PROBING THE (S)QGP WITH STRANGENESS

Boris HIPPOLYTE (IPHC - Université de Strasbourg)
OUTLINE

- evolution of the system in heavy-ion collisions
- the importance of the references: pp, pA, dA...
- to be in chemical equilibrium or not to be (?)
- news from strangeness enhancement front
- hadronisation: recombination vs. fragmentation
  ➡ baryon/meson ratio
  ➡ fluid-dynamics: $v_2$ and constituent quark scaling
- radial flow and rescattering in the hadronic phase
- tomography
- summary (more a “wish-list”)
EVOLUTION OF THE SYSTEM CREATED IN H-I COLLISIONS

- Initial pre-equilibrium state
- hard parton scattering & jet production
- QGP formation
- QGP expansion and cooling
- Phase transition:
  - Hadronic Phase:
    - chemical freeze-out
    - rescattering then kinetic freeze-out.

Probing the whole evolution of the system with the strange hadrons created in heavy-ion collisions:
- jet flavour content, $R_{AA}$, strange particle flow, resonances, multi-strange (with low hadronic x-section)...

With hadronic states, many observables can be studied in order to characterise the properties of the Quark Gluon Plasma.
EVOLUTION OF THE SYSTEM CREATED IN H-I COLLISIONS

- Initial pre-equilibrium state
  → gluonic fields (Color Glass Condensate) Glasma
- hard parton scattering & jet production
- QGP formation
  → thermalisation of strongly interacting partons
- QGP expansion and cooling
  → 3D+1 relativistic viscous hydrodynamics
- Phase transition:
  → Lattice QCD, Cross-Over
- Hadronic Phase:
  → chemical freeze-out
  → rescattering then kinetic freeze-out.

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REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

- the shapes of $p_T$ spectra in AA are compared to pp, p/dA collisions
  - minimum bias pp are very often used a reference for AA
  - spectra are precisely measured up to high $p_T$ and vs. beam energy

$\Rightarrow$ $p_T$-spectra shapes change more vs. multiplicity than vs. colliding energy;
$\Rightarrow$ not only $p_T$-spectra and $<p_T>$ but $p_T$ ratios (see forthcoming talks);
$\Rightarrow$ difficulties for models, not only kaons (strangeness) but protons (baryons);
$\Rightarrow$ good references ? collective effects ? (e.g. color reconnection in PYTHIA, initial boost in EPOS...)
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STAR Collaboration,

M. Ivanov (ALICE Collaboration),
NPA 904-905 2013 (2013) 162c

CMS Collaboration, CMS-FSQ-12-014,
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CMS Collaboration, CMS-FSQ-12-014,
+ arXiv:1307.3442 (pPb)
TO BE IN EQUILIBRIUM OR NOT TO BE

- mid-rapidity $p_T$-integrated production of hadrons: description by statistical thermal models
  - Baryo-chemical potential $\mu_B$
  - Chemical freeze-out temperature $T_{ch}$
  - Strangeness (non-)equilibrium parameter: $\gamma_s$

提问：等时性和不同等时性中 strangeness (partonic / hadronic phases) 的饱和

2006 predictions:

- Equilibrium

- Non-Equilibrium

2006 predictions for LHC energies:
- 质子-质子对撞
- 中子-质子对撞
- $\mu_B$ 值
- $T_{ch}$ 值
- $\gamma_s$ 值

- “explosive” system
- eq. vs. non-eq. driven by $K/\pi$
- low $p/\pi$ lower $T_{ch}$
- $p\bar{p}$ annihilation but small $p/\pi$ centrality dep.
- agreement LQCD: $T_c \sim 155$ MeV
- flavour dependence for $T_c$?
STRANGENESS ENHANCEMENT

- From Pb-Pb to Au-Au to Pb-Pb: SPS (x2) to RHIC...

\[ \frac{\text{Yield} / \langle N_{\text{part}} \rangle}{\langle N_{\text{part}} \rangle} \text{ relative to pBe} \]

- see ALICE talks for the final (not “preliminary”) enhancement at 2.76 TeV
- is pp a good reference? is \( \langle N_{\text{part}} \rangle \) the proper scale?
- any saturation for the strange baryon production?
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HADRONISATION: RECOMBINATION VS. FRAGMENTATION

Hadronisation of 1 parton: fragmentation

If phase space is filled with partons: hadronisation via recombination/coalescence

The in vacuo fragmentation of a high $p_T$ quark competes with the in medium recombination of lower momentum quarks

a) 6 GeV/c pion from 1x 10 GeV/c quark fragmentation
b) 6 GeV/c pion from 2x 3 GeV/c quark recombination
c) 6 GeV/c proton from 3x 2 GeV/c quark recombination

Baryon/Meson ratios
Constituent Quark Scaling (e.g. $v_2$)
Correlations via Soft+Hard contributions

⇒ “...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma.” Fries et al., PRC 68, 044902 (2003)
⇒ fully compatible with an explosive system and “sudden hadronisation”?
⇒ validate recombination with light quarks before invoking it for heavy flavours...
Important evolutions for the soft sector:

**PYTHIA:** v6.2 $\Rightarrow$ v6.3/4
- Multiple Parton Interactions (M.P.I) treatment (part.-part. interactions and isr/fsr)
- Interleaved pT-ordered showers
- Color reconnection annealing

**PDF:** CTEQ5 $\Rightarrow$ CTEQ6
- Gluon distribution function (visible at low $Q^2$)

$\Rightarrow$ baryon / strangeness creation mechanisms in pp, collectivity?
**BARYON /MESON RATIOS: SYSTEM DEPENDENCE**

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BARYON /MESON RATIOS: ENERGY DEPENDENCE

Calculation implies assumption on transverse radial flow extrapolation

Fries and Müller,
EPJ C34, S279 (2004)

Amplitude for mixed ratio predicted to be the same at LHC than for RHIC but the turnover and limit are shifted to higher \( p_T \)
FLUID-DYNAMICS: AZIMUTHAL ANISOTROPY

- $v_2 + \text{PID}$: probing mass and constituent quark dependence

STAR Collaboration, PRC 88 (2013) 14902

$\phi$ (2$\sigma$)! ncq scaling appears to work

none!
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FSM 2013 | Birmingham | Monday July the 22nd | B. Hippolyte

F. Noferini, NPA 904-905 (2013) 483c

$\rightarrow$ splitting of baryon and mesons

$\rightarrow$ leaving very little (no) room for ncq scaling at the LHC...
COOLING AND RESCATTERING

- Dense then dilute hadronic phase (3D+1 hydro + UrQMD results)!
- Systematics on radial flow and kinetic freeze-out temperature $T_{\text{kin}}$
  - blast-wave parametrisation (with known caveats...)
  - top RHIC to LHC energies (5% central): increase of $<\beta_T>$ by 10% (0.60$c$ to 0.65$c$)
    constant $T_{\text{kin}} \sim 95$ MeV

- radial flow increase from most peripheral collisions at $\sqrt{s_{NN}} = 7.7$ GeV to most central Au-Au events at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV;
- additional information from strangeness (including resonance) studies.
TOMOGRAPHY: PROBING THE OPACITY OF THE QGP

- use energetic partons produced during the early stages of the collision
  → fragmentation in vacuum
  → propagation with energy loss in the coloured medium: flavour dependence
  → colourless probes for benchmarking

experimentally:

1) \[ R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \]

2) Hadron angular correlations:
   \[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d\Delta \eta \, d\Delta \varphi} = \frac{S(\Delta \eta \Delta \varphi)}{B(\Delta \eta \Delta \varphi)} \]

3) Gamma-jet angular correlations

differentially:

- several reference systems (pp, pA, dA)
- light (strangeness) and heavy flavour dependence
- centrality (and event plane) dependence
- energy (beam and jet) dependence
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IDENTIFIED $R_{CP}$ AT RHIC (BEAM ENERGY SCAN)

X. Zhang (STAR Collaboration), NPA 904-905 (2013) 543c

- $R_{CP}$ (0-5%)/(40-60%) |$y$|<0.5 except for $\phi$ which is (0-10%)/(40-60%);
- grey band normalisation from $N_{bin}$;
- statistical uncertainties only.

➡ not unity nor clear species splitting below 19.6 GeV
➡ suppression for $K^0_s$ above 27 GeV
➡ enhancement for baryons
IDENTIFIED $R_{AA}$ AND $R_{dA}$ AT RHIC (200 GeV)

PHENIX Collaboration, arXiv:1304.3410

- separation between $\phi$ and proton
- no high $p_T$ suppression but clear baryon enhancement for $dA$
- consistent with no suppression in $dA$ for the $\phi$
SUMMARY: STRANGENESS (WORK-)SHOPPING LIST

- comparison of $p_T$ spectra with 3D+1 hydro + UrQMD
- more results on reference colliding systems (pp, pA, dA)
- more constrains for coalescence/recombination mechanism
- constructive discussion on equilibrium vs non equilibrium for strangeness
- for (multi-)strange and resonances:
  - kinetic freeze-out parameters
  - azimuthal anisotropy coefficients (up to high $p_T$)
- tomography ($R_{AA}$, 2-part angular and gamma-jet/s-hadron correlations):
  - flavour / system (AA, pp, pA, dA) / energy (RHIC BES to LHC) / centrality dependence

Many thanks for your attention!

Thanks a lot to the organisers for the invitation...