‘Little Bang’
The first 3 weeks ...

- Heavy Ion Physics at LHC
- First look at Pb-Pb
  - Final (published) results
  - Ongoing Analysis
Matter under Extreme Conditions

- ‘state of matter’ at high temperature & energy density: ‘The QGP’
  - ground state of QCD & primordial matter of the Universe
  - partons are **deconfined** (not bound into composite particles)
  - **chiral symmetry** is restored (partons are ~ massless)
  - ‘the stuff at high T where ordinary hadrons are no longer the relevant d.o.f’

- **Mission of URHI**
  - **search** for the QGP phase
  - **measure** its properties
  - **discover** new aspects of QCD in the strongly coupled regime

**Physics is QCD:**
strong interaction sector of the Standard Model
(where its strong !)
Role of LHC after RHIC/SPS

- **Search** for the ‘QGP’ is essentially over
- **Discovery** of QGP is well under way (with fantastic results & surprises at RHIC)
- **Measuring** QGP parameters has just begun

- **1) Quantitative differences**
  - significantly different state of QGP in terms of energy density, lifetime, volume
  - large rate for ‘hard probes’: jets, heavy quark states (b,c,γ, J/Ψ),…

- **2) Test & validate** the HI ‘Standard Model’ (< 10 years old!)
  - QGP: very strongly interacting (almost) perfect liquid
  - Test predictions/extrapolations from RHIC to LHC
    - example: flow ('soft')
    - Quarkonia suppression ('hard')

- **3) ‘Precision’ measurements of QGP parameters**
  - Quantitative and systematic study of the new state of matter
    - **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient** q (jet quenching), Debye screening mass (Quarkonia suppression), …
  - Confront data with Theory and Models:
    - **standard tools**: Lattice QCD, pQCD, Thermo- and Hydrodynamics, …
    - **new tools**: AdS/CFT (‘duality’), Classical QFT (‘Colour Glass Condensate’)

- **4) Surprises?**
  - we are dealing with QCD in the strong coupling limit!
‘Jet Quenching’

Jet quenching: jet $E$ -> jet $E'$ ($=E-\Delta E$) + soft gluons ($\Delta E$)

modified jet fragmentation function via matter induced gluon radiation/scattering

$\Rightarrow$ QGP properties

$\Rightarrow$ how much energy is lost? (measures e.g. $q^\perp$)

- most difficult question, may depend on jet cone $R$, $p_t$-cutoff, ..

$\Rightarrow$ how is it lost? (e.g. multiple soft or few hard gluons ?)

- look at soft part of $f(z)$, $p_t < 2-5$ GeV

$\Rightarrow$ ‘response of QGP’ (shock waves, Mach cones ??)

- properties of bulk matter around jet, $p_t \sim 1$ GeV
Charged Jets

- Jets in ALICE (TPC)
  - we see qualitatively a similar effect
  - quantitative analysis is ongoing
    - small acceptance (statistics), => need full 2010 data
    - try to include low $p_t$ (study $p_t$-cut off dependence of imbalance)
‘Jet Quenching’ as seen by p_t spectra

- Suppression of high p_t particles (\sim leading jet fragments)
  - Minimum \( R_{AA} \sim 1.5 - 2 \times \) smaller than at RHIC
  - Rising with p_t! (ambiguous at RHIC!)
  - Accuracy limited by pp reference
    \Rightarrow need pp at 2.76 TeV!

\[
R_{AA}(p_T) = \frac{1}{N_{\text{ev}}^{AA}} \frac{d^2N_{\text{ch}}^{AA}/d\eta dp_T}{\langle N_{\text{coll}} \rangle \frac{1}{N_{\text{ev}}^{pp}} \frac{d^2N_{\text{ch}}^{pp}/d\eta dp_T}{}}
\]

Data driven Interpolation
900 GeV & 7 TeV
or using NLO for change in shape
7 TeV * NLO (2.76 TeV)/NLO(7 TeV)

Including CDF data
0.9 TeV * NLO (2.76 TeV)/NLO(0.9 TeV)

Paper to be submitted today
High $p_T$ Particle Correlations

Trigger Particle: highest $p_T$ particle in event ($p_{Tt}$)
Associate Particle: all the others ($p_{Ta}$)
Jet Quenching seen by High $p_T$ Correlations

- classic ‘jet quenching signal’
  - away side correlation in central Pb-Pb washed out up to $p_{T,\text{trig}} > 10$ GeV

$P_T$ associated $2 - 6$ GeV

$p+p$ (7 TeV)
- ‘near’ side
- ‘away’ side

Star@RHIC
$p_{T,\text{trig}}$ 8-15 GeV
Jet Quenching (?) seen via Multiparticle Correlations

- "Autocorrelation":
  \[ \frac{d^2N_{ch}}{d\Delta\eta d\Delta\phi} (\text{signal})/ \frac{d^2N_{ch}}{d\Delta\eta d\Delta\phi} (\text{mixed events}) \]

- **pp 51-140**
- **Pb 80-90%**
- \( p_T > 1.5 \text{ GeV/c} \)

- **PbPb peripheral**
- **PbPb central**

- **'near side ridge':**
  - striking effect, not really understood
  - response of QGP to jet quenching?
  - initial state gluon radiation?
  - ???

- **same/mixed a.u.**

- **00-05%**
  - \( p_T > 1.5 \text{ GeV/c} \)
Role of LHC after RHIC/SPS

1) **Quantitative differences**
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   - large rate for ‘hard probes’: jets, heavy quark states (b,c,Y,J/Ψ),…

2) **Test & validate** the HI ‘Standard Model’

3) **‘Precision’ measurements** of QGP parameters

4) **Surprises?**
1) What’s the Difference?

- **Multiplicity and Energy density $\varepsilon$:**
  - $dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)
  - sometewh on high side of expectations
  - growth with $\sqrt{s}$ faster in AA than pp ($\sqrt{s}$ dependent ‘nuclear amplification’)

- **Energy density $\approx 3 \times$ RHIC (fixed $\tau$)**
  - lower limit, likely $\tau_0$(LHC) $< \tau_0$(RHIC)

Who gets it right and why?

- \(\frac{dN_{ch}}{d\eta}\) as function of centrality (normalised to \('overlap volume' ~ N_{\text{participants}}\))
  - soft process: \(\frac{dN_{ch}}{d\eta} \sim \) number of scattered nucleons (strings, participants, ...)
    - ‘nuclear amplification’ should be energy independent
  - (very) hard processes: \(\frac{dN_{ch}}{d\eta} \sim \) number of nucleon-nucleon collisions
    - getting more important with \(\sqrt{s}\) & with centrality

- DPMJET MC
  - gets it right for the wrong reason

- HIJING MC
  - strong centr. dependent gluon shadowing

- Others
  - saturation models:
    - Color Glass Condensate, ‘geometrical scaling’ from HERA/ photonuclear react.

Important constraint for models sensitive to details of saturation
What’s the Difference?

- **Volume and lifetime:**
  - Identical particle interferometry (HBT, Bose-Einstein correlations)
    - QM enhancement of identical Bosons at small momentum difference
    - measures Space-Time evolution of the ‘dense matter’ system in heavy ions coll.
  - **Volume** ≈ 2 x RHIC (≈ 300 fm³)
    - ‘comoving’ volume!
  - **Lifetime** ≈ +20% (≈ 10 fm/c)

\[ (E, \vec{p}) \rightarrow (\tau, \vec{X}) \]

**Preliminary: Under Collaboration Review**

- ‘Volume’ at decoupling
- ‘Lifetime’: from collision to ‘freeze-out’ (hadron decoupling)

Alice error: stat + syst

Much more information from HBT about the Space-Time evolution available.
Role of LHC after RHIC/SPS

1) **Quantitative differences**

2) **Test & validate** the HI ‘Standard Model’
   - QGP = very strongly interacting (almost) perfect liquid
     - Test predictions/extrapolations from RHIC to LHC
     - examples: flow (‘soft’) **Quarkonia suppression** (‘hard’)

3) ‘**Precision**’ measurements of QGP parameters

4) **Surprises**?
2) Testing the HI ‘Standard Model’

- Elliptic Flow: one of the most anticipated answers from LHC
  - **experimental observation**: particles are distributed with azimuthally anisotropic around the scattering plane
  - **Are we sure Hydro interpretation is correct?**

Elliptic Flow $v_2$ as interpreted by *Hydrodynamics*

- Pressure gradient converts spatial anisotropy $\rightarrow$ momentum anisotropy
- $\rightarrow$ particle yield anisotropy
Testing the HI ‘Standard Model’

- Hydro seems to work very well for first time at RHIC
  - LHC prediction: modest rise (Depending on EoS, viscosity, speed of sound, dN_{ch}/dη, ..)
  - ‘better than ideal is impossible’
  - experimental trend & scaling predicts large increase of flow
  - ‘RHIC = Hydro is just a chance coincidence’

BNL Press release, April 18, 2005:
Data = ideal Hydro
"Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

LHC will either
confirm the RHIC interpretation
(and measure parameters of the QGP EoS)

OR

Multiplicity ?????????????
First Elliptic Flow Measurement at LHC

- $v_2$ as function of $p_t$
  - practically no change with energy!
  - extends towards larger centrality/higher $p_t$?

- $v_2$ integrated over $p_t$
  - 30% increase from RHIC
  - $<p_t>$ increases with $\sqrt{s}$
  - pQCD powerlaw tail?
  - Hydro predicts increased ‘radial flow’
  - very characteristic $p_t$ and mass dependence; to be confirmed!

17 Nov: arXiv:1011.3914, acc. PRL

STAR at RHIC

ALICE

RHIC

+30%
Testing the HI ‘Standard Model’

- Hydro passed the first test!
  - many more tests of Hydro and the HI-SM to come….

CERN Press release, November 26, 2010:
‘confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid).’
Testing Quarkonia Suppression

- Interpretation of SPS & RHIC results ambiguous
  - HI–SM: $J/\Psi (Y', Y'')$ suppression stronger at LHC, $Y$ suppression depends on $T$
  - extension to HISM: $J/\Psi$ enhancement, $Y'$, $Y''$ suppression
  - recombination of charm pairs to $J/\Psi$ may mask suppression at RHIC

- Partial answer expected from this years data
  - normalisation (measured/expected) ongoing
  - $Y$ family will need integrated $L \sim 1-2$ nb$^{-1}$

\[ M_{\mu\mu} \text{ (GeV/c}^2\text{)} \]

\[ \text{Events/0.05 GeV/c}^2 \]

\[ N_{Y'} = 479 \pm 82 \]
\[ m_{J/\Psi} = 3.088 \pm 0.015 \text{ GeV/c}^2 \]
\[ \sigma_{J/\Psi} = 0.084 \pm 0.013 \text{ GeV/c}^2 \]

Pb-Pb Min. Bias
fraction of data
expect few 1000 $J/\Psi$
total by end 2010
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   - Confront with Theory and Models:
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4) Surprises ?

Precision measurements are still a long way ahead, but it looks like we will get there!
3) Towards Precision Measurements

- **Sensitivity to fluid viscosity $\eta$**
  - Quantitative results will need much more time and more experimental input …
  - elliptic flow with identified particles, radial flow ('radial expansion'),
    better determination of initial geometry, …

![Graph showing $v_2$ vs. centrality percentile]

AdS/CFT limit: $\eta$/Entropy = $1/4\pi$
Strangeness in Pb-Pb

\[ K_S^0 \]

ALICE Performance
01/12/2010

\[ \Lambda \]

ALICE Performance
01/12/2010

Mass: 1.672 GeV
\[ \sigma = 0.003 \text{ GeV} \]

ALICE Performance
29.11.2010
PbPb at 2.76 TeV

Mass: 1.322 GeV
\[ \sigma = 0.002 \text{ GeV} \]
Charm in Pb-Pb

‘Jet quenching’ with heavy quarks:
Energy loss depends on
- color charge (quark/gluon)
- mass (light/heavy quarks)
Anti-Nuclei

PbPb @ $\sqrt{s_{NN}} = 2.76$ TeV

$dE/dx$ signal in TPC (a.u.)

Rigidity $\frac{p}{Z}$ (GeV/c)

~ 2 M Pb-Pb Min Bias events
‘Single Events’

- ‘Properties of average events instead of average event properties’

- \( v_2 = 0.070566 \)
Summary

- LHC is a fantastic ‘Big Bang’ machine
  - even for LHC standards, speed and quality of ion run is outstanding
  - unprecedented powerful and complementary set of detectors
  - physics looks to be even more interesting than anticipated

While waiting for Mr. Higgs and Ms. Susy, there is plenty of exciting physics (and fun) exploring QCD in a new domain, where the strong interaction is really strong!

- Looking forward to the ‘terra incognita’ of HI at LHC

Big THANKS to the CERN crew from ion source all the way to LHC

Hic sunt Leones!