

# SMASH: A new transport approach for FAIR energies

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in collaboration with V. Steinberg and H. Petersen

J. Weil *et al.*, Phys.Rev. C94 (2016) no.5, 054905  
DO, Hannah Petersen, J.Phys. G44 (2017) no.3, 034001



July 6, 2017

# Outline

- SMASH transport model

[J. Weil et al., Phys.Rev. C94 \(2016\) no.5, 054905](#)

- ▶ Particle species
- ▶ Interactions: collisions, decays, potentials
- ▶ Initial conditions

- Comparing SMASH results to FOPI and HADES data

- ▶ Multiplicities
- ▶ Spectra
- ▶ Flows
- ▶ Dileptons

- Local forced thermalization at high density using SMASH

[DO, Hannah Petersen, J.Phys. G44 \(2017\) no.3, 034001](#)

# SMASH transport model

SMASH: Simulating Many Accelerated Strongly-Interacting Hadrons

J. Weil *et al.*, Phys.Rev. C94 (2016) no.5, 054905

- Monte-Carlo solver of relativistic Boltzmann equations

BUU type approach, testparticles ansatz:  $N \rightarrow N \cdot N_{\text{test}}$ ,  $\sigma \rightarrow \sigma / N_{\text{test}}$

- Degrees of freedom

- ▶ most of established hadrons from PDG up to mass 3 GeV
- ▶ mesons: 44 non-strange mesons, 12 strange mesons
- ▶ baryons: 17 N, 8 Δ, 14 Λ, 10 Σ, 6 Ξ, 2 Ω
- ▶ strings via Pythia 8

- Interactions:  $2 \leftrightarrow 2$  and  $2 \rightarrow 1$  collisions, decays, potentials

- Initial conditions:

- ▶ “collider” - elementary or AA reactions,  $E_{\text{beam}} \gtrsim 0.5 A$  GeV
- ▶ “box” - infinite matter simulations

detailed balance tests, computing transport coefficients, thermodynamics of hadron gas

- ▶ “sphere” - expanding system

comparison to analytical solution of Boltzmann equation, Tindall *et al.*, Phys.Lett. B770 (2017) 532-538

- ▶ “list” - hadronic afterburner after hydrodynamics

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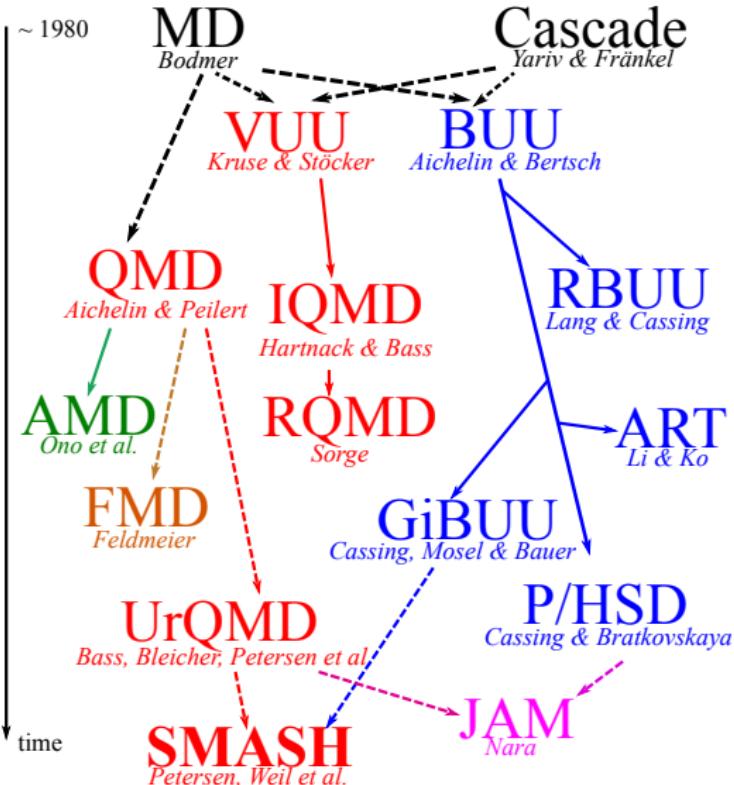
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# SMASH and its ancestors



- first C++ code in this historical chain
- written from scratch
- started coding in 2013
- under *git* version control from the very beginning

thanks to Steffen Bass

# Interactions in SMASH

- Resonance formation and decay

Ex.  $\pi\pi \rightarrow \rho \rightarrow \pi\pi$ , quasielastic scattering  
 $\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$

- (In-)elastic  $2 \rightarrow 2$  scattering

Ex.  $NN \rightarrow NN$ ,  $NN \rightarrow N\Delta$ ,  $NN \rightarrow \Delta\Delta$ ,  $KN \rightarrow \Lambda\pi$   
parametrized cross-sections  $\sigma(\sqrt{s}, t)$  or  
isospin-dependent matrix elements  $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

Via Pythia 8

- Potentials

only change equations of motion

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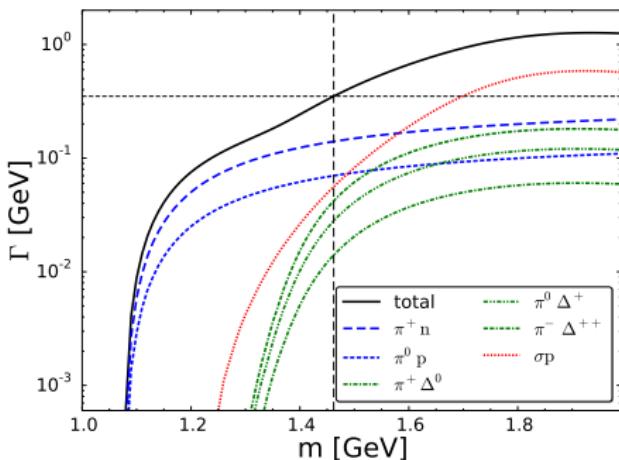
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$N(1440)^+$



For every resonance:

- Breit-Wigner spectral function  $\mathcal{A}(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - M_0^2)^2 + m^2 \Gamma(m)^2}$
- Mass dependent partial widths  $\Gamma_i(m)$

Manley formalism for off-shell width [Manley and Saleski, Phys. Rev. D 45, 4002 \(1992\)](#)  
Total width  $\Gamma(m) = \sum_i \Gamma_i(m)$

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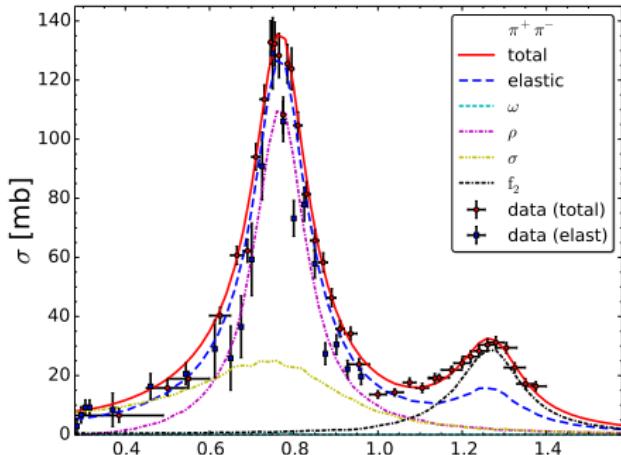
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- $2 \rightarrow 1$  cross-sections from detailed balance relations



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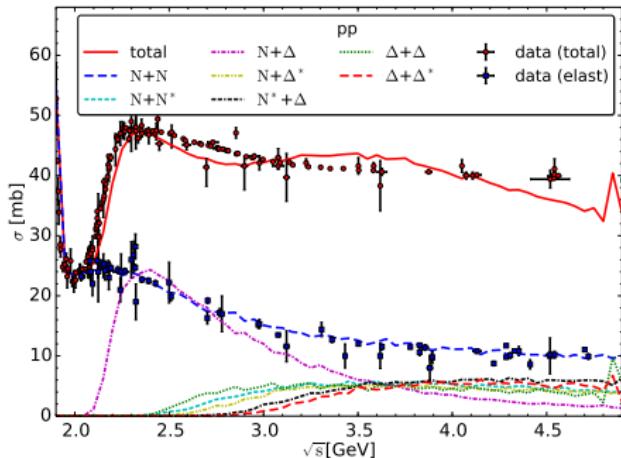
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only change equations of motion



- $NN \rightarrow NN^*$ ,  $NN \rightarrow N\Delta^*$ ,  $NN \rightarrow \Delta\Delta$ ,  $NN \rightarrow \Delta N^*$ ,  $NN \rightarrow \Delta\Delta^*$

angular dependencies of  $NN \rightarrow XX$  cross-sections implemented

- Strangeness exchange  $KN \rightarrow K\Delta$ ,  $KN \rightarrow \Lambda\pi$ ,  $KN \rightarrow \Sigma\pi$

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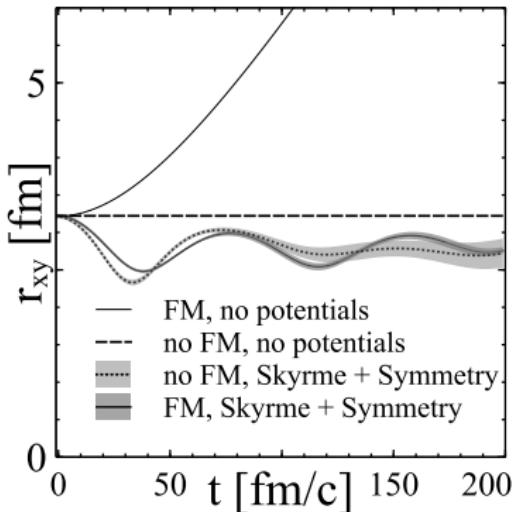
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Transverse radius of Cu nucleus.



- Skyrme and symmetry potential

$$U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}} \frac{\rho_{I3}}{\rho_0}$$

$\rho$  - Eckart rest frame baryon density

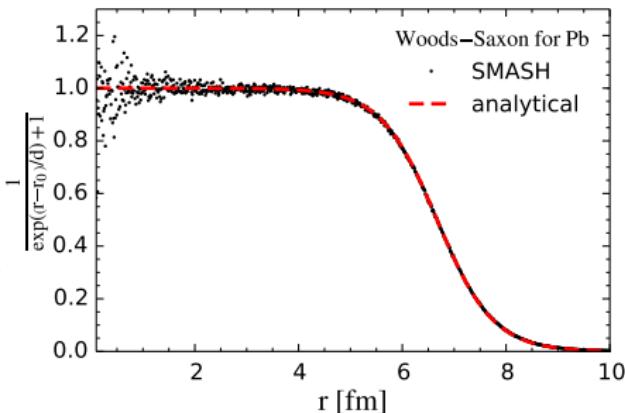
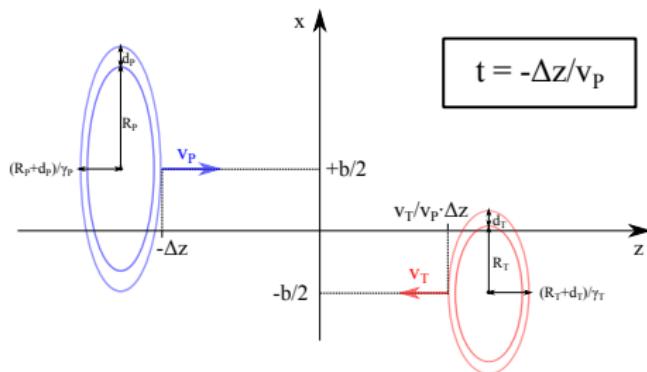
$\rho_{I3}$  - Eckart rest frame density of  $I_3/I$

$a = -209.2$  MeV,  $b = 156.4$  MeV,  $\tau = 1.35$ ,  $S_{\text{pot}} = 18$  MeV

corresponds to incompressibility  $K = 240$  MeV

assures stability of a nucleus with Fermi motion

# Nucleus collision

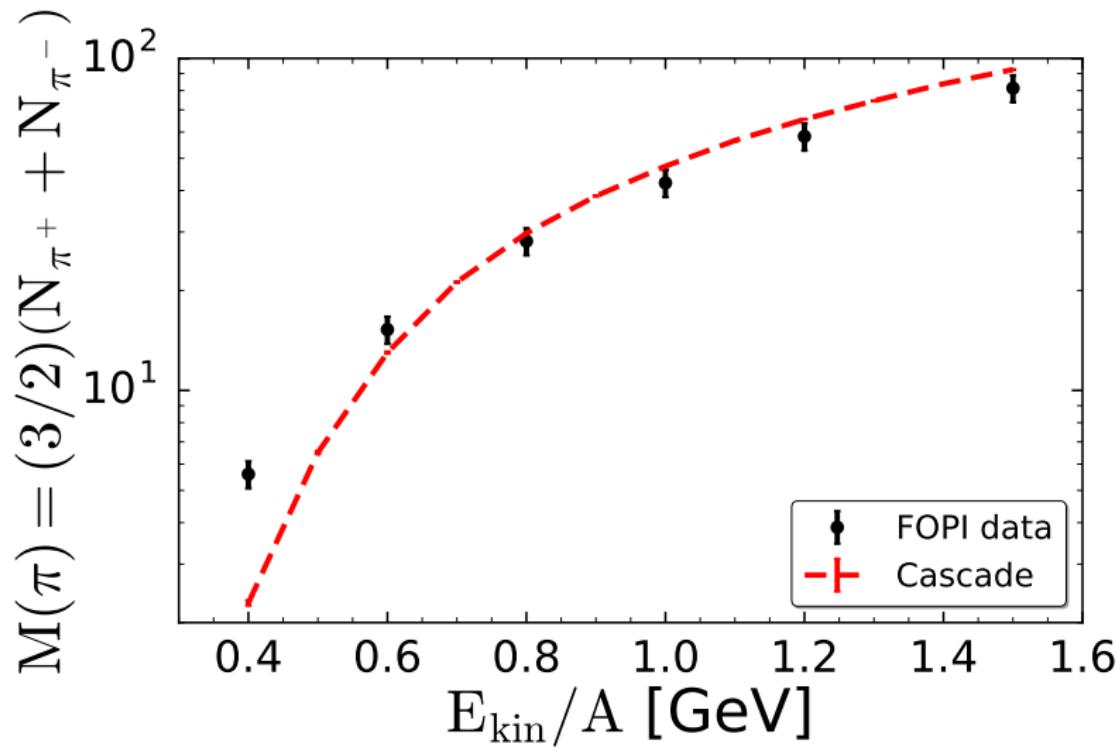


- Center of mass or fixed target frame
- Woods-Saxon distribution of nucleons  $\frac{dN}{d^3r} = \frac{\rho_0}{\exp\left(\frac{r-r_0}{d}\right)+1}$
- Nucleons are sampled independently  $\implies$  no correlations
- Deformed nuclei also possible

# FOPI pion multiplicities in central Au+Au with SMASH

FOPI - experiment in GSI, Darmstadt (Germany)

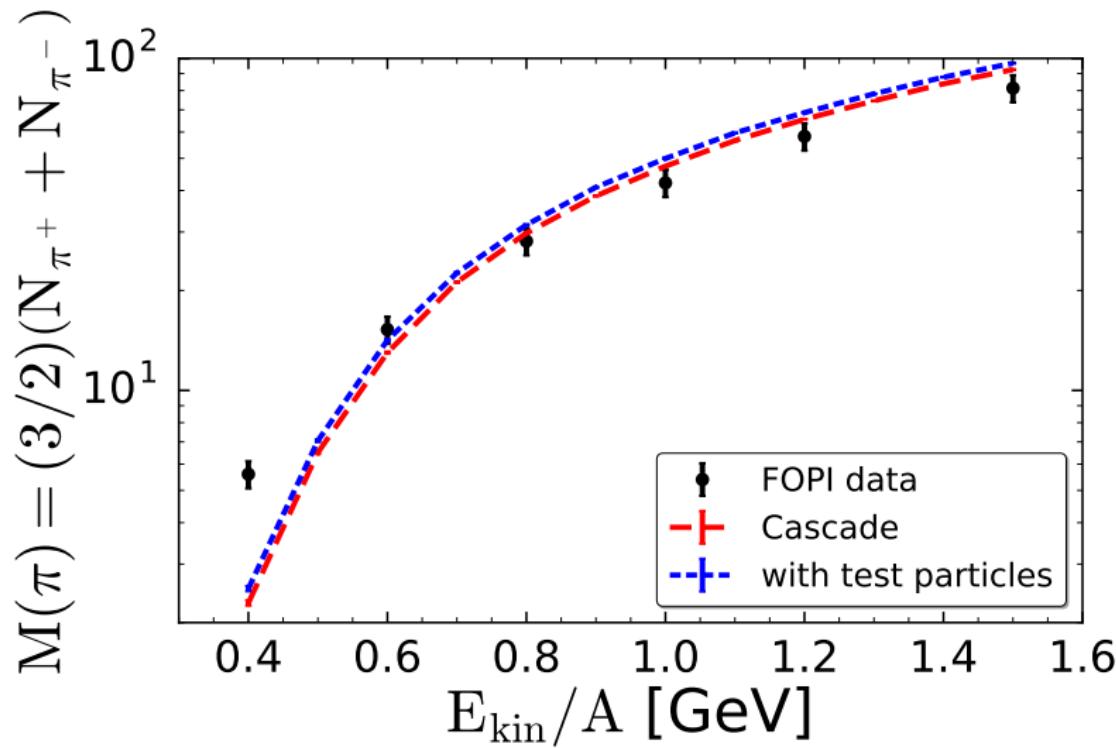
one of the goals - extracting parameters of nuclear matter potentials



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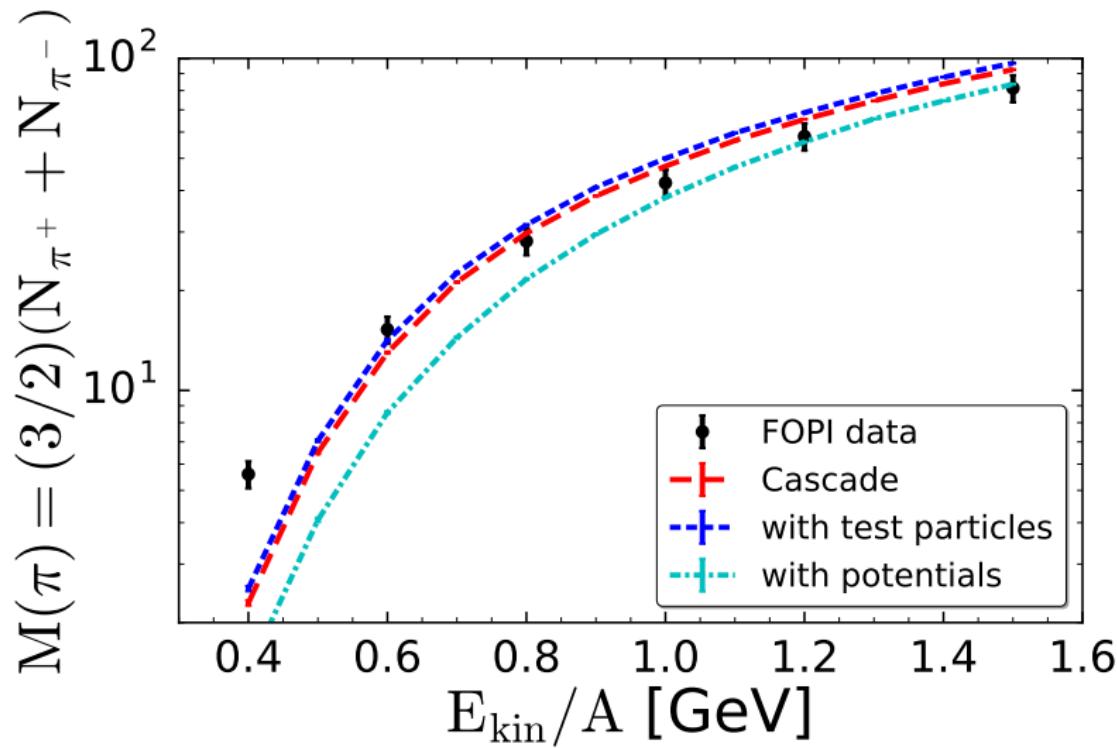
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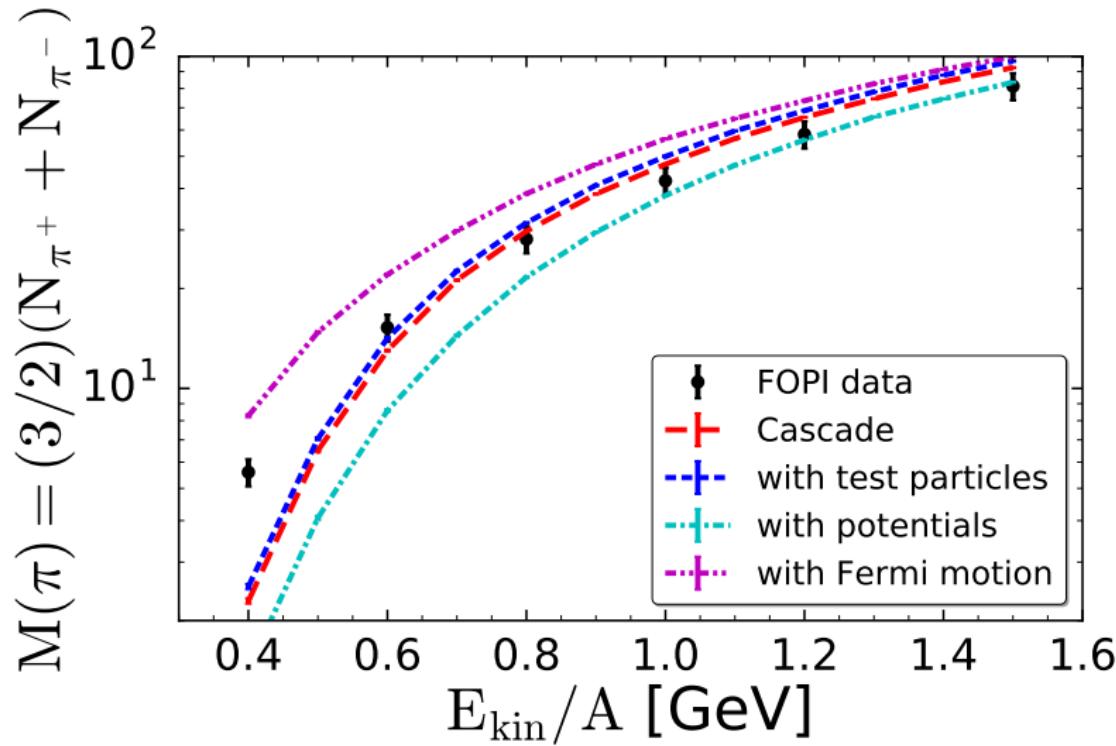
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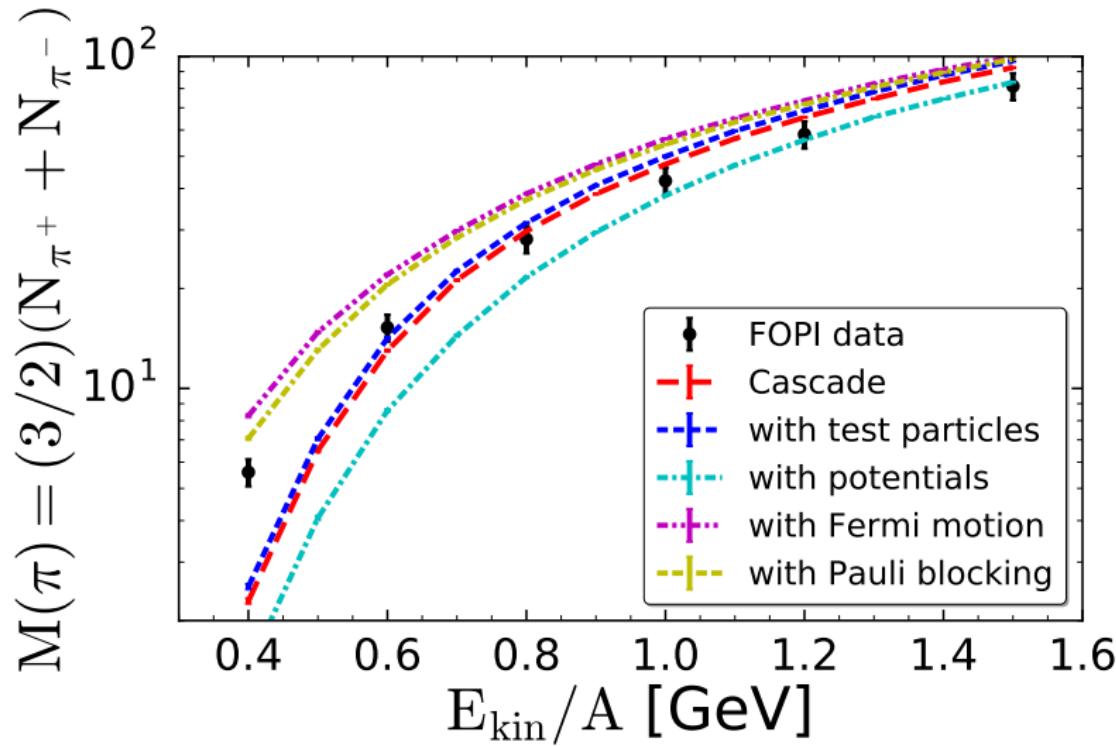
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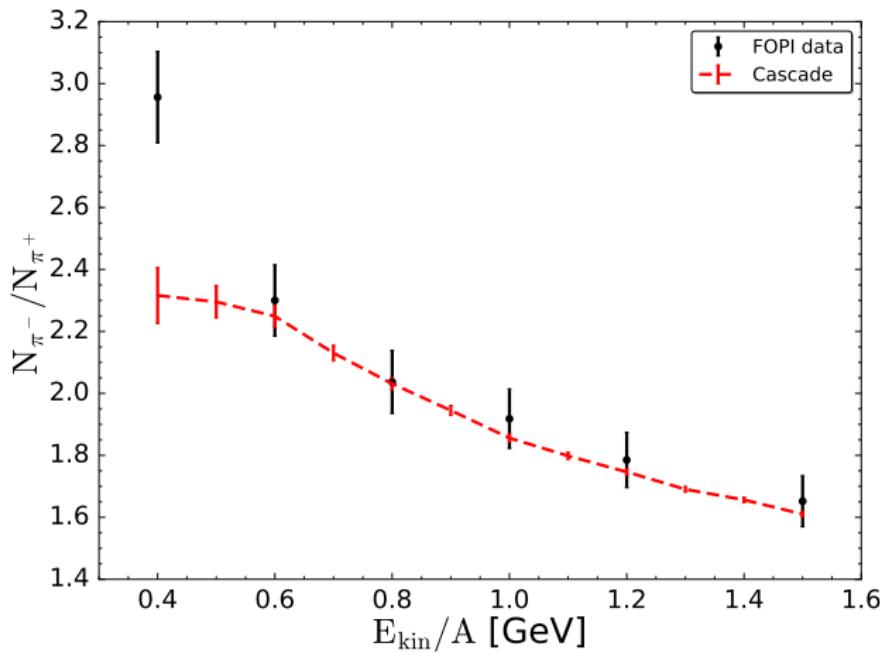


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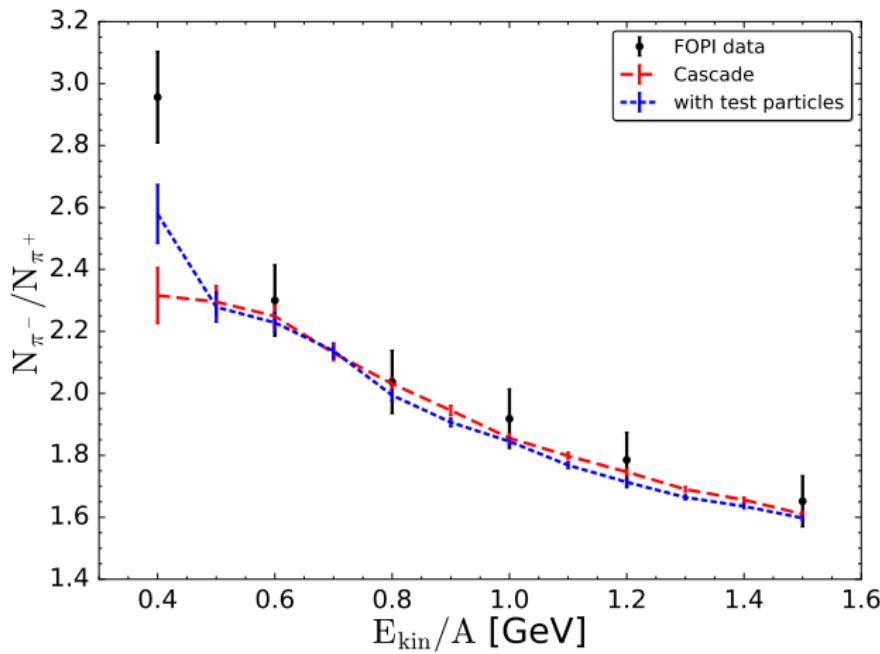


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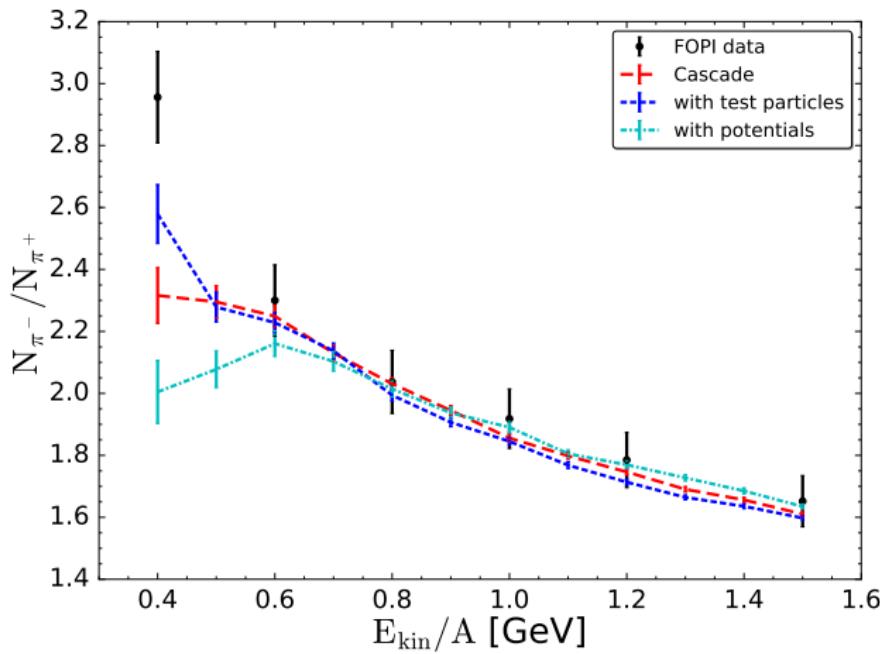


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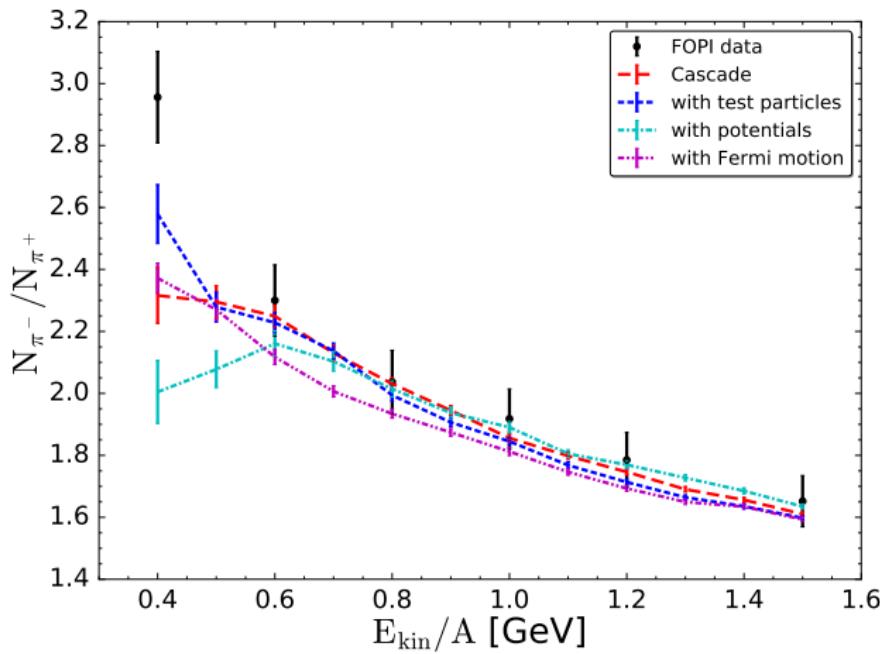


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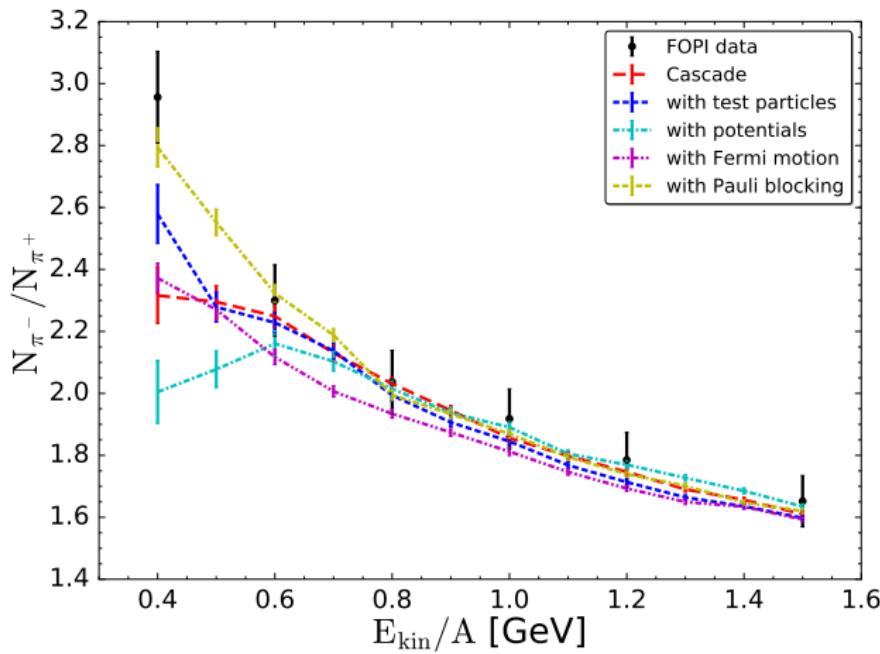


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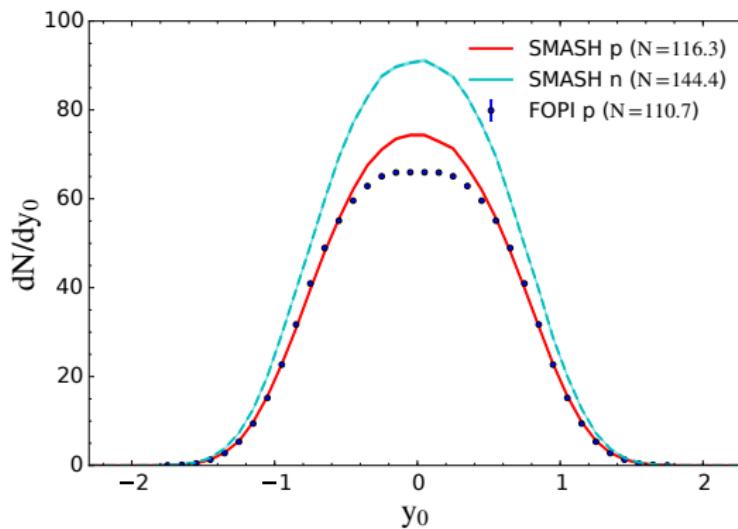
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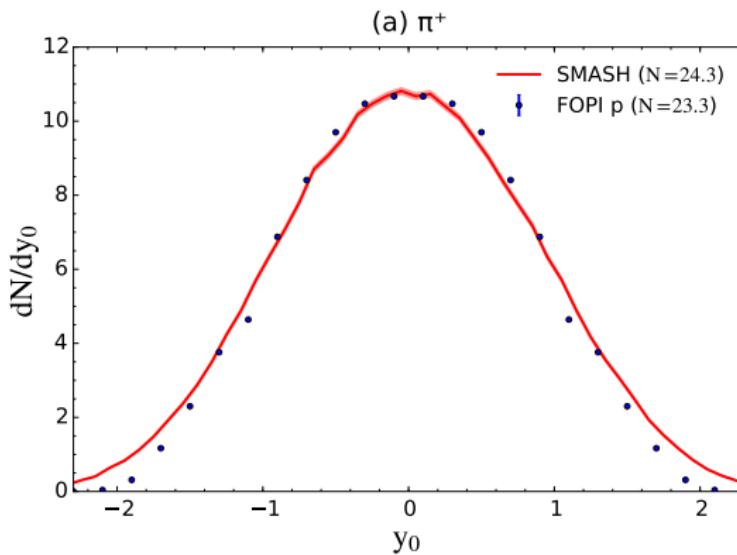
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- Centrality  $b_0 < 0.15$   
 $b_0 := \frac{b}{b_{\max}}, b_{\max} := 1.15 \text{ fm } (A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}})$
- Using  $ERAT := \frac{E_T}{E_L}$  variable for centrality selection
- Clustering afterburner to distinguish protons from light nuclei



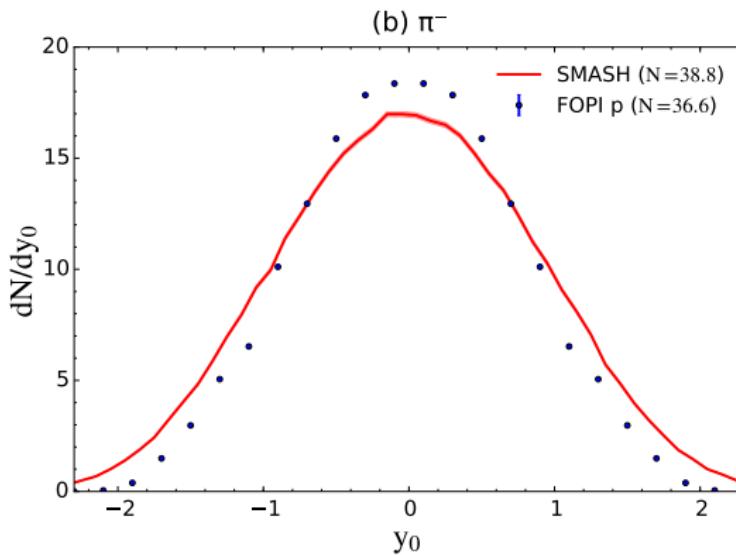
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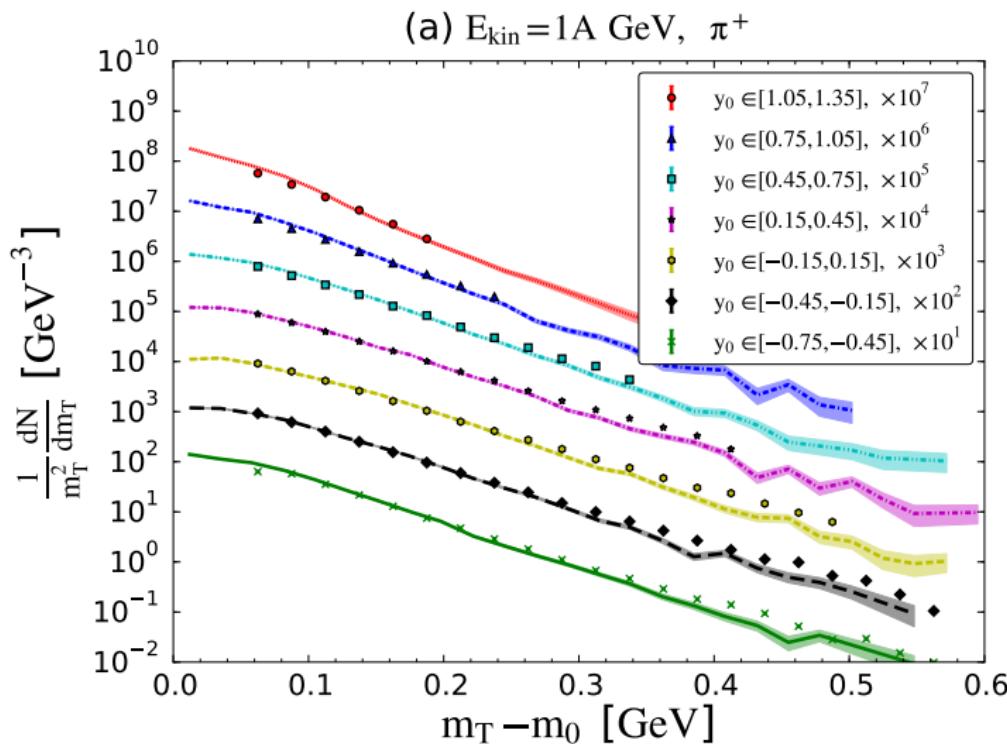
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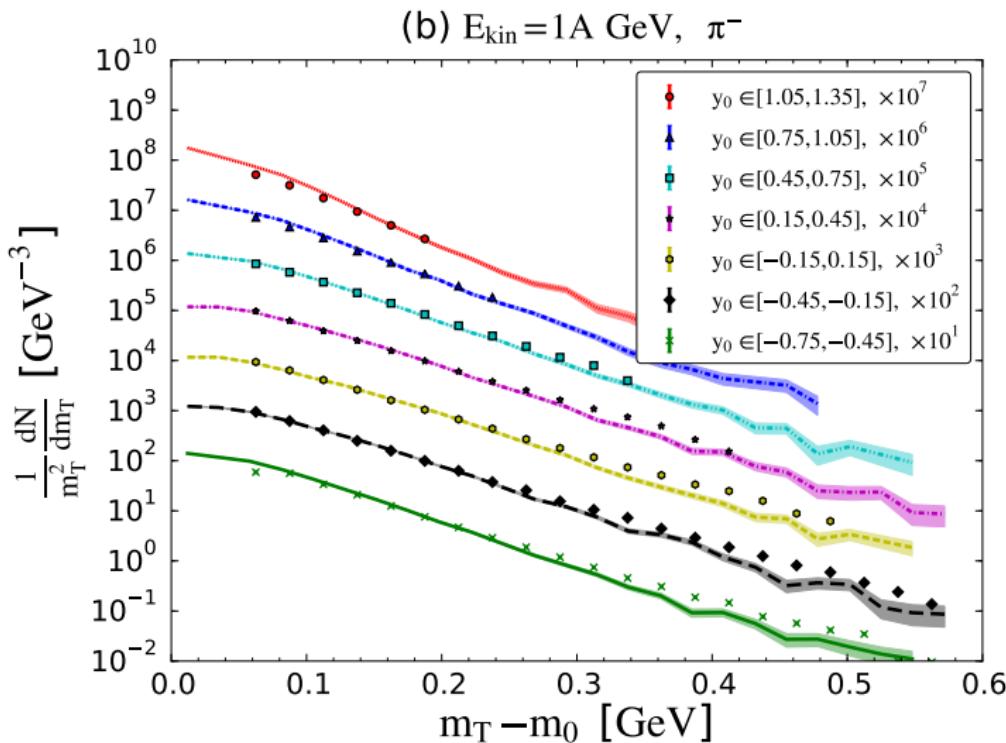
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HADES - experiment in GSI, Darmstadt (Germany), see talk by T. Galatyuk



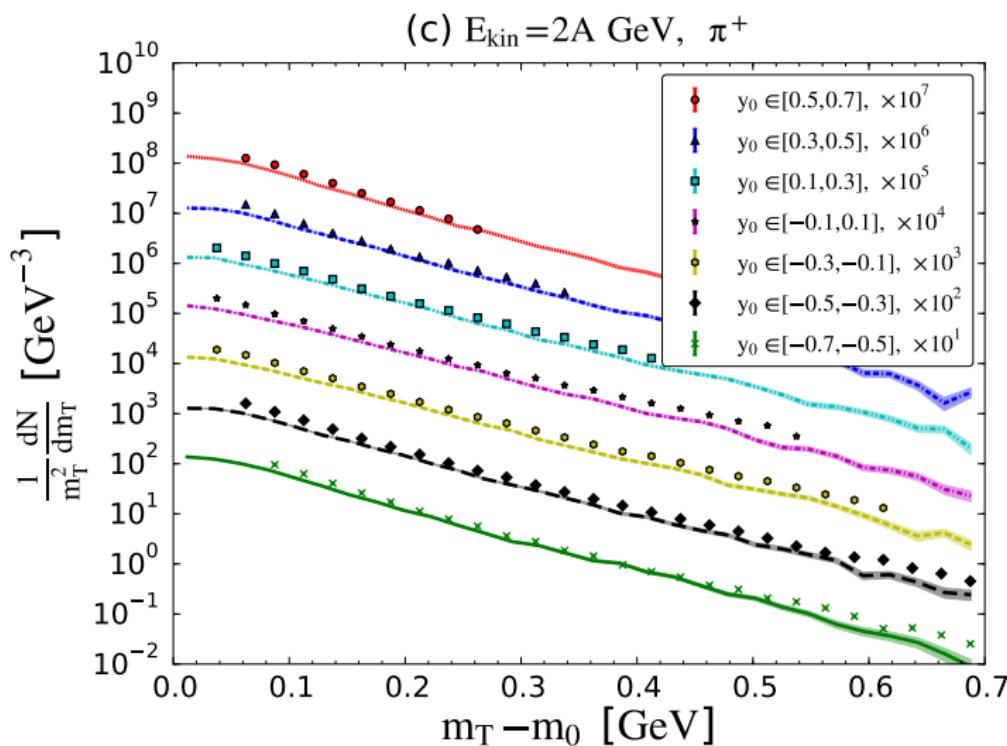
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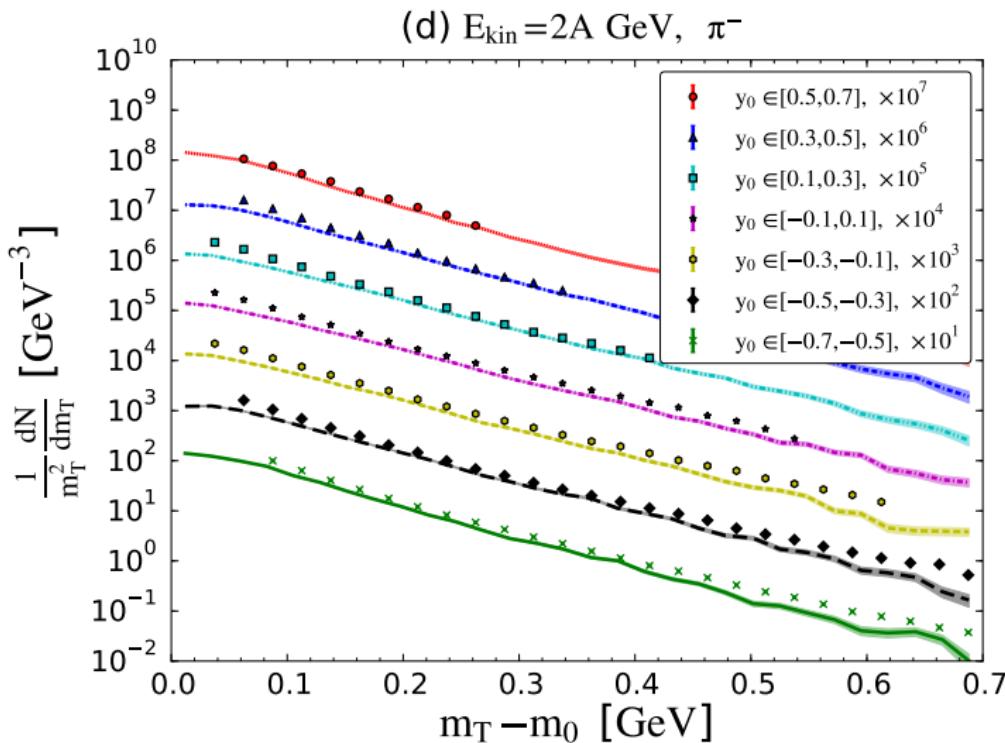
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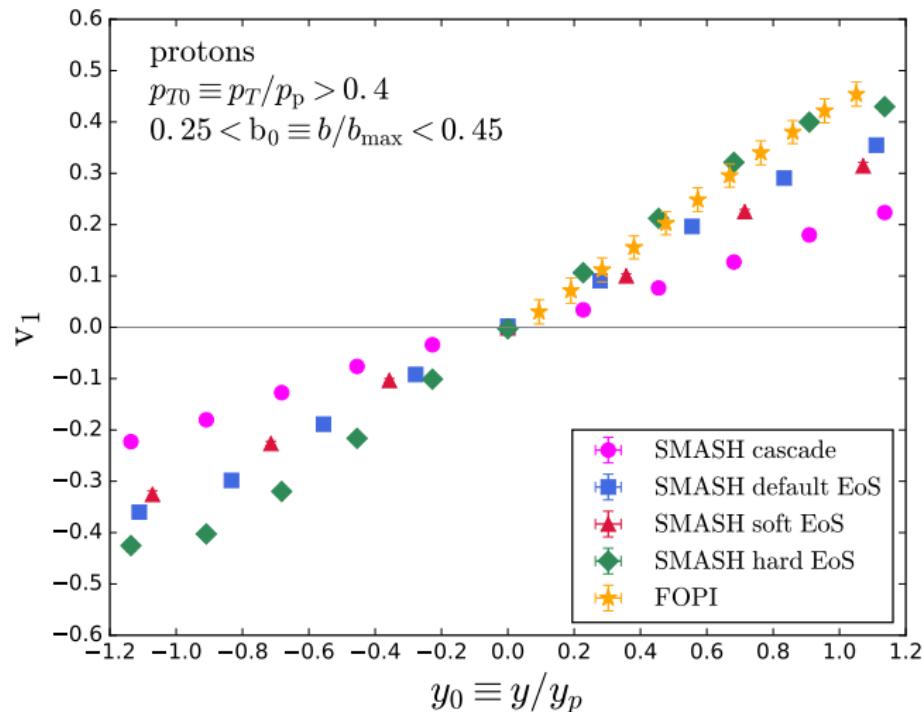


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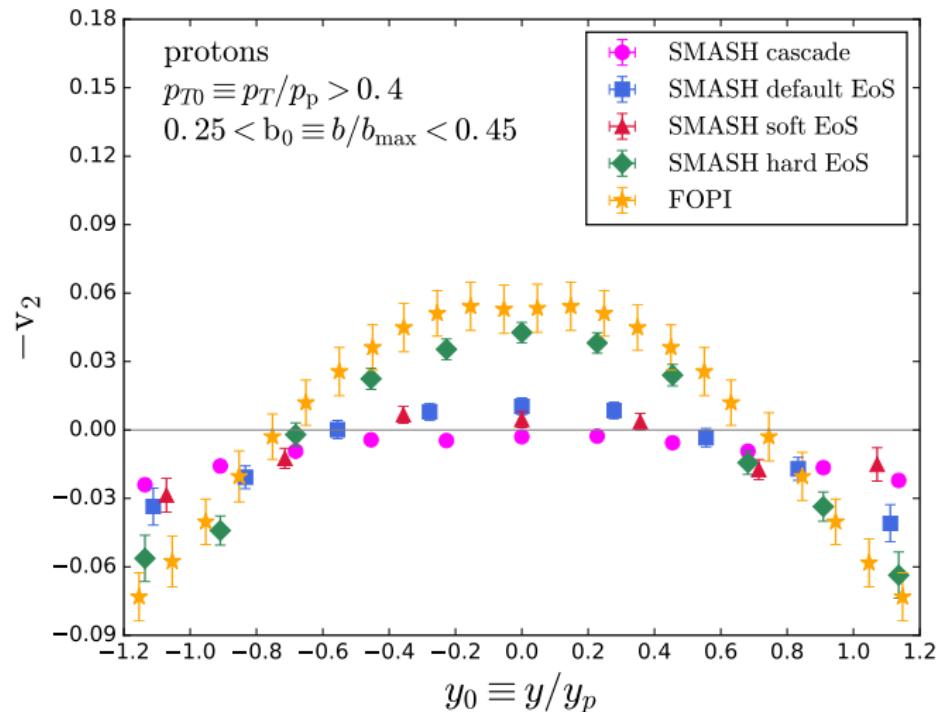


# FOPI Au+Au: flow at $E_{Kin} = 1.5 A$ GeV



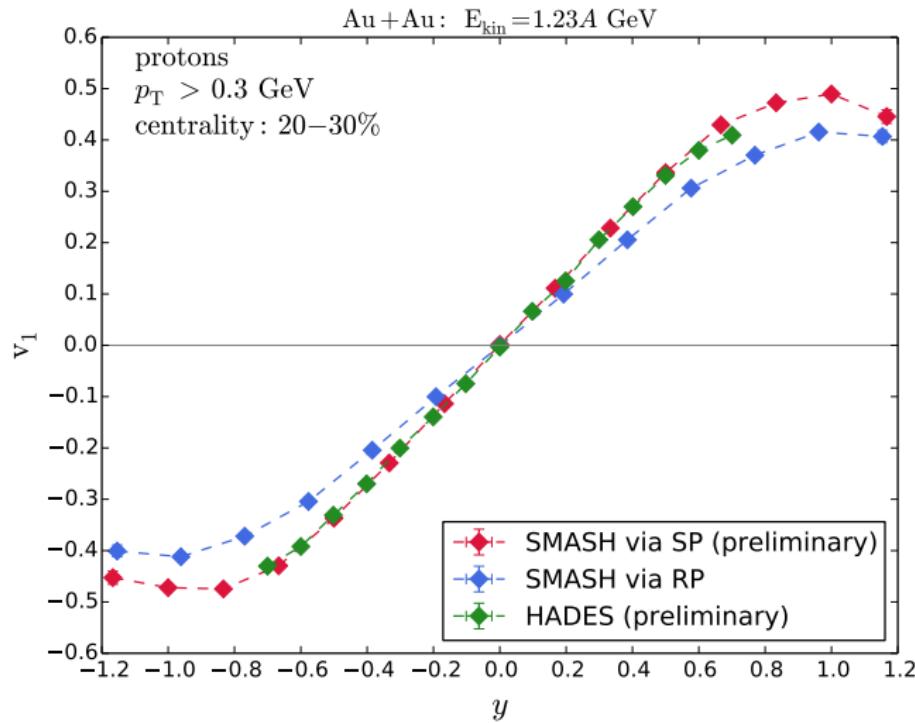
thanks to M. Mayer

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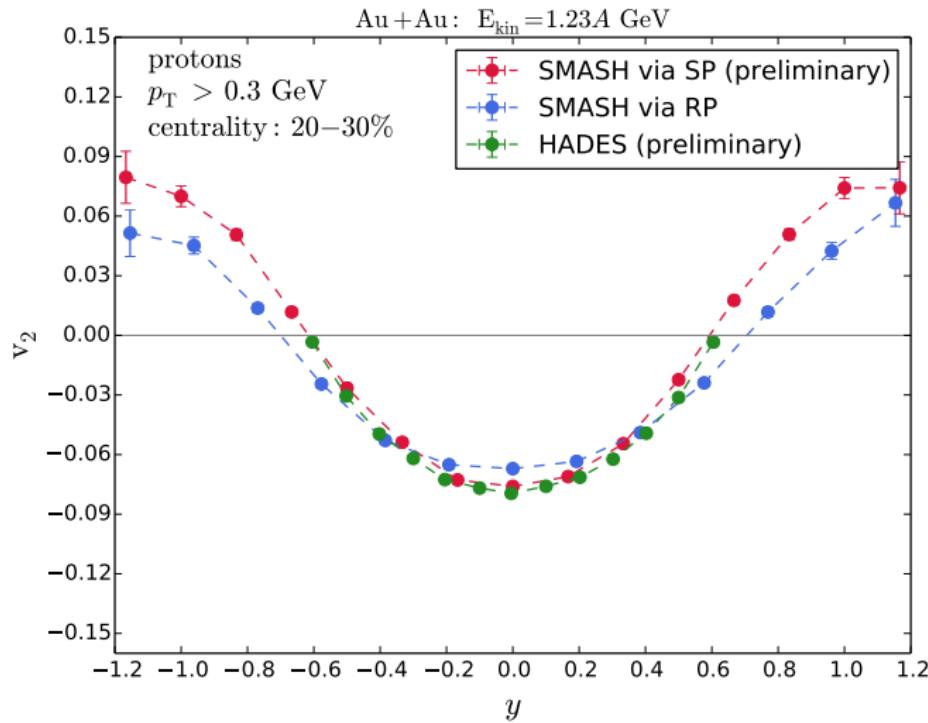
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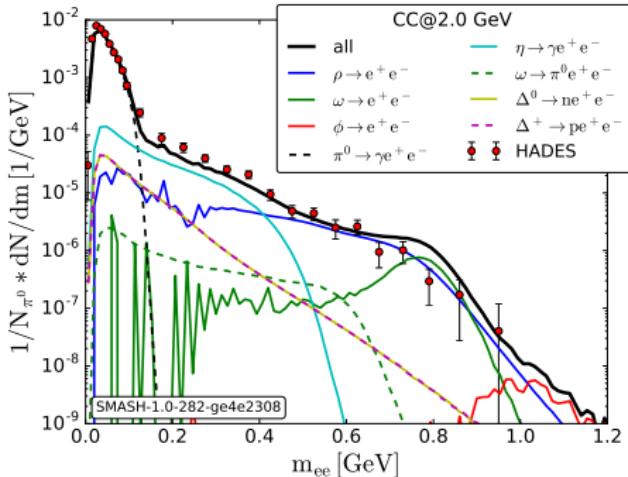
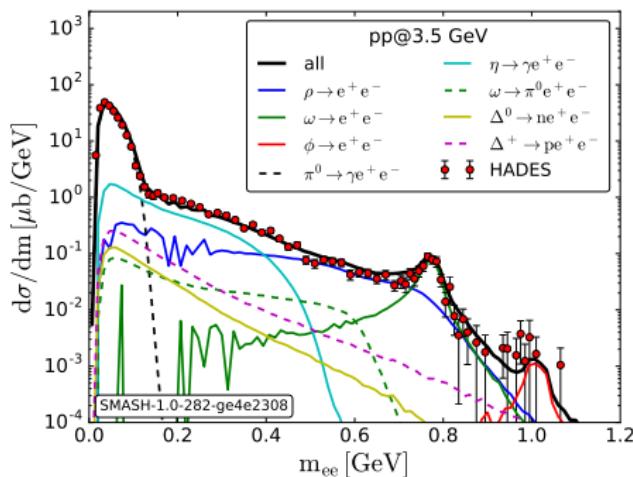


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# Dileptons with SMASH

HADES p+p 3.5 GeV and CC 2.0 GeV

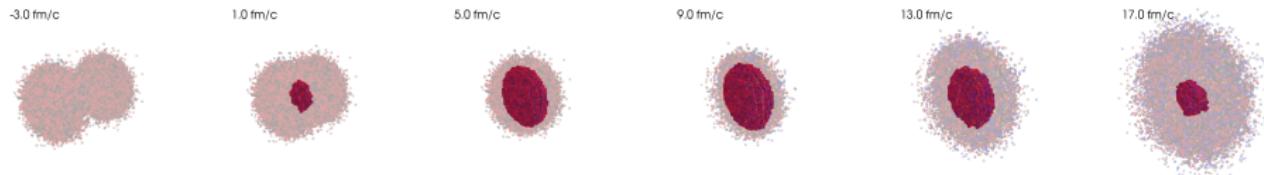
- Dilepton decays included into spectral functions of hadrons  
specifically SMASH feature
- Shining method  $\implies$  need less statistics



thanks to J. Staudenmaier

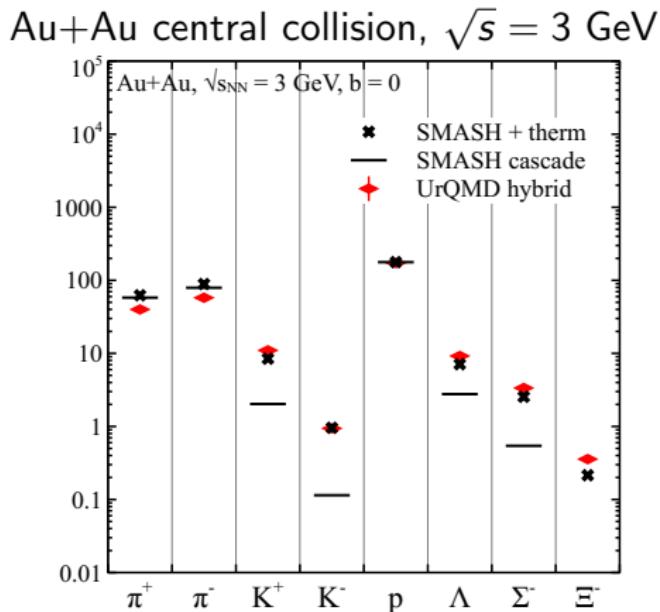
# Forced canonical thermalization

- Applicability of Boltzmann equation breaks at large density  
 $l_{mfp} \gg \lambda_{Compton}$  does not hold anymore
- Switching to hydrodynamics at high density?  
A possible and established way  
however has difficulties, especially at low collision energies  
DO, Petersen, Phys.Rev. C91 (2015) no.2, 024906
- Suggestion: local forced thermalization in the regions of high density  
Effectively simulates intensive interactions and/or formation of quark-gluon plasma  
DO, Petersen, J.Phys. G44 (2017) no.3, 034001



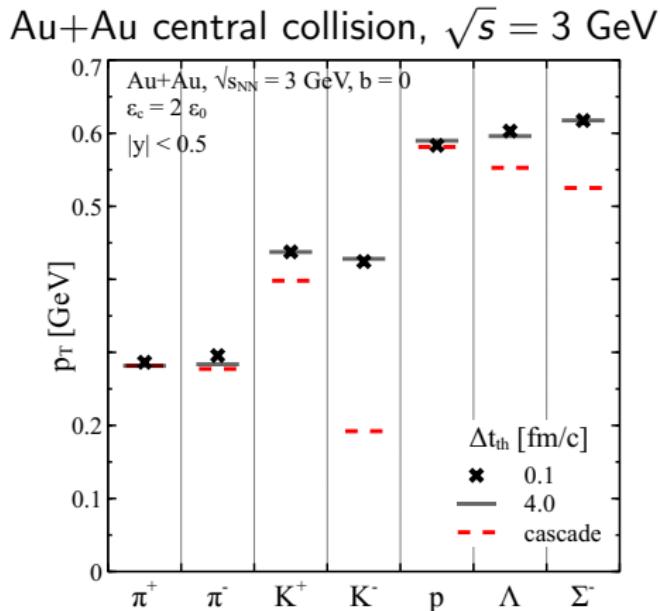
central Au+Au collision,  $E_{kin} = 2$  GeV,  $N_{test} = 100$ , purple region - thermalization region,  
energy density of switching  $0.3$  GeV/fm $^3$

# Effects of forced thermalization: multiplicities



Thermalization leads to strangeness enhancement - similarly to UrQMD hybrid

# Effects of forced thermalization: transverse momenta



Thermalization leads to pressure isotropization and transversve push

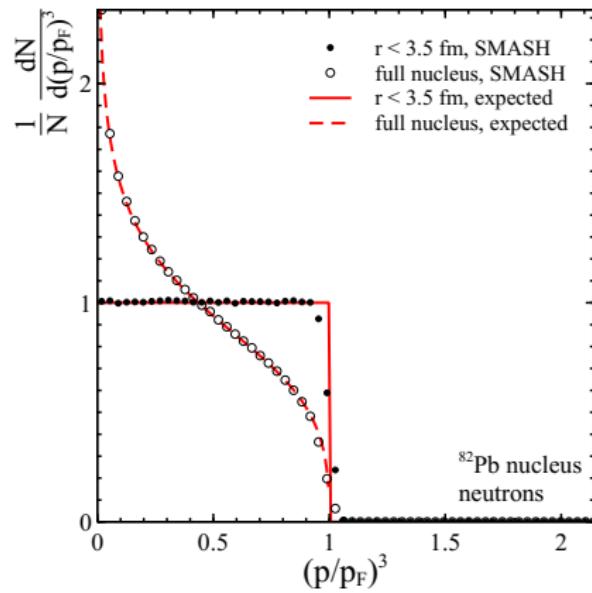
# Summary

- New C++ transport code SMASH is capable to describe heavy ion collisions at FAIR energies:
  - ▶ pion spectra
  - ▶ flows
  - ▶ dileptons
- $\frac{\pi^-}{\pi^+}$  in  $A + A$  at  $E_{Kin} = 0.4 A$  GeV is very sensitive to Fermi motion and Pauli blocking, not only potentials
- Forced thermalization is a perspective method to simulate high-density regime

# Thank you for your attention!

# Fermi motion

- Nucleons are fermions  $\implies$  Pauli blocking
- Filling Fermi-sphere in momentum space,  $p_F(\vec{r}) = \hbar c (3\pi^2 \rho(\vec{r}))^{1/3}$
- Sampling momenta  $p_i$  from Fermi-sphere in the nucleus rest frame
- Boost:  $p'_{iz} = \gamma(p_{iz} + \beta E_i) = \gamma p_{iz} + \frac{p_A}{M_A} \frac{M_A}{A} = p_{\text{beam}} + \gamma p_{iz}$



# Pauli blocking

- Boltzmann equation:

$$p^\mu \frac{\partial f}{\partial x^\mu} = \frac{1}{2} \int \frac{d^3 p_2}{E_2} \frac{d^3 p'_1}{E_1} \frac{d^3 p'_2}{E'_2} \times W(p_1, p_2 \rightarrow p'_1, p'_2) \\ \times (f'_1 f'_2 - f f_2)$$

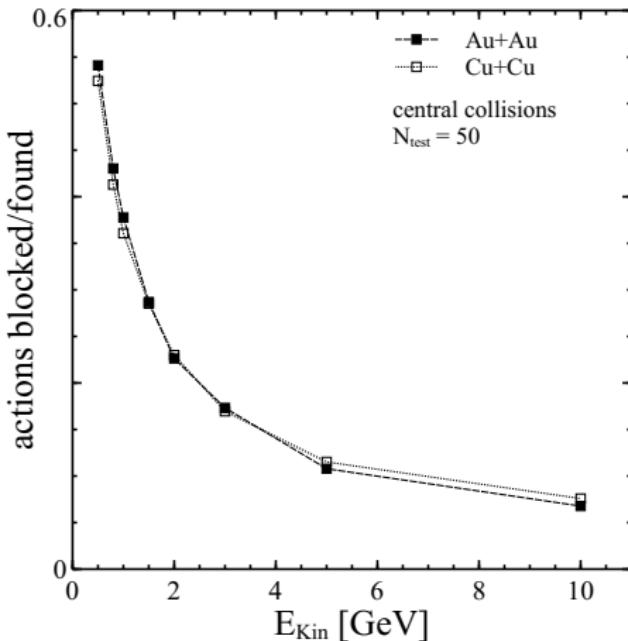
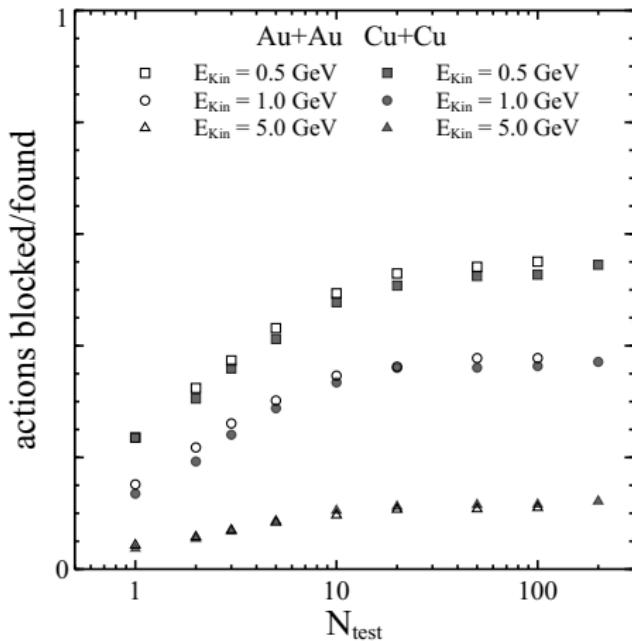
- Boltzmann-Uehling-Uhlenbeck equation

$$p^\mu \frac{\partial f}{\partial x^\mu} = \frac{1}{2} \int \frac{d^3 p_2}{E_2} \frac{d^3 p'_1}{E_1} \frac{d^3 p'_2}{E'_2} \times W(p_1, p_2 \rightarrow p'_1, p'_2) \\ \times (f'_1 f'_2 (1 \pm f)(1 \pm f_2) - f f_2 (1 \pm f'_1)(1 \pm f'_2))$$

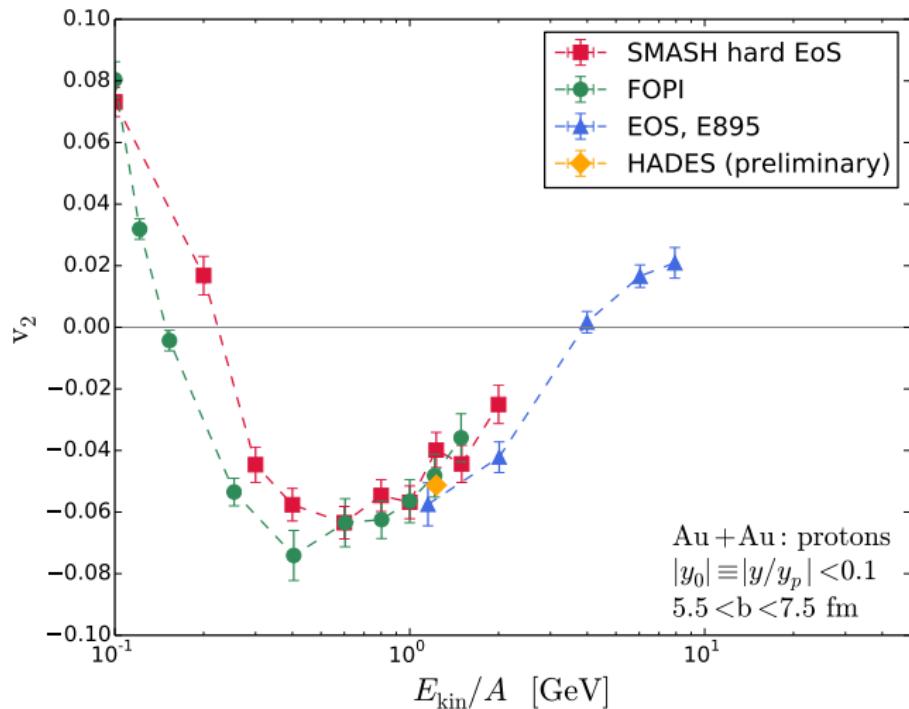
- $(1 - f)$  as a multiplicative factor to cross-section
- Reject reactions with probability  $1 - \prod_i (1 - f_i)$ 
  - ▶ Product over all fermions in final state
  - ▶  $f_i$  - phase-space density at fermion position

# Pauli blocking II

- Computing phase-space density requires statistics  $\implies$  large  $N_{\text{test}}$
- At large energies Pauli blocking is not important



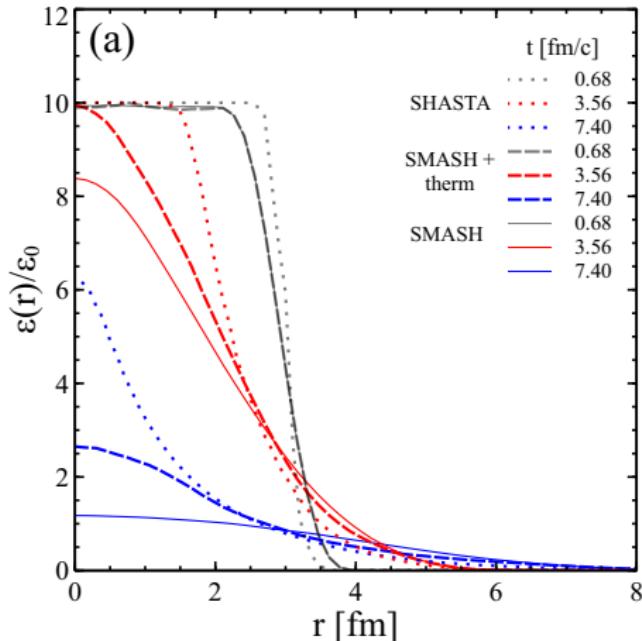
# Integrated elliptic flow



thanks to M. Mayer

# Forced thermalization: expanding sphere setup

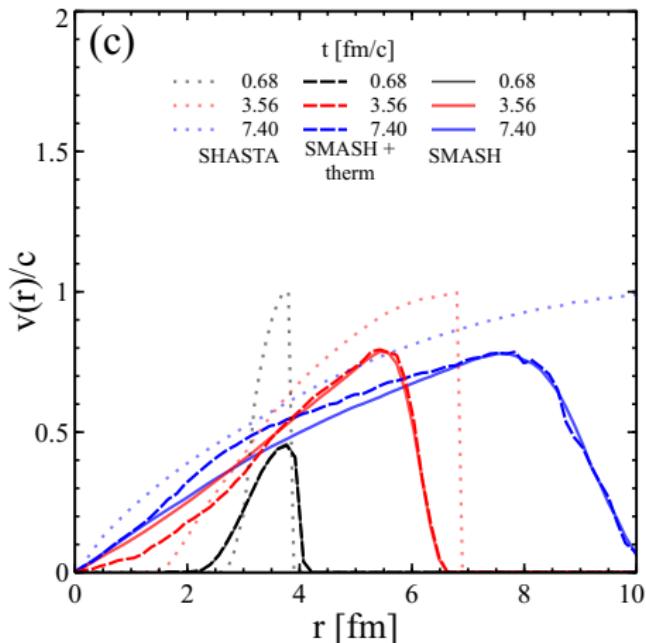
Evolution of  $R = 3$  fm sphere, initial  $\epsilon = 10\epsilon_0$ ,  $n_B = 0$ .  
Thermalization at  $\epsilon > 2\epsilon_0$  every  $\Delta t_{th} = 1$  fm.



SMASH + thermalization is between transport and hydro

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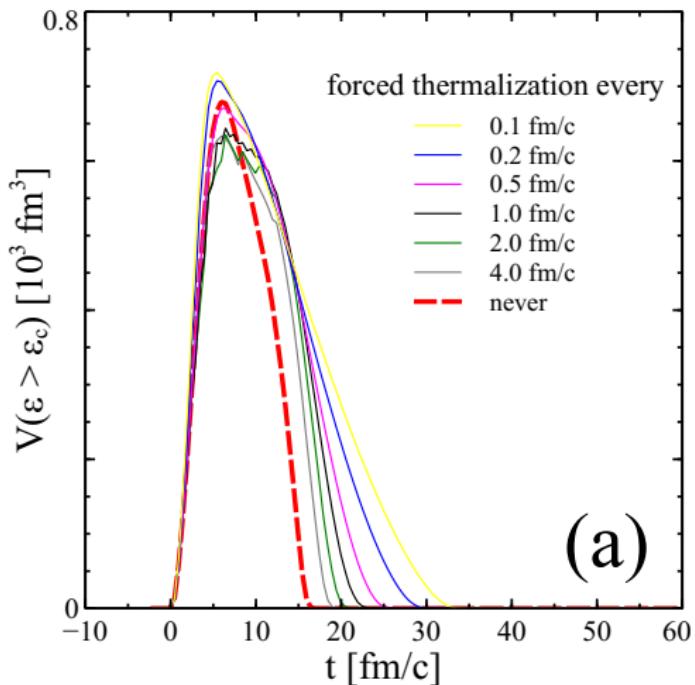
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# Effects of forced thermalization

Au+Au central collision,  $\sqrt{s} = 3 \text{ GeV}$ ,  $\epsilon_c = 2\epsilon_0$



High-density region exists longer

# $\langle T \rangle$ and $\langle \mu_B \rangle$ in the thermalization region

