Future of Heavy Ion Physics at the LHC
LHC Heavy Ion Program

LHC Heavy Ion Data-taking
Design: Pb + Pb at $\sqrt{s_{NN}} = 5.5$ TeV
(1 month per year)

- LHC Collider Detectors
  - ATLAS
  - CMS
  - ALICE

John Harris (Yale)
Heavy Ions at the LHC

- **Determine Initial Conditions** – *What is the extent of shadowing, saturation, CGC?*
  - sets the stage for particle production / dynamics

- **Expect different timescales, interaction times, higher energy (T) w.r.t RHIC!**
  - **Does system still equilibrate rapidly?**
    - Thermal model still apply? → $T$ still $\sim T_c$ (lattice QCD)?
  - **Does it flow?**
    - Elliptic Flow change? → $v_2$ still saturated? More or less $v_2$? $p_T$ dependence?
  - **Is the QGP still strongly- (or weakly-) coupled?**
    - Impact on energy loss!!

- **Understand parton energy loss!** – *What are the microscopic processes?*
  - $\rightarrow$ mass and flavor dependence?
  - $\rightarrow$ use high $p_T$ jets & tag heavy quark jets

- **Understand response of the medium!**
  - Strongly interacting quarks and gluons $\rightarrow$ away-side response?

- **Color screening of the medium!**
  - Deconfinement? (compare LQCD), initial T, other effects $\rightarrow$ $J/\psi$ & $Y$ states
Probable LHC Near-term Heavy Ion Program

2010 (official)
- 18 – 31 Oct: Change-over from p + p to Pb + Pb
- 1 – 28 Nov: $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb for physics

2011 (anticipated)
- November timeframe: $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb for physics
- 2010 – 2011: increasing $L \rightarrow$ integral luminosity $\int L \, dt \sim 25 \mu b^{-1}$

2012 (official)
- Shutdown for maintenance, installation & repairs

2013
- 1 month $\sqrt{s_{NN}} = 5.5$ TeV Pb + Pb for physics

2014
- 1 month $\sqrt{s_{NN}} = 5.5$ TeV Pb + Pb for physics to reach $\int L \, dt \sim 1 \text{ nb}^{-1}$

2015
- 1 month* $\sqrt{s_{NN}} = 5.5$ TeV p + Pb and Pb + p for physics
- * Possibly longer than 1 month due to proton injector shutdown/upgrade
- lighter A + A possible
# 2010-2011: Early Heavy Ion Running

<table>
<thead>
<tr>
<th>Metric</th>
<th>Early (2010/11)</th>
<th>Design/Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s per nucleon pair</td>
<td>TeV</td>
<td>2.76</td>
</tr>
<tr>
<td>Initial Luminosity (L₀) – to increase with time (2010 → 2011, 2013, 2014)</td>
<td>cm⁻²s⁻¹</td>
<td>1.25 x 10²⁵</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>1350</td>
</tr>
<tr>
<td>β*</td>
<td>m</td>
<td>2</td>
</tr>
<tr>
<td>Pb ions/bunch</td>
<td></td>
<td>7 x 10⁷</td>
</tr>
<tr>
<td>Transverse norm. emittance</td>
<td>µm</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity half life (1,2,3 expts.)</td>
<td>h</td>
<td>τ(IBS)=7-30</td>
</tr>
</tbody>
</table>

Initial interaction rate: 100 Hz (10 Hz central collisions \( b = 0 – 5 \) fm)  

\(~10^8\) interaction/\(10^6\)s (~1 month)  

In two years: 2 x10⁷ central collisions, integrated luminosity 25 µb⁻¹
Prospects (ala ALICE) for “First Physics”

- **First physics** is NOW – pp important reference data for heavy-ions
  - Examples:
    - multiplicity distribution, baryon transport
    - identified particle spectra
    - measurement of charm cross section major input to pp QCD physics

- **First $10^5$ PbPb events**: global event properties
  - multiplicity, rapidity density, charged particle spectra
  - elliptic flow

- **First $10^6$ PbPb events**: source characteristics and spacetime evolution
  - identified particle spectra, resonances
  - differential flow analysis
  - particle correlations, interferometry

- **First $10^7$ PbPb events**: high-$p_T$ and heavy flavors
  - suppression, “jet” quenching, heavy flavor energy loss
  - charmonium production

- **Eventual goals**: bulk properties of medium & parton energy loss mechanisms
  - energy density, temperature, pressure
  - heat capacity/entropy, viscosity, sound velocity, opacity
  - susceptibilities, order of phase transition
Event Characterization (baseline, shadowing, CGC, ....)
- Multiplicity, centrality, transverse momentum and pseudo-rapidity distributions

Bulk Properties of the Medium (T, \( \mu \), ...)
- Particle ratios, hadronic resonances

Chiral Symmetry Restoration
- Short-lived resonances & medium-modified masses

Collision Dynamics (space-time evolution, transport properties)
- Momentum correlations (3D HBT – one of first measurements)
- Collective Flow (radial, anisotropic)
- Baryon number transport

Fluctuations
- Event-by-event – particles, momentum, ...
**Example – $v_2$ Predictions for the LHC**

- **$v_2$ by ALICE in 1$^{st}$ Pb + Pb Run**
  - Identified particle $v_2$
  - as a function of centrality
  - to at least $p_T = 10$ GeV/c
  - resonances, strangeness
  - including charm!

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**Figure 1:**
- $v_2$ plotted against multiplicity for RHIC and LHC, showing differences in $v_2$ values.
- RHIC and LHC are marked on the graph.

**Figure 2:**
- Graph showing $v_2/\varepsilon$ for Au+Au Charged collisions at $b=6.3\text{fm}$.
- The graphs show different scenarios:
  - CGC+hydro, $T^\text{th}=100\text{MeV}$
  - CGC+hydro, $T^\text{th}=169\text{MeV}$
  - CGC+hydro+cascade

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John Harris (Yale)

High Energy and Nuclear Physics in the Far Future, BNL, 8 June 2010
**Heavy Flavor at LHC**

**Significant increase at LHC**
- Abundance of heavy flavors probe early times, calculable
  \[ \sigma_{cc} (LHC) \sim 10 \sigma_{cc} (RHIC) \]
  \[ \sigma_{bb} (LHC) \sim 100 \sigma_{bb} (RHIC) \]

**Heavy Quarkonia**
- J/$\psi$ suppression (or enhancement?)
- $\Upsilon$ suppression (statistics limited)

**Open Charm & Beauty**
- Open charm and beauty $p_T$ spectra
  - Displaced vertices: D- & B-mesons (e.g. $D^0 \rightarrow K^-\pi^+$, $B \rightarrow e^+ + \text{hadrons}$)
- Heavy quark in-medium energy loss $\rightarrow$ Mass/color charge dependence
$J/\psi (Y) \rightarrow \mu^+\mu^-$ at LHC

Heavy Quarkonia

- ~10k $J/\psi$ per experiment
- in several $p_T$ bins up to 10 GeV/c
- in ALICE down to $p_T = 0$
- Several 100 $\psi'$ per experiment, but low S/B & significance
- ~100 $Y$ in ALICE, low background
- ~500 $Y$ in ATLAS/CMS, but low S/B

0.5 nb$^{-1}$ at $\sqrt{s_{NN}} = 5.5$ TeV
Heavy Quarks in ALICE - $p_T$ Coverage

$D^0 \rightarrow K\pi$

$B \rightarrow e + X$

Simulation for $\sqrt{s_{NN}} = 5.5$ TeV
(10$^7$ central Pb-Pb events, 10$^9$ pp events)

also for $\sqrt{s_{NN}} = 2.75$ TeV in 2010 & 2011
Charm $p_T$ spectrum to 15 GeV/c
High $p_T$ Particles and Jet Rates at LHC

Hard probe physics measurements:
- High $p_T$ hadron (PID) suppression ($R_{AA}$)
- Di-hadron $\Delta\phi$ correlations to $\sim 100$ GeV/c
- Jet spectra & shapes
- $\gamma$, $Z$, $\gamma$-jet ($Z$-jet) corr's (statistics?)

Hard Probe statistics with 0.5 nb$^{-1}$ in ALICE/ATLAS/CMS:
- inclusive jets: $E_T \sim 200-325$ GeV
- dijets: $E_T \sim 170-250$ GeV
- $\pi^0$: $p_T \sim 75-150$ GeV/c
- inclusive $\gamma$: $p_T \sim 45-100$ GeV

John Harris (Yale) High Energy and Nuclear Physics in the Far Future, BNL, 8 June 2010
Charged Hadrons in CMS – High $p_T$ Trigger

ATLAS/CMS spectra $p_T$ reach $\sim 300$ GeV/c for high luminosity run
$\sim 60-100$ GeV/c for 2010-2011

Courtesy B. Wyslouch

John Harris (Yale)
Jets in Pb + Pb at LHC

25 \mu b^{-1} + trigger on hard processes

\[
\text{Pb+Pb} \ (\langle N_{\text{coll}} \rangle = 440) \\
\sqrt{s_{\text{NN}}} = 2.75 \text{ TeV} \\
R = 0.4 \\
\int L = 25 \mu b^{-1} \\
\sigma_{\text{Pb+Pb}} / \sigma_{\text{p+p}} = 100 \\
|\eta| < 4.5
\]

\[\text{# jets (p}_{T}^{\text{jet}})\]

\[10^7 \quad 10^6 \quad 10^5 \quad 10^4 \quad 10^3 \quad 10^2 \]

50 100 150 200 \[p_{T}^{\text{jet}} \text{ (GeV/c)}\]

W. Vogelsang
diff. yield

\sim 10k \text{ Jets per } E_{T} \text{ bin needed for fragmentation studies. } E_{T} \text{ reach of exp’s:}

\begin{align*}
\text{ATLAS/CMS } p_{T} \text{ reach } & \sim 140 \text{ GeV/c for 2010-2011} \\
\text{ALICE } p_{T} \text{ reach } & \sim 70 \text{ GeV/c for 2010-2011}
\end{align*}

John Harris (Yale)
Jet Shapes & Fragmentation in Pb + Pb in ATLAS

25 \mu b^{-1} + trigger on hard processes

Inclusive Jet Spectrum

\begin{align*}
\frac{1}{N_{jet}} \frac{1}{dN/dE_T} (\text{d}^2N/dE_Tdz) &
\end{align*}

E_T (GeV)

\begin{align*}
\frac{1}{N_{jet}} \frac{1}{dN/d\eta_T} (\text{d}^2N/d\eta_Tdz) &
\end{align*}

\begin{align*}
\frac{1}{N_{jet}} \frac{1}{dN/d\eta_T} (\text{d}^2N/d\eta_Tdz) &
\end{align*}

Courtesy P. Steinberg
ALICE Inclusive Jet Cross Section Measurement Capabilities with EMCal

p+p $\sqrt{s}=5.5$ TeV
Anti-$k_T$ $R=0.4$

Pb+Pb $\sqrt{s}_{NN}=5.5$ TeV
10% Central
Anti-$k_T$ $R=0.4$
$\hat{q}=14$ GeV$^2$/fm
Jets in ALICE with EMCal: $R_{AA}$

Central Pb+Pb $\sqrt{s_{NN}}=5.5$ TeV

Jet systematic uncertainties small!

Measurements possible to 200 GeV – statistically and systematically

John Harris (Yale)
LHC Design & Machine Upgrade Plans – Impact on Heavy Ion Program
RHIC and LHC Designs – the BIG Difference

RHIC: Independent bending field for the two beams

LHC: Identical bending field in both apertures of two-in-one dipole

Kinematics of Colliding Nuclei in LHC

LHC’s two-in-one design requires fixed rigidity of beams:

\[ p_{\text{Pb}} / Z_{\text{Pb}} = p_{\text{proton}} \]

<table>
<thead>
<tr>
<th></th>
<th>p-p</th>
<th>Pb-Pb</th>
<th>p-Pb</th>
<th>d-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E / \text{TeV} )</td>
<td>7</td>
<td>574</td>
<td>(7,574)</td>
<td>(7,574)</td>
</tr>
<tr>
<td>( E_N / \text{TeV} )</td>
<td>7</td>
<td>2.76</td>
<td>(7,2.76)</td>
<td>(3.5,2.76)</td>
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<tr>
<td>( \sqrt{s} / \text{TeV} )</td>
<td>14</td>
<td>1148</td>
<td>126.8</td>
<td>126.8</td>
</tr>
<tr>
<td>( \sqrt{s_{\text{NN}}} / \text{TeV} )</td>
<td>14</td>
<td>5.52</td>
<td>8.79</td>
<td>6.22</td>
</tr>
<tr>
<td>( y_{\text{CM}} )</td>
<td>0</td>
<td>0</td>
<td>2.20</td>
<td>2.20</td>
</tr>
<tr>
<td>( y_{\text{NN}} )</td>
<td>0</td>
<td>0</td>
<td>-0.46</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

\[ \sqrt{s_{\text{NN}}} \sim 2 \, c \, p_{\text{proton}} \, (Z_1 \, Z_2 / A_1 \, A_2)^{1/2} \]

\[ y_{\text{NN}} = \frac{1}{2} \log (Z_1 \, A_2 / A_1 \, Z_2) \]

**LHC Machine Operation & Upgrade Plans**

- **Phase 1** – Linac4 on track, connection to PS ~ 2014/2015
- Rough estimate of 200-300 fb$^{-1}$ by 2017
- IR upgrade could be delayed to ~2017
- Parallel effort on LHC crab cavities
LHC Machine Luminosity Upgrade Plans & Longer Term Upgrades

~ forecast from Steve Myers and Roger Bailey

shutdown for Linac4 connection

IR upgrade + crab cavities

Reach 500 fb\(^{-1}\), lifetime limit of IR quadrupoles (LHC PR 633)
**LHC Heavy Ion Luminosity Increase**

- **Pb design Luminosity (may be optimistic!)**
  - \( L_0 = 10^{27} \text{ cm}^{-2} \text{ s}^{-1}, \langle L \rangle \sim 0.3 - 0.5 \ L_0 \)
  
  “LHC heavy ion year” assume = 10^6 \text{ s} \rightarrow \int L_0 \text{ dt} \sim 0.5 \text{ nb}^{-1}

- **Examples of signals with limited statistics**
  - \( \Upsilon \) suppression
    - 7000 \( \Upsilon \), 1000 \( \Upsilon'' \) per Pb + Pb year in ALICE (> 10^5 J/\psi in NA60)
  - \( \gamma \)-jet correlations
    - 1000 \( \gamma \)-jet events/year with \( p_T > 30 \text{ GeV/c} \)
    - Fragmentation functions at large \( z \) require x 10 more!

  \( \rightarrow \) 3-4 years operation at 4-5 x \( L_0 \) provides x 10 increase in statistics!

- **Implications for ALICE**
  - Minor detector modifications necessary to benefit from 5 x \( L_0 \)
  - Limitation is TPC (pile-up, NOT space charge)
    - TPC designed for \( \text{d}N_{ch}/\text{d}y = 8000 \), expectation is 2000 – 4000
    - Rate increase possible (pile-up acceptable for high \( p_T \) physics, faster gas if needed)
LHC Detector Upgrade Plans & Heavy Ions
ATLAS Upgrade Plans*

Phase 1 (~ 2015)
- Tracker upgrade – Insertable B-Layer
  - present tracker inner layer reaches rad limit after 1 year of design $L$
  - insertable inner layer with smaller radius beam pipe
- Fast Track Trigger (proposal being developed)
  - add Level 1.5 tracking hardware trigger for B-tagging
- Forward Physics Upgrade (proposal)
  - far forward – 420 and 220 m distance from IP
    - using 3D silicon sensors with < 10 ps timing
    - diffractive production of Higgs
    - forward physics

Phase 2 (~ 2019 to utilize sLHC $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$)
- Tracker upgrade – replace entire tracking system
  - very rad hard silicon pixel (3D?) upgrade
- Trigger/DAQ upgrade – continuing upgrades to L1 & L2, introduce L1.5 triggers
  - sLHC goal at L1 – 100KHz rate (~400 interactions per crossing)

* http://www.slac.stanford.edu/exp/atlas/upgrade/

John Harris (Yale)  High Energy and Nuclear Physics in the Far Future, BNL, 8 June 2010
**CMS Upgrade Plans**

**Near Term (2012)**

- Hadron Calorimeter Upgrades
  - improve triggers on muons and forward jets
- New Beam Pipe and Luminosity Monitors (Diamond)
  - easier pixel detector installation → B-tagging

**Phase 1 (~ 2015)**

- Tracker upgrade – New Pixel System
  - low mass, faster readout → reduce deadtime, improve B-tagging
- Hadron Barrel and Endcap Calorimeter Upgrade
  - electronics & trigger upgrades, long segmentation improvement for Higgs ch’s
- Muon Trigger & Reconstruction Upgrade
  - $1.1 < |\eta| < 1.8$, $2.1 < |\eta| < 2.4$
  - W acceptance and Higgs channels

**Phase 2 (~ 2019 to utilize sLHC $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$)**

- Replace Tracker, Trigger, Endcap Calorimeter
ALICE Specific Upgrades Now for Heavy Ions

- ALICE designed primarily for Heavy Ion Physics.
  - Optimized for Pb + Pb multiplicities / luminosities ($10^{27}$–$10^{28}$ cm$^{-2}$ s$^{-1}$)

- ALICE plans only indirectly linked to LHC high luminosity upgrade
  - Some limitations to maximum Pb + Pb luminosity improved by sLHC luminosity upgrade: improvements in collimation essential.

- ALICE has evolved considerably from initial Technical Proposal, largely due to new data from RHIC.
  - Transition Raditaion Detector (TRD) approved much later than other central detectors, expected to be complete by 2011.
  - New EM calorimeter (EMCal), important for jet measurements proposed/approved(LHCC)/funded by US-Italy-France
    - 40% installed, rest complete by 2011 & next installation period.
  - New Dijet electromagnetic calorimeter (Dcal) for di-jets & $\pi^0$-jets proposed/approved/funded by US-Japan-France-Italy-China
    - Complete by 2012 shutdown & installation period.
ALICE Upgrade Plans Beyond 2010-11

- 2nd generation vertex detector (smaller beam-pipe)
  - for improved heavy quark physics
Inner Tracking System Upgrade

- **x2 impact parameter resolution** (for $p_T < 1 \text{ GeV/c}$)
  - Increases charm sensitivity x100
  - Access to charmed baryons
    - Charm B/M big issue for reco!
  - Allows study of exclusive B decays
  - Allows total B x-section to $p_T \sim 0$
  - Improves flavor tagging

- **Techniques?**
  - Thinnest / smallest beam pipe (a la CDF)
    - Reduce $R = 2.9 \text{ cm}$ to $\sim 1.3 \text{ cm}$
    - Reduce thickness from present $800 \ \mu\text{m}$ to $400 \ \mu\text{m}$
  - New pixel technology
    - Thinner ($\leq 200 \ \mu\text{m} + 150 \ \mu\text{m}$)
    - Higher granularity ($\leq 150 \ \mu\text{m} \times 425 \ \mu\text{m}$)
ALICE Upgrade Plans Beyond 2010-11

• 2\textsuperscript{nd} generation vertex detector (smaller beam-pipe)
  – for improved heavy quark physics

• PID for $p_T \sim 5 – 20$ GeV/c (based on results from RHIC)
  – for PID particle & resonance spectra/correlations, flow, recombination,…..
Very High Momentum PID Upgrade (VHMPID)

- \( p_T > 10 \text{ GeV/c} \) necessary to study
  - Flavor-dep jet fragmentation / quenching
  - Gluon vs quark origin of jet
  - \( p + p \) flavor-dep multiparticle production

- Technique
  - RICH detector with mirrors
    - Gas radiator (\( \text{C}_4\text{F}_{10} \)?)
    - Maximum length \(~80\) cm
  - Photon detector
    - MWPC with CsI photon converter & pad readout (HMPID technology)
    - Thick GEM (\( \geq 2 \) layers) with CsI photo-converter (promising results)
  - Dedicated trigger logic to select high \( p_T \)
    - Use TRD detector and/or
      - New trigger detector - 4 GEM layers & algorithm selecting high \( p_T \)
      - Use opposite EMCAL detector to trigger on high energy jets
ALICE Upgrade Plans Beyond 2010-11

• 2\textsuperscript{nd} generation vertex detector (smaller beam-pipe)
  – for improved heavy quark physics

• PID for $p_T \sim 5 – 20$ GeV/c (based on results from RHIC)
  – for PID particle & resonance spectra/correlations, flow, recombination,…..

• New detectors for forward physics (low-x in pA & AA)
  – Forward calorimeter for $\pi^0$
**ALICE Forward Physics Upgrade**

- **Forward Experimental Study**
  - Strong effects expected at large $\eta$
    - gluon shadowing
    - gluon saturation, CGC?

- **At LHC like at RHIC**
  - Small $x$ region – forward at large $\eta$
    - Present ALICE accessibility – $\mu$ arm

- **Add a Forward Calorimeter**
  - Highly segmented ($\perp$, $||$) EM-Cal
    - $3.6$ m from vertex
    - $2.3 < \eta < 4.0$
  - to measure
    - $\pi^0$, $1 < p_T < 50$ GeV/c
    - jets, $20 < E_T < 100$ GeV

- **Extending forward coverage to**
  - $4.5 < |\eta| < 6.5$ region and beyond
ALICE Upgrade Plans *Beyond 2010-11*

- 2nd generation vertex detector (smaller beam-pipe)
  - for improved heavy quark physics
- PID for $p_T \sim 5 – 20$ GeV/c (based on results from RHIC)
  - for PID particle & resonance spectra/correlations, flow, recombination, …
- New detectors for forward physics (low-x in pA & AA)
  - Forward calorimeter for $\pi^0$
- DAQ & HLT Upgrade
  - more sophisticated & selective triggers
- Extend EMCal
  - expand di-jet and gamma-jet Physics reach
- Improve muon spectrometer – tracking before absorber
- Increase rate capability of TPC
  - (faster gas, increased R/O speed)
A Possible LHC Mid-term Heavy Ion Program

2010 (official) – $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb for physics (4 weeks)
2011 (anticipated) – $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb for physics (4 weeks)
2012 (official) – Shutdown for maintenance, installation & repairs
2013 – $\sqrt{s_{NN}} = 5.5$ TeV Pb + Pb for physics
2014 – $\sqrt{s_{NN}} = 5.5$ TeV Pb + Pb for physics
   6 month shutdown - LINAC 4, vertex detector upgrades
2015 – $\sqrt{s_{NN}} = 5.5$ TeV p + Pb & Pb + p, (lighter A + A, p + p) for physics
2016 – $\sqrt{s_{NN}} = 5.5$ TeV lighter A + A, p + p for physics
   6 month shutdown – IR detector upgrade
2017 – $\sqrt{s_{NN}} = 5.5$ TeV lighter A + A, p + p for physics
2018 – $\sqrt{s_{NN}} = 5.5$ TeV high L Pb + Pb for hard probe physics
   6 month shutdown – IR Quads & detector upgrades
2019 – $\sqrt{s_{NN}} = 5.5$ TeV high L Pb + Pb for hard probe physics
2020 – $\sqrt{s_{NN}} = 5.5$ TeV high L Pb + Pb for hard probe physics
   6 month shutdown – …. upgrades
Future Heavy Ion Programs at RHIC and LHC

To investigate properties of hot QCD matter at $T \sim 150 - 1000$ MeV!

John Harris (Yale)
High Energy and Nuclear Physics in the Far Future, BNL, 8 June 2010