Quark Matter 2011

An Evening with MUSIC

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Elliptic and Triangular Flows in 3+1D Viscous Hydrodynamics with Fluctuating Initial Conditions

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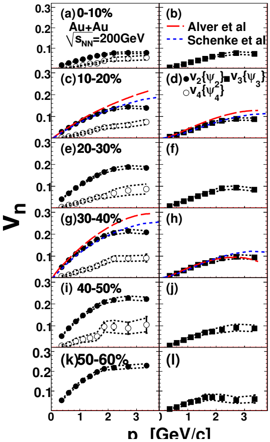
McGill

MUSIC Team

- C. Gale
- S. Jeon
- B. Schenke
- C. Young

Plan

To get here: Phenix (arXiv:1105.3928) ALICE (arXiv:1105.3865)



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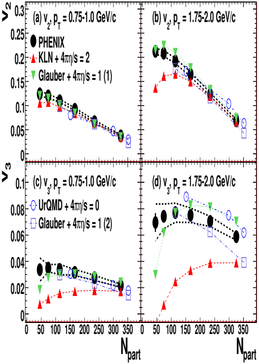

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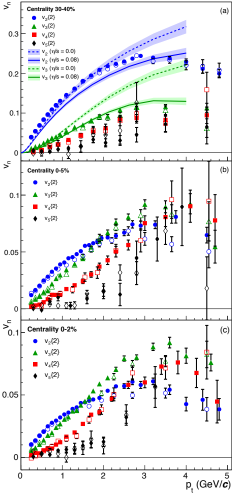
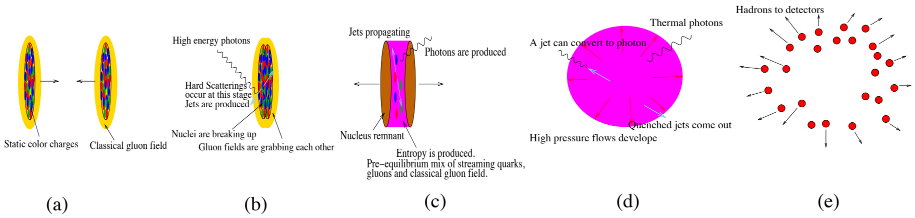


ALICE

Stages of Heavy Ion Collisions



(a) Before collision

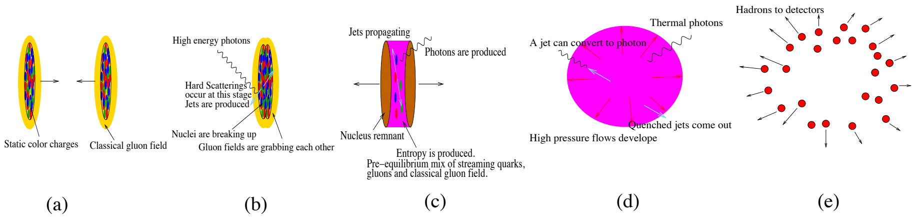
(b) Initial state - Mostly gluon field dynamics

(c) Pre-equilibrium stage - QGP forming. Jets created. Freeze-out

(d) Hydrodynamics - From $\sim 0.5\,\mathrm{fm}/c$ at RHIC. Jets propagating.

(e) Hadronic stage - Hydro/Cascade $\rightarrow$ Freeze-out.

Stages of Heavy Ion Collisions



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MUSIC

MUScl for Ion Collisions

MUSCL: Monotone Upstream-centered Schemes for Conservation Laws

MUSIC

- 3+1D parallel implementation of Kurganov-Tadmor Scheme [Jour. of Comp. Phys. **160**, 241 (2000)] with an additional baryon current
- Ideal *and* Viscous Hydro
- Sophisticated Freeze-out surface construction
- Full resonance decay (3+1D version of Kolbe and Heinz)
- Many different equation of states including the newest from Huovinen and Petreczky
- *Event-by-Event!*

Kurganov-Tadmor

- Finite volume method for conservation laws
- No need for a Riemann solver
- Method of lines (i.e. a bunch of coupled O.D.E.'s) possible
- Small $O(|\Delta \mathbf{x}|^3)$ numerical viscosity
- In a flat space, strictly conserves energy, momentum and charges
- Deals with discontinuities very well

Hydrodynamics

- Conservation laws

$$\partial_\mu \langle T^{\mu\nu} \rangle = 0$$

- $T^{\mu\nu}$ has 10 d.o.f. Cons. laws provide 4 constraints $\Longrightarrow$ No dynamical content.
- Energy density and flow vector

$$T^{\mu\nu} u_\nu = -\varepsilon u^\mu$$

- u^μ: Time-like eigenvector of $T^{\mu\nu}$. Normalized to $u^\mu u_\mu = -1$.
- ε: Local energy density
- This is always possible since $T^{\mu\nu}$ is real and symmetric.

Hydrodynamics

- So far:

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu + H^{\mu\nu}$$

  with

$$H^{\mu\nu} u_\nu = 0$$

- This is just math. No physics input except that u^μ is time-like and $\varepsilon \geq 0$.
- Physics - Small scale physics is thermal $\Longrightarrow$ Local equilibrium
  - $H^{\mu\nu} = (g^{\mu\nu} + u^\mu u^\nu)P(\varepsilon) + \pi^{\mu\nu}[\varepsilon, u]$ with $\pi^{\mu\nu} u_\nu = 0$
  - Ideal Hydro: $\pi^{\mu\nu} = 0$
  - Viscous Hydro:

$$\pi^{ij} = -\frac{\eta}{2}\left(\partial^i u^j + \partial^j u^i - g^{ij}(2/3)\nabla\cdot\mathbf{u}\right) - \zeta g^{ij}\nabla\cdot\mathbf{u}$$

Solving Ideal Hydro from t to $t + \Delta t$

- Solve $\partial_0 T^{0\nu} = -\partial_i T^{i\nu}$ for $T^{0\nu}(t + \Delta t)$
- From $T^{0\nu}$, reconstruct ε and u^μ at $t + \Delta t$ and $P = P(\varepsilon)$.
- Reconstruct

$$T^{i\nu}(t + \Delta t) = \varepsilon u^i u^\nu + (g^{i\nu} + u^i u^\nu)P$$

Viscous MUSIC

- Right now shear viscosity only.
- Viscosity effect implemented following H. Song's thesis (0908.3656)

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}D\pi_{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\mu\rangle} + \frac{4}{3}\tau_\pi\pi^{\mu\nu}(\partial_\alpha u^\alpha)\right)$$

  which comes from Baier, Romatschke, Son, Starinets, Stephanov (0712.2451) by setting other transport coefficients to zero.
- Transverality is preserved by the evolution.

Physics from Hydro – What are we trying to learn?

- What is the nature of the initial condition?
- Do we reach local equilibrium in heavy ion collisions?
- How hot is it?
- How viscous is QGP?
- (Is there a phase transition? If so what kind?)

Physics from Hydrodynamics

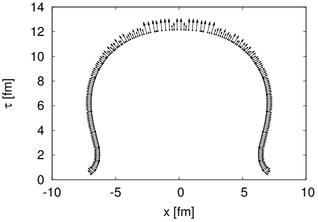
- Basic hydro observable: Single particle spectrum
- **Cooper-Frye**

$$\frac{dN_i}{dy\, d^2 p_T} = g_i \int_\Sigma f(u^\mu p_\mu) p^\alpha d\Sigma_\alpha$$

with

$$f(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{e^{(-u^\mu p_\mu - \mu_i)/T} \pm 1}$$

and the freeze-out surface Σ:



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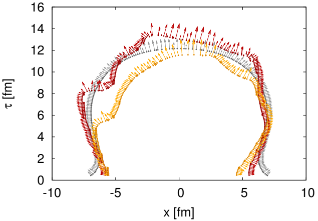

Physics from Hydrodynamics

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$$f(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{e^{(-u^\mu p_\mu - \mu_i)/T} \pm 1}$$

and the freeze-out surface Σ:

Theory goal: Infer *experimental* u^μ, μ_i and T by *theoretical* calculation of single particle spectra

Note: For viscous hydro $\delta f = f_0(1 \pm f_0) p^\alpha p^\beta W_{\alpha\beta} \frac{1}{2(\varepsilon + P) T^2}$

Physics from Hydrodynamics

- Information content of single particle spectra

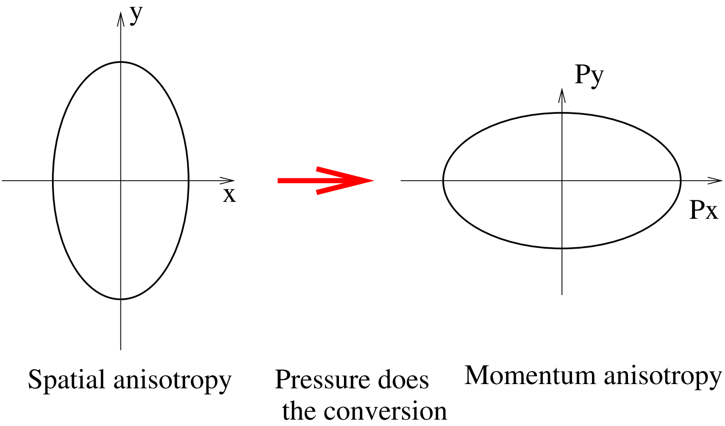
$$\frac{dN_i}{dy\, d^2p_T} = \frac{dN_i}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_{i,n}(p_T, y)\cos(n\phi)\right)$$

- “Flow”: $v_{i,n}(p_T)$
- Came from

$$\varepsilon(\mathbf{x}_T, \eta) = \varepsilon(r_T, \eta)\left(1 + \sum_{n=1}^{\infty} 2\epsilon_n(r_T, \eta)\cos(n\phi)\right)$$

  - *Pressure* converts it into $v_{i,n}(p_T)$
  - History matters

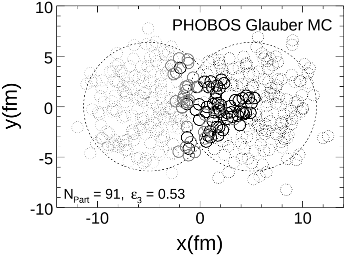
- Elliptic Flow

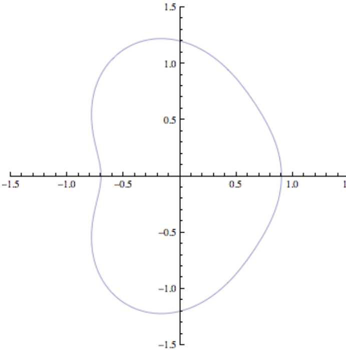


Physics from Hydrodynamics

- Triangular Flow

Alver and Roland, Phys.Rev.C81:054905, 2010





- Triangular Flow

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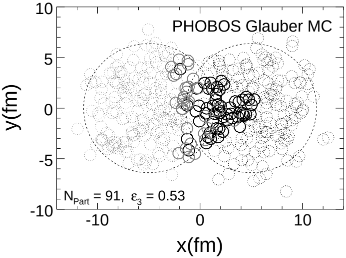
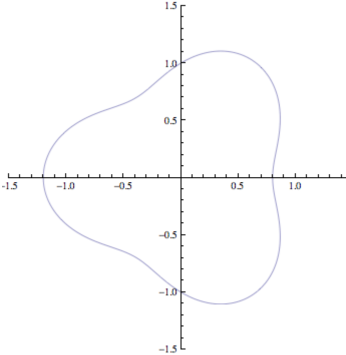




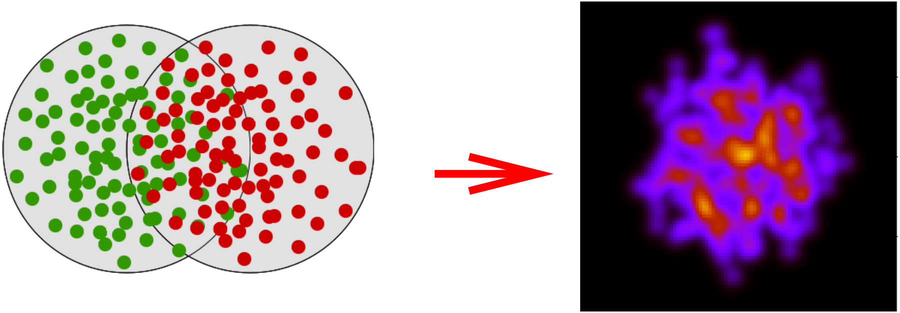
cos(3ϕ) component only

Why both?

- Elliptic flow: Sensitive to the overall almond shape
- Triangular flow: Less so. More local in the sense that average initial condition gives zero v_3.
- Triangular flow: Expect more sensitivity to η/s. Two possible reasons:
  - Viscosity smears out lumps.
  - Viscosity reduces differential flow - Triangle is “rounder” than ellipse
- Goal: Get $dN/p_T dpTdy$, v_1, v_2, v_3 and v_4 right at the same time to constrain η/s better.

Lumpy MUSIC

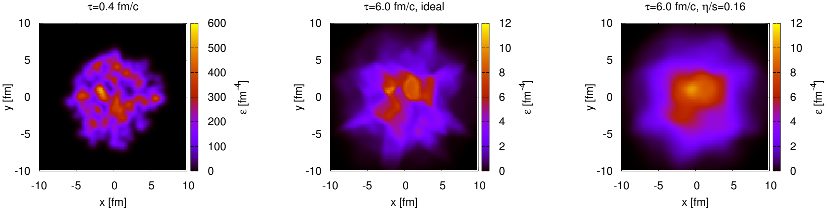
Initial condition is lumpy (Glauber with gaussian energy profile):



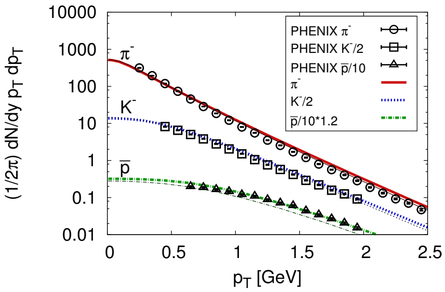
Ideal hydro

E-by-E

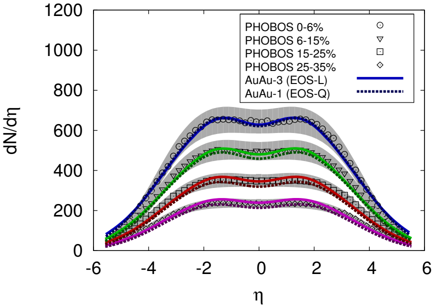
Ideal vs. Viscous



- Hadron spectrum using EoS-Q (Azhydro) and EoS-L (Huovinen Petreczky)

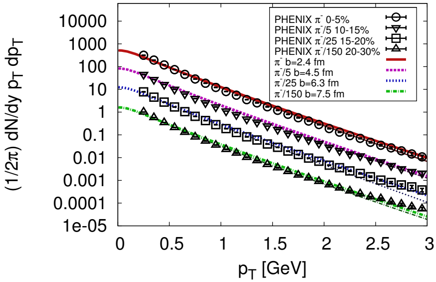


Ideal. p_T spectrum for hadrons.

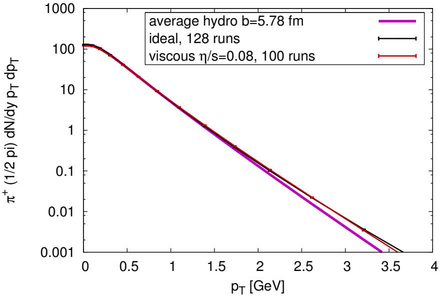


Ideal. $dN/d\eta$ for hadrons

- Pion spectrum using EoS-Q and EoS-L



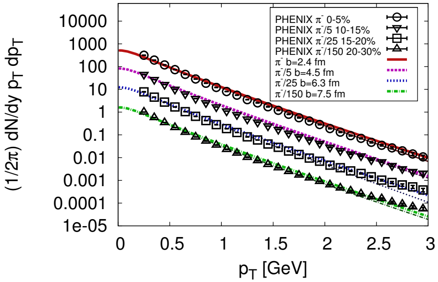
Ideal.
Pion spectrum: Centrality dependence



p_T spectrum comparison

Get particle spectra right

- Pion spectrum using EoS-Q and EoS-L



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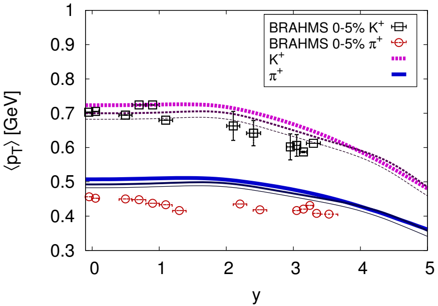
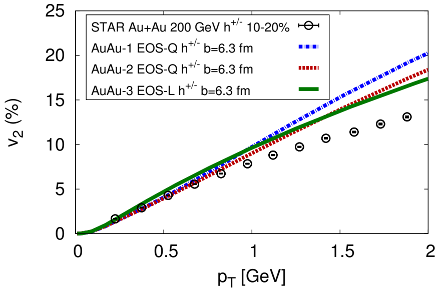


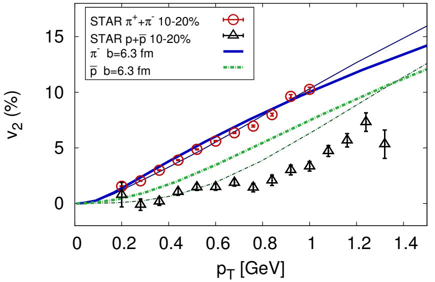
Ideal. Average p_T

Flow in Ideal MUSIC (average initial condition)

- Elliptic flow



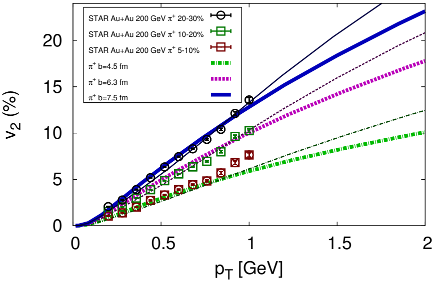
Elliptic flow of hadrons



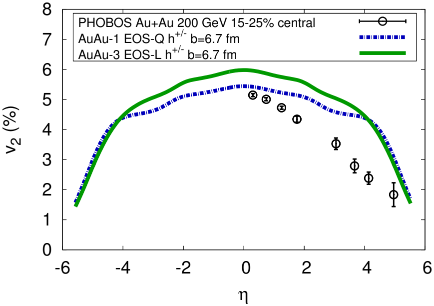
Elliptic flow: Mass dependence

Flow in Ideal MUSIC (average initial condition)

- Elliptic flow



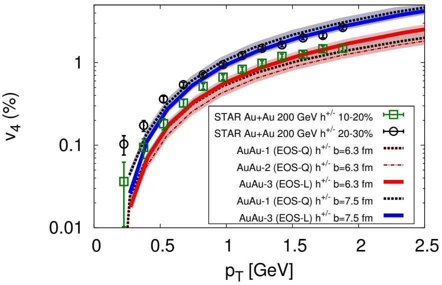
Elliptic flow: Centrality dependence



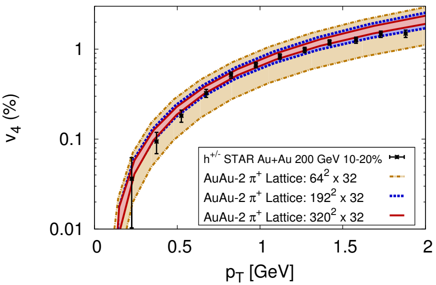
Elliptic flow: Rapidity dependence

Flow in Ideal MUSIC (average initial condition)

- V_4



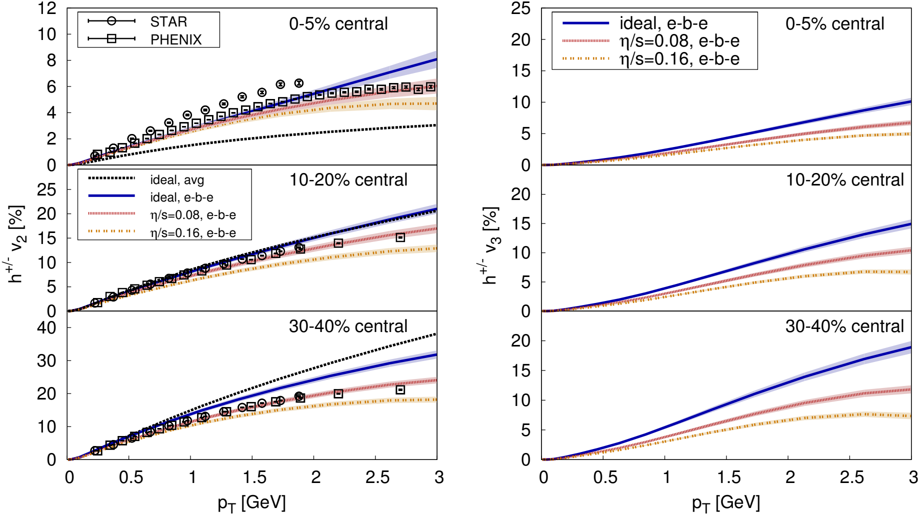
v_4: p_T dependence



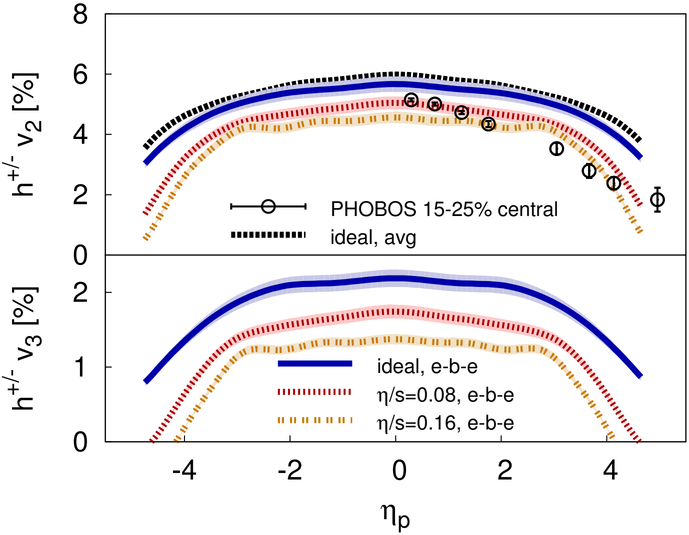
v_4: Sensitivity to the grid orientation unless the grid is super-fine

Viscous Lumpy MUSIC

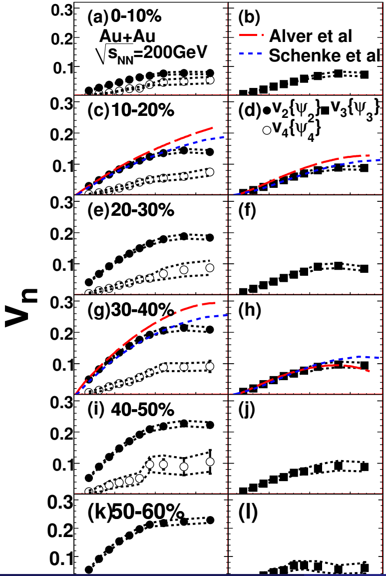
- v_2 and v_3 p_T dependence (Resonances up to ϕ)

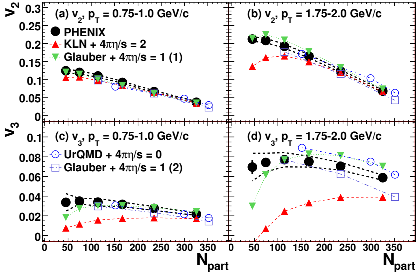


Resonances up to ϕ



Phenix (arXiv:1105.3928)

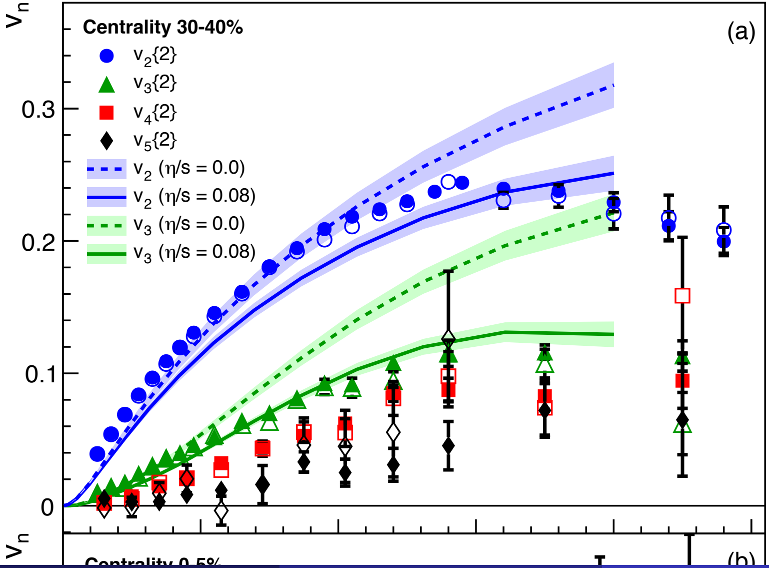




v_3: Our *Predictions* (Green Triangles)

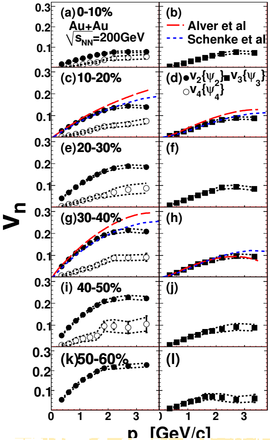
Confronting new data

Our *predictions* vs ALICE data (arXiv:1105.3865)



MUSIC Summary

Got here!



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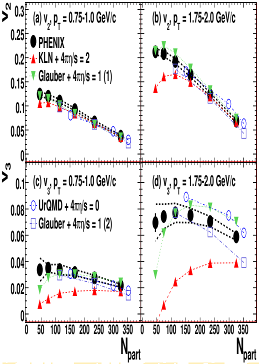

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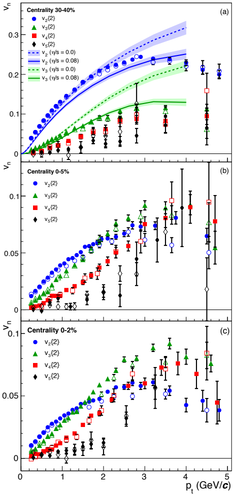
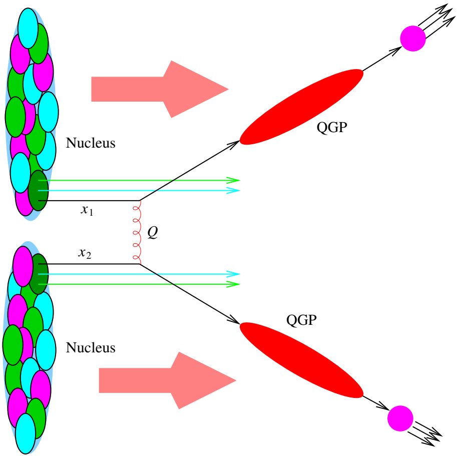


ALICE

MUSIC Summary

- 3+1D Ideal Hydro – Good to have several implementations
- 3+1D Viscous Lumpy Hydro – First!
- v_3 is non-zero because initial conditions are lumpy.
- Sophisticated Hyper-surface finding algorithm for freeze-out
- Spectra and v_n – Under control. Compares well with both RHIC and LHC data.
- A step towards a comprehensive simulation model of Heavy Ion Collisions

Jets propagating inside QGP



$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd}$$
$$\times\, f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f)$$
$$\times\, \frac{d\sigma_{ab\to cd}}{dt}$$
$$\times\, \mathcal{P}(x_c \to x'_c | T, u^\mu)$$
$$\times\, D(z'_c, Q)$$

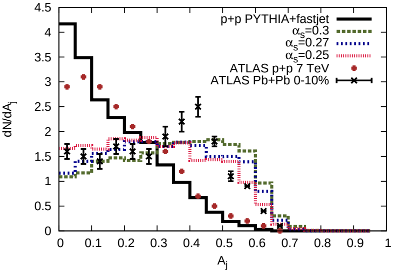
This is what we need.

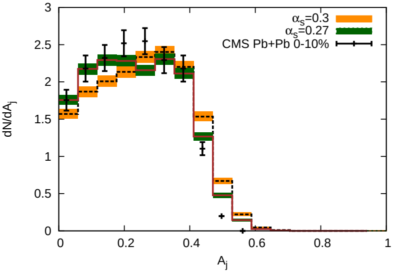
$\int_{\text{geom}} \mathcal{P}(x_c \to x'_c | T, u^\mu) D(z'_c, Q)$: Medium modified frag. function

$\mathcal{P}(x_c \to x'_c | T, u^\mu)$: Evolution within Hydro background

MARTINI

- Modular Algorithm for Relativisitic Treatment of heavy IoN Interaction
- Propagates PYTHIA jets in MUSIC background
- Uses leading order thermal QCD collision & radiation rates
- Full jet reconstruction with FASTJET





Young, Schenke, Jeon, Gale, arXiv:1103.5769
ATLAS, PRL 105 (2010) 252303

CMS, arXiv: 1102.1957 (2011)