Soft QCD program at the LHC is extremely large. Not possible to cover anywhere near all of it in 25 minutes. A few areas

- Minimum Bias Results
- Min Bias with particle ID
- Correlations and Event Shape Results
- Underlying Event Results
Minimum Bias

- Minimum bias is **experimentally** defined (by the trigger or some other phase-space cuts).
- It is a measure of what happens *on average* when you collide two protons.
- It is important because it forms a background to the higher $p_T$ physics.
- Multiple independent collisions (a.k.a pile-up) are min bias, which provides a background plus noise contamination of signal.
- Fluctuations in the “average” event can look like signal.
- Therefore we need min bias to be well modelled by Monte Carlo = compare measurements to different MC tunes.
Charged particle multiplicity distributions

Note slight differences between phase space and event definition. $|\eta| < 2.5$ (ATLAS), 2.4 (CMS) or 1.0 (ALICE). ATLAS and ALICE use events with $> 1$ charged particle inside their $\eta$ acceptance, whereas CMS define “non-single diffractive” sample.
Pseudo-Rapidity distributions

More similar event definitions this time
ALICE, ATLAS and CMS defined a common set of cuts for easy comparison of MB results: $|\eta| < 0.8$, $p_T > 500$ MeV or 1 GeV. All events with $N_{ch} > 1$. 

\[ \eta \leq 0.8, \quad p_T > 500 \text{ MeV or 1 GeV.} \] 

\[ N_{ch} > 1 \]
Min Bias with Particle ID
Min Bias with Particle ID

- Particle ID can provide useful input to hadronisation models
- Are the pT spectra of individual particle species well modelled?
- Ratio of e.g. $\Delta / Ks$ shows baryon production rate relative to meson
- $\bar{p} / p$ ratio gives an indication of baryon production (two baryons in initial beams)

Generators not doing a great job of this
Alice have measured π, k and p pT spectra at 900 GeV collision energy.

Comparison to MC shows different discrepancies for different species.

Particle Id by dE/dx and time of flight (β=length travelled/time)
LHCb performed a similar measurement for neutral Ks @ 900 GeV
ratio of p/p̄ bar production gives an indication of baryon production (beam baryon number = 2)

Lambda/ Lambda-bar production shows similar
Two-Particle Correlations

- The existence of correlations between final state particles is an indication that there is a common origin for their production.

- Simple example: decays of clusters could give rise to particles close together in $\eta$ and $\phi$.

- Another example: if radiation is emitted at a given angle, $\phi_0$, then there will tend to also be emission close to $\pi - \phi_0$ because of momentum conservation.

- In general, the pattern of correlations can be quite complicated. Models of soft QCD dynamics (as encapsulated in Monte Carlo generators) need to be able to describe this.
Two-Particle Correlations

- Two particle correlations consist of a foreground and a background.

- Foreground = take $\Delta \eta$ and $\Delta \phi$ between each pair of particles in an event. Fill a 2D histogram with those values.

- Falls with $\Delta \eta$ because of phase space, but there is also structure (e.g. peak at 0,0).

\[
F(\Delta \eta, \Delta \phi) = \left\langle \frac{2}{N_{ch}(N_{ch} - 1)} \sum_{i} \sum_{j \neq i} \delta_{\eta_i - \eta_j - \Delta \eta} \delta_{\phi_i - \phi_j - \Delta \phi} \right\rangle
\]

Foreground is normalised by dividing by total number of events.

- Means that each track has the same weight in the distribution, regardless of the track multiplicity of the event.

- $N_{ch} = \text{number of (charged) particles in the event}$
Two-Particle Correlations

- For the background take the $\Delta \eta$ and $\Delta \phi$ between particle pairs in **independent** events.

- Accounts for the phase space effect plus some other detector effects

- **Divide** the foreground by the background to give the observable

$$B(\Delta \eta) = \int_{-2.5}^{2.5} \int_{-2.5}^{2.5} d\eta_1 d\eta_2 \delta(\eta_1 - \eta_2 - \Delta \eta) \left. \frac{dN_{ch}}{d\eta} \right|_{\eta = \eta_1} \left. \frac{dN_{ch}}{d\eta} \right|_{\eta = \eta_2}$$

Note the different normalisation: the background is normalised by dividing by the number of entries (= the no. of tracks) to give unit integral
Two-Particle Correlations

Easier to compare to MC by integrating over $\Delta \phi$

$\Delta \eta$ distribution (by integrating the foreground and background separately over $\{0, \pi\}$ at 7 TeV and 900 GeV)
Two-Particle Correlations

$\Delta \phi$ distribution (by integrating the foreground and background separately $\Delta \eta$ over $\{0, 2\}$ at 7 TeV and 900 GeV)

Integrating over $\Delta \phi$ region that does not include main peak - we see the away side recoil, but a dip on the near side

$\Delta \phi$ distribution (by integrating the foreground and background separately $\Delta \eta$ over $\{2, 5\}$ at 7 TeV and 900 GeV)

Double peak due to back-to-back recoil. Similar to some underlying event distributions
Two-particle Correlations at higher multiplicity

- In a specific region of phase space, \( N_{\text{ch}}(p_T > 400 \text{ MeV}) \geq 110 \), and for particles with \( 1 \text{ GeV} < p_T < 3 \text{ GeV} \), CMS observe an interesting ridge showing long range correlations between tracks.

- Interpretation is open for debate...
Two-particle Correlations at higher multiplicity

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Same 2D plot in profile
Soft Diffraction

- Diffraction is the low t (momentum exchange) limit of scattering processes.
- Results from the exchange of (composite) colourless objects - a large and important contribution to the total cross section.
- Exchange of colour singlet is typically accompanied by a rapidity “gap” devoid of radiation in the detector.
- ATLAS has measured the cross section as a function of that gap size.
- Gap defined as a region with no track of pT > 200 MeV and no calorimeter cell with an energy deposit above a noise pedestal.
- The noise pedestal is defined such that the probability for a noisy cell to exceed the threshold is 0.00014.
Bose Einstein Correlations

- Determine $dN/dQ \ (Q^2 = (p_1 - p_2)^2)$ for all pairs of like-sign charged particles in each event.

- Do same for un-correlated particles (mixed events)

- Take the ratio

- Final state pions are **bosons**, therefore they may originate from the same quantum state (hence require like-signed particles)

- This would show up as an increase as $Q \rightarrow 0$
Underlying Event
Measurements
Underlying Event

- Underlying event is a **feature** of (Monte Carlo) **models** that describes what happens to the part of the proton that does not participate in the hard scatter.

- Secondary soft interactions between the proton remnants.

- Important because it can add radiation to your final state, fake your signal, mess up your jets.

- Related to, but **not** the same as min bias.

- There are a set of observables to which the underlying event models can be compared and their parameters tuned...
Underlying Event

- Identify leading particle or track or calo-cluster in each event

- Define 3 regions relative to this:
  - Toward: $|\Delta \phi| < 60^\circ$
  - Away: $|\Delta \phi| > 120^\circ$
  - Transverse: $60^\circ < |\Delta \phi| < 120^\circ$

- Determine pT sum, multiplicity, av. pT of tracks and other observables in each region
Underlying event

- Shows $\Delta \phi$ distribution of $p_T$ from leading track
- Spike at $\Delta \phi = 0$ -> radiation correlated to the leading track
- Increase as $\Delta \phi$ -> $\pi$ corresponds to recoil radiation
- This structure gets more obvious as lead $p_T$ increases (emergence of jets)
- Note the dip in between (the transverse region)
Transverse Region

**Av. Multiplicity**

![Graph showing Av. Multiplicity for lead track jets with different x-axis scales.](image)

**Av. pT sum**

![Graph showing Av. pT sum for lead track jets with different x-axis scales.](image)

**Lead Track**

![Graph showing Lead Track Jet with different x-axis scales.](image)

*(difference to lead track shows in different x axis scale)*
Transverse Region

Av. pT per particle

Pythia overshoots $\langle p_T \rangle$, Herwig undershoots (a bit)

Ratio of pT sum at 900GeV: 7 TeV. Shows energy evolution of the underlying event
ATLAS has performed the same measurement using neutral particles in the calorimeter together with tracks for charged particles.
CMS have a preliminary measurement of UE in Drell-Yan $\mu\mu$ production.

Here the direction of the di-$\mu$ system is the towards region and is most sensitive to the underlying event (because an electro-weak interaction is responsible for the $\mu$)
The first year of data from the LHC has led to a panoply of new soft physics results. These valuable results have already fed into Monte Carlo tuning efforts, and will continue to do so. Could only show a small selection here. More coming in the future...