Predictions for the LHC: an Overview

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Heavy Ion Collisions at the LHC - Last Call for Predictions
organized by N.A., N. Borghini, S. Jeon and U.A. Wiedemann,
arXiv:0711.0974 (93/170/82 contributions/authors/institutes).
Contents:

A. The bulk:
A.1. Multiplicities.
A.2. Azimuthal asymmetries.
A.3. Hadronic flavor observables.

B. Hard and EM probes:
B.1. High-$p_T$ observables and jets.
B.2. Heavy quarks and quarkonium.
B.3. Leptonic probes and photons.

Only predictions for PbPb.

See also Borghini and Wiedemann, arXiv:0707.0654.
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A.1. Multiplicities.
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Only predictions for PbPb.

Remark: I assume that a RHIC- (and possibly SPS-) tested model can be reliably extrapolated to the LHC. The huge lever arm in energy will eventually falsify some of them.

See also Borghini and Wiedemann, arXiv:0707.0654.
A.1. Multiplicities (I):

Predictions for the LHC: an Overview: A. The bulk observable, key input in almost all other predictions.

To unify the discussion, I ‘rescale’ to \( dN_{\text{ch}}/d\eta |_{\eta=0} \) for \( N_{\text{part}}=350 \) using a Monte Carlo (Amelin et al., EPJC22(2001)149):

Predictions for the LHC: an Overview: A. The bulk
A.1. Multiplicities (II):

\[ \frac{dN_{\text{ch}}}{d\eta} |_{\eta=0} \text{ in Pb+Pb at } \sqrt{s_{\text{NN}}} = 5.5 \text{ TeV for } N_{\text{part}} = 350 \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolschin et al.</td>
<td>corr., RDM</td>
</tr>
<tr>
<td>Porteboeuf et al.</td>
<td>EPOS</td>
</tr>
<tr>
<td>Kharzeev et al.</td>
<td>saturation</td>
</tr>
<tr>
<td>Jeon et al.</td>
<td>data driven, limiting frag.</td>
</tr>
<tr>
<td>Fujii et al.</td>
<td>fcBK evolution</td>
</tr>
<tr>
<td>Eskola et al.</td>
<td>corr., EKS98+geom. sat.</td>
</tr>
<tr>
<td>El et al.</td>
<td>corr., BAMPS</td>
</tr>
<tr>
<td>Dias de Deus et al.</td>
<td>percolation</td>
</tr>
<tr>
<td>Chen et al.</td>
<td>corr., AMPT+gluon shad.</td>
</tr>
<tr>
<td>Capella et al.</td>
<td>DPM+Gribov shad.</td>
</tr>
<tr>
<td>Busza PHOBOS</td>
<td>data driven, limiting frag.</td>
</tr>
<tr>
<td>Bopp et al.</td>
<td>corr., DPMJET III</td>
</tr>
<tr>
<td>Topor Pop et al.</td>
<td>corr., HIJING/Bb v2.0</td>
</tr>
<tr>
<td>Armesto et al.</td>
<td>geom. scaling</td>
</tr>
<tr>
<td>Albacete</td>
<td>corr., rcBK evolution</td>
</tr>
<tr>
<td>Abreu et al.</td>
<td>corr., logistic evol. eq.</td>
</tr>
</tbody>
</table>

Predictions for the LHC: an Overview: A. The bulk
A.1. Multiplicities (II):

\[ dN_{ch}/d\eta \mid _{\eta=0} \text{ in Pb+Pb at } \sqrt{s_{NN}} = 5.5 \text{ TeV for } N_{\text{part}} = 350 \]

- Wolschin et al.
- Porteboeuf et al.
- Kharzeev et al.
- corr., RDM
- EPOS
- saturation
- data driven, limiting frag.
- corr., DPMJET III
- corr., HIJING/B\bar{B} v2.0
- geom. scaling
- corr., rcBK evolution
- corr., logistic evol. eq.

- **Generic expectation:** less than 2000.
- **Most models include now a large degree of collectivity:** strong gluon shadowing, strong color fields, saturation,...
A.2. Azimuthal asymmetries: $v_2$

$p_T$-integrated $v_2$ is expected to increase from RHIC to the LHC: origin? Hydro predictions do not coincide with naive extrapolations.

From BW.
A.2. Azimuthal asymmetries: $v_2$ in hydro

Drescher et al., smaller deviation from ideal hydro limit than at RHIC.

Bluhm et al., QPM EOS, results < RHIC at low $p_T$.

Eskola et al.; hydro valid for $p_T < 4$ GeV (also Arleo et al.).

Kestin et al.

Predictions for the LHC: an Overview: A. The bulk
A.2. Azimuthal asymmetries: $v_2$ in hydro

Drescher et al., smaller deviation from ideal hydro valid for $p_T < 4$ GeV (also Arleo et al.).

⇒ Generic expectation: $v_2$ similar or slightly decreasing at low $p_T$.
⇒ A strong decrease would probably signal an increase in $\eta/s$, but initial conditions have to be settled.

Kestin et al.

Eskola et al.; hydro valid for $p_T < 4$ GeV (also Arleo et al.).

Predictions for the LHC: an Overview: A. The bulk
A.2. Azimuthal asymmetries: \( v_2 \) in others

Porteboeuf et al., EPOS, hydro core, \( v_2 \sim \text{RHIC} \).

Chen et al., AMPT, parton + hadron transport.

Molnar, MPC parton cascade, fixed \( \eta/s=0.08 \).

Capella et al., comovers.

Predictions for the LHC: an Overview: A. The bulk
A.2. Azimuthal asymmetries: $v_2$ in others

- **Porteboeuf et al.**, EPOS, hydro core, $v_2 \approx$ RHIC.

Chen et al., AMPT, parton + hadron transport.

- **Generic expectation**: $v_2$ increases at low $p_T$.
- **A strong increase is not expected in any hydro description.**

Molnar, MPC parton cascade, fixed $\eta/s=0.08$.

Capella et al., comovers.
A.3. Hadr. flavor observ.: statistical

Andronic et al., equilibrium values for $\mu_b=0.8$ MeV, $T=161$ MeV.

Kraus et al., (grand-)canonical, $T$ and $R_c$ may be determined.

Rafelski et al., non-equilibrium scenarios; non-strange resonances reduced.

Predictions for the LHC: an Overview: A. The bulk
Andronic et al., equilibrium values for $\mu_b = 0.8 \text{ MeV}, T = 161 \text{ MeV}$.

Different statistical scenarios may be distinguished.

This becomes of great importance for open charm and charmonium: different scenarios lead to marked differences in production.

Rafelski et al., non-equilibrium scenarios; non-strange resonances reduced.
A.3. Hadr. flavor observ.: baryons at low $p_T$

$p\bar{p}<4$ at $\eta=0$ (Bj: Topor Pop et al., Bopp et al.; hydro: Eskola et al.; EPOS: Porteboeuf et al., RDM: Wolschin et al.).

Hydro and recombination predict larger baryon/meson ratios than models with higher string tension; the latter predicts Cronin for protons.

Predictions for the LHC: an Overview: A. The bulk
A.3. Hadr. flavor observ.: baryons at low $p_T$

$p-p\bar{p}<4$ at $\eta=0$ (BJ: Topor Pop et al., Bopp et al.; hydro: Eskola et al.; EPOS: Porteboeuf et al., RDM: Wolschin et al.).

> Cronin effect for protons will strongly constrain models.

> Ratios will further clarify the hadronization mechanism.

> A large $b-b\bar{b}$ at $\eta=0$ would be a real surprise.
A.4. Correlations at low $p_T$: HBT

Sinyukov et al., HKM; also Karpenko et al., FASTMC.

<table>
<thead>
<tr>
<th>RHIC/LHC for π's</th>
<th>Chen et al., AMPT, $b=0$, $0.3&lt;k_T&lt;1.5$</th>
<th>Chojnacki et al., 0712.0947, hydro+stat., $b=1$ fm, $k_T=0.3$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{out}}$</td>
<td>3.60/4.23</td>
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</tr>
<tr>
<td>$R_{\text{side}}$</td>
<td>3.52/4.70</td>
<td>4.3/5.3-6.3</td>
</tr>
<tr>
<td>$R_{\text{long}}$</td>
<td>3.23/4.86</td>
<td>6.1/7.6-8.6</td>
</tr>
</tbody>
</table>

Hydro: same problems as at RHIC - $R_{\text{out}}$ ($k_T$), $R_{\text{side}}$($k_T$), $R_{\text{out}}$ $>>$ $R_{\text{side}}$; out- → in-plane shape.

Frodermann et al.

Predictions for the LHC: an Overview: A. The bulk
A.4. Correlations at low $p_T$: HBT

- R’s increase from RHIC to the LHC in all models.
- But the predictive power is limited by the problems at RHIC.
- Dissipative effects on HBT are not well understood yet.

<table>
<thead>
<tr>
<th>Model</th>
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Hydro: same problems as at RHIC - $R_{out}(k_T)$, $R_{side}(k_T)$, $R_{out} >> R_{side}$; out- $\rightarrow$ in-plane shape.
B. Hard probes: benchmark

Predictions for the LHC: an Overview: B. Hard and EM probes
To avoid this uncertainty within the LHC frame, an accurate control of the benchmark will be required (as it was at RHIC).
B.1. High-\(p_T\) observ.: \(R_{AA}\) for light flavors

Predictions for the LHC: an Overview: B. Hard and EM probes
$R_{\text{PbPb}}(p_T=20,50 \text{ GeV}, \eta=0)$ in central Pb+Pb at $\sqrt{s_{\text{NN}}}=5.5 \text{ TeV}$

Wang et al., $\pi^0$, 5% ($\langle E_0 \rangle \sim 3.3 E_0^{\text{RHIC}}$), WW eloss+1d exp., shadowing
Vitev, $\pi^0$, 10%, GLV+g-feedb.+cold eloss, $dN/dy \sim 1.7-3.3 (dN/dy)^{\text{RHIC}}$
Pantuev, charged, $N_{\text{part}}=350$, $t_{\text{QGP}}=1.2 \text{ fm} \sim 0.5 (t_{\text{QGP}})^{\text{RHIC}}$
Lokhtin et al., charged, 10% ($dN^g/d\eta \sim 2700$), rad.+coll. eloss in MC
Kopeliovich et al., $\pi^0$, 10%, early hadronization
Liu et al., $\pi^+$, $p_T^{\text{highest}}=40$, 10%, 2$\leftrightarrow$2 w. conv., transv. exp.
Jeon et al., $\pi^0$, $p_T^{\text{highest}}=40$, 10% ($\lambda=1 \text{ fm}$), BH eloss+QW, $\Delta E/E=(\Delta E/E)^{\text{RHIC}}$
Wicks et al., $\pi^0$, 10%, rad.+coll. eloss, $dN^g/d\eta \sim 1.75-2.9 (dN^g/dy)^{\text{RHIC}}$
Qin et al., charged, 10% ($dN^\text{ch}/d\eta \sim 2500$), AMY+hydro, $\alpha_s=0.25-0.33$
Renk et al., $\pi^0$, 10% ($dN^\text{ch}/d\eta \sim 2500$), BDMPS QW with hydro evol.
Dainese et al., $\pi^0$, 10%, BDMPS QW with WS, $\hat{q} \sim 2-7 \hat{q}^{\text{RHIC}}$
Cunqueiro et al., $\pi^0$, 10% ($dN^\text{ch}/d\eta \sim 1500$), percolation
Capella et al., $\pi^0$, 10% ($dN^\text{ch}/d\eta \sim 1800$), comovers, kinematics
Radiative energy loss favors $R_{AA} \sim 0.1 - 0.2$ at $p_T \sim 20$ GeV and increasing with increasing $p_T$. 

Predictions for the LHC: an Overview: B. Hard and EM probes
B.1. High-\(p_\text{T}\) observ.: hadrochemistry and FF

Modification of hadrochemistry due to elastic + conversions, rad. eloss or modified jet radiation.

Modified fragmentation functions, both for jets (elastic+radiative in PYQUEN) and for the hadron-triggered case (WW rad. model).

Predictions for the LHC: an Overview: B. Hard and EM probes
B.1. High-\(p_T\) observ.: hadrochemistry and FF

Modification of hadrochemistry due to elastic + conversions, rad. eloss or modified jet radiation.

Chemical composition and more differential observables will be key to establish the mechanism underlying jet quenching.

Fragmentation functions, both for jets (elastic+radiative in PYQUEN) and for the hadron-triggered case (WW rad. model).

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: $R_{AA}$ for heavy

pQCD-based models valid for hadronization outside the medium, so for high $p_T$ (see also Vitev).

Double ratios $B/D$ are sensitive to mass effects until quite high $p_T$ and offer possibilities to discriminate models for HQ jet quenching (Horowitz et al.).

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: $R_{AA}$ for heavy

- LHC will provide $R_{AA}$ for both leptons and mesons.
- Double ratios will become available.
- This will clarify the mechanism for HQ jet quenching and hadronization.

Double ratios $B/D$ are sensitive to mass effects until quite high $p_T$ and offer possibilities to discriminate models for HQ jet quenching (Horowitz et al.).

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: quarkonia suppr.

Andronic et al.: dependence on charm cross section; Thews et al.: $p_T$-broadening to verify recombination, with uncertainties from cold matter effects (Kang et al.).

Vogt: $p_T$-dependent screening, no regeneration; H. Liu et al., suppression at larger $p_T$.

Capella et al., 0712.4331, comovers+reco.
B.2. HQ and quarkonium: quarkonia suppr.

Andronic et al.: dependence on charm cross section; Thews et al.: p_{T}-broadening to verify

Considerable uncertainties both in the production and in the suppression mechanisms limit our predictive power.

Vogt: p_{T}-dependent screening, no regeneration; H. Liu et al., suppression at larger p_{T}.

Capella et al., 0712.4331, comovers+reco.
High $p_T$: quenching in fragmentation (also Arleo).

Low $p_T$: new effects e.g. conversions, thermal,... expected (also Rezaeian et al.).

Predictions for the LHC: an Overview: B. Hard and EM probes
B.3. Leptonic probes and photons: photons

Predictions for the LHC: an Overview: B. Hard and EM probes

High $p_T$: quenching in fragmentation (also Arleo).
Low $p_T$: new effects e.g. conversions, thermal,... expected (also Rezaeian et al.).

⇒ At the LHC, all the regions up to very high $p_T$ can be studied.
⇒ Control of the benchmark, from pp to PbPb, key to disentangle thermal production.
B.3. Leptonic probes and photons: dileptons

Ratio $\gamma/\gamma^*$ shows a plateau at large $p_T$ of thermal origin, independently of details of expansion, EOS, ...

Dremin: Cherenkov radiation as the origin of the ‘broadening’ of the $\rho$.

Predictions for the LHC: an Overview: B. Hard and EM probes
B.3. Leptonic probes and photons: dileptons

Ratio $\gamma/\gamma^*$ shows a plateau at large $p_T$ of thermal origin, independently of details of expansion, EOS,...

- Both low and high $M$ and $p_T$ required to disentangle different mechanisms.
- But the huge HQ contribution looks really challenging.

Predictions for the LHC: an Overview: B. Hard and EM probes
### RHIC-tested models face the LHC era

<table>
<thead>
<tr>
<th>Observable at RHIC</th>
<th>Standard interpretation</th>
<th>Prediction for the LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low multiplicity</td>
<td>Strong coherence in particle production</td>
<td>$dN_{ch}/d\eta</td>
</tr>
<tr>
<td>$v_2$ in agreement with ideal hydro</td>
<td>Almost ideal fluid</td>
<td>Similar or smaller $v_2(p_T)$</td>
</tr>
<tr>
<td>Strong jet quenching</td>
<td>Opaque medium</td>
<td>$R_{AA}(20 \text{ GeV}) \sim 0.1-0.2$ for $\pi^0$</td>
</tr>
</tbody>
</table>

* This picture has motivated new theoretical developments: application of AdS/CFT, early thermalization, viscous hydro, CGC,...

* Major deviations from expectations will enlarge our understanding of Ultra-Relativistic Heavy-Ion Collisions: naive extrapolations tend to disagree with those from successful models at RHIC.

* New experimental observables at LHC: higher $p_T$, jets, higher quarkonium states,... demand new theoretical tools.

Predictions for the LHC: an Overview
To conclude: a little bit of history

Predictions for the LHC: an Overview
To conclude: a little bit of history

‘95: ALICE TDR
PbPb@6 ATeV
b<3 fm

Charged multiplicity for $\tau=0$ in central Pb+Pb at $\sqrt{s_{NN}}=5.5$ TeV

Predictions for the LHC: an Overview
To conclude: a little bit of history


Predictions for the LHC: an Overview
Forward $R_{pA}(p_T)$ as a probe of high density dynamics: saturation for light (Armesto et al., Boer et al.) and heavy (Fujii et al., Tuchin), or absence of saturation (Arsene et al.); $\Lambda$ polarization (Boer et al.).

Within CGC, total shadowing due to fluctuations (Kozlov et al.) or running coupling effects.
A.4. Correlations at low $p_T$ (II):

Bauchle et al., Mach cones in hydro, peak displaced from naive expectation; Betz et al., gradual energy deposition required. Other mechanism possible: Cherenkov (Dremin), and instabilities (Mannarelli et al.) - unstable modes for jets with speed larger than $c_s$, which peak at larger angles for larger speed.

Dias de Deus et al.: FB correlations may help to establish the dynamics of particle production.

Predictions for the LHC: an Overview: A. The bulk
Backup II: fluctuations

\[ \psi^N_{N_1/N_2} = \frac{dN_1}{dy} \nu^N_{N_1/N_2} \]

\[ \nu^N_{N_1/N_2} = \left( \sigma^N_{N_1/N_2} \right)^2 = \sigma^2_{N_1/N_2} - \left( \sigma^P_{N_1/N_2} \right)^2 = \frac{\langle N_1(N_1 - 1) \rangle}{\langle N_1 \rangle^2} + \frac{\langle N_2(N_2 - 1) \rangle}{\langle N_2 \rangle^2} - 2 \frac{\langle N_1N_2 \rangle}{\langle N_1 \rangle\langle N_2 \rangle} \]

Torrieri: fluctuations in particle ratios as a tool to verify the statistical model and decide which ensemble or non-eq. situation holds.

Cunqueiro et al.: multiplicity fluctuations determined by the number of coherent particle sources, possibility to verify phase transition scenarios.

Figure 71: Scaled variance on negatively charged particles, from up to down, LHC, RHIC and SPS.

Predictions for the LHC: an Overview
First-principle calculations of $q_{\text{hat}}$ in the vacuum correlator model (Antonov et al.), in N=4 SYM (H. Liu et al.) and in ThFT with coherence effects (Casalderrey et al.).

Inclusion of elastic eloss in DGLAP-like evolution (Pirner et al.) and consideration of a dynamical medium in GLV eloss (Djordjevic et al.).
B.2. HQ and quarkonium: reference

Arsene et al., Gribov shadowing (HT).

Vogt, effect of npdf’s (LT: EKS and nDSg): results very similar to other approaches.

Kopeliovich et al., LT+HT process-dependent shadowing.

Conesa del Valle et al.: muons from W,Z as a reference for $R_{AA}$.

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: reference

Vogt, effect of npdf’s (LT: EKS and nDSg): results very similar.

Arsene et al., Gribov shadowing (HT).

J/psi

Upsilon

y

y

PbPb/pp

PbPb/pp

5.5 TeV pp

14 TeV pp

pPb most welcome for the benchmark.

Kopeliovich et al., LT+HT process-dependent shadowing.

Conesa del Valle et al.: muons from W,Z as a reference for $R_{AA}$.

Predictions for the LHC: an Overview: B. Hard and EM probes
### B.2. HQ and quarkonium: ratios

<table>
<thead>
<tr>
<th>( D^-/D^+ )</th>
<th>( D_0/D_0 )</th>
<th>( D^{*-}/D^{**} )</th>
<th>( D_s^-/D_s^+ )</th>
<th>( \bar{\Lambda}_c/\Lambda_c )</th>
<th>( D^+/D_0 )</th>
<th>( D^{**}/D_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00(0)</td>
<td>1.01(0)</td>
<td>1.01(0)</td>
<td>1.00(1)</td>
<td>1.00(1)</td>
<td>0.425(18)</td>
<td>0.387(15)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( D_s^+/D_0 )</th>
<th>( \bar{\Lambda}_c/D_0 )</th>
<th>( \psi'/\psi )</th>
<th>( \eta_c/\psi )</th>
<th>( \chi_c1/\psi )</th>
<th>( \chi_c2/\psi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.349(14)</td>
<td>0.163(16)</td>
<td>0.031(3)</td>
<td>0.617(14)</td>
<td>0.086(5)</td>
<td>0.110(8)</td>
</tr>
</tbody>
</table>

Andronic et al.: ratios at equilibrium in the statistical model.

Kuznetsova et al.: strangeness over-saturation may lead to modifications in the ratios and to a suppression in the production of ccbar states.

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: ratios

Andronic et al.: ratios at equilibrium in the statistical model.

Chemical composition studies will have implications on recombination models for quarkonium.

Strangeness over-saturation may lead to modifications in the ratios and to a suppression in the production of ccbar states.

Predictions for the LHC: an Overview: B. Hard and EM probes
B.2. HQ and quarkonium: others

Table 7: Upper bound on quarkonium dissociation temperatures.

<table>
<thead>
<tr>
<th>state</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$J/\psi$</th>
<th>$\Upsilon'$</th>
<th>$\chi_b$</th>
<th>$\Upsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{dis}}$</td>
<td>$\leq T_c$</td>
<td>$\leq T_c$</td>
<td>$1.2T_c$</td>
<td>$1.2T_c$</td>
<td>$1.3T_c$</td>
<td>$2T_c$</td>
</tr>
</tbody>
</table>

Mocsy et al., dissociation $T$ in potential models.

H. Liu et al., screening lengths through the medium, new suppression at larger $p_T$ if produced inside the medium.

Zhang et al., thermal charm at NLO.

Gonçalves et al., charm in UPC, test of production and npdf’s.
Backup III: others

Becattini et al.: in peripheral collisions, a highly spinning QGP may be formed → decreasing $\mu_b$, larger $v_2$, polarization.

Stocker et al.: creation of black holes in HIC due to low-scale extra dimensions: suppression of dijets, remnants.

Lee et al.: coalescence formation of charmed exotic, multiquark hadrons, test of particle production mechanism.

Lokhtin et al.: exotic phenomena in HE CR, like alignment of tracks, may become visible at the LHC.

Predictions for the LHC: an Overview