MPI model in Herwig++

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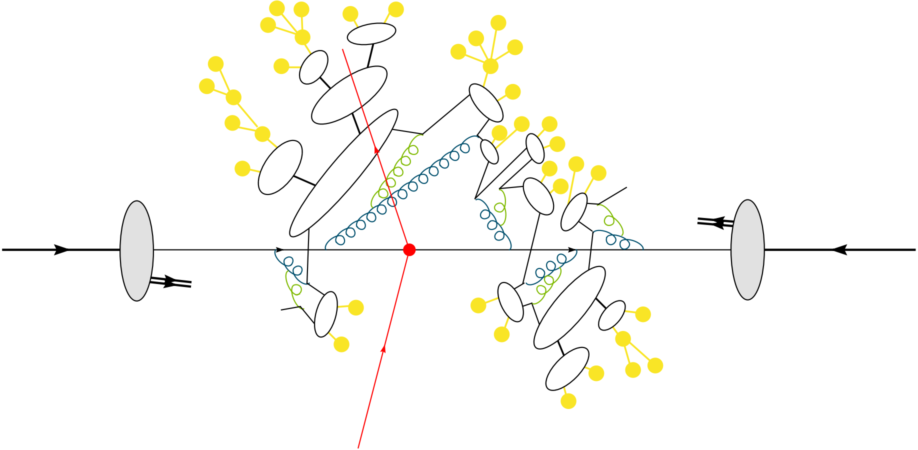
Hadron–Hadron and Cosmic Ray Interactions
at Multi TeV Energies
ECT* Trento, 29 Nov–3 Dec 2010

MPI model with *Manuel Bähr, Jon Butterworth, Mike Seymour*.

New studies, new colour reconnection model with
Christian Röhr, Andrzej Siodmok

pp Event Generator



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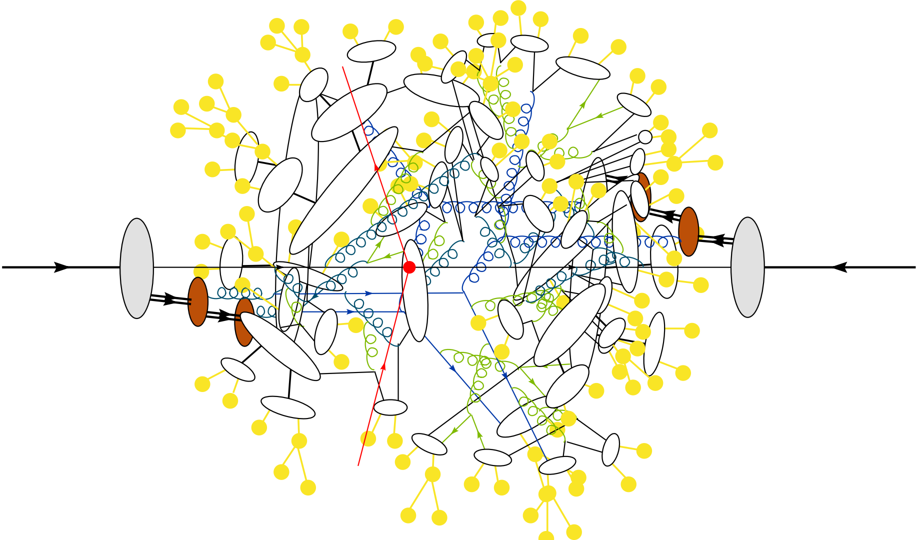

Some Herwig++ features

- Many SM hard processes available. BSM cascades with spin correlations. LH files.
- BSM physics included.
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- CKKW type matching with truncated showers general machinery, tested for e^+e^-, DY, γ+j.

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UA5 model (deprecated, only for reference)

- Included from Herwig++ 2.0. [Herwig++, hep-ph/0609306]
- Little predictive power.
- Only gets averages right, not large (and interesting!) fluctiations $\rightarrow$ mini jets.
- 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 Superseded by `JIMMY`.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, $p_t \geq p_t^{\rm min}$. [Bähr, SG, Seymour, JHEP 0807:076]
- Similar to `JIMMY`.
- Good description of harder Run I UE data (Jet20).

Underlying event in Herwig++

Semihard+Soft UE

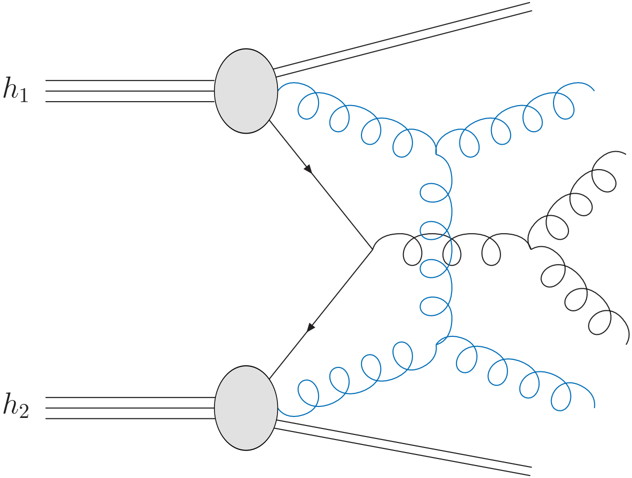
- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions $p_t < p_t^{\min}$.
- Theoretical work with simplest possible extension. [Bähr, Butterworth, Seymour, JHEP 0901:065]
- "Hot Spot" model. [Bähr, Butterworth, SG, Seymour, 0905.4671]
- No development since then (currently at v2.4.2), but new data. First look.
- New developments in this talk.

This talk

- Constrain parameter space from Tevatron.
- First look at LHC data.
- How well does it work out of the box?

Eikonal model basics

Mulitple hard interactions



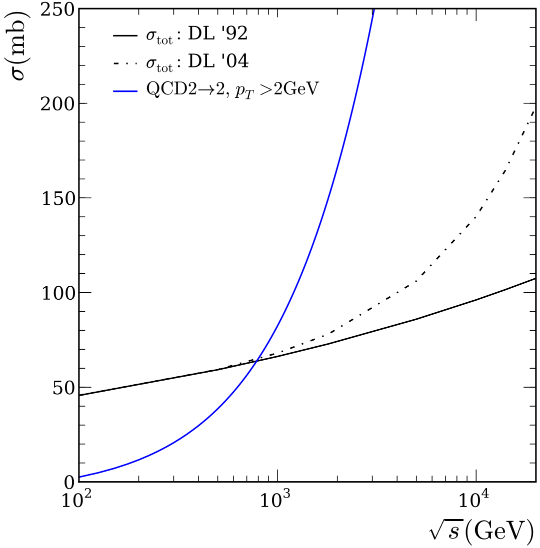
Eikonal model basics

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

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

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}:

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

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

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

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

Eikonal model basics

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

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

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

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

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&\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^{\mathrm{inc}}(s;p_t^{\mathrm{min}}) \ .
\end{aligned}$$

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

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

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

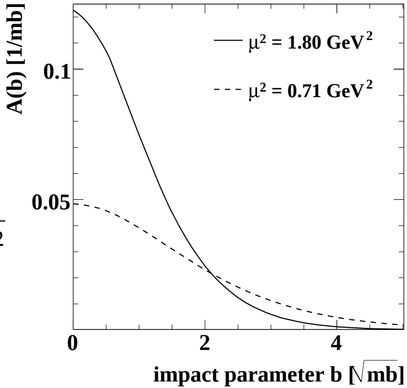
Overlap function

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

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

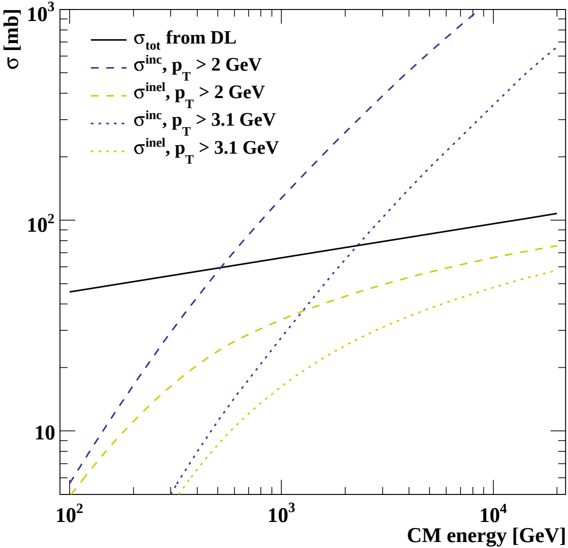
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.

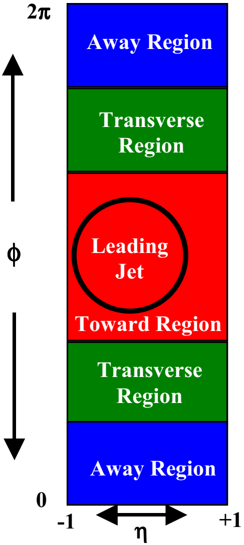


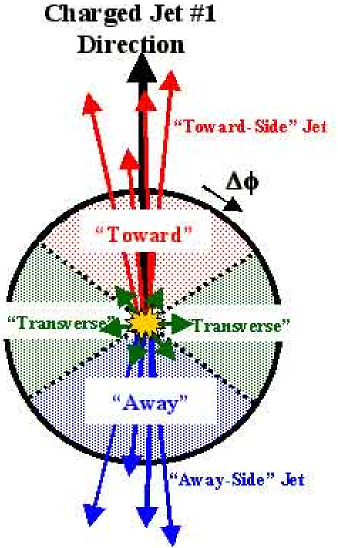
$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.

Unitarized cross sections



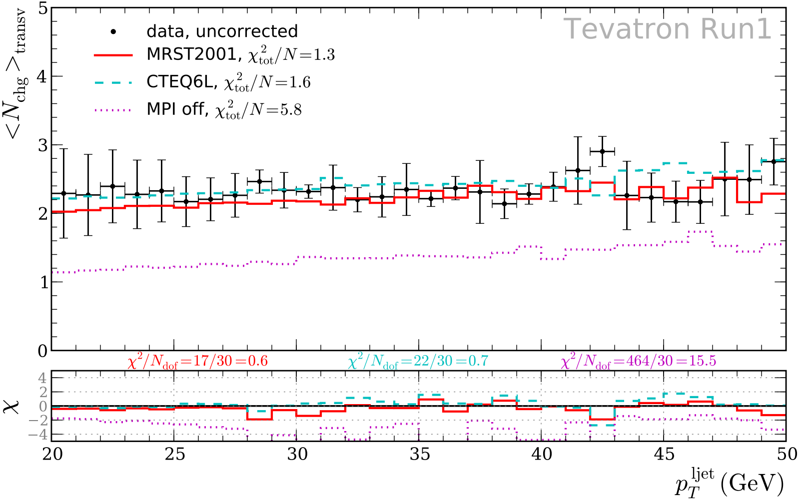
Rick Field's analysis





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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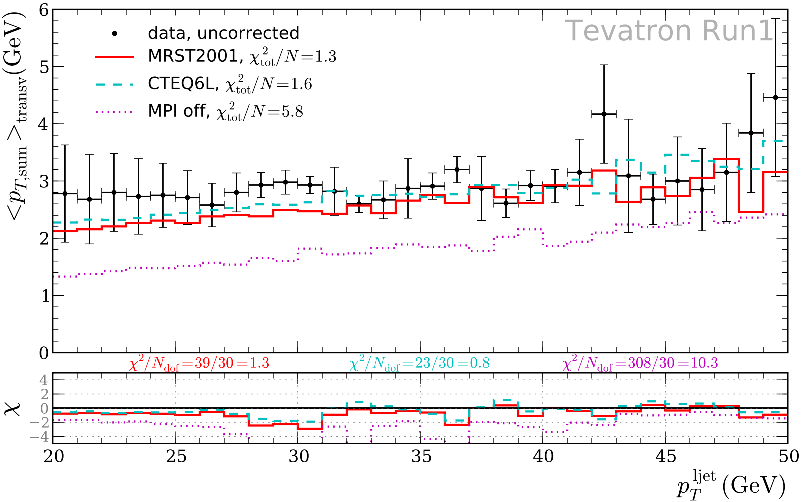


Only $p_T^{\rm ljet} > 20\,{\rm GeV}$.

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:

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

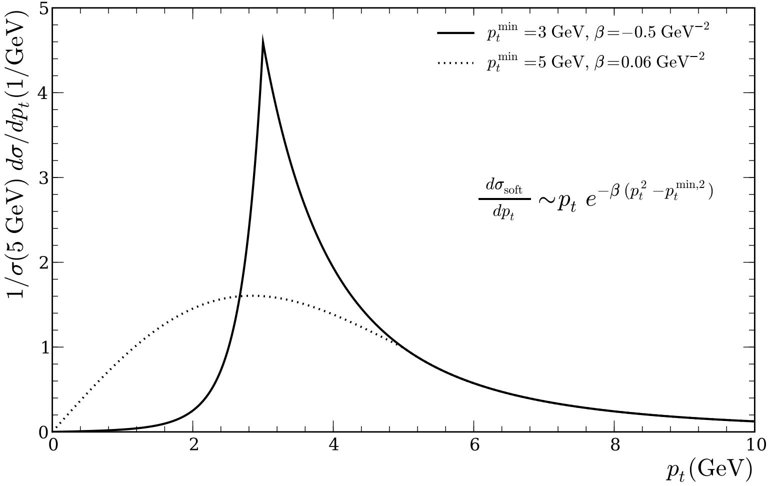
Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

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 $\sigma_{\text{soft}}^{\text{inc}}$

Exploit knowledge of σ_{tot} in eikonal model:

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

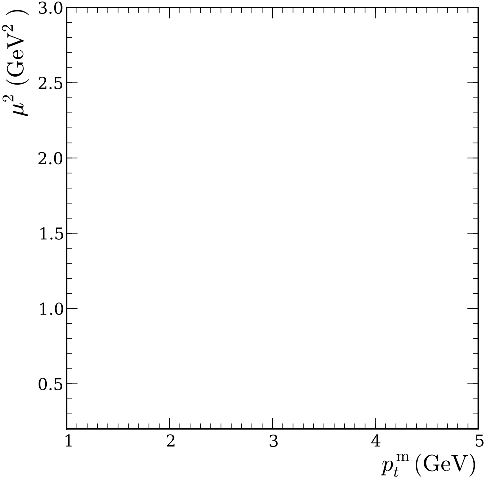
σ_{tot} well measured. Fixes $\sigma_{\text{soft}}^{\text{inc}}$.

Energy extrapolation from Donnachie–Landshoff

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

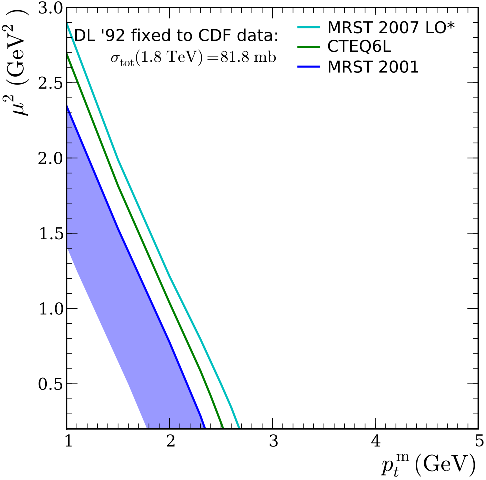
Constraints at the Tevatron

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



Constraints at the Tevatron

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



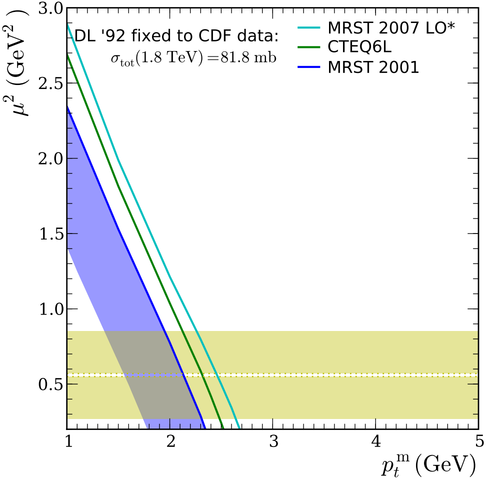
Constraints at the Tevatron

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

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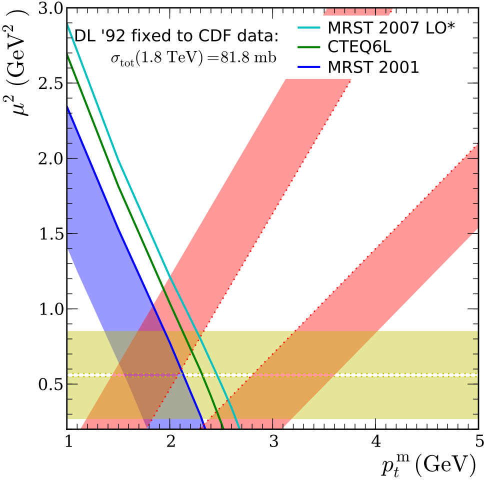
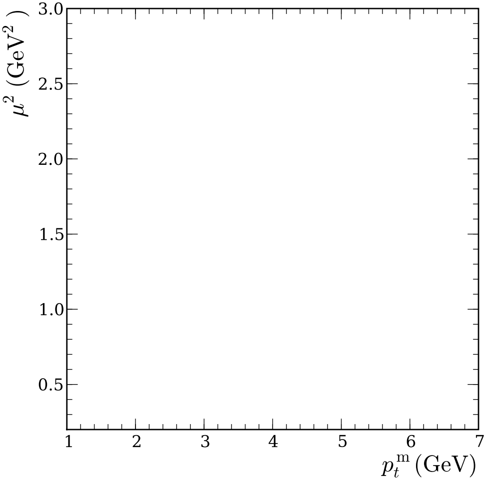
- Final state tune of **semi-hard** MPI (MRST2001)



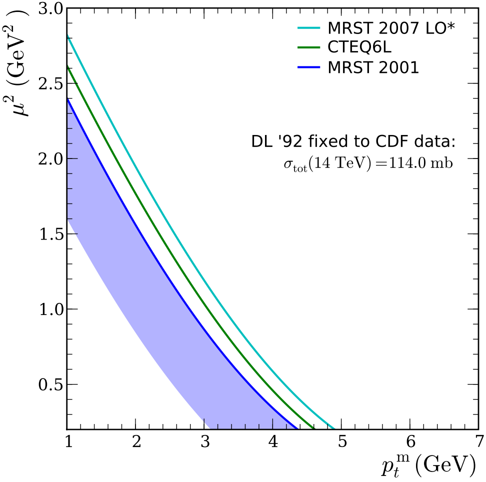
Constraints at the LHC

- 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



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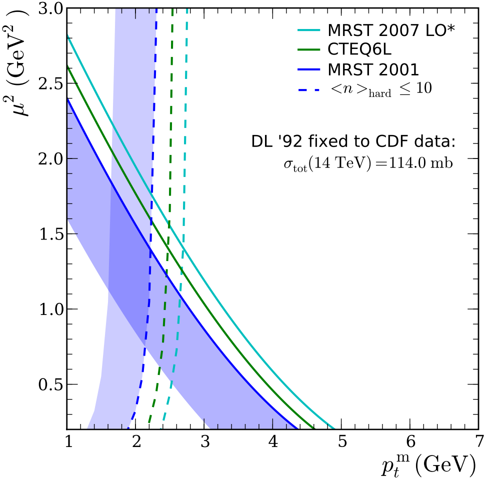
- Require $\bar{n}_{\text{hard}} < 10$

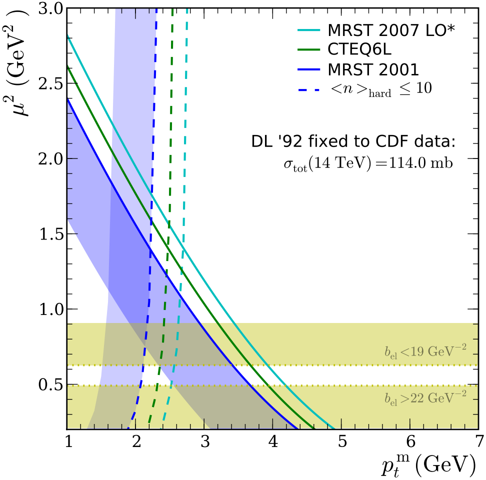


Constraints at the LHC

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



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:

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

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

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

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→ 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 $\sigma_{\text{soft}}^{\text{inc}}$ in

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

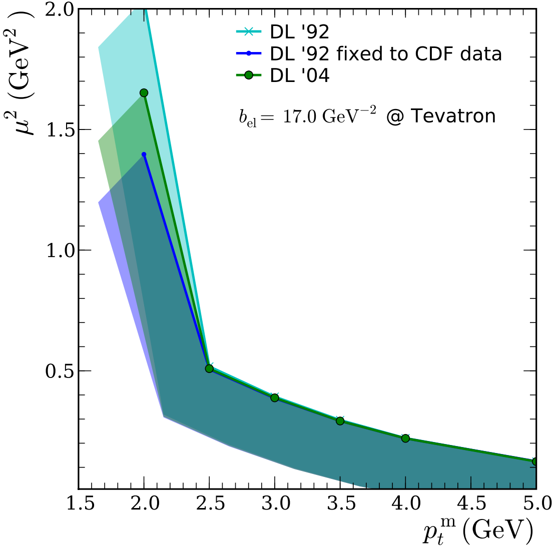
from two constraints. Require simultaneous description of σ_{tot} and b_{el} (measured/well predicted),

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

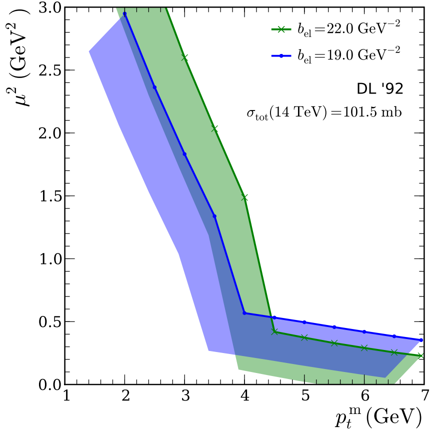
$$b_{\text{el}}(s) \stackrel{!}{=} \int \mathrm{d}^2\vec{b}\,\frac{b^2}{\sigma_{\text{tot}}}\left(1 - \mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) .$$

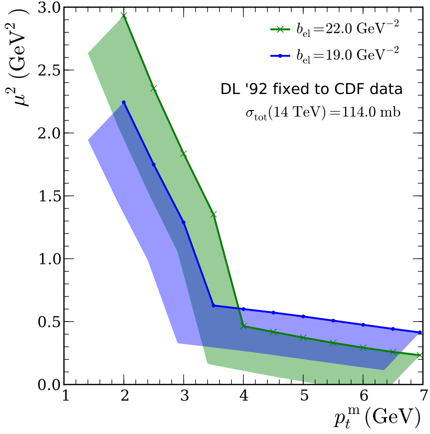
Tevatron parameter space

Only one constraint: describe σ_{tot} and b_{el}.



Same for LHC except for uncertainty in b_{el} and σ_{tot}.



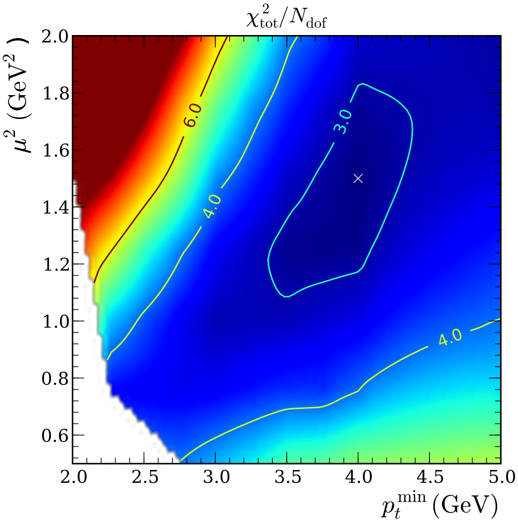


Tevatron Run I final states

- 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.

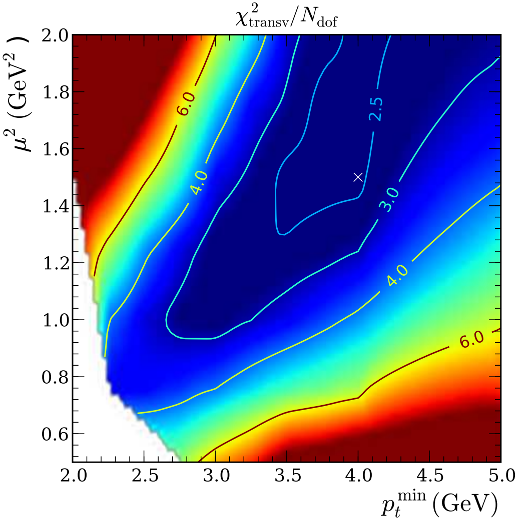
Parameter space at Tevatron

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

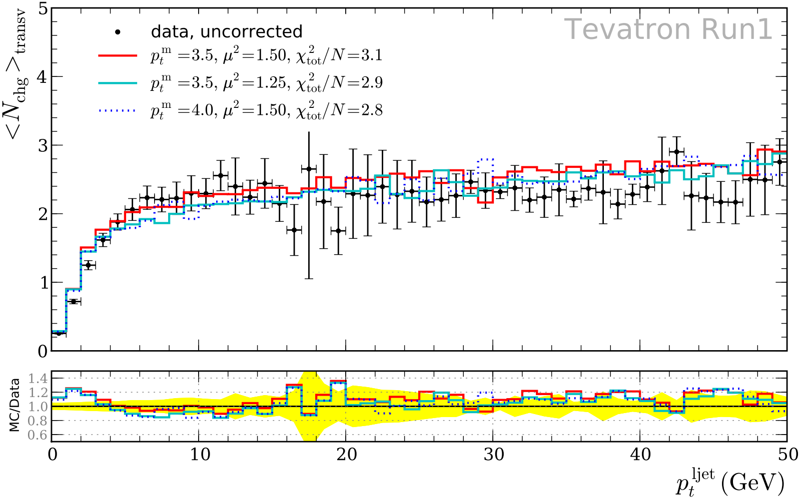


Parameter space at Tevatron

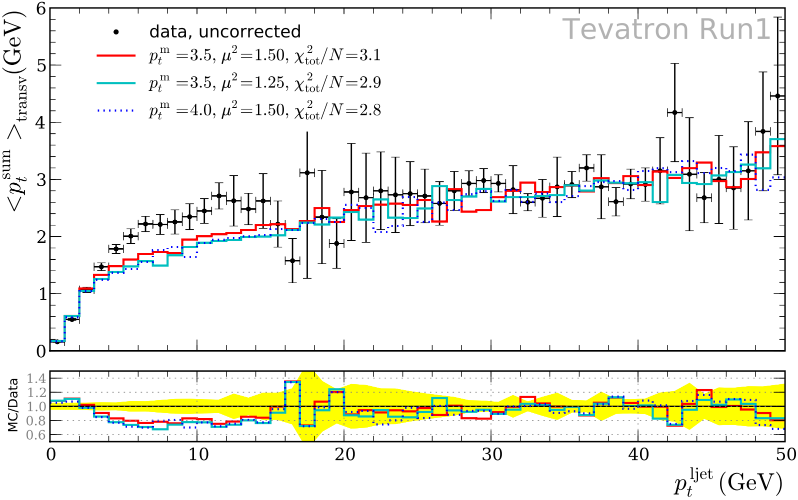
- χ^2 for Rick's Run1 Jet analysis for **all** regions
- only the transverse region



Detailed look at observables: Transverse Region



Detailed look at observables: Transverse Region



On to the LHC

What we have so far:

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

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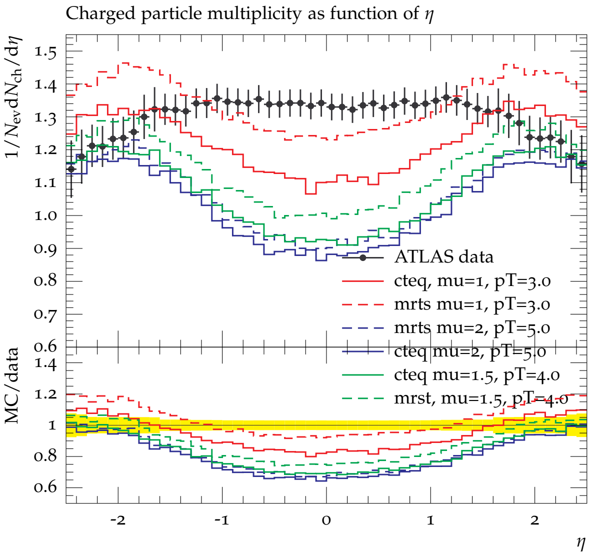
$\Longrightarrow$ *Look at LHC results (900 GeV).*

- ATLAS charged particles in Min Bias.
- Convenient as the analysis was quickly available in RIVET ;-)
- Three points from 'valley' $(p_t^{\rm min}/{\rm GeV}, \mu^2/{\rm GeV}^2) = (3.0, 1.0); (4.0, 1.5); (5.0, 2.0)$

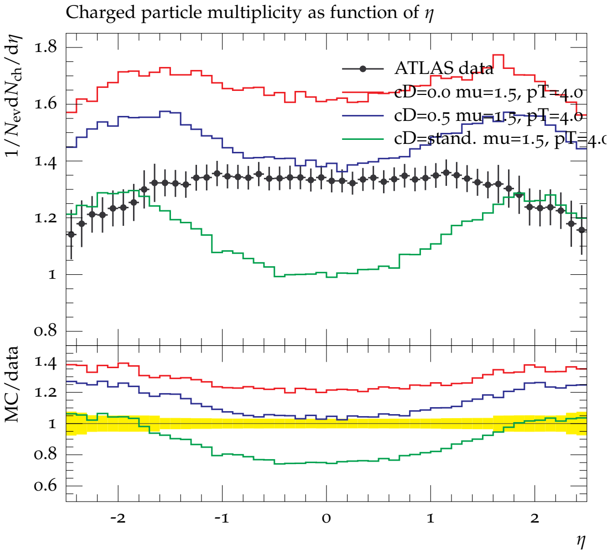
First plots against LHC data

Choice of PDF set (CTEQ61l vs MSTW LO** (our default)).



First plots against LHC data

Colour structure of soft events.



First plots against LHC data

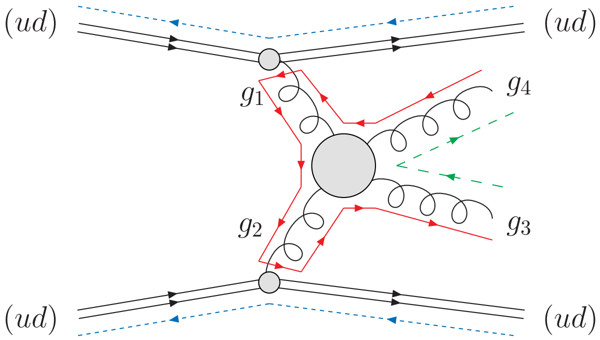
- Not so nice.
- Despite very good agreement with Rick Field's CDF UE analysis.
- Observe sensitivity to colour structure.

Colour structure

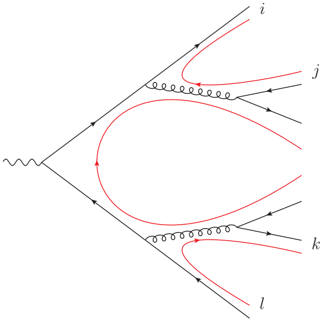
Sensitivity to parameter

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

(as opposed to hard QCD).



Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

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

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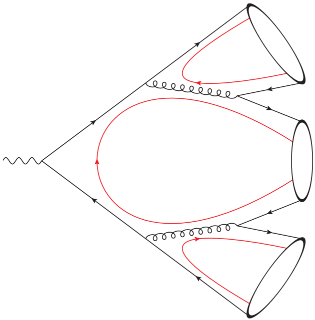

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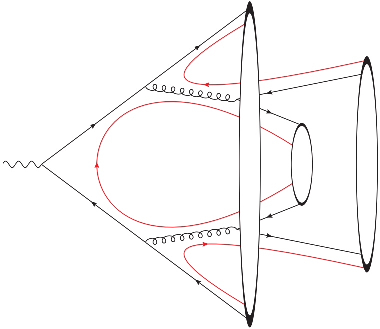

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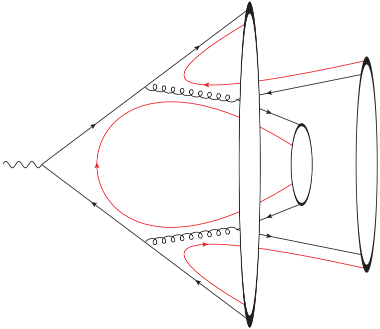


Extend cluster hadronization:

- 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,

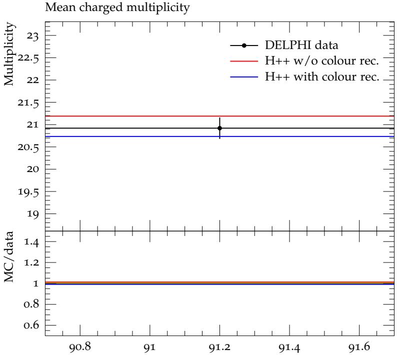
$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

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

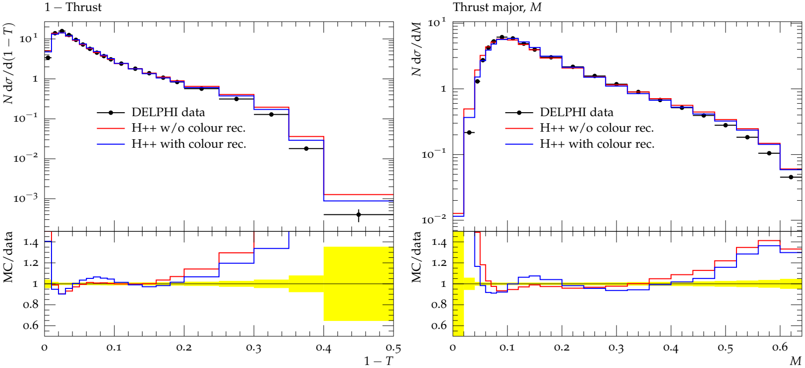
LEP tune with new model

- Hadronization sensitive to CR model.
- Proper study requires re–tune to LEP data.
- Used PROFESSOR.

LEP tune with new model



LEP tune with new model



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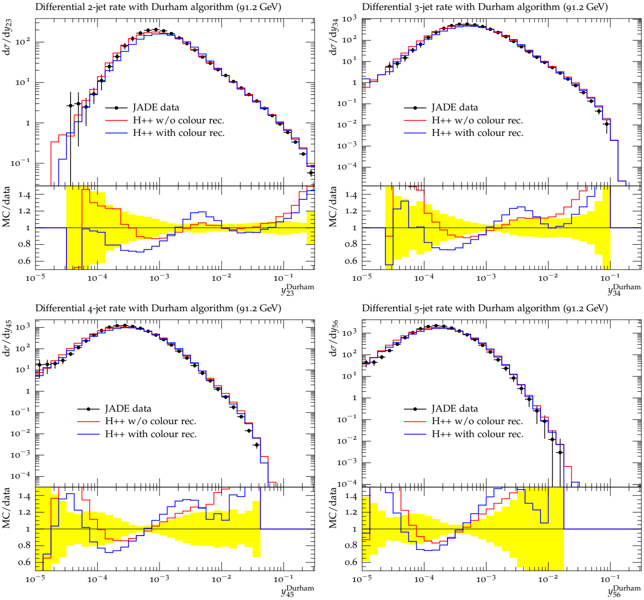

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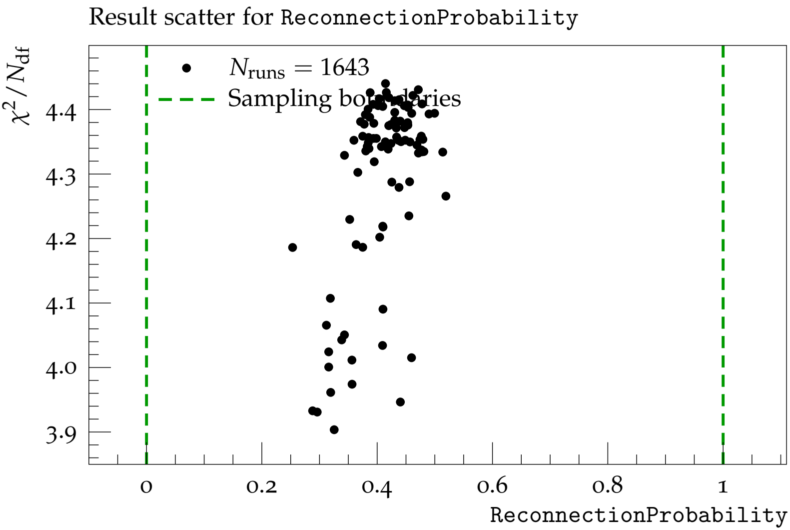
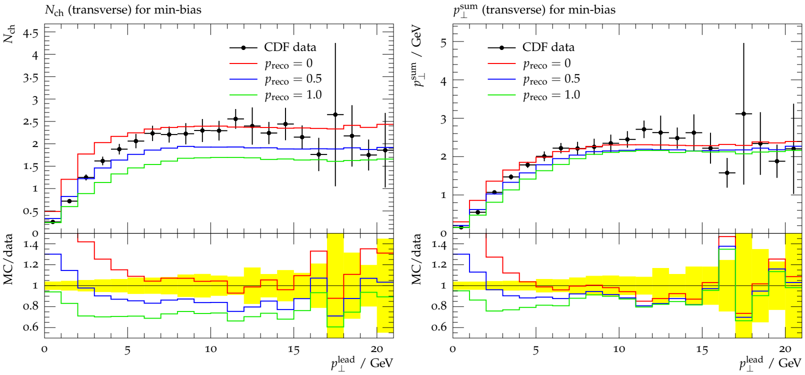


LEP tune with new model

- Hadronization sensitive to CR model.
- Proper study requires re–tune to LEP data.
- Used PROFESSOR.

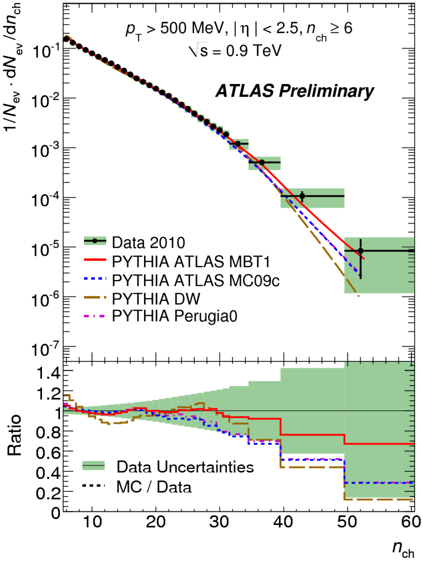
- Agreement on same level as w/o CR model.

A quick look at CDF data



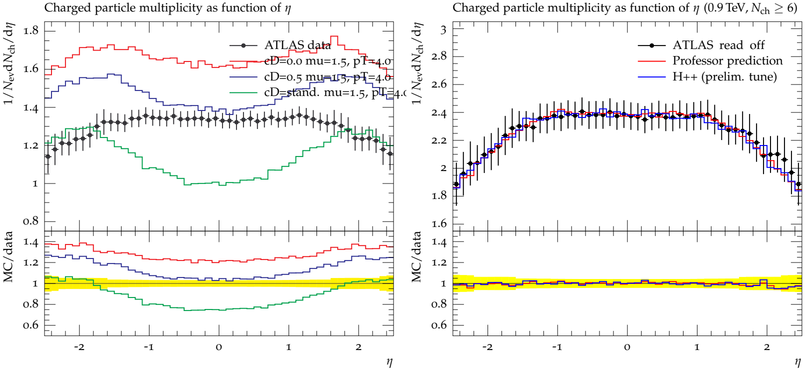
Sensitivity different for the two observables.

Comparison with MinBias ATLAS data



- Proper comparison: lack of diffraction in Herwig++!
- ATLAS $N_{ch} \geqslant 6$ analysis.
- **Unfortunately:** plots public, data not.
- We use **EasyNData**
  P. Uwer [arXiv:0710.2896]
- Read off error $\ll$ error bars.

Comparison with MinBias ATLAS data (900 GeV)



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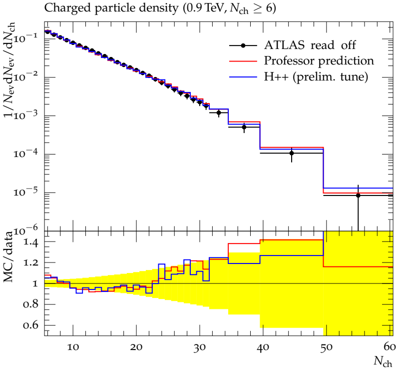

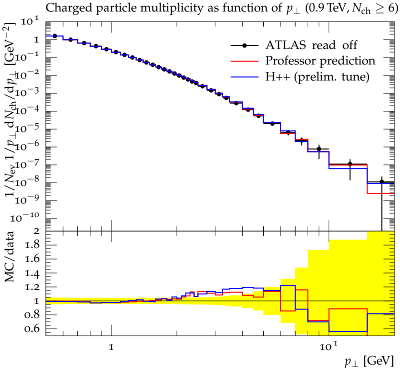

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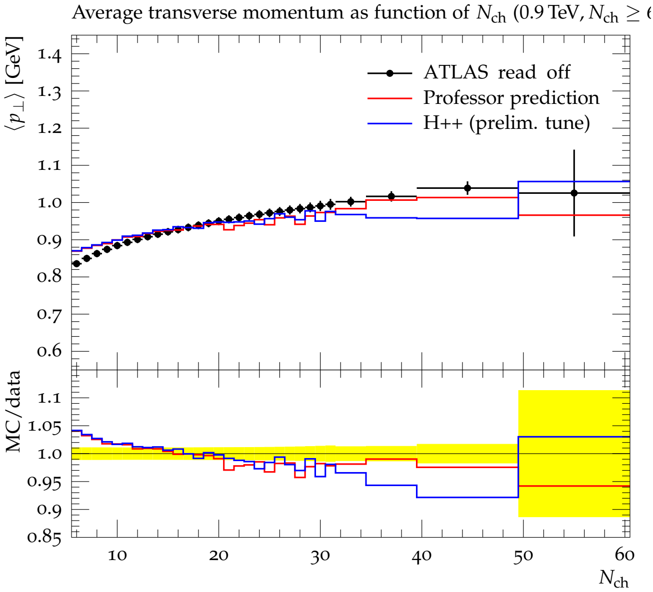
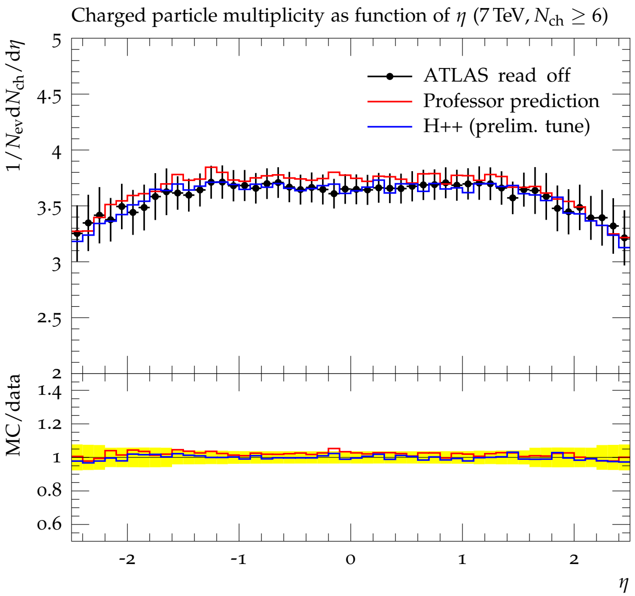


Comparison with MinBias ATLAS data (7 TeV)



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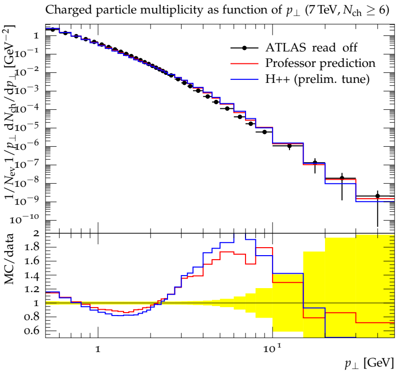

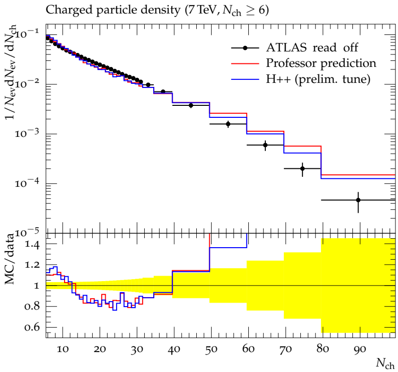

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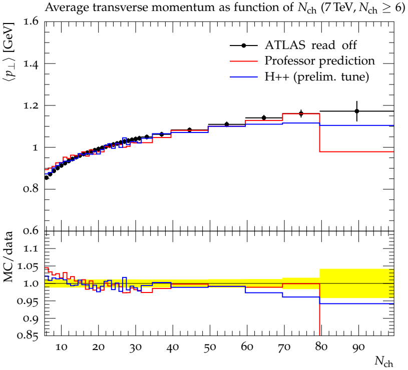
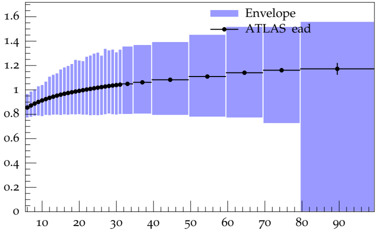
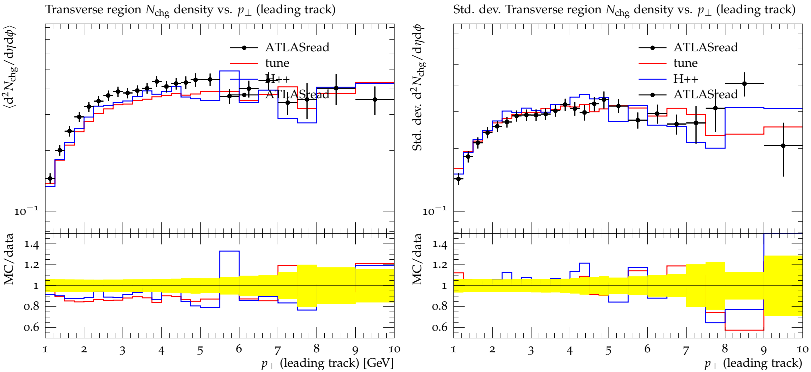




Underlying Event (900 GeV)



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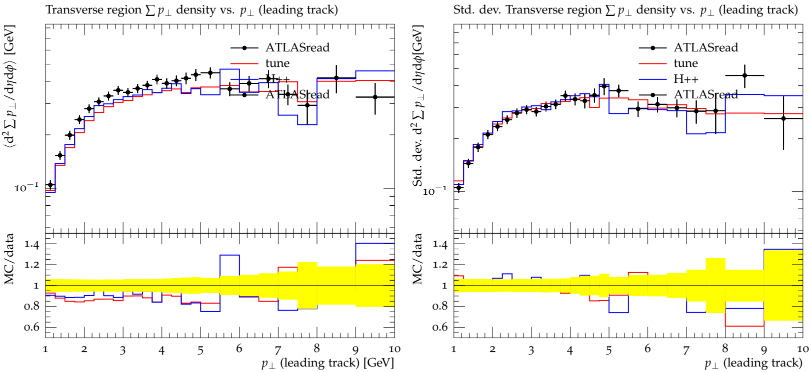
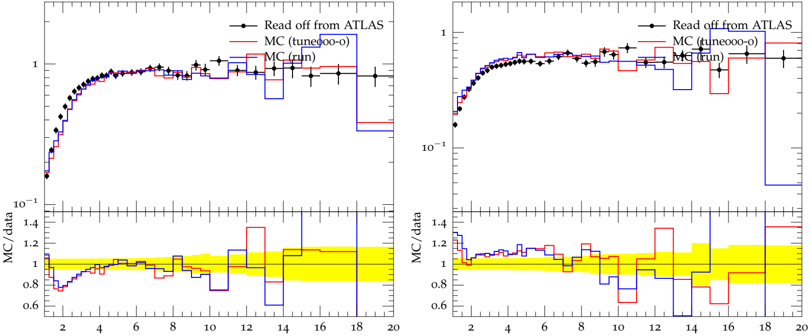


Underlying Event (7 TeV)

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



Dip at 2 GeV: mistake in data analysis?

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

Preliminary results

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

Conclusions

- MPI UE/Min Bias model in Herwig++.
- Close connection to σ_{tot} and σ_{el} via unitarization.
- Exploited to constrain free parameters and used Run I data.
- First look at LHC data within these constraints.
- Need colour reconnection model.
- First tunes to 900 GeV and 7 TeV Min Bias ($N_{\text{ch}} \geq 6$) data give good results.
- Non–diffractive physics under good control

Outlook

Open questions

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

More to come:

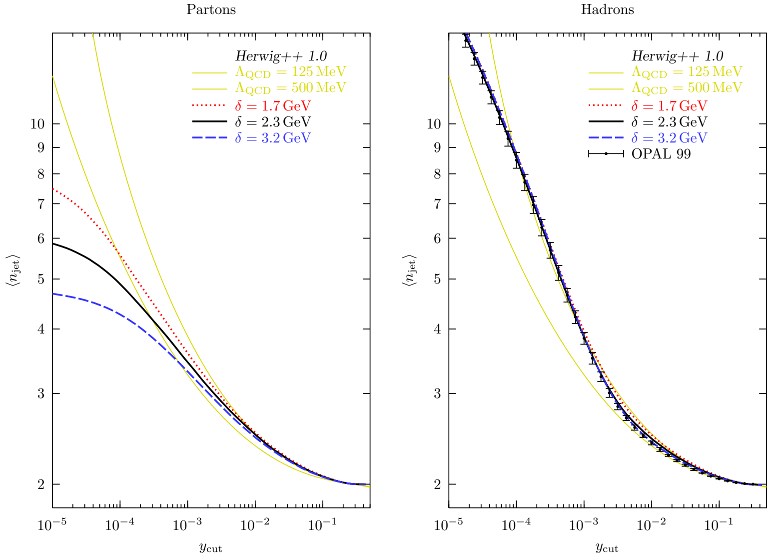
- Model for diffraction.
- Further checks of consistency.
- In future release Herwig++ 2.5 (out very soon).
- Better look at energy dependence.
- Universal tune of UE parameters?

Stay tuned!

Extra slides

Example, outdated

Smooth interplay between shower and hadronization.



Example, outdated

$$R_n = \sigma(n\text{–jets})/\sigma(\text{jets})$$

$$R_6 = \sigma(>5\text{–jets})/\sigma(\text{jets})$$