Angular Momentum in HICs via SMASH

**Motivation**

- Large orbital angular momentum $L \sim \mathcal{O}(10^6 \hbar)$ in non-central HICs create global polarization of $\Lambda$ hyperons at mid-rapidity

- Angular momentum of the fireball directly related to vorticity (spin-orbit coupling) as fundamental property of the QGP

- Dynamical description of $L$ within a transport approach yields predictions where the biggest transfer of OAM to the QGP is expected

**Our Approach**

- Hadronic transport approach for a dynamical non-equilibrium description of HICs at low beam energies

- Including all hadrons up to $m \sim 2.35 \text{ GeV}$

- Effective solution of the relativistic Boltzmann equation

\[
p^\mu \partial_\mu f(x, p) + m_i F^{\mu \nu} \partial_\nu f(x, p) = C^i_{\text{coll}}
\]

**Collisions**

Collisions are performed at a finite distance according to the geometrical interpretation of the cross section

**Maximal $L$ Transfer**

- **Energy dependence** of impact parameter $b_{\text{max}}$ for which the remaining angular momentum $L_r$ becomes maximal

- More angular momentum is deposited at mid-rapidity in more central collisions and at lower beam energies

**System Size**

- **System size dependence** of the ratio of the fireball’s angular momentum over the initial angular momentum $L_r / L_0$

**Conclusion**

- We find a maximum $L_r$ impact parameter $b_{\text{max}}$ which is nearly energy independent for a broad energy range, $b_{\text{max}} \in [4.5 \text{ fm}, 6.6 \text{ fm}]$

- We observe a higher transfer of initial angular momentum to the fireball at lower beam energies and in more central collisions.

- Future: Implementation of spin DoF to describe polarization in nuclear collisions

\[
\begin{align*}
N. \text{ Sass et al, in preparation} \\
\text{Au-Au, } \sqrt{S_{\text{NN}}} = 2.41 \text{ GeV} \\
\text{Fermi Motion: Frozen} & \quad \text{Fermi Motion: Off} \\
\text{Au-Au, } \sqrt{S_{\text{NN}}} = 200 \text{ GeV} \\
\end{align*}
\]
**General Setup**

- Geometric collision criterion
  \[ d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \]
  \[ d_{\text{trans}} = (\vec{r}_a - \vec{r}_b)^2 + \frac{(\vec{p}_a - \vec{p}_b) \cdot (\vec{p}_a - \vec{p}_b)}{(\vec{p}_a - \vec{p}_b)^2} \]
- Test particle method: \( \sigma \rightarrow \sigma \cdot N_{\text{test}}^{-1} \), \( N \rightarrow N \cdot N_{\text{test}} \)

**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
  - \( \rho_0 \): nuclear ground state density
  - \( d \rightarrow 0 \): Hard sphere limit

**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

**Resonances**

- Particles with widths < 10 keV treated as stable
- Unstable particles assigned a relativistic Breit-Wigner spectral function
  \[ \mathcal{A}(m) = \frac{2 \mathcal{N}}{\pi (m^2 - M_0^2)^2 + m^2 \Gamma(m)^2} \]
  - \( m \): resonance mass
  - \( M_0 \): pole mass
  - \( \Gamma(m) \): width function
  - \( \mathcal{N} \): normalization
- Decay width of two body decay \( R \rightarrow ab \) by treatment of Manley et al.
  \[ \Gamma_{R\rightarrow ab} = \frac{\Gamma_{R\rightarrow ab}^0}{\rho_{ab}(M_0)} \]
  \[ \Gamma_{R\rightarrow ab}^0 = \Gamma_{R\rightarrow ab}(M_0) \]
  \[ \rho_{ab}(M_0) \]: mass integrals over resonance spectral functions

**Additional Information**

- Insight into SMASH
- Quark Matter 2022
- Geometric collision criterion
- Test particle method: \( \sigma \rightarrow \sigma \cdot N_{\text{test}}^{-1} \), \( N \rightarrow N \cdot N_{\text{test}} \)
- Sampling of the initial nuclei in coordinate space according to the Woods-Saxon distribution
- 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
- Particles with widths < 10 keV treated as stable
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- Decay width of two body decay \( R \rightarrow ab \) by treatment of Manley et al.

http://smash-transport.github.io
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 higher nuclei rapidities.

Secondary collisions at higher beam energies shift the flattening of $L_{sp}$ and $L_r$ to later times.
Angular Momentum Conservation

- At $\sqrt{s_{NN}} = 8.7$ GeV protons collide elastically (~1/3) and inelastically (~2/3).
- Geometrical Interpretation of the cross section breaks angular momentum conservation in binary in/elastic collisions.
- Collective „loss“ of angular momentum in Au-Au collisions amounts to 3.5% for small impact parameters.
- Additional momenta by Fermi motion potentially increase non-conservation of angular momentum.

N. Sass et al., in preparation

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$\sqrt{s_{NN}} = 8.7$ GeV
**STAR Measurement**

- Weak decay $\Lambda \rightarrow p + \pi^-$ emits proton predominantly in spin direction of $\Lambda$

- The (phase-space) **averaged polarization** is determined by the azimuthal angle distribution of the proton’s momentum

- $\Lambda$ is identified by extrapolation of the measured daughter particles ($p, \pi^-$)

- Summation over many events yields a distinct peak in the invariant-mass distribution at the $\Lambda$ mass