FIAS Frankfurt Institute for Advanced Studies

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Baryon Resonances in Hadronic Transport Models

Hannah Petersen

28.11.17, WASA@GSI/FAIR Meeting, Darmstadt

SFB-TR-211
Strong-interaction matter
under extreme conditions

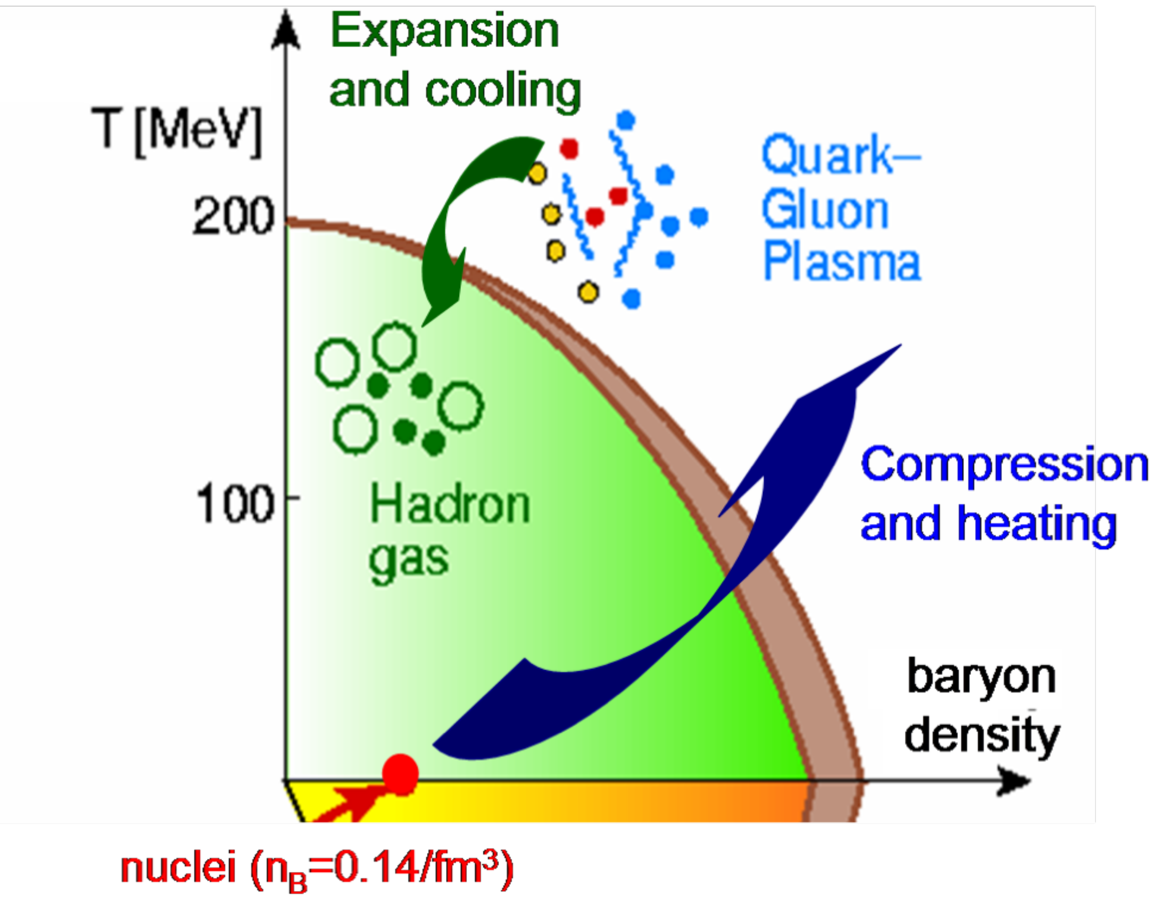
DFG Deutsche Forschungsgemeinschaft

HIC for FAIR
Helmholtz International Center

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

The QCD Phase Diagram

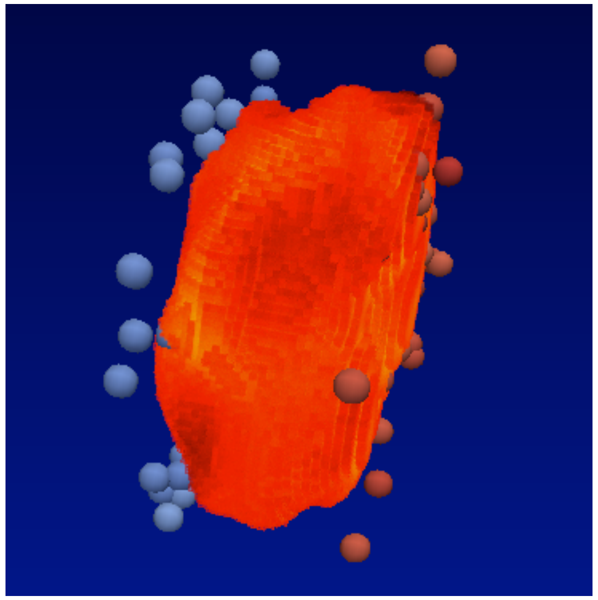
- Main goals of heavy ion research



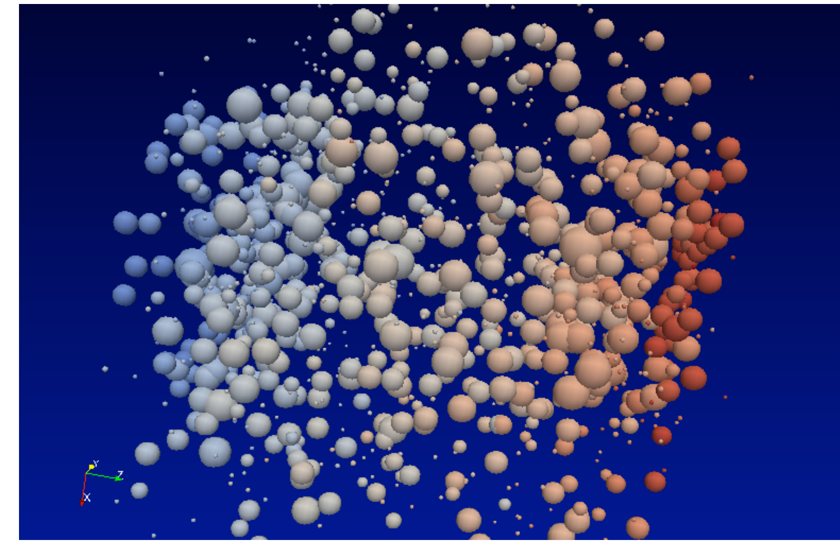
- **Questions** to be answered:
  - What is the temperature and the density? What are the relevant degrees of freedom?
  - Phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- Understand the structures in the phase diagram
- Investigate the properties of the quark-gluon plasma
- **Focus** in this talk: Hadron/Resonance dynamics in heavy ion collisions at low beam energies as a baseline

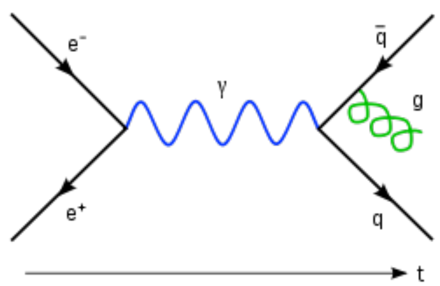
Transport Approaches



Dynamical description of heavy ion reactions

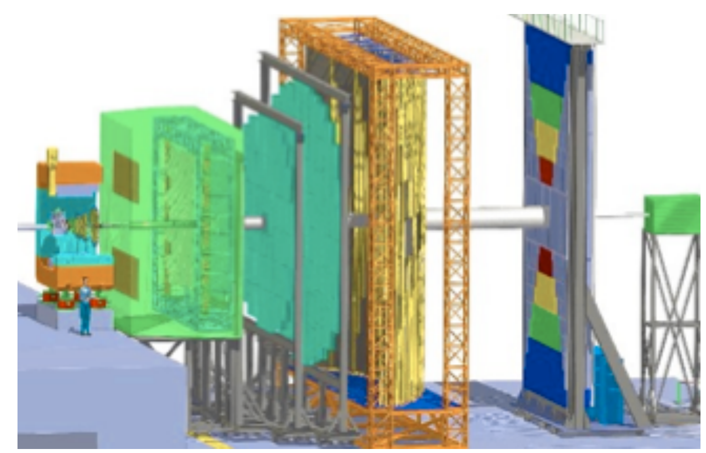


Fundamental field theory of strong interactions (QCD)



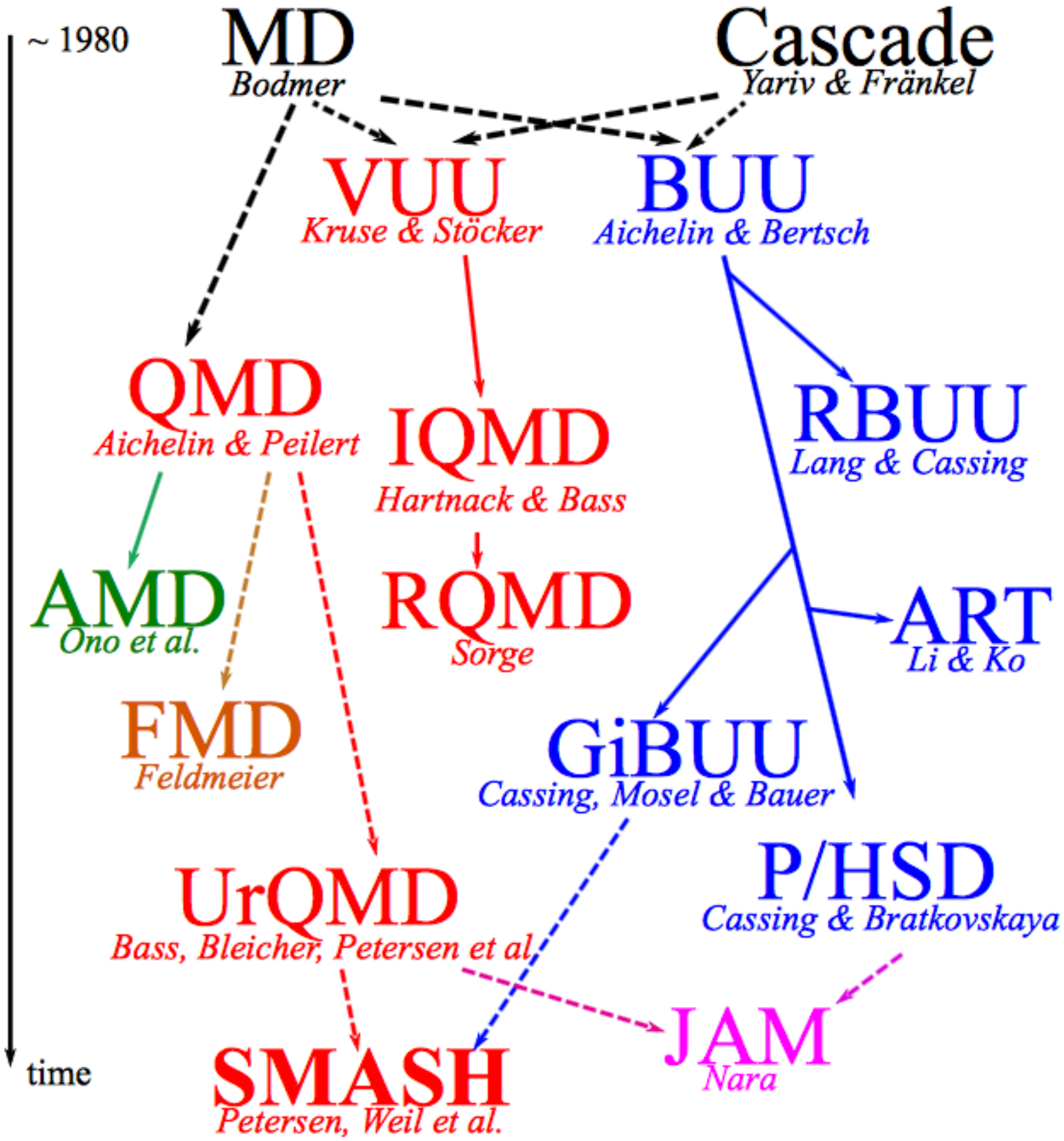
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

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

History of Transport Models



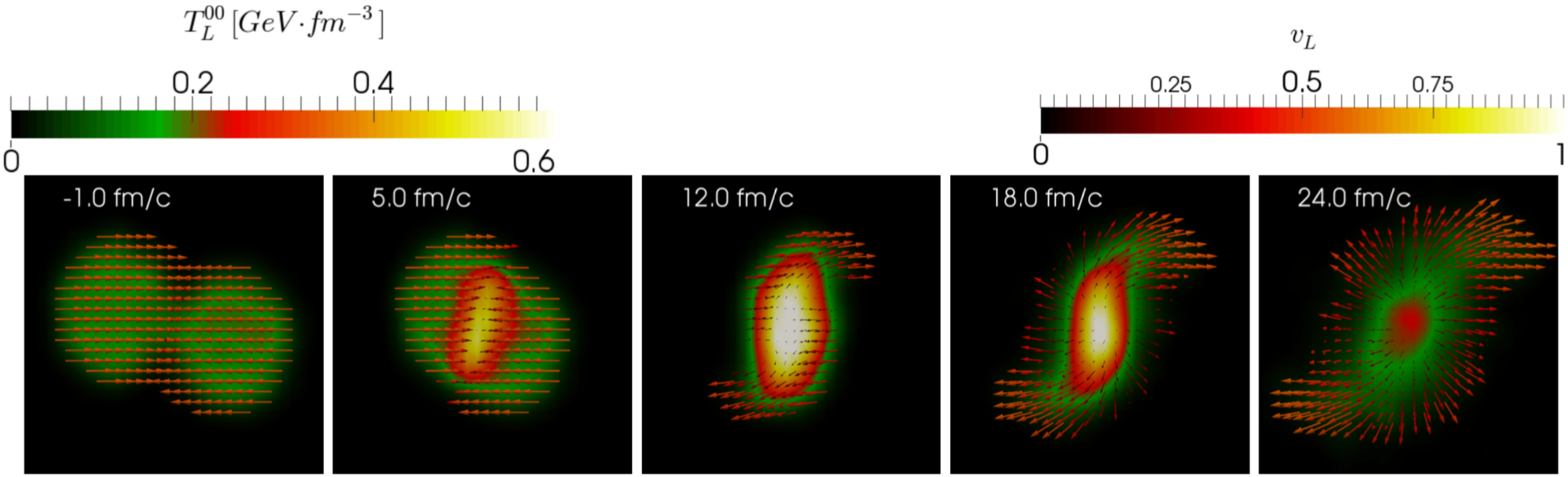
thanks to Steffen Bass

- Hadronic transport approaches are **successfully** applied for decades
- Goals for new code:
  - **Reference** for hadronic system with vacuum properties
  - Modeling of **non-equilibrium** phase transition

SMASH*

- New hadronic transport approach:
  - Comparison to results from FOPI/HADES/KAOS
  - Predictions for observables at FAIR/NICA/BES
  - 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

General Setup

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

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

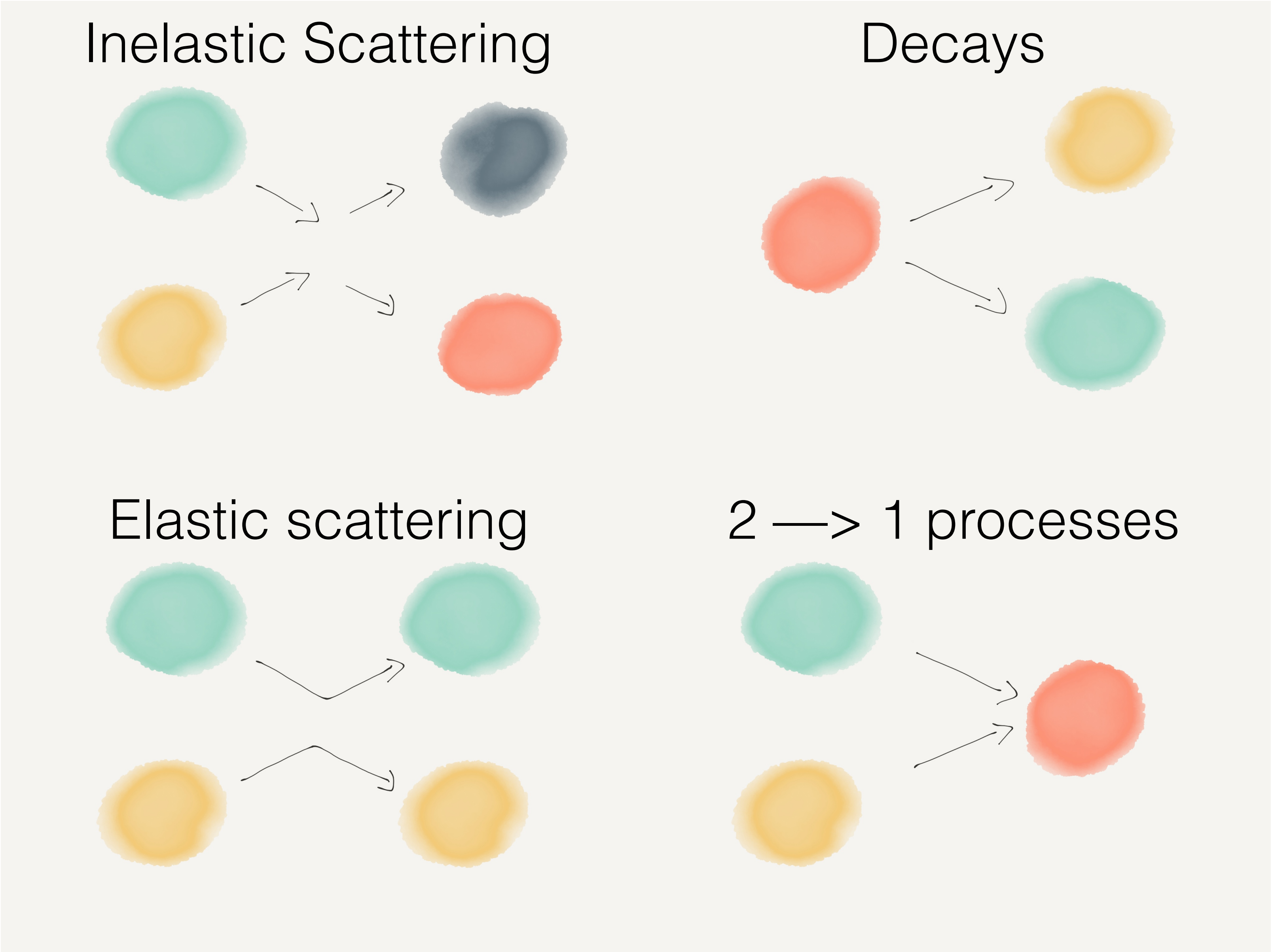
- Geometric collision criterion

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

- Test particle method
- Degrees of freedom: Established hadrons from PDG
  - 56 mesons, 17N, 8Δ, 14Λ,10Σ, 6Ξ,2Ω
- **Full information** about particle positions and momenta is available at all times

Collision Term

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



- Uncertainties due to unknown resonance properties

Resonances

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

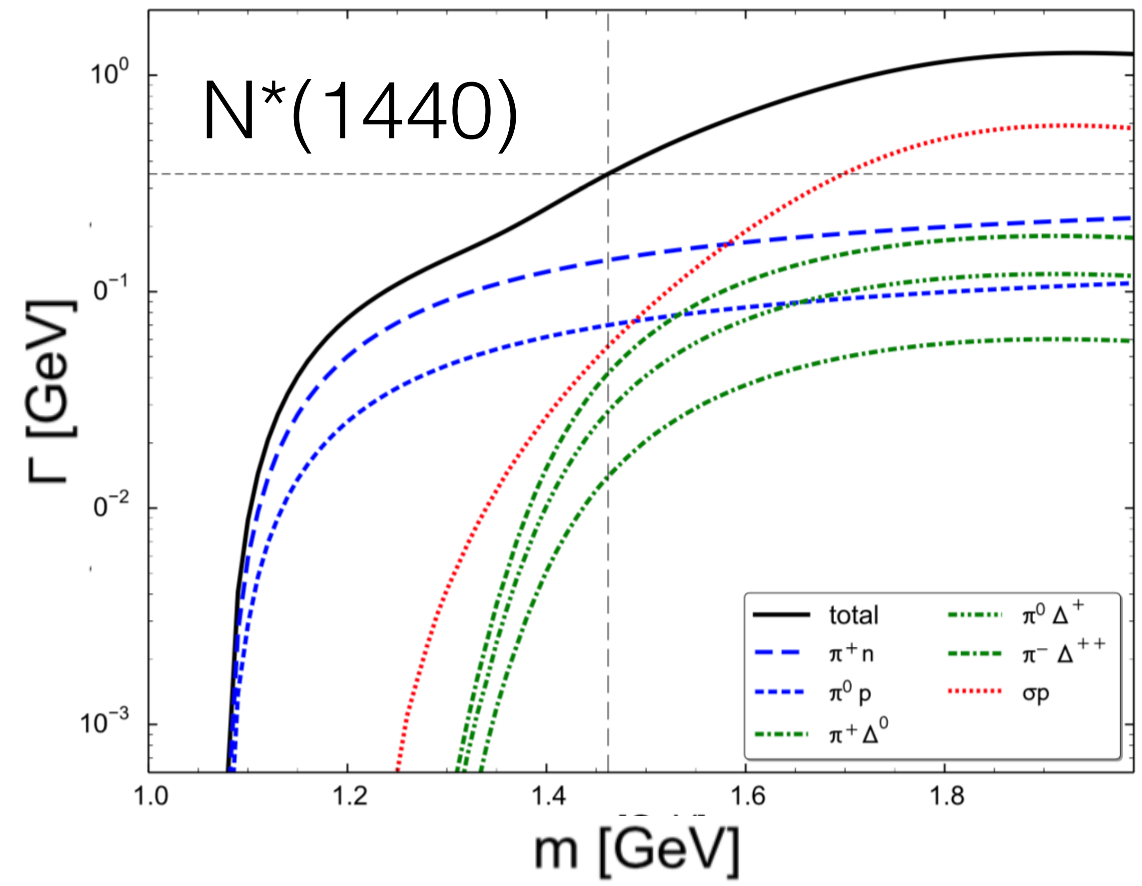
$$\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma(m)}{(m^2 - M_0^2)^2 + m^2\Gamma(m)^2}$$

- (Off-shell) 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)

Baryons and Baryonic Resonances

- Crucial degrees of freedom in low energy collisions at high density

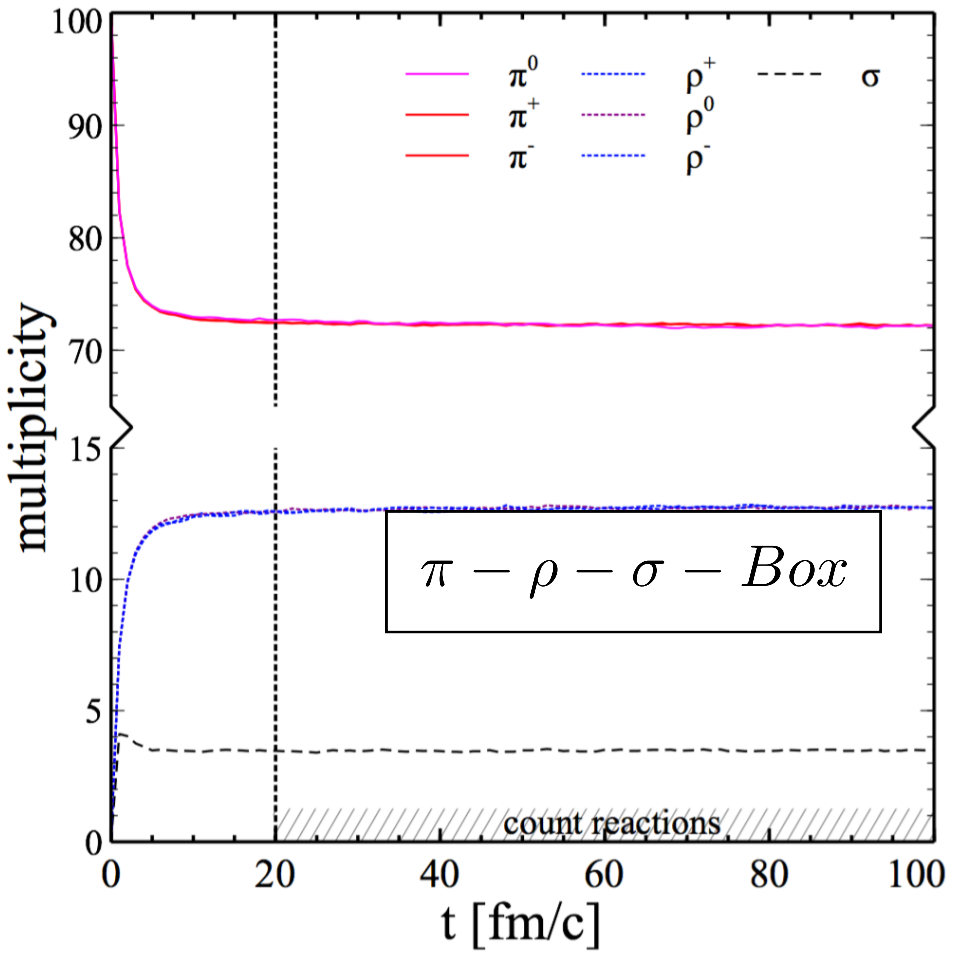
N	0.938	0
$N(1440)$	1.462	0.350
$N(1520)$	1.515	0.115
$N(1535)$	1.535	0.150
$N(1650)$	1.655	0.140
$N(1675)$	1.675	0.150
$N(1680)$	1.685	0.130
$N(1700)$	1.700	0.150
$N(1710)$	1.710	0.100
$N(1720)$	1.720	0.250
$N(1875)$	1.875	0.250
$N(1900)$	1.900	0.200
$N(1990)$	1.990	0.500
$N(2080)$	2.000	0.350
$N(2190)$	2.150	0.500
$N(2220)$	2.220	0.400
$N(2250)$	2.250	0.470

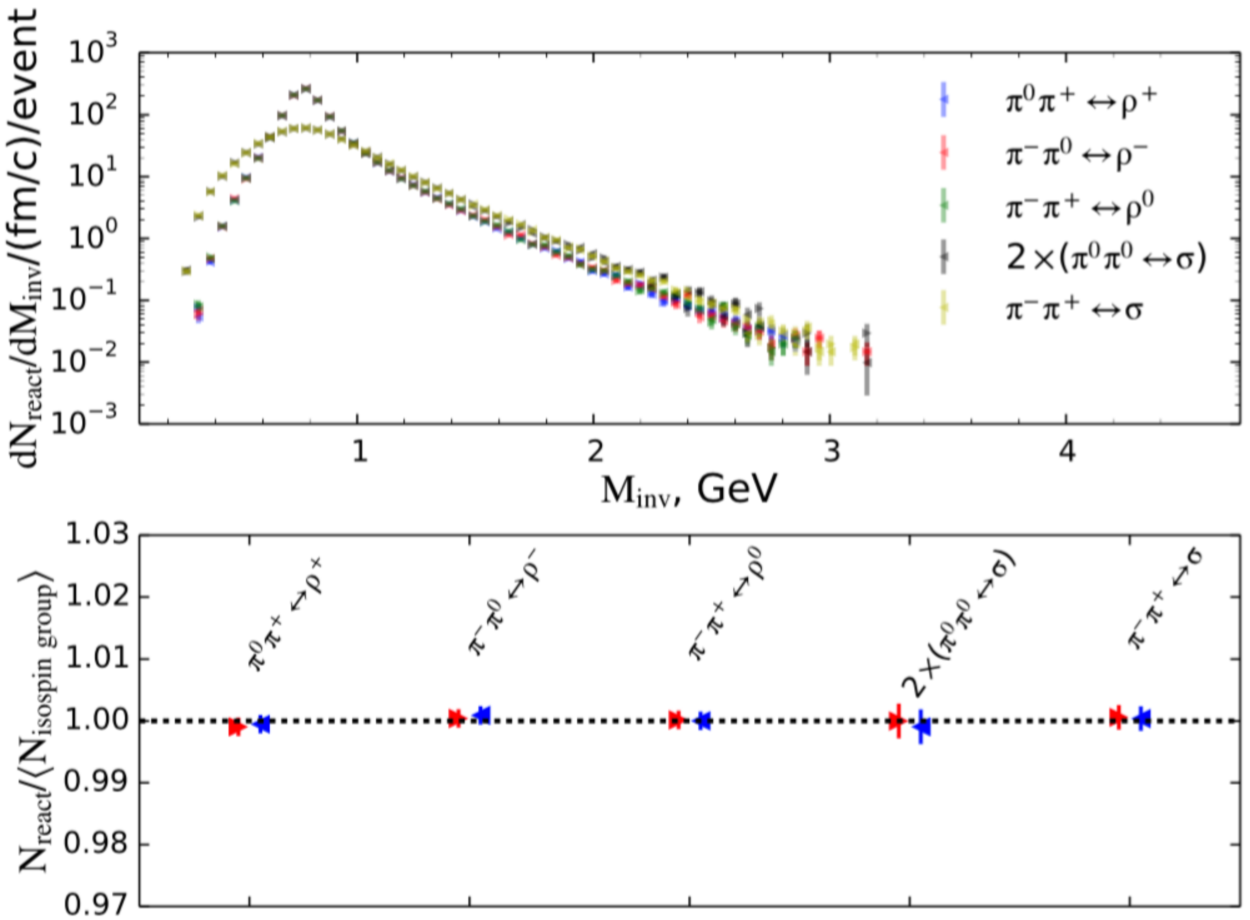
Δ	1.232	0.117
$\Delta(1620)$	1.630	0.140
$\Delta(1700)$	1.700	0.300
$\Delta(1905)$	1.880	0.330
$\Delta(1910)$	1.890	0.280
$\Delta(1920)$	1.920	0.260
$\Delta(1930)$	1.950	0.350
$\Delta(1950)$	1.930	0.285

Λ	1.116	0	3122
$\Lambda(1405)$	1.405	0.0505	13122
$\Lambda(1520)$	1.520	0.0156	3124
$\Lambda(1600)$	1.600	0.1500	23122
$\Lambda(1670)$	1.670	0.0350	33122
$\Lambda(1690)$	1.690	0.0600	13124
$\Lambda(1800)$	1.800	0.3000	43122
$\Lambda(1810)$	1.810	0.1500	53122
$\Lambda(1820)$	1.820	0.0800	3126
$\Lambda(1830)$	1.830	0.0950	13126
$\Lambda(1890)$	1.890	0.1000	23124
$\Lambda(2100)$	2.100	0.2000	3128
$\Lambda(2110)$	2.110	0.2000	23126
$\Lambda(2350)$	2.350	0.1500	9903128
Σ	1.189	0	3222, 3212, 3112
$\Sigma(1385)$	1.385	0.036	3224, 3214, 3114
$\Sigma(1660)$	1.660	0.100	13112, 13212, 13222
$\Sigma(1670)$	1.670	0.060	13224, 13214, 13114
$\Sigma(1750)$	1.750	0.090	23112, 23212, 23222
$\Sigma(1775)$	1.775	0.120	3226, 3216, 3116
$\Sigma(1915)$	1.915	0.120	13226, 13216, 13116
$\Sigma(1940)$	1.940	0.220	23114, 23214, 23224
$\Sigma(2030)$	2.030	0.180	3118, 3218, 3228
$\Sigma(2250)$	2.250	0.100	9903118, 9903218, 9903228
Ξ	1.321	0	3322, 3312
$\Xi(1530)$	1.532	0.009	3324, 3314
$\Xi(1690)$	1.690	0.030	203312, 203322
$\Xi(1820)$	1.820	0.024	13314, 13324
$\Xi(1950)$	1.950	0.060	103316, 103326
$\Xi(2030)$	2.030	0.020	203316, 203326
Ω	1.672	0	3334
$\Omega(2250)$	2.252	0.055	203338

Detailed Balance

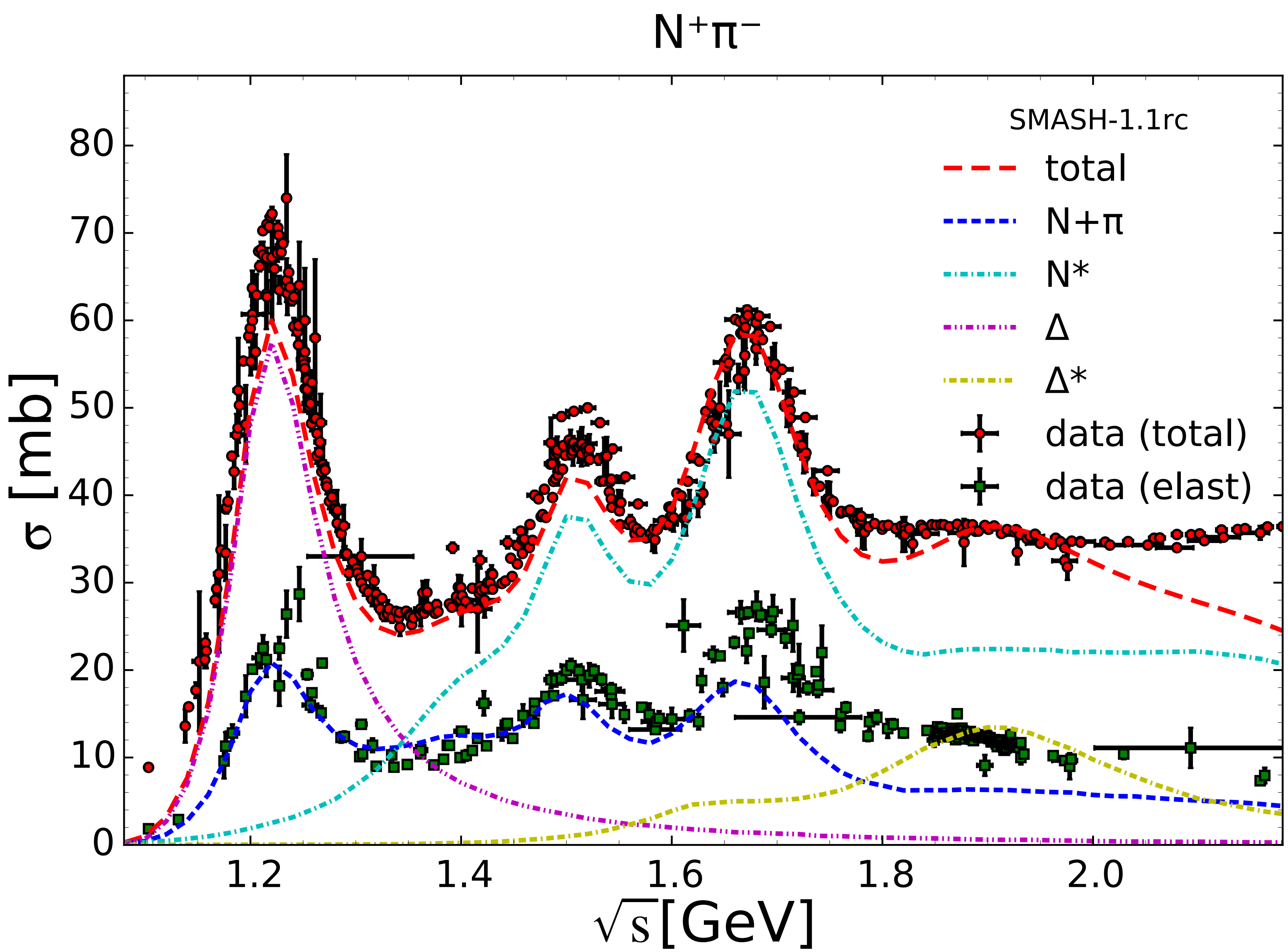
- Inverse absorption cross section calculated from production cross section
- Conservation of detailed balance (only 1 <—> 2 or 2 <—> 2 processes)





- Test: Full hadron gas indicating most violating processes

Elementary Cross Sections

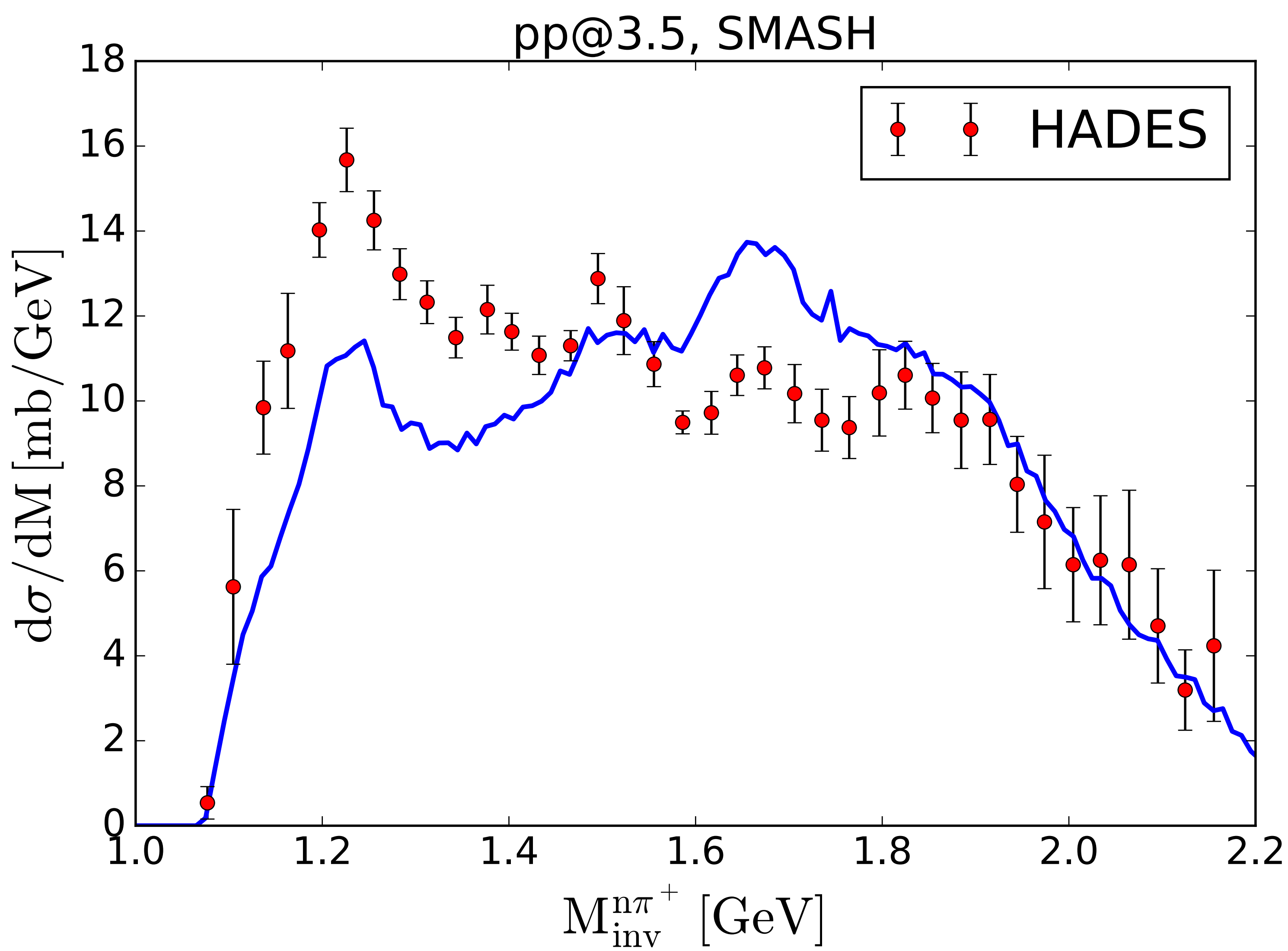


- Many resonance contributions to inelastic cross section
- Total cross section is sum of individual channels (not parameterized)

Exclusive Cross Section

HADES, Eur. Phys. J., A50 (2014)

$$pp \rightarrow pn\pi^+$$



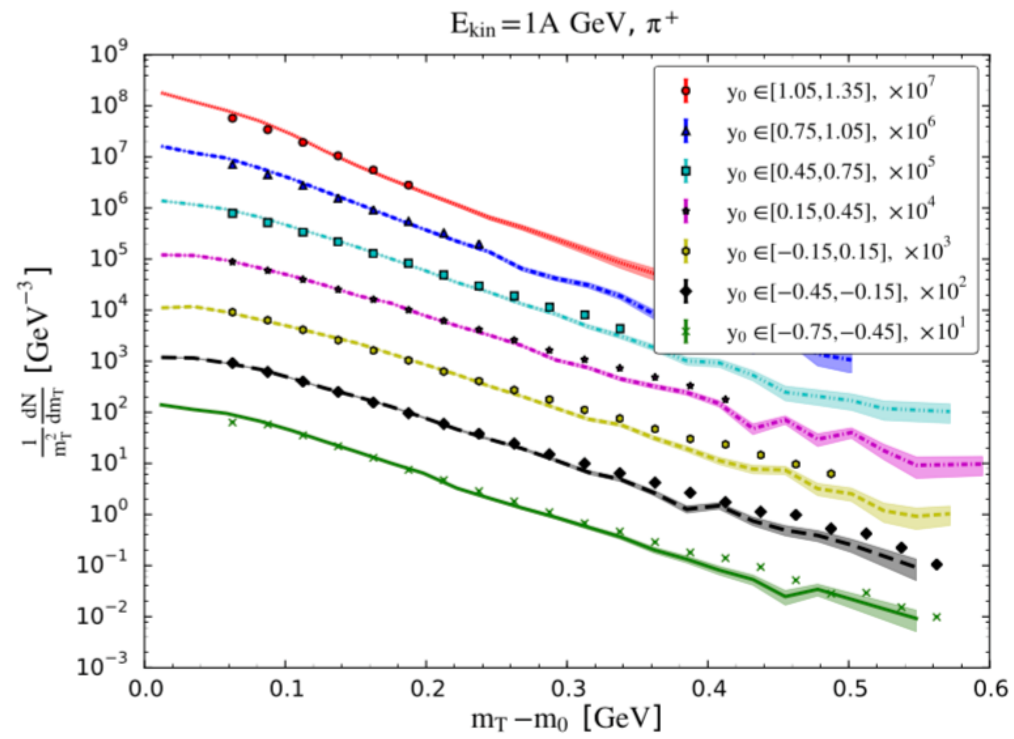
J.Weil et al, Phys. Rev. C 94 (2016)

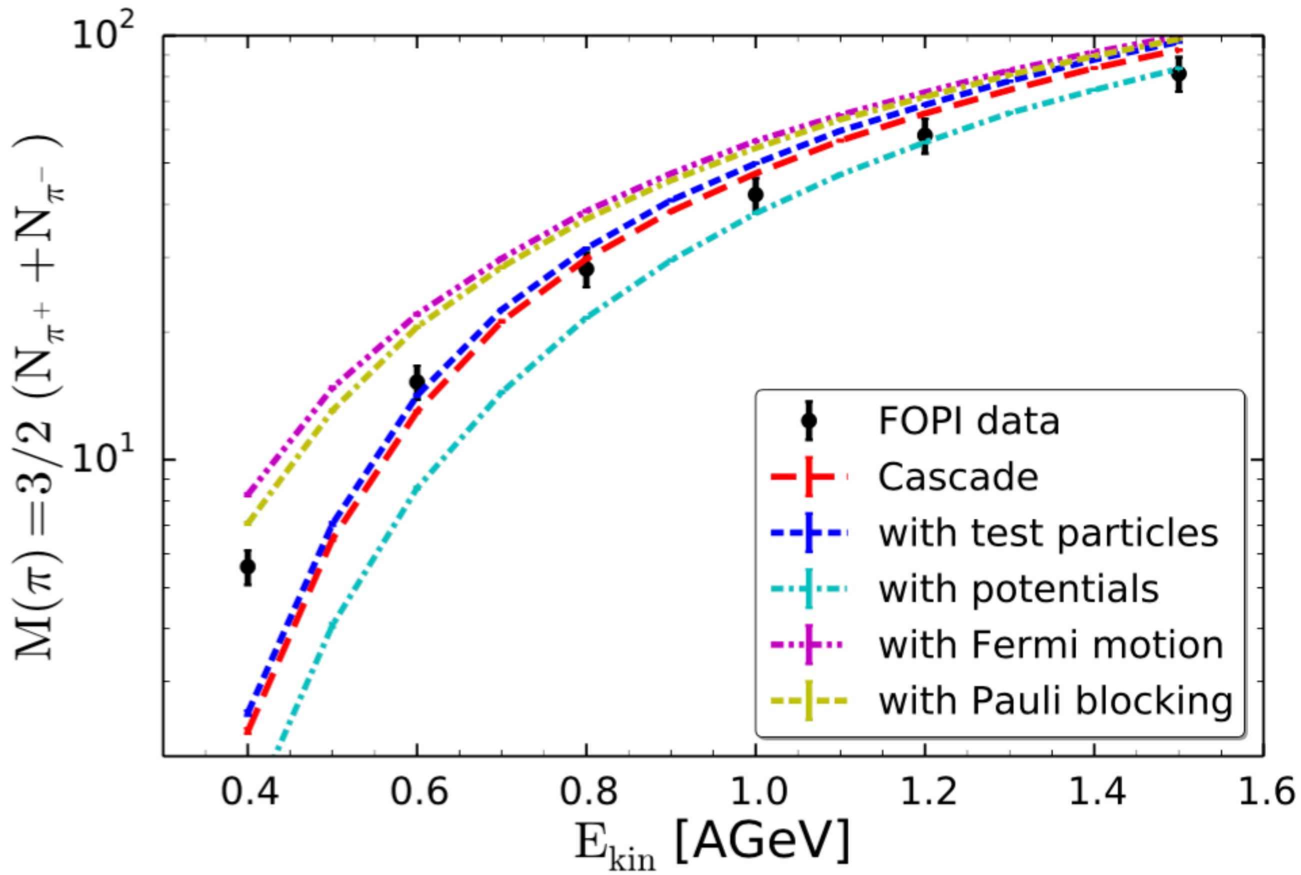
- Invariant mass spectrum of $n\pi^+$
- Probes baryonic resonance production cross section in primary NN reactions
- Comparison to experimental data similar to UrQMD

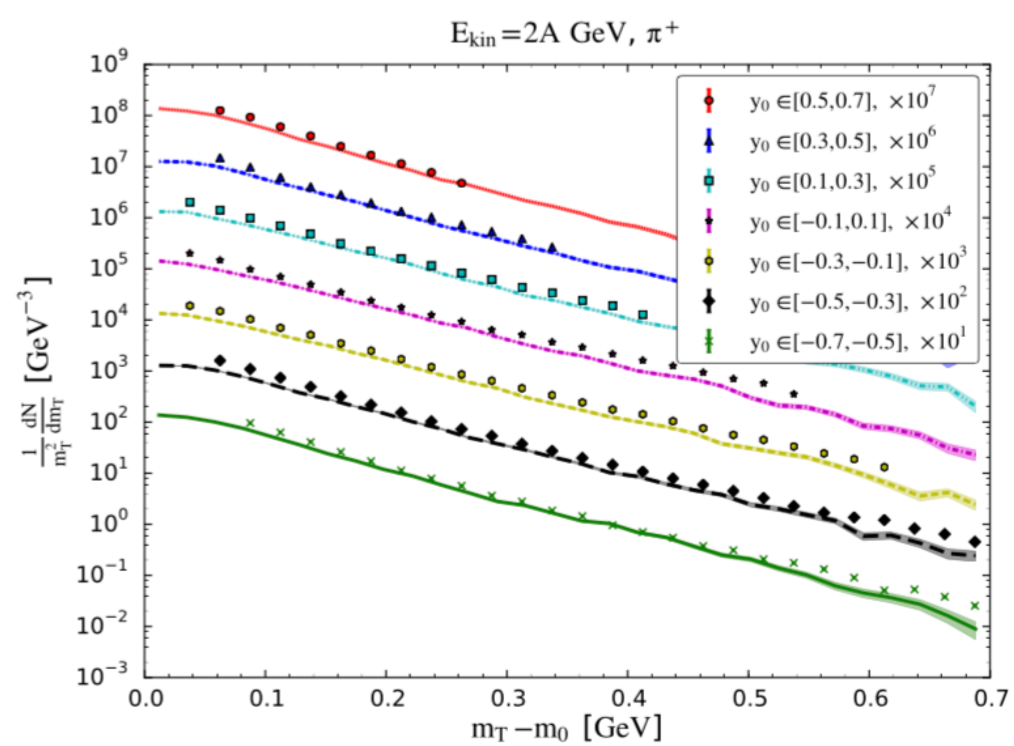
S.A. Bass et al, Prog. Part. Nucl. Phys. 41 (1998)

Pion Production in Au+Au

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



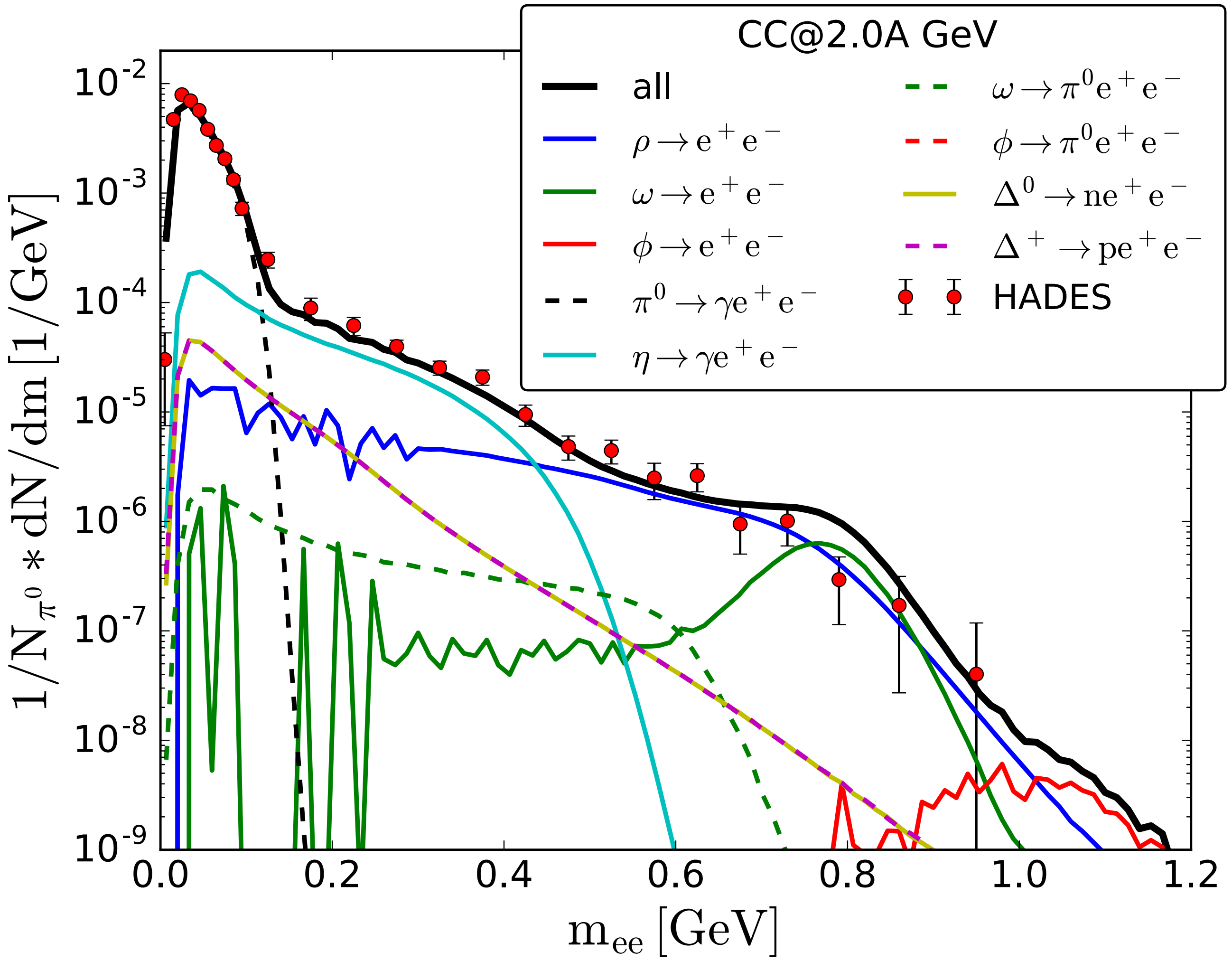




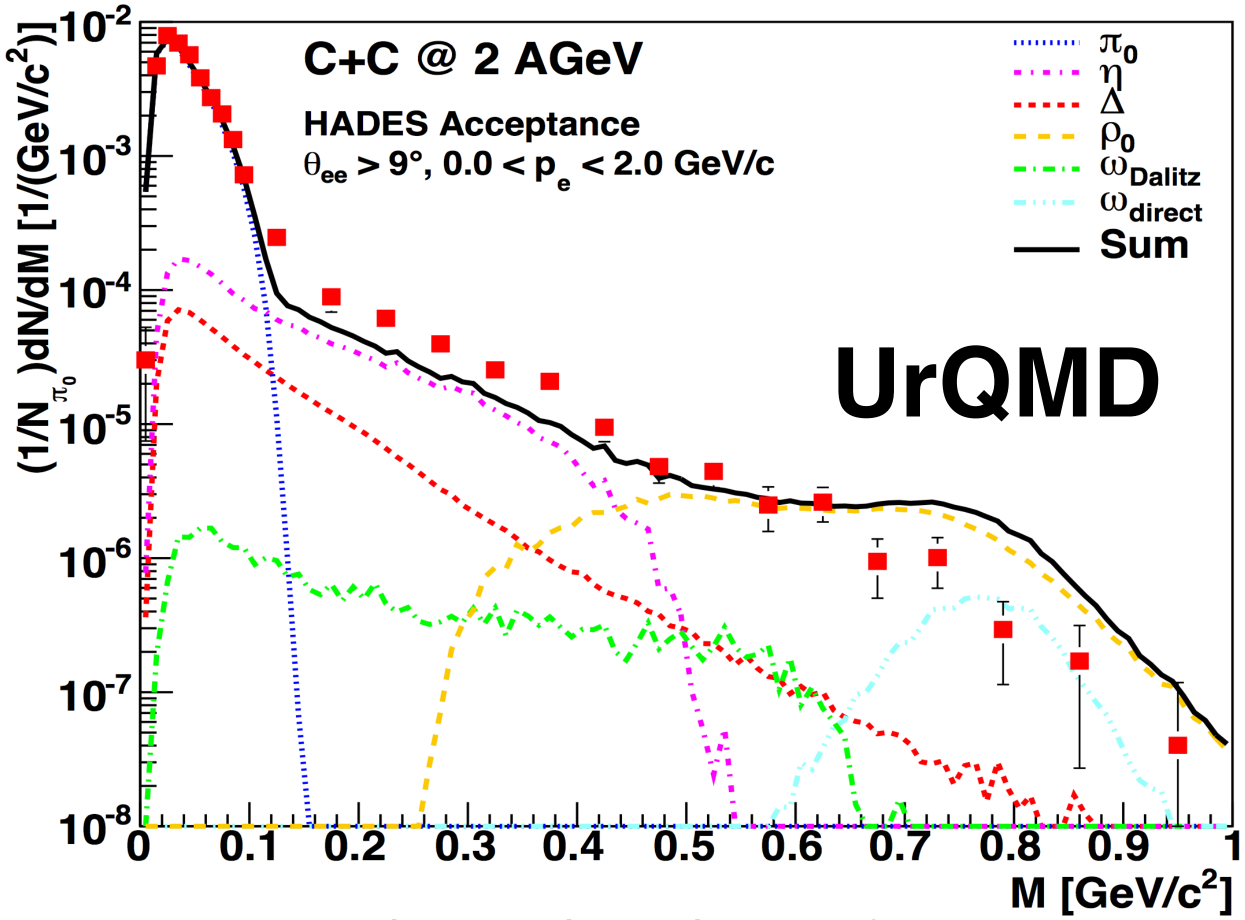
J. Weil et al, PRC 94 (2016)

Dilepton Production

by J. Staudenmaier, paper in preparation



HADES, PRL 98 (2007)



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

- SMASH and UrQMD compare very similar to data
- Different vector meson thresholds
- Work in progress: Detailed study from elementary collisions to heavy ions and afterburner for RHIC/LHC

Dileptons in SMASH

by J. Staudenmaier

- Dileptons are sensitive probes for resonance properties
- 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)
- What do dileptons tell us about baryon resonances?

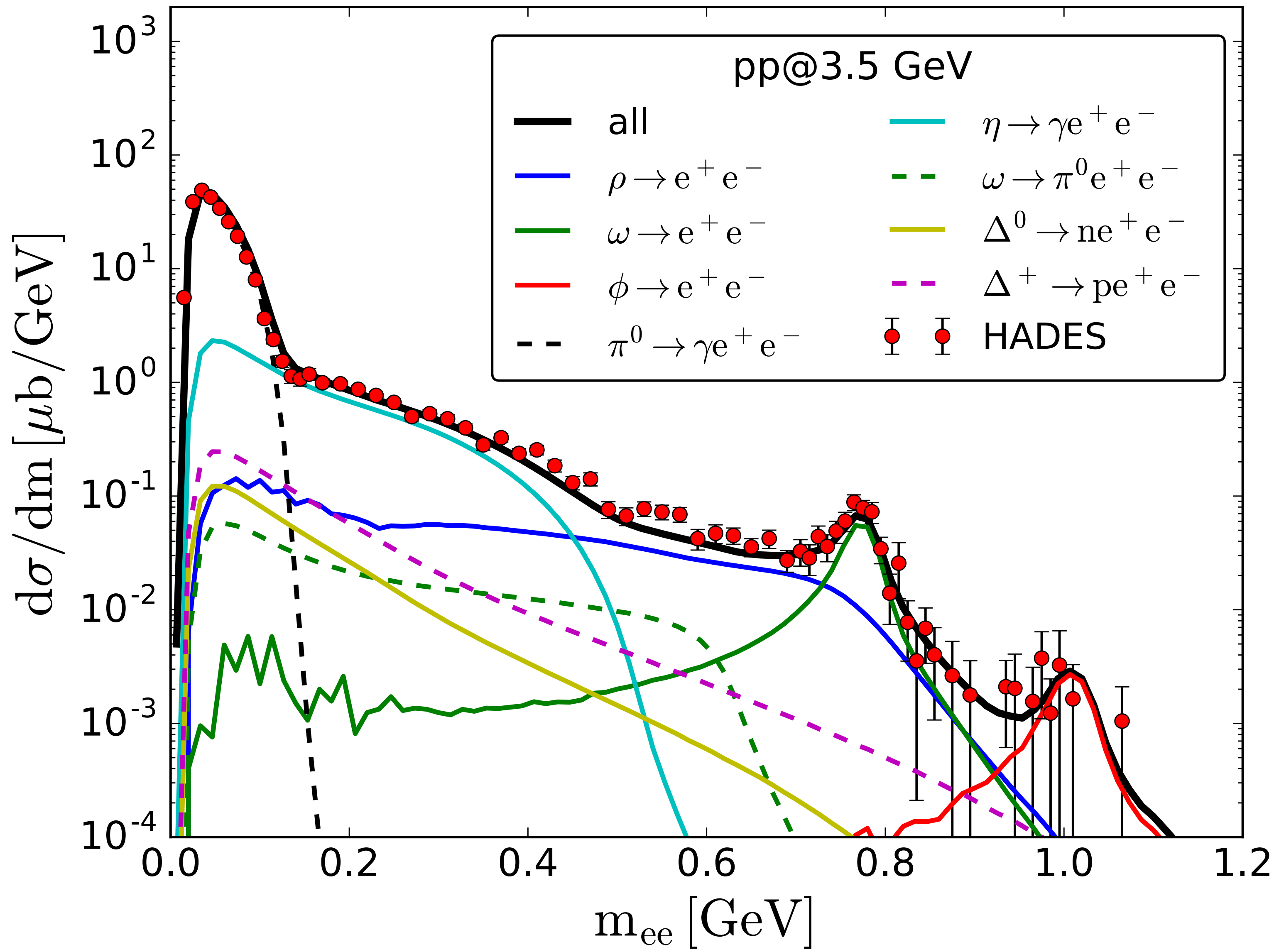
Dilepton Decays
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\phi \to e^+e^-$
$\pi \to e^+e^-\gamma$
$\eta \to e^+e^-\gamma$
$\eta' \to e^+e^-\gamma$
$\omega \to e^+e^-\pi^0$
$\phi \to e^+e^-\pi^0$
$\Delta^+ \to e^+e^-p$
$\Delta^0 \to e^+e^-n^0$

Elementary Reactions

- pp collisions as vacuum baseline

by J. Staudenmaier

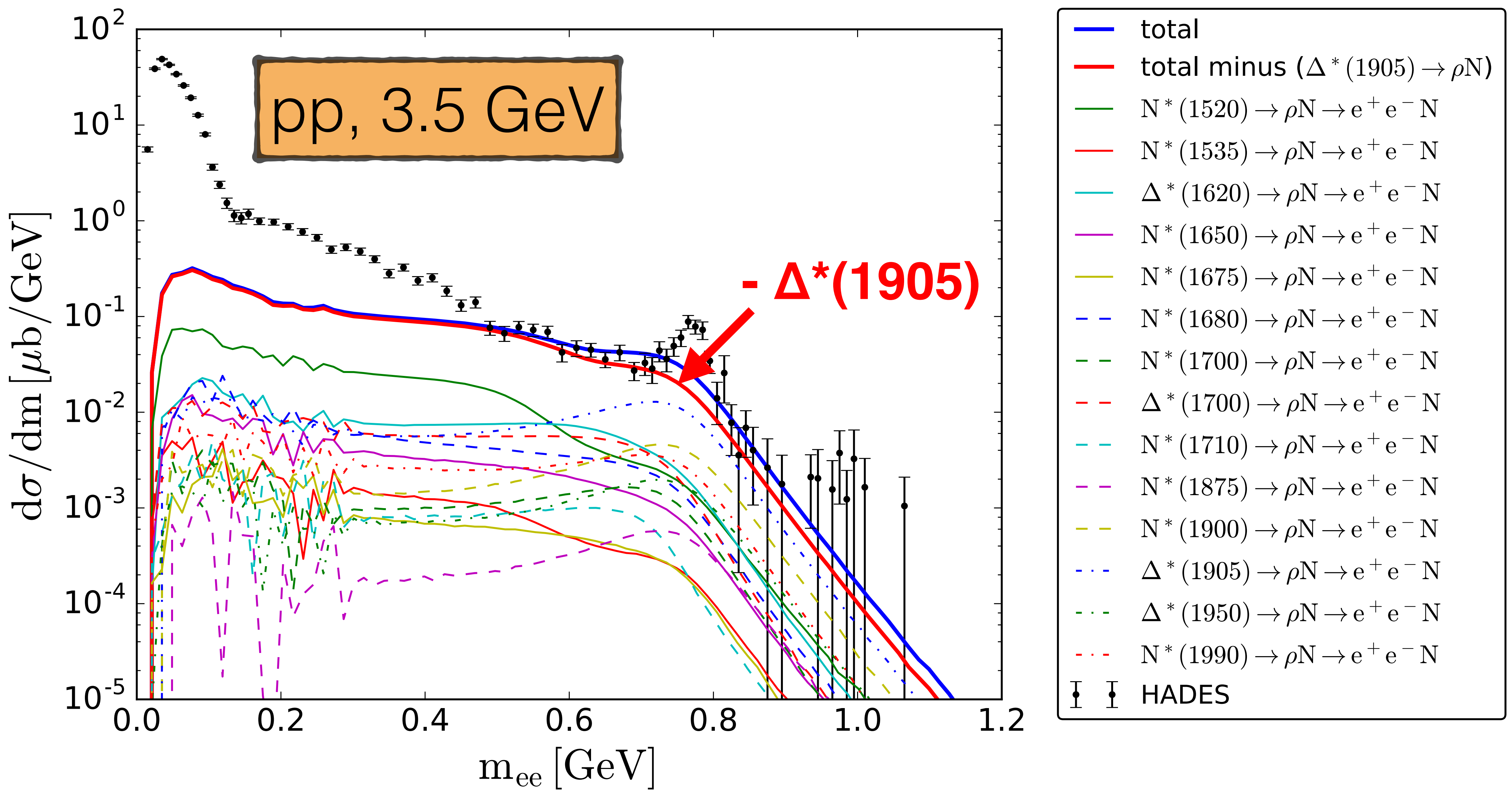
HADES, Eur.Phys.J. A48 (2012)



- Vector meson contributions below hadronic threshold
- Coupling to baryon resonances is crucial

Origin of ρ meson

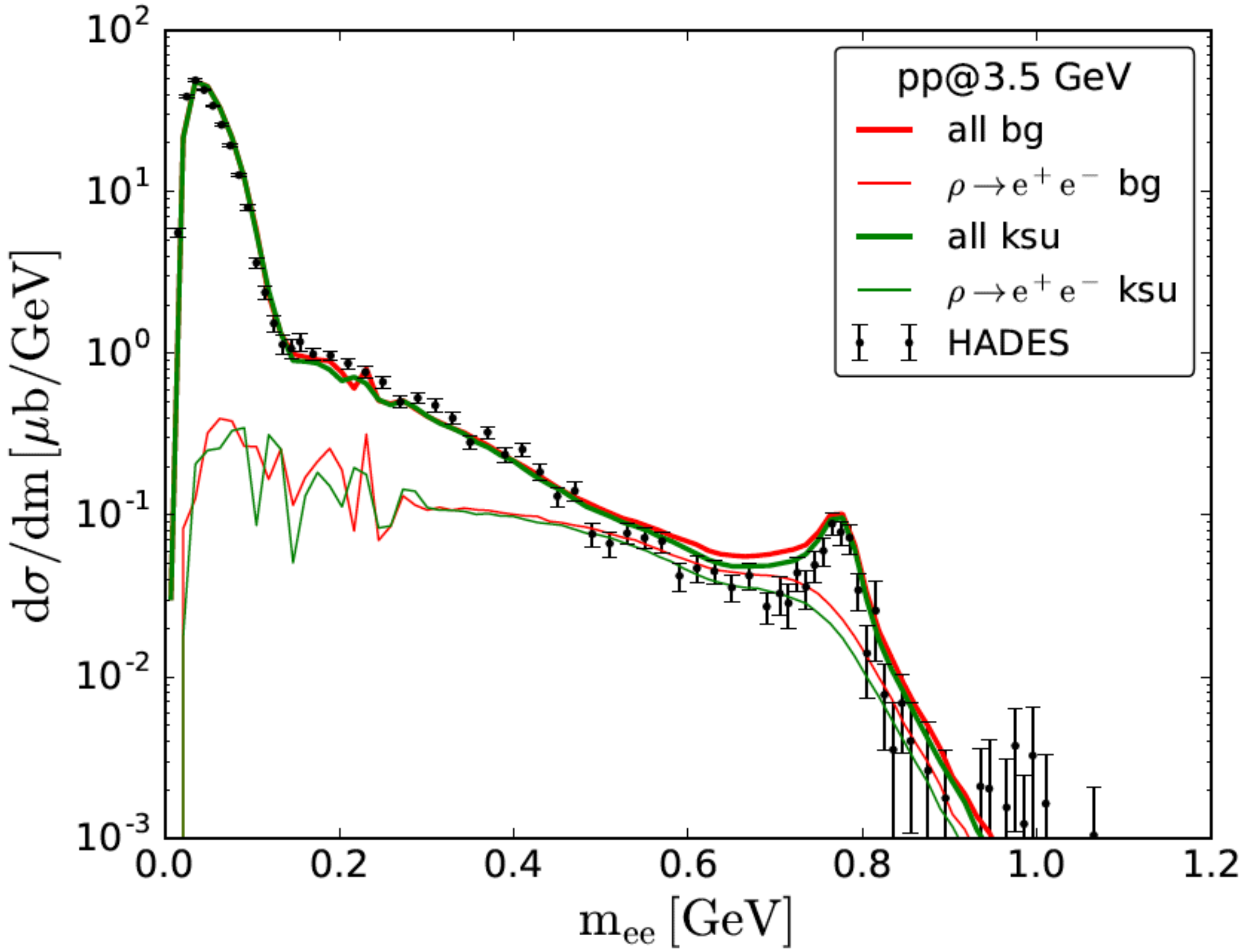
by J. Staudenmaier



- ρ originates from different baryonic resonance decays
- Dominant contribution for pole mass region: Δ*(1905)

Different PWA Results

- Adjusting branching ratios of N*(1720) and Δ*(1905)



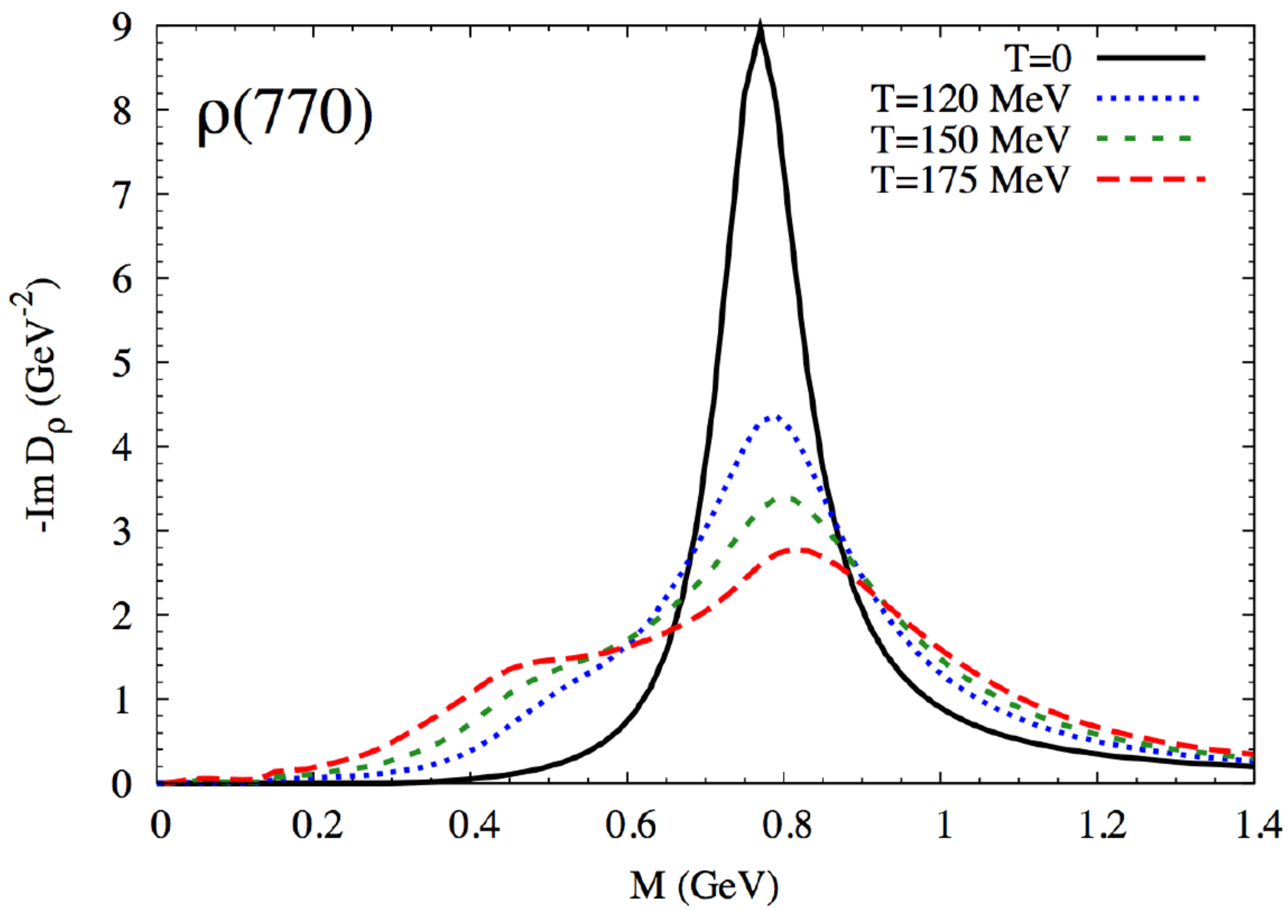
- Δ*(1905)-> ρN
  BG 0.42
  KSU < 0.14
- N*(1720)-> ρN
  BG 0.10
  KSU 0.01

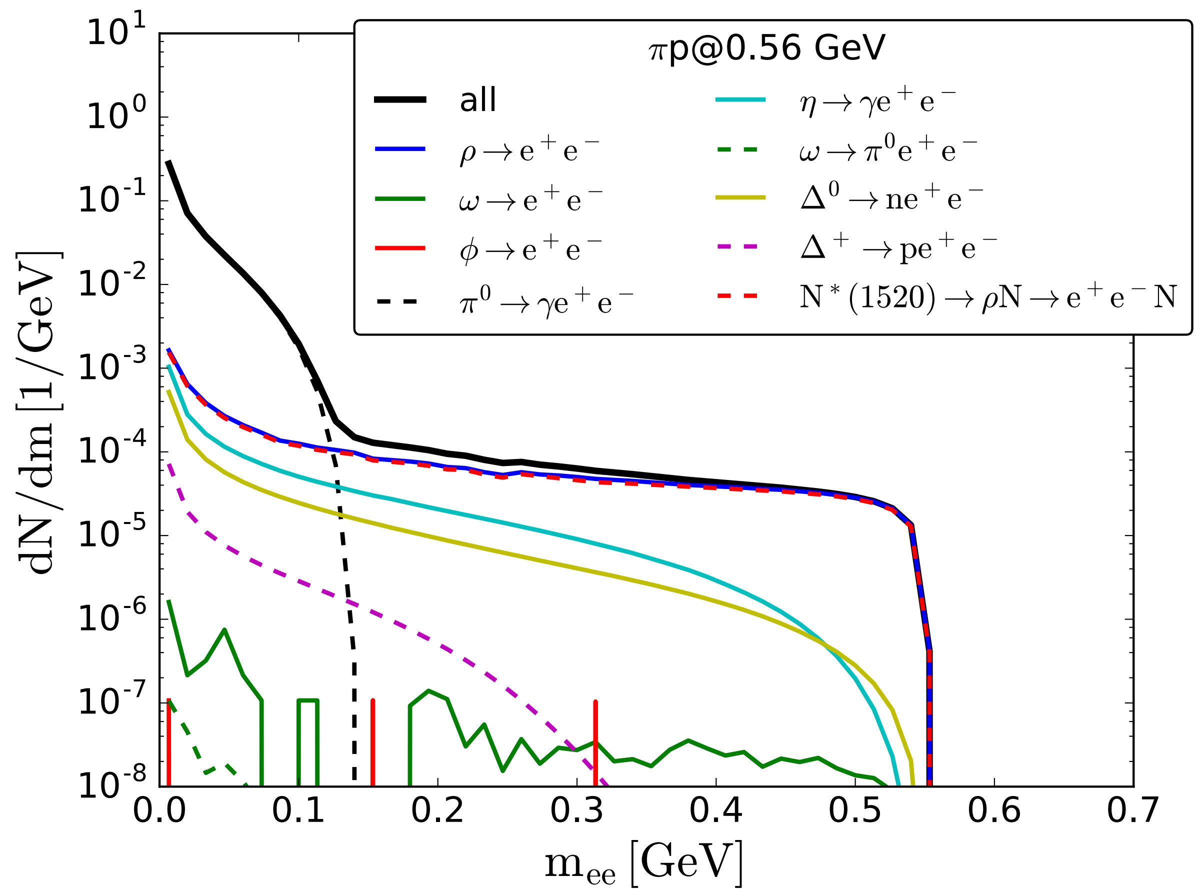
BG: A. V. Anisovich et al. EPJA 48, 2012
KSU: M. Shrestha and D. M. Manley, PRC 86, 2012

- Dileptons are sensitive to changes in properties of high mass baryon resonances
- KSU values lead to better agreement with data

Role of N*(1520)

- N*(1520) responsible for change in ρ mass distribution





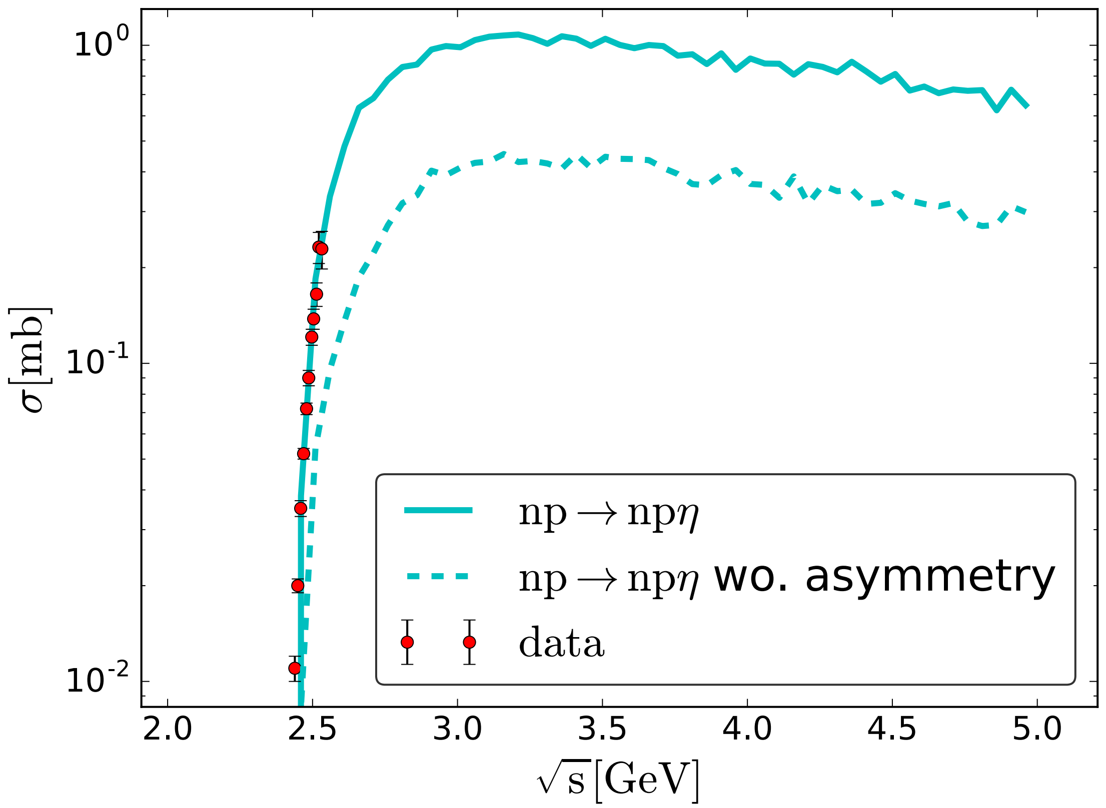
Rapp, Wambach, van Hees, Landoldt-Börnstein (2010)

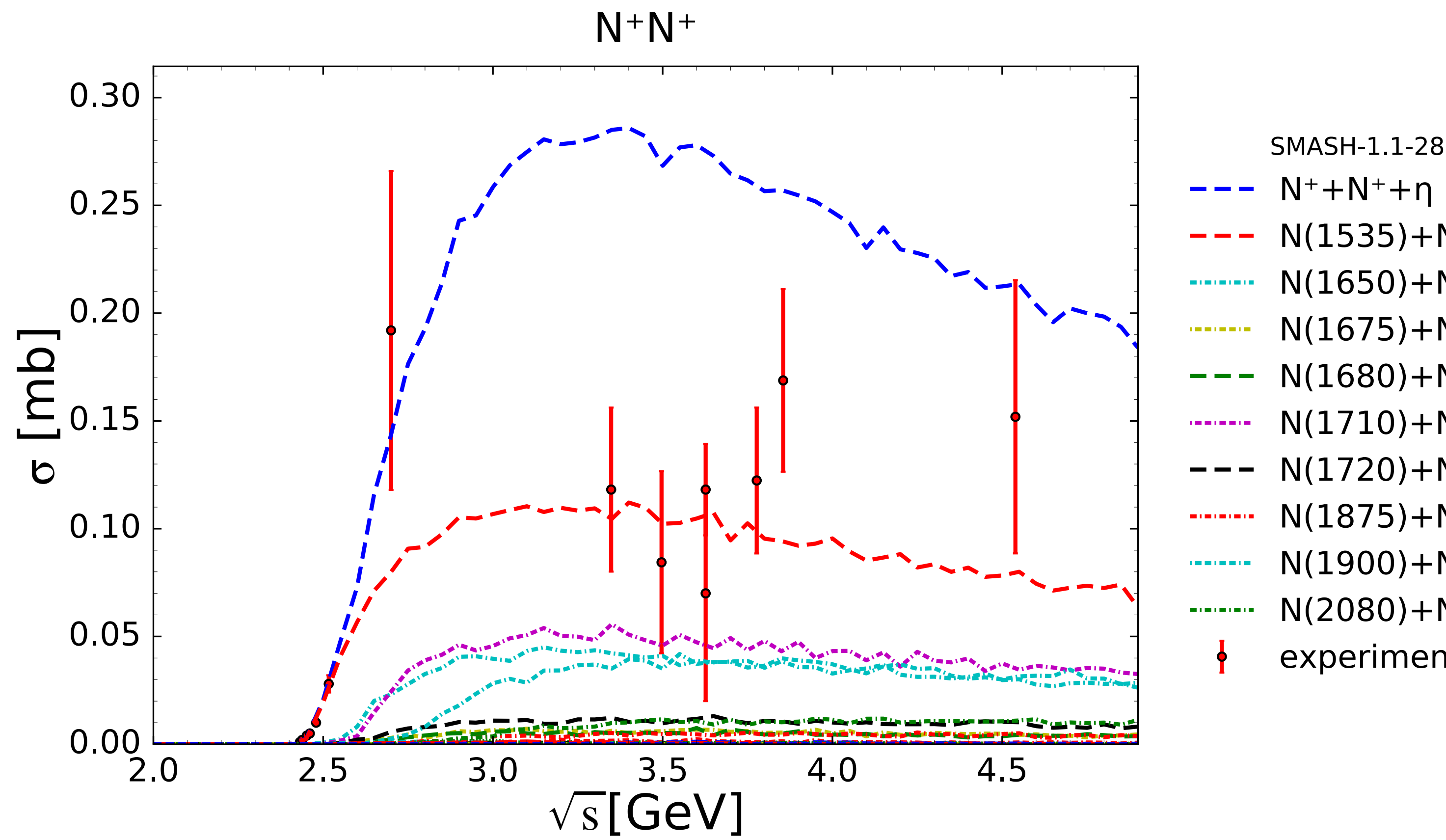
- PDG (in the 2016 edition) suggests that the ρ decay does not exist
- New data for dilepton production from pions beam will help to clarify the situation

η Meson Production

- Isospin asymmetry between pn and pp reactions has to be taken into account

V. Steinberg and J. Staudenmaier



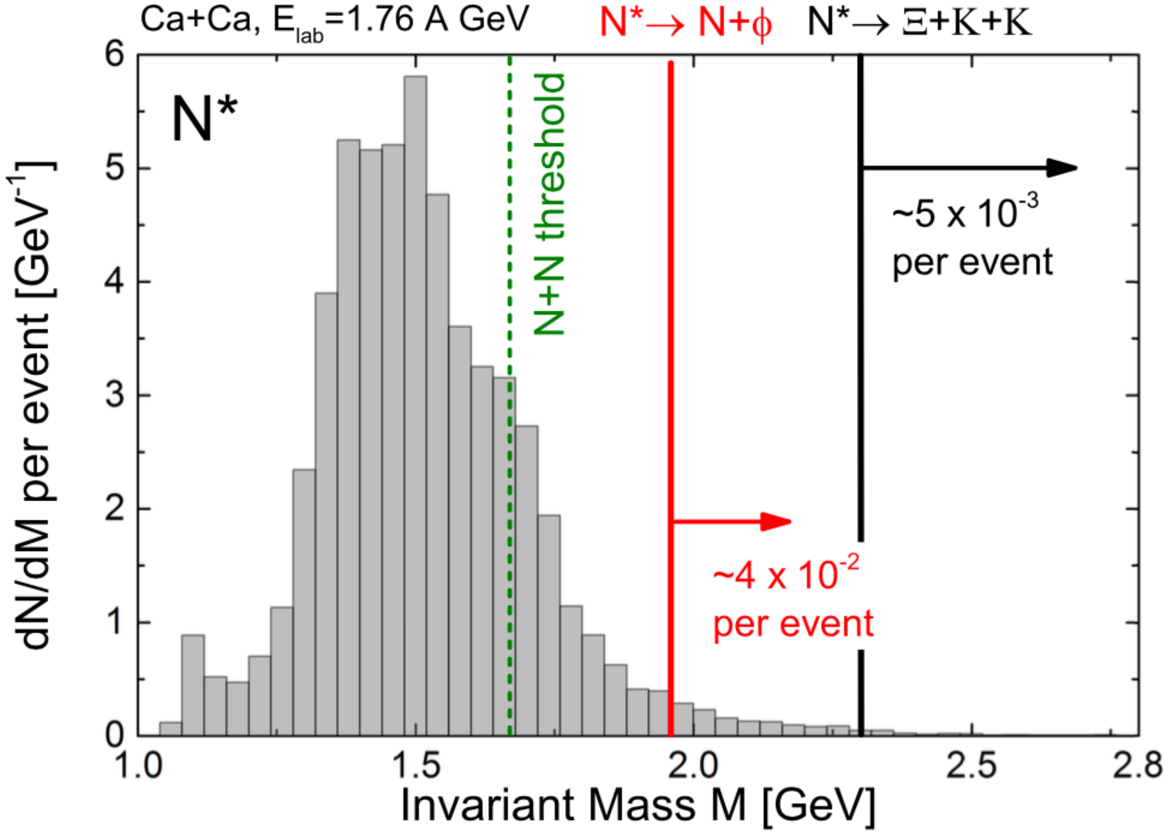


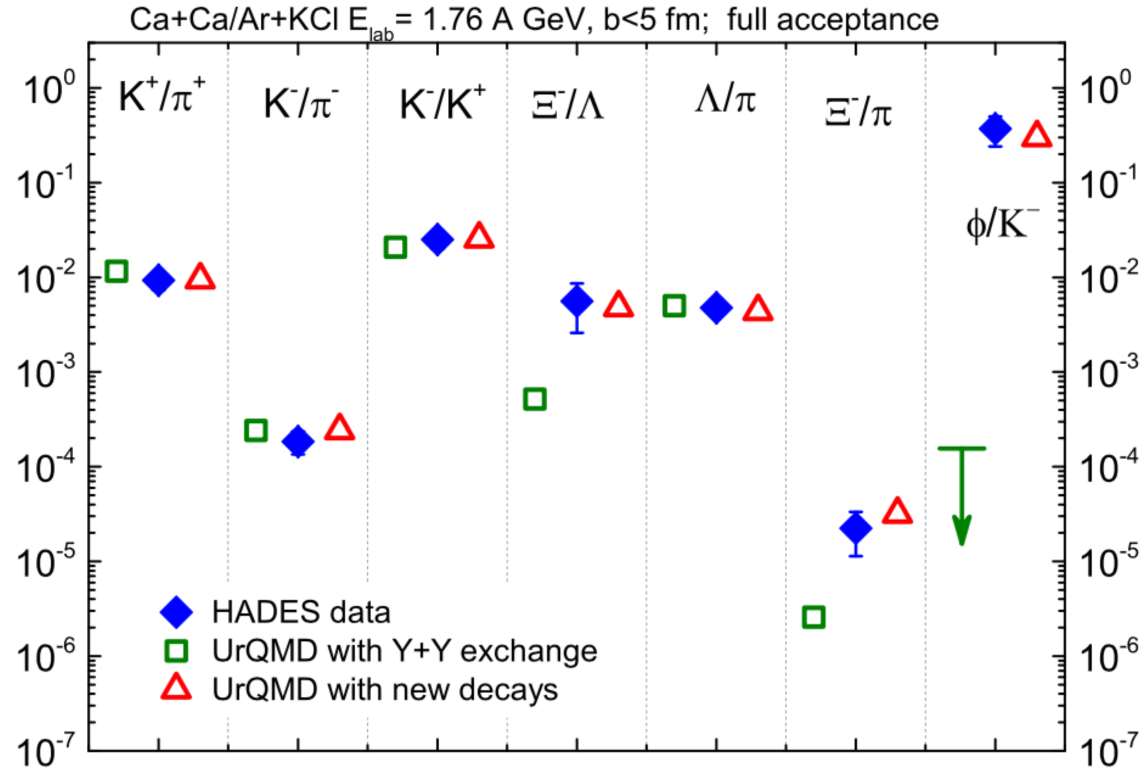
- Direct measurements in elementary reactions suggest too low η yield -> Increase spoils dilepton spectra
- Precise data for exclusive channel

Φ/Ξ yields at SIS-18

- UrQMD hadronic transport approach with additional high mass resonances

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



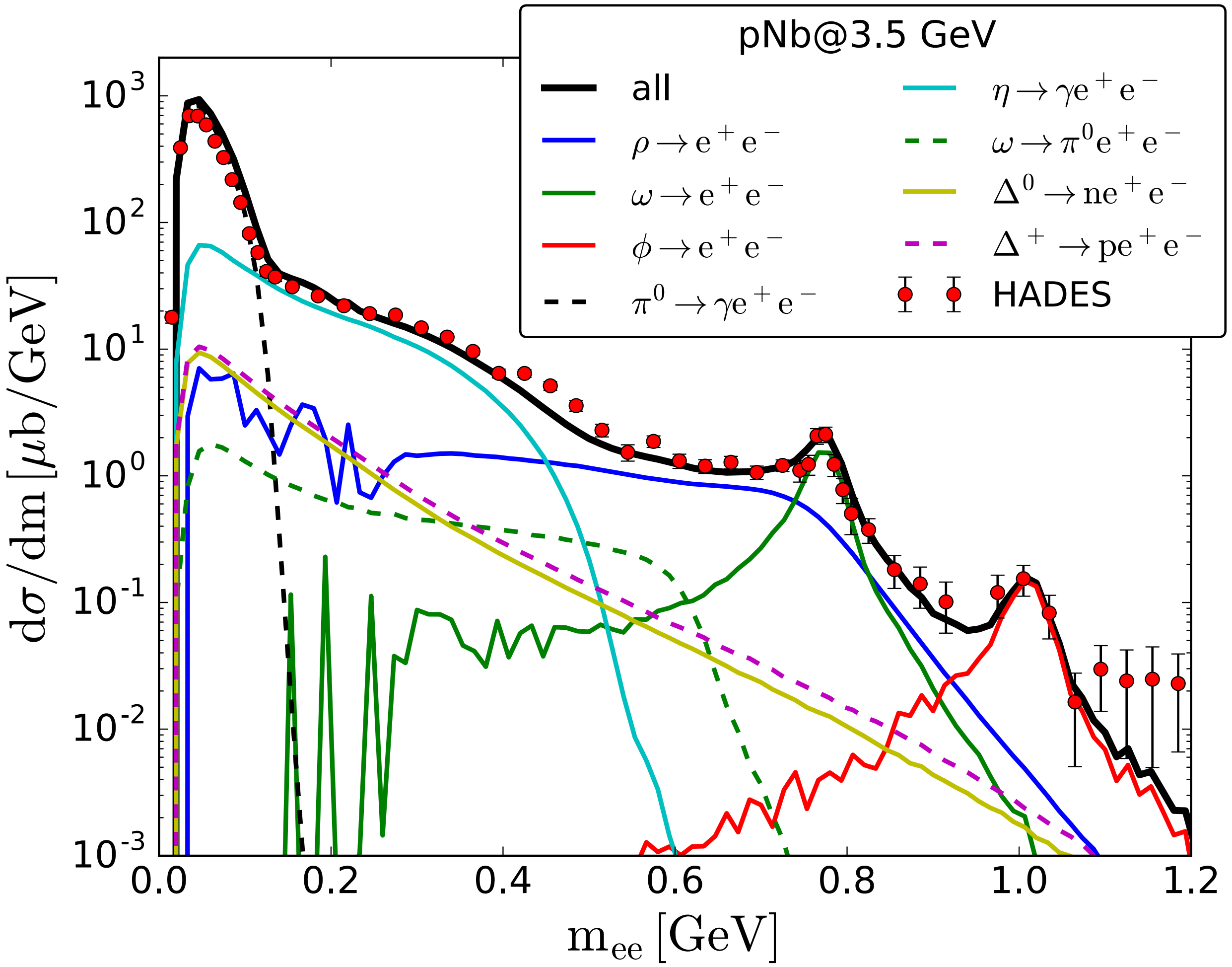


- Sub-threshold Φ and Ξ production is visible
- Decay channels of high N* resonances unknown

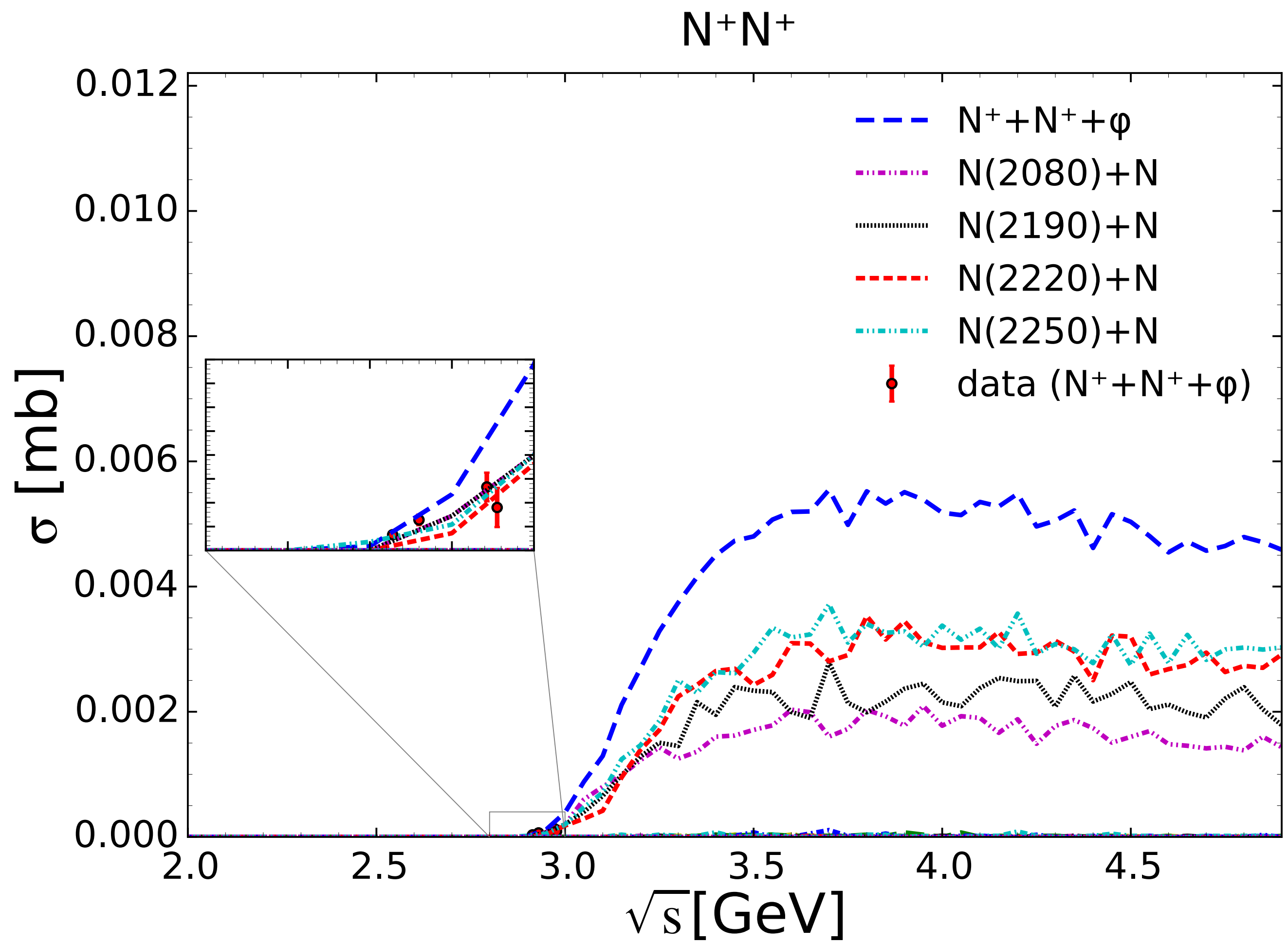
Φ Production in SMASH

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

HADES, Phys.Lett. B715 (2012)



V. Steinberg and J. Staudenmaier

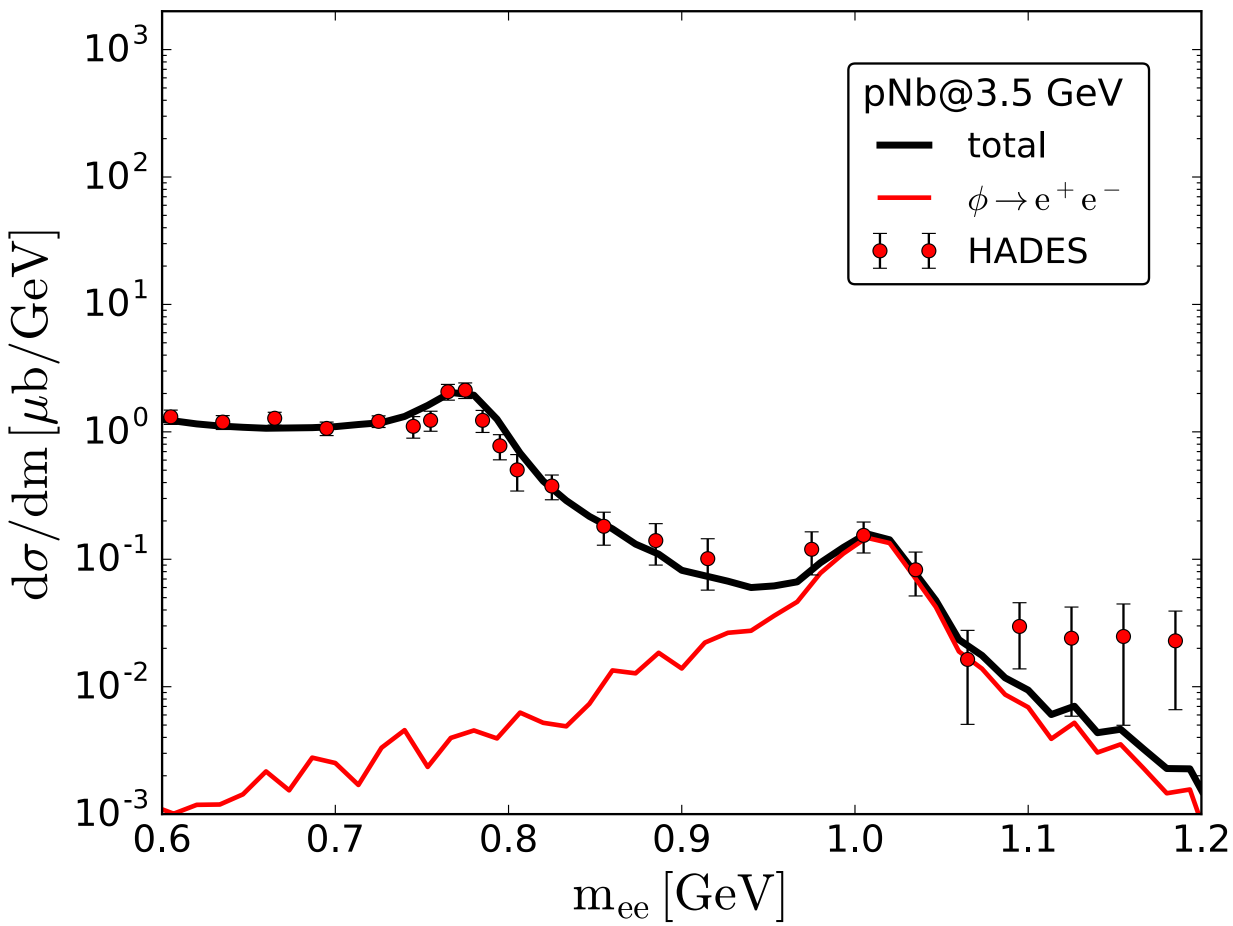


- Work in progress: prediction for Φ production in heavy ion collisions

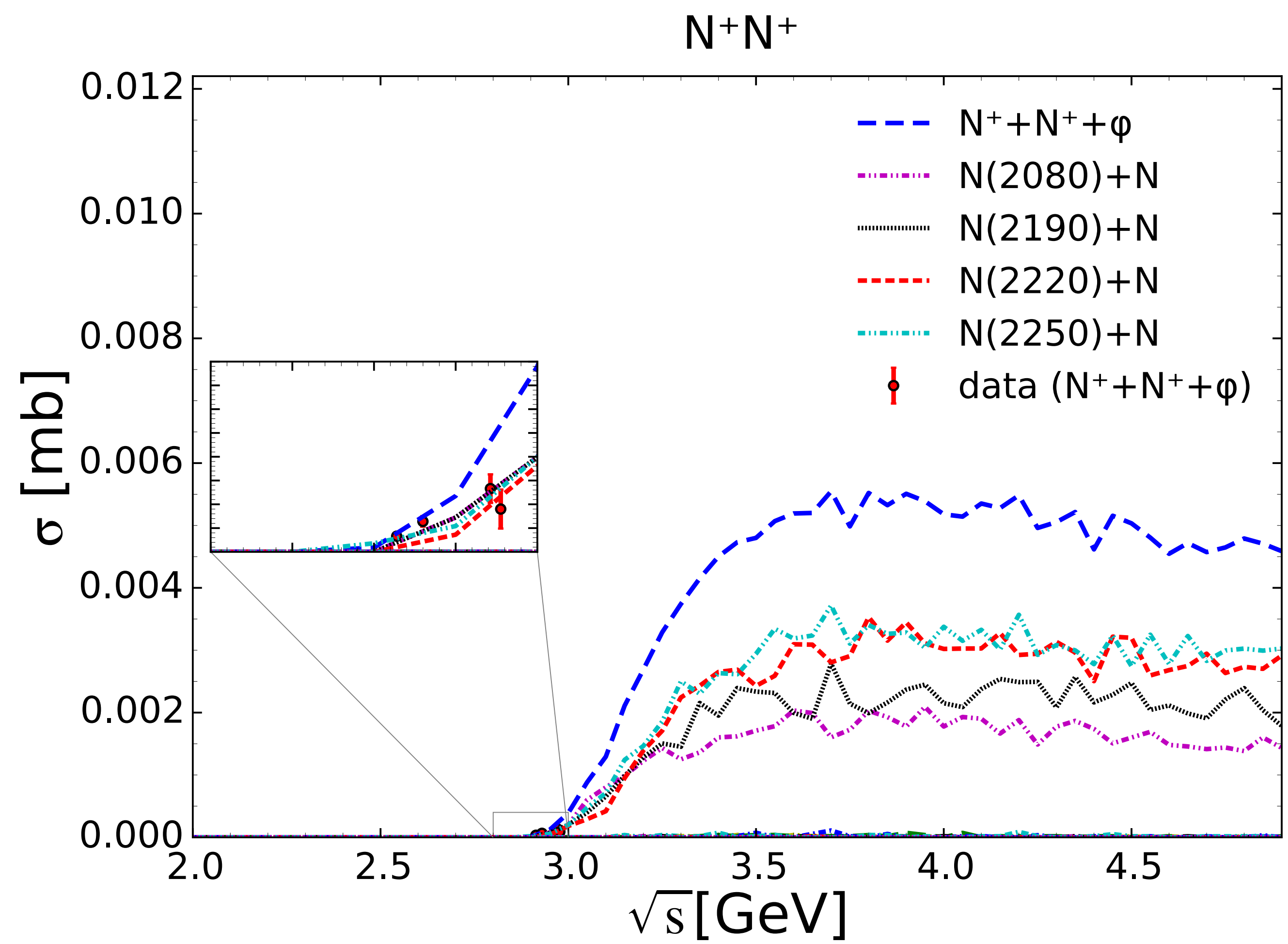
Φ Production in SMASH

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

HADES, Phys.Lett. B715 (2012)



V. Steinberg and J. Staudenmaier



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

Strangeness Production

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

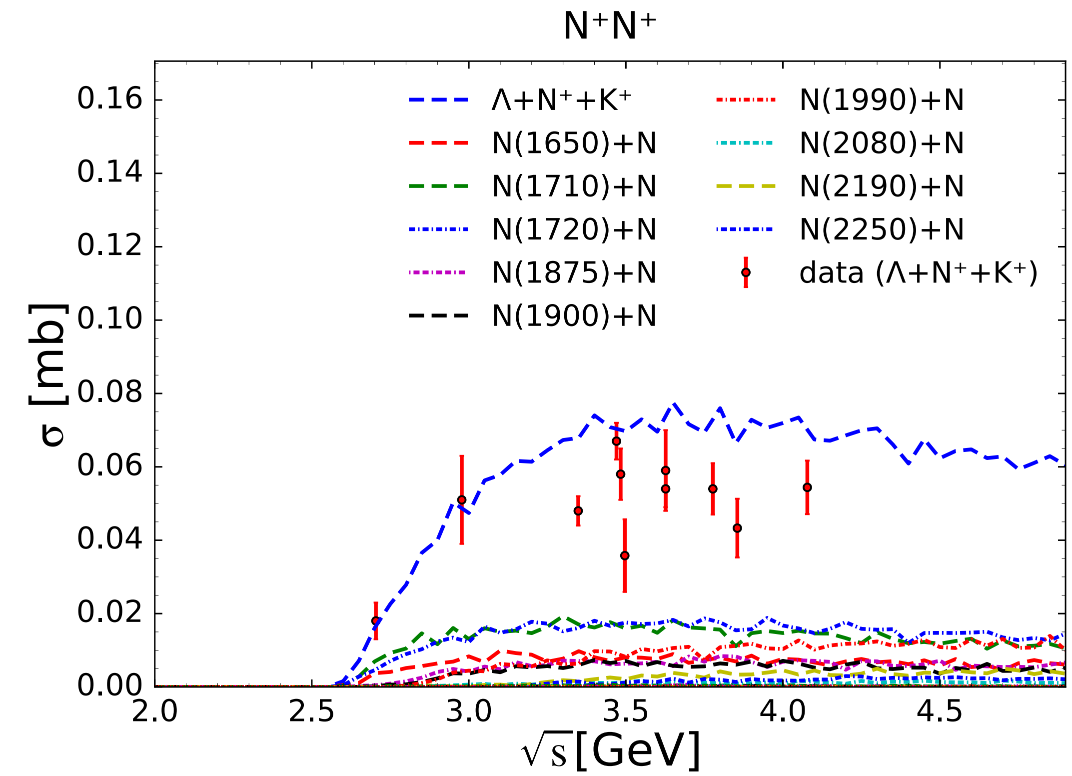
$$NN \to NN^*/\Delta^* \to NYK$$

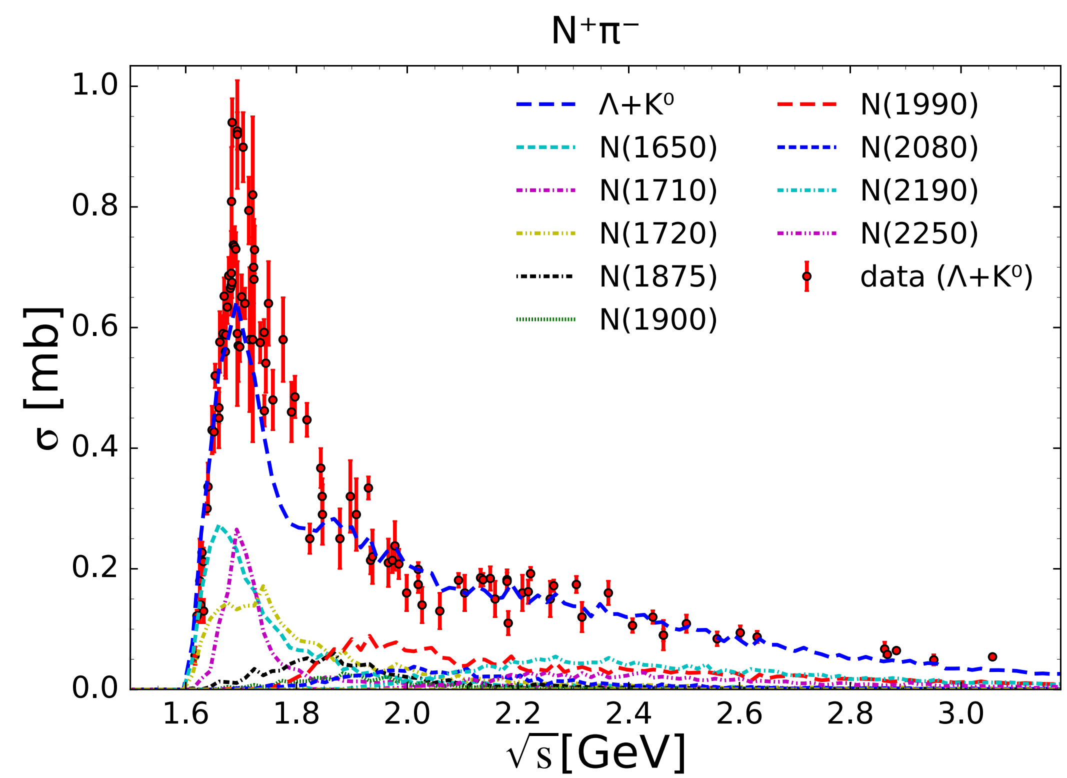
K^- production:

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

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%

- Elementary cross-sections provide constraints





by V. Steinberg

Summary and Outlook

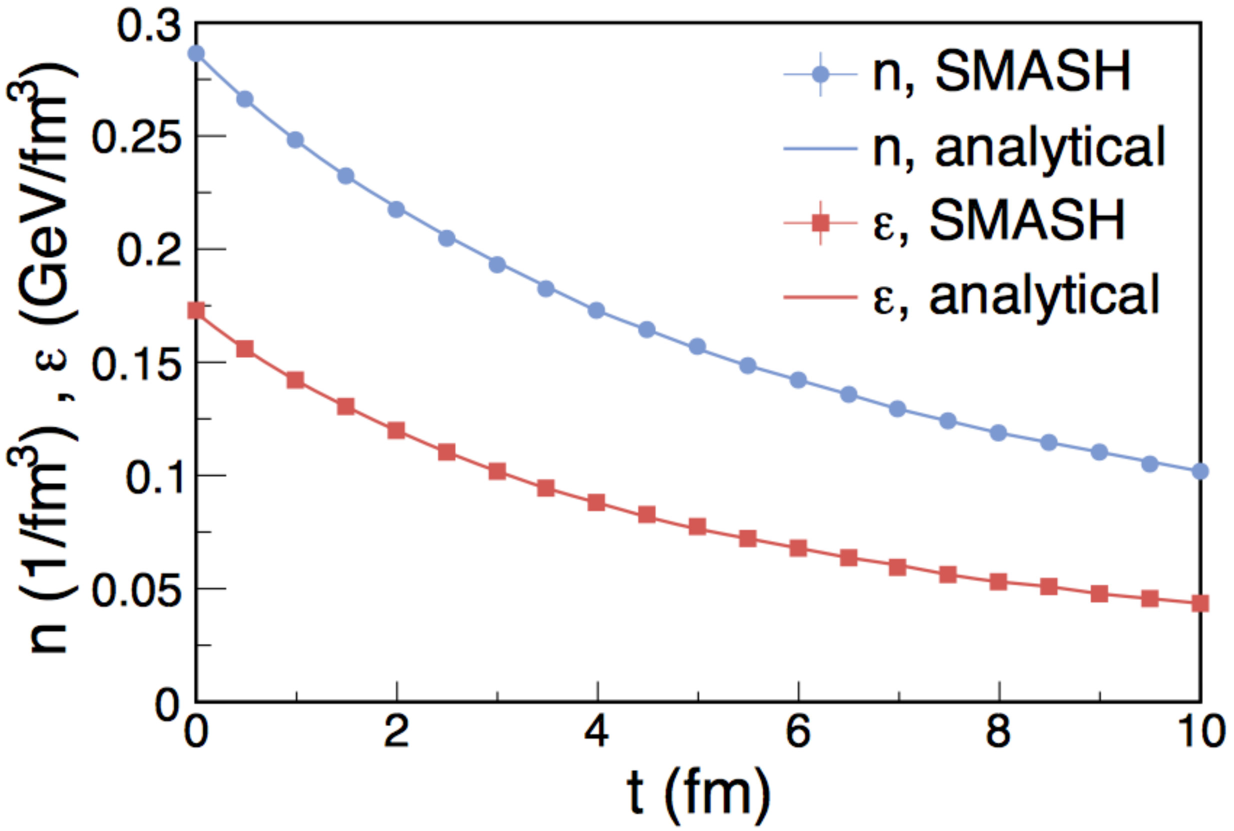
- New hadronic transport approach SMASH
  - Bulk observables are in reasonable agreement with experimental data
  - Electromagnetic observables are integrated
- Baryon resonances are of major importance to understand heavy ion collisions in the high baryon density regime (HADES and CBM at GSI/FAIR)
- Data for elementary and heavy ion reactions is crucial to constrain properties of resonances
- Outlook:
  - Publications on dileptons and strangeness
  - Implementation of high-energy cross-sections
  - Publication of source code

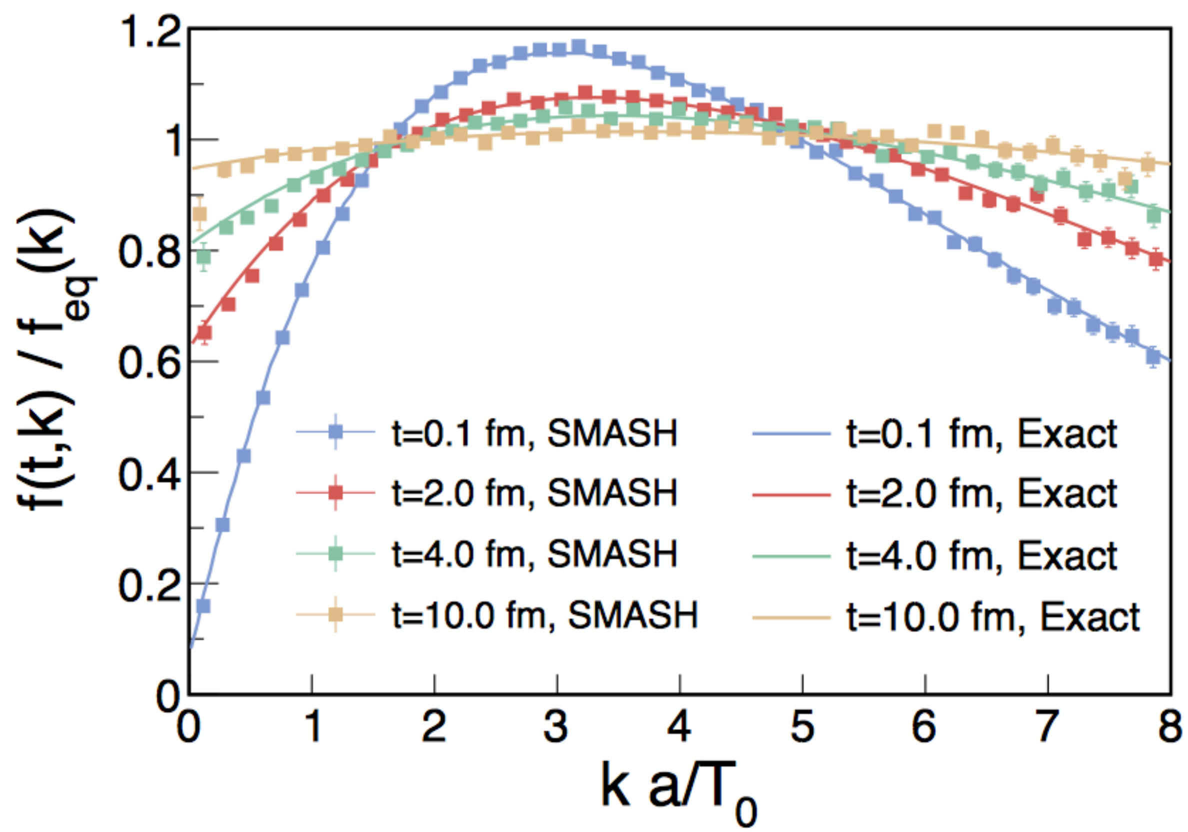
Backup

Analytic Solution

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

- Comparison to analytic solution of Boltzmann equation within expanding metric





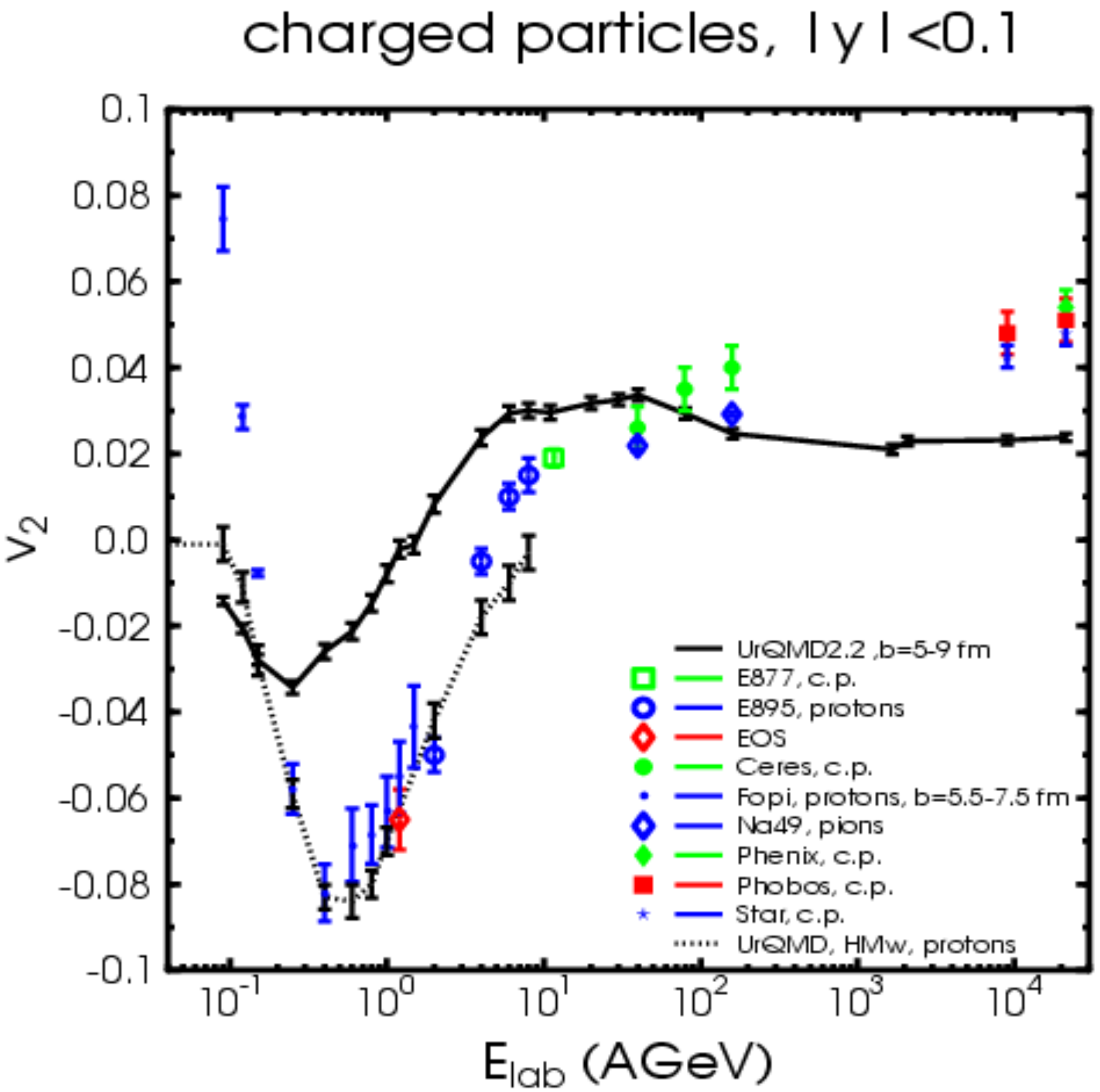
- Perfect agreement proves correct numerical implementation of collision algorithm

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

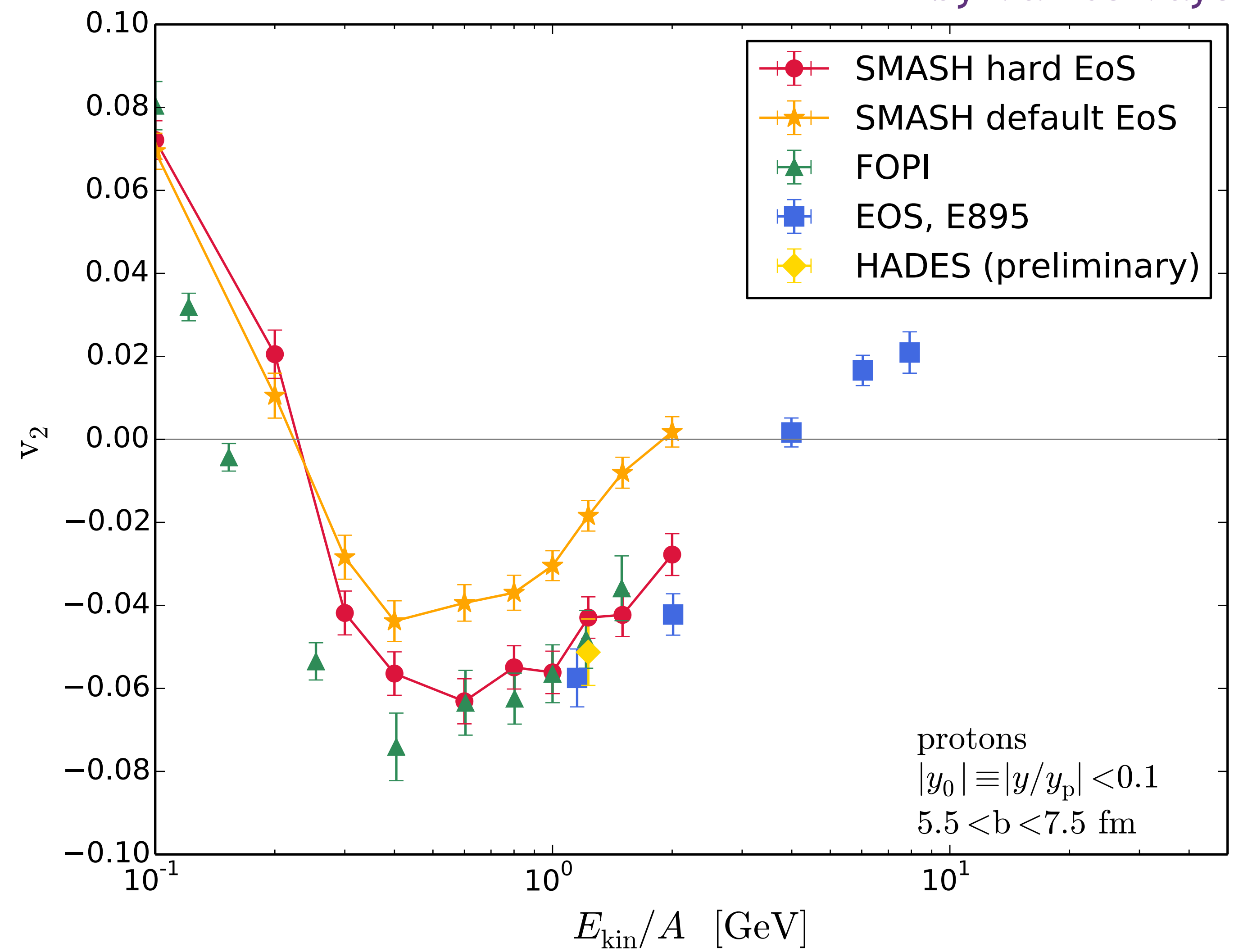
Collective Flow -v_2

- 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

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