Vorticity in the QGP liquid and Lambda polarization at the RHIC Beam Energy Scan

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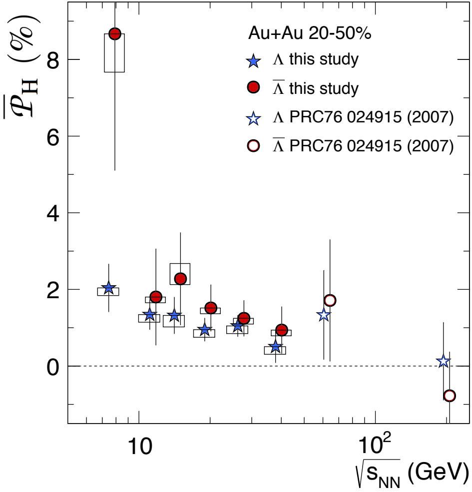
IK, Becattini `arXiv:1610.04717`
Becattini, IK, Lisa, Upsal, Voloshin `arXiv:1610.02506`

Highlight: recent Λ polarization measurement

STAR Collaboration, `arXiv:1701.06657`



"First clear positive signal of global polarization in heavy ion collisions!"

Theory side: polarization of fermions in fluid

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32

(also Ren-hong Fang, Long-gang Pang, Qun Wang, Xin-nian Wang, ICTS-USTC-16-05, arXiv:1604.04036)

For the spin $\frac{1}{2}$ particles produced at the particlization surface:

$$S^{\mu}(p) = \frac{1}{8m} \frac{\int d\Sigma_{\lambda} p^{\lambda} f(x,p) \cdot (1 - f(x,p)) \varepsilon^{\mu\nu\rho\sigma} p_{\sigma} \partial_{\nu} \beta_{\sigma}}{\int d\Sigma_{\lambda} p^{\lambda} f(x,p)}$$

where $\beta_{\mu} = \frac{u_{\mu}}{T}$ is the inverse four-temperature field.

The polarization depends on the the thermal vorticity $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu})$.

- polarization is close or equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients

Existing polarization calculations from hydro models

All for $\sqrt{s_{\rm NN}} \geq 62.4$ GeV.

- F. Becattini, L.P. Csernai, D.J. Wang, and Y.L. Xie,
  Phys. Rev. C 88, 034905 (2013)
  IC from Yang-Mills dynamics + 3D ideal hydro
  $\sqrt{s_{\rm NN}} = 200$ GeV Au-Au, $P_J \approx 3\%$
- F. Becattini, G. Inghirami et al., Euro Phys. J. C 75:406 (2015)
  Glauber IC + parametrized rapidity dependence
  $\sqrt{s_{\rm NN}} = 200$ GeV, $b = 11.6$ fm, $P_J \approx 0.2\%$
- Long-Gang Pang, Hannah Petersen, Qun Wang, Xin-Nian Wang,
  arXiv:1605.04024
  AMPT IC + 3D viscous hydro
  $\sqrt{s_{\rm NN}} = 62.4, 200, 2760$ GeV; P_J around few per mille.

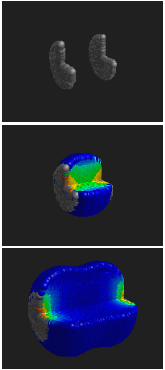
All done for $\sqrt{s_{\rm NN}} = 62.4$ GeV and above!

What hydro picture gives us at lower collision energies, where preliminary measurements report essentially non-zero polarization?

Tool for investigation: cascade+hydro(+cascade) model for BES

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

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



Challenges at lower collision energies:

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

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

The model: UrQMD + vHLLE (+ UrQMD)

Pre-thermal evolution: UrQMD cascade until $\tau = \tau_0 = const$, $\tau_0 = \frac{2R}{\gamma v_z}$
Fluctuating initial state, event-by-event hydrodynamics

Hydrodynamic phase:

$$\partial_{;\nu} T^{\mu\nu} = 0, \quad \partial_{;\nu} N^{\nu} = 0 \qquad < u^{\gamma} \partial_{;\gamma} \pi^{\mu\nu} >= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^{\gamma}$$

* Bulk viscosity $\zeta = 0$, charge diffusion=0
vHLLE code: free and open source. Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle

Fluid→particle transition and hadronic phase

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

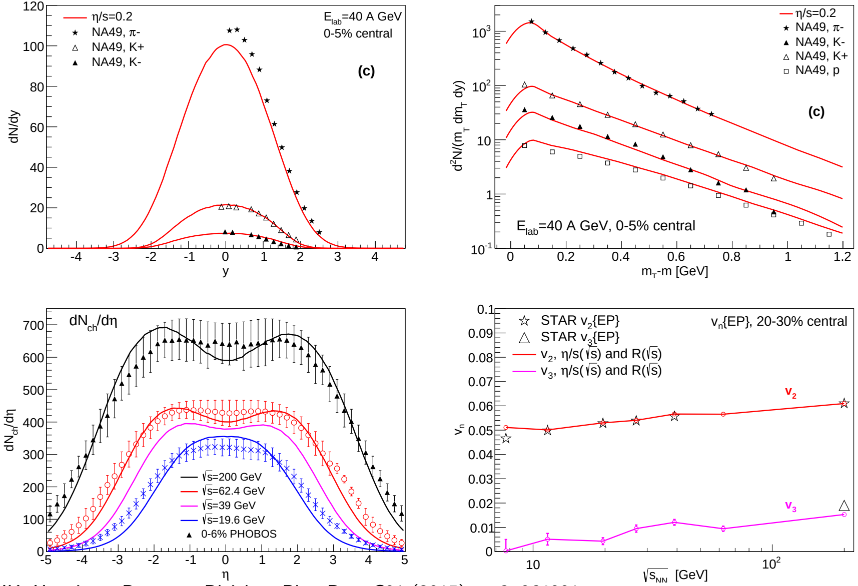
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

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

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

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

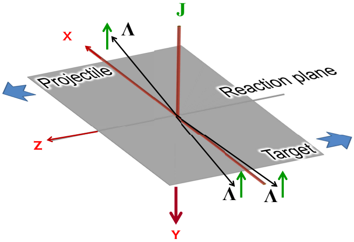
Validating the model for bulk hadronic observables



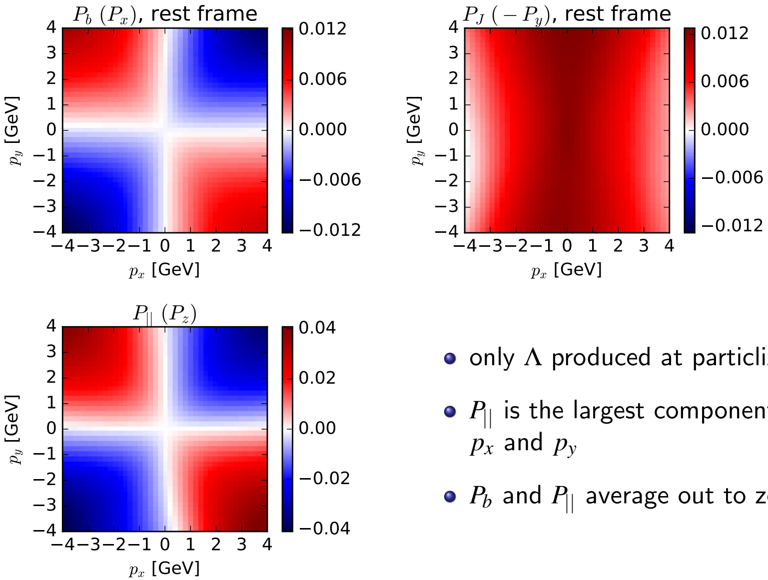
IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

Λ polarization signal from the model

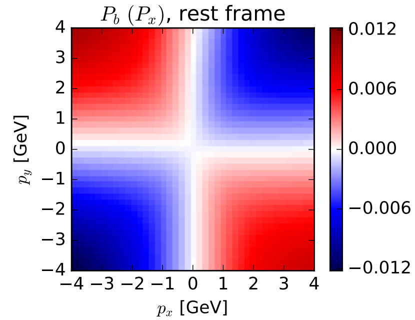
geometry sketch:

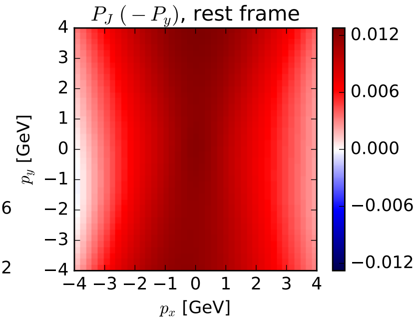


p_T differential polarization of Λ, $\sqrt{s_{NN}} = 19.6$ GeV, 40-50% Au-Au



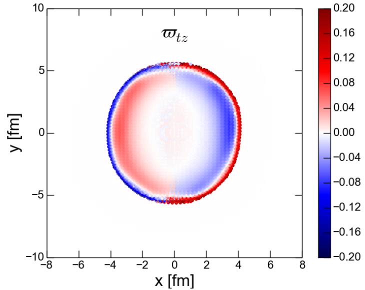
- only Λ produced at particlization
- $P_{||}$ is the largest component at large p_x and p_y
- P_b and $P_{||}$ average out to zero

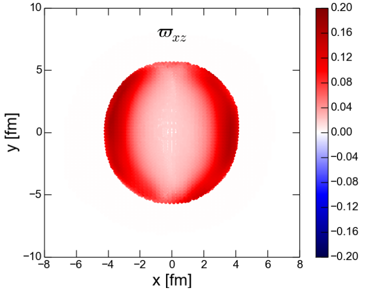




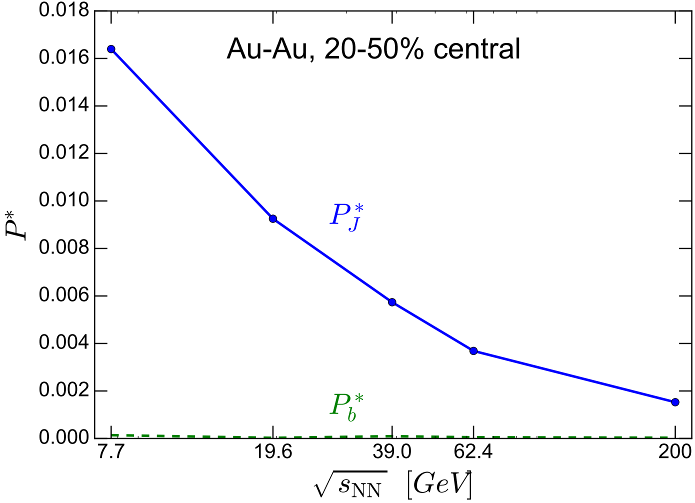
$P_b \propto \varpi_{tz} p_y$ ⇕

$P_J \propto \varpi_{xz} p_0$ ⇕



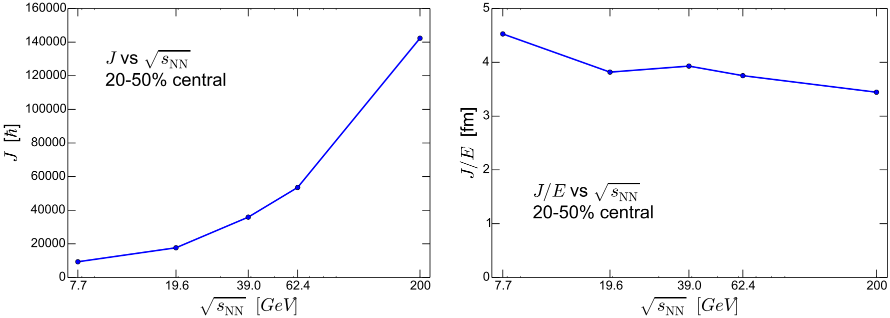


Collision energy dependence



Is it a manifestation of larger fireball angular momentum at lower $\sqrt{s_{NN}}$?

Not really: J_y actually increases with increase of $\sqrt{s_{\rm NN}}$.



- Total angular momentum increases with increasing energy of the fireball.
- J_y/E shows weak dependence on $\sqrt{s_{\rm NN}}$.

Why does P_J increase at lower BES energies?

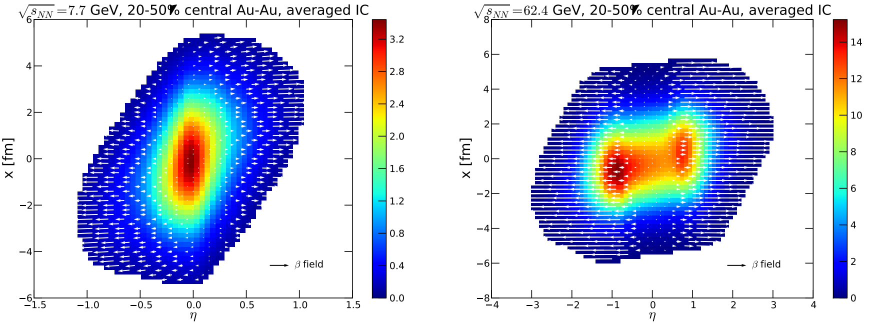
1) Different initial vorticity distribution:

baryon stopping at lower $\sqrt{s_{\rm NN}}$

$\Downarrow$

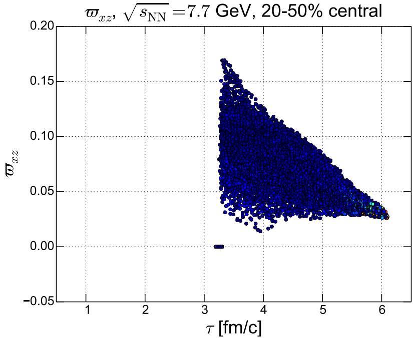
shear flow in beam direction

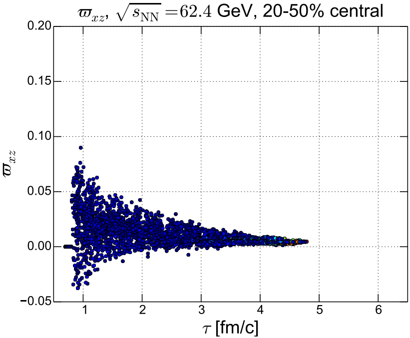
transparency at higher $\sqrt{s_{\rm NN}}$



Why does P_J increase at lower BES energies?

2) Longer hydrodynamic evolution at higher $\sqrt{s_{NN}}$ further dilutes the vorticity

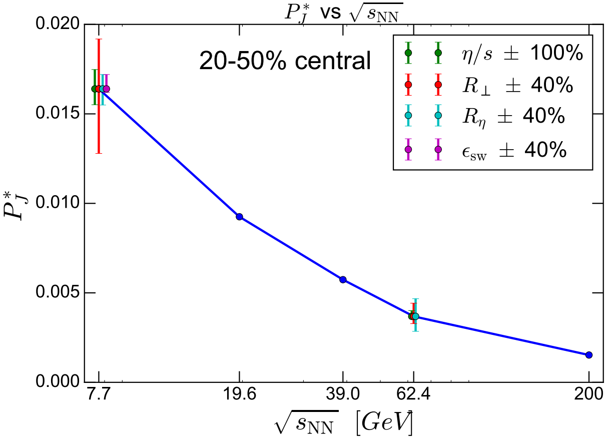




Figs: Distribution of xz component of thermal vorticity (responsible for P_J at $p_x = p_y = 0$) over particlization hypersurface.

- these two effects result in lower polarization at higher collision energies

Sensitivity to parameters of the model



Initial state:
$R_\perp$: transverse granularity
R_η: longitudinal granularity

Fluid phase:
η/s: shear viscosity of fluid

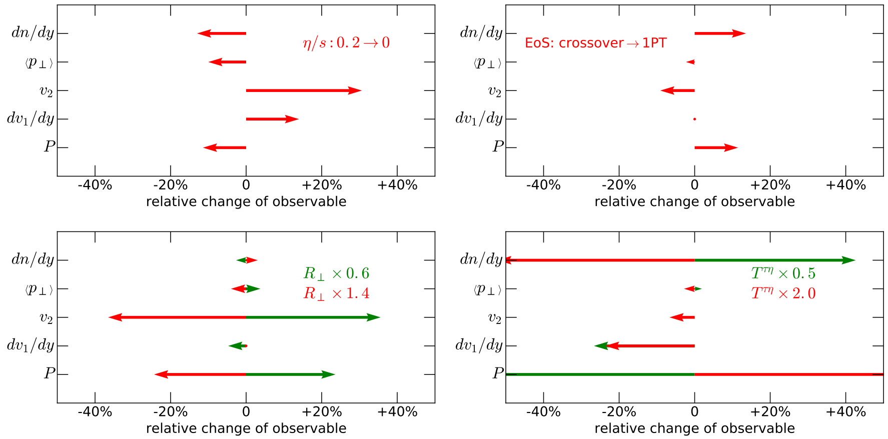
Particlization criterion:
$\varepsilon_{\rm sw} = 0.5$ GeV/fm^3

Collision energy dependence is robust with respect to variation of the parameters of the model.

A closer look at the parameter dependence

NEW

$\sqrt{s_{NN}} = 7.7$ GeV



- Polarization observable is more sensitive to details of initial state rather than to details of hydro evolution.
- No sensitivity on the value of particlization energy density ε_{sw}.

Interactions in the post-hydro stage

NEW

Only about 25% of Λ are thermal ones! The rest is coming from resonance decays.

Spin (polarization) transfer in two-body resonance decay: $\mathbf{S}^*_{\Lambda,\Sigma^0} = C_{X\to\Lambda,\Sigma^0}\cdot\mathbf{S}^*_X$

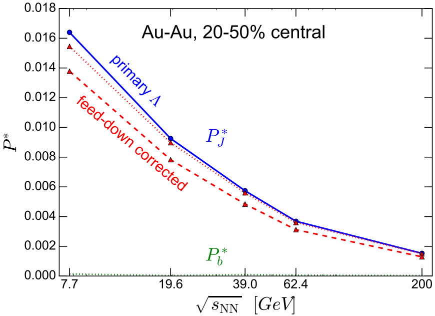
Direct $X\to\Lambda$ and two-step $X\to\Sigma^0\to\Lambda$ decays are taken into account.

$$\mathbf{S}^*_\Lambda = \frac{N_\Lambda \mathbf{S}^*_{\Lambda,\text{prim}} + \sum_X N_X \mathbf{S}^*_X\left[C_{X\to\Lambda}b_{X\to\Lambda} - \frac{1}{3}C_{X\to\Sigma^0}b_{X\to\Sigma^0}\right]}{N_\Lambda + \sum_X b_{X\to\Lambda}N_X + \sum_X b_{X\to\Sigma^0}N_X}$$

X	J^P	$\frac{S_X}{S_{\Lambda,\text{prim}}}$	$C_{X\to\Lambda,\Sigma^0}$	$\frac{S_{\Lambda(X)}}{S_{\Lambda,\text{prim}}}$
Σ^0	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1385)$	$(3/2)^+$	5	$1/3$	$5/3$
$\Lambda(1405)$	$(1/2)^-$	1	1	1
$\Lambda(1520)$	$(3/2)^-$	5	$-1/5$	-1
$\Lambda(1600)$	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1660)$	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1670)$	$(3/2)^-$	5	$-1/5$	-1

Dotted: primary$+\Sigma^0+\Sigma(1385)$

Dashed: primary$+\Sigma^0+\cdots+\Sigma(1670)$

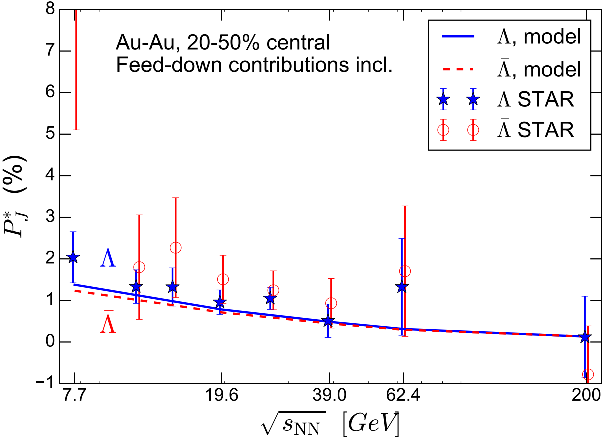


What is not taken into account (yet):

- Λ and Σ^0 actively rescatter in hadronic phase
- Elastic rescatterings are expected to randomize the spin orientation, thus suppressing the polarization signal.

Λ and $\bar{\Lambda}$: UrQMD+vHLLE vs experiment

NEW



- Λ within experimentan error bars.
- Much smaller and opposite sign $\bar{\Lambda}$-Λ splitting. Only $\mu_{\rm B}$ effect in the model, and it is small.
- MHD interpretation: vorticity creates the average $\Lambda+\bar{\Lambda}$, magnetic field makes the splitting.
- Magnetic field at particlization?

Summary

Λ polarization is calculated in UrQMD + 3D EbE viscous hydro model for $\sqrt{s_{NN}} = 7.7 \ldots 200$ GeV A+A collisions.

- We observe a strong increase of mean Λ polarization towards lowest RHIC BES energies.
- The calculated Λ polarization is (almost) within the experimental error bars.
- The collision energy dependence is robust with respect to variation of model parameters.
- The polarization is sensitive to the parameters of the initial state, and can be used to constrain it.
- Feed-down from Σ^0 and $\Sigma(1385)$ counterplay and leave the polarization almost unchanged. As more resonances are included, the resulting Λ polarization goes down by 15%.
- Elastic rescatterings are expected to suppress the calculated polarization signal.

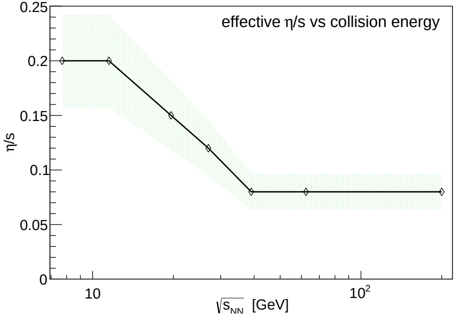
Backup material

Parameter values used to approach the basic hadronic observables

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).

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901