Underlying event in Herwig++

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MC group meeting, DESY HH, 20 July ’09

Work with Manuel Bähr, John Butterworth, Mike Seymour
(thanks to Manuel for most of the slides!)

UA5 model

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 Superseded by `JIMMY`.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

Underlying event in Herwig++

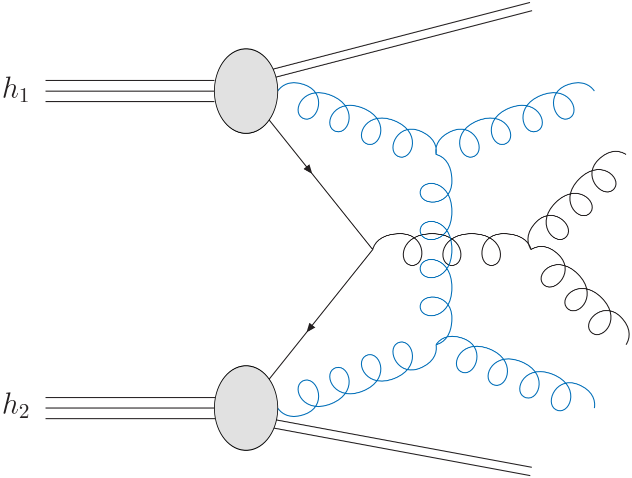
Soft UE

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions $p_t < p_t^{\min}$.
- Relation to total cross section, Exploration of parameter space.
- Extrapolation to LHC?
- Theoretical work with simplest possible extension.

  [Bähr, Butterworth, Seymour, JHEP 0901:065]
- "Hot Spot" model. [Bähr, Butterworth, SG, Seymour, 0905.4671]

Eikonal model basics

Mulitple hard interactions



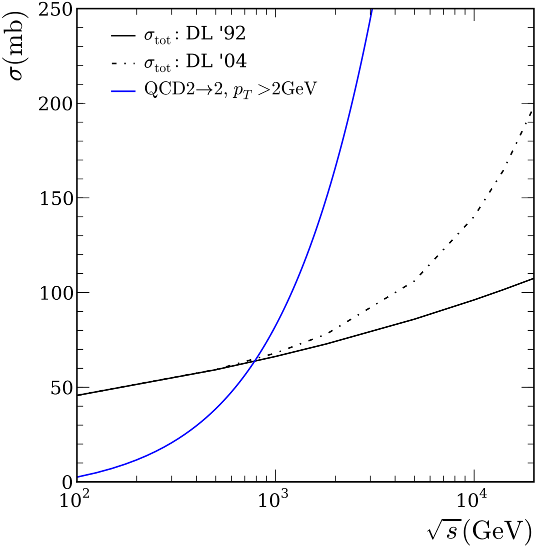
Eikonal model basics

Starting point: hard inclusive jet cross section.

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

$\sigma^{\mathrm{inc}} > \sigma_{\mathrm{tot}}$ eventually (for moderately small $p_t^{\min}$).

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 $\Rightarrow$ 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,

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

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

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

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

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

Then we get σ_{inel}:

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

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

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

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

Eikonal model basics

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

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

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

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

Eikonal model basics

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

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

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

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

Overlap function

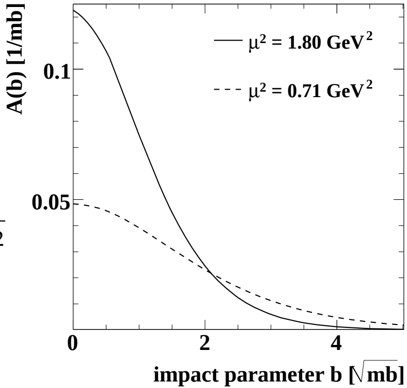
$$A(b) = \int d^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

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

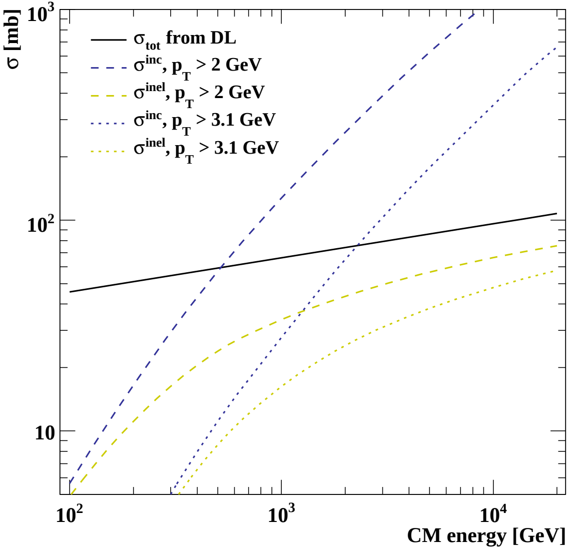
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

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

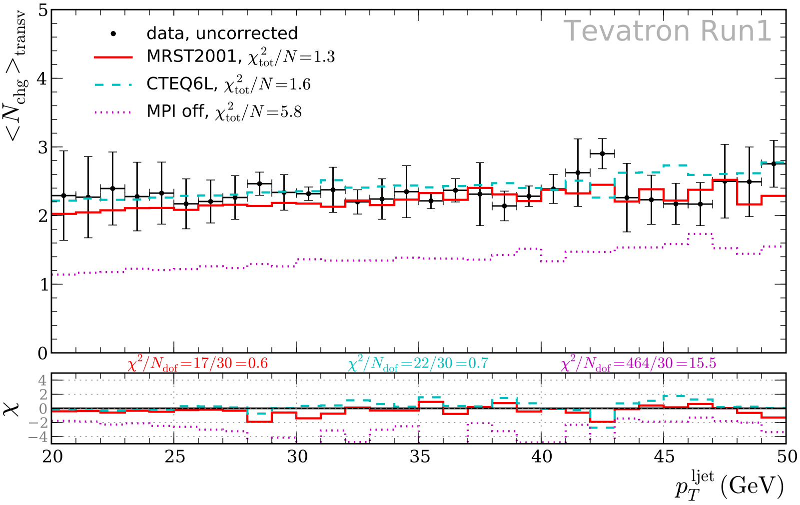
$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.



Unitarized cross sections



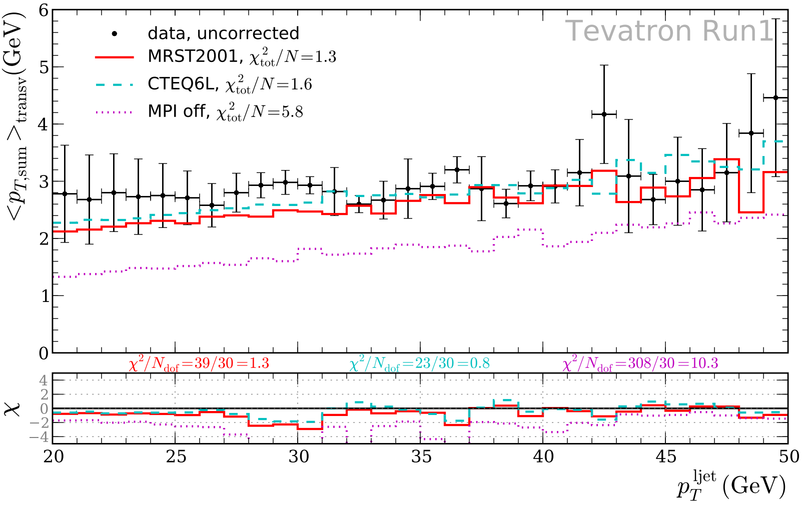
Good description of Run I Underlying event data ($\chi^2 = 1.3$).



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

Semi hard underlying event

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



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

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:

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

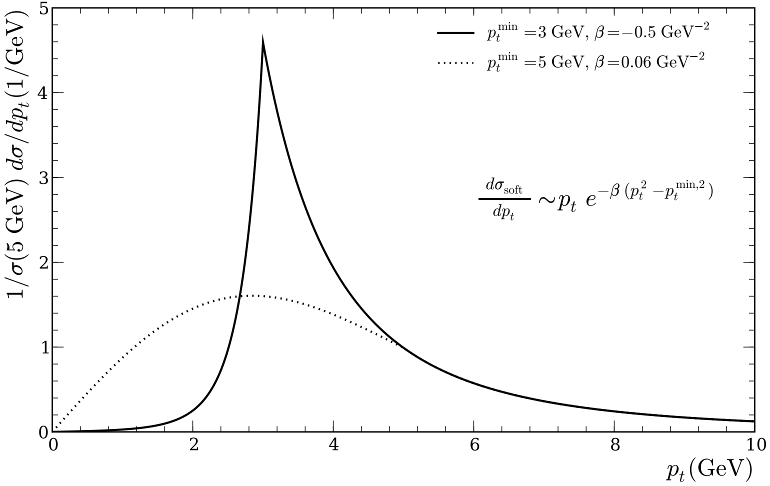
Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

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

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:

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

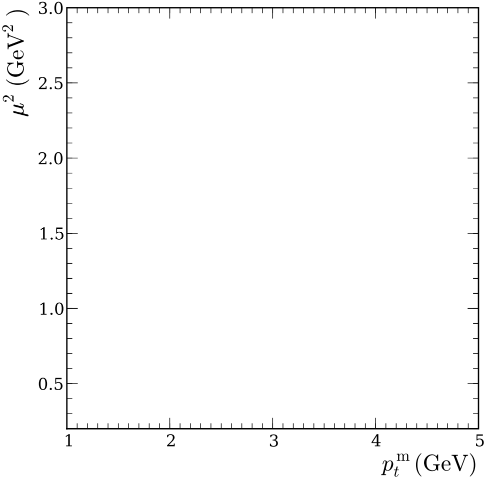
σ_{tot} well measured. Fixes $\sigma_{\text{soft}}^{\text{inc}}$.

Energy extrapolation from Donnachie–Landshoff

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

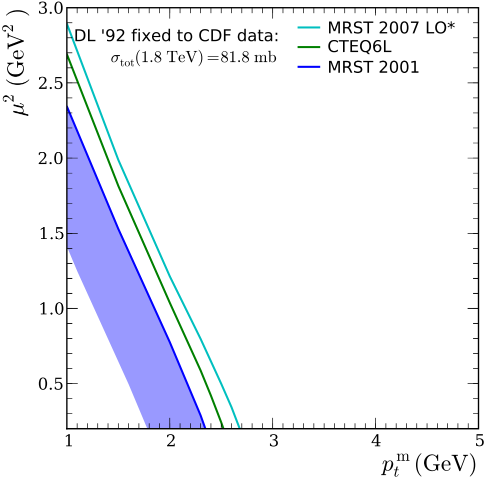
Constraints at the Tevatron

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



Constraints at the Tevatron

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



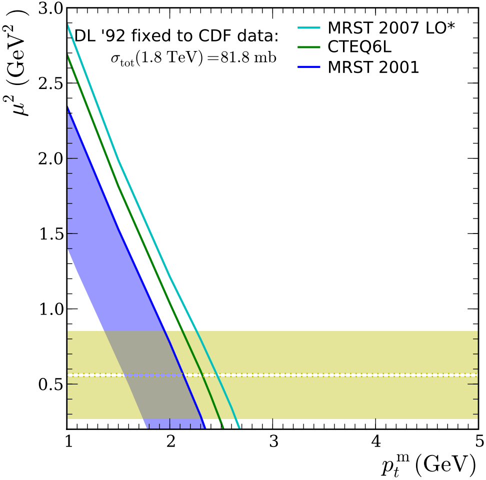
Constraints at the Tevatron

- 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 $(p_t^{\min}, \mu)$.
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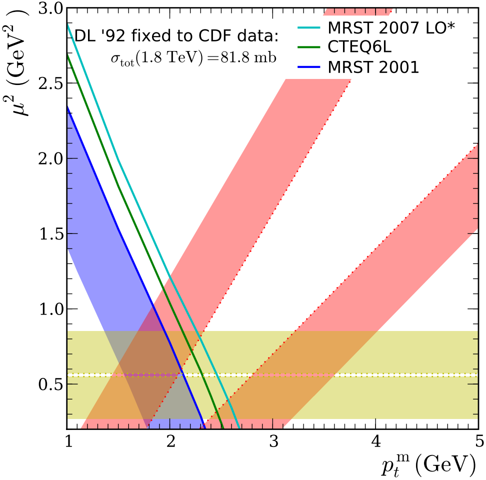
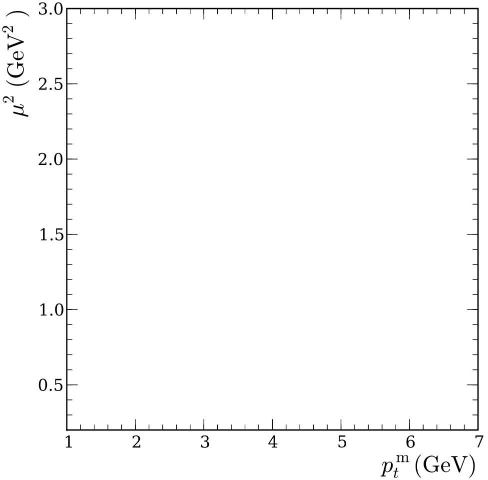
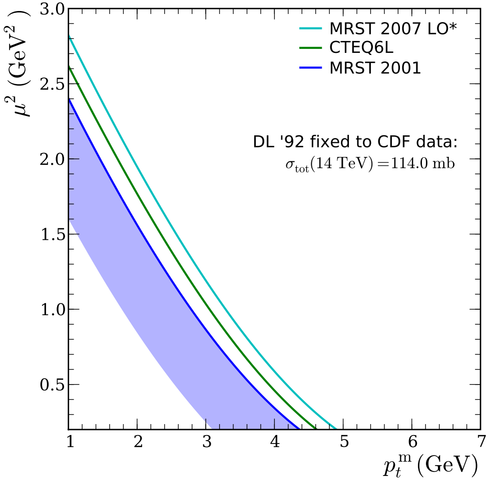
- Final state tune of **semi-hard** MPI (MRST2001)



- What to expect at 14 TeV?



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



Constraints at the LHC

- What to expect at 14 TeV?
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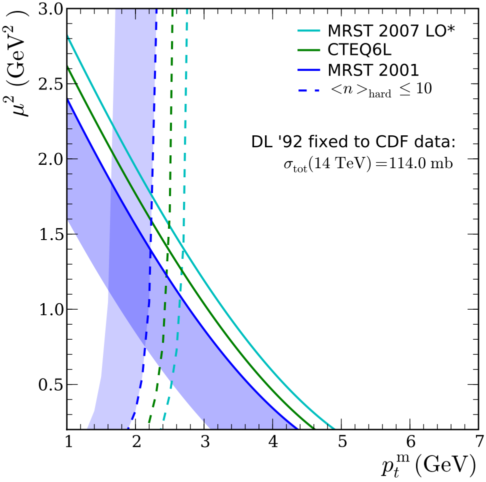
- Require $\bar{n}_{\text{hard}} < 10$



- What to expect at 14 TeV?
- $\sigma_{\mathrm{soft}}^{\mathrm{inc}} > 0$ mb. σ_{tot} from Regge fit
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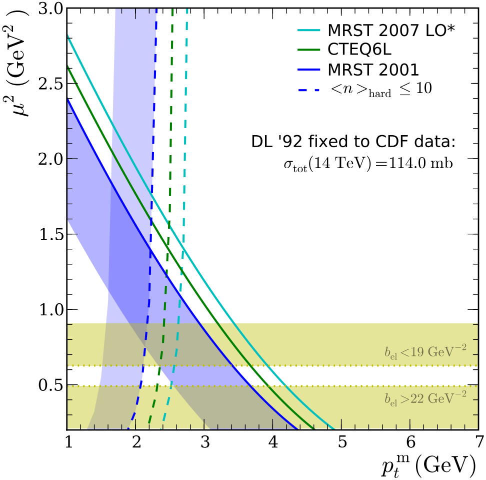
- Require elastic t-slope to be correctly described. Get range of possible measurements from DL '92 and predictions for b_{el}

[Khoze, Martin, Ryskin, 0710.2494]

[Gotsman, Levin, Maor, 0708.1506]



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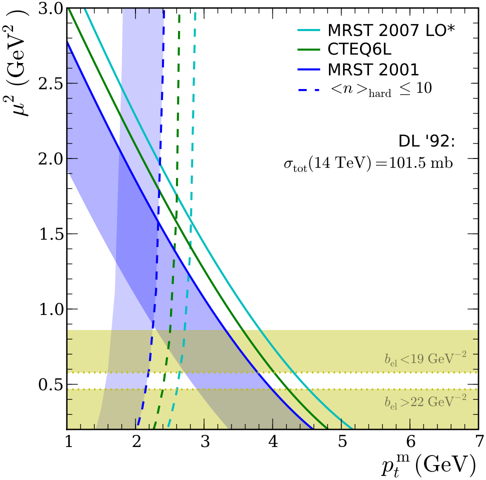

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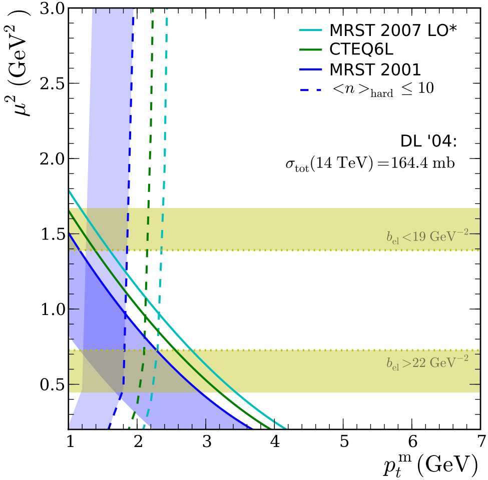


Observations

- $\sigma_{\rm soft}^{\rm inc}$ 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 $\gamma + 3j$:

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

$\rightarrow$ 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

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

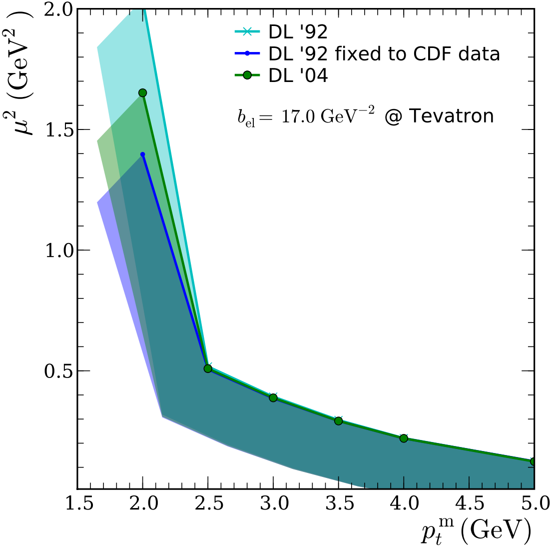
from two constraints. Require simultaneous description of $\sigma_{\rm tot}$ and $b_{\rm el}$ (measured/well predicted),

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

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

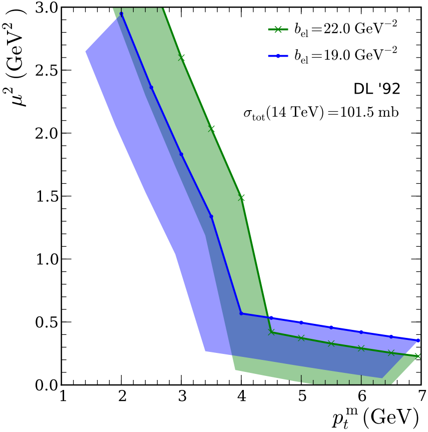
Tevatron parameter space

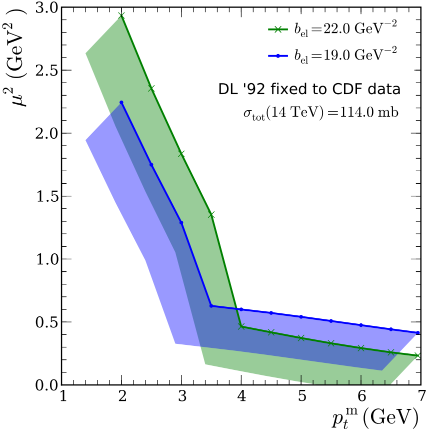
Only one constraint: describe σ_{tot} and b_{el}.



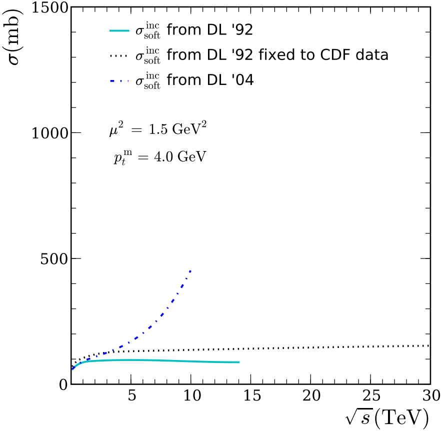
LHC parameter space

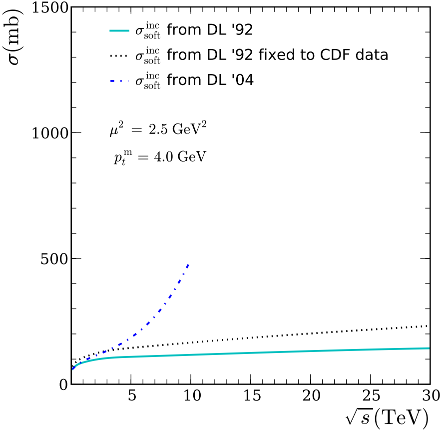
Same for LHC except for uncertainty in b_{el} and σ_{tot}.





Resulting soft cross section



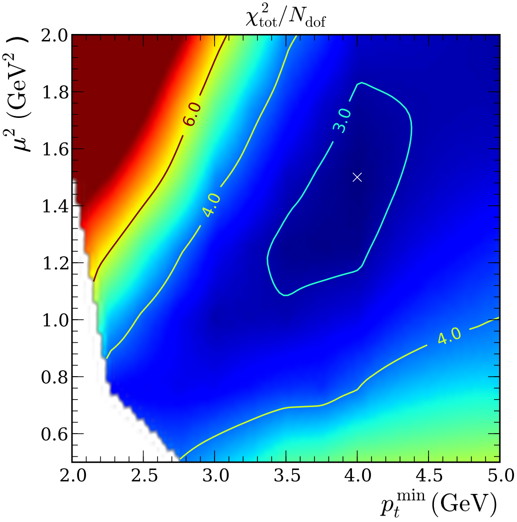


Tevatron Run I final states

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

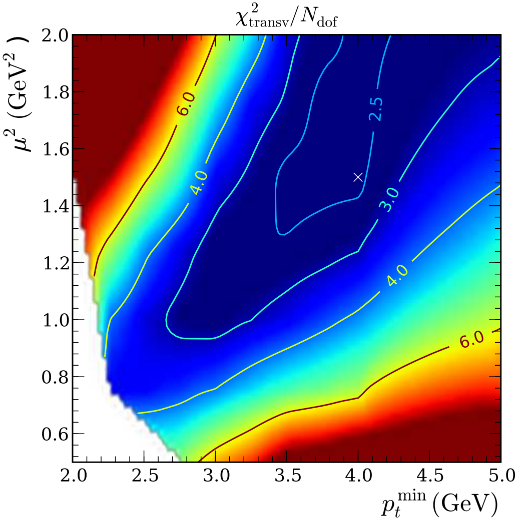
Parameter space at Tevatron

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

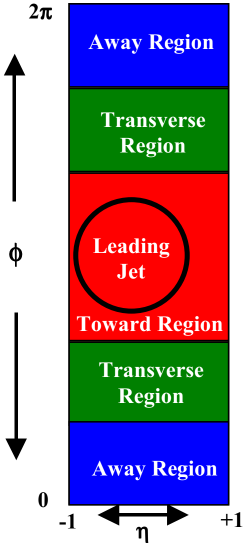


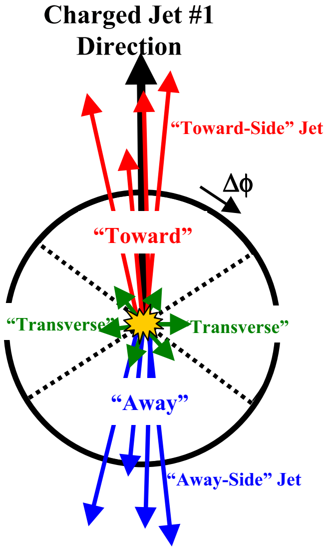
Parameter space at Tevatron

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

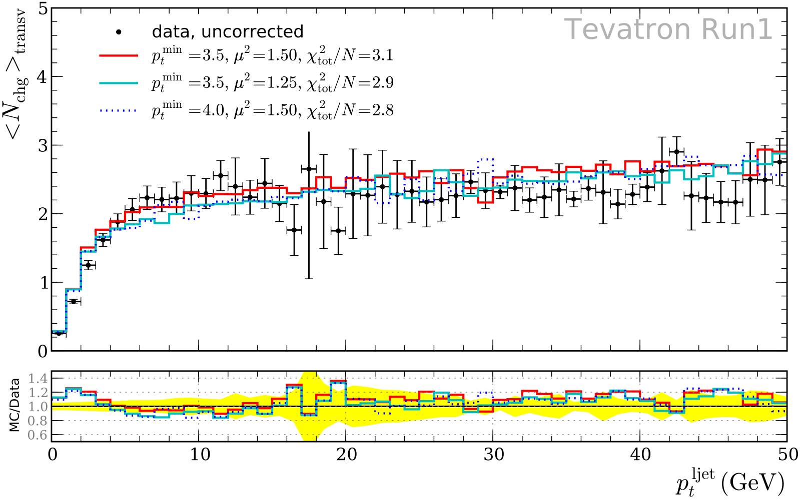


Rick Field's analysis





Detailed look at observables: Transverse Region



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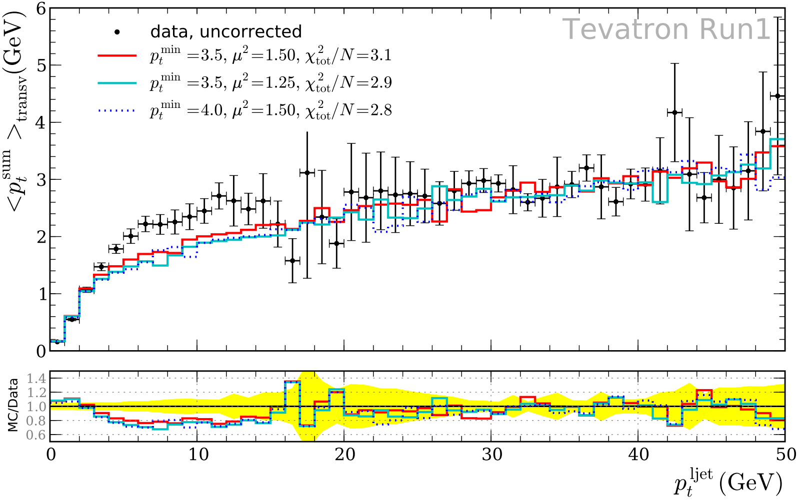
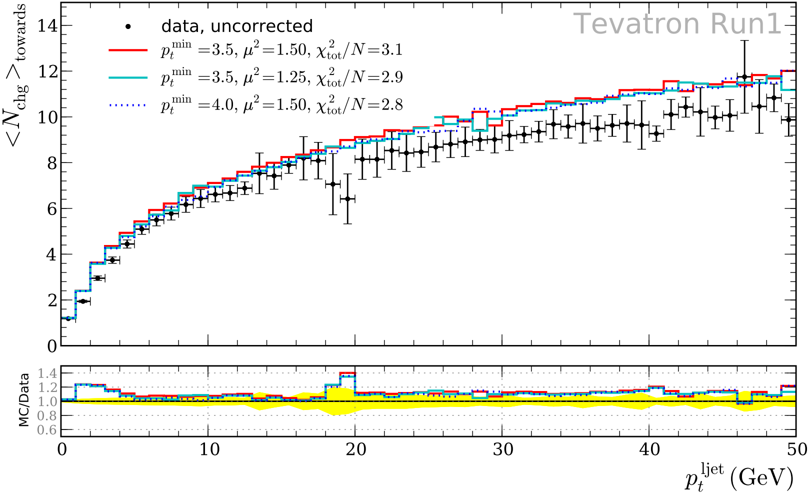
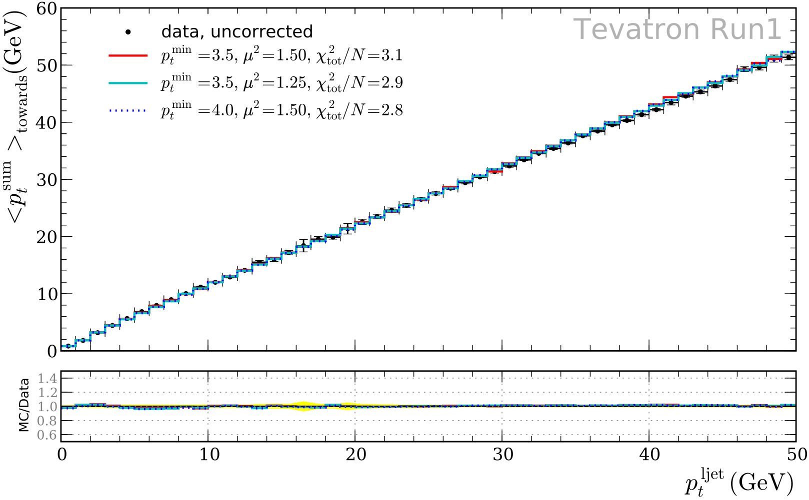


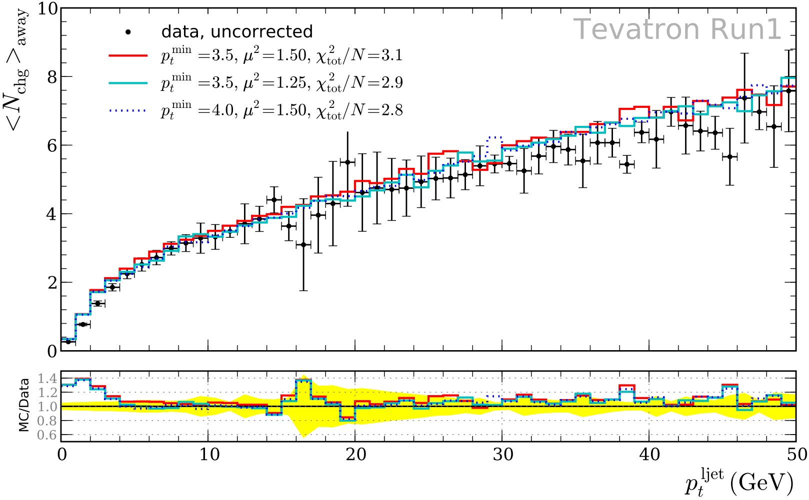
Detailed look at observables: Towards Region



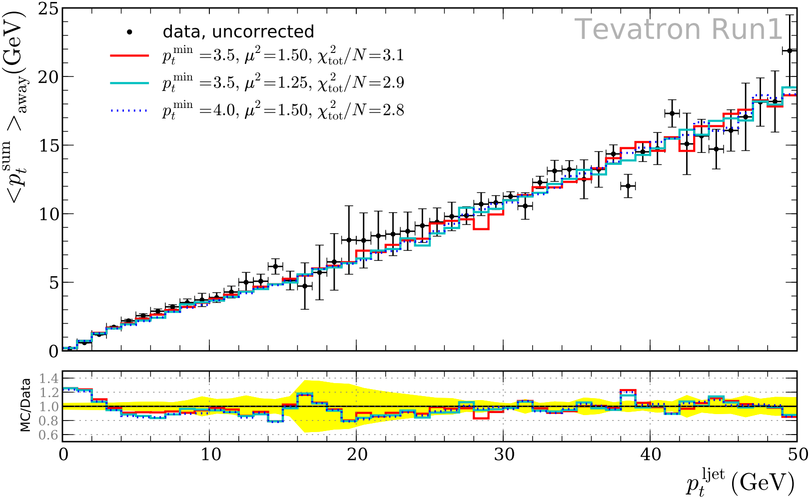
Detailed look at observables: Towards Region



Detailed look at observables: Away Region



Detailed look at observables: Away Region



Conclusions

- MPI UE model implemented in Herwig++.
- Min Bias implemented in Herwig++ (first time in Herwig!).
- Close connection to σ_{tot} and σ_{el} via unitarization.
- Exploited to constrain free parameters.
- Used Run I data on top to give outlook to parametes at LHC energies.

Outlook

Herwig++ UE:

- Currently looking into Run II Jet20 and Drell–Yan UE analysis.
- Observed some tension between the two data sets for our UE description.

Some Herwig++ news:

- v2.4 out soon.
- Even more POWHEG matched NLO processes.
- Sophisticated CKKW matching for e^+e^-.
- PDF LO** sets used.
- Different PDFs for hard ME and UE.
- even more bugs fixed.
- ....

Short term studentships

- Come to one of our nodes and work with generator authors on a topic of interest.
- CERN, Durham, Karlsruhe, Lund, UCL.
- 3-6 months.
- Fully funded by MCnet.
- Monthly deadline.
- www.montecarlonet.org