Future of heavy-ion program at the LHC

Wei Li (Rice University)

Many thanks to Pasquale Di Nezza, Laure Marie Massacrier
Heavy-ion experiments at the LHC

HI program at the LHC expanded significantly beyond the originally planned scope of four experiments taking data and producing highly competitive results.

Design: PbPb at $\sqrt{s_{NN}} = 5.5$ TeV (4 weeks per year)
Complementarity!
Heavy-ion physics at the LHC

We have discovered a strongly-coupled QGP, which shows striking behavior as a nearly perfect fluid. But we still know little about: why it flows and what is flowing?

Approach: probing the QGP with multitude of probes at the LHC.
Heavy Ions at Run 1 + 2015

Integrated NN luminosity

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>PbPb</td>
<td>2.76</td>
</tr>
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$\sim 0.7 \text{ nb}^{-1}$ for PbPb
Future

LS2:
- ALICE major upgrades
- LHCb major upgrades
- CMS/ATLAS Phase 1 upgrade

Future:
- Run 2
- Run 3
- Run 4

Ultimate goal:
- PbPb $L_{int} \sim 10 \text{ nb}^{-1}$
- Peak interaction rate: $\sim 50 \text{ kHz}$
ALICE future upgrade strategy

High precision measurements of rare probes from low to high $p_T$ scale, with focus on heavy flavors

Detector capabilities requirements:
• Excellent tracking resolution at low $p_T$
• High statistics $\Rightarrow$ High readout rate
• Excellent PID capability

Major upgrades planned during LS2 (2019-2020)
Quantifying the QGP – heavy flavor

Open heavy flavor: collective flow to probe early thermalization

Not as easy to trigger on at low and intermediate $p_T$
ALICE upgrade

- New Inner Tracking System (ITS)
- TPC with GEM based readout
- Improved readout for TOF, ZDC, TRD, MUON ARM
- New Central Trigger Processor
- New DAQ/Offline architecture
- New Muon Forward Tracker (MFT)
ALICE TPC upgrade

Upgrade objective:

Continuous readout of PbPb events at 50kHz

Currently limited at 3.5kHz mainly due to ion back flow (IBF)

New GEM readout
Low-mass dileptons with upgraded TPC

Current rate capability

![Graph showing the current rate capability with PbPb events at \( S_{NN} = 5.5 \text{ TeV} \), 0 - 10%, 2.5E7 events. Legend includes contributions from various processes: Sum, Rapp in-medium SF, Rapp QGP, cocktail w/o \( \rho \) (± 10%), \( c\bar{c} \rightarrow ee \) (± 20%), and 2.5E7 'measured'. Syst. err. bkg. (± 0.25%).]

Upgraded rate capability

![Graph showing the upgraded rate capability with PbPb events at \( S_{NN} = 5.5 \text{ TeV} \), 0 - 10%, 2.5E9 events. Legend includes contributions from various processes: Sum, Rapp in-medium SF, Rapp QGP, cocktail w/o \( \rho \) (± 10%), \( c\bar{c} \rightarrow ee \) (± 20%), and 2.5E9 'measured'. Syst. err. bkg. (± 0.25%).]
## ALICE ITS upgrade

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<td>7</td>
</tr>
<tr>
<td>Rapidity coverage</td>
<td>$</td>
<td>\eta</td>
</tr>
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<td>1.1% $X_0$</td>
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| Spatial resolution   | 12 x 100 $\mu$m$^2$  
                      | 35 x 20 $\mu$m$^2$  
                      | 20 x 830 $\mu$m$^2$ | 5 x 5 $\mu$m$^2$  |
| Max Pb-Pb readout rate | 1 kHz     | 100 kHz     |

Higher rate and resolution!
ALICE ITS upgrade

Higher rate and resolution!

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|                       | $35 \times 20 \, \mu m^2$
|                       | $20 \times 830 \, \mu m^2$ | $\sim 5 \times 5 \, \mu m^2$ |
| Max Pb-Pb readout rate| 1 kHz        | 100 kHz     |
Heavy flavor physics with upgraded ALICE

Current

Upgraded

Precision studies of $c$ and $b$ down to $p_T \sim 0$ GeV/c
Heavy flavor physics with upgraded ALICE

Data-driven separation of prompt vs non-prompt $D^0$

Direct reconstruction of $B$ with non-prompt $J/\psi$
Heavy flavor physics with upgraded ALICE

Higher $s$ abundance in QGP

$\Rightarrow$ $D_s$ enhanced if from in-medium hadronization

First time in PbPb!

Hadronization via thermal vs coalescence?
CMS/ATLAS strategy

Focusing on

✧ high statistics, very high $p_T$ hard probes
✧ Large acceptance $\Rightarrow$ long-range correlations
✧ Flexible trigger capability $\Rightarrow$ rare events

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<th>Run 3+4</th>
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<td>2010–2011 2.76 TeV 160 $\mu$b$^{-1}$</td>
<td>HL-LHC 5.5 TeV 10 nb$^{-1}$</td>
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<td><strong>Jet $p_T$ reach (GeV/$c$)</strong></td>
<td>$\sim$ 300</td>
<td>$\sim$ 1000</td>
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<tr>
<td><strong>Dijet ($p_{T,1} &gt; 120$ GeV/$c$)</strong></td>
<td>50k</td>
<td>$\sim$ 10M</td>
</tr>
<tr>
<td><strong>b-jet ($p_T &gt; 120$ GeV/$c$)</strong></td>
<td>$\sim$ 500</td>
<td>$\sim$ 140k</td>
</tr>
<tr>
<td><strong>Isolated $\gamma$ ($p_T^{\gamma} &gt; 60$ GeV/$c$)</strong></td>
<td>$\sim$ 1.5k</td>
<td>$\sim$ 300k</td>
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<td>$-$</td>
<td>$\sim$ 10k</td>
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<td><strong>$W$ ($p_T^W &gt; 50$ GeV/$c$)</strong></td>
<td>$\sim$ 350</td>
<td>$\sim$ 70k</td>
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<tr>
<td><strong>$Z$ ($p_T^Z &gt; 50$ GeV/$c$)</strong></td>
<td>$\sim$ 35</td>
<td>$\sim$ 7k</td>
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x60 $L_{\text{int}}$ and x3 from $\sqrt{s}$
Quantifying the QGP – high-\(p_T\) hard probes

“Golden probes” of QGP

\(\gamma+\text{jet}\)

\(Z+\text{jet}\)

First look at run 1&2 for proof of principle
Quantifying the QGP – high-$p_T$ hard probes

Statistical reach of 10 nb$^{-1}$
Phase I upgrades for ATLAS/CMS

**Pixel detectors**: add 1 measurement point
- ATLAS: Insertable Barrel Layer - 2015 (LS1)
- CMS: Full replacement - end 2016

**Calorimeters**: increase granularity for trigger
- ATLAS: new Front End in Liquid Argon (barrel & endcaps) - LS2 (2018)
- CMS: New photo-detectors for HF/HE/HB (also anomalous signal) - From 2015 to LS2

**Muon systems**: complete coverage - improve forward resolution for trigger
- ATLAS: coverage - 2015 New forward disks - LS2
- CMS: Complete coverage of CSCs and RPCs
  Increase CSC read-out granularity - 2015

**Trigger/DAQ**: improve bandwidth & processing
- ATLAS: New Back-End electronics - LS2
  and Fast Track Trigger (FTK) input at High Level Trigger - before LS2
Key Phase II Upgrades

Current at conceptual design and R&D level. Mainly driven by HL-LHC pp program.

- “Megaherz” DAQ
  - 1MHz readout rate for 150PU pp events
  - 100kHz readout rate for PbPb: entire event selection based on full reconstruction in the HLT

- Tracker Upgrade
  - 4 layer Pixel system, coverage: $|\eta|<2.4 \rightarrow |\eta|<4$
  - New SiStriptracker: fast readout necessary for the MHz DAQ

- High Granularity Calorimetry
  - Better handle on jet constituents
Heavy ion program at LHCb

First heavy ion run in 2013: $L_{\text{int}} \sim 1.6 \text{ nb}^{-1}$ for pPb

Collider mode

Fixed target mode

$p$   $\rightarrow$   Pb

$\sqrt{s_{NN}} = 8.2 \text{ TeV}$

$p$   $\rightarrow$   Gas (He, Ne, Ar...)

$\sqrt{s_{NN}} = 110 \text{ GeV}$

Pb   $\rightarrow$   Pb

$\sqrt{s_{NN}} = 5.0 \text{ TeV}$

Pb   $\rightarrow$   Gas (Ne, Ar)

$\sqrt{s_{NN}} = 69 \text{ GeV}$

LHCb preliminary 2015 pNe data

J/ψ

D$^0$

entries / 16 MeV/c$^2$

entries / 8 MeV/c$^2$

$\mu^+ \mu^-$ invariant mass (MeV/c$^2$)

π K invariant mass (MeV/c$^2$)
Heavy ion program at LHCb

Participated in the PbPb run in 2015

Currently limited to peripheral (50-100%) events due to detector granularity

Plan to upgrade VERTex LOCator (silicon strips) at LS2 to improve granularity and reach full centrality for run 3-4
Summary

Era of precisely quantifying the sQGP at the LHC heavy ion programs

Successful run 1+2 HI program for all 4 experiments

Future upgrades on the way to bring exciting new opportunities of heavy-ion physics in the coming decade
Backup