



FIAS Frankfurt Institute
for Advanced Studies



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SMASH

A new Hadronic Transport Approach

Hannah Petersen

15.05.18, Quark Matter 2018, Venice, Italy



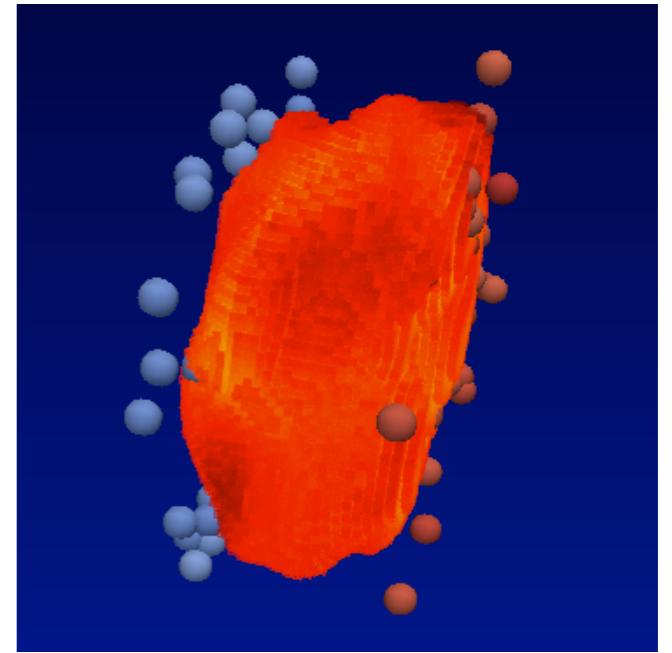
DAAD

HIC for **FAIR**
Helmholtz International Center

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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:
 - Feng Li
 - Sangwook Ryu
 - Vinzent Steinberg
 - Jean-Bernard Rose
 - Jan Staudenmaier
 - Anna Schäfer
 - Justin Mohs
 - Jan Hammelmann
 - Jonas Rothermel
 - Markus Mayer
- in US/Serbia:
 - Juan M. Torres-Rincon
 - Dmytro Oliynychenko
 - LongGang Pang
 - Jussi Auvinen



Subset of the group in November 2016

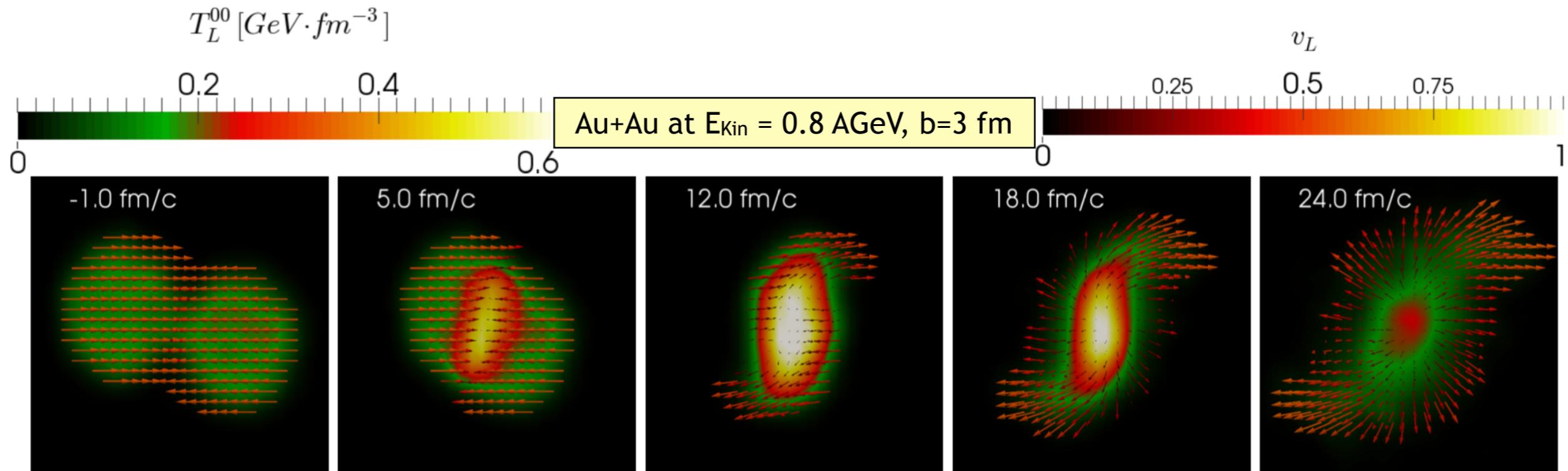
*only people whose results appear in this presentation

SMASH*

- Hadronic transport approach:

J. Weil et al, PRC 94 (2016)

- 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, Redmine, Doxygen, (ROOT)



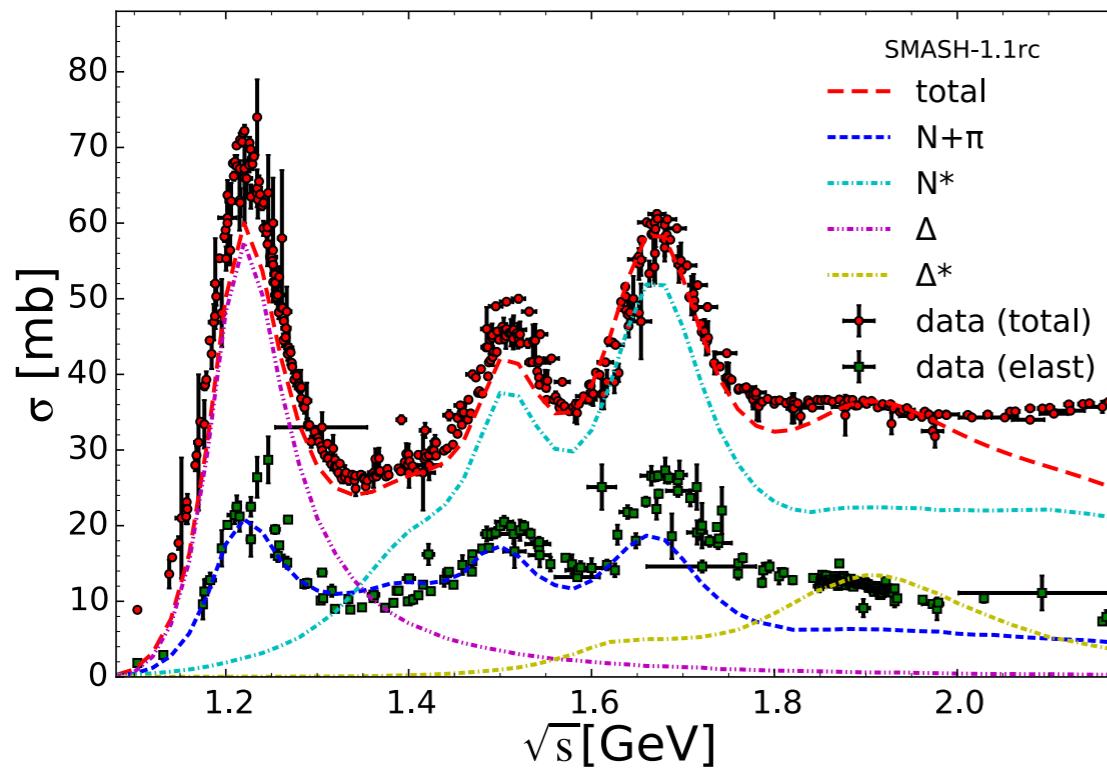
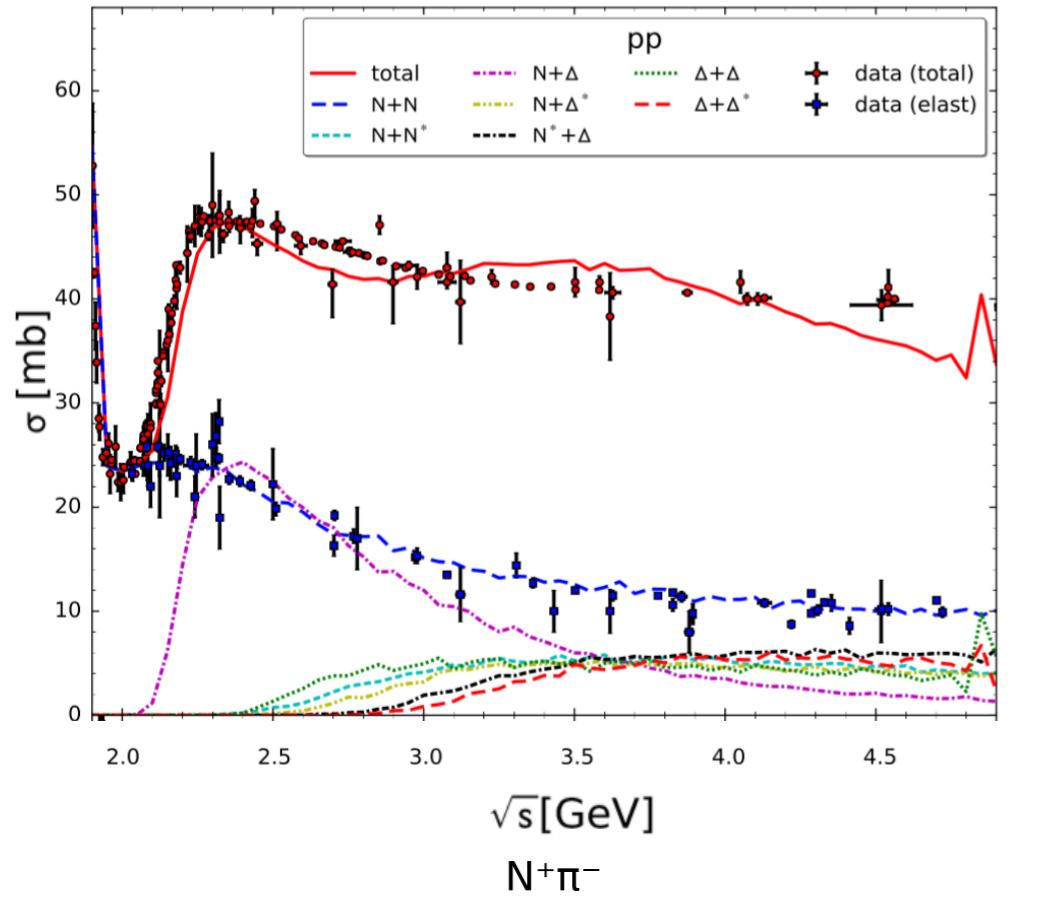
* Simulating Many Accelerated Strongly-Interacting Hadrons

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_{1270}
N_{1535}	Δ_{1905}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_0 1710$	$f_2 2010$		K_{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_{21770}
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_3^* 1780$
N_{1875}		Λ_{1890}				σ_{800}		$a_2 1320$		K_{21820}
N_{1900}		Λ_{2100}					h_{1170}			$K_4^* 2045$
N_{1990}		Λ_{2110}				ρ_{776}		π_{11400}		
N_{2080}		Λ_{2350}				ρ_{1450}	b_{11235}	π_{11600}		
N_{2190}	<ul style="list-style-type: none"> • Isospin symmetry • Perturbative treatment of non-hadronic particles (photons, dileptons) 					ρ_{1700}				
N_{2220}							a_{11260}	η_{21645}		
N_{2250}						ω_{783}			ω_{31670}	
						ω_{1420}				
						ω_{1650}				

- Easily configurable by human-readable input files

Elementary Cross Sections



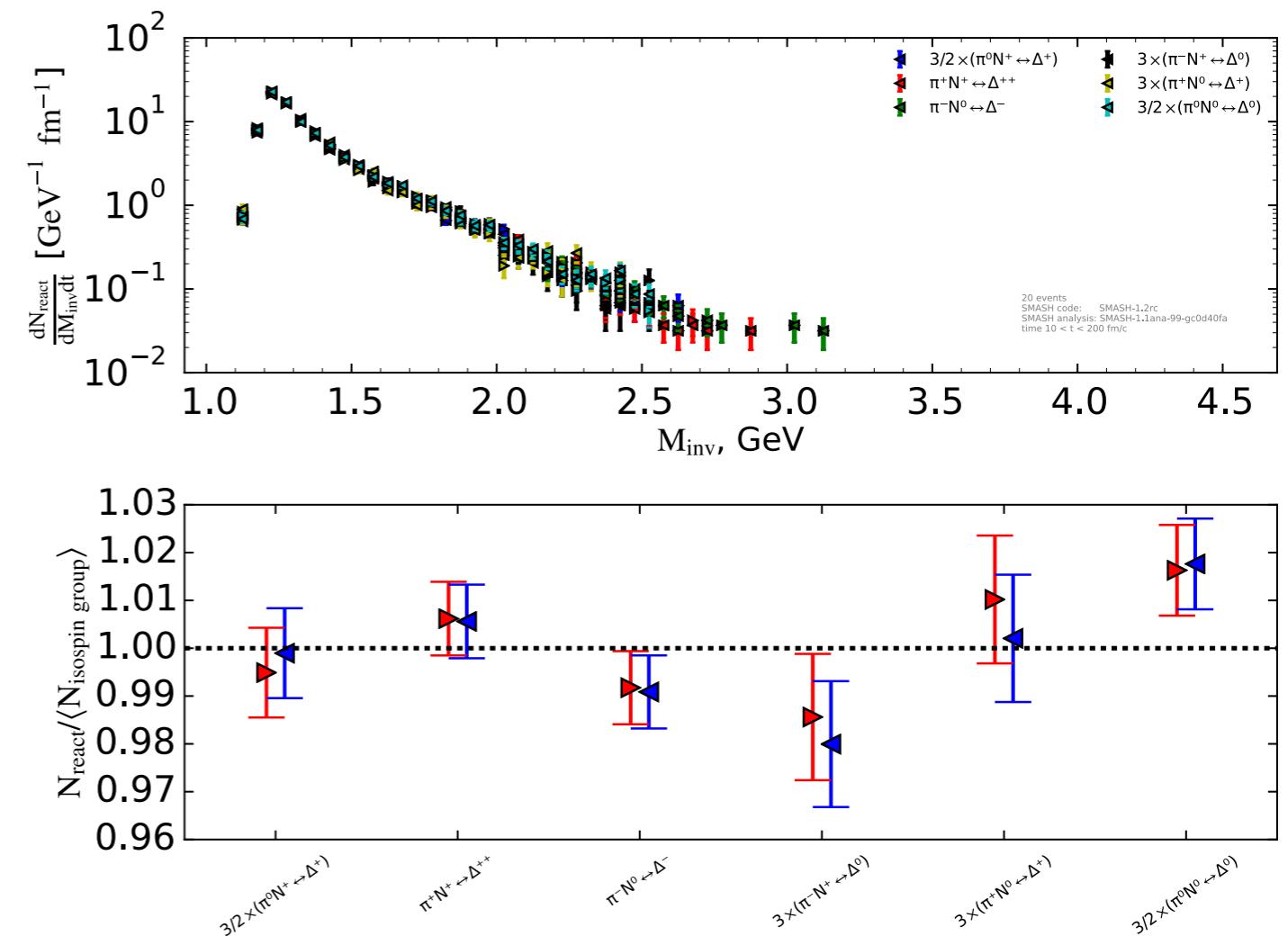
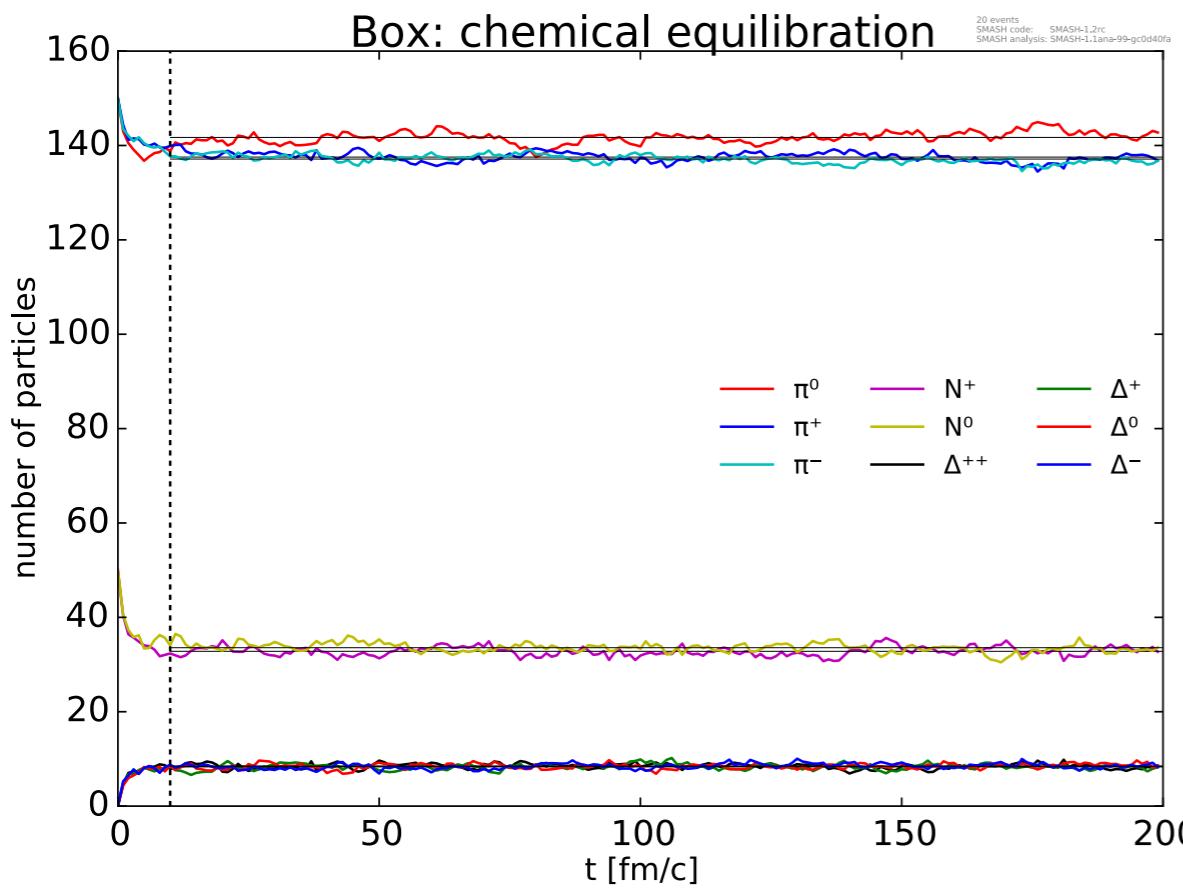
J. Weil et al, PRC 94 (2016)

- Total cross section for $pp/p\pi$ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of data up to 4.5/2 GeV
- String excitation by PYTHIA: work in progress

Detailed Balance

- Inverse absorption cross section calculated from production cross section
- Conservation of detailed balance (only $1 \leftrightarrow 2$ or $2 \leftrightarrow 2$ processes)

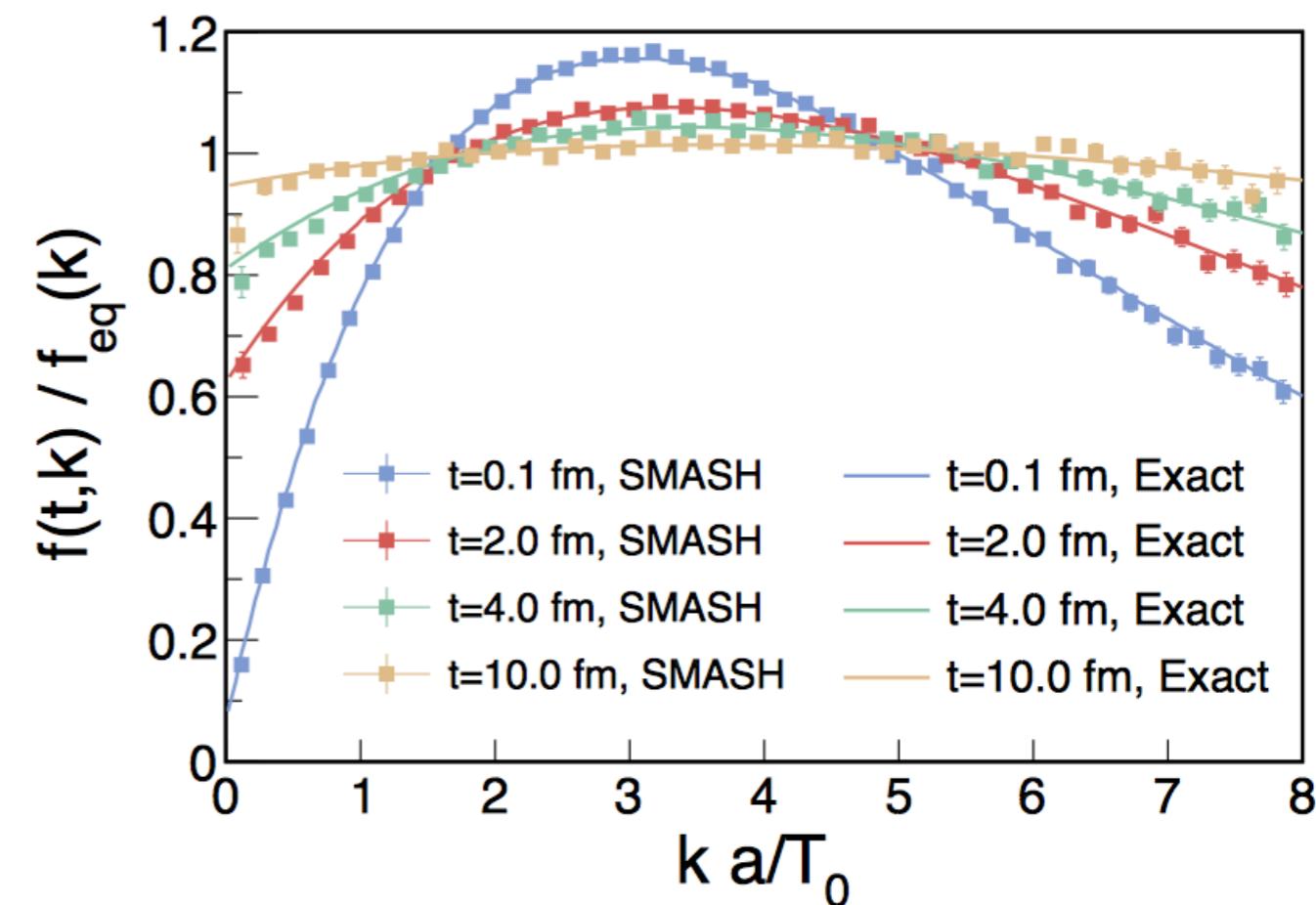
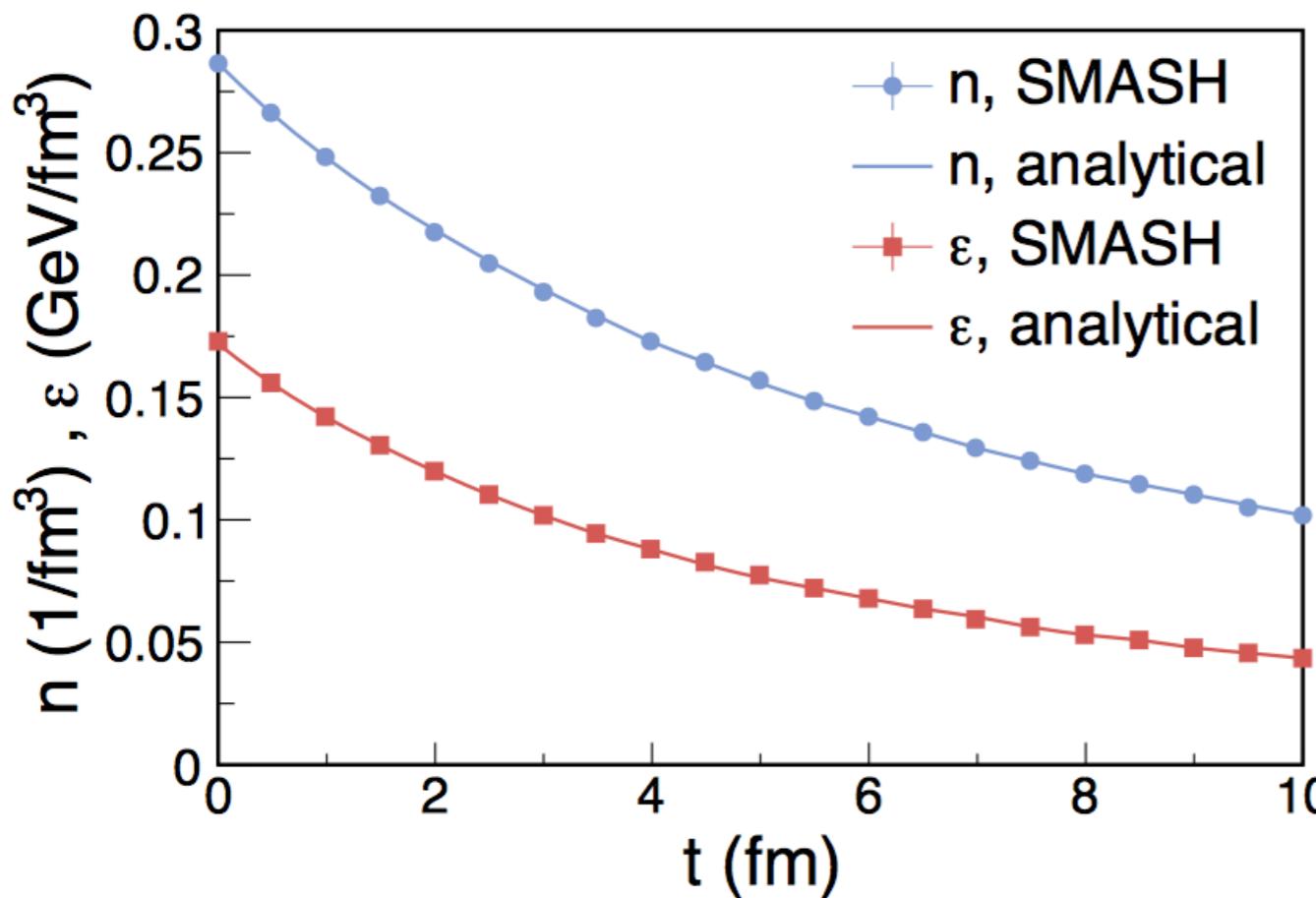
J. Weil et al, PRC 94 (2016)



- Infinite matter calculations \rightarrow Important cross-check

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric



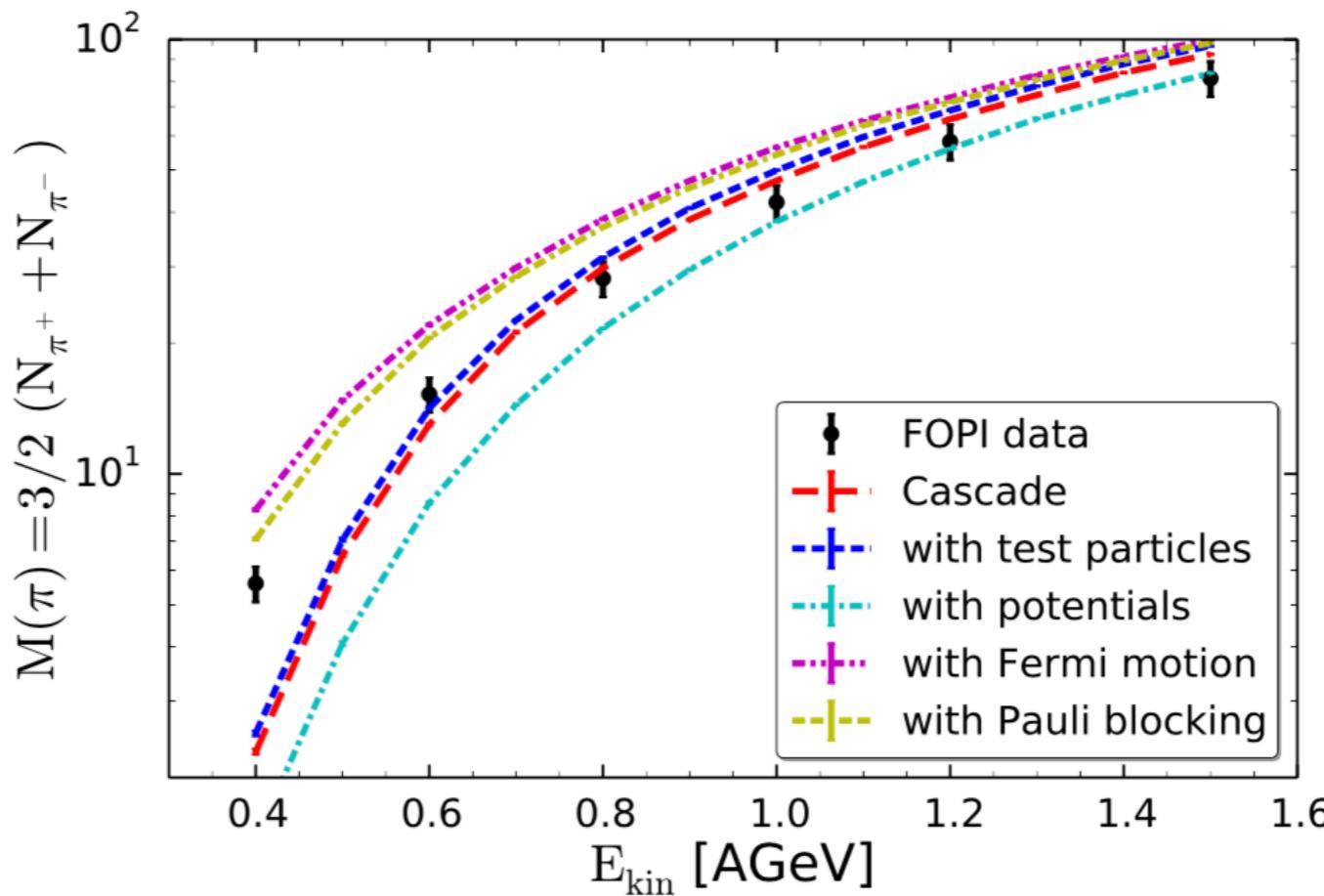
- Perfect agreement proves correct numerical implementation of collision algorithm

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

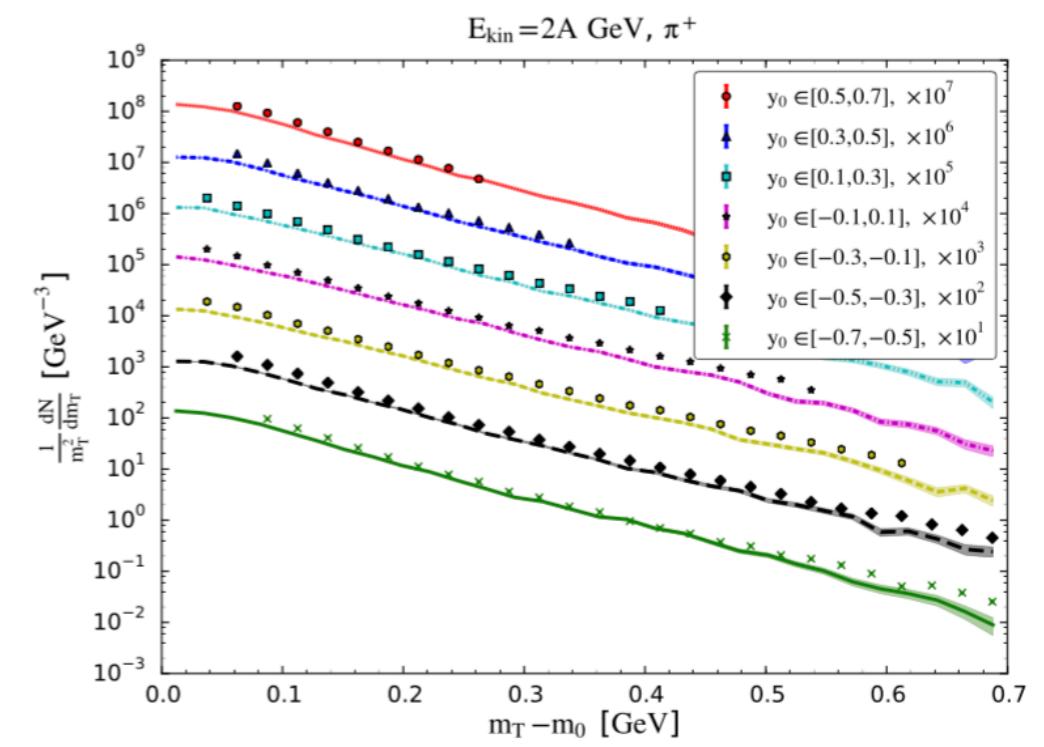
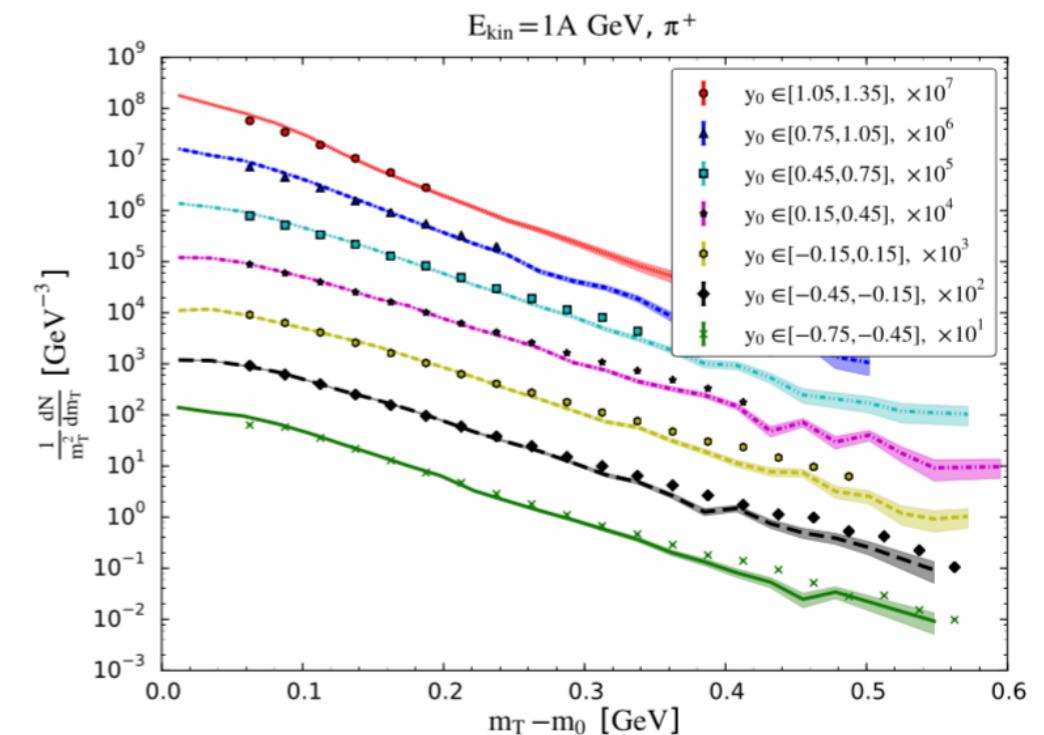
J. Tindall et al., PLB 770 (2017)

Pion Production in Au+Au

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



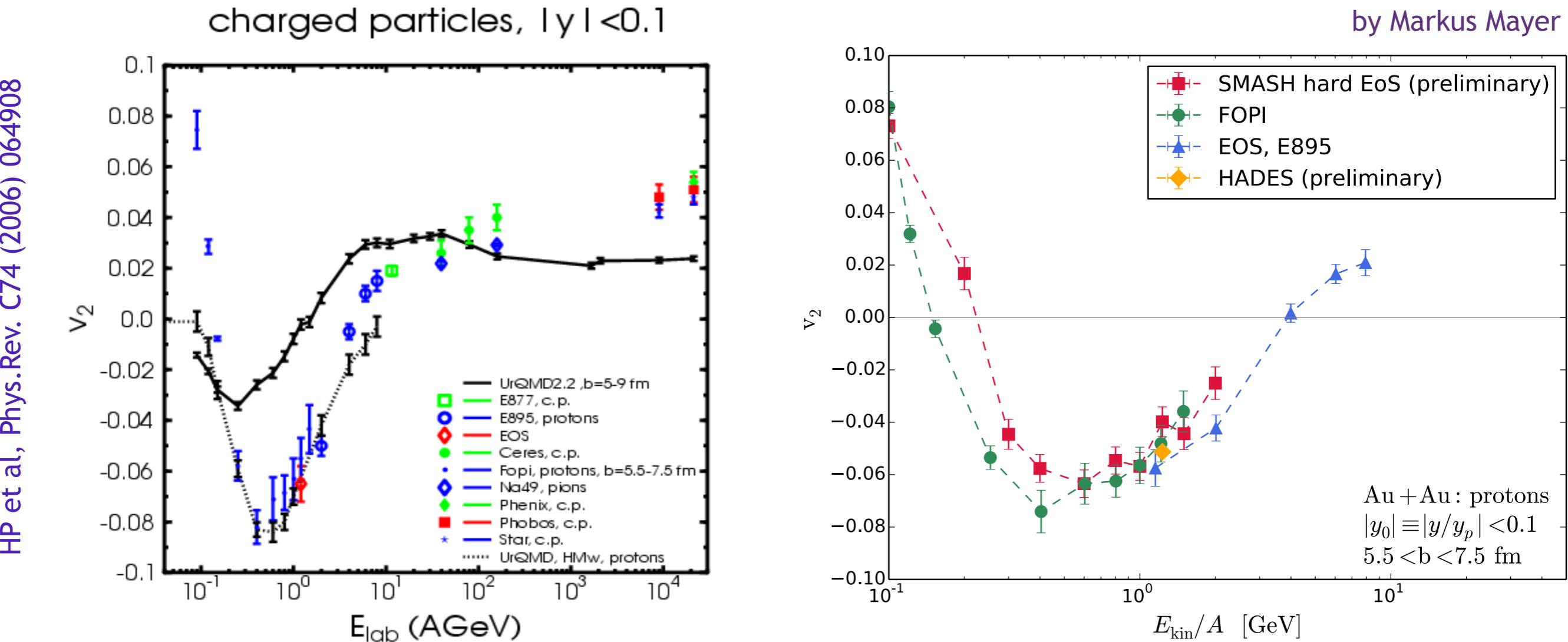
Note: consecutive addition of features



J. Weil et al, PRC 94 (2016)

Collective Flow - v_2

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



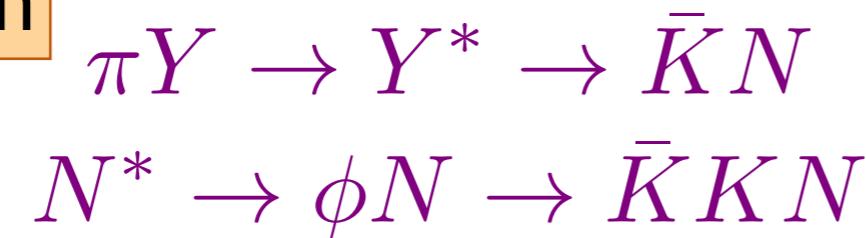
- SMASH agrees well with previous UrQMD calculation for v_2 excitation function

Strangeness Production

K⁺ production

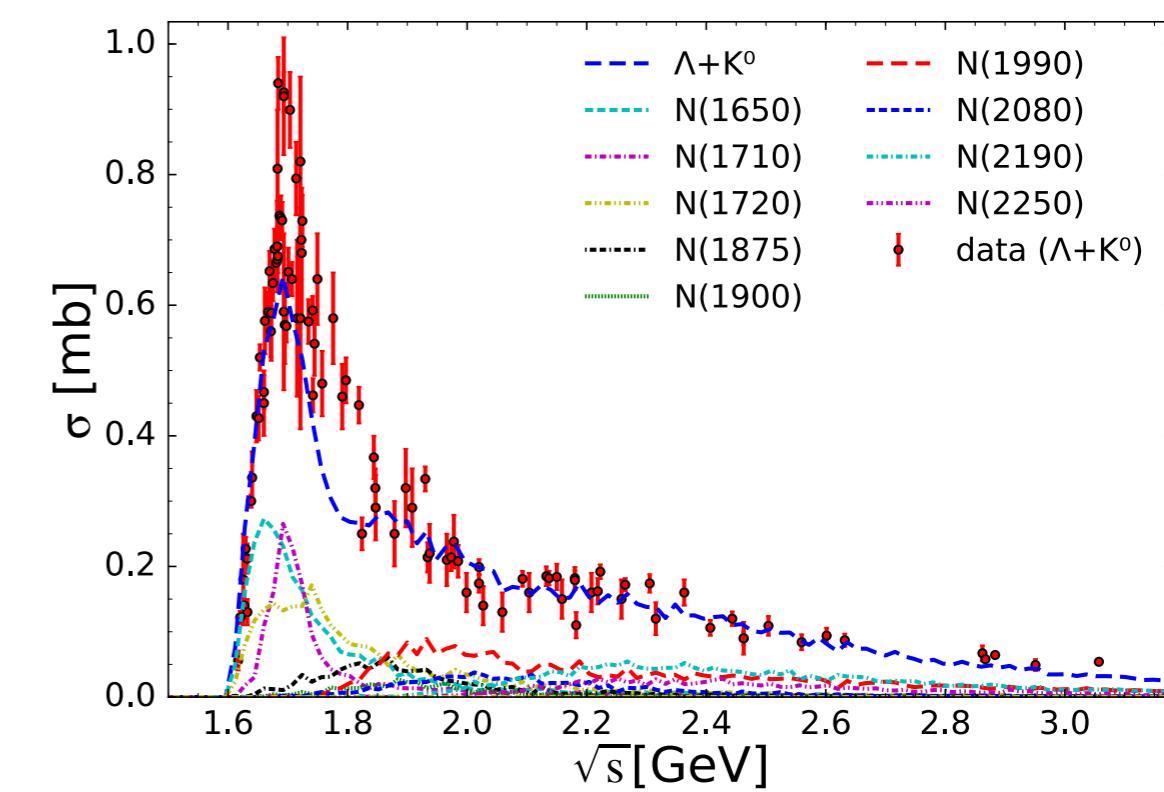
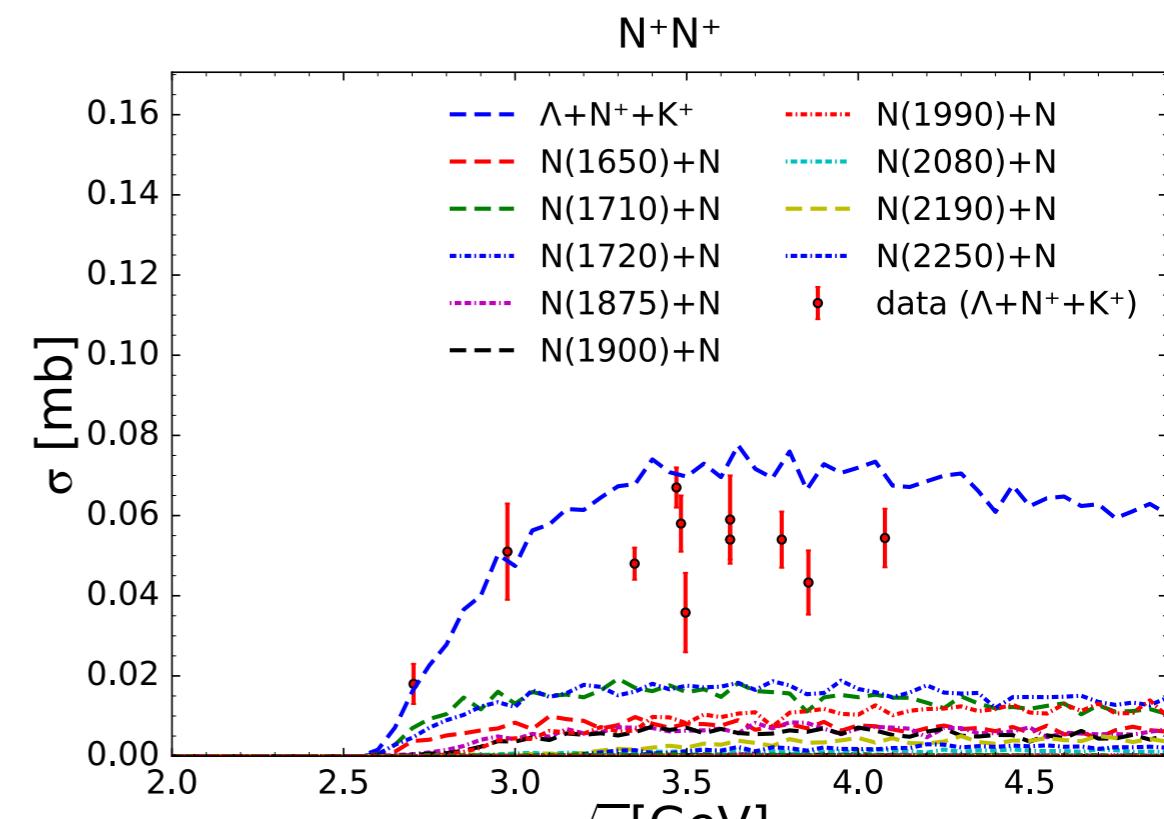


K⁻ production



- Elementary exclusive cross-sections provide constraints on resonance properties

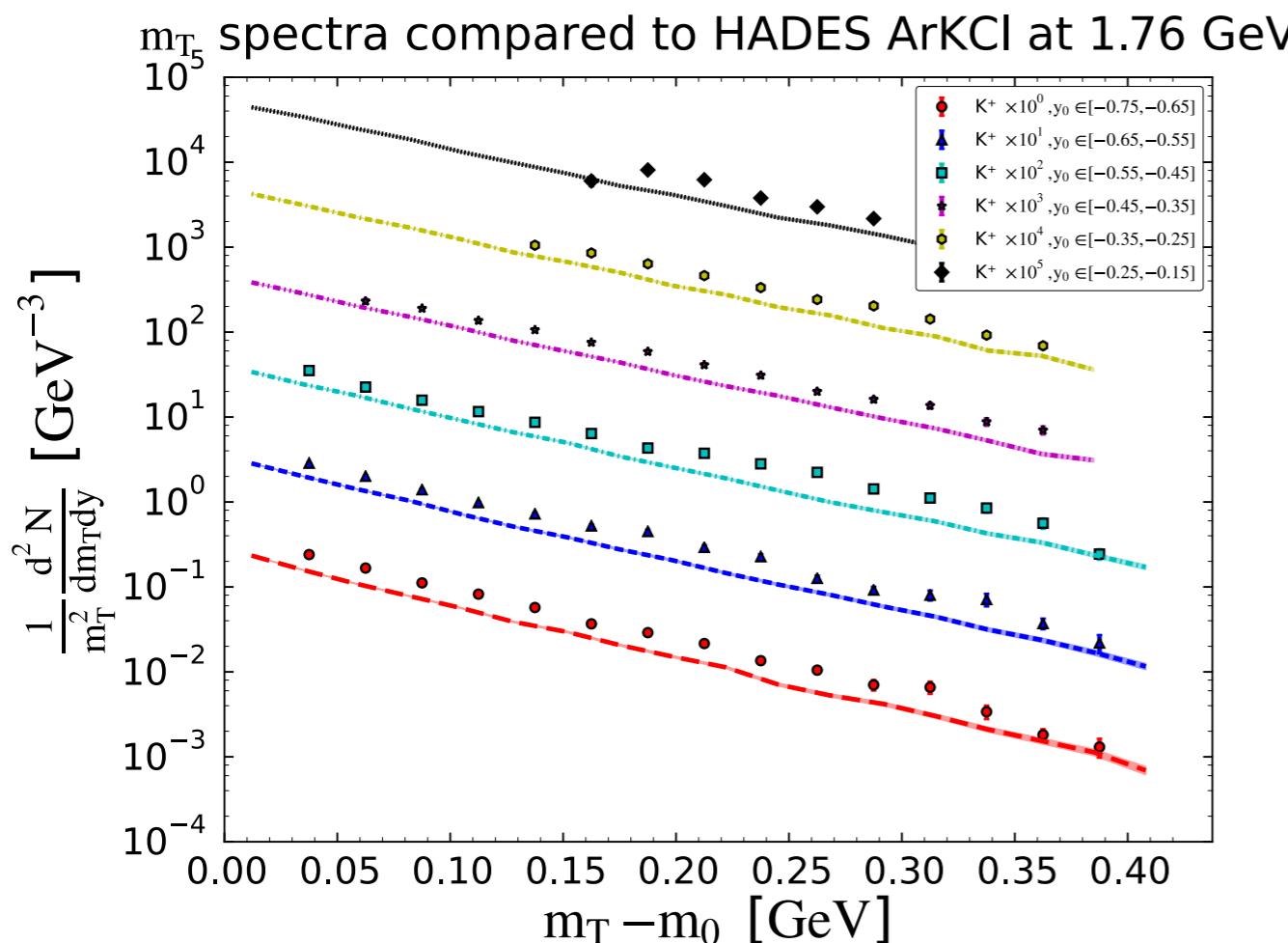
resonance	branching ratio $N^* \rightarrow \Lambda K$		
	PDG	HADES	SMASH
$N(1650)$	5 – 15%	$7 \pm 4\%$	4%
$N(1710)$	5 – 25%	$15 \pm 10\%$	13%
$N(1720)$	4 – 5%	$8 \pm 7\%$	5%
$N(1875)$	> 0	$4 \pm 2\%$	2%
$N(1880)$		$2 \pm 1\%$	
$N(1895)$		$18 \pm 5\%$	
$N(1900)$	2 – 20%	$5 \pm 5\%$	2%
$N(1990)$			2%
$N(2080)$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



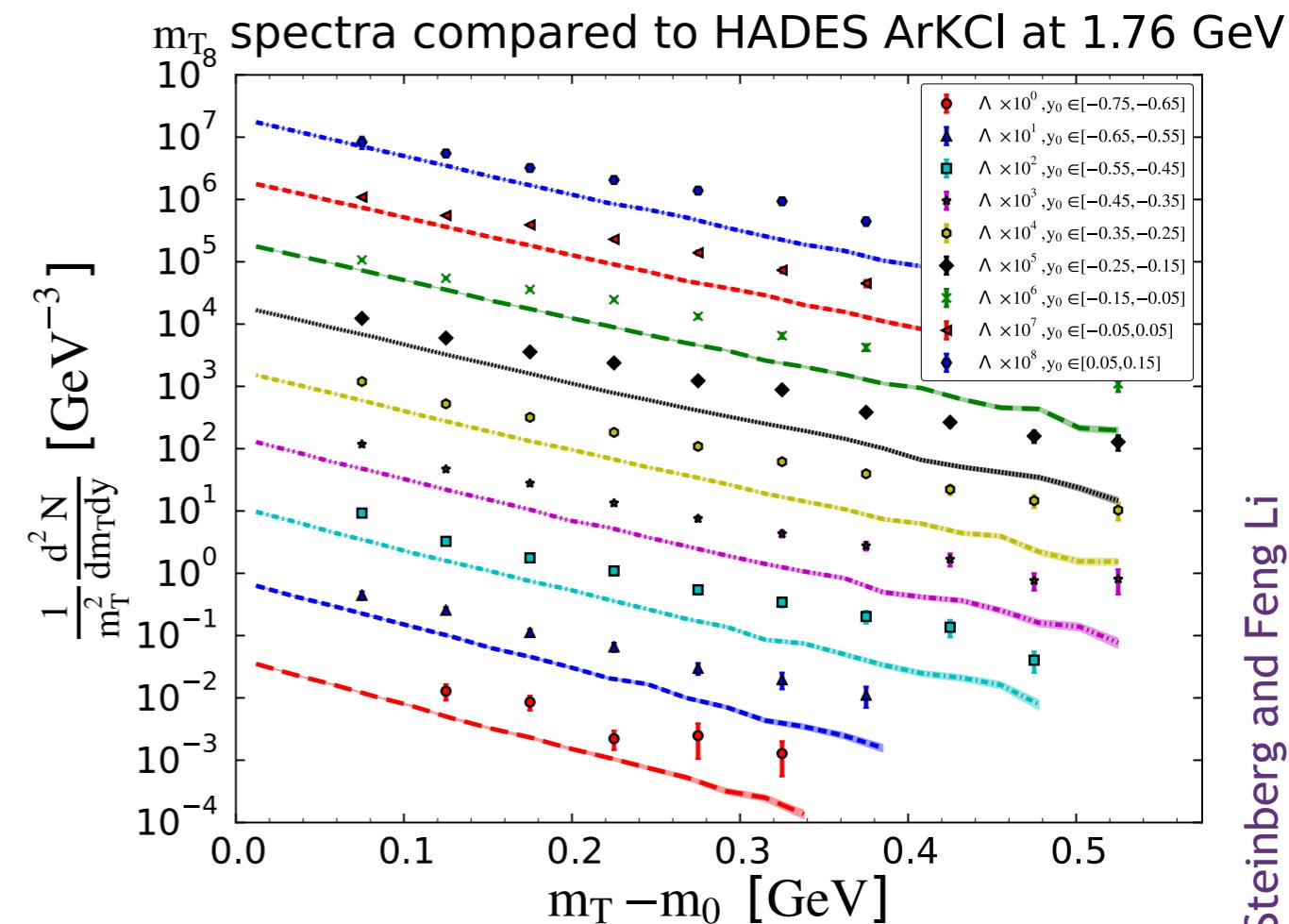
Strangeness Production

- Kaons and Lambdas in heavy ions:

Kaons



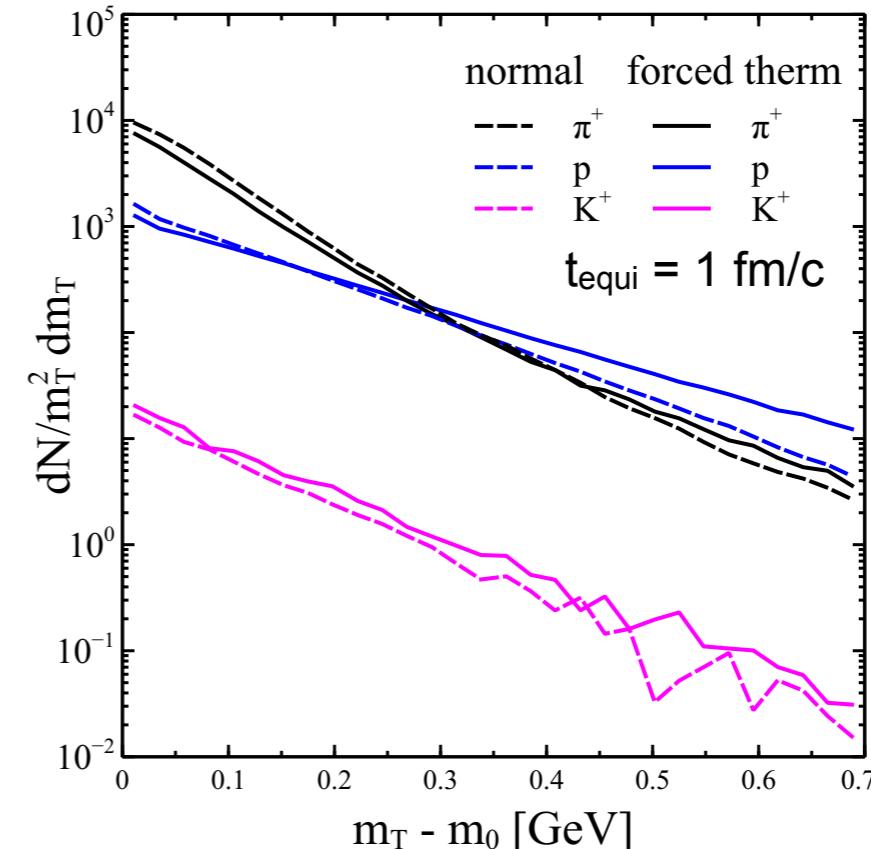
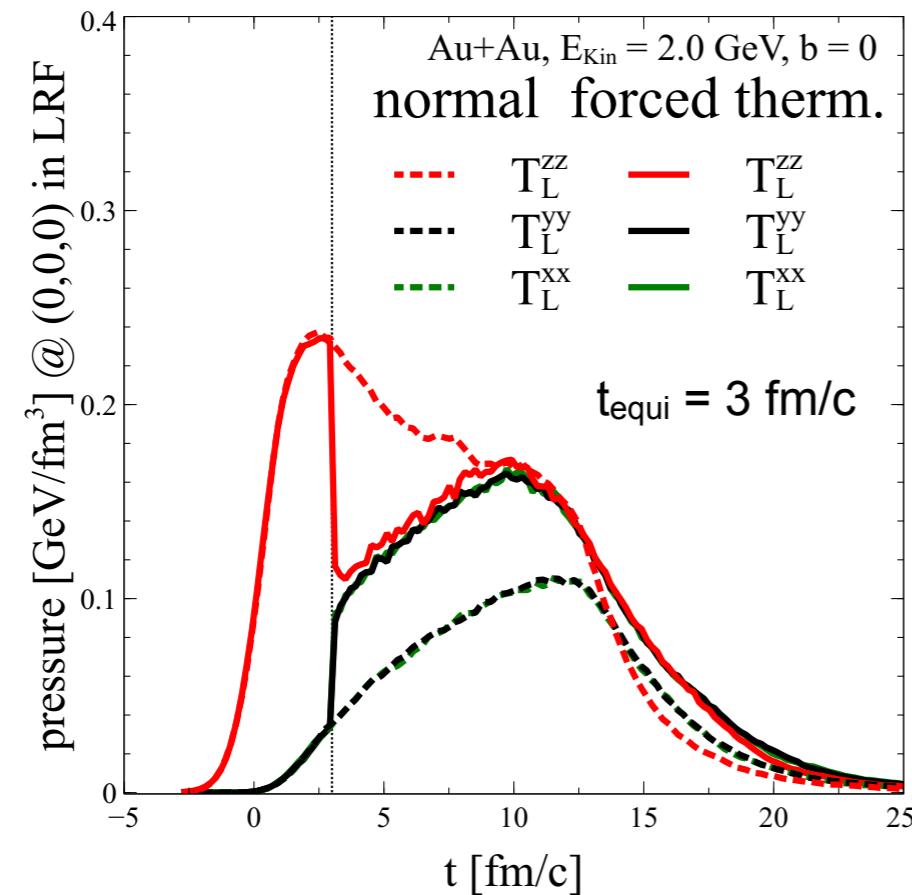
Λ 's



- Ongoing work: Centrality dependence, 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

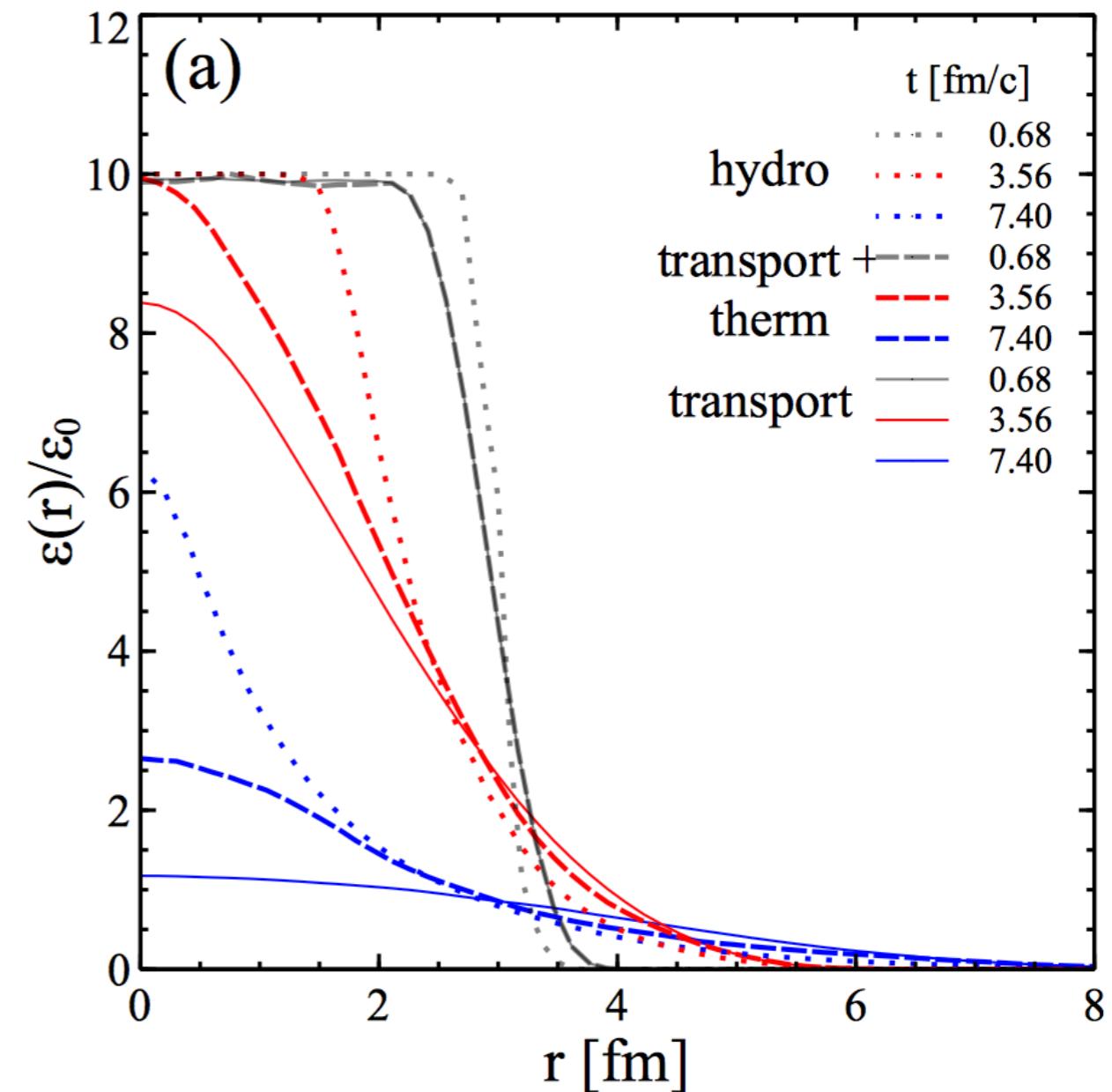
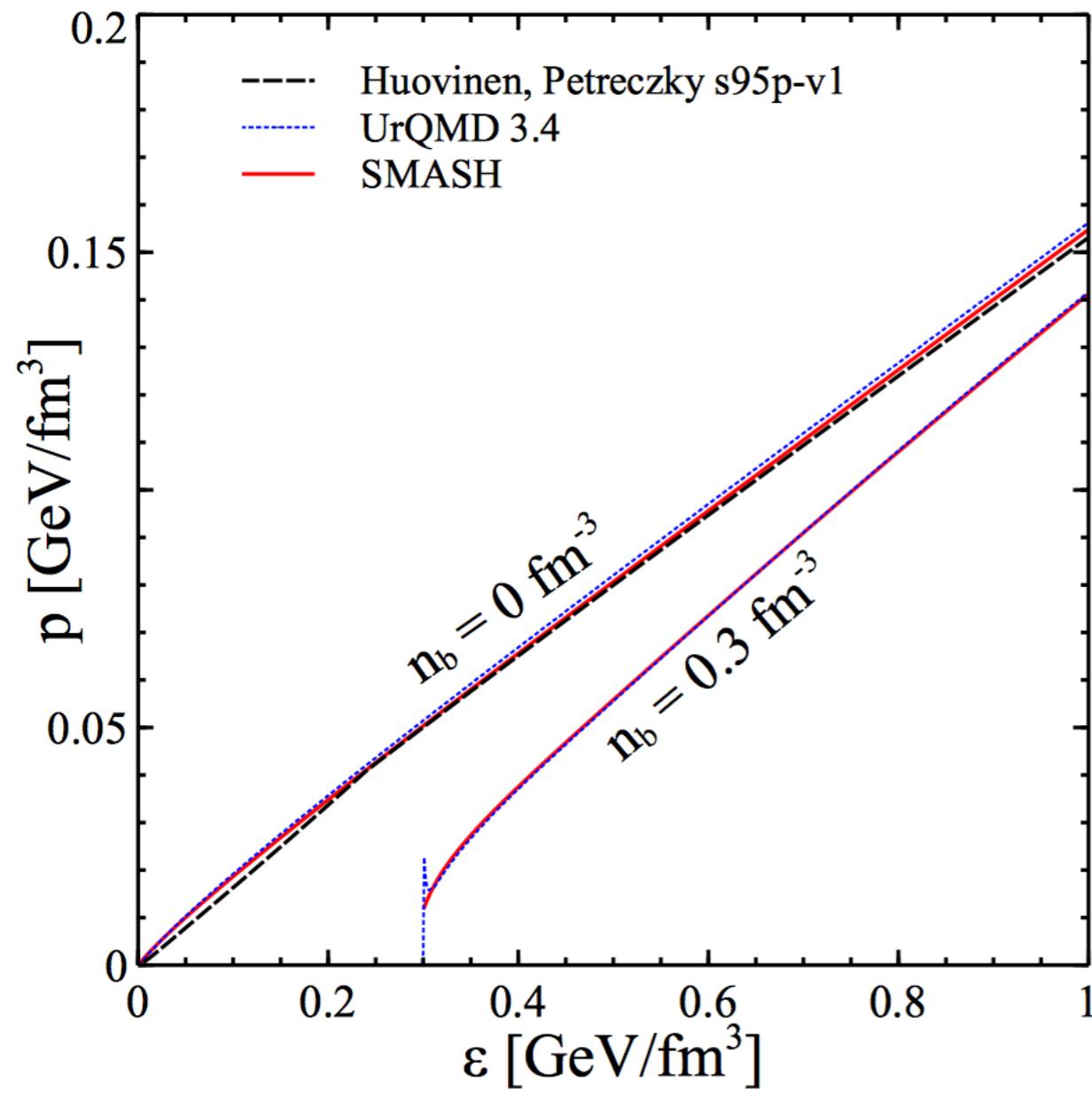


- Spectra are more „thermal“ and strangeness enhanced

Dmytro Oliinychenko, HP, JPG 44, 2017

EoS and Hydro Comparison

- Equation of state fits lattice hadron gas

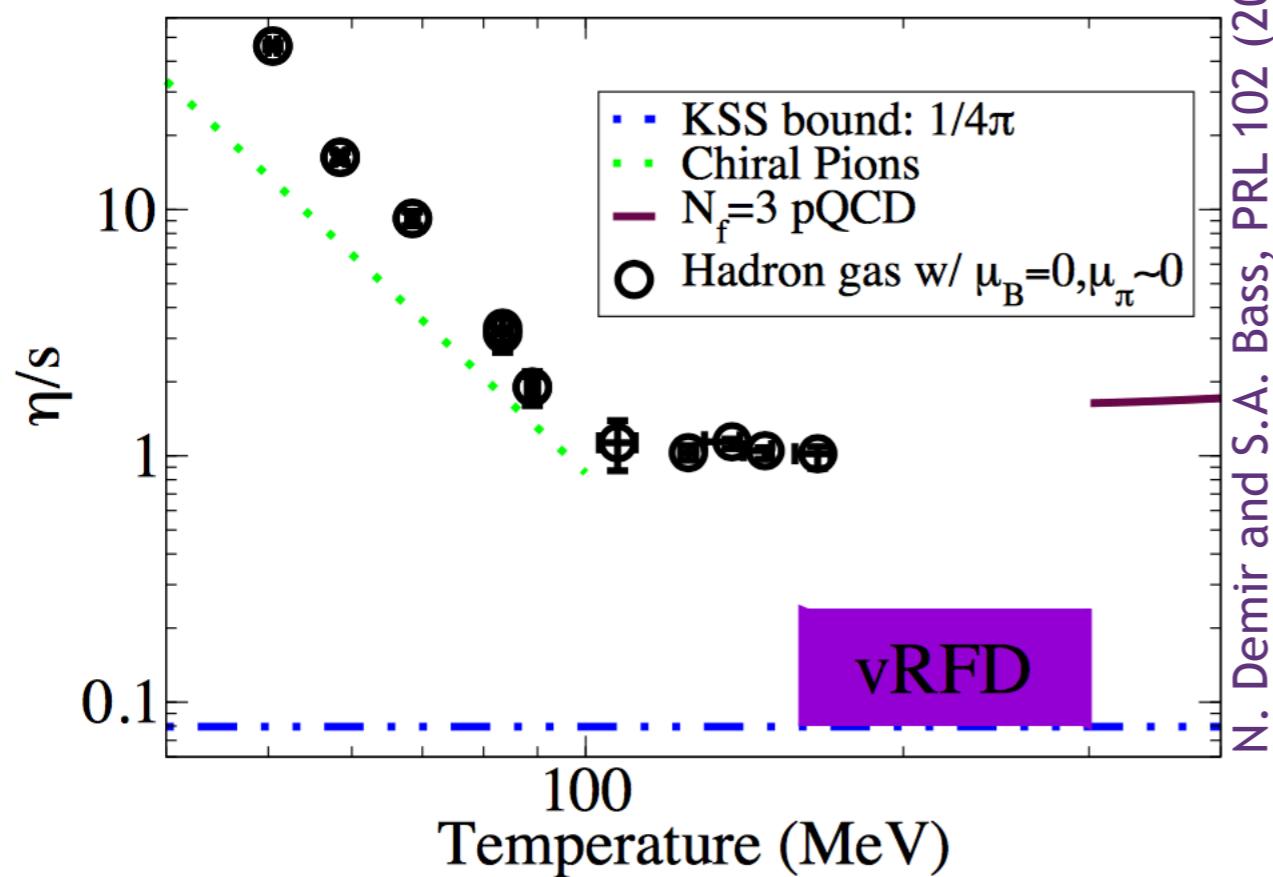


- Interpolation between transport and hydrodynamics

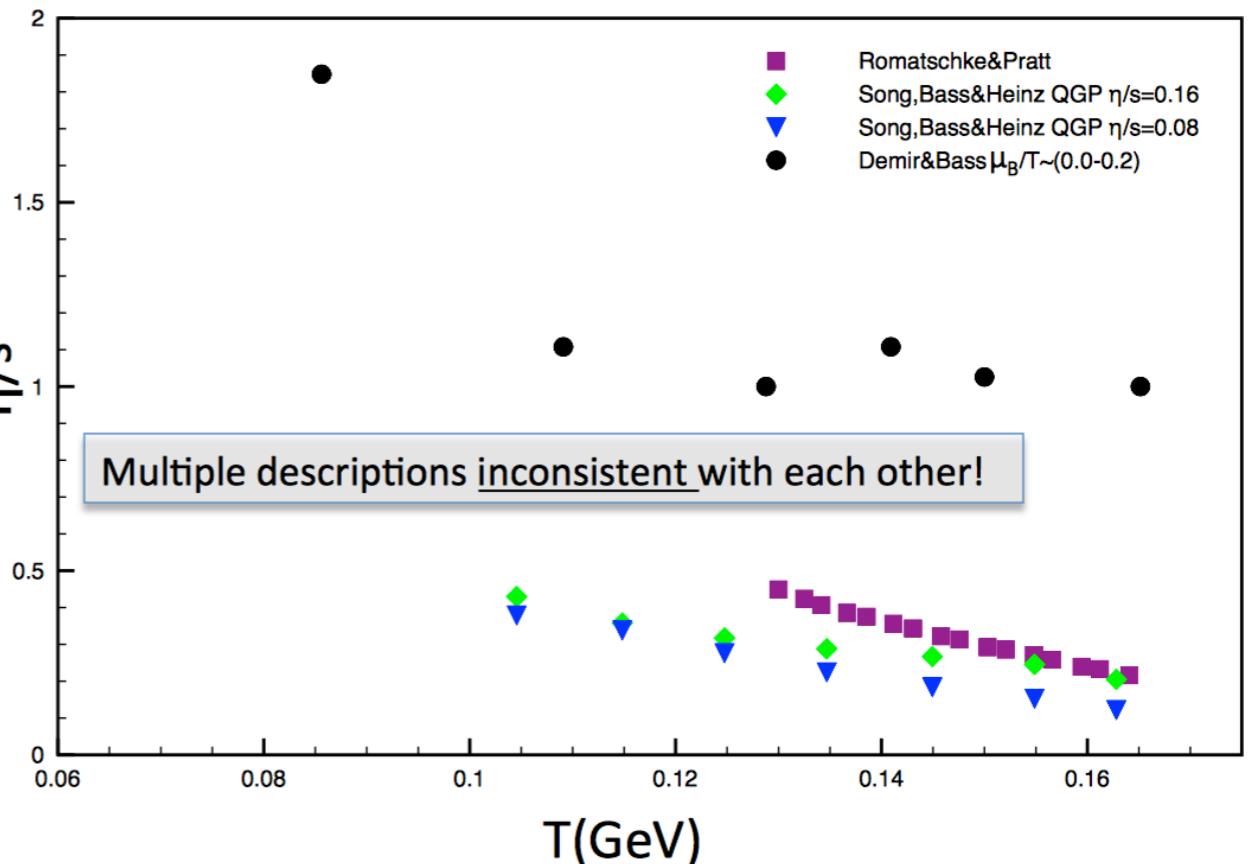
Dmytro Oliinychenko, HP, JPG 44, 2017

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?

See talk by Jean-Bernard Rose today at 3.20 PM (Thermodynamics and Hadron Chemistry I)

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

Dileptons in SMASH

- Dileptons produced by resonance decays

J. Staudenmaier et al., arXiv: 1711.10297

- 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

$$\rho \rightarrow e^+ e^-$$

$$\omega \rightarrow e^+ e^-$$

$$\phi \rightarrow e^+ e^-$$

$$\pi \rightarrow e^+ e^- \gamma$$

$$\eta \rightarrow e^+ e^- \gamma$$

$$\eta' \rightarrow e^+ e^- \gamma$$

$$\omega \rightarrow e^+ e^- \pi^0$$

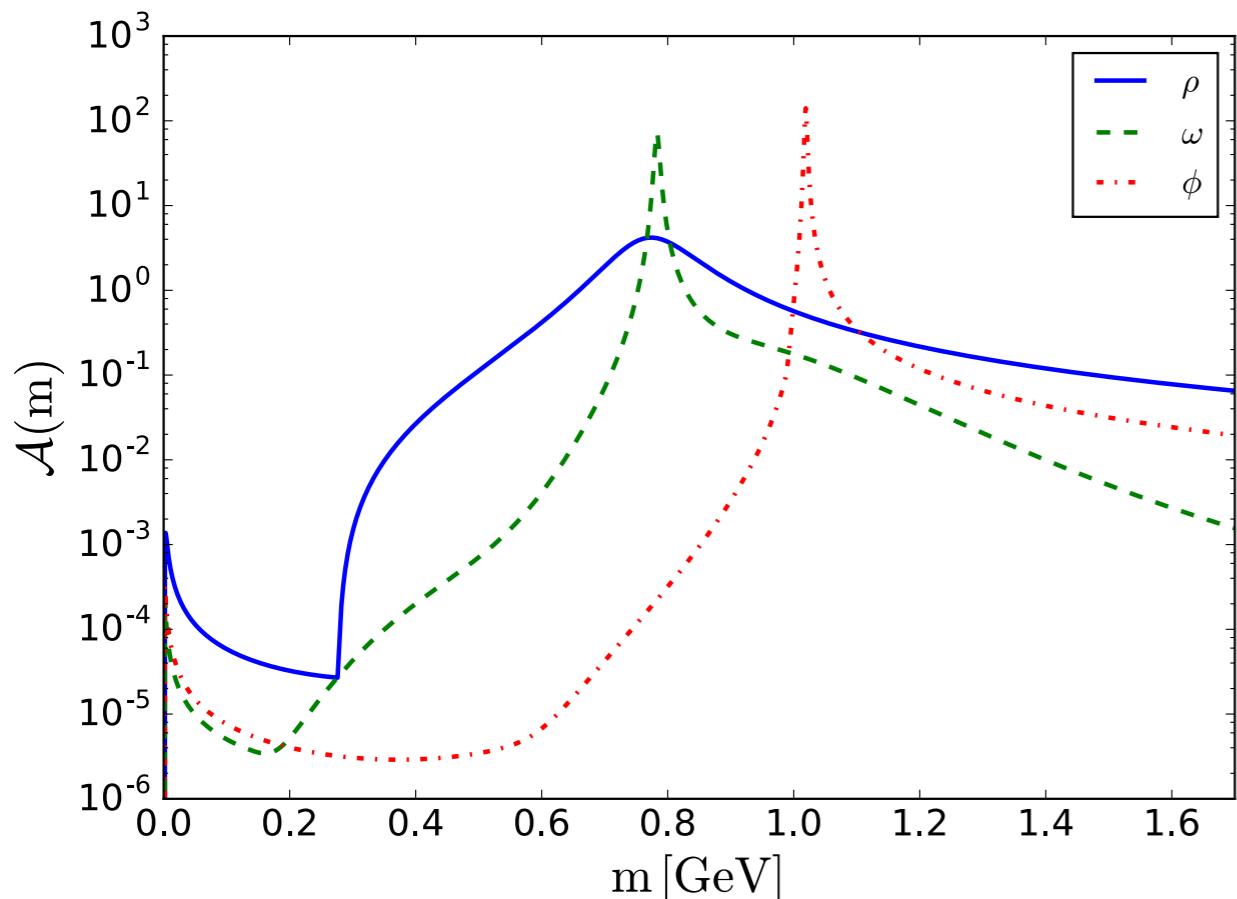
$$\phi \rightarrow e^+ e^- \pi^0$$

$$\Delta^+ \rightarrow e^+ e^- p$$

$$\Delta^0 \rightarrow e^+ e^- n^0$$

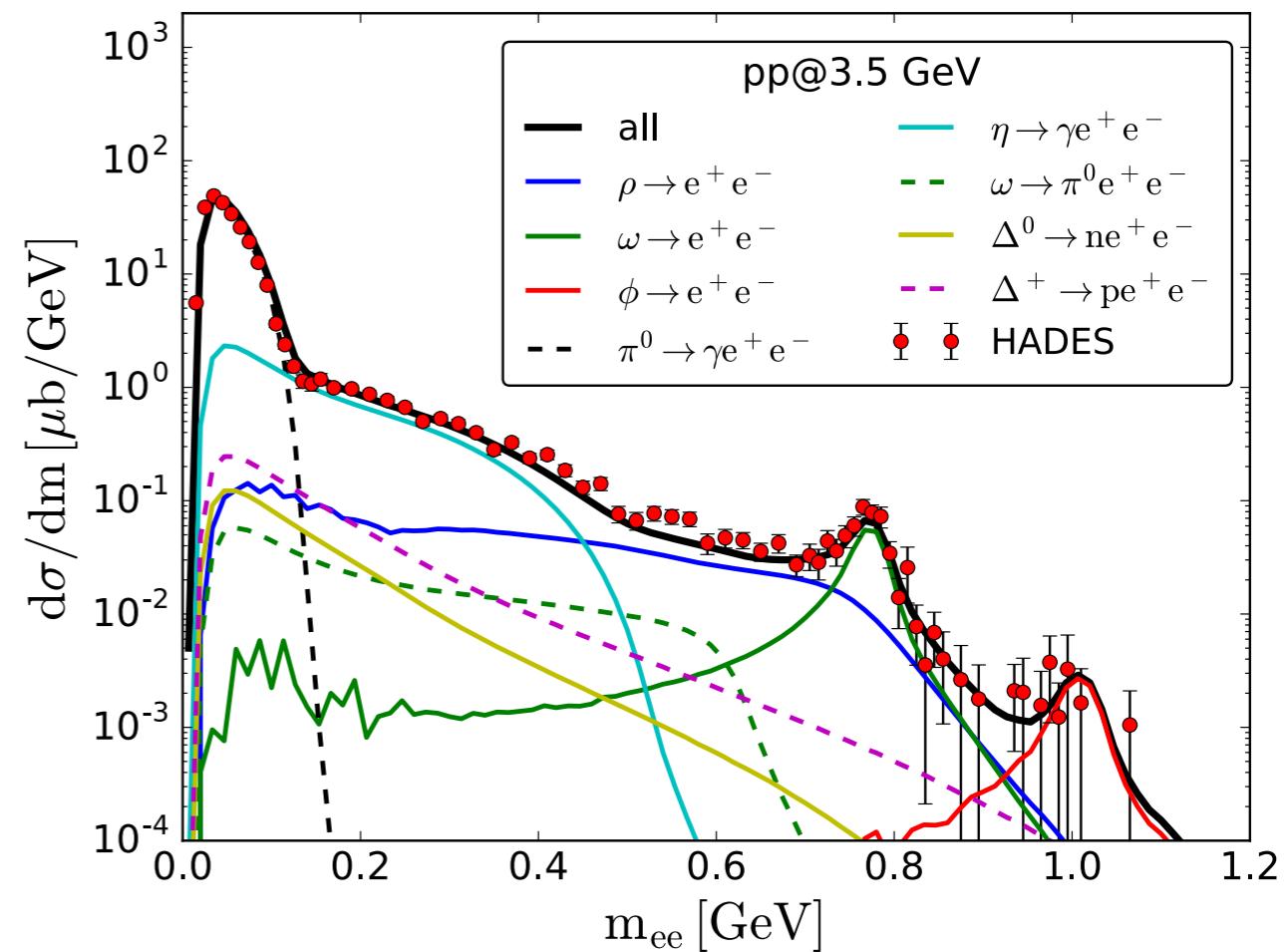
Elementary Collisions

- Contributions of vector meson spectral functions below hadronic thresholds



J. Staudenmaier et al., arXiv: 1711.10297

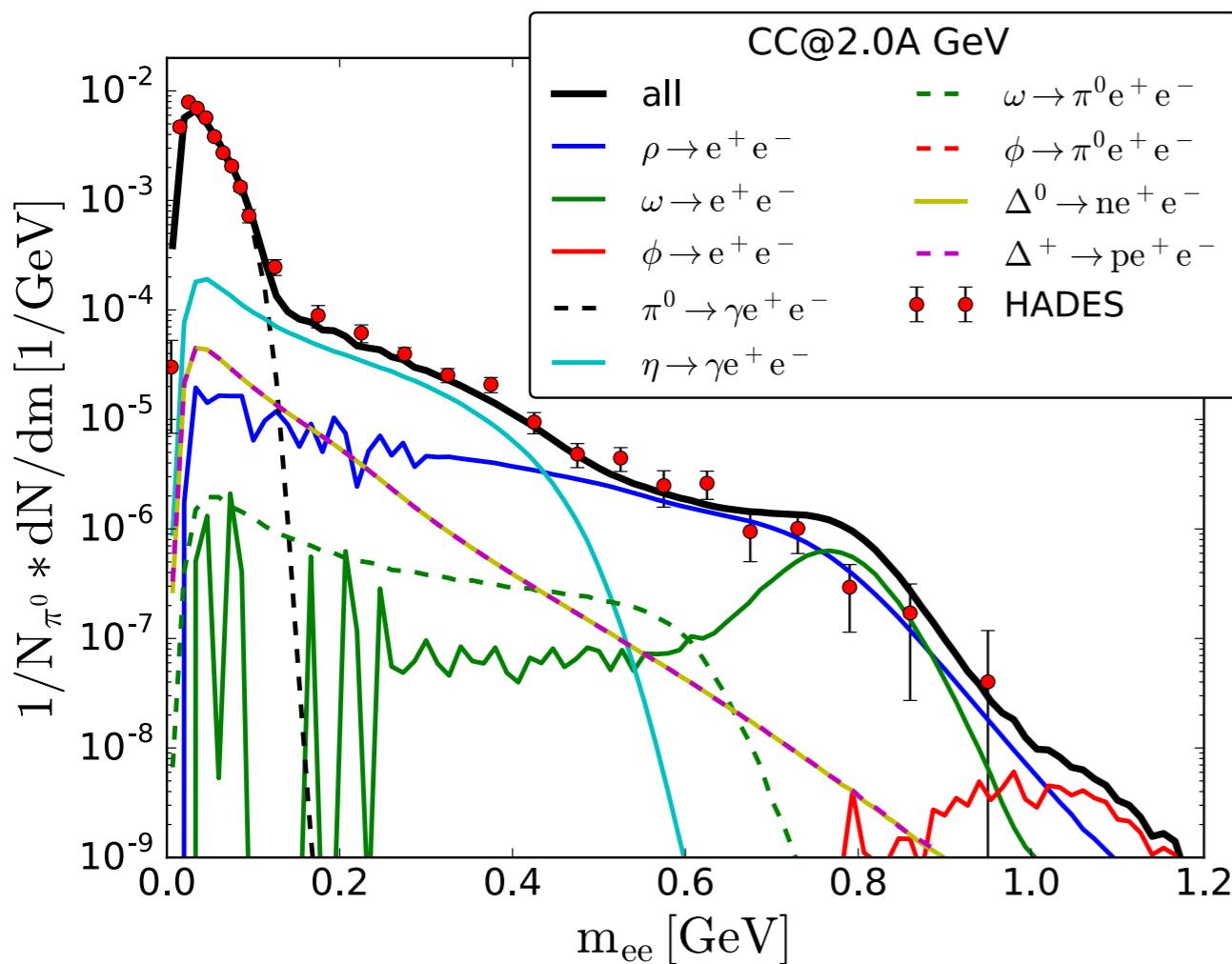
HADES, Eur.Phys.J. A48 (2012)



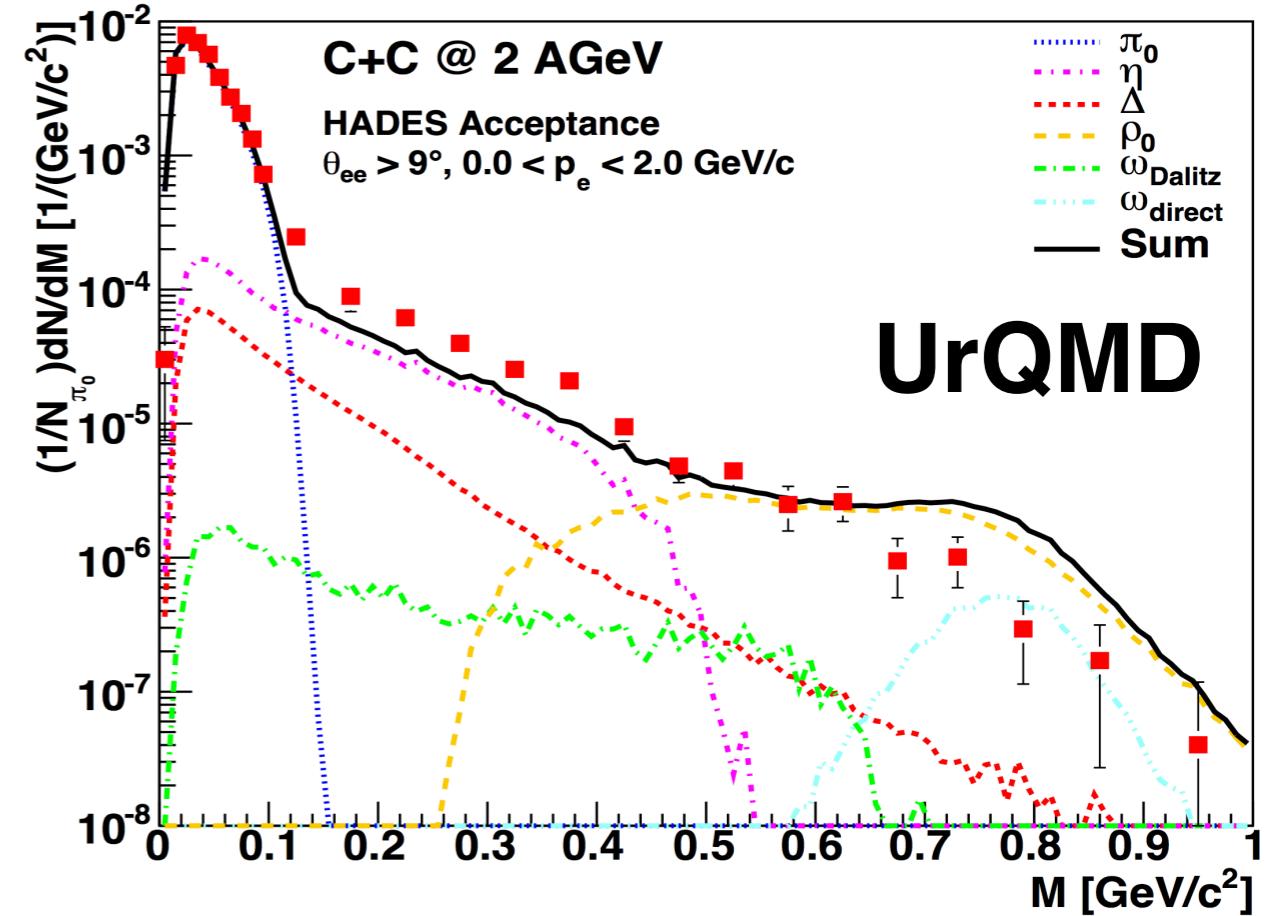
- Very nice agreement with HADES measurement

Dilepton Production

HADES, PRL 98 (2007)



J. Staudenmaier et al, arXiv: 1711.10297



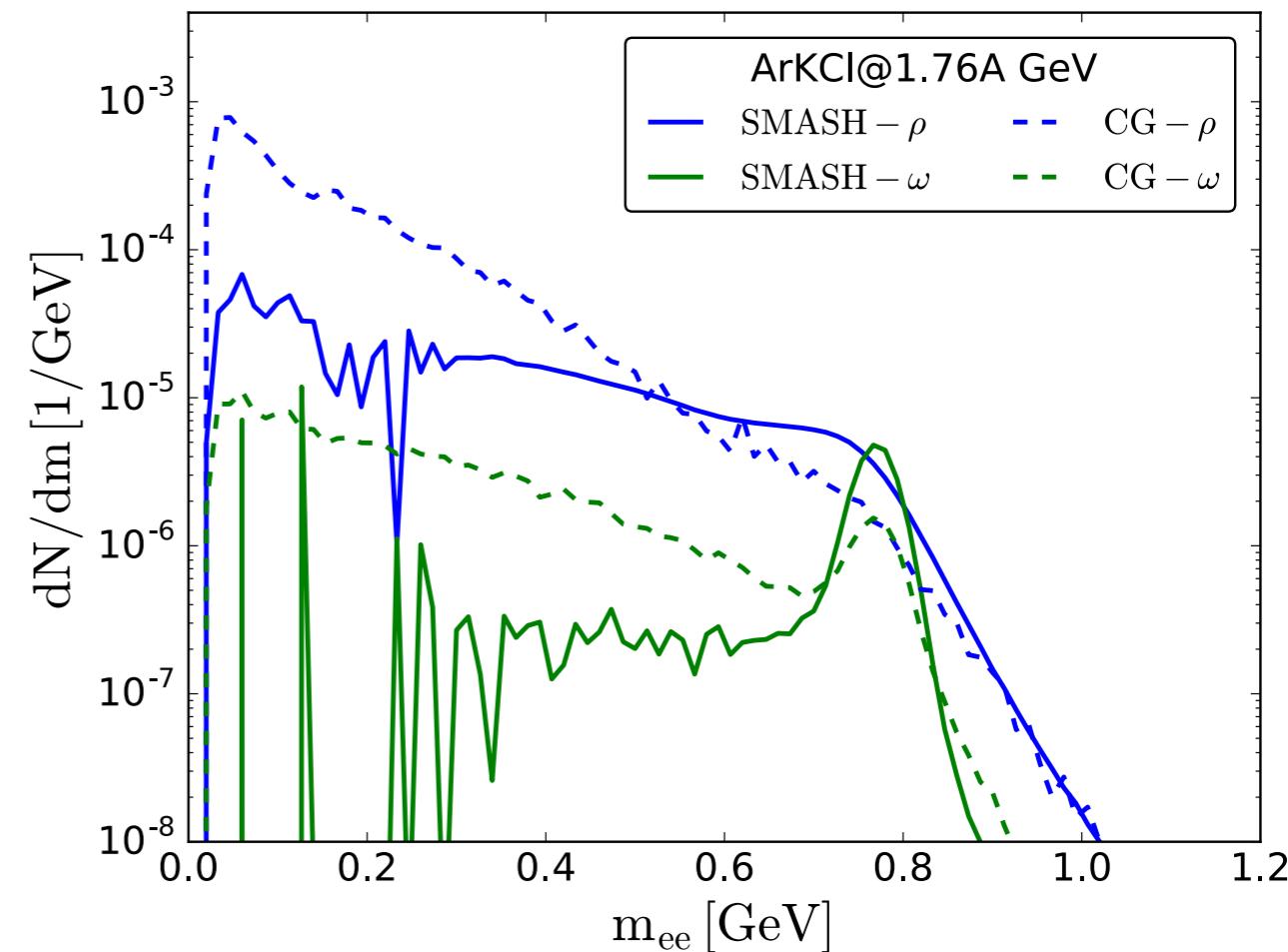
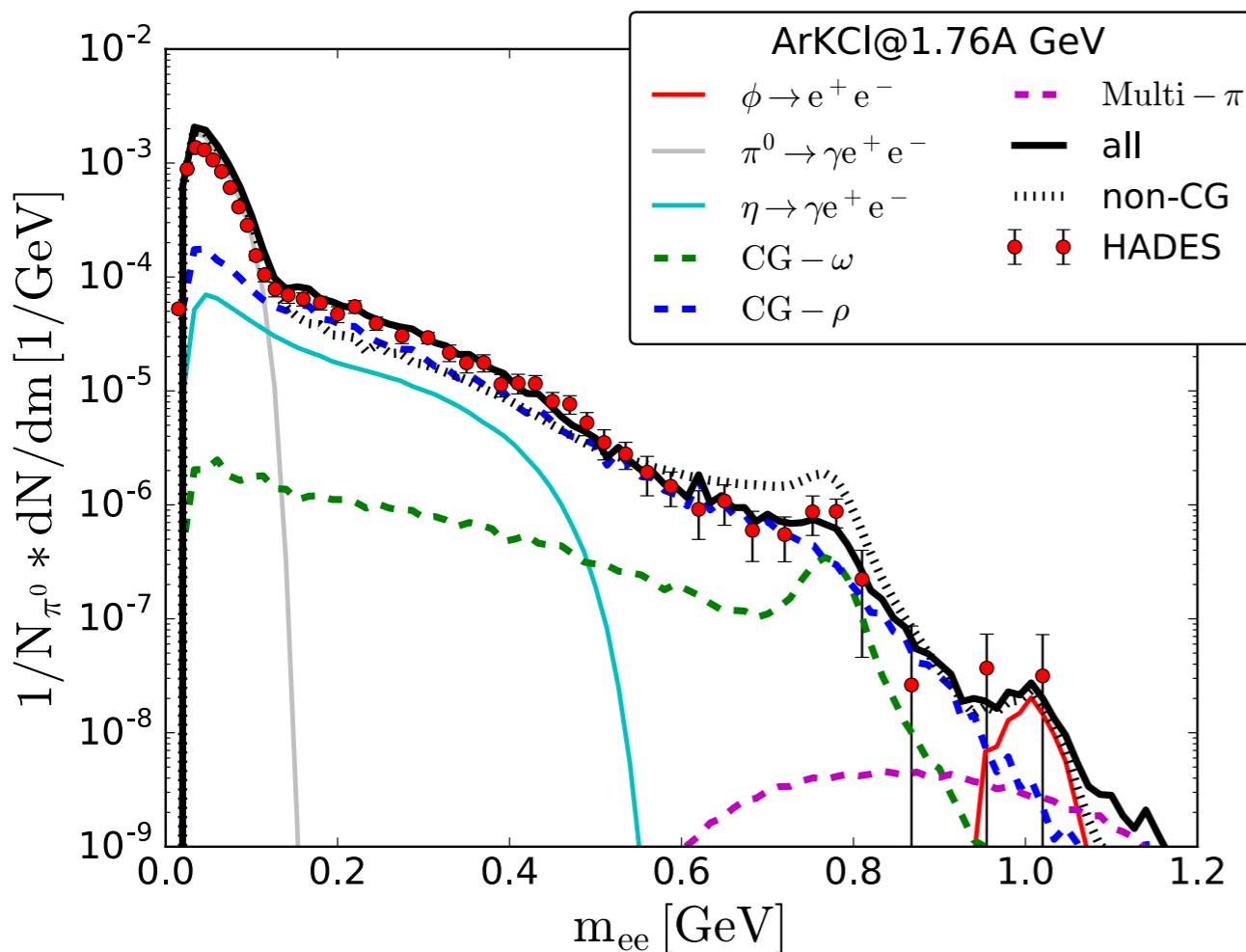
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

- SMASH and UrQMD compare very similar to data
- Different vector meson thresholds 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., arXiv: 1711.10297



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

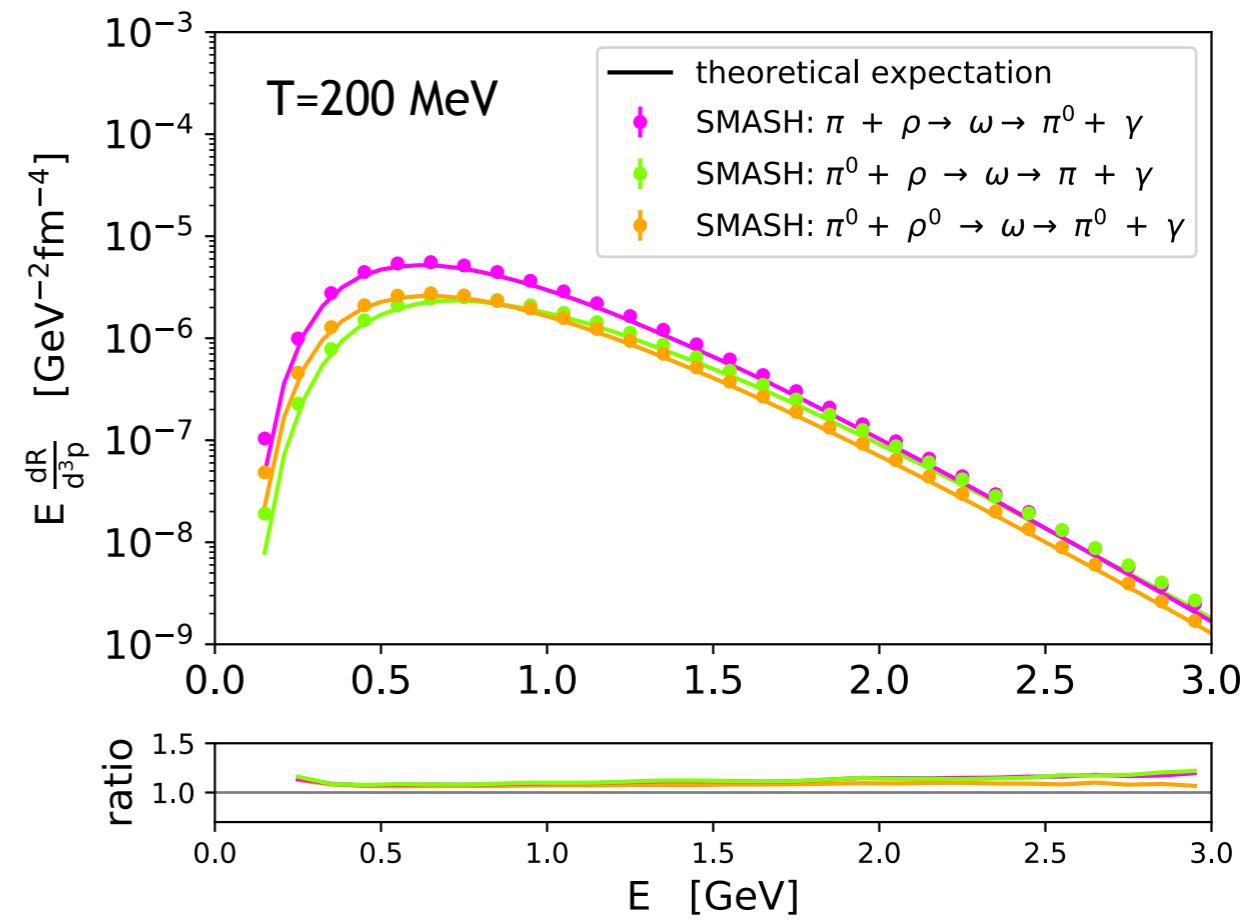
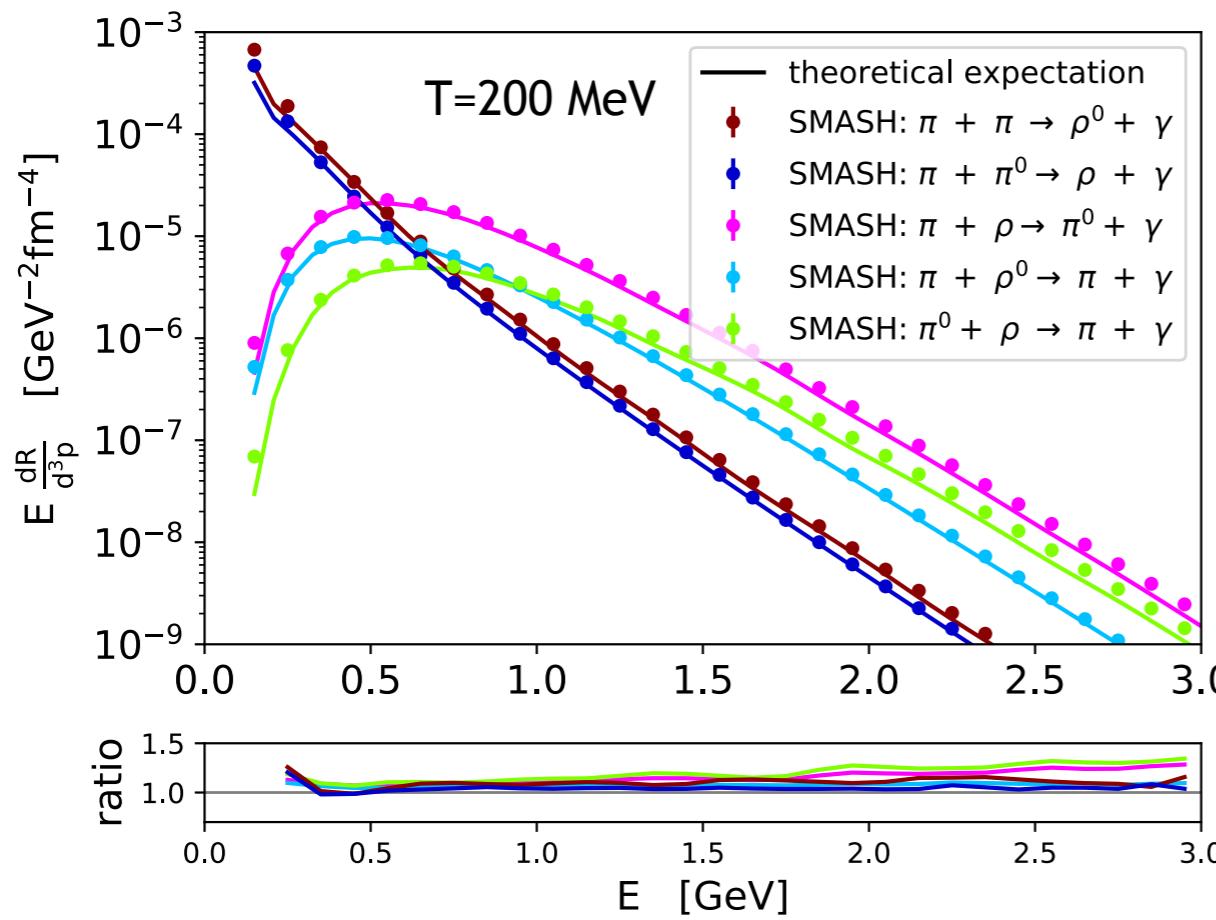
S. Endres et al., PRC 92, 2015
R. Rapp et al, EPJA 6, 1999, PRC 63, 2001

J. Staudenmaier et al, arXiv: 1711.10297

Photons

- Perturbative photon production in hadronic scatterings of pions and ρ mesons
- Cross-sections calculated within effective field theory

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



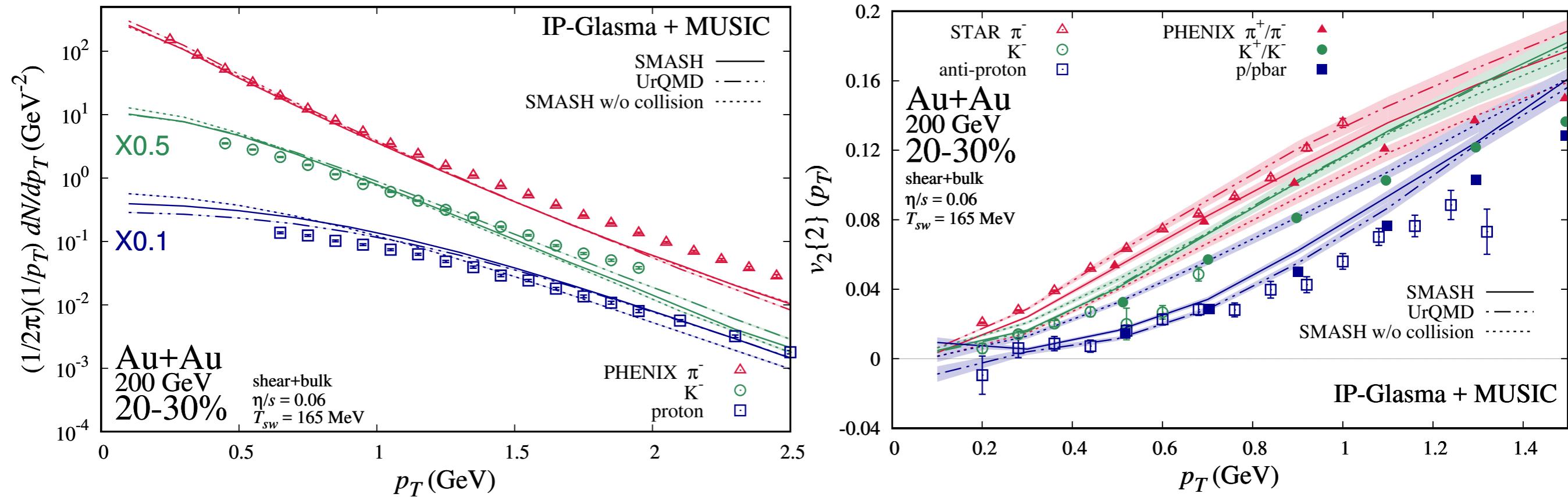
by Anna Schäfer

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

Afterburner

- Optional: Global conservation laws and broad mass distributions for resonances at particlization

MUSIC+UrQMD from S. Ryu et al, PRC 97 (2018)
by Sangwook Ryu



- Results for bulk observables are similar as within UrQMD
- Work in progress: Annihilation and AQM cross-sections

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
 - Electromagnetic radiation is incorporated
 - First results for afterburner calculation look promising
- Electromagnetic radiation from the non-equilibrium hadronic stage
- Multi-particle scattering and improved interfaces to hydrodynamic evolution
- Publication of the source code in 2018!

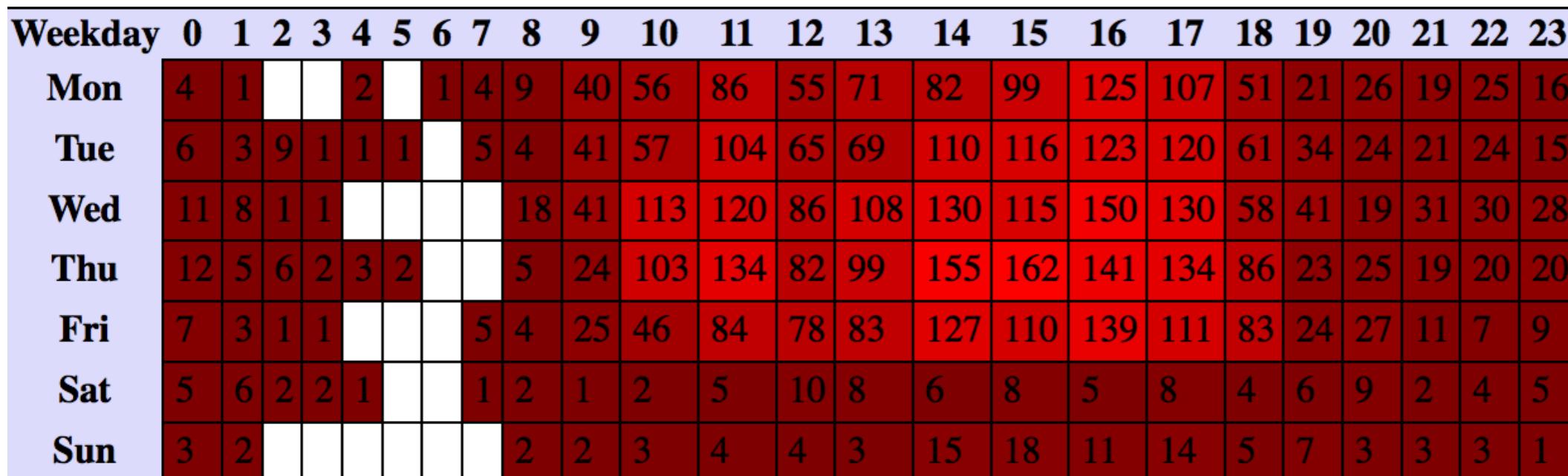
Posters and Talks

- Poster Session, today at 5PM:
 - #266. *Benchmark of microscopic hadronic direct photon emission in thermal equilibrium* by Anna Schäfer, Jonas Rothermel
 - #236. *Dilepton production and resonance properties within a new hadronic transport approach* by Jan Staudenmaier
 - #342. *Bulk observables within hybrid approach for heavy ion collisions with SMASH afterburner* by Sangwook Ryu
 - #637. *Electric conductivity of a hadron gas* by Jan Hammelmann
 - #677. *Can Baryon Stopping be understood within the String Model?* by Justin Mohs
 - #764. *Strangeness production at SIS energies* by Vinzent Steinberg
- Talk, today at 3.20 PM:
 - *Shear viscosity and resonance lifetimes in the hadron gas* by Jean-Bernard Rose, Thermodynamics and Hadron Chemistry I
- Unrelated to SMASH: Parallel talk, Monday, May 14th at 5.50 PM:
 - *Correlated gluonic hot spots meet symmetric cumulants data at LHC energies* by Alba Soto-Ontoso

Fun Facts and Figures

- 1 PhD, 5 MSc, 9 BSc thesis completed so far
- 1033 active days, 5605 commits by 21 authors

Language	files	blank	comment	code
C++	126	2823	5885	29855
C/C++ Header	95	2191	10953	8730
CMake	2	44	58	474
Python	1	9	16	44
YAML	3	15	32	30
SUM:	227	5082	16944	39133



Day	Total (%)
Mon	900 (16.06%)
Tue	1014 (18.09%)
Wed	1239 (22.11%)
Thu	1262 (22.52%)
Fri	985 (17.57%)
Sat	102 (1.82%)
Sun	103 (1.84%)

extracted by git statistics on April 27 2018, commits per day and time

- Estimated total cost of SMASH so far: 1,25 Mio USD

generated using David A. Wheeler's 'SLOCCount' on April 27 2018

Backup

General Setup

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

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

- Particles represented by Gaussian wave packets
- Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \quad d_{\text{trans}}^2 = (\vec{r}_a - \vec{r}_b)^2 - \frac{((\vec{r}_a - \vec{r}_b) \cdot (\vec{p}_a - \vec{p}_b))^2}{(\vec{p}_a - \vec{p}_b)^2}$$

- Test particle method

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

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

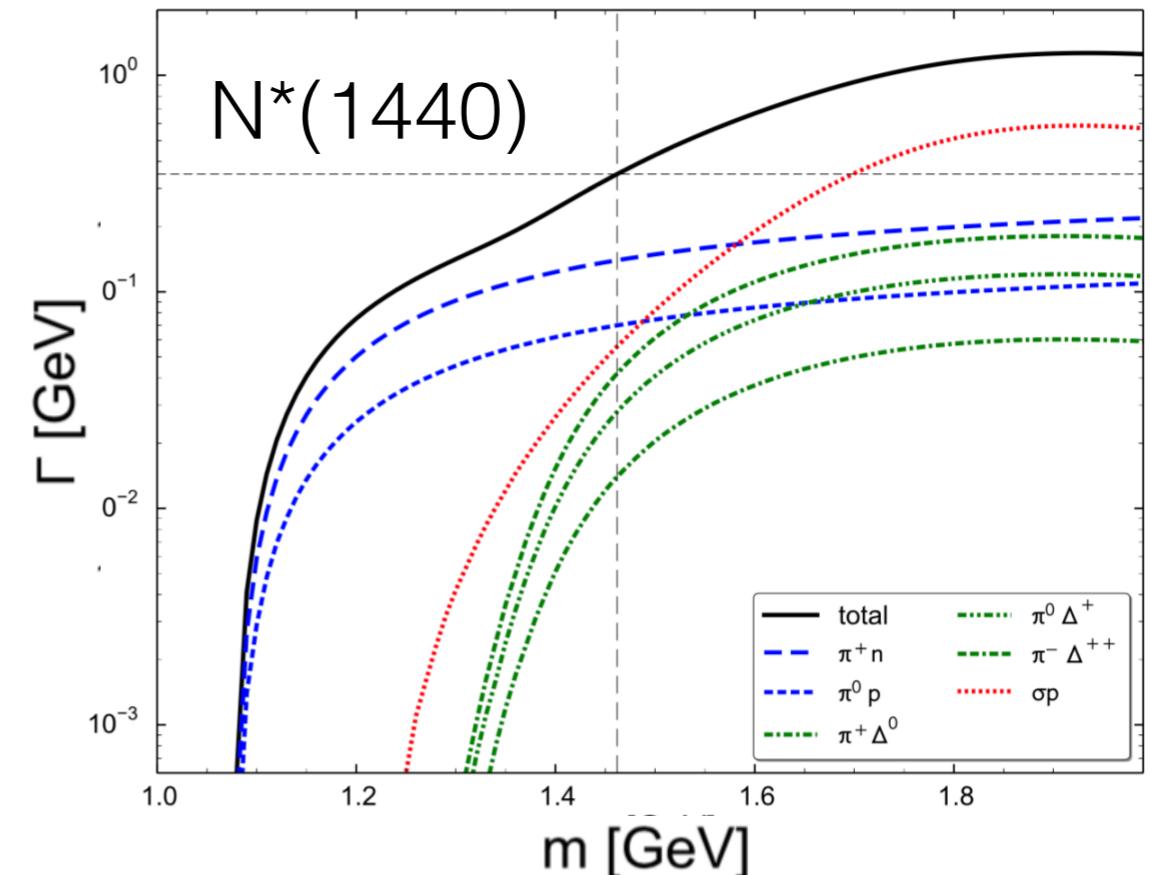
Resonances

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

- Decay widths
 - Particles stable, if width < 10 keV
 (π, η, K, \dots)
 - Treatment of Manley et al

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

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



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

Treatment of Manley

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

- Scaling of on-shell decay width:

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

- Definition of rho-function:

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

Blatt Weisskopf functions

$$B_0^2 = 1$$

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

...

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

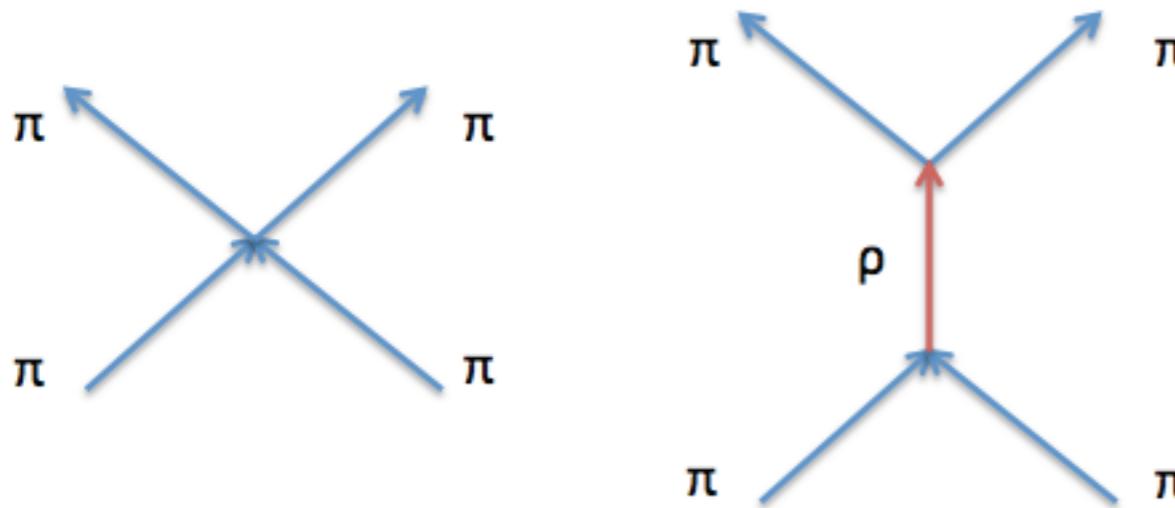
- Hadronic Form Factor:

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

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

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

