Feed-down effects on Λ and $\overline{\Lambda}$ polarizations in heavy-ion collisions at NICA energies. The role of Σ^0 hyperons.

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Heavy-ion collisions

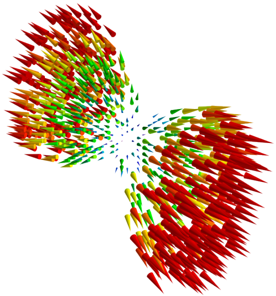
- Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

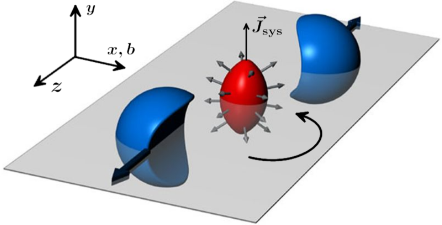
$$\boldsymbol{L} \quad \longrightarrow \quad \langle \boldsymbol{\omega} \rangle = \langle \mathrm{rot}\, \boldsymbol{v} \rangle$$

- The vorticity leads to the *global particle polarization*

  F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338** (2013)
  F. Becattini, M.A. Lisa, Annu. Rev. Nucl. Part. Sci. **70** (2020)

- The vorticity field may have *rich space-time structure*
  - **Femto-vortex sheets**:
    M.I. Baznat, K.K. Gudima, A.S. Sorin, and O.V. Teryaev, Phys. Rev. C **93** (2016)
  - **Vortex rings**:
    Yu.B. Ivanov, A.A. Soldatov, Phys. Rev. C **97** (2018)





Global Λ and $\bar{\Lambda}$ polarization

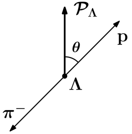
- The $\mathbf{\Lambda}$ and $\bar{\mathbf{\Lambda}}$ are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the $\mathbf{\Lambda}$-hyperon spin

- In the hyperon *rest frame*, the decay product distribution is

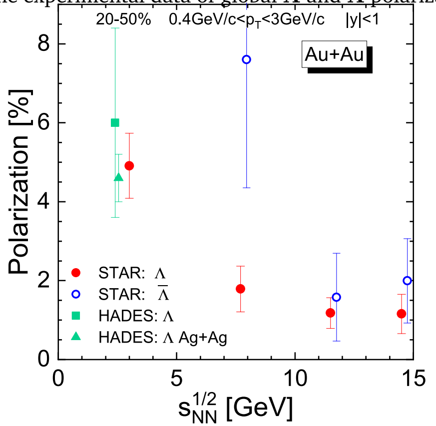
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}\cos\theta)$$

$$\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$

according to direction $\mathcal{P}_{\mathrm{H}}$



- The experimental data of global $\mathbf{\Lambda}$ and $\bar{\mathbf{\Lambda}}$ polarization



L. Adamczyk et al., Nature **548** (2017)
R.A.Yassine et al. (HADES Coll.) arXiv:2207.05160

Polarization of particles with spin in vorticity field

- **The thermodynamic approach**

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

  Relativistic thermal vorticity:

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \beta_\nu = \frac{u_\nu}{T}$$

  Spin vector:

$$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1 \pm n(x,p))\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta$$

  s – spin, p_δ – 4 momentum of particle
  We assume the Boltzmann limit $(1 \pm n(x,p)) \approx 1$

  Polarization: $\mathbf{P} = \mathbf{S}^*/s$, where $\mathbf{S}^*$ spin vector in rest frame

PHSD

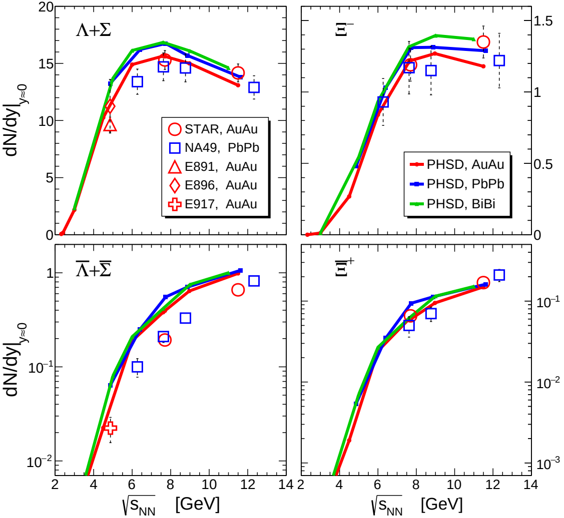
- The **PHSD transport model** as a heavy-ion collisions framework

  W. Cassing, E.L. Bratkovskaya,
  Phys. Rev. C **78** (2008)
  Nucl. Phys. A **831** (2009)

- Good description of a large number of experimental observables

  O. Linnyk, E.L. Bratkovskaya, W .Cassing,
  Prog. Part. Nucl. Phys. **87** (2016)

- The **PHSD** performance test



The fluidization procedure: Landau frame

- Transition from kinetic to hydrodynamic description via *fluidization* procedure:

$$T^{\mu\nu}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} \frac{p^{\mu}_{i_a}(t)\, p^{\nu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \mathcal{N} = \int \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right)\, d^3x,$$

$$J^{\mu}_{B}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} B_{i_a} \frac{p^{\mu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right) - \text{smearing function},$$

$$u_{\mu} T^{\mu\nu} = \varepsilon\, u^{\nu}, \qquad n_B = u_{\mu} J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$

- Equation of State: **Hadron resonance gas**
  L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin, Phys. Atom. Nucl. **72** (2009)

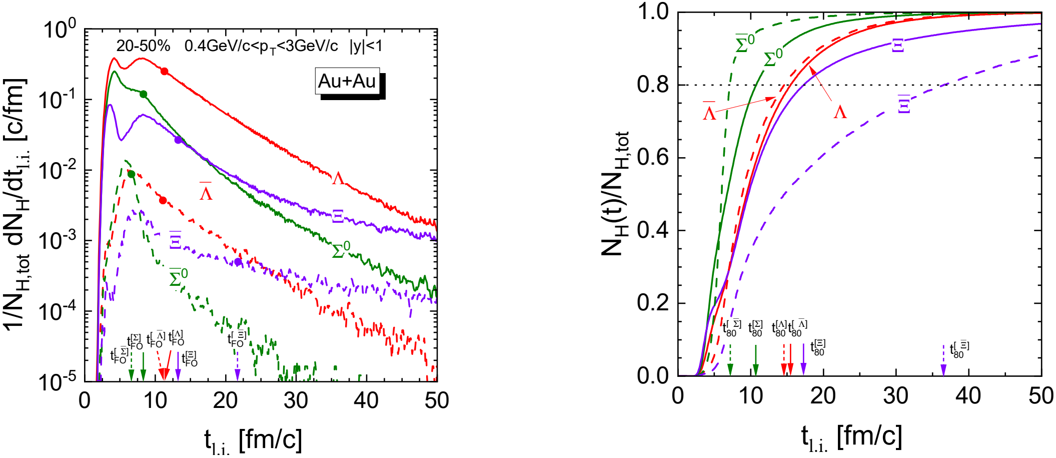
- *The fluidization criterion*: *fluidize only cells with* $\varepsilon > 0.05\,\mathrm{GeV/fm^3}$!

- *Spectators separation*: spectators moves with approximately beam rapidity $|y - y_{\mathrm{b}}| \leq 0.27$
  Spectator nucleons do not form fluid!

- *Propagation of hadrons in mean field is switched off.*

Rates of final hyperon production

- **Trace to time of the last interaction, AuAu@7.7GeV**



Strong decays are already naturally included.

Different freeze-out can lead to different polarization.

Polarization of particles with spin in vorticity field

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  s – spin, p_δ – 4 momentum of particle

  Polarization: $\mathbf{P} = \mathbf{S}^*/s$
  $\mathbf{S}^*$ spin vector in rest frame

- **Interaction/production point**

✠ *No "Medium":* $\varepsilon < 0.05 \mathrm{GeV/fm}^3$
$\Rightarrow$ *No thermal vorticity* $\varpi_{\mu\nu} = 0$

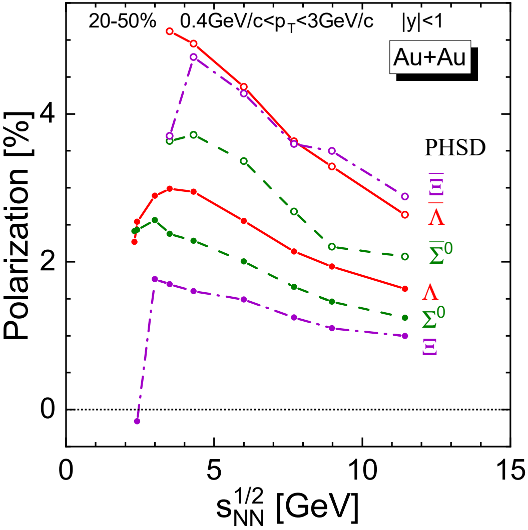
Elastic or inelastic process:
"Medium": particle is polarized.
No "Medium": zero polarization.

Strong decays:
$\Sigma^* \to \Lambda + \pi, \quad \Xi^* \to \Xi + \pi$
spin transfer $C_{\Lambda\,\Sigma^*} = C_{\Xi\,\Xi^*} = 1/3$

$$S_{Doughter} = C_{D\,P}\, S_{Parent}$$

- **Particles gone into infinity carry info about last interaction point.**

Polarization of different species of hyperons



The Λ and $\bar{\Lambda}$ polarization

- *The feed-down effects*

strong: *is already included*

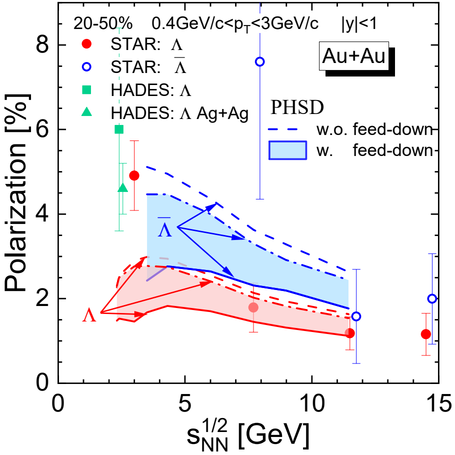
weak: $\Xi \to \Lambda + \pi \quad c\tau = 4.91 - 8.71\,cm$

EM: $\Sigma^0 \to \Lambda + \gamma \quad c\tau = 2.2 \times 10^4\,fm$

Spin transfer coefficients:

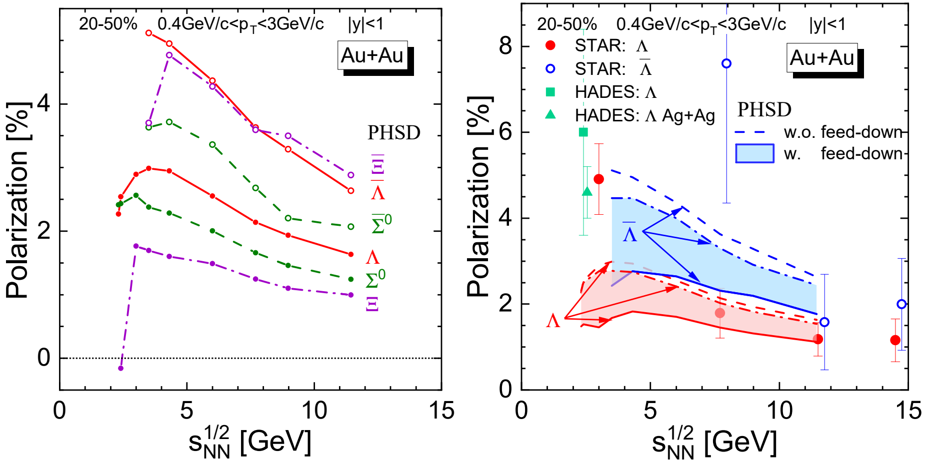
$C_{\Lambda\,\Xi^-} = 0.927$, $C_{\Lambda\,\Xi^0} = 0.900$,

$C_{\Lambda\,\Sigma^0} = -1/3$



- The polarization of $\mathbf{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3\,\text{GeV}$. The *maximum* of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4\,\text{GeV}$
- The polarization of $\bar{\mathbf{\Lambda}}$ *larger in 1.5 – 2 times* than $\mathbf{\Lambda}$. At $\sqrt{s_{NN}} \geq 11.5\,\text{GeV}$ *agrees* with experimental data, but at $\sqrt{s_{NN}} \leq 7.7\,\text{GeV}$ *less*

The Ξ polarization (Λ from Ξ)?!



weak decay: $\Xi \to \Lambda + \pi \quad c\tau = 4.91 - 8.71cm$

no contamination from Σ^0

Conclusions

- The polarization of the $\mathbf{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4$ GeV. The polarization of $\bar{\mathbf{\Lambda}}$ *larger in* $1.5 - 2$ *times* than $\mathbf{\Lambda}$. It *agrees* with experimental data at $\sqrt{s_{NN}} = 11.5$ GeV, but is *less* at $\sqrt{s_{NN}} = 7.7$ GeV.
- Strong polarization suppression is caused by the *feed-down from* $\mathbf{\Sigma^0}$ *and* $\bar{\mathbf{\Sigma}}^{\mathbf{0}}$ hyperons.
- Uncertainty in ratio of Σ^0 to Λ production leads to big uncertainty in measured global polarization of Λ hyperons.
- The experimental study of global polarization of Ξ (maybe Ω) is suggested as the best probe for the Λ polarization.

MPD: polarization transfer

Statistical model + PHSD give direction $\hat{\mathbb{P}}$ and probability $|\mathbb{P}|$ to have some polarization.

- The meaning of polarization

$$|\mathbb{P}| = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

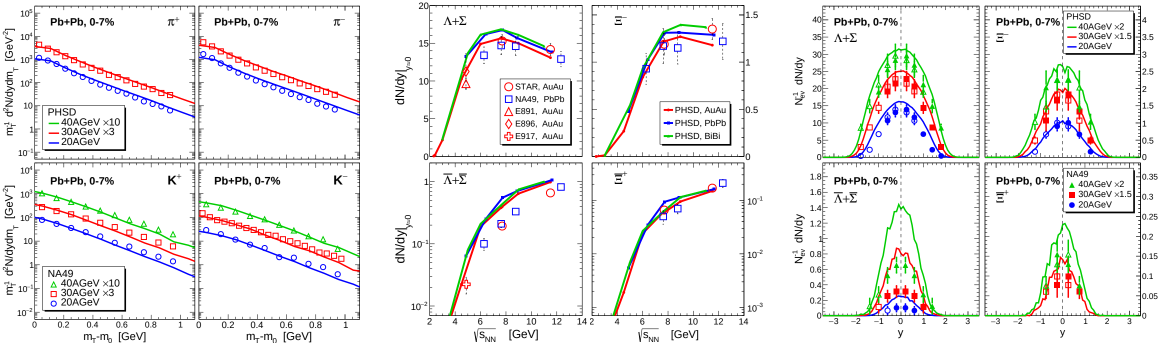
- **Polarization (transfer PHSD→MPD) is unit vector $\hat{\mathbf{n}} = \pm\hat{\mathbb{P}}$ according to probability:**

$$p_\uparrow = \frac{1}{2}\left(1 + |\mathbb{P}|\right) \qquad p_\downarrow = \frac{1}{2}\left(1 - |\mathbb{P}|\right)$$

- **Polarization transfer in decays in MCStack $\hat{\mathbf{n}}_D = \pm\hat{\mathbf{n}}_P$ is done according to probability of spin flop:**

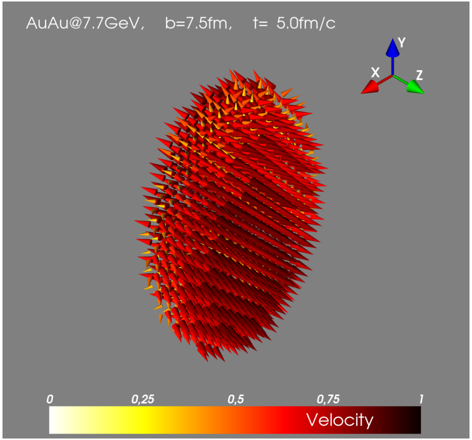
$$\Xi \to \Lambda: \; p_\downarrow = C_{\Lambda\,\Xi}, \qquad \textit{but for } \Sigma^0 \to \Lambda: \; p_\downarrow = 1 - |C_{\Lambda\,\Sigma^0}|.$$

The PHSD performance



Velocity and vorticity fields

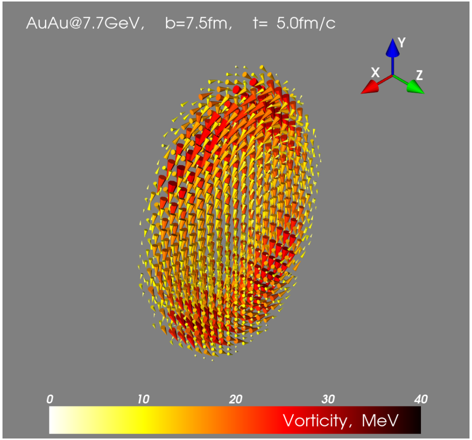
$\omega_{\text{STAR}} \approx 10^{22}\,\text{s}^{-1} \approx 6.6\,\text{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\text{GeV}/\text{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\text{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



Hydrodynamic vorticity field

$\boldsymbol{\omega} = \text{rot}\,\boldsymbol{v}$

for clarity draw only $|\boldsymbol{\omega}| > 5\,\text{MeV}/\hbar$

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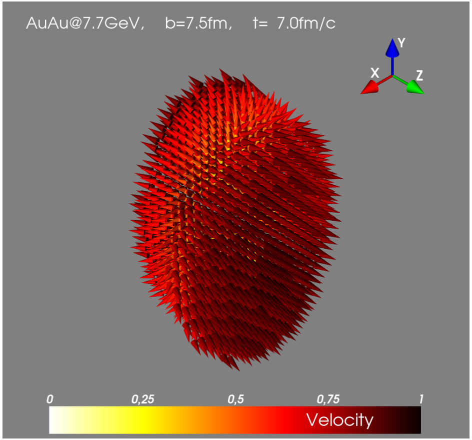

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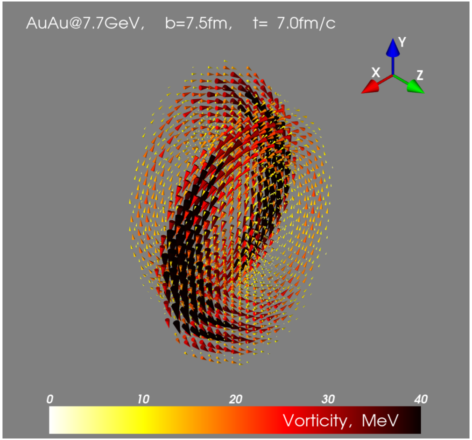

Hydrodynamic vorticity field

$\boldsymbol{\omega} = {\rm rot}\, \boldsymbol{v}$

$|\boldsymbol{\omega}|_{\rm max} \approx 67.1\, MeV/\hbar!$

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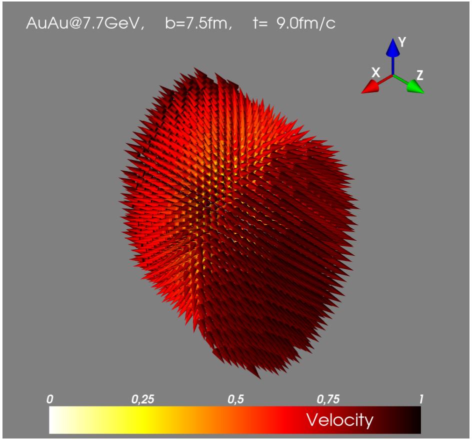

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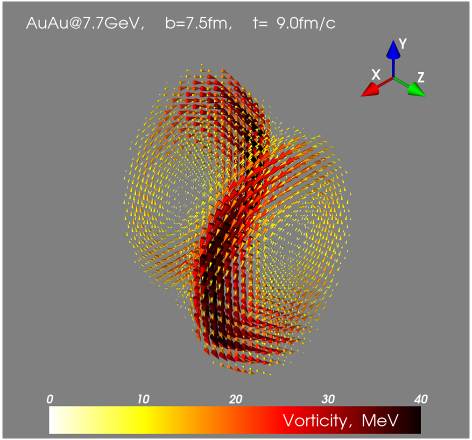

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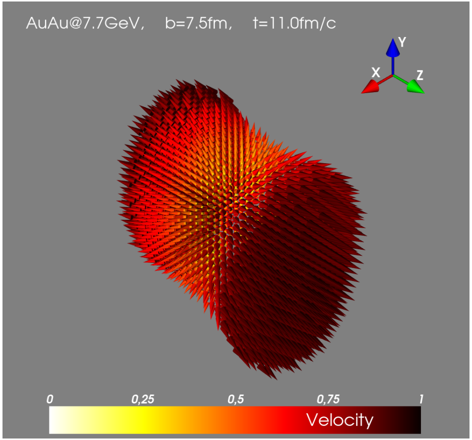

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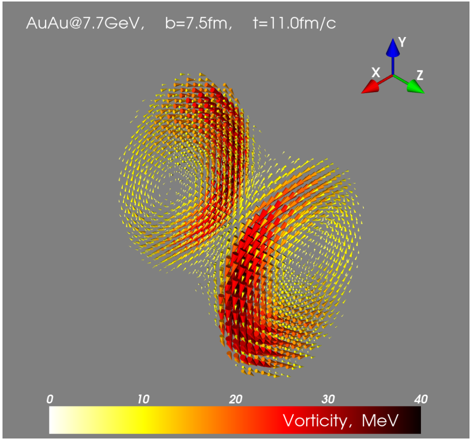

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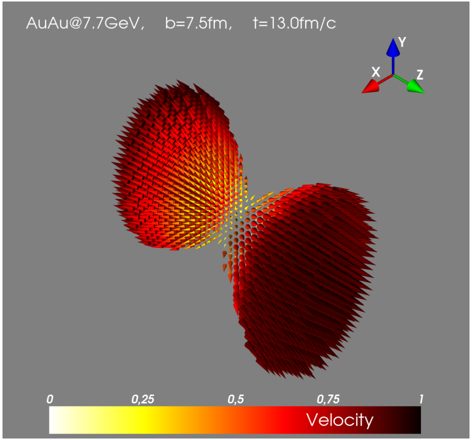

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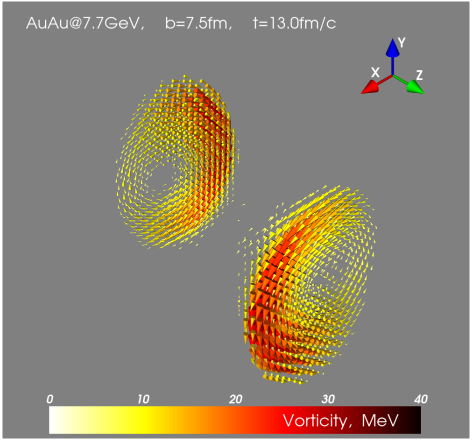

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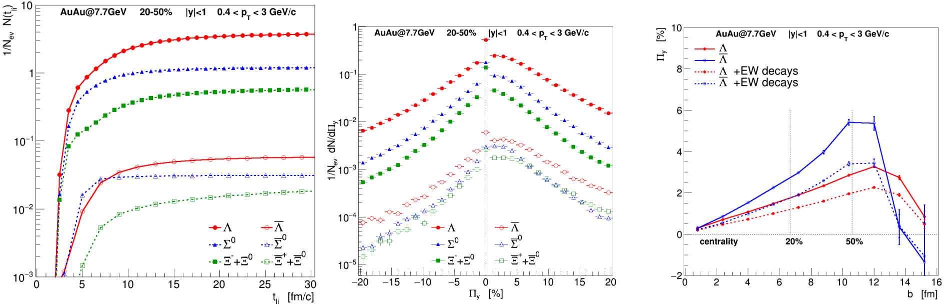
AuAu@7.7GeV 20-50% |y|<1 0.4 < p_T < 3 GeV/c
$1/N_{ev}$ $N(t_{li})$
t_{li} [fm/c]
Λ
$\overline{\Lambda}$
Σ^0
$\overline{\Sigma}^0$
$\Xi^- + \Xi^0$
$\overline{\Xi}^+ + \overline{\Xi}^0$
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$1/N_{ev}$ $dN/d\Pi_y$
Π_y [%]
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Π_y [%]
Λ +EW decays
$\overline{\Lambda}$ +EW decays
centrality
20%
50%
b [fm]