Contents:

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2. Radiative energy loss.

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5. Heavy-ion collisions at the LHC.

The usual tool to compute particle production is **collinear factorization** (for \( Q \sim E_{cm} \gg \Lambda_{QCD} \)):

- **Nuclear corrections** - no medium, QGP or not - to parton densities and fragmentation functions **poorly known**.

- **Nuclear effects** usually discussed through the ratio measured/expected: *nuclear modification factor*, \( R_{AB}^{k}(y, p_{T}) = \frac{dN_{AB}^{k}}{dN_{pp}^{k}} \) in absence of nuclear effects.

Heavy-Ion Collisions (II): 1. Basic ideas.
• $x_i$: momentum fraction of hadron N (in A) taken by parton i.
• $z$: momentum fraction of parton i taken by hadron h.
• Scales: $Q$, $\mu_F$ for factorization, $\mu_R$ for renormalization.
• f’s and D’s evolved according to DGLAP.
• DGLAP evolution and partonic $\sigma$ computed at NLO (order $\alpha_s^2$, ...) for all observables of interest (h, H, $\gamma$, DY, jets).
• Need of resummation of large logs (e.g. $\log(M_Q/p_T)$).

Heavy-Ion Collisions (II): 1. Basic ideas.
Radiation: dead cone, ang. ordering

\[ dP_i = \frac{dx_i}{x_i} \frac{dk_{T,i}^2}{k_{T,i}^2}, \quad \omega_i = x_i E, \quad \theta_i^2 \sim \frac{k_{T,i}^2}{\omega_i^2} \]

\[ Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2 \]

\[ x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0 \]

Angular ordering: \(|qqbarg> \rightarrow |qqbar> + |g>\)

\[ D_{qq} = \theta_{qq} t_{coh}, \quad t_{coh} \sim \omega / k_T^2, \quad D_g \sim 1 / k_T \]

\[ D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T \theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}} \]

Radiation: dead cone, ang. ordering

$\theta_{q\bar{q}} = 0.1$

Collinear divergence

Massless
Charm
Bottom

Dead cone angle: $\theta_0 = m/E$

$D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T\theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}}$

Medium effects:

- **Collinear factorization** (for $Q \sim E_{cm} > \Lambda_{QCD}$) is assumed to hold in the medium, with nuclear pdf’s evolved using DGLAP and medium-modified fragmentation functions:

$$D_{i \rightarrow h}^{med}(x, Q^2) = \int_0^1 \frac{d\epsilon}{1 - \epsilon} P(\epsilon) D_{i \rightarrow h}^{vac} \left( \frac{x}{1 - \epsilon}, Q^2 \right)$$

- Fragmentation like in vacuum: outside the medium which should be true for large energies (or $p_T$ for $\eta=0$).
- $P(\epsilon)$: probability to lose some energy (quenching weights) by any kind of energy loss mechanism, either collisional through multiple collisions, or radiative through multiple gluon emission. The latter is suppose to be the dominant phenomenon at large energies.
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Consider the de-coherence process $|qg> \rightarrow |q>+|g>$ (P I) and define the transport coefficient $qhat=\mu^2/\lambda$.

\[
\phi = \frac{k_T^2}{2\omega} \Delta z \sim 1 \Rightarrow \omega, k_T^2 \ll 1 \text{ suppressed} \quad \frac{\hat{q}L}{2\omega} L = \frac{\omega_c}{\omega} \sim 1 \Rightarrow \omega > \omega_c \text{ suppressed}
\]

$\Rightarrow$ IRC safe!!!!

\[
\hat{t}_{coh} \sim \frac{\hat{q} \omega}{\langle k_T^2 \rangle} \sim \langle k_T^2 \rangle, \quad \langle k_T^2 \rangle \approx \sqrt{\hat{q} \omega}
\]

\[
-\frac{dE}{dz} = \int d\omega \frac{1}{t_{coh}} \omega \frac{dI}{d\omega} \bigg|_{secat} \approx \alpha_s C_R \int^{\omega_c} d\omega \sqrt{\hat{q}} \omega \Rightarrow -\Delta E \propto \alpha_s C_R \hat{q} L^2
\]
Medium-modified gluon radiation through interference of production and rescattering.

Two parameters define the medium: one characterizing the density and strength of interactions with the medium, plus the length (geometry, dynamical expansion).

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Medium-modified gluon radiation through interference of production and rescattering.

Two parameters define the medium: one characterizing the density and strength of interactions with the medium, plus the length (geometry, dynamical expansion).

Heavy-Ion Collisions (II): 2. Radiative energy loss.

Models:

\[ \frac{\omega \, dI_{\text{med}}}{[d\omega \, d\kappa^2]} \]

- \( \omega / \omega_c = 10^{-2} \)
- \( \omega / \omega_c = 10^{-1} \)
- \( \omega / \omega_c = 1 \)
- \( \omega / \omega_c = 10 \)

\[ \kappa^2 = k_T^2 / (q\hat{a} L) \]
Radiative eloss: light hadrons (I)

Heavy-Ion Collisions (II): 2. Radiative energy loss.

Radiative energy loss (dN/dy = 1100)
Radiative energy loss

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Radiative $\epsilon_{\text{loss}}$: light hadrons (II)

Heavy-Ion Collisions (II): 2. Radiative energy loss.

NA et al '09

[Graphs and plots showing radiative energy loss]
Radiative e loss: non-photonic e’s

- Prediction from radiative energy loss: $\Delta E(g) > \Delta E(q) > \Delta E(Q)$.
- Non-photonic electrons not conclusive: benchmark, hadronization, collisional, resonances, dynamical medium ...
- Very difficult observable: disentangle c, b, heavy mesons,...

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Radiative e-loss: limitations

- The extracted value of $q_{\text{hat}}$ depends on medium model $1 < q_{\text{hat}} < 15$ GeV$^2$/fm $\Rightarrow$ interface with realistic medium.

- Calculations done in the high-energy approximation: only soft emissions energy-momentum conservation imposed a posteriori $\Rightarrow$ Monte Carlo.

- Multiple gluon emission: Quenching Weights independent (Poissonian) gluon emission: assumption! $\Rightarrow$ Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

- No role of virtuality in medium emissions; medium and vacuum treated differently $\Rightarrow$ modified DGLAP evolution.
Radiative energy loss: limitations

- The extracted value of $q_{\text{hat}}$ depends on the medium model:
  $1 < q_{\text{hat}} < 15$ GeV$^2$/fm$^2$ interface with realistic medium.
- Calculations done in the high-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori.
- Monte Carlo.
- Multiple gluon emission: Quenching Weights, independent (Poissonian) gluon emission: assumption.
- Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).
- No role of virtuality in medium emissions; medium and vacuum treated differently: modified DGLAP evolution.

NEW: Mehtar-Tani et al '10-'11

Leading Log ($\omega \rightarrow 0$)

$\Delta_{\text{med}} \rightarrow 0$ (Coherence)

$\Delta_{\text{med}} \rightarrow 1$ (Decoherence)

$$dN_{q,\gamma^*}^{\text{tot}} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta} \left[ \Theta(\cos \theta - \cos \theta_{q\bar{q}}) + \Delta_{\text{med}} \Theta(\cos \theta_{q\bar{q}} - \cos \theta) \right].$$

Total decoherence in opaque media

$$dN_{q,\gamma^*}^{\text{tot}} \big|_{\text{opaque}} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta}.$$

Heavy-Ion Collisions (II): 2. Radiative energy loss.
• **Assumption**: hadronization is not affected by the medium: looks OK at RHIC for \( p_T > 7\text{-}10 \text{ GeV} \).

• **The splittings are modified**: either radiatively (Q-PYTHIA) or radiative+collisionally (JEWELL, PYQUEN); or the evolution is enlarged due to momentum broadening (YaJEM).

• **Underlying ingredients**: factorization no emission/emission/no emission/... (Sudakov/splitting/Sudakov/...) holds in the medium, and the evolution scale \((t,k_T,\Theta)\) can be related with the medium length \(\rightarrow\) both to be proved (Jet Calculus in a medium).
Monte Carlo (II):

- The MC’s generically reproduce the **expectations**:
  → Particle spectrum softens (jet quenching).
  → Emission angle enlarges (jet broadening).
  → Intra-jet multiplicity enlarges.
Monte Carlo (II):

- Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-’cone’ medium modification).

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Monte Carlo (II):

The MC's generically reproduce the expectations:

- Particle spectrum softens (jet quenching).
- Emission angle enlarges (jet broadening).
- Intra-jet multiplicity enlarges.

\[ \text{Q-PYTHIA} \quad \left( t_1, z_1 \right) \quad \left( t_2, z_2 \right) \quad k_T = z(1-z)t \]

\[ \text{z-axis} \quad \theta \quad E_{\text{jet}} \quad l_{\text{coh}} = 2 \omega / k_T^2 \]

Missing items: e.g.

Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-'cone' medium modification).

Medium-induced gluon radiation modifies the color structure of the shower.

[not included yet] parameters versus out-of-cone medium modification.

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Jets (I):

- Single-particle inclusive distributions suffer from several biases: steep partonic spectrum which enhances small energy losses (trigger bias), geometric bias towards the surface, ...

- They come from our inability to reconstruct the energy of the ‘parton’: we cannot distinguish a low energy, little degraded one from a high energy, highly degraded one.

*Jets are the most direct of all hard probes of the medium.*

As close as you can get to the original quark or gluon near its time of creation

Heavy-Ion Collisions (II): 2. Radiative energy loss.

Salam, 0906.1833

- Jets come with a definition: clustering or reconstruction algorithm.
Jets (I):

- Single-particle inclusive distributions suffer from several biases: steep partonic spectrum which enhances small energy losses (trigger bias), geometric bias towards the surface, ...
- They come from our inability to reconstruct the energy of the 'parton': we cannot distinguish a low energy, little degraded one from a high energy, highly degraded one.

First results appeared in HP2008!

Heavy-Ion Collisions (II): 2. Radiative energy loss.
Jets (II):

- Techniques for **background subtraction** (the underlying event), designed to deal with the pileup at the LHC, can be applied in HI.
- Note: typically several 100 GeV are deposited per unit in $\eta \times \Phi$.

An example hard event

$p_T \sim 100 \text{ GeV}$

Generated with Pythia

Mixed into LHC HI environment

HydJet, $dN_{ch}/dy \sim 1600$
Heavy-Ion Collisions (II): 2. Radiative energy loss.

- Techniques for background subtraction (the underlying event), designed to deal with the pileup at the LHC, can be applied in HI.
- Note: typically several 100 GeV are deposited per unit in $\eta \times \Phi$. 

![Jet spectrum graph](image)
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$R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{AF_2^\text{nucleon}(x, Q^2)}$

- $R=1$ indicates the absence of nuclear effects.

- $R \neq 1$ discovered in the early 70’s.

- Each region demands a different explanation.

- I will be mostly interested in small $x$ (<0.1) relevant for high energies: isospin effects neglected.

Heavy-Ion Collisions (II): 3. DIS on nuclei.
$R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{AF_2^{nucleon}(x, Q^2)}$

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- $R \neq 1$ discovered in the early 70's.
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Heavy-Ion Collisions (II): 3. DIS on nuclei.
Global fits:

→ Data in EPS09 ($Q^2, M^2 > 1.69$ GeV$^2; p_T > 1.7$ GeV): 92 from DY (E-772 and 886), 20 from $\pi^0$ (PHENIX), rest up to 929 from DIS (E-135, EMC, NMC). Neutrino data under discussion.

⇒ Cross sections computed in collinear factorization
⇒ Define

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^p(x, Q^2)}$$

⇒ Using a known set for free protons (CTEQ, MRST....)
⇒ and DGLAP evolution of the nuclear and free proton PDFs
⇒ Find the minimum of $\chi^2$

---

Heavy-Ion Collisions (II): 3. DIS on nuclei.
Global fits:

→ **Eskola ’94**: DGLAP for nuclei.

→ **EKS98**: first global analysis, LO, DIS+DY.

→ Others non global analysis: Indumathi-Zhu, FGS.

→ **nDS** (2003): 1st NLO, DIS.

→ **HKM, HKN** (2001-07): NLO, $\chi^2$ minimization, DIS+DY.

→ **EKPS07**: LO, error analysis, 1st look at RHIC data.

→ **EPS08**: LO, BRAHMS forward data (factorization check).

→ **EPS09**: NLO, $\chi^2$ minimization, error analysis.
Global fits:

→ **Eskola ’94**: DGLAP for nuclei.

→ **E1**

→ **O**

→ **nI**

→ **H**

→ **E1**

→ **E1**

→ **E1**

→ **E1**

→ **E1**

→ **E1**

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Heavy-Ion Collisions (II): 3. DIS on nuclei.
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**DGLAP/BFKL:**

\[ dP_i = \frac{dx_i}{x_i} \frac{dk_{T,i}^2}{k_{T,i}^2}, \quad \omega_i = x_i E, \quad \theta_i^2 \simeq \frac{k_{T,i}^2}{\omega_i^2} \]

\[ x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0 \]

**A) DGLAP (DLA):**

\[ Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2 \]

\[ \int_{Q_0}^{Q_n} dP_{n-1} \int_{Q_0}^{k_{T,n-1}} dP_{n-2} \ldots \int_{Q_0}^{k_{T,2}} dP_1 \propto \left[ \frac{\alpha_s N_c}{\pi} \ln \frac{Q_n}{Q_0} \right]^n \]

**B) BFKL:**

\[ \int_{x_n}^{x_0} dP_{n-1} \int_{x_{n-1}}^{x_0} dP_{n-2} \ldots \int_{x_2}^{x_0} dP_1 \propto \left[ \frac{\alpha_s N_c}{\pi} \ln \frac{x_0}{x_n} \right]^n \]

- Both of them lead to a gluon distribution at small \( x \) behaving like \( xg(x, Q^2) \propto x^{-\lambda} \) at fixed \( Q^2, \lambda \approx 0.2-0.3 \) in data.
At small $x$ (gluon dominated), with the gluon increasing exponentially, we go from a linear regime: 

$$\Delta x_g \propto K \otimes x_g,$$

to a non-linear, recombination one whose first correction reads: 

$$\Delta x_g \propto K \otimes x_g - c(x_g)^2.$$
Unitarity: 

\[ F_2(x, Q^2) = \frac{Q^2}{4 \pi^2 \alpha_{em}} (\sigma_T + \sigma_L) \]

\[ \sigma_{T,L}(x, Q^2) = \int_0^1 dz \int db \, dr \, |\Psi_{T,L}(z, Q^2, r)|^2 N(b, r, x) \]

- **Unitarity** (probability conservation in QM) implies that the (imag forward) scattering amplitude \( N \leq 1 \) (optical theorem \( \Rightarrow \sigma \propto N \)). But \( x g(x, Q^2) \propto \int Q^2 \, dk^2 \phi(x, k^2) \), \( \phi(x, k^2) \propto \int \frac{d^2r}{r^2} e^{ik \cdot r} N(x, r) \)

so \( xg(x, Q^2) \propto x^{-\lambda} \) at fixed \( Q^2 \)
is not compatible with unitarity. The most celebrated dipole model is GBW, \( Q_s^2 \propto x^{-\lambda} \).

\[ N^{GBW}(r, Y=0) = 1 - \exp \left[ - \left( \frac{r^2 Q_s^2}{4} \right) \right] \]
Unitarity:

\[ \gamma^* \]

\[ l - z \]

\[ r \]

\[ b \]

\[ N(r) \]

MV i.c. (dashed)
GBW i.c. (solid)
\[ x = 10^{-2}, 5 \times 10^{-5}, 5 \times 10^{-9} \]

so \[ x g(x, Q^2) \propto x^{-\lambda} \] at fixed \( Q^2 \) is not compatible with unitarity. The most celebrated dipole model is GBW, \( Q_s \)

The ‘phase’ diagram:

Our aims: understanding

● The implications of unitarity in a QFT.

● The behavior of QCD at large energies.

● The hadron wave function at small $x$.

● The initial conditions for the creation of a dense medium in heavy-ion collisions.

Origin in the early 80’s: GLR, Mueller et al, McLerran-Venugopalan.
Arguments:

- At small enough $x$ for the projectile to interact coherently with the whole hadron, the CGC offers a description of the hadron wave function.\\
\[ x \leq \frac{1}{2m_N R_A} \sim 0.1 A^{-1/3} \]

- The RG equation for the slow/fast separation (JIMWLK) was derived for scattering of a dilute projectile on a dense target. Gluon $\# \!$ becomes as high as it can ($\alpha_s^{-1}$) be below $Q_s^2$.

- Its mean-field version (the Balitsky-Kovchegov equation, $P2$) is used for phenomenology: numerically and analytically understood.
The key feature of data is geometric scaling \((\text{Golec-Biernat et al})\).

\[
\tau = \frac{Q_s^2(x)}{Q_s^2(x)}, \quad \tau_D = \frac{Q_s^2(x_P)}{Q_s^2(x)}\quad \text{at fixed } \beta, \quad \tau_V = \frac{Q_s^2 + M_V^2}{Q_s^2(x_P)}
\]

Marquet et al

\[
Q_s^2(x) = \left(\frac{x_0}{x}\right)^\lambda
\]

\[
\lambda_{(GBW)} \sim 0.25 \div 0.3
\]

Gonçalves et al

\[\beta = 0.04 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]

\[\beta = 0.1 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]

\[\beta = 0.2 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]

\[\beta = 0.4 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]

\[\beta = 0.85 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]

\[\beta = 0.90 \text{ for } Q_s^2 \text{ in } (5-90) \text{ GeV}^2\]
Geometric scaling also found in eA:

\[
\frac{\sigma^A_{\gamma^*}(\tau_A)}{\pi R_A^2} = \frac{\sigma^p_{\gamma^*}(\tau_A)}{\pi R_p^2}
\]

\[
\frac{Q_{s,A}^2}{Q_{s,p}^2} = \left( \frac{A \pi R_p^2}{\pi R_A^2} \right)^{\frac{1}{\delta}} \Rightarrow \frac{\tau_A}{\tau_p} = \left( \frac{\pi R_A^2}{A \pi R_p^2} \right)^{\frac{1}{\delta}}
\]

\[\delta = 0.79 \pm 0.02 \ (x < 0.02)\]
pA at RHIC:

- Control experiment for initial state effects in AA: Cronin effect in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities was predicted by small-x evolution (BK).

\[
R_{dAu} = \frac{dN^{dAu}_{\eta \eta^2 b d^2 p}}{N_{coll} dN^{pp}_{\eta \eta^2 b d^2 p}}
\]

JLA-Armesto-Kovner-Salgado-Wiedemann
Kharzeev-Kovchegov-Tuchin

\[ R_{dAu} \rightarrow y \rightarrow \infty \quad A^{-(1-\gamma/\delta)/3} (f c) \]
\[ A^{-1/3} (r c, \text{fluctuations}) \]
Using factorization, multiplicities (evolution with centrality and pseudorapidity) can be computed.

\[ \frac{1}{N_{\text{part}}} \frac{dN_{AA}^g}{d\eta} \bigg|_{\eta=0} \approx \left\{ \begin{array}{l} \sqrt{s}^\lambda \ln \left( \sqrt{s}^\lambda N_{\text{part}} \right) \\ \sqrt{s}^\lambda N_{\text{part}}^{\frac{1-\delta}{3\delta}} \end{array} \right. \]

Kharzeev-Levin
Nardi
Armesto-Salgado
Wiedemann

Now it has been done with the available NLO-BK machinery.

Geometric scaling is enough: factorization of geometry and energy dependences.

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Present status:

<table>
<thead>
<tr>
<th>Observable at RHIC</th>
<th>Standard interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low multiplicity ($\sim 2/3$ expectations $dN_{ch}/d\eta</td>
<td>_{\eta=0} \sim 1000$ for central collisions)</td>
</tr>
<tr>
<td>$v_2$ in agreement with ideal hydro ($\eta/s \sim \text{a few}/(4\pi)$)</td>
<td>Almost ideal fluid, very fast thermalization/isotropization, strongly/weakly coupled!?</td>
</tr>
<tr>
<td>Strong jet quenching ($R_{AA}(10$ GeV)$\sim 0.2$ for $\pi^0$, disappearance of back-to-back correlations)</td>
<td>Opaque partonic medium, radiative(+elastic) energy loss, weak/strong interaction with the medium!?</td>
</tr>
</tbody>
</table>

All these observation have triggered new theoretical developments (e.g. how to treat a strongly coupled system - AdS/CFT) to:

- Check our theoretical explanations of the probes.
- Constrain our understanding of medium properties.

Heavy-Ion Collisions (II): The picture from RHIC.
Open problems:

• Highlight: the medium created in the collisions is dense, $\sim 10 \text{ GeV/fm}^3$, partonic and behaves very early like a quasi-ideal fluid; strong collectivity: scQGP. New theoretical developments:

A) Why the medium gets thermalized so early ($\tau < 1 \text{ fm}$)? Instabilities, perturbative HO processes, strong coupling phenomena (studied in N=4 SYM using the AdS/CFT correspondence), CGC.

B) The value of qhat is? too large for pQCD: strong coupling?

C) Why the viscosity is so low? How to do viscous hydro?

D) Differential observables; and jet-medium interactions?
LHC started accelerating ion beams on 04.11.2010: 2.76 ATeV.

1st collisions on 07.11.2010; now ~ $10^8$ recorded events in ALICE+ATLAS+CMS in 1 month.


12 papers until now:
* ALICE: 6 (2 on multiplicities, 2 on flow, 1 on jet quenching, 1 on interferometry).
* ATLAS: 2 (1 on jets, 1 on $J/\Psi$ and $Z$).
* CMS: 4 (1 on jets, 1, on $W/Z$, 1 on correlations, 1 on quarkonia).

+ many new results in QM2011 (http://qm2011.in2p3.fr/).

Heavy-Ion Collisions (II): 5. LHC.
A Large Ion Collider Experiment

- **EMCAL**
  - $\gamma$, $\pi^0$, jets

- **T0/V0**
  - Trigger

- **L3 Magnet**
  - $B = 0.5T$

- **ACORDE**
  - Cosmic trigger

- **HMPID**
  - PID (RICH) @ high $p_T$

- **TRD**
  - Electron ID (TR)

- **PMD**
  - $\gamma$ multiplicity

- **TPC**
  - Tracking, PID (dE/dx)

- **PHOS**
  - $\gamma$, $\pi^0$, jets

- **FMD**
  - Charged multiplicity

- **IT5**
  - Low $p_T$ tracking
  - PID + Vertexing

- **Dipole Magnet**

- **TOF**
  - PID

- **MUON arm**
  - $\mu$-pairs

- **Not shown:**
  - ZDC (at ±116m)
A PbPb event
ALICE data on multiplicities:

- Multiplicity larger than expected in data-driven extrapolations.
- In agreement with saturation models (based on the behavior of the small-x glue).
- Problems to reconcile the energy behavior of pp and AA.
ALICE data on centrality:

- Behavior compatible with factorization between energy and centrality dependences, as suggested by saturation.

NA et al. '04

Heavy-Ion Collisions (II): 5. LHC.
Azimuthal asymmetries:

- Behavior compatible with hydro extrapolations from RHIC assuming that $\eta$ is $\approx$ or slightly larger.
- The scQGP claims remain.
- Many things to be settled.
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- Behavior compatible with hydro extrapolations from RHIC assuming that $\eta$ is $\approx$ or slightly larger.
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Heavy-Ion Collisions (II): 5. LHC.
Azimuthal asymmetries:

- Behavior compatible with hydro extrapolations from RHIC assuming that $\eta$ is $\approx$ or slightly larger.
- The scQGP claims remain.
- Many things to be settled.

Heavy-Ion Collisions (II): 5. LHC.
Results for $R_{AA}$:

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{\text{evi}})d^2N_{\text{ch}}^{AA}/d\eta dp_T}{(N_{\text{coll}})(1/N_{\text{pp}}^{\text{evi}})d^2N_{\text{ch}}^{pp}/d\eta dp_T};$$

- Behavior compatible with radiative $\varepsilon$loss.
- Similar for charged hadrons and for jets?!
- Reference crucial!!! (pp@2.76 TeV done).

Heavy-Ion Collisions (II): 5. LHC.
Results for $R_{AA}$:

$R_{AA}(p_T) = \frac{dN_{ch}}{d^2p_T^*} = \frac{dN_{ch}}{d^2p_T^*}$

- Behavior compatible with radiative $e_\text{loss}$.
- Similar for charged hadrons and for jets?!
- Reference crucial!!! (pp@2.76 TeV done).

Interpolations using:
- 1.96 to 7
- 0.9 to 7

NLO QCD Jets

Heavy-Ion Collisions (II): 5. LHC.
LHC-specific: dijets

anti-$k_T$, $D=0.4$

$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta \phi > \frac{\pi}{2}$

$E_{T2}=E_{T1}/2 \Rightarrow$

$A_J=1/3$

- CMS got similar results, plus particles.

Heavy-Ion Collisions (II): 5. LHC.
LHC-specific: dijets

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \cos \Delta \phi > \frac{\pi}{2} \]

\[ E_{T2} = E_{T1}/2 \Rightarrow A_J = 1/3 \]

- CMS got similar results, plus particles.

Heavy-Ion Collisions (II): 5. LHC.
Small kick to the gluons which go ‘out-of-cone’ may lead to this additional jet-energy ‘degradation’.

- $E_{\text{gluon}} < \sqrt{q_{\text{hat}}L}$ gives $q_{\text{hat}}L = 50-100$ GeV$^2$, in rough agreement with RHIC extrapolations.
- In pp there is already a lot of degradation ($\langle x \rangle$ differs $\sim 10\%$).
Dijets (II):

Jets are involved observables...

- Small kick to the gluons which go 'out-of-cone' may lead to this additional jet-energy 'degradation'.

\[ E_{\text{gluon}} < \sqrt{q^2_L} \] gives \[ q^2_L = 50 - 100 \text{ GeV}^2 \], in rough agreement with RHIC extrapolations.

- In pp there is already a lot of degradation (\( \langle x \rangle \) differs \( \sim 10\% \)).

Heavy-Ion Collisions (II): 5. LHC.
Quarkonia:

- J/ψ results do not show enhancement.
- Higher BBbar states show larger suppression (CMS): thermometer?

Heavy-Ion Collisions (II): 5. LHC.
Rapidity correlations (I):

- $\eta$-elongated structure in the two-particle correlation in the near and away side regions.
- Present in high multiplicity pp@LHC (CMS, 7 TeV) and in central AuAu@RHIC and PbPb@LHC.

Heavy-Ion Collisions (II): 5. LHC.
Long range rapidity correlations in particle production appear naturally in several models: string models with a varying number of them, CGC, ...

Origin of the elongation in $\eta$ for the ridge unsettled yet: coupling fragmentation $\leftrightarrow$ flowing medium, ISR, flow itself ($v_3$),...
<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>

- Quite a bit for less than 5 weeks of data taking!!!

- The very first data seem, at first sight, not to be in dispute with the claims at RHIC - the problems remain, too.

- LHC offers new opportunities, both enlarging the lever arm (in energy, in $p_T$, ...) for existing observables and offering new ones (identified heavy quarks, jets, correlations,...). Fun has just begun!!!
**Summary:**

**Plans (tentative!?):**

* PbPb @ 2.76 ATeV: four weeks at the end of 2011; at least 3 times the luminosity in 2010. End of 2012?
* pPb @ 4.4 ATeV: studies during the PbPb run in 2011, run at the end of 2012?

- Quite a bit for less than 5 weeks of data taking!!!
- The very first data seem, at first sight, not to be in dispute with the claims at RHIC - the problems remain, too.
- LHC offers new opportunities, both enlarging the lever arm (in energy, in $p_T$, ...) for existing observables and offering new ones (identified heavy quarks, jets, correlations, ...). Fun has just begun!!!

Heavy-Ion Collisions (II): 5. LHC.
Backup:
<table>
<thead>
<tr>
<th>Model</th>
<th>Diagrams</th>
<th>Ingredients</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASW</td>
<td><img src="image" alt="ASW Diagram" /></td>
<td>Static scattering centers, Poissonian QW</td>
<td>qhat</td>
</tr>
<tr>
<td>GLV / WHDG (elastic)</td>
<td><img src="image" alt="GLV Diagram" /></td>
<td>FF in eA, modified DGLAP</td>
<td>dN_{g}/dy,T / \alpha_s,T</td>
</tr>
<tr>
<td>GMW</td>
<td><img src="image" alt="GMW Diagram" /></td>
<td>HTL medium, rate eqs.</td>
<td>\langle FF \rangle or qhat,T</td>
</tr>
<tr>
<td>AMY (elastic)</td>
<td><img src="image" alt="AMY Diagram" /></td>
<td></td>
<td>\alpha_s,T</td>
</tr>
</tbody>
</table>

Heavy-Ion Collisions (II): Backup.
Embedding in a medium:

- Calculation of eloss has to be embedded in a geometry:
  - Homogeneous piece of fixed length \( \Rightarrow q_{\text{hat}} \sim 1 \text{ GeV}^2/\text{fm}. \)
  - Density diluting as \( 1/\tau \Rightarrow q_{\text{hat}} \sim 1 \text{ GeV}^2/\text{fm}. \)
  - Medium as overlap (\( N_{\text{coll}} \)), \( T_A(s)T_B(b-s) \Rightarrow q_{\text{hat}} \sim 10 \text{ GeV}^2/\text{fm}. \)
  - Hydrodynamical medium \( \Rightarrow \kappa \sim 2-4. \)

\[
\hat{q}(\xi) = K\hat{q}_{\text{QGP}} \simeq K \cdot 2e^{3/4}(\xi)
\]

Note: production points sampled as \( N_{\text{coll}} \) or \( N_{\text{part}}. \)

Heavy-Ion Collisions (II): Backup.
Radiative $e_{\text{loss}}$: light hadrons (II)

Heavy-Ion Collisions (II): Backup.
Radiative $e_{loss}$: light hadrons (II)

$\chi^2$ vs $K = \hat{q}/[2e^{3/4}]$

- $R_{AA}$
- $I_{AA}$
- Small-$\tau$ extrapolation

- Case i: $\hat{q}(\tau) = 0$ for $\tau < \tau_0$
- Case ii: $\hat{q}(\tau) = \hat{q}(\tau_0)$ for $\tau < \tau_0$
- Case iii: $\hat{q}(\tau) = \hat{q}(\tau_0)/\tau^{3/4}$ for $\tau < \tau_0$

$R_{AA}$ vs $K = \hat{q}/[2e^{3/4}]$

- $R_{AA}$
- $I_{AA}$
- Total

$p_T [\text{GeV}]$

$z_T$

Heavy-Ion Collisions (II): Backup.
Radiative e\textit{loss: limitations}

• The extracted value of \textit{qhat} depends on medium model \(1<q_{\text{hat}}<15 \text{ GeV}^2/\text{fm} \Rightarrow \) interface with realistic medium.

• Calculations done in the high-energy approximation: \textit{only soft emissions} energy-momentum conservation imposed a posteriori \(\Rightarrow\) Monte Carlo.

• \textit{Multiple gluon emission: Quenching Weights} independent (Poissonian) gluon emission: assumption! \(\Rightarrow\) Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

• No role of \textit{virtuality} in medium emissions; medium and vacuum treated \textit{differently} \(\Rightarrow\) modified DGLAP evolution.
Radiative e\textsubscript{loss}: limitations

- The extracted value of q\textsubscript{hat} depends on medium model 1<q\textsubscript{hat}<15 GeV\textsuperscript{2}/fm ⇒ interface with realistic medium.

\[ \omega \frac{dI}{d\omega} = \int_{0}^{k_{T}^{2,\text{max}}} dk_{T}^{2} \omega \frac{dI}{d\omega dk_{T}^{2}}, \quad \Delta E = \int_{0}^{E} d\omega \omega \frac{dI}{d\omega} \]

- Calculations done in the high-energy approximation: only soft emissions;

\[ P(\Delta E) = \omega \frac{dI}{d\omega} = \int_{0}^{k_{T}^{2,\text{max}}} dk_{T}^{2} \omega \frac{dI}{d\omega dk_{T}^{2}}, \quad \Delta E = \int_{0}^{E} d\omega \omega \frac{dI}{d\omega} \]

- Multiple gluon emission: Quenching Weights, independent (Poissonian) gluon emission: assumption! Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

\[ P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_{i} \frac{dI(\omega_{i})}{d\omega} \right] \delta \left( \Delta E - \sum_{i=1}^{n} \omega_{i} \right) \exp \left[ - \int d\omega \frac{dI}{d\omega} \right] \]

- No role of virtuality in medium emissions, medium and vacuum treated \textbf{differently} ⇒ modified DGLAP evolution.

Heavy-Ion Collisions (II): Backup.
$F_2^A(x, Q^2) = \frac{Q^2(1-x)}{4\pi^2\alpha_{EM}}\sigma_{\gamma^*A}$

$Q^2$ is the transverse resolution.

$x$ is the momentum fraction (IMF).

$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$ at LO.

- $F_2^{(1)}(x, Q^2) = F_2^{(1)}(x)$ at large $Q^2$: Bjorken scaling, point-like partons.
- $F_2(x) = 2xF_1(x)$: Callan-Gross relation, spin 1/2 quarks.
- I will be interested in small $x$ i.e. large energies $W$.

Heavy-Ion Collisions (II): Backup.
At LO

\[ Q^2 \partial_{Q^2} \left( \begin{array}{c} q_i(x, Q^2) \\ \bar{q}_i(x, Q^2) \\ g(x, Q^2) \end{array} \right) = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} \frac{x}{\xi} & 0 & \frac{x}{\xi} \\ 0 & P_{q_i q_j} \left( \frac{x}{\xi} \right) & P_{q_i g} \left( \frac{x}{\xi} \right) \\ \frac{x}{\xi} & P_{g q} \left( \frac{x}{\xi} \right) & P_{g g} \left( \frac{x}{\xi} \right) \end{pmatrix} \begin{pmatrix} q_j(x, Q^2) \\ \bar{q}_j(x, Q^2) \\ g(x, Q^2) \end{pmatrix} \]
Heavy-Ion Collisions (II): Backup.

**DGLAP:**

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Splitting</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td>$P_{qg} = C_F \left[ \frac{1-x^2}{(1-x)_+} + \frac{3}{2} \delta(1-x) \right]$</td>
</tr>
<tr>
<td><img src="image2" alt="Diagram" /></td>
<td>$P_{gq} = C_F \left[ \frac{1+(1-x)^2}{x} \right]$</td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td>$P_{gg} = T_R \left[ x^2 + (1-x)^2 \right]$</td>
</tr>
<tr>
<td><img src="image4" alt="Diagram" /></td>
<td>$P_{gg} = 2C_A \left[ \frac{x}{(1-x)_+} + (1-x) \left( x + \frac{1}{x} \right) \right] + \frac{11C_A-4n_f}{6} T_R \delta(1-x)$</td>
</tr>
</tbody>
</table>

At LO

$$Q^2 \partial_{Q^2} \begin{pmatrix} q_i(x, Q^2) \\ \bar{q}_i(x, Q^2) \\ g(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j} \left( \frac{x}{\xi} \right) & 0 & P_{q_i g} \left( \frac{x}{\xi} \right) \\ 0 & P_{q_i q_j} \left( \frac{\xi}{x} \right) & P_{q_i g} \left( \frac{\xi}{x} \right) \\ P_{g q} \left( \frac{x}{\xi} \right) & P_{g q} \left( \frac{\xi}{x} \right) & P_{g g} \left( \frac{x}{\xi} \right) \end{pmatrix} \begin{pmatrix} q_j(x, Q^2) \\ \bar{q}_j(x, Q^2) \\ g(x, Q^2) \end{pmatrix}$$
• HERA provides most of the available information, covering a large part of what is required for the LHC.

Heavy-Ion Collisions (II): Backup.
HERA provides most of the available information, covering a large part of what is required for the LHC.
Global fits:

→ All experimental data where you rely on collinear factorization.
→ Several groups: MSTW, CTEQ, NNPDF, ZEUS, H1, Alekhin.
→ Error analysis using variants of the Hessian method.
→ Analysis at LO, NLO and even NNLO (MSTW).
→ Initial conditions for several pdf’s: CTEQ, MSTW
  \[ f_i(x,Q_0^2)=A_i x^{b_i} (1-x)^{c_i} \],...
  As many restrictions as possible (e.g. u\bar{u}=, ≠ d\bar{d}): around 40 parameters in MSTW and CTEQ (ZEUS, H1 smaller number). NNPDF: around 400 parameters.

Heavy-Ion Collisions (II): Backup.
Global fits:

Sea decomposition at small $x$ difficult.
Global fits:

Heavy-Ion Collisions (II): Backup.
Two scattering case (P1):

\[ i\tau_n(q = 0) = -\sigma_A^n \]

\[ q = p' - p \]

\[ T_A(x_T) = \int_{-\infty}^{+\infty} dx_+ \rho_A(x_+, x_T) \]

\[ c(p_+, p'_+) i\tau_1(q) = \mathrm{it}_{\text{forw}} c(p_+, p'_+) A \int d^2 x_T T_A(x_T) e^{-i x_T \cdot (p'_T - p_T)} \]

\[ \Rightarrow \sigma_A^1 = A \sigma \]

\[ c(p_+, p'_+) i\tau_2(q) = c(p_+, p'_+) A (A - 1) (i\tau_{\text{forw}})^2 \]

\[ \times \int \frac{d^2 k_T}{(2\pi)^2} dx_{1+} dx_{2+} d^2 x_{1T} d^2 x_{2T} \exp \left( -i k_T^2 (x_{2+} - x_{1+}) / (2 p_+) \right) \]

\[ \times \exp\left( -i [x_{1T} \cdot (k_T - p_T) + x_{2T} \cdot (p'_T - k_T)] \rho_A(x_{1+}, x_{1T}) \right) \]

\[ \times \rho_A(x_{2+}, x_{2T}) \theta(x_{2+} - x_{1+}), \]
Two scattering case (P1):

\[ i (q = 0) = i t_{\text{forw}} = -\sigma \]
\[ i T_n (q = 0) = -\sigma^n_A \]
\[ q = p' - p \]

\[ T_A (x_T) = \int_{-\infty}^{+\infty} dx_+ \rho_A (x_+, x_T) \]

\[ c (p_+, p'_+) i T_1 (q) = i t_{\text{forw}} c (p_+, p'_+) A \int d^2 x_T \, T_A (x_T) \, e^{-ix_T \cdot (p'_T - p_T)} \Rightarrow \sigma_A^1 = A \sigma \]

\[ c (p_+, p'_+) i T_2 (q) = c (p_+, p'_+) A (A - 1) (it_{\text{forw}})^2 \]
\[ \times \int \frac{d^2 k_T}{(2\pi)^2} \, dx_{1+} \, dx_{2+} \, d^2 x_{1T} \, d^2 x_{2T} \, \exp \left( -ik_T^2 (x_{2+} - x_{1+}) / (2p_+) \right) \]
\[ \times \exp(-i [x_{1T} \cdot (k_T - p_T) + x_{2T} \cdot (p'_T - k_T)] \rho_A (x_{1+}, x_{1T}) \]
\[ \times \rho_A (x_{2+}, x_{2T}) \theta (x_{2+} - x_{1+}), ) \]
Coherence length, shadowing (P1):

\[ \exp \left[ -i k_T^2 \frac{(x_{2+} - x_{1+})}{(2p_+)} \right] = \exp \left[ -i \frac{(x_{2+} - x_{1+})}{l_c} \right], \text{ with } l_c = \frac{2p_+}{k_T^2} \]

A) \quad p_+ \rightarrow 0 \quad \Rightarrow i \mathcal{T}_2(q) \rightarrow 0

B) \quad p_+ \rightarrow \infty, \exp \left[ -i \frac{(x_{2+} - x_{1+})}{l_c} \right] \rightarrow 1

\[
i \mathcal{T}_2(q) = \frac{A(A-1)}{2} (it_{\text{forw}})^2 \int d^2 x_T \, e^{-ix_T \cdot (p'_T - p_T)} T_A^2(x_T),
\]

\[
\sigma_A^2 = -\frac{A(A-1)}{2} \int d^2 x_T \left[ T_A(x_T) \sigma \right]^2
\]

The lifetime of the qqbar fluctuation is \( \geq R_A \) for \( x \leq 0.1A^{-1/3} \).

\[
\tau \sim \frac{1}{Q} \times \frac{E_{\text{lab}}}{Q} \approx \frac{W^2}{2m_{\text{nucleon}} Q^2} \approx \frac{1}{2m_{\text{nucleon}} x}
\]
Global fits:

\[ \chi^2 \approx \chi_0^2 + \sum_{i,j} \delta a_i H_{ij} \delta a_j \quad H_{ij} = \frac{1}{2} \left. \frac{\partial^2 \chi^2}{\partial a_i \partial a_j} \right|_{a=a^0} \]

\[ \Delta \chi^2 = \sum_i \left( \frac{\Delta \chi^2(z_i^+)}{2N} + \frac{\Delta \chi^2(z_i^-)}{2N} \right) \approx \sum_i \frac{(z_i^+)^2 + (z_i^-)^2}{2N} \]

\[ S_0 = (0, 0, 0, \ldots, 0) \]

\[ S_1^\pm = \pm \delta z_1^\pm (1, 0, 0, \ldots, 0) \]

\[ S_2^\pm = \pm \delta z_2^\pm (0, 1, 0, \ldots, 0) \]

\[ \vdots \]

\[ (\Delta X^+)^2 \approx \sum_k \left[ \max \left\{ X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0 \right\} \right]^2 \]

\[ (\Delta X^-)^2 \approx \sum_k \left[ \max \left\{ X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0 \right\} \right]^2 \]

**Note:** any error analysis is linked to a functional form for the i.c. (NNPDF implies more flexibility); pdf’s errors to be used, too.

*Heavy-Ion Collisions (II): Backup.*
Global fits:

Note: any error analysis is linked to a functional form for the i.c. (NNPDF implies more flexibility); pdf’s errors to be used, too.

Heavy-Ion Collisions (II): Backup.
The BK equation:

Neglecting the difference between $<W^+ W W^+ W>_{\text{tar}}$ and $<W^+ W>_\text{tar}<W^+ W>_\text{tar}$:

BK equation.

Neglecting the dependence on impact parameter:

$$\frac{\partial N(r, Y)}{\partial Y} = \int \frac{d^2 z}{2\pi} K(\vec{r}, \vec{r}_1, \vec{r}_2) \left[ N(r_1, Y) + N(r_2, Y) - N(r, Y) - N(r_1, Y)N(r_2, Y) \right]$$

$$K(\vec{r}, \vec{r}_1, \vec{r}_2) = \tilde{\alpha}_s \frac{r^2}{r_1^2 r_2^2}, \quad \tilde{\alpha}_s = \frac{\alpha_s N_c}{\pi}$$

$$\phi(Y, k, b) = \int \frac{d^2 r}{2\pi r^2} e^{i\vec{k} \cdot \vec{r}} N(Y, r, b)$$

Neglecting the dependence on impact parameter:

$$\frac{\partial \phi(y, k)}{\partial y} = H_{BFKL} \otimes \phi(y, k) - \phi^2(y, k), \quad y = \tilde{\alpha}_s Y$$

Heavy-Ion Collisions (II): Backup.
This suppression is compatible with ugd+factorization (diluted-dense): IIM, DHJ, in agreement with $ep + A^{1/3}$ prescription for $Q_s^2$. It is also compatible with the ratio of geometric $ep/eA$ scaling functions.

**Warning:** $<x_A> > 0.02$, and such suppression also happens at SPS/FNAL energies: finite energy corrections, eloss?
**Azimuthal correlations may also indicate small-$x$ dynamics: tale of the two-particle inclusive distributions (Baier et al, Kovchegov et al, Marquet).**

\[
\frac{d\sigma}{dy_1 dy_2 d^2p_1 d^2p_2 d\Delta\phi}
\]

**Charm production described (also Kharzeev et al, Tuchin).**

---

**Heavy-Ion Collisions (II): Backup.**
Initial conditions for hydrodynamical evolution are a key ingredient in those calculations. CGC gives larger eccentricity: room for viscosity or larger equilibration times.

Uncertainties at the nuclear periphery (NP region).

**Heavy-Ion Collisions (II): Backup.**
AA at RHIC:

- CGC may offer initial conditions for QGP formation: transverse fields transform into longitudinal (Glasma) (Lappi et al, Romatschke et al).

- QCD basis for good old string models.

\[ \langle n_B \rangle_F = a + b n_F, \quad b \equiv D_{FB}^2 / D_{FF}^2, \]

\[ b = \frac{1}{1 + c \alpha_s^2}. \]

- Correlations in rapidity are a place to look for such origin of particle production (Capella et al, NA et al, Dumitru et al, Fukushima et al).

Heavy-Ion Collisions (II): Backup.
Multiplicities:

$dN_{\text{ch}}/d\eta$ in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV for $N_{\text{part}} = 350$

- ASW-like ($\lambda = 0.26$)
- Levin et al.
- HIJING 2.0
- Wolschin et al.
- Sarkisyan et al.
- Sa et al.
- Porteboeuf et al.
- Mitrovski et al.
- Lokhtin et al.
- Kharzeev et al.
- Jeon et al.
- Humanic.
- Fujii et al.
- Eskola et al.
- Il et al.
- Dias de Deus et al.
- Chen et al.
- Capella et al.
- Chaudhuri
- Bzdak
- Busza
- Bopp et al.
- Topor Pop et al.
- Armesto et al.
- Armesto et al.
- Arleo et al.
- Albacete
- Abreu et al.

ALICE

- geom. scaling
- corr., saturation
- strong gluon shad.
- corr., RDM
- CQM + Landau hydro
- corr., PACIAE
- EPOS
- corr., UrQMD
- corr., HYDJECT++
- saturation
- data driven, limiting frag.
- corr., NN superposition
- fcBK evolution
- corr., EKS98+geom. sat.
- corr., BAMPS
- percolation
- corr., AMPT+gluon shad.
- DPM+Gribov shad.
- log. extrap.
- corr., wounded diq. mod.
- data driven, limiting frag.
- corr., DPMJET III
- corr., HIJING/BB v2.0
- PSM
- geom. scaling
- corr., log. extrap.
- corr., rcBK evolution
- corr., logistic evol. eq.
W/Z (LHC-specific):

- First Z/W measurement in heavy-ion collisions!!! Benchmark (npdfs) for future.

Heavy-Ion Collisions (II): Backup.
LHC and beyond:

Heavy-Ion Collisions (II): Backup.
LHC and beyond:

Heavy-Ion Collisions (II): Backup.
LHC and beyond:

**ALICE**
- Jets
- Photons
- Hadrons
- D's $|\eta| < 0.9$
- B's $2.4 < |\eta| < 4$

**LHC Experiments:**
- Atlas and CMS
- Atlas and CMS rapidity plateau

**Colliders:**
- LHeC
- HERA
- EIC

**1105.3919**

- **Q^2 (GeV^2)**
  - $10^8$
  - $10^7$
  - $10^6$
  - $10^5$
  - $10^4$
  - $10^3$
  - $10^2$
  - $10^1$

- **Q^2_{sat,Pb}(x)**

**Present DIS+DY**

- **E-Pb (LHeC)**
  - (70 GeV - 2.5 TeV)

- **e-Au (eRHIC)**
  - (10 GeV - 100 GeV)

**Fixed-target data:**
- NMC
- E772
- E139
- E665
- EMC

**nuclear DIS - F_2(x,Q^2)**

- Proposed facilities:
  - LHeC
  - eRHIC

**DdE, arXiv:0706.4182**

Heavy-Ion Collisions (II): Backup.