Soft-QCD at Hadron Colliders

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Outline

• Hadron Colliders (quick recap)
• What is soft-QCD? Why do we care?
• soft-QCD models / Monte Carlo Event Generators
• A selection of soft-QCD measurements
Hadron colliders: recap

LHC: $pp$ @ 0.9, 2.36, 2.76 and 7 TeV (so far…)

Tevatron: $p\bar{p}$ @ 0.3, 0.63, 0.546, 0.9, 1.8 and 1.96 TeV
What is soft-QCD?

• **QCD** = Quantum ChromoDynamics (i.e. the strong force)
• **soft** = low momentum transfer
• These are the dominant types of interaction at hadron colliders
What is soft-QCD?

cross-section for any interaction (dominated by soft-QCD)

cross-section for Higgs production

At the LHC only 1 in every ~10 billion interactions would produce a Higgs (if it exists at all...)
What is soft-QCD?

Elastic interaction: \( A(p_A) + B(p_B) \rightarrow A(p_A') + B(p_B') \)

Inelastic interaction: \( A + B \rightarrow \sum x_i (\neq A + B) \)

Dominant processes in inelastic hadron-hadron interactions:

- Non-Diffractive (ND) \( \sigma \sim 49 \text{ mb} \)
- Single-Diffractive-Dissociation (SD) \( \sigma \sim 14 \text{ mb} \)
- Double-Diffractive-Dissociation (DD) \( \sigma \sim 9 \text{ mb} @ 7 \text{ TeV} \)

\( \mid P = \) Pomeron (quantum numbers of the vacuum)
Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:

The **Underlying Event (UE)** is everything not associated with the **hard parton-parton interaction**
Why do we care?

• These processes cannot be calculated from first principles (the strong coupling blows up at low scales and perturbative calculations are not possible). What is going on at these scales?
• soft-QCD affecting the high $p_T$ physics program at hadron colliders:
  – Pileup: LHC ~20 proton-proton interactions at the same time, they will almost always be soft-QCD processes
  – Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes
  – Therefore we had better have a good model of these processes! Can affect simulations of lepton ID, $E_T^{\text{miss}}$ resolution, jets, jet vetos,…
Pileup

Important for understanding 20 pp interactions on top of your Higgs!!
Monte Carlo Event Generators

• See Glen Cowan’s course next week for all the details
• In brief:
  – Theoretical tools that simulate events at colliders
  – Extensively used to simulate signal and background processes, to help us understand our data and enable us to make measurements
  – High $p_T$ interactions are calculated using perturbation theory
  – Soft-QCD processes use phenomenological models with theoretical motivation that must be validated against data
  – These models contain parameters that must be tuned to the data
  – It is therefore necessary to make measurements of soft-QCD processes
Soft-QCD models

e.g. Pythia

QCD 2→2 scattering \[ \sim \alpha_s^2(p_T^2)/p_T^4 \]

Dampen divergence at low \( p_T \) \[ \sim \alpha_s^2(p_T^2 + p_{T_0}^2)/(p_T^2 + p_{T_0}^2)^2 \]

smaller \( p_{T_0} \) → more low \( p_T \) activity

Screening: At low \( p_T \) wavelength of exchanged particle becomes too large to resolve colour charges

\[ p_{T_0} = P_1 \left(\frac{E_{\text{COM}}}{1.8 \text{ TeV}}\right)^{P_2} \]
The soft-QCD models need to include MPI
Matter distribution in proton described by double Gaussian

\[ P_3 = \text{fraction in core Gaussian} \]
\[ P_4 = \frac{a_2}{a_1} \]

(denser matter distribution \(\rightarrow\) more multiple interactions \(\rightarrow\) more activity)
Experimental Measurements

1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations
1. Minimum Bias
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**Minimum bias** adj. experimental term, to select events with the minimum possible requirements that ensure an inelastic collision occurred.

- Exact definition depends on detector (and analysis)
- Typically measure kinematics (multiplicity, $p_T$ and $\eta$ spectra, etc) of charged particles in “minimum bias” events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions

Charged particles moving through a magnetic field will bend by an amount inversely proportional to $p_T$

e.g. ATLAS: (a) At least two charged particles with $p_T > 100$ MeV, $|\eta| < 2.5$ (most inclusive)
   (b) At least six charged particles with $p_T > 500$ MeV, $|\eta| < 2.5$ (suppresses diffraction)

**definition of minimum bias in each analysis**
Measurement philosophy

How should you do a measurement that is optimally useful for theory validation and MC tuning?

✓ Correct measurements for detector inefficiencies and resolutions (e.g. measure $p_T$ spectrum of charged particles, not of ATLAS tracks)
✓ No extrapolations into regions not “seen” by ATLAS (such as very low $p_T$ or far-forward particles)
  - We measure what we see, not what the MC tells us we should have seen!
✓ No corrections for diffractive events (rather make reproducible cuts that suppress diffraction) Non-Single-Diffractive
  - On an event-by-event basis we do not know what process occurred
Triggering the events

- Measurement performed with early data
- Few interactions per crossing (mean ~ 0.007)
  - ~ No additional interactions
  - But … 99.3% of beam crossings have no interaction!
- Need to “trigger” on inelastic interactions
- Use Minimum Bias Trigger Scintillators (very inclusive)

Minimum Bias Trigger Scintillator disks trigger on any charged particle with $2.09 < |\eta| < 3.84$
Correcting the data

- Trigger efficiency from data (small “control” sample recorded with different trigger)
- Tracking efficiency from Monte Carlo with GEANT detector simulation (systematic uncertainties determined from checks with data)
η spectra

\[ n_{\text{ch}} \geq 6, \ p_T > 500 \text{ MeV}, \ |\eta| < 2.5 \]
\[ \text{ATLAS } \sqrt{s} = 7 \text{ TeV} \]

- \( dN_{\text{ch}}/d\eta \): Number of charged particles per unit \( \eta \)
- All but Pythia AMBT1 are tuned to Tevatron data
- Slight increase in activity in AMBT1 (achieved by a denser proton)
$n_{ch} \geq 6, p_T > 500$ MeV, $|\eta| < 2.5$

ATLAS $\sqrt{s} = 7$ TeV

$1/N_{ev} \cdot dN_{ch}/d\eta$

lower $p_T$ particles

$1/N_{ev} \cdot dN_{ch}/d\eta$

$\eta$ spectra

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particle multiplicity

$n_{ch} \geq 6, p_T > 500 \text{ MeV}, |\eta| < 2.5$
ATLAS \( \sqrt{s} = 7 \text{ TeV} \)

$n_{ch} \geq 2, p_T > 100 \text{ MeV}, |\eta| < 2.5$
ATLAS \( \sqrt{s} = 7 \text{ TeV} \)
Results at 0.9, 2.36 and 7 TeV

$1/N_{ev} \cdot dN_{ch}/d\eta$

$n_{ch} \geq 1, p_T > 500 \text{ MeV}, |\eta| < 2.5$

ATLAS

Higher energy $\rightarrow$ probing more partons
1. Minimum Bias

2. Underlying Event

3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations
Reminder: Underlying Event

Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:

The **Underlying Event (UE)** is everything not associated with the **hard parton-parton interaction**.
Underlying Event Measurements

- How can we make measurements of the particle activity from the Underlying Event?
  - Simple technique pioneered by CDF during Tevatron Run I
  - e.g. in di-jets: the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)
How can we make measurements of the particle activity from the Underlying Event?

- Simple technique pioneered by CDF during Tevatron Run I
- e.g. in di-jets: the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)
• Define the direction of the “hard scatter” (highest $p_T$ jet /particle)
• Study the activity (# of particles or $\Sigma p_T$) in the region “transverse” to the hard scatter

$60^\circ < |\Delta \Phi| < 120^\circ$
Underlying Event Measurements

PT_{sum} vs the Azimuthal Angle from Charged Jet1

Charged Jet #1 Direction

- "Toward"
- "Transverse"
- "Away"

Δϕ

PT(chgjet1) > 2 GeV/c
PT(chgjet1) > 5 GeV/c
PT(chgjet1) > 30 GeV/c

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Underlying Event Measurements

![Graph showing transverse region, min-bias](#)

- CDF p\(\bar{p}\) data \(\sqrt{s} = 1.8\) TeV
- PYTHIA ATLAS MBT1
- PYTHIA ATLAS MC09c tune
- PYTHIA Perugia0 tune
- PYTHIA DW tune

Proton matter distribution
Inconsistency between LHC and Tevatron results? Currently analysing 2.76 TeV LHC and 0.9 TeV Tevatron data to resolve the issue.
Underlying Event in $Z \rightarrow ll$

Charged Particle Density: $dN/d\eta d\phi$

CDF Run 2
data corrected
pyAW generator level

"Drell-Yan Production"
$70 < M(\text{pair}) < 110$ GeV

"Away"

"Toward"

"Transverse"

Charged Particles ($|\eta|<1.0$, PT$>0.5$ GeV/c)
excluding the lepton-pair

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Soft-QCD
Double parton scattering

The high $p_T$ tails of the Underlying Event… (not really soft-QCD anymore)
1. Minimum Bias
2. Underlying Event
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Inelastic cross-section measurement

\[ \sigma_{\text{inel}} = \frac{N^{\text{evts}} - N^{\text{bck}}}{\varepsilon \times \mathcal{L}} \]

1. \(N^{\text{evts}}\): count inelastic collisions
2. \(\varepsilon\): Correct for detector efficiency
3. \(\mathcal{L}\): Normalise with luminosity

Minimum Bias Trigger Scintillators:

\[ 2.09 < |\eta| < 3.84 \]

\[ N^{\text{evts}} = \# \text{ events with } \geq 2 \text{ counters above threshold} \]

\[ \sigma_{\text{inel}} (\xi > 5 \times 10^{-6}) = 60.3 \pm 0.05(\text{stat}) \pm 0.5(\text{syst}) \pm 2.1(\text{lumi}) \text{ mb} \]

Measurement restricted to region in which we are sensitive (e.g. at least one charged particle with \(|\eta| < 3.84\))
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations
Gap cross-section

- Diffractive events tend to have large “rapidity gaps”
- Measure $\sigma$ vs $\Delta \eta$ (large $\Delta \eta$ dominated by diffraction)

Calorimeters: $|\eta| < 4.9$
Inner Tracking Detector: $|\eta| < 2.5$
\( s = 7 \text{ TeV} \)
\( p_T > 200 \text{ MeV} \)

\( \eta = 4.9 \)
\( \Delta \eta = -4.9 \)

**ATLAS Preliminary**
Other diffractive processes

Not really soft-QCD anymore….

Higgs?

CDF II

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Soft-QCD
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5. Particle Correlations
Two particle correlations

$$R(\Delta \eta, \Delta \phi) = \frac{F(\Delta \eta, \Delta \phi) - B(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

( + normalisation factors)

F : all particle pairs in same event
B : pair particles from different events

1D projections on $\Delta \eta$ axis:
($\Delta \phi$ projections not shown)
Summary

• Soft-QCD processes must be measured to help constrain phenomenological models and tune Monte Carlos

• Many measurements including
  – Minimum Bias
  – Underlying Event
  – Total cross-section
  – Diffraction
  – Particle correlations

• Models are being retuned (and new ones developed) to improve the description
  – Some tension is seen between LHC and Tevatron data

• Important to get it right as can affect: lepton ID, $E_T^{\text{miss}}$ resolution, jets, jet vetos,…