Minimum bias and the underlying event: towards the LHC

I.Dawson, C.Buttar and A.Moraes

University of Sheffield

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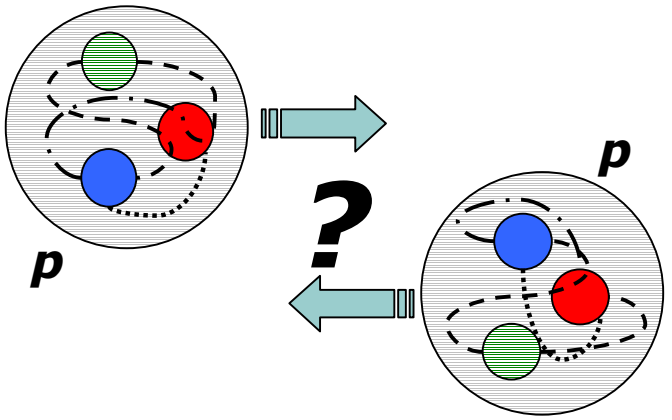
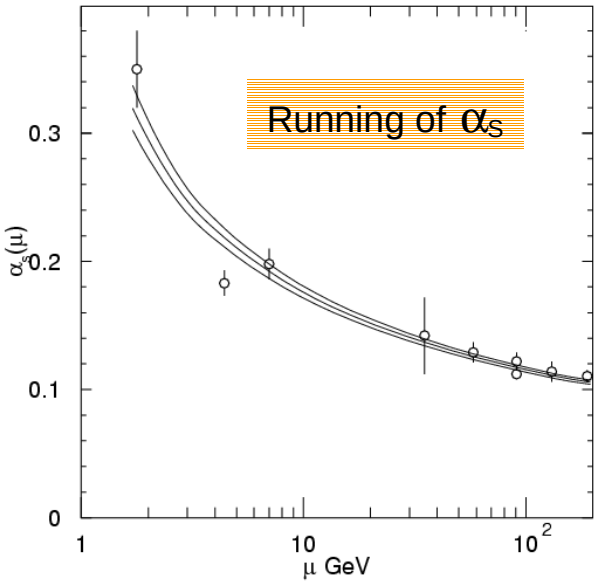
Introduction

- Inelastic hadron-hadron collisions are dominated by soft (low-p_T) interactions. Occasionally we get a hard scatter.
  - Important to model both the soft and hard components in MCs so that:
    - the impact on physics backgrounds can be assessed
    - the impact on detector performance can be evaluated
- We also expect the effects of multiple-parton interactions to become significant at the LHC.
  - New measurements
  - Impact on physics backgrounds?
- Perturbative QCD is very successful when applied to hard processes, but cannot be applied to the soft interactions. Alternative approaches are therefore required.





Definitions

Minimum bias events

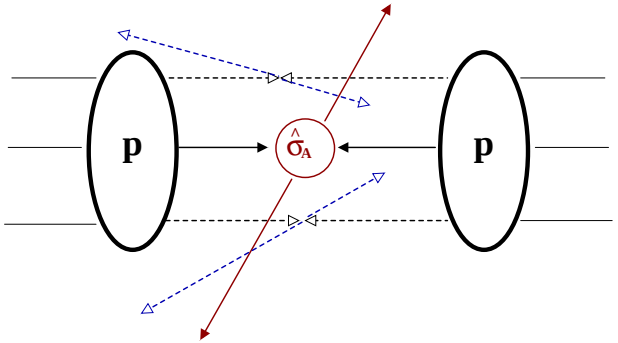
- Inelastic hadron-hadron events selected with an experiment's "minimum bias trigger".
- Usually associated with inelastic non-single-diffractive events (e.g. UA5, E735, CDF … ATLAS?)

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

- Need minimum bias data if want to:
  1) Study general characteristics of proton-proton interactions
  2) Investigate multi-parton interactions and the structure of the proton etc.
  3) Understand the underlying event: impact on physics analyses?

The underlying event

- The "soft part" associated with hard scatters



- In parton-parton scattering, the UE is usually defined to be everything except the two outgoing hard scattered jets:
  1) Beam-beam remnants.
  2) Additional parton-parton interactions.
  3) ISR + FSR

- Can we use "minimum bias" data to model the "underlying event"?
  - At least for the beam-beam remnant and multiple interactions?

Models for hadron-hadron collisions

- Need to connect hard scattering processes (perturbative QCD) to the soft processes (non-perturbative models).

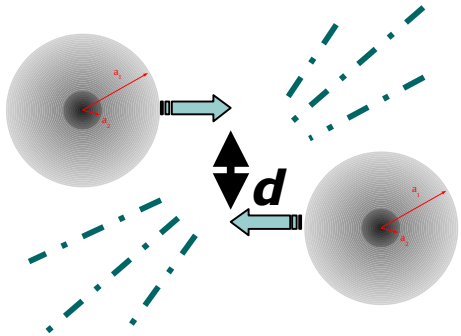
PYTHIA

- Attempts to extend perturbative high-pt picture down to the low-p_T region.
  - Parton-parton cross section become larger than proton-proton - interpreted as multiple parton interactions

$$\sigma_{\text{int}} = \int_{p(T\,\text{min})}^{s/4} \frac{d\sigma}{dp_t^2} dp_t^2$$

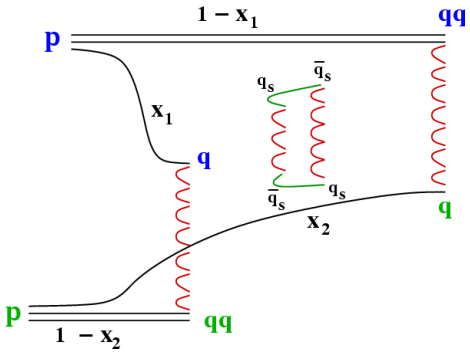
- Decreasing $p_{T\text{min}}$ increases number of parton-parton interactions, and vice-versa.

- Multiple interaction model needed to describe data.
  - Correlations introduced via a **varying impact parameter**.



PHOJET

- Developed mainly for soft and semi-hard particle production.
  - Implements ideas of **Dual Parton Model** for low-p_T processes.
  - Multiple **Pomeron** exchanges give rise to sea-quark multi-chains
- Unlike PYTHIA, HERWIG etc., PHOJET not developed for Standard Model (and beyond) physics analyses.
  - Limited to production mechanisms of strong interactions.
  - However, useful tool for **MB** and **UE** studies where jets are involved.



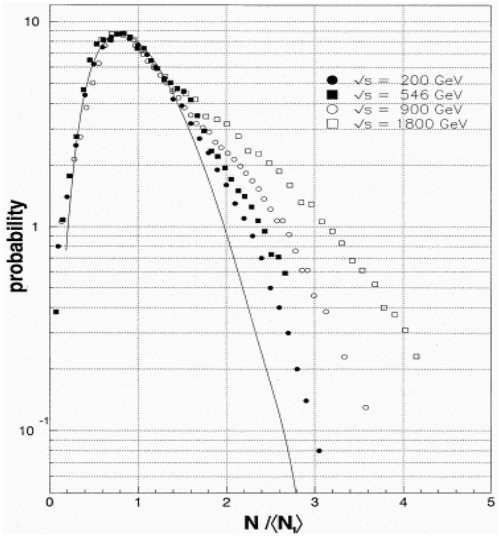
Multiple interaction measurements

1) Violation of KNO scaling

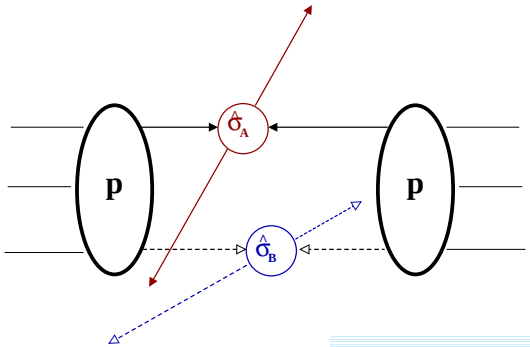
- Multiplicity distributions expected to "scale" for single parton-parton interactions. Deviations attributed to multiparton interactions

Phys. Lett. B 435 (1998) 453

E735 data



2) Double parton scattering measurement (CDF)



$p\bar{p} \rightarrow \gamma/\pi^0 + 3jets + X$

$$\sigma_{DP} = m\frac{\sigma_A \sigma_B}{2\sigma_{eff}}$$

Phys. Rev. D **56** (7) 3811 (1997).

What about the LHC?

- Similar measurements to CDF/E735
- But watch out for backgrounds!

E.g. $p + p \rightarrow WH + X$, with $H \rightarrow b\bar{b}$ and $W \rightarrow l\bar{\nu}$

Nuc. Phys. B 92 (2001) 130

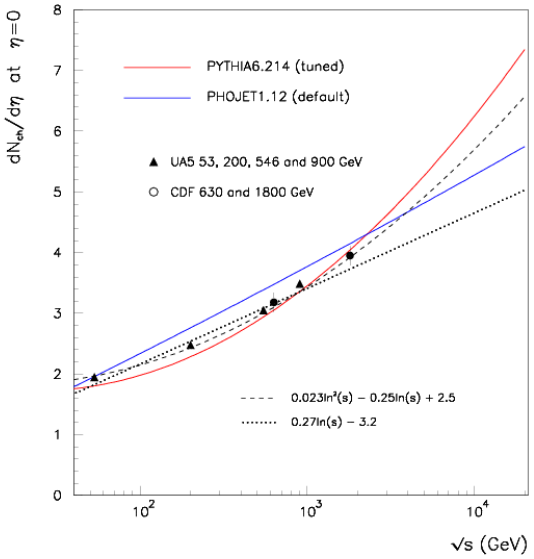
- Central jet veto in Higgs VBF channel?

Some general characteristics of minimum bias data

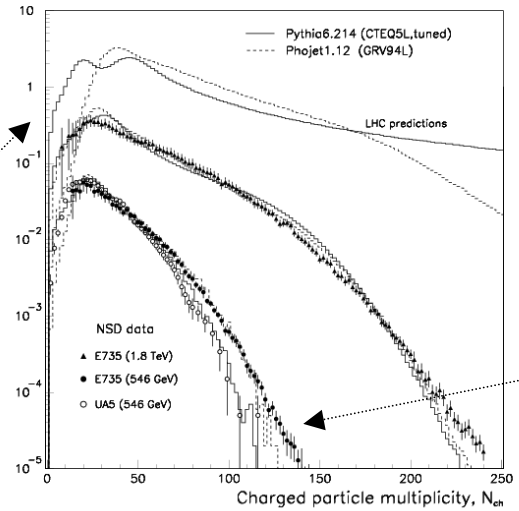
- How does average charged particle multiplicity increase with energy?

$$N_{ch} = a + b.\log(s) + c.\log^2(s)$$

  - A $\log^2(s)$ term indicates extra parton interactions?



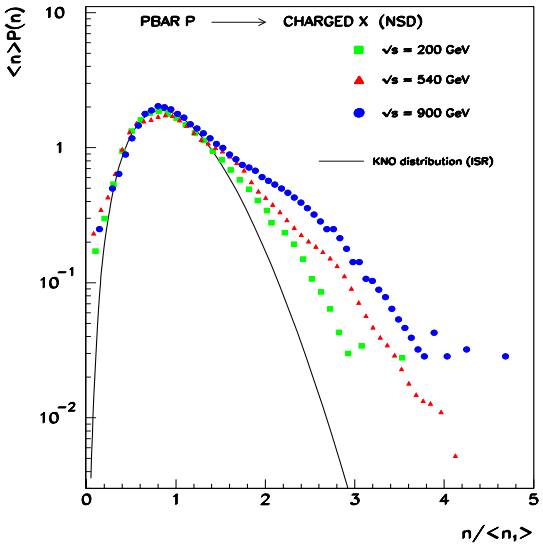
- How does particle multiplicity fluctuate on an event by event basis?
  - The dispersion gives information on multiple interactions



Differences in model predictions!

Violation of KNO scaling?

PYTHIA "likes" UA5
PHOJET "likes" E735!

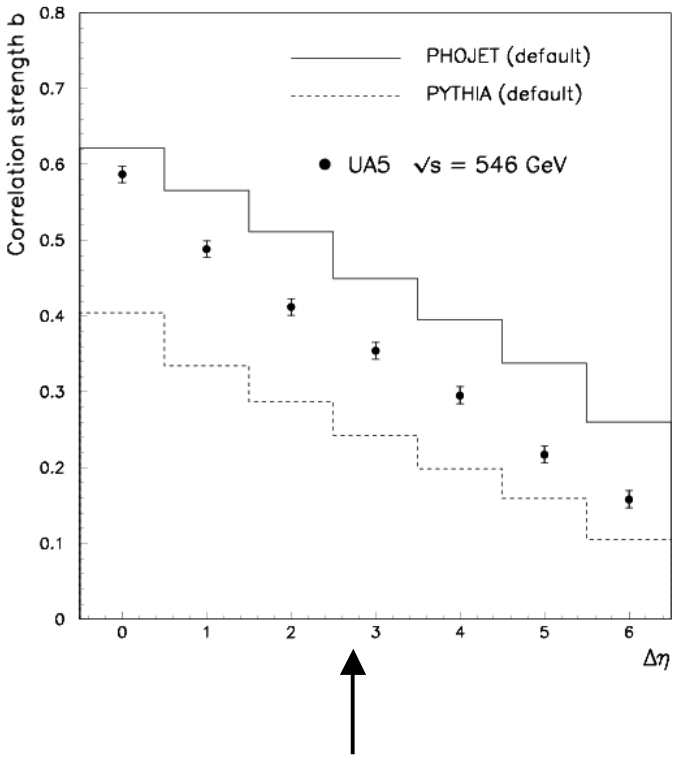


Some general characteristics of minimum bias data

Multiplicity correlations

- Forward-backward correlations defined as:

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_B \rangle}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$



- Correlations attributed to “extra” partons or chains being produced in the central rapidity region.
  - Gives information about type of “cluster” decay

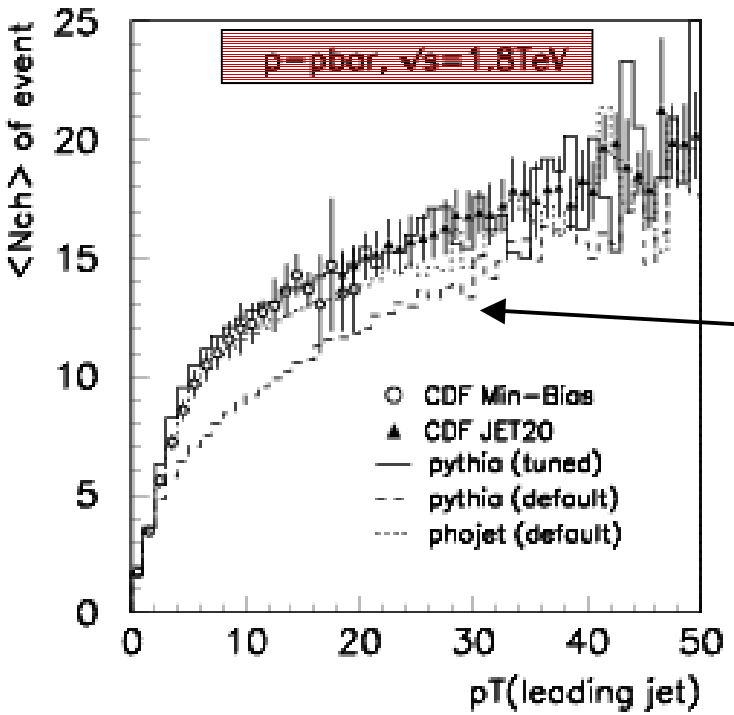
- Correlation achieved in default PYTHIA using multiple interaction scenario
  - Switching on “varying impact parameter” model in PYTHIA gives results similar to PHOJET.

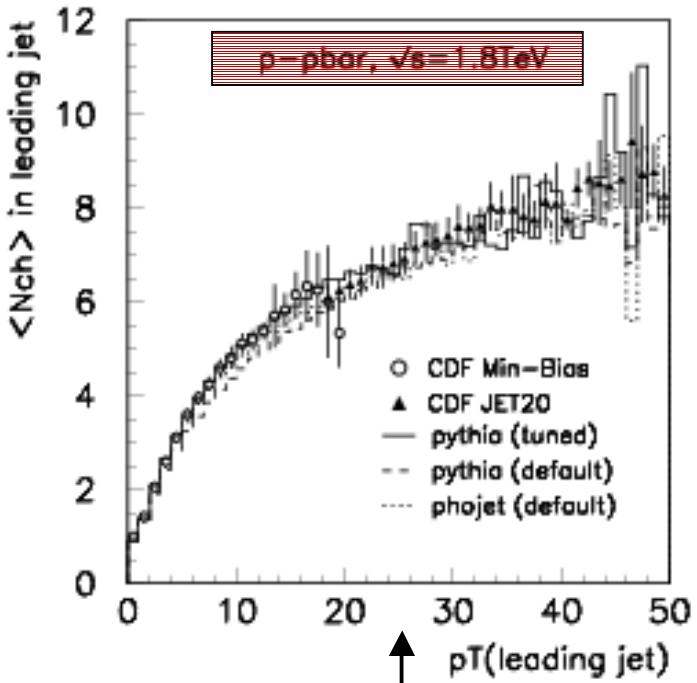
Underlying event in charged jet evolution

- Jets defined in η - ϕ space using a simple cone algorithm for charged particles having a $p_T > 0.5$ GeV/c and $|\eta| < 1$

CDF data:

➢ **Phys. Rev. D, 65 (2002)**





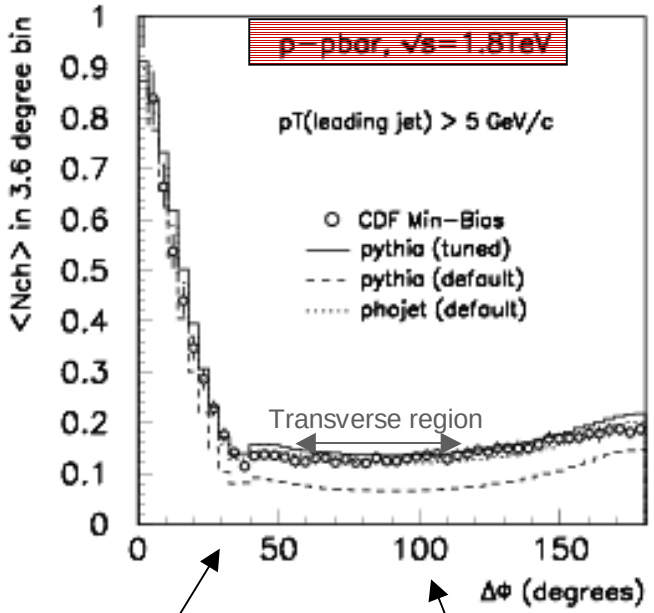
PYTHIA needs to be "tuned" to give "extra" event activity in the "underlying event". Default PHOJET used.

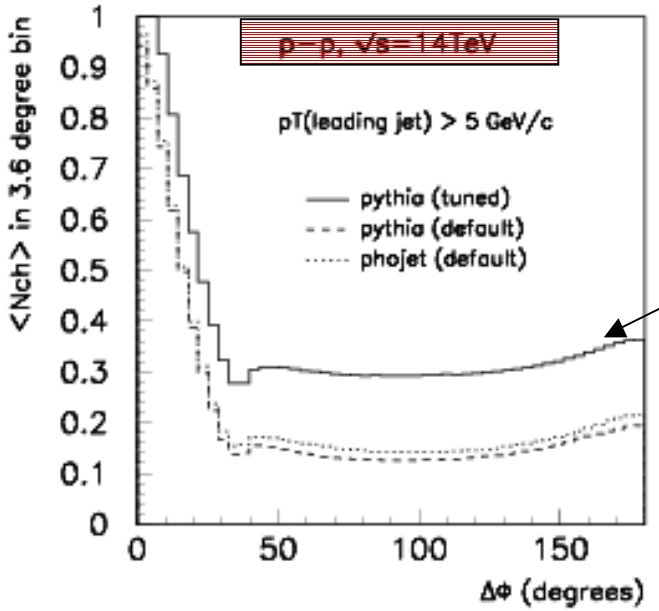
Both PYTHIA and PHOJET describe characteristics of leading jet quite well.

Underlying event in charged jet evolution

- More interesting is "**transverse region**", defined in terms of azimuth ϕ.
  - Particle density and energy flow in the "transverse regions" is very sensitive to the "**underlying event**" (beam-beam remnants, multiple interactions, ISR + FSR)

Also interesting to "split" transverse region into "TransMin" and "TransMax". Hard components of UE should be in "Transmax".





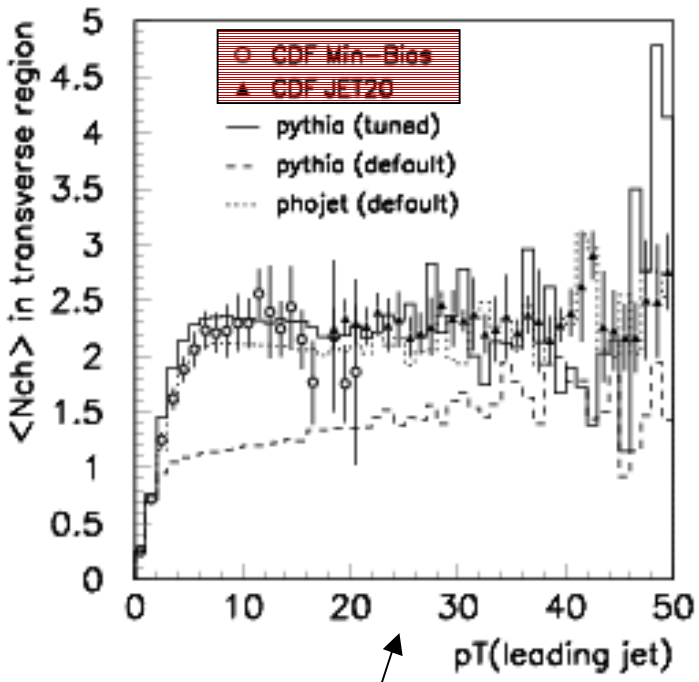
LHC predictions differ by a factor of two in "transverse region"
Need to investigate further:
1) Energy dependence
2) TransMin/Max etc.
3) PDFs

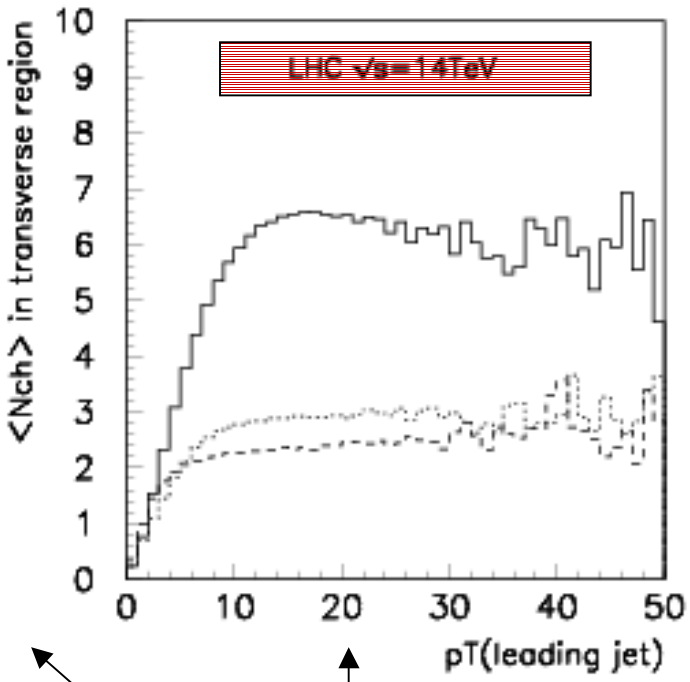
Good agreement between tuned-PYTHIA and PHOJET and data at CDF energies.

Particle density in "transverse" region greater than that expected from MB data. However, what about "TransMin"?

Underlying event in charged jet evolution

- How does particle density in “transverse region” vary with leading jet p_T ?





Again, default PYTHIA does not give enough “activity” in “transverse region”. (Need to increase correlations in multiple interactions.) Tuned-PYTHIA and PHOJET agree well with data.

PYTHIA predicts significant increase in event activity in the UE at the LHC. While tuned-PYTHIA and PHOJET both agree well with CDF data, their predictions at LHC energies differ by more than a factor of 2.

Summary

- Collecting “minimum bias” data is important for:
  1) Studying general characteristics of proton-proton interactions
  2) Making double (triple?) parton scattering cross section measurements
  3) Understanding the underlying event in hard scatters

- Multiple interactions gives a natural way of explaining the event activity for both minimum bias and the underlying event.
  - The multiple interaction models used in PYTHIA and PHOJET are able to describe both MB and UE data.

- Extrapolating current model predictions to LHC energies suggests a factor of two uncertainty is justified for charged particle density in the underlying event for jets with $p_T > 10$ GeV/c.
  - Studies over the next few years along with data from Tevatron and HERA should improve the predictions. However will ultimately need “minimum bias measurements” at the LHC. (First measurements at LHC?)

- Measurements from different LHC experiments should be complementary:
  - LHC-b tracks charged particles to higher rapidities than ATLAS or CMS
  - ALICE tracks charged particles down to lower momenta than ATLAS or CMS