Heavy Ion Results of the CMS Experiment

Bożena Boimska
National Centre for Nuclear Research
on behalf of the CMS Collaboration
Outline

- Introduction
- Experimental results: PbPb vs. pPb
  - Jet–quenching effect
  - Quarkonia production
  - Signals of (possible) collective behavior
- Results for pp collisions at 13 TeV
- Summary

39 published/submitted papers
~30 Physics Analysis Summaries (PAS)
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Only some selected results presented today …
Introduction

CMS detector

EM Calorimeter (ECAL) Hadron Calorimeter (HCAL)

Hadron System

3.8 T Magnet

Tracker (Pixels and Strips) Collision Centrality

Forward Hadron Calorimeter (HF)

Collision Centrality

Muon System

\[ \eta = - \ln (\tan \theta/2) \]
Heavy–ion oriented data samples

<table>
<thead>
<tr>
<th>Period</th>
<th>System</th>
<th>Energy (TeV)</th>
<th>Rec. Lumi.</th>
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</thead>
<tbody>
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<td>2010</td>
<td>p+p</td>
<td>7</td>
<td>6.2 nb⁻¹</td>
</tr>
<tr>
<td>2010</td>
<td>Pb+Pb</td>
<td>2.76</td>
<td>7 µb⁻¹</td>
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<tr>
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<td>150 µb⁻¹</td>
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<tr>
<td>2011</td>
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<td>230 nb⁻¹</td>
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<tr>
<td>2013</td>
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<td>5.02</td>
<td>35 nb⁻¹</td>
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<tr>
<td>2013</td>
<td>p+p</td>
<td>2.76</td>
<td>5.4 pb⁻¹</td>
</tr>
<tr>
<td>2015</td>
<td>p+p</td>
<td>13</td>
<td>270 nb⁻¹</td>
</tr>
</tbody>
</table>

Data included from 2015-11-19 14:39 to 2015-11-23 06:28 UTC

Data included from 2015-11-25 09:59 to 2015-12-13 12:09 UTC

B. Boimska (NCBJ)  Epiphany Conference, Cracow, 08.01.2016
Experimental results

Nuclear modification factor

Study of jet quenching by looking at magnitude of particle yield suppression.

\[
R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2N_{AA}}{dp_T d\eta} / \frac{d^2N_{pp}}{dp_T d\eta}
\]

\[
\begin{align*}
R_{AA} > 1 & \text{ enhancement} \\
R_{AA} = 1 & \text{ no medium effects} \\
R_{AA} < 1 & \text{ suppression}
\end{align*}
\]

PbPb 2.76 TeV

Isolated γ
\[W \rightarrow \mu \nu\]
\[Z^0 \rightarrow \mu^+ \mu^-\]

Colorless probes (control probes) are not modified by the medium

Production scales with \(N_{\text{coll}}, R_{AA} \approx 1\)

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Experimental results

Nuclear modification factor

PbPb 2.76 TeV

- Charged hadrons & b–quarks are suppressed, $R_{AA} < 1$

- Colorless probes are unsuppressed
- Hadrons are modified (jet quenching)
- Less b–hadron suppression at low $p_T$

B. Boimska (NCBJ)  Epiphany Conference, Cracow, 08.01.2016
Nuclear modification factor

Experimental results

PbPb 2.76 TeV

- Colorless probes are unsuppressed
- Hadrons and jets are modified (jet quenching)
- Less b–hadron suppression at low $p_T$; b–jets are similar to q/g jets

Jet $R_{AA} \approx 0.5$
First measurement of b–jet $R_{AA}$

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Epiphany Conference, Cracow, 08.01.2016
Experimental results

Nuclear modification factor: PbPb vs. pPb

Charged particles

At high $p_T$:

Enhancement in pPb collisions, $R_{pA} > 1$

Suppression in PbPb collisions, $R_{AA} < 1$

Similar trend in $R_{pA}$ and $R_{AA}$ as a function of $p_T$

Need pp reference data at 5.02 TeV to reduce systematics
**Experimental results**

**Nuclear modification factor: PbPb vs. pPb**

**Charged particles**

- CMS Preliminary
- pPb L = 35 nb$^{-1}$; PbPb L = 150 μb$^{-1}$
- Charged particles $R_{AA}$ (0-5%) $|\eta|<1$
- Charged particles $R_{pA}$ $|\eta_{CM}|<1$

**Jet suppression observed in PbPb collisions is the final state effect**

For pPb $R_{pA} \approx 1$
For PbPb $R_{AA} < 1$

**Jets**

- pPb $\sqrt{s_{NN}} = 5.02$ TeV
- PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- Inclusive jet $R_{AA}$ (0-5%) $|\eta|<2$
- Inclusive jet $R_{pA}$ $|\eta_{CM}|<0.5$

**Experimental results**

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Experimental results

Nuclear modification factor: PbPb vs. pPb

b–Jets

Inclusive Jets

For central PbPb: b–jets show similar suppression to inclusive jets, $R_{AA} \approx 0.5$

For pPb: inclusive and b–jets are not suppressed, $R_{pA} \approx 1$

No jet flavor dependence is observed

For pPb: $\sqrt{s_{NN}} = 5.02$ TeV

For central PbPb: $\sqrt{s_{NN}} = 2.76$ TeV

arXiv: 1510.03373
PRL 113 (2014) 132301
Experimental results

Dijet events in PbPb collisions

Dijet Imbalance

Event fraction

50-100%

0-10%

Asymmetry: \( A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \)

Energy deposits in calorimeters:

Dijet \( p_T \) imbalance quantified by asymmetry \( A_J \)

\( \Rightarrow \) Dijet \( p_T \) imbalance \( (A_J) \) increases with centrality

\( \Rightarrow \) Direct observation of jet quenching in central PbPb collisions

- exp. DATA
- ref. DATA

PRC 84 (2011) 024906
PLB 712 (2012) 176
Experimental results

Dijet events in PbPb collisions

Dijet Imbalance

Event fraction

Asymmetry: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

Dijet Azimuthal Correlation

Event fraction

$\Delta \phi = |\phi_{jet1} - \phi_{jet2}|$

Experimental results

Dijet $p_T$ imbalance ($A_J$) increases with centrality

- Direct observation of jet quenching in central PbPb collisions

- Jets remain essentially back-to-back ($\Delta \phi \sim \pi$) for all centralities

- Propagation of high $p_T$ partons in dense nuclear medium does not lead to a strong angular decorrelation

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PRC 84 (2011) 024906
PLB 712 (2012) 176
Experimental results

**Photon–jet events in PbPb collisions**

Direct measure of the jet energy loss is the ratio of jet to photon $p_T$: 

$$x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$

- **exp. DATA**
- **ref. DATA (PYTHIA+HYDJET)**

Jets lose about 15% of their initial energy.

$p_T$ imbalance larger for more central collisions.

Photon does not interact with the medium:
- provides initial parton $p_T$
- provides initial parton direction.
Experimental results

Photon–jet events in PbPb collisions

Direct measure of the jet energy loss is the ratio of jet to photon $p_T$:

$$x_{J\gamma} = \frac{p_{T,\text{Jet}}}{p_{T,\gamma}}$$

- exp. DATA
- ref. DATA (PYTHIA+HYDJET)

Jets lose about 15% of their initial energy.

$p_T$ imbalance larger for more central collisions

Azimuthal Correlation:

$$\Delta \phi_{J\gamma} = \left| \phi^{\text{Jet}} - \phi^{\gamma} \right|$$

Photon and jet are ‘back–to–back’ ($\Delta \phi_{J\gamma} \sim \pi$), also for other centralities.

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**Dijet events in pPb collisions**

**Dijet Imbalance**

- $p_{T,1} > 120$, $p_{T,2} > 30$ GeV/c
- $|\eta| < 3$, $\Delta\phi_{1,2} > 2\pi/3$

$<p_{T,2}/p_{T,1}>$ vs $E_T^{|\eta|>4}$ (GeV)

- $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp
- no jet quenching observed

Centrality characterized by $E_T$ at large $|\eta|$

**pPb at $\sqrt{s_{NN}}=5.02$ TeV**

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B. Boimska (NCBJ)  
Epiphany Conference, Cracow, 08.01.2016
Dijet events in pPb collisions

**Dijet Imbalance**

\[ \frac{p_{T,2}}{p_{T,1}} \]

- \( p_{T,1} > 120, p_{T,2} > 30 \text{ GeV/c} \)
- \( |\eta| < 3, \Delta \phi_{1,2} > 2\pi/3 \)

\[
\langle \frac{p_{T,2}}{p_{T,1}} \rangle
\]

- \( \text{PYTHIA (pp)} \)
- \( \text{pPb} \)

\( \Rightarrow \frac{p_{T,2}}{p_{T,1}} \) for pPb dijets the same as in pp

\( \Rightarrow \) no jet quenching observed

- Jets remain back-to-back (\( \Delta \phi \sim \pi \)) for all centralities

**Dijet Azimuthal Correlation**

\[
\Delta \phi_{1,2} = |\phi_{jet1} - \phi_{jet2}|
\]

- Centrality characterized by \( E_T \) at large \( |\eta| \)

- \( E_T^{|\eta|>4} < 20 \text{ GeV} \)
- \( E_T^{|\eta|>4} > 40 \text{ GeV} \)
Experimental results

Dijet events in PbPb collisions

Where does the lost energy go?

„missing” $p_T^{\parallel}$:

$$p_T^{\parallel} = \sum_{\text{Tracks}} -p_{T, \text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$

Sum the projections of $p_T$ of all reconstructed charged tracks (in the event) onto leading jet axis

Study dependence of mean „missing” $<p_T^{\parallel}>$ on dijet asymmetry $A_J$

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$ – leading jet
$p_{T,2}$ – subleading jet
"Missing" $p_T^{\parallel}$ vs. $A_j$

Radial dependence of the momentum balance:

Momentum balance restored when summing over all particles in the event, independently of $A_j$.

In-cone excess of high $p_T$ tracks is balanced by out-of-cone low $p_T$ tracks. Momentum difference in the dijet is balanced by low $p_T$ particles at large angles relative to the jet axis.
Experimental results

"Missing" $p_T^{\parallel}$ vs. $A_J$

New analysis: projection of $p_T$ for reconstructed charged tracks onto $\phi_{\text{Dijet}}$

$$p_T^{\parallel} = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Dijet}}).$$

Missing $p_T$ from high $p_T$ particles increases as a function of $A_J$ in the leading–jet direction

- **pp:** balanced by 2–8 GeV/c particles in the subleading–jet direction
- **central PbPb:** balanced by softer particles with $p_T < 2$ GeV/c
Experimental results

"Missing" $p_T^{||}$ vs. $\Delta$

$$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$

Inclusive $A_J$

Experimental results

Inclusive $A_J$

Cumulative curves quite similar

Excess towards subleading jet

Excess towards leading jet

$pp$ vs. $0-30\%$ PbPb

CMS $pp$

$0-30\%$ PbPb

Cumulative curves quite similar

$\langle p_T^{||} \rangle$ [GeV]

$0.5 \, 1 \, 1.5$

$pp$

$0-30\%$ PbPb

$p_T > 120, p_T > 50$ GeV/c

$|\eta_1|, |\eta_2| < 0.5, \Delta \phi_{1,2} > 5\pi/6$

anti-$k_T$ Calo R=0.3

$|\eta_{\text{trk}}| < 2.4$

$p_T^{\text{trk}}$ (GeV/c):

- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 4.0
- 4.0 - 8.0
- 8.0 - 300.0

$\Phi > 0.5$

$\Delta$

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arXiv:1509.09029
Experimental results

"Missing" $p_T^{\parallel}$ vs. $\Delta$

Excess towards subleading jet

Excess towards leading jet

Inclusive $A_J$

High-$p_T$ imbalance at small $\Delta$

$$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$

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Experimental results

"Missing" $p_T^{||}$ vs. $\Delta$

Inclusive $A_J$

High-$p_T$ imbalance at small $\Delta$

Balanced by low-$p_T$ particles in subleading jet direction
Extends up to large $\Delta$

$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$

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Is jet fragmentation affected?

Measure Fragmentation Functions to check if energy loss mechanisms modify fragmentation of partons.

Jet Fragmentation Function:

\[ \frac{1}{N_{Jet}} \frac{dN_{Track}}{d\xi} \]

where \( \xi = \ln(1/z) = \ln\left(\frac{p_{Jet}^{Track}}{p_{Track}^{Jet}}\right) \)

- \( z \) – fraction of parton’s momentum carried by hadron

Experimental results

High \( p_T \) particles

- Low \( p_T \) particles

Central PbPb:

For high \( p_T \) particles (in jet cone) fragmentation as in pp

Suppression of intermediate \( p_T \) particles

Enhancement of low \( p_T \) particles

Centrality dependent modification of jet fragmentation functions in PbPb collisions

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Experimental results

Is jet fragmentation affected?

Ratio of Jet Fragmentation Functions:

\[ \xi = \ln(1/z) = \ln\left(\frac{p_{Jet}}{p_{Track}}\right) \]

- No modification of jet fragmentation function in pPb with respect to the interpolated pp reference
- Without modification in jet \( R_{pPb} \) and \( FF_{pPb} \), the observed PbPb modification can be attributed to the final–state hot nuclear matter effect

pPb collisions

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Experimental results

**Sequential melting of quarkonia**

- In **QGP**, color screening (Debye screening) leads to melting of quarkonia → *suppression of quarkonium yields*.
- Quarkonium states have different binding energies (radii) → they melt at different temperatures of the created medium.

Quarkonia: mass, binding energy and radius

<table>
<thead>
<tr>
<th>state</th>
<th>state</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass(GeV)</td>
<td>3.10</td>
<td>3.53</td>
<td>3.69</td>
<td></td>
</tr>
<tr>
<td>$\Delta E$ (GeV)</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$r_o$(fm)</td>
<td>0.25</td>
<td>0.36</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>state</th>
<th>$Y(1S)$</th>
<th>$Y(2S)$</th>
<th>$Y(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass(GeV)</td>
<td>9.46</td>
<td>10.0</td>
<td>10.36</td>
</tr>
<tr>
<td>$\Delta E$ (GeV)</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>$r_o$(fm)</td>
<td>0.28</td>
<td>0.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Centrality–integrated $R_{AA}$ vs. binding energy

Note: $6.5<p_T<30$ GeV for $J/\psi$ and $\psi(2S)$

$R_{AA} = \frac{(Yield \ in \ AA)}{N_{COLL}(AA) \times (Yield \ in \ pp)}$

Less bound states are more suppressed than tighter bound ones → sequential suppression of quarkonia

PRL 109 (2012) 222301
PRL 113 (2014) 262301
PAS–HIN–12–014

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**Experimental results**

**ϒ production in pp and PbPb**

Updated results: statistics for pp data x20; improved reconstruction for PbPb

PAS–HIN–15–001

Dimuon spectra $\rightarrow$

**ϒ(1S), ϒ(2S) dependence on:**

centrality ($N_{\text{part}}$)

- **ϒ suppression dependence on centrality observed and suppression is stronger for excited state**
- **ϒ suppression does not depend on kinematics ($p_T$ and $y$)**

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**Experimental results**

**Y production in pp, pPb and PbPb**

### Y(nS)/Y(1S) ratio, centrality integrated

![Graph showing Y(nS)/Y(1S) ratio for pp, pPb, and PbPb](image)

- Relative production of excited state (Y(2S) or Y(3S)) to ground state Y(1S) more suppressed in pPb than in pp.
- In PbPb stronger suppression than in pPb collisions.

### Y(2S)/Y(1S) ratio vs. multiplicity

![Graph showing Y(2S)/Y(1S) ratio vs. multiplicity for p+p, p+Pb, and Pb+Pb](image)

- Y(2S)/Y(1S) decreases with event multiplicity for all systems.

**N_{tracks}** - number of tracks with p_T>400MeV/c and |η|<2.4

Same physical mechanisms present in pp, pPb and PbPb collisions??
Two–particle correlations

Signal pair distribution:

\[
S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d \Delta \eta d \Delta \phi}
\]

Background pair distribution:

\[
B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{mix}}}{d \Delta \eta d \Delta \phi}
\]

Associated hadron yield per trigger:

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \Delta \eta d \Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}
\]

\[\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}}\]
\[\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}\]
Experimental results

Two-particle correlations: Pb+Pb, p+Pb, p+p

"Ridge" observed for all systems:

- Pb Pb 2.76 TeV
- p Pb 5.02 TeV
- p p 7 TeV

long-range ($\Delta \eta$), near-side ($\Delta \phi \approx 0$) correlations

Unexpected "ridge" in high-multiplicity pp collisions

JHEP 07 (2011) 076
EPJC 72 (2012) 2012

PLB 718 (2013) 795
PLB 724 (2013) 213

JHEP 09 (2010) 091
Experimental results

**Two–particle correlations: Pb+Pb, p+Pb, p+p**

"Ridge" observed for all systems:

<table>
<thead>
<tr>
<th>System</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb</td>
<td>2.76 TeV</td>
</tr>
<tr>
<td>p+Pb</td>
<td>7 TeV</td>
</tr>
<tr>
<td>p+p</td>
<td>5.02 TeV</td>
</tr>
<tr>
<td>p+p</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

Fluctuations of the initial geometry and hydrodynamic evolution

Origin unknown for the small systems:
- hydrodynamic behavior ?
- initial–state gluon saturation (CGC) ?
- ...

Energy dependence study for pp collisions: 7 TeV (Run1) and 13 TeV (Run2)

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Charged hadron multiplicity in pp@13TeV

First LHC Run2 publication

PLB 751 (2015) 143

Experimental results

Pseudo-rapidity distribution

Energy dependence

$\left[ \frac{dN_{ch}}{d\eta} \right]_{|\eta|<0.5} = 5.49 \pm 0.01\text{(stat)} + 0.17\text{(syst)}$ for inelastic events

Energy dependence as expected
Experimental results

Two–particle correlations in pp at 13 TeV

Low multiplicity

High multiplicity

"Ridge" in high–multiplicity pp collisions at 13 TeV

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Experimental results

$\Delta \phi$–projected correlation function

Comparison for pp collisions: ○ 7 TeV and ● 13 TeV

Increasing $p_T$

For (2 < $|\Delta \eta| < 4$)

Increasing multiplicity

1.0 < $p_T$ < 2.0 GeV/c, 2.0 < $p_T$ < 3.0 GeV/c, 3.0 < $p_T$ < 4.0 GeV/c

CMS

N_{trk} < 35

Increasing multiplicity

N_{trk} < 80 (35 ≤ N_{trk} < 90)

N_{trk} < 105 (80 ≤ N_{trk} < 110)

N_{trk} ≥ 105 (N_{trk} ≥ 110)

$1.0 < p_T < 2.0 \text{ GeV/c}$

$2.0 < p_T < 3.0 \text{ GeV/c}$

$3.0 < p_T < 4.0 \text{ GeV/c}$

Increasing $p_T$

Experimental results

arXiv:1510.03068
Integrated associated yield

$p_T$ and multiplicity dependence:

- No collision energy dependence observed
- Effect is most evident in the intermediate transverse momentum region ($1 < p_T < 2 \text{ GeV/c}$)
- Approximately linear increase with multiplicity for $N_{\text{trk}}^{\text{offline}} > 40$
Experimental results

Integrated associated yield

Comparison $pp$ vs. $pPb$ vs. $PbPb$

Strong collision system size dependence of the associated yields

arXiv:1510.03068
Elliptic ($v_2$) and triangular ($v_3$) flow harmonics

Azimuthal anisotropy harmonics determined from a Fourier decomposition of long-range two-particle $\Delta\phi$ correlation functions

$PLB$ 724 (2013) 213

Experimental results

Elliptic flow ($v_2$) reflects the medium response to the initial collision geometry

Triangular flow ($v_3$) reflects fluctuations of the initial geometry

PbPb and pPb collisions are similar:

$\Rightarrow v_2$ and $v_3$ increase with multiplicity for both systems

$\Rightarrow$ However, the magnitude of $v_2$ smaller in pPb than in PbPb

$\Rightarrow v_3$ in PbPb and pPb coincide for all multiplicities (but very different collision geometry for PbPb and pPb)

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Experimental results

Correlations of strange and charged hadrons

"Ridge" observed for $K_S^0 - h$ and $\Lambda - h$ correlations in high-multiplicity $pPb$ collisions

(c) CMS $pPb \sqrt{s_{NN}} = 5.02$ TeV, $L_{int} = 35$ nb$^{-1}$

220 $\leq$ $N < 260$

1 $< p_T^{big} < 3$ GeV

1 $< p_T^{assoc} < 3$ GeV

(d) CMS $pPb \sqrt{s_{NN}} = 5.02$ TeV, $L_{int} = 35$ nb$^{-1}$

220 $\leq$ $N < 260$

1 $< p_T^{big} < 3$ GeV

1 $< p_T^{assoc} < 3$ GeV

High-multiplicity p Pb 5.02 TeV

PLB 742 (2015) 200
Experimental results

\( v_2 \) and \( v_2/n_q \) of strange hadrons

**p-Pb** high-multiplicity events

**Pb-Pb** peripheral events

Same multiplicity bin for pPb and PbPb

\( v_2 \) shows mass ordering in pPb and PbPb: at low \( p_T \), smaller \( v_2 \) values for heavier particles

Mass ordering more clear in pPb than in PbPb \( \rightarrow \) stronger radial flow in pPb ??

\( v_2 \) scaled by the number of constituent quarks: NCQ scaling observed \( \rightarrow \) indication of partonic degrees of freedom in the initial stage of the collision

Scaling better in pPb than in PbPb

\[
KE_T = \sqrt{m^2 + p_T^2} - m
\]

B. Boimska (NCBJ)

Epiphany Conference, Cracow, 08.01.2016
**Experimental results**

$v_3$ and $v_3/n_q$ of strange hadrons

- **p-Pb** high-multiplicity events
- **Pb-Pb** peripheral events
- Same multiplicity bin for pPb and PbPb

Similar species dependence of $v_3$ to that of $v_2$ found

Mass ordering observed for $v_2$ and $v_3$ results supports presence of collective behavior in both systems (pPb and PbPb)
Summary

Results from Run1 presented for PbPb, pPb and pp collisions. First results from pp collisions at 13 TeV (Run2) also shown.

PbPb and pPb collisions:

Jet quenching
- Suppression observed for central PbPb is a final state effect
  - No flavor dependence measured at high $p_T$
- High–$p_T$ excess of jet tracks on leading jet side compensated by low–$p_T$ excess of jet tracks on subleading jet side, which extends to large angles
- Jet fragmentation function modified in PbPb and not in pPb

Quarkonia production
- Sequential melting of quarkonium states observed in PbPb
- $\Upsilon$ suppression depends on collision centrality and does not depend on kinematics
- $\Upsilon(2S)/\Upsilon(1S)$ ratio decreases with event multiplicity

Collective behavior
- Results for ”ridge” and elliptic ($v_2$) and triangular ($v_3$) flow similar in PbPb and high–multiplicity pPb collisions

pp collisions:
- ”Ridge” observed also in high–multiplicity pp collisions at 7 TeV and 13 TeV