Experimental status of heavy-ion collisions at LHC
Outline

1. Collectivity in p-Pb vs. PbPb
2. Energy loss (jet, $\gamma$-jet, heavy quarks)
3. Melting temperature, quark recombination via quarkonia production
4. Summary

*Note: This talk is not intend to a complete review of LHC HI results, but rather to show selected recent results (from QM14 w/ personal bias), try to summarize the current understanding of LHC HIC.
1. Collectivity (pPb and PbPb)

Highest pPb multiplicity ~ 55-60% Pb-Pb.
• ALICE preliminary results of $p_T$ spectra in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

• Shown here are for $\pi$, $K$, $p$, $K^0$, $\Lambda$, $\Xi$, $\Omega$

• Fitted by the blast wave model (global fit).
$T_{\text{kin}}$ vs. $\langle \beta_T \rangle$ in blast wave

- Coherent fit for $\pi$, $K$, $p$, $K^0$, $\Lambda$, $\Xi$, $\Omega$ for different centrality (pp, pPb, PbPb)

- At same $N_{ch}$, $\langle \beta_T \rangle$ larger in p-Pb than in that in Pb-Pb, but also, $\langle \beta_T \rangle$ similarly large in pp and p-Pb (at same $N_{ch}$) with large T.

- Strong correlation between $T$ and $\langle \beta_T \rangle$. 
Similar large radii ($R_{\text{long}}$ up to 5 fm) in pPb & PbPb at the same $N_{\text{ch}}$. Scaling with multiplicity and $k_T$ (dynamical behavior).
Di-Hadron Correlations in p-p & p-Pb

- First observation of ridge structure in high multiplicity p-p (CMS).
- Also confirmed in p-Pb high multiplicity events.
- Alway side ridge structure is observed in high multiplicity p-Pb.

**p-p (N \geq 110)**

CMS \( N \geq 110, 1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c \)

\[
\Delta \eta = 5.02 \text{ TeV}, N_{\text{trk}} \geq 110
\]

\( 1 < p_T < 3 \text{ GeV}/c \)

**p-Pb (N \geq 110)**

CMS p+Pb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)

\[
1 < p_T < 3 \text{ GeV}/c
\]

ATLAS \( \int L = 1 \mu\text{b}^{-1} \)

\[
0.5 < p_T < 4 \text{ GeV}
\]

- CMS, JHEP 1009 (2010) 91
- CMS, PLB 718 (2012) 795
- ATLAS, PRL 110, 182302 (2013)
Double ridge structure in p-Pb

- Extract double ridge structure by subtracting p-p jet like distribution in p-Pb (60-100%) from central p-Pb (0-20%).
- Confirmed that near and away side ridges are almost same structure, a la "Double ridge".
- Strong correlation between near and away side yields, suggesting the same origin.
Multi-particle correlations (PbPb vs. pPb)

- Observed non-flow effect in $v_2\{2\}$.
- $v_2$ stays large when calculated with multi-particles.
- $v_2\{4\}=v_2\{6\}=v_2\{8\}=v_2\{LYZ\}$ within 10%
- Suggest collectivity in p-Pb.
1. Adjust p+Pb $p_T$ scale by 4/5 to account for difference in $<p_T>$ (Teany et al.) for ATLAS data.

2. Pb+Pb $v_2$ and $v_4$ multiplied by 0.66 to match p+Pb

- Compare p+Pb and Pb+Pb
- Good agreement between p-Pb and Pb-Pb when including $p_T$, $v_2$, $v_4$ rescaling
- $v_2$ for $\pi$, $K$, $p$ (ALICE) and $K_{s0}$, $\Lambda$ (CMS)
- Very similar behaviour for $v_2$ in Pb-Pb, i.e, Mass ordering & crossing
Quark number scaling test in pPb

Quark number scaling of $v_2$.

- Comparison in p-Pb and Pb-Pb in same $N_{ch}$.

- Seems better in pPb.
Remarkable similarity in $v_3$ as a function of multiplicity in p-Pb and Pb-Pb
Now on PbPb;
towards precession measurements of identified particle $v_2$
- ALICE data of $v_2$ measured for $\pi$, K, $K^0$, p, $\phi$, $\Lambda$, $\Xi$, $\Omega$

- Mass ordering ($p_T < 2.5$ GeV/$c$).
Number of quark constituent scaling violated by ~20% in particular in central collisions ($p_T/n_q > 1$ GeV/c)
Closer look at $\phi$ meson $v_2$ (Pb-Pb)

- $v_2$ at low $p_T$ follows mass ordering
- $v_2$ at high $p_T$ close to $p$ in central, and close to $\pi$ in mid-central

- In central collisions $p$ and $\phi$ $p_T$ spectra have similar shape up to $\sim 4$ GeV/c, as expected from radial flow.

- Indicated that mass (and not number of constituent quarks) is main driver of $v_2$ and spectra in central only?

Pb-Pb: $p/\phi$ ratio vs $p_T$

\begin{align*}
\text{Pb-Pb: } p/\phi \text{ ratio vs } p_T \\
80-90\% & \quad 0-10\% \\
10-20\% & \quad 30-40\%
\end{align*}
2. Energy loss
1) Large energy imbalance is observed in central Pb-Pb.

\[ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

\( p_{T,1} \): leading jet
\( p_{T,2} \): sub-leading jet

2) Large \( A_J \): low momentum particle (< 4 GeV/c) emitted at large angle on away side.
\( \gamma \)-jet: jet tomography

- \( \gamma \) as a calibrated probe of jet energy.
- Significant change in \( R_{J\gamma} \), \( <x_{J\gamma}> \) compared to PYTHIA and pp.

\[
< x_{J\gamma} > = \frac{p_T^{jet}}{p_T^\gamma}
\]

\( R_{J\gamma} \): fraction of photons with jet partner

$\gamma$-jet in pPb, PbPb

- $R_{J\gamma} = \text{fraction of photons with a jet of } p_{T, \text{jet}} > 30 \text{ GeV}$
- Jet energy is essentially unmodified in pPb.
Jet spectra in Pb-Pb, p-p

**pp 2.76 TeV**

**Pb-Pb 2.76 TeV**

- ATLAS: in different $y$ and centrality, up to $p_T < 400$ GeV
Jet $R_{AA}$: centrality and $y$ dep.

- Jet $R_{AA}$ vs $p_T$ and $y$.
- Factor of $\sim 2$ suppression up to jet $p_T$ of 400 GeV.
- Slow increase with increasing jet $p_T$, may vary with centrality.
Jet $R_{AA}$: centrality and $y$ dep.

- $R_{AA}$ monotonically decreases vs $N_{\text{part}}$
- $R_{AA} \approx 0.8$ in 60-80%,
- $R_{AA} \approx 0.4$ in 0-1% at lower jet $p_T$
- No significant dependence on rapidity observed
- Even though both spectrum shape and $q/g$ fractions vary with $y$
Jet Fragmentation in PbPb

- Ratios of $D(z)$ vs centrality, using baseline peripheral (60-80%)
- In addition to features previously seen (modification of small $z$ (low $p_T$)), indication of an enhancement at large $z$
Jet Fragmentation in PbPb

- Enhancement at large $z$ (or $p_T$) clearer for smaller jet radii ($R = 0.2, 0.3$).
D mesons $R_{AA}$ and $v_2$

- D mesons are also strongly suppressed.
- **significant non-zero $v_2$ for D.**
Charm vs. Bottom

- $R_{AA}$ for charmed meson (D) vs. bottom meson ($J/\psi$ from B decay).
- First indication of a flavor dependence of $R_{AA}$.
- $R_{AA}^B > R_{AA}^D$
Now on pPb;
Jet/heavy q in pPb
Unmodified for charged hadron and jet in pPb.
Jets coming from b (second vertex)
As suppressed as incl. jets ($R_{AA} \approx 0.5$)
Not suppressed in pPb ($R_{pA} \approx 1$)
Jet in pPb, $R_{AA}$, $y$ dep.

- Inclusive jet in pPb, no $y$ dependence seen
ATLAS observes a strong variation in jet yield with centrality at high $p_T$ or forward rapidities.
Jet $R_{pPb}$ (centrality dep.)

- If inclusive $R_{pPb} \sim 1$ and $R_{CP}$ shows such effects, necessarily;
  - Peripheral enhancement
  - Central suppression

Some explanations:
- Geometrical effect (proton special configuration, protons with larger $x$ partons have a reduced soft cross section)
- It is still unclear for this effect...
B meson in p-Pb

$B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^*$, $B_s \rightarrow J/\psi \phi$

- **Showing no modification** (large uncertainty, incl. the FONLL ref)
RpPb for heavy quark

- Showing no modification for D, $b(\rightarrow c)\rightarrow e$, $c,b \rightarrow \mu$

\[ \text{ALICE Preliminary} \]

\[ b(\rightarrow c)\rightarrow e \]

\[ p-Pb, \sqrt{s_{_{NN}}} = 5.02 \text{ TeV}, -1.06 < y_{_{CMS}} < 0.14 \]

\[ \text{ALICE Preliminary} \]

\[ b \rightarrow \mu \]

\[ p-Pb, \sqrt{s_{_{NN}}} = 5.02 \text{ TeV}, \mu^- \rightarrow c,b \text{ decays} \]

\[ 2.5 < y_{_{CMS}} < 3.54 \]

\[ \text{ALICE Preliminary} \]
3. Melting temperature for quarkonia, and recombination
Dissociation temperature

Melting excited $\Upsilon$ states
- Suppression of ground state $\Upsilon(1S)$, and excited states $\Upsilon(2S)$ and $\Upsilon(3S)$.
- Consistent with the sequential melting scenario, $\Upsilon(3S) > \Upsilon(2S) > \Upsilon(1S)$. 

Excited states in pPb: less suppressed than in PbPb

Excited/ground state ratio appears to vary w.r.t. the pPb and pp event multiplicity (at mid-rapidity)
$J/\psi$ (color screening vs. regeneration)

- $J/\psi$ measured at mid-rapidity $|y| < 0.9$, by $e^+e^-$ at LHC.
- Compared to RHIC mid-rapidity data.
- Significant larger $R_{AA}$ than those at RHIC.
J/ψ measured at forward-rapidity 2.5 < y < 4, by μ⁺μ⁻ at LHC.

Compared to RHIC forward data.

Significant larger $R_{AA}$ than those at RHIC.

Suppression is stronger than that at mid-rap.
$J/\psi$ (color screening vs. regeneration)

- $J/\psi$ $R_{AA}$ is enhanced at low $p_T$.
- Compatible with models including regeneration.
• \( J/\psi \) produced via regeneration of thermal de-confined c-quarks should show a non zero \( v_2 \).

• **Data:** Hint of non-zero \( v_2 \).

• Consistent with the transport model with regeneration.
Summary

- **p-Pb**
  - High multi. events: collectivity, similar to those in Pb-Pb, but not same.
  - Inclusive hard probes (jet, γ-jet, heavy q) do not show modification.
  - Indication of centrality dep. of jet yields in high $p_T$ (ATLAS).

- **Pb-Pb**
  - $\phi$: mass effect dominant in central only?
  - Stronger suppression for D than that for B.
  - J/psi: importance of regeneration of cc-bar, non-zero $v_2$. 
Questions to be answered in Run-1/2

1. What is the driving force of collectivity in p-Pb and p-p high multiplicity events?
   - Multi-parton int. is the only cause?
   - Role of CGC?

2. Medium response to jet.
   - Measurements of hard + soft interaction, i.e. soft observables w/ jet axis.

   - di-jet, γ-jet, h(π⁺⁻)-jet, correlations etc. w.r.t. reaction plane.
Thank you for your attentions!