High-\(p_T\) processes measured with ALICE

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on behalf of the ALICE Collaboration

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Motivation

- The production of hadrons at high $p_T$ is suppressed in AA collisions compared to superposition of nucleus-nucleus collisions (RHIC / LHC)
- Suppression is a consequence of energy loss of partons traversing the Quark-Gluon-Plasma (QGP)
- Understanding the suppression goes towards understanding the medium properties of the QGP
- Energy loss in the QGP (high $p_T$):
  - Medium density and size: $dN/dp_T$, $R_{AA}$, $v_2$
  - Color charge (Casimir factor): $\Delta E_q < \Delta E_g$
  - Parton mass (dead cone effect): $\Delta E_b < \Delta E_c < \Delta E_{u,d,s}$
ALICE – A Large Ion Collider Experiment

ALICE has excellent PID capabilities. Particle identification possible in the $p_T$ range 0.1-50 GeV/c.
Pb-Pb runs: Nov. 2010 and 2011

Pb-Pb central (0-5%)
\[ dN_{\text{ch}} / d\eta = 1584\pm74 \]
ALICE, PRL 105, 252301 (2010)

Pb-Pb event in ALICE TPC

Pb+Pb @ \sqrt{s} = 2.76 \text{ ATeV}
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
\[ R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \]

- Suppression pattern depends on collision centrality
- Largest suppression in the central collisions (factor 7 at \( p_T \sim 7 \text{ GeV}/c \))
**R_{AA} vs. collision centrality**


**Charged particles**

- Strongest suppression vs. collisions centrality for $5 < p_T < 7$ GeV/c
- Factor $\sim 1.2$ stronger suppression vs. $<N_{\text{part}}>$ compared to RHIC (at all $p_T$)
- Similar suppression vs. $dN_{\text{ch}}/d\eta$ compared to RHIC

- 30 $< p_T < 50$ GeV/c
- 20 $< p_T < 30$ GeV/c
- 15 $< p_T < 20$ GeV/c
- 5 $< p_T < 7$ GeV/c
- PHENIX 5 $< p_T < 7$ GeV/c

\[ \langle N_{\text{part}} \rangle \]

\[ dN_{\text{ch}}/d\eta \]

\[ 2.76 \text{ TeV} \]

\[ \text{ALICE, Pb-Pb, } |y| < 0.8 \]

\[ \text{pp syst. uncertainty} \]

\[ < 50 \text{ GeV/c} \]

\[ 30 < p_T < 50 \text{ GeV/c} \]

\[ 20 < p_T < 30 \text{ GeV/c} \]

\[ 15 < p_T < 20 \text{ GeV/c} \]

\[ 5 < p_T < 7 \text{ GeV/c} \]

\[ \text{PHENIX 5} < p_T < 7 \text{ GeV/c} \]
$R_{AA}$ comparison - central collisions

**Charged particles**

- Selected models available before preliminary data
- A variety of energy loss formalisms are used (radiative, elastic, ...)
- An increase of $R_{AA}$ vs. $p_T$ is seen for all the models
- Agreement with CMS

Radiative:

Elastic (T.R.):
- Phys. Rev. C 84 (2011) 014906

TOWARDS JETS WITH IDENTIFIED PARTICLES

Light flavor (u,d,s)
$R_{AA}$ for charged pions

charged particle spectra arXiv:1208.2711

\begin{itemize}
  \item \(2 < p_T < 7\) GeV/c: pion \(R_{AA}\) < charged particle \(R_{AA}\) (centrality dependence)
  \item \(p_T > 7\) GeV/c: pion \(R_{AA}\) = charged particle \(R_{AA}\)
\end{itemize}
$R_{AA}$ for charged kaons

charged particle spectra arXiv:1208.2711

- Kaon $R_{AA}$ = charged particle $R_{AA}$ ($p_T > 3$ GeV/c)
$R_{AA}$ for (anti-)protons

charged particle spectra arXiv:1208.2711

- $3 < p_T < 7$ GeV/c: proton $R_{AA} >$ charged particle $R_{AA}$ (centrality dependence)
- $p_T > 7$ TeV: proton $R_{AA} =$ charged particle $R_{AA}$
Central collisions (0-5%):
- $3 < p_T < 7$ GeV/c: proton $R_{AA} >$ pion or kaon $R_{AA}$
- $p_T > 7$ TeV: pion $R_{AA} =$ kaon $R_{AA} =$ proton $R_{AA}$

Peripheral collisions (60-80%):
- Pion $R_{AA} =$ kaon $R_{AA} =$ proton $R_{AA}$

- Different particle spectra in Pb-Pb at $p_T < 7$ GeV/c
- High-$p_T$ parton fragmentation seems not to be affected by the medium
# Towards Jets with Identified Particles

Heavy flavor (c,b)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>CT (~ μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c, b \rightarrow e$</td>
<td></td>
</tr>
<tr>
<td>$b \rightarrow e$</td>
<td>$500 \mu m$</td>
</tr>
<tr>
<td>$c, b \rightarrow \mu$</td>
<td></td>
</tr>
<tr>
<td>$D^0 \rightarrow K \pi$</td>
<td>$122.9 \mu m$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K \pi \pi$</td>
<td>$311.8 \mu m$</td>
</tr>
<tr>
<td>$D^{*+} \rightarrow D^0 \pi$</td>
<td></td>
</tr>
<tr>
<td>$D_s^{+} \rightarrow K K \pi$</td>
<td>$149.9 \mu m$</td>
</tr>
</tbody>
</table>
Heavy flavor $R_{AA}$ vs. collision centrality

- Similar suppression pattern of D mesons and heavy flavor muons
- Beauty $R_{AA}$: suppression of non-prompt $J/\psi$ consistent with heavy flavor muons
- Light flavor $R_{AA} <$ heavy flavor $R_{AA}$?
  - Not conclusive from these data...

ALICE, arXiv:1203.2160
ALICE, PRL 109(2012)112301
CMS, JHEP 05 (2012)063
Heavy flavor $R_{AA}$ vs. $p_T$ in central collisions

- Similar suppression of heavy flavor in central Pb-Pb collisions
- D meson $R_{AA}$ consistent with $R_{AA}$ of heavy flavor decay $e/\mu$ taking into account $p_T^e \sim 0.5p_T^{HF}$ at high-$p_T$
- D meson $R_{AA} = \text{pion } R_{AA} = \text{charged particle } R_{AA}$
**R\(_{AA}\) vs. reaction plane - D mesons**

Path length dependence of the heavy quark energy loss.

\[
R_{AA}(\phi) = R_{AA}(1+2v^2 \cos(2\phi))
\]

- \(\phi \sim 0\) (in-plane)
- \(\phi \sim \pi/2\) (out-of-plane)

- \(R_{AA}\) in-plane > \(R_{AA}\) out-of-plane (centrality 30-50%)
- contribution from elliptic flow at low \(p_T\)?
- path length dependence of energy loss at high \(p_T\)?
TOWARDS FULL JET RECONSTRUCTION IN Pb-Pb COLLISIONS

Jet in ALICE EMCAL (2011)
Jet measurement with ALICE

- Full jet reconstruction should recover most of the radiated energy
- First step: Jet $R_{AA}$
  - $R_{AA} \sim 1 \rightarrow$ energy is recovered
  - $R_{AA} < 1 \rightarrow$ out-of-cone radiation
- Next steps: study transverse and longitudinal distribution of fragments
- ALICE case
  - In 2010: No Pb-Pb data with full EMCAL $\rightarrow$ only charged jet measurement
  - In 2011: EMCAL installation completed: charged and neutral jets
Charged jet spectra in Pb-Pb (0-10%)

**Experimental challenge** – huge background from underlying event(s)

\[ p_{T,jet}^{ch} = p_{T,jet}^{rec} - \rho \times A_{jet} \pm \sigma \times \sqrt{A_{jet}} \]

**Corrected charged jet spectra**

- Event-by-event background \( (\rho \times A_{jet}) \) estimated using k\(_T\) algorithm
- Background fluctuations \( (\sigma \times \sqrt{A_{jet}}) \) are quantified using random cones and embedding of high p\(_T\) probes (*JHEP 1203 (2012) 53*), and corrected for via unfolding

- Similar p\(_T\) spectra for inclusive jets and jets with the leading track selection
  - Unfolding deals correctly with background at low p\(_T\)
  - Rather weak softening of the fragmentation in Pb-Pb
Jet quenching – charged jets in Pb-Pb

JEWEL (Zapp et al.) arXiv:1111.6838

- Strong charged jet suppression in central collisions
  - $R_{AA} \sim 0.2\text{-}0.4$ (with Pythia pp reference)
  - $R_{CP} \sim 0.3\text{-}0.5$ (0-10% / 50-80%) – similar for inclusive jets and jets with selected leading track
Jet structure

- Pythia reproduces fragmentation well in pp ($\sigma(R=0.2)/\sigma(R=0.4)$)
- $R=0.2$ / $R=0.3$ in central and peripheral Pb-Pb collisions consistent with vacuum jets
Summary

• Strong suppression of light and heavy flavor production at high $p_T$ in central Pb-Pb collisions
• Different suppression for protons compared to pions and kaons at $p_T < 7$ GeV/c (different particle spectra in Pb-Pb)
• Similar suppression of pions, kaons and protons at high $p_T$ (parton fragmentation seems not to be modified by the medium)
• Light flavor $R_{AA} = D$ meson $R_{AA}$ at high $p_T$ in central Pb-Pb collisions
• Charged jets in Pb-Pb
  – Strong suppression in central collisions (0-10%)
  – $R=0.2 / R=0.3$ in central and peripheral collisions consistent with vacuum jets
  – Rather weak softening of the fragmentation in Pb-Pb collisions
• Neutral + charged jet analysis in Pb-Pb is finalizing
BACKUP
Nuclear Modification Factor – $R_{AA}$

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- $R_{AA}$ quantify in medium effects
- $\langle T_{AA} \rangle$ - nuclear thickness function from Glauber model of AA collisions
- At LHC, first $R_{AA}$ published by ALICE

Today focus on intermediate and high $p_T$ with extended $p_T$ reach.

\( p_T \) spectra in Pb-Pb

**Charged particles**

- \( p_T = 0.15-50 \) GeV/c
- \( p_T \) spectral shape changes with collision centrality
- \( p_T \) spectra in central Pb-Pb dramatically different from pp reference
High-$p_T$ particle identification: TPC $dE/dx$

\[ \frac{d^2 N_i}{d\eta dp_T} = \frac{d^2 N_{ch}}{d\eta dp_T} \times \frac{\epsilon_i}{\epsilon_{ch}} \times \frac{N_i}{N_{ch}} \times \frac{\eta}{\sinh^{-1}\left(\frac{p_T \sinh(\eta)}{\sqrt{p_T^2 + m_i^2}}\right)} \]

$i = \pi, K, p$

arXiv:1208.2711v1 [hep-ex]
$p_T$ spectra for $\pi/K/p$

- High-$p_T$ particle identification using TPC dE/dx: $\pi$ ($p_T > 2$ GeV/c) and $K$, $p$ ($p_T > 3$ GeV/c)
- Possible $p_T$ reach up to 50 GeV/c
proton / pion ratio in pp and Pb-Pb
$R_{AA}$ - heavy flavor decay electrons

Suppression around factor of 1.5-3 for $p_T > 3$ GeV/c

ATLAS, PLB 707 (2012) 438
$R_{AA}$ - heavy flavor decay muons

- pp reference measured at the same collision energy
- Suppression in central collisions around factor of 2-4 for $p_T > 4$ GeV/c
- Weaker suppression ($R_{AA} \sim 0.7$) in semi-peripheral (40-80%) collisions
• pp reference (7 TeV pp scaled for $p_T < 20$ GeV/c, extrapolation for $p_T > 20$ GeV/c)
• Suppression in central collisions (0-7.5%) around factor of 5 at $p_T = 10$ GeV/c
Proton / pion enhancement – bulk matter

The enhancement seems to be a bulk effect (Misha Veldhoen, arXiv:1207.7195).

Particle production in jets is not affected by medium.
JETLIKE AZIMUTHAL DIHADRON CORRELATION

Jet quenching measurement via leading hadron azimuthal correlations
Jet quenching measurement via leading hadron azimuthal correlation

**Intermediate pT di-hadrons:** Strong modification of the recoil-jet indicates **substantial partonic interaction within the medium** $\rightarrow$ quenching

**Near side** ($\Delta\phi \sim 0$): selecting jets with little interaction

**Quantify jet suppression:**
- Compare yields in Pb-Pb and pp: $I_{AA}$
- Compare yields in Pb-Pb central and peripheral: $I_{CP}$

**Strong suppression**
$I_{AA} = \text{yield in Pb-Pb} / \text{yield in pp}$

ALICE, PRL 108, 092301 (2012)

- Trigger particles: $8 < p_{T,\text{trig}} < 15 \text{ GeV/c}$
- Associated particles: $p_{T,\text{assoc}} < p_{T,\text{trig}}$
- Non-jet background subtraction: flat pedestal, $v_2$ flow, $\eta$-gap

- Near side: enhanced particle yield in central collisions ($I_{AA} \sim 1.2$)
- Away side: strong suppression in central collision ($I_{AA} \sim 0.6$)
- No yield modification in peripheral collisions
- Small contribution from elliptic flow $v_2$ (mostly at low-$p_T$)
$I_{\text{CP}} = \text{yield in central Pb-Pb} / \text{yield in peripheral Pb-Pb}$

- Near side: enhancement $I_{\text{CP}} \sim 1.2$ consistent with $I_{\text{AA}} (0-5\%)$
- Away side: strong suppression ($I_{\text{CP}} \sim 0.6$)
Jet reconstruction in Pb-Pb collisions

Experimental challenge – huge background from underlying event(s)

\[ p_{T,jet}^{ch} = p_{T, jet}^{rec} - \rho \times A_{jet} \pm \sigma \times \sqrt{A_{jet}} \]

- \( p_{T, jet}^{rec} \) – from JetFinder (anti-k\( _T \) algorithm)
  - track \( p_T > 150 \) MeV/c
- \( \rho \) = median (\( p_{T,jet}/\text{area} \)) determined event-by-event (k\( _T \) algorithm)
- \( \sigma \) – background fluctuations due to:
  - statistics (Poisson limit)
  - flow (global dynamics)
  - mini-jets (local dynamics)
  - others?...
Background fluctuations

Experimental challenge – huge background from underlying event(s)

- Background fluctuations estimated using
  - Random cones
  - High-\(p_T\) track embedding
  - Pythia jet embedding
  - Jet spectrum scaled to 20 GeV
- Good agreement between all methods

\[
\delta p_{T, jet}^{ch} = p_{T, jet}^{rec} - \rho \times A_{jet} - p_T^{embed}
\]
Inclusive jet pp cross section

**Fully reconstructed jets**
- Charged particles from TPC and ITS
- Gammas and neutral pions from EMCAL
- Jet energy scale shift (~20-25%)
  - Unmeasured neutrons and $K^0_L$
  - Tracking efficiency
  - EMCAL residual hadronic background
  - E-by-e fluctuations

**Good agreement between measurement and NLO calculations and Pythia8**