Introduction to Monte Carlo Event Generators

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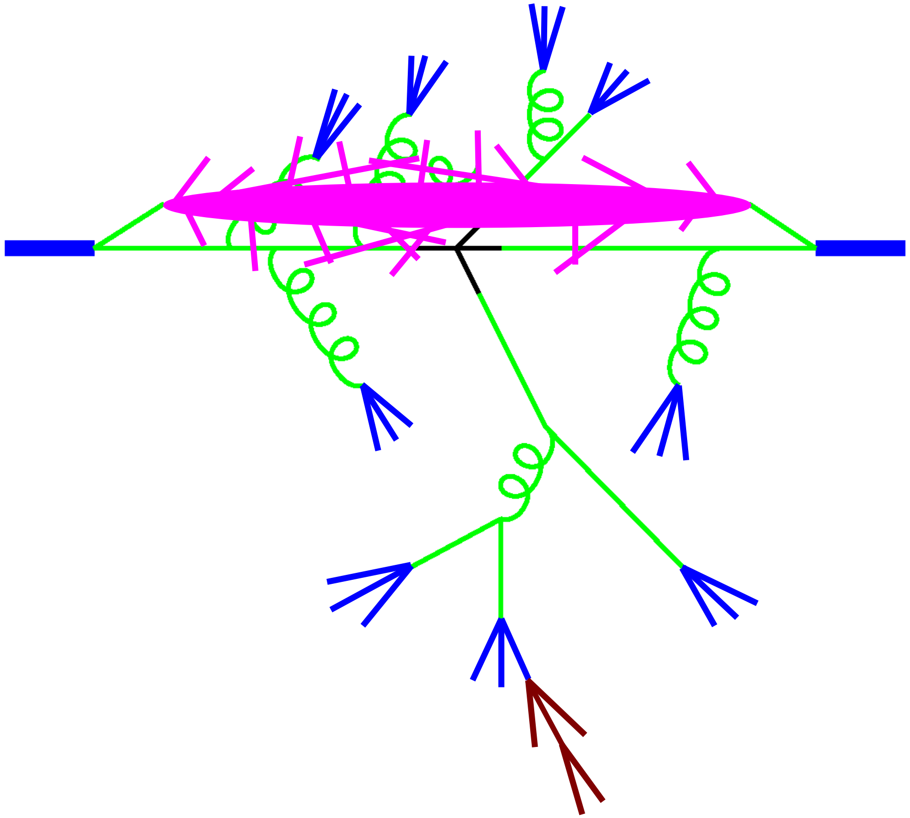
Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays

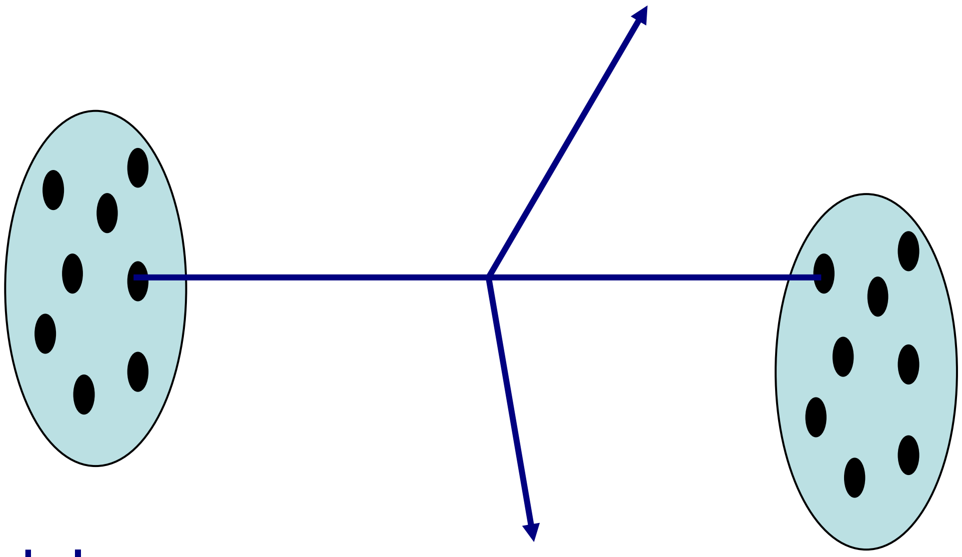


Intro to Monte Carlo Event Generators

1. Monte Carlo technique / hard process
2. Parton showers
3. Hadronization
4. Underlying Event / Soft Inclusive Models

The Underlying Event

- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?

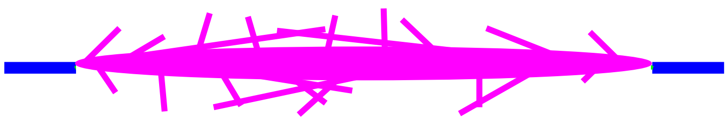


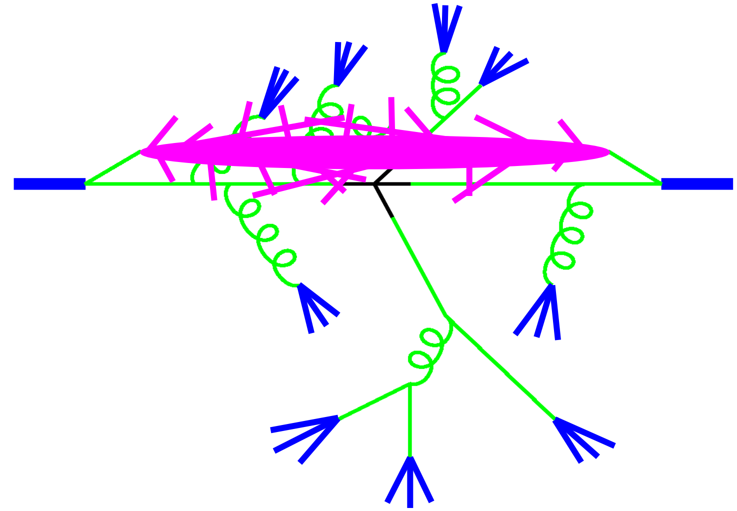
Two models:

- Non-perturbative: Soft parton—parton cross section is so large that the remnants always undergo a soft collision.
- Perturbative: 'Hard' parton—parton cross section huge at low p_t, high energy, dominates inelastic cross section and is calculable.

The Basics: event classes

‘Minimum bias’ collision and underlying event





Minimum bias = experimental statement

Models = zero bias? i.e. inclusive sample of all inelastic (non-diffractive?) events

CERN-PH-TH-2010-298 KA-TP-40-2010
Cavendish-HEP-10/21 DCPT/10/202
MAN/HEP/2010/23 IPPP/10/101
SLAC-PUB-14333 LU TP 10-28
HD-THEP-10-24 MCnet-11-01

General-purpose event generators for LHC physics

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Abstract

We review the physics basis, main features and use of general-purpose Monte Carlo event generators for the simulation of proton-proton collisions at the Large Hadron Collider. Topics included are: the generation of hard-scattering matrix elements for processes of interest, at both leading and next-to-leading QCD perturbative order; their matching to approximate treatments of higher orders based on the showering approximation; the parton and dipole shower formulations; parton distribution functions for event generators; non-perturbative aspects such as soft QCD collisions, the underlying event and diffractive processes; the string and cluster models for hadron formation; the treatment of hadron and tau decays; the inclusion of QED radiation and beyond-Standard-Model processes. We describe the principal features of the Ariadne, Herwig++, Pythia 8 and Sherpa generators, together with the Rivet and Professor validation and tuning tools, and discuss the physics philosophy behind the proper use of these generators and tools. This review is aimed at phenomenologists wishing to understand better how parton-level predictions are translated into hadron-level events as well as experimentalists wanting a deeper insight into the tools available for signal and background simulation at the LHC.

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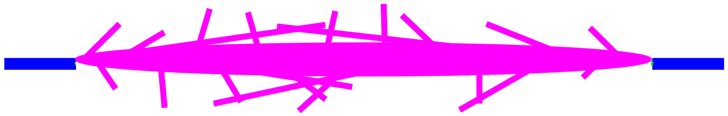
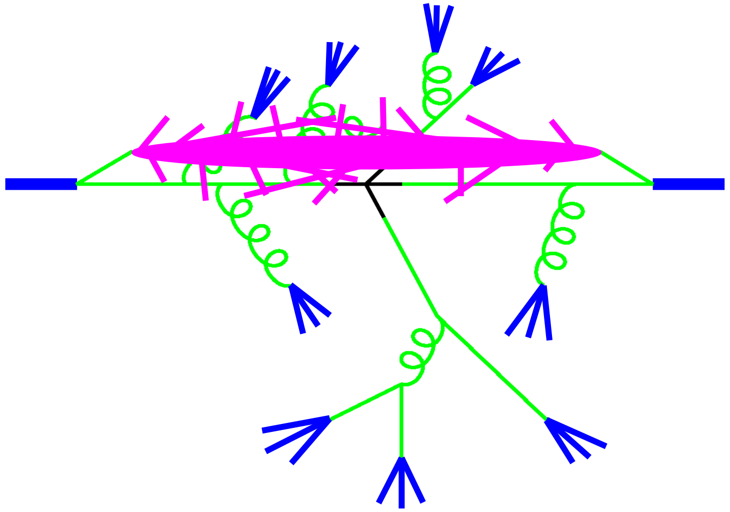
The Basics: event classes

‘Soft inclusive’ events and the underlying event

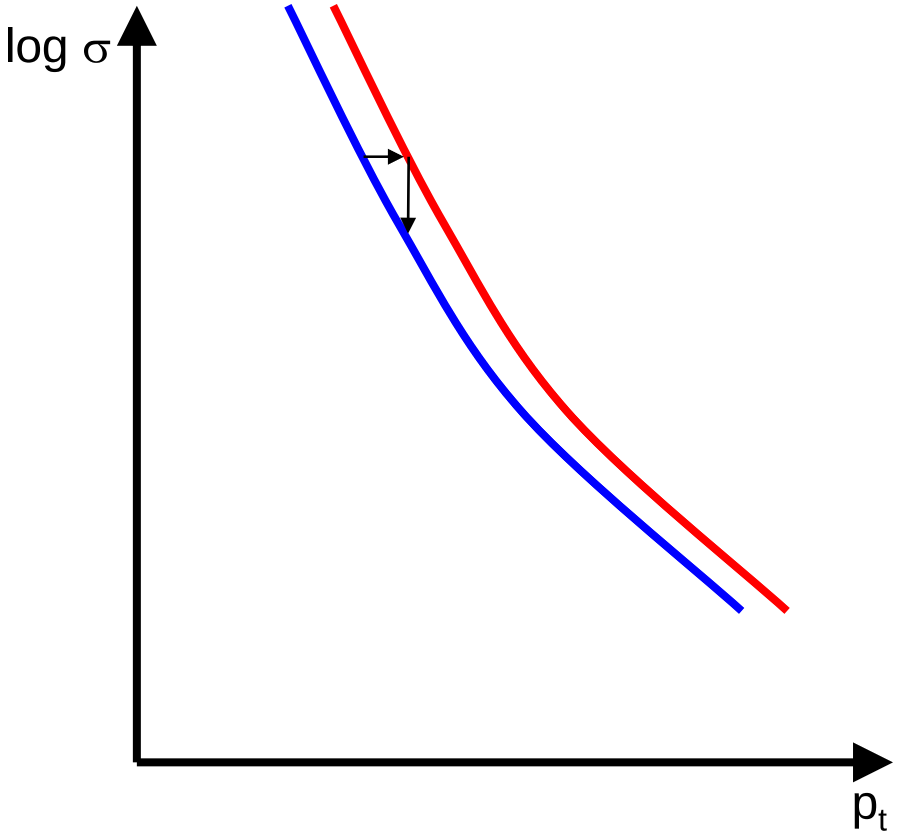




How similar are they?

Fluctuations and correlations play crucial role

Fluctuations and correlations



Steep distribution → small sideways shift = large vertical

Rare fluctuations can have a huge influence

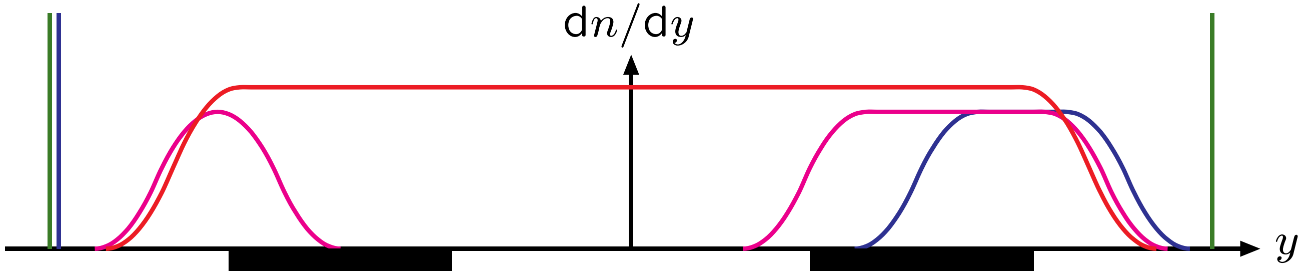
$1/p_t^n \rightarrow n$th moment

→ corrections depend on physics process

The Basics – what's what

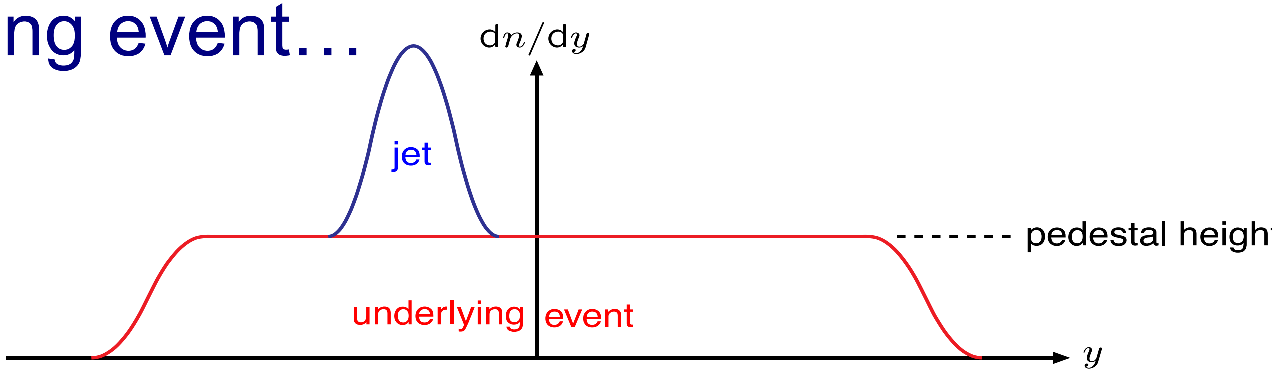
- Soft inclusive collisions…

$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \ldots + \sigma_{\text{non-diffractive}}$$



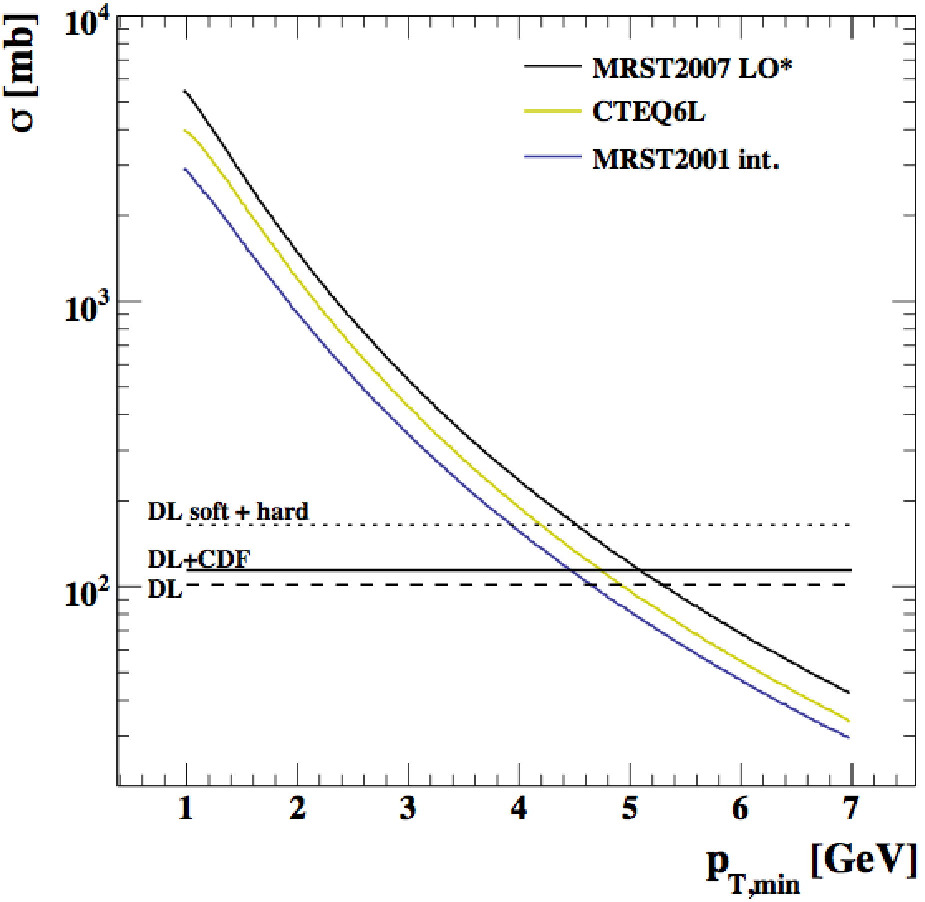
reality: $\sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}}$

- Underlying event…



The Basics: Multiparton Interaction Model

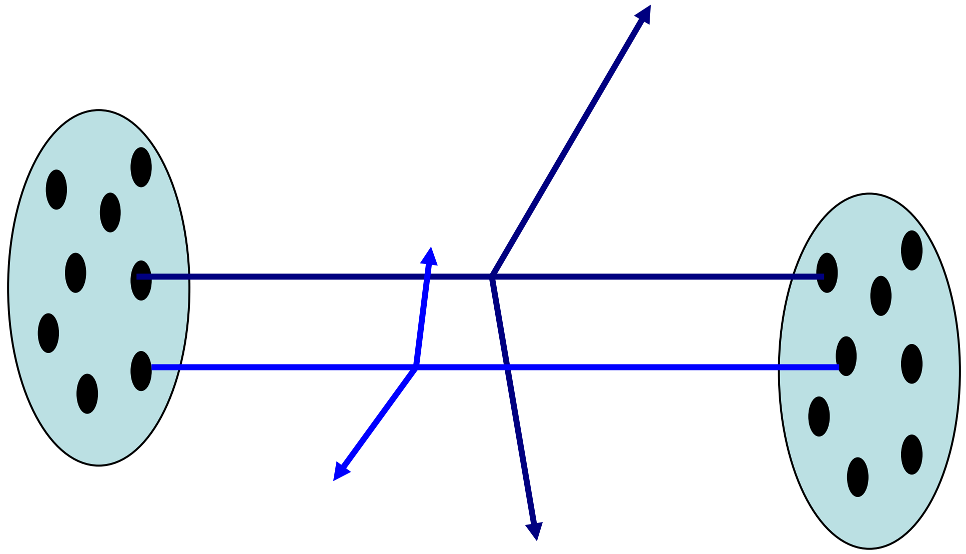
For small $p_{t\,min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.



The Basics: Multiparton Interaction Model

For small $p_{t\ min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.

→ More than one parton—parton scatter per proton—proton



Sjöstrand, van Zijl, Phys. Rev. D36 (1987) 2019

Need a model of spatial distribution within proton

→ Perturbation theory gives you n-scatter distributions

Matter Distributions

- Usually assume *x* and *b* factorize

$$n_i(x,b;\mu^2,s) = f_i(x;\mu^2)\,G(b,s)$$

- and *n*-parton distributions are independent

$$n_{i,j}(x_i,x_j,b_i,b_j) = n_i(x_i,b_i)\,n_j(x_j,b_j)$$

$\Rightarrow$ scatters Poissonian at fixed impact parameter

$$\sigma_n = \int d^2b\,\frac{(A(b)\sigma^{inc})^n}{n!}\exp(-A(b)\sigma^{inc})$$

$$A(b) = \int d^2b_1 G(b_1)\,d^2b_2 G(b_2)\,\delta(b-b_1+b_2)$$

The Herwig Model (formerly known as Jimmy+Ivan)

- Take eikonal+partonic scattering seriously

$$\sigma_{tot} = 2\int d^2b \left(1 - e^{-\frac{1}{2}A(b)\sigma_{inc}}\right)$$

$$B = \left[\frac{d}{dt}\left(\ln\frac{d\sigma_{el}}{dt}\right)\right]_{t=0} = \frac{1}{\sigma_{tot}}\int d^2b\, b^2 \left(1 - e^{-\frac{1}{2}A(b)\sigma_{inc}}\right)$$

- given form of matter distribution $\Rightarrow$ size and σ_{inc}

Bähr, Butterworth & MHS, JHEP 0901:067, 2009

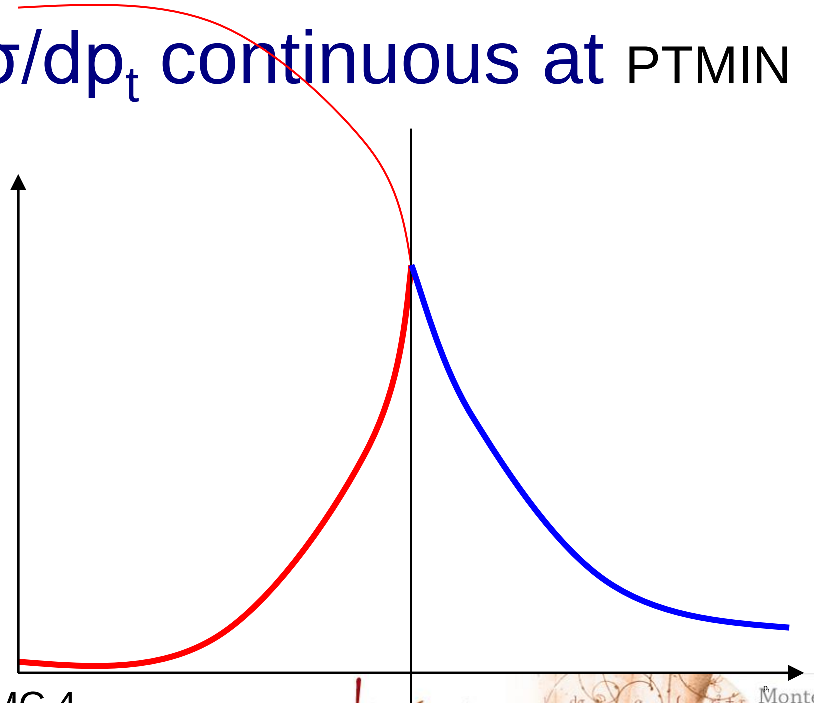
- too restrictive $\Rightarrow$

$$\sigma_{tot} = 2\int d^2b \left(1 - e^{-\frac{1}{2}(A_{\rm soft}(b)\sigma_{\rm soft,inc} + A_{\rm hard}(b)\sigma_{\rm hard,inc})}\right)$$

- $\Rightarrow$ two free parameters

Final state implementation

- Pure independent perturbative scatters above PTMIN
- Gluonic scattering below PTMIN with total $\sigma_{soft,inc}$ and Gaussian distribution in p_t
- $d\sigma/dp_t$ continuous at PTMIN



$\rightarrow$ possibility that entire process could be described perturbatively?

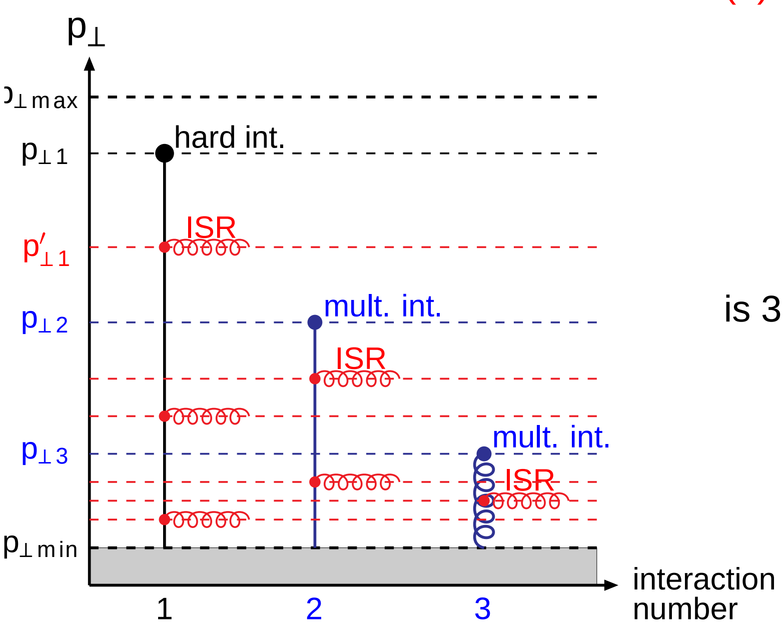
Pythia implementation

(4) Evolution interleaved with ISR (2004)

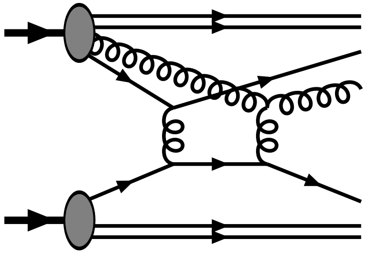
- Transverse-momentum-ordered showers

$$\frac{dP}{dp_\perp} = \left(\frac{dP_{MI}}{dp_\perp} + \sum \frac{dP_{ISR}}{dp_\perp}\right) \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{dP_{MI}}{dp'_\perp} + \sum \frac{dP_{ISR}}{dp'_\perp}\right) dp'_\perp\right)$$

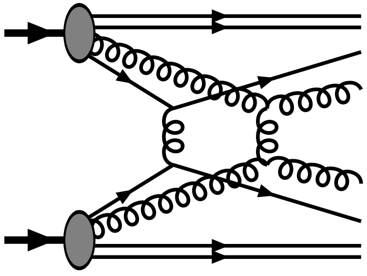
with ISR sum over all previous MI



(5) Rescattering

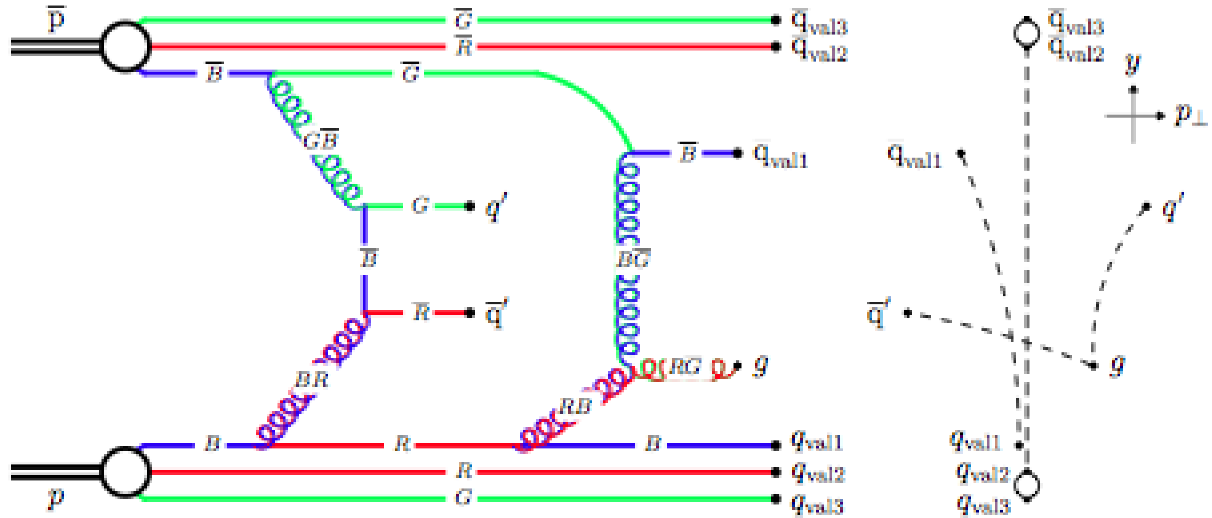


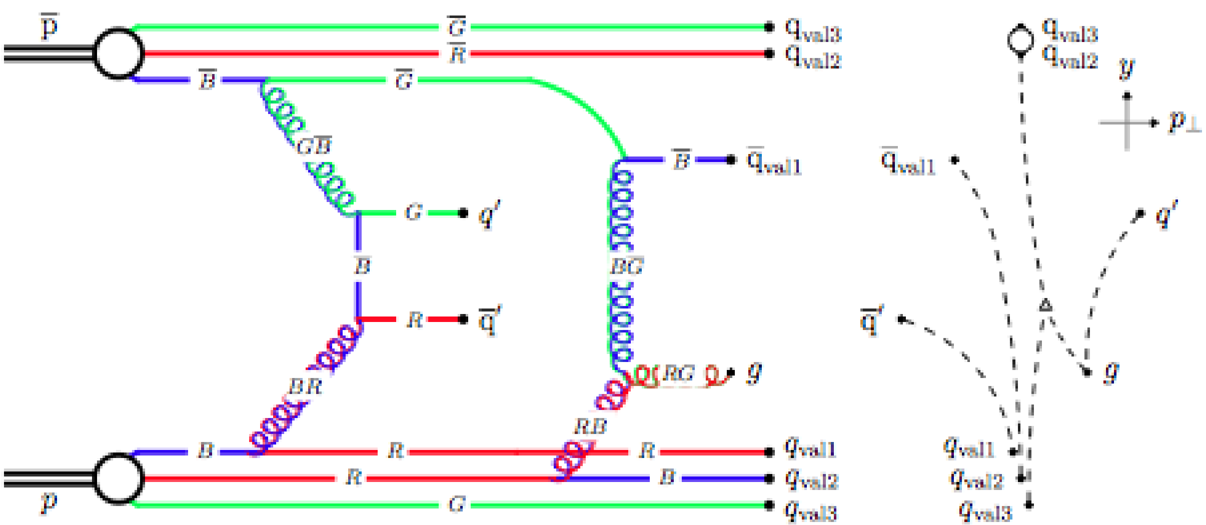
is 3 → 3 instead of 4 → 4:



Colour correlations

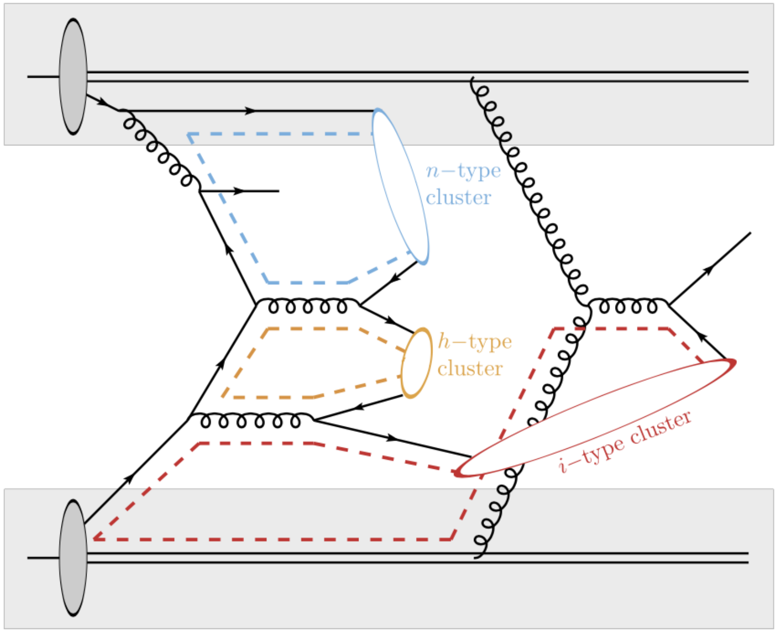
Can have a big influence on final states



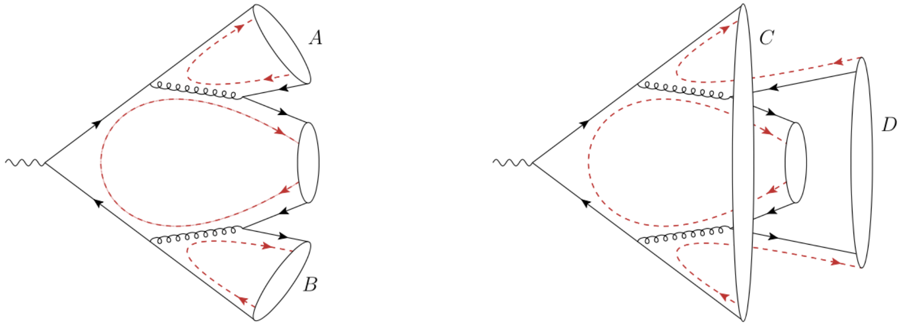


Colour reconnection

- Multi-parton hadron collisions involve a lot of coloured partons!

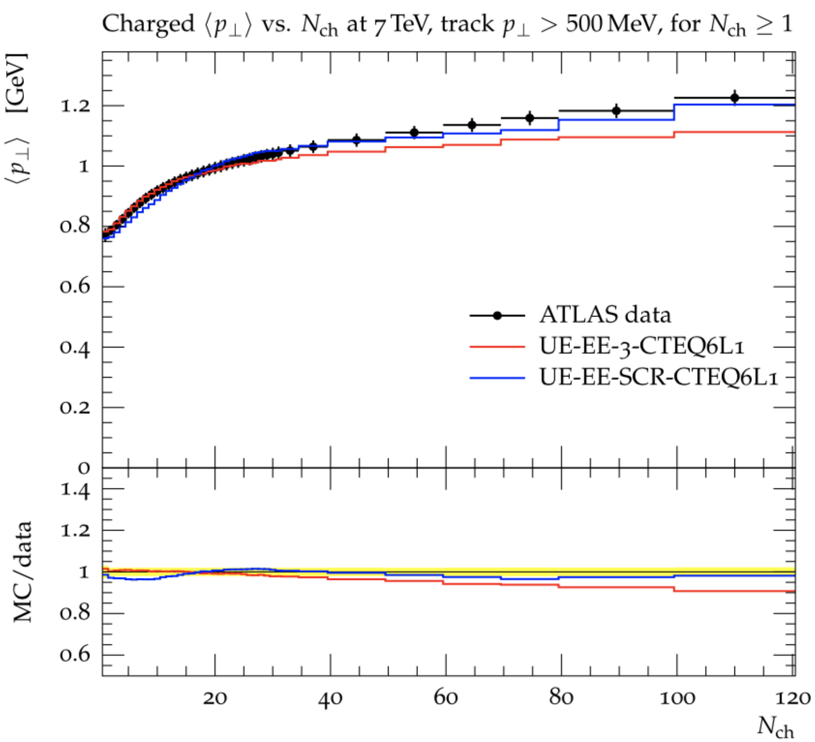


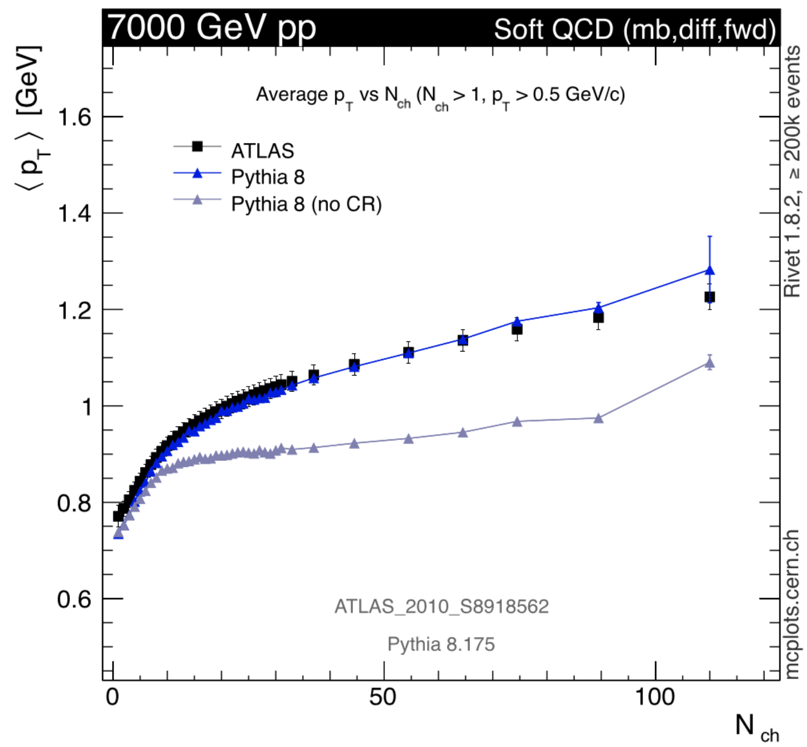
Beyond leading N_c, colour labels are not unique



Colour reconnection

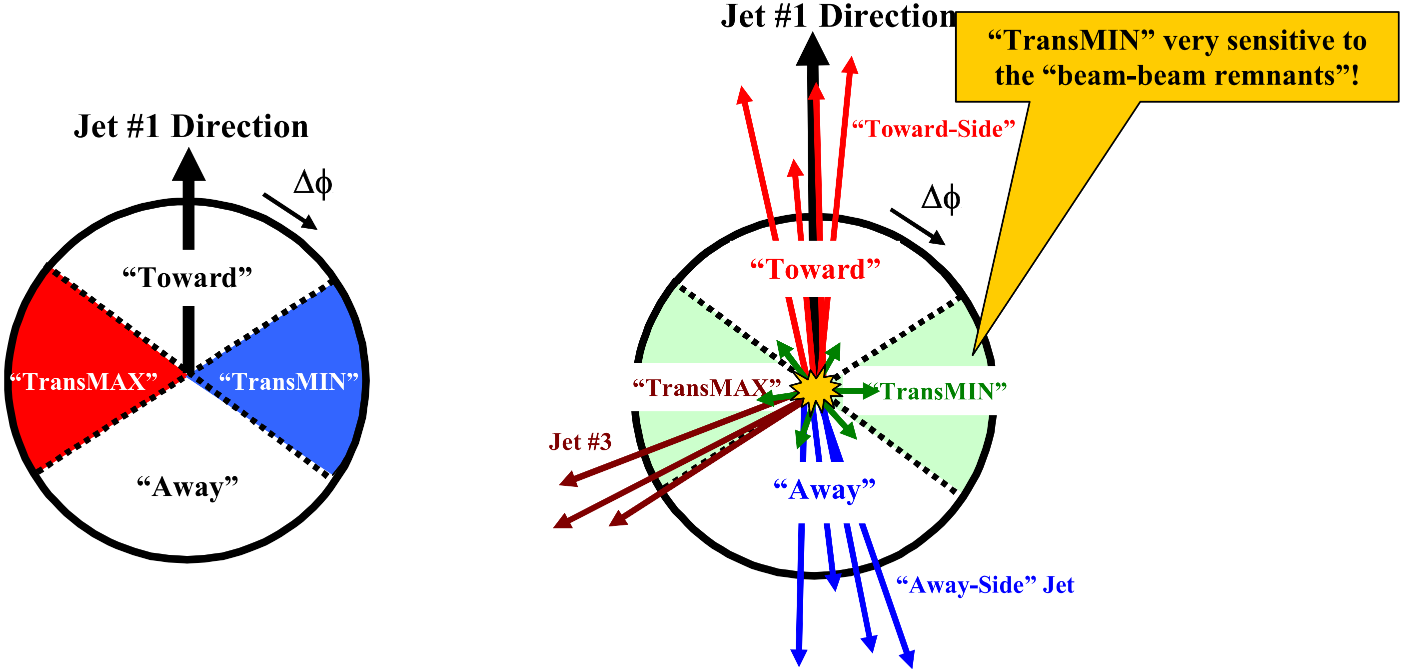
Crucial to describe underlying event and soft inclusive data





Underlying event measurements

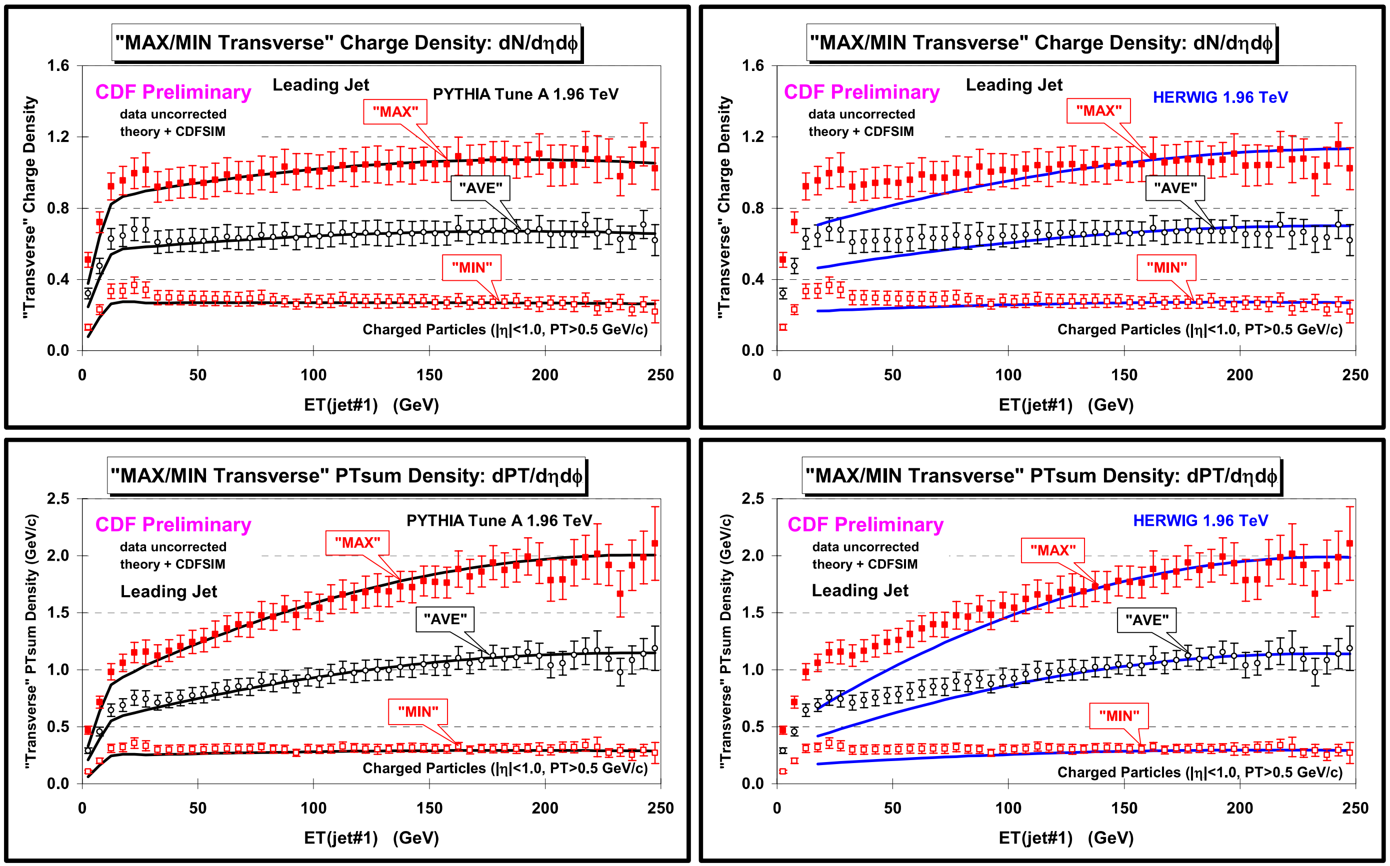
“MAX/MIN Transverse” Densities



- **Define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

Underlying event measurements

PYTHIA Tune A **HERWIG**



Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Conclusions on UE/MB

- Despite ~25 year history, multi-parton interaction models are still in their infancy
- LHC experiments'
  - step up in energy
  - high efficiency, purity and phase space coverage
  - emphasis on physical definition of observables

  have given us a huge amount of *useful* data
- existing models describe data well with tuning
- need more understanding of correlations/corners of phase space/relations between different model components

Conclusions on UE/MB

- don’t forget that jet corrections depend on correlations and high moments of distributions and are physics-process dependent

Summary

- Hard Process is very well understood: firm perturbative basis
- Parton Shower is fairly well understood: perturbative basis, with various approximations
- Hadronization is less well understood: modelled, but well constrained by data. Extrapolation to LHC ~ reliable.
- Underlying event least understood: modelled and only weakly constrained by existing data. Extrapolation?

- Always ask "What physics is dominating my effect?"