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Universality of QCD Hadronization

Reinhard Stock

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

The Veneziano-Webber Model

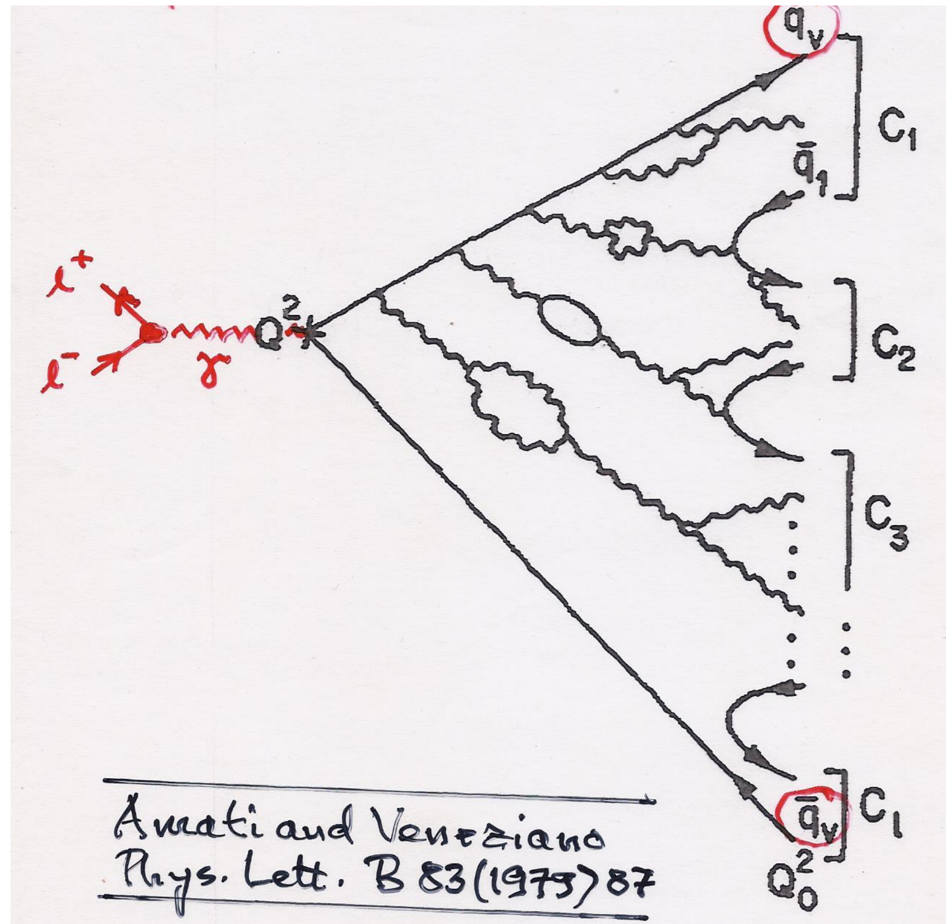
e^+e^- Annihilation to Hadrons: QCD DGLAP

Note: the photon is “virtual”:
It has E_{CM} but no P_{CM}!
For “real” particles: $E^2 = p^2 + m^2$

Virtuality ≈ virtual mass!

End of pQCD phase: spatial order of color in “cluster” regions:

“Color pre-confinement!”



QCD Evolution in di-jet Hadronization: The Singlet Cluster Mass Spectrum

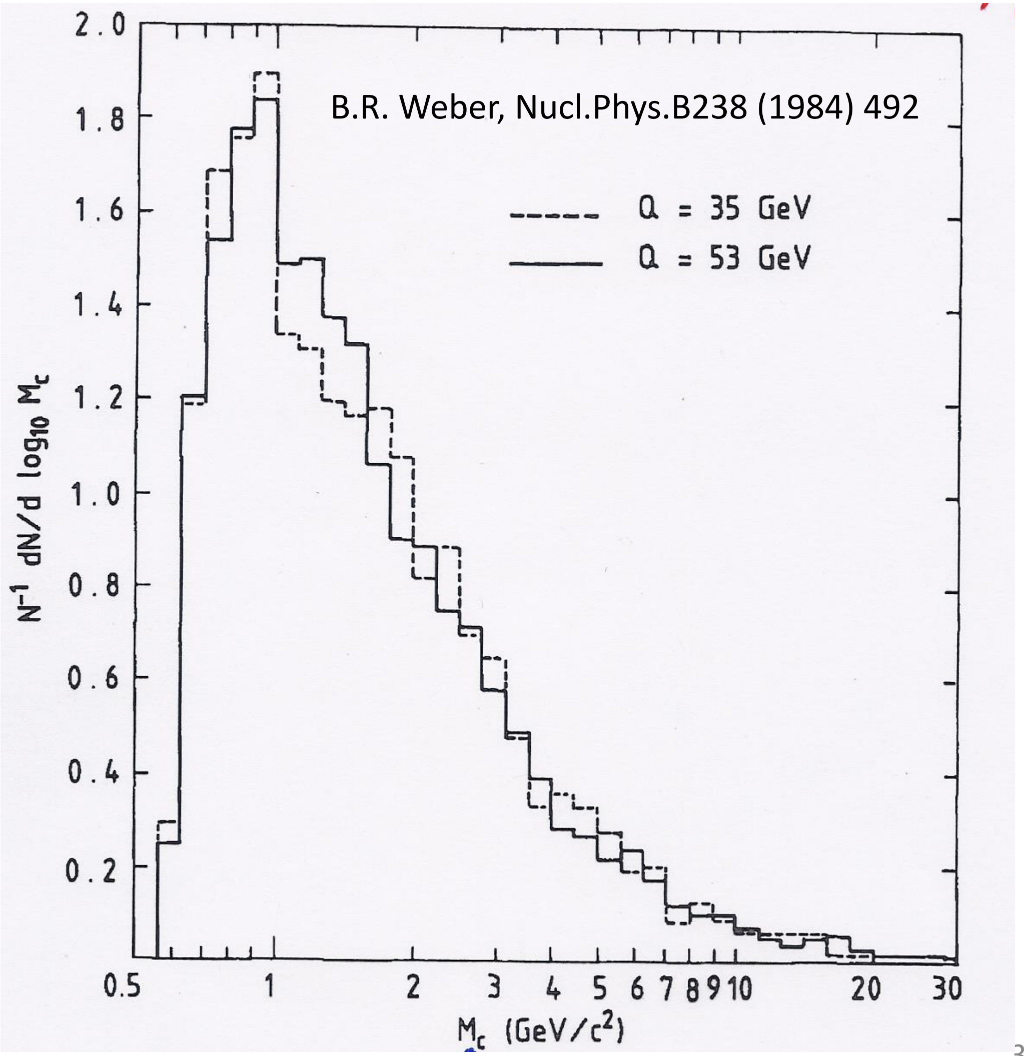
The Code "HERWIG"
pQCD invariant mass of clusters gets reinterpreted in non-pertubative language:

"Condensates, hadronic mass"

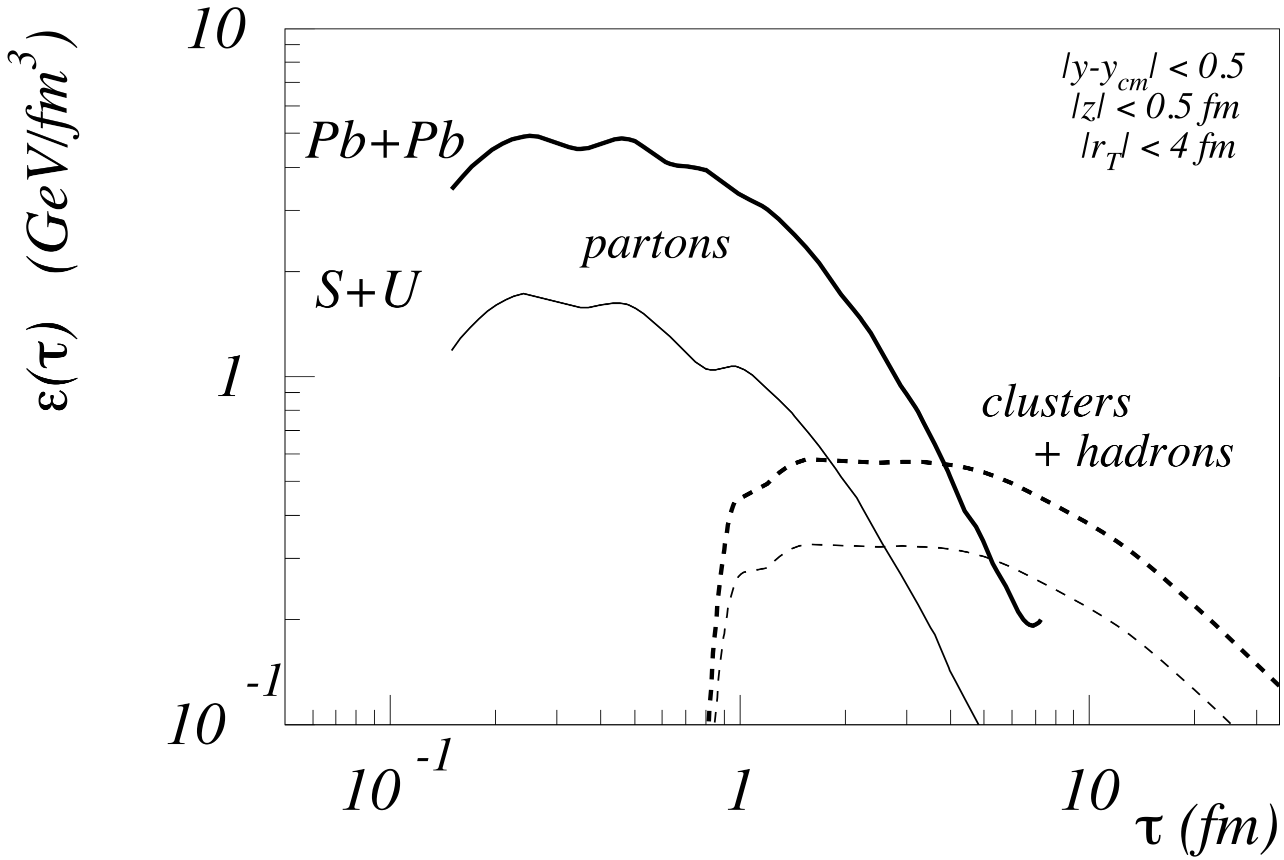
↓

Statistical decay into on-shell hadron spectrum

Phase space dominance



Parton Cascade Description of Heavy-Ion Collisions at CERN ? (Klaus Geiger, 1998)



Evolution of mid-rapidity energy density (J.Ellis and K.Geiger Phys.Rev. D54 (1996) 1967)

Note: Hadron formation occurs at about 0.7 GeV/fm^3

Like in the statistical Hadronization Model

The Hagedorn Legacy: Statistical Hadronization Model

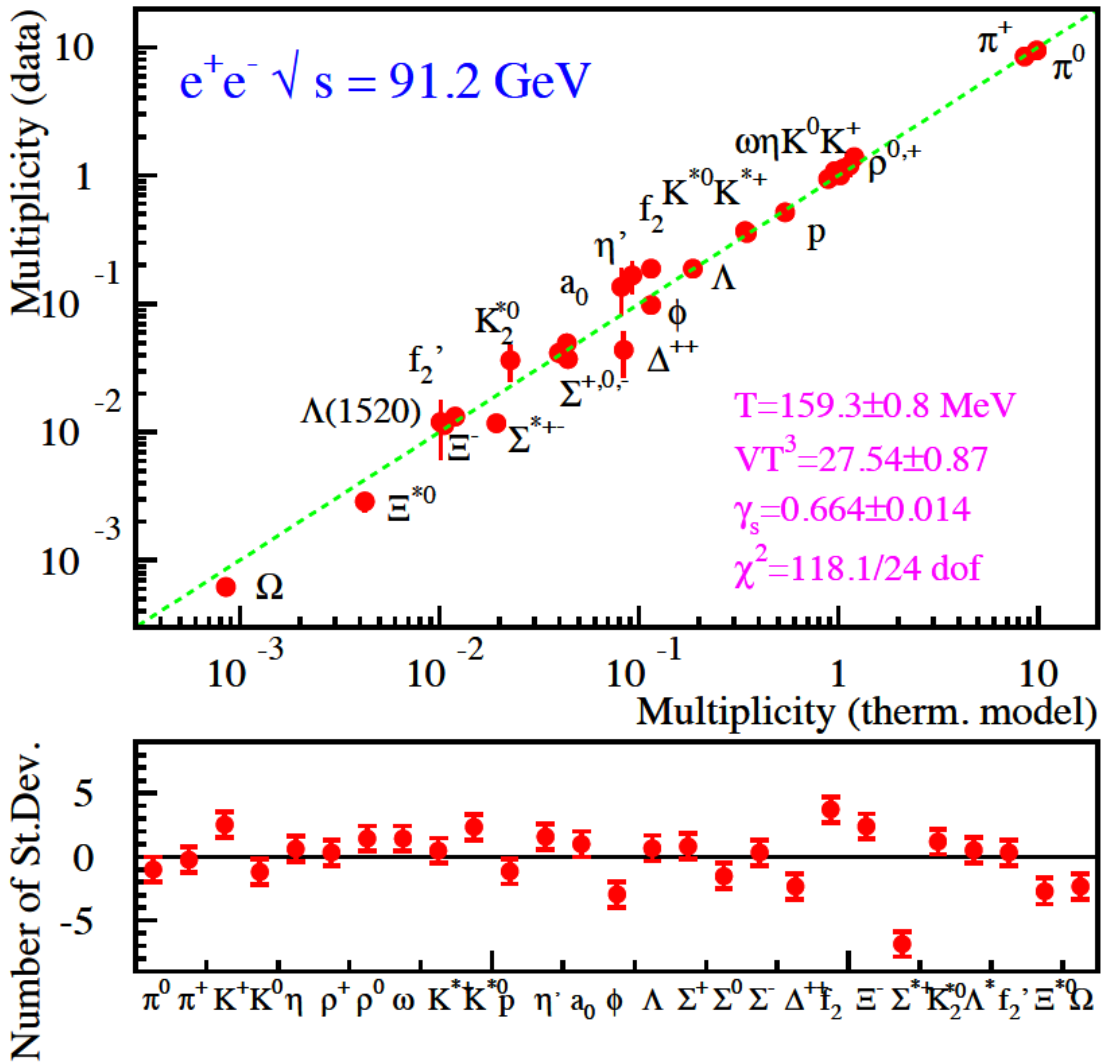
Francesco Becattini
Nucl.Phys. A702 (2002) 336

LEP data

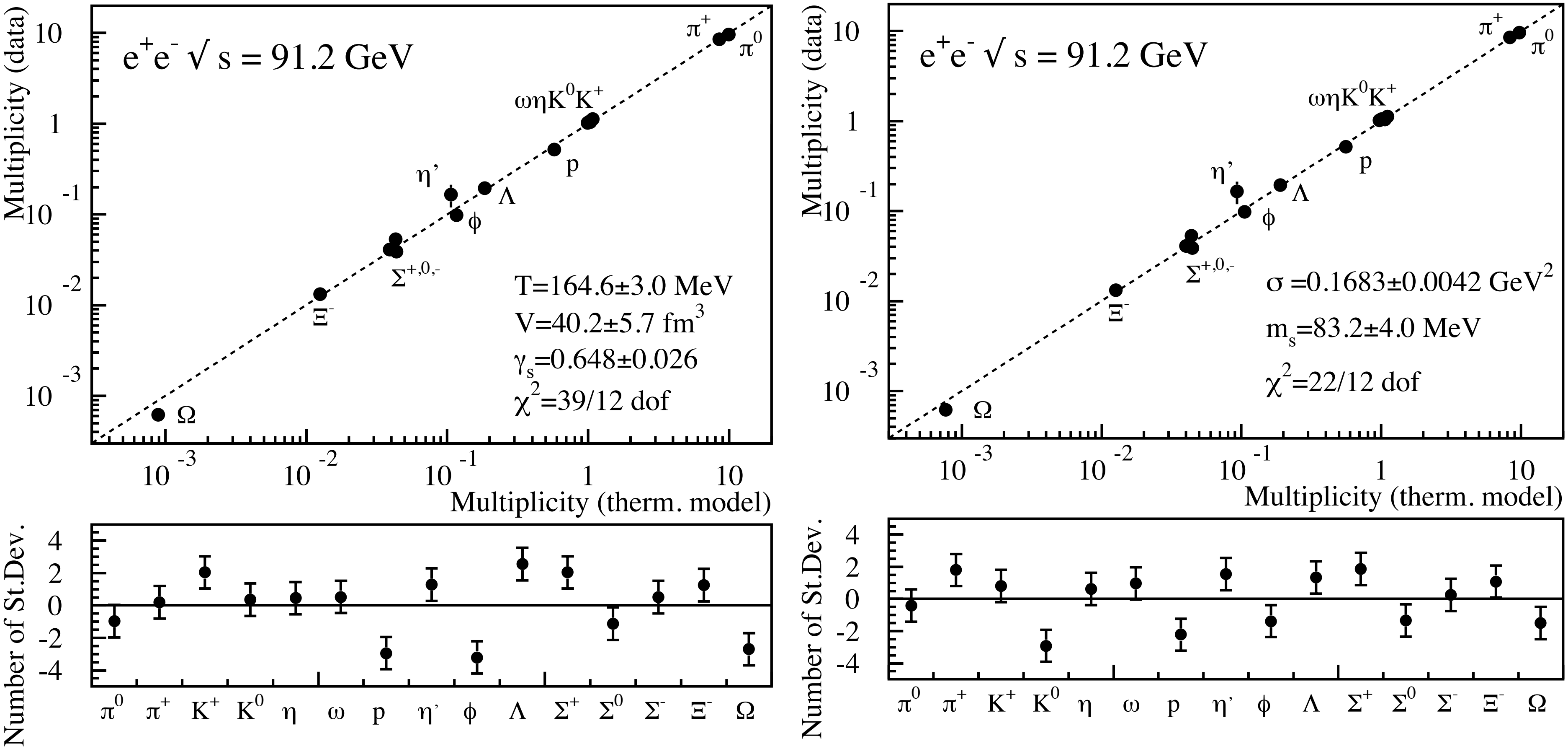
Canonical statistical model analysis

T≈160 MeV the hadronization temperature

Phase space weights plus quantum number conservation



A more Recent Version of e^+e^- Annihilation Analysis (2008)



F.Becattini, P.Castorina, J.Manninen and H.Satz Eur.Phys.J. C56 (2008) 493

T=164 MeV

The Statistical Hadronization Model

R. Hagedorn 1967-71

for recent reference: F. Becattini et al., PRC 69(04)24905

Fireball decay → Grand Canonical Gibbs ensemble of hadron/resonances $\{i\}$

The species i are populated according to their "statistical weights", expressed by the "partition functions" Z_i, where

$$\ln Z_i = \frac{g_i V}{6\pi^2 T} \int_0^\infty \frac{d^4 k}{E_i(k) \exp\{(E_i(k)-\mu_i)/T\} \pm 1}$$

$E_i^2(k) = k^2 + m_i^2$: in vacuum energy of species i

μ_i the "hadro-chemical potential" " "

Parameters: V = system volume, T, μ

Grand Canonical Model II

Note: the terms $\exp\{(E_i - \mu_i)/T\}$ in the denominator ≡ the "Maxwell punishment factor"

regulating the abundance of species i in the ensemble $\{i\}$

Multiplicity $M_i = V \cdot n_i$ where $n_i = \frac{T}{V} \frac{\partial}{\partial \mu_i} \ln Z_i$

$$\rightsquigarrow M_i = \frac{g_i V}{(2\pi)^2} \int \frac{k^2 dk}{\exp\{(E_i(k) - \mu_i)/T\} \pm 1}$$

g_i is the degeneracy "Landé" factor of

μ_i: is the parameter of the Grand Canonical Ensemble that assures e.g. baryon-number conservation by modifying the vacuum penalty factor

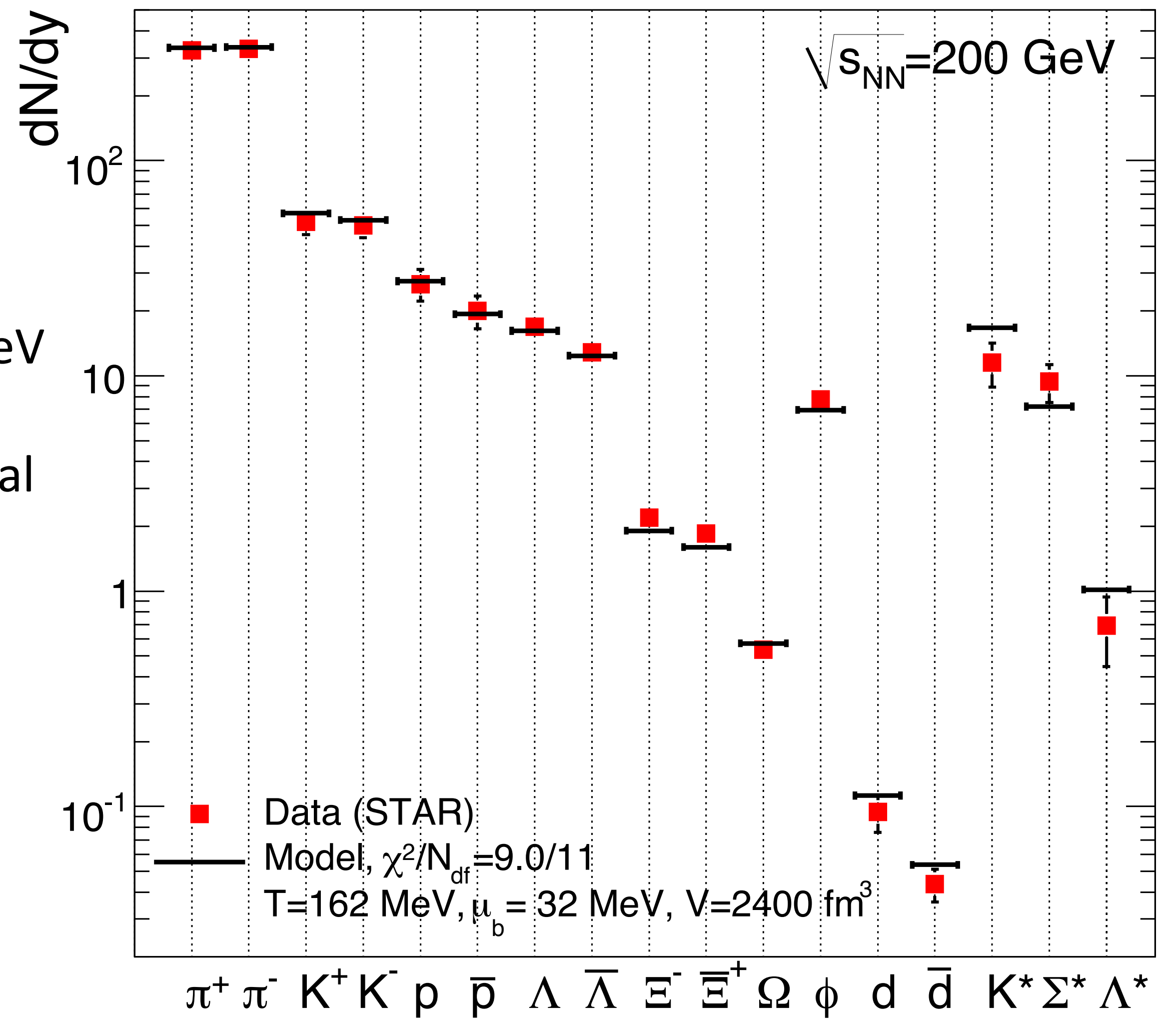
Statistical Hadronization Model in A+A Collisions

P. Braun-Munzinger, J.Stachel
arXiv:0901.2500 (2009)

RHIC data, Au+Au, 200 GeV

Grand Canonical statistical model analysis

T≈162 MeV the hadronization temperature ?

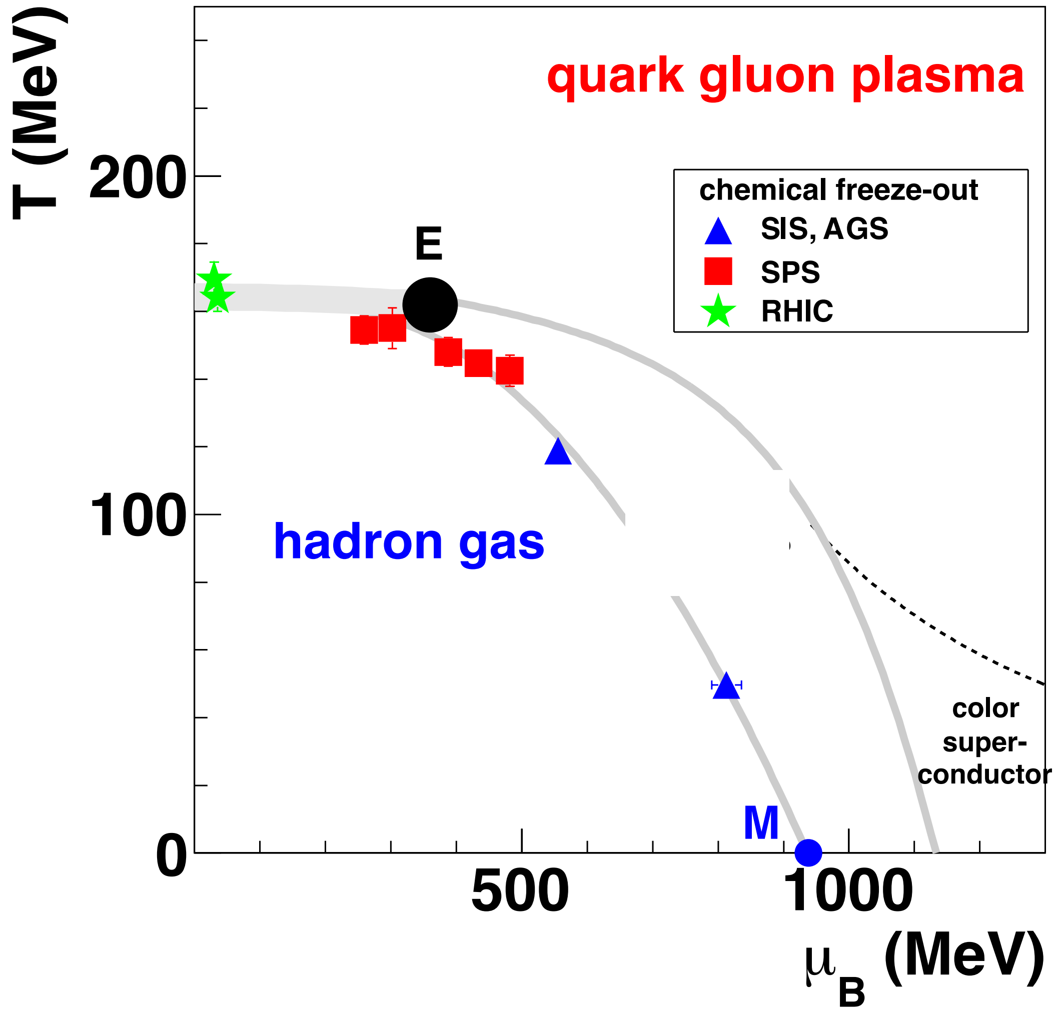


Sketch of the QCD Phase Diagram

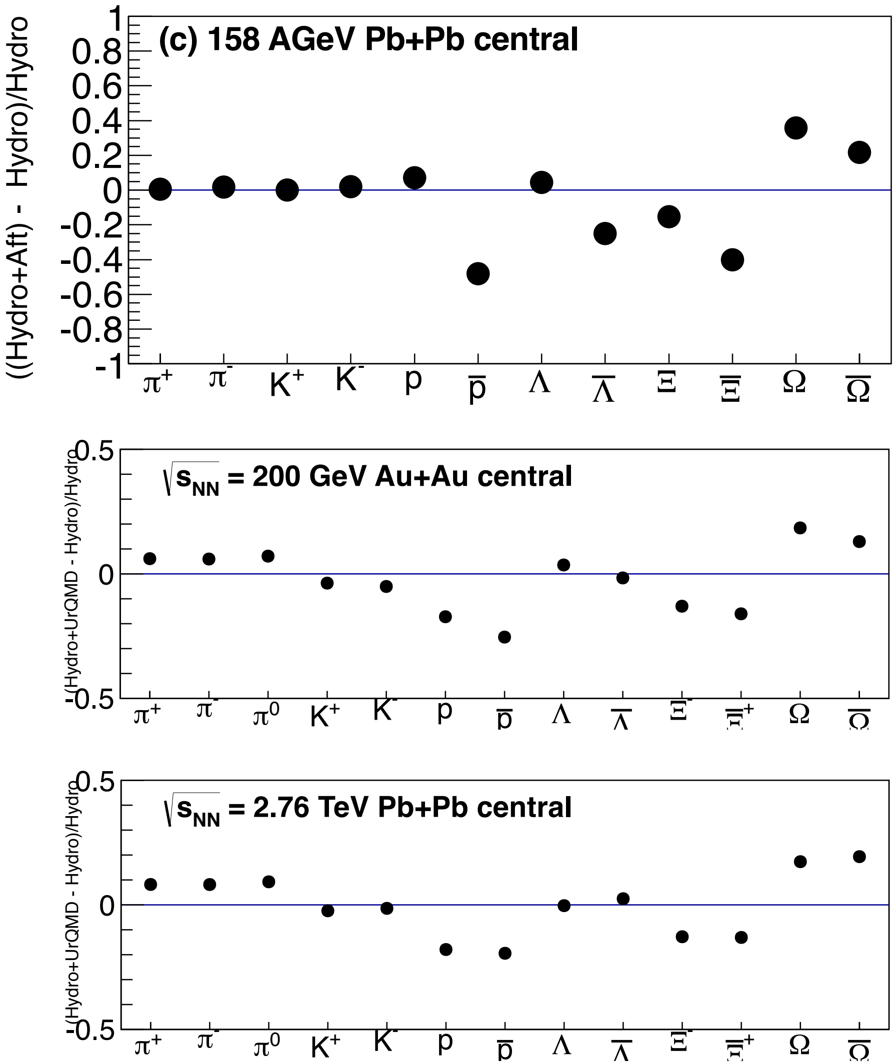
Assumption in the stat. model analysis:

Hadron abundances freeze out directly at QCD hadronization and thus survive the hadronic expansion stage

TRUE?



UrQMD Study of Hadronic Expansion Effects on Hadron Yields



- Employ the recent hybrid version of UrQMD:
  - Hydrodynamic (3+1) phase until energy density < 1 GeV/fm3, plus hadronic emission à la Cooper-Frye.
  - Attach UrQMD hadronic expansion as an "afterburner" stage.

- Compare hadronic yields directly after Cooper-Frye with those after the "afterburner" stage.

SERIOUS ANNIHILATION EFFECTS in baryon and antibaryon sector!

Regeneration also active.

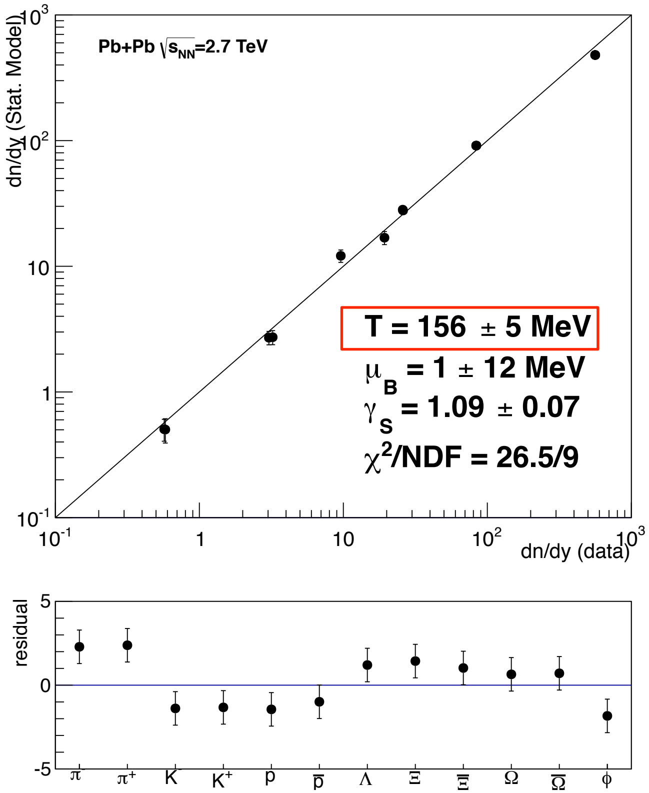
- Effect depends on energy

Survival factors from UrQMD

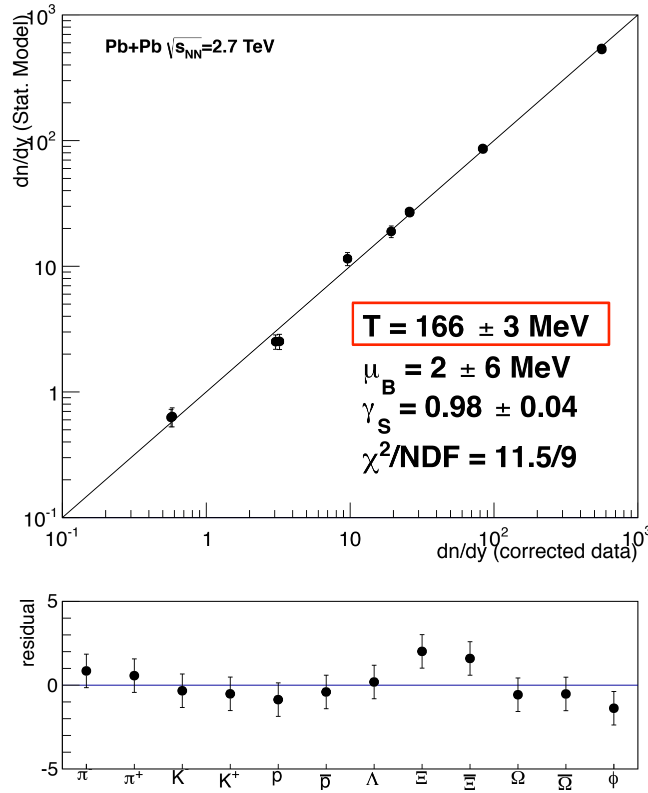
LHC at 2.76 TeV, Central Pb+Pb

F.Becattini et al., arXiv:1212.2431 **(accepted by PRL)**

Standard SM fit



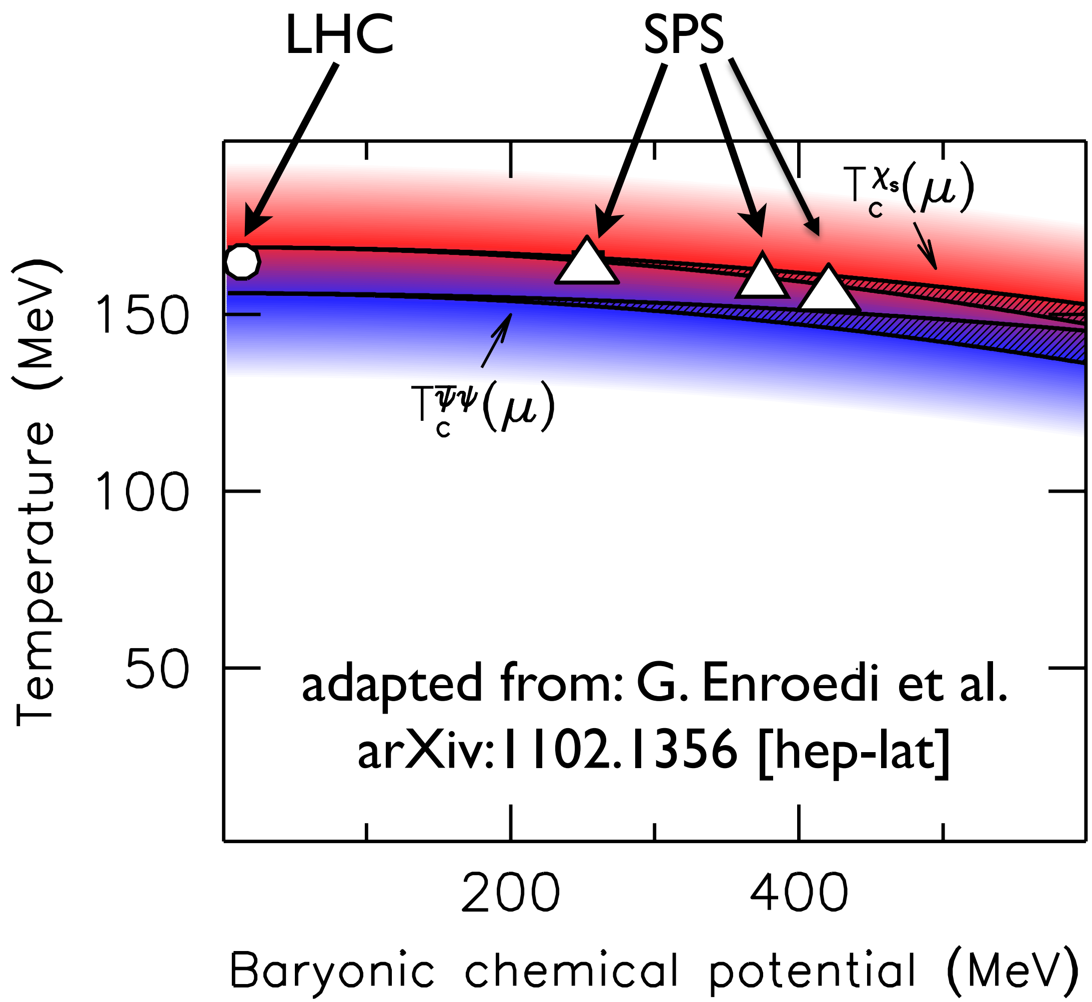
Apply correction factors



T as in e^+e^- Annihilation

Data: ALICE collaboration, preliminary Quark Matter 2012

Freeze-out revisited:
The Phase Diagram



F.Becattini et al., arXiv:1212.2431 **(accepted by PRL)**