# Non-equilibrium dilepton production in hadronic transport approaches

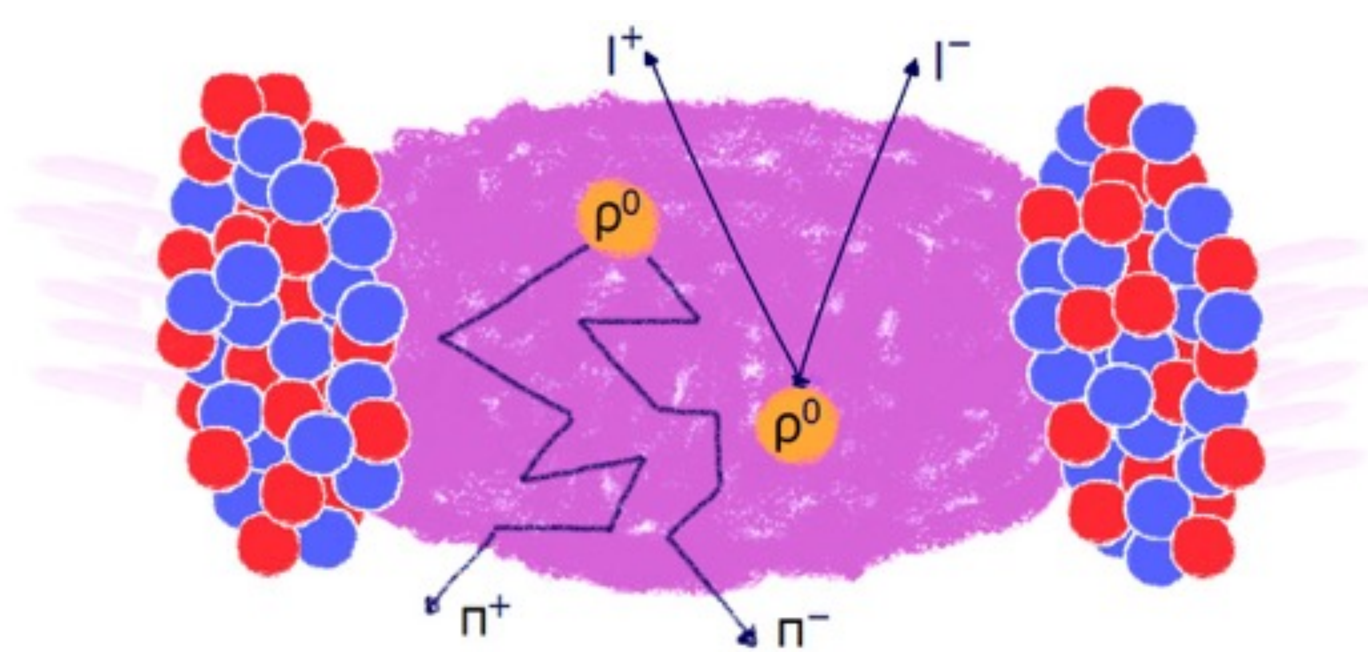
Jan Staudenmaier, G. Vujanovic, J. Weil, U. Heinz
and H. Petersen

*Hot Quarks 2016, Padre Island, Texas, USA*

# Motivation

- Why use dileptons?
  - only electromagnetic interaction: clean probe for hadronic matter
  - extract medium properties and medium modification over whole lifetime of collision

    —> valuable to constrain dynamical models



# Motivation

- no description from first principles for HIC —> need for models
  - understand experimental data
  - combination of approaches for description of HIC
- Transport models
  - late dilute stages (e.g. important for identified particle spectra)
  - non-equilibrium
  - low beam energy collisions

| **stage** | **model** |
|---|---|
| early | non-equilibrium initial state (e.g. fluctuating color fields/strings) |
| hot & dense | relativistic dissipative hydrodynamics with equation of state from QCD lattice calculations |
| dilute | hadronic tansport |

# SMASH

- new hadronic transport approach for dilute non-equlibrium stages of HIC and low energy collisions
- SMASH = **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- developed in group of Hannah Petersen at FIAS with modern tools (C++, Git, Redmine, Doxygen), version 0.9
- goal: standard reference for hadronic system with vacuum properties
- recent paper: *J.Weil et al, arXiv:1606.06642*

# General Setup

- transport models based on the relativistic Boltzmann equation

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

- Collision Criterion: geometric criterion

$$d_{\rm trans} < d_{\rm int} = \sqrt{\frac{\sigma_{\rm tot}}{\pi}}$$

- modes: nuclear collisions, infinite matter calculations, afterburner for hydrodynamic simulations

- features: Test Particle Method, Mean-Field potentials, Fermi motion, Pauli blocking

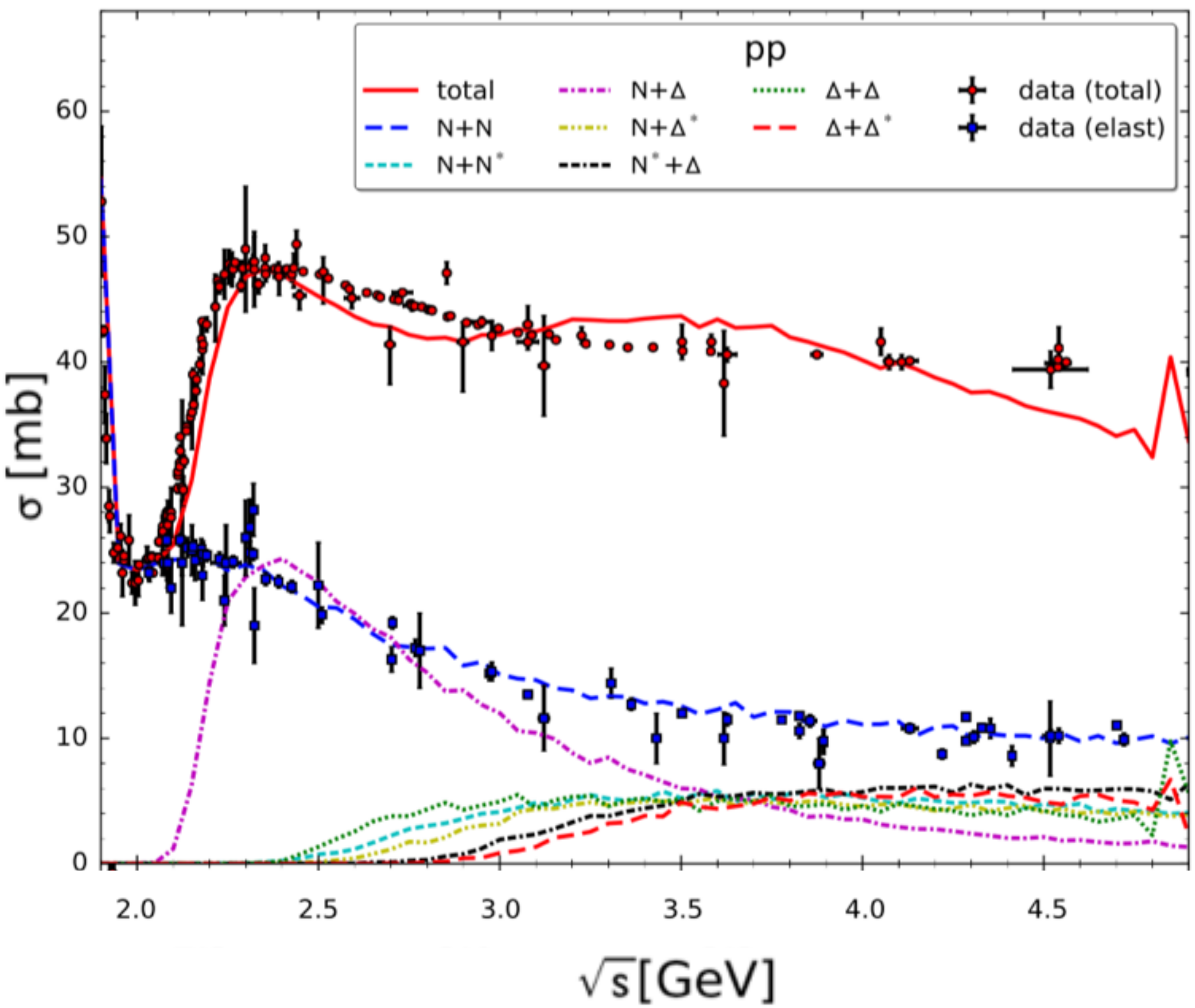
# Degrees of Freedom

| Mesons | Baryons |
|---|---|
| $\pi,\ \eta$ | $N + 16\, N^*$ states |
| $\rho,\ \omega,\ \phi$ | $\Delta + 7\, \Delta^*$ states |
| $f_2$ | $\Lambda + 7\, \Lambda^*$ states |
| $\sigma$ | $\Sigma + 16\, \Sigma^*$ states |
| $K, K^*(892), K^*(1410)$ | $\Xi,\ \Omega$ |

+ antiparticles

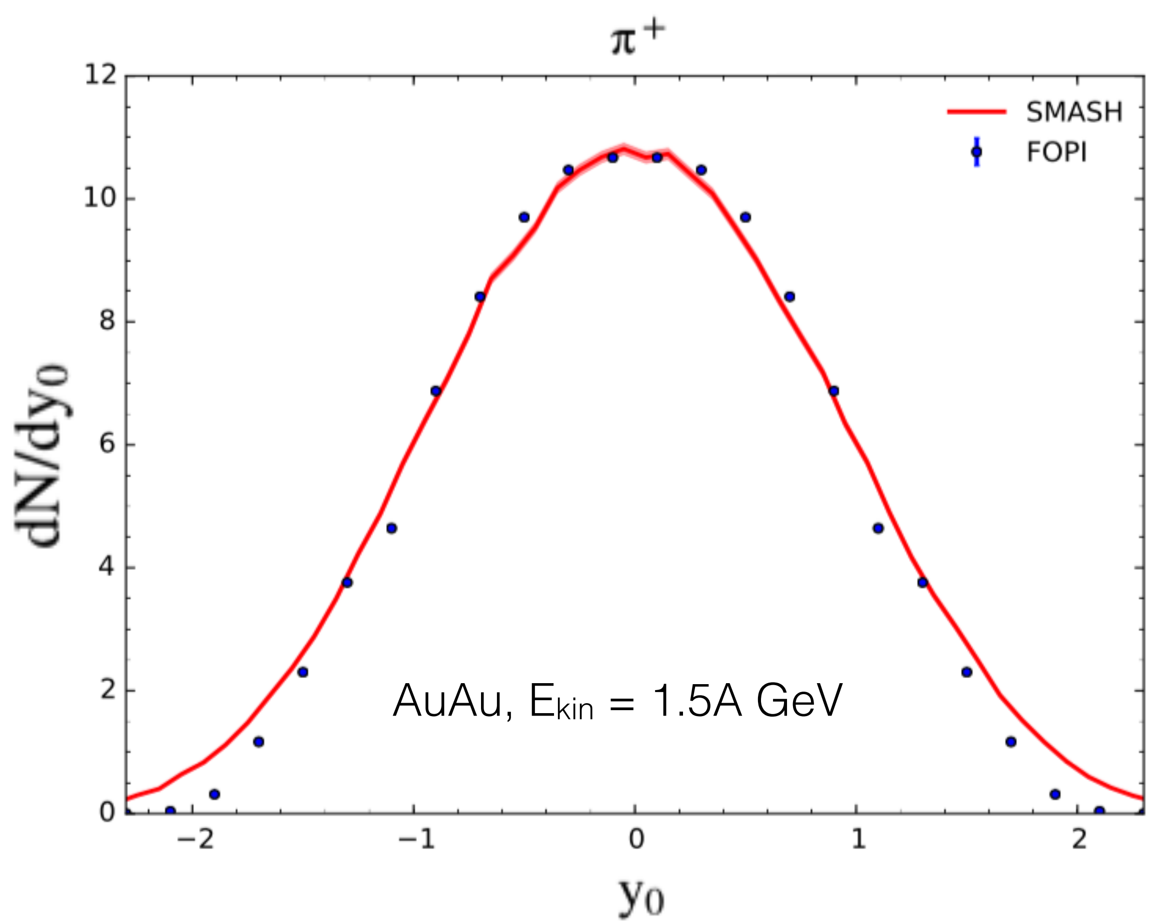
- all (well-established) hadrons from PDG up to a mass of 2 GeV
- isospin symmetry
- perturbative treatment of non-hadronic particles (photons, leptons)

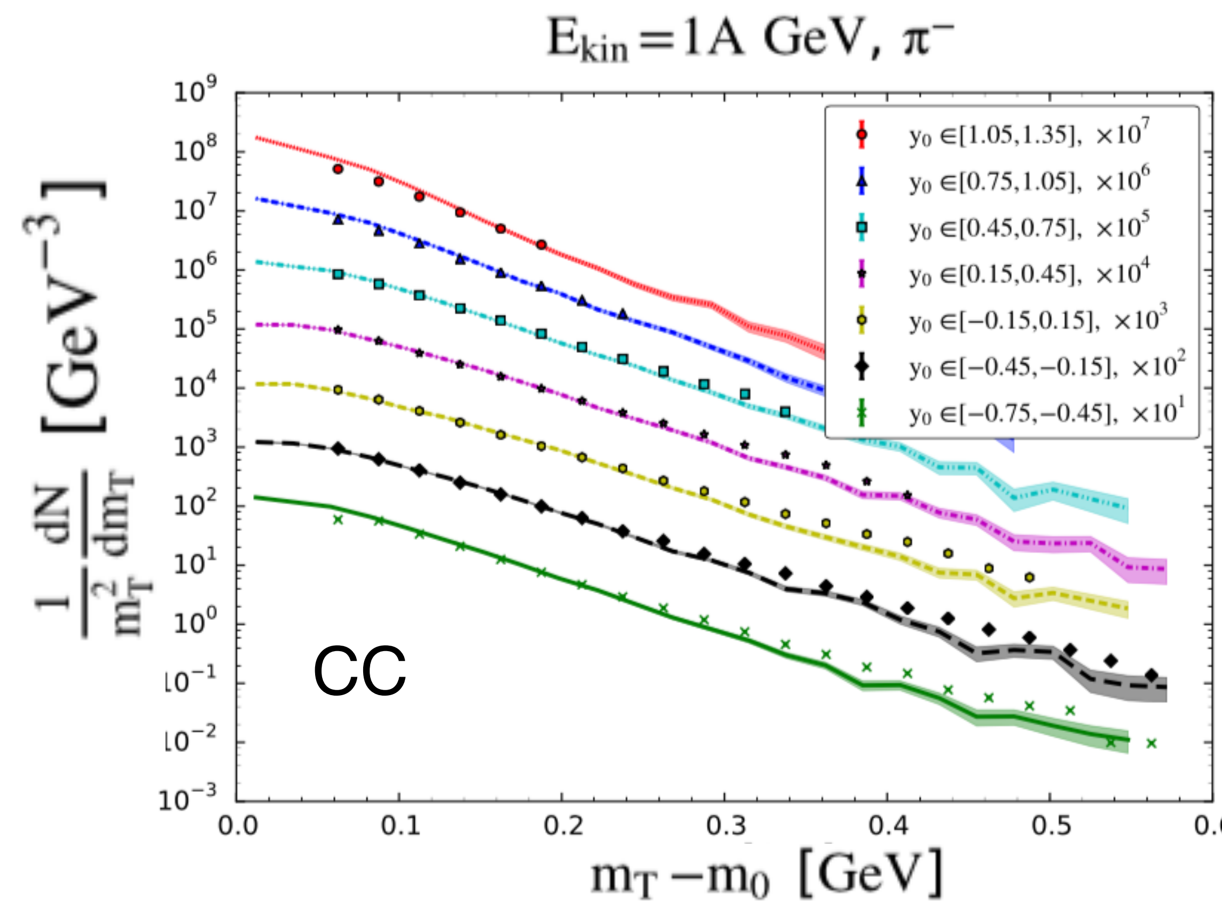
# Elementary Cross Sections




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

# Results for HIC



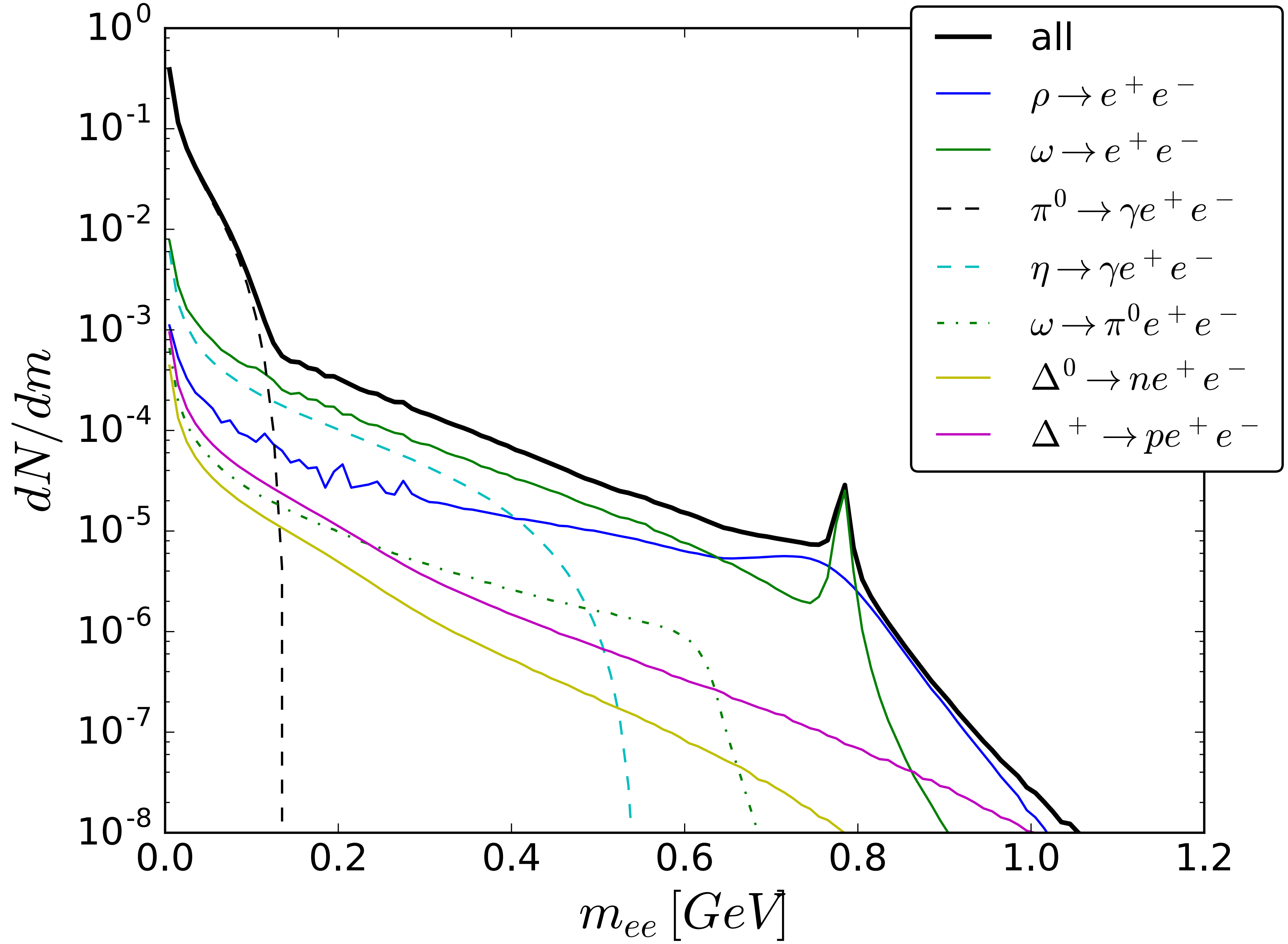

- shape of pion rapidity spectra reproduced
- transverse mass spectra compared with HADES data are in good agreement

# Dileptons in SMASH

- direct and Dalitz dilepton decay channels
- rare e.m. decays —> 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)

| Direct Decays |
| --- |
| $\rho^0 \to l^+ l^-$ |
| $\omega \to l^+ l^-$ |
| $\phi \to l^+ l^-$ |
| **Dalitz Decays** |
| $\pi^0 \to e^+ e^- \gamma$ |
| $\eta \to e^+ e^- \gamma$ |
| $\omega \to e^+ e^- \pi^0$ |
| $\Delta^+ \to e^+ e^- p$ |
| $\Delta^o \to e^+ e^- n$ |

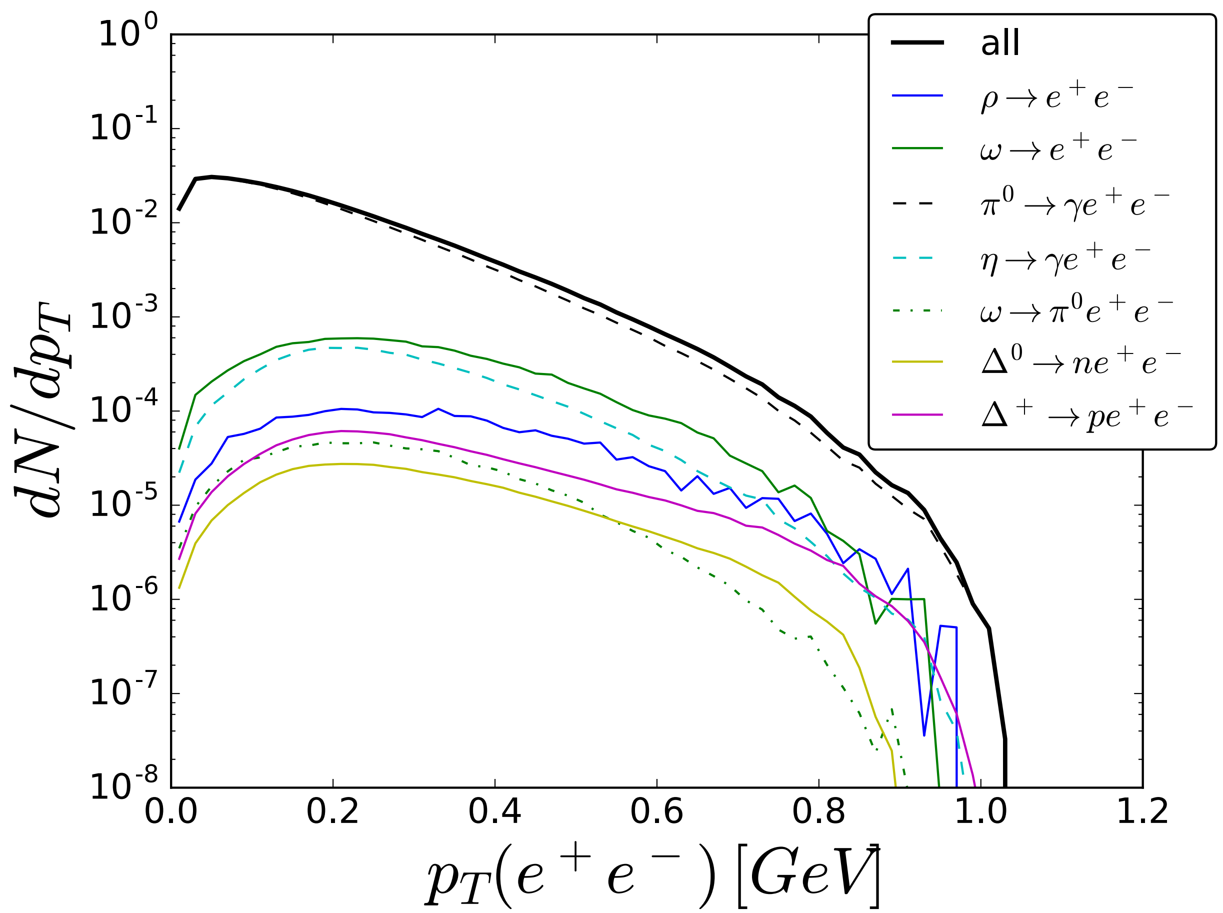
# Dilepton Spectrum

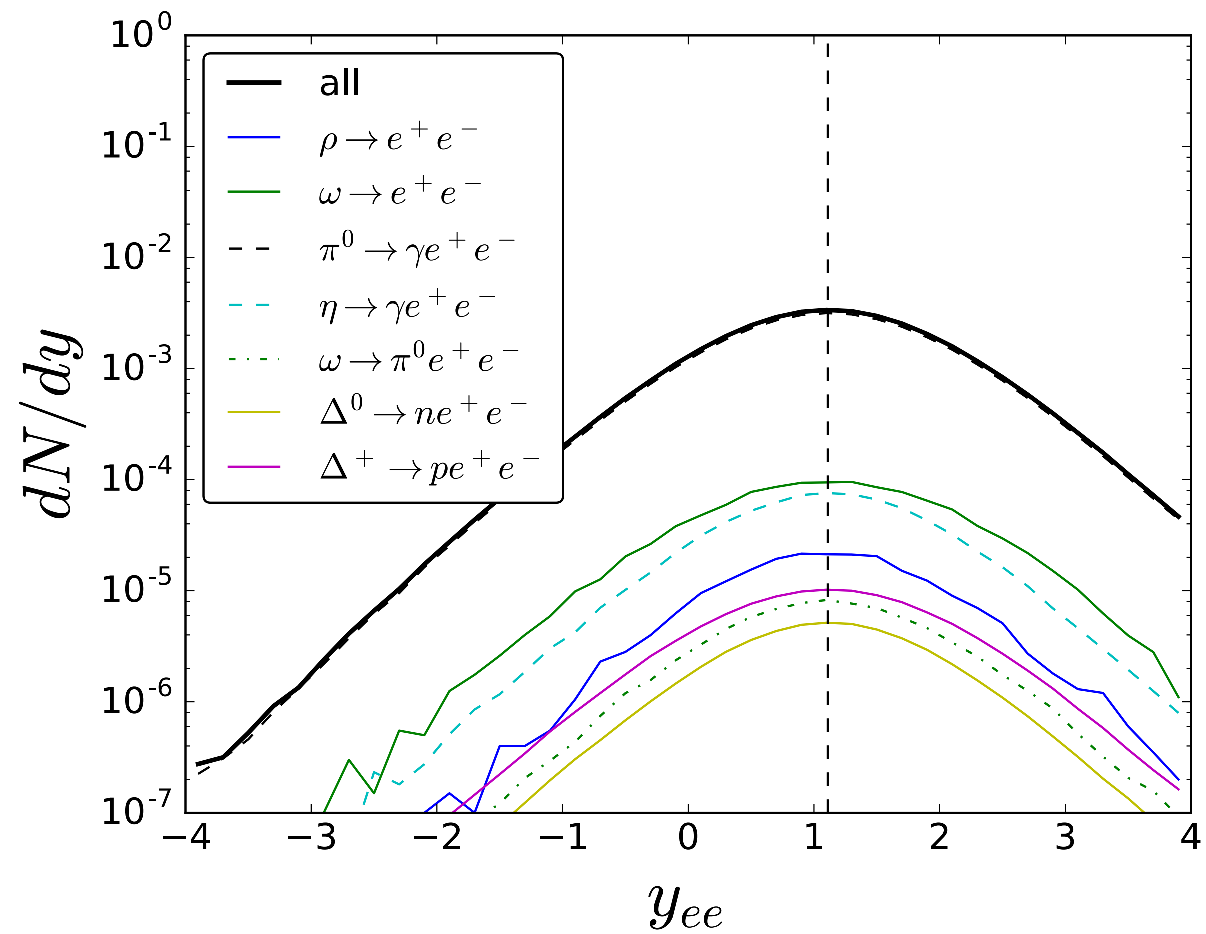



- invariant mass spectrum for pp collision with $E_{kin}$ = 3.5 GeV

# $p_T$ and y Spectra

pp, 3.5 GeV



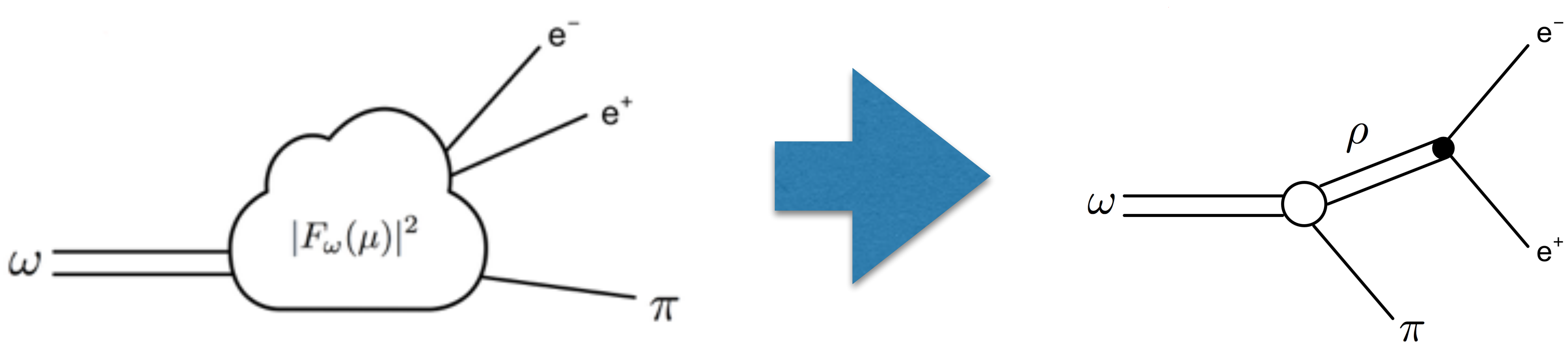




- dominant contribution from pion decays
- rapidity spectrum shifted due to fixed-target setup

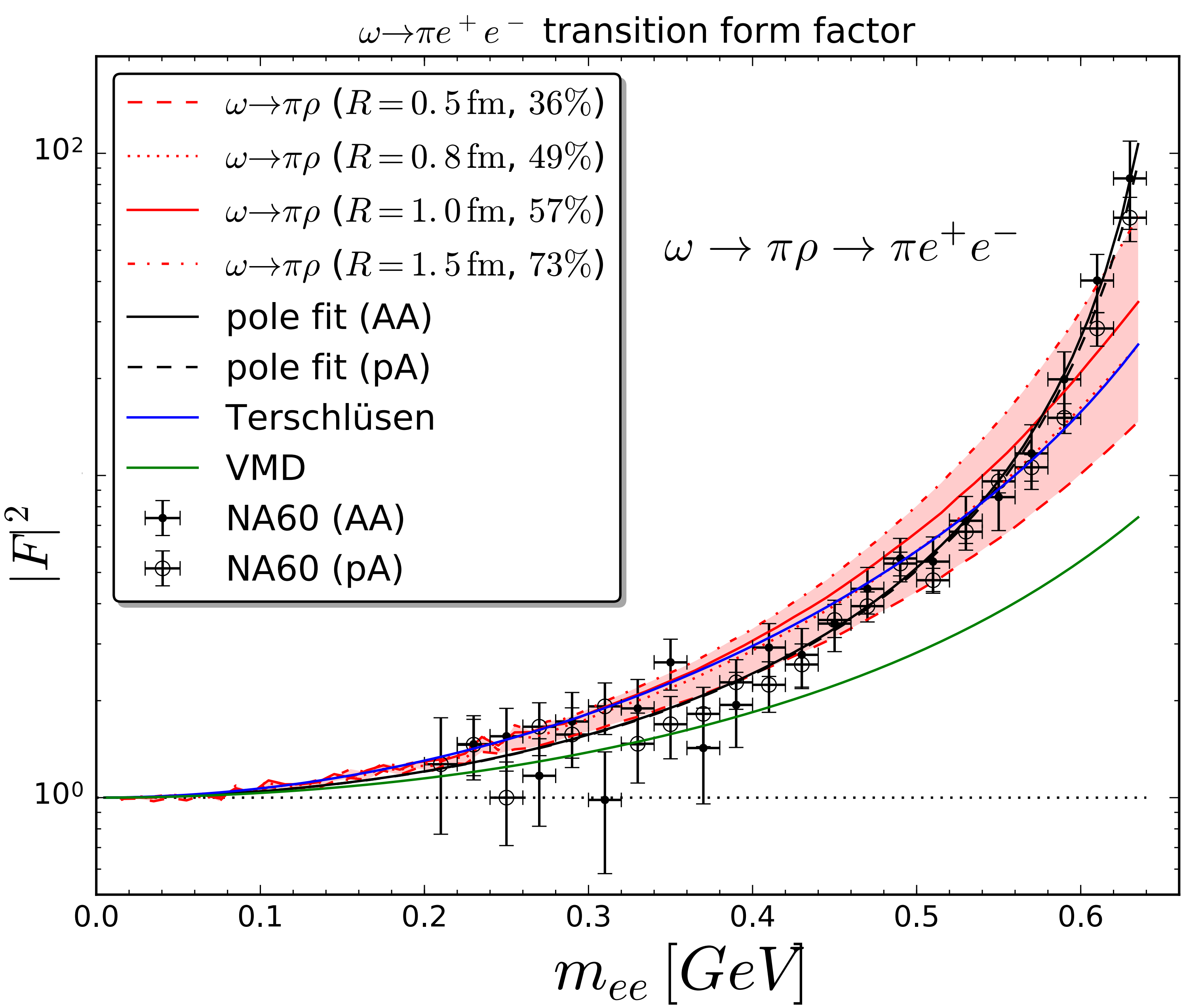
# Form Factors

- 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 $\omega$ decay into 3π: $\omega \to \rho\pi \to 3\pi$ (VMD-inspired)



# Form Factors




- 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*

# Hybrid Approach

*in coll. with G. Vujanovic and U. Heinz*

Motivation

- study the behaviour of e.m. radiation in hydrodynamics relative to transport models

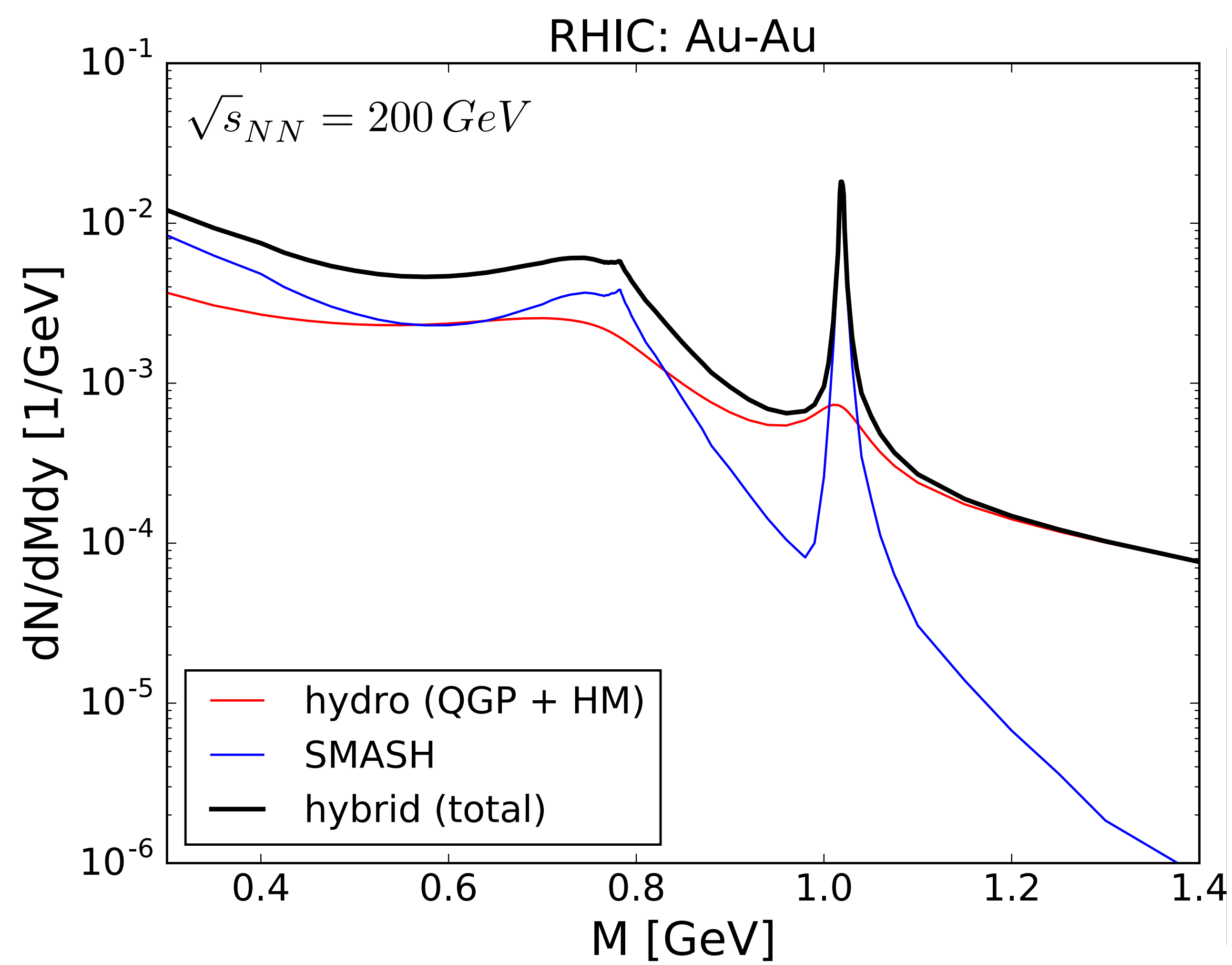
Model

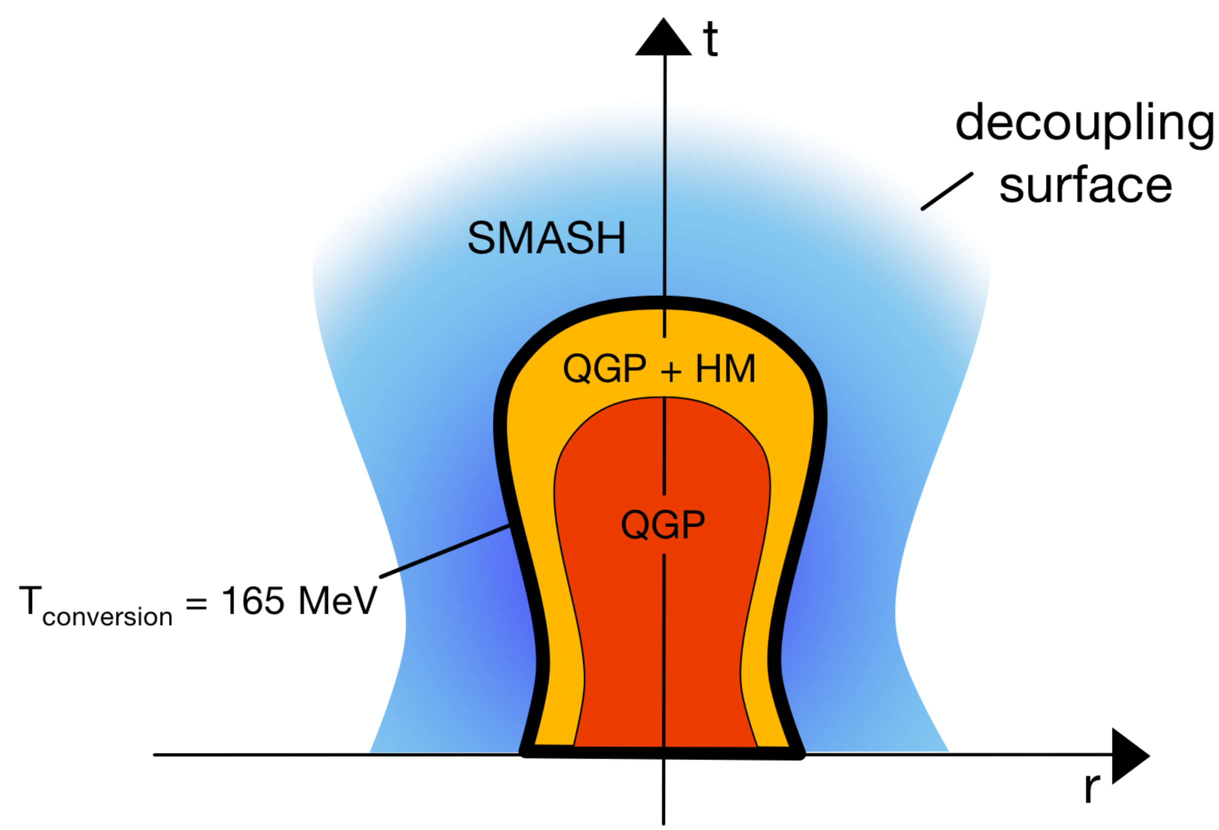
- initialize (*iSS*) transport model (*SMASH*) on the chemical freeze-out hypersurface of hydrodynamical model (*MUSIC*)

*arXiv:1409.8164*

- combine dilepton radiation from hydro model with dilepton emission from transport model

# First Result




- preliminary result
- MUSIC setup: IP-Glasma inital conditions, followed by visc. hydro (incl. Bulk and Shear viscosity), $T_{conversion}$ = 165 MeV

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

- thermal dilepton emission from hydro by G. Vujanovic (preliminary)

*PRC 94, 014904 (2016)*

# Summary + Outlook

## Summary

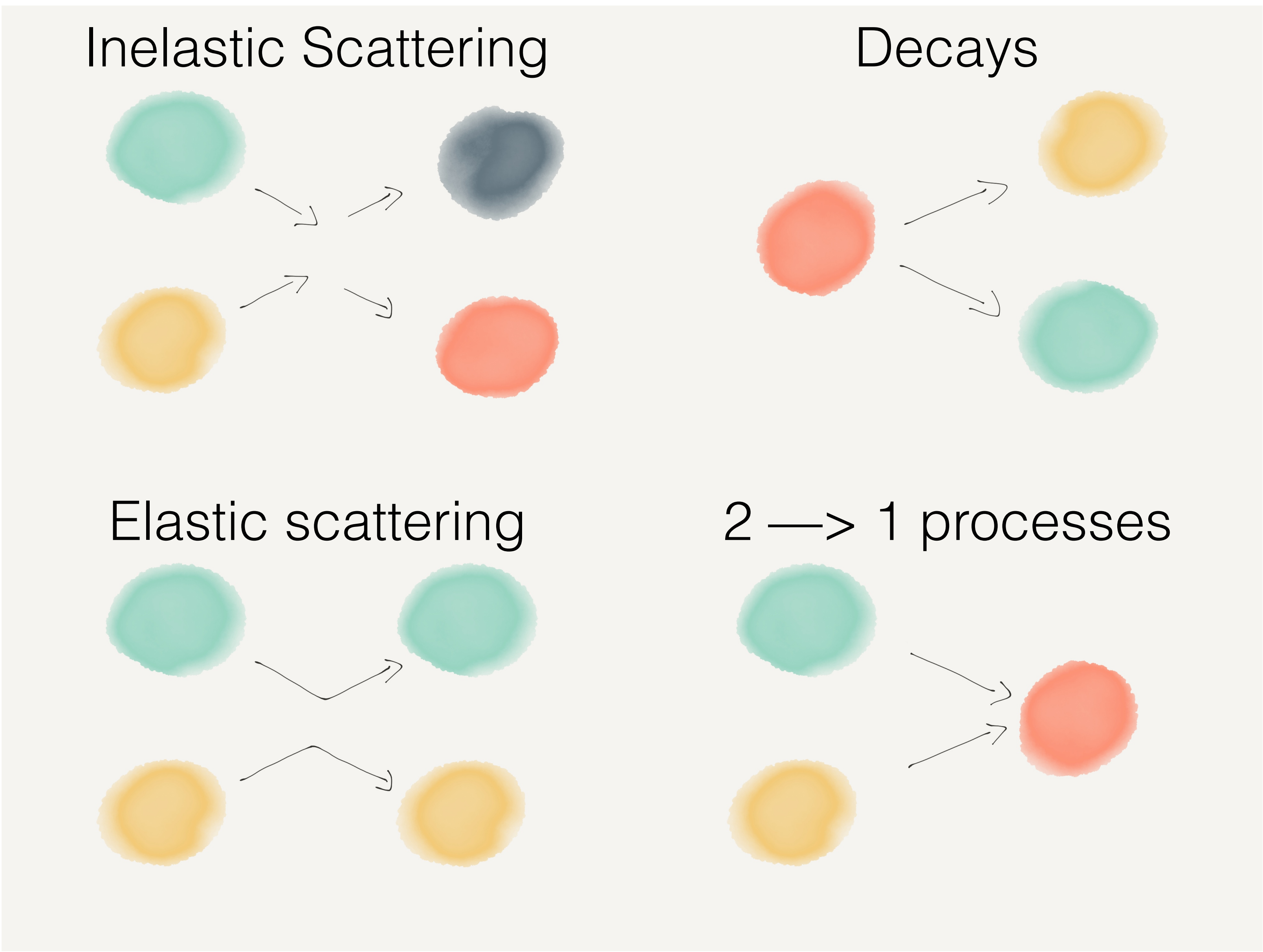
- transport models, like SMASH, are important to describe the late dilute stages of HIC
- dileptons can be used to study the properties of resonances and the e.m. transition form factor of the $\omega$ Dalitz decay
- dilepton production from the hybrid approach yields first results

## Outlook

- compare dilepton production in SMASH to HADES data for low energy collisions
- conduct a systematic study with the hybrid model in order to compare with the dilepton radiation from a pure hydrodynamical approach
- SMASH: String fragmentation, Photons, …

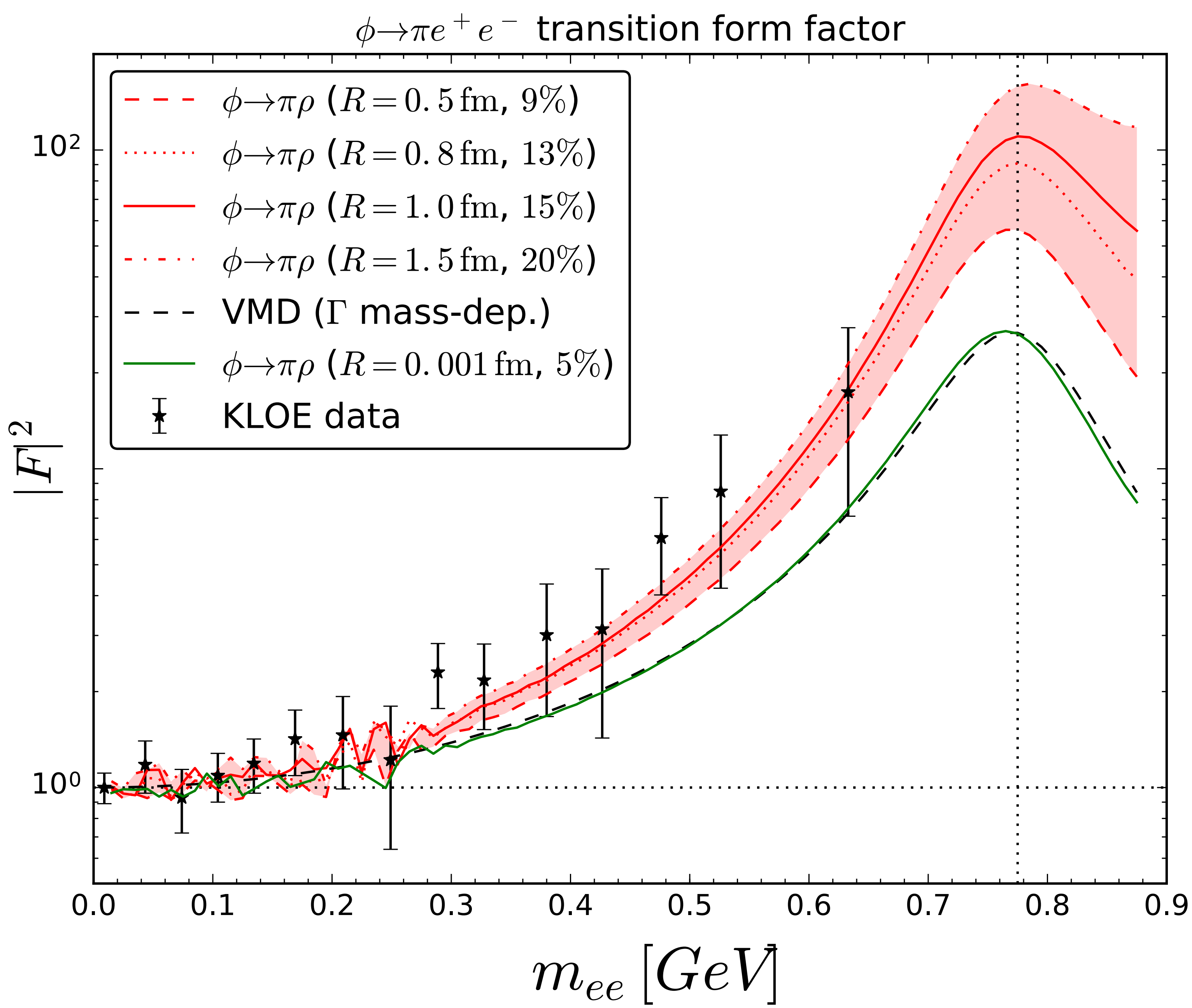
# Backup Slides

# Collision Term



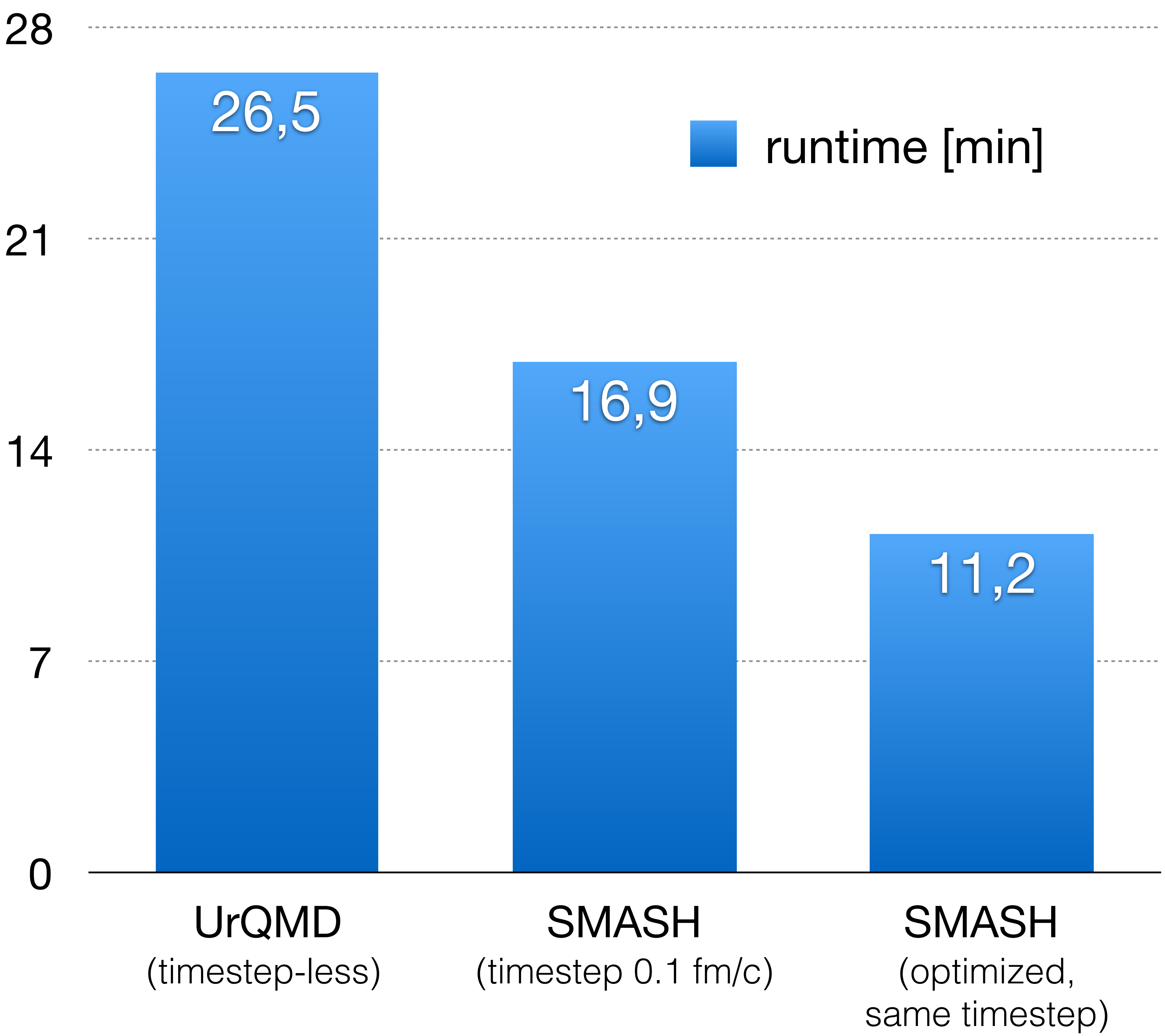

- in few GeV energy regime decay and excitation of resonances dominate hadronic cross section
- no string fragmentation yet

# Form Factors




- same ansatz for the Phi 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 as „simple“ VMD

# Performance compared to UrQMD

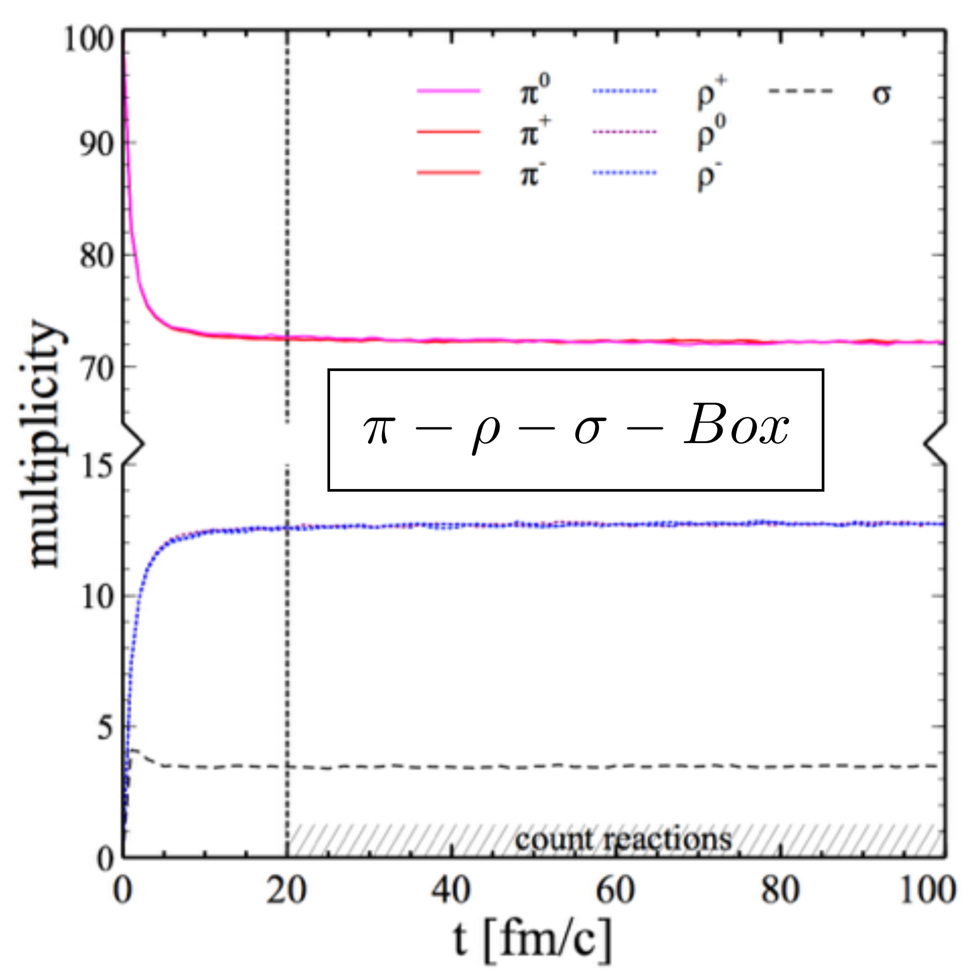


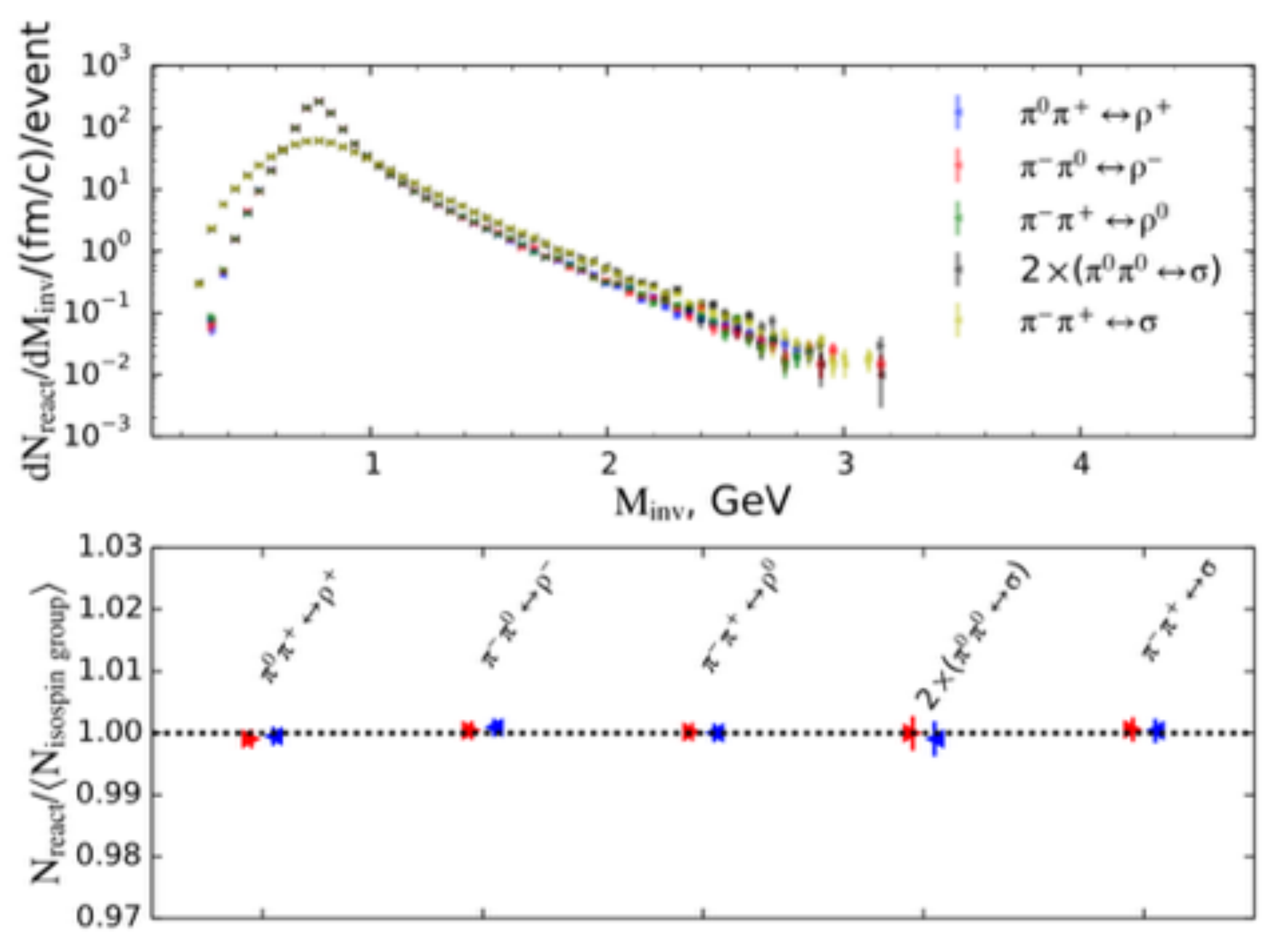

| Setup | |
|---|---|
| System | central AuAu collision |
| Kinetic Energy | 3 AGeV |
| $N_{events}$ | 1000 |
| Machine | FIAS office desktop |
| End Time | 20 fm/c |
| Output | final particles |

—> more than 35% faster with the more expensive timestep-based evolution (more than 55% with optimizations)

# Detailed Balance

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

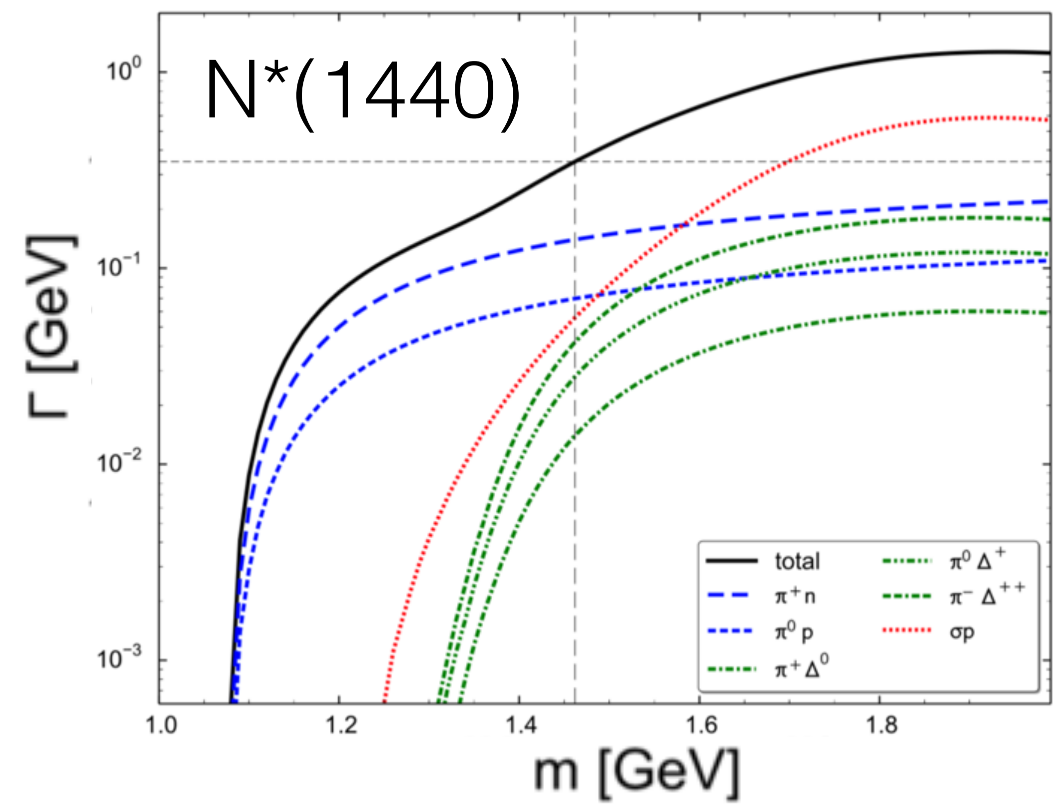


# Resonances

- 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)*

# 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

$$B_0^2 = 1$$

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

$$\ldots$$

- hadronic Form Factor:

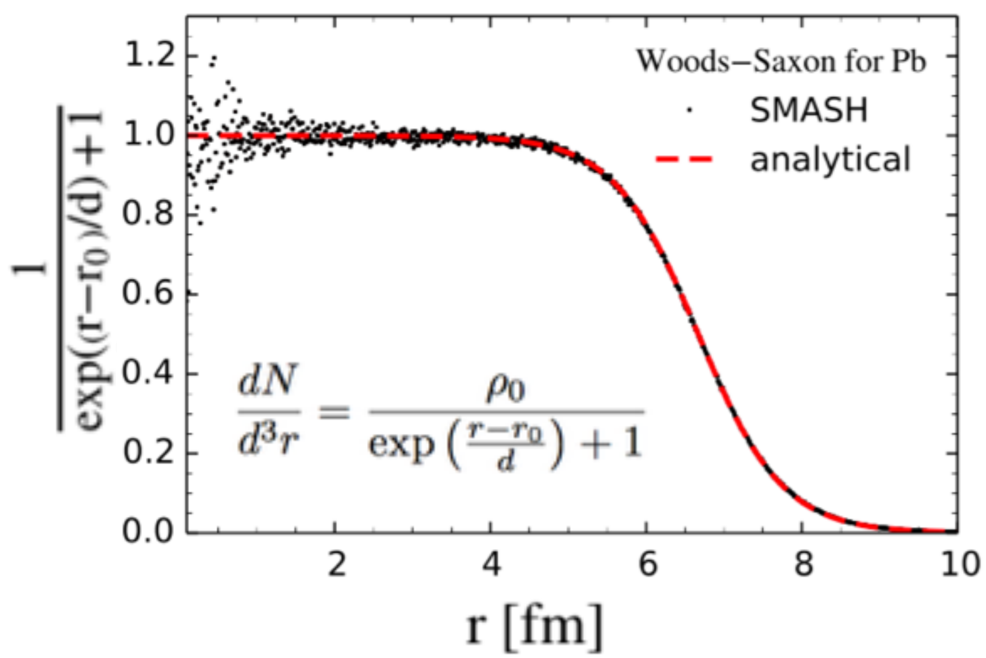
$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + 1/4(s_0 - M_0^2)^2}{\lambda^4 + \left(m^2 - 1/2(s_0 + M_0^2)\right)^2}$$

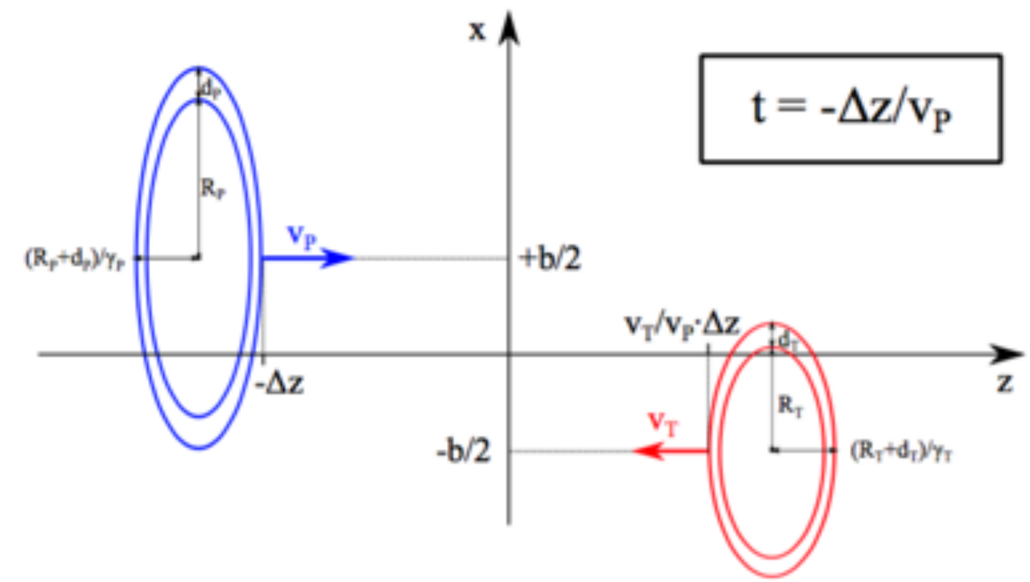
| decay | $\lambda$ [GeV] |
|---|---|
| $\pi\rho$ | 0.8 |
| unstable mesons (e.g. $\rho N$, $\sigma N$) | 1.6 |
| unstable baryons (e.g. $\pi\Delta$) | 2.0 |
| two unstable daughters (e.g. $\rho\rho$) | 0.6 |

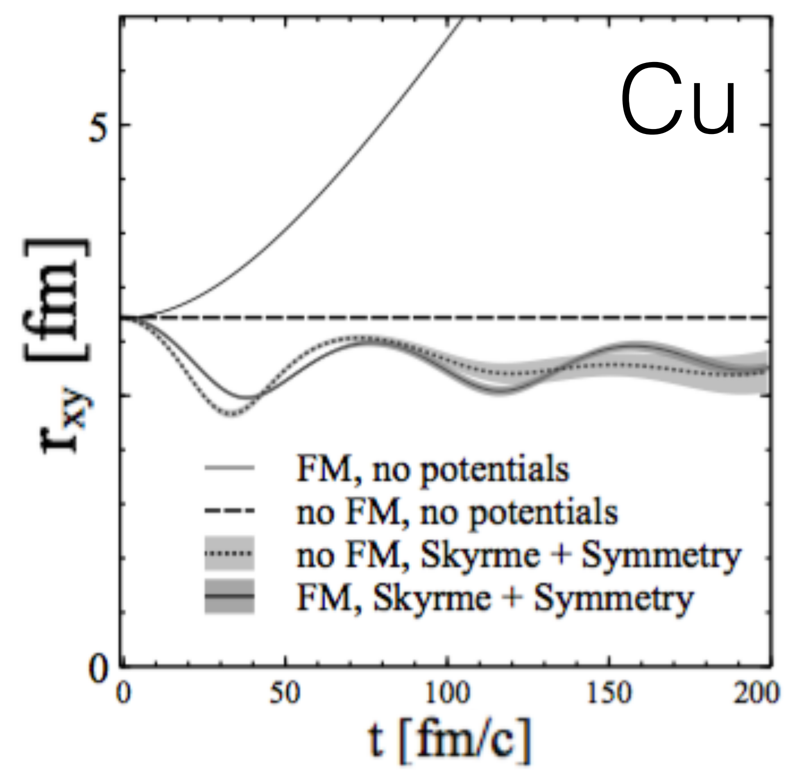
*M. Post, S. Leupold, U. Mosel, Nucl. Phys. A 741, 81 (2004)*

# Initial Conditions

- <u>Nuclear Collisions</u>
  - Woods-Saxon distribution in coordinate space




  - *optional:* deformed nuclei
  - *optional:* Fermi Motion

# Fermi Motion

- momentum distribution of nucleons in nucleus = uniform distribution with $0 \leq |\vec{p}| \leq p_F(\vec{r})$ („Fermi sphere“)
- radius depends on density of nulceons:

$$p_F(\vec{r}) = \hbar c(3\pi^2\rho(\vec{r}))^{1/3}$$

# Pauli Blocking

- probabality that action is blocked

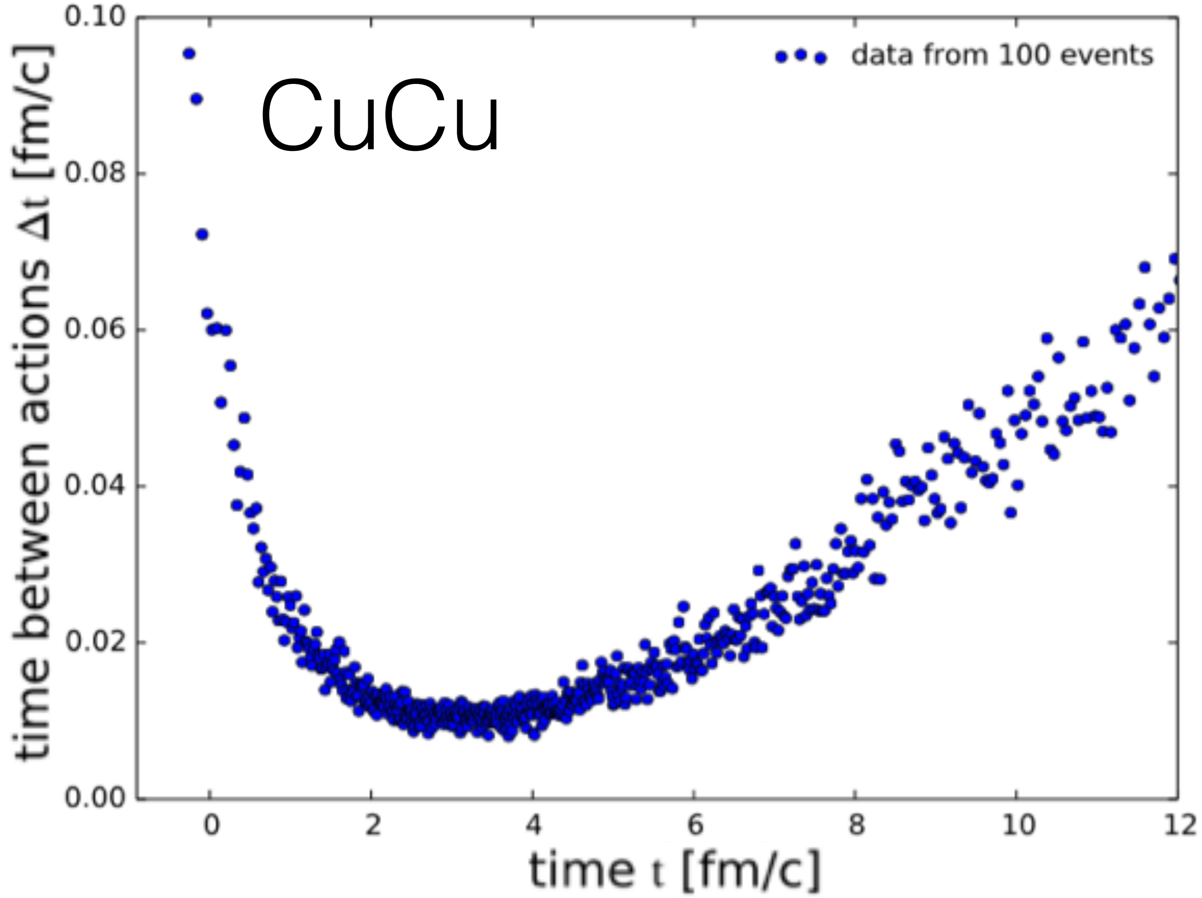
$$1 - \prod_i (1 - f_i)$$

i: final states of reaction
$f_i$: phase space density of species i

- „derivation" from Boltzmann-Uehling-Uhlenbeck-equation

# General Setup

- Time Steps
  - time steps either fixed or adaptive
  - one interaction per timestep per particle, afterwards propagation
  - also possible: timestep-less mode




- Mean-field potentials

$$U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}}\frac{\rho_{I3}}{\rho_0}$$

*Xu et al, arXiv:1603.08149*