Vorticity and polarization in SMASH via a coarse-grained approach

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Transport Meeting

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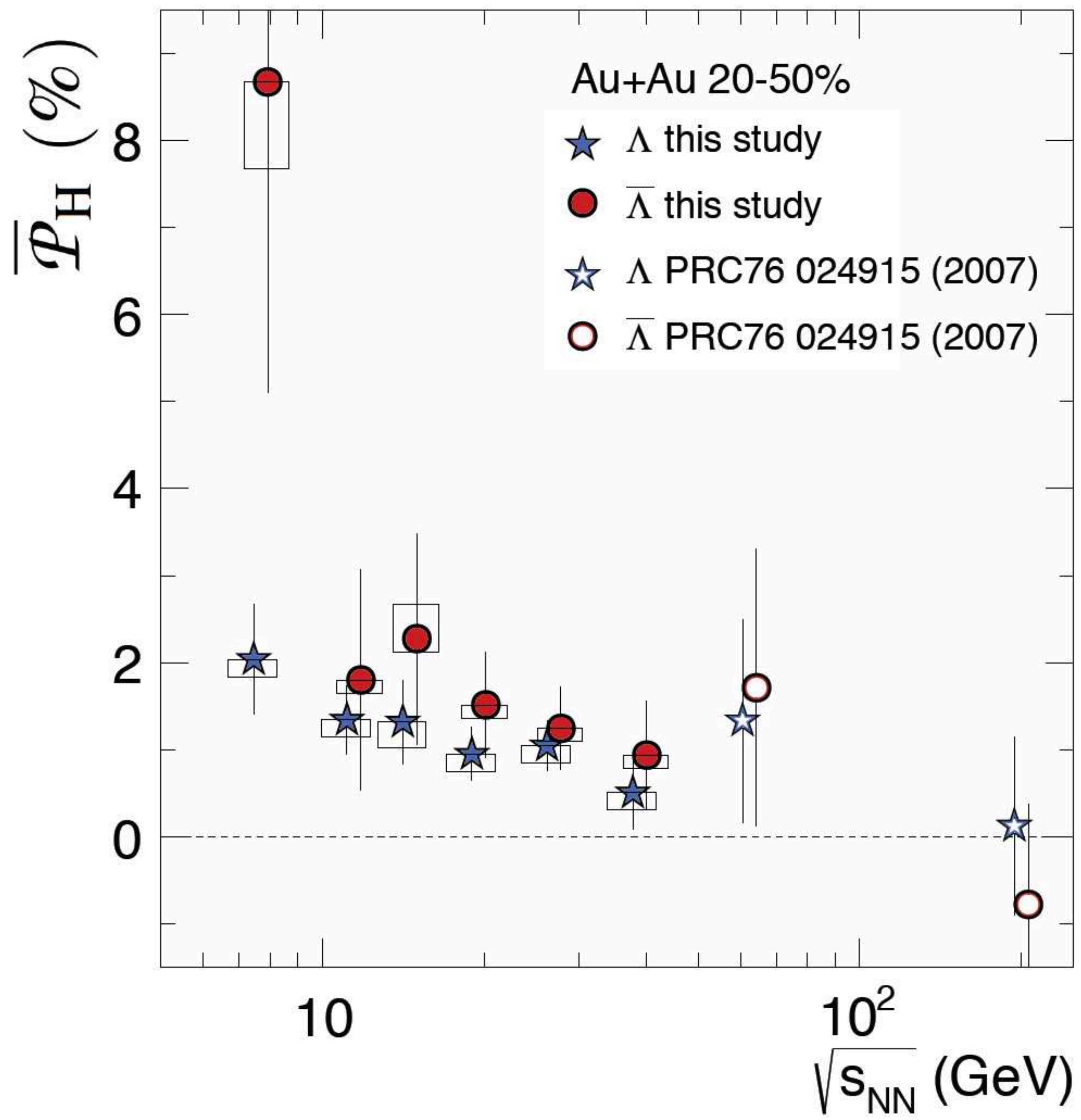
Motivation

STAR Collaboration (at RHIC) findings in 2017

- Angular momentum of order $1000\hbar$ (in non-central collisions)
- Alignment between angular momentum and spin of emitted particles
- Λ (and $\bar{\Lambda}$) hyperons chosen for analysis
    - Proton of weak decay ($\Lambda \rightarrow p + \pi^-$) tends to be emitted along spin direction of Λ (self-analyzing)



L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

SMASH transport approach

Simulating Many Accelerated Strongly-interacting Hadrons

smash

- Relativistic hadronic transport approach based on

Relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{coll}$$

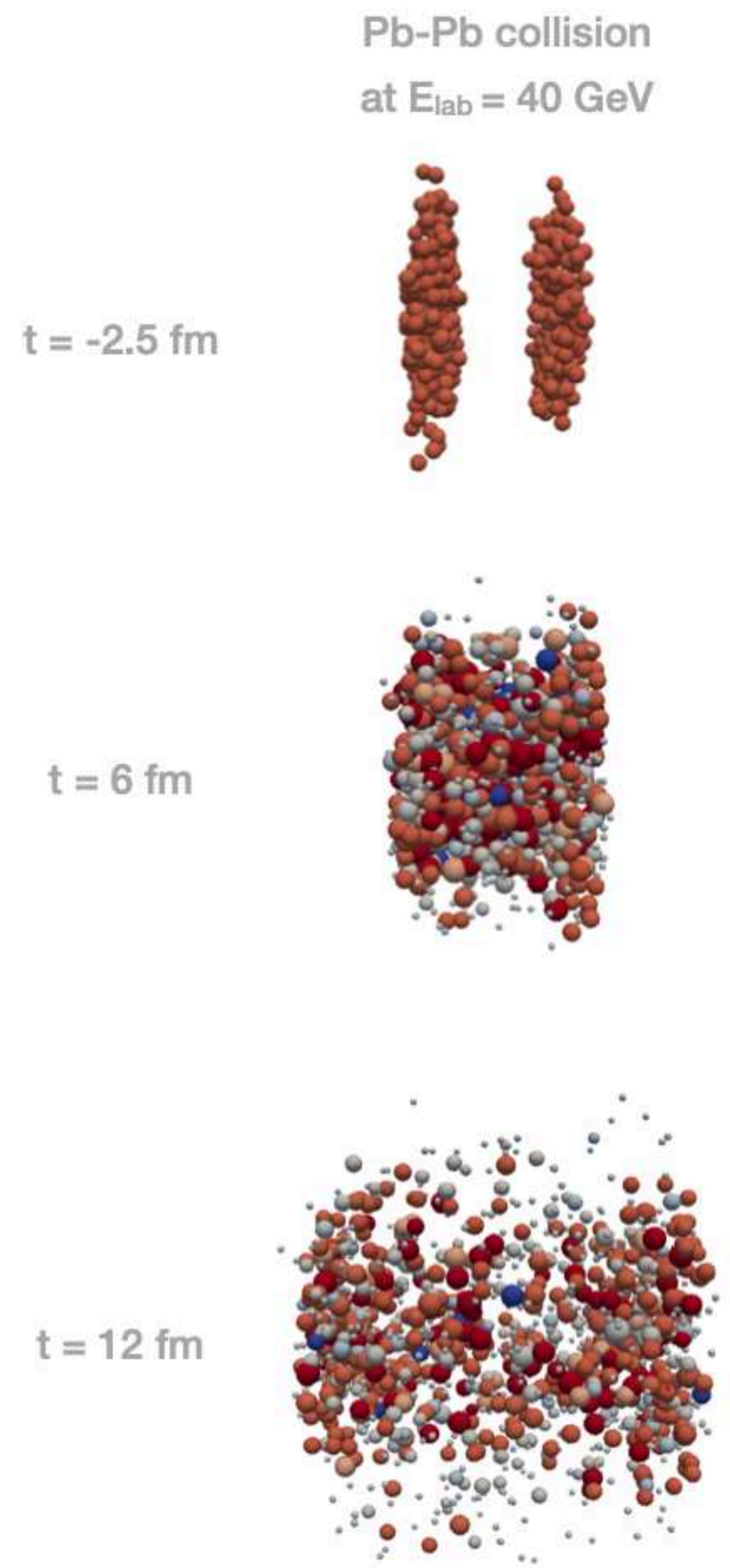
(no potentials used in this work, hence $F^\alpha = 0$)

Geometrical collision criterion

$$d_{trans} < d_{int} = \sqrt{\frac{\sigma_{tot}}{\pi}}$$

- Includes all hadrons from the PDG (2018) up to m ~ 2.35 GeV
- Publicly available at www.smash-transport.github.io

DOI 10.5281/zenodo.3484711



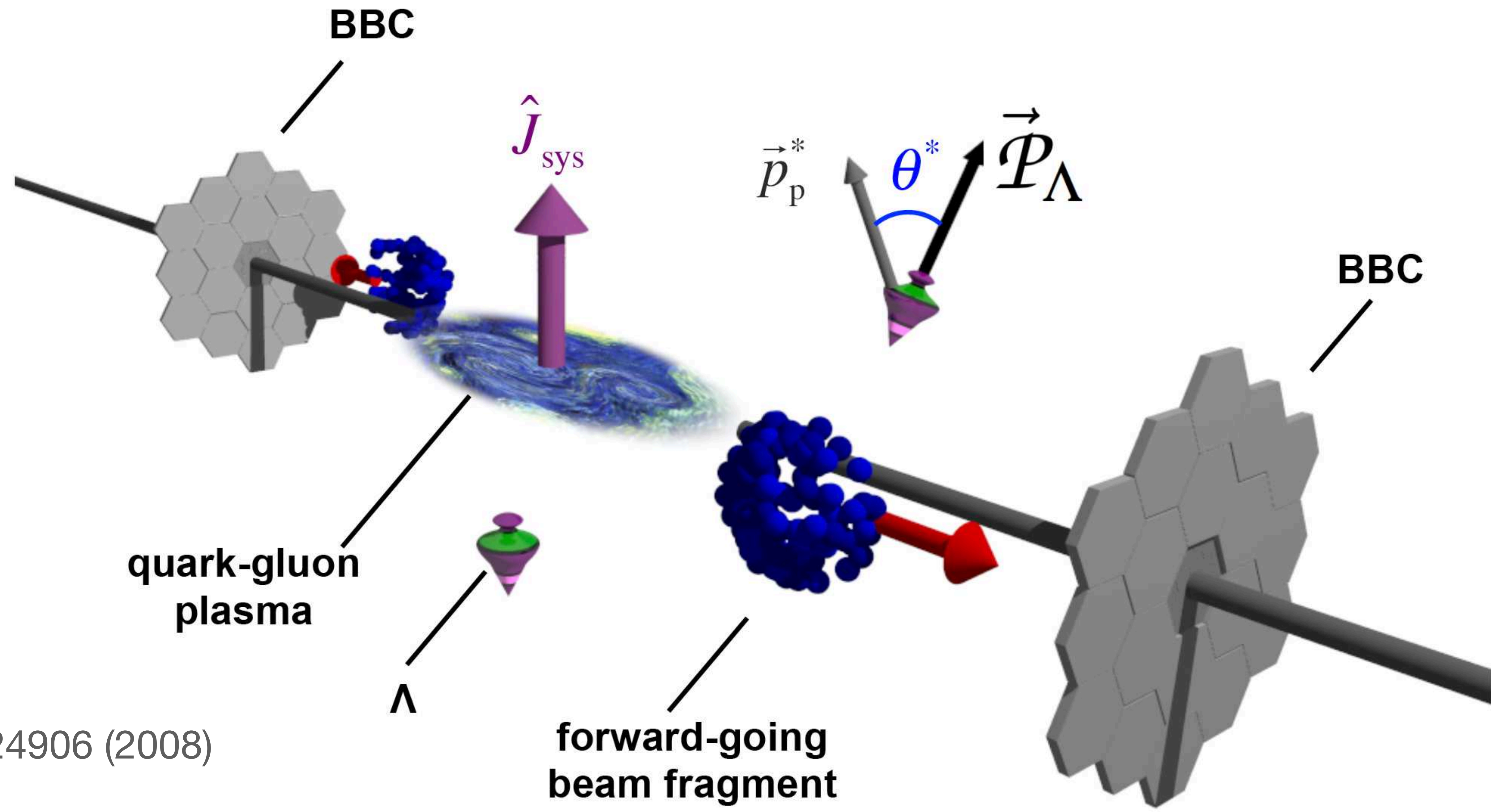
J. Weil et al., Phys. Rev. C 94, 054905 (2016)

Global polarization of Λ hyperons

Global polarization

$$P = \frac{\langle \mathbf{S}^* \rangle \cdot \mathbf{J}}{|\langle \mathbf{S}^* \rangle| \cdot |\mathbf{J}|} \xrightarrow[|\mathbf{J}| \approx \mathbf{J}_y]{|\langle \mathbf{S}^* \rangle| = 1/2} P = 2 \cdot \langle \mathbf{S}^* \rangle_y$$

Hui Li et al., arXiv:1704.01507v2 [nucl-th]; F. Becattini et al., Phys. Rev. C 77.2, 024906 (2008)



Picture
L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

Λ spin 4-vector

$$S^\mu(x,p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\nu \varpi_{\rho\sigma}(x)$$

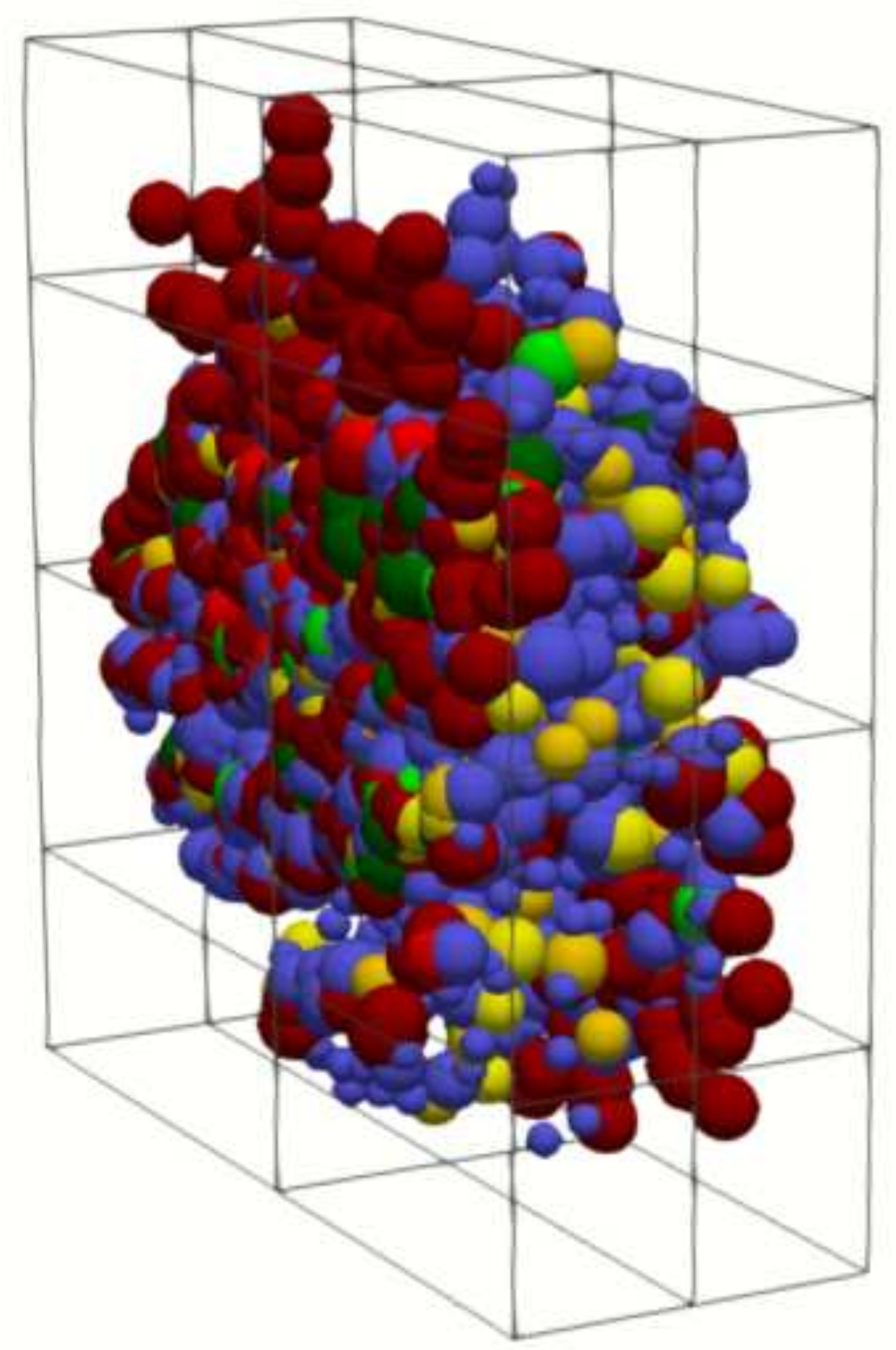
Thermal vorticity

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

O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)

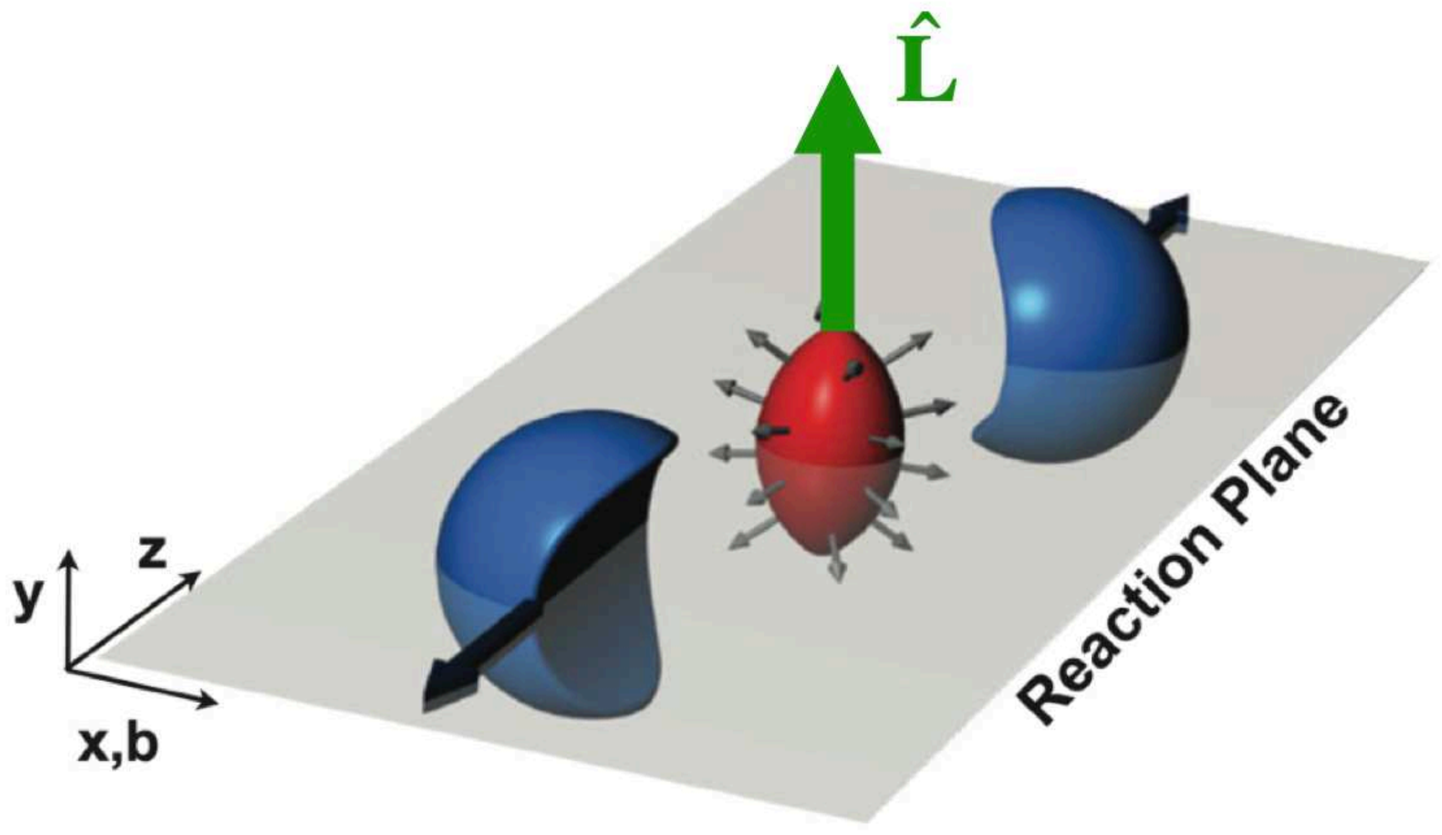
Coarse-grained approach

- Space divided into many small cells
  - Done by SMASH which provides thermodynamic output ($T^{\mu\nu}$, Landau velocity, $j^\mu_Q, j^\mu_B, j^\mu_S$)
- Averaging over many events calculating vorticity and spins of emitted Λ
  - Done by codes written by Gabriele Inghirami
    Publicly available at www.github.com/gabriele-inghirami/

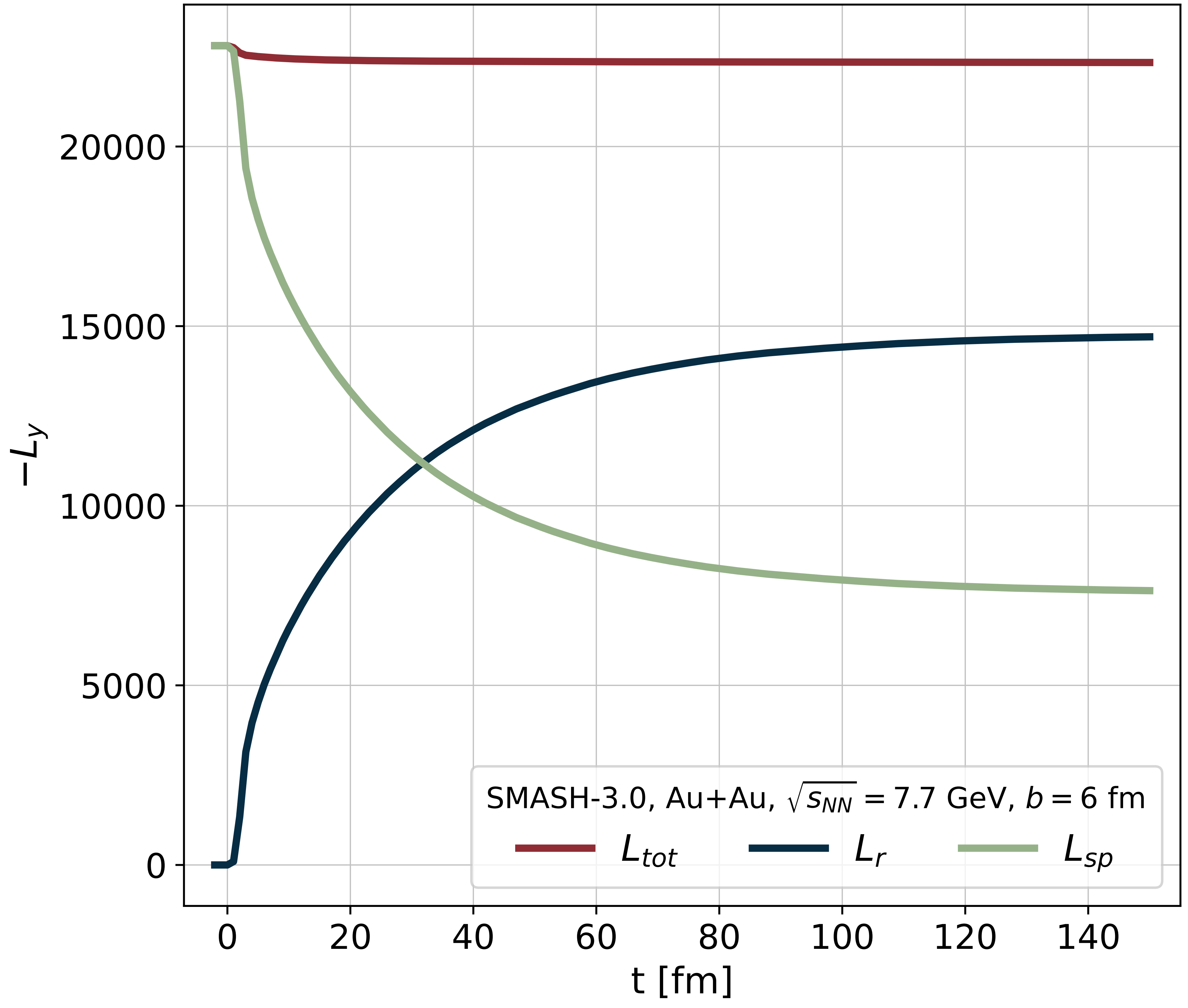


Global angular momentum in SMASH

- SMASH-3.0 shows high global angular momentum in line with STAR statement of order $1000\hbar$ (in the first few Fermi)

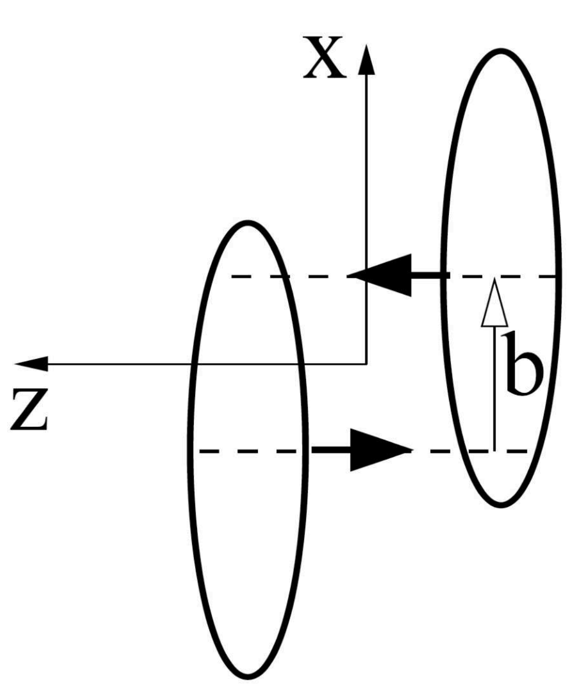


Picture R. Snellings, New J. Phys. 13, 055008 (2011)

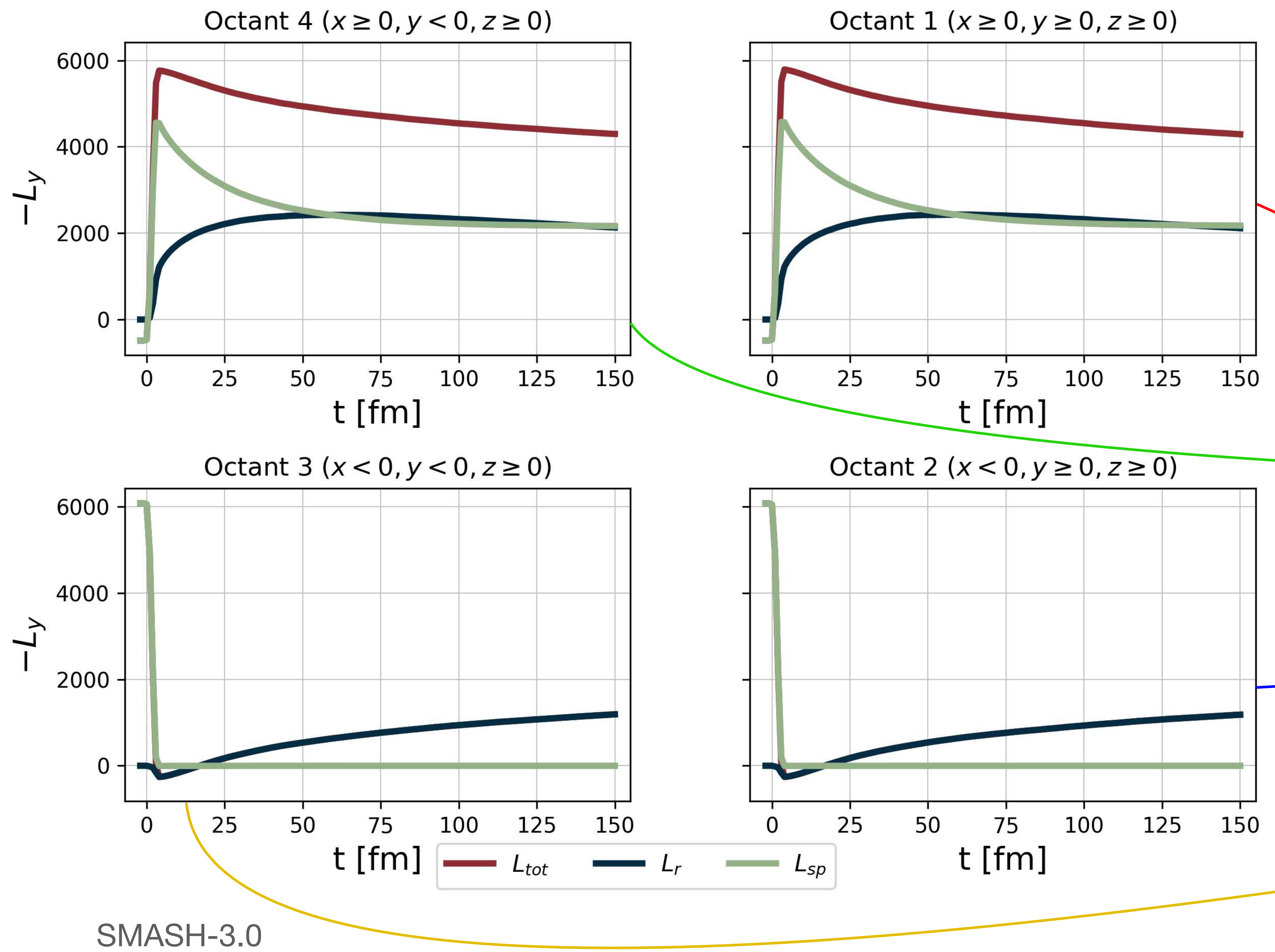


Angular momentum per octant

Coordinate space

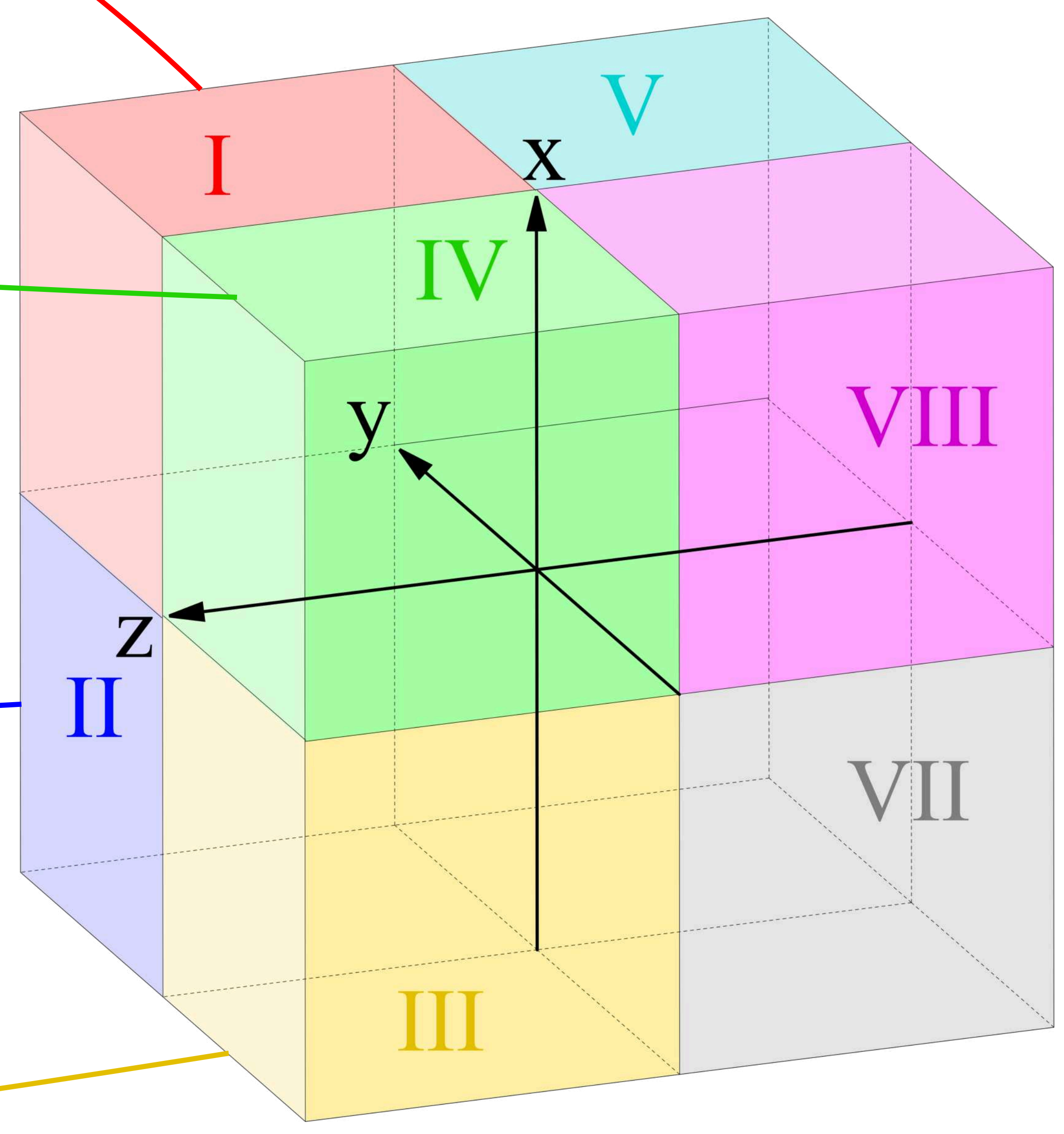


Collision sketch (modified)
Z. Liang et al.,
arXiv:nucl-th/0410079v5



SMASH-3.0

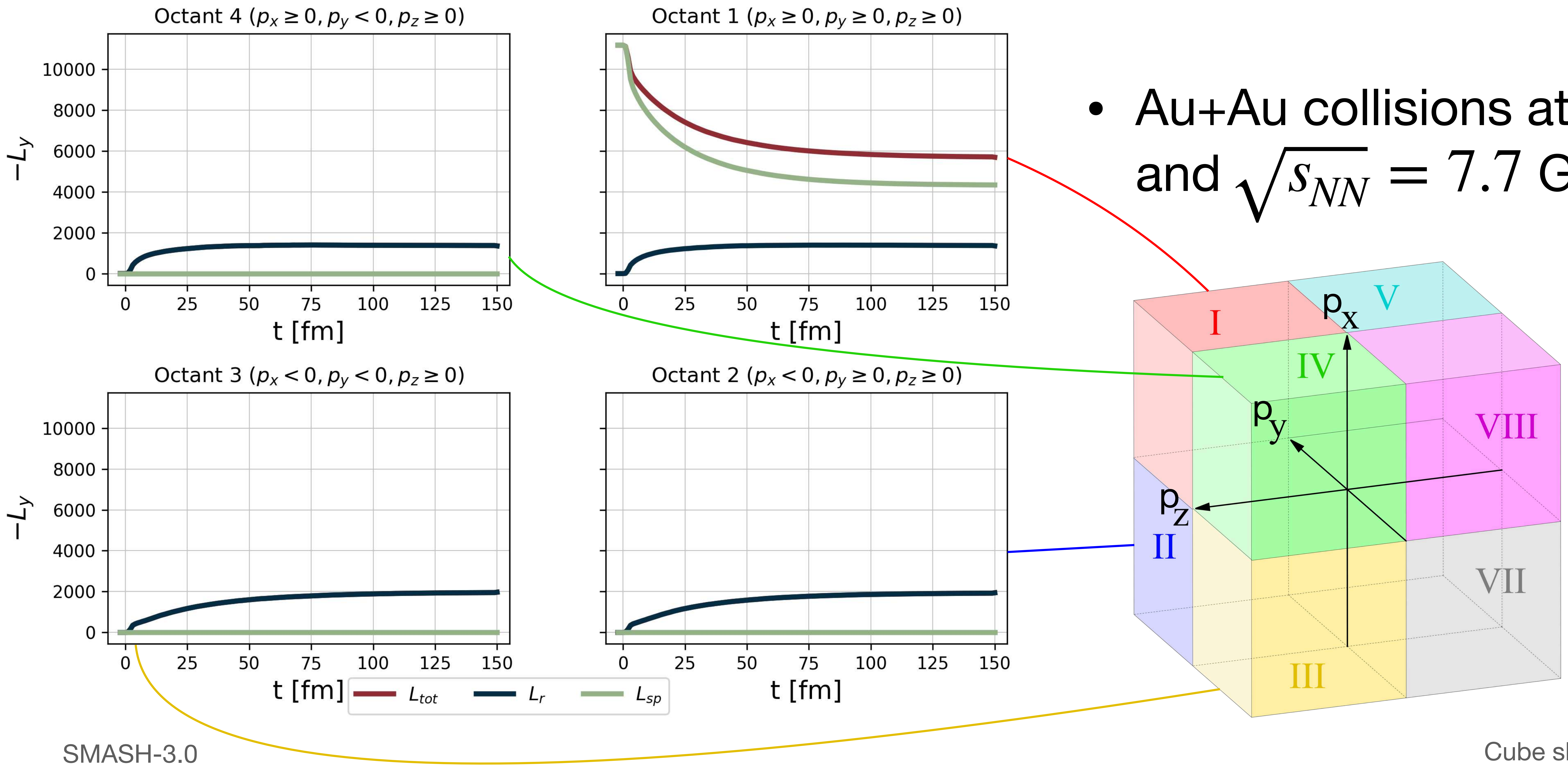
- Au+Au collisions at $b = 6$ fm and $\sqrt{s_{NN}} = 7.7$ GeV



Cube sketch (modified)
https://de-academic.com/dic.nsf/dewiki/1045183

Angular momentum per octant

Momentum space



- Au+Au collisions at $b = 6$ fm and $\sqrt{s_{NN}} = 7.7$ GeV

SMASH-3.0

Cube sketch (modified)
https://de-academic.com/dic.nsf/dewiki/1045183

Hyperon decay in SMASH

- Weak & electromagnetic decays in SMASH disabled by default
- Following decays do not occur and mother particles are stable in SMASH
  - $\Lambda \to p + \pi^-$
  - $\Sigma^0 \to \Lambda + \gamma$
  - $\Xi^0 \to \Lambda + \pi^0$
  - $\Xi^- \to \Lambda + \pi^-$
  - Ω decays into Λ, Ξ^0 or Ξ^-

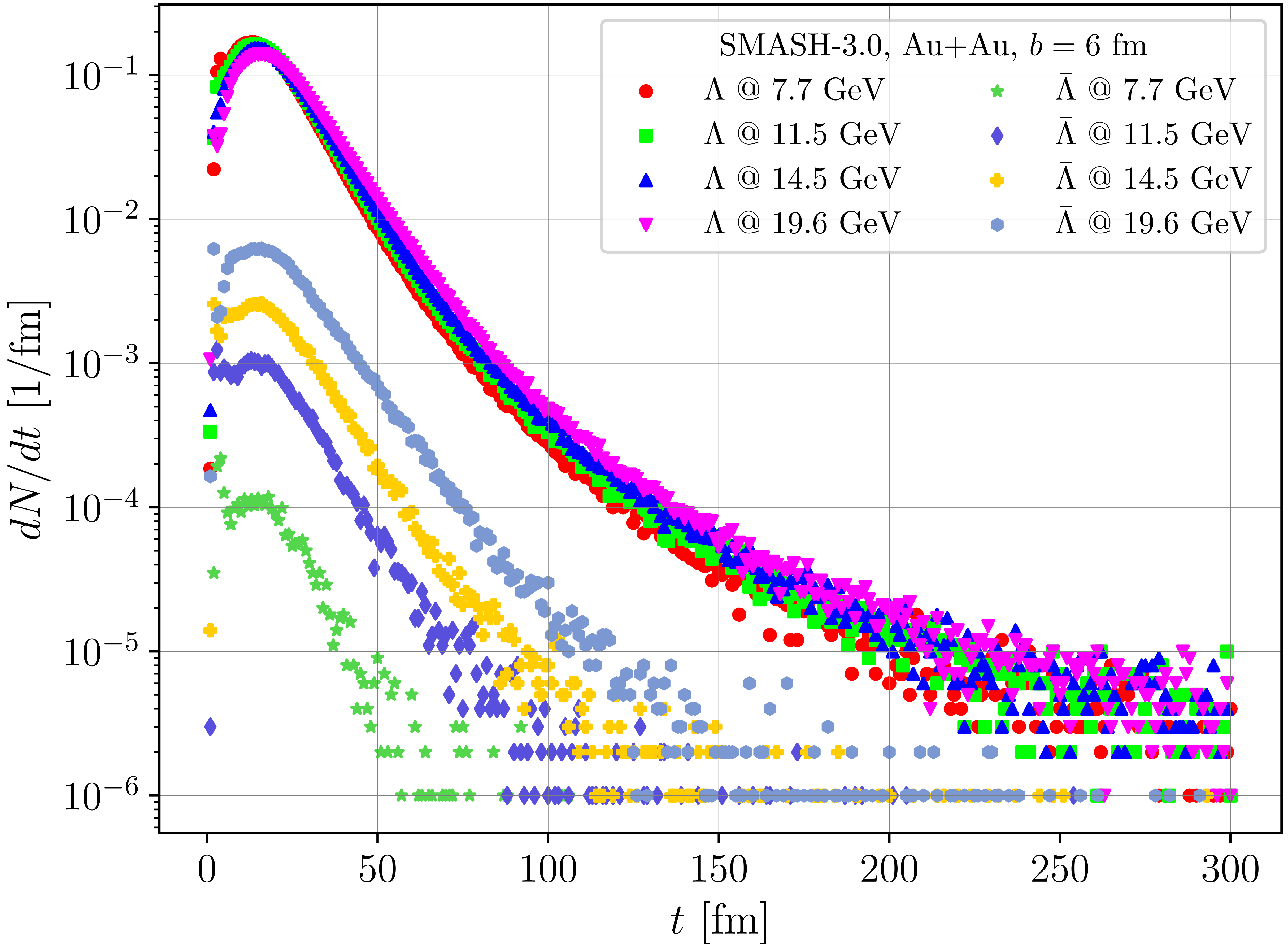
Λ and $\bar{\Lambda}$ emission time evolution

- **Chemical freeze-out**: Point in time where last inelastic collision of a particle takes place

- **Kinetic freeze-out**: Interaction point of last elastic collision

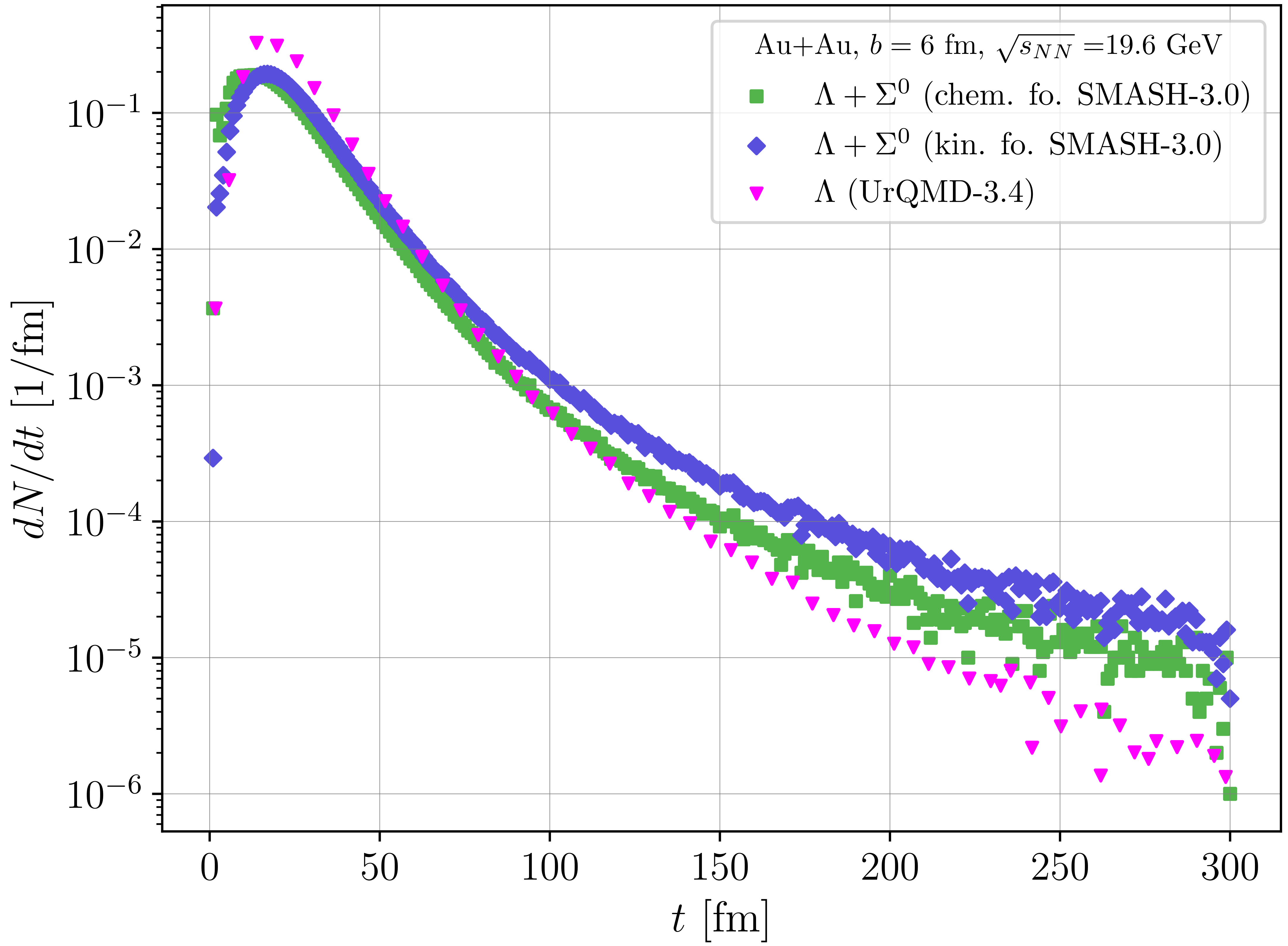
L. Kumar, Nucl. Phys. A 931 (2014)

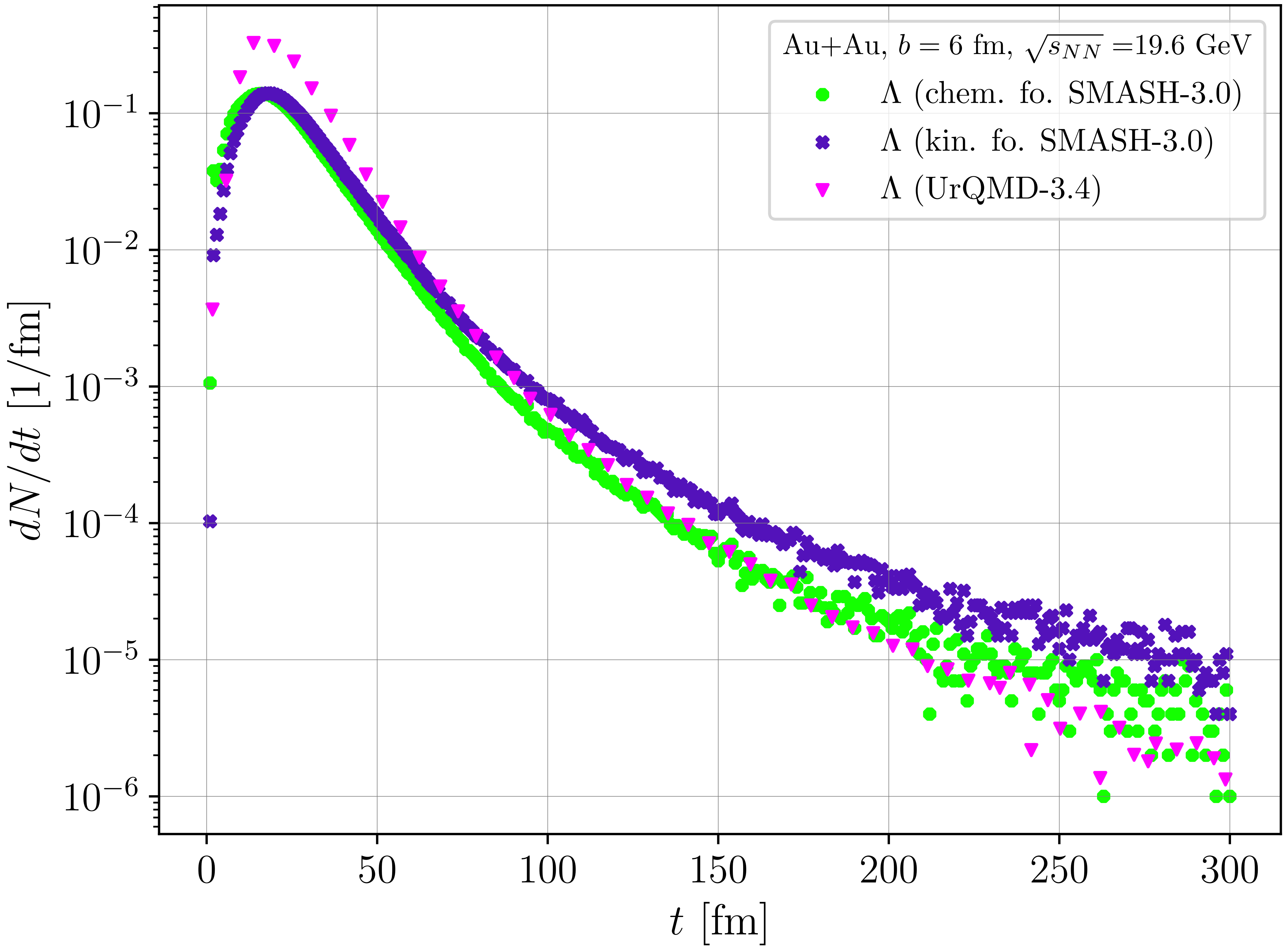
Chemical freeze-out



Λ and $\Lambda + \Sigma^0$ emission time evolution

Chemical and kinetic freeze-out compared to UrQMD data

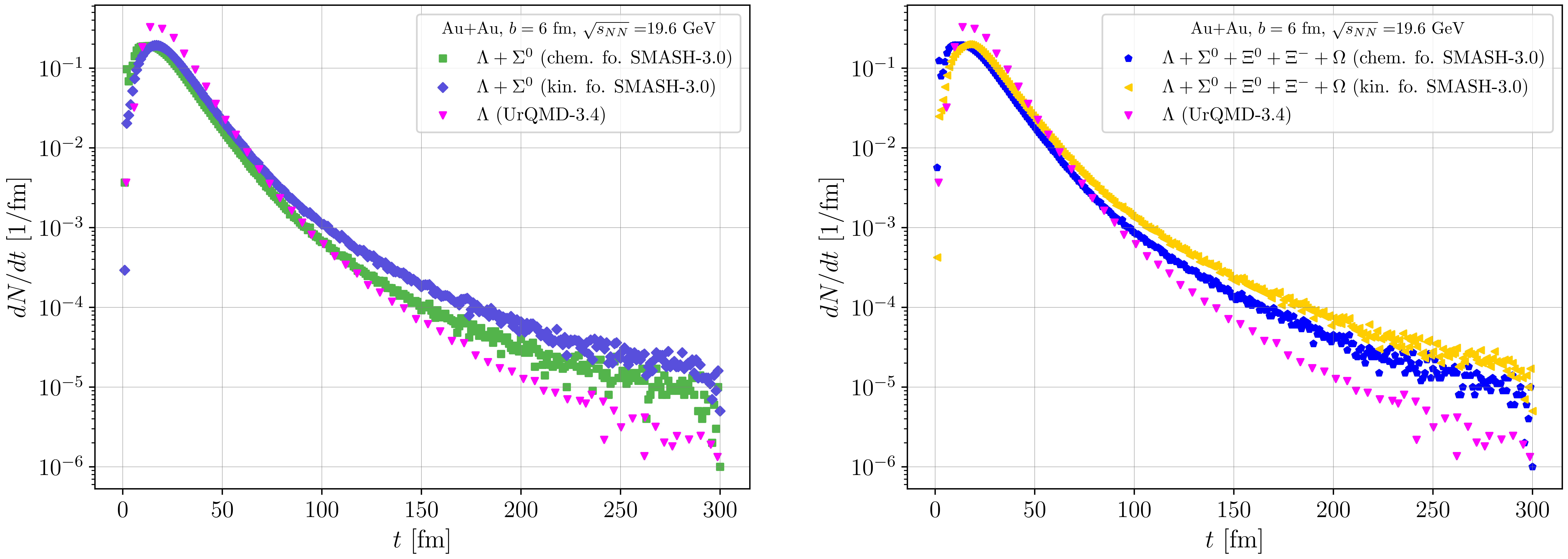




UrQMD data: O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)

$\Lambda + \Sigma^0 + \Xi^0 + \Xi^- + \Omega$ emission time evolution

Chemical and kinetic freeze-out compared to UrQMD data

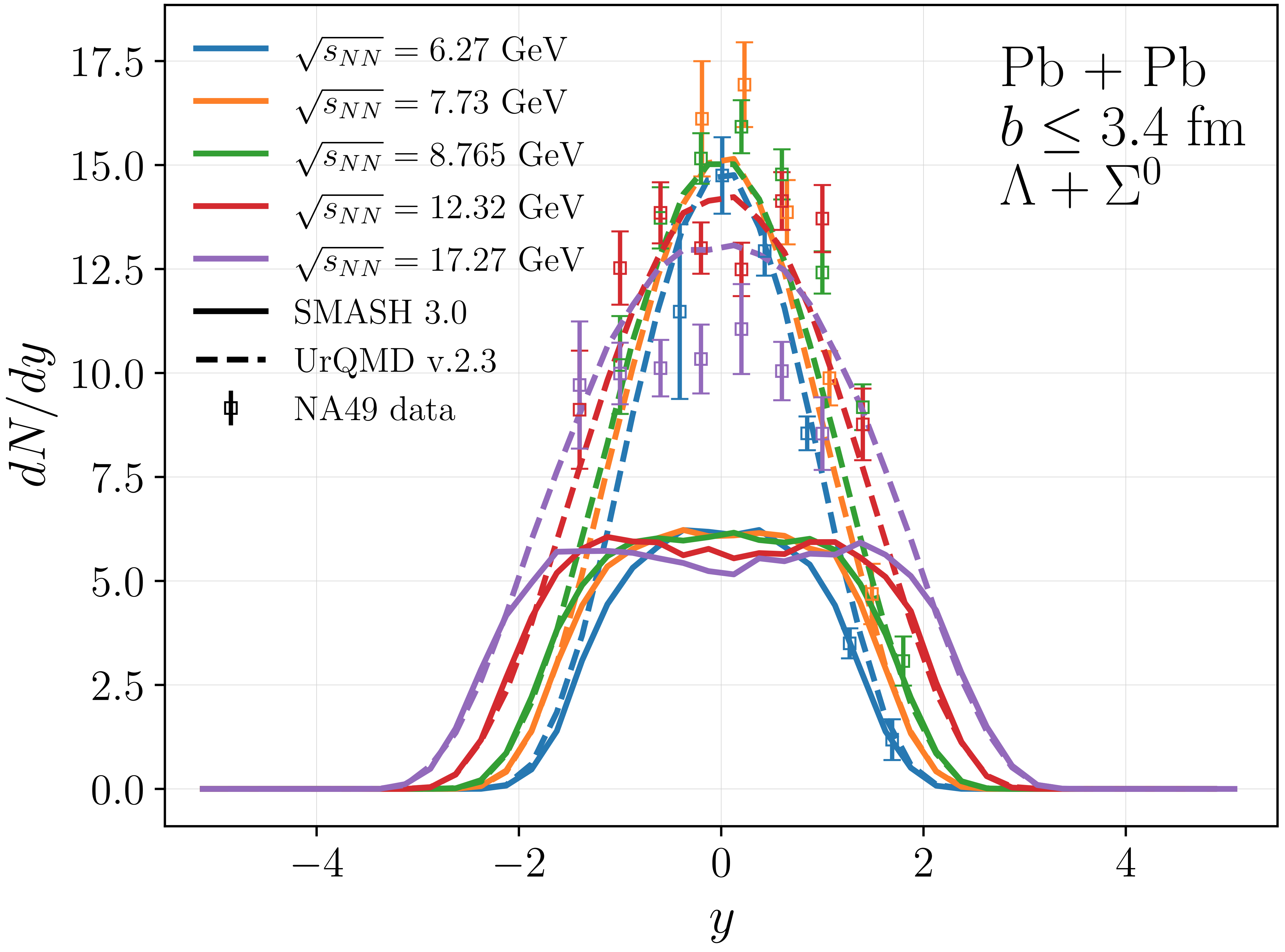


UrQMD data: O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)

$\Lambda + \Sigma^0$ production yields

SMASH, UrQMD, and NA49 experimental data

- Deviation by factor of 2 from UrQMD and experimental data
  - Strangeness production in SMASH too low…
    V. Steinberg et al., Phys. Rev. C 99.6 (2019), 064908
  - … leading to lower hyperon yields

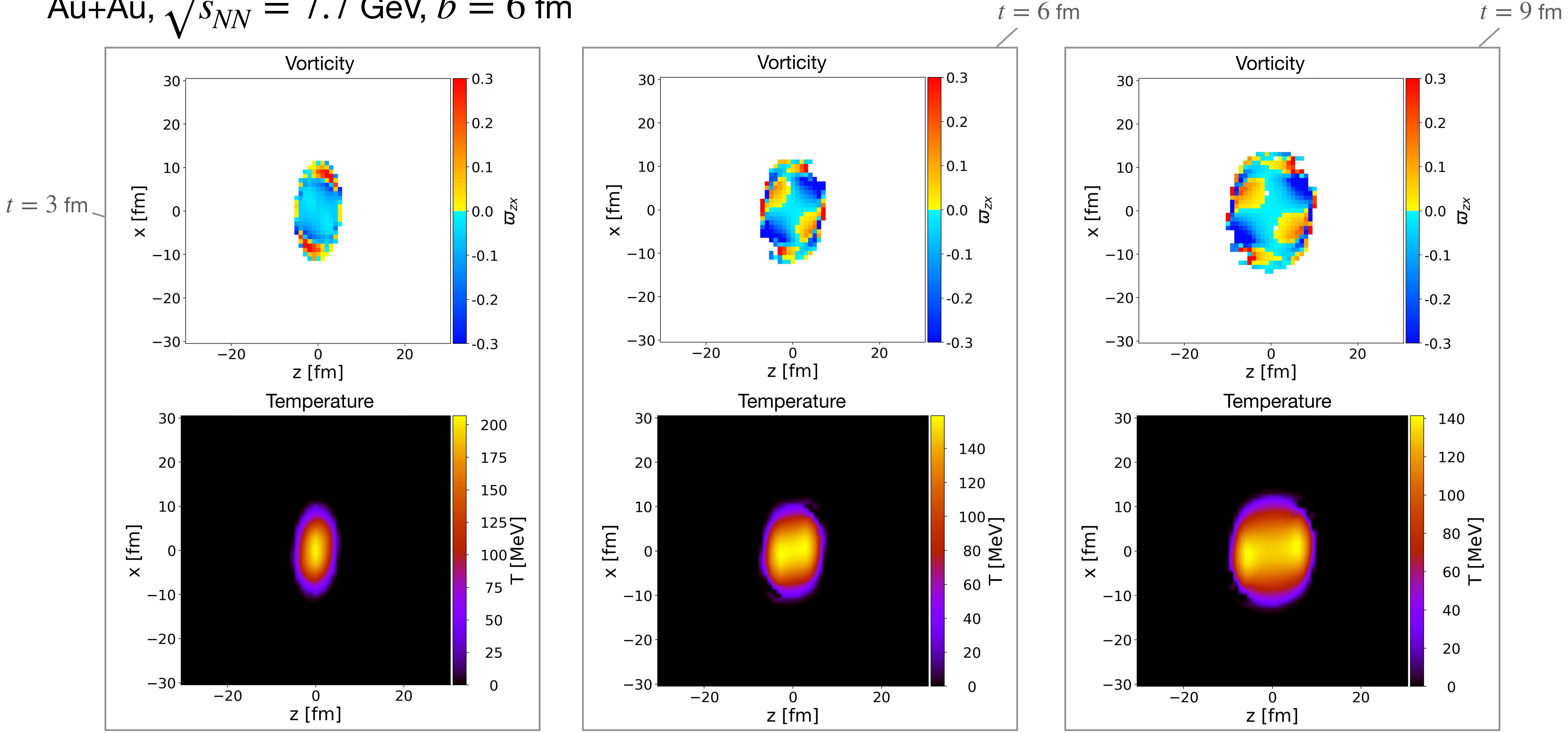


UrQMD data: H. Petersen et al., arXiv:0805.0567v1 [hep-ph]
NA49 data: C. Blume et al., Journal of Physics G: Nuclear and Particle Physics 31.6 (2005), s685

Vorticity in the reaction plane

UrQMD EoS used to calculate vorticity
D. Zschiesche et al., Phys. Lett. B 547, 7 (2002)

Au+Au, $\sqrt{s_{NN}} = 7.7$ GeV, $b = 6$ fm



SMASH-3.0

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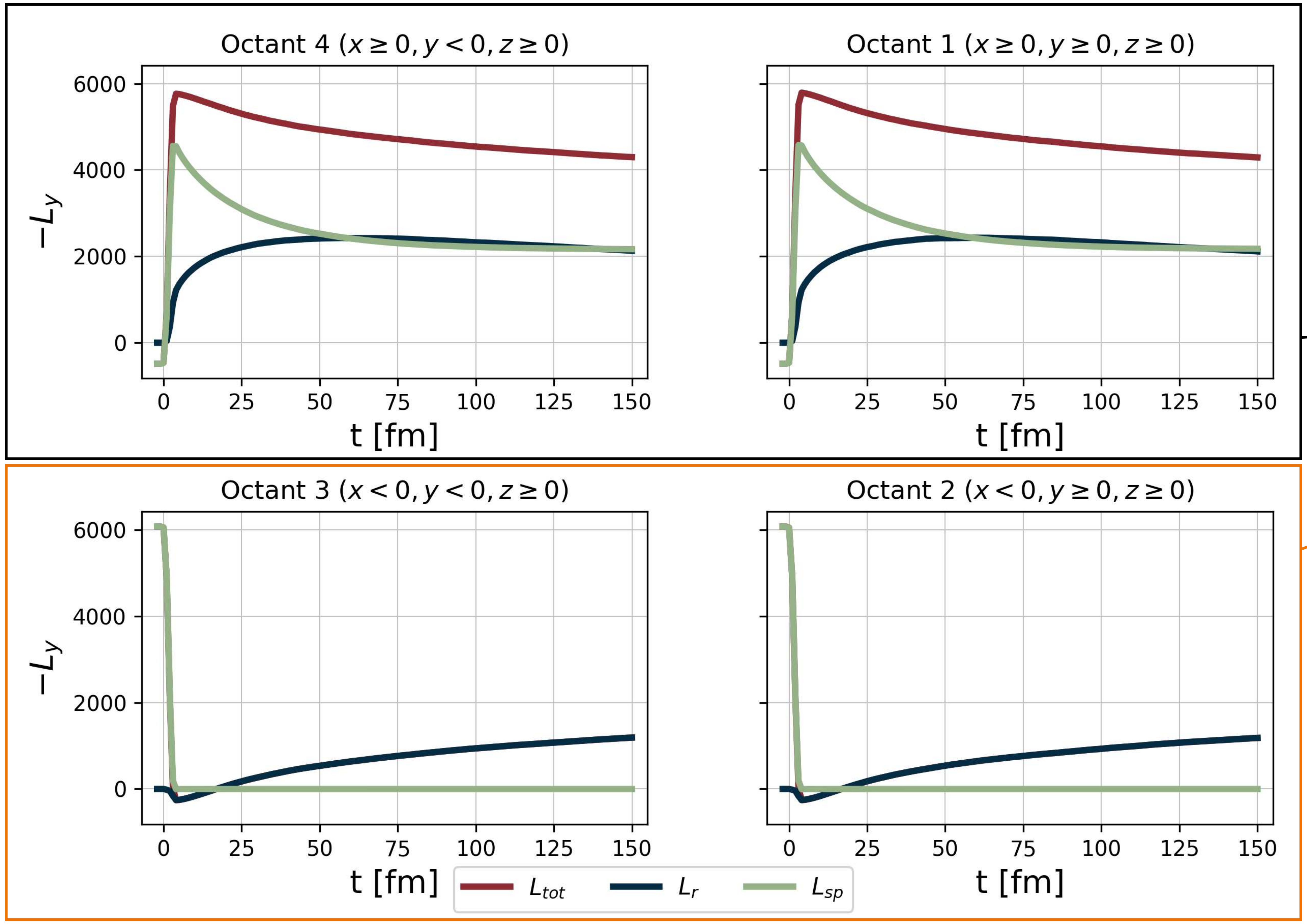
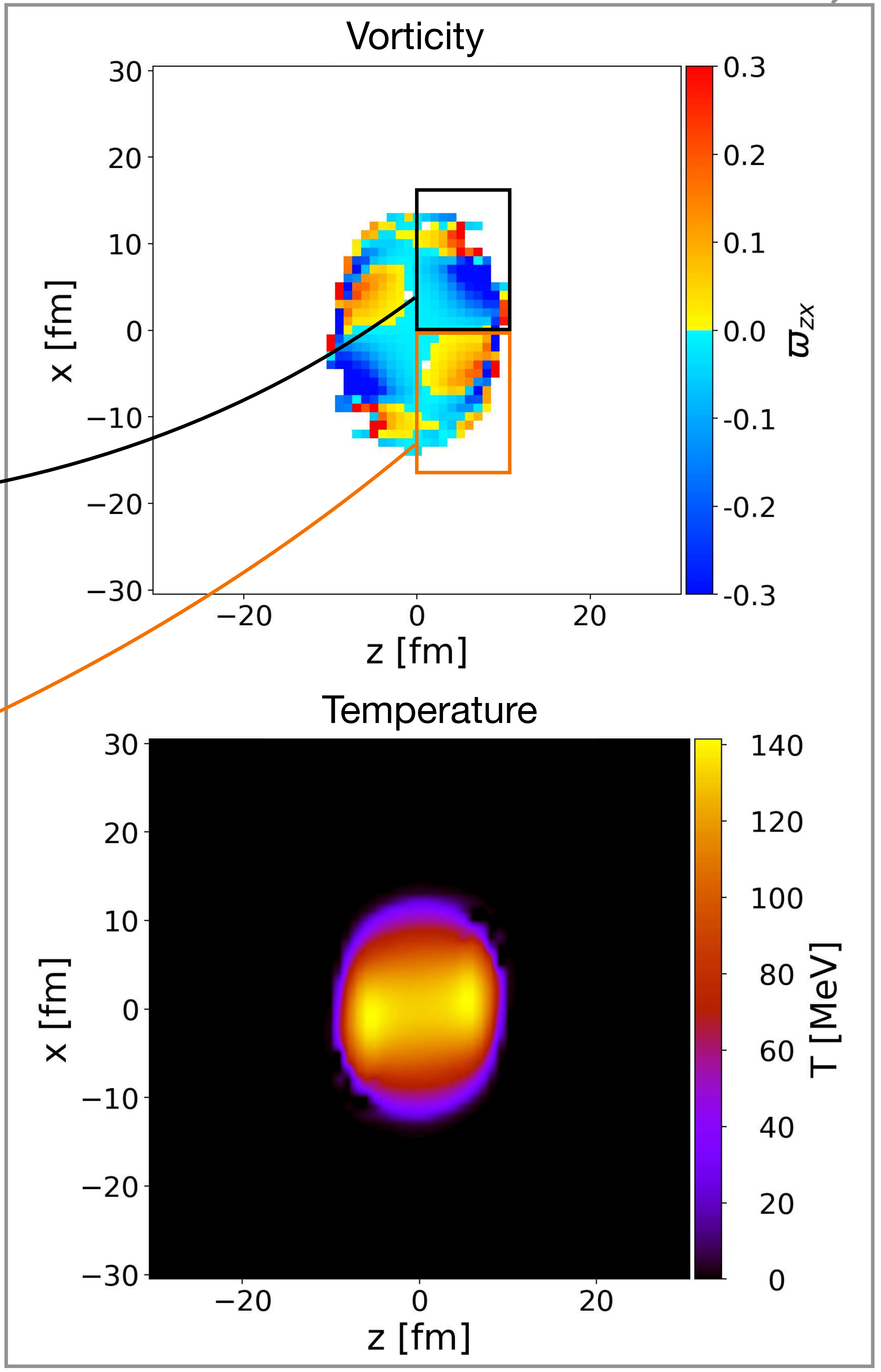


$t = 9$ fm



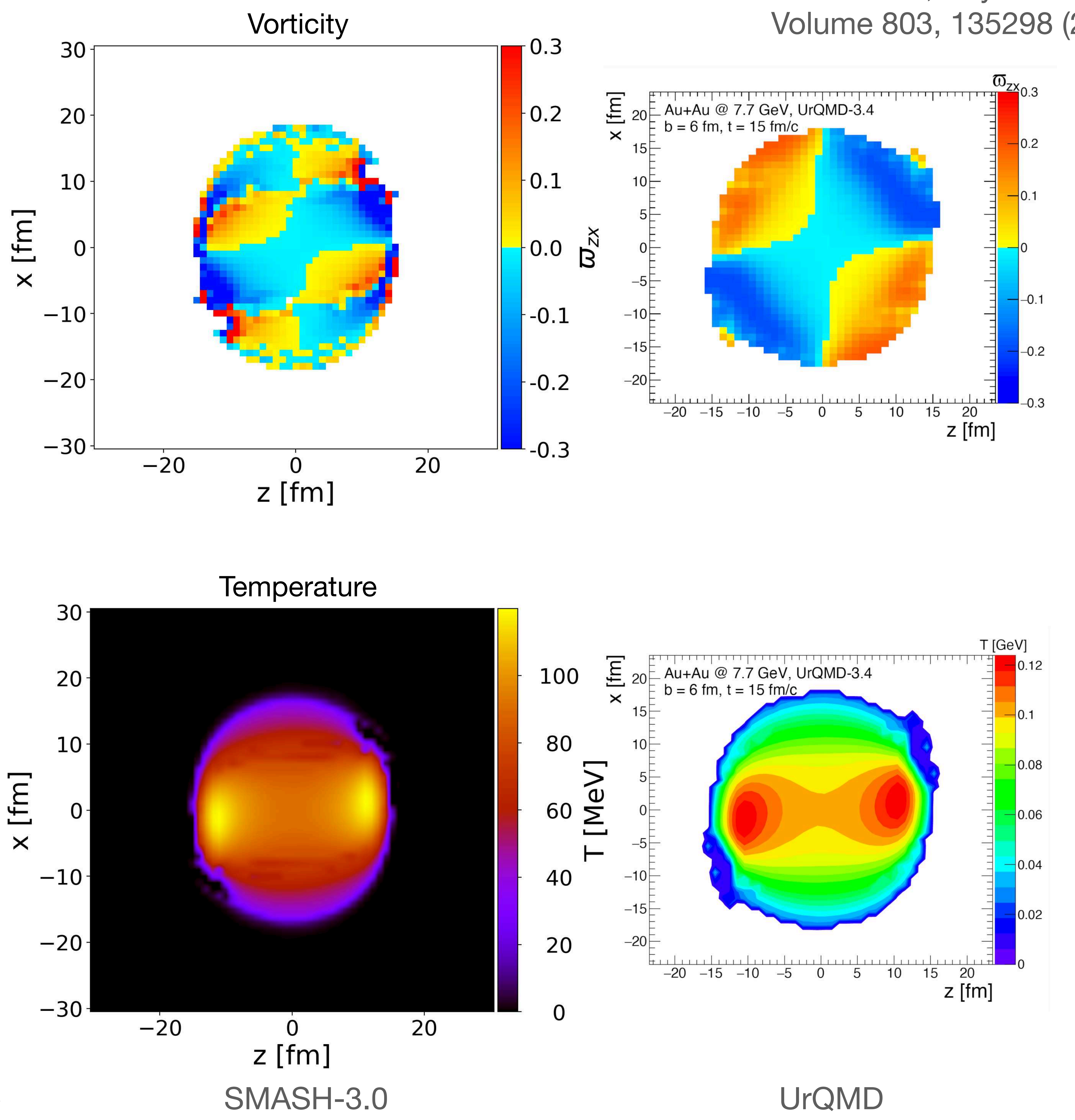
SMASH-3.0

Vorticity in the reaction plane

Au+Au, $\sqrt{s_{NN}} = 7.7$ GeV, $b = 6$ fm, $t = 15$ fm

- “Central area” of SMASH and UrQMD vorticity similar
- “Upper and lower area” different
- Vorticity dependent on used equation of state

O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)



UrQMD EoS used to calculate SMASH vorticity
D. Zschiesche et al., Phys. Lett. B 547, 7 (2002)

Global Hyperon Polarization

Global polarization

$$P = \frac{\langle \mathbf{S}^* \rangle \cdot \mathbf{J}}{|\langle \mathbf{S}^* \rangle| \cdot |\mathbf{J}|} \xrightarrow[|\mathbf{J}| \approx \mathbf{J}_y]{|\langle \mathbf{S}^* \rangle| = 1/2} P = 2 \cdot \langle \mathbf{S}^* \rangle_y$$

Hui Li et al., arXiv:1704.01507v2 [nucl-th]; F. Becattini et al., Phys. Rev. C 77.2, 024906 (2008)

- Computation of polarization with time and spatial emission points of the Λ hyperons and vorticity of fluid cells

Λ spin 4-vector

$$S^\mu(x, p) = -\frac{1}{8m} \epsilon^{\mu\nu\rho\sigma} p_\nu \varpi_{\rho\sigma}(x)$$

Thermal vorticity

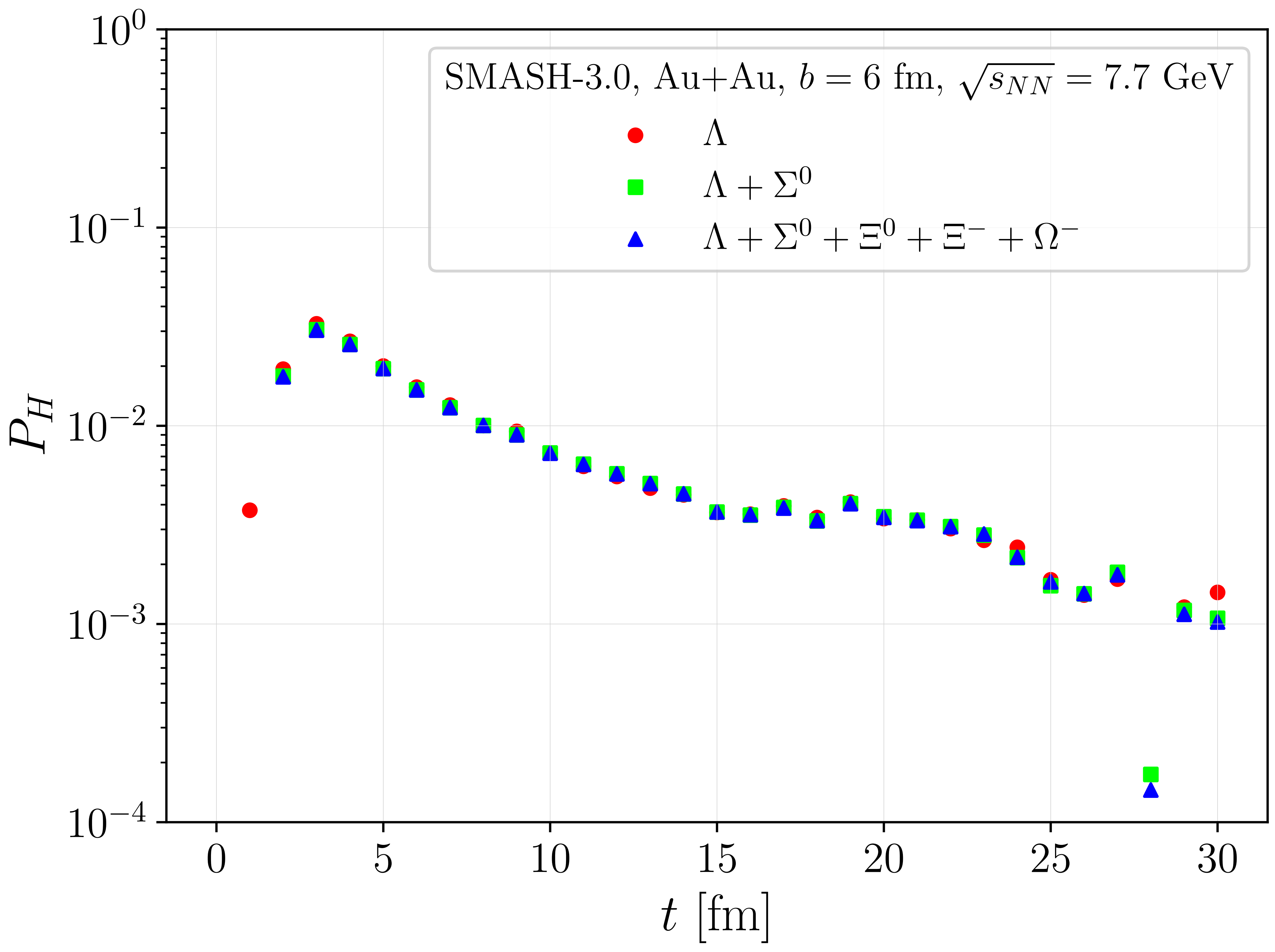
$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu) \quad \text{with} \quad \beta_\mu = \frac{u_\mu}{T}$$

O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)

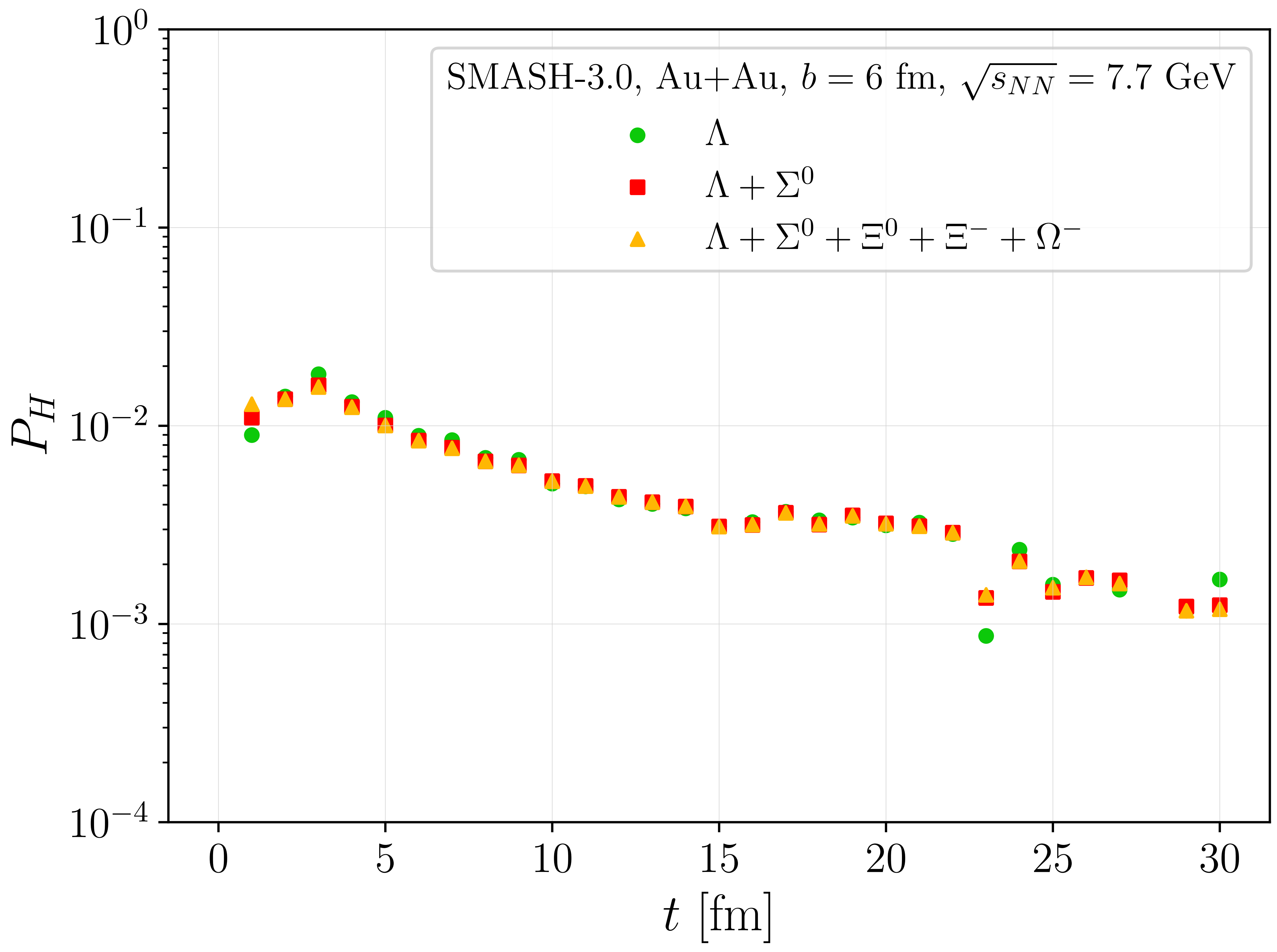
Global Hyperon Polarization

Feed-down contributions

Chemical freeze-out



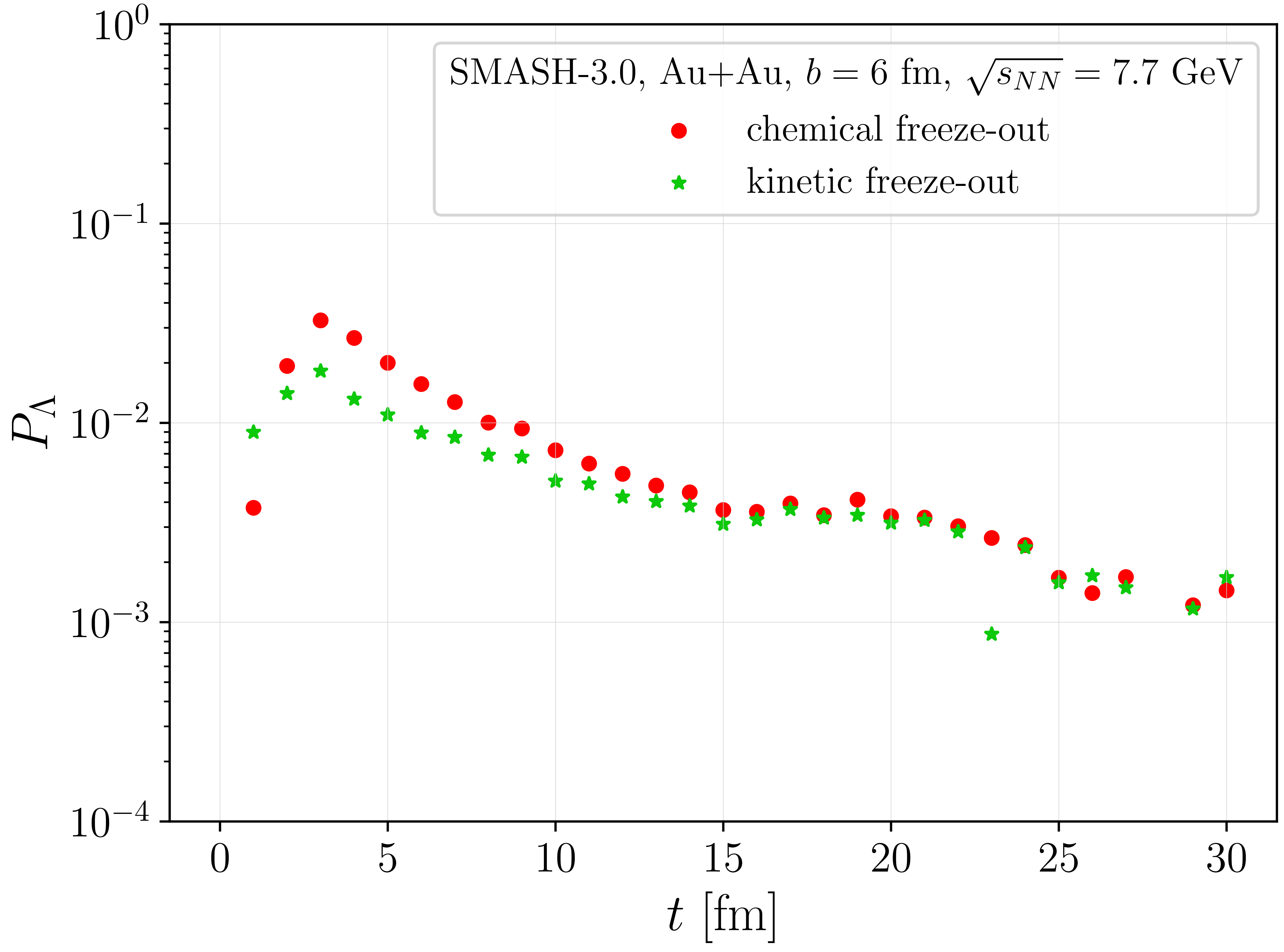
Kinetic freeze-out



Global Λ Polarization

Chemical vs. kinetic freeze-out

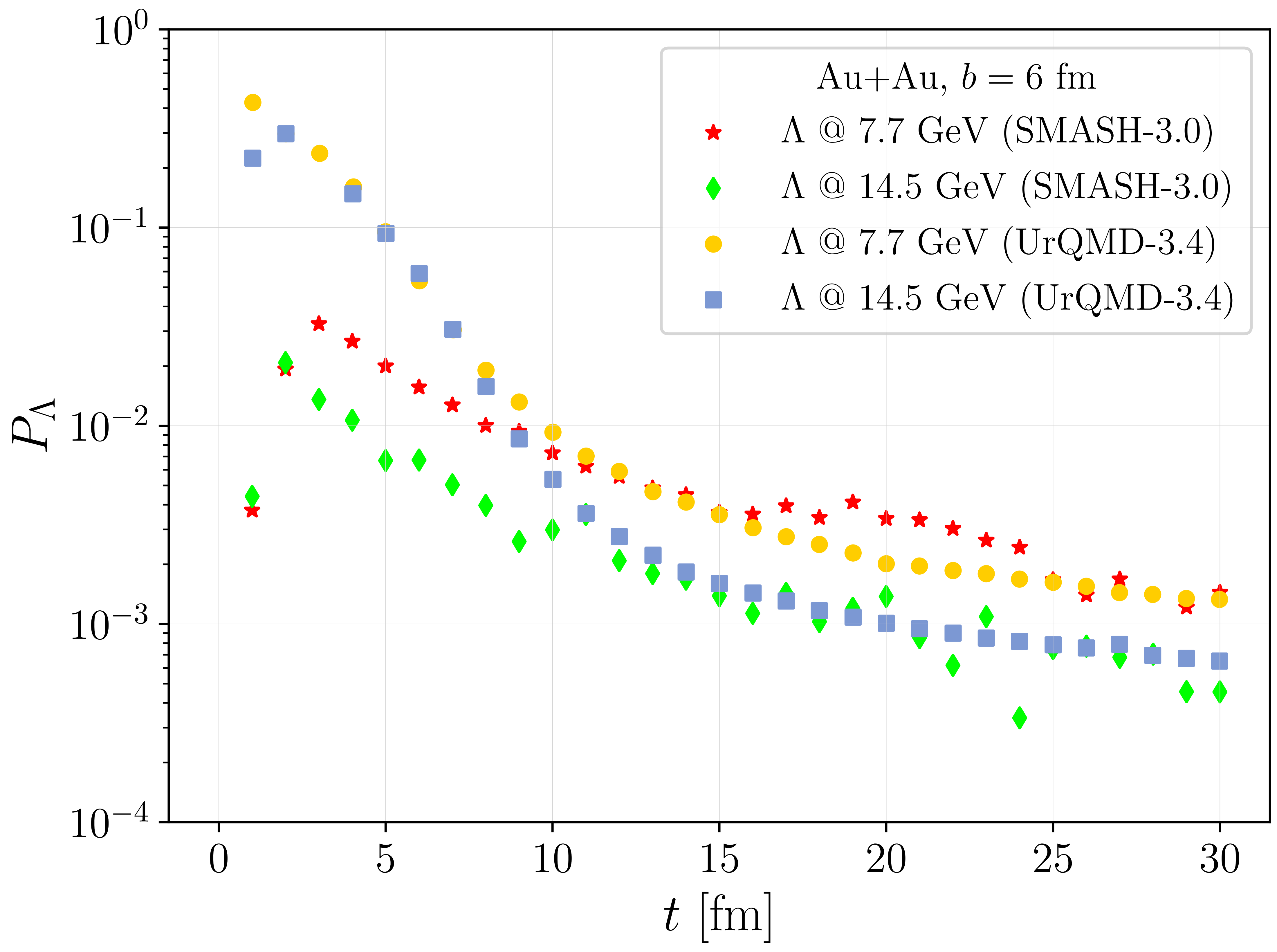
- Feed-down contributions negligible
  - Only Λ polarization taken into account
- Chemical freeze-out polarization higher than kinetic one
  - Possible explanation:
    Vorticity drop per cell due to system expansion $\Rightarrow$ lower "kinetic freeze-out" polarization



Global Λ Polarization

SMASH-3.0 vs. UrQMD

- Possible reasons for differences:
  - EoS has impact on vorticity
    $\Rightarrow$ impact on polarization
  - Last elastic and inelastic interaction dependent on cross sections leading to a shift in emission times of the hyperons
    $\Rightarrow$ impact on polarization



Summary and outlook

- Summary
  - Global angular momentum and per octant meet expectations
  - Polarization dependent on freeze-out definition and EoS
  - Feed-down contributions from $\Sigma^0 + \Xi^0 + \Xi^- + \Omega$ negligible for polarization
  - SMASH's global Λ polarization differs significantly from UrQMD's
- Outlook
  - Study the vorticity and polarization dependence of different EoS
  - Investigate the impact of the difference in cross sections between SMASH and UrQMD

Backup Slides

SMASH transport approach

Simulating Many Accelerated Strongly-interacting Hadrons

smash

- Effective solution of the relativistic Boltzmann equation
  $$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial_\alpha^p f_i(x,p) = C_{coll}^i$$
- Geometrical collision criterion
  $$d_{trans} < d_{int} = \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad d_{\text{trans}}^2 = (\vec{r}_a - \vec{r}_b)^2 - \frac{((\vec{r}_a - \vec{r}_b)\cdot(\vec{p}_a - \vec{p}_b))^2}{(\vec{p}_a - \vec{p}_b)^2}$$
- Includes all hadrons from the PDG(2018) up to m ~ 2.35 GeV
- Publicly available at www.smash-transport.github.io

DOI 10.5281/zenodo.3484711

J. Weil et al., Phys. Rev. C 94, 054905 (2016)

Global polarization of Λ hyperons

- Λ spin 4-vector at space-time point x $$S^{\mu}(x,p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_{\nu}\varpi_{\rho\sigma}(x)$$
- Thermal vorticity $$\varpi_{\mu\nu} = \frac{1}{2}(\partial_{\nu}\beta_{\mu} - \partial_{\mu}\beta_{\nu})$$ with $\beta_{\mu} = \frac{u_{\mu}}{T}$
- Λ spin 4-vector in local rest frame $$\mathbf{S}^{*}(x,p) = \mathbf{S} - \frac{\mathbf{p}\cdot\mathbf{S}}{E_p(m+E_p)}\cdot\mathbf{p}$$ with $E_p = \sqrt{\mathbf{p}^2 + m^2}$
- Average of over all Λs emitted $$\langle\mathbf{S}^{*}\rangle = \frac{1}{N}\sum_{i=1}^{N}\mathbf{S}^{*}(x_i,p_i)$$
- Global polarization $$P = \frac{\langle\mathbf{S}^{*}\rangle\cdot\mathbf{J}}{|\langle\mathbf{S}^{*}\rangle|\cdot|\mathbf{J}|}$$

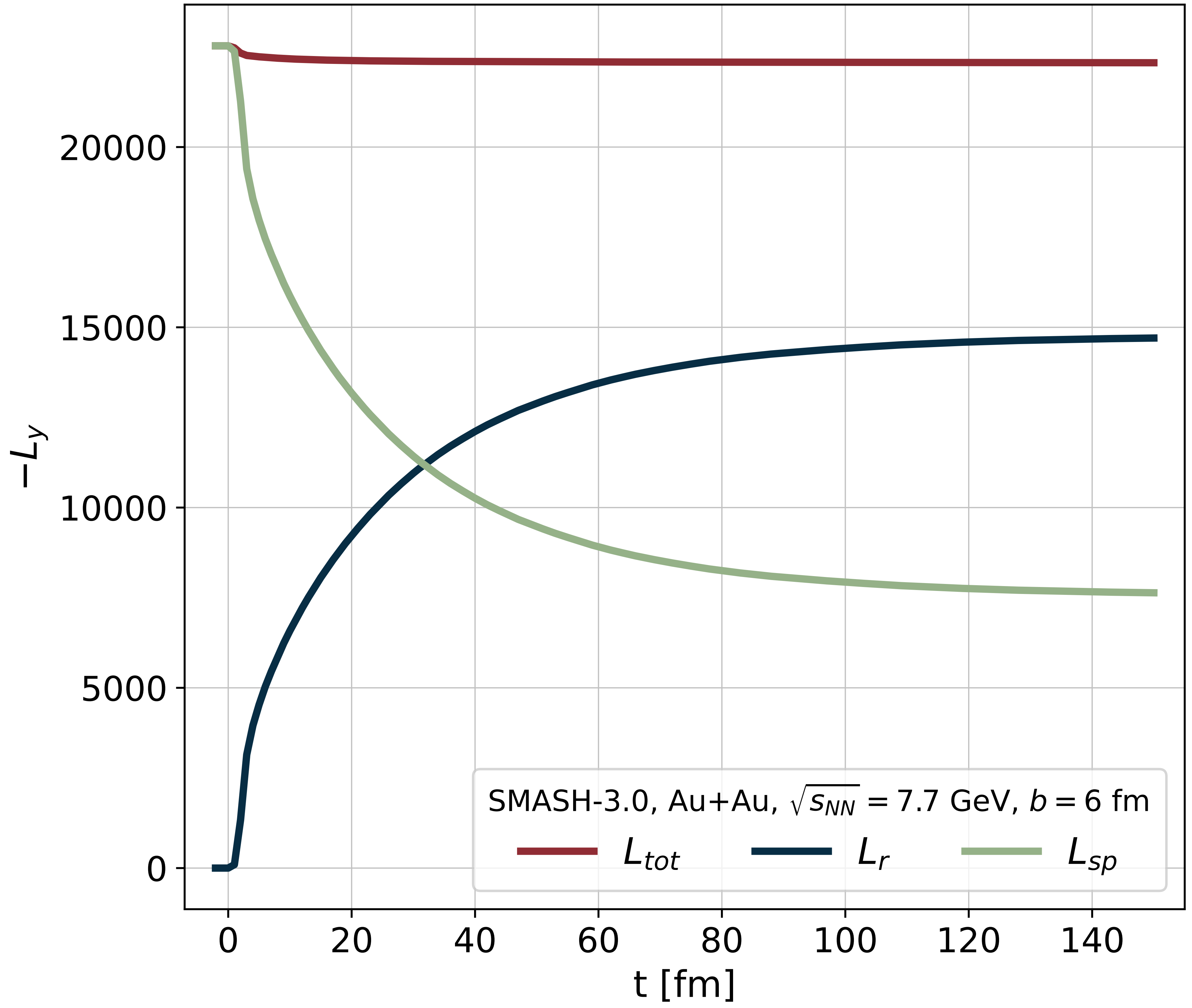
O. Vitiuk et al., Physics Letters B Volume 803, 135298 (2020)

Global angular momentum in SMASH

- Angular momentum conservation is violated in SMASH (as in all transport approaches)
    - Geometrical collision criterion enables instantaneous interactions over finite distances N. Sass et al., Phys. Rev. C 108.4, 044903 (2023)

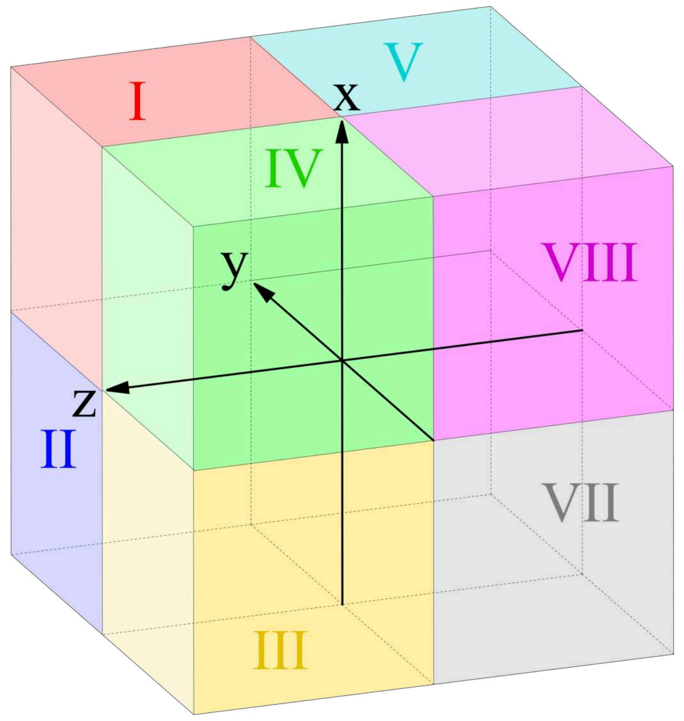
Geometrical collision criterion

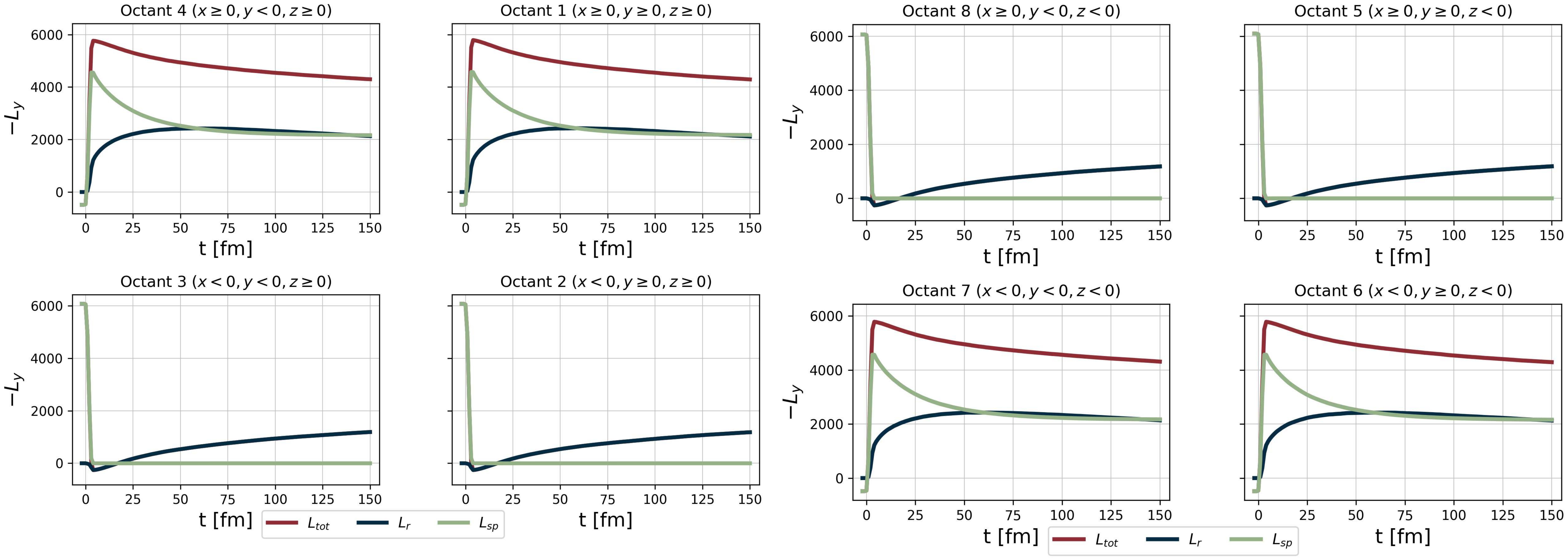
$$d_{trans} < d_{int} = \sqrt{\frac{\sigma_{tot}}{\pi}}$$



Angular momentum per octant

Coordinate space, Au+Au collisions at $b = 6$ fm and $\sqrt{s_{NN}} = 7.7$ GeV

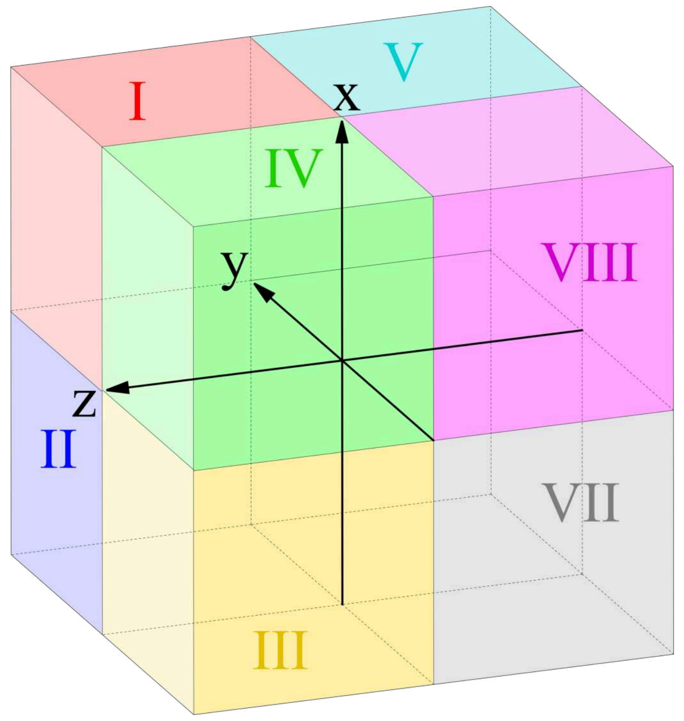


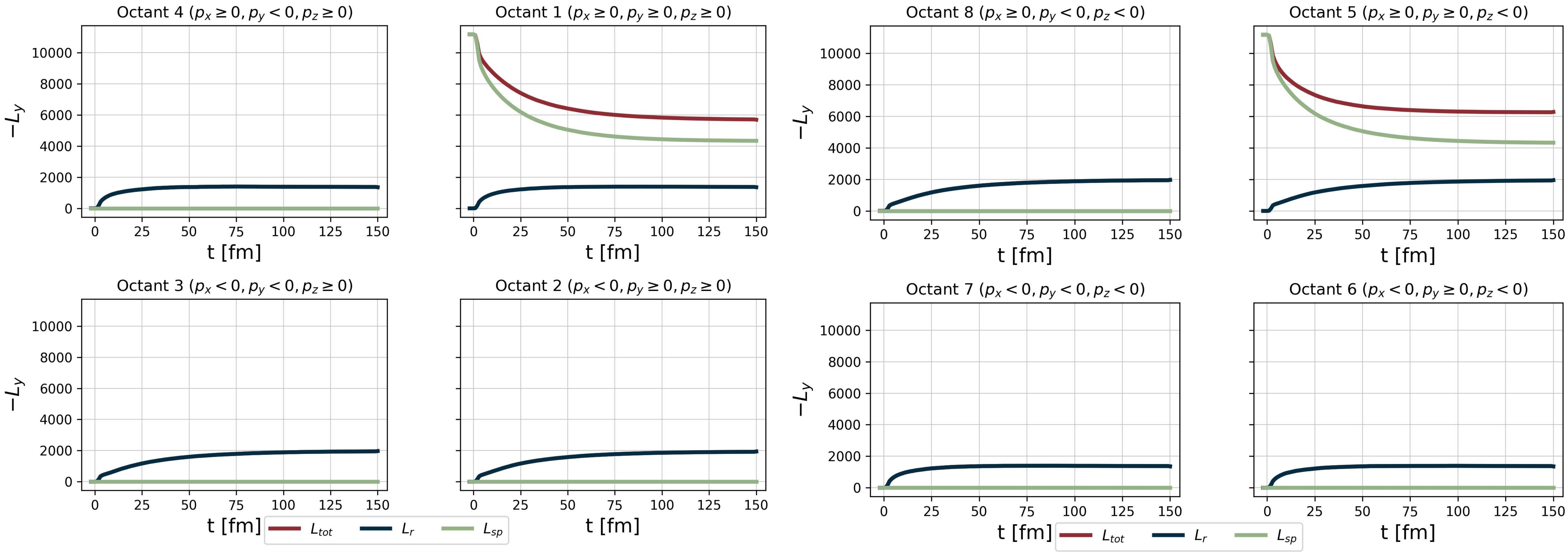


SMASH-3.0

Angular momentum per octant

Momentum space, Au+Au collisions at $b = 6$ fm and $\sqrt{s_{NN}} = 7.7$ GeV

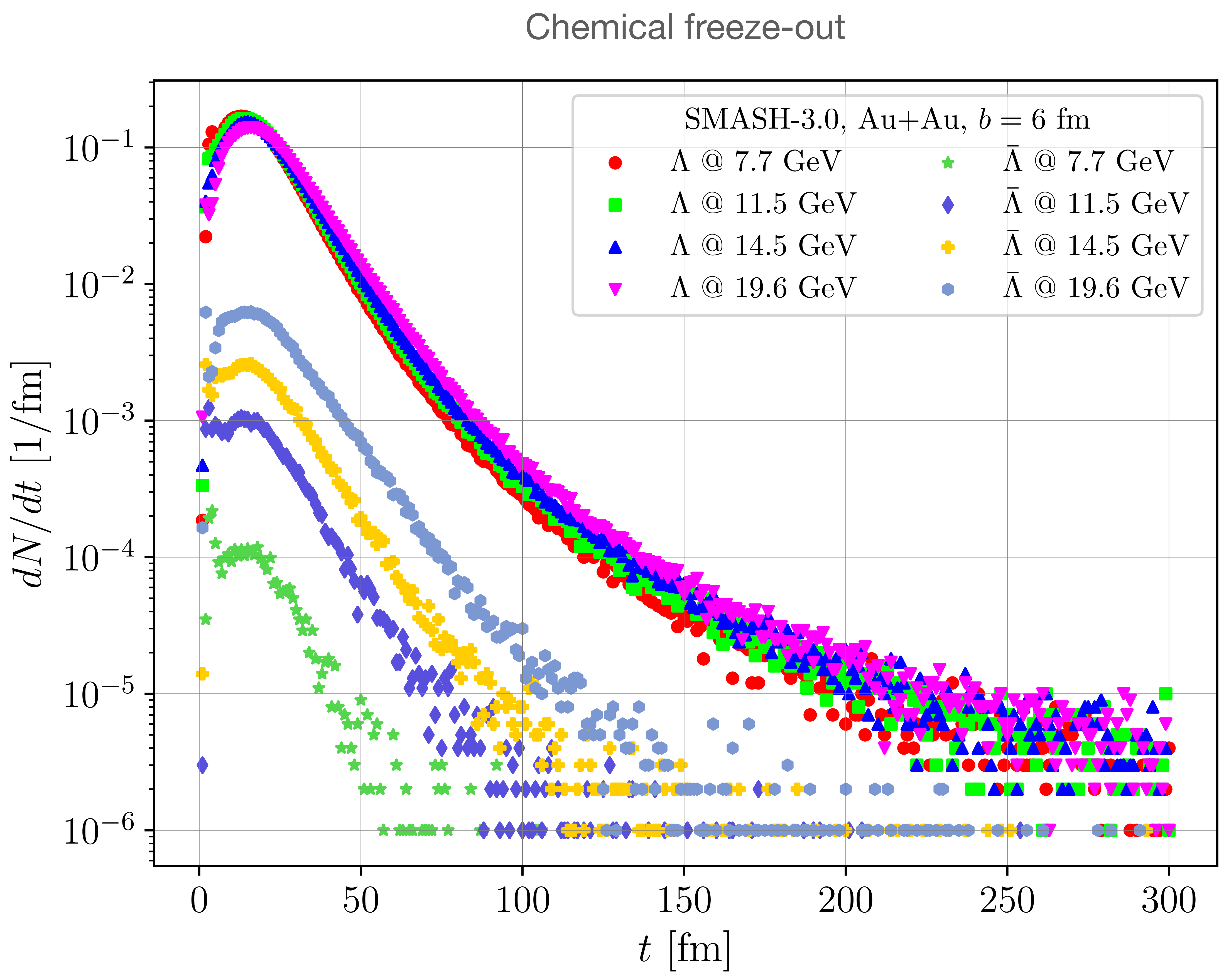


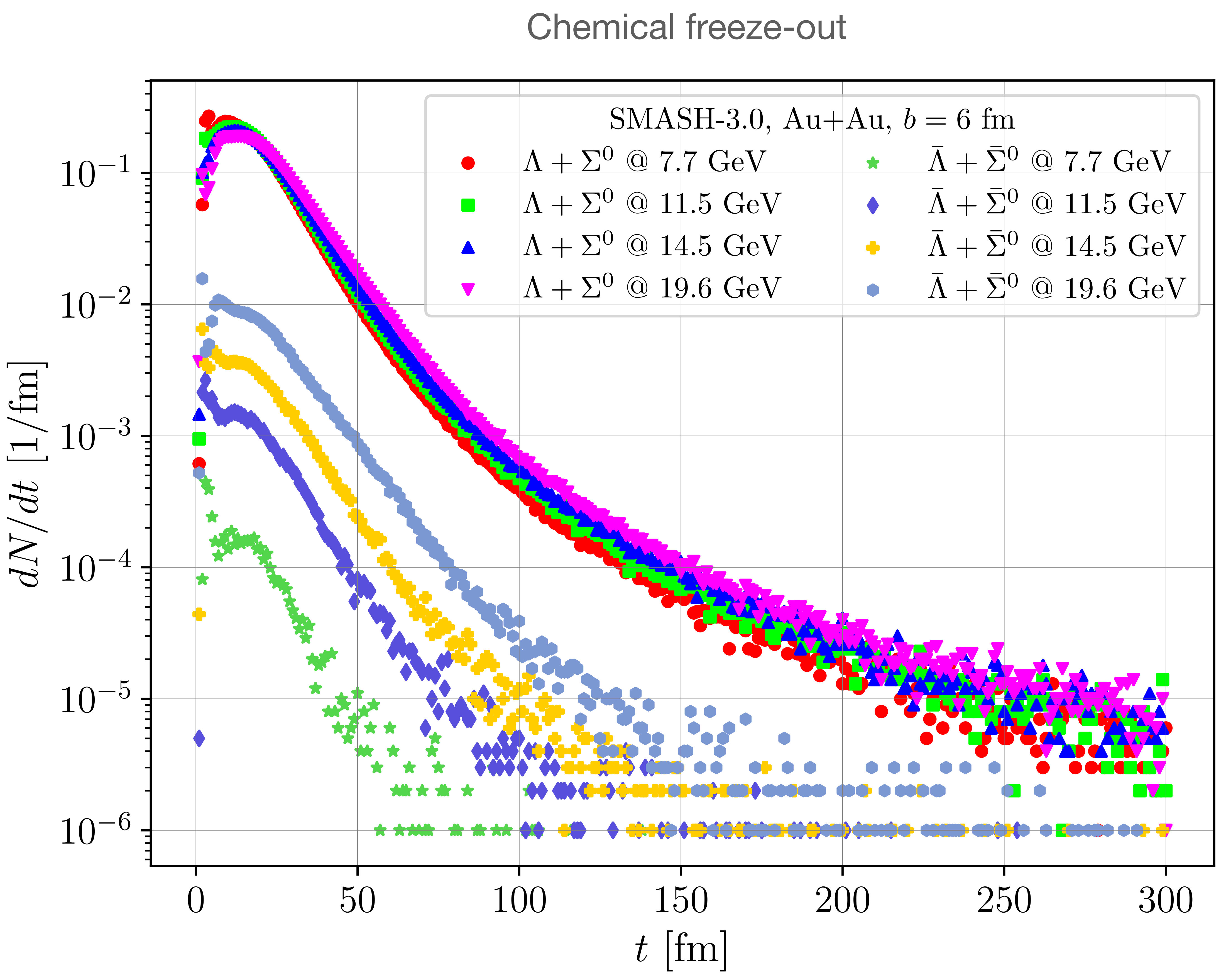


SMASH-3.0

Λ and $\Lambda + \Sigma^0$ emission time evolution

Chemical freeze-out

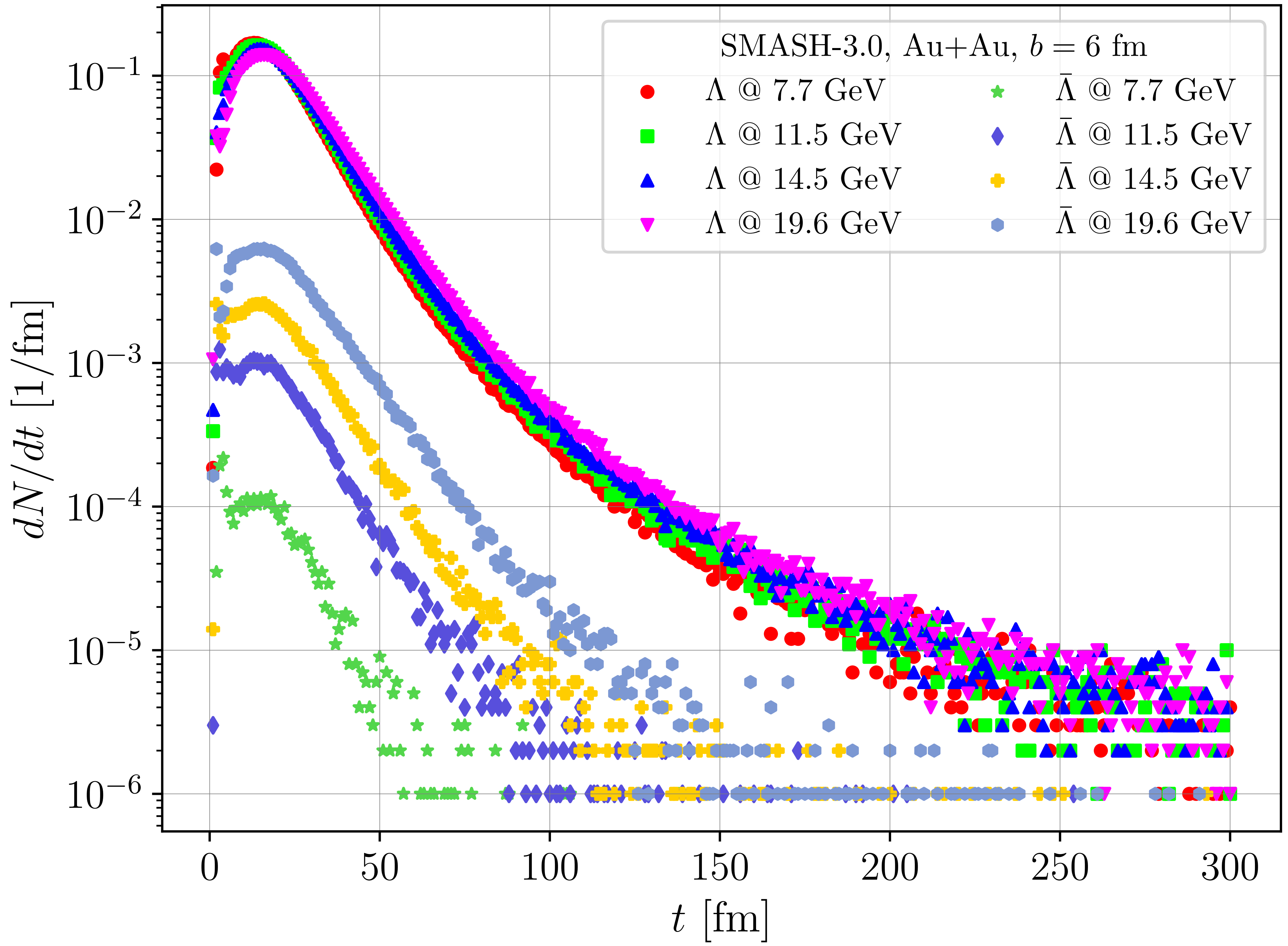




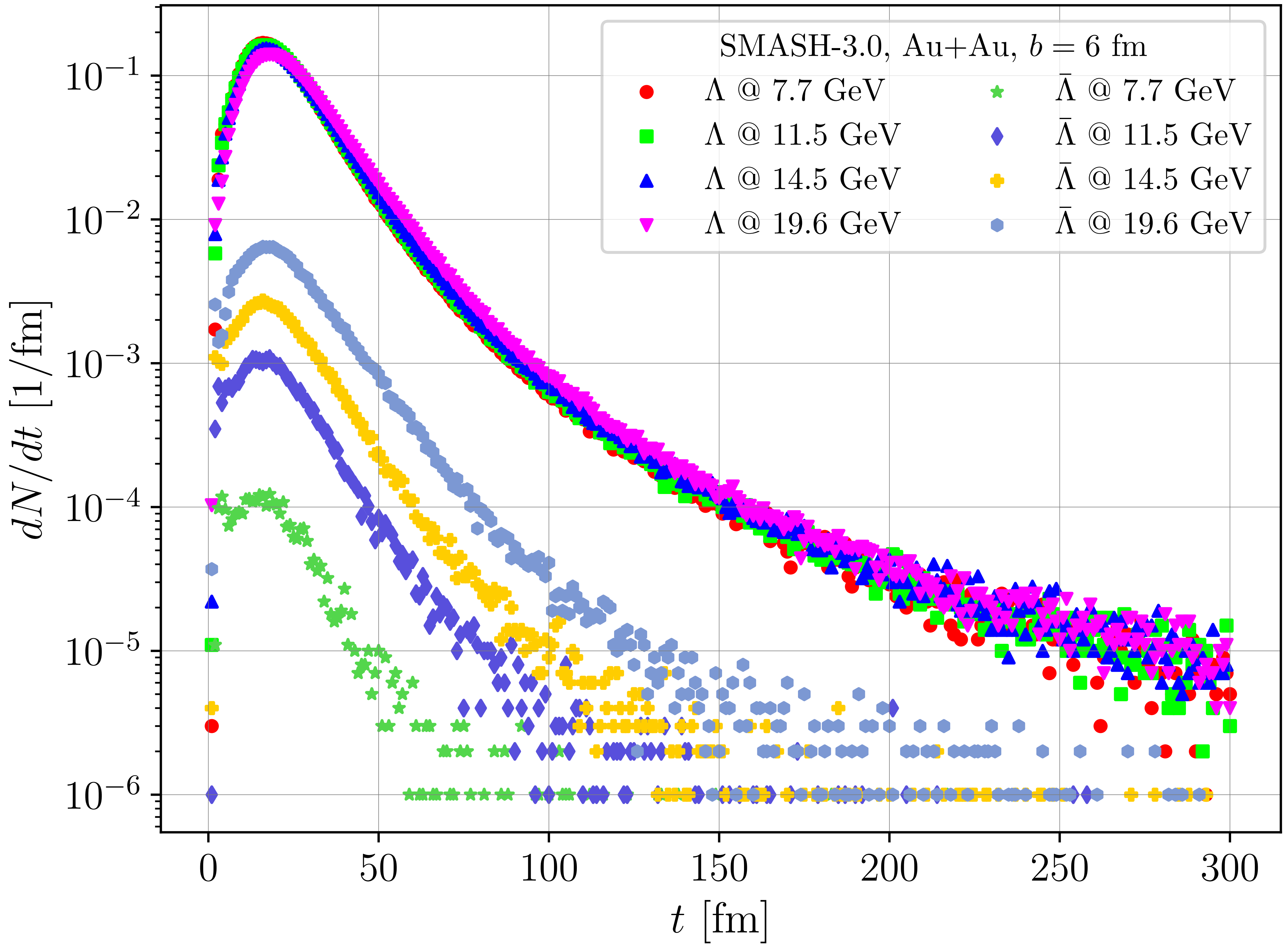
Λ and $\bar{\Lambda}$ emission time evolution

Chemical vs. kinetic freeze-out

Chemical freeze-out

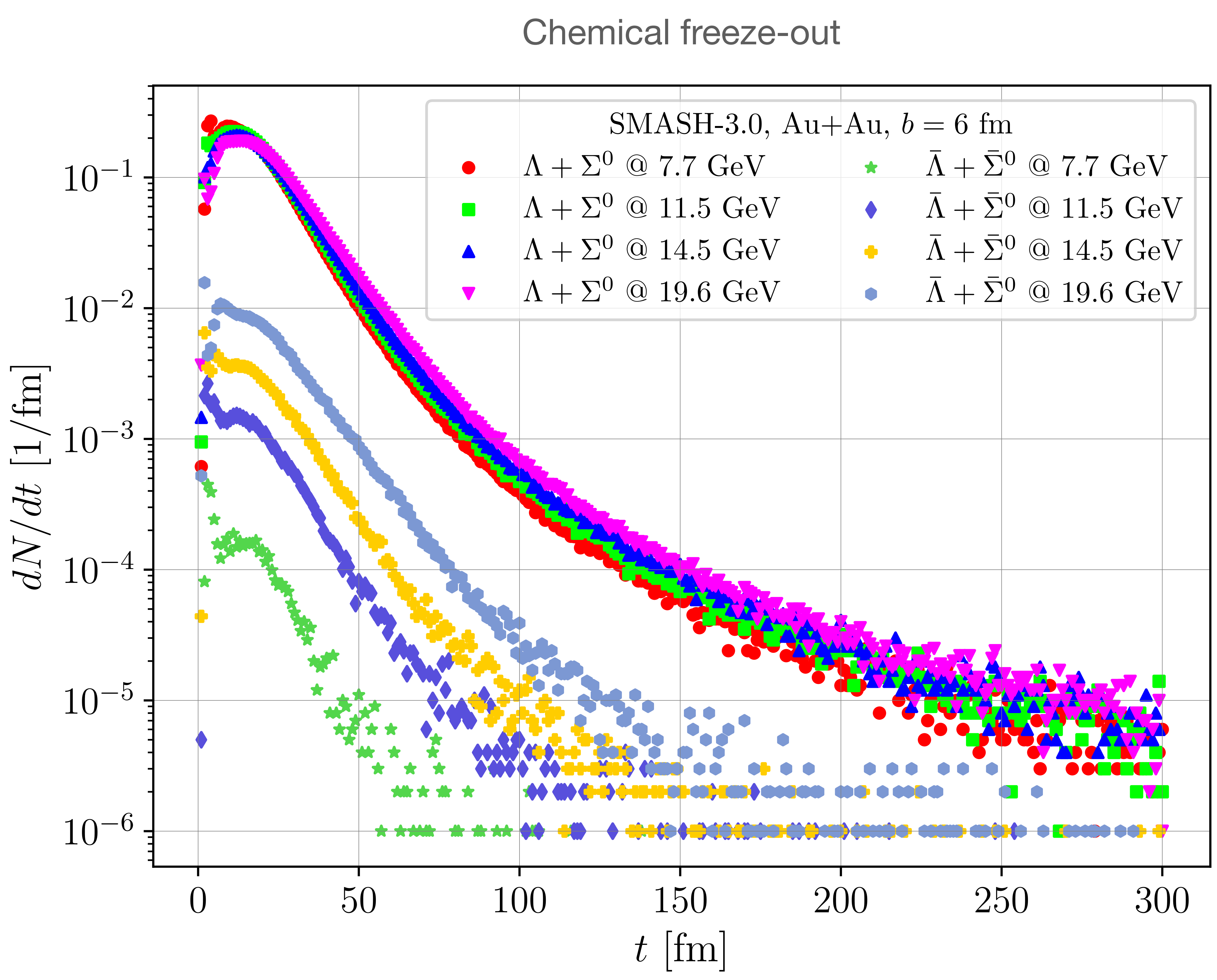


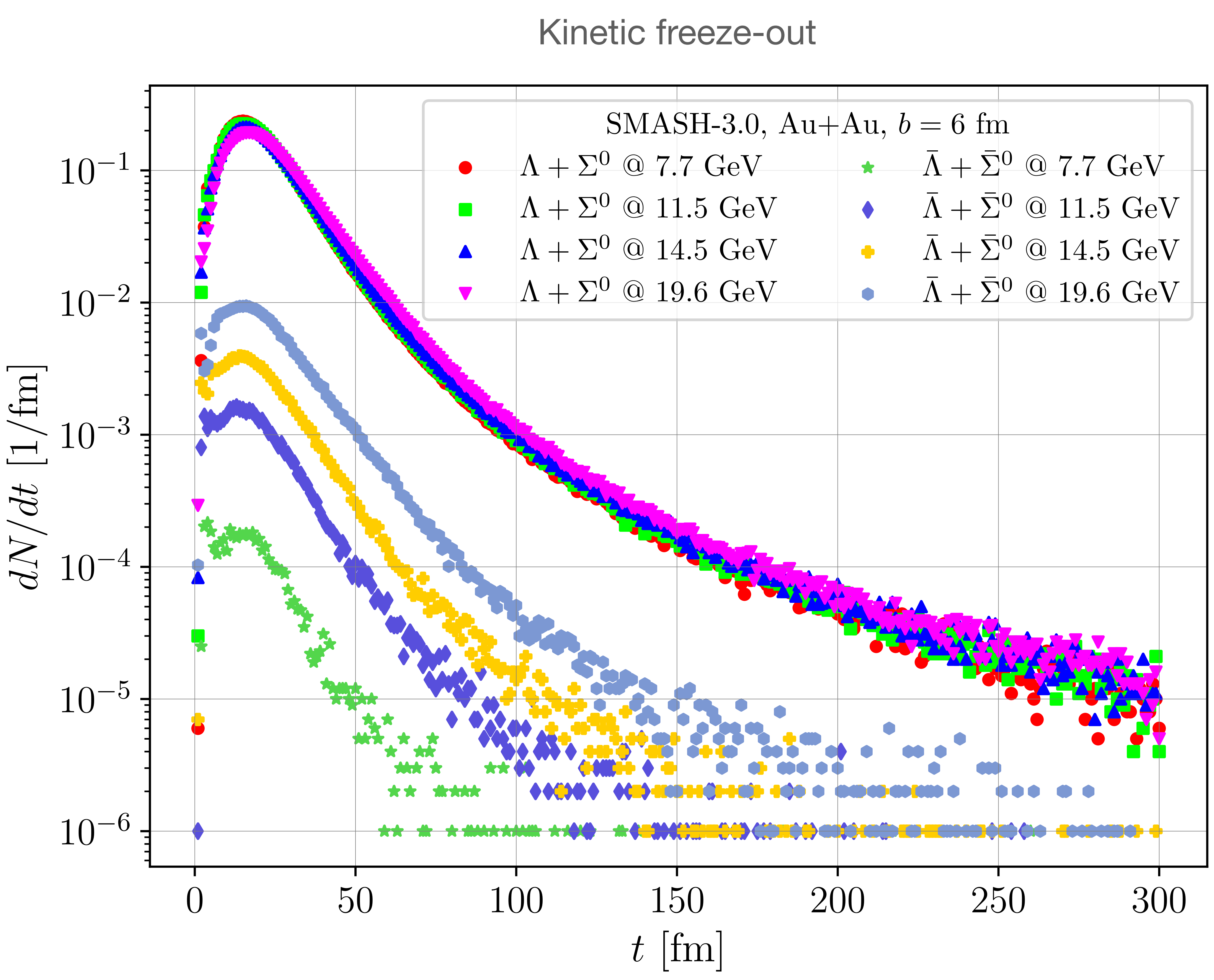
Kinetic freeze-out



$\Lambda + \Sigma^0$ and $\bar{\Lambda} + \bar{\Sigma}^0$ emission time evolution

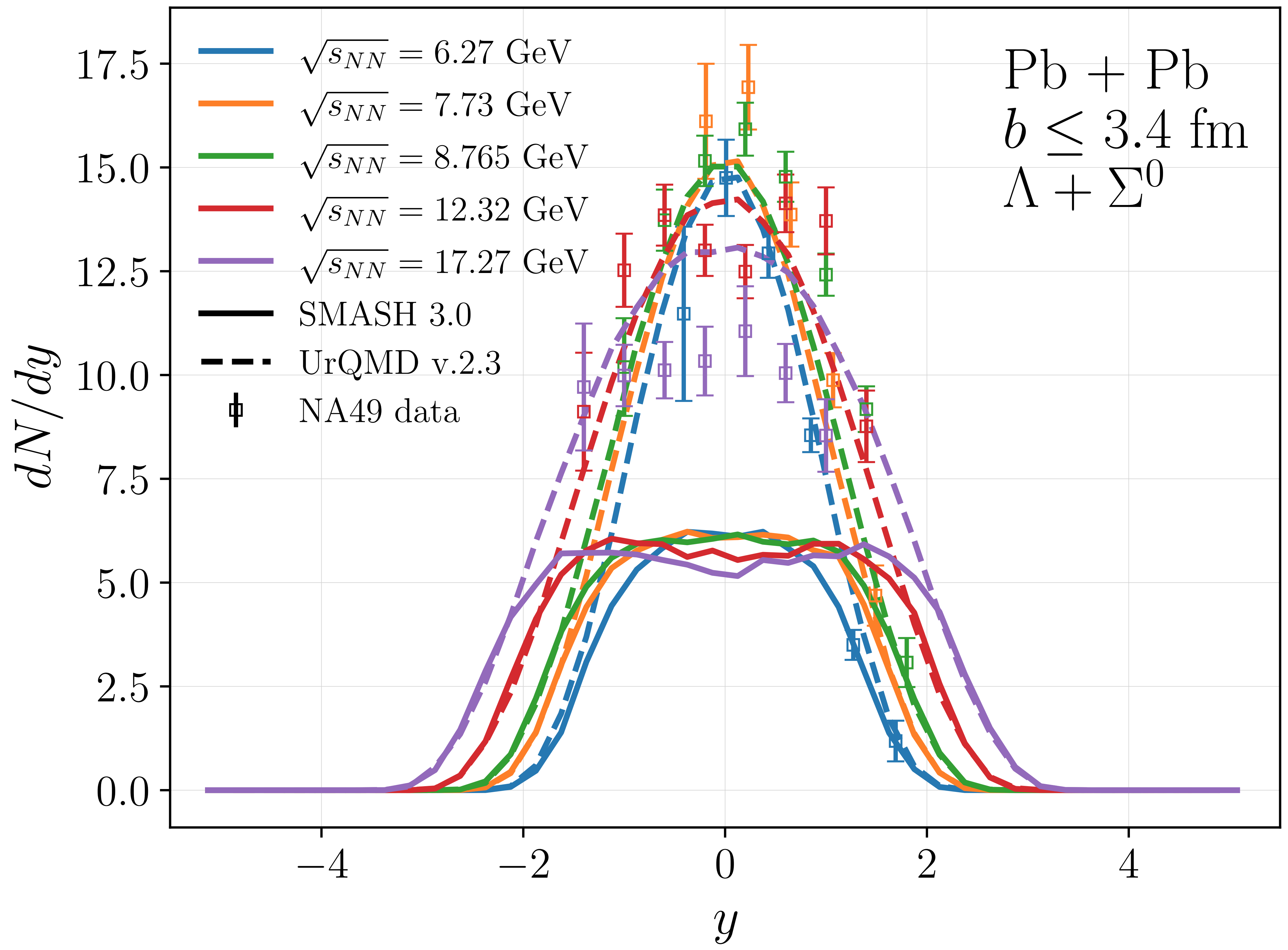
Chemical vs. kinetic freeze-out

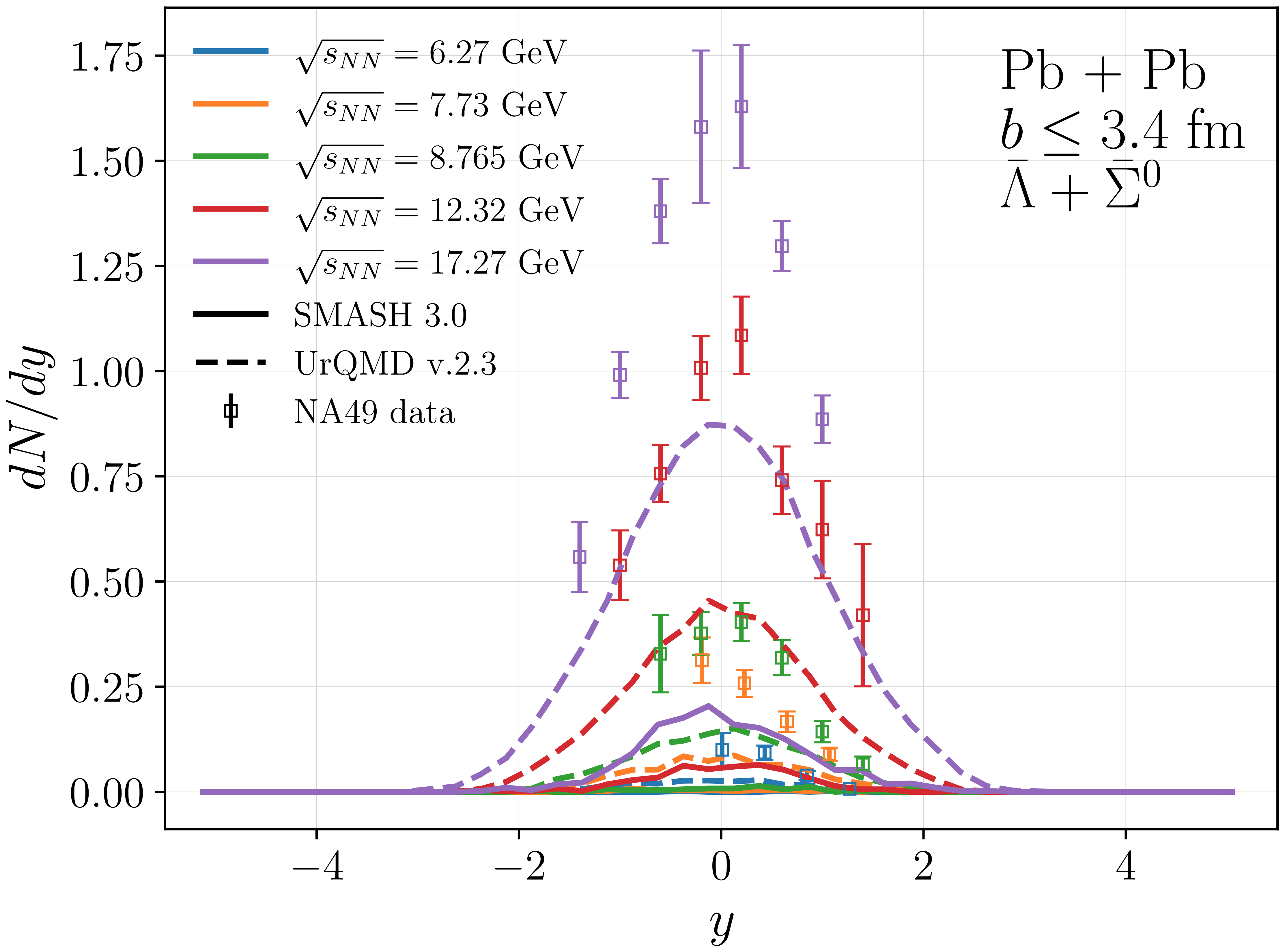




Λ and $\bar{\Lambda}$ production yields

SMASH vs. UrQMD vs. NA49 experimental data



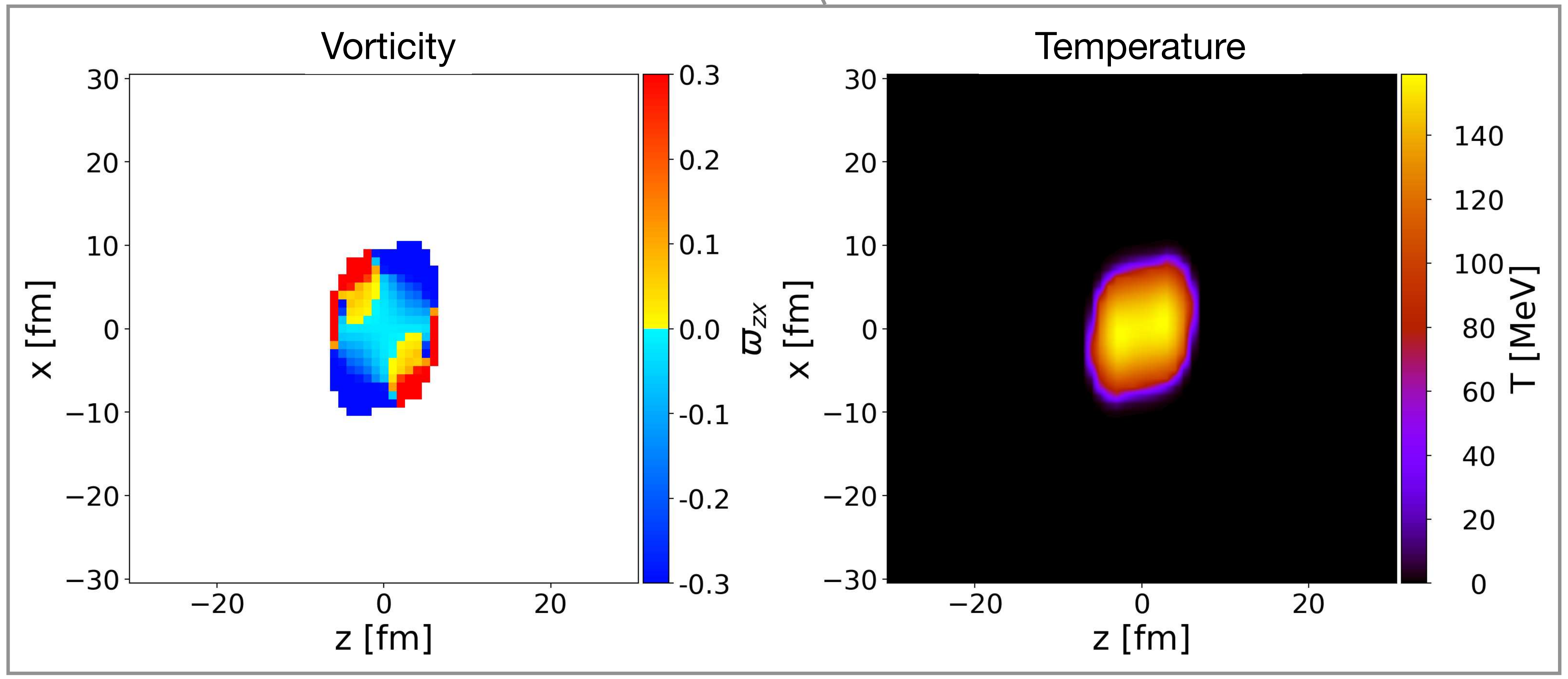


UrQMD data: H. Petersen et al., arXiv:0805.0567v1 [hep-ph]
NA49 data: C. Blume et al., Journal of Physics G: Nuclear and Particle Physics 31.6 (2005), s685

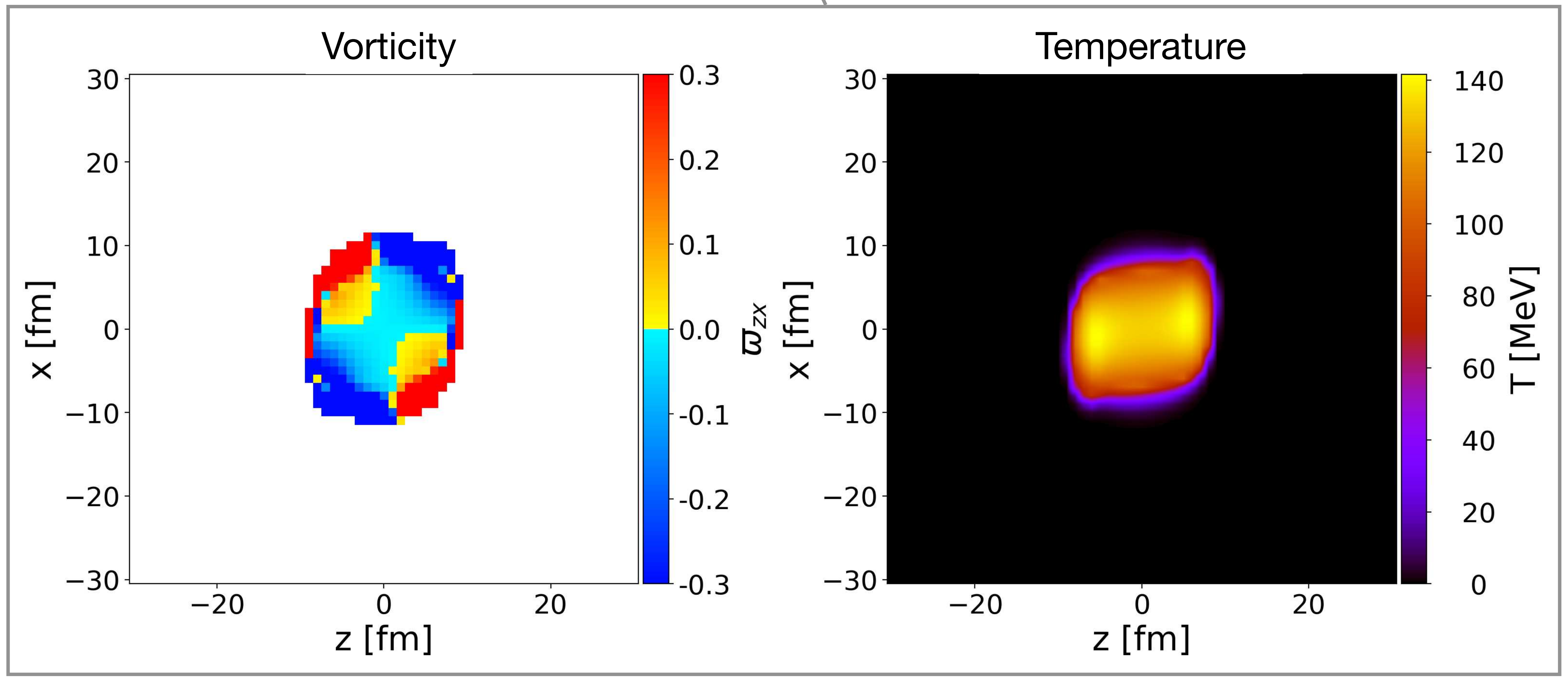
Vorticity in the reaction plane

SMASH-3.0

$t = 6$ fm

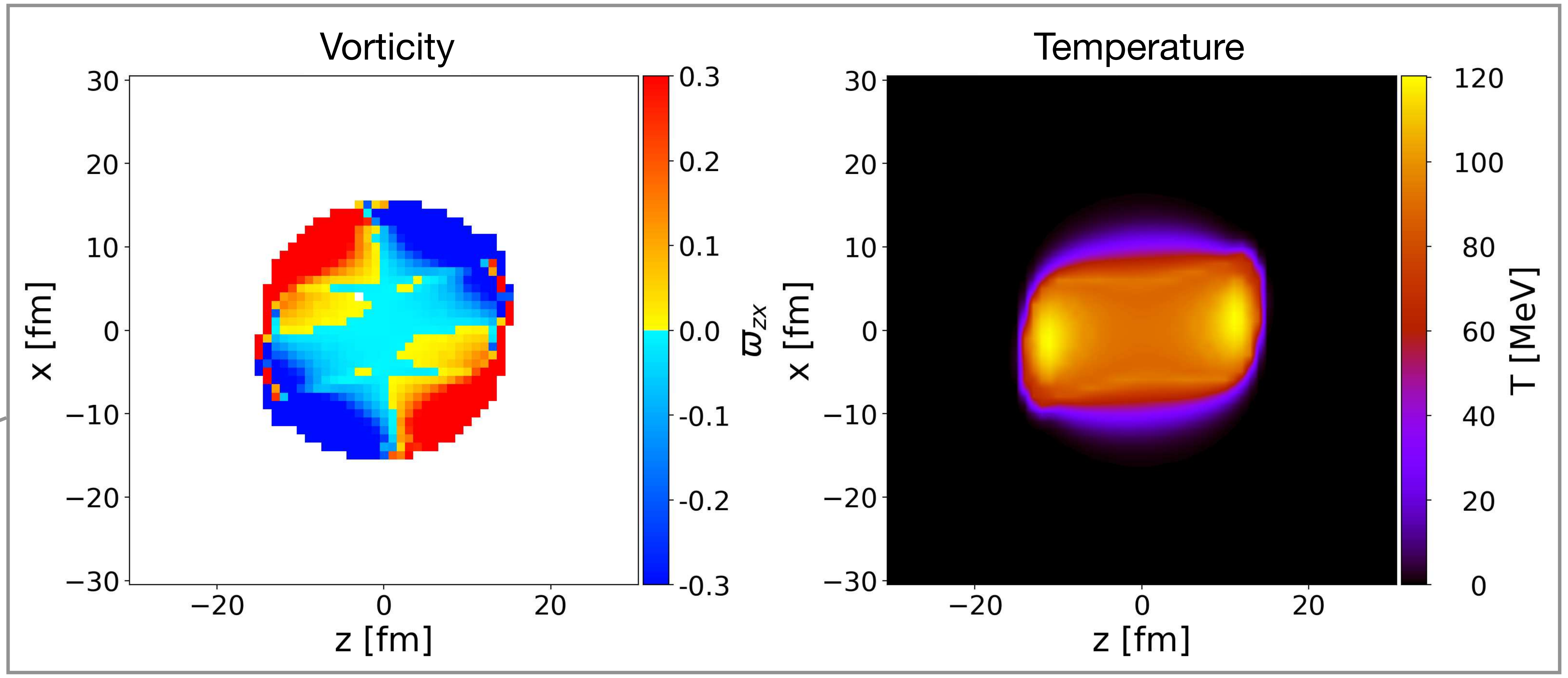


$t = 9$ fm



- SMASH hadron resonance gas EoS
  A. Schäfer et al., arXiv:2109.08578v1 [hep-ph]
- Au+Au, $\sqrt{s_{NN}} = 7.7$ GeV, $b = 6$ fm
- Reaction plane: $\vec{p}_{\text{beam}} \times \vec{b}$

$t = 15$ fm



SMASH settings

- Angular momentum $N = 2000$:
  - Global Fermi motion frozen, per octant Fermi motion off
- Λ emission time evolution $N = 10^6$
- Vorticity and polarization plots:
  - $\sqrt{s_{NN}} = 7.7$ GeV $N = 50000$, $\sqrt{s_{NN}} = 14.5$ GeV $N = 30000$
- Λ rapidity spectra $N = 2000$
- Fermi motion “frozen” was used if not stated otherwise