Beam energy scan using a viscous hydro+cascade model

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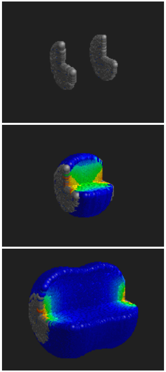
(cascade+)hydro+cascade framework for the Beam Energy Scan

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

thermalization (initial state → hydrodynamic phase); particlization (hydrodynamic phase → hadronic cascade)



- Initial state: thick pancakes
  - boost ivariance is not a good approximation $\rightarrow$ need for 3 dimensional evolution
  - ~~CGC picture loses its applicability~~
    CGC picture needs revision
- Baryon and electric charges
  - obtained from the initial state
  - included in hydro phase
  - taken into account at particlization
- Fluctuations in initial state, viscosity, afterburner

Pictures taken from: `https://www.jyu.fi/fysiikka/tutkimus/suurenergia/urhic`

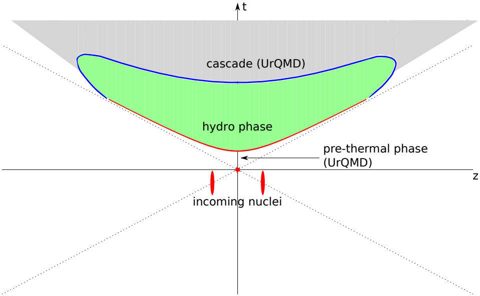
The model

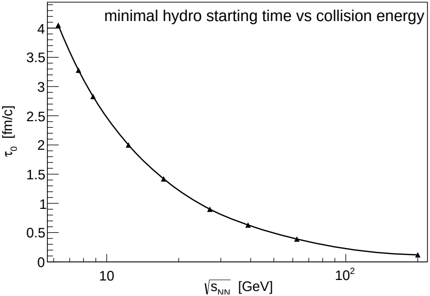
Initial stage

Pre-thermal evolution: UrQMD cascade, which involves PYTHIA for $\sqrt{s} \gtrsim 10$ GeV scatterings

The scatterings are allowed until $\tau = \sqrt{t^2 - z^2} = \tau_0$ (red curve)

The minimal value of τ_0 is
$\tau_0 = \frac{2R}{\gamma v_z}$, when two nuclei completely pass through each other.

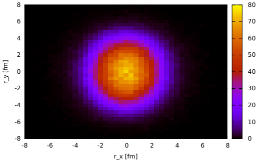




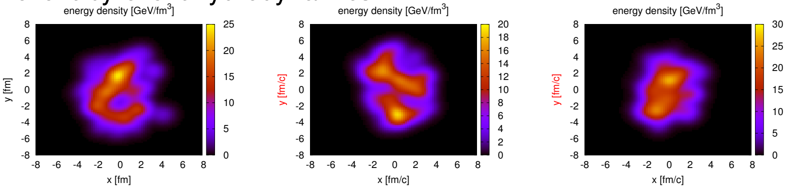
“Thermalization” (fluidization)

The pre-thermal evolution does not lead to a thermalized state at τ_0. Therefore, $\tau = \tau_0$ the energy, momentum and charges of initial state particles are mapped to hydro grid:

- (avIC) Averaged initial state from many pre-thermal UrQMD evolutions + single-shot hydrodynamics



- (fIC) A single pre-thermal UrQMD event + Gaussian smearing + event-by-event hydrodynamics:



Hydrodynamic stage

The hydrodynamic equations: local energy-momentum and charge conservation

$$\partial_{;\nu} T^{\mu\nu} = \partial_{\nu} T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0, \quad \partial_{;\nu} N^{\nu} = 0 \tag{1}$$

where (we choose Landau definition of velocity)

$$T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} - (p + \Pi)(g^{\mu\nu} - u^{\mu} u^{\nu}) + \pi^{\mu\nu} \tag{2}$$

Evolutionary equations for shear/bulk, coming from **Israel-Stewart** formalism:

$$< u^{\gamma} \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_{\pi}} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^{\gamma} \tag{3a}$$

* Bulk viscosity $\zeta = 0$, charge diffusion=0

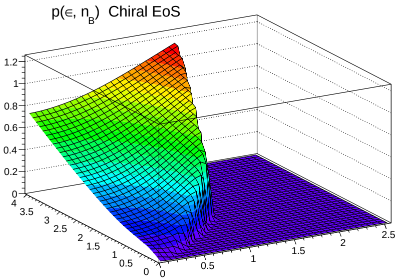
vHLLE code: free and open source. Comput. Phys. Commun. 185 (2014), 3016
http://cpc.cs.qub.ac.uk/summaries/AETZ_v1_0.html
https://github.com/yukarpenko/vhlle

Equations of state in the fluid stage

Chiral model

J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

- good agreement with lattice QCD at $\mu_B = 0$
- crossover type PT between confined and deconfined phases at all μ_B

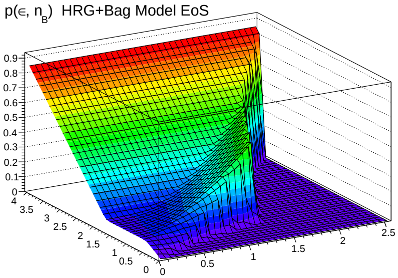


Hadron resonance gas + Bag Model

P.F. Kolb, et al, Phys.Rev. C 62, 054909 (2000)

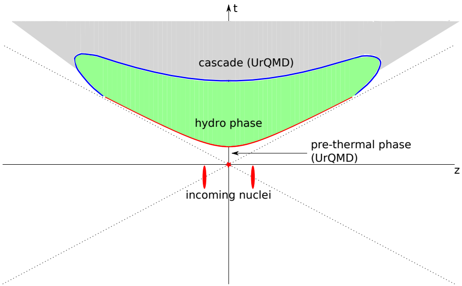
(a.k.a. `EoS Q`)

- hadron resonance gas made of u, d quarks including repulsive meanfield
- Maxwell construction resulting in 1^{st} order PT



Fluid→particle transition and hadronic phase

$\varepsilon = \varepsilon_{sw} = 0.5$ GeV/fm^3 (blue curve), when the system is in hadronic phase:
$\{T^{0\mu}, N_b^0, N_q^0\}$ of hadron-resonance gas = $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid



▷ Momentum distribution from Landau/Cooper-Frye prescription:

$$p^0 \frac{d^3 n_i}{d^3 p} = \int \left(f_{\text{l.eq.}}(x,p) + \delta f(x,p)\right) p^\mu d\sigma_\mu$$

▷ Cornelius subroutine* is used to compute $\Delta\sigma_i$ on transition hypersurface.

▷ Hadron gas phase: UrQMD cascade is employed after particlization surface.

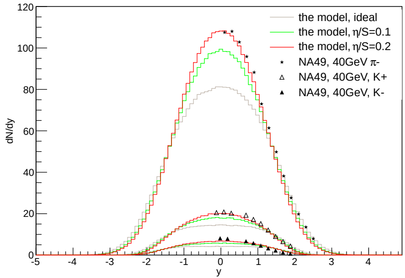
*Huovinen and Petersen, *Eur.Phys.J.* A **48** (2012), 171

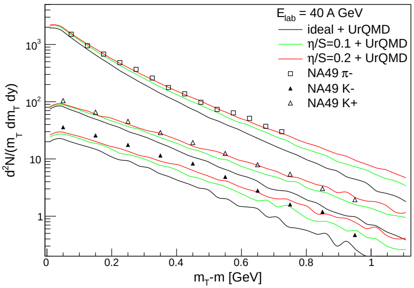
Results

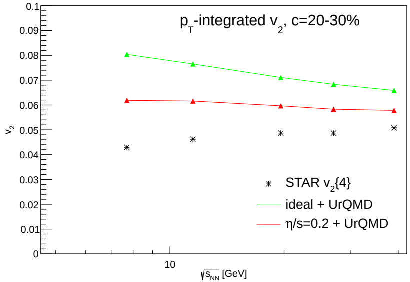
Averaged initial state + **non**-EbE hydro

Parameters fixed to:
$\eta/s = 0$ or 0.2
$\varepsilon_{\text{sw}} = 0.5$ GeV/fm^3

dn/dy and $p_\perp$ are nicely reproduced for SPS energies ($E_{\text{lab}} = 30 - 158$ GeV), but $p_\perp$-integrated v_2 is not



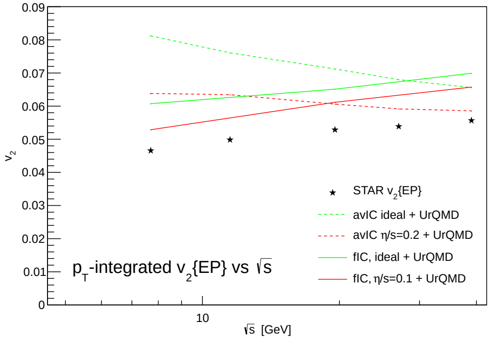




Fluctuating initial state + EbE hydro

Gaussian smearing of energy, momentum and charges at fluidization:

$$\Delta P^{\alpha}_{ijk} = P^{\alpha} \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2\right)$$
$$\Delta N^{0}_{ijk} = N^{0} \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2\right)$$



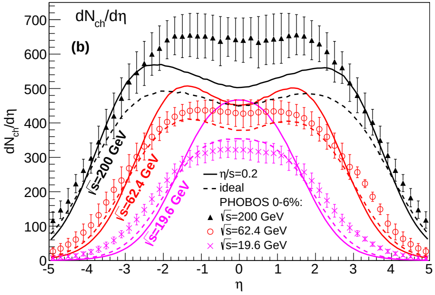
$R_\perp = R_\eta = 1$ fm
$\varepsilon_{\rm sw} = 0.5$ GeV/fm^3

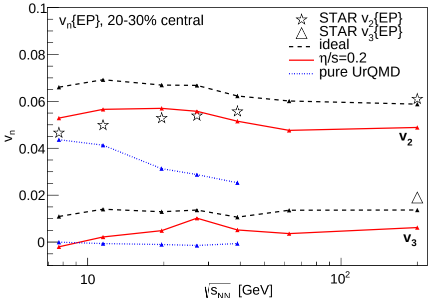
dashed: average IC
solid: fluctuating IC

$v_2(\sqrt{s_{NN}})$ trend is reproduced with fIC!

Fluctuating initial state + EbE hydro: extending to full BES range

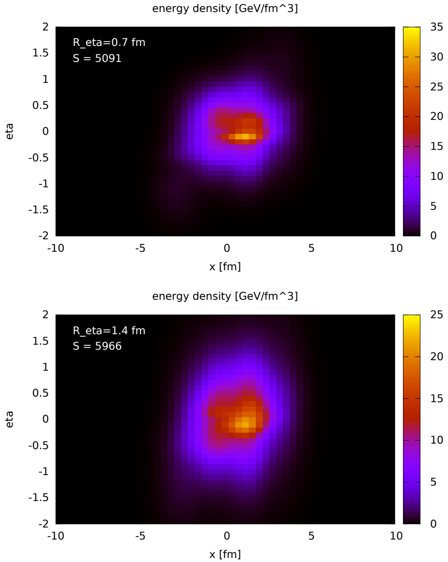
$$R_\perp = R_\eta = 1 \text{ fm}, \quad \tau_0 = \max\left\{ \frac{2R}{\gamma v_z}, 1\mathrm{fm/c} \right\}, \quad \varepsilon_{\mathrm{sw}} = 0.5 \text{ GeV/fm}^3$$





Parameter tuning needed?

Smearing matters



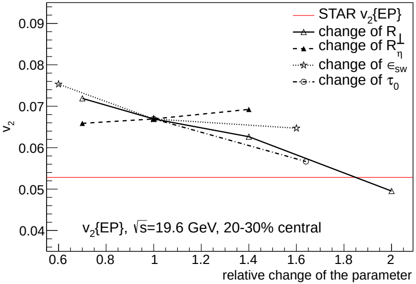
Same total energy: $E = 1473$ GeV

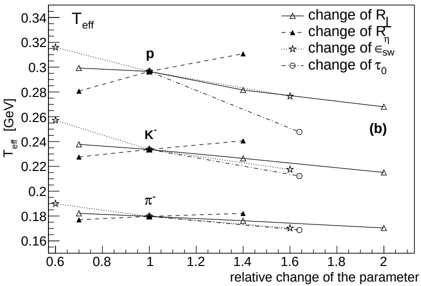
Learning parameter dependence

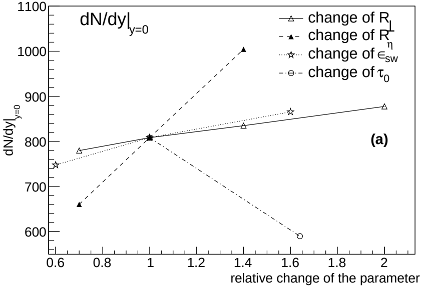
Response of the observables:

- $T_{\rm eff}$, inverse slope of p_T spectrum
- dN/dy at midrapidity
- p_T integrated $v_2\{\rm EP\}$

to the change of every parameter with respect to its default value.







Learning parameter dependence (2)

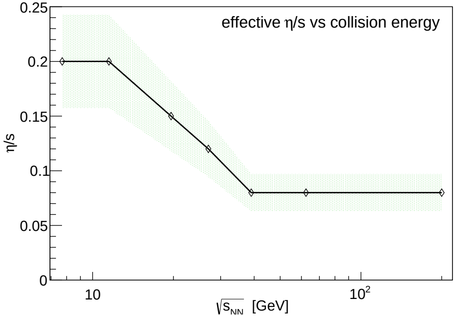
par. $\uparrow$	$R_\perp$	R_z	η/s	τ_0	$\varepsilon_{\rm crit}$
$T_{\rm eff}$	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$
dN/dy	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$
v_2	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$

Parameter values used to approach the data

EoS: Chiral model, $\varepsilon_{sw} = 0.5$ GeV/fm^3.

$\sqrt{s}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_z [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9*	1.0	0.7	0.08
62.4	0.7*	1.0	0.7	0.08
200	0.4*	1.0	1.0	0.08

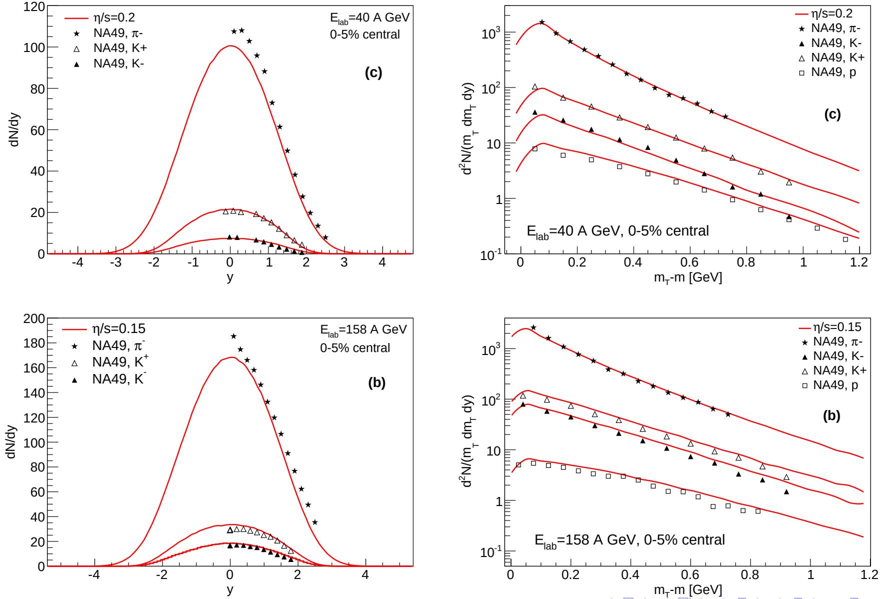
*here we increase τ_0 as compared to $\tau_0 = \frac{2R}{\gamma v_z}$.



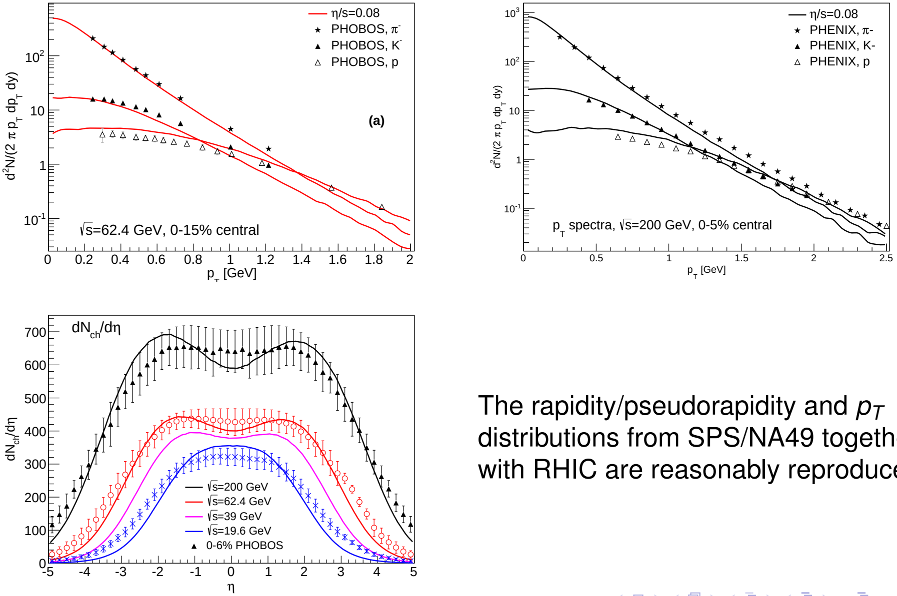
Green band:
same v_2 and $\pm 5\%$ change in T_{eff}.

! Actual error bar would require a proper χ^2 fitting of the model parameters (and enormous amount of CPU time).

40 + 158 A GeV PbPb SPS ($\sqrt{s} = 8.8$ and 17.3 GeV)



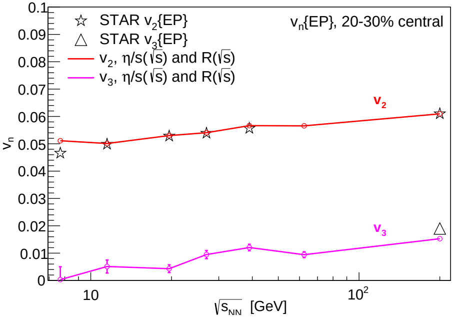
RHIC BES + top RHIC



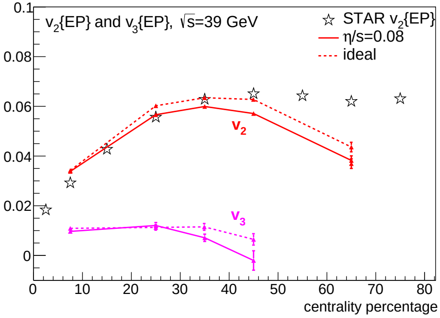
The rapidity/pseudorapidity and p_T distributions from SPS/NA49 together with RHIC are reasonably reproduced.

Elliptic and triangular flows at RHIC BES + top RHIC

v_2, v_3 vs collision energy



v_2, v_3 vs centrality



EoS dependence, hyperon polarization and HBT: in my Workshop talk

Summary

3+1D EbE UrQMD + viscous hydro + UrQMD model:

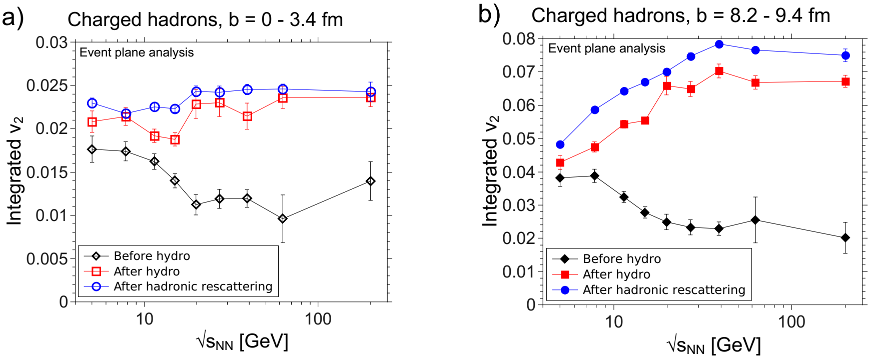
- pre-termal stage: UrQMD
- 3+1D viscous hydrodynamics
- EoS at finite μ_B: Chiral model, `EoS Q`

Conclusions:

- The model is applied for Au+Au collisions @BES + Pb-Pb @SPS.
- Observables do depend on the way the initial state is constructed, and parameters of the fluidization procedure.
- Eyeball parameter adjustment results in a reasonable reproduction of basic hadronic observables.
- Much more rigorous analysis of the parameter space: see next talk by Jussi

Outlook:
At lower end of the BES, pre-hydro stage in a “sandwich” approach is too long:

UrQMD 3.4, J. Auvinen, H. Petersen, Phys.Rev.C 88:064908,2013



This can be overcome with multi-fluid dynamics (with cold nuclear matter IC), or with an IC model allowing for dynamical fluidization.