Hadronic Probes of Highly Excited QCD Matter

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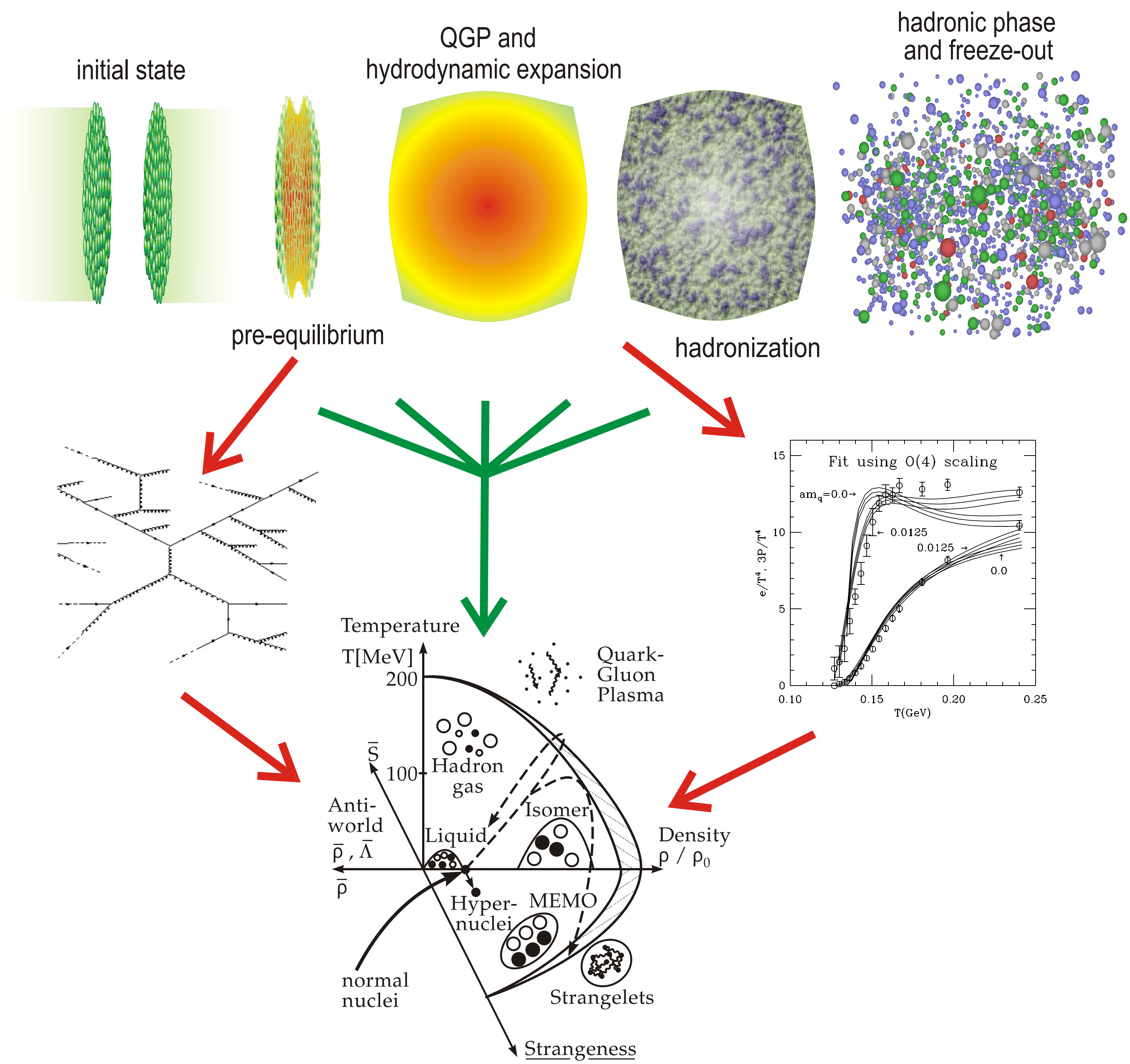
- Beyond the smoking gun: probing the QGP equation of state
- Overview of hadronic probes
- Critical discussion: ambiguities and model dependencies

Probing the QGP equation of state

Finding evidence for deconfinement (e.g. a QGP) is only the **first step** in exporing a **novel domain of elementary matter**!



Overview of hadronic probes

system characteristics	observable
deconfinement indicators	strangeness enhancement,
	charge fluctuations
energy density, initial conditions	stopping: dN/dy, $dN/d\eta$
temperature, chem. potential	energy-spectra, particle ratios
pressure, compressibility	collective flow
hadron source space-time volume	HBT source-radii
early vs. late hadronization	balance functions
ashes of the plasma	strangelets

Strangeness enhancement

Theoretical concepts:

- in pp collisions s and $\bar{s}$ production is suppressed compared to $u, d, \bar{u}, \bar{d}$ due to higher mass
- in a QGP q-densities of all q-species are similar

⇒ strangeness enhancement (J. Rafelski, B. Müller)

Assumptions:

- zero baryochemical potential, $T > m_s$
- thermal equilibrium

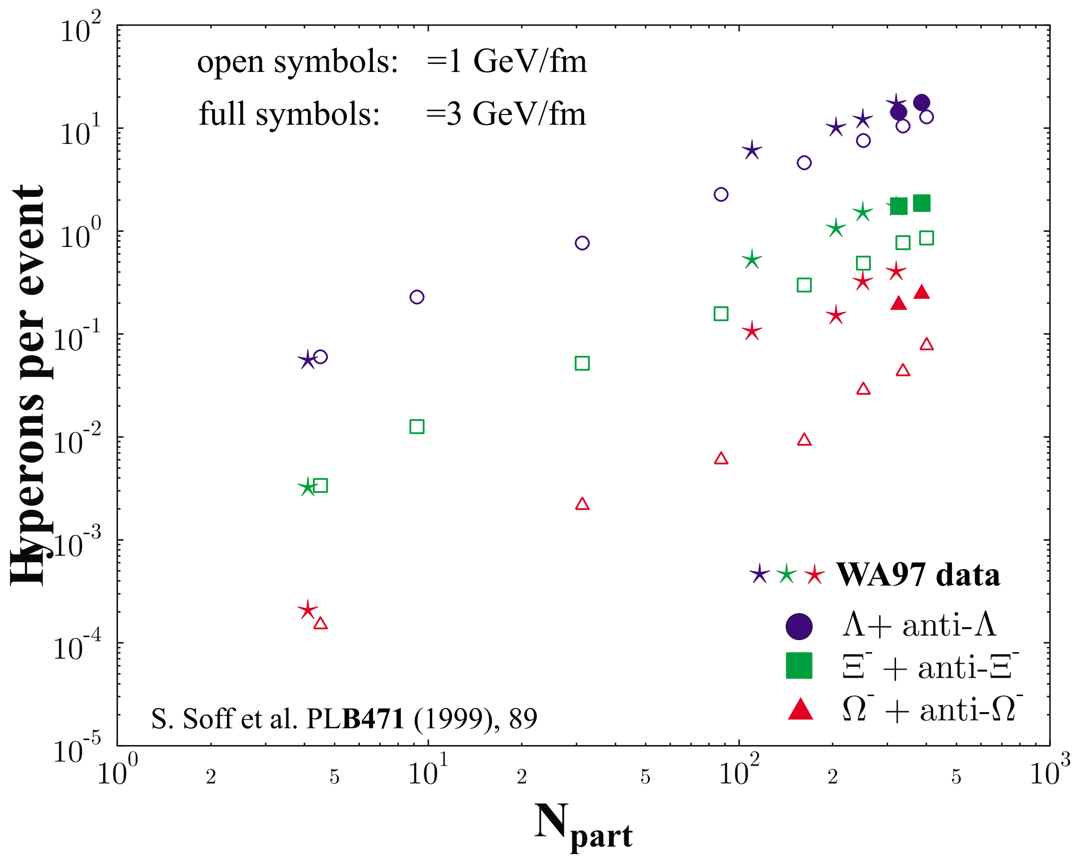
Caveats:

- hadron ratios after hadronization are similar to those of a hadrochemical equilibrium model (s-dilution due to larger volume of a hadrongas)
- equilibrium assumption invalid in RHIC's
- strangeness enhancement on hadronic level via multistep processes

UrQMD Frankfurt Nantes NSCL

Strangeness-Enhancement: Signature of Deconfinement?

p,Pb (158 A GeV) Pb



in string-models, strangeness production is suppressed by:

$$\gamma_s = \frac{P(s\bar{s})}{P(q\bar{q})} = \exp\left(-\frac{\pi(m_s^2 - m_q^2)}{2\kappa}\right) \qquad \kappa: \text{ string-tension}$$

- @ high density: increase κ from 1 GeV/fm to 3 GeV/fm

$\rightarrow$ γ_s increases from 0.3 to 0.65

$\rightarrow$ transition from constituent to current quark masses

$\Rightarrow$ phase of nearly massless particles: chiral transition?

Strangeness Enhancement at the SPS: QGP in Chemical Equilibrium?

- in a QGP the rates for producing $s\bar{s}$ quarks are much higher than in a hadron gas at the same temperature

→ strangeness enhancement as QGP signature (Rafelski & Müller 1982)

SPS data:
- shows strong strangeness enhancement
- can be fitted with a statistical model

→ sudden freeze-out of chemically equilibrated QGP?

(Rafelski & Letessier 1995; Braun-Munzinger & Stachel 1996)

However:

PCM & Hydro: lifetime of plasma too short for chemical equilibration!

(Matsui, Svetitsky & McLerran 1986; Geiger & Kapusta 1993)

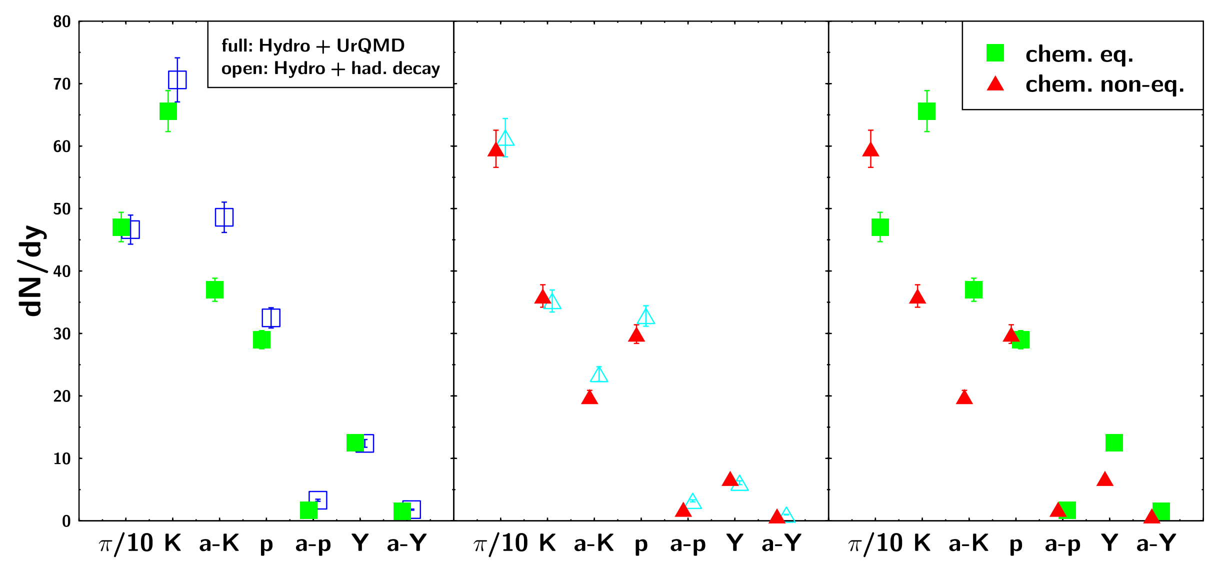
→ can the hadronic phase push strangeness towards equilibrium?

Strangeness equilibration in hadronic phase?

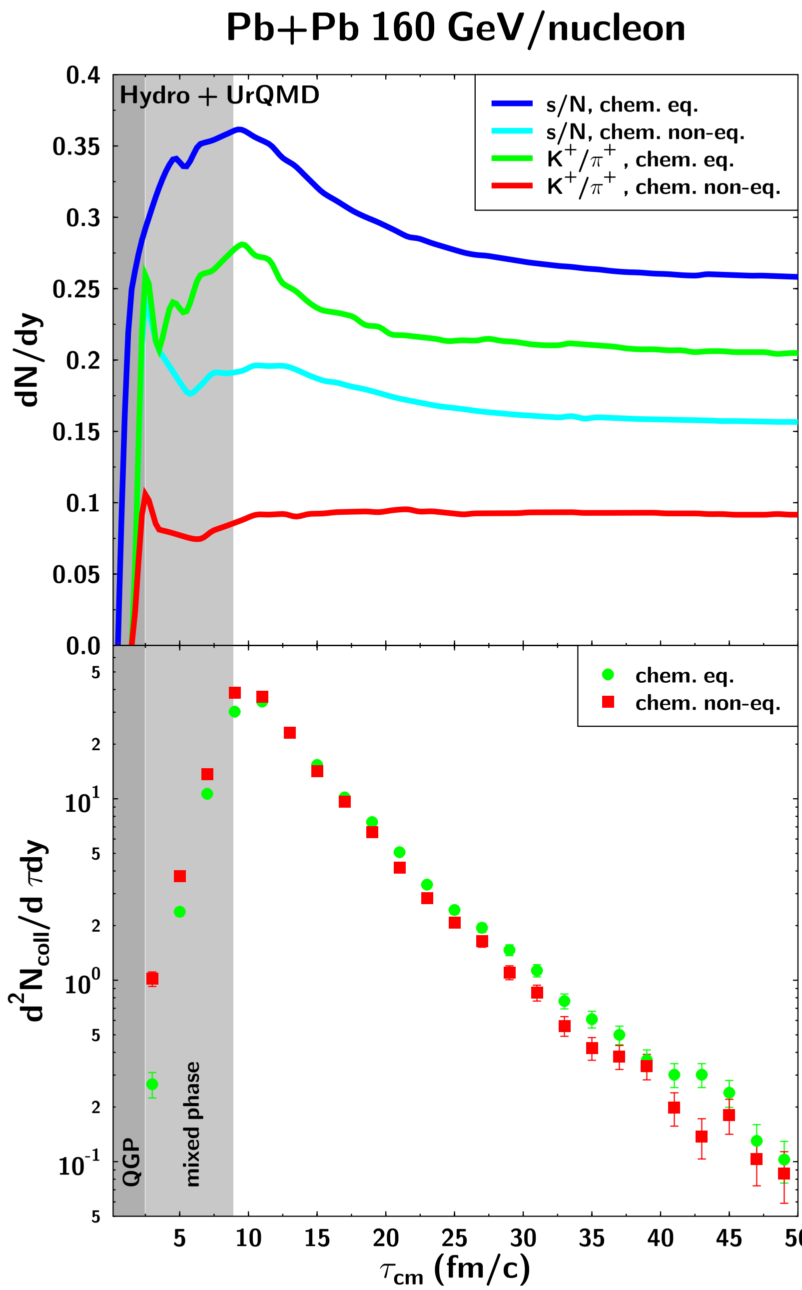
- Hydro+UrQMD: QGP dynamics with subsequent hadronic phase
- UrQMD models ideal hadron gas in infinite volume/time limit

→ study hadronic reaction dynamics & hadro-chemistry starting with chem. equilibrated vs. non-equilibrated QGP

- chemically non-equilibrated QGP is modeled via the introduction of a strangeness suppression factor at hadronization (keep E_T const.)



Strangeness evolution in had. phase

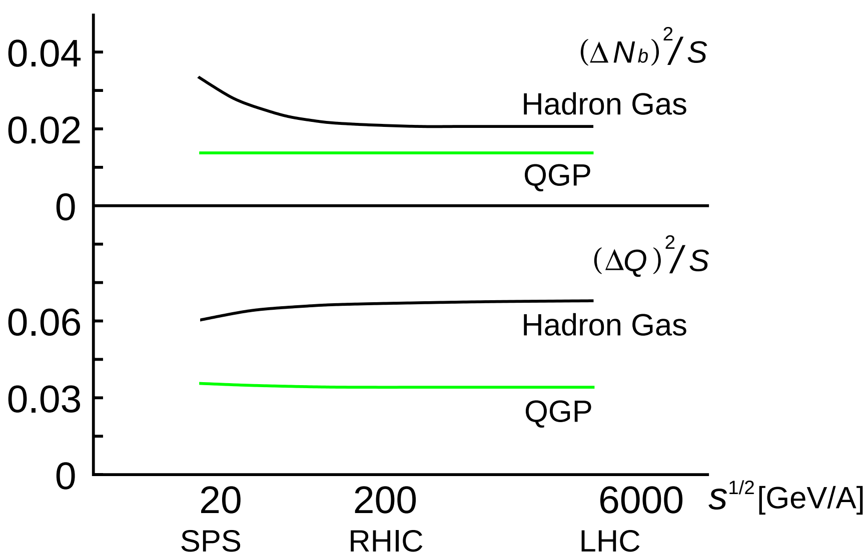


- collision rates nearly identical in both cases
- different time-evolution of s/N and K/π

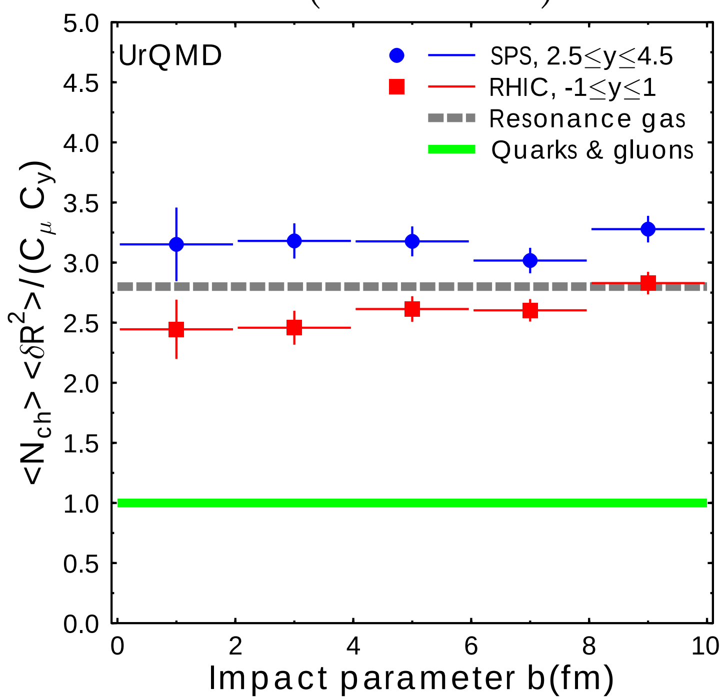
$\rightarrow$ hadronic phase cannot compensate strangeness non-equilibration!

Charge fluctuations as QGP signature

Asakawa, Heinz & Müller:



Jeon & Koch (& Bleicher):



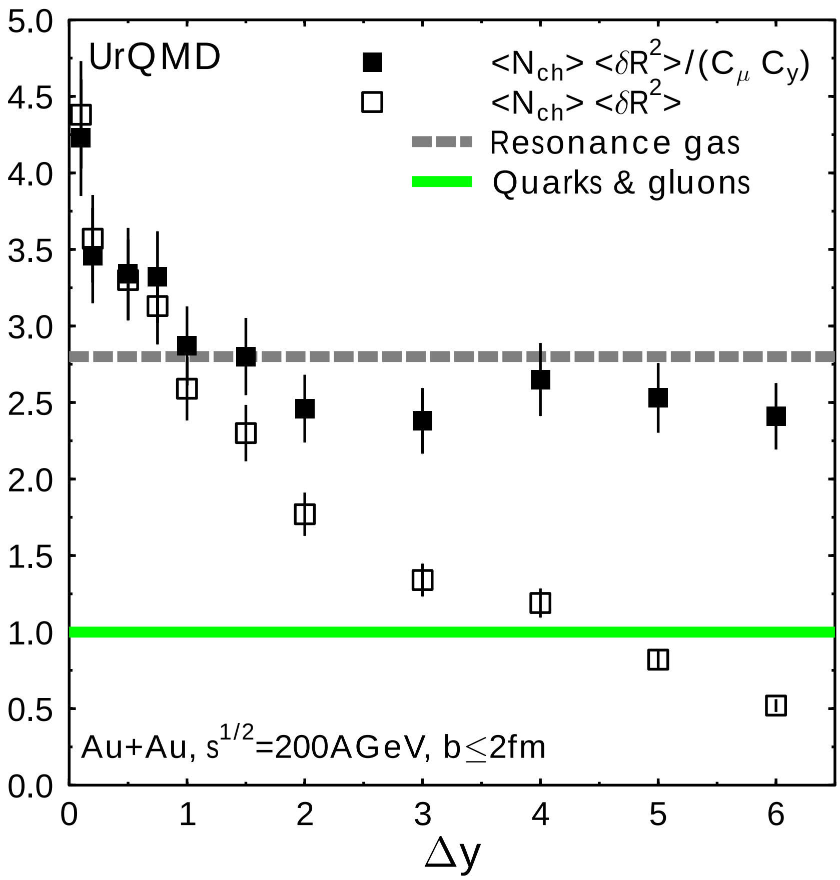
- fluctuations of *conserved* quantities differ between QGP and HG

→ rapid expansion of the system (and *kinetic slowdown*) may allow for survival of QGP fluctuations

Charge fluctuations: critical discussion

survival and observability of QGP fluctuations depend on

- specific QGP scenario: ideal parton gas
- hadronization dynamics and time-scale
- relaxation time vs. life-time of hadronic phase
- finite acceptance and finite net charge effects



Stopping: probing initial conditions

Theoretical concept:

- longitudinal momentum is converted into transverse momentum and produced particles

⇒ zone of high energy density is created

- best studied via dN/dy and dN/dη distributions
  - dN/dy very sensitive to:
    1) baryon-number transport
    2) collective effects (minijets, parton rescattering)
    3) shadowing (PDFs)

  → powerful tool for verifying/falsifying models

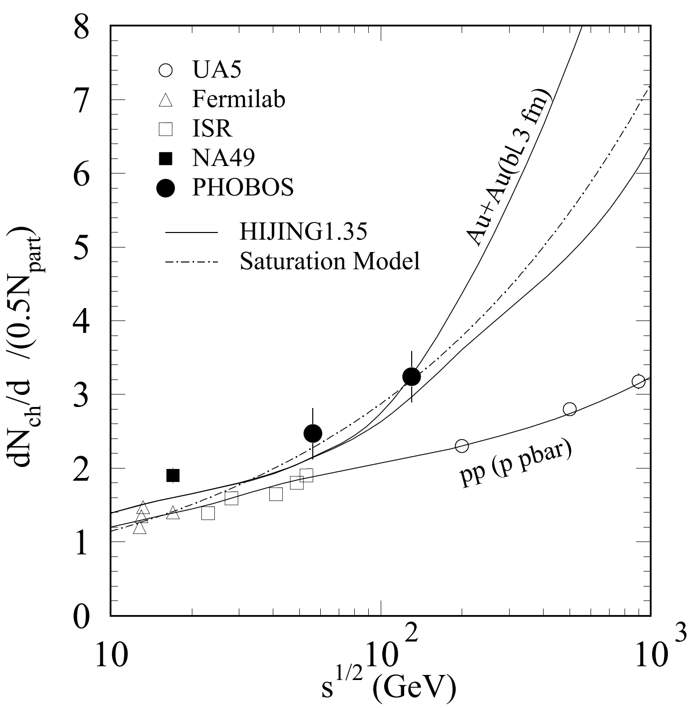
  - estimate energy density via:

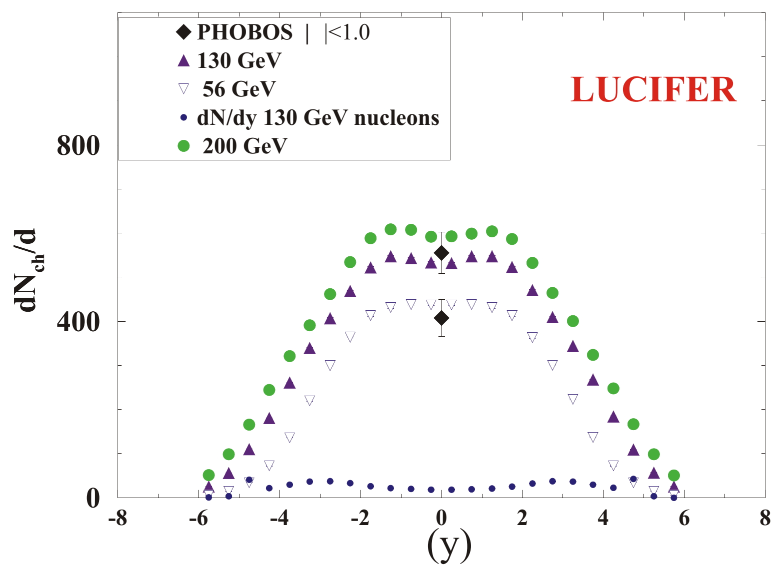
$$\varepsilon = \frac{m_t}{\tau_0 \cdot A} \left. \frac{\mathrm{d}N}{\mathrm{d}y} \right|_{y=y_{c.m.}}$$

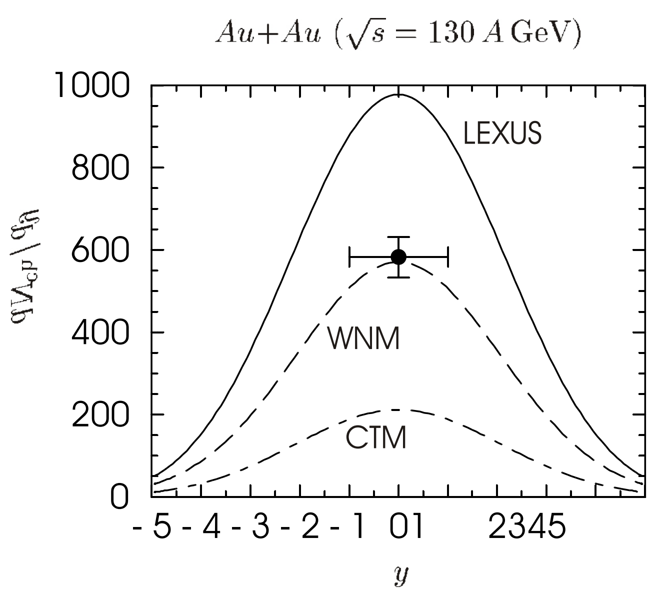
caution: only valid as rule of thumb!

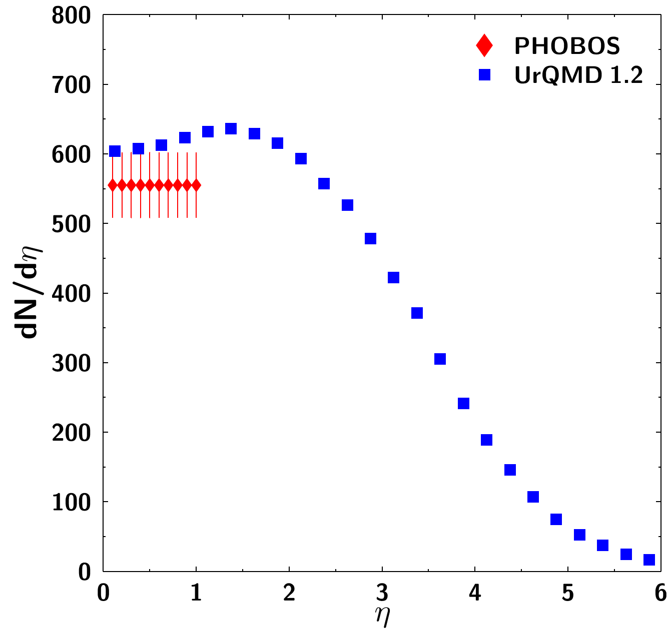
– strong dependence on τ_0 which is uncertain by at least a factor of 2!

PHOBOS data: model comparisons









a number of very diverse models all reproduce PHOBOS

→ need many different observables to constrain physics!

dN/dη: parameter dependencies

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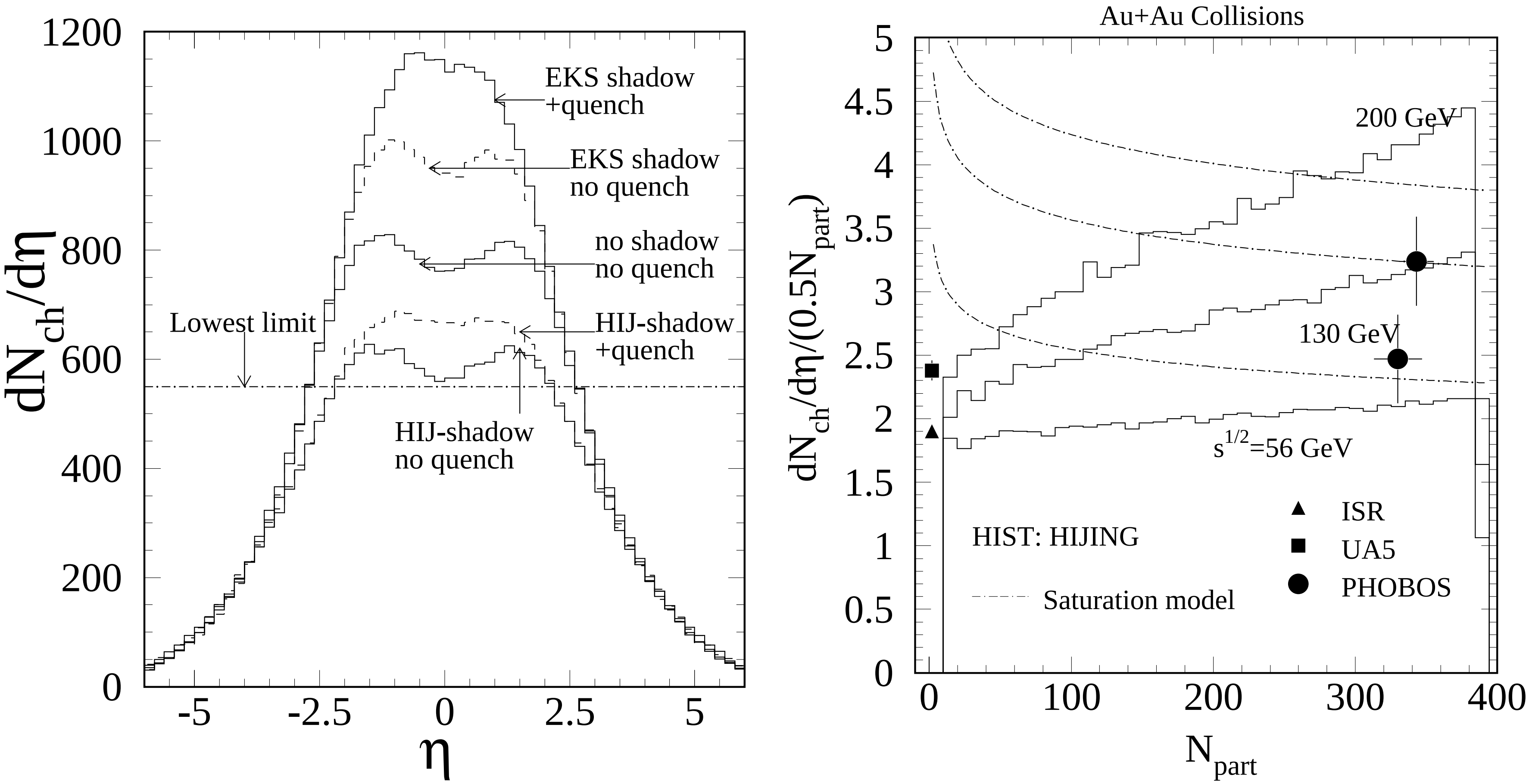


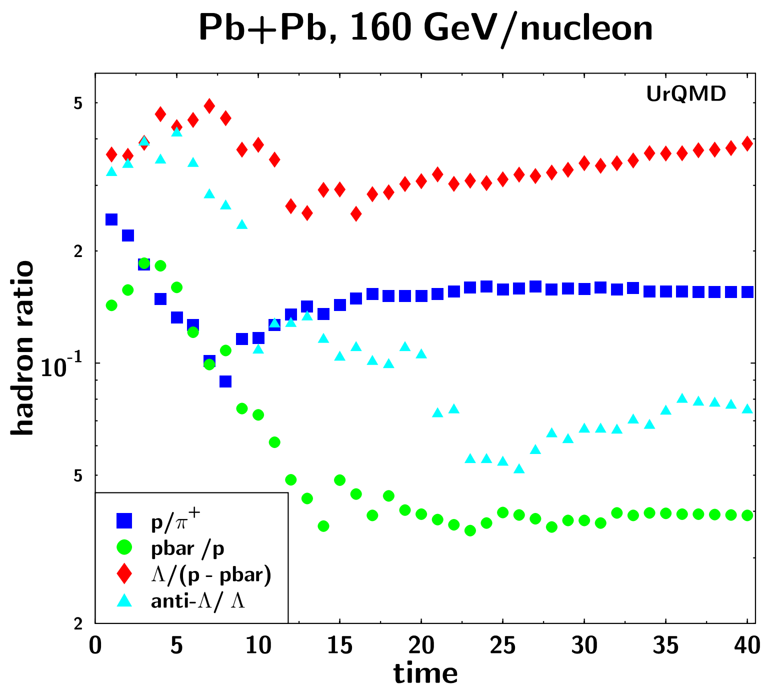
+ strong sensitivity to physics input (e.g. shadowing, jet-quenching)

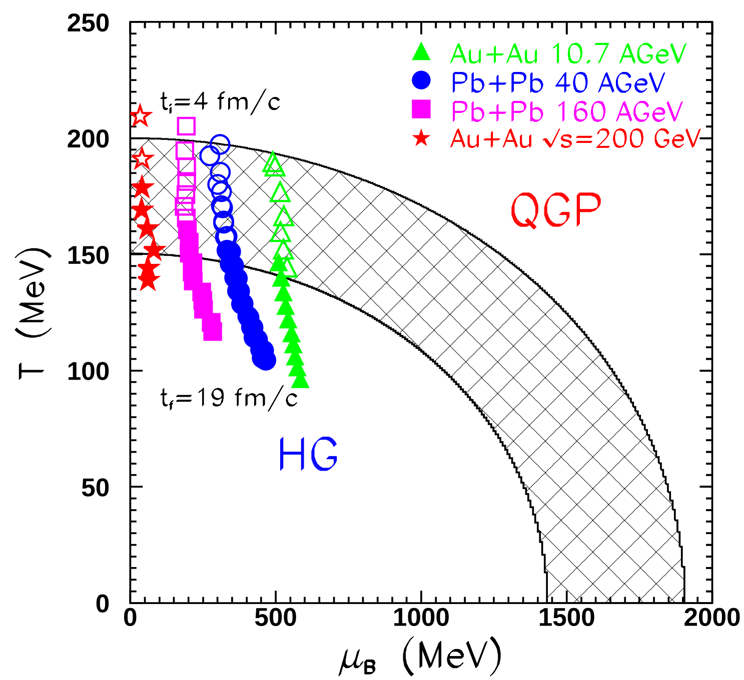
– parameter dependencies introduce ambiguities in interpretation

→ use multi-dimensional parameter dependencies to constrain findings

Hadron ratios: Time-Evolution

→ do ratios really reflect the *thermodynamic properties* of the system?





- ratios change rapidly with time: → no static pressure-cooker
- restrict analysis to central cell:

→ continuous evolution through series of *steady states*

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Collective flow I

Theoretical concept:

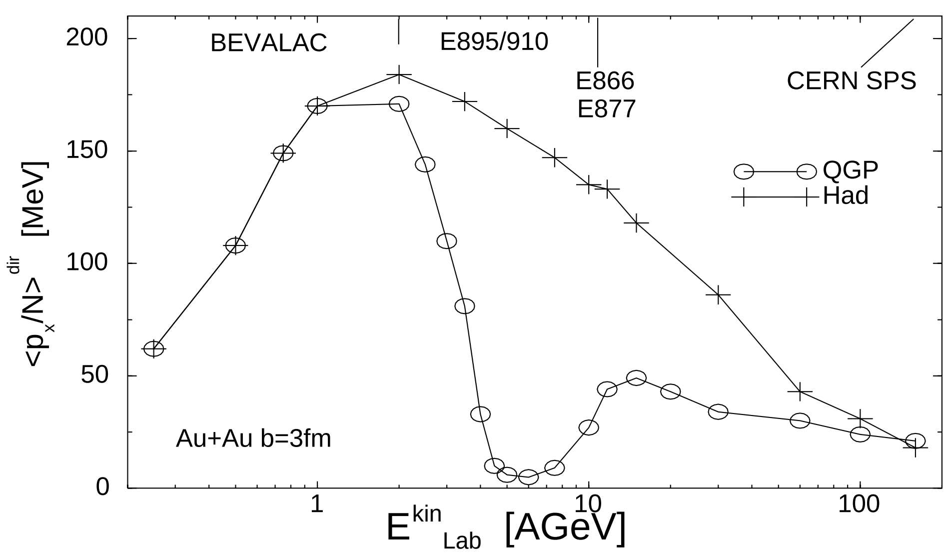
- Transverse directed flow is directly linked to the pressure $P(\rho, S)$ in the reaction zone:

$$\vec{p}_x = \int_t \int_A P(\rho, S)\, \mathrm{d}A\, \mathrm{d}t$$

- NFD and microscopic models predict collective flow
- softening of the EoS: reduction of c_s in the phase transition region

→ reduction of $\vec{p}_x$

⇒ flow excitation function could yield direct evidence for deconfinement phase transition



Collective flow II

Three different forms of collective flow exist:

1. **directed flow (v_1,$p_{x,dir}$):**
   - deflection of spectators from dense reaction zone
   - magnitude of deflection sensitive to $\int P(\rho, S)$
2. **elliptic flow (v_2):**
   - studied at midrapidity via $v_2 = \langle \cos 2\phi \rangle$

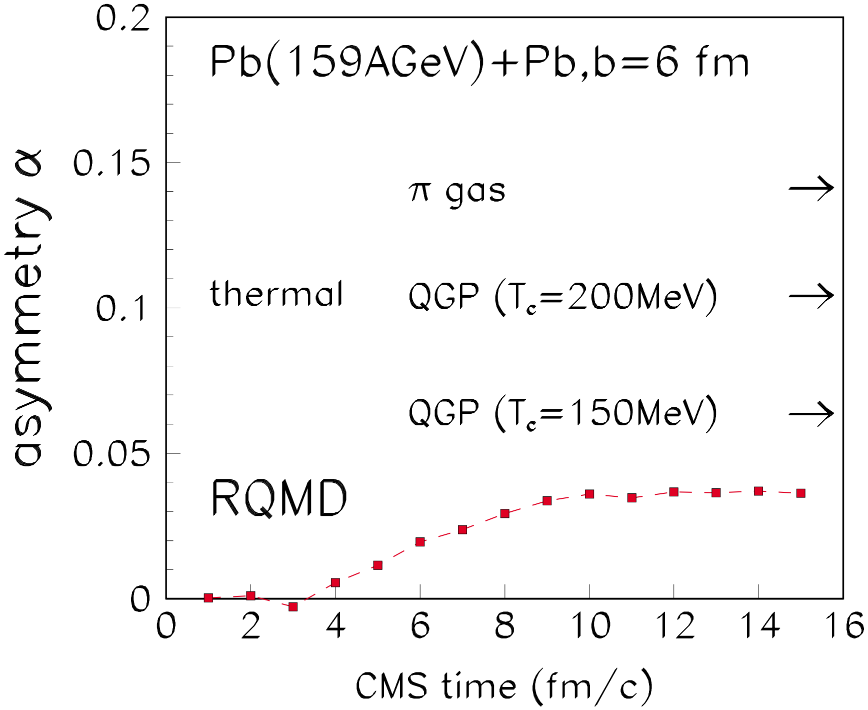
   → asymmetry of emission out-plane vs. in-plane
   - high sensitivity to EoS predicted

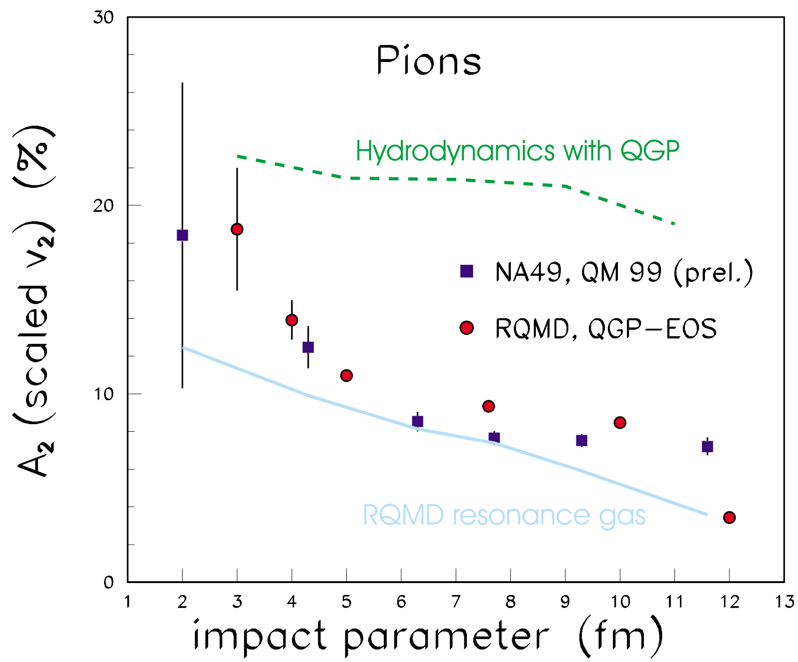
   → emission of highly compressed matter mostly during early reaction stage
3. **radial flow (β_t):**
   - isotropic expansion of participant zone
   - measurable via slope parameter of spectra:

$$T^* = T\sqrt{\frac{1 + \langle \beta_t \rangle}{1 - \langle \beta_t \rangle}} \quad \text{(blue-shifted temperature)}$$

   → early decoupling of multistrange baryons may yield QGP expansion velocity at hadronization

Elliptic flow as QGP probe





- momentum space asymmetry α develops during early reaction stage

→ strong sensitivity to QGP vs. HG scenario

→ configuration space asymmetry A_2 shows characteristic impact parameter dependence for QGP EoS

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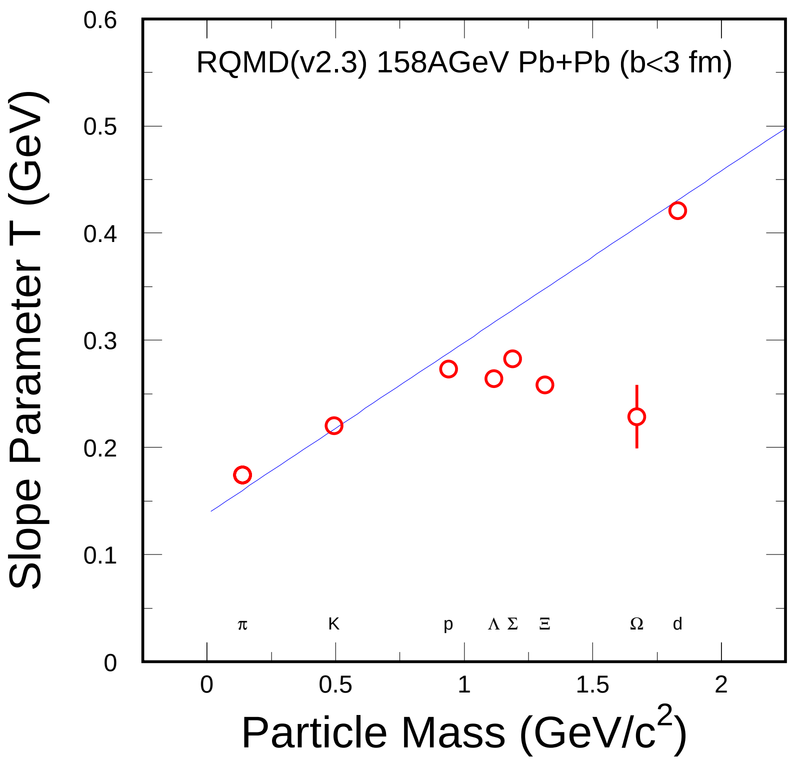
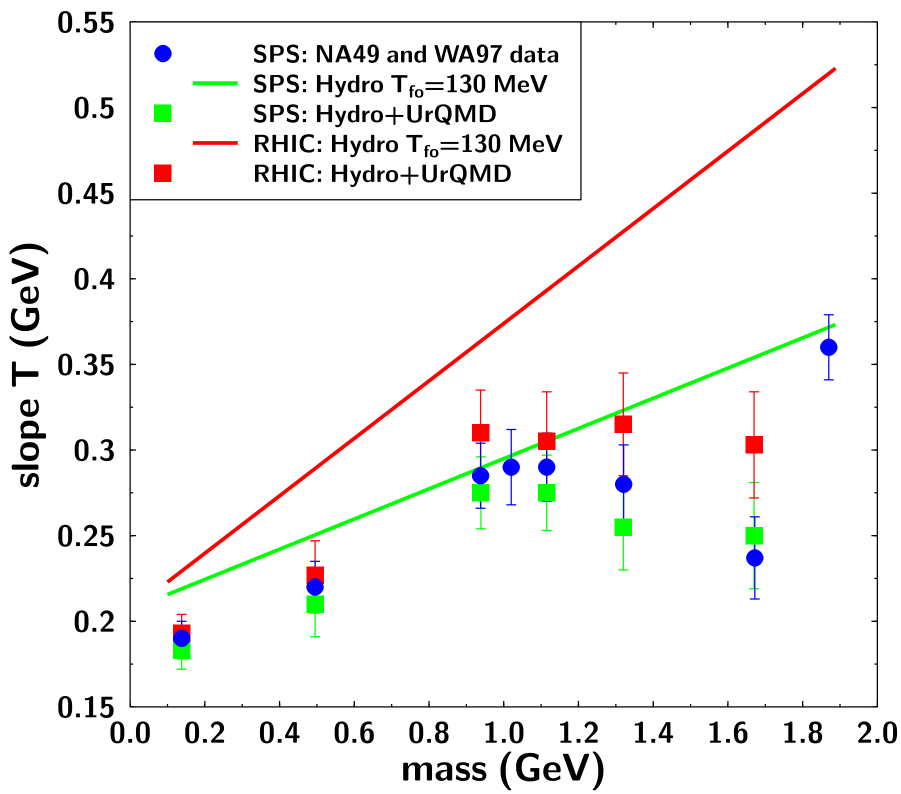
Spectra of Multi-Strange Baryons: Model Predictions





- hydrodynamics predicts linear increase of slope vs. hadron-mass
- models with and without QGP-formation predict fall in slopes for Ξ, Ω

$\rightarrow$ key feature: flavor-dependence of cross-sections (reduced for Ξ, Ω)

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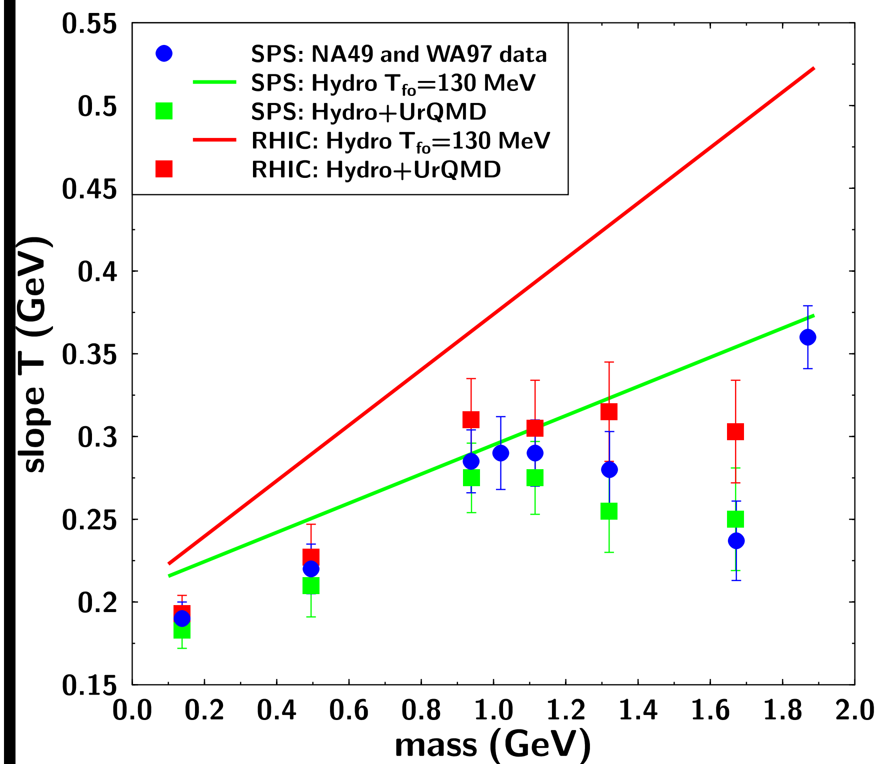
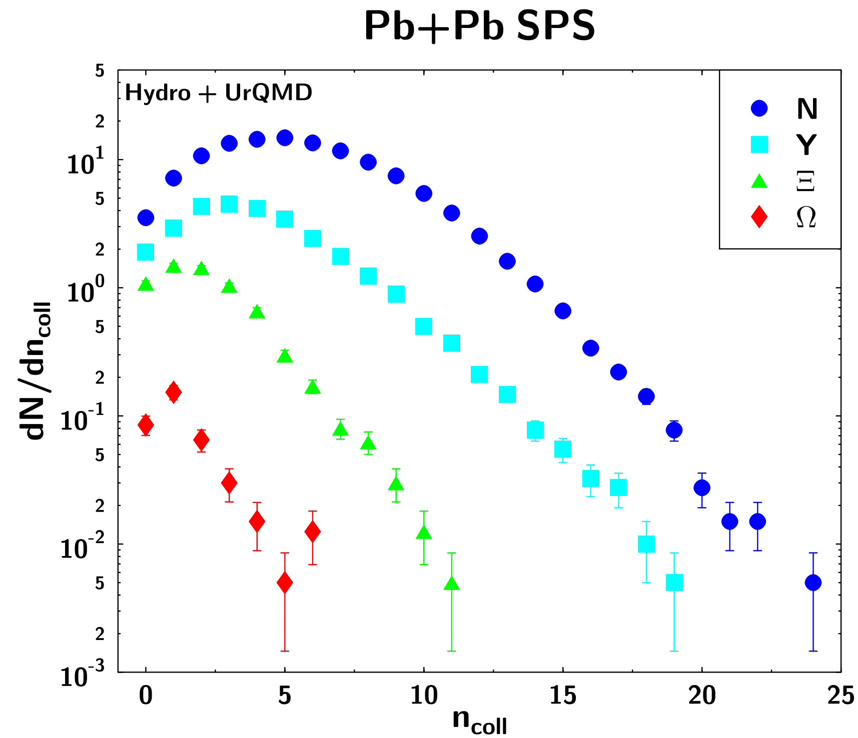
Mass-dependence of m_T-slope parameters





- Hydro: linear mass-dependence of slope parameter, strong radial flow
- Hydro+Micro: softening of slopes for multistrange baryons

$\rightarrow$ early decoupling due to low collision rates

$\Rightarrow$ nearly direct emission from the phase boundary

- RHIC: FO occurs closer to hadronization hypersurface than at SPS

Space-time picture of the reaction: HBT correlations

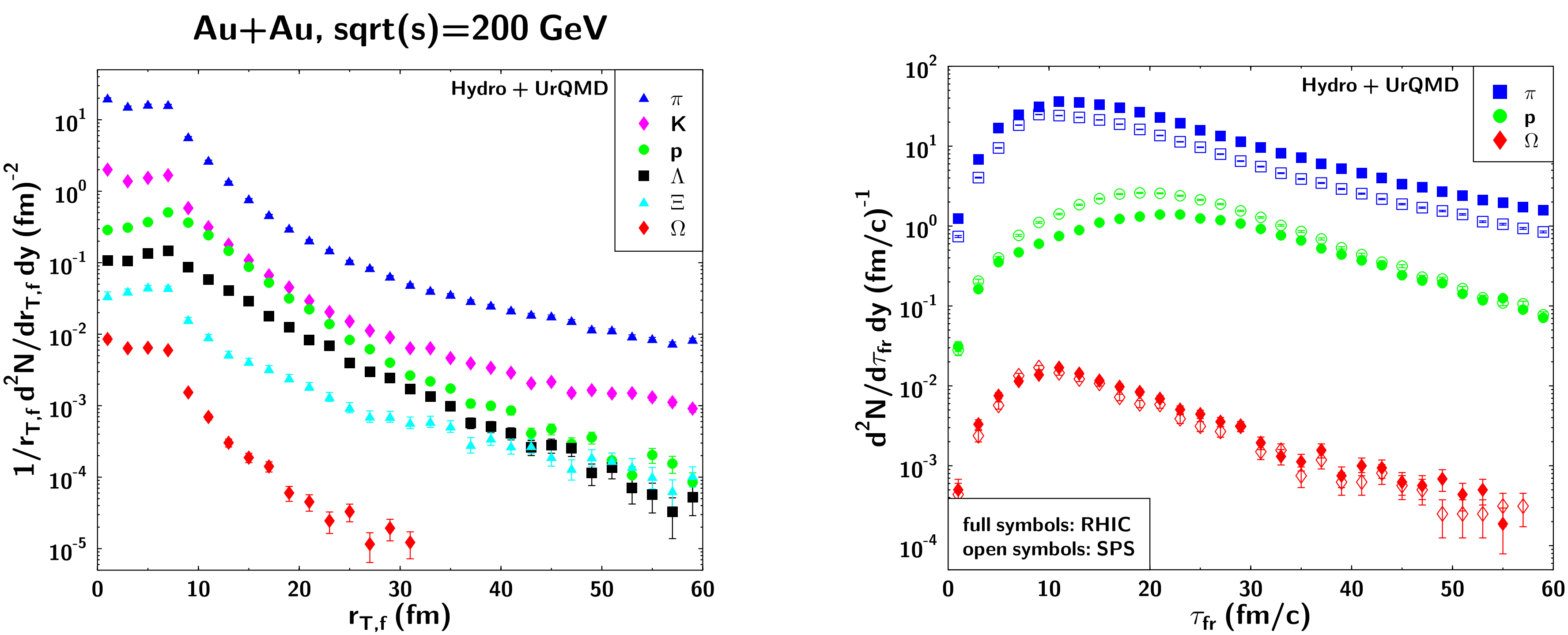
Goal: determine volume and lifetime of system

→ two-particle correlation functions (identical particles) can be utilized to determine longitudinal and transverse radii, lifetime and flow-pattern of the particle source at freeze-out

- first introduced by Hanbury-Brown and Twiss for photons to measure angular diameter of a star
- prolonged lifetime of system (→ softening of the EoS) in mixed phase may be observed via enhancement of the ratio R_{out}/R_{side}:
  - R_{out} : lifetime of source
  - R_{side} : transverse size of source

  ⇒ for a phase-transition a ratio of $R_{out}/R_{side} \approx 2$ is expected

Freeze-out conditions for different hadron spezies



RHIC	π	K	p	Y	Ξ	Ω
$\langle \tau_{fr} \rangle$ (fm/c)	23.1	22.7	25.8	27.4	32.2	9.3
$\langle r_{T,f} \rangle$ (fm)	9.5	10.2	11.3	11.6	14.2	7.3

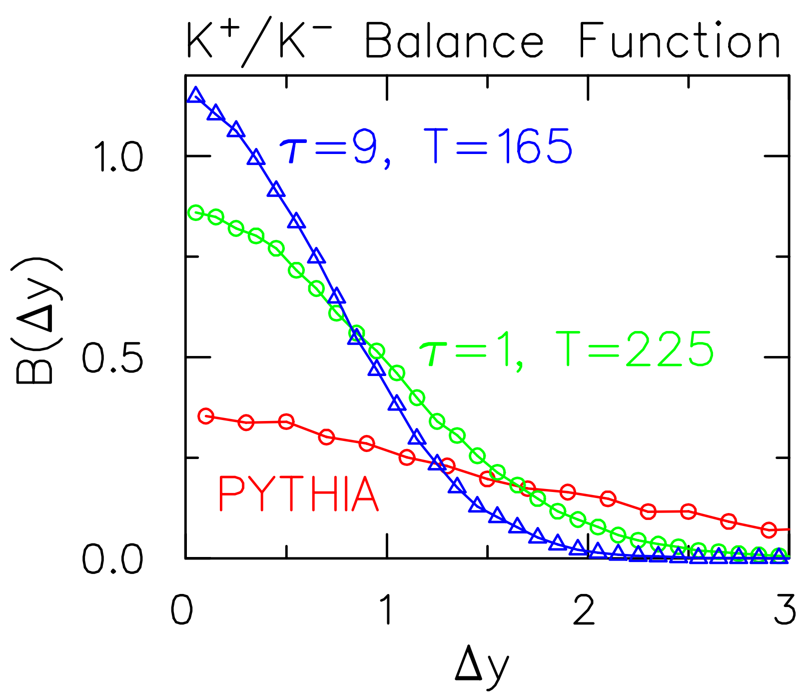
- no sharp freeze-out, broad distributions
- only minute changes in lifetime from SPS to RHIC

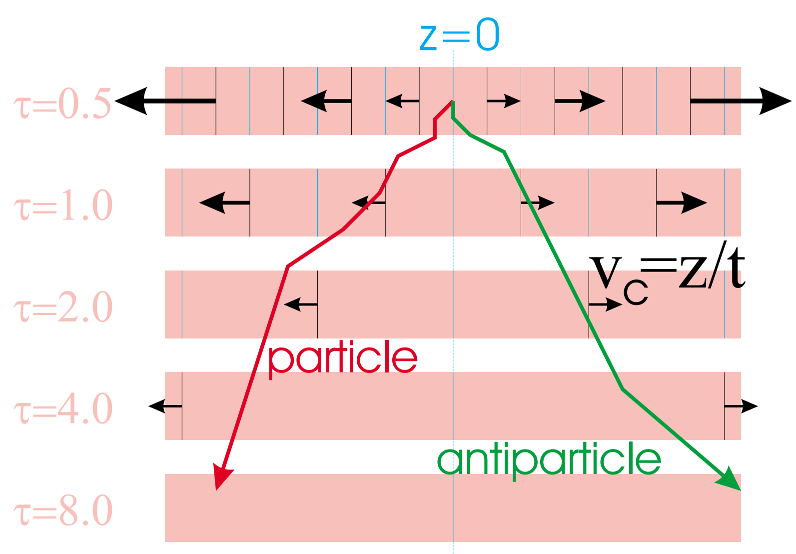
Balance Functions: probing hadronization time

$$B(\Delta y) \equiv \sum_y \{\rho(+Q, y+\Delta y | -Q, y) - \rho(-Q, y+\Delta y | -Q, y)\}$$

$B(\Delta y)$ narrower for late-stage hadronization for two reasons:

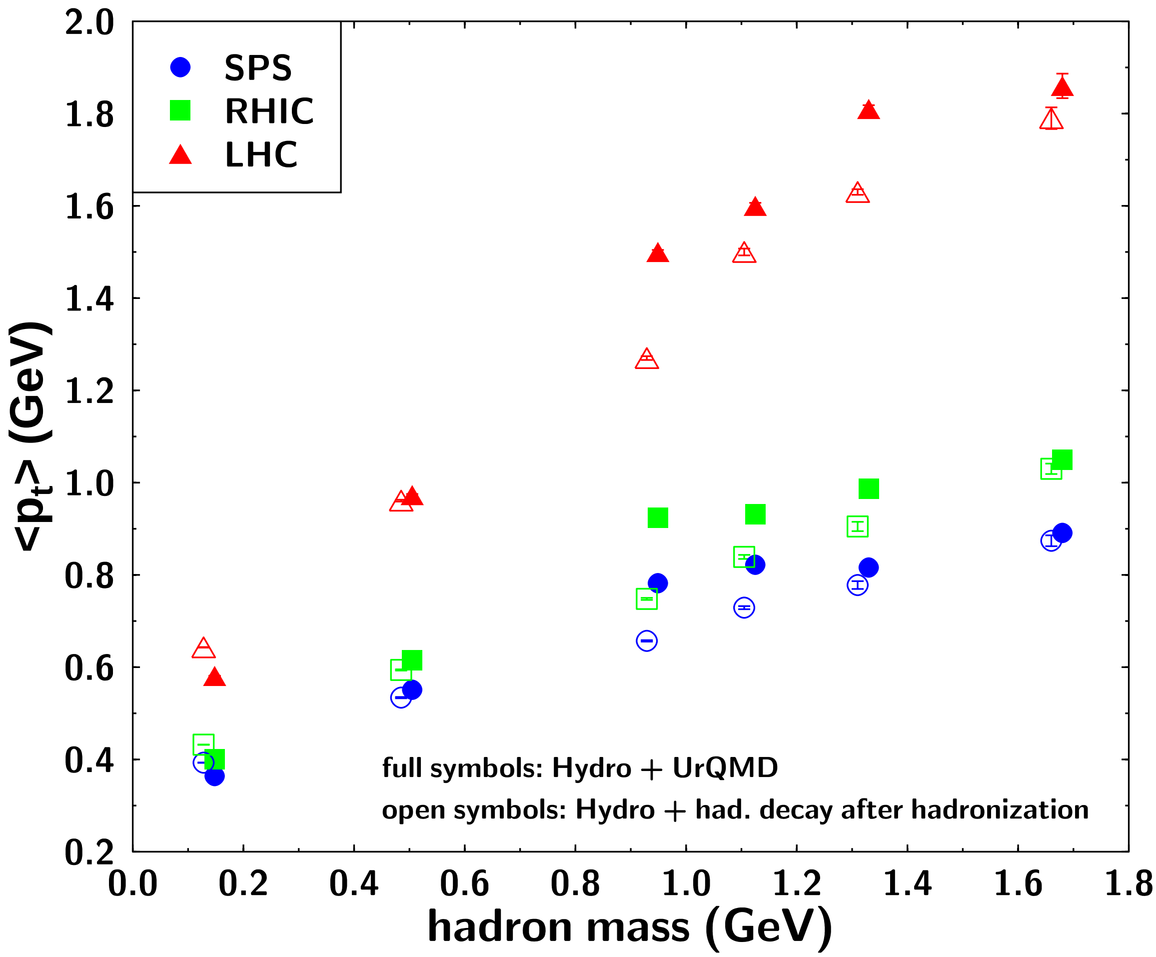
1. lower T: $\langle \Delta y \rangle \approx \sqrt{2T/M}$
2. high initial dv/dz: diffusion separates early-produced pairs





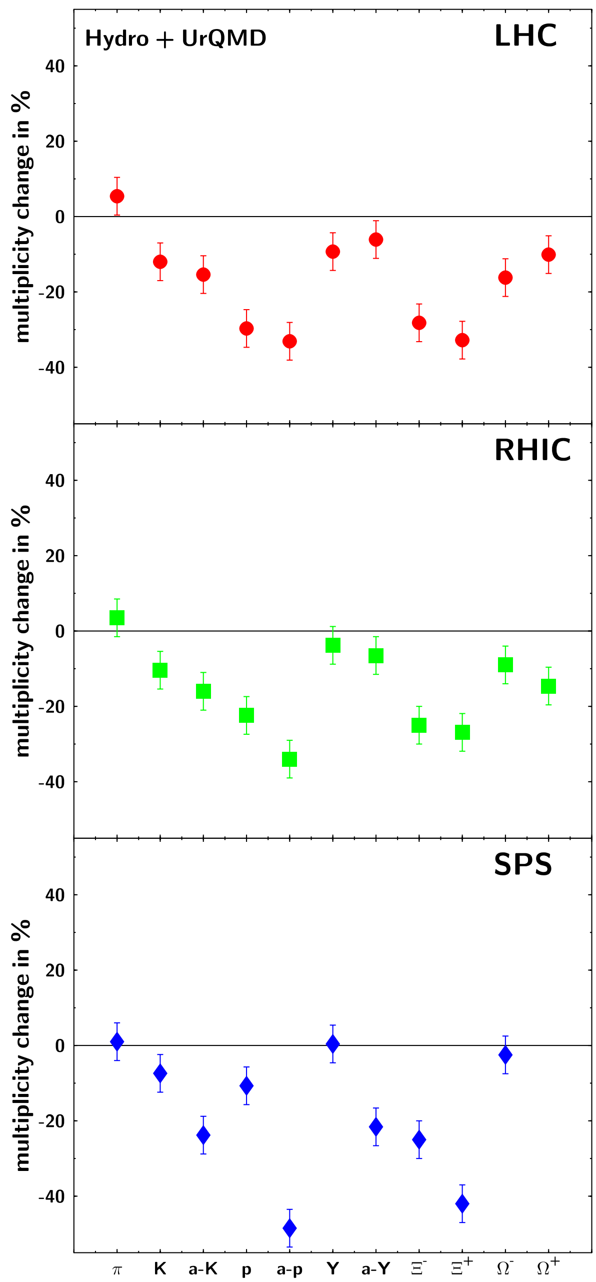
$\Rightarrow$ **$B(\Delta y)$ provides clear signature of late stage hadronization**

$\langle p_t \rangle$ vs. Hadron Mass



- $\langle p_t \rangle$ is a robust alternative to extracting T^* via fit from m_t spectra
- systematics are similar for SPS, RHIC and LHC
- Ω's rescatter more at LHC than at SPS due to higher meson density

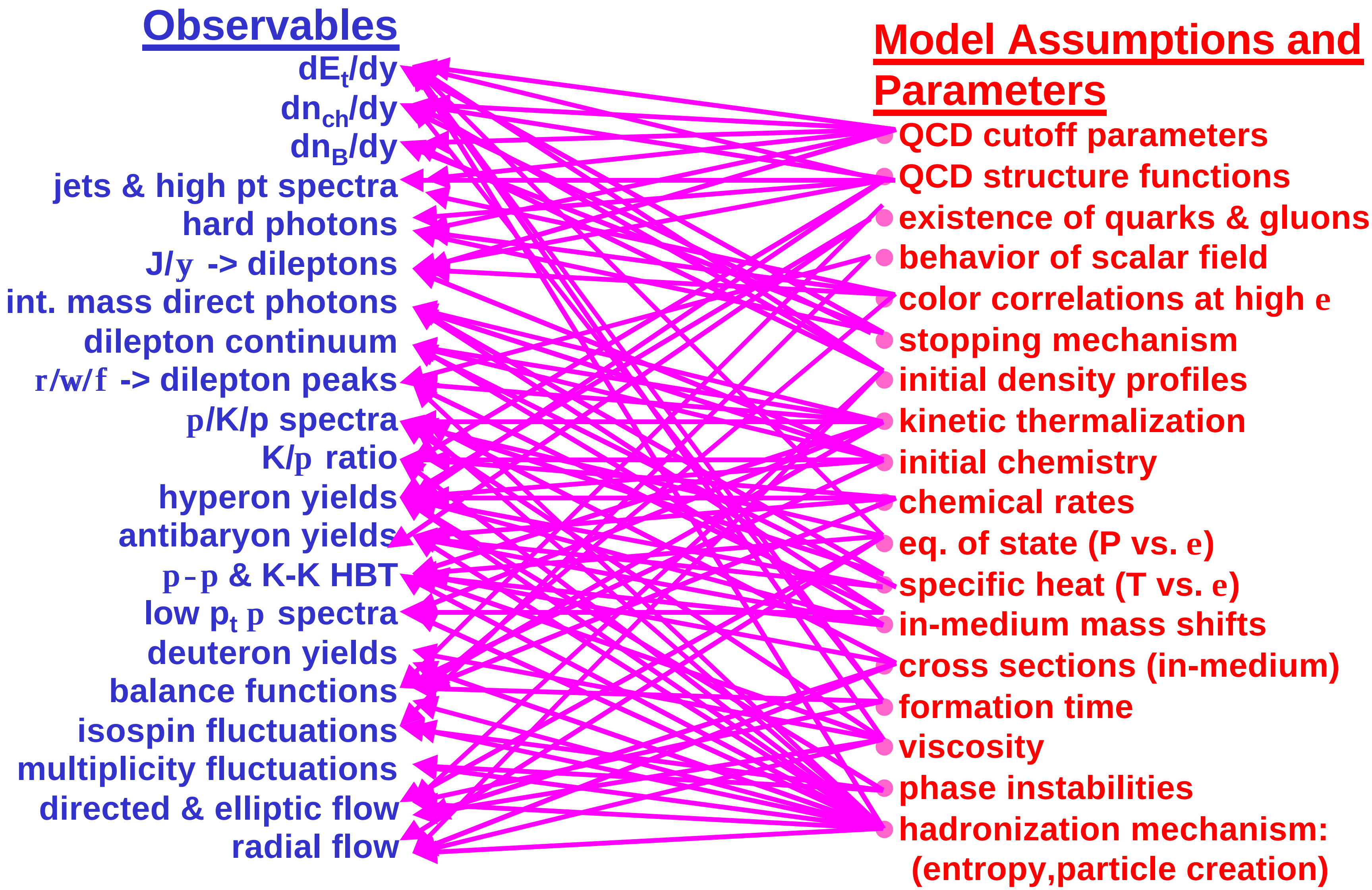
Chemistry of the Hadronic Phase: Rescattering and Particle Yields



- rescattering changes yields up to 40 %

⇒ no chemical freeze-out at phase-boundary

Model Dependencies



Hadronic probes: summary

\+ make up bulk of the matter under investigation

\+ easy to measure, large statistics available

\+ sensitive to almost every aspect of the QGP EoS

\- final state interactions need to be accounted for

\- extraction of EoS only with model assumptions possible

\- multidimensional dependencies between model parameters and observables

Hadronic probes are an indispensable and extremely versatile set of tools for probing the QGP equation of state and solving the puzzle of ultra-relativistic heavy-ion collisions!