High energy heavy-ion collisions - hot QCD in a lab

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so far...

- High energy heavy-ion collisions:
  - hot medium; thermal [statistical hadronization] particle emission
  - QGP flows as almost perfect fluid - well described by viscous hydrodynamics - transport coefficient constrained
  - slow evolution with energy - similar medium over large span of energies - role of mean free path vs. medium size...
  - QGP is opaque to high energy jets (dense medium) - transport coefficient constrained (first syst. results)
Contents (3/3)

• Jet quenching measurements with reconstructed jets
• Heavy-flavor in-medium
• Quarkonia in hot QGP
• Novel phenomena - connection between soft-QCD pp, pA (small systems) and AA
Energy-loss - QGP state effect!

Color charged probes suppressed
Color neutral probe production scales with Nbin collisions
pA collisions: suppression is an effect of QGP

\[ R_{AA} = \frac{1}{<N_{\text{coll}}>} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \]

Throughout the talk: \( R_{AA} = \text{QCD in medium} / \text{QCD in vacuum} \)

Note: only colored probes quenched; pA: jet quenching is a in-medium effect
Jet quenching

- a partonic effect

- better measure with reconstructed jets (integration of hadronic DOF)

=> more details from in-medium jet (shower) structure modifications
RAA: extreme scenarios

\[ P(\Delta E) - \text{probability for parton to loose } \Delta E \]

Scenario I

\[ P(\Delta E) = \delta(\Delta E_0) \]

"Energy loss"

"Shift" to lower pT

Scenario II

\[ P(\Delta E) = a \delta(0) + b \delta(E) \]

"Absorption"

"Shift" in yield

\[ P(\Delta E) \text{ encodes the full energy loss process} \]

\[ \text{RAA not sensitive to energy loss distribution, details of mechanism...} \]
Jet $R_{AA}$

$R_{AA} = \frac{\text{#(jets observed in AA collision per N-N (binary) collision)}}{\text{#(jets observed per p-p collision)}}$

$R_{AA} < 1$: medium induced out-of-cone radiation

ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

Anti-$k_T$ $R = 0.2$ | $|\eta_{jet}| < 0.5$

$p_T^{lead,ch} > 5$ GeV/c

Longitudinal modification:
- out-of-cone: energy lost, loss of yield, di-jet energy imbalance
- in-cone: softening of fragmentation

Transverse modification:
- out-of-cone: increase acoplanarity $k_T$
- in-cone: broadening of jet-profile

LHC: Estimates (on average) of about 10-20 (10%) GeV radiated out of cone - similar result at RHIC
Jet $R_{AA}$

$R_{AA} =$ 

$\#(\text{jets observed in AA collision per N-N (binary) collision})$

$\#(\text{jets observed per p-p collision})$

$R_{AA} < 1$: medium induced out-of-cone radiation

$R_{AA}$ for jets $\sim 0.6$ at 0.2 TeV all the way to 1 TeV

$\Rightarrow$ a constant "shift" $\Rightarrow$ a TeV jet loses/injects tens (100?) of GeV into the medium
LHC: Di-jet asymmetry

\[ A_j \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

Warning: \( A_j \) is sensitive to background fluctuations! Need proper treatment in the data.

First jet quenching (with fully reconstructed jets) report from LHC

Note (backup): No de-correlation also seen at RHIC: PHENIX in Cu+Cu; also remember the 2-hadron correlations...
Recoil jet (2) energy-loss as a function of trigger jet (1) $p_T$

$\langle p_{T,2}/p_{T,1}\rangle$

CMS

PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $\int L dt = 150$ nb$^{-1}$

pp $\sqrt{s} = 2.76$ TeV, $\int L dt = 231$ nb$^{-1}$

PYTHIA+HYDJET

$50-100\%$

$20-50\%$

$0-20\%$

$\Delta \phi_{12} > \frac{2\pi}{3}$

$0.5$

$0.6$

$0.7$

$0.8$

$0.9$

$-0.1$

$-0.2$

$-0.3$

$-0.4$

$-0.5$

$150$

$200$

$250$

$300$

$350$

$p_{T,1}$ (GeV/c)

$p_{T,2}$ (GeV/c)

Vacuum reference

Data in PbPb

Ratio follows the PYTHIA+HYDJET reference with the same rate - constant offset over 200 GeV in $p_T$. 

$\Delta_{\phi_{12}} > \frac{2\pi}{3}$
Probing structure of QGP

Jet quenching via hadron-jet coincidences

A picture in QCD: Shower in a QGP

Ratio of azimuthal correlations is sensitive to medium induced accoplanarity and large angle parton-medium scatterings

Azimuthal correlations:
No medium induced accoplanarity (consistent with CMS and ATLAS)
Limit on rate of scatterings - sensitivity to medium homogenity - magnitude of the effect TBD - shower evolution vs. large angle scatterings
Note: photons expected to probe the complete "geometry" of the medium

$\Delta E > 0$ (?)

$\Delta E = 0$

$\Rightarrow$ no "surface bias"
Direct photon(-jet) measurement

An experimental chart... of the effort(!)
Direct photon(-jet) measurement

- Signal photon-jet
- Background from dijet
- Contribution from uncorrelated multiple interaction/fake

Signal region estimated from event mixing method using minimum-bias data.

Photon-Jet
Background Photon–Jet
Background Photon–UE Combinatorics
Photon–UE Combinatorics

Estimated from event mixing method using minimum-bias data.
Photon\(_{\Delta E=0}\)-jet\(_{\Delta E>0}\)

Fit
\[
\frac{1}{N_{J\gamma}} \frac{dN_{J\gamma}}{d\Delta \phi_{J\gamma}} = \frac{e^{(\Delta \phi - \pi)/\sigma}}{(1 - e^{-\pi/\sigma}) \sigma}
\]

Range: \(\Delta \phi > 2\pi/3\)

"Width" consistent with vacuum
**Photon**^{(\Delta E=0)}-jet^{(\Delta E>0)}

The asymmetry ratio \( x_{J\gamma} = \frac{p_{T}^\text{Jet}}{p_{T}^\gamma} \) is used to quantify the photon+jet momentum imbalance.

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**Figure 3:** Ratio of \( N_p \) to \( N_J \) in bins of increasing centrality for PbPb collisions as well as that for pp data at 2.76 TeV, showing consistency to the MC reference. However, the poor statistics of the pp data and jet photon selections used in the simulation (shaded histogram) in bins of increasing centrality left to right. The error bars on (filled circles) compared to pp data at 2.76 TeV do not allow a discrimination between these two tunes.

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**3.2 Photon+jet momentum imbalance**

\( D_{HYDJET} \) results. The resulting fit results. The resulting fit results. The resulting fit results. The resulting fit results.

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**3.4 Systematic uncertainties**

The uncertainty due to the photon angular resolution is negligible, less than 10%.

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**Photons that have an associated jet passing the analysis**

\( \phi_{J\gamma} \sim \text{the fraction of isolated photons} \)

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**Peripheral events**

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**Central events**

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Even better? Z-jet!

LHC... yet again: an amazing machine...

\[ \text{Z}(\rightarrow \mu^+\mu^-) - \text{jet} \]

\[ \text{Z}(\rightarrow e^+e^-) - \text{jet} \]
Even better? Z-jet!

LHC... yet again: an amazing machine...

- $Z \rightarrow e^+e^-, \mu^+\mu^-$, $p_T > 60$ GeV
- Jet: anti-$k_T$, $R=0.2, 0.3, 0.4$, $p_T > 25$ GeV, $|\eta| < 2.1$
- Z-jet separation $> \pi/2 \rightarrow 37$ events for $L_{\text{int}} = 0.15$ nb$^{-1}$

- Suppression of the $\langle p_T^{\text{jet}} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions
Internal structure of jets & in-medium modifications
\( \iff \) jet quenching
Substructure of jets

- The problem:
  - How does a multi-parton object (shower) interacts with the medium (dynamical picture)?
  - The answer depends on the medium properties: resolution scale of the medium
  - Understanding the jet substructure in terms of sub-shower elements (not hadrons) may provide a critical input => insight to partonic process (jet quenching) at the partonic (internal jet energy flow) level

Distributions (some) - analytically calculable in vacuum => calibrated reference for QGP effects
Modified jet fragmentation - an expectation from jet quenching

\[ \xi = \ln \left( \frac{E_{\text{jet}}}{p_{\text{hadron}}} \right) \]

Jet vector

Projection

hadron

High momentum hadrons

Low momentum hadrons

\[ \zeta = \ln(\sqrt{z}) \]

\[ z = \frac{p}{E} \]
Jet fragmentation in Heavy-ion collisions

Jet quenching via large dijet energy imbalance

- Dijets, calorimeters only
- Leading $p_T > 120$ GeV/c
- Sub-leading $p_T > 50$ GeV/c

Overview of CMS experimental results

$p_T$ imbalance, increasing with centrality

Back-to-back 'I ~ S for all centralities

$pp$ vs. $PbPb$, 50 - 100% vs. $PbPb$ 0 - 10%

Jet fragmentation

$R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$

$\zeta = \ln(1/z)$  
$z = pT/E$

$\bullet$ Enhancement at low $z$, suppression at $z \approx 0.1$
$\bullet$ No modification at high $z$
$\bullet$ Similar results found for $R=0.2$ and 0.3 jets
Jet fragmentation in Heavy-ion collisions

Jet shapes

Low-pT

High-pT

\[ \rho(r) = \frac{1}{\delta r N_{\text{jet}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in [r_a, r_b]} p_{T,\text{track}}}{p_{T,\text{jet}}} \]

\[ r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2} \leq 0.3 \]
Jet fragmentation in Heavy-ion collisions

CMS jet shape: \( \rho(r) \) - differential energy density within the jet - here shown as a function of \( r \) - distance to the jet axis

Non trivial (monotonous) energy redistribution due to quenching; rigid core

CMS Preliminary
\[ \int L \, dt = 129.0 \mu b^{-1} \]

- **PbPb** \( s=2.76 \) TeV
- **pp** reference

Ak PF, \( R=0.3 \)

- \( p_T^{\text{jet}}>1 \text{ GeV/c} \)
- \( |\eta_{\text{jet}}|<2 \)

\( p_T^{\text{jet}}>100 \text{ GeV/c} \)

Dijets, calorimeters only

Leading \( p_T \)\n
- \( T > 1 \text{ GeV} \)
- \( |\eta|<2 \)

Sub-leading \( p_T \)\n
- \( 0.1 < T < 0.2 \text{ GeV/c} \)
- \( |\eta|<2 \)

CMS jet shape: \( \rho(r) \)

\[ \rho(r) = \frac{\text{d}E}{\text{d}r} \]

Different centrality bins for 

- 0-10%
- 10-30%
- 30-50%
- 50-100%

Imbalance,

\[ \int |\Delta E| \, dt = 129.0 \mu b^{-1} \]

**References** in the jet-

Non trivial (monotonous) energy redistribution due to quenching; rigid core
New picture of jets: Sub-jet analysis

- Critical angle (decoherence)
- Radiation as total charge
- Radiation as independent charges
- Vacuum-like fragmentation within each substructure

Casalderrey-Solana, Iancu JHEP (2012)
Casalderrey-Solana Mehtar-Tani, Salgado, KT PLB (2013)
Sub-jet structure observables

Vacuum: Altarelli-Parisi splitting function
No flavor dependence
Weak dependence on jet $p_T$

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Many more used in pp collisions (Higgs search for example) - a growing number being applied to jets in heavy-ion collisions (rapidly evolving understanding)
Splitting function in AA

Modifications at large $\frac{M}{p_T}$ for $z_{cut}=0.1$ & $\beta=0$; no modifications for $z_{cut}=0.5$ & $\beta=1.5$ (jet core)

**CMS Preliminary**

140 < $p_{T,jet}$ < 160 GeV

- PbPb
- Smeared pp

Small modifications to the jet core (no mods. at RHIC) Distribution of particles to large angles (inducing large jet masses) - increase small $z_g$ [deplete large $z_g$]
Heavy-flavor in medium
Parton in-medium energy loss: elastic (collisional) and inelastic (radiative)...

Longitudinal drag coeff. (collisional) $\hat{e}$

$p_T$ diffusion (radiative) $\hat{q}$

Reminder: at high-E radiative processes dominate...
Is parton energy loss different for gluons, light-quarks and heavy-quarks?

**Expectation:** \( \Delta E_g > \Delta E_{\text{light-}q} > \Delta E_{\text{heavy-}q} \)

- **Casimir (color factor):**
  - gluons "glue" better to the medium than quarks
- **"Dead-cone" effect:**
  - mass of the parent quark
  - \( \theta < \frac{m}{E} \) is suppressed

\( \Rightarrow \) \( R_{AA} \text{pions} < R_{AA} \text{D-mesons} < R_{AA} \text{B-mesons} \)

Reminder: at high-\( E \) radiative processes dominate...
Parton energy-loss: gluons vs. quarks

\[ \Delta E \propto \alpha_s C_R \hat{q} L^2 \]

- Energy loss depends on parton:
  - Casimir factor \((C_R = 3 \text{ for gluons and } 4/3 \text{ for quarks})\)
  - Mass of the quark (dead cone effect): radiation suppressed for angles \(\theta < m/E\)

\[ \Delta E_{\text{gluon}} > \Delta E_{\text{quark}} \]
\[ \Delta E_{\text{light-q}} > \Delta E_{\text{heavy-q}} \]

- Does it persist at low-\(p_T\) as:

\[ R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \]
**Heavy-flavor reconstruction**

Semi-leptonic decays (c,b)

Displaced J/ψ (from B decays)

Jet b-tagging

Full reconstruction of D meson hadronic decays

\begin{align*}
D^0 &\rightarrow K^-\pi^+ \\
D^+ &\rightarrow K^-\pi^+\pi^+ \\
D^{*+} &\rightarrow D^0\pi^+ \\
D_s^+ &\rightarrow K^-K^+\pi^+
\end{align*}
Production in p-p

ALICE, JHEP 1201 (2012)

CMS, PRL 106 (2011) 112001

pQCD agree with data within uncertainties
Open charm and Y/F-electrons suppressed ($R_{AA} < 1$)

Number of models explain the data qualitatively - need for better precision in data

Energy loss for charm similar to light flavor? Caveat: gluon splitting within parton shower

Some indication for parton mass dependent in-medium energy loss (relatively low-$p_T$ electrons [yet $b$-dominated] compared to pion $R_{AA}$) - also see next slide...
Heavy-flavor suppression in QGP

Comparison of prompt D-mesons (charm) with non-prompt J/ψ (proxy for beauty) consistent with mass dependent in-medium energy loss.

Integrated \( p_T \) \( R_{AA} \ll 1 \)
Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
- $v_2(b) < v_2(c)$

Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
- Transported through the full system evolution
Due to their large mass, $c$ and $b$ quarks should take longer created in the medium to be influenced by the collective.

Heavy-flavor flows with the medium plane reaction include hadronisation via quark recombination, in addition to independent fragmentation. The MC@SHQ interaction processes, while the BAMPS-el+rad [48], LBT [50], MC@SHQ [47] and PHSD [46] calculations underestimated the D-meson feed-down.

The average D-meson species, shown in the bottom panel of Fig. 1, was computed using the elliptic flow $v_2$, $v_2^{[EP]}$, $v_2^{[SP]}$ and $v_2$ (parcles), which is dominated by the pion component, is compatible at these points.

The average of the three non-strange D-meson species is compared with theoretical calculations. The vertexing and tracking of charged particles, which is dominated by the pion component, is compatible at these points.

The uncertainty of the average $v_2$, calculated using POWLANG with fragmentation, is similar to that of $v_2^{[EP]}$. The vertexing and tracking of charged particles, which is dominated by the pion component, is compatible at these points.

The average $v_2$, $v_2^{[EP]}$, $v_2^{[SP]}$ and $v_2$ (parcles) are consistent with each other and they are larger than zero in the $v_2^{[EP]}$ interval (1–16 GeV/c).

The $v_2^{[EP]}$ for $|y| < 0.9$, $v_2^{[SP]}$ and $v_2$ (parcles) are consistent with each other and they are larger than zero in the $v_2^{[EP]}$ interval (1–16 GeV/c). The vertexing and tracking of charged particles, which is dominated by the pion component, is compatible at these points.

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Case study: HF sensitivity to the in-medium energy loss

Two regions (a qualitative selection) - light vs. heavy (charm)-flavor
Lower $p_T$: below 5 GeV (parton energy ~ 10 GeV?) => different $v_2$ & different $R_{AA}$ (coll. E-loss)
Higher $p_T$: above 5 GeV (parton energy > 10 GeV) => similar $R_{AA}$ => radiative E-loss
Case study: H/F sensitivity to the in-medium energy loss

Two regions (a qualitative selection) - light vs. heavy (charm) - flavor

Lower \( p_T \): below 5 GeV (parton energy \( \sim 10 \) GeV?) \( \Rightarrow \) different \( v_2 \) & different \( R_{AA} \) (coll. E-loss)

Higher \( p_T \): above 5 GeV (parton energy \( > 10 \) GeV) \( \Rightarrow \) similar \( R_{AA} \) \( \Rightarrow \) radiative E-loss
Case study: HF sensitivity to the in-medium energy loss

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**H/F results from RHIC**

Despite vastly different centrality selections - a similar picture at RHIC: 
- $R_{AA}$ of D at high-$p_T$ similar to light-hadrons
- D flows within the medium (similar to strange-hadrons) - mass scaling

Spatial diffusion within QGP needed to describe the data

Electrons from B-hadrons => beauty less suppressed than charm (low-$p_T < 5$)
- Needs better precision(!)

...more measurements: non-prompt J/$\gamma$; di-leptons
Transverse & longitudinal diffusion
- consistent picture
- temperature and/or density dependence?

Work in progress: complete parton shower in-(dynamic) medium evolution; inclusion of heavy-quarks (theory community - JETSCAPE Collaboration for example)
Quarkonia: $q$-$q\bar{q}$ in medium
Charmonium suppression

QGP signature proposed by Matsui and Satz, 1986

In the plasma phase the interaction potential is expected to be screened beyond the Debye length $\lambda_D$ (analogous to e.m. Debye screening):

- Charmonium (cc) and bottomium (bb) states with $r > \lambda_D$ will not bind; their production will be suppressed (qgbar states will “melt”).

$\lambda_D$ (Debye length from lattice QCD)

$\chi_c (0.59 \text{ fm})$

$\psi (0.56 \text{ fm})$

$\psi (0.29 \text{ fm})$

$\Upsilon (0.13 \text{ fm})$

$1/\langle r \rangle \ [\text{fm}^{-1}]$

$T/T_c$

$\Upsilon (1S)$

$\chi_b (1P)$

$J/\psi (1S)$ $\Upsilon (2S)$

$\chi_b (2P)$ $\Upsilon (3S)$

$\chi_c (1P)$ $\psi (2S)$

Mocsy, EPJ C 61 (2009) 705


**Inclusive J/ψ**

- **Prompt J/ψ**
- **Non-Prompt J/ψ** from B decays
- **Direct J/ψ**
- **Feed-down from ψ’ and χ_c**

- **Non-prompt J/ψ** become significant towards higher \( p_T \) (20–30%)!

- Reconstruct \( \mu^+\mu^- \) vertex

- Simultaneous fit of \( \mu^+\mu^- \) mass and pseudo-proper decay length

\[
\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}
\]

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**2010 data:** JHEP 1205 (2012) 063

**2011 data:** CMS PAS HIN-12-014

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**CMS Preliminary**

\[ \text{PbPb} \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ L_{\text{int}} = 150 \mu b^{-1} \]

- \( \ell_{J/\psi} < 2.4 \)
- \( 6.5 < p_T < 30 \text{ GeV}/c \)
- Cent. 0-100%

**Data**

- Total fit
- Background + non-prompt

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**2010 data:** JHEP 1205 (2012) 063

**2011 data:** CMS PAS HIN-12-014
Inclusive $J/\psi \rightarrow \mu^+\mu^-$, Pb-Pb $s_{NN}=2.76$ TeV and Au-Au $s_{NN}=0.2$ TeV

- ALICE, 2.5<y<4, $p_T<8$ GeV/c  global syst. = ± 15%
- PHENIX, 1.2<y<2.2, $p_T>0$ GeV/c  global syst. = ± 9.2%

**ALICE**: $2.5 < y < 4$
**PHENIX**: $1.2 < y < 2.2$

Recombination needed to explain $R_{AA}$ at the LHC

$J/\psi$ enhanced/re-generated at low-$p_T$

High-$p_T$ $J/\psi$ suppressed (similar magnitude at LHC & RHIC)

Strong suppression in central as compared to peripheral collisions
**ϒ(nS)/ϒ(1S) Single Ratios**

### CMS pp $\sqrt{s} = 2.76$ TeV

- $|y| < 2.4$
- $p_T^\mu > 4$ GeV/c
- $L_{\text{int}} = 230$ nb$^{-1}$

- Data
- Total fit
- Background

### CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- Cent. 0-100%, $|y| < 2.4$
- $p_T^\mu > 4$ GeV/c
- $L_{\text{int}} = 150$ µb$^{-1}$

- Data
- Total fit
- Background

<table>
<thead>
<tr>
<th>Ratio</th>
<th>PP Value</th>
<th>PbPb Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}</td>
<td>_{PP}$</td>
<td>$0.56 \pm 0.13 \pm 0.02$</td>
</tr>
<tr>
<td>$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}</td>
<td>_{PP}$</td>
<td>$0.41 \pm 0.11 \pm 0.04$</td>
</tr>
</tbody>
</table>

Ratios not corrected for acceptance and efficiency
Events / (0.1 GeV/c)

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
Cent. 0-100%, $|y| < 2.4$
$L_{\text{int}} = 150 \mu b^{-1}$

$p_T^\mu > 4$ GeV/c

Mass($\mu^+\mu^-$) [GeV/c$^2$]
Quarkonia suppression at the LHC

Figure 7: (Left): Dimuon invariant mass distribution in the mass region for minimum bias PbPb collisions. The dashed blue line shows the line shape obtained from a fit to the spectrum in pp collisions at the same collision energy, normalized to the $(1S)$ peak. (Right): Minimum bias $R_{AA}$ for all quarkonia states measured by CMS. For $(3S)$ the upper limit (95% CL) is given. Points are from [8], [9], and [10].

Medium properties, e.g., in particular the initial temperature. The sequential suppression of the three $(nS)$ states in the order of their binding energies is plainly visible in the comparison of the pp line shape and the PbPb data, following expectations for their dissolution in a hot QCD medium. The suppression relative to pp for the individual states was found to be about 2, 8, and larger than 10, for $(1S)$, $(2S)$ and $(3S)$ respectively. The dependence is further quantified in Fig. 7(right), which shows the $R_{AA}$ factors for the charmonium and bottomonium states in minimum bias PbPb collisions as a function of their binding energies. Although a detailed comparison will need to take the different $p_T$ cuts for $c$ and $b$ states into account, the expected decrease of the suppression (i.e. increase in $R_{AA}$) is once again observed for states with increasing binding energy. Further experimental studies using data from a future pPb run at LHC will be necessary to understand the possible cold nuclear matter effects in the observed quarkonium suppression and to allow quantitative evaluation of the underlying medium properties.

7. Summary

Using the high statistics data set collected in 2011, CMS has greatly extended the $p_T$ reach, precision and scope of measurements related to the key properties of the strongly interacting medium formed in heavy collisions. Ultra-central collisions provide a new testing ground for models of the initial state and the hydrodynamic expansion, while high-$p_T$ anisotropy measurements characterize the path length dependence of parton energy loss. Earlier jet quenching measurements have been complemented by various studies of nuclear modification factors for unsuppressed probes such as $Z^0$'s and $W$'s, which provide a reference for the suppression seen in inclusive jets and, for the first time, in b-tagged jets. The suppression of inclusive jets confirms the results seen in inclusive charged hadrons, and complements the information from high-$p_T$ dijet imbalance measurements. Modifications to the jet fragmentation properties have been studied with jet shape and fragmentation function measurements, which demonstrate a moderate, but
Unexpected novel effects...
Long-range correlation structure in high-multiplicity pp collisions

Long-range correlation double structure in high-multiplicity pPb collisions

Similar observations made by ATLAS & LHCb

Long range correlations are intimately related to initial stages - early times - \( \sim 10^{-24}\)s.

Do we fully understand initial stages of nuclear collisions? - No (!).

ALICE: + (not shown) indication of \( v_2 \rangle HF \) in p-Pb collisions (muon-hadron correlations)
Long range correlations are intimately related to initial stages - early times - $\sim 10^{-24}$s.

Do we fully understand initial stages of nuclear collisions? - No (!).

ALICE: + (not shown) indication of $v_2 > H/F$ (?) in $p$-$Pb$ collisions (muon-hadron correlations)

P. Bozek et al., Phys Rev Lett 111, 172303
Strangeness - striking continuous evolution with event multiplicity from pp to AA

All this while jet quenching is not present in pPb collisions...

Limit obtained using hadron-jet correlations ($\Delta E < 0.05$)
Quem mandou isso?

Recently new result from pPb...

- $v_2$ for $p_T < 3$ GeV/c is compatible with zero
- $v_2$ in $3 < p_T < 6$ GeV/c is positive with a total significance of $5\sigma$
  - Comparable to values from central Pb-Pb collisions
"Quem mandou isso?"

$J/\psi$ flow similar in magnitude in $p$-$Pb$ as compared to $Pb$-$Pb$. Similar mechanism? MPI dominance in high-multiplicity collisions? (see poster by C. Jahnke)
Long range rapidity correlations are a chronometer

\[ \tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right) \]

Long range correlations sensitive to very early time (fractions of a femtometer \(\sim 10^{-24}\) seconds) dynamics in collisions
Possible explanations?

Collectivity from Interference

Urs Achim Wiedemann
CERN TH Department

Solutions to the “Flow w/o quenching” puzzle in pp / pA

1. Quantitative Explanation: maintain that $v_n$ result from final state interactions
   - small jet quenching effects must be seen in pp/pA
     for techniques to detect them, see e.g. Mangano, Nachman arXiv:1708.08369
   - Theory improvements needed to relate jet quenching and $v_n$ signals.

2. High-density Scenario: azimuthal correlations from a saturated initial state (“CGC”)
   Altinoluk, Armesto, Beuf, Dumitru, Gotsman, Jalilian-Marian, Iancu, Kovner, Lappi, Levin,
   Lublinsky, McLerran, Skokov, Schlichting, Venugopalan, ....
   - UE (underlying event) physics in pp multi-purpose MC event generators based on dilute system of up to O(10) MPIs (multi parton interactions)
   - If saturated initial state needed to describe pp UE, then dramatic implications: Torbjorn go home.
   - One needs to understand whether initial density effects are necessary for azimuthal correlations.

3. High-density Scenario: strongly coupled fluid paradigm (à la AdS/CFT) for pp/pA
   - small jet quenching effects must be seen in pp/pA
   - UE model radically different from that in MC generators

4. Low-density Scenario: fluid dynamics negligible,
   azimuthal correlations from escape mechanism
   - mechanism to be understood quantitatively outside a MC code
   - small jet quenching effects must be seen in pp/pA
   - mild extension of UE model of multi-purpose MC generators

5. Low-density Scenario: Collectivity from interference
   - No initial density and no initial asymmetry, no final state interactions
   - Contribution to $v_n$ from QM interference & color correlations?
   - does not imply jet quenching in pp/pA
   - natural extension of UE model of multi-purpose MC generators

No definite answer at this point...
Notes on the future

- LHC Run-3 (Run-2 ends 2019)
  - 10/nb AA data (10^11 events!)
  - Potentially another pPb run (202X?)
- RHIC: new sPHENIX experiment
  - High rate jet detector (high statistics jets)
- Electron-Ion collider?
  - A USA based machine (RHIC? JLAB?)
  - Construction 2025+
- Future Circular Collider?
  - 40TeV PbPb Collisions (100 TeV pp machine)
An appetizer... Heavy-ion perspective on FCC but also high-lumi LHC

"Time" tomography of the medium with boosted tops (accessible at sLHC but also some at high-luminosity LHC)

$\bar{t}t \rightarrow b\bar{b} + \ell + 2\text{ jets} + E_T$

http://www.int.washington.edu/talks/WorkShops/int_17_1b/People/Apolinario_L/Apolinario.pdf

Jet Reconstruction

1 (isolated) muon, $p_T > 25$ GeV, $|\eta| < 2.5$.  
1 (isolated) lepton, $p_T > 25$ GeV, $|\eta| < 2.5$.  
2 b jets (assumed 70% efficiency each)  
$\geq 2$ non-b jets

L. Apolinário, G. Salam (CERN), C. A. Salgado (USC) (IST), G. Milhano (IST and CERN),
Summa summarum

★ Hot QGP created in heavy-ion collisions flows as almost perfect liquid and it is opaque to most energetic colored probes

★ Significant progress in both qualitative and quantitative understanding of the gross medium properties; improved detailed modelling; dynamic description of jet quenching in progress; a ”standard model” of heavy-ion collisions solidified... and then ...

★ Nature of collective phenomena found in small systems that qualitatively (and quantitatively) resemble observations from heavy-ion collisions is under intense investigations - mini-QGP in pp, pA at high-energies? vs. initial stage correlations/coherence effects dominating in small systems?

★ Plan for the next (10?) years: detailed understanding of inner workings of QGP on the microscopic level
• Plenty left out / more to discuss:

• di-leptons (chiral symmetry - LHC Run-3), search for Chiral Magnetic Effect, balance functions, importance/impact of nuclear PDFs, jet hadrochemistry, details of the so-called underlying event - soft-QCD - some of these discussed elsewhere (see talks by Gustavo Gil Da Silveira, Arthur Moraes) - QCD at the LHC; detailed LHC-RHIC comparisons; dAu collision results from RHIC
As ondas são anjos que dormem no mar,
Que tremem, palpitem, banhados de luz...

Thank you for now!

Muito obrigado, eu poderia ter feito parte do workshop!
Thanks!

Thanks to all the listed for the graphics/slides shamelessly stolen for the purpose of this talk


- For the material by collaborations: ALICE, ATLAS, CMS, PHENIX, STAR, LHCb