Dilepton production and resonance properties within a new hadronic transport approach

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Gojko Vujanovic, Uli Heinz & Hannah Elfner

ECT* workshop: Electromagnetic Radiation from Hot and Dense Hadronic Matter

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DFG
CRC-TR 211 Strong-interaction matter under extreme conditions
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Dileptons in hadronic transport

- Emission of dileptons in dilute/ not equilibrated systems
- Complementary constraint to hadronic observables…

  … on the dynamical evolution of the system

  … on the resonance description
- Disentangle medium effects to resonance properties

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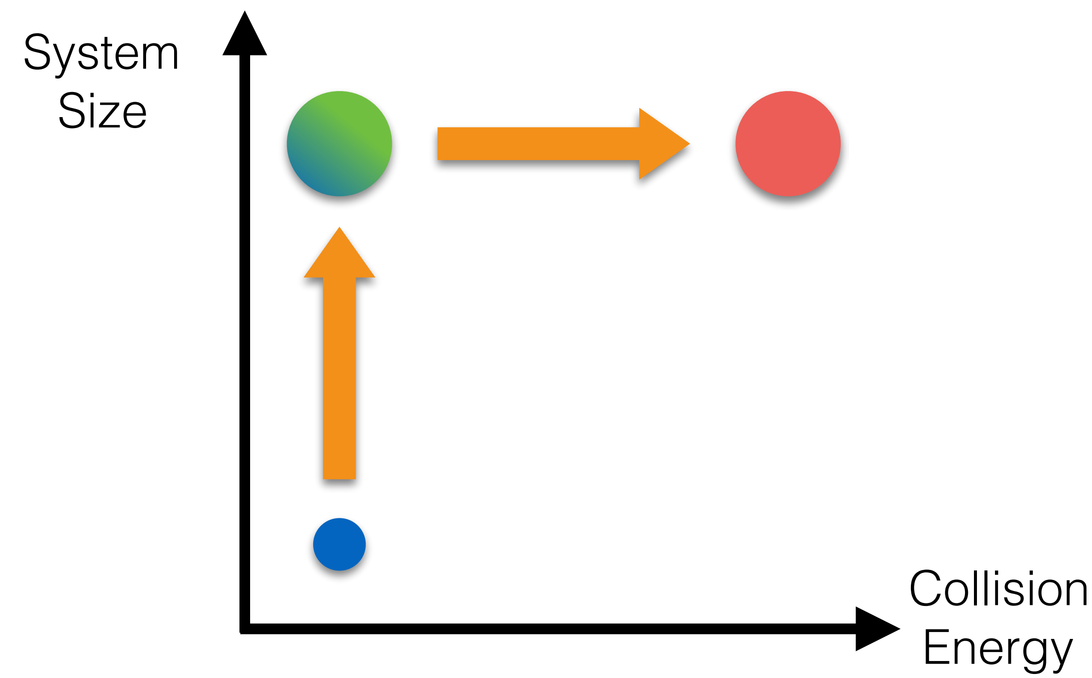
Dilepton production within 3 different approaches

1. **Hadronic Transport**
2. *Coarse-graining*
3. *Hybrid*



SMASH*

* **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons

J.Weil et al, Phys. Rev. C 94, 054905 (2016)

- New transport approach for dilute non-equilibrium stages of HIC and low energy collisions
- **Goal**: standard reference for hadronic system with vacuum properties
- **Scenarios**: nuclear collisions, infinite matter, afterburner for hydrodynamic simulations

See also Anna Schäfer's Talk

- **Features**: geometric collision criterion, Test Particle Method, Mean-Field potentials, Fermi motion, Pauli blocking
- **Degrees of freedom**: all well-known particles from PDG up to a mass of 2 GeV

$$\pi, \eta, \eta', \rho, \omega, \phi, K, \ldots \qquad N, N^*, \Delta, \Delta^*, \ldots$$

  - perturbative treatment of non-hadronic particles (photons, leptons)

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smash

Now publicly available to use and contribute:

https://github.com/smash-transport/smash

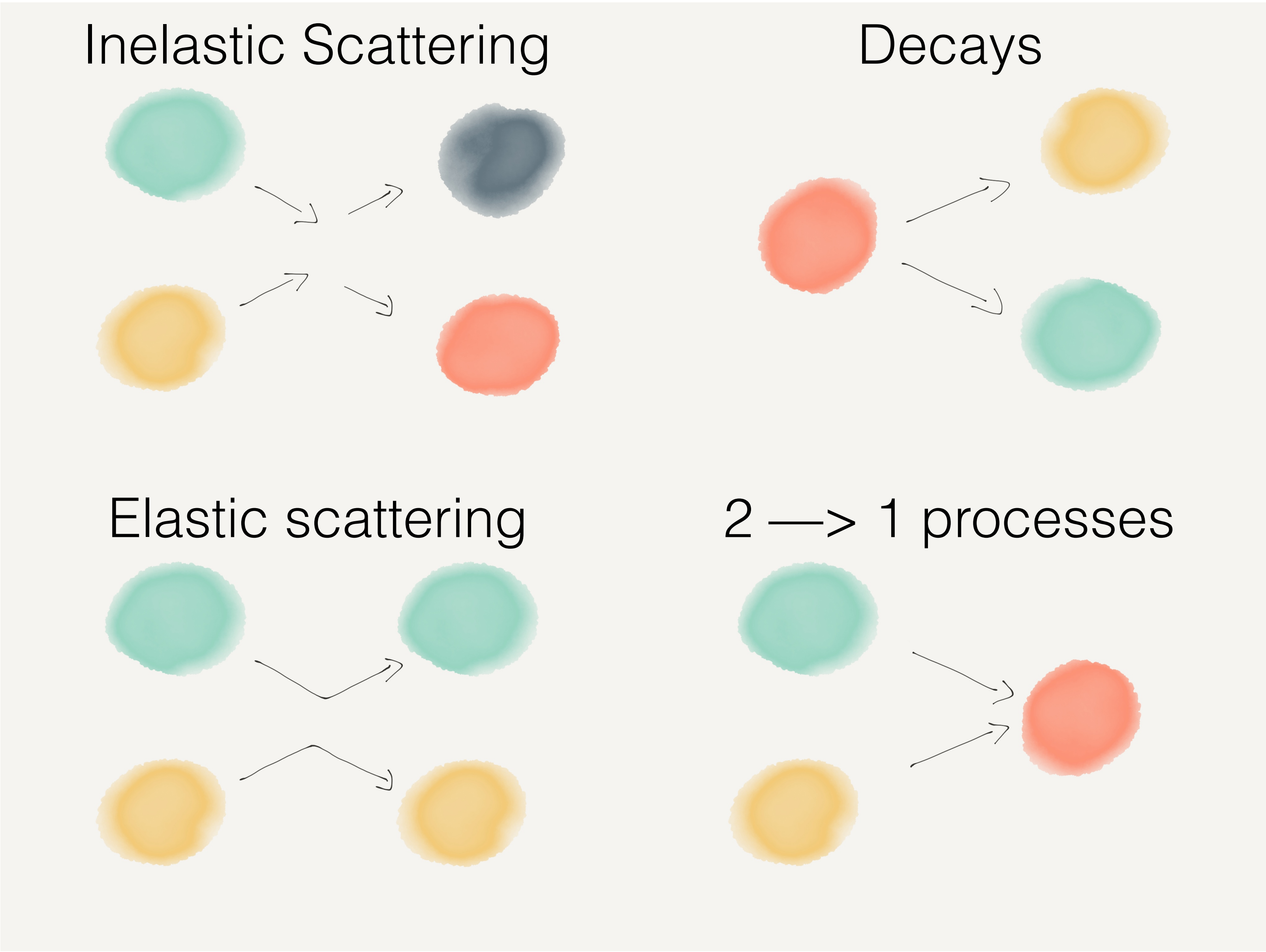
or

https://smash-transport.github.io

SMASH-1.5

Collision Term

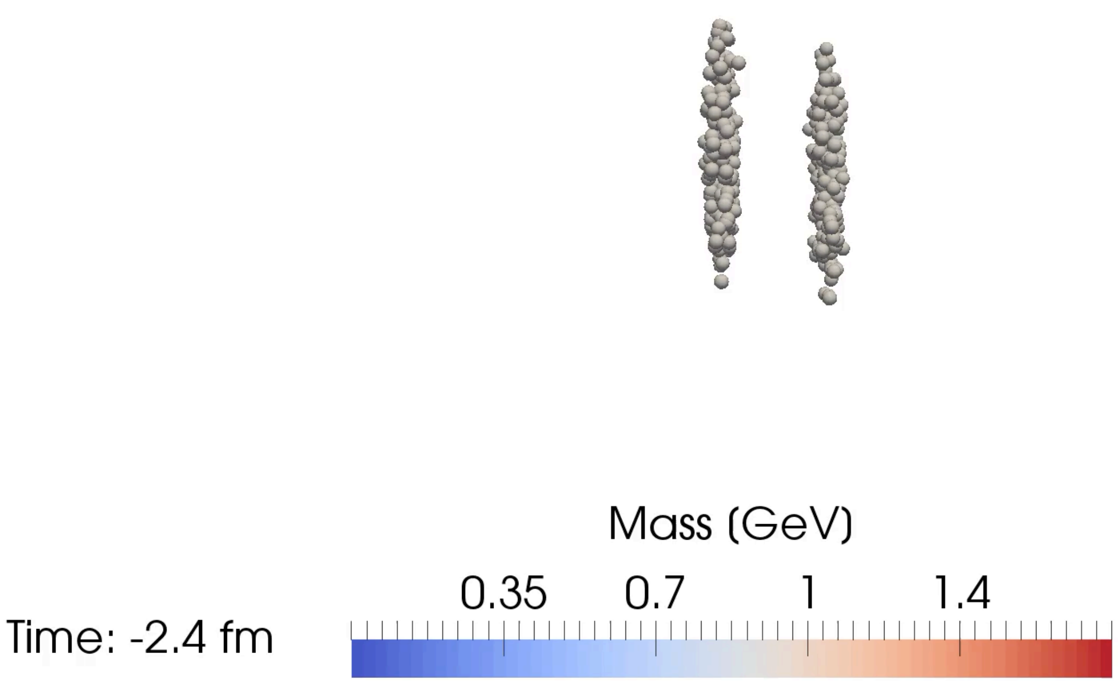
$$p^\mu \partial_\mu f_i(x,p) + m_i \partial^p_\alpha F^\alpha f_i(x,p) = C^i_{\text{coll}}$$



- In few GeV energy regime decay and excitation of resonances dominate hadronic cross section
- High energy scatterings: string fragmentation with pythia

Collision Term

Calculation for Pb-Pb at 17.3 GeV



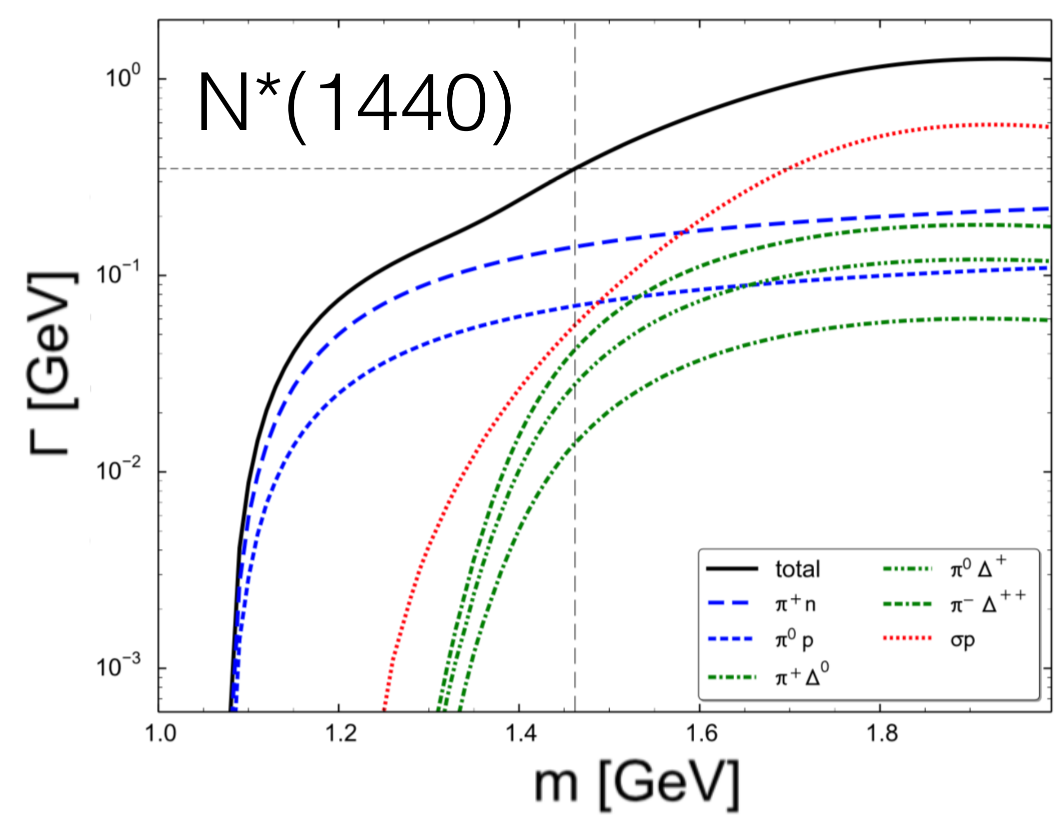
- In few GeV energy regime decay and excitation of resonances dominate hadronic cross section
- High energy scatterings: string fragmentation with pythia

Resonances

- Spectral Function

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

  - All unstable particles ("resonances“) have relativistic Breit-Wigner spectral functions



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

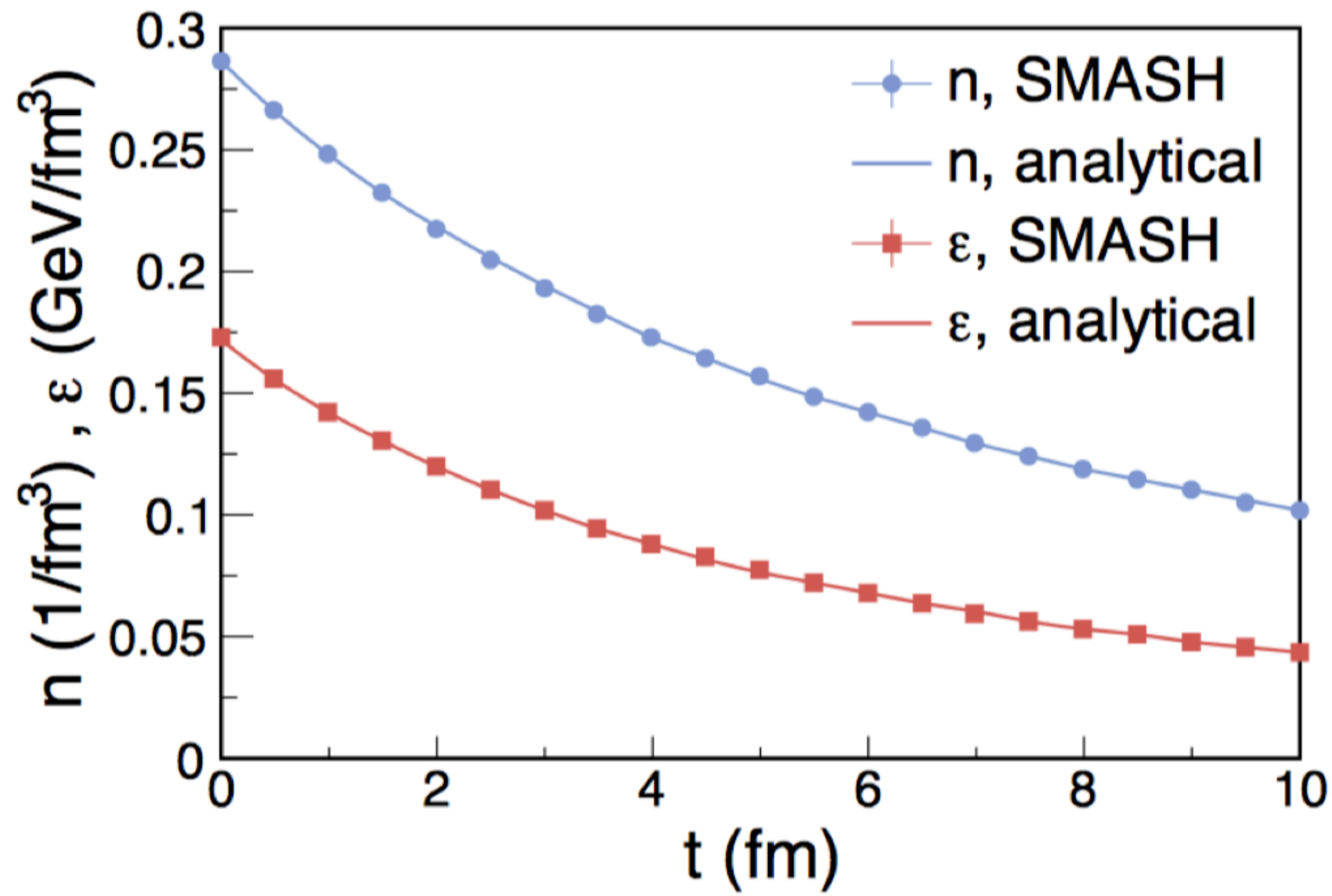
with other resonance properties

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

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

Analytic Solution

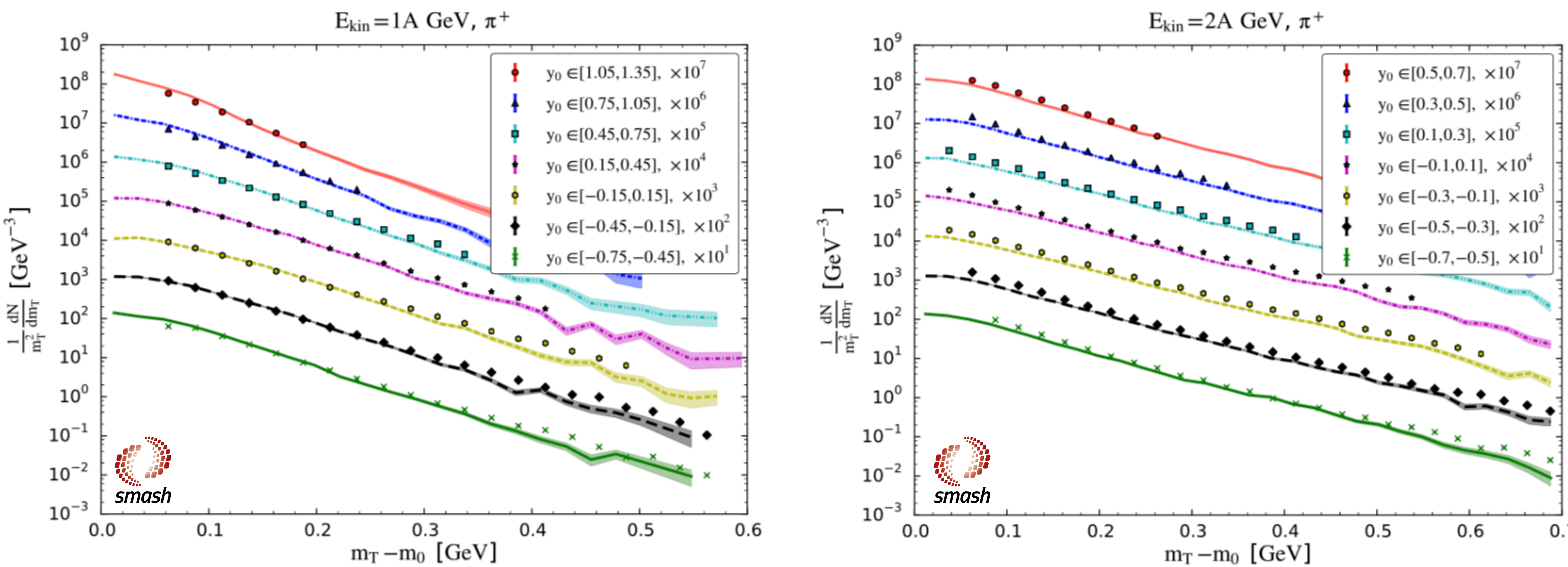
- Comparison to analytic solution of Boltzmann equation within expanding metric
- Perfect agreement proves correct numerical implementation of collision algorithm



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

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

Pion Production



- Pion production in comparison with HADES data for carbon-carbon reactions at a few GeV
- Nice agreement with SIS data

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)
- For more details and results:

JS, J. Weil, V. Steinberg, S. Endres, H. Petersen
Phys. Rev. C 98, 054908

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

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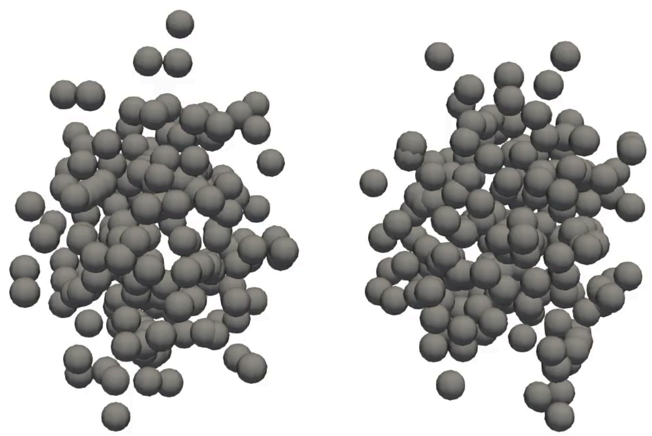
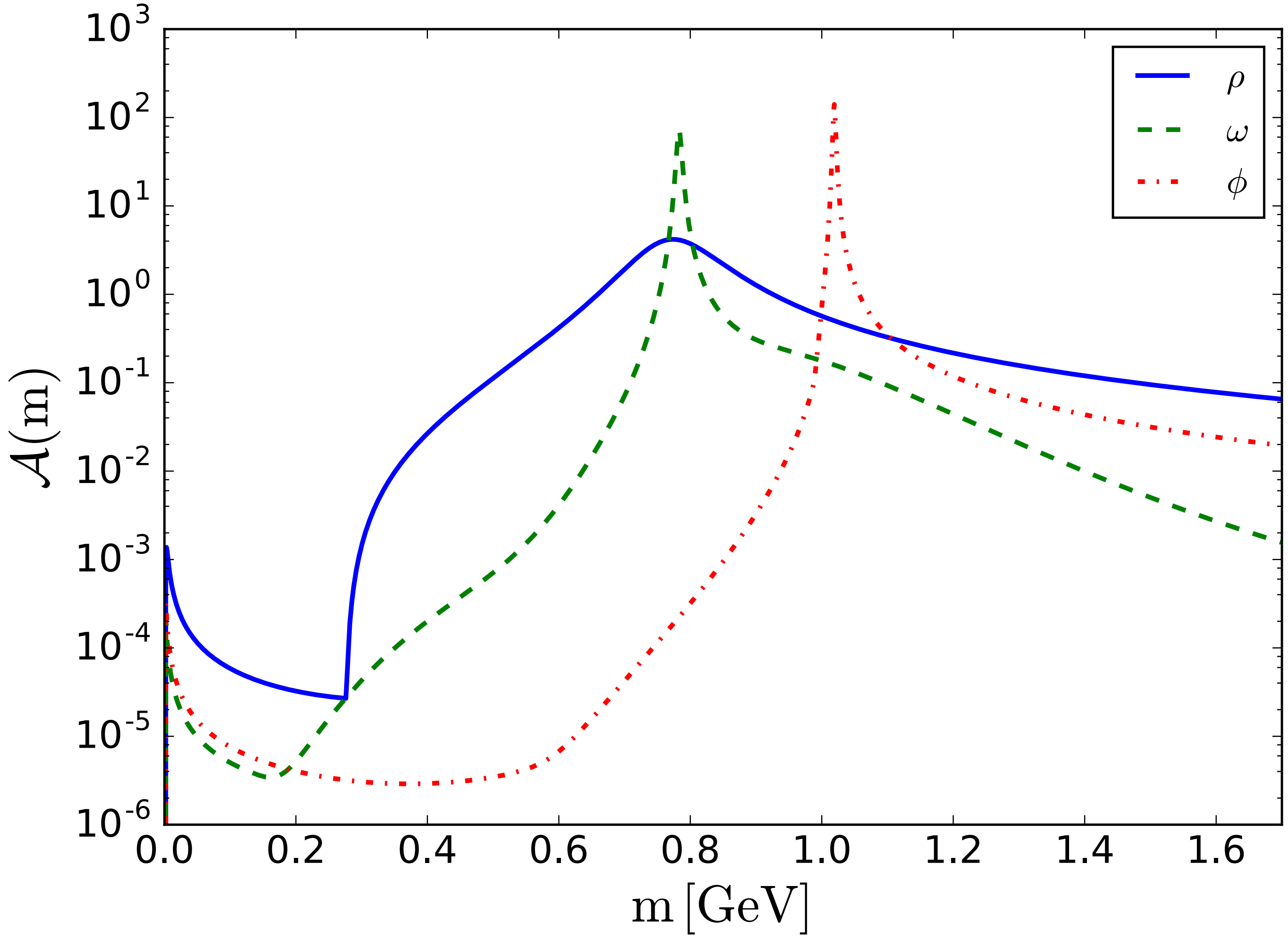
AuAu at 1.23A GeV



by J. Mohs

Spectral functions

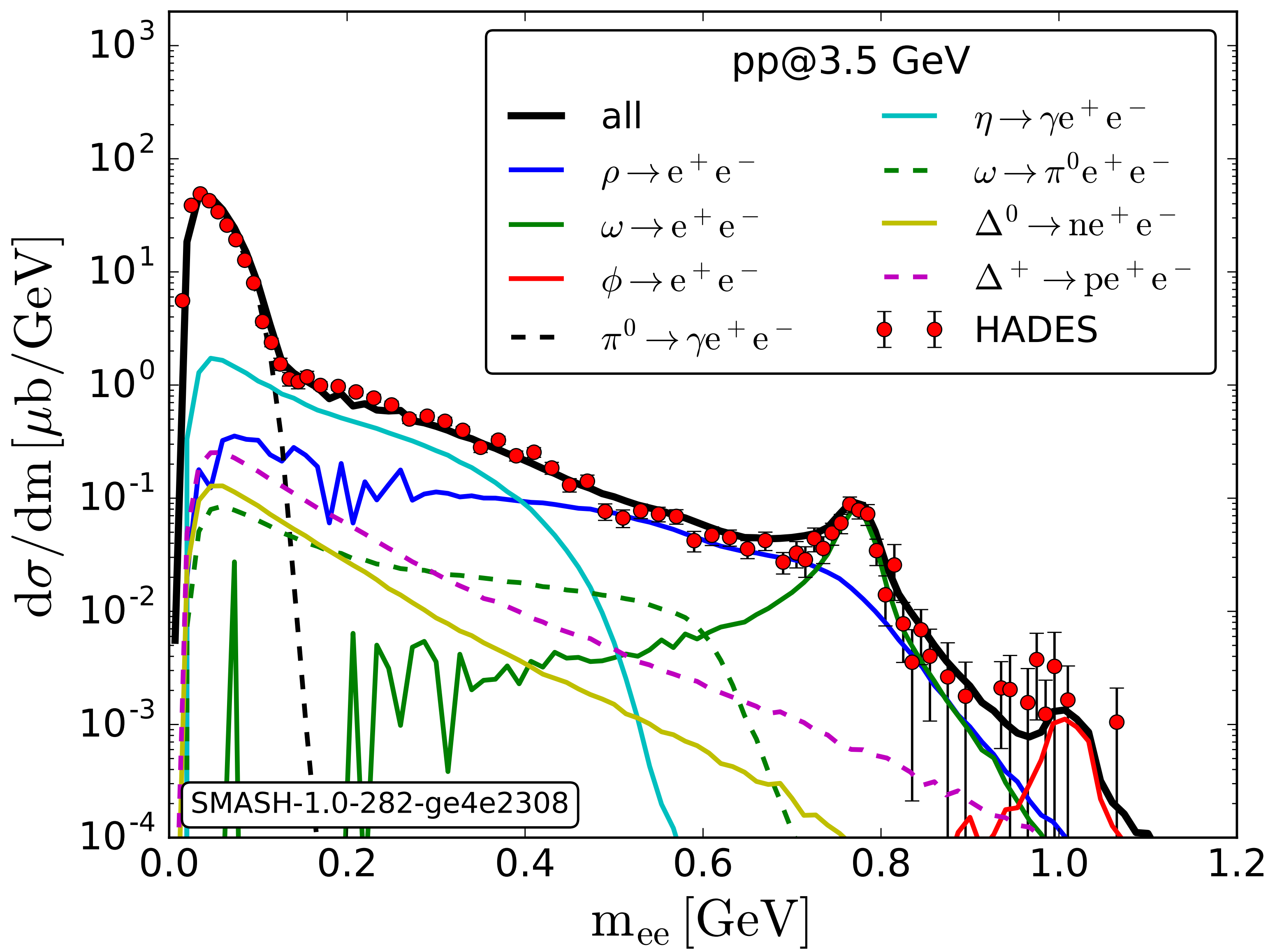


- Spectral function for vector mesons take dilepton decay into account
- Contributions below hadronic threshold from dilepton decay width

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

Elementary reactions

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

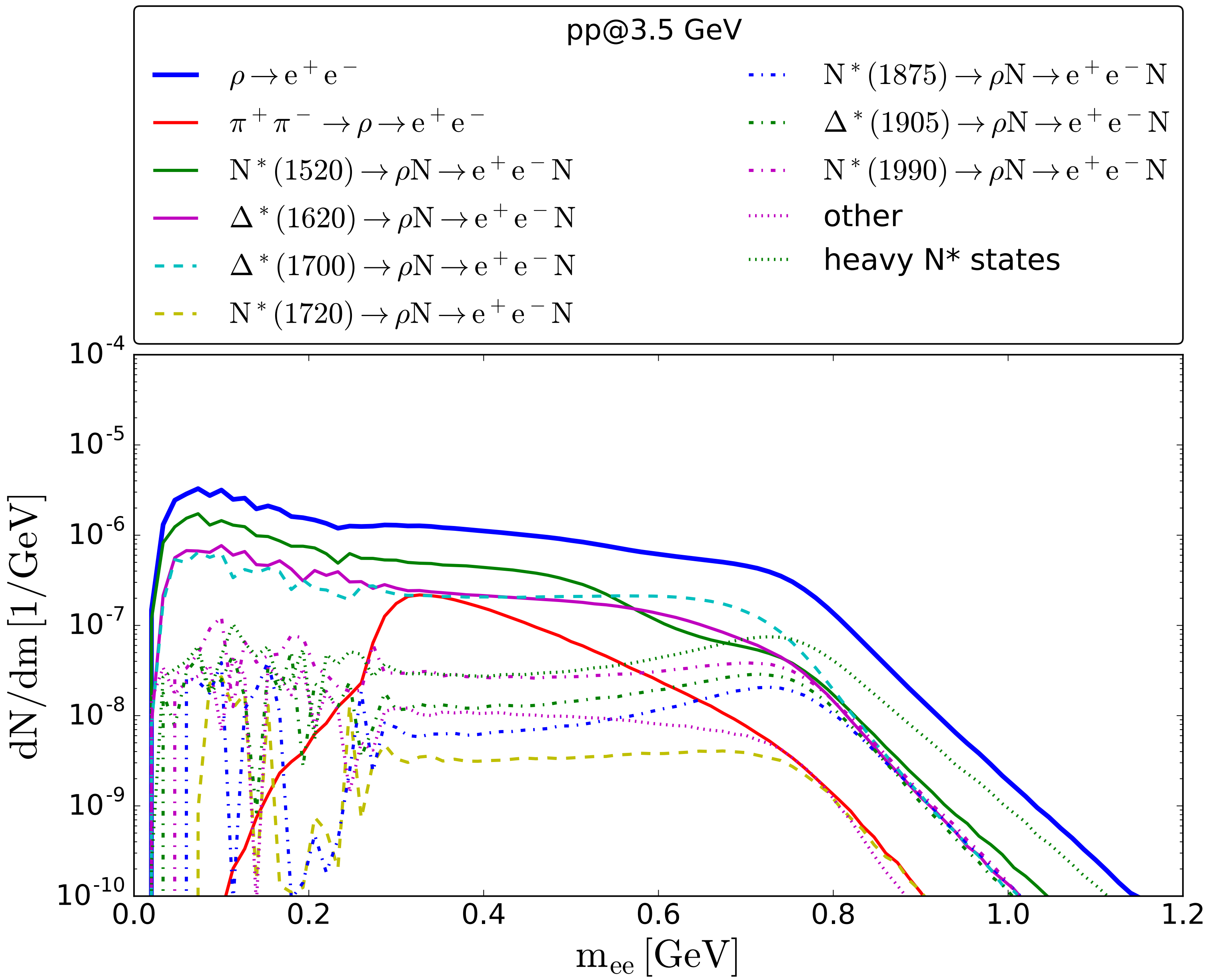


pp, 3.5 GeV

- Invariant mass spectrum for pp collision with E_{kin} = 3.5 GeV
- Constraining elementary reaction baseline
- Sub-threshold contributions by direct vector mesons decays
- Very good agreement with data

ρ origin in dilepton spectra

pp, 3.5 GeV

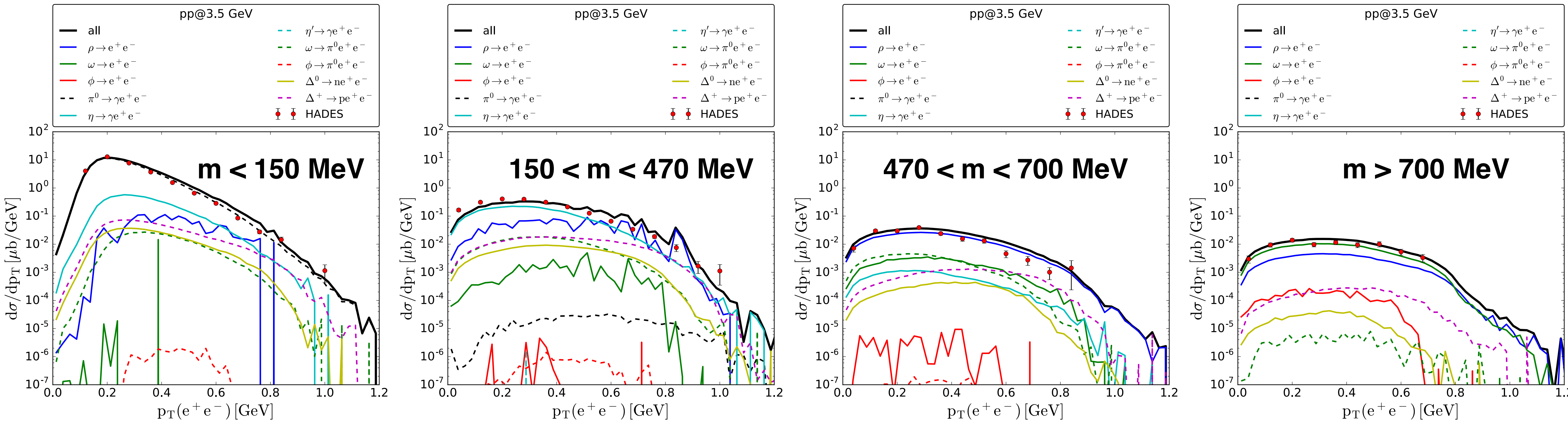


- Different processes that produce ρ that decays into di-electrons
- Valuable to understand the broad ρ contribution
- Mostly baryonic resonance decays, plus small pion annihilation
- Sub-threshold contribution by light baryonic resonance decays

Elementary reactions

pp, 3.5 GeV

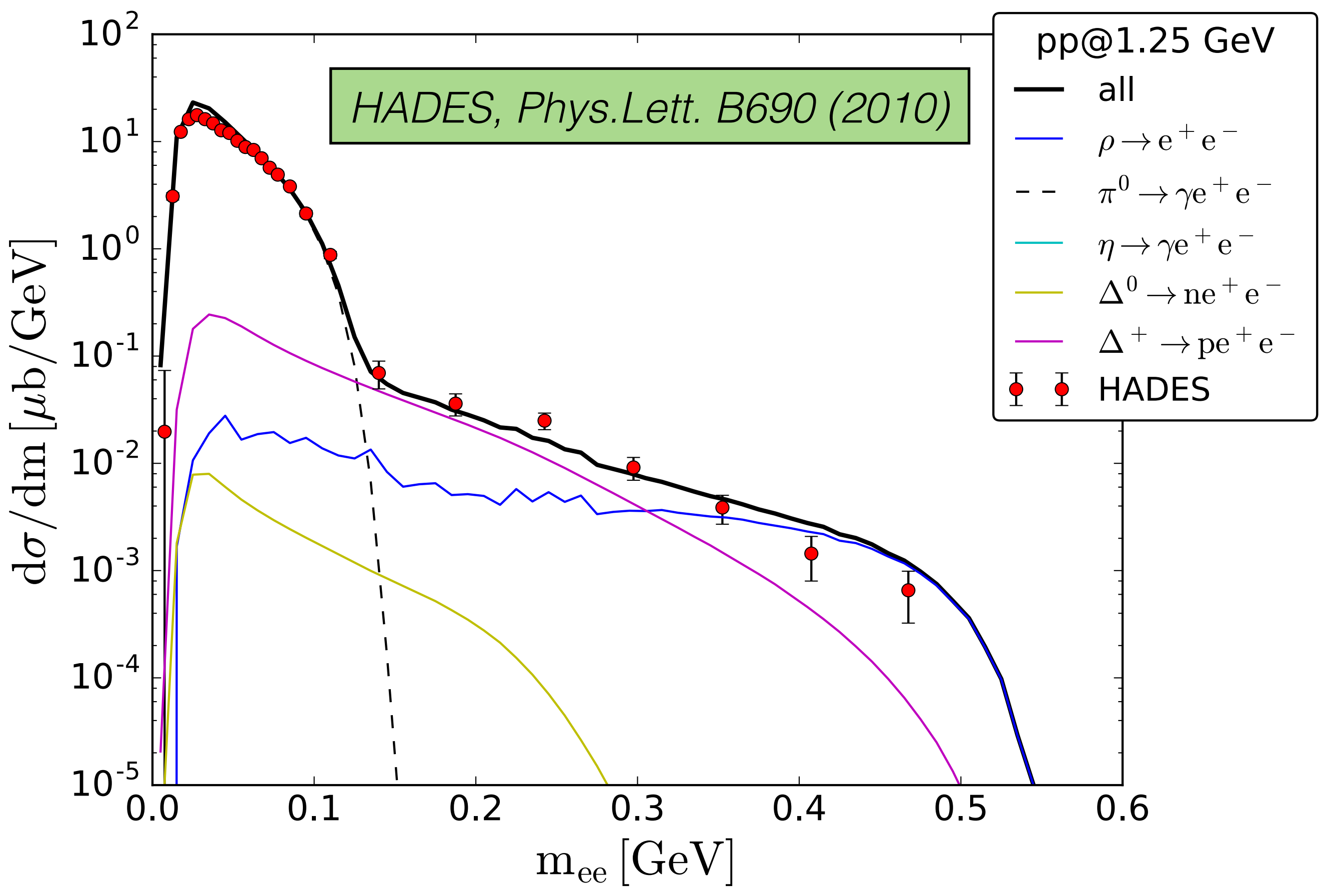
HADES, Eur.Phys.J. A48 (2012)



- Comparison of p_T spectra for different invariant mass windows
- Reasonable agreement for elementary reactions in all regions of phase space (also y)

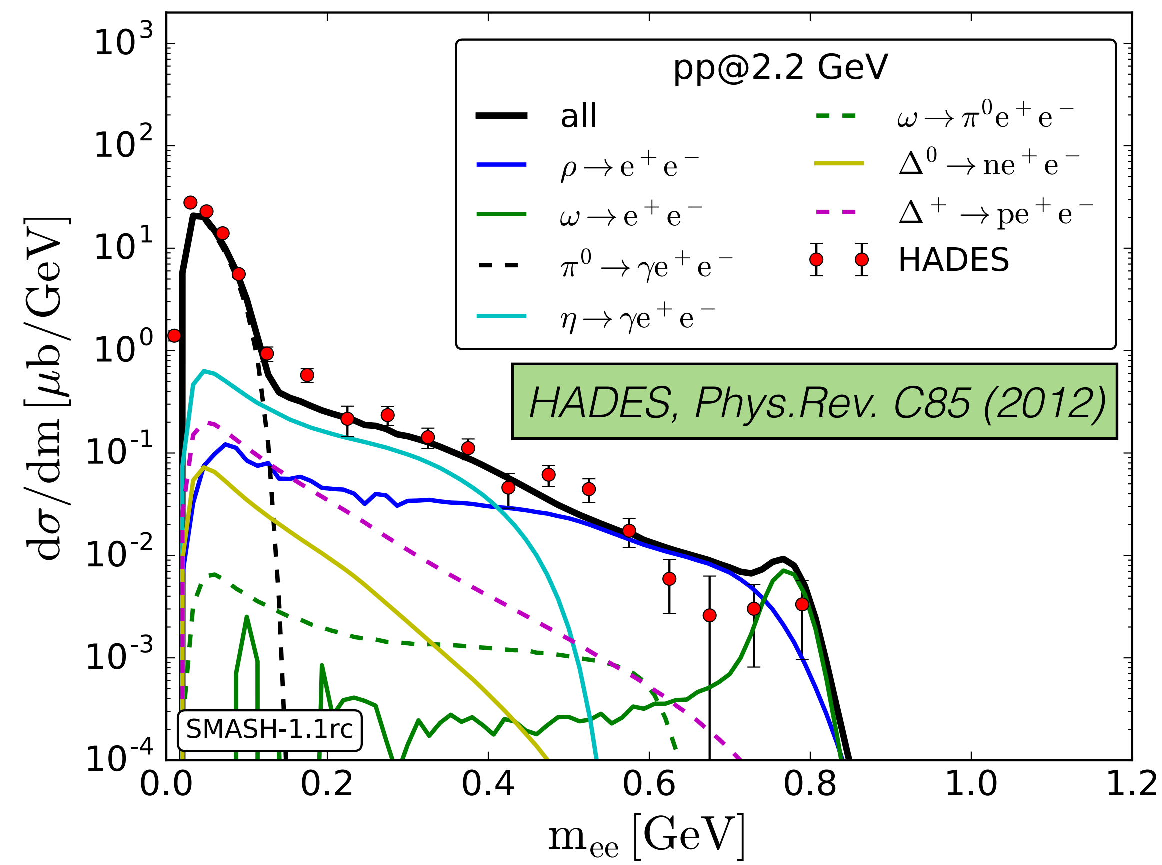
Elementary reactions

pp, 1.25 GeV



- Dominant channels are π, ρ, Δ
- Agreement with data

pp, 2.2 GeV



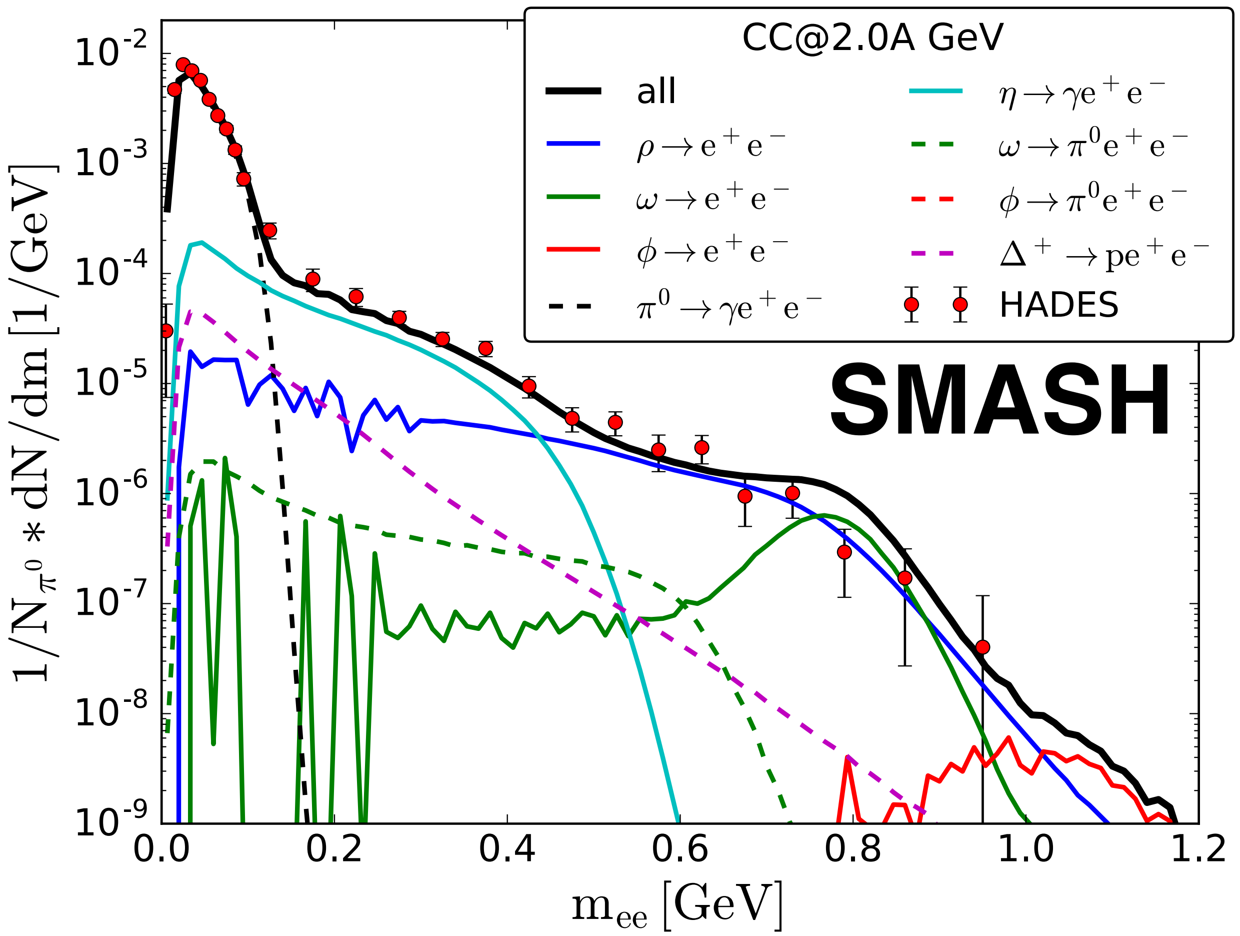
- Above η threshold
- Slight overproduction in high invariant mass region

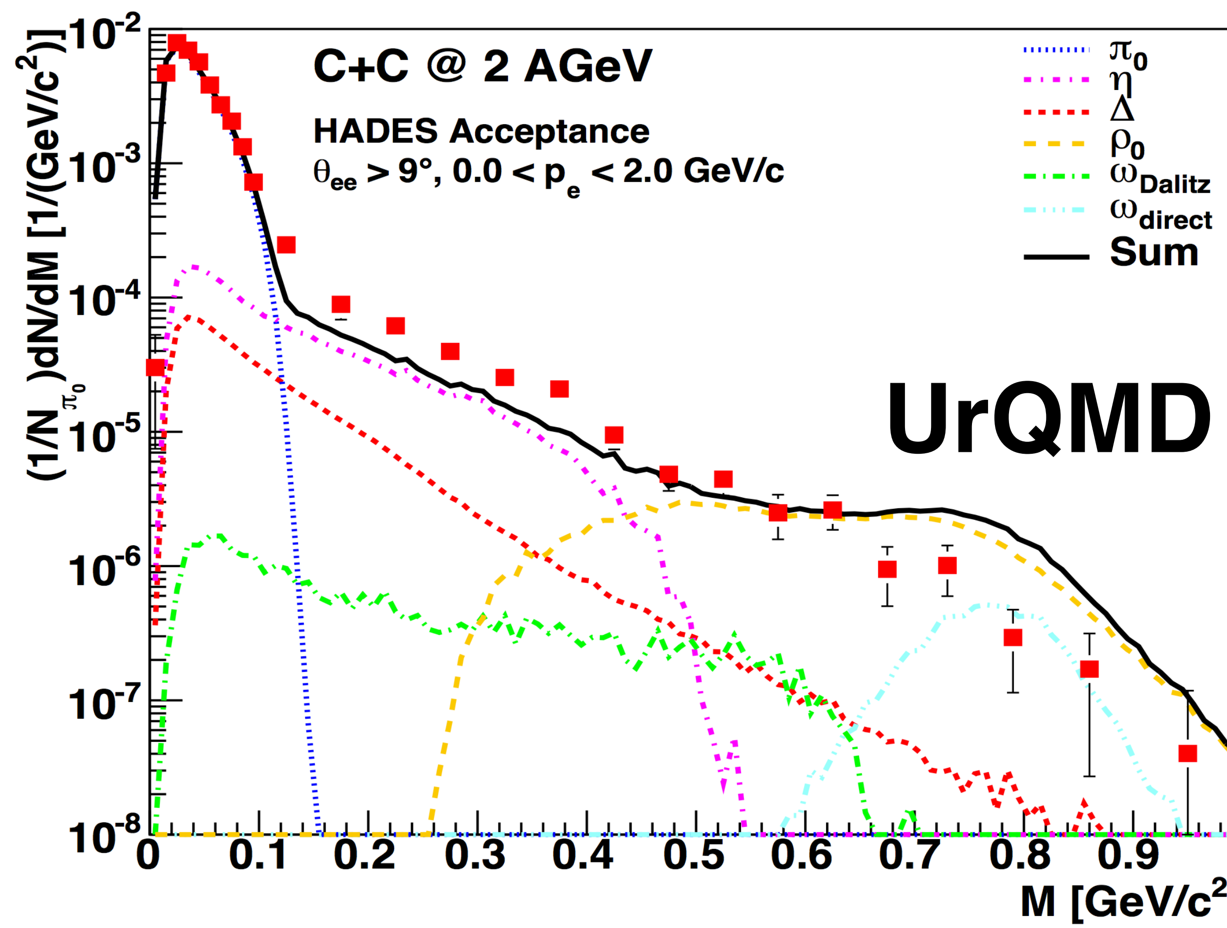
Small systems

HADES, Phys.Rev.Lett. 98 (2007)

CC, 2.0 AGeV

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



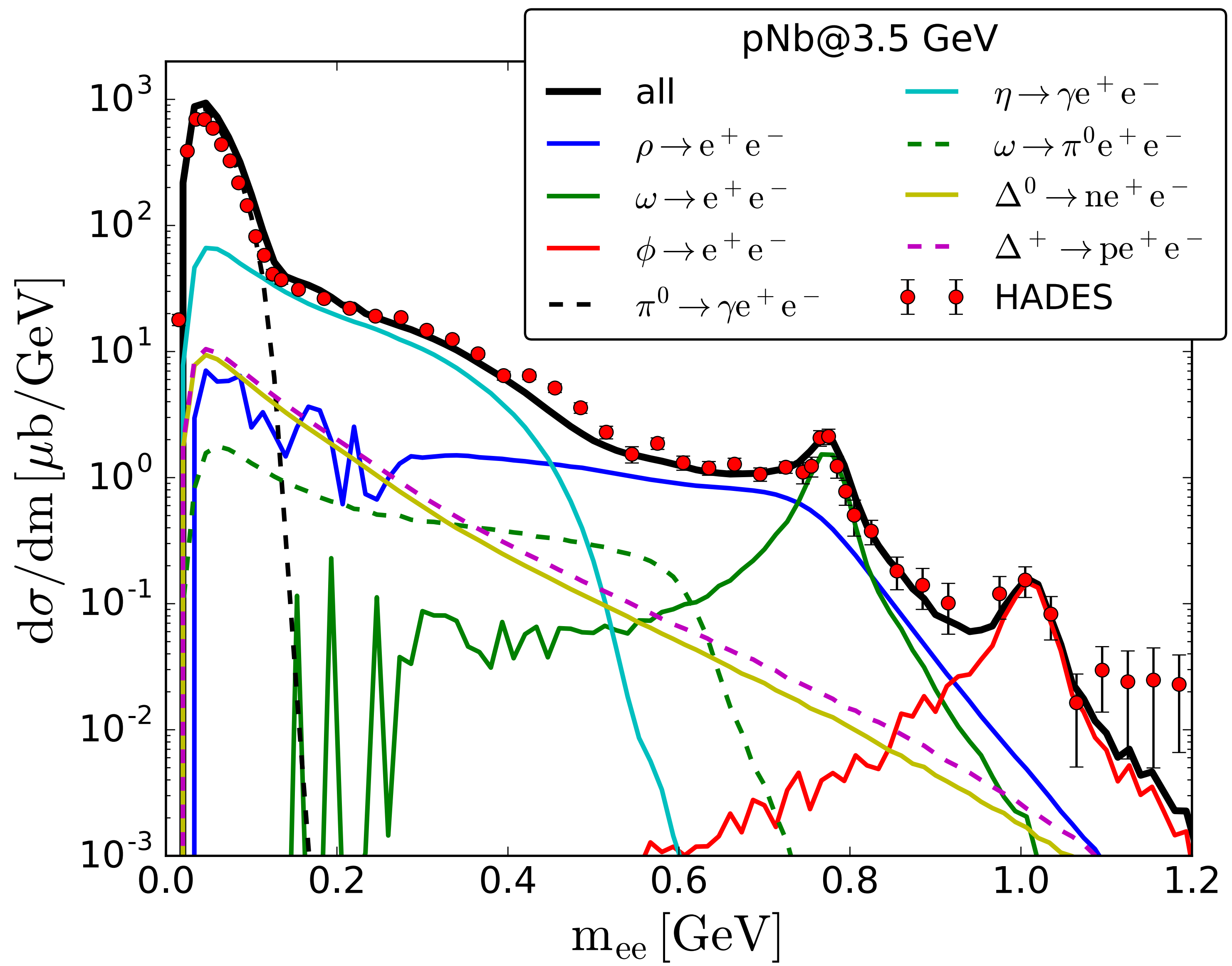


- SMASH and UrQMD compare similar to data
- Different vector meson thresholds

—> Good description for „small“ systems

Cold nuclear matter

HADES, Phys.Lett. B715 (2012)



pNb, 3.5 GeV

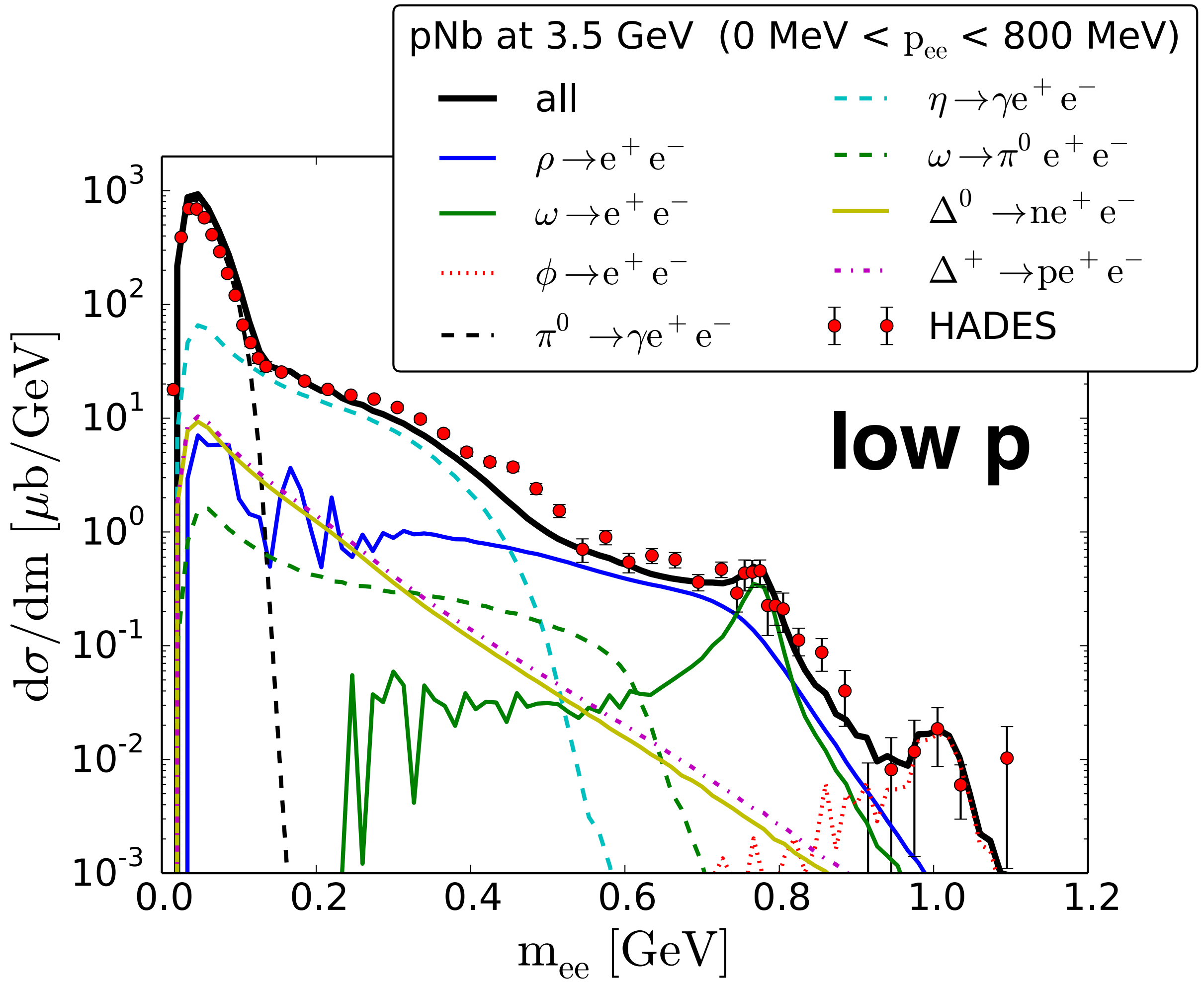
- pNb: cold nuclear matter scenario
- Φ peak used to constrain B.R.

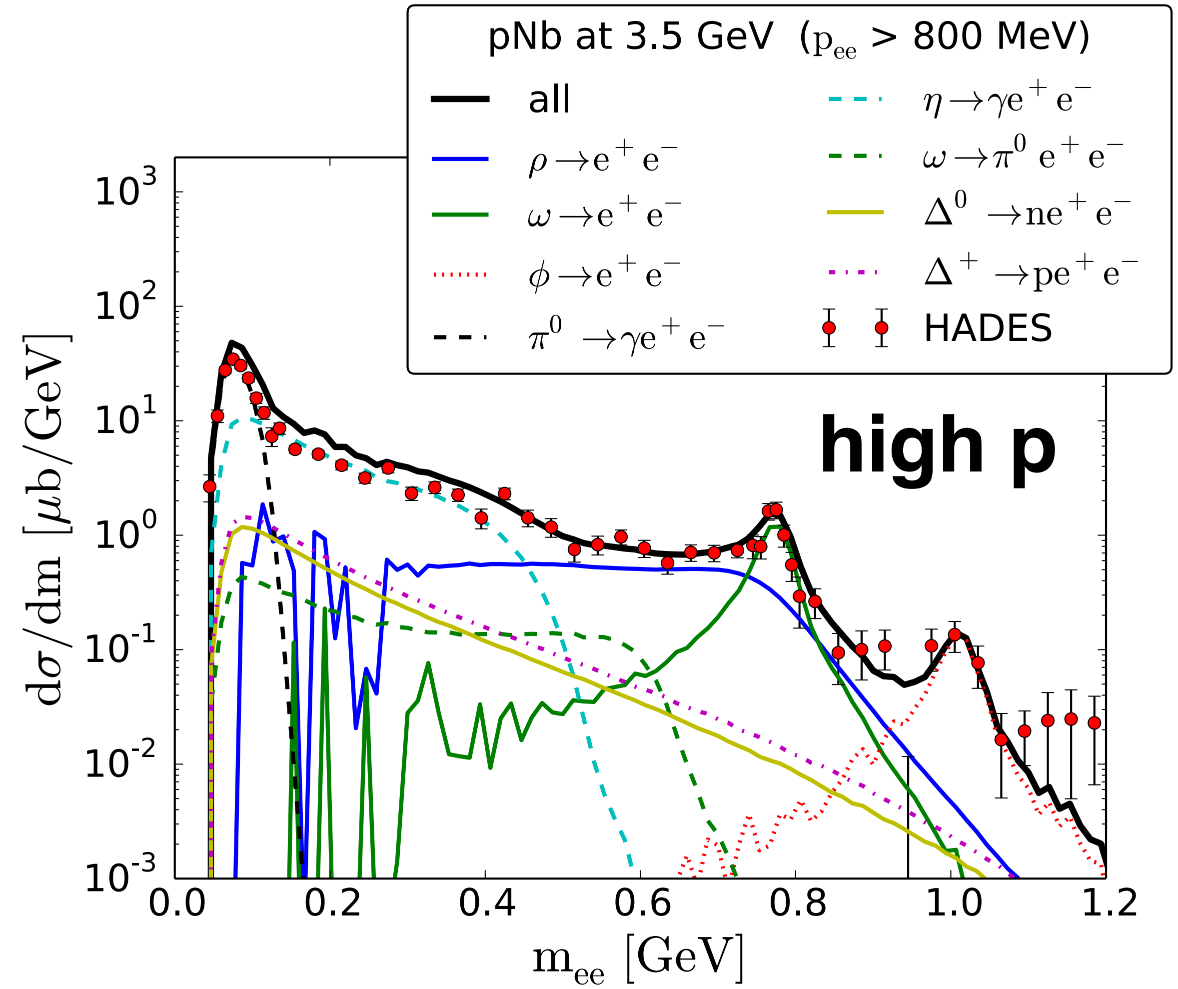
$$N^* \to N\phi$$

Steinberg et al., arXiv:1809.03828

- Effect of medium?!

Cold nuclear matter





- Underestimation around 0.5 GeV for long traversal of medium (low p)
- Resonance peaks are suppressed due to absorption

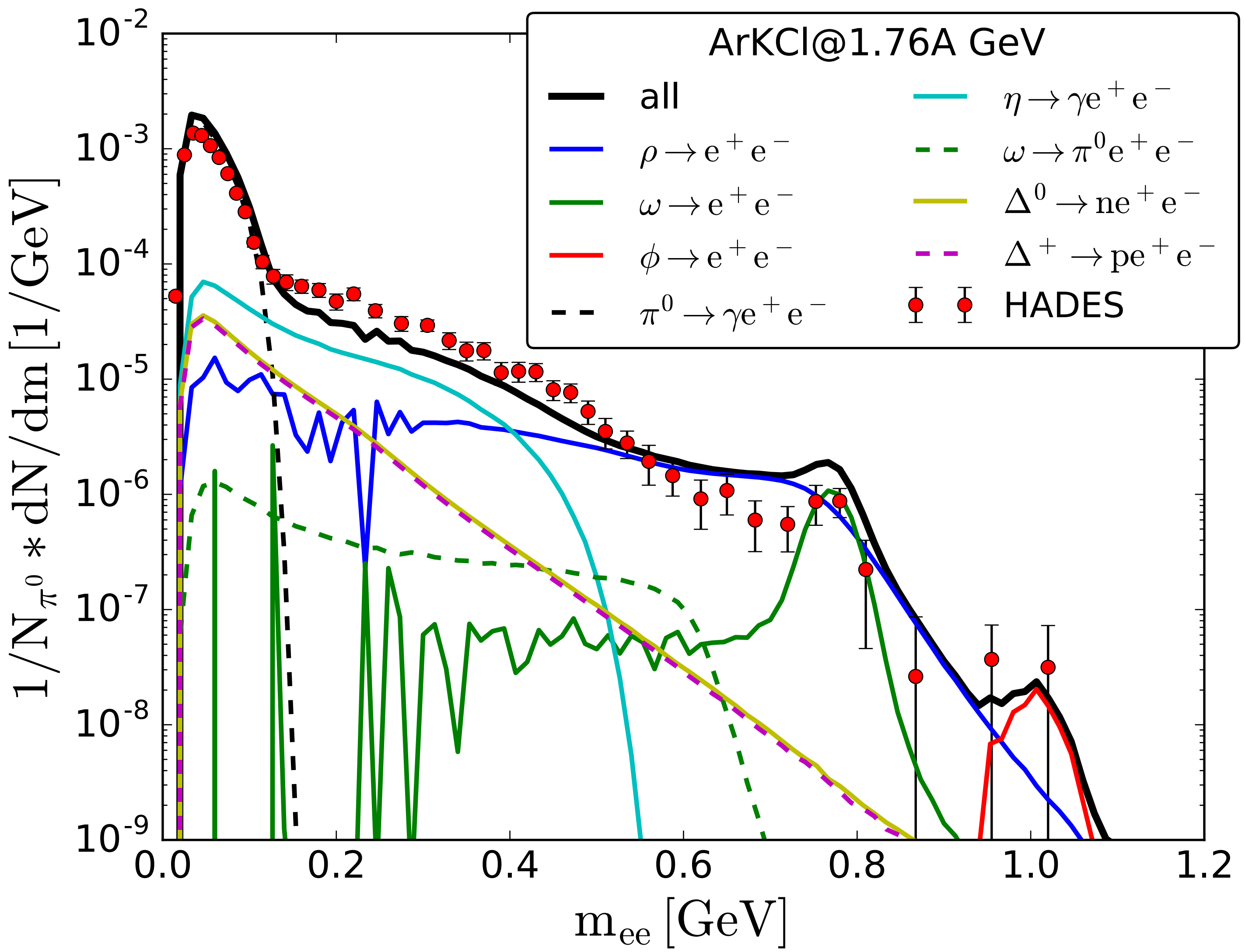
pNb, 3.5 GeV

HADES, Phys.Lett. B715 (2012)

Large systems

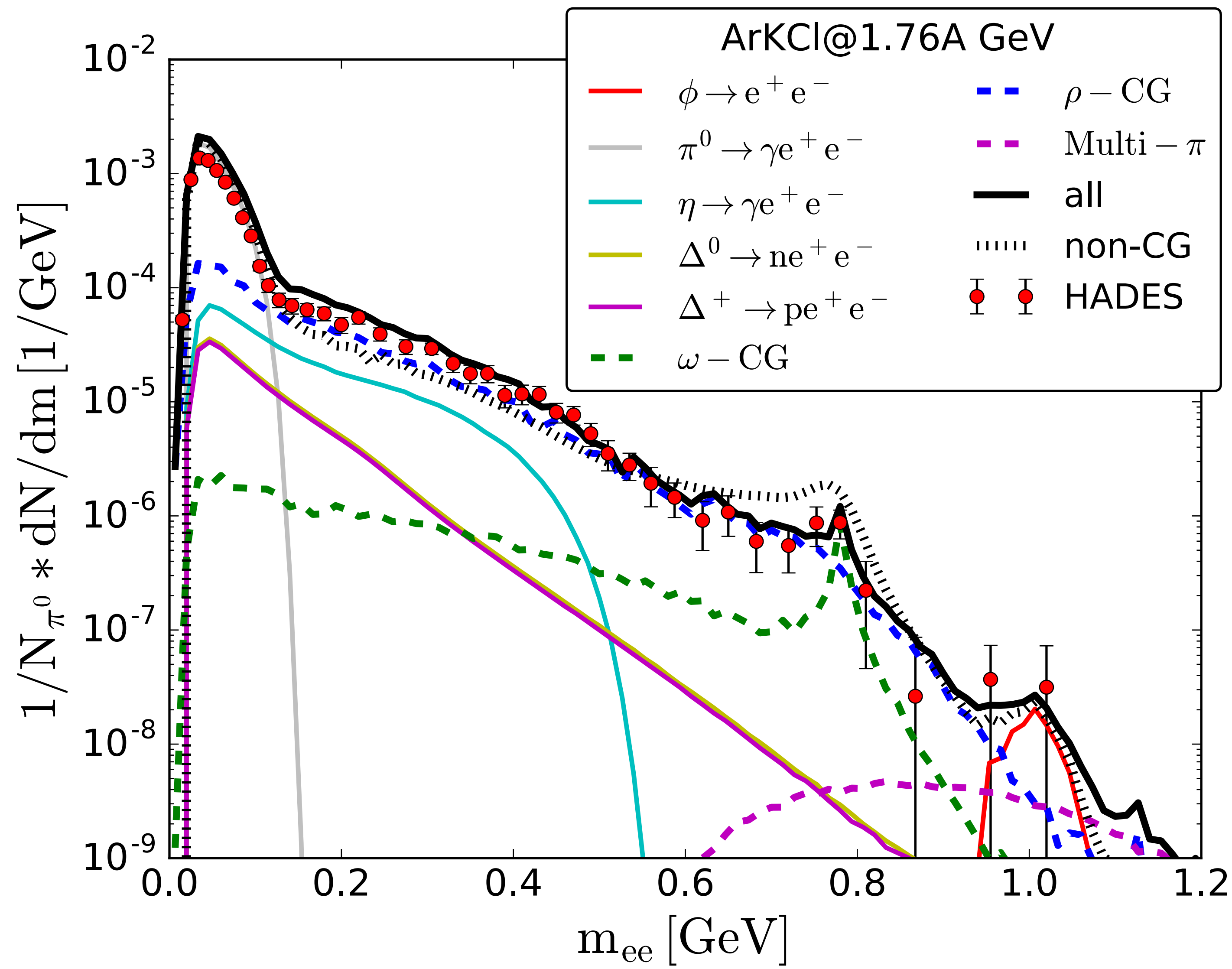
ArKCl, 1.76 AGeV

HADES, Phys.Rev. C84 (2011)



- ArKCl: example for larger system
- Overestimation in ρ pole mass region + underestimation in intermediate mass region
- Vacuum resonances description insufficient? Explicit medium modifications necessary?

Coarse-graining approach



See also Hendrik van Hees' Talk

- Coarse-graining approach by Stephan Endres on SMASH evolution

  Endres et al, Phys.Rev. C92 (2015)

- Employs in-medium spectral function of vector mesons (ρ and ω)

  Rapp, Wambach, Eur. Phys. J. A6 (1999)

- Agreement with data suggest invariant mass spectrum of ArKCl sensitive to medium effects

Coarse-graining approach

Upcoming systematic comparison of different coarse-graining approaches

*JS, H. Elfner (**CG SMASH**)*

*F. Seck, T. Galatyuk (**CG GSI/Texas**)*

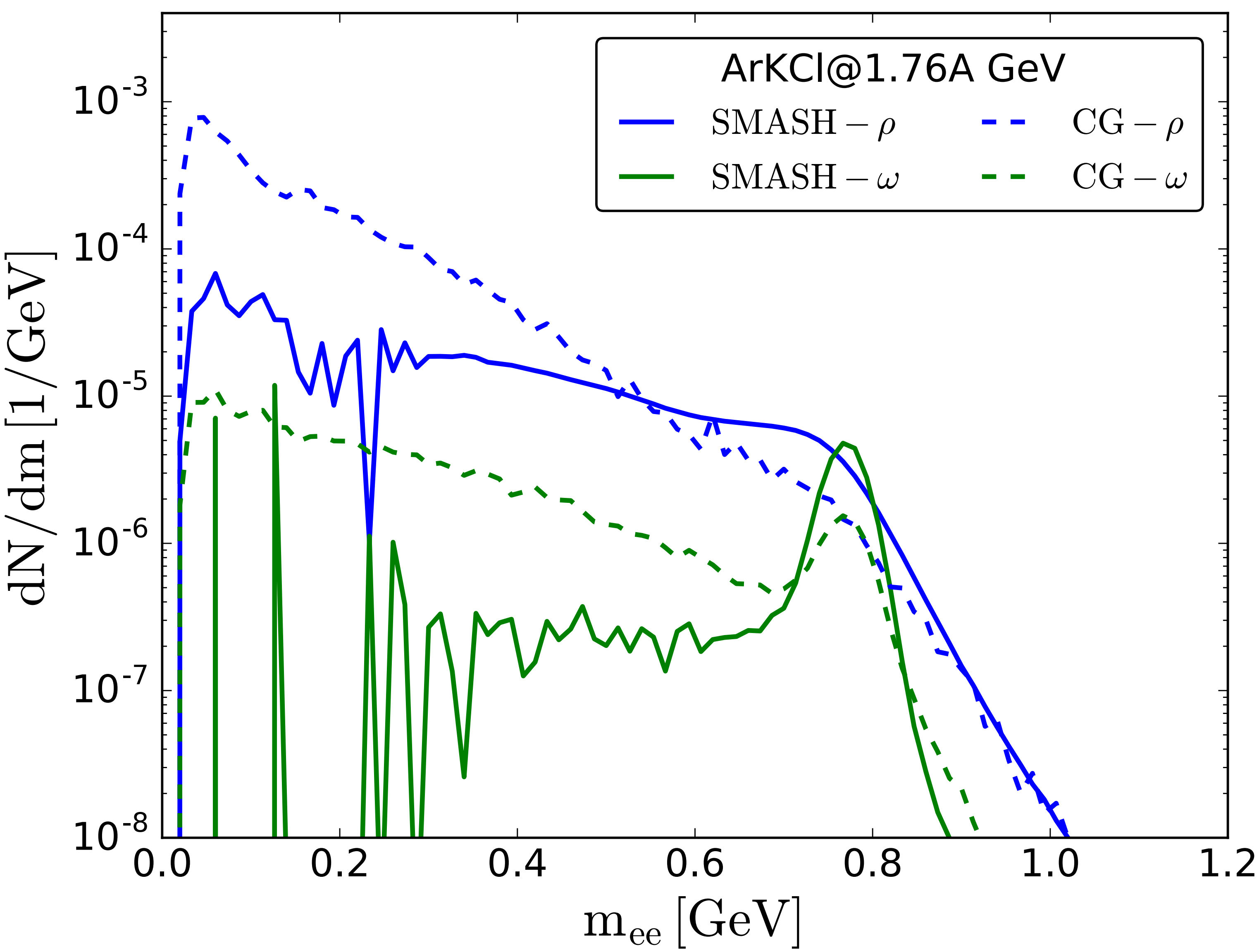
*H.v. Hees (**CG FRA**)*

P. Moreau, E. Bratkovskaya

CRC-TR 211
Strong-interaction matter under extreme conditions

Study systematic uncertainties in theoretic approach

Vector-meson contributions



- Direct comparison between vacuum and medium modified vector meson dilepton yields
- Shift from pole mass region to low mass tail
- Coupling between ρ and baryons in nuclear matter leads to low-mass tail for SMASH

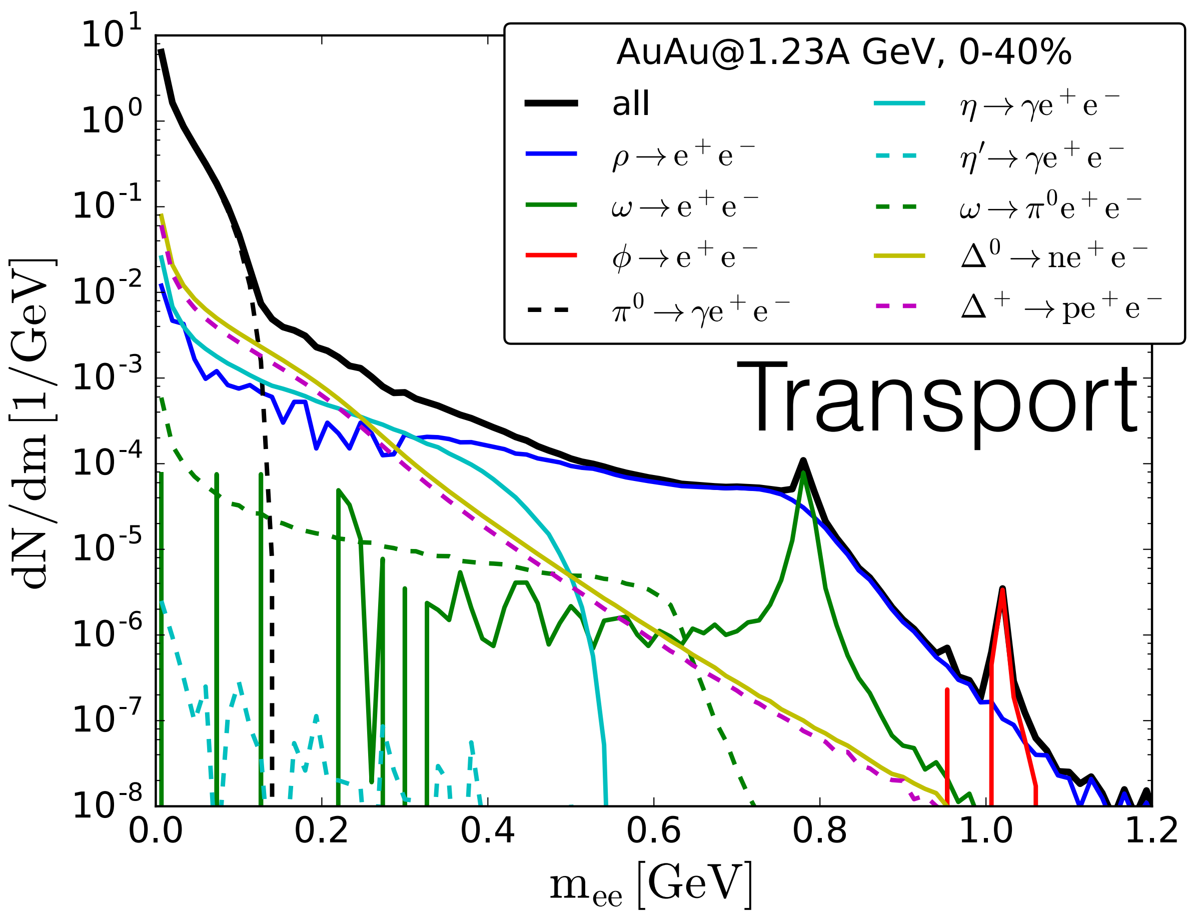
$$B^* \to N\rho \to Ne^+e^-$$

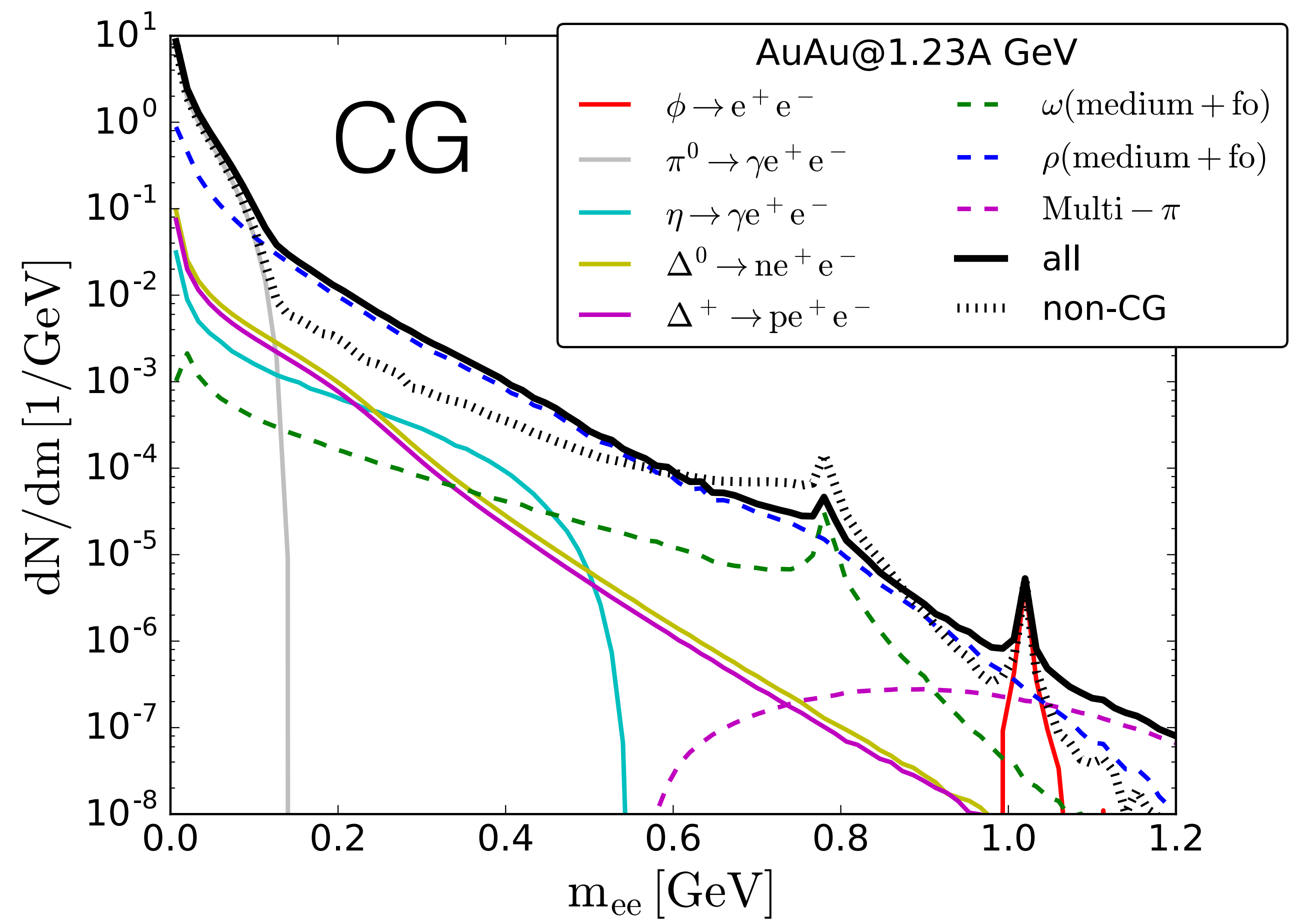
„Disentangle effects of the medium“

Predictions for HADES

AuAu, 1.23 AGeV

See also Teytana Galatyuk's and Szymon Harabsz's Talk

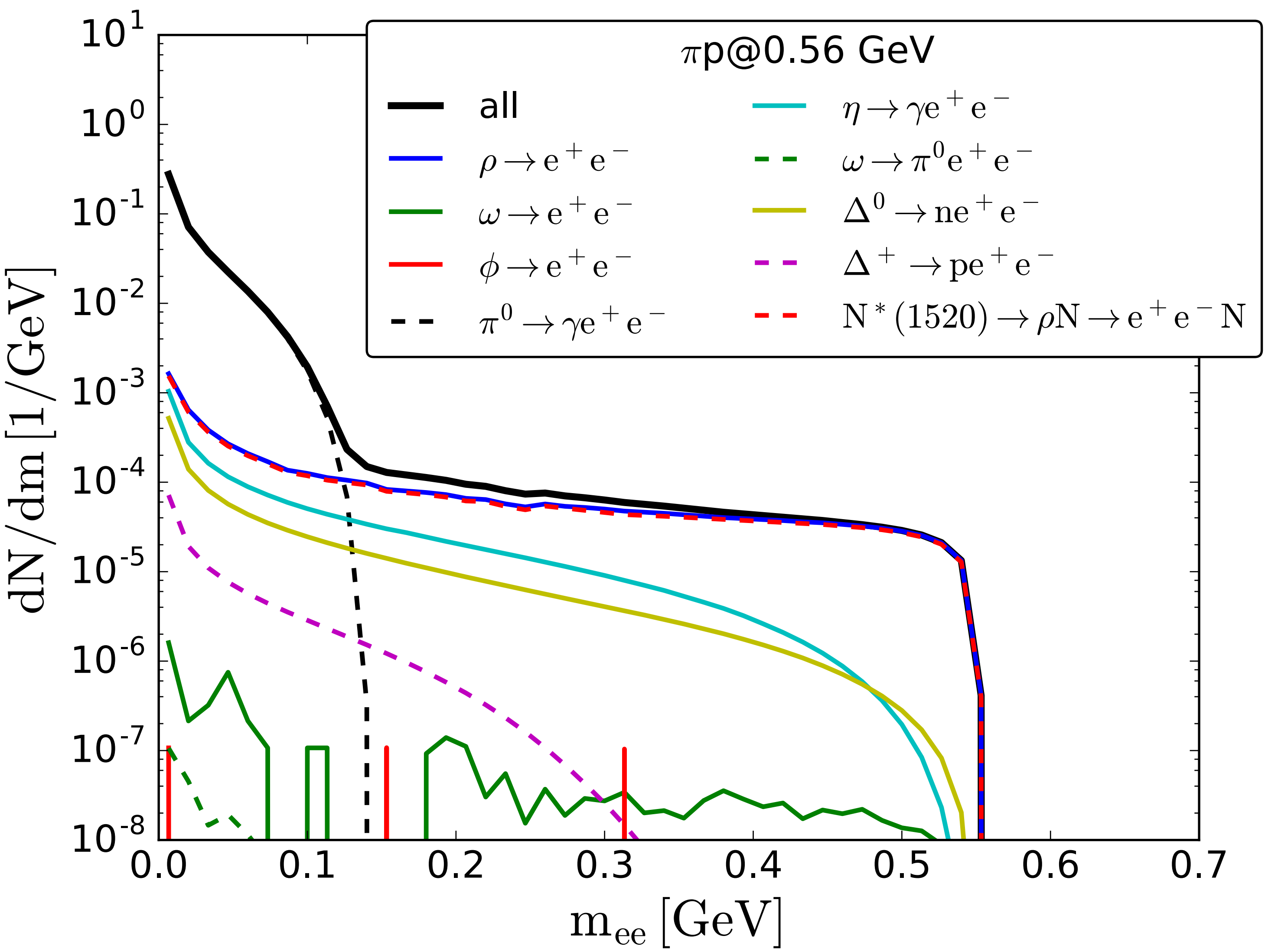




- Heavier system: sensitivity to medium effects increased

Pion beam

πp, 0.56 GeV



- N*(1520) dominant contribution to ρ yield
- Probe ρ - N*(1520) coupling and treatment of N*(1520) dilepton Dalitz decays
- Spectrum with VMD for N*(1520) Dalitz

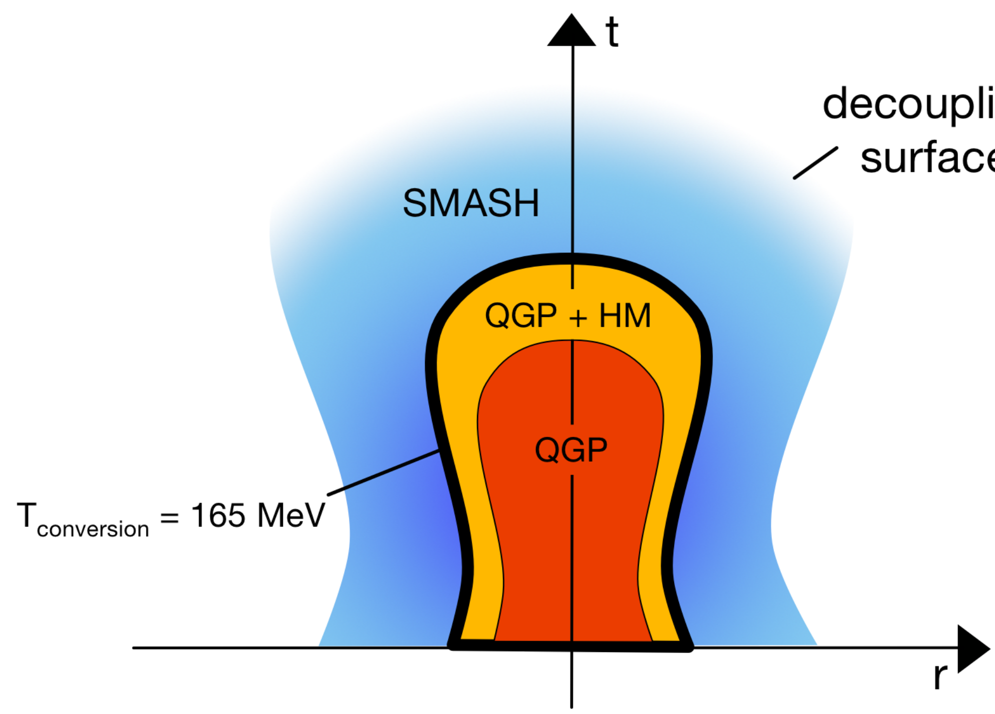
$$N^*(1520) \to \rho N \to e^+e^-N$$

Hybrid

PRC 93, 044906 (2016)
PRL 115, 132301 (2015)

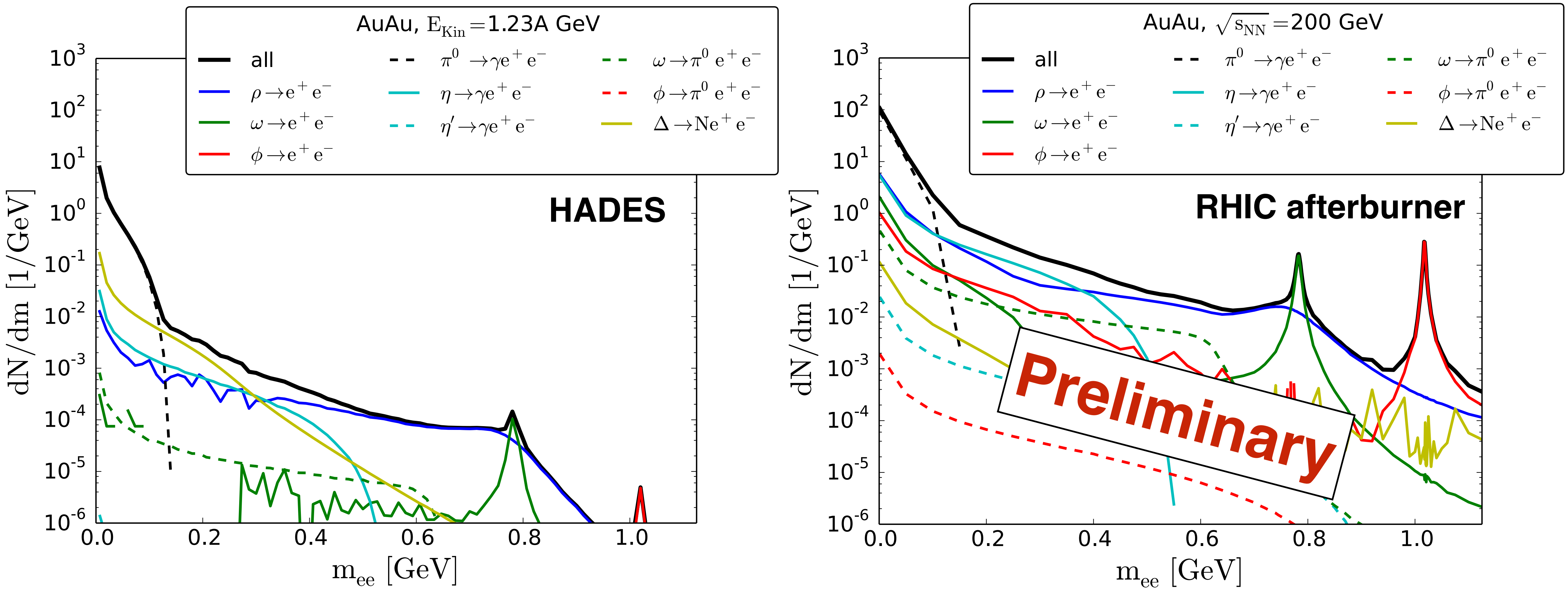
- Study dilepton production for RHIC and LHC energies
- Hybrid approach: combine dilepton radiation from hydrodynamics (MUSIC) and hadronic afterburner (SMASH) *PRC 94, 014904 (2016)* ↔ See also Charles Gale's Talk

in coll. with G. Vujanovic and U. Heinz



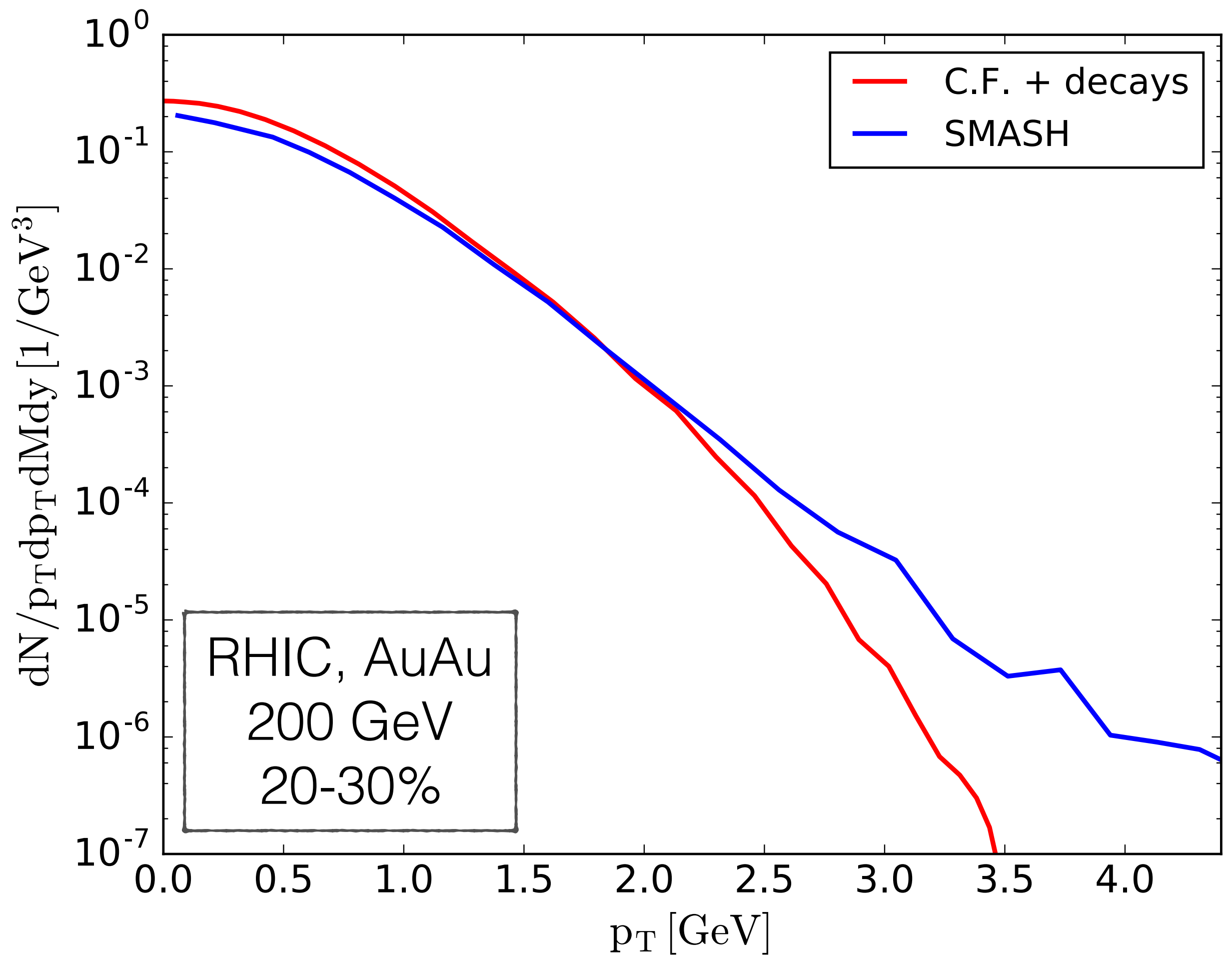
What is the effect of adding a hadronic afterburner (and with that re-scattering) on the different dilepton observables dN/dM, dN/dp$_T$, v$_2$?

Comparison for different energies



- Comparison for hadronic transport evolution in AuAu collisions between HADES and RHIC energies
- Large difference of total yield and shape
- High mass region, in particular Φ meson, more pronounced

Preliminary Result

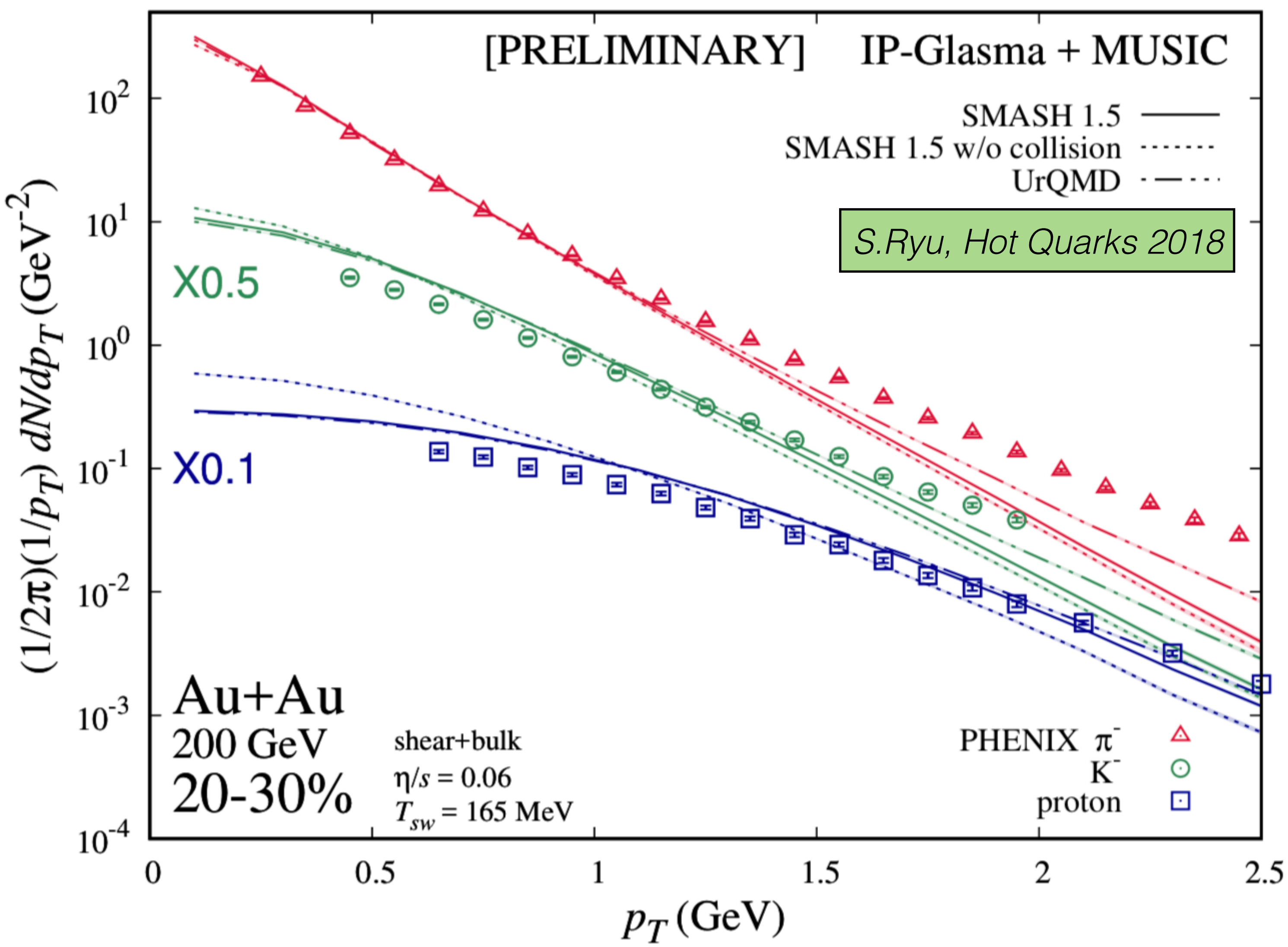


- Comparison between dilepton radiation for SMASH afterburner and free streaming (Cooper-Frye sampling and decays)
- Mean-p_T increases for hadronic afterburner as expected

Hadronic afterburner spectra

D. Oliinychenko, arXiv:1809.03071

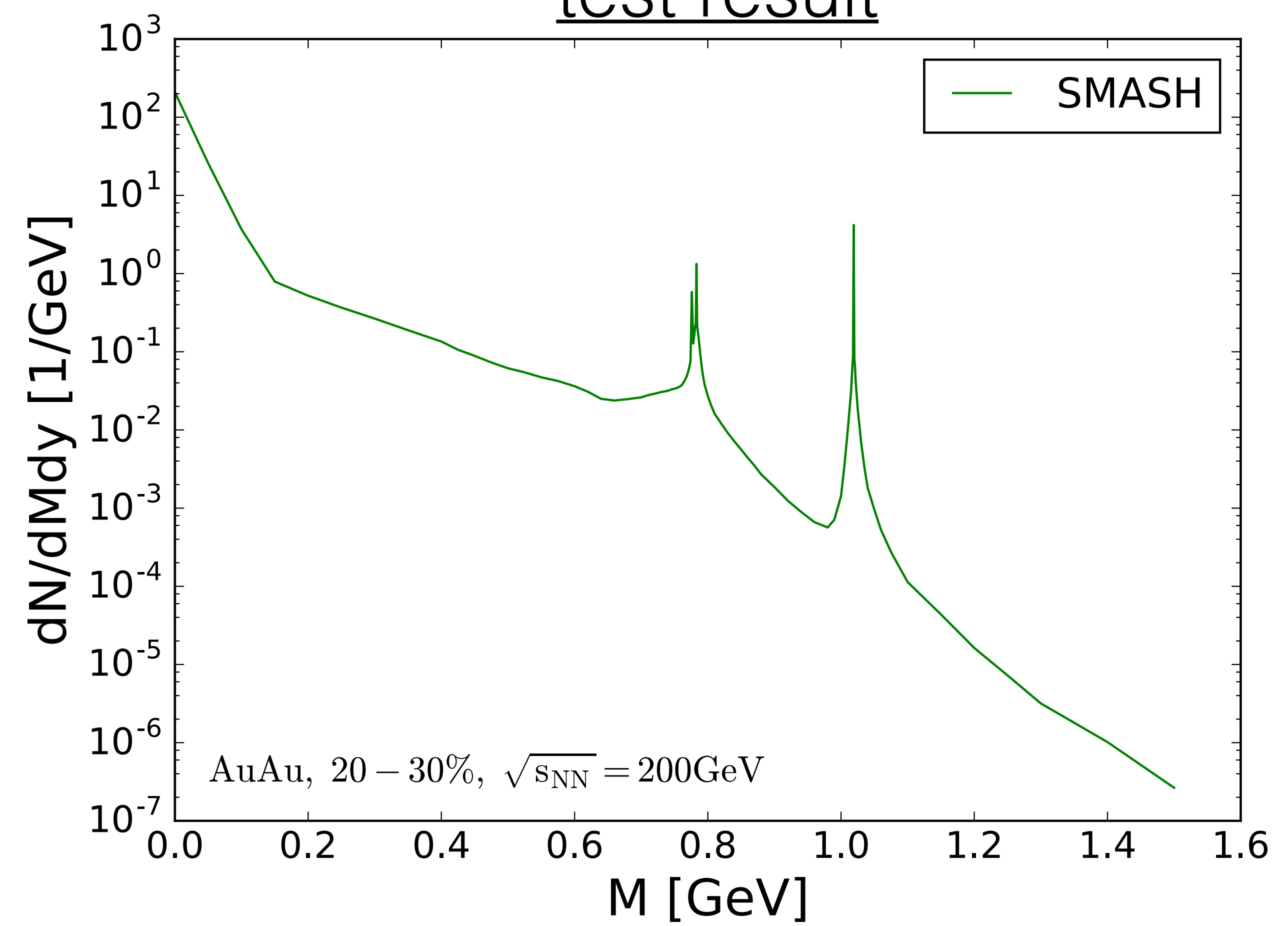
- Same mean-p_T increase through re-scattering e.g for proton
- Results for proton and for K and π at low p_T consistent with UrQMD
- Deviation for K and π at higher p_T under investigation



Cooper-Frye Sampling

- Usually all resonances sampled on pole mass
- Issue: leads to sharp peaks in dilepton invariant mass spectrum
- Modified C.F. sampling with broad mass distribution by S. Ryu

test result



1. Sample avg. multiplicity with S.F.: $n_0 + \delta n_{\mathrm{bulk}} \quad \rightarrow \quad \langle n_0 + \delta n_{\mathrm{bulk}} \rangle_{\mathcal{A}}$

2. Sample particle masses according to $\mathcal{P}(M) \propto [n_0(M) + \delta n_{\mathrm{bulk}}(M)]\, \mathcal{A}(M)$

Summary

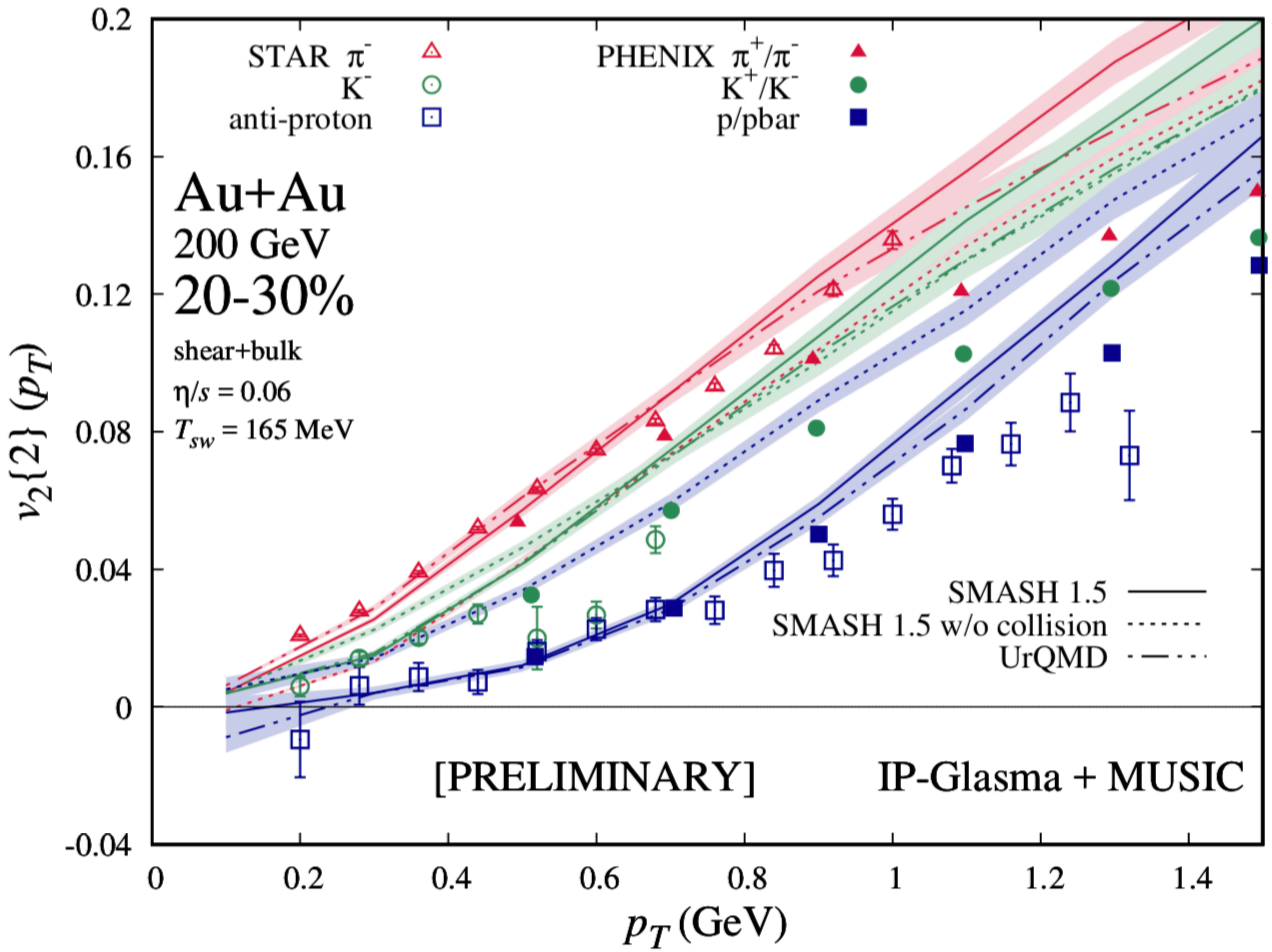
1. Dilepton production for low energies and small system in comparison with HADES data verifies approach → „***baseline***“

2. New **direct comparison** of vector-meson contributions **with coarse-graining** → compare medium effects

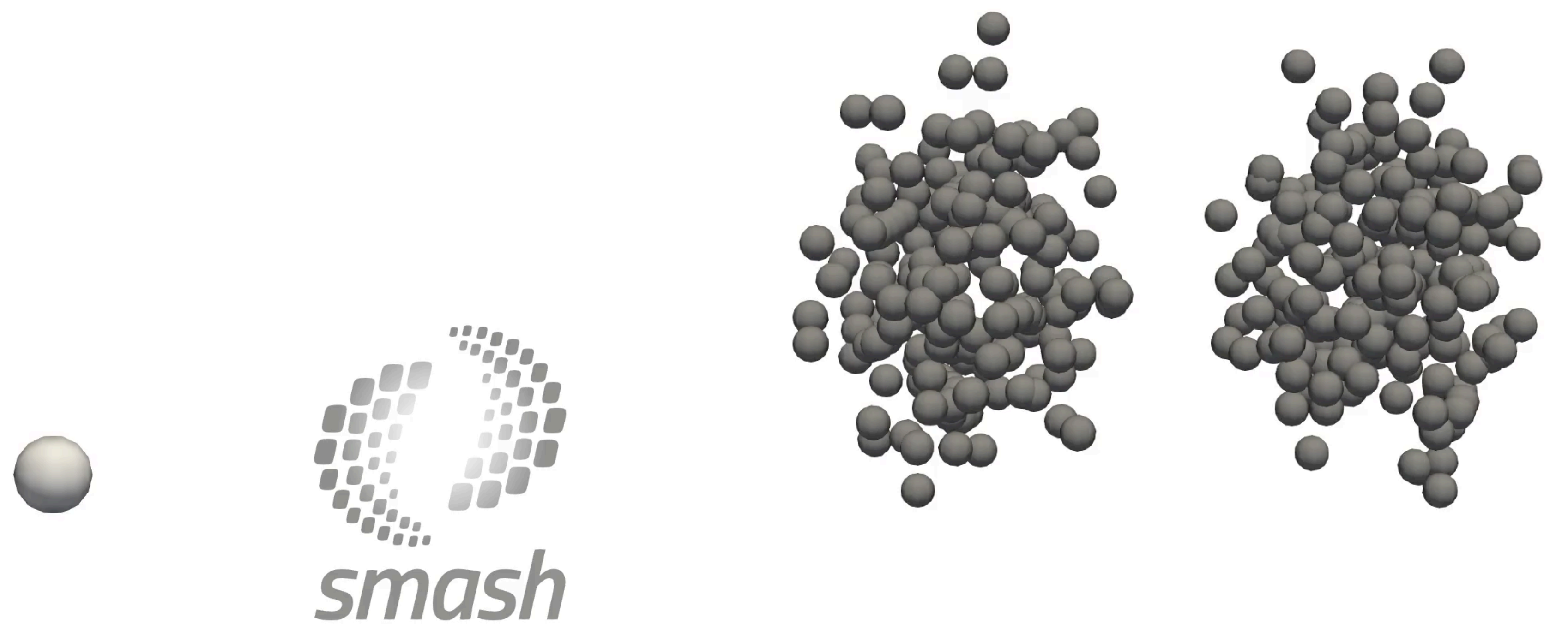
3. Progress in C.F.-sampling and afterburner interactions enables **study of re-scattering effects for higher energies** within hybrid approach

Backup Slides

Afterburner v_2



Movies *shining*



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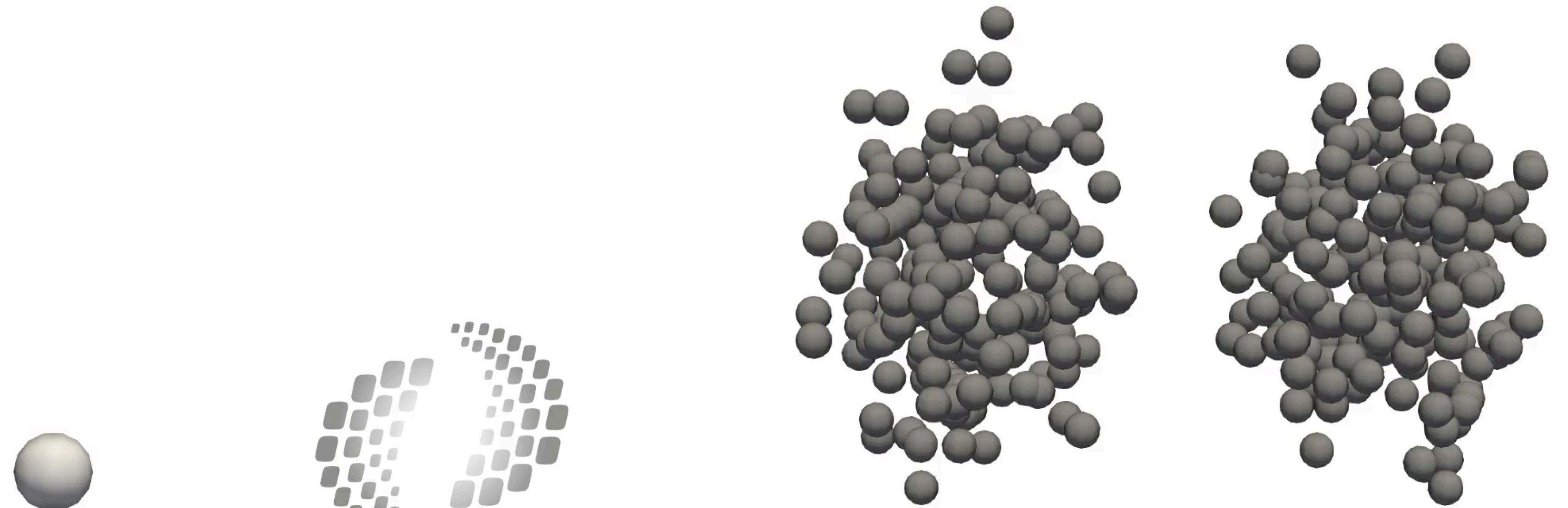
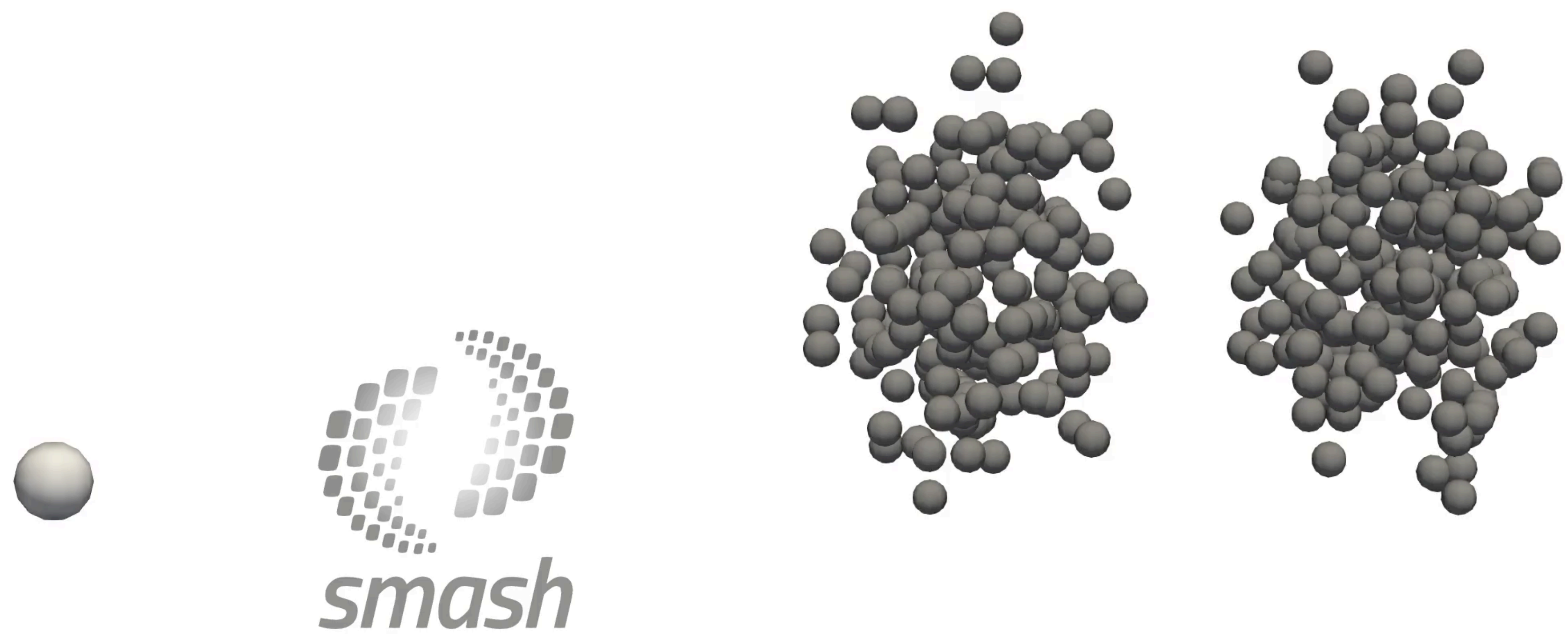
Movies *shining*



smash

By J. Mohs

Movies *shining*



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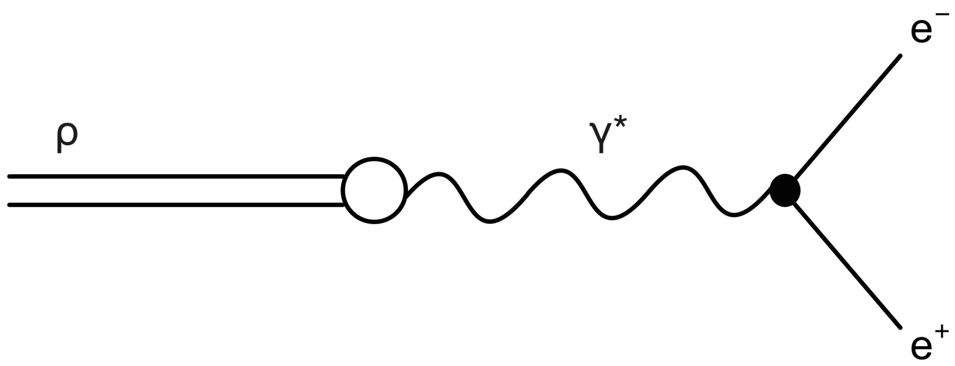
Partial widths



Parametrization for partial widths

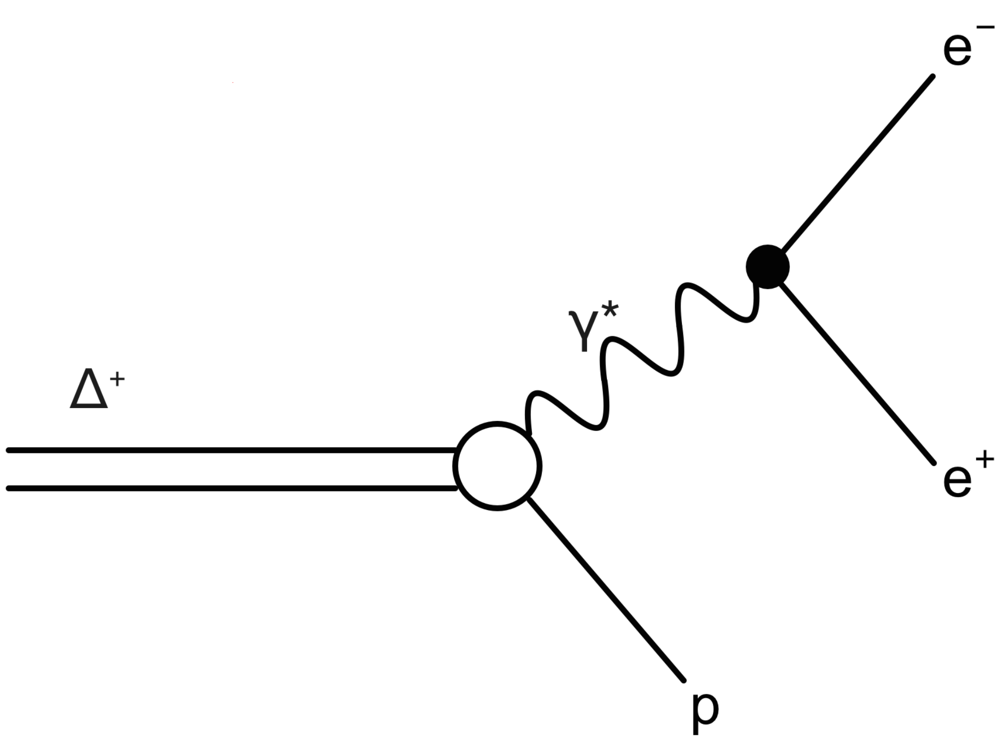
- direct decays treated via *Vector Meson Dominance* (VMD)
- coupling between hadronic and electromagnetic sector via vector meson
- partial width for vector mesons $V = \rho^0, \omega, \phi$ taken from Li and Ko (Nucl. Phys. 1996):

$$\Gamma_{V \to l^+ l^-}(\mu) = \frac{\Gamma_{V \to l^+ l^-}(M_{pole})}{M_{pole}} \frac{M_{pole}^4}{\mu^3} \sqrt{1 - \frac{4m_l^2}{\mu^2}} \left(1 + \frac{2m_l^2}{\mu^2}\right)$$

Differential widths

Dalitz decays

- form factor for photon-hadron coupling
- partial width through integration of differential width
- no phase space correction ($m_e \approx 0$)



Differential widths

Overview: Parametrization for differential widths of dalitz decays

- dalitz decays of $P = \pi^0, \eta$ taken from Landsberg (Phys. Rept. 1985):

$$\frac{d\Gamma_{P\to\gamma e^+e^-}}{d\mu} = \frac{4\alpha}{3\pi}\frac{\Gamma_{P\to\gamma\gamma}}{\mu}\left(1-\frac{\mu^2}{m_P^2}\right)^3 |F_P(\mu)|^2$$

$$F_{\pi^0}(\mu) = 1 + b_{\pi^0}\mu^2\,, \quad b_{\pi^0} = 5,5\,\mathrm{GeV}^{-2}$$

$$F_\eta(\mu) = \left(1-\frac{\mu^2}{\Lambda_\eta^2}\right)^{-1}, \quad \Lambda_\eta^2 = 0,676\,\mathrm{GeV}$$

- ω dalitz decays taken from Bratkovskaya and Cassing (Nucl. Phys. 1997):

$$\frac{d\Gamma_{\omega\to\pi^0e^+e^-}}{d\mu} = \frac{2\alpha}{3\pi}\frac{\Gamma_{\omega\to\pi^0\gamma}}{\mu}\left[\left(1+\frac{\mu^2}{m_\omega^2-m_\pi^2}\right)^2 - \frac{4m_\omega^2\mu^2}{(m_\omega^2-m_\pi^2)^2}\right]^{3/2} |F_\omega(\mu)|^2$$

with $|F_\omega(\mu)|^2 = \frac{\Lambda_\omega^4}{(\Lambda_\omega^2-\mu^2)^2+\Lambda_\omega^2\Gamma_\omega^2}$

- Δ dalitz decay by Krivoruchenko et al (Phys. Rev. 2002):

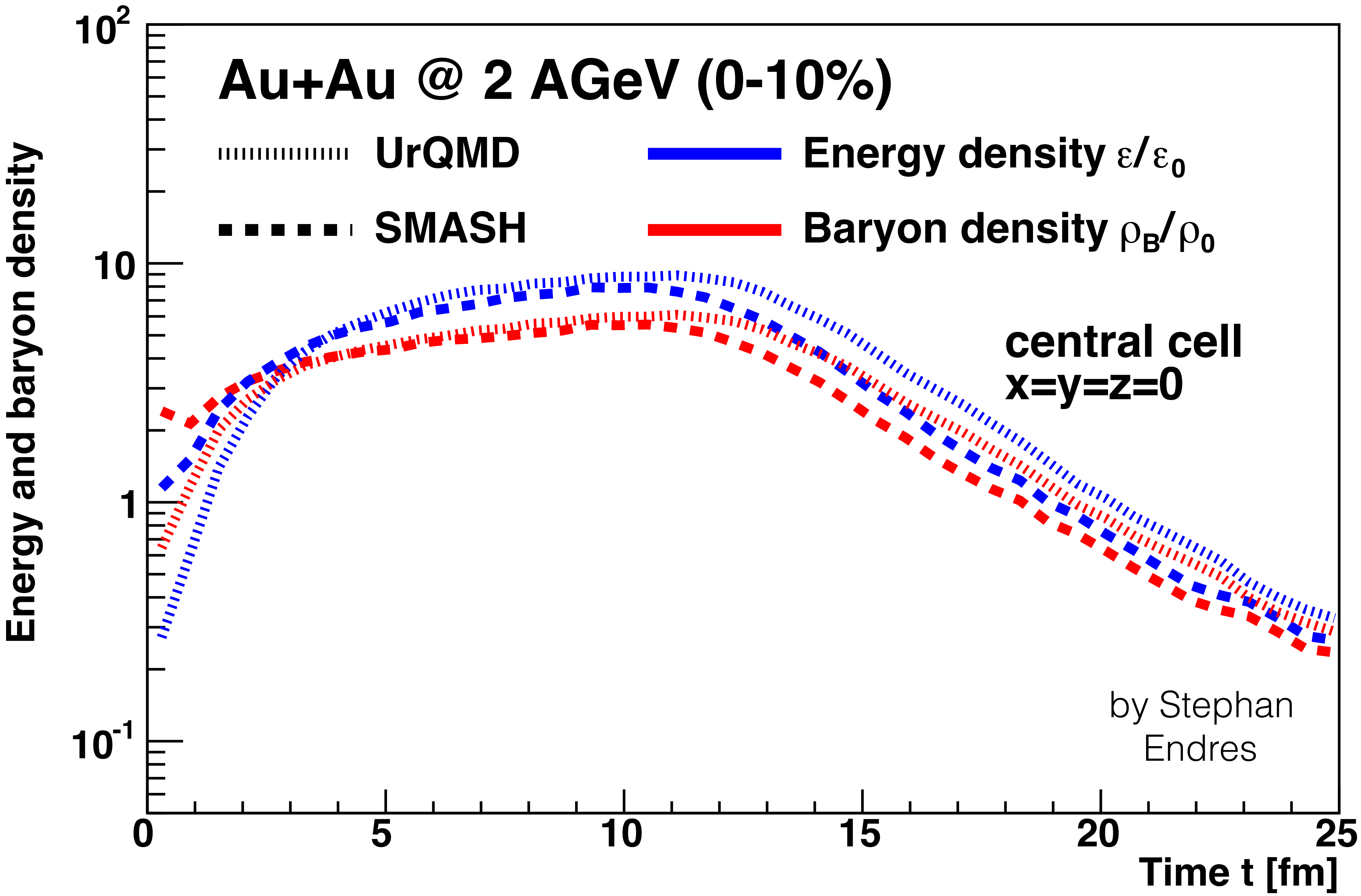
$$\frac{d\Gamma_{\Delta\to Ne^+e^-}}{d\mu} = \frac{2\alpha}{3\pi}\frac{\Gamma_{\Delta\to N\gamma^*}(\mu)}{\mu}$$

$$\Gamma_{\Delta\to N\gamma^*}(\mu) = \frac{\alpha}{16}\frac{(m_\Delta+m_N)^2}{m_\Delta^3 m_N^2}[(m_\Delta+m_N)^2-\mu^2]^{1/2} \times [(m_\Delta-m_N)^2-\mu^2]^{3/2}|F_\Delta(\mu)|^2$$

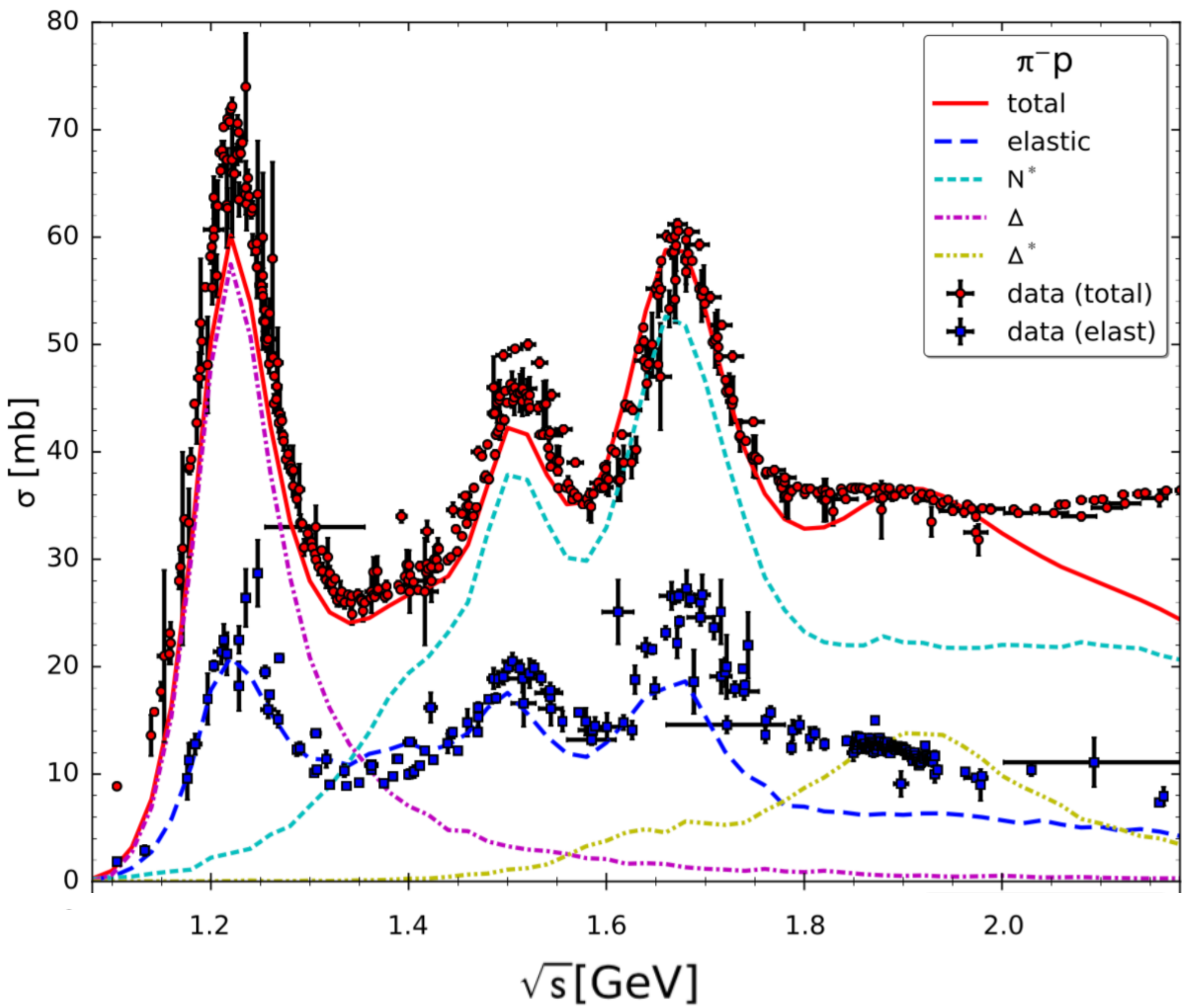
$|F_\Delta(\mu)|$ assumed constant (ongoing debate)

Comparison to UrQMD

time evolution of density at center of collision is very similar

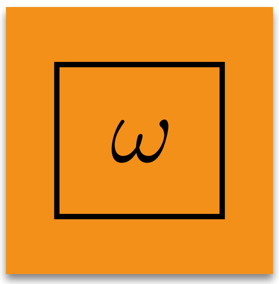


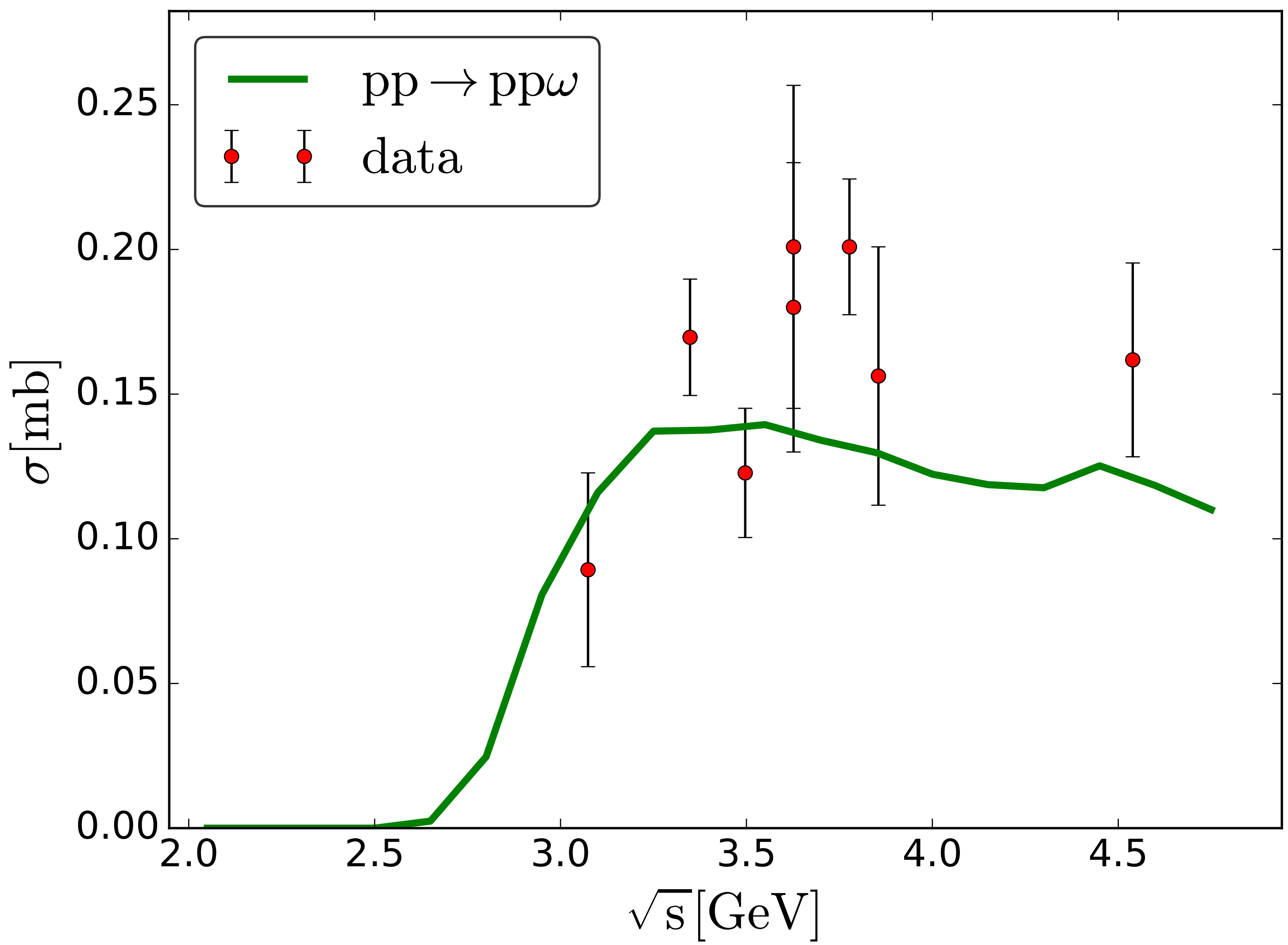
Total Cross Section



- total π-p cross section
- lowest excitation from Δ, additional contributions from N* and Δ*
- compatible with data up to 2 GeV

Exclusive Cross Section



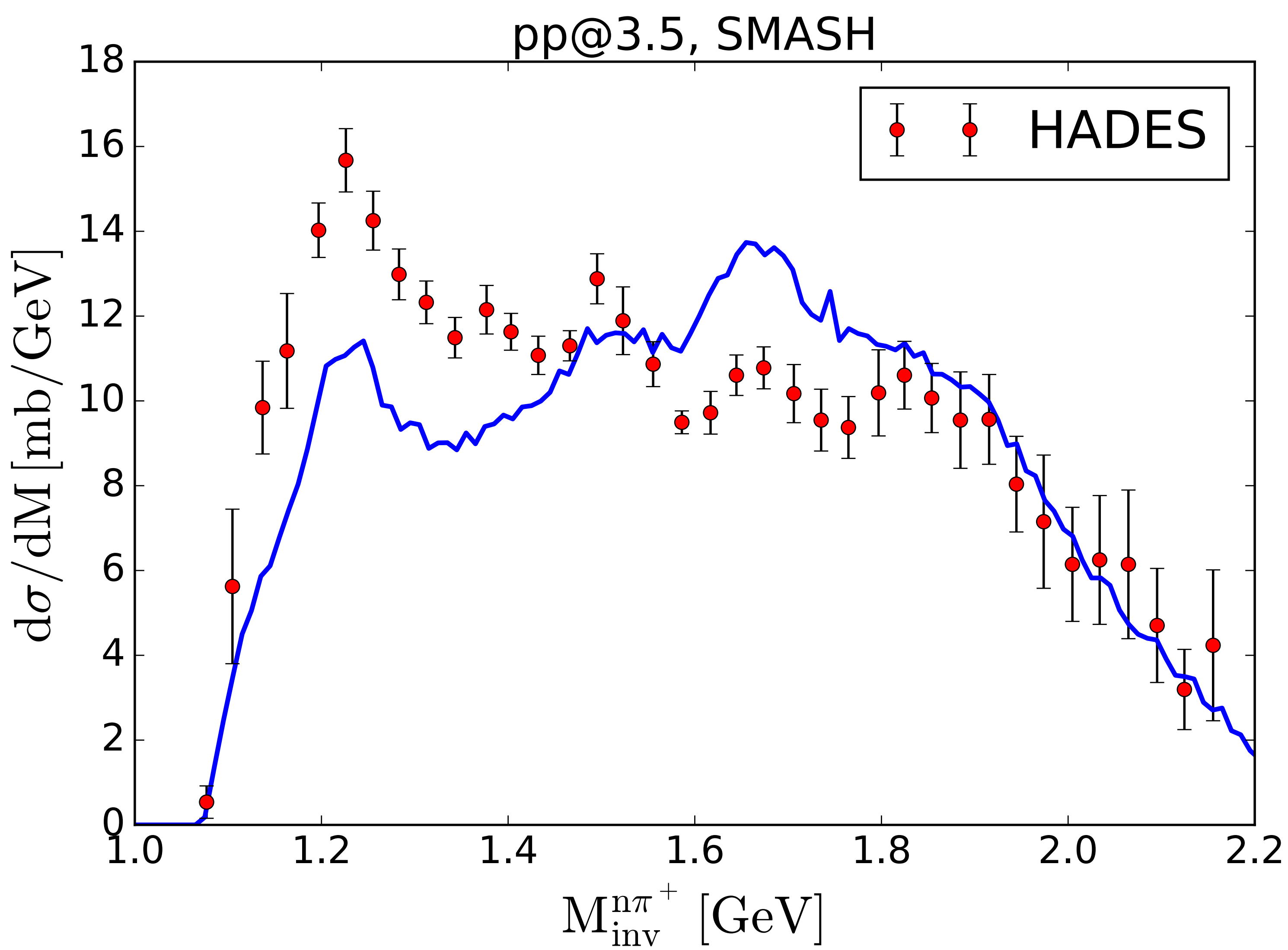


- investigating the exclusive production cross section of resonances
- exclusive production of ω via $pp \to pp\omega$
- reasonable agreement with data for different energies

Exclusive Cross Section

$pp \rightarrow pn\pi^+$

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



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

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

- invariant mass spectrum of $n\pi^+$
- probes baryonic resonance production cross section in primary NN reactions
- work in progress
- comparison to experimental data similar to UrQMD

Rapidity spectra pp@3.5 GeV

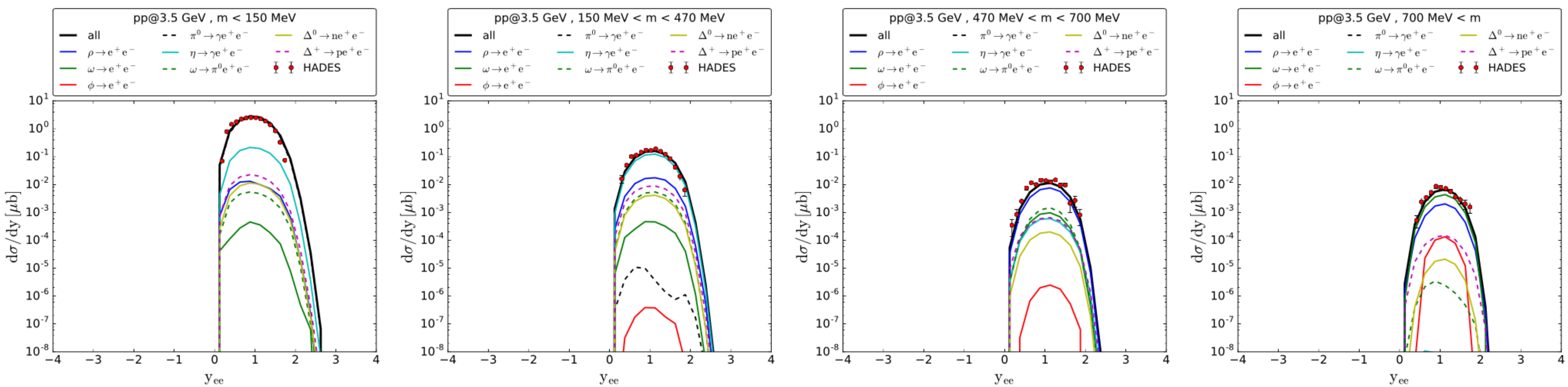
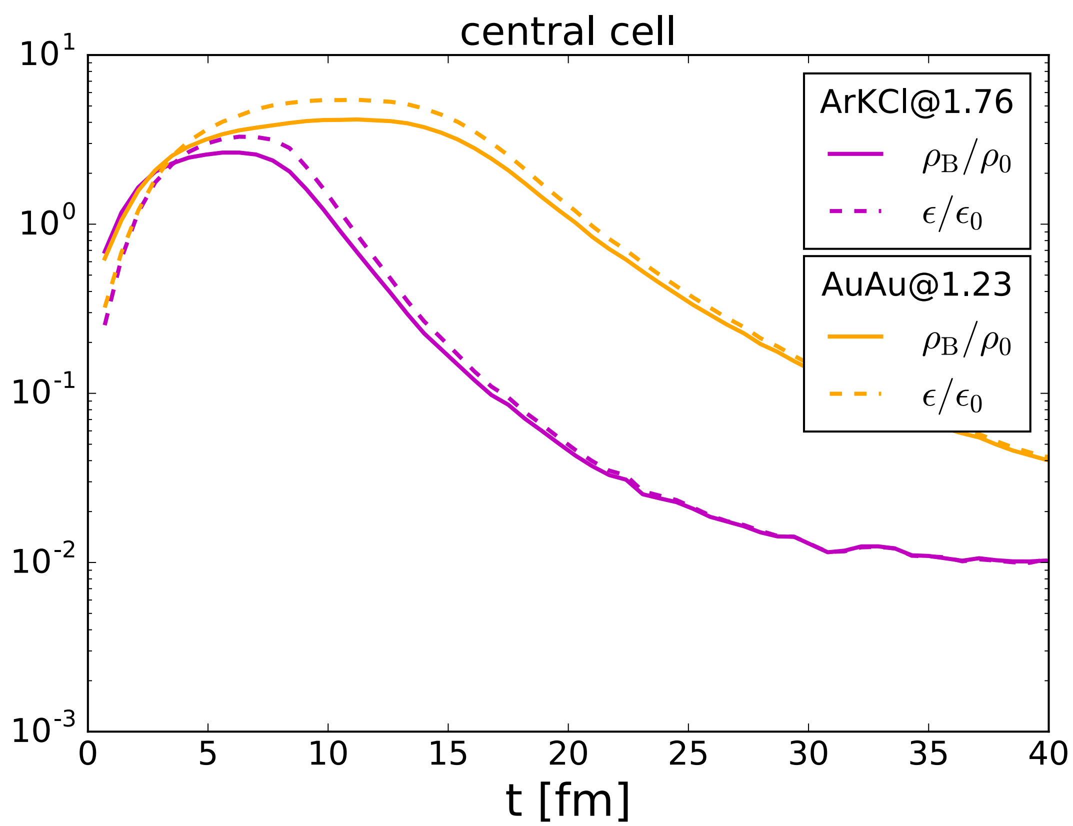
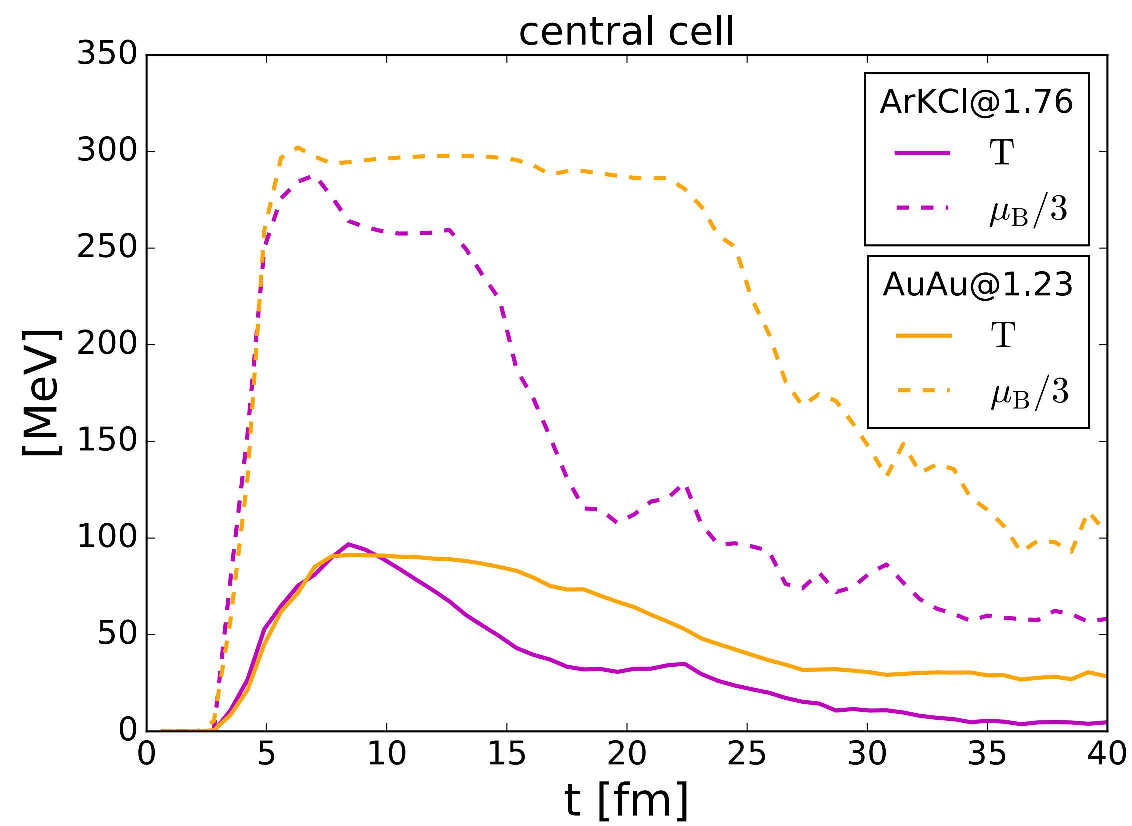


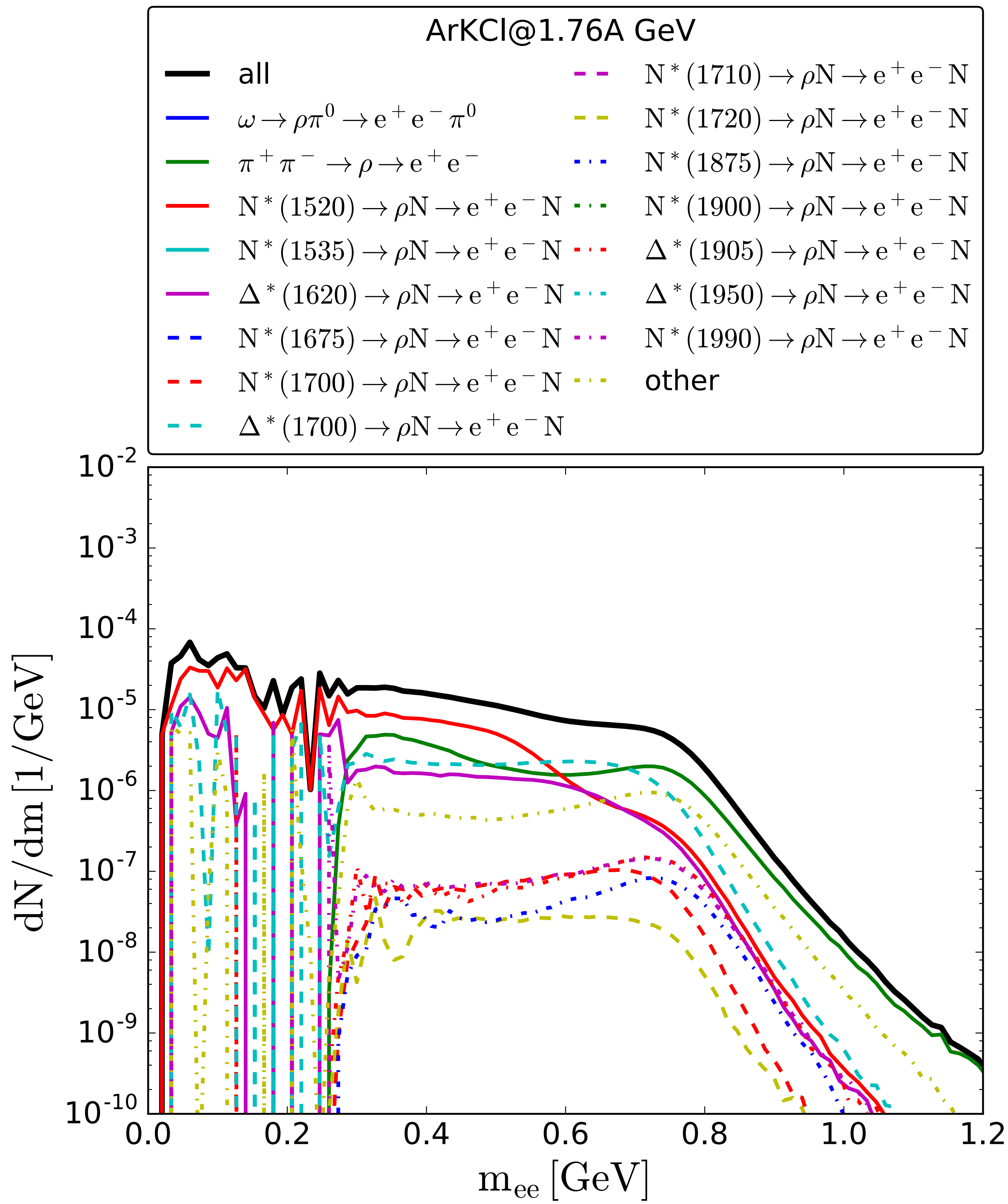
FIG. 24. Rapidity spectra of di-electrons produced by pp collisions at $E_{\mathrm{kin}} = 3.5\,\mathrm{GeV}$ in different invariant mass windows. Experimental data from [15].

CG evolution

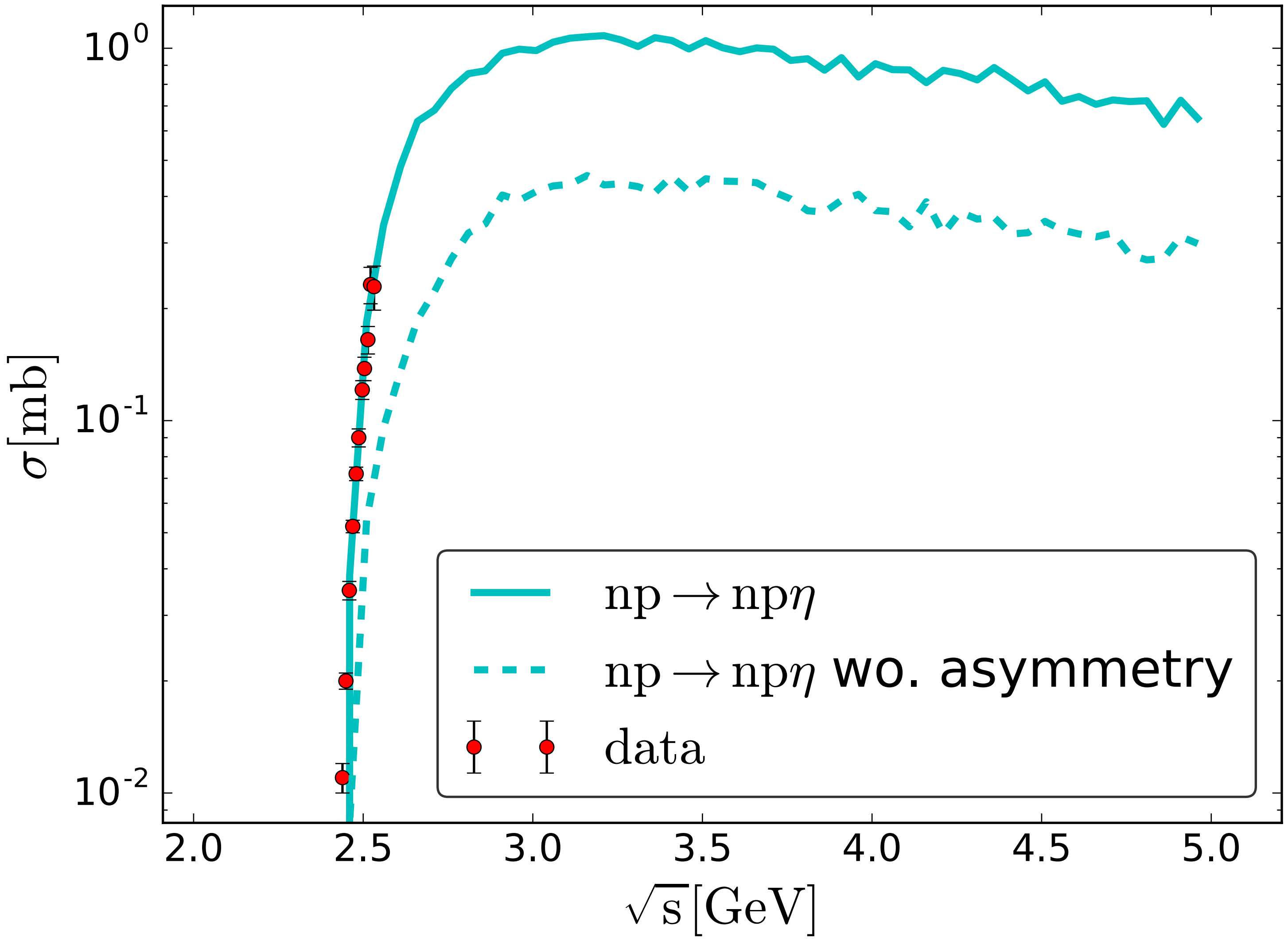




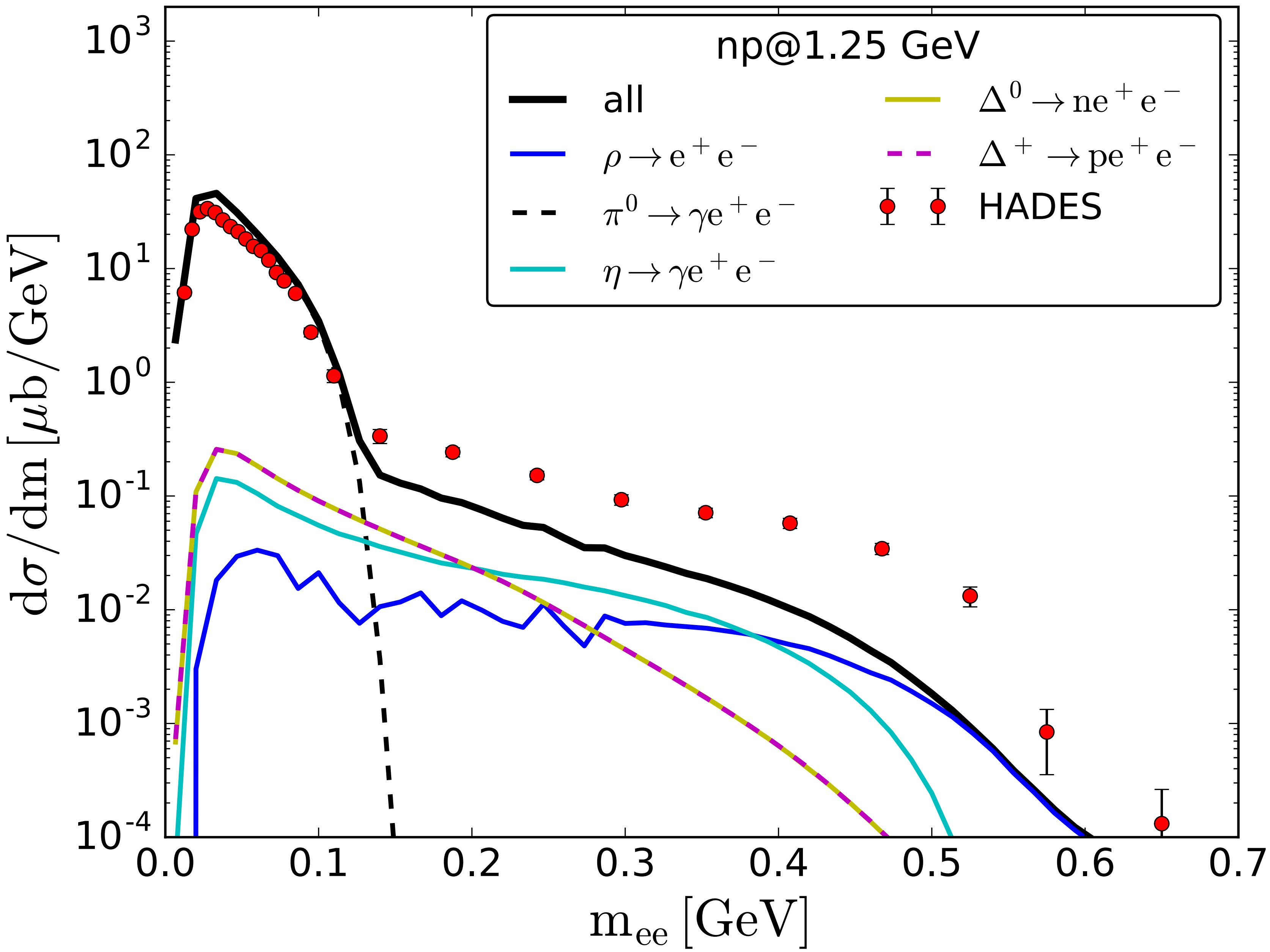
Rho origin in ArKCl



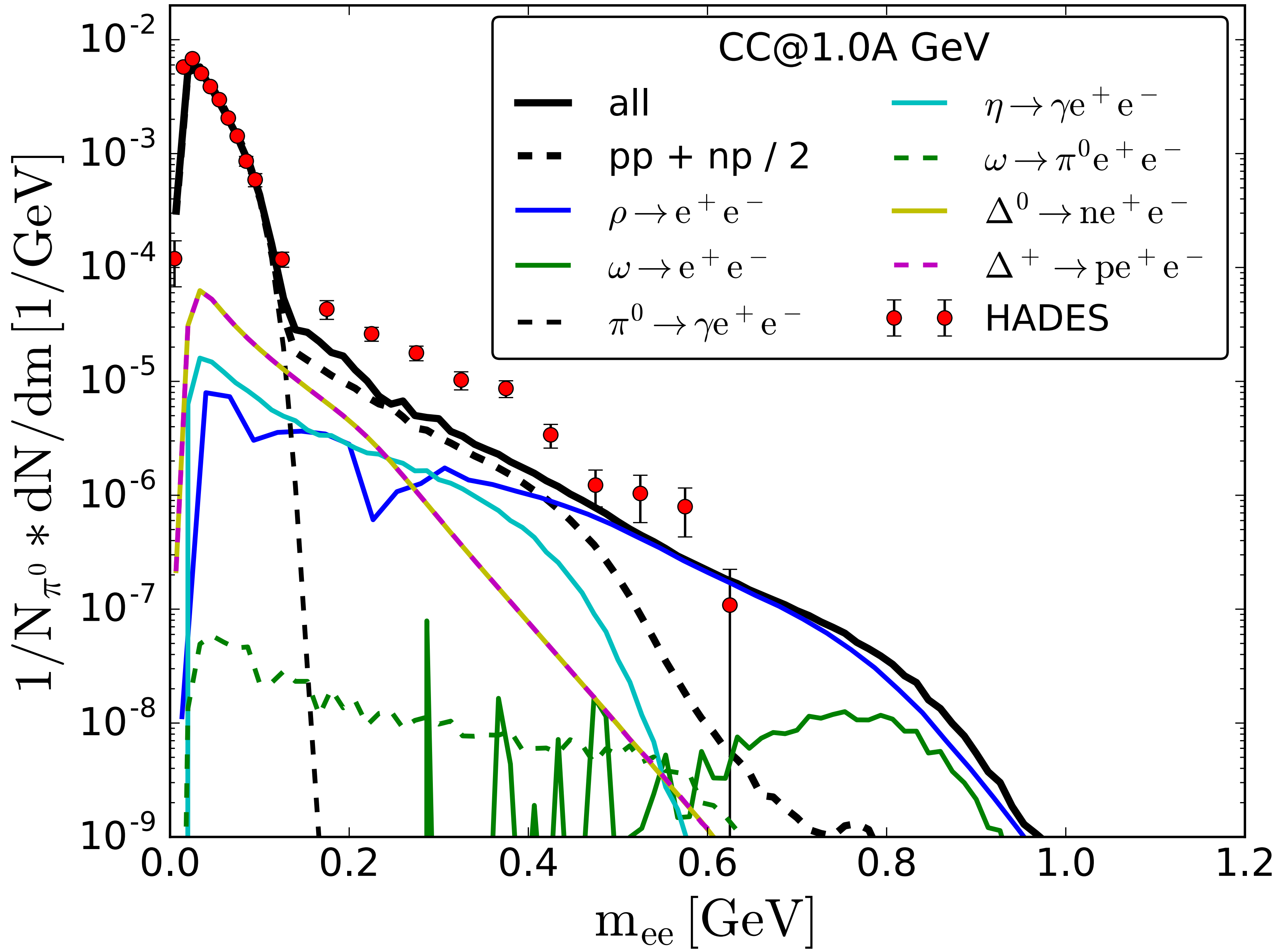
Eta Cross Section



d(n) + p


np@1.25 GeV
all
$\rho \to e^+e^-$
$\pi^0 \to \gamma e^+e^-$
$\eta \to \gamma e^+e^-$
$\Delta^0 \to ne^+e^-$
$\Delta^+ \to pe^+e^-$
HADES
$d\sigma/dm\,[\mu b/GeV]$
$m_{ee}\,[GeV]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

CC @ 1.0 A GeV



CC@1.0A GeV
all
pp + np / 2
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\pi^0 \to \gamma e^+e^-$
$\eta \to \gamma e^+e^-$
$\omega \to \pi^0 e^+e^-$
$\Delta^0 \to ne^+e^-$
$\Delta^+ \to pe^+e^-$
HADES
$1/N_{\pi^0} * dN/dm\,[1/GeV]$
$m_{ee}\,[GeV]$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.0
0.2
0.4
0.6
0.8
1.0
1.2

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:

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

Blatt Weisskopf functions

$$B_0^2 = 1$$

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

$$\dots$$

- 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

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

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- Bullet Point 1
- Bullet Point 2
- Bullet Point 3