Underlying Event and Soft Inclusive Events in Herwig++

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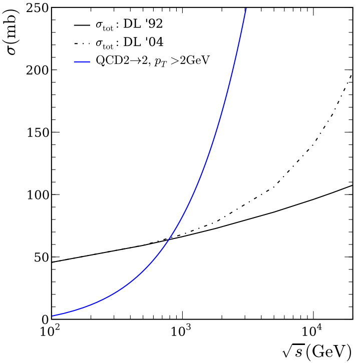
QCD@LHC 2011, St. Andrews, 22-26 August 2011

1. Multi-parton interactions in Herwig++
   - brief introduction
2. Summary of tuning status
   - Energy extrapolation and more
3. Colour reconnection
   - new developments and characteristics

Inclusive hard jet cross section in pQCD:

$$\sigma^{\text{inc}}(s, p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}\,2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$



$\sigma^{\text{inc}} > \sigma_{\text{tot}}$ eventually

Interpretation:

- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

MPI model basics

Assume a factorization of **b** and x dependence in the proton structure function,

$$G(x, \mathbf{b}, Q^2) = \underbrace{f(x, Q^2)}_{\text{PDF}} \cdot \overbrace{S(\mathbf{b})}^{\text{spatial parton distribution}}$$

Leads to average number of parton collisions

$$\bar{n}(b, s) = A(b) \cdot \sigma^{\text{inc}}(s, p_t^{\text{min}})$$

with the overlap function

$$A(b) = \int \mathrm{d}^2 b' \; S_A(\mathbf{b}') \; S_B(\mathbf{b} - \mathbf{b}')$$

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$$G(x, \mathbf{b}, Q^2) = \underbrace{f(x, Q^2)}_{\text{PDF}} \cdot \overbrace{S(\mathbf{b})}^{\text{spatial parton distribution}}$$

Leads to average number of parton collisions

$$\bar{n}(b, s) = A(b) \cdot \sigma^{\text{inc}}(s, p_t^{\text{min}})$$

R. Corke and T. Sjöstrand consider x-dependent spatial distribution [arXiv:1101.5953]

$$A(b,\mu) = \int \mathrm{d}^2 b' \; S_A(\mathbf{b}') \; S_B(\mathbf{b}-\mathbf{b}')$$

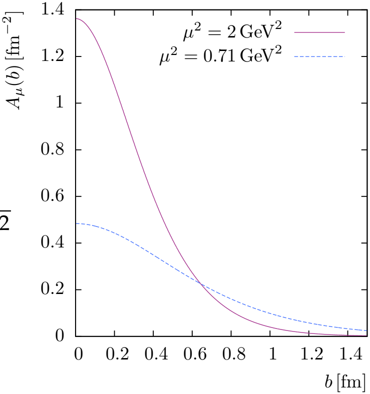
$S(\mathbf{b})$ from electromagnetic FF:

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

But μ^2 *not fixed* to the *electromagnetic* 0.71 GeV^2.

Free for colour charges.

$\Rightarrow$ free model parameter: μ^2



Connection to eikonal model

In the parton model we find

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

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

$$\sigma_{\text{inel}} = \int \mathrm{d}^2 b \left(1 - \mathrm{e}^{-2\chi(\mathbf{b},s)}\right)$$

$$\Rightarrow \chi(\mathbf{b}, s) = \frac{1}{2}\bar{n}(b, s) = \frac{1}{2}\left(A(b,\mu) \cdot \sigma_{\text{hard}}^{\text{inc}}(s, p_t^{\text{min}})\right) \, .$$

Hot Spot model (soft MPI)

So far: hard multiple interactions

Extension to soft interactions with

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

So far: hard multiple interactions

Extension to soft interactions with

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

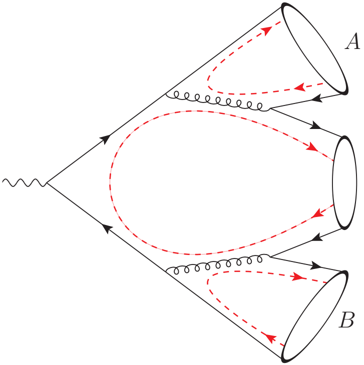
Require simultaneous description of σ_{tot} and b_{el} (measured/well predicted),

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

$$b_{\text{el}}(s) = \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\ln\frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t}\right)\right]_{t=0} \stackrel{!}{=} \int \mathrm{d}^2b \frac{b^2}{\sigma_{\text{tot}}}\left(1 - \mathrm{e}^{-\chi_{\text{tot}}(b,s)}\right) .$$

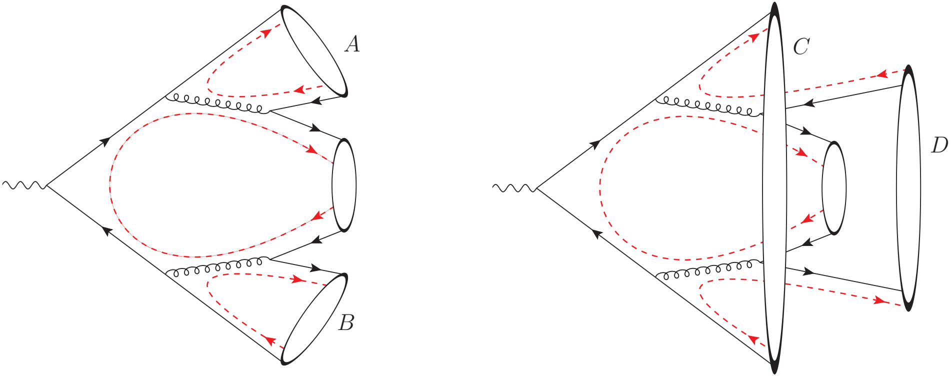
$\Rightarrow$ This fixes the two parameters μ_{soft} and $\sigma_{\text{soft}}^{\text{inc}}$

Only free parameters in the end: $p_t^{\min}$ and μ^2



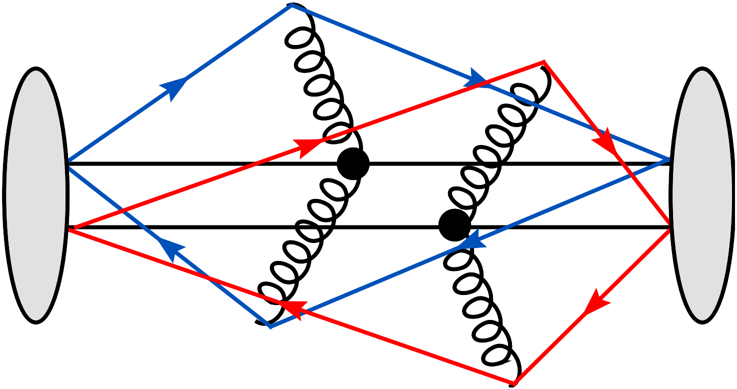
- perturbative QCD provides *preconfinement*
- i.e. small cluster masses $M_{\text{cl}} \gtrsim M_{\text{parton}\,1} + M_{\text{parton}\,2}$

Colour reconnection in Herwig++



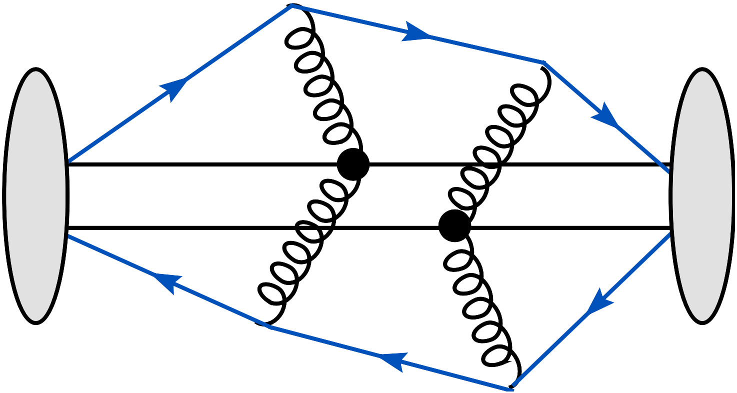
- perturbative QCD provides *preconfinement*
- i.e. small cluster masses $M_{\mathrm{cl}} \gtrsim M_{\mathrm{parton\,1}} + M_{\mathrm{parton\,2}}$
- improved description of soft events/UE at hadron colliders: manually reduce cluster masses
- $M_C + M_D < M_A + M_B$

Colour reconnection in hadron collisions



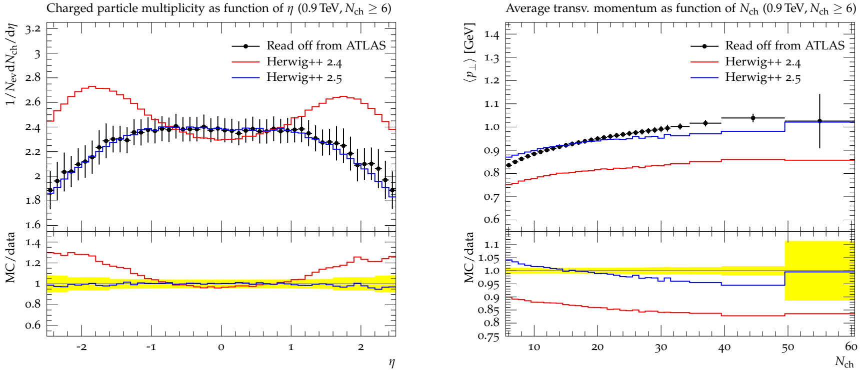
- colour connections to proton remnants
- MPI leads to even more colour charge

Colour reconnection in hadron collisions



- colour connections to proton remnants
- MPI leads to even more colour charge
- shorten string length $\hat{=}$ reduce cluster masses
  $\hat{=}$ mimic preconfinement

Colour reconnection + tuning



red: no CR, tuned to Tevatron

blue: with CR + tuned to LHC

⇒ "soft inclusive" model requires colour reconnection

Colour reconnection has small effects in e^+e^- annihilation (understood, $\rightarrow$ see later)

$\Rightarrow$ tuning procedure factorizes :

- can use (well tested) default LEP tune for parton shower and hadronization parameters
- tune only MPI parameters to hadron collider data:

$$p_t^{\min},\ \mu^2,\ p_{\text{disrupt}},\ p_{\text{reconnection}}$$

Our best tunes with these ingredients:

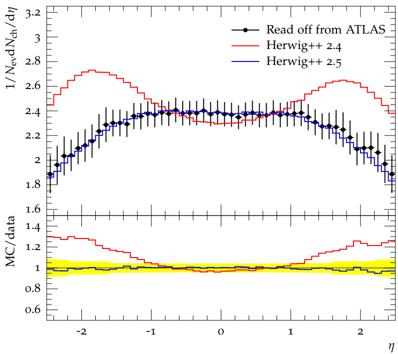
$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	$\uparrow$	$\sim$
1800	?	✓	?
7000	✗	$\downarrow$	✗

900 GeV and 7 TeV MB	ATLAS_2010_S8918562
900 GeV and 7 TeV UE	ATLAS_2010_S8894728
1800 GeV UE	CDF_2001_S4751469

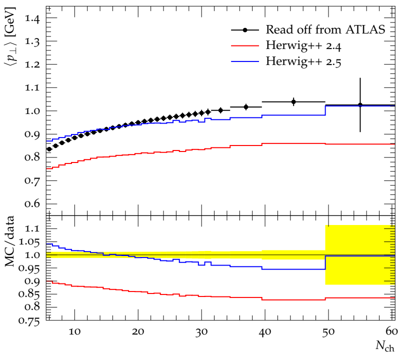
Our best tunes with these ingredients:

$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	↑	∼
1800	?	✓	?
7000	✗	↓	✗

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



Average transv. momentum as function of N_{ch} (0.9 TeV, $N_{ch} \geq 6$)



Our best tunes with these ingredients:

$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	↑	∼
1800	?	✓	?
7000	✗	↓	✗

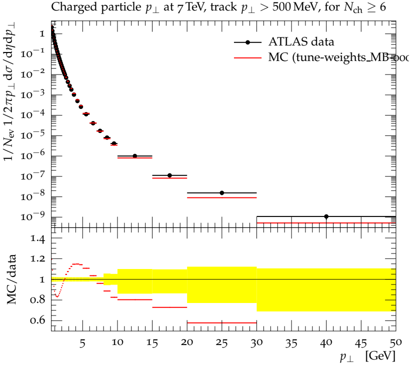
Herwig++ has no model for diffraction

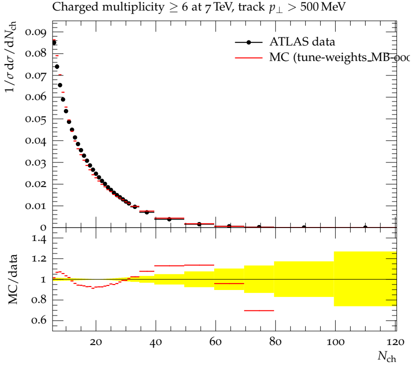
⇒ consider diffraction-suppressed data only (e.g. $N_{\rm ch} \geq 6 + p_T > 500$ MeV)

⇒ put only few effort in describing MinBias at 1.8 TeV

Our best tunes with these ingredients:

$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	↑	∼
1800	?	✓	?
7000	✗	↓	✗





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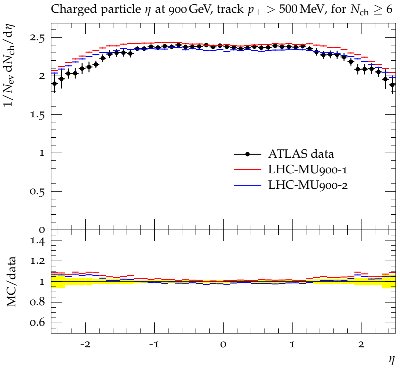
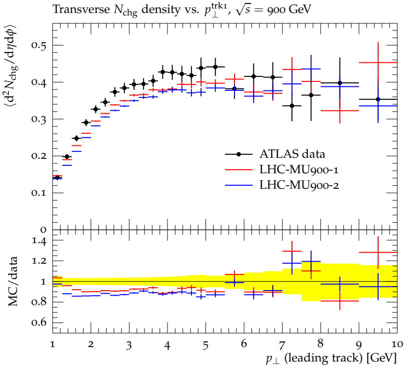
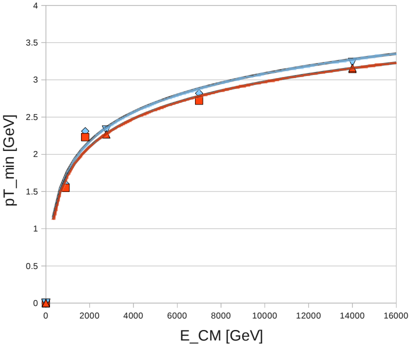


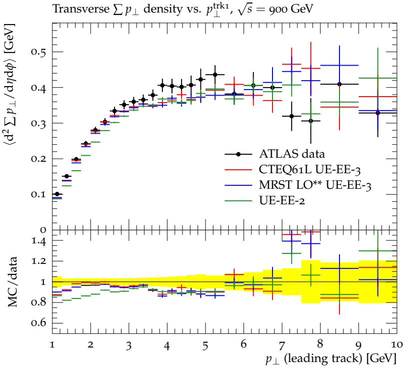


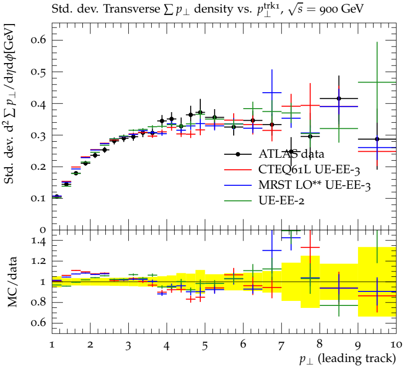
Make predictions for other energies?

- not possible to have all parameters energy-independent
- but: $p_t^{\min}$ energy-dependent, and all else fixed

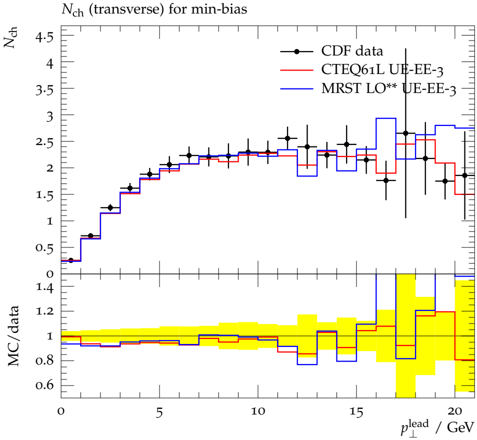


Energy extrapolation tuning (UE at 0.9 TeV)

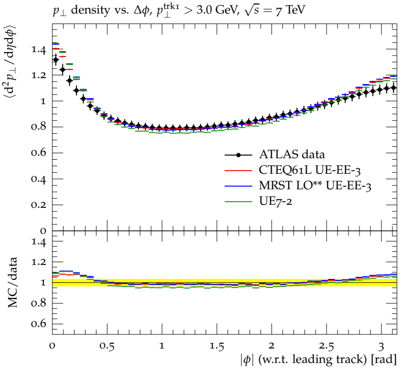


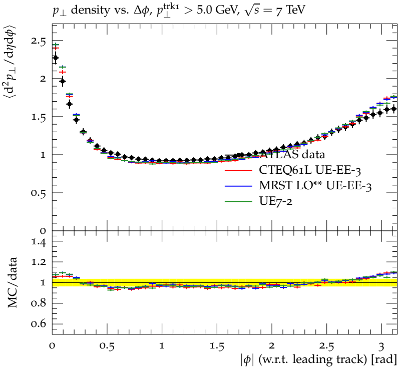


Energy extrapolation tuning (UE at 1.8 TeV)



Energy extrapolation tuning (UE at 7 TeV)





"Single" UE tune for different energies

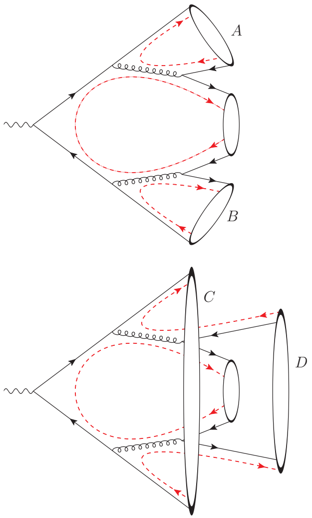
$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	$\uparrow$	$\sim$
1800	?	✓	?
7000	✗	$\downarrow$	✗

$\sqrt{s}$/GeV	MB	UE	MB+UE
900	✓	↑	∼
1800	?	✓	?
7000	✗	↓	✗

Can we improve the "soft inclusive" model?
→ pile-up!

Back to colour reconnection

Original CR model (in Herwig++ 2.5)

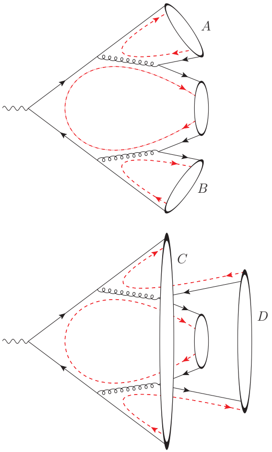


In simplified terms:

- always aims at finding lightest clusters, C and D, with

$$m_C + m_D < m_A + m_B$$

- But: each cluster is offered for colour reconnection once
- non-deterministic , since sensitive to the chosen sequence $\rightarrow$ unphysical?



Reduce sum of (squared) cluster masses,

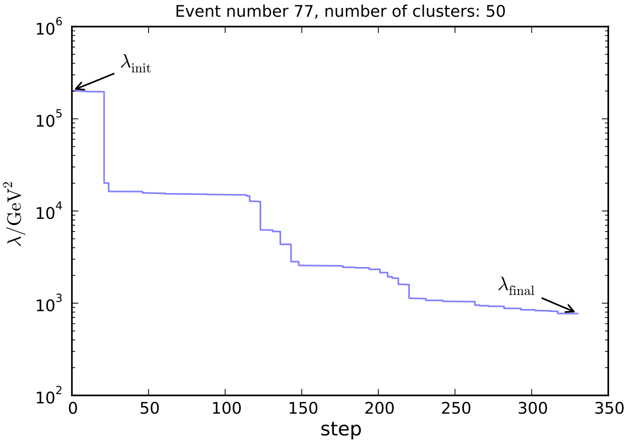
$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2 ,$$

using a simulated annealing algorithm:

- try random swaps $(A, B \to C, D)$
  - always accept the steps that reduce λ
  - accept 'bad' steps $(\lambda_2 > \lambda_1)$ with Boltzmann probability,

$$p = \exp\left[-(\lambda_2 - \lambda_1)/T\right]$$

- $T_{\text{start}} \sim \text{median}\{|\Delta\lambda|, \text{a few dry-run swaps}\}$
- gradually decrease T

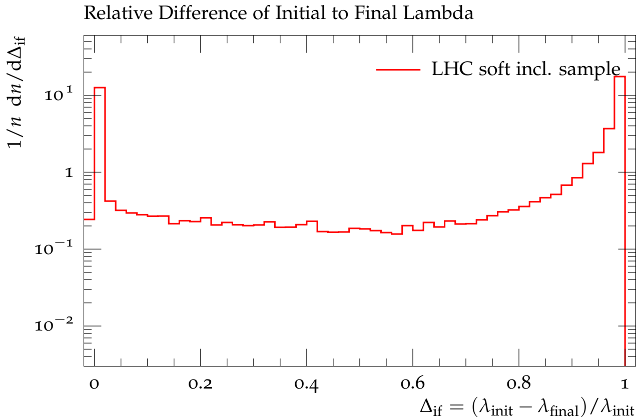


$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2$$

- CR breaks up very heavy clusters
- λ often reduced by large factor

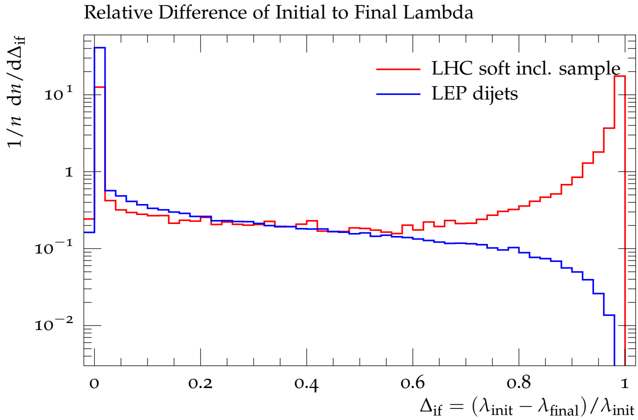
Quantifying the effect of colour reconnection

$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2$$



Quantifying the effect of colour reconnection

$$\lambda \equiv \sum_{i \in \{\text{clusters}\}} m_i^2$$

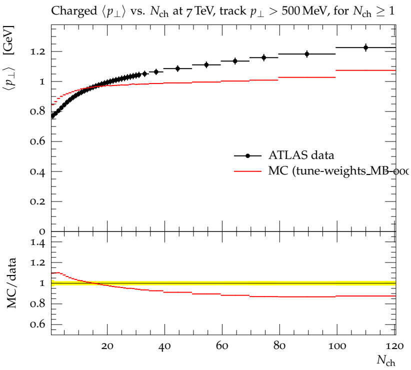


observe extreme decrease of λ in hadron collisions only

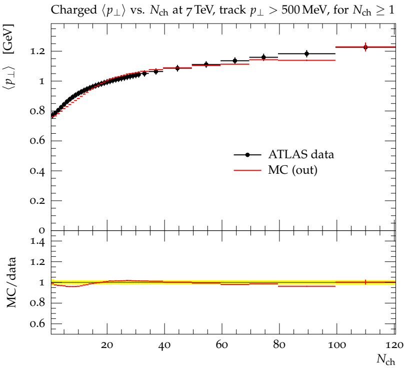
$\Rightarrow$ almost no colour reconnection at LEP!

Tuning with the statistical CR model

ATLAS MinBias at 7000 GeV slightly better now:



original colour reconnection



statistical colour reconnection

Conclusions

- current MPI model describes UE data well with tuning
- energy extrapolation for UE possible (UE-EE-3 out soon)
- statistical colour reconnection improves description of MinBias at 7 TeV
- common tunes for MB and UE
  - for 900 GeV possible (MU-900-2)
  - 7 TeV work in progress
- new tunes and plots are published here:

  `http://projects.hepforge.org/herwig/trac/wiki/MB_UE_tunes`

Outlook

- x-dependent matter profile
- achieve better common tunes for MB and UE (if possible)
- validate/improve "soft inclusive" model with data from Tevatron energy scan
- model for diffraction

BACKUP SLIDES

Assume independent scatters
⇒ number m of scatters Poisson-distributed,

$$\mathcal{P}_m(b,s) = \frac{\bar{n}(b,s)^m}{m!} e^{-\bar{n}(b,s)}$$

(with impact parameter b and $\bar{n}$ scatters on average)

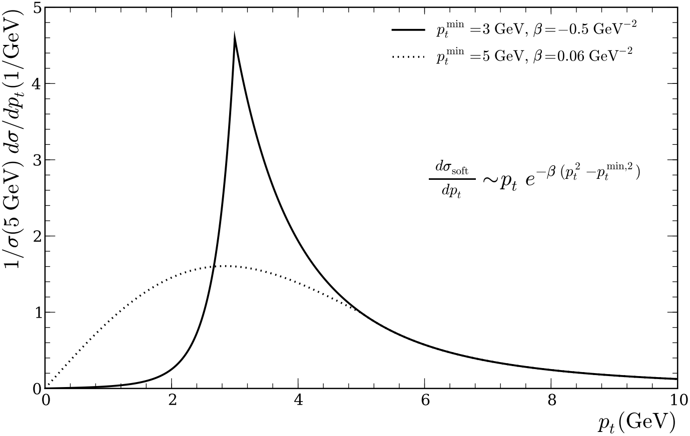
Sample number m of scatters according to

$$P_m(s) = \frac{\sigma_m}{\sum_{k=1}^{\infty} \sigma_k} \ ,$$

with the cross section for m scatters

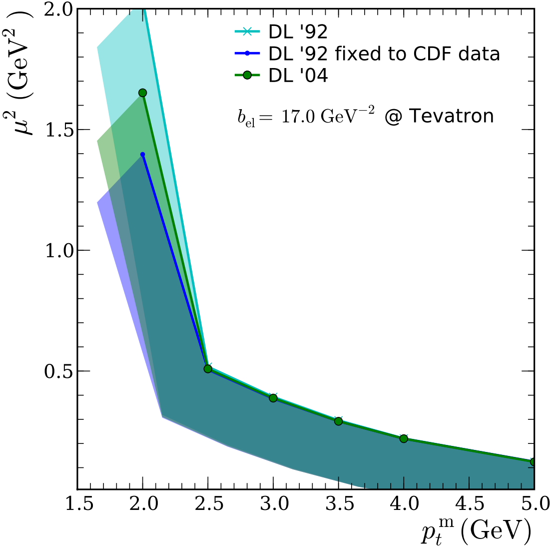
$$\sigma_m(s) = \int \mathrm{d}^2 b \ \mathcal{P}_k(b,s)$$

Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$



Restricted MPI parameter space

Constraints:
describe σ_{tot} and b_{el}.



Heavy clusters