MC Developments in Herwig++
— Min Bias and Underlying Event —

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Physics at the LHC, DESY HH, 7–11 June 2010

Work with Manuel Bähr, John Butterworth, Mike Seymour, Andrzej Siodmok

Underlying event in Herwig++

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 $\to$ mini jets.
- Was default in fHerwig. Superseded by `JIMMY`.

[JM Butterworth, JR Forshaw, MH Seymour, ZP C72 637 (1996)]

Underlying event in Herwig++

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.

This talk

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

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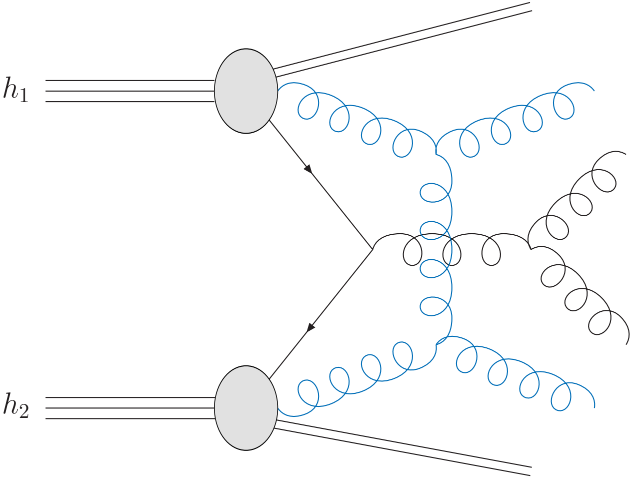
- First look at LHC data.
- How well does it work out of the box?

- Enough flexibility in parameter space?
- Model too simple?
- pdfs/modelling of MPI pdfs?

Mulitple hard interactions



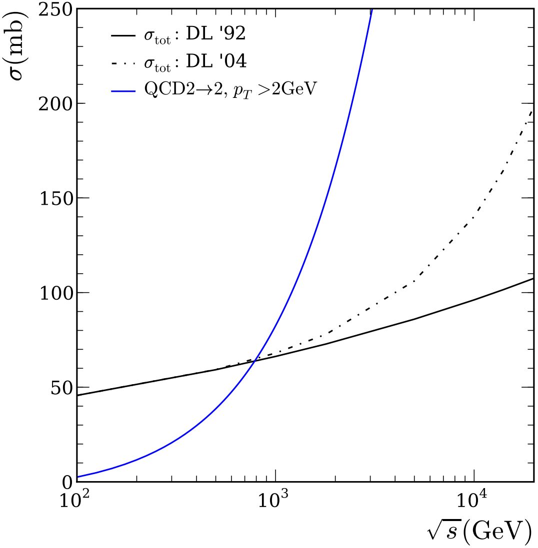
Eikonal model basics

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 ⇒ 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,

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

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

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

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

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

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

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

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

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

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

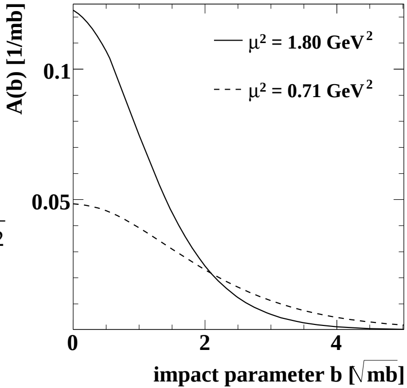
Overlap function

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

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

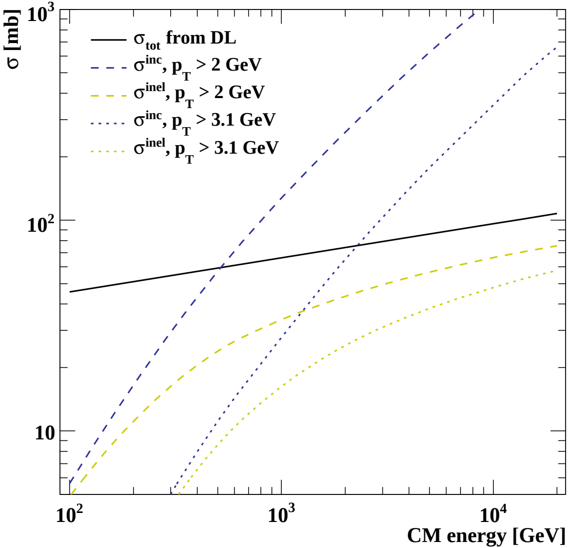
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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



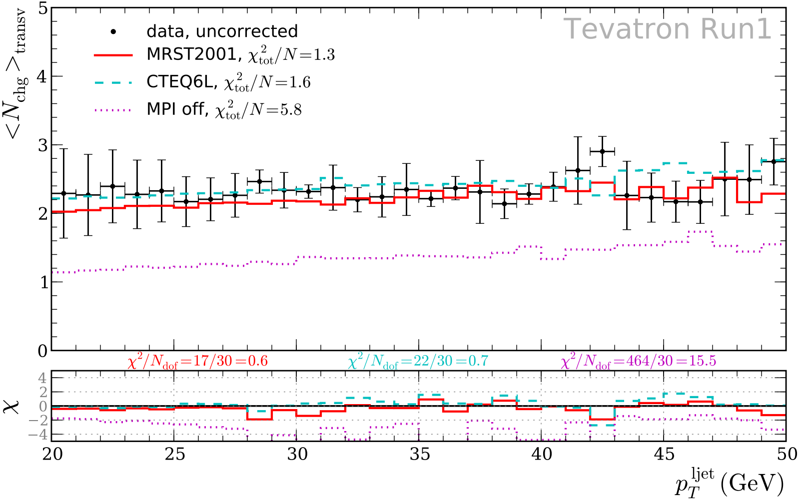
$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\mathrm{min}}$.

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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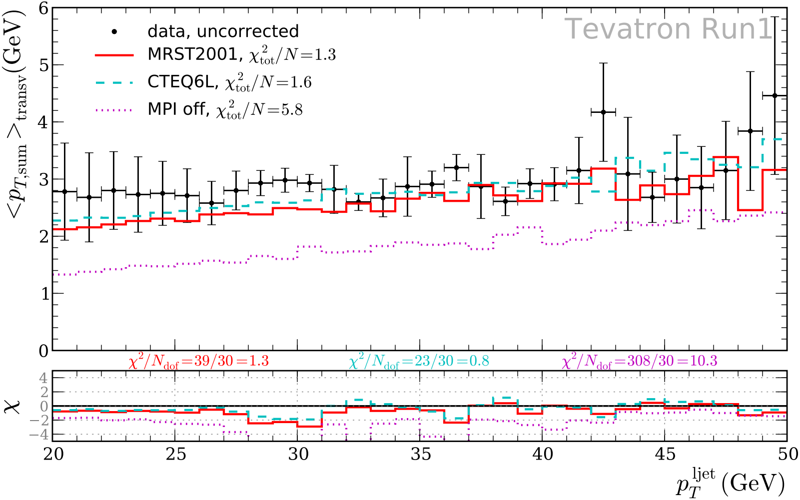


Only $p_T^{\rm ljet} > 20\,\text{GeV}$.

Soft eikonal

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

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

Similar structures of eikonal functions:

$$\chi_{\rm soft} = \frac{1}{2} A_{\rm soft}(\vec{b}) \sigma^{\rm inc}_{\rm soft}$$

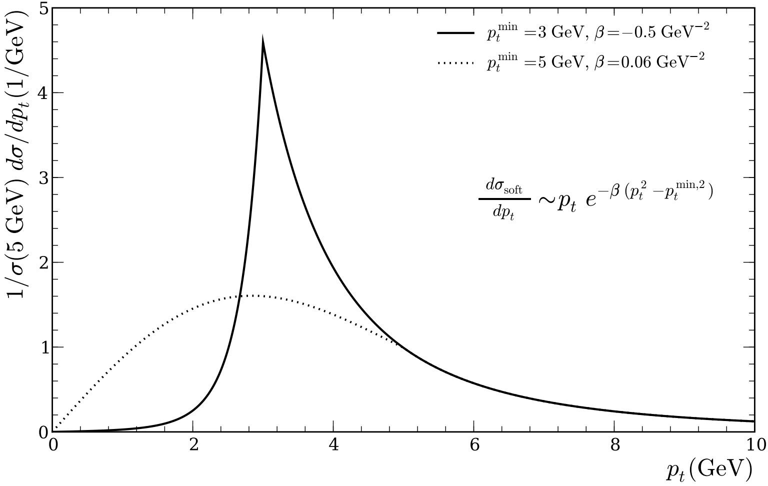
Simplest possible choice: $A_{\rm soft}(\vec{b};\mu) = A_{\rm hard}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

One new parameter $\sigma^{\rm inc}_{\rm soft}$.

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:

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

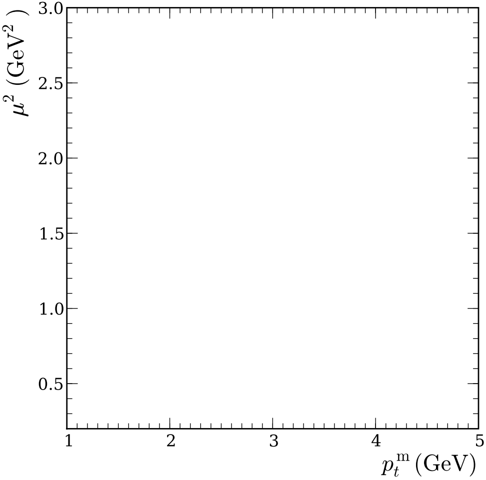
σ_{tot} well measured. Fixes $\sigma_{\mathrm{soft}}^{\mathrm{inc}}$.

Energy extrapolation from Donnachie–Landshoff

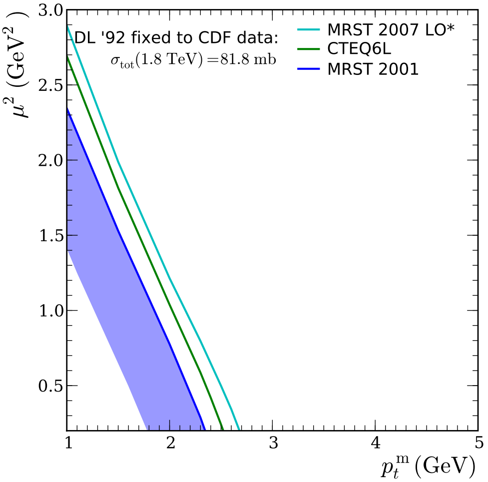
- DL '92 [D&L, PLB296, 227 (1992)]
- DL '92 normalized at TVT
- DL '04 [D&L, PLB595, 393 (2004)]

Constraints at the Tevatron

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



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



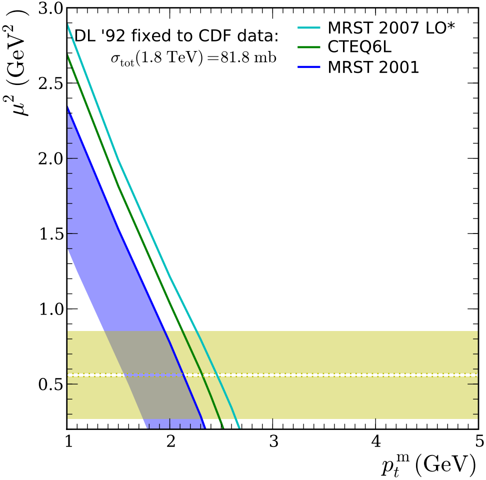
Constraints at the Tevatron

- 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

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



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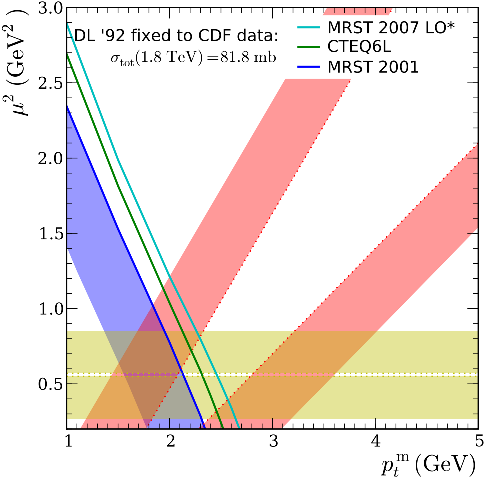
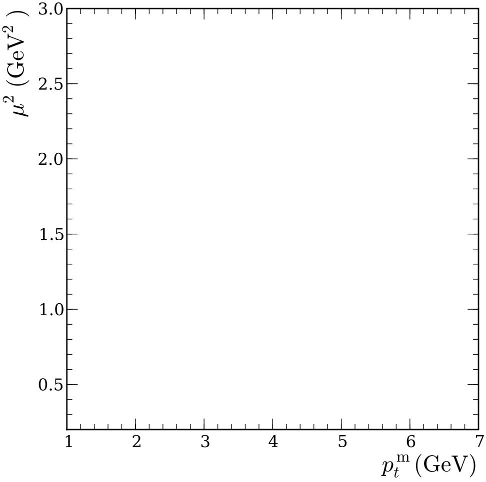
- Final state tune of **semi-hard** MPI (MRST2001)



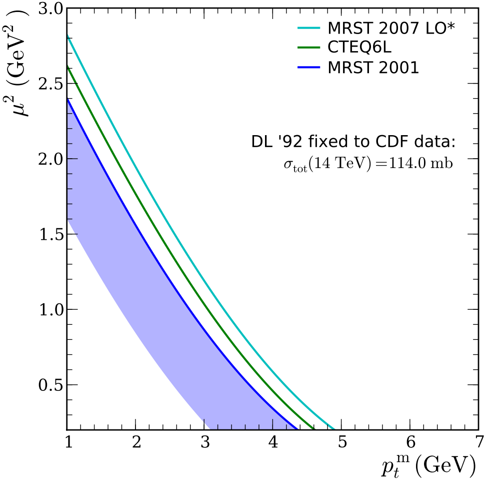
Constraints at the LHC

- What to expect at 14 TeV?

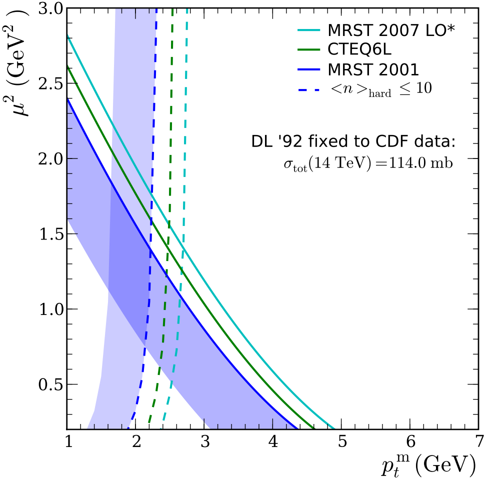


Constraints at the LHC

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



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

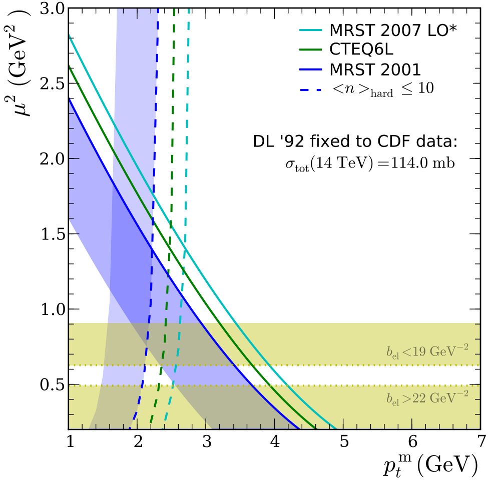


Constraints at the LHC

- What to expect at 14 TeV?
- $\sigma_{\text{soft}}^{\text{inc}} > 0$ 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

- $\sigma_{\text{soft}}^{\text{inc}}$ 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_{el} fixes μ^2 at Tevatron:

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

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

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

Observations

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$\rightarrow$ 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 $\mu_{\rm soft}$ and $\sigma^{\rm inc}_{\rm soft}$ in

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

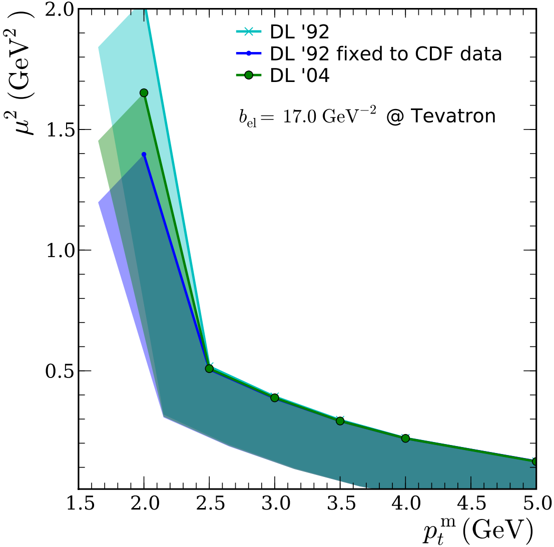
from two constraints. Require simultaneous description of $\sigma_{\rm tot}$ and $b_{\rm el}$ (measured/well predicted),

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

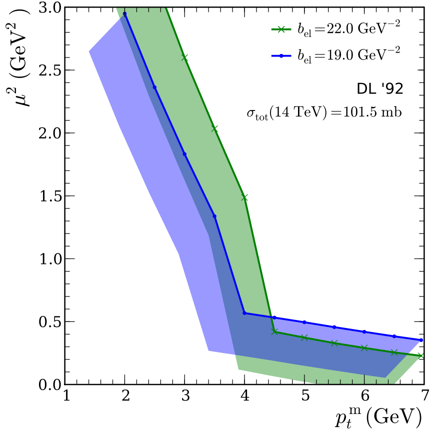
$$b_{\rm el}(s) \stackrel{!}{=} \int {\rm d}^2\vec{b}\,\frac{b^2}{\sigma_{\rm tot}}\left(1 - {\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) .$$

Tevatron parameter space

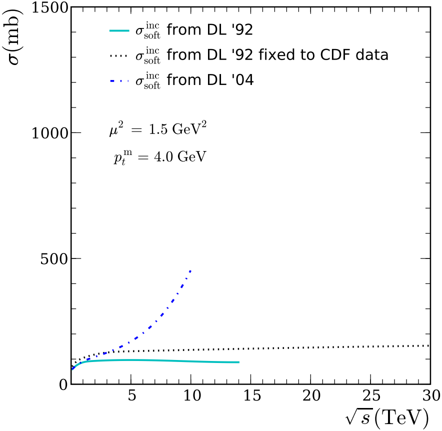
Only one constraint: describe σ_{tot} and b_{el}.

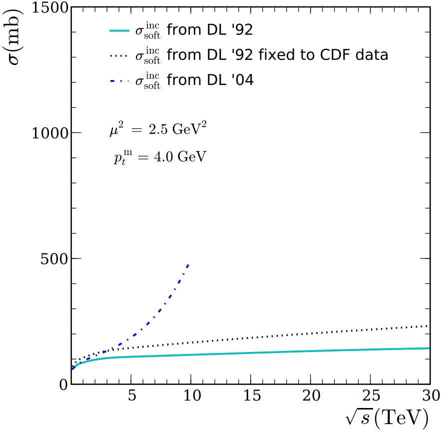


Same for LHC except for uncertainty in $b_{\rm el}$ and $\sigma_{\rm tot}$.



Resulting soft cross section



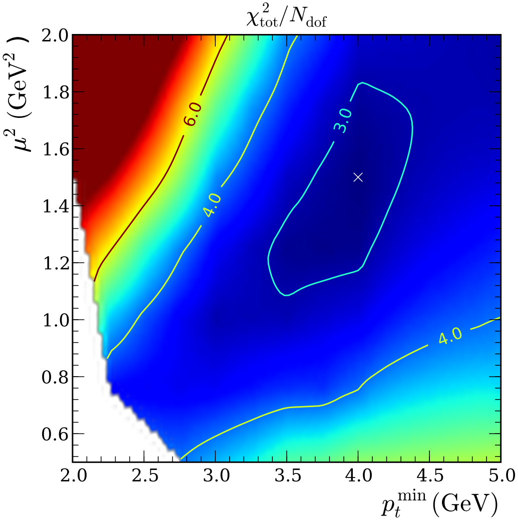


Tevatron Run I final states

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

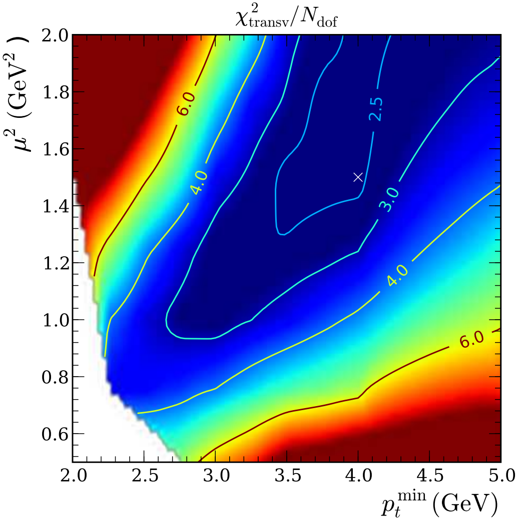
Parameter space at Tevatron

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

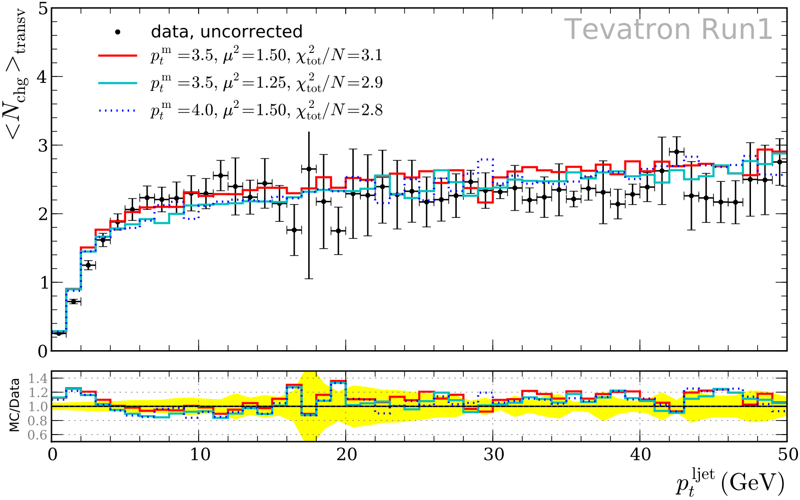


Parameter space at Tevatron

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



Detailed look at observables: Transverse Region



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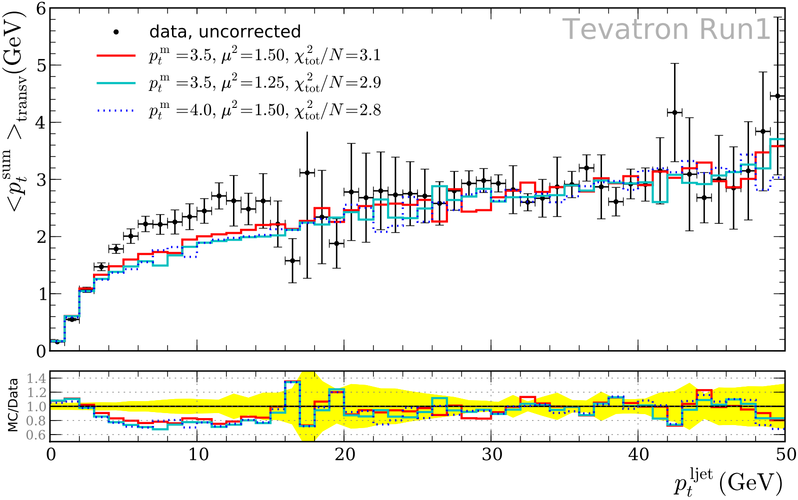

On to the LHC

What we have so far:

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

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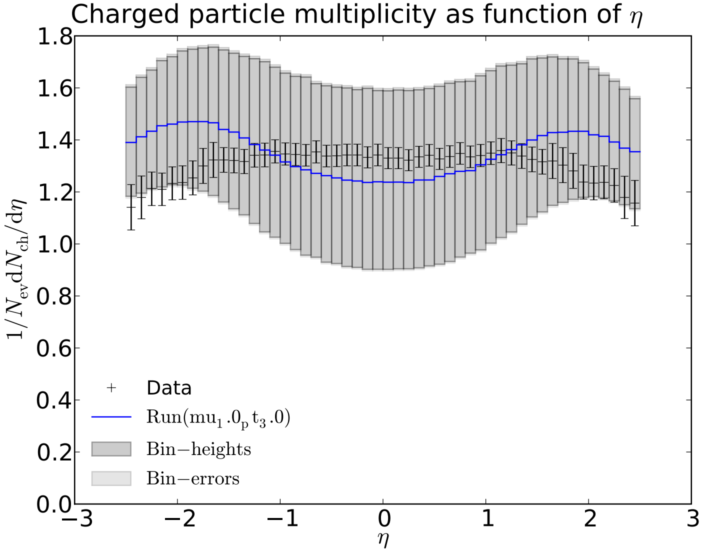
$\Longrightarrow$ *Look at LHC results (900 GeV).*

- ATLAS charged particles in Min Bias
  (→ G. Brandt yesterday [207]).
- Already in RIVET ;-)
- Three points from 'valley'
  $(p_t^{\min}/\text{GeV}, \mu^2/\text{GeV}^2) = (3.0, 1.0); (4.0, 1.5); (5.0, 2.0)$

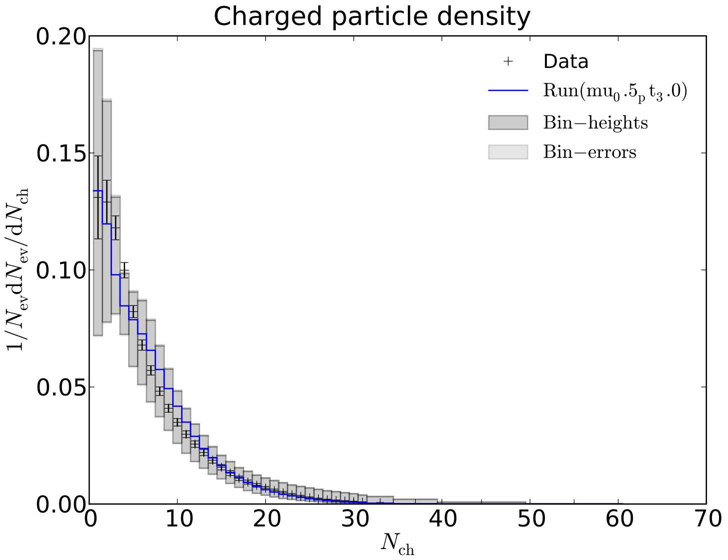
First plots against LHC data

Variation over the constrained parameter space



First plots against LHC data

Variation over the constrained parameter space



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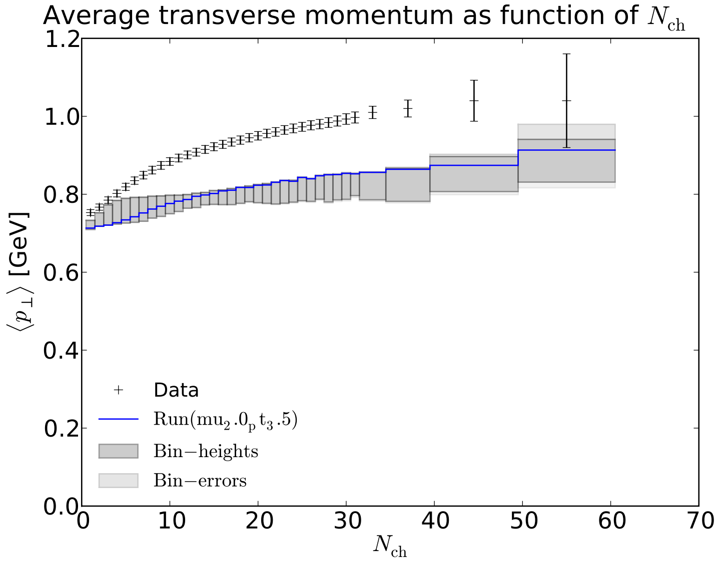
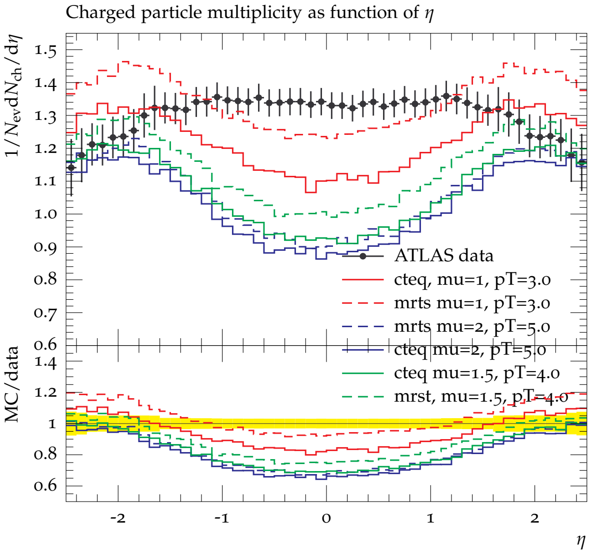


Choice of PDF set.



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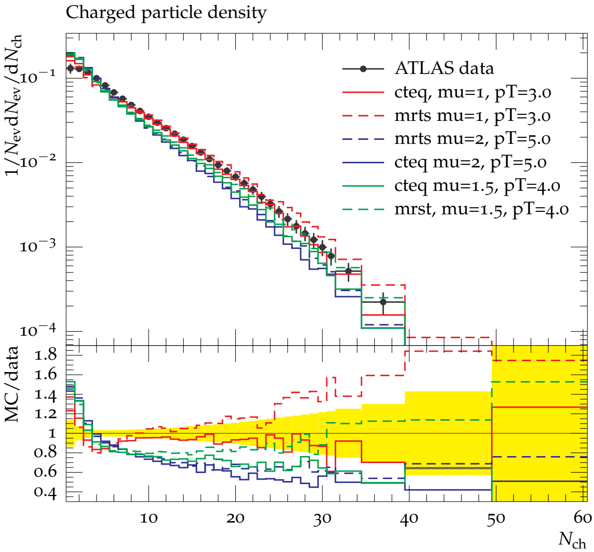
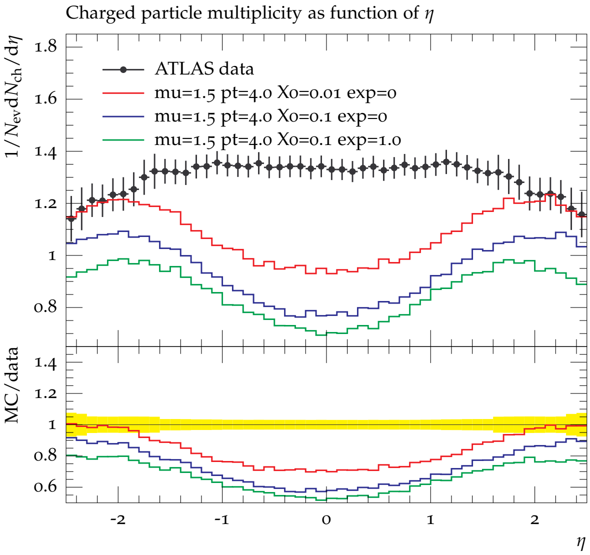


First plots against LHC data

Sensitivity to pdf at small x via simple model.



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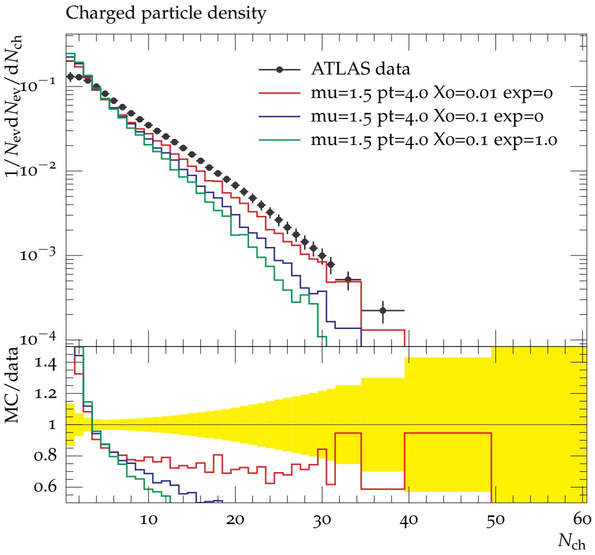
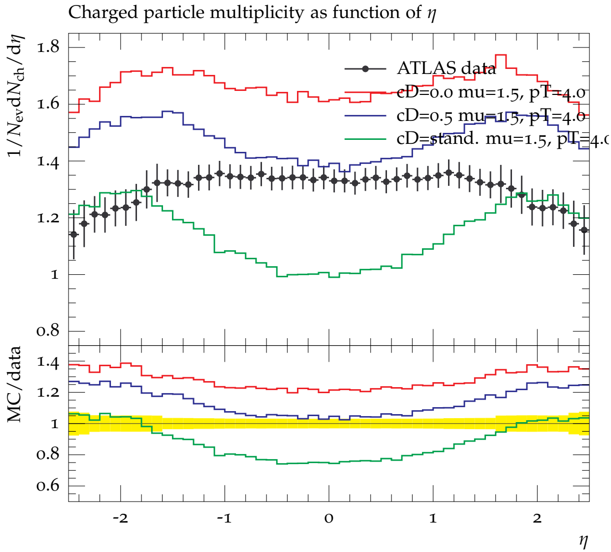
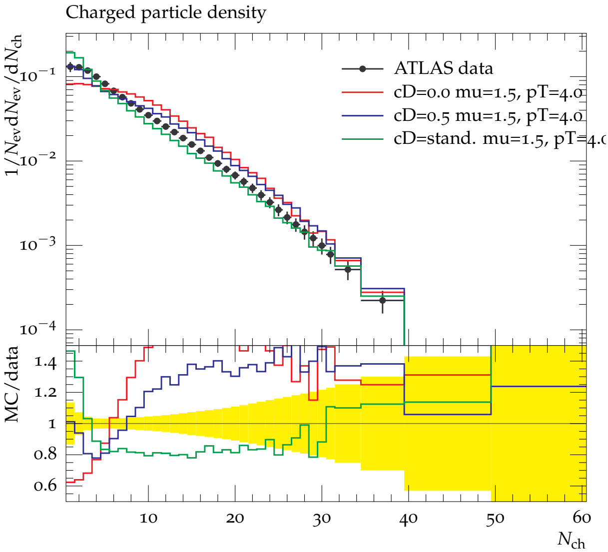


Colour structure of soft events.



First plots against LHC data

Colour structure of soft events.



Summary

- MPI UE/Min Bias model in Herwig++.
- Close connection to σ_{tot} and σ_{el} via unitarization.
- Exploited to constrain free parameters.
- Used Run I data on top.
- First look at LHC data within these constraints.

Conclusions

- Freedom in parameter space allows to adjust normalization.
- Model too simplistic for shapes?
- Treatment of remnant pdfs too naive?
- More involved overlap function?
  With Energy dependent parameters?
- New implementation of colour reconnection model to be tested!
- Stay tuned!

Extra slides

Rick Field’s analysis