# SHRiMPS

## The new Minimum Bias Model in SHERPA

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# Outline

# Intoduction

## SHRiMPS

Soft & Hard Reactions involving Multiple Pomeron Scattering

- minimum bias and underlying event model based on KMR model
- KMR model: multi-channel eikonal model with partonic interpretation of pomeron
- describes soft and semi-hard QCD, diffraction, elastic scattering and cross sections

## Motivation

- pile-up is minimum bias
- many analyses (e.g. VBF) depend on topologies with rapidity gaps

$\Rightarrow$ need good control over survival probability of rapidiy gaps, minimum bias interactions and underlying event

# $s$-Channel Unitarity, Cross Sections and Eikonals

- optical theorem relates total cross section $\sigma_{\rm tot}$ to elastic forward scattering amplitude $A(s,b)$
- in eikonal model elasic amplitude given by sum of all Regge exchange diagrams:

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

- 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 $\sum_i |a_i|^2 = 1$
- 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,

$$\mathcal{F}_{1,2}(q_\perp) = \beta_0^2(1\pm\kappa)\frac{\exp\left[-\frac{(1\pm\kappa)\xi q_\perp^2}{\Lambda^2}\right]}{\left[1+\frac{(1\pm\kappa)q_\perp^2}{\Lambda^2}\right]^2}$$

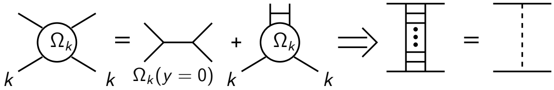
# Khoze-Martin-Ryskin Model

## 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 $\Delta$ being probability for emitting an additional gluon per unit rapidity

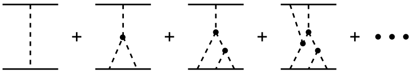
# Khoze-Martin-Ryskin Model

## Rescattering

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

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

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

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

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

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

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

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

# Selecting Gross Features of Scattering Mode

## Quasi-elastic

- choose elastic or (single or double) low mass diffraction
- fix $t$ according to Fourier transform of integrand of cross section
- if diffraction outgoing state is N*(1440)

only two Good-Walker states

## Inelastic

- if inelastic is chosen, fix $\{ik\}$ according to partial contribution
- fix **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 $\mathbf{b} = \mathbf{b}_1 + \mathbf{b}_2$:

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

# Initialising the ladders

- fix $\hat{s}_{\min}$ for each eikonal separately such that

$$\hat{\sigma}_{ik} = \int\limits_{\hat{s}_{\min}}^{\hat{s}_{\max}} \frac{\mathrm{d}\hat{s}}{2\hat{s}} \int\limits_{-y_{\max}}^{y_{\max}} \mathrm{d}y \, \frac{x_+ F_1(x_+, 0) x_- F_2(x_-, 0)}{\hat{s}} \left(\frac{\hat{s}}{\hat{s}_{\min}}\right)^{\eta} = \sigma_{\text{inel}}^{ik}$$

- effective intercept

$$\eta = \Delta \exp\left[-\frac{\lambda}{2}\left(\Omega_i(b_1, b_2, 0) + \Omega_k(b_1, b_2, 0)\right)\right]$$

- decompose protons using infra-red continued pdf's
- initial state weight

$$\mathcal{P}_{\text{IS}} = \left(\frac{\hat{s}}{\hat{s}_{\min}}\right)^{\eta}$$

- after each ladder, check of momentum of incoming hadrons exhausted

therefore $N_{\text{ladders}} \leq N_{\text{naive}}$

# Inelastic Scattering: Generating Emissions

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

$$\mathcal{S}(y_0, y_2) = \exp\left\{ -\int_{y_0}^{y_2} \mathrm{d}y_1 \int \mathrm{d}k_\perp^2 \, \frac{C_A \alpha_s(k_\perp^2)}{\pi Q_0^2 \left(\frac{k_\perp^2}{Q_0^2}\right)^\eta} \times \min\left(\frac{Q_0^2}{q_{01,\perp}^2}, \frac{q_{01,\perp}^2}{Q_0^2}\right)^{\frac{C_A}{\pi}\alpha_s(q_{01,\perp}^2)|y_1 - y_0|} \times \left(\frac{1 - \exp\left[-\frac{\lambda(q_{01}^2, q_{12}^2)}{2}\Omega_i(y_1)\right]}{\frac{\lambda(q_{01}^2, q_{12}^2)}{2}\Omega_i(y_1)}\right) \left(i \leftarrow k\right) \right\}$$

$\Rightarrow$ Regge dynamics generates dynamical Pomeron intercept with $\langle \Delta \rangle = 0.1 \ldots 0.2$

# 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

$$\mathcal{P}_1 = \left[1 - \frac{1 - \exp(-\tilde{\Delta}_\Omega/2)}{\tilde{\Delta}_\Omega/2}\right]^2$$

with

$$\tilde{\Delta}_\Omega(q_1^2, q_2^2) = \lambda^2 \frac{\left|\Omega_{i/k}(y_1) - \Omega_{i/k}(y_2)\right|}{\min(\Omega_{i/k}(y_1), \Omega_{i/k}(y_2))}$$

# Inelastic Scattering: Generating Emissions

## after having filled the entire ladder

- find hardest octet exchange and correct with ME to account for correct form of parton-parton scatter
- allow radiated gluons to develop parton shower

## rescattering

- BFKL resums ladders within ladders → rescattering
- rescatter probability

$$\mathcal{P}_{\text{resc}} = \left[1 - \frac{1 - \exp(-\tilde{\Delta}_\Omega)}{\tilde{\Delta}_\Omega}\right] \frac{1}{N_{\text{resc}}!} \left(\frac{s_{12}}{\max(s_{12}, s_{\min})}\right)^{1+\eta}$$

# Status

- tuned inclusive quantities

  more than one parameter set fits

- first attempt to tune exclusive quantities

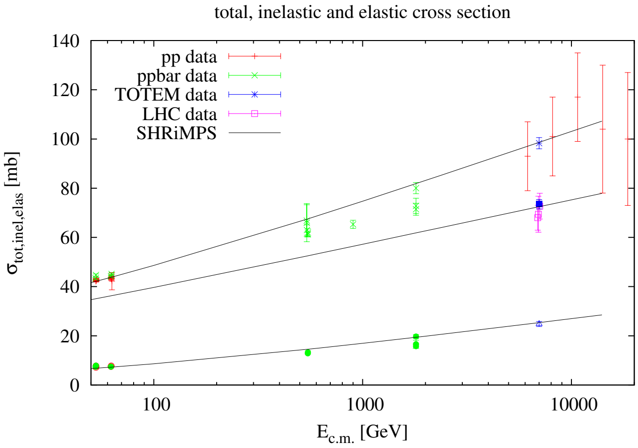
  work very much in progress

- released $\alpha$-version with SHERPA 1.4.0

  with known issues and not fully functional

- plan to release fully functional version as SHERPA 1.4.1 soon

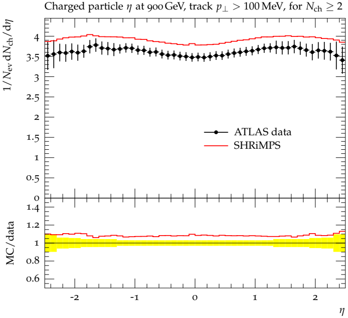
# Cross Sections

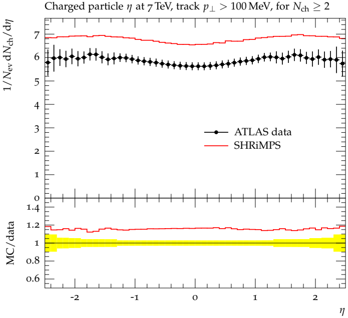


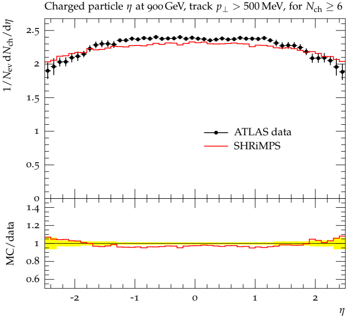

$$\Delta = 0.21,\ \lambda = 0.40,\ \delta y = 0.98$$

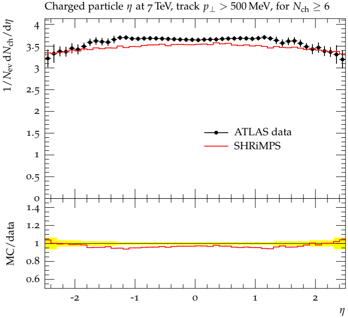
$$\beta_0^2 = 20.1\,\mathrm{mb},\ \Lambda^2 = 0.77\,\mathrm{GeV}^2,\ \kappa = 0.20,\ \xi = 0.10$$

# Minimum Bias @900 GeV & 7 TeV



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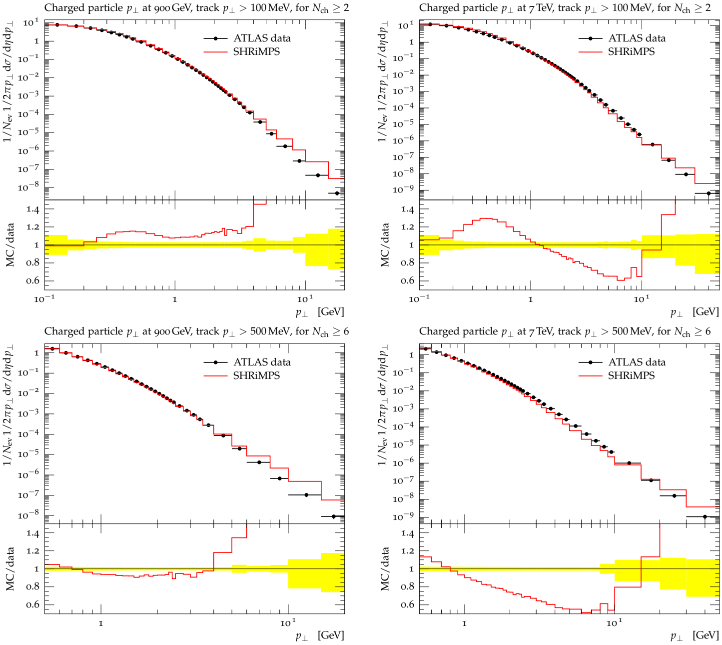

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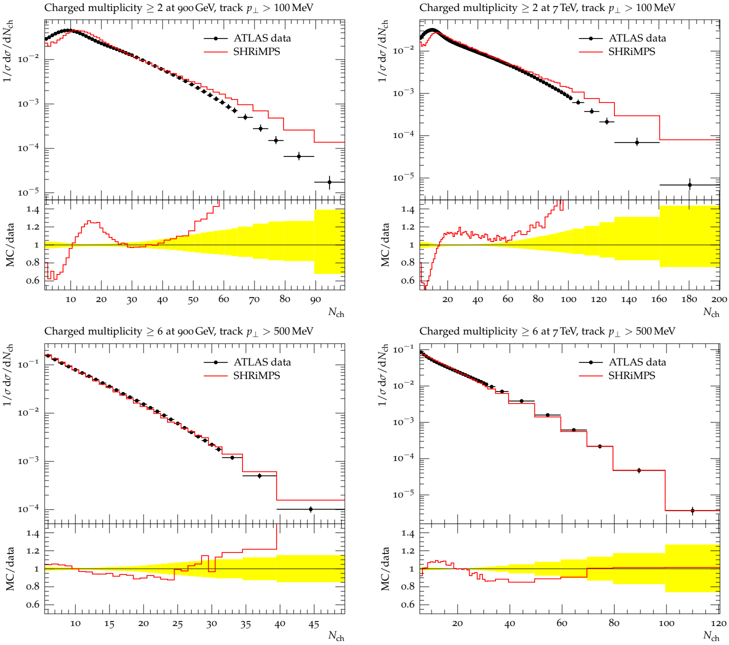

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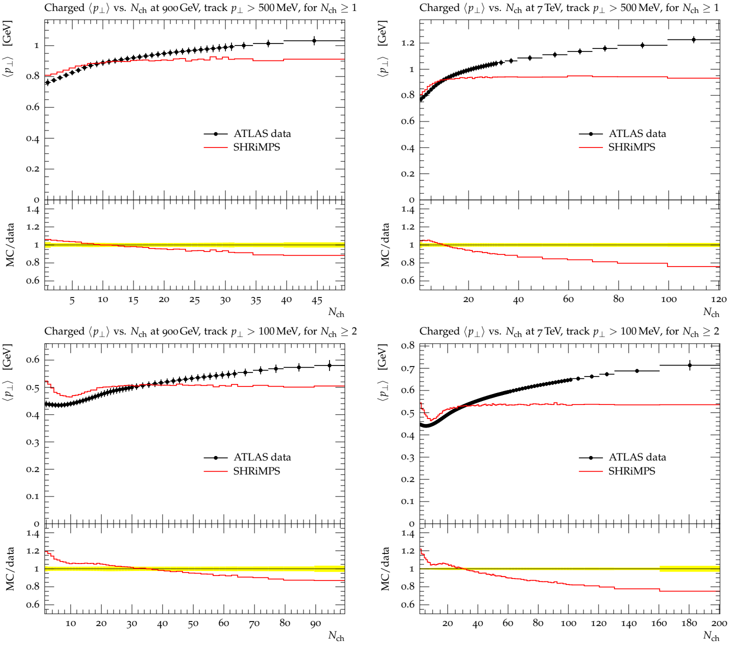
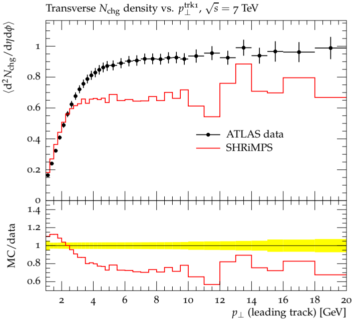
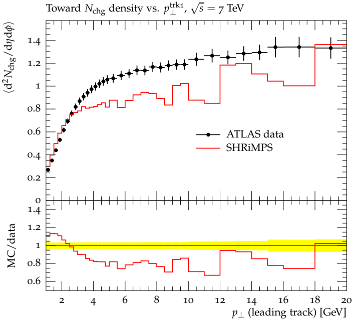
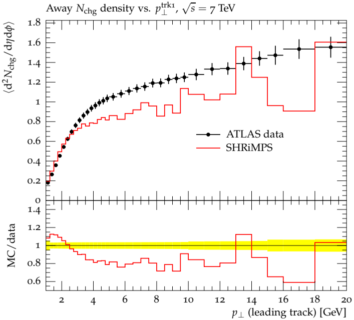


# Underlying Event @7 TeV



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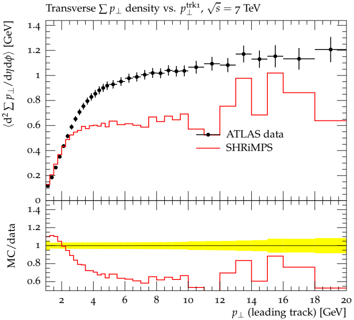


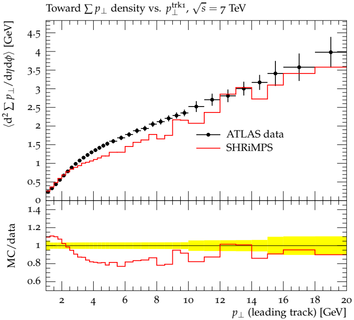


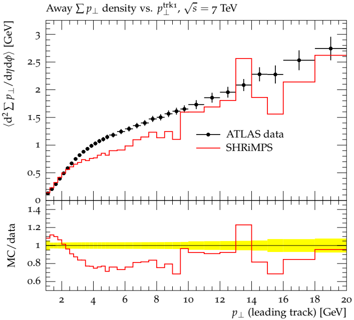

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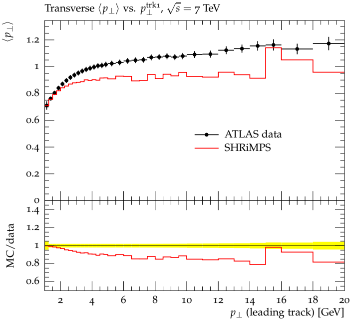


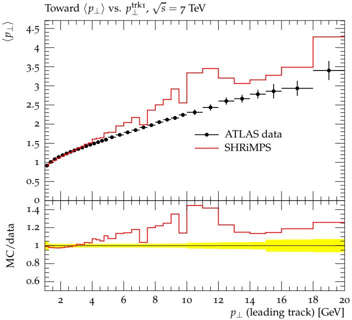


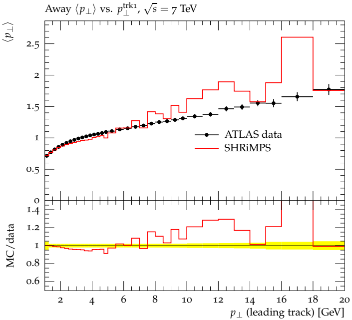

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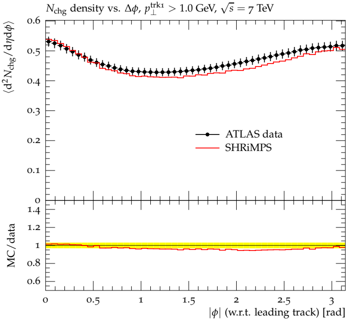
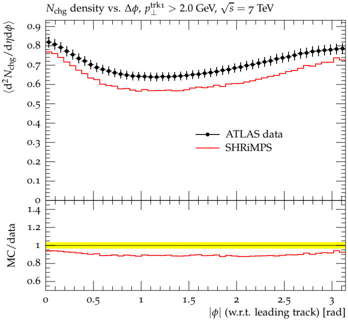
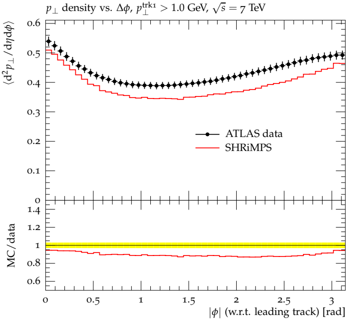
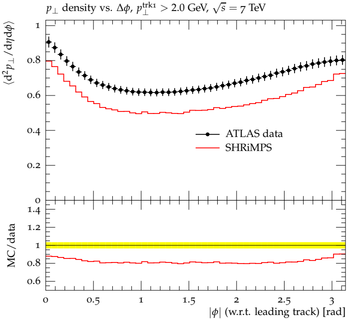


# Conclusions & Outlook

## Conclusions

- potentially important signals depend on our understanding of minimum bias
- convincing model for inclusive properties by KMR
- SHRiMPS: consistent model for soft and semi-hard QCD based on KMR model

## Outlook

- validate the physics/tune the parameters SHERPA 1.4.1
- formulate as underlying event model
  straight forward but has to be implemented
- and as model for dynamic generation of intrinsic $k_\perp$
- include secondary Reggeon (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

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

- 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

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

- 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:

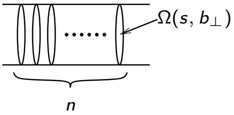
$$A(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$$

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

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

- pictorially:

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



# Single-Channel Eikonal Model

- cross sections in eikonal model

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

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

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

# 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):
  $$|p\rangle = \sum_i a_i|\phi_i\rangle, \text{ where } \langle\phi_i|\phi_k\rangle = \delta_{ik} \text{ and } \sum_i |a_i|^2 = 1$$
- 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

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

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

# 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