Heavy-Ion Prospects for HL-LHC

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(on behalf of ALICE, ATLAS, CMS, LHCb)

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30.10.17
Heavy-Ion Physics at the Energy Frontier

- LHC is precision machine for heavy-ion physics
  - Has set standard for measurements of particle production, collective flow and energy loss

Yield vs. Species

- 12 species!

C(Δφ) vs. Δφ

- 0-1%

$p_{T\text{miss}}$ vs. $A_J$

- CMS

$R_D(z)$ vs. $z$

- ATLAS Preliminary

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Heavy-Ion Physics at the Energy Frontier

- LHC is a discovery machine for heavy-ion physics
  - Quarkonia melting and J/ψ regeneration
  - Collective-like effects in small systems
Open Questions

• Underlying dynamics
  – Macroscopic QGP transport properties measured with accuracy
  – What is the underlying dynamics? I.e. the model describing long wavelength (ideal fluid) and short wave-length ("quenching") behavior
  – What are the (relevant) degrees of freedom / microscopic structure?
  – How to derive behavior from QCD?

• QGP onset (as a function of system size)
  – Traditionally, onset of QGP physics expected (leading to postulation of smoking gun observables). Reality more complex…
  – Smooth onset to first order in many observables, with some fine structure to second order
  – Huge potential to learn about underlying dynamics, i.e. non-perturbative QCD
Heavy Ions at the LHC

• Run 2:
  – Pb-Pb: few nb$^{-1}$ (0.7 nb$^{-1}$ in 2015, ~1 nb$^{-1}$ in 2018) at $\sqrt{s_{NN}} = 5$ TeV
  – p-Pb at 5 and 8 TeV (185 nb$^{-1}$ in 2016)
  – pp reference at Pb-Pb energy (5 TeV, Nov 2017)

• LS2:
  – LHC injector upgrades; bunch spacing reduced to 50 ns
  – Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  – Experiments’ upgrades (also LS3)

• Runs 3+4:
  – Request for Pb-Pb: >10 nb$^{-1}$
    (ALICE: 10 nb$^{-1}$ at 0.5T + 3 nb$^{-1}$ at 0.2T)
  – In line with projections by machine:
    3.1 nb$^{-1}$/month (Chamonix 2017)

\[ \sigma_{\text{hadr,PbPb}} = 8 \text{ barn} ! \]

HL-LHC for heavy ions begins in Run 3 !
Detector Upgrades
most relevant to heavy-ion physics

• **ALICE (LS2)**
  – New inner tracker: precision and efficiency at low $p_T$
  – New pixel forward muon tracker: precise tracking and vertexing for $\mu$
  – TPC upgrade + readout + online data reduction $\times 100$ faster readout (continuous)

• **ATLAS (LS2/LS3)**
  – Fast tracking trigger (LS2): high-multiplicity tracking
  – Calorimeter and muon upgrades (LS2): electron, $\gamma$, muon triggers
  – ZDC replacement planned (LS2): radiation hardness, granularity
  – Completely new tracker (LS3): tracking and b-tag up to $\eta=4$

• **CMS (mainly LS3)**
  – Extension of forward muon system (LS2): muon acceptance
  – Completely new tracker (LS3): tracking and b-tag up to $\eta=4$
  – Upgrade forward calorimeter (LS3): forward jets in HI

• **LHCb (LS2)**
  – Triggerless readout, full software trigger, higher granularity detectors: impact on tracking performance in Pb-Pb being studied
  – Fixed-target programme with SMOG + possible extensions
Trigger/Readout Strategies

ALICE
• Main focus on “untriggerable” signals (extremely low S/B)
• Trigger approach: write all events at 50 kHz in Pb-Pb
e.g. ALICE: \(\approx 1.1 \text{ TB/s} \quad \text{O}\textsuperscript{2} \text{ facility} \quad \approx 90 \text{ GB/s} \) (50 kHz)
• Increase of minimum-bias sample \(x100\) wrt Run-2

LHCb
• Similar strategy than ALICE, but rates to be defined

ATLAS/CMS
• Main focus on muon, jet, displaced track triggers
• Trigger approach: strong event number reduction
e.g. CMS: 50 kHz \(\rightarrow\) \(\approx 10 \text{ kHz} \quad \text{L1} \rightarrow \text{HLT} \rightarrow \approx 3 \text{ kHz}\)
• Increase of minimum-bias (rare-trigger) sample \(x5 \) (\(x10\)) wrt Run-2
Heavy-Ion Physics in Run 3 and 4

Precision Physics

• Energy loss / $q_{\text{hat}}$
  – Jets, $b,\gamma,Z$-jets, di-jets, colour/mass dep.
• Probe chiral symmetry restoration at $\mu_B = 0$
• QGP deconfinement and temperature
  – Quarkonia dissociation and regeneration
• Charm interaction with QGP
• Temperature dep. of transport coefficients
• Behaviour across system size
• High $Q^2$ and high-$x$ nPDFs
• Ultraperipheral collisions
• Production of nuclei

Novel Directions

• Jet substructure
  – probe medium degree of freedom
• QGP temperature evolution
• Beauty thermalization
• Critical fluctuations, link to lattice QCD
• Collective behaviour of few particle systems
• Saturation at small $x$
• Light by light scattering
• Antihypernuclei and dibaryon

Existing documents: ALICE Upgrade LOI | MFT | ITS | MTK
ATLAS projections | ITk

CMS HI HL-LHC projections
HI Town Meeting | Input to ESPG
Heavy Flavour

- Study QGP with tagged probe produced only initially which preserves identity during medium lifetime
- Do heavy quarks thermalize?
  - Charm and beauty $v_2$ down to $p_T = 0$
- How does charm recombine from the QGP?
  - $D_s/D$, $\Lambda_c/D$, $\Lambda_b/B$ ratio
- Charm cross-section to $p_T = 0$
  - Reduce regeneration model uncertainties
- Beauty transport compared to lattice QCD
Flavour dependence of energy loss
- Charm and beauty $R_{AA}$

Precise measurement of photon-jet and Z-jet asymmetry

Suppression at TeV scale

Flavour dependence of fragmentation function

Jet substructure observables
- Medium-modified splitting
- Colour coherence
- Probe QGP degrees of freedom (quasiparticles vs. fields)
Quarkonia

- J/ψ flow precision measurement
- Compare states with different binding energy
  - Melting and regeneration
  - Formation models
- Bottomonia flow in reach

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<th>Y(1S)</th>
<th>Y(2S)</th>
<th>Y(3S)</th>
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<td>270k</td>
<td>40k</td>
<td>7k</td>
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(in CMS in 10nb⁻¹)
(Low-mass) Dileptons

- Time dependence of QGP temperature
  - Black body radiation from QGP
- Change of $\rho$ spectral function when chiral symmetry is restored
- LHCb potential to be explored (pp, p-Pb, Pb-Pb)
Small Systems

- pp and p-Pb collisions initially only discussed as reference
- Today: novel field, studying non-perturbative “heavy-ion” like effects in absence of large medium
- HL: search for collective effects in HF, thermal radiation, quenching
- What is smallest droplet of matter showing collective behavior?
- Origin of collectivity in few particle system? (color reconnection, gluon interference, escape, …)
Further Directions

• Ultraperipheral collisions
  – Light-by-light scattering
  – Photo-nuclear collisions $\rightarrow$ nPDFs

• Light nuclear states
  – Dynamical coalescence vs. statistical thermal production
  – Discovery of (anti-)(hyper-)nuclei and (strange) dibaryons
  – Precision of $^3\Lambda$H lifetime and spectrum

• Lighter ions
  – Increase of hard yields and system-size dependence
  – Potential in overall programme and optimal species to be established
p-Pb and Fixed Target

- Nuclear PDFs
- Saturation
- Forward access to $x = 10^{-6}$
- Fixed target with SMOG system in LHCb
- Top
  - Recent “discovery” in p-Pb
  - Probe large $Q^2$ – large $x$ region
  - HL: 10xstats allows rapidity dep. measurement
    - and “discovery” in Pb-Pb
      (500-900 ttbar rec. expected)

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Parallel Session Structure

• WG5 aims
  – Sharpen and document physics program for Run 3 and 4
  – Explore future directions beyond Run 4 and for HE-LHC

| Session 1 | Tuesday 11:00 – 13:00 | 4-3-006 | Guided discussion: Heavy flavour and Quarkonia
|           |                     |       | Talk: Radiation/low-mass dileptons |
| Session 2 | Tuesday 14:00 – 16:00 | 160-1-009 | Guided discussion: Jets/energy loss
|           |                     |       | Guided discussion: Flow/correlations |
| Session 3 | Tuesday 16:30 – 18:30 | 160-1-009 | Guided discussion: Flow/correlations (cont.)
|           |                     |       | Guided discussion: Small systems |
| Session 4 | Wednesday 9:00 – 10:30 | 40-S2-A01 | Talk: Cosmic ray physics
|           |                     |       | Guided discussion: nPDFs/small-x/UPC |
| Session 5 | Wednesday 11:00 – 13:00 | 40-S2-A01 | Talk: Identified spectra and nuclei
|           |                     |       | Open question session: LHC and beyond |
Summary

- Heavy-ion physics addresses fundamental aspects of QCD in particular in the non-perturbative regime

- Heavy ions are and will be an integral part of the LHC program
  – with precision physics and discoveries

- ALICE, ATLAS, CMS and LHCb promise rich physics results

We wish you a productive workshop!