Hadron Production at CMS in pp Collisions at $\sqrt{s} = 0.9, 2.4$ and 7.0 TeV

KEITH ULMER
UNIVERSITY OF COLORADO
Motivation

- Most LHC collisions are not hard interactions
  - Majority of particles produced with low transverse momentum
  - Particle production not always reliably calculable in QCD
- Soft hadron production is modeled phenomenologically
  - Experimental input is crucial for theoretical models
  - LHC opens up a new energy regime to test old models and develop new ones
- Must understand QCD processes well
  - Dominant backgrounds for many new physics searches
  - Provide reference for heavy ion results
The CMS detector

Forward Calorimeter
The CMS tracker

- Diameter = 2.4m
- Length = 5.4m
- 75 million channels
- 220 m² of silicon
- Design operation -10° C

- Inside 3.8 T field
- Cooler temperature to slow radiation damage
- Coverage up to $|\eta| < 2.4$ with $\geq 3$ pixel hits and $\geq 10$ strip hits
- Efficiency $>99\%$ for central muons
Outline of physics results

- Charged hadron production rate vs $\eta$ and $p_T$ and $\langle p_T \rangle$
  - JHEP 02:041, 2010 (at $\sqrt{s} = 0.9$ and 2.36 TeV)
  - PRL 105:022002, 2010 (at $\sqrt{s} = 7.0$ TeV)

- Charged hadron multiplicity at $\sqrt{s} = 0.9$, 2.36, and 7.0 TeV
  - CMS-PAS-QCD-10-004
    - [CMS-PAS-QCD-10-004](http://cdsweb.cern.ch/record/1279343?ln=en)

- Strange particle production rates vs $y$ and $p_T$ and $\langle p_T \rangle$ at $\sqrt{s} = 0.9$ and 7.0 TeV
  - CMS-PAS-QCD-10-007
    - [CMS-PAS-QCD-10-007](http://cdsweb.cern.ch/record/1279344?ln=en)
Trigger and event selection

- Results presented are normalized to non-single-diffractive events (NSD)
  - Trigger on signal in scintillation counters consistent with pp collision from coincident beams
- Select events with
  - Forward calorimeter cluster with $E \geq 3$ GeV on both sides ($2.9 < |\eta| < 5.2$)
  - Reconstructed primary vertex
- Reject beam halo and beam background events
- Correct for trigger inefficiencies and SD contributions from MC simulation
3 methods for finding charged tracks

- Consistency of 3 different methods ensures robustness of results
  - Counting barrel pixel clusters
    - Efficient for $p_T \geq 30$ MeV/c
    - Insensitive to misalignment
  - Count 2-hit barrel pixel tracklets
    - Efficient for $p_T \geq 50$ MeV/c
    - Less sensitive to beam backgrounds
  - Full tracking (pixels + strips)
    - Efficient for $p_T \geq 100$ MeV/c
    - Also provides $p_T$ measurement
Results: charged hadron $dN/d\eta$

- Shapes similar at different energies
- Good agreement with other measurements
- Bands show systematic error (~5%)
  - Largest contribution from correction to NSD event selection
- Multiplicity at $\eta \approx 0$ rises with $\sqrt{s}$ (as expected)
- Rate of rise at 7 TeV exceeds most predictions
Results: charged hadron $p_T$

- Transverse momentum spectra and $\langle p_T \rangle$ measured for $|\eta| < 2.4$
  - Fit with Tsallis function: exponential at low $p_T$ and power law tail
- Spectra grow in transverse momentum with higher $\sqrt{s}$
- Models bracket the observed increase
Measuring charged hadron multiplicity

- Full tracking used to measure primary charged hadron multiplicity
- Use MC to correct for efficiency to select NSD events with a good primary vertex
- Obtain true multiplicity distribution from measured distribution with a Bayesian unfolding method
  - Corrects for track reconstruction efficiency, acceptance and tracks from secondary particles

\[
\begin{align*}
\text{Fraction of total charged hadrons (} & P_n \text{)} \\
|\eta| < 0.5 & \quad |\eta| < 2.4 \\
|\eta| < 1.5 & \quad |\eta| < 2.4 \\
|\eta| < 2.4 & \quad |\eta| < 1.5 \\
\end{align*}
\]
Results: charged hadron multiplicity

- KNO scaling: $\Psi(z) = \langle n \rangle P_n$ shown to be independent of $\sqrt{s}$ for scale invariant particle production
  - True for $|\eta| < 0.5$, violated for $|\eta| < 2.4$
- Large tail at high $n$ also reflected in steep rise in $\langle n \rangle$ with $\sqrt{s}$

| $|\eta| < 0.5$ |
|---------------|
| CMS 0.9 TeV |
| CMS 7.0 TeV |

| $|\eta| < 2.4$ |
|---------------|
| CMS 0.9 TeV |
| CMS 7.0 TeV |
Different models for simulation have varying degrees of success—no model gets everything right at 7 TeV.

Pythia 8 models total multiplicity well, but predicts too many high $p_T$ particles at large multiplicities.
Strange particle reconstruction

- and $\Lambda$ (+ c.c.) reconstructed in decays to $\pi^-\pi^+$ and $\pi^-p$
- $\Xi^-$ (+ c.c.) reconstructed in decays to $\Lambda\pi^-$
- Long-lived particles identified by displaced vertices ($c\tau = 2.7-7.9$ cm)
- All results shown for $|y| < 2.0$

- Validate understanding of reconstruction efficiency by finding correct lifetime in data
Results: strange particle $dN/dp_T$ 

- Fit for yields and correct for efficiency in bins of $p_T$ 
  - Reweight MC to account for discrepancy in $\Lambda/\Xi^-$ kinematic distributions between data and MC
Results: strange particle $dN/dy$

- Results vs rapidity compared to Pythia predictions

- Significantly more strangeness in data than MC
  - Discrepancy grows with increasing mass, strangeness and $\sqrt{s}$
  - Factor of 3 for $\Xi^-$ at $\sqrt{s} = 7$ TeV!
Conclusions

- CMS is operating well, and taking full advantage of the luminosity delivered by the LHC
  - Proton collisions at $\sqrt{s} = 7$ TeV represent a large jump in energy with lots of new terrain to explore
- Hadron production studies have already provided surprises
  - Charged hadron multiplicity distribution scaling law is violated
  - Strange particle production is greatly enhanced compared to Pythia predictions
- We’re deepening our understanding of QCD in a new energy regime, and providing the foundation for more surprises yet to come…
Extra slides
Cluster counting method

- Cluster length should be a function of pitch and track angle
  - Reject too-short clusters inconsistent with originating at the primary (loopers, secondaries etc.)
- Correct measured rates for remaining non-primary tracks
- Independent results obtained for all three pixel barrel layers
Tracklet method

- Use all three independent combinations of pixel barrel layer pairs
- Compute $\Delta \eta$ and $\Delta \phi$ for each pair
  - $\eta$ and $\phi$ defined at the angles between the primary vertex and one of the tracklet hits
  - $\Delta \eta$ and $\Delta \phi$ are the differences in $\eta$ and $\phi$ between the two tracklet hits
- Use sidebands in $\Delta \phi$ to subtract combinatorial backgrounds
- Correct for efficiency, weak decays, and secondaries with MC
Tracking method

- Use iterative step approach to track building
- Require compatibility with beam spot and primary vertex
  - Sensitive to beamspot position and alignment
- Track cleaning based on cluster shape helps keep fake rate low
- Good agreement between data and MC in number of hits on track
Comparison of $dN/d\eta$ results

- Three methods produce consistent results
  - Average used a final CMS result
Tsallis function

- Tsallis function:
  - $m = \text{particle mass}$, $n$ and $T$ are shape parameters and $C$ is a normalization parameter

Track multiplicity unfolding

- Corrections are a significant effect
- Uncertainties obtained from full covariance matrix calculated with a resampling technique
Moments of track multiplicity

- Normalized moments of charged hadron multiplicity
  - Flat distributions for $|\eta| < 0.5$, as predicted by GNO scaling
  - Rising distributions for $|\eta| < 2.4$ in violation of GNO scaling
$\langle p_T \rangle$ with predictions

- PYTHIA $\langle p_T \rangle$ rises too fast for events with many tracks
- Modeled better by PHOJET
Strange particle efficiencies

- Reconstruction efficiency of $\Lambda$ and $\Xi^-$
  - Including branching fractions, trigger, acceptance, and reconstruction efficiencies
Strange particle $\langle p_T \rangle$ scaling

$\langle p_T \rangle$ as a function of $\sqrt{s}$ for $\Lambda$ and $\Xi^-$ compared to charged hadrons