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ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

SOFT QCD AT ATLAS AND CMS
In 15 Minutes...

- Inelastic cross section
  - ATLAS and CMS at 13 TeV
- Minimum bias
  - Charged Particle distributions at 13 TeV from CMS and ATLAS
  - Energy Flow at 13 TeV from CMS
- Underlying event
  - Event shapes at 7 TeV from ATLAS
Non–Perturbative – cannot be calculated

Important to constrain phenomenological models

used to estimate pile-up

ATLAS and CMS measure a fiducial cross sections first and then correct to the total.

The fiducial volume is defined by the total mass of particles measured on either side of the largest rapidity gap ($M_X$) and $\sqrt{s}$

$$\xi = \frac{M_X^2}{s}$$

Kinematically limited to $M_X > m_p$ ($\xi > 6 \times 10^{-9}$)

Fiducial limit is approximately $M_X > 13 m_p$ ($\xi > 10^{-6}$)
Event Selection election: 2 hits in Minimum Bias Trigger Scintillator (MBTS) counters

Corrections and systematics are evaluated using Pythia 8, EPOS LHC and QGSJET-II

- Allows for variations in the diffractive model
- Comparison between inclusive and single sided event selections are used to constrain the diffractive component
2 Fiducial regions

- Hadronic Forward Calorimeters (HF) Only
  - $3.0 < |\eta| < 5.2$
  - Can add asymmetric region $-6.6 < \eta < -5.2$
    - CASTOR ($B = 0 T$)
    - Extends fiducial region down to $M_x > 4.1 \ m_p (\xi > 10^{-6})$

- Pythia 6 and 8 used with a variety of models (and tunes)

- $E > 5 GeV$ in either of the HF, or Castor (if included)
ATLAS and CMS measurements show good agreement, phenomenological models over predict the value

CMS fiducial: $\sigma = 65.77 \pm 0.03$ (stat.) $\pm 0.76$ (sys.) $\pm 1.78$ (lum.) mb
CMS (with CASTOR) fiducial: $\sigma = 66.85 \pm 0.06$ (stat.) $\pm 0.44$ (sys.) $\pm 1.96$ (lum.) mb
CMS total: $\sigma = 71.26 \pm 0.06$ (stat.) $\pm 0.47$ (sys.) $\pm 2.09$ (lum.) $\pm 2.72$ (extr.) mb
ATLAS fiducial: $\sigma = 65.2 \pm 0.8$ (exp.) $\pm 5.9$ (lum.) mb
ATLAS total: $\sigma = 73.1 \pm 0.9$ (exp.) $\pm 6.6$ (lum.) $\pm 3.8$ (extr.) mb
probes the transition between perturbative and non-perturbative calculations

- non-perturbative at low $p_T$, perturbative and high $p_T$

Often used to tune free parameters in models.

- used to validate model of pile-up simulation
3.9 M zero-bias events, $\langle \mu \rangle = 1.3$

Selection criteria:
- one primary vertex, ($|z| < 15$ cm, 2 tracks, $d_0 < 0.2$ cm)
- Track selection: $p_T > 0.5$ GeV, $|\eta| < 2.4$

Correction from Detector Level to Stable Particle Level done in categories defined by energy (or lack thereof) in the HF
- SD, NSD, inelastic-enhanced
- inclusive region ignores input from HF

Analysis corrections based on PYTHIA8 CUETP8M1 and EPOS LHC
MINIMUM BIAS CHARGED PARTICLE DISTRIBUTIONS

COMPARISONS BY CLASSIFICATION

CMS-PAS-FSQ-15-008

- NSD Selection:
  - Good Description:
    - EPOS
    - Pythia8
    - CUETM1

- SD Selection best described by:
  - Pythia8 MBR 4C
  - Herwig does poorly
170 \mu b^{-1} with low beam currents, \langle \mu \rangle = 0.005

Selection Criteria:

- Track selection:
  - \( p_T > 0.5 \text{ GeV}, |\eta| < 2.5, 1 \text{ primary vertex [2 tracks} \ (p_T > 0.1 \text{ GeV})] \)

Bayesian unfolding to get the true \( p_T \) distribution

Bayesian unfolding from \( N_{\text{Track}} \) to \( N_{\text{particle}} \)

Dominant Uncertainty is from non-closure of unfolding
EPOS-LHC does consistently better,

QGSJET is the most systematically different
CMS and ATLAS distributions agree and are best reproduced by EPOS LHC.
HERWIG does a better job with the inclusive samples.
Pythia under predicts the distributions as the energy increases.

EPOS does a good job across the range of LHC energies.
PSEUDO RAPIDITY DEPENDANCE ON ENERGY FLOW

- 0.06 nb$^{-1}$, with 0.05 < $<\mu>$ <1.5
- Calorimeter based energy flow at 3.15 < $|\eta|$ < 6.6
- Study of beam fragmentation
  - important information about energy in the forward direction
    - reflected in MC $<\mu>$ reweighing
- Two Regions
  - Soft inclusive (activity on both sides $E_{\text{Tower}}$ > 4 GeV) and
  - NSD enhanced (activity on only one side $E_{\text{Tower}}$ > 5 GeV)
- Correction to particle level calculated as average of:
  - PYTHIA8 tune MONASH 2013,
  - PYTHIA8 tune 4C with MBR model,
  - EPOS-LHC and QGSJETII.4
In the pre-CASTOR bins the agreement degrades as $|\eta|$ increases.
Characterisation of the underlying event in Z Boson events as a function of the $p_T$ of the Z Boson

- $1.1 \text{ fb}^{-1}$ of low $\mu$ data
- complicated pile-up correction

Distributions are unfolded based on Bayesian unfolding to account for non-primary particle, detector efficiencies and resolution effect

Observables in two classes:

- Not-sensitive to the number of particles
  - Spherocity, Transverse Thrust
- Explicit dependance on the number of particle
  - $n_{\text{CH}}$
EVENT SHAPE OBSERVABLES

TRANSVERSE THRUST AND SPHEROCITY

\[ 0 \quad S \quad 1 \]

\[ 1 \quad T \quad 2/\pi \]
predictions get better with increasing pT

Herwig is consistently better
Electron and Muon channels are similar

Pythia is consistently better
WHAT HAVE WE LEARNED?

- ATLAS and CMS are taking slightly different, complementary approaches to the characterisation of the soft QCD regime
  - ATLAS and CMS measurements of these regions agree, and should help to constrain soft QCD models in order to allow for a better description of data at 13 TeV
- Things that work well at 13 TeV:
  - EPOS – LHC does a good job of the central inclusive region
- At 7 TeV
  - Pythia 8.212 – Topology based variables
  - Herwig 7.0 – multiplicity based variables
SOFT QCD RESULTS

ATLAS AND CMS CONTINUE TO MAKE GOOD PROGRESS TOWARDS A COMPLETE SET OF SOFT QCD MEASUREMENTS

- ATLAS Track-based Minimum Bias at 8 TeV arXiv:1603.02439
- ATLAS Hadronic Event shapes in Z events arXiv:1602.08980
- CMS Underlying event measurements with leading particles and jets in pp collisions at $\sqrt{s} = 13$ TeV CMS-PAS-FSQ-15-007
- CMS Dijet production with a large rapidity gap between the jets CMS-PAS-FSQ-12-001
- CMS Event generator tunes obtained from underlying event and multiparton scattering measurements EPJC 76 (2016) 155
- CMS Measurement of exclusive $\pi^+\pi^-\pi^+\pi^-$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV CMS-PAS-FSQ-12-004

AND MANY MORE •••
Comparison between minimum bias, and Z boson dist.