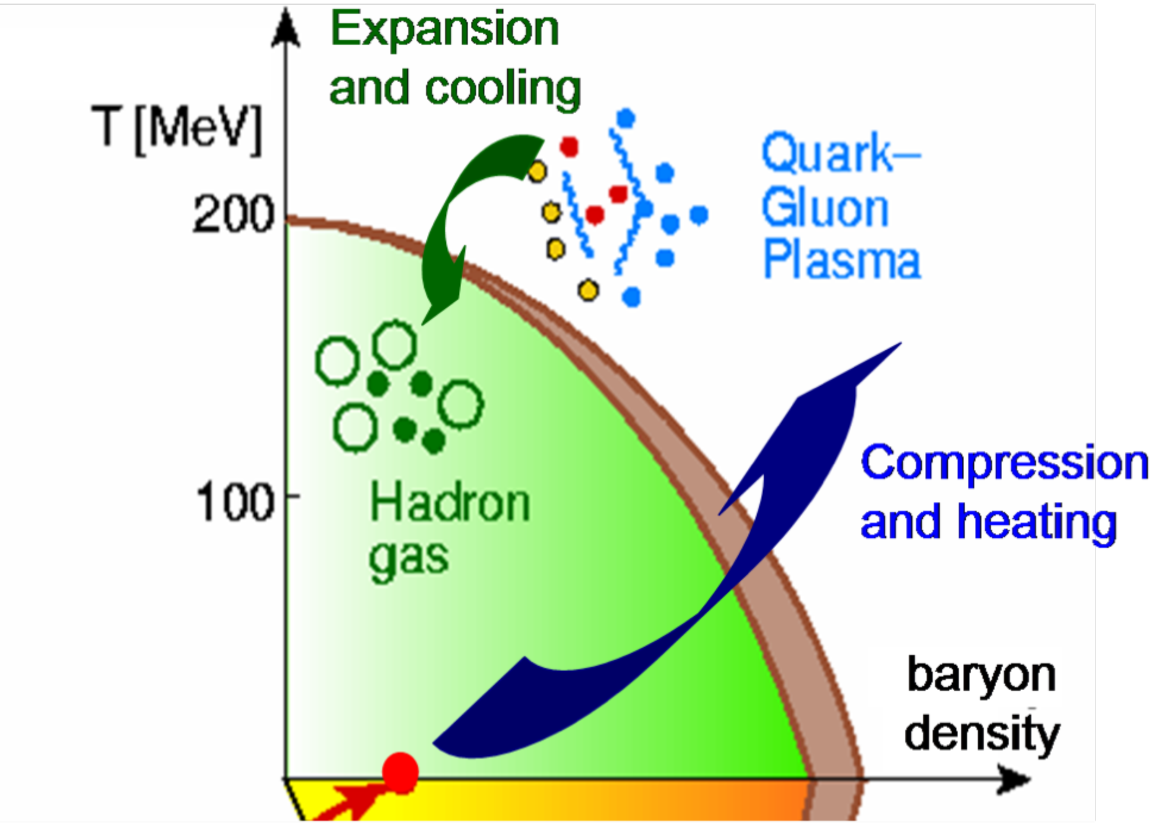
Resonance properties and transport coefficients in SMASH

Hannah Petersen

16.04.18, NED 2018, Varadero, Cuba

The QCD Phase Diagram

- Main goals of heavy ion research

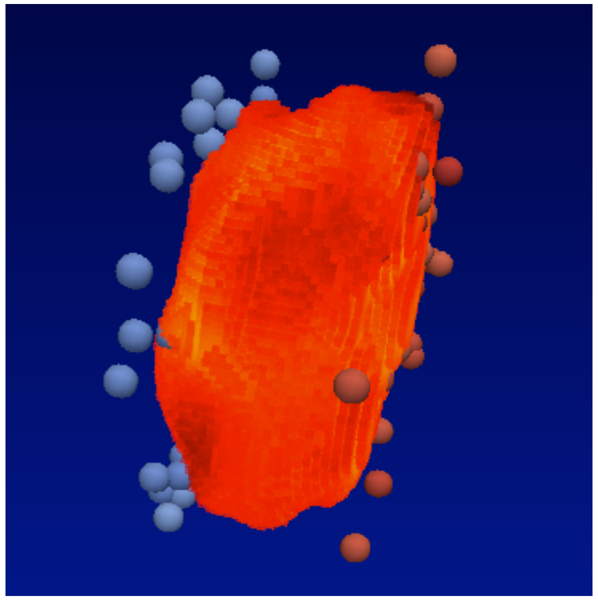


nuclei (n_B=0.14/fm³)

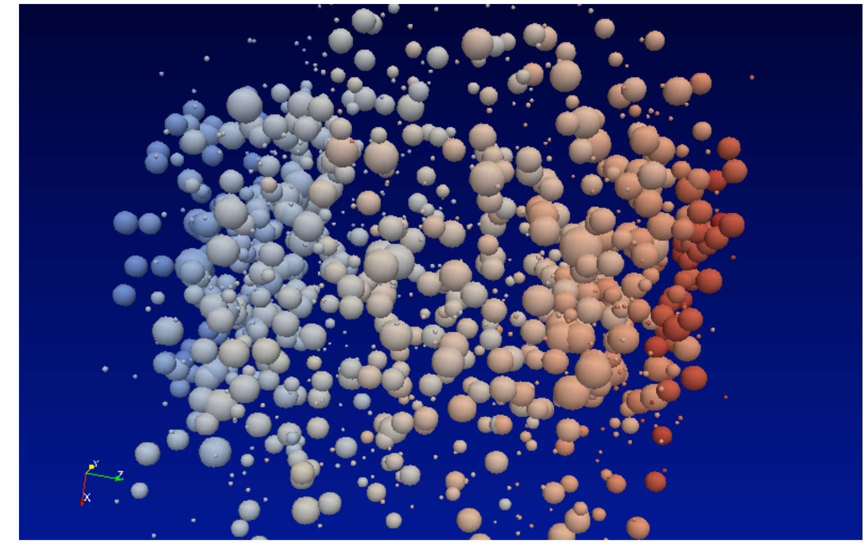
- **Questions** to be answered:
  - What is the temperature and the density? What are the relevant degrees of freedom?
  - Phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- Understand the structures in the phase diagram
- Investigate the properties of the quark-gluon plasma
- **Focus** in this talk: Hadron/Resonance dynamics and transport coefficients (η/s and electric conductivity)

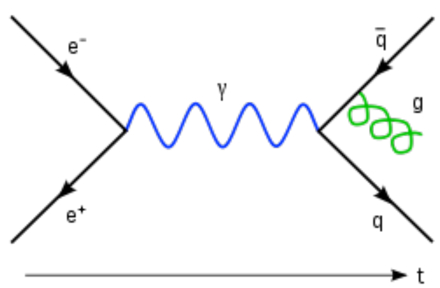
Transport Approaches



Dynamical description of heavy ion reactions

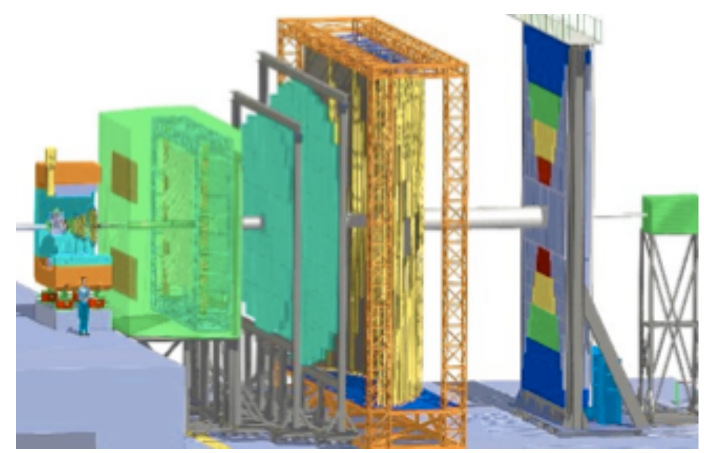


Fundamental field theory of strong interactions (QCD)



$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Measurements in the detector (CBM@FAIR)



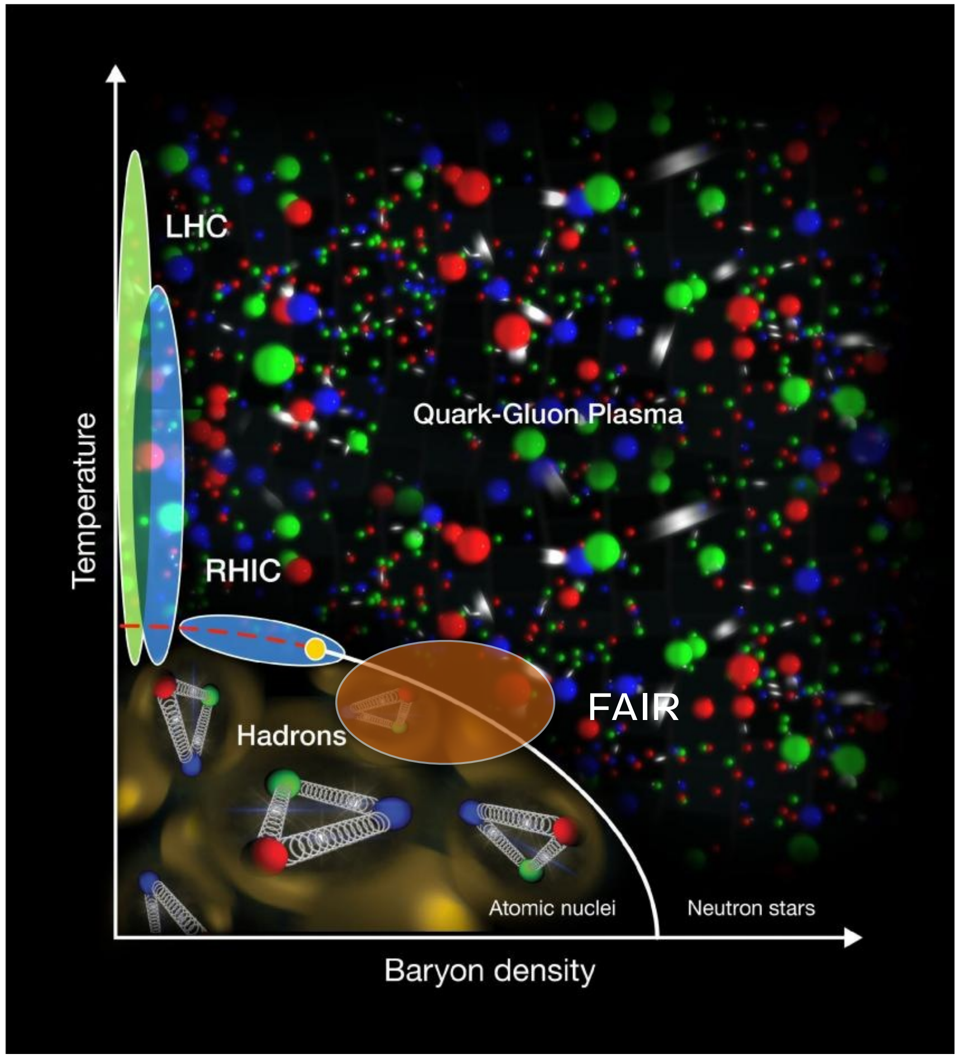
- **Theoretical models** are essential to gain insights about the properties of the hot and dense stage of the reaction

Outline

- Hadronic transport approach
  - SMASH: content and validation
  - Bulk observables at GSI-SIS energies
  - Strangeness production at threshold
  - Dilepton production and resonance properties
- Transport coefficients of the hadron gas
  - Green-Kubo formalism and its application
  - Shear viscosity over entropy ratio
  - Electric conductivity in simple systems
- Summary and Outlook

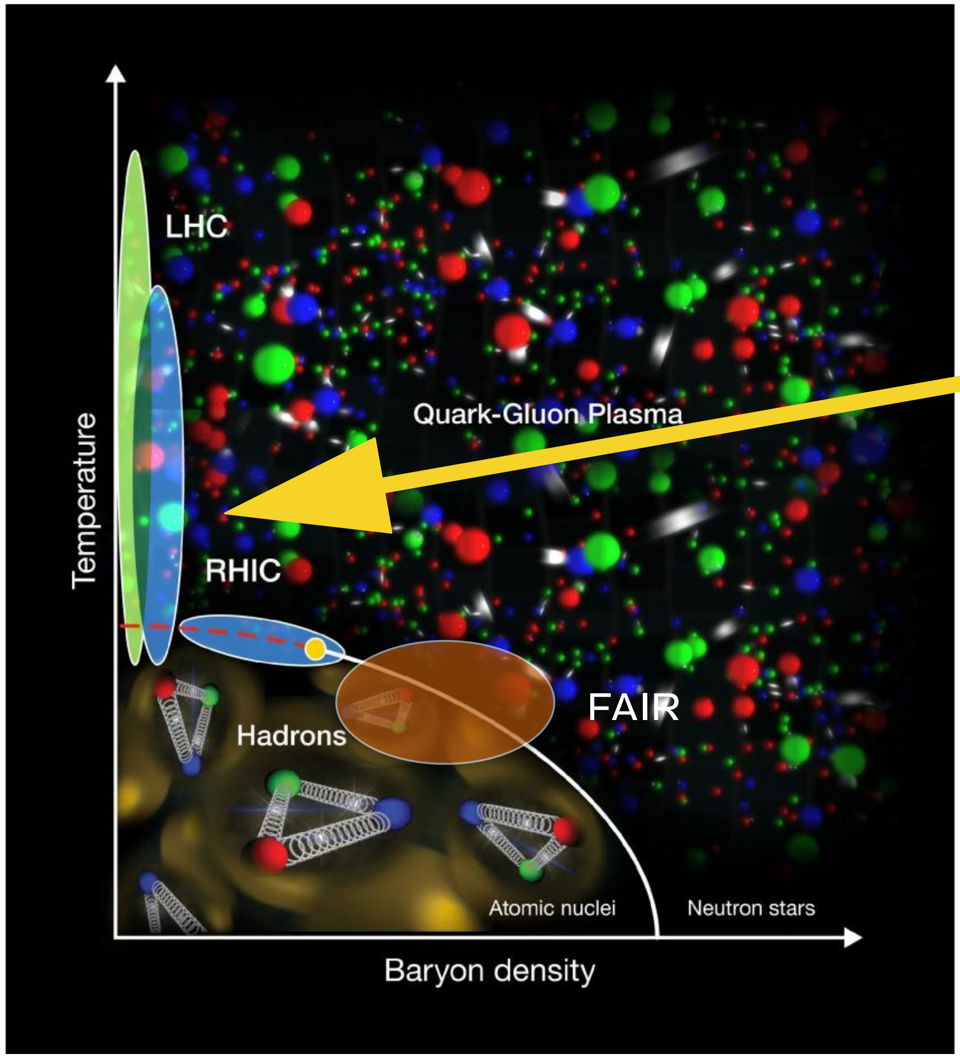
Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



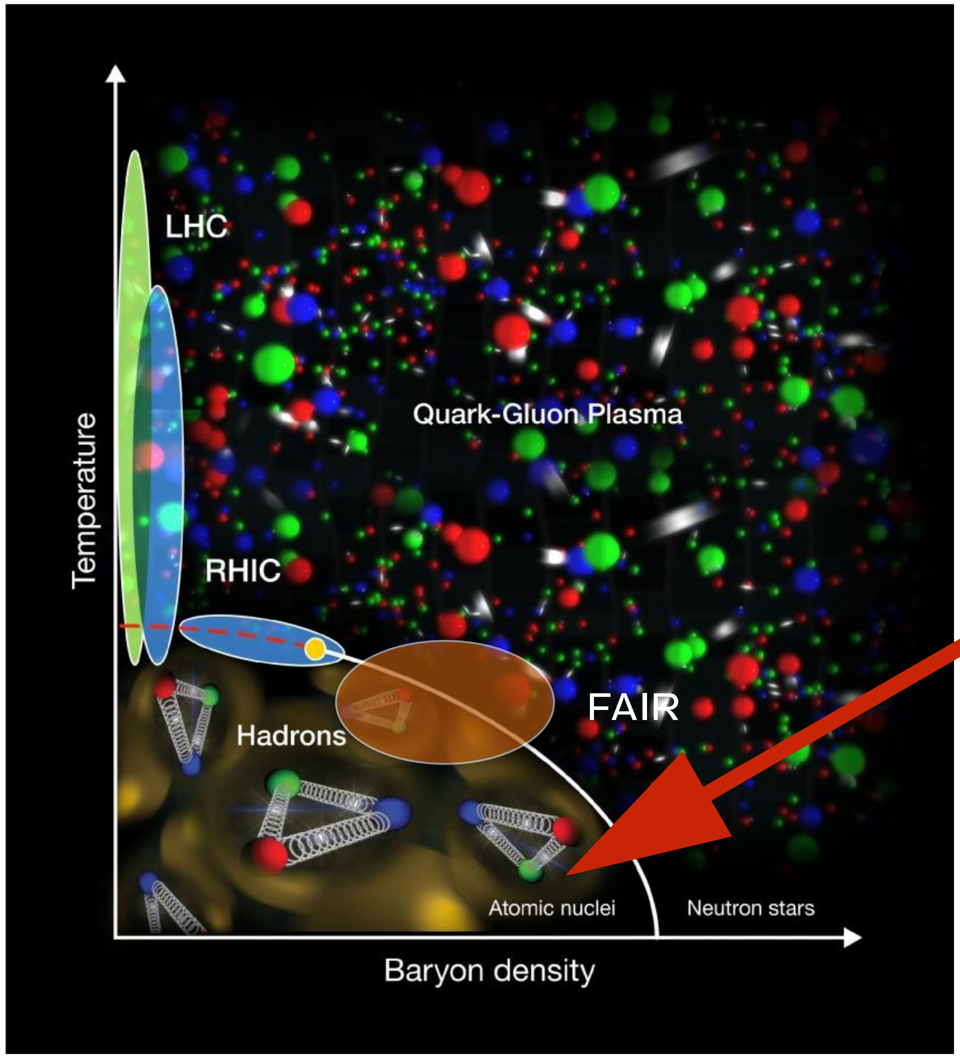
‚Standard model‘ at high energies ($\sqrt{s_{\rm NN}}$ = 39 GeV-5.5 TeV+):

- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic transport

—> Refinement and Bayesian multi-parameter analysis

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



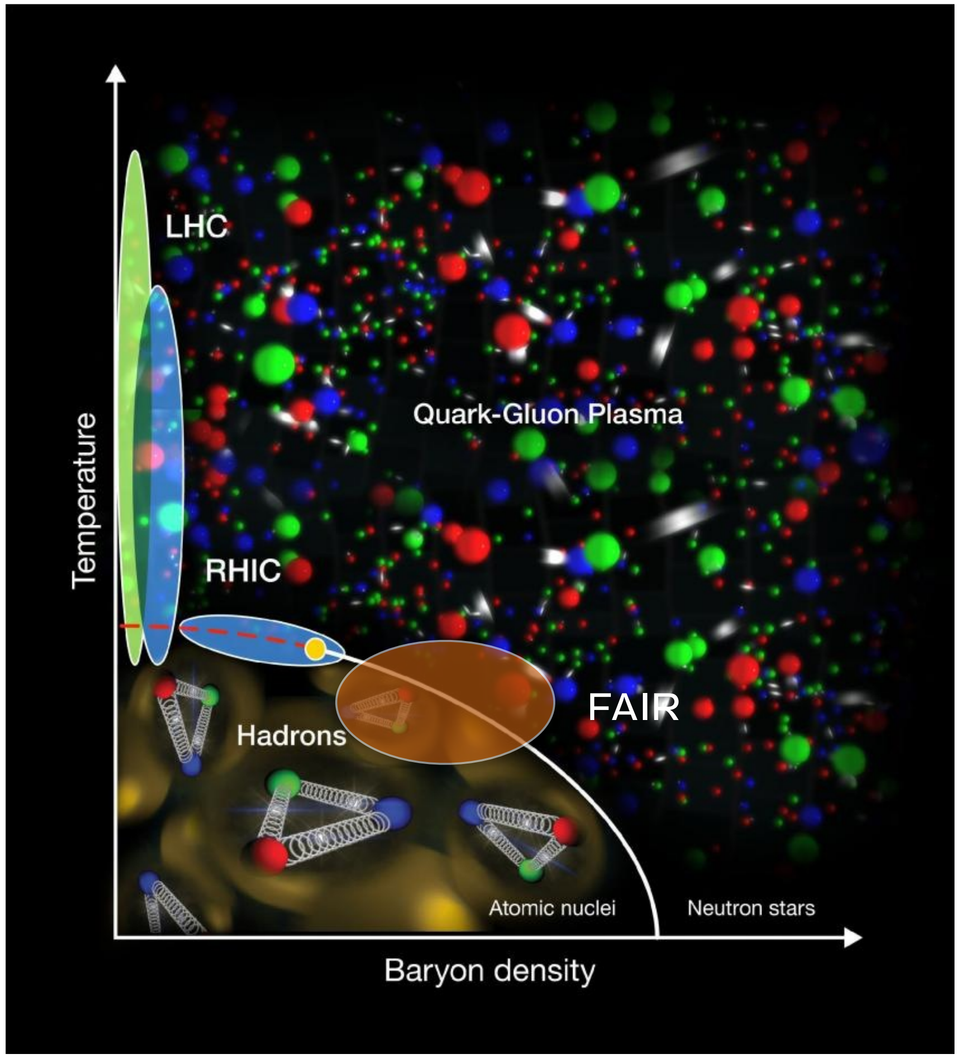
At very low beam energies ($\sqrt{s_{\rm NN}}$ < 3 GeV):

- **Hadronic** transport approaches
- Resonance dynamics
- Nuclear potentials

—> High density phase?
Multi-particle interactions?

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



‚**Standard model**' at high energies ($\sqrt{s_{\rm NN}}$ = 39 GeV-5.5 TeV+)

Hadron transport at very low beam energies ($\sqrt{s_{\rm NN}}$ < 3 GeV)

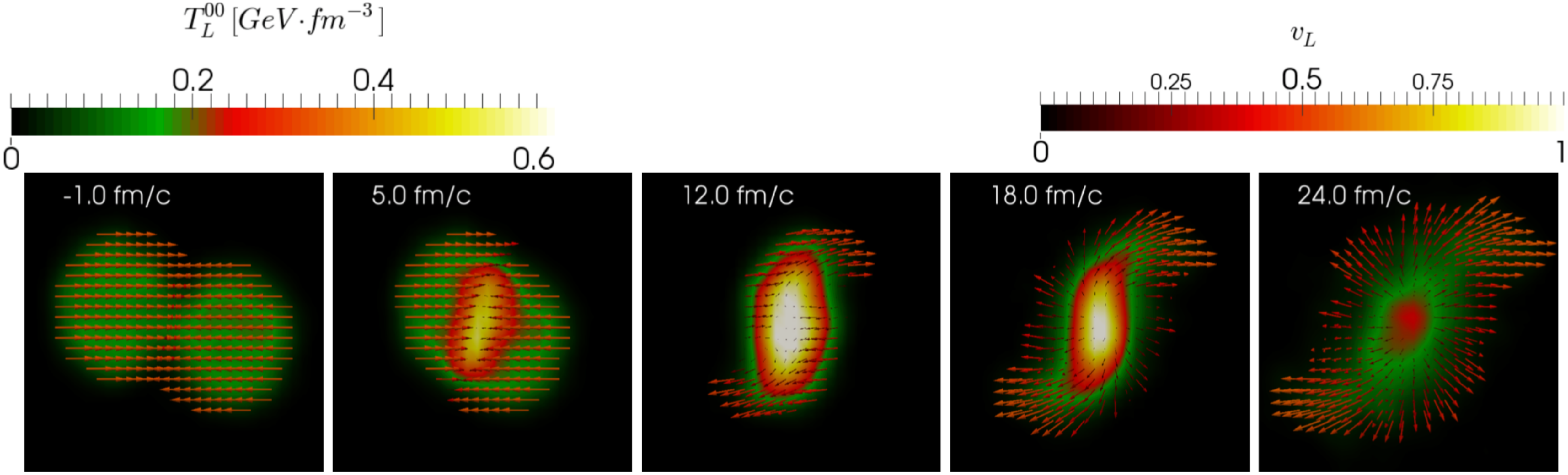
- How to **interpolate** between the two? Transport with hydro bubbles? Hydro with transport corona?
- How to model the phase transition/critical point?

Hadronic transport approach

SMASH*

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

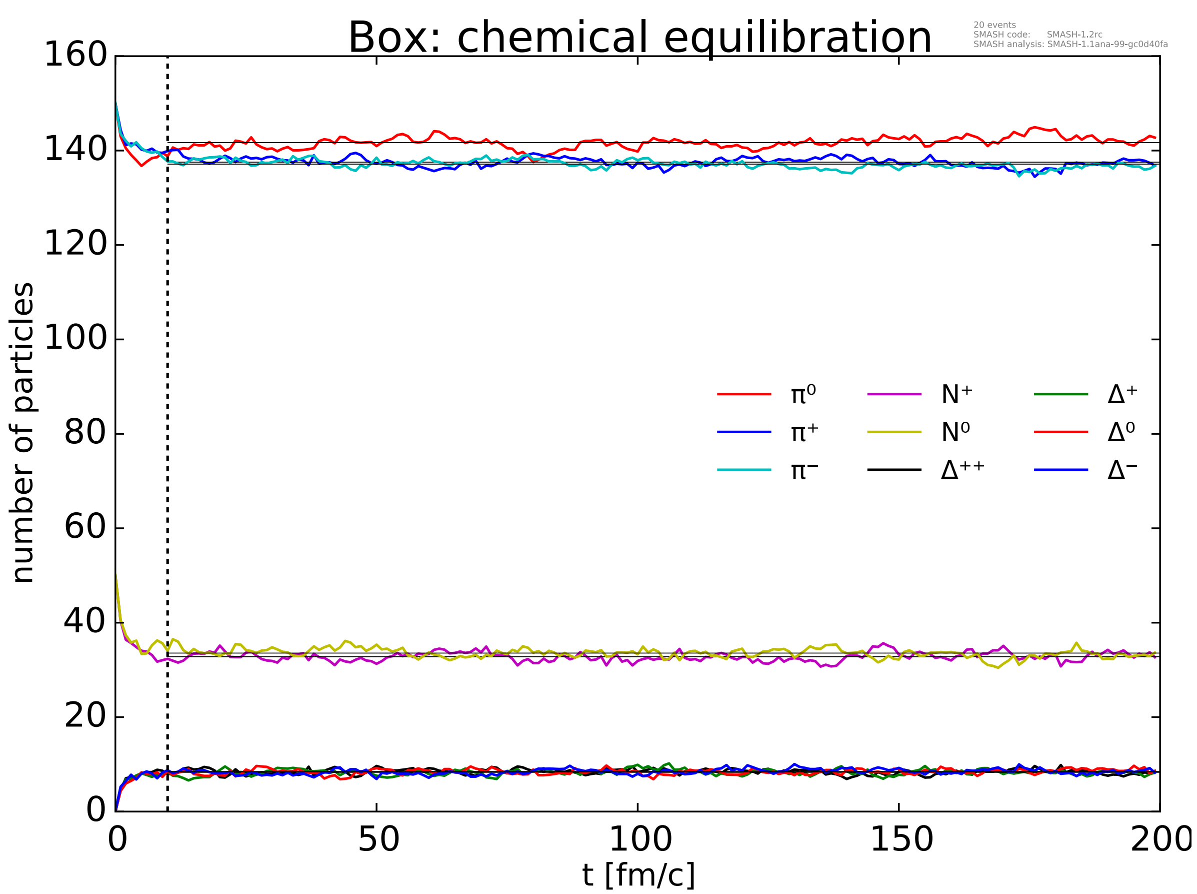
J. Weil et al, PRC 94 (2016)

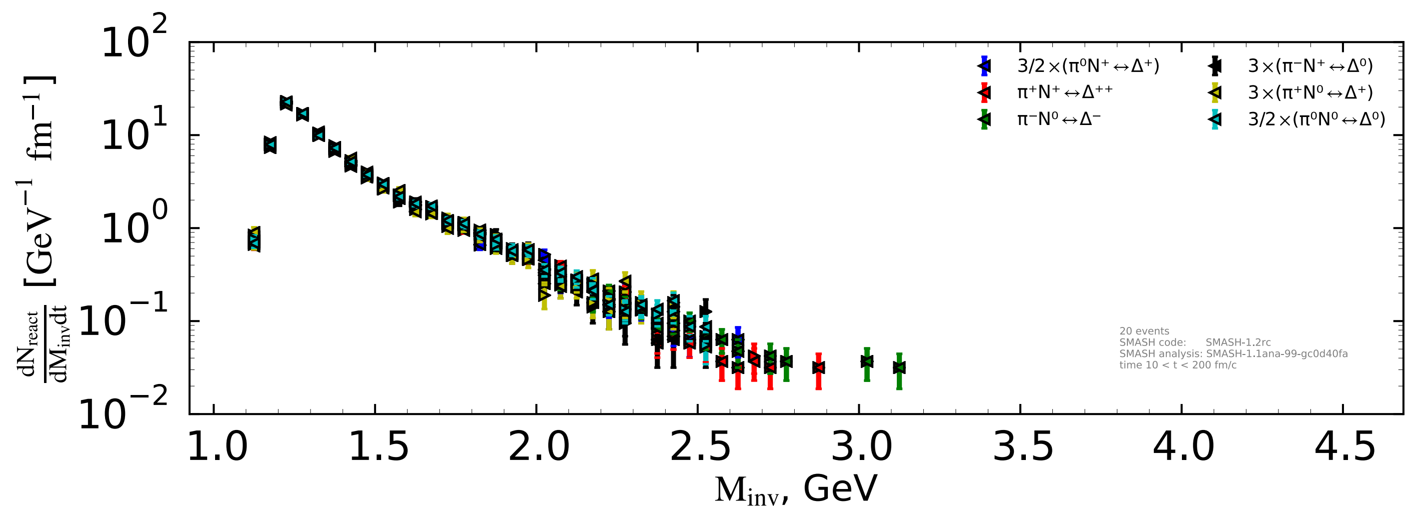


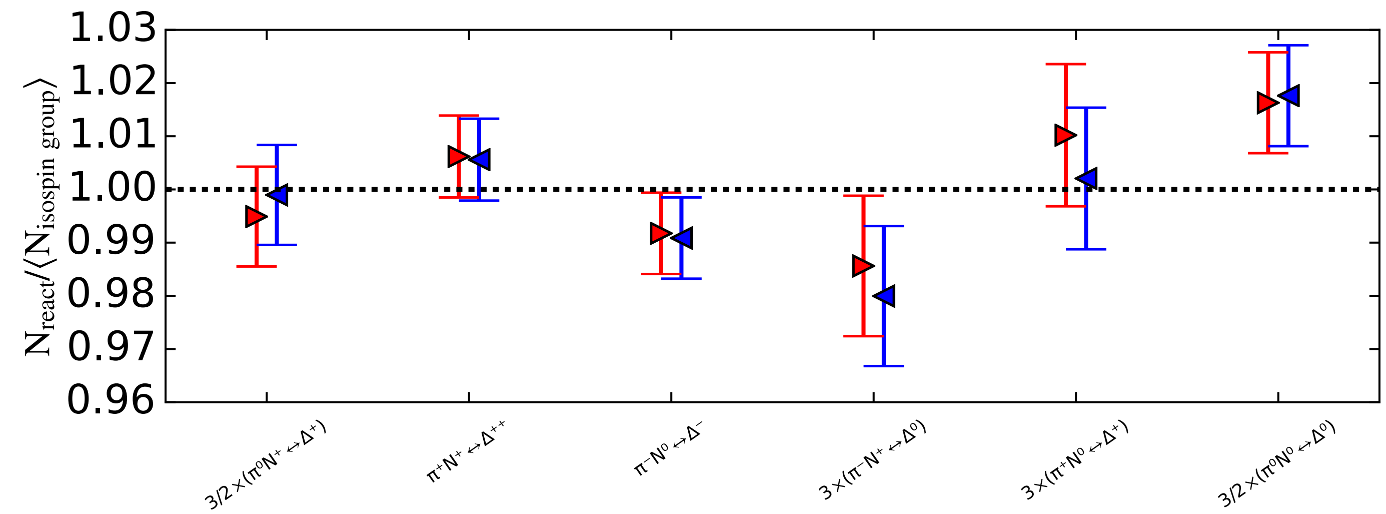
* Simulating Many Accelerated Strongly-Interacting Hadrons

Detailed Balance

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

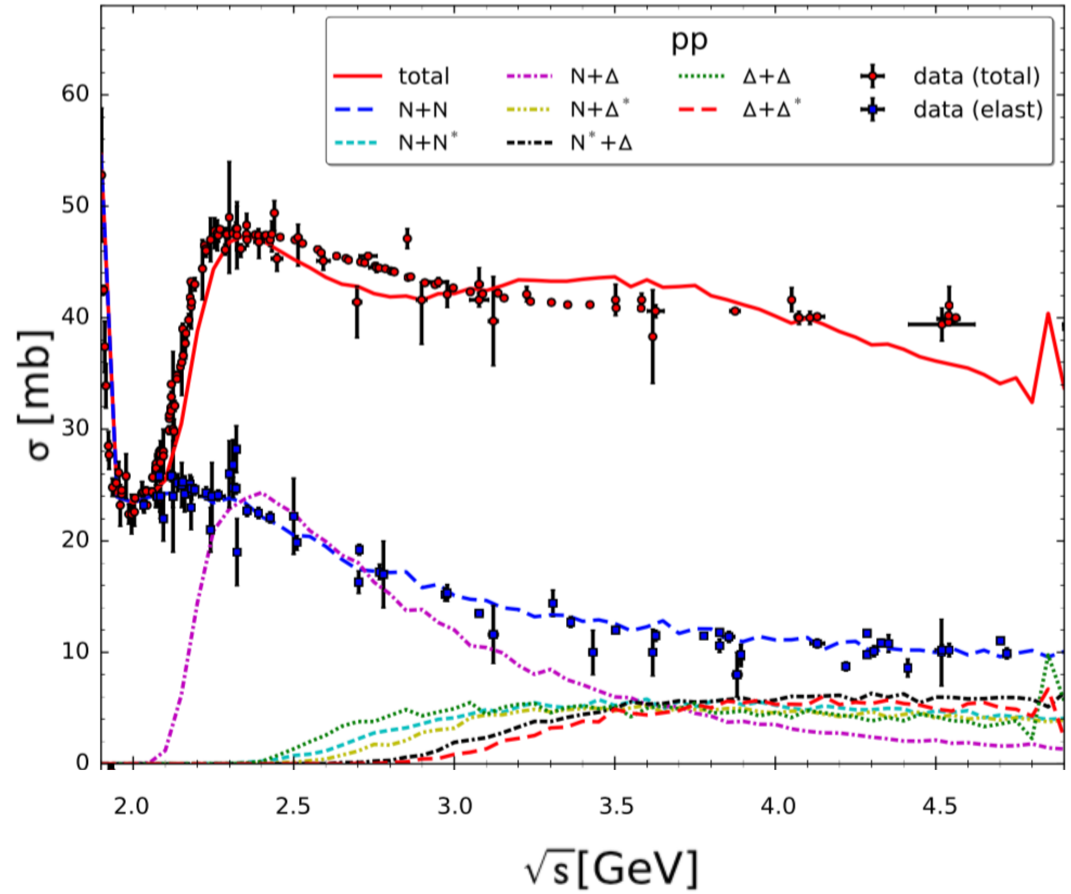


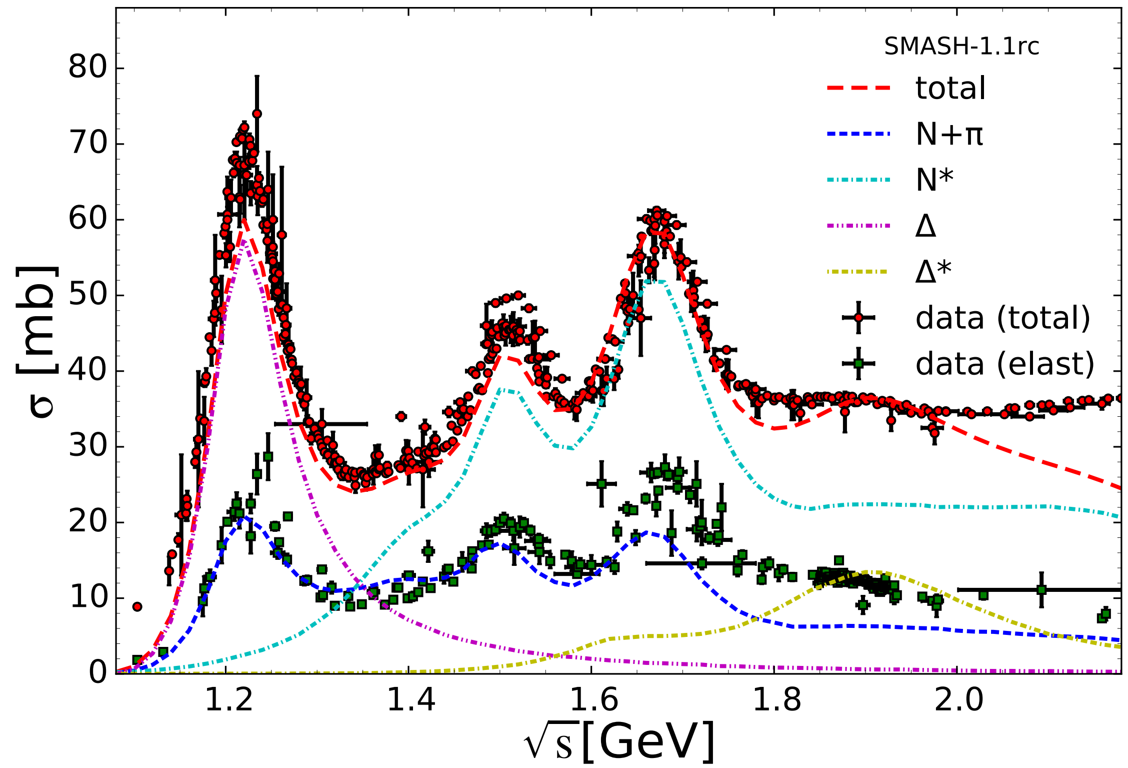




- Test: Full hadron gas indicating most violating processes

Elementary Cross Sections

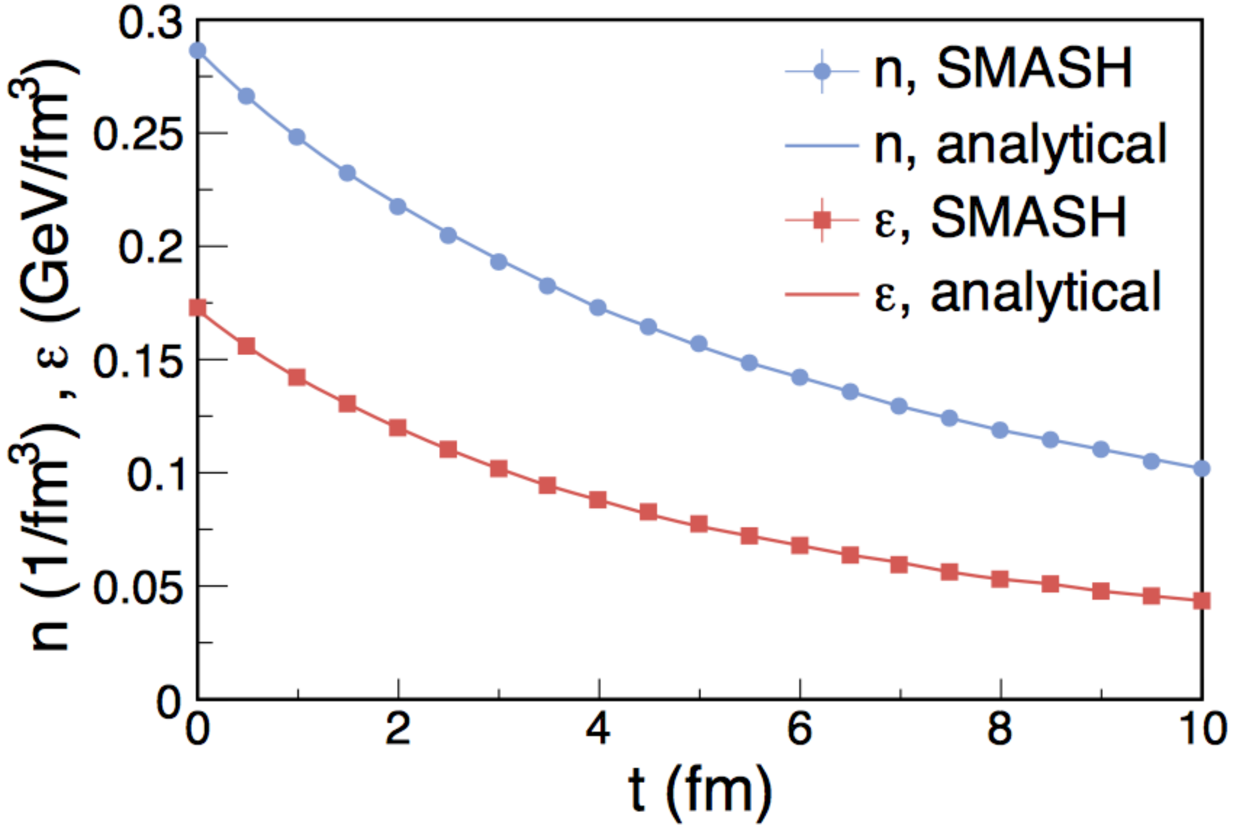


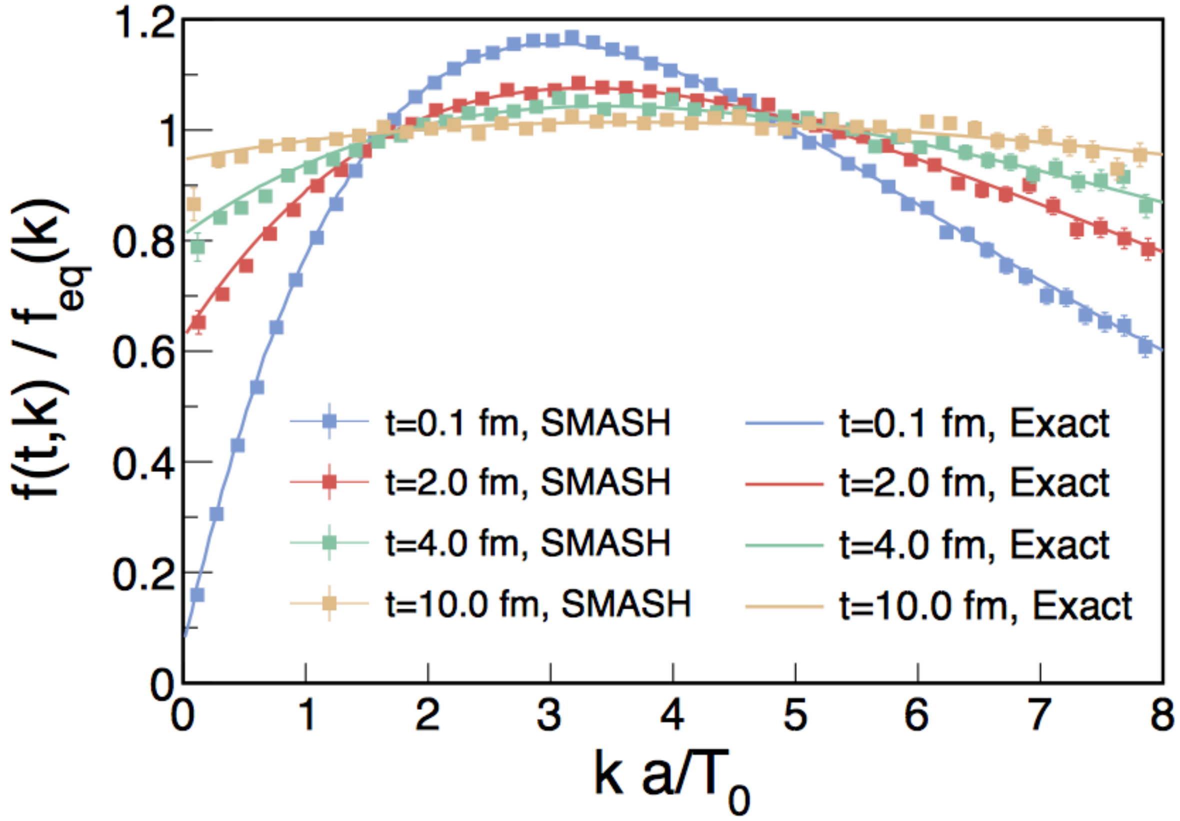


- Total cross section for pp/pπ collisions
- Parametrised elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of data up to 4 - 4.5 GeV
- String excitation by PYTHIA: work in progress

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





- Perfect agreement proves correct numerical implementation of collision algorithm

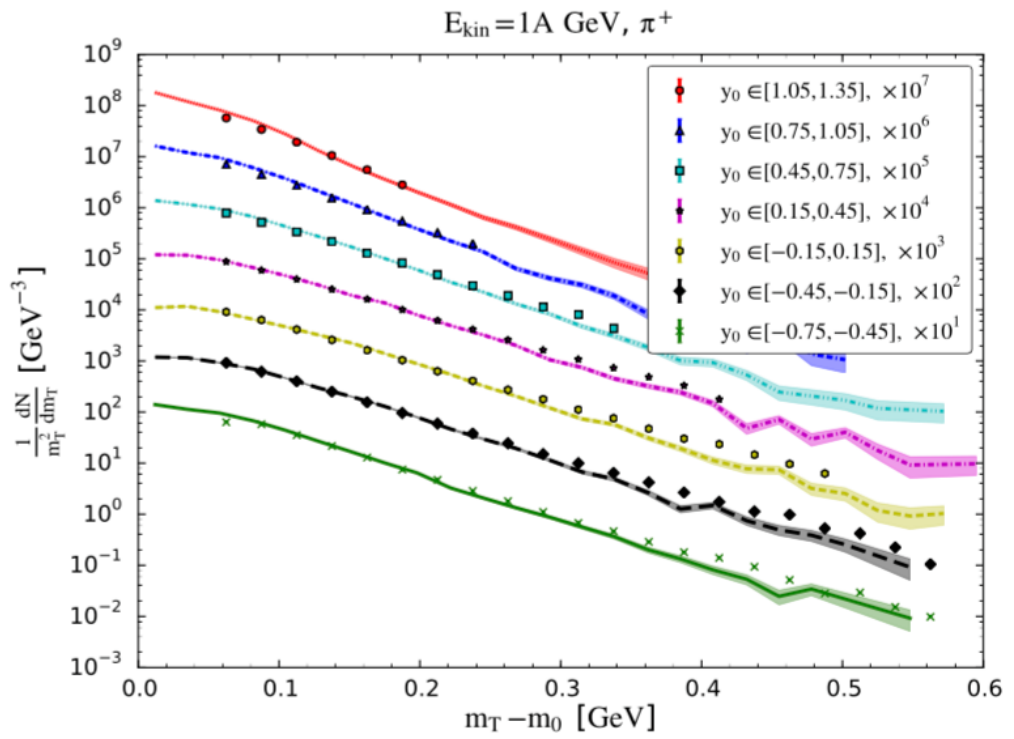
J. Tindall, J. M. Torres-Rincon, J.-B. Rose and HP, PLB 770 (2017)

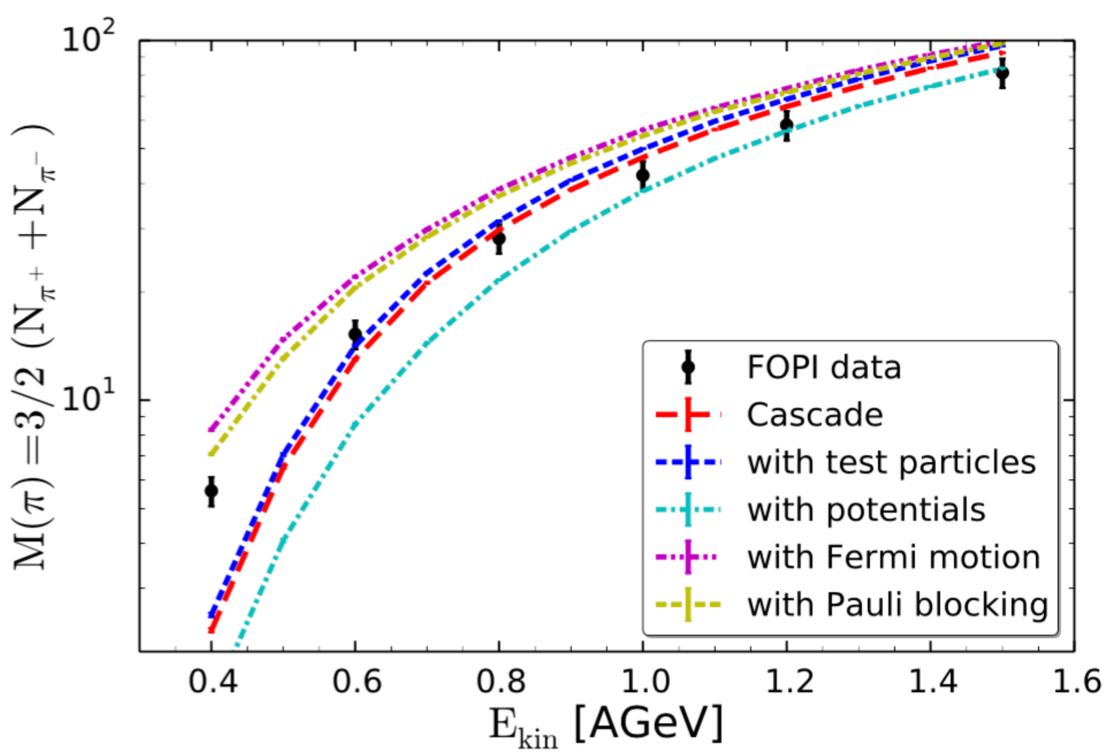
Bulk observables at GSI-SIS

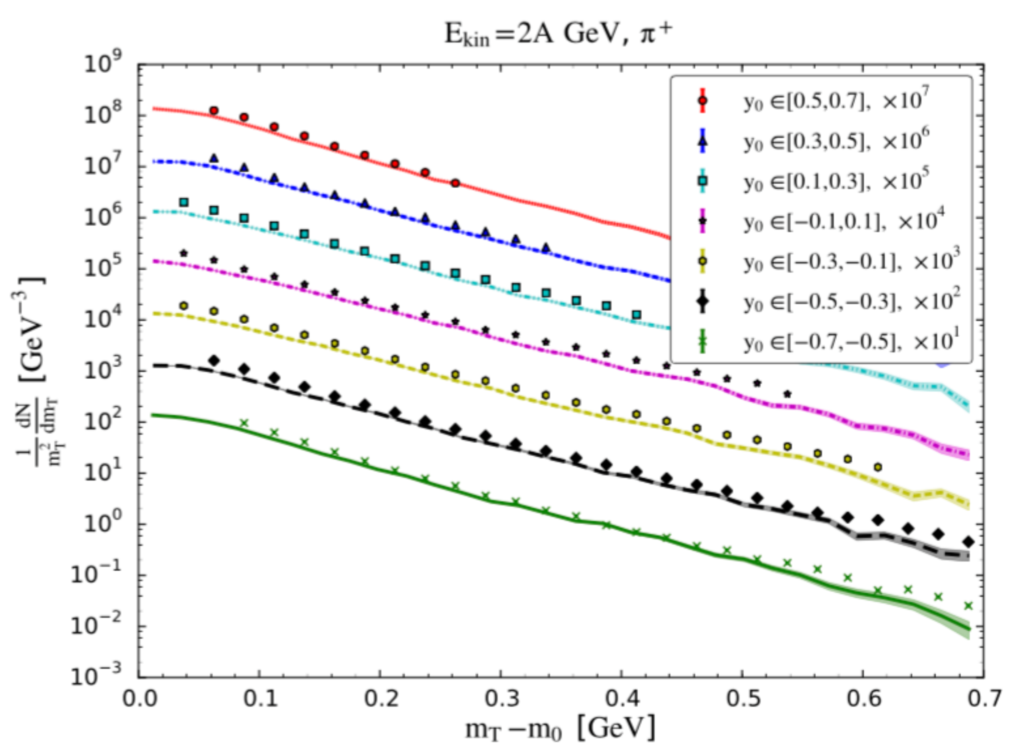
J. Weil et al, arXiv:1606.06642, PRC 94 (2016)
M. Mayer et al in preparation

Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Slightly too high pion multiplicities







J. Weil et al, PRC 94 (2016)

Collective Behaviour

- Potentials in SMASH
  - Basic Skyrme and symmetry potential

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

  - 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

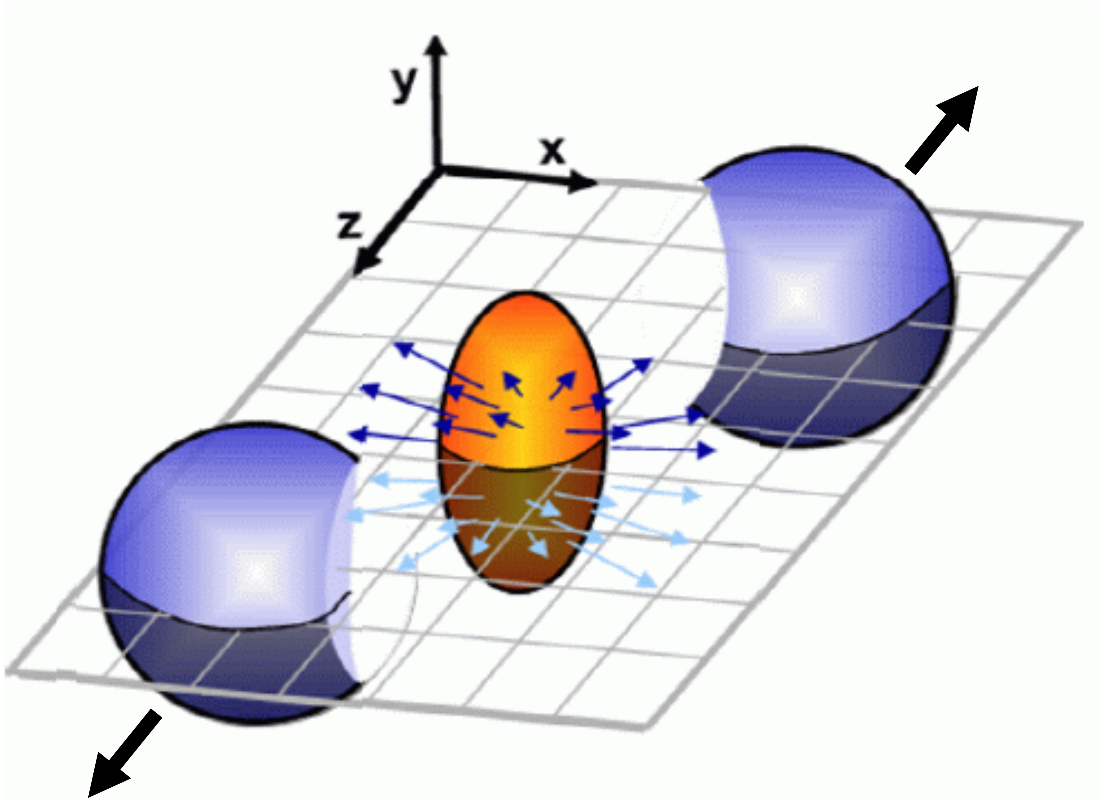
  - Default values according to recent transport code comparison

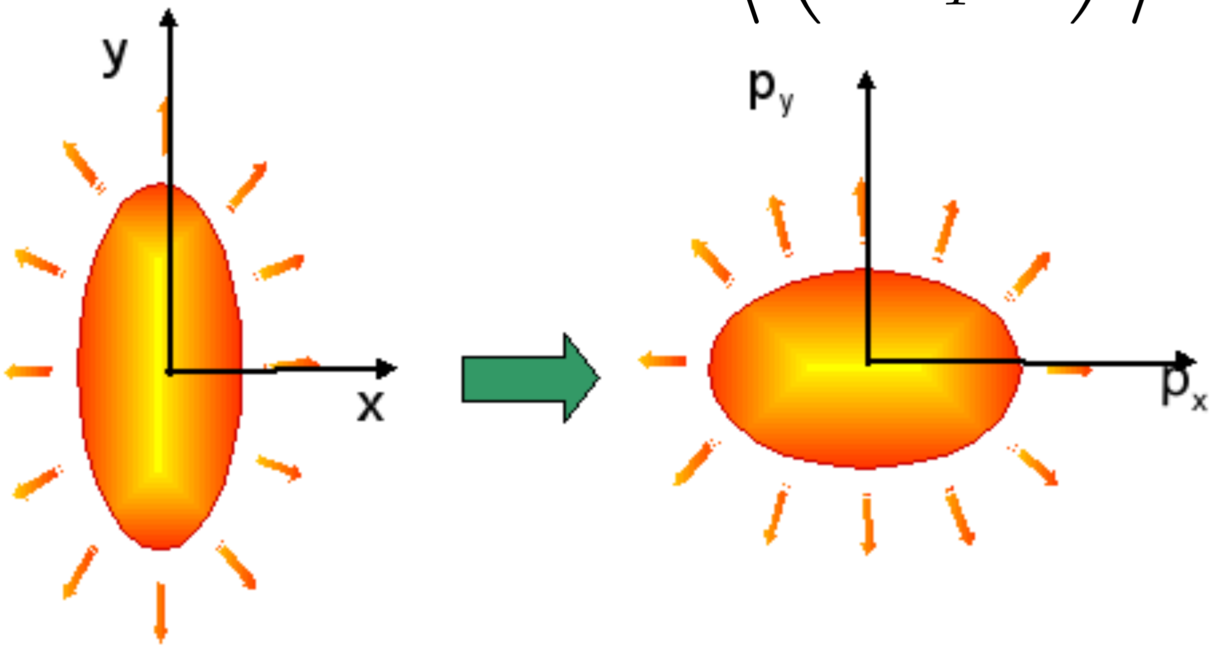
J. Xu et al., PRC 93 (2016)

Elliptic Flow

Second coefficient of the Fourier expansion of the azimuthal particle distribution:

$$v_2 = \left\langle \left(\frac{p_x^2 - p_y^2}{p_T^2} \right) \right\rangle$$





Coordinate space asymmetry
→ momentum space **anisotropy**

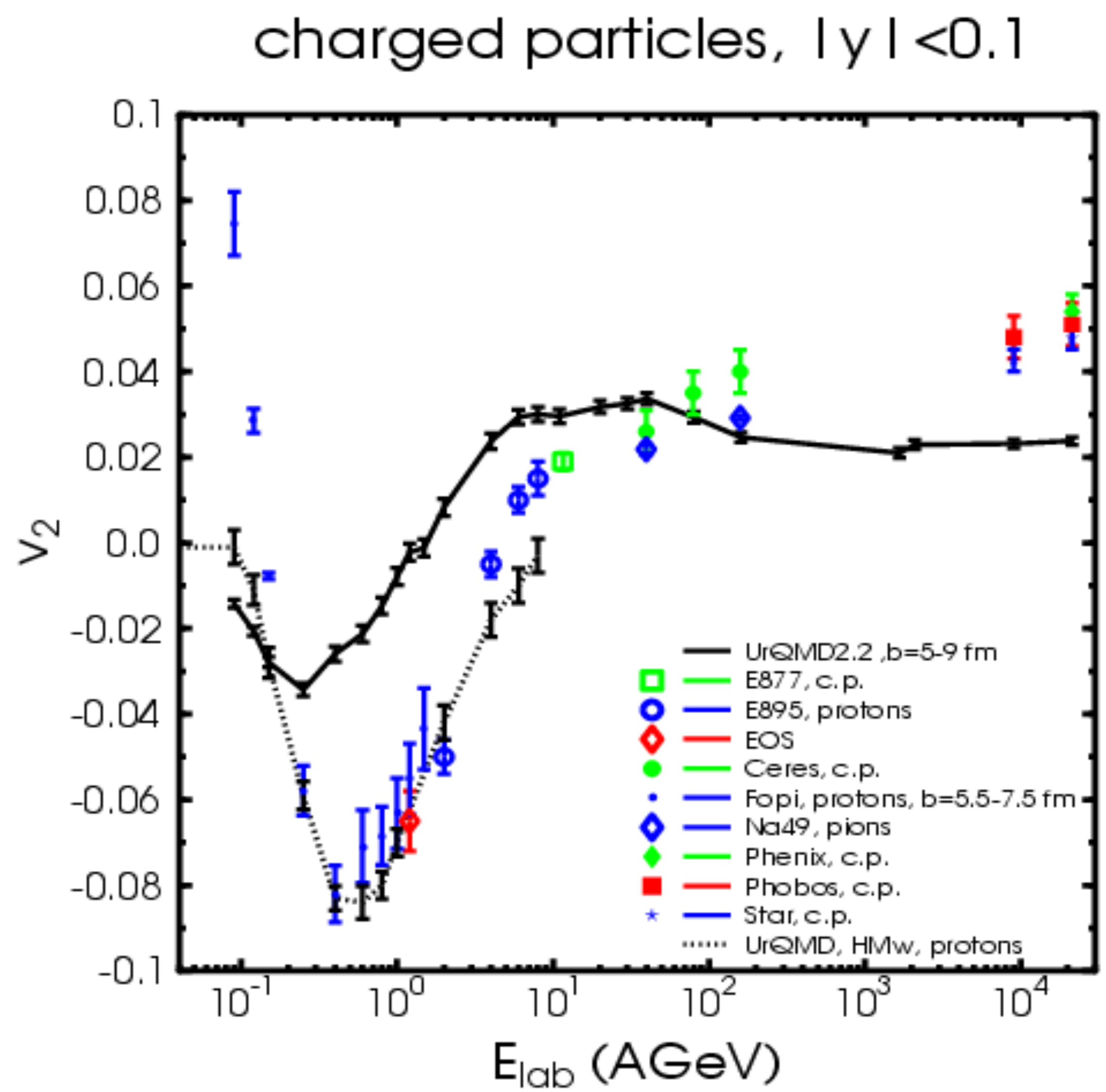
Flow is sensitive to the pressure as a function of time

-> equation of state of nuclear matter?

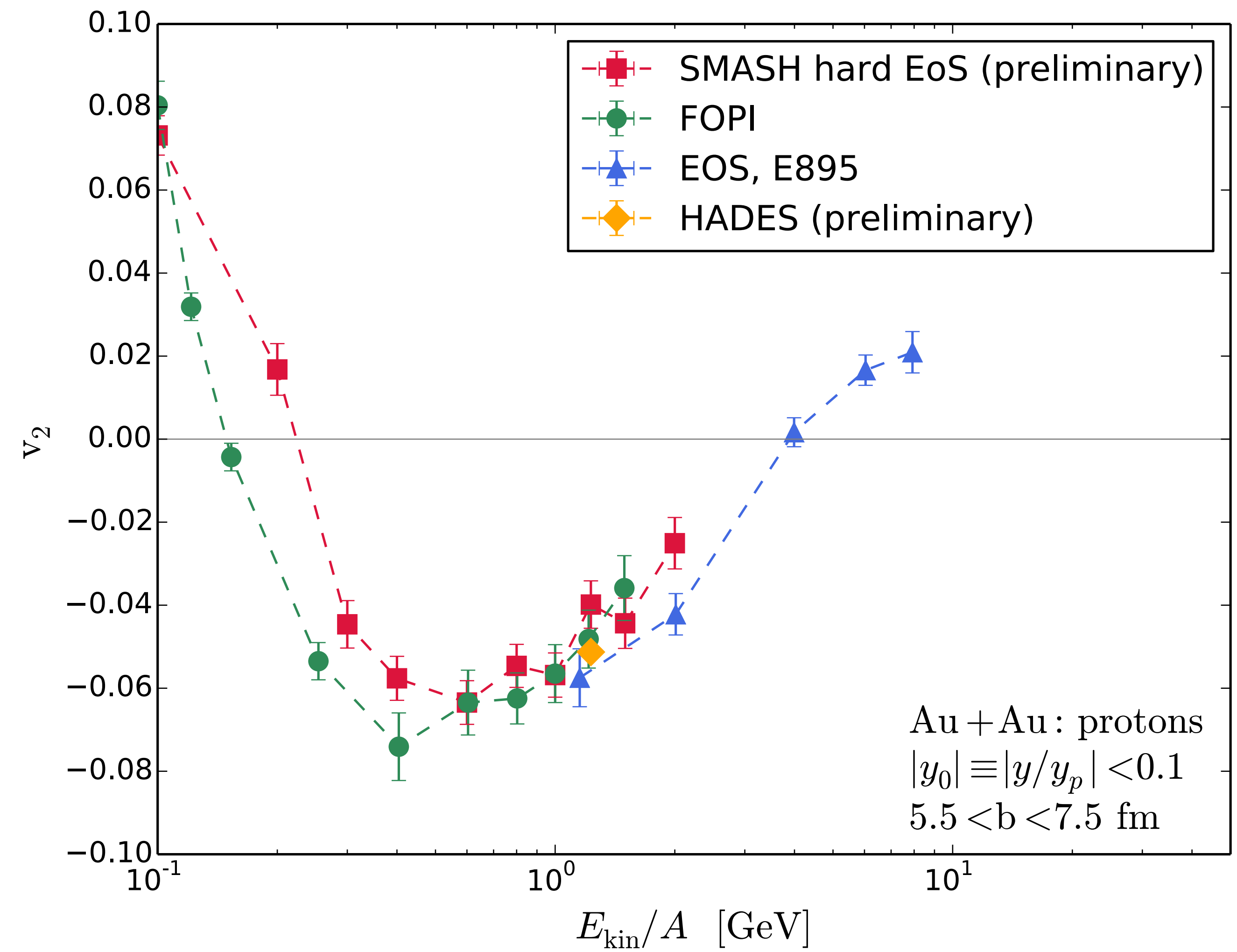
Collective Flow -v_2

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

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



by Markus Mayer



- SMASH agrees well with previous UrQMD calculation for v_2 excitation function

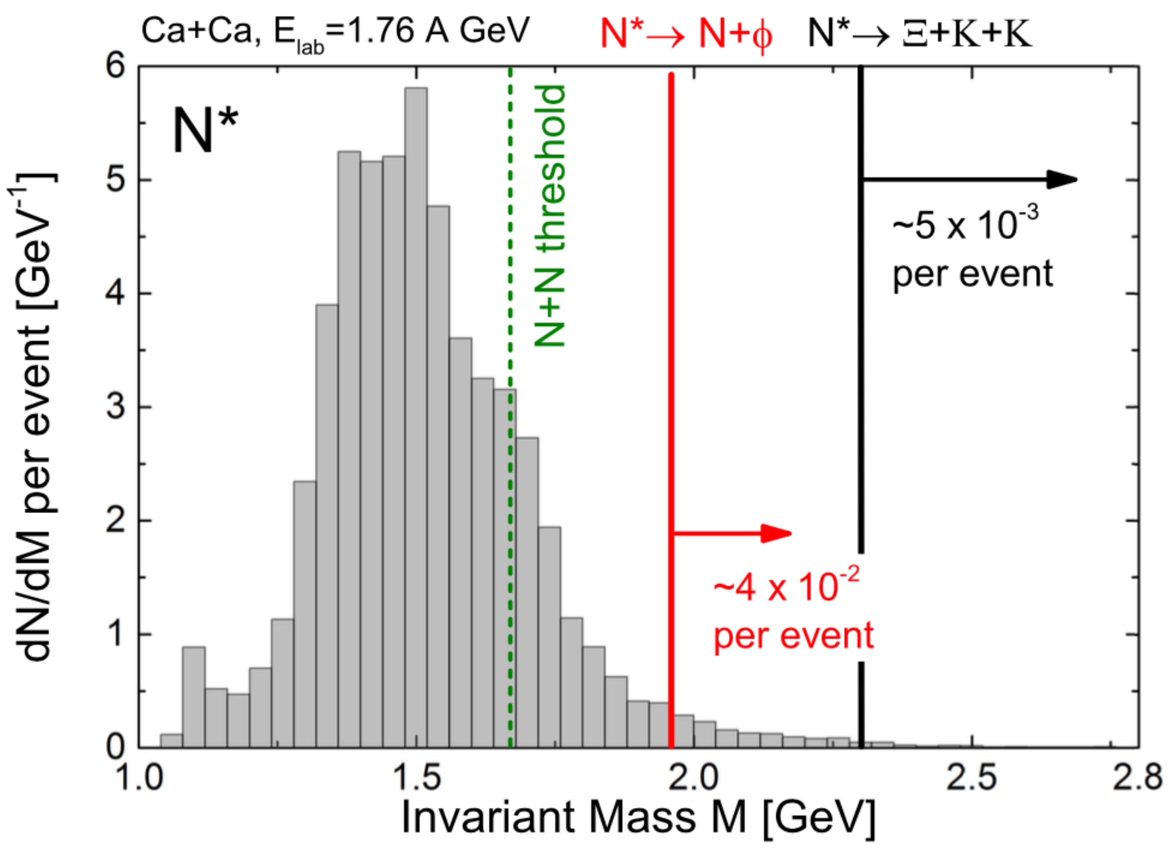
Strangeness at GSI-SIS

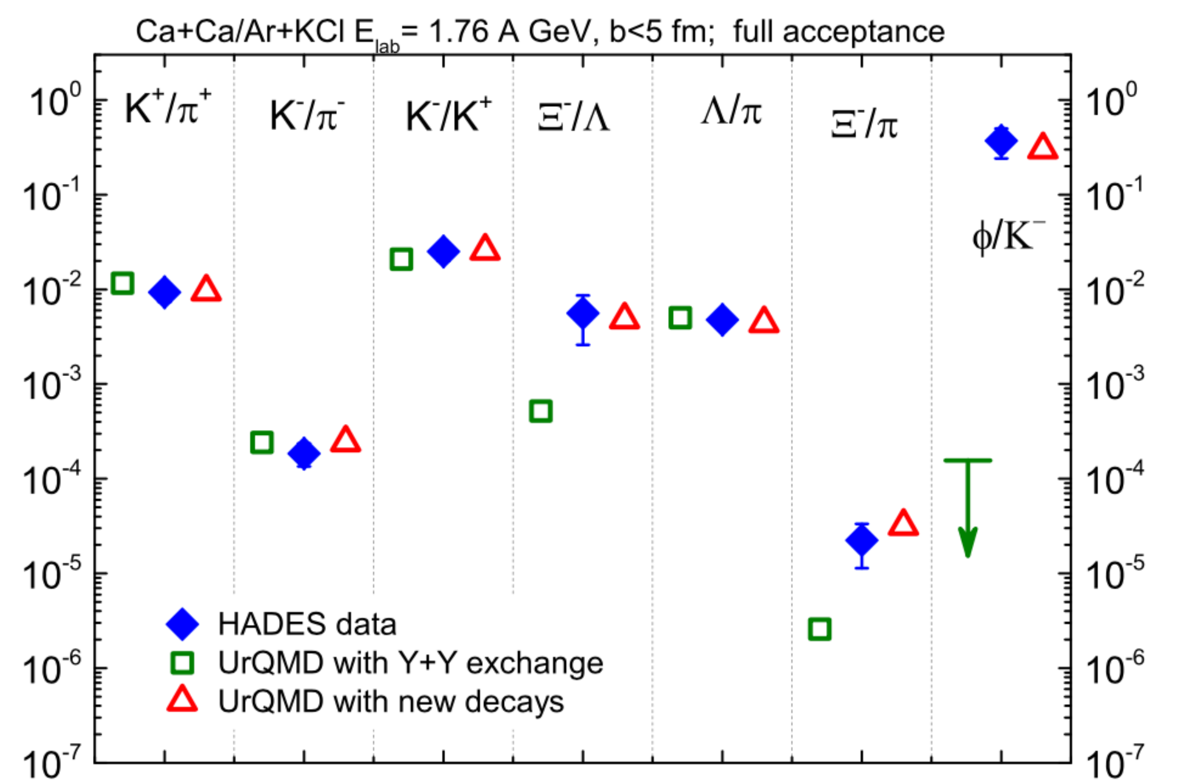
V. Steinberg et al in preparation

Φ/Ξ yields at SIS-18

- UrQMD hadronic transport approach with additional high mass resonances

J. Steinheimer and M. Bleicher. JPG43 (2016)



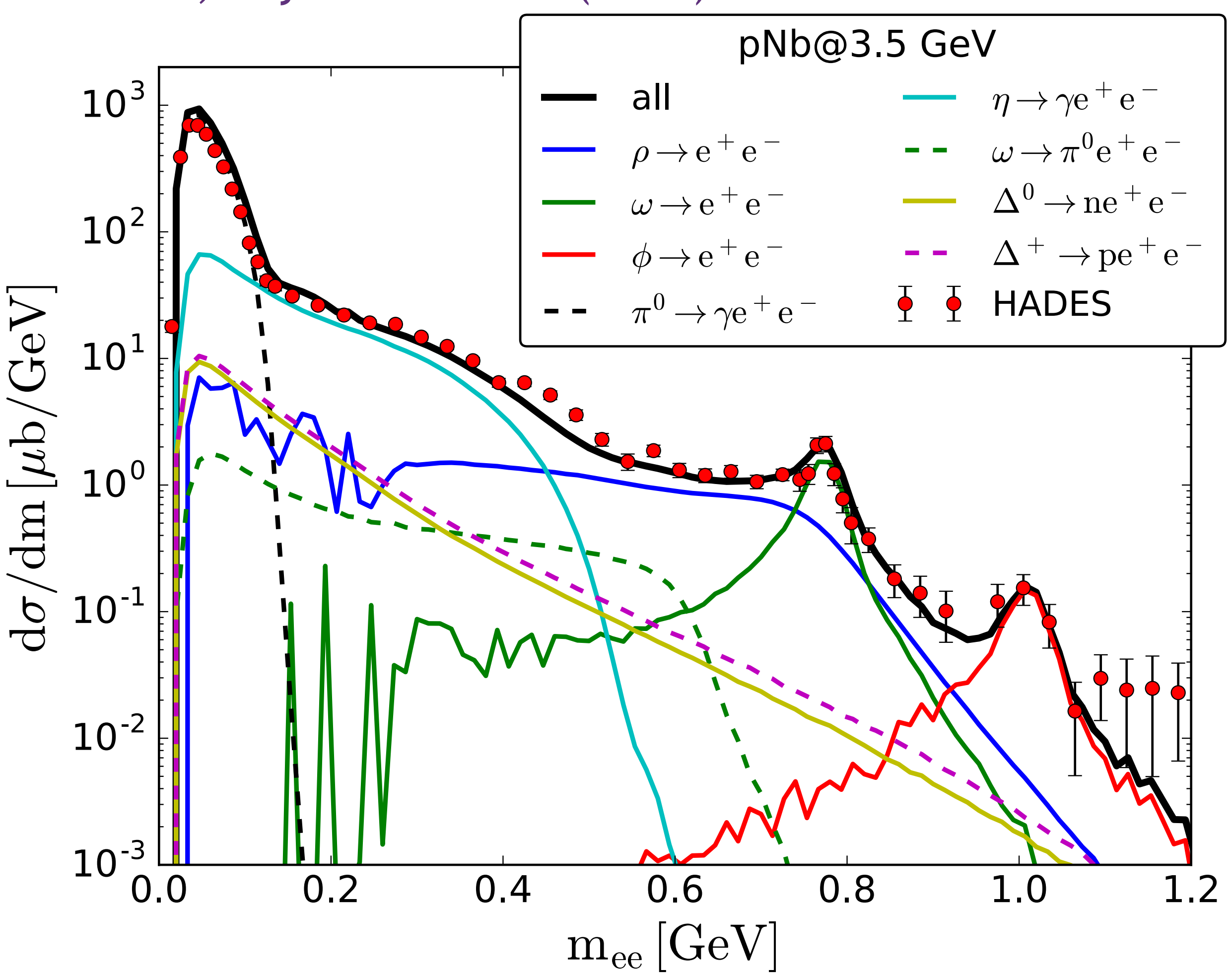


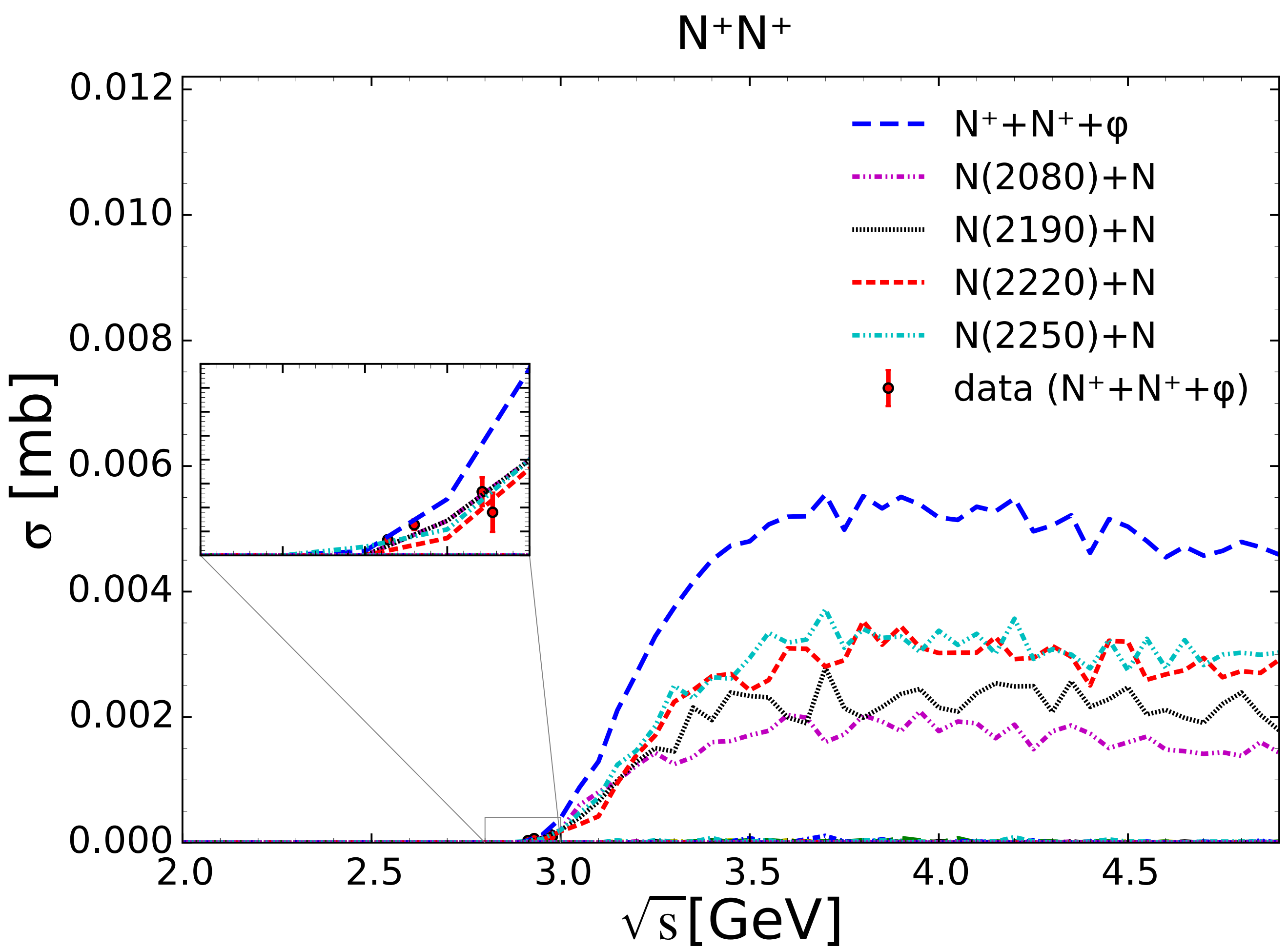
- Sub-threshold Φ and Ξ production is visible
- Decay channels of high N* resonances unknown

Φ Production in SMASH

- Independent data sets to constrain production cross-section from dileptons and elementary reactions

HADES, Phys.Lett. B715 (2012)



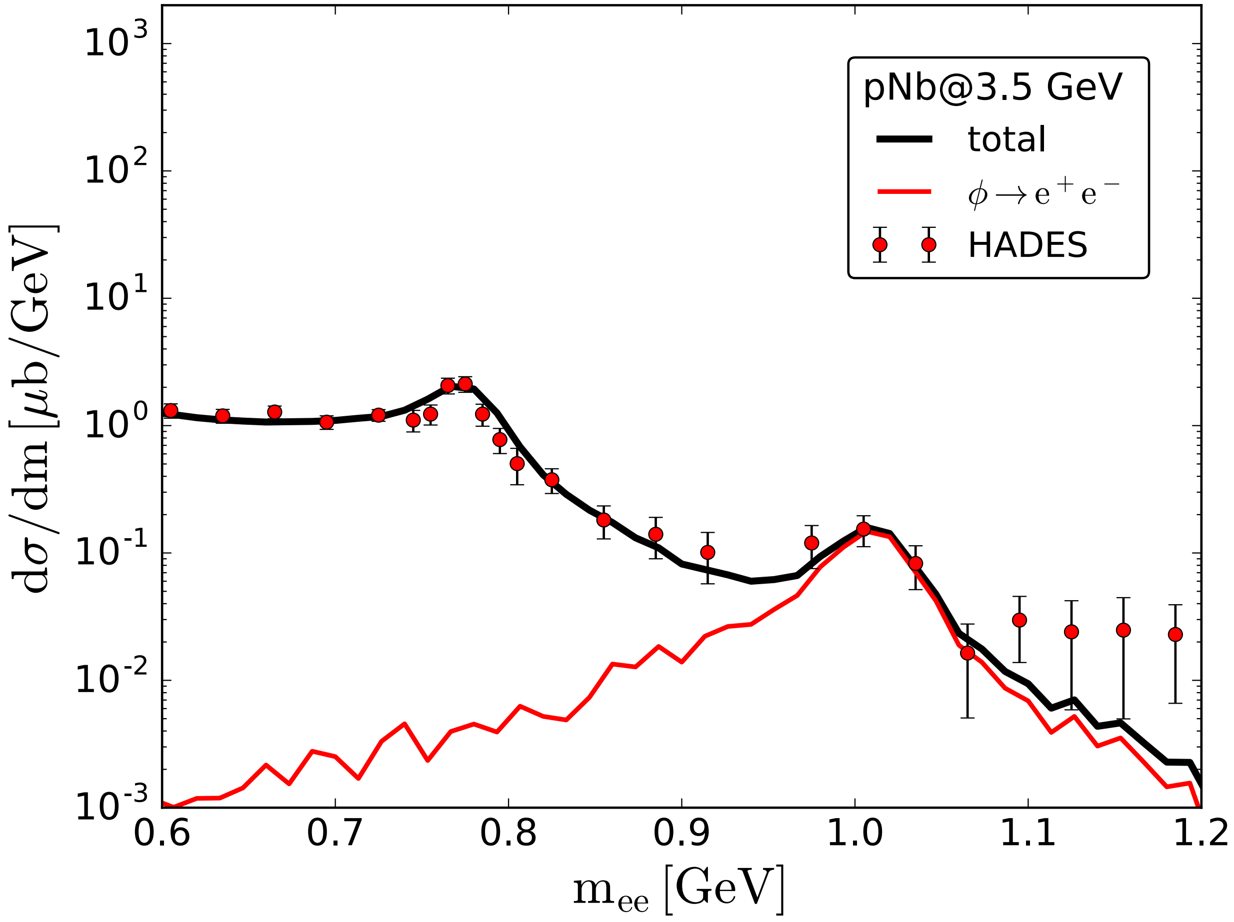


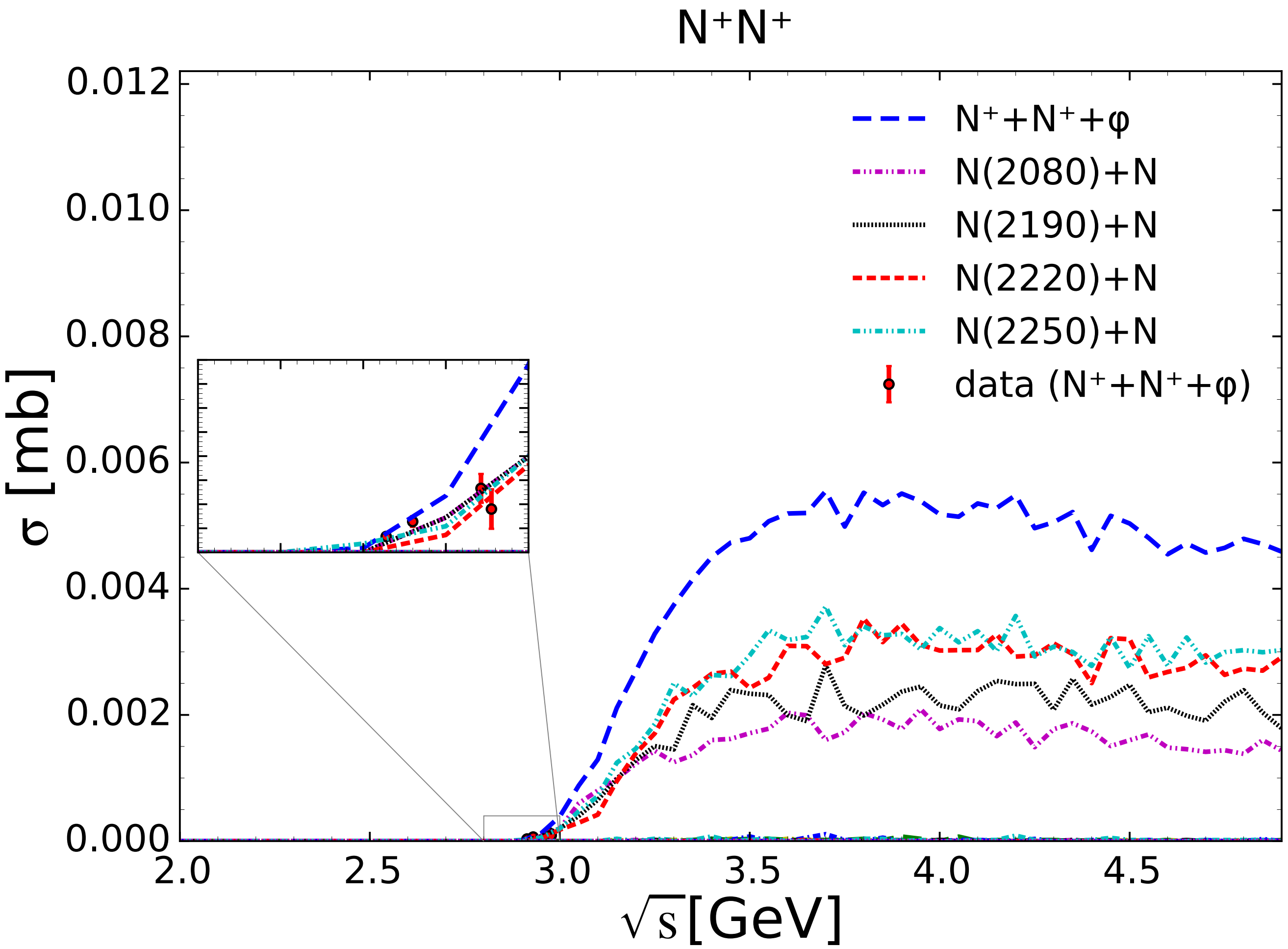
- Work in progress: prediction for Φ production in heavy ion collisions

Φ Production in SMASH

- Independent data sets to constrain production cross-section from dileptons and elementary reactions

HADES, Phys.Lett. B715 (2012)





- Work in progress: prediction for Φ production in heavy ion collisions

Strangeness Production

- Elementary cross-sections provide constraints

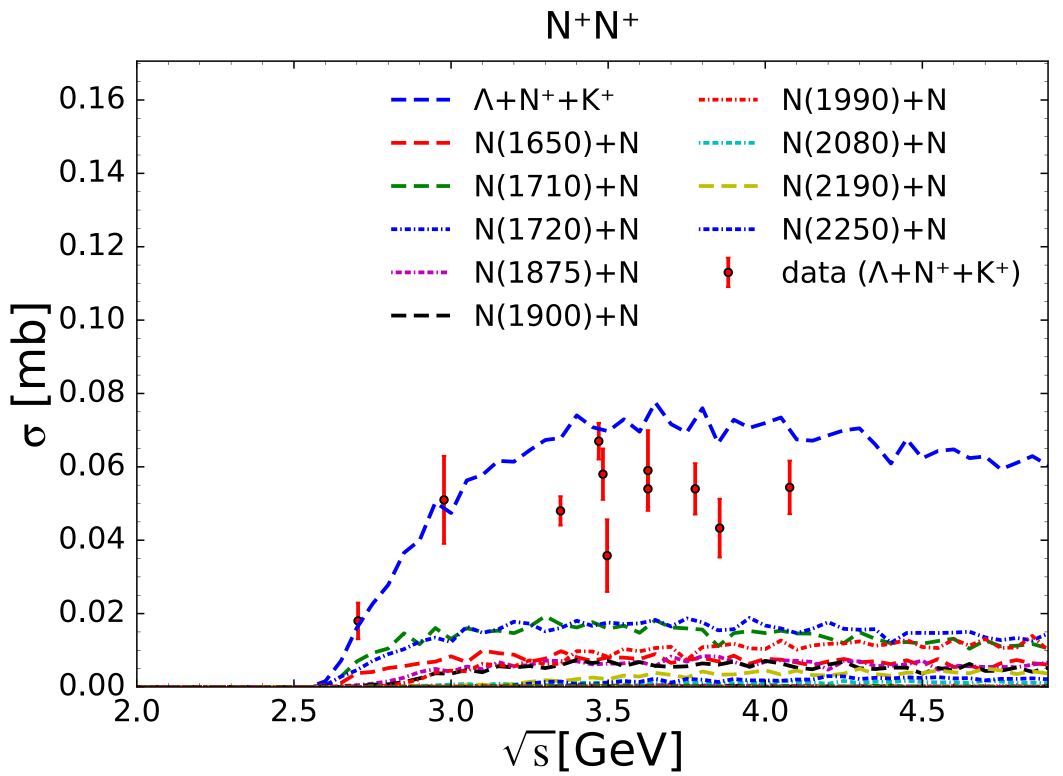
K^+ production ($Y \in \{\Lambda, \Sigma\}$):

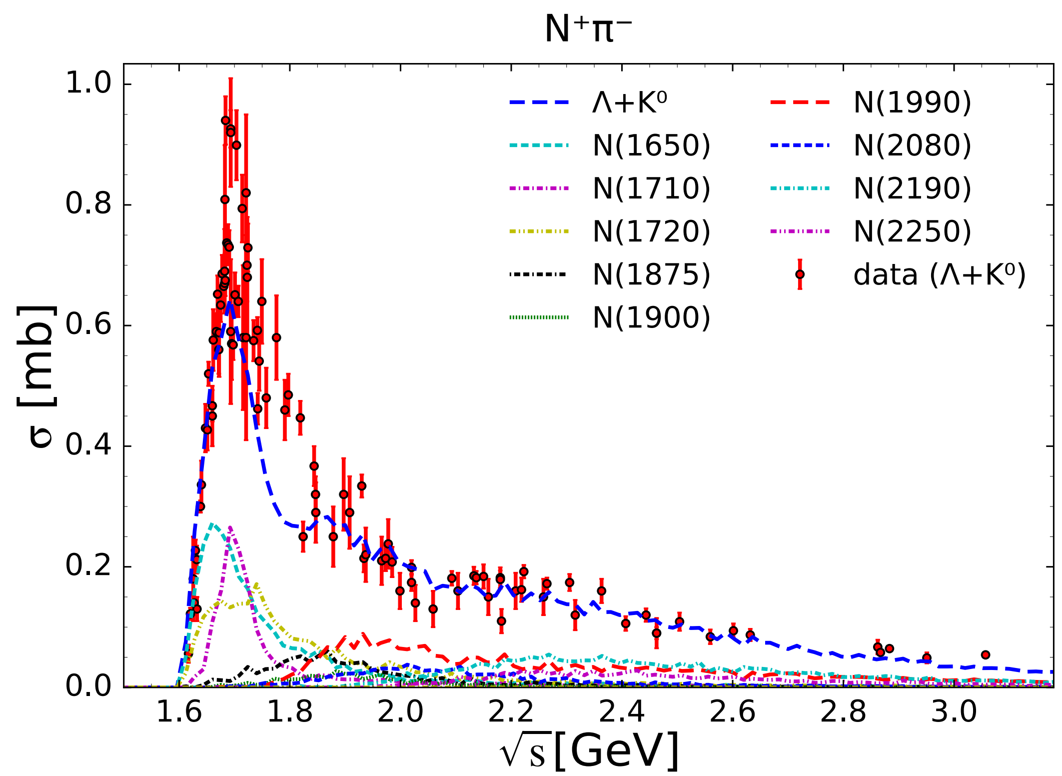
$$NN \to NN^*/\Delta^* \to NYK$$

K^- production:

$$NN \to N^*/\Delta^* ... \to Y ... \to Y^* ... \to \bar{K} ...$$
$$\pi Y \leftrightarrow \bar{K} N$$

resonance	branching ratio $N^* \to \Lambda K$ 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%

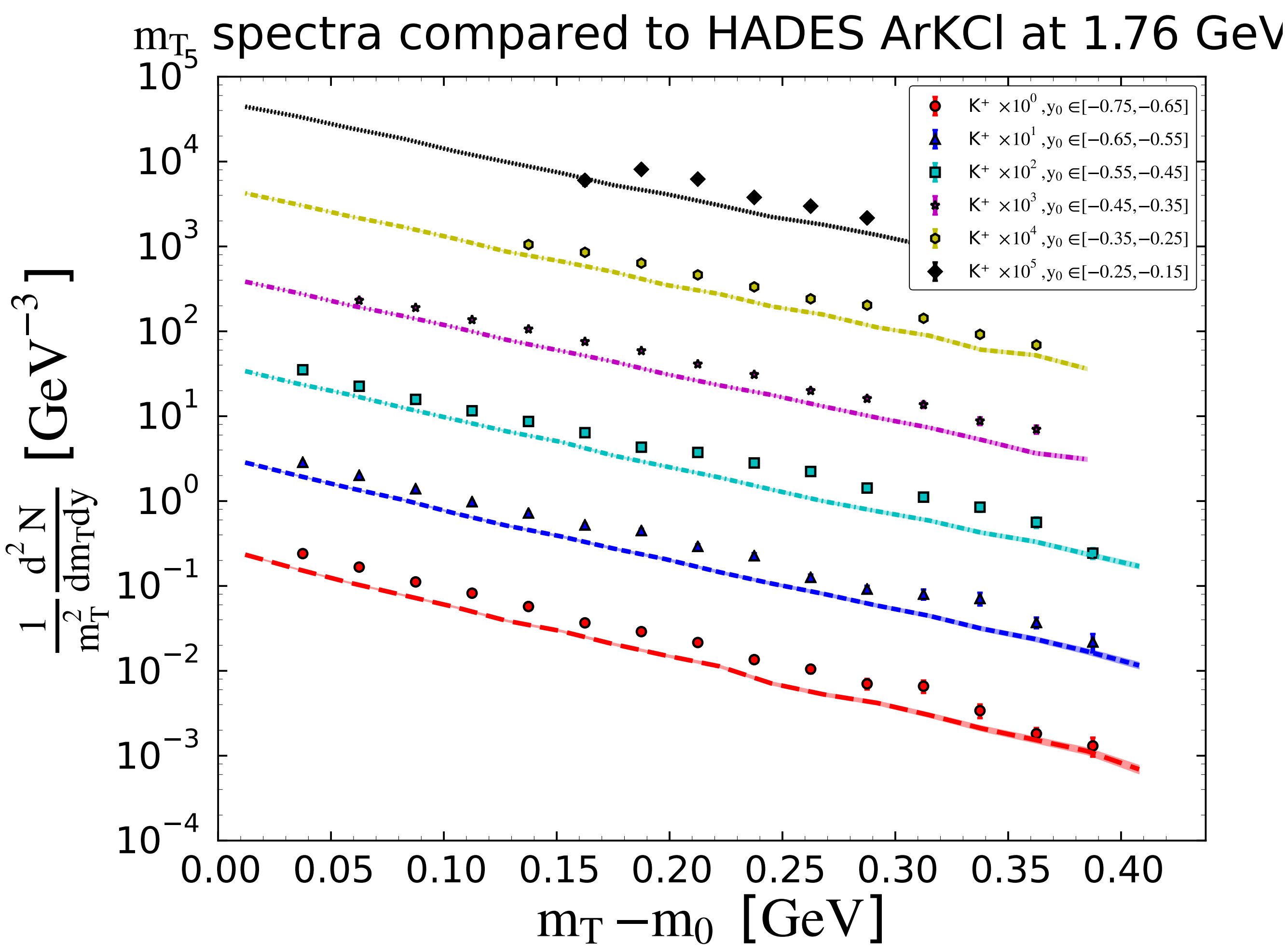




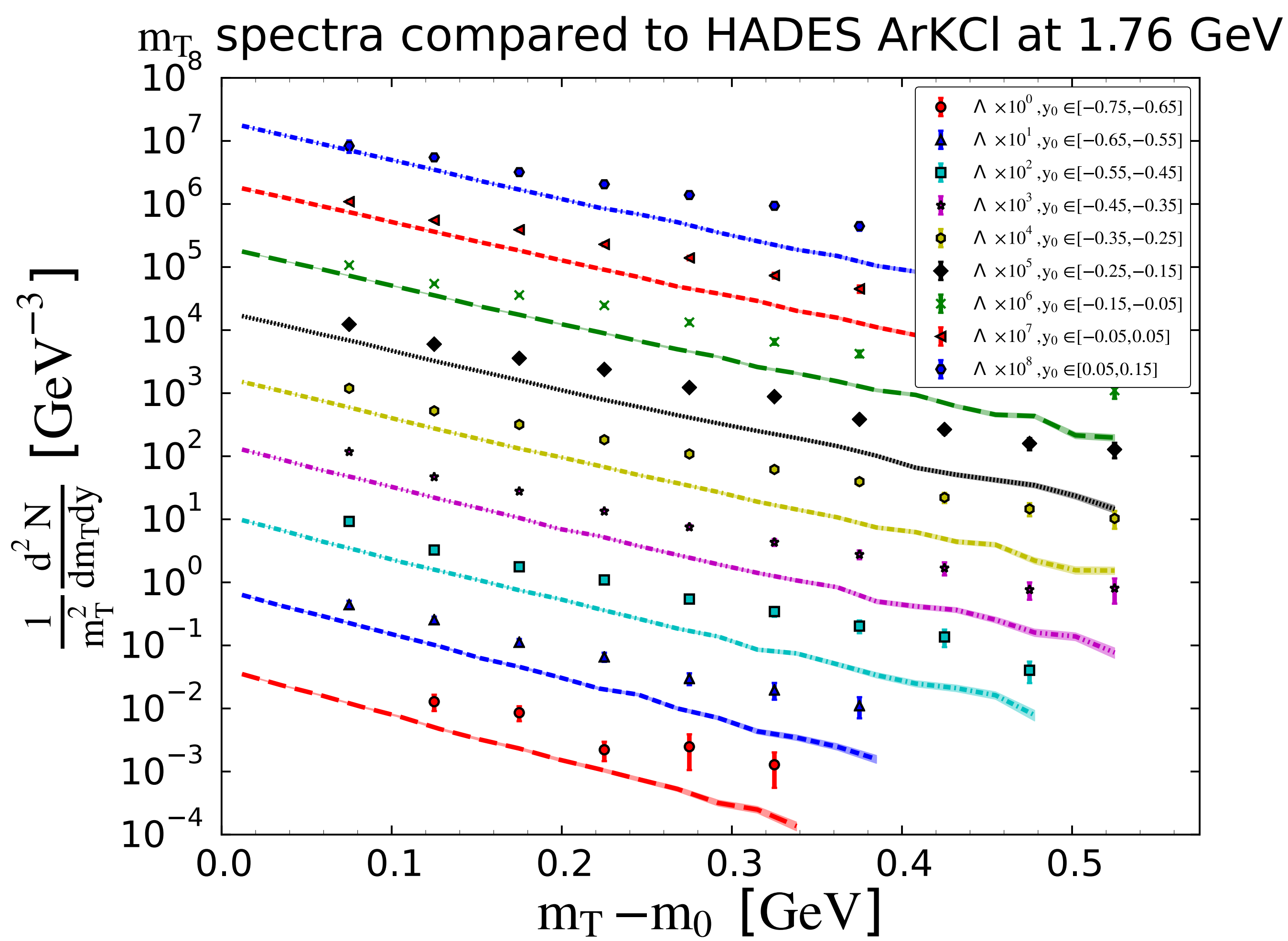
Strangeness Production

- Kaons and Lambdas in heavy ions:

Kaons



Λ's



- Ongoing work: Centrality dependence, predictions for pion beam and hyperon potentials

Dilepton Production

J. Staudenmaier, J. Weil, V. Steinberg, S. Endres and HP,
arXiv: 1711.10297

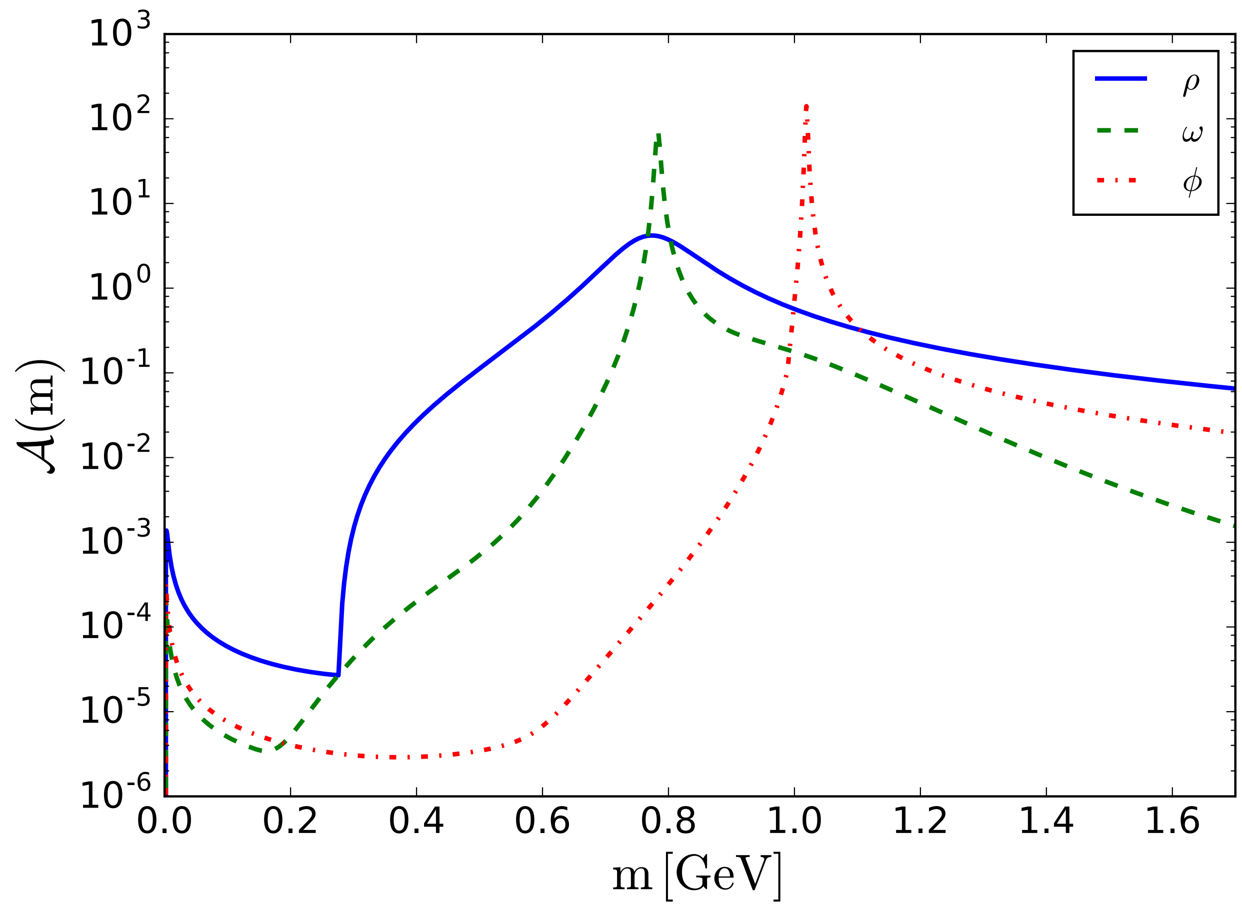
Dileptons in SMASH

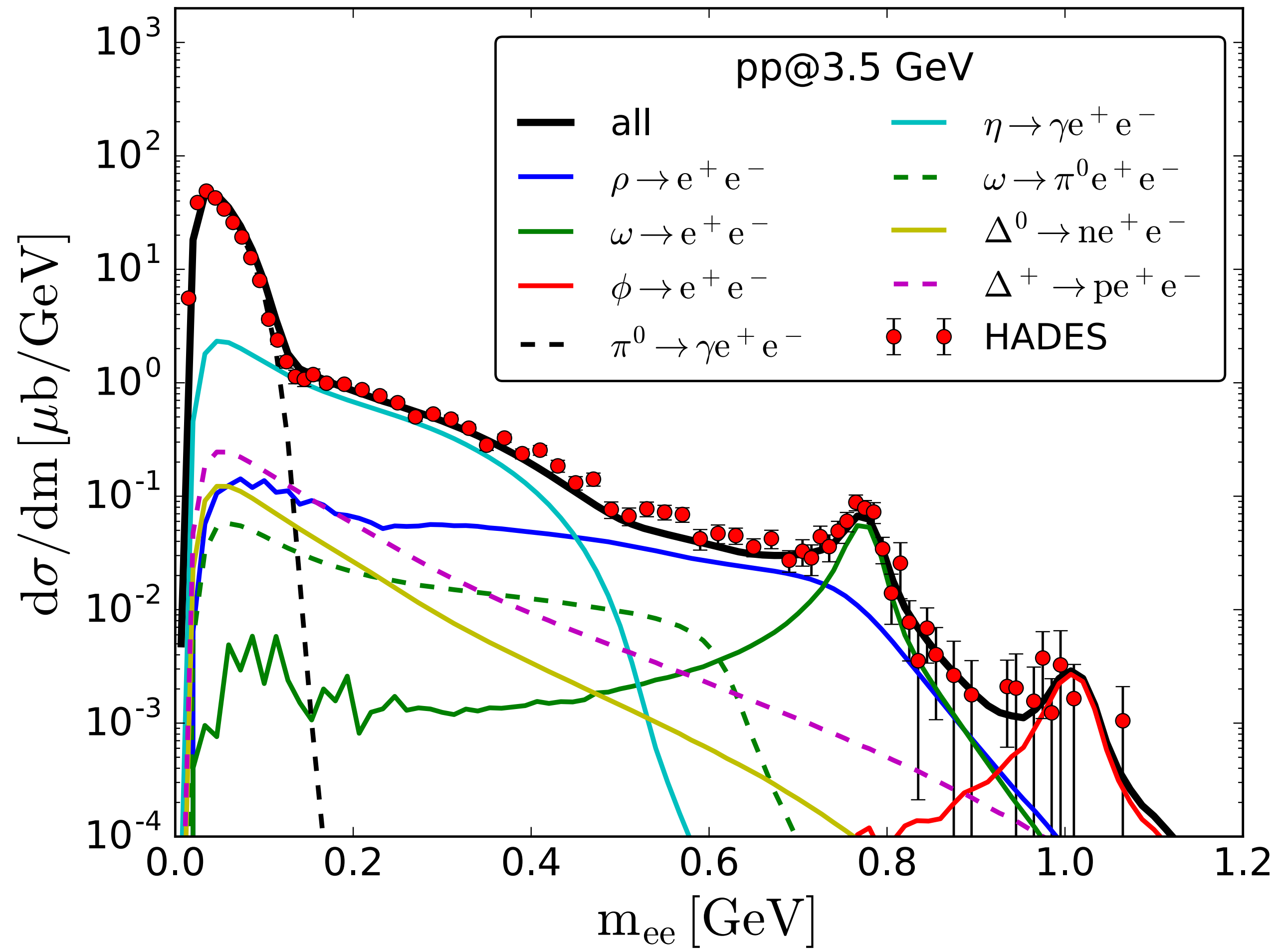
- Dileptons produced by resonance decays
- Direct and Dalitz dilepton decay channels
- Rare e.m. decays —> Time-Integration-Method / *Shining*
  - Continuously perform dilepton decays and weight them by taking their decay probability into account (better statistics)
- Acceptance correction for HADES detector possible

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

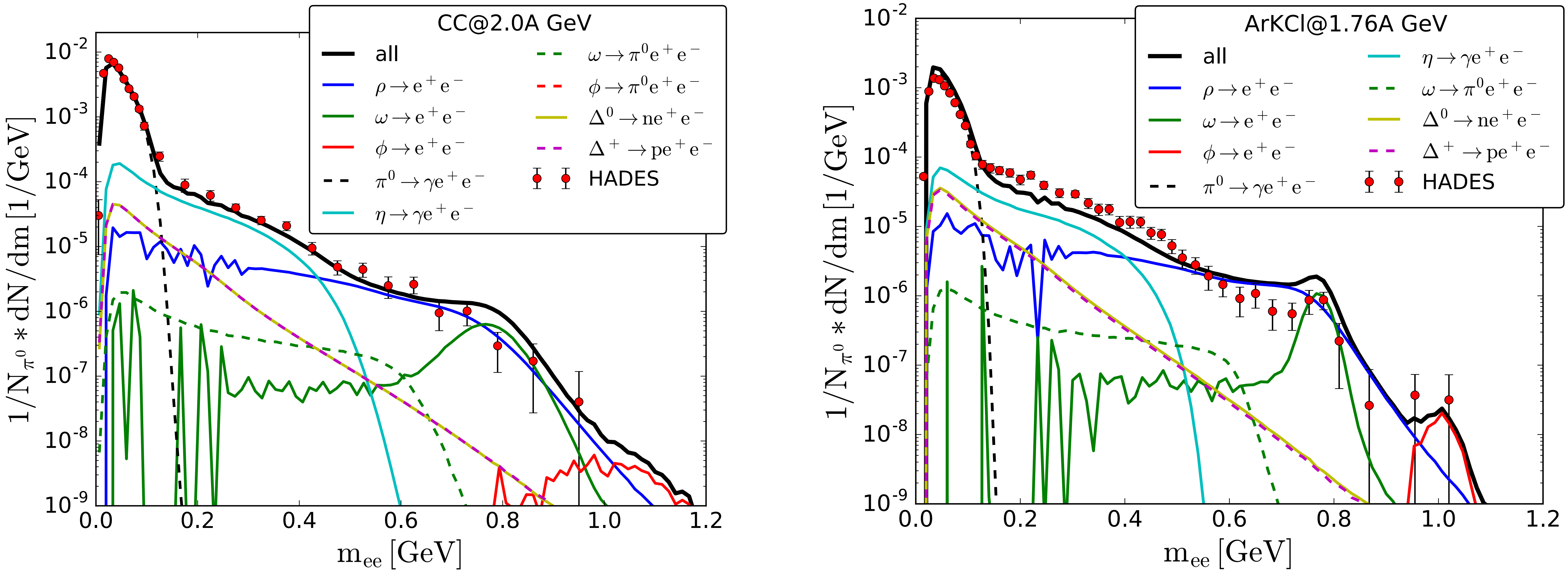




- Very nice agreement with HADES measurement

Vacuum Properties

- Hadron transport with collisional broadening sufficient for C+C collisions

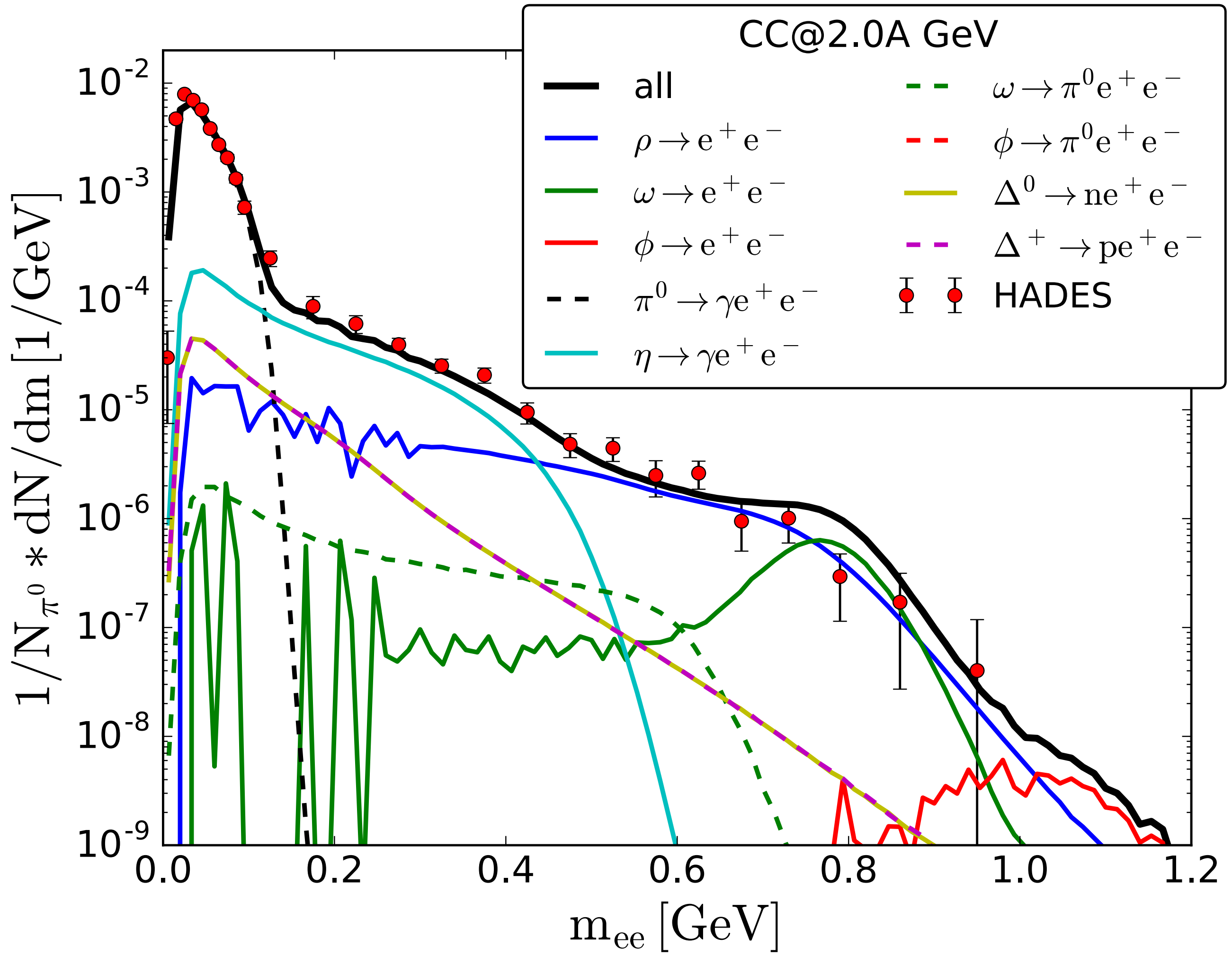


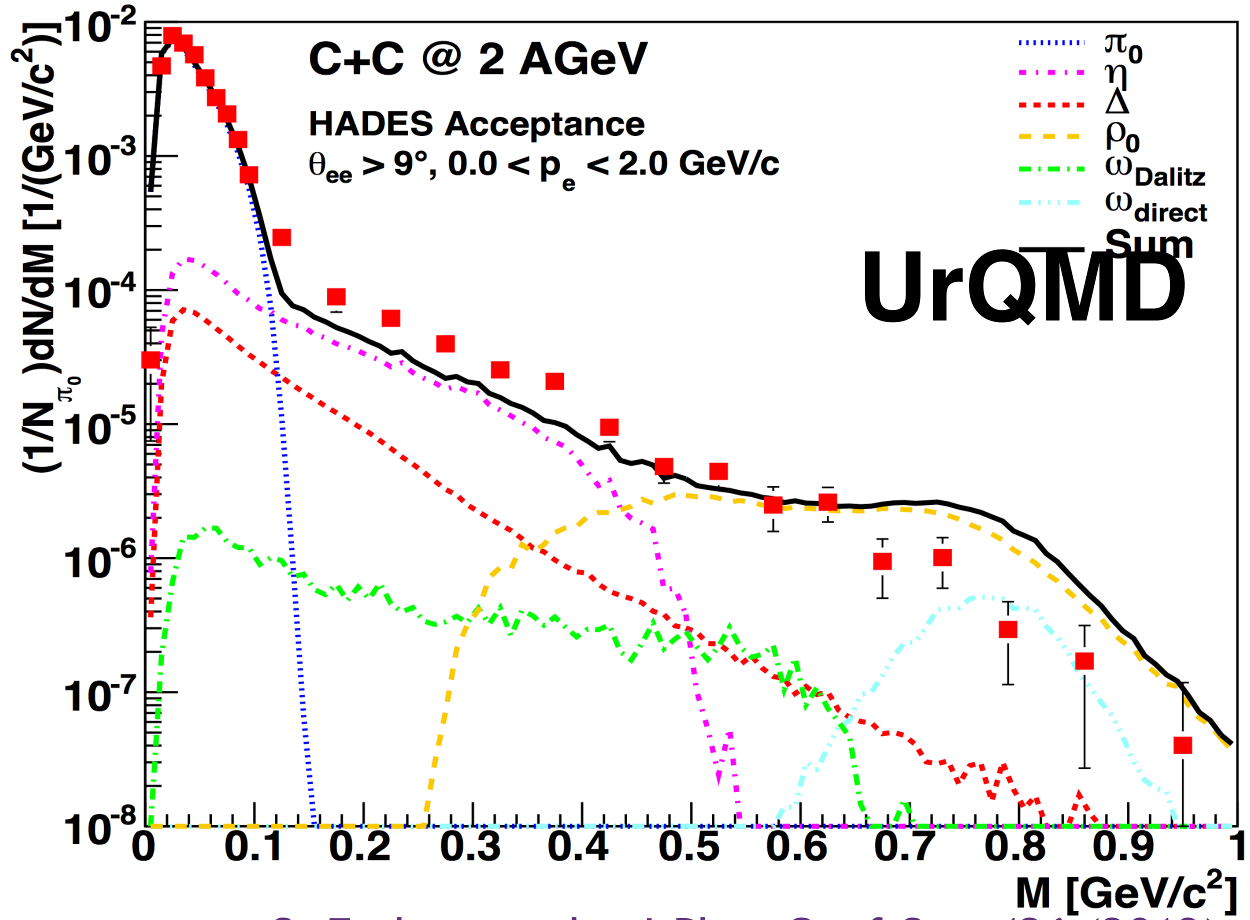
- For larger systems (ArKCl) excess in intermediate mass region

Dilepton Production

HADES, PRL 98 (2007)

J. Staudenmaier et al, arXiv: 1711.10297



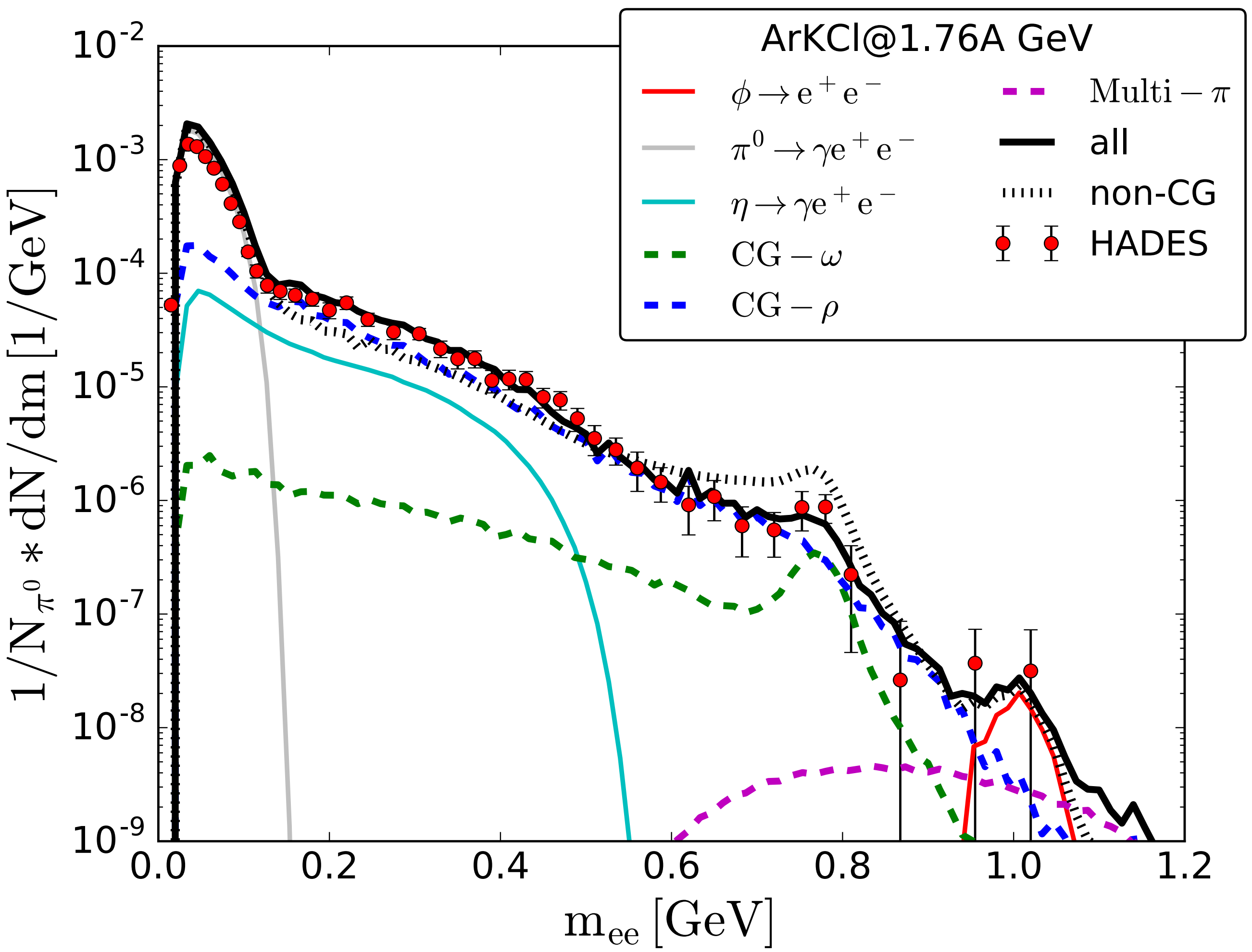


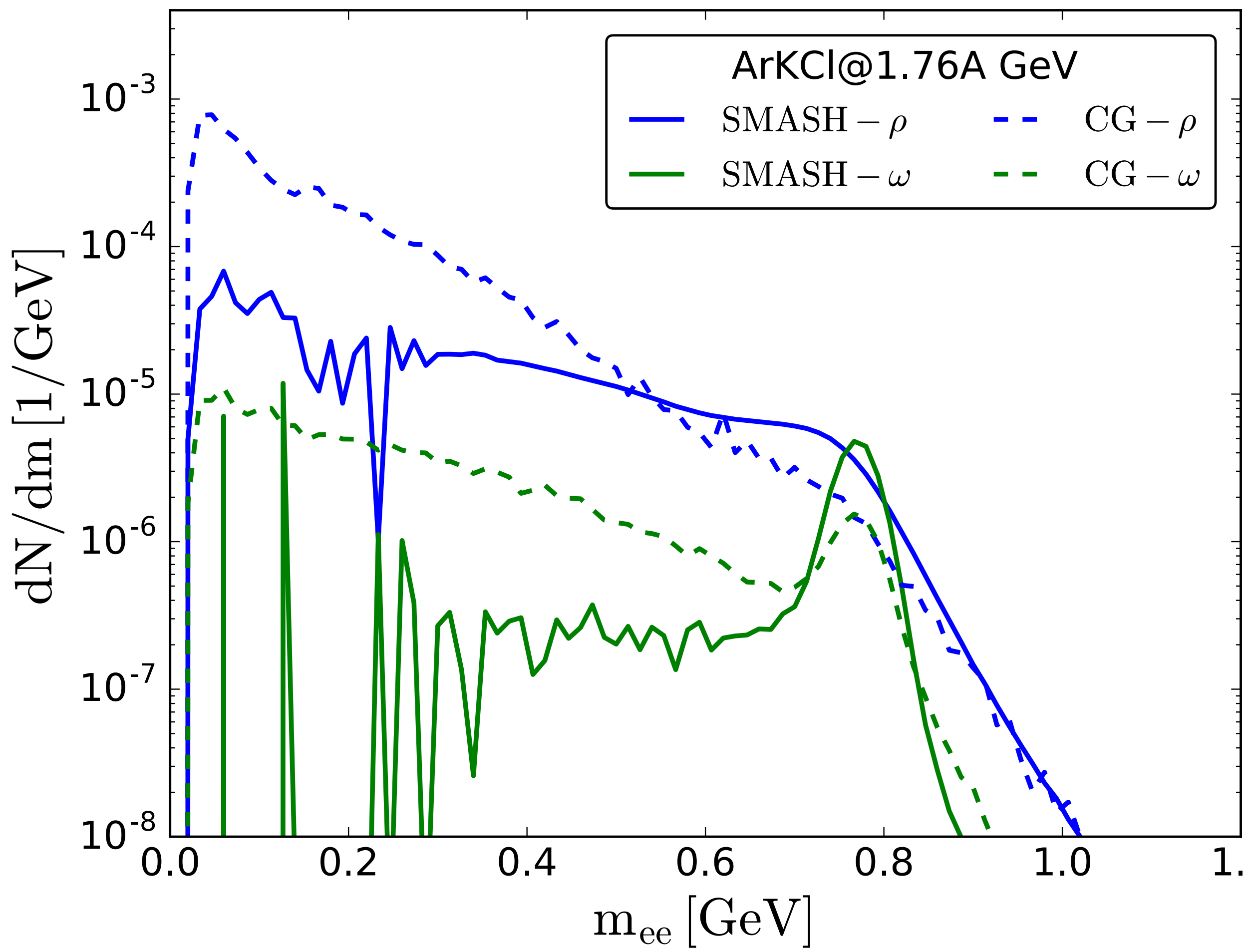
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

- SMASH and UrQMD compare very similar to data
- Different vector meson thresholds

Medium Modifications

- Medium modified spectral functions are applied on a coarse-grained transport evolution





- Very nice agreement with HADES data
- Waiting for Au+Au results..

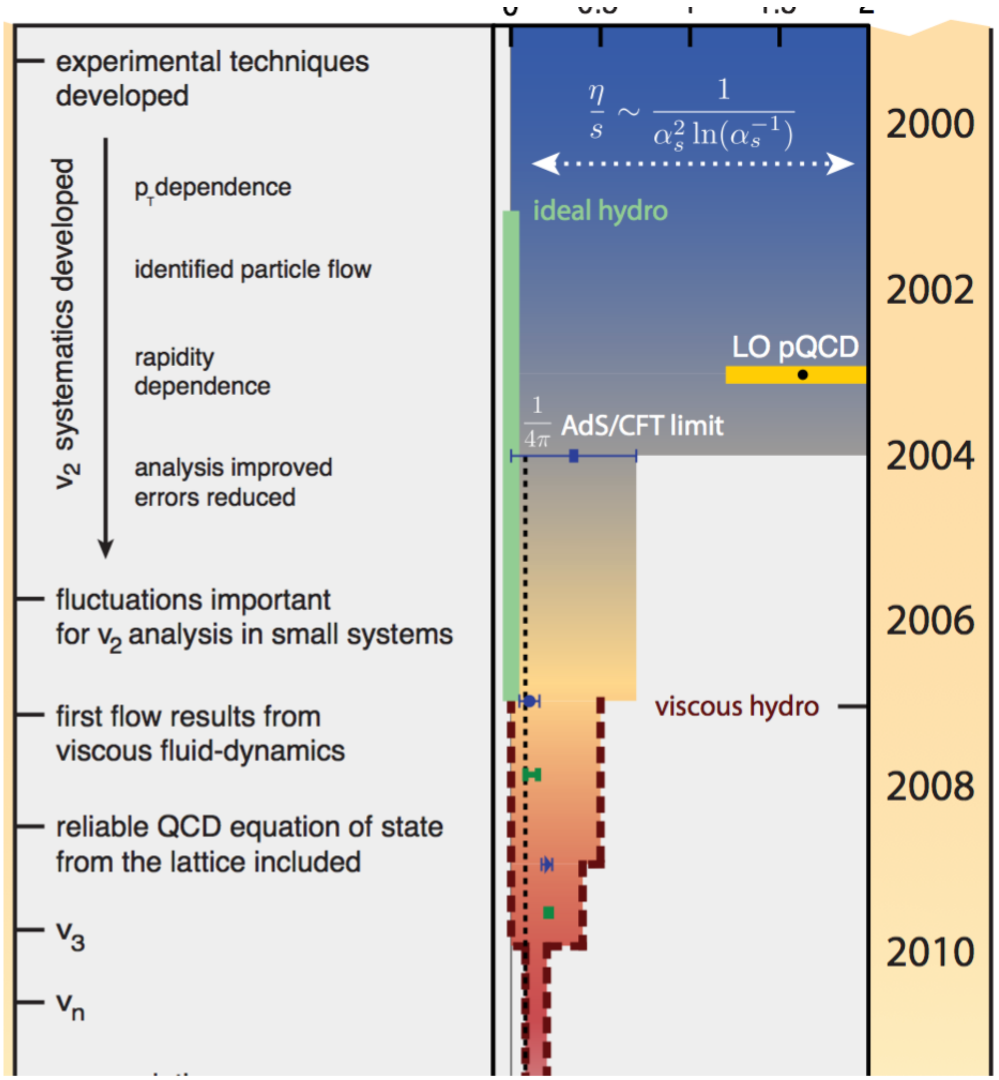
Transport coefficients

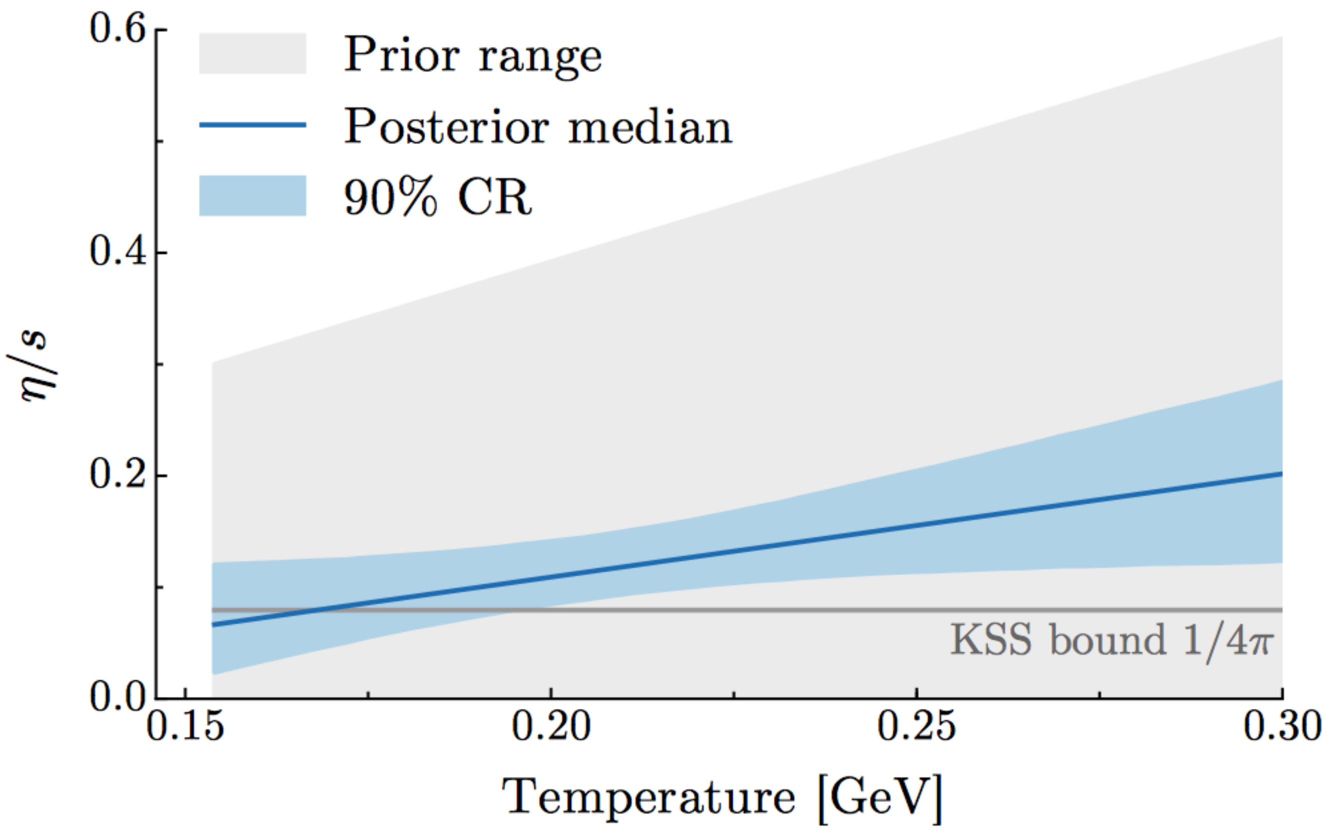
J.-B. Rose, J. M. Torres-Rincon, A. Schäfer, D. Oliinychenko and HP,
arXiv: 1709.00369 and 1709.03826
and J. Hammelmann et al, in preparation

Transport Coefficients

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

RHIC White paper, 2012



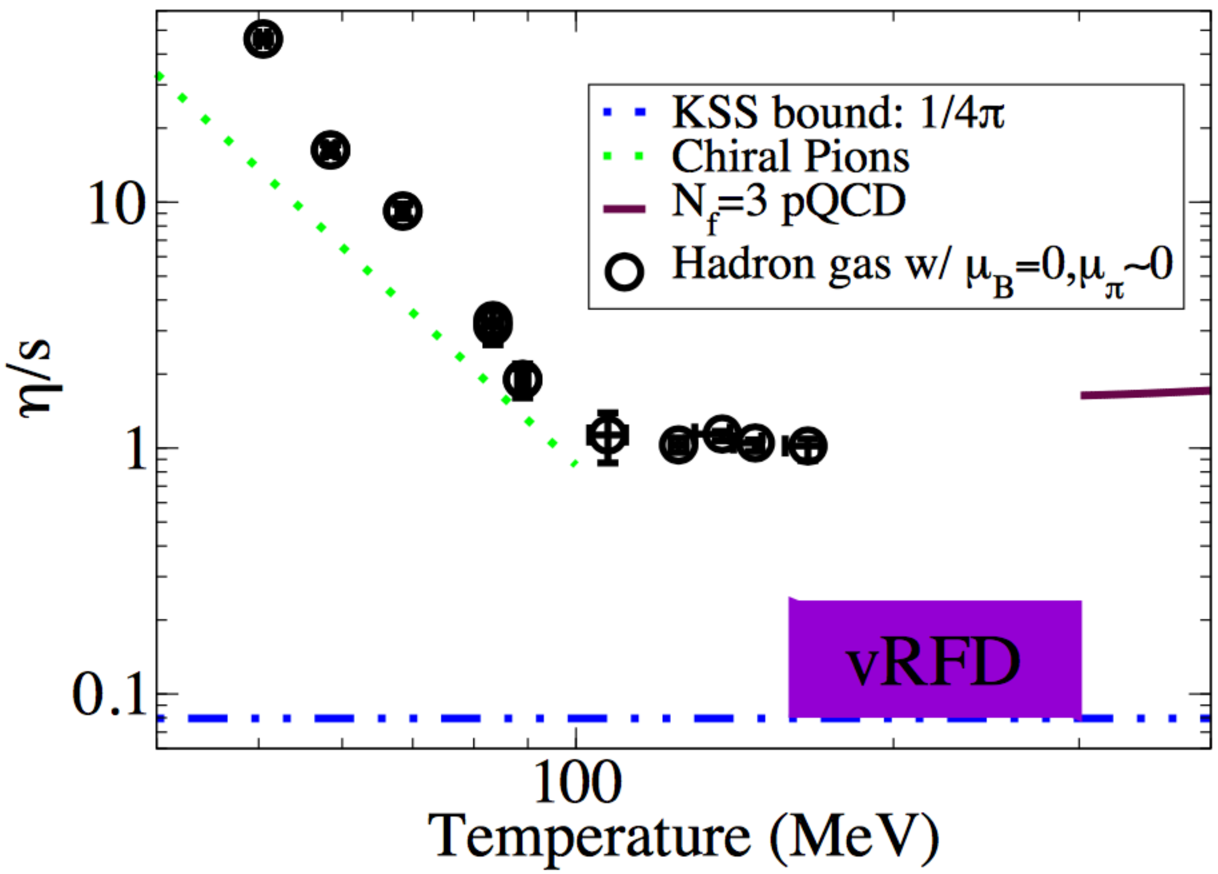


J. Bernhard et al, Phys.Rev. C94 (2016)

- Application of Bayesian techniques allows extraction of temperature dependence

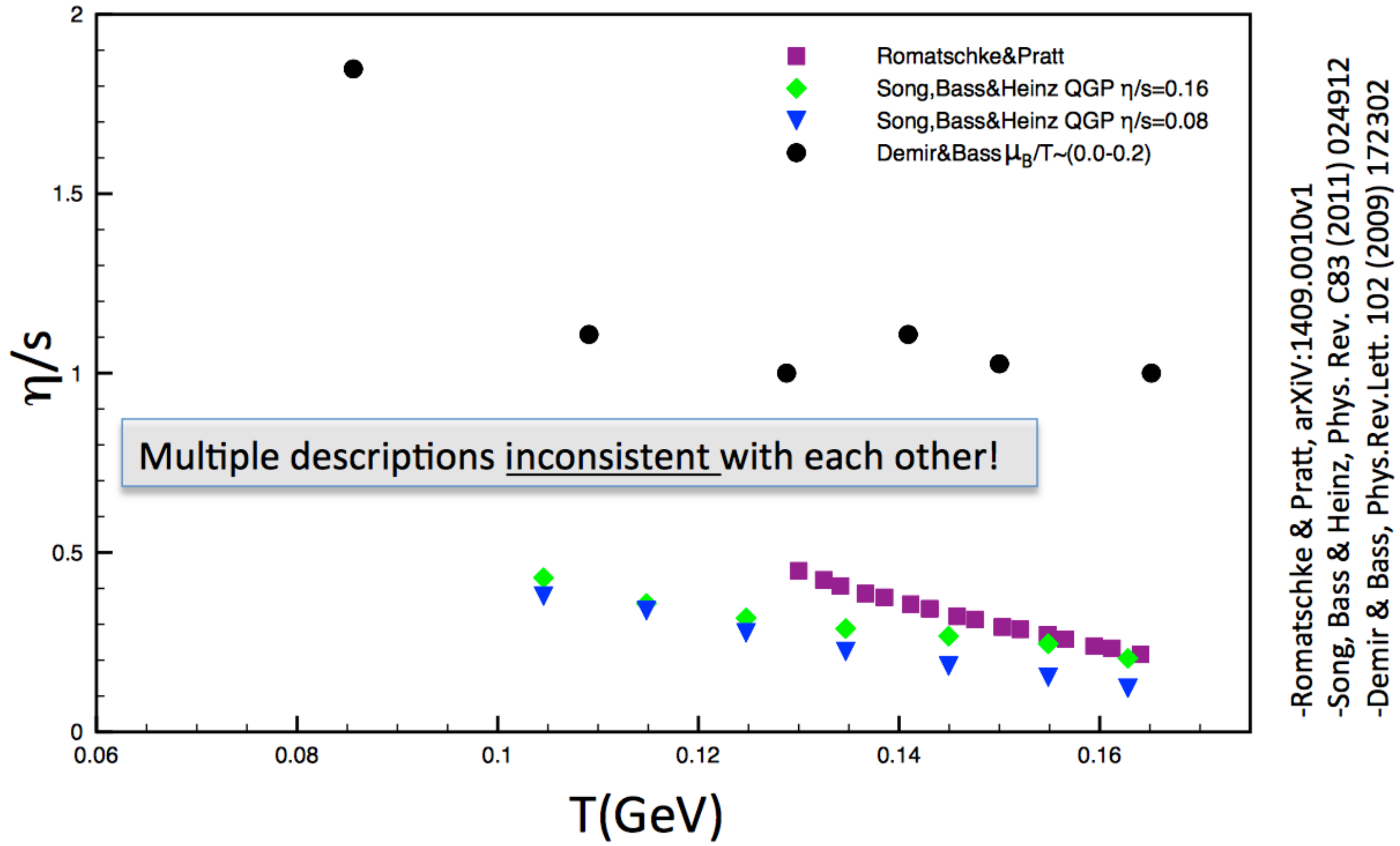
Existing Results - Discrepancy

Green-Kubo formalism
UrQMD



N. Demir and S.A. Bass, Phys.Rev.Lett. 102 (2009)

Discrepancy with
hydro-inspired B3D and VISHNU



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

Shear Viscosity over Entropy Density

- Box with periodic boundary condition in chemical and thermal equilibrium
- Entropy is calculated via Gibbs formula from thermodynamic properties
- The shear viscosity is extracted following the Green-Kubo formalism:

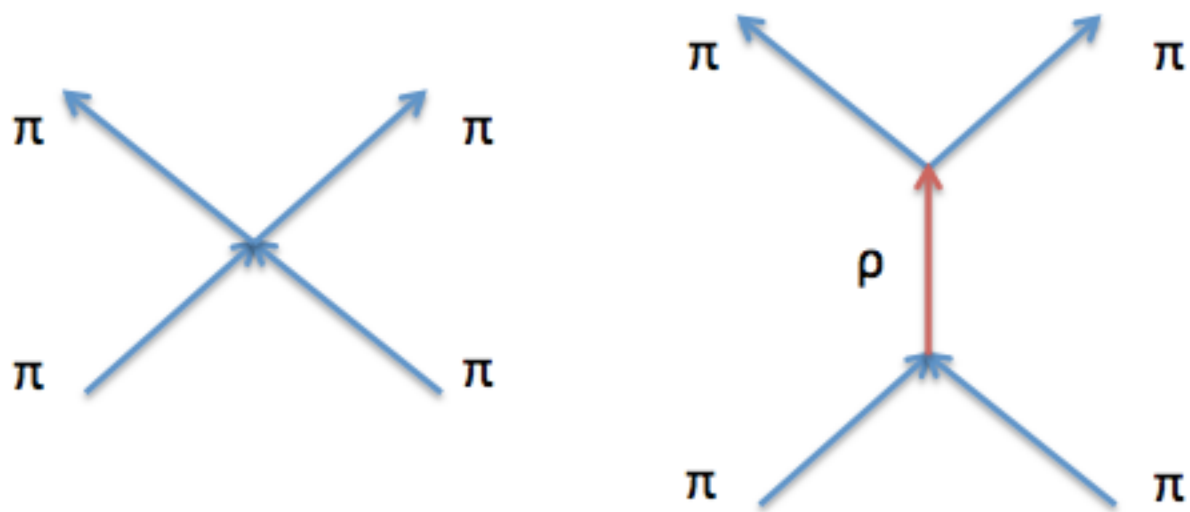
$$\eta = \frac{V}{T}\int_0^\infty C^{xy}(t)dt \qquad C^{xy}(t) = \frac{1}{N}\sum_s^N T^{xy}(s)T^{xy}(s+t)$$

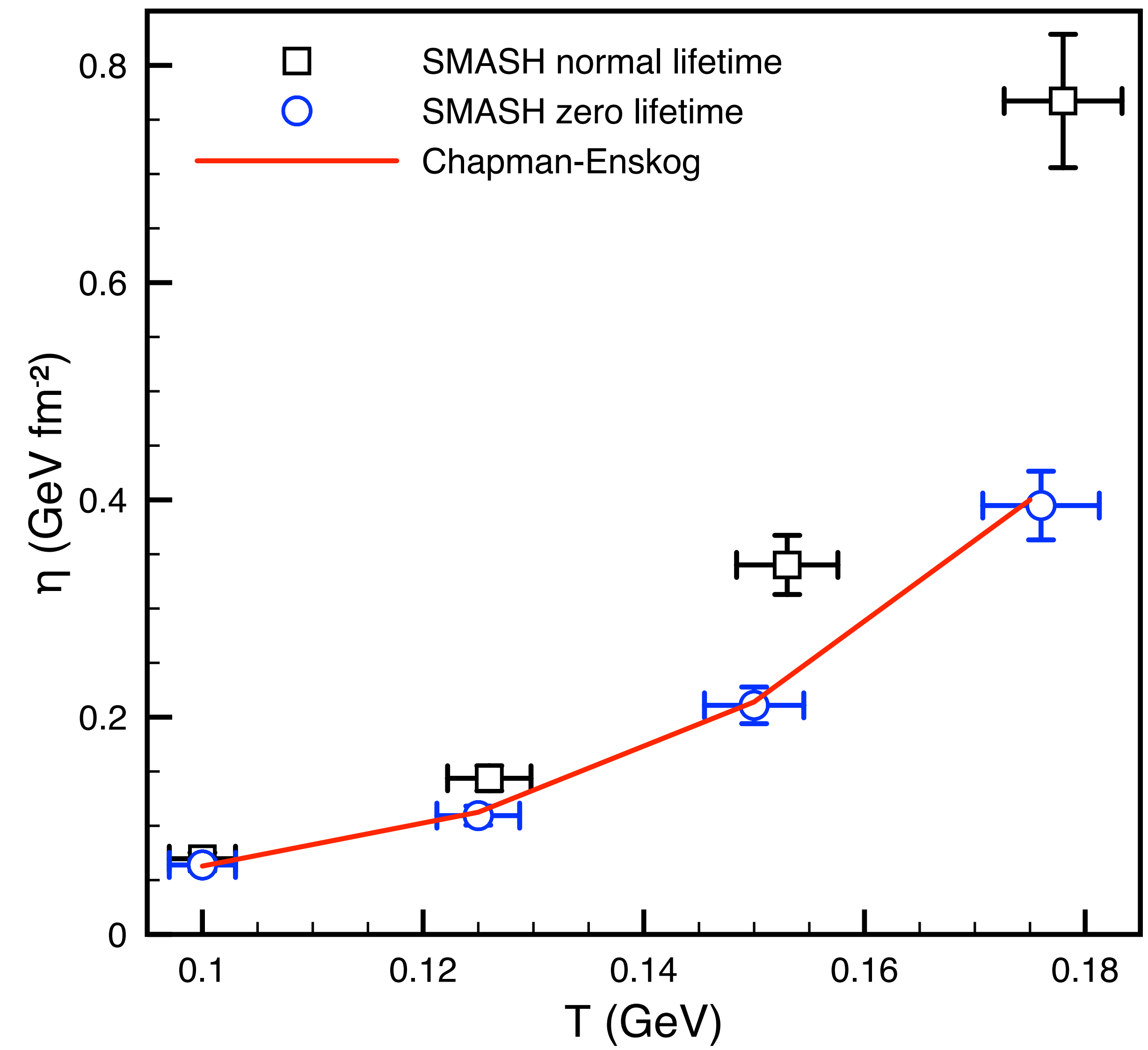
$$T^{\mu\nu} = \frac{1}{V}\sum_i^{N_{part}} \frac{p_i^\mu p_i^\nu}{p_i^0} \qquad C^{xy}(t) \simeq C^{xy}(0)\exp\left(-\frac{t}{\tau}\right)$$

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

Resonance Dynamics

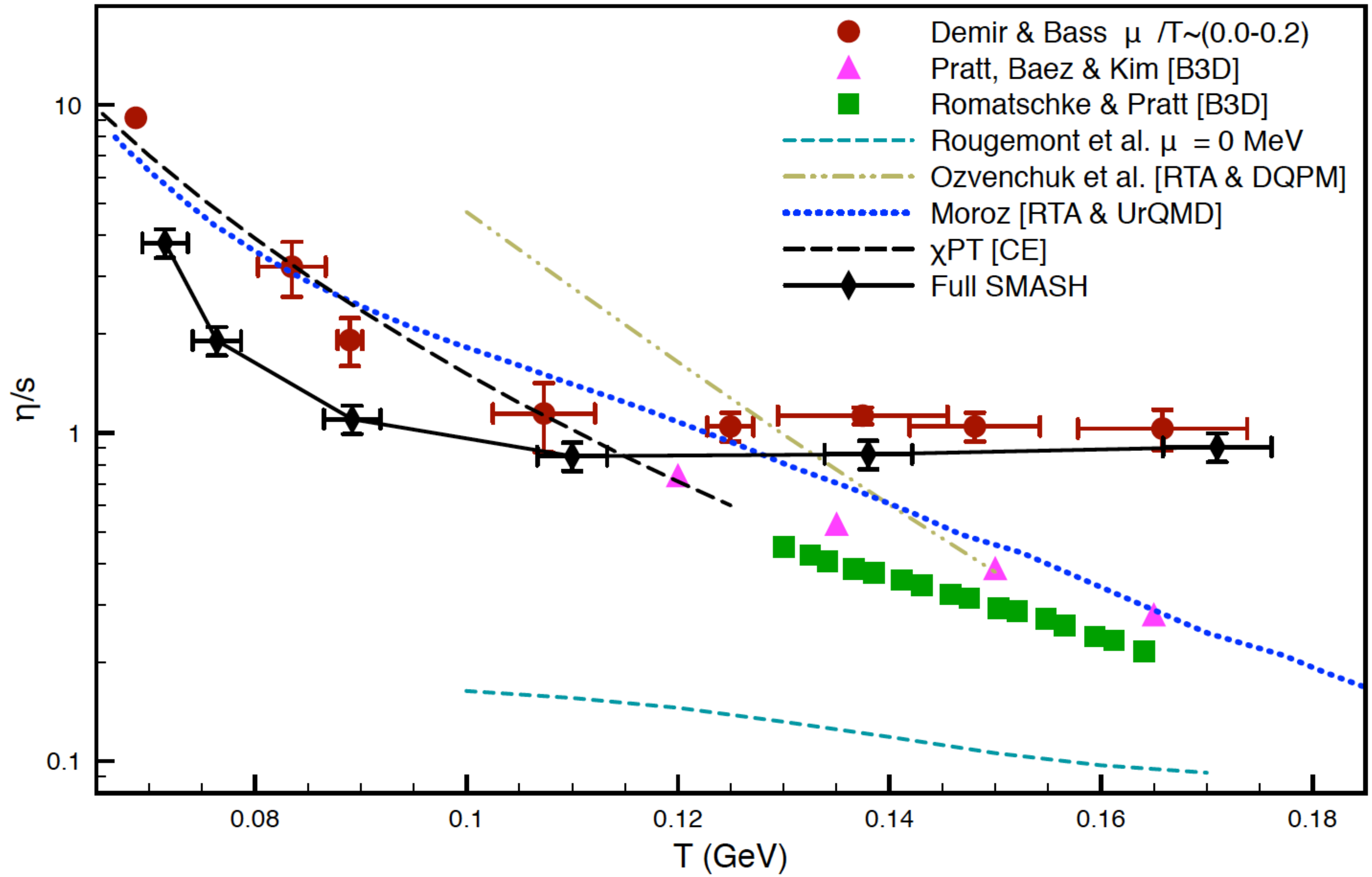
- Energy-dependence of cross-sections is modelled via resonances
- Point-like in analytic calculation and finite lifetime in transport approach





- Agreement recovered by decreasing ρ meson lifetime

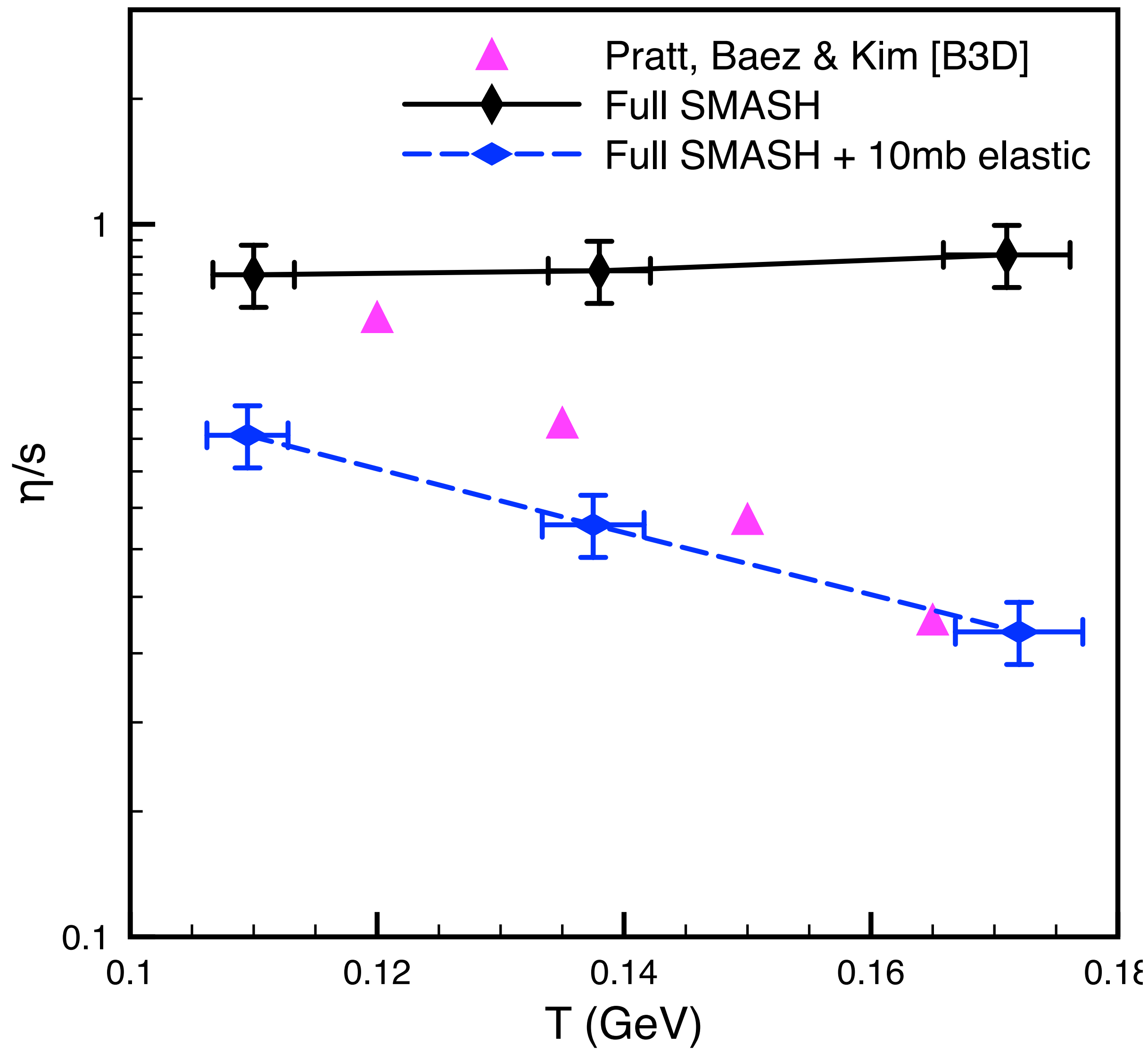
Comparison to Literature

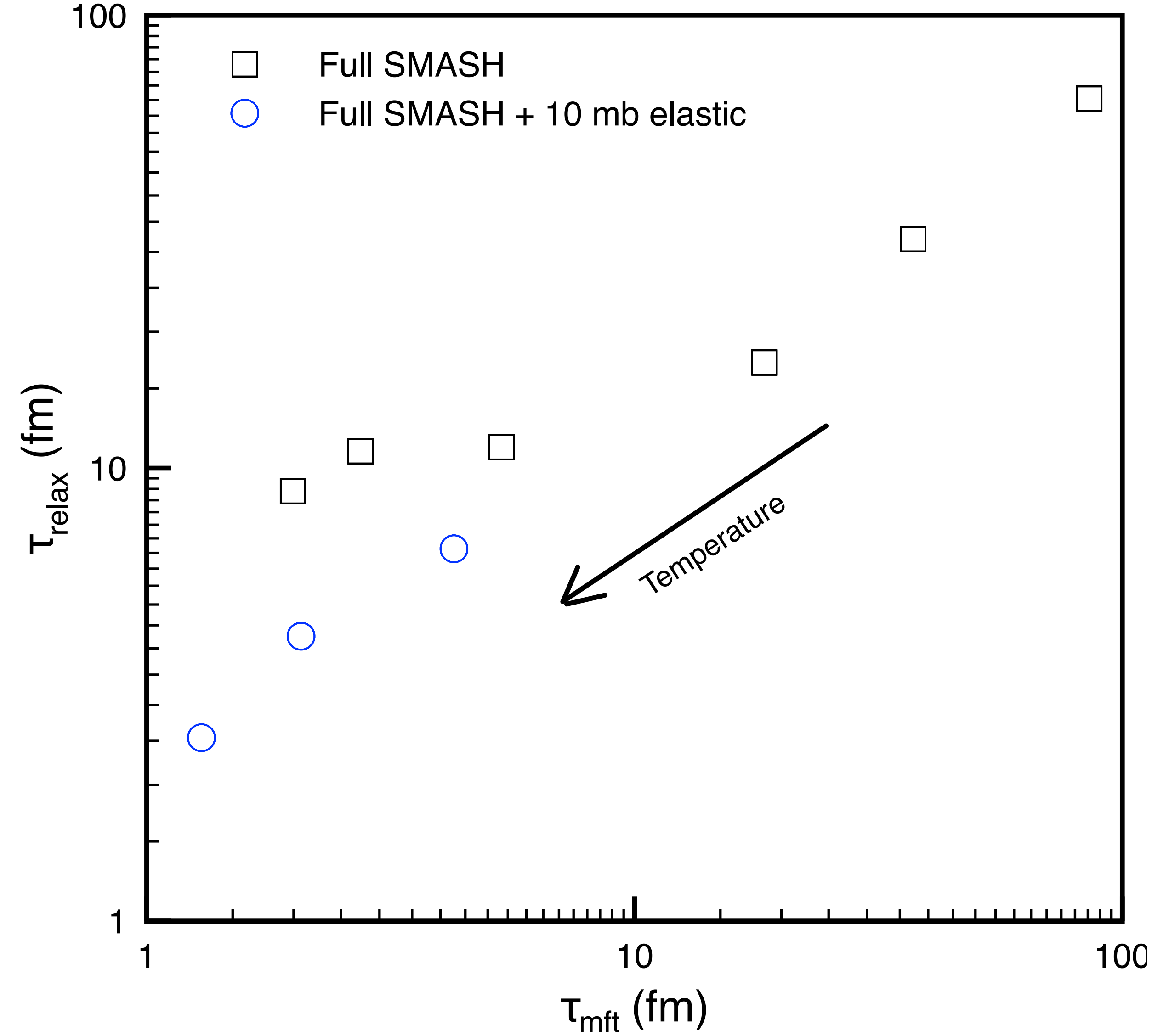


- Closest similarity to Bass/Demir result as expected

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

Electric Conductivity

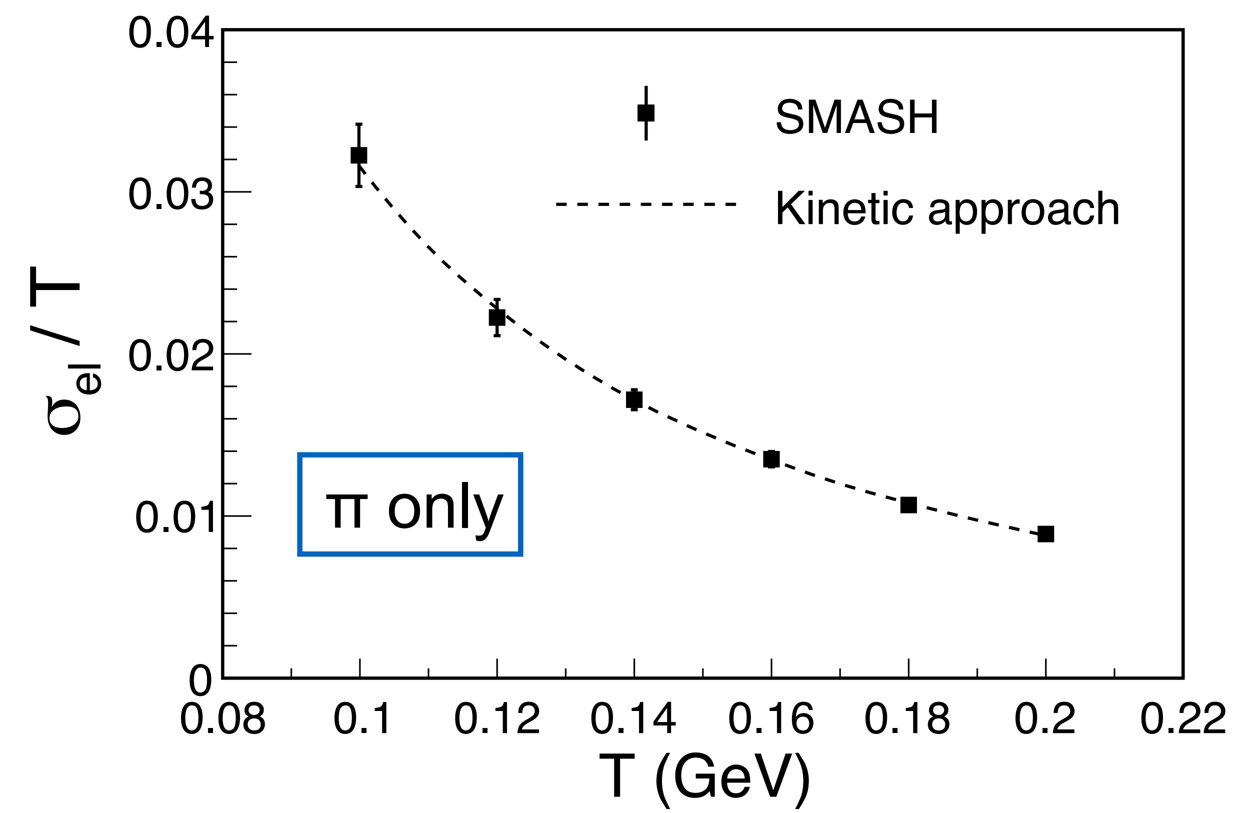
- Comparison to linear response kinetic theory to validate our approach

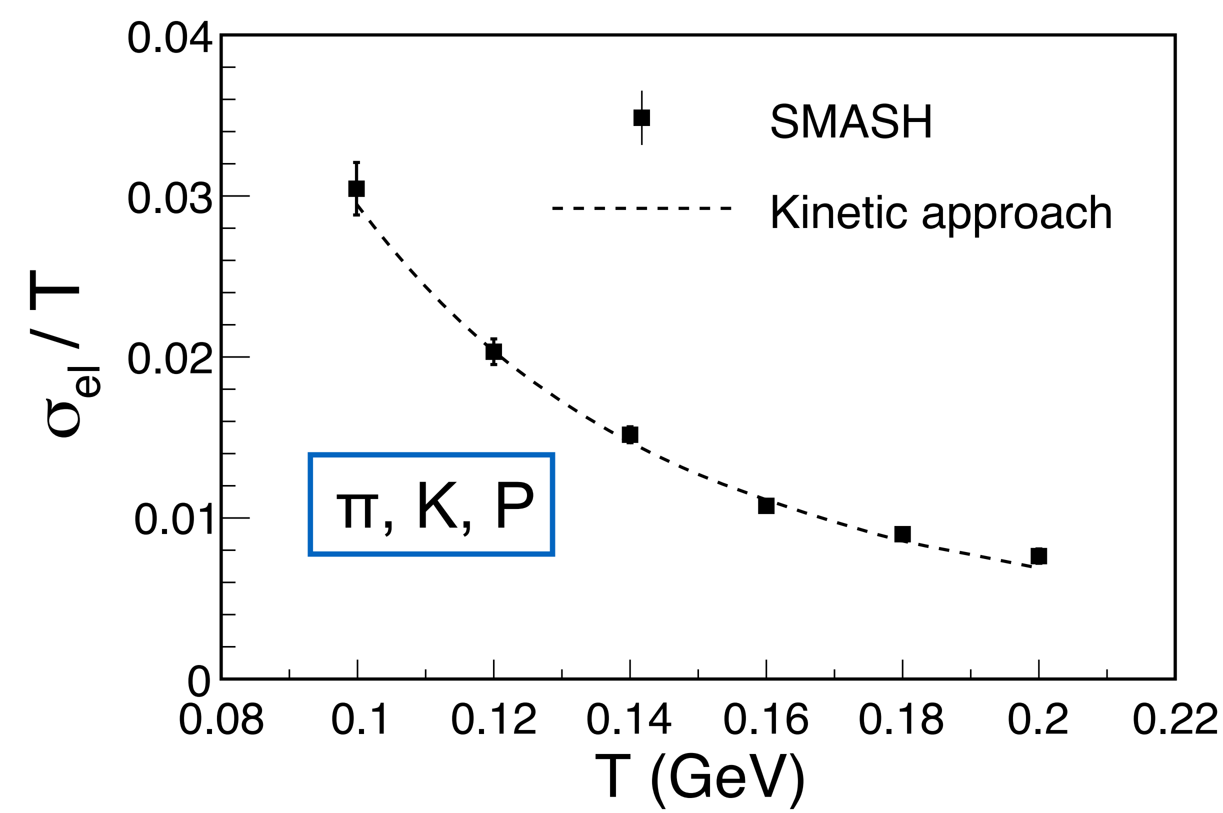
Greif et al, Phys.Rev. D93 (2016)

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

$$\sigma_{el} = \frac{VC(0)\tau}{T}$$

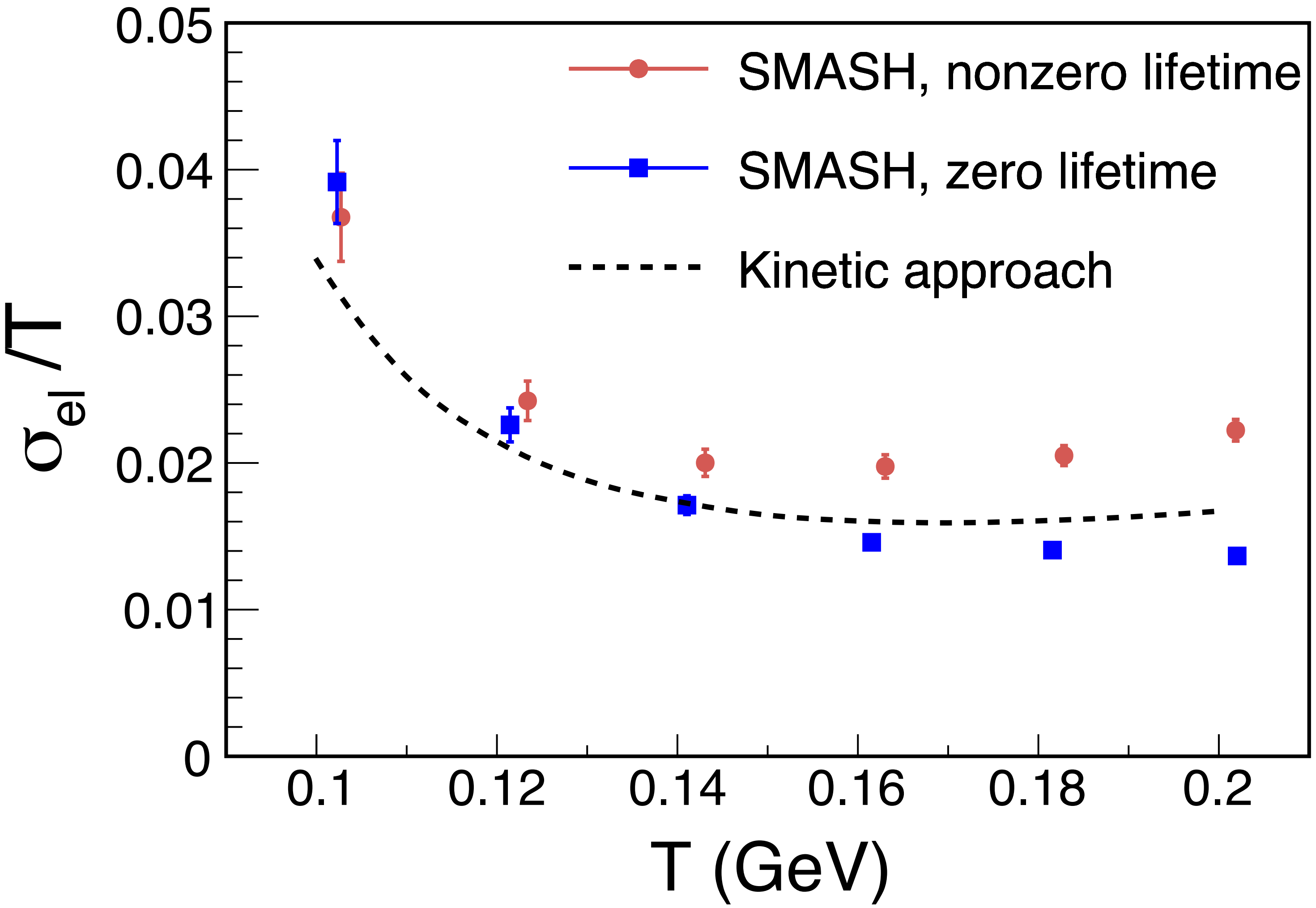
- Infinite matter with constant σ = 30 mb





Effect of Lifetime

- ρ-π system is again affected by the lifetime



- Work in progress: Understand the differences between analytic calculation and SMASH results

Summary and Outlook

- SMASH has been developed as a new hadronic transport approach
  - Bulk observables are in reasonable agreement with experimental data
  - Strangeness production based on cross-section from elementary reactions
  - Electromagnetic observables are integrated
- Shear viscosity and electric conductivity have been calculated via Green-Kubo formalism
  - Comparison to analytic results are used for validation
  - Resonance lifetimes have large impact on relaxation dynamics in both cases
- Future: Afterburner calculations at RHIC/LHC

Backup

General Setup

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

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\mathrm{coll}}$$

- Particles represented by Gaussian wave packets
- Geometric collision criterion

$$d_{\mathrm{trans}} < d_{\mathrm{int}} = \sqrt{\frac{\sigma_{\mathrm{tot}}}{\pi}} \qquad d^2_{\mathrm{trans}} = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

- Test particle method

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

Resonances

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

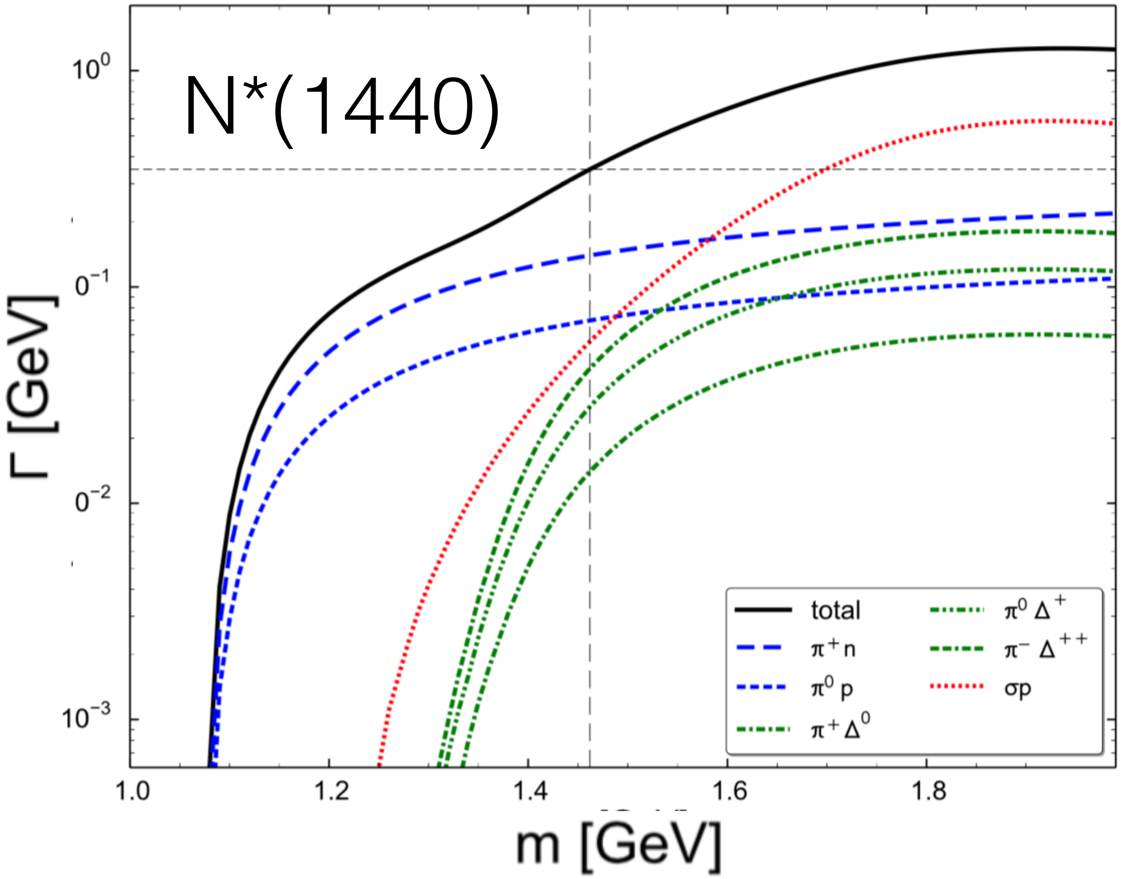
$$\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma(m)}{(m^2 - M_0^2)^2 + m^2\Gamma(m)^2}$$

- Decay widths
  - Particles stable, if width < 10 keV

$$(\pi,\ \eta,\ K, \ldots)$$

  - Treatment of Manley et al

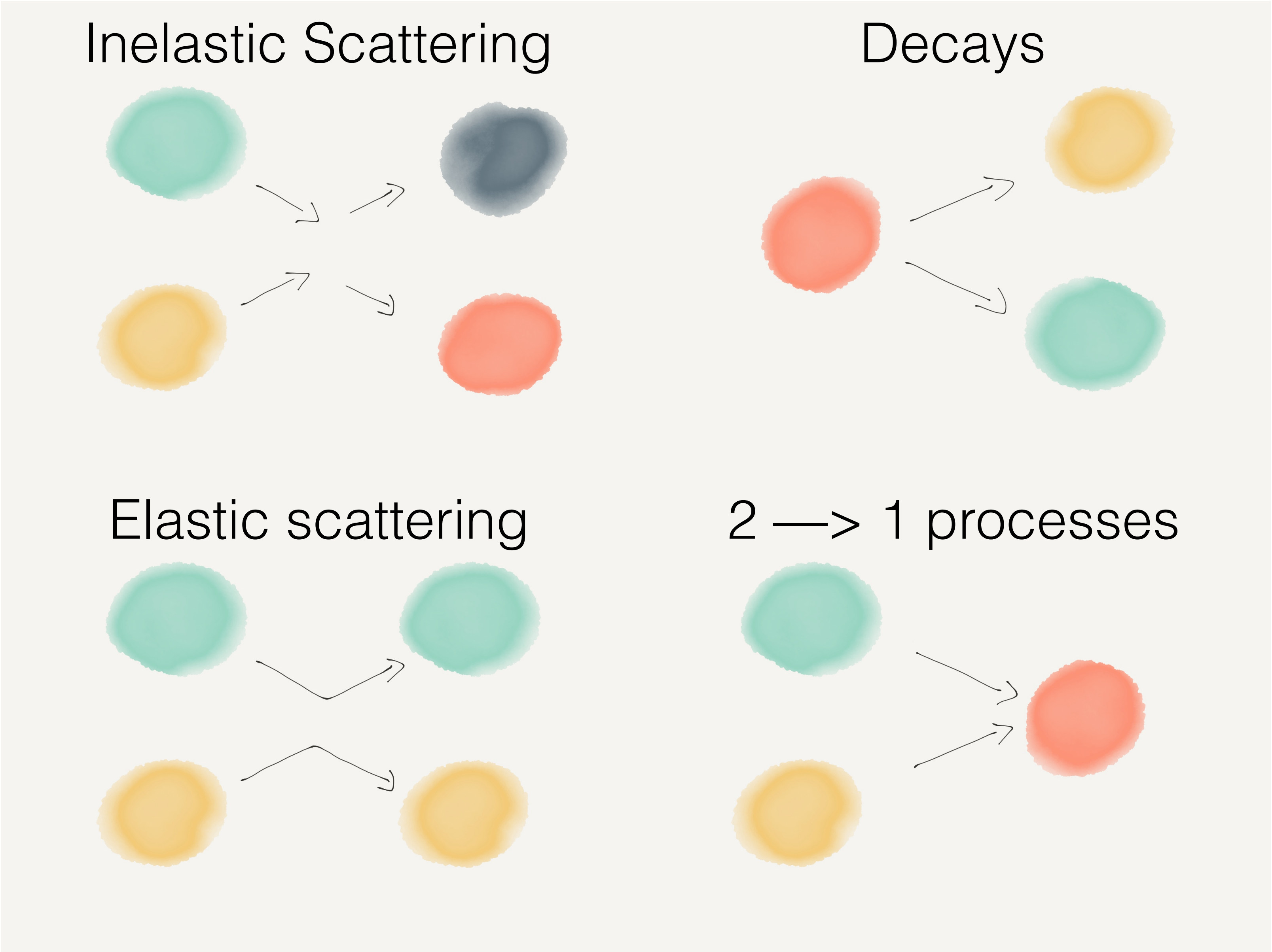
$$\Gamma_{R\to ab} = \Gamma^0_{R\to ab} \frac{\rho_{ab}(m)}{\rho_{ab}(M_0)}$$



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

Collision Term

- In few GeV energy regime decay and excitation of resonances dominate hadronic cross section



- No string fragmentation yet

Treatment of Manley

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

- Scaling of on-shell decay width:

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

- Definiton of rho-funtion:

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

Blatt Weisskopf functions

$$B_0^2 = 1$$

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

$$\ldots$$

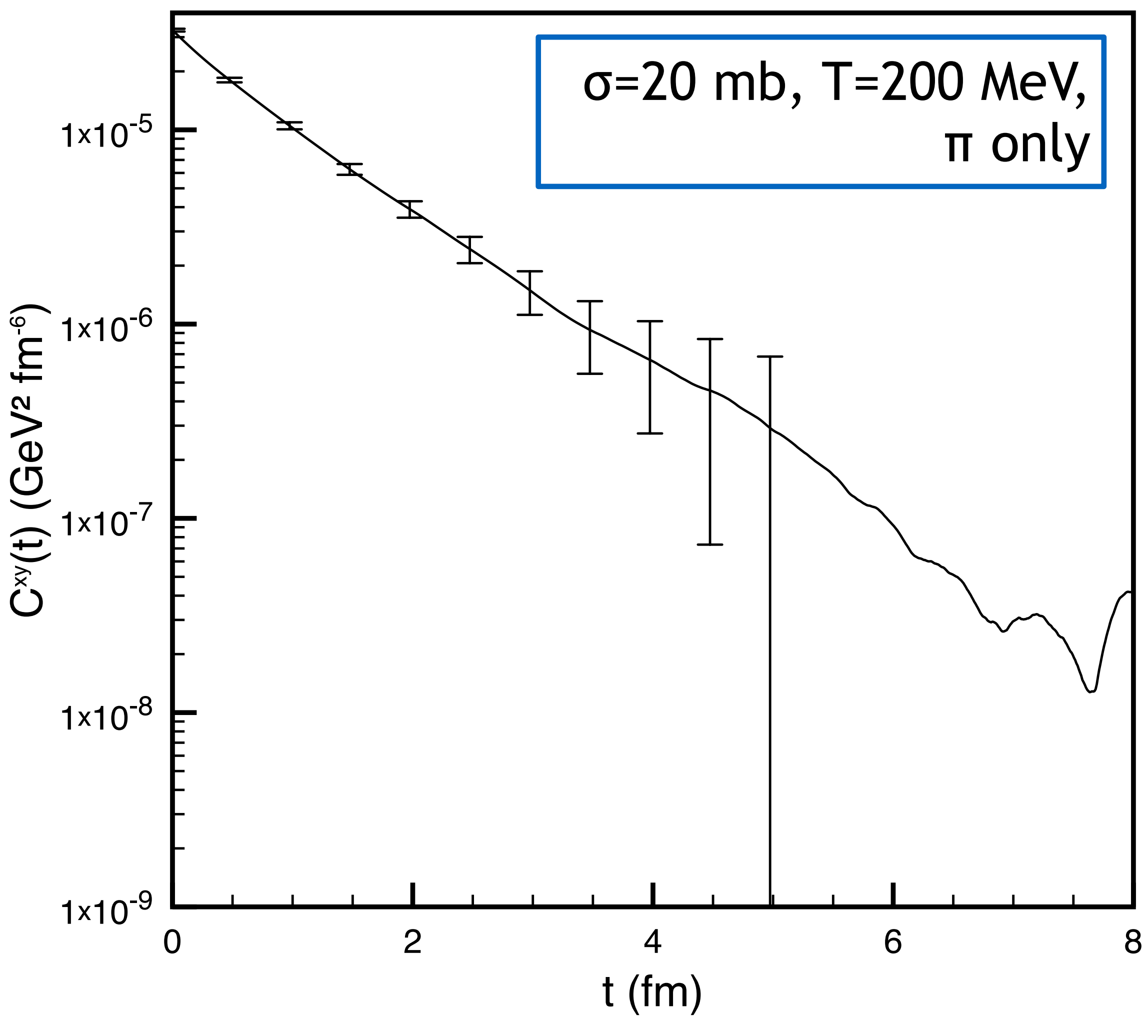
M. Post, S. Leupold, U. Mosel, Nucl. Phys. A 741, 81 (2004)

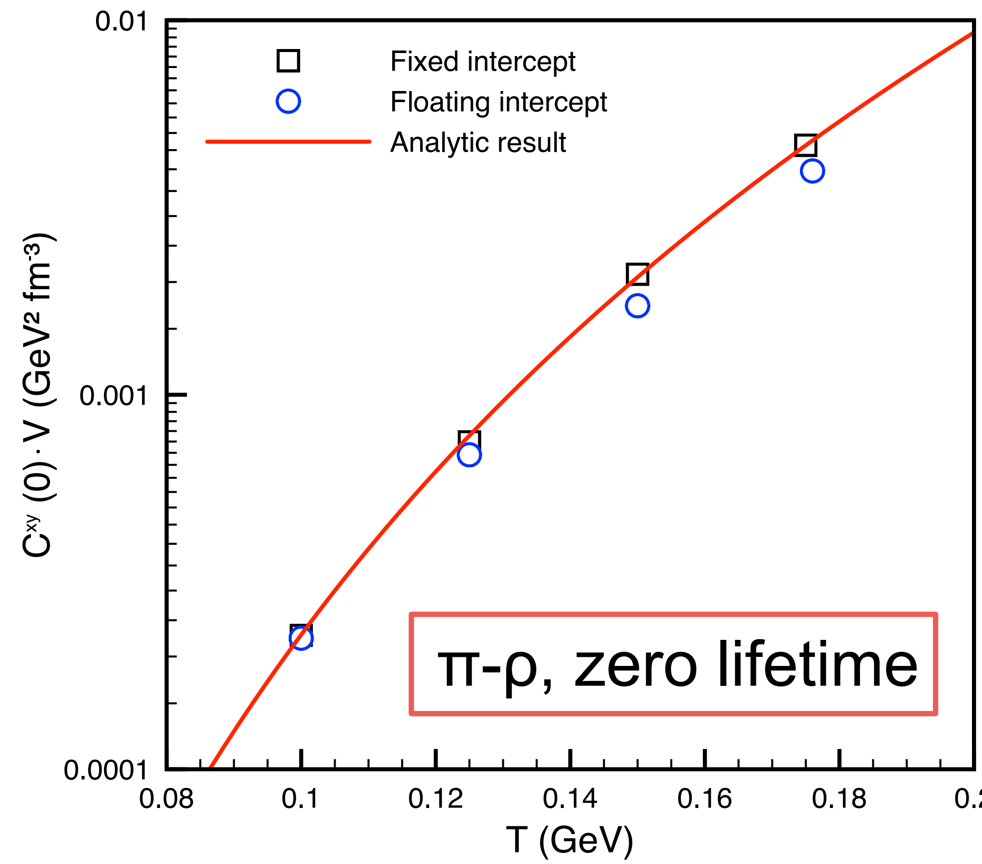
- Hadronic Form Factor:

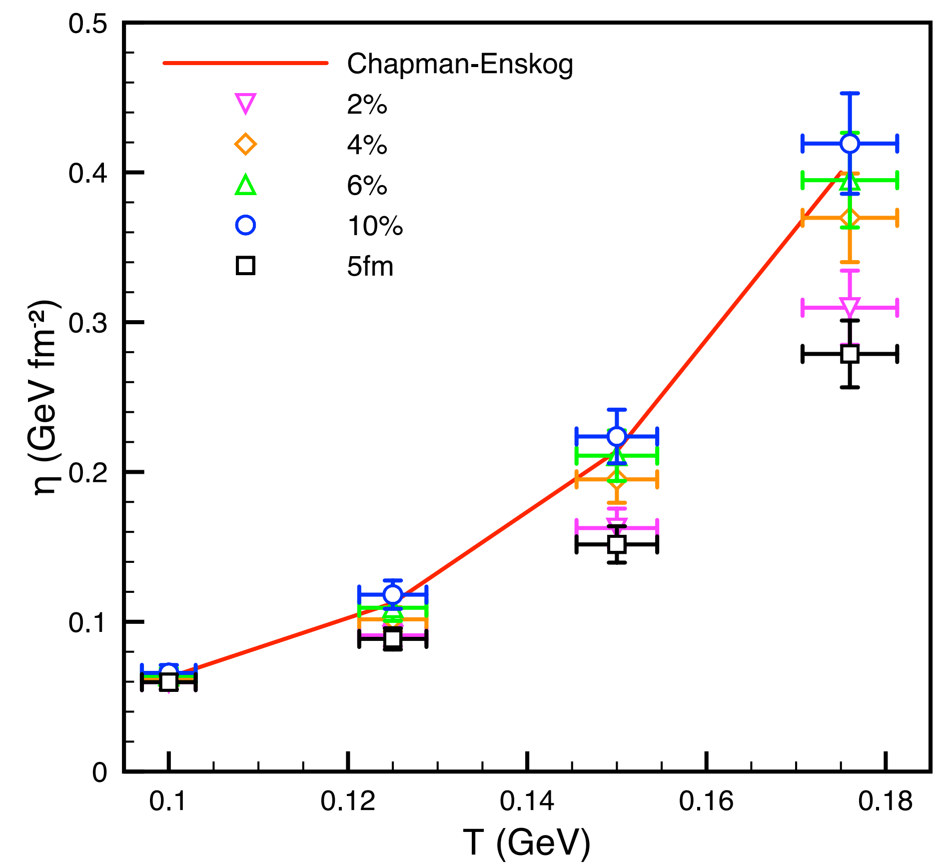
$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + 1/4(s_0 - M_0^2)^2}{\lambda^4 + \left(m^2 - 1/2(s_0 + M_0^2)\right)^2}$$

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

Correlation Function Systematics



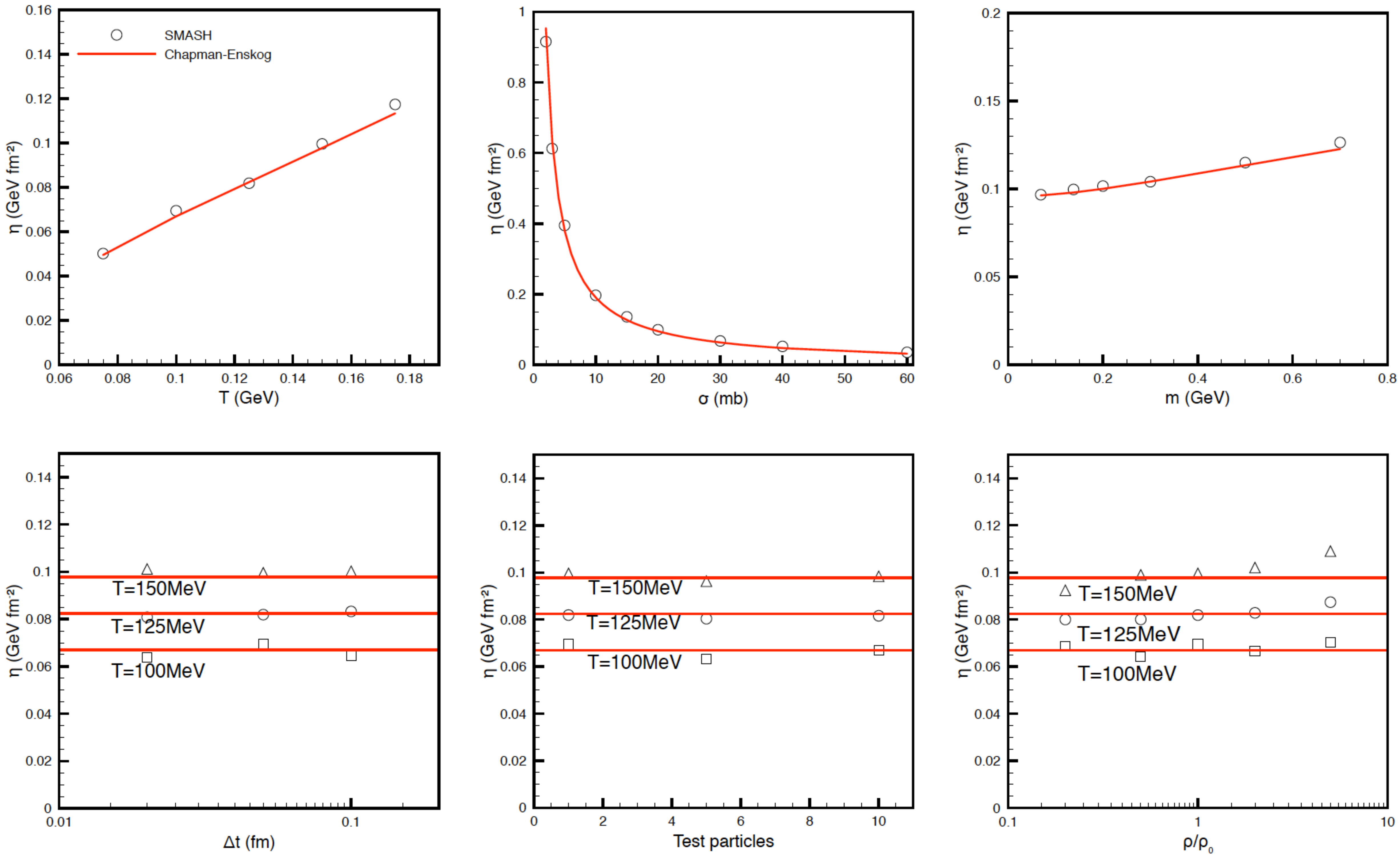




- Important details:
  - Fixed intercept and 6% cut-off agree best with analytic expectations

J.-B. Rose et al, arXiv:1709.00369

Pion Gas - Chapman-Enskog



- Analytic results are well reproduced