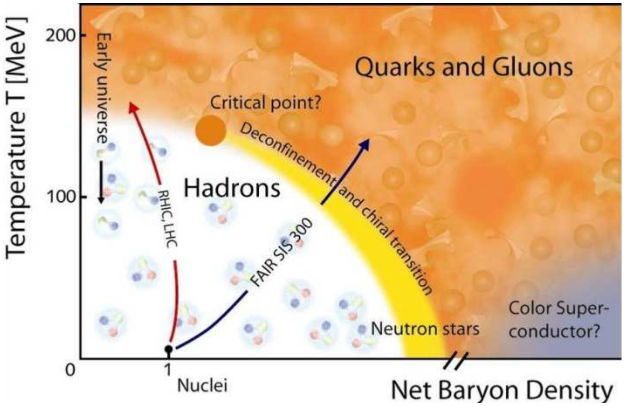
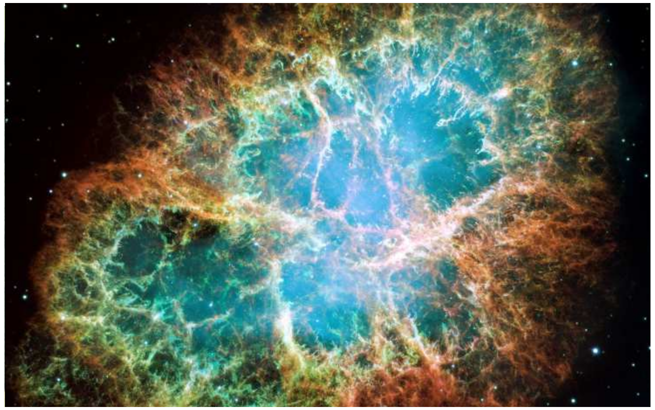


# Benchmark calculations for heavy ion collisions

Yvonne Leifels

*GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt*

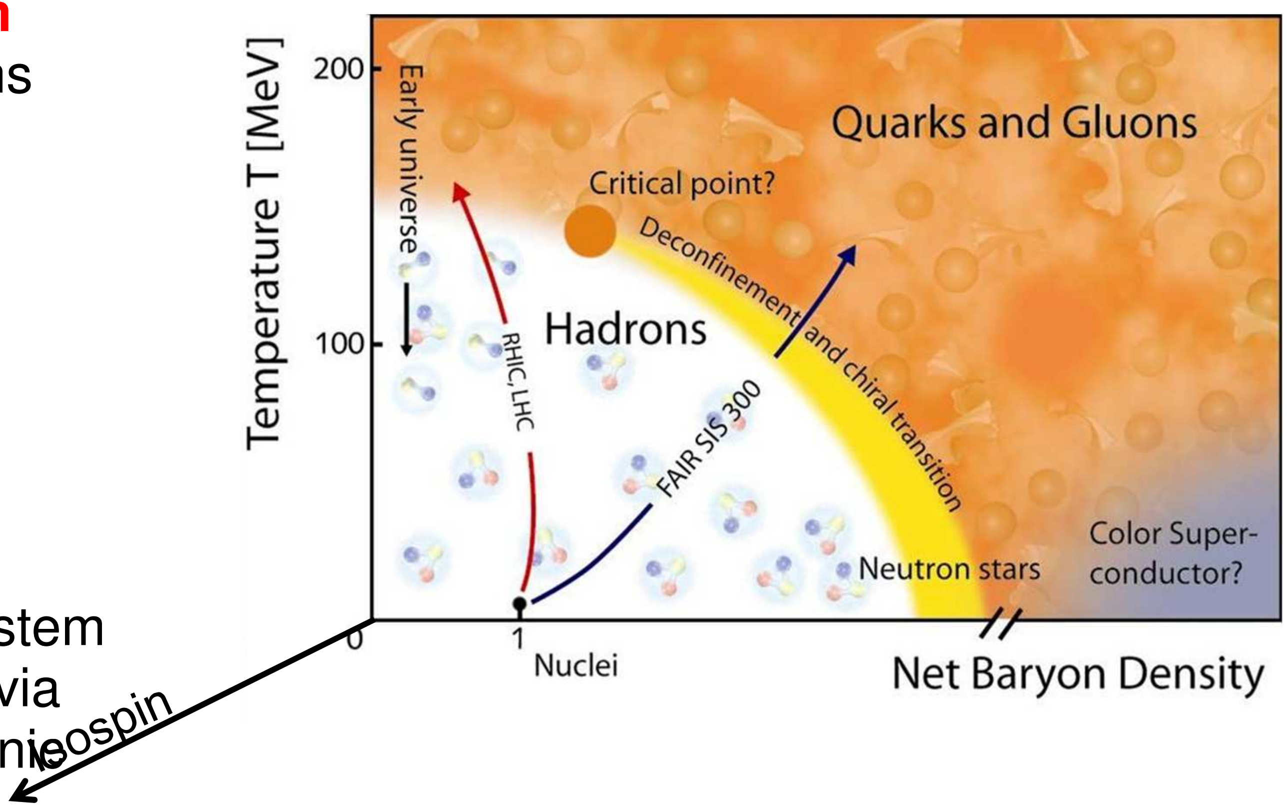
Challenges to transport models for heavy ion collisions, ECT*, 20.-25.5.2019

# Outline

- Introduction
  - heavy ion collisions and transport models
- Transport models
  - succeses
  - open issues
- Benchmarking transport models
  - vs experimental data
  - vs reference data set
- Tools and infrastucture
  - data repositories
  - software repositories
- Summary and Conclusion

# Heavy ion reactions

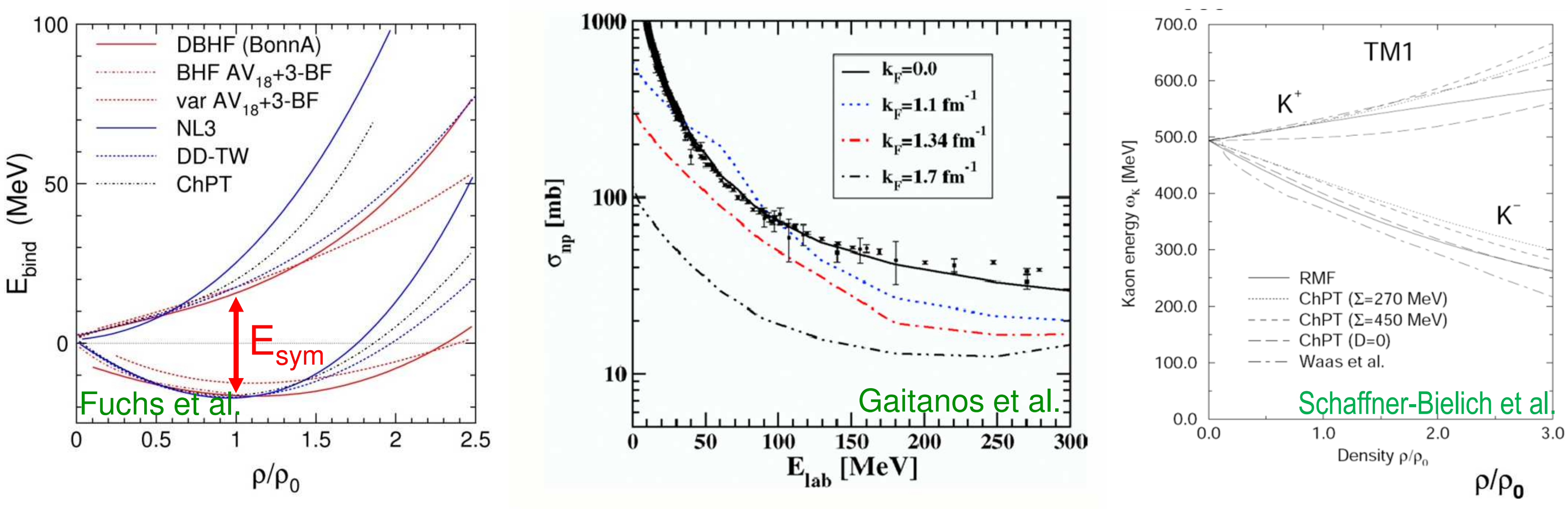
Access
**QCD phase diagram**
by heavy ion collisions




- finite, dynamical system
- extract information via modeling the hadronic phase

➡ microscopic transport models

# Heavy ion reactions




Not only nuclear matter equation of state

'Trivial' in-medium effects

- Fermi motion
- Pauli-blocking
- collisional broadening

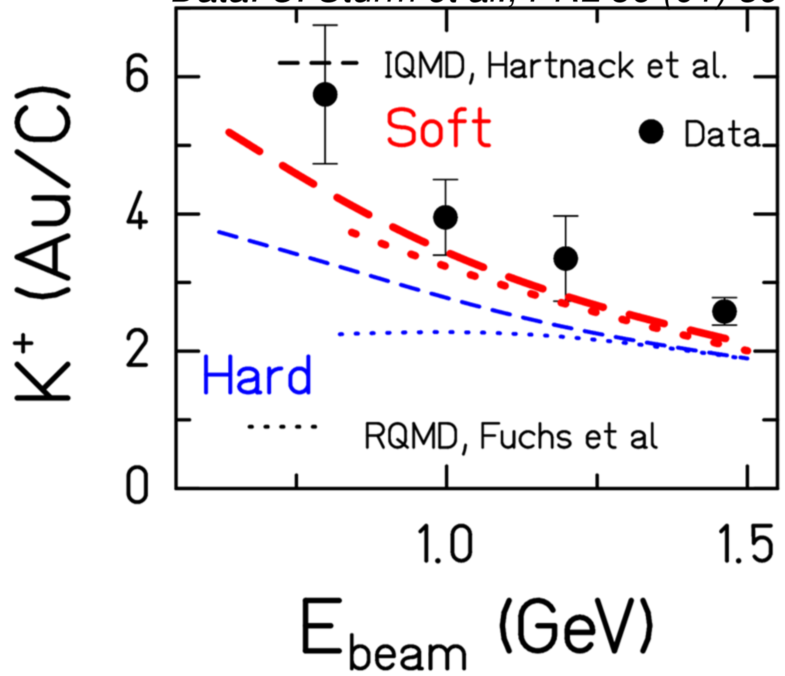
'Non trivial'

- resonances
- Meson-Baryon coupling
- restauration of chiral symmetry
- bound states
- clustering

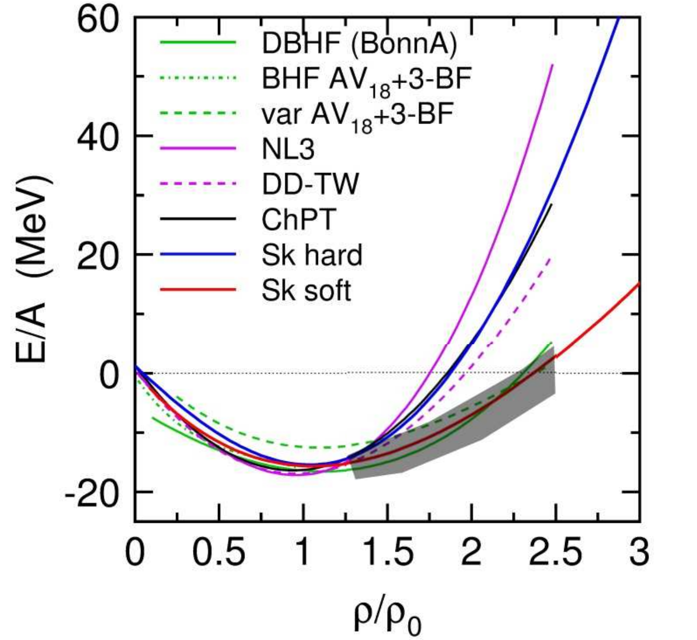
# SUCCESS OF TRANSPORT MODELS

# Heavy ion collisions and strangeness

*Data: C. Sturm et al., PRL 86 (01) 39*



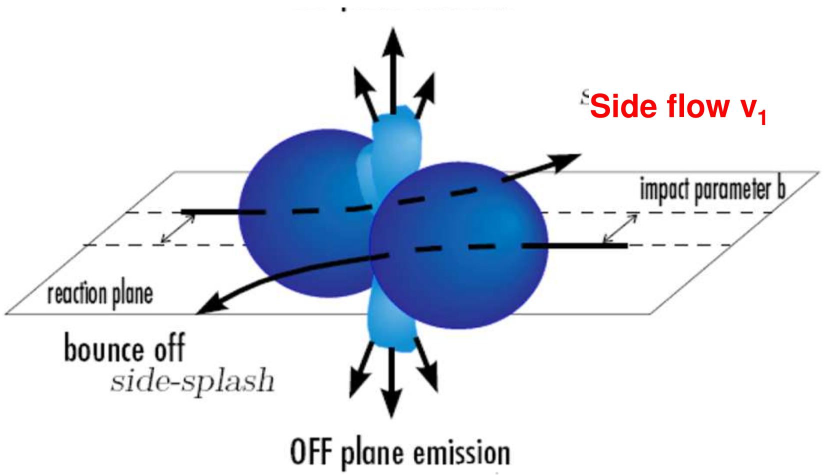

*Theory: Fuchs+Wolter, EPJA (2006)*




- Kaon yield ratio
  - strong sensitivity to EOS due production via multistep reactions
    ~ density reached
    ~ 1/compressibility
- robust observable
  - independent on unknown or not well determined model ingredients

- sensitivity to compressibility largest below threshold
- relevant density ~$2\rho_0$

# Heavy ion collisions – collective flows




$$\varphi' := \varphi - \Phi_R$$

$$\frac{d^3N}{p_t dp_t dy d\varphi'} \propto (1 + 2v_1 \cos(\varphi') + 2v_2 \cos(2\varphi') + \ldots)$$

Fourier expansion coefficients

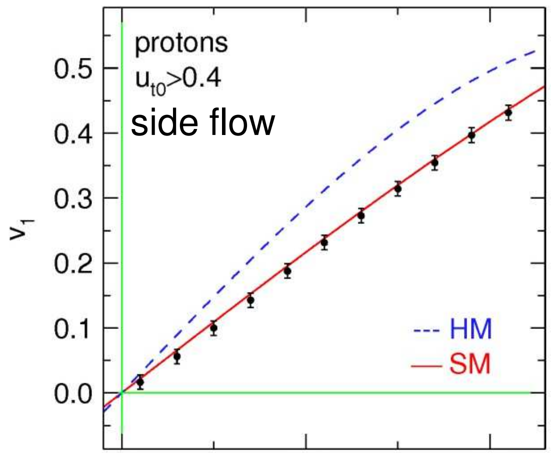
$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos \varphi' \rangle$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\varphi' \rangle$$

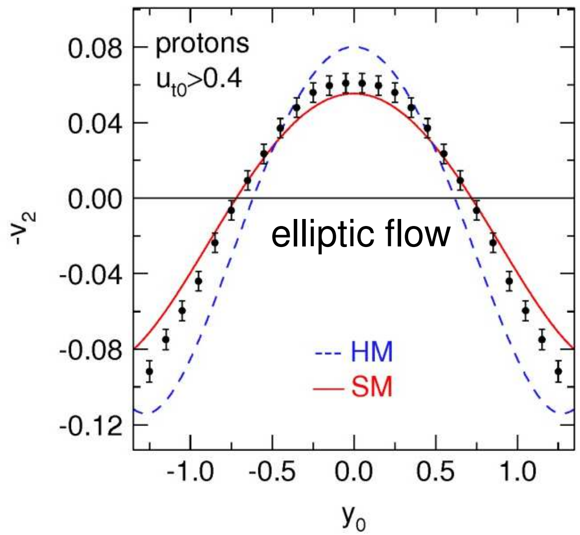
Discovery at Bevalac

*H.A. Gustafsson, et al., Phys. Rev. Lett. 52 (1984) 1590.*
*R.E. Renfordt, et al., Phys. Rev. Lett. 53 (1984) 763.*

Au+Au 1A GeV 3.5<b<6.3 fm



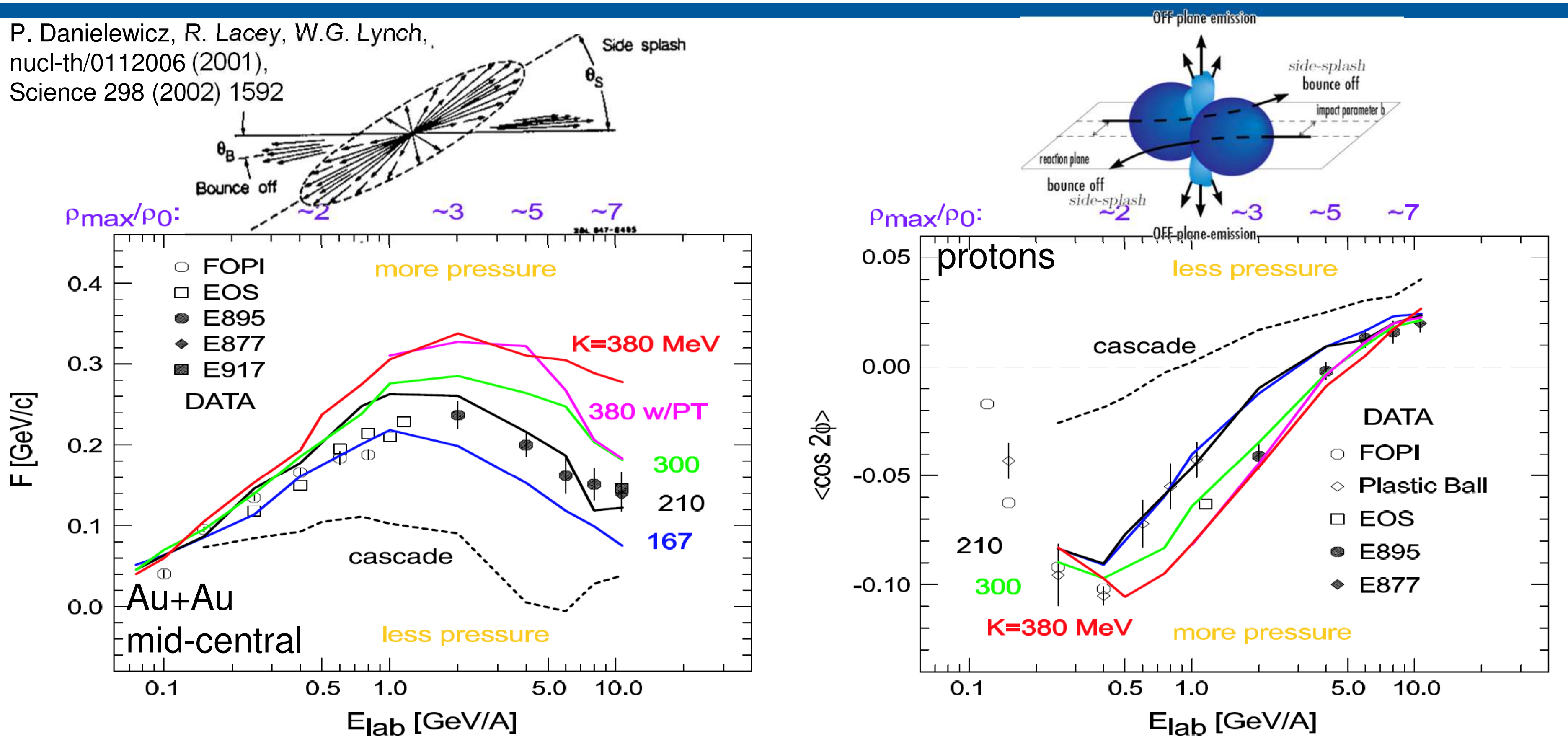

Model predictions: IQMD




W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

# Directed flow constraints for symmetric matter EOS

P. Danielewicz, R. Lacey, W.G. Lynch, nucl-th/0112006 (2001), Science 298 (2002) 1592

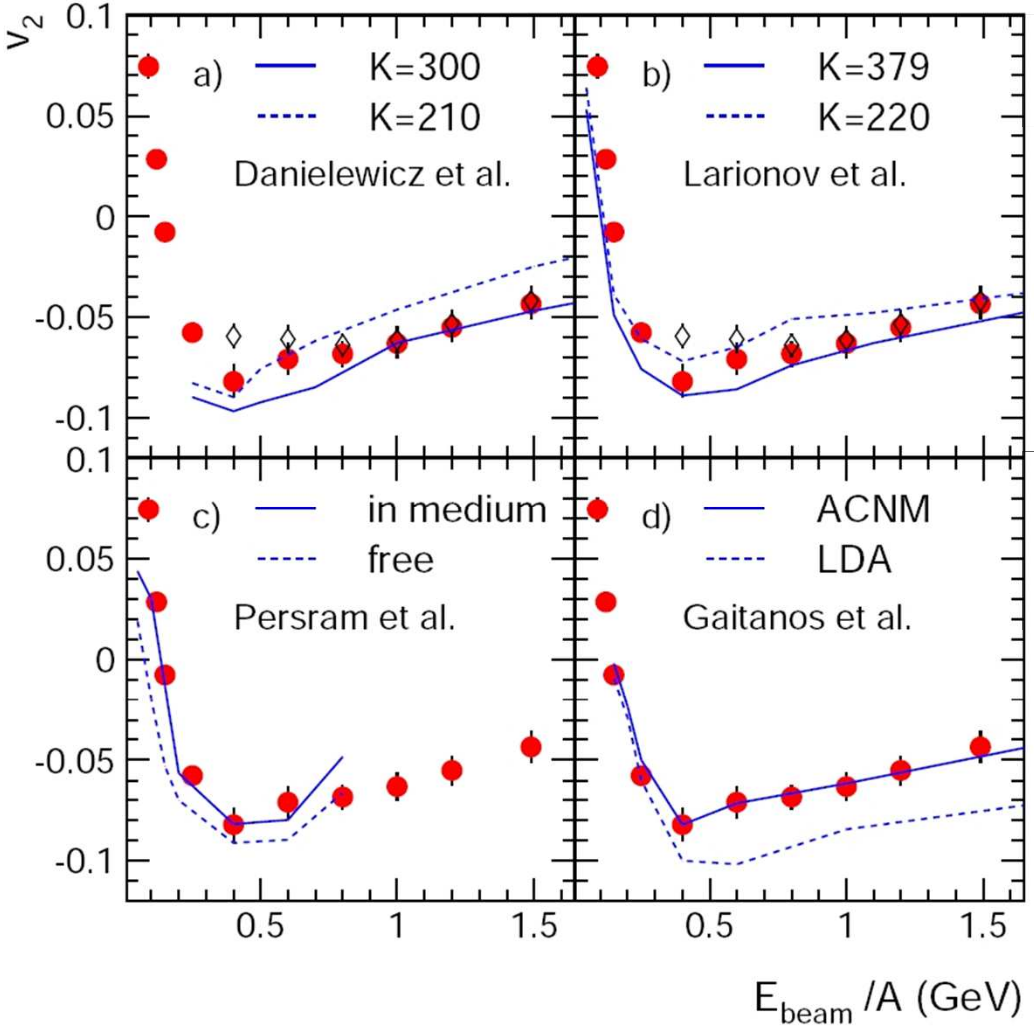



- additional constraints needed on momentum dependence of NN potential and in-medium cross sections

# Elliptic flow

Au+Au elliptic flow in mid-central collisions compared to predictions from BUU models

*A. Andronic et al. Phys.Lett. B612 (2005) 173-180*




Influence of the EOS

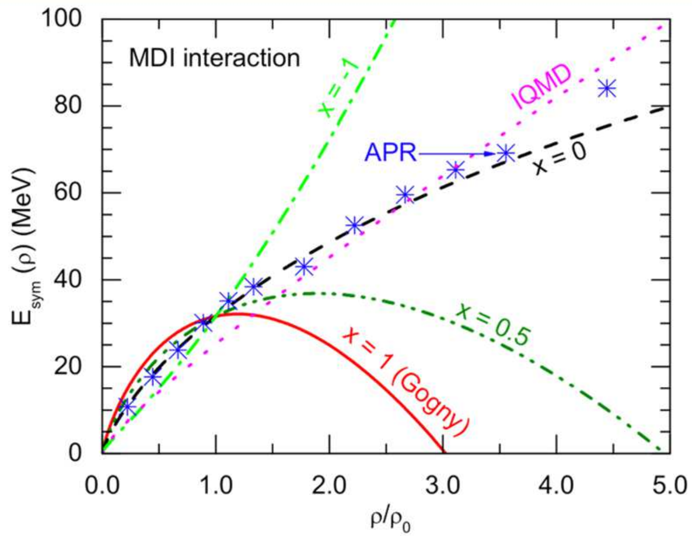
In-medium effects with soft EOS

Constraining input parameters with experimental data
→ more rigorously

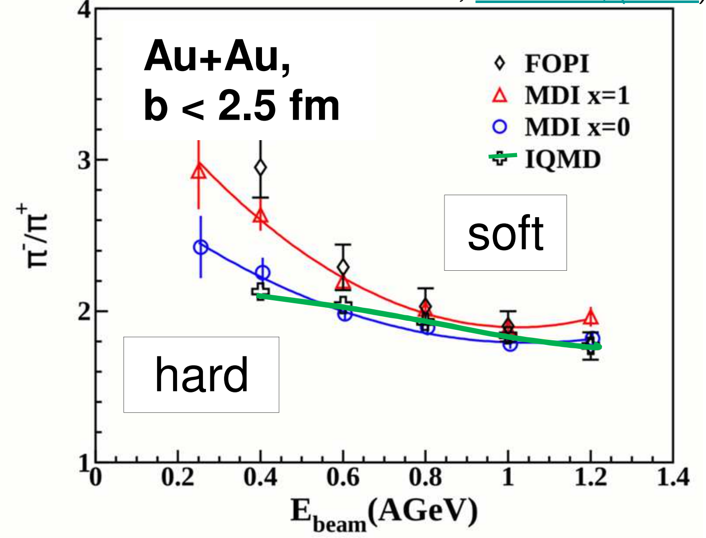
# Pion production and the symmetry energy

- symmetry energy influences n/p ratio → nn, np, pp collisions
- hard SE $\quad \frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$
- inconsistent with other experimental results
- other effects influence pion productio
  - pion optical potential, self energies, different for $\pi^-$ and $\pi^+$
  - production via Δ resonances, potential
  - s- vs p-wave production
- also with a hard SE: $\quad \Rightarrow \frac{\pi^-}{\pi^+}\uparrow$

Compare model results with experimental data
→ more rigorously




*Data: W. Reisdorf et al., NPA 781 (2007)*
*Calculations: Z. Xiao et al, PRL 102, (2009)*



# BENCHMARKING TRANSPORT MODELS

# Benchmarking of transport models

**Performance evaluation**

What is being evaluated?

Predictions of transport codes

How does one define performance?

Deviation of code predictions from (experimental) data?
But not describing experimental data may also be a result
and gives room for improvement

Benchmark:

Set of experimental data, which needs to be defined

# Benchmarking transport codes

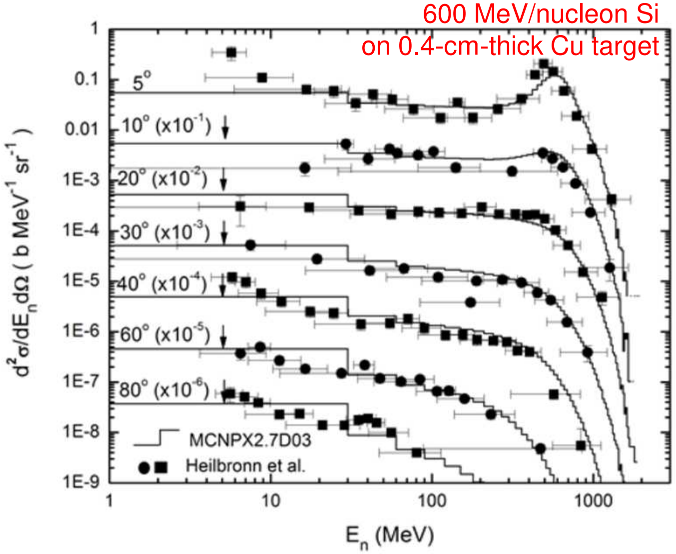
Important for radiation studies

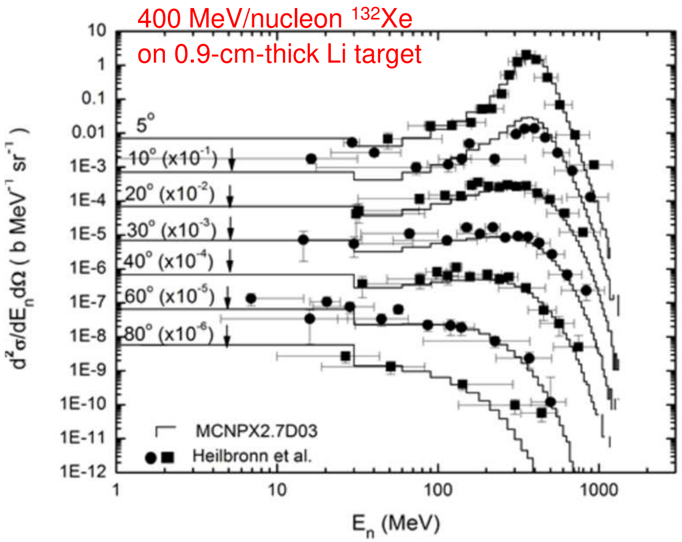
- medical applications
  - radiation therapy
- accelerator construction
  - shielding
- space research
  - biological impact of radiation on humans during long term space missions

Heavy ion induced radiation

- precise fragmentation cross sections needed

*R.M. Ronningen et al.,*
*Benchmarking transport Codes FLUKA, HETC-HEDC MARS15, MCNPX, PHITS (2013)*



# Benchmarking transport models for heavy ion collisions with FRS data

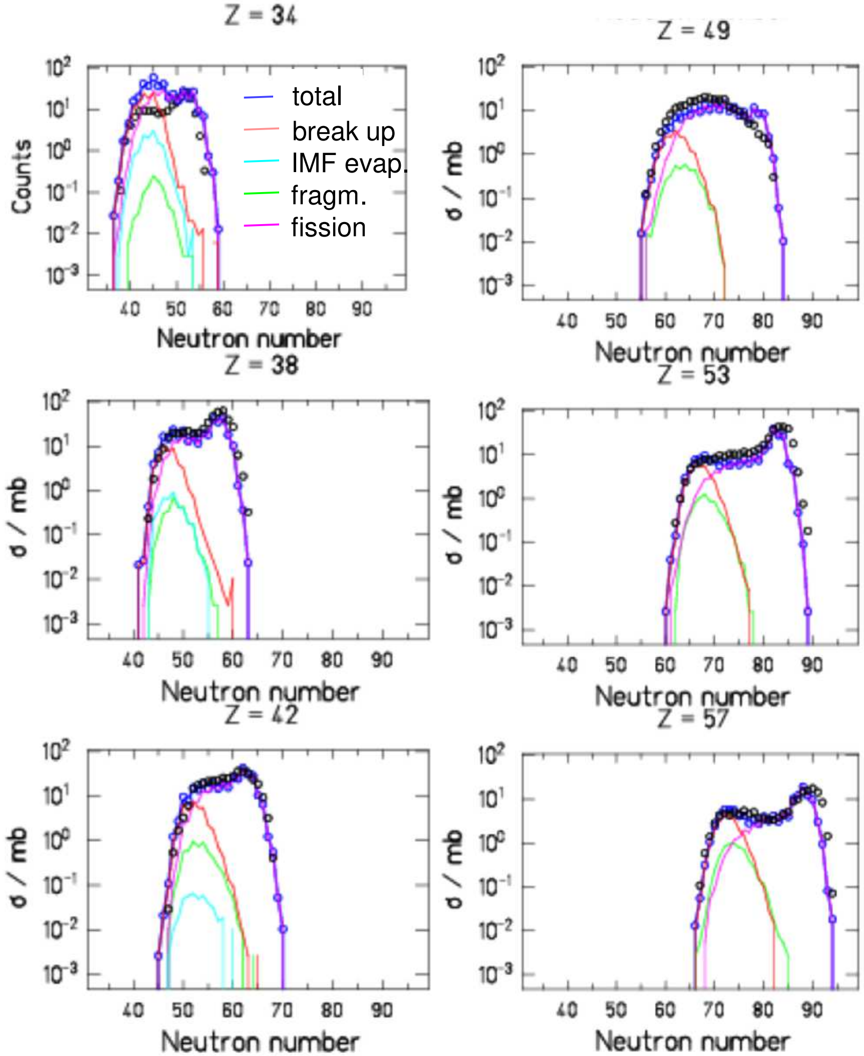
Important

- detector development
  - feasibility of experiments
  - physics performance

Benchmarking of Abrabla*

- two step abrasion/ablation model to simulate heavy ion collisions at relativistic energies
  - fragmentation
  - break up
  - evaporation
  - fission
- SINURSE project
  part of the EU financed Integrating Activity ENSAR/2/ERINS
  - theoretical models
  - simulation tools
  - analysis environments

U+Pb 1000 MeV/u




*J.-J. Gaimard, K.H. Schmidt, Nucl. Phys. A351(1991)709
*http://www.ensarfp7.eu/what-is-ensar/deliverables/jra05-sinurse*

# Benchmarking with FOPI data

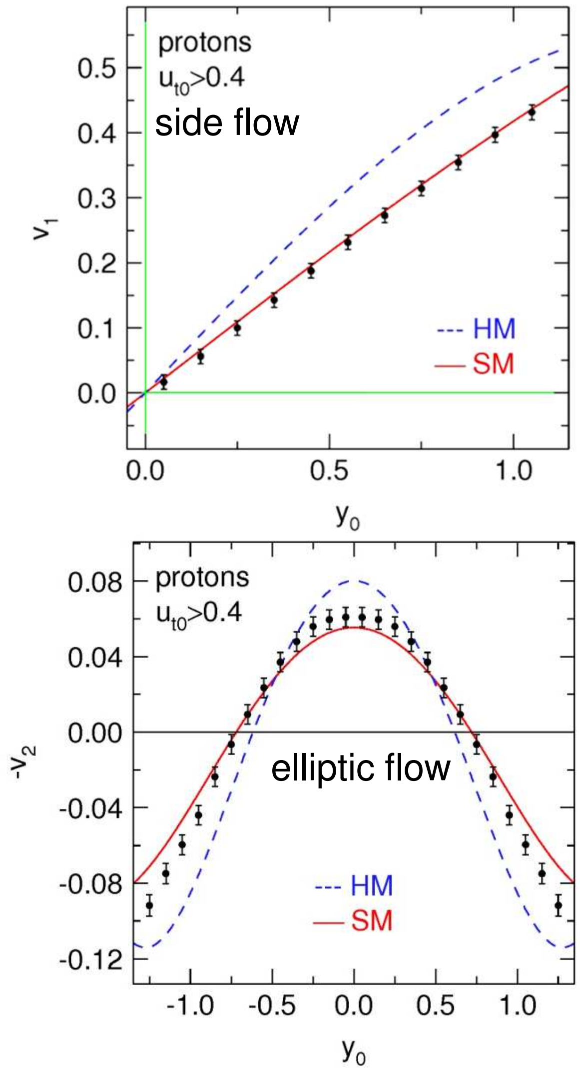
**Benchmark data**
- flow Au+Au collisions 0.9-1.5AGeV
- pion production → inelastic cross sections, momentum dependence
- stopping → elastic cross section

**Calculations done with IQMD* (UrQMD**)**
- parameters determined from elementary experimental data
    - cross sections
    - momentum dependence
- same input parameters for all comparisons

**C. Hartnack et al., EPJA 1 (1998) 151*
*** Q. Li et al.*

**Methods:**
- Clusterization minimum spanning tree
- FOPI filter for centrality
- particle acceptance
- analysis method
- reaction plane determination

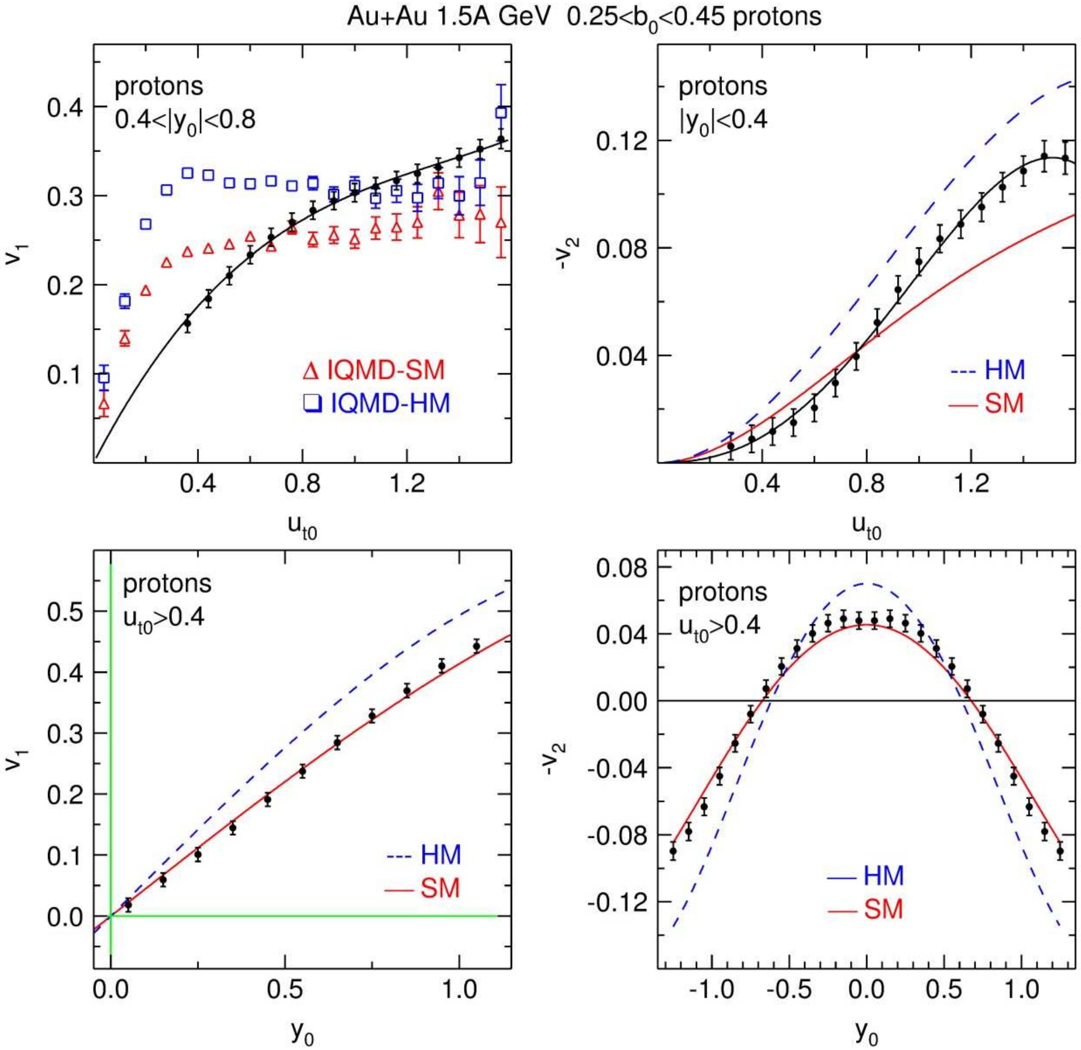
Au+Au 1A GeV 3.5<b<6.3 fm

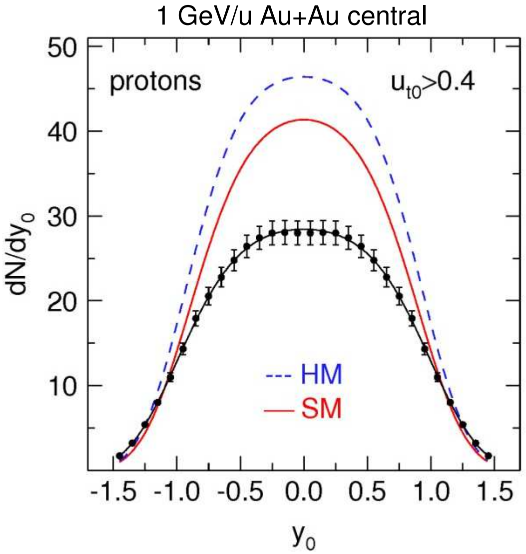



*W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1*

# Flows of protons at higher energies

*W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)*




No perfect agreement, perhaps due to too low cluster yields in the model

talk of Arnaud LeFevre

# Benchmarking

**Benchmark data**

- strangeness production from KaoS, FOPI and HADES
- yields, spectra, flow of kaons and hyperons
- pion production

**Agreement was needed on input parameters**

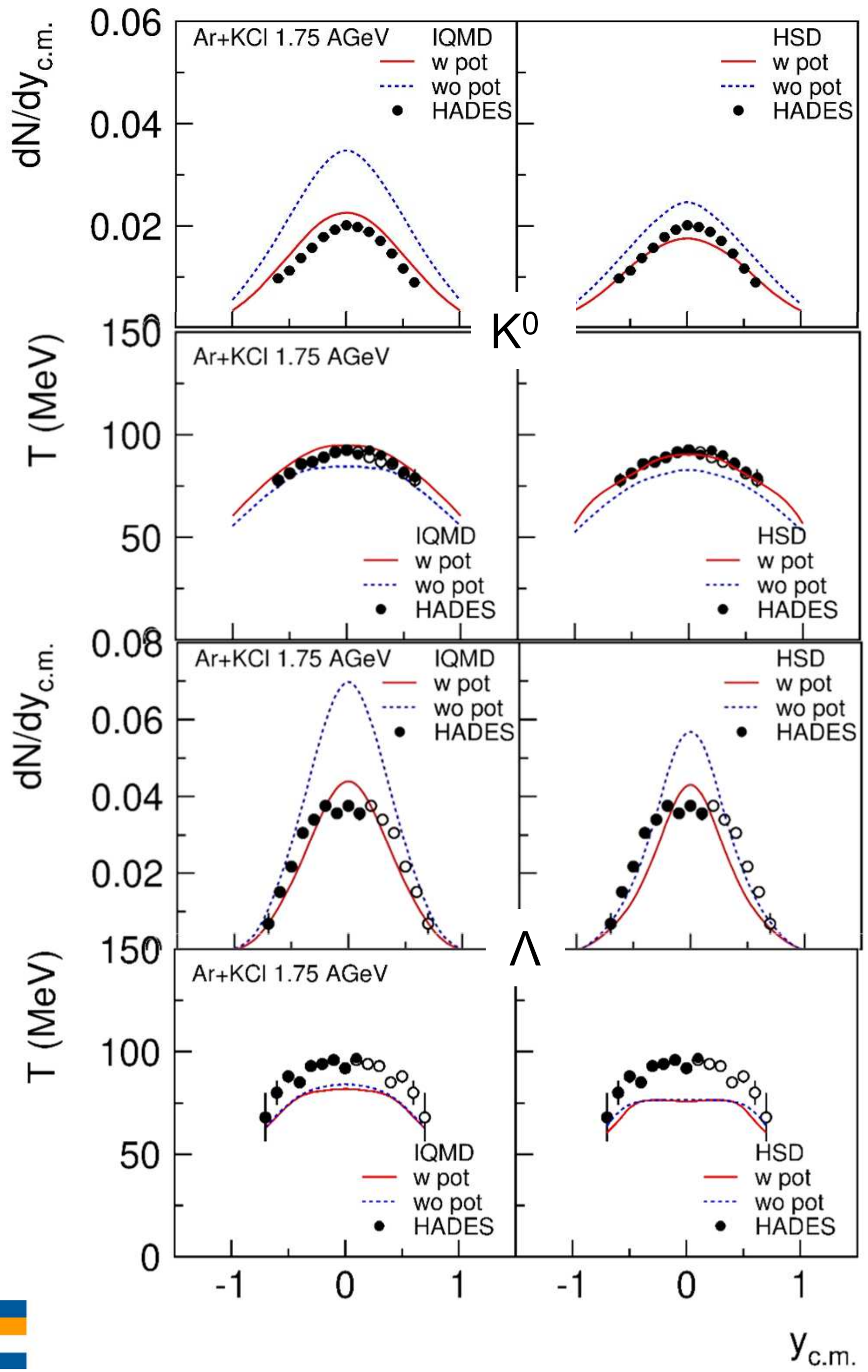
- kaon production cross sections
- propagation

**Codes: HSD and IQMD**

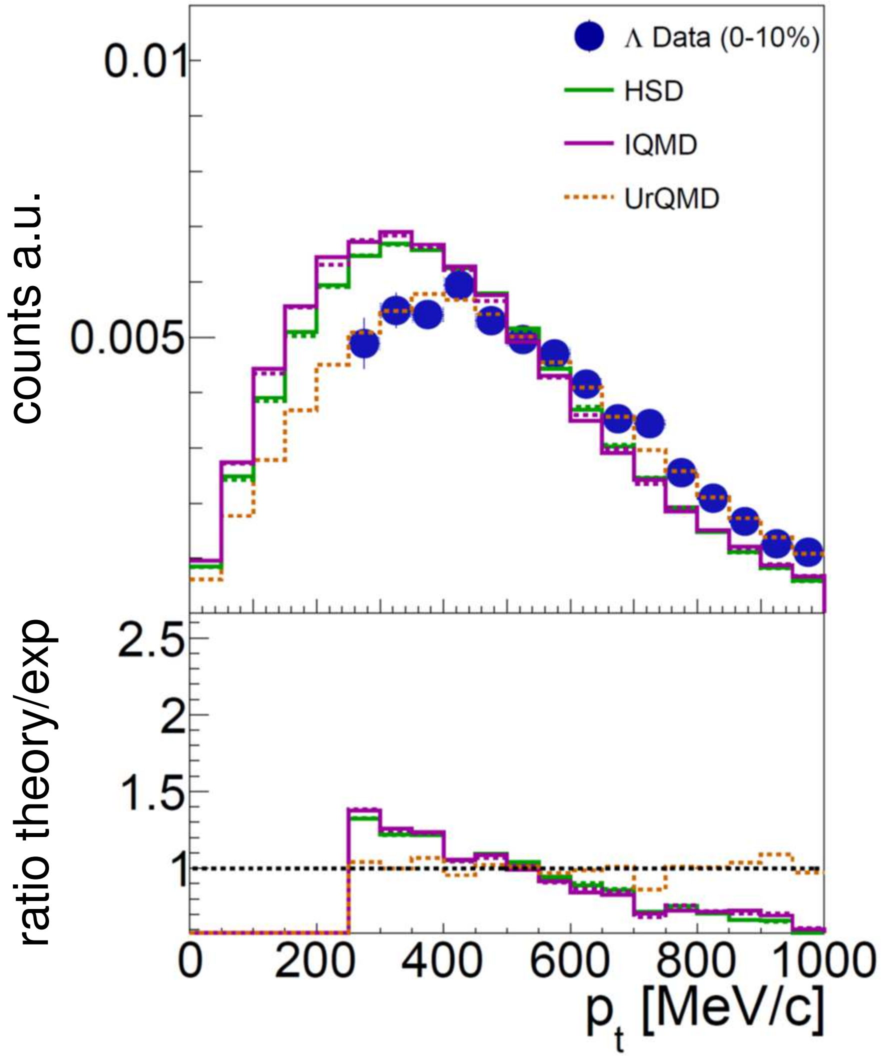
**Problem**

- centrality selection
- experimental acceptance and analysis

*C. Hartnack et al., Phys. Rep. 2012*



# Hyperon production in Au+Au collisions




HADES
Au+Au central
1.23 GeV/u

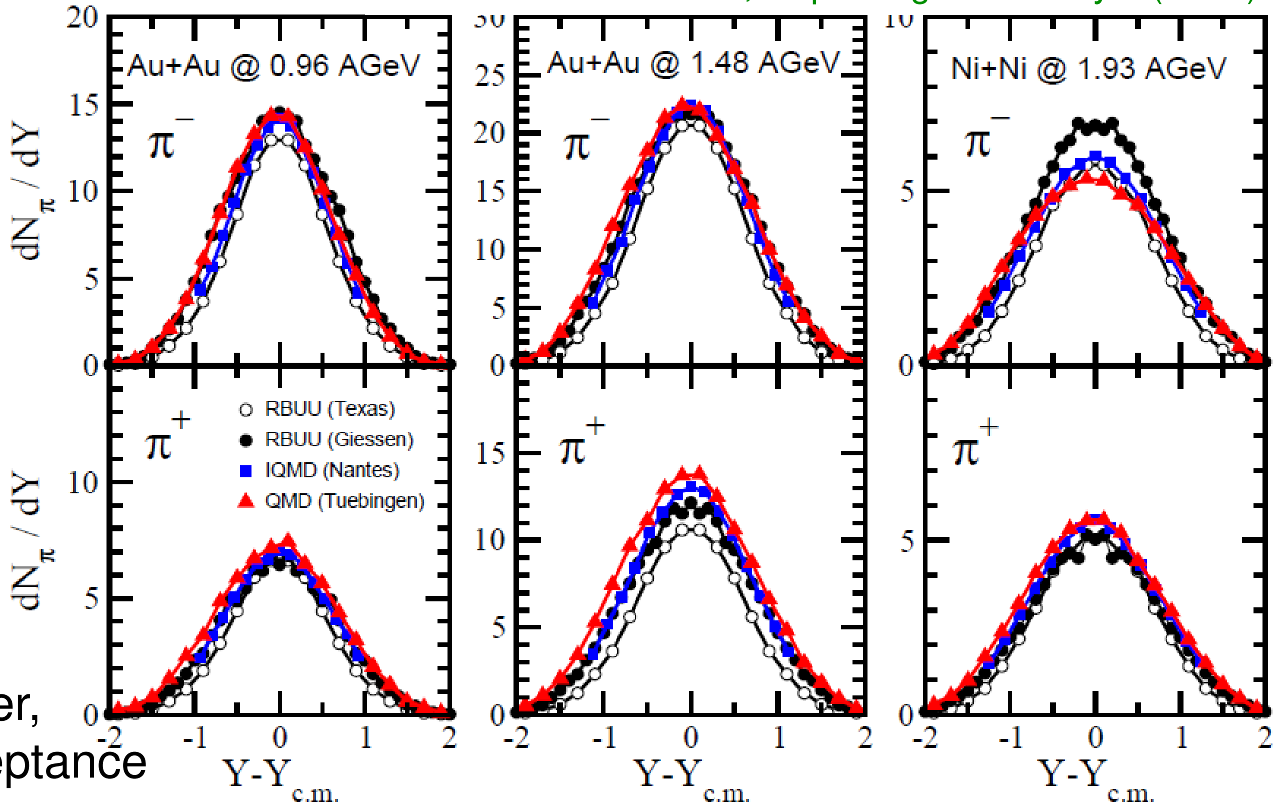
UrQMD describes shape of spectra best

- re-scattering cross section
- production process (via resonances)
- ???

IQMD uses rather old parametrization
ΛN rescattering

# Benchmarking

C. Fuchs, Rep. Prog. Nucl. Phys. (2005)

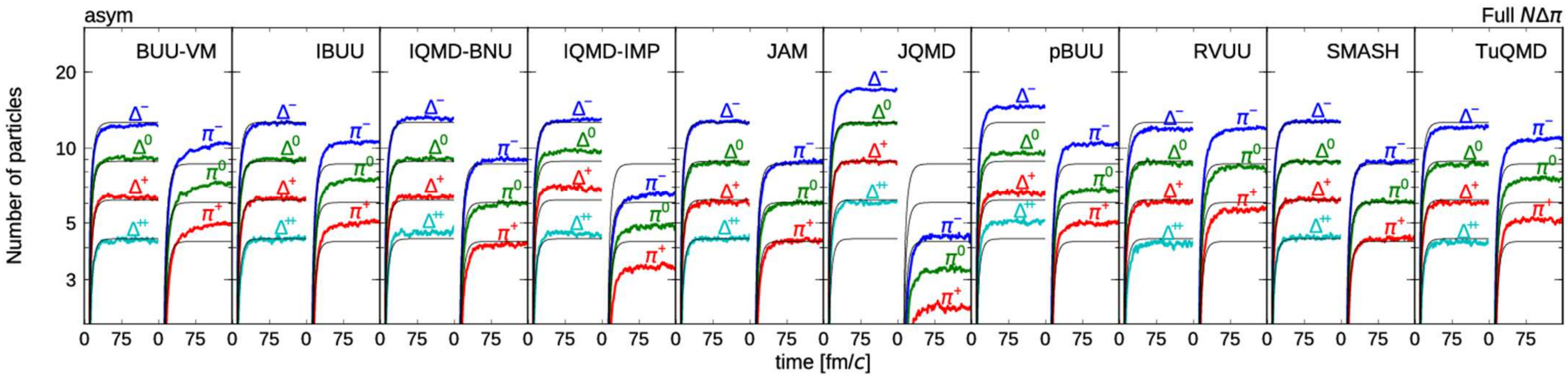



Comparison to
a reference model!

- same impact parameter,
- same cuts, same acceptance
- standard output
- standard analysis routine
- agreement on cross sections, Delta lifetimes, detailed balance (Trento 2001/2003)

*E.E. Kolomeitsev, C. Hartnack, H.W. Barz, M. Bleicher, E. Bratkovskaya, W. Cassing, L.W. Chen, P. Danielewicz, C. Fuchs, T. Gaitanos, C.M. Ko, A. Larionov, M. Reiter, Gy. Wolf, J. Aichelin, J. Phys. G 31 (2005) 741.*

# Benchmarking




Comparison to theoretical reference data

- pion production via NN↔NΔ and Δ↔Nπ processes
- box calculation at normal nuclear matter density and T=60 MeV
- yields and collision rates are compared to numerical (not Monte-Carlo) solution of the relativistic Boltzmann equation

*A.Ono et al., arXiv:1904.02888*

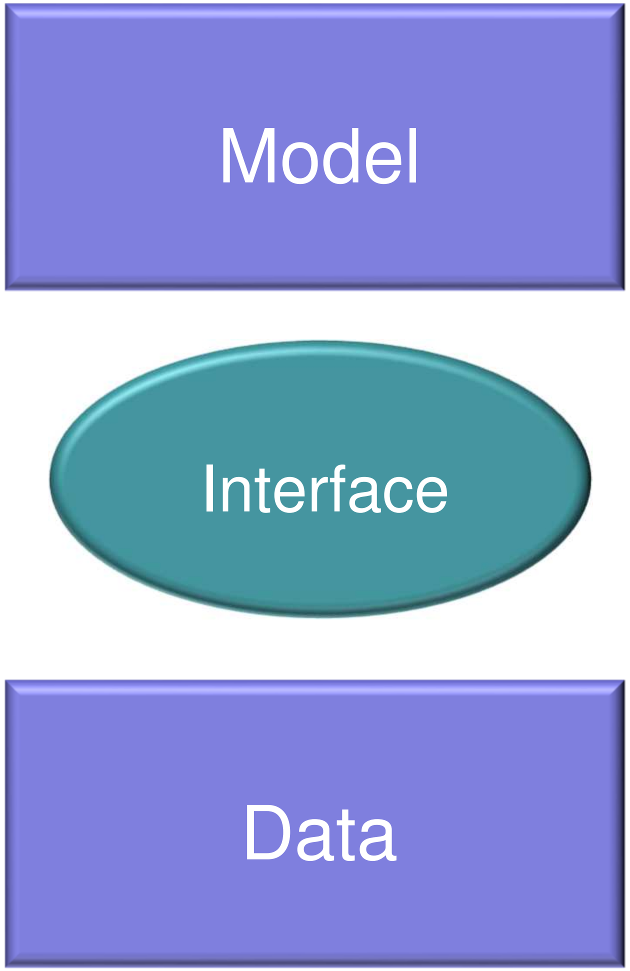
# COMPARING TO EXPERIMENTAL DATA

# Benchmarking

General aspects

- models
  - *open source*
  - *standard outputs*
- experimental data
  - *open access data repositories*
- systematic comparison between model and theory
  - standardized analysis routines

- benchmark results should published in repositories



# Common data base of experimental data


INVENIO Get started Features Examples Documentation Community Roadmap Blog

Follow news and updates on Invenio world

Back

## Invenio RDM: a turn-key open source research data management platform

Lars Holm Nielsen Apr 29, 2019 Invenio

**CERN has partnered with 10 multidisciplinary institutions and companies to build a turn-key open source research data management platform called Invenio RDM, and grow a diverse community to sustain the platform.**

The Invenio RDM project is funded by the CERN Knowledge Transfer Fund, as well as all the participating partners, including:

- Brookhaven National Laboratory (US)
- Caltech Library (US)
- Data Futures (UK)
- Helmholtz Zentrum Dresden-Rossendorf (DE)
- Northwestern University (US)
- OpenAIRE (GR)
- TIND (NO)
- Tubitak (TK)
- University of Hamburg (DE)
- University of Münster (DE)

The project has an ambitious one year schedule in which it will deliver:

- Invenio RDM - A research data management platform based on Zenodo and Invenio v3 Framework.
- A community of public and private institutions to sustain Invenio RDM.
- Minimum two existing repositories migrated to Invenio RDM, with Zenodo being one of them.

The key to successfully achieving the ambitious schedule is that Invenio RDM will be based on Zenodo that have already been successfully validated over the past 5 years.

Our vision in the next five-years, is to make Invenio RDM a world-leading extensible research data management platform used by research institutions all around the world and with businesses providing services, support and customizations on top of Invenio

RDM: Zenodo and Invenio based development by an international collaboration headed by CERN

To be defined within the community
- format
- meta data

Data

# Rivet
## Robust independent validation of experiment and theory

- Rivet home
  - Professor
  - YODA
  - Contur
  - MCplots
  - AGILe
- Downloads
  - New analyses
- Analyses
  - Standard analyses
  - Analysis changelog
  - Writing an analysis
  - Submitting analyses
- Analysis coverage & wishlists
  - General
  - No searches/HI
  - Searches
  - Heavy ion
  - Submitting analyses
- Documentation
  - Getting started
  - Rivet via Docker
  - Manuals & tutorials
  - Troubleshooting / FAQ
  - Changelog
  - Writing an analysis
  - Submitting analyses
  - Code documentation (doxygen)
- Source code
- Contact

### Rivet

The Rivet toolkit (Robust Independent Validation of Experiment and Theory) is a system for validation of Monte Carlo event generators. It provides a large (and ever growing) set of experimental analyses useful for MC generator development, validation, and tuning, as well as a convenient infrastructure for adding your own analyses.

Rivet is the most widespread way by which analysis code from the LHC and other high-energy collider experiments is preserved for comparison to and development of future theory models. It is used by phenomenologists, MC generator developers, and experimentalists on the LHC and other facilities.

**Features**

- Object-oriented C++ framework for analysis algorithms
- Ever-increasing collection of analyses, more than 400 so far...
- Python interface and suite of user-friendly data handling scripts
- Large collection of generator-independent event analysis tools
- Automatic caching of expensive calculations, for efficiently running many analyses on each event
- Flexible system for fast detector effect simulation in BSM analyses
- Close matching of standard observables to experimental analysis definitions
- Reference data connection to HepData, avoid hard-coding

The Rivet user manual is kept up to date on the arXiv (1003.0694 [hep-ph]).

The C++ MC generators Herwig and Sherpa have convenient user interfaces for producing input events for Rivet analysis, as well as built-in Rivet support. Users may find the Sacrifice interface convenient for running Pythia 8, and the AGILe steering interface useful for older Fortran generators like PYTHIA6 and HERWIG6.

**2019-05-09: Rivet release 2.7.1**

We are very pleased to release Rivet 2.7.1, an increment of the 2.7 release series which adds a large number of machinery and analysis bugfixes and improvements, including better Python 3 compatibility, and more contributed analyses.

The 2.7.x series itself introduced several major new features. Many of these should be considered to be experimental, in that they may not work perfectly and may therefore be modified in coming minor releases. Many of the new features are related to heavy ion analyses and will not affect any other analyses in previous release. But some changes will be noticeable to non-heavy-ion users.

The most visible change is that the size of the produced yoda files has doubled. This is done in order to enable having reentrant finalize. The produced yoda files will thus include the same analysis objects as previous versions, but will be supplemented by the same objects in the state they were before finalize() was called. These objects will

**WANTED: Analysis code**

We need your analyses! Preserving analysis logic in a re-runnable, re-interpretable form is a key part of scientific reproducibility and impact at the LHC and other HEP experiments. If you are member of an experimental collaboration, please have a look at our wishlist and help us by providing us with Rivet analyses for your publications. This will also ensure that your measurements get used (and cited)!

**MCnet studentships!**

Would you like to work on a short project involving Monte Carlo event generators?

MCnet offers 3-6 month fully funded studentships for current PhD students.

See montecarlonet.org for more information!

**Docker container for Rivet**

A fully working and relaively lightweight Rivet container is available with all dependencies necessary for plotting. We suggest this to be used in tutorials and for people eager to try out Rivet. A short documentation showing how to use Rivet in three simple steps is given at our **Docker instructions**

docker

**docker pull hepstore/rivet**

# Benchmark data

Define a set of observables yields

- stopping
- flow ....
- particle production

and a set of systems, energies and impact parameters

- Au+Au, Sn+Sn, C+C, p+A
- 1 MeV/u ... 5.5 TeV/u
- central, half central….

What is the most important bench mark data?

Data

# Summary

**Systematik benchmarking* of theoretical models with experimental data is a pre-requisit to draw reliable conclusions on equation of state of nuclear matter, in-medium effects….**

**Process steps:**

- Identify experimental benchmark data
- Ensure its availability in a data repository
- Decide on infrastructure and methods
- Program/collect analysis codes
- Do the calculations and analysis of data
- Routinely publish the results in a repository

# FAIR in 2025


THANK YOU TO MY COLLABORATOS
A. LeFevre, C. Hartnack, E. Bratkovskaya, J. Aichelin
THANK YOU FOR YOUR ATTENTION


FAIR