Angular Momentum in Heavy Ion Collisions via SMASH

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CRC-TR 211 Strong-interaction matter under extreme conditions

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

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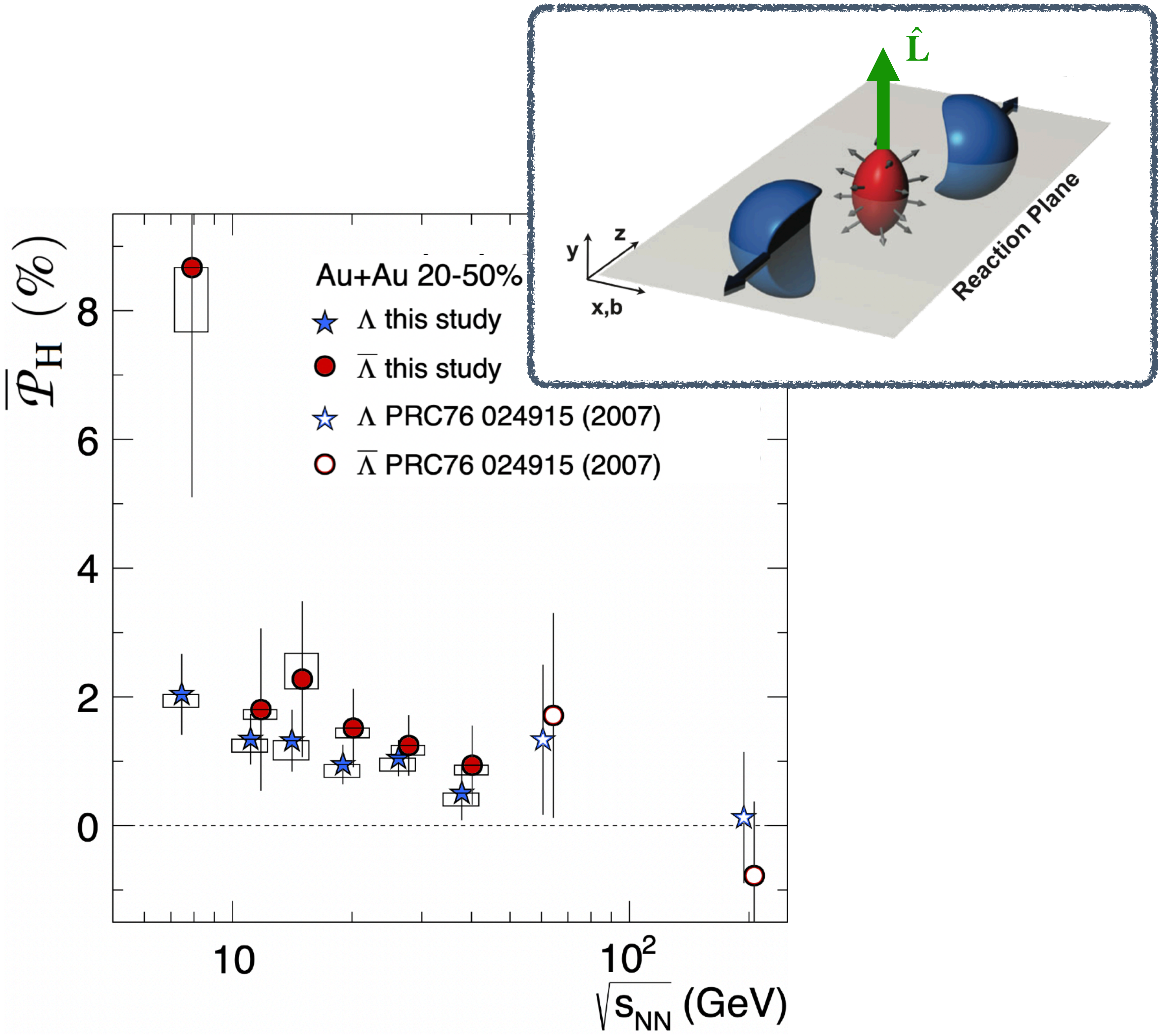


L. Adamczyk *et al.* [STAR], Nature 548 (2017), 62-65

Snellings 2011 *New J. Phys.* 13 055008 (adoption)

STAR Measurement

- Global spin-polarization of Λ hyperons in non-central Au+Au collisions at $\sqrt{s_{NN}}$= 3 - 200 GeV and mid-rapidity
- Hyperon polarization is a direct hint of vorticity of the QGP
- Polarization decreases for lower beam energies

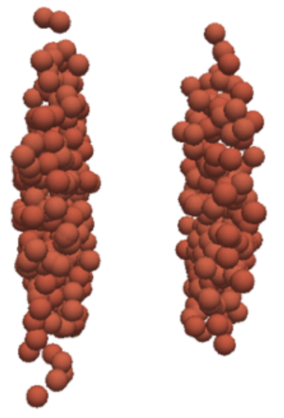
Why Angular Momentum?

- Angular momentum of the nuclei is the **driver of spin polarization** in heavy-ion collisions by inducing vorticity
- To **model hyperon polarization**, the dynamic description of angular momentum transfer to the fireball is crucial
- Detailed understanding of the dynamics is important to identify **phase transition signals**

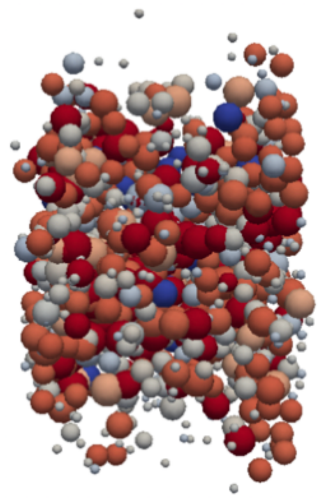
SMASH

Pb-Pb collision at E_{lab} = 40 GeV

t = -2.5 fm



t = 6 fm



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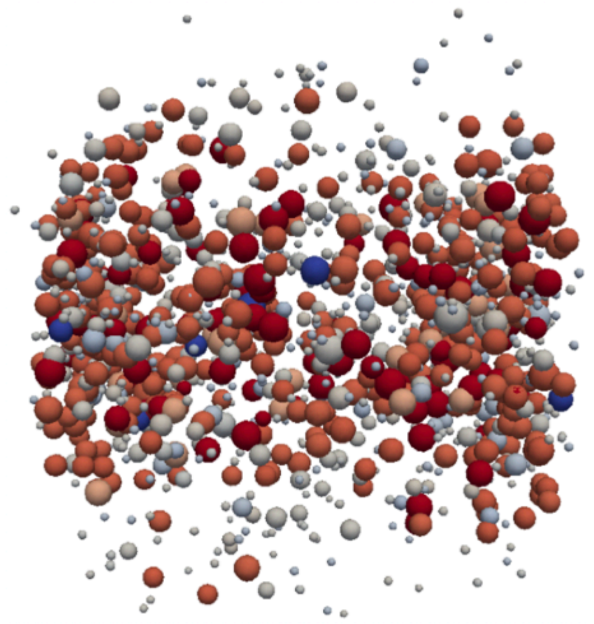
t = 12 fm



http://smash-transport.github.io

Hadronic Transport Approach smash *

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

- *Simulating Many Accelerated Strongly-Interacting Hadrons
- Dynamical non-equilibrium description of HICs at low beam energies (FAIR) and late stage rescattering at high beam energies (RHIC/LHC)
- Includes all hadrons up from the PDG to m ~ 2.35 GeV

SMASH Setup

- Effective solution of the relativistic Boltzmann equation

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

- Geometric collision criterion

$$d_{trans} < d_{int} = \sqrt{\frac{\sigma_{tot}}{\pi}} \qquad d^2_{trans} = (\vec{r}_a - \vec{r}_b)^2 - \frac{((\vec{r}_a - \vec{r}_b)\cdot(\vec{p}_a - \vec{p}_b))^2}{(\vec{p}_a - \vec{p}_b)^2}$$

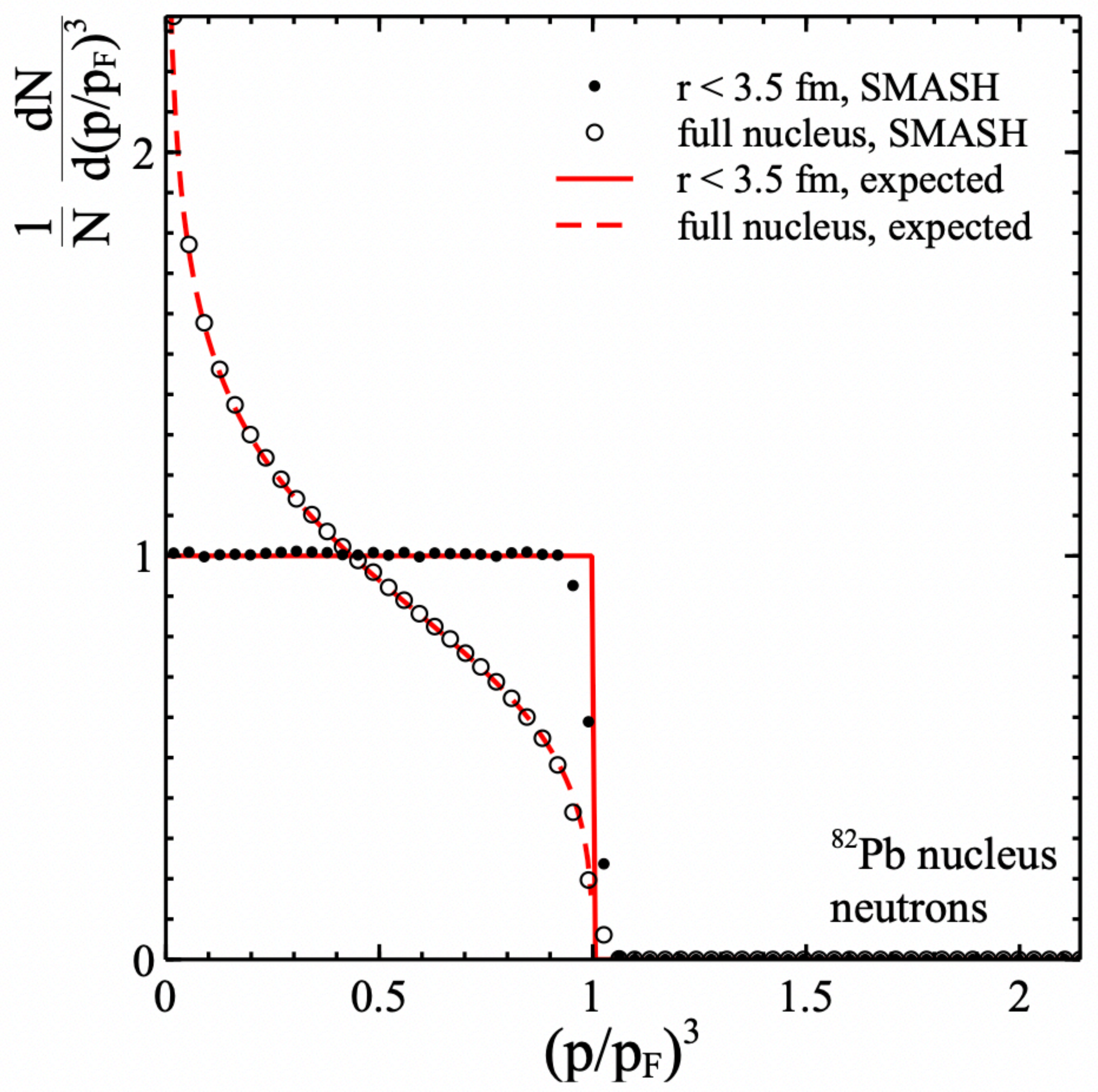
- Test particle method $\sigma \rightarrow \sigma \cdot N^{-1}_{test}$, $N \rightarrow N \cdot N_{test}$

Angular Momentum & Fermi Motion in SMASH

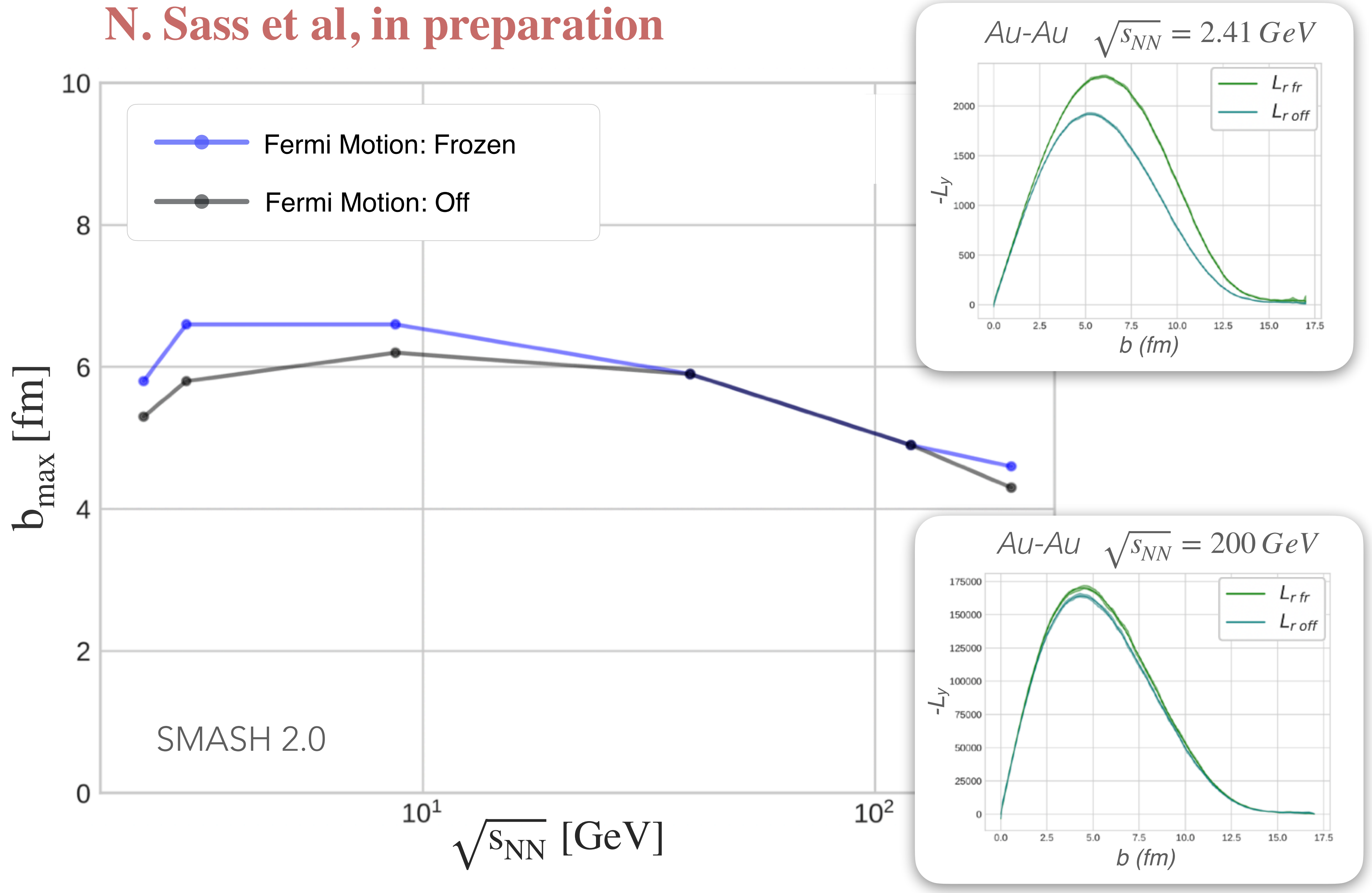
- SMASH accesses the full phase-space information of every particle and thus its angular momentum
- **Fermi motion:** nucleonic momentum distribution due to Pauli exclusion principle
- In the ground state nucleus, nucleon momentum distribution corresponds to a uniformly filled Fermi sphere with radius

$$p_F(\vec{r}) = \hbar c \left(3\pi^2 \rho(\vec{r})\right)^{\frac{1}{3}}$$

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

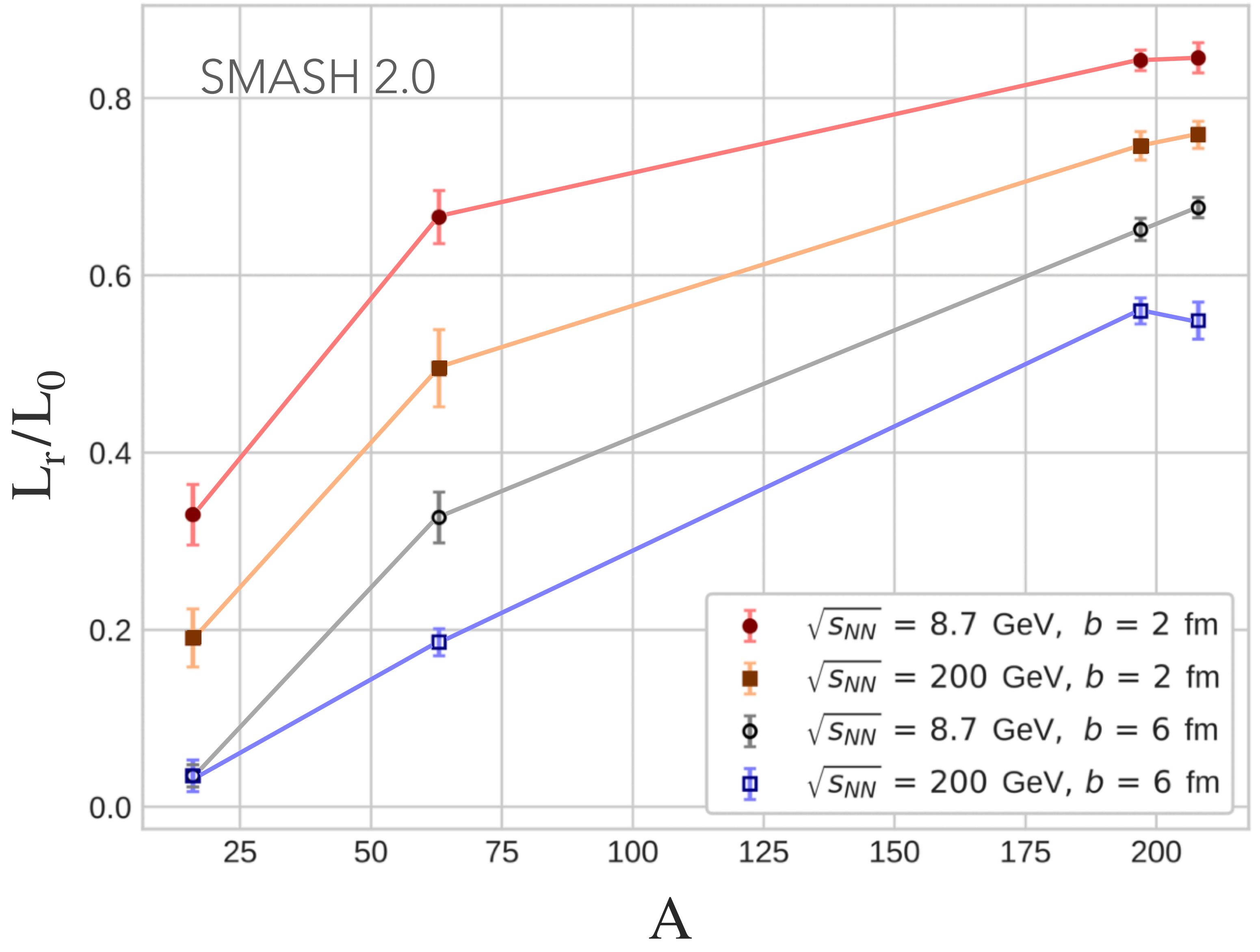


N. Sass et al, in preparation



- **Energy dependence** of impact parameter b_{max} for which the remaining angular momentum L_r becomes maximal
- **Fermi motion** induces additional angular momentum into the system

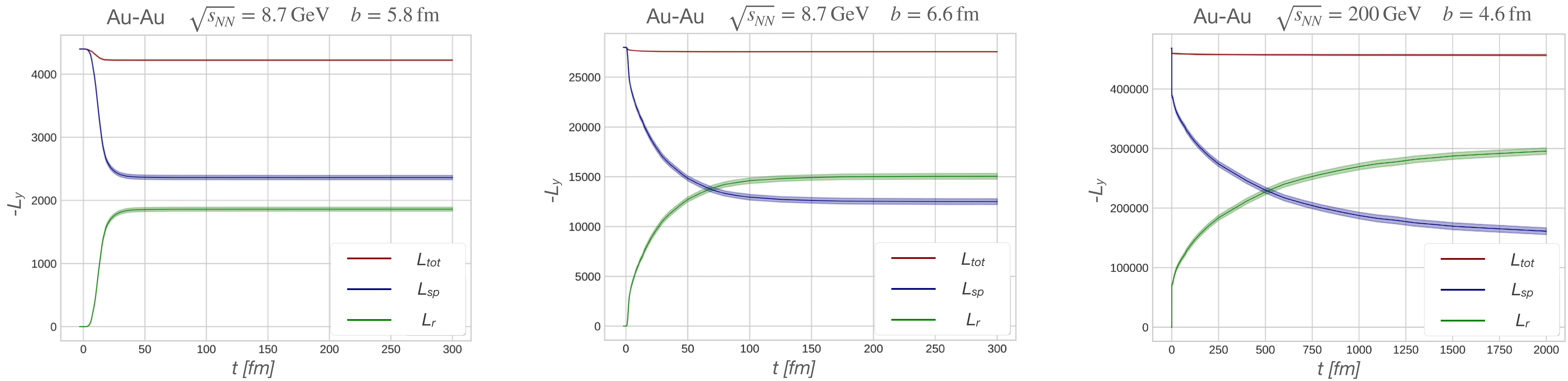
N. Sass et al, in preparation



- **System size dependence** of the ratio of the fireball's angular momentum over the initial angular momentum L_r / L_0
- More angular momentum is deposited at mid rapidity in more central collisions and at lower beam energies

Angular Momentum Evolution

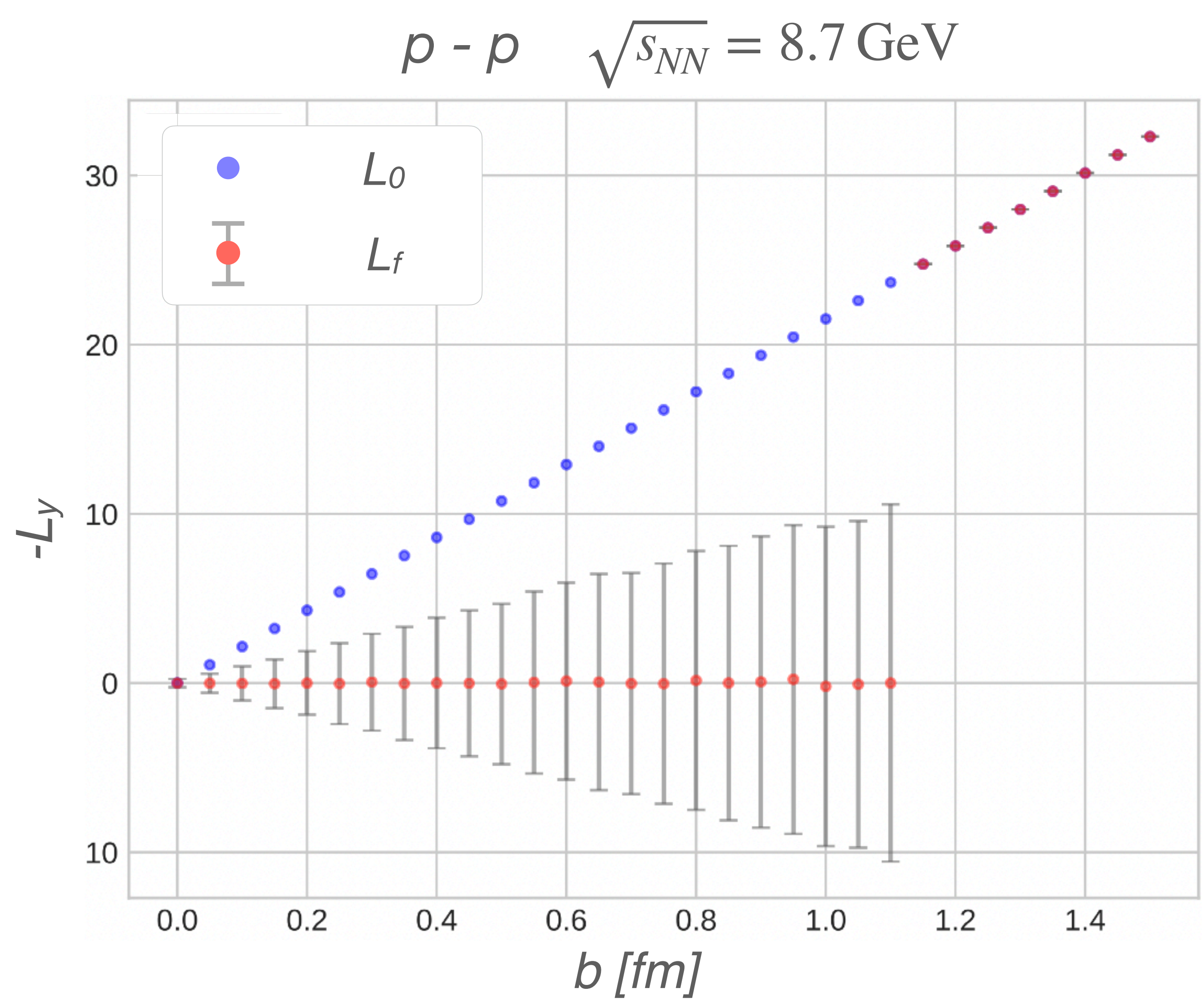
N. Sass et al, in preparation



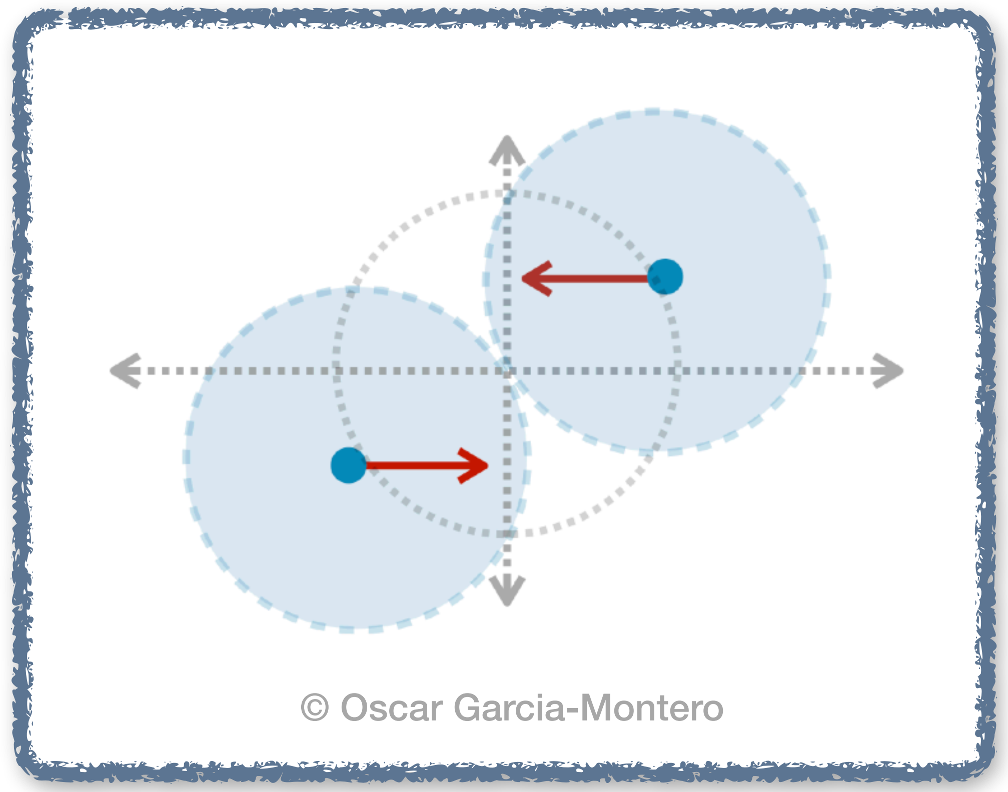
- Secondary collisions at higher beam energies shift the flattening of L_{sp} and L_r to later times
- We observe a kink in the total angular momentum at the time when both nuclei collide
  → Broken angular momentum conservation
- For higher beam energies the kink occurs at smaller times due to faster time evolution

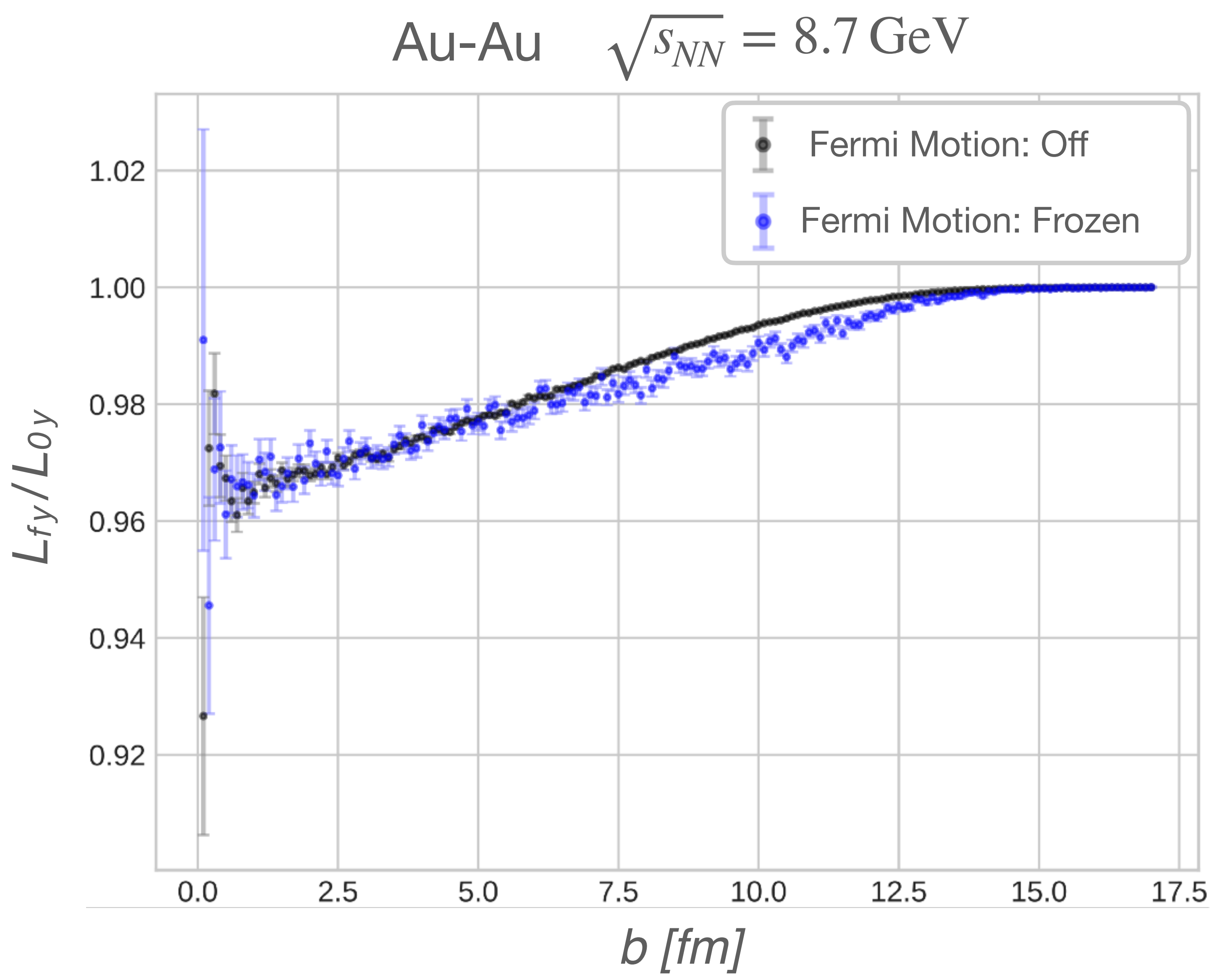
Angular Momentum Conservation

- Collective „loss" of angular momentum in Au-Au collisions amounts to 3.5% for small impact parameters
- Additional momenta by Fermi motion slightly increase non-conservation of angular momentum
- Geometrical Interpretation of the cross section breaks angular momentum conservation in binary in/elastic collisions



N. Sass et al, in preparation





Treating Conservation in Elastic Scatterings

Calculate the change in angular momentum ΔL and mass moment ΔK for each binary collision:

$$\Delta \overrightarrow{L} = (\overrightarrow{x}_1 - \overrightarrow{x}_2) \times \overrightarrow{p} - (\overrightarrow{x}'_1 - \overrightarrow{x}'_2) \times \overrightarrow{p}'$$

$$\Delta \overrightarrow{K} = (t_1 - t_2)(\overrightarrow{p} - \overrightarrow{p}') - (\overrightarrow{x}_1 - \overrightarrow{x}'_1)E_1 - (\overrightarrow{x}_2 - \overrightarrow{x}'_2)E_2$$

Get the corrected positions of the scattered particles restricting collision trajectories to a plane and solving

$$\Delta \overrightarrow{L} = 0\,, \quad \Delta \overrightarrow{K} = 0$$

LINEAR SYSTEM

$$\begin{aligned}
-p'_y x'_1 + p'_y x'_2 + p'_x y'_1 - p'_x y'_2 &= \Delta_{[x,y]} \\
E'_1 x'_1 + E'_2 x'_2 &= \Delta_x \\
p'_z x'_1 - p'_z x'_2 - p'_x z'_1 + p'_x z'_2 &= \Delta_{[z,x]} \\
E'_1 z'_1 + E'_2 z'_2 &= \Delta_z \\
-p'_z y'_1 + p'_z y'_2 + p'_y z'_1 - p'_y z'_2 &= \Delta_{[y,z]} \\
E'_1 y'_1 + E'_2 y'_2 &= \Delta_y
\end{aligned}$$

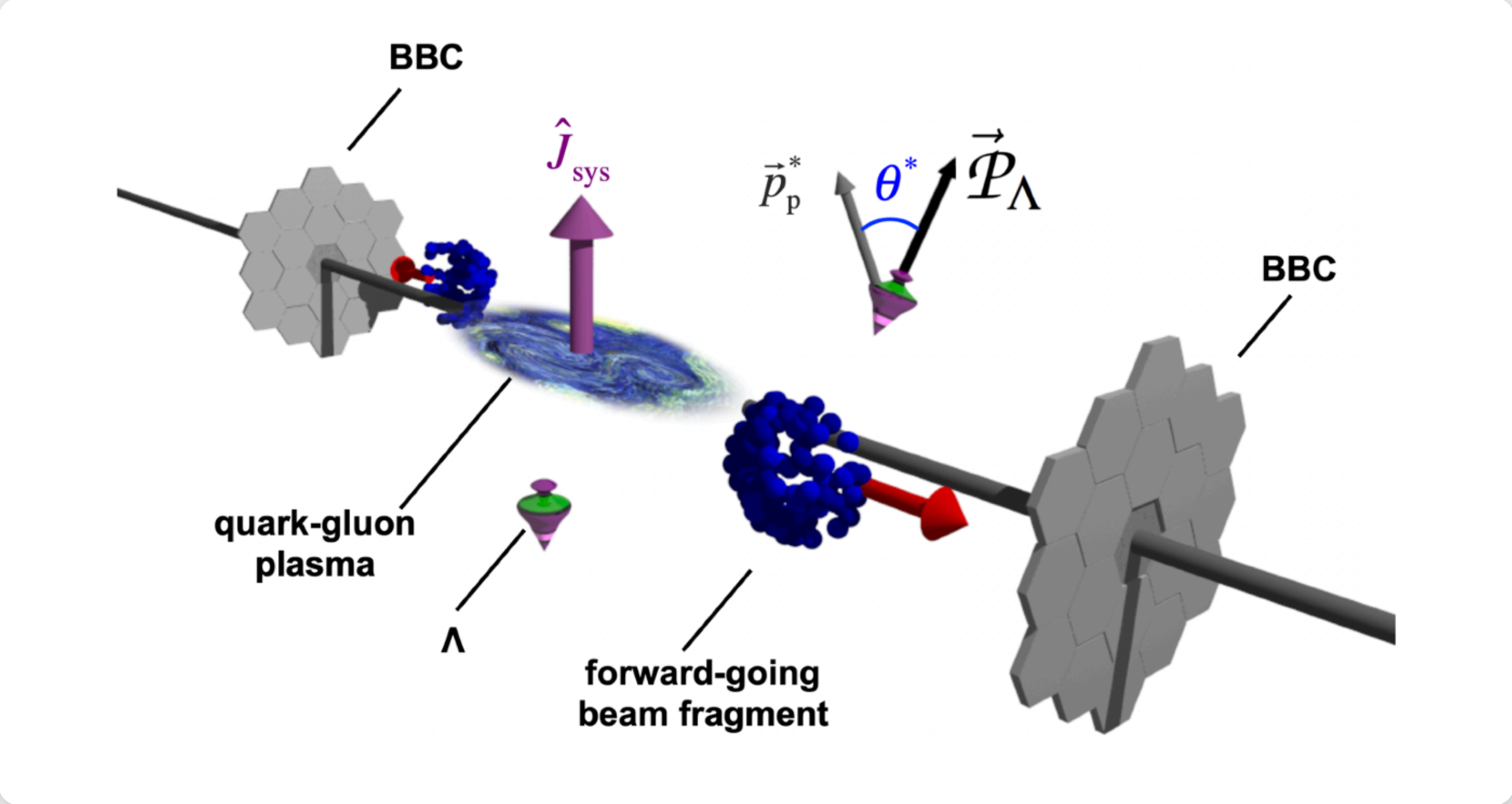
Conclusion & Outlook

- Impact parameter b_{max} for which the angular momentum of the fireball becomes maximal is nearly energy independent for a broad energy range
  → $b_{max} \in [\, 4.5 \text{ fm}, 6.6 \text{ fm} \,]$ for $\sqrt{s_{NN}} \in [\, 2.41 \text{ GeV}, 200 \text{ GeV} \,]$
- Higher relative transfer of initial angular momentum to the fireball in more central collisions
- Fermi motion induces additional angular momentum
- Predictions for expectation of high angular momentum is important for future experimental measurements
- Detailed understanding of the dynamics is crucial for extracting phase transition signals
- Long-term goal: Implementing spin degrees of freedom to describe hadronic polarization within the transport approach

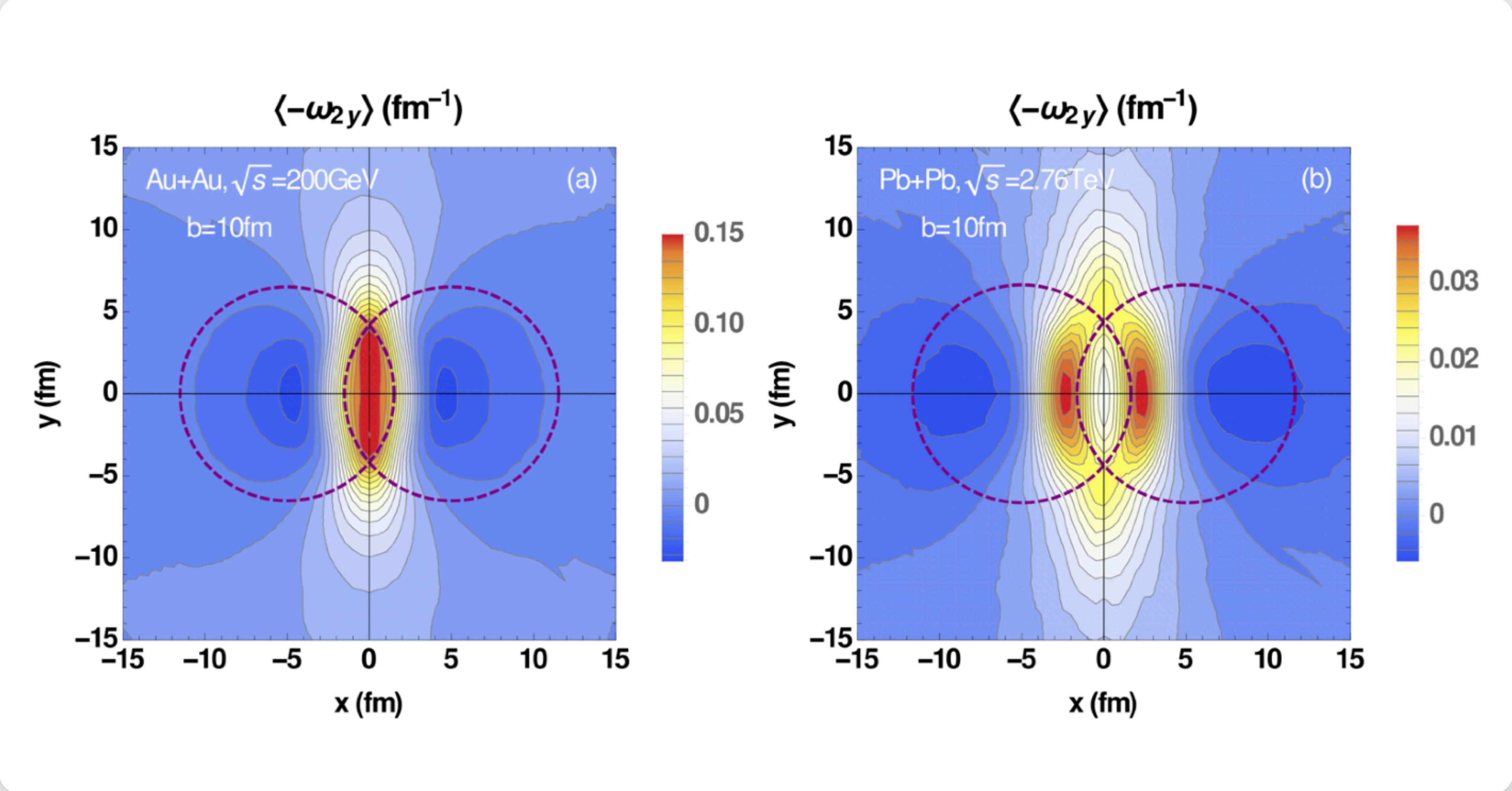
Backup Slides

Spin Polarization

L. Adamczyk *et al.* [STAR], Nature 548 (2017), 62-65



Deng and Huang, Phys. Rev. C 93 (2016) no.6, 064907



- Spin polarization: Alignment of particle spins with system's angular momentum
- Non-central heavy-ion collisions induce vorticity and orbital angular momentum in the QGP
- Studying polarization observables might give hints of magnetic fields as another source for polarization (Chiral Magnetic Effect)

Global polarization of quarks & anti-quarks due to spin-orbit coupling → **Hadronization** → Global polarization of Λ hyperons and other hadrons species

SMASH

Initial Conditions

Sampling of the initial nuclei in coordinate space according to the Woods-Saxon distribution

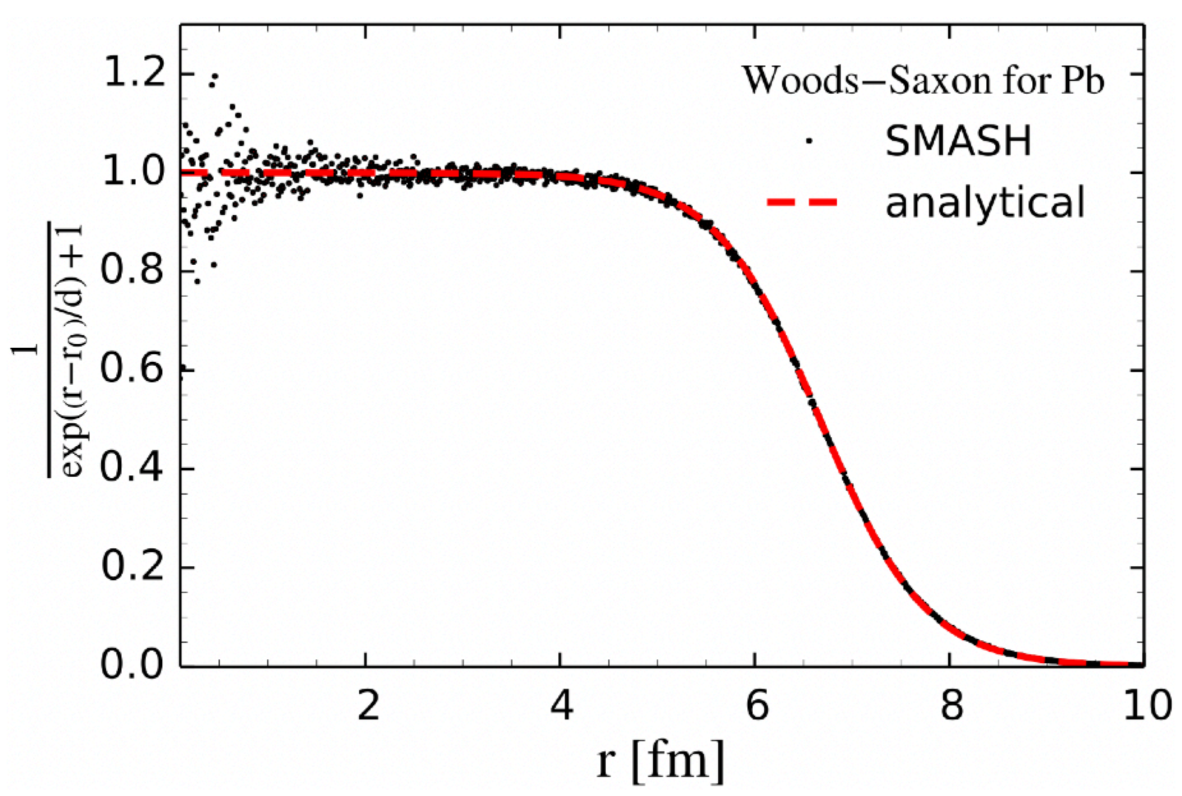
$$\frac{dN}{d^3r} = \frac{\rho_0}{\exp\left(\frac{r-r_0}{d}+1\right)}$$

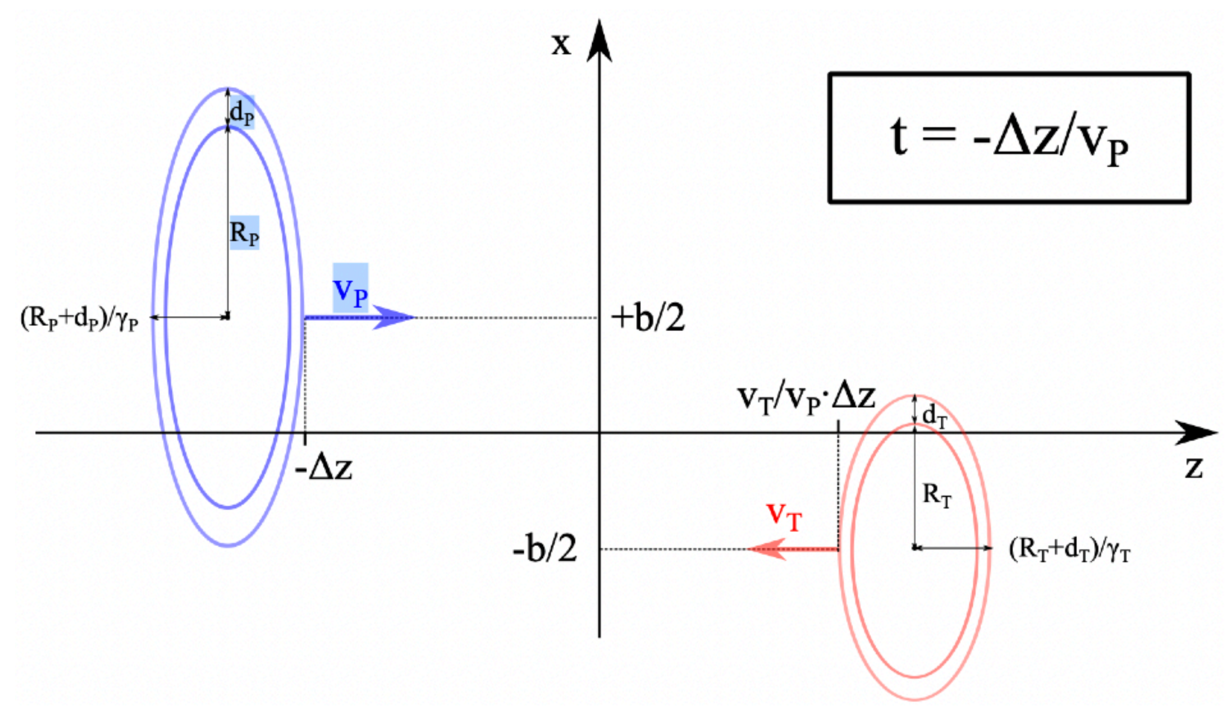
d: diffusiveness of the nucleus

ρ_0: nuclear ground state density

- Hard sphere limit: $d \to 0$

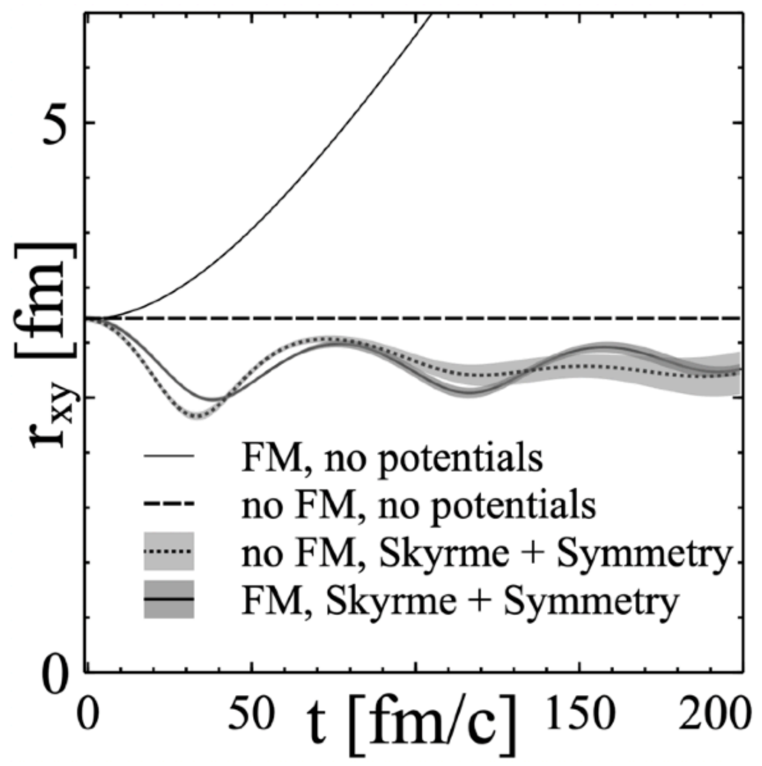
J. Weil *et al.*, Phys.Rev.C 94 (2016) 5, 054905





Fermi Motion

- Nuclei get additional momenta
- Nuclei are „stable“ if additional potentials are turned on
- „Frozen“ Fermi motion only considered for collision and turned off for propagation



J. Weil *et al.*, Phys.Rev.C 94 (2016) 5, 054905

Resonances

- Particles with widths $< 10\,\mathrm{keV}$ treated as stable
- Unstable particles assigned a relativistic Breit-Wigner spectral function

$$\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi}\frac{m^2\Gamma(m)}{(m^2-M_0^2)^2+m^2\Gamma(m)^2}$$

m: resonance mass

M_0: pole mass

$\Gamma(m)$: width function

$\mathcal{N}$: normalization

- Decay width of two body decay $R \to ab$ by treatment of Manley et al.

$$\Gamma_{R\to ab} = \Gamma^0_{R\to ab}\frac{\rho_{ab}(m)}{\rho_{ab(M_0)}}$$

$\rho_{ab}(m)$: mass integrals over resonance spectral functions

$\Gamma^0_{R\to ab} = \Gamma_{R\to ab}(M_0)$

Angular Momentum And Impact Parameter

- Angular Momentum as function of the impact parameter shows a distinct maximum at a single b_{max}
- Qualitative agreement with predictions from geometrical Glauber model

Becattini et al, Phys. Rev. C77:024906, 2008