Herwig++ versus p-p data at the LHC.

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in collaboration with
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on behalf of Herwig++ group

Karlsruhe Institute of Technology

Winter Workshop on Recent QCD Advances at the LHC
ÉCOLE DE PHYSIQUE des HOUCHES

Les Houches, 14 February 2011

Outline

This talk:

- Introduction - Underlying Event in Herwig++
- Colour structure
- Results: MB and UE @ 900 GeV and @ 7 TeV
- New Release - Herwig++ 2.5
- Outlook

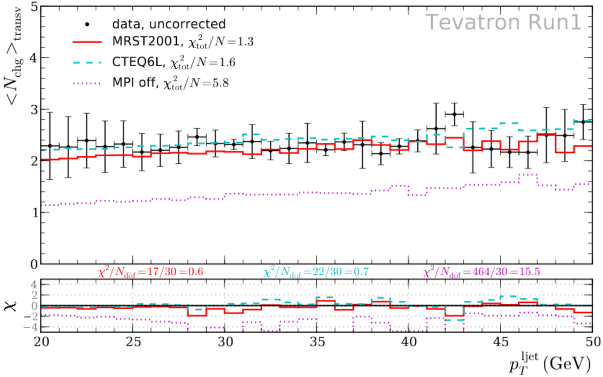
UA5 model (deprecated, only for reference)

- 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 Superseded by JIMMY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).

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

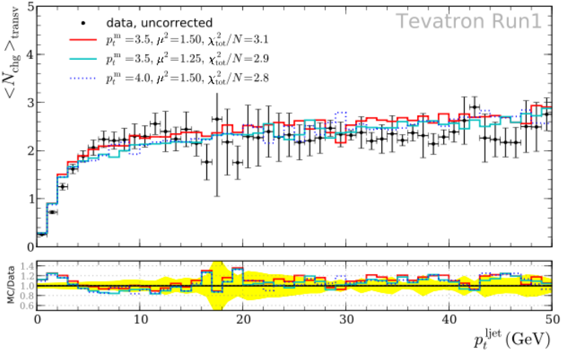


Only $p_T^{ljet} > 20\,\mathrm{GeV}$.

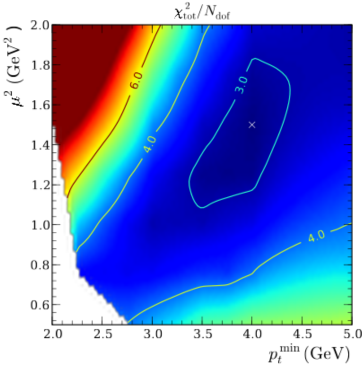
Semihard+Soft UE

- 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]

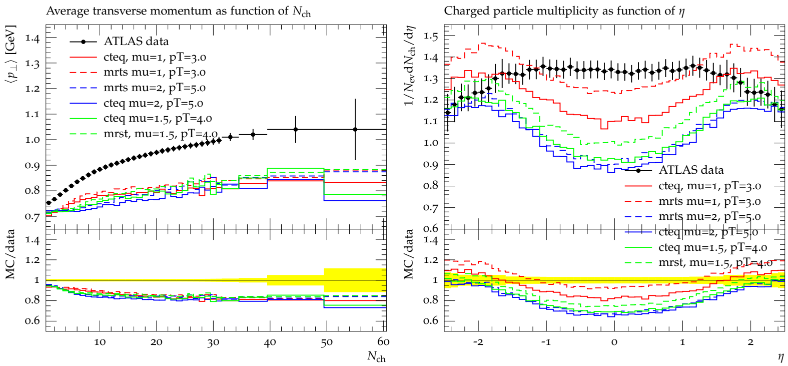
For details look at Herwig++ talk at MB & UE WG - 06 September 2010 - link


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

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



- 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`.



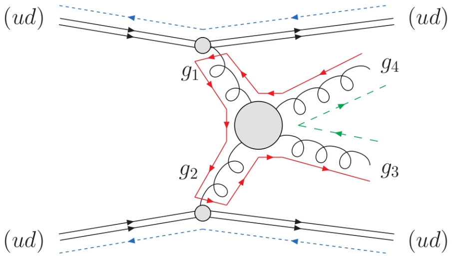
- Choice of PDF set (CTEQ6l1 vs MSTW LO**)

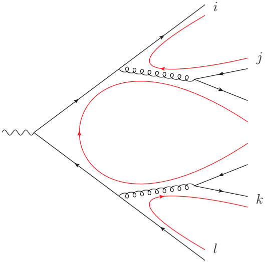
Colour Structure of the Underlying Event

- Colour Reconnection (parameter p_{reco}) - Included from Herwig++ 2.5
- Colour Distribution - only Soft UE (parameter p_{CD})
- Retuning to LEP data needed.
- Tests of Colour Reconnection model.

For details look at Herwig++ talk at MB & UE WG - 06 September 2010 - link

- 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.



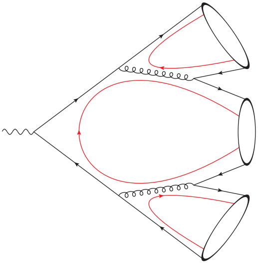


Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement*
  $\Rightarrow$ 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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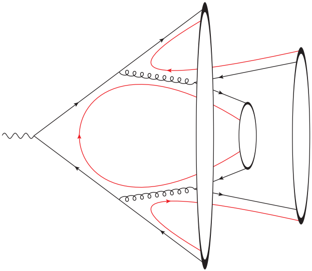

Extending the hadronization model in Herwig(++):

- 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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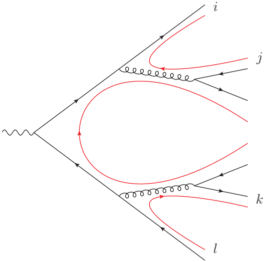

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- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
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Implementation[1]

- 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

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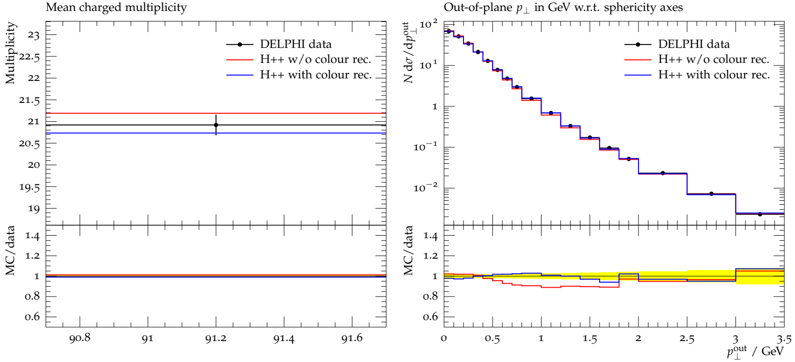
Can we still describe the LEP data similar to Herwig++ w/o colour reconnection?



We repeated tuning of the hadronization to the LEP data (above 2 examples). Both tunings (with and w/o colour rec.) seems to describe the data at the same level.

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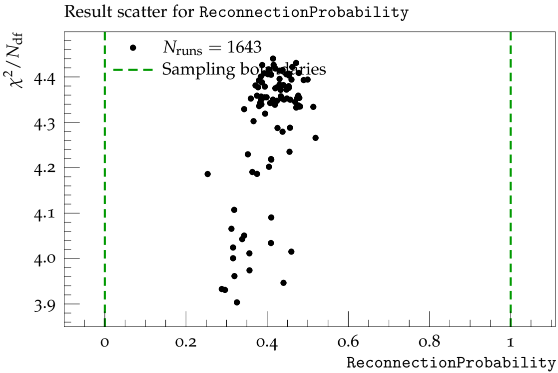


Prefered by LEP data is: $0.2 \leq p_{reco} \leq 0.6$

Colour Reconnection model tests

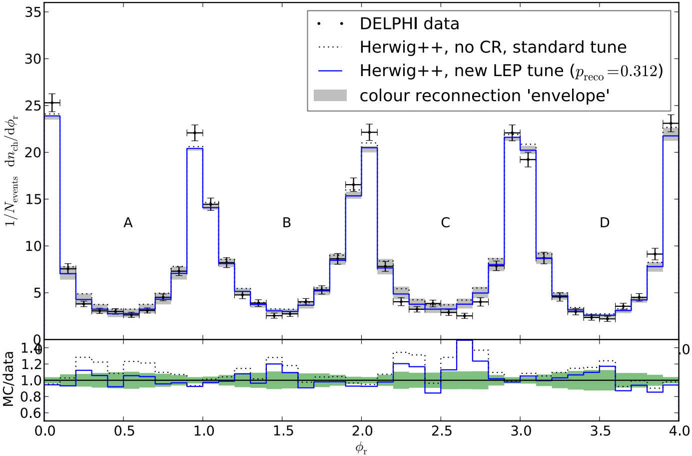
We used two LEP analyses (sensitive to color reconnection) to test the new model:

- OPAL Collaboration arXiv:hep-ex/0306021v1:
  "Tests of models of color reconnection and a search for glueballs using gluon jets with a rapidity gap"
- DELPHI Collaboration, Eur. Phys. J. C51 (2007) 249-269],
  particles flow in $WW \to 4j$ at LEP

Result:

- Herwig++ with and w/o colour rec. seems to describe these data at the same level.

Retrospective: particle flow in $WW \to 4j$ at LEP

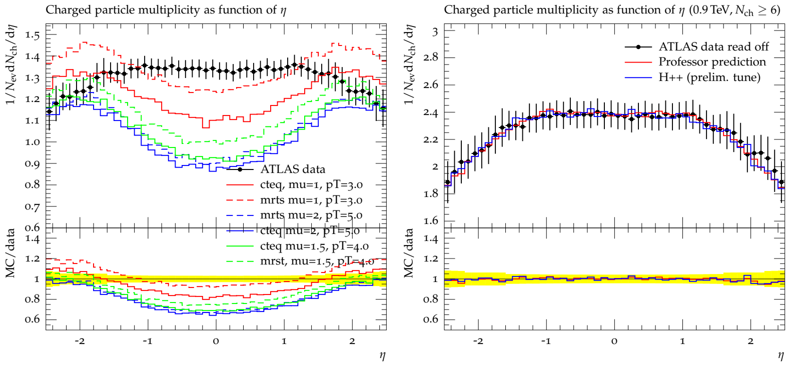


- small effects here
- marginal improvement (if at all)

data from [DELPHI Collaboration, Eur. Phys. J. C51 (2007) 249-269]

Proper comparison: lack of diffraction in Herwig++!

We used a diffractive suppressed sample with cut: $N_{ch} \geq 6$, $p_T > 500\ MeV$, $|\eta| < 2.5$



Many thanks to the Professor team for help and hints how to use their program!

[A. Buckley , H. Hoeth , H. Lacker, H. Schulz, j. Eike von Seggern, Eur.Phys.J.C65, 2010.]

MinBias ATLAS 900 GeV

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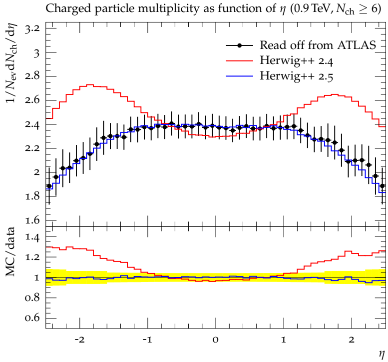

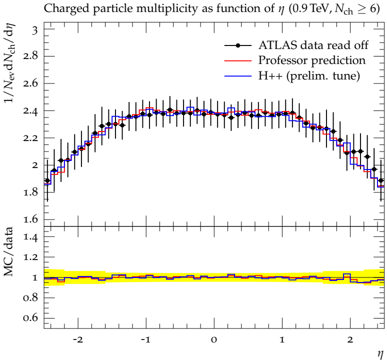

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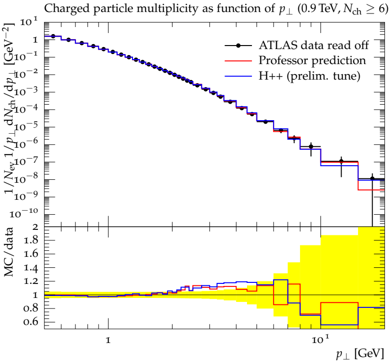

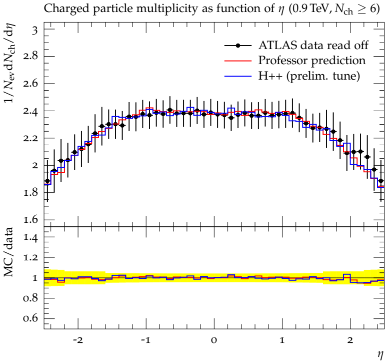

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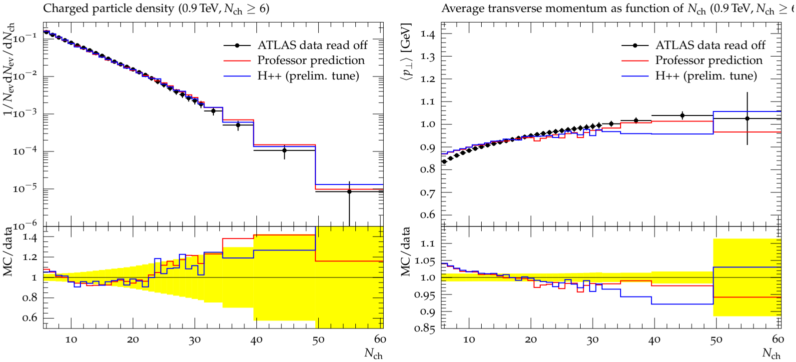

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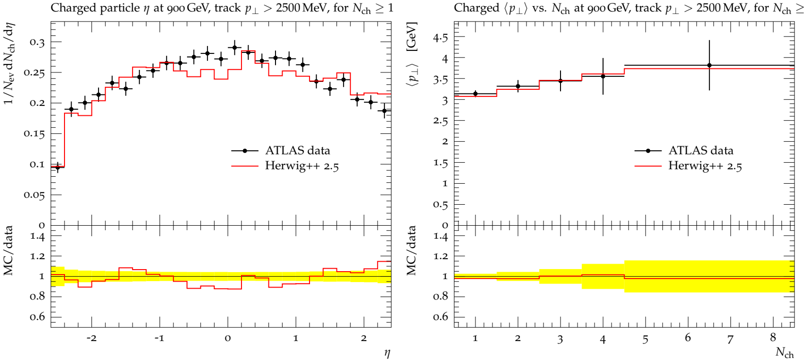
2nd MB ATLAS publication [arXiv 1012.5104], more phase spaces.
$N_{ch} \geq 1,\ p_T > 2500\ MeV,\ |\eta| < 2.5$



This was not tuned! We used tune to ATLAS MB data for $N_{ch} \geq 6,\ p_T > 500\ MeV$ presented in MB&UE WG in September 2010

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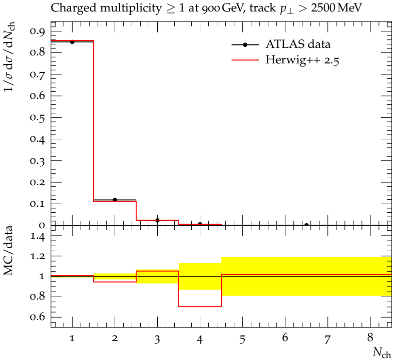

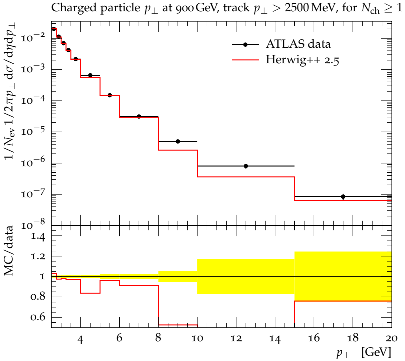

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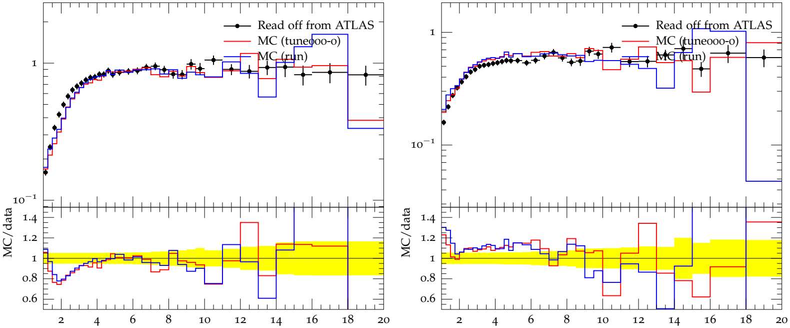
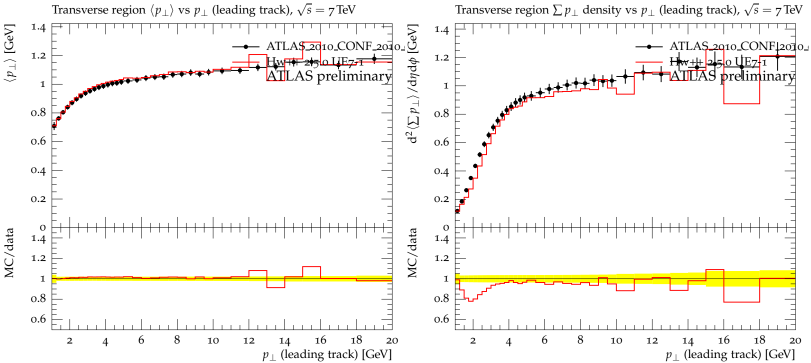
Underlying Event 7000 GeV (ATLAS-CONF-2010-029)

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



Slide from MPI@LHC 2010 in Glasgow

$p_t^{min} = 3.2\,GeV\,,\quad \mu^2 = 0.81\,GeV^2,\quad p_{\text{reco}} = 0.61,\quad p_{\text{disrupt}} = 0.34$



Those observables (in transverse region) were used for the tuning.

Underlying Event 7000 GeV

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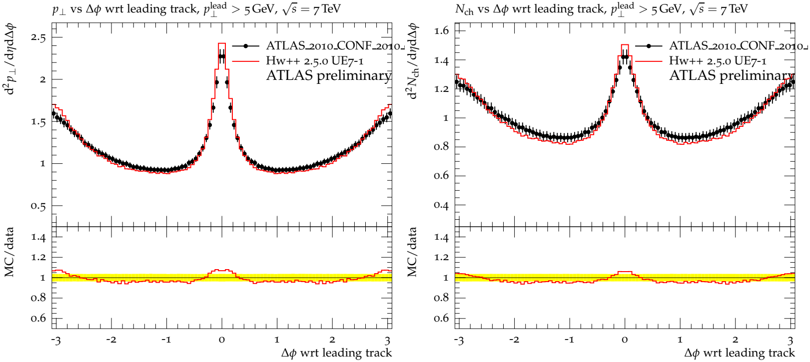

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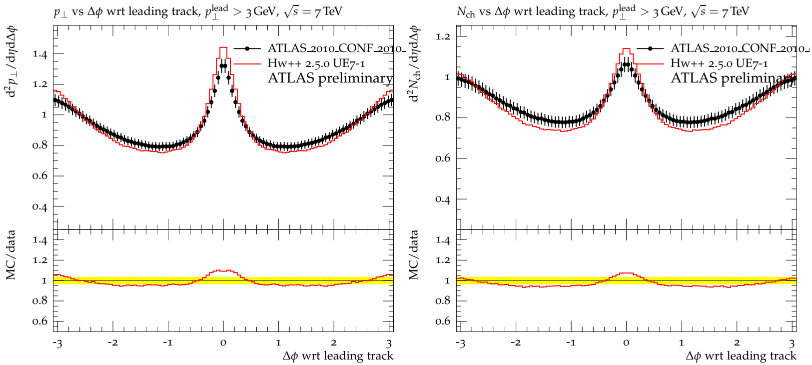

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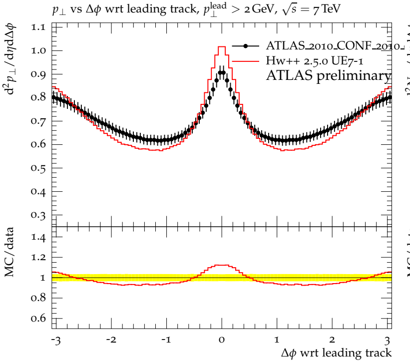
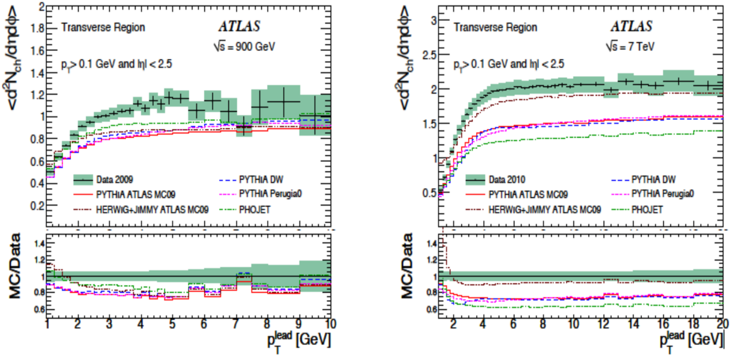
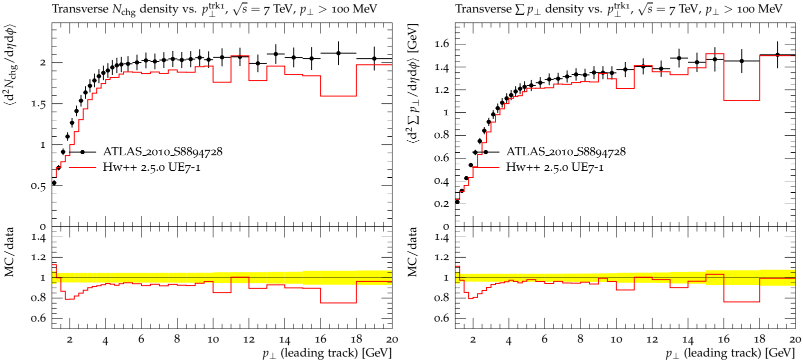


Particle Density vs. P_T^{lead}



Particle density increases by a factor of ~2 but
The conclusion is the same

This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow



In Glasgow Arthur Moraes asked us how it would look like for $p_T = 100$
Tunes (input files, plots) are available at Herwig++ wiki page.

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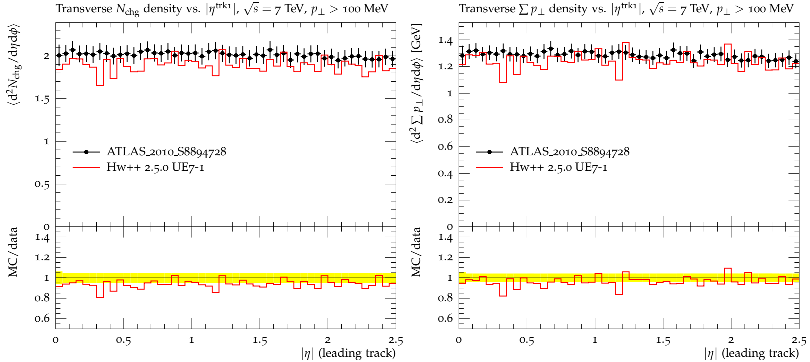

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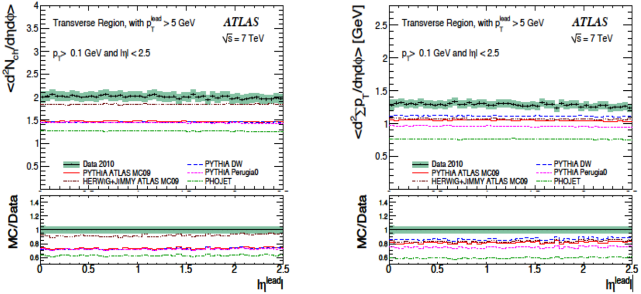
Particle Density, Scalar ΣP_T vs. η^{lead}



Lower particle activities in MC tunes
Particle density & scalar ΣP_T independent of η^{lead}

New release: Herwig++ 2.5

Herwig++ 2.5

- POWHEG NLO parton shower matching scheme with:
  - Vector Boson Pair Production
  - $e^+e^- \longrightarrow q\bar{q}$
  - Higgs Decay
- MC@NLO program now can be use with Herwig++
- Colour Reconnection
- Diffractive and Photon Initiated Processes
- BSM Physics
  (ADD Model, Leptoquarks, NMSSM, Transplanckian Scattering)
- New Matrix Elements

For details please look at release note.

Summary:

- New implementation of colour reconnection is validated, also tested against LEP analyses and seems to work well.
  You can test it - Herwig++ 2.5!
- First tunes to 900 GeV and 7000 GeV Min Bias ($N_{ch} \geqslant 6$) and UE give good results.
- Tunes (input files, plots) are/will be available at Herwig++ wiki page.
- Non-diffractive physics under good control

Open questions:

- Treatment of remnant pdfs too naive?
- More involved overlap function (x-dependent)?
- Energy dependent parameters?
- New model of diffraction R&D

Outlook:

- Look at more data from LHC experiments (strange particle and proton production), different PDF sets, more tunes.
- Minimum bias/underlying event/diffraction under constant improvement!
- Stay tuned!

Starting point: hard inclusive jet cross section.

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

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

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

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 $a(\vec{b},s) = \frac{1}{2i}(\mathrm{e}^{-\chi(\vec{b},s)} - 1)$

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

$\chi(\vec{b},s)$ 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

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

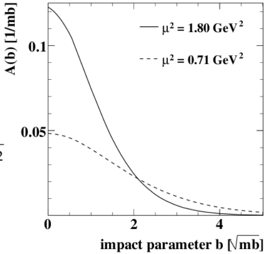
where $A(b)$ is the partonic overlap function of the colliding hadrons

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

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

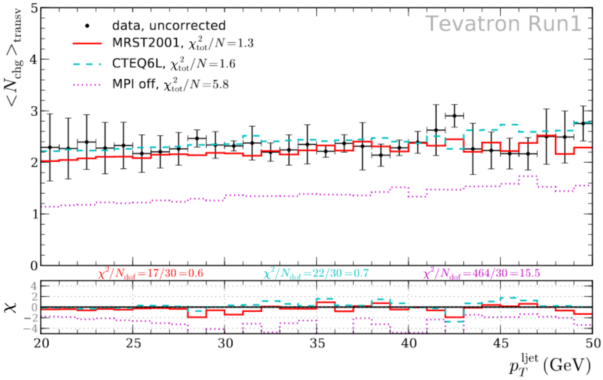
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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



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

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



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

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

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

Similar structures of eikonal functions:

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

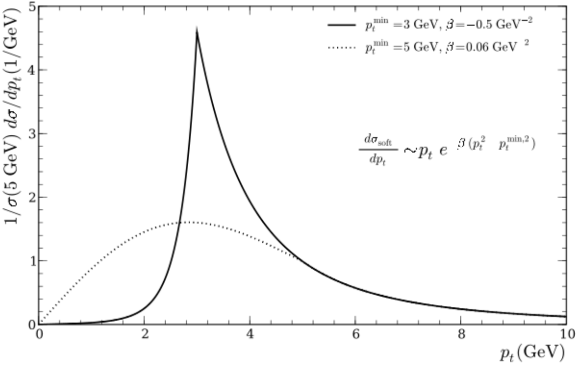
Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

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 μ_{soft} and $\sigma^{\mathrm{inc}}_{\mathrm{soft}}$ in

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

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

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

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

Sum up:

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

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.