Monte Carlos — Part V

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GK Mass Spectra Symmetry
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Outline

- Part I — Basics
  - Introduction
  - Monte Carlo techniques
- Part II — Perturbative physics
  - Hard scattering
  - Parton showers
- Part III — Merging/Matching
  - Matrix element corrections
  - Merging multiple tree level MEs with parton showers
  - Matching NLO and parton showers
- Part IV — Non–perturbative physics
  - Hadronization
  - Hadronic decays
  - Comparison to data
- Part V — Multiple Partonic Interactions
  - Minimum Bias/Underlying Event in data
  - Modelling

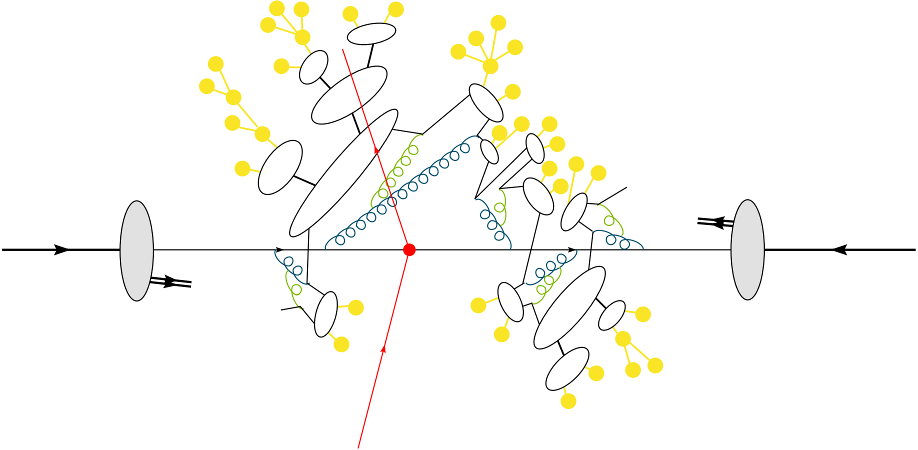
Outline Part V

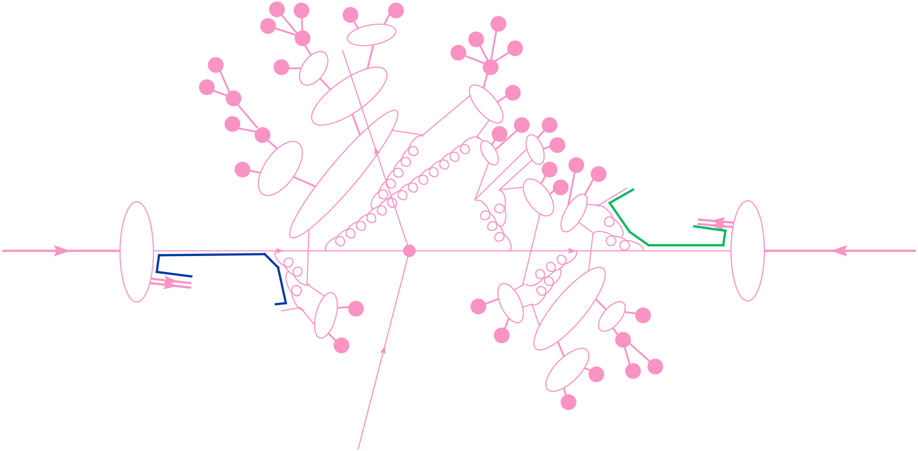
- Collider cross sections
- Zero bias, Min bias, Underlying event
- Inclusive $\to$ exclusive. The structure of underlying events.
- Multiple interactions.

Disclaimer

- Follow history of Herwig UE modelling.
- Modelling in Pythia/Sherpa somewhat similar.
- Most recent developments differ.
  - Pythia: interleaved showering/MPI.
  - Sherpa: current model similar
    new development: BFKL chains, integration with Diffraction.

pp Event Generator





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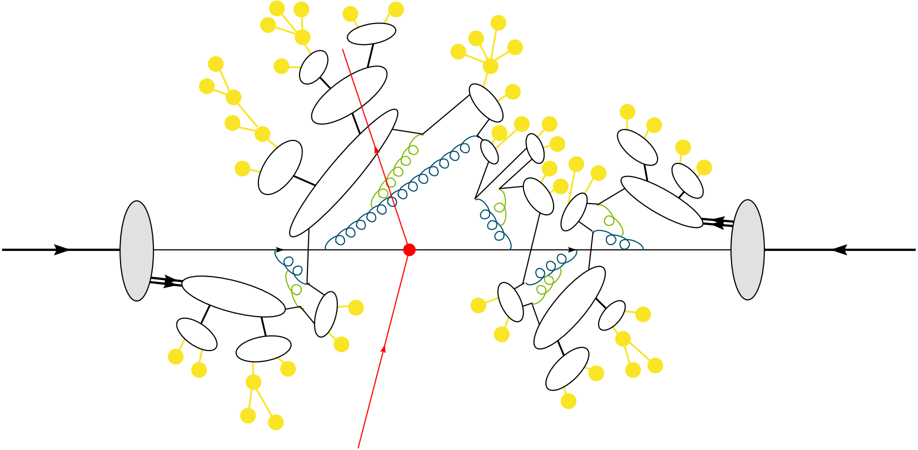
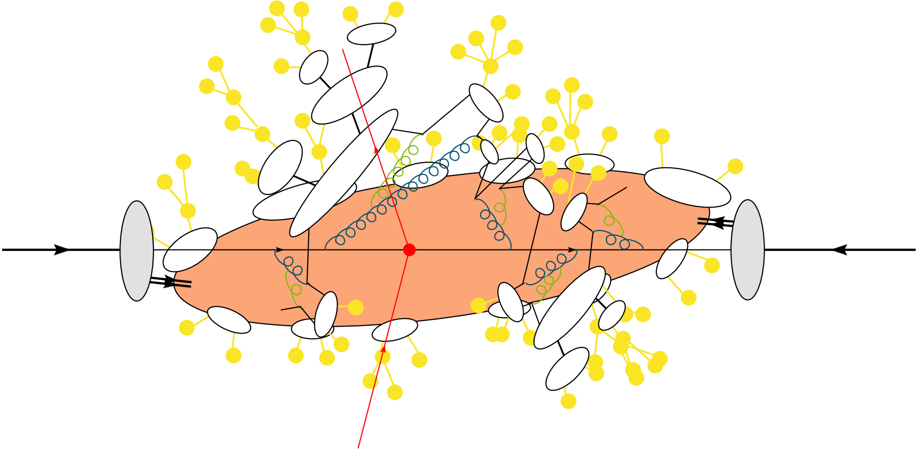


No UE model

Just remnant clusters

- Simplest model?
- Connects loose colour ends and produces some N_{ch}.
- No extra transverse energy.
- Fails.

pp Event Generator



UA5 model

- Produce $\langle n \rangle$ extra clusters, flat in y, with soft $p_\perp$ sprectrum.
- Included from Herwig++ 2.0. [Herwig++, hep-ph/0609306]
- Little predictive power.
- Only gets averages right, not large (and interesting!) fluctiations $\to$ mini jets.
- Was default in fHerwig. Superseded by `JIMMY`.

[JM Butterworth, JR Forshaw, MH Seymour, ZP C72 637 (1996)]

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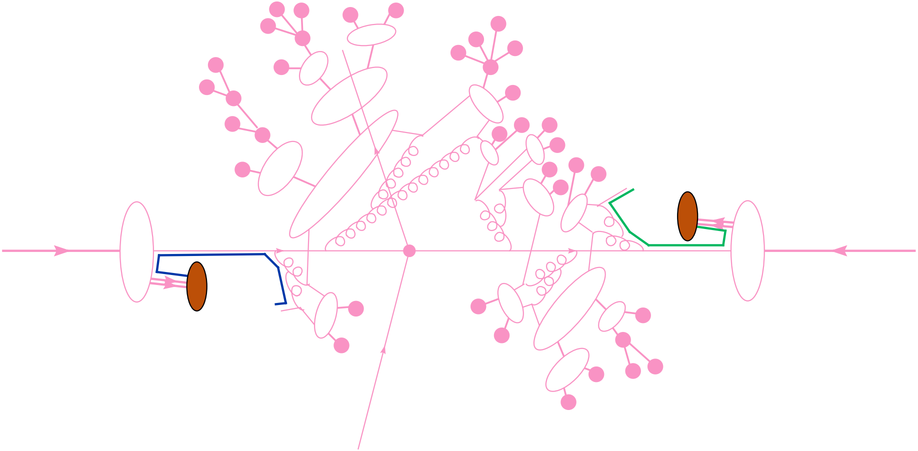

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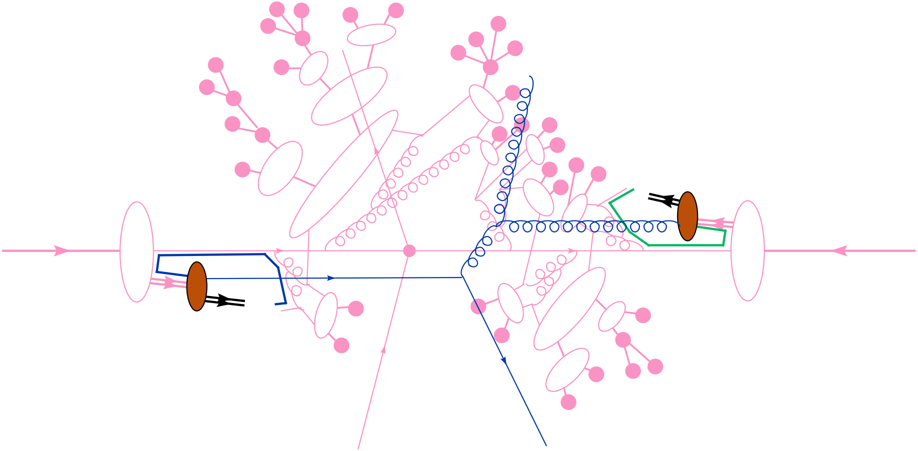

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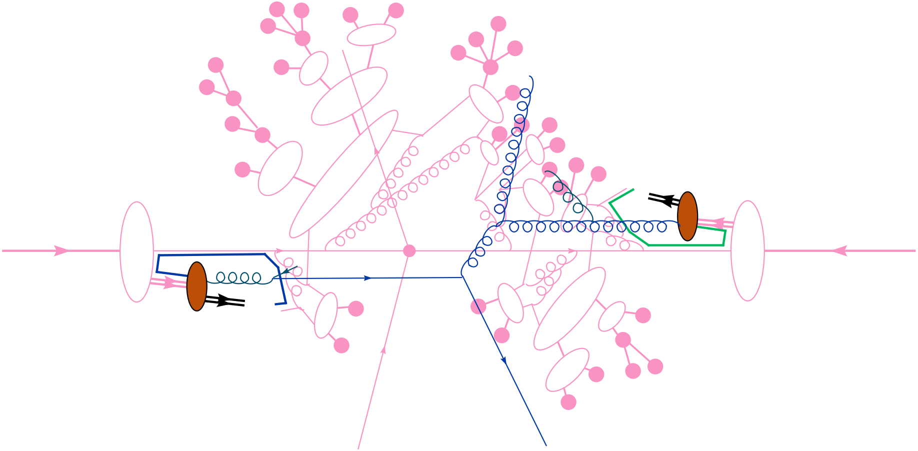

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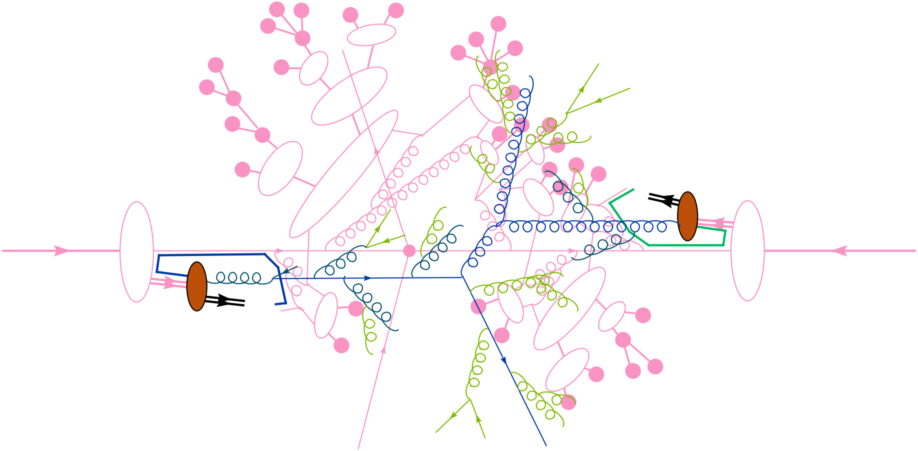

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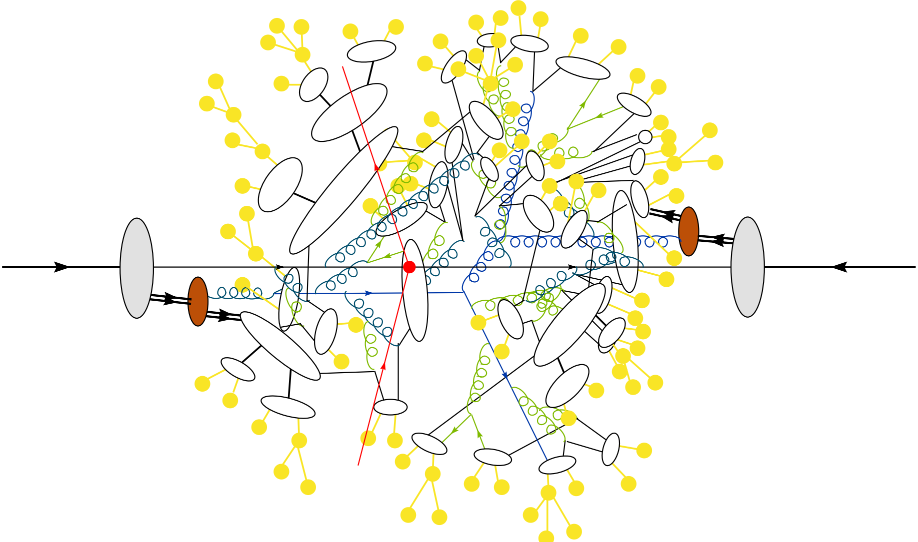

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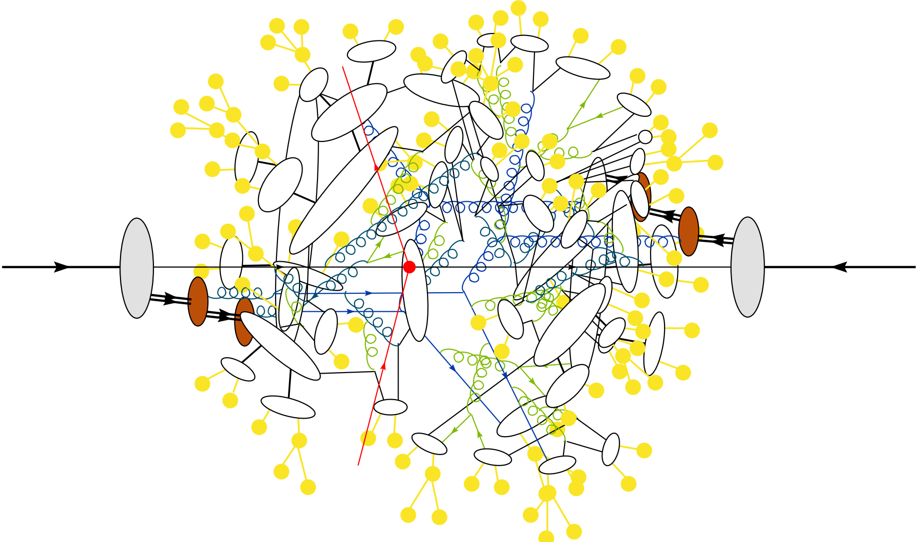
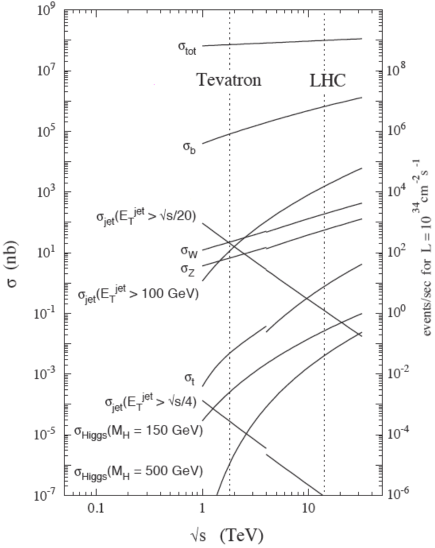


Min Bias/Underlying event in data

Collider cross sections

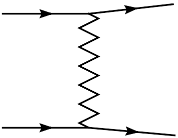
$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{SD}} + \overbrace{\sigma_{\text{DD}} + \underbrace{\sigma_{\text{soft}} + \sigma_{\text{hard}}}_{\sigma_{\text{ND}}}}^{\sigma_{\text{NSD}}}$$

Collider cross sections



What is the Underlying event?

$$\sigma_{\text{tot}} = \color{red}{\sigma_{\text{el}}} + \sigma_{\text{SD}} + \overbrace{\sigma_{\text{DD}} + \underbrace{(\sigma_{\text{soft}} + \sigma_{\text{hard}})}_{\sigma_{\text{ND}}}}^{\sigma_{\text{NSD}}}$$



elastic

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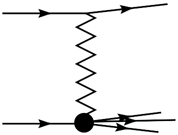

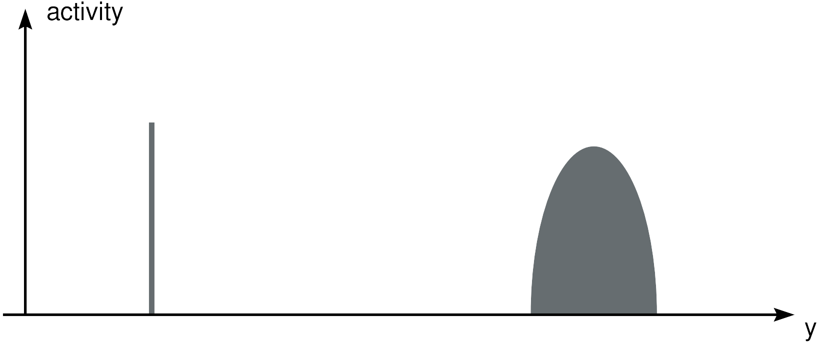

single diffractive

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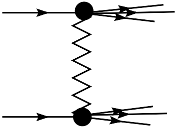

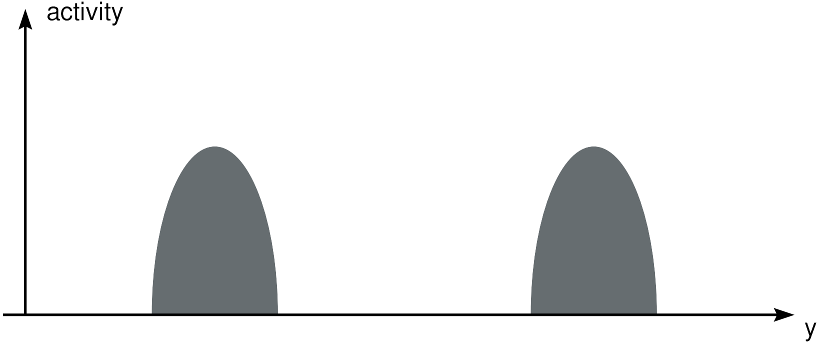

double diffractive

What is the Underlying event?

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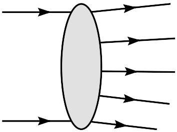

(multiple/soft) interactions

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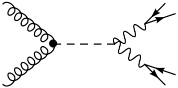

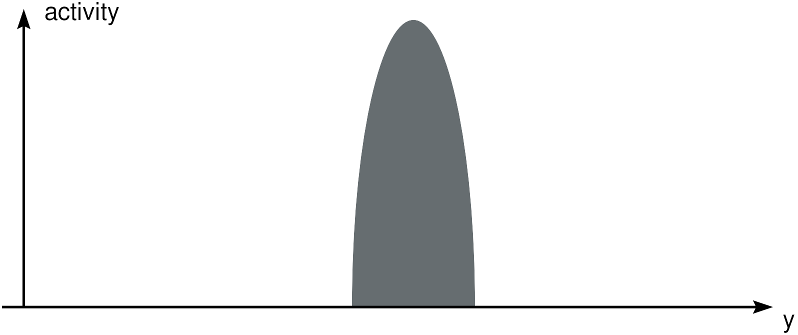

hard scattering

What is the Underlying event?

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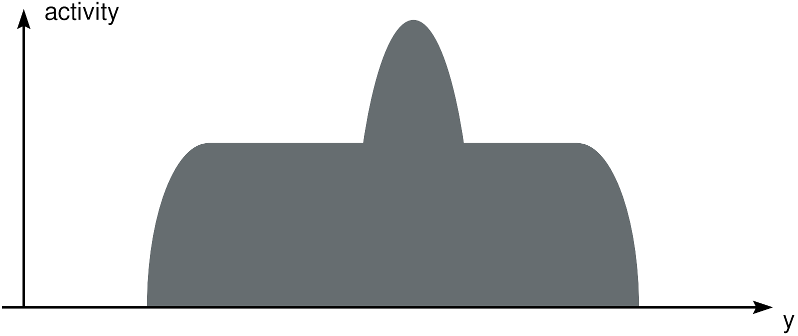

hard scattering + underlying event

What is the Underlying event?

"Everything except the process of interest."

- Experimentalist: "includes parton showers etc."
- MC author: "everything on top of primary hard process."

The Underlying event (UE) is everywhere in the detector.

- Cannot select UE
- May spoil measurements.
- What characteristics?
- Hard?
- Soft?

Why should I learn about it?

- UE comes with every event.
- Can't trigger/select it away.
- Gives additional tracks and calorimeter hits, in the same cells as your signal.
- Jet energy scale determination.
- Important systematic error.
- Jets where your signal shouldn't give any (VBF).

Triggers

- Zero bias
  - *Every* event in a perfect 4π detector.

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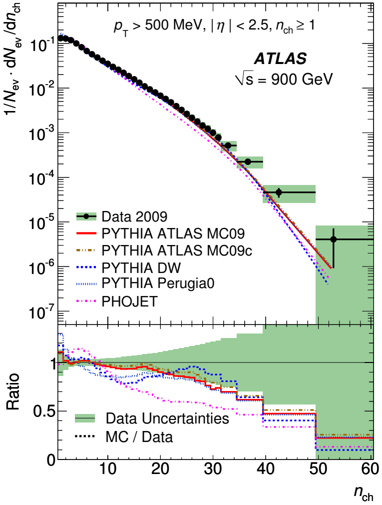
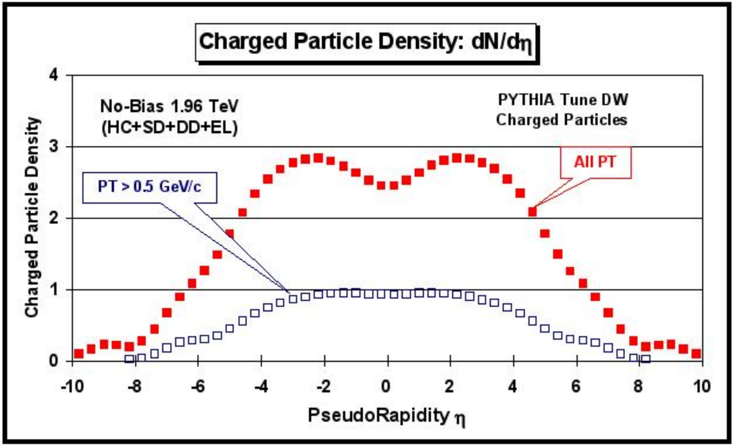
Physics in MB and UE very similar.

Charakteristics of MB events

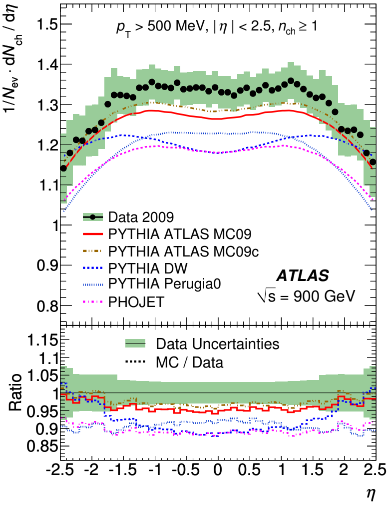
N_{ch}



$dN/d\eta$ Zero bias vs min bias (Tevatron)

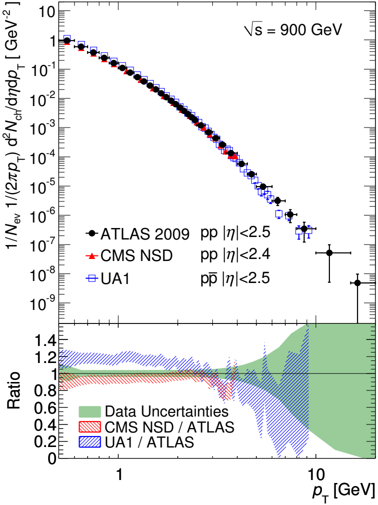


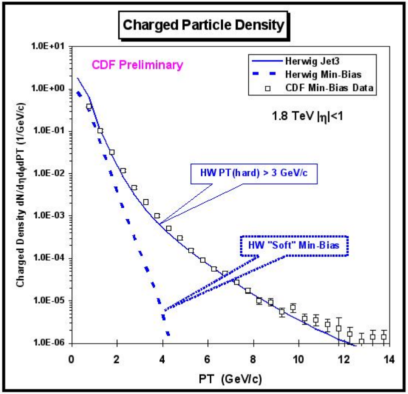
$dN/d\eta$ ATLAS



Charakteristics of MB events

$p_\perp$ spectra of all particles





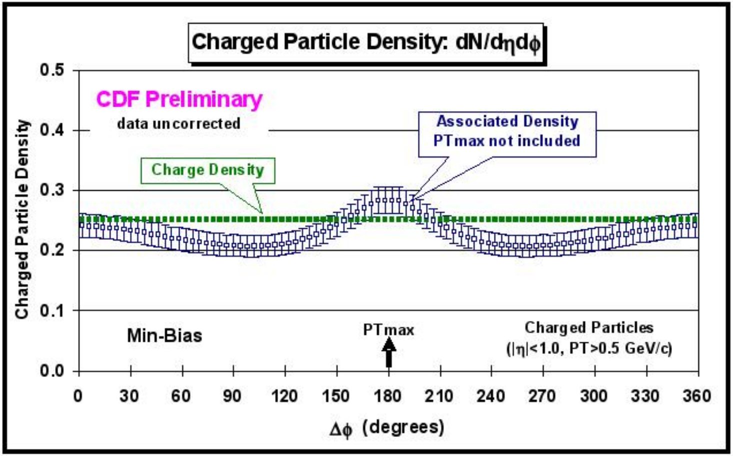
Charakteristics of MB events

- Inclusive quantities have to be correct, of course.
- Already show, that soft component is important in modelling.

Charakteristics of MB events

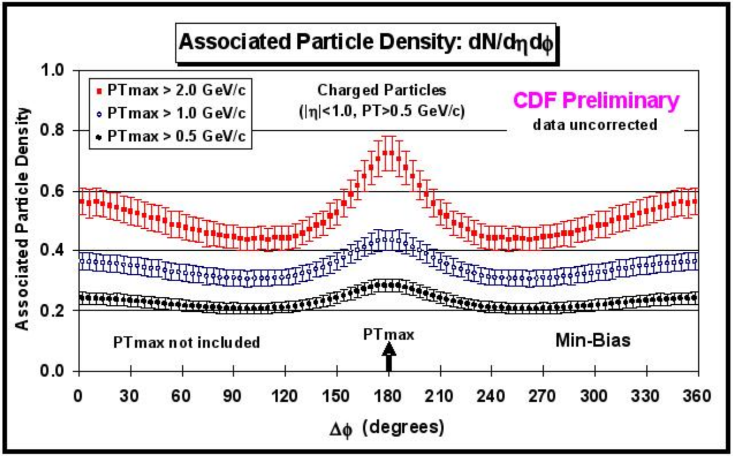
- Inclusive quantities have to be correct, of course.
- Already show, that soft component is important in modelling.
- Don't tell much about morphology of event.
- $\rightarrow$ look at distributions inside detector.
- $\rightarrow$ leading particles.

Measure $\Delta\phi$ relative to leading particle/jet/track.



Azimuthal distributions

Measure $\Delta\phi$ relative to leading particle/jet/track.



Azimuthal distributions

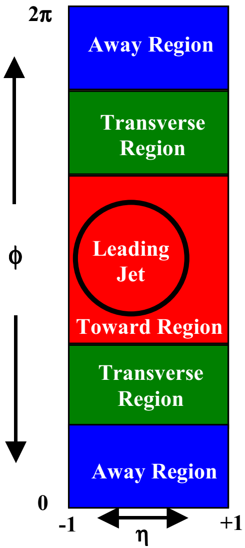
Observation:

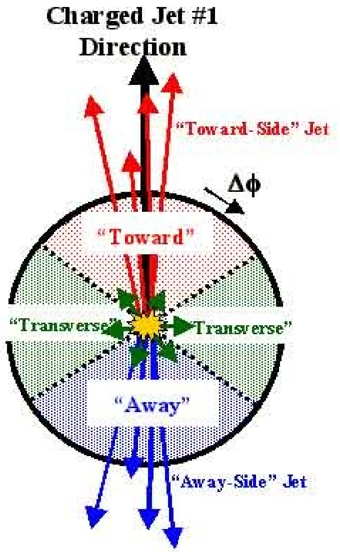
- Events not flat. Have ‘leading object’.
- Harder leading object:
  - $\rightarrow$ harder recoil.
  - $\rightarrow$ more activity everywhere, also transverse.

Trigger: The harder leading object, the more jets are inclusively just below this threshold (pedestal effect).

Closer look at transverse region!
“Rick Field analysis”.

Towards, away, transverse

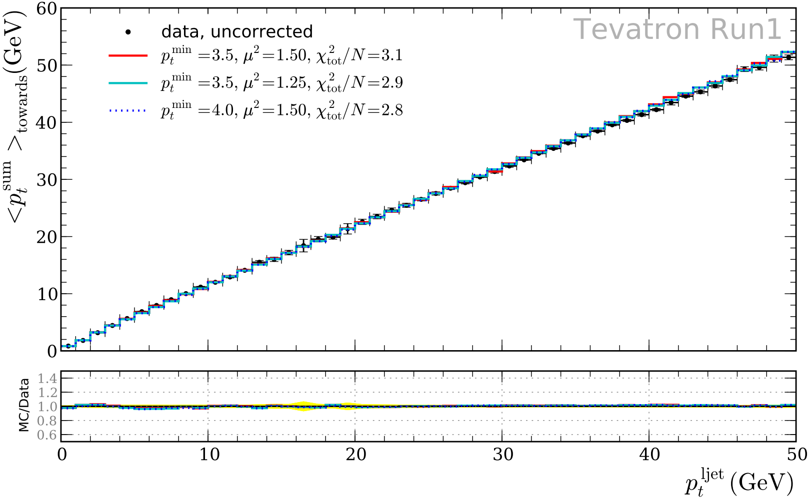




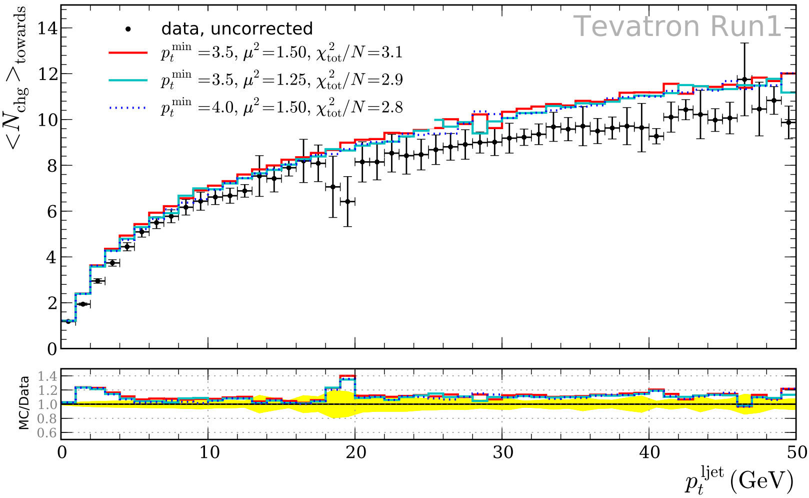
Measurements of the UE: separate from hard bit of event.

- How big is the ‘activity’ in the different regions?
- How does it depend on the leading object?
- If UE is really *underlying*,
  should decouple from leading event.

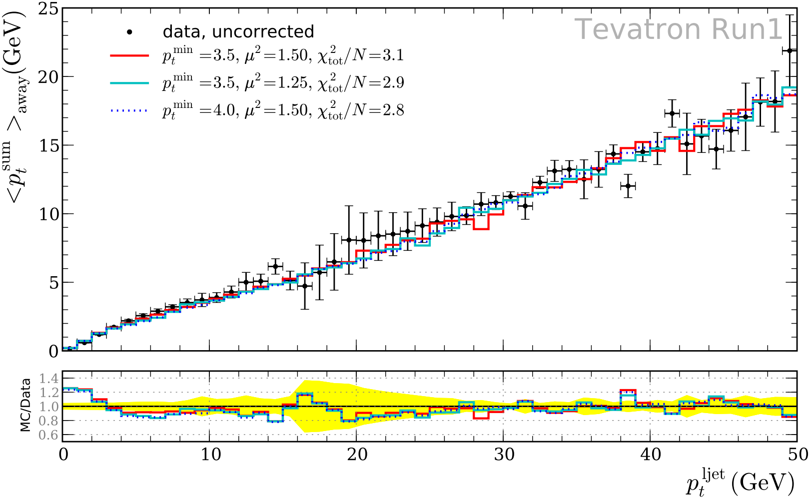
Detailed look at observables: Towards Region



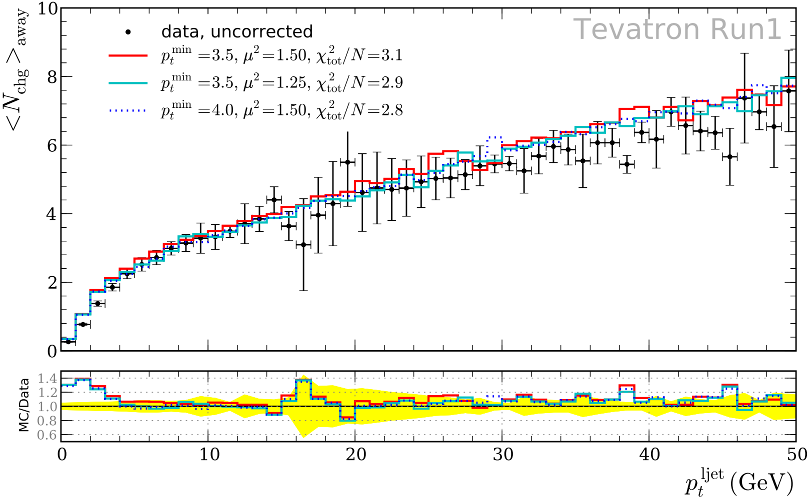
Detailed look at observables: Towards Region



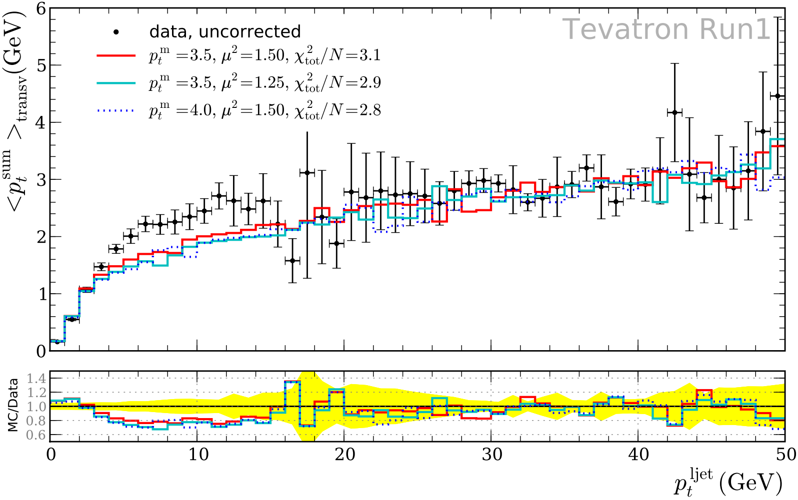
Detailed look at observables: Away Region



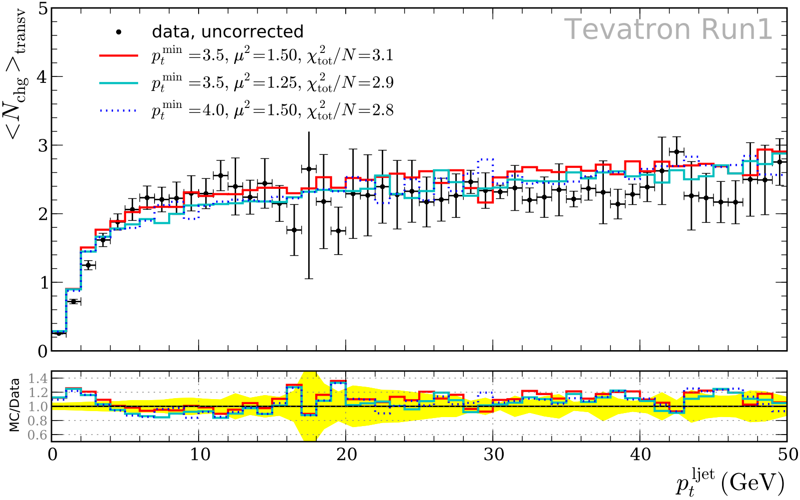
Detailed look at observables: Away Region



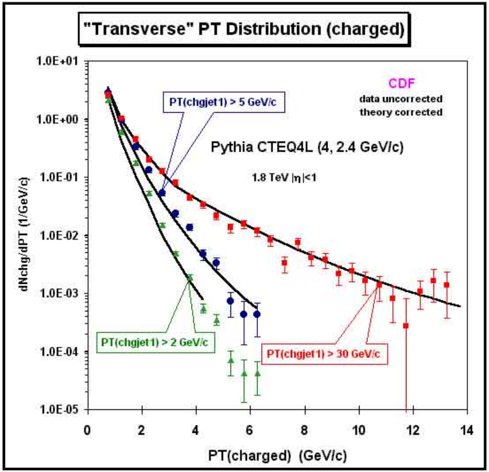
Detailed look at observables: Transverse Region



Detailed look at observables: Transverse Region

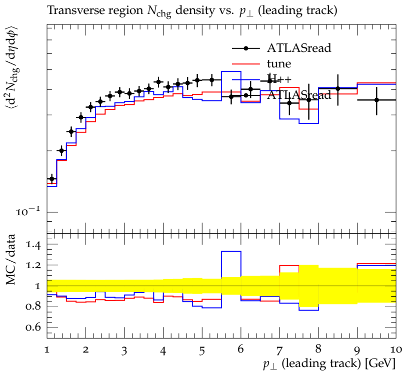


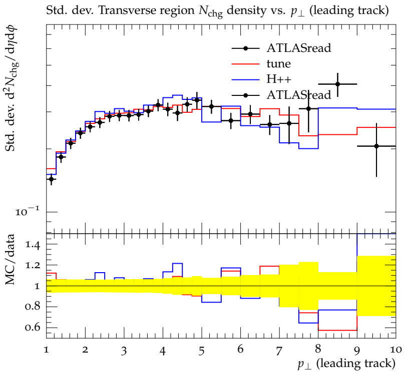
Spectrum in transverse region



Not only average important. The UE has a jetty substructure!

Also include Std deviation!





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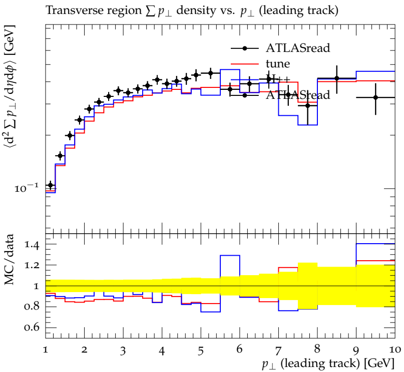
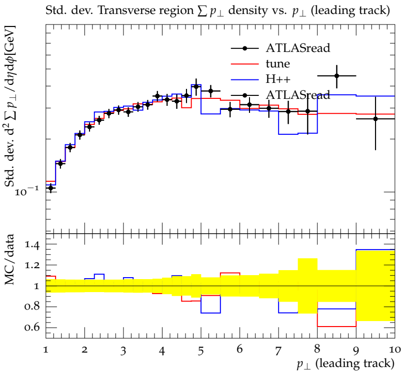
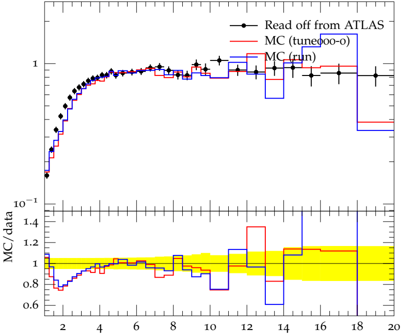
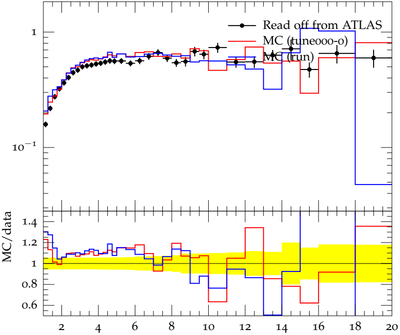




N_{ch}/StdDev transverse vs p_t^{lead}/GeV.



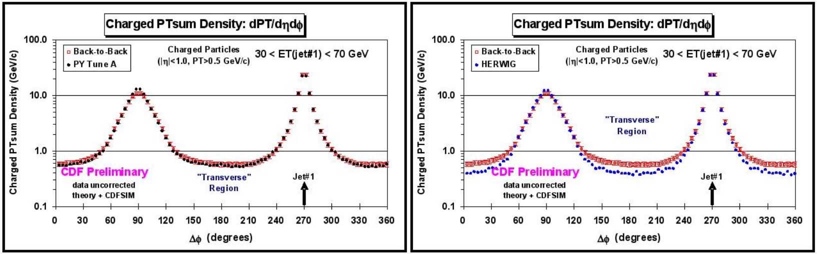


So far

- Idea of decoupling UE from hard event seems to hold.
- UE has jetty structure.
- Must contain hard physics as well.

More azimuthal distributions

Require at least two nearly b2b jets.
Dominated by hard physics.



Old Herwig soft model not sufficient.

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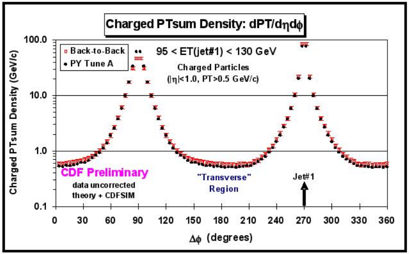
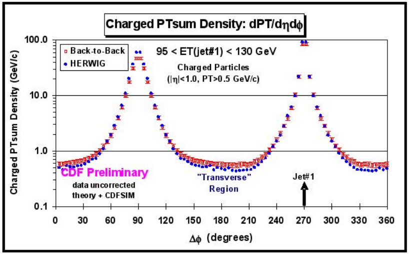
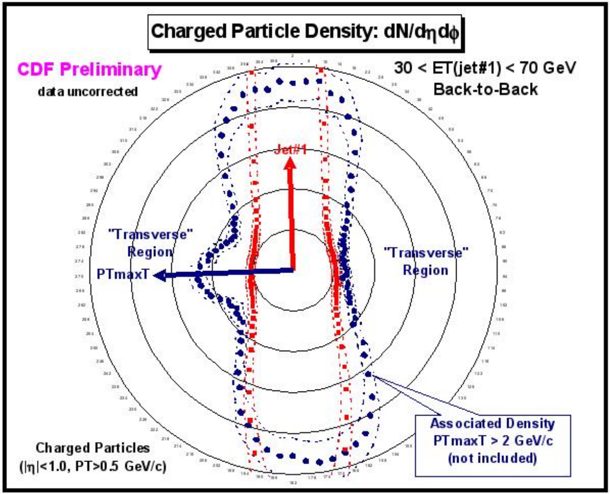




Better with harder jets.

Now select the hardest of the two transverse regions only (TransMAX): associated distribution:



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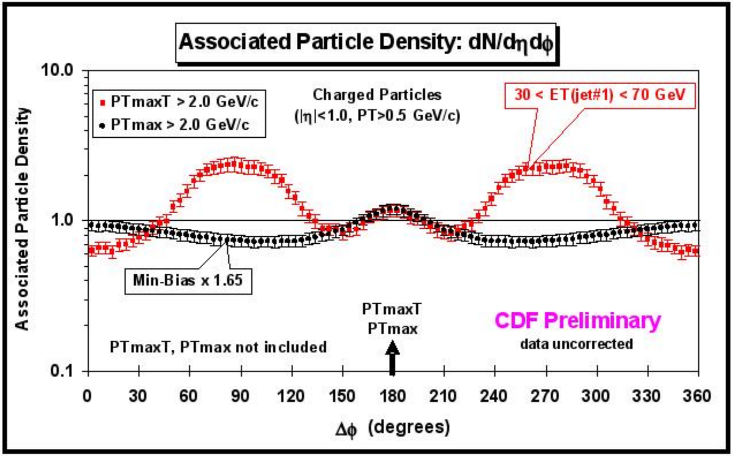
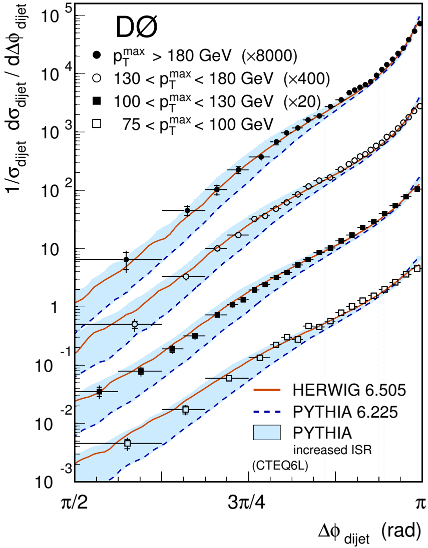


Birth of 3rd jet $\sim$ leading jet in MinBias

Hard dijets



Angles between hard jets modeled by parton showers.

Towards modelling

- Leading jet in Minimum bias $\sim$ 3rd jet in back–to–back sample.
- UE and MB really seem to reflect the same physics.
- Hard component important.
- Hard jets not sufficient
  (but well described $\rightarrow$ D0 dijet angular decorrelation).

Hard jets in the UE via multiple interactions?

- Additional Partonic $2 \rightarrow 2$ interactions (MPI).
- No correlation with hard event.

N_{ch} distribution (vs UA5; Sjöstrand, van Zijl (1987))

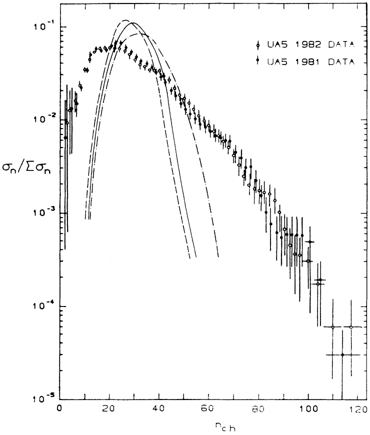


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

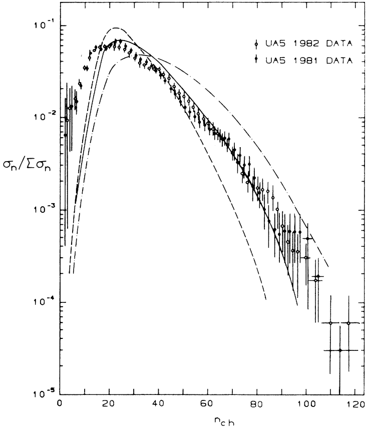


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

no MPI (left)/MPI (right).

Indirect evidence for MPI

FB correlation in η bins (vs UA5; Sjöstrand, van Zijl (1987))

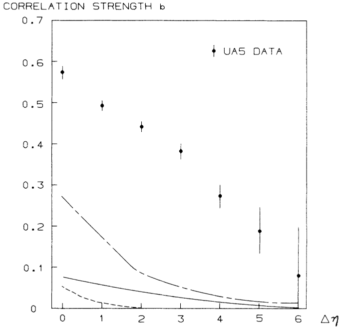


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

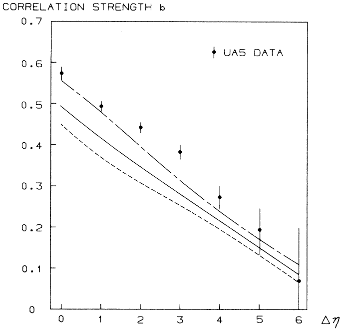
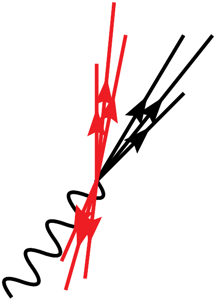


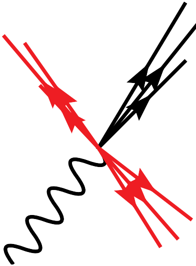
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

no MPI (left)/MPI (right).

Evidence for MPI

Angle ϕ from 4 final state objects (jets, γ).

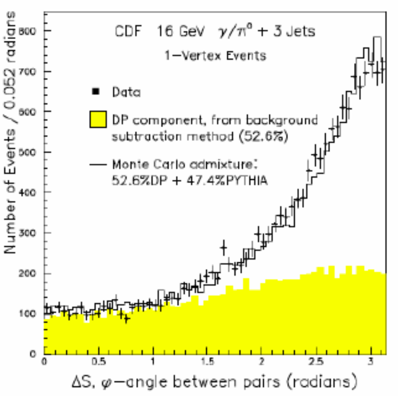




Evidence for MPI

Angle ϕ from 4 final state objects (jets, γ). CDF ('97).

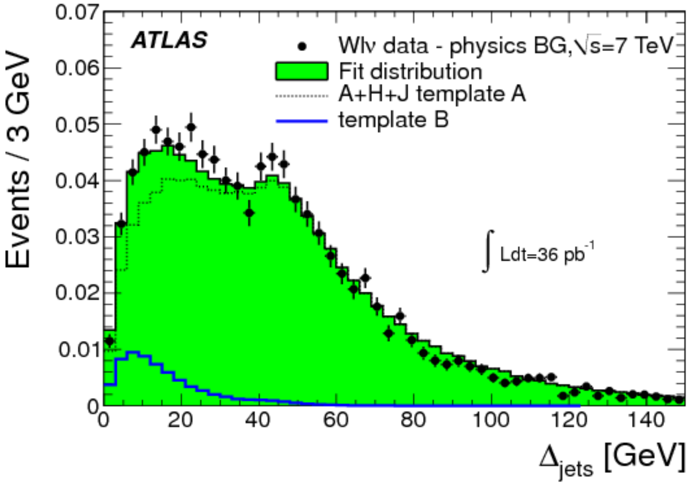
$$\phi = \angle(\vec{p}_1 \pm \vec{p}_2, \vec{p}_3 \pm p_4)$$



53% double parton scattering needed!

Evidence for MPI

Angle ϕ from 4 final state objects (jets, γ). LHC 2013 ($W^{\pm}$).



$\Delta_{\text{jets}} = |\vec{p}_T^{J1} + \vec{p}_T^{J2}| \sim 0$ for DPI.

Modelling (in Herwig++)

Semihard UE

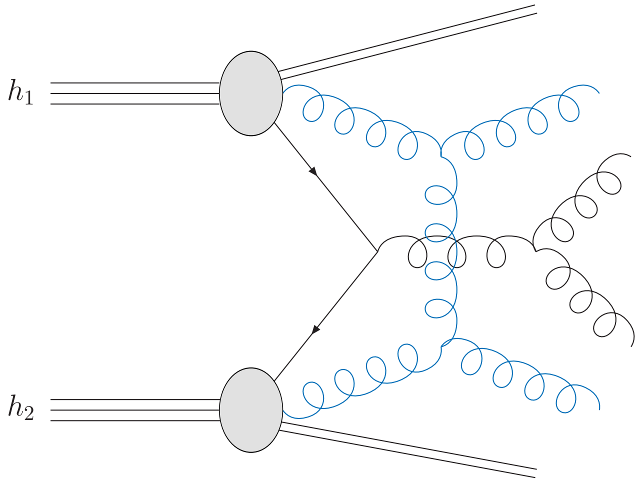
- Default from Herwig++ 2.1. [Herwig++, 0711.3137]
- Multiple hard interactions, $p_t \leq p_t^{\mathrm{min}}$. [Bähr, SG, Seymour, JHEP 0807:076]
- Similar to JIMMY.
- Good description of harder Run I UE data (Jet20).

Underlying event in Herwig++

Soft UE

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions $p_t < p_t^{\rm min}$.
- Relation to total cross section, Exploration of parameter space.
- Extrapolation to LHC?
- Theoretical work with simplest possible extension.
  [Bähr, Butterworth, Seymour, JHEP 0901:065]
- “Hot Spot” model. [Bähr, Butterworth, SG, Seymour, 0905.4671]

Mulitple hard interactions



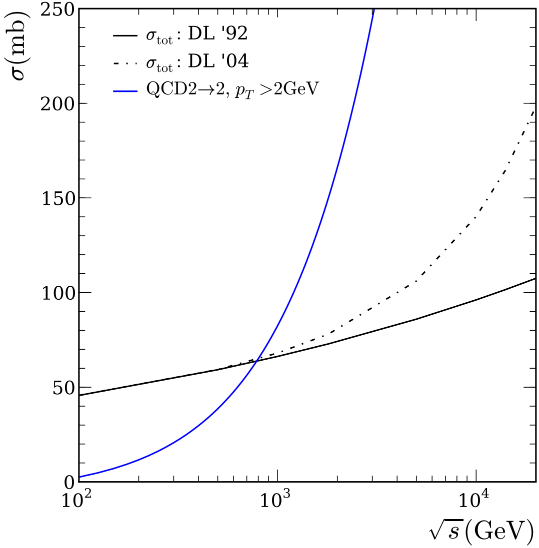
Eikonal model basics

Starting point: hard inclusive jet cross section.

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

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

Eikonal model basics



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

Interpretation: $\sigma^{\rm inc}$ counts *all* partonic scatters that happen during a single *pp* collision $\Rightarrow$ more than a single interaction.

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

Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

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

Then we get σ_{inel}:

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

Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

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Then we get σ_{inel}:

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

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.

Eikonal model basics

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

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|)$$

Eikonal model basics

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

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

Eikonal model basics

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

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

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$$\times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|)$$

$$= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\min}) \ .$$

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

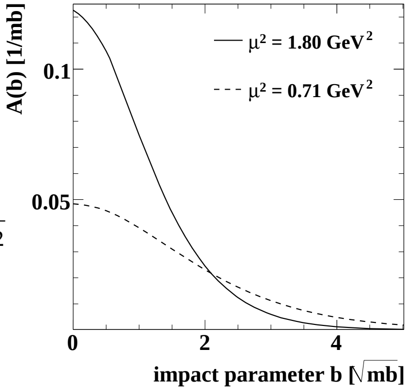
Overlap function

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

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

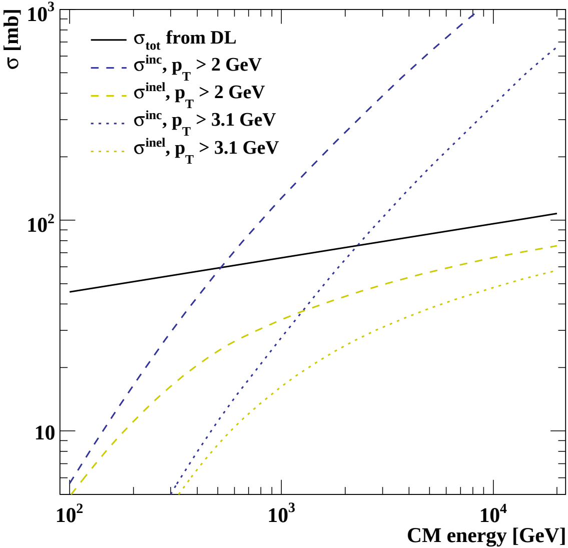
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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



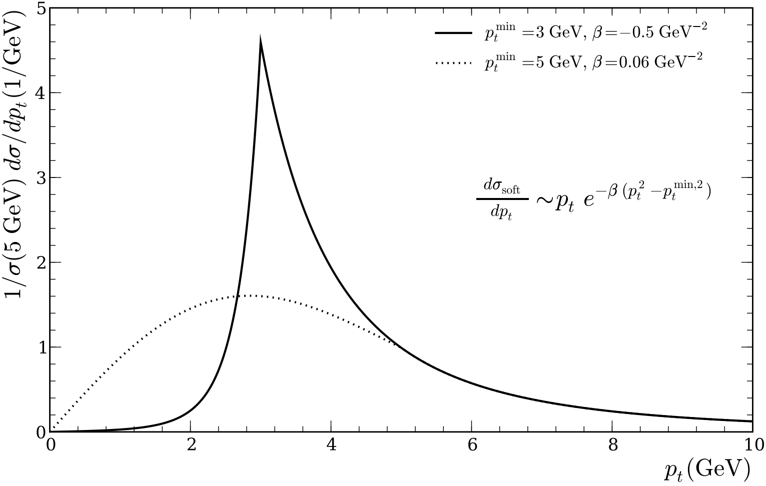
⇒ Two main parameters: $\mu^2, p_t^{\min}$.

Unitarized cross sections



Extending into the soft region

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



Hot Spot model

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

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

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

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

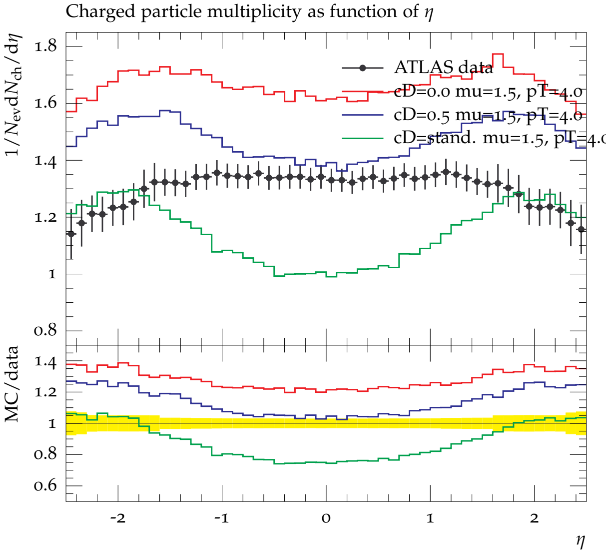
$$b_{\rm el}(s) \stackrel{!}{=} \int {\rm d}^2\vec{b}\,\frac{b^2}{\sigma_{\rm tot}}\left(1 - {\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) \ .$$

First plots against LHC data

- Not all aspects well described.
- Despite very good agreement with Rick Field's CDF UE analysis.
- Observe sensitivity to colour structure.

First plots against LHC data

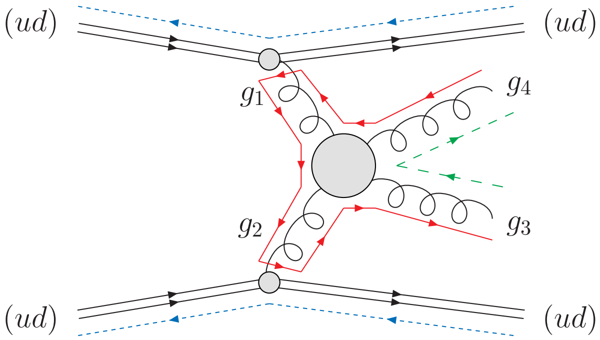
Colour structure of soft events.



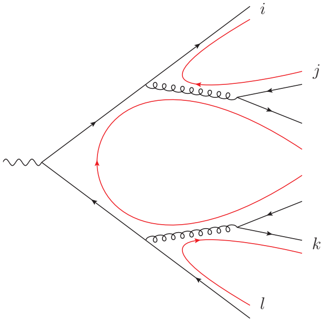
Sensitivity to parameter

$$\texttt{colourDisrupt} = P(\text{disrupt colour lines})$$

(as opposed to hard QCD).



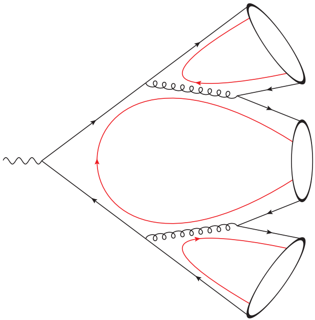
Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs

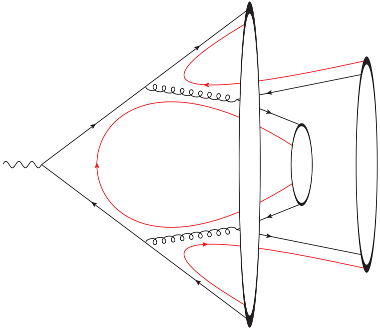
Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

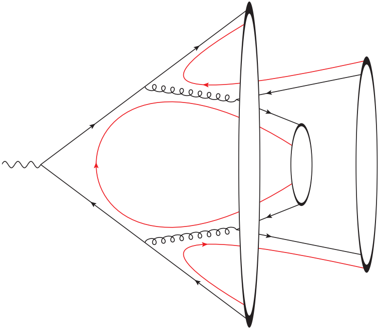
- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*

Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$



Extend cluster hadronization:

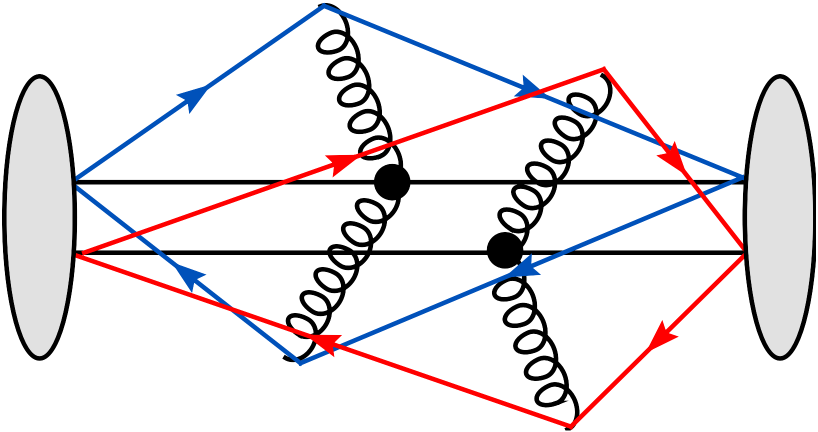
- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$

- Allow CR if the cluster mass decreases,

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

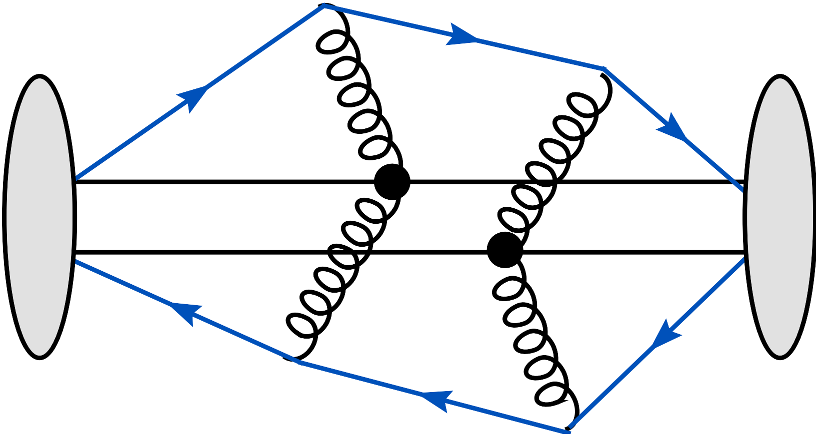
- Accept alternative clustering with probability p_{reco} (model parameter) $\Rightarrow$ this allows to switch on CR smoothly

Colour reconnection at hadron colliders



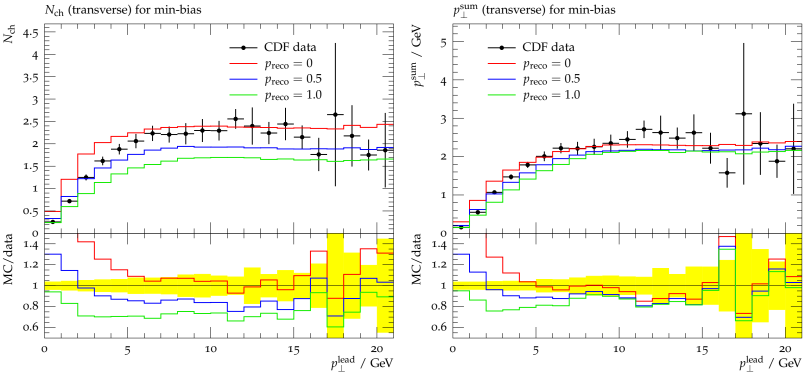
- Colour preconfinement
- Shorten colour string/lower mass clusters.

Colour reconnection at hadron colliders



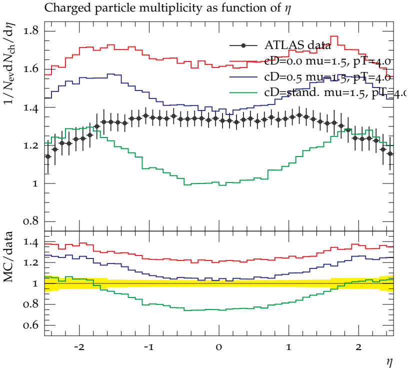
- Colour preconfinement
- Shorten colour string/lower mass clusters.

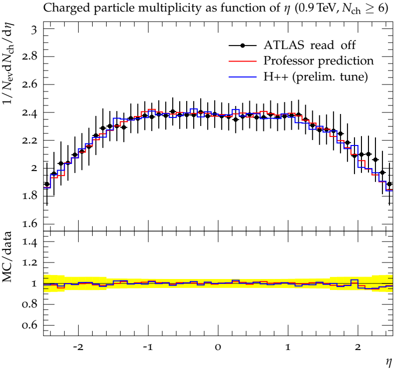
A quick look at CDF data



Sensitivity different for the two observables.

Comparison with MinBias ATLAS data (900 GeV)





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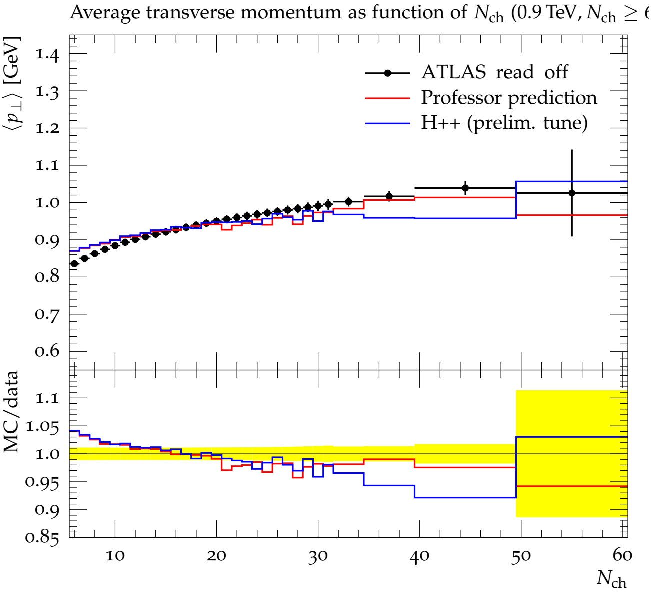
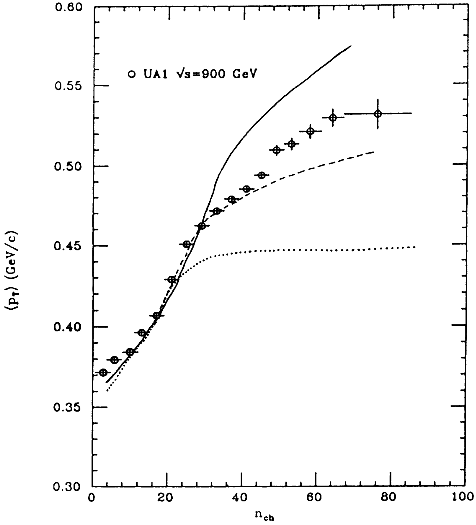


Colour reconnections



- Sensitivity to CR already known from UA5.
- (From Sjöstrand / van Zijl)

Summary

- MPI (with colour reconnections) currently model of choice.
- Describes averages *and* fluctuations.
- Not always universal, but all models tunable.
- soft component needed for MB modelling.
- Constraints from inclusive cross sections.
- Different emphasis on hard/soft modelling between generators.
- Many details still only models.

Take home

At hadron colliders:

- Underlying event is everywhere.
- Min bias is everywhere (pile–up).
- Both contain similar physics.
- The underlying event is “lumpy”.
  It contains soft AND hard physics.
  Important to get fluctuations as well as averages.
- Important effects based on Multiple Partonic Interactions.

Modelling in Herwig++:

- MPI model well capable to describe recent data.
- Colour reconnections vital for model.
- No Diffraction in model.

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Outline Part V

- Collider cross sections
- Zero bias, Min bias, Underlying event
- Inclusive $\rightarrow$ exclusive. The structure of underlying events.
- Multiple interactions.

Outline

- Part I — Basics
  - Introduction
  - Monte Carlo techniques
- Part II — Perturbative physics
  - Hard scattering
  - Parton showers
- Part III — Merging/Matching
  - Matrix element corrections
  - Merging multiple tree level MEs with parton showers
  - Matching NLO and parton showers
- Part IV — Non–perturbative physics
  - Hadronization
  - Hadronic decays
  - Comparison to data
- Part V — Multiple Partonic Interactions
  - Minimum Bias/Underlying Event in data
  - Modelling