

September 6th 2023

Angular Momentum in Heavy Ion Collisions via SMASH



N. Sass *et al.*, arXiv:2212.14385v1

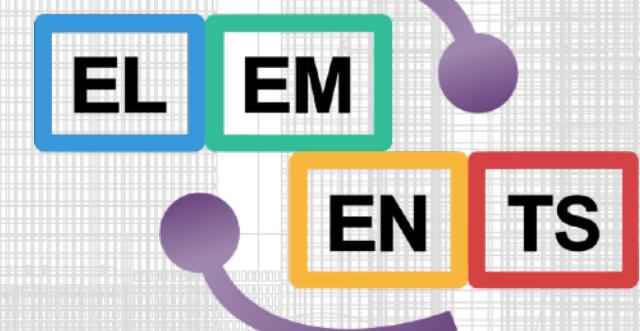
Nils Sass

in collaboration with Oscar Garcia-Montero,
Marco Müller and Hannah Elfner

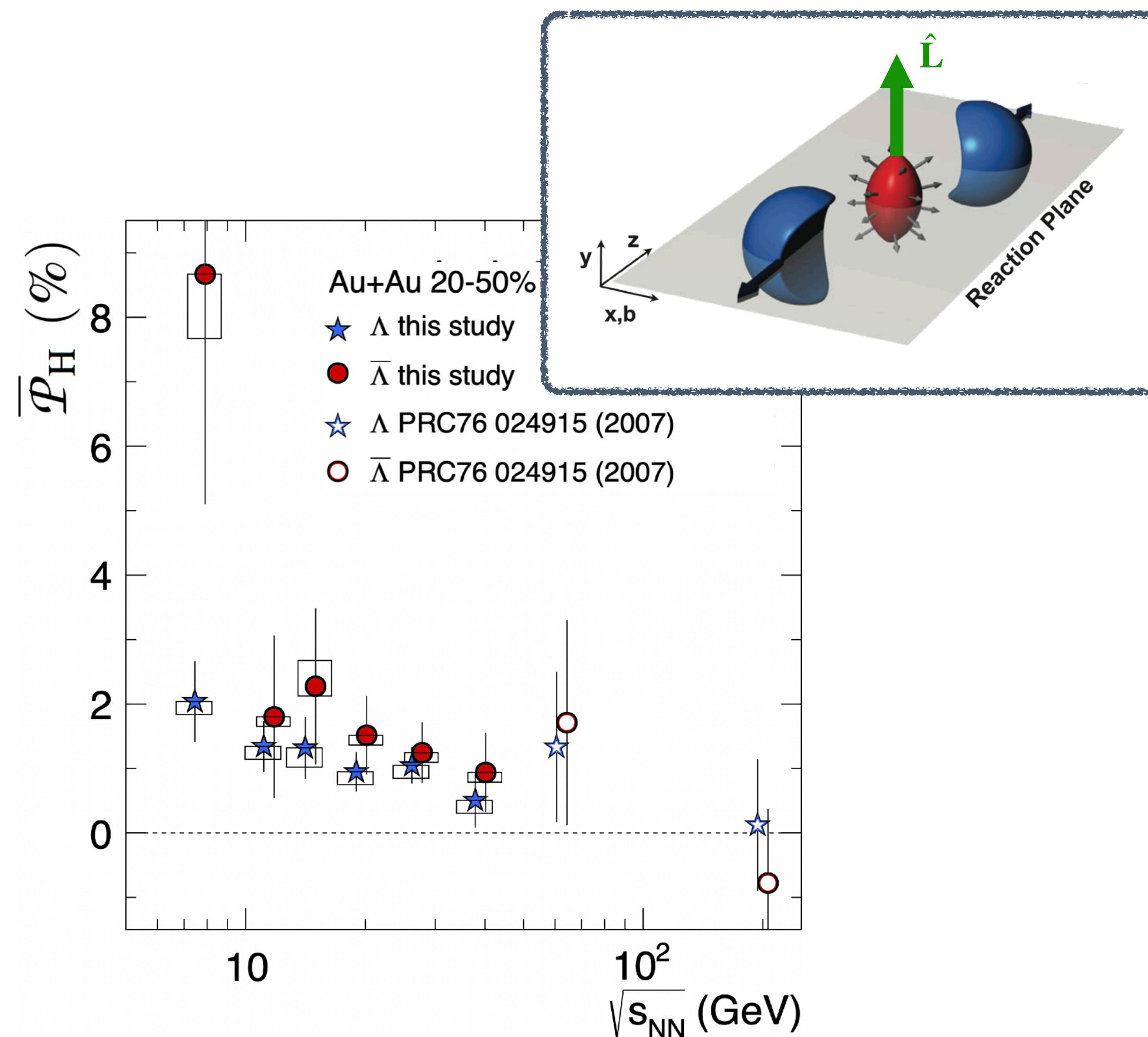


HGS-HIRe *for FAIR*
Helmholtz Graduate School for Hadron and Ion Research

CRC-TR 211
Strong-interaction matter
under extreme conditions



Signals of Polarization



L. Adamczyk *et al.* [STAR], Nature 548 (2017), 62-65
Snellings 2011 New J. Phys. 13 055008 (adoption)
Huang *et al.*, Lect.Notes Phys. 987 (2021) 281-308

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 in the fireball
- Polarization increases for lower beam energies

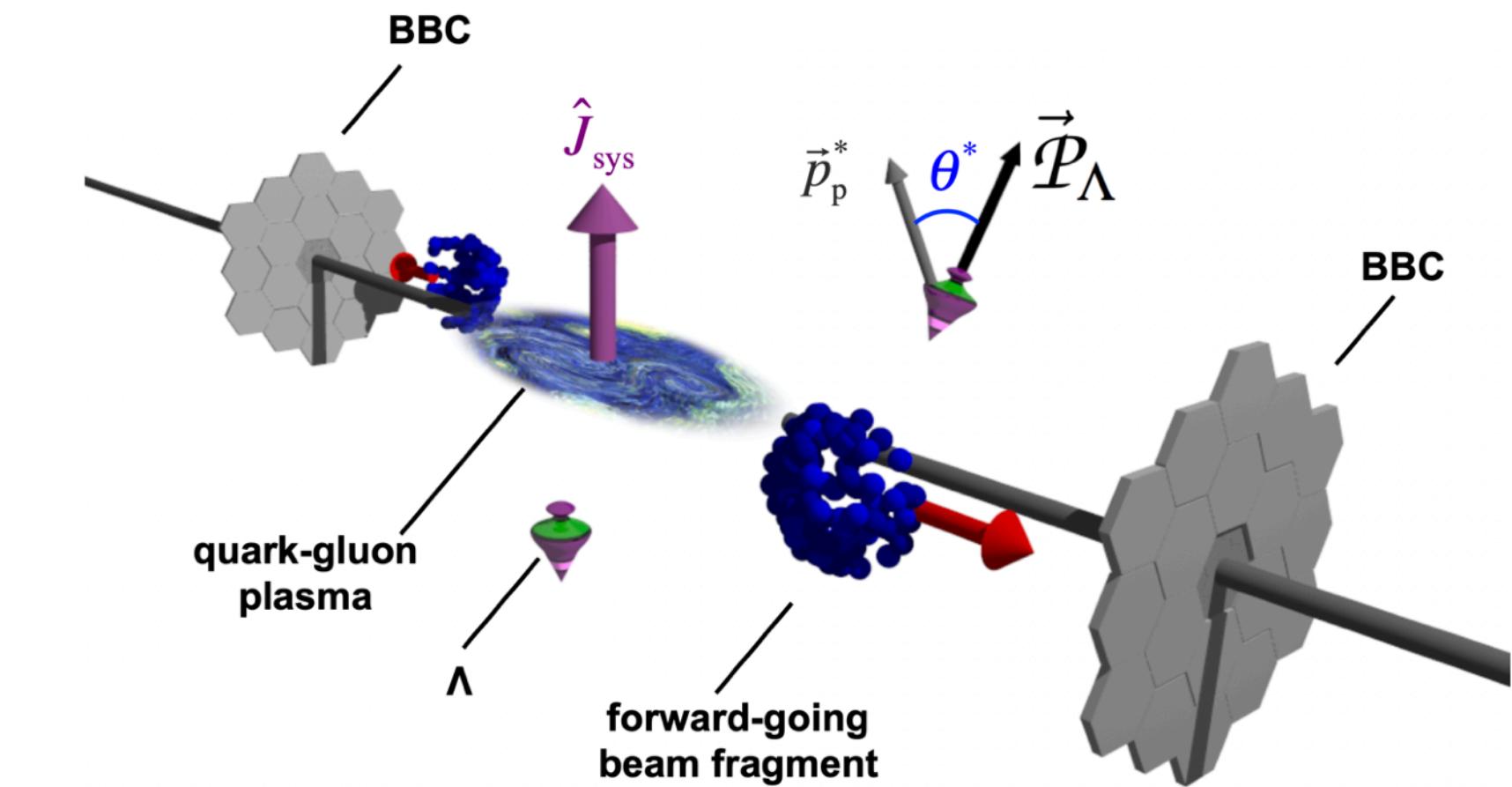
Spin Polarization

- Non-central heavy-ion collisions induce a large orbital angular momentum and vorticity in the fireball

Z. T. Liang & X. N. Wang, Phys. Rev. Lett. 94, 102301 (2005)
S. A. Voloshin, EPJ Web Conf. 171 (2018) 07002
S. Ryu, V. Jupic, C. Shen, Phys. Rev. C 104, 054908 (2021)

- Spin polarization is mainly driven by thermal vorticity

F. Becattini *et al.*, Phys. Rev. Lett. 127 (2021) 27, 272302



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

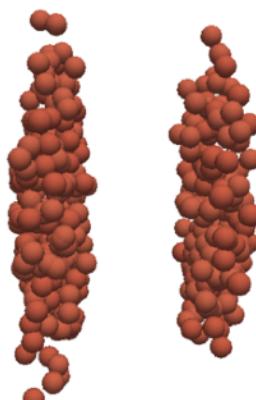
Why Angular Momentum?

- 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

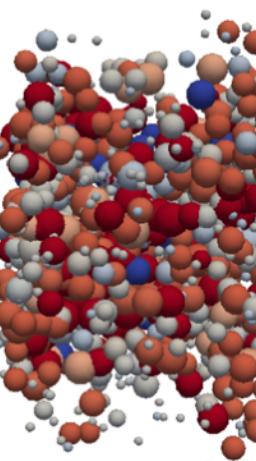
Other Contributions

- David Wagner (Poster), 09/05/2023, 5.30pm
"Alignment from spin-1 hydrodynamics"
- Andrea Palermo (Talk), 09/06/2023, 2.20pm
"Exact Polarization of Particles of Any Spin at Global Equilibrium"

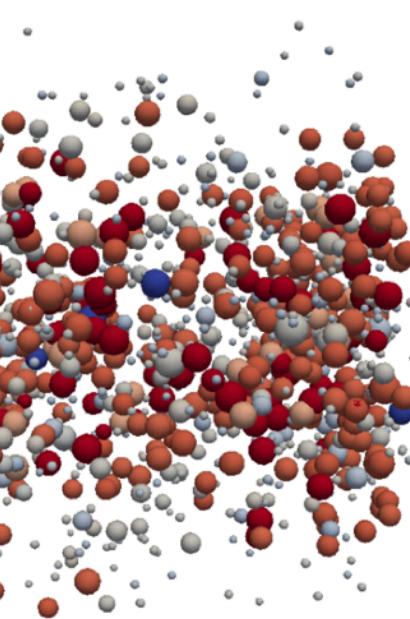
Pb-Pb collision
at $E_{\text{lab}} = 40 \text{ GeV}$



$t = -2.5 \text{ fm}$



$t = 6 \text{ fm}$



$t = 12 \text{ fm}$

<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 (GSI/FAIR) and late stage rescattering at high beam energies (RHIC/LHC)
- Includes all hadrons from the PDG(2018) up to $m \sim 2.35 \text{ GeV}$

SMASH Setup

- Effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x, p) + m_i F^\alpha \partial_\alpha^p f_i(x, p) = C_{\text{coll}}^i$$

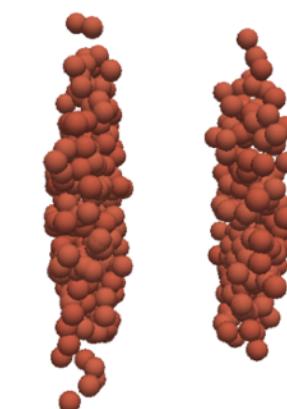
- Geometric collision criterion

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

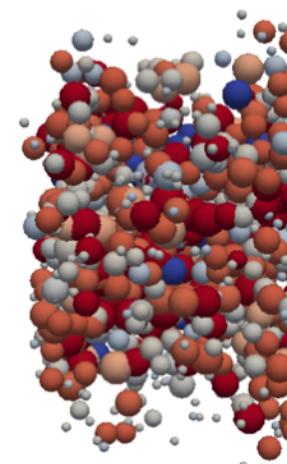
- Test particle method $\sigma \rightarrow \sigma \cdot N_{\text{test}}^{-1}$, $N \rightarrow N \cdot N_{\text{test}}$

Pb-Pb collision
at $E_{\text{lab}} = 40 \text{ GeV}$

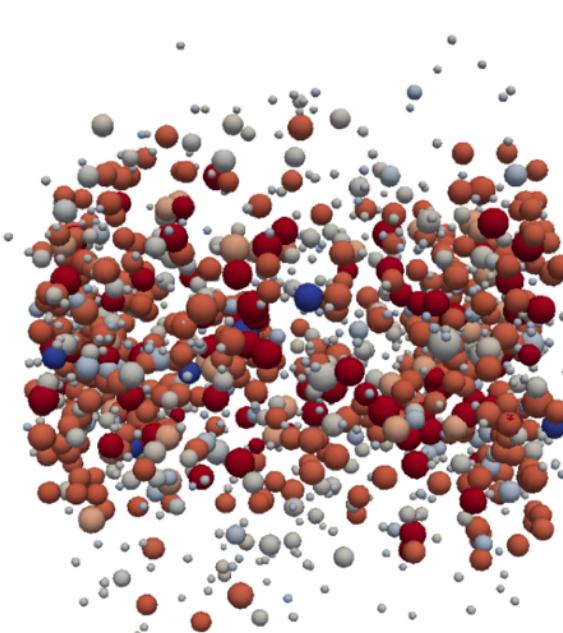
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SMASH Modi

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

IC

Initial condition generator for hydrodynamic models

Collider

Elementary or AA reactions

Box

Infinite matter simulations

Afterburner

Hadronic rescattering following hydrodynamic expansion

Library

Include SMASH as library in third party codes

→ Output

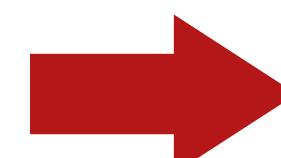
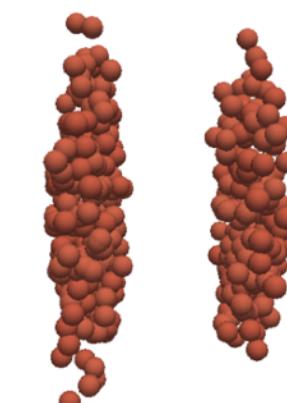
OSCAR, Binary, HepMC, YODA (Rivet), ROOT, VTK ...

Nucleus Properties

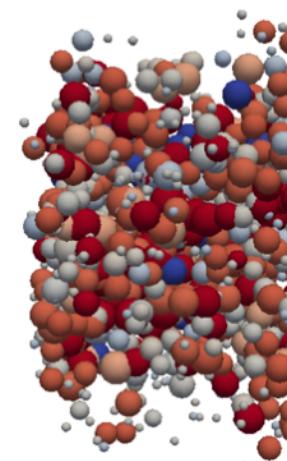
- **Fermi motion:** Optional sampling of isotropic Fermi momenta per nucleon
$$p_F(\vec{r}) = \hbar c \left(3\pi^2\rho(\vec{r})\right)^{\frac{1}{3}}$$
- **Potentials:** Optional inclusion of (momentum dependent) potentials to prevent nucleus destabilization when Fermi motion is enabled

Pb-Pb collision
at $E_{\text{lab}} = 40 \text{ GeV}$

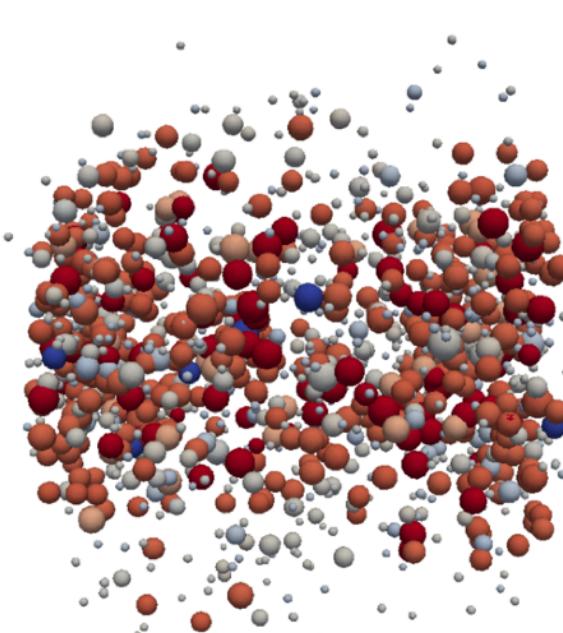
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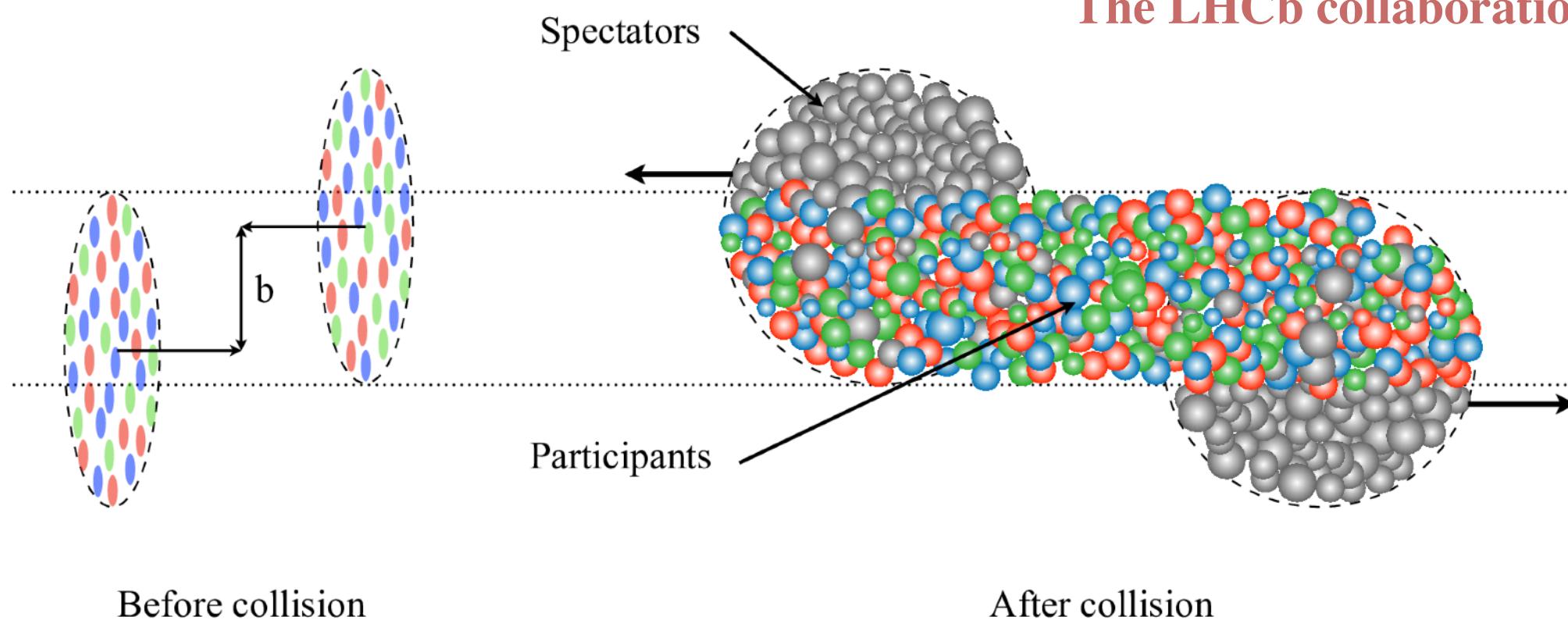
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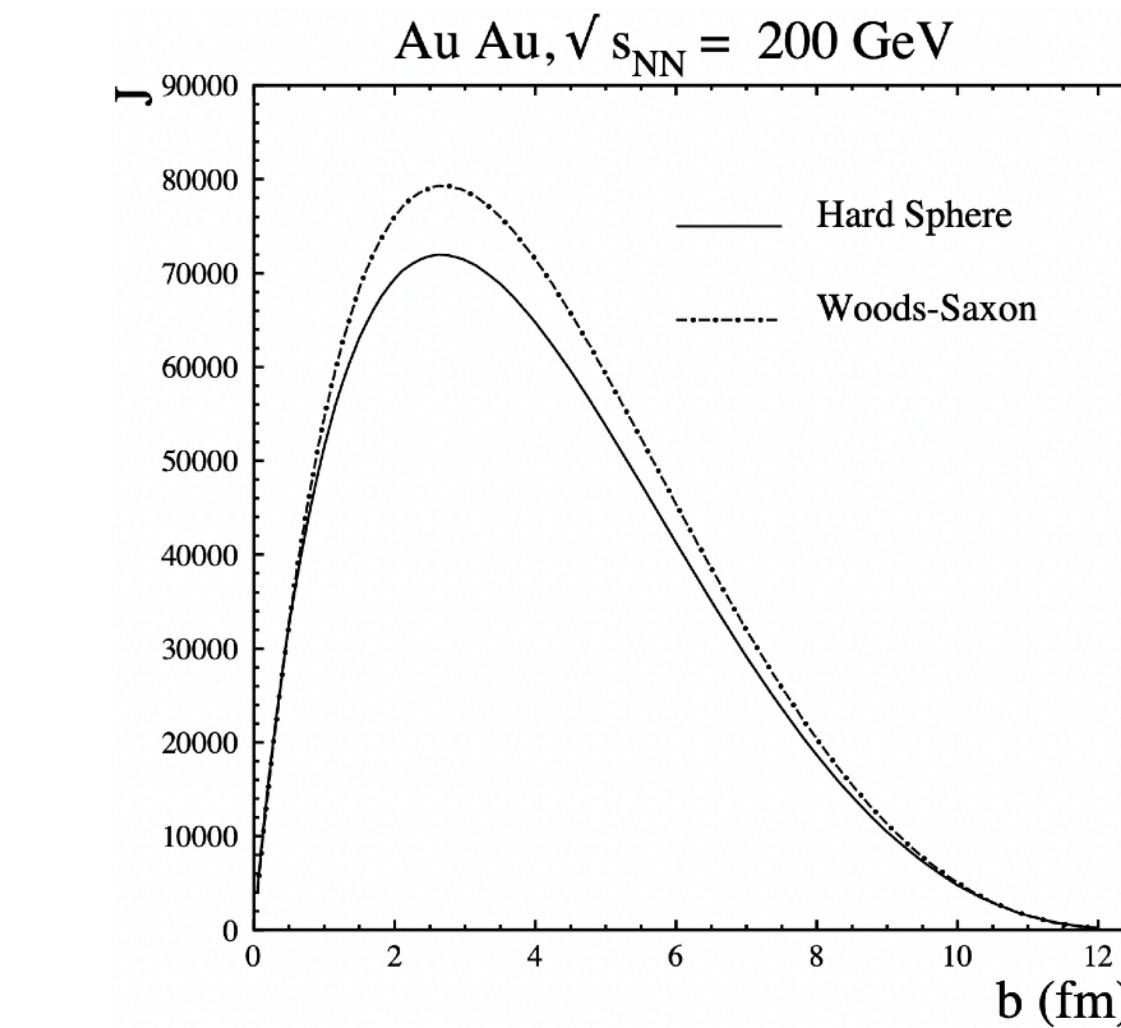
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Angular Momentum And Impact Parameter

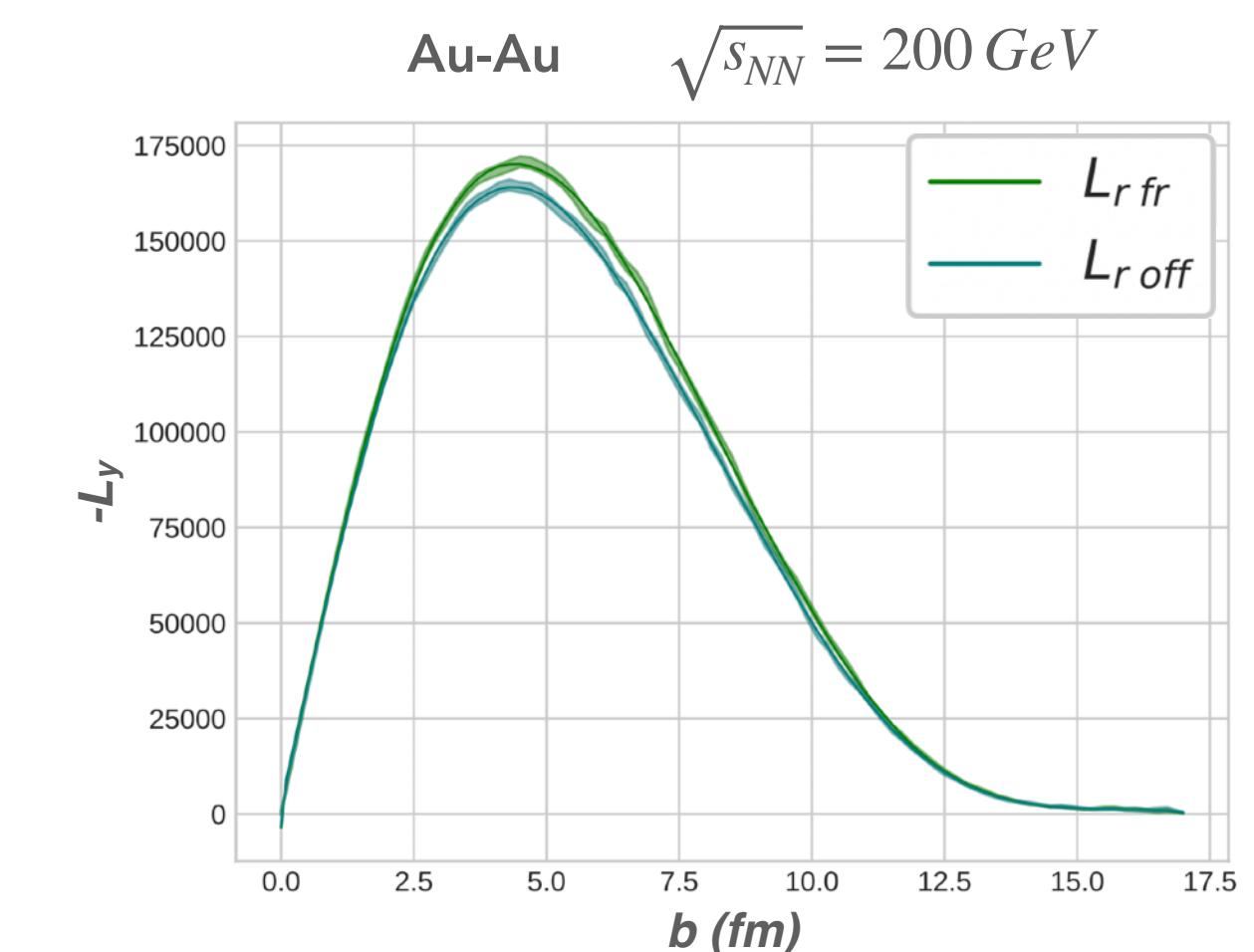
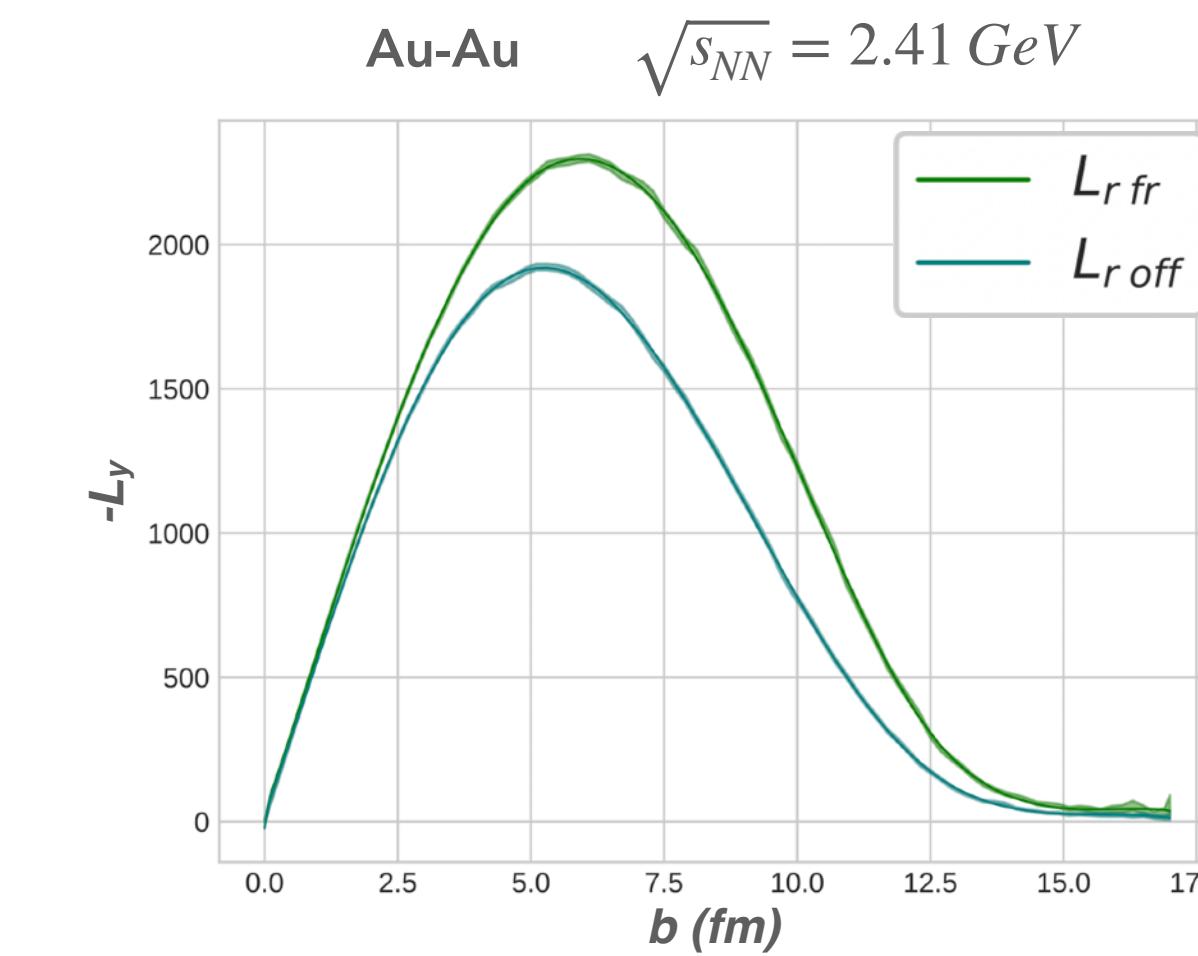
Comparison with Glauber Model



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

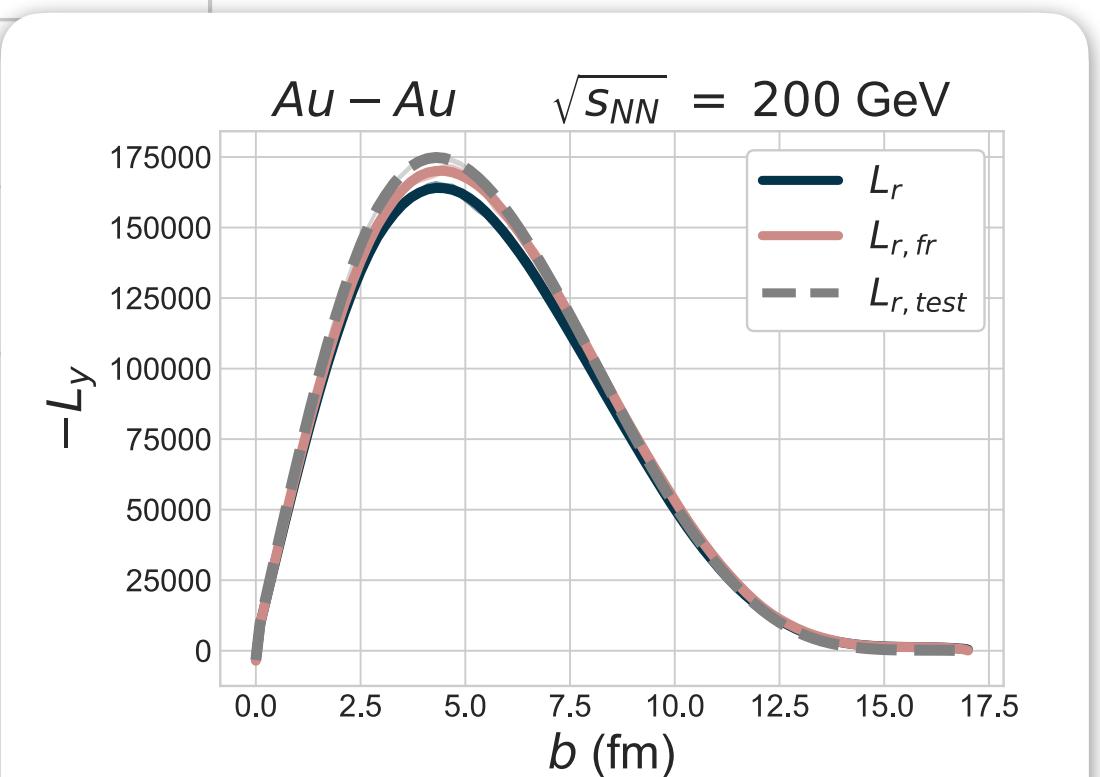
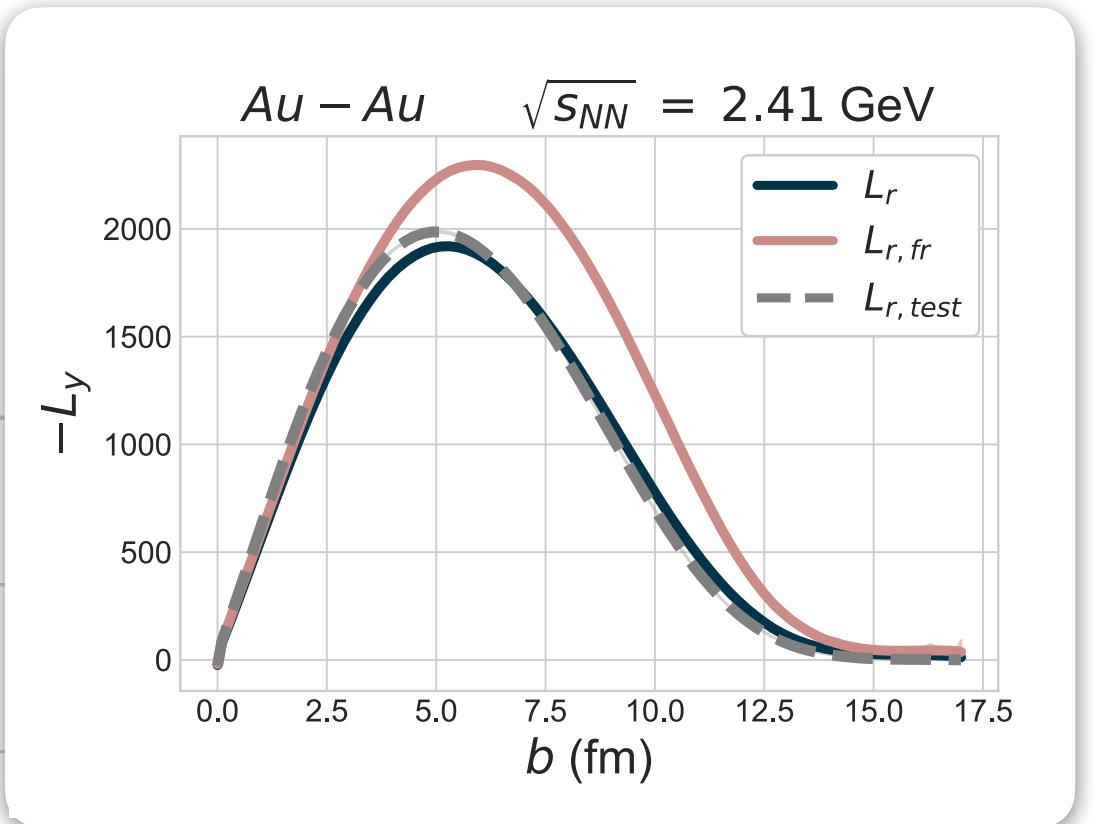
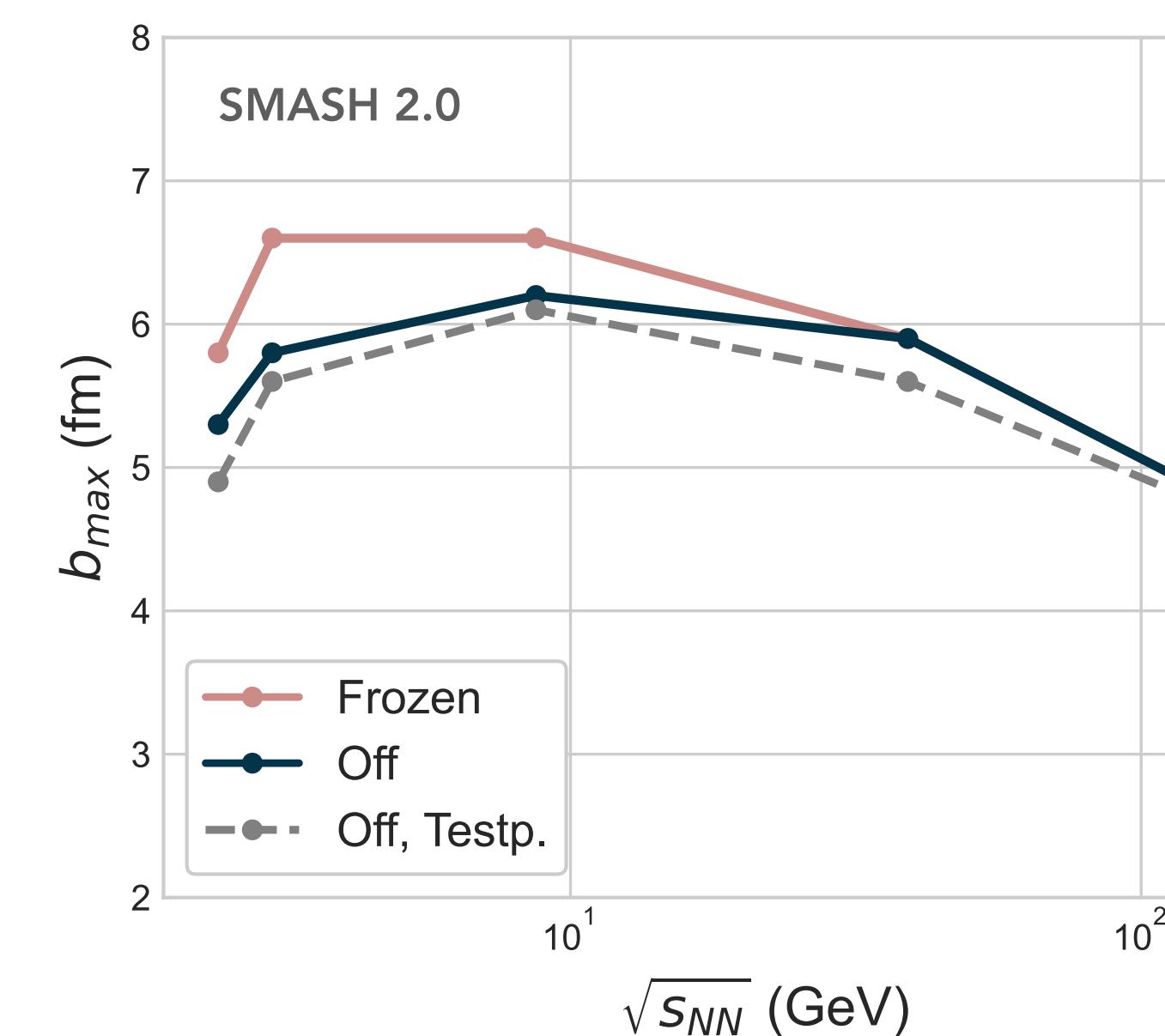


- Angular Momentum as function of the impact parameter shows a distinct maximum at a single b_{\max}
- We find a qualitative agreement with predictions from geometrical Glauber model



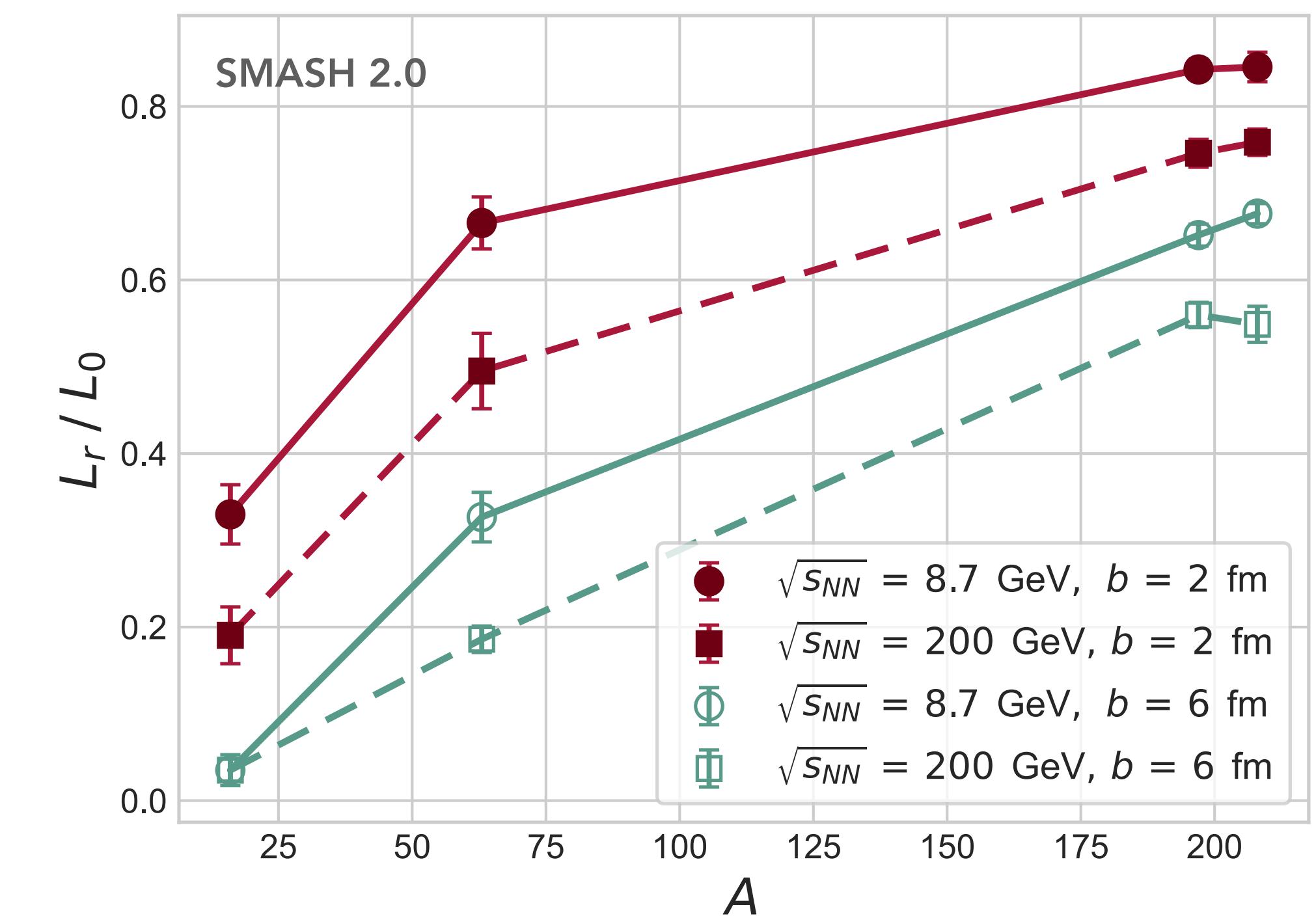
Impact Parameter Dependence

- Minor energy dependence of the impact parameter b_{\max} of the maximum in the participant's angular momentum L_r
- Maximum of L_r mainly determined by the geometry of the collision which does not change
- Fermi motion induces additional angular momentum into the system

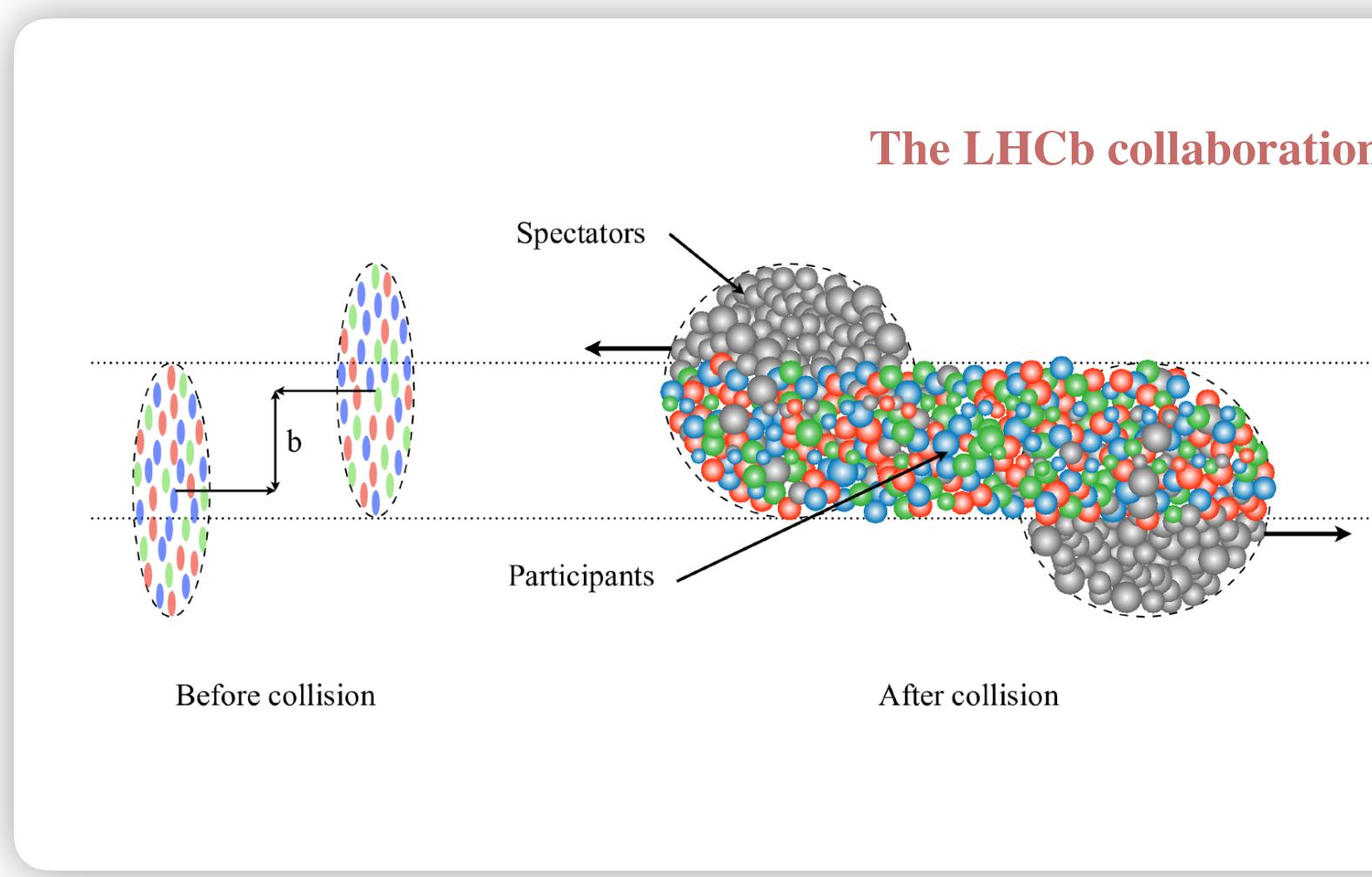
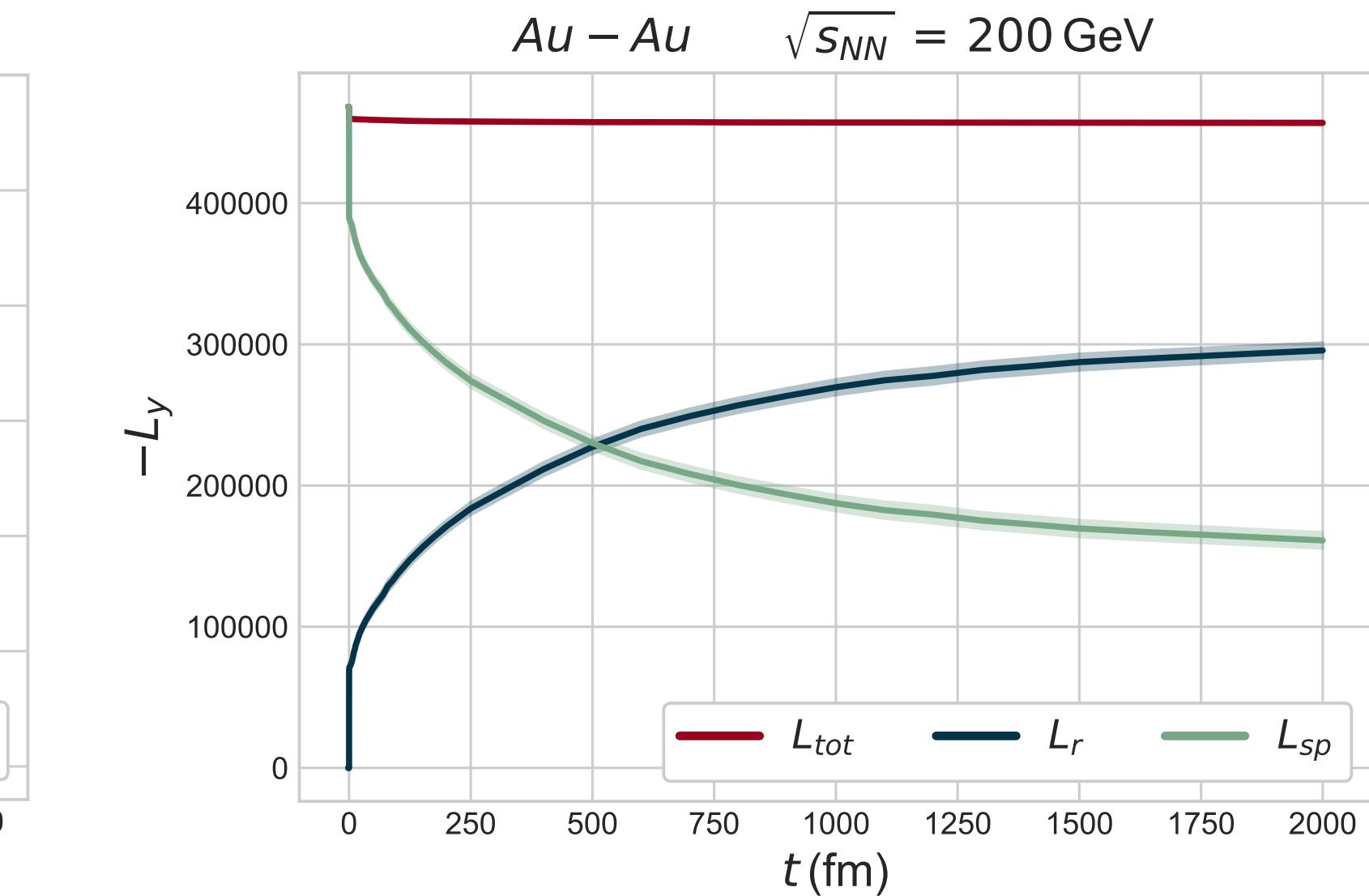
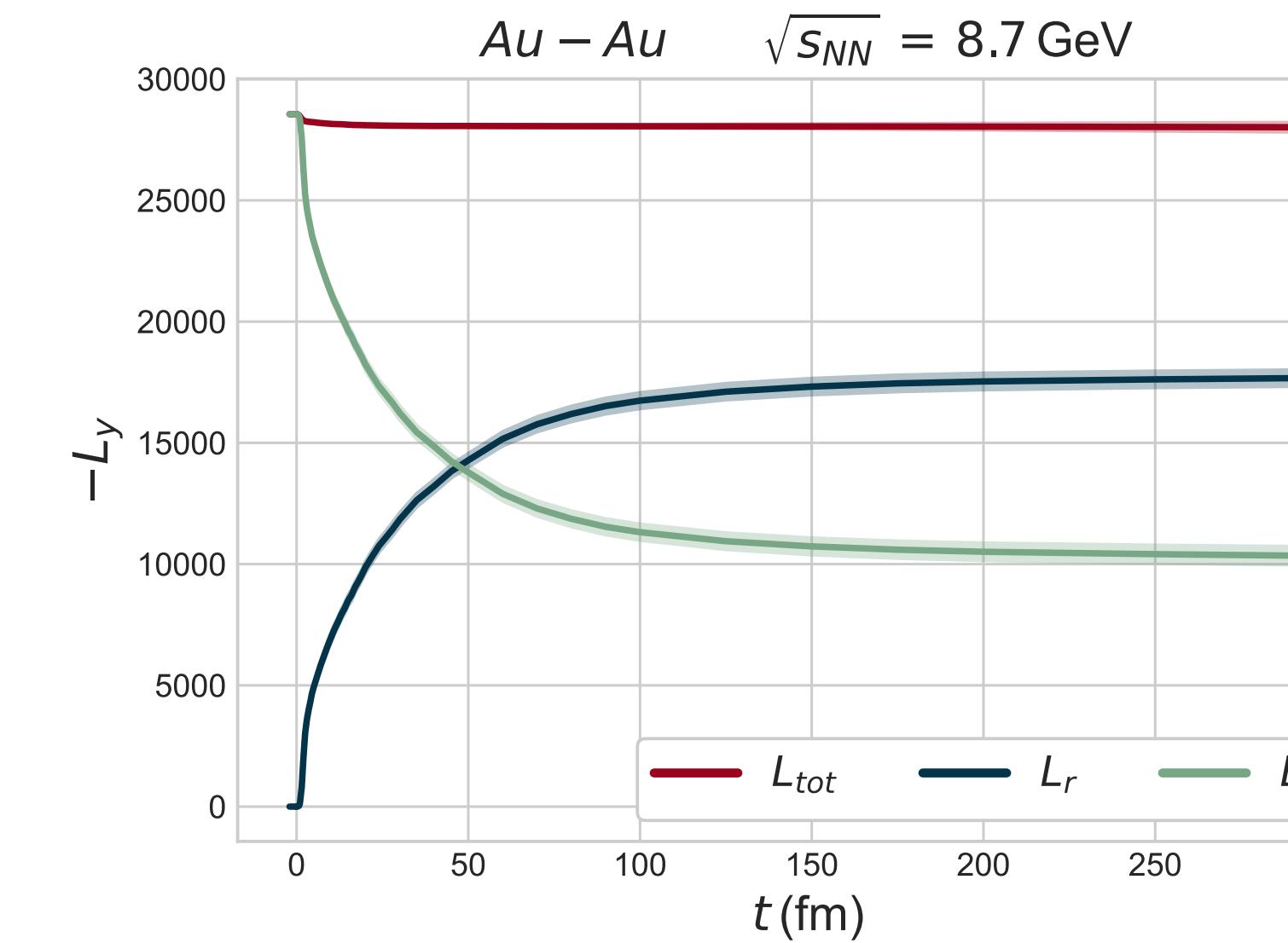
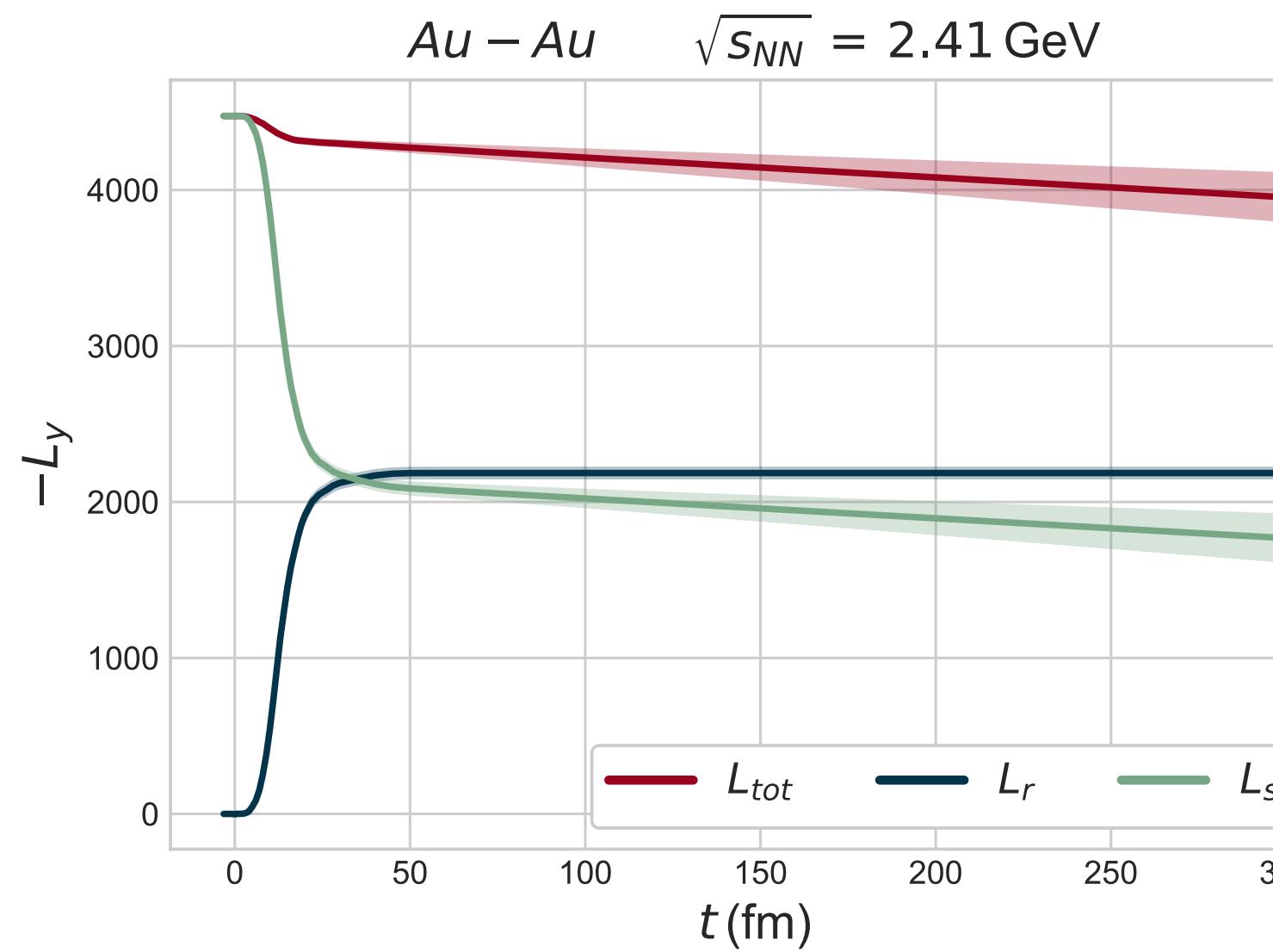


System Size Dependence

- Simulated nuclei (system size) for A-A collisions:
 $A = \{ {}^{16}O, {}^{63}Cu, {}^{197}Au, {}^{208}Pb \}$
- System size dependence of the ratio of the fireball's angular momentum over the initial angular momentum L_r / L_0
- Larger deposition of angular momentum in the interaction region at mid-rapidity in more central collisions and at lower beam energies



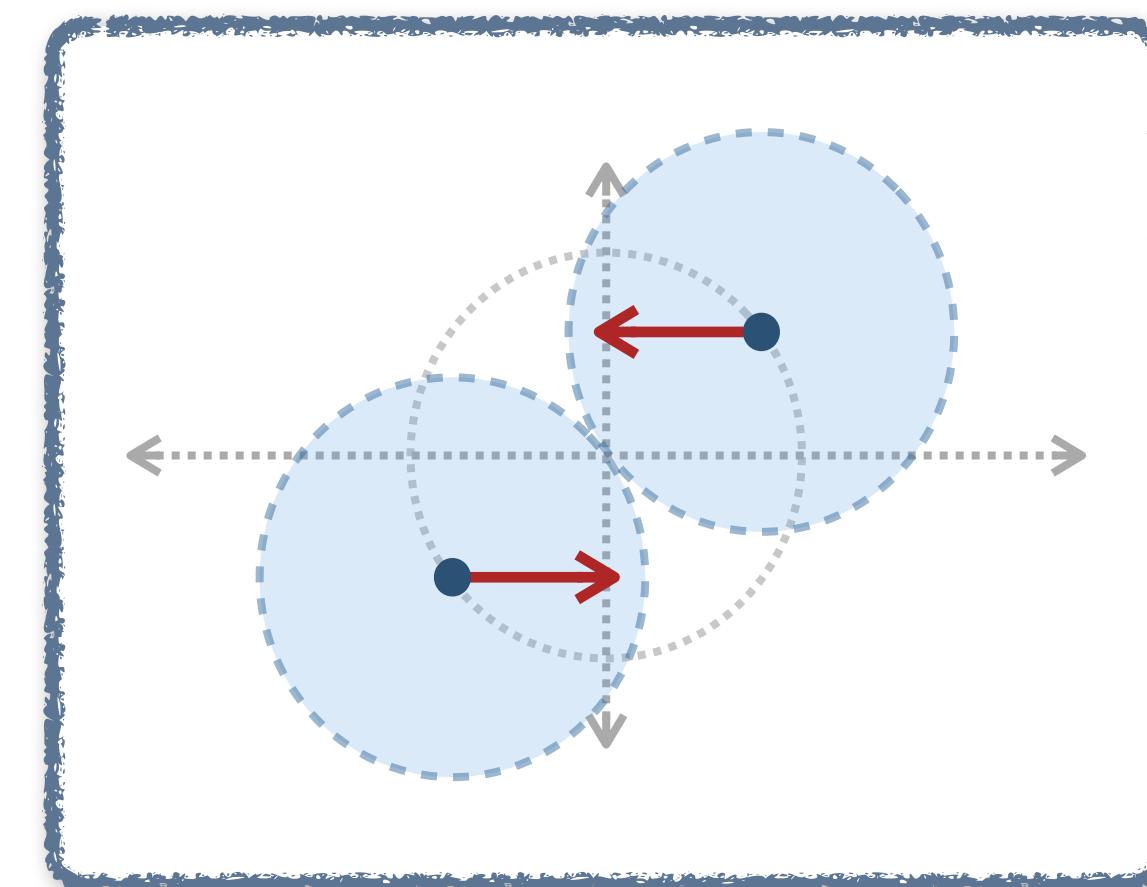
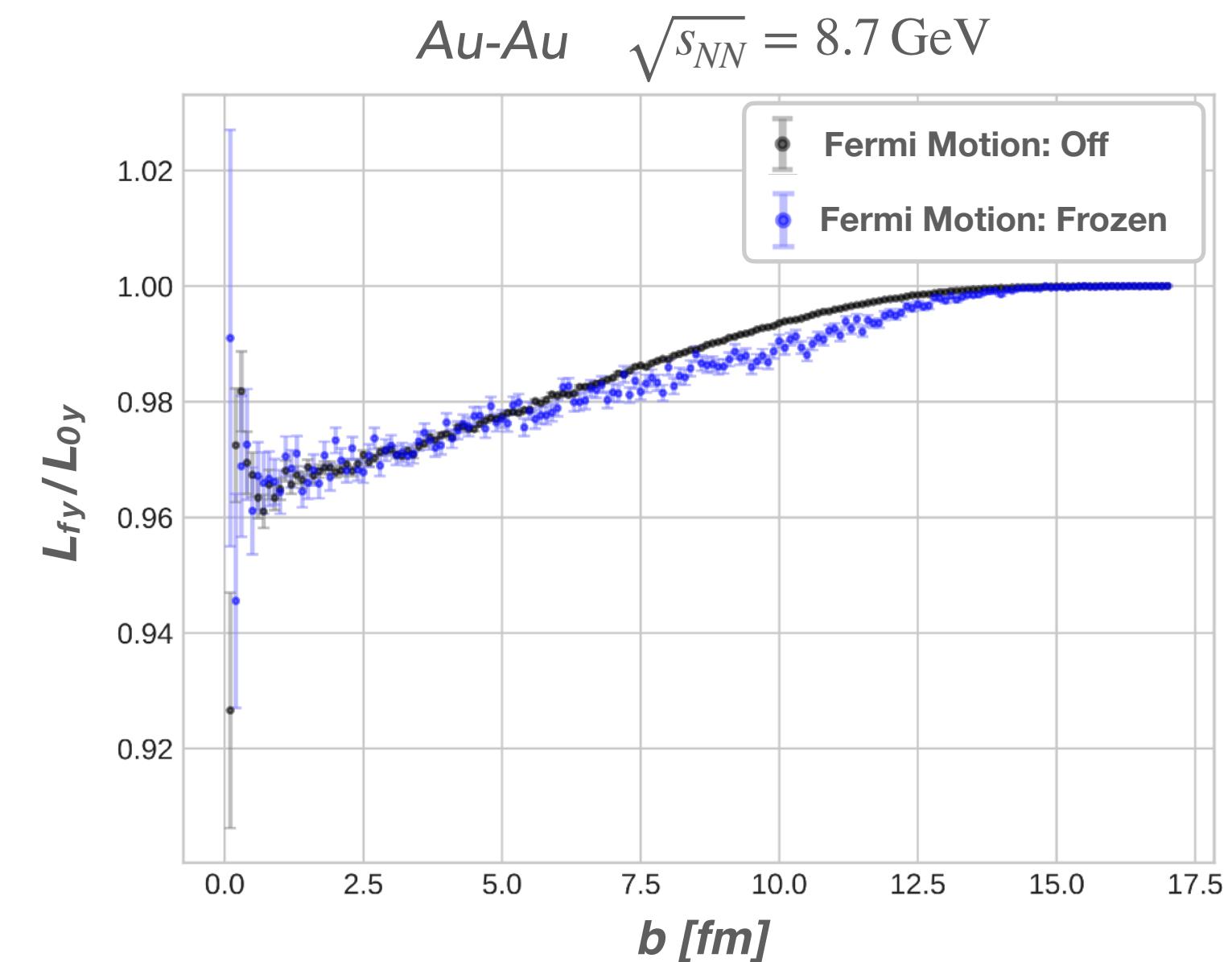
Angular Momentum Evolution



- 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 Lorentz contraction

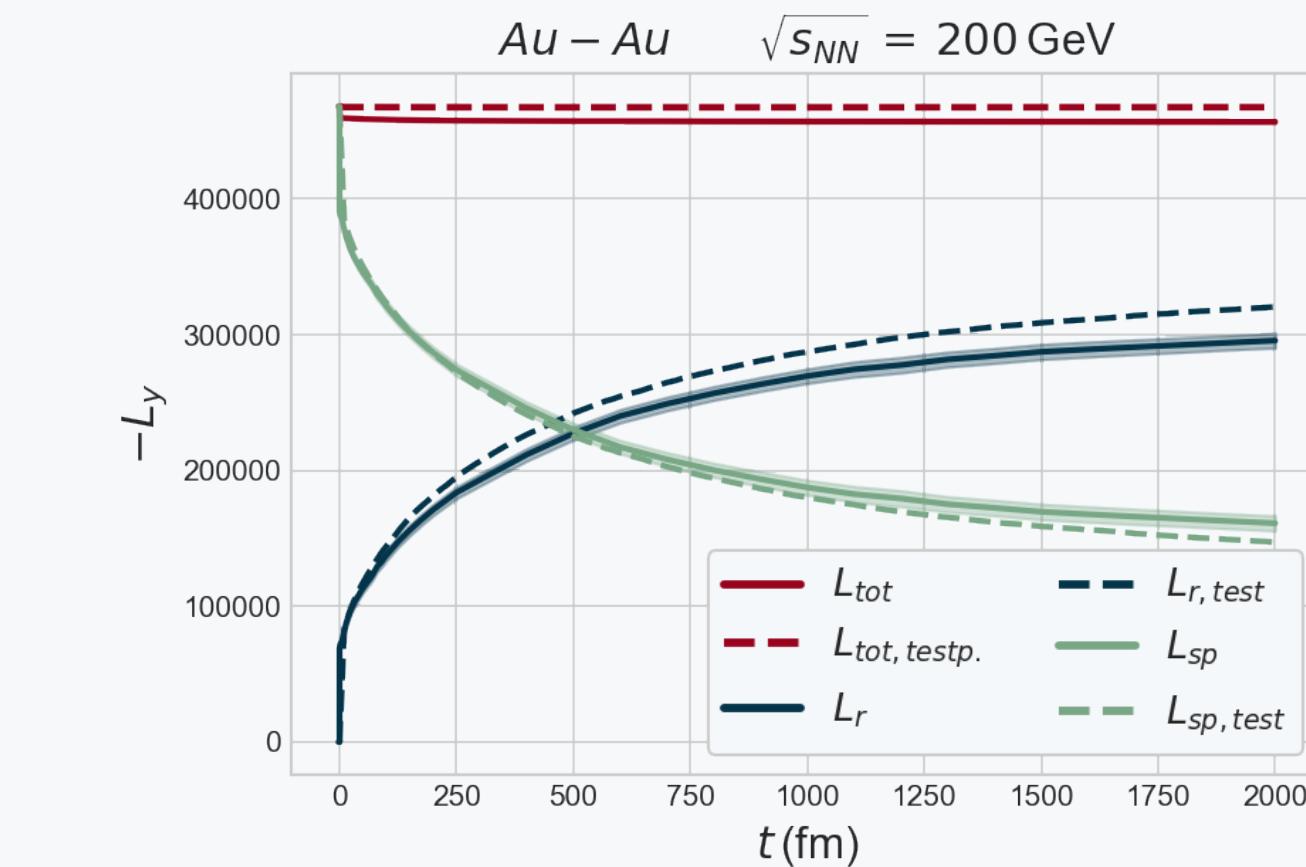
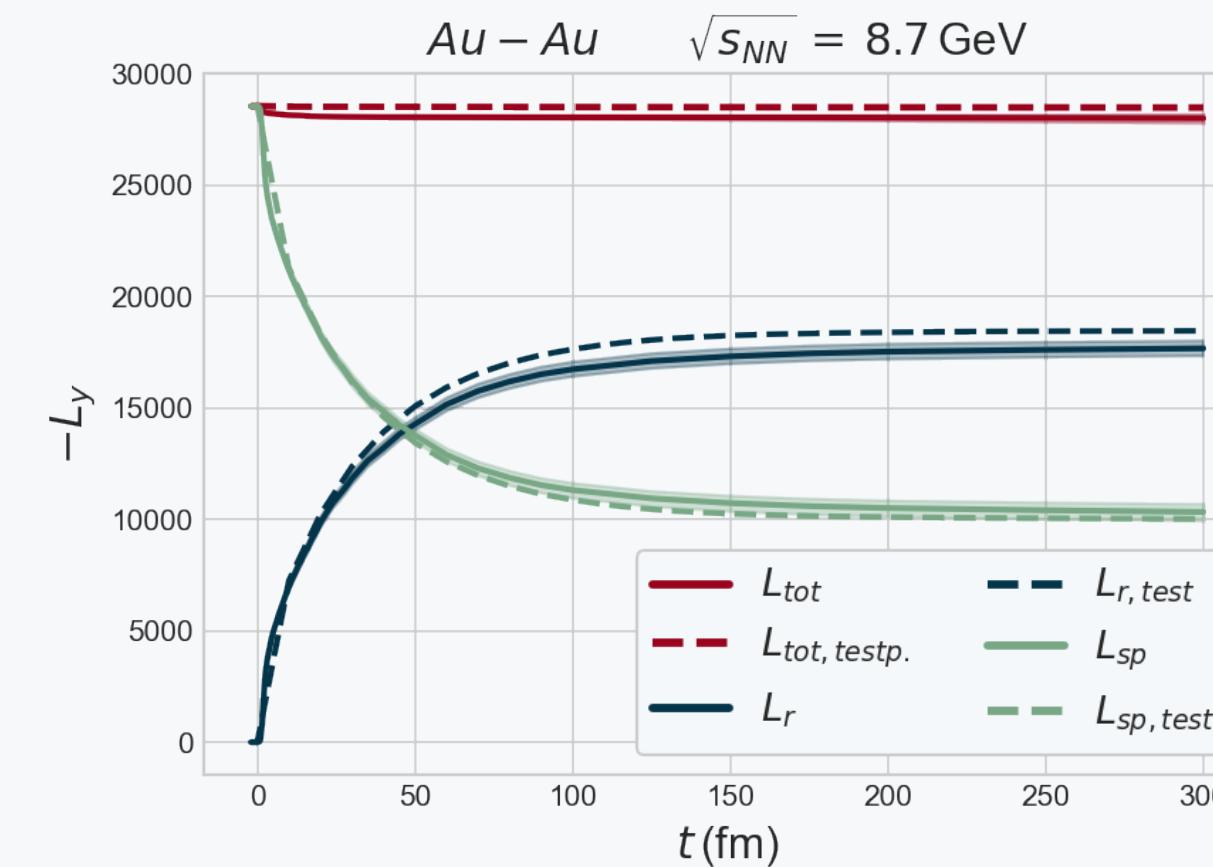
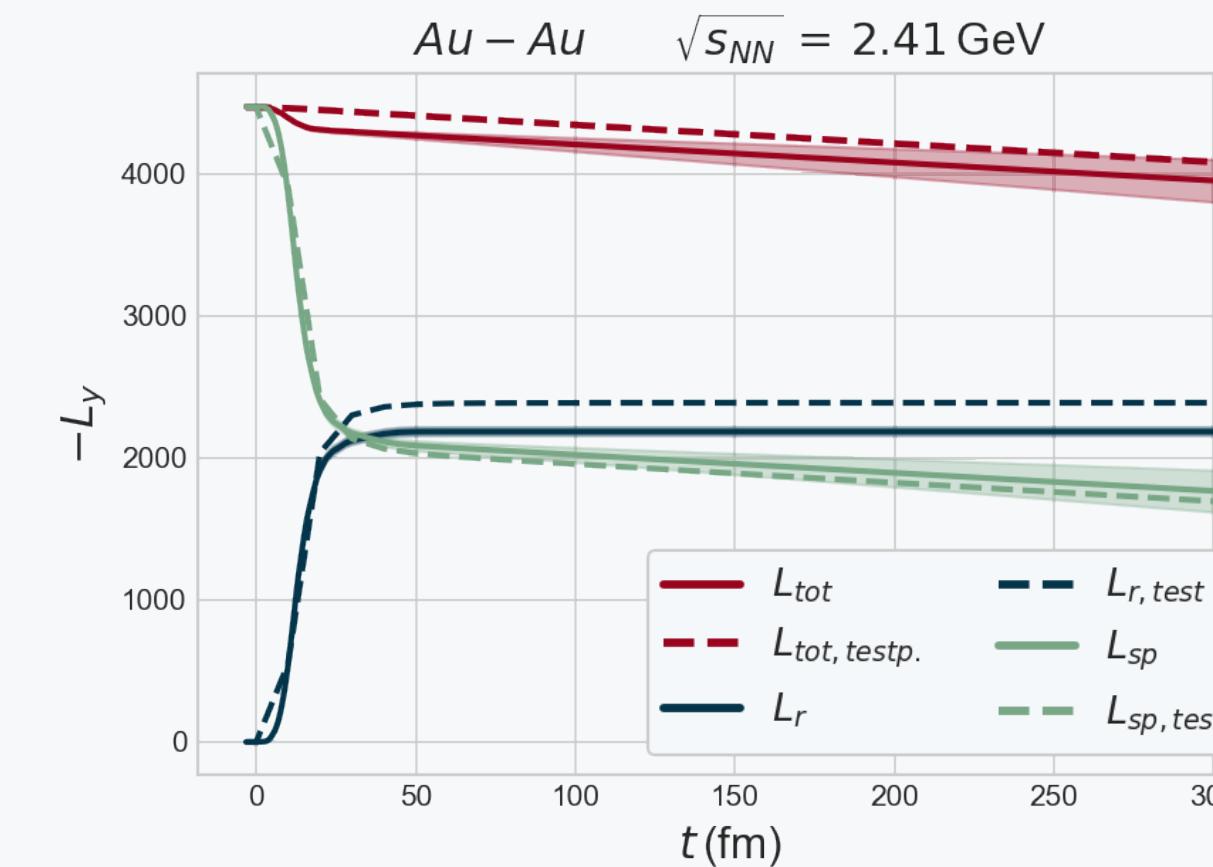
Angular Momentum Conservation

- 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
- Geometric Interpretation of the cross section breaks angular momentum conservation in binary collisions



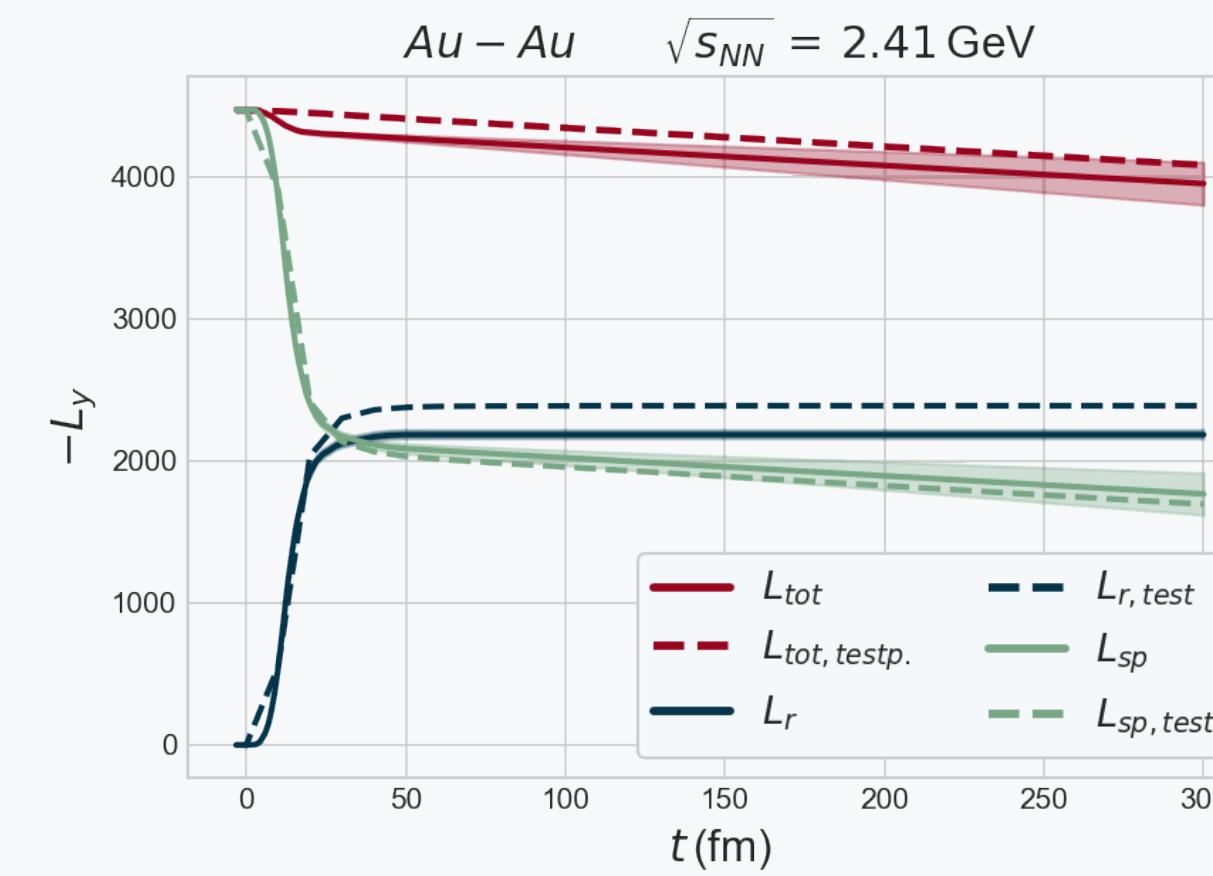
Conserving Angular Momentum

Test Particles

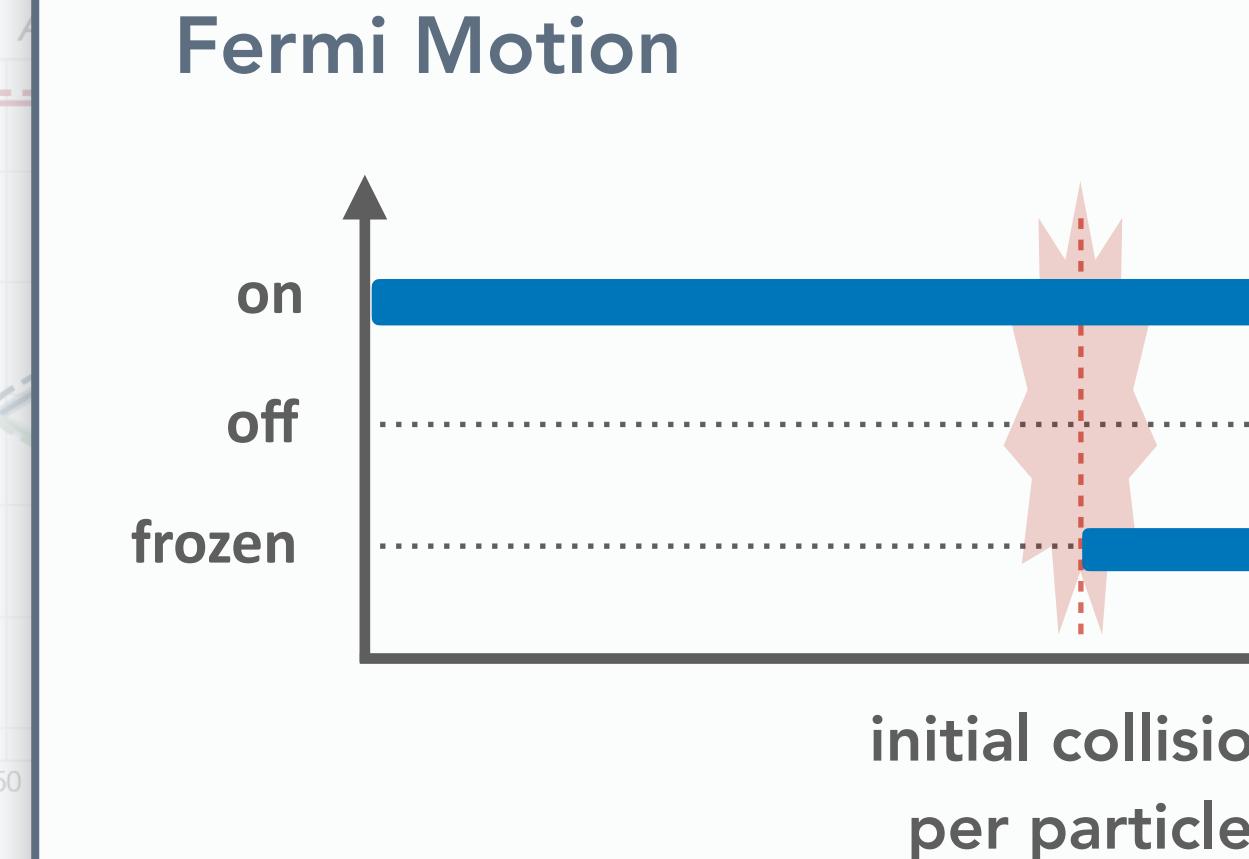


Conserving Angular Momentum

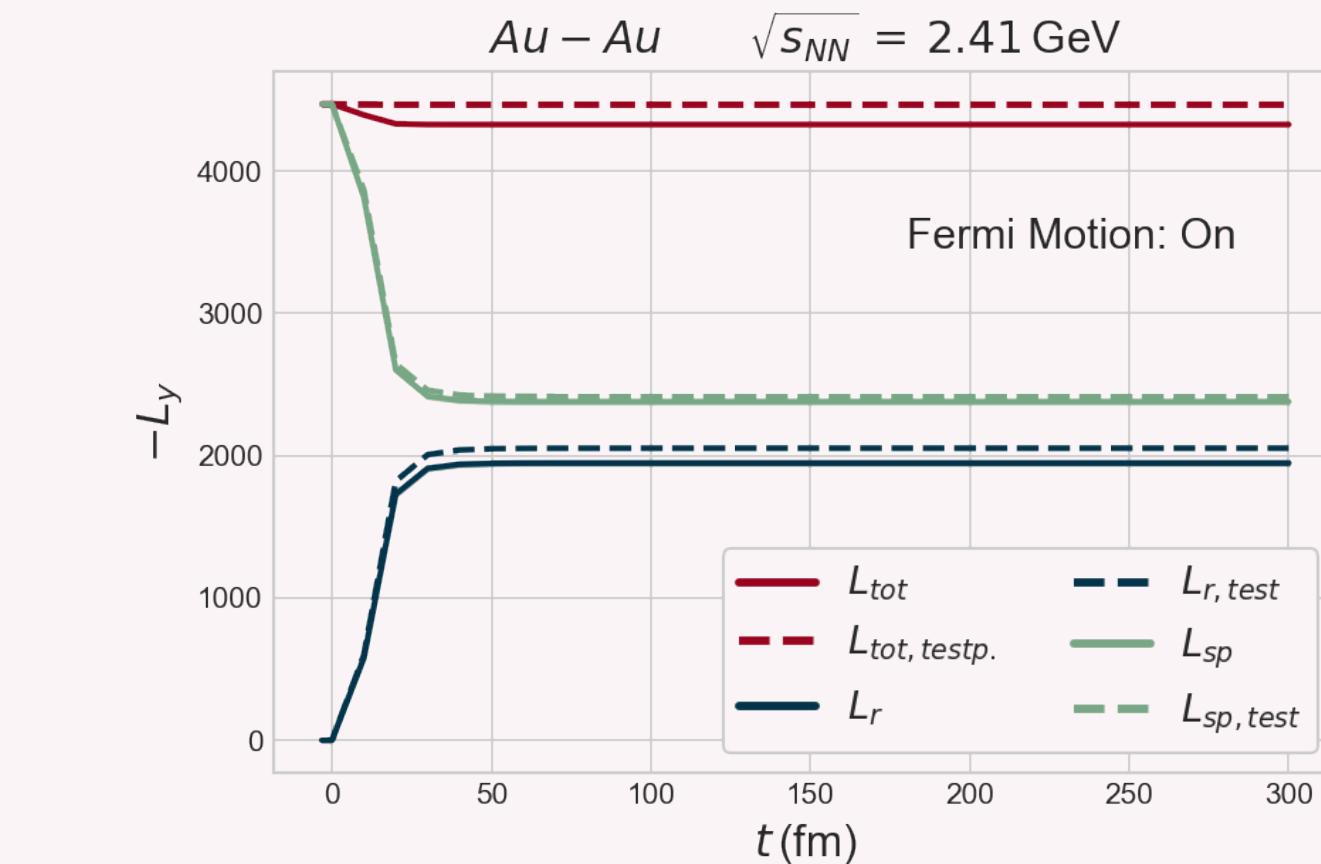
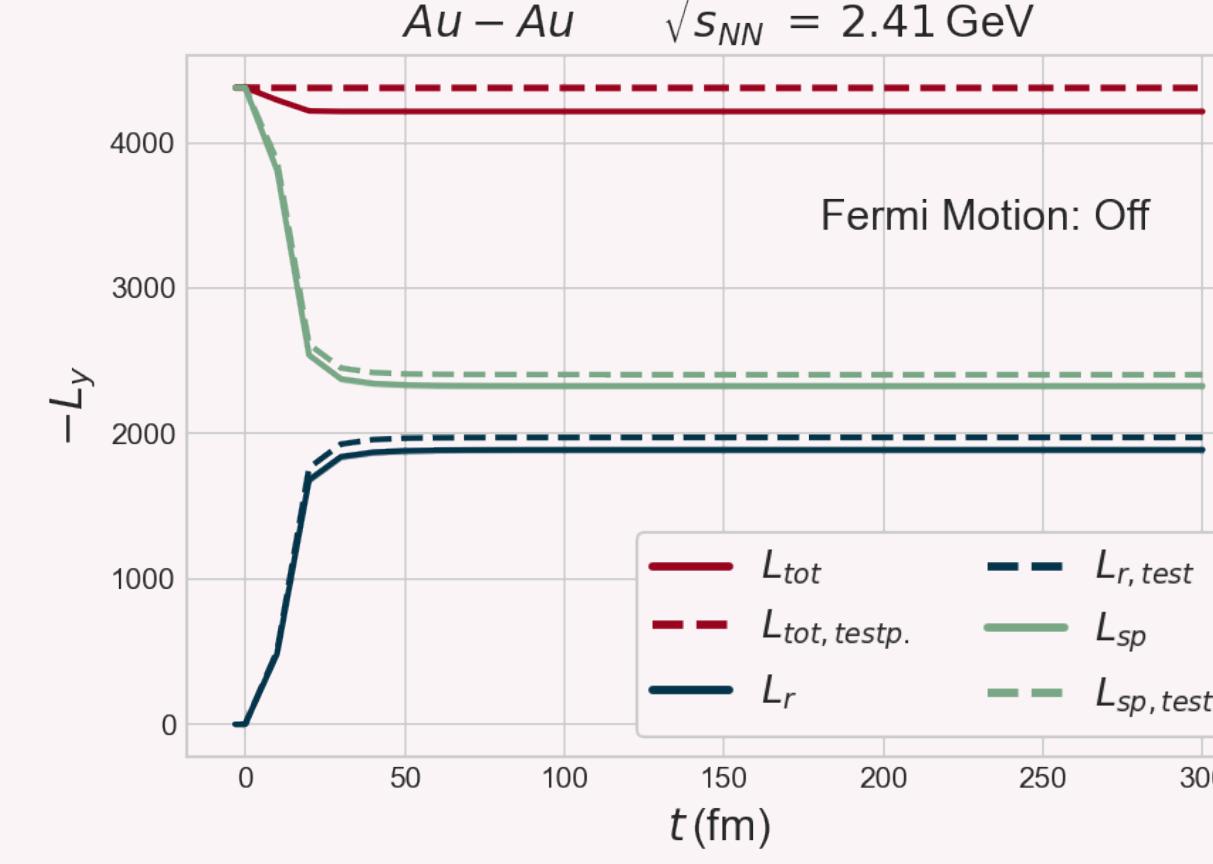
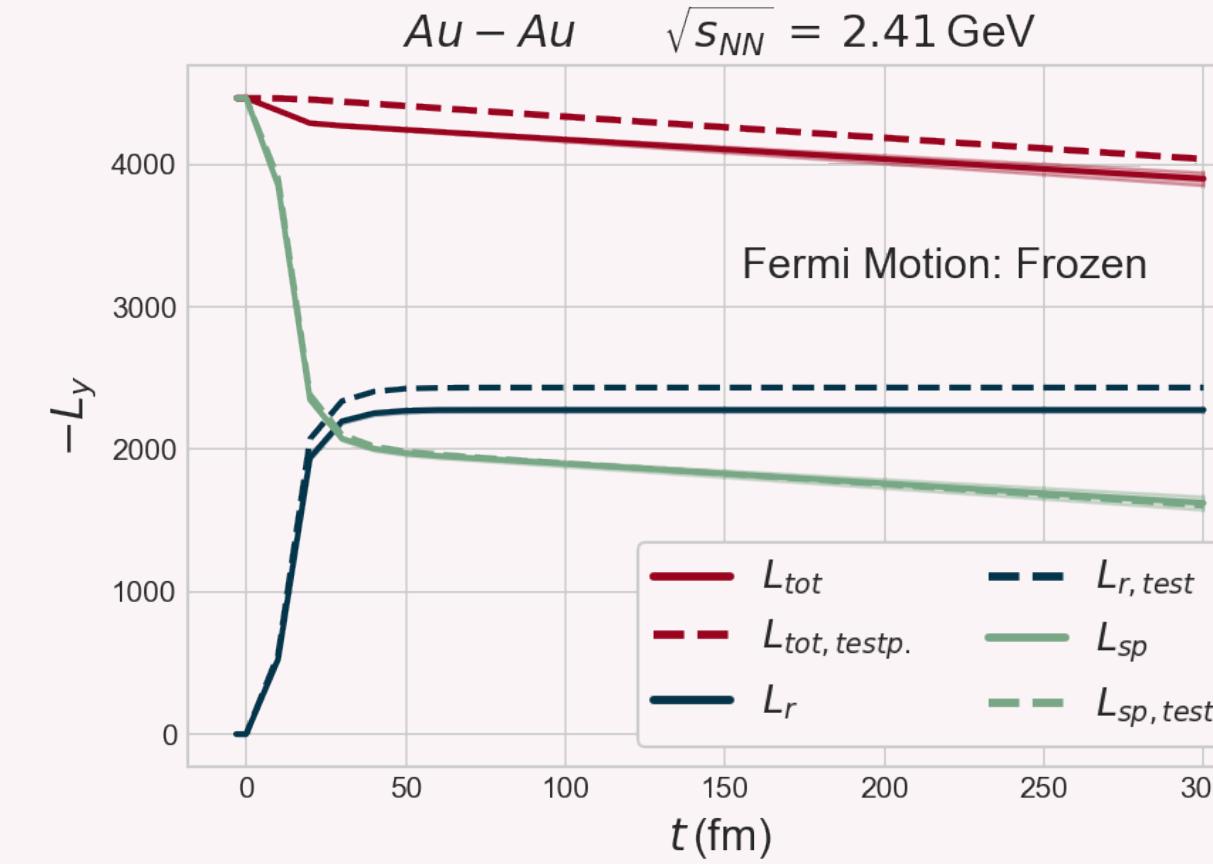
Test Particles



Fermi Motion



Fermi Motion



Conclusion & Outlook

CONCLUSION

- Impact parameter b_{\max} for which the angular momentum of the fireball becomes maximal is nearly **energy independent**
- Higher relative transfer of initial angular momentum to the fireball in more central collisions
- Test particle method and Fermi motion treatment restore **angular momentum conservation**
- Predictions for expectation of high angular momentum is important for future experimental measurements

OUTLOOK

- Implementing **spin degrees of freedom** to describe hadronic polarization within the transport approach
- Analyzing **vorticity from SMASH** within a coarse-grained approach

Posters by Other Group Members

Initial State

Poster Title

Event-by-event comparison of initial state models with momentum space information in a hybrid approach

Presenter

Niklas Götz

Id & Link

178 



Jets

Poster Title

Effects of hadronic reinteraction on jet fragmentation from small to large systems

Presenter

Hendrik Roch

Id & Link

530 

EM Probes

Poster Title

Dilepton anisotropic flow from hadronic transport

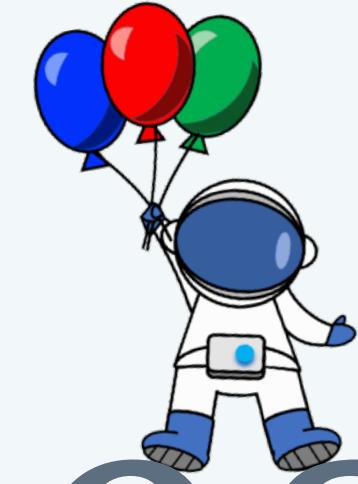
Presenter

Renan Hirayama

Id & Link

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Backup Slides



Insight into SMASH

Initial Conditions

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

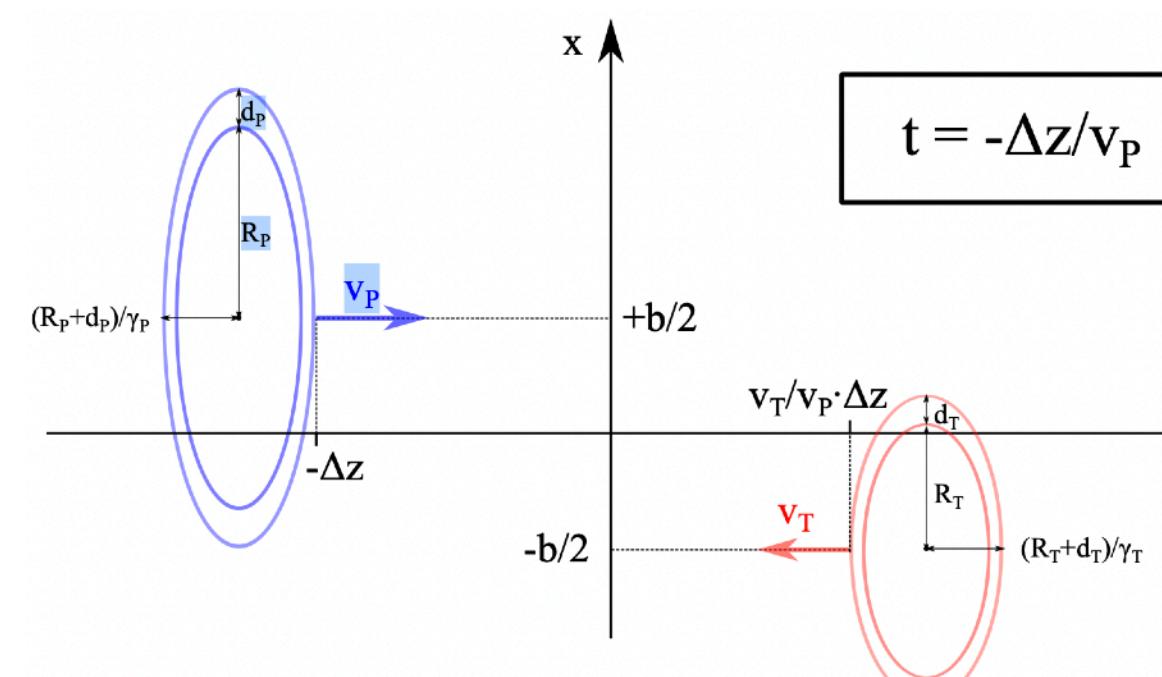
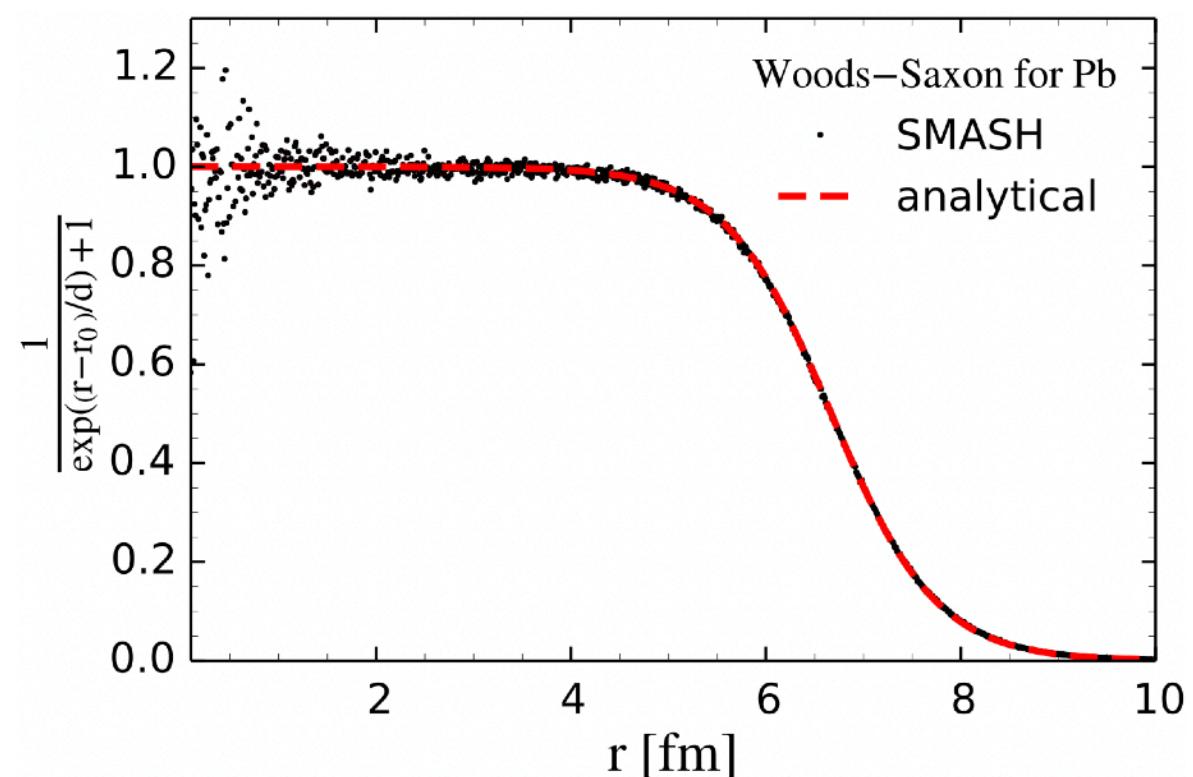
$$\frac{dN}{d^3r} = \frac{\rho_0}{\exp\left(\frac{r - r_0}{d} + 1\right)}$$

d : diffusiveness of the nucleus

ρ_0 : nuclear ground state density

- Hard sphere limit: $d \rightarrow 0$

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



Resonances

- Particles with widths < 10 keV treated as stable
- Unstable particles assigned a relativistic Breit-Wigner spectral function

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

m : resonance mass
 M_0 : pole mass
 $\Gamma(m)$: width function
 \mathcal{N} : normalization

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

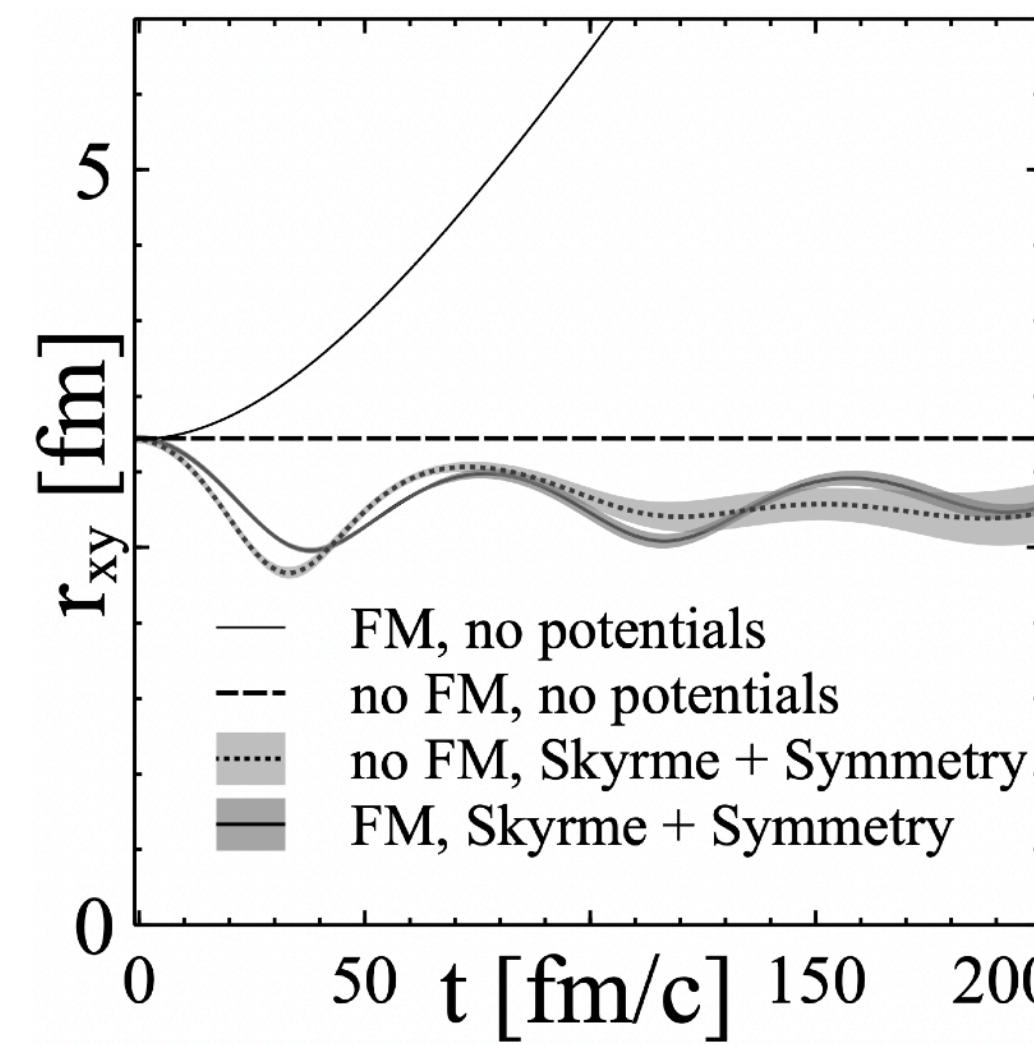
$$\Gamma_{R \rightarrow ab} = \Gamma_{R \rightarrow ab}^0 \frac{\rho_{ab}(m)}{\rho_{ab}(M_0)}$$

$\rho_{ab}(m)$: mass integrals over resonance spectral functions
 $\Gamma_{R \rightarrow ab}^0 = \Gamma_{R \rightarrow ab}(M_0)$

Fermi Motion

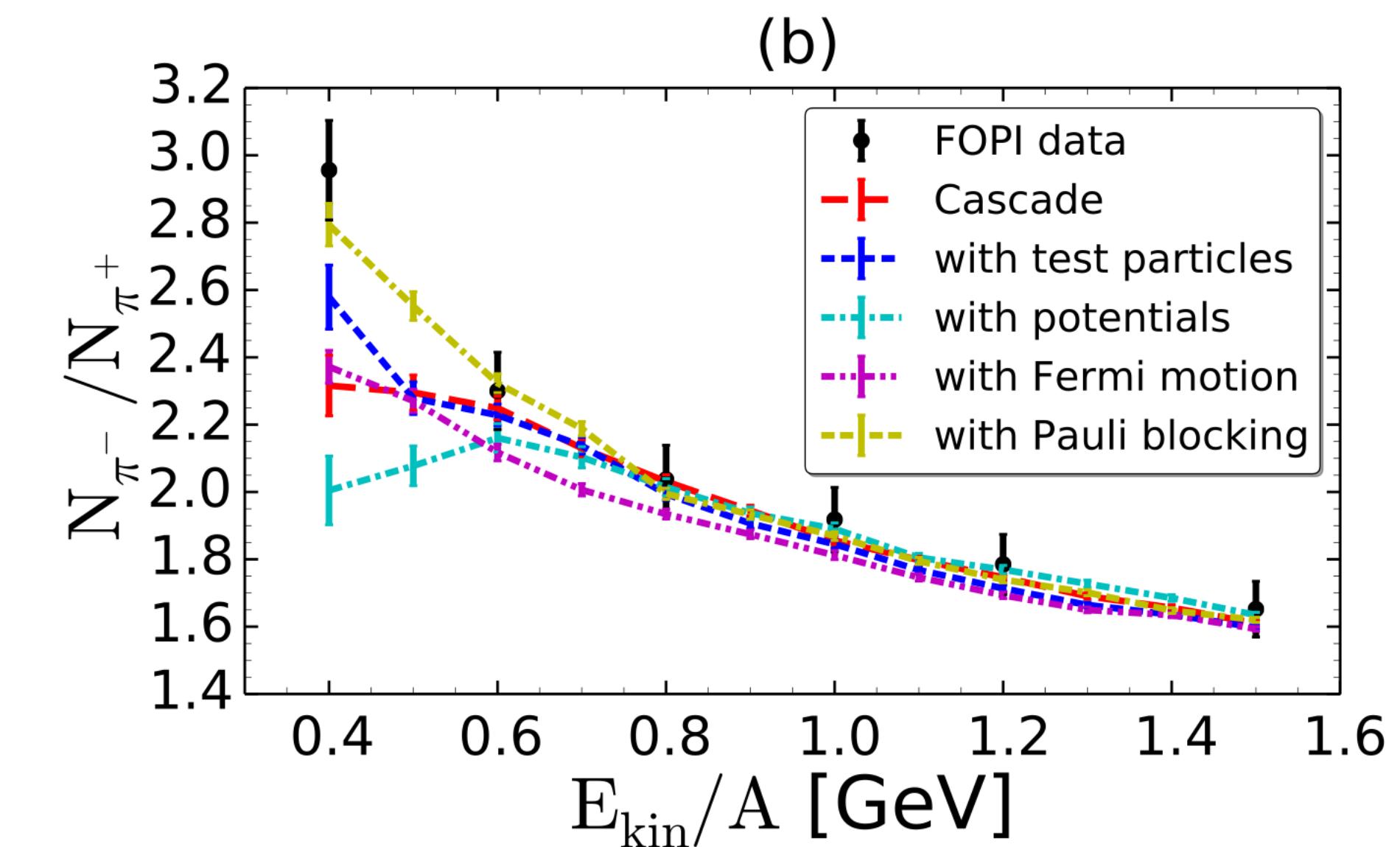
Nuclei Stability

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

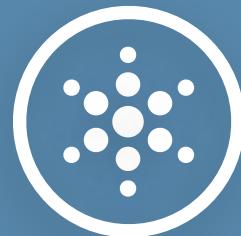


J. Weil *et al.*, Phys.Rev.C 94 (2016) 5, 054905

Pion Production



- Successive consideration of the following features: 20 test particles, Skyrme and symmetry potentials, Fermi motion, Pauli blocking
- Fermi motion needed to match FOPI data for pion production



Test Particles

- Per particle N_{test} test particles are sampled such that

$$N \rightarrow N N_{\text{test}}$$

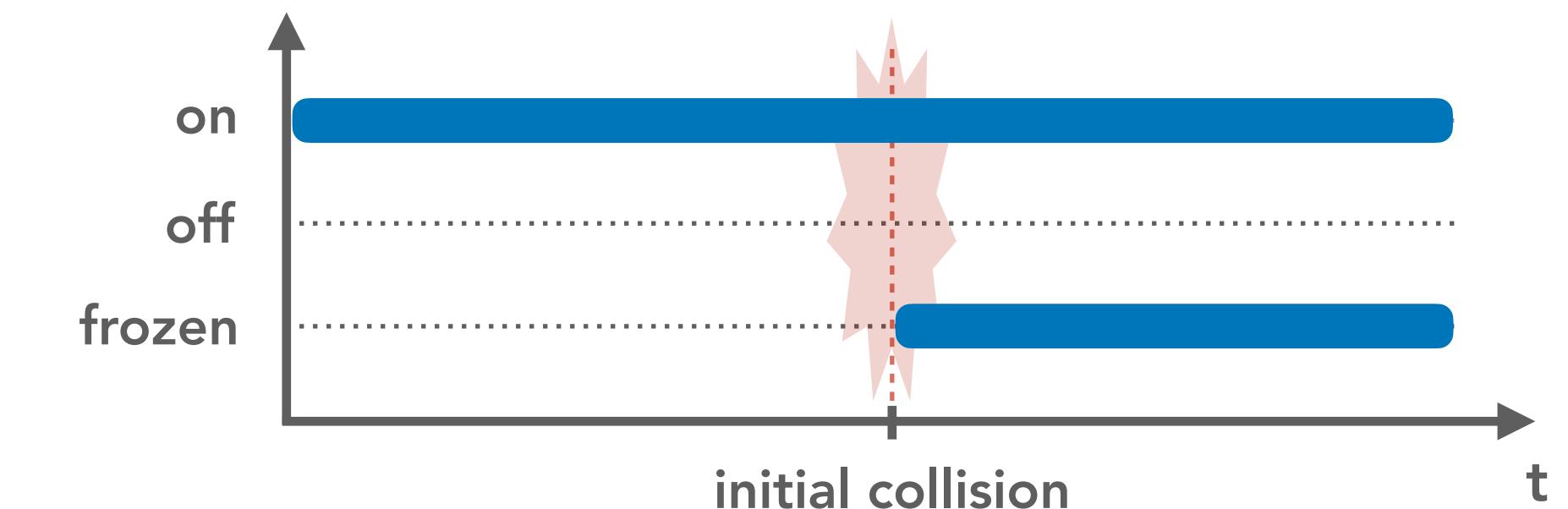
$$\sigma \rightarrow \sigma N_{\text{test}}^{-1}$$

- Test particle method leaves scattering rate unchanged
- Rescaling of cross sections make binary interactions more local



Fermi Motion

- Nucleons get additional isotropic momentum according to Fermi sphere
- SMASH implements Fermi motion with 3 modi: **on**, **off**, **frozen**



Why Do We Lose Angular Momentum?

Scenario 1

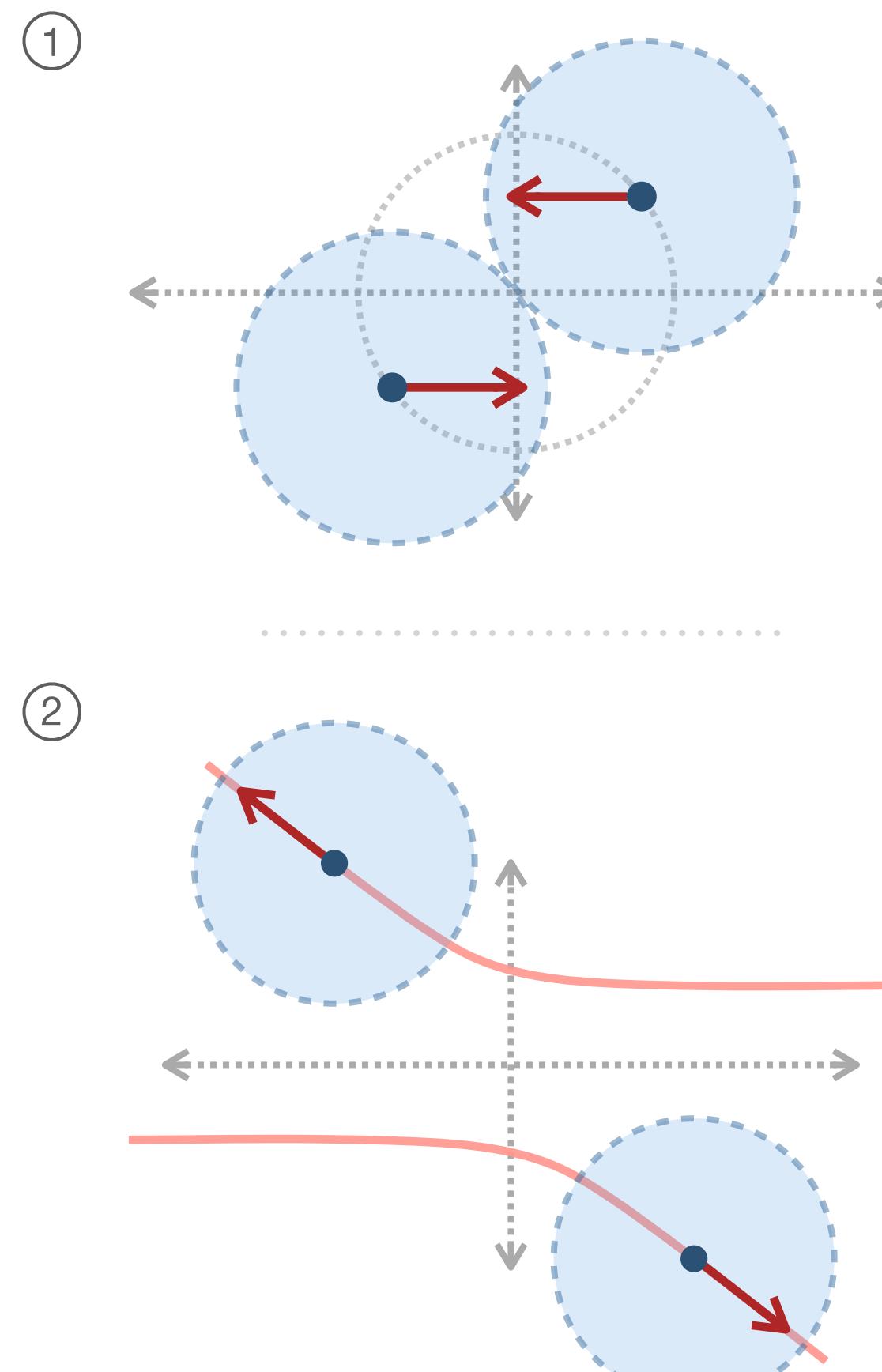
- Particles scatter at finite distance according to their effective cross sections

Scenario 2

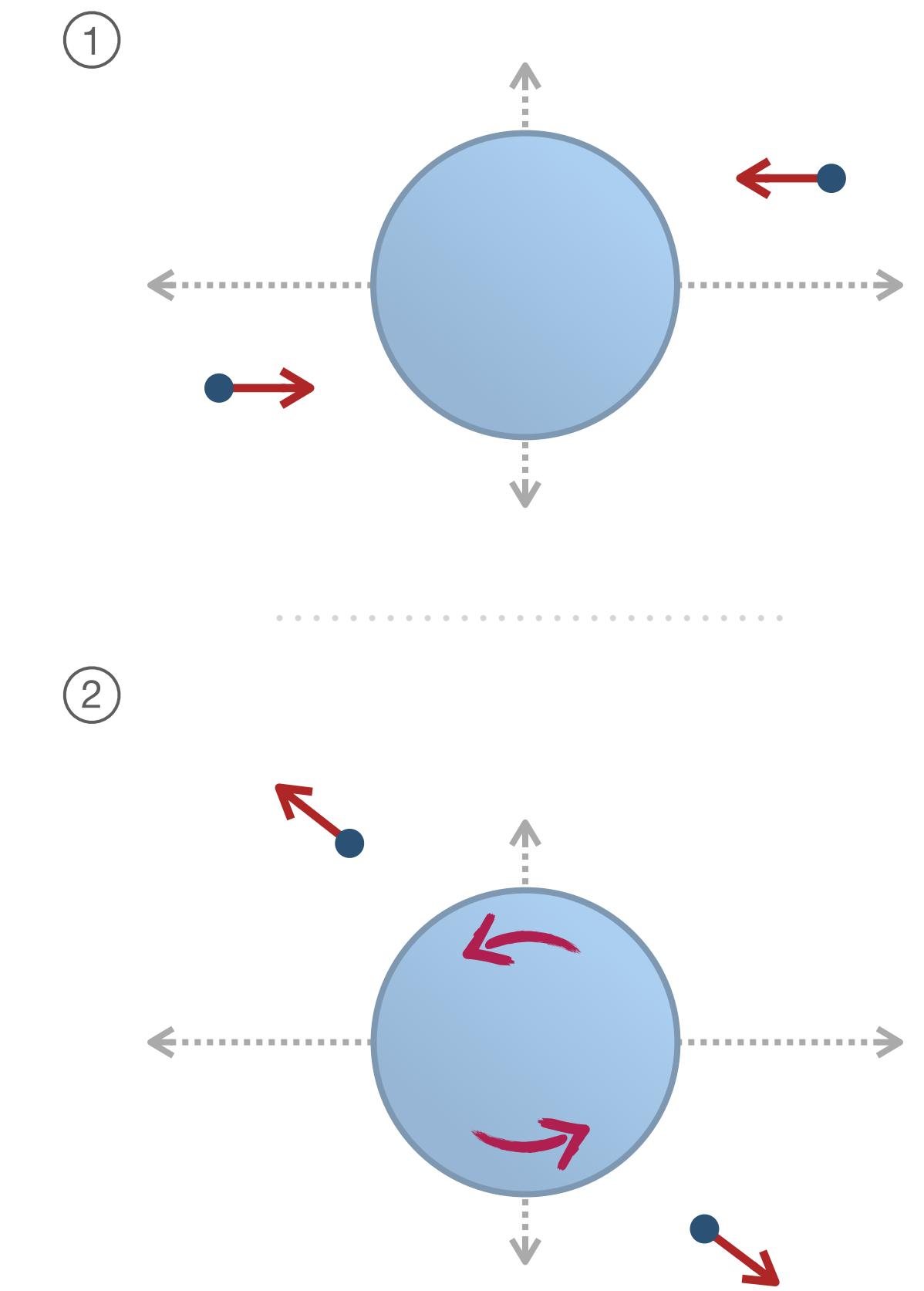
- Particles scatter at an imaginary cylinder
- After scattering, the cylinder spins around its transverse axis

→ Non-locality reduces angular momentum of binary interactions

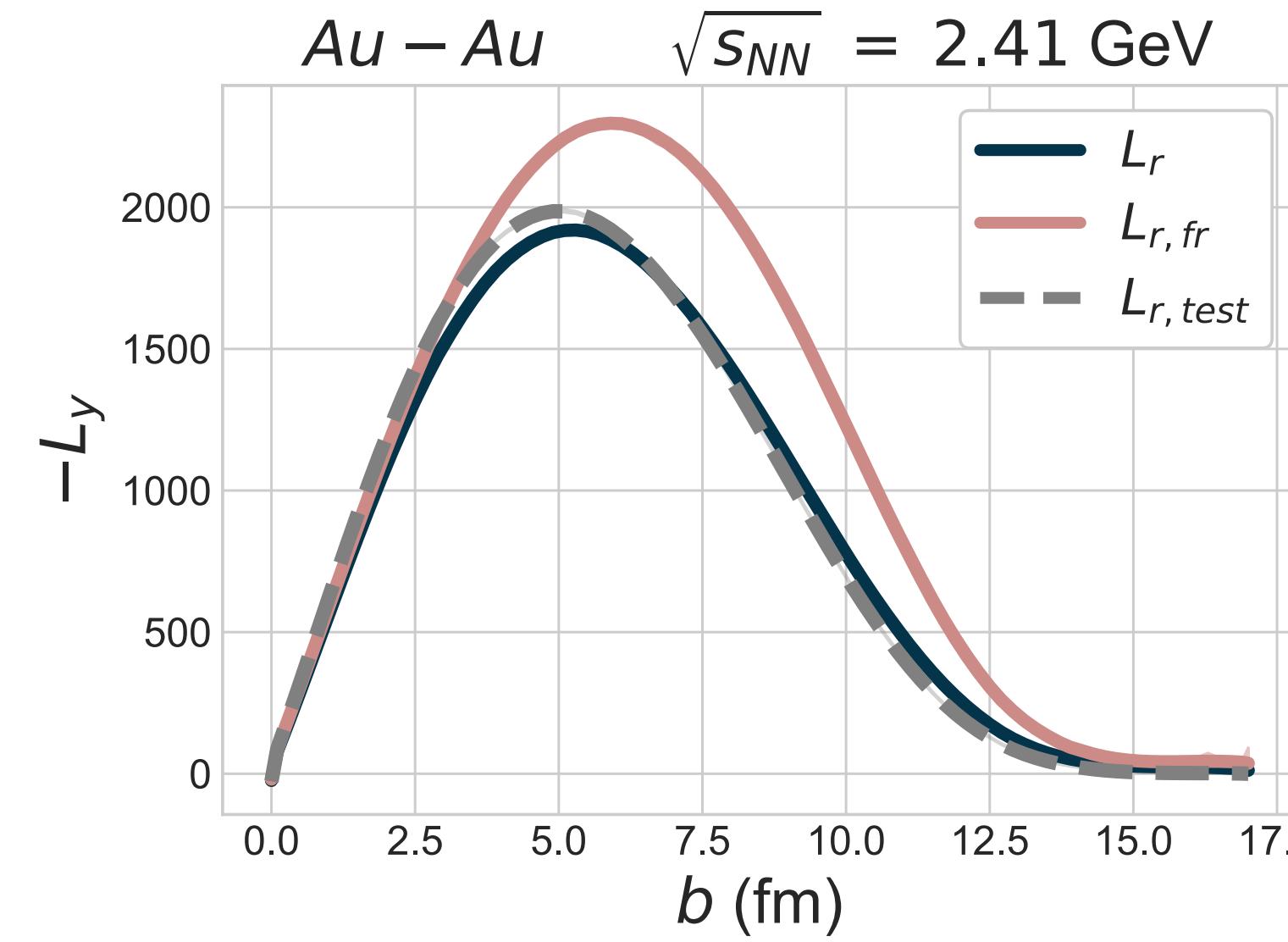
Scenario 1



Scenario 2



Fermi Motion Contribution to Angular Momentum



Isotropy only true in nucleus rest frame

In the lab frame (after Lorentz boost) the angular momentum of nucleon i is given by

$$\begin{aligned}-L'_{y,i} &= x_i (\gamma p_{z,i} - \beta \gamma E_i) - (\gamma z_i - \beta \gamma t) p_{x,i} \\ &= -\gamma L_{y,i} - \beta \gamma (x_i E_i - p_{x,i} t)\end{aligned}$$

Summing over all nucleons with $\sum_i p_{x,i} t = 0$ (isotropy in transverse plane)

$$-L'_y = -\gamma L_y - \sum_i \gamma \beta x_i E_i$$

Fermi motion increases nucleon energy

Why do isotropically sampled Fermi momenta increase L_y ?

$$E_i = E_i^{\text{nuc.}} + E_i^{\text{Fermi}}$$

Non-vanishing contribution to L_y from Fermi momenta