The underlying event in Herwig++

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Status

- Fully working model included from `Herwig++ 2.1` onwards. It allows for the simulation of multiple partonic interactions (MPI) to describe the underlying event (UE). Same functionality and physics than `JIMMY`.
- Overview available in *Herwig++ Physics and Manual* [arXiv:0803.0883]
- A more detailed description including tuning results: [arXiv:0803.3633, MB, S. Gieseke and M. H. Seymour]

Outline

Outline

Definition

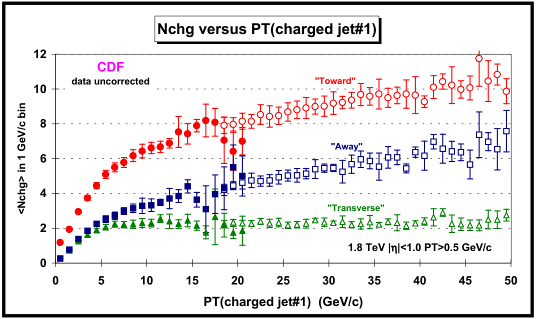
Underlying Event: All particles from a single particle collision except those from the process of interest.

- Definition excludes Pile-Up
- Includes QCD radiation (perturbative), Hadronization (nonperturbative) and Multiple Interactions (MI)
- MI is the subject of this talk. Can be subdivided into semi-hard (pert.) additional scatters + soft scatters
- MI is not necessarily what you see in Min-Bias. Peripheral vs. central pp collisions!

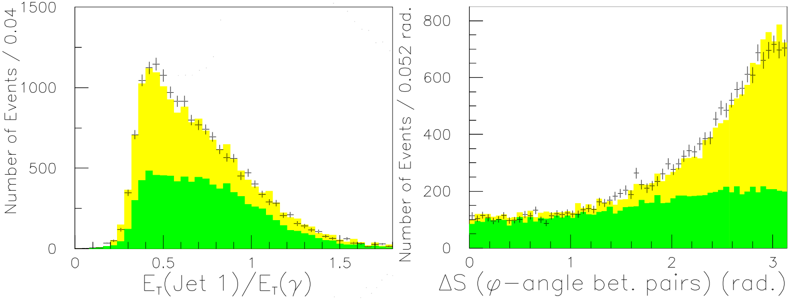
Indirect evidence

Different observables that can only be described using a model for multiple partonic interactions:

- Overall charged particle multiplicity @ UA5
- Forward-backward multiplicity correlation @ UA5 (hadronisation effects too local)
- CDF studies using topological event-by-event selections. Pedestal effect clearly visible.



Direct evidence: Double parton scattering
[CDF coll. PRD 56, 3811 (1997)]



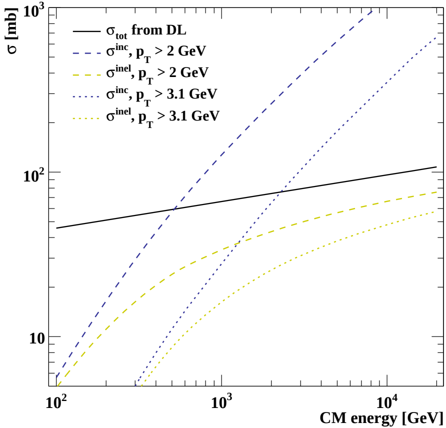
- AFS and UA2 required DP contribution. Best measurement so far by CDF (CMS: Similar measurement [F. Bechtel])
- $\gamma + 3$ jets with $E_T^{\gamma} > 16$ GeV + $E_T^{jets} > 5$ GeV analysed
- Need 53 % DP events to describe data (single collision vertex)
- No kinematic correlation between the two scatterings found!

Outline

Model details

based on [Butterworth, Forshaw, Seymour '96]

- Starting point: The inclusive cross section $pp \to jj$ with $p_T > p_T^{\rm min}$ ($\sigma^{\rm inc}$) may exceed $\sigma_{\rm total}$
  $\sigma^{\rm inc} = \int dx_1 dx_2 dp_T^2 \; f(x_1) f(x_2) \frac{d\hat{\sigma}}{dp_T^2}$
- Source: Proliferation of low x partons, which increases the probability of more than one partonic collision



- Unitarization of $\sigma^{\rm inc}$:

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

- Impact parameter dependence is capable of describing the pedestal effect
- Assuming $\sigma^{\text{inc}} = \bar{n} \cdot \sigma_{\text{inel}}$ implies uncorrelated scatters!
  $\rightarrow P_m(b,s) = \frac{\bar{n}(b,s)^m}{m!} e^{-\bar{n}(b,s)}$
- Average multiplicity at fixed impact parameter

$$\bar{n}(b,s) = \sum_{ij} \frac{1}{1+\delta_{ij}} \int d^2 b_2 \, dx_1 \, dx_2 \int_{p_T^{min}} dp_T^2$$

$$\frac{d\hat{\sigma}_{ij}}{dp_T^2} \; D_{i/A}(x_1, p_T^2, |\vec{b}_2|) \; D_{j/B}(x_2, p_T^2, |\vec{b} - \vec{b}_2|)$$

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$$\bar{n}(b,s) = A(b) \cdot \sigma^{\mathrm{inc}}(s; p_T^{\mathrm{min}})$$

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$$\bar{n}(b,s) = A(b) \cdot \sigma^{\rm inc}(s; p_T^{\rm min})$$

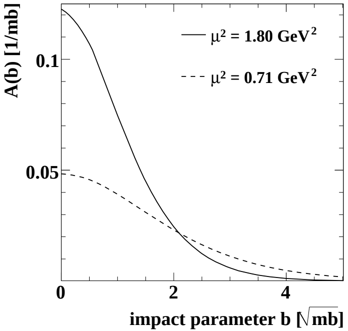
- Compare to $\sigma_{\rm inel} = \int {\rm d}^2 b \; \left[1 - \; e^{-2\chi(b,s)}\; \right]$

$$\sigma_{\rm inel} = \int d^2 b \sum_{m=1}^{\infty} \frac{\bar{n}(b,s)^m}{m!}\, e^{-\bar{n}(b,s)} = \int d^2 b (1 - \; e^{-\bar{n}(b,s)}\;)$$

$$\rightarrow \chi(b,s) = \tfrac{1}{2}\bar{n}(b,s)$$

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)!



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

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

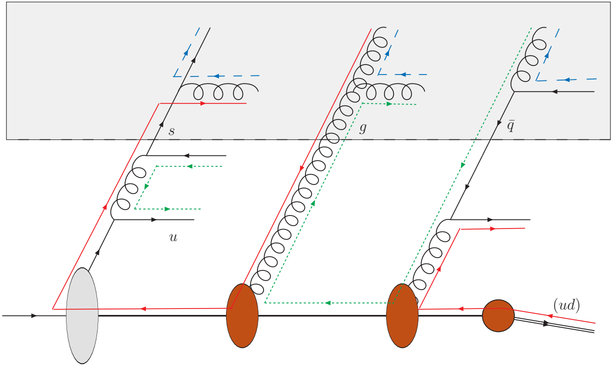
$\longrightarrow$ main parameters: $p_T^{\mathrm{min}}, \mu^2$

Outline

Eventflow

- Create the hard scattering and invoke parton showers on it
- Draw multiplicity and create the additional scatters
- Get subprocess, kinematics ($p_T^{\mathrm{min}} \leftrightarrow$ no min-bias!) and colour flow from dijet differential cross section. (PYTHIA: freedom to select subprocesses, colour flow)
- Start parton showers on additional subprocesses (possible veto due to energy-momentum conservation)
- Colour connect all interactions and the proton remnants
- Hadronization
- Decays

Colour connections and forced splittings



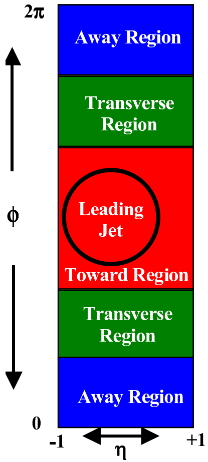
- Forced splitting to valence quarks always present (cluster hadronization prerequisite)
- Force backward evolution to end on gluons for additional interactions, i.e. extract only sea quarks and gluons.
- Study sensitivity of colour connections ($\langle p_T \rangle$ vs. N_{ch})

Outline

Exp. analysis

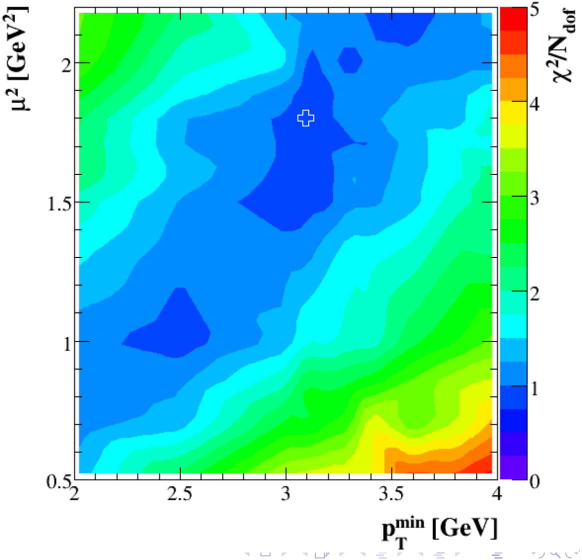
R. Field's TVT analysis; PRD65,092002

- non standard jet algorithm used to reconstruct the jet with the largest scalar ptsum from charged particle tracks: leading jet
- define 3 regions with respect to ϕ of the leading jet: towards, transverse, away
- plot $\langle N^{chg} \rangle$ and $\langle p_{T,sum}^{chg} \rangle$ for each of these regions
- comparison of `Herwig++ 2.1.3` to detector level data by applying 92% track efficiency (like the original experimental analysis)



Parameter Scan
all regions

- 120 points with 1M fully generated events each
- $\chi^2 = 4 \ \cong 2\sigma$ contour
- correlation between μ^2 and $p_T^{\rm min}$ as it should be:
  $p_T^{\rm min} \uparrow \to \ \sigma^{\rm inc} \downarrow \to \ \langle n \rangle \downarrow$
  $\mu^2 \uparrow \to \ \langle n \rangle \uparrow$
- favoured region around $p_T^{\rm min} \approx 3$ GeV



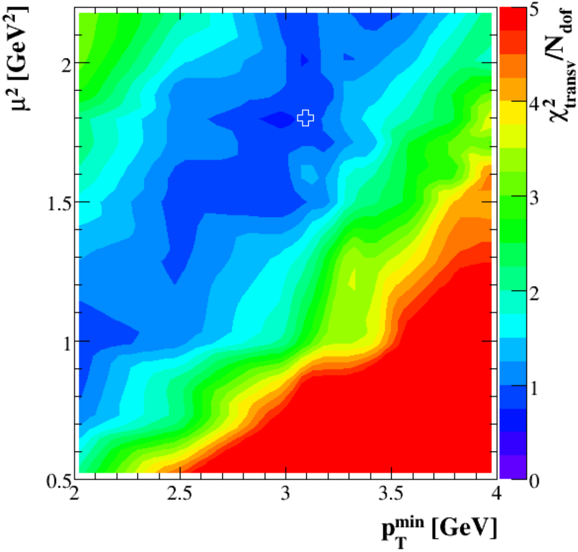
Parameter Scan

only transverse region

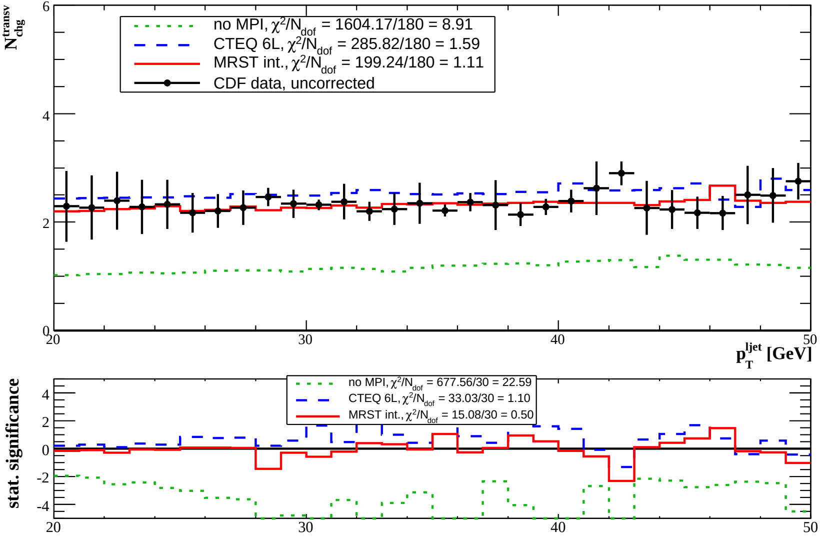
- MPI are isotropic
- *transverse* region receives the least contribution from the hard matrix element and parton showers

$\longrightarrow$ well suited to study MPI

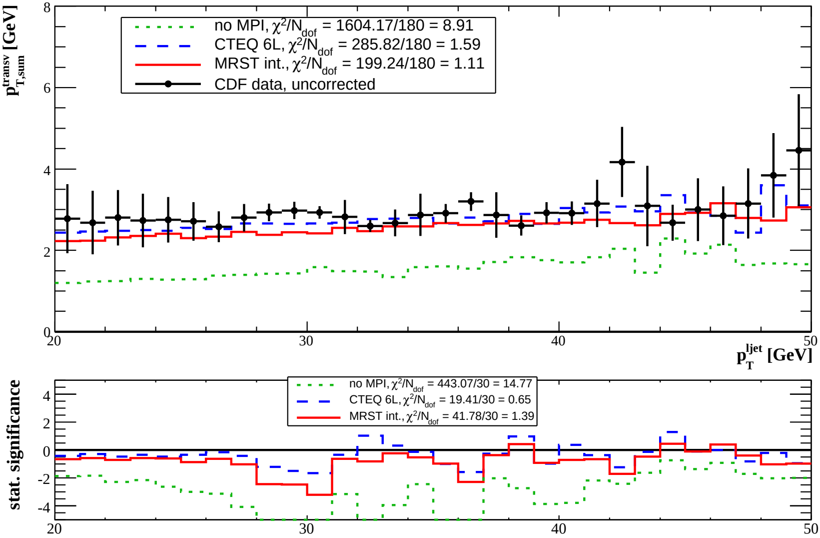
- minimum is confirmed $\rightarrow$ use $p_T^{\min} = 3.1$ GeV and $\mu^2 = 1.8$ GeV^2 as default tune.



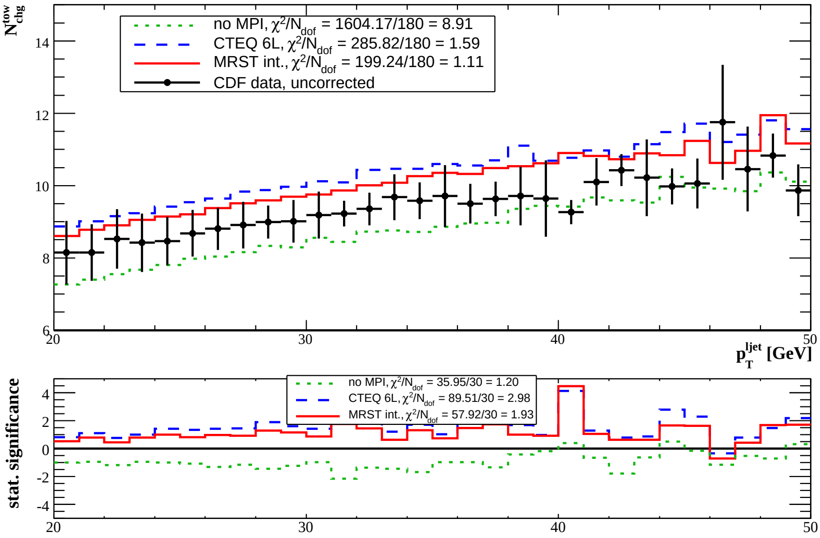
Best fit: N^{chg}_{transv}



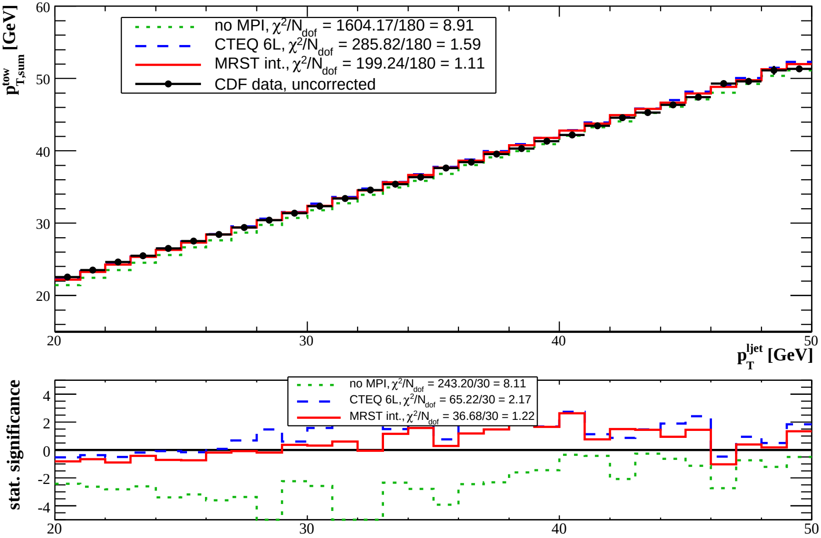
Best fit: $p_{T,sum}^{transv}$



Best fit: N^{chg}_{tow}



Best fit: $p_{T,sum}^{tow}$



Outline

Why should I care about PDF uncertainties?

- Overall uncertainties large compared to the PDF induced ones
- However for a fixed parameter set, the intrinsic PDF uncertainties may “survive” the event generation and enter the exclusive final state. Has been shown, that that is **not** the case for parton showers. [Gieseke, 2004]
- Tuning to LHC data “eliminates” uncertainties, except for PDF induced ones.
- Extracting PDF’s and usage of different PDF’s may be affected (depending on the requested accuracy)

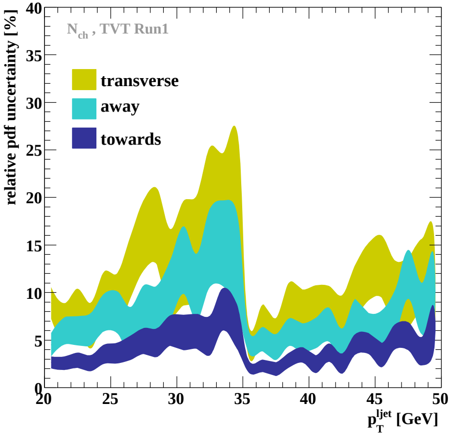
PDF uncertainties on the final state

- PDF influence enters exclusive final state via UE model. Cross section reweighting may not be enough.
- CTEQ6M and its 40 error sets with

$$\Delta X = \frac{1}{2}\left(\sum_{i=1}^{N_p}\left[X(S_i^+) - X(S_i^-)\right]^2\right)^{1/2}$$

used to quantify it. y-axis in the plot is $\Delta X / X(S_0)$

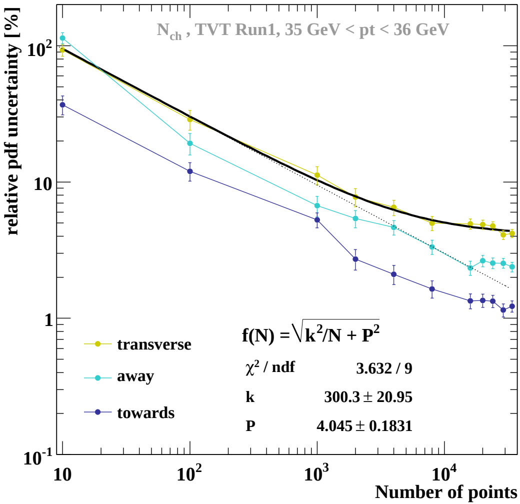
- First attempt: large statistical uncertainties overlay the real PDF error



PDF uncertainties contd.

- Restrict analysis to the first unbiased bin (number of events in this bin: N)
- Statistical error should scale like $1/\sqrt{N}$
- use the assumption of a constant PDF induced error (P) to fit the points.
- 20M events/PDFset:

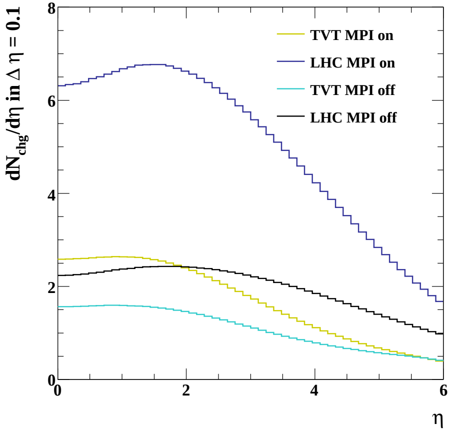
observable	P
$\langle N_{chg} \rangle_{transv}$	4.0 %
$\langle p_T^{sum} \rangle_{transv}$	4.5 %



Outline

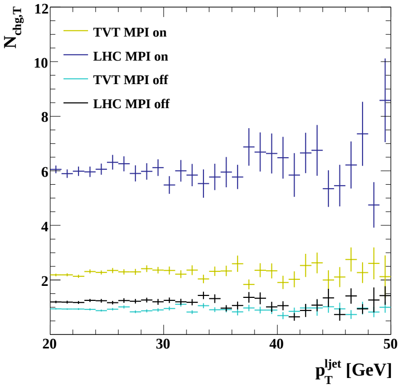
LHC extrapolation

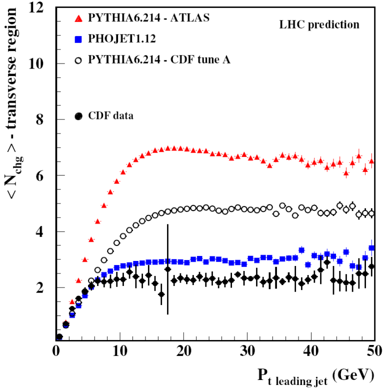
- All parameters left on their values obtained from the fit to Tevatron data
- Factor of 3 activity increase in the central region
- comparison to other generators...



LHC extrapolation contd.

Use transverse region as benchmark.





extracted from: *Hera and the LHC* proceedings [Alekhin et al. 2005]

Outline

Idea

Ongoing work with Jon Butterworth and Mike Seymour. Inspired by [hep-ph/0207283, I. Borozan and M. H. Seymour]

- Eikonal model allows the calculation of the total *pp* cross section at high energies
- Use the total cross section to fix the amount of scatters (cross section) below p_T^{min}. σ_{tot} =Donnachie & Landshoff
- Model consistency at LHC implies constraints on the parameter space $(p_T^{\mathrm{min}}, \mu^2)$

Details

- Total cross section is

$$\sigma_{\mathrm{tot}} = 2 \int \mathrm{d}^2 b \, \left[1 - e^{-\chi(b,s)} \right] \tag{1}$$

- Intrinsic p_T cutoff (p_T^{min}):

$$\chi(b,s) = \frac{1}{2} A(b) \cdot \sigma_{\mathrm{hard}}^{\mathrm{inc}}(s; p_T^{\mathrm{min}}) \tag{2}$$

- Include scatters below p_T^{min}, assuming

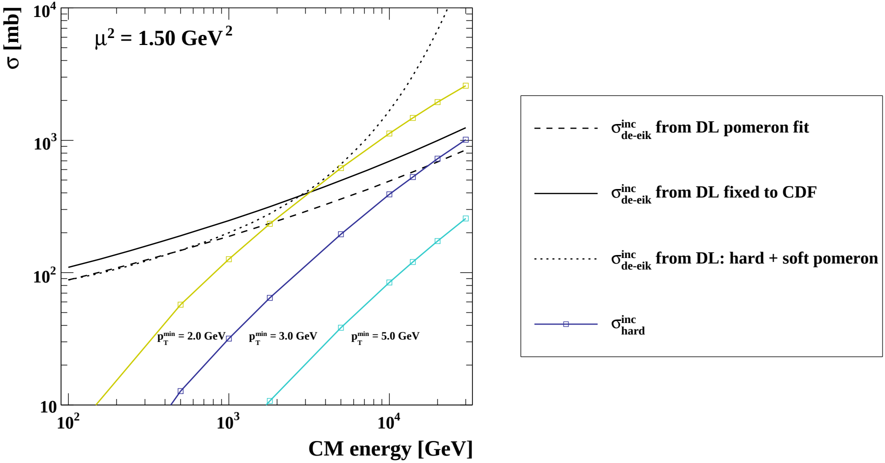
$$\chi(b,s) = \frac{1}{2} A(b) \cdot (\sigma_{\mathrm{hard}}^{\mathrm{inc}} + \sigma_{\mathrm{soft}}^{\mathrm{inc}}) \tag{3}$$

- σ_{tot} is a function of $\sigma_{\mathrm{de-eik}}^{\mathrm{inc}} = \sigma_{\mathrm{hard}}^{\mathrm{inc}} + \sigma_{\mathrm{soft}}^{\mathrm{inc}}$

Outline

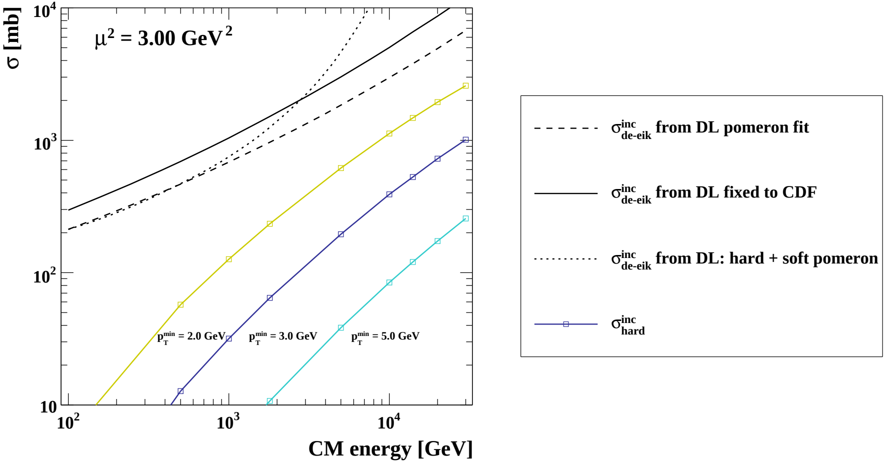
De-eikonalized cross sections

$$\sigma_{\text{tot}} = 2 \int \mathrm{d}^2 b \, \left[1 - e^{-\frac{1}{2} A(b) \cdot (\sigma_{\text{hard}}^{\text{inc}} + \sigma_{\text{soft}}^{\text{inc}})} \right]$$



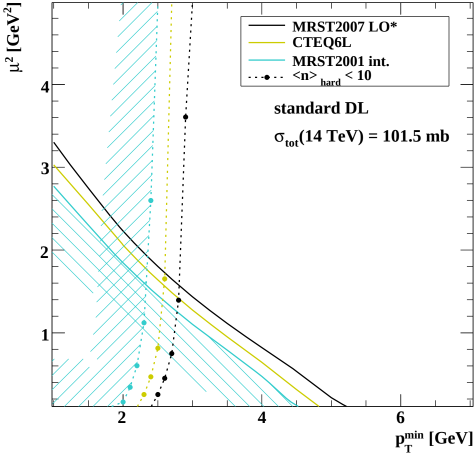
De-eikonalized cross sections

$$\sigma_{\rm tot} = 2\int {\rm d}^2 b \left[1 - e^{-\frac{1}{2}A(b)\cdot(\sigma^{\rm inc}_{\rm hard}+\sigma^{\rm inc}_{\rm soft})}\right]$$



Parameter space

- Solid curves: Points where $\sigma_{\text{soft}}^{\text{inc}} = 0$ mb.
- Experience showed that $n_{int} \gtrsim 10$ is very hard to establish due to energy-momentum conservation.
- Large spread in $\sigma_{\text{tot}}(14\text{ TeV})$ leads to significant different boundaries.



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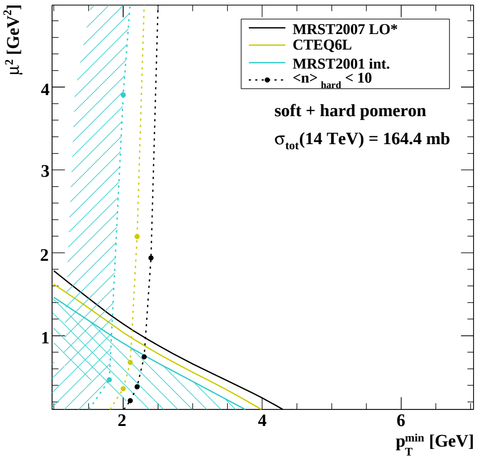

Conclusions

- The presented model describes the Tevatron data
- Our model gives similar LHC results than PYTHIA with energy dependent parameters

Next steps:

- Modelling of the non perturbative scatters, i.e. $p_T \in (0, p_T^{min})$ to enable the simulation of minimum bias events.
  Analytic model and region of validity ✓
  ToDo: MC implementation
- PDF uncertainty for LHC final states (GRID)
- Double/multiple parton scattering (hard processes) + low p_T jets, e.g. $\gamma + 3j$, like sign W's, b-jets. (completed, not released yet)