SMASH transport model for hadronic reactions

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Workshop on two-pion and e+e- production in hadronic reactions

Orsay, 2018

Outline

- Introduction
- Model description: SMASH
- Results for

  … hadronic cross sections

  … e.m. form factors

  … dilepton production

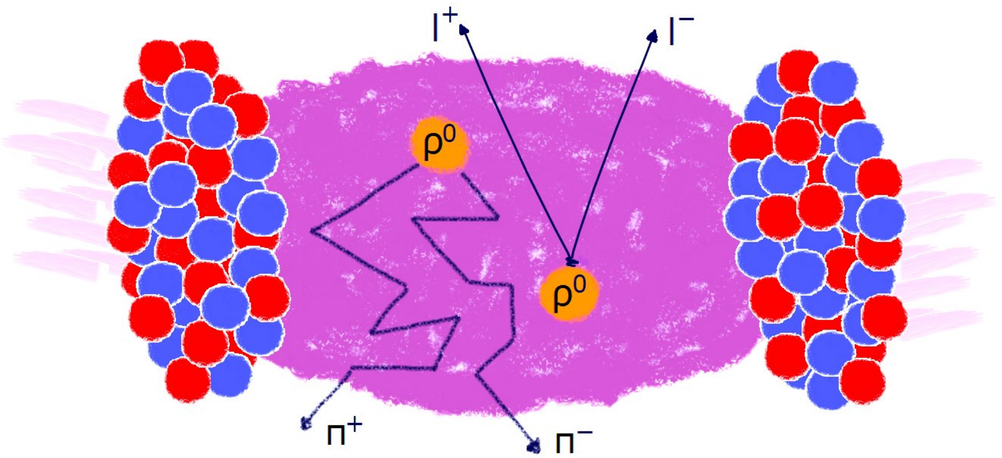
Motivation

- elementary reactions offer one of the most important constraints for transport models
- probe for the resonance description (vacuum properties)
- measured cross sections for e.g. pion production valuable to constrain branching ratios, decay modes, cross section etc.

Dileptons

- only electromagnetic interaction: clean probe for hot and dense matter

- extract medium properties and medium modifications over whole lifetime of collision



Complementary constraint:

- on the dynamical evolution of the system
- on the resonance description (in vacuum and medium)

starting point = elementary reactions

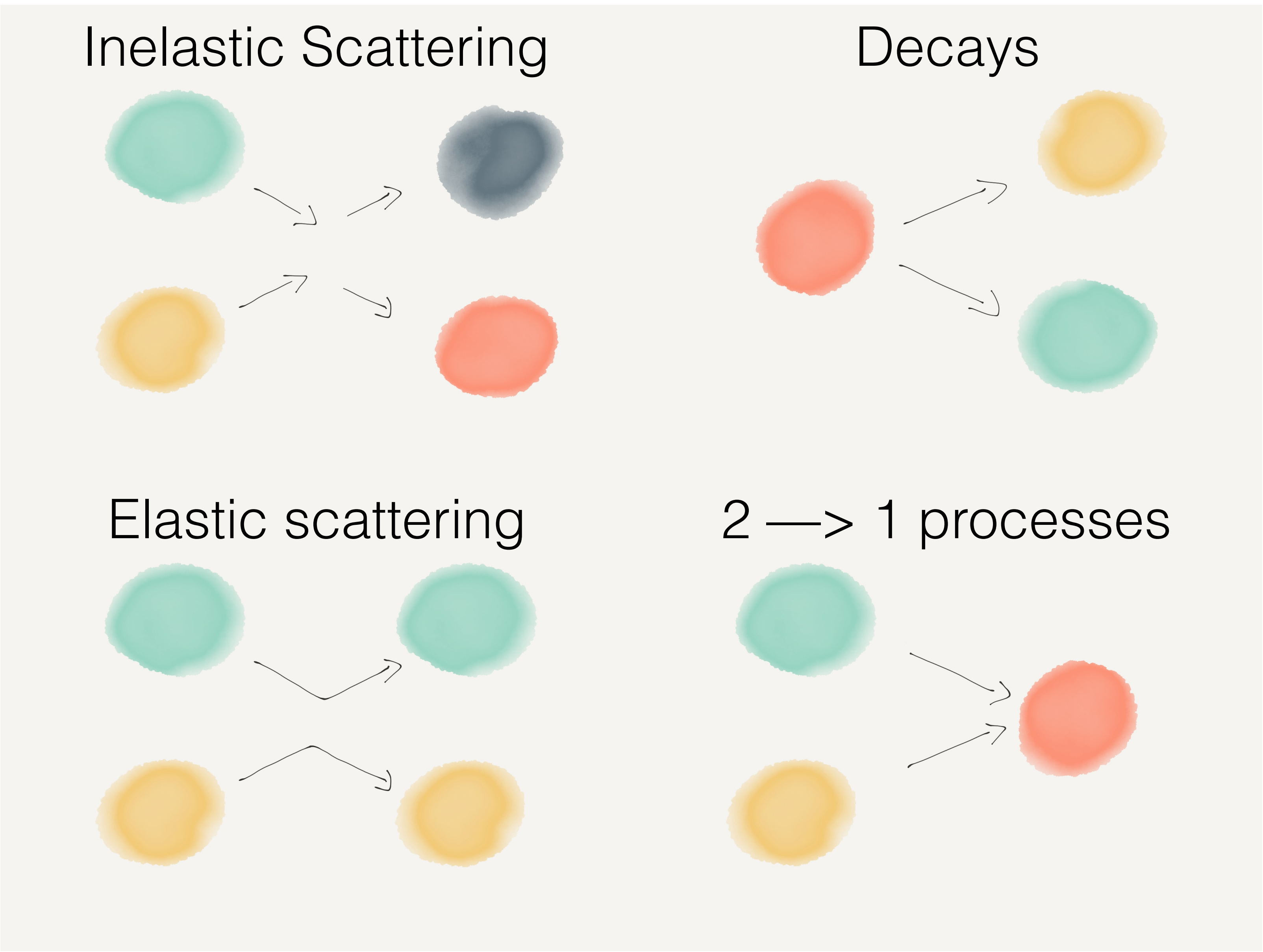
SMASH*

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

- new modern 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
- 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 $\pi, \eta, \eta', \rho, \omega, \phi, K, \ldots \quad N, N^*, \Delta, \Delta^*, \ldots$
  - perturbative treatment of non-hadronic particles (photons, leptons)

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

Collision Term



- in few GeV energy regime decay and excitation of resonances dominate hadronic cross section
- work in progress: include string fragmentation

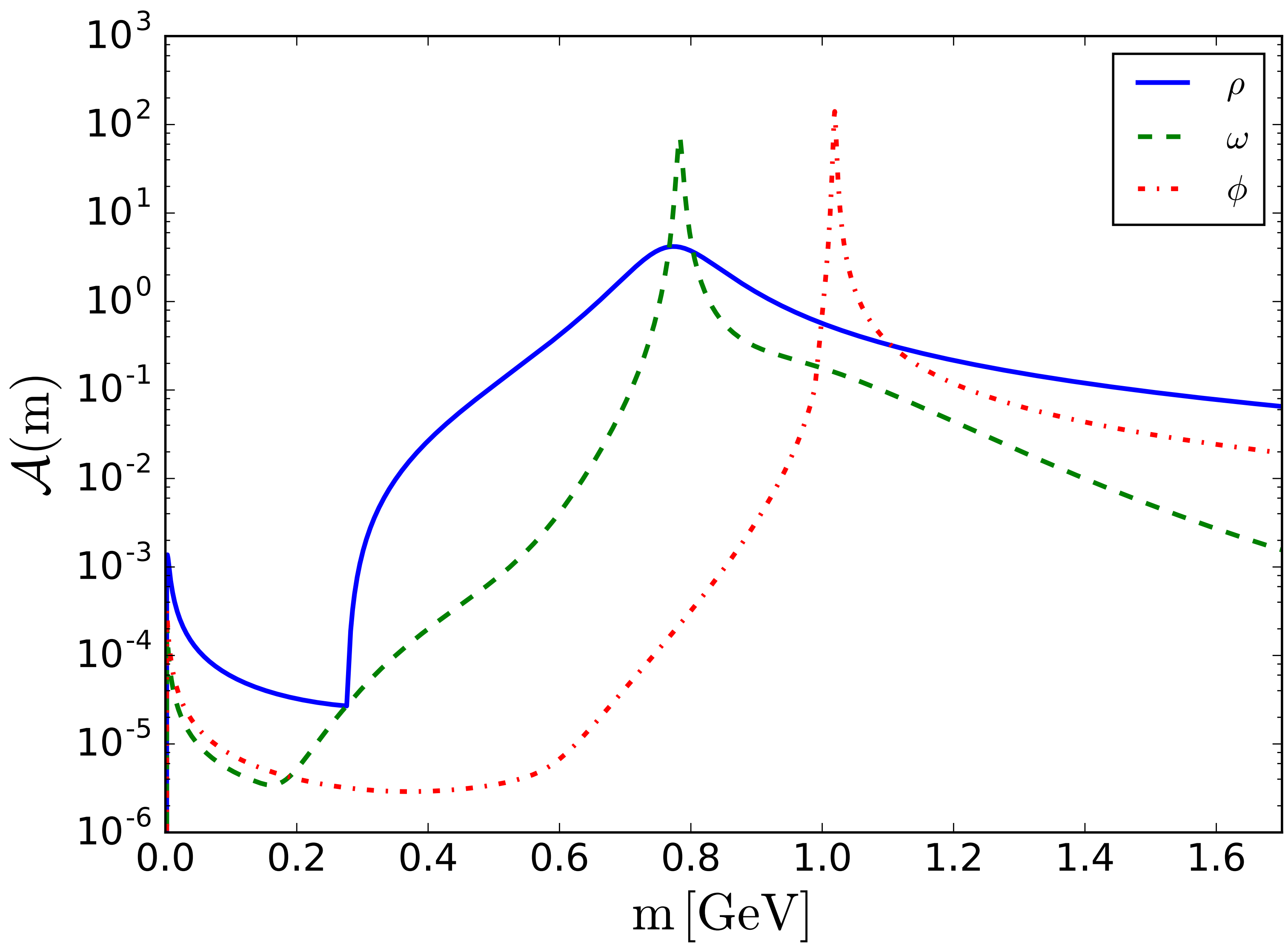
Dileptons in SMASH

- 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 details and more results:

JS, J. Weil, V. Steinberg, S. Endres, H. Petersen
arXiv:1711.10297

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

Spectral Functions

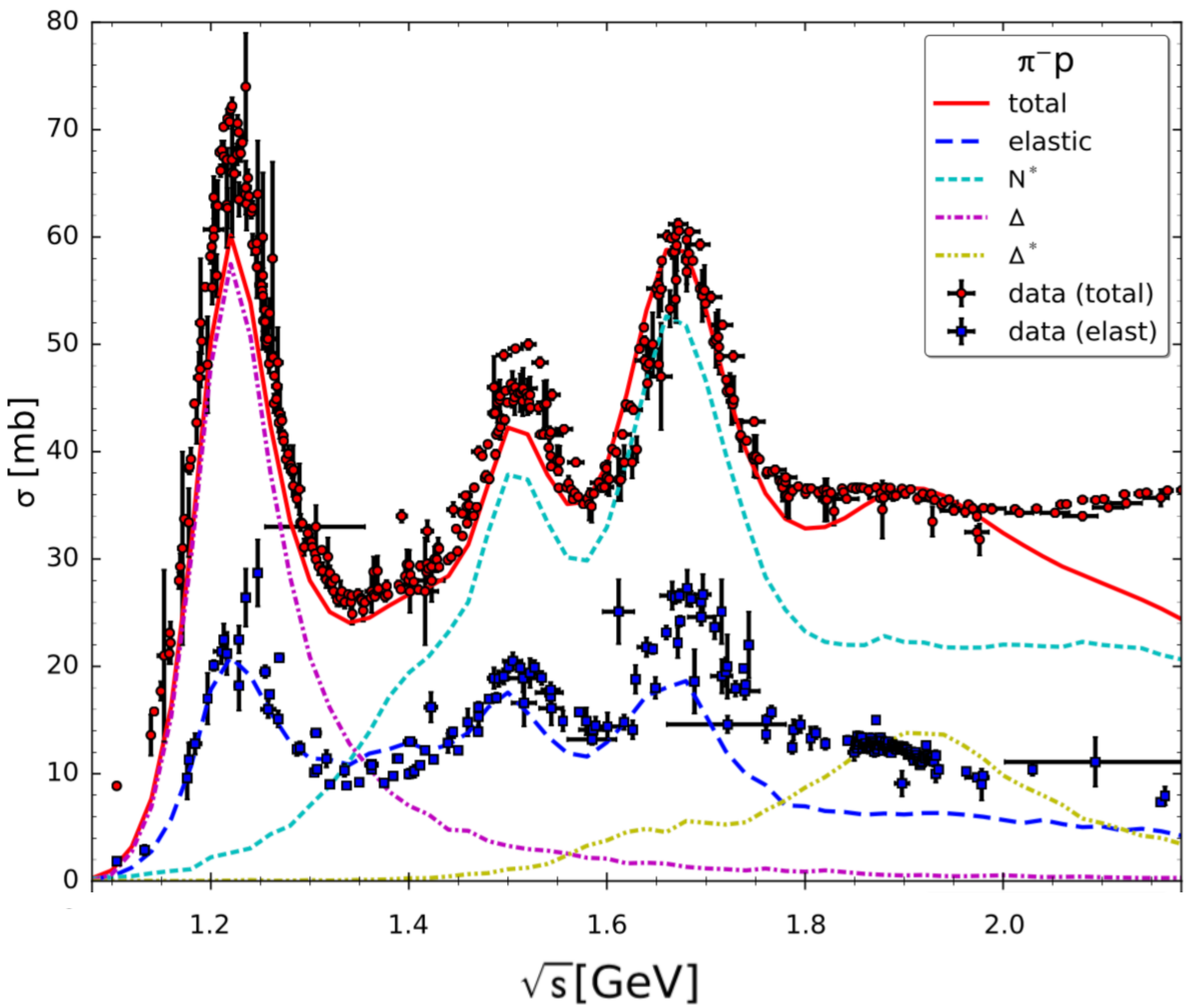


- relativistic Breit-Wigner (no density or temperature dependence —> vaccum)
- spectral function for vector mesons take dilepton decay into account
- contributions below hadronic threshold from dilepton decay width

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

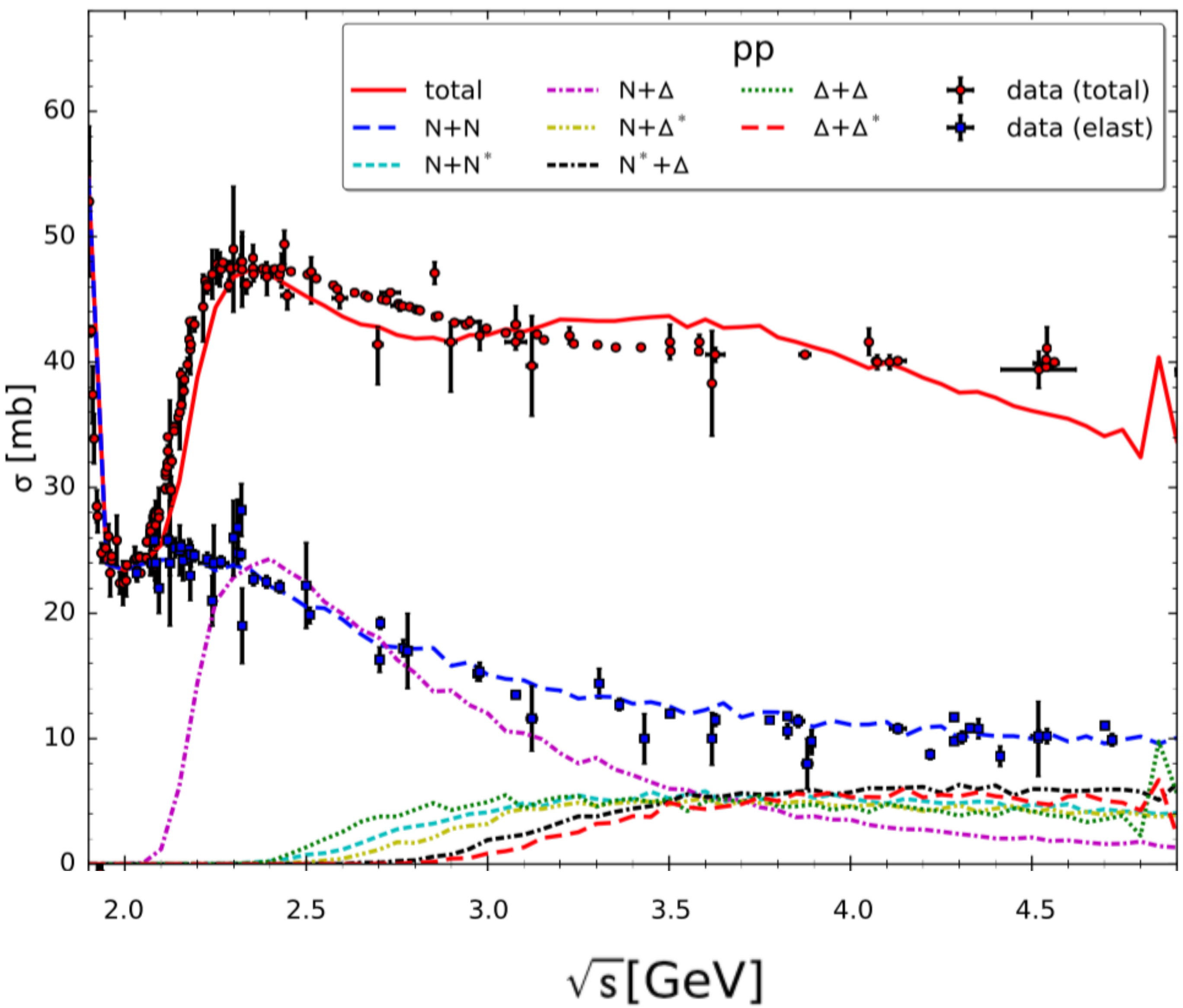
Results

Total Cross Section



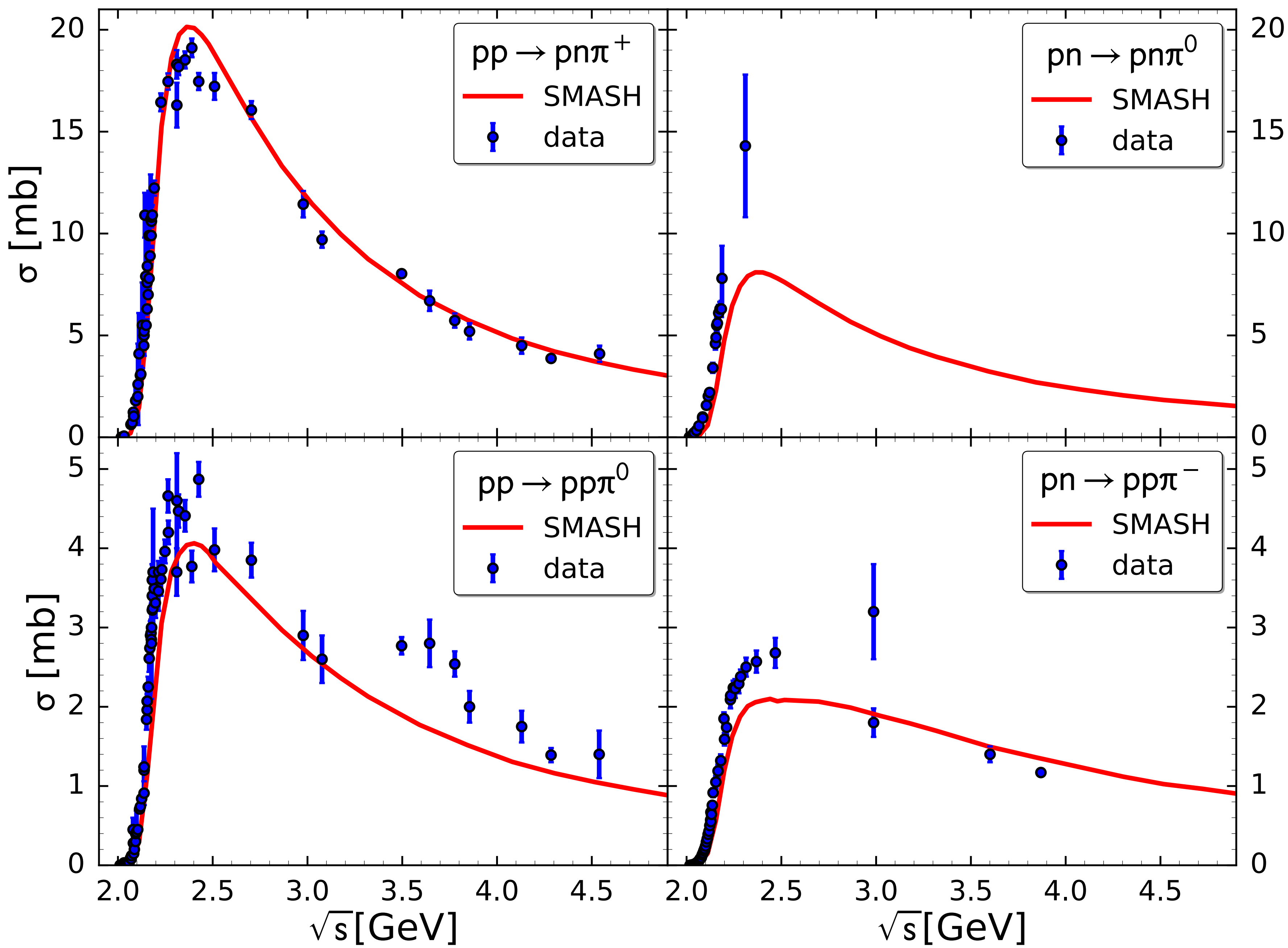
- total π^-p cross section
- lowest excitation from Δ, additional contributions from N^* and Δ^*
- compatible with data up to 2 GeV

Total Cross Section



- total pp cross section
- parametrized elastic cross section
- many resonance contributions to inelastic cross section
- reasonable description of data up to 4 - 4.5 GeV

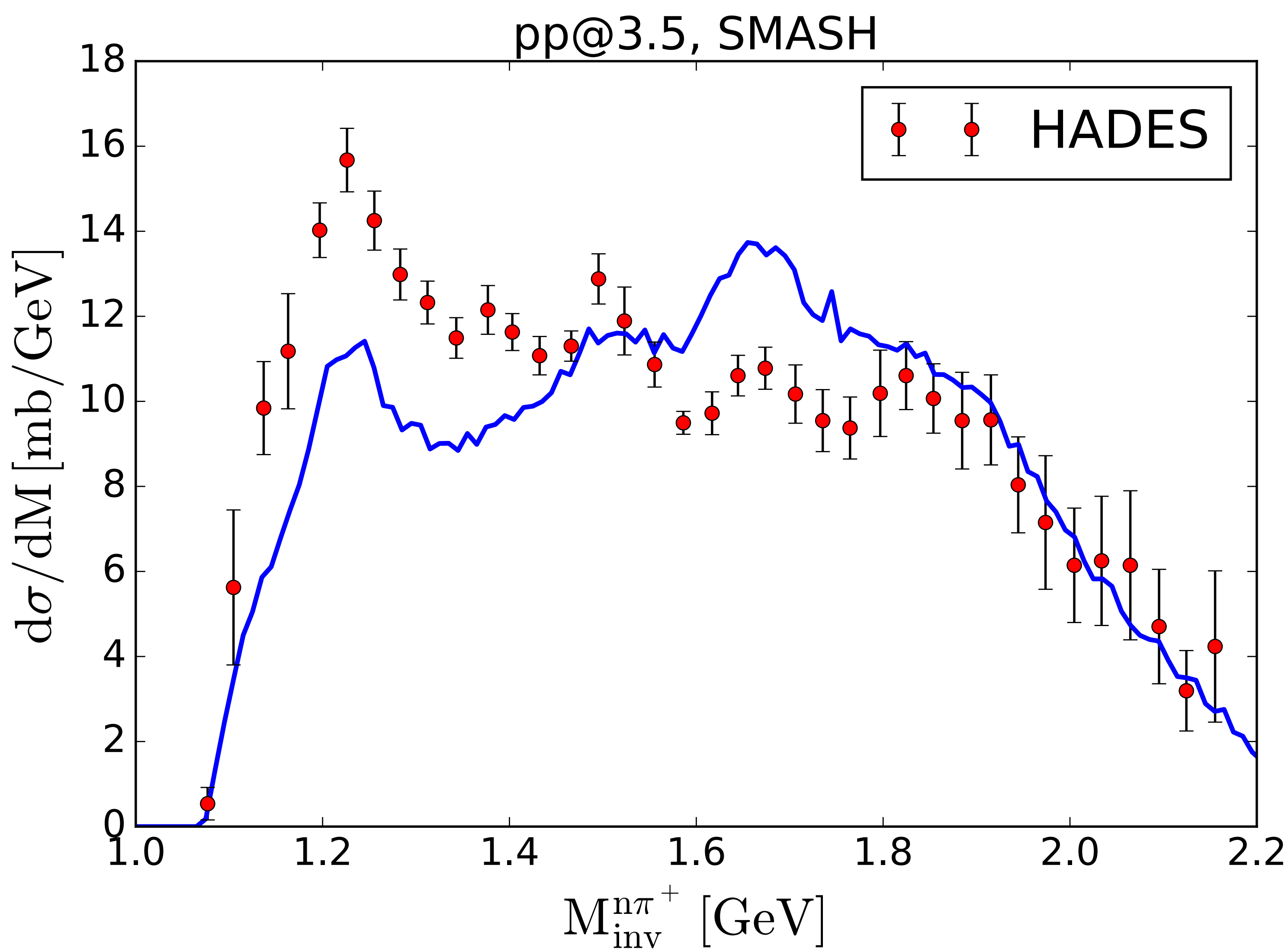
Single Pion Production



- exclusive cross section for single pion production in NN collisions
- dominant contribution from Δ resonance
- overall reasonable agreement with data

Exclusive Cross Section

$$pp \to pn\pi^+$$



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

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

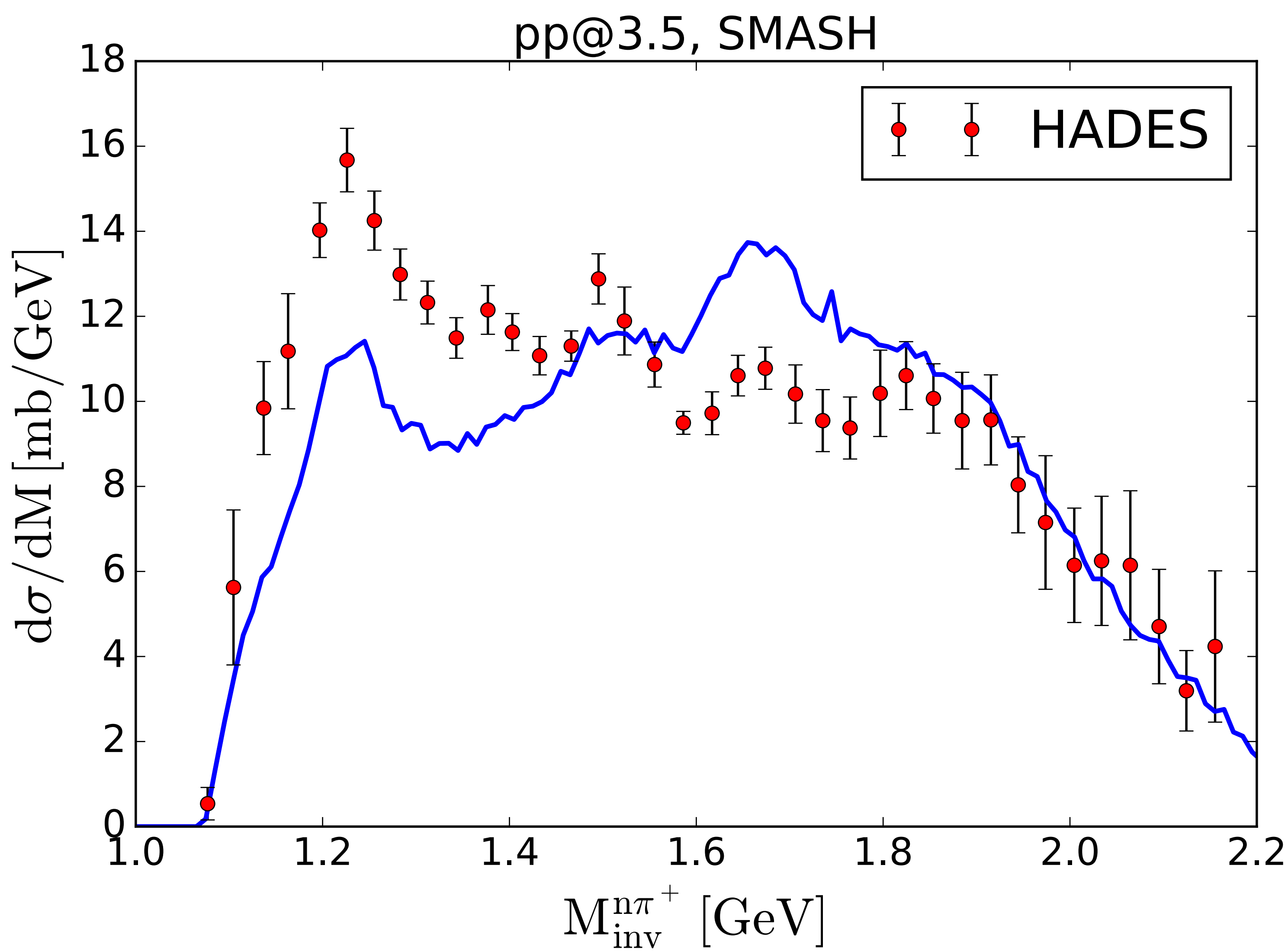
HADES, Eur. Phys. J., A50 (2014)

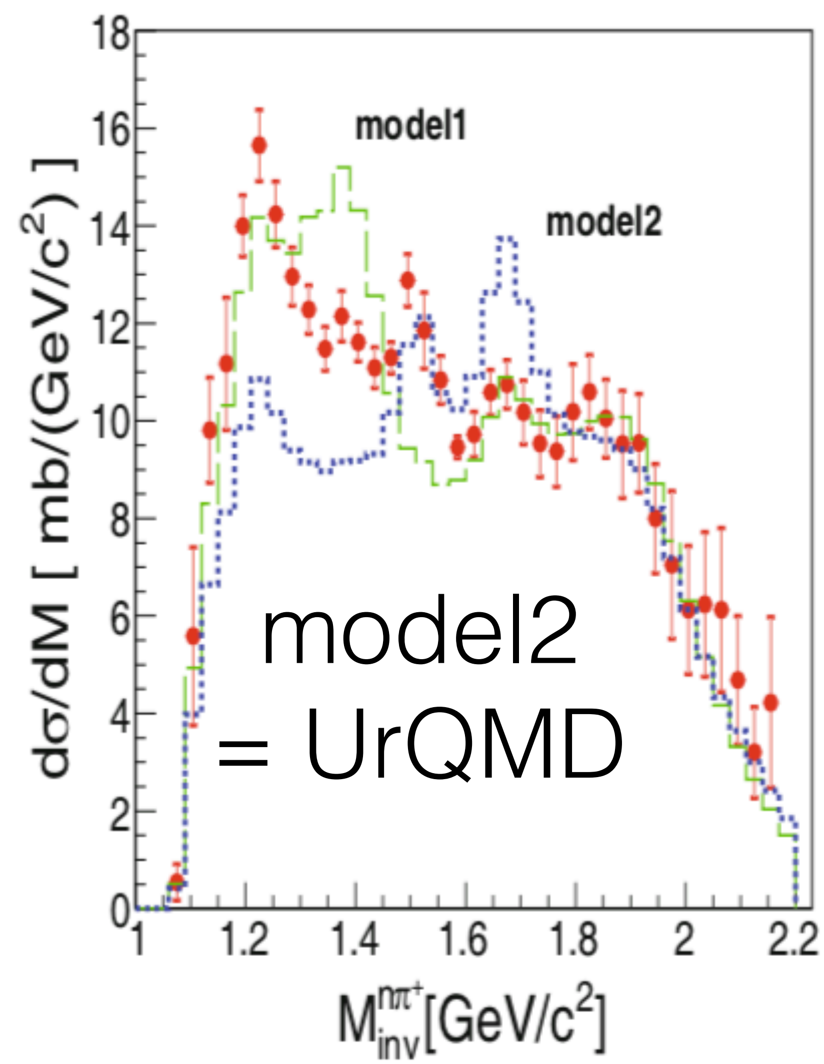
- invariant mass spectrum of $n\pi^+$
- probes baryonic resonance production cross section in primary NN reactions
- work in progress
- comparison to experimental data similar to UrQMD

Exclusive Cross Section

$pp \rightarrow pn\pi^+$

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





model2
= UrQMD

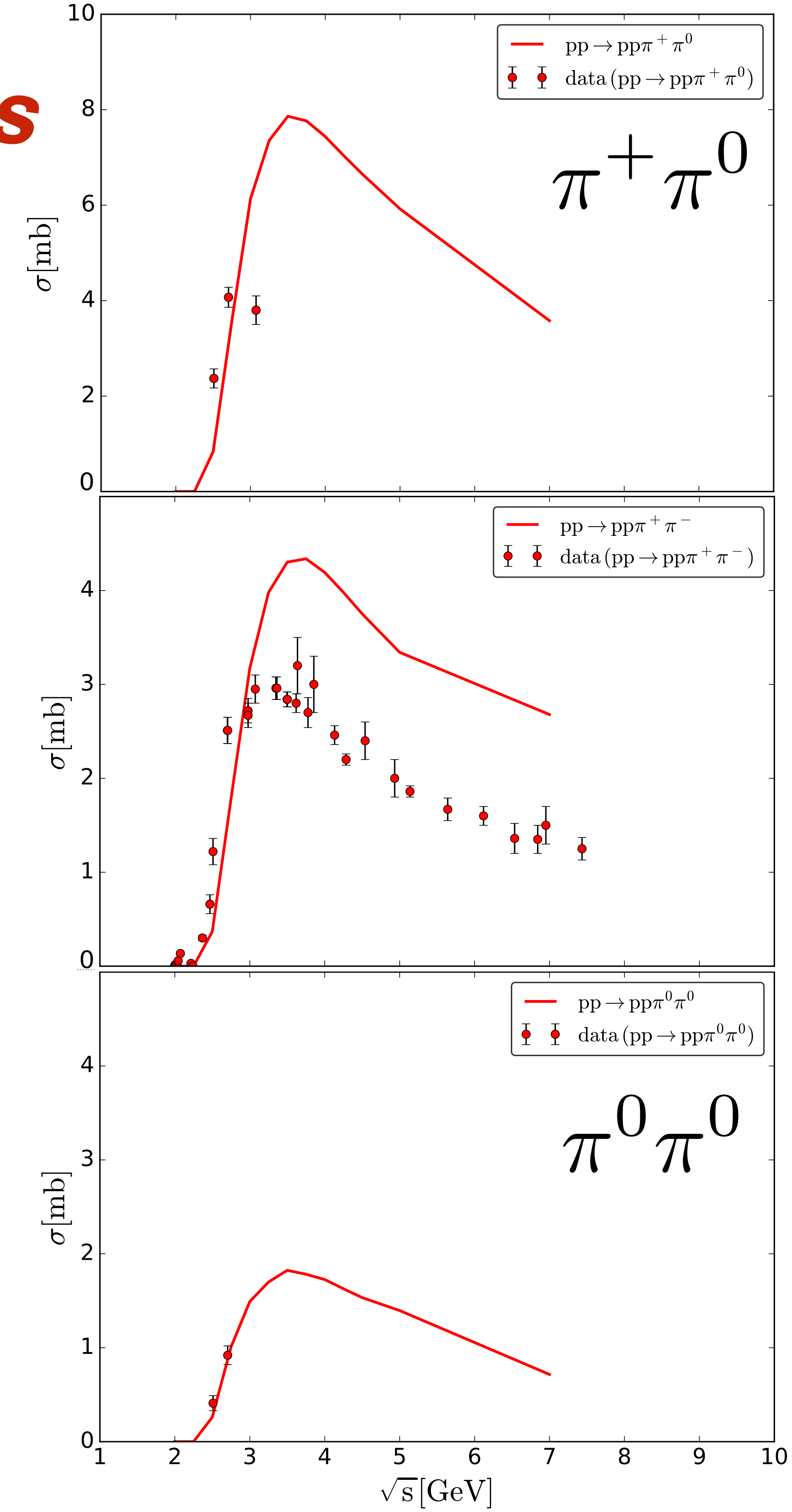
J.Weil et al, Phys. Rev. C 94 (2016)

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

Two-Pion Production

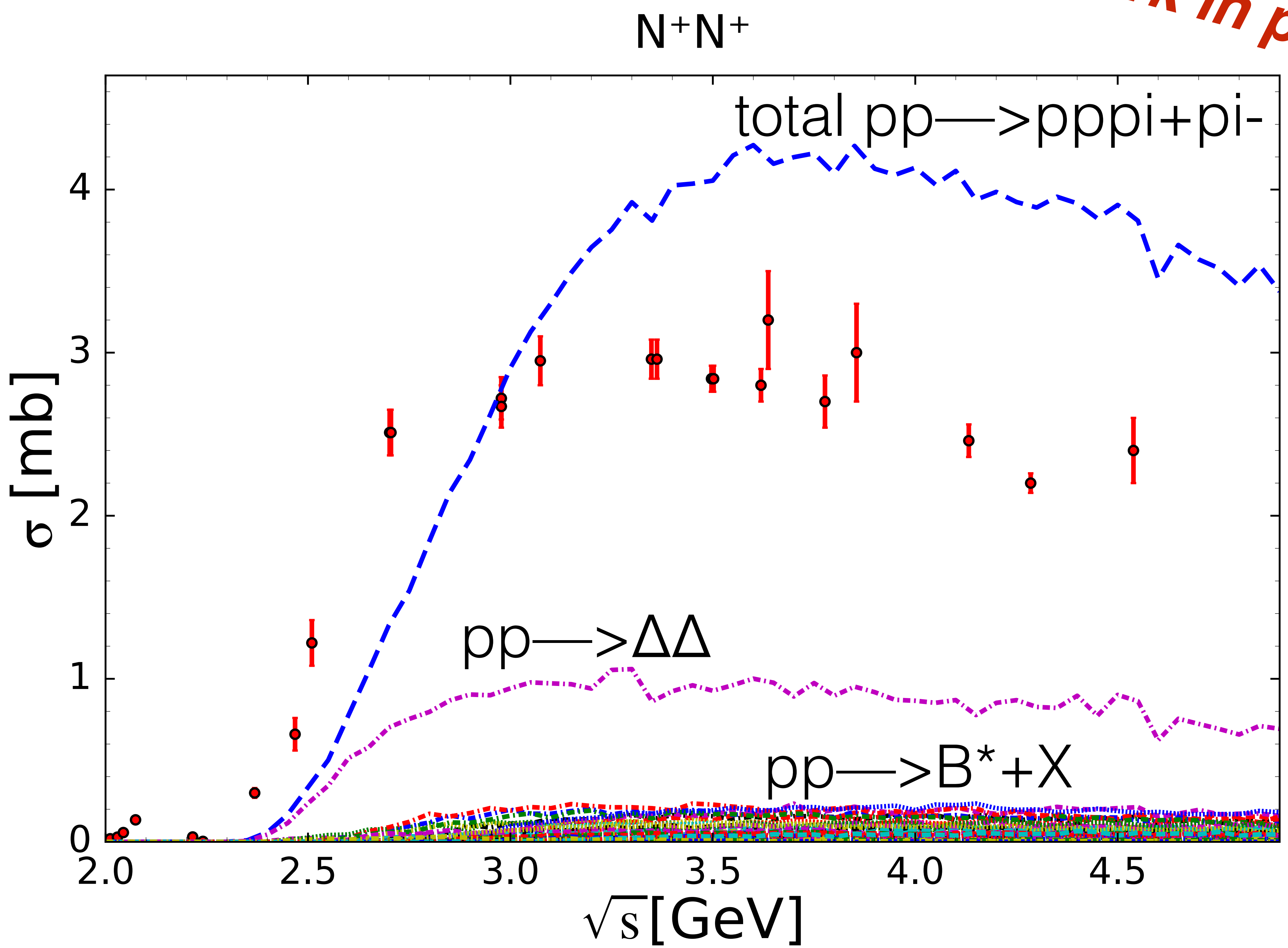
work in progress

- current status for exclusive cross section for two-pion production in pp collisions
- experimental data not as well described (e.g. in $\pi^+\pi^-$)
- potential solutions:
  - improved matrix elements for NN →ΔΔ (ΔΔ=dominant contribution)
  - constrain B.R. for heavy resonances
- feedback welcome

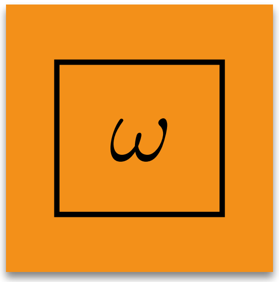


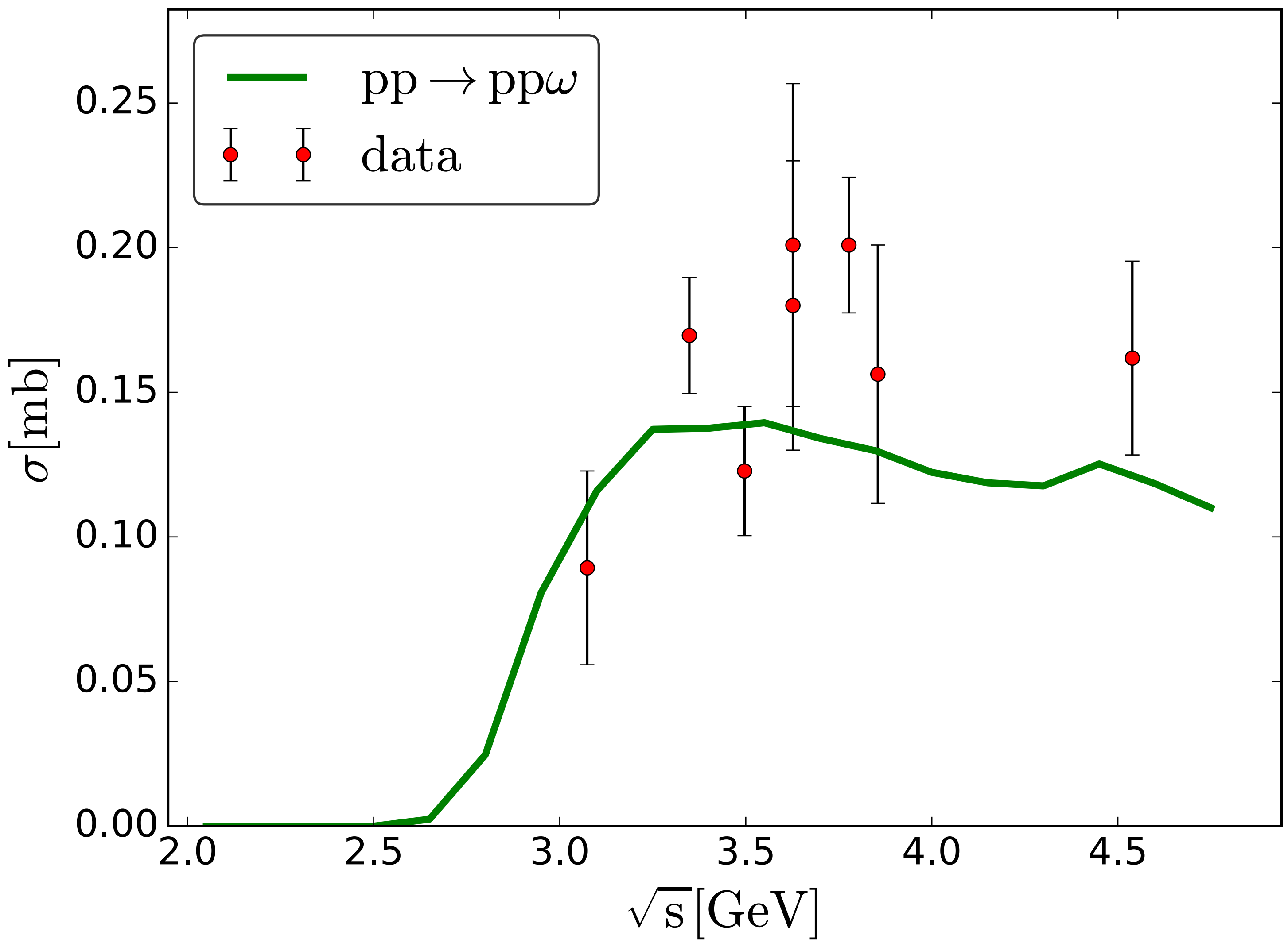
Two-Pion Contributions

work in progress



Exclusive Cross Section

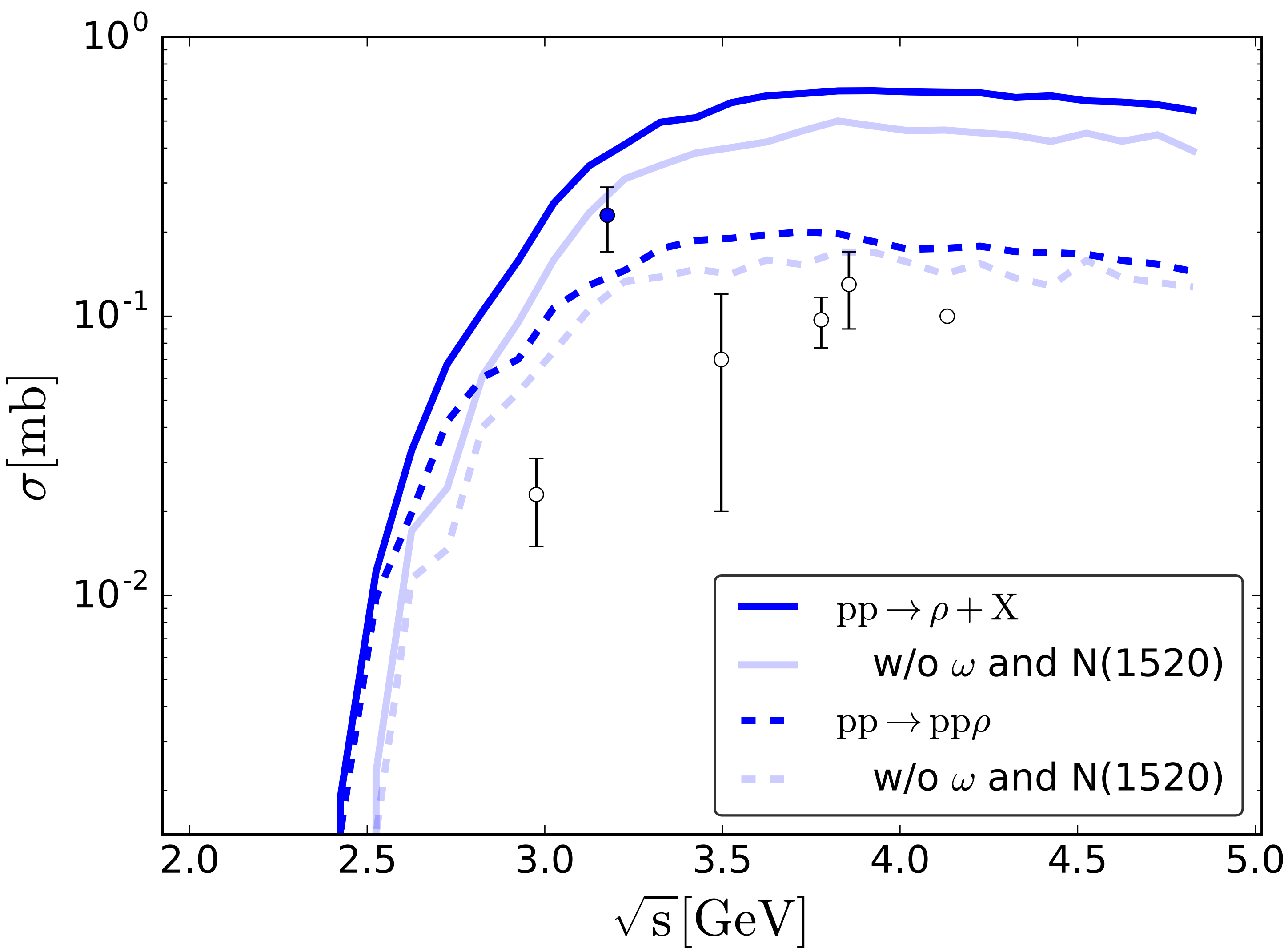




- investigating the exclusive production cross section of resonances
- exclusive production of ω via $pp \rightarrow pp\omega$
- reasonable agreement with data for different energies

Exclusive Cross Section

ρ



- inclusive and exclusive production of ρ mesons in proton-proton
- overshooting for inclusive cross section may be caused by two step treatment of decays e.g.

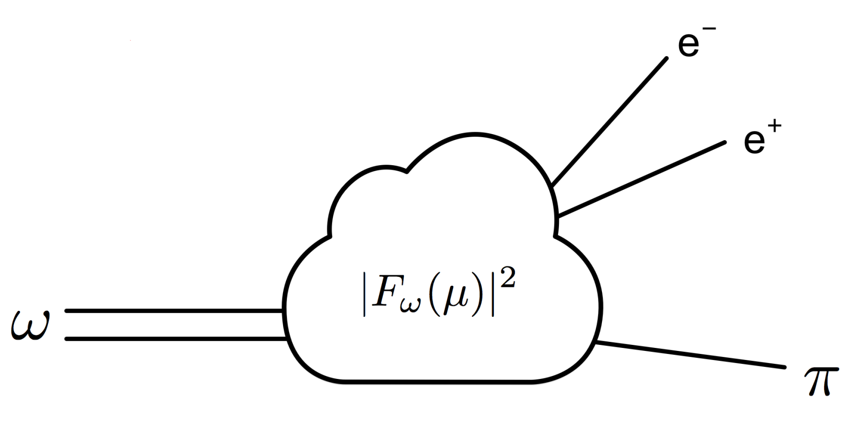
$$N^*(1520) \rightarrow N\rho \rightarrow Ne^+e^-$$

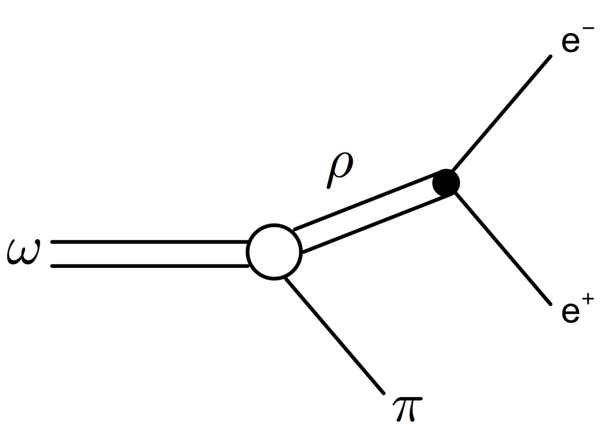
$$\omega \rightarrow \pi\rho \rightarrow 3\pi$$

Form Factors

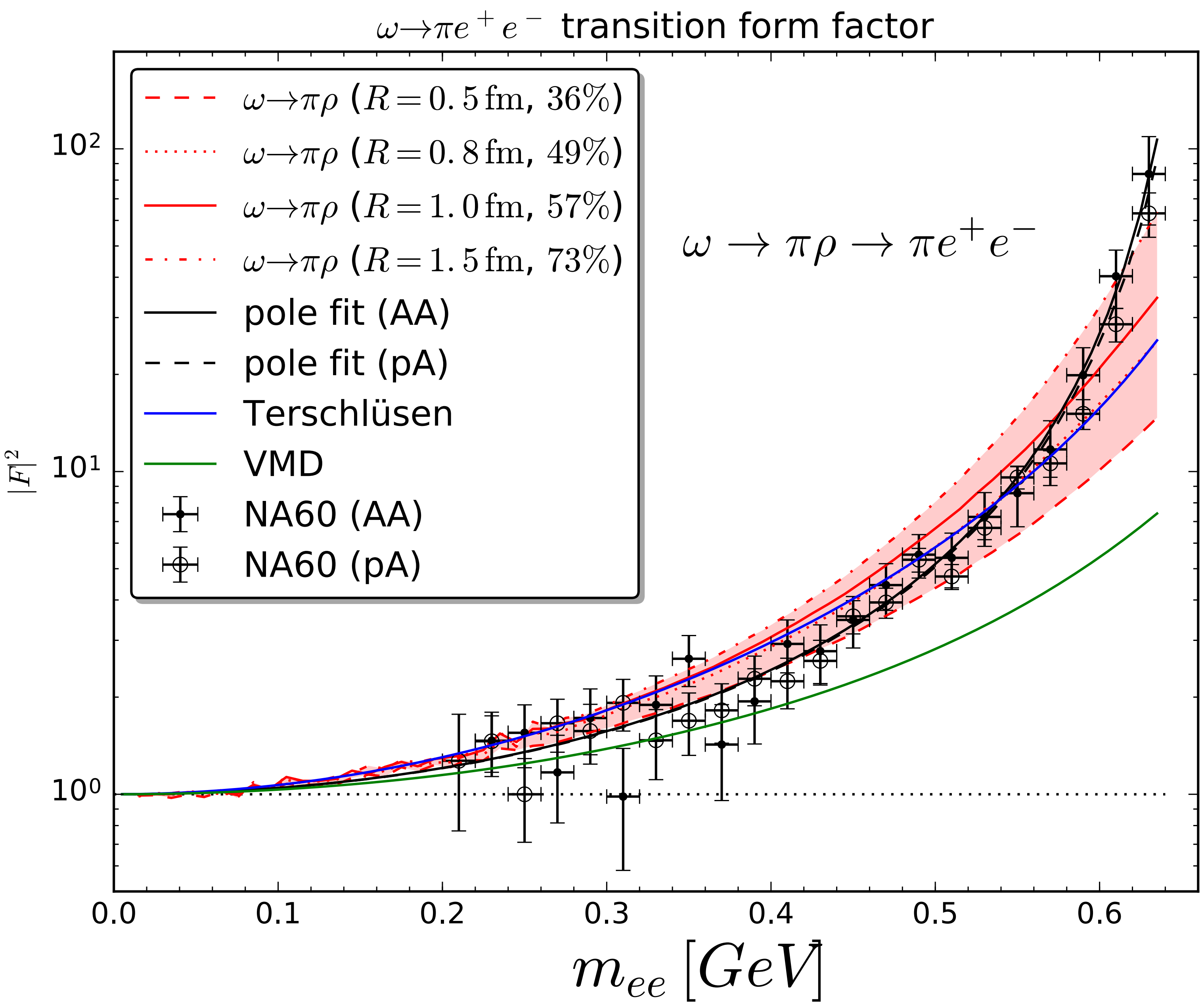
Form Factors

- dilepton routine was used to investigate the e.m. transition form factor of the omega dilepton Dalitz decay $\omega \to \pi^0 e^+ e^-$ *J. Weil, JS, Hannah Petersen, arXiv:1604.07028v1*
- decay described by two steps similar to hadronic ω decay into 3π: $\omega \to \rho\pi \to 3\pi$ (VMD-inspired)





Form Factors: ω



- comparison of our ansatz with NA60 data

Phys.Lett. B677 (2009) 260-266

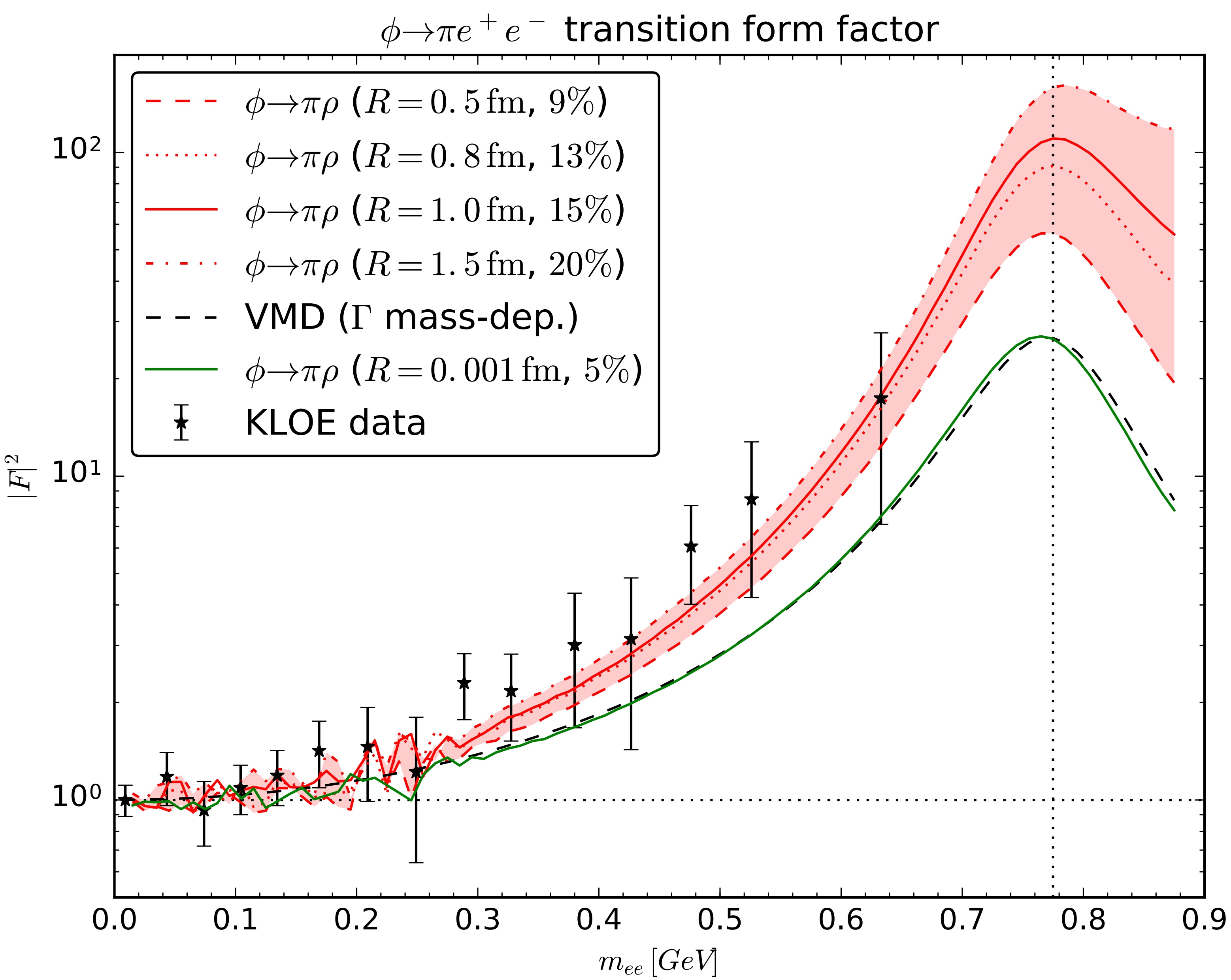
- variation of B.R. and cutoff-parameter R
- description of data with B.R. of 57% possible

$$B.R.(\omega \to 3\pi) = 89\%$$

- also compatible with Terschlüsen approach

Terschlüsen, Strandberg, Leupold and Eichstädt, Eur. Phys. J. A 49 116

Form Factors: Φ

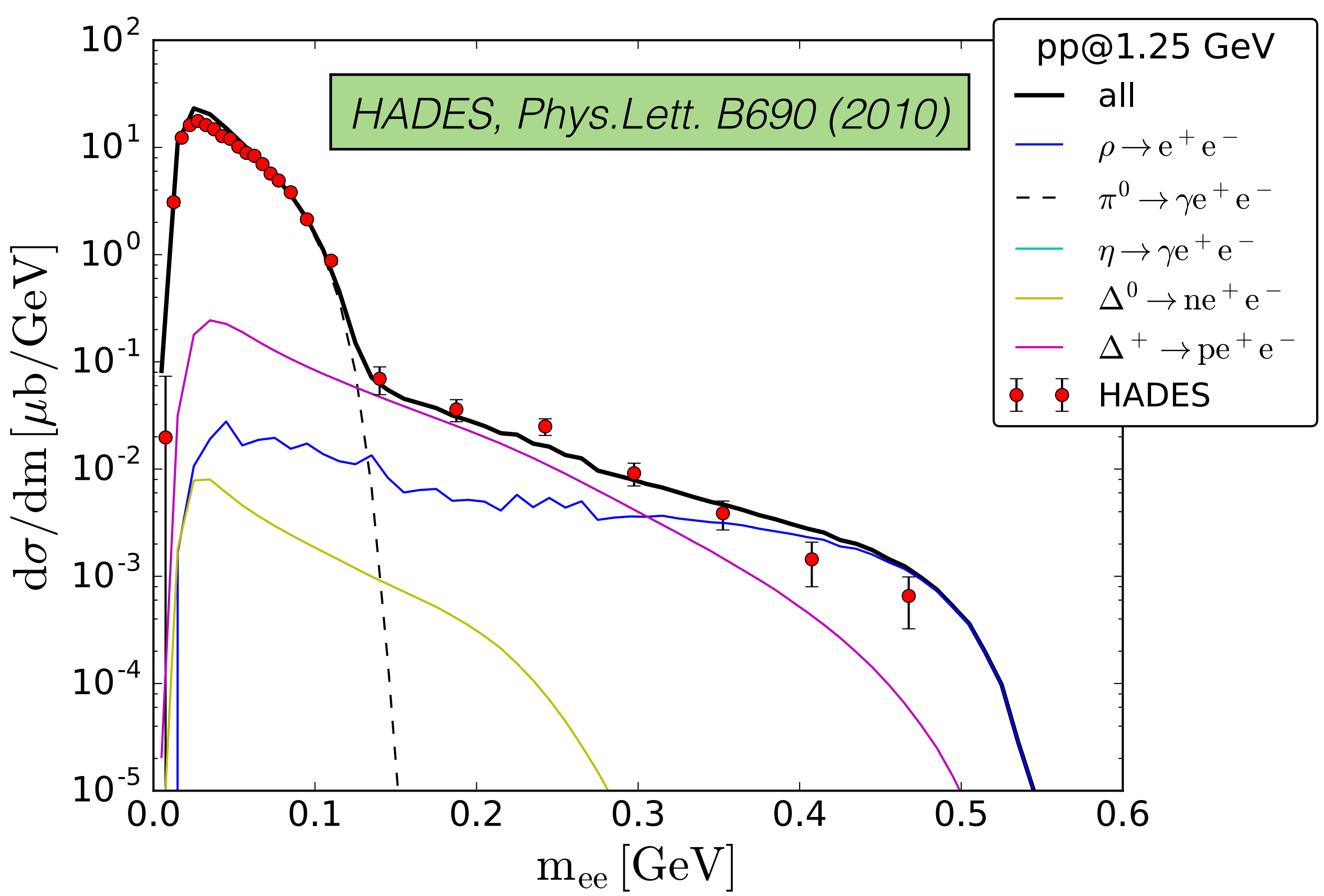


- same ansatz for the Φ meson
- comparison with data from KLOE *Phys. Lett. B 757 (2016) 362*
- description of data suggests B.R. of 15% $B.R.(\phi \to 3\pi) = 15\%$
- again better description than „simple“ VMD

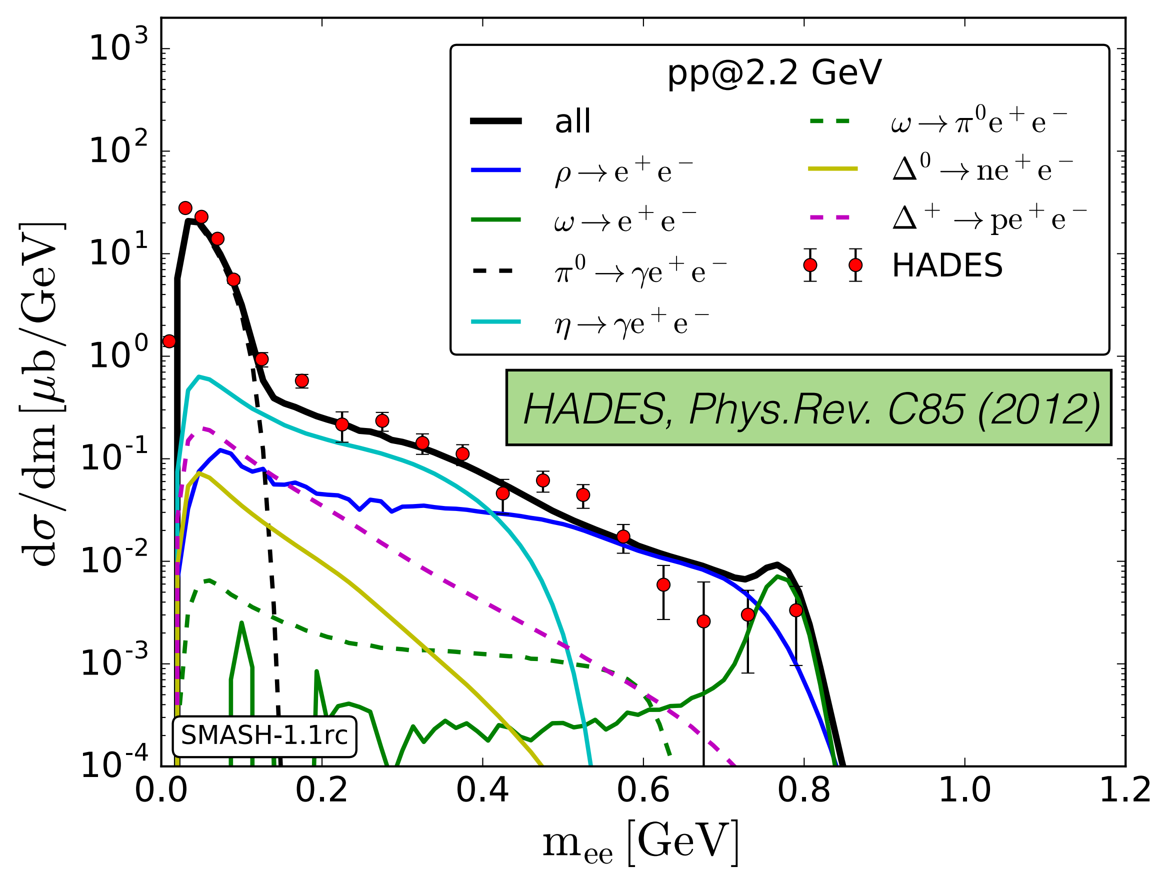
Dileptons

Low Energy pp Collisions

pp, 1.25 GeV



pp, 2.2 GeV

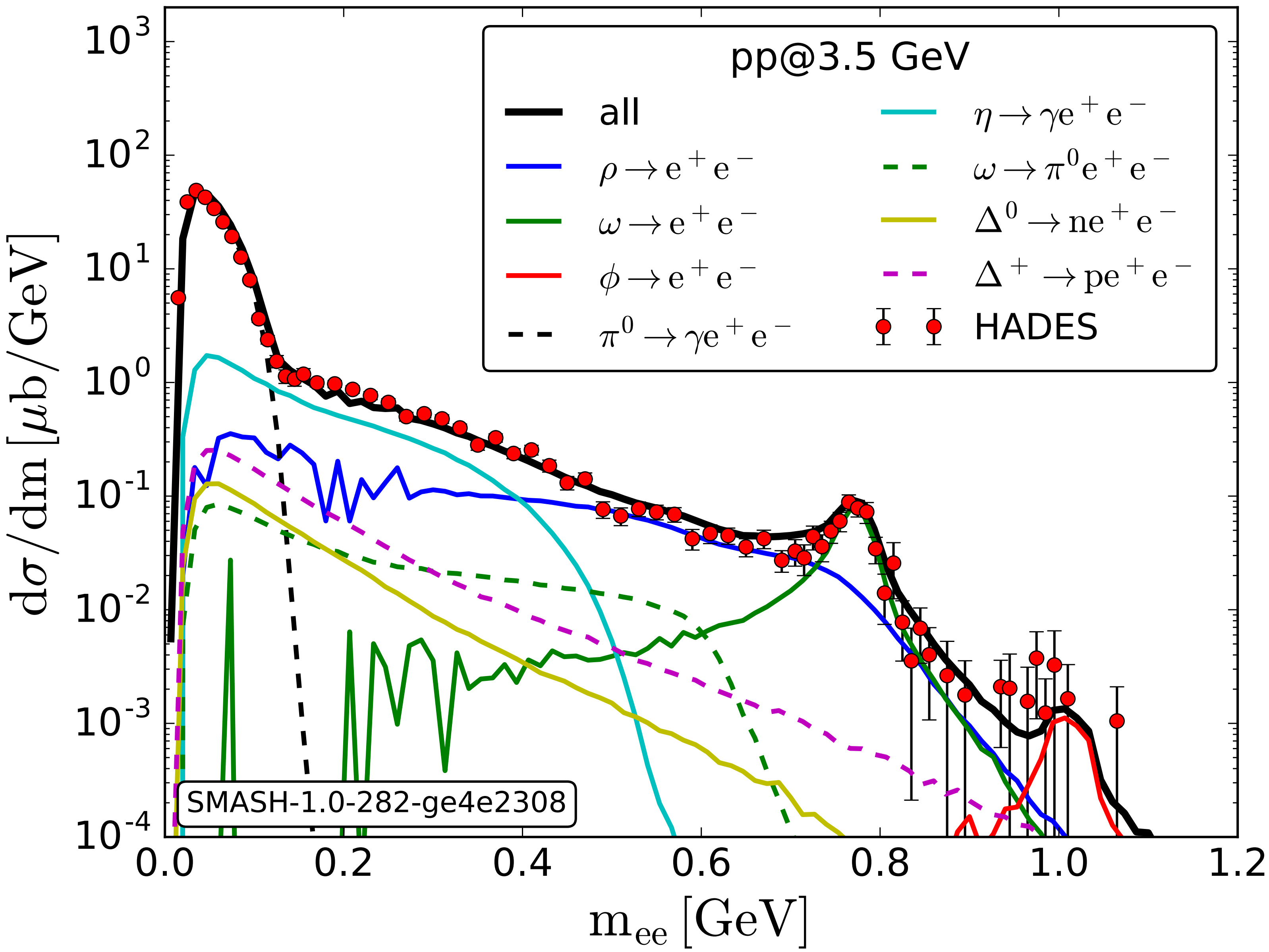


- dominant channels are π, ρ, Δ
- agreement with data

- above η threshold
- slight overproduction in high invariant mass region

Low Energy pp Collisions

pp, 3.5 GeV



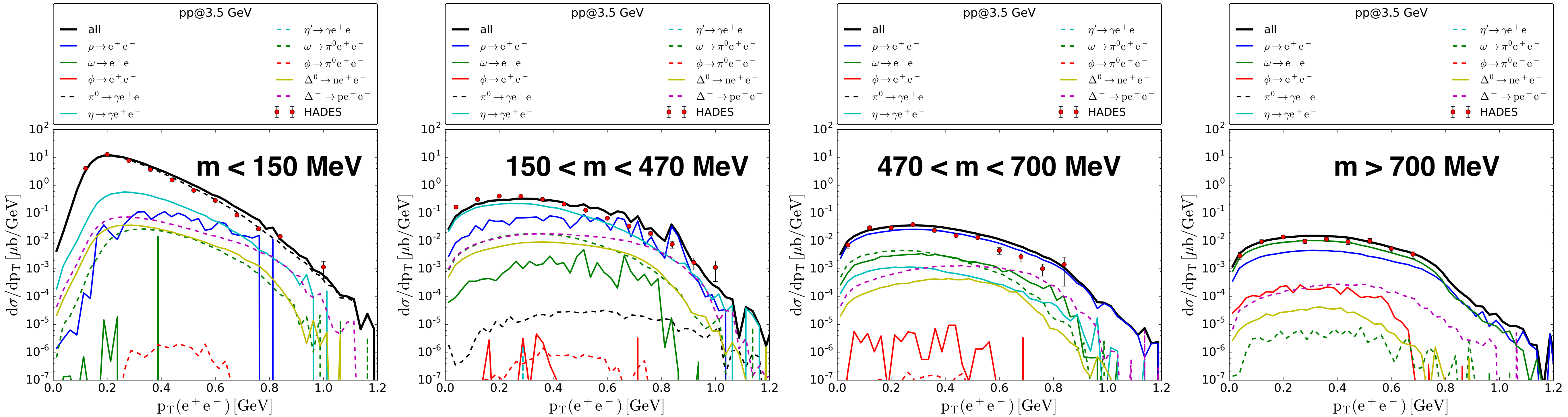
- invariant mass spectrum for pp collision with E_{kin} = 3.5 GeV
- constraining elementary reaction baseline
- sub-threshold contributions by direct vector mesons decays
- very good agreement with data

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

p_T Spectra

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

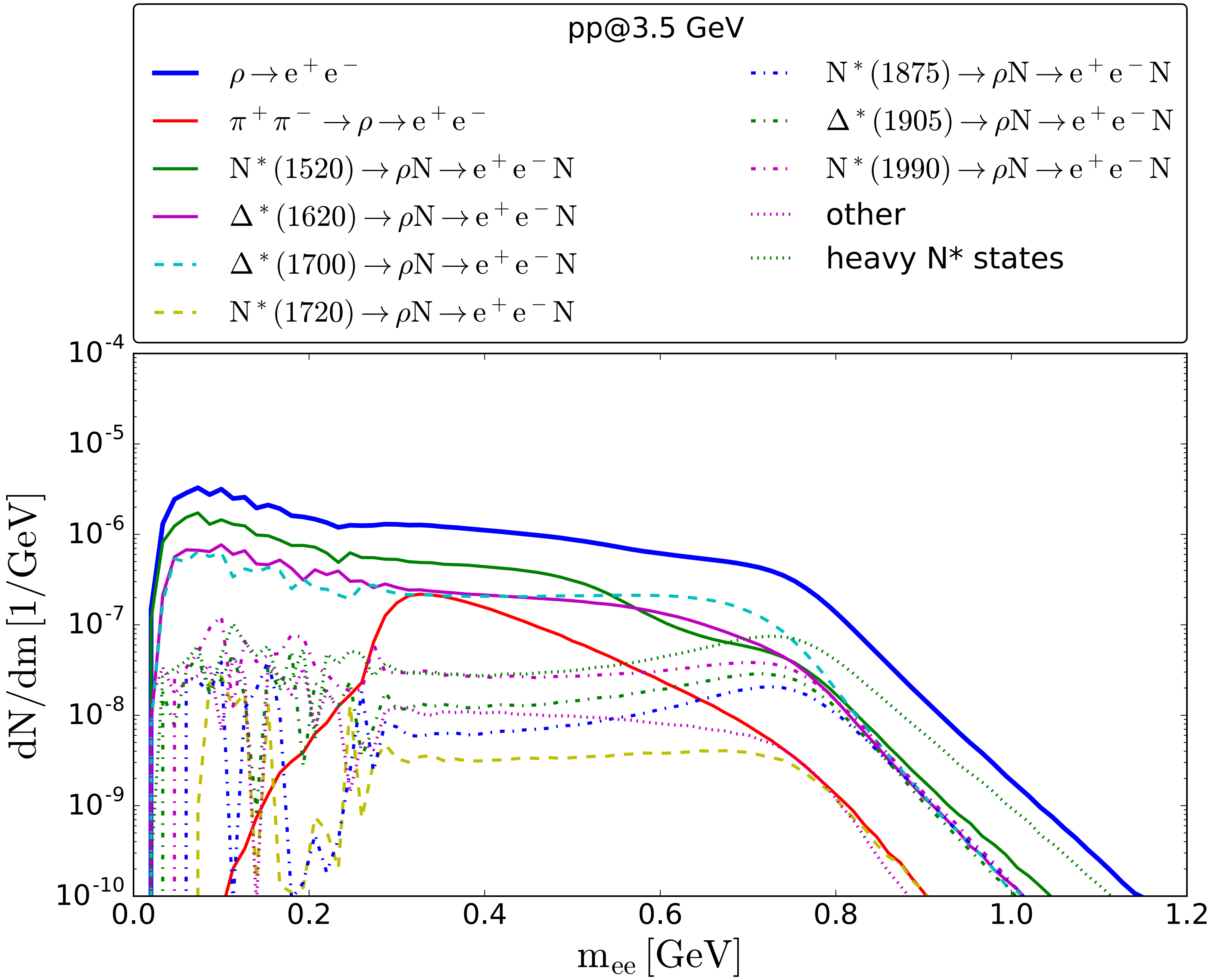
pp, 3.5 GeV



- comparison of p_T spectra for different invariant mass windows
- reasonable agreement for elementary reactions in all regions of phase space

ρ Origin in Dilepton Spectra

pp, 3.5 GeV



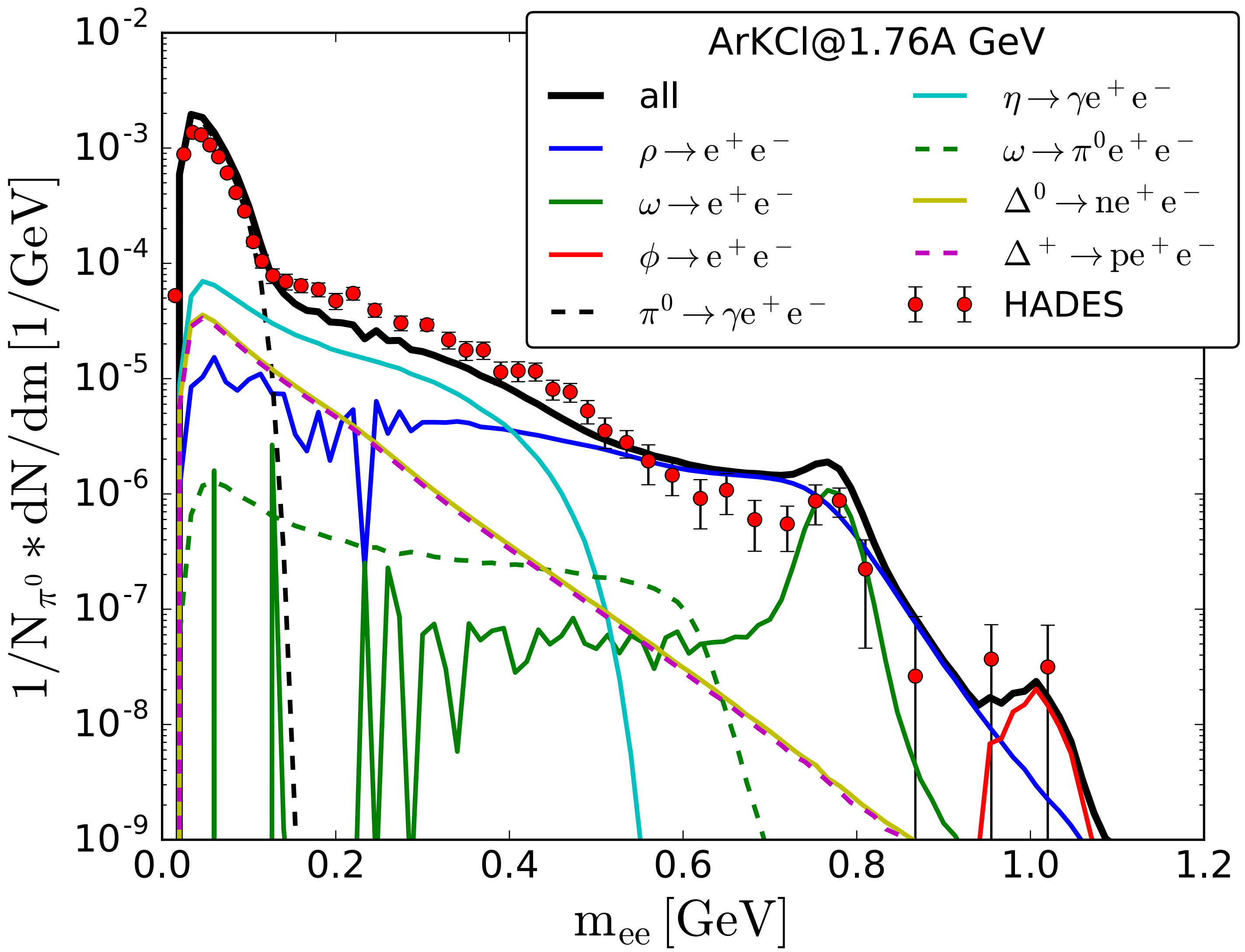
- different processes that produce ρ that decays into di-electrons
- valuable to understand the broad ρ contribution
- mostly baryonic resonance decays, plus small pion annihilation
- sub-threshold contribution by light baryonic resonance decays

Larger Systems: ArKCl

ArKCl, 1.76 AGeV

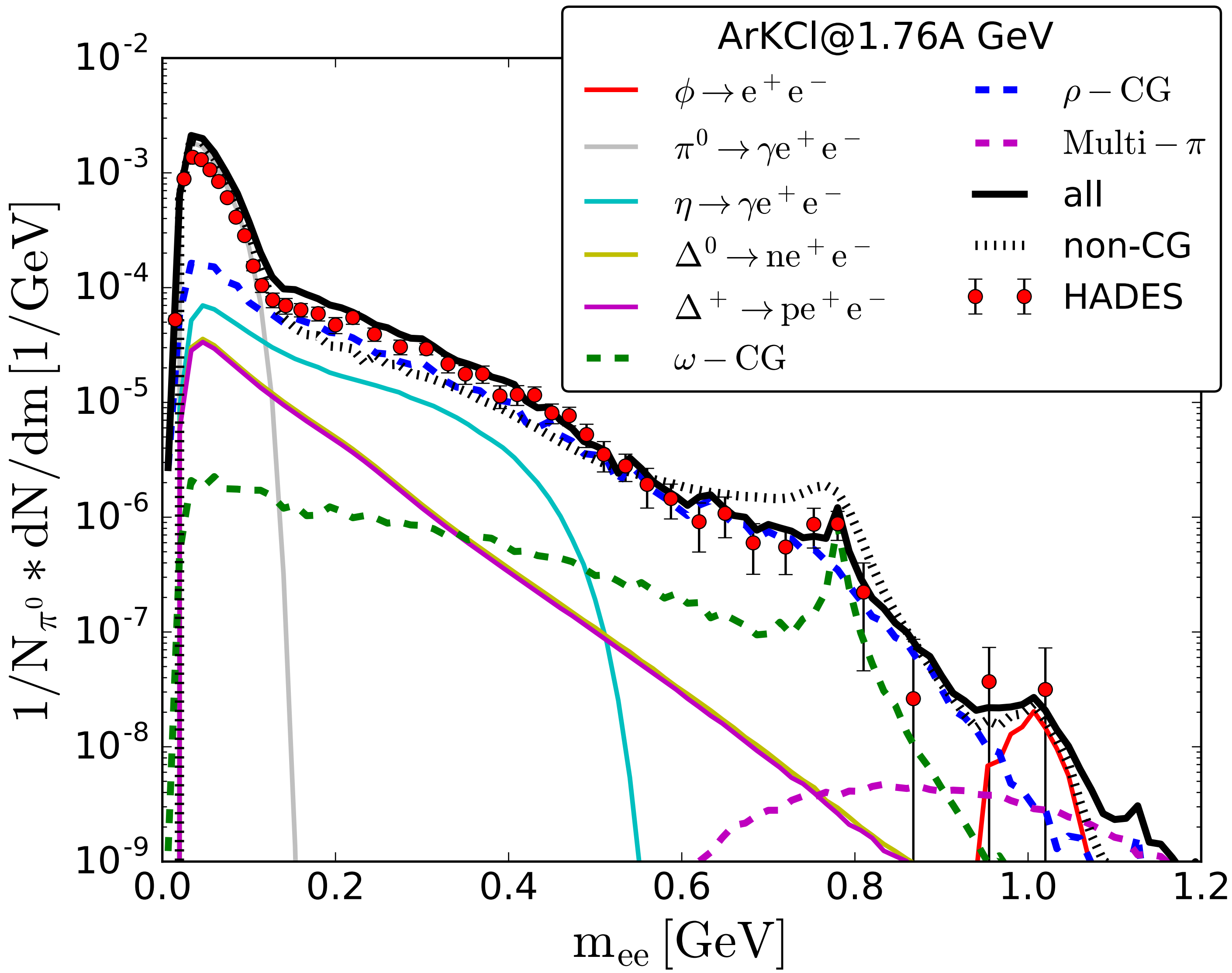
HADES, Phys.Rev. C84 (2011)

based on elementary baseline explore medium effects in larger systems



- ArKCl: example for larger system
- overestimation in rho pole mass region + underestimation in intermediate mass region
- vacuum resonances description insufficient? explicit medium modification necessary?

Coarse-Graining Approach



- coarse-graining approach by Stephan Endres on SMASH evolution

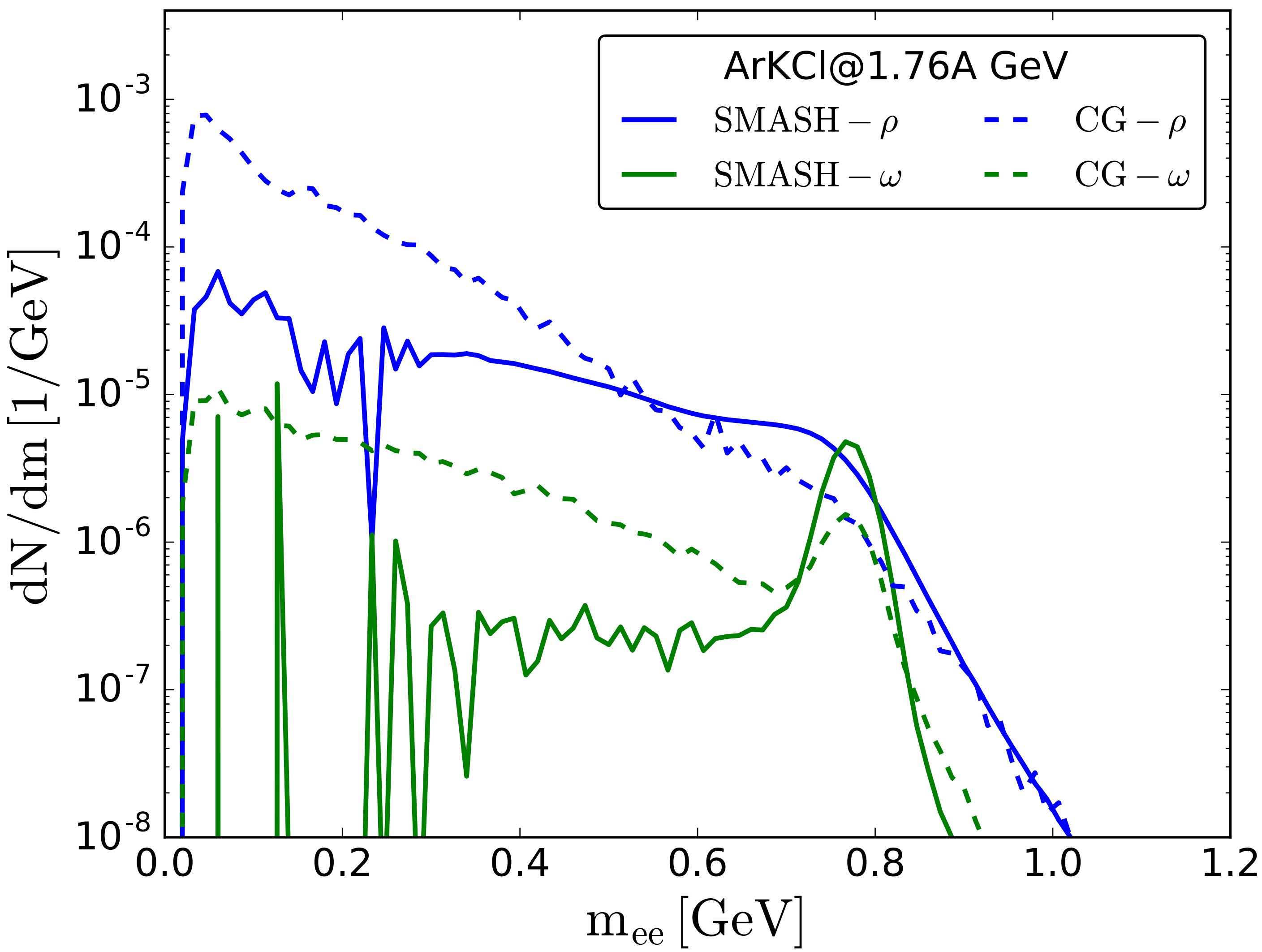
  Endres et al, Phys.Rev. C92 (2015)

- 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

Vector-meson Contributions

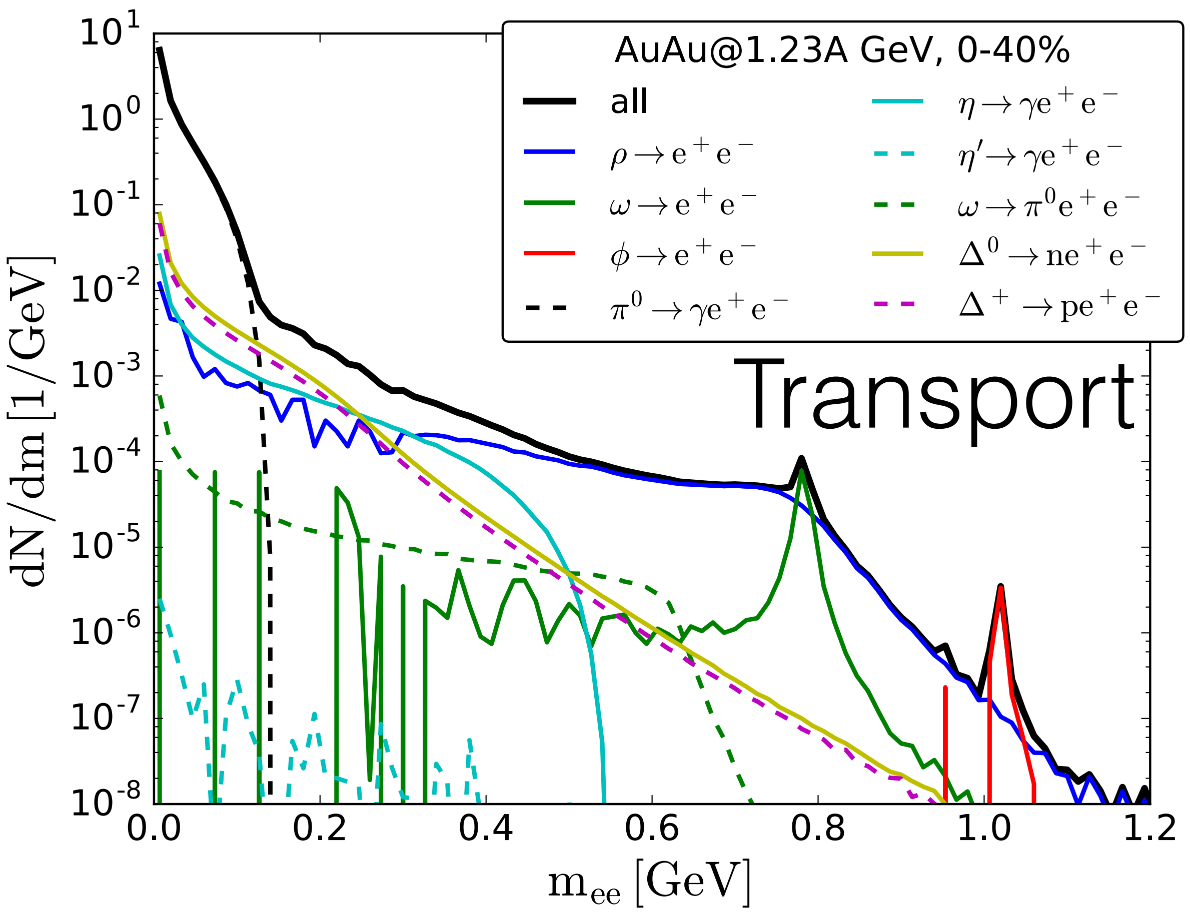


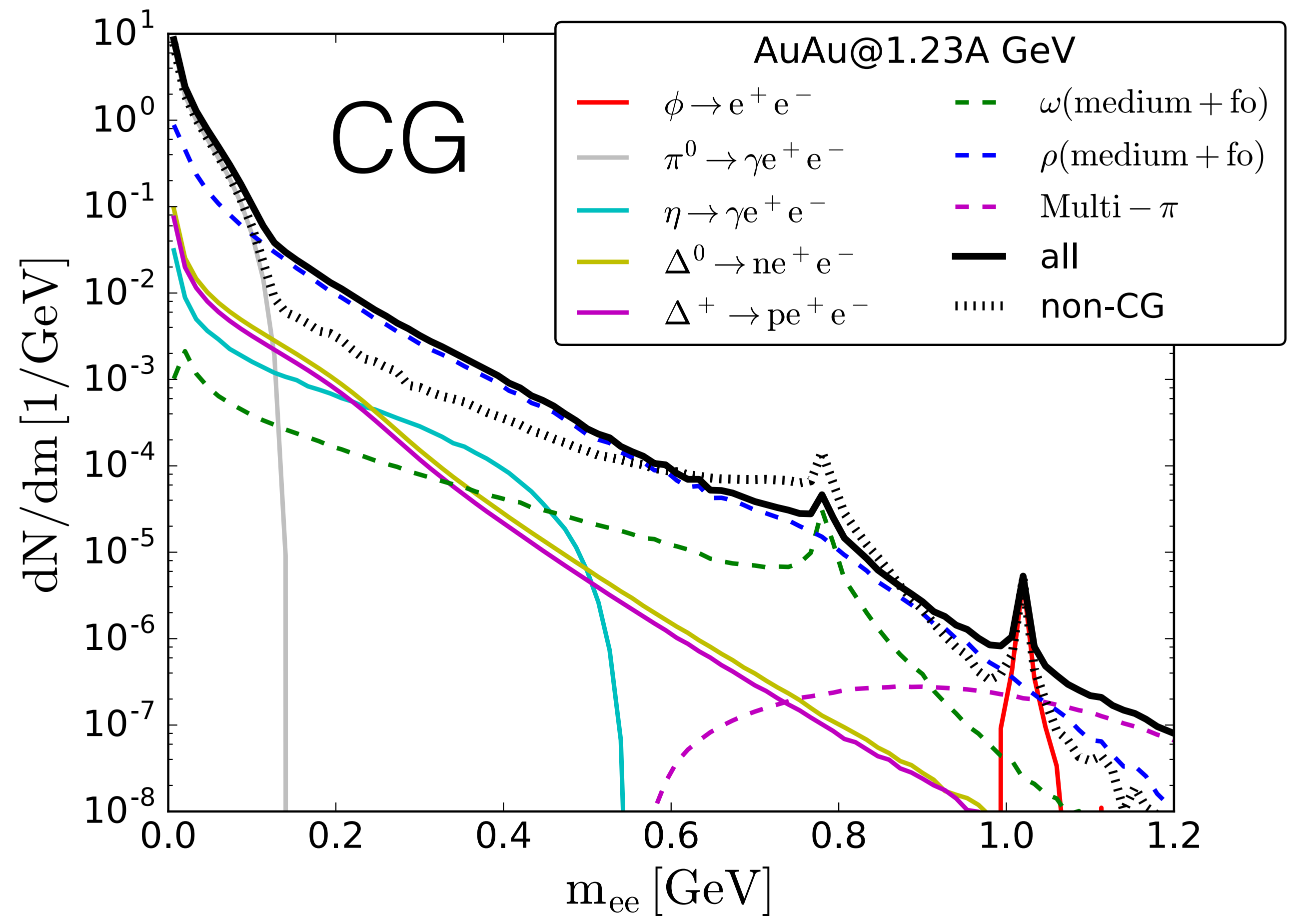
- comparison between vacuum and medium modified vector meson dilepton yields
- shift from pole mass region to low mass tail
- coupling between ρ and baryons in nuclear matter leads to low-mass tail for SMASH

$$\boxed{B^* \rightarrow N\rho \rightarrow Ne^+e^-}$$

Predictions for HADES

AuAu, 1.23 AGeV

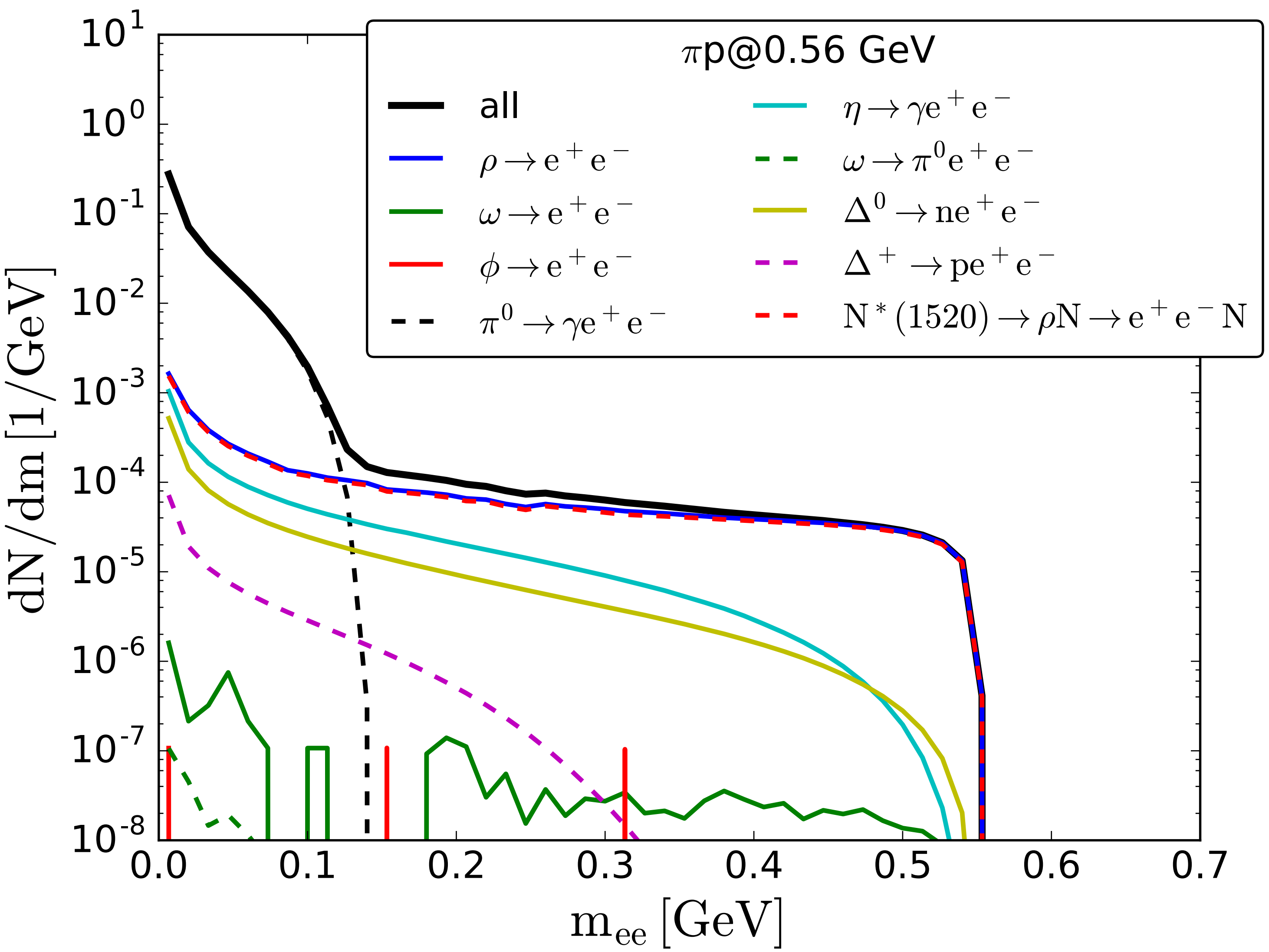




- heavier system: sensitivity to medium effect increased

Predictions for HADES

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

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

Summary

Hadronic transport approaches offer excellent framework to study low-energy reactions.

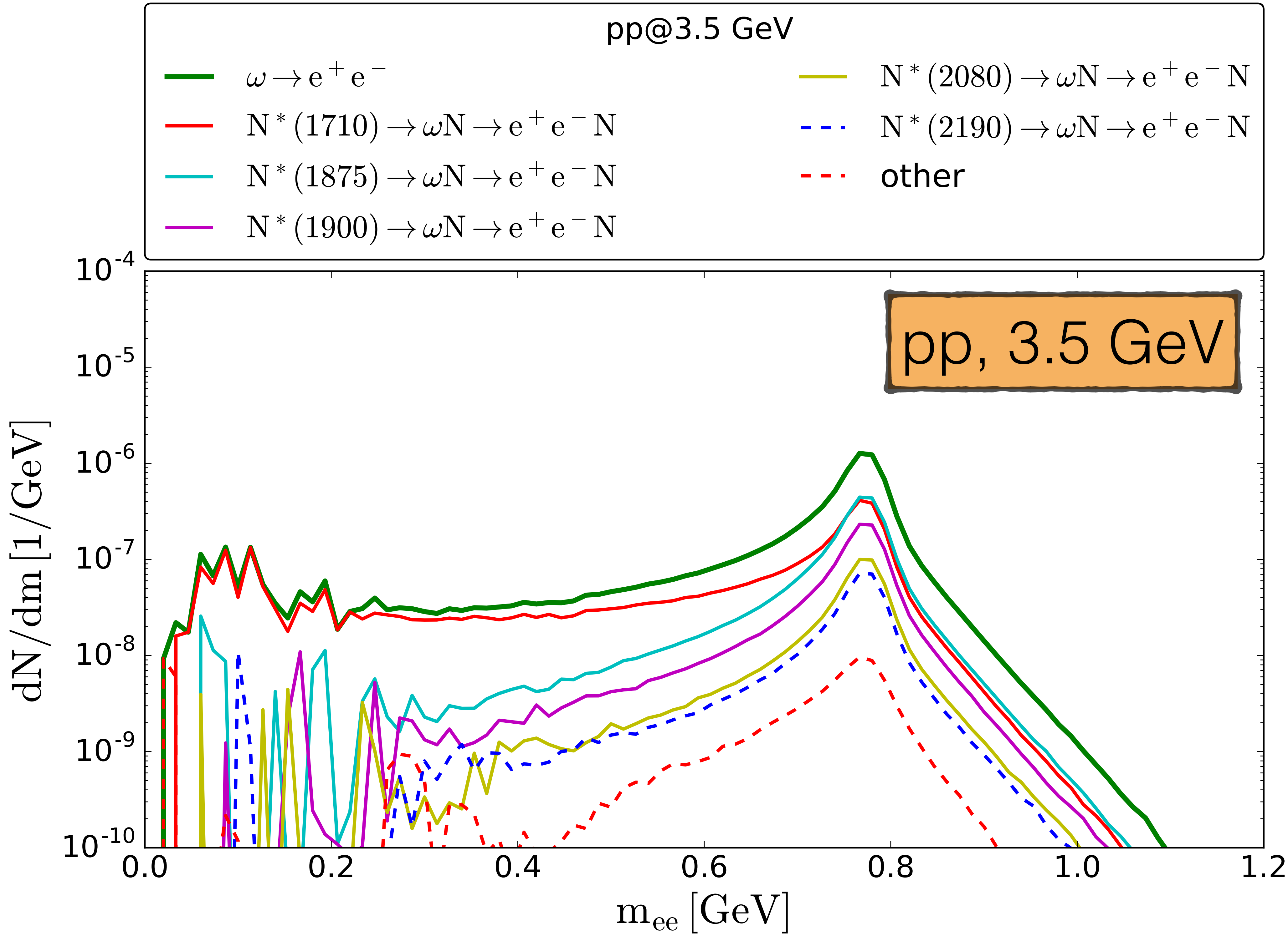
1. Total hadronic cross section agree with data for low energies
2. „Strict-VMD“ used to study the e.m. form factor of dilepton Dalitz decay of ω and Φ
3. Dilepton production for elementary reactions indispensable baseline to probe medium effects

—> SMASH will be open-sourced later this year

—> looking forward to new experimental results from HADES

Backup

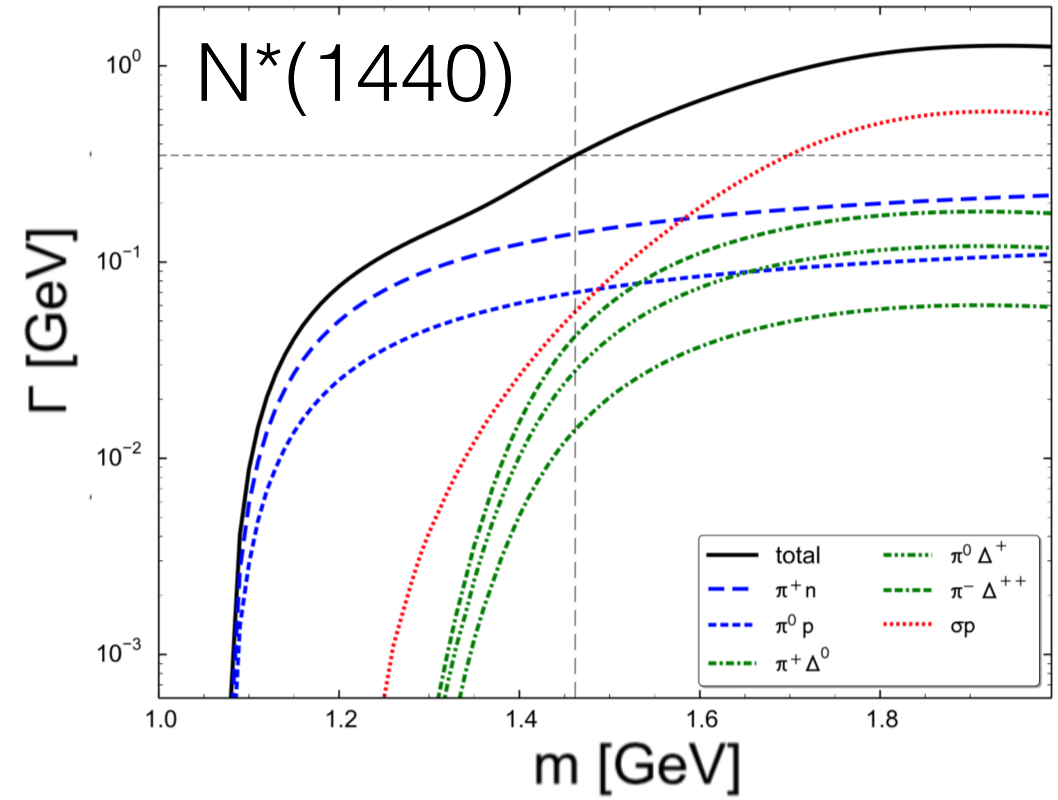
Omega Origin in Dilepton Spectra



Resonances

- Spectral Function
  - all unstable particles ("resonances“) have relativistic Breit-Wigner spectral functions

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

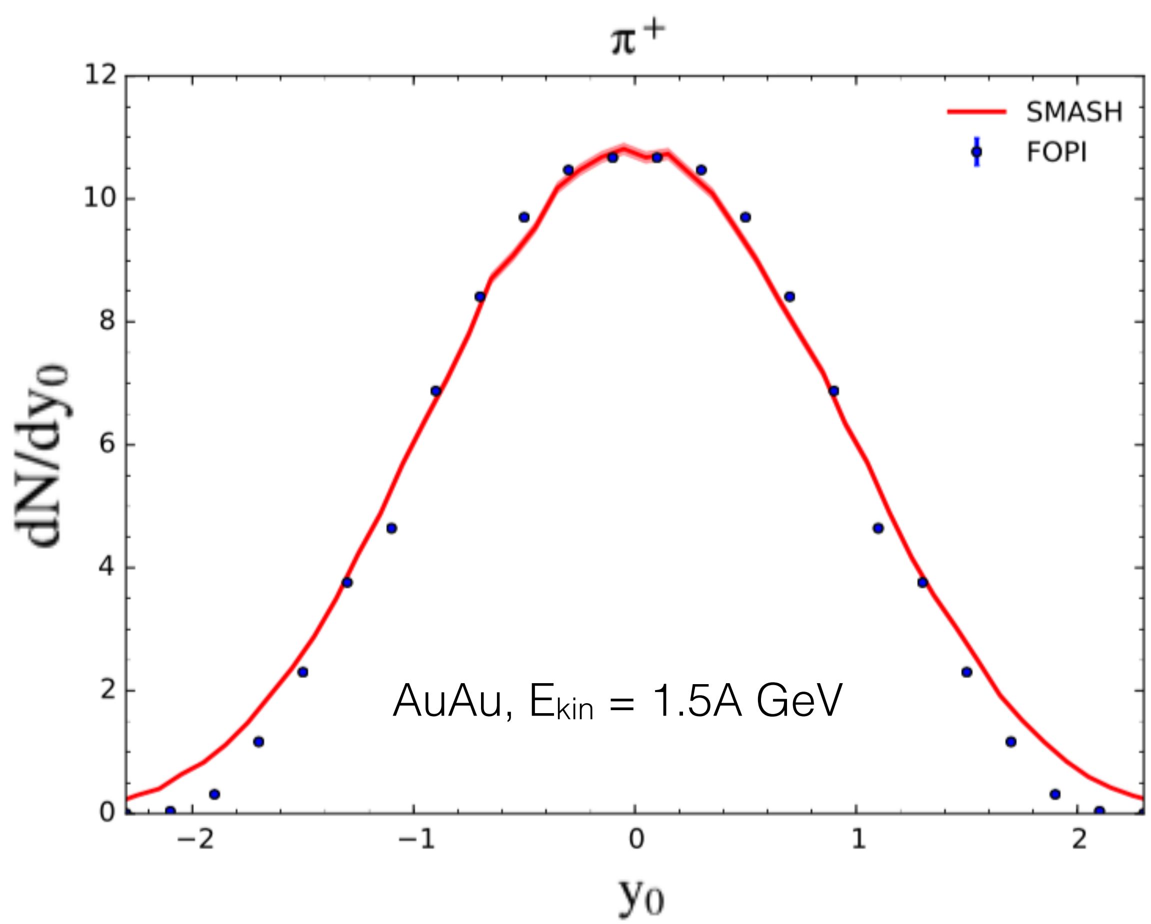


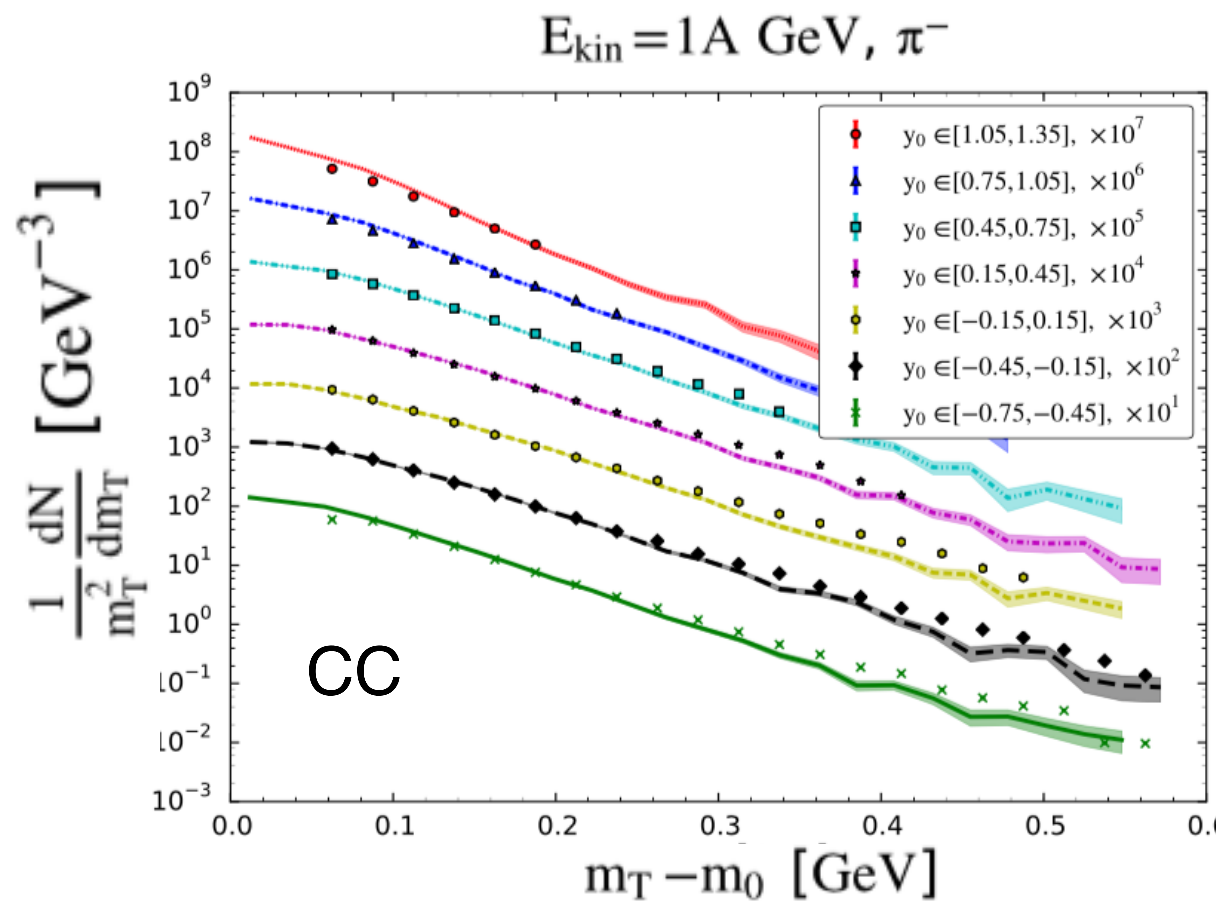
- Decay Widths
  - particles stable, if width < 10 keV $(\pi,\, \eta,\, K, ...)$
  - treatment of Manley et al

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

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

Results for HIC

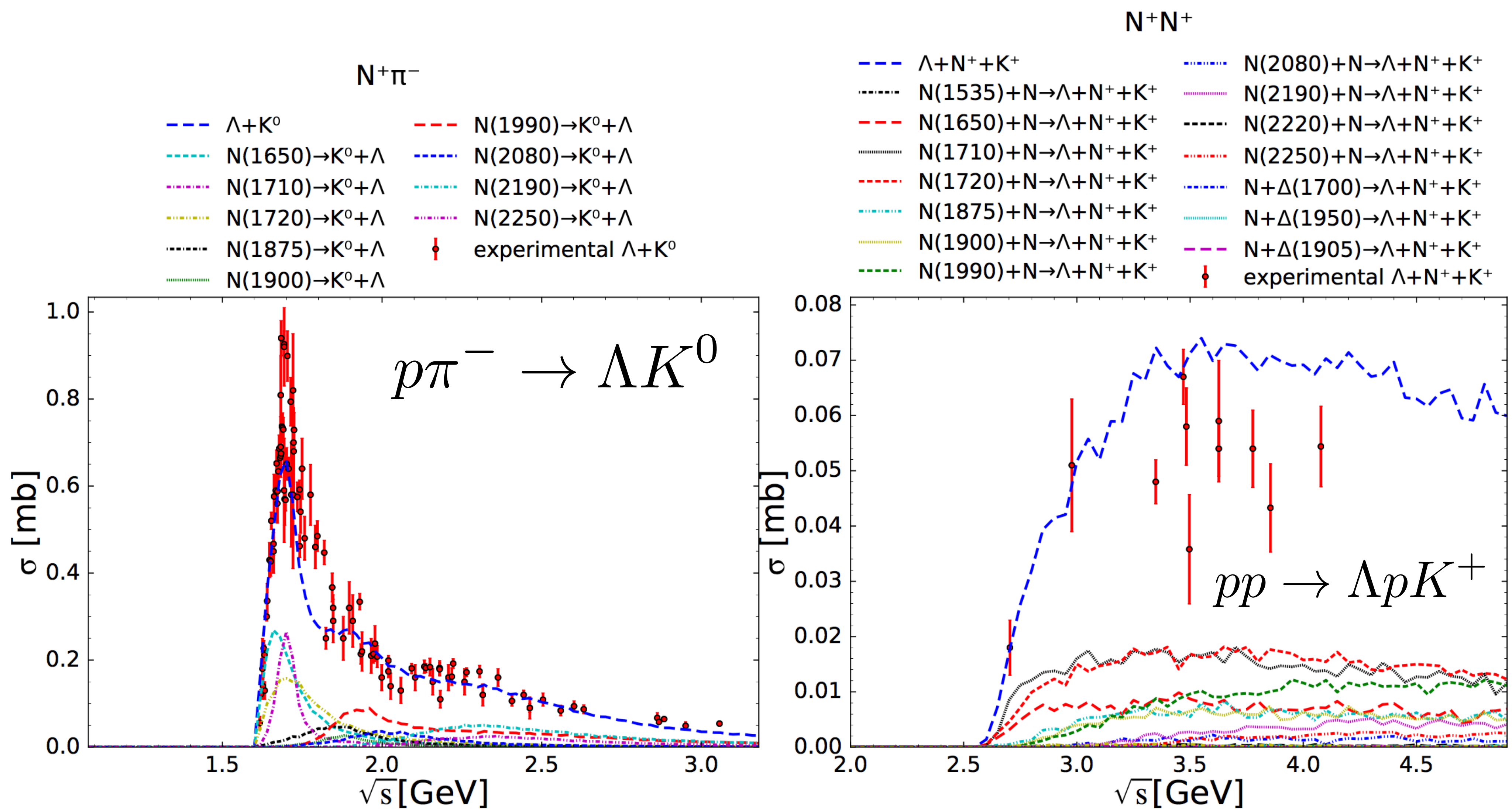




- shape of pion rapidity spectra reproduced
- transverse mass spectra compared with HADES data are in good agreement

Exclusive Cross Section

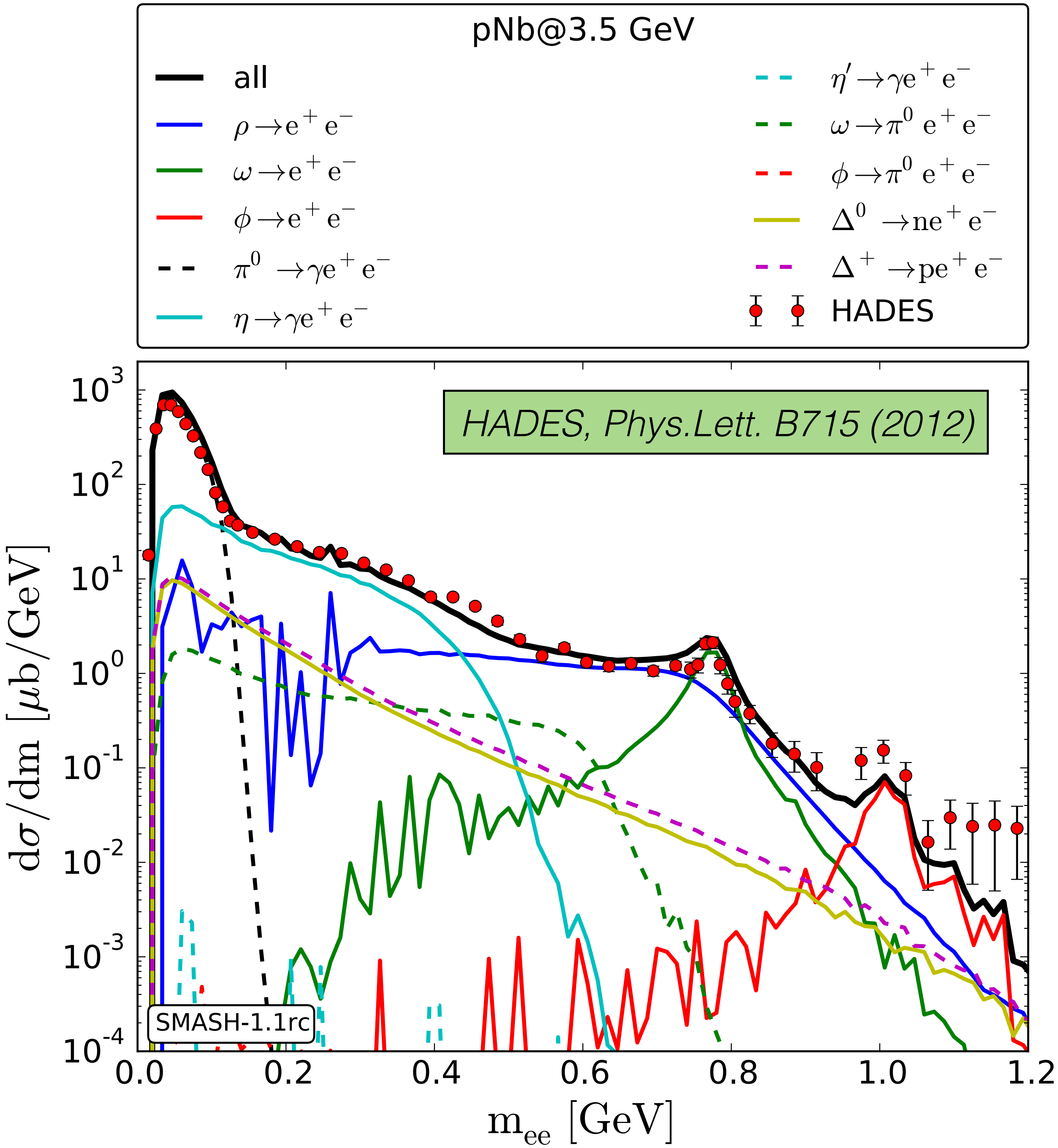
Λ



- B.R. constraint by exclusive production cross section of Λ hyperons
- building on data from PDG and PWA *Münzer, Fabbietti, arxiv:1703.01978 (2017)*

$$\boxed{N^* \rightarrow \Lambda K}$$

p+A



pNb, 3.5 GeV

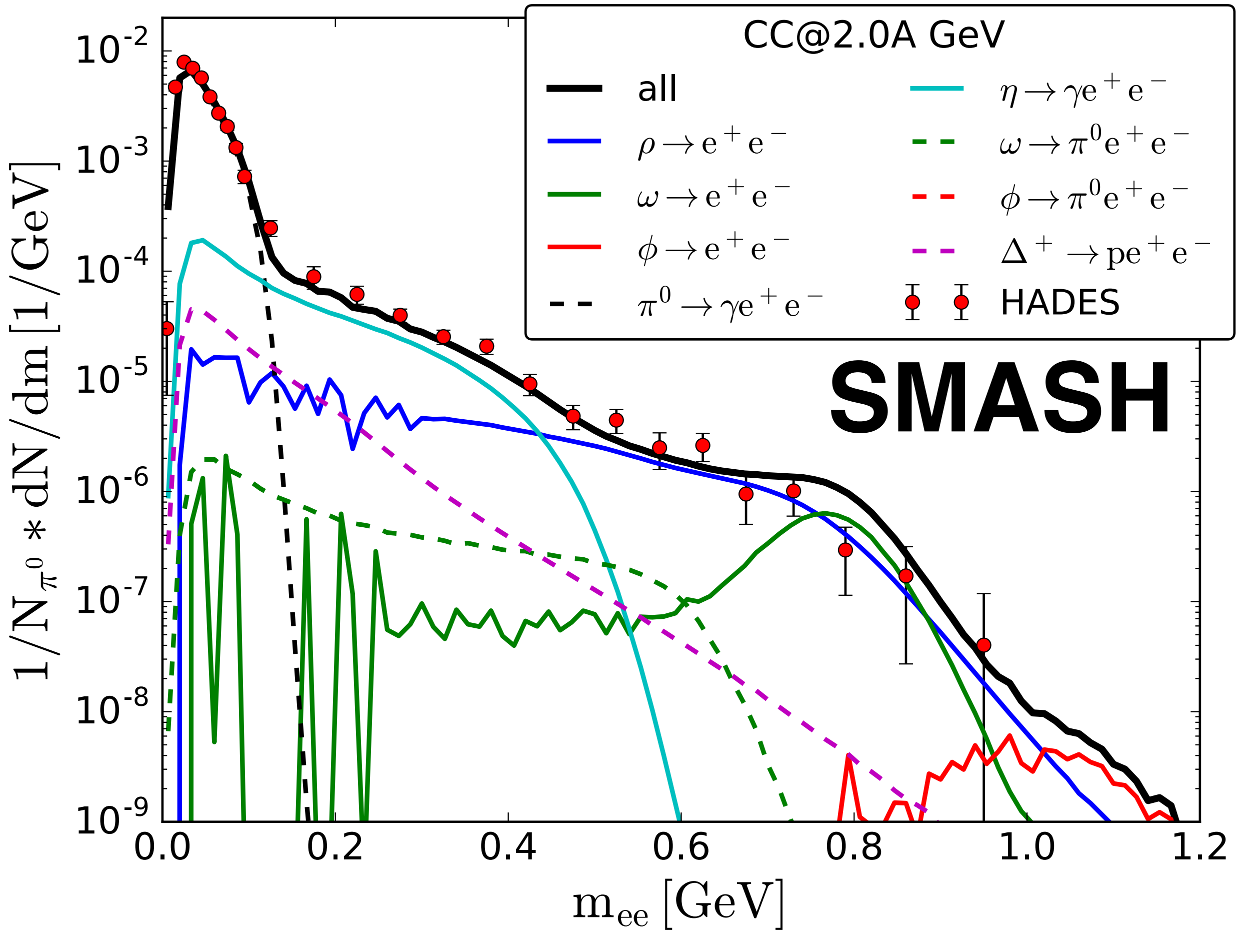
- pNb: cold nuclear matter scenario
- example for small system
- clear Φ peak, underestimated

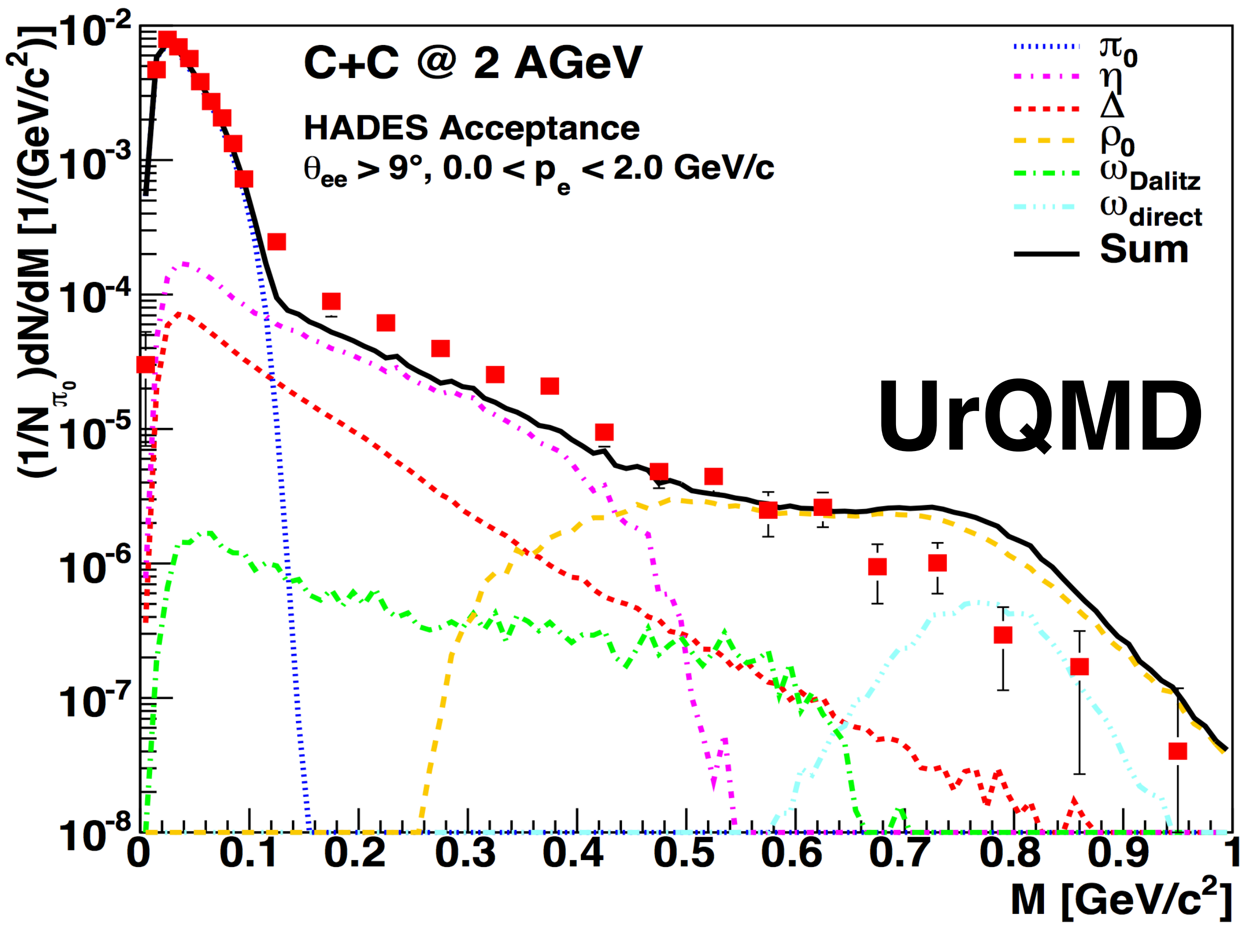
A+A

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

CC, 2.0 AGeV

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



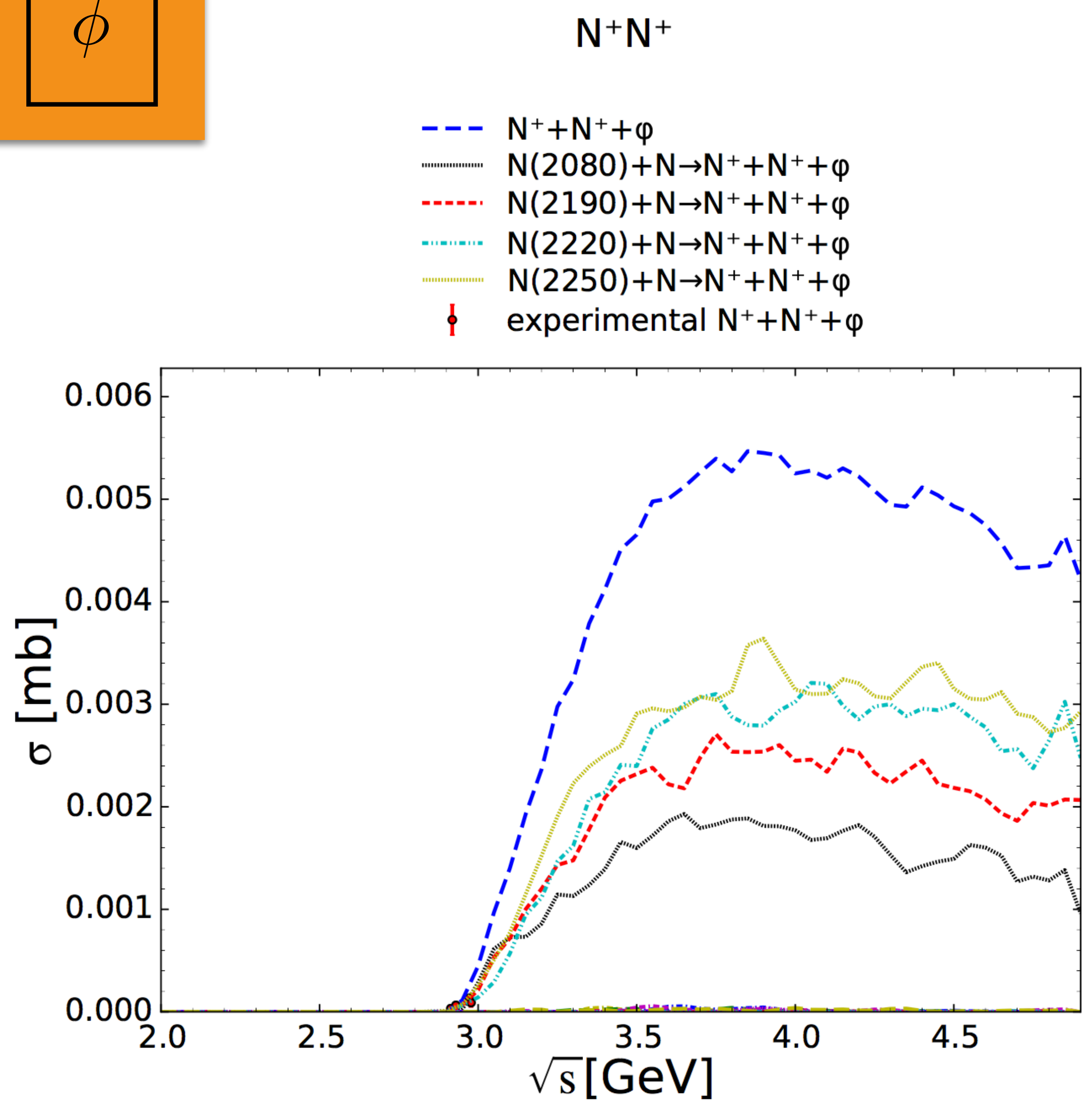


- SMASH and UrQMD compare similar to data
- different vector meson thresholds

—> good description for "small" pNb + CC system

Φ Production

$\boxed{\phi}$



- simplified ansatz for Φ production: fixed B.R. for heavy N*(>2000) resonances

J. Steinheimer et al., J. Phys. G43.1 (2016)

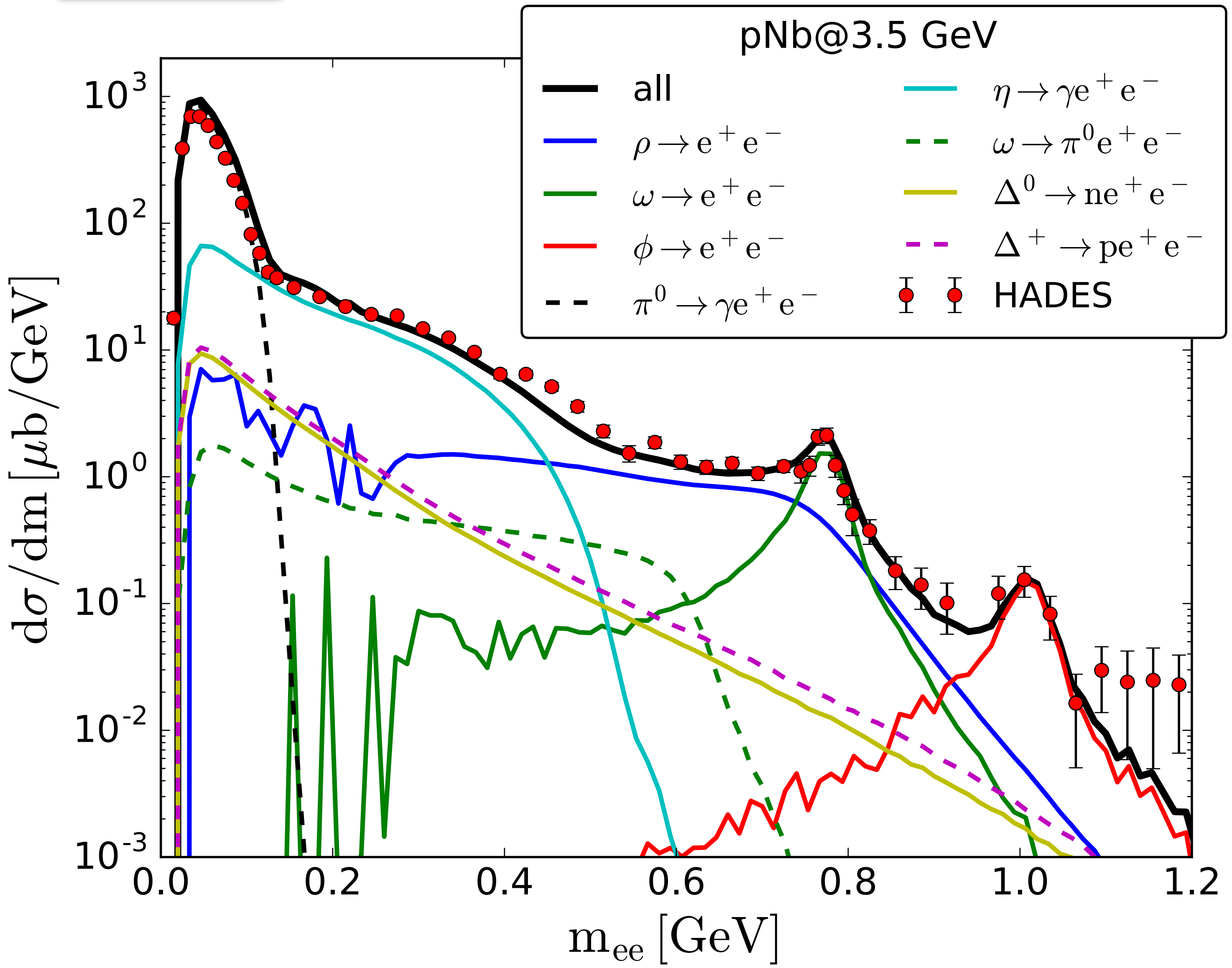
- experimentally not well known: not constrained by cross section
- constrain resonance properties with dileptons

$$\boxed{N^* \to N\phi}$$

Φ Production

ϕ

HADES, Phys.Lett. B715 (2012)



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J. Steinheimer et al., J. Phys. G43.1 (2016)

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$$\boxed{N^* \to N\phi}$$

Rapidity spectra pp@3.5 GeV

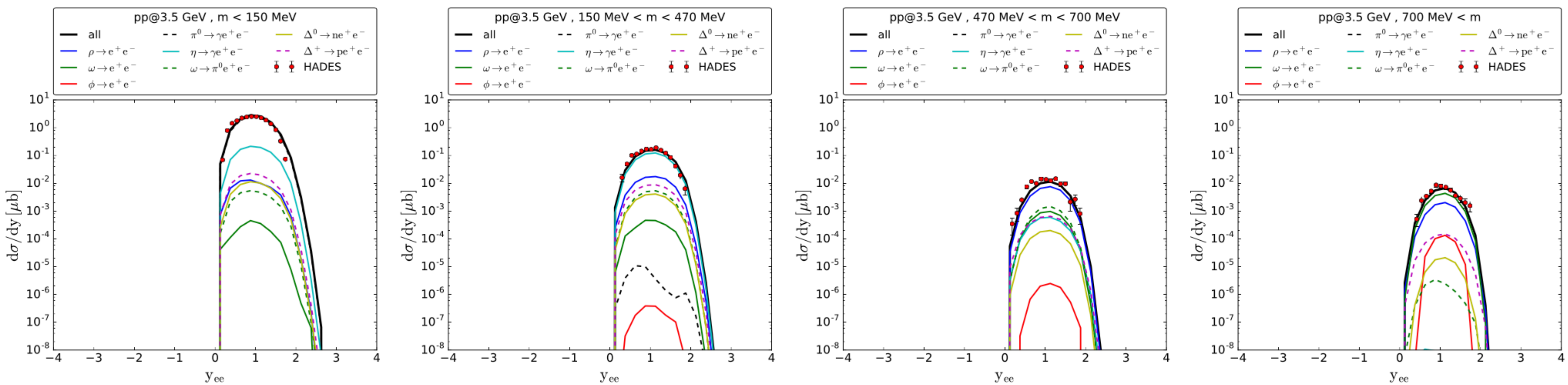
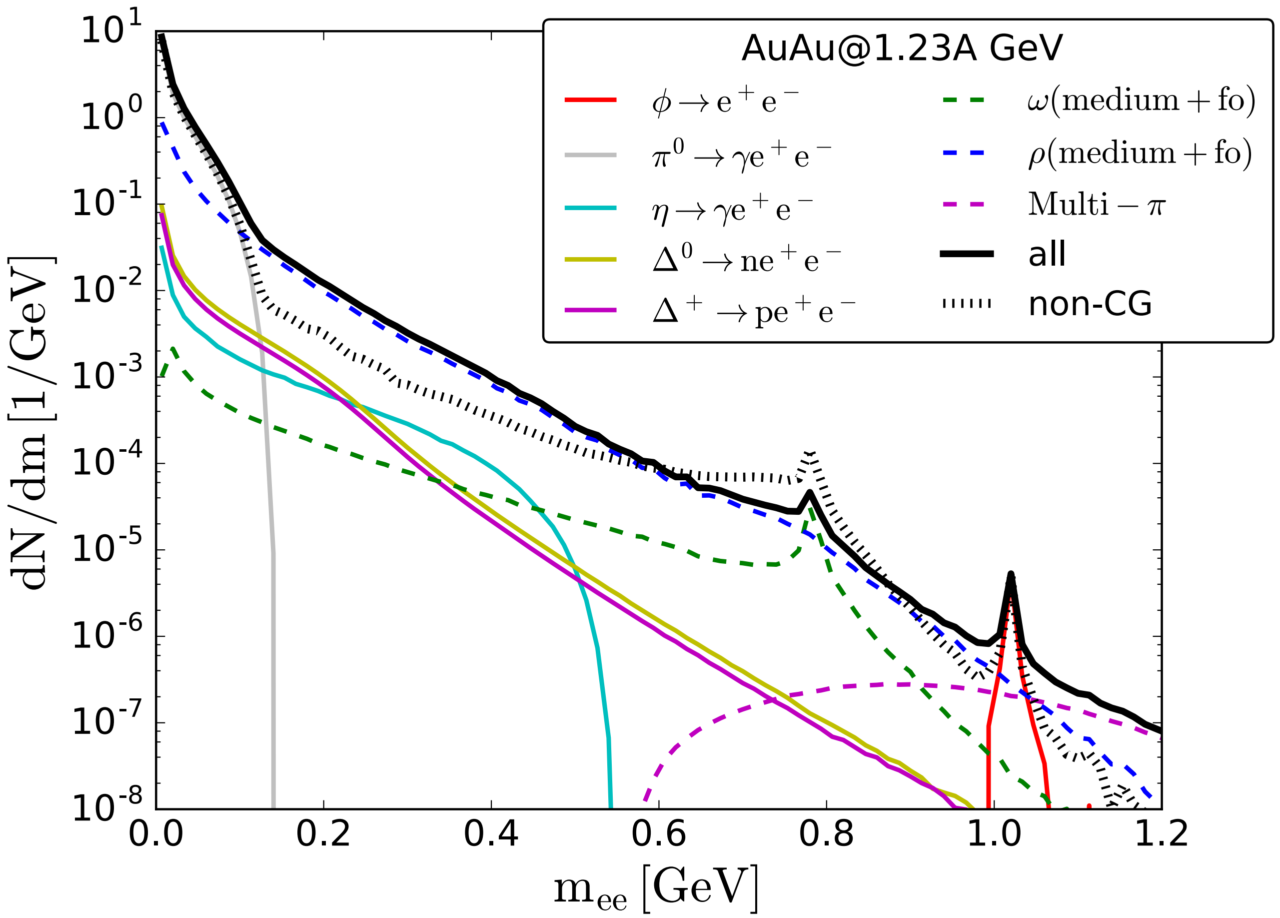
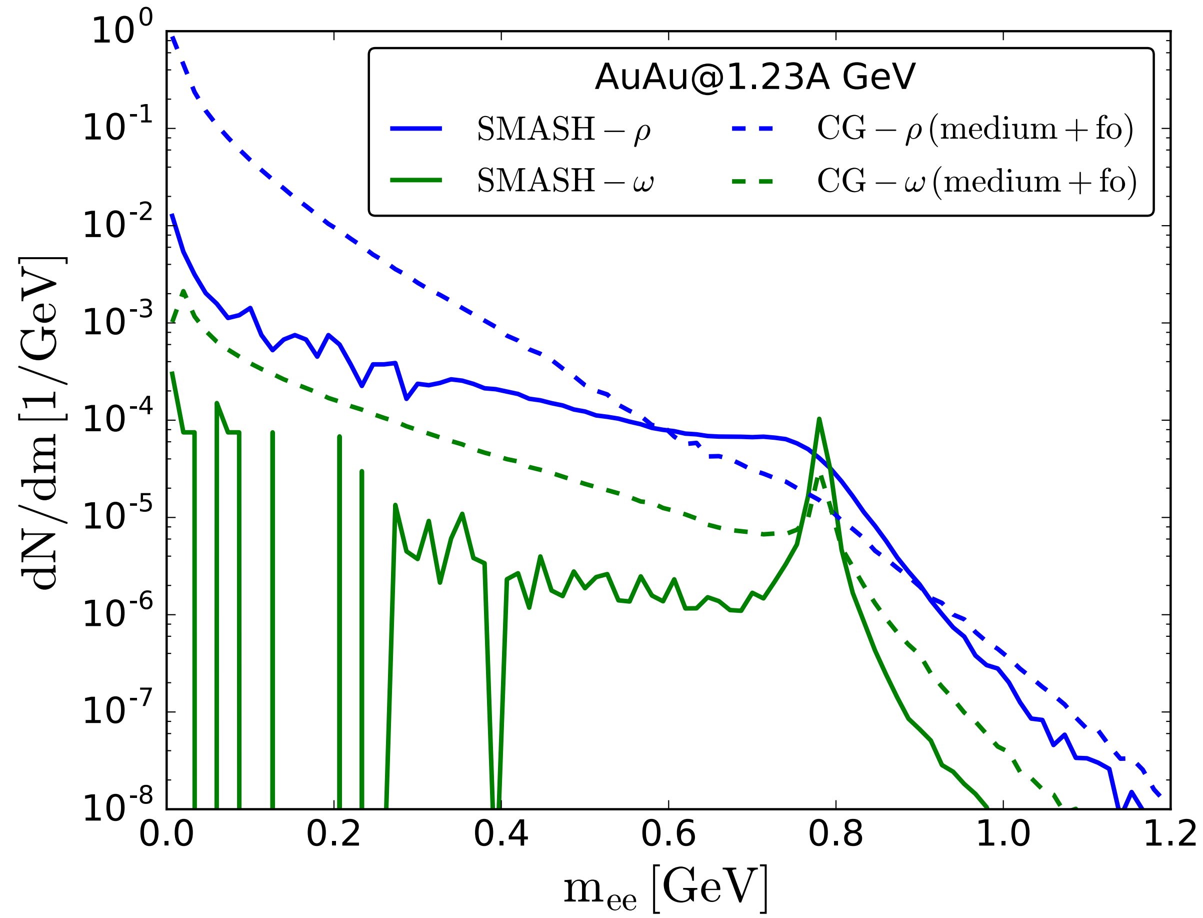


FIG. 24. Rapidity spectra of di-electrons produced by pp collisions at $E_{\mathrm{kin}} = 3.5\,\mathrm{GeV}$ in different invariant mass windows. Experimental data from [15].

CG: AuAu

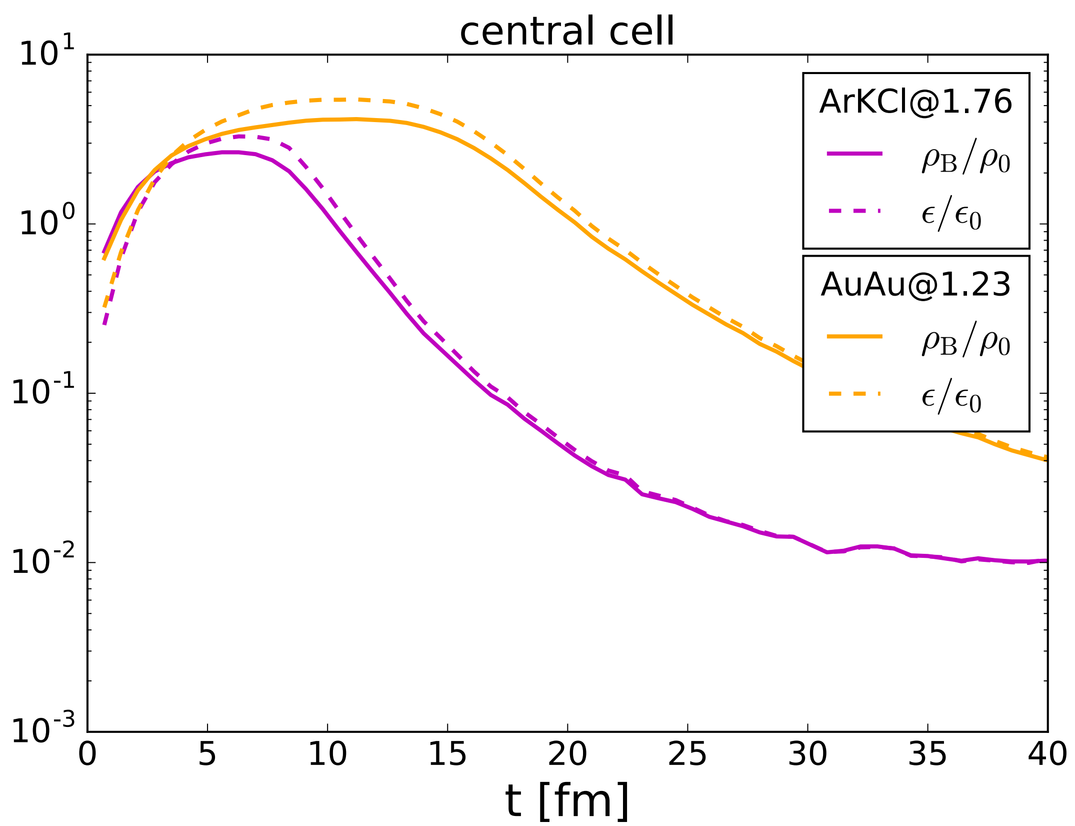


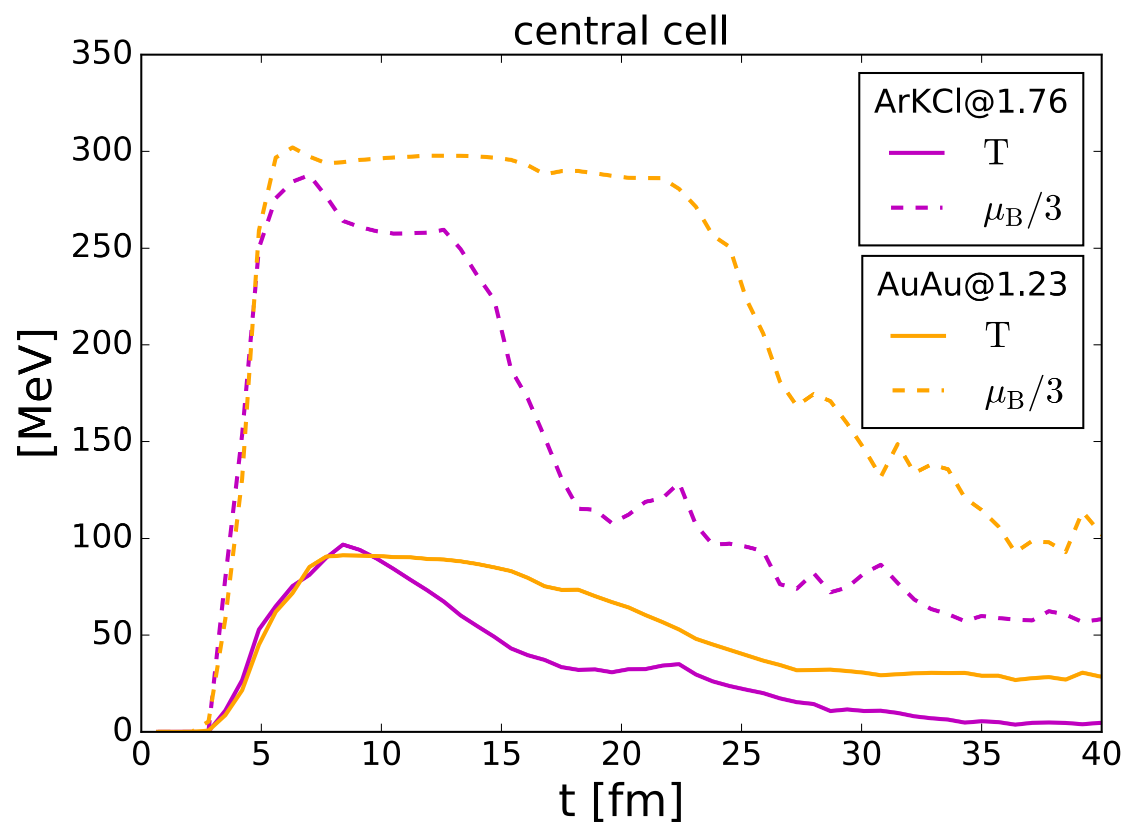
AuAu@1.23A GeV
$\phi \rightarrow e^+e^-$
$\pi^0 \rightarrow \gamma e^+e^-$
$\eta \rightarrow \gamma e^+e^-$
$\Delta^0 \rightarrow ne^+e^-$
$\Delta^+ \rightarrow pe^+e^-$
ω(medium + fo)
ρ(medium + fo)
Multi − π
all
non-CG
dN/dm [1/GeV]
m_{ee} [GeV]



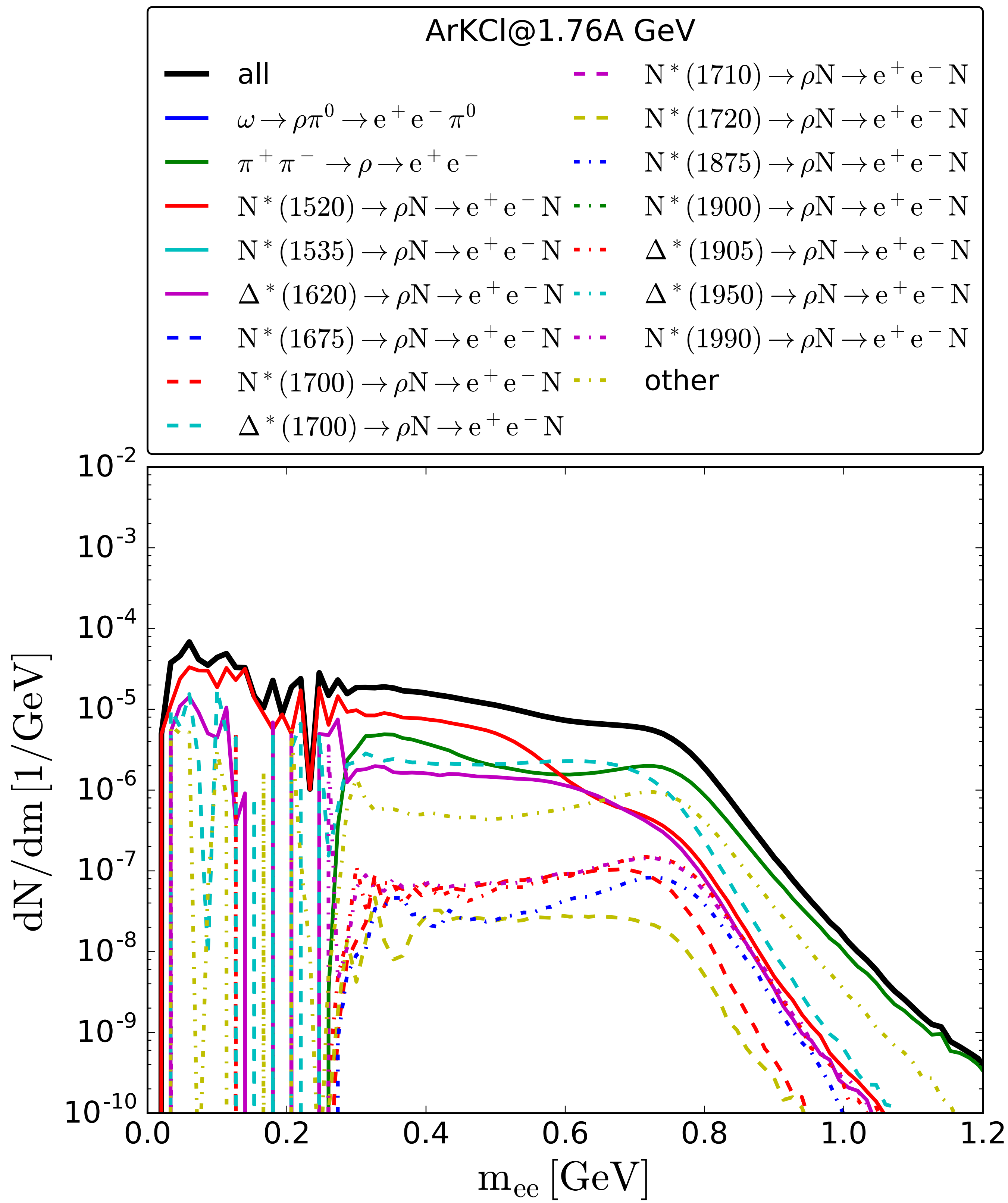
AuAu@1.23A GeV
SMASH − ρ
SMASH − ω
CG − ρ (medium + fo)
CG − ω (medium + fo)
dN/dm [1/GeV]
m_{ee} [GeV]

CG evolution

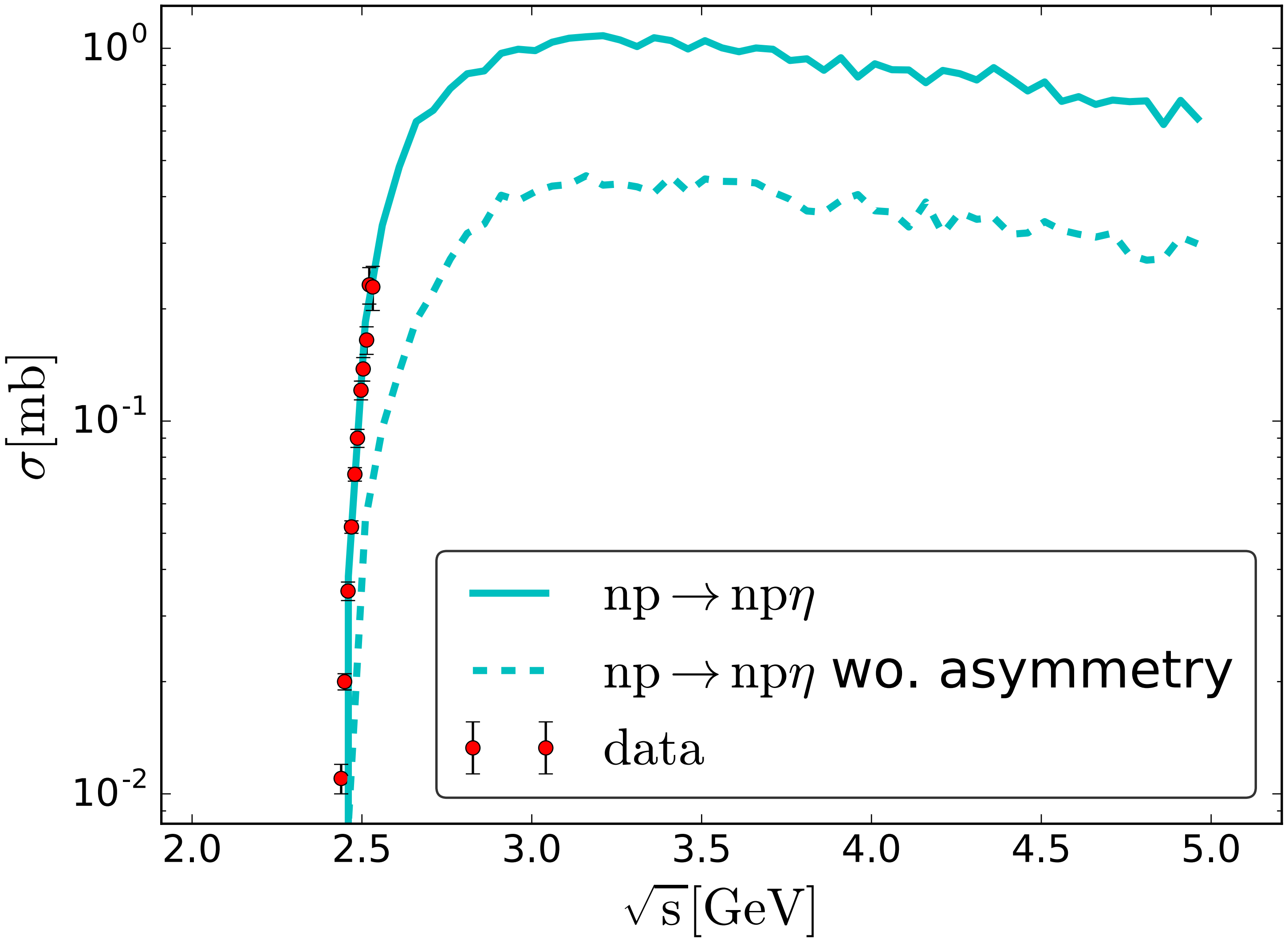




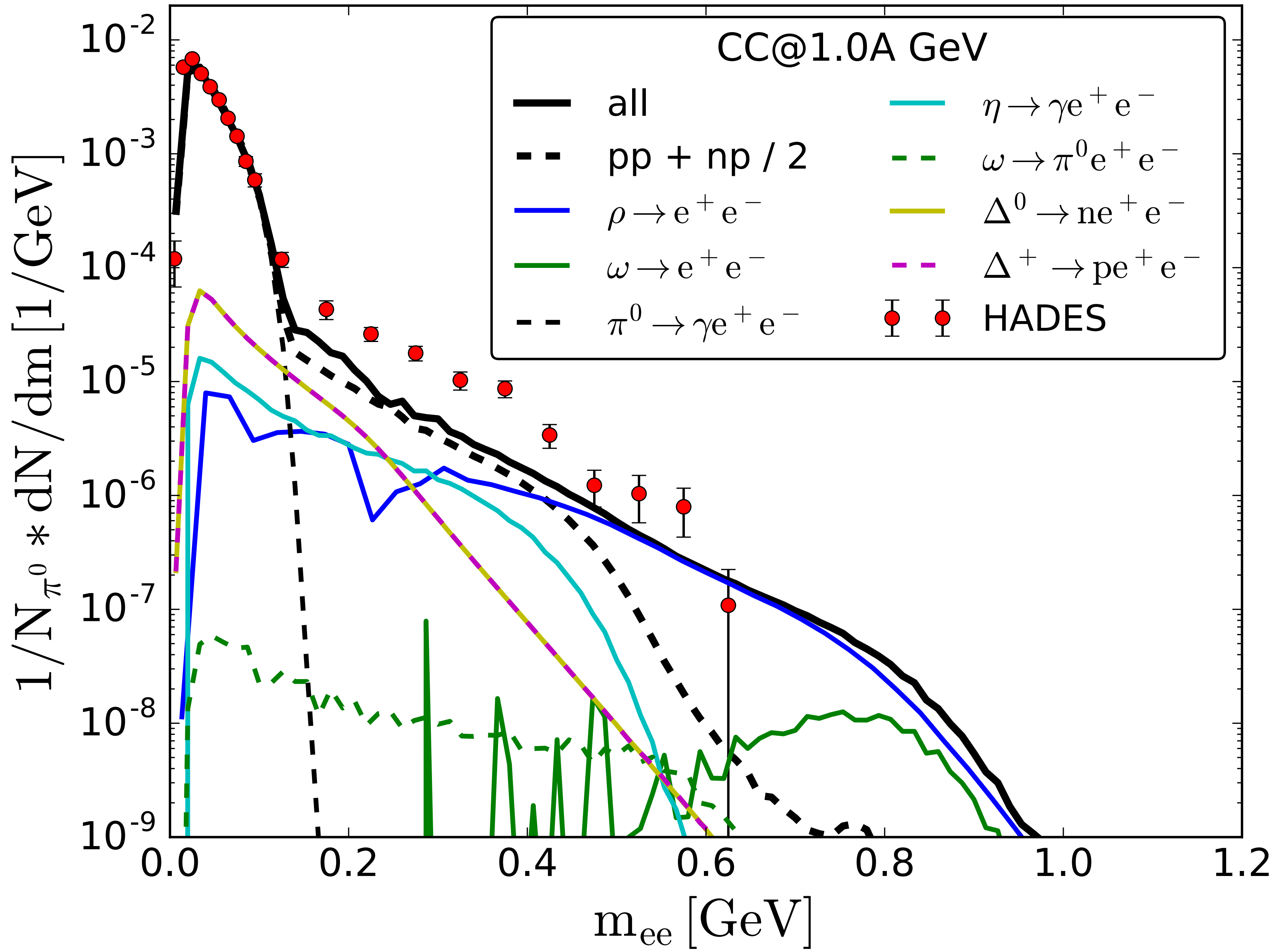
Rho origin in ArKCl



Eta Cross Section

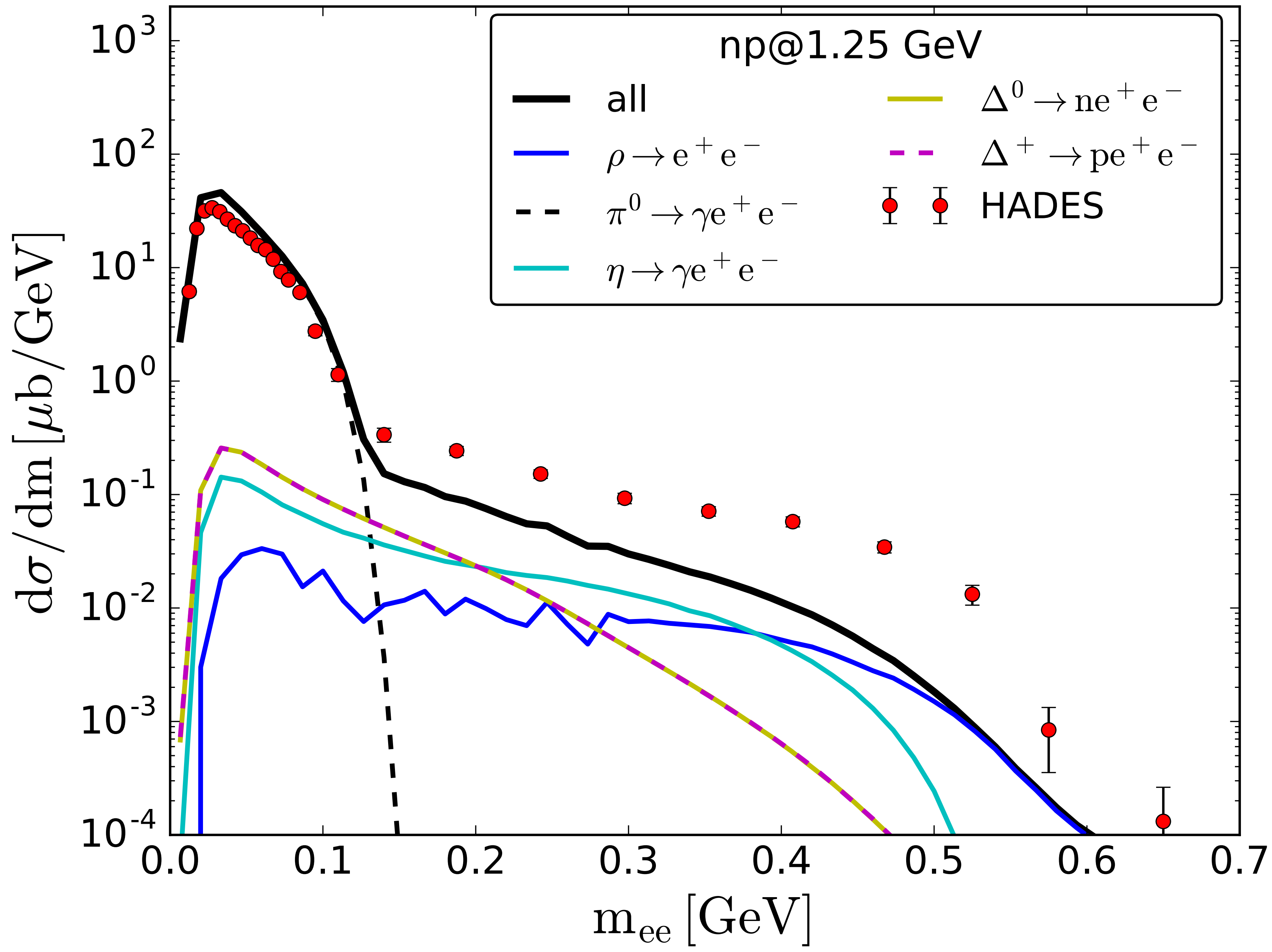


CC @ 1.0 A GeV



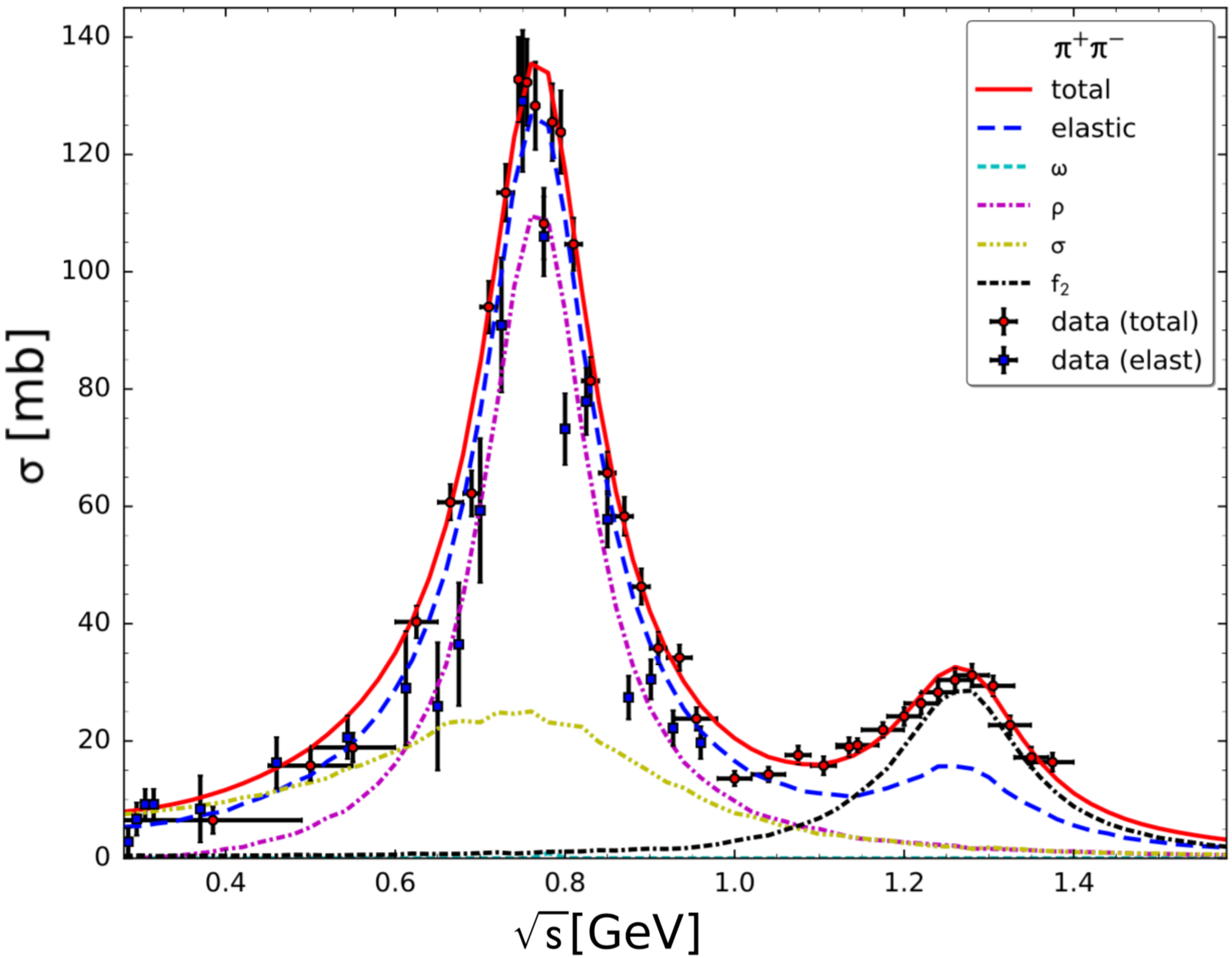
CC@1.0A GeV
all
pp + np / 2
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\pi^0 \to \gamma e^+e^-$
$\eta \to \gamma e^+e^-$
$\omega \to \pi^0 e^+e^-$
$\Delta^0 \to ne^+e^-$
$\Delta^+ \to pe^+e^-$
HADES
$1/N_{\pi^0} * dN/dm\,[1/GeV]$
$m_{ee}\,[GeV]$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}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

d(n) + p



np@1.25 GeV
all
$\rho \rightarrow e^+e^-$
$\pi^0 \rightarrow \gamma e^+e^-$
$\eta \rightarrow \gamma e^+e^-$
$\Delta^0 \rightarrow ne^+e^-$
$\Delta^+ \rightarrow pe^+e^-$
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

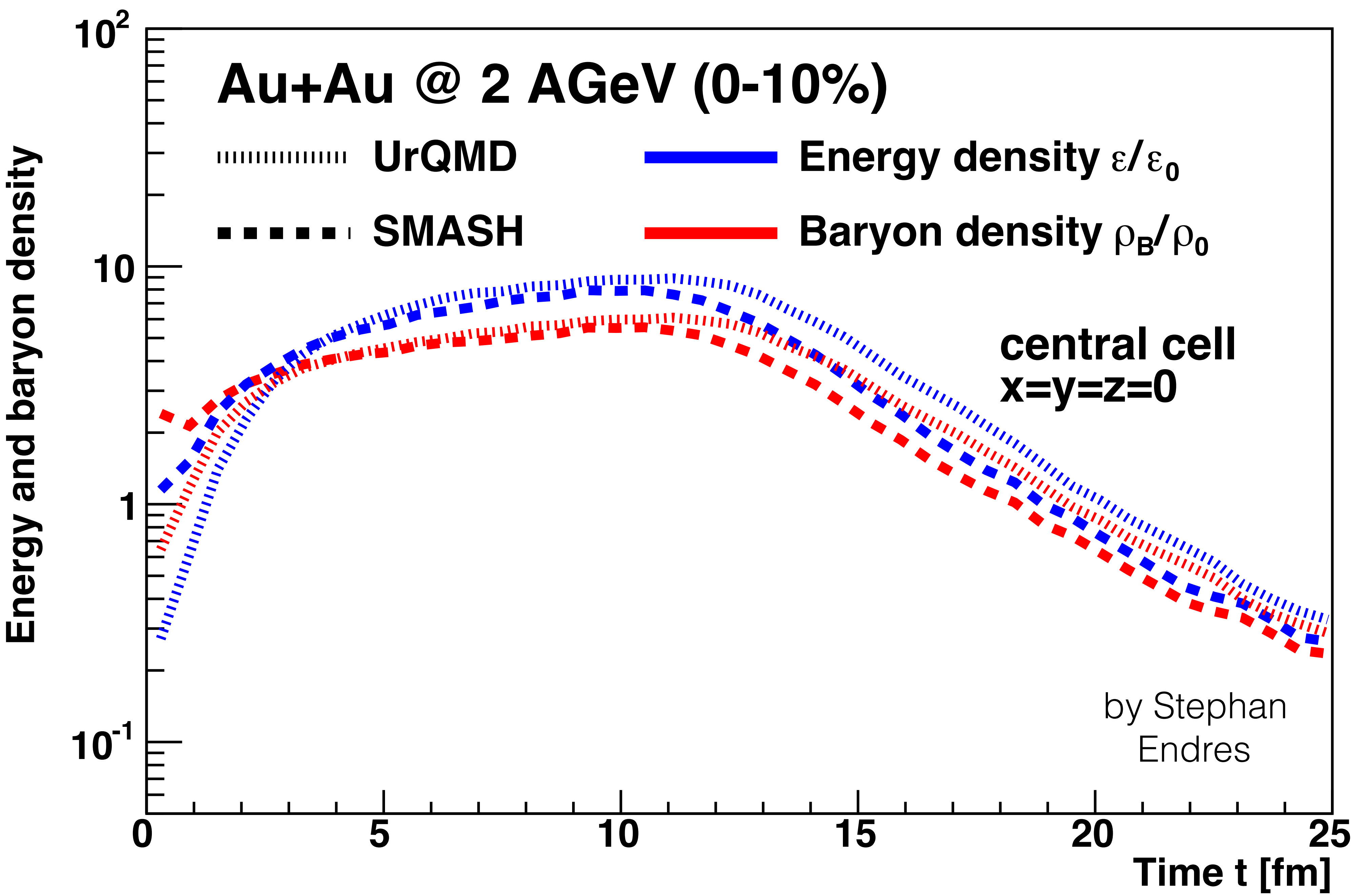
Elementary Cross Sections



- cross section for purely mesonic Pion scattering
- clear resonance pattern
- dominant contributions are the ρ and f_2 states

Comparison to UrQMD

time evolution of density at center of collision is very similar



SMASH status

- ☑ cross section described via resonances (few GeV)
- ☑ production of e.m. observables („integrated“)
- ☑ „exotic“ channels (*additive quark model*) $\Delta + \Lambda$
- ☐ baryon-antibaryon-annihilation + string fragmentation $p + \bar{p}$

<u>new results:</u>

- ☑ comparison with analytic solution of the Boltzmann equation J. Tindall, J. Torres-Rincon, J.B. Rose, H. Petersen, arXiv:1612.06436
- ☑ *„hydro bubbles“* - forced thermalisation of dense regions D. Oliinychenko, Hannah Petersen, arXiv:1609.01087

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)