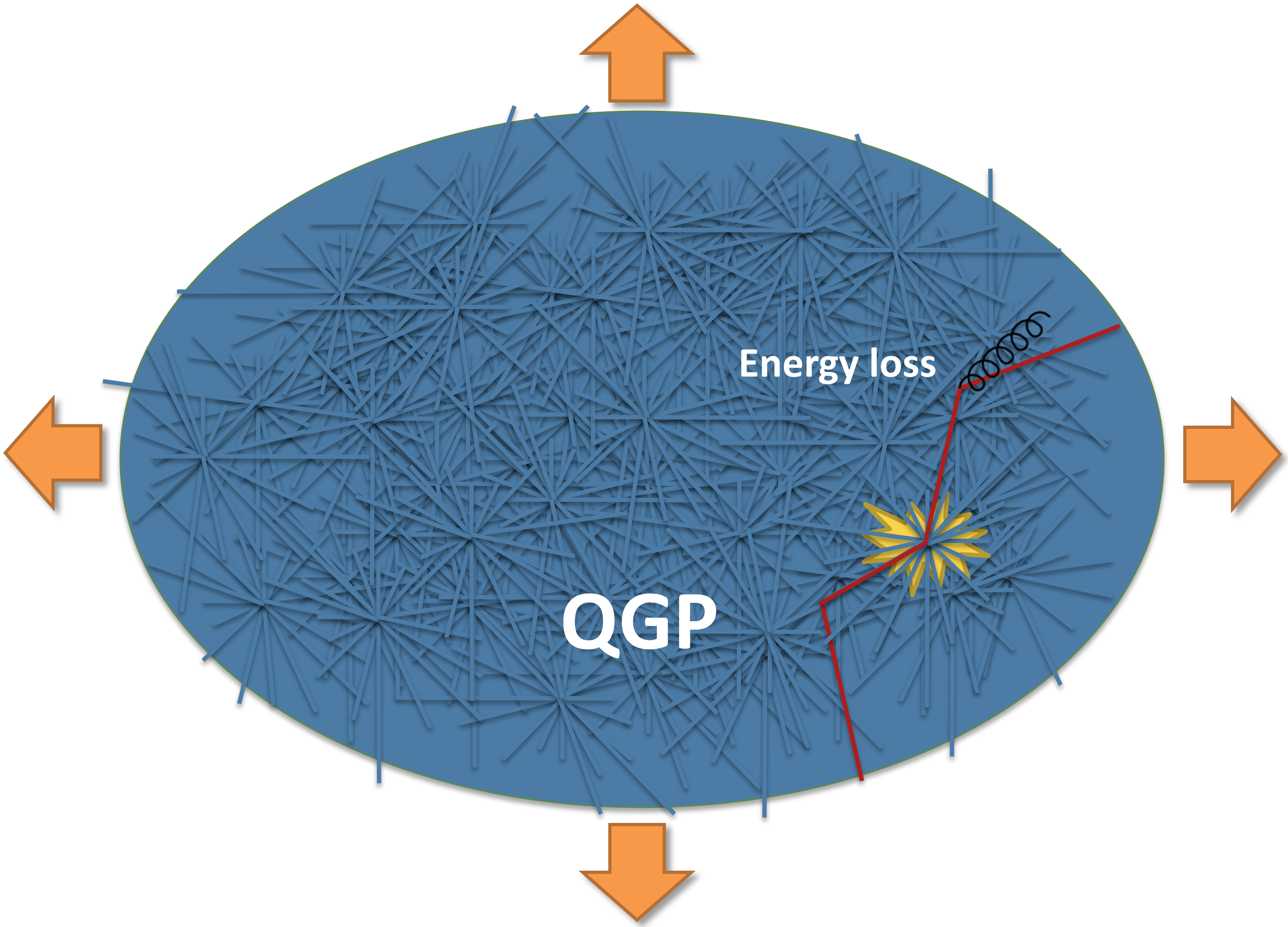
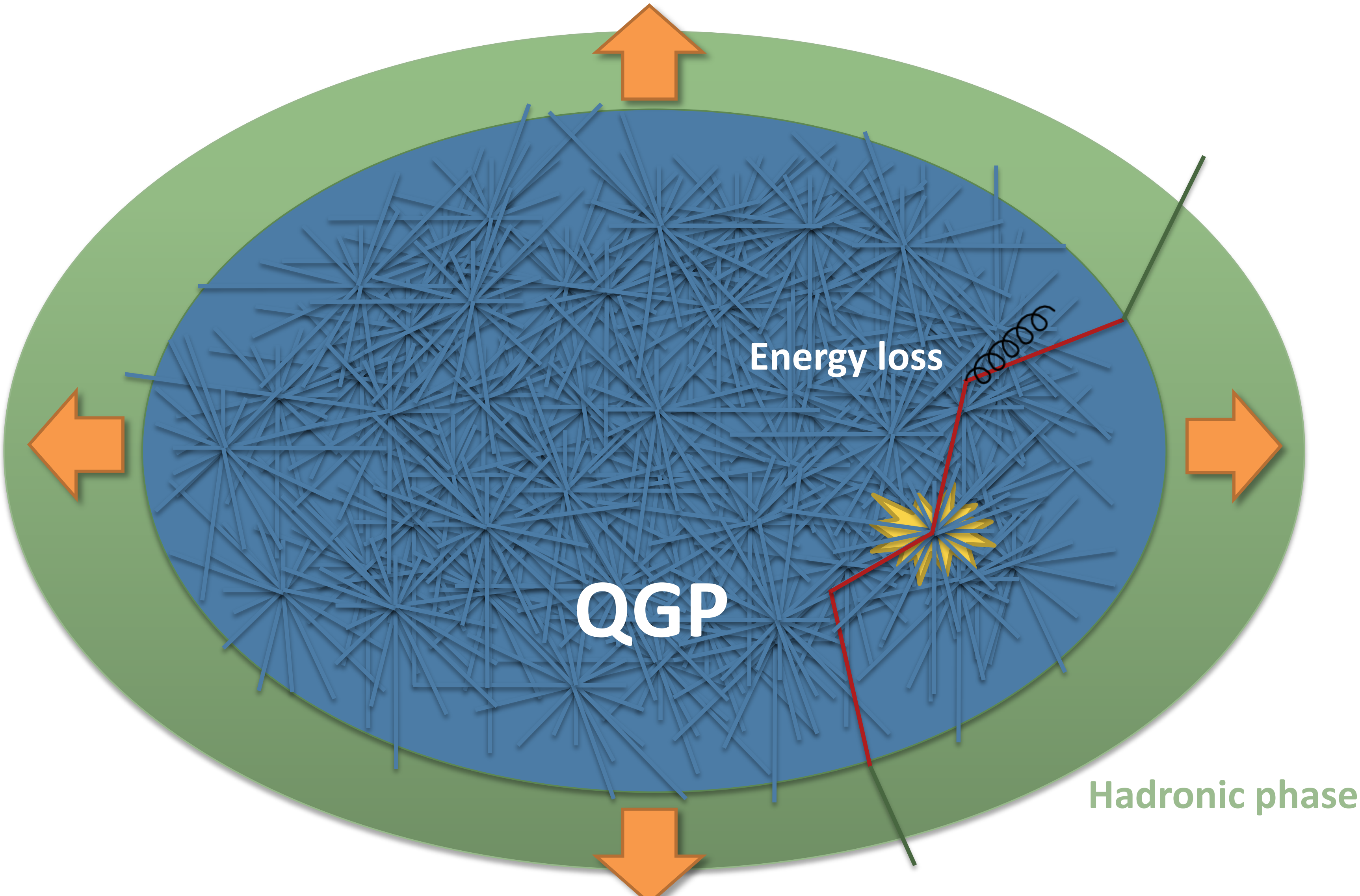


Sketch of heavy ion collision

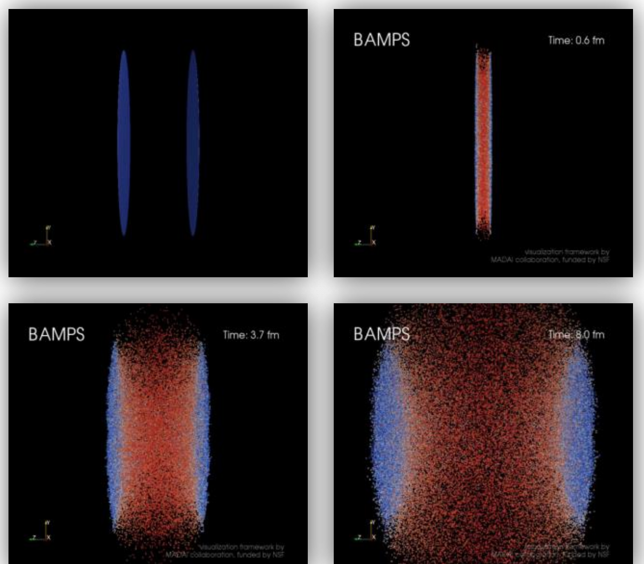


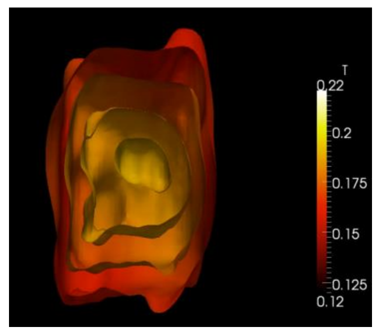
Sketch of heavy ion collision



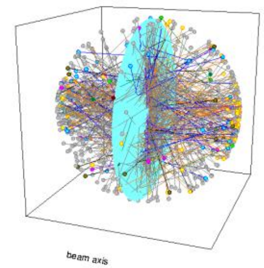
Heavy-ion collisions are complex !

Dynamical bulk description

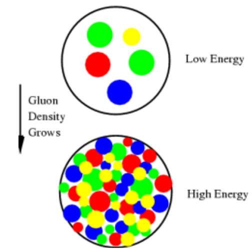




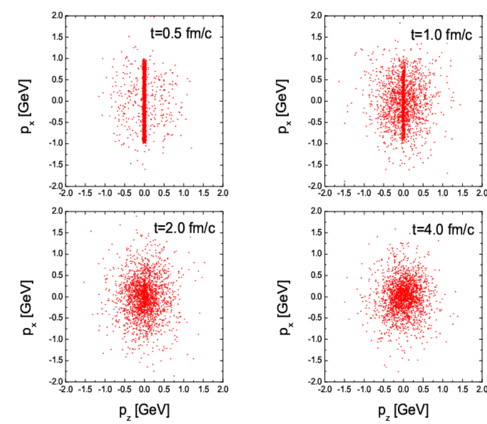
Glauber



Gluon saturation



Early thermalisation



No model can describe all aspects of the QGP evolution

Nuclear modification factor R_{AA}

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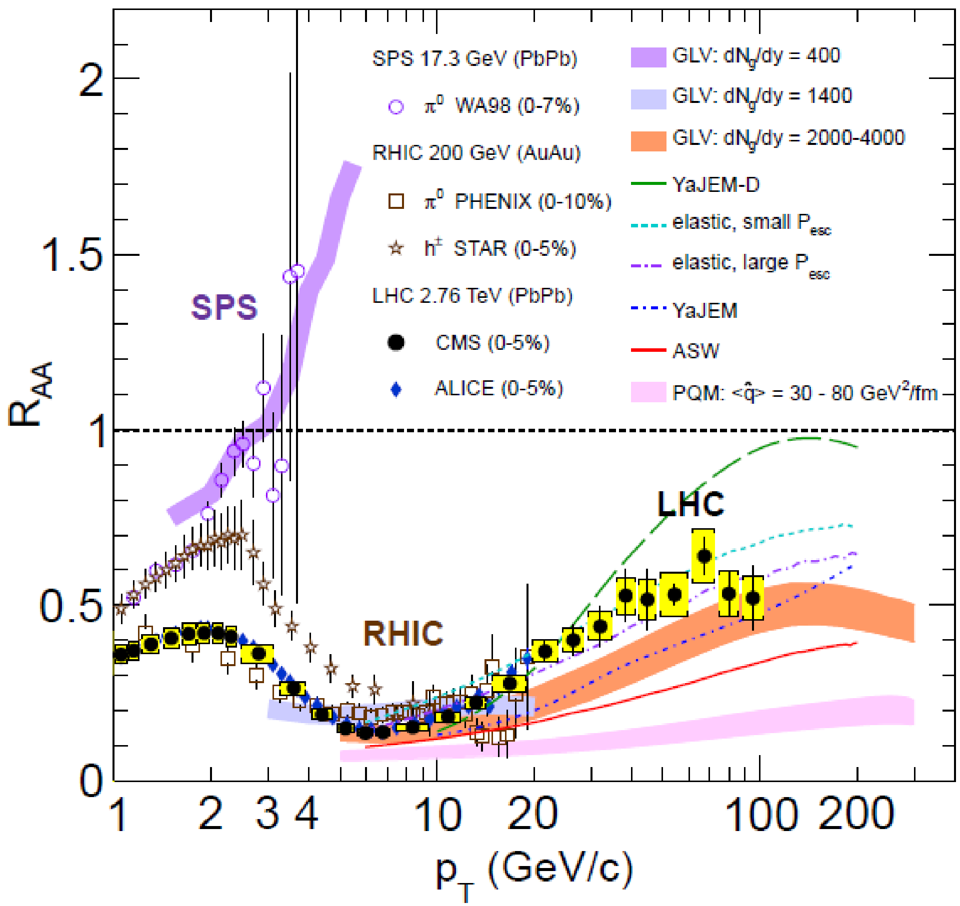
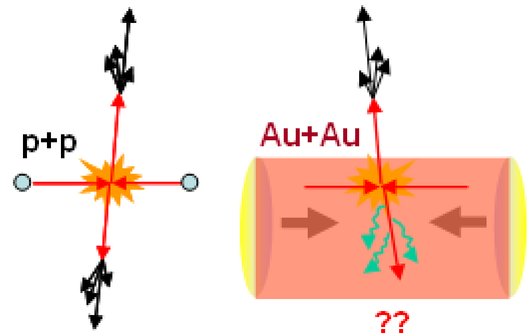
Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T dy|_{A+A}}{N_{\text{bin}}\, dN/dp_T dy|_{p+p}}$$



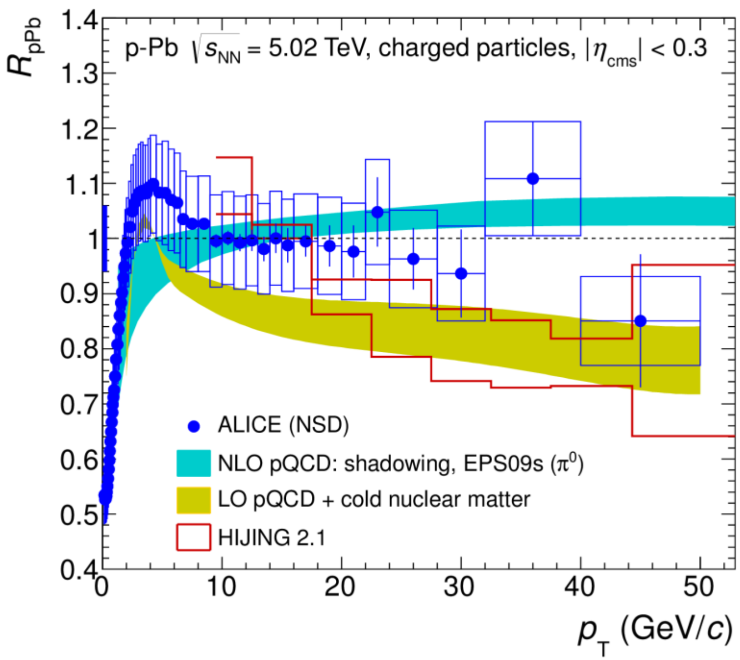


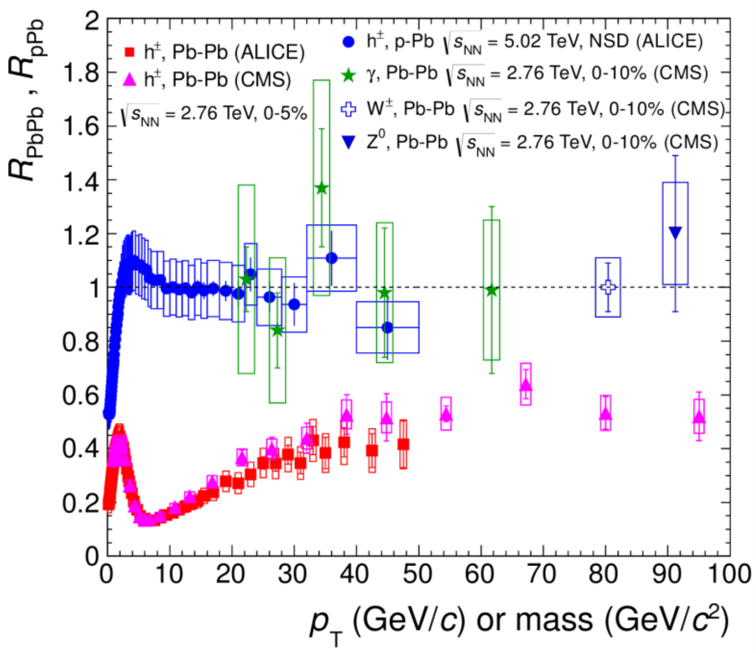
Successfully described by perturbative QCD

CMS, Eur. Phys. J. C72 (2012)

Jet quenching vs "cold" matter / EW observables

ALICE, PRL 110 (2013) 082302





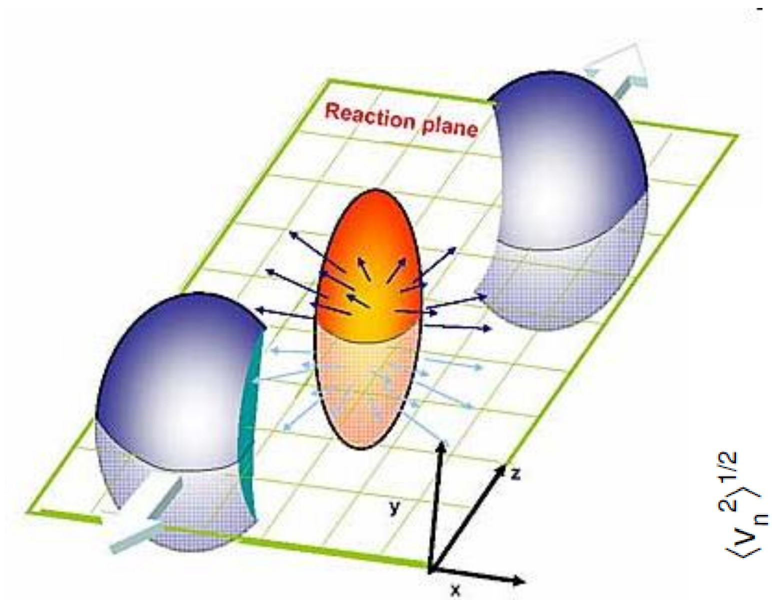
No indication of any departure from unity in p+Pb

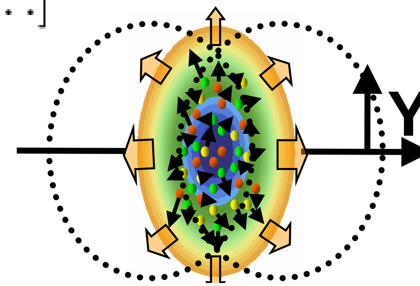
… provide experimental demonstration that suppression =

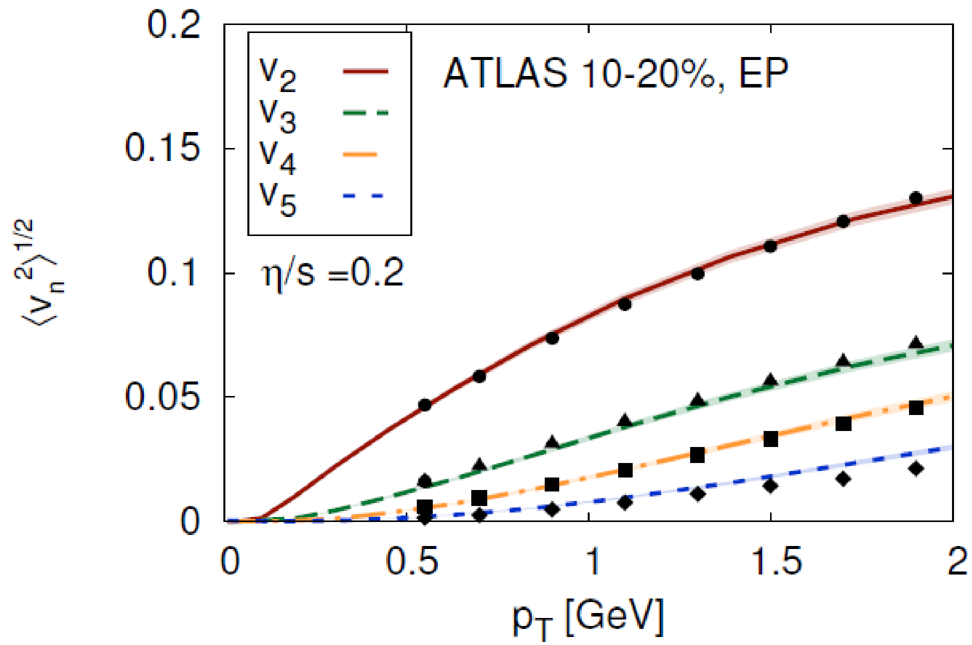
parton energy loss

Elliptic flow v_2

$$\frac{d^3N}{p_T dp_T dy d\phi}(p_T, y, \phi) = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2v_2(p_T, y)\cos(2\phi) + \ldots\right]$$







Successfully described by

(viscous) hydrodynamics

(… but no microscopic information)

Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys. Rev. Lett. 110 (2013)

Relativistic viscous fluid dynamics

- **Basic equations: energy and momentum conservation**

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

energy density (ε), pressure (P), flow velocity (u^μ), viscous correction ($\Pi^{\mu\nu}$)

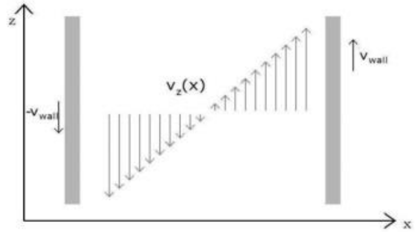
- **Constituent equations for $\Pi^{\mu\nu}$**

$$\Delta^\mu_\alpha \Delta^\nu_\beta (u\cdot\partial)\Pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\Pi^{\mu\nu} - S^{\mu\nu}) - \frac{4}{3}(\partial\cdot u)\Pi^{\mu\nu}$$

$$\frac{F_z}{A} = -\eta \frac{\partial v_z}{\partial x}$$

with $S^{\mu\nu} = \eta\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}(\partial\cdot u)\right)$

$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ and $\nabla^\nu = \Delta^{\mu\nu}\partial_\nu$



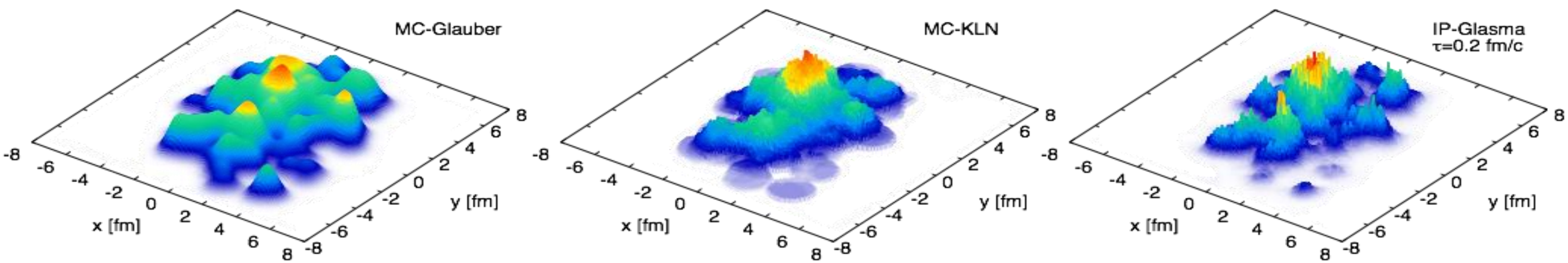
η : shear viscosity

τ_π : relaxation time

- **Equation of state $P(\varepsilon)$ relates thermodynamic pressure to the energy density**

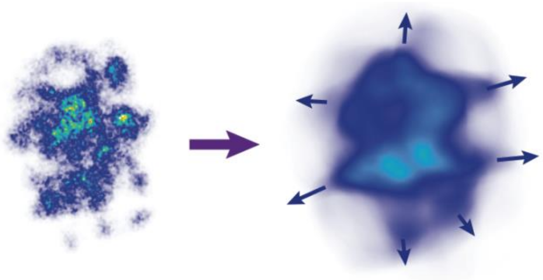
Initial conditions

- Models need to provide input for fluid dynamic simulations: initial energy density, flow velocities, shear stress tensor
- Initial conditions fluctuate from event to event
- Main source of fluctuations: nucleon positions
- Different models give different *energy density distributions*



C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

Anisotropic flow



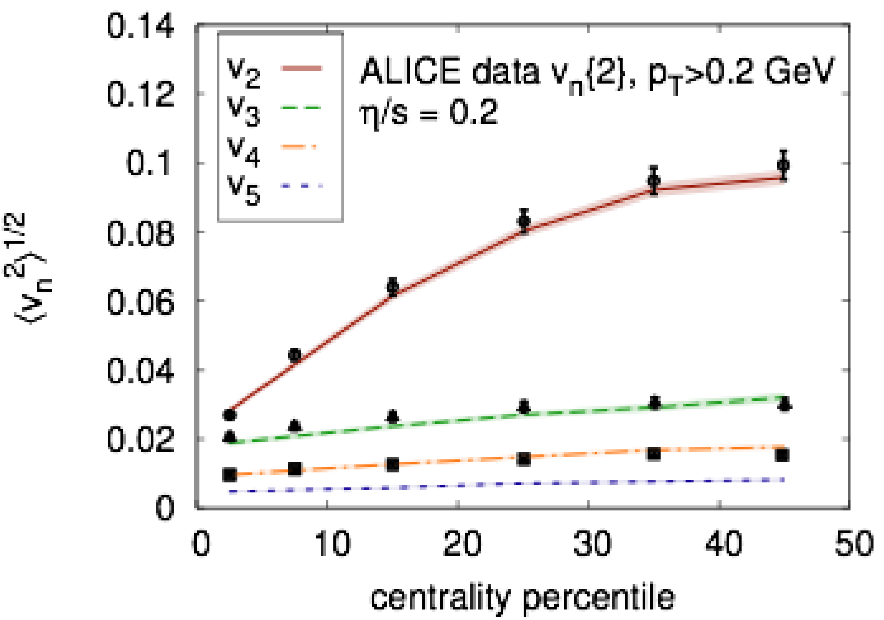
- System expands
- Initial shape is converted into particle momentum distribution
- Quantify its azimuthal anisotropy via Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n (2v_n \cos(n\phi))\right)$$

- Compare IP-Glasma+MUSIC simulation with ALICE data
- Extracted shear viscosity to entropy density ratio:

$$\eta/s = 0.2$$

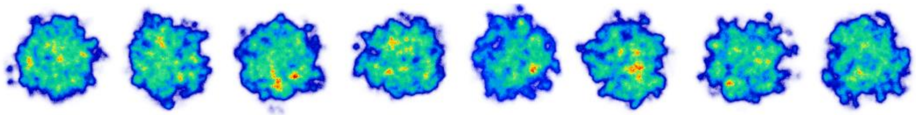
➢ Almost perfect fluidity!



Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys.Rev.Lett.110 (2013) 012302

Event-by-event fluctuations

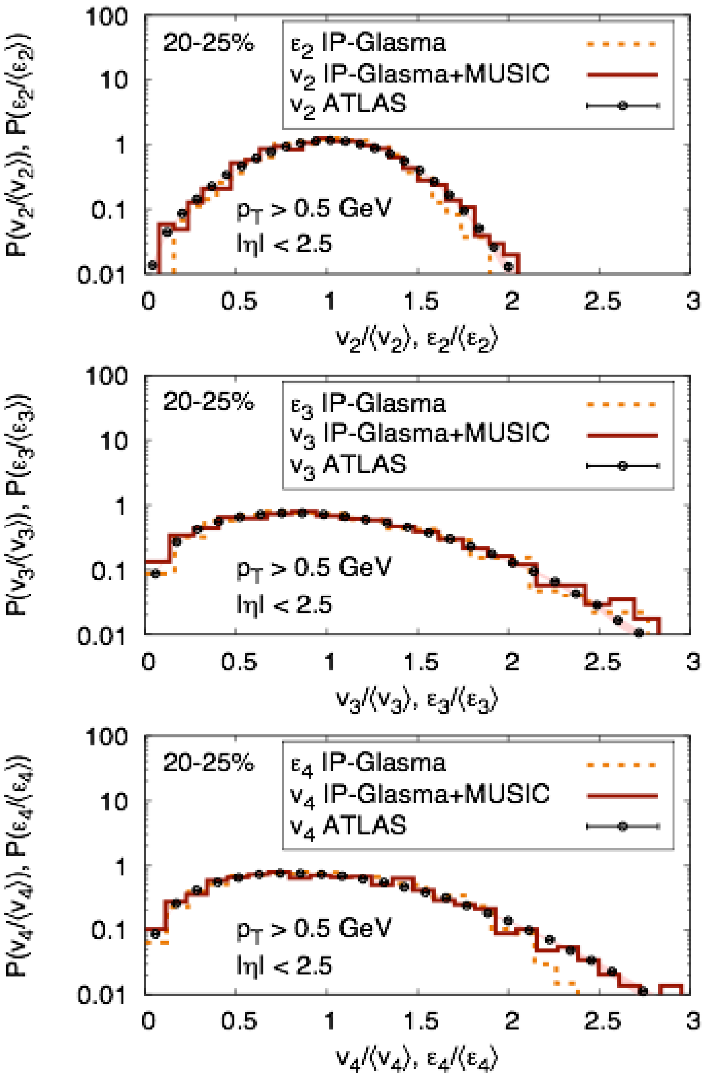
- Each event produces different v_n



- Event-by-event distributions of v_n are also well reproduced by the simulations

- Fluid dynamics correctly describes the bulk dynamics of heavy-ion collisions

$$\eta/s = 0.2$$



Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys.Rev.Lett.110 (2013) 012302

Identified hadrons π, K, p: Elliptic flow / p_t – spectra

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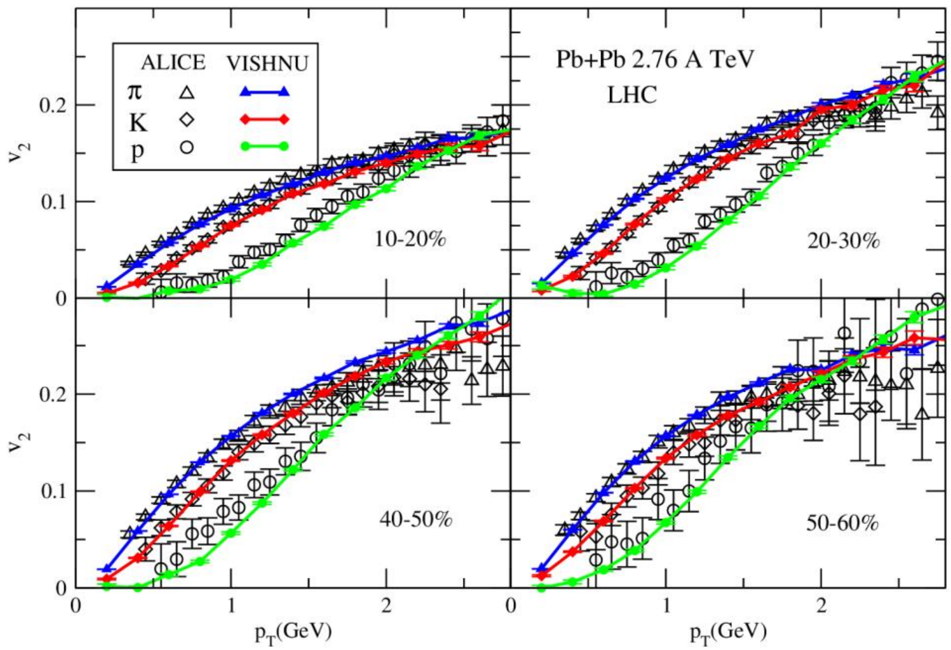
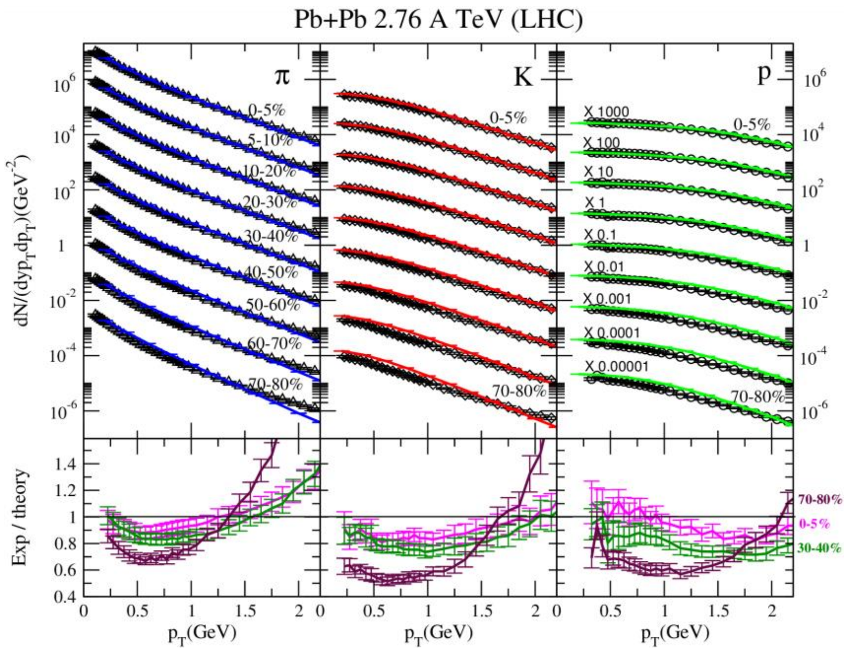
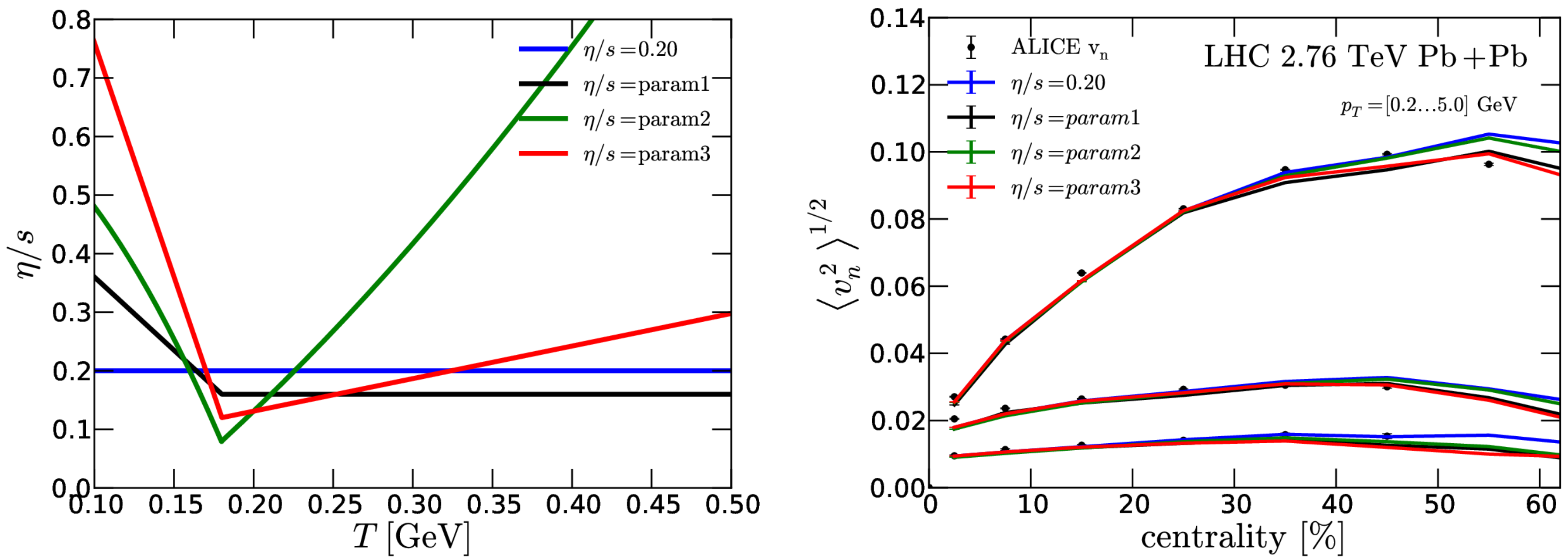




H. Song, S. Bass and U. Heinz, Phys. Rev. C 89, 0349119 (2014)

(2+1)-D viscous hydro + UrQMD (VISHNU), $(\frac{\eta}{s})_{QGP} = 0.16$

$\eta/s(T)$ from LHC v_ns



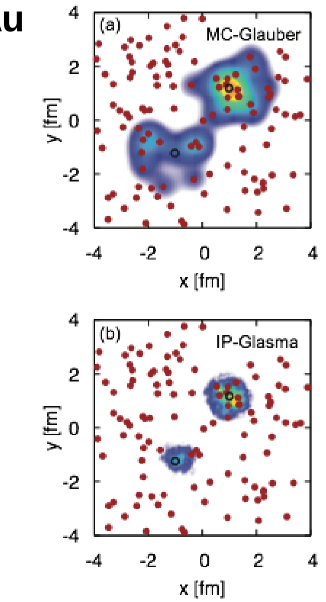
Paatelainen, Eskola, Niemi and Tuominen, Phys. Lett. B 731, 126 (2014)

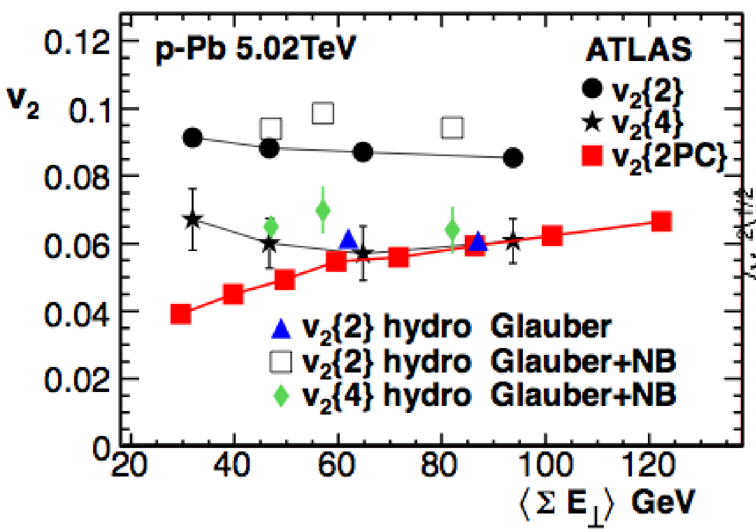
… temperature dependence of the shear viscosity / entropy density ?

Evidence for fluid behavior in p+A collisions?

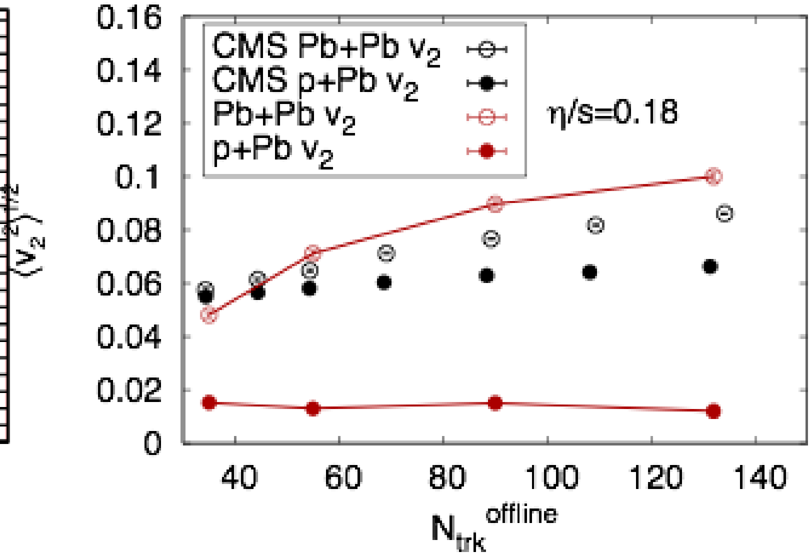
- Experiments find similar v_n in p+A as in A+A collisions CMS Collaboration, Phys.Lett. B724, 213 (2013)
- Can fluid dynamics work in such small systems? Viscous corrections become very large
- Initial state strongly depends on model
- Some models work, some do not. **Not yet settled…**

d+Au





Bozek, Broniowski, Phys.Rev. C88 (2013) 014903



Schenke, Venugopalan,arXiv:1405.3605 (2014)

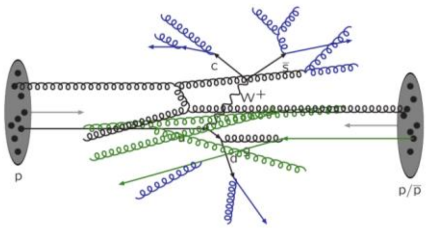
Transport dynamics via Boltzmann equation

BAMPS: Boltzmann Approach to Multi-Parton Scatterings

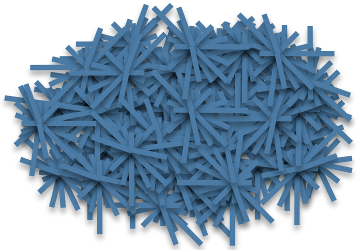
- **3+1 dimensional, fully dynamic parton transport model**
- **Boltzmann equations for on-shell partons with pQCD interactions**

$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}_i}{E_i}\frac{\partial}{\partial \mathbf{r}}\right) f_i(\mathbf{r},\mathbf{p}_i,t) = \mathcal{C}_i^{2\to 2} + \mathcal{C}_i^{2\leftrightarrow 3} + \ldots$$

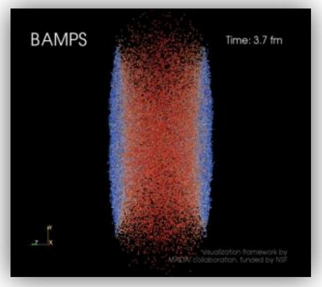
Z. Xu & CG,
Phys. Rev. C71 (2005)
Phys. Rev. C76 (2007)



PYTHIA-Glauber

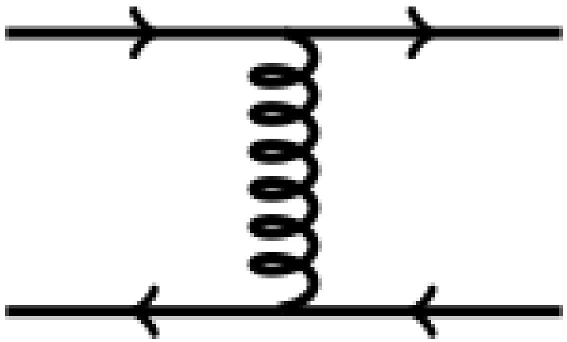


$$AA = pp \times N_{\text{binary}}$$



noneq. QGP

Elastic collisions



- **Leading-order pQCD cross sections**

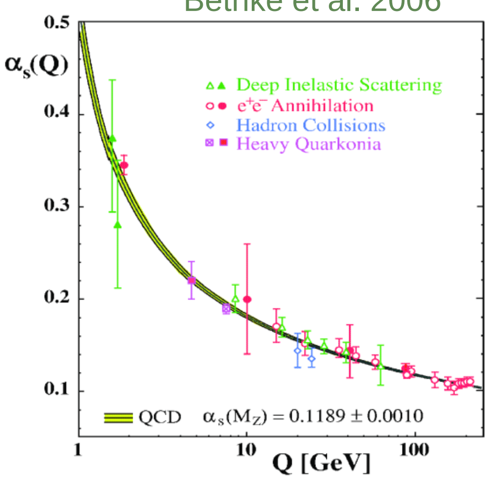
$$\left|\overline{\mathcal{M}}_{qq'\to qq'}\right|^2 = \frac{64\pi^2}{9}\alpha_s^2(t)\frac{u^2+s^2}{[t-m_D^2(\alpha_s(t))]^2}$$

- **Divergences screened by Debye mass**

- **Running coupling**

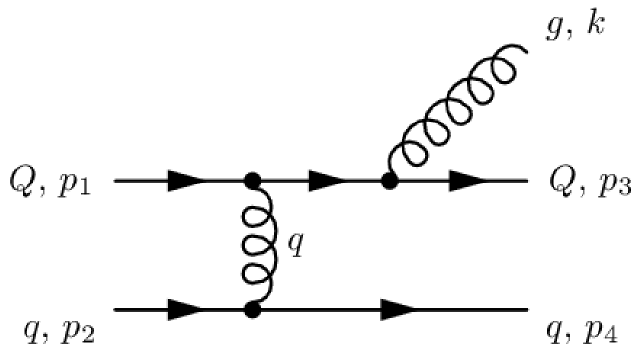
$g\,g \to g\,g$		
$g\,g \to q\,\bar{q}$		
$q\,\bar{q} \to g\,g$	and	$q\,\bar{q} \to q'\,\bar{q}'$
$q\,g \to q\,g$	and	$\bar{q}\,g \to \bar{q}\,g$
$q\,\bar{q} \to q\,\bar{q}$		
$q\,q \to q\,q$	and	$\bar{q}\,\bar{q} \to \bar{q}\,\bar{q}$
$q\,q' \to q\,q'$	and	$q\,\bar{q}' \to q\,\bar{q}'$

Bethke et al. 2006



Inelastic collisions

$$\begin{array}{lll} g\,g \leftrightarrow g\,g\,g & & \\ q\,g \leftrightarrow q\,g\,g & \text{and} & \bar{q}\,g \leftrightarrow \bar{q}\,g\,g \\ q\,\bar{q} \leftrightarrow q\,\bar{q}\,g & & \\ q\,q \leftrightarrow q\,q\,g & \text{and} & \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g \\ q\,q' \leftrightarrow q\,q'\,g & \text{and} & q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g \end{array}$$



Improved Gunion-Bertsch matrix element:

$$\left|\overline{\mathcal{M}}_{X\to Y+g}\right|^2 = \left|\overline{\mathcal{M}}_{X\to Y}\right|^2\, P_g$$

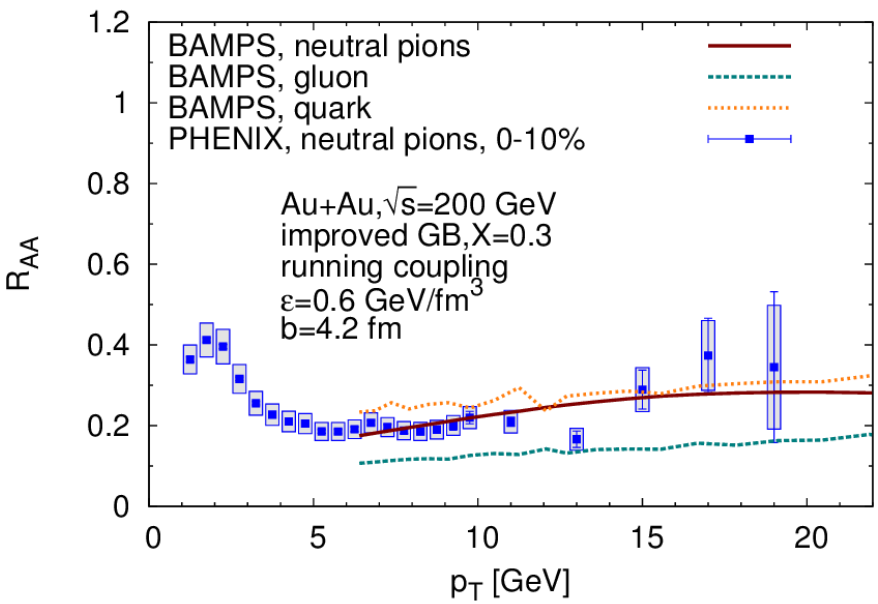
$$P_g = 48\pi\alpha_s(k_\perp^2)\,(1-\bar{x})^2 \times \left[\frac{\mathbf{k}_\perp}{k_\perp^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2\,(\alpha_s(k_\perp^2))}\right]^2$$

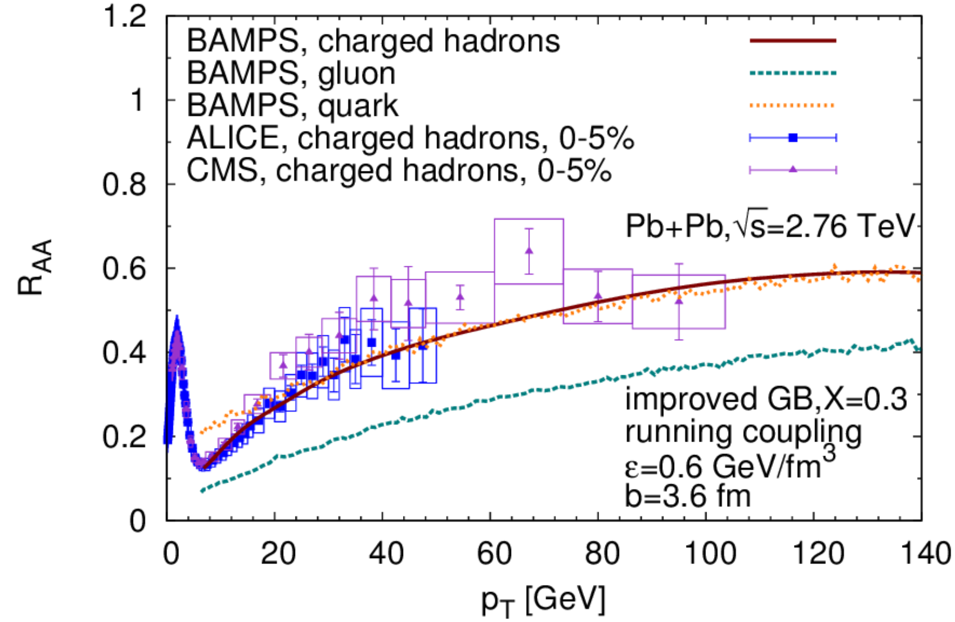
Effective QCD LPM effect:

Mean free path $\lambda > X\,\tau$ **Gluon formation time**

**Fochler, Uphoff, Xu, CG
Phys. Rev. D88 (2013)**

Nuclear modification factor R_{AA}

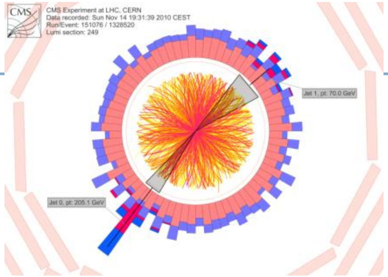


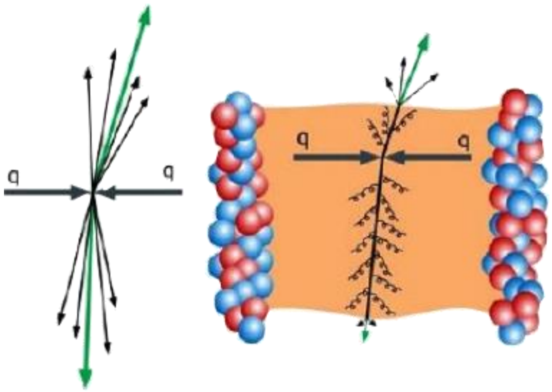


Uphoff et al, arXiv:1401.1364

- Hadronization of high p_t partons with AKK fragmentation functions
- LPM parameter fixed by comparison to RHIC data
- Realistic suppression both for RHIC and LHC

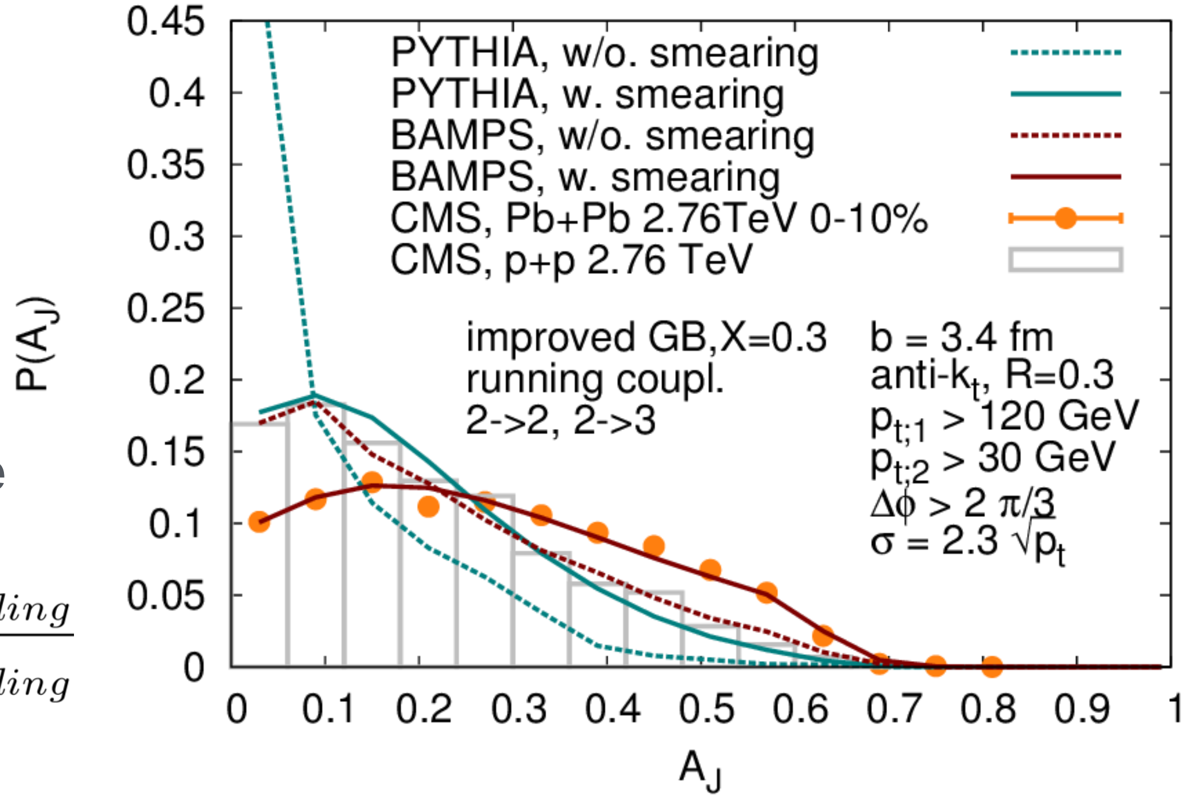
Reconstructed jets





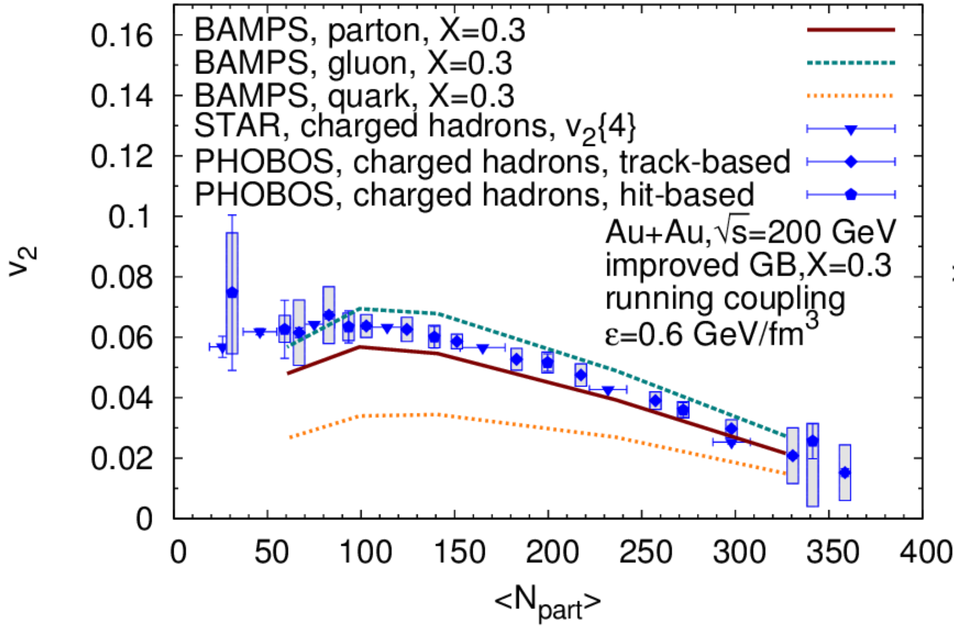
Momentum imbalance

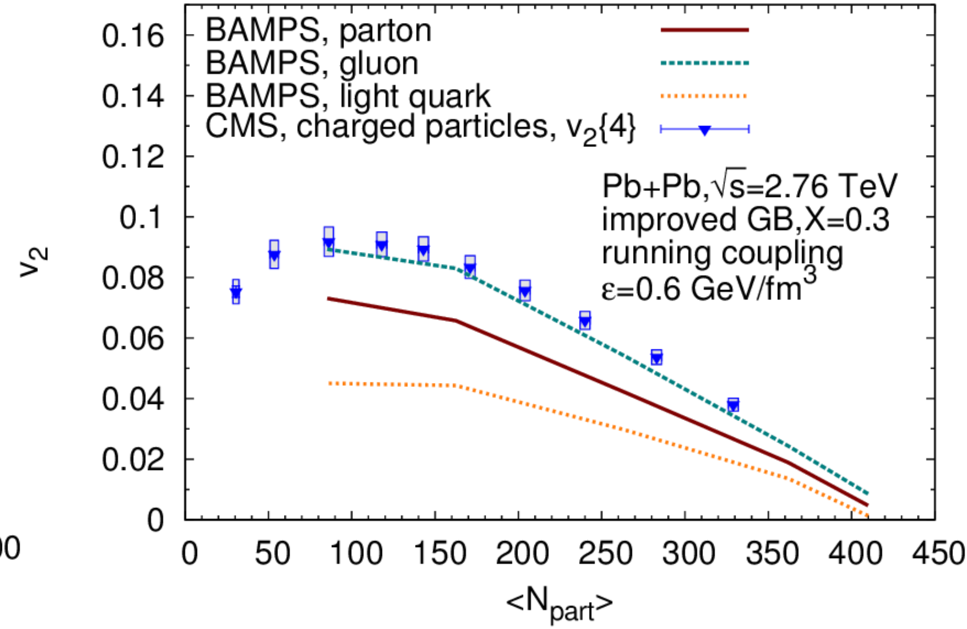
$$A_J = \frac{p_{t;leading} - p_{t;subleading}}{p_{t;leading} + p_{t;subleading}}$$



Senzel et al, arXiv:1309.1657

Elliptic flow v_2

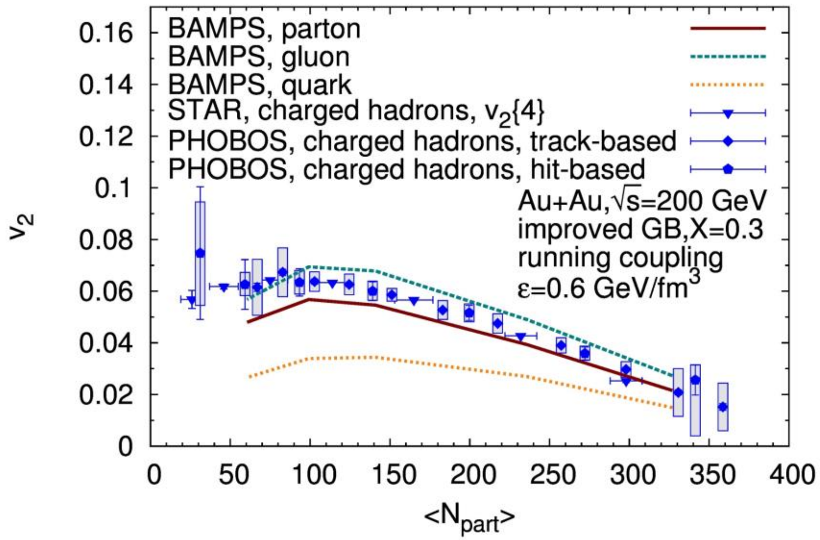




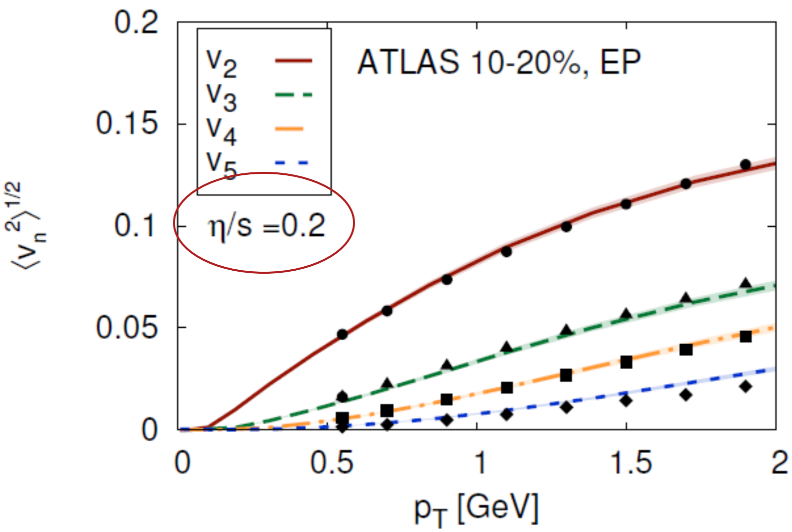
Uphoff et al, arXiv:1401.1364

- Same pQCD interactions lead to a sizeable elliptic flow for bulk medium
- No hadronization for bulk medium $\longrightarrow$ no hadronic after-burner

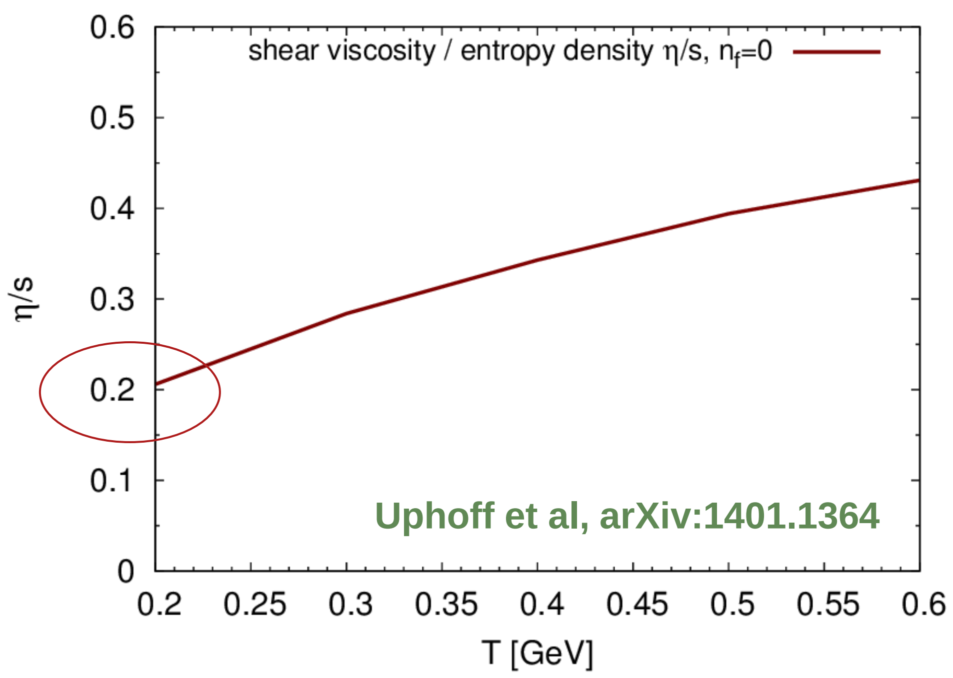
Shear viscosity as QGP transport parameter



Reason for large elliptic flow:
Small shear viscosity to entropy density ratio



From parameters to calculations:



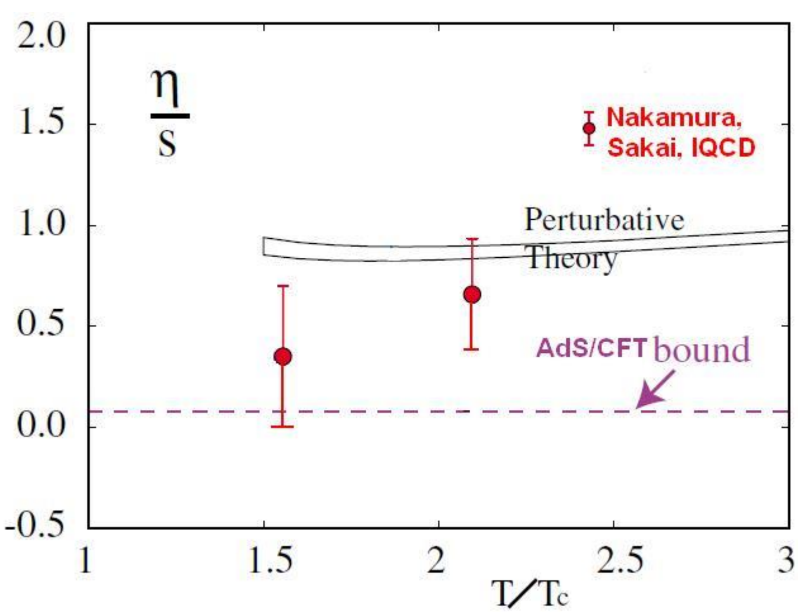
Microscopic transport theory
…gives QGP transport coefficients

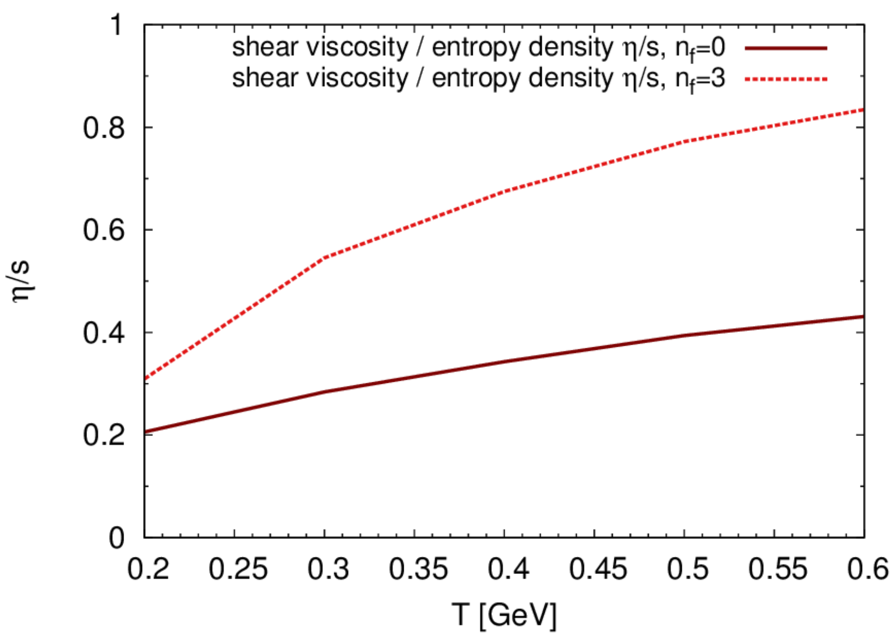
-Shear viscosity η
- bulk viscosity ζ
- heat conductivity κ
- electric conductivity σ

Other coefficients of interest:
Heavy quark diffusion constants, susceptibilites,…

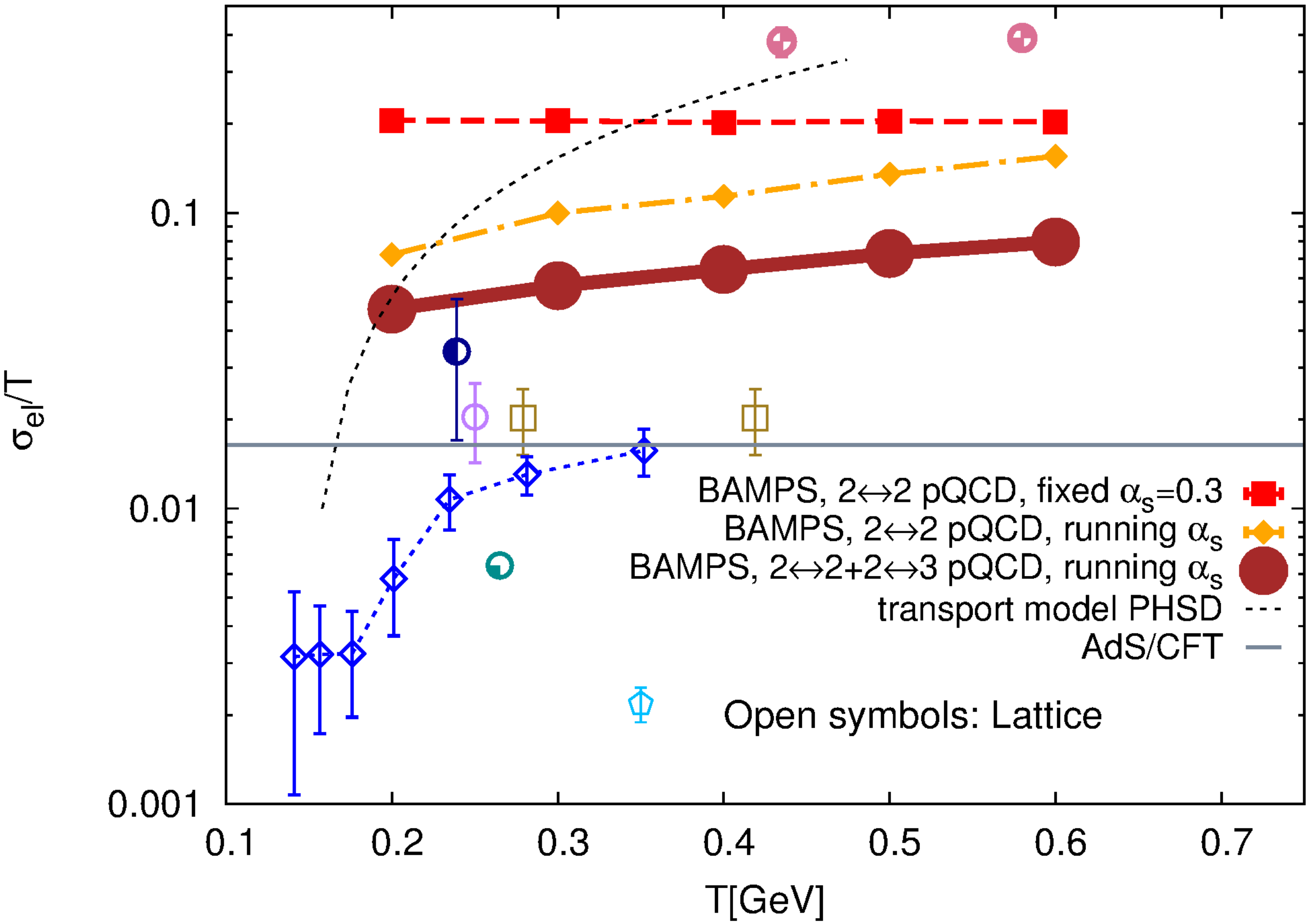
Green-Kubo relation:

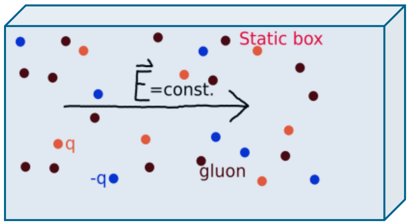
$$\eta = \frac{1}{10T}\int_0^\infty dt \int_V d^3r \left\langle \pi^{ij}(r,t)\pi^{ij}(0,0)\right\rangle$$





… electric conductivity





$$j = \sigma_{\rm el} E$$

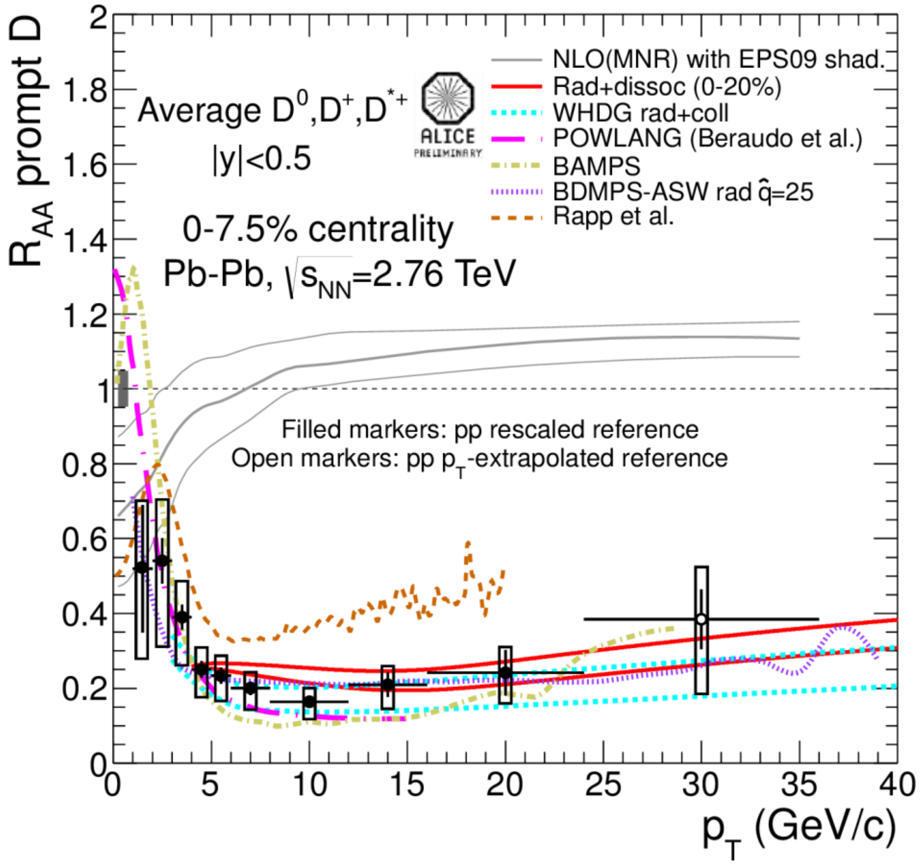
Green-Kubo relation:

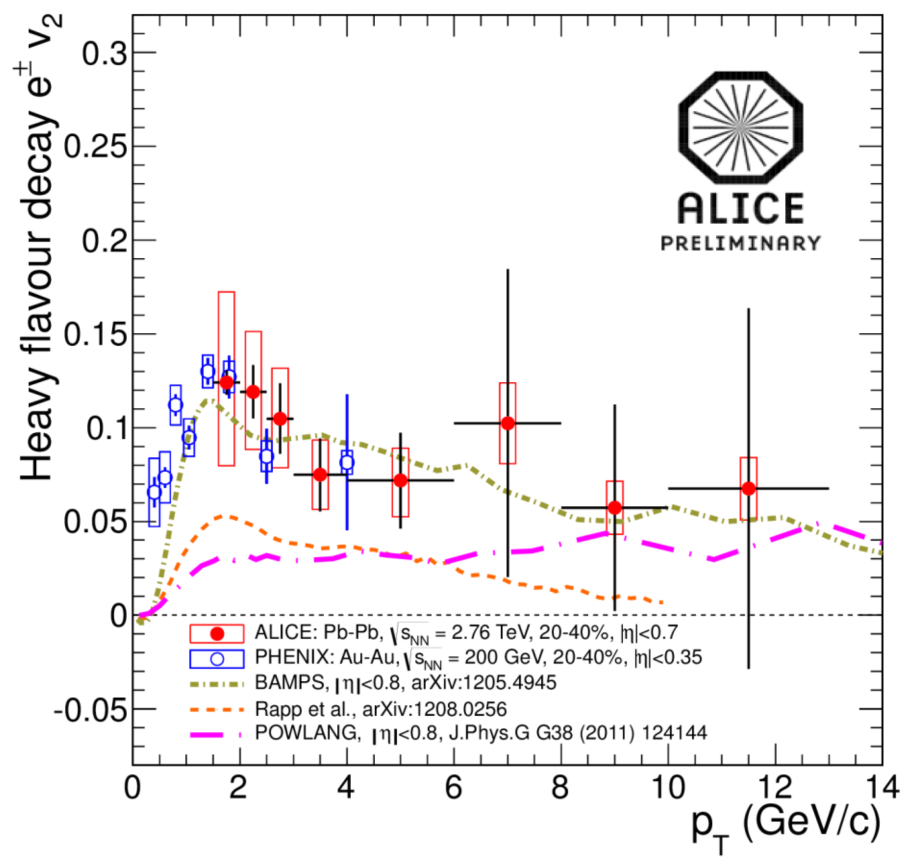
$$\sigma_{\rm el} = \frac{V}{T} \int_0^\infty \langle j_x(0) j_x(t) \rangle \, dt$$

Lattice theory versus transport theory

… and learn about the (strongly) interacting QGP

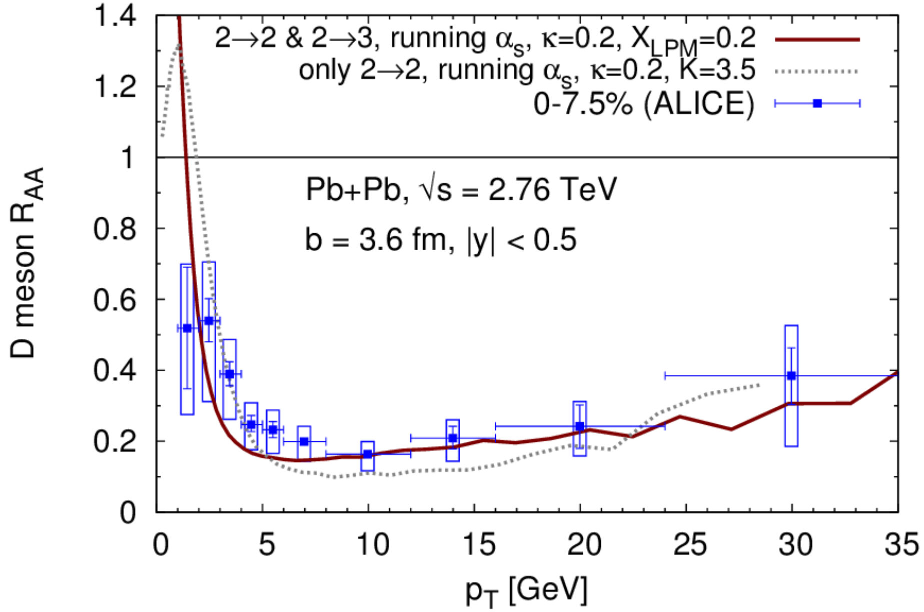
Heavy flavor R_{AA} and v_2 at LHC

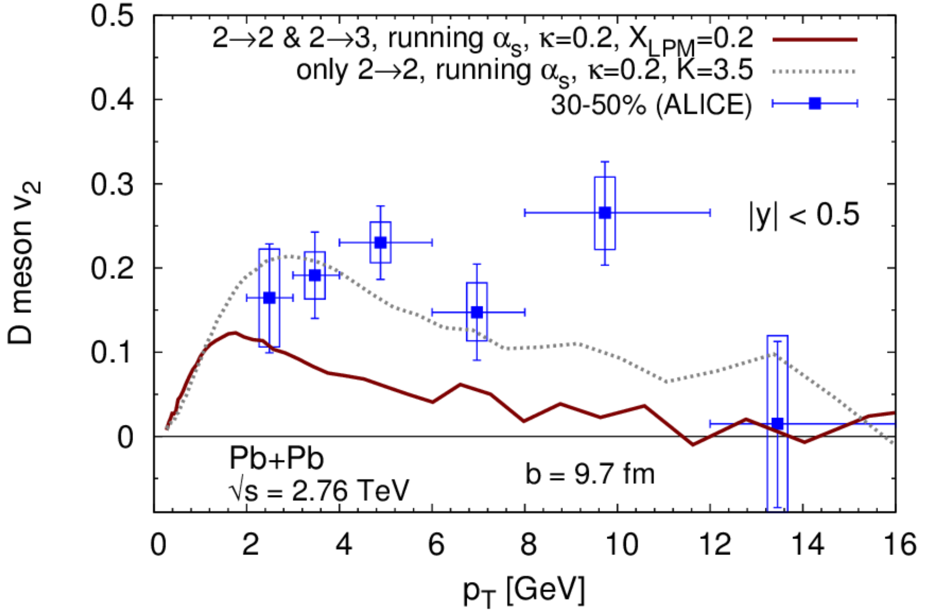




D meson R_{AA} and v_2 at LHC

ALICE data, QM12





Uphoff, Fochler, Xu, CG, Phys. Lett. B 717 (2012),
Uphoff, Fochler, Xu, CG, arXiv: 1408.2964

Heavy flavor R_{AA} and v_2 simultaneously seems difficult

Conclusions & Outlook

- Heavy-ion collisions provide an unique opportunity for investigating QCD matter under extreme conditions
- Strong collective behavior of the QGP is successfully described by fluid or transport dynamics
- Both at RHIC and the LHC, hard probes (high p_t and heavy flavor) are quenched while traversing the QGP
- Transport coefficients allow a connection between dynamical models and lattice QCD
- What can we learn for heavy-ion collisions from smaller systems (p+p, p+A, …)?

Thank you for your attention.

Heavy quark energy loss mechanism

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Perturbative QCD

- Djordjevic, Gyulassy
- Buzatti, Gyulassy
- Sharma, Vitev
- Armesto, Cacciari, Dainese, Salgado, Wiedemann
- Nahrgang, Gossiaux, Aichelin
- Cao, Bass
- Mazumder, Bhattacharyya, Alam, Das
- **JU, Fochler, Xu, Greiner**
- …

Elastic scatterings + **Radiative processes**

Elastic scatterings:

- Moore, Teaney
- Gossiaux, Aichelin
- Alberico, Beraudo, et al.
- **JU, Fochler, Xu, Greiner**
- Meistrenko, JU, Greiner, Peshier
- Young, Schenke, Gale
- …

Radiative processes:

- Abir, Jamil, Mustafa, Srivastava
- …

Resonance scattering

- v.Hees, Greco, Rapp
- He, Fries, Rapp
- Lang, v.Hees, Bleicher
- …

AdS/CFT

- Horowitz, Gyulassy
- Chesler, Lekaveckas, Rajagopal
- …

Heavy flavor and charged hadron R_{AA} at LHC

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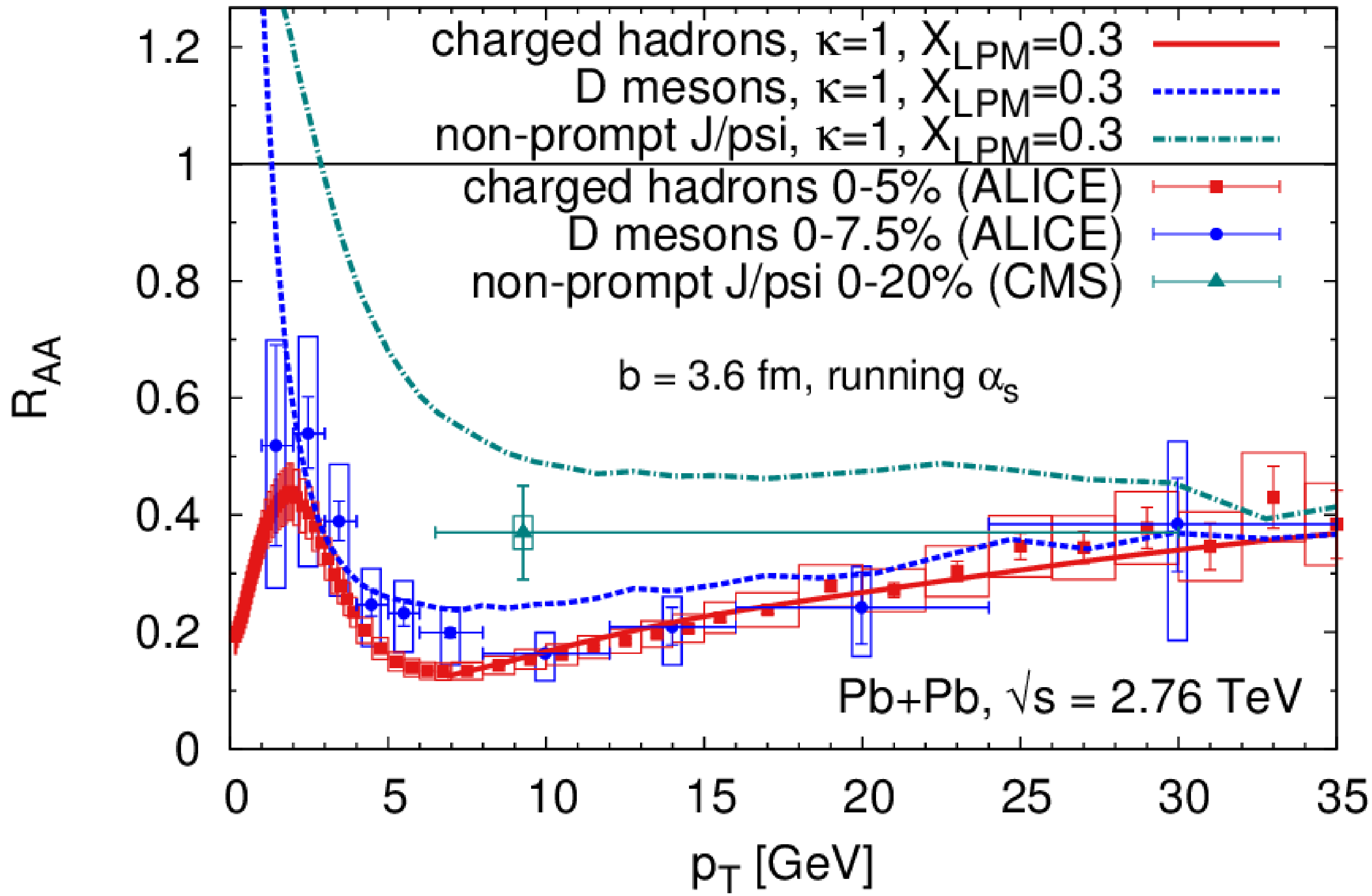

Initial heavy flavor spectrum

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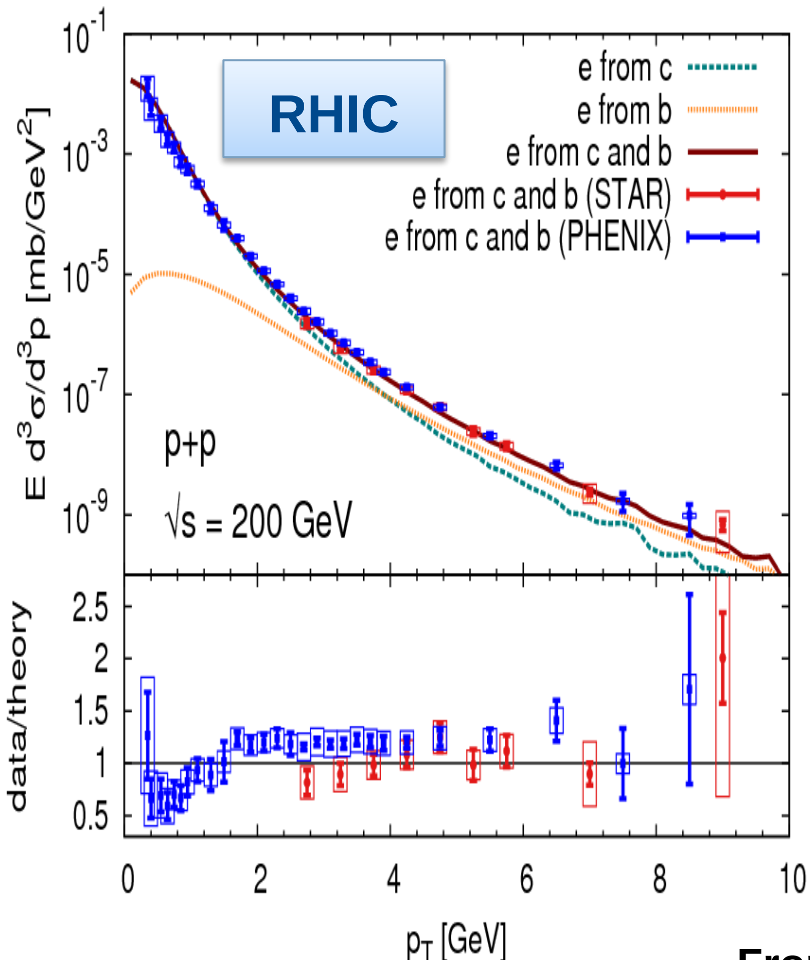
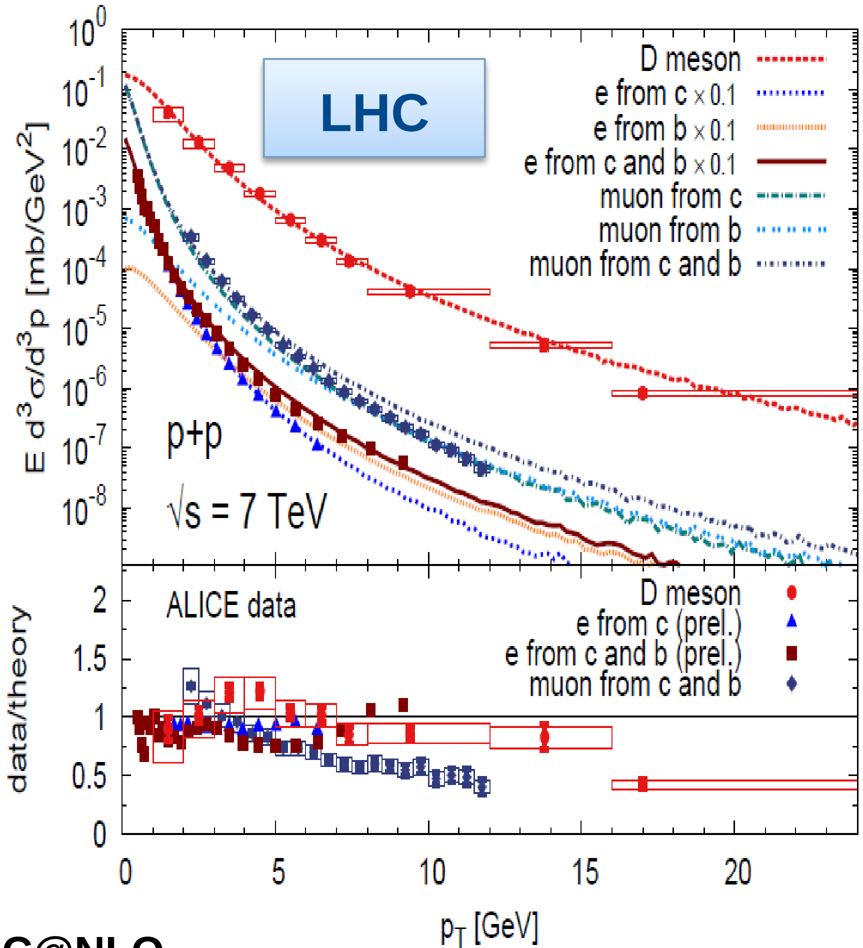




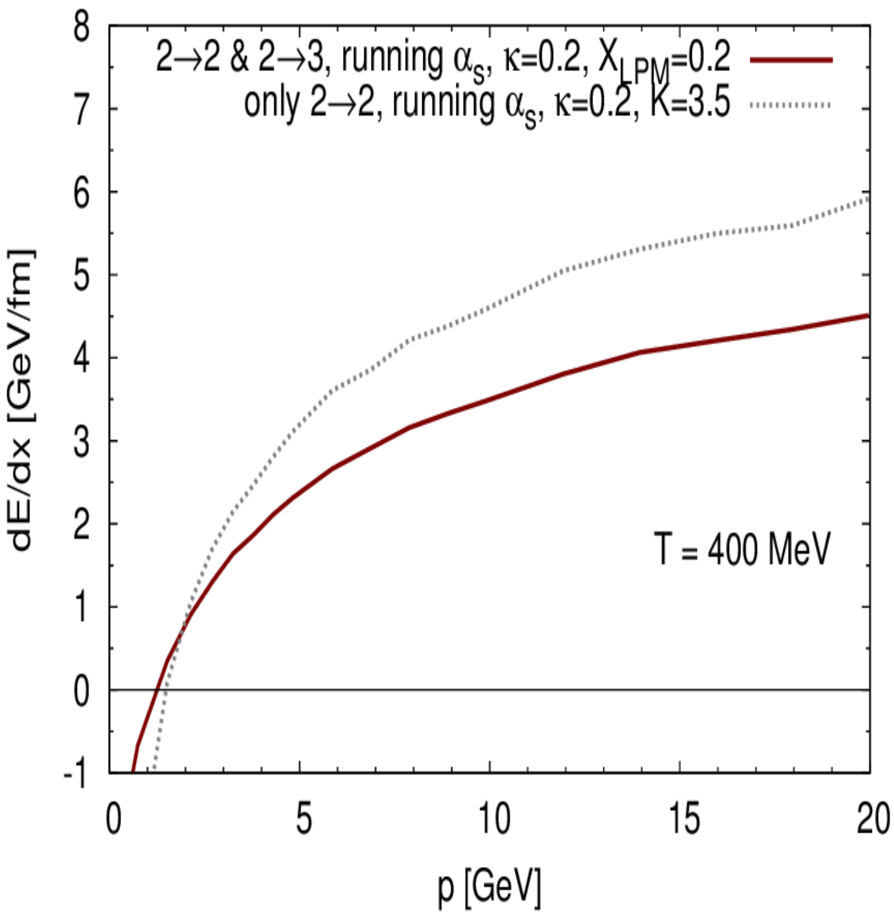
From MC@NLO

JU, Fochler, Xu, Greiner
Phys. Rev. C84 (2011)

JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

Energy loss and transport cross section

Energy loss
in static medium



Transport cross section
in static medium