NA61/SHINE at the CERN SPS

Be+Be at 150A GeV/c

December 2011

History, status and future of multi-particle production in high energy collisions
Disclaimer on history:

"Histories of science are as far from objective truth as can be imagined (as those given to the population in George Orwell's 1984)."

_Thomas Samuel Kuhn (1922-1996)_
Experimental and theoretical status

**SOFT DOMAIN**

99.9999%

\[ f(m_T) - \exp(-m_T/0.170) \]

weak correlations

validity of statistical approaches

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**HARD DOMAIN**

0.0001%

\[ f(m_T) - m_T^{-8} \]

strong correlations

validity of dynamical (pQCD-based approaches)

---

\[ m_T = (m^2 + p_T^2)^{1/2}, \]

\[ E = m_T \cosh(y), \]

\[ f(m_T) = 1/m_T \frac{dn}{dm_T} \]

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SKETCH: p+p at 50 GeV
Experimental discoveries

"statistical" models of particle production in high energy collisions

"dynamical" models of particle production in high energy collisions

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"statistical"

all final(micro)-states are equally probable

"dynamical"

some final-states are more probable than others

Problems: define all possible final(micro)-states define probability distribution
maximal indeterminism

- all states are equally probably

- micro-canonical ensemble

- statistical models

maximal determinism

- only a single state has non-zero probability

- classical dynamical models
<table>
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<th>Discovery</th>
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Pioneering discoveries with cosmic-rays:

-1947: **pion** (emulsion, *Powell et al.*)
-1947: **kaon and Λ** (cloud chamber, *Rochester, Butler*)

Systematic studies with accelerators:

-1953: Cosmotron at BNL - **3 GeV**
-1954: Bevatron at LBL - **3 GeV**
-1959: PS at CERN - **28 GeV**
-1960: AGS at BNL - **33 GeV**
-1967: U-70 at IHEP - **70 GeV**
-1976: Main Ring at FNAL - **500 GeV**
-1976: SPS at CERN - **400 GeV**

...  
-2000: RHIC - **20 000 GeV**
-2009: LHC - ***30 000 000 GeV***

≈1950 Discoveries of hadrons

2010: about 1000 hadronic states

maximum energy in the fixed target system
Pioneering ideas/models:

-1950: E. Fermi
  statistical hadron production: \( T = T_I \sim s_{NN}^{1/4} \)

-1951: I. Pomeranchuk
  freeze-out at \( T = T_{FO} \approx m_\pi \)

-1953: L. D. Landau
  hydrodynamical expansion from \( T_I \) to \( T_{FO} \)
  \( T = f(m, v_T, T_{FO}) \)

-1965: R. Hagedorn
  statistical hadron production at \( T = T_H \approx 160 \) MeV

\[ m_T = (m^2 + p_T^2), \quad E = m_T \cosh(y), \quad f(m_T) = 1/m_T \frac{dn}{dm_T} \]
Pioneering ideas/models:

-1941: W. Heisenberg
  **S-matrix theory as a theory of particle interactions**

  **Regge theory**

≈1970: G. Veneziano, S. Mandelstam
  **string model**

-1976: A. Bialas, M. Bleszynski, W. Czyz
  **wounded nucleon model**

\[ \langle N \rangle_{AB} = w_{AB}/2 \cdot \langle N \rangle_{NN} \]
≈ 1960/70  Discoveries of quarks and gluons

Pioneering ideas/experiments:

- 1964: M. Gell-Mann, G. Zweig
  quark model of hadron classification

- 1965: D. Ivanenko, D. Kurdgelaidze
  quark matter in superdense star cores

- 1968: SLAC experiments: deep inelastic scattering
  discovery of partons (now $q$, $\bar{q}$ and $g$)

  quantum chromodynamics as theory of strong interactions

≈ 1975: E. Shuryak
  QCD quark-gluon plasma ($T_c \approx 500$ MeV)

- 1979: experiments at DESY: three-jet events
  discovery of gluons
≈1980/00  statistical QGP hadronization

statistical parton production

Pioneering ideas/models:

-1975: N. Cabibbo, G. Parisi
  \[ T_c = T_h \approx 160 \text{ MeV} \]

-1991: J. Rafelski
  **statistical QGP hadronization**

≈1995: M.G., M. Gorenstein
  **statistical production of partons at \( T > T_c \) and of hadrons at \( T < T_c \) transition at the SPS energies**
Pioneering ideas/models:

-1977: R. Field, R. Feynman
  **pQCD-based model of high $p_T$ phenomena**

≈1980: J. Rafelski, B. Mueller, T. Matsui, H. Satz
  **QCD-inspired models of QGP signals, strangeness enhancement and $J/\psi$ suppression**

  **QCD-inspired parton cascade and hadronization model**

\[ f(m_T) \sim m_T^{-P} \]
Discoveries of strongly interacting matter and its phase transition

Pioneering ideas/experiments:

-1980/00: AGS/SPS/RHIC experiments with heavy ions
discovery of strongly interacting matter
(large volume, in ≈equilibrium, hydrodynamic expansion)

≈2000: NA49 at the CERN SPS
discovery of phase transition of strongly interacting matter
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Disclaimer on status:
"CERN was built in order to find out how strong interactions work. After 50 years we still do not know the answer."

Lucien Montanet (1930-2003),
the sixth physicists to be employed at CERN
Basic experimental tools: accelerators
Basic experimental tools: experiments

Bubble Chamber at PS
p+p at 7 GeV

CMS at LHC
p+p at 7 TeV
Basic products and messengers: hadrons

Number of mesons and baryons up to mass m

Broniowski, Florkowski, Glozman
Expereimental and theoretical status

**SOFT DOMAIN**
99.9999%
\[ f(m_T) = \exp(-m_T/0.170) \]
weak correlations

validity of statistical approaches

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THRESHOLD
(no data)

SKETCH: p+p at 50 GeV
String and Wounded Nucleon Models

A+B at 20 GeV

\[ \langle K+\bar{K} \rangle / \langle \pi \rangle \]

NA35/49 at the CERN SPS

strangeness enhancement

String and Wounded Nucleon Models

SOFT/DYNAMICAL
QCD-inspired models of QGP signals: strangeness enhancement

\[ \frac{\langle K^+ \rangle_{\text{AA}}}{\langle K^+ \rangle_{\text{pp}}} \]

\[ \frac{\langle K^+ \rangle_{\text{AA}}}{\langle \pi^+ \rangle_{\text{pp}}} \]

\( \sqrt{s_{\text{NN}}} \) (GeV)

\( \text{strangeness enhancement:} \)

increases with decreasing collision energy

interpretation as the QGP is far from obvious
Discoveries of strongly interacting matter (A)

success of hadron-resonance gas model in describing hadron yield systematics from AGS, SPS, RHIC and LHC?
Discoveries of strongly interacting matter (B)

Success of hydrodynamical models in describing hadron spectra/(anisotropic flow)

Systematics from AGS, SPS, RHIC and LHC

NA49: Pb+Pb at 17 GeV

+Broniowski, Florkowski at RHIC
Discoveries of strongly interacting matter (C)

SOFT/STATISTICAL

NA49: Pb+Pb at 17 GeV

non-statistical effects (e.g. collective flow) are large and sensitive to properties of the early stage (e.g. phase transition)
Discoveries of the phase transition (A)

SOFT/STATISTICAL

1998 predictions

2011 data

statistical hadrons

statistical partons

F [GeV^{1/2}] (\approx \sqrt{s_{NN}})

K^+/\pi^+ (y=0)

\sqrt{s_{NN}} (GeV)

Pb+Pb

Pb+Pb

Au+Au

AGS

SPS(NA49)

RHIC

LHC(ALICE)

rapid changes in energy dependence of hadron production properties provide evidence for the phase transition
Discoveries of the phase transition (B)

SOFT/STATISTICAL

1998 predictions

statistical hadrons

statistical partons

2011 data

K⁻

Pb+Pb  Au+Au
AGS
SPS(NA49)
RHIC
LHC(ALICE)

rapid changes in energy dependence of hadron production properties provide evidence for the phase transition
pQCD-based model of high $p_T$ phenomena

Field, Feynman: asymptotic free theory:

$\propto p_T^{-4}$

$\propto p_T^{-8}$

CDF

parton distribution, parton fragmentation, 2 $\rightarrow$ 3 processes, conservation laws

$\rho + \bar{\rho}$ at 1.8 TeV
Event-by-event fluctuations (A)

→ rich experimental data on single particle spectra in Pb+Pb and p+p interactions from several GeV to several TeV

→ but due to an incomplete acceptance of detectors poor data on event-by-event fluctuations
Event-by-event fluctuations (B)

SOFT/STATISTICAL/DYNAMICAL

No data on A+A collisions to test the very different predictions.
Onset of Deconfinement:
early stage hits transition line, observed signals: kink, horn, step

Critical Point:
freeze-out close to critical point, and system large enough, expected signal: a hill in fluctuations

Past:
strategy of NA49 at the CERN SPS

Present and future:
strategy of NA61/SHINE at the CERN SPS
Properties of the transition line (B)  
SOFT/STATISTICAL

Study properties of the phase transition

quark gluon plasma

LHC

RHIC AFTER

SPS NICA

hadrons

SIS-18 SIS-100

color superconductor

T (MeV)

μ_B (MeV)
Properties of the transition line (C)

Search for the critical point: freeze-out close to critical point, and system large enough, expected signal: a hill in fluctuations

Stephanov et al., PRD60:114028
NA61/SHINE, PoS CPOD2006:016
Towards unified description (A)
SOFT+HARD/STATISTICAL/DYNAMICAL

SKETCH: p+p at 50 GeV

statistical approaches

pQCD-based approaches

THRESHOLD
Towards unified description (A)

SOFT+HARD/STATISTICAL/DYNAMICAL

Towards unified description of multi-particle production in high energy collisions:

- solve QCD or develop quantitative approximations in the soft region

- extend statistical/hydrodynamical approaches to the hard region, fluctuations and collisions of small systems (e.g. p+p, p+Pb, Be+Be) (e.g. volume/temperature fluctuations, hydrodynamics of unstable medium)

- new ideas
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