Simulating Many Accelerated Strongly-interacting Hadrons

SMASH

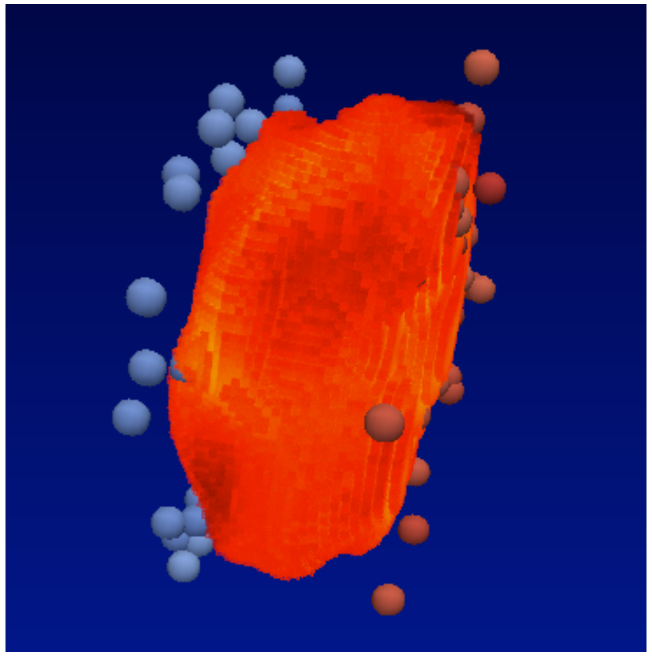
Hannah Elfner

21.02.19, Virtual Meeting NA61-Theory

Introduction and Setup

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

The SMASH Team

- in Frankfurt:
  - Sangwook Ryu
  - Vinzent Steinberg
  - Jean-Bernard Rose
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Jan Hammelmann
  - Jonas Rothermel
  - Damjan Mitrovic
  - Natey Kübler
- in US/Serbia:
  - Dmytro Oliinychenko
  - LongGang Pang
  - Jussi Auvinen

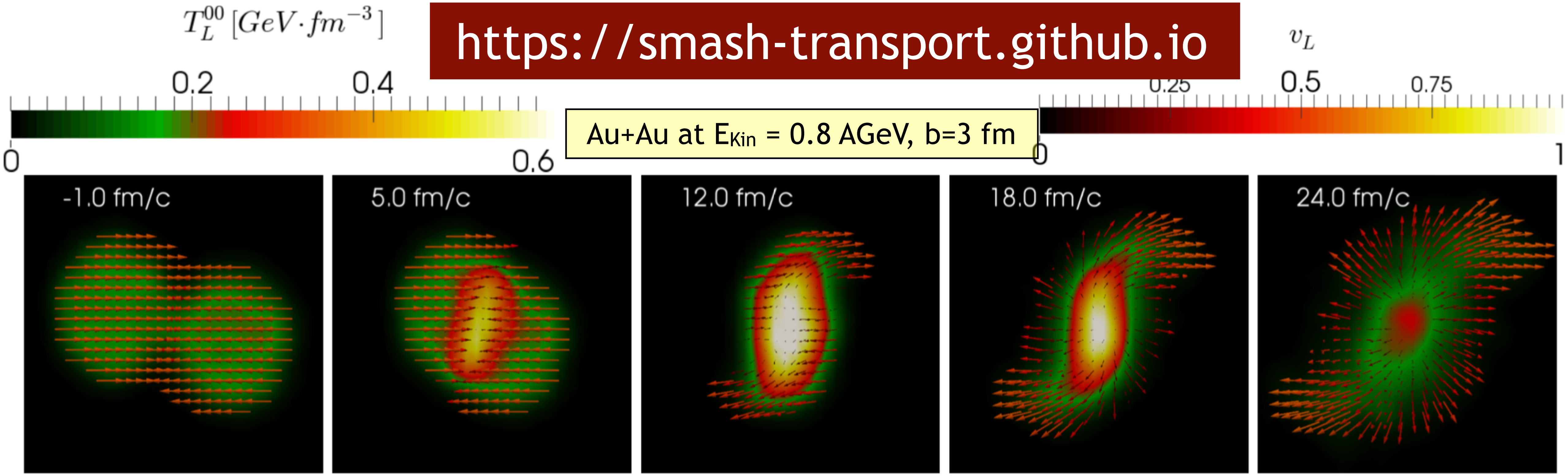
Subset of the group in November 2016

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

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

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

$$d^2_{\mathrm{trans}} = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

As in UrQMD

- Test particle method

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

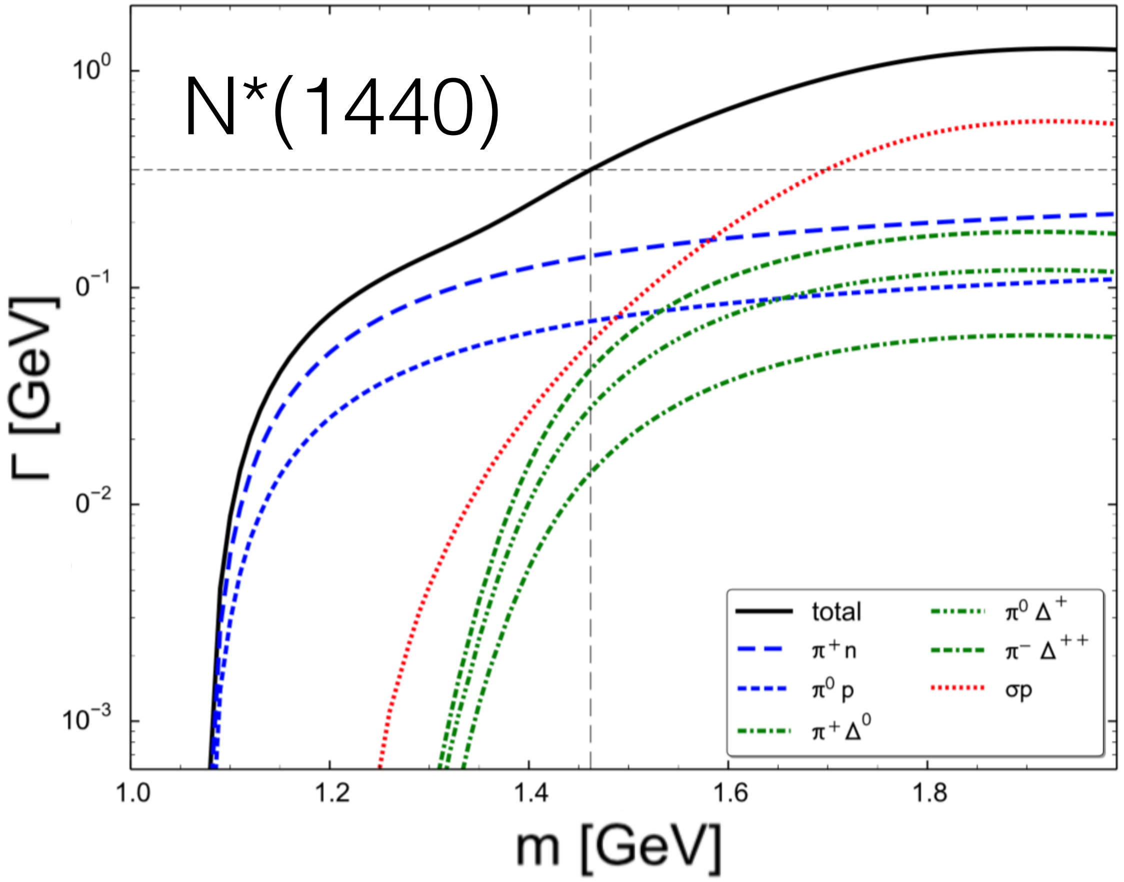
$$N \mapsto N \cdot N_{\mathrm{test}}$$

Resonances

As in GiBUU

- 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)

Degrees of Freedom

N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^-_{1672}	π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^-_{2250}	π_{1300}	$f_{0\ 1370}$	$f'_{2\ 1525}$		K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
N_{1535}	Δ_{1905}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
N_{1650}	Δ_{1910}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
N_{1675}	Δ_{1920}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
N_{1680}	Δ_{1930}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
N_{1700}	Δ_{1950}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\ 1285}$		K^*_{1680}
N_{1710}		Λ_{1820}	Σ_{2030}			η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_3^*{}_{1780}$
N_{1875}		Λ_{1890}				σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
N_{1900}		Λ_{2100}					$h_{1\ 1170}$			$K_4^*{}_{2045}$
N_{1990}		Λ_{2110}				ρ_{776}		$\pi_{1\ 1400}$		
N_{2080}		Λ_{2350}				ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
N_{2190}						ρ_{1700}				
N_{2220}							$a_{1\ 1260}$	$\eta_{2\ 1645}$		
N_{2250}						ω_{783}				
						ω_{1420}		$\omega_{3\ 1670}$		
						ω_{1650}				

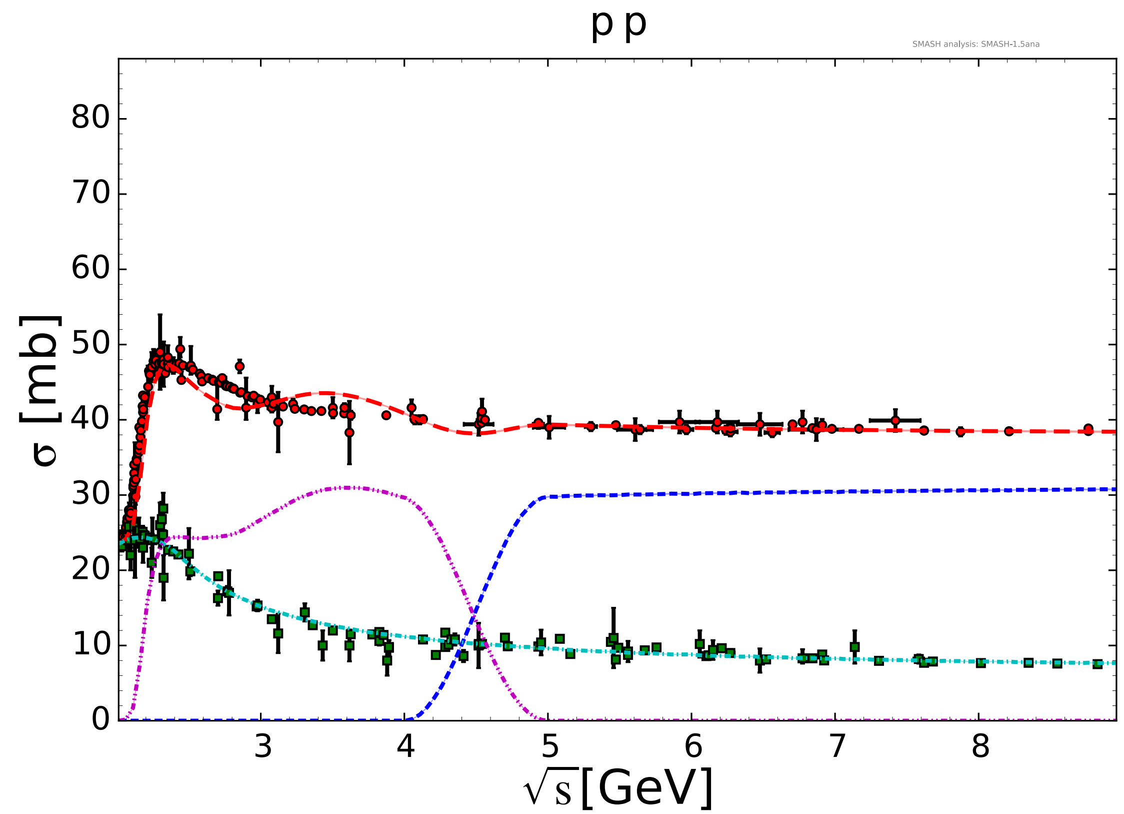
- Isospin symmetry
- Perturbative treatment of non-hadronic particles (photons, dileptons)

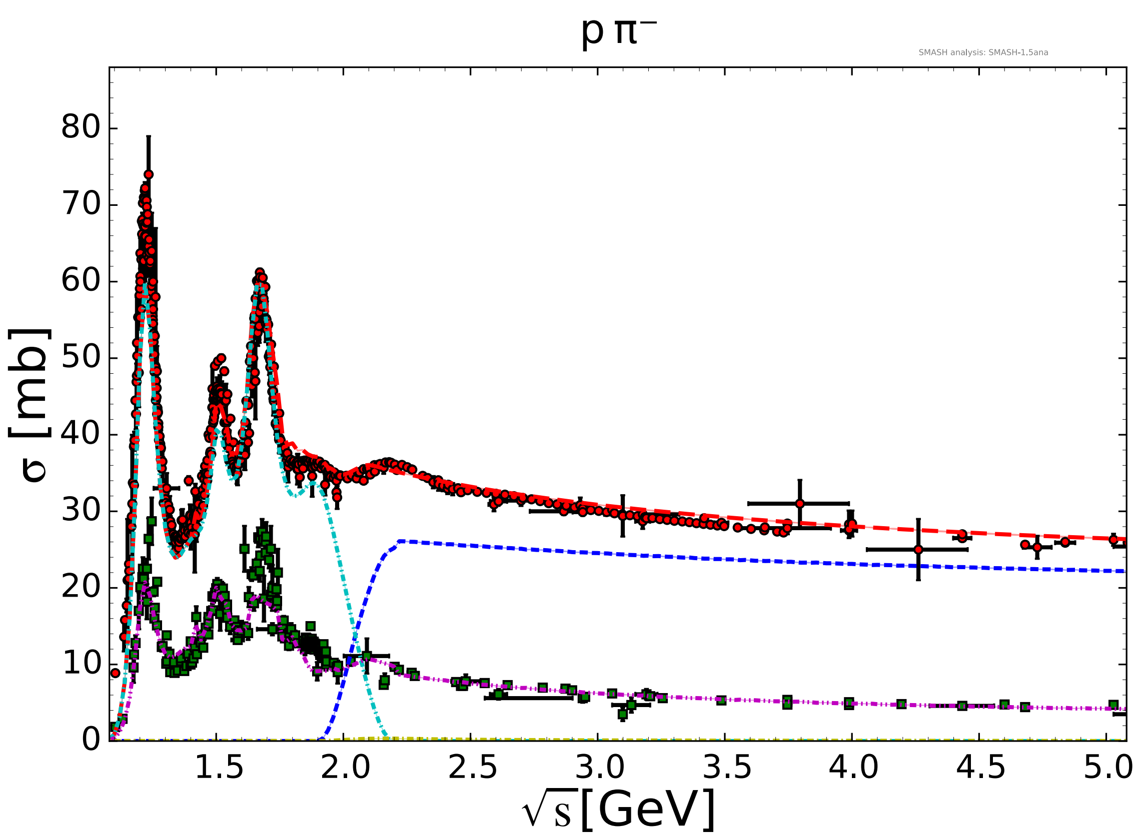
Similar to UrQMD,
But many more states

- Easily configurable by human-readable input files

Basic Tests

Elementary Cross Sections





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

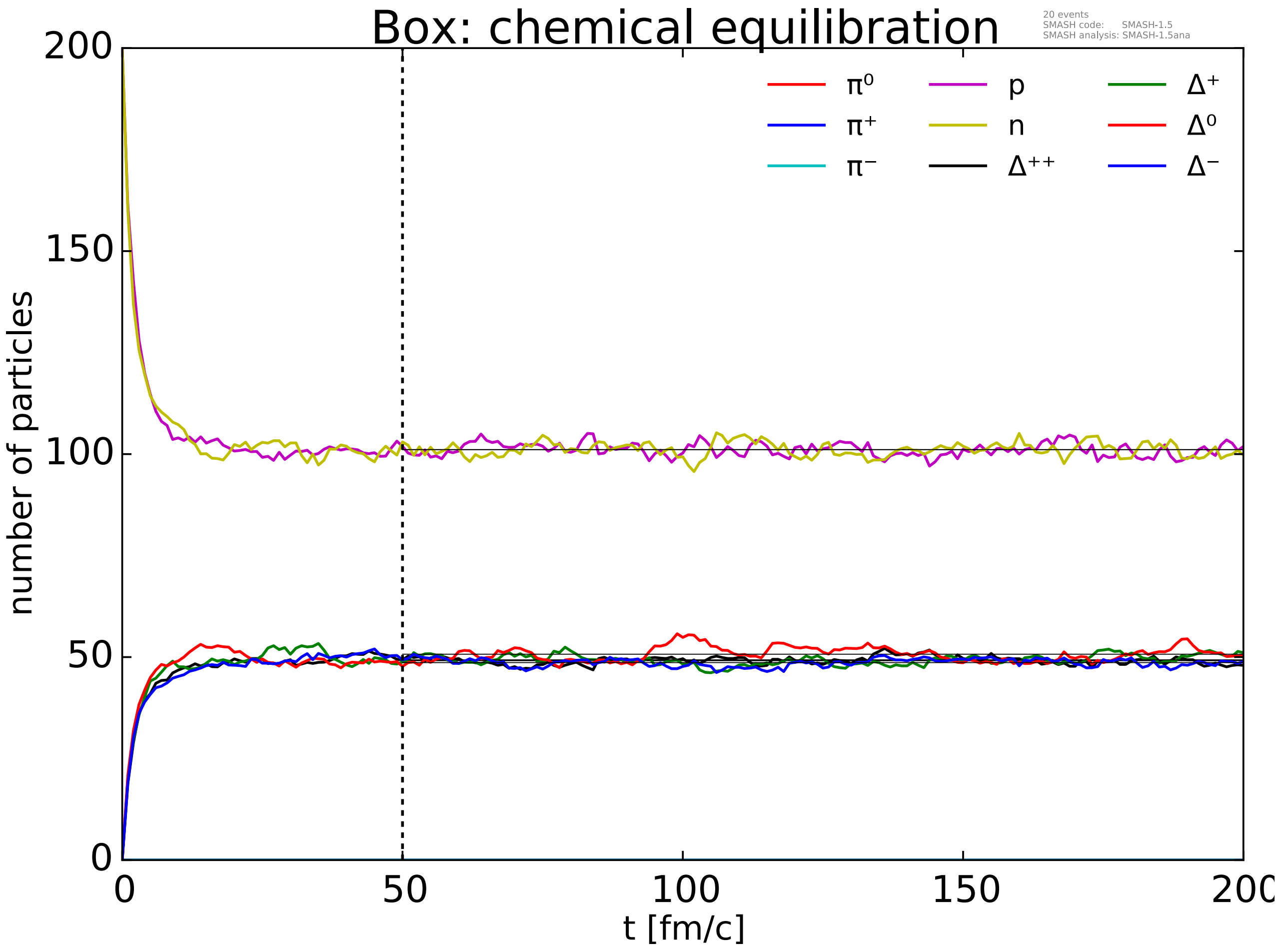
- Total cross section for pp/ pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Soft strings a la UrQMD and hard strings via Pythia 8

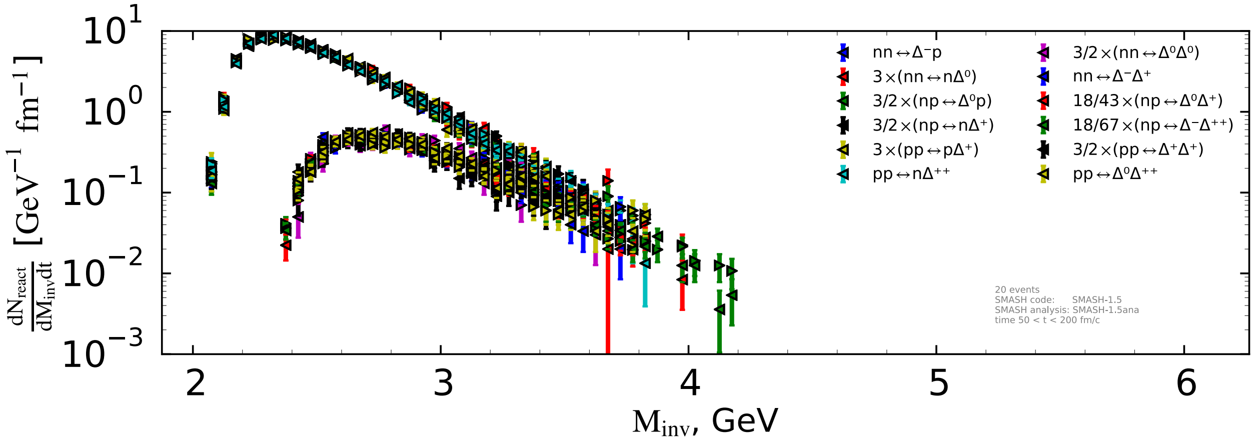
Detailed Balance

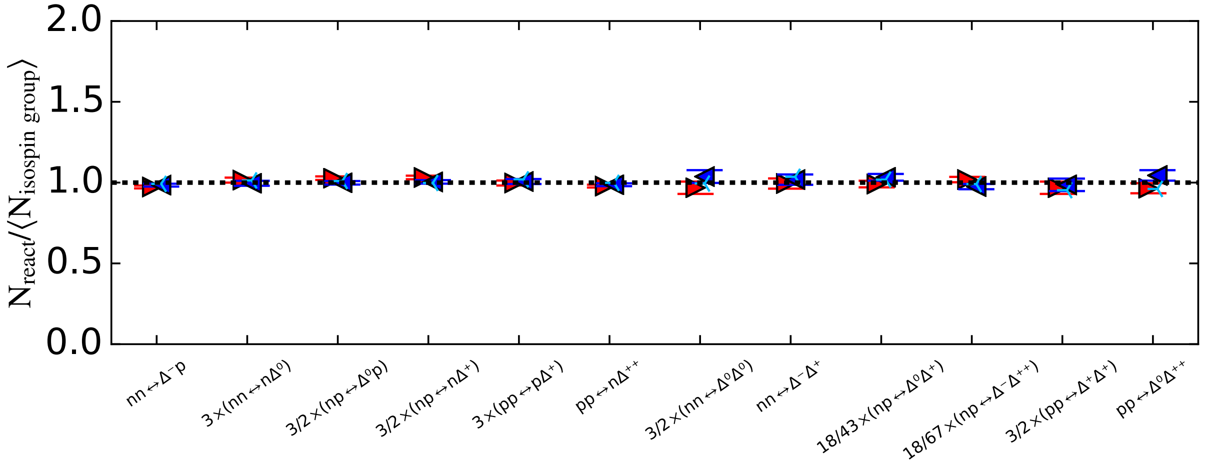
- Inverse absorption cross section calculated from production cross section

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

- Conservation of detailed balance (only 1 <—> 2 or 2 <—> 2 processes)



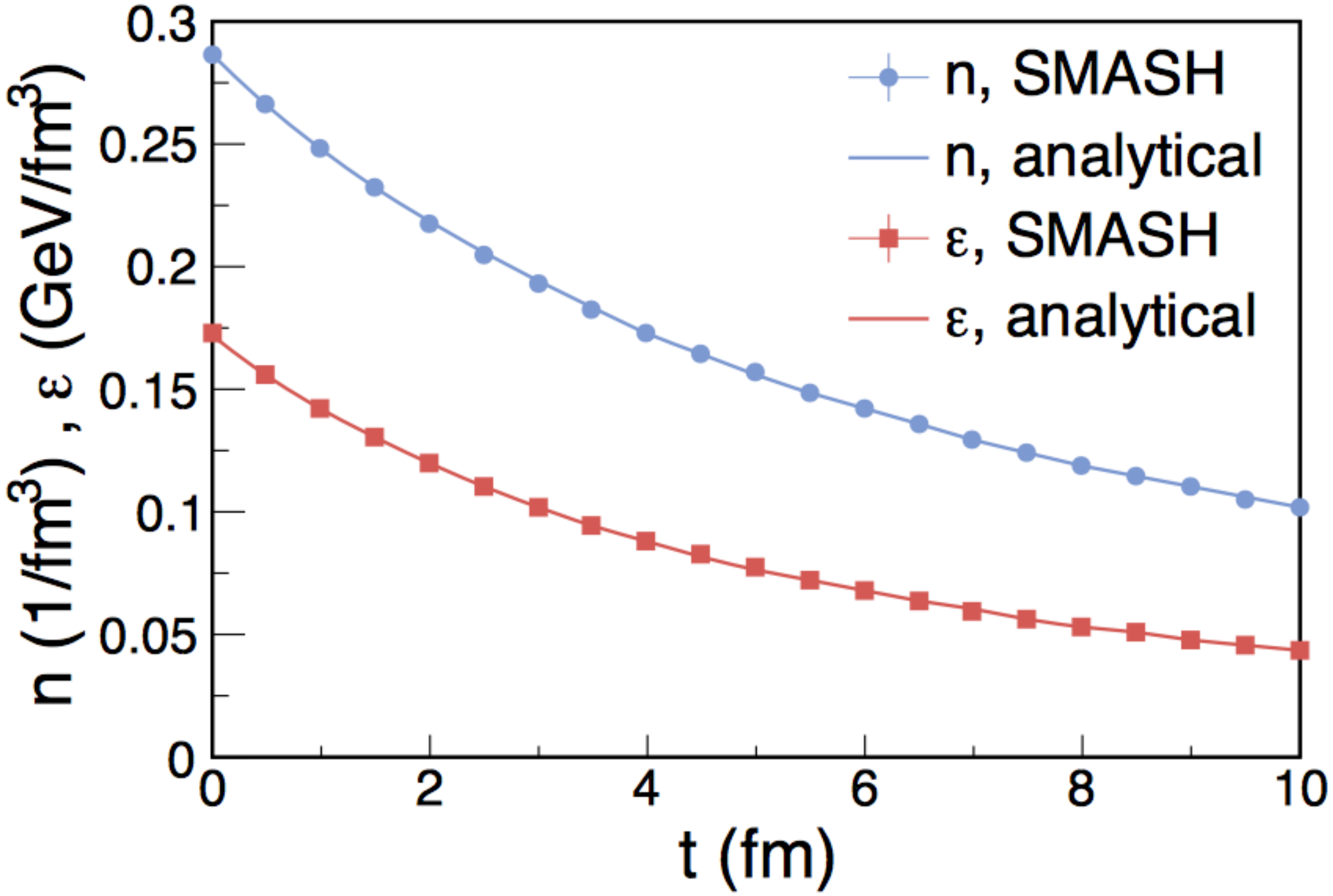


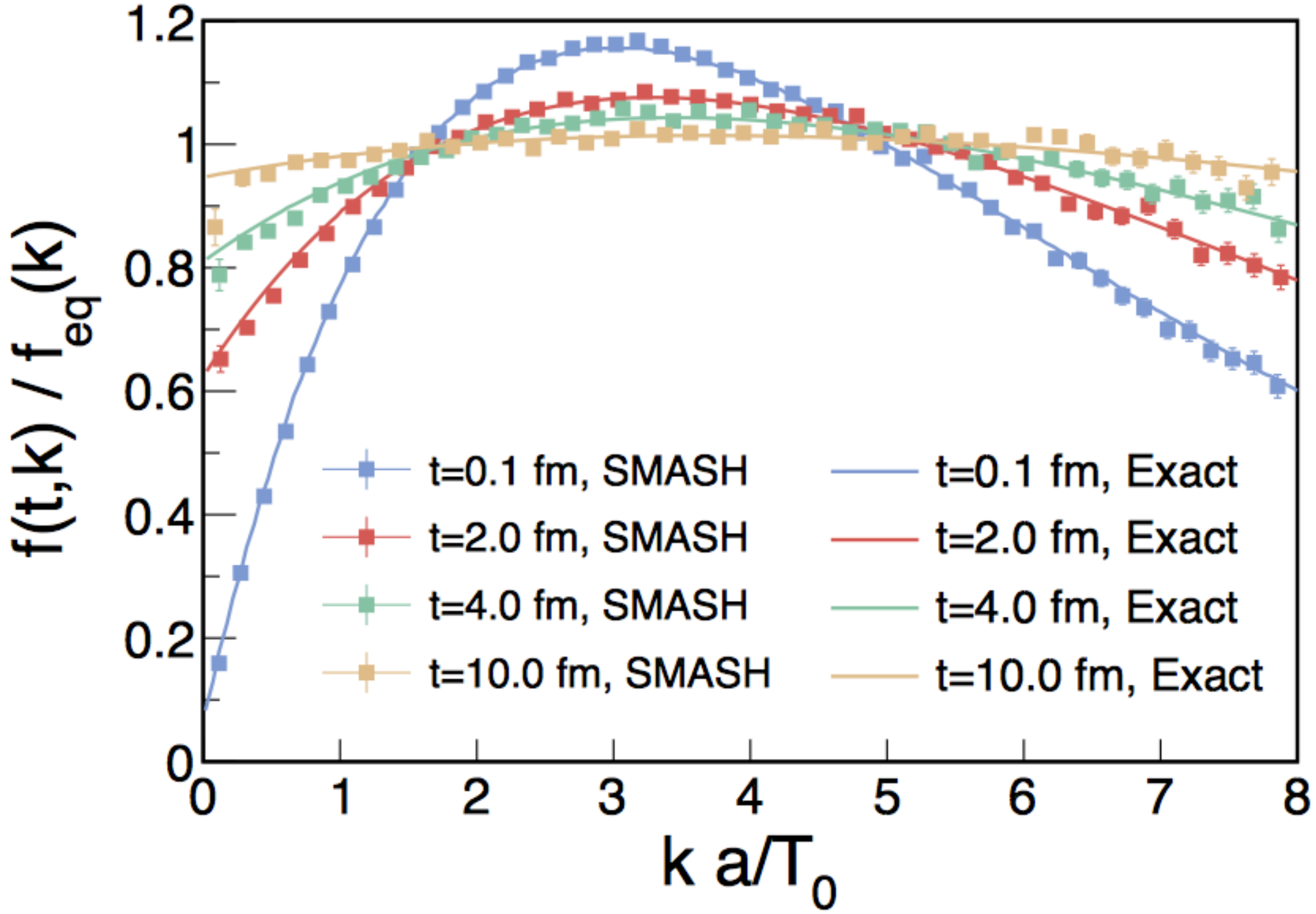


- Infinite matter calculations —> Important cross-check

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





- Perfect agreement proves correct numerical implementation of collision algorithm

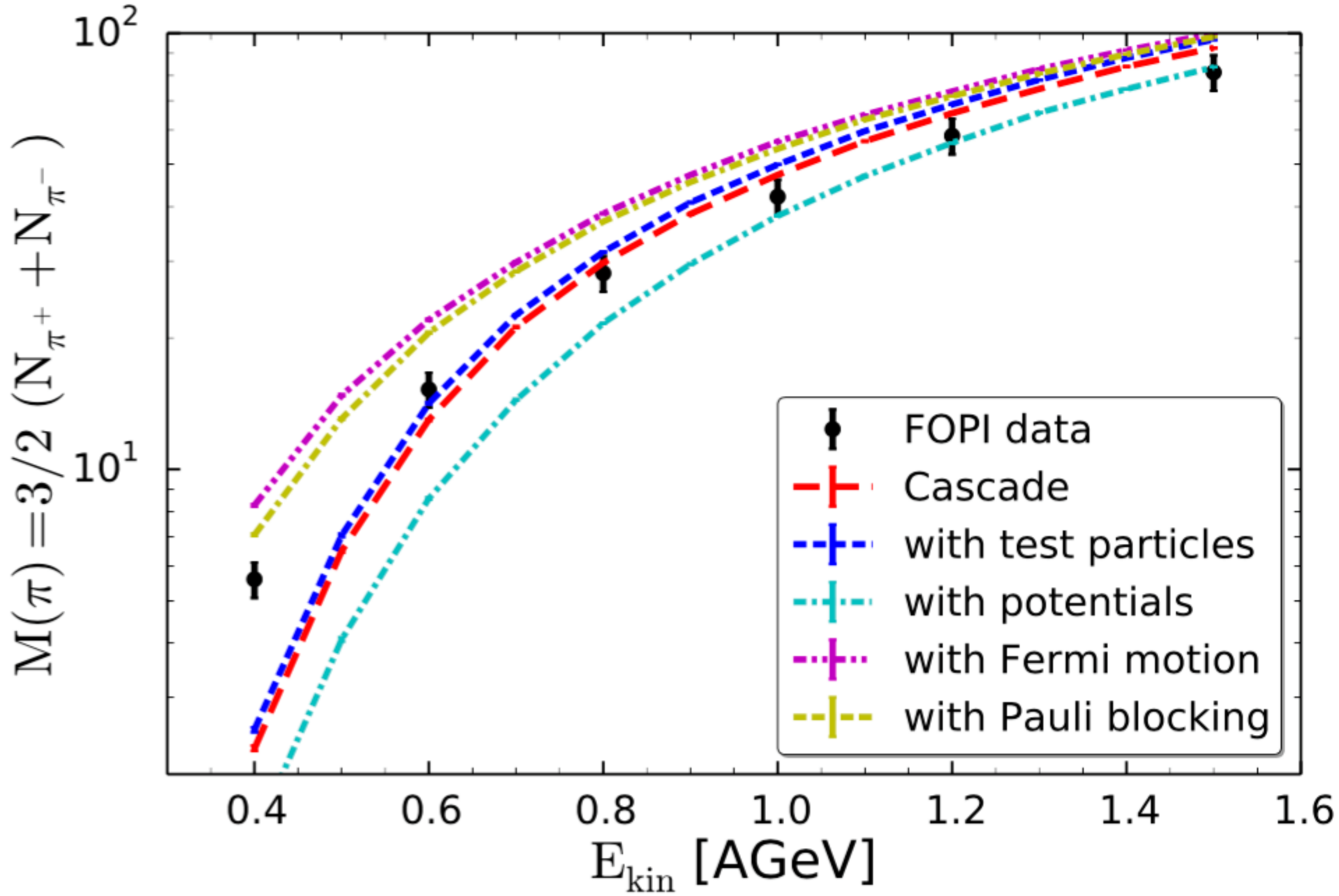
D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

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

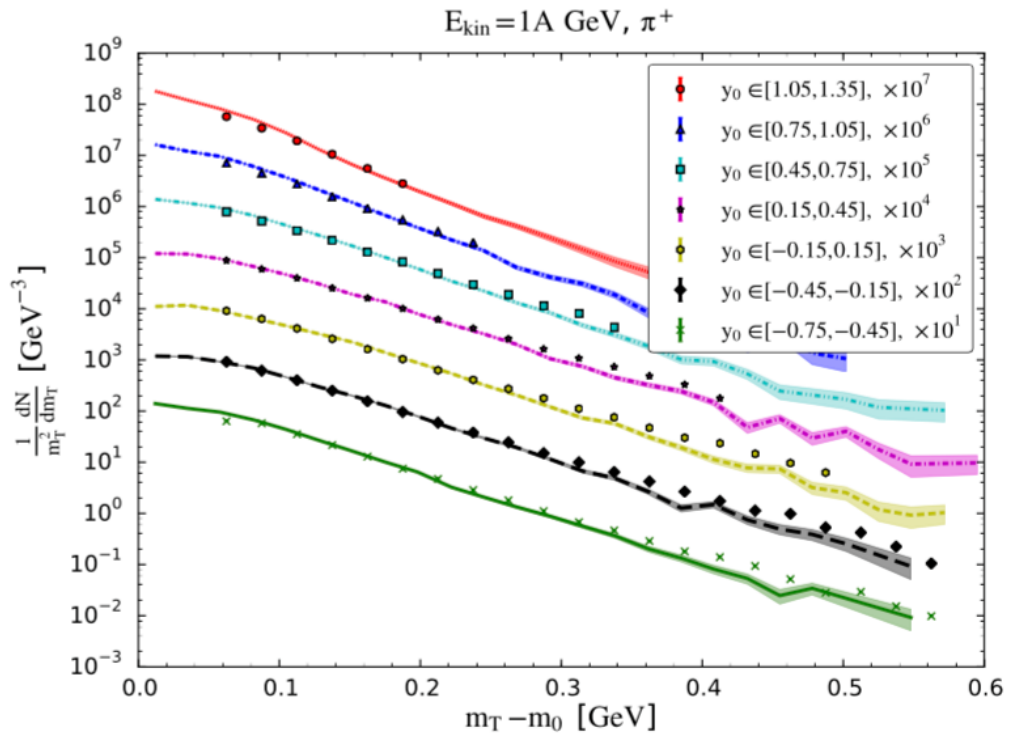
Hadron Production at SIS-18

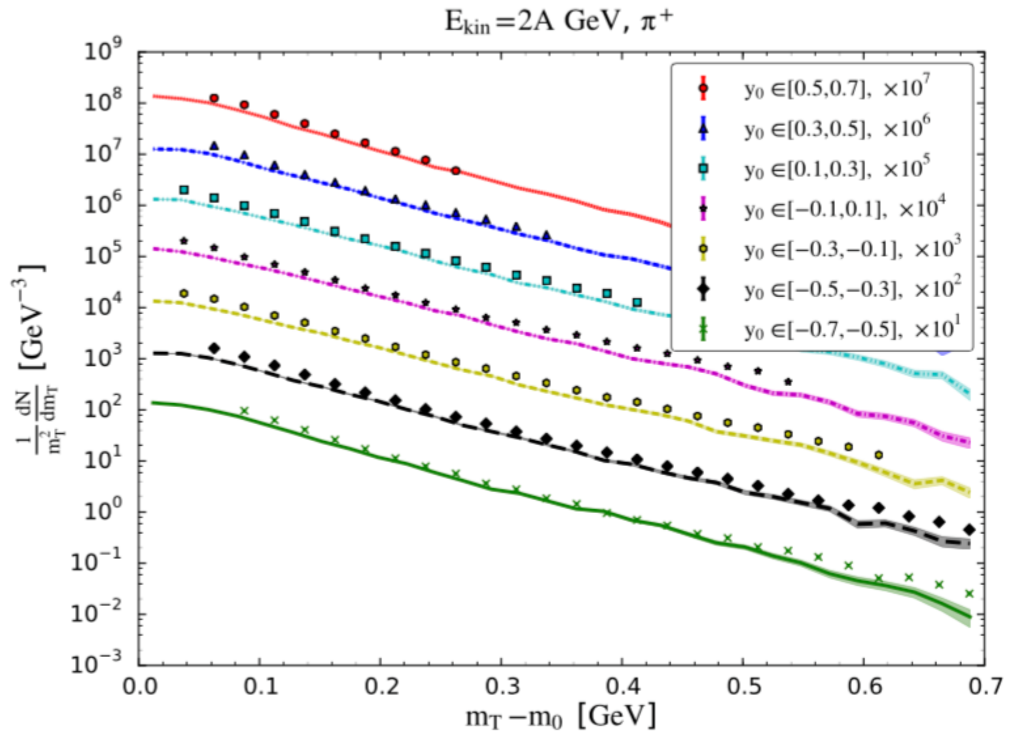
Pion Production in Au+Au

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



Note: consecutive addition of features



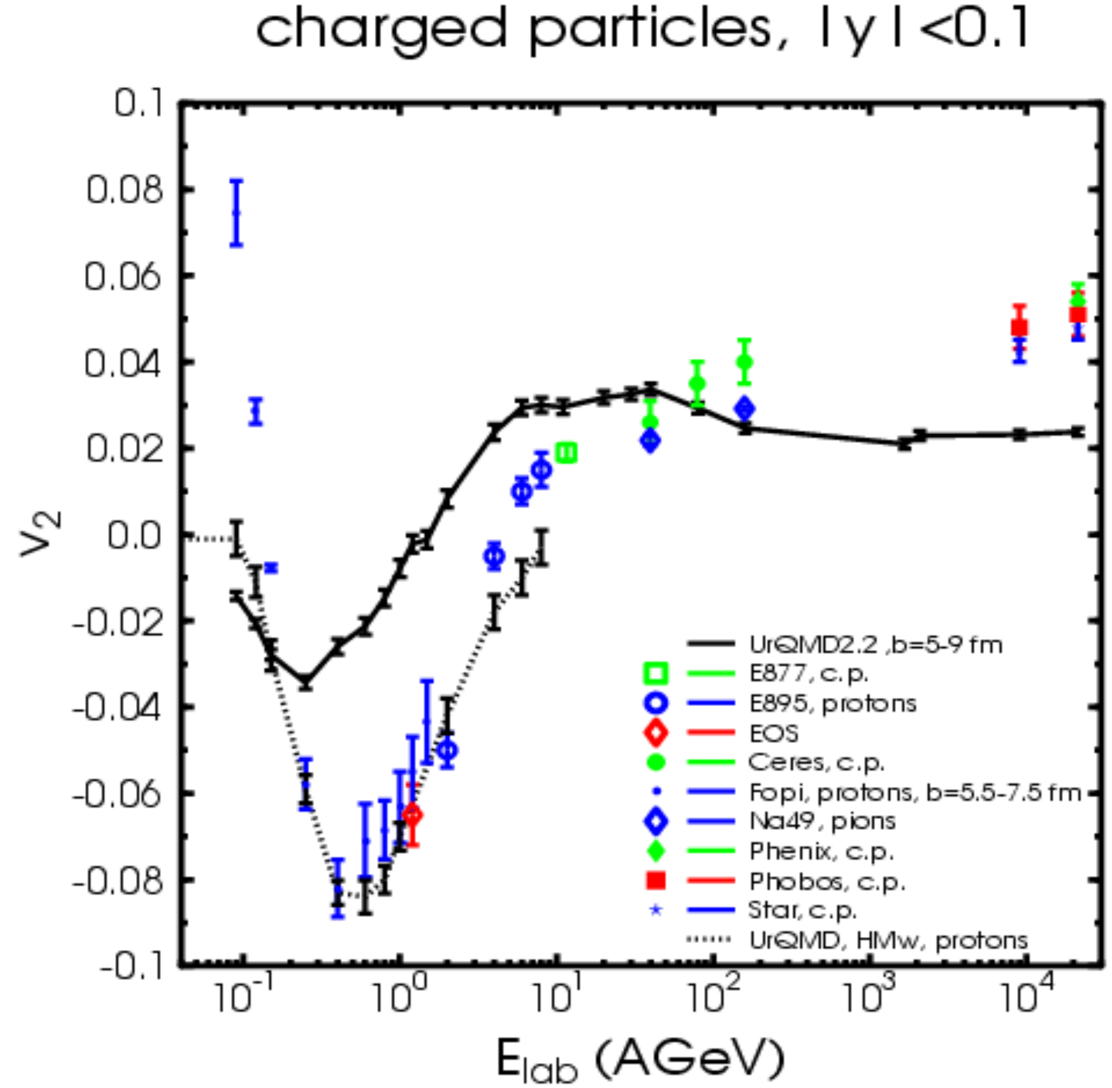


J. Weil et al, PRC 94 (2016)

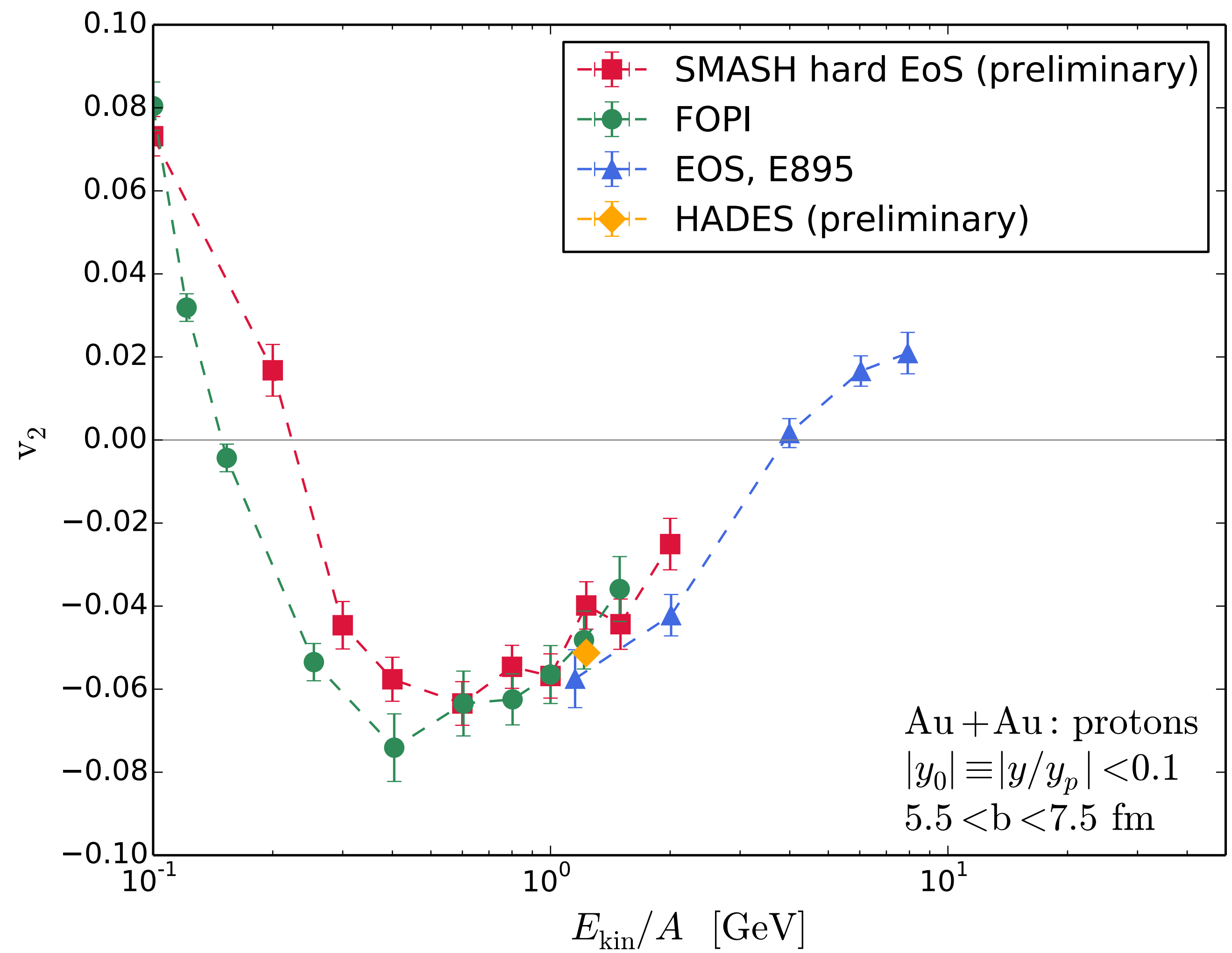
Collective Flow -v_2

- 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 Production

K+ production

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

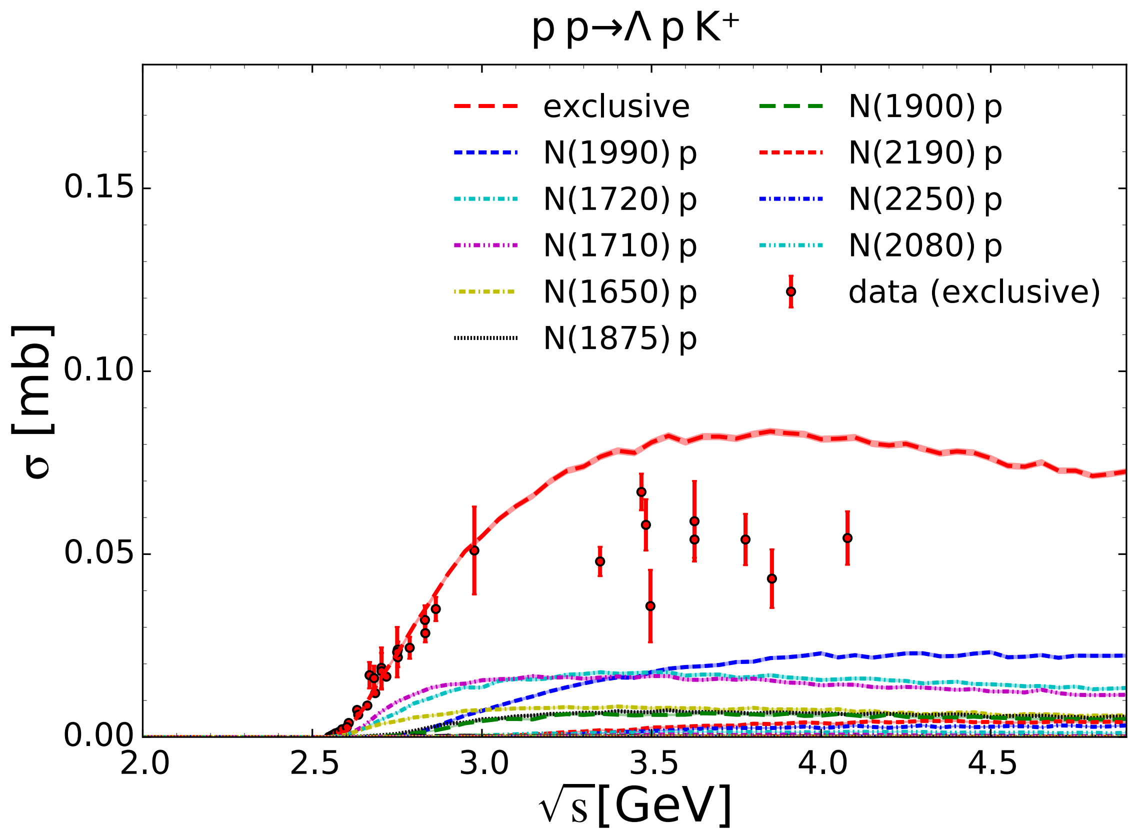
K- production

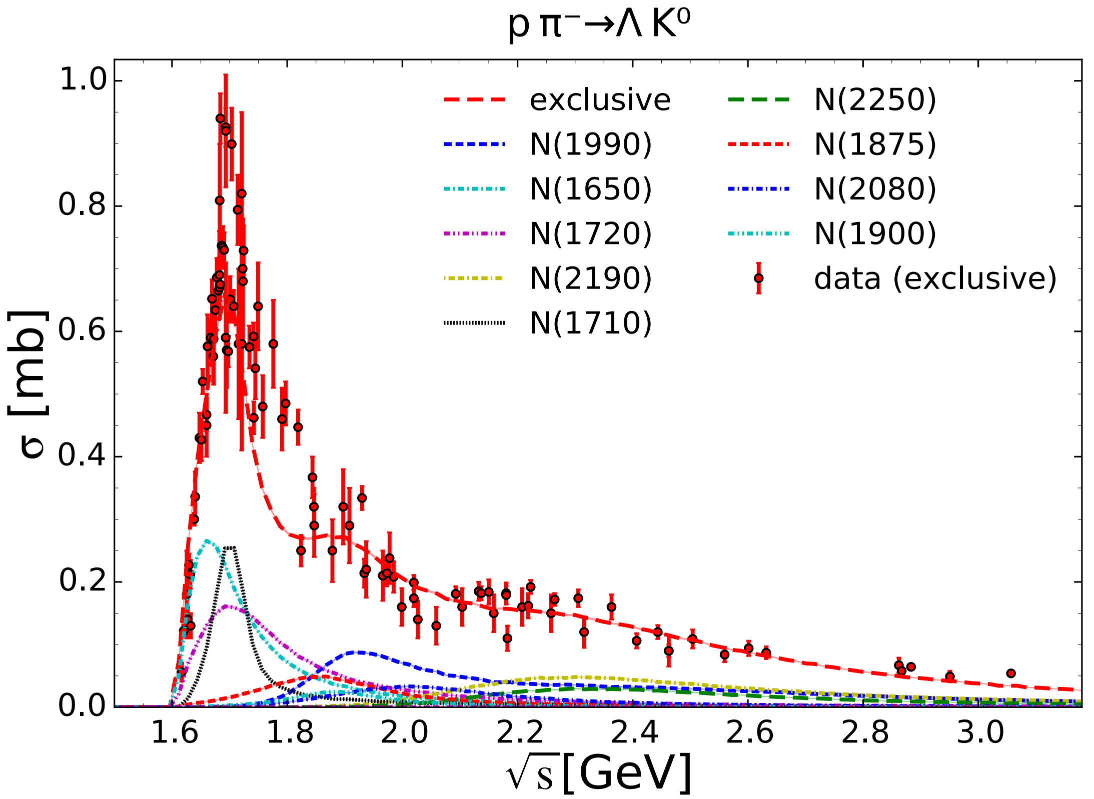
$$\pi Y \rightarrow Y^* \rightarrow \bar{K}N$$

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

- 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%



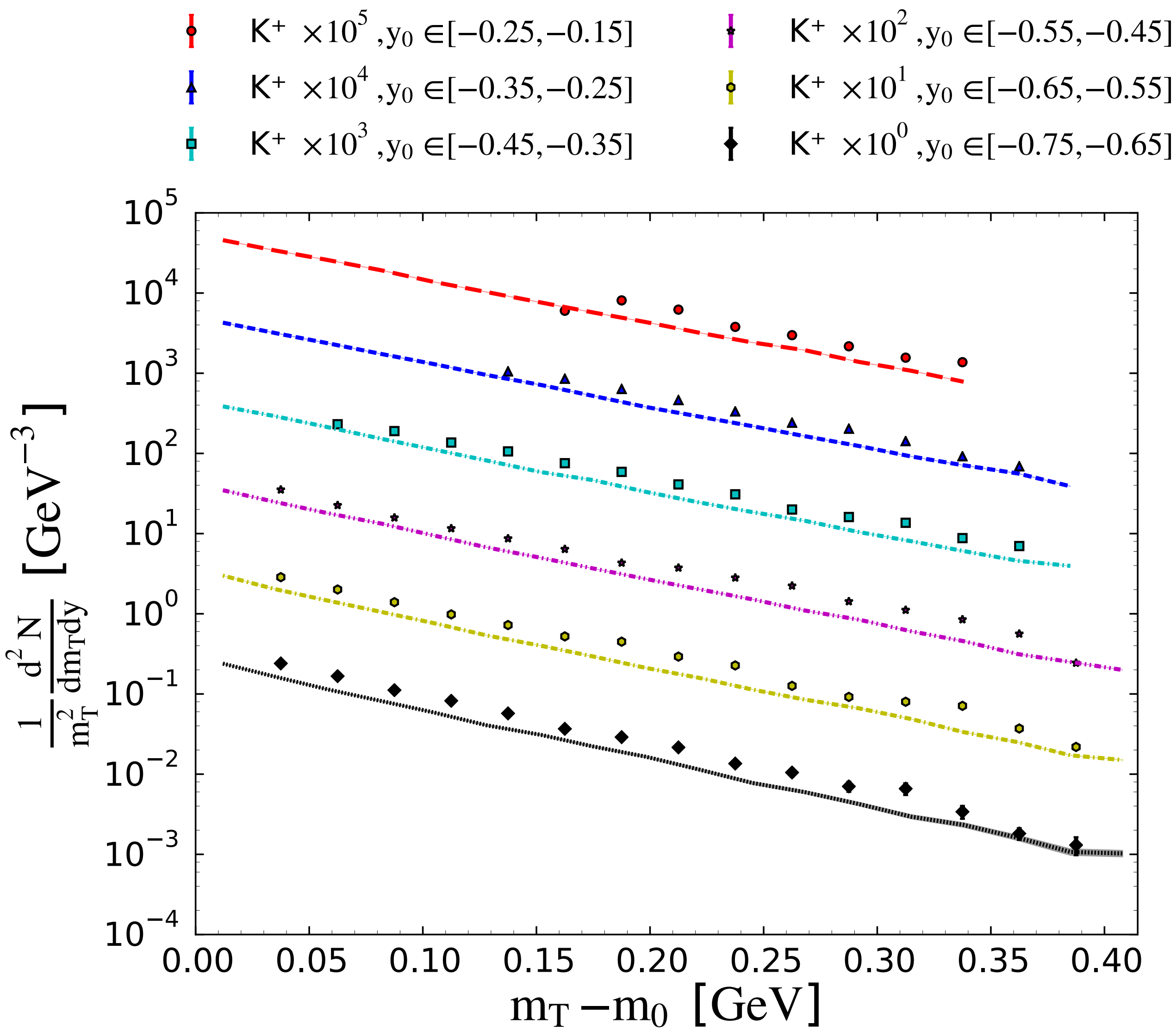


V. Steinberg et al., arXiv:1809.03828

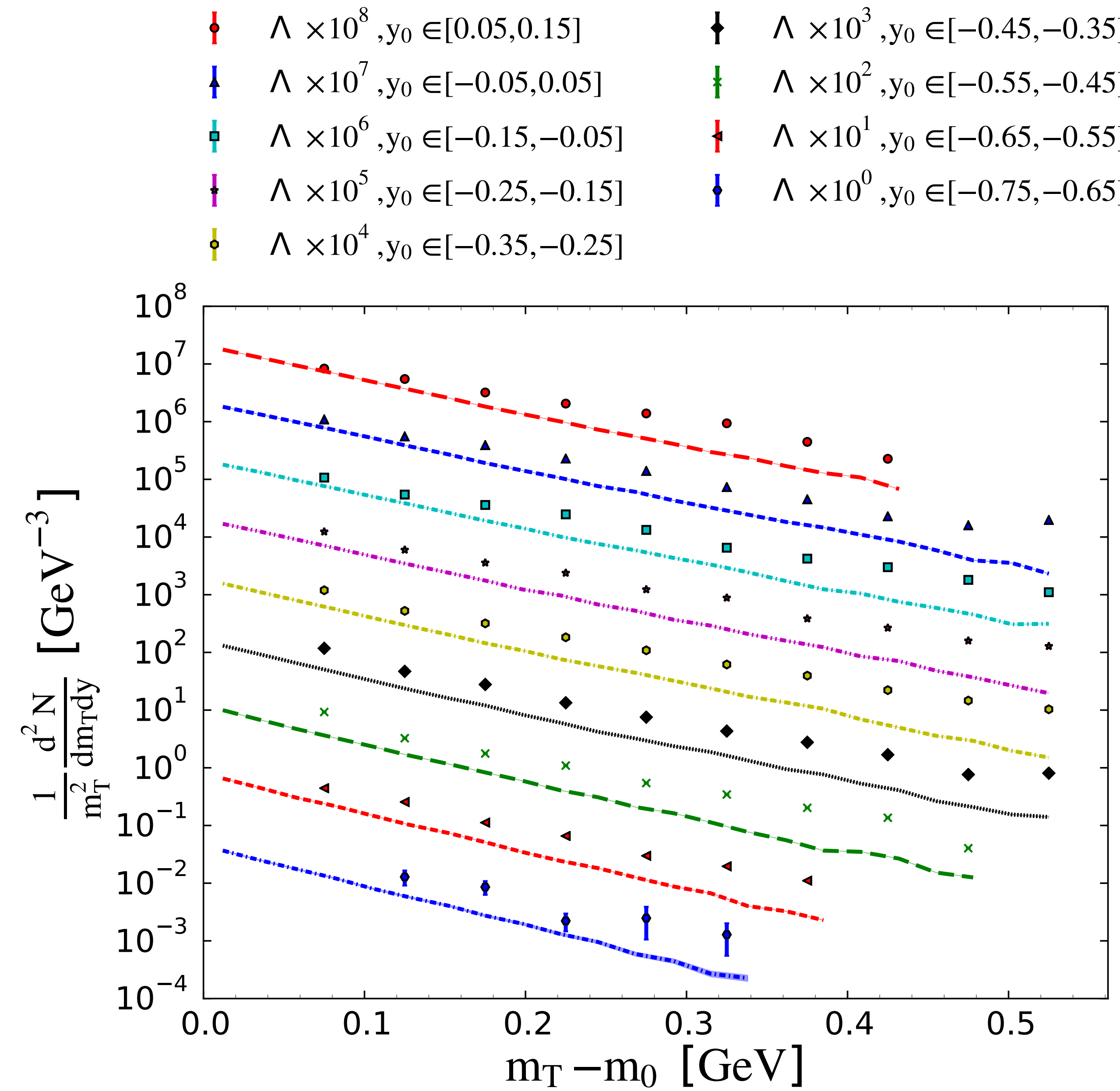
Strangeness Production

- Kaons and Lambdas in Ar+KCl:

Kaons



Λ's

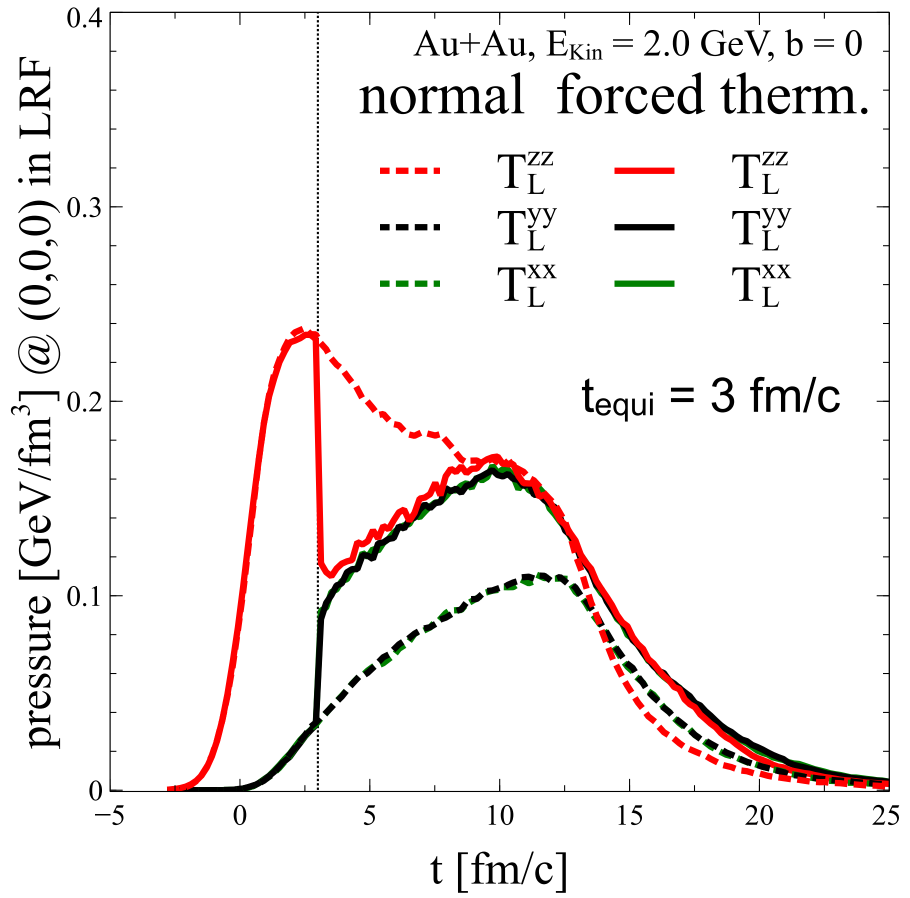


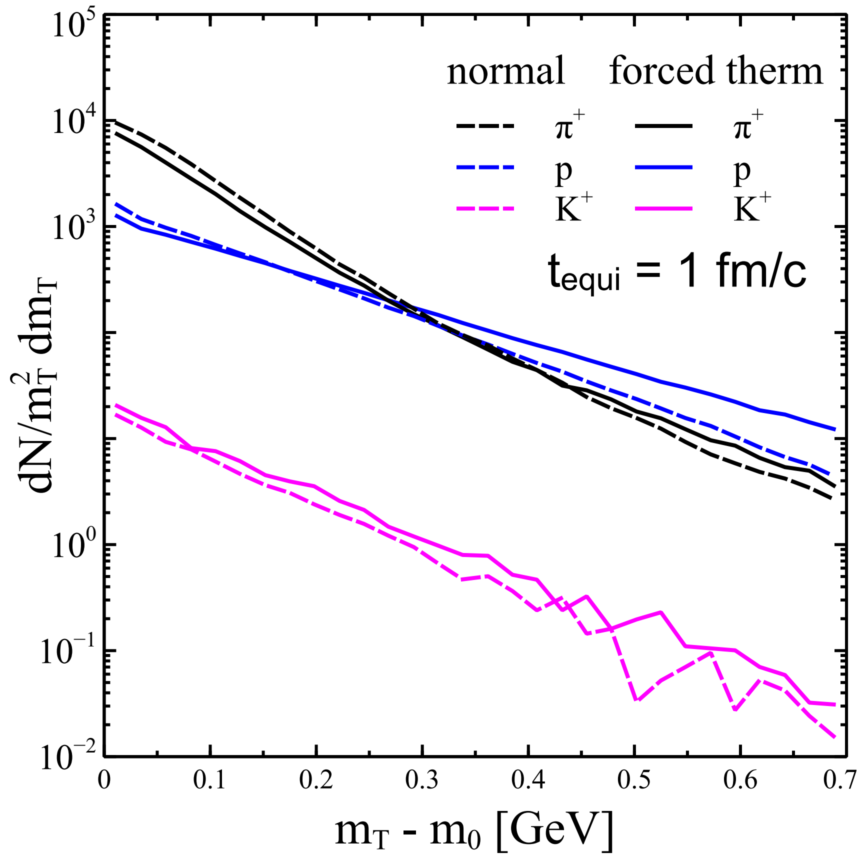
V. Steinberg et al., arXiv:1809.03828

- Ongoing work: system size dependence and predictions for pion beam and hyperon potentials

Effective N-particle Scattering

- At higher densities multi-particle scattering becomes important -> here: extreme limit
- Above 0.3 GeV/fm³ local kinetic equilibrium is enforced by replacing the distribution function with a thermal one



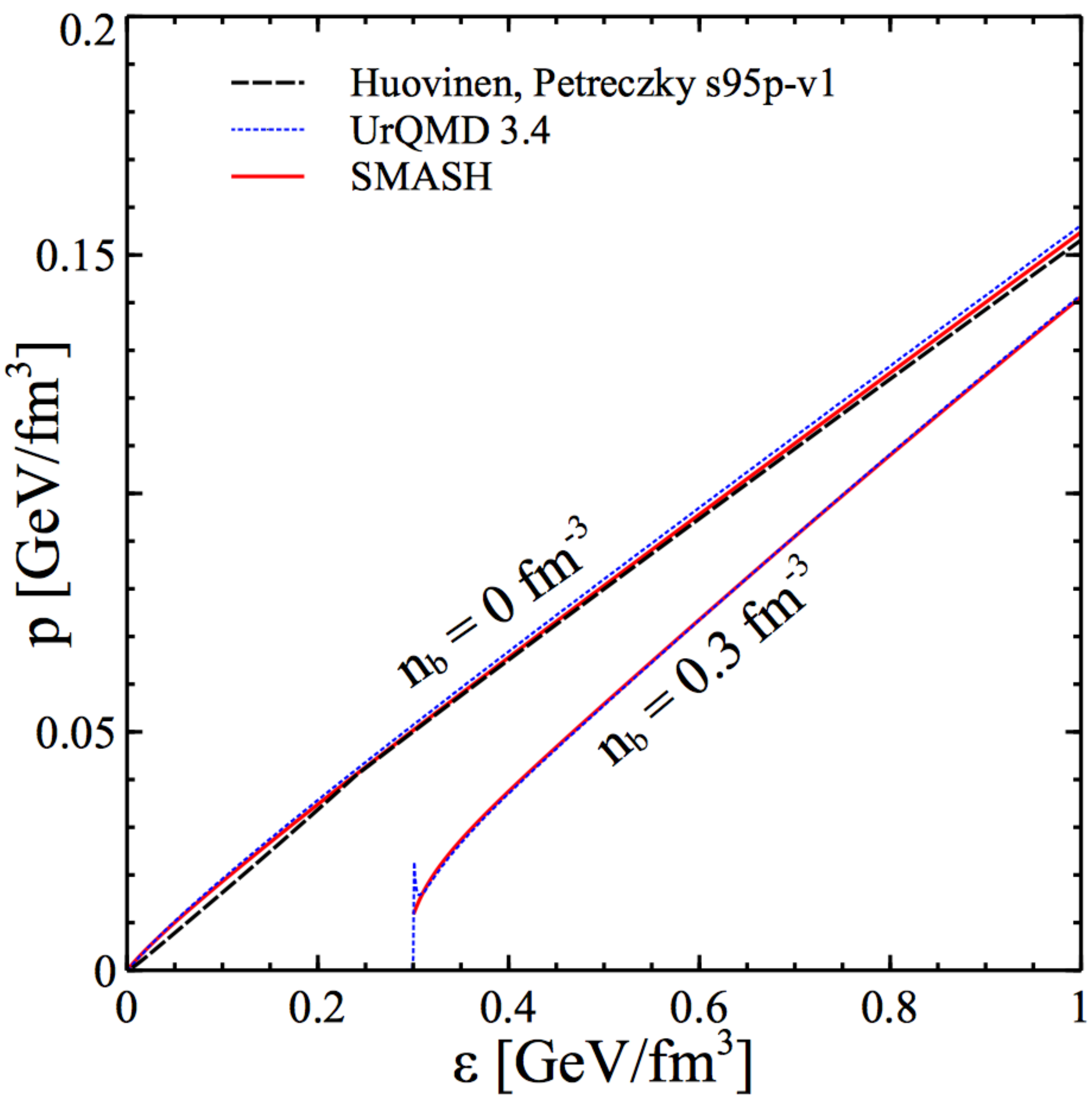


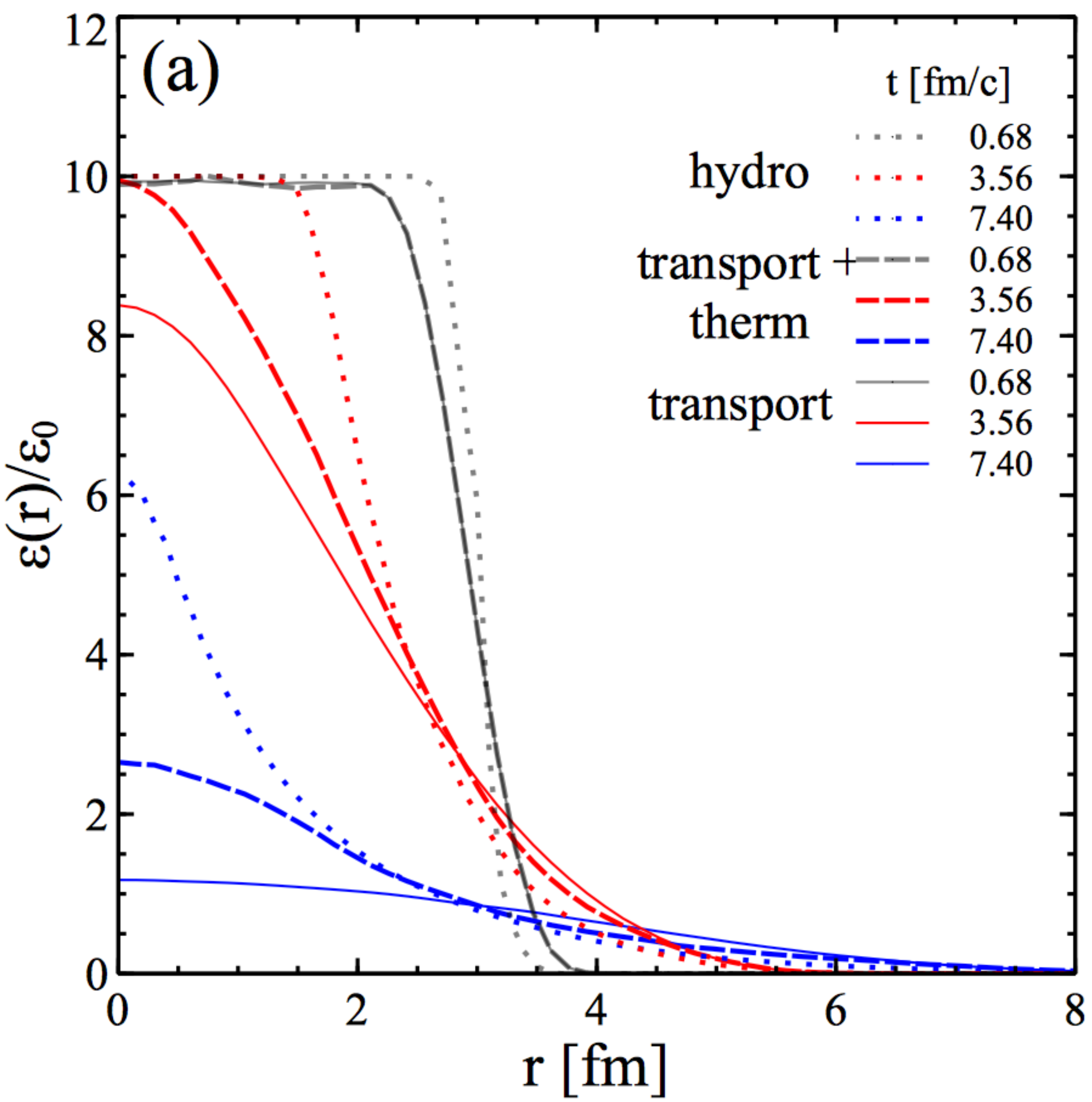
- Spectra are more „thermal“ and strangeness enhanced

Dmytro Oliinychenko, HP, JPG 44, 2017

EoS and Hydro Comparison

- Equation of state fits lattice hadron gas





- Interpolation between transport and hydrodynamics

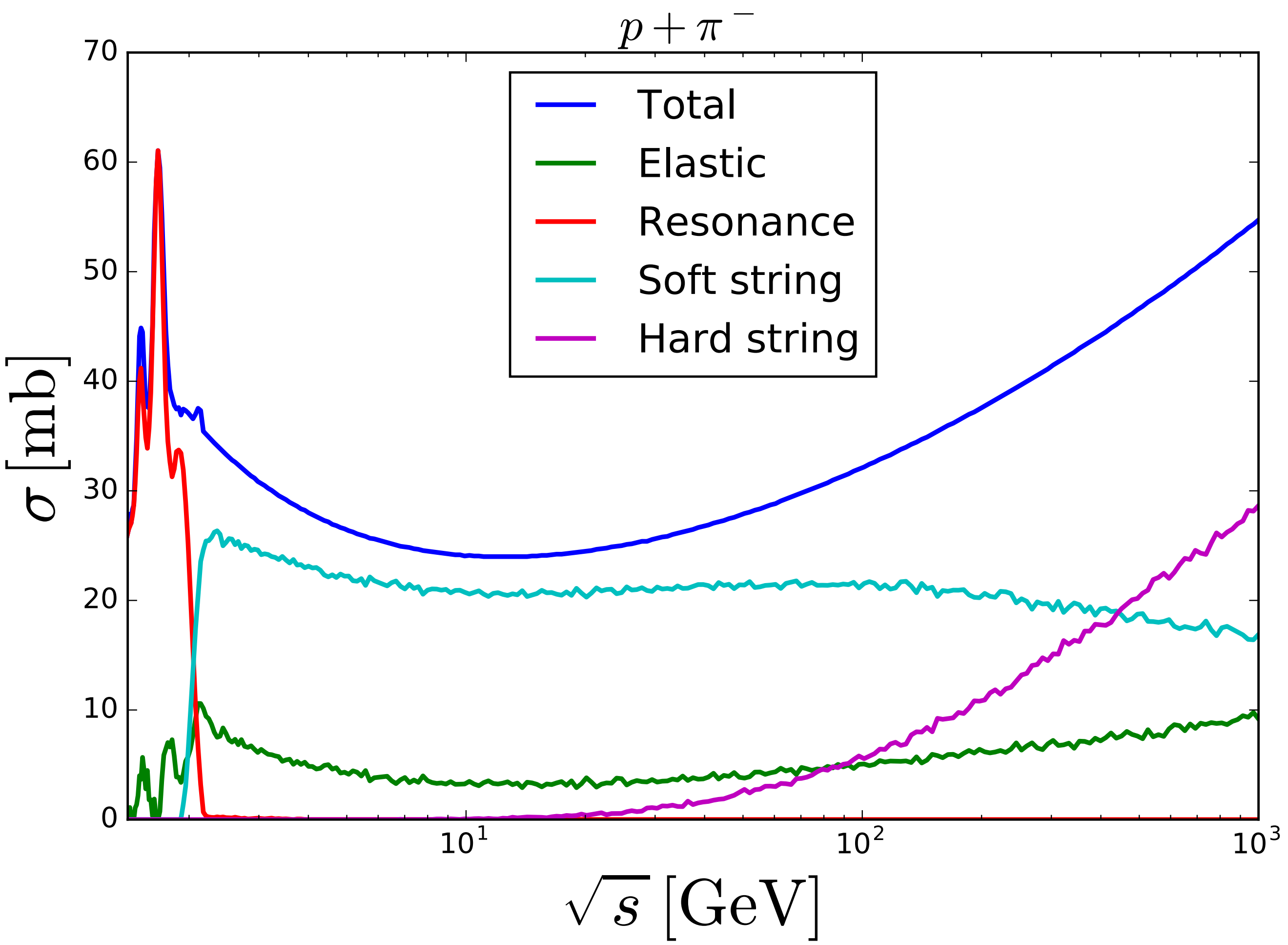
Dmytro Oliinychenko, HP, JPG 44, 2017

Strings and Stopping

Moving to Higher Energies

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

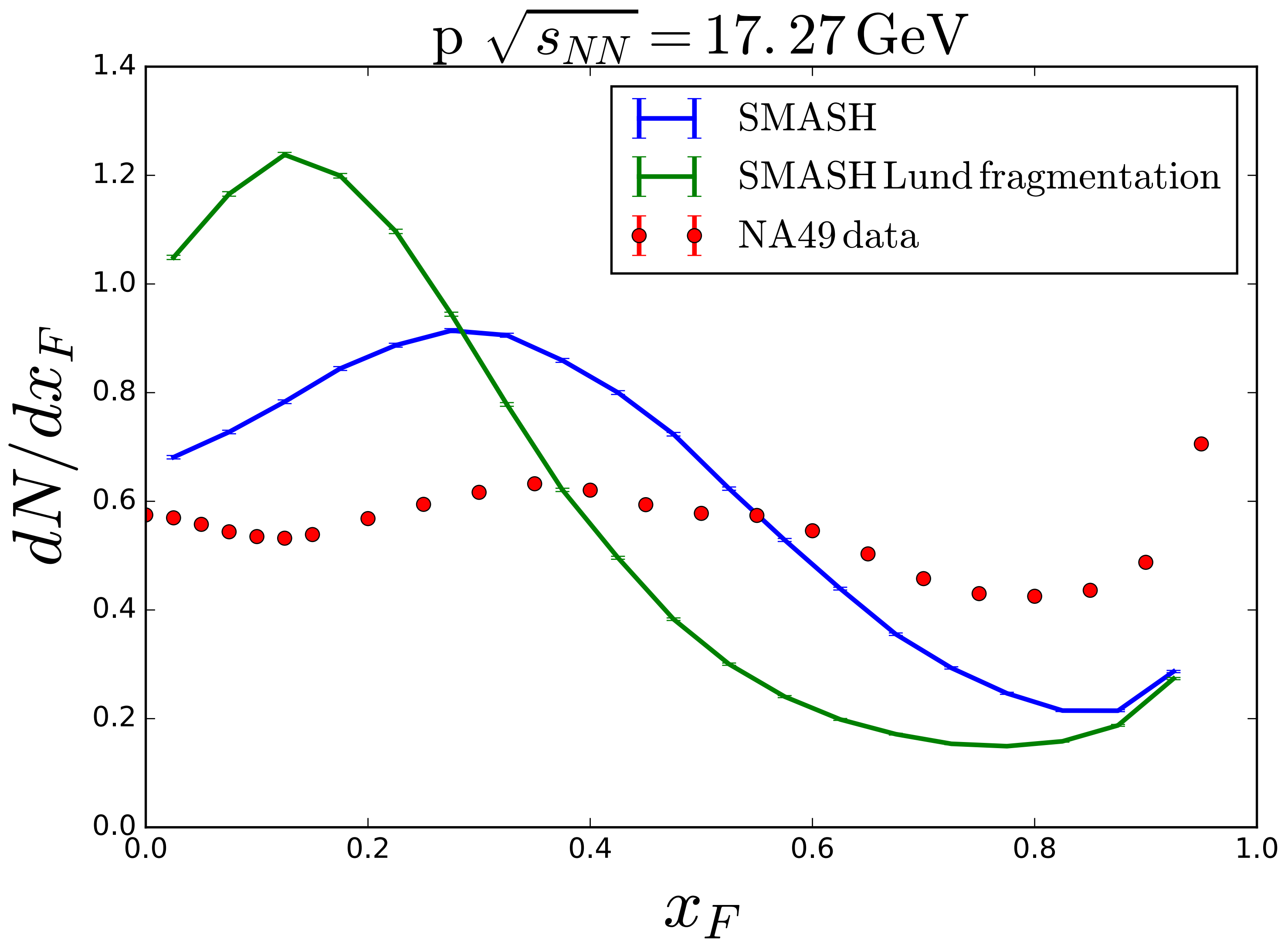
- **Soft strings**
  - Pythia is only employed for fragmentation
  - single-diffractive, double diffractive and non-diffractive processes
- **Hard strings**
  - Fully treated by Pythia
  - All species mapped to pions and nucleons



J. Mohs and S. Ryu

Fragmenting Leading Baryons

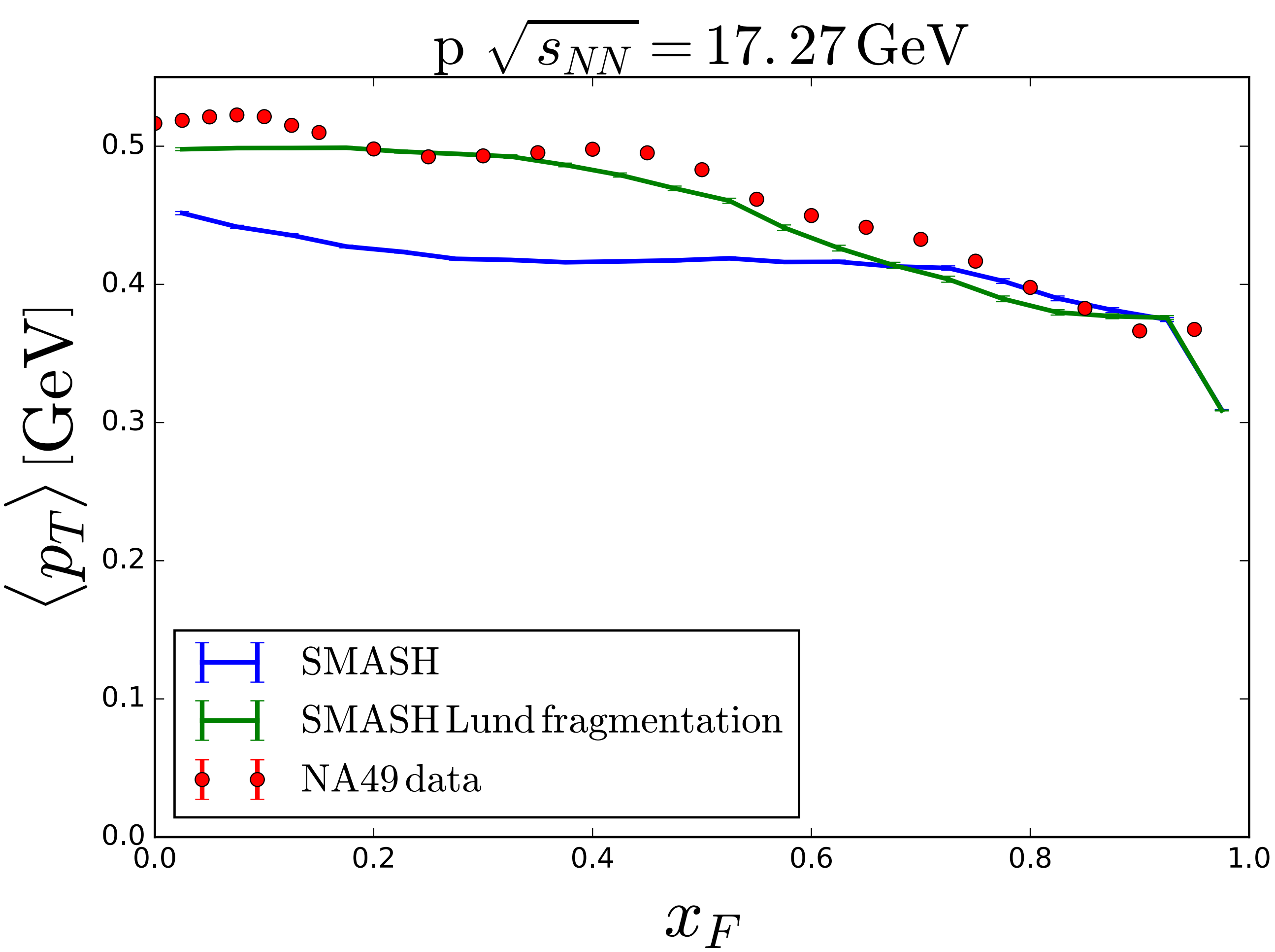
- Different fragmentation function for leading baryons to increase longitudinal momentum of protons

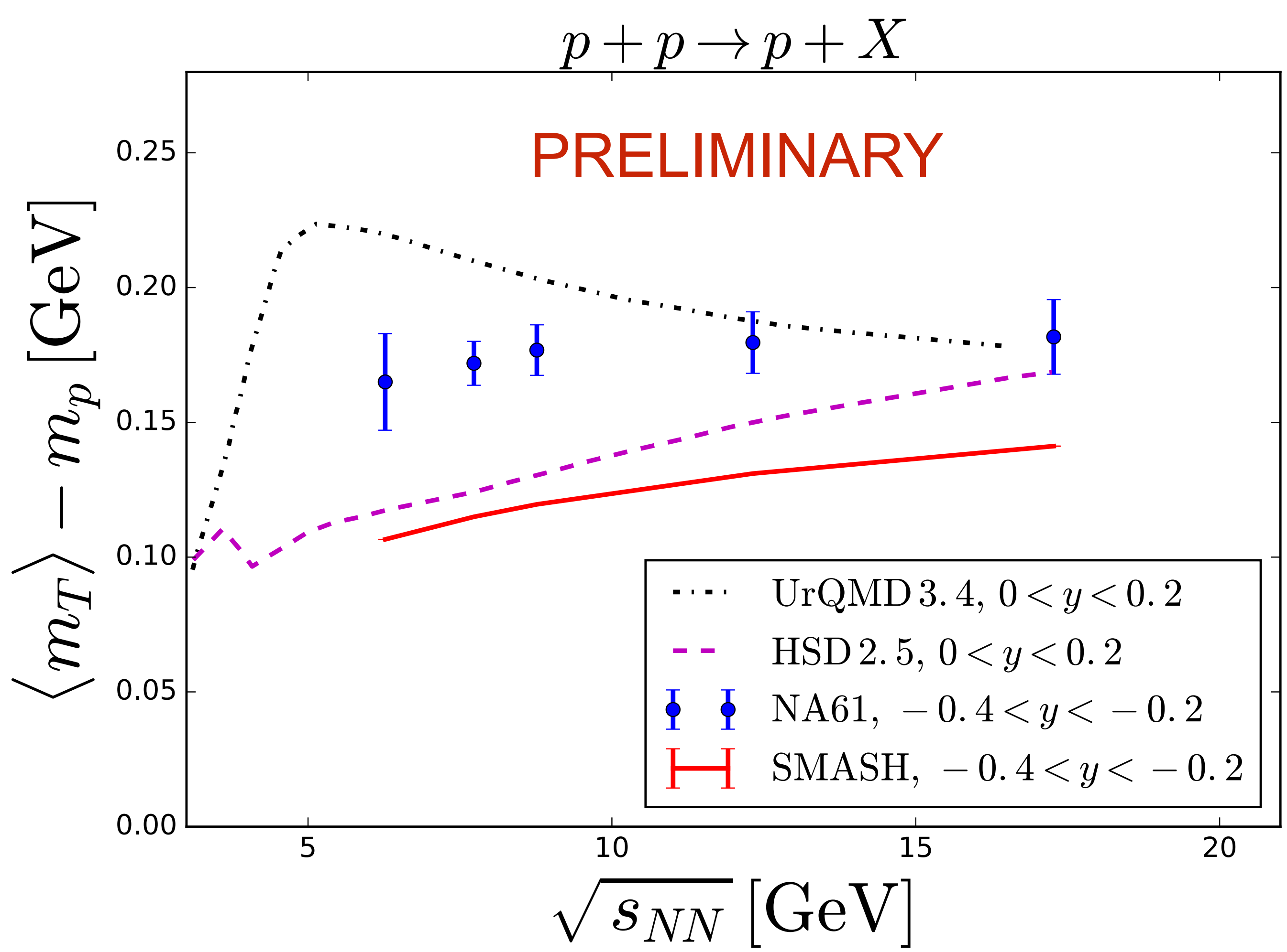


- Slightly better agreement for Feynman x distribution

Transverse Momentum

- Benchmark in elementary collisions

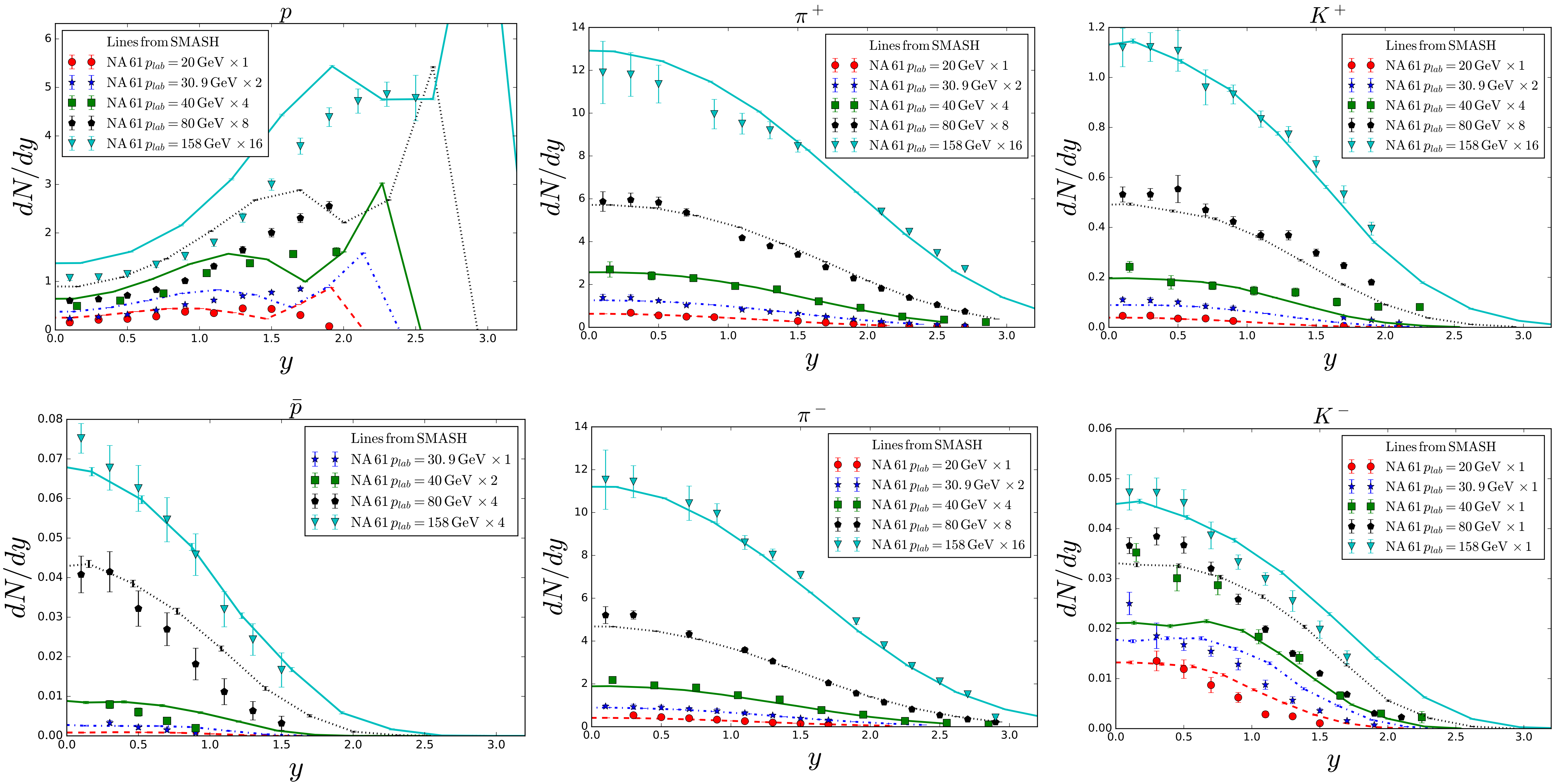




- Mean p_T for small Feynman x is too low
- Work in progress: Improve implementation of fragmentation

$$x_F = \frac{p_z}{p_{z,beam}}$$

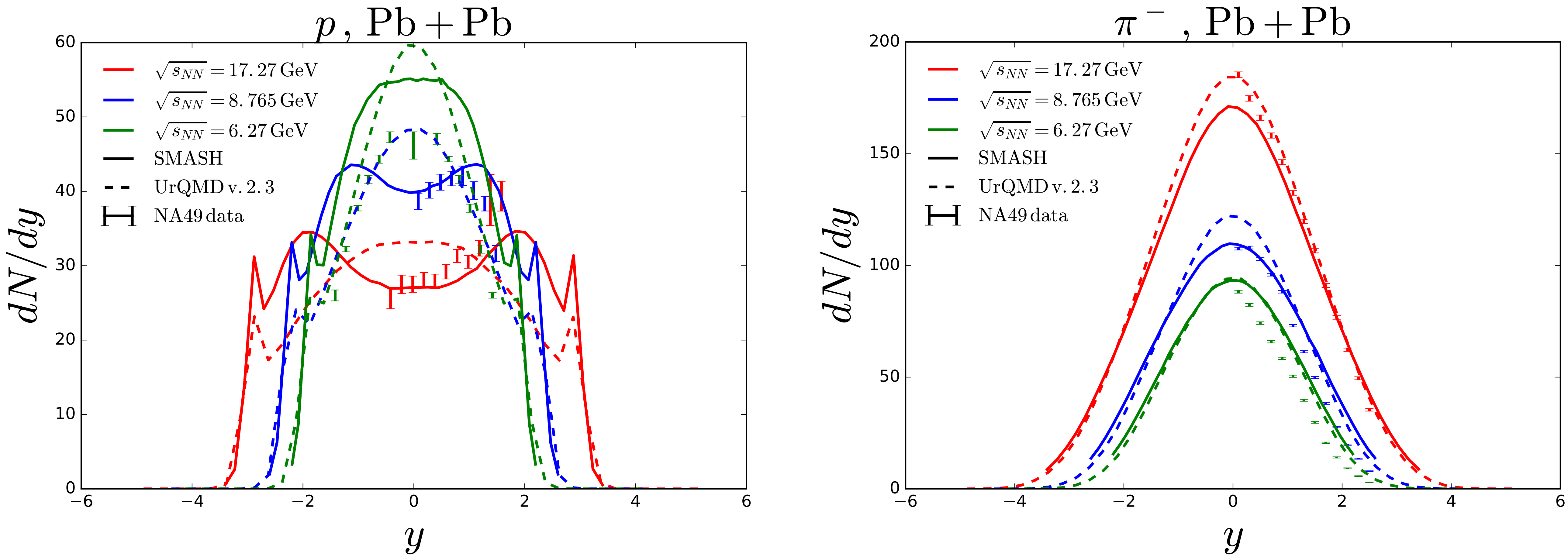
Results in pp



- Fragmentation function, strangeness suppression and diquark suppression tuned to reproduce data

Results in AA

- Baryon stopping well reproduced
- At low beam energies, clusters have to be subtracted

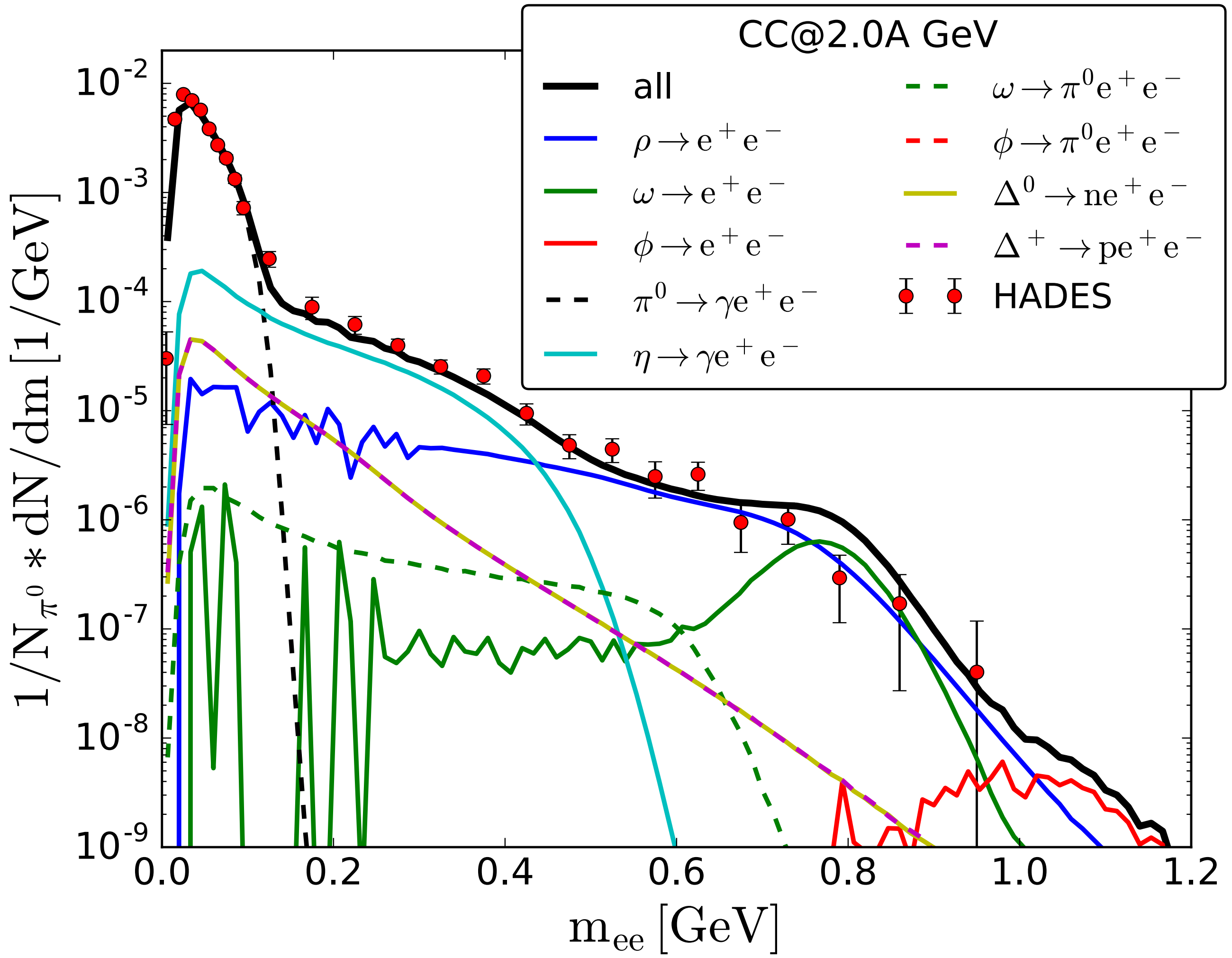


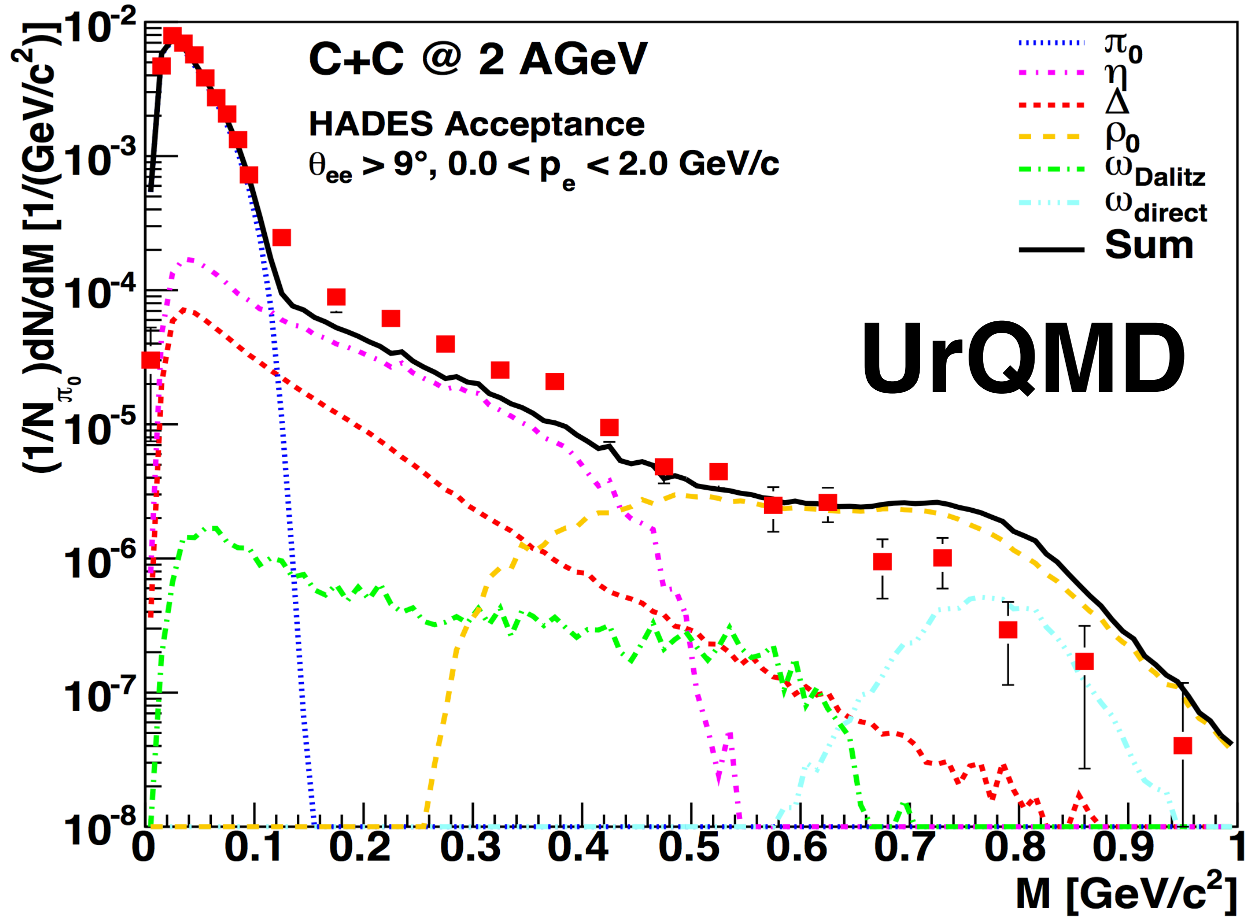
- Shape of pion spectrum agrees with data
- Work in progress: Study influence of formation times and cross-section scaling factors

Electromagnetic Probes

Dilepton Production

HADES, PRL 98 (2007)





J. Staudenmaier et al, PRC 98 (2018)

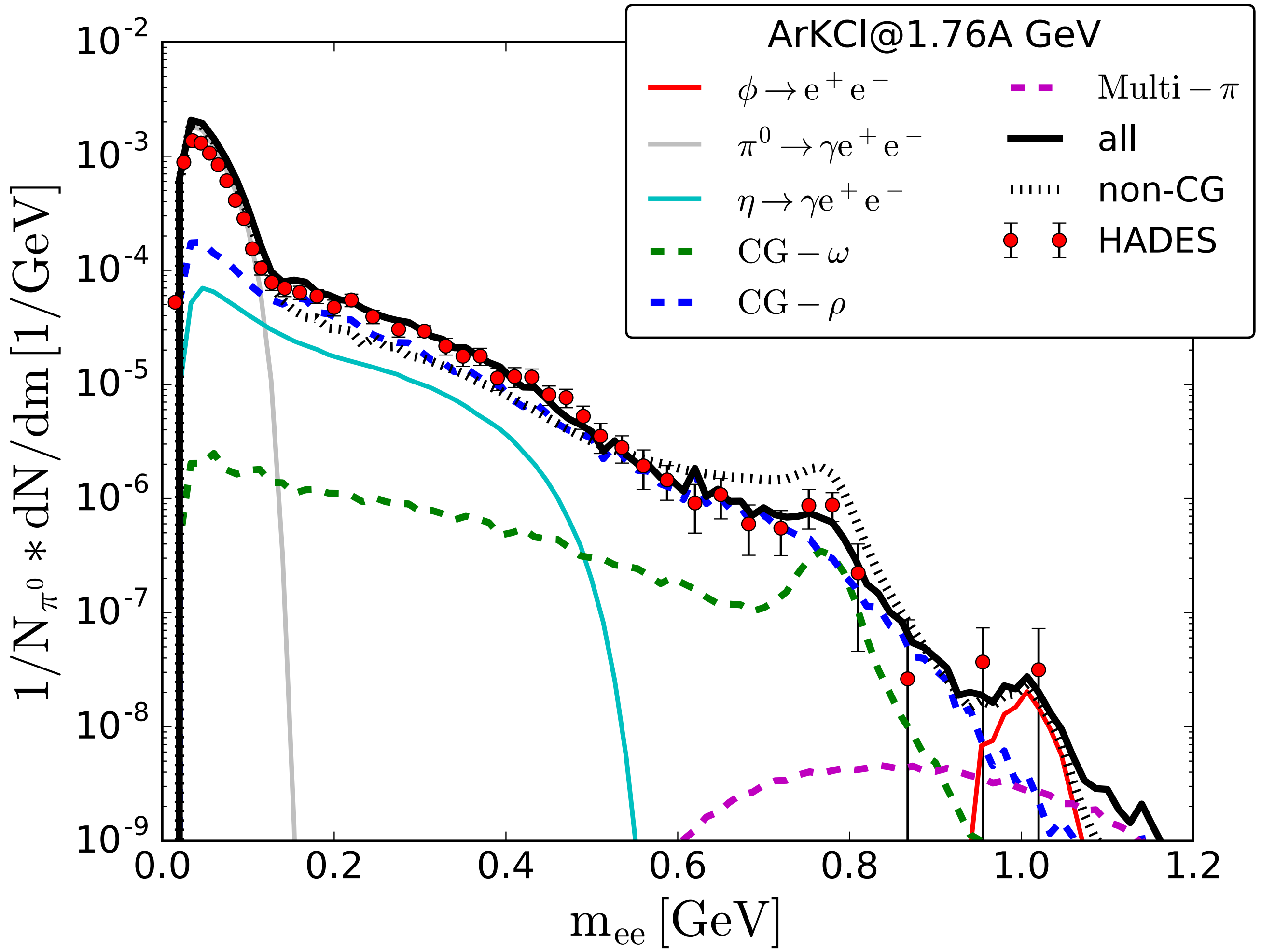
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

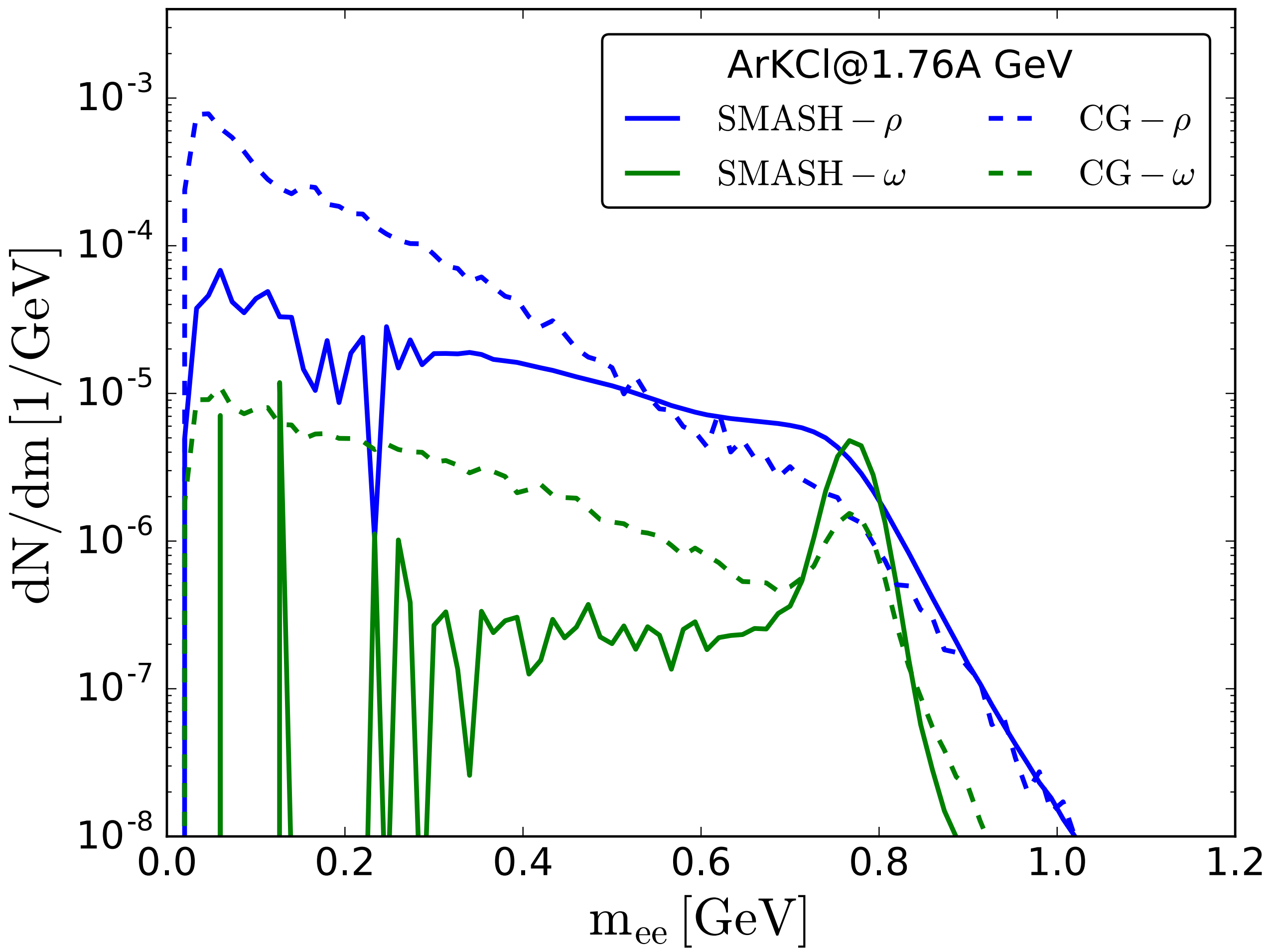
- SMASH and UrQMD compare very similar to data
- Different vector meson thresholds at low masses
- Adjusted branching ratios of N* and Δ resonances for ρ peak

Medium Modifications

- Dynamical collisional broadening is included in default SMASH calculation

J. Staudenmaier et al., PRC98 (2018)





- Coarse-grained transport evolution allows for full medium-modified spectral function

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

- First time: Comparison of both approaches based on the same medium evolution

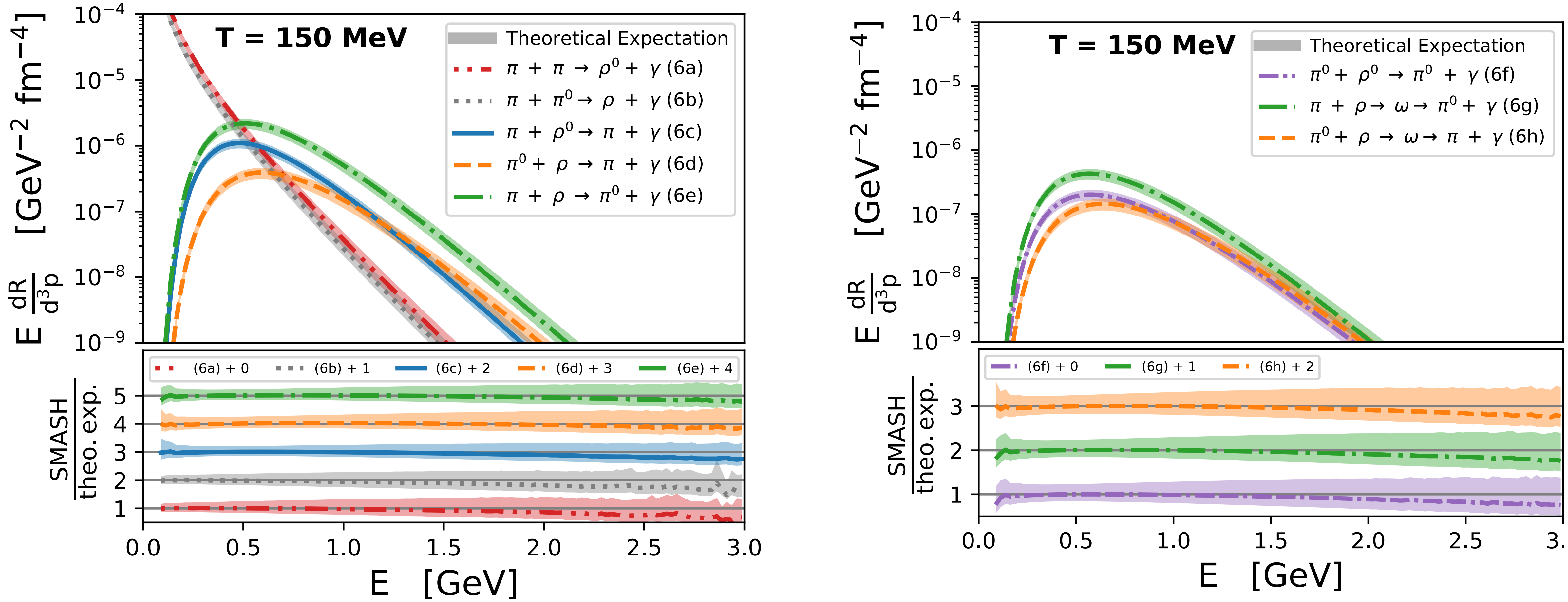
J. Staudenmaier et al, PRC 98 (2018)

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



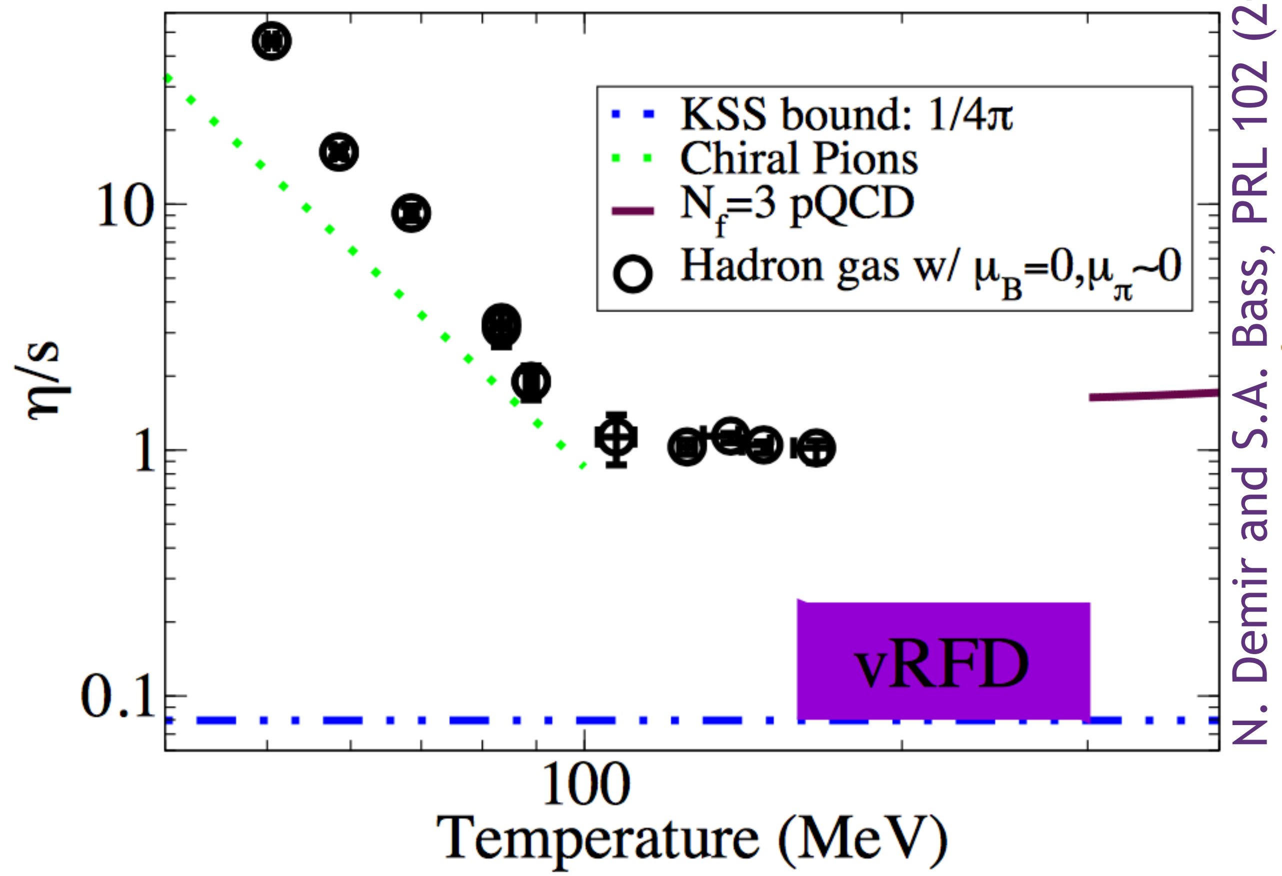
- Rates in thermal box nicely reproduced
- Next: Photons from late non-equilibrium stage at RHIC/LHC including bremsstrahlung

by Anna Schäfer and Jonas Rothermel

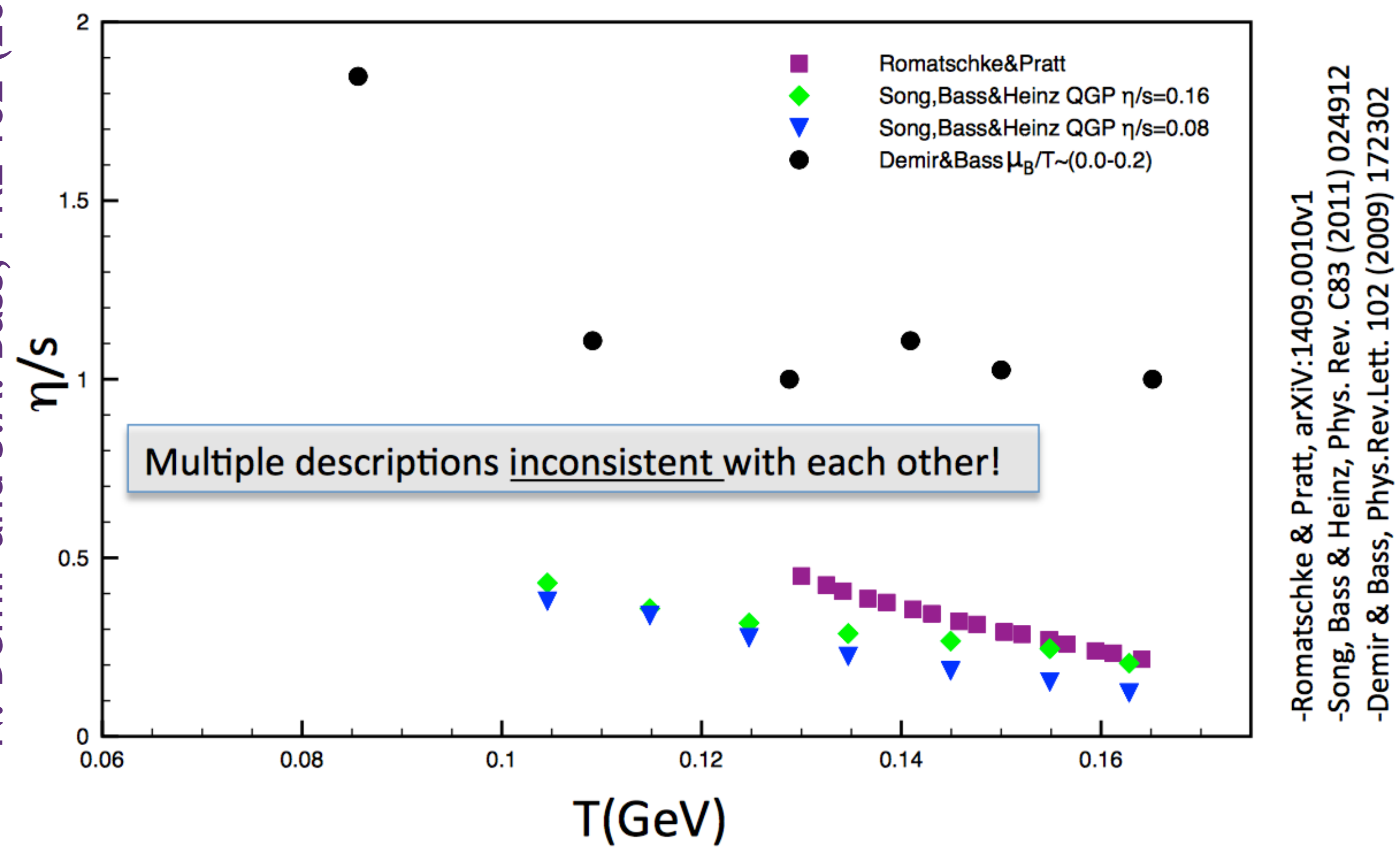
Transport Coefficients

Shear Viscosity of the Hadron Gas

Green-Kubo formalism
UrQMD



Discrepancy with
hydro-inspired B3D and VISHNU

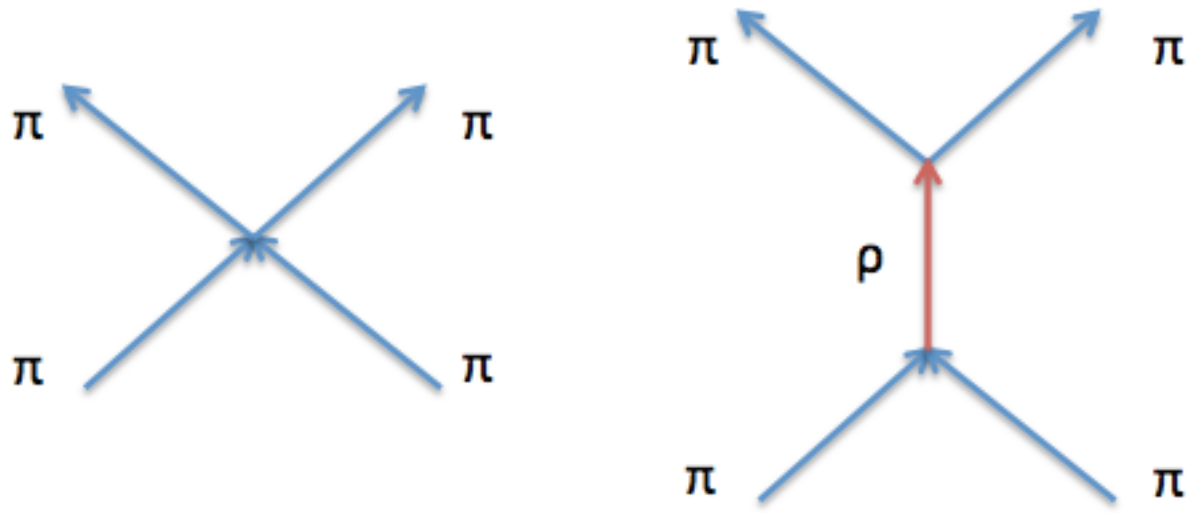


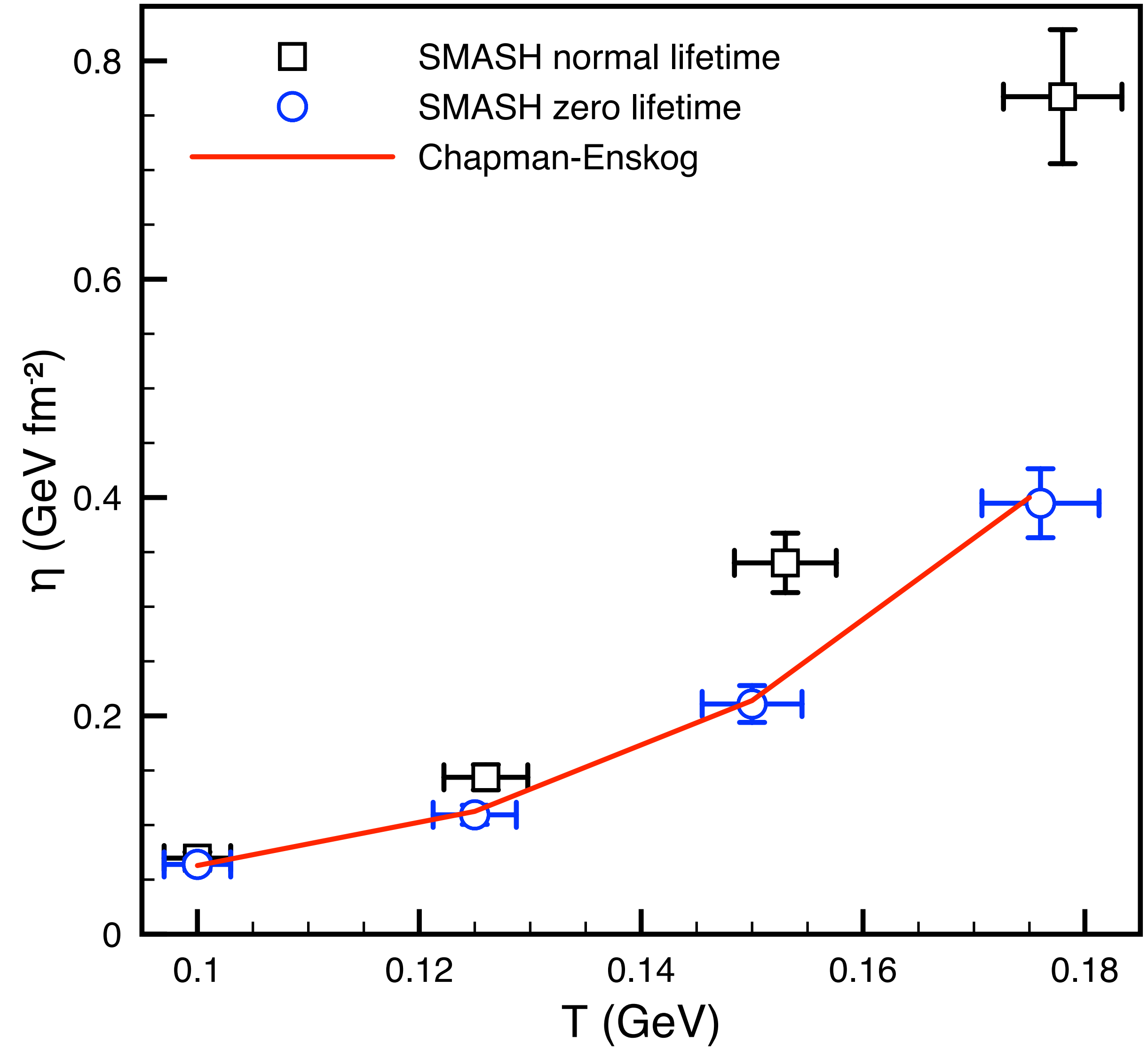
- Long standing question: Why are the results so different from each other?

J.-B. Rose, J. M. Torres-Rincon, A. Schäfer, D. Oliinychenko and HP, arXiv: 1709.00369 and 1709.03826

Resonance Dynamics

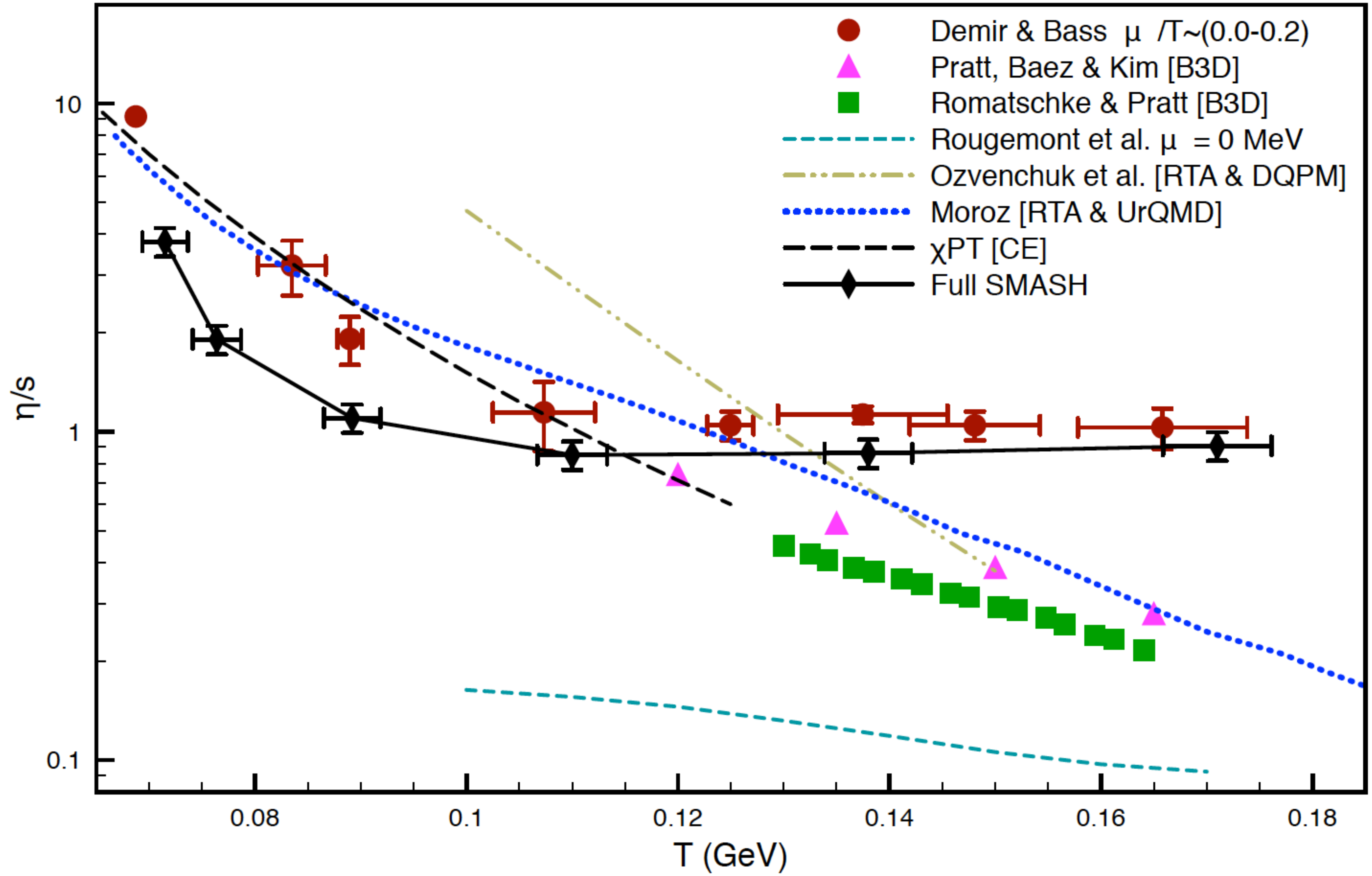
- Energy-dependence of cross-sections is modeled via resonances
- Point-like in analytic calculation and finite lifetime in transport approach





- Agreement recovered by decreasing ρ meson lifetime

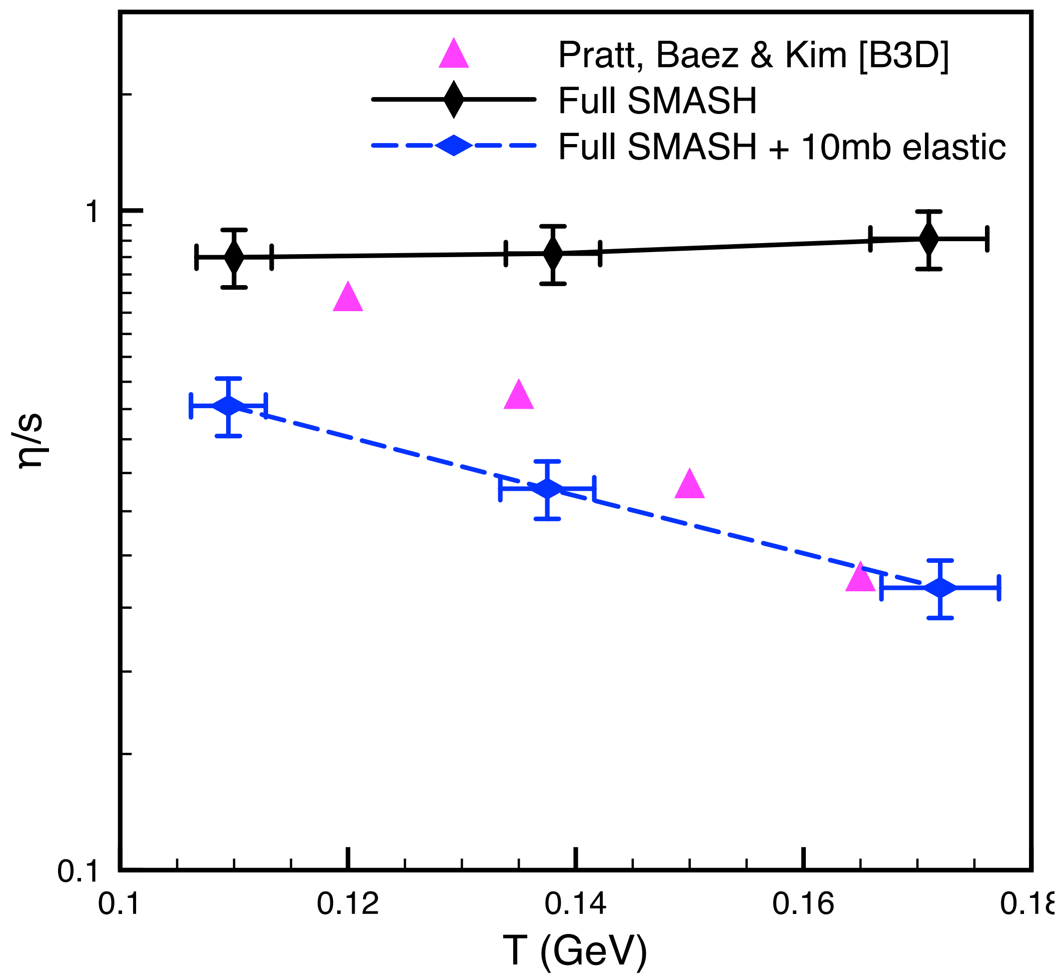
Comparison to Literature

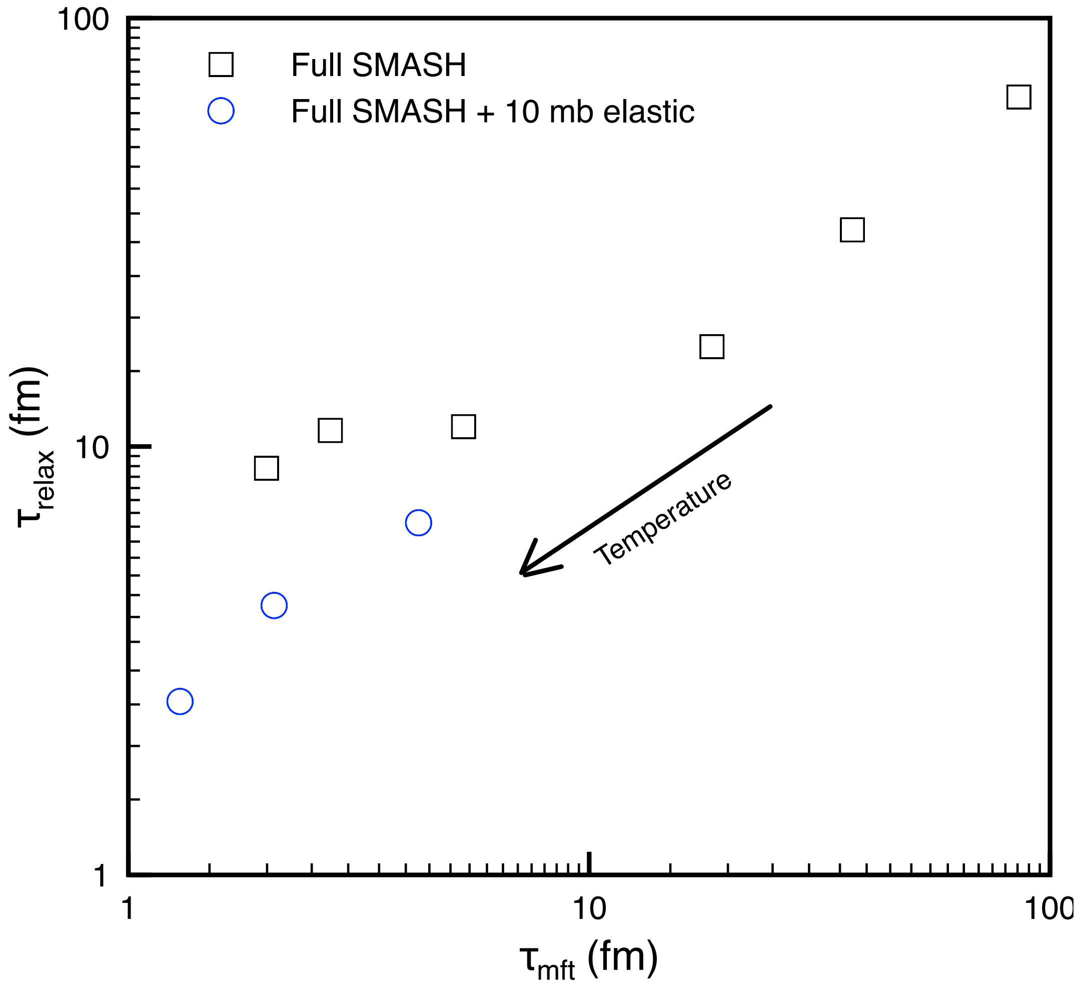


- Closest similarity to Bass/Demir result as expected

Point-like Interactions

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



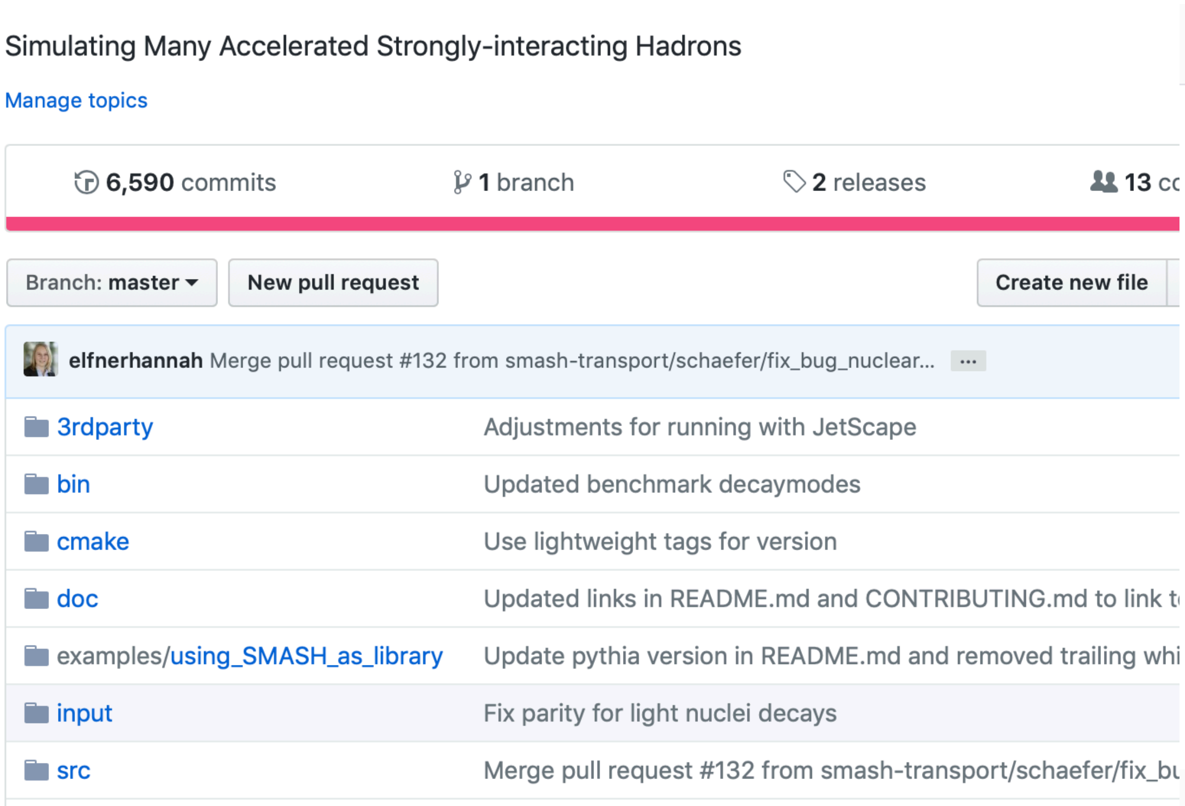


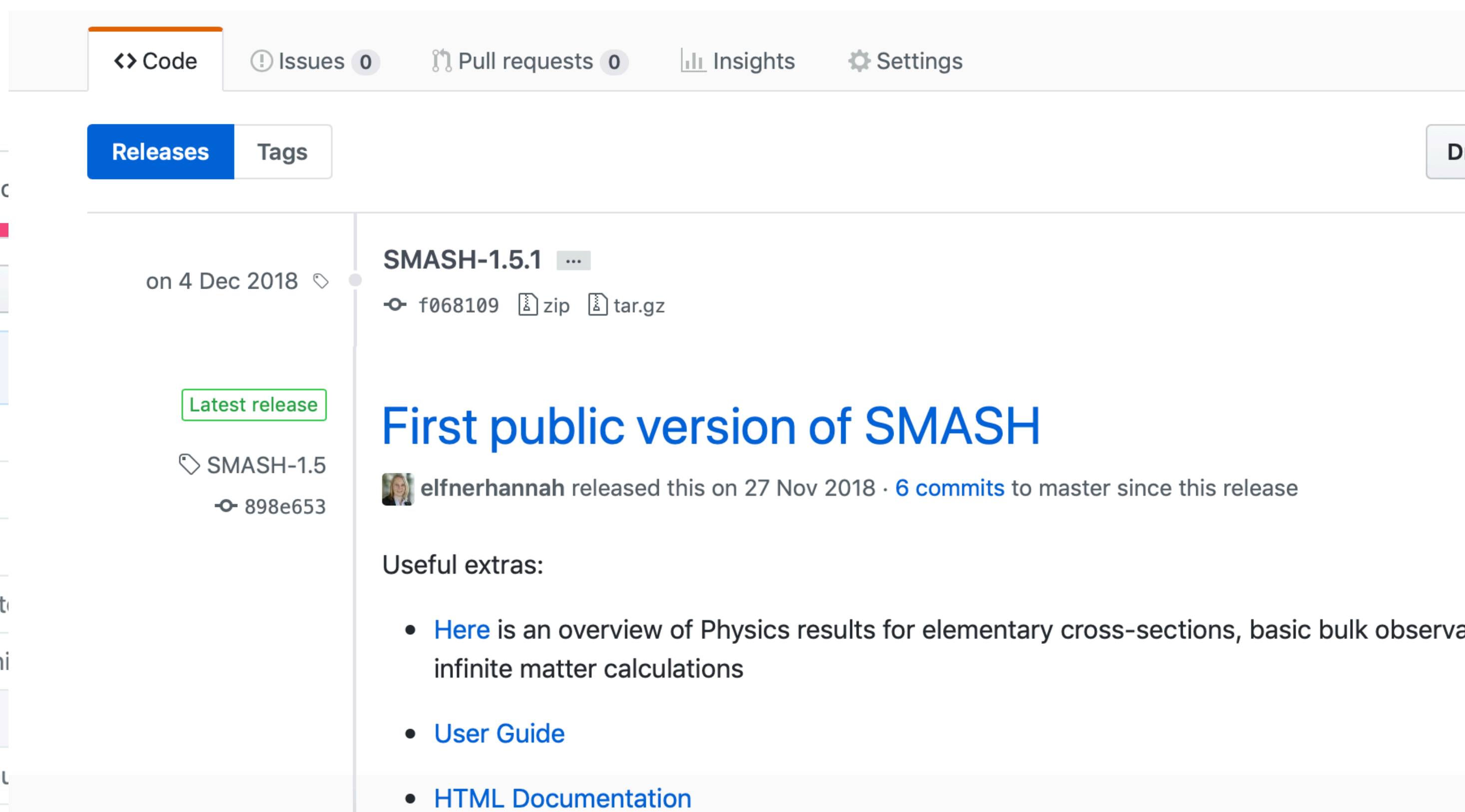
- Approximately linear relationship between relaxation time and mean free time is recovered
- Recent work on electric conductivity

J. Hammelmann et al., arXiv: 1810.12527

How to Use SMASH?

- Visit the webpage to find publications
  https://smash-transport.github.io
- Download the code at
  https://github.com/smash-transport/smash
- Checkout the Analysis Suite at
  http://theory.gsi.de/~smash/analysis_suite/SMASH-1.5/
- Find user guide and documentation at
  https://github.com/smash-transport/smash/releases





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-sections from elementary reactions
  - Investigation of baryon stopping within string model
  - Electromagnetic radiation is incorporated
- Afterburner for high-energy heavy-ion collisions (module within JETSCAPE)
- Multi-particle scattering and improved interfaces to hydrodynamic evolution
- Source code is public and ready to use!

Backup

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

Dileptons in SMASH

J. Staudenmaier et al., arXiv: 1711.10297

- 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

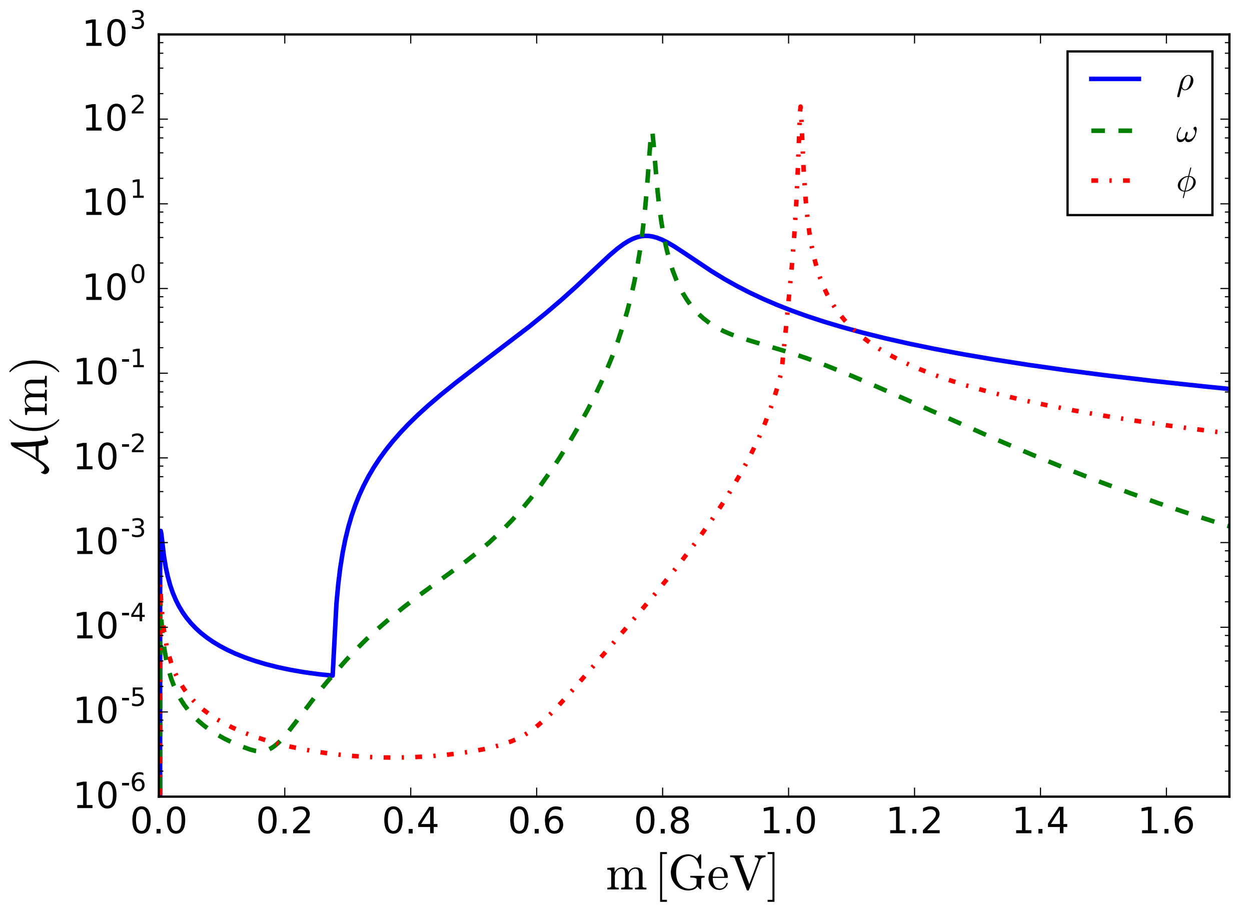
  – Continuously perform dilepton decays and weight them by taking their decay probability into account (better statistics)
- Detailed constraints on resonance properties

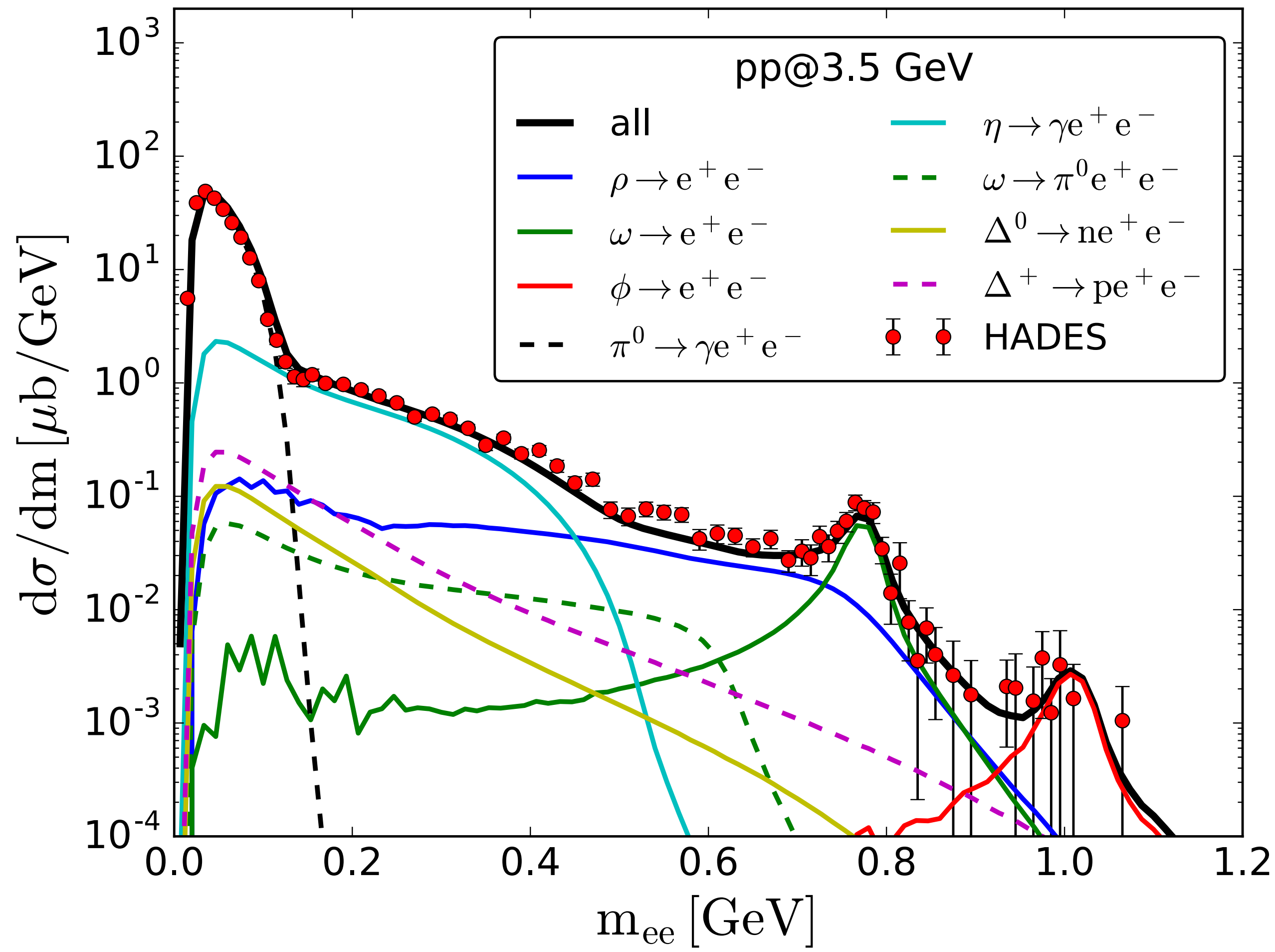
Dilepton Decays
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\phi \to e^+e^-$
$\pi \to e^+e^-\gamma$
$\eta \to e^+e^-\gamma$
$\eta' \to e^+e^-\gamma$
$\omega \to e^+e^-\pi^0$
$\phi \to e^+e^-\pi^0$
$\Delta^+ \to e^+e^-p$
$\Delta^0 \to e^+e^-n^0$

Elementary Collisions

- Contributions of vector meson spectral functions below hadronic thresholds

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





J. Staudenmaier et al., arXiv: 1711.10297

- Very nice agreement with HADES measurement