Underlying Event II

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Outline

- Lecture I — Underlying Event: Introduction.
  - Triggers, harder triggers, experimental facts.
- Lecture II — Underlying Event: Modelling.
  - Mostly Herwig++

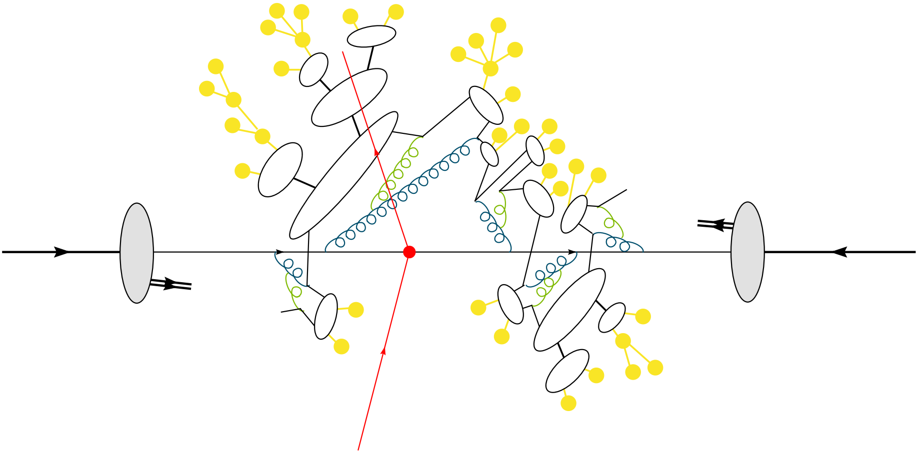
Outline Lecture II

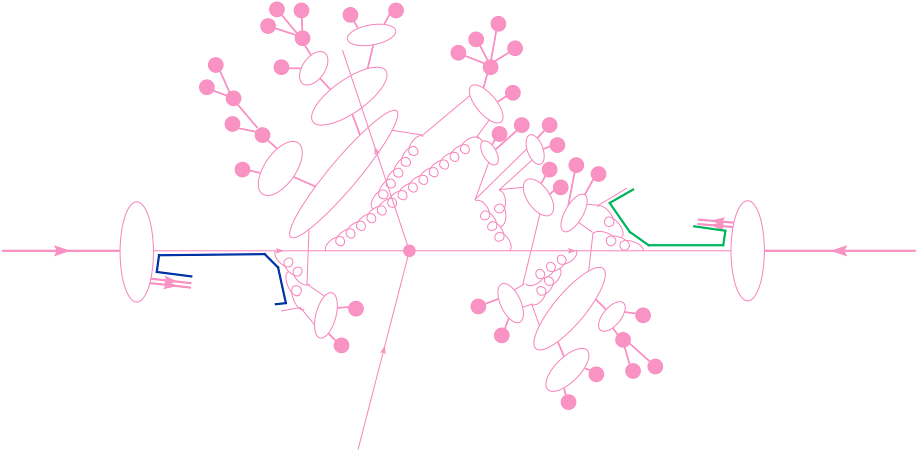
- Soft UE model (UA5).
- Hard MPI model.
- Soft MPI model.

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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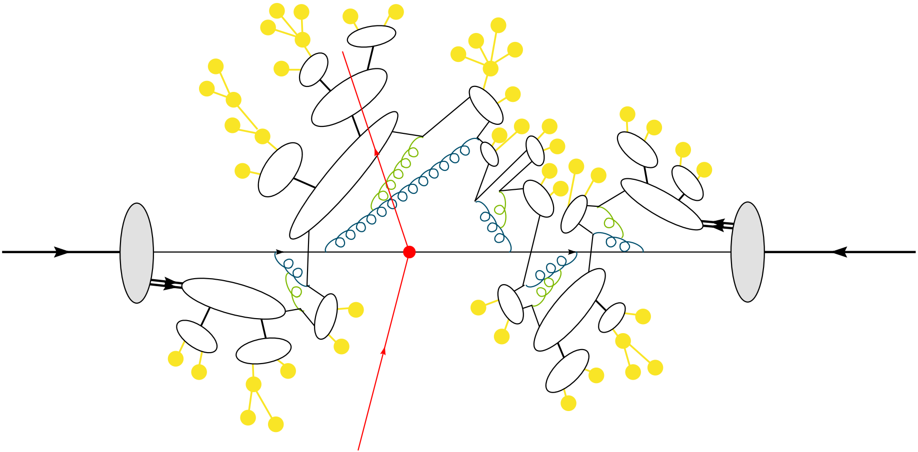
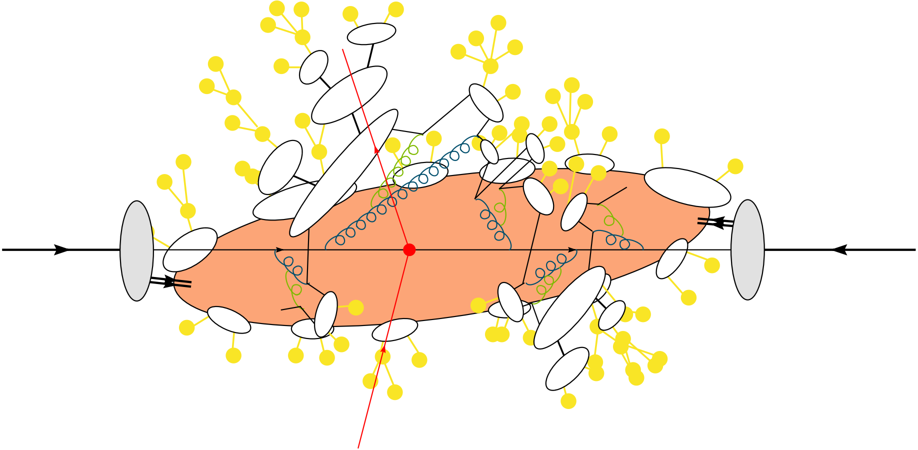


No UE model

Just remnant clusters

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

pp Event Generator



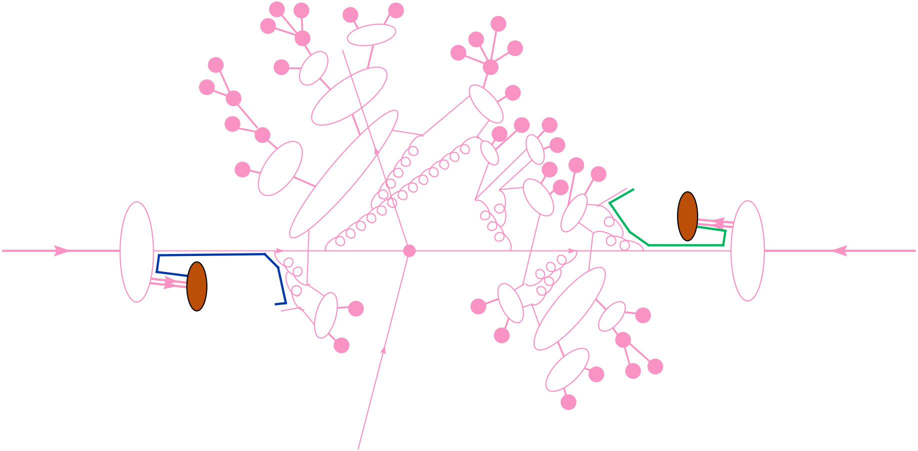
UA5 model

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 Superseded by `JIMMY`.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)]

pp Event Generator



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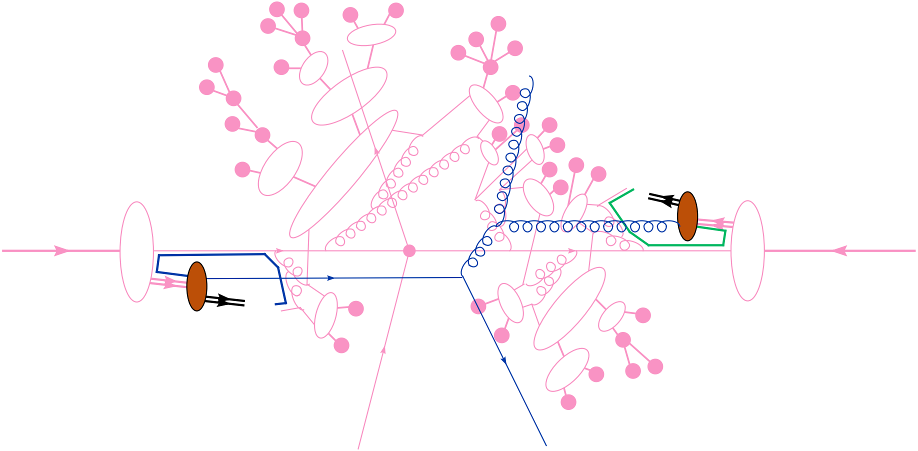

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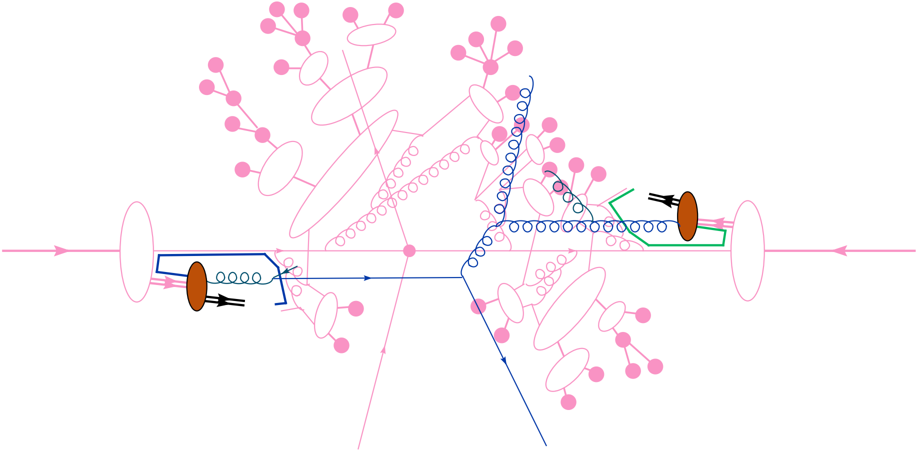

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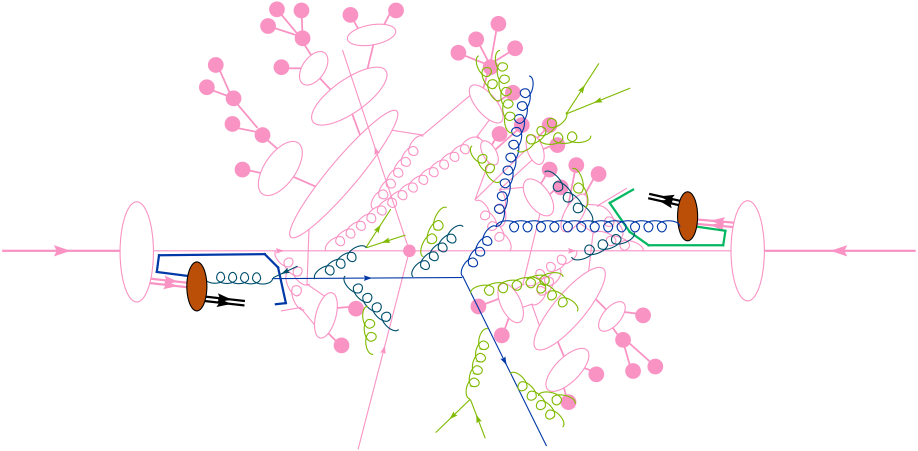

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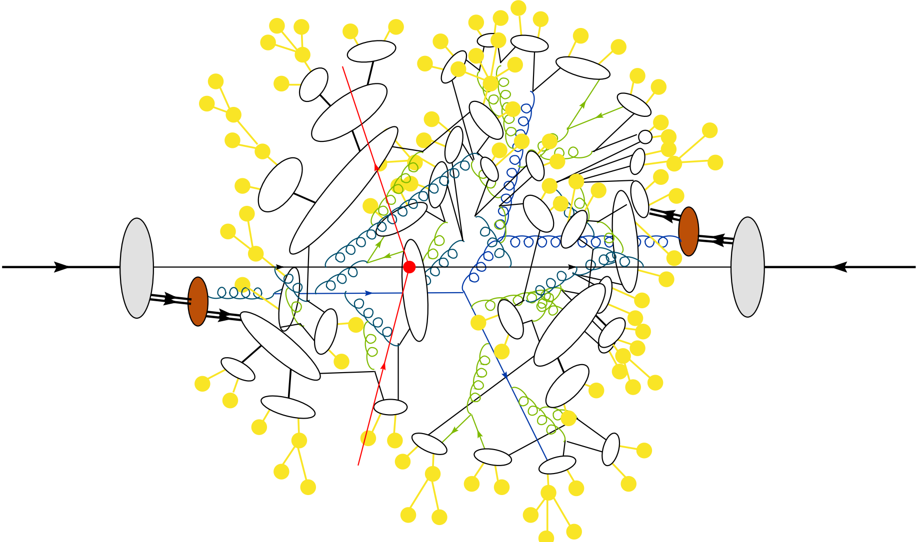

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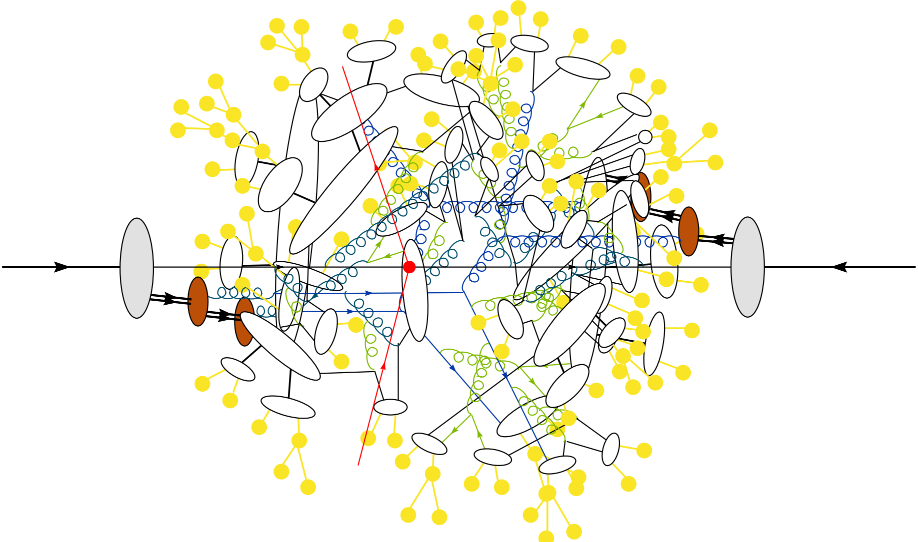


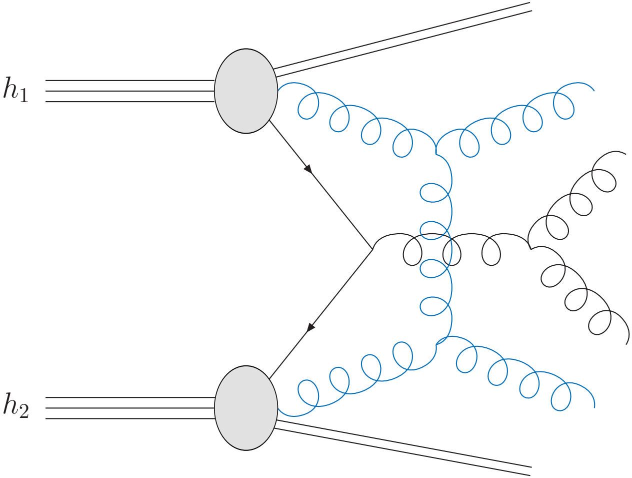
Semihard UE

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

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



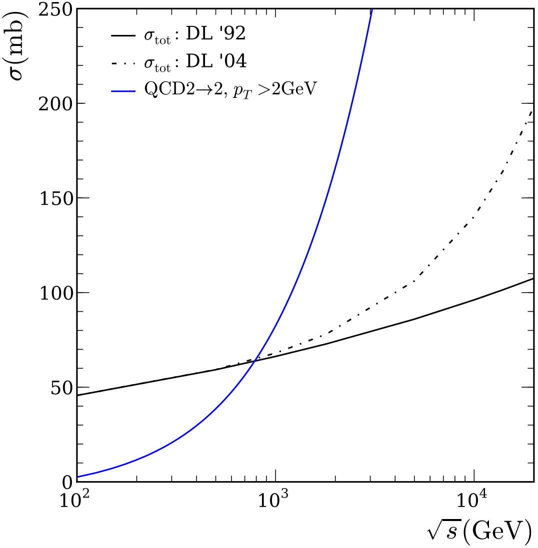
Eikonal model basics

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,

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

Then we get $\sigma_{\rm inel}$:

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

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

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:

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

Eikonal model basics

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

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

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

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

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

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

Overlap function

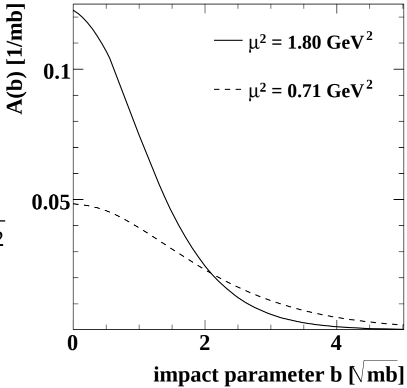
$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

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

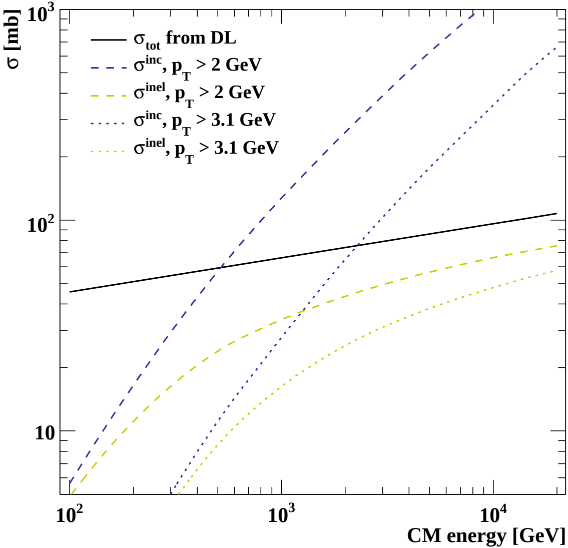
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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

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

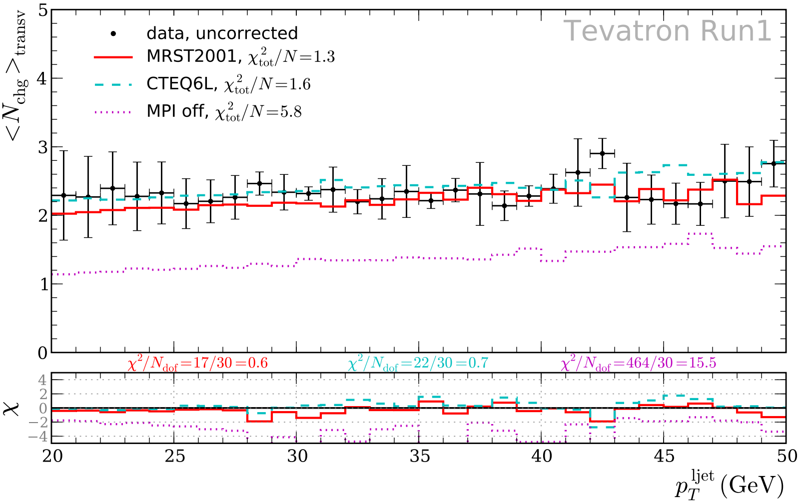


Unitarized cross sections



Semi hard underlying event

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



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

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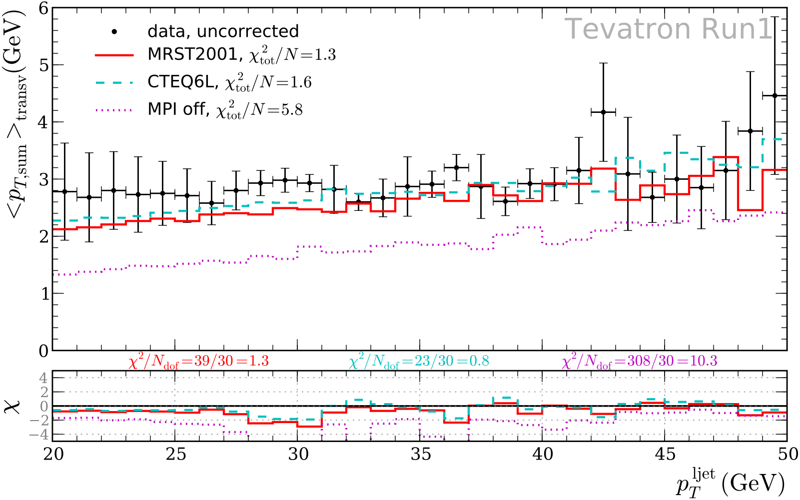


Only $p_T^{\rm ljet} > 20\,{\rm GeV}$.

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:

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

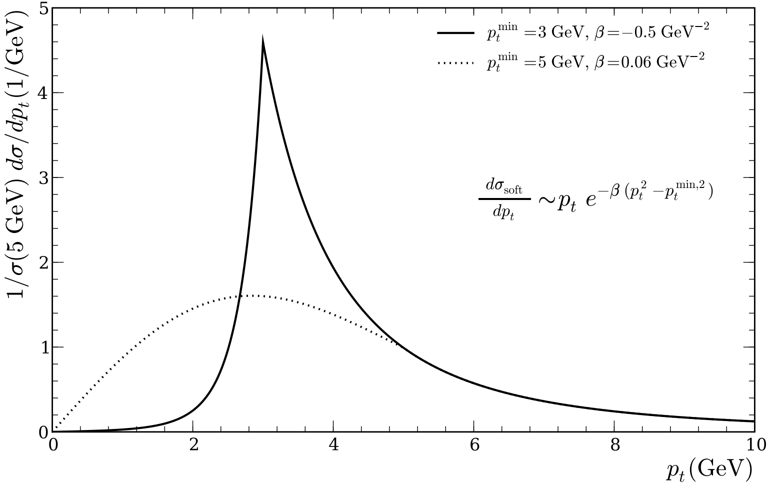
Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

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

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)



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

Exploit knowledge of σ_{tot} in eikonal model:

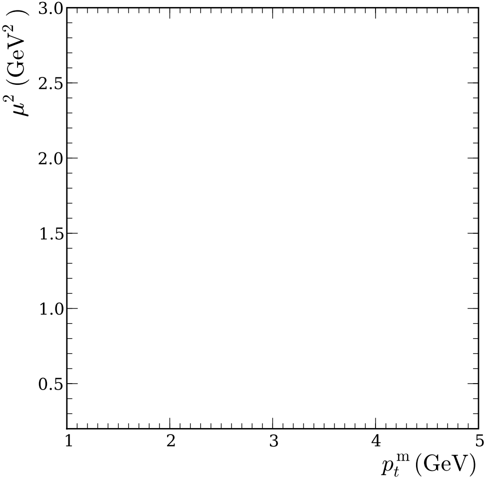
$$\sigma_{\mathrm{tot}} = 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\chi_{\mathrm{tot}}(\vec{b},s)}\right)$$
$$= 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\frac{A(\vec{b};\mu)}{2}(\sigma_{\mathrm{hard}}^{\mathrm{inc}}+\sigma_{\mathrm{soft}}^{\mathrm{inc}})}\right)$$

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

Energy extrapolation from Donnachie–Landshoff

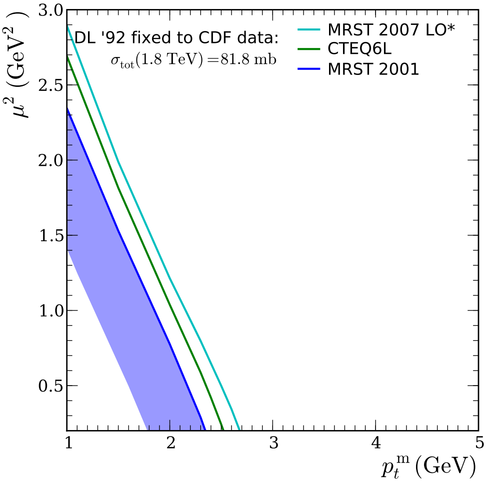
- DL ’92 [D&L, PLB296, 227 (1992)]
- DL ’92 normalized at TVT
- DL ’04 [D&L, PLB595, 393 (2004)]

- Find constraints on $(p_t^{\min}, \mu)$.



Constraints at the Tevatron

- Find constraints on $(p_t^{\min}, \mu)$.
- Require $\sigma_{\text{soft}}^{\text{inc}} > 0$ mb, while describing σ_{tot}.

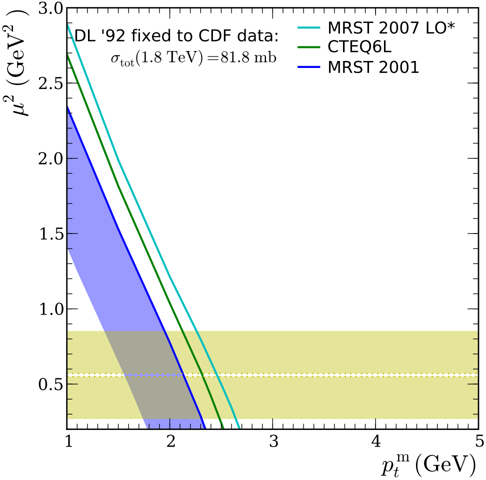


- Find constraints on $(p_t^{\min}, \mu)$.
- Require $\sigma_{\text{soft}}^{\text{inc}} > 0$ mb, while describing σ_{tot}.
- Require elastic t-slope,

$$b_{\text{el}}(s) = \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\ln \frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t}\right)\right]_{t=0},$$

to be correctly described

$$b_{\text{el}}(s) = \int \mathrm{d}^2\vec{b}\,\frac{b^2}{\sigma_{\text{tot}}}\left[1 - \mathrm{e}^{-\chi_{\text{tot}}}\right] .$$



Constraints at the Tevatron

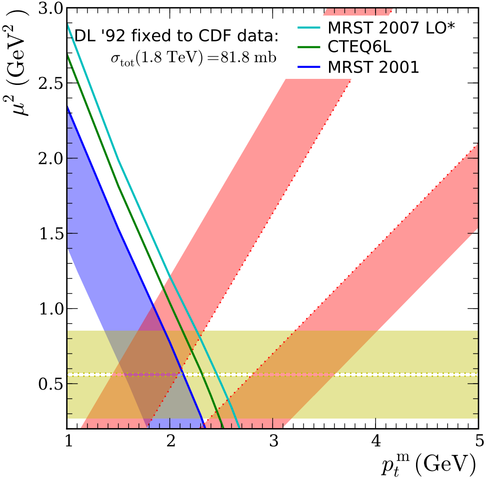
- Find constraints on $(p_t^{\min}, \mu)$.
- Require $\sigma_{\rm soft}^{\rm inc} > 0$ mb, while describing $\sigma_{\rm tot}$.
- Require elastic t-slope,

$$b_{\rm el}(s) = \left[\frac{{\rm d}}{{\rm d}t}\left(\ln \frac{{\rm d}\sigma_{\rm el}}{{\rm d}t}\right)\right]_{t=0},$$

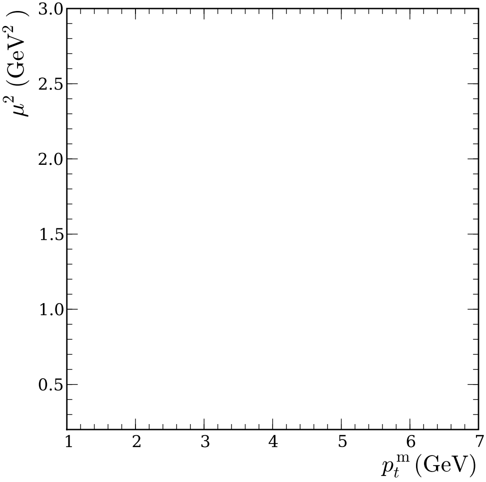
to be correctly described

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

- Final state tune of **semi-hard** MPI (MRST2001)

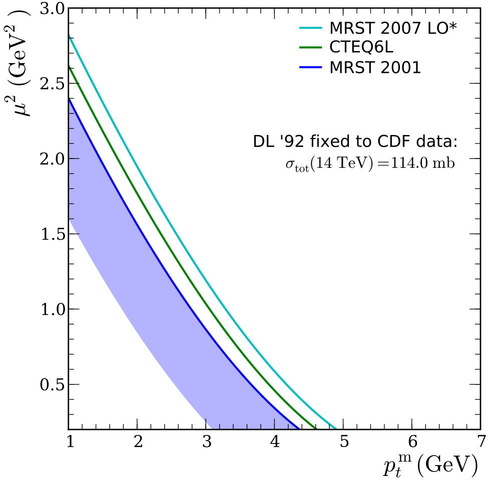


- What to expect at 14 TeV?

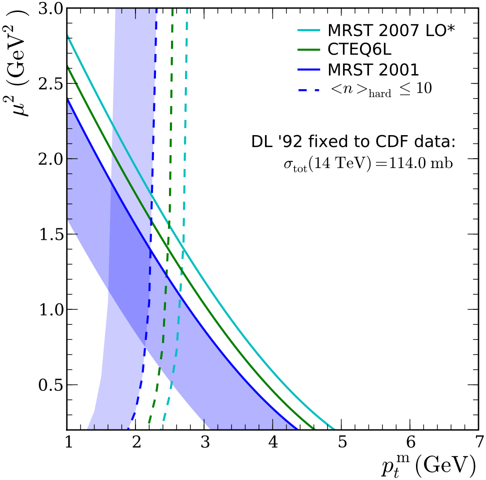


Constraints at the LHC

- What to expect at 14 TeV?
- $\sigma_{\text{soft}}^{\text{inc}} > 0$ mb. σ_{tot} from Regge fit



- What to expect at 14 TeV?
- $\sigma_{\rm soft}^{\rm inc} > 0$ mb. $\sigma_{\rm tot}$ from Regge fit
- Require $\bar{n}_{\rm hard} < 10$

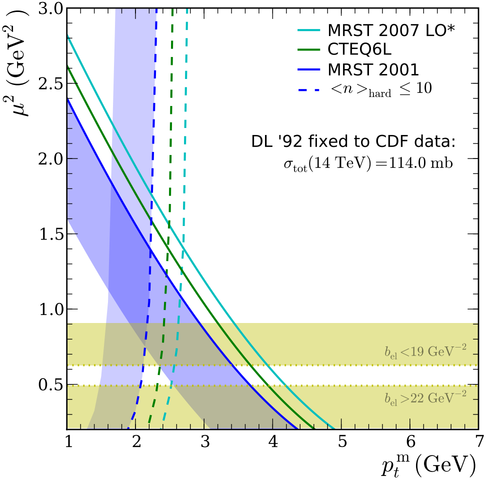


Constraints at the LHC

- What to expect at 14 TeV?
- $\sigma_{soft}^{inc} > 0$ mb. σ_{tot} from Regge fit
- Require $\bar{n}_{hard} < 10$
- Require elastic t-slope to be correctly described. Get range of possible measurements from DL '92 and predictions for b_{el}

[Khoze, Martin, Ryskin, 0710.2494]

[Gotsman, Levin, Maor, 0708.1506]



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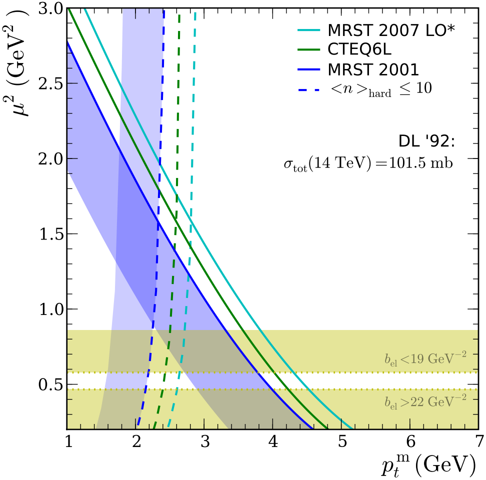

Constraints at the LHC

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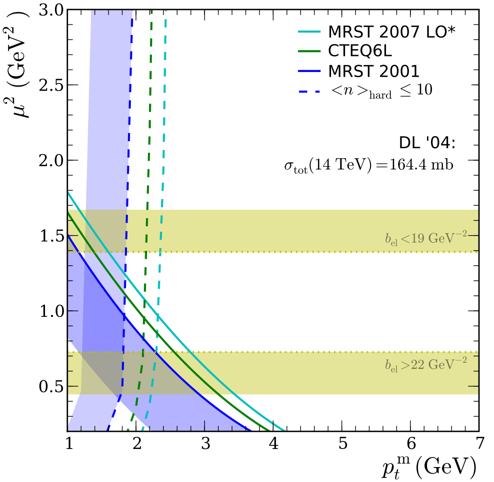


Observations

- $\sigma_{\rm soft}^{\rm inc}$ rises artificially fast (expect $\sim s^{0.08}$).
- Forced to have energy dependent parameters (would like to have the choice, i.e. let measurements decide).
- Measurement of $b_{\rm el}$ fixes μ^2 at Tevatron:

$$\mu^2 = 0.56 \pm 0.01\,{\rm GeV}^2$$

$\sigma_{\rm eff} = (\int {\rm d}^2\vec{b} A^2(b))^{-1}$ as measured by CDF in $\gamma + 3j$:

$$\mu^2 = 3.0 \pm 0.5{\rm GeV}^2\ .$$

→ Relax the constraint of identical overlap functions:

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

If $\mu > \mu_{\rm soft}$: Hot Spots

Hot Spot model

Fix the two parameters μ_{soft} and $\sigma^{\text{inc}}_{\text{soft}}$ in

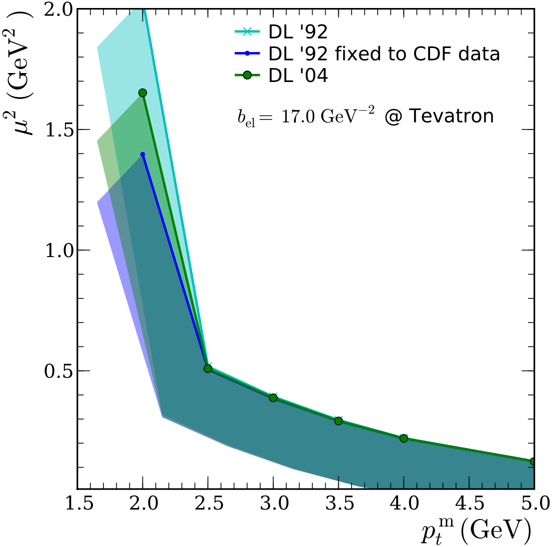
$$\chi_{\text{tot}}(\vec{b},s) = \frac{1}{2}\left(A(\vec{b};\mu)\sigma^{\text{inc}}\text{hard}(s;p_t^{\text{min}}) + A(\vec{b};\mu_{\text{soft}})\sigma^{\text{inc}}_{\text{soft}}\right)$$

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

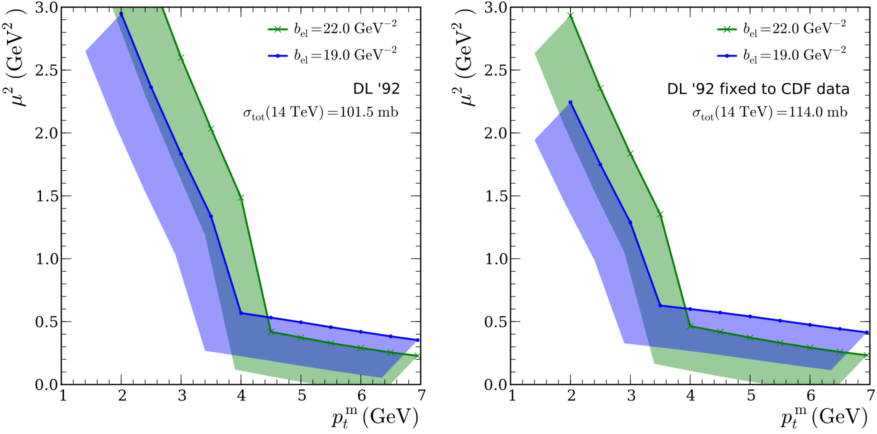
$$\sigma_{\text{tot}}(s) \stackrel{!}{=} 2\int \mathrm{d}^2\vec{b}\left(1 - \mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) \ ,$$

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

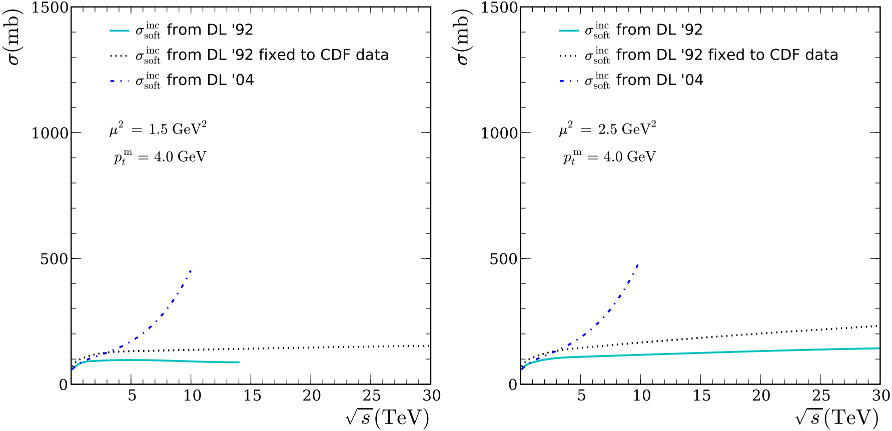
Only one constraint: describe $\sigma_{\rm tot}$ and $b_{\rm el}$.



Same for LHC except for uncertainty in $b_{\rm el}$ and $\sigma_{\rm tot}$.



Resulting soft cross section

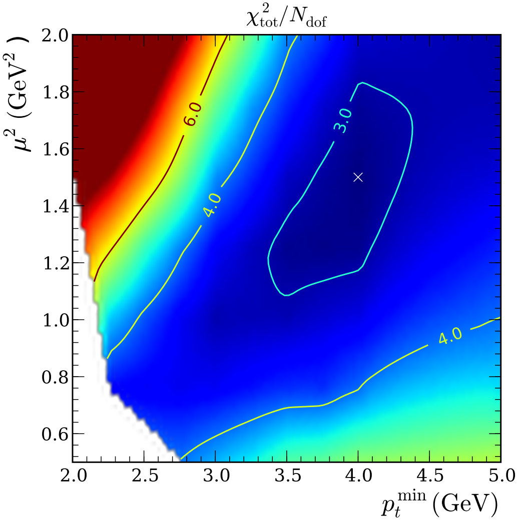


Tevatron Run I final states

- 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 $(p_t^{\min}, \mu^2)$.
- Look at χ^2/dof for Tevatron Run I data in the $(p_t^{\min}, \mu^2)$ plane.

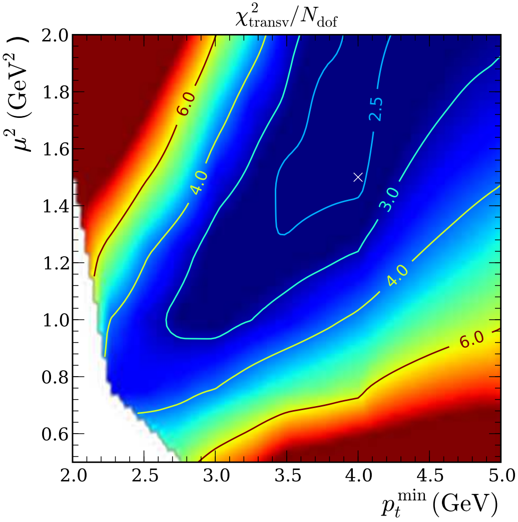
Parameter space at Tevatron

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

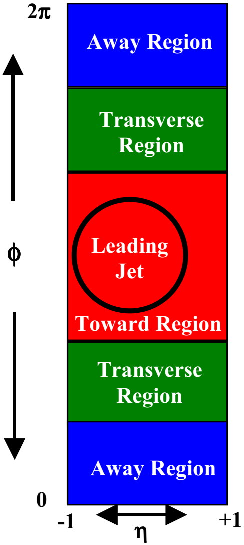


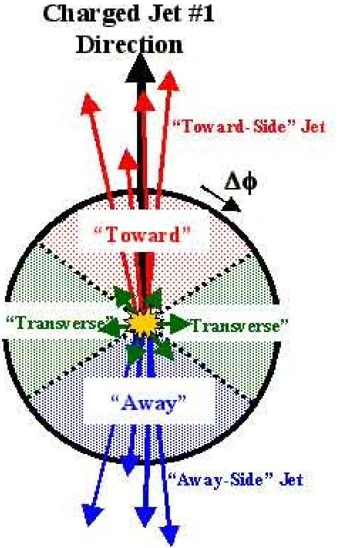
Parameter space at Tevatron

- χ^2 for Rick's Run1 Jet analysis for **all** regions
- only the transverse region

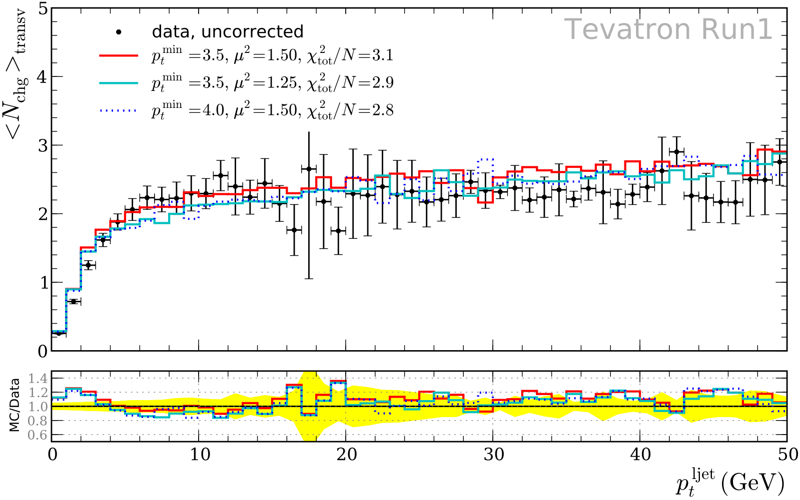


Rick Field's analysis

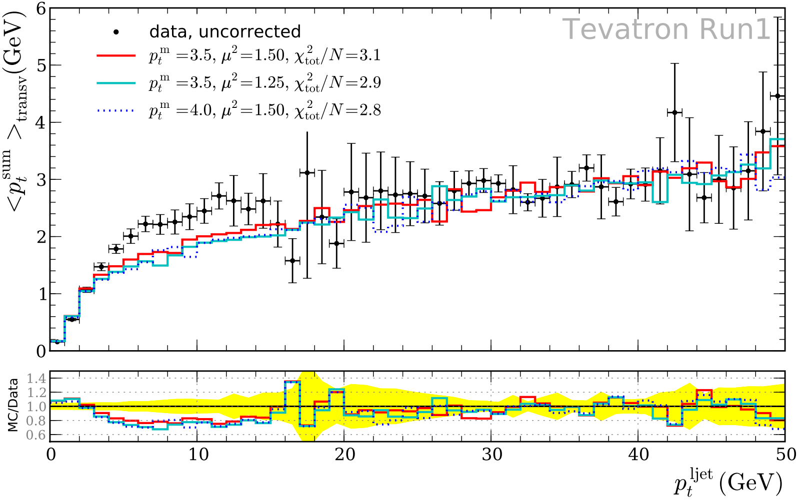




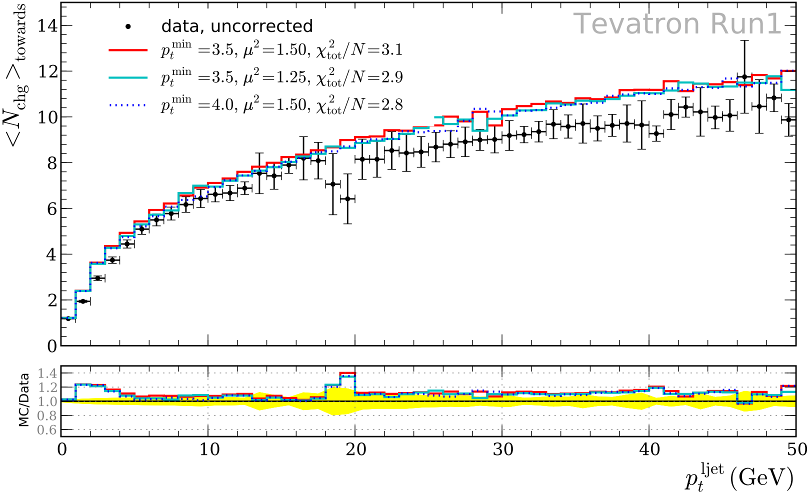
Detailed look at observables: Transverse Region



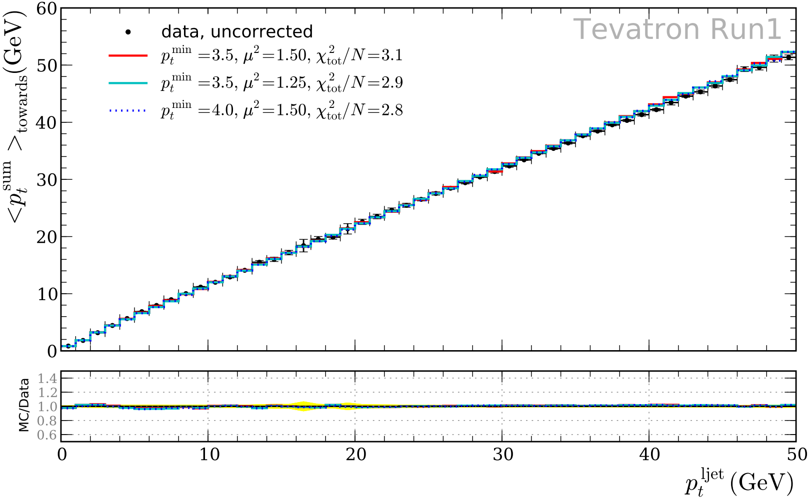
Detailed look at observables: Transverse Region



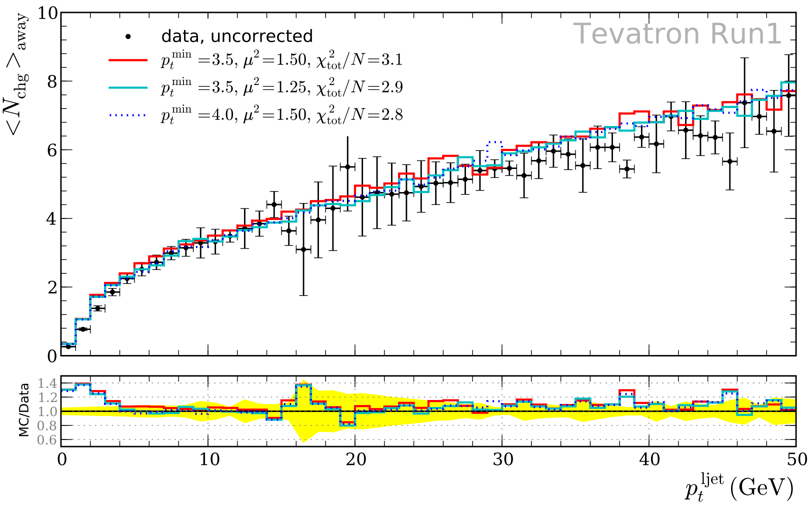
Detailed look at observables: Towards Region



Detailed look at observables: Towards Region



Detailed look at observables: Away Region



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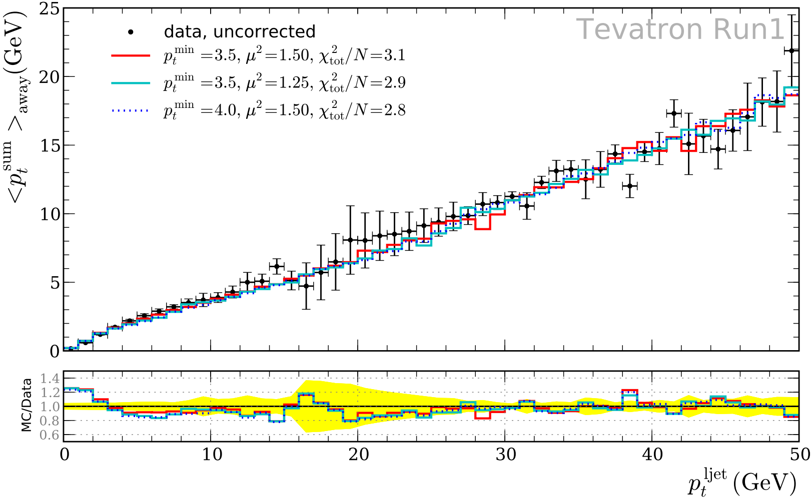
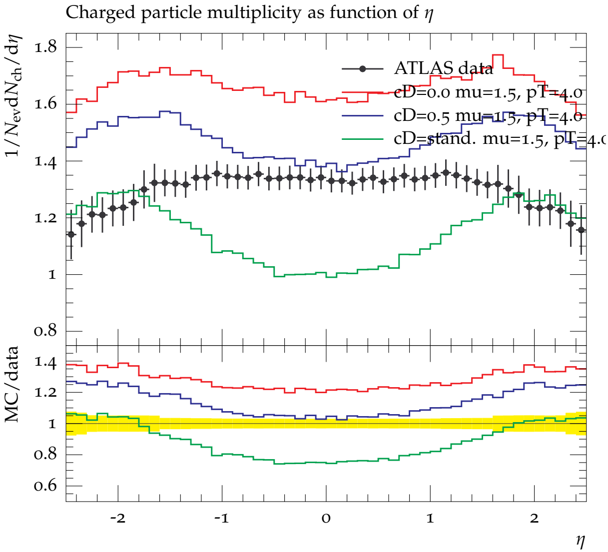


First plots against LHC data

- 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.

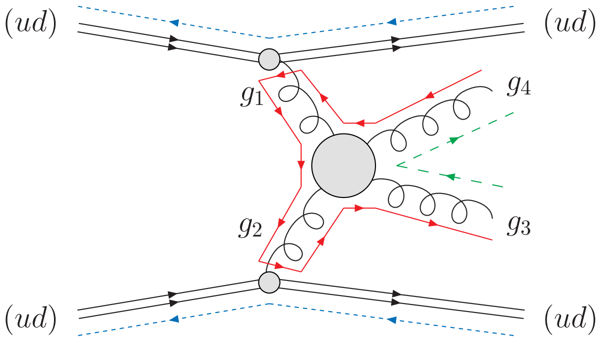


Colour structure

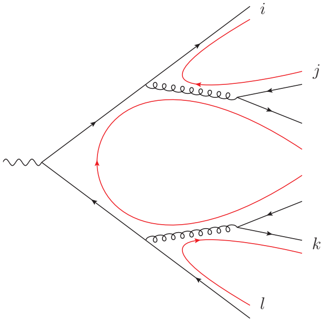
Sensitivity to parameter

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

(as opposed to hard QCD).



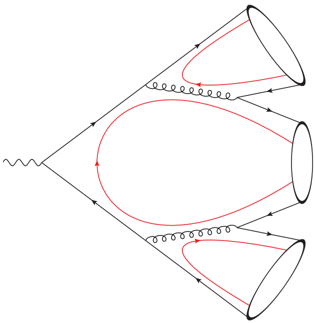
Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

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

Colour reconnection (CR) in Herwig++



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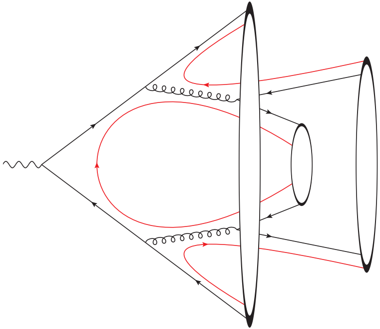

Extend cluster hadronization:

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

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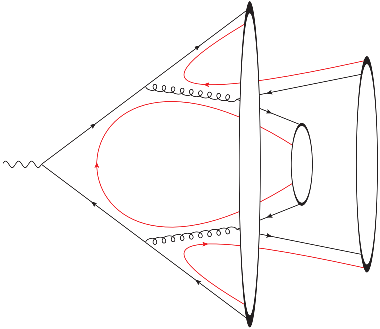


Extend cluster hadronization:

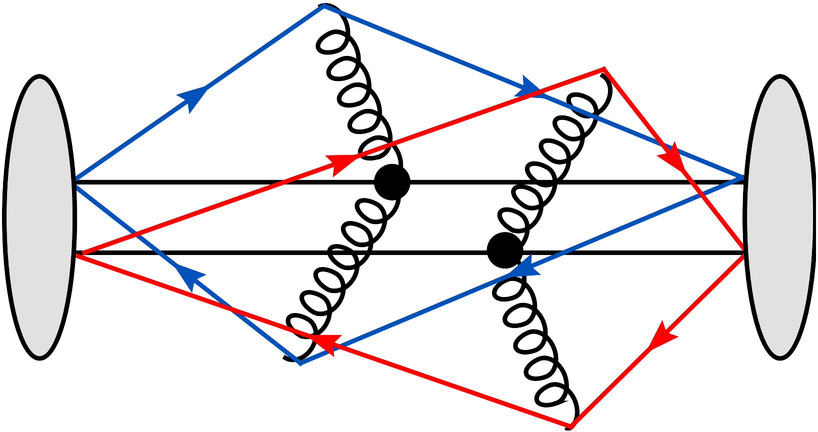
- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs
- → *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$

- Allow CR if the cluster mass decreases,

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

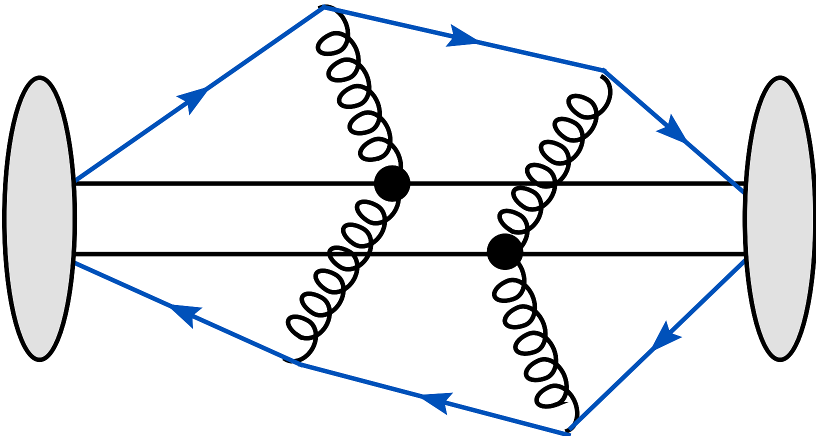
- Accept alternative clustering with probability p_{reco} (model parameter) ⇒ this allows to switch on CR smoothly

Colour reconnection at hadron colliders



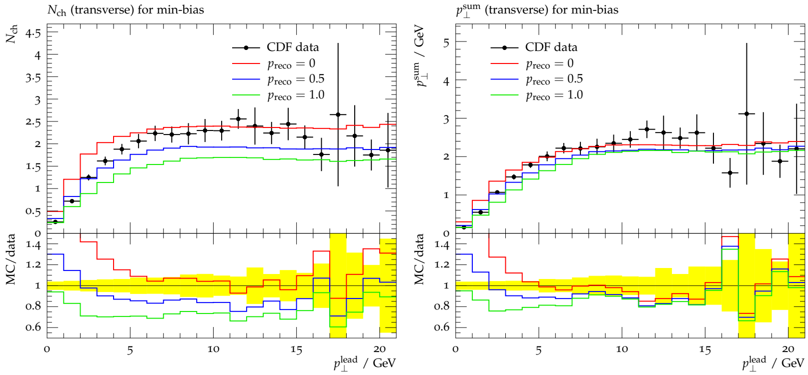
- Colour preconfinement
- Shorten colour string/lower mass clusters.

Colour reconnection at hadron colliders



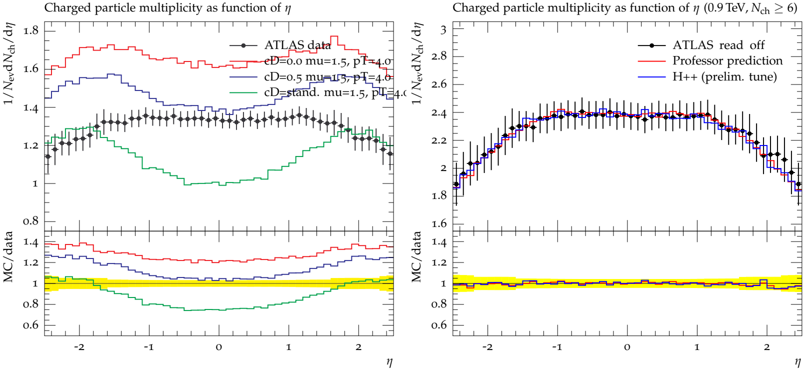
- Colour preconfinement
- Shorten colour string/lower mass clusters.

A quick look at CDF data

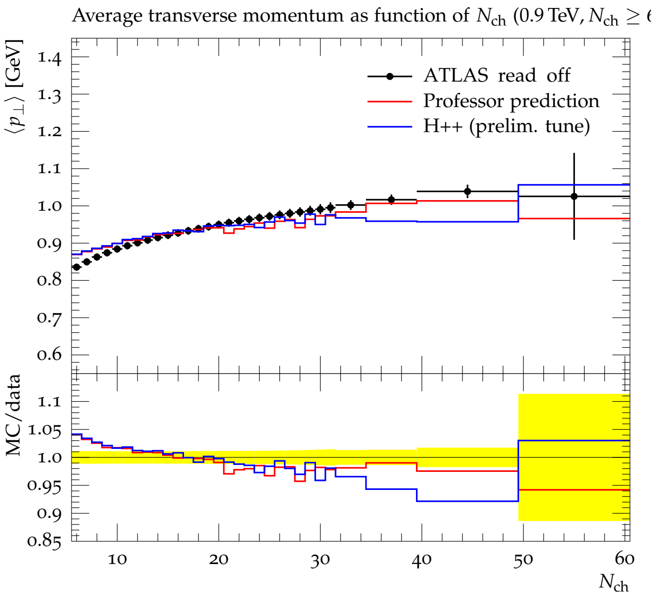


Sensitivity different for the two observables.

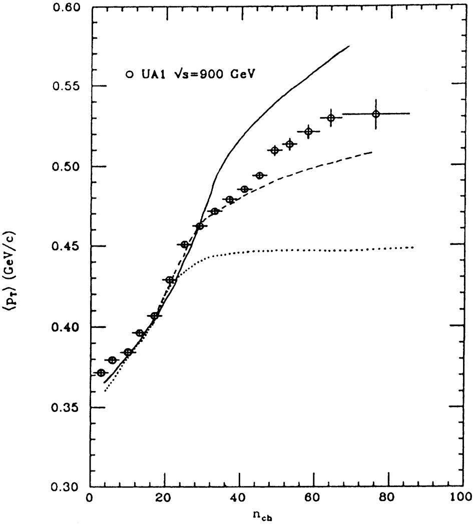
Comparison with MinBias ATLAS data (900 GeV)



Comparison with MinBias ATLAS data (900 GeV)



Colour reconnections



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

LHC

- Also works well at 2.36 TeV and 7 TeV.
- See also talk of A. Knutsson.
- Need new tunes.
- Lack of energy dependence.
- Centrality dependence only inclusive.

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.