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Multiparton interactions in Herwig

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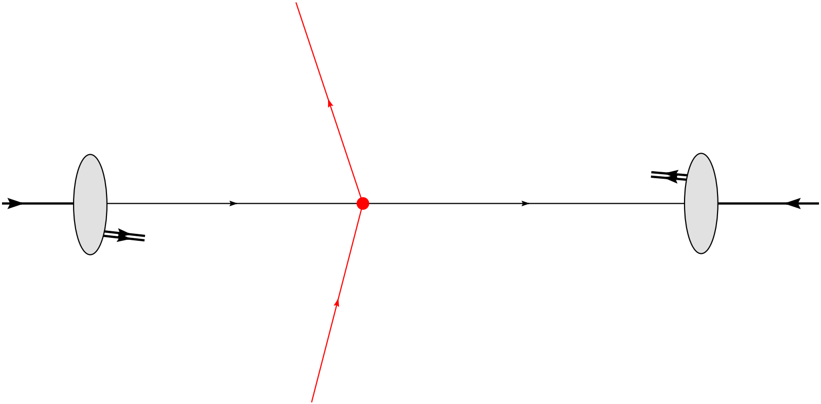
Table of Contents

Herwig Monte Carlo Event Generator

- Herwig is a general-purpose event generator for high energy lepton-lepton, lepton-hadron and hadron-hadron collisions.
- Special emphasis is put on the accurate simulation of QCD radiation.
- The event in Herwig is simulated including these steps:
  - Elementary hard process,
  - Initial and final state parton showers,
  - Decay of heavy objects,
  - Multiple interactions (hard and soft),
  - Hadronization and
  - Hadron decays.

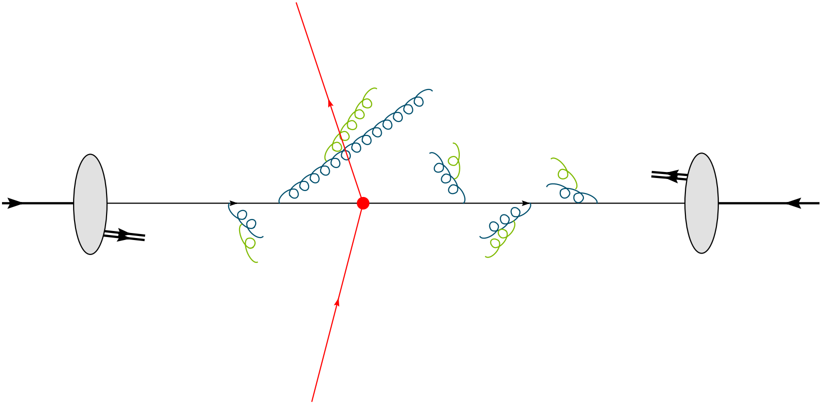
[**Eur.Phys.J. C58 (2008) 639-707**]

pp event generator in Herwig



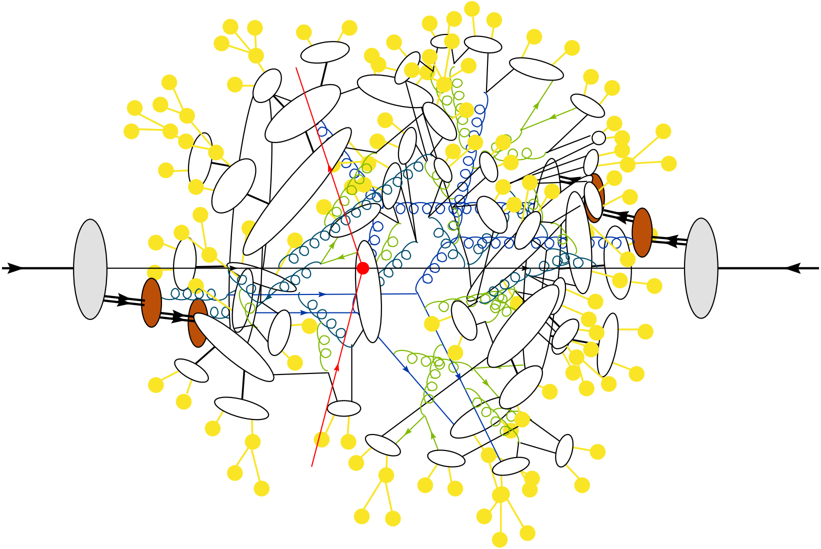
Taken from Stefan Gieseke

pp event generator in Herwig



Taken from Stefan Gieseke

pp event generator in Herwig



Taken from Stefan Gieseke

Herwig 7

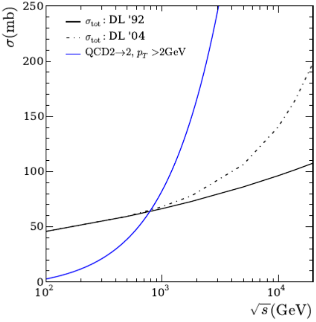
Recently released:

- Herwig++ 3.0 $\rightarrow$ Herwig 7.0
- No distinction anymore between HERWIG and Herwig++; we refer to it as Herwig from now on.
- Most new features have to do with NLO calculations of hard processes with matching to angular-ordered and dipole shower modules.
- The focus of this talk:
  - review of semi-hard and soft multiple parton interactions,
  - recent development in diffraction and colour structure of soft scatters.

Multiple Parton Interactions (MPI) - motivation

- Inclusive jet cross section above transverse momentum p_T

$$\sigma_{\mathrm{H}}^{inc}(s, p_T^{\min}) = \int dx_1 dx_2 d\hat{t}\, \Theta\left(p_T - p_T^{\min}\right) \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \times \left(f_{i|h1}(x_1, \mu^2) f_{i|h2}(x_2, \mu^2) \frac{d\sigma_{ij\hat{\to}kl}}{d\hat{t}}(x_1 x_2 s, t) \right)$$



- Cross section increases with s.
- At moderate values of s, exceeds total cross section.
- A way to resolve this contradiction is MPI.

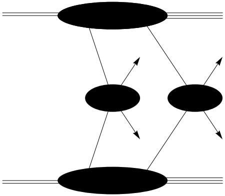
[M. Bähr's talk at MPI@LHC 08.]

MPI - definitions and applications

- Several scatterings between partons in the same hadron collision.
- Important for understanding min-bias processes and the underlying event.
- Underlying event - all activity in a hadronic collision not related to the hard process, e.g. initial-state radiation, additional scatters in the collision, etc.
- Jet measurements - sensitive to the underlying event; jet algorithms gather all particles in the vicinity of the leading initial hard parton.
- Min-bias - events selected with least trigger bias possible; constitute the majority of the events in hadronic collisions.

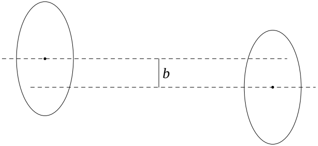
MPI in Herwig

- Multiple scattering in a pp collision:



- Mean pairs of interactions at a given impact parameter b:

$$\langle n(b,s)\rangle = \mathcal{L}_{\mathrm{partons}} \otimes \hat{\sigma}_H,$$



$\mathcal{L}_{\mathrm{partons}}$ - parton luminosity;
$\hat{\sigma}_H$ - partonic hard scattering cross section for $p_T > p_T^{\mathrm{min}}$.

[**J.M. Butterworth et al., Z.Phys. C72 (1996) 637-646**].

MPI in Herwig (cont'd)

Assumption:

$$d\mathcal{L}_{\text{partons}} = A(b) n_{h_1}(x_1) n_{h_2}(x_2) dx_1 dx_2$$

Profile function $A(b)$ was factored out. We have:

$$\int d^2 b A(b) = 1.$$

$n_{h_i}(x_i)$ - parton densities of hadrons (parton flavor is omitted); After performing the convolution:

$$\langle n(s,b) \rangle = A(b) \sigma_H^{\text{inc}}(s),$$

$\sigma_H^{\text{inc}}(s)$ - inclusive scattering cross section. Assumption: scatters are uncorrelated; probability of having m scatters:

$$P_m(A(b)\sigma^{\text{inc}}) = \frac{(\langle n(b,s) \rangle)^m}{m!} \exp\left(- \langle n(s,b) \rangle\right)$$

Multi-reggeon interactions - AGK rules

- Eikonal model n pomeron amplitude

$$\mathcal{A}^{(n)}(s,b) = \frac{1}{2i}\frac{(-\chi(s,b))^n}{n!}, \quad \text{with } \chi(s,b) = -2i\mathcal{A}^{(1)}(s,b)$$

- Using AGK rules, the k cut pomeron cross section is

$$\sigma_k(s) = \int d^2b \frac{(2\chi)^k}{k!} \exp(-2\chi)$$

MPI - eikonal model

- Jet production cross section due to exactly k uncorrelated hard interactions

$$\sigma_k(s) = \int d^2b\, P_k(A(b)\sigma^{\rm inc}) = \int d^2b \frac{\left(A\sigma_{\rm H}^{\rm inc}\right)^k}{k!} \exp\left(-A\sigma_{\rm H}^{\rm inc}\right)$$

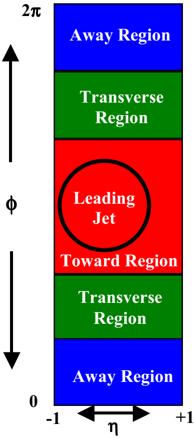
- Similar to the eikonal model if $\chi_{\rm H}(s,b) = \frac{1}{2}A(b,\mu)\sigma_{\rm H}^{\rm inc}(s, p_T^{\rm min})$.
- We have introduced the parameter μ explicitly which is tuned in Herwig.
- Prob. of having n scatters, given there is one:

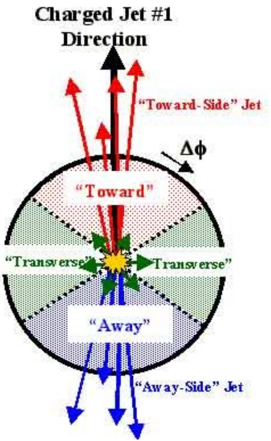
$$P_{n\geq 1}(\sigma^{\rm inc}) = \frac{\int d^2b P_n(A(b)\sigma^{\rm inc})}{\int d^2b \sum_{k=1}^{\infty} P_k(A(b)\sigma^{\rm inc})} = \frac{\sigma_n(\sigma^{\rm inc})}{\sigma_{{\rm inel}(\sigma^{\rm inc})}}$$

- This expression is the basis of underlying event calculations. Describes well the data (**[M. Bähr, S. Gieseke, and M. H. Seymour JHEP 07 (2008), 076)]**).

Underlying event - Tevatron

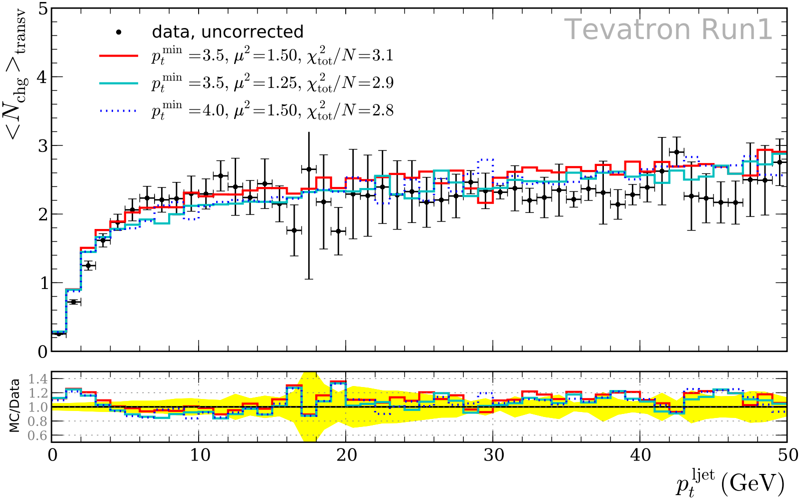
- The direction of the leading jet is used to partition the event into three parts: towards, away and transverse.





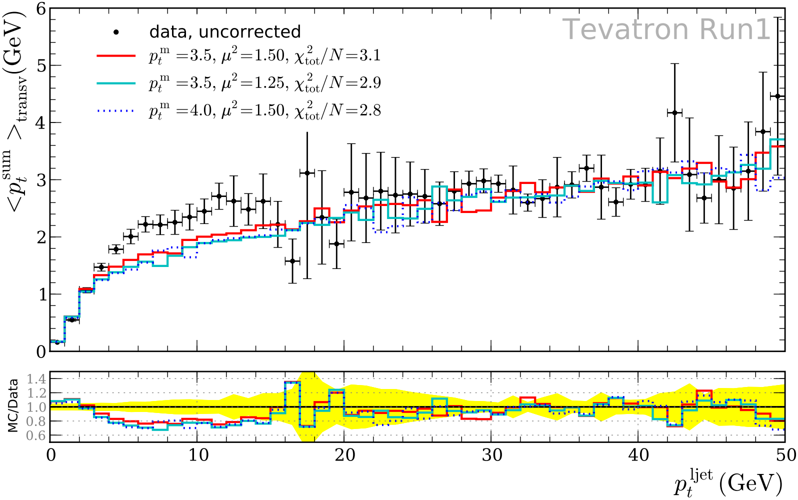
[Phys. Rev. D65 (2002) 092002]

Underlying event - Tevatron



[JHEP 0807 (2008) 076]

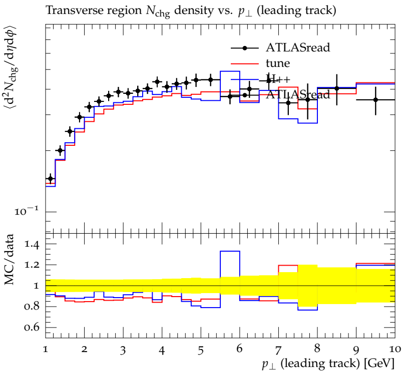
Underlying event - Tevatron

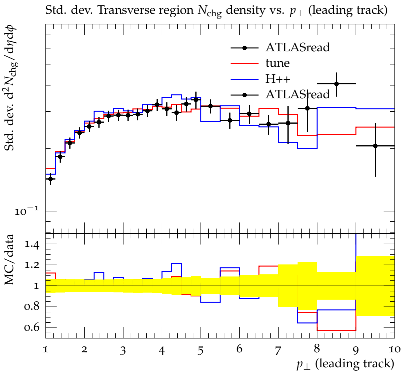


[JHEP 0807 (2008) 076]

Underlying event - ATLAS (900 GeV)

Also include Std deviation!

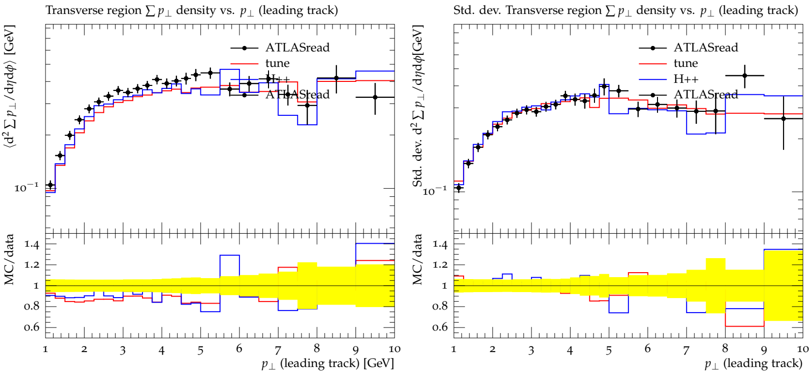




taken from Stefan Gieseke

Underlying event - ATLAS (900 GeV)

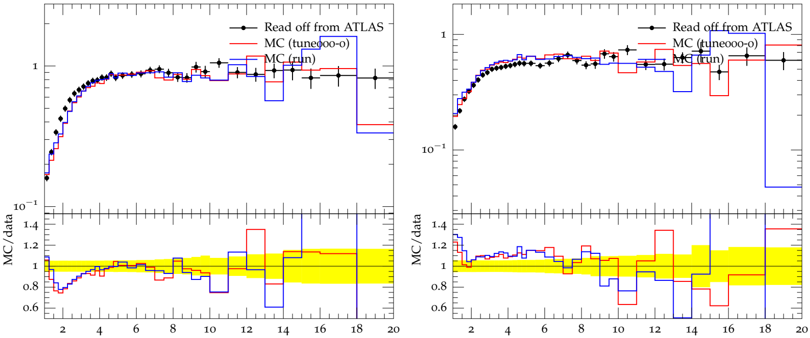
Also include Std deviation!



taken from Stefan Gieseke

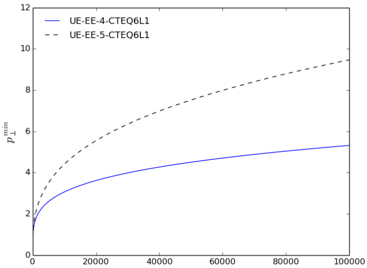
Underlying event - ATLAS (7 TeV)

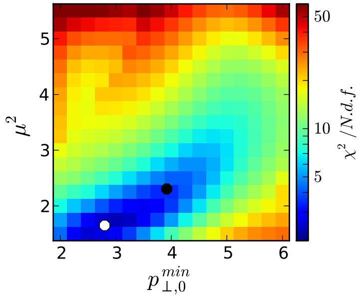
N_{ch}/StdDev transverse vs p_t^{lead}/GeV.



taken from Stefan Gieseke

Underlying event - Energy extrapolation to 100 TeV

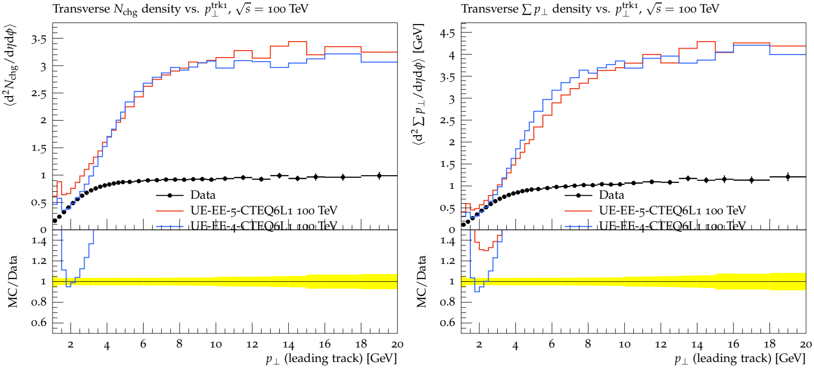




taken from Andrzej Siodmok

- Different tunes give similar results due to the strong correlation between $p_\perp^{min}$ and μ^2.

Underlying event - Energy extrapolation to 100 TeV



taken from Andrzej Siodmok

Soft interactions

- Extend the model to include interactions with $p_T < p_T^{\mathrm{min}}$.
- Add to the eikonal function the soft contribution ([**JHEP 09 (2002), p. 015**]):

$$\chi(s,b) = \chi_H(s,b) + \chi_S(s,b) = \frac{1}{2}\left[A(b,\mu)\sigma_H^{\mathrm{inc}}(s,p_T^{\mathrm{min}}) + A(b,\mu_s)\sigma_s^{\mathrm{inc}}\right]$$

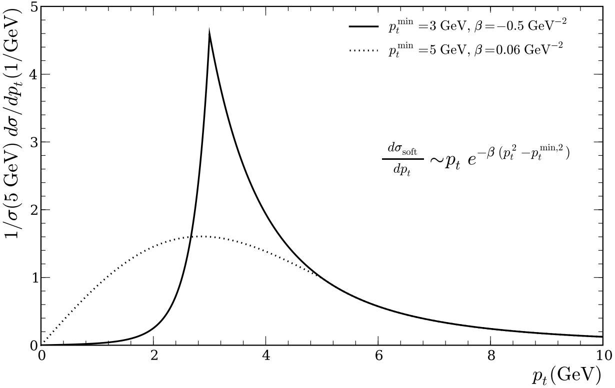
- The cross section for j soft and k hard uncorrelated interactions

$$\sigma_{jk} = \int d^2b \frac{(2\chi_S)^j}{j!}\frac{(2\chi_H)^k}{k!}\exp\left[-2(\chi_S + \chi_H)\right]$$

- σ_s^{inc} and μ_s are obtained by fitting to experimental data.

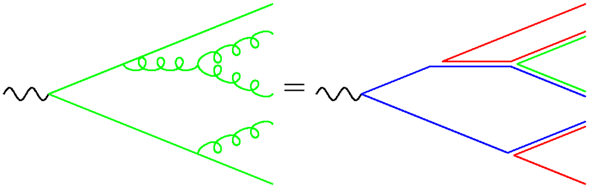
Soft interactions

- Generic (nonperturbative) gluon-gluon interactions are generated at $p_T < p_T^{\mathrm{min}}$. We require $d\sigma_{\mathrm{H}}^{\mathrm{inc}}/dp_T^2$ to match the soft counterpart at $p_T = p_T^{\mathrm{min}}$.



Hadronization

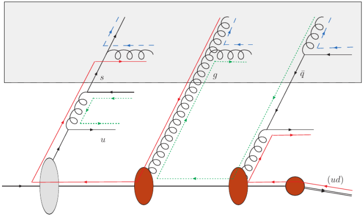
- After parton shower and MPI, quarks and gluons must hadronize.
- The basis for hadronization in Herwig is the colour preconfinement property - cluster model:



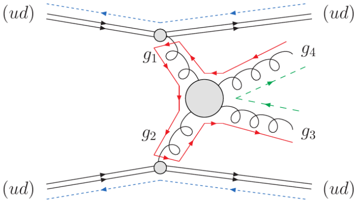
- Nonperturbative gluon splitting to quark-antiquark pair.
- Large N_c limit: non-planar graphs are subleading.

Colour connections

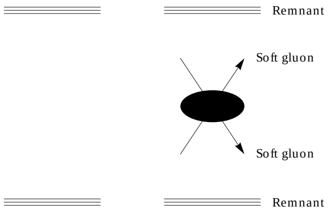
- Event with multiple hard subprocesses



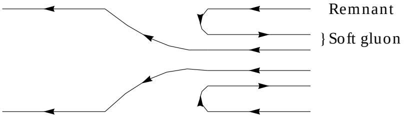
- Soft subprocess with disrupted color lines (exceptional case)



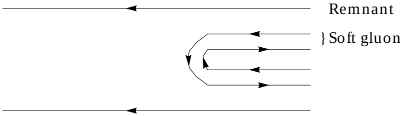
Colour connections in Herwig



The current connections are



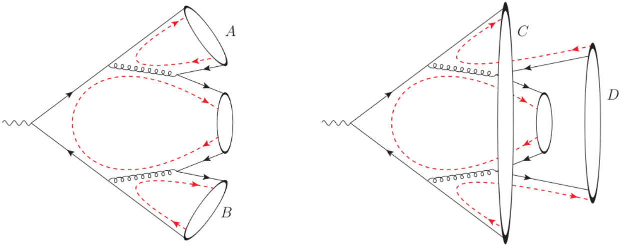
and



Colour reconnection

- Allow reshuffling of clusters (rs) + (lm) if total mass is lower:

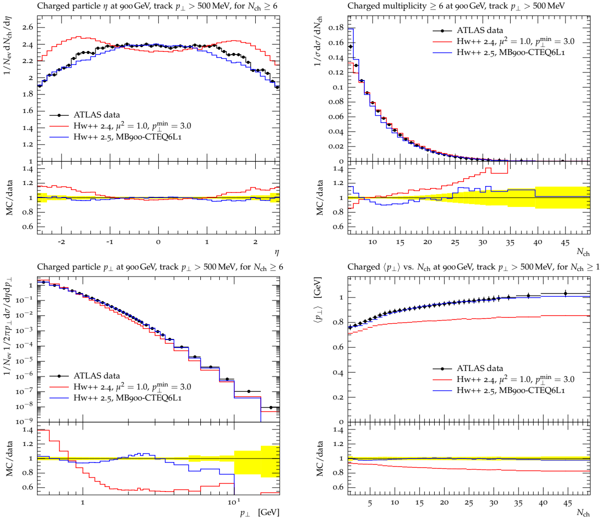
$$M_{rl} + M_{sm} < M_{rs} + M_{lm}$$



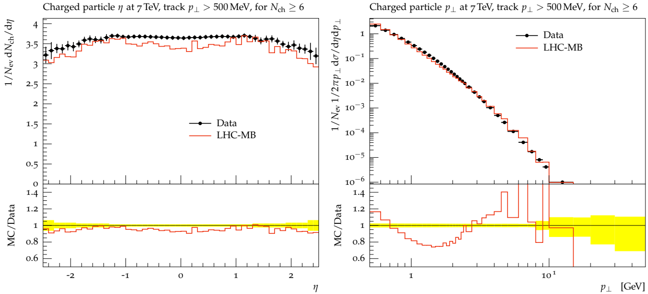
[Eur.Phys.J.C72 (2012) 2225]

Min-bias ATLAS (900 GeV)

- Good agreement with data; example from **[Eur.Phys.J.C72 (2012) 2225]**



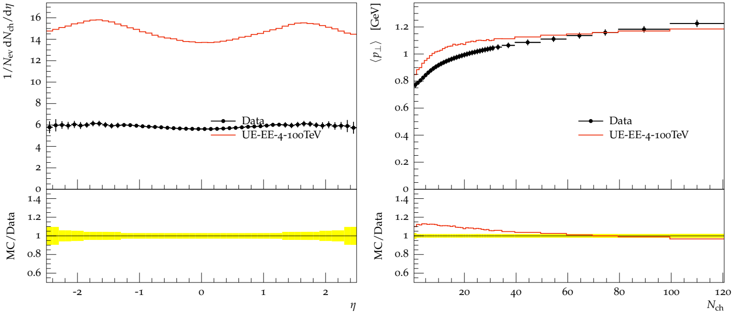
Min-bias ATLAS (7 TeV)



Data taken from [**New J.Phys. 13 (2011) 053033**]. Plotted with Rivet.

- Default Herwig 7.0 soft MPI model; default tune.

Min-bias - Energy extrapolation to 100 TeV

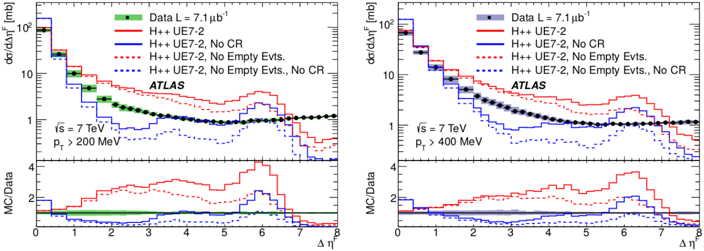


taken from Andrzej Siodmok

- Only the underlying event is tuned.

Challenge: the “Bump” problem

- Forward pseudorapidity gap $\Delta\eta^F$. Defined as the larger of two pseudorapidities from the last particle to the edge of the detector.



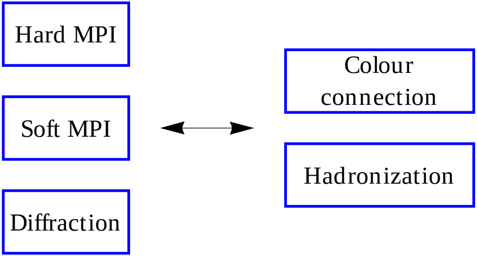
(a) (b)

[Eur.Phys.J. C72 (2012) 1926]

- Too many events with large rapidity gaps, especially if colour reconnection is switched on.

MPI - summary

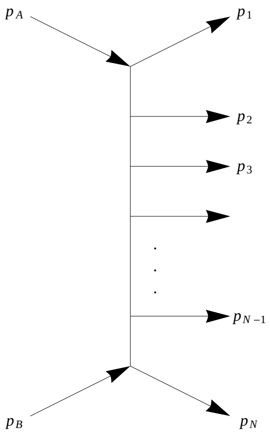
- Miminum bias model includes the following pieces:



- Soft diffraction is not implemented in Herwig 7.0.
- In the following we construct a new soft interaction model and soft diffraction model.

Soft scatter kinematics - Multi-peripheral ladder

- Consider one pomeron cut; $N \sim \log E_{cm}/m_{\perp}$,
- $p_{i+} = (1 - x_1)\cdots(1 - x_{i+1})x_i p_{A+},\ x_i \simeq 1/2.$

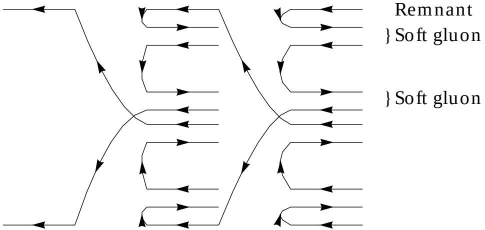


[**Phys.Rept. 28 (1976) 1-143**]

- Ordering in rapidity.
- No correlations.
- Amplitude not large when sub-energies $s_{i,i+1} = (p_i + p_{i+1})^2$ large.
- Challenges for Herwig:
  - What are color connections.
  - what is the multiplicity.

Colour connection of multiple ladders

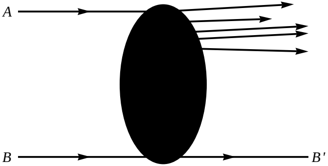
- Many pomeron cuts; average number $\langle n(s,\mu_s)\rangle = A(b,\mu_s)\sigma_s(s)$.
- Colour connections:

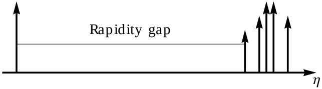


- Needs to be tuned and matched with the hard MPI.

Diffraction in hadron collisions

Events with rapidity gaps





Cross section behaves as

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{-B|t|} \simeq \left.\frac{d\sigma}{dt}\right|_{t=0} (1 - B|t|)\,,$$

in analogy with diffraction in optics

$$I(\theta) \simeq I(0)\left(1 - Bk^2\theta^2\right).$$

A definition: diffraction is a high energy process in which no quantum numbers are exchanged between colliding particles.

Generating diffractive events

- From Regge theory, for single diffraction, we have:

$$\frac{d^2\sigma^{SD}}{dM^2dt} \sim \left(\frac{s}{M^2}\right)^{\alpha_{\mathbb{P}}(0)} e^{\left(B_0+2\alpha' \ln\left(\frac{s}{M^2}\right)\right)t}$$

- Similarly for double diffraction

$$\frac{d^2\sigma^{DD}}{dM_1^2dM_2^2dt} \sim \left(\frac{s}{M_1^2}\right)^{\alpha_{\mathbb{P}}(0)} \left(\frac{s_0}{M_2^2}\right)^{\alpha_{\mathbb{P}}(0)} e^{\left(b+2\alpha' \ln\left(\frac{ss_0}{M_1^2M_2^2}\right)\right)t}.$$

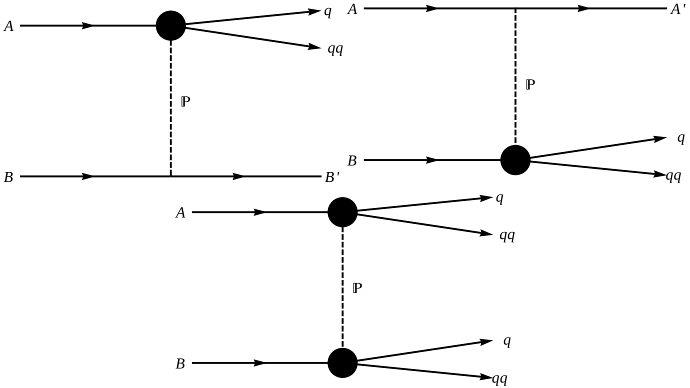
where b is very small and $s_0 \simeq 1/\alpha'$. We also use the following values of parameters:

  - $\alpha(0) = 1.058$,
  - $B_0 = 10.1\ \mathrm{GeV}^{-2}$,
  - $\alpha' = 0.25\ \mathrm{GeV}^{-2}$.

Damping factor $(1 - M^2/s)$ was used to include points in phase space not covered by Regge theory.

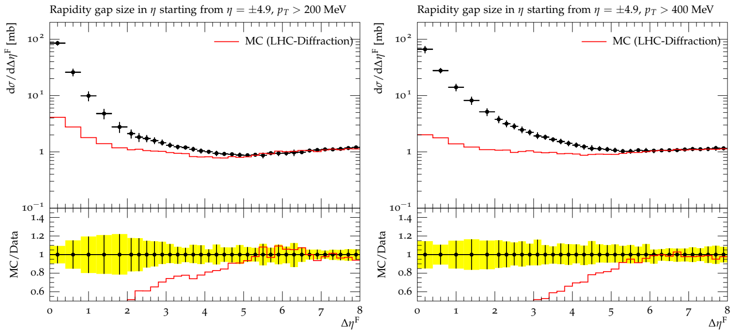
Diffractive events in Herwig

- We implement soft diffraction in Herwig by modelling it with the following matrix element



- Quark (q) and diquark (qq) form a cluster with diffractive mass, stretched along the dissociated proton.

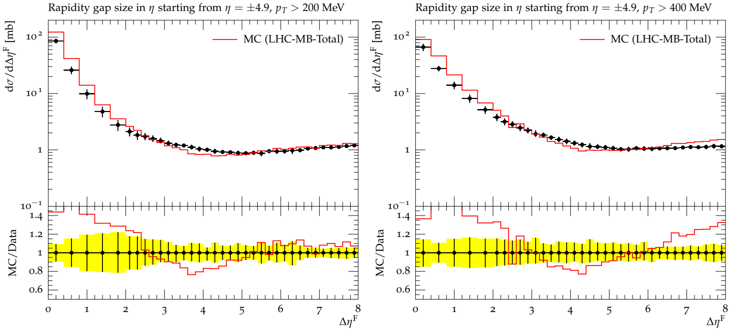
Diffraction (preliminary) results



(Data taken from [**Eur.Phys.J. C72 (2012) 1926**]. Plotted with Rivet.)

- Reproduces well the plateau.
- Relative weight between single and double diffraction may need to be tuned simultaneously with other parameters.

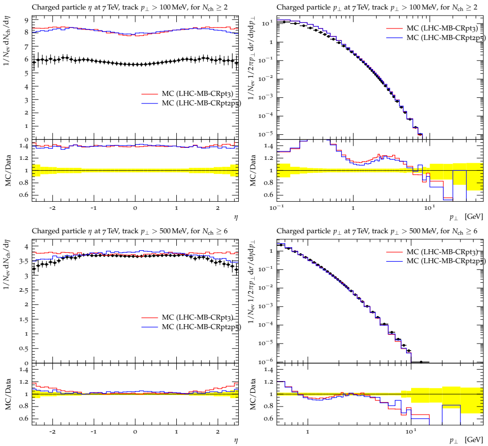
Combining min-bias and diffractive runs (preliminary)



(Data taken from [**Eur.Phys.J. C72 (2012) 1926**]. Plotted with Rivet.)

- The soft interaction model still produces rapidity gaps.
- Tuning needed to get the correct multiplicity.

Min-bias with the new soft model (preliminary)



- Plots with $p_\perp^{min} = 2$ and 3 GeV.
- Correlation between $p_\perp^{min}$ and μ may not exist anymore, therefore we have one more tunable parameter.

Summary and outlook

- We reviewed the hard and soft MPI models in Herwig.
- Good agreement with data.
- Challenge: the so-called “bump” problem: the soft interaction model in Herwig produces too many events with large rapidity gaps.
- To address the problem we:
  - modified the soft interaction model and
  - implemented soft diffraction.
- Preliminary results show qualitative improvement, but more work is needed.

- Proper tuning has to be done and other observables should be checked as well.
- Diffraction and soft interaction model have to be sampled properly.