Modelling Underlying Events and Minimum Bias Physics

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- Relating "minimum bias" and "underlying event"
- Models on the market (with some details on JIMMY)
- What can we believe?

Minimum Bias

- A “minimum bias” event is what one would see with a totally inclusive trigger.
- A single particle-particle (i.e. proton-proton) interaction.
- Average event is has low transverse energy, low multiplicity. Many are elastic and/or diffractive.
- Many minimum bias events per bunch crossing at LHC. Will be seen if they accompany an “interesting” event which is triggered.

Underlying Event

- Several definitions possible
  - Everything except the LO process of interest.
  - Everything except the hard/interesting process.
  - All particles from a single particle collision except the process of interest.
- The third option is most commonly used, though still has ambiguities. The first is wrong in principle.
- Implies a distinction between coherent radiation (parton showers, other higher order corrections) and incoherent “remnant-remnant” interactions.

Underlying Event

- May be hard (i.e. contain high p_T scatters) or soft.
- Will not simply be the equivalent of a minimum bias event added to the process of interest – correlations are very significant.
- Related to minimum bias events – use them to study correlations etc...
- Related to forward particle production – rescattering models; leading protons and neutrons.
- Related to survival probability for rapidity gaps – incoherent remnant interactions fill the gap.

Models on the Market

- “Soft” bulk scattering
  - HERWIG soft underlying event (Webber/UA5)
- Hard 2->2 Scattering
  - PYTHIA (several options) (Sjostrand & van Zijl, Sjostrand & Skands)
  - HERWIG (JIMMY) (JMB, Forshaw, Seymour)
- Soft “partonic” scatters matched to hard 2->2 scatters
  - PYTHIA (several options) (Sjostrand & van Zijl, Sjostrand &Skands), PHOJET (Engel)

HERWIG Soft Underlying Event

- Parameterisation of UA5 inelastic charged multiplicity distribution.
- Exponentially falling p_T distribution, flat rapidity distribution.
- No dependence on parton densities.
- Tunable (see HERWIG 6 manual for details), but lack of an underlying physical model makes extrapolation (e.g. to high energies) extremely suspect.

Eikonal Hard Scattering Models

- Basic idea: At low x, parton densities become very high. Taken to its limit, this means that either:
  - The dijet cross section calculated perturbatively exceeds the expected total cross section (from Regge fits) *(PYTHIA approach)*
  - The hard part of the total cross section calculated perturbatively violates unitarity *(JIMMY approach)*
- Either way, something has gone wrong with the physical assumption that each hadron-hadron event has at most one parton-parton scatter.

Eikonal Hard Scattering Models

- Solution: assume Poisson statistics and either the total cross section from Regge fits (PYTHIA), or something about the matter distribution in the proton (JIMMY) and Eikonalise the cross section.
- Mean number of scatters per event = σ(dijet)/ σ(total)
- Multiplicity distribution depends upon details of the model.

JIMMY's Eikonal Model

- All scatters treated on an equal footing.
- For fixed impact parameter (b) all scatters are independent. Correlations arise via b dependence of overlap.
- Total cross section for events with n scatters of a given type (e.g. type **a**) is calculated from the parton cross sections, the PDF and the eikonal formalism.

$$\sigma_n = \int d^2b \, \frac{(A(b)\sigma_a)^n}{n!} e^{-A(b)\sigma_a},$$

A(b) is the area overlap function

JIMMY's Eikonal Model

- This is the master formula. It is used to derive the probability that an event has exactly **n** scatters, given that is has at least one. This is pretabulated at the start of a JIMMY run.
- This is used to generate events. Momentum conservation dynamically modifies this during the run (can reduce the amount of multiple scattering).
- The total cross section for events having at least one scatter of type **a** is modified (unitarised) by the program at the end of a run based on the actual number of multiple-scattering events which occurred.

Practical Problems with JIMMY's Simple Eikonal Model

- Event type **a** is QCD 2->2 scattering (the only implemented process in JIMMY), typically we want to see the effect of low p_T multiple scatters on a high p_T rare event. To get the low p_T multiple scatters, PTMIN must be set low, which is very inefficient.
- Would also like to see the effect of QCD multiple scatters on other rare processes (type **b**). Not possible with the old JIMMY.

Practical Problems with JIMMY's Simple Eikonal Model

- To calculate the probability of an event having n scatters of type **a** and **m** of type **b**, the formula is:

$$\sigma_{n,m} = \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}} \, \frac{(A(b)\sigma_{\mathrm{b}})^m}{m!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}}$$

- Or, if **m** is a subset of **n** (e.g. The higher p_T scatters)

$$\sigma_{n,m} = \int \mathrm{d}^2 b \, \frac{(A(b)\,(\sigma_{\mathrm{a}} - \sigma_{\mathrm{b}}))^{n-m}}{(n-m)!} \, \mathrm{e}^{-A(b)(\sigma_{\mathrm{a}}-\sigma_{\mathrm{b}})} \, \frac{(A(b)\sigma_{\mathrm{b}})^m}{m!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}}$$

- To tabulate such results at the start requires prior knowledge of the cross section for **b** as well as **a** and is very awkward in the old set up.

Approximate, approximate...

- In (almost?) all cases of interest, **a**=QCD 2->2 scattering, and **b** is a much smaller cross section.
- Work in the approximation that the chance of >1 scatter of type **b** is negligible.
- Probability of n scatters of type **a** and at least one of type **b** is:

$$P(n|m \geq 1) = \frac{\int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}} \left(1 - \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}}\right)}{\int \mathrm{d}^2 b \left(1 - \mathrm{e}^{-A(b)\sigma_{\mathrm{b}}}\right)}, \qquad n \geq 0$$

Since σ_{b} is small, we can expand the exponentials and obtain

$$P(n|m \geq 1) \approx \int \mathrm{d}^2 b \, A(b) \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}}, \qquad n \geq 0.$$

Approximate, approximate...

- For the special case where **b** is a subset of **a**, there is a problem with double counting – scatters of type **a** can produce **b**-type events.
- Fixed by vetoing higher p_T scatters:
  - If a scatter of type a is also of type **b**, reject the **m**th type b scatter with probabilty 1/**m**
- Continuous at the boundary between **a** and **b**, correct to first order in σ_b

How to run it...

- JIMMY underlying event option JMUEO.
- JMUEO=0. Old JIMMY. QCD 2->2 Cross section is Eikonalised, best for “minimum bias” physics (p_T>PTMIN)
- JMUEO<>0 (default).
  - 1-> QCD 2->2 with PTMIN<>PTJIM
  - 2-> small cross section “**b**”. Multiple scatters PT>PTJIM. PTMIN may or may not be relevant, depending on the process **b**.
- PTJIM and JMUEO (and other JIMMY parameters) are in jimmy.inc

Multiparton Interactions in PYTHIA

- Average number of scatters determined from Regge fits to total cross sections. Multiplicity distribution from Poisson statistics (default – no impact parameter dependence).
- Various options for matching hard scatters to soft “gluon-gluon” scatters via hard cutoff or smooth turnoff below some p_T.
- By default the p_T cutoff also has an energy dependence (rises slowly with s).

Multiparton Interactions in PYTHIA

- “Dual core size” proton models to increase fluctuations -> leads to an impact parameter dependence similar to that in JIMMY – hard scatters are in central collisions which have more hard scatters...
- Scatters ordered in p_T, and x is rescaled after each -> means in general the x probed is not as low as in JIMMY
- Sophisticated treatment of colour, flavour and momentum correlations in the remnants.
- Cannot yet be tuned on photon-proton events.

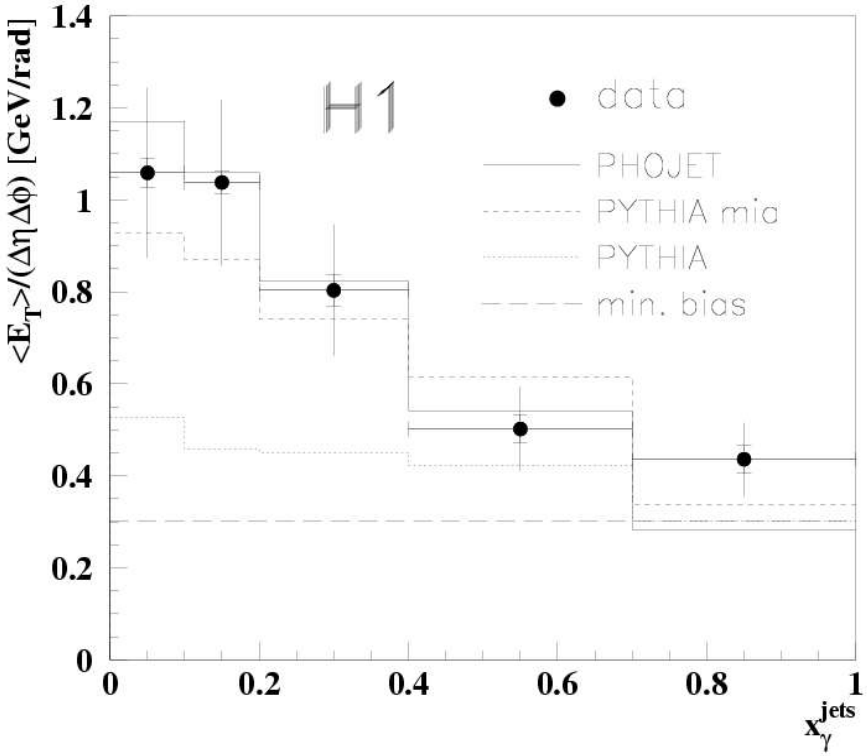
Multiple Interactions in PHOJET

- Both soft and hard scatters treated together (seperated by a p_T cut).
- Multiple (cut) pomeron exchange gives realistic multiplicity fluctuations.
- Most parameters determined from fits to total, elastic and diffractive cross sections using Regge theory and the dual parton model.
- Used extensively in photon-hadron & photon-photon events as well as hadron-hadron.
- Not a general purpose MC.

So what to trust?

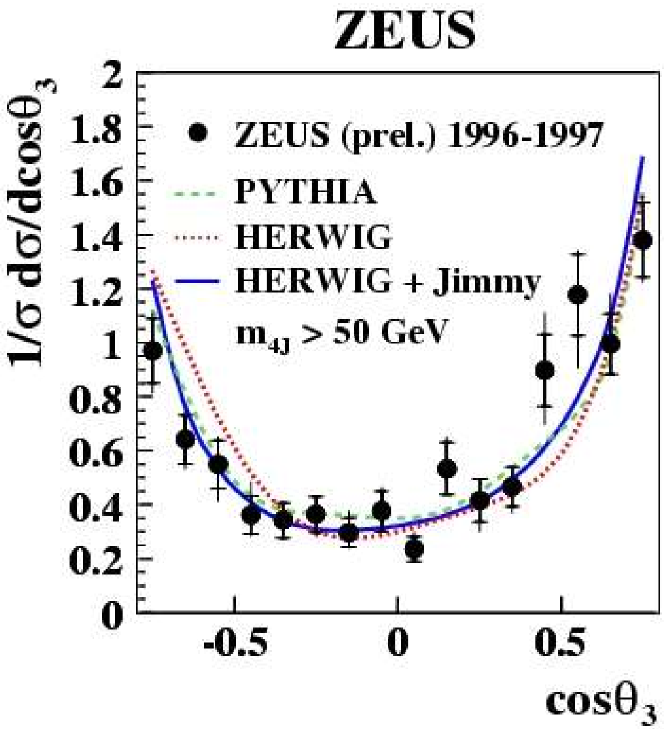
- There is fairly convincing evidence from UA5, Tevatron and HERA that multiparton interactions take place. Certainly these are the only models which have the power to describe the data.

e.g. Energy flow outside jets in resolved photon only modelled by MI models...

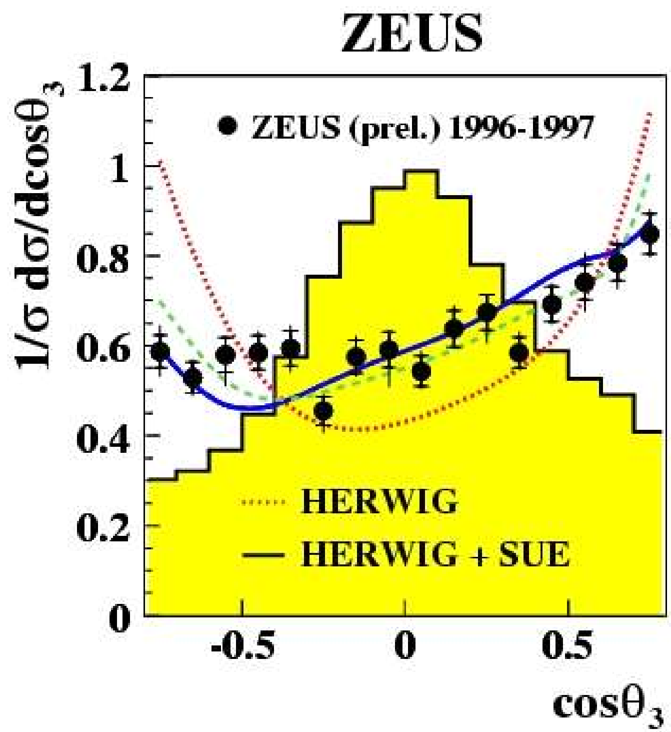


Four-jet cross sections

Photoproduction, jet transverse energy > 6 (5) GeV.

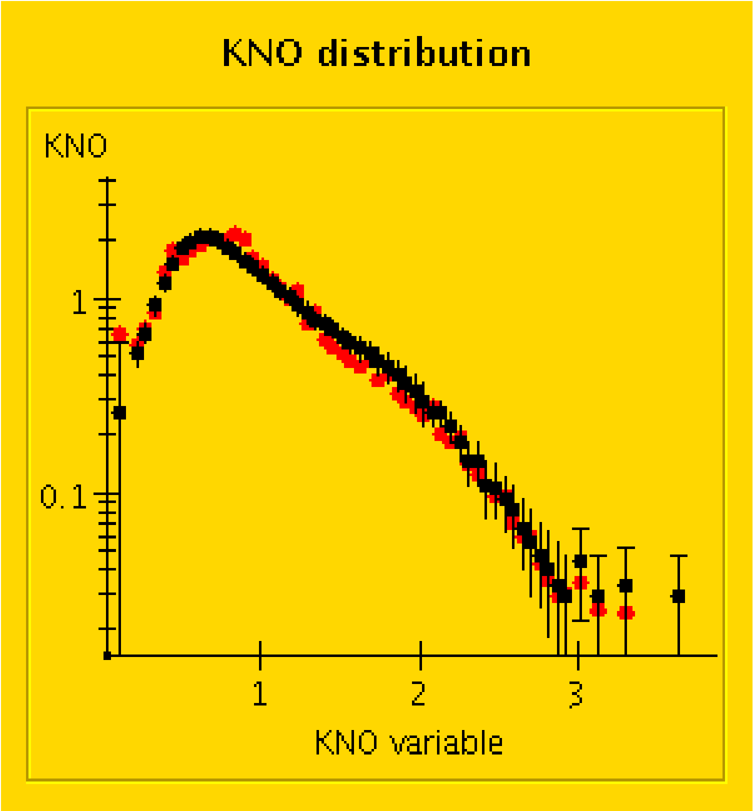


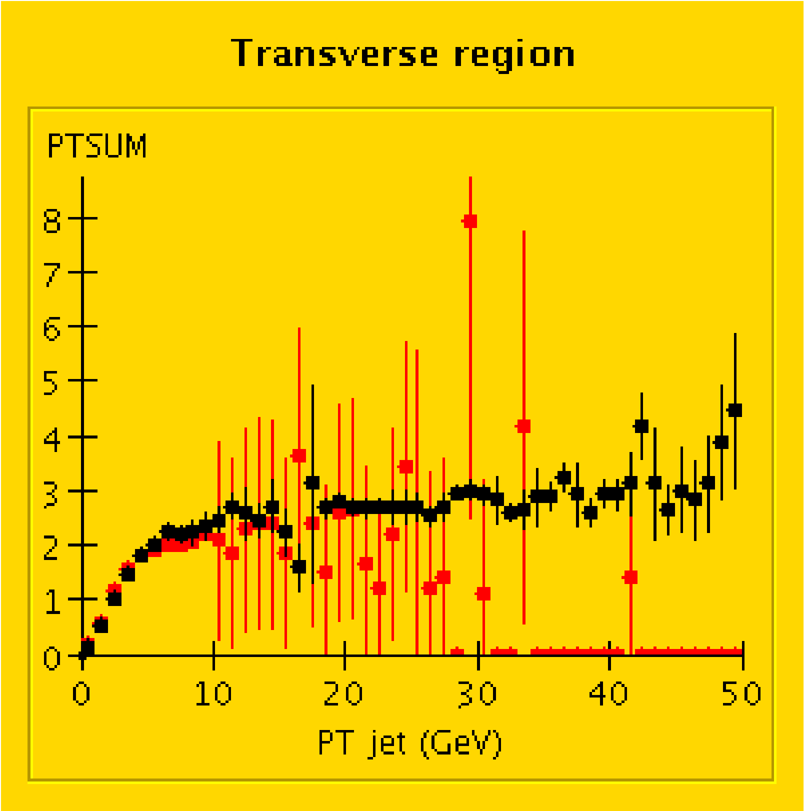
Four jet Mass > 50 GeV. QCD (LO+PS) doing well.



No mass cut. Need something else. Multiparton interaction models are favoured.

Proton-antiproton multiplicity distributions





UA5 (KNO plot – sensitive to correlations/fluctuations

CDF (Region transverse to jet – sensitive to incoherent activity)

Key Parameters

- Parton distribution
  - More low x partons => more scatters
- Matter (impact parameter) distribution
  - Smaller, denser proton means more scatters
- Minimum transverse momentum of hard scatters
  - Sets the minimum x probed for a given centre-of-mass energy
  - May have energy dependence itself (in PYTHIA)

Other Connected Areas

- Rapidity gaps and survival probabilities
  - Probably determined by this physics
- Leading baryon production (neutrons and protons)
  - "Rescattering" is multiple interactions
- Total cross section
  - in some models: unitarity implies multiple interactions
- Low x PDFs and saturation.
  - The multiparton interaction rate at LHC is sensitive to $x < 10^{-7}$

Summary

- An important and poorly understood area of physics which will affect everything we measure in ATLAS to a greater or lesser extent.
- We need (and have some) good models based on sound physics.
- This is not enough – the extrapolations are large and the assumptions are many. Need to define a set of “reasonable” models by comparing to the full set of available relevant data.
- This is underway:
  - C.Buttar, A.Moraes,I.Dawson, R.Field, JMB, M. Wing...
  - JetWeb ->

JetWeb

- Collect data (+HEPDATA = CEDAR)
- Collect the knowledge of how to make the plots (kinematics, cuts, event shape variables, jet finders -> HZTOOL)
- Compile library of comparisons to which LHC data can be added when it arrives.
- Provide a sensible set of underlying event models which can be used to estimate systematic errors and optimise measurements to minimise their sensitivity to these effects.

URLs

- PYTHIA
  - http://www.thep.lu.se/~Torbjorn/Pythia.html
- HERWIG/JIMMY
  - http://hepwww.rl.ac.uk/theory/seymour/herwig
  - http://jimmy.hep.ucl.ac.uk
- PHOJET
  - http://www-ik.fzk.de/~engel/phojet.html
- JETWEB
  - http://jetweb.hep.ucl.ac.uk
- HZTOOL
  - http://hztool.hep.ucl.ac.uk