Phenomenology of heavy-ion collisions

How can one characterize what is created in a heavy-ion collision?

Focus on “collective phenomena” present in nucleus-nucleus collisions, but absent in $pp$ collisions (“condensed matter physics of QCD”)

Establish a reference, in which collective effects are absent.

Quantify the deviation from these benchmarks in nucleus-nucleus collisions.

Analyze the origin of these deviations.
First measurement: multiplicity

number $N_{\text{ch}}$ of charged particles $\propto \frac{(PP_{12} + PN_{12})}{2}$

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Nucleon-nucleon cross-section

\[ \sigma_{\text{tot}} \]

\[ \sigma_{\text{NN inel}}^{\text{PYTHIA}} \]

\[ \sigma_{\text{elastic}} \]

\[ \sqrt{s_{\text{NN}}} \, (\text{GeV}) \]

Multiplicility distribution

Vary the equivalent number of nucleon-nucleon collisions between $\bar{N}_{\text{part}}^{AB}(b)$ and $\bar{N}_{\text{coll}}^{AB}(b)$:

$$\bar{N}_{AB}(b) = \left( \frac{1 - x}{2} \bar{N}_{\text{part}}^{AB}(b) + x \bar{N}_{\text{coll}}^{AB}(b) \right) \bar{N}_{NN}$$

Probability $P(n,b)$ to find a multiplicity $n$ in a particular $A$-$B$ collision at impact parameter $b$:

- Gaussian around $\bar{N}_{AB}(b)$, with some dispersion;
- given by a Monte-Carlo simulation.

Event-multiplicity distribution:

$$\frac{dN_{\text{evts}}}{dn} = \int db \ P(n,b) \left\{ 1 - \left[ 1 - \sigma_{NN}^{\text{inel}} T_{AB}(b) \right]^{AB} \right\}$$

probability that an inelastic process occur
Multiplicity distribution

Au+Au at $\sqrt{s_{NN}} = 200$ GeV

Multiplicity distribution

\[
\frac{dN_{\text{evts}}}{dn} = \int db \, P(n, b) \left\{ 1 - \left[ 1 - \sigma_{NN}^{\text{inel}} T_{AB}(b) \right]^{AB} \right\}
\]
Multiplicity vs. geometry
Multiplicity vs. geometry

Cross-checking Glauber theory

Multiplicity at projectile rapidity vs. at midrapidity
Pseudorapidity distributions

Collision centralities: 0–6%, 6–15%, 15–25%, 25–35%, 35–45%, 45–55%
(missing / not shown at the lower two energies)

Rapidity distributions

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    xlabel={$y$},
    ylabel={$dN/dy$},
    xmin=0, xmax=5,
    ymin=0, ymax=300,
    xtick={0,1,2,3,4,5},
    ytick={0,100,200,300},
    legend pos=north east,
]
\addlegendimage{only marks, mark=*, color=red, mark size=2pt}
\addlegendentry{$\pi^+$}
\addlegendimage{only marks, mark=o, color=orange, mark size=2pt}
\addlegendentry{$\pi^-$}
\addlegendimage{only marks, mark=triangle*, color=blue, mark size=2pt}
\addlegendentry{$K^+ (\times 4)$}
\addlegendimage{only marks, mark=triangle, color=blue, mark size=2pt}
\addlegendentry{$K^- (\times 4)$}
\end{axis}
\end{tikzpicture}
\end{center}

Multiplicity at mid-rapidity

Beware: in fact, at $\eta=0$, not $\gamma=0$!
Charged hadron multiplicity

Au-Au collisions 0-6% centrality

The graph shows the charged hadron multiplicity $dN_{ch}/d\eta$ as a function of the pseudorapidity $\eta$ for different energies (200 GeV, 130 GeV, 62.4 GeV, 19.6 GeV). The data is presented in a plot with error bars for each point.
Charged hadron multiplicity

Au-Au collisions 0-6% centrality

We boost everything to the rest frame of one nucleus ("projectile")

"limiting fragmentation"

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\[ \ln \sqrt{s_{NN}} \]

Charged hadron multiplicity grows like

\[ -y_{\text{beam}} \] at LHC

\( \eta' = \eta - y_{\text{beam}} \)

Charged hadron multiplicity

Au-Au collisions 0-6% centrality

Busza 2004; N.B. & Wiedemann 2008
Charged hadron multiplicity

The naive extrapolation of RHIC data yields \( \frac{dN^{ch}}{d\eta} \approx 1100 \) at \( \eta = 0 \) -increase, in opposition to conventional power-law rise.
Charged hadron multiplicity

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\[ \ln \sqrt{s_{NN}} \] -increase, in opposition to conventional power-law rise

Heavy Ion Collisions at the LHC
Last Call for Predictions
Monday May 14th to Friday June 8th 2007

- Hijing + baryon junctions: 3500
- EPOS (multiple scattering): 2500
- pQCD minijets + saturation (EKRT) of produced gluons: 2570
- AMPT (Hijing+ZPC): \( \approx 2500 \)
- Percolating strings:
  - DMPJET III: \( \approx 1900 \)
  - Pajares et al.: 1500–1600
- 2-component + shadowing: \( \approx 1700 \)
- “Geometric scaling” (Armesto, Salgado, Wiedemann): 1700–1900
- Gluon saturation (Kharzeev, Levin, Nardi 2000–05): 1800–2100
- B-K eq.+ running coupling (Albacete, Kovchegov): \( \approx 1400 \)
- “CGC” (Gelis, Stasto, Venugopalan): 1000–1400
- ALCOR (quark–antiquark plasma + recombination): 1250–1830 = \( \frac{dN^{\text{ch}}}{dy} \)
Net baryon-number density

\[ \frac{dN}{dy_{\text{net-protons}}} \]

- AGS (E802, E877, E917)
- SPS (NA49)
- RHIC (BRAHMS)

\( y_{\text{CM}} \)
Transverse-momentum spectrum

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Au+Au, p+p

\[ \frac{h^+ + h^-}{2} \]

\[ 1/(2\pi p_T) \frac{d^2 N}{dp_T^2} \big|_{p_T=0} \big( (\text{GeV}/c)^2 \big) \]

bulk: "soft particles"

\[ \propto \bar{N}_{\text{part}}(b) \]

high-\(p_T\) particles

\[ \propto \bar{N}_{\text{coll}}(b) \]