Minimum Bias with SHRiMPS in SHERPA

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Outline

Introduction

KMR model in a nutshell

SHRiMPS model: exclusive final states

Comparison to data

Wrap-up

Why care about Minimum Bias?

Interesting in its own right

- most complete view of physics at LHC
- includes elastic scattering, low and high mass diffraction, central exclusive production, inelastic interactions, hard scattering, ...
- so far not completely understood
- fun processes like elastic Higgs production
- TOTEM experiment designed to study soft QCD

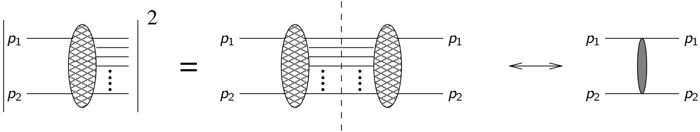
Important for hard physics

- intimately connected to underlying event
  - affects all measurements at the LHC
  - for instance: jet vetos in VBF
- pile-up is minimum bias

Introduction

- optical theorem

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

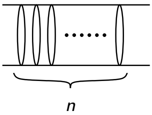


- grey blob: exchange of vacuum quantum numbers
- compute $\mathcal{A}_{\text{el}}$
  - Khoze-Martin-Ryskin (KMR) model
- cut to obtain differential total cross section
  - allows for MC event generation
  - SHRiMPS model
    Soft and Hard Reactions involving Multi-Pomeron Scattering

Eikonal models

- eikonal ansatz:

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



- Good-Walker states (diffractive eigenstates):

$$|p\rangle = \sum_{i=1}^{N_{\rm GW}} a_i|\phi_i\rangle$$

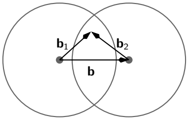
- allows for low mass diffractive excitations
- one single-channel eikonal Ω_{ik} per combination of Good-Walker states

$$\left(1 - e^{-\Omega(s,b)/2}\right) \to \sum_{i,k=1}^{N_{\rm GW}} |a_i|^2|a_k|^2\left(1 - e^{-\Omega_{ik}(s,b)/2}\right)$$

KMR approach

eikonal Ω_{ik}: product of two parton densities $\omega_{i(k)}$

$$\Omega_{ik}(s,\mathbf{b}) = \frac{1}{2\beta_0^2}\int d\mathbf{b}_1 d\mathbf{b}_2\, \delta^2(\mathbf{b}-\mathbf{b}_1+\mathbf{b}_2)\omega_{i(k)}(y,\mathbf{b}_1,\mathbf{b}_2)\omega_{(i)k}(y,\mathbf{b}_1,\mathbf{b}_2)$$



- $\omega_{i(k)}$: density of GW state i in presence of state k
- $\omega_{i(k)}$ obey evolution equation in rapidity
- boundary conditions: (dipole) form factors

KMR model: evolution equations

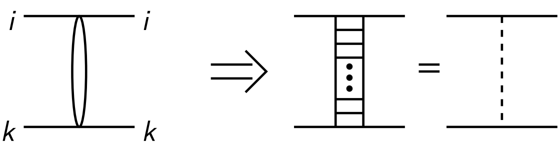
Bare Pomeron Contribution

- evolution equation for parton density

$$\frac{d\omega_{i(k)}(y)}{dy} = \Delta\omega_{i(k)}(y)$$
$$\frac{d\omega_{(i)k}(y)}{dy} = \Delta\omega_{(i)k}(y)$$

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

probability for emitting an additional gluon per unit rapidity



KMR model: evolution equations

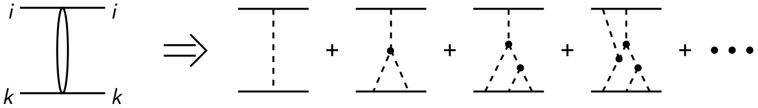
Rescattering

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

$$\frac{d\omega_{i(k)}(y)}{dy} = \Delta\omega_{i(k)}(y)\left[\frac{1-e^{-\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right]\left[\frac{1-e^{-\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right]$$

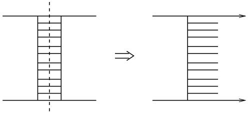
$$\frac{d\omega_{(i)k}(y)}{dy} = \Delta\omega_{(i)k}(y)\left[\frac{1-e^{-\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right]\left[\frac{1-e^{-\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right]$$

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



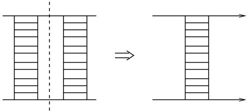
SHRiMPS model

- cutting a simple diagram:



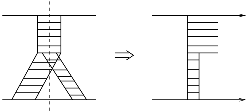
  - inelastic scattering

- a even simpler diagram:

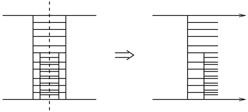


  - elastic scattering

- cutting a triple-pomeron vertex:



  - colour singlet exchange
  - high mass diffraction



  - rescattering

Global event properties

select elastic, low-mass diffractive or inelastic mode

according to cross sections

Elastic and low-mass diffractive

- fairly straight forward

Inelastic

- fix combination of colliding GW states

  according to contribution to inelastic cross section

- fix impact parameter
- assume ladders to be independent
- number of ladders: Poissonian with parameter Ω_{ik}
- for each ladder fix transverse position $\mathbf{b}_{1,2}$

Generating Ladders

- decompose protons using infra-red continued pdf's
- generate emissions using pseudo Sudakov form factor

$$\mathcal{S}(y_0, y_1) = \exp\left\{ -\int_{y_0}^{y_1} \mathrm{d}y \int \mathrm{d}k_\perp^2 \, \frac{C_A \alpha_s(k_\perp^2)}{\pi k_\perp^2} \times \left(\frac{q_\perp^2}{Q_0^2}\right)^{\frac{C_A}{\pi}\alpha_s(q_\perp^2)\Delta y} \times \left(\frac{1 - e^{\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2}\right) \left(\frac{1 - e^{\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2}\right) \right\}$$

QCD; Regge weight; rescattering weight

- infra-red continuation

Generating Ladders

- decompose protons using infra-red continued pdf's
- generate emissions using pseudo Sudakov form factor
- infra-red continuation
- dynamical Q_0^2
- t-channel propagators can be colour singlets or octets
  probabilities for these depend on parton densities and λ
- generates dynamical Δ
- correct hardest emission to pQCD MEs
- allow for parton showering

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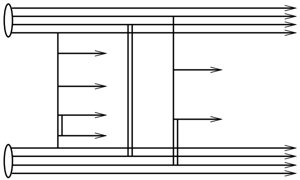
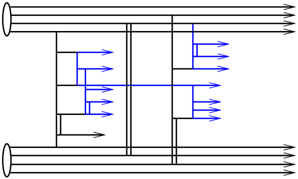


Rescattering & Hadronisation

Rescattering

- partons may exchange rescatter ladders
- rescatters of rescatters of rescatters...



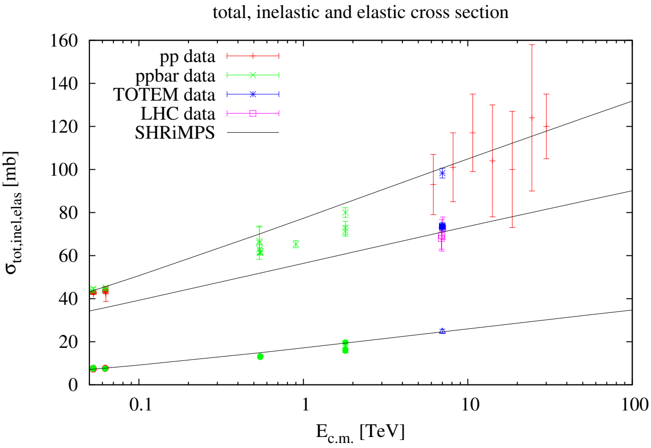
Hadronisation

- colour reconnections
- probability for colour swap decreases with distance

similar to PYTHIA model

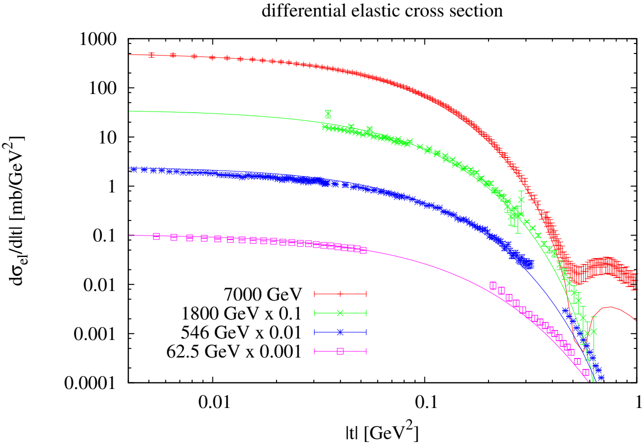
- hadronisation with SHERPA's cluster hadronisation

Cross Sections

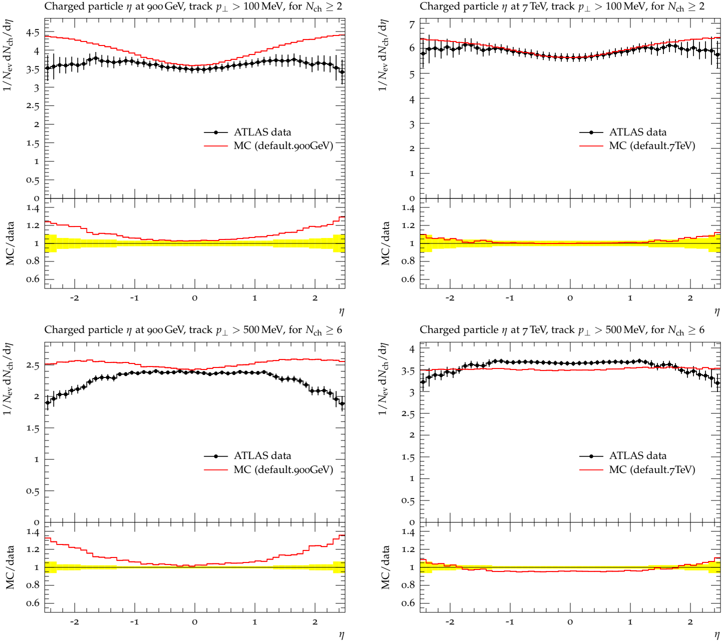


$$\Delta = 0.25,\ \lambda = 0.35,\ \beta_0^2 = 25\,\text{mb}$$

Differential Elastic Cross Section



Minimum Bias @900 GeV & 7 TeV



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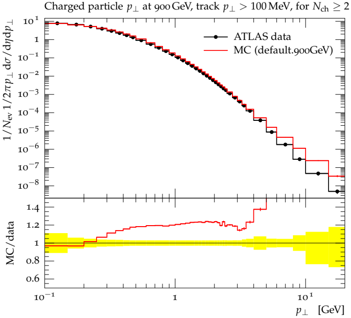

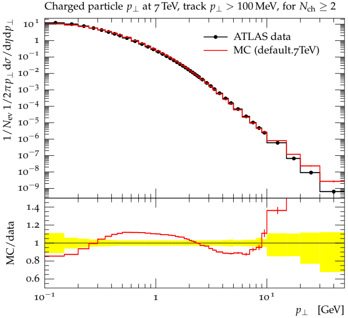

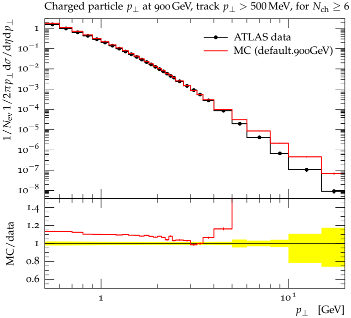

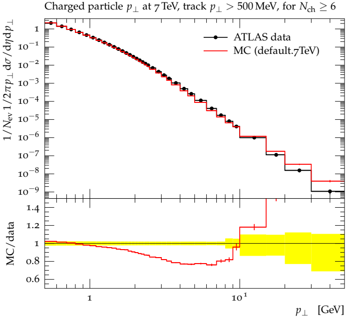

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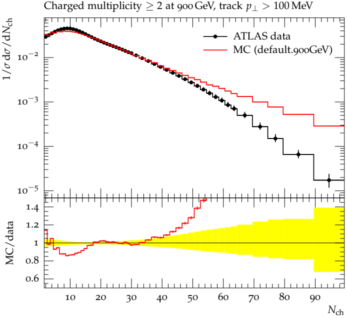

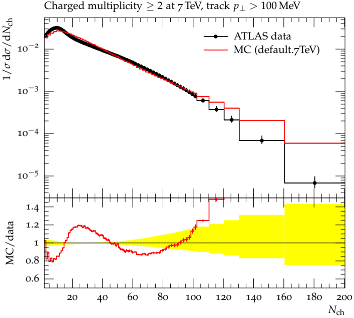

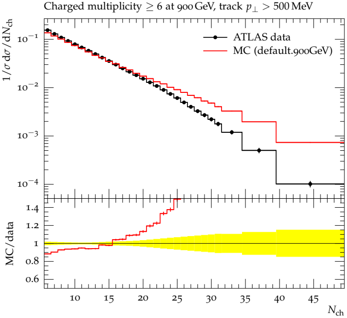

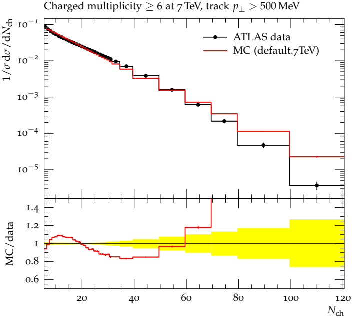

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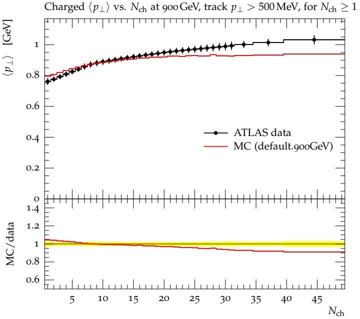
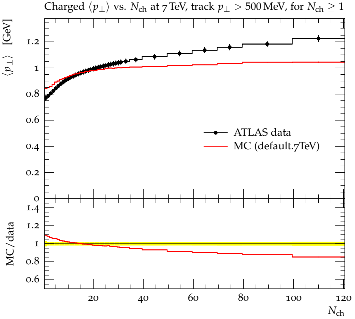
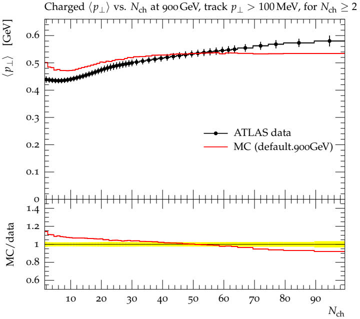
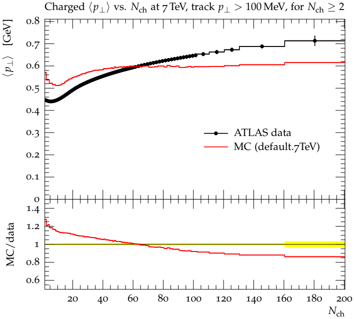
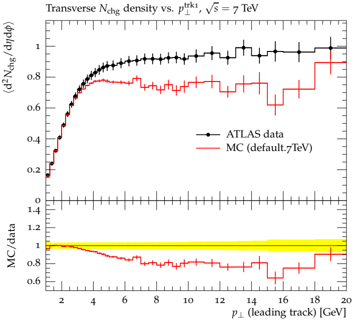


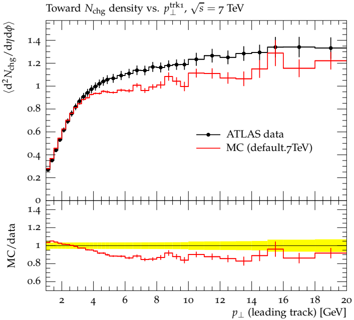


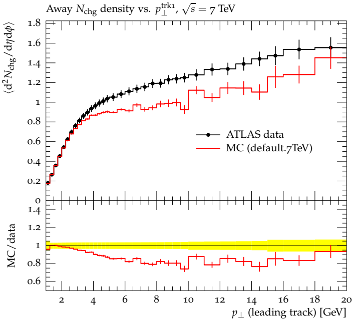




Underlying Event @7 TeV







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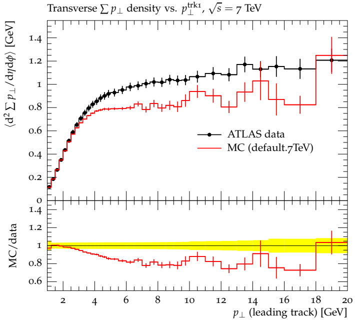

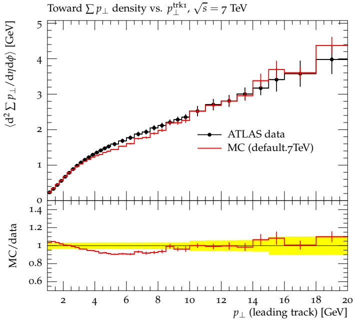

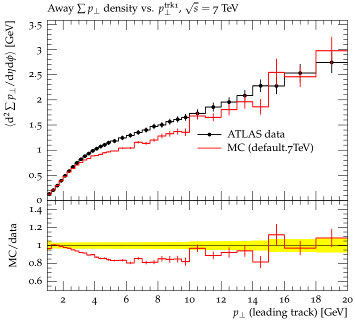

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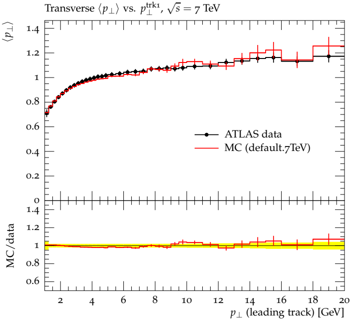
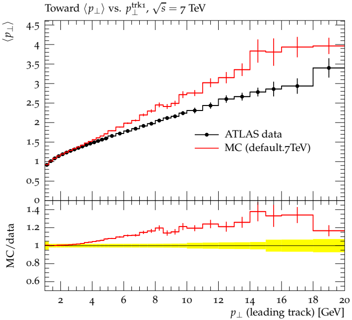
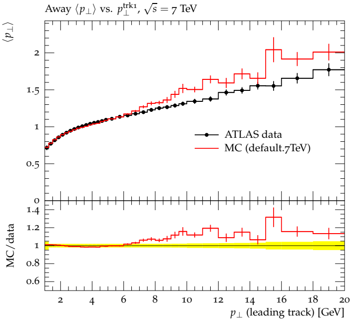
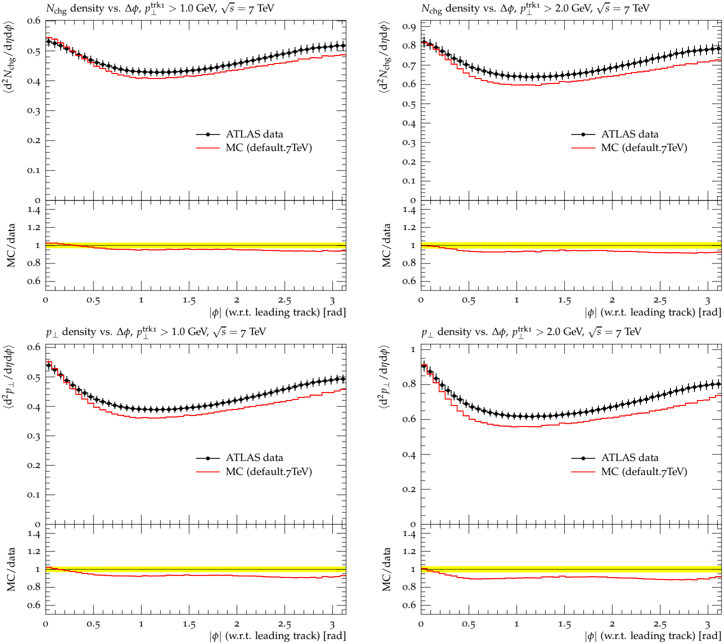


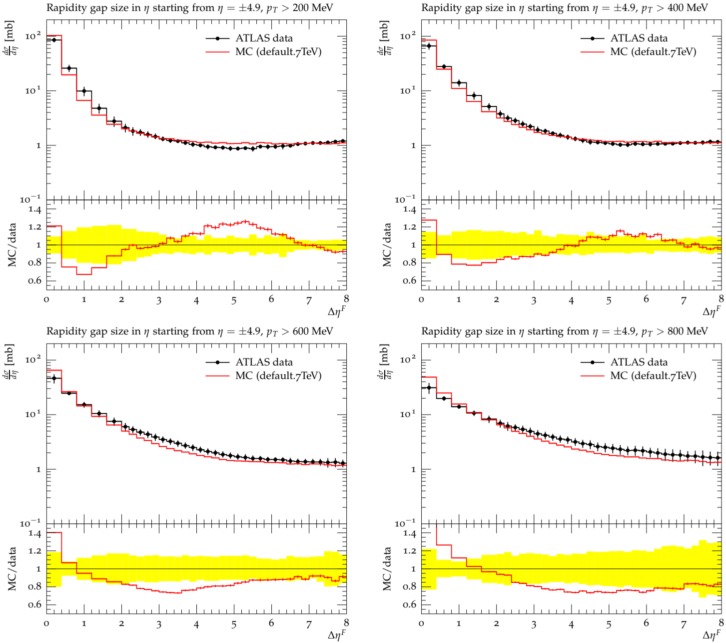




Underlying Event @7 TeV



Rapidity Gap Cross Section @7 TeV



Wrap-up

Status

- model for soft & semi-hard QCD based on KMR model
- complete picture including all interactions

  elastic, low & high mass diffractive, inelastic
- describes data reasonably well
- included in SHERPA 2.0.0

Outlook

- finish tuning and publish paper
- formulate as underlying event model
- include secondary Reggeons (quarks)
- allow for open and closed heavy flavour production

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

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

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

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

- cross sections

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

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

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

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

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

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

Selecting the Modes

- select elastic vs. inelastic processes according to

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

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

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

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

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

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