Heavy Ion Physics at the LHC
What's new ? What's next ?

- Short pre-LHC history
  - Reminder of main SPS/RHIC results
- Selected Results from the LHC
  - New light on old puzzles
  - Towards measuring QGP properties
  - Discoveries
- Open Issues/Questions
QGP: Matter under extreme conditions
- Macroscopic partonic matter ('QCD thermodynamics')
- Deconfinement/Color Conductivity
- Chiral Symmetry Restoration
The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.

Based on a (unpublished) 'common assessment' of results from ~ half dozen experiments collected & published over the course of the SPS Pb program (1994 - 2000)

http://arxiv.org/abs/nucl-th/0002042v1

in today's LHC speak: '.. a QGP-like state ..'
Main Results from SPS

- **strangeness enhancement**
  - in general: thermal particle production
  - predicted for thermal system (partonic?)

- 'anomalous' J/ψ suppression predicted as deconfinement signal

- low mass lepton pair enhancement
  - 'rho melting', sign of chiral symmetry restoration?

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- the experimental results have stood the test of time
- interpretations may have changed over time
- essence of the statements was & is correct (in my view)

**evidence for a new state of matter at the SPS energy range**

however, today more 'compelling' than in 2000!
(later SPS results, RHIC energy scan, LHC)
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

Based on a (published) comprehensive (re)analysis of the first years of RHIC (2000 - 2004)


These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective

.. created a new state of hot, dense matter out of the quarks and gluons .., but it is a state quite different and even more remarkable than had been predicted.

in today's LHC speak: not '
..the QGP ..' but '
.. a QGP ..': sQGP

sQGP: strongly interacting QGP
Main Results from RHIC

- **strong elliptic flow**
  - $\Rightarrow$ maximum possible i.e. 'ideal liquid' ($\eta/s \approx 0$)
  - mostly produced in the early phase (partonic?)

- **direct 'thermal' photons**
  - $\Rightarrow$ 'hot matter'
  - data: inverse slope $T \sim 220 \pm 20$ MeV
  - model dependent $T_0$: 300 - 600 MeV

- **high $p_T$ suppression 'jet-quenching'**
  - very strongly interacting (large energy loss)

Note: sQGP is described by its experimental properties
Also here, all experimental results AND their implied QGP characteristics stood the test of time: More remarkable than predicted!
Design Energy:
14 TeV (pp)
1150 TeV (PbPb)
What is left to do at LHC?

- **What is different?** Same physics with..
  - different 'matter:' increased energy (up to factor ~30 in $\sqrt{s}$)
    - QGP will be *hotter - larger - longer living*
    - large cross section for 'hard probes': high $p_T$, jets, heavy quarks,…
  - different experiments: new generation, large acceptance state-of-the-art detectors
    - Atlas, CMS, Alice, [LHCb, for pA]

- **Where is progress@LHC?**
  (very limited & personal selection)
  - New Light on Old Problems (NLOP)
    - hadronisation/particle production
    - quarkonia suppression
  - Towards Precision Measurements (PM) of QGP parameters
    - elliptic flow: viscosity $\eta/s$
    - jet quenching: opacity $q^\wedge$
  - Discoveries
    - the 'Ridge': long range correlations in pp & pA
NLOP I: Particle Production

- Hadronisation is non-pertubative
  - phenomenological models ('event generators') with many parameters
    - strings or clusters, $\text{PPAR}(x), x=1,..n$
- Statistical ('thermal') models: accurate to $O(10\%)$ (no 'a priori' justification)
  - particle with mass $m$ produced in 'heat bath $T$' according to phase space
  - $P(m) \sim e^{-(m/T)}$

$T_{ch}$: 160-170 MeV  $\gamma_s$: 0.9-1 (AA), 0.5-0.6 (pp)

strangeness enhancement = QGP signal?

- $T_{ch}$ Temperature (ch='chemical')
- $\mu_b$ Baryo-chemical potential (baryon conservation)
- $\gamma_s$ Strangeness suppression

Data

- RHIC pp $\sqrt{s_{NN}} = 200$ GeV
  - $T=170.1\pm3.5$ MeV
  - $VT^3=135\pm60$
  - $\gamma_s=0.569\pm0.031$
  - $\chi^2=15.6/14$ dof

- SPS Pb-Pb
  - $T=157.8\pm1.9$ MeV
  - $\mu_B=247.4\pm7.7$ MeV
  - $\gamma_s=0.843\pm0.033$
  - $\chi^2=16.9/9$ dof

Model

- $\Lambda(1520)$
- $\Omega+\bar{\Omega}$
- $K^0$
- $p$
- $K^+$
- $\phi$
- $\Lambda(1520)$
- $\Omega$
Dynamical Origin of Thermal Ratios?

- 'born into equilibrium' \((e^+e^-, \text{ pp, AA})\)
  - yields \(\sim\) QCD \(\times\) (hadronic) phase space
  - \(\textit{pp} \ \gamma_s < 1: \text{QCD, } m_s\)
  - \(\textit{AA} \ \gamma_s \approx 1: \text{ thermo-dynamics in parton phase}\)

  \(\Rightarrow \textbf{BUT: } e^+e^-, \text{ pp: why } T_c \approx T_{ch} \text{ AA: why don't we see parton equilibrium?}\)

- 'evolving into equilibrium' (AA)
  - thermodynamics in hadron phase
  - arbitrary (eg pp-like) initial hadron ratios + inelastic reactions
  - reach equilibrium close to phase boundary \((T_{ch} < T_c)\)
    \(\text{A + B} \leftrightarrow \text{C + D + E}\)

  \(\Rightarrow \textbf{BUT: } \text{dynamic system (expansion & cooling) } \Rightarrow \text{ expect sequential freeze-out?}\)
  - hadrons with large inelastic \(\sigma\) should freeze out later (lower T)!

In this picture, statistical models work
- in AA by design (thermodynamics),
- in pp/e^+e^- by accident (dominance of PS).
Conceivable, but limited direct evidence.
Particle Ratios at LHC

- **pp**: Less well described than at lower energies!
  - fits 2 ratios with 2 parameters ($T$, $\mu_B$)
  - maybe finally 'hard QCD processes' (ME, dynamics) become visible over PS?

![Graph showing particle ratios at different energies](image-url)
Strangeness is enhanced +30% (K), > factor 3 (Ω)
γ_s = 1, like thermal model
p/π off by factor > 1.5 from predictions!
suppressed, not enhanced, compared to pp

initially very surprising result (safest prediction for LHC !)

Particle Ratios Pb-Pb

Pb-Pb \sqrt{s_{NN}} = 2.76 TeV, 0-20% centrality
pp \sqrt{s} = 7 TeV

(Prediction, no fit)

\begin{align*}
\text{Thermal Model } & T = 164 \text{ MeV}, \mu_b = 1 \text{ MeV}, \gamma_s = 1 \\
\end{align*}
NLOP I: Current Explanations

- Sequential Freeze-out
  - hadronic final state reactions
  - but: more art than science..
  - many unknown $\sigma$ (e.g. $\Lambda + \Omega \rightarrow n\pi + mK$)
  - detailed balance (e.g. $p + p \leftrightarrow 5\pi$)

Questions 1: Hadronisation

Unanticipated deviations at LHC from the Statistical Model (pp&AA)

- Evidence against the SM?
- Make the 'mysteriously successful' SM more reasonable by showing expected/conceivable deviations? (NLO-corrections)
- In either case, can we use these results to make progress?
NLOP II: Quarkonia Suppression

Heavy Flavor $c\bar{c}$ / $b\bar{b}$

hard collisions (pQCD@$\tau \approx 0$)

'diffuse' (colour conductivity)

'melt' (deconfinement)

- J/$\Psi$ suppression similar at RHIC and SPS!
  - should depend on Energy (Temperature/Density)
    - 1) **No J/$\Psi$ melting** at both SPS & RHIC ($T > 1.5 - 2\, T_c$)?
      only weakly bound states ($\Psi'$ & $\chi$) melt.
    - 2) **More J/$\Psi$ melt** at RHIC than at SPS
      but 'by chance' cancellation from regeneration ($c\bar{c}$ recombination)?
J/ψ: Consistent with Melting + Regeneration!

J/ψ $R_{AA}$: centrality dependence

- ALICE (Pb-Pb $s_{NN} = 2.76$ TeV), 2.5 < $y$ < 4, $p_T$ > 0 (preliminary)
- PHENIX (Au-Au $s_{NN} = 0.2$ TeV), 1.2 < |$y$| < 2.2, $p_T$ > 0 (arXiv:1103.6269)

LHC > RHIC

J/ψ $R_{AA}$: $p_T$ dependence

- Inclusive J/ψ, centrality 0%-90%, 2.5 < $y$ < 4 (global sys. ± 7%)

Recombination/Coalescence:

- Purist: Dirt effect, obscures deconfinement
- Pragmatist: Deconfinement signal!

Deconfinement $\leftrightarrow$ colour conductivity

'partons roam freely over large distance'

Regeneration more important at
- central: $\sim N_c^2$
- low $p_T$: phase space

Forward $y$ ~ 3

Central $y$ = 0
Y suppression

- **Y(1S), ~ 50% direct**
  - direct Y not suppressed?

- **Y(2S) (~ J/Ψ)**
  - up to 5 x stronger suppression than Y(1S)

- **Y(3S) ~ gone**
  - Y(3S)/Y(1S) < 0.1 (95%CL)

**Sequential suppression**

as expected from deconfinement!!

Caveats:

- **Feed-downs** from the many bb states to be sorted out
- **Initial State Effects** (to be estimated from pA)
NLOP II: Quarkonium Suppression

- J/ψ, the HP par excellence: 'well calibrated (pQCD) smoking gun'

Matsui & Satz, 1986:

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Questions 2: Quarkonia Production

- Regeneration (if confirmed): Dirt effect or Deconfinement signal?
- Sequential Y suppression: Settles the deconfinement case?
- If neither, what else would be needed from experiments? (besides smaller errors)
Flow in Heavy Ion Collisions

- **Elliptic Flow** $v_2$
  - Initial Conditions
    - e.g. Geometry
      - eccentricity $\varepsilon_2 = (y^2 - x^2)/(y^2 + x^2))$
  - Fluid Properties
    - e.g. shear viscosity $\eta$
      - usually use Viscosity/Entropy ($\eta/s$ dimensionless)

Fourier analysis: $dN/d\phi = 1 + 2v_2 \cos(2\phi) + \ldots$

Spatial deformation

Anisotropic flow

Azimuthal ($\phi$) pressure gradients

Anisotropic particle density

Pressure $\Delta p_x > \Delta p_y$
QGP: The 'perfect Liquid'

- **Perfect liquid** ➔ **Viscosity** $\eta/s \approx 0$
  - large interaction cross section $\sigma$ in the liquid

- unexpected result
  - QGP though to behave like a gas (i.e. weakly interacting)

- closest Theory prediction $\eta/s > 1/4\pi \approx 0.08$
  - AdS/CFT: ('QCD analogue')
    - (Conformal Field Theory in Anti-de Sitter Space)
  
  - conjectured Quantum limit:
    - $\eta/s = 1/4\pi$
    - mfp $\lambda \approx$ Compton wavelength

- **Pre-LHC limit**: $\eta/s < (3-6) \times 1/4\pi$
  - initial conditions
    - (pressure/energy distribution) not known precisely enough

\[ \eta = \frac{\sqrt{2mkT}}{\sigma} \]
Initial Conditions

- **Around 2010**
  - 2) Event-by-Event fluctuations → more complicated shapes (higher order)

- suggested in 2010 but controversial, higher $v_n$ where not directly 'seen' in the data

Fourier series: $dN/d\phi = 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots$

- Elliptic, $v_2$
- Triangular, $v_3$
overwhelming and unambiguous evidence: complex structures from E-b-E hydro flow
- interference of different harmonics
- all characteristics as expected from hydro: strength, mass/centrality/momentum dependence

Two Particle Correlation projection on $\phi$

$V_1 + V_2 + V_3 + V_4 + V_5$

$\eta-\phi$ Two Particle Correlation (Atlas)

Ridge
Valley

$V_3$ for $\pi/K/p$
mass dependence typical for hydro!
A most amazing Discovery

- The 'face' of the collision zone, (state-of-art for 20 years)
  - including 'warts & wrinkles' of each event
- progress in precision measurements of $\eta/s$
- higher harmonics large sensitivity to viscosity
- discriminate & constrain models & geometry

Hydro Calculation
From Leading Order ..

- elliptic flow $v_2$

.. to NLO ...

- higher harmonic flows $v_3, \ldots v_6$

.. to NNLO ...

- correlation between harmonic symmetry planes via geometry constraints
- correlation between harmonic symmetry planes via non-linear interactions in the hydro evolution (mode mixing)

leading to better limits on $\eta/s$

Better limit, but not yet good enough.

Aim for measurement ($<30\%$ ?) of $\eta/s$!

- $\eta/S < 1/4\pi \Rightarrow$ conjectured limit is wrong
- $\eta/S > 1/4\pi \Rightarrow$ measure $\sigma$ in QGP
- $\eta/S \approx 1/4\pi \Rightarrow$ AdS/CFT quantum corrections? $O(10-30\%)$

pre-LHC

$4\pi\eta/s < 3-6$

post-LHC

$4\pi\eta/s < 2-3$


May 2013 Stockholm J. Schukraft

TPM-I: Quantum Jump in Exp. & Theory
TPM-II: Jets & 'Jet-quenching'

- Partons loose energy $\Delta E$ when traversing a medium
  - $\text{Jet}(E) \rightarrow \text{Jet } (E' = E - \Delta E) + \text{soft particles}(\Delta E)$
  - QCD energy loss $\Delta E$ expected to depend on:
    - $\hat{q}$: 'opacity' = property of medium ('radiation length of QGP')
    - $L$: size of medium ($\sim L$ (elastic) $\sim L^2$ (radiative) $\sim L^3$ (AdS/CFT))
    - $c_q$: parton type (gluon > quark)
    - $f(m)$: quark mass (light $q$ > heavy $Q$)
    - $f(E)$: jet energy ($\Delta E = \text{constant}$ or $\sim \ln(E)$)

Jet quenching measures

- 'Stopping power' of QGP
  - $\Delta E \sim f(m) \times c_q \times \hat{q} \times L^n \times f(E)$

1) How much energy is lost?
   - Measure jet imbalance $E - E'$
2) Where (and how) is it lost?
   - Measure radiated energy $\Delta E$
3) Shows expected scaling?
   - Vary $L$, $m$, $E$, ...
Observation of Jet Quenching

- Observed at RHIC in 2001
  - via suppression of 'leading fragments' (not enough energy to see jets)
    - qualitative clear effect, quantitative interpretation difficult & model dependent

- Very striking at LHC
  - many unbalanced \((E_1 \neq E_2)\) jets and 'monojets'

\(R_{AA}\): measured / expected yield

Energy flow in \(\eta-\phi\) plane

Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

Atlas
CMS
Alice

102 GeV
47 GeV
1) How much Energy is lost?

- Di-Jet energy balance $A_j$
  \[ A_j = \frac{(P_{T1} - P_{T2})}{(P_{T1} + P_{T2})} \]

$P_{T1} \approx P_{T2}$

$<\Delta E> \approx 20$ GeV (wide distribution)

Medium is VERY strongly interacting ('opaque')
(but within expectations)

2) Energy dependence

- jet quenching $\Delta E \sim \ldots$

roughly as expected
(weak dep. on Energy)

(CMS PLB 712 (2012) 176)

jet quenching

$\Delta E \sim f(m) \times c_q \times \hat{q} \times L^n \times f(E)$

GY Qin & BM
PRL 106 (2011) 162302
2) Where (& how) is it lost?

**Di-jet angular correlation $\Delta\phi_{12}$**

![Graph showing di-jet angular correlation](image)

**Unexpected Result:**
- Jets remain back-to-back like in pp (little additional broadening from radiated Energy)
- Radiated energy appears in **low energy hadrons**, far away from the jet (CMS PRC 84 (2011) 024906)
4) Mass & Color Charge Dependence

- Measure Heavy Quarks (c,b) versus $\pi$ (gluon fragmentation dominates $\pi$ at LHC)

- Requires better statistics & quantitative comparison with models

\[ R_{AA} = \text{measured/expected} \sim \text{AA/pp} \]

\[ \Delta E \sim f(m) \times c_q \times q \times L^n \times f(E) \]

**Expectation:**

\[ \Delta E(\pi) > \Delta E(D) > \Delta E(B) \]

- quon ↔ quark
- light ↔ heavy

**Hints** for the expected hierarchy

less strong than naively expected

**Needs better statistics & quantitative comparison with models**
The first LHC Discovery (pp, Sept 2010)

- long range rapidity 'ridge' in 2-particle correlations
- visible in the highest multiplicity pp collisions
- arguably still the most unexpected LHC discovery

If we are here today it is because we didn’t succeed to kill it.

We have therefore submitted the paper to expose our findings to the scrutiny of the scientific community at large.

G. Tonelli, CERN/INFN/UNIPI

CERN LPCC/EP/PP SEMINAR

September, 21 2010
• Spawned a large number of different explanations
  ⇒ mostly rather ad hoc, very speculative, or outright weird

• Color Glass Condensate CGC: 'first principles' theory
  ⇒ classsical FT in high density limit (small x, small Q²)
  ⇒ 'new state of cold & dense parton matter'
  ⇒ some success describing aspects of ep, pp, eA:
    geometric scaling, low-x, particle production, ..
  ✰ however, no 'smoking gun' so far…

• Collective flow (Hydro) ?
  ⇒ vaguely similar correlations in nucleus-nucleus
Ridges everywhere..

- Ridge is much stronger in pPb (end 2012)!
  - and is, in fact, a 'double ridge'
  - even and odd components ($v_2$, $v_3$)
  - collective multiparticle (i.e., not 'jet' like)
  - now also seen in dAu at RHIC! (tbc)
  - strength $\approx$ as predicted by some hydro models

\[ \text{CMS pPb 5 TeV} \]
\[ \text{ATLAS pPb 5 TeV} \]
\[ \text{ALICE pPb 5 TeV} \]
CGC in trouble?
- mini-jet like correlation (4 part. << 2 part. ?), no odd harmonics ($v_3$), ...

Collective 'Hydro-like' flow in pA (& pp) ??
- energy/particle density quiet comparable to AA (eg high $N_{ch}$ pp@LHC ≈ Cu-Cu mid-central @RHIC)
- system size only few fm$^3$ ??
  - however, hydro has no intrinsic size, only ratio's: $\lambda/r$, and $\lambda \approx 0$ ! (from $\eta/s$)
  - a proton@LHC is more like a small nucleus (dozens of partons, MPI,..) !

additional measurements should tell
- mass dependence of ridge ($\pi$, K, p)
- other collective signals (eg radial flow via $p_T$ spectra, expansion via HBT/BE correlations)

In either case, more than a curiosity
- CGC
  - discovered a 'new state of matter'
  - smoking gun for new 'first principle' limit of QCD
- Hydro
  - dazzling: a system the size of a single hadron behaves like 'macroscopic matter'
  - 'extra dimension' for QGP study: size !
  - finite size effects => correlation & coherence length, time scales, ....

New State of Matter created at CERN which features many of the characteristics of the theoretically predicted Colour Glass Condensate.

RHIC Scientists found "Colorful Glass" to serve the Perfect Liquid

Rewrite the textbooks at least change the title from 'Heavy Ion physics' to ..
Questions 3: (assuming hydro explanation for ridge)

Similar hadronisation (particle ratios), now signs of collectivity in pp?

pp, pA, AA: What, if anything, is qualitatively different?

- Does this make AA more pp-like? (no 'new state of matter)
- Or pp more AA like? (QGP 'matter' everywhere in dense systems > few fm$^3$)
  How small can it get?

- Is there another smoking gun for CGC in pA at LHC? (should be, x < 10$^{-3}$-10$^{-5}$)
- If not, is there still a science case for an electron-ion collider?
The Questions:

**Questions 1: Hadronisation**

Unanticipated deviations at LHC from the Statistical Model (pp&AA)
- Evidence against the SM ?
- Make the 'mysteriously successful' SM more reasonable by showing expected/conceivable deviations ? (NLO-corrections)
- In either case, can we use this to make progress ?

**Questions 2: Quarkonia Production**

- Regeneration (if confirmed): Dirt effect or Deconfinement signal ?
- Sequential Y suppression: Settles the deconfinement case ?
- If neither, what else would be needed from experiments ? (besides smaller errors)

**Questions 3: (assuming hydro explanation for ridge)**

Similar hadronisation (particle ratios), now signs of collectivity in pA (& pp) ?

**pp, pA, AA: What, if anything, is qualitatively different ?**
- Does this make AA more pp-like (no 'new state of matter) ?
- Or pp more AA like (QGP 'matter' in all dense hadronic systems > few fm³) ?
- Is there another smoking gun for CGC in pA at LHC (there should be, x < 10⁻³-10⁻⁵) ?
- If not, is there still a science case for an electron-ion collider ?
What's next for HI?

- **short/medium term at LHC** \((\approx 5 \text{ y})\)
  - complete (& solve ?) the **quarkonia puzzle** (deconfinement)
  - quantify 'other effects' (pA), measure \(\Psi'\), better \(Y\)
  - theory: needs progress in calculating melting temperatures!
  - **Hydro**: increased precision/sophistication \((\text{e.g. } 30\% \text{ in } \eta/s \ ??)\)
  - solve the 'ridge' mystery (CGC vs Hydro vs ??)
  - any other sign of CGC in pA@LHC ? (e.g. monojets at large \(y\) => LHCb)
  - **pA at LHC could make (or break ?) the science case for eRHIC/EIC**

- **medium/longer term LHC** \((\approx 10 \text{ y, including exp/LHC upgrades})\)
  - comprehensive & precise **energy loss** ("jet-quenching") \((\text{needs HF,} \gamma\text{-jet})\)
  - **chiral symmetry restoration** ? \(\text{e.g. much better low mass lepton pairs(NA60)}\)

- **Outside LHC** (not part of this presentation)
  - 'Phase Transition Line' & 'Tri-critical Point'
  - matter at high baryon density (compression)
    - FAIR@GSI, NICA@DUBNA
    - RHIC energy scan, SPS fixed target
  - where starts the 'normal' (hadronic) matter ?
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Similar hadronisation (particle ratios), now signs of collectivity in pA (& pp)?
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- Or pp more AA like (QGP 'matter' in all dense hadronic systems > few fm$^3$)?
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- If not, is there still a science case for an electron-ion collider?
Spares
A challenge for model
Inclusive $J/\psi$ suppression measurements both in central and forward regions for $p_T>0$:

- from $N_{\text{part}} > 100$ suppression independent of centrality
- in central collisions, less suppression than at RHIC
- $R_{AA}$ decreases by 40% from $y=2.5$ to $y=4$
$e^+e^- \sqrt{s} = 91.2$ GeV

$T = 159.3 \pm 0.8$ MeV
$\chi^2 = 118.1/24$ dof

$\gamma = 0.664 \pm 0.014$
Mapping the Phase Boundary

QGP boundary measured 'particle freeze-out' boundary ($\varepsilon \approx 0.5$ GeV/fm$^3$)