SMASH: Status and Results

Hannah Elfner

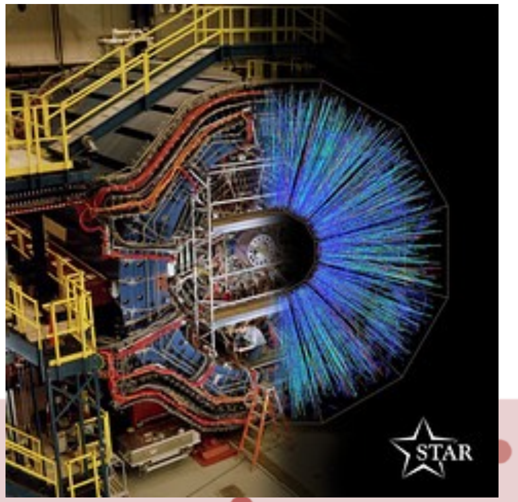
September 22nd, 2020, Beijing Seminar Series

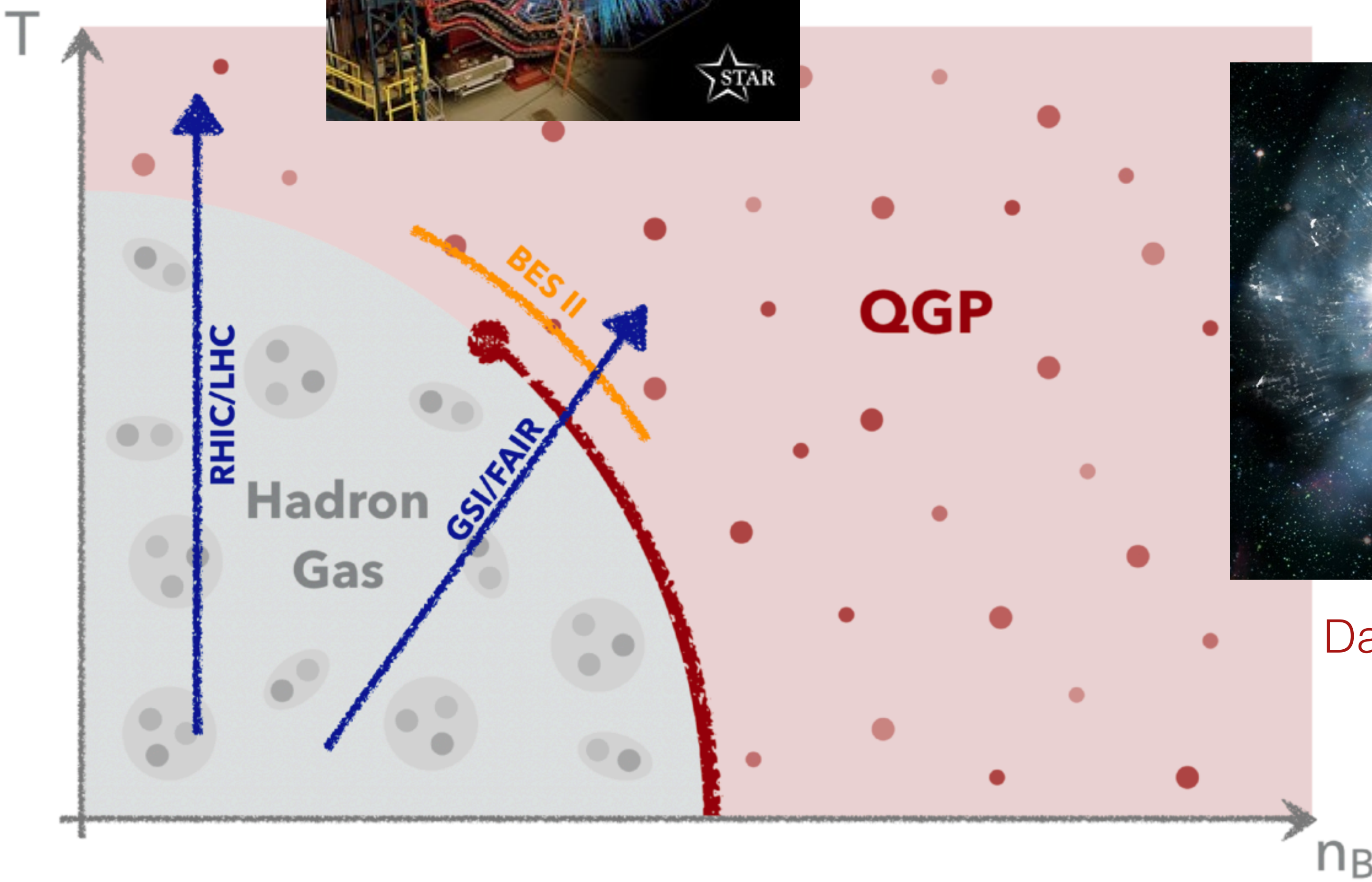
Introduction

The QCD Phase Diagram

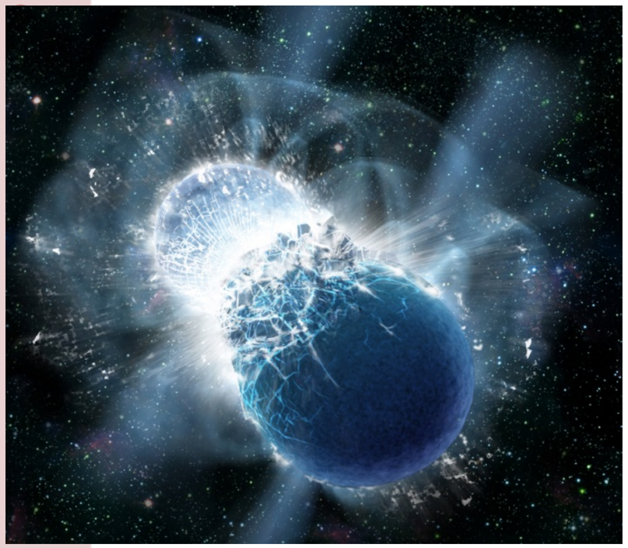
- **Main goals** of heavy-ion research:

STAR experiment at RHIC





- What are the relevant degrees of freedom at high densities?
- Phase transition, critical endpoint?
- Properties of neutron star mergers?

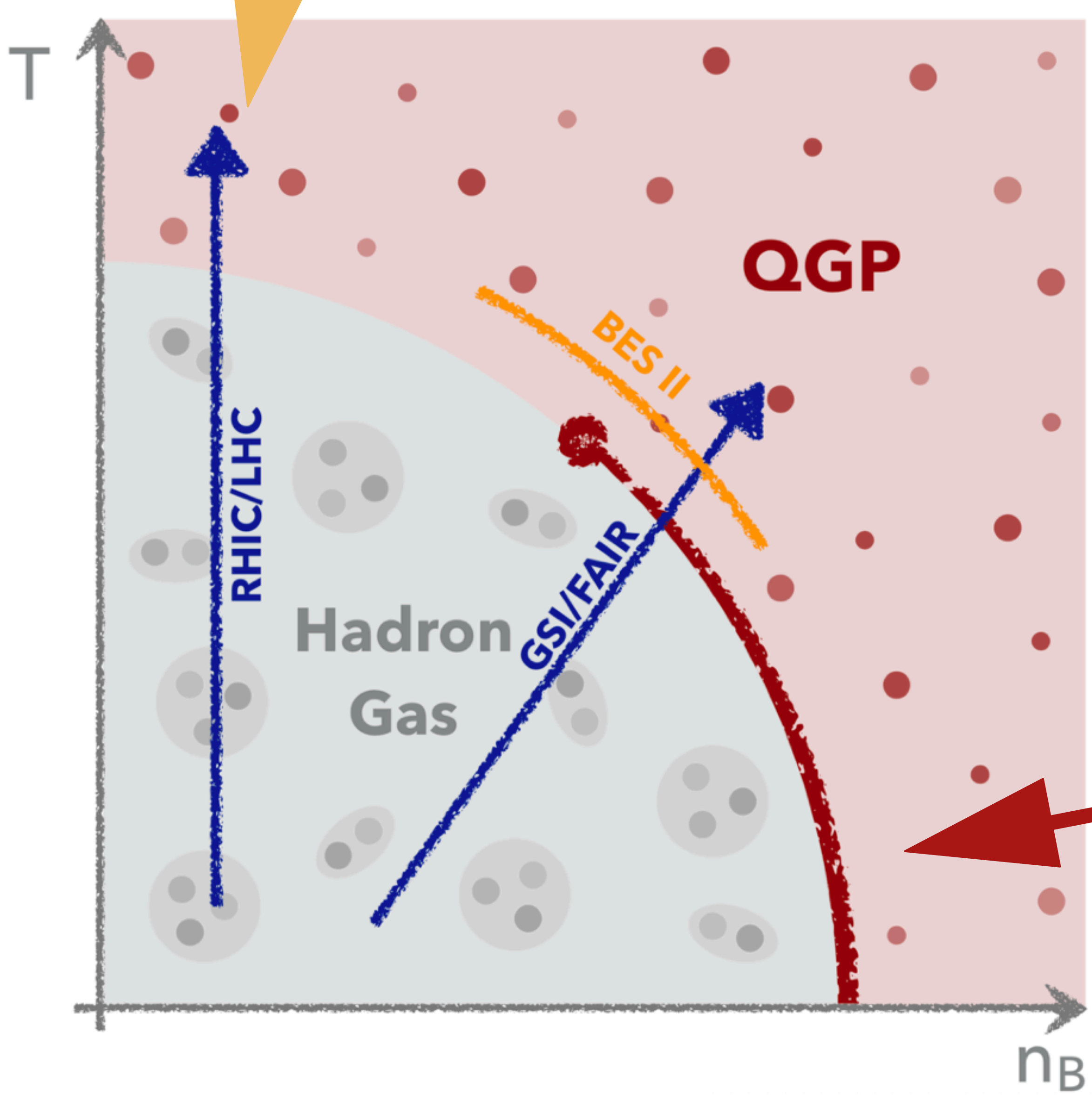


Dana Berry, SkyWorks Digital, Inc

Relevant for neutron star mergers as detected by gravitational waves (GW170817)

Dynamical Modeling

Standard approach at high energies
- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic rescattering



- ***Status***: Two regimes with well-established approaches
- Goals:
  - Constraint on the equation of state of nuclear matter
  - Determine limit of applicability of hadronic transport approach
  - Predict qualitative signatures of first order phase transition

Standard approach at low beam energies
- Hadronic transport approaches
- Resonance dynamics
- Nuclear potentials

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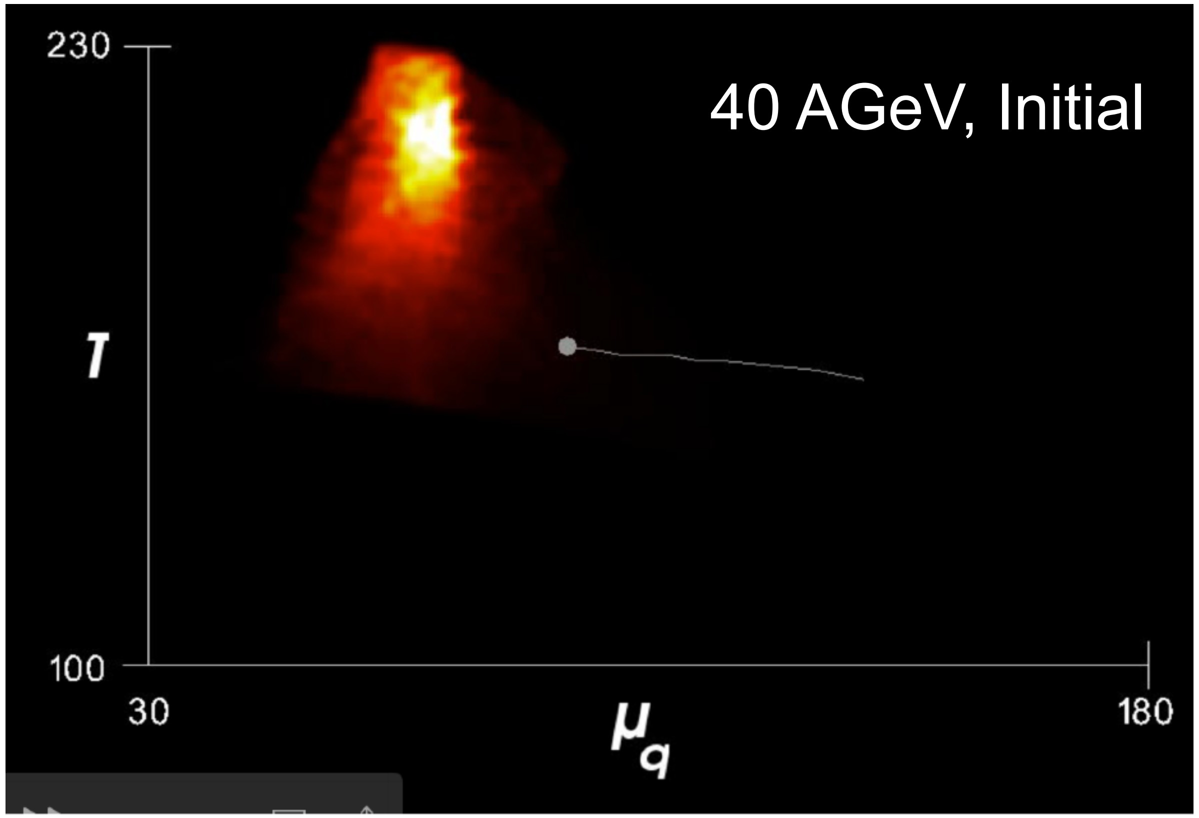
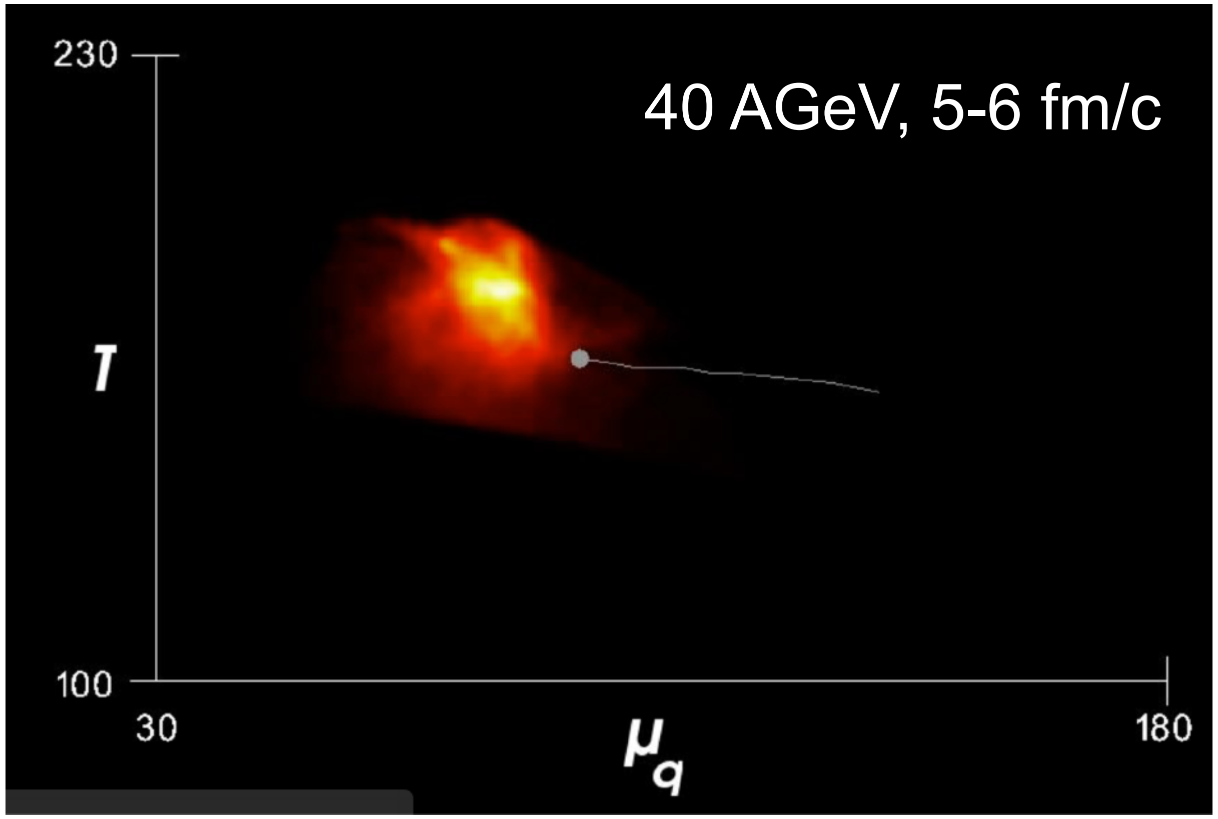
Finite System Size

- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables

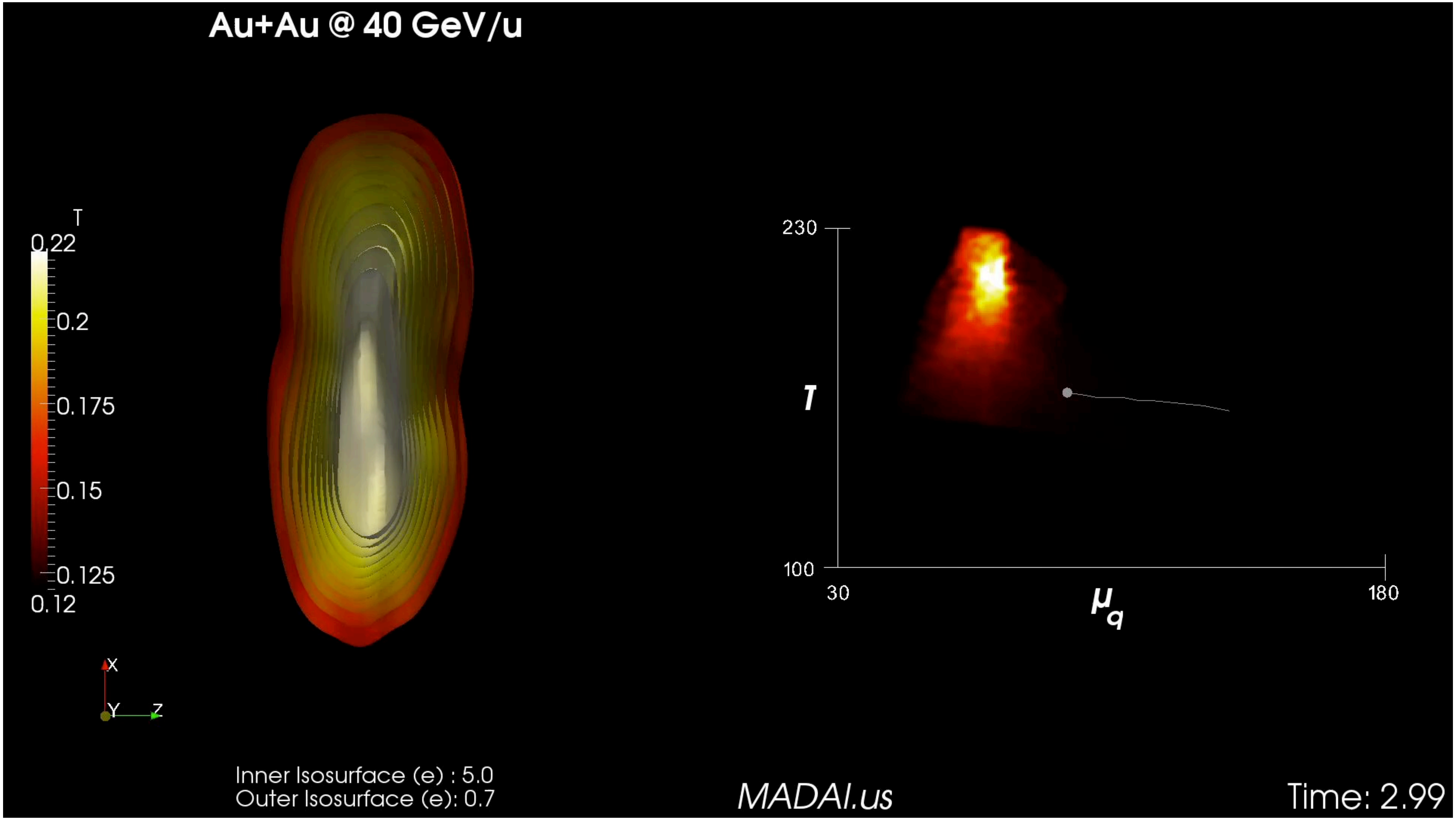




S. Bass et al, arXiv:1202.0076, CPOD 2011

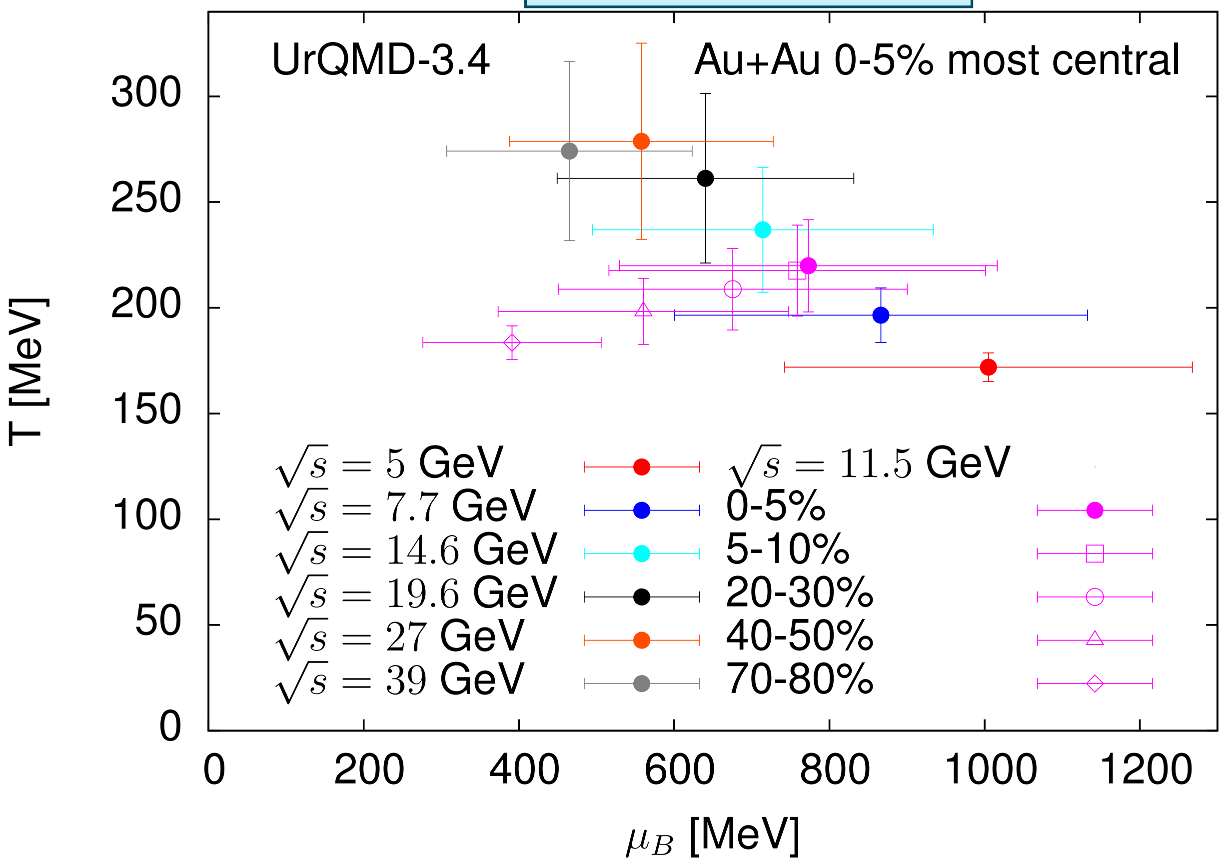
- Detailed dynamical modeling is required:
  - EoS and transport coefficients in the whole phase diagram
  - Non-equilibrium dynamics at the phase transition

Time Evolution in Phase Diagram

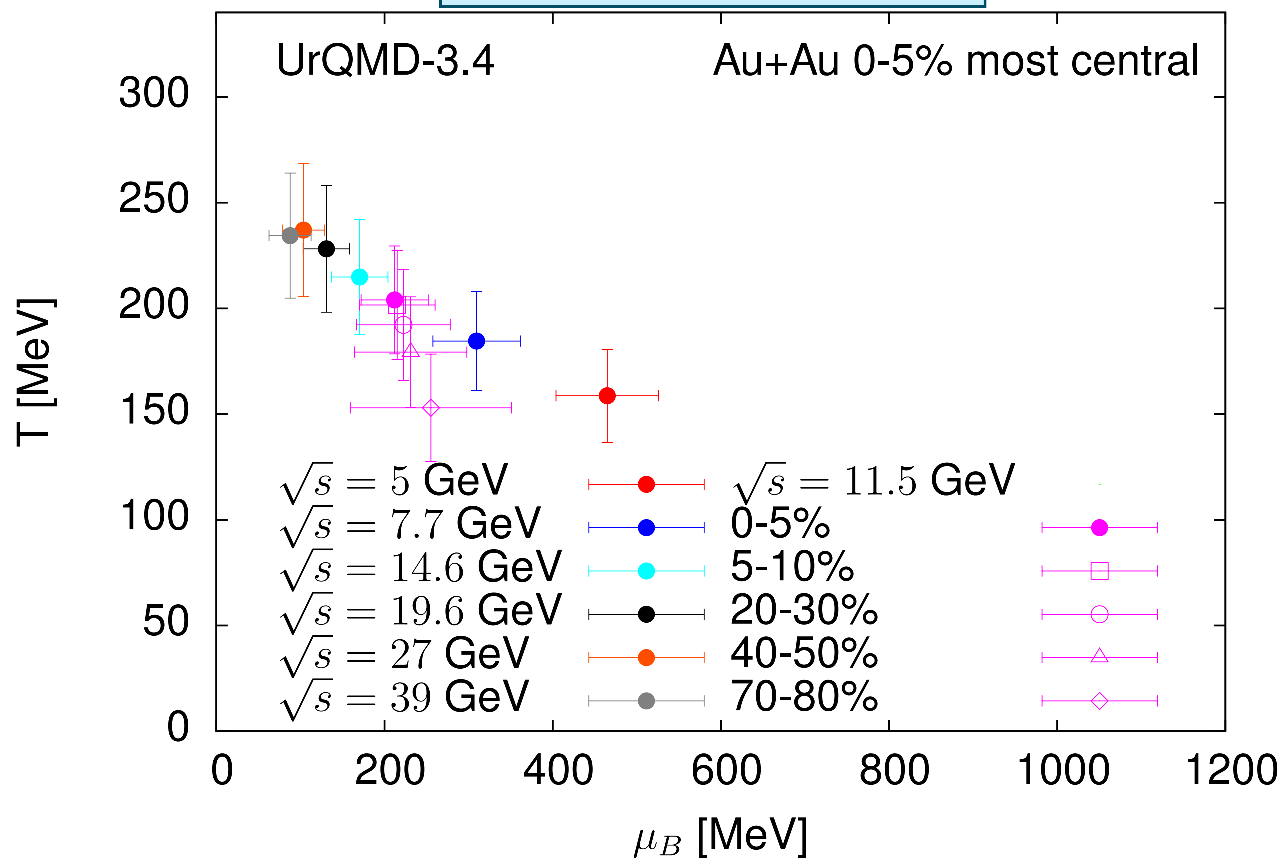


Experimental Access to Phase Diagram

Chiral EoS



Hadron Gas EoS



G. Gräf, J. Steinheimer, UrQMD-3.4 on urqmd.org

- Event-by-event fluctuations negligible, but sizable spread in **single** events ➞ Different centralities increase spanned regions
- Absolute values are highly dependent on the Equation of State/ degrees of freedom
- Scan in rapidity windows might allow to divide spacing even more

FAIR Construction Site

- FAIR construction is in progress on GSI campus

May 2020, SIS-100 tunnel,
GSI Helmholtzzentrum für Schwerionenforschung, D. Fehrenz/GSI/FAIR

Visualization of FAIR,
GSI Helmholtzzentrum für Schwerionenforschung, ion42

- High luminosity at beam energies up to Au+Au at 11A GeV

Outline

- Motivation and introduction
- New hadronic transport approach
  - SMASH ingredients and validation
  - Particle production at SIS-18
  - Baryon stopping and hybrid approach
  - Electromagnetic probes
- Transport coefficients
  - Shear viscosity and lifetimes
  - Bulk viscosity and slow modes
  - Cross-conductivities and degrees of freedom
- Next steps and outlook

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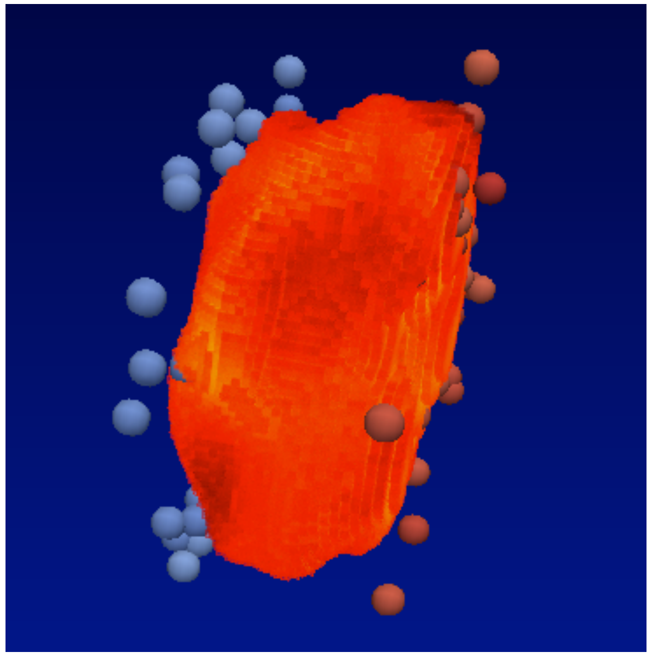
SMASH
A Hadron Transport Approach

Why a new Approach?

- Hadronic transport approaches are successfully applied for the dynamical evolution of heavy ion collisions
- Hadronic non-equilibrium dynamics is crucial for
  - Full/partial evolution at low/ intermediate beam energies
  - Late stage rescattering at high beam energies (RHIC/LHC)



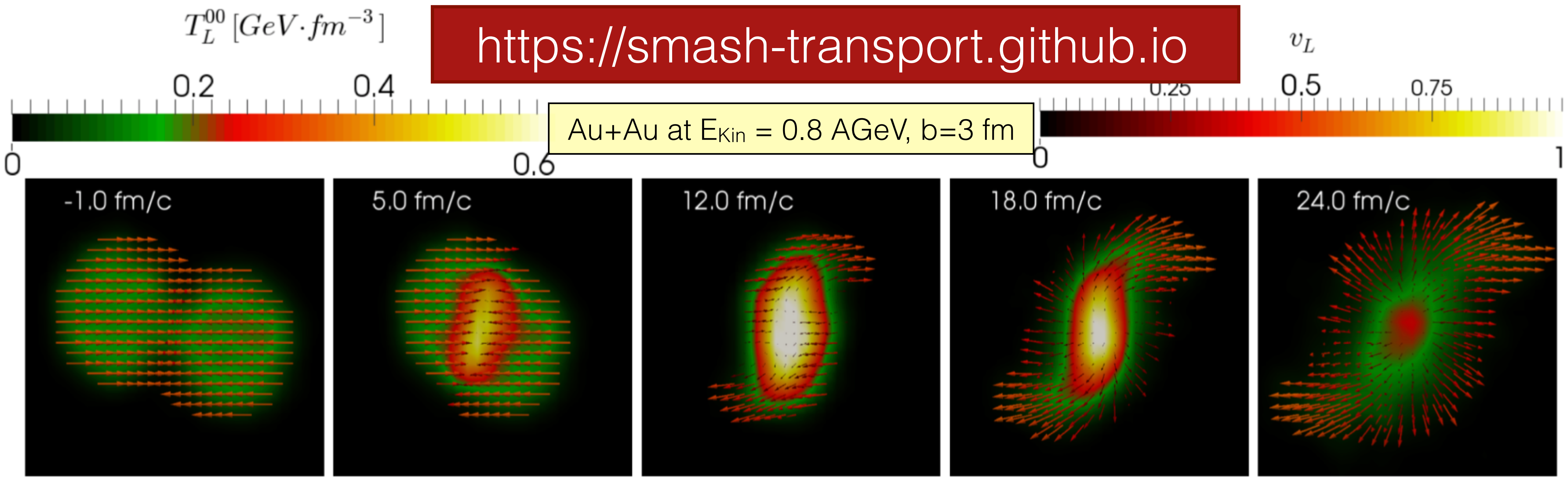
- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, (ROOT)

https://smash-transport.github.io



* Simulating Many Accelerated Strongly-Interacting Hadrons

The SMASH Team

- In Frankfurt:
  - Oscar Garcia-Montero
  - Vinzent Steinberg
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Jan Hammelmann
  - Damjan Mitrovic
  - Natey Kübler
  - Philip Karan
  - Martha Ege
  - Jannis Gebhard
- In US/China:
  - Dmytro Oliinychenko
  - Agnieszka Wergieluk
  - Xiang-Yu Wu

Group excursion in September 2020

General Setup

- Transport models provide an effective solution of the relativistic Boltzmann equation

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

- Particles represented by Gaussian wave packets for density calculations
- Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}$$

$$d_{\text{trans}}^2 = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

As in UrQMD

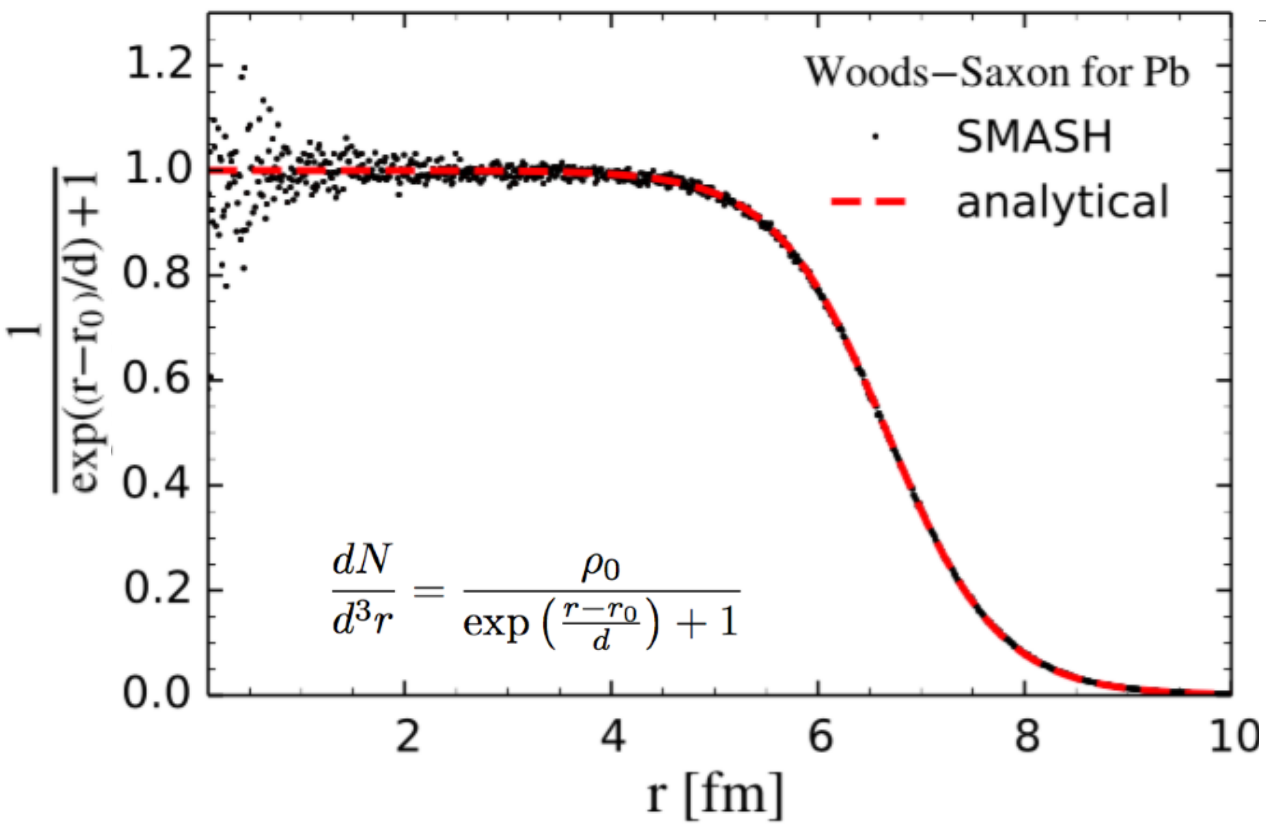
- Test particle method

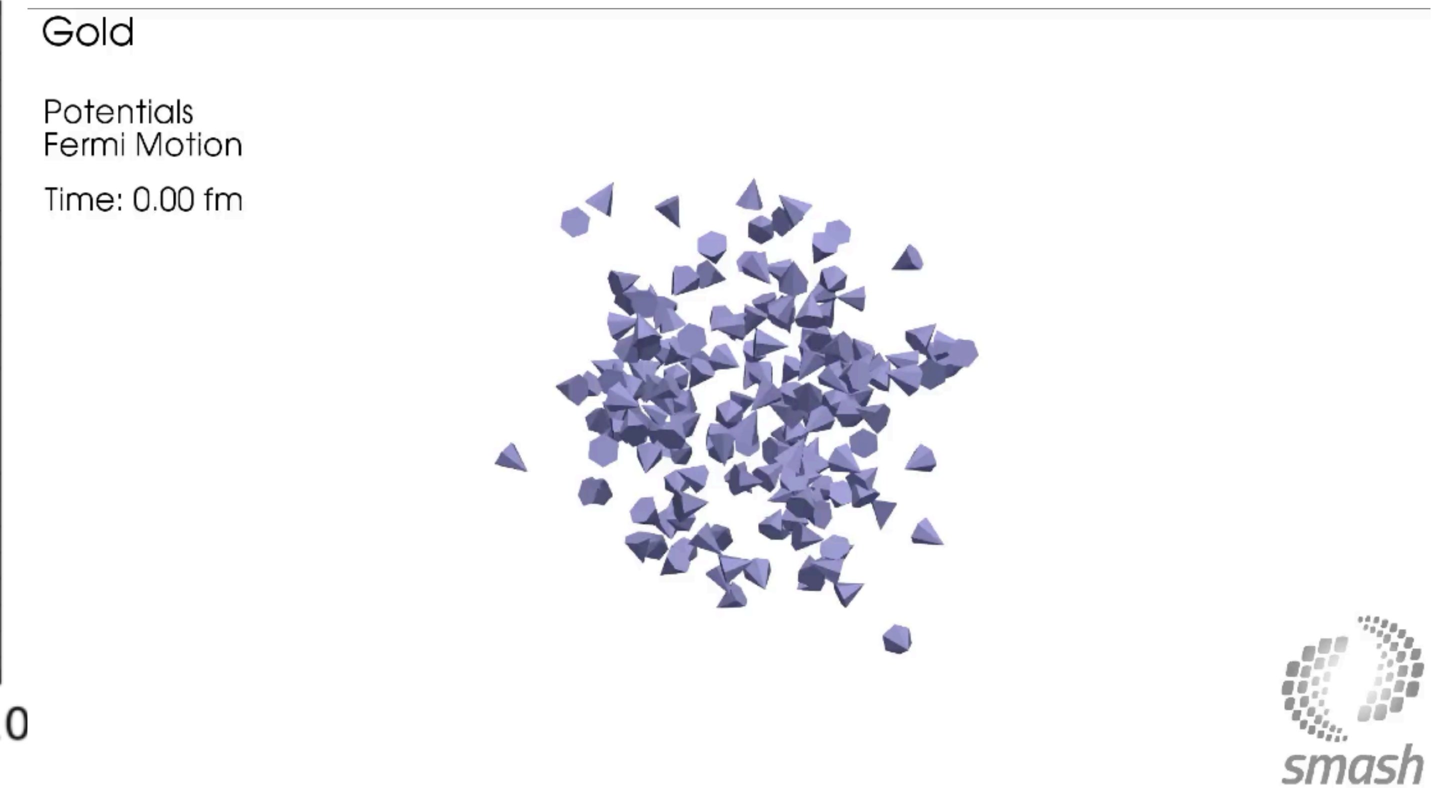
$$\sigma \mapsto \sigma \cdot N_{\text{test}}^{-1}$$

$$N \mapsto N \cdot N_{\text{test}}$$

Initial Conditions

- Nuclear Collisions
  - Woods-Saxon distribution in coordinate space

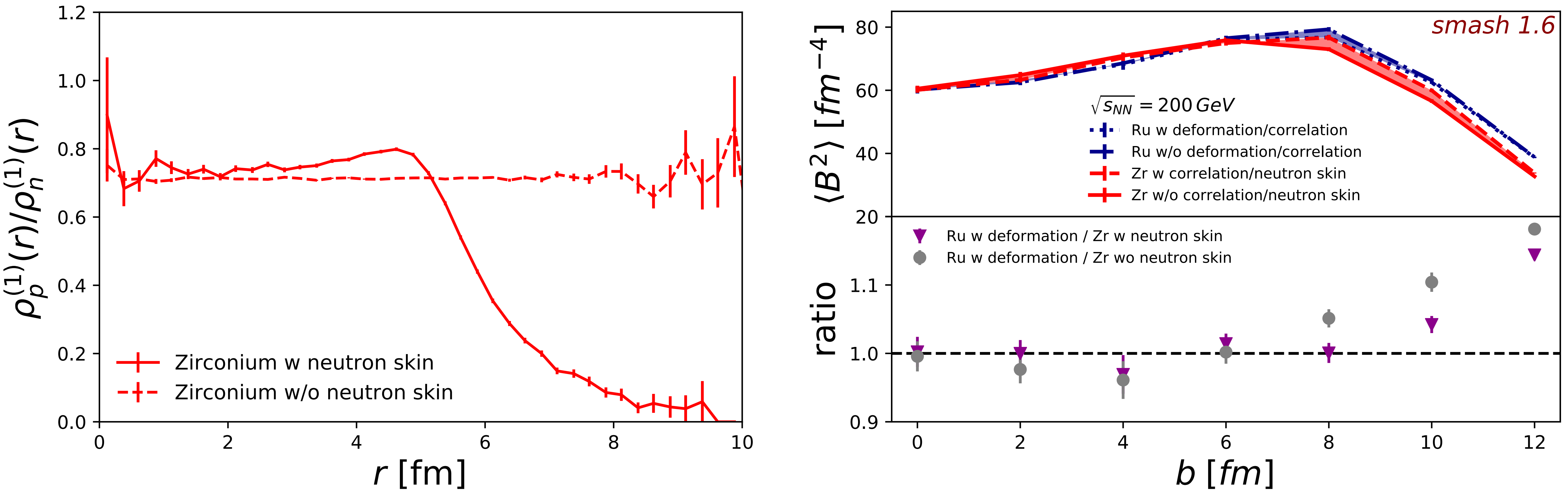




  - *optional:* deformed nuclei and (frozen) Fermi motion
  - *optional*: read-in of more realistic initial states with correlations, neutron skin

Exploration of Neutron Skin

- Comparison of charge distribution in the initial state with and without neutron skin effect, also correlations included
- SMASH is applied until full overlap of nuclei



- Difference in magnetic fields of RuRu and ZrZr collisions reduced by neutron skin

J. Hammelmann, A. Soto-Ontoso, M. Alvioli, HE and M. Strikman, *Phys.Rev.C* 101 (2020)

Degrees of Freedom

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

As of SMASH-1.7

Unflavored				Strange
π_{138}	$f_{0\,980}$	$f_{2\,1275}$	$\pi_{2\,1670}$	K_{494}
π_{1300}	$f_{0\,1370}$	$f_2'{}_{1525}$		K^*_{892}
π_{1800}	$f_{0\,1500}$	$f_{2\,1950}$	$\rho_{3\,1690}$	$K_{1\,1270}$
	$f_{0\,1710}$	$f_{2\,2010}$		$K_{1\,1400}$
η_{548}		$f_{2\,2300}$	$\phi_{3\,1850}$	K^*_{1410}
η'_{958}	$a_{0\,980}$	$f_{2\,2340}$		$K_0^*{}_{1430}$
η_{1295}	$a_{0\,1450}$		$a_{4\,2040}$	$K_2^*{}_{1430}$
η_{1405}		$f_{1\,1285}$		K^*_{1680}
η_{1475}	ϕ_{1019}	$f_{1\,1420}$	$f_{4\,2050}$	$K_{2\,1770}$
	ϕ_{1680}			$K_3^*{}_{1780}$
σ_{800}		$a_{2\,1320}$		$K_{2\,1820}$
	$h_{1\,1170}$			$K_4^*{}_{2045}$
ρ_{776}		$\pi_{1\,1400}$		
ρ_{1450}	$b_{1\,1235}$	$\pi_{1\,1600}$		
ρ_{1700}				
	$a_{1\,1260}$	$\eta_{2\,1645}$		
ω_{783}				
ω_{1420}		$\omega_{3\,1670}$		
ω_{1650}				

- + corresponding antiparticles
- Perturbative treatment of photons and dileptons
- Isospin symmetry

- Mesons and baryons according to particle data group
- Isospin multiplets and anti-particles are included

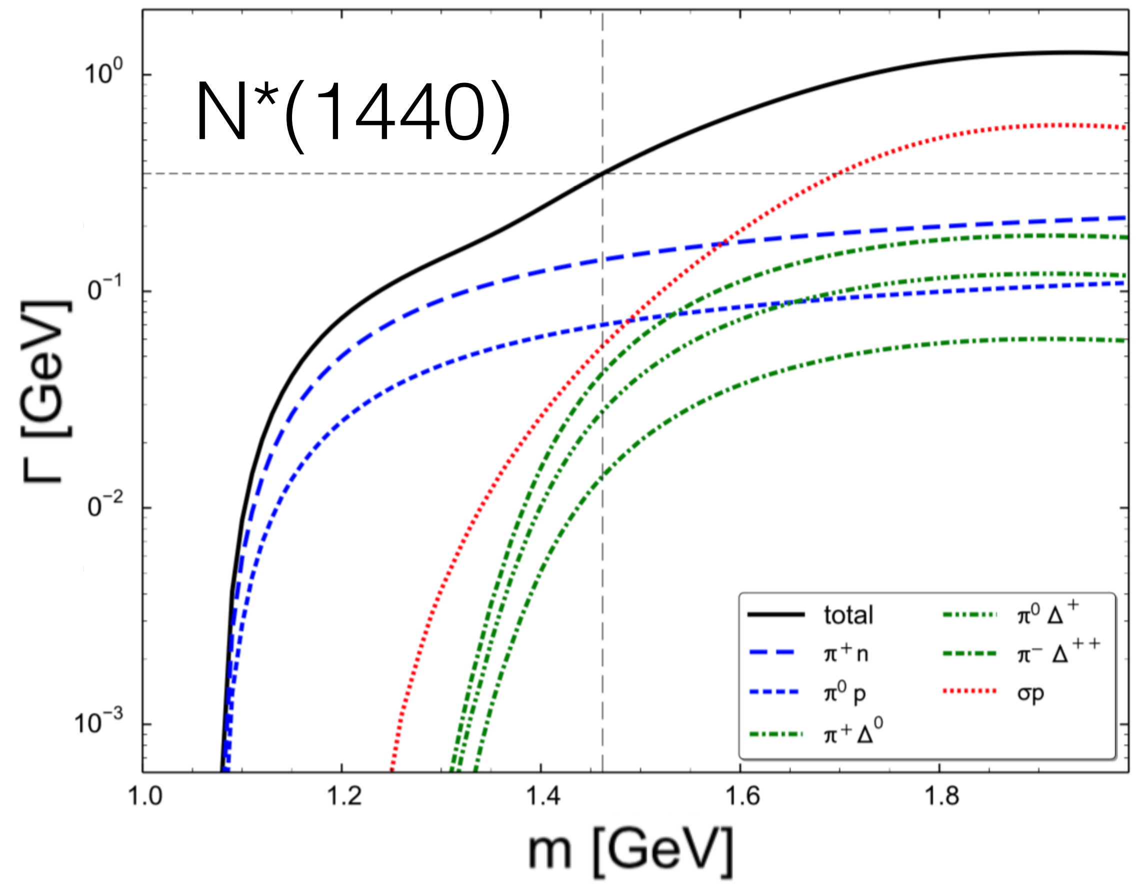
Resonances

- Spectral function
  - All unstable particles („resonances“) have relativistic Breit-Wigner spectral functions

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

- Decay widths
  - Particles stable, if width < 10 keV $(\pi,\ \eta,\ K, ...)$
  - Treatment of Manley et al

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

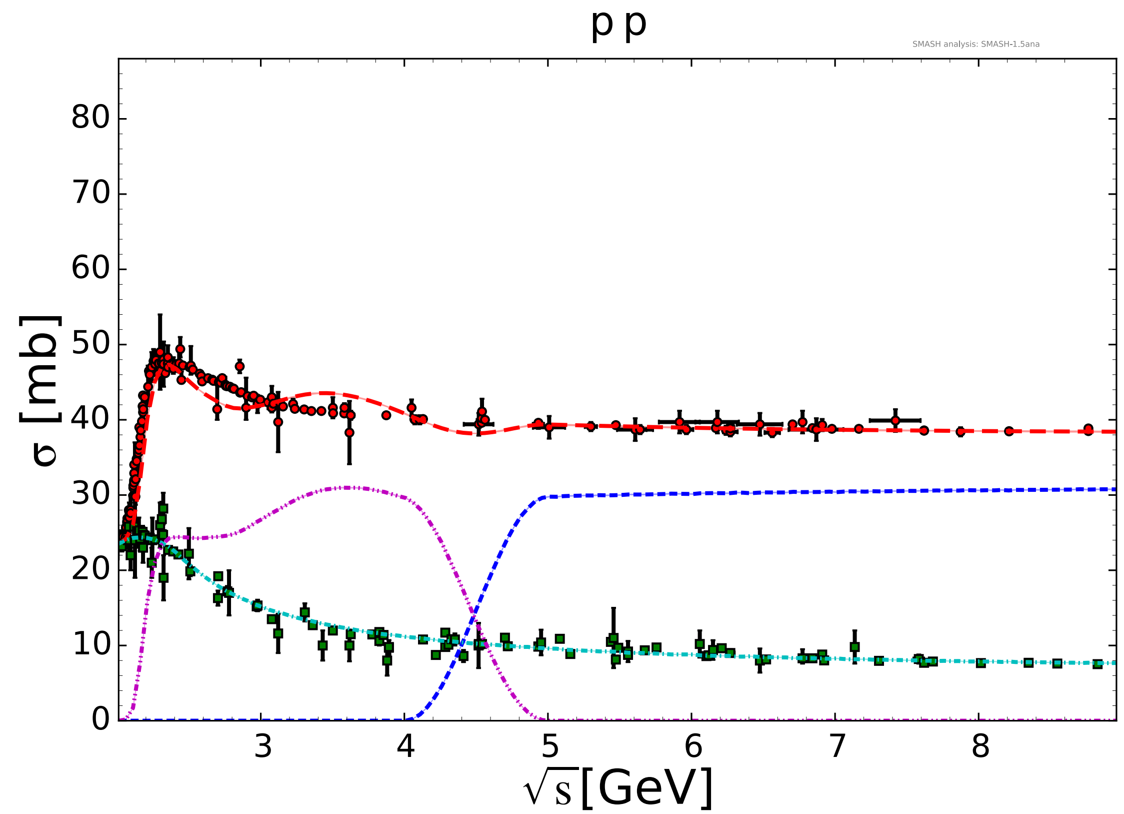


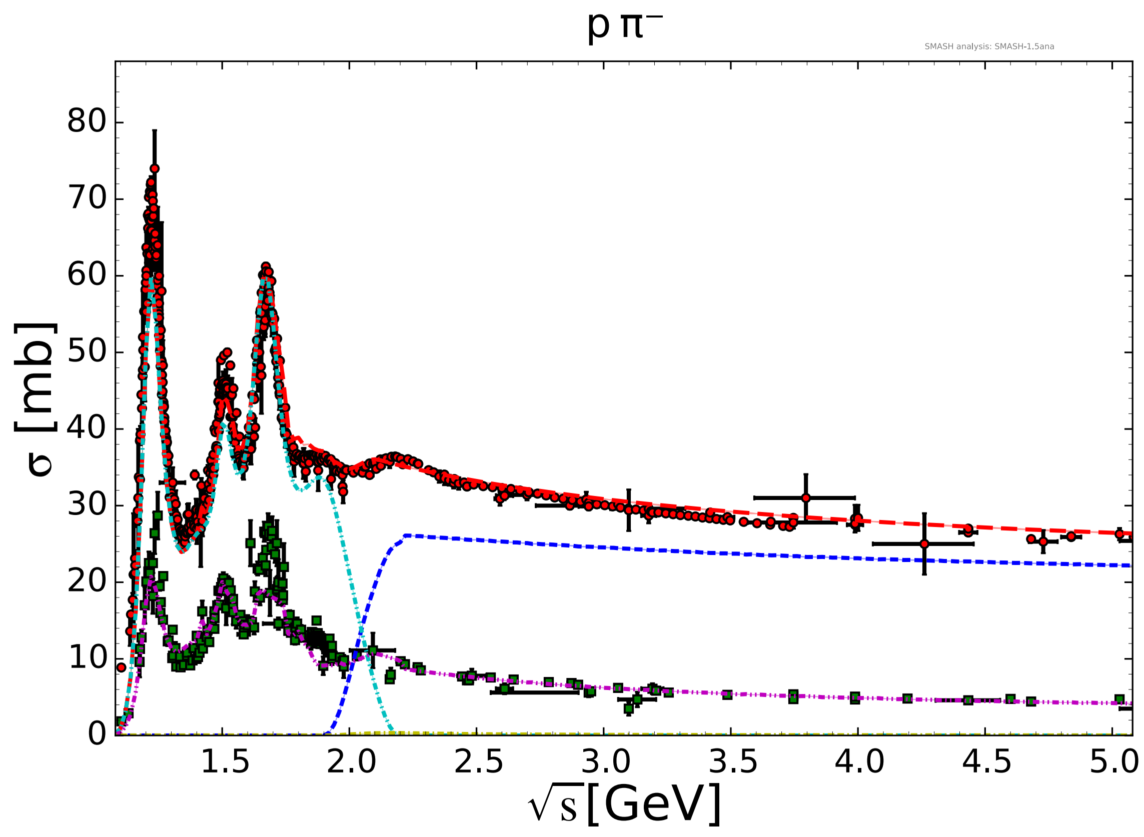
D. M. Manley and E. M. Saleski, Phys. Rev. D 45, 4002 (1992)

As in GiBUU

Validation

Elementary Cross Sections





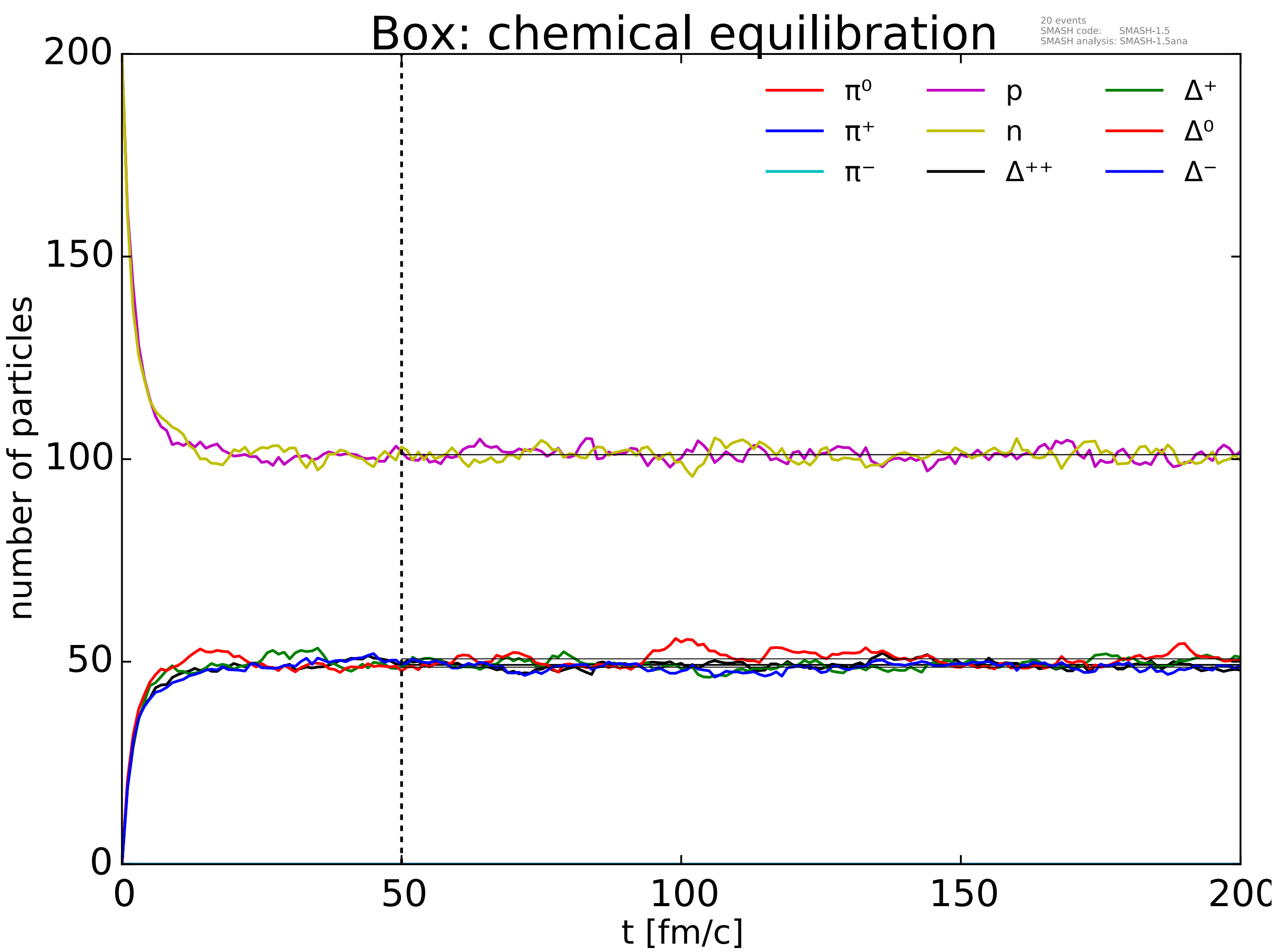
- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Soft strings a la UrQMD and hard strings via Pythia 8

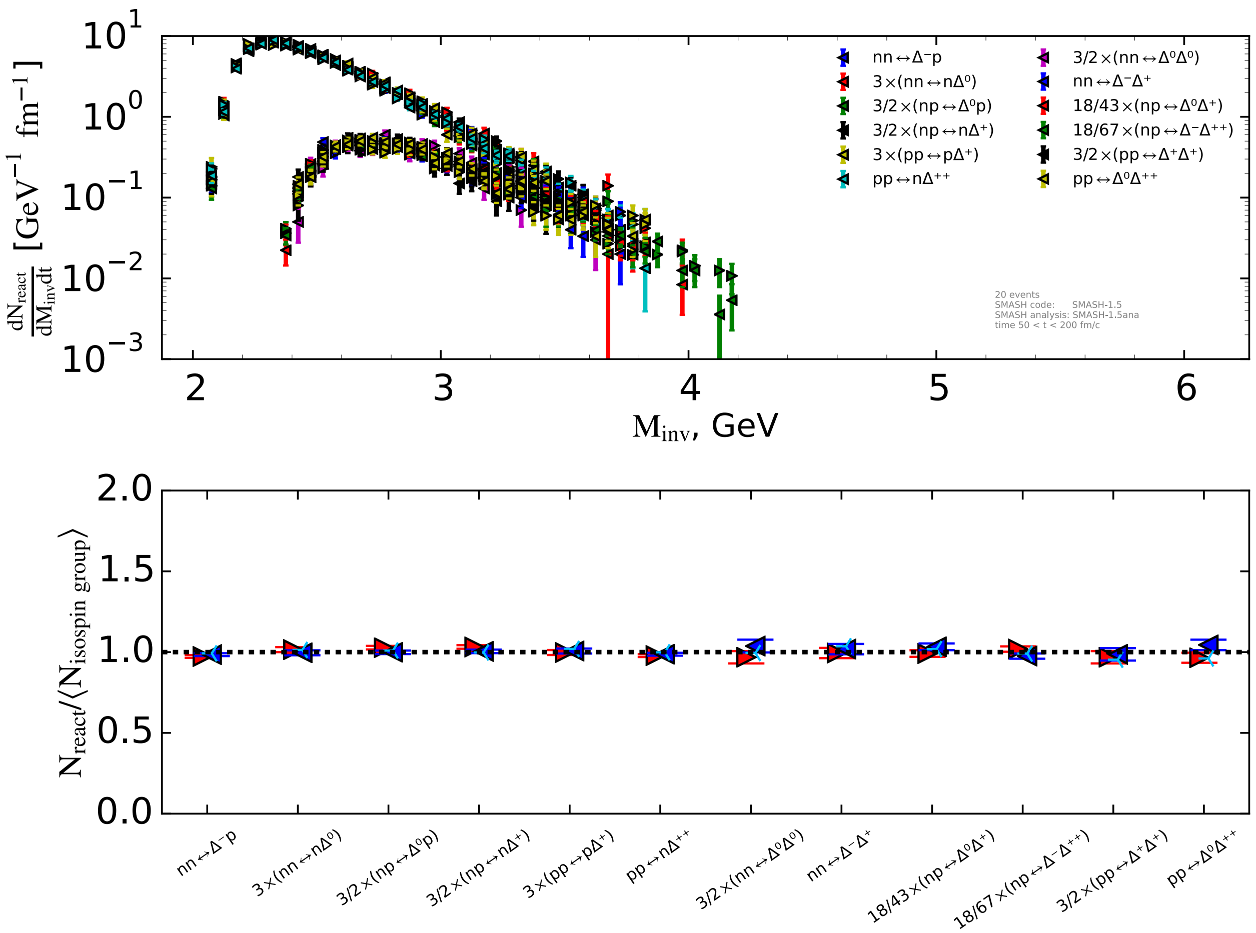
J. Weil et al, PRC 94 (2016), updated SMASH-1.5

Detailed Balance

- Inverse absorption cross section calculated from production cross section
- Conservation of detailed balance (only 1 <—> 2 or 2 <—> 2 processes)

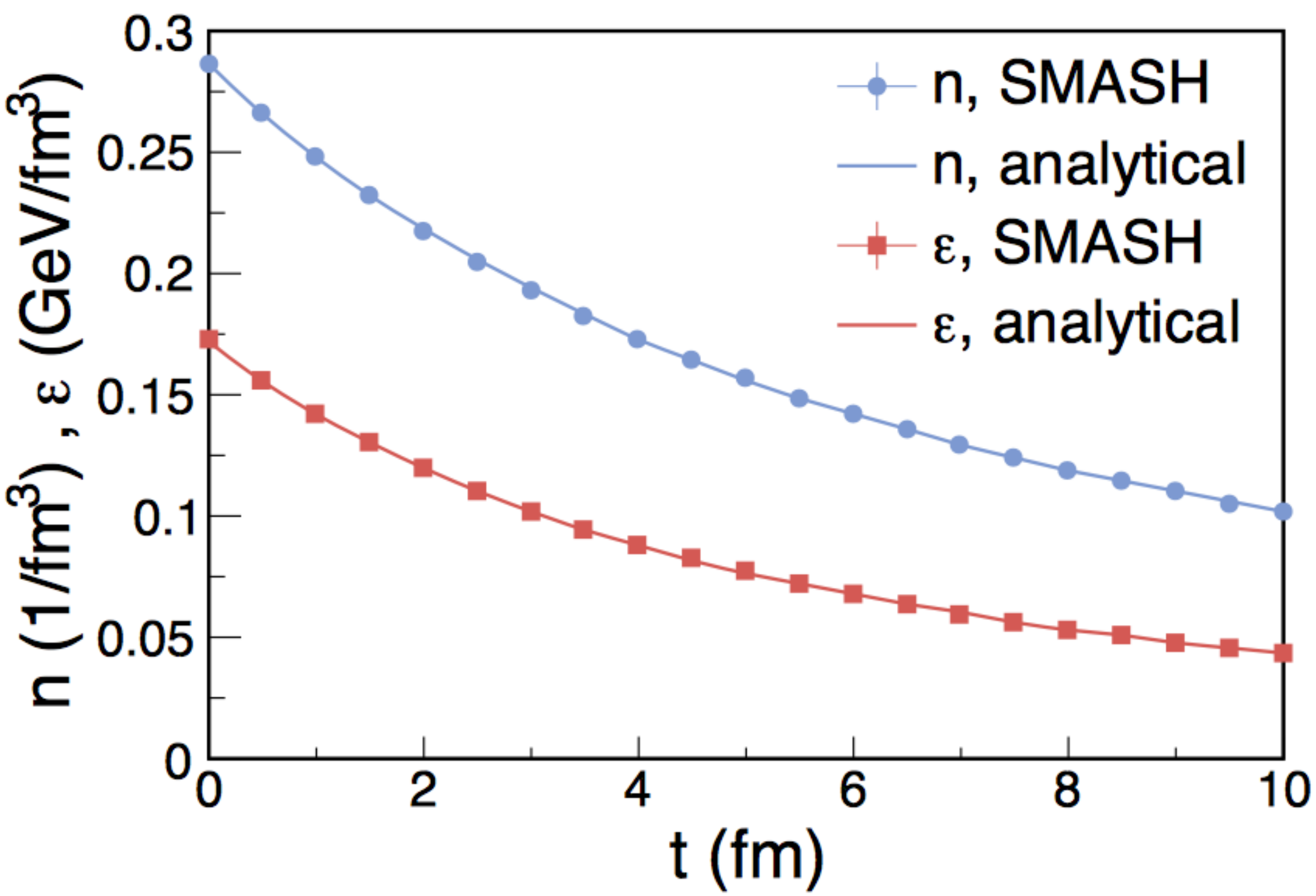
J. Weil et al, PRC 94 (2016), updated SMASH-1.5

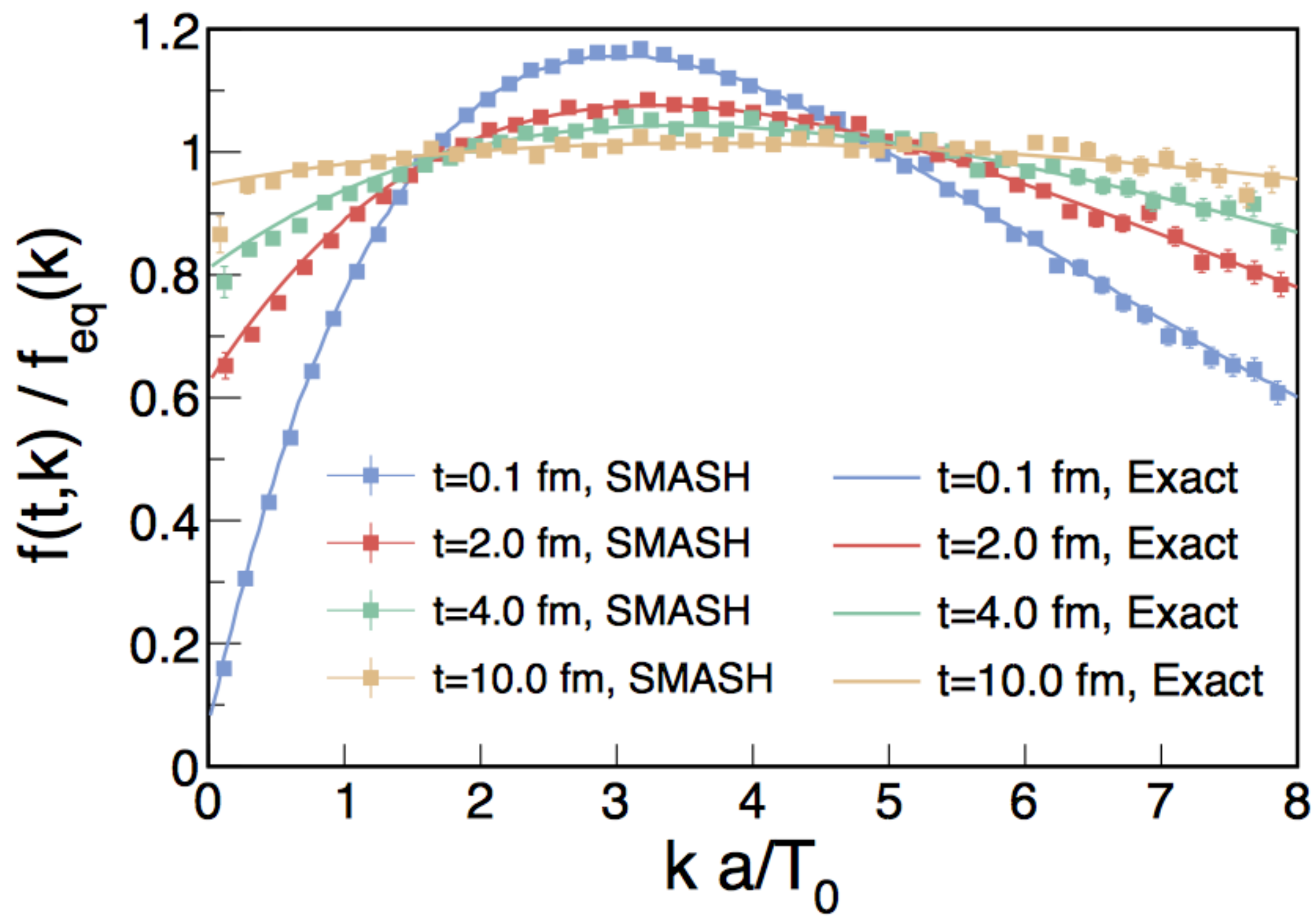




Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





- Perfect agreement proves correct numerical implementation of collision algorithm

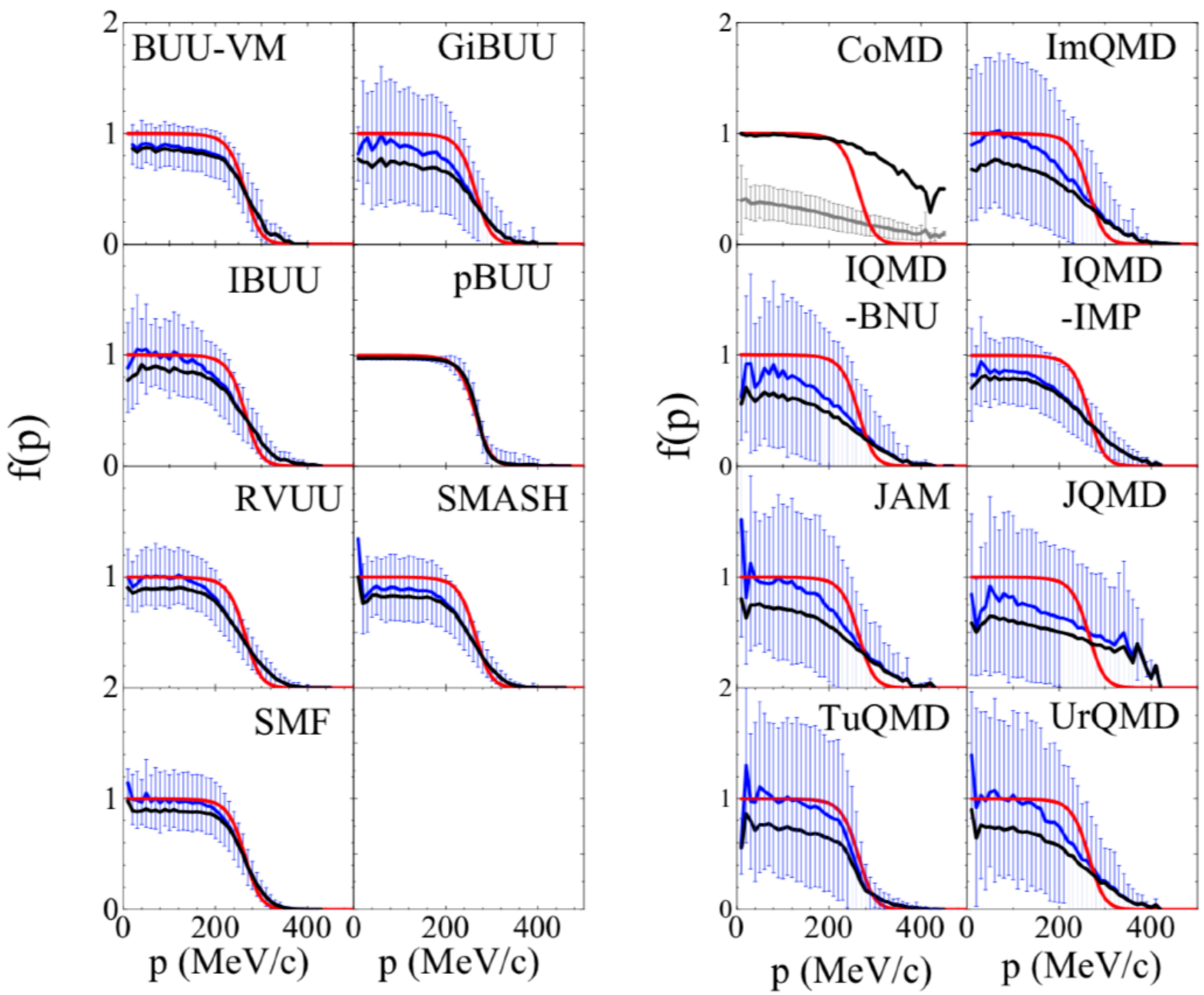
D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

J. Tindall et al., PLB 770 (2017)

Transport Code Comparison

Comparison of heavy-ion transport simulations: Collision integral in a box

Ying-Xun Zhang,[1,2,*] Yong-Jia Wang,[3,†] Maria Colonna,[4,‡] Pawel Danielewicz,[5,§] Akira Ono,[6,¶] Manyee Betty Tsang,[5,**] Hermann Wolter,[7,††] Jun Xu,[8,‡‡] Lie-Wen Chen,[9] Dan Cozma,[10] Zhao-Qing Feng,[11] Subal Das Gupta,[12] Natsumi Ikeno,[13] Che-Ming Ko,[14] Bao-An Li,[15] Qing-Feng Li,[3,11] Zhu-Xia Li,[1] Swagata Mallik,[16] Yasushi Nara,[17] Tatsuhiko Ogawa,[18] Akira Ohnishi,[19] Dmytro Oliinychenko,[20] Massimo Papa,[4] Hannah Petersen,[20,21,22] Jun Su,[23] Taesoo Song,[20,24] Janus Weil,[20] Ning Wang,[25] Feng-Shou Zhang,[26,27] and Zhen Zhang[14]



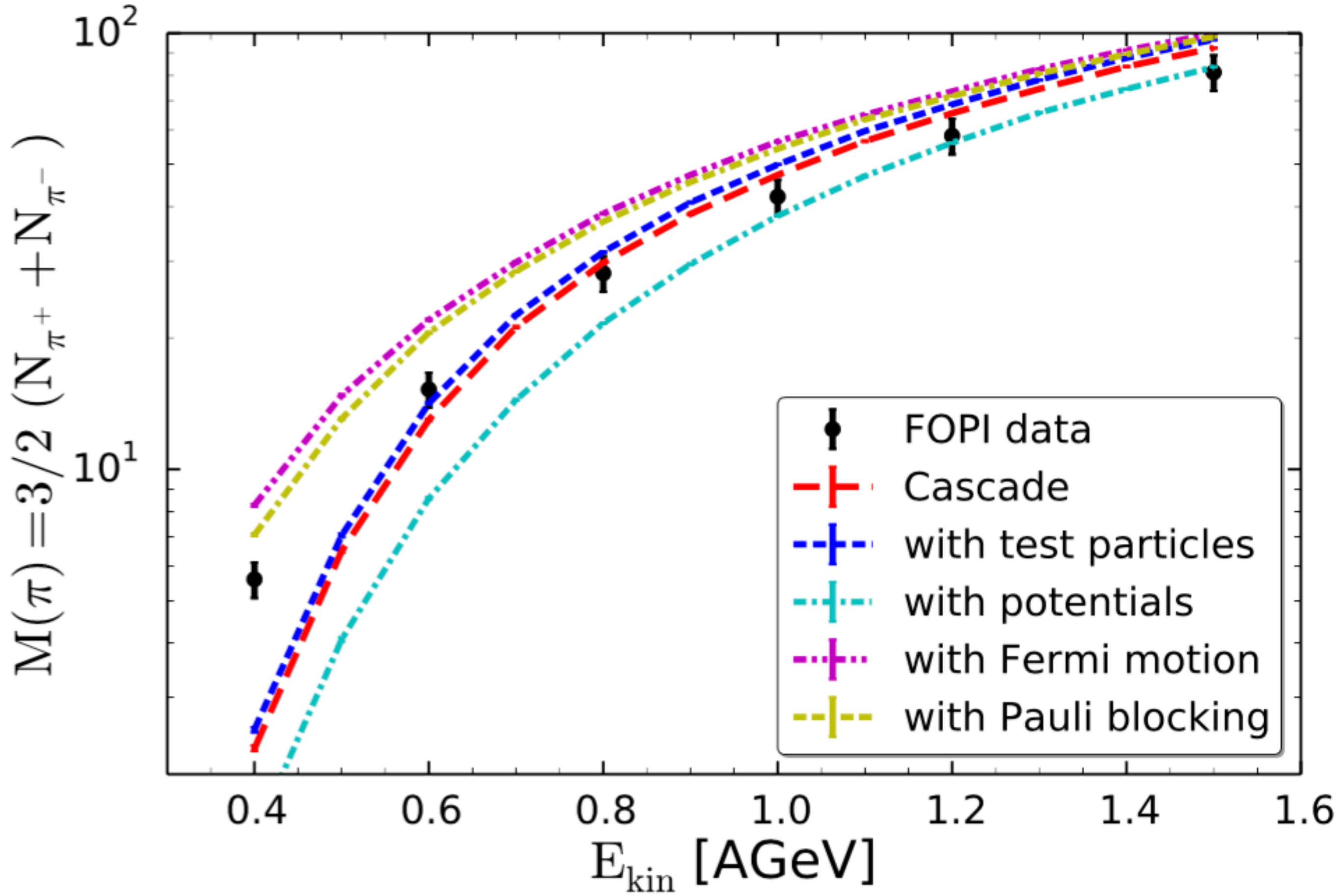
- Occupation probabilities in momentum space
- blue: mean and variance)
- red: initial
- black: Pauli blocking

Phys.Rev. C97 (2018) no.3, 034625
and on Delta-Nucleon-Pion system
A. Ono et al, PRC 100 (2019)

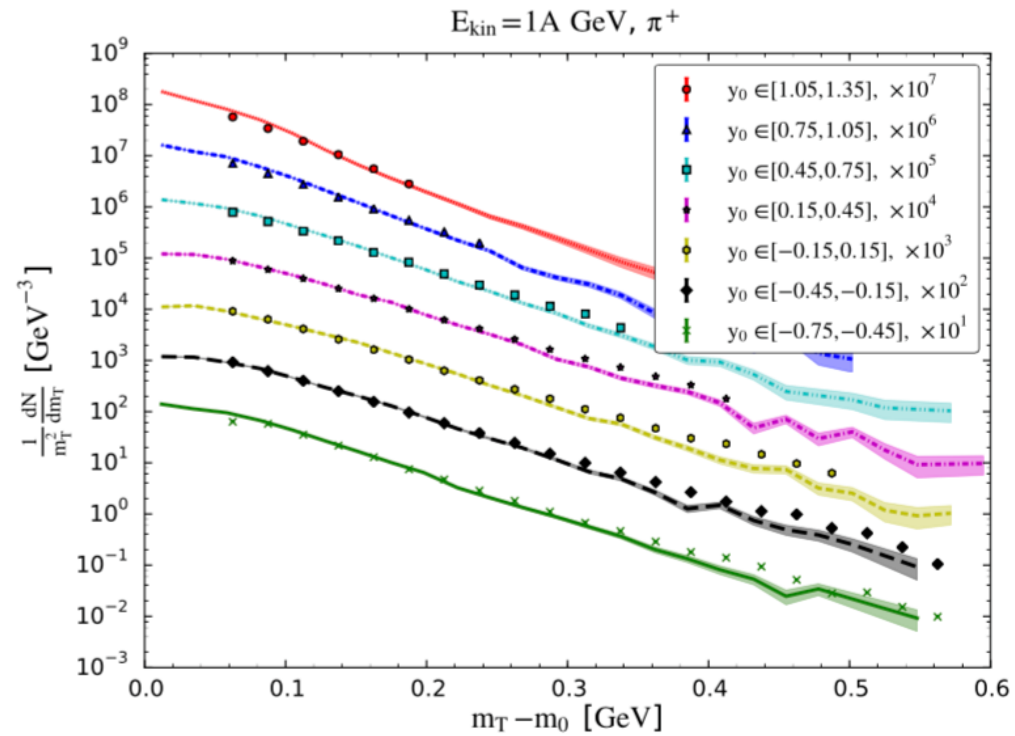
Hadron Production at SIS-18

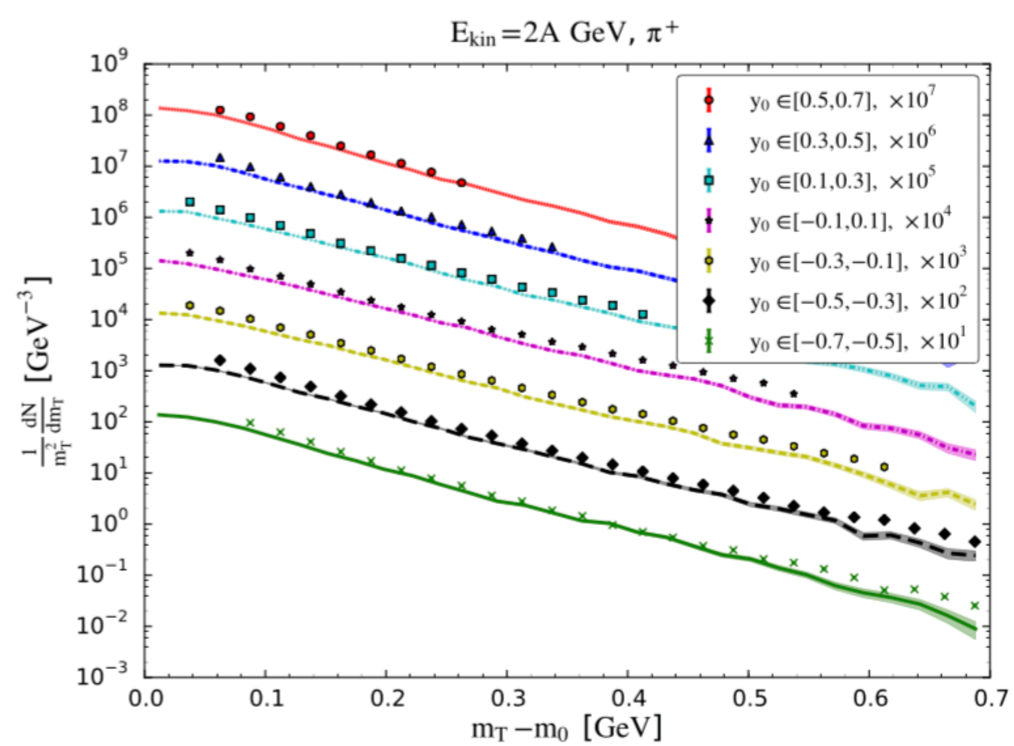
Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Nice agreement with SIS experimental data



Note: consecutive addition of features





J. Weil et al, PRC 94 (2016)

Collective Behaviour

- Potentials in SMASH
  - Basic Skyrme and symmetry potential

$$U_{\mathrm{Skyrme}} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\tau \qquad U_{\mathrm{Symmetry}} = \pm 2 S_{\mathrm{Pot}} \frac{\rho_{I_3}}{\rho_0}$$

  - Describes interactions between nucleons, repulsive at high densities

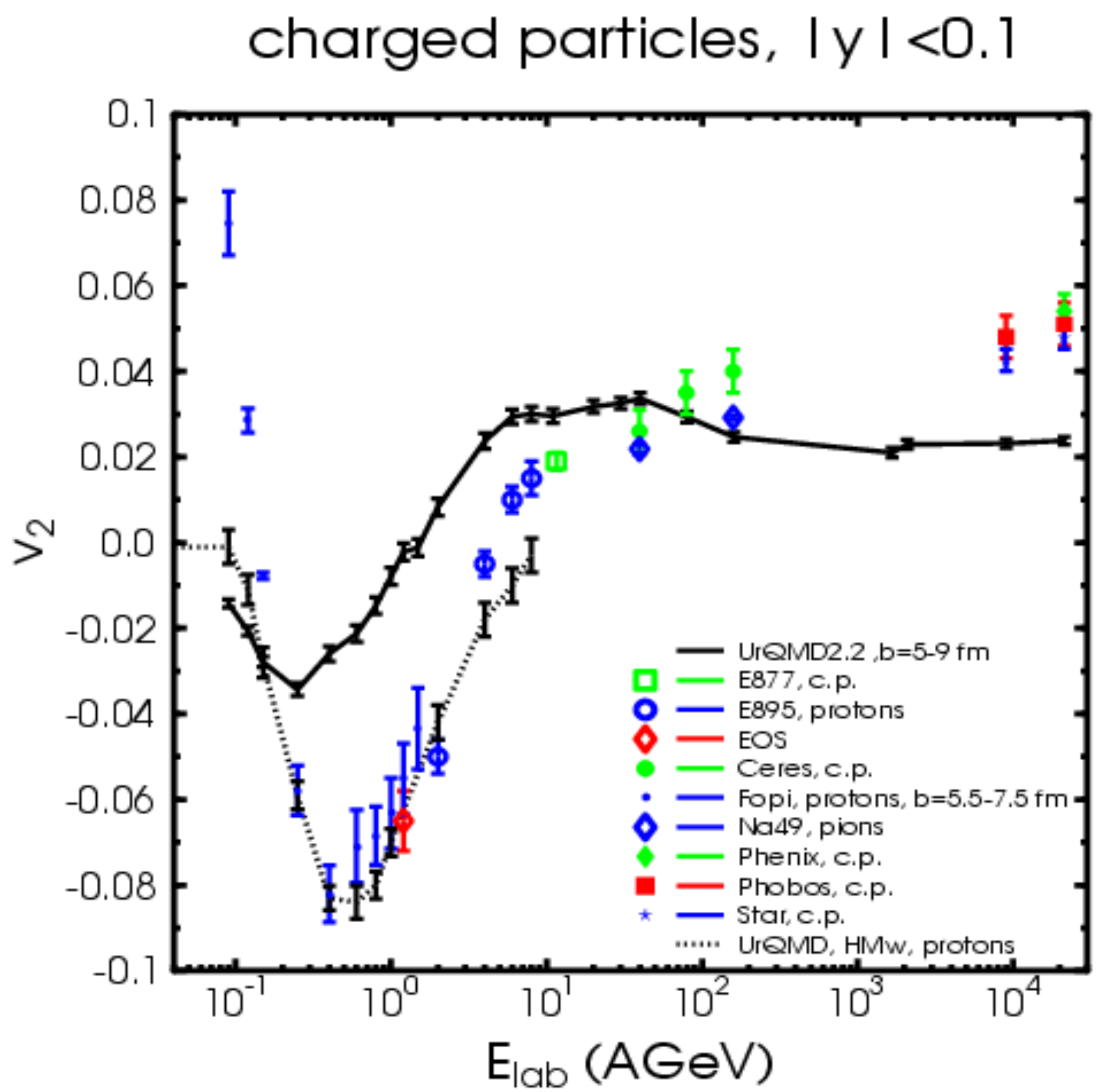
	soft EoS	default EoS	hard EoS
α	-356.0 MeV	-209.2 MeV	-124.0 MeV
β	303.0 MeV	156.4 MeV	71.0 MeV
τ	1.17	1.35	2.00
κ	200 MeV	240 MeV	380 MeV

  - Default values according to transport code comparison

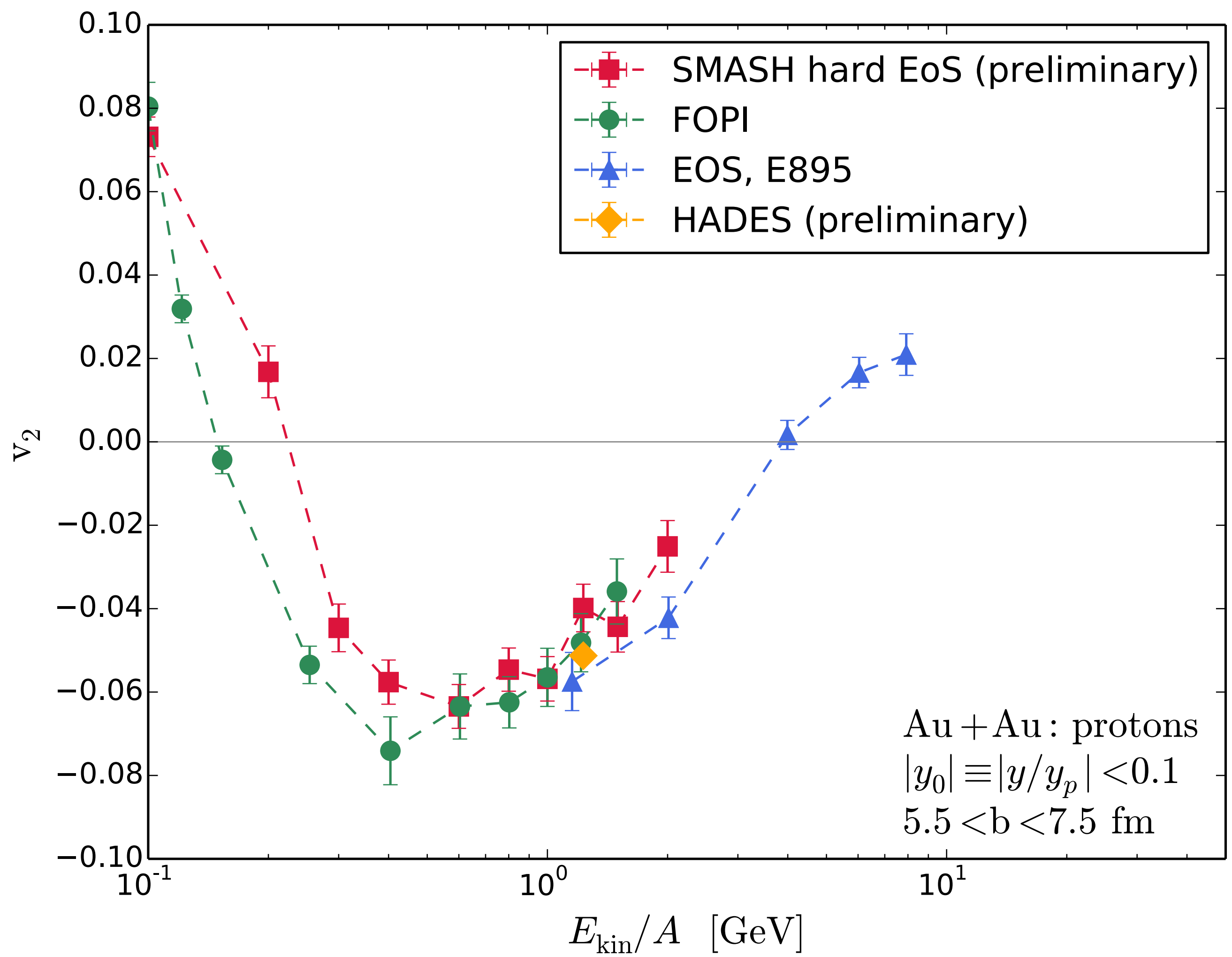
J. Xu et al., PRC 93 (2016)

Collective Flow -v_2

- Directed and elliptic flow are compared to available data from FOPI and HADES



HP et al, Phys.Rev. C74 (2006) 064908

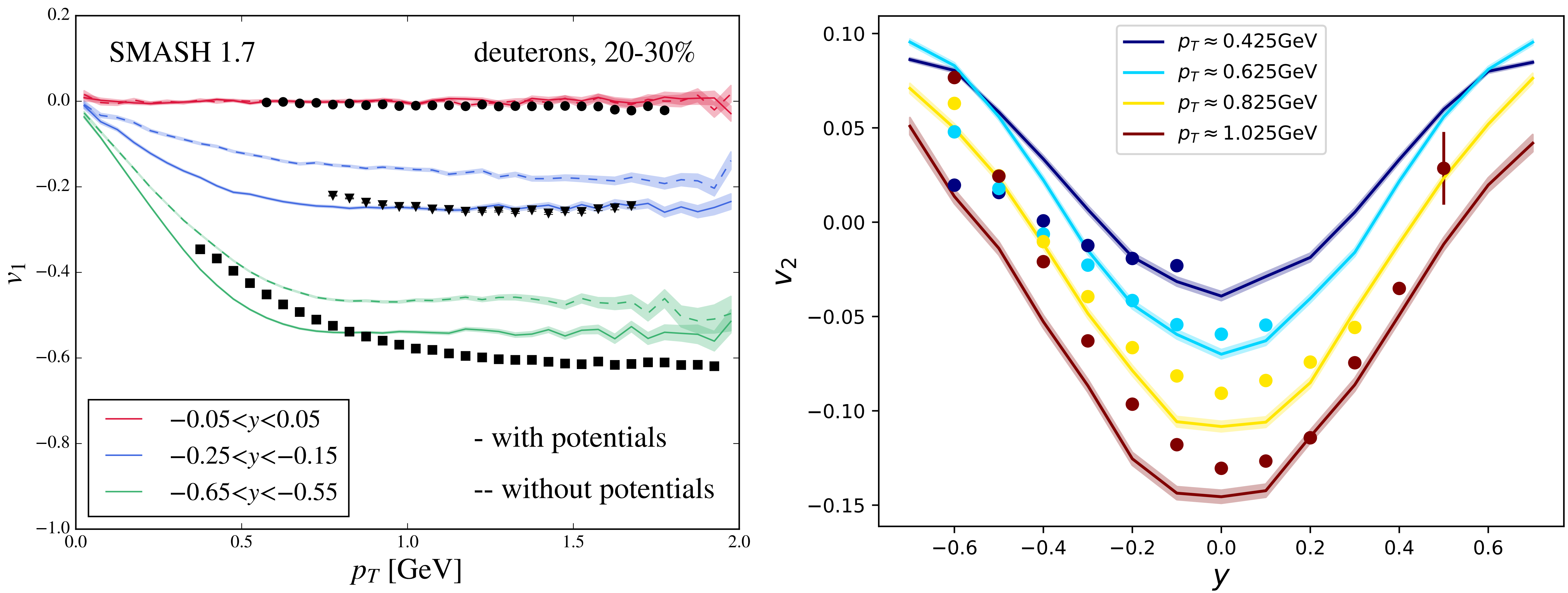


H.Petersen (now Elfner) et al, NPA 982, 2019

- SMASH agrees well with previous UrQMD calculation

Deuteron Flow in AuAu at 1.23 AGeV

- At low beam energies the deuterons (and larger clusters) compose ~50% of the baryons in the systems



J. Mohs, M. Ege, HE, in preparation

- Directed and elliptic flow compare reasonably well with the same production cross-sections used at higher energies

See D. Oliinychenko, LongGang Pang, HE and V. Koch, Phys.Rev. C99 (2019) and *MDPI Proc.* 10 (2019)

Strangeness Production

K+ production

$$NN \rightarrow NN^*/\Delta^* \rightarrow NYK$$

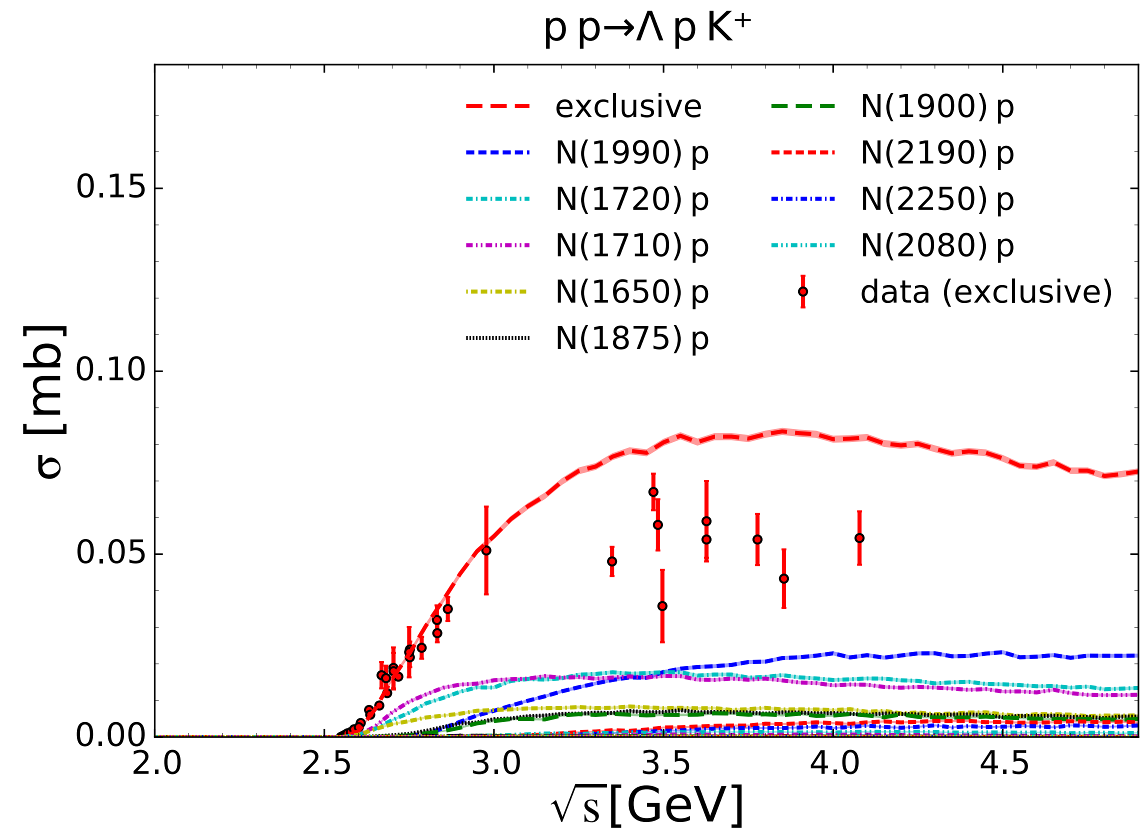
K- production

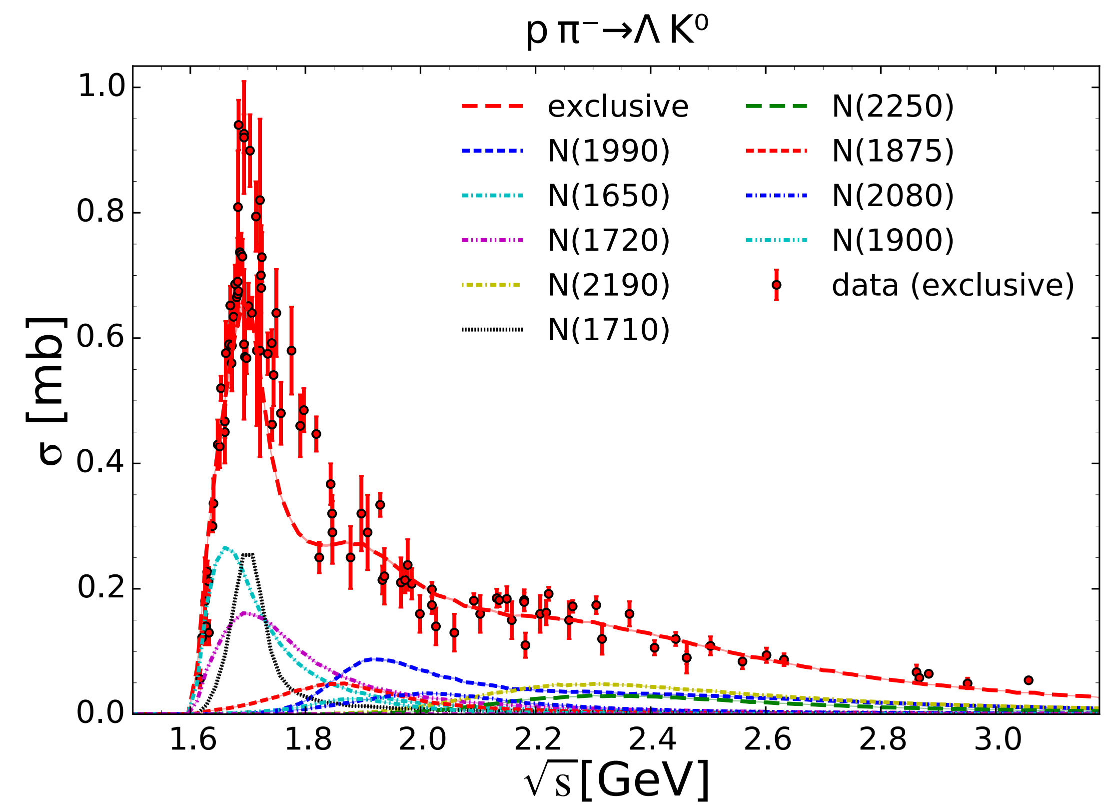
$$\pi Y \rightarrow Y^* \rightarrow \bar{K}N$$

$$N^* \rightarrow \phi N \rightarrow \bar{K}KN$$

- Elementary exclusive cross-sections provide constraints on resonance properties

resonance	branching ratio $N^* \rightarrow \Lambda K$ PDG	HADES	SMASH
$N(1650)$	$5-15\%$	$7 \pm 4\%$	4%
$N(1710)$	$5-25\%$	$15 \pm 10\%$	13%
$N(1720)$	$4-5\%$	$8 \pm 7\%$	5%
$N(1875)$	> 0	$4 \pm 2\%$	2%
$N(1880)$		$2 \pm 1\%$	
$N(1895)$		$18 \pm 5\%$	
$N(1900)$	$2-20\%$	$5 \pm 5\%$	2%
$N(1990)$			2%
$N(2080)$			0.5%
$N(2190)$	$0.2-0.8\%$		0.8%
$N(2220)$			0
$N(2250)$			0.5%

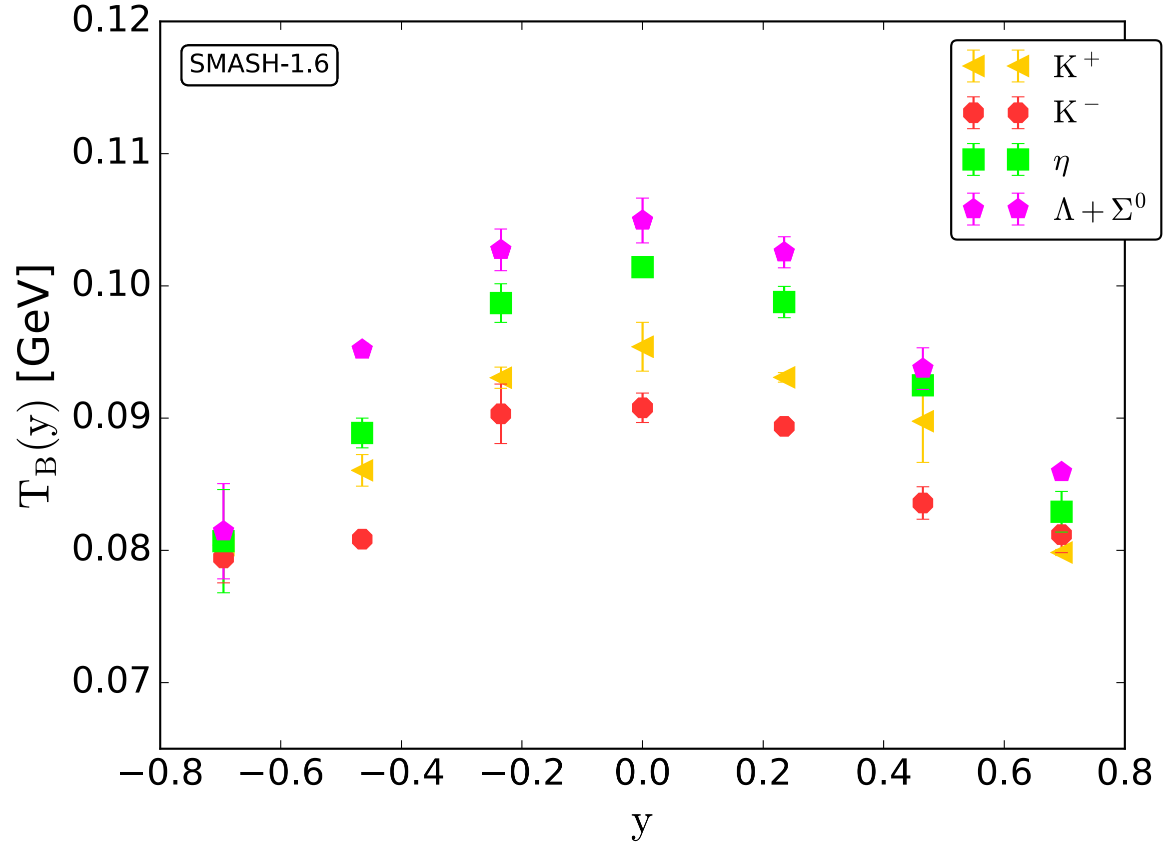


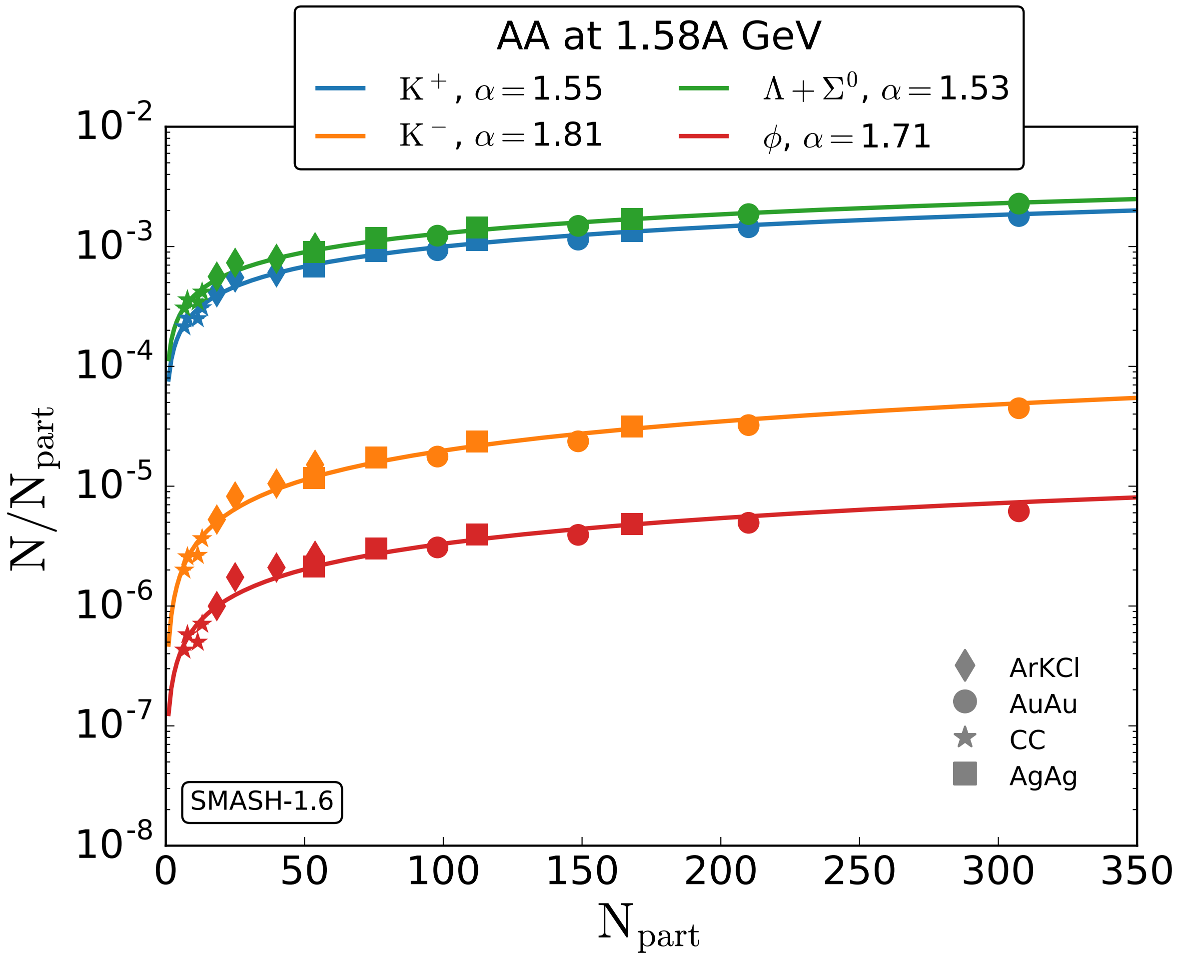


V. Steinberg et al., Phys.Rev.C 99 (2019) and 1912.09895

Strangeness Production

- Predictions for AgAg at 1.58A GeV (data taken by HADES in spring 2019)





- Effective kinetic freeze-out temperatures from transverse mass spectra are reasonable
- N_{part} scaling across system sizes looks qualitatively similar to HADES findings

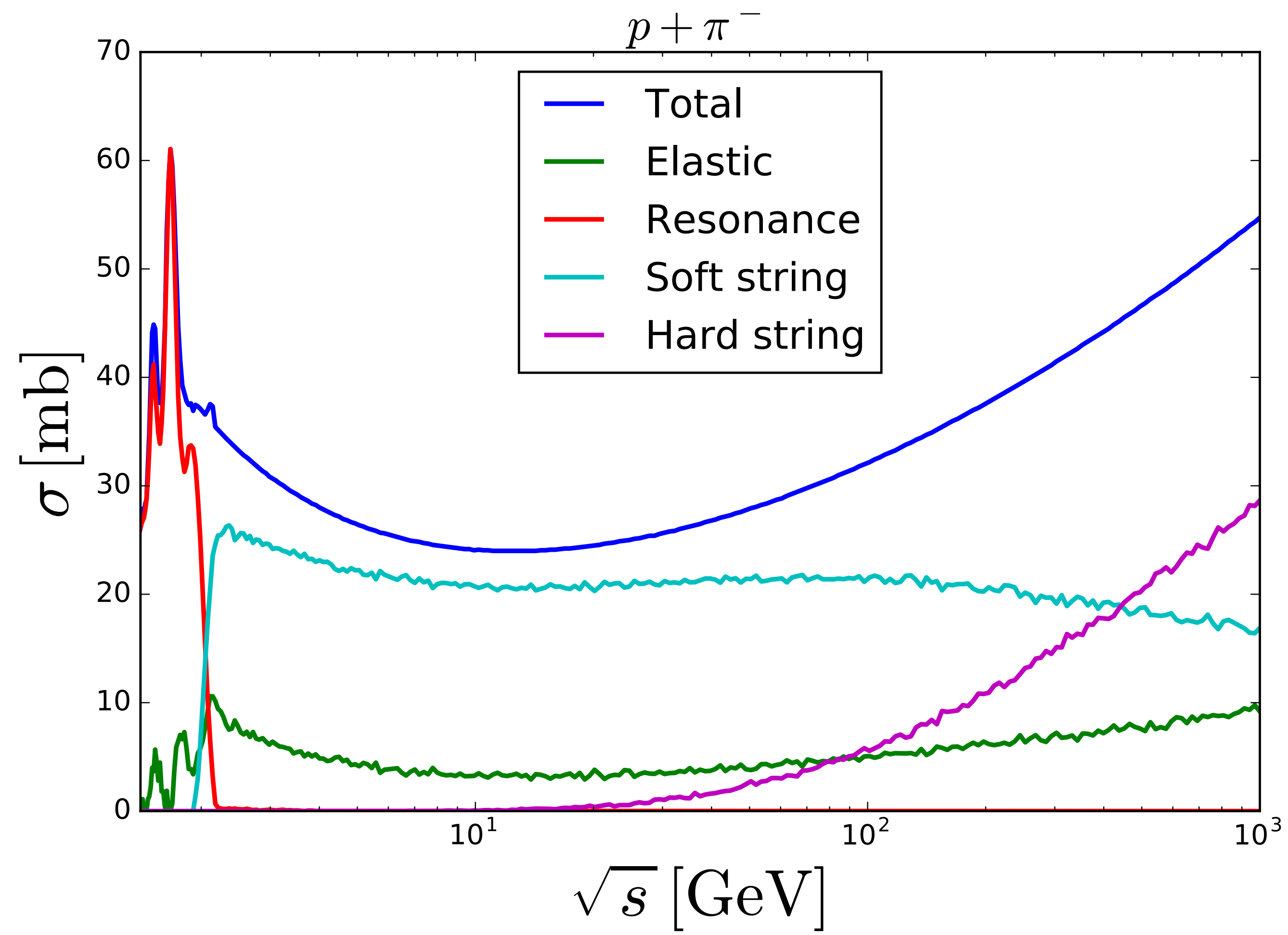
J. Staudenmaier, N. Kübler and HE, arXiv: 2008.05813

Moving to Higher Energies

- High energy cross-section is dominated by string excitation and fragmentation

J. Mohs, S. Ryu and HE, *J.Phys.G* 47 (2020)

- Soft strings
  - Pythia is only employed for fragmentation
  - Single-diffractive, double diffractive and non-diffractive processes

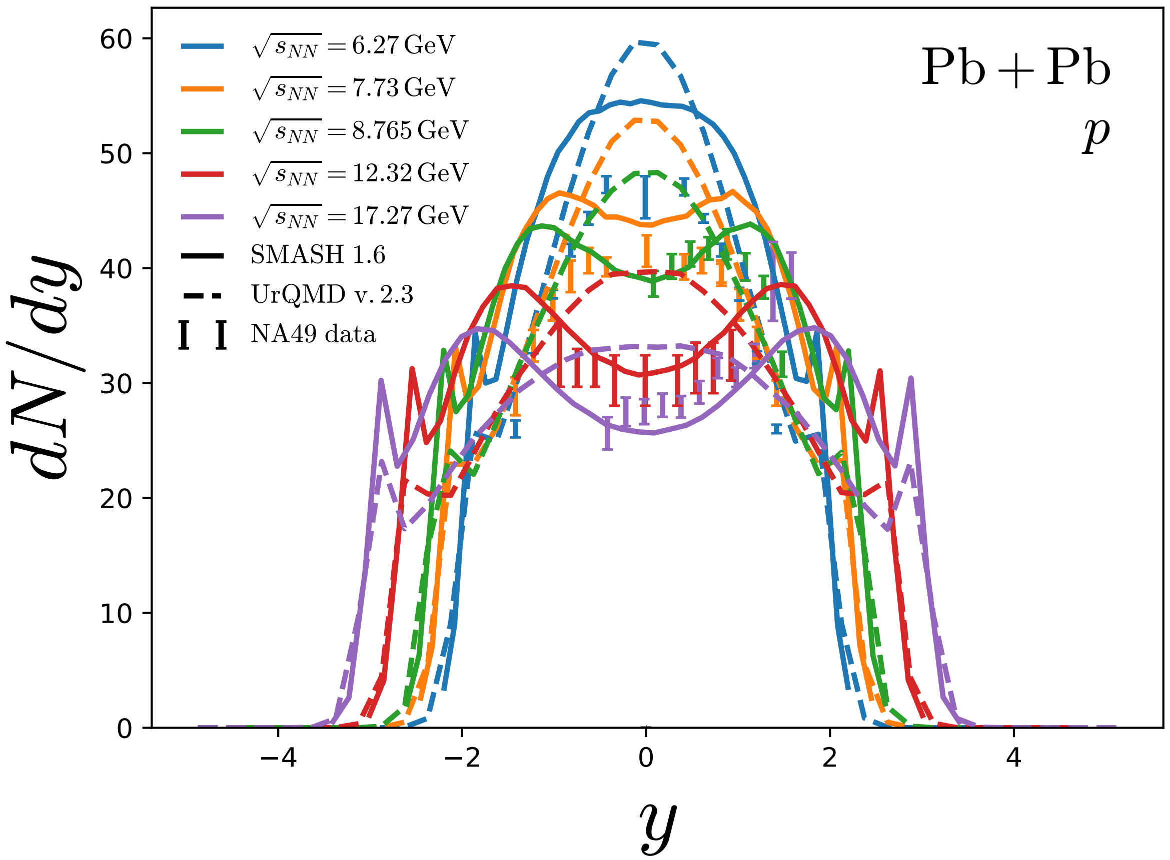


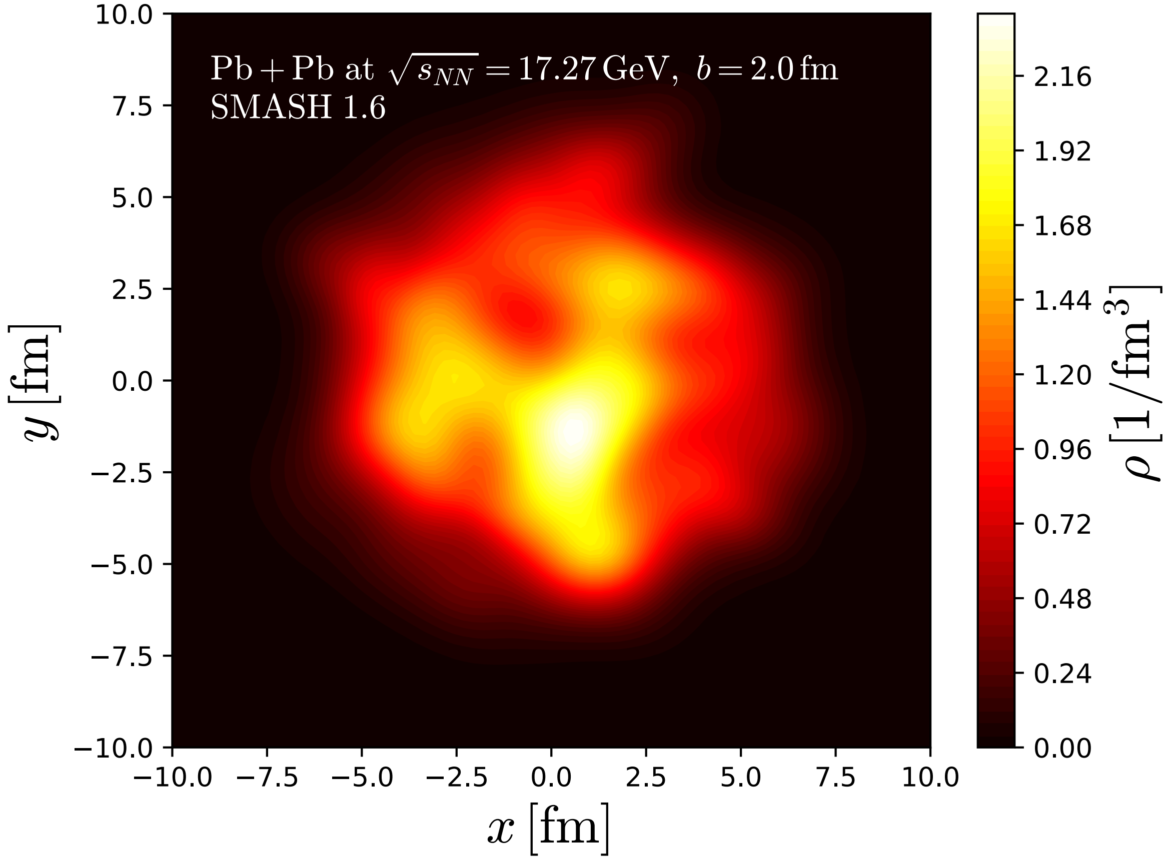
- Hard strings
  - Fully treated by Pythia
  - All species mapped to pions and nucleons

- Note: SMASH-2.0 will include optimised Pythia calls to reduce run-time

Baryon Stopping and Initial State

- All parameters of the string model are tuned to elementary pp data from SPS
- Proton rapidity spectrum is described over a large range of beam energies





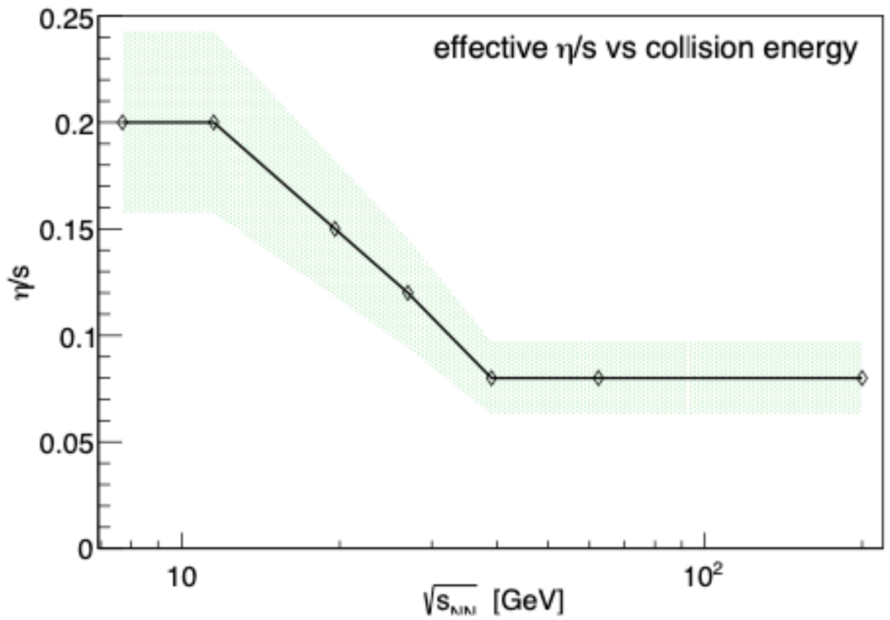
J. Mohs, S. Ryu, HE *J.Phys.G* 47 (2020)

- Outlook: Employ SMASH as dynamical initial state

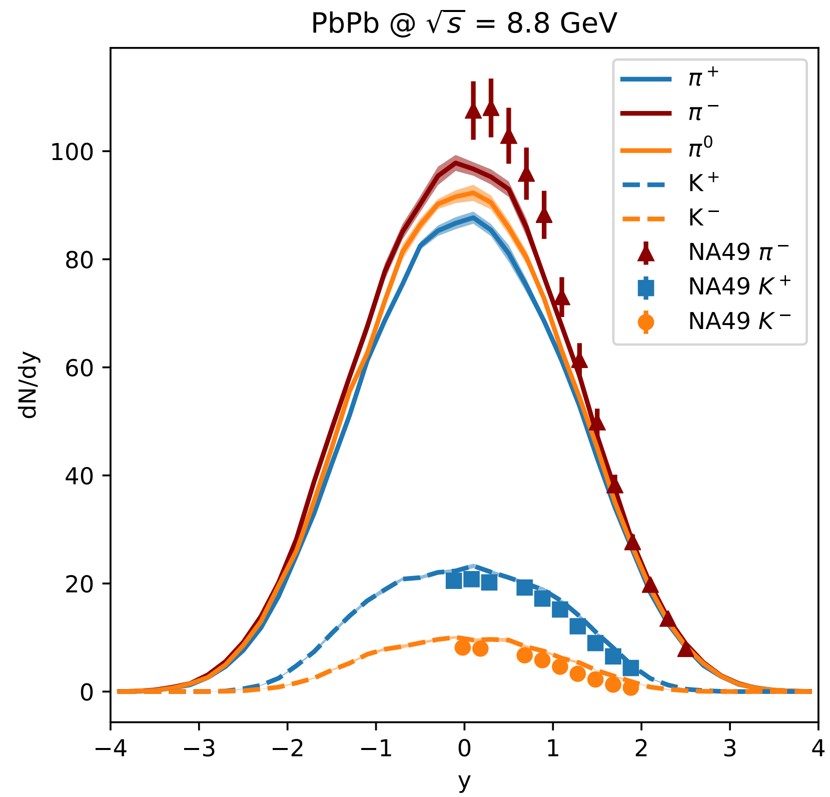
SMASH Hybrid Approach

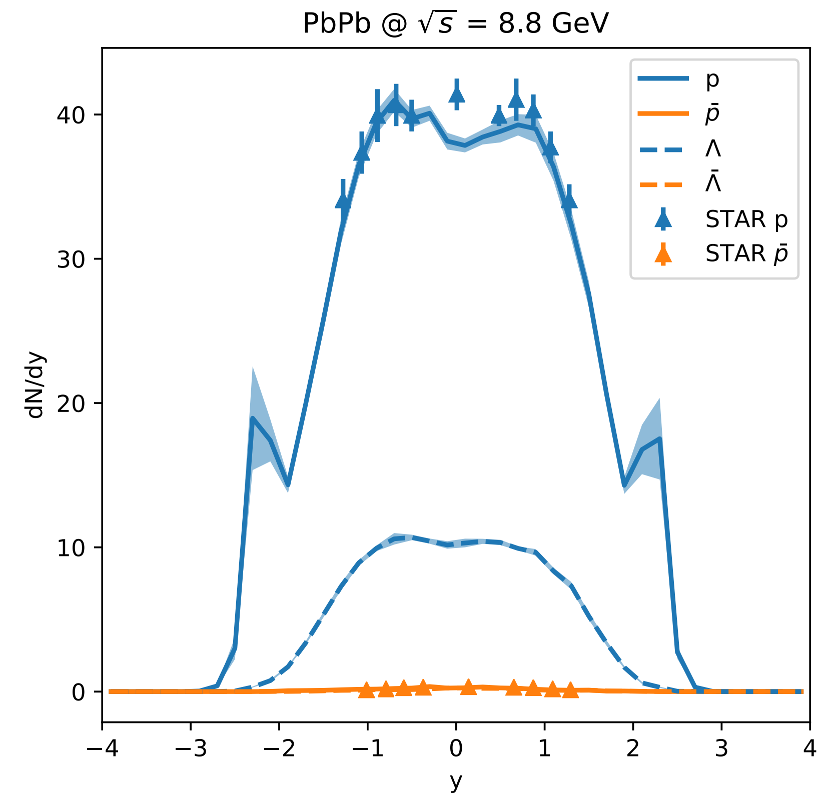
- Full event-by-event SMASH+vHLLE+SMASH hybrid approach with η/s =0.2 and constant τ initial state for Pb+Pb collisions at $\sqrt{s_{NN}} = 8.8$ GeV

A. Schäfer et al in preparation



Y. Karpenko et al, Phys.Rev.C 91 (2015)

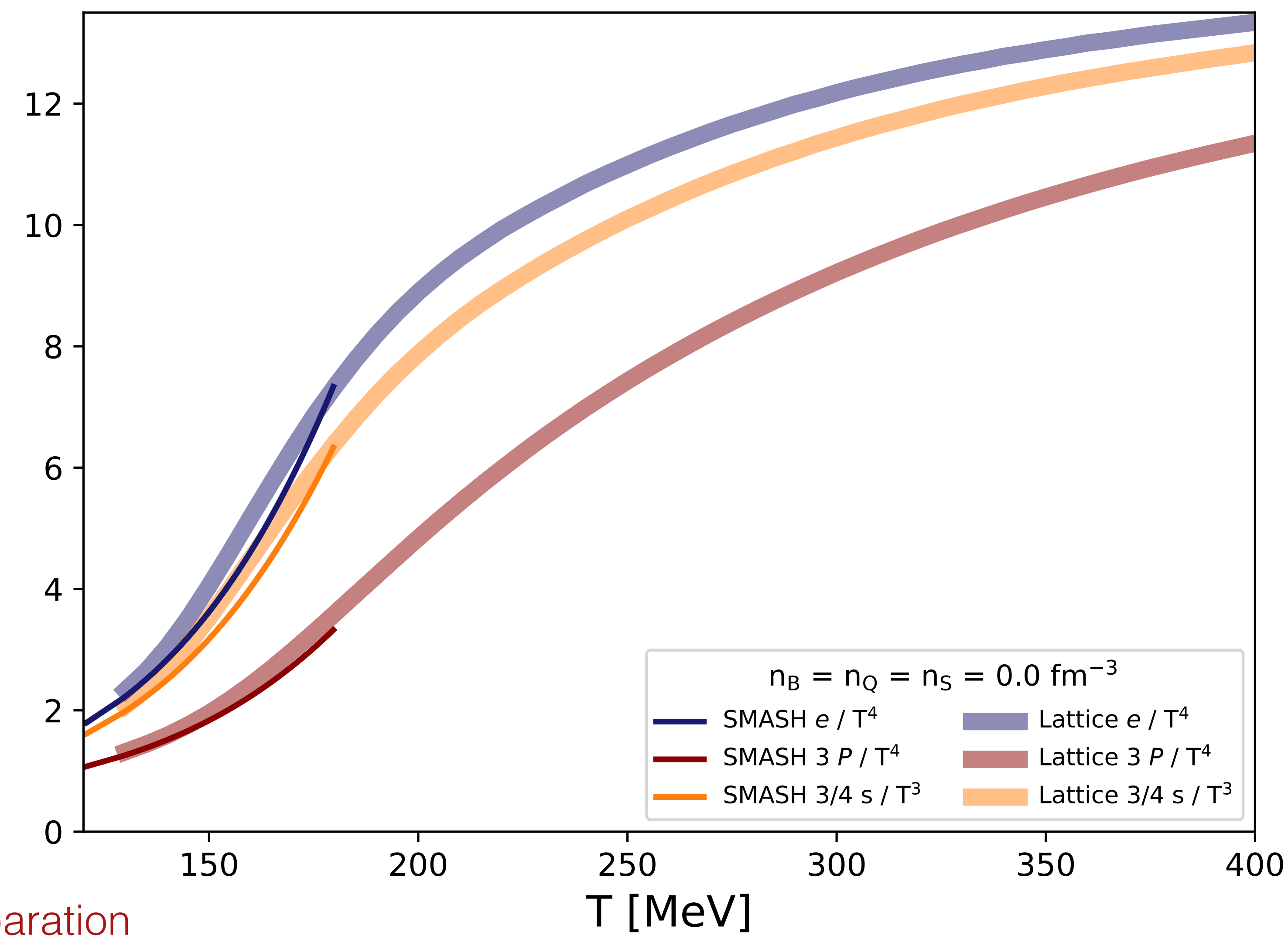




- Chiral equation of state for evolution matched to SMASH equation of state in final timestep
- Comparison to other equations of state is work in progress

SMASH Equation of State

- 4D EoS is calculated, on the hypersurface typically μ_B=250-450 MeV, μ_Q=70-110 MeV and μ_S = +/-50 MeV



A. Schäfer et al in preparation

Lattice data from Bazavov et al, PRD 90 (2014)

- Full modular hybrid and EoS parametrization/tables will be published with SMASH-2.0 this Fall

Electromagnetic Probes

Dileptons in SMASH

- Dileptons produced by resonance decays
- Direct and Dalitz dilepton decay channels
- Electromagnetic decays are rare —> Time-Integration-Method / *Shining*
  Phys.Lett. B259 (1991) 162-168
  – Continuously perform dilepton decays and weight them by taking their decay probability into account (better statistics)
- Detailed constraints on resonance properties

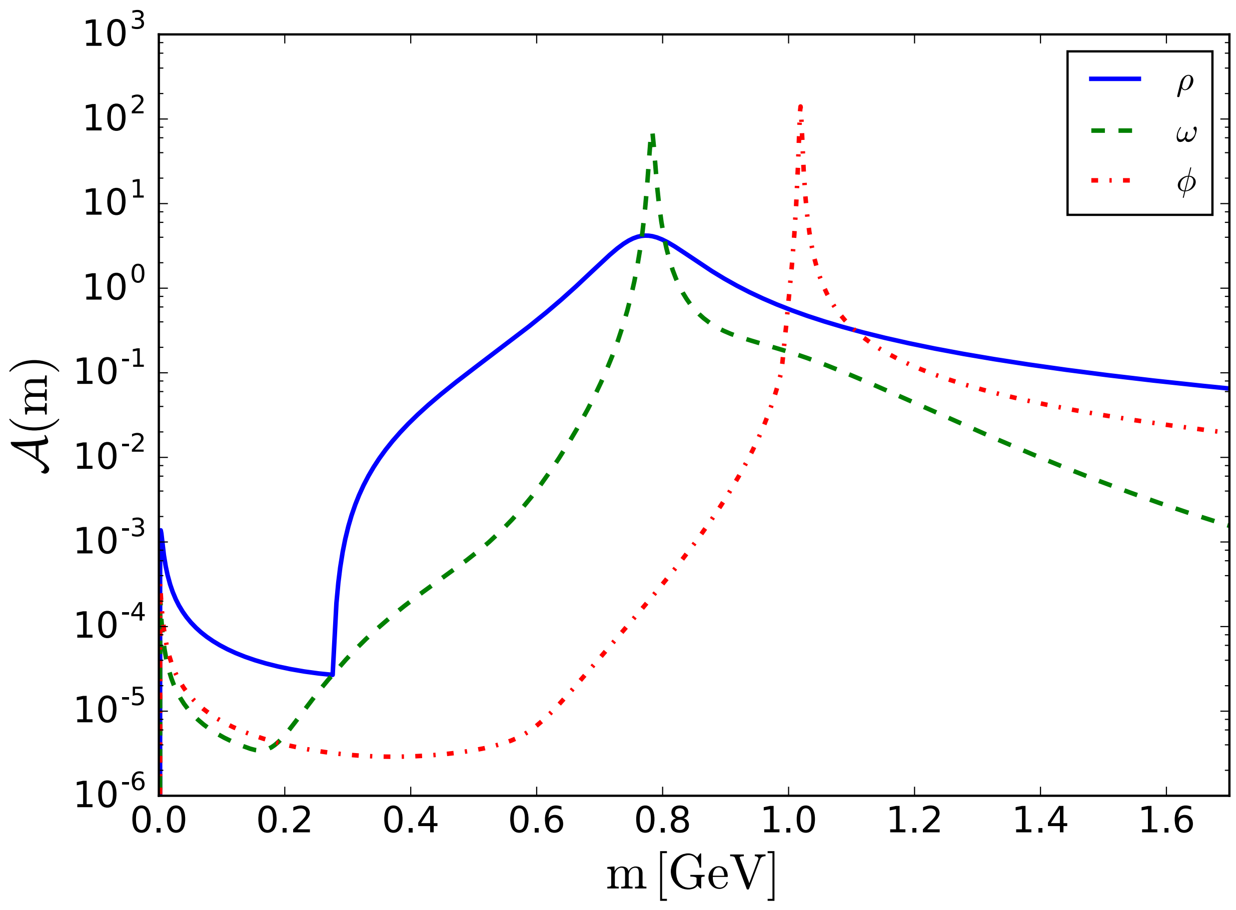
J. Staudenmaier et al, Phys.Rev. C98 (2018) no.5, 054908

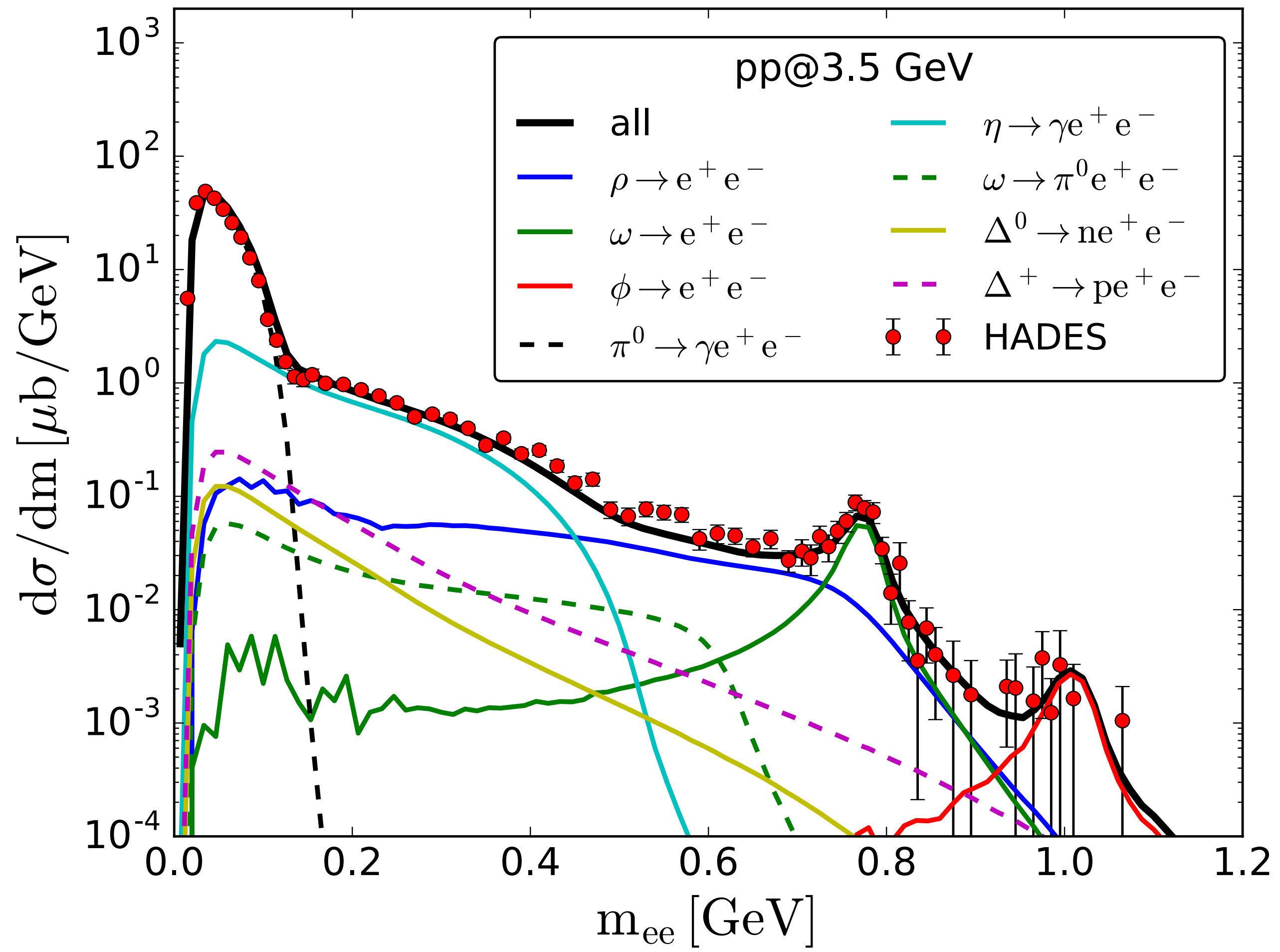
Dilepton Decays
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\phi \to e^+e^-$
$\pi \to e^+e^-\gamma$
$\eta \to e^+e^-\gamma$
$\eta' \to e^+e^-\gamma$
$\omega \to e^+e^-\pi^0$
$\phi \to e^+e^-\pi^0$
$\Delta^+ \to e^+e^-p$
$\Delta^0 \to e^+e^-n^0$

Elementary Collisions

- Contributions of vector meson spectral functions below hadronic thresholds

HADES, Eur.Phys.J. A48 (2012)





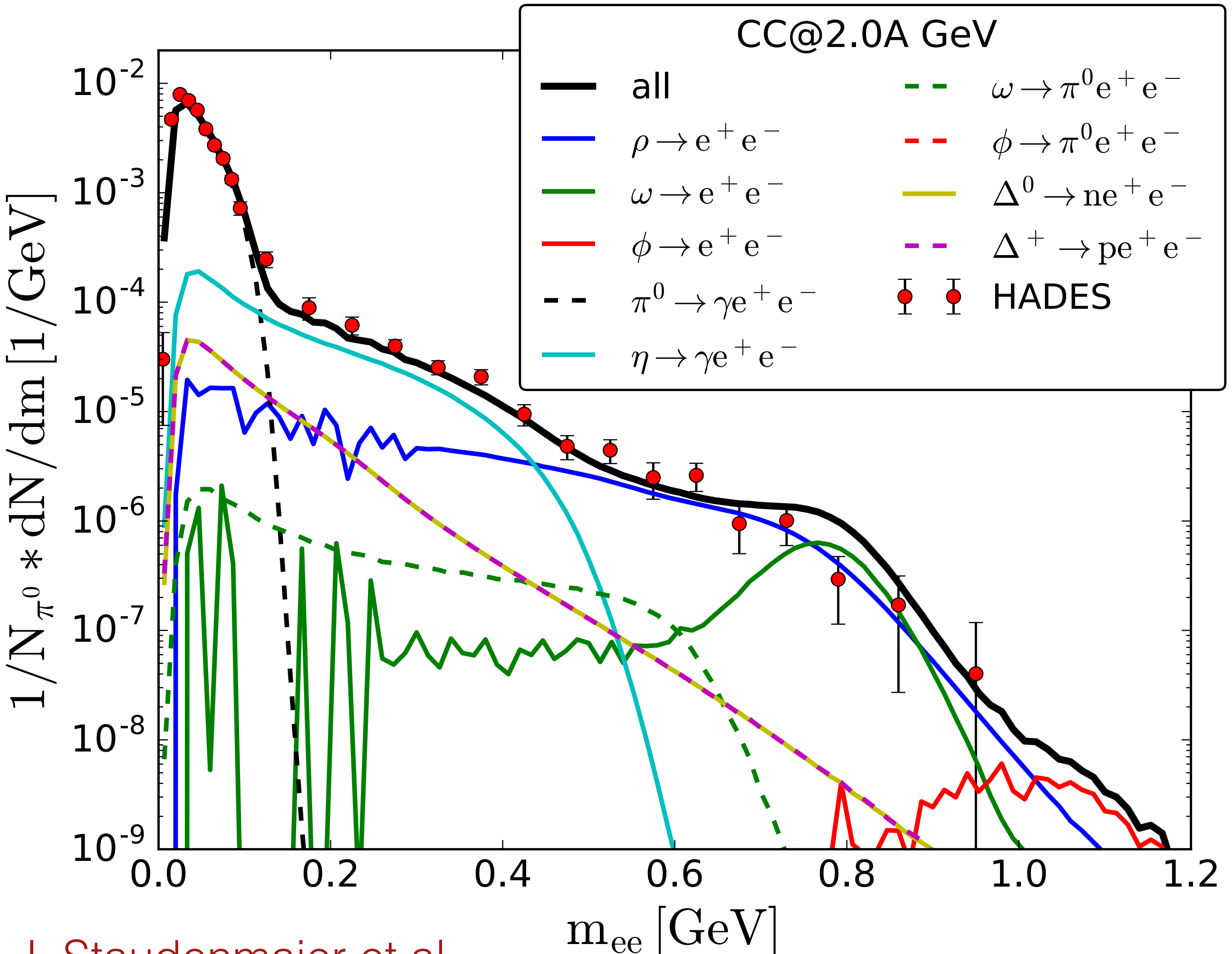
J. Staudenmaier et al,
Phys.Rev. C98 (2018) no.5, 054908

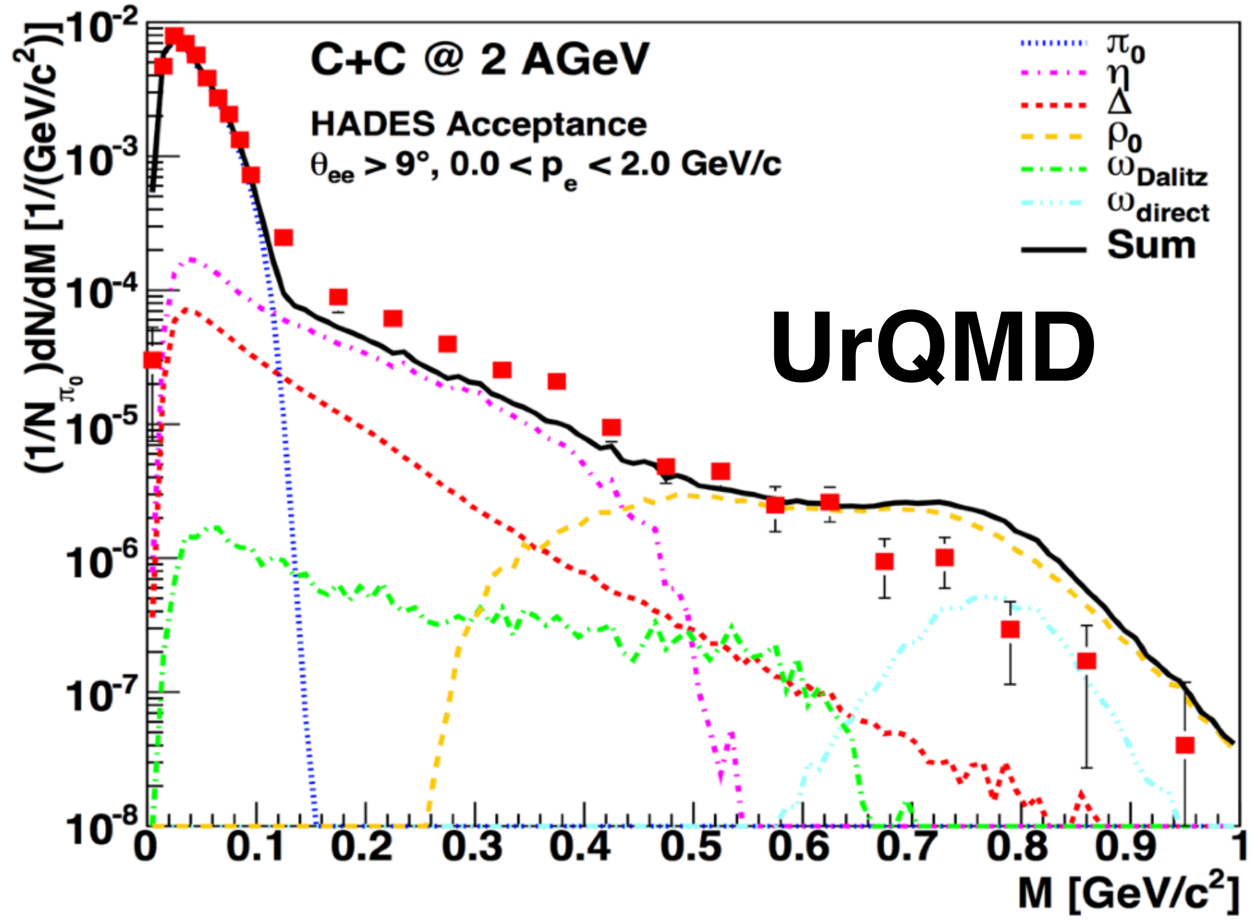
- Very nice agreement with HADES measurement

Dilepton Production

- SMASH and UrQMD compare very similar to data

HADES, PRL 98 (2007)





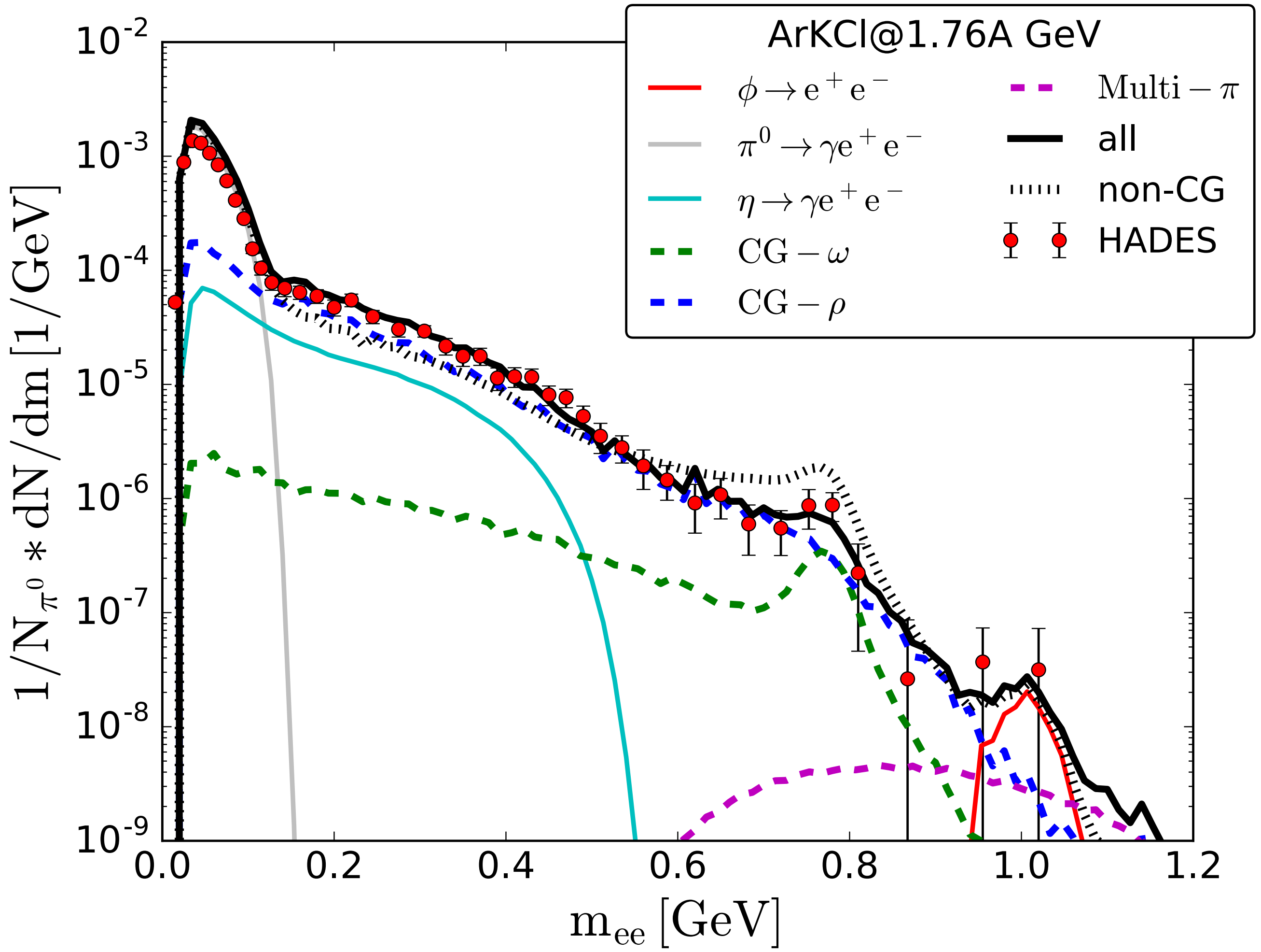
J. Staudenmaier et al, Phys.Rev. C98 (2018) no.5, 054908

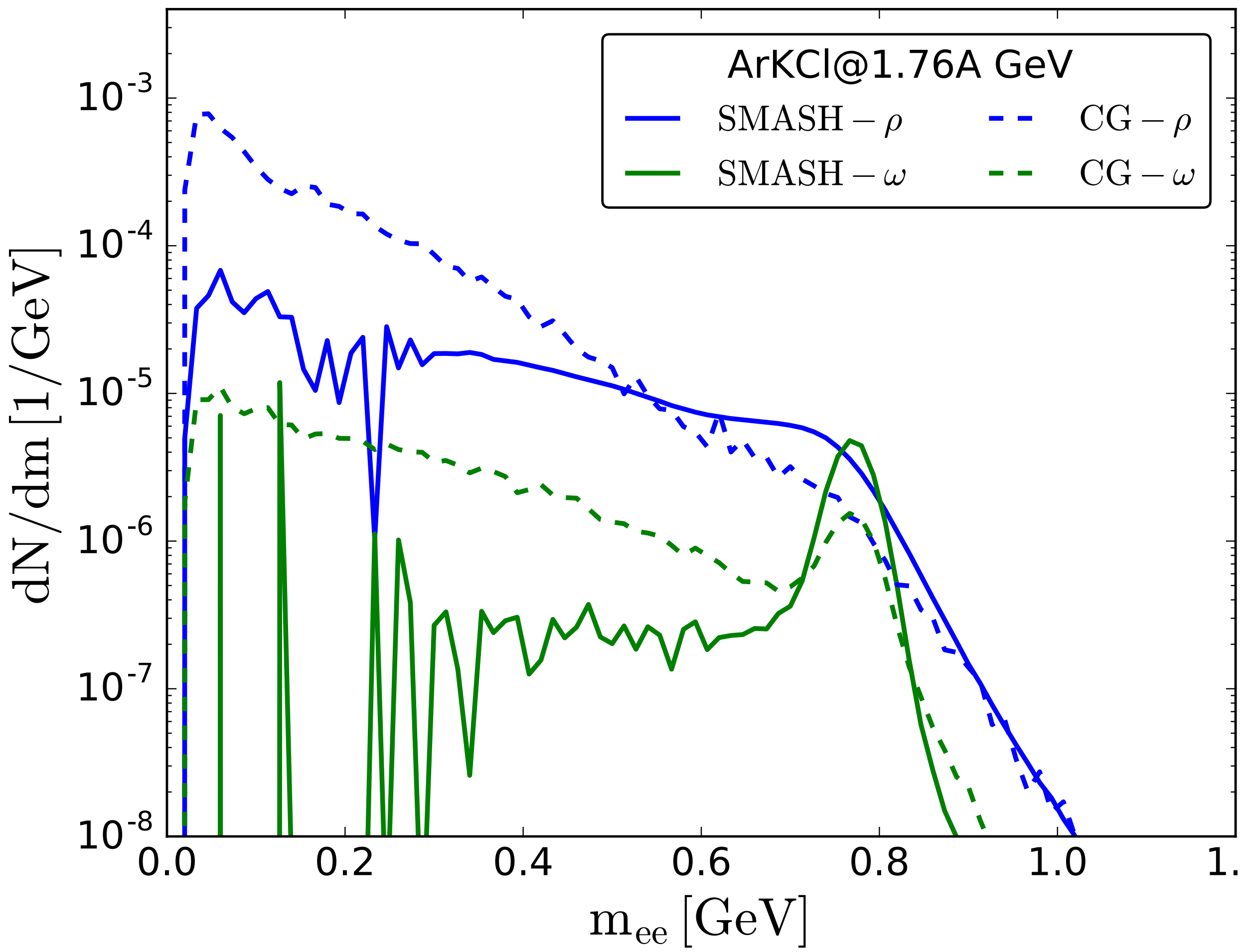
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

- Different vector meson thresholds at low masses
- Adjusted branching ratios of N* and Δ resonances for ρ peak

Medium Modifications

- Dynamical collisional broadening is included in default SMASH calculation



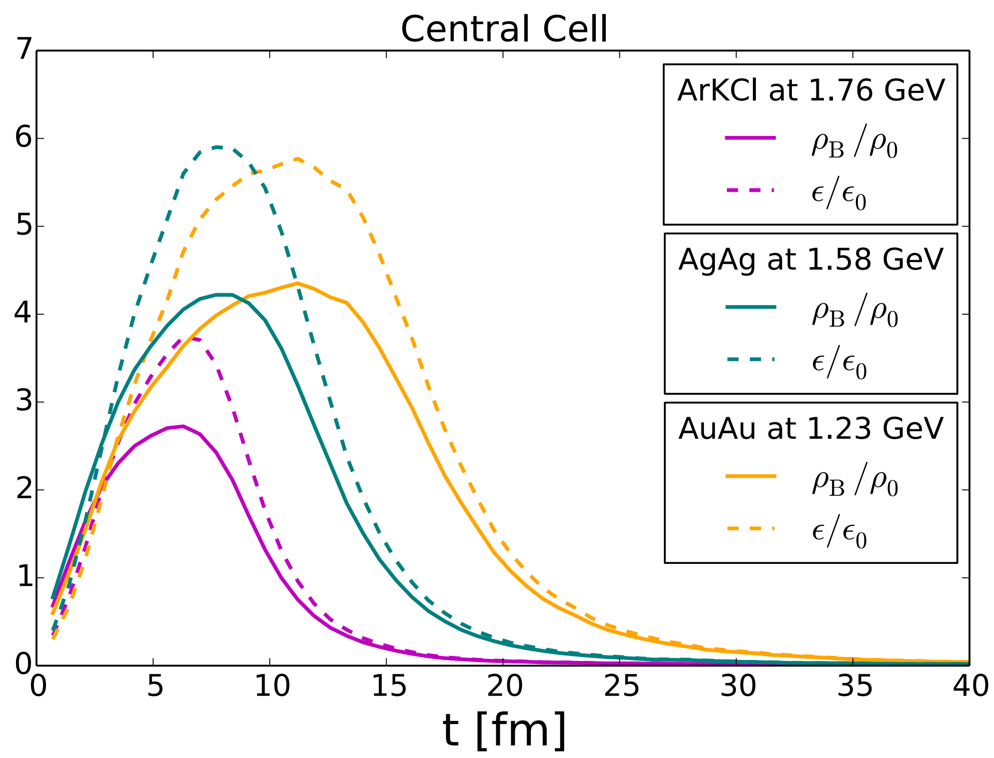


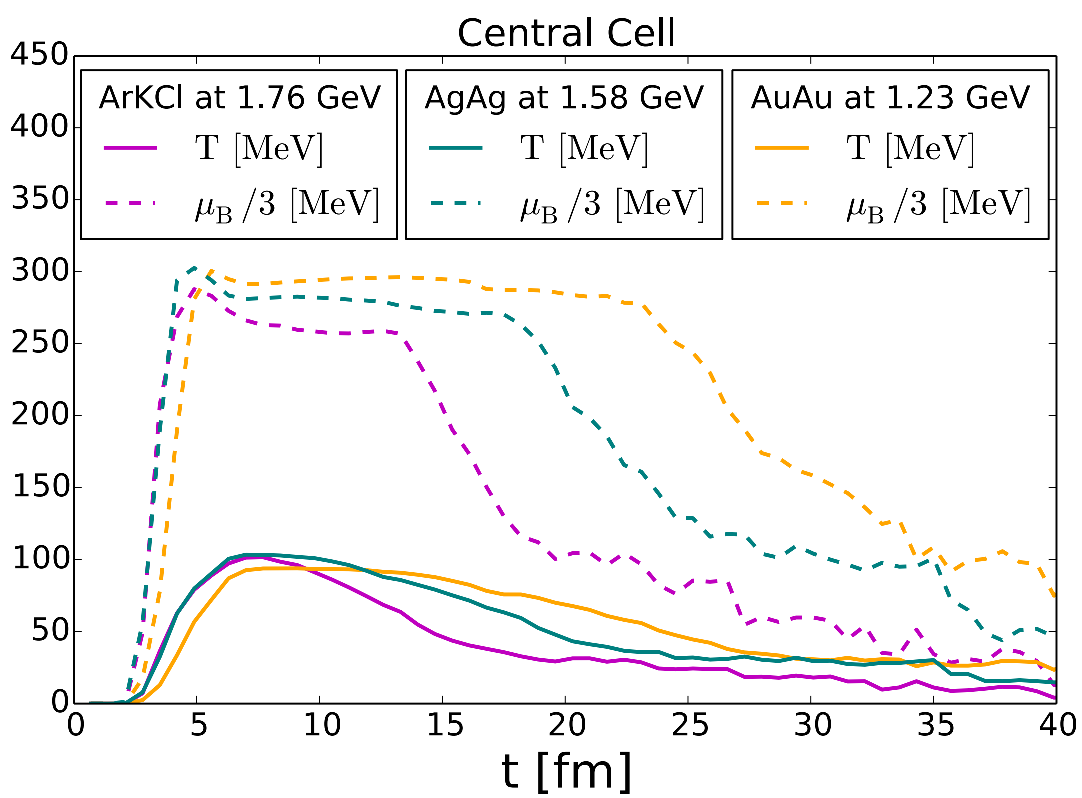
- Coarse-grained transport evolution allows for full medium-modified spectral function
- First time: Comparison of both approaches based on the same medium evolution

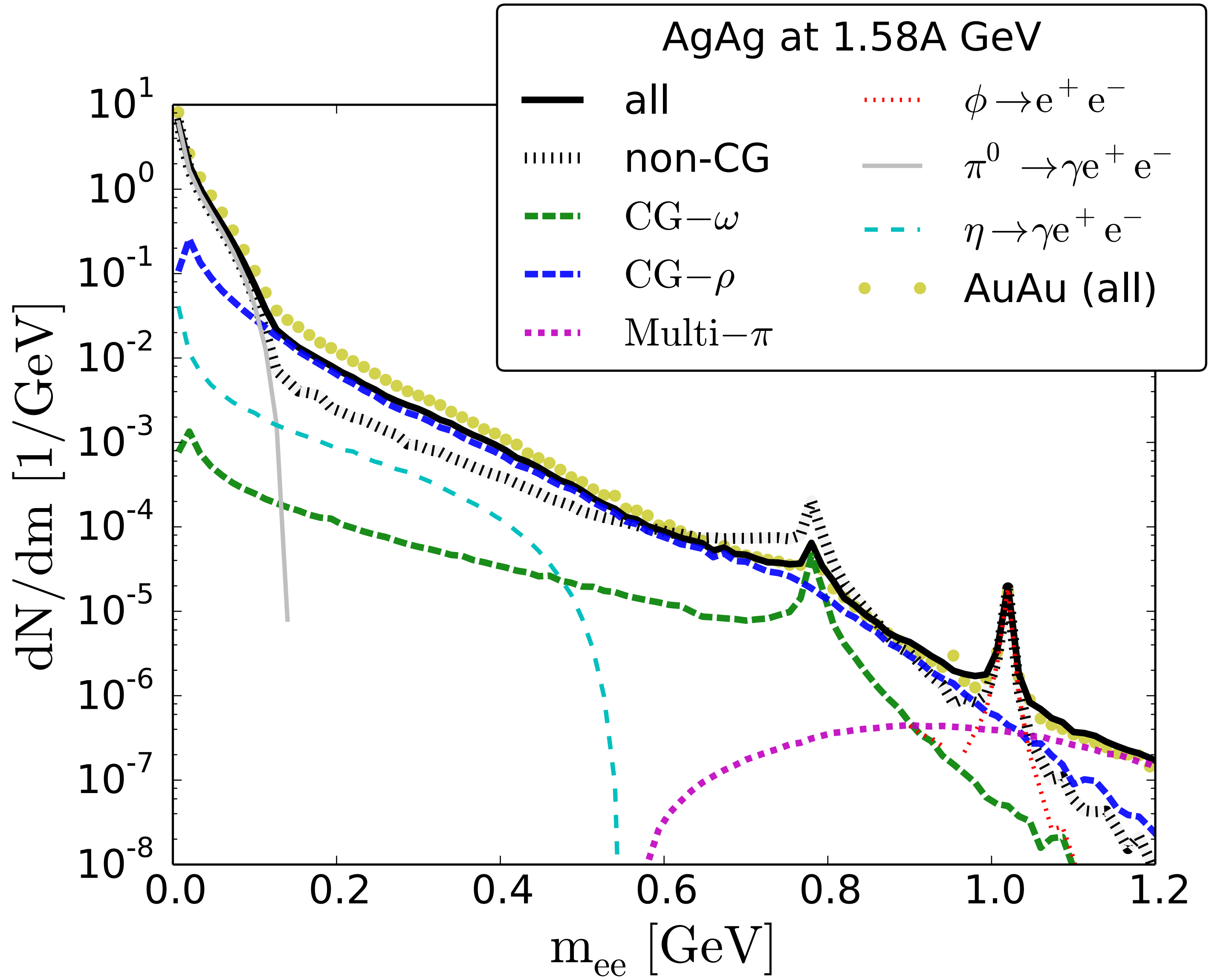
S. Endres et al., PRC 92, 2015
R. Rapp et al, EPJA 6, 1999, PRC 63, 2001

J. Staudenmaier et al, Phys.Rev. C98 (2018) no.5, 054908

AgAg Predictions







- Invariant mass spectrum very similar in smaller system at higher energy

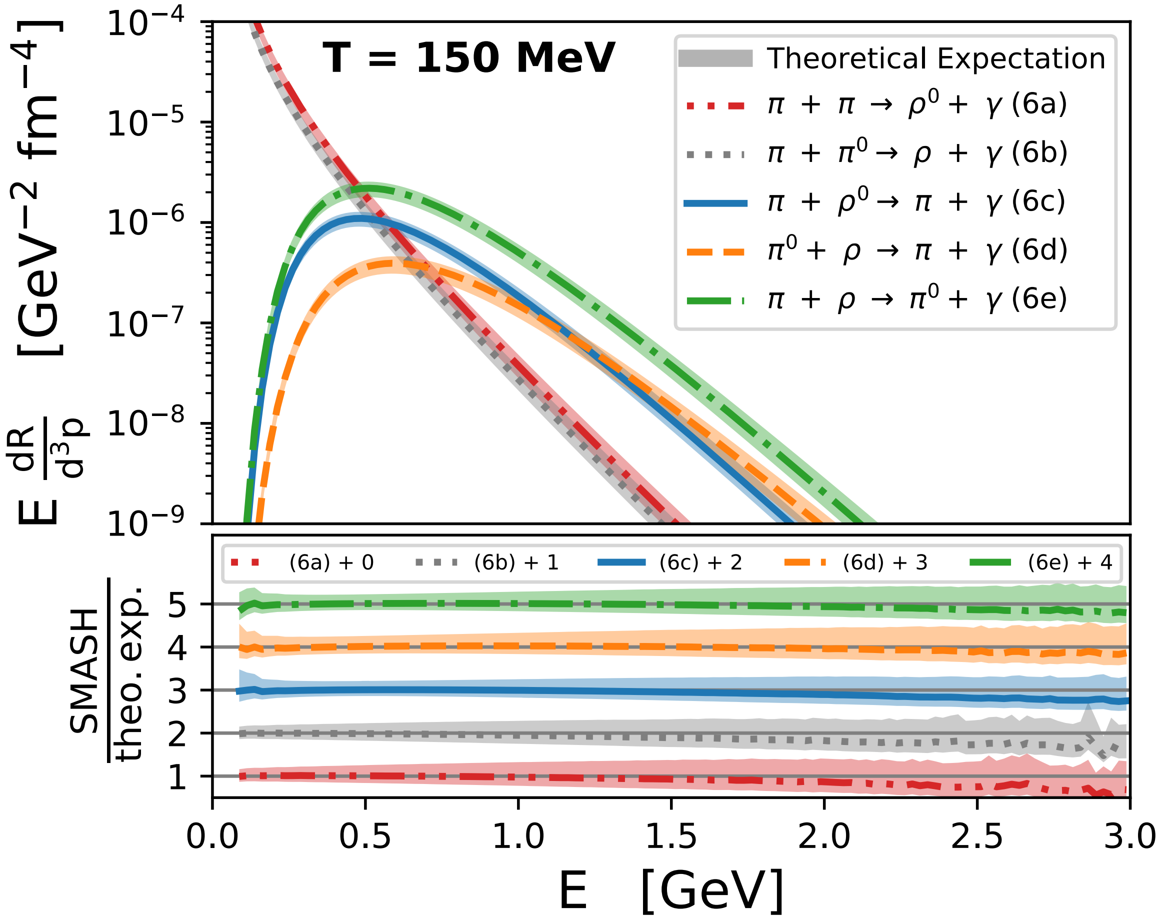
J. Staudenmaier, N. Kübler and HE, arXiv: 2008.05813

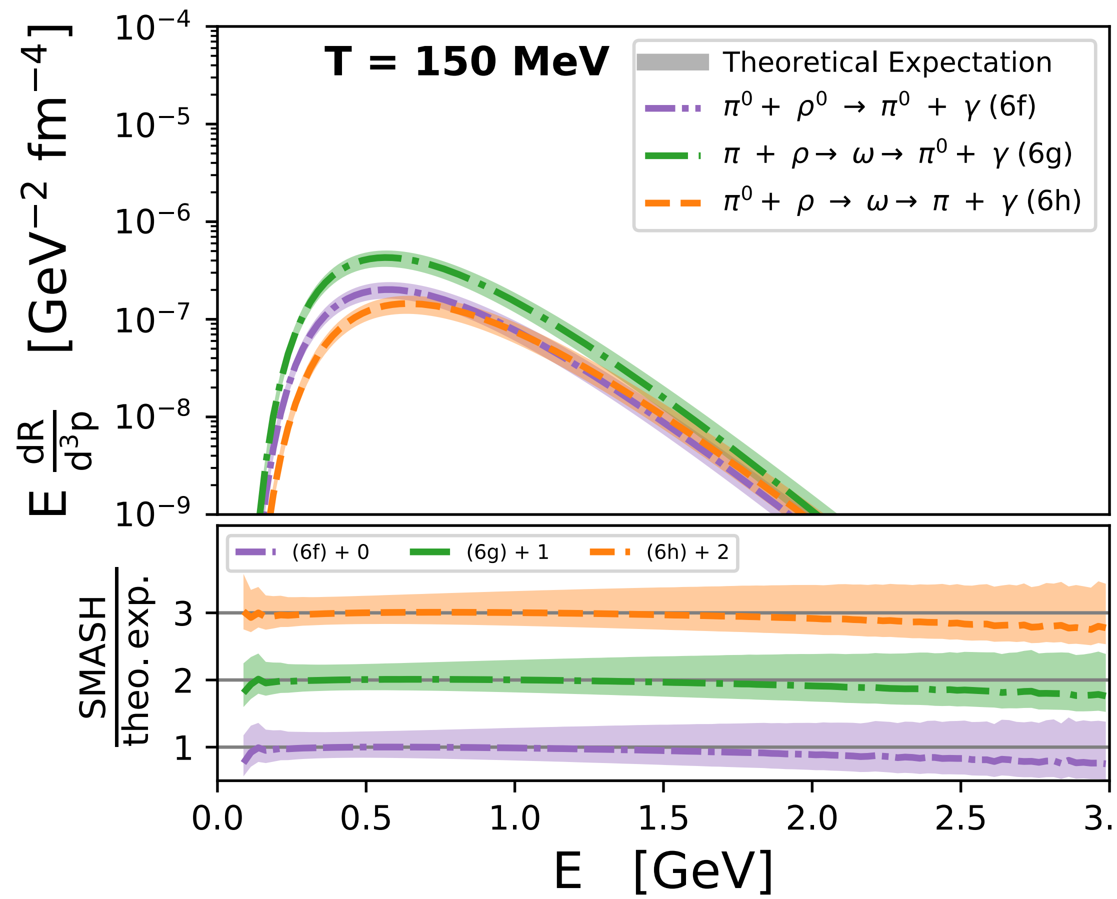
Photons

- Perturbative photon production in hadronic scatterings of pions and ρ mesons

Turbide et al.: Int.J.Mod.Phys. A19 (2004)

- Cross-sections calculated within effective field theory





- Rates in thermal box nicely reproduced

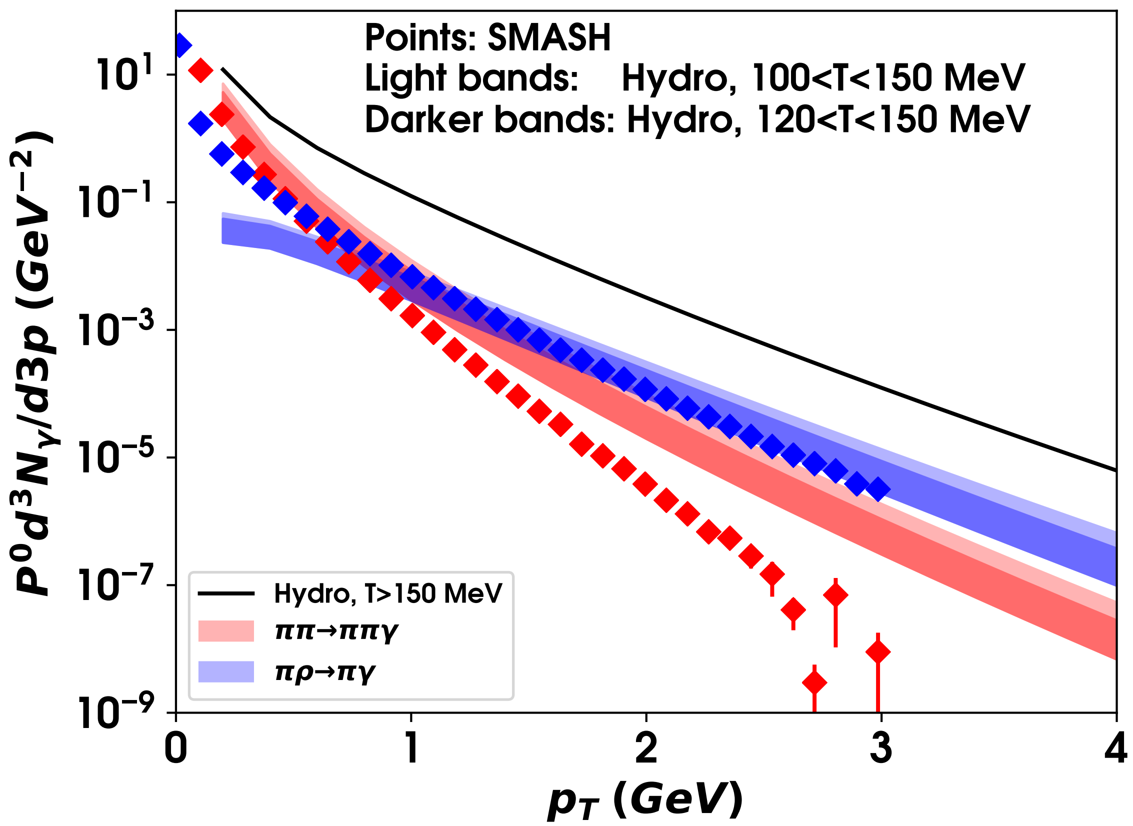
A, Schäfer et al, arXiv:1902.07564

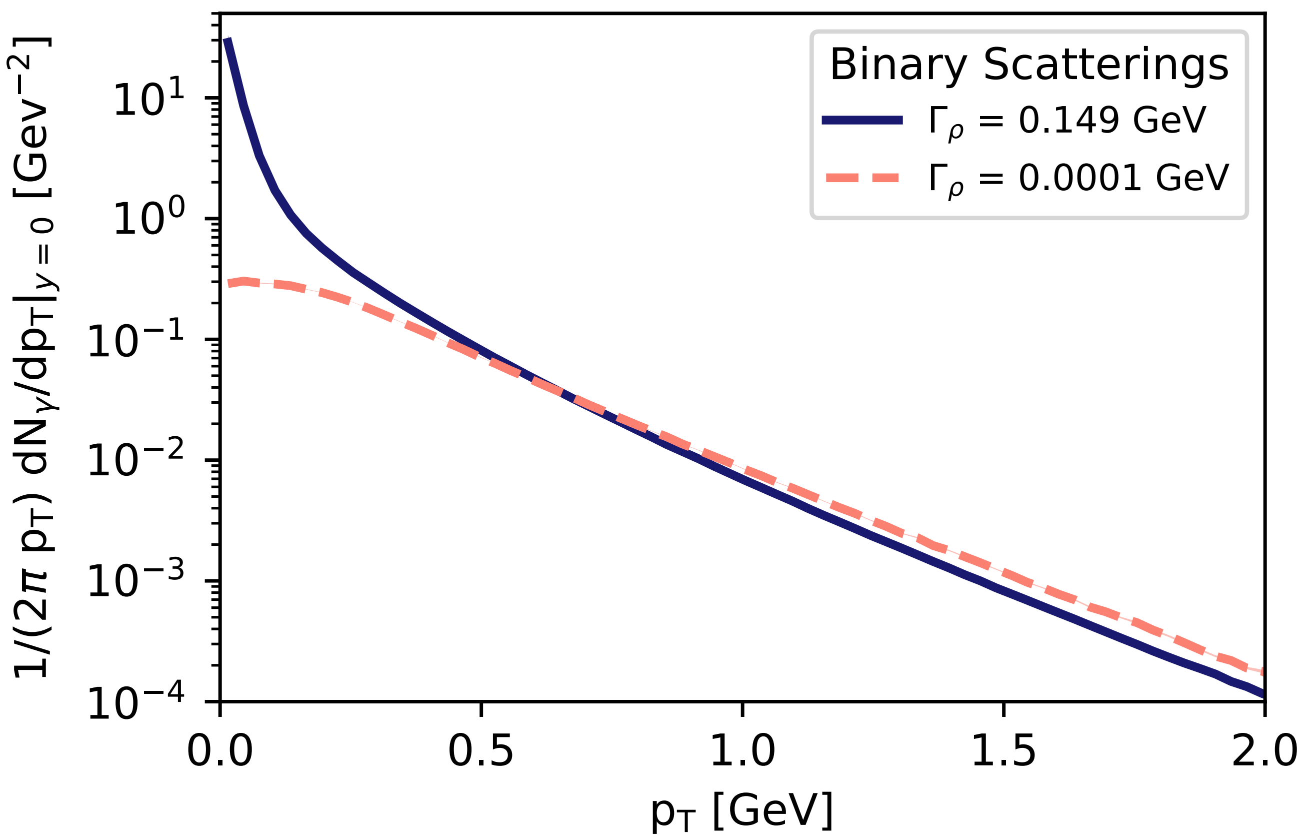
- Next: Photons from late non-equilibrium stage at RHIC/LHC including bremsstrahlung

Preliminary Results

- Comparison of thermal versus non-equilibrium photon production from the hadronic stage

A. Schäfer et al, in preparation (in collaboration with J.-F. Paquet and C. Gale)





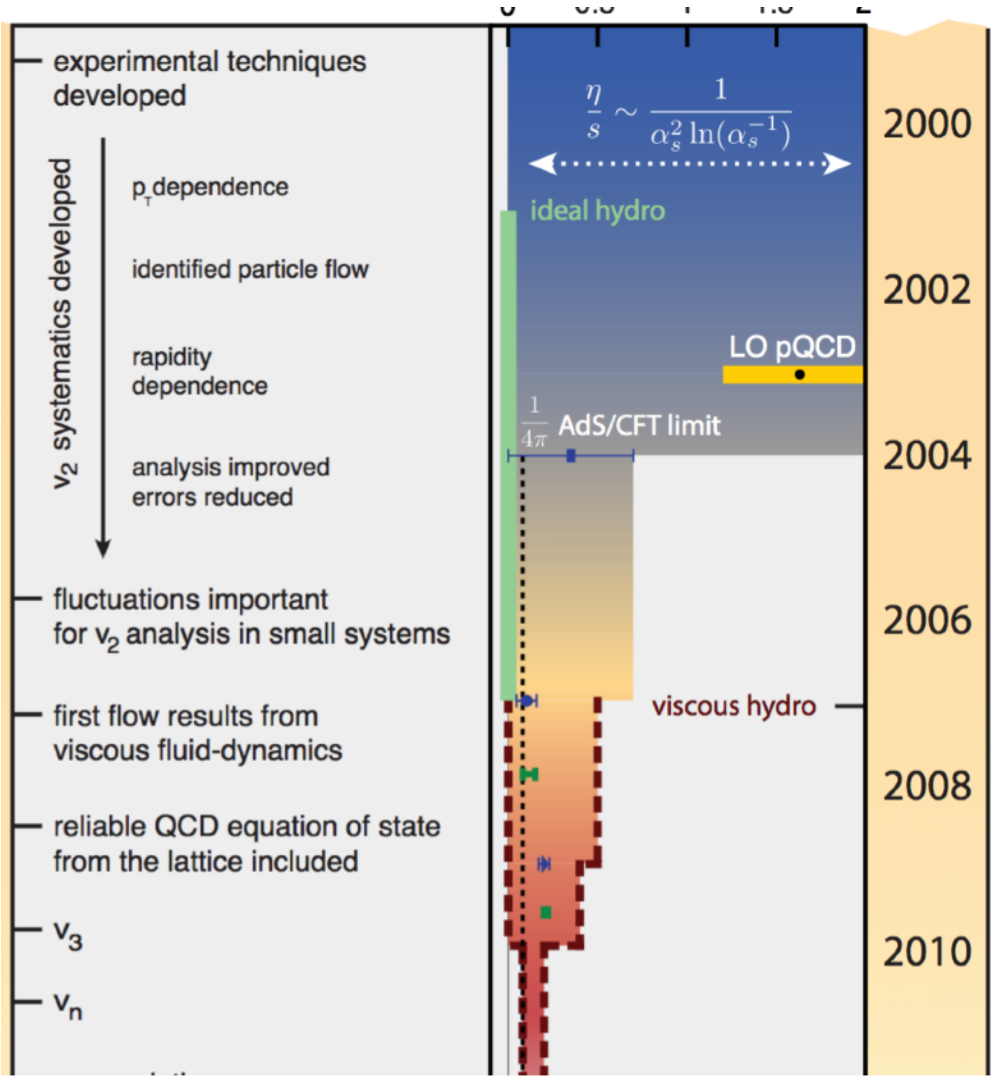
- Including the finite width of the ρ meson leads to a sizeable difference at low momenta due to larger available phase space

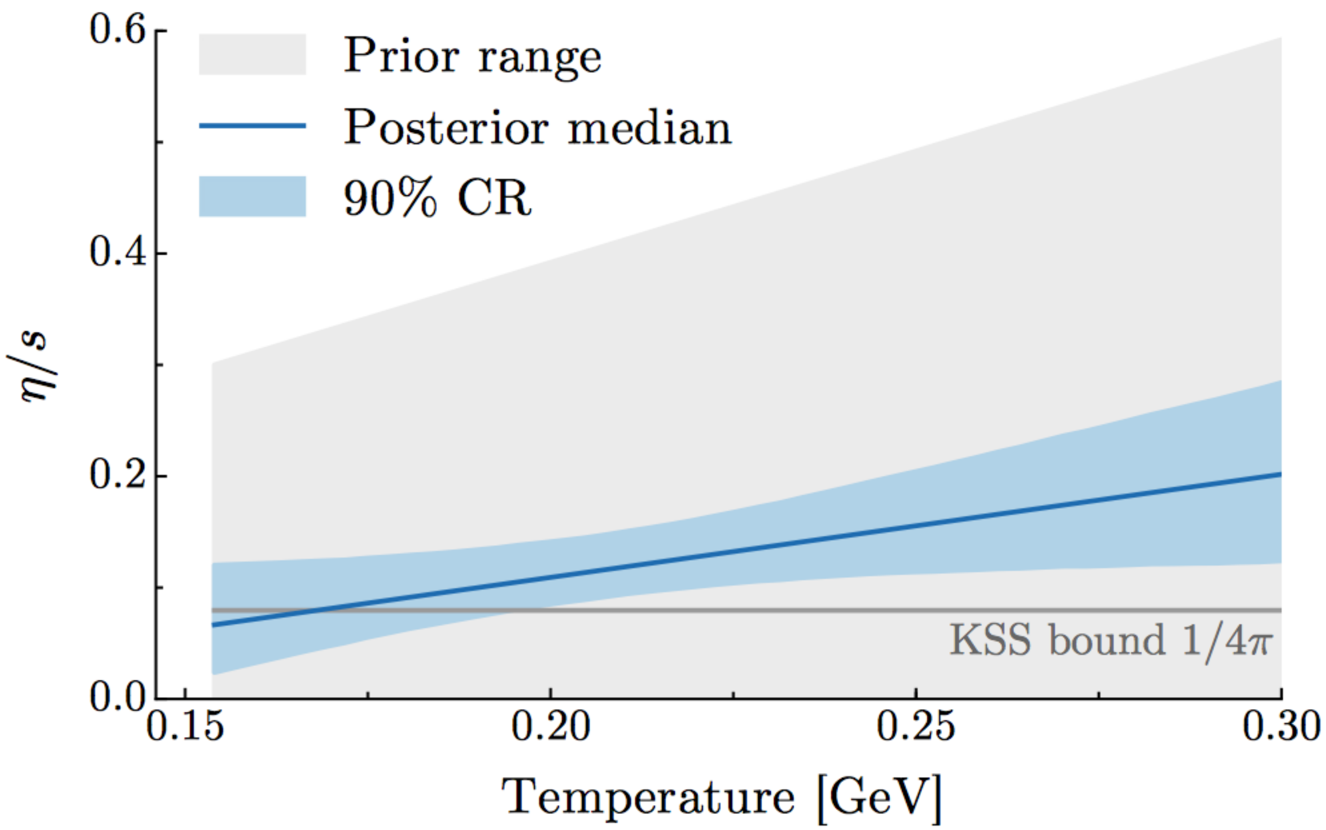
Transport Coefficients

Transport Coefficients

- Within hydrodynamics/hybrid approaches the shear viscosity is an input parameter

RHIC White paper, 2012





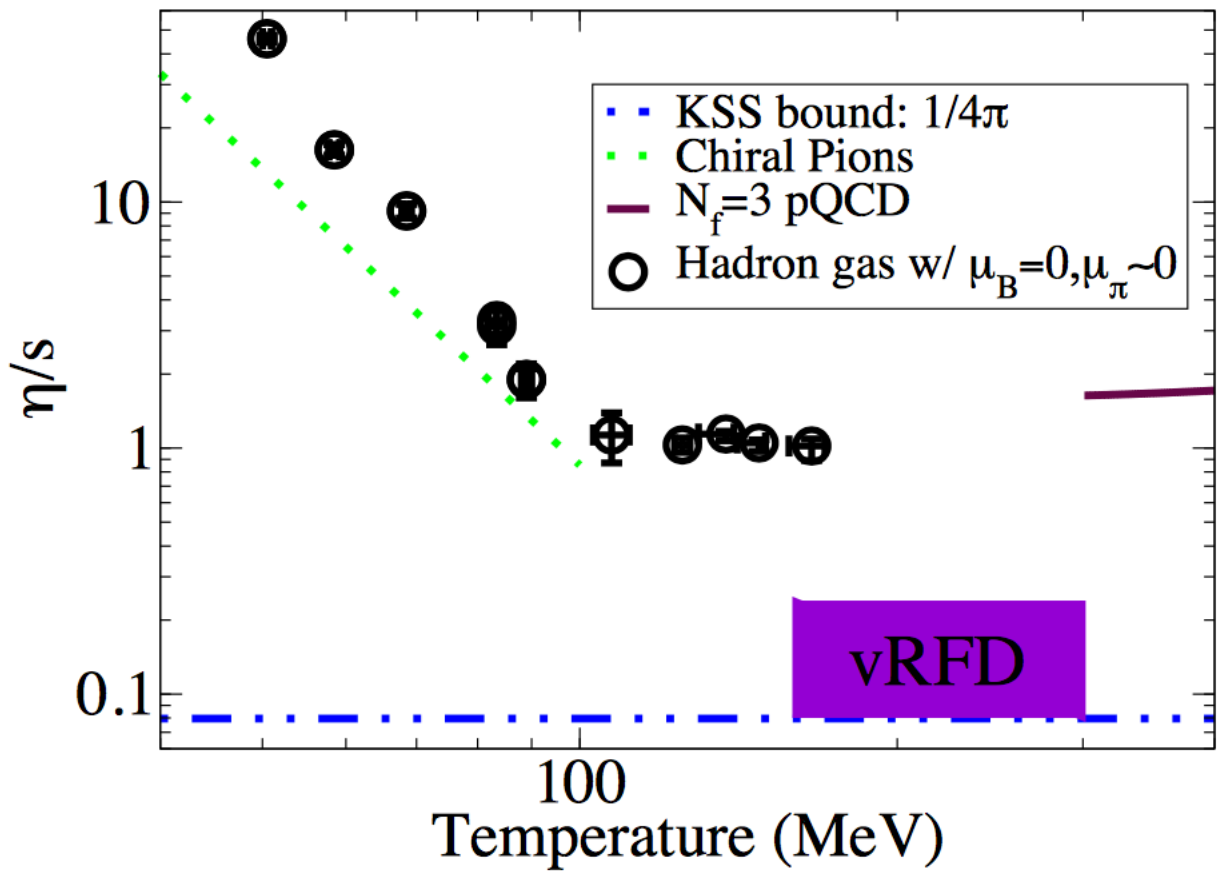
J. Bernhard et al, Phys.Rev. C94 (2016)

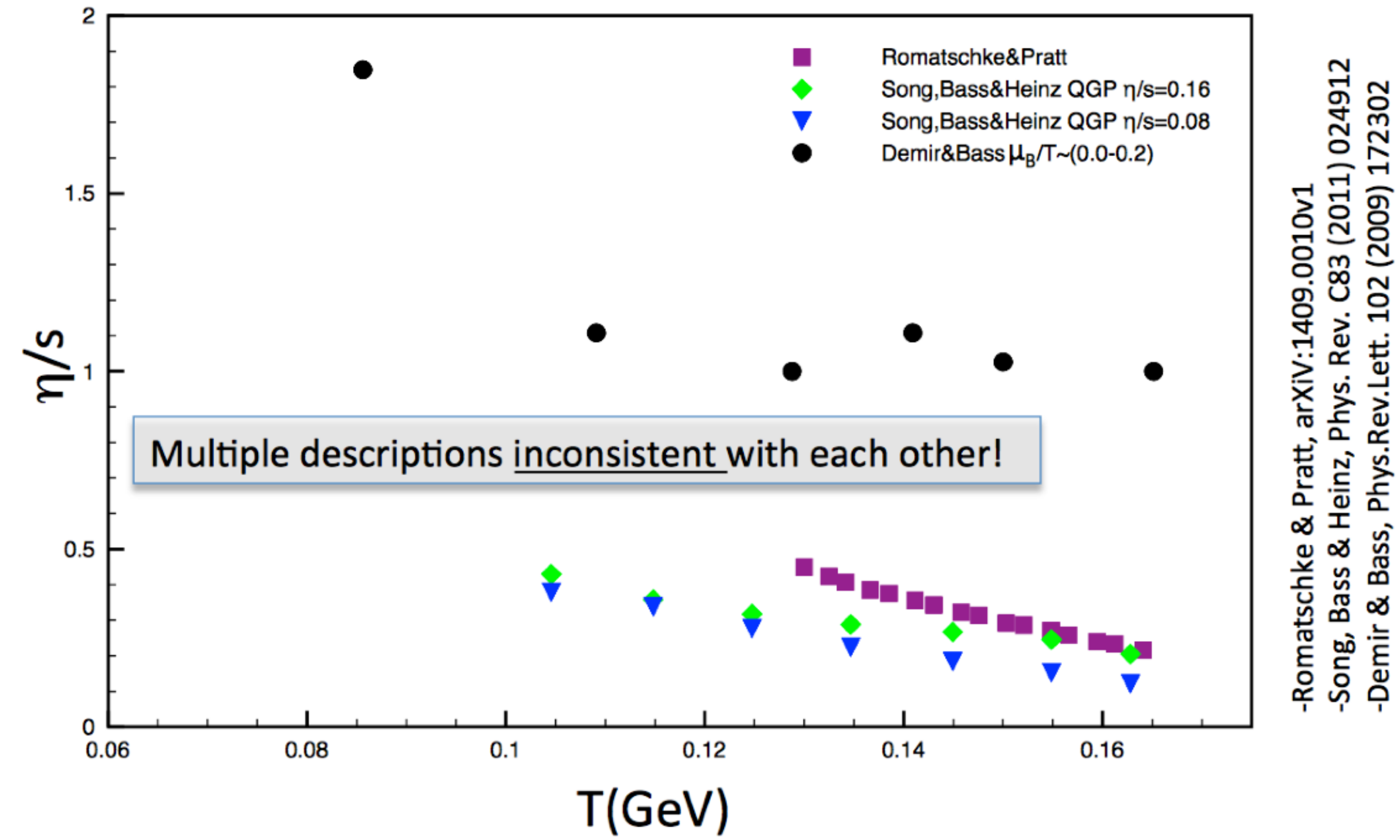
- The low temperature part corresponds to a hadron gas with its interactions

Shear Viscosity of the Hadron Gas

Green-Kubo formalism
UrQMD

Discrepancy with
hydro-inspired B3D and VISHNU





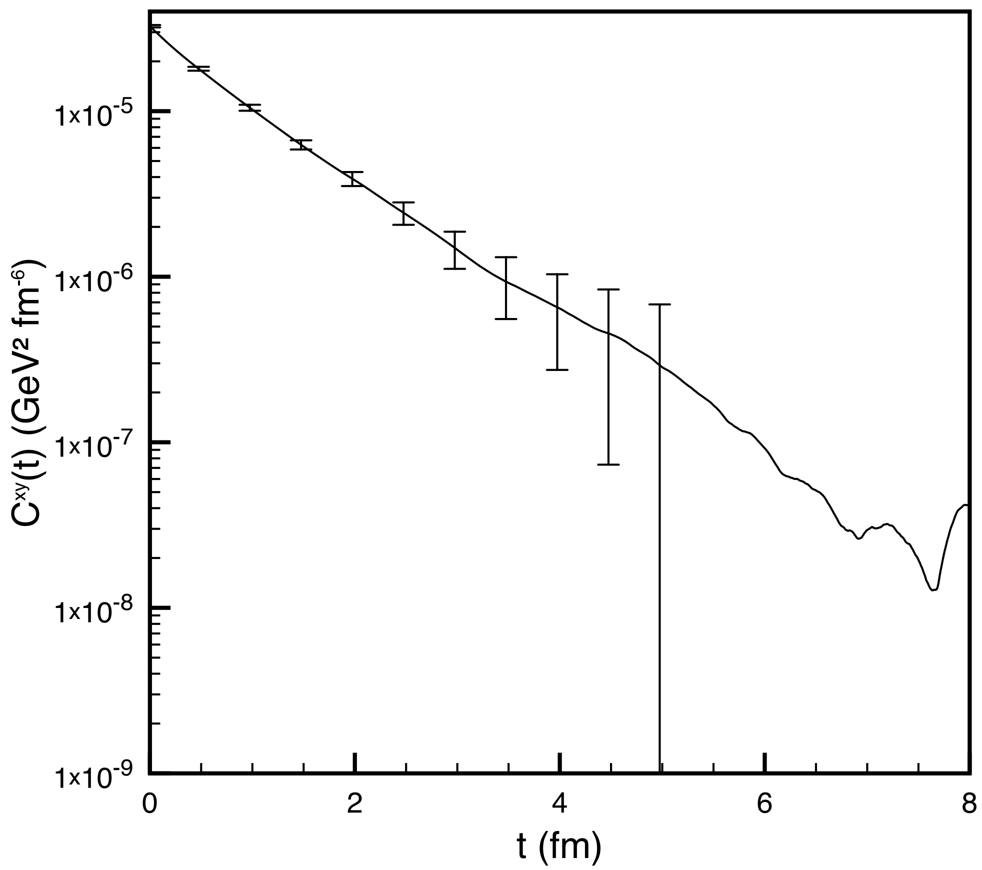
N. Demir and S.A. Bass, PRL 102 (2009)

- Long standing question: Why are the results so different from each other?

J.-B. Rose, J. M. Torres-Rincon, A. Schäfer, D. Oliinychenko and HP, PRC97 (2018) and JPCS 1024 (2018)

Shear Viscosity over Entropy Density

- Hadron gas in thermodynamic equilibrium realised by box with periodic boundary conditions
- Entropy is calculated via Gibbs formula from thermodynamic properties
- The shear viscosity is extracted following the Green-Kubo formalism:



$$T^{\mu\nu} = \frac{1}{V} \sum_i^{N_{part}} \frac{p_i^\mu p_i^\nu}{p_i^0}$$

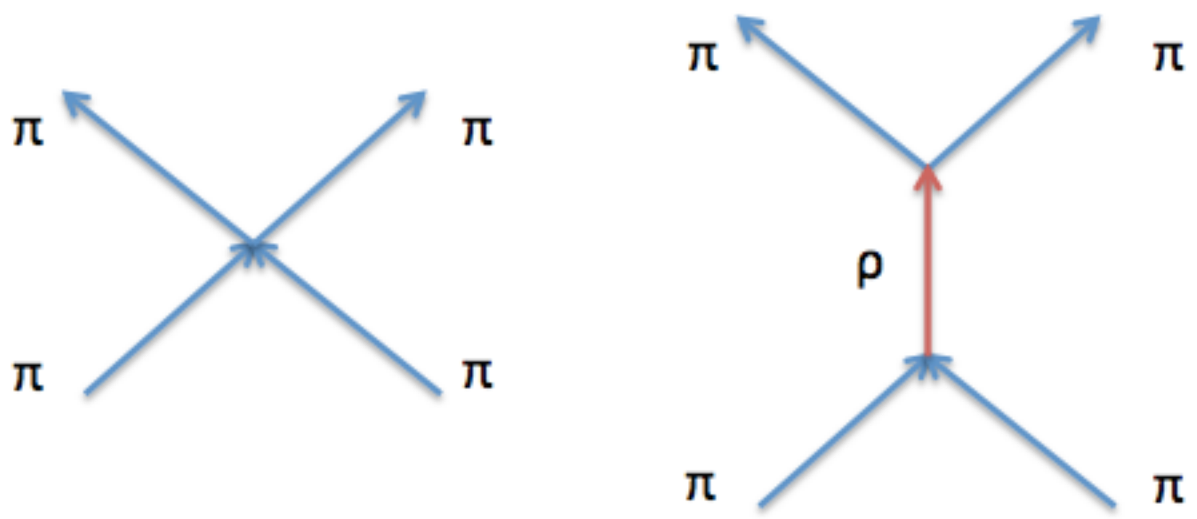
$$C^{xy}(t) = \frac{1}{N} \sum_s^N T^{xy}(s) T^{xy}(s+t)$$

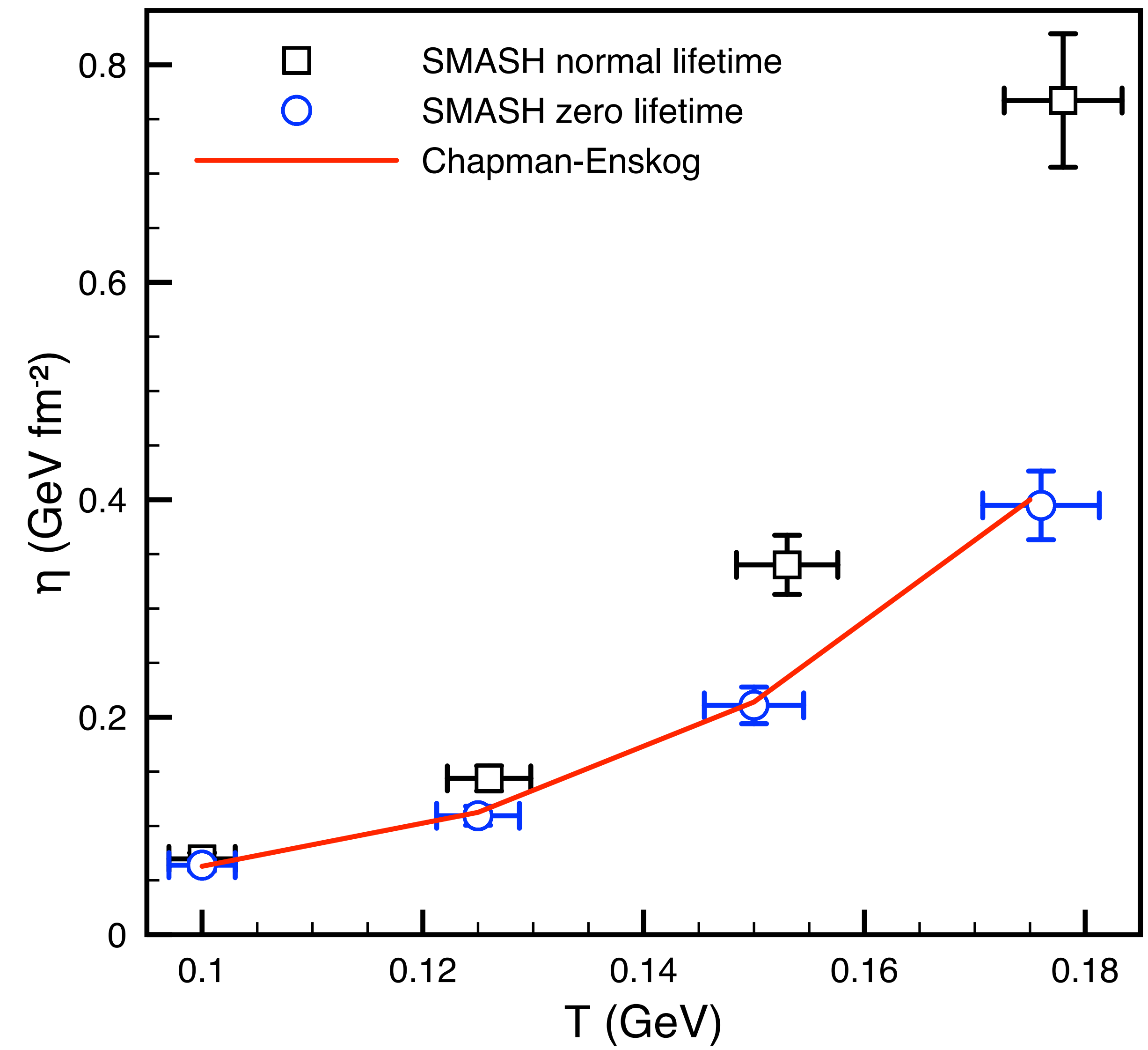
$$C^{xy}(t) \simeq C^{xy}(0) \exp\left(-\frac{t}{\tau}\right)$$

$$\eta = \frac{V C^{xy}(0) \tau}{T}$$

Resonance Dynamics

- Energy-dependence of cross-sections is modelled via resonances
- Point-like in analytic calculation and finite lifetime in transport approach

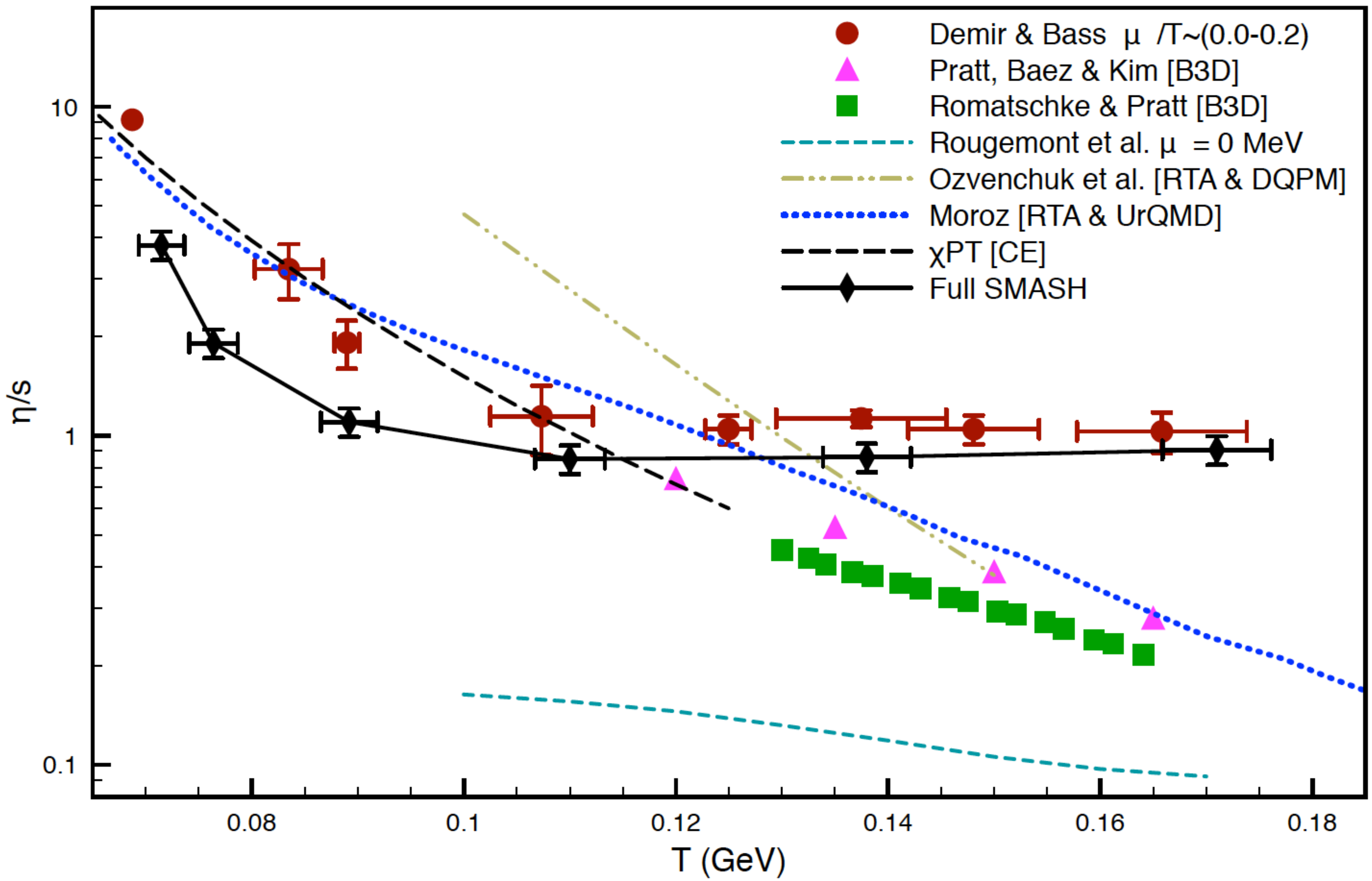




- Agreement recovered by decreasing ρ meson lifetime

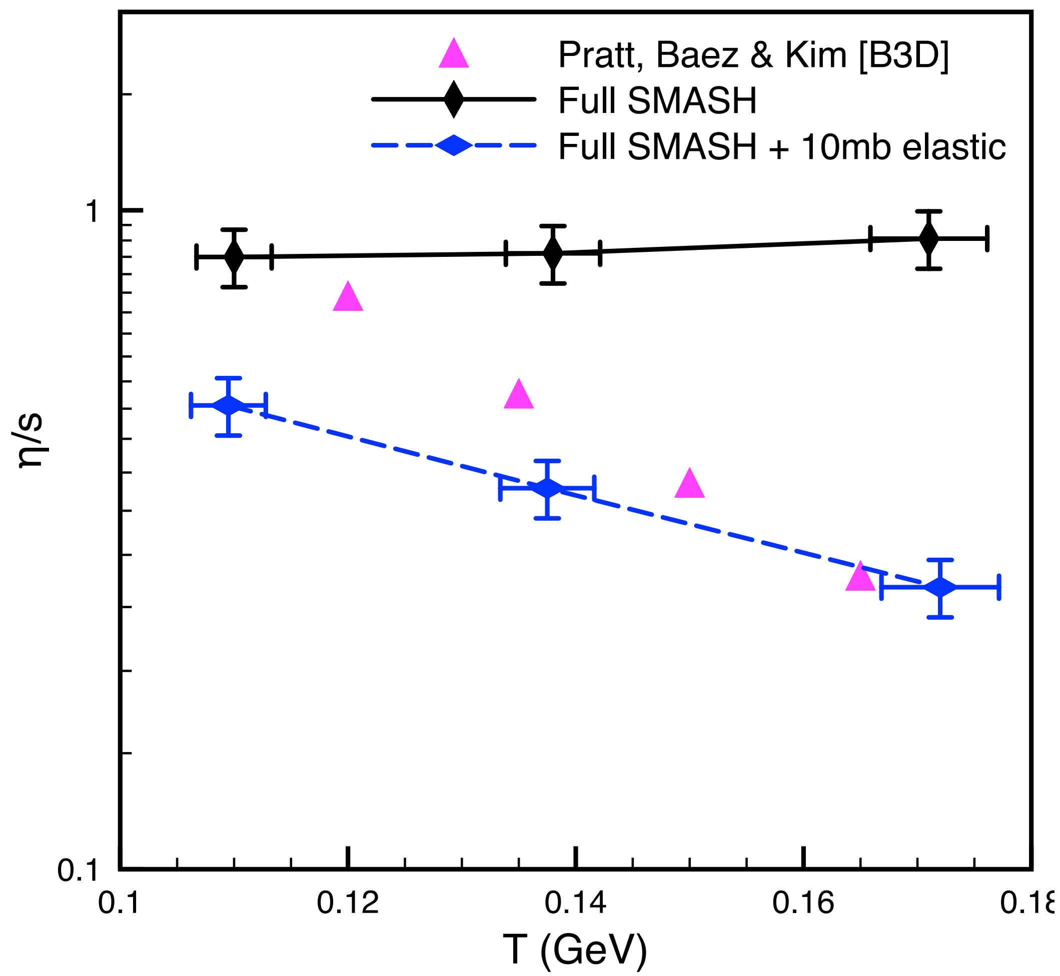
Comparison to Literature

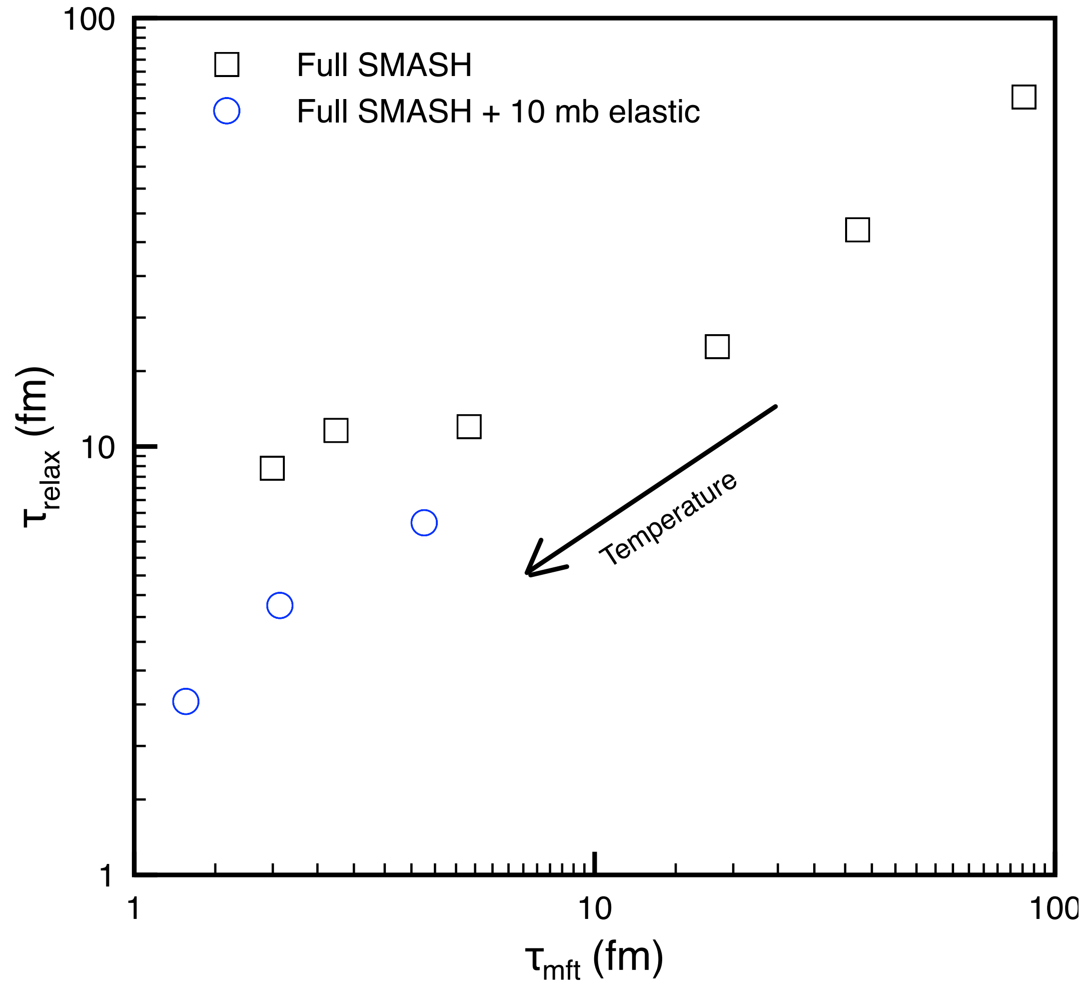
- Closest similarity to Bass/Demir result as expected



Point-like Interactions

- Adding a constant elastic cross section leads to agreement with B3D result



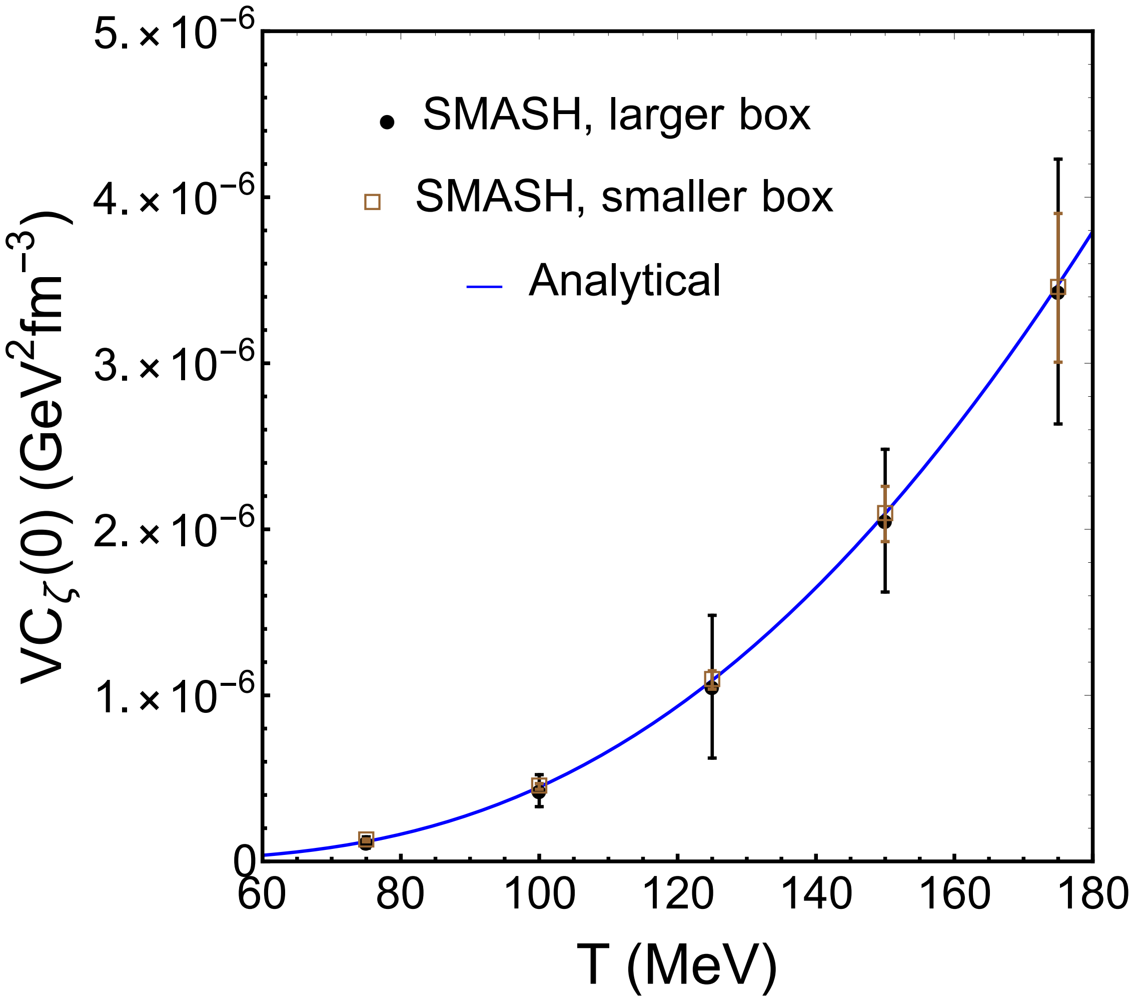


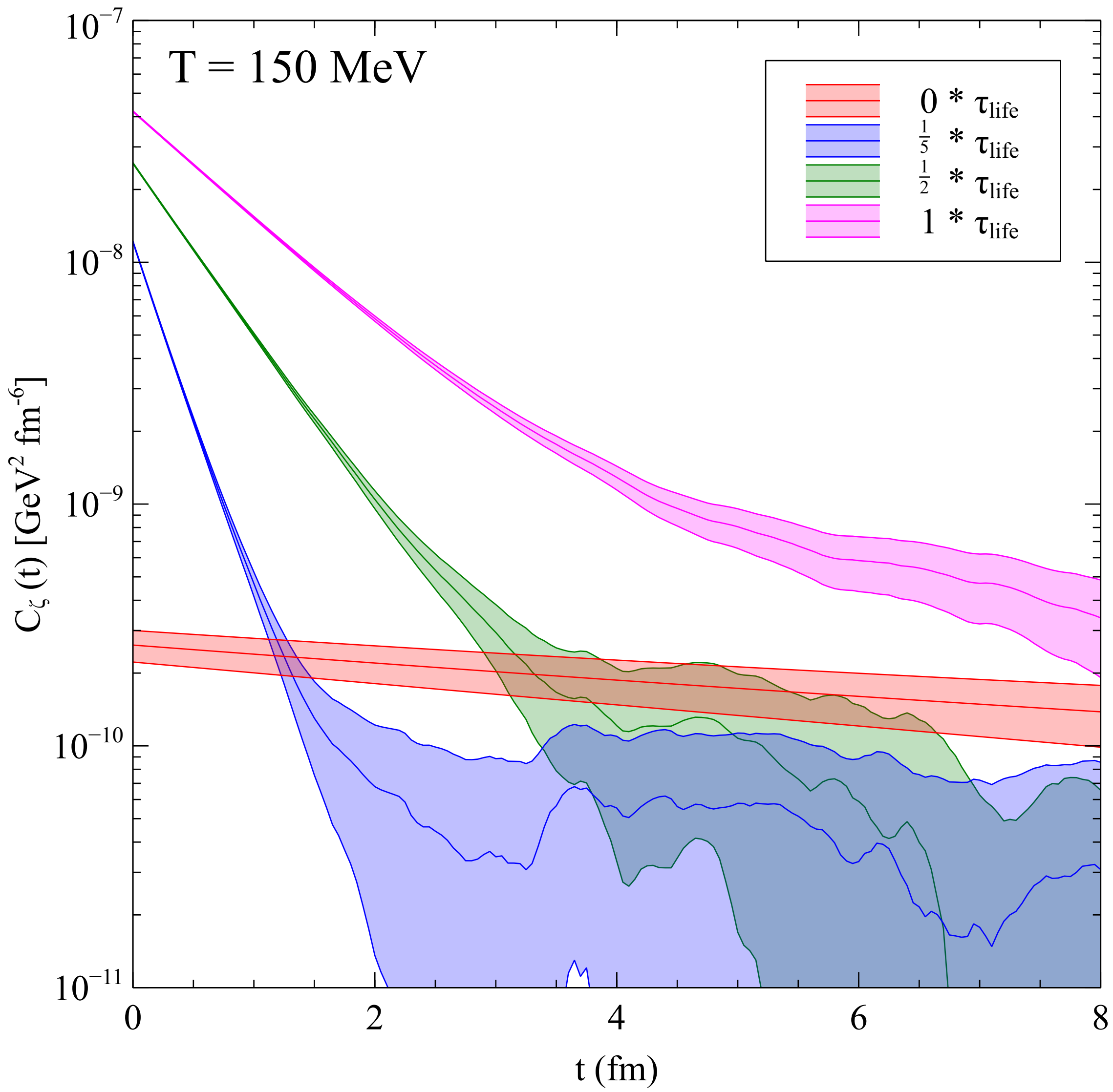
- Approximately linear relationship between relaxation time and mean free time is recovered
- Viscosity constrains the hadronic interactions

Bulk Viscosity of the Hadron Gas

- Bulk viscosity is very sensitive to the resonances and their dynamics

J.-B. Rose, J. M. Torres-Rincon and HE, arXIv: 2005.03647

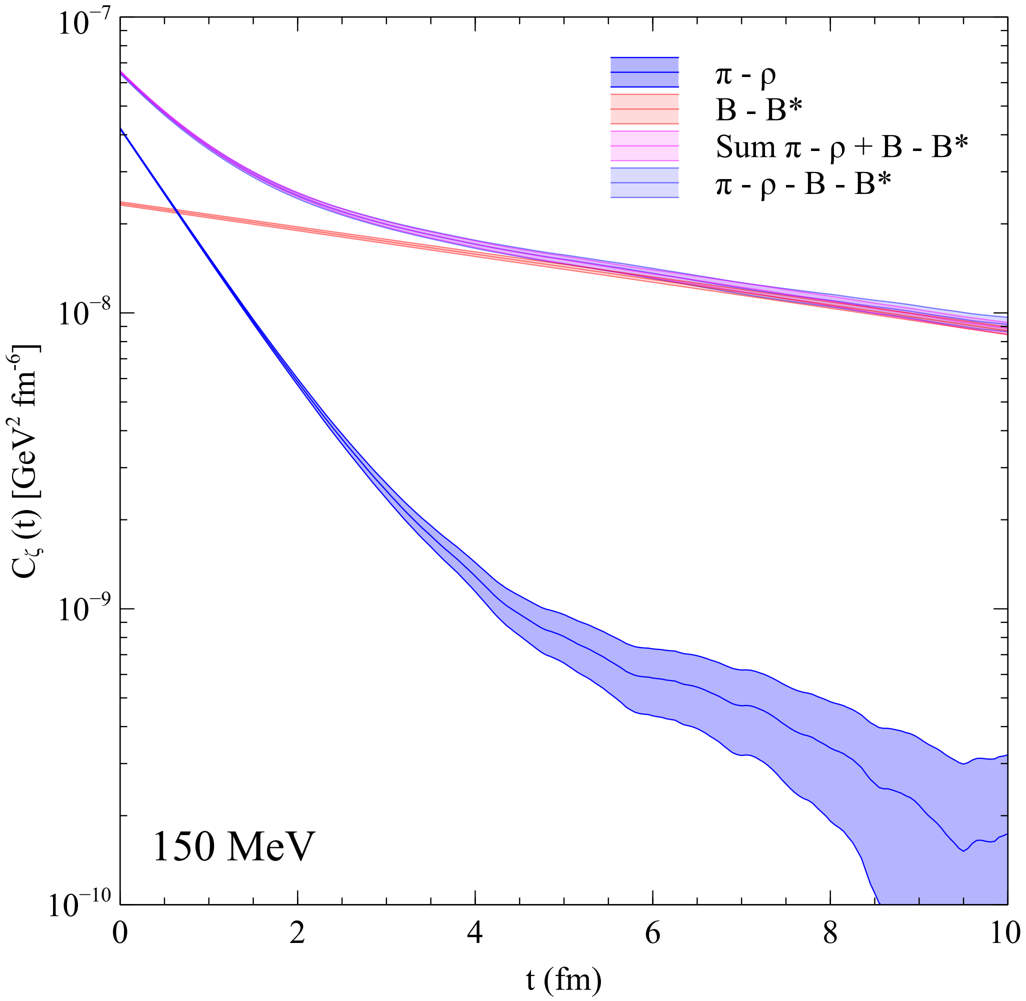


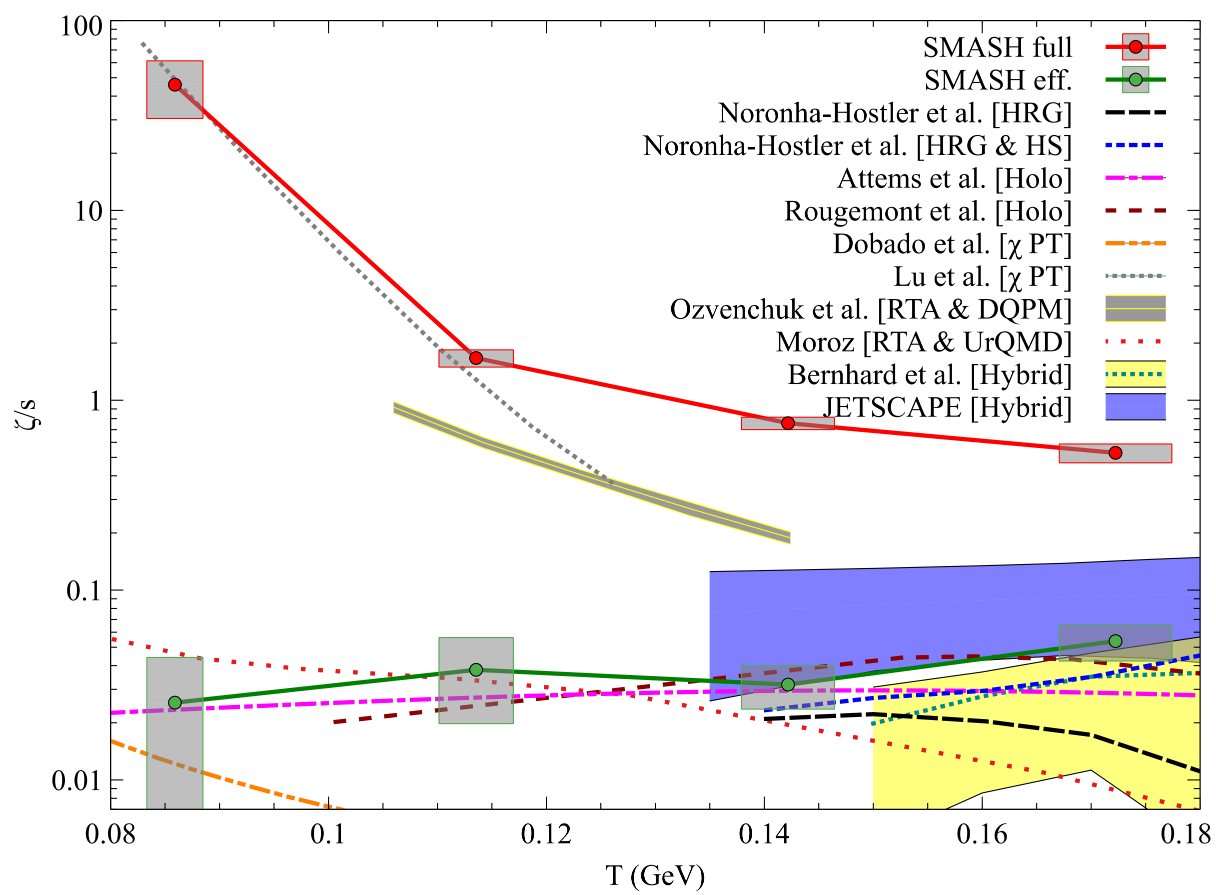


- Comparison to analytic solution successful, but correlation function is very sensitive to life time assumptions

Effective Bulk Viscosity

- Tail of correlation function is dominated by slow modes that are not relevant for the evolution of heavy-ion collisions





J.-B. Rose, J. M. Torres-Rincon and HE, arXIv: 2005.03647

- The effective bulk viscosity excluding slow modes is in accordance with findings from Bayesian analysis

Electric Conductivity

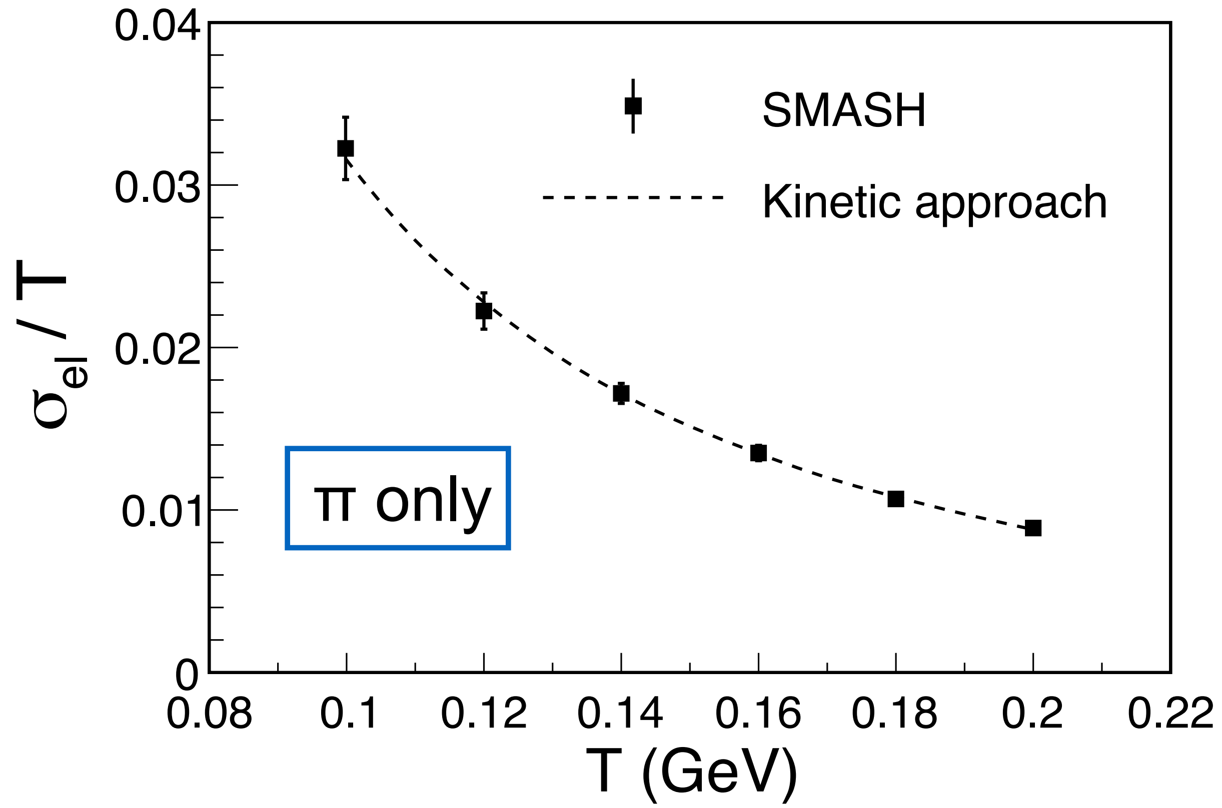
- Comparison to linear response kinetic theory to validate our approach

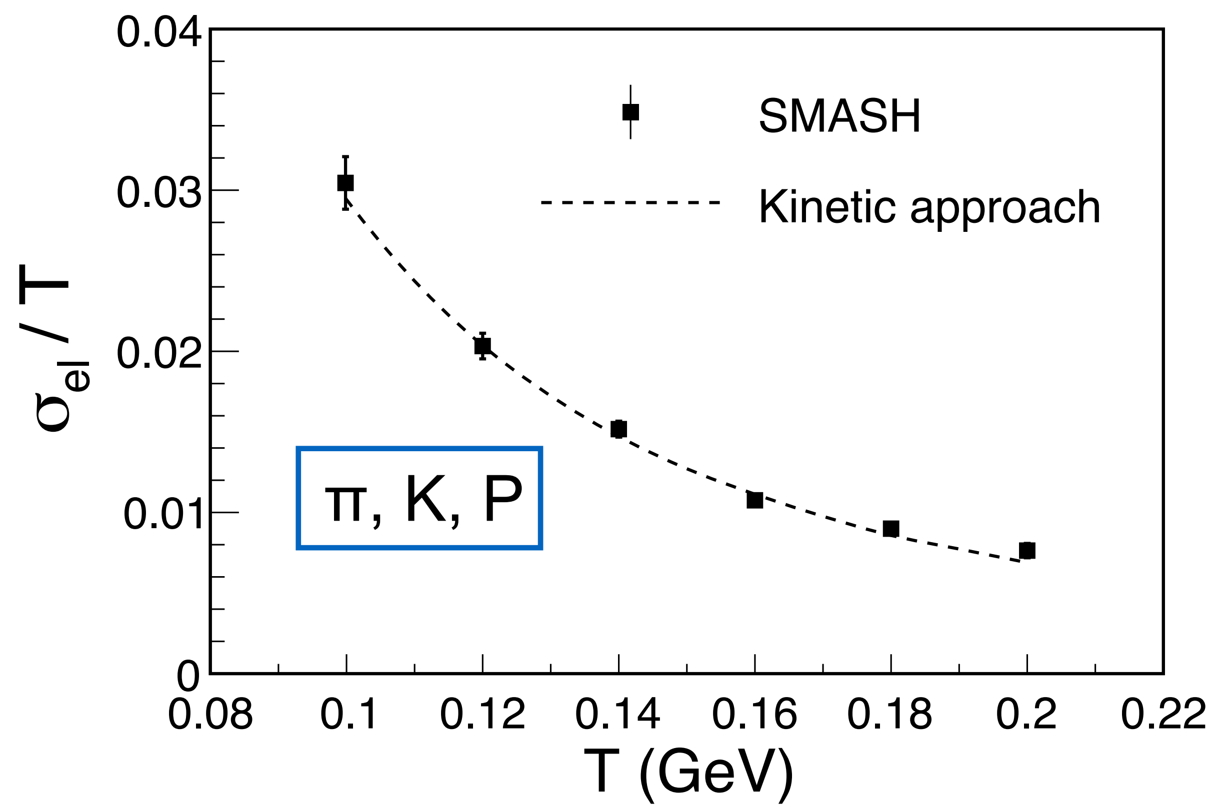
Greif et al, Phys.Rev. D93 (2016)

$$\sigma_{el} = \frac{V}{T}\int_0^\infty \langle j_i(0) j_i(t)\rangle dt \qquad \sigma_{el} = \frac{VC(0)\tau}{T}$$

- Infinite matter with constant σ = 30 mb

J. Hammelmann et al, Phys.Rev. D99 (2019) no.7, 076015

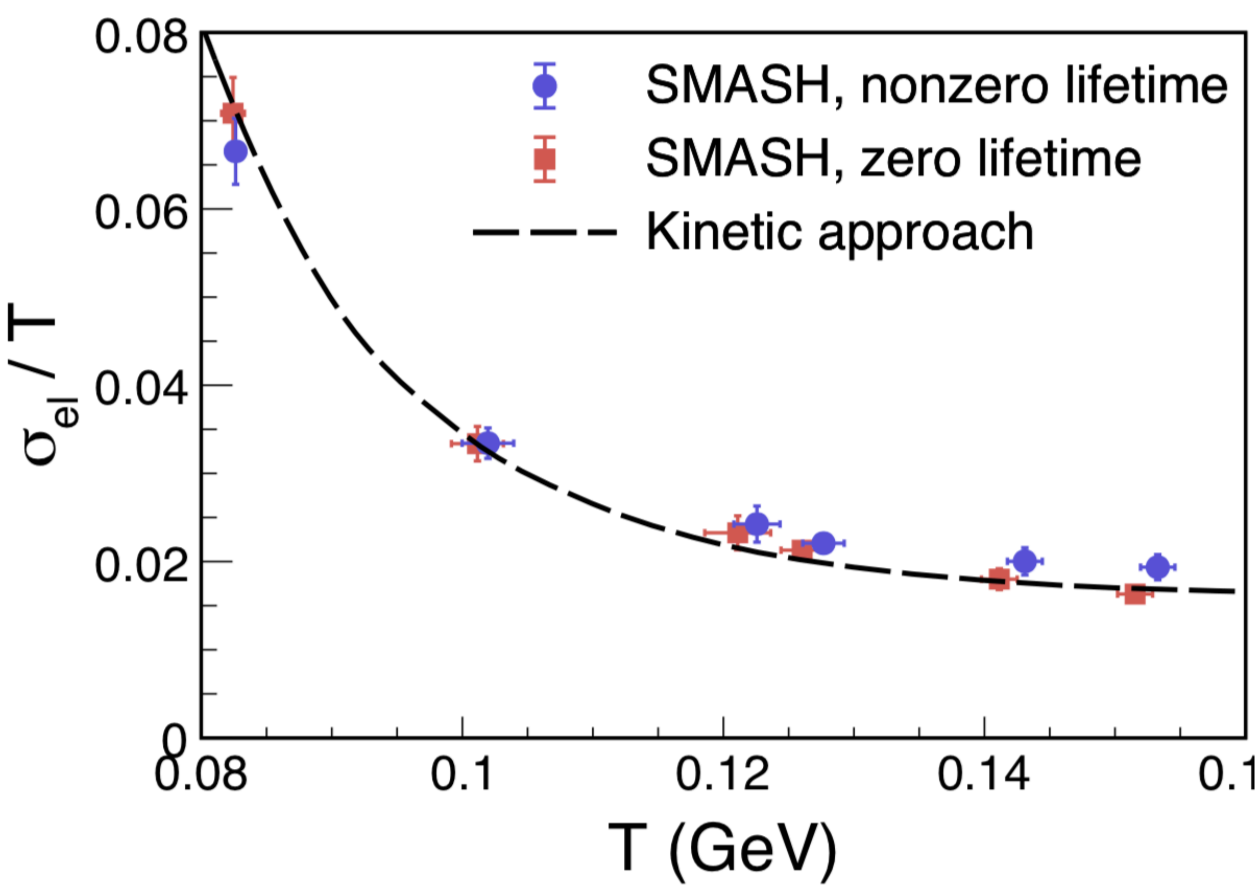


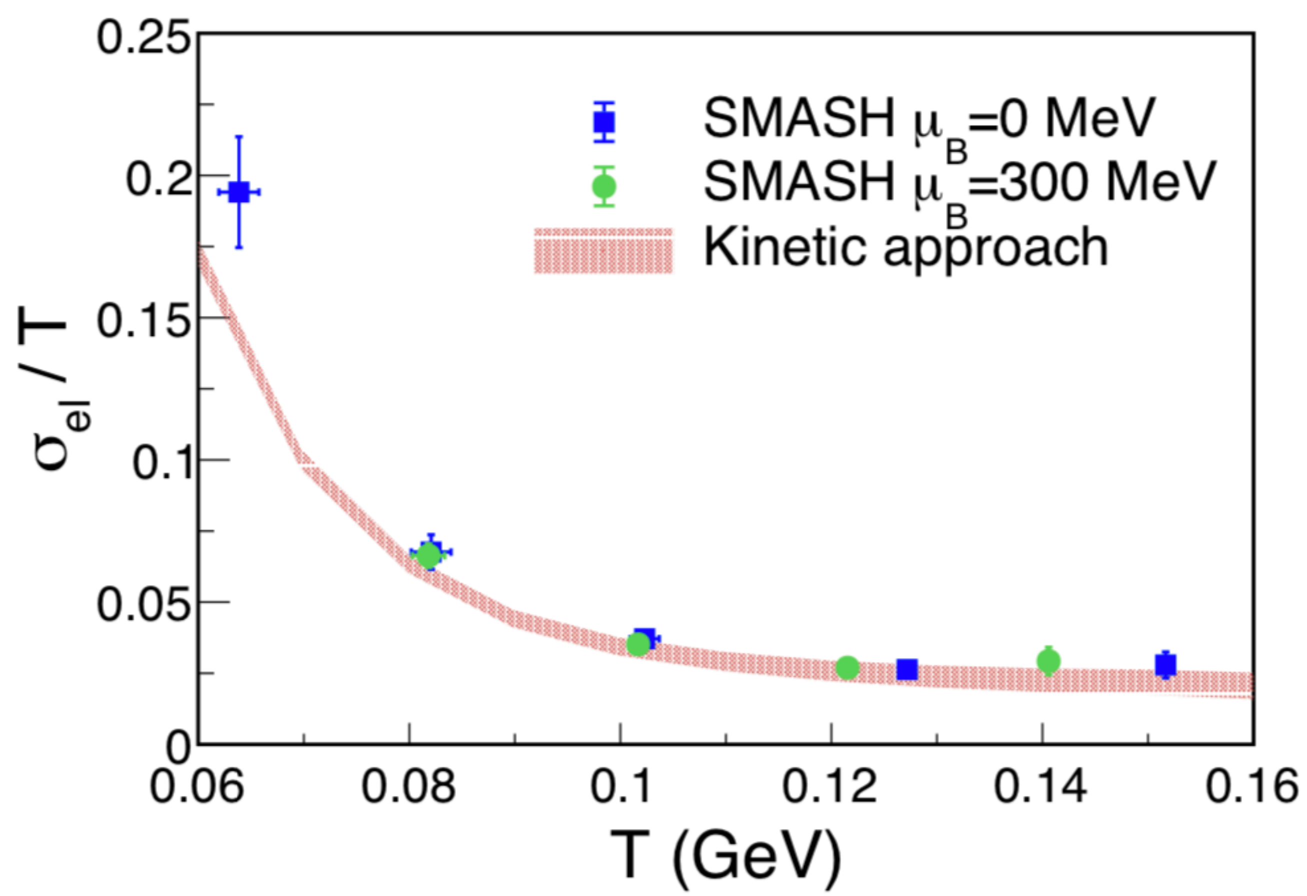


Influence of Lifetime

- Results for electric conductivity are independent of resonance lifetimes

J. Hammelmann et al, Phys.Rev. D99 (2019) no.7, 076015

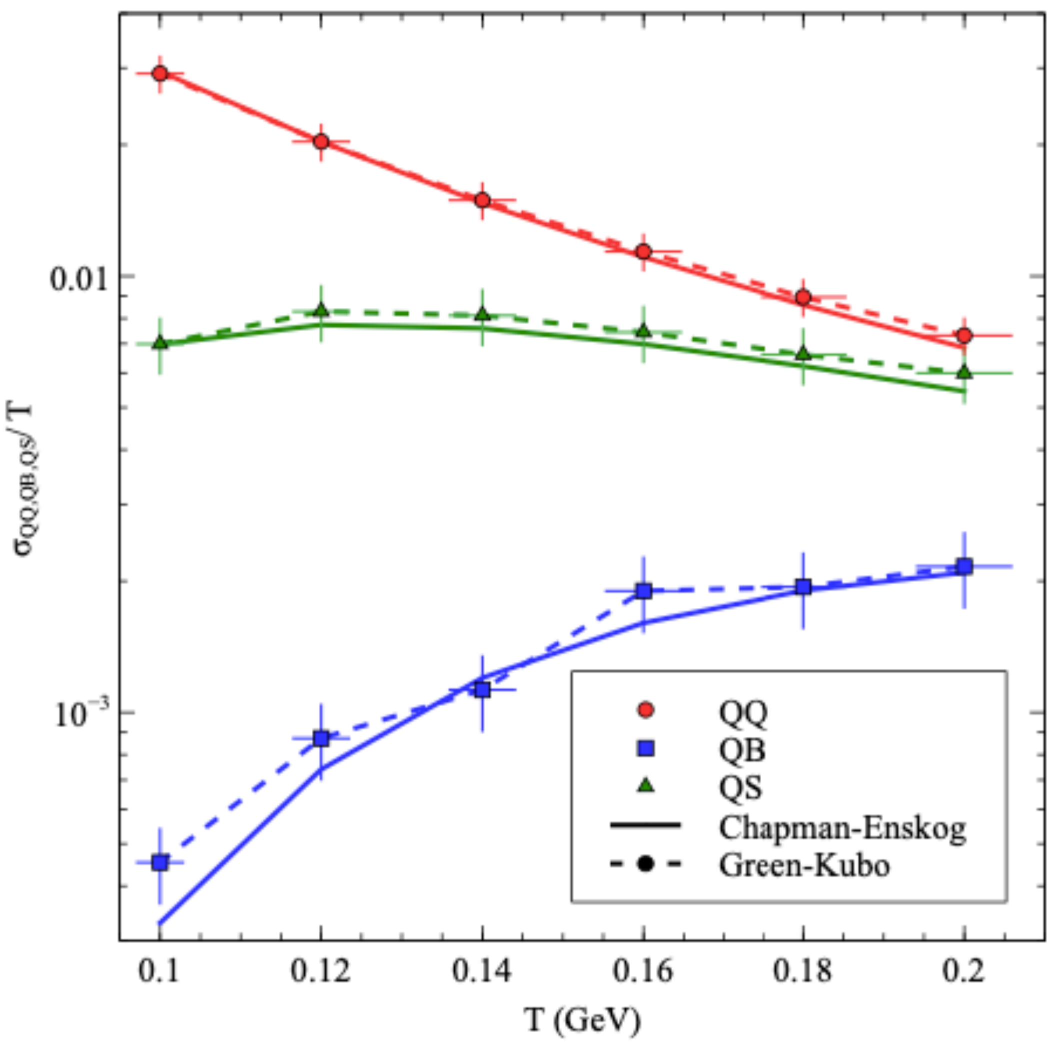


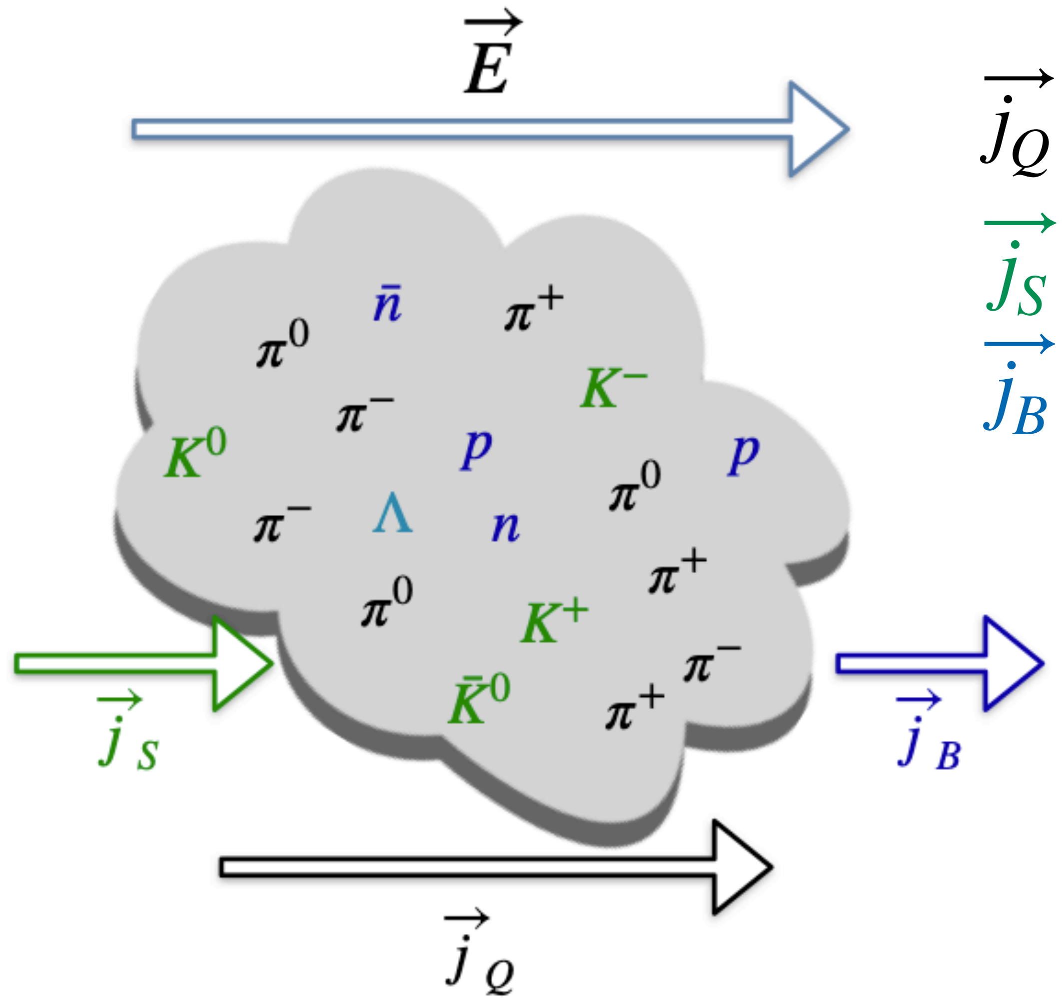


- Electric current relaxes already at formation of resonances and not only at the decay (full momentum exchange)

Cross-Conductivities

- The different species in a hadron gas have mixed quantum numbers, currents develop and mix J.-B. Rose et al, *Phys.Rev.D* 101 (2020)



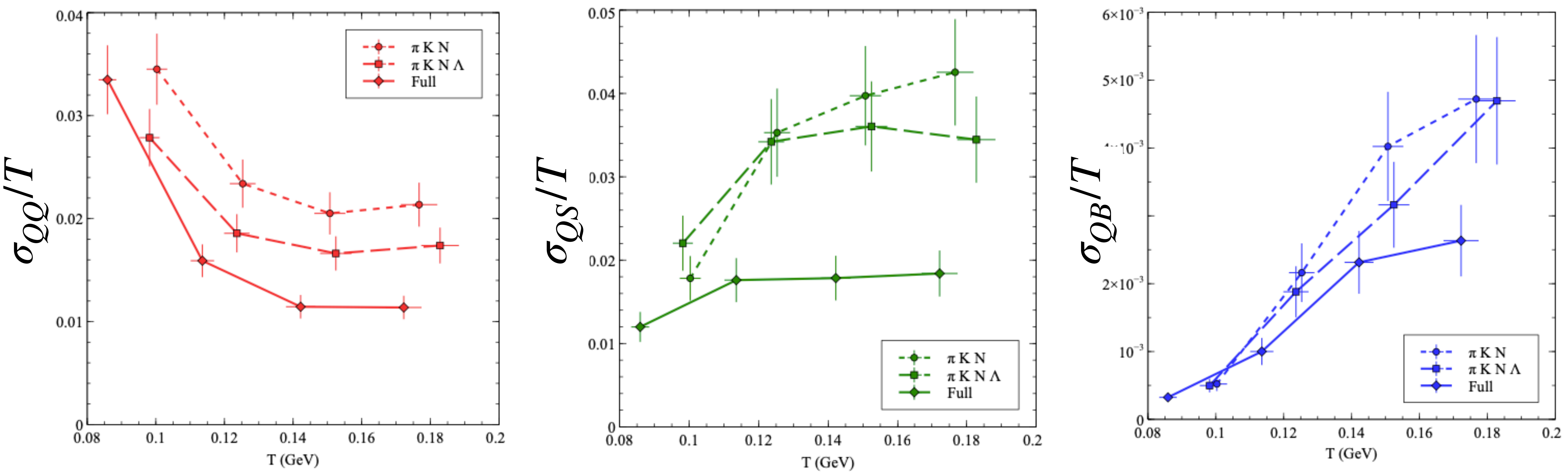


$$\vec{j}_Q = \sigma_{QQ}\vec{E}_Q$$
$$\vec{j}_S = \sigma_{QS}\vec{E}_Q$$
$$\vec{j}_B = \sigma_{QB}\vec{E}_Q$$

- Comparison in simple π-K-P system to analytic calculation successful

Cross-Conductivities

- All conductivities are highly dependent on the degrees of freedom employed in the calculation



J.-B. Rose et al, *Phys.Rev.D* 101 (2020)

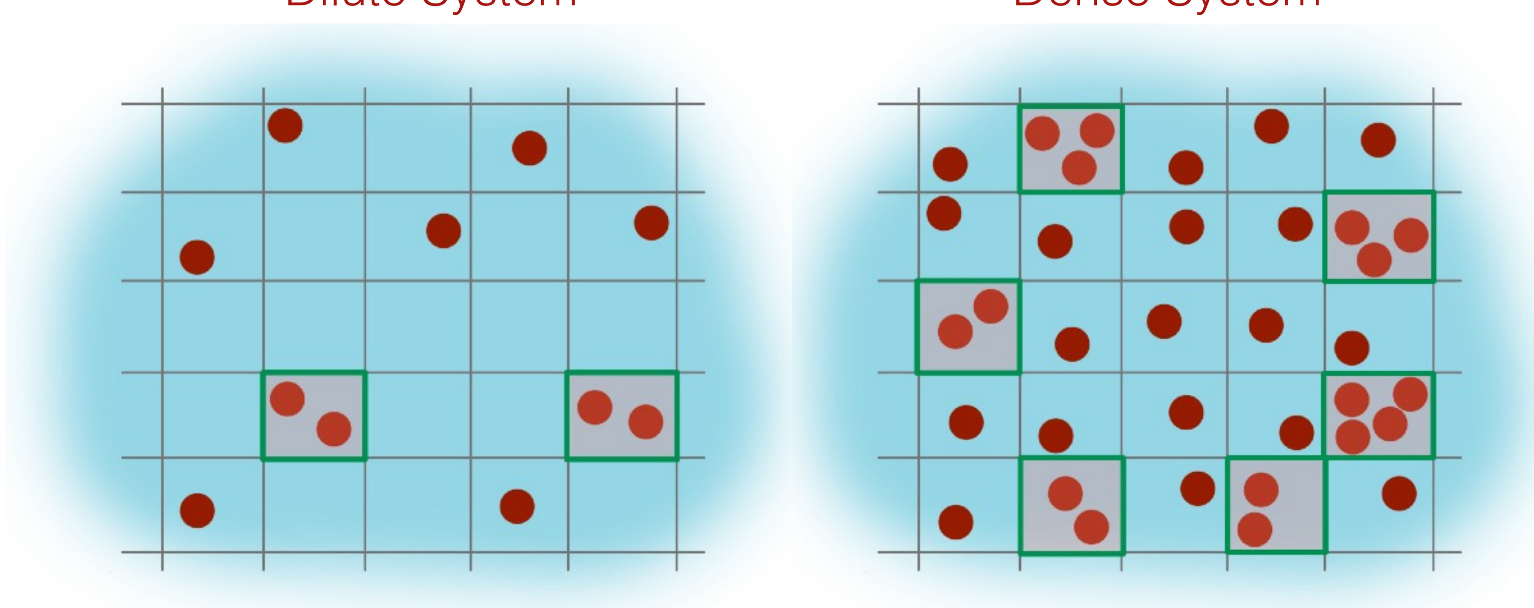
- Potential to constrain active degrees of freedom in the hadron gas by comparison to future lattice results
- In progress: Calculation of full diffusion matrix

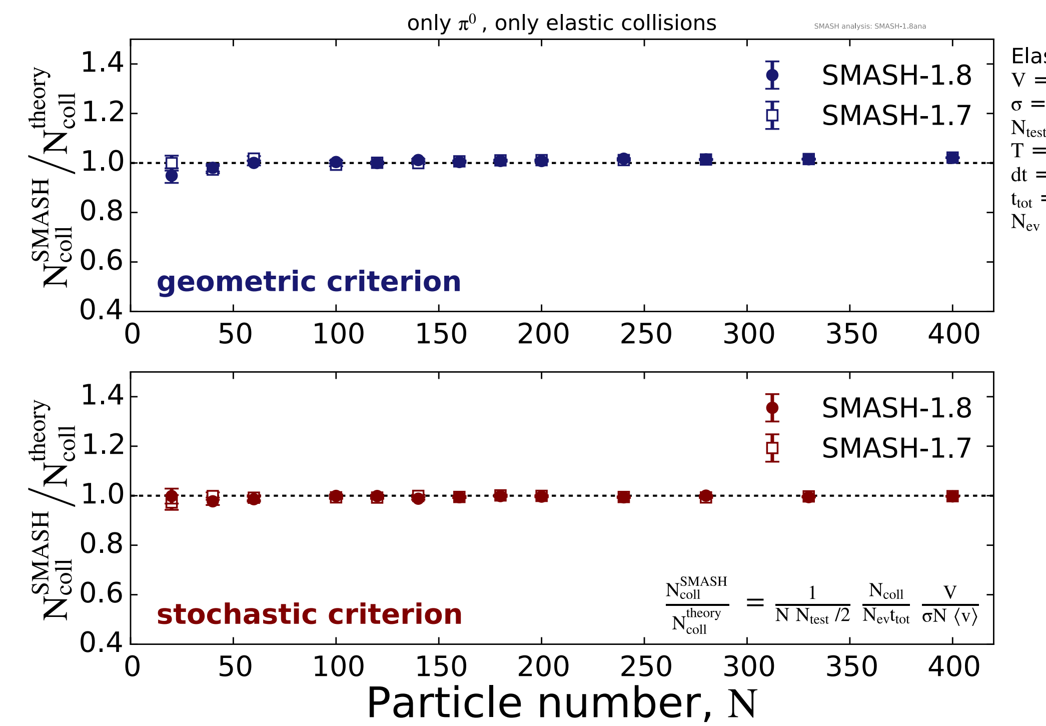
Outlook

Multi-Particle Interactions

- At high densities multiparticle interactions will become relevant

By J. Staudenmaier



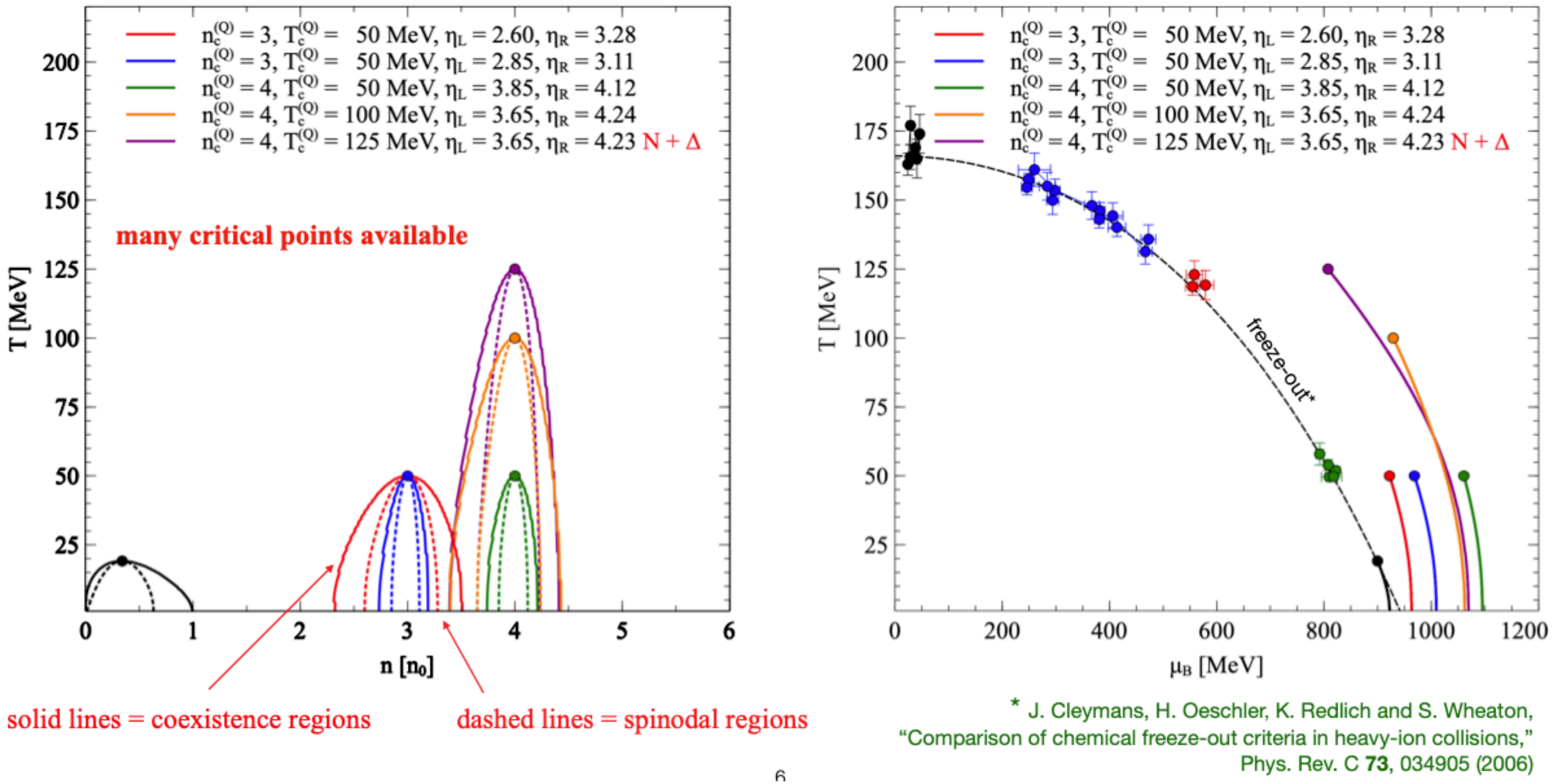


  - $\omega \leftrightarrow 3\pi$, $B\bar{B} \leftrightarrow 5\pi$, $M \leftrightarrow N$

- 2<->2, 2<->1, 3<->1 and 2<->3 is implemented
- Application to interesting physics cases is in progress

More Sophisticated Potentials

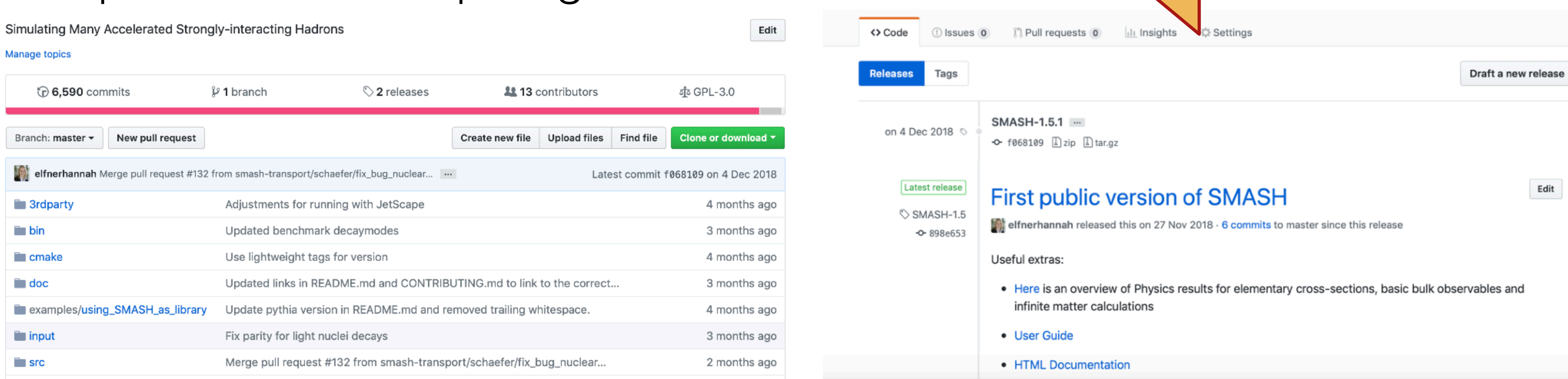
- Relativistic mean field based on density functional theory
- Vector interaction has been implemented in SMASH
- Parameters are tuned to correspond to a certain EoS



A. Wergieluk and V. Koch, BEST collaboration, annual meeting May 2020

How to Use SMASH?

- Visit the webpage to find publications and link to SMASH-1.8 results
  https://smash-transport.github.io
- Download the code at
  https://github.com/smash-transport/smash
- Checkout the Analysis Suite at
  https://github.com/smash-transport/smash-analysis
- Find user guide and documentation at
  https://github.com/smash-transport/smash/releases
- Animations and Visualization Tutorial under
  https://smash-transport.github.io/movies.html



Summary and Outlook

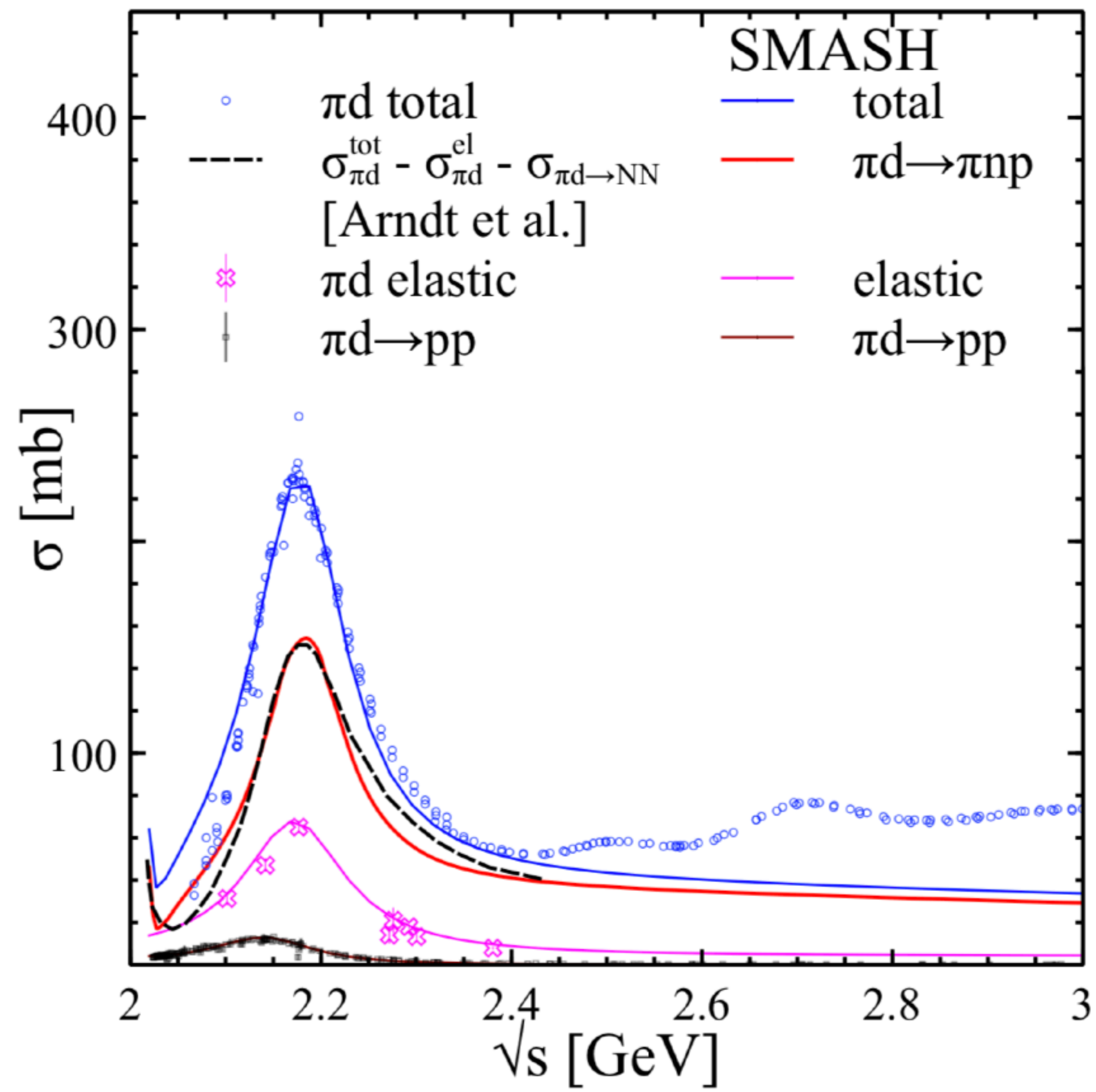
- SMASH has been developed as a new hadronic transport approach
  - Bulk observables are in reasonable agreement with experimental data
  - Strangeness and deuteron production is investigated
  - Electromagnetic radiation is incorporated
  - Baryon stopping within string model
  - Transport coefficients sensitive to resonance properties
- Afterburner for high-energy heavy-ion collisions (module within JETSCAPE/XSCAPE)
- Multi-particle scattering and improved interfaces to hydrodynamic evolution
- Source code is public and ready to use!

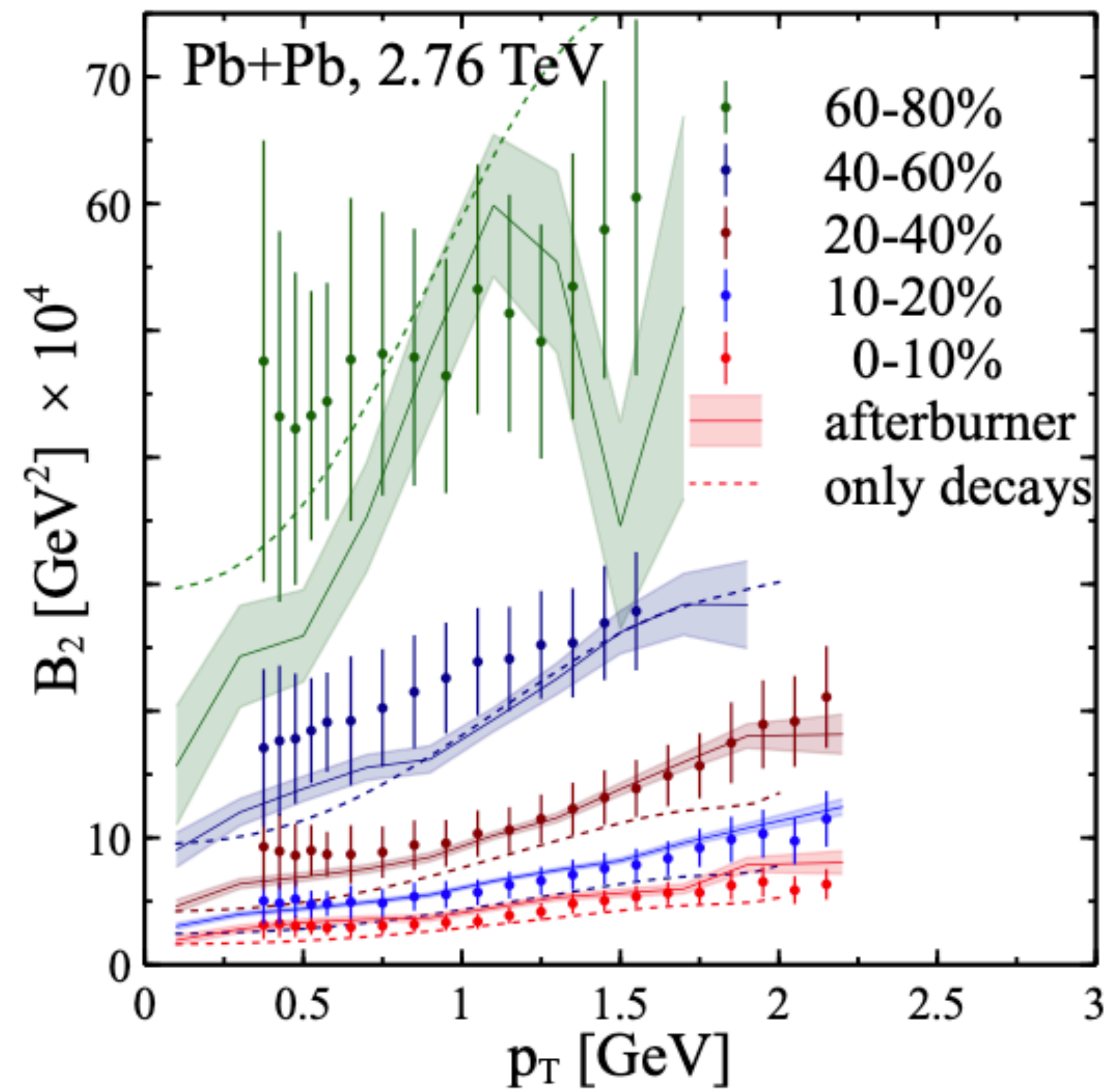
Backup

Deuteron Production

- Deuterons and their cross-sections are implemented in SMASH
- During rescattering at LHC interactions with pions dominate

D. Oliinychenko, LongGang Pang, HE and V. Koch, Phys.Rev. C99 (2019) and *MDPI Proc.* 10 (2019)





- B_2 is nicely reproduced even including centrality dependence
- See also D. Oliinychenko a few weeks ago

Treatment of Manley

- Scaling of on-shell decay width:

D. M. Manley and E. M. Saleski, Phys. Rev. D 45, 4002 (1992)

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

- Definiton of rho-function:

$$\rho_{ab}(m) = \int dm_a dm_b \mathcal{A}_a(m_a)\mathcal{A}_b(m_b) \times \frac{|\vec{p}_f|}{m} B_L^2(|\vec{p}_f|R)\mathcal{F}^2_{ab}(m)$$

Blatt Weisskopf functions

$$B_0^2 = 1$$

$$B_1^2(x) = x^2/(1+x^2)$$

...

- Hadronic Form Factor:

M. Post, S. Leupold, U. Mosel, Nucl. Phys. A 741, 81 (2004)

$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + 1/4(s_0 - M_0^2)^2}{\lambda^4 + \left(m^2 - 1/2(s_0 + M_0^2)\right)^2}$$

decay	λ [GeV]
$\pi\rho$	0.8
unstable mesons (e.g. ρN, σN)	1.6
unstable baryons (e.g. $\pi\Delta$)	2.0
two unstable daughters (e.g. $\rho\rho$)	0.6