SMASH: development and applications

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Non-equilibrium QCD and transport

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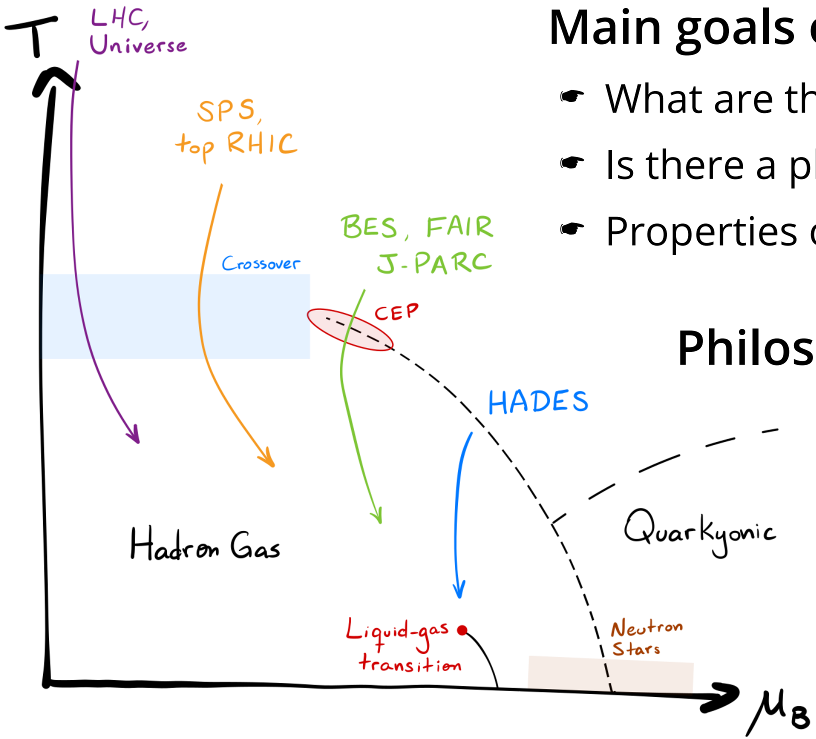
Introduction

Simulating Many Accelerated Strongly-interacting Hadrons



Main goals of our field:

- What are the relevant degrees of freedom at high densities?
- Is there a phase transition, critical endpoint?
- Properties of neutron star and their mergers?

Philosophy: to learn *new Physics*, we need a good baseline

SMASH: General purpose BUU hadronic transport, with underlying relativistic Boltzmann equation

$$p^\mu \frac{\partial f_i(x,p)}{\partial x^\mu} + m_i \frac{\partial\left[K^\mu f_i(x,p)\right]}{\partial p^\mu} = C_i^{\mathrm{coll}}$$

Outline

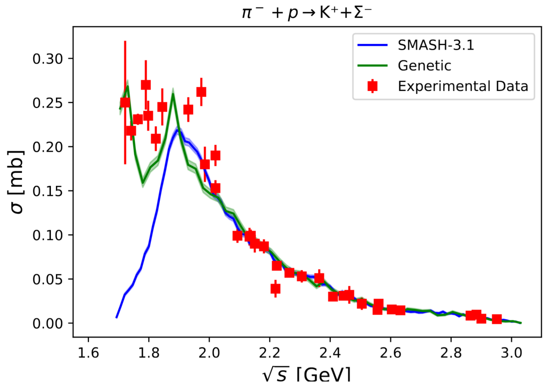
- Basics of the SMASH approach
- Mean-field and studying the equation of state
- Beyond transport: coupling to hydrodynamics
- How rescattering affects fluctuation observables
- Dynamics of light nuclei production
- Beyond hadrons: hard and EM probes
- Clean code strategy

Basic ingredients

Degrees of freedom

Baryons						
N		Δ	Λ		Σ	Ξ
N_{938}	N_{1875}	Δ_{1232}	Λ_{1116}	Λ_{1810}	Σ_{1189}	Ξ_{1321}
N_{1440}	N_{1900}	Δ_{1620}	Λ_{1405}	Λ_{1820}	Σ_{1385}	Ξ_{1530}
N_{1520}	N_{1990}	Δ_{1700}	Λ_{1520}	Λ_{1830}	Σ_{1660}	Ξ_{1690}
N_{1535}	N_{2060}	Δ_{1900}	Λ_{1600}	Λ_{1890}	Σ_{1670}	Ξ_{1820}
N_{1650}	N_{2080}	Δ_{1905}	Λ_{1670}	Λ_{2100}	Σ_{1750}	Ξ_{1950}
N_{1675}	N_{2100}	Δ_{1910}	Λ_{1690}	Λ_{2110}	Σ_{1775}	Ξ_{2030}
N_{1680}	N_{2120}	Δ_{1920}	Λ_{1800}	Λ_{2350}	Σ_{1915}	**Ω**
N_{1700}	N_{2190}	Δ_{1930}			Σ_{1940}	Ω_{1672}
N_{1710}	N_{2190}	Δ_{1950}			Σ_{2030}	Ω_{2250}
N_{1720}	N_{2220}				Σ_{2250}	

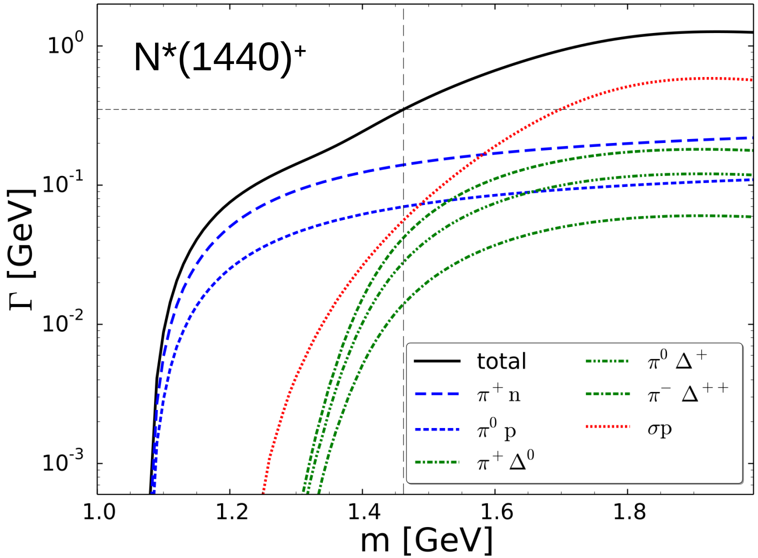
Mesons						
Light					Strange	
π_{138}	$\pi_{1(1600)}$	$a_{0(980)}$	σ_{800}	$f_2'{}_{(1525)}$	K_{494}	$K_2^*{}_{(1430)}$
$\pi_{(1300)}$	$\pi_{2(1670)}$	$a_{1(1260)}$	$f_{0(980)}$	$f_{0(1710)}$	$K^*{}_{892}$	$K^*{}_{(1680)}$
$\pi_{1(1400)}$	$\pi_{(1800)}$	$a_{2(1320)}$	$f_{2(1275)}$	$f_{2(1950)}$	$K_{1(1270)}$	$K_{2(1770)}$
η_{548}	$\eta_{(1405)}$	$a_{0(1450)}$	$f_{1(1285)}$	$f_{2(2010)}$	$K_{1(1400)}$	$K_3^*{}_{(1780)}$
η'_{958}	$\eta_{(1475)}$	$a_{4(2040)}$	$f_{0(1370)}$	$f_{4(2050)}$	$K^*{}_{(1410)}$	$K_{2(1820)}$
$\eta_{(1295)}$	$\eta_{2(1645)}$	φ_{1019}	$f_{1(1420)}$	$f_{2(2300)}$	$K_0^*{}_{(1430)}$	$K_4^*{}_{(2045)}$
ρ_{778}	$\rho_{3(1690)}$	$\varphi_{(1680)}$	$f_{0(1500)}$	$f_{2(2340)}$		
$\rho_{(1450)}$	$\rho_{(1700)}$	$\varphi_{3(1850)}$	ω_{783}	$\omega_{(1650)}$		
	$b_{1(1235)}$	$h_{1(1170)}$	$\omega_{(1420)}$	$\omega_{3(1670)}$		



CB Rosenkvist, H Elfner (2025) PRC 112

- Hadrons with 3 or 4-star rating from Particle Data Group
- Isospin symmetry assumed → $m_{\pi^0} = m_{\pi^\pm} = 138\ \mathrm{MeV}$
- N* and Δ* properties (mass and BR) recently tuned to strangeness production via a genetic algorithm

Spectral functions & decay widths



- Threshold ~ masses of decay products
- Δ baryon much narrower than σ meson
- Isospin symmetry determines BR in a multiplet:

$$1 \otimes \frac{3}{2} \to \frac{1}{2} \Rightarrow \Gamma_{\pi^+\Delta^0} : \Gamma_{\pi^0\Delta^+} : \Gamma_{\pi^-\Delta^{++}} = 2:3:6$$

- Philosophy: vacuum properties

$$\mathcal{A}^{\rm vac}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma^{\rm dec}(m)}{\left(m^2 - M_0^2\right)^2 + m^2\Gamma^{\rm dec}(m)^2}$$

Breit-Wigner distribution

- Resonance lifetimes ~ inverse width

$$P_{\rm dec}(t) = 1 - e^{-\Gamma^{\rm dec}(m)t}$$

$$\Gamma_R^{\rm dec}(m) = \sum_{\{ab\}} \Gamma_{R\to ab}(m)$$

- Mass-dependence a la Manley-Saleski

$$\Gamma_{R\to ab}(m) = {\rm BR}(R\to ab)\,\Gamma_0 \frac{\rho_{ab}(m)}{\rho_{ab}(M_0)}$$

$$\rho_{ab}(\sqrt{s}) = \int {\rm d}m_a\,{\rm d}m_b\,\mathcal{A}_a^{\rm vac}(m_a)\mathcal{A}_b^{\rm vac}(m_b)\frac{|\mathbf{p}_{\rm cm}|}{\sqrt{s}}B_L^2(|\mathbf{p}_{\rm cm}|)\mathcal{F}_{ab}^2(\sqrt{s})$$

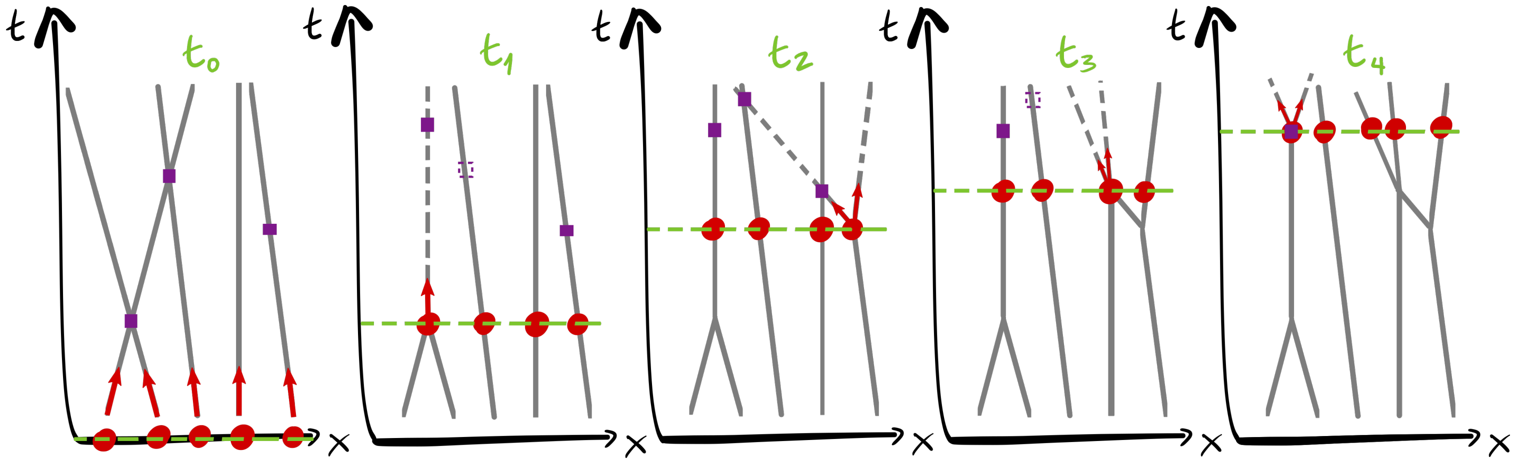
Available phase space

Actions & cascade

$$p^{\mu}\frac{\partial f_i(x,p)}{\partial x^{\mu}} + m_i \frac{\partial\left[K^{\mu} f_i(x,p)\right]}{\partial p^{\mu}} = C_i^{\text{coll}}$$

0

Without mean-field, trajectories between interactions are straight lines!



Action: Generic *possible* interaction in collision term

SMASH searches for upcoming actions between particles and propagates, performing them according to a given criterion and time-ordering, ignoring now-invalid actions

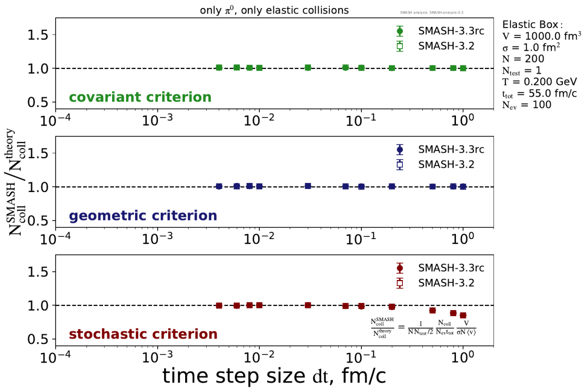
Collision criteria

Geometric → covariant $\pi d_\perp^2 \leq \sigma_{ab}$

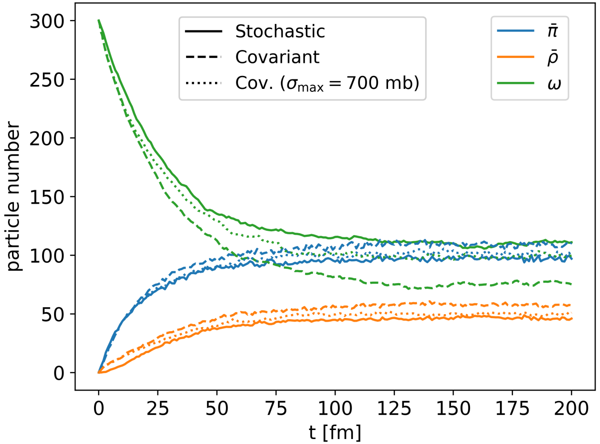
$$d_\perp^2 = |\vec{x}|^2 - \frac{(\vec{x}\cdot\vec{p})^2}{|\vec{p}|^2} \longrightarrow d_\perp^2 = -x^2 - \frac{p_a^2(p_b\cdot x)^2 + p_b^2(p_a\cdot x)^2 - 2(p_a\cdot x)(p_b\cdot x)(p_a\cdot p_b)}{(p_a\cdot p_b)^2 - p_a^2 p_b^2}$$

$$t_c = -\frac{\vec{x}\cdot\vec{v}}{|\vec{v}|^2} \longrightarrow t_c = \frac{1}{2}\frac{(P\cdot x)(P\cdot p) - P^2(p\cdot x)}{(p_a\cdot p)(P\cdot p_b) - (p_b\cdot p)(P\cdot p_a)}$$

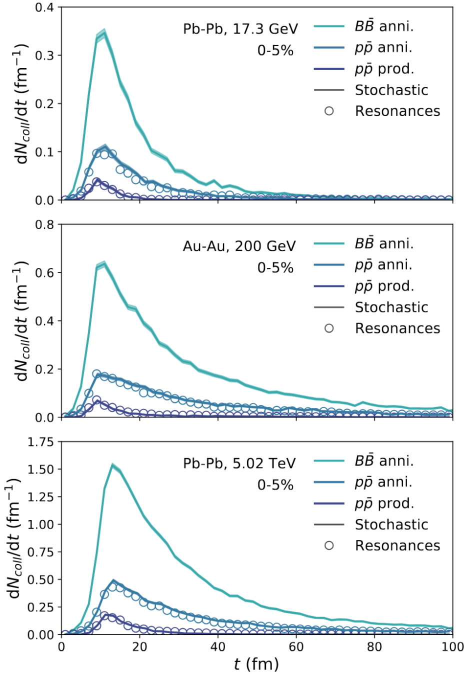
Stochastic $P_{ab\to X} = \frac{\Delta t}{\Delta^3 x} v_{\rm rel}\sigma_{ab\to X}$



Geometric criterions misbehave in edge cases (resonances away from pole mass)



Consistent reaction rates in $p\bar{p} \leftrightarrow 5\pi$



Interaction cross sections

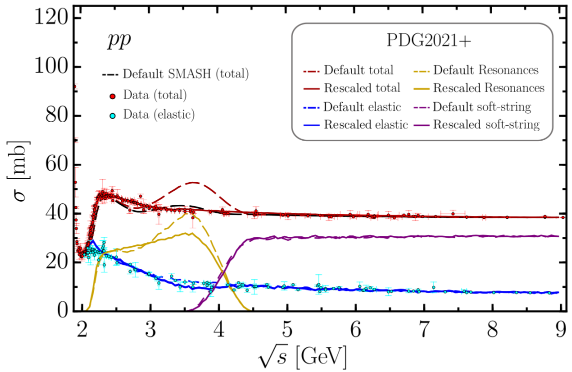
- **Total cross section:** built from partial processes or parametrized from data
  BottomUp
  TopDown
- **Resonances** for low energies

$$\sigma_{ab\to R}(\sqrt{s}) = \frac{g_R}{g_a g_b}(\delta_b^a + 1)\frac{2\pi^2}{p_{\rm cm}^2}\Gamma_{ab\to R}(\sqrt{s})\mathcal{A}_R(\sqrt{s})$$

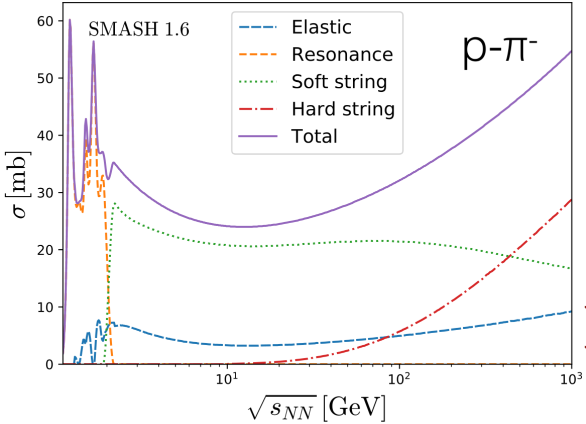
Detailed balance

- **PYTHIA strings** for high interaction energies + formation time for leading hadrons
- **Elastic** (BB and MB) and **Binary inelastic** (NN and NK) scattering parametrized
- **AQM rescaling** for colliding resonances

$$\sigma_{AB} = \sigma_{pp}\frac{n_q^A}{3}\frac{n_q^B}{3}\left(1-0.4x_s^A\right)\left(1-0.4x_s^B\right)$$



J.S.S. Martin, RGH, et al. [arXiv:2309.01737]



J. Mohs, S. Ryu and H. Elfner, J.Phys.G 47 (2020)

Mean-field potentials
& Equation of state

Numerical algorithm

$$f(\mathbf{r},\mathbf{p}) = \frac{1}{N_{\text{test}}}\sum_{j}^{N_{\text{test}}} G(\mathbf{r}-\mathbf{r}_i)\delta^3(\mathbf{p}-\mathbf{p}_i)$$

Testparticle ansatz

smash

Equations of motion

$$\dot{\mathbf{r}}_i = \frac{\mathbf{p}_i}{\sqrt{p_i^2+m^2}} + \nabla_p U$$

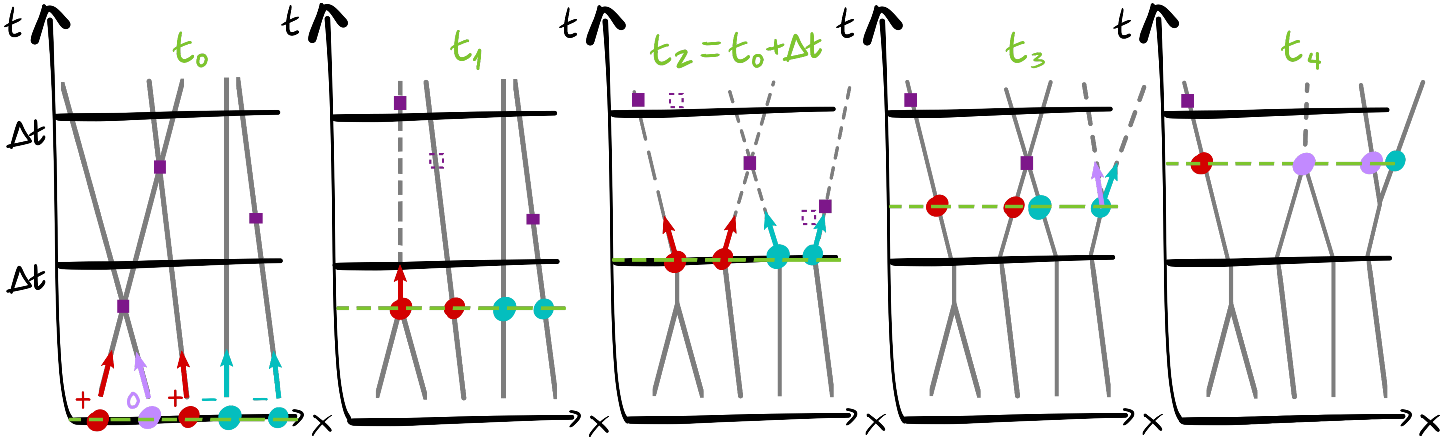
$$\dot{\mathbf{p}}_i = -\nabla_r E_i$$

Divide spacetime in 4D lattice cells

$$E = \sqrt{p^2+m^2} + U(\rho_B,\mathbf{p})$$

Evaluated in LRF

At each timestep, **r** and **p** are updated (Euler). Inbetween, particles propagate and actions are performed as in cascade.



Available potentials

- NN potential: **Skyrme** + **Symmetry**

$$U_{\text{Skyrme}} = A\left(\frac{\rho_B}{\rho_0}\right) + B\left(\frac{\rho_B}{\rho_0}\right)^{\tau}$$

$$U_{\text{sym}} = \pm S_{\text{pot}}\left(\frac{\rho_{I_3}}{\rho_0}\right)$$

Only for baryons

- Alternative: fully relativistic **VDF**

$$A^{\mu} = \sum_{i=1}^{N} C_i \left(\frac{\rho}{\rho_0}\right)^{b_i-2} \frac{j^{\mu}}{\rho_0}$$

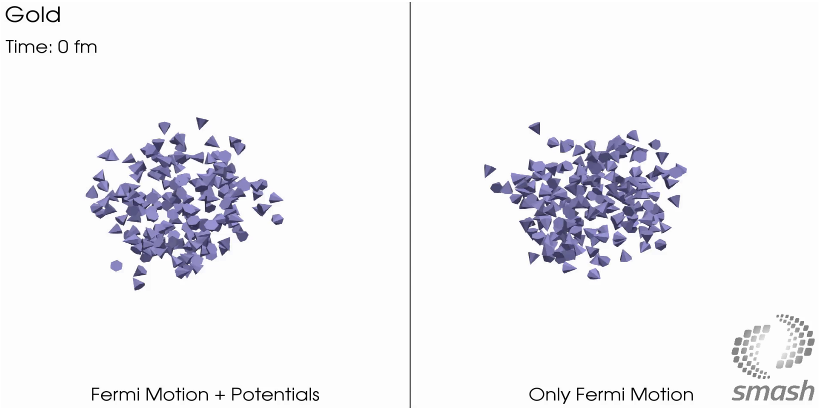
A. Sorensen, V. Koch (2021) PRC 104 3

- **Coulomb** (magnetostatic)

$$\mathbf{E}(\mathbf{r}_j) = \sum_{i\neq j} \frac{\rho(\mathbf{r}_i)(\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3}\Delta V$$

$$\mathbf{B}(\mathbf{r}_j) = \sum_{i\neq j} \mathbf{j}(\mathbf{r}_i) \times \frac{\mathbf{r}_j - \mathbf{r}_i}{|\mathbf{r}_j - \mathbf{r}_i|^3}\Delta V$$

Without nuclear potential,



it potentially goes nuclear!

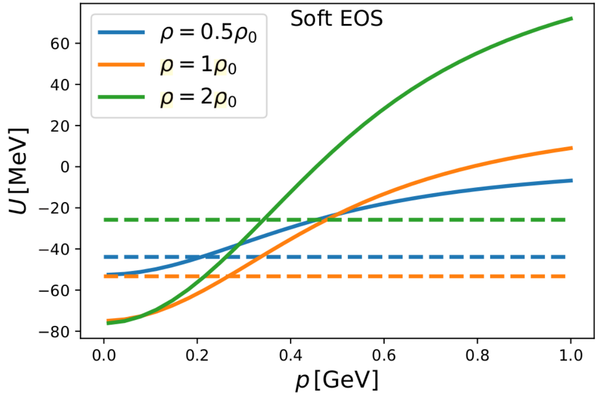
Momentum dependence

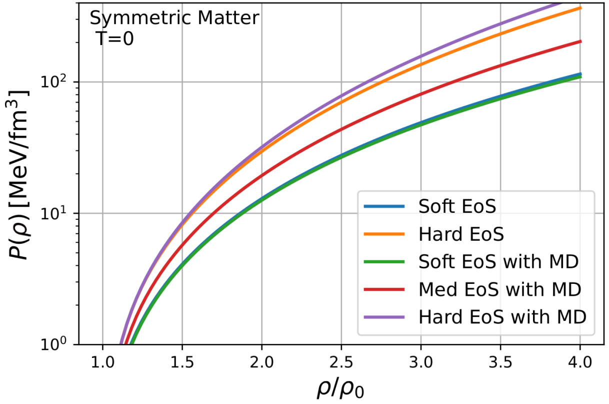
Optical model: experimental data depends on kinetic energy of probe

$$U_{\rm MD} = \frac{2C}{\rho_0} g \int \frac{d^3p'}{(2\pi)^3} \frac{f(\mathbf{r},\mathbf{p}')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2}$$

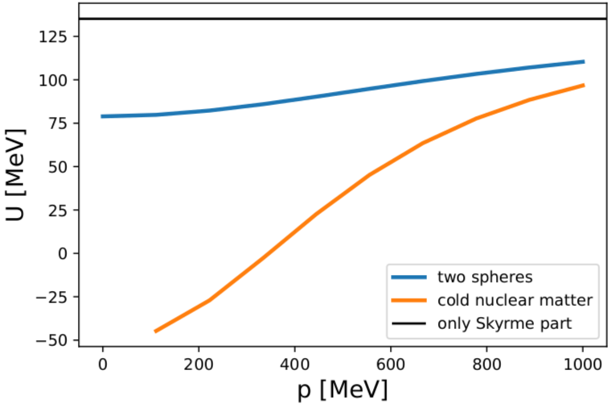
G. M. Welke et al. (1988) Phys.Rev.C 38
Used in GiBUU: O. Buss et al. (2012) Phys.Rept. 512

Analytical solution by assuming cold nuclear matter $f(\vec{r},\vec{p}) = \Theta(p_F - p)$





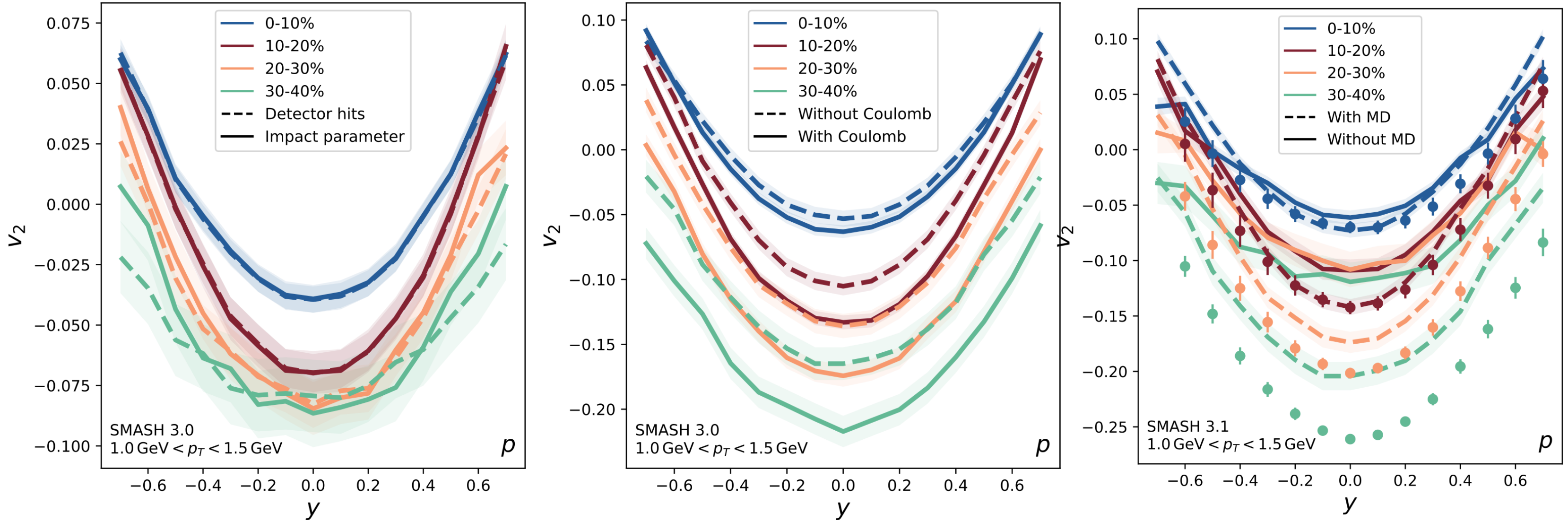
Reasonable?



J. Mohs (2025) PhD thesis

Bayesian analysis

- SMASH with different mean field settings vs. HADES flow data for protons and deuterons in 4 centrality classes
- Many events required to calculate flow coefficients → Gaussian process



Centrality selection does not matter at midrapidity

Coulomb potential important and included

Momentum dependence crucial for elliptic flow strength

Maximum posterior parameters

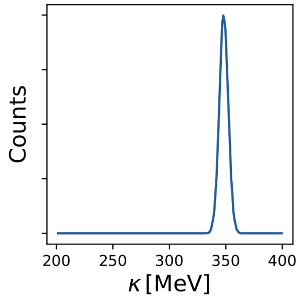
68.3% confidence:

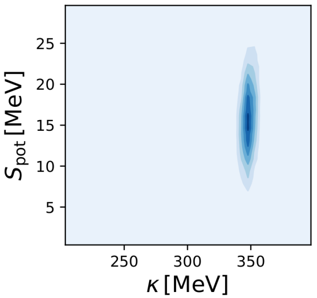
$$\kappa = 348.2^{+4.0}_{-3.9}\,\mathrm{MeV}$$

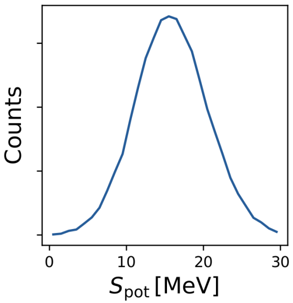
Relatively stiff

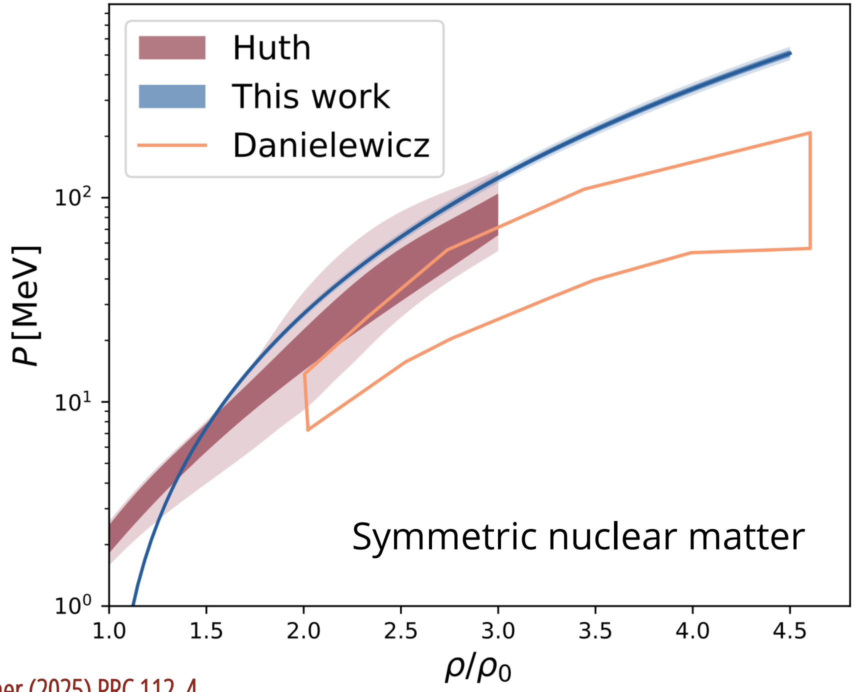
$$S_{\mathrm{Pot}} = 15.8^{+4.7}_{-4.6}\,\mathrm{MeV}$$

Consistent with previous studies but not so sensitive



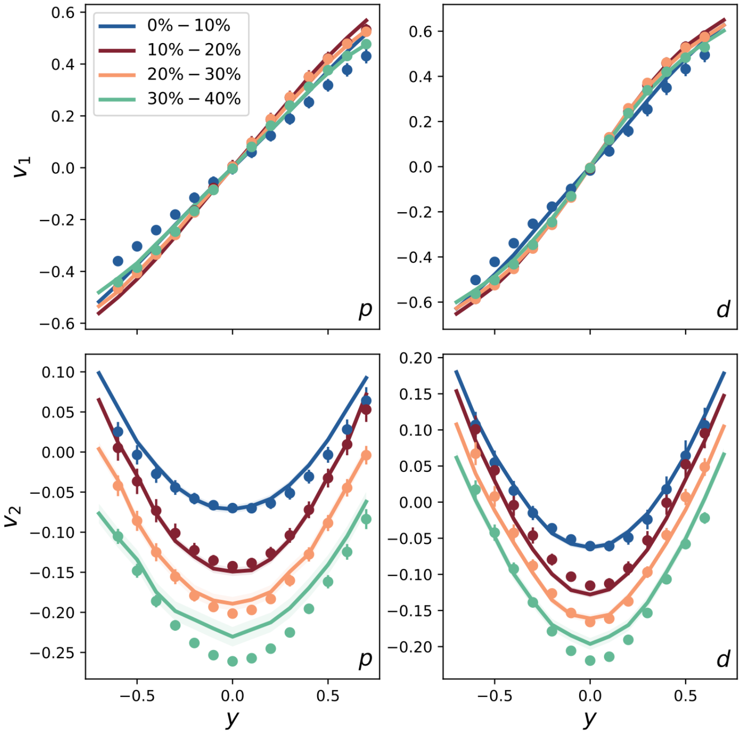


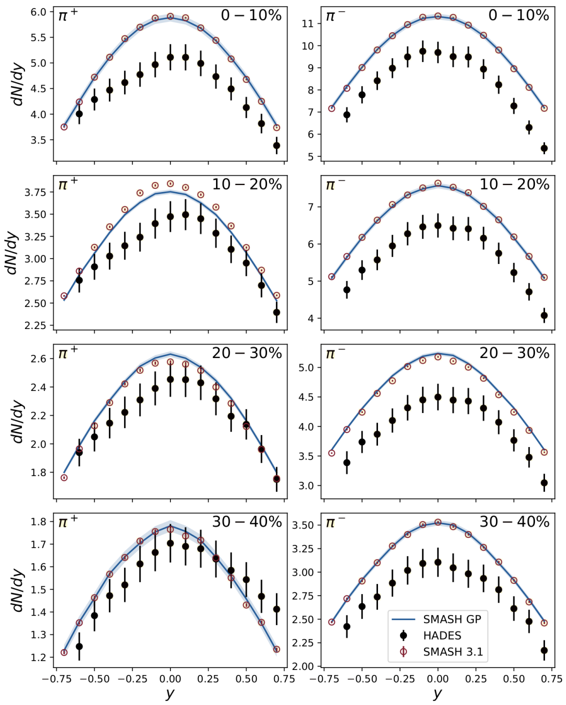




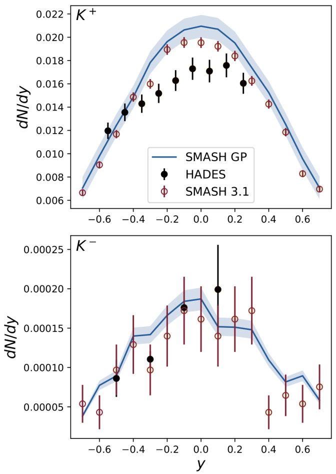
J. Mohs, S. Spies, H. Elfner (2025) PRC 112 4

Comparison to data





J. Mohs (2025) PhD thesis



Good agreement for baryons, but not meson spectra

Symmetry potential for all hadrons?

J. Mohs, S. Spies, H. Elfner (2025) PRC 112 4

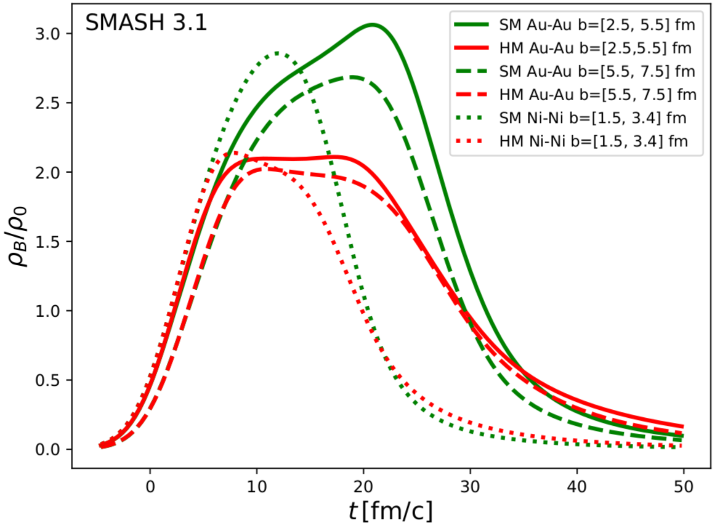
Evolution of the medium

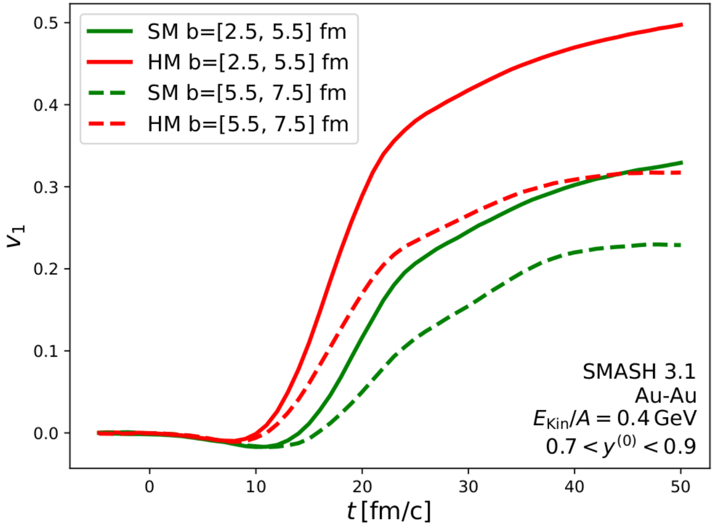
Without Coulomb!

- Densities, medium lifetime, and consequently directed flow scale with system size as expected

- Soft EoS allows for more compression → weaker bounce-off

Central
3-cell

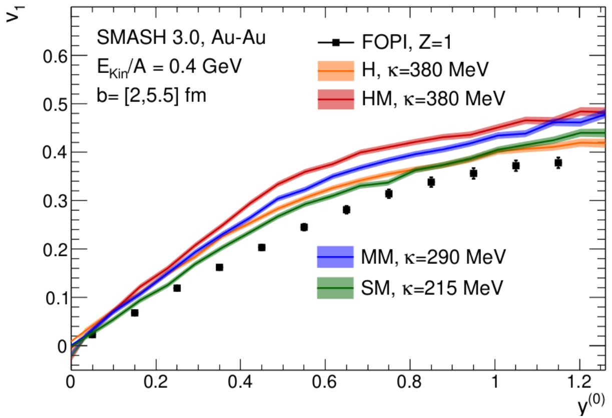


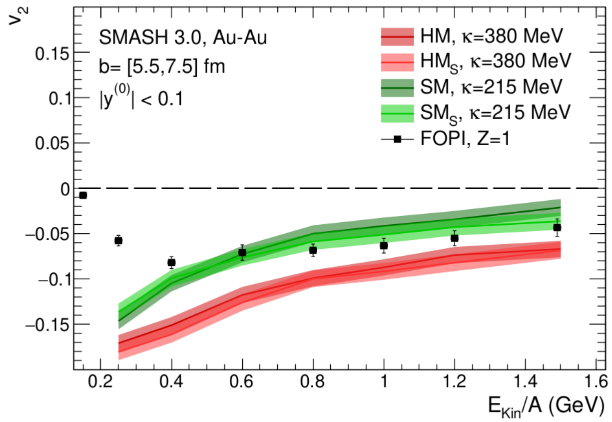


L. Tarasovicova, J. Mohs, A. Andronic, H. Elfner and K.-H. Kampert EPJA 60 (2024), FAIR-NRW network

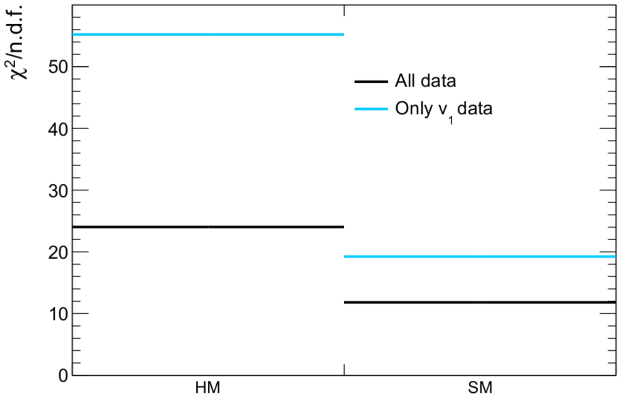
Comparison to FOPI

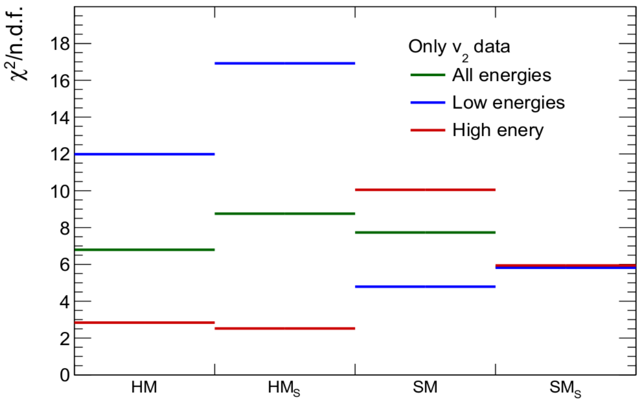
Without Coulomb!





- Overall data (spectra and flow) favors soft momentum dependent EoS, v_1 alone as well
- v_2 at high energies asks for hard MD EoS, but soft MD is not very far off





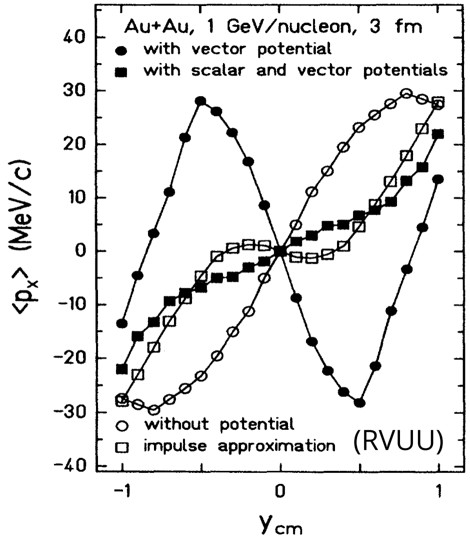
L. Tarasovicova, J. Mohs, A. Andronic, H. Elfner and K.-H. Kampert EPJA 60 (2024), FAIR-NRW network

Interlude: kaon flow & KN potential

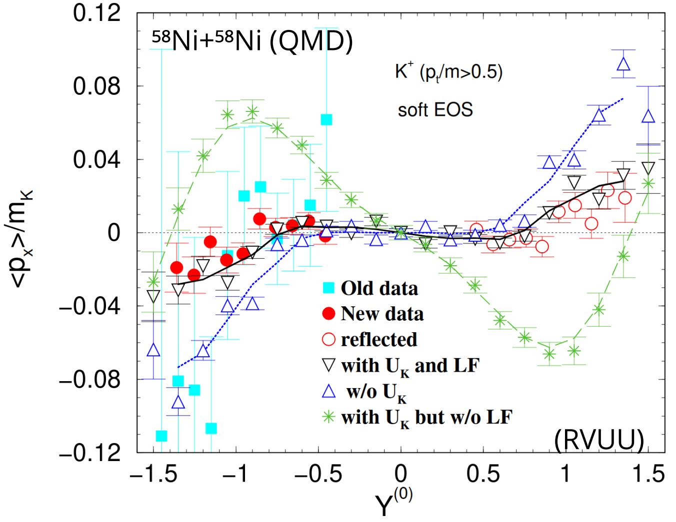
FOPI and E895 data consistent with **repulsive vector + attractive scalar** KN potential

$$U(\rho, \mathbf{k}) = \omega(\rho, \mathbf{k}) - \omega_0(\mathbf{k})$$
$$= \sqrt{\mathbf{k}^2 + m_K^2 - \frac{\Sigma_{KN}}{f_\pi^{*2}}\rho_s + V_0^2} \pm V_0 - \sqrt{\mathbf{k}^2 + m_K^2}$$

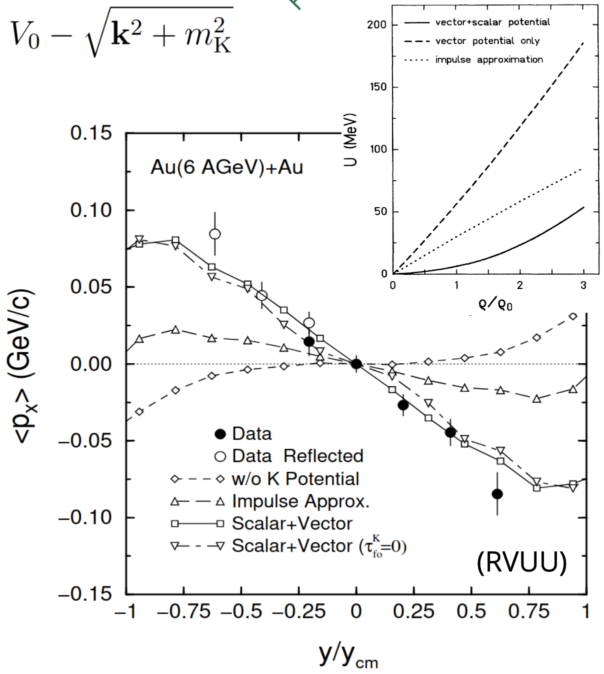
+Lorentz Force



G. Q. Li, C. M. Ko, and Bao-An Li (1995) PRL 74(2)



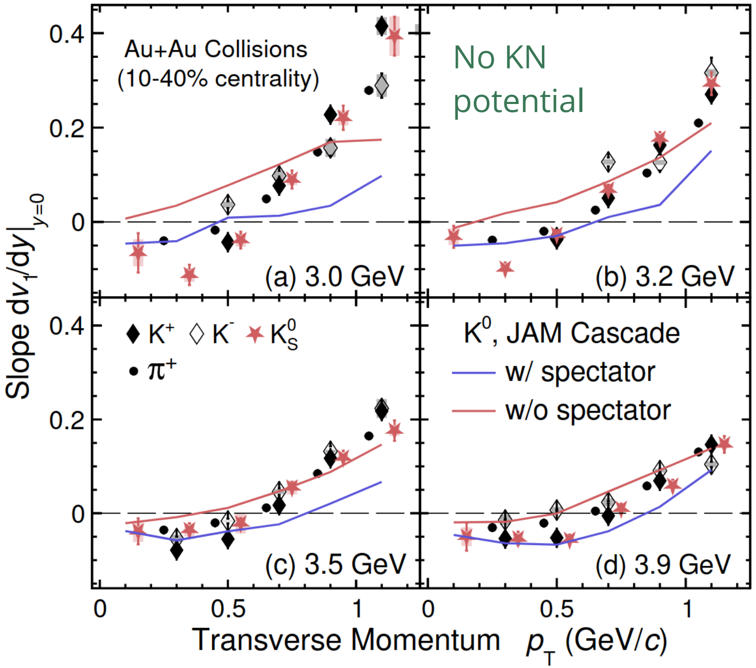
Y.M. Zheng, C. Fuchs, A. Faessler, and Y.P. Yan (2004) PRC 69



S. Pal, C. M. Ko, Z. Lin, B. Zhang (2000) Phys.Rev.C62

Interlude: kaon flow & KN potential

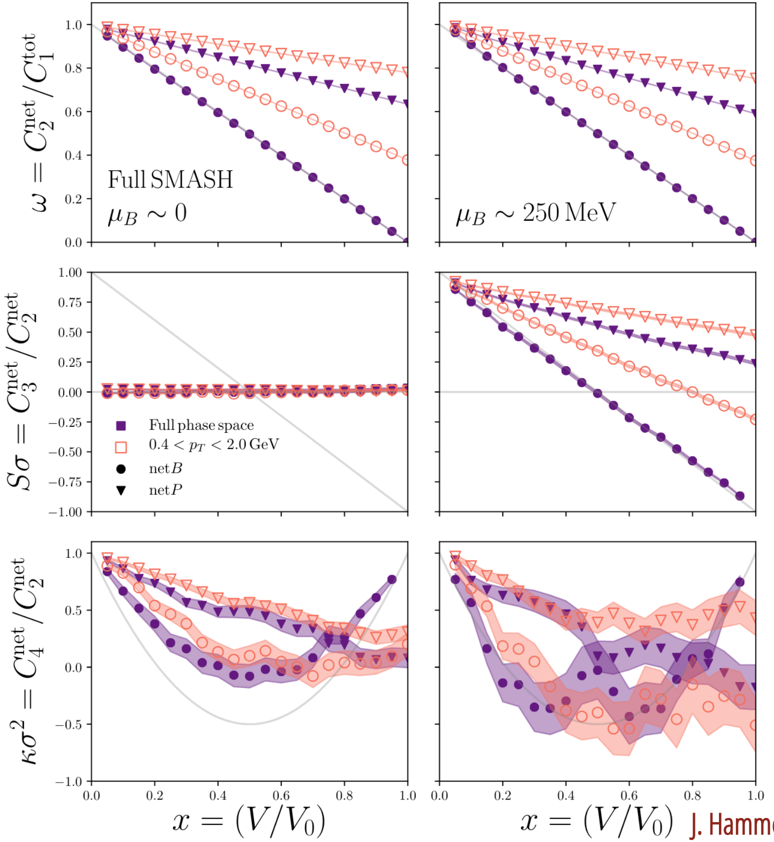
But! STAR analysis from this year says it might due spectator shadowing



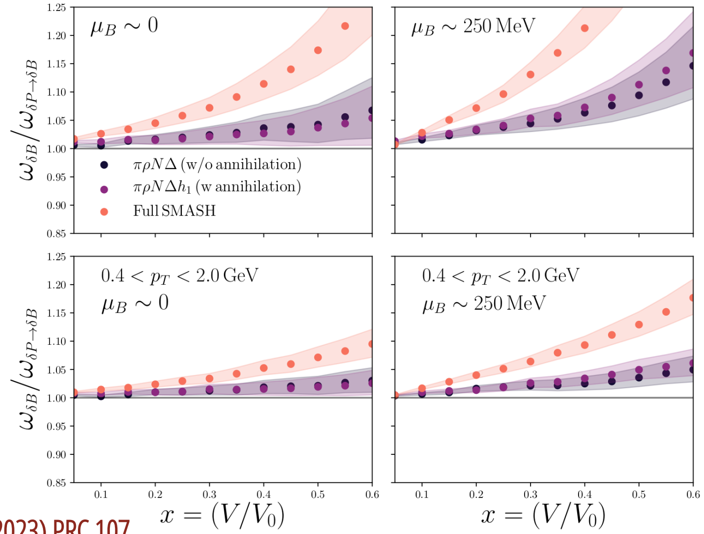
STAR Collaboration, 2503.23665 [nucl-ex]

Fluctuation observables

Effect of conservation laws



- Charges are conserved in every interaction
- Are net-proton fluctuations good proxies for net-baryon?
- Dependence on phase space volume available



J. Hammelmann et al. (2023) PRC 107

Survival of critical fluctuations

Critical fluctuations of σ field contribute to the net/total particle number cumulant

$$\langle(\delta\sigma)^n\rangle_c = \left(\frac{T}{VH_0}\right)^{n-1} \frac{\partial^{n-1}M}{\partial h^{n-1}}\bigg|_r$$

Taken from Ising mapping

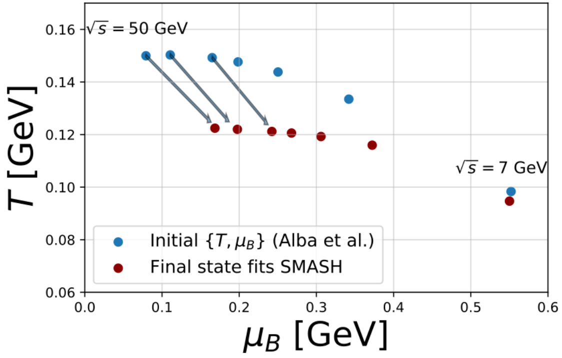
M. Bluhm et al. (2017) EPJC 77, 210

$$\kappa_n^{\text{net}} = \kappa_n^p + (-1)^n\kappa_n^{\bar{p}} + (-1)^n\langle(V\delta\sigma)^n\rangle_c(I_p - I_{\bar{p}})^n$$

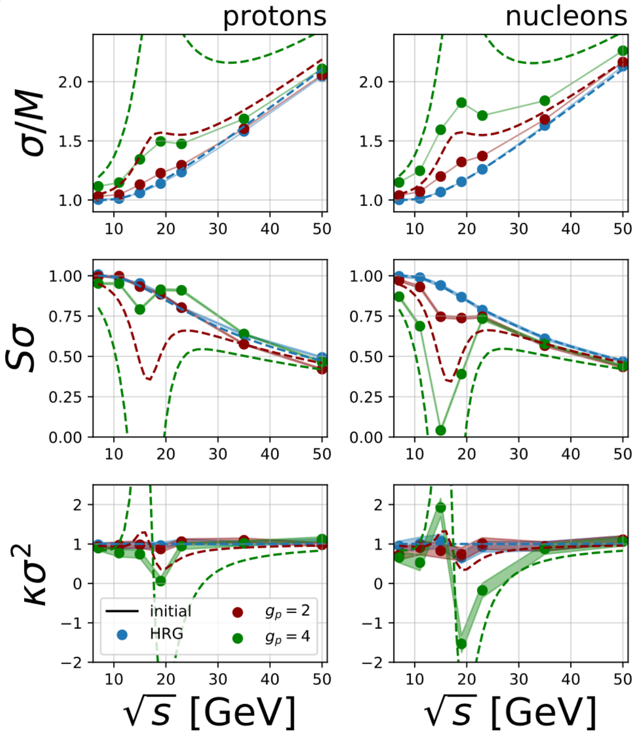
$$\kappa_n^{\text{tot}} = \kappa_n^p + \kappa_n^{\bar{p}} + (-1)^n\langle(V\delta\sigma)^n\rangle_c(I_p + I_{\bar{p}})^n$$

$$I_i = \frac{g_i d_i}{T}\int \frac{d^3k}{(2\pi\hbar)^3}\frac{f^0_{i,k}}{\gamma_{i,k}}$$

Generate distributions with above cumulants and plug into expanding sphere, using full SMASH hadronic dynamics



Signal can survive only if coupling is strong enough



J. Hammelmann et al. (2024) PRC 110

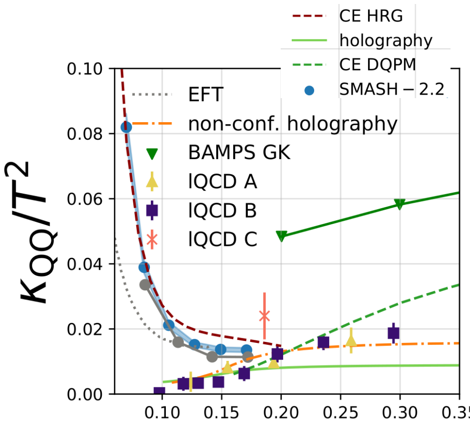
Transport coefficients

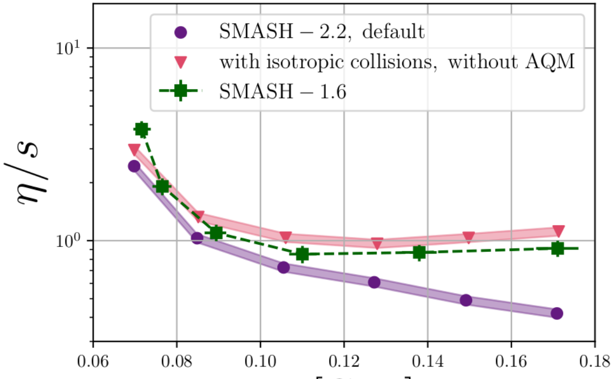
Shear viscosity and conductivities for conserved charges (B,Q,S) as functions of temperature

$$\eta = \frac{V}{T}\int \langle T^{ij}(t)T^{ij}(0)\rangle dt$$

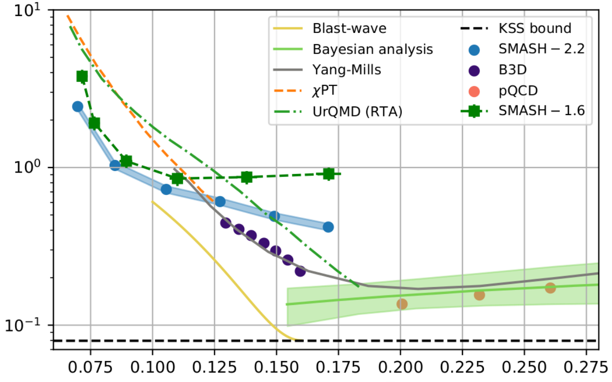
$$\kappa_{ij} = \frac{V}{3}\int \langle \vec{J}_i(t)\vec{J}_j(0)\rangle dt\,.$$

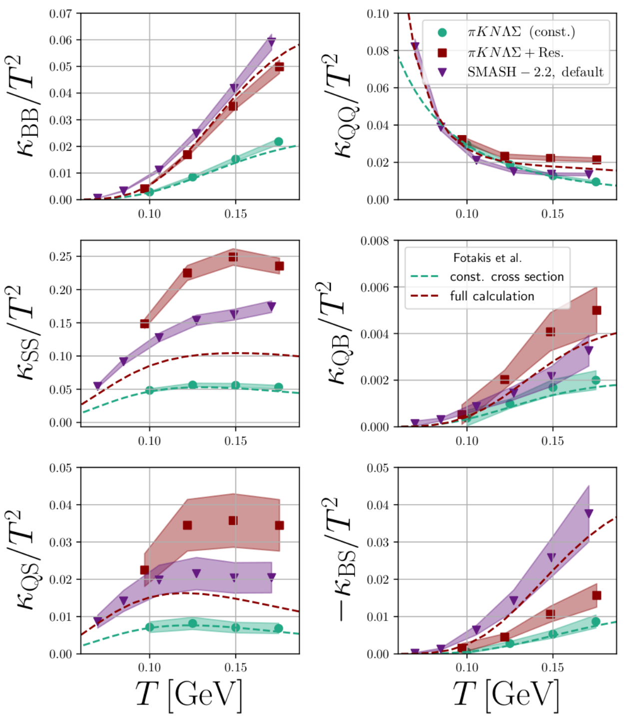
Kubo formula





J. Hammelmann PhD thesis (2024)





J. Hammelmann, J. Staudenmaier and H. Elfner (2025), PRC 111

Coupling to hydrodynamics

Hybrid approach

https://github.com/smash-transport/smash-vhlle-hybrid

smash

- Modular hybrid approach for high and intermediate energy HICs
- Hybrid-handler: Framework for testing and integration of modules
- Fully open source and public

SMASH

- Woods-Saxon nuclei
- Fluid formed at nuclear passing time τ_0

P. Huovinen et al.: EPJA 48 (2012)
Iu. Karpenko et al.: CPC 185 (2014)

vHLLE

- (3+1)D Israel-Stewart
- Cornelius routine for hypersurface finding

smash-hadron-sampler

- Cooper-Frye particlization
- Viscous corrections

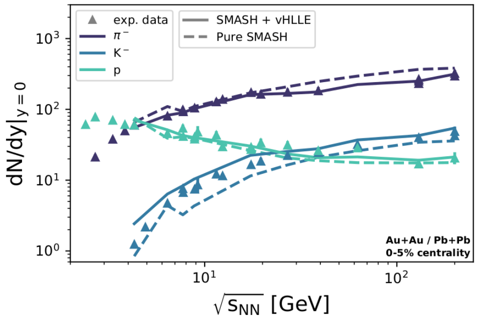
Iu. Karpenko et al.: PRC 91, 064901 (2015)
A. Schäfer et al., EPJA 58 (2022)

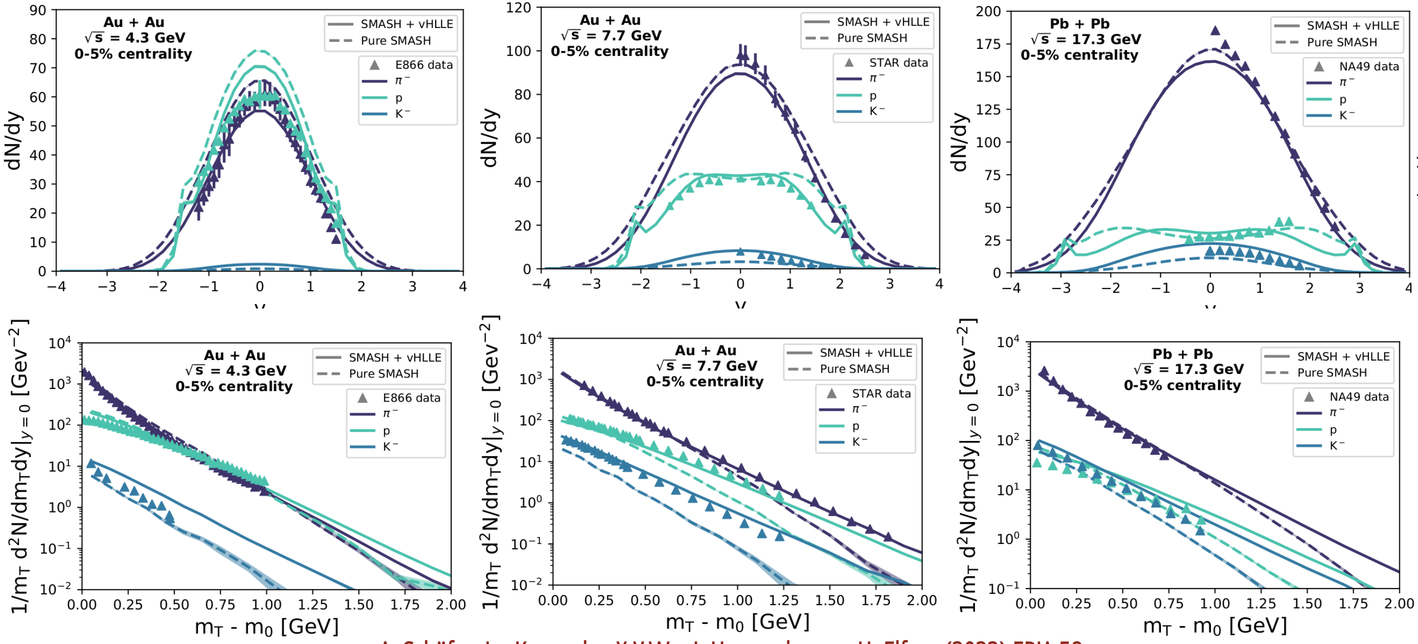
SMASH

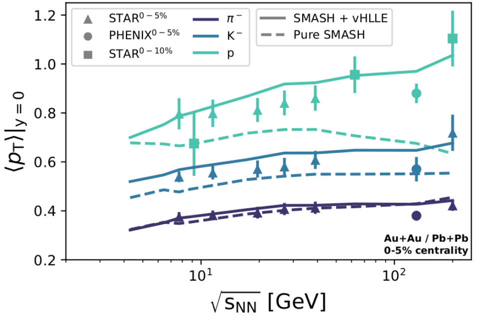
- Hadronic rescattering until freezeout

Spectra and excitation functions

- Hybrid approach in decent agreement with measurements
- Midrapidity yields and m_T spectra well described over large range of beam energies by hybrid (<p_T> too small in pure SMASH)



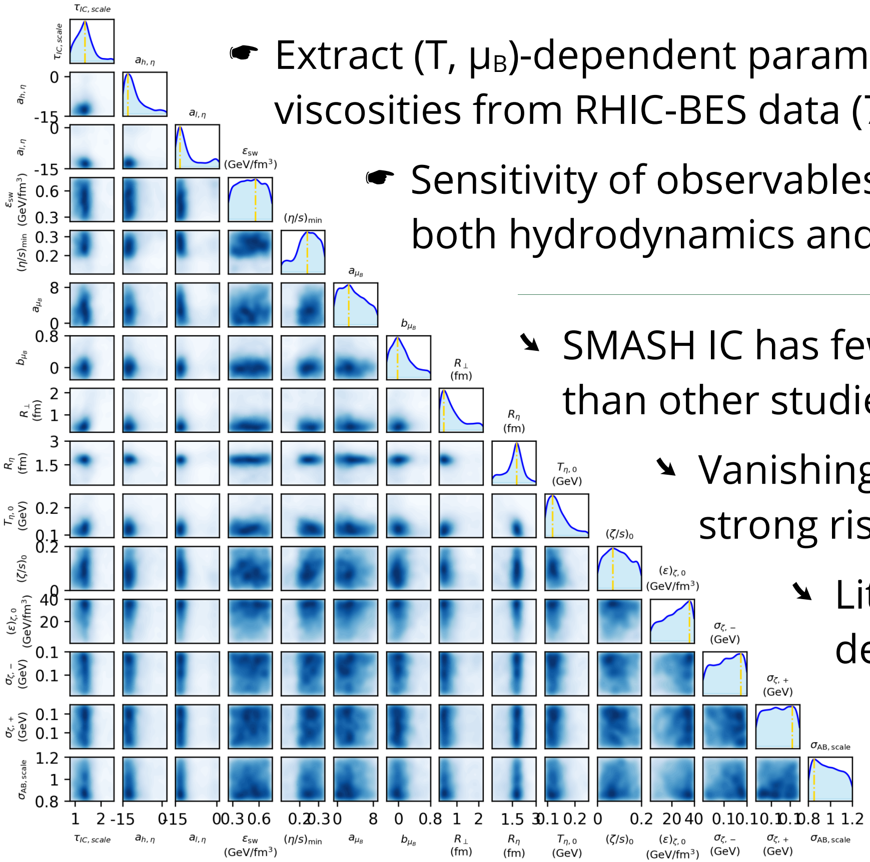




Smearing/viscosity was tuned for each energy individually and kept constant

A. Schäfer, Iu. Karpenko, X-Y Wu, J. Hammelmann, H. Elfner (2022) EPJA 58

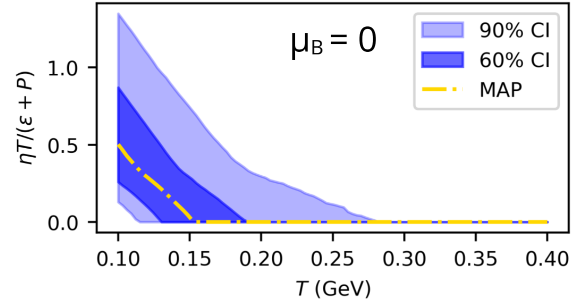
Bayesian analysis

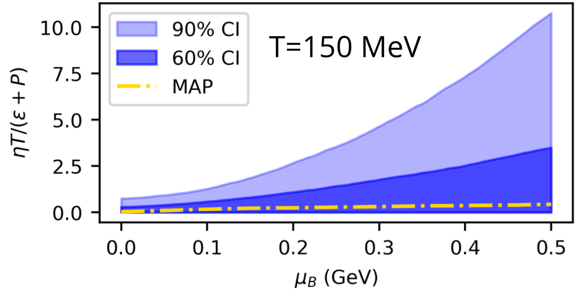


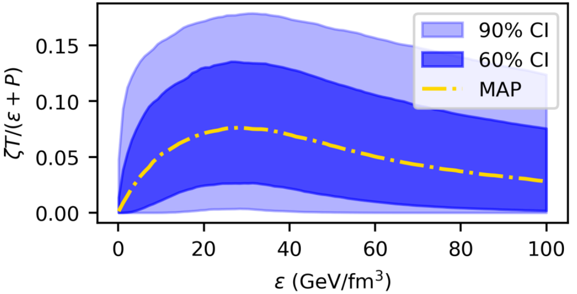
- ☛ Extract (T, μ_B)-dependent parameterizations of viscosities from RHIC-BES data (7.7, 19.6, 200 GeV)
  - ☛ Sensitivity of observables on parameters from both hydrodynamics and hadronic transport

---

- ➘ SMASH IC has fewer free parameters than other studies in literature
  - ➘ Vanishing shear viscosity and strong rise in hadronic regime
    - ➘ Little constraints on μ_B dependence
      - ➘ Finite bulk viscosity required



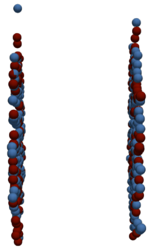




N. Götz, Iu. Karpenko, and H. Elfner. (2025) PRC 112
Earlier analysis on similar data: Shun et al. (2024) PRL 132

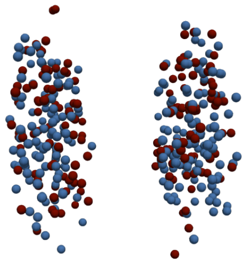
Hydro at lower energies?

$\sqrt{s_{NN}} = 200\ \text{GeV}$



$\gamma = 106$

$\sqrt{s_{NN}} = 5\ \text{GeV}$

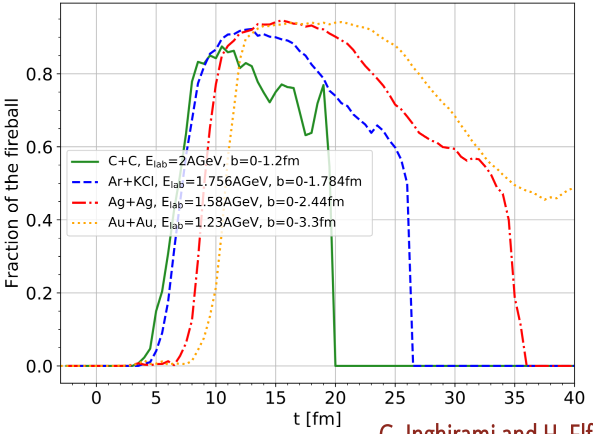


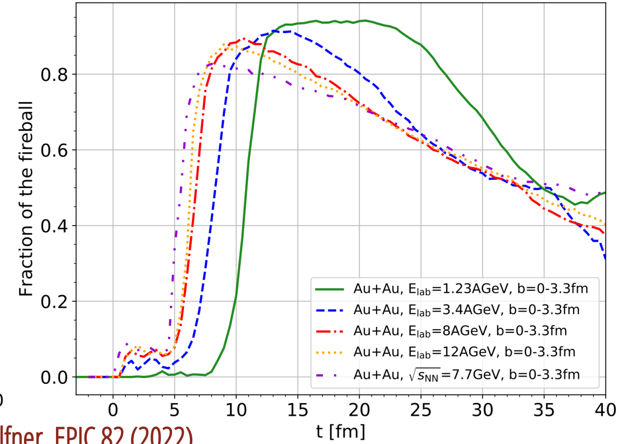
$\gamma = 2.7$

X: pressure anisotropy
Y: off-diagonality in $T^{\mu\nu}$

Coarse-grained SMASH

Fraction of the fireball close to local equilibrium (X, Y < 0.3)





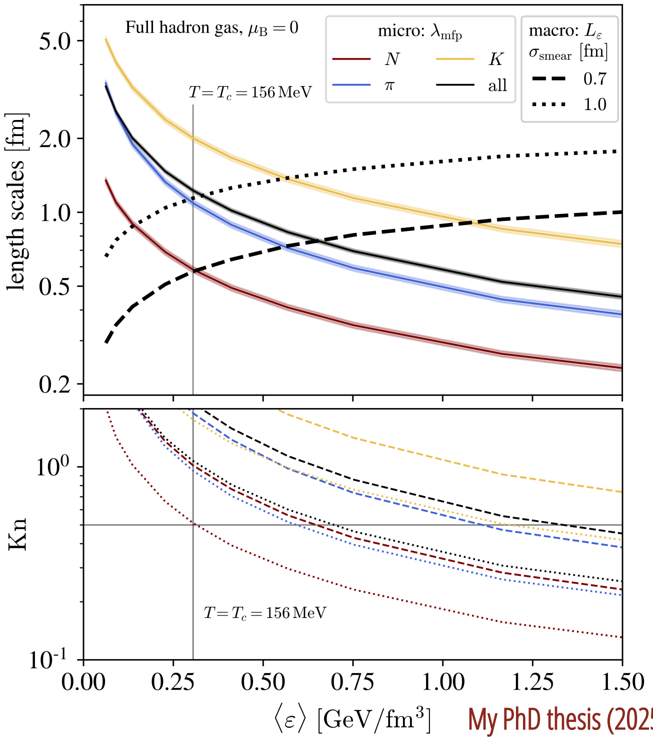
G. Inghirami and H. Elfner, EPJC 82 (2022)

- Hadronic medium is partially “thermalized” even at low energies
- **IF** we use hydrodynamics, the initial conditions cannot be isochronous

Local equilibration

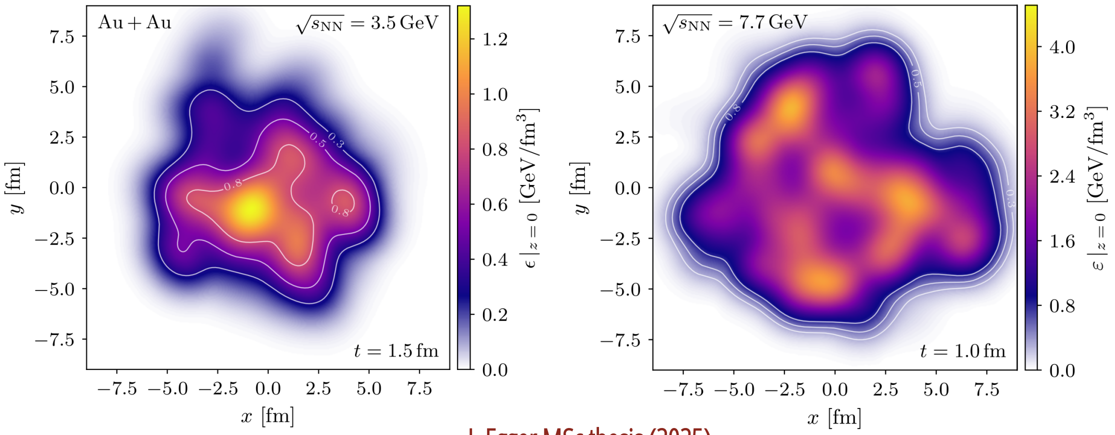
Box calculation

$$\frac{1}{L_\varepsilon}(t,x) \equiv \left|\frac{\nabla\varepsilon(t,x)}{\varepsilon(t,x)}\right|$$



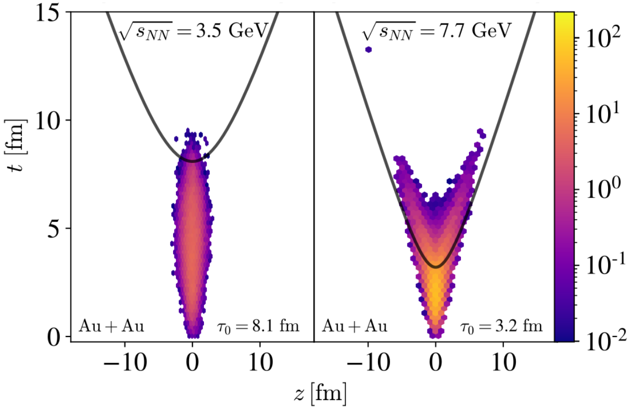
My PhD thesis (2025)

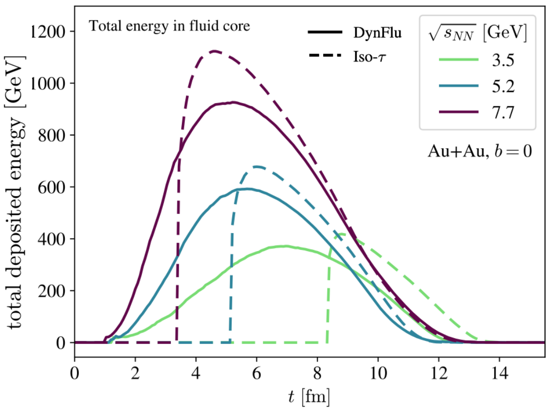
- Mean free path and Knudsen number decrease with temperature, thus with local energy density
- We can use this to decide dynamically which regions of spacetime should become fluid
- Stricter threshold → less fluid
- Automatic core-corona separation

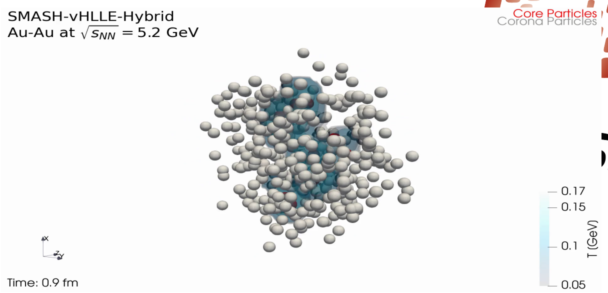


J. Egger MSc thesis (2025)

Dynamic fluidization

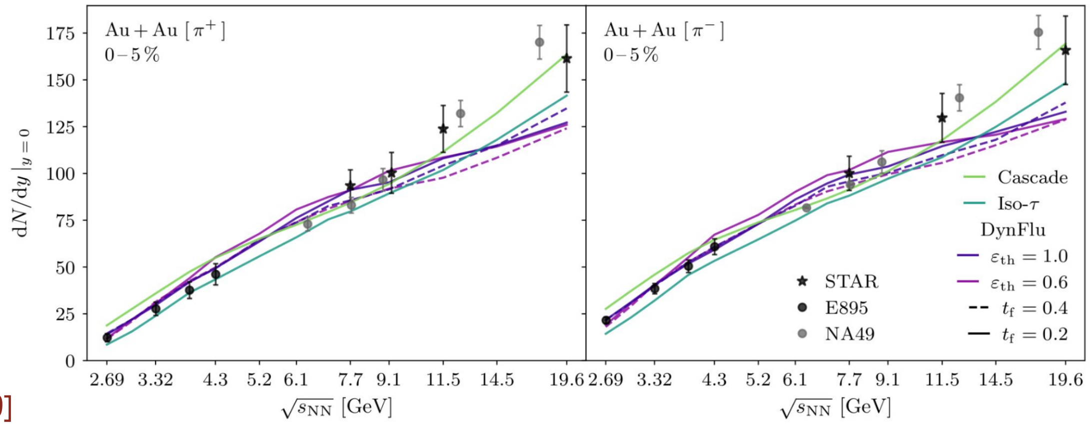






Core particles kept in IC to contribute to calcuation of $T^{\mu\nu}$

- Spacetime fluidization converges towards iso-τ at higher energies
- Much smoother deposition of hot matter in the fluid
- Results without retuning parameters
- Effective extension of hybrid model to lower energies



R. G-H. et al. (2025) [2507.19389]

Production of light nuclei

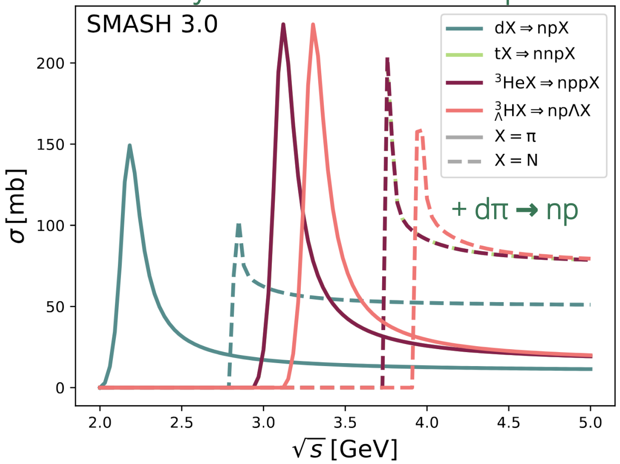
Setup & rate equations

smash

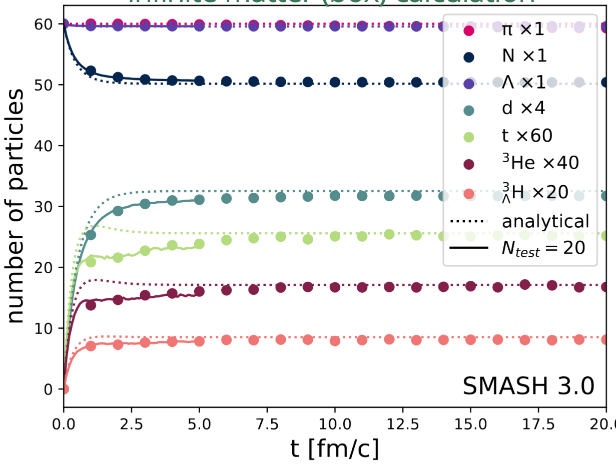
Using hypersurface from hydro:

- Sample particles directly (similar to statistical hadronization model)
- Run through SMASH as afterburner and apply coalescence afterwards
- Run SMASH with dynamic reactions for light nuclei

Catalysis reactions + dπ ➞ np



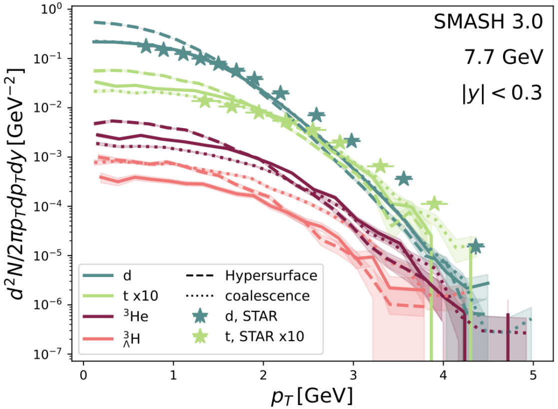
Infinite matter (box) calculation



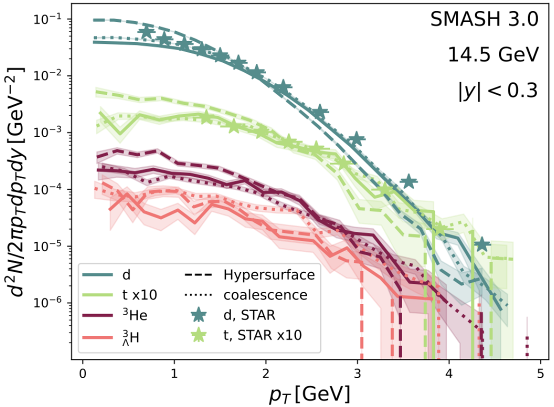
- The stochastic collision criterion allows for multi-particle reactions
- Equilibrium yields in very good agreement
- Thermalization process is faster than analytic solution
- 10 testparticles are sufficient

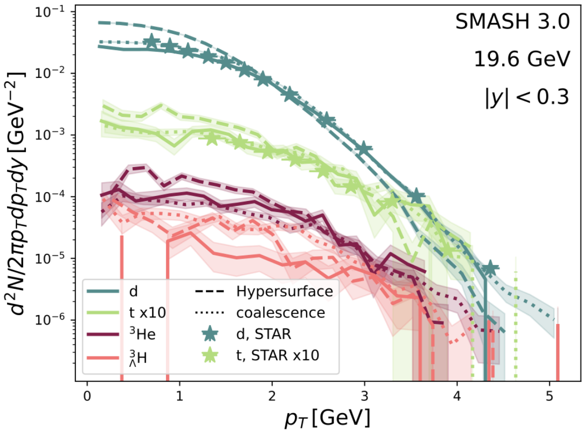
M. Ege, J. Mohs, J. Staudenmaier and H. Elfner (2025) PRC 112 5

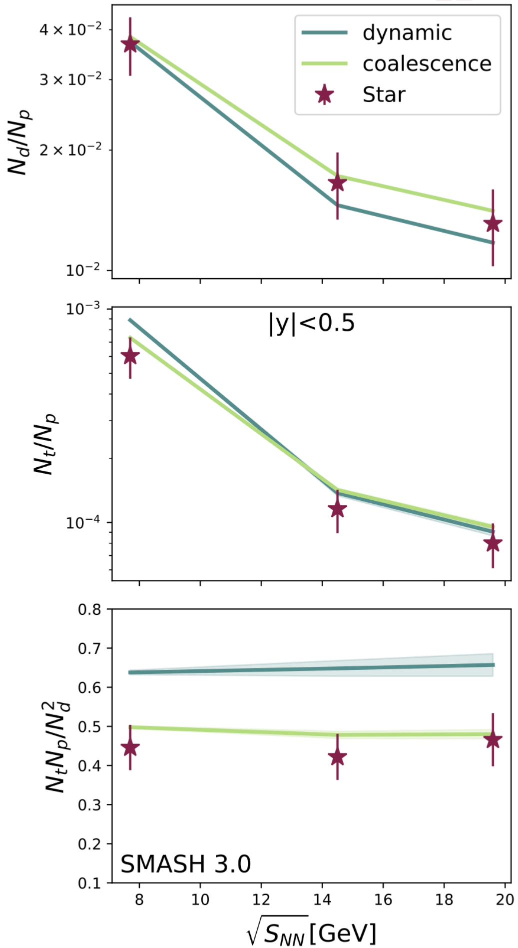
Particle ratios & pT spectra



- Rescattering necessary to describe shape of the low momentum spectra
- Small differences between coalescence and dynamic processes
- Single ratios well described, while double ratio slightly deviates

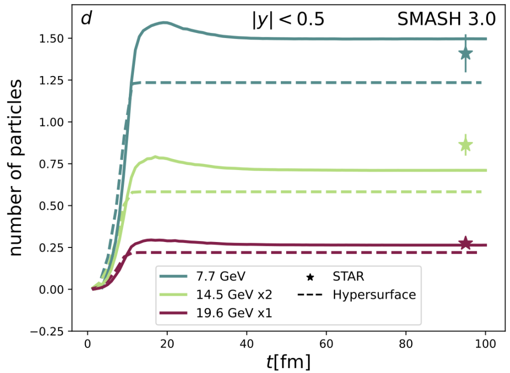


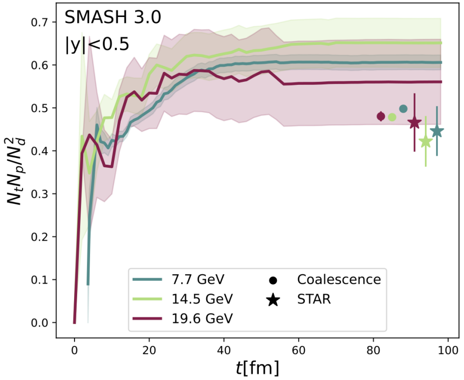


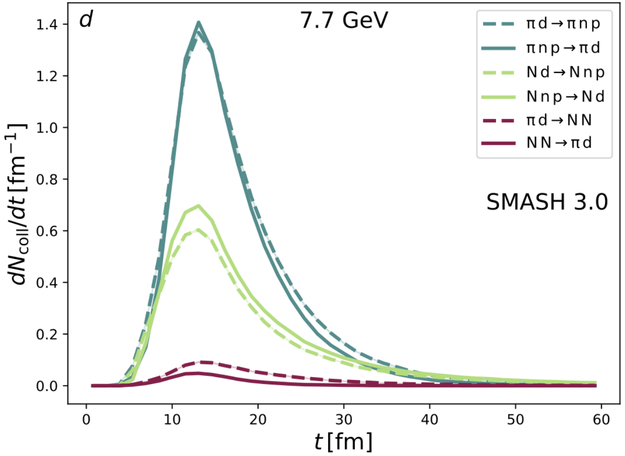


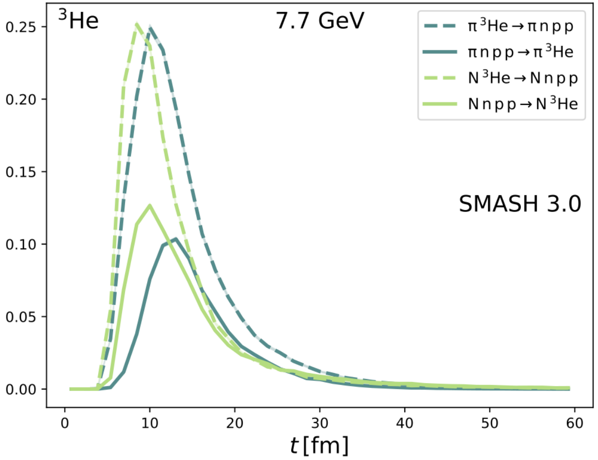
Dynamical evolution

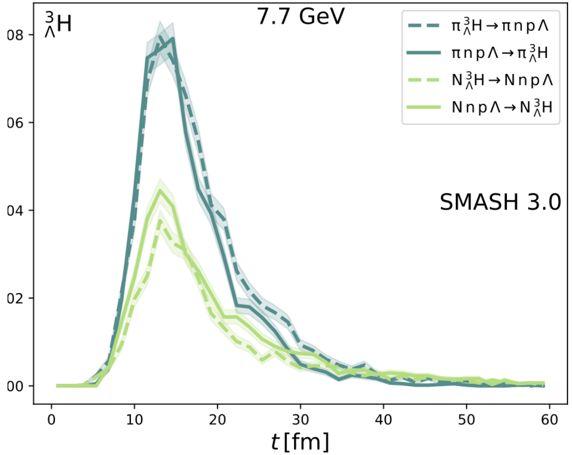
- Non-trivial time evolution cancels in double ratio
- Many late stage collisions happen
- Production and destruction of light nuclei may balance each other











M. Ege, J. Mohs, J. Staudenmaier and H. Elfner (2025) PRC 112 5

Electromagnetic and hard probes

Dileptons in SMASH

- Dileptons produced perturbatively by the hadrons
- Resonances: time-integration/shining method
- No in-medium modification → only dynamically generated broadening of spectral functions
- To match data, some resonances need coarse graining + in-medium rates

Continuously perform dilepton radiation and weight them by taking the decay probability into account

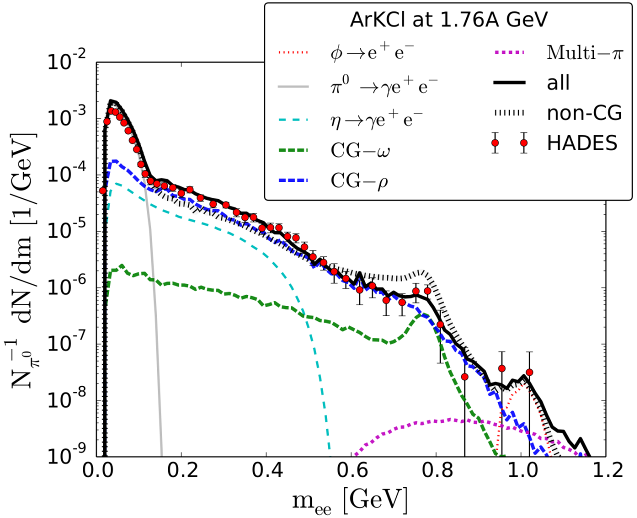
Dalitz

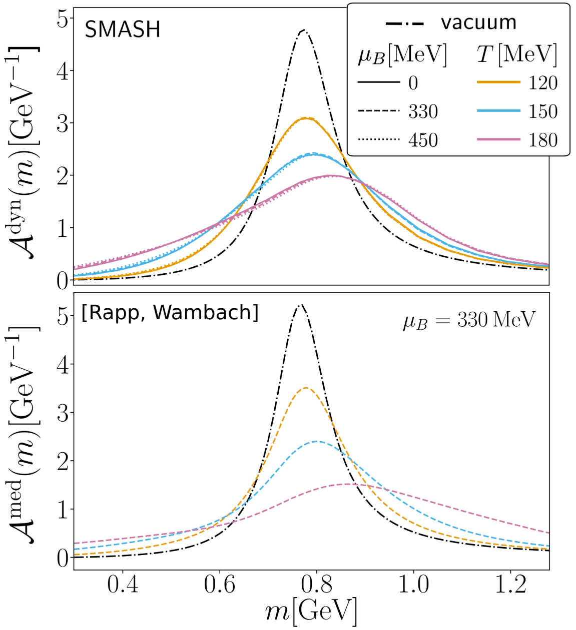
$$\pi \to e^+e^-\gamma$$
$$\eta \to e^+e^-\gamma$$
$$\eta' \to e^+e^-\gamma$$
$$\omega \to e^+e^-\pi^0$$
$$\phi \to e^+e^-\pi^0$$
$$\Delta^+ \to e^+e^-p$$
$$\Delta^0 \to e^+e^-n^0$$

Direct

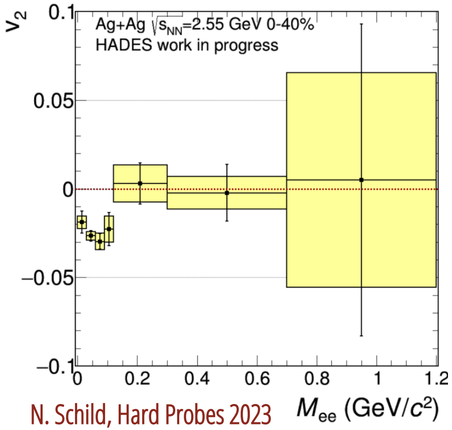
$$\rho \to e^+e^-$$
$$\omega \to e^+e^-$$
$$\phi \to e^+e^-$$

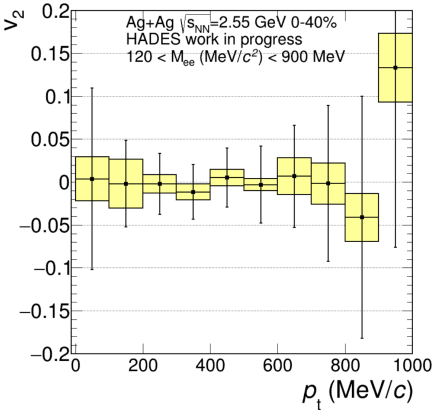
J. Staudenmaier et al., PRC 98 (2018)
R.G.-H. et al. (2023) PRC 107(2)





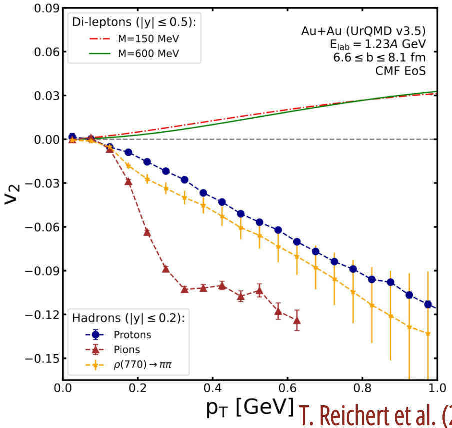
Flow of dielectrons



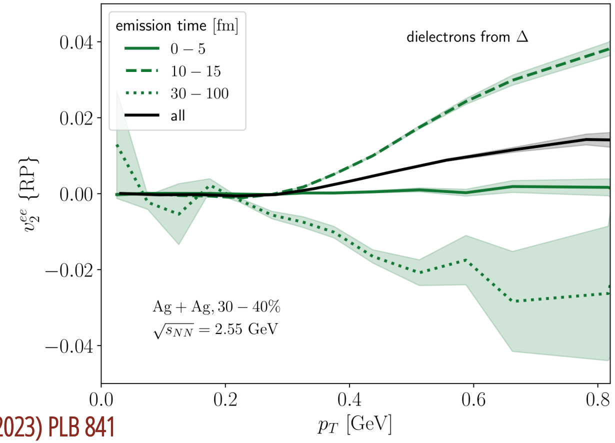


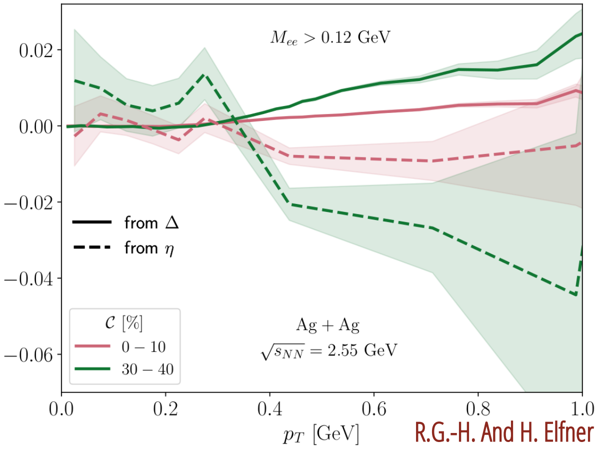
N. Schild, Hard Probes 2023

- HADES measures dielectron flow in AgAg@1.76 AgeV collisions
- “Zero” flow in resonance region
- Actually caused by cancellation between in- (early) and out-of-plane (late) contributions



T. Reichert et al. (2023) PLB 841





R.G.-H. And H. Elfner (2024) PRC 110

Flow of dielectrons

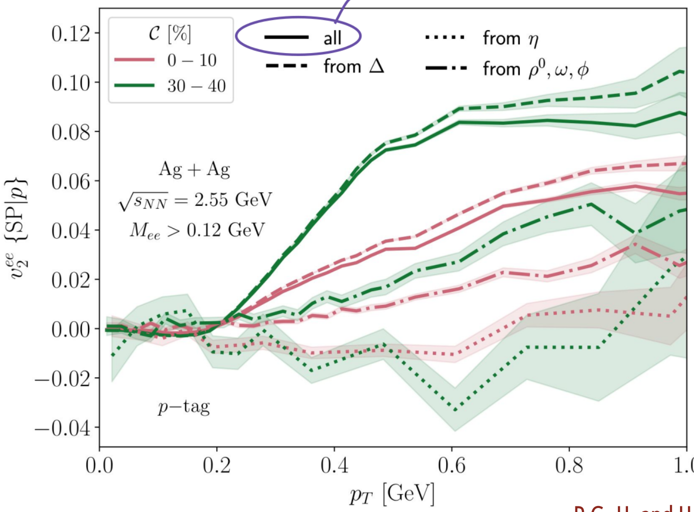
Event flow vector

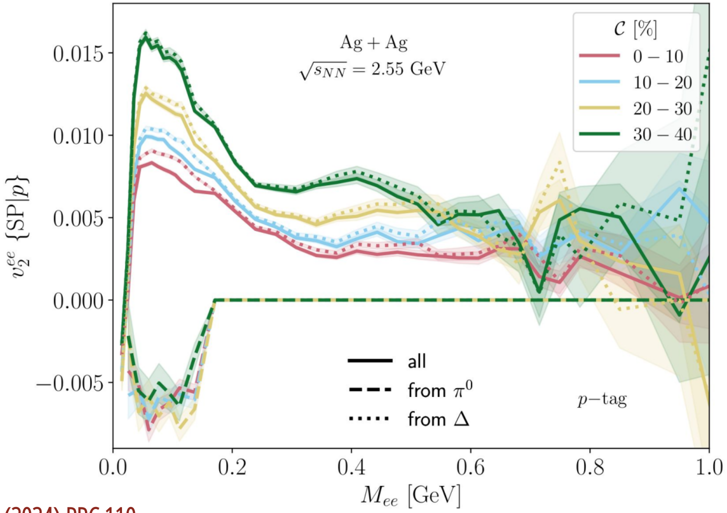
$$\mathbf{q}_n^X(\Omega) = \frac{1}{N_X(\Omega)} \sum_{k\in\Omega}^{N_X} e^{in\phi_k}$$

By **tagging** the dielectrons with a specific selection of hadrons, we can experimentally track the resonances

$$v_{ll}\{\mathrm{SP}|h\}(\Omega) \equiv \frac{\mathrm{Cov}\left[\mathbf{q}_{ll}(\Omega), \mathbf{q}_h\right]}{\sqrt{\langle |q_h|^2\rangle}}$$

can be measured





R.G.-H. and H. Elfner (2024) PRC 110

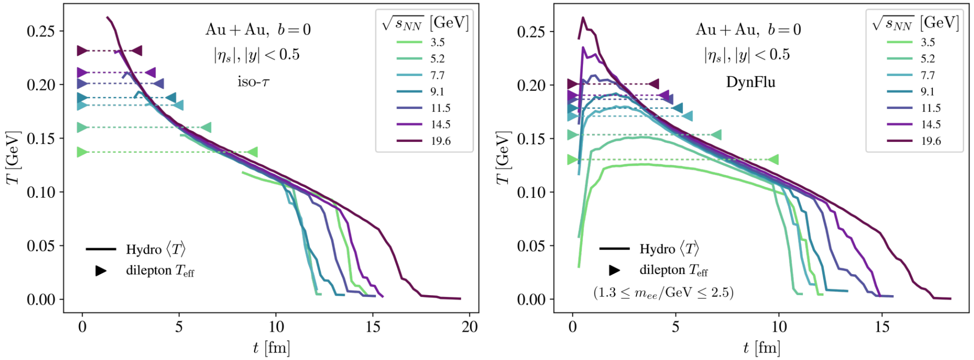
Dielectrons in the hybrid

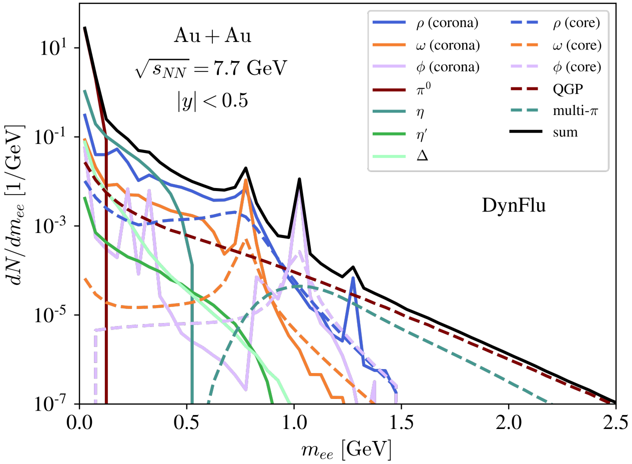
$$\frac{dN}{dm_{ee}} \propto m_{ee}^{3/2} \exp\left(-\frac{m_{ee}}{T}\right)$$

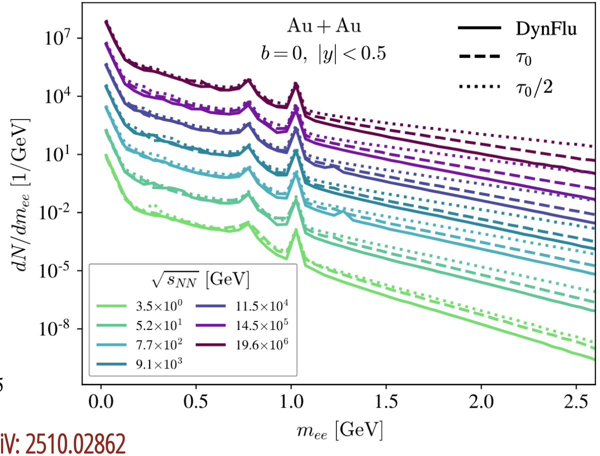
SMASH corona: shining method

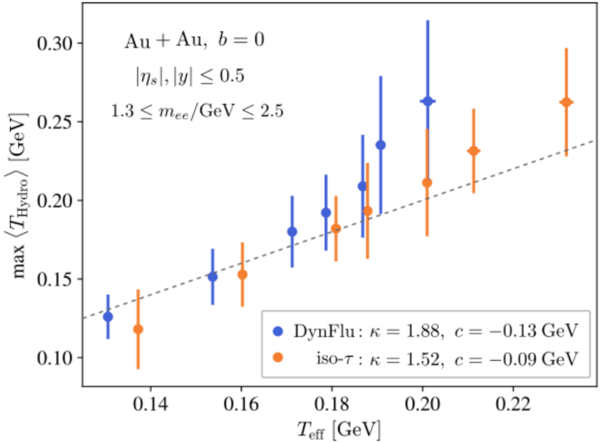
vHLLE core: thermal rates (same as in CG)

☛ Compare the different initializations







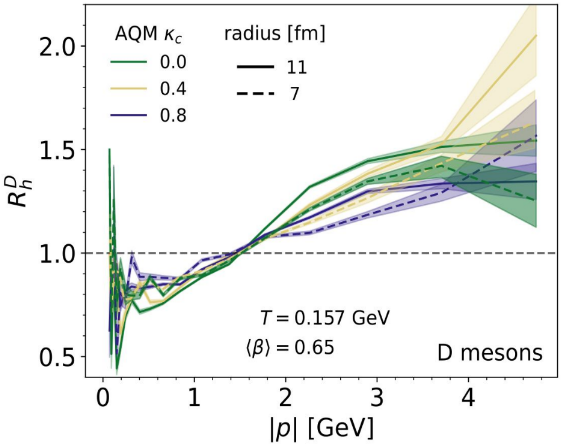


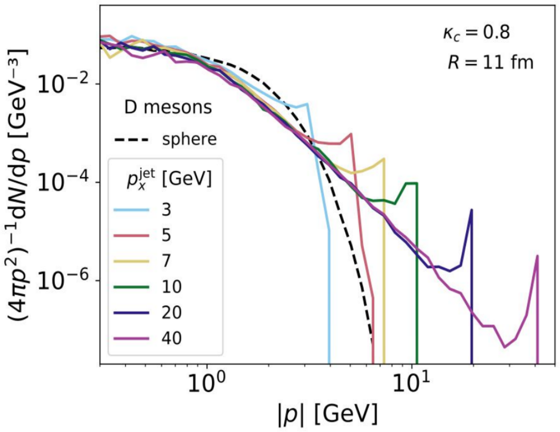
R.G.-H. et al. (2025) arXiV: 2510.02862

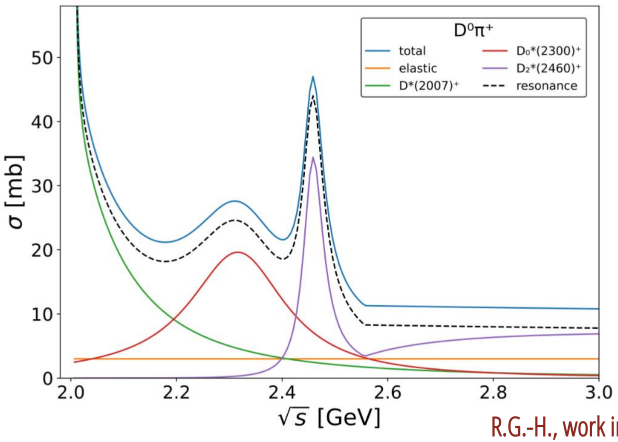
Heavy flavor rescattering

Toy model setup:

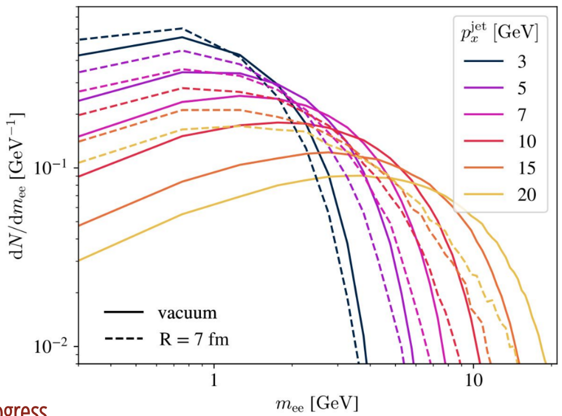
- Sphere of thermalized hadron gas (T, V, μ_B from SHM)
- Jet-like particles from the origin
- PDG resonances, AQM $\sigma_{elastic}$

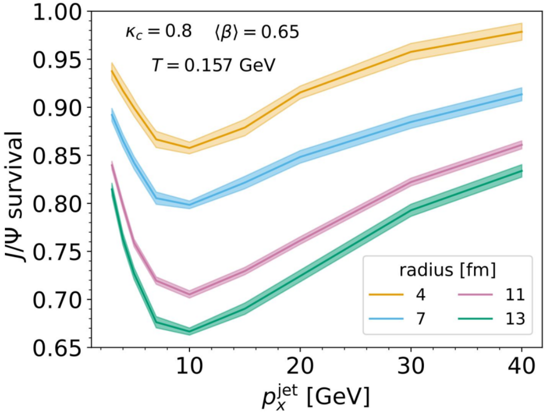






R.G.-H., work in progress





Software development

The SMASH team

smash

In Frankfurt

- Hannah Elfner
- Alessandro Sciarra
- Renan Góes-Hirayama
- Carl Rosenkvist
- Lucas Constantin
- Shi-Lei Tao sup. by Ben-Wei Zhang
- Qian-Ru Lin sup. by Long-Gang Pang
- Sebastian Ostrowski
- Jakob Lohr
- Nils Sass
- Robin Sattler
- Antonio Bozic
- Vinzent Pott
- Manou Engel
- Luis Velez

In USA/Spain/Slovakia

- Agnieszka Sorensen
- Hendrik Roch
- Oscar García-Montero
- Zuzana Paulinyová

Bouldering with group in November

Clean coding

https://smash-transport.github.io/

smash

Version 3.3 out last week !

Strict rules for software development

- Each newly implemented feature goes through internal review (pull requests)
- ~100 unit and functional tests catch bugs before merging to development branch
- Specific error handling prevent wrong usage
- Enforced documentation and user guide
- Completely open source codebase

```
WARN     DecayModes   : Branching ratios of 53 hadrons were renormalized by more than 1% to have sum 1.
INFO           Main   : Config hash: e57de317391abb160fd7de1154bbd8e8d169a69439245152f6e85bd6ba9f20fd
INFO       Collider   : Fermi motion is ON.
INFO     Experiment   : End time: 50 fm
                        -- Collider Modus:
                        sqrt(S) (nucleus-nucleus) = 154.489 GeV
                        sqrt(S) (nucleon-nucleon) = 2.41389 GeV
                        Projectile:
                          #particles   #testparticles   mass [GeV]   radius [fm]  diffusiveness [fm]
                                  64              640       60.032         4.265                0.54
                        Target:
                          #particles   #testparticles   mass [GeV]   radius [fm]  diffusiveness [fm]
                                  64              640       60.032         4.265                0.54
INFO     Experiment   : Using 10 testparticles per particle.
INFO     Experiment   : Using 20 parallel ensembles.
INFO    FindScatter   : Evaluating total cross sections from parametrizations only for measured processes.
INFO     Experiment   : Pauli blocking is ON.
INFO     Experiment   : Added output Particles of format Oscar2013
INFO     Experiment   : Potentials are ON. Timestep is 0.1
FATAL          Main   : SMASH failed with the following error:
                        Can't use Skyrme and VDF potentials at the same time!
```

Collision term

The `Collision_Term` section in the input file can be used to configure SMASH interactions. Before describing each possible key in detail, it is useful to give some taste with a couple of examples.

A real life example

The following section in the input file configures SMASH to include all but strangeness exchange involving 2 ↔ 2 scatterings, to treat N + Nbar processes as resonance formations and to not force decays at the end of the simulation. The elastic cross section is globally set to 30 mbarn and the $\sqrt{s}$ cutoff for elastic nucleon + nucleon collisions is 1.93 GeV. All collisions are performed isotropically and 2 ↔ 1 processes are forbidden.

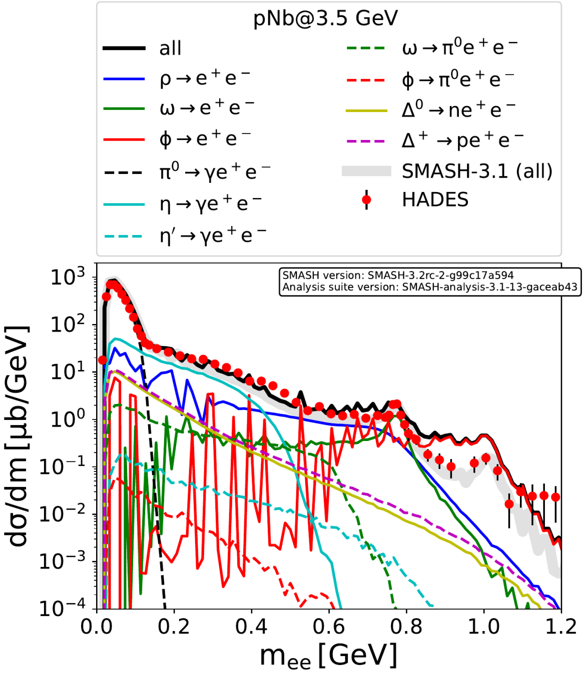
```
Collision_Term:
    Included_2to2: ["Elastic","NN_to_NR","NN_to_DR","KN_to_KN"
    Two_to_One: true
    Force_Decays_At_End: false
    NNbar_Treatment: "resonances"
    Elastic_Cross_Section: 30.0
    Elastic_NN_Cutoff_Sqrts: 1.93
    Isotropic: true
```

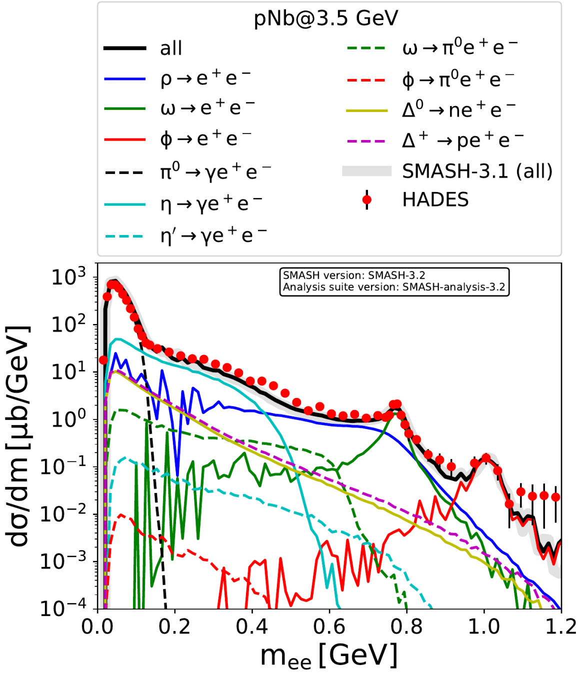
Analysis suite

http://theory.gsi.de/~smash/analysis_suite/current/

Collection of basic physics results to compare the new changes to the model, which also helps to catch bugs undetectable via tests

When changing resonance properties to improve strangeness production, Carl did not initially constrain the BR(N*→NΦ)



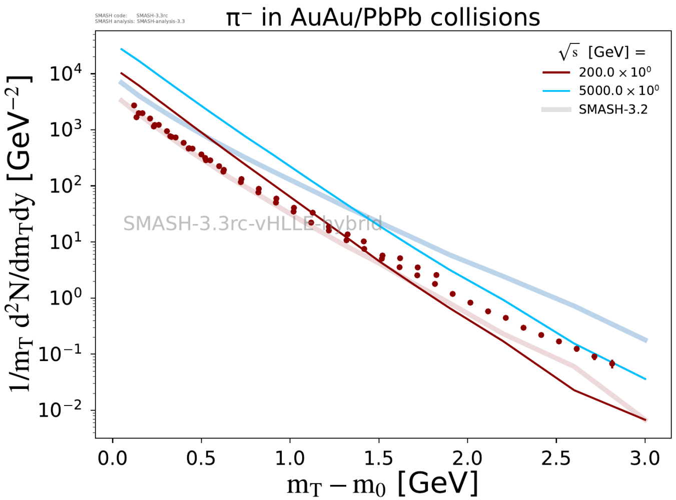


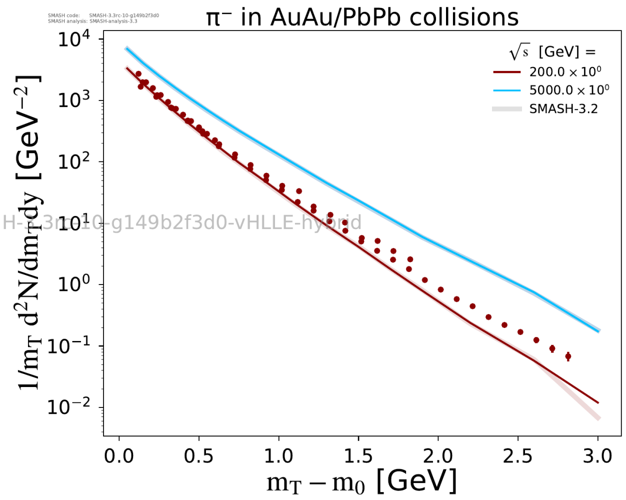
Analysis suite

http://theory.gsi.de/~smash/analysis_suite/current/

Collection of basic physics results to compare the new changes to the model, which also helps to catch bugs undetectable via tests

When adding infrastructure of a custom input for the afterburner calculations, I forgot to set the formation time of entering particles





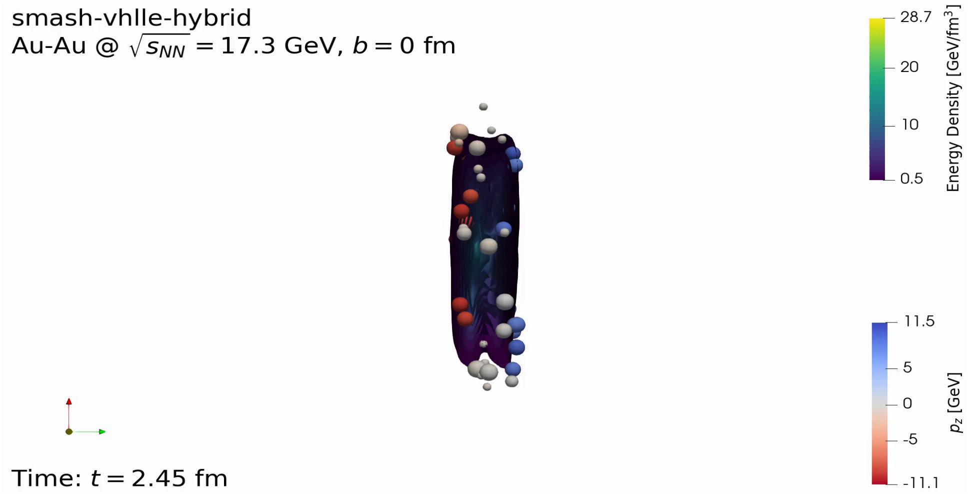
Visualization

https://smash-transport.github.io/movies.html

smash

- Useful tool for science communication Paraview tutorial
- Identify potential issues in the model when something looks wrong or unphysical

The SMASH-hadron sampler was not adjusted to vHLLE providing spacetime four vectors in Cartesian coordinates (needed for DynFlu)



Summary

SMASH and **SMASH-vHLLE hybrid** approaches are available to the public and we support you with your calculations

- Bulk observables are in reasonable agreement with experimental data
- Momentum dependent nuclear potentials compared to FOPI and HADES flow data, suggesting constraints for equation of state
- Fluctuation observables survive rescattering for a strong enough σ-field coupling
- Bayesian analysis for transport coefficients as a function of (T, μ_B)
- Hybrid model extended to lower energies with a dynamic core-corona separation
- Light nuclei can be created and destroyed dynamically via multiparticle scatterings, similar but distinct results to coalesence approach
- Dilepton flow carries interesting information on resonance contributions
- Heavy flavor hadrons now included in the degrees of freedom