Hot strong matter

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We want to produce and analyze properties of quark-gluon plasma (QGP) and properties of transition between QGP and HG

**Quark-gluon plasma** – a system of deconfined quarks and gluons; existed probably after Big Bang
Space-time evolution of heavy ion collision

$T \sim 90-140$ MeV, $\varepsilon \sim 0.05$ GeV/fm$^3$
thermal freeze-out – particles momenta fixed
(end of elastic interactions); decays still possible

$T \sim 150-170$ MeV, $\varepsilon \sim 0.6$ GeV/fm$^3$
chemical freeze-out – chemical composition fixed
(end of inelastic interactions)

Temperature decreases during expansion $\Rightarrow T_{\text{chem}} \geq T_{\text{therm}}$

$T \sim 230-600$ MeV (SPS-LHC)
$\varepsilon \sim 3$ GeV/fm$^3$ (SPS), $\varepsilon > 5/15$ GeV/fm$^3$ (RHIC/LHC)

QGP life-time before hadronization ~ few fm/c

parton formation and thermalization
formation time $\tau_0 \sim 1$ fm/c at top SPS
and ~ 0.6 fm/c at top RHIC energies

K. Grebieszkow, DIS 2014
Phase diagram of water is well established

The properties of the transition between hadron gas and QGP still need to be discovered

1\textsuperscript{st} order phase transition

\[ \mu_B - \text{reflects net baryon density} \]

\[ \rho_0 \sim 10^{14} \text{ g/cm}^3 \text{ (normal nucl. matt.)} \]

\[ T \sim 10^5 - 10^9 \text{ K} \]
Very interesting region of the phase diagram covered by CERN SPS

1. Evidence for **onset of deconfinement** (kink, horn, step) is observed by NA49 at $\sqrt{s_{NN}} \approx 7.6$ GeV (PR C77, 024903 (2008))

2. **Critical point** of strongly interacting matter may be located at SPS energies

- $(T_{CP}, \mu_{B}^{CP}) = (162(2), 360(40))$ MeV
  (Fodor, Katz, JHEP 0404, 050 (2004))

- $\mu_{B}^{CP} = 360$ MeV $\Leftrightarrow E_{CP} \approx 50A$ GeV ($\sqrt{s_{NN}} = 9.7$ GeV)
  (Beccatini, Manninen, Gaździcki, PR C73, 044905 (2006))

- $(T_{CP}/T_{c}, \mu_{B}^{CP}/T_{CP}) = (\sim 0.96, \sim 1.8)$
  $(\mu_{B} \sim 290$ MeV), $T_{c}$ – cross-over temp. at $\mu_{B} = 0$
  (Datta, Gavai, Gupta, NP A904-905, 883c (2013))

- $(T_{CP}, \mu_{B}^{CP}) = (0.927(5)T_{c}, 2.60(8)T_{c}) = (\sim 157, \sim 441)$ MeV
  (Li et al. RIKEN-BNL Workshop, Oct. 4, 2011, http://www.bnl.gov/fcrworkshop/)

CP should be searched above the energy of the onset of deconfinement

$E_{CP} > E_{OD} \approx 30A$ GeV (NA49 data)

30A GeV $\Leftrightarrow \sqrt{s_{NN}} = 7.6$ GeV
LHC and top RHIC energies
“QGP desert”
we study QGP properties
To compare $p_T$ spectra in $p+p$, $p+A$, $A+A$:

**Nuclear Modification Factor $R$**

\[
R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{\text{Invariant yield}}{AA} \quad \frac{\text{Invariant yield}}{pp}
\]

\[
R_{CP}(p_T) = \frac{N_{coll}^\text{PERIPH}}{N_{coll}^\text{CENTRAL}} \frac{\text{Invariant yield}}{CENTRAL} \quad \frac{\text{Invariant yield}}{PERIPH}
\]

**Expected:**
- Soft processes (low $p_T$) $\rightarrow$ participant scaling ($R_{AA} < 1$)
- Hard processes (high $p_T$) $\rightarrow$ binary collisions ($N_{coll}$) scaling ($R_{AA} = 1$)

**Cronin effect** (in $p+A$, $d+Au$, etc.) $\rightarrow$ probably due to initial elastic multiple low-momentum scattering of the parton (from projectile nucleon) on target nucleons. Before the final hard parton+parton interaction the projectile parton already has got $p_T \neq 0$.

Jet quenching as a signature of hot and dense matter

Suppression of high $p_T$ particles predicted in: Bjorken, FERMILAB-PUB-82-59-THY; Bjorken, PR D27, 140 (1983); Wang et al. PRL 68, 1480 (1992); Gyulassy et al. PL B243, 432 (1990)
Strong suppression (factor 5), but not seen for photons (they do not interact strongly with the medium) ⇒ observed suppression is a final state effect (interpreted as parton energy loss while traveling through hot and dense medium).

Gluon density in the medium (y - rapidity)
\[ dN_g/dy \approx 1400 \Leftrightarrow T \approx 400 \text{ MeV} \]
(d'Enterria, NP A827, 356c (2009))

Expected energy losses (for \( E_{\text{parton}} = \text{const.} \)) due to induced gluon radiation in dense color medium:
\[ \Delta E_{\text{rad}}(g) > \Delta E_{\text{rad}}(q_{\text{light}}) > \Delta E_{\text{rad}}(c) > \Delta E_{\text{rad}}(b) \]

But at top RHIC suppression seems to be similar for light and heavy particles

QM2012 slides (Dong, Tlusty, Xie) and NP A904-905, 639c (2013); final results in STAR, arXiv:1404.6185v1
similar behaviour in U+U at 193 GeV →
Trzeciak (for STAR), WWND 2014

K. Grebieszkow, DIS 2014
**LHC, Pb+Pb**

- **Suppression** (at min. $p_T=6-7$ GeV/c) stronger than at RHIC
- Heavy D mesons suppressed on similar level as charged particles but suppression of beauty smaller
  \[ R_{AA}(D) \sim R_{AA}(\pi) \leq R_{AA}(B \rightarrow J/\psi) \]

\[ \Delta E(c) > \Delta E(b) \quad \rightarrow \quad R_{AA}(D) < R_{AA}(B) \]

Indication of larger energy loss for charm than for beauty

*Non-prompt J/psi – from B decays*

*Jena (for ALICE), WWND 2014: Grelli (for ALICE), arXiv:1310.7366v1*

K. Grebieszkow, DIS 2014
Collectivity in A+A collisions

- For central collisions ($b=0$ fm) → radial flow only
- For non-central collisions ($b\neq0$) → flow is anisotropic (directed flow $v_1$, elliptic flow $v_2$, higher harmonics)

\[ E \frac{d^3 N}{dp^3} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left( 1 + 2 v_1 \cos (\phi - \Phi_R) + 2 v_2 \cos [2(\phi - \Phi_R)] + ... \right) \]

Initial spatial anisotropy + rescattering → pressure gradients → anisotropy in momentum space (more particles in-plane than out-plane)

\[ \phi = \text{atan} \frac{p_y}{p_x} \]

Directed flow
Elliptic flow
Isotropic emission (1 represents radial flow)

K. Grebieszkow, DIS 2014
(\(p_T\) integrated) **elliptic flow grows with energy**...

... and for higher energies scales with the number of constituent quarks \(n_q\)
- “NCQ scaling”

In coalescence models of hadronization (they assume QGP phase!) \(v_2^q\) – elliptic flow of quark, then:

\[
v_2^{\text{MESON}}(p_T) \approx 2v_2^q \left(\frac{p_T}{2}\right)
\]

\[
v_2^{\text{BARION}}(p_T) \approx 3v_2^q \left(\frac{p_T}{3}\right)
\]

---

**top RHIC, Au+Au**

\(v_2\) scales with \(n_q\) – proof of **partonic collectivity** (flow is originally developed on quark level; quarks flow in QGP)

**partonic collectivity – key QGP signature at top RHIC energies**

\[
KE_T = m_T - m = \sqrt{m^2 + p_T^2} - m
\]

Heinz, Phys. Scripta 78, 028005 (2008) [arXiv:0805.4572]
\( \phi \) mesons are as heavy as protons but their \( v_2 \) is as for \( \pi \) mesons \( \rightarrow n_q \) is important! Not mass

's' quarks flow similarly to light 'u' and 'd' quarks \( \Rightarrow \) argument for partonic collectivity (developed mostly in deconfined phase)

\( \phi \) and \( \Omega \) particles have small cross sections for hadronic interactions and probably freeze-out earlier \( \rightarrow \) promising observable of the early stage (they should be less affected by later stage hadronic interactions).

Thus results suggest that the significant part of collectivity was developed in partonic stage
Elliptic flow of heavy flavours

Heavy quarks may also flow with matter! Like stones flowing with the stream

Flow of D mesons similar to that for light particles → charm quarks participate in the collective flow of the expanding medium

Hidden charm (J/ψ) $v_2 > 0$ (at RHIC $\approx 0$)

Heavy-flavour decay $\mu^\pm$ and $e^\pm$ (from 'c' and 'b' decays) also experience anisotropic expansion of the medium ($v_2 > 0$)

Heavy quarks may also flow with matter! Like stones flowing with the stream

LaPointe (for ALICE), WWND 2014;
LaPointe (for ALICE), arXiv:1401.6858
At LHC and top RHIC energies QGP is produced in heavy systems: Pb+Pb, Au+Au

What about light and intermediate mass systems ??
Suppression of high $p_T$ particles seen even in peripheral Pb+Pb where $\langle N_{\text{coll}} \rangle$ is only twice higher than $\langle N_{\text{coll}} \rangle$ in p+Pb

- Charged particles in p+Pb do not show suppression (similar observation for d+Au at top RHIC energy); in ALICE $R_{\text{pPb}} \approx 1$ up to $p_T \approx 50$ GeV/c (Verweij, WWND 2014)

Heavy D mesons in p+Pb collisions also do not show suppression

Suppression of high $p_T$ particles in central and peripheral Pb+Pb is not due to initial-state effects, but rather due to final state interactions in a hot medium (QGP opaque to energetic partons)

K. Grebieszkow, DIS 2014
Evidence of collective flow in small systems

- Mass ordering of $v_2$ in Pb+Pb (and Au+Au at top RHIC) qualitatively reproduced (at lower $p_T$) by hydrodynamical models (not shown) and understood as due to radial flow; hydro: $v_2 \sim (p_T - \langle v_T \rangle) m_T / T$

- Qualitatively similar behaviour in high multiplicity p+Pb (and d+Au) collisions. Does p+Pb (d+Au) flow?

Another evidence of radial flow in p+Pb → increase of $\langle p_T \rangle$ with increasing particle mass (see Loizides, arXiv:1308.1377v2); the same behaviour is well known in Pb+Pb (PR C88, 044910 (2013)) and reproduced by hydrodynamical models. For radial flow: $\langle p_T \rangle \sim m v_T$
**Static source**  
\[ T_{(slope)} = T_{\text{freeze-out(fo)}} \]  
(thermal freeze-out)

**Expanding source**  
\[ T_{(slope)} \approx T_{\text{freeze-out(fo)}} + \frac{1}{2} m_i \langle v_T \rangle^2 \]  
(example for non relativistic case: \( p_{T,i} \ll m_i \))

Boltzmann-type distribution:  
\[ \frac{dN}{dp_T} \propto p_T \exp\left(-\frac{m_T}{T}\right) \]

**Flow like behaviour** (increase of T with mass) becomes much stronger for highest multiplicities

... more precisely:

**Thermal freeze-out parameters** (\( T_{fo}, \langle \beta_T \rangle \)) fitted within **Blast Wave model**  
(Schnedermann et al., PR C48, 2462 (1993); see also ALICE (Pb+Pb): PR C88, 044910 (2013))

\[
\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r \, dr \, m_T \left( \frac{p_T \sinh \rho}{T_{fo}} \right) I_0 \left( \frac{m_T \cosh \rho}{T_{fo}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{fo}} \right)
\]

\[ I_0, K_1 \text{- modified Bessel functions} \]

\[ \rho(r) = \tanh^{-1} \beta_T(r); \quad \beta_T(r) \equiv \beta_T(\text{surf})(r/R)^n \quad R \text{ – fireball radius} \]

- Pb+Pb (central): \( \langle \beta_T \rangle = 0.65c \) (10% higher than at RHIC)
- Central p+Pb: \( \langle \beta_T \rangle \approx 0.5c \); similar values in p+p

→ **sign of collectivity in p+Pb and p+p?**

Timmins (for ALICE), WWND 2014
SPS and lower RHIC energies
“boiling water”

we study phase transition region
and search for the critical point

Dedicated energy scan programs:
SPS: NA49 and NA61/SHINE
RHIC Beam Energy Scan (BES): STAR and PHENIX

http://soul-amp.blogspot.com/2008/01/boiling-water-photo-weird-photos-of.html

K. Grebieszkow, DIS 2014
R\textsubscript{CP} for charged hadrons: jet quenching disappear at lower energies (absence of dense medium) → "turn-off" of QGP signature

Partonic effects become less important at lower energies and cold nuclear matter effects (Cronin) start to dominate

See also HIJING results (Sumbera (for STAR), arXiv:1312.2718) with jet quenching off

**RHIC STAR BES, Au+Au**

R\textsubscript{AA} for neutral pions: suppression of high p\textsubscript{T} (> 6 GeV/c) neutral pions similar at \(\sqrt{s\textsubscript{NN}} = 200\) and 62.4 GeV and smaller at 39 GeV

Mitchell (for PHENIX), PoS CPOD 2013, 003 [arXiv:1308.2185]
Observation of breaking of NCQ scaling at lower energies as a new method of estimation of the onset of deconfinement energy?

For lower energies difference between $v_2$ of particle and antiparticle → "turn-off" of QGP signature

Breaking of partonic collectivity at lower energies may be interpreted as a change of degrees of freedom in the system departing from QGP region?

$v_2$ scaling with $n_q$ – favors partonic degrees of freedom
breaking of $v_2$ scaling with $n_q$ – favors hadronic degrees of freedom

K. Grebieszkow, DIS 2014
Directed flow $v_1$ was considered to be sensitive to 1$^{st}$ order phase transition (softening of EOS) Csernai, Rohrich, PL B458, 454 (1999); Stoecker, NP A750, 121 (2005); Brachmann et al. PR C61, 024909 (2000).

Expected: non-monotonic behaviour (positive $\rightarrow$ negative $\rightarrow$ positive) of proton $dv_1/dy$ as a function of beam energy - “collapse of proton flow”

$v_1$ slopes always negative for pions and antiprotons

$v_1$ slopes for protons and net-protons change signs at lower energies and show minimum at 10-20 GeV (15 GeV planned in BES-II)

→ consistent with hydro models with 1$^{st}$ order PT

$y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$

$y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$

$10-40\%$ Centrality

 RHIC
STAR BES, Au+Au

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

$10$ $10^2$

$dv_1/dy |_{y=0}$

$0.05$

$0$

$-0.05$

$0$

$0.01$

$0$

$0.02$

$0.04$

$0.06$

$0.08$

$0.1$

$10$ $10^2$

$\sqrt{s_{NN}}$ (GeV)
Can we estimate the energy threshold for deconfinement even more precisely?

(the lowest energy sufficient to create a partonic system)

Motivation: **Statistical Model of the Early Stage (SMES)**
Gaździcki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)

- **“kink”**
  - entropy $S \cong 4 N_\pi$
  - QGP
  - HG cont.
- **“horn”**
  - HG cont.
  - QGP
  - mixed phase
- **“step”**
  - HG
  - QGP
  - mixed phase

Fermi variable
$$F \equiv \left[ \frac{\sqrt{s_{NN}} - 2m_N}{\sqrt{s_{NN}}} \right]^{1/4}$$

- $1^{st}$ order phase transition to QGP between top AGS and top SPS energies $\sqrt{s_{NN}} \approx 7$ GeV
- number of internal degrees of freedom ($ndf$) increases HG $\rightarrow$ QGP (activation of partonic degrees of freedom)
- total entropy and total strangeness are the same before and after hadronization (cannot decrease QGP $\rightarrow$ HG)
- mass of strangeness carriers decreases HG $\rightarrow$ QGP ($m_\Lambda, K, ... > m_s$)
- constant temperature and pressure in mixed phase

K. Grebieszkow, DIS 2014
Onset of deconfinement in NA49 (PR C77, 024903 (2008))

Verification of NA49 results and interpretation by STAR and ALICE

APP B43, 609 (2012); for details see Rustamov https://indico.cern.ch/conferenceDisplay.py?confId=144745

\[ E_{\text{beam}} = 30 \text{A GeV} \iff \sqrt{s_{\text{NN}}} = 7.6 \text{ GeV} \]

**Kink:** increased entropy

Pions measure early stage entropy. In SMES (APP B30, 2705 (1999)): \( \langle \pi \rangle/N_w \sim (ndf)^{1/4} \)

Change of slope around 30A GeV; no change of slope in p+p data (not shown)

\[ \langle \pi \rangle = 1.5 \left( \langle \pi^+ \rangle + \langle \pi^- \rangle \right) \]

\[ F \approx \sqrt{s_{\text{NN}}} \] for \( \langle \pi \rangle \) at LHC was estimated based on ALICE \( N_{\text{ch}} \) measurement

**Horn:** decrease of strangeness carrier masses (rise → saturation) and of strangeness to entropy ratio (step down)

Sharp peak observed at 30A GeV (not seen in p+p)

**Step:** constant \( T \) and \( p \) in mixed phase

Inverse slope of \( m_T \) spectra: strong rise at AGS, plateau at SPS, rise towards RHIC

STAR BES points confirm NA49 measurements; LHC point supports the interpretation
The signatures of the onset of deconfinement energy are seen at middle SPS energies for heavy systems: Pb+Pb, Au+Au

What about light and intermediate mass systems??
NA61/SHINE heavy ion program (part I)

SHINE – SPS Heavy Ion and Neutrino Experiment
Successor of the NA49 experiment

Comprehensive scan in the whole SPS energy range ($E_{\text{beam}} = 13A-158A GeV \iff \sqrt{s_{NN}} = 5.1-17.3 GeV$) with light and intermediate mass nuclei

Study of the properties of the onset of deconfinement

Search for the onset of the horn / kink / step, etc. in collisions of light nuclei; additional analysis of fluctuations and correlations (azimuthal, particle ratios, etc.)

Estimated (NA49) and expected (NA61) chemical freeze-out points according to PR C73, 044905 (2006)
First A+A results from NA61:

**Is Beryllium heavy?**

Compared to other metals by the density of the solid state, Beryllium is quite light.

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Transverse mass spectra of $\pi^-$ mesons:

- $p+p$ spectra are exponential
- Convex shape of Pb+Pb and Be+Be spectra
- Spectra fitted in the range: $0.2 < m_T - m_\pi < 0.7$ GeV/c$^2$

\[
\frac{dn}{dm_T} = A m_T \exp\left(\frac{-m_T}{T}\right)
\]

Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)
Static source

\[ T_{\text{slope}} = T_{\text{freeze-out}} \]  
(thermal freeze-out)

Expanding source

\[ T_{\text{slope}} = T_{\text{freeze-out}} + \text{effect of radial flow} \]

Inverse slope parameter \((T)\) of transverse mass spectra of \(\pi^-\) mesons

- \(T\) at the top SPS is significantly larger in Be+Be than in p+p ⇒ possible evidence of transverse collective flow in Be+Be collisions at higher SPS energies
- Beryllium looks heavy at 150\(A\) GeV/c (top SPS)

\[ T_{\text{BeBe}} \approx T_{\text{pp}} \]

\(T_{\text{BeBe}} > T_{\text{pp}}\)

Analysis of other particles (K, p, etc.) → coming soon → BW fits

Analysis of other observables (kink, horn, step) → coming soon

Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

K. Grebieszkow, DIS 2014
Lattice results - minimum of sound velocity (softest point of EOS) close to the temperature of QGP↔hadron gas transition

\[ c_s^2 = \frac{dp}{d\varepsilon} \]

\( p \) - pressure  
\( \varepsilon \) - energy density

Borsanyi et al. JHEP 1011, 077 (2010)

“Dale” plot → studying the properties of the onset of deconfinement

Hydrodynamical Landau model
Shuryak, Yad. Fiz. 16, 395 (1972):

\[ \sigma_y^2(\pi^-) = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \ln\left(\sqrt{s_{NN}/2m_p}\right) \]

- Minimum in Pb+Pb at middle SPS energies
- The dale may be present also in p+p reactions!
Fluctuations and correlations can help to locate the critical point of strongly interacting matter

Analogy to critical opalescence – **enlarged fluctuations close to the critical point**. For strongly interacting matter, maximum ofCP signal expected when freeze-out happens near CP

Critical opalescence is observed in most liquids (including water)

“As the fluid cools down under conditions such that it passes near the end point of the boiling transition, it goes from transparent to opalescent to transparent as the end point is approached and then passed. This non-monotonic phenomenon is due to scattering of light on critical long wavelength density fluctuations (...)”

Stephanov, Rajagopal, Shuryak, PR D60, 114028 (1999)

http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/videos/laser1.mov
RHIC BES studied: net-charge and net-proton fluctuations (STAR, arXiv:1402.1558; Mohanty, 1402.3818), $p_T$ correlations, particle ratio (chemical) fluctuations (Sahoo, WWND 2014) → no clear non-monotonic behaviour, no clear evidence of CP in the energy scan of Au+Au collisions

**NA61/SHINE heavy ion program (part II)**

Search for the critical point

Search for a maximum of CP signatures (hill of fluctuations): fluctuations of $N$, average $p_T$, etc., intermittency, when system freezes out close to CP

Non-monotonic dependence of critical point signal on control parameters (energy, centrality)

K. Grebieszkow, DIS 2014
**Average $p_T$ and multiplicity fluctuations: dependence on phase diagram coordinates**

$\Phi_{p_T}$ – measures event-by-event $p_T$ fluctuations ($\Phi_{p_T}=0$ → no fluct. / correlations; strongly intensive)

$\omega$ – scaled variance (variance / mean) of multip. distrib. ($\omega=0$ → no fluct., $\omega=1$ → Poisson; intensive)

http://www.ujk.edu.pl/homepages/mryb/10thworkshop/files/slides/grebieszkow.pdf → other measures in NA49 and NA61

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**Graphs:**

- **$\Phi_{p_T}$ vs. $T_{chem}$:**
  - Two locations of CP considered
  - $\xi$(Pb+Pb)=6 fm ↓, $\xi$(p+p)=2 fm (dashed), and 3 fm ↓, 1 fm (solid)

- **$\omega$ vs. $\mu_B$ (MeV):**
  - Maximum of $\Phi_{p_T}$ and $\omega$ observed for C+C and Si+Si
  - Data are consistent with the CP$_2$ predictions

- **$\mu_B$ vs. $\Phi_{p_T}$:**
  - NA49: forward-rapidity region; see NP A830, 547C (2009) for details

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K. Grebieszkow, DIS 2014
Comparison of $p_T$ fluctuations between $p+p$ and $Pb+Pb$ collisions (NA49: PR C79, 044904 (2009)) in the NA49 phase-space cuts. No significant difference is observed.

NA61: $p+p$ in NA49 acceptance
NA49: 7.2\% Pb+Pb

No indications of critical point in the energy scan of Pb+Pb (NA49) and p+p (NA61)

We are waiting for the results from Be+Be, Ar+Ca, and Xe+La

K. Grebieszkow, DIS 2014
New period in the experimental study of A+A collisions at the SPS energy range started in 2009 with the p+p energy scan of NA61/SHINE at the CERN SPS

CERN SPS (NA61)
BNL RHIC (STAR, PHENIX)
JINR NUCLOTRON-M (BM@N)
JINR NICA (MPD)
GSI FAIR SIS-100/300 (HADES+CBM, CBM)

2009(11) ↑
2009 ↑
2010 ↑
2015 ↑
2017 ↑
2018/19(2025?) ↑
Summary:

- **LHC, top RHIC energies → studying properties of QGP**
  - The existence of QGP in Au+Au / Pb+Pb collisions at high energies is well established, but
  - Some interesting measurements suggesting that collectivity may be present also in high multiplicity p+p and p(d)+A collisions ⇒ p+p and p(d)+A is not only boring reference to A+A interactions! Radial flow can be present also in light Be+Be system at higher SPS energies!

- **SPS, RHIC Beam Energy Scan energies → studying transition region ...**
  - Several observables (RHIC BES and NA49 → dv$_1$/dy, NCQ scaling of $v_2$, $R_{AA}$, kink, horn, step, dale, etc.) showing that the energy threshold for deconfinement in Pb+Pb / Au+Au collisions is located close to middle SPS energies
  - Very interesting to check whether QGP may be also created in smaller systems → energy scan with small and intermediate mass systems in NA61

... and looking for the critical point

- **Fluctuations of average $p_T$, multiplicity, multiplicity of low mass $\pi^+\pi^-$ pairs and protons** (see NA49: PR C81, 064907 (2010) and arXiv:1208.5292v2 for the last two) tend to a maximum in Si+Si collisions at top SPS. It might be connected with CP at SPS energies → strong motivation for future experiments
- It is the beginning of the story! Much more effort is needed both from experimental (corrections, proper measures of fluctuations, etc.) and theoretical (lattice, models with predicted magnitudes of fluctuation measures at CP) side
Back-up slides
Theory (lattice calculations at $\mu_B = 0$)

Experiment (Bjorken model)

For central collisions:

$$
\varepsilon_{Bj} = \frac{\text{energy}}{\text{volume}} \approx \frac{1}{\pi R^2 \tau_0} \left[ \frac{dE_T}{dy} \right]_{y^* = 0}
$$

$$R = 1.12 A^{1/3}$$

$$
\left[ \frac{dE_T}{dy} \right]_{y^* = 0} = \langle m_T \rangle \left[ \frac{dN}{d y} \right]_{y^* = 0}
$$

thus:

$$
\varepsilon_{Bj} \approx \frac{\langle m_T \rangle}{\pi R^2 \tau_0} \left[ \frac{dN}{d y} \right]_{y^* = 0}
$$

More recent results:

$T_c = 154 \pm 8 \text{(stat.)} \pm 1 \text{(sys.)} \text{ MeV}$ (HotQCD),

$T_c = 155 \pm 3 \text{(stat.)} \pm 3 \text{(sys.)}$ (Wuppertal-Budapest)

NP A904-905, 318c (2013); NP A904-905, 270c (2013)

$\varepsilon/T^4 \sim \# \text{ degrees of freedom}$

$\varepsilon_{Bj} \approx 3.2 \text{ GeV}/(\text{fm}^2\text{c})$

for $\tau_0 \approx 1 \text{ fm/c} \Rightarrow \varepsilon_{Bj} \approx 3.2 \text{ GeV/fm}^3$

$\varepsilon_{Bj} \approx 5 \text{ GeV}/(\text{fm}^2\text{c})$

for $\tau_0 \approx 1 \text{ fm/c} \Rightarrow \varepsilon_{Bj} \approx 5 \text{ GeV/fm}^3$

$\varepsilon_{Bj} \approx 9 \text{ GeV/fm}^3$

$LHC \varepsilon_{Bj} \approx 15-16 \text{ GeV}/(\text{fm}^2\text{c})$

for $\tau_0 \approx 1 \text{ fm/c} \Rightarrow \varepsilon_{Bj} \approx 15-16 \text{ GeV/fm}^3$

for $\tau_0 \approx 0.6 \text{ fm/c}$ (hydro describ. spectra PR C85, 064915 (2012))

$\Rightarrow \varepsilon_{Bj} \approx 25-27 \text{ GeV/fm}^3$

for $\tau_0 \approx 0.3 \text{ fm/c} \Rightarrow \varepsilon_{Bj} \approx 50-53 \text{ GeV/fm}^3$
Jet quenching as a signature of hot and dense matter

Two-particle correlations in azimuthal angle (left)

Trigger particle (high $p_T$) combined with associated particles and $\Delta\phi$ calculated for each pair

Disappearance (= $p_T$ reduction!) of away-side jet due to parton passage through dense and hot medium; effect not seen in d+Au and p+p (not shown here)

ATLAS, central Pb+Pb at $\sqrt{s_{NN}}=2.76$ TeV

Direct (w/o 2-part. corr.) observation of jet quenching at LHC

PRL 105, 252303 (2010)

K. Grebieszkow, DIS 2014
Electrons / muons from HF decays
(from semi-leptonic decays of D and B mesons i.e. $D^0 \rightarrow e^+ K^- \nu_e$)
Quenching of whole jets on similar level at RHIC (→ see central Cu+Cu) and LHC. Suppression factor ≈ 2 ($R_{AA}$ close to 0.5)

Reminder: suppression of high $p_T$ particles ($R_{AA}$ for hadrons, not jets) was about a factor of 5 for top RHIC ($R_{AA}$ at high $p_T$ was close to 0.2) and for LHC about a factor of 7 in minimum of $R_{AA}$ and factor of 2 after increase of $R_{AA}$ (for $p_T$ of hadrons ≈ 100 GeV/c, see CMS results)
Suppression of hadrons and jets at LHC

Verweij (for ALICE), WWND 2014

**p+Pb**

- No suppression in p+Pb
- Strong suppression in Pb+Pb

Jet suppression in heavy ion collisions is not initial state effect
$v_2$ scaling with $n_q$ at LHC looks a bit worse than at RHIC ...
Mass splitting stronger for more central collisions $\rightarrow$ stronger radial flow

Stronger radial flow but pure hydro calculations do not describe well the most central collisions.

Viscous hydro model (VISH2+1, CGC initial condition with $\eta/s = 0.20$) quantitatively reproduce the mass splitting of $v_2$ (better in peripheral collisions). In central collisions overestimation of proton $v_2 \rightarrow$ proton might freeze-out later (with larger radial flow); results suggest also important role of hadronic interactions in reproducing proton $v_2$.

$\rightarrow$ see VISHNU hybrid model = (2+1)D viscous hydrodynamics + microscopic hadronic transport model when baryon and anti-baryon annihilation processes (below a switching temperature of 165 MeV) are included, Song, Bass, Heinz, arXiv:1311.0157.

K. Grebieszkow, DIS 2014
A possible evidence of radial flow was observed also in high multip. p+p collisions!

Source radii from **femtoscopy (HBT) analysis** → Hunbury, Brown, Twiss, Nature 178, 1046 (1956)

\[ k = \frac{1}{2} (\vec{p}_1 + \vec{p}_2) \quad k_T = \frac{1}{2} |p_{T,1} + p_{T,2}| \]

\[ C(q) \sim \frac{1}{R} \]

C(q) – correlation function for identical bosons (i.e. \( \pi \pi \)); pairs from the same event divided by uncorrelated pairs (mixed event pairs)

Miśkowiec (for ALICE) PoS WPCF2011, 001
[arXiv: 1204.1224]

- **Decrease of HBT radii with increasing** \( k_T \) in A+A was interpreted as due to **transverse collective expansion**: faster particles (higher momenta) show regions of smaller sizes → expansion

- At LHC such behaviour seen for high multiplicity p+p events! **Collectivity developed in high multiplicity p+p collisions at LHC?**

Such effects seen also in 0-10% central d+Au at top RHIC → see Mwai (for PHENIX), WWND 2014

K. Grebieszkow, DIS 2014
Color reconnection (CR) – color string formation between final partons from independent hard scatterings → see T. Sjostrand, arXiv:1310.8073

Unlike hydrodynamics, CR mechanism acts on a microscopic level, and therefore does not require formation of thermalized medium in a small system

CR can mimic “flow-like” trends seen in p+p data

Note: CR = coherent effects between strings = some form of collectivity
EPOS3, B. Guiot, Y. Karpenko, T. Pierog, K. Werner
arXiv:1312.1233, arXiv:1307.4379

- Initial conditions:
  - Gribov-Regge multiple scattering approach,
  - elementary object = Pomeron = parton ladder,
  - using saturation scale $Q_s \propto N_{part} s^\lambda$

- Core-corona approach
to separate fluid and jet hadrons

- Viscous hydrodynamic expansion, $\eta/s = 0.08$

- Statistical hydrodynamic expansion, final state hadronic cascade

**p+Pb, 5.02 TeV**

Mass splitting (as in Pb+Pb) due to flow

Perhaps we can apply hydrodynamics to high-multiplicity p+p and p+A collisions. The interaction region is small but dense.
Taken in STAR (old + BES-I)
Au+Au at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4, 130, 200$ GeV
Cu+Cu at $\sqrt{s_N} = 22.5, 62.4, 200$ GeV

Planned in STAR BES-II (collider mode):
Au+Au at $\sqrt{s_{NN}} = 7.7, 11.5, 15, 19.6$ GeV (high stat.)

Planned in STAR BES-II (fixed target mode):
Au+Au at $\sqrt{s_{NN}} = 3, 3.5, 4, 4.5$ GeV

Kumar (for STAR), arXiv:1311.3426; Lisa, WPCF 2013; Mitchell, CPOD 2013

- **Time Projection Chamber**
  inside Magnet; measurement of dE/dx and p. **Time of Flight**
detectors. **Silicon Vertex Tracker** for measuring short-living particles.
**Electro-Magnetic Calorimeter.**

- Uniform acceptance, independent of energy.
Four large volume **Time Projection Chambers (TPCs)**: VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of dE/dx and p. **Time of Flight (ToF)** detector walls.

**Projectile Spectator Detector (PSD)** for centrality measurement (energy of projectile spectators) and determination of reaction plane; resolution of 1 nucleon (!) in the studied energy range (important for fluctuation analysis).

**Taken in NA49:**
p+p, C+C, Si+Si, Pb+Pb (MB) at $\sqrt{s_{_{NN}}}=17.3$ GeV
central Pb+Pb at $\sqrt{s_{_{NN}}}=6.3, 7.6, 8.7, 12.3, 17.3$ GeV

**Taken in NA61** (successor of NA49):
p+p at $\sqrt{s_{_{NN}}}=5.1, 6.3, 7.7, 8.8, 12.3, 17.3$ GeV
Be+Be at $\sqrt{s_{_{NN}}}=5.1, 6.2, 7.6, 8.7, 11.8, 16.7$ GeV

**Planned in NA61:**
Ar+Ca at $\sqrt{s_{_{NN}}}=5.1, 6.3, 7.6, 8.8, 12.3, 17.3$ GeV
Xe+L at $\sqrt{s_{_{NN}}}=5.1, 6.3, 7.6, 8.8, 12.3, 17.3$ GeV

**Planned (needs approval) in NA61:**
Pb+Pb at $\sqrt{s_{_{NN}}}=5.1, 6.3, 7.6, 8.8, 12.3, 17.3$ GeV (high stat.)

NA61; Be+Be at $\sqrt{s_{_{NN}}}=16.7$ GeV
<p>$v_1 = \frac{p_x}{p_T}$, where $p_T = \sqrt{p_x^2 + p_y^2}$</p>

$$v_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$$

Protons “antiflow” in NA49 (around midrapidity); not seen in UrQMD (left; no PT)

NA49: PR C68, 034903 (2003)

Stoecker, NP A750, 121 (2005)
Predictions of hydrodynamical models

Directed flow from ideal hydrodynamics with Hadronic (HM) and QGP EOS. “Antiflow” (neg. slope) wiggle in the proton flow visible in case of 1st order PT. Csernai, Rohrich, PL B458, 454 (1999)

\(<p_x^{\text{dir}/N}>\) for Au+Au at b=3 fm. Triangles are for purely hadronic EOS, circles are for EOS with PT. Solid lines - three-fluid model, with (large circles) or without (small circles) dynamical unification. Brachmann et al. PR C61, 024909 (2000)
“The energy dependence of proton $dv_1/dy$ involves an interplay between $v_1$ of protons associated with baryon number transported from the initial beam rapidity to the vicinity of mid-rapidity, and the directed flow of protons from particle-antiparticle pairs produced near mid-rapidity. (...)

Assuming antiproton directed flow as a proxy for the directed flow of pair produced protons, the proposed net-proton slope can be constructed from

$$[v_1(y)]_p = r(y)[v_1(y)]_{anti-p} + [1-r(y)][v_1(y)]_{net-p}$$

where $r(y)$ is the observed rapidity dependence of the ratio of antiprotons to protons at each beam energy.”
$\langle \pi^+ / N_w \rangle$

$F \simeq \sqrt{s_{NN}}$

$T (\text{MeV})$

$K^+$

$A+A: $

- NA49
- AGS
- $p+p$
- RHIC

$\langle K^+ / \pi^+ \rangle (y=0)$

$E_s$ calculated from $\pi$, $K$ and $\Lambda$ yields in $4\pi$. Proposed as a measure of strangeness to entropy ratio (SMES)

$\rightarrow E_s$ shows distinct peak at $30A \text{ GeV}$

$\rightarrow$ Described (predicted) only by model assuming phase transition (SMES)

$\rightarrow$ Effect on $\langle K^+ / \langle \pi^+ \rangle$ even more pronounced at mid-rapidity
Difference in $\langle K^+ \rangle$ and $\langle K^- \rangle$ production due to different sensitivity to baryon density. At SPS energies lambdas have significant influence on total strangeness production (anti-lambdas not)

$$\bar{s} \rightarrow K^+, K^0, \Lambda$$

$$s \rightarrow K^-, K^0, \Lambda$$

$\langle K^+ \rangle / \langle \pi^+ \rangle$ proportional to strangeness/entropy

$\langle K^- \rangle / \langle \pi^- \rangle$ additionally sensitive to baryon density
Particle yields ($\pi$, $K$, $p$, $\Lambda$, etc.) or ratios of yields at mid-rapidity or at $4\pi$ acceptance are used as input to thermal model. After implementation of conservation laws (baryon number, strangeness, charge, etc.) fit parameters are $T_{ch}$ and $\mu_B$ (event. also fireball volume in case of yields)

Horn in the hadron gas model  (Andronic, Braun-Munzinger, Stachel, NP A772, 167 (2006))
Parametrization of $T_{ch}$, $\mu_B$ as a function of energy; relative maximum in $\langle K^+\rangle/\langle \pi^+\rangle$ ratio as a consequence of saturating $T_{ch}$ and decreasing $\mu_B$ with increasing energy  (Limiting temperature reached somewhere at SPS)

→ So far problems: HGM overestimated relative kaon yields from 30A GeV on

Extended version of hadron gas model
(arXiv:0812.1186; APP B40, 1005 (2009))

Inclusion of (not measured) higher-mass resonances in the model spectrum improves description of $K/\pi$ data: These resonances feed-down predominantly into pions → increased pion yield

Warning: in this HGM extension unmeasured states are included!
Step: constant $T$ and $p$ in mixed phase
(NA49, PR C77, 024903 (2008))

→ Inverse slope: strong rise at AGS, plateau at SPS, rise towards RHIC
(not seen in p+p)

→ Consistent with constant temperature and pressure in mixed phase (latent heat) – SMES;
Gorenstein et al., PL B567, 175 (2003)

→ Models without phase transition do not reproduce the data

→ Hydro model with deconfinement phase transition at SPS describes data
(Hama et al., Braz. J. Phys. 34, 322 (2004))
Kink and step plots – studying the properties of the onset of deconfinement

π multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p collisions (kink). The two dependences cross at about 40A GeV

Inverse slope parameters T of $m_T$ spectra at the SPS energies show different behavior in central Pb+Pb (step) than in p+p (smooth increase)

NA61 precision sufficient to study properties of the onset of deconfinement

Inverse slope parameter of transverse mass spectra of $\pi^-$ mesons

Beryllium looks heavy at 150A GeV/c!

Energy dependence of T parameter in Be+Be similar to Pb+Pb

Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

K. Grebieszkow, DIS 2014
m_\text{T} spectra in p+p collisions at 158 GeV/c fitted with Blast Wave model

\[ \frac{dN_i}{m_T dm_T dy} = A_i m_T K_1 \left( \frac{m_T \cosh \rho}{T} \right) I_0 \left( \frac{p_T \sinh \rho}{T} \right) \]

\[ \rho = \text{atanh} \beta_T \]

Transverse mass spectra are approximately exponential in p+p interactions. In central Pb+Pb collisions the exponential dependence is modified by the transverse flow.

Transverse mass spectra are approximately exponential in p+p interactions. In central Pb+Pb collisions the exponential dependence is modified by the transverse flow.

Grebieszkow, PoS CPOD2013, 004
baryons, K^+

anti-baryons, K, \( \phi \)

\[ T = 125 \pm 3 \text{ MeV} \]
\[ \beta_T = 0.48 \pm 0.01 \]
\[ \chi^2/\text{NDF} = 100/41 \]

\[ T = 121 \pm 3 \text{ MeV} \]
\[ \beta_T = 0.48 \pm 0.01 \]
\[ \chi^2/\text{NDF} = 49/41 \]

158A GeV

Grebieszkow, CPOD 2013 (slides)

K. Grebieszkow, DIS 2014
\[
\langle \Delta p_{t,i} \Delta p_{t,j} \rangle = \frac{1}{N_{\text{event}}} \sum_{k=1}^{N_{\text{event}}} \frac{C_k}{N_k(N_k - 1)} , \quad C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left( p_{t,i} - \langle p_t \rangle \right) \left( p_{t,j} - \langle p_t \rangle \right)
\]

where M and N are multiplicities of different particles species.
For strongly interacting matter long range baryon density fluctuations expected
A picture supported by lattice calculations

Baryon density fluctuations appear to diverge for some critical value of the baryochemical potential

Effect of critical point extends over a critical region with \( \sigma(\mu_B) \) and \( \sigma(T) \) \( \Rightarrow \) we do not need to hit precisely the critical point because a large region can be affected!

quark number susceptibility: \( \chi_q \equiv \partial n_q / \partial \mu_q \),
\( T_0 \) – critical temperature for \( \mu_q = 0 \) (\( \mu_B = 3\mu_q \))
Scaled variance $\omega$ of multiplicity distribution

- Intensive measure
- For Poisson N distribution $\omega=1$
- In Model of Independent Sources $\omega(N_s \text{ sources}) = \omega(1 \text{ source}) + \langle n \rangle \omega_{N_s}$
  \[ \langle n \rangle \text{ - mean multiplicity from a single source; } \omega_{N_s} \text{ - fluctuations in } N_s \]

$\omega$ is strongly dependent on $N_s$ fluctuations (it is intensive but not strongly intensive)

Φ_x measure (ZP C54, 127 (1992)) of fluct. ($x=\vec{p}_T$, $\phi$, $Q$)

- In MIS: $\Phi_x(N_s \text{ sources}) = \Phi_x(1 \text{ source})$
- For Independent Particle Model (not corr. emission) $\Phi_x=0$
- In superposition model $\Phi_x$ is independent of $N_s$ and $N_s$ fluctuations (strongly intensive)

Intermittency in low mass $\pi^+\pi^-$ pair density fluctuations in $p_T$ space

- Proper mass window and multiplicity required
- Mixed events used as reference
- Power-law behavior from $\sigma$ mode expected: $\Delta F_2 \sim (M^2)^{\phi_2}$
- Critical QCD prediction $\phi_2 = 2/3$

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**Mathematical Formulas**

\[ \omega = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle} \]

\[ z_x = x - \bar{x} \quad \bar{x} - \text{inclusive average} \]

\[ \Phi_x = \sqrt{\frac{\langle Z_x^2 \rangle}{\langle N \rangle}} - \sqrt{\bar{z}_x^2} \]

\[ 2D \text{ transv. momentum factorial moments:} \]

\[ F_p(M) = \frac{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i (n_i - 1) \ldots (n_i - p + 1) \rangle}{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i^p \rangle} \]

\[ M^2 \text{ - number of cells in } p_T \text{ space of di-pion} \]

\[ p_{\pi\pi} = p_{\pi^+} + p_{\pi^-} \]

\[ n_i \text{ - number of reconstruc. di-pions in } i \text{-th cell} \]

\[ \Delta F_2(M) \text{ - combinatorial background subtracted (by use of mixed events) second factorial moment} \]

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K. Grebieszkow, DIS 2014
Critical point predictions for multiplicity and transverse moment. fluctuations

**Magnitude of fluctuations at CP** from Stephanov, Rajagopal, Shuryak PR D60, 114028 (1999)
with correlation length \( \xi = \min (c_1 A^{1/3}, c_2 A^{1/9}) = \)
min (limit due to finite system size, limit due to finite life time)
(M. Stephanov, private communication)
where \( c_1 \) and \( c_2 \) are fixed such that
- \( \xi(Pb+Pb) = 6 \text{ fm} \) and \( \xi(p+p) = 2 \text{ fm} \) \( (c_1 = 2, c_2 = 3.32) \)
- \( \xi(Pb+Pb) = 3 \text{ fm} \) and \( \xi(p+p) = 1 \text{ fm} \) \( (c_1 = 1, c_2 = 1.66) \)

**Width of CP region in \((T, \mu_B)\) plane** based on Hatta, Ikeda PR D67, 014028 (2003)
\( \sigma(\mu_B) \approx 30 \text{ MeV} \) and \( \sigma(T) \approx 10 \text{ MeV} \)

**Chemical freeze-out parameters**, \( T(A, \sqrt{s_{NN}}) \) and \( \mu_B(A, \sqrt{s_{NN}}) \) from Beccatini et al. PR C73, 044905 (2006)

**Location of the Critical Point:**
two examples considered
- \( \mu_B(CP_1) = 360 \text{ MeV} \) \( (Fodor, Katz JHEP 0404, 050 (2004)) \)
  \( T(CP_1) \approx 147 \) (chemical freeze-out temperature \( T_{chem} \)
  for central Pb+Pb at \( \mu_B = 360 \text{ MeV} \))
- \( \mu_B(CP_2) \approx 250 \text{ MeV} \) \( (\mu_B \text{ for } A+A \text{ collisions at } 158A \text{ GeV}) \)
  \( T(CP_2) = 178 \text{ MeV} \) \( (T_{chem} \text{ for } p+p \text{ collisions at } 158 \text{ GeV}) \)

\[ K. \text{ Grebieszkow, DIS 2014} \]
System size dependence (p+p, C+C, Si+Si, and Pb+Pb) of average $p_T$ and multiplicity fluctuations at 158A GeV

- Energy dependence of average $p_T$ and multiplicity fluctuations for central Pb+Pb

- Maximum of $\Phi_{p_T}$ and $\omega$ for C+C and Si+Si at 158A GeV
- No significant energy dependence

Forward-rapidity, limited azimuthal acceptance

- 1% most central
- (semi)central

For energy dependence of $\Phi_{p_T}$ important cut on $y^*$ to get rid of artificial effect of event-by-event centrality fluctuations while studying only forward-rapidity → for details see separate paper KG, PR C76, 064908 (2007)
Comparison of $p_T$ fluctuations for NA49 A+A and NA61 p+p collisions in the same (NA49) acceptance

- **Forward-rapidity**
  
  $1.1 < y_\pi < 2.6$;
  
  $y_p < y_{\text{beam}} - 0.5$

- **Common** (for all energies)
  
  limited azimuthal angle

Similar behaviour for Pb+Pb and p+p; difference only for negatively charged particles

- **Forward-rapidity**
  
  $1.1 < y_\pi < 2.6$

- **Wide azimuthal angle**
  
  nearly as available at 158A GeV

Details of CP predictions (curves) for $\Phi_{pT}$

$\rightarrow$ NP A830, 547C (2009)

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Grebieszkow (for NA61 and NA49), X Polish Workshop on Relativistic Heavy-Ion Collisions, (XII 2013)

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K. Grebieszkow, DIS 2014
Pion-pion intermittency analysis

The analog of critical opalescence is detectable through intermittency analysis in transverse momentum space (power-law behavior of factorial moments expected)

**Idea:** $\sigma$-field fluctuations at the critical point (density fluctuations of zero mass $\sigma$-particles produced in abundance at CP)

Antoniou et al. NP A761, 149 (2005), Anticic et al., PR C81, 064907 (2010)

**Why:**
- $\sigma$ at $T<T_c$ may reach the two-pion threshold ($2m_\pi$) and decay into two pions, thus density fluctuations of di-pions with $m_{\pi^+\pi^-}$ close to $2m_\pi$ incorporate $\sigma$-field fluctuations at CP
- Local density fluctuations expected both in configuration and momentum space

**Method:** Intermittency analysis in $p_T$ space of reconstructed di-pions ($\pi^+\pi^-$ pairs) with invariant mass just above $2m_\pi$

For each event all possible pairs with $m_{\pi^+\pi^-}$ in small kin. window above two-pion threshold:

\[
F_2(M) = \frac{1}{N} \sum_{i<j} \frac{\left| n_i \times n_j \right|^2}{n_i \times n_j} \left( \frac{1}{N} \sum_{i<j} \frac{1}{n_i \times n_j} \right)
\]

$Si+Si$ at 158A GeV

K. Grebieszkow, DIS 2014
For Si+Si $\Delta F_2$ measures fluctuations which are much higher than those from HIJING.

Fluctuations in the freeze-out state of Si+Si system approaching in size the prediction of critical QCD (the remaining departure, $\phi_{2,\text{max}} \approx 0.33 \pm 0.04$ instead of $2/3$, may be due to freezing out at a distance from CP)

... (net)proton intermittency analysis to be published soon
Summary of critical point search in NA49
System size dependence \((p+p, C+C, Si+Si, Pb+Pb)\) of fluctuations at 158A GeV

- \(\xi(Pb+Pb)=6\) fm \(\downarrow\) \(\xi(p+p)=2\) fm (dashed), and 3 fm \(\downarrow\) 1 fm (solid)

- \(CP\) assumed at freezout of \(p+p\) at 158A GeV

- Fluctuations of
  - average \(p_T\)
  - multiplicity
  - average azimuthal angle (\(?\))
  - multiplicity of \(\pi^+\pi^-\) pairs
  - net-proton density tend to a maximum in Si+Si (Si+A) collisions at 158A GeV

→ strong motivation for future experiments