A new model for Minimum Bias and the Underlying Event in Sherpa

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Outline

Introduction: Why Minimum Bias Events?

The bird's eye view

- name suggests: most complete view of physics (at the LHC or any other experiment)
- as such: intellectual challenge
  up to now no complete model including all facets - elastic scattering, diffractive events & hard jets - on the same footing
- intimate connection to underlying event
- first day physics at the LHC

For example

- Higgs search strategies at LHC largely rely on event topologies with rapidity gaps (VBF process, diffractive Higgs, ...)
- essential for S/B: rapidity gap and its survival probaility

Introduction: Why Minimum Bias Events?

Upshot

- gap survival depends on: extra jets & underlying event
- only former calculable from first principles (PT)
- underlying event completely model dependent
- general problem: access to implementable models that (analytically) predict rapidity gap survival probability
- need a straw-man to test and validate ideas:
  central diffractive production processes
- therefore important to have model embedding hard and semi-hard QCD, diffraction, elastic scattering
- so far, no such a model has never been directly implemented in a standard MC like PYTHIA, HERWIG etc. - only specific codes available (e.g. ExHume)

s-Channel Unitarity and Cross Sections

- optical theorem relates total cross section $\sigma_{\rm tot}$ to elastic forward scattering amplitude $\mathcal{A}(s,t)$ through

$$\sigma_{\rm tot}(s) = \frac{1}{s}\,\mathrm{Im}[\mathcal{A}(s,t=0)]$$

- rewrite $\mathcal{A}(s,t)$ as $A(s,b)$ in impact parameter space

$$\mathcal{A}(s,t=-\mathbf{q}_\perp^2) = 2s\int \mathrm{d}\mathbf{b}\, e^{i\mathbf{q}_\perp\cdot\mathbf{b}} A(s,b)$$

- cross sections

$$\begin{aligned}\sigma_{\text{tot}}(s) &= 2\int \mathrm{d}\mathbf{b}\,\mathrm{Im}[A(s,b)]\\ \sigma_{\text{el}}(s) &= 2\int \mathrm{d}\mathbf{b}\,|A(s,b)|^2\\ \sigma_{\text{inel}}(s) &= \sigma_{\text{tot}}(s)-\sigma_{\text{el}}(s)\end{aligned}$$

- N.B.: real part of $A(s,b)$ vanishes

Single-Channel Eikonal Model

- in eikonal model elasic amplitude given by sum of all Regge exchange diagrams:

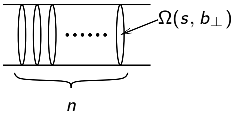
$$A(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$$

- $\Omega(s,b)$ is called eikonal or opacity
- eikonal is Fourier transform of two-particle irreducible amplitude $a(s,q_\perp)$

$$\Omega(s,b) = \frac{-i}{4\pi^2}\int d\mathbf{q}_\perp\, e^{i\mathbf{q}_\perp\cdot\mathbf{b}_\perp}\, a(s,q_\perp)$$

- pictorially:

$$\mathrm{Im}A(s,b) = \sum_{n=1}^{\infty}$$



Single-Channel Eikonal Model

- cross sections in eikonal model

$$\sigma_{\text{tot}}(s) = 2\int d\mathbf{b}\,\left(1 - e^{-\Omega(s,b)/2}\right)$$

$$\sigma_{\text{el}}(s) = 2\int d\mathbf{b}\,\left(1 - e^{-\Omega(s,b)/2}\right)^2$$

$$\sigma_{\text{inel}}(s) = \int d\mathbf{b}\,\left(1 - e^{-\Omega(s,b)}\right)$$

Multi-Channel Eikonals

Motivation

- impossible to describe "diffractive excitation" (like e.g. $p \to N(1440)$) with one eikonal only: such processes are a consequence of the internal structure of the colliding hadrons
- for description employ high-energy limit:
  in this limit the Fock states of the hadrons "frozen",

  (lifetime of fluctuations $\tau = E/m^2$ large)

  and each component can interact separately, destroying coherence of the colliding hadrons

Multi-Channel Eikonals

Good-Walker states

- introduce Good-Walker states (diffractive eigenstates):
  $|p\rangle = \sum_i a_i|\phi_i\rangle$, where $\langle\phi_i|\phi_k\rangle = \delta_{ik}$ and $\sum_i |a_i|^2 = 1$
- these states diagonalise the $\mathcal{T}$-matrix:
  $$\langle\phi_i|\mathrm{Im}\mathcal{T}|\phi_k\rangle = T_k^D\delta_{ik}$$
- therefore only "elastic scattering" of these states
- N.B.: use two states (more later),
  $$|p,\, N^*\rangle = \frac{1}{\sqrt{2}}\left[|\phi_1\rangle \pm |\phi_2\rangle\right],$$
  related to two different form factors,
  $$\mathcal{F}_{1,2}(q_\perp) = \beta_0^2(1\pm\kappa)\frac{\exp\left[-\frac{(1\pm\kappa)\xi q_\perp^2}{\Lambda^2}\right]}{\left[1+\frac{(1\pm\kappa)q_\perp^2}{\Lambda^2}\right]^2}$$

Multi-Channel Eikonals

Cross sections with Good-Walker states

- decompose incoming state $|j\rangle = a_{jk}|\phi_k\rangle$ and write
$$\langle j|\mathrm{Im}\mathcal{T}|j\rangle = \sum_k |a_{jk}|^2 T_k \equiv \langle T\rangle$$
- allows to write cross sections as

$$\begin{aligned}
\frac{d\sigma_{\text{tot}}}{d\mathbf{b}} &= 2\text{Im}\langle j|\mathcal{T}|j\rangle = 2\langle T\rangle \\
\frac{d\sigma_{\text{el}}}{d\mathbf{b}} &= |\langle j|\mathcal{T}|j\rangle|^2 = \langle T\rangle^2 \\
\frac{d\sigma_{\text{el+SD}}}{d\mathbf{b}} &= |\langle \phi_k|\mathcal{T}|j\rangle|^2 = \sum_k |a_{jk}|^2 T_k^2 = \langle T^2\rangle \\
\frac{d\sigma_{\text{SD}}}{d\mathbf{b}} &= \langle T^2\rangle - \langle T\rangle^2
\end{aligned}$$

- single diffraction given by statistical dispersion of absorption probabilities of diffractive eigenstates

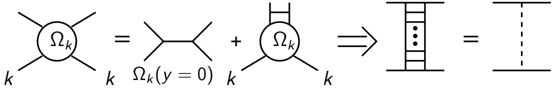
Khoze-Martin-Ryskin Model

Bare Pomeron Contribution

- evolution equation for elastic bare Pomeron exchange amplitude

$$\frac{\mathrm{d}\Omega_k(y)}{\mathrm{d}y} = \Delta\Omega_k(y)$$

where $\Delta = \alpha_{\mathbb{P}}(0) - 1$



- can be interpreted as evolution of parton density of "hadron" k with Δ being probability for emitting an additional gluon per unit rapidity

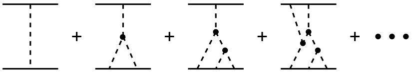
Khoze-Martin-Ryskin Model

Rescattering

- high density & strong coupling regime $\rightarrow$ rescattering important ($\Longleftrightarrow$ large triple pomeron vertex)
- sum over rescattering/absorption diagrams on k and i

$$\frac{\mathrm{d}\Omega_k(y)}{\mathrm{d}y} = \Delta\Omega_k(y)e^{-\lambda[\Omega_k(y)+\Omega_i(y)]/2}$$

with $\lambda = g_{3\mathbb{P}}/g_{\mathbb{P}N}$



- multi-pomeron diagrams give rise to high mass dissociation

Khoze-Martin-Ryskin Model

Boundary Condition

boundary condition for parton densities: hadron form factor

$$\begin{aligned} \Omega_i(\mathbf{b}_1, \mathbf{b}_2, -Y/2) &= F_i(\mathbf{b}_1^2) \\ \Omega_k(\mathbf{b}_1, \mathbf{b}_2, Y/2) &= F_k(\mathbf{b}_2^2) \end{aligned}$$

Eikonal

eikonal given by overlap of parton densities

$$\Omega_{ik}(\mathbf{b}) = \frac{1}{2\beta_0^2} \int d\mathbf{b}_1 d\mathbf{b}_2 \, \delta^2(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) \Omega_i(\mathbf{b}_1, \mathbf{b}_2, y) \Omega_k(\mathbf{b}_1, \mathbf{b}_2, y)$$

Selecting the Modes

- select elastic vs. inelastic processes according to

$$\sigma_{\text{tot}}^{pp} = 2\int d\mathbf{b} \sum_{i,k=1}^{S} \left\{ |a_i|^2 |a_k|^2 \left[1 - e^{-\Omega_{ik}(b)/2} \right] \right\}$$

$$\sigma_{\text{inel}}^{pp} = \int d\mathbf{b} \sum_{i,k=1}^{S} \left\{ |a_i|^2 |a_k|^2 \left[1 - e^{-\Omega_{ik}(b)} \right] \right\}$$

$$\sigma_{\text{el}}^{pp} = \int d\mathbf{b} \left\{ \sum_{i,k=1}^{S} \left[|a_i|^2 |a_k|^2 \left(1 - e^{-\Omega_{ik}(b)/2} \right) \right] \right\}^2$$

Selecting Gross Features of Scattering Mode

- if elastic is chosen, fix t according to

$$\frac{d\sigma_{\rm el}}{dt} = \frac{1}{4\pi}\left\{\int d\mathbf{b}\, e^{i\mathbf{q}_\perp\cdot\mathbf{b}} \sum_{i,k}\left[|a_i|^2\,|a_k|^2\left(1-e^{-\Omega_{ik}(b)/2}\right)\right]\right\}^2 .$$

- if inelastic is chosen, fix $\{ik\}$ according to partial contribution and **b** according to integrand,

$$\mathcal{P}_{ik}(b) = \pi b\left(1-e^{-\Omega_{ik}(b)}\right)$$

Inelastic Scattering: Generating Ladders

- assume no correlations between ladders
- select (naive) number of (primary) ladders to be exchanged according to Poissonian:

$$\mathcal{P}_{n=N_{\text{naive}}-1} = \frac{[\Omega_{ik}(b)]^n}{n!} \exp[-\Omega_{ik}(b)]$$

- for each ladder, fix $\mathbf{b}_{1,2}$ with $\mathbf{b} = \mathbf{b}_1 + \mathbf{b}_2$:

$$\frac{d\Omega_{ik}(b)}{d\mathbf{b}_1} = \frac{1}{2}\Omega_i(\mathbf{b}_1, \mathbf{b}_2)\Omega_k(\mathbf{b}_1, \mathbf{b}_2)$$

Inelastic Scattering: Generating Ladders

- for each ladder pick incoming particles:
  primary (beam particles) or secondary (rescattering)
  - $\hat{\sigma}_{\text{prim}} = \frac{x_1 f_1(x_1, 0) x_2 f_2(x_2, 0)}{2\hat{s}} \left(\frac{\hat{s}}{\hat{s}_{\min}}\right)^{1+\eta}$
  - $\hat{\sigma}_{\text{sec}} = \frac{1}{2\hat{s}} \left(\frac{\hat{s}}{\hat{s}_{\min}}\right)^{1+\eta}$
  - $\eta = \Delta \exp\left[-\frac{\lambda}{2}\left(\Omega_{i(k)}(b_1, b_2, 0) + \Omega_{(i)k}(b_1, b_2, 0)\right)\right]$
  - $\hat{s}_{\min}$ calculated for each eikonal separately
  - need infra-red continued pdf's
- after each ladder, check momentum of incoming hadrons
  if E_1 or E_2 exhausted terminate exchanging ladders
  therefore $N_{\text{ladders}} \leq N_{\text{naive}}$

Inelastic Scattering: Generating Emissions

- assume emissions to be ordered in rapidity
- generate emissions with Sudakov form factor

$$\mathcal{S}(y_0, y_1) = \exp\left\{ -\int\limits_{y_0}^{y_1} \mathrm{d}y \int \mathrm{d}k_\perp^2 \, \frac{\alpha_s(k_\perp^2 + K_0^2)}{(k_\perp^2 + K_0^2)} \right.$$
$$\times \left[\frac{K_0^2}{q^2 + K_0^2}\right]^{\frac{3\alpha_s(q^2+K_0^2)}{\pi}|y-y_0|}$$
$$\left. \times \exp\left[-\frac{\lambda}{2}\left(\Omega_{i(k)}(y) + \Omega_{(i)k}(y)\right)\right]\right\}$$

$\Rightarrow$ Regge dynamics generates dynamical Pomeron intercept with $\langle\Delta\rangle = 0.1\ldots0.2$

Inelastic Scattering: Generating Emissions

for each emission

- generate gluon's rapidity from Sudakov form factor
- construct kinematics
- for each t-channel propagator select colour

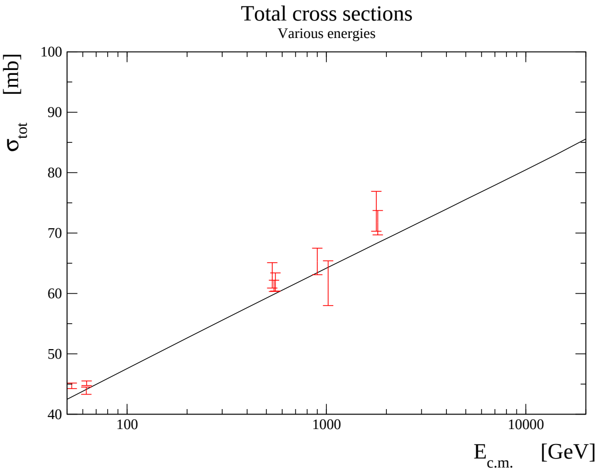
(assume only colour singlet and octet exchange)

$$\mathcal{P}_1 \propto \left\{1 - \exp\left[-\frac{1}{2}\left(\frac{\Omega_i(y_{i+1})}{\Omega_i(y_i)} - 1\right)\right]\right\}^2$$

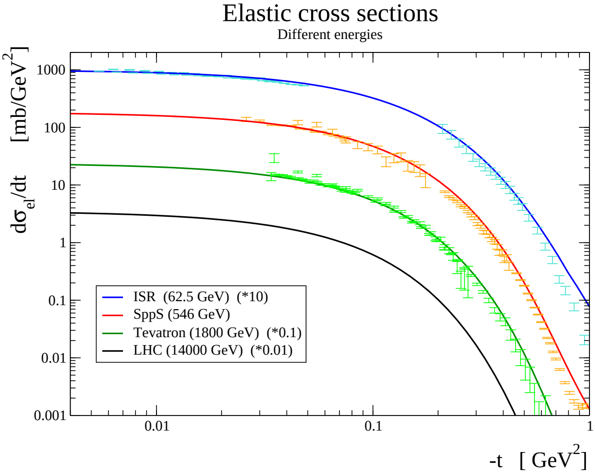
after having filled the entire ladder

- find hardest octet exchange and correct with ME to account for correct form of parton-parton scatter

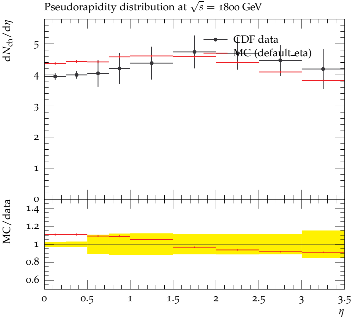
Total Cross Section

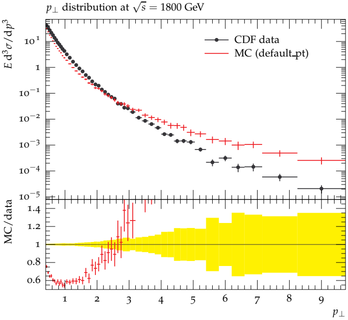


Elastic Cross Section

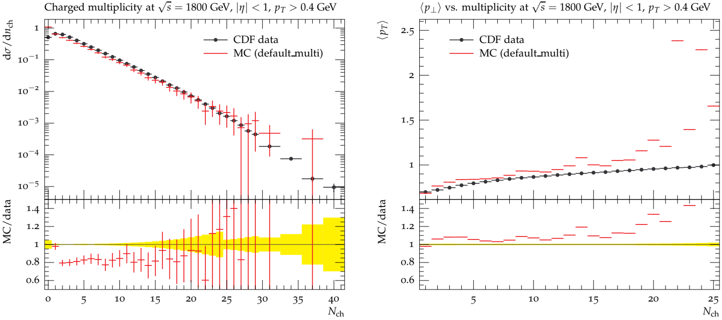


Minimum Bias from CDF ($p\bar{p}$ @1800 GeV)





Minimum Bias from CDF ($p\bar{p}$ @1800 GeV)



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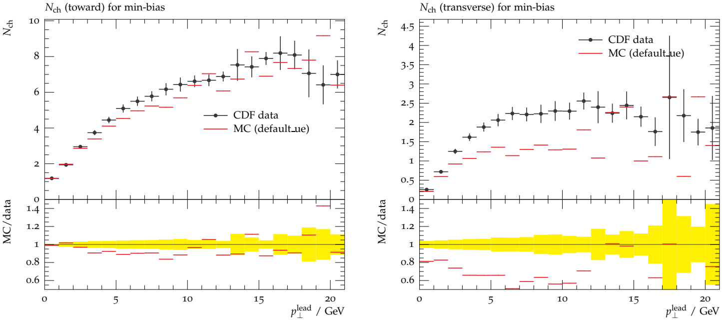

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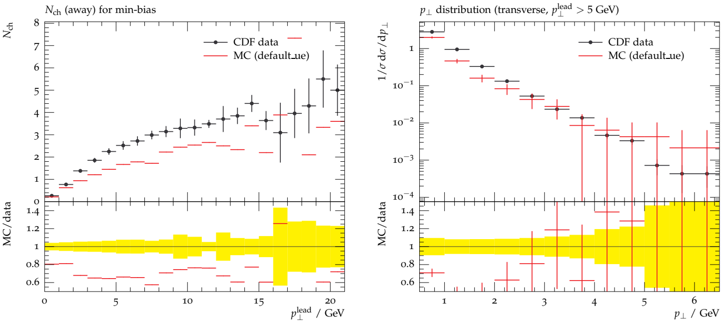

Conclusions

- understanding of minimum bias physics an essential part of first years of running at the LHC
- potentially important signals depend on our understanding of minimum bias
- various models on the market, most sophisticated ones so far basing on eikonal picture
- convincing model for inclusive properties by KMR
- however, up to now no model available that describes all aspects of minimal bias (total xsec, elastic scattering, diffraction, jet production) in one unified framework and is capable of modelling exclusive final states
- started implementing a model based on KMR

Outlook

- Next steps (short timescale):
  - validate the physics/tune the parameters
  - single and double low-mass diffraction (implemented but requires validation)
  - formulate as underlying event model (easy but has to be implemented)
  - formulate as model for dynamic generation of intrinsic $k_\perp$
  - publish the module as part of SHERPA 1.3.
- Near future:
  - include secondary Reggeon (quarks!)
  - allow for open and closed heavy flavour production
  - include $k_\perp$ dependence into differential equations

Multi-Channel Eikonals

Comments

- if all components of j, i.e. all eigenstates ϕ_k, experienced same absorption:
  $\longrightarrow$ dispersion vanishes
  $\longrightarrow$ diffractive production cross section vanishes
- this happens in black disc limit ($T_k = 1$), at small b
- consequence: already at Tevatron energies diffractive production processes due to large b
- this region responsible for small t components
- also: there eikonal (equivalent to optical density, opacity) is small
  $\longrightarrow$ large rapidity gap survival probability

(due to small density, only few scatters)

Aside: continued pdf's

- sea (anti)quarks: scale down to vanish as $Q^2 \to 0$
- valence quarks: transform to pure valence contribution as $Q^2 \to 0$
- same shape as valence quarks as $Q^2 \to 0$, scale to satisfy momentum sum rule