Soft interactions in Herwig++

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University of Karlsruhe

First international workshop on
Multiple Partonic Interactions at the LHC,
Perugia, October 2008

Herwig++

- Main focus of this talk: Underlying event and MPI
- However, also other exciting new features will be available with the imminent next release (Herwig++ 2.3)
  - single W and Z, Higgs in gluon fusion and WH, ZH associated Higgs production at NLO QCD in the POWHEG scheme
  - 3 body BSM decays and off-shell effects
  - Sophisticated baryon decays to match the degree of precision in the meson decays
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Status semi-hard MPI

- Fully working model included from `Herwig++ 2.1` onwards. It allows for the simulation of semi-hard ($p_t \geq p_t^{\mathrm{min}}$) multiple partonic interactions (MPI) to describe the underlying event (UE). Same functionality and physics than `JIMMY`.

→ Detailed description including tuning results:
[arXiv:0803.3633, MB, S. Gieseke and M. H. Seymour]

- Main focus of this talk: Extension to soft ($p_t < p_t^{\mathrm{min}}$) scatters partly written up in [arXiv:0806.2949, MB, J. M. Butterworth and M. H. Seymour] ; all in [arXiv:??, MB, PhD thesis]

Outline

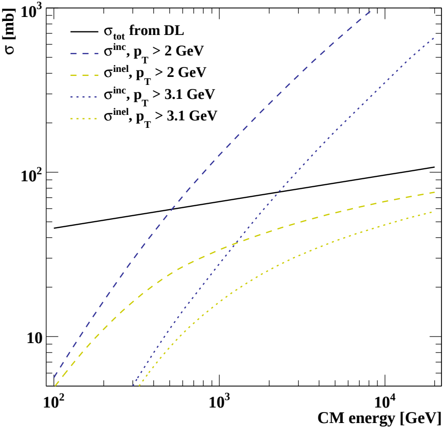
Outline

Model basics

based on [Butterworth, Forshaw, Seymour '96]

- Starting point: The inclusive cross section $pp \to jj$ with $p_t > p_t^{\min}$ ($\sigma_{\rm hard}^{\rm inc}$) may exceed $\sigma_{\rm tot}$
  $\sigma_{\rm hard}^{\rm inc} = \int {\rm d}x_1{\rm d}x_2{\rm d}p_t^2 \;\; f(x_1)f(x_2)\frac{{\rm d}\hat\sigma}{{\rm d}p_t^2}$
- Source: Proliferation of low x partons, which increases the probability of more than one partonic collision: $\sigma^{\rm inc} = \bar{n}\cdot\sigma_{\rm inel}$
- Unitarization of $\sigma_{\rm hard}^{\rm inc}$:

$$a(\mathbf{b},s) = \frac{1}{2\imath}\left[\,e^{-\chi(\mathbf{b},s)} - 1\right] \to \sigma_{\rm inel} = \int {\rm d}^2\mathbf{b}\;\left[1 - \;e^{-2\chi(\mathbf{b},s)}\,\right]$$



Semi-hard part of the eikonal

- Impact parameter dependence is capable of describing the pedestal effect
- Distribution of additional scatters can be derived in field theory: $P_m(\mathbf{b},s) = \frac{\bar{n}(\mathbf{b},s)^m}{m!}\, e^{-\bar{n}(\mathbf{b},s)}$
- Average multiplicity at fixed impact parameter

$$\bar{n}(\mathbf{b},s) = \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}^2\mathbf{b}_2 \mathrm{d}x_1 \mathrm{d}x_2 \int_{p_t^{\min}} \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}\, D_{i/A}(x_1, p_t^2, |\mathbf{b}_2|)\, D_{j/B}(x_2, p_t^2, |\mathbf{b}-\mathbf{b}_2|)$$

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$$\bar{n}(\mathbf{b}, s) = A(\mathbf{b}) \cdot \sigma_{\mathrm{hard}}^{\mathrm{inc}}(s; p_t^{\mathrm{min}})$$

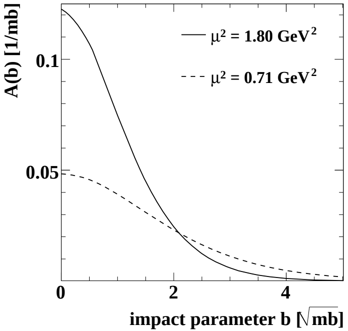
- Determination of χ: $\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\mathbf{b} \left[1 - e^{-2\chi(\mathbf{b},s)}\right]$

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

$$\rightarrow \chi_{\mathrm{QCD}}(\mathbf{b}, s) = \frac{1}{2}\bar{n}(\mathbf{b}, s) = \frac{1}{2}A(\mathbf{b})\sigma_{\mathrm{hard}}^{\mathrm{inc}}$$

Overlap function

- $A(b)$ is the overlap function of the two colliding particles
- Convolution of individual spatial parton distributions: $G_h(\mathbf{b})$
- Individual distributions are proportional to EM form-factors. But μ is not fixed to the radius measured there (0.71 GeV^2)!



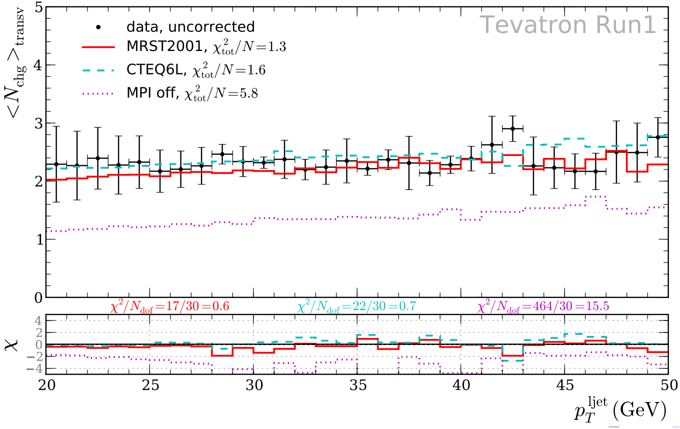
$$A(b = |\mathbf{b}|) = \int d^2\mathbf{b}' G_{h_1}(|\mathbf{b}'|)\ G_{h_2}(|\mathbf{b} - \mathbf{b}'|)$$

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

$\longrightarrow$ main parameters: $p_t^{\min}, \mu^2$

Results

- semi-hard MPI model describes the CDF Run1 UE data very well (overall $\chi^2 = 1.3$)
- However, soft scatters are intrinsically missing



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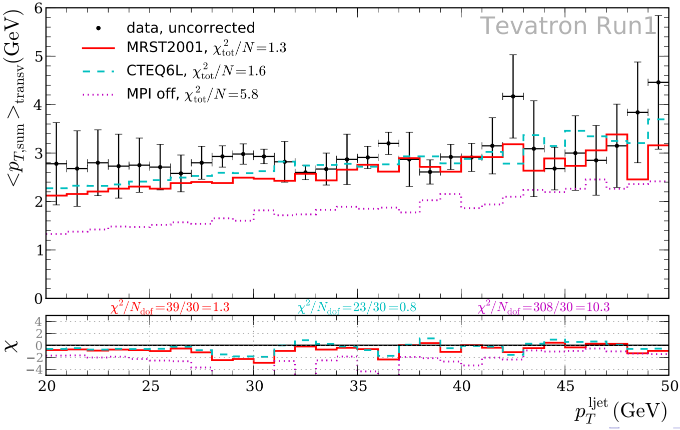

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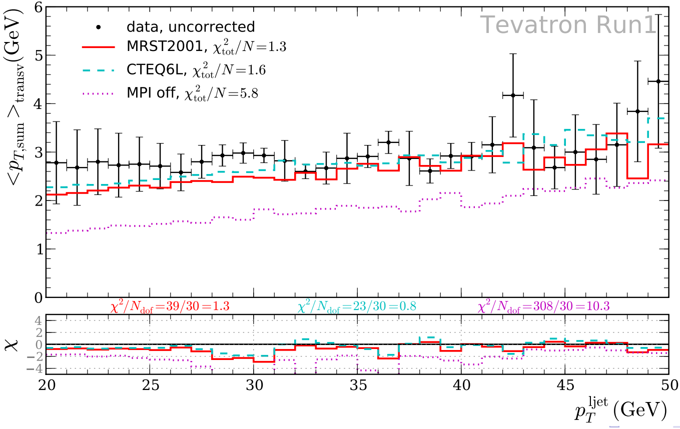

Outline

$\chi_{\rm soft}(\mathbf{b}, s)$

- When we use $\chi_{\rm QCD}(\mathbf{b}, s)$, we mean

$$\chi_{\rm tot}(\mathbf{b}, s) = \chi_{\rm QCD}(\mathbf{b}, s) + \chi_{\rm soft}(\mathbf{b}, s)$$

- Assume similar structure for $\chi_{\rm soft}(\mathbf{b}, s)$ and $\chi_{\rm QCD}(\mathbf{b}, s)$:

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

  where $\sigma^{\rm inc}_{\rm soft}$ is a free parameter of our model.
- Choose simplest Ansatz for $A_{\rm soft}$, $A_{\rm soft}(b) \equiv A(b; \mu)$, which then leads to:

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

Determination of $\sigma_{\rm soft}^{\rm inc}$

- Exploit the connection to the total cross section within the eikonal model:

$$\sigma_{\rm tot}(s) = 2\int \mathrm{d}^2\mathbf{b} \quad \left[1 - \; e^{-\chi_{\rm tot}(\mathbf{b},s)}\right] \; ,$$

- Use experimental total cross section values to fix $\sigma_{\rm soft}^{\rm inc}$ accordingly (for fixed CM energy).
- For $\sqrt{s} > 2$ TeV: Get $\sigma_{\rm tot}$ from the Regge fit by Donnachie & Landshoff
  1. DL '92 [arXiv:hep-ph/9209205, D & L]
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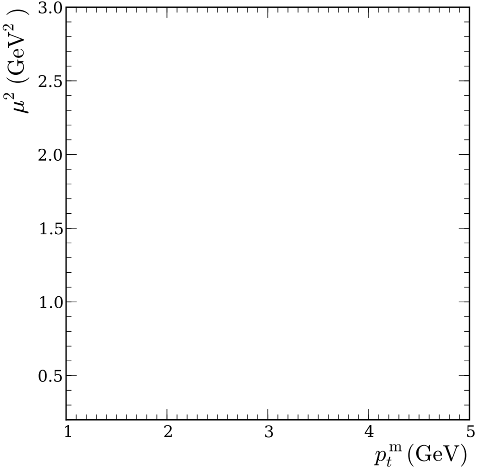
Tevatron parameter space

- Find constraints on the parameter choices
- Require $\sigma_{\text{soft}}^{\text{inc}} > 0$ mb, while describing the total cross section
- 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 $b_{\text{el}}(s) = \int \mathrm{d}^2\mathbf{b}\ \frac{b^2}{\sigma_{\text{tot}}}\left[1 - e^{-\chi_{\text{tot}}(\mathbf{b},s)}\right]$
- Final state tune of **semi-hard** MPI (approximate constraint for MRST2001)



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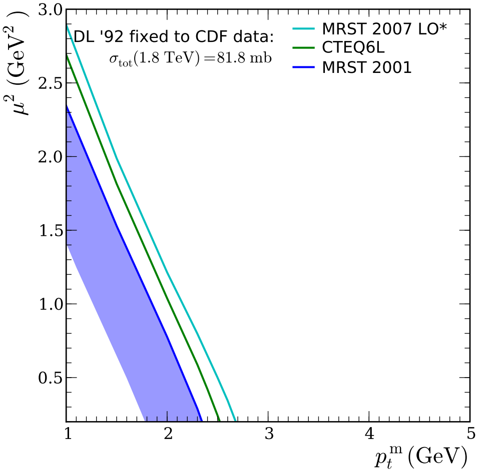

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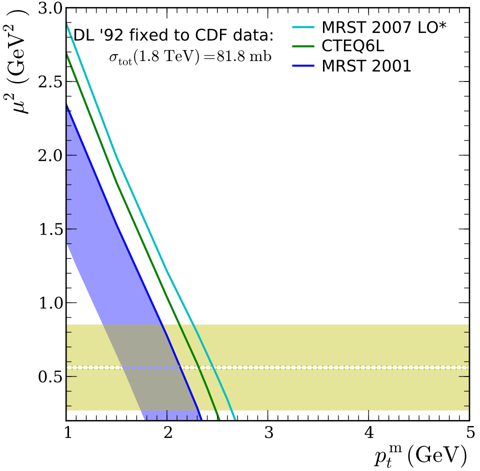

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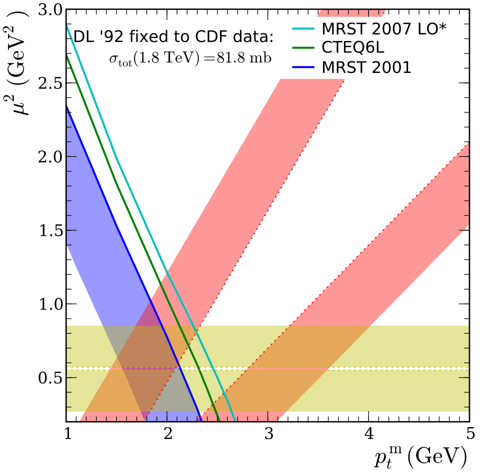
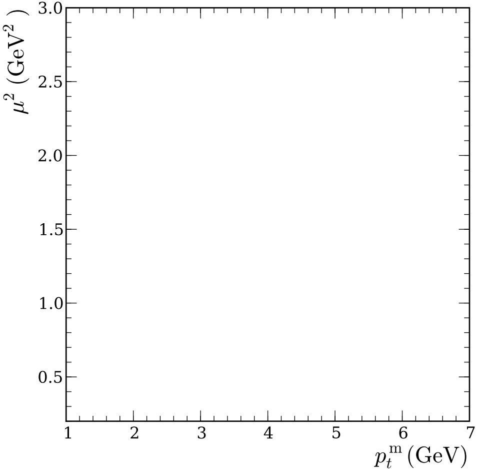


LHC parameter space

- What to expect from measurements 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 vs. e.g. [arXiv:0710.2494, Khoze, Martin, Ryskin] , [arXiv:0708.1506, Gotsman, Levin, Maor] predictions



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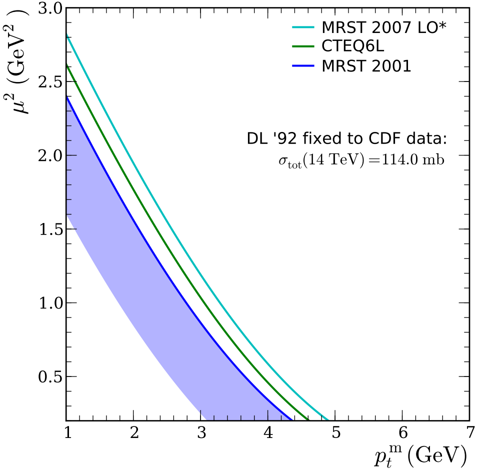

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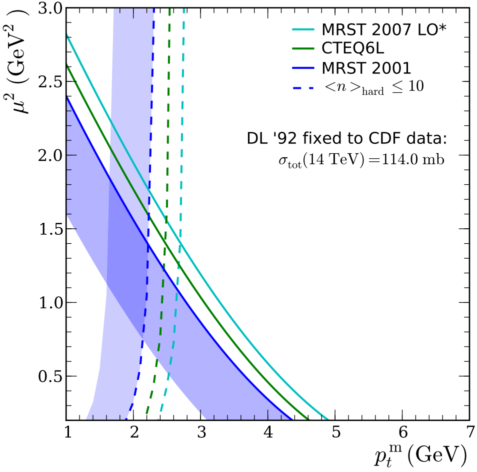

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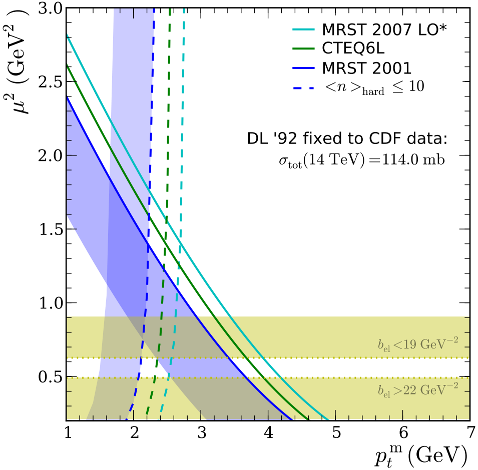

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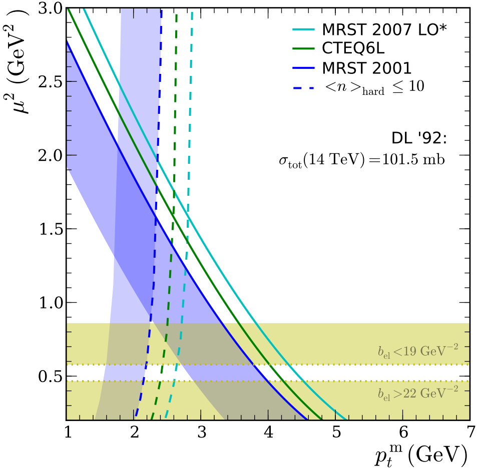

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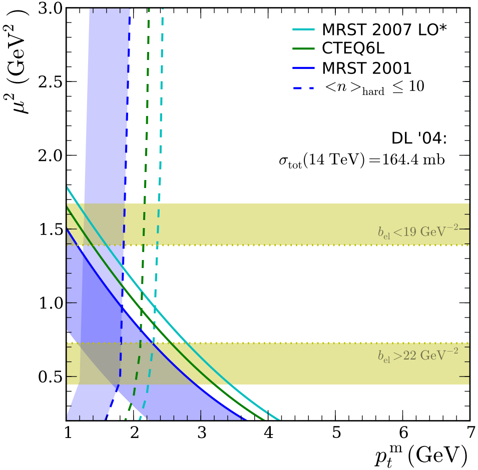


Observations

- $\sigma_{\rm soft}^{\rm inc}$ 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)
- The measurement of the elastic t-slope fixes μ^2 at Tevatron:

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

$\sigma_{\rm eff} = \left(\int {\rm d}^2\mathbf{b}\ A^2(b)\right)^{-1}$ as measured by CDF in the $\gamma + 3j$ channel suggests:

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

$\rightarrow$ Relax the constraint of identical overlap functions:

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

If $\mu > \mu_{\rm soft}$: Hot Spots

Outline

Fixing parameters

- Basis:

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

- Instead of introducing a new parameter, we fix $\mu_{\rm soft}, \sigma_{\rm soft}^{\rm inc}$ by requiring $\sigma_{\rm tot}, b_{\rm el}$ to be correctly described simultaneously

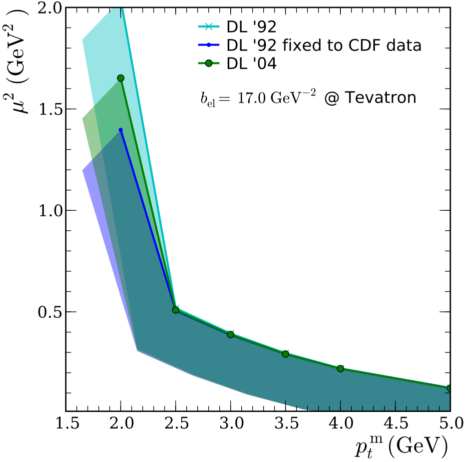
$$\sigma_{\rm tot}(s)^{\rm measured} - 2\int {\rm d}^2\mathbf{b}\ \left[1 - e^{-\chi_{\rm tot}(\mathbf{b},s)}\right] \stackrel{!}{=} 0$$

$$b_{\rm el}(s)^{\rm measured} - \int {\rm d}^2\mathbf{b}\ \frac{b^2}{\sigma_{\rm tot}}\left[1 - e^{-\chi_{\rm tot}(\mathbf{b},s)}\right] \stackrel{!}{=} 0$$

Tevatron parameter space

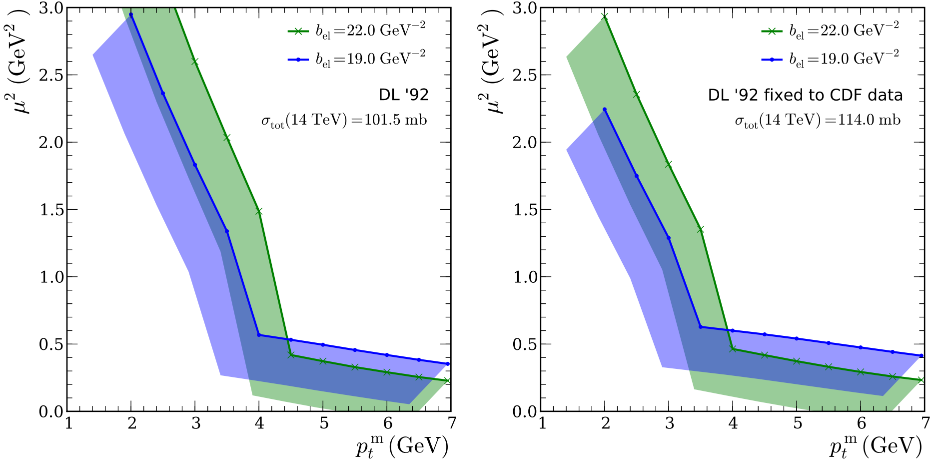
Only one constraint:

Correct total cross section and elastic slope

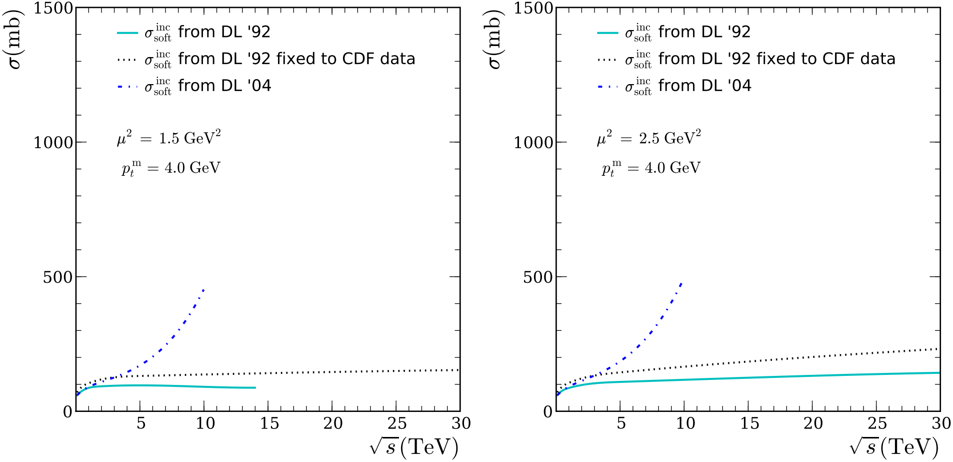


LHC parameter space

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



Resulting soft cross section



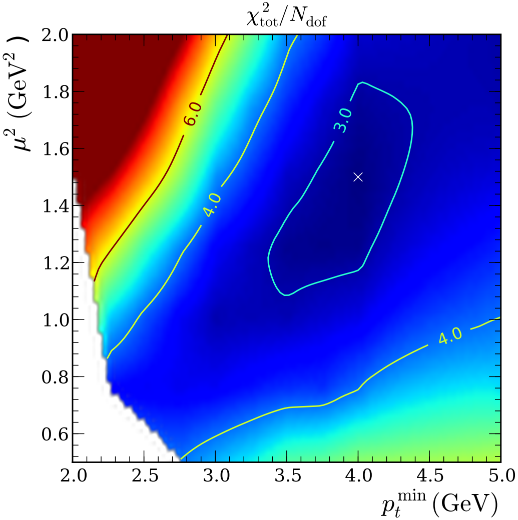
Outline

Intro

- So far: Indirect constraints from total and elastic cross sections
- Eikonal model is used to calculate the multiplicities of semi-hard and soft additional scatters in our MC implementation (which I have no time to talk about)
- Now use the results from that implementation to fit the remaining free parameters $(p_t^{\min}, \mu^2)$ to data

Parameter space at Tevatron

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



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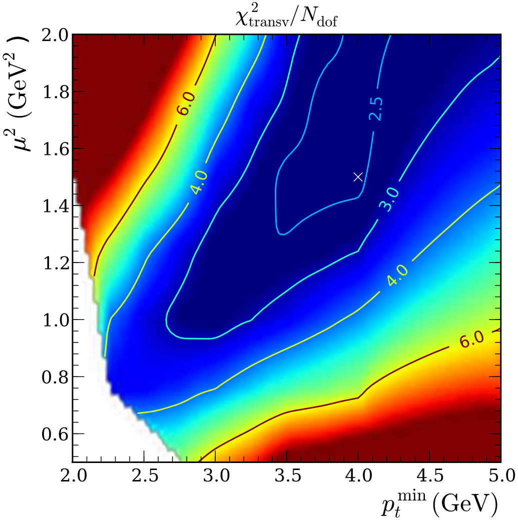
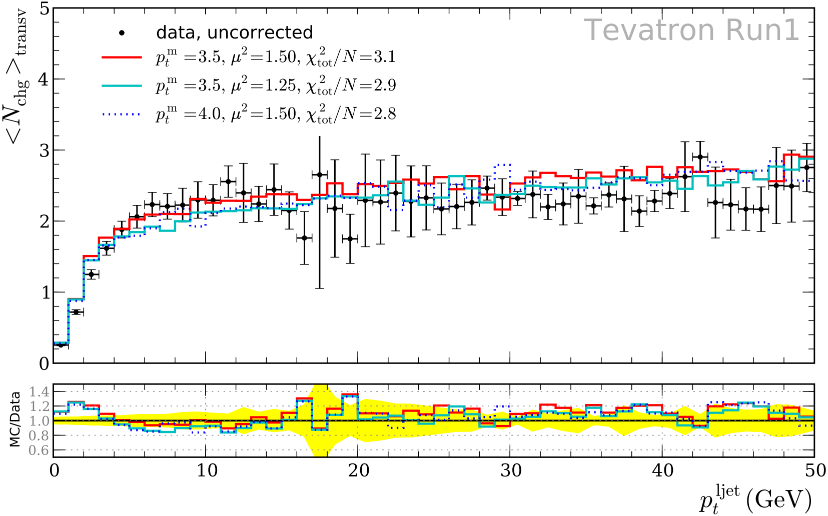


Detailed look at observables: Transverse Region



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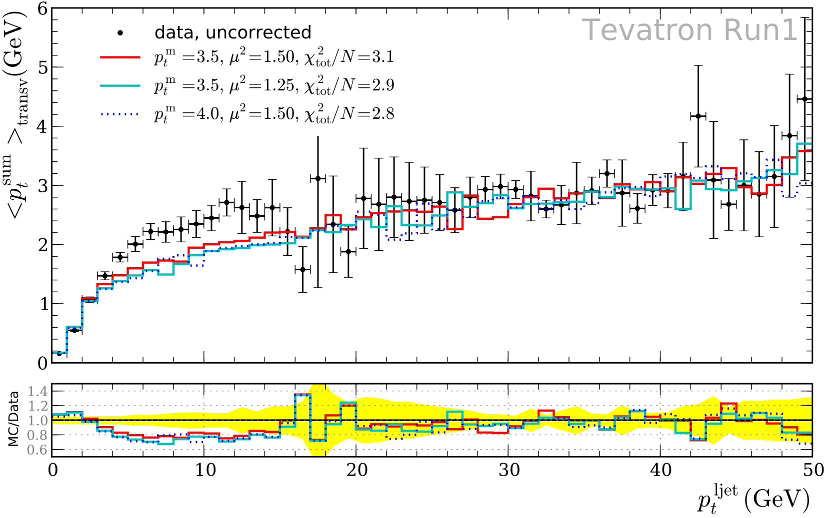

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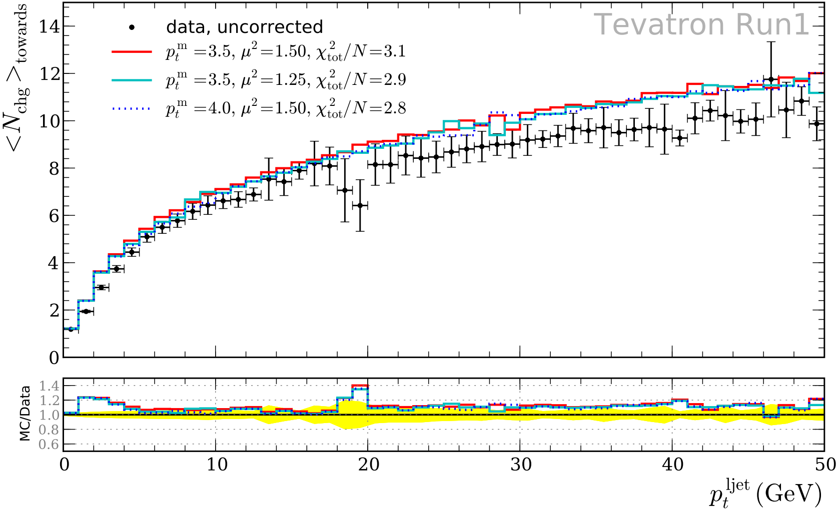
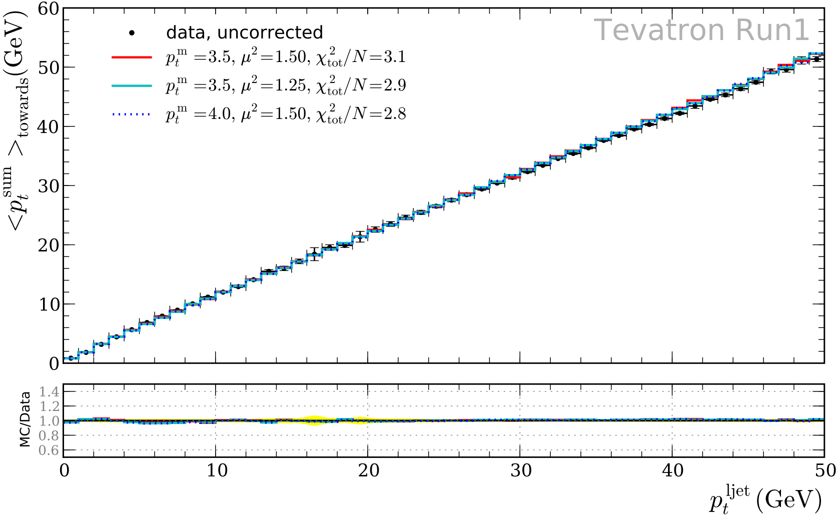
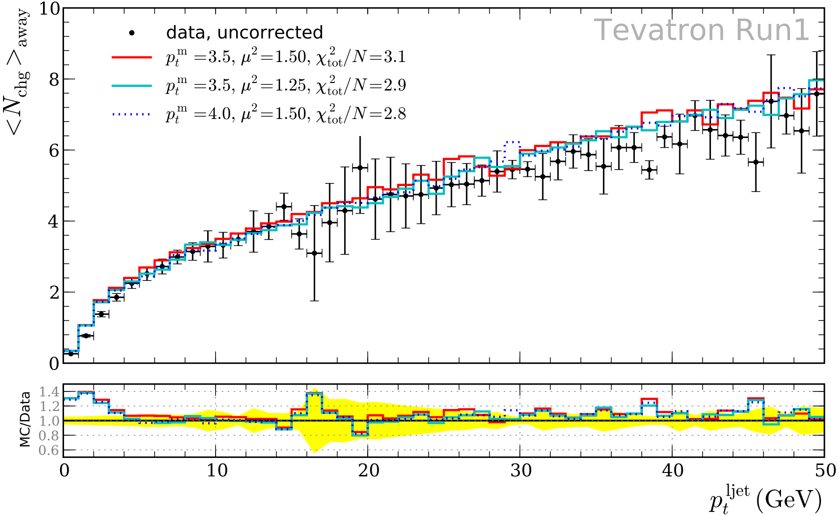


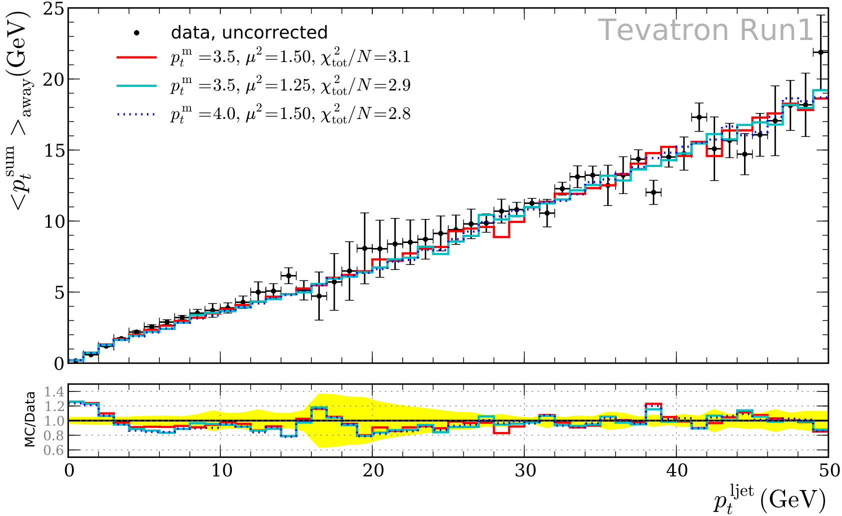
Detailed look at observables: Towards Region



Detailed look at observables: Away Region



Detailed look at observables: Away Region



Things to do

So far: Implemented the new model and tuned to CDF's Run1 data

1. Look at Run2 MinBias data (see talk by Niccolo Moggi)
2. Look at UE in DY (see talks by Rick Field and Hendrik Hoeth)
3. Look at Older MinBias data
4. Look at New LHC data

5. Look into possible energy dependence of spatial parton distributions (see talks by Ted Rogers and Rohini Godbole)
6. Consistently incorporate diffractive interactions
7. Allow the possibility of colour reconnections

Conclusions

- We extended the existing model to soft partonic interactions. First time MinBias is available in `Herwig` ever!
- The ue activity is directly coupled to the total and elastic cross section
  - Large impact of first measurements of these quantities at LHC
  - Extrapolation to larger energies constraint by predictions for these quantities
- Hot-Spot model to describe inconsistency between $\sigma_{\rm eff}$ and $b_{\rm el}$
- Fully exclusive simulation of multiple hard scatterings + low p_t jets possible (again no time to talk about it), e.g. $\gamma j + jj$, like sign W's, several b-jet pairs (... you name it) with arbitrary and independent cuts.

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