Monte Carlo Event Generators

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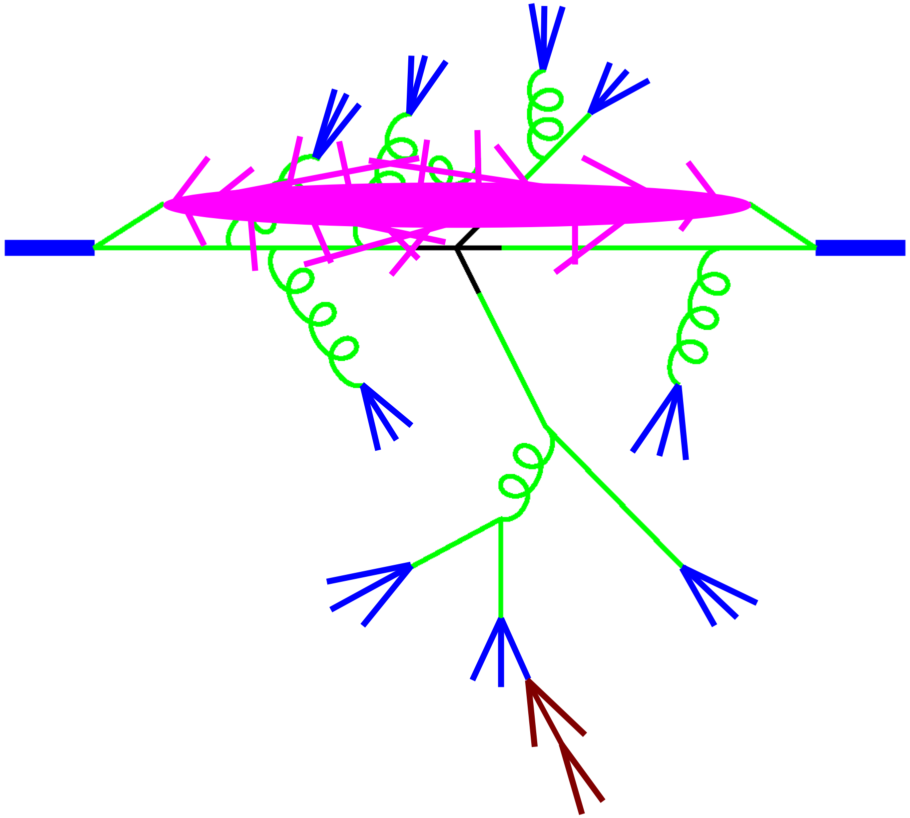
Structure of LHC Events

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



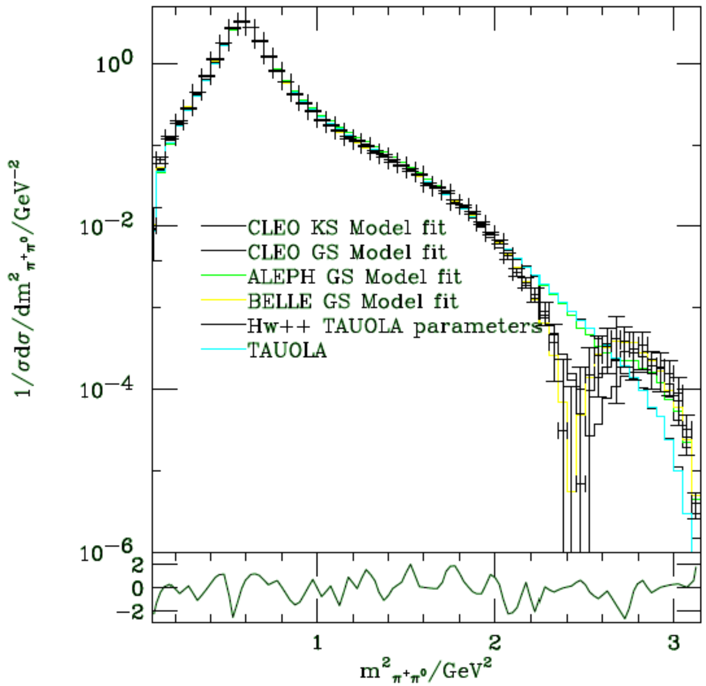
Secondary Decays and Decay Tables

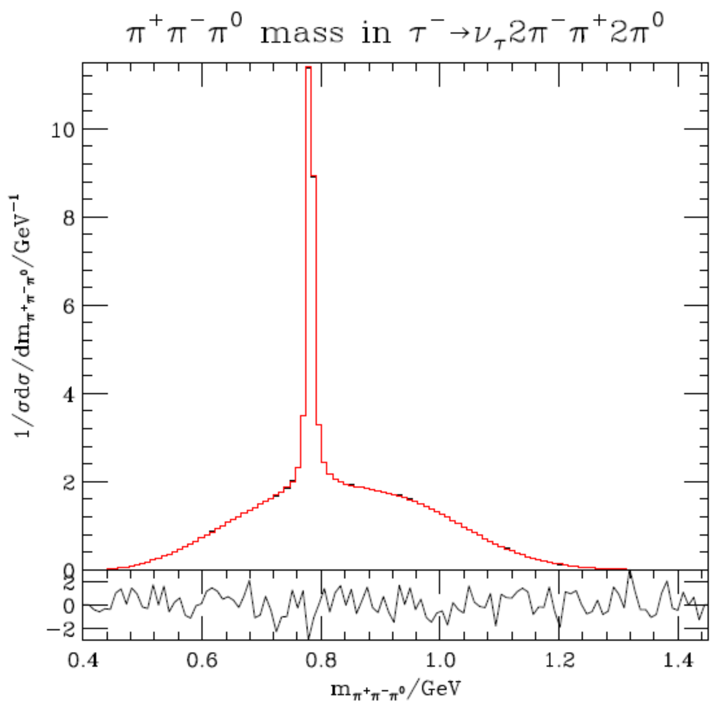
- Often forgotten ingredient of event generators:
  - String and cluster decay to some stable hadrons but mainly unstable resonances
  - These decay further "according to PDG data tables"
    - Matrix elements for n-body decays
  - But…
    - Not all resonances in a given multiplet have been measured
    - Measured branching fractions rarely add up to 100% exactly
    - Measured branching fractions rarely respect isospin exactly
  - So need to make a lot of choices
  - Has a significant effect on hadron yields, transverse momentum release, hadronization corrections to event shapes, …
  - Should consider the decay table choice part of the tuned set

Secondary particle decays

- Previous generations typically used external packages, e.g. TAUOLA, PHOTOS, EVTGEN
- Sherpa & Herwig++ contain at least as complete a description in all areas…
- without interfacing issues (c.f. τ spin)

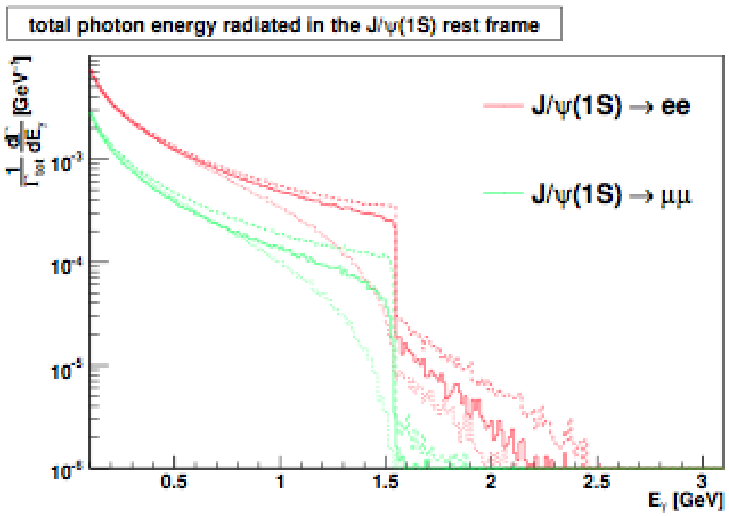
Tau Decays



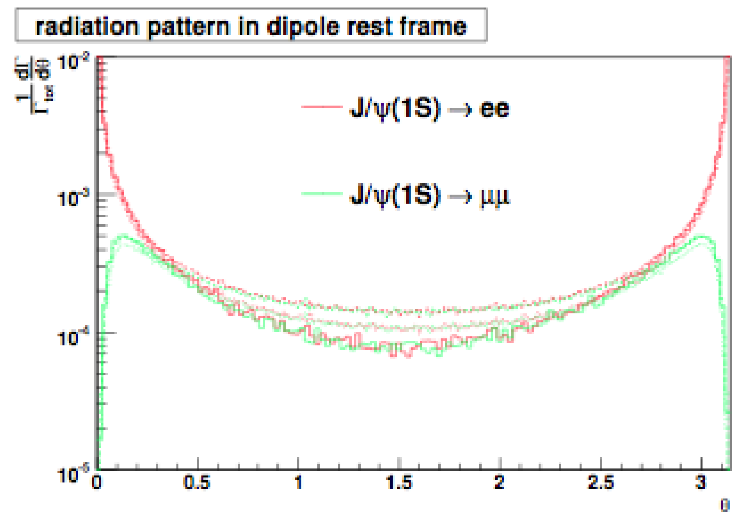


Mass spectrum of ππ in $\tau\to\pi\pi\nu_\tau$ for various models and example of mass distribution in $\tau\to5\pi\nu_\tau$ comparing Herwig++ and TAUOLA.

Leptonic hadron decays: $J/\psi \to \ell\bar{\ell}$



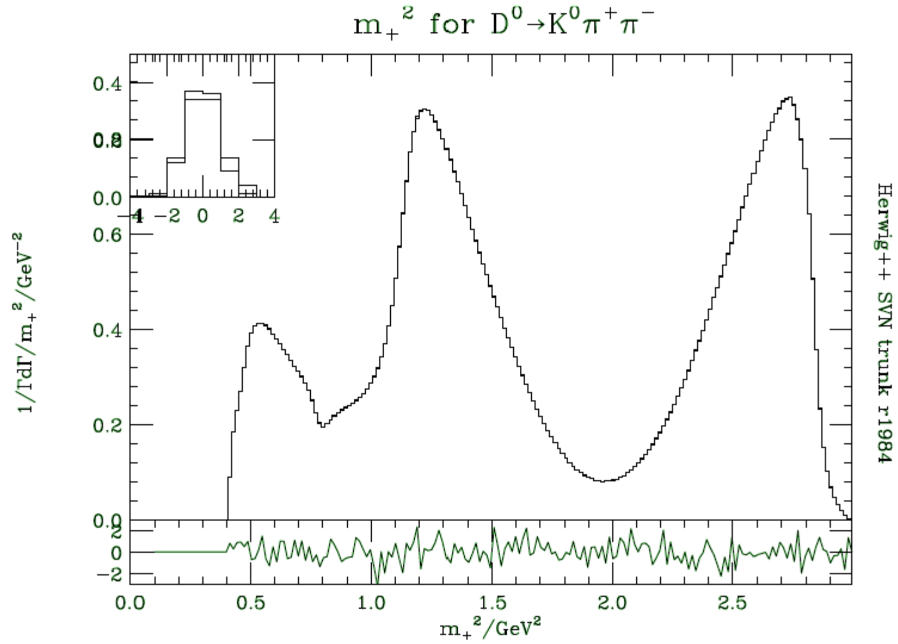
total radiated energy in the J/ψ rest frame

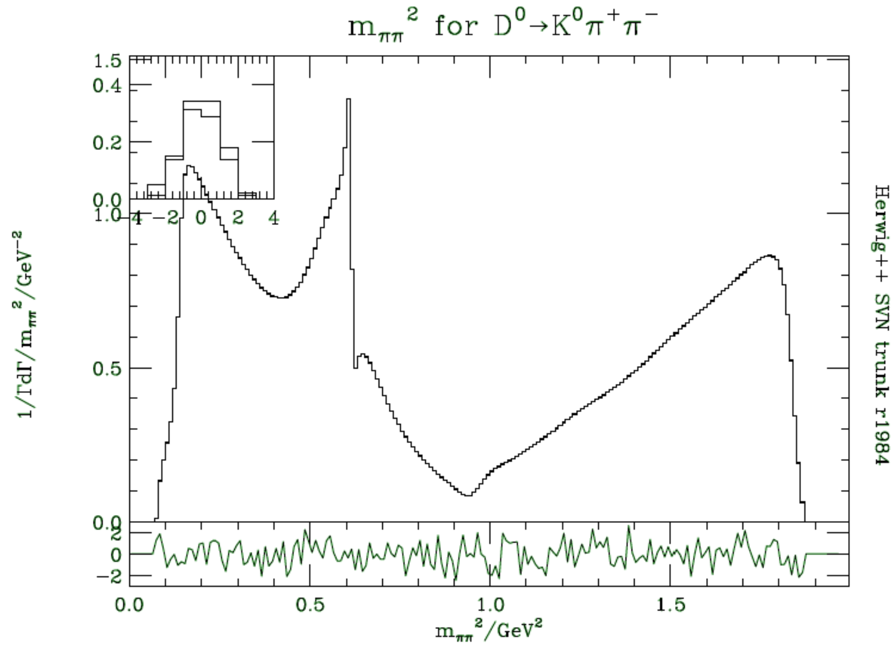


angular spectrum in the rest frame of the dipole

- soft only (dotted)
- collinear approximated ME (dashed)
- exact ME (solid)

D→Kππ

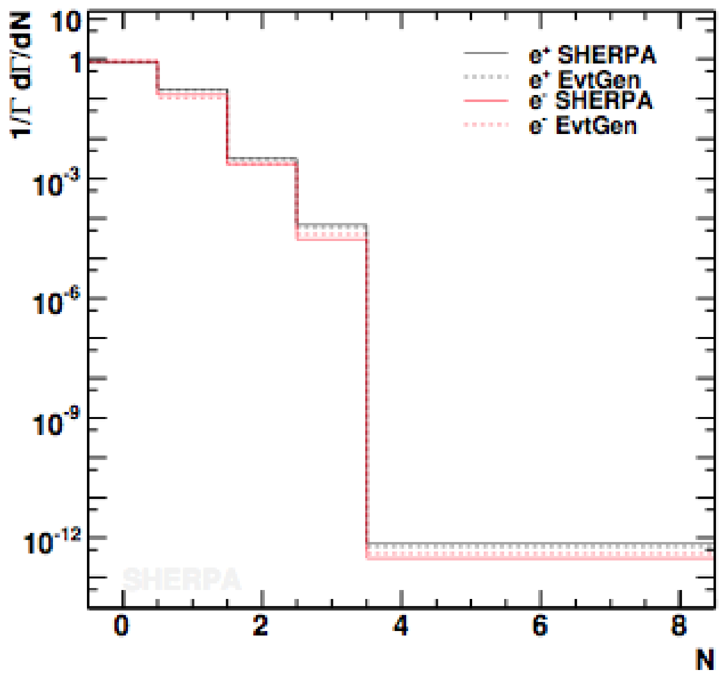




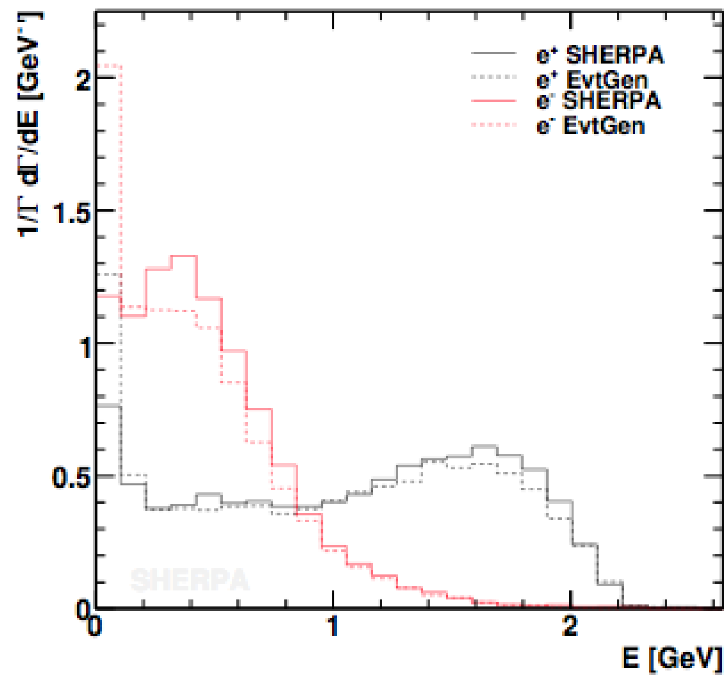
Comparison of Herwig++ and EvtGen implementations of the fit of Phys. Rev. D63 (2001) 092001 (CLEO).

Inclusive observables for B^+ decay

Electron multiplicity



Electron energy spectrum



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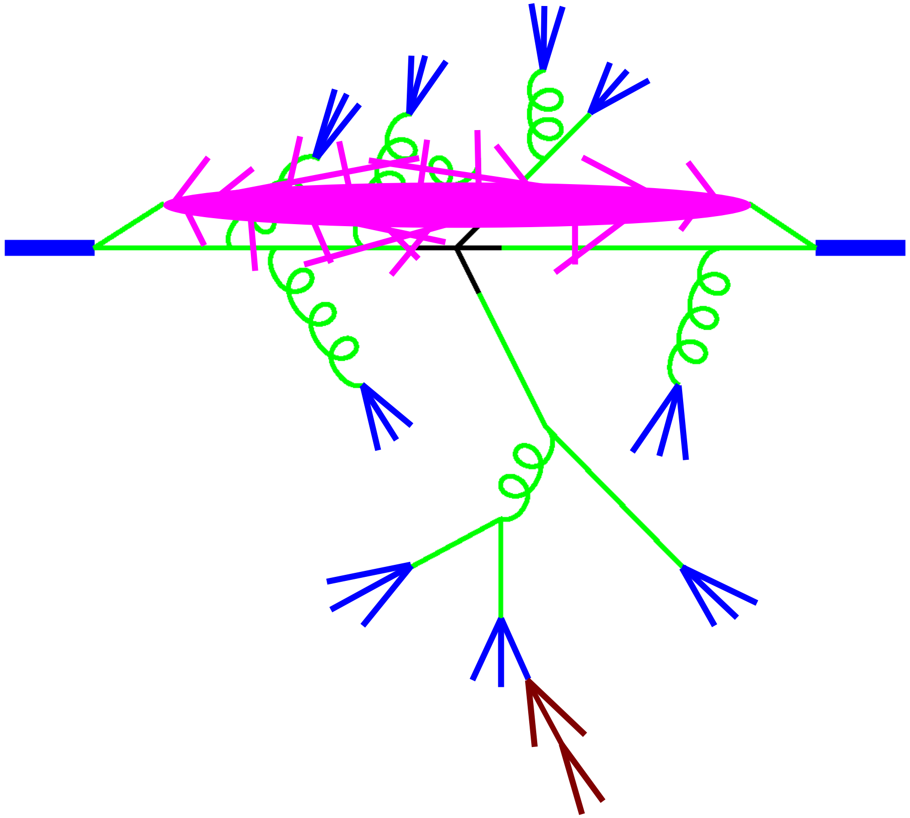
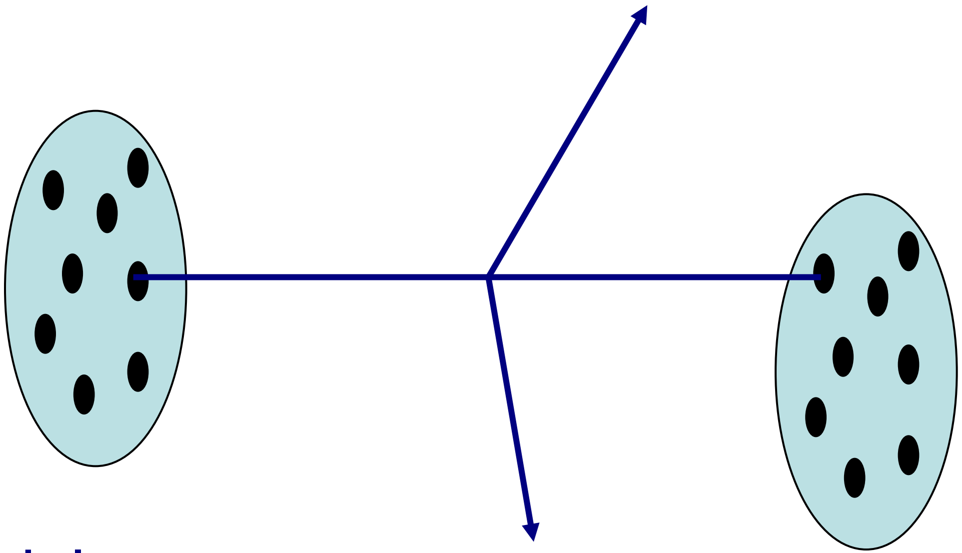


The Underlying Event

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

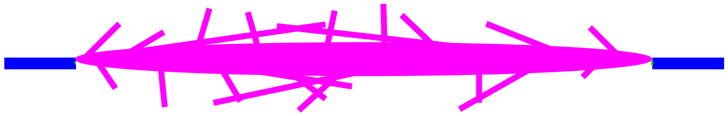


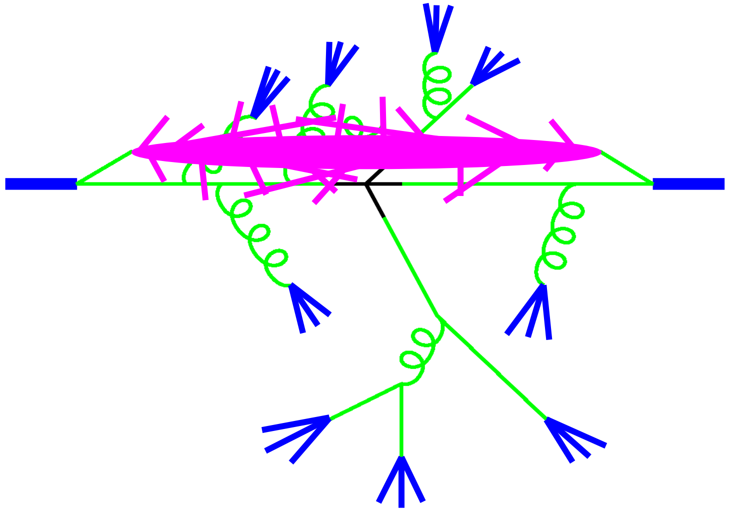
Two models:

- 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

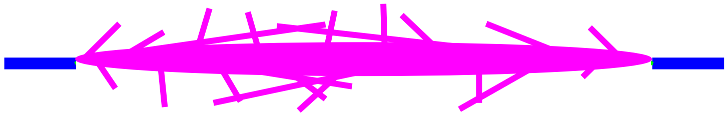
We review the physics basis, main features and use of general-purpose Monte Carlo event generators for the simulation of proton-proton collisions at the Large Hadron Collider. Topics included are: the generation of hard-scattering matrix elements for processes of interest, at both leading and next-to-leading 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.

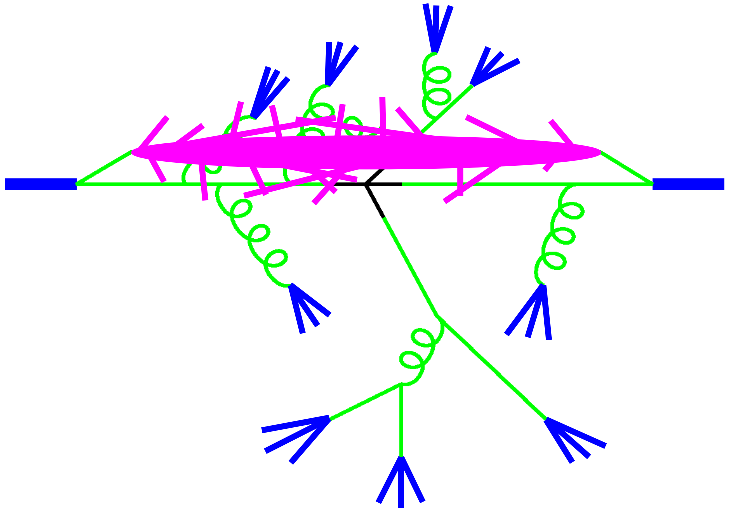
Event Generators 3

Preprint submitted to Physics Reports *January 13, 2011*

The Basics: event classes

'Soft inclusive' events and the underlying event

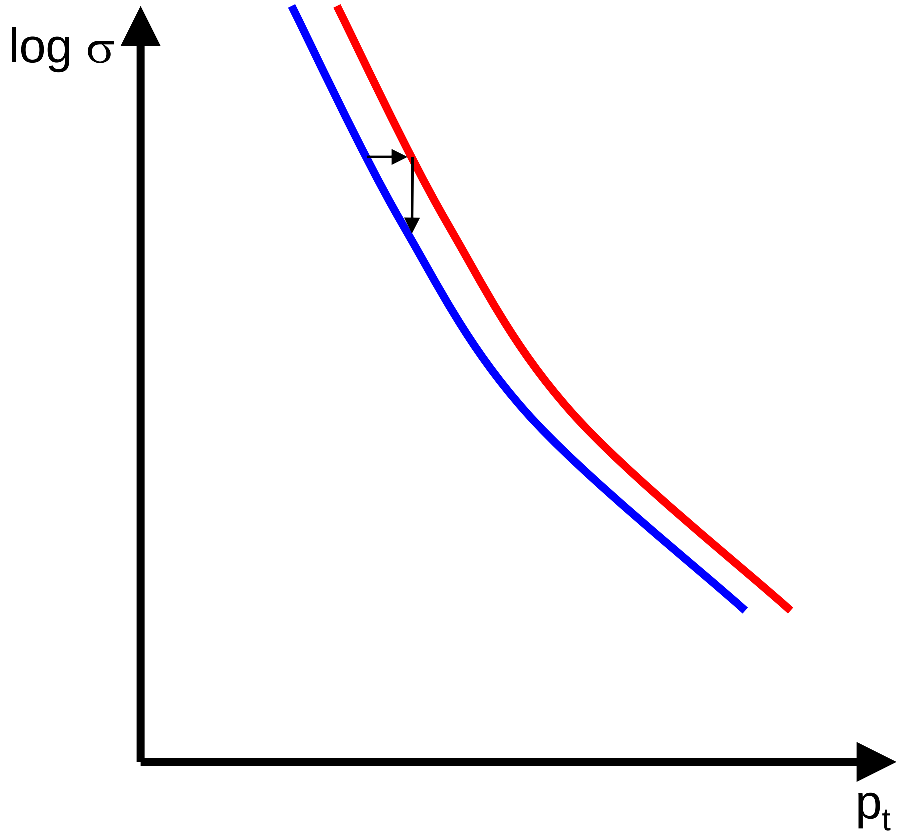




How similar are they?

Fluctuations and correlations play crucial role

Fluctuations and correlations



Steep distribution) small sideways shift = large vertical

Rare fluctuations can have a huge influence

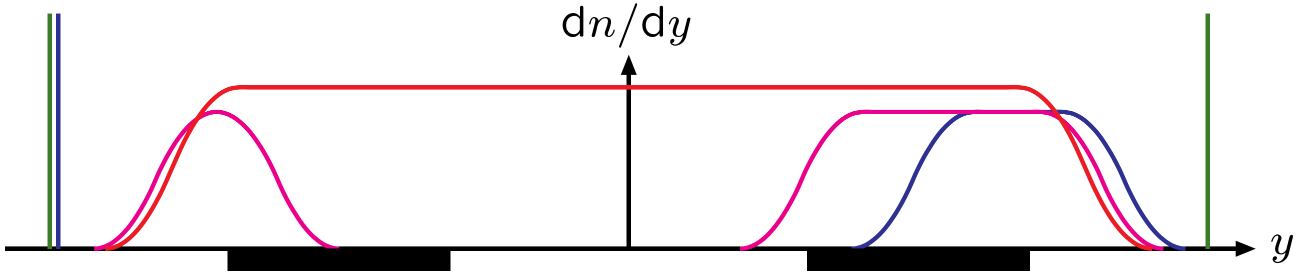
$1/p_t^n \rightarrow n$th moment

) corrections depend on physics process

The Basics – what's what

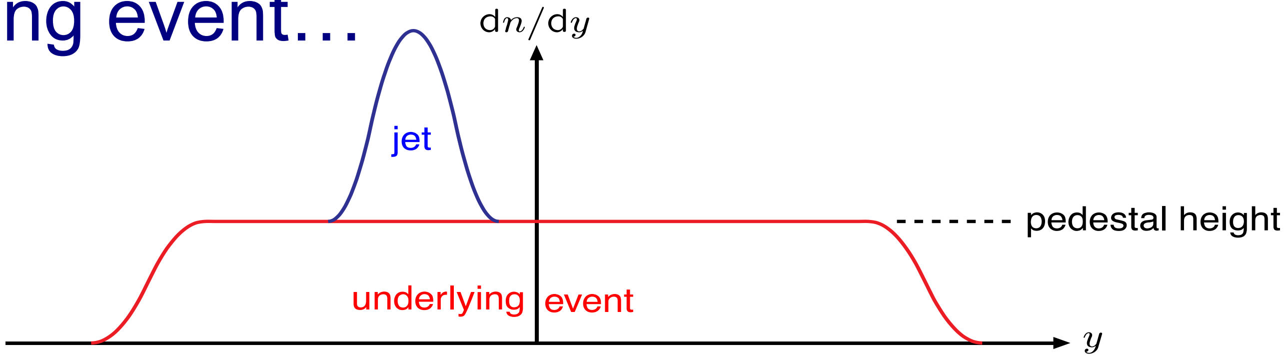
- Soft inclusive collisions…

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



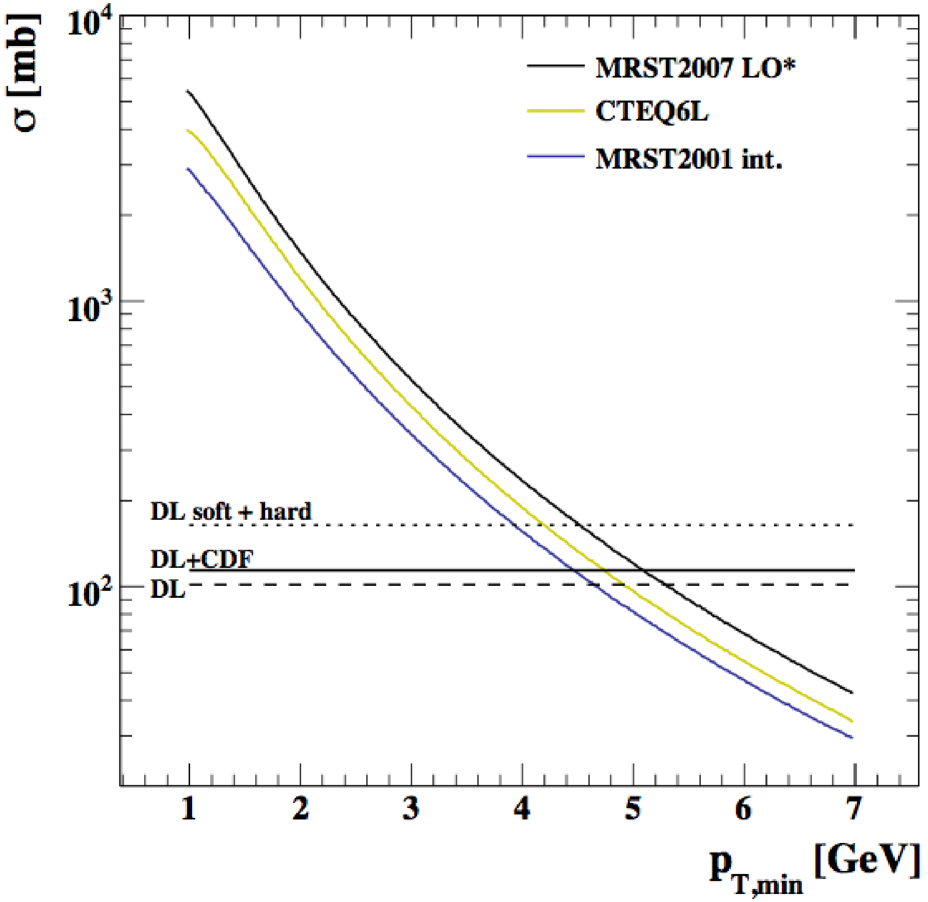
reality: $\sigma_{\rm min-bias} \approx \sigma_{\rm non-diffractive} + \sigma_{\rm double-diffractive} \approx 2/3 \times \sigma_{\rm tot}$

- Underlying event…



The Basics: Multiparton Interaction Model

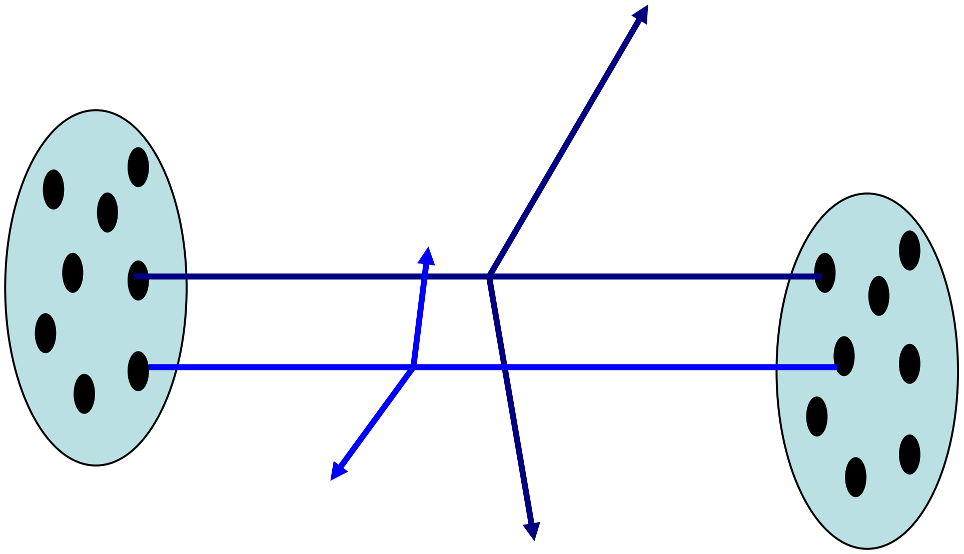
For small $p_{t\,min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.



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 (→ see later)

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

- and *n*-parton distributions are independent (→ see soon)

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

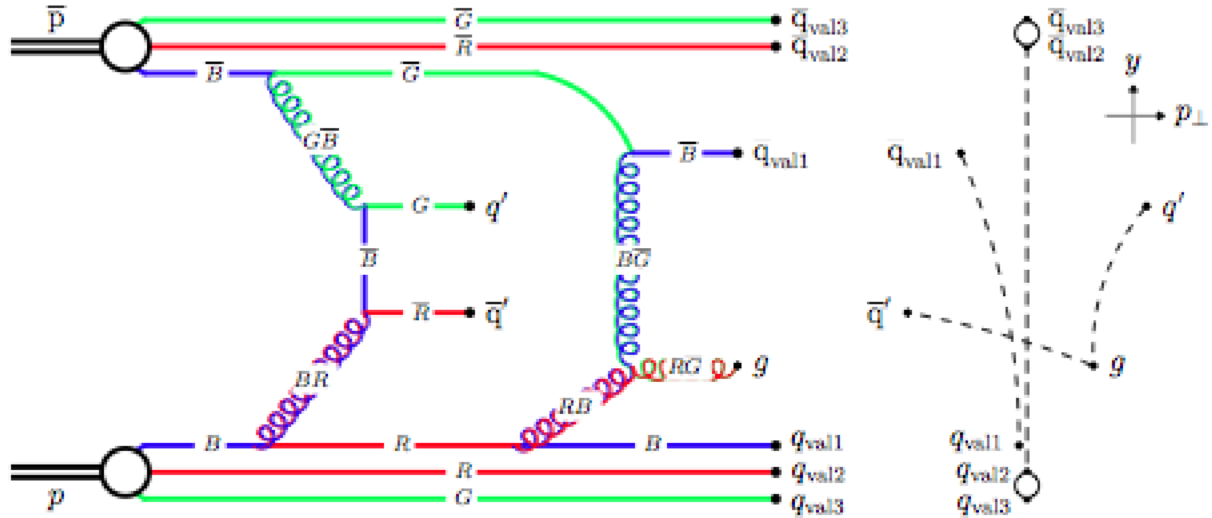
⇒ scatters Poissonian at fixed impact parameter

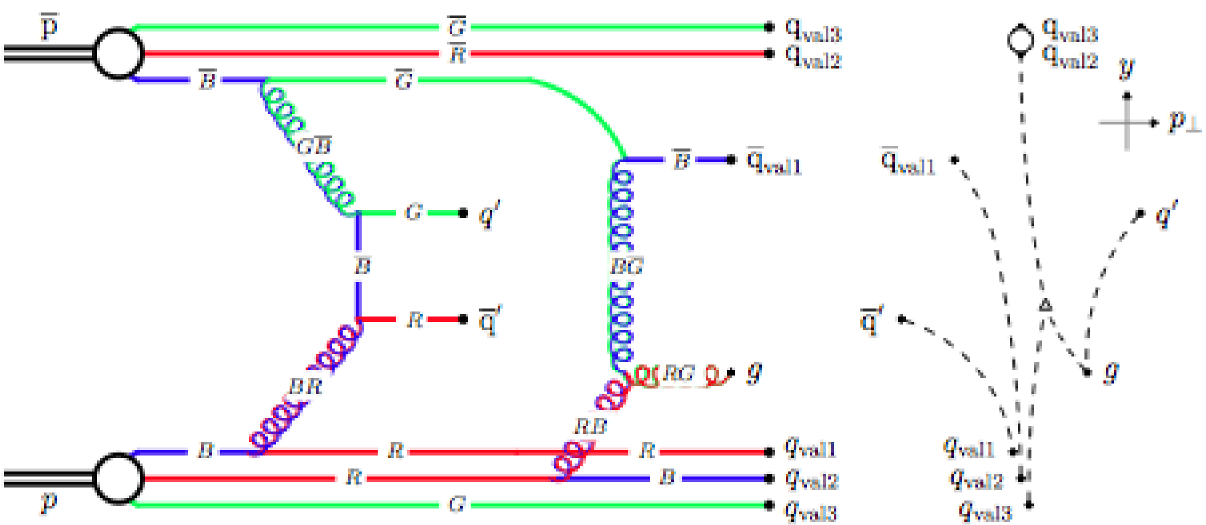
$$\sigma_n = \int d^2b\, \frac{(A(b)\sigma^{inc})^n}{n!} \exp(-A(b)\sigma^{inc})$$

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

Colour correlations

Can have a big influence on final states





→ see later

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 ⇒ size and ¾$_{\text{inc}}$

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

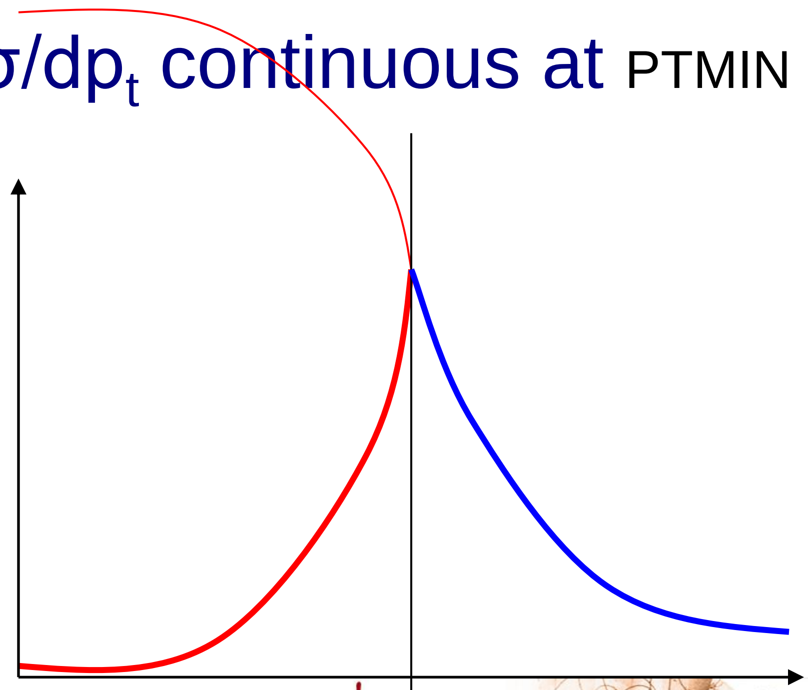
- too restrictive ⇒

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

- ⇒ 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

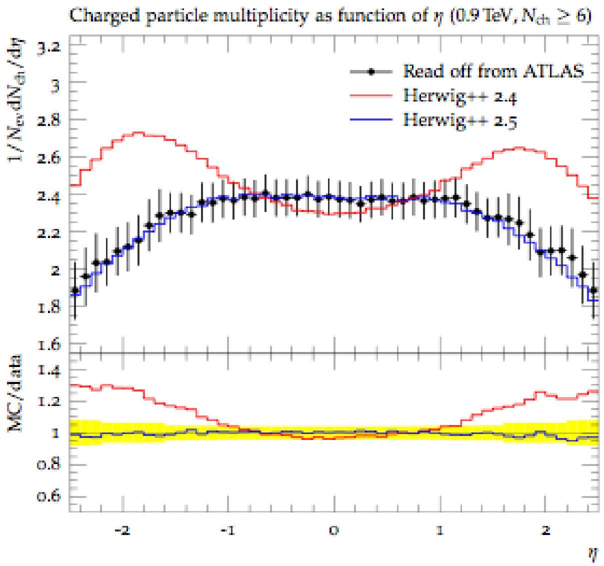


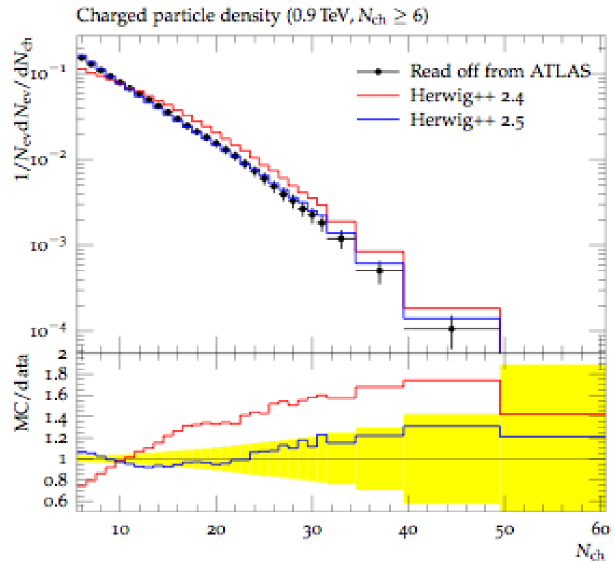
$\rightarrow$ possibility that entire process could be described perturbatively?

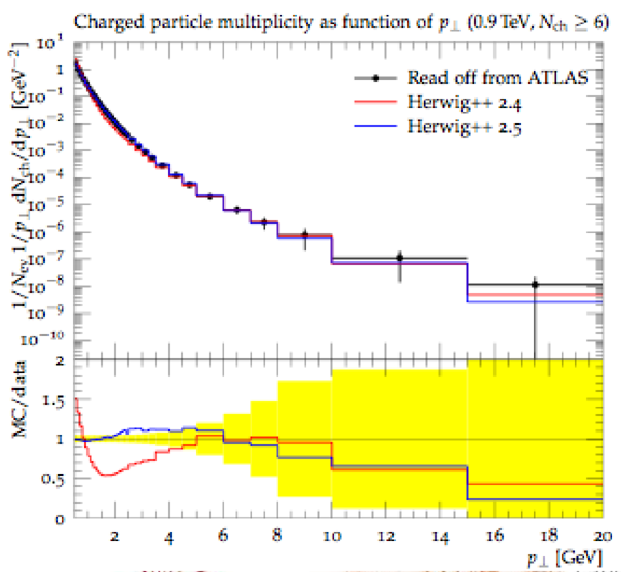
Colour reconnection model

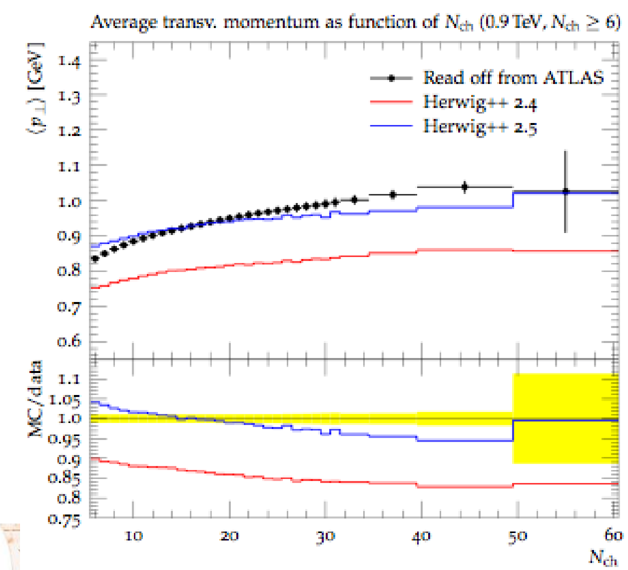
- Röhr, Siodmok and Gieseke have implemented a new model based on momentum structure
- Refit LEP-I and LEP-II data
- Conclusion: hadronization parameters correlated with reconnection probability, but good fit can be obtained for any value of p_{reco}

Colour reconnection model/MPI tuning









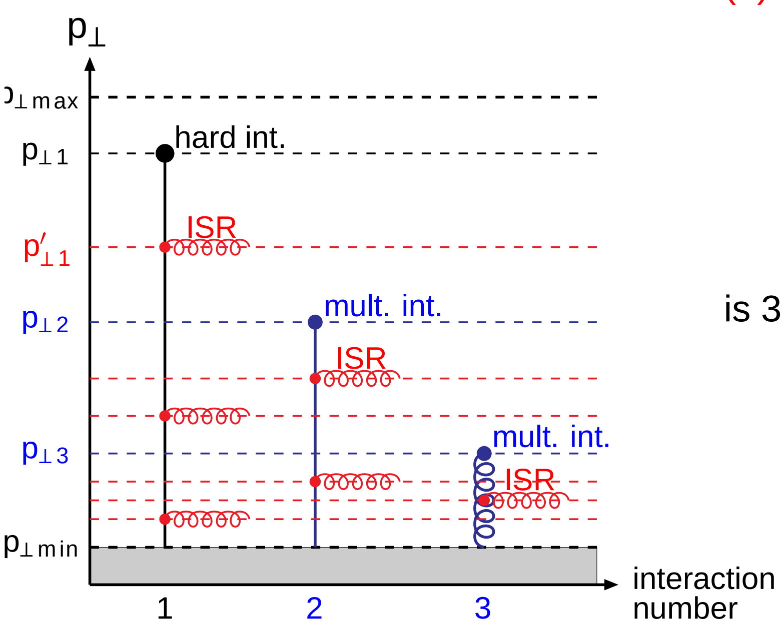
Pythia implementation

(4) Evolution interleaved with ISR (2004)

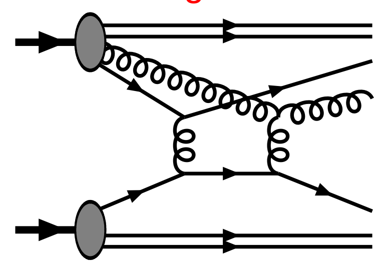
- Transverse-momentum-ordered showers

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

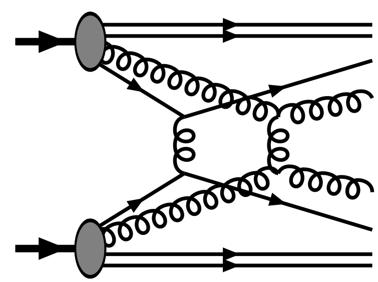
with ISR sum over all previous MI



(5) Rescattering



is 3 → 3 instead of 4 → 4:



x-dependent matter distributions

- Most existing models use factorization of x and b
  - or (Herwig++) crude separation into hard and soft components (simple hot-spot model)
- R.Corke and T.Sjöstrand, arXiv:1101.5953 consider Gaussian matter distribution with width

$$a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

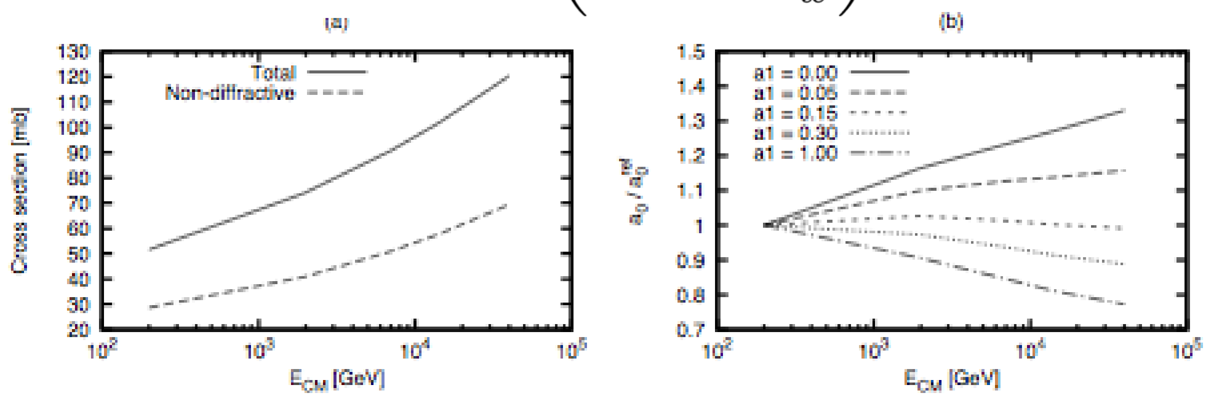


Figure 1: (a) The rise of the total and non-diffractive pp cross section with energy, and (b) the ratio $a_0(E_{\mathrm{CM}})/a_0(200\,\mathrm{GeV})$, over the same energy range, for a set of different a_1 values

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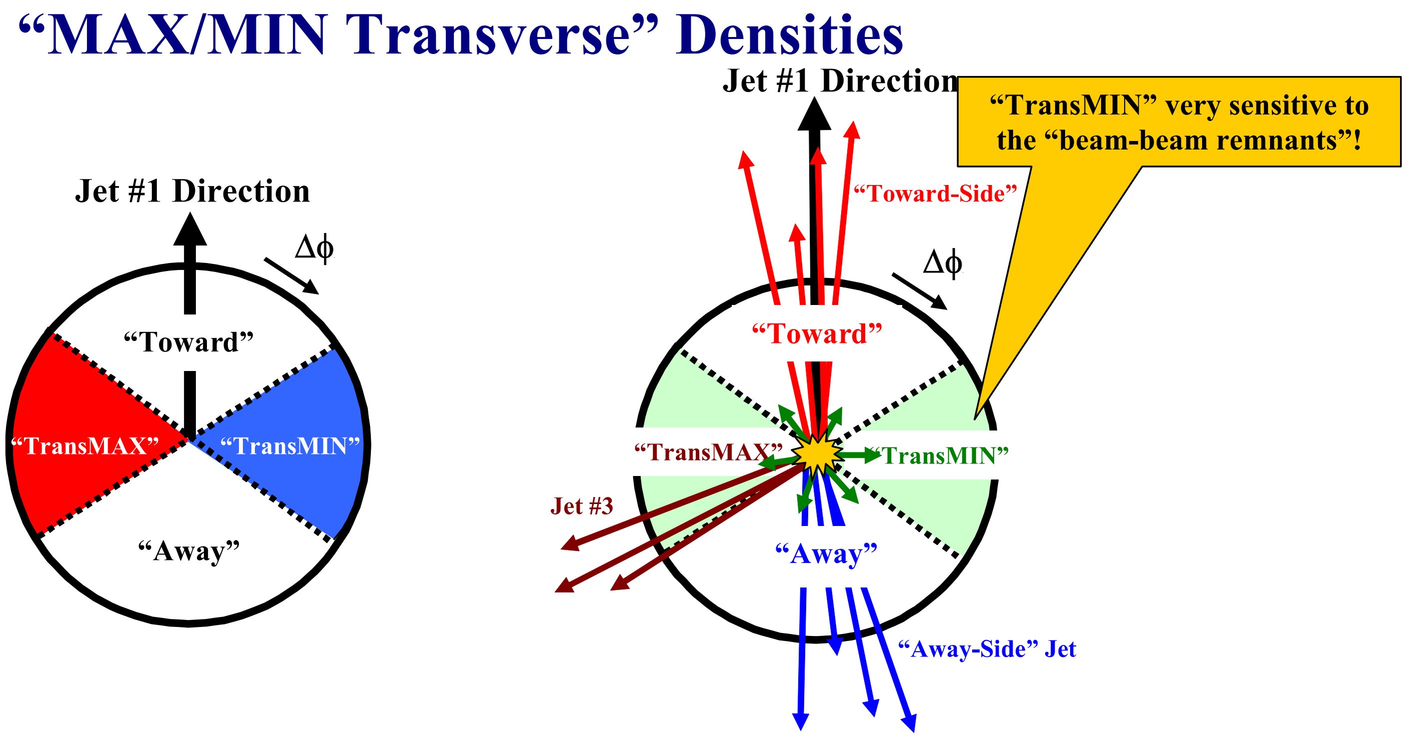
$$a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x} \right)$$

- for $a_1 \approx 0.15$, matter distribution can be E-indep

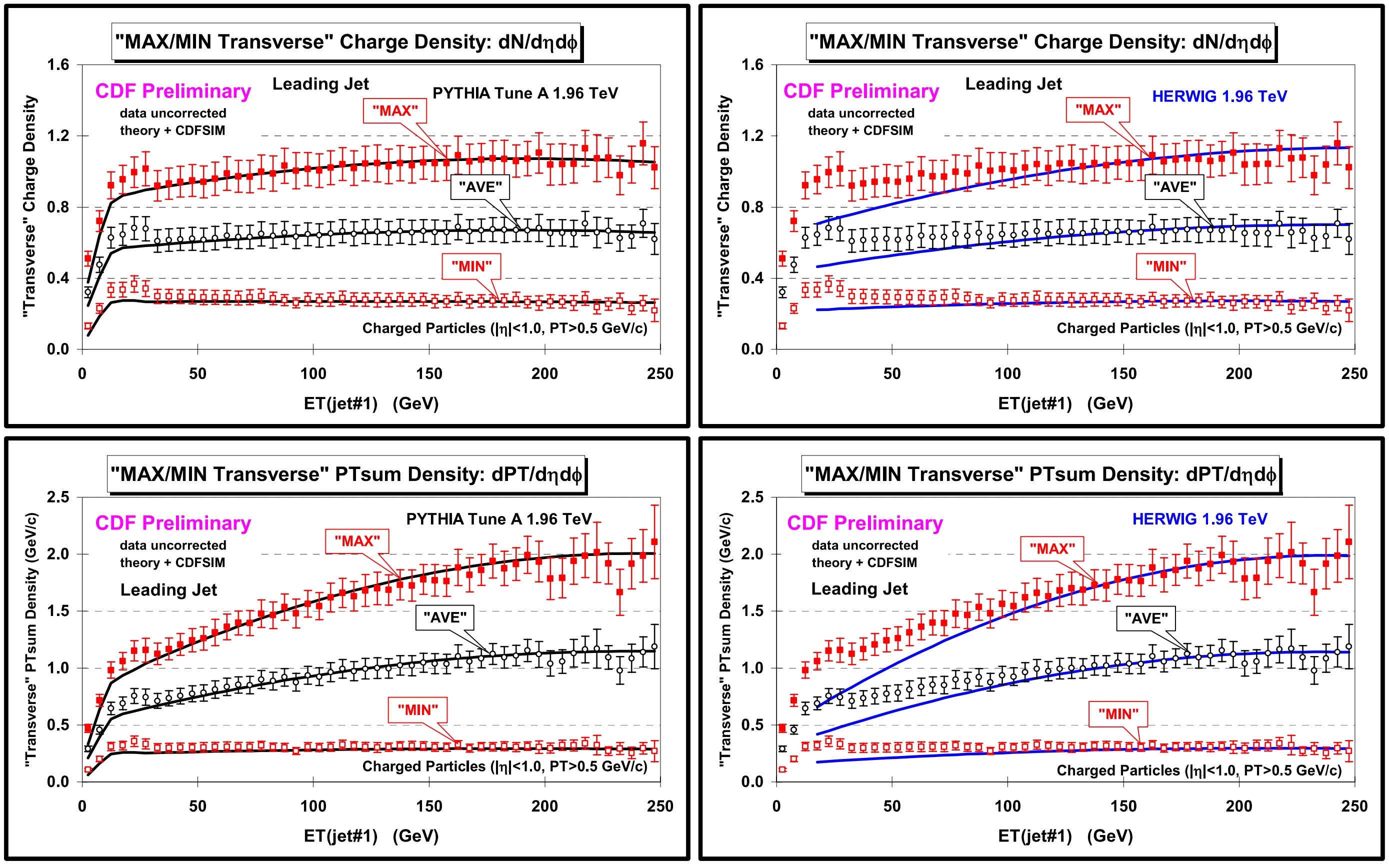
Underlying event measurements



- **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?”