# Hydrodynamic modelling of QCD matter in heavy ion collisions at RHIC Beam Energy Scan

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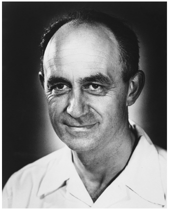
IK, P. Huovinen, H. Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)

# The starting point: Landau model

for multiparticle production process in nucleon-nucleon collisions at BeV(TeV) energies

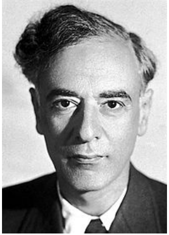
**Fermi model,** Prog. Theor. Phys., **5**, 570, (1950):

- Secondary particles are created in the Lorentz contracted volume $V = \frac{4\pi}{3} a^3 \frac{2Mc^2}{\sqrt{s}}$, $a = \hbar/\mu c$ is the size of nucleon meson cloud
- Particles are born in statistical equilibrium (because of strong interaction and small volume), and immediately escape in a “frozen state”
- The model is applied to describe the angular distribution of produced pions



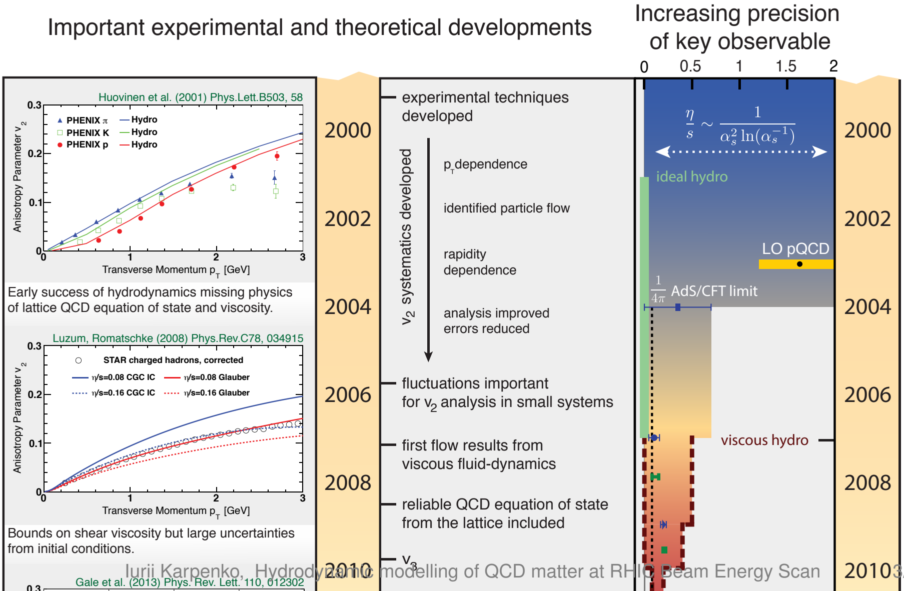
**Landau model,** Izv. Ak. Nauk SSSR, Ser. Fiz., **17**, 51 (1951); Nuovo Cimento Suppl., **3**, 15 (1956):

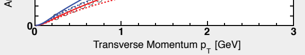
- Causality problems for noncentral collisions
- The initial volume $V$ expands (hydrodynamically!)
- As the mean free path becomes comparable to the system size, it disintegrates into separate particles. This happens when $T \approx \mu$, the pion mass.



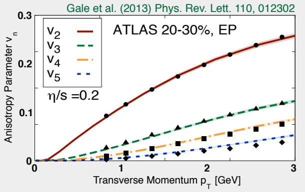
# Modern history: hydro for ultrarelativistic AA collisions, $\sqrt{s_{NN}} = 200$ GeV (full RHIC), 2760 GeV (LHC)

Figure taken from: C. Gale, S. Jeon, B. Schenke, Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)

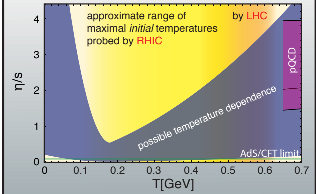





Bounds on shear viscosity but large uncertainties from initial conditions.




Higher moments constrain viscosity and fluctuating initial conditions better, but temperature dependence of η/s is not yet determined.




To determine (η/s)(T) different initial temperatures need to be accessible. Only possible with combined data from LHC and RHIC beam energy scan.

2008

2010

2012

2014

2022

viscous fluid dynamics

reliable QCD equation of state from the lattice included

$v_3$

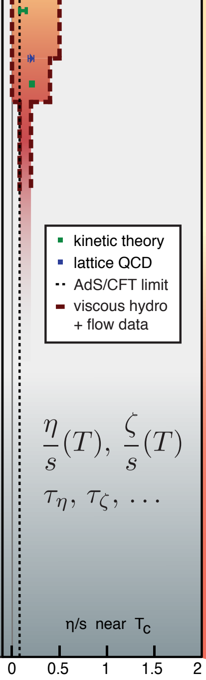
$v_n$

$v_n$ correlations

$P(v_n)$

RHIC BES-II upgrade required to

- measure lower bound to ~10%
- determine (η/s)(T) dependence
- measure bulk viscosity and relaxation times
- constrain initial state and its fluctuations




$$\frac{\eta}{s}(T),\ \frac{\zeta}{s}(T)$$

$$\tau_\eta,\ \tau_\zeta,\ \ldots$$

2008

2010

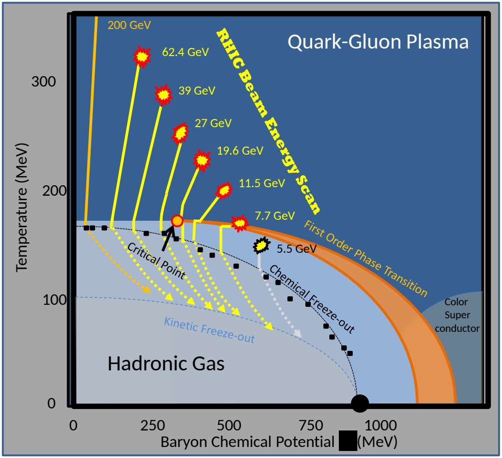
2012

2014

2022

# Motivation of my work: going back to 'lower' energies

We want to understand whether the fluid is created at lower energies, find its transport properties ($\eta/s$,...) and constrain its EoS.

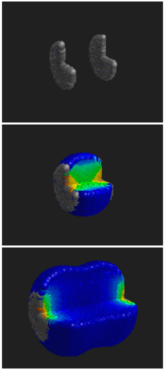



Picture taken from: G. Odyniec, Acta Phys. Polon. B 43, 627 (2012).

# Tools

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

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



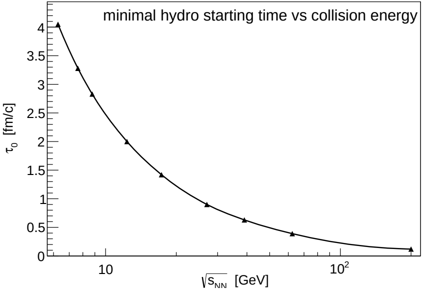
- Initial state: thick pancakes
  - boost ivariance is not a good approximation $\rightarrow$ need for 3 dimensional evolution
  - CGC picture does not work well either
- Initial state: fluctuations
- Baryon and electric charges
  - obtained from the initial state
  - included in hydro phase
  - taken into account at particlization

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

# The model

# Initial (pre-thermal) stage

- pre-thermal evolution: UrQMD cascade (involving PYTHIA)
- scatterings allowed until $\sqrt{t^2 - z^2} = \tau_0$
- minimal starting time is $\tau_0 = \frac{2R}{\gamma v_z}$

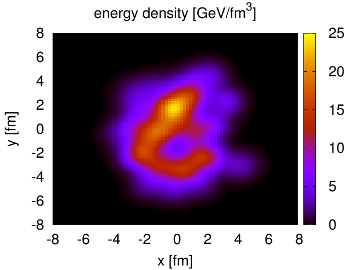



**"Thermalization"**

At $\tau = \tau_0$ the energy/momentum $P^\alpha$, baryon and electric charges $N^0$ of every particle are deposited into fluid cells according to:

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

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



# Hydrodynamic stage

The hydrodynamic equations:

$$\partial_{;\nu} T^{\mu\nu} = 0, \quad \partial_{;\nu} N^{\nu} = 0$$

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

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

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

`vHLLE` code: free and open source. Comput. Phys. Commun. 185 (2014), 3016

`https://github.com/yukarpenko/vhlle`

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# Fluid→particle transition and hadronic phase

- Cooper-Frye prescription at $\varepsilon = \varepsilon_{\text{sw}}$:

$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

$$f(x,p) = f_{\text{eq}} \cdot \left( 1 + (1 \mp f_{\text{eq}}) \frac{p_{\mu} p_{\nu} \pi^{\mu\nu}}{2T^2(\varepsilon + p)} \right)$$

- $\Delta\sigma_i$ using Cornelius subroutine*
- Hadron gas phase: back to UrQMD cascade

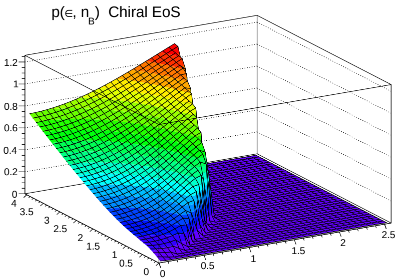
*Huovinen and Petersen, *Eur.Phys.J.* A **48** (2012), 171

# 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 $\mu_B$

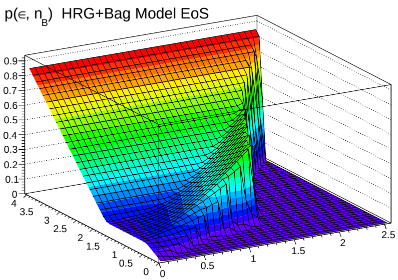



## Hadron resonance gas + Bag Model

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

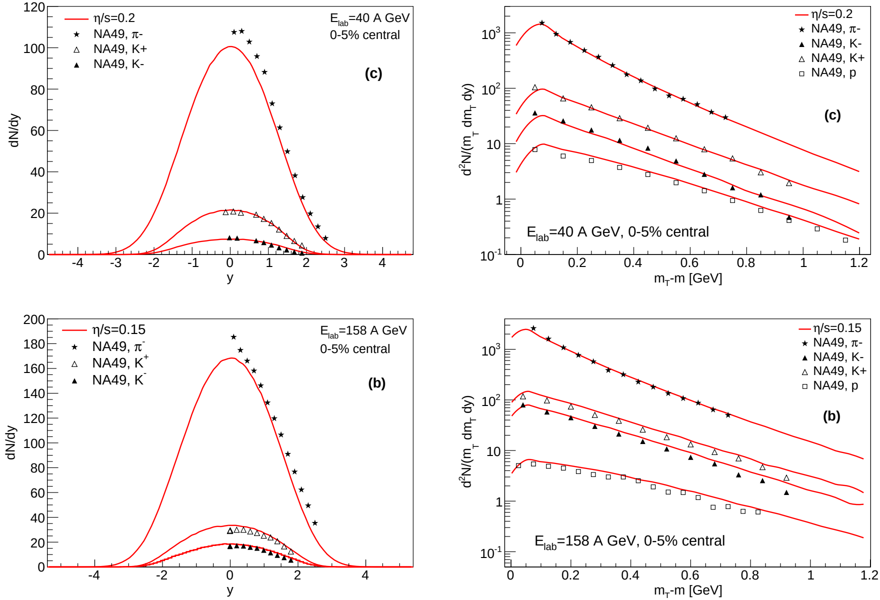
(a.k.a. `EoS Q`)

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



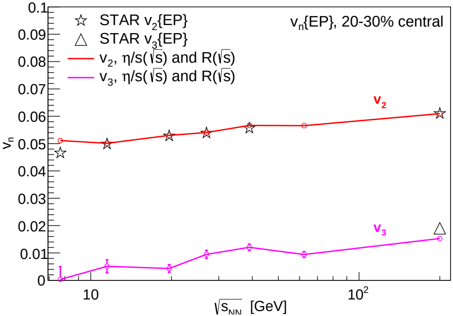
# Results

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



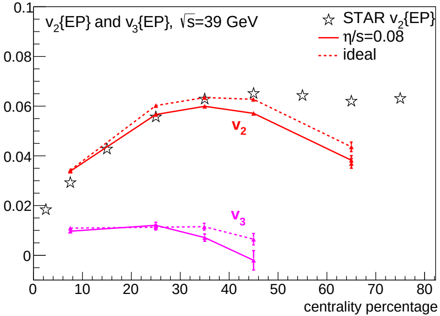
# Elliptic and triangular flows at RHIC BES + top RHIC

## $v_2, v_3$ vs collision energy




$v_3$: prediction!

## $v_2, v_3$ vs centrality



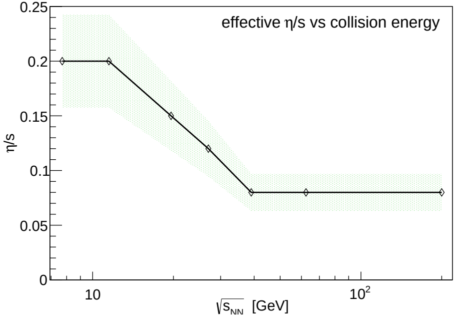

Peripheral events: too strong smearing for smaller system

# Parameter values used to approach the data

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

| $\sqrt{s}$ [GeV] | $\tau_0$ [fm/c] | $R_\perp$ [fm] | $R_z$ [fm] | $\eta/s$ |
|---|---|---|---|---|
| 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 |

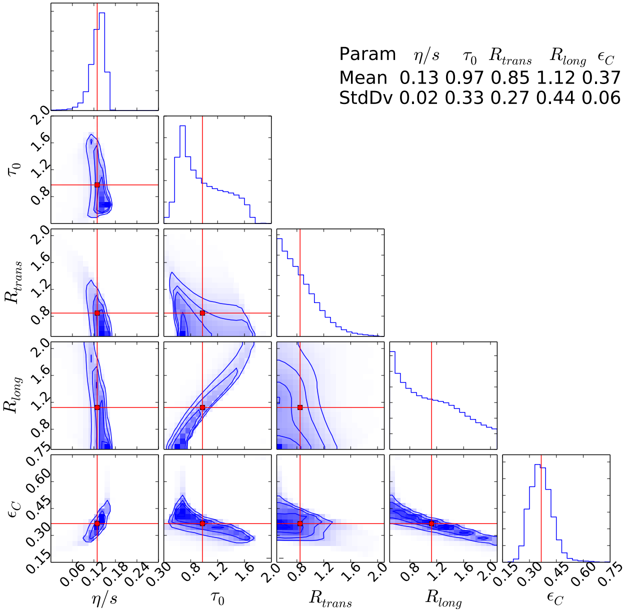
*here we increase $\tau_0$ as compared to $\tau_0 = \frac{2R}{\gamma v_z}$.




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

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

# $\eta/s$ determination, not estimate? J. Auvinen, analysis at $\sqrt{s_{NN}} = 62.4$ GeV

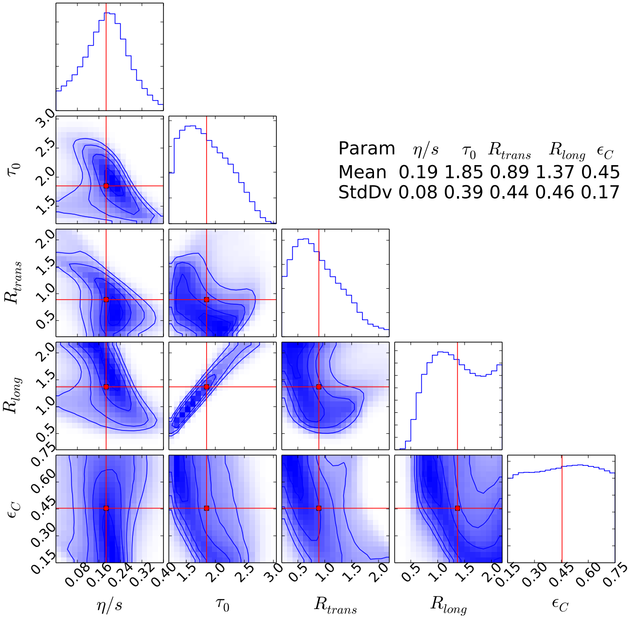



| Param | $\eta/s$ | $\tau_0$ | $R_{trans}$ | $R_{long}$ | $\epsilon_C$ |
|---|---|---|---|---|---|
| Mean | 0.13 | 0.97 | 0.85 | 1.12 | 0.37 |
| StdDv | 0.02 | 0.33 | 0.27 | 0.44 | 0.06 |

This hybrid model
+
Gaussian processes (emulator)
+
Markov chain Monte Carlo

done by J. Auvinen (Duke Univ.)

# $\eta/s$ determination, not estimate? J. Auvinen, analysis at $\sqrt{s_{NN}} = 19.6$ GeV



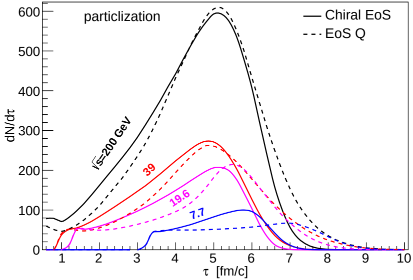

| Param | $\eta/s$ | $\tau_0$ | $R_{trans}$ | $R_{long}$ | $\epsilon_C$ |
|---|---|---|---|---|---|
| Mean | 0.19 | 1.85 | 0.89 | 1.37 | 0.45 |
| StdDv | 0.08 | 0.39 | 0.44 | 0.46 | 0.17 |

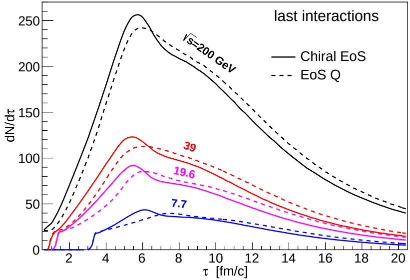
This hybrid model
+
Gaussian processes (emulator)
+
Markov chain Monte Carlo

done by J. Auvinen (Duke Univ.)

# EoS dependence: Chiral EoS vs 'EoS Q'

Take same parameters but change the EoS:

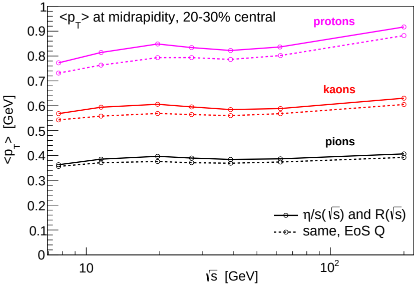


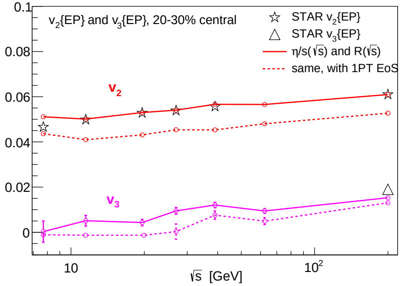




- EoS Q increases the average duration of hydro phase, especially at lower collision energies.
- But the difference is smeared by the cascade

# EoS dependence: Chiral EoS vs 'EoS Q'

- Final multiplicities and rapidity distributions are unchanged.




- EoS Q results in slightly less radial flow → mean $p_T$ is decreased.
- The biggest effect is for the elliptic flow.

# Summary

3+1D EbE viscous hydro + UrQMD model for $\sqrt{s_{NN}} = 7.7 \ldots 200$ GeV A+A collisions:

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

Conclusions:

- Adjustment to experimental data suggests $\eta/s = 0.2 \to 0.08$ when $\sqrt{s} = 7.7 \to 200$ GeV, modulo initial state (UrQMD) and EoS (Chiral model) used.
  - Rigorous analysis with emulator is ongoing (by J. Auvinen, Duke Univ.).
- Hydrodynamic evolution is affected by EoS, which leads to change in $v_2$.

Current projects at INFN Firenze (F. Becattini):

- Hyperon polarization and vorticity in QGP liquid
- Multi-fluid hydrodynamics

# Backup slides

# Strategy to compare to experiment

- Run the model with default values of the parameters:
  $\eta/s = 0$, $R_\perp = R_\eta = 1$ fm, $\varepsilon_{\rm sw} = 0.5$ GeV/fm$^3$, Chiral EoS
- Observe a difference with the experimental data
- Learn how variations of parameters affect the observables in the model[1]
- Adjust the parameters at each collision energy to approach the data

Shorter hydro phase $\Rightarrow$ stronger dependence on the initial state

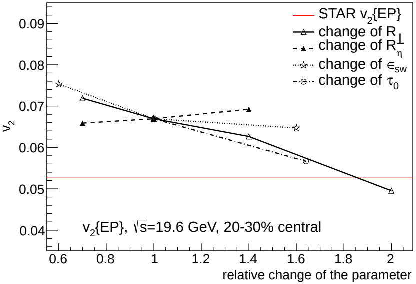
[1] see backup slides

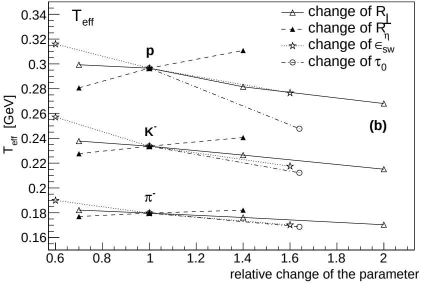
# Learning parameter dependence

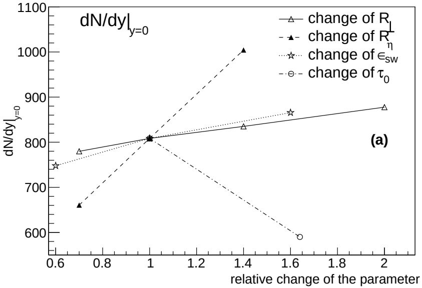
Response of the observables:

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

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



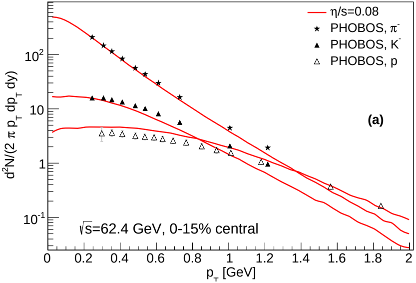



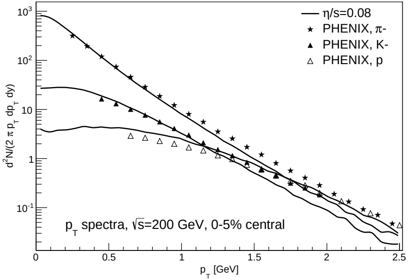



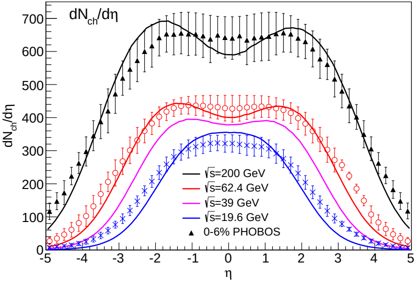
# Learning parameter dependence (2)

| par. $\uparrow$ | $R_\perp$ | $R_z$ | $\eta/s$ | $\tau_0$ | $\varepsilon_{\rm crit}$ |
|---|---|---|---|---|---|
| $T_{\rm eff}$ | $\downarrow$ | $\uparrow$ | $\uparrow$ | $\downarrow$ | $\downarrow$ |
| $dN/dy$ | $\uparrow$ | $\uparrow$ | $\uparrow$ | $\downarrow$ | $\uparrow$ |
| $v_2$ | $\downarrow$ | $\uparrow$ | $\downarrow$ | $\downarrow$ | $\downarrow$ |

# RHIC BES + top RHIC




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