Identified particles in pPb collisions by CMS

Ferenc Siklér
Wigner RCP, Budapest

for the CMS Collaboration

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Outline

- Charged $\pi$, K, and p in pPb at $\sqrt{s_{NN}} = 5.02$ TeV
  - Results are public: arXiv:1307.3442 (hep-ex), submitted to EPJC, under review (+data points)

  - Trigger, tracking, vertexing
    $p_T > 0.1$ GeV/c; double sided trigger ($3 < |\eta| < 5$)
  - Energy deposits and energy loss rate
  - Determination of particle yields
  - Corrections

  - Inclusive measurements
  - Multiplicity-dependent measurements

  - Comparisons to pp
    (CMS EPJC 72 (2012) 2164, +HepData) and to PbPb (ALICE arXiv:1303.0737) results

  With emphasis on particle spectra and ratios
Analysis techniques

[Diagram of CMS detector with labeled components such as silicon tracker, crystal calorimeter, forward hadron calorimeter, magnet yoke, superconducting solenoid magnet, hadron calorimeter, muon chambers, and one of the 15 detector sections.]
• Hadron spectra
  – Long history both in high energy particle and nuclear physics
  – One of the simplest and most relevant physics quantities
  – Scaling properties of particle production; predictions of models and generators
  – Origin of near-side ridge: needs radial flow or not
  – PID: $p < 1.20$ for $\pi^\pm$, $p < 1.05$ for $K^\pm$, and $p < 1.70$ GeV/c for $p/\bar{p}$

  Accessible region is also limited by $\eta$ acceptance of the tracker

  Final results are given for $|y_{lab}| < 1$
## Trigger, event definition

- **Data**
  - Low pile-up (0.15%) short run (about 4 hours) collected in Sep 2012
  - About 2 million events; uncertainties are dominated by systematics

- **Online and offline triggers**
  - Coincidence of signals from both BPTX devices
  - At least one pixel track
  - Coincidence of at least one forward calorimeter (HF) tower with more than 3 GeV energy on each side
  - Beam-halo and beam-induced background events were suppressed

- **We corrected to a simple event definition**, closest to actual trigger
  - Double-sided selection (DS):
  - At least one particle with $E > 3$ GeV on both sides
    ($-5 < \eta < -3$ and $3 < \eta < 5$)
  - With DS we select 94-97% of inelastic collisions

Ranges from AMPT, EPOS LHC, Hijing
Trigger, tracking performance

- **Trigger corrections**
  - The DS trigger efficiency is close to 1: EPOS, Hijing generators

- **Tracking corrections**
  - Acceptance, efficiency, fake tracks, unfolding $p_T$ bias and resolution

- **Non-primaries**
  - Feed-down tuned with data via measuring $K_S^0$ and $\Lambda/\bar{\Lambda}$ spectra; secondaries

  Excellent tracking performance, for pions down to $p_T = 0.1$ GeV/c
The central quantity is the most probable energy loss rate $\varepsilon$ along a reference length $l_0$.

Probability of an energy loss $y$, along a path length $l$

$$P(y|\varepsilon, l)$$ has exponential and Gaussian parts.

Analytical model with few (4) parameters; a very good match.
Most probable energy loss rate $\varepsilon$

- **Estimation of** $\log \varepsilon$, for each track
  - We have the properly corrected deposits $y_i$ along the trajectory
  - Minimize the joint energy-deposit $\chi^2$ for a track
  - False hit removal (energy deposit outliers)
  - We get the estimate of $\log \varepsilon$
Fits in \((\eta, p_T)\) bins

- **Template fits**
  - They are not Gaussians: use tracks in data
  - Keep all quantities, but regenerate energy deposits with the parametrization

High quality fits, good \(\chi^2/\text{ndf}\)
Fits in $\left(\eta, p_T\right)$ bins

Total momentum range used for physics is limited by systematic uncertainty

We give results in $|y_{lab}| < 1$ (dictated by PID capabilities)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty of the source [%]</th>
<th>Propagated yield uncertainty [%]</th>
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</thead>
<tbody>
<tr>
<td>Fully correlated, normalisation</td>
<td></td>
<td></td>
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<tr>
<td>Correction for event selection</td>
<td>3.0 (1.0)</td>
<td>3.0 (1.0)</td>
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<tr>
<td>Pileup correction (merged and split vertices)</td>
<td>0.3</td>
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<tr>
<td>Mostly uncorrelated</td>
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<td>Pixel hit efficiency</td>
<td>0.3</td>
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<tr>
<td>Misalignment, different scenarios</td>
<td>0.1</td>
<td>0.3</td>
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<tr>
<td>Mostly uncorrelated, ((y, p_T)) dependent</td>
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<tr>
<td>Acceptance of the tracker</td>
<td>1–6</td>
<td>1</td>
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<tr>
<td>Efficiency of the reconstruction</td>
<td>3–6</td>
<td>3</td>
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<tr>
<td>Multiple-track reconstruction</td>
<td>50% of the corr.</td>
<td>–</td>
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<tr>
<td>Misreconstructed-track rate</td>
<td>50% of the corr.</td>
<td>0.1</td>
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<tr>
<td>Correction for secondary particles</td>
<td>20% of the corr.</td>
<td>0.2</td>
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<td>Fitting (\log \varepsilon) distributions</td>
<td>1–10</td>
<td>1</td>
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Consistent propagation of uncertainties (mapping, fits, unfolding, integration)
Physics results

- Identified particles in pPb collisions in CMS

![Graphs showing physics results](image-url)
**Results – $p_T$ spectra**

Statistical (error bars) and systematic uncertainties (boxes)
The fully correlated normalization uncertainty (not shown) is around 3.0%

Tsallis-Pareto: \[
\frac{d^2N}{dydp_T} = \frac{dN}{dy} \cdot C(m, n, T) \cdot p_T \left[1 + \left(\frac{m_T - m}{nT}\right)\right]^{-n}
\]

The fits are of good quality
Results – $p_T$ spectra

Generators predict too steep $p_T$ distributions, except EPOS LHC

Logarithmic scale
Results – ratios vs $p_T$

- $p_T$ dependence
  - $K/\pi$ ratios are well approximated by EPOS LHC
  - There are substantial deviations in case of $p/\pi$ ratios
  - Ratios of opp charged pions and kaons are compatible with 1, indep of $p_T$
Track multiplicity classes

• How?
  – take the measured $d^2N/d\eta dp_T$ values
  – use adjusted MC corrections (take PID ratios from data)
  – correct for low $p_T$ part ($p_T < 0.1$ GeV/c), assuming a linear startup with $p_T$
  – no Tsallis fits are needed here

• The classes

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<tbody>
<tr>
<td>$\langle N_{tracks} \rangle$</td>
<td>8</td>
<td>19</td>
<td>32</td>
<td>45</td>
<td>58</td>
<td>71</td>
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<td>198</td>
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<tr>
<td>$\langle N_{tracks} \rangle_{p_T&gt;0.4\text{GeV/c}}$</td>
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<td>95</td>
<td>103</td>
<td>110</td>
<td>117</td>
<td>125</td>
</tr>
</tbody>
</table>

Collect data in $N_{rec}$, plot results in (theoretical) $\langle N_{tracks} \rangle$ bins
We give the corresponding fully corrected $N_{tracks}$ values in $|\eta| < 2.4$

$N_{tracks}$ – Poor man’s centrality measure ;-)
Results – multiplicity dependence

The values with increasing multiplicity are successively shifted by 0.1 units along the vertical axis

Unchanged (pion) vs changed shapes (kaons)
Results – multiplicity dependence

CMS

$pPb, \sqrt{s_{NN}} = 5.02$ TeV, $L = 1 \mu b^{-1}$

$\langle N_{\text{tracks}} \rangle = 235$

Strong change
Cross ratios
- $K/\pi$ and $p/\pi$ ratios are or slowly rising; EPOS LHC looks best

Opposite charge ratios
- The ratios are close to 1, no dependence on $\langle N_{\text{tracks}} \rangle$
Results – $\langle p_T \rangle$ – multiplicity dependence

Calculated using MC technique followed by numerical integration
Error bars show the combined $\sqrt{\text{stat}^2 + \text{syst}^2}$ errors, boxes give systematic only
AMPT and Hijing 2.1 underpredict the measured values
Good description by EPOS LHC: includes explicit hydrodynamic treatment
• Observations
  – Differences between data and generators
  – Pion $T$ values are well described by models
Comparisons – $\sqrt{s}$ dependence – pp vs pPb

The curves show parabolic ($dN/dy$) or linear ($\langle p_T \rangle$) interpolation in log-log scale.

Yields in pPb are generally three times higher than in pp at same $\sqrt{s}$

Consistent with $(\langle \nu \rangle + 1)/2$ expectation; $\langle \nu \rangle \approx 6$ (aver no of projectile collisions)

In case of $\langle p_T \rangle$, the increase is about 20% for pions and protons, 10% for kaons.
Comparisons – \( \sqrt{s} \) dependence – pPb

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Comparisons – $\sqrt{s}$ dependence – pp vs pPb

**Observations**

- For low track multiplicity ($N_{\text{tracks}} \lesssim 40$), pPb behaves very similarly to pp.
- At higher multiplicities ($N_{\text{tracks}} \gtrsim 50$) the $\langle p_T \rangle$ curve for pPb gets flatter.
- This can be understood, since in the former case mostly peripheral pPb collisions are present with a few proton-nucleon collisions.
- By asking for more produced particles those collisions are chosen, where the projectile proton collided with the thick disk of the lead nucleus.
Comparisons – $\sqrt{s}$ dependence – pp vs pPb vs PbPb

- Observations
  - Highest multiplicity pPb interactions yield higher $\langle p_T \rangle$ than in central PbPb collisions (ALICE arXiv:1303.0737), or reach those values in case of pp
  - In the PbPb case even the most central collisions possibly contain a mix of soft and hard nucleon-nucleon interactions
  - In case of pp or pPb specifically the most violent interaction or sequence of interactions are selected

pp (0.9, 2.76, 7 TeV), pPb (5.02 TeV), PbPb (2.76 TeV, periph to central bands)
Comparisons – $\sqrt{s}$ dependence – pp vs pPb vs PbPb

- Observations
  - Interestingly, at higher multiplicities, the pPb curves for all particle types can be reasonably approximated by taking the pp values and multiplying their $N_{\text{tracks}}$ coordinate by a factor of 1.8.
  - In other words, a pPb collision with a given $N_{\text{tracks}}$ is similar to a pp collision with $0.55 \times N_{\text{tracks}}$ produced charged particles in the $|\eta| < 2.4$ range.
Inverse slope parameters

Fit with $p_T \exp(-m_T/T')$

Multiplicity dependence, data (left) vs MC (right)

Pions are only fitted if $p_T > 0.4$ GeV/c, kaons and protons for all $p_T$

Linear dependence on mass with a slope that increases with particle multiplicity

Interesting comparison to models (radial flow?); worked better for pp with Pythia
Summary

• Results
  – Measured spectra of identified charged hadrons with a double-sided trigger for in pPb $\sqrt{s_{NN}} = 5.02$ TeV; as a function of track multiplicity

• Conclusions
  – Particle production at LHC energies is strongly correlated with event multiplicity in both pp and pPb, rather than with the center-of-mass energy of the collision or with the masses of the colliding nuclei
  – Common underlying physics mechanism: at TeV energies, the characteristics of particle production are constrained by the amount of initial parton energy that is available in any given collision
  – At high multiplicities, a pPb collision with a given $N_{\text{tracks}}$ is similar to a pp collision with $0.55 \times N_{\text{tracks}}$ produced charged particles in the $|\eta| < 2.4$ range
  – Highest multiplicity pPb interactions yield higher $\langle p_T \rangle$ than in central PbPb collisions, or reach those values in case of pp

Thank you for your attention!