Underlying Event & Soft Inclusive Physics
Part I

Andrzej Siódmok

CERN, Theory Division & IFJ, Cracow

Monte Carlo School NCC/ICTP-SAIFR School and Workshop,
São Paulo, 27th April 2015

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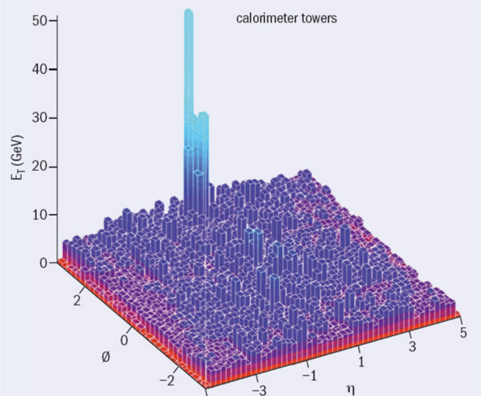
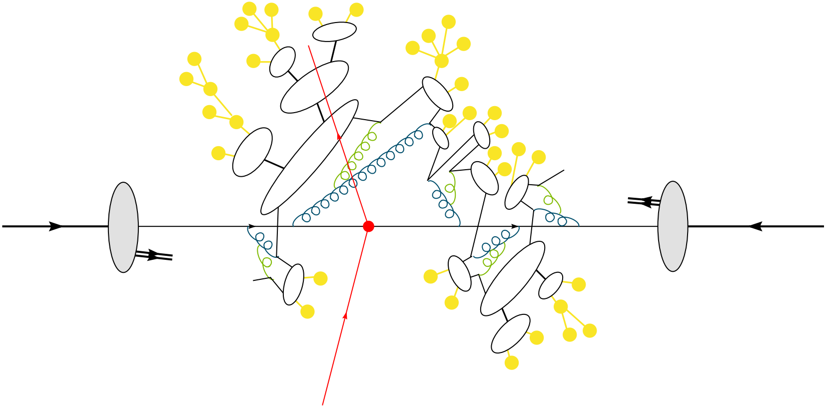


pp Event Generator



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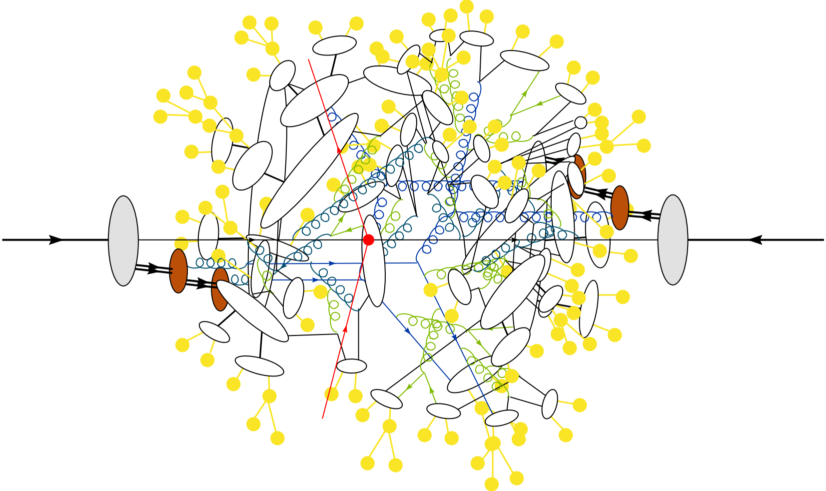

pp Event Generator

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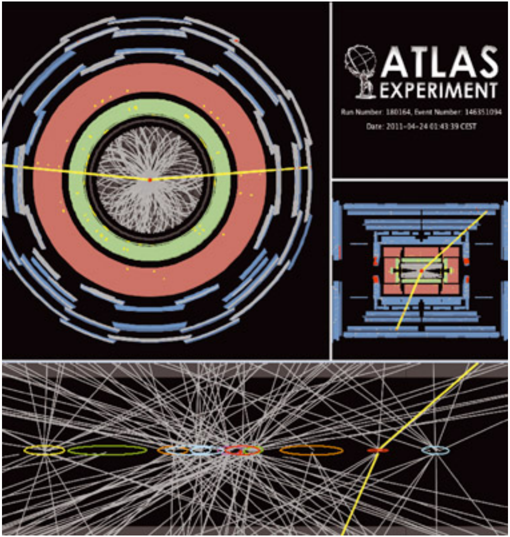

Outline

This talk:

- Definition and Motivation
- Example of MPI model

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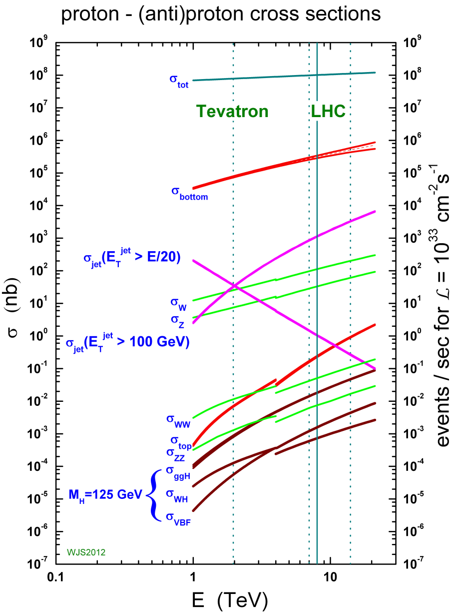
- Definition and Motivation
- Example of MPI model- Multiple Partonic Interaction model not ~~Message Passing Interface~~ :)
- Colour structure of an event
- Summary

Thursday's talk:

- Overview of MPI models
- Tuning tools - Professor
- Comparison with some LHC data
- CDF Min Bias “factorization” mystery
- Outlook

Definitions and Motivation

Zero and Minimum Bias measurements



- the "interesting" (high transverse momentum, high mass...) events are often quite a small fraction of the total number of collisions.
- most of interactions are "soft"
- and also underlying event is assumed to be mostly soft
- pile-up interactions are "soft" as well

Zero and Minimum Bias measurements

- “Zero bias” - Every event in a perfect 4π detector (or maybe almost perfect FELIX - A full acceptance detector at the LHC by Bjorken).
- A “minimum bias“ event is what one would see with a totally inclusive trigger. All events, with a minimum bias from restricted trigger conditions.
- In practice this definition depends on the experiment’s trigger! Two examples:
    1. ATLAS, Minimum Bias Trigger Scintillator ($2.1 < |\eta| < 3.8$), single arm MBTS trigger fired, primary vertex reconstructed, phase spece: $p_T > 500(100)$ MeV, $|\eta| < 2.5$, $n_{ch} \geq 1 \quad (2, 6, 20)$
    2. CDF (2009), Minimum bias trigg. BBC ($3.2 < |\eta| < 5.9$), coincidence in time of signals in both forward and backward modules, primary vertex reconstructed, phase spece: $p_T > 400$ MeV, $|\eta| < 1.0$
- Typical observables:

$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}} \quad \text{and} \quad \langle p_{\mathrm{T}} \rangle \text{ vs. } n_{\mathrm{ch}},$$

Underlying Event

- We define an interesting hard process
- Underlying Event = Everything except the hard/interesting process (and initial- and final-state showers)

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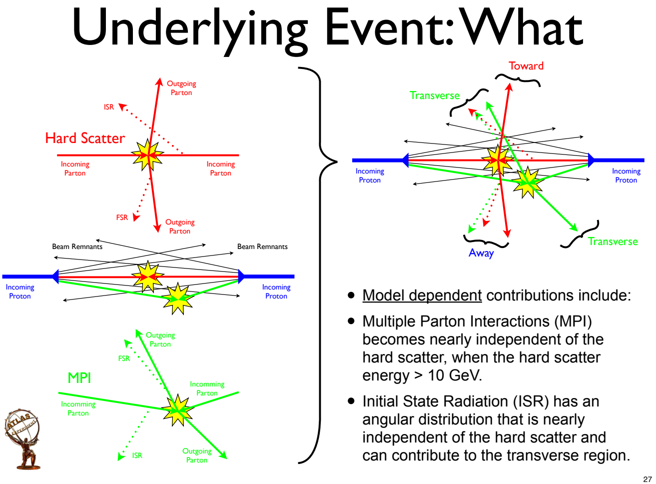
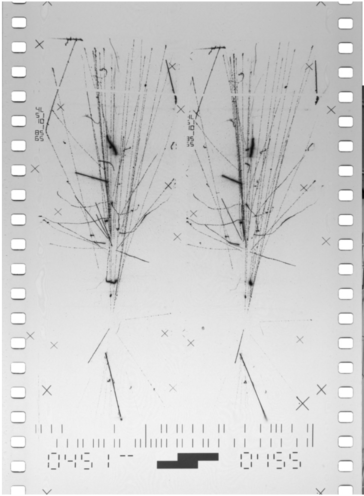


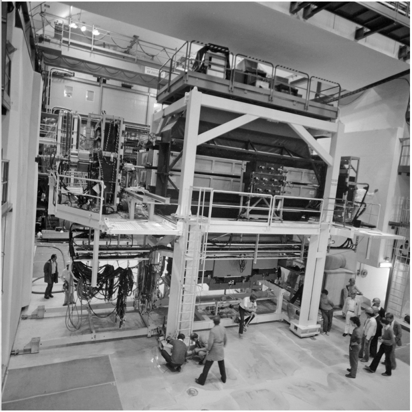
Underlying Event: What

- Model dependent contributions include:
- Multiple Parton Interactions (MPI) becomes nearly independent of the hard scatter, when the hard scatter energy > 10 GeV.
- Initial State Radiation (ISR) has an angular distribution that is nearly independent of the hard scatter and can contribute to the transverse region.

Motivation - how do we know MPI exists?

UA5 experiment at the SPS - proton-antiproton 540 GeV c.m.





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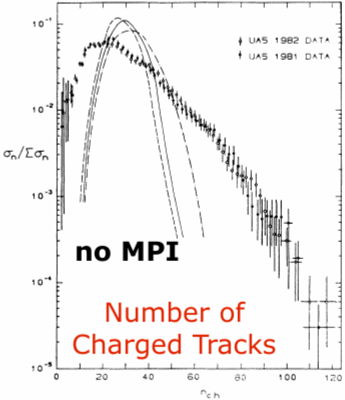


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

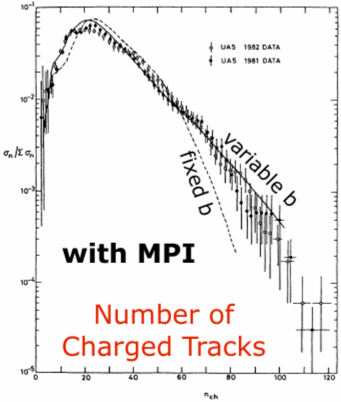


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

Sjöstrand & v. Zijl,
Phys.Rev.D36(1987)2019

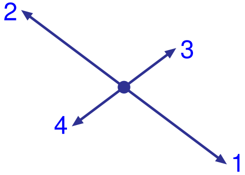
Motivation - how do we know MPI exists?

Direct observation of multiple interactions

Five studies: AFS (1987), UA2 (1991), CDF (1993, 1997), D0 (2009)

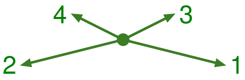
Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ
as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

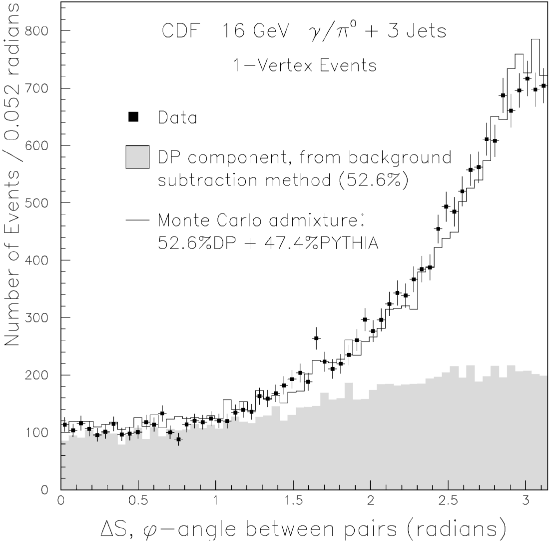
Double BremsStrahlung



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

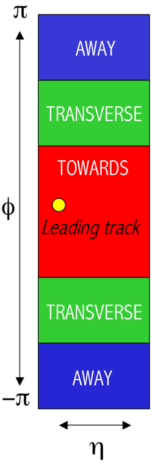
Motivation - how do we know MPI exists?

CDF: Double parton scattering in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$
[Phys. Rev. D 56, 3811-3832 (1997)]



Motivation - how do we know MPI exists?

CDF Run II



On event-by-event basis:

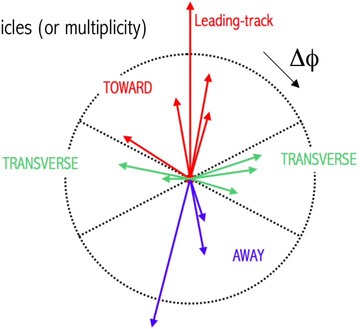
1) Identify the leading object in the event

2) Build **TRANSVERSE REGIONS** w.r.t. it

3) Compute Σp_T of charged particles (or multiplicity) in the different regions

SETTINGS:

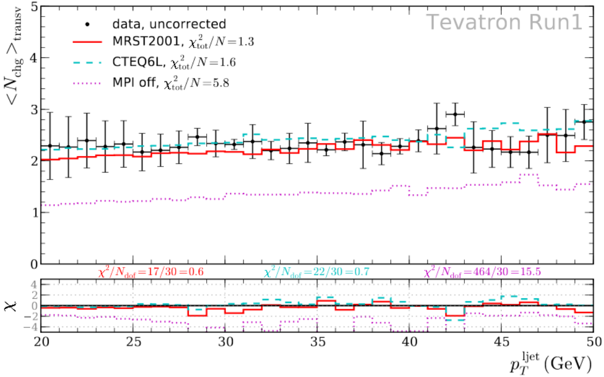
- pT > 0.5 GeV/c (tracks and leading-track)
- leading-track not included in distributions

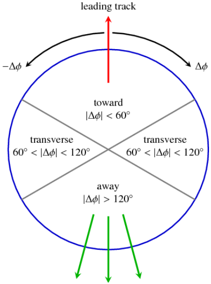


Motivation - how do we know MPI exists?

CDF Run II

Good description of Run I Underlying event data ($\chi^2 = 1.3$).





Only $p_T^{\text{ljet}} > 20\,\text{GeV}$.

Why should we be interested?

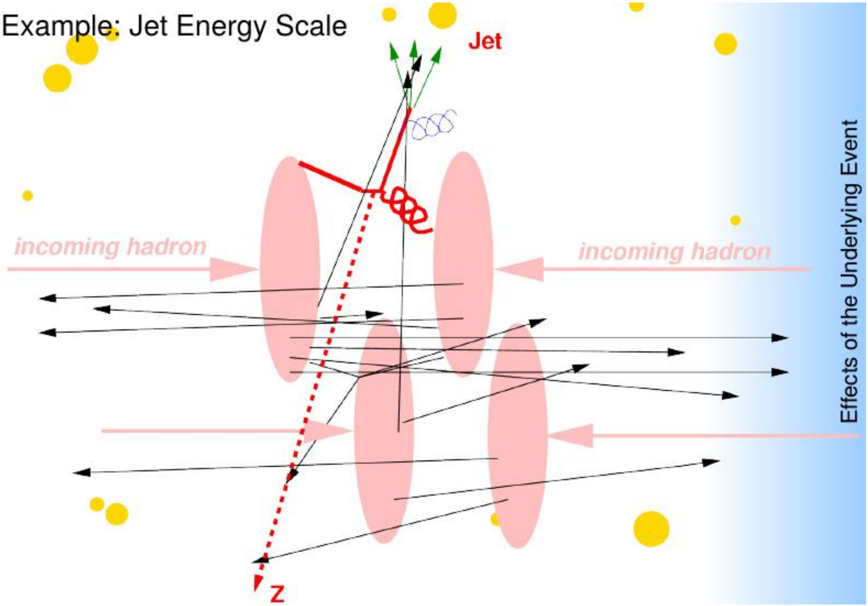
1. Quantum Chromodynamics (QCD)
    - Can we predict/understand the properties of hadrons?
    - Connection with:
        - diffraction
        - saturation
        - confinement
        - total cross section

2. Experiments
    - These effects are often formally suppressed for inclusive cross sections.
    - In practice, their significance can be enhanced by
        - experimental acceptance
        - cuts to suppress backgrounds
        - their impact on detector calibration
        - the need to measure more exclusive quantities
        - missing E_T reconstruction
        - Photon/lepton isolation
        - Mass reconstruction (see Jon's talk on Friday)

Example: Jet Energy Scale

- Leptonic energy scale typically much better known than the hadronic/jet energy scale.
- To determine response to hadronic jets, typically look for well measured leptonic processes (e.g. $Z \to e^+e^-$) and balance leptons against jets.
- This balance is affected by the environment of the event.

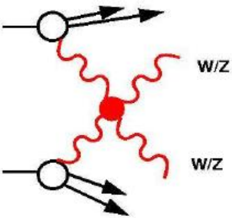
Example: Jet Energy Scale

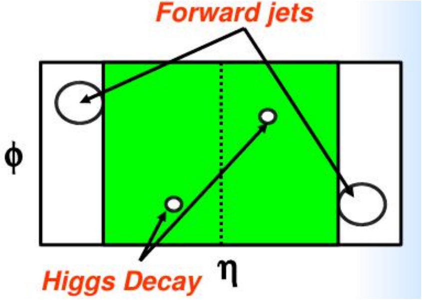


Title: ”Effects of the Underlying Event“ by Jonathan Butterworth

Example: Minijet veto

- In some processes there is no colour exchange between the protons.
- Suppression of QCD radiation in the event;
  Important signature for reducing backgrounds.
- No suppression in activity from MPI





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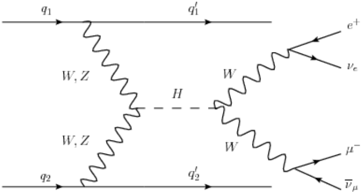

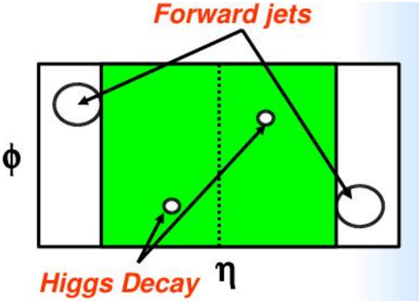

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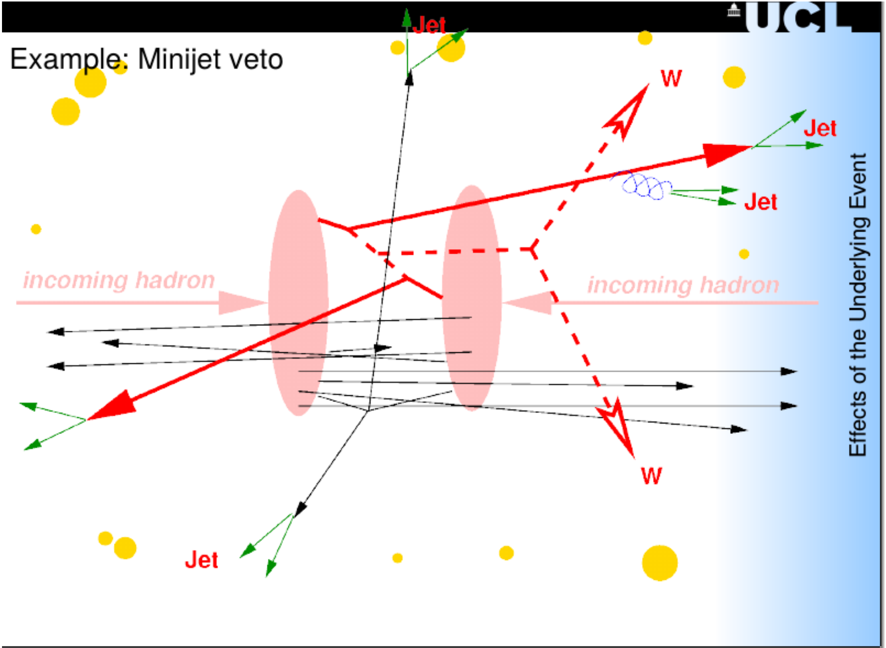


Example: Minijet veto

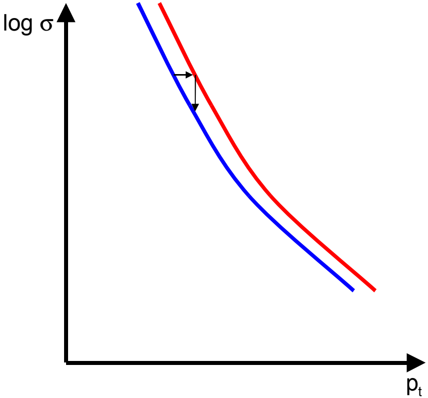
Effects of the Underlying Event

Motivation - is it really important?

Motivation:

- The minimum bias/underlying event is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
- First LHC results are Minimum Bias and Underlying Event!
  Alice: [0911.5430], CMS [1002.0621], ATLAS [1003.3124] so it must be important ;)
- These will be particularly relevant for the LHC as, when it is operated at design luminosity, rare signal events will be embedded in a background of more than 20 near-simultaneous minimum-bias collisions.
- Any realistic experiment simulation event generator needs to be able to model these effects.
- “Don’t worry, we will measure and subtract it” But... fluctuations and correlations crucial

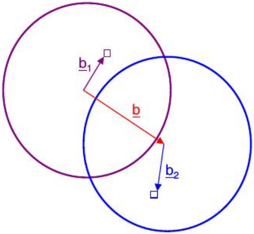
Motivation - is it really important?

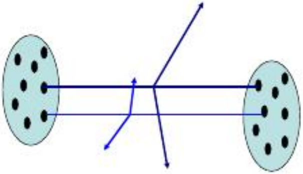


- Steep distribution ⇒ small sideways shift = large vertical
- Rare fluctuations can have a huge influence

Modeling the Underlying Event

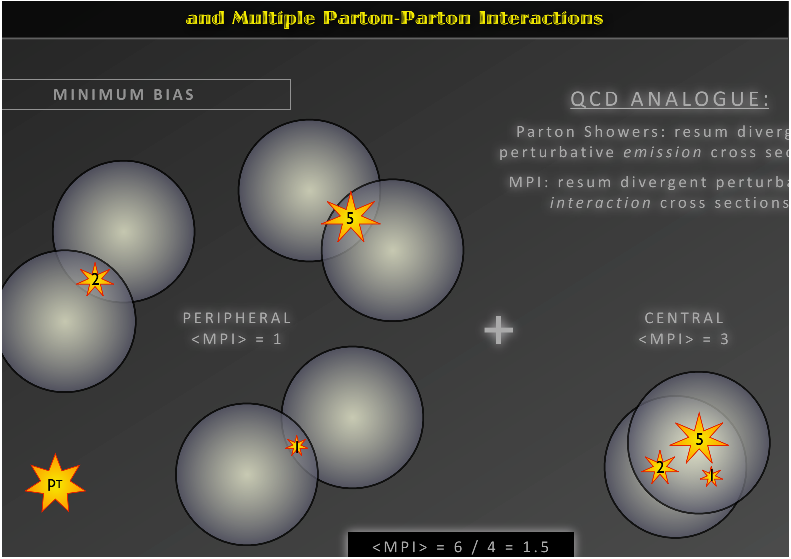
Expect impact parameter (b) dependence:





Semi hard underlying event

Taken from Peter Skands:



and Multiple Parton-Parton Interactions

MINIMUM BIAS

QCD ANALOGUE:

Parton Showers: resum diverg
perturbative *emission* cross sec

MPI: resum divergent perturb
interaction cross sections

PERIPHERAL
<MPI> = 1

+

CENTRAL
<MPI> = 3

<MPI> = 6 / 4 = 1.5

Evolution of MPI model in Herwig++

Semihard UE

- Default from Herwig++ 2.1. [Herwig++, 0711.3137]
- Multiple hard interactions, $p_t \geqslant p_t^{\mathrm{min}}$ [Bähr, Gieseke, Seymour, JHEP 0807:076]
- Similar to JIMMY [J. M. Butterworth, J. R. Forshaw and M. H. Seymour, Zeit. fur Phys. C72]
- Good description of harder Run I UE data (Jet20).

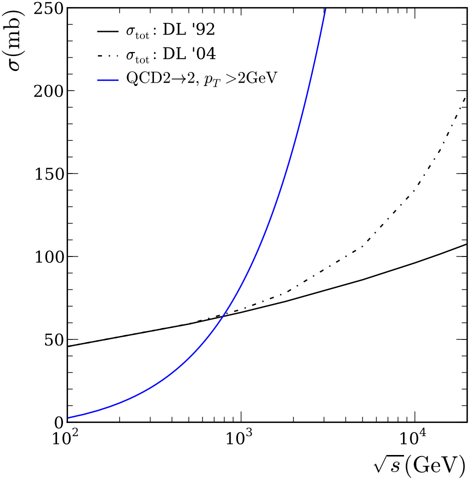
Eikonal model basics

Starting point: hard inclusive jet cross section.

$$\sigma^{\mathrm{inc}}(s;p_t^{\mathrm{min}}) = \sum_{i,j} \int_{p_t^{\mathrm{min}\,2}} \mathrm{d}p_t^2 f_{i/h_1}(x_1,\mu^2) \otimes \frac{\mathrm{d}\hat{\sigma}_{i,j}}{\mathrm{d}p_t^2} \otimes f_{j/h_2}(x_2,\mu^2)\,,$$

$\sigma^{\mathrm{inc}} > \sigma_{\mathrm{tot}}$ eventually (for moderately small p_t^{min}).

Eikonal model basics



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$\sigma^{\mathrm{inc}} > \sigma_{\mathrm{tot}}$ eventually (for moderately small p_t^{min}).

Interpretation: σ^{inc} counts *all* partonic scatters that happen during a single *pp* collision ⇒ more than a single interaction.

$$\sigma^{\mathrm{inc}} = \bar{n}\sigma_{\mathrm{inel}}\,.$$

where σ_{inel} is the cross section for having one or more jet pairs above p_t^{min}.

Eikonal model basics

Use eikonal approximation (= independent scatters[1]). Leads to Poisson distribution, at fixed impact parameter, $b \equiv |b|$, the probability for m partonic interactions:

$$P_m(\vec{b}, s) = \frac{\bar{n}(\vec{b}, s)^m}{m!} \mathrm{e}^{-\bar{n}(\vec{b}, s)} \; .$$

Then we get σ_{inel}:

$$\sigma_{\text{inel}} = \int \mathrm{d}^2\vec{b} \sum_{n=1}^{\infty} P_m(\vec{b}, s) = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\bar{n}(\vec{b}, s)}\right) \; .$$

---

[1] Real life momentum/flavor conservation suppresses high-m tail + other physical correlations

Eikonal model basics

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Cf. σ_{inel} from scattering theory in eikonal approx. with scattering amplitude $a(\vec{b},s) = \frac{1}{2i}(e^{-\chi(\vec{b},s)} - 1)$

$$\sigma_{\text{inel}} = \int d^2\vec{b} \left(1 - e^{-2\chi(\vec{b},s)}\right) \qquad \Rightarrow \qquad \chi(\vec{b},s) = \frac{1}{2}\bar{n}(\vec{b},s) \ .$$

$\chi(\vec{b},s)$ is called *eikonal* function.

---

[1] Real life momentum/flavor conservation suppresses high-m tail + other physical correlations

Eikonal model basics

Calculation of $\bar{n}(\vec{b}, s)$ from parton model assumptions:

$$\begin{aligned}\bar{n}(\vec{b}, s) &= L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\ &= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\ &\qquad \times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|)\end{aligned}$$

Eikonal model basics

Calculation of $\bar{n}(\vec{b}, s)$ from parton model assumptions:

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&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}) \,.
\end{aligned}$$

$$\Rightarrow \quad \chi(\vec{b}, s) = \tfrac{1}{2}\bar{n}(\vec{b}, s) = \tfrac{1}{2}A(\vec{b})\sigma^{\text{inc}}(s; p_t^{\text{min}}) \,.$$

Eikonal model basics

From assumptions:

- at fixed impact parameter b, individual scatterings are independent,
- the distribution of partons in hadrons factorizes with respect to the b and x dependence.

we get the average number of partonic collisions at a given b value is

$$\bar{n}(b,s) = A(b)\sigma^{inc}(s; p_t^{\min}) = 2\chi(b,s)$$

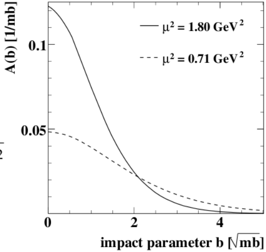
where $A(b)$ is the partonic overlap function of the colliding hadrons

$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b}-\vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

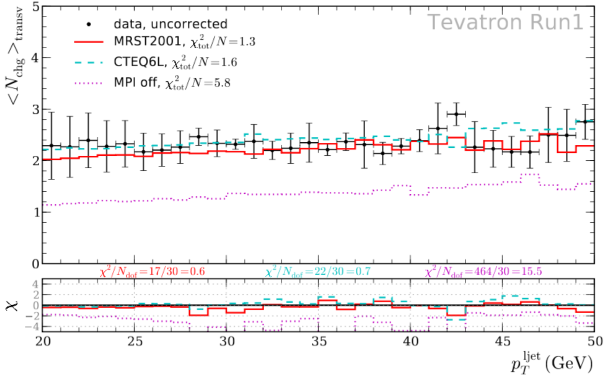
But μ^2 *not fixed* to the *electromagnetic* 0.71 GeV^2. Free for colour charges.

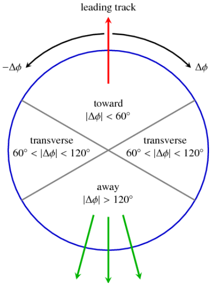


⇒ Two main parameters: $\mu^2, p_t^{\min}$.

Semi hard underlying event

Good description of Run I Underlying event data ($\chi^2 = 1.3$).





Only $p_T^{\rm ljet} > 20\,{\rm GeV}$.

Evolution of MPI model in Herwig++

Semihard+Soft UE

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions, $p_t \leqslant p_t^{\min}$ [Bähr, Gieseke, Seymour, JHEP 0807:076]
- Theoretical work with simplest possible extension. [Bähr, Butterworth, Seymour, JHEP 0901:065]
- "Hot Spot" model. [Bähr, Butterworth, Gieseke, Seymour, 0905.4671]

Soft eikonal

So far only hard MPI.
Now extend to soft interactions with

$$\chi_{\text{tot}} = \chi_{QCD} + \chi_{\text{soft}}.$$

Similar structures of eikonal functions:

$$\chi_{\text{soft}} = \frac{1}{2} A_{\text{soft}}(\vec{b}) \sigma^{\text{inc}}_{\text{soft}}$$

Simplest possible choice:
$A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

$$\chi_{\text{tot}} = \frac{A(\vec{b};\mu)}{2} \left(\sigma^{\text{inc}}_{\text{hard}} + \sigma^{\text{inc}}_{\text{soft}} \right) .$$

One new parameter $\sigma^{\text{inc}}_{\text{soft}}$.

Fixing $\sigma_{\text{soft}}^{\text{inc}}$

Exploit knowledge of σ_{tot} in eikonal model:

$$\begin{aligned}\sigma_{\text{tot}} &= 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right)\\ &= 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\frac{A(\vec{b};\mu)}{2}(\sigma_{\text{hard}}^{\text{inc}}+\sigma_{\text{soft}}^{\text{inc}})}\right)\end{aligned}$$

σ_{tot} well measured. Fixes $\sigma_{\text{soft}}^{\text{inc}}$.

Energy extrapolation from Donnachie–Landshoff

- DL ’92 [D&L, PLB296, 227 (1992)]
- DL ’92 normalized at TVT
- DL ’04 [D&L, PLB595, 393 (2004)]

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Energy extrapolation from Donnachie–Landshoff

- DL '92 [D&L, PLB296, 227 (1992)]
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Model turned out to be too simple.
→ Relax the constraint of identical overlap

$$A_{\text{soft}}(b) = A(b, \mu_{\text{soft}})$$

Hot Spot model

Extension to soft MPI, $p_t < p_t^{\min}$

Fix the two parameters $\mu_{\rm soft}$ and $\sigma^{\rm inc}_{\rm soft}$ in

$$\chi_{\rm tot}(\vec{b},s) = \frac{1}{2}\left(A(\vec{b};\mu)\sigma^{\rm inc}\text{hard}(s;p_t^{\min}) + A(\vec{b};\mu_{\rm soft})\sigma^{\rm inc}_{\rm soft}\right)$$

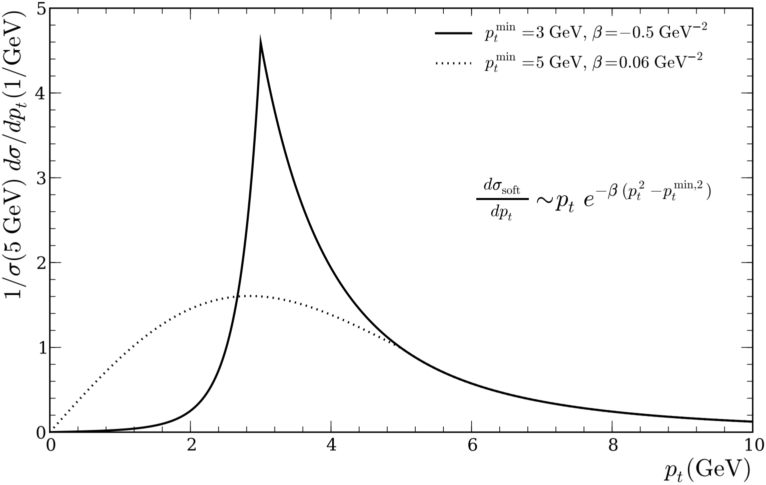
from two constraints. Require simultaneous description of $\sigma_{\rm tot}$ and $b_{\rm el}$ (measured/well predicted),

$$\sigma_{\rm tot}(s) \overset{!}{=} 2\int {\rm d}^2\vec{b}\left(1-{\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) ,$$

$$b_{\rm el}(s) \overset{!}{=} \int {\rm d}^2\vec{b}\,\frac{b^2}{\sigma_{\rm tot}}\left(1-{\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) .$$

Extension to soft MPI, $p_t < p_t^{\min}$

Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$
(here: p_t integral kept fixed)

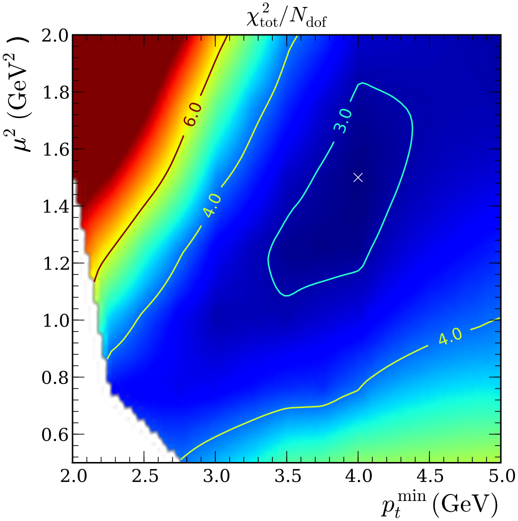


Tevatron Run I final states

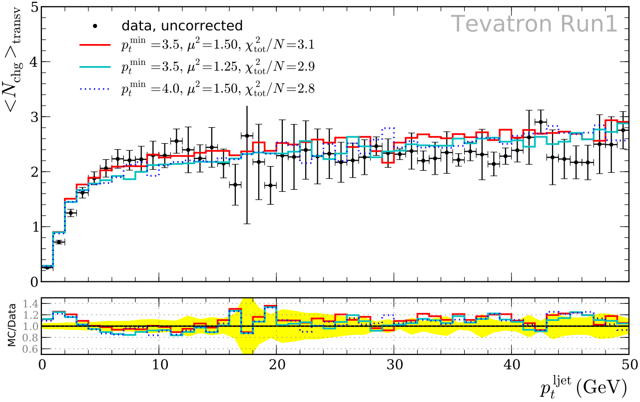
- So far: only indirect constraints from σ_{tot} and σ_{el}.
- Now use model in Herwig++ with $\bar{n}(\vec{b}, s)$ as input for MPI.
- Remaining free parameters $(p_t^{\mathrm{min}}, \mu^2)$.
- Look at χ^2/dof for Tevatron Run I data in the $(p_t^{\mathrm{min}}, \mu^2)$ plane.

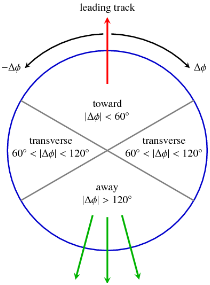
Parameter space at Tevatron

- χ^2 for Rick's Run1 Jet analysis for **all** regions



Detailed look at observables: Transverse Region





On to the LHC

What we have so far:

- Unitarized jet cross sections
- Fulfil constaints from σ_{tot} and σ_{el}.
- Simple model with similar overlap functions.
- No additional (explicit) energy dependence.
- Left with freedom in parameter space.

On to the LHC

What we have so far:

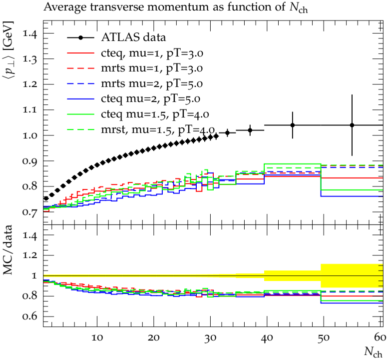
- Unitarized jet cross sections
- Fulfil constaints from $\sigma_{\rm tot}$ and $\sigma_{\rm el}$.
- Simple model with similar overlap functions.
- No additional (explicit) energy dependence.
- Left with freedom in parameter space.

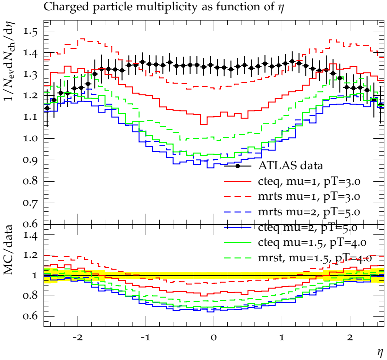
$\Longrightarrow$ *Look at LHC results (900 GeV).*

- ATLAS charged particles in Min Bias.
- Convenient as the analysis was quickly available in RIVET ;-)
- Three points from 'valley'
  $(p_t^{\rm min}/{\rm GeV}, \mu^2/{\rm GeV}^2) = (3.0, 1.0); (4.0, 1.5); (5.0, 2.0)$

Look at LHC results (900 GeV)

- ATLAS charged particles in Min Bias ($N_{ch} \geq 1,\ p_T > 500MeV,\ |\eta| < 2.5$)
- Convenient as the analysis was quickly available in `RIVET`.

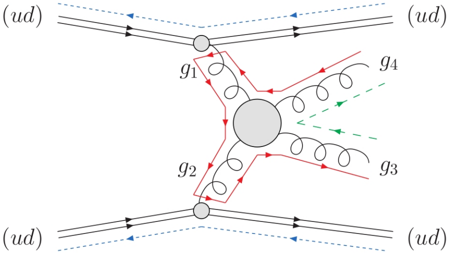

Average transverse momentum as function of $N_{\rm ch}$


Charged particle multiplicity as function of η

- oops, not so nice...
- despite very good agreement with Rick Field's CDF UE analysis.
- choice of PDF set (CTEQ6ll vs MSTW LO** (our default))
- Failure of a physically motivated model usually points to more, interesting physics ... colour structure?

Colour structure

- Colour structure of the soft interactions, $p_t \leqslant p_t^{\rm min}$
  Sensitivity to parameter:
  - `colourDisrupt` = P(disrupt colour lines) as opposed to hard QCD.
  - `colourDisrupt` = 1, completely disconnected.



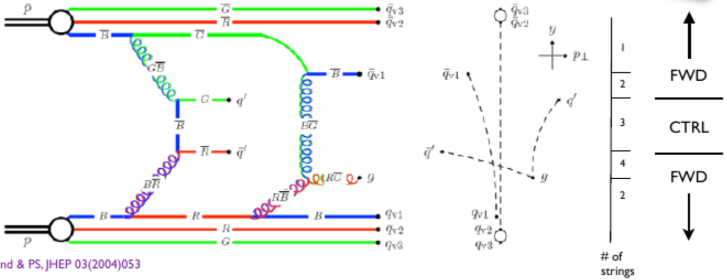
Colour Structure of the Underlying Event

Colour Structure of the Underlying Event multiple interactions, even when soft, can cause non-trivial changes to the colour topology of the colliding system as a whole, with potentially major consequences for the particle multiplicity in the final state

Each MPI (or cut Pomeron) exchanges color between the beams

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053

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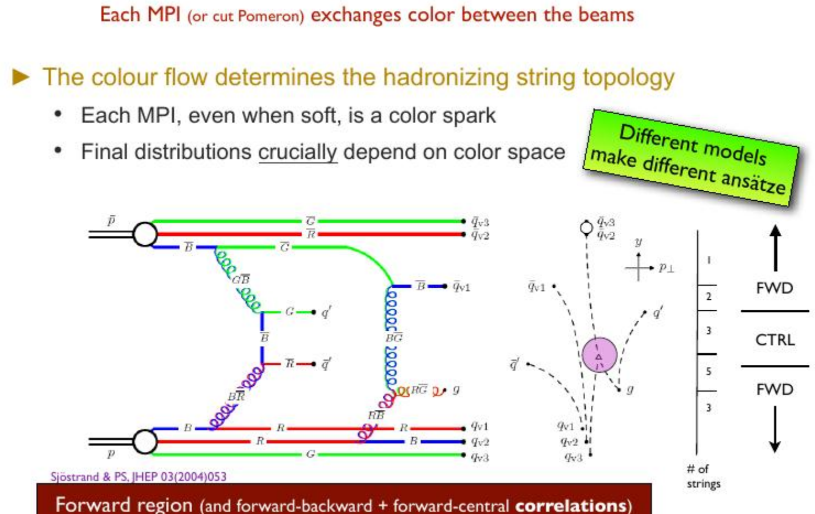

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▶ The colour flow determines the hadronizing string topology

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Different models make different ansätze

Sjöstrand & PS, JHEP 03(2004)053

Forward region (and forward-backward + forward-central **correlations**)

Underlying event in Herwig++

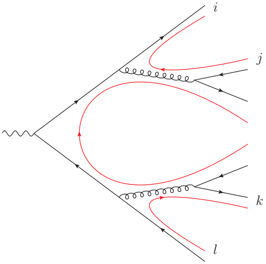
Colour Structure of the Underlying Event multiple interactions, even when soft, can cause non-trivial changes to the colour topology of the colliding system as a whole, with potentially major consequences for the particle multiplicity in the final state

- plain Colour Reconnection (pCR) (parameter p_{reco}) - Included from Herwig++ 2.5, [Gieseke, Rohr, AS, Eur.Phys.J. C72 (2012)]
- Colour Disrupt - only Soft UE (parameter p_{CD})

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components
- p_{reco} - colour reconnection
- p_{CD} - colour structure of the Soft UE

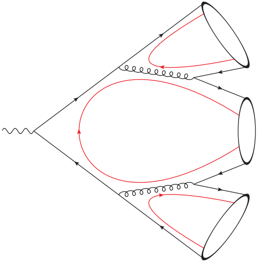
Colour reconnection (CR) in Herwig++



Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*

Colour reconnection (CR) in Herwig++



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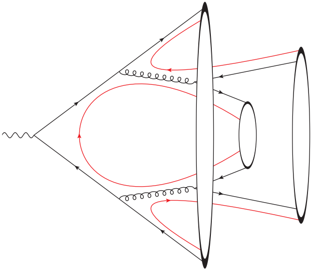
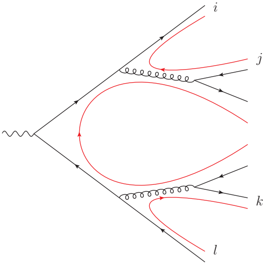
Colour reconnection (CR) in Herwig++



Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

Colour reconnection (CR) in Herwig++



Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

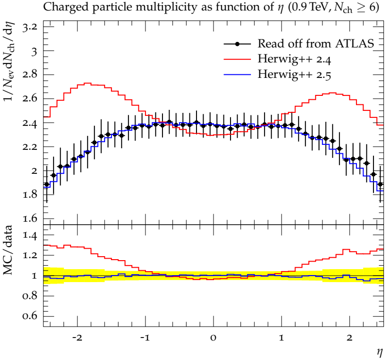
Implementation

- Allow CR if the cluster mass decreases,

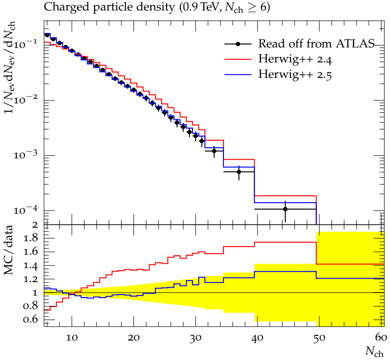
$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

  where $M_{ab}^2 = (p_a + p_b)^2$ is the (squared) cluster mass
- Accept alternative clustering with probability p_{reco} (model parameter) ⇒ this allows to switch on CR smoothly

MinBias ATLAS 900 GeV

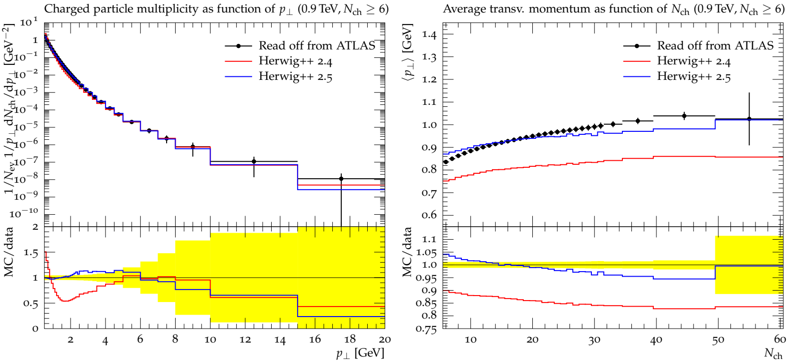


Charged particle multiplicity as function of η (0.9 TeV, $N_{\mathrm{ch}} \geq 6$)



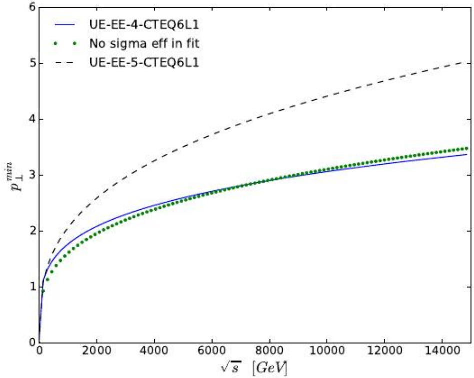
Charged particle density (0.9 TeV, $N_{\mathrm{ch}} \geq 6$)

MinBias ATLAS 900 GeV

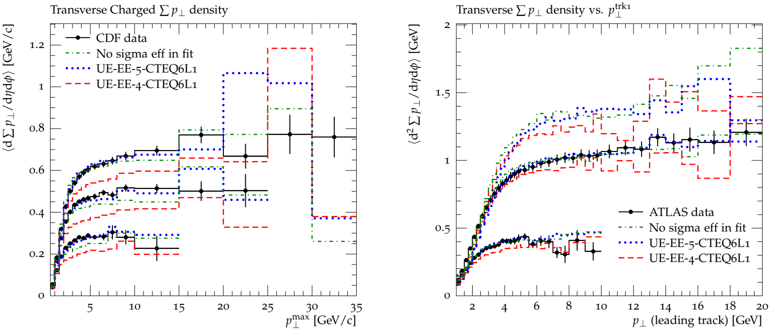


Energy interpolation

- Not possible to fit with energy-independent parameters (different parameters for different energies).
- Possible to fit with energy-dependent $p_t^{\text{min}} = p_{t,0}^{\text{min}} \left(\frac{\sqrt{s}}{E_0}\right)^b$ and all else energy-independent.
- Interpolation to $\sqrt{s} = 2760$ GeV



Transverse charged Particle $\sum p_T$


CDF (300, 900, 1960 GeV)

LHC (900, 7000 , 1400 GeV)

Legend:

- No sigma eff. in fit (only UE data in fit) - blue lines
- UE-EE-5-CTEQ6L1 - both sigma eff. and UE data in fit $\sigma_{eff.} = 14.8$ mb).
- UE-EE-4-CTEQ6L1 - old tune - only UE data in fit.

[M. H. Seymour, and AS, JHEP 1310 (2013) 113]

Summary

Summary:

- Motivation and experimental evidence for MPI
- Example of MPI model - MPI in Herwig++
  - This was just a basics - there are many details which I had no time to talk about and ”The Devil is in the detail“ ...
- Colour structure of an event
- Energy extrapolation

Thursday’s talk:

- Overview of MPI models
- Tuning tools - Professor
- Comparison with some LHC data
- CDF Min Bias “factorization” mystery
- Outlook

Thank you for your attention!