SMASH transport model for hadronic reactions

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


• 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)

* Simulating Many Accelerated Strongly-interacting Hadrons
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 $\rightarrow$ 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:

<table>
<thead>
<tr>
<th>Dilepton Decays</th>
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<tbody>
<tr>
<td>$\rho \rightarrow e^+e^-$</td>
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<td>$\omega \rightarrow e^+e^-$</td>
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<td>$\phi \rightarrow e^+e^-$</td>
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<td>$\pi \rightarrow e^+e^-\gamma$</td>
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<td>$\eta \rightarrow e^+e^-\gamma$</td>
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<td>$\eta' \rightarrow e^+e^-\gamma$</td>
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<td>$\omega \rightarrow e^+e^-\pi^0$</td>
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<tr>
<td>$\phi \rightarrow e^+e^-\pi^0$</td>
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<tr>
<td>$\Delta^+ \rightarrow e^+e^-p$</td>
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<tr>
<td>$\Delta^0 \rightarrow e^+e^-n^0$</td>
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JS, J. Weil, V. Steinberg, S. Endres, H. Petersen
arXiv:1711.10297
Spectral Functions

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

\[ A(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - M_0^2)^2 + m^2 \Gamma(m)^2} \]
Results
Total Cross Section

- total $\pi$-p cross section
- lowest excitation from $\Delta$, additional contributions from $N^*$ and $\Delta^*$
- 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 $\Delta$ resonance
- overall reasonable agreement with data
Exclusive Cross Section

\[ pp \rightarrow pn\pi^+ \]

- 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

\[ J.\text{Weil et al, Phys. Rev. C 94 (2016)} \]
\[ S.A. \text{Bass et al, Prog. Part. Nucl. Phys. 41 (1998)} \]

Exclusive Cross Section

\[ pp \rightarrow pn\pi^+ \]


\[ m_{\text{inv}}^{n\pi^+} \text{ [GeV]} \]

\[ \frac{d\sigma}{dM} \text{ [mb/(GeV/c^2)]} \]
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 $NN \to \Delta\Delta$ ($\Delta\Delta=$dominant contribution)
  • constrain B.R. for heavy resonances
  • feedback welcome
Two-Pion Contributions

N^+N^+

total pp → ppππ + π^-

pp → ΔΔ

pp → B^* + X

work in progress
Exclusive Cross Section

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

- inclusive and exclusive production of $\rho$ mesons in proton-proton

- overshooting for inclusive cross section may be caused by two step treatment of decays e.g.

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

$$\omega \rightarrow \pi\rho \rightarrow 3\pi$$
Form Factors
Form Factors

- The dilepton routine was used to investigate the electromagnetic transition form factor of the omega dilepton Dalitz decay $\omega \to \pi^0 e^+ e^-$.

- The decay is described by two steps similar to the hadronic $\omega$ decay into $3\pi$: $\omega \to \rho\pi \to 3\pi$ (VMD-inspired).

$|F_\omega(\mu)|^2$
Form Factors: $\omega$

- Comparison of our ansatz with NA60 data

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

- Variation of B.R. and cutoff-parameter $R$

- Description of data with B.R. of 57% possible

- Also compatible with Terschlüsen approach

Form Factors: $\Phi$

- same ansatz for the $\Phi$ meson

- comparison with data from KLOE

- description of data suggests B.R. of 15%

- again better description than „simple“ VMD


$B.R.(\phi \to 3\pi) = 15\%$
Dileptons
Low Energy pp Collisions

- dominant channels are $\pi$, $\rho$, $\Delta$
- agreement with data above $\eta$ threshold
- slight overproduction in high invariant mass region
Low Energy pp Collisions

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

p_T Spectra


**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: example for larger system
- Overestimation in rho pole mass region + underestimation in intermediate mass region
- Vacuum resonances description insufficient? Explicit medium modification necessary?

ArKCl, 1.76 AGeV

based on elementary baseline explore medium effects in larger systems

HADES, Phys. Rev. C84 (2011)
Coarse-Graining Approach

- coarse-graining approach by Stephan Endres on SMASH evolution

- employs in-medium spectral function of vector mesons ($\rho$ and $\omega$)

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

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**ArKCl@1.76A GeV**

- $\phi \rightarrow e^+e^-$
- $\pi^0 \rightarrow \gamma e^+e^-$
- $\eta \rightarrow \gamma e^+e^-$
- $\Delta^0 \rightarrow n e^+e^-$
- $\Delta^+ \rightarrow p e^+e^-$
- $\omega \rightarrow CG$
- $\rho \rightarrow CG$
- Multi-$\pi$
- all
- non-CG
- HADES

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Vector-meson Contributions

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

\[ B^* \rightarrow N\rho \rightarrow Ne^+e^- \]
Predictions for HADES

**AuAu, 1.23 AGeV**

- heavier system: sensitivity to medium effect increased

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Predictions for HADES

- **N*(1520)** dominant contribution to $\rho$ yield
- probe $\rho$ - $N^*(1520)$ coupling and treatment of $N^*(1520)$ dilepton Dalitz decays
- spectrum with VMD for $N^*(1520)$ Dalitz

\[ N^*(1520) \rightarrow \rho N \rightarrow e^+e^- N \]
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 $\omega$ and $\Phi$

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

pp@3.5 GeV

- $\omega \to e^+ e^-$
- N*(1710) → ωN → e^+ e^− N
- N*(1875) → ωN → e^+ e^− N
- N*(1900) → ωN → e^+ e^− N
- N*(2080) → ωN → e^+ e^− N
- N*(2190) → ωN → e^+ e^− N
- other
Resonances

- **Spectral Function**
  - 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

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

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

Results for HIC

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

- B.R. constraint by exclusive production cross section of \( \Lambda \) hyperons
- building on data from PDG and PWA

\[ p\pi^- \rightarrow \Lambda K^0 \]

\[ pp \rightarrow \Lambda p K^+ \]

\[ N^* \rightarrow \Lambda K \]

p+A

- pNb: cold nuclear matter scenario
- example for small system
- clear $\Phi$ peak, underestimated
SMASH and UrQMD compare similar to data

different vector meson thresholds

—> good description for "small“ pNb + CC system
**Φ Production**

- simplified ansatz for Φ production: fixed B.R. for heavy N*(>2000) resonances
- experimentally not well known: not constrained by cross section
- constrain resonance properties with dileptons

\[ N^* \rightarrow N\phi \]
**Φ Production**

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\[ N^* \rightarrow N\phi \]
FIG. 24. Rapidity spectra of di-electrons produced by pp collisions at $E_{\text{kin}} = 3.5\text{ GeV}$ in different invariant mass windows. Experimental data from [15].
CG: AuAu

![Graph of AuAu@1.23A GeV showing various decay channels and their distributions in the m_{ee} [GeV] range.](image)

- \( \phi \to e^+ e^- \)
- \( \pi^0 \to \gamma e^+ e^- \)
- \( \eta \to \gamma e^+ e^- \)
- \( \Delta^0 \to n e^+ e^- \)
- \( \Delta^+ \to p e^+ e^- \)

- \( \omega \) (medium + free)
- SMASH \( \rho \)
- CG \( \rho \) (medium + free)
- SMASH \( \omega \)
- CG \( \omega \) (medium + free)

- Muti - \( \pi \)
- All
- Non-CG

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CG evolution

![Graphs showing the evolution of central cell properties over time for ArKCl@1.76 and AuAu@1.23. The graphs plot various quantities such as $\rho_B/\rho_0$, $\epsilon/\epsilon_0$, $T$, and $\mu_B/3$ as functions of time (t [fm]).]
Rho origin in ArKCl

![Graph showing the distribution of rho mesons in ArKCl at 1.76 GeV](image)

The graph illustrates the distribution of rho mesons in ArKCl, showing the mass spectrum of electron-positron pairs ($m_{ee}$) with the density of events (dN/dm) for different decay modes. The modes are color-coded and include:

- $N^* (1710) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1720) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1875) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1520) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1535) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1900) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1675) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1905) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1670) \rightarrow \rho N \rightarrow e^+ e^- N$
- $N^* (1990) \rightarrow \rho N \rightarrow e^+ e^- N$
- $\Delta^* (1620) \rightarrow \rho N \rightarrow e^+ e^- N$
- $\Delta^* (1950) \rightarrow \rho N \rightarrow e^+ e^- N$
- $\Delta^* (1700) \rightarrow \rho N \rightarrow e^+ e^- N$
- Other modes

The graph is used to analyze the contribution of different resonances to the rho meson spectrum in ArKCl.
Eta Cross Section

\[ \sigma \text{[mb]} \]

\[ \sqrt{s} \text{[GeV]} \]

np → npη
np → npη wo. asymmetry
data
CC @ 1.0 A GeV

Graph showing the distribution of various decay channels in CC neutrino scattering at 1.0 A GeV. The legend includes channels such as $\eta \rightarrow \gamma e^+ e^-$, $\omega \rightarrow \pi^0 e^+ e^-$, $\Delta^0 \rightarrow n e^+ e^-$, and $\Delta^+ \rightarrow p e^+ e^-$, among others. The data is compared with the HADES experiment results.
d(n) + p
Elementary Cross Sections

- cross section for purely mesonic Pion scattering
- clear resonance pattern
- dominant contributions are the $\rho$ and $f_2$ states
Comparison to UrQMD

time evolution of density at center of collision is very similar

**Figure Description:**

- **Graph Title:** Au+Au @ 2 AGeV (0-10%)
- **Y-axis:** Energy and baryon density
- **X-axis:** Time t [fm]
- **Graph Legend:**
  - **UrQMD**
  - **Energy density** $\epsilon/\epsilon_0$
  - **SMASH**
  - **Baryon density** $\rho_B/\rho_0$
- **Central Cell:** x=y=z=0
- **Other Information:**
  - Central cell evolution similar by Stephan Endres
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 \( p + \bar{p} \)

New results:

- Comparison with analytic solution of the Boltzmann equation
  

- "Hydro bubbles" - forced thermalisation of dense regions
  
  D. Oliynychenko, Hannah Petersen, arXiv:1609.01087
Treatment of Manley


• 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:

\[ \rho_{ab}(m) = \int dm_a dm_b A_a(m_a) A_b(m_b) \]

\[ \times \frac{|\vec{p}_f|}{m} B_L^2(|\vec{p}_f| R) F_{ab}^2(m) \]

• hadronic Form Factor:

\[ F_{ab}(m) = \frac{\lambda^4 + 1/4(s_0 - M_0^2)^2}{\lambda^4 + (m^2 - 1/2(s_0 + M_0^2))^2} \]

Blatt Weisskopf functions

\[ B_0^2 = 1 \]

\[ B_1^2(x) = x^2/(1 + x^2) \]

\[ \ldots \]