Soft QCD results in ATLAS and CMS

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Claire Gwenlan, Oxford
on behalf of the ATLAS and CMS Collaborations

Outline
- inelastic and diffractive cross section measurements
- charged particle distributions
- differential transverse energy flow
- charged particle event shapes
- identified particle production
- charged particle correlations
**Soft QCD at Hadron Colliders**

- **soft QCD physics** (low momentum transfer, strong force interactions) **dominates** total cross section
- … but **not well understood**; description involves **non-perturbative QCD**; relies on phenomenological models

- intimately linked to measurements of **high momentum transfer observables** e.g.
  inclusive jet cross sections; **influences** missing transverse momentum measurements, isolation cuts etc.

- **particle yields** and **kinematic distributions** essential for understanding physics of **hadron production**, including relative roles of **soft** and **hard** contributions

- **soft QCD distributions** can be used to both **test phenomenological models** and to **adjust** (tune) parameters of **existing MC models** to give best description of data

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**wealth of results available from ATLAS and CMS**

**shown today:** selected highlights (since last EPS)
(see talk by R. Kumar for MPI and DPS studies)
Inelastic Cross Section Measurements

- total inelastic cross section (ATLAS, CMS)
- inelastic and diffractive cross sections as function of rapidity gaps (ATLAS, CMS)

- inclusive:
  - $\sigma_{\text{total}} = \sigma_{\text{inelastic}} + \sigma_{\text{elastic}}$
  - $\sigma_{\text{inelastic}} = \sigma_{\text{non-diffractive}} + \sigma_{\text{diffractive}}$
  - minimum bias triggers accept a fraction of the $\sigma_{\text{total}}$

- diffractive:
  - $\sigma_{\text{diffractive}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}}$
  - event topology characterised by rapidity gap due to exchange of colourless object

Diffractive channels constitute around 25–30% of $\sigma_{\text{inelastic}}$ at LHC energies

C. Gwenlan, soft QCD results at ATLAS and CMS, EPS13
**Total Inelastic Cross Section**

CMS Coll., PLB 722 (2013) 5

- **ATLAS & CMS**: measurements over limited acceptance $\xi = (M_x)^2/s > 5 \times 10^{-6}$, (where $M_x =$ invariant mass of particles selected using largest rapidity gap in event) $\eta_{\text{min}}$

- ATLAS: ≥2 Minimum Bias Trigger Scintillator (MBTS) hits
- CMS: ≥5 GeV in forward hadronic calorimeters (HF)

- CMS: count number of pileup vertices
- assume number of inelastic $pp$ interactions $(n)$, in given bunch crossing, follows Poisson distribution:

\[
P(n) = \frac{(L \cdot \sigma_{\text{inel}})^n}{n!} e^{-L \cdot \sigma_{\text{inel}}}
\]

- fit to extract inelastic cross section $\sigma_{\text{inel}}$
- presented as function of minimum number of tracks used to build vertices
\( \Delta \eta_F \) as a function of \( \Delta \eta_F \)

- non-diffractive events dominate at small gaps
- diffractive plateau observed for large gaps

CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV}, L = 20.3 \text{ \( \mu \)b}\)^{-1}

\[ \frac{d\sigma}{d\Delta \eta_F} [\text{mb}] \]

- increasing particle threshold requirement results in more ND events with large gaps; confirms that inclusive events are dominated by low \( p_T \) production

\[ \Delta \eta_F = \text{largest empty pseudorapidity interval, from edge of detector} \]

\[ \Delta \eta_F \]

- typical detector signature

PYTHIA8 models provide reasonable description
Diffractive Cross Sections

SD, DD diffractive events \textit{discriminated} based on topology

\begin{align*}
\xi &= \frac{(M_X M_Y)^2}{(s m_p)^2} \\
\Delta \eta &= \eta_{\text{max}} - \eta_{\text{min}}
\end{align*}

\text{CMS Preliminary } \sqrt{s} = 7 \text{ TeV, } L = 16.2 \mu \text{b}^{-1}

- SD and DD: central rapidity gap data
- MBR (Minimum Bias Rockefeller): Regge-based model; hadronisation tuned to describe diffractive masses at lower energy; CD included in PYTHIA for first time (arXiv:1205.1446)

- PYTHIA8-MBR model able to describe data

SD2: CASTOR forward calorimeter used to discriminate between SD/DD
Particle Production

- charged particle distributions (CMS)
- transverse energy flow (ATLAS)
- event shapes (ATLAS)
- charged particle correlations (ATLAS)
- identified particle production (ATLAS, CMS)
probe kinematics in inclusive & non-single-diffractive (NSD) events

- two event samples:
  - inclusive: tracks in T2 in either forward or backward hemisphere
  - NSD-enhanced: tracks in both hemispheres
- two $p_T$ regions: study soft and hard scattering

- level of MC agreement varies with $p_T$ and topology of event

($p_T$ distribution of leading particle also measured)
**Hard and Soft Particles as function of Multiplicity**

- classify tracks as those inside (intra-jet) or outside jets

- probe different mechanisms of multi-particle production via study of jet and underlying event properties as function of multiplicity

- PYTHIA tunes here provide better description of multiplicity dependence c.f. Herwig++

- all MCs have difficulty at high multiplicity

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CMS Coll., PAS FSQ-12-022
Differential transverse energy flow

probe particle kinematics in inclusive pp interactions

- charged and neutral particles included
- uses full acceptance of ATLAS calorimeter
- important complementary measurement to charged particle distributions

MCs underestimate activity in forward region

changing proportion of diffractive events in MC has little effect on shape; some sensitivity to choice of proton PDFs observed

- measured also in dijet events (transverse region), sensitive to underlying event
Event shapes

Event shape variables describe **geometric properties** of energy flow in the final state.

- **1– transverse thrust:**
  \[ \tau_\perp = 1 - T_\perp = 1 - \max \sum_i \frac{|\vec{p}_T^i \cdot \hat{n}|}{\sum_i |\vec{p}_T^i|} \]

- **prevalence of spherical events**

- **PYTHIA Z1** provides best description

- **transverse sphericity:**
  measure of transverse sum $p_T^2$ with respect to event axis

  \[ S_\perp = \frac{2\lambda_2^{x,y}}{\lambda_1^{x,y} + \lambda_2^{x,y}} ; \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \left[ \frac{p_{x,i}^2}{p_{x,i} p_{y,i}^2} \right] \]

  where $\lambda_2^{x,y} < \lambda_1^{x,y}$ are the two eigenvalues of $S_{xy}$

- **ATLAS Coll., arXiv:1207.6915 v2**

- **Updated!**
Event shapes

Event shape variables describe geometric properties of energy flow in the final state.

- dependence on $p_T, \text{lead}$ and $\Sigma p_T$:

  - event shape distributions measured in bins of $p_T, \text{lead}$
  - events more jet-like with increasing $p_T, \text{lead}$

  [Graphs showing data and Monte Carlo predictions for $p_T, \text{lead}$ and $\Sigma p_T$]

  *average values* as function of $\Sigma p_T$ and $N_{\text{ch}}$ also measured

  *MCs* fail to reproduce data at high $\Sigma p_T$

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Measurement now extended from $\Sigma p_T = 100$ to 150 GeV
Forward-Backward (FB) multiplicity & $\Sigma p_T$ correlations in symmetrically opposite $\eta$ regions

measuring correlations as function of $\eta$ separation and $p_T$ probes both hard and soft contributions

\begin{align*}
\rho^n_{FB} &= \frac{\sum x^n_F x^n_B}{N \sigma^n_F \sigma^n_B} \\
\rho^{pT}_{FB} &= \frac{\sum x^{pT}_F x^{pT}_B}{N \sigma^{pT}_F \sigma^{pT}_B}
\end{align*}

$\rho^{n\text{FB}}$: in a forward-backward $\eta$ region is the normalised covariance between the two distributions, relative to the mean value of each

measured at $\sqrt{s} = 900\text{GeV} & 7\text{TeV}$
• measured correlations adequately described by recent MC tunes

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ATLAS Coll., JHEP 1207 (2012) 019
- ... however, MCs have difficulty describing features of other available correlation data
Identified Particle Production

- $K^0_s$, $\Lambda$ (ATLAS); $\pi$, $K$, $p$ (CMS)

Strange particle yield less well described by MC

difficulty in describing $\Lambda$ data at high $p_T$

measurements available at $\sqrt{s} = 900\text{GeV}$, $2.76\text{TeV}$ & $7\text{TeV}$
Summary

- LHC provides rich laboratory for studying soft QCD
- wealth of data from ATLAS and CMS on event characteristics, particle properties and correlations available at the hadron level

- measurements of inelastic cross sections made by experiments using different methods
- many aspects of particle production well described by recent MC models/tunes …
- … however, deficiencies still apparent: high multiplicities, forward region, certain particle correlation measurements, strange particles, …

- wide variety of measurements presented here can be used to further our understanding and improve MC models and tuning

all public results available at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Soft_QCD
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ#All_public_results
Backups
soft QCD measurements rely heavily on:

- **inner tracking detectors** \((p_T > 100\text{ MeV}, \ |\eta| < 2.5)\)
- electromagnetic and hadronic calorimeters
  \((|\eta| < 3 \text{ (EM)}; \ |\eta| < 5 \text{ (had)}; \ ET \ more \ than \ a \ few \ hundred \ MeV)\)
- other crucial components for measurements shown here:
  - triggering:
    - ATLAS Minimum Bias Trigger Scintillators (MBTS);
    - CMS Beam Scintillation Counters (BSC), Beam Pick-up Timing (BPTX) devices
  - CMS + TOTEM telescopes
  - CASTOR: CMS very forward calorimeter

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Monte Carlos and Tuning

- soft QCD distributions are compared to variety of Monte Carlos (MC) models

- **PYTHIA6** and **Pythia8**:
  - virtuality or $p_T$ ordered shower; Lund string hadronisation; MPI model for inclusive and underlying event data
    - **ATLAS**: P6 AMBT1, AMBT2B and P8 A2 (uses ATLAS minimum bias data);
    - P6 AUET2B, P8 AU2 (uses ATLAS underlying event data)
    - **CMS**: P6 Z1, Z2(*) (uses CMS underlying event data; different PDFs)
    - **author**: P6 Perugia2011 (uses LHC minimum bias); P8 4C (uses LHC min. bias and underlying event)
    - **pre-LHC tunes**: P6 DW, D6T (both virtuality ordered showers), ATLAS MC09 and P8 Tune 1

- **Herwig++**:
  - angular ordered shower; cluster hadronisation; MPI model to describe underlying event data
    - **author**: UE7-2, UE-EE-3 tunes to LHC underlying event data

- **other dedicated MCs/tunes**:
  - PHOJET, based on dual parton model; author tune to pre-LHC minimum bias data
  - EPOS, air shower MC based on parton and hydrodynamical models; author tune to variety of pp and AA data
  - QGSJET, air shower MC based on quark-gluon string model, and Gribov’s Reggeon approach
Total Inelastic Cross Section

- model dependent extrapolations to total inelastic cross section
- dominant uncertainties from luminosity determination and (MC model dep.) extrapolation
- (TOTEM measurements of total and total inelastic cross sections also shown)

CMS Preliminary

- $\sigma_{\text{tot}}^{pp}$
- $\sigma_{\text{inel}}^{pp}$
- $\sigma_{\text{tot}}^{p\bar{p}}$
- $\sigma_{\text{inel}}^{p\bar{p}}$

- ATLAS 2011
- CMS PAS QCD-11-002
- CMS PAS FWD-11-001
- ALICE 2011
- TOTEM$_{\text{total}}$ 2011
- TOTEM$_{\text{inel}}$ 2011

CMS Coll., PAS FWD-11-001, PAS QCD-11-002

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ATLAS Coll., Nature Commun. 2 (2011) 463
- comparison with other MC models
- ... and to ATLAS data (bottom right)

- note, hadron level definitions for ATLAS & CMS not identical: forward gap size starts at $\eta = \pm 4.9$ (ATLAS) or $\eta = \pm 4.7$ (CMS)

- CMS measurement extends previous ATLAS result by 0.4 units of gap size
Inclusive Hadron Production

normalised leading track p_T distribution

CMS Preliminary  Inclusive pp \( \sqrt{s} = 8 \text{ TeV} \)

\[
\frac{1}{N} \frac{dN_{\text{ch}}}{dp_T, \text{leading}} \text{[GeV]}^{-1}
\]

- CMS (p_T > 0.4 GeV)
- Pythia8 4C
- Pythia6 Z2*
- QGSJetII-04
- EPOS LHC
- Herwig++ EE3C

MC/Data

0.8 1 1.2
0.8 1 1.2

integrated leading track p_T distribution

CMS Preliminary  Inclusive pp \( \sqrt{s} = 8 \text{ TeV} \)

\[
D(p_{T_{\text{min}}, \text{leading}}) \text{[GeV]}^{2}
\]

- CMS (p_T > 0.4 GeV)
- Pythia8 4C
- Pythia6 Z2*
- QGSJetII-04
- EPOS LHC
- Herwig++ EE3C

MC/Data

0.8 1 1.2
0.8 1 1.2

CMS Coll., PAS FSQ-12-026
Differential transverse energy flow

probe particle kinematics in inclusive pp interactions

sensitivity to diffractive contribution

sensitivity to choice of PDF

- diffractive contribution halved and doubled (in PYTHIA8 4C)
- affects amount of activity (diffractive events softer on average); little affect on shape

- replace PDF CTEQ6L1 \(\Rightarrow\) MSTW2008LO
- decreases amount of energy in central region and increases it in forward region
- due to increase of low and high-x gluon fractions with respect to mid-x fraction

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Differential transverse energy flow

ATLAS Coll., JHEP 11 (2012) 033

ATLAS \( \sqrt{s} = 7 \text{ TeV} \)

\[ \frac{d^2 \Sigma E_T}{d \eta d \phi} \begin{cases} \text{Data} \\
\text{Py6 AMBT1} \\
\text{Py6 AUET2B:CTEQ6L1} \\
\text{Py6 DW} \\
\text{Py8 4C} \\
\text{H++ UE7-2} \\
\text{EPOS LHC} \end{cases} \]

MC Data

\[ \begin{array}{c}
0.8 \\
1.2 \\
0.5 \\
1 \\
2 \\
2.5 \\
3 \\
3.5 \\
4 \\
4.5 \\
\end{array} \]

\[ \begin{array}{c}
0 \\
0.5 \\
1 \\
1.5 \\
2 \\
2.5 \\
3 \\
3.5 \\
4 \\
4.5 \\
\end{array} \]

Also measured with dijet selection; probe particle kinematics in the underlying event

Measurement in transverse region; defined by direction of leading jet

- Central region reasonably described (except by EPOS)
- MCs underestimate activity in forward region
- Recent PYTHIA6 tunes describe ratio the best
Hard and Soft Particles as function of Multiplicity

charged particle $p_T$ density in ring zones as function of distance $R$ to jet axis; different multiplicity bins

underlying event tracks

Intra-jet tracks

Low multiplicity bin

High multiplicity bin
Event shapes

Event shape variables describe geometric properties of energy flow in the final state.

thrust minor: out of event plane energy flow

\[ T_M = \frac{\sum_i |p_T^i \cdot \hat{n}_M|}{\sum_i p_T^i} \]

defined by thrust axis (\(\hat{n}_T\)) and beam axis (\(\hat{z}\)):

\[ \hat{n}_M = \hat{n}_T \times \hat{z} \]

- average value as function of N\(_{ch}\)
Identified Particle Production

- $\pi, K, p$ (CMS)

- discrepancies observed in description of proton $<p_T>$ at high multiplicity, and as function of $\sqrt{s}$