Herwig++ and Minimum Bias and Underlying Events

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in collaboration with
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This talk:

- Introduction - Underlying event in Herwig++
- New data! ATLAS @ 900 GeV
- Colour structure
- ATLAS MinBias and UE @ 900 GeV and @ 7 TeV
- Outlook

UA5 model (deprecated, only for reference)

- Included from Herwig++ 2.0. [Herwig++, hep-ph/0609306]
- Little predictive power.
- Was default in fHerwig. Superseded by JIMMY
  [JM Butterworth, JR Forshaw, MH Seymour, ZP C72 637 (1996)]

Semihard UE

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

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]

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}).

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

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

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}:

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

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

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

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

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

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

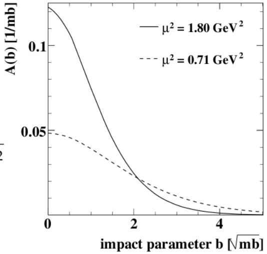
where $A(b)$ is the partonic overlap function of the colliding hadrons

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

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

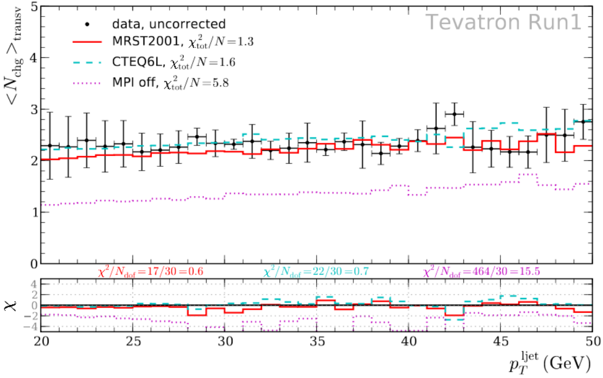
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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



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

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



Only $p_T^{ljet} > 20$GeV.

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

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

Similar structures of eikonal functions:

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

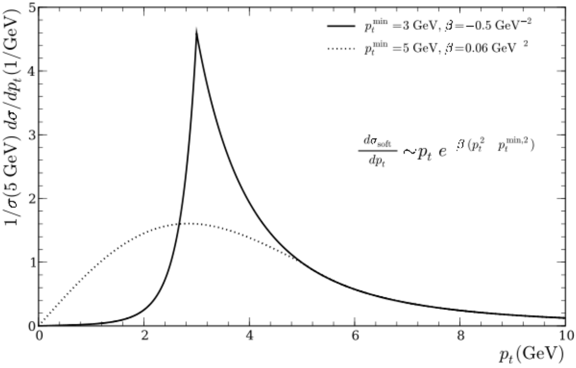
Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

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

Taking the Tevatron data together with the wide range of possible values of σ_{tot} considered at LHC, we see that this model is to simple.

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



Extension: Relax the constraint of identical overlap functions:

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

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),

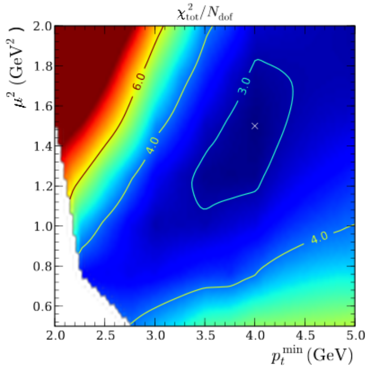
$$\sigma_{\rm tot}(s) \stackrel{!}{=} 2\int {\rm d}^2\vec{b}\left(1-{\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) ,$$

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

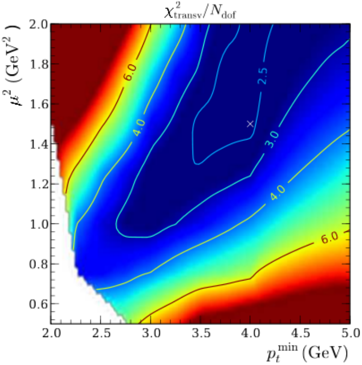
Sum up:

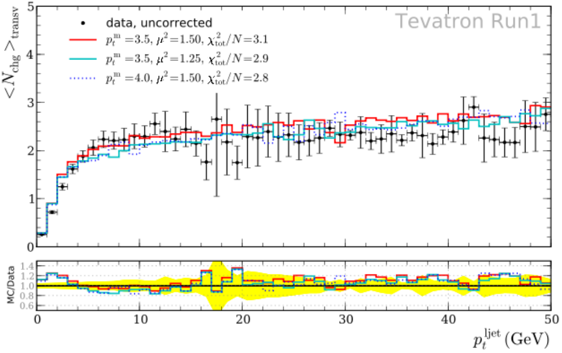
$\Rightarrow$at the end of the day we have two main parameters: μ^2, p_t^{min}.

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

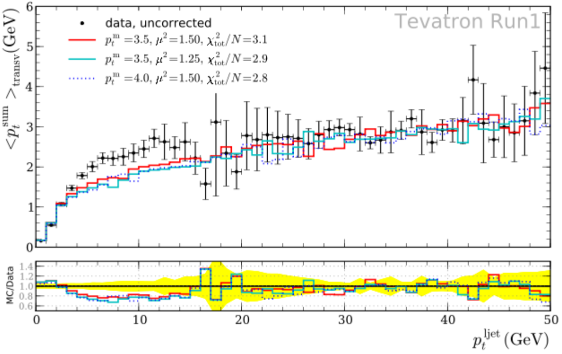


- χ^2 for Rick's Run1 Jet analysis for **all** regions
- only the transverse region





data, uncorrected
$p_t^m = 3.5$, $\mu^2 = 1.50$, $\chi^2_{tot}/N = 3.1$
$p_t^m = 3.5$, $\mu^2 = 1.25$, $\chi^2_{tot}/N = 2.9$
$p_t^m = 4.0$, $\mu^2 = 1.50$, $\chi^2_{tot}/N = 2.8$
Tevatron Run1
$< N_{chg} >_{transv}$
MC/Data
p_t^{ljet} (GeV)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$p_t^m = 3.5, \mu^2 = 1.50, \chi^2_{tot}/N = 3.1$
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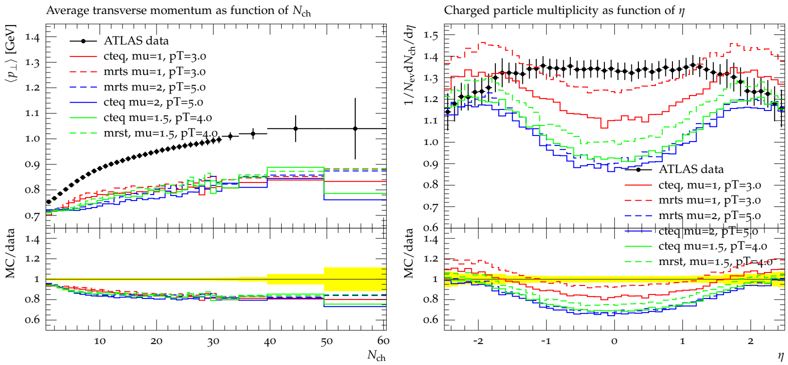
$p_t^m = 4.0, \mu^2 = 1.50, \chi^2_{tot}/N = 2.8$
Tevatron Run1
$<p_t^{sum}>_{transv}$ (GeV)
MC/Data
p_t^{ljet} (GeV)

What we have so far:

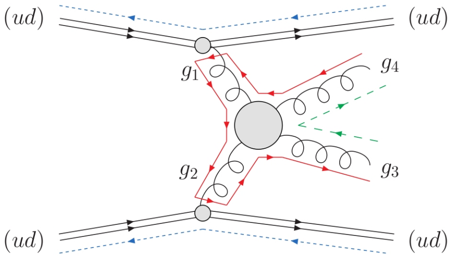
- Unitarized jet cross sections
- Fulfil constaints from σ_{tot} and b_{el}.
- Simple model with similar overlap functions.
- No additional (explicit) energy dependence.
- Left with freedom in parameter space.
- Good description of the TVT data.

- ATLAS charged particles in Min Bias.
- Convenient as the analysis was quickly available in RIVET.



- Ups, not so nice...
- Despite very good agreement with Rick Field's CDF UE analysis.
- Choice of PDF set (CTEQ6ll vs MSTW LO** (our default))
- Colour structure?

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



Look at LHC results (900 GeV)

- ATLAS charged particles in Min Bias.
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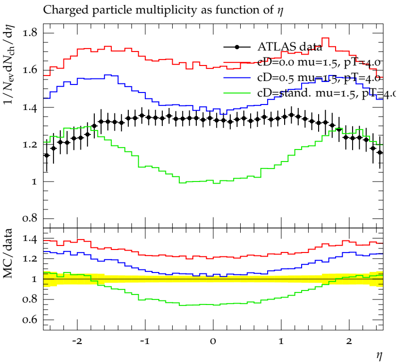
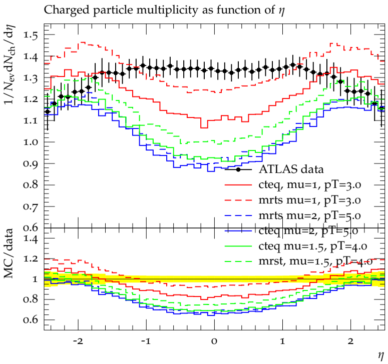
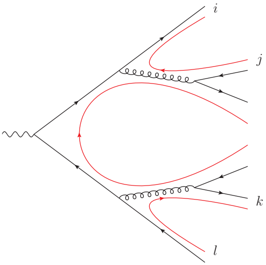




- Not nice...
- Despite very good agreement with Rick Field's CDF UE analysis.
- Colour structure of soft events.

  $p_{disrupt}$ = probability of disruption (default = 1, completaly disconected).

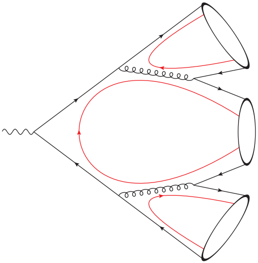


Extending the hadronization model in Herwig(++):

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

[1] For details look at Christians Röhr's Diploma thesis

Colour reconnection (CR) in Herwig++



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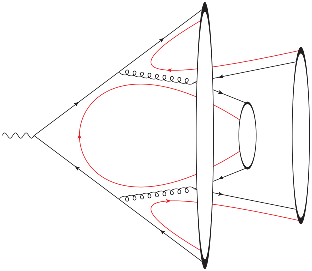

Extending the hadronization model in Herwig(++):

- 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

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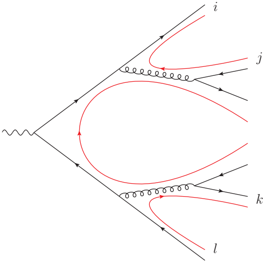

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- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
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Implementation[1]

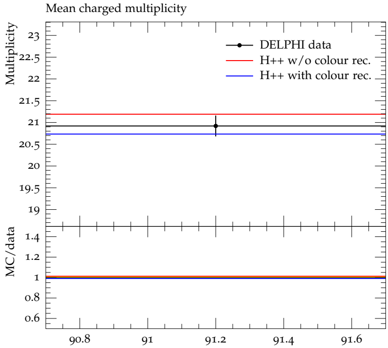
- Allow CR if the cluster mass decreases,

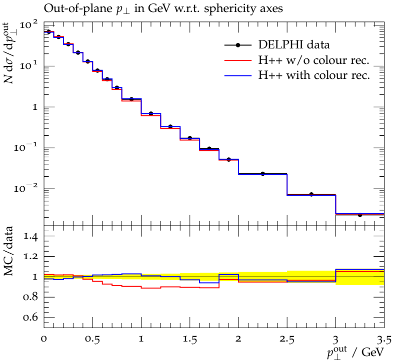
$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

  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

[1] For details look at Christians Röhr's Diploma thesis

- Hadronization sensitive to CR model.
- Proper study requires re-tune to LEP data.
- Many thanks to the Professor team for help and hints how to use their program!





Agreement on same level as w/o CR model.

LEP tune

- Hadronization sensitive to CR model.
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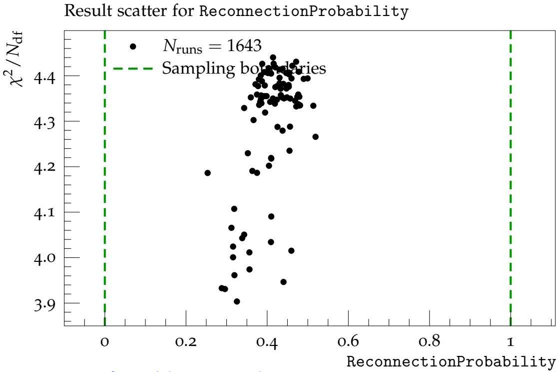
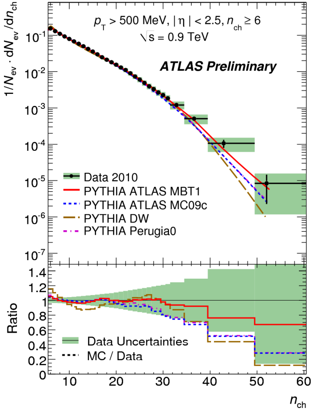


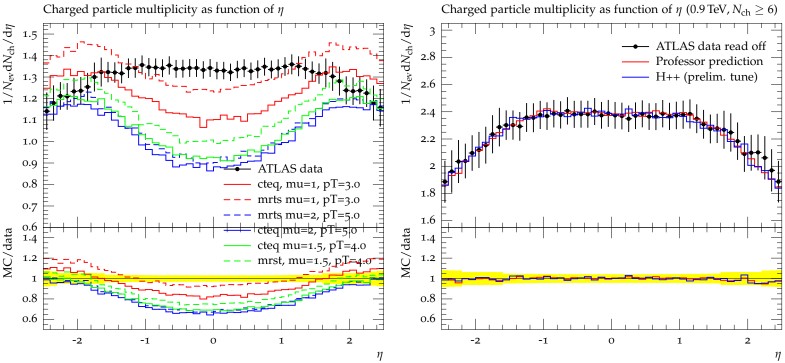
Prefered by LEP data is: $0.2 \leq p_{reco} \leq 0.6$

Proper comparison: lack of diffraction in Herwig++!

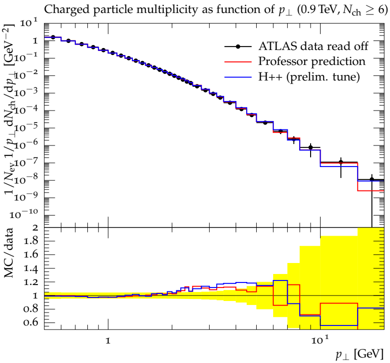


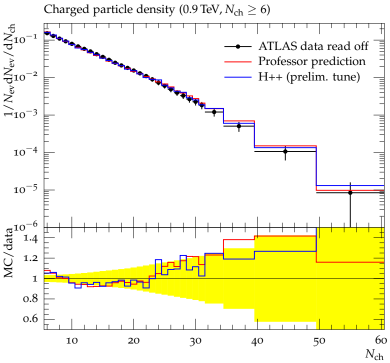
- We used a diffractive suppressed sample with cut: $N_{ch} \geqslant 6$
- **Attention:** The ATLAS graphs for $N_{ch} \geqslant 6$ are public, but the data points are not. We read the data points from the plots using:
  - **EasyNData** - Peter Uwer [arXiv:0710.2896]
  - **DataThief** - B. Tummers, http://datathief.org/
  - **g3data** - J. Frantz, http://www.frantz.fi/software/g3data.php
  - some other tricks ...

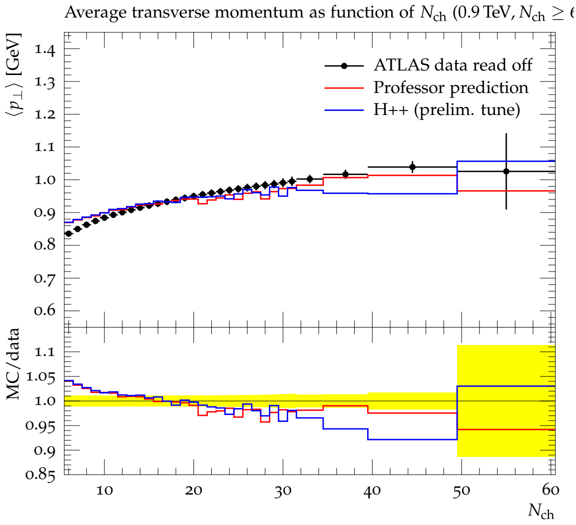
MinBias ATLAS 900 GeV

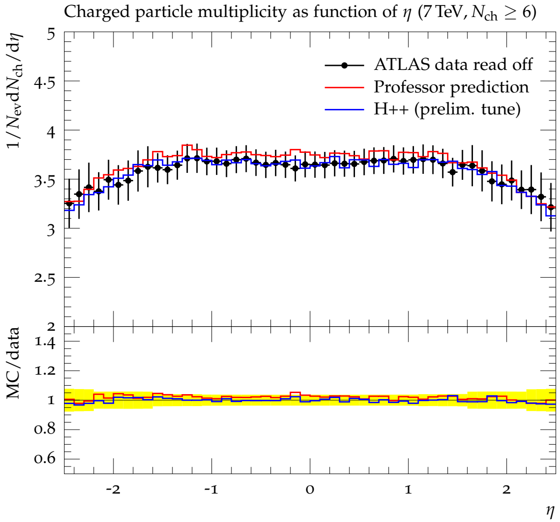


MinBias ATLAS 900 GeV

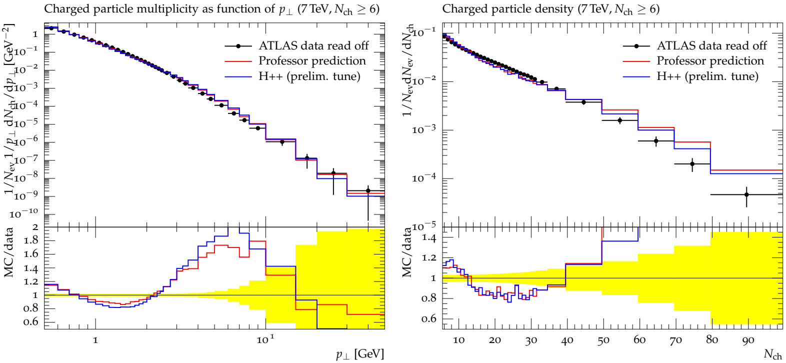




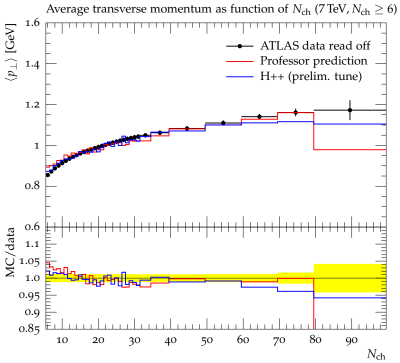

Average transverse momentum as function of N_{ch} (0.9 TeV, $N_{\mathrm{ch}} \geq 6$
$\langle p_\perp \rangle$ [GeV]
ATLAS data read off
Professor prediction
H++ (prelim. tune)
MC/data
N_{ch}
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
1.1
1.05
1.0
0.95
0.9
0.85
10
20
30
40
50
60

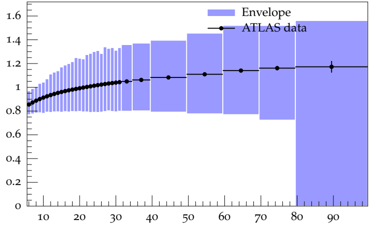

Charged particle multiplicity as function of η (7 TeV, $N_{ch} \geq 6$)
$1/N_{ev} dN_{ch}/d\eta$
5
4.5
4
3.5
3
2.5
2
ATLAS data read off
Professor prediction
H++ (prelim. tune)
MC/data
1.4
1.2
1
0.8
0.6
-2
-1
0
1
2
η

MinBias ATLAS 7000 GeV

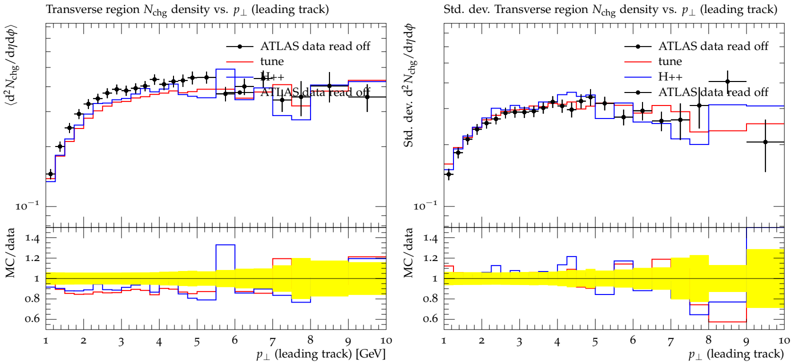


MinBias ATLAS 7000 GeV





Underlying Event 900 GeV (ATLAS-CONF-2010-029)



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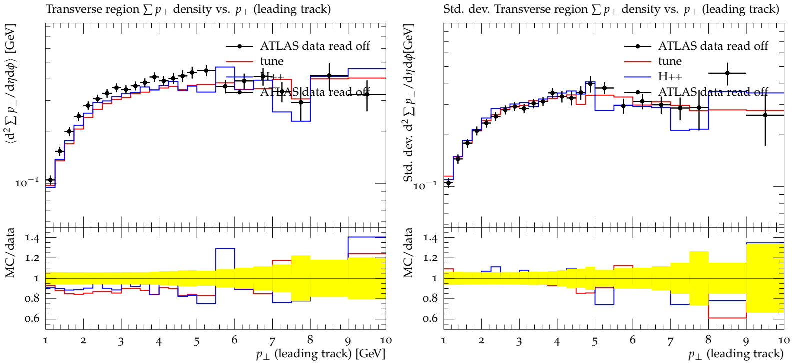
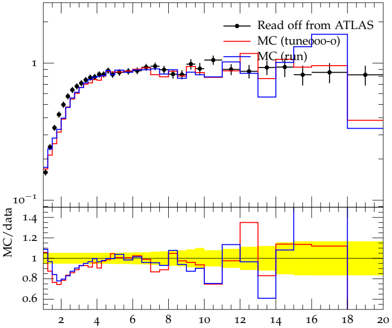
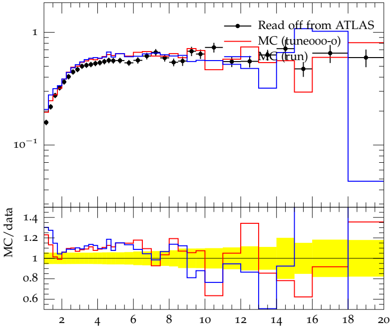


N_{ch} / StdDev transverse vs p_t^{lead} / GeV





MinBias ($N_{ch} \geqslant 6$)/UE tunes

Preliminary results:

- 900 GeV MB/UE
  $p_t^{min} = 2.6\,\text{GeV}, \quad \mu^2 = 1.1\,GeV^2, \quad p_{\text{reco}} = 0.48, \quad p_{\text{disrupt}} = 0.43$
- 7 TeV MB
  $p_t^{min} = 5.2\,GeV\,, \quad \mu^2 = 1.8\,GeV^2, \quad p_{\text{reco}} = 0.55, \quad p_{\text{disrupt}} = 0.68$
- 7 TeV UE
  $p_t^{min} = 3.2\,GeV\,, \quad \mu^2 = 0.81\,GeV^2, \quad p_{\text{reco}} = 0.61, \quad p_{\text{disrupt}} = 0.34$

- First look at LHC data.
- Need colour reconnection model.
- First tunes to 900 GeV and 7000 GeV Min Bias ($N_{ch} \geqslant 6$) give good results.
- Non-diffractive physics under good control

Open question:

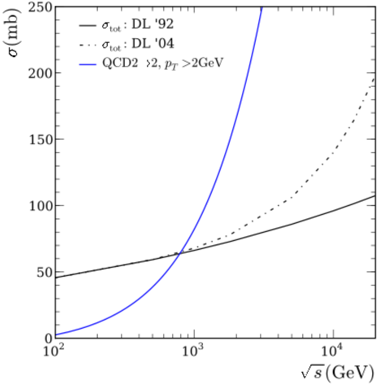
- Treatment of remnant pdfs too naive?
- More involved overlap function?
  With Energy dependent parameters?
- Understanding of colour reconnection?

More to come:

- Model for diffraction.
- Further checks of consistency.
- In future release Herwig++ 2.5 (out very soon).
- Better look at energy dependence.
- Universal tune of UE parameters?

Stay tuned!

Backup slides



σ_{tot} : DL '92
σ_{tot} : DL '04
QCD2 ›2, p_T >2GeV
σ(mb)
250
200
150
100
50
0
10^2
10^3
10^4
$\sqrt{s}$(GeV)

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

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

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

Donnachie and Landshoff [6, 7]. We will use three different variations;

1. The *standard* parameterisation from [6] with the following behaviour at high energies:

$$\sigma_{\text{tot}} \sim 21.7\ \text{mb} \cdot \left(\frac{s}{\text{GeV}^2}\right)^{0.0808} \rightarrow \sigma_{\text{tot}}(14\ \text{TeV}) = 101.5\ \text{mb}\,. \tag{6.1}$$

2. Using the same energy dependence but normalising it to the measurement [139] by CDF:

$$\sigma_{\text{tot}} \sim 24.36\ \text{mb} \cdot \left(\frac{s}{\text{GeV}^2}\right)^{0.0808} \rightarrow \sigma_{\text{tot}}(14\ \text{TeV}) = 114.0\ \text{mb}\,. \tag{6.2}$$

3. Using the most recent fit [7], which takes the contributions from both hard and soft Pomerons into account:

$$\sigma_{\text{tot}} \sim 24.22\ \text{mb} \cdot \left(\frac{s}{\text{GeV}^2}\right)^{0.0667} + 0.0139\ \text{mb} \cdot \left(\frac{s}{\text{GeV}^2}\right)^{0.452} \rightarrow \sigma_{\text{tot}}(14\ \text{TeV}) = 164.4\ \text{mb}\,. \tag{6.3}$$

The elastic slope parameter, b_{el} , defined in terms of the differential elastic scattering cross section, $d\sigma/dt$, as

$$b_{el} = \left[\frac{d}{dt}\left(ln\frac{\sigma}{dt}\right)\right]_{t=0}$$

$$b_{el} = \frac{1}{\sigma_{tot}} \int d^2\mathbf{b} b^2[1 - e^{-\chi(\mathbf{b},s)}]$$

In the Donnachie-Landshoff parameterisation, this is given by:

$$b_{el} = 2\alpha^{'} ln\frac{s}{s_0}$$