Introduction to the UrQMD model

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Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Hadron cascade (standard mode)

- Based on the propagation of hadrons
- Rescattering among hadrons is fully included
- String excitation/decay (LUND picture/PYTHIA) at higher energies
- Provides a solution of the relativistic Boltzmann eq.:

\[ p^\mu \cdot \partial_\mu f_i(x^\nu, p^\nu) = C_i \]

The collision term C includes more than 100 hadrons

### List of included particles in the hadron cascade

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>( \Delta )</th>
<th>( \Lambda )</th>
<th>( \Sigma )</th>
<th>( \Xi )</th>
<th>( \Omega )</th>
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- Binary interactions between all implemented particles are treated
- Cross sections are taken from data or models
- Resonances are implemented in Breit-Wigner form
- No in-medium modifications
Baryon-baryon scattering cross section

- Phase space x matrix element:
  \[ \sigma_{tot}^{BB}(\sqrt{s}) \propto (2S_D + 1)(2S_E + 1) \frac{\langle p_{D,E} \rangle}{\langle p_{A,C} \rangle} \frac{1}{s} |\mathcal{M}|^2 \]

- Matrix element is fitted to data for groups of resonance channels

- Detailed balance is fulfilled for the inverse reaction:
  \[ \sigma(y \rightarrow x) p_y^2 g_y = \sigma(x \rightarrow y) p_x^2 g_x \]
Meson-baryon scattering cross section (resonances)

\[ \sigma_{MB}(\sqrt{s}) = \sum_{R=\Delta,N^*} \langle j_B, m_B, j_M, m_M \parallel J_R, M_R \rangle \frac{2S_R + 1}{(2S_B + 1)(2S_M + 1)} \times \frac{\pi}{p_{cm}^2} \frac{\Gamma_{R-\Delta} \Gamma_{tot}}{(M_R - \sqrt{s})^2 + \Gamma_{tot}^2/4} \]
Meson-meson scattering

- Meson-meson scattering in the resonance region is treated in analogy to the meson-baryon scattering.
- At higher energies, also t-channel excitation is taken into account.
At energies above 100 GeV (CM-energy) the early intermediate state can not be modeled by strings and particles alone.

To take the local equilibration and the phase transition to a QGP into account, a hydrodynamic phase is introduced.

This is known as hybrid model (Boltzmann +hydrodynamics), hybrid models have become the standard at RHIC and LHC energies.

Hybrid model

• Initial State:
  o Initialization of two nuclei
  o Non-equilibrium hadron-string dynamics
  o Initial state fluctuations are included naturally

• 3+1d Hydro +EoS:
  o SHASTA ideal relativistic fluid dynamics
  o Net baryon density is explicitly propagated
  o Equation of state at finite $\mu_B$

• Final State:
  o Hypersurface at constant energy density
  o Hadronic rescattering and resonance decays within UrQMD

P. Huovinen, H. P. EPJ A48 (2012) 171
Hybrid model details: Initial State

- Contracted nuclei have passed through each other
  \[ t_{\text{start}} = \frac{2R}{\gamma v} \]
  - Energy is deposited
  - Baryon currents have separated
- Energy-, momentum- and baryon number densities are mapped onto the hydro grid
- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade

(J.Steinheimer et al., PRC 77,034901,2008)

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**Hybrid model details: Equations of State**

**Ideal** relativistic one fluid dynamics:

\[ \partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu (n u^\mu) = 0 \]

- HG: **Hadron gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- CH: **Chiral EoS** from quark-meson model with first order transition and critical endpoint (most realistic)
- BM: **Bag Model EoS** with a strong first order phase transition between QGP and hadronic phase

D. Rischke et al., NPA 595, 346, 1995,
D. Zschiesche et al., PLB 547, 7, 2002
Papazoglou et al., PRC 59, 411, 1999
Experiments observe \textbf{finite number} of hadrons in detectors

\textbf{Hadronization} controlled by the equation of state

Sampling of particles according to \textbf{Cooper-Frye} should:
- Respect \textbf{conservation laws}, maybe even locally?
- Introduces fluctuations on its own

\[
E \frac{dN}{d^3p} = \int_{\sigma} f(x, p)p^\mu d\sigma_\mu
\]

\textbf{Cooper-Frye hyper-surface at transition from hydro to transport}

Sophisticated 3D hypersurface finder to resolve interesting structures in event-by-event simulations
Petersen, Huovinen, arXiv:1206.3371
Hybrid approaches are very successful for the description of the dynamics.
Comparison to low energy data (small systems)

- Baryon energy loss in line with data at low energies

S. Sombun, M. Bleicher et al, arXiv:1805.11509

Proton and deuteron rapidity distribution in p+Be, p+Au reaction at $E_{\text{lab}}=14.6$ AGeV

Proton and deuteron rapidity distribution for Si +Au reactions at $E_{\text{lab}}=14.6$ AGeV
Side remark on anti-deuterons

Anti-proton and anti-deuteron rapidity distribution for Si+Au reactions at $E_{\text{lab}}=14.6$ AGeV

- Substantial amount of anti-deuteron production even near threshold
- Relevance for dark matter...

$d/p$ and anti-$d$/anti-$p$ ratios as function of energy, UrQMD vs data vs thermal model

S. Sombun, M. Bleicher et al, arXiv:1805.11509
How well is the energy deposition described?

Rapidity shift of the baryons:

\[
\langle \delta y \rangle = y_p - \frac{2}{\langle N_{\text{part}} \rangle} \int_0^\infty y \frac{dN_{B^{-}\overline{B}}}{dy} dy,
\]

Width (root-mean-square) of the charged particle rapidity distributions for p+p and Au+Au reactions

- Good description of the energy loss of leading baryons
- consistency with growing width of charged particle rapidity density

Comparison to low energy data (large systems)

- Charged pion rapidity distribution: Model vs. data from NA49 for different center-of-mass energies
- Charged particle production at central and forward rapidities in line with data

Yields of different particle species are well reproduced, both at midrapidity and integrated over $4\pi$.


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Left: Energy dependence of midrapidity particle yields in Au+Au/Pb+Pb reaction

Right: Energy dependence of integrated particle yields in Au+Au/Pb+Pb reaction
Detailed transverse momentum studies – low energy

- Energy dependence (from top to bottom) of transverse momentum spectra in Au+Au/Pb+Pb reactions

- Transverse momentum distributions of different particle species are well reproduced as compared to data.

E. Bratkovskaya, M. Bleicher et al, PRC69 (2004) 054907
• Marcus Bleicher, CERN 10/2018
Transverse momentum dynamics and lateral distributions

**Transverse momentum spectra in proton+proton collisions at various energies**


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Lateral distribution functions in VEM, from various model combinations, scaled to QGSJET01+UrQMD
Low energy model important at large distances
Small systems at high energies

- Good description of charged particle rapidity distribution for small systems

How does the (hybrid-)model work for heavy ion collision systems at LHC?

- Charged particle production as function of centrality (participating nucleons) in Pb+Pb, 2.76 TeV
- Transverse momentum distribution of charged particle at midrapidity in Pb+Pb, 2.76 TeV

Good description of data in hybrid mode of the model

Summary

- UrQMD is a well benchmarked model for the description of hadron-hadron, hadron-nucleus and nucleus-nucleus collisions.
- Particle yields, spectra and baryon-stopping in line with data (especially at low energies)
- In hybrid mode it is applicable up to LHC energies
- In standard cascade mode (no hydro) the model needs seconds for the simulation of a single event.
- However, hybrid calculations are slow at LHC energies (up to 1h per event)

→ well suited as low energy model for cosmic rays