

SHERPA

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Outline

SHERPA: overview

Soft QCD model: SHRiMPS

Introduction

Eikonal models

The KMR model

Exclusive final states: SHRiMPS

Comparison to data

Summary

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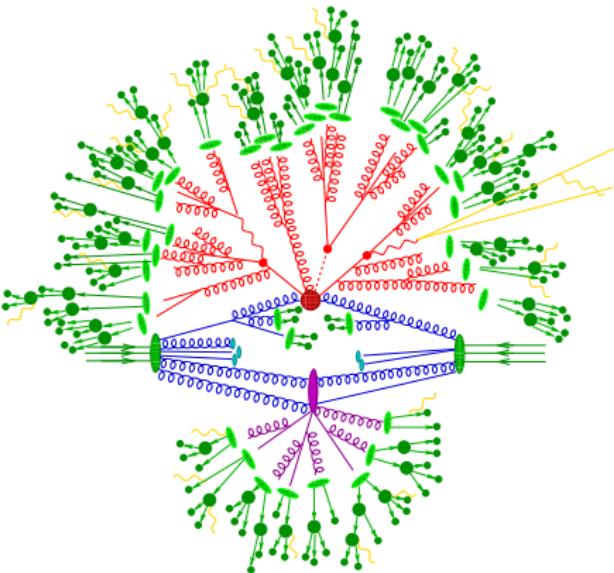
Exclusive final states: SHRiMPS

Comparison to data

Summary

SHERPA: a multi-purpose event generator

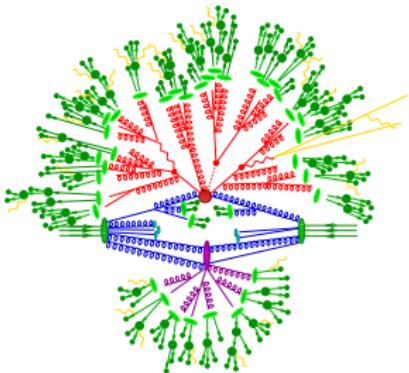
$$d\sigma_{\text{final state}} = d\sigma_{\text{hard process}} \mathcal{P}_{\text{QCD rad.}} \mathcal{P}_{\text{hadronisation}} \mathcal{P}_{\text{decays}} \mathcal{P}_{\text{QED rad.}} \mathcal{P}_{\text{MPI}}$$



- ▶ integrates cross section
 - ▶ generates events: sets of particles distributed according to $d\sigma_{\text{final state}}$
 - ▶ can calculate any observable
no new calculation for new observable
 - ▶ relies on separation of scales

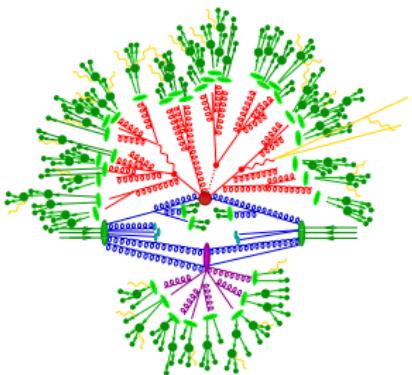
<http://sherpa.hepforge.org>

Hard process



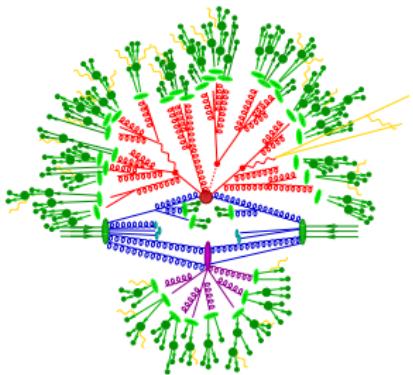
- ▶ hard scattering matrix elements (ME)
 - ▶ calculated at fixed order in perturbation theory
 - ▶ SHERPA's (tree level) matrix element generators: AMEGIC++ and COMIX
 - ▶ loop matrix elements for NLO event generation from external codes
 - ▶ SHERPA provides
 - ▶ LO ME + parton shower
 - ▶ NLO ME + parton shower (MC@NLO)
 - ▶ LO multi-jet merging
 - ▶ NLO multi-jet merging

Parton showers



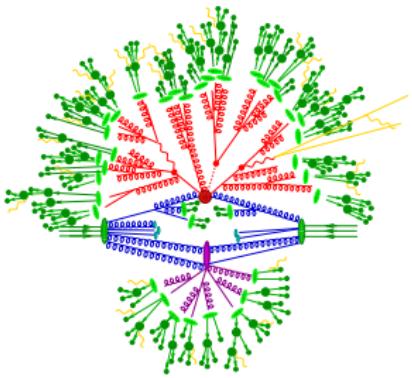
- radiative corrections in QCD → QCD bremsstrahlung
 - initial and final state parton shower
 - explicit DGLAP evolution
 - resummation of collinear logs in QCD
 - perturbative calculation, but not fixed order
 - leading log (LL) accuracy with some sub-leading (NLL) pieces
 - SHERPA's partons showers:
CSSHOWE and DIRE

Hadronisation



- ▶ conversion of partons into hadrons
 - ▶ non-perturbative long-distance physics
 - ▶ phenomenological models
 - ▶ have to be tuned to data
 - ▶ process independent by factorisation arguments
 - ▶ in SHERPA: cluster hadronisation (AHADIC++)

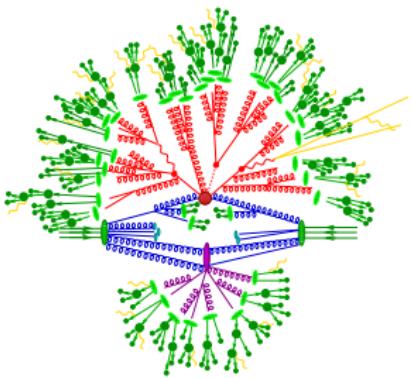
Decays



- ▶ hadron decays
 - ▶ τ decays
 - ▶ EM, weak & strong decays
 - ▶ weak neutral meson mixing
 - ▶ many-body decays
 - ▶ polarisation, angular correlations
 - ▶ tables of decay channels + matrix elements
 - ▶ in SHERPA: HADRONS++

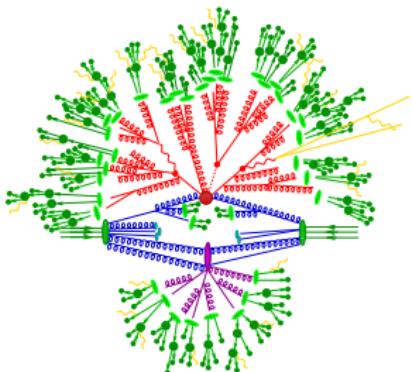
QED radiation

- ▶ collinear resummation → DGLAP
- ▶ resummation of soft photons à la YFS
 - ▶ resummation of soft-photon logs in massive Abelian gauge theories
 - ▶ collinear logs can be added order by order, but not resummed
 - ▶ no ordering of emissions
 - ▶ coherent radiation off charged multipole
- ▶ simultaneous QCD & QED DGLAP evolution
- ▶ cannot combine QCD DGLAP & YFS
- ▶ apply YFS to non-QCD final state
- ▶ in SHERPA: PHOTONS++



Multiple parton interactions

- ▶ more than one parton-parton interaction per proton-proton collision
- ▶ gives rise to additional activity
→ underlying event
- ▶ beyond factorisation theorems
→ need to model
- ▶ related to minimum bias physics, i.e. reactions without hard scattering
- ▶ underlying event model similar to PYTHIA's: AMISIC++
- ▶ soft QCD model: SHRIMPS



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Soft QCD model: SHRiMPS

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The KMR model

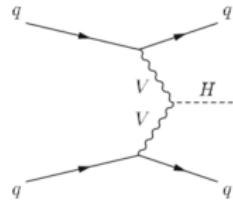
Exclusive final states: SHRiMPS

Comparison to data

Summary

Motivation for studying soft QCD

- ▶ minimum bias: most complete view on strong interaction
interesting in its own right
- ▶ pile-up is minimum bias
- ▶ minimum bias related to underlying event
- ▶ underlying event present in all processes, e.g.
 - ▶ Higgs measurements in VBF channel depend on rapidity gaps

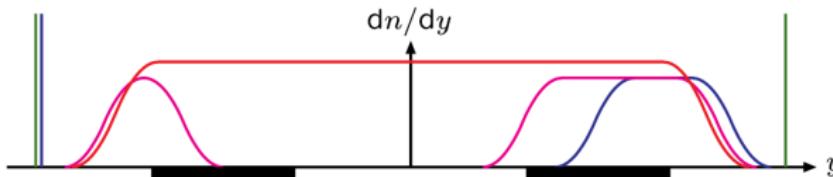


- ▶ rapidity gap survival probability depends on underlying event
- ▶ **SHRImps**: comprehensive model of soft QCD scattering

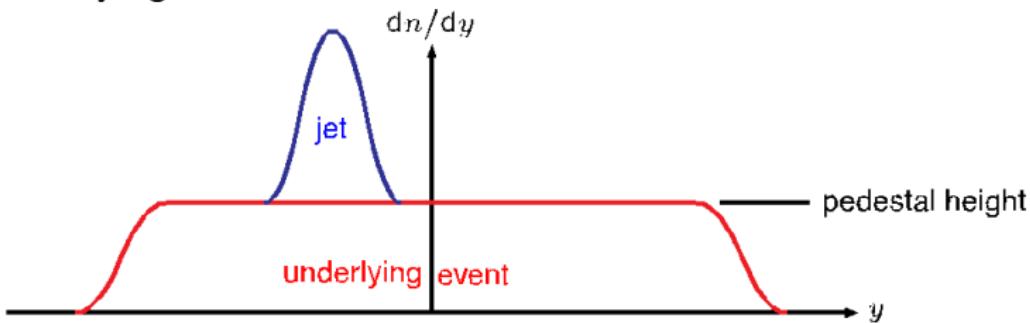
Classification of processes

- #### ► soft inclusive collision

$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single diffractive}} + \sigma_{\text{double diffractive}} + \sigma_{\text{non-diffractive}}$$



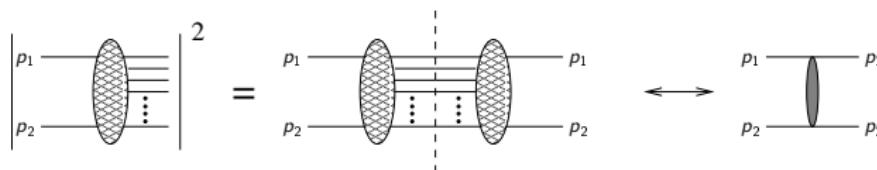
- #### ► underlying event



SHRiMPS: 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}_{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

s-Channel Unitarity and Cross Sections

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

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

- ▶ cross sections

$$\sigma_{\text{tot}}(s) = 2 \int d\mathbf{b} \text{Im}[A(s, b)]$$

$$\sigma_{\text{el}}(s) = 2 \int d\mathbf{b} |A(s, b)|^2$$

$$\sigma_{\text{inel}}(s) = \sigma_{\text{tot}}(s) - \sigma_{\text{el}}(s)$$

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

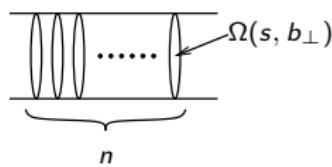
Single-Channel Eikonal Model

- ▶ in eikonal model elastic 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: Fourier transform of two-particle irreducible amplitude
- ▶ pictorially:

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



Single-Channel Eikonal Model

- ▶ cross sections in eikonal model

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

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

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

Multi-channel eikonals

Motivation

- ▶ (low mass) diffractive excitation consequence of internal structure of colliding hadrons
- ▶ impossible to describe in single eikonal model
- ▶ **high-energy limit:** Fock states of the hadrons “frozen”
lifetime of fluctuations $\tau = E/m^2$ large
- ▶ each component can interact separately
- ▶ destroys coherence of 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:

$$\langle \phi_i | \text{Im} \mathcal{T} | \phi_k \rangle = T_k^D \delta_{ik}$$

- therefore only “elastic scattering” of these states
- one **single-channel eikonal** Ω_{ik} per combination of Good-Walker states

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

Multi-channel eikonals

Cross sections

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

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

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

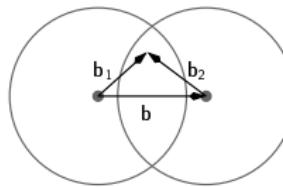
$$\sigma_{\text{el}+2\text{sd}+\text{dd}}^{pp}(s) = \int d\mathbf{b} \sum_{i,k=1}^{N_{GW}} |a_i|^2 |a_k|^2 \left(1 - e^{-\Omega_{ik}(s,b)/2}\right)^2$$

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: form factors

here: dipole form

Evolution equations: bare Pomeron contribution

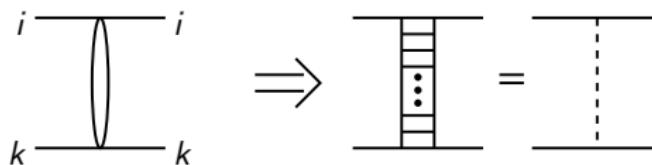
- ▶ evolution equation for parton density

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

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

where $\Delta = \alpha_P(0) - 1$

probability for emitting an additional gluon per unit rapidity



Evolution equations: rescattering

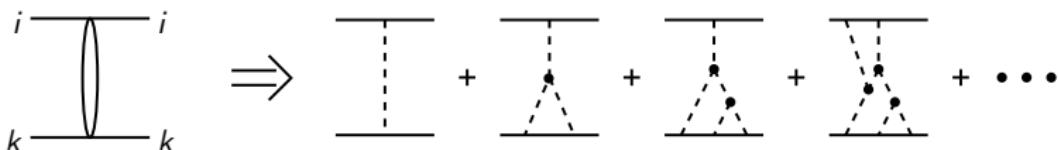
- ▶ high density & strong coupling regime → **rescattering**
large triple pomeron vertex

$$\frac{d\omega_{i(k)}(y)}{dy} = \Delta\omega_{i(k)}(y) \mathcal{W}_{\text{abs}}^{(ik)}(y)$$

$$\frac{d\omega_{(i)k}(y)}{dy} = \Delta\omega_{(i)k}(y) \mathcal{W}_{\text{abs}}^{(ik)}(y)$$

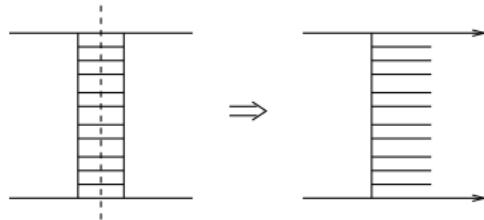
- ▶ absorption/rescattering weight

$$\mathcal{W}_{\text{abs}}^{(ik)}(y) = \left[\frac{1 - e^{-\lambda\omega_{i(k)}(y)/2}}{\lambda\omega_{i(k)}(y)/2} \right] \left[\frac{1 - e^{-\lambda\omega_{(i)k}(y)/2}}{\lambda\omega_{(i)k}(y)/2} \right] \quad \text{with} \quad \lambda = g_{3P}/g_{PN}$$



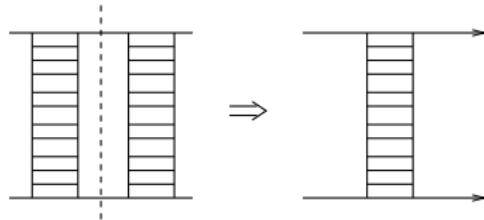
SHRiMPS model

- ▶ cutting a simple diagram:



▶ inelastic scattering

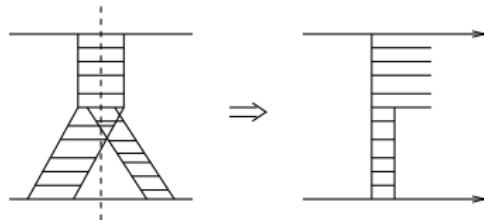
- ▶ a even simpler diagram:



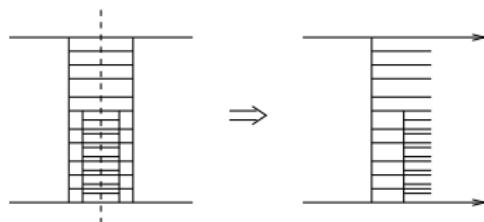
▶ elastic scattering

SHRiMPS model

- ▶ cutting a triple-pomeron vertex:



- ▶ colour singlet exchange
- ▶ high mass diffraction



- ▶ rescattering

- ▶ in SHRiMPS: directly generate cut diagrams

Global event properties

Selecting the mode

- ▶ select elastic, low-mass diffractive or inelastic mode
 - according to cross sections

Elastic and low-mass diffractive channels

- ▶ momentum transfer obtained from differential cross section

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

- ▶ low mass diffraction: analogously

Global event properties

Inelastic channel

- ▶ fix combination of colliding GW states
according to contribution $\sigma_{\text{inel}}^{(ik)}$ to inelastic cross section
- ▶ select impact parameter according to $d\sigma_{\text{inel}}^{(ik)}/d\mathbf{b}$
- ▶ number of ladders: Poissonian in eikonal Ω_{ik}
ladders are independent
- ▶ for each ladder fix transverse position $\mathbf{b}_{1,2}$

$$\frac{d\Omega_{ik}(s, \mathbf{b})}{d\mathbf{b}_1} \propto \omega_{i(k)}(\mathbf{b}_1, \mathbf{b}_2) \omega_{(i)k}(\mathbf{b}_1, \mathbf{b}_2)$$

with $\mathbf{b}_2 = \mathbf{b} - \mathbf{b}_1$

Generating primary ladders

- ▶ have to determine incoming partons
- ▶ ansatz based on reggeized t -channel exchange cross section

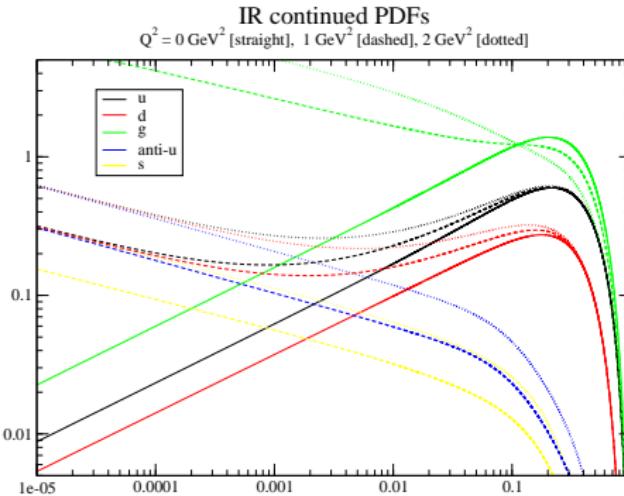
$$\hat{\sigma}_{\text{inel}}^{(ik)}(s) = \frac{1}{2s} \sum_{j,l} \int_{s_{\min}}^s d\hat{s} \int d\hat{y} \left[f_{j/h_1}(x_1, \mu_F^2 = 0) f_{l/h_2}(x_2, \mu_F^2 = 0) \left(\frac{\hat{s}}{s_{\min}} \right)^{\eta_{ik}} \right]$$

with $\eta_{ik} = \Delta \cdot \mathcal{W}_{\text{abs}}^{(ik)}(0)$

- ▶ adjust s_{\min} to match $\sigma_{\text{inel}}^{(ik)}$ obtained from eikonals
- ▶ fixes distribution of $x_{1,2}$
- ▶ requires infra-red parton distribution functions

IR-continued pdf's

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



Generating emissions

- ▶ in high energy limit gluon emissions strongly ordered in y
- ▶ generate emissions using pseudo Sudakov form factor

$$S(y_0, y_1) = \exp \left\{ - \int_{y_0}^{y_1} dy \int dk_\perp^2 \frac{C_A \alpha_s(k_\perp^2)}{\pi k_\perp^2} \left(\frac{Q_0^2}{q_\perp^2} \right)^{\frac{C_A}{\pi} \alpha_s(q_\perp^2) \Delta y} W_{\text{abs}}^{(ik)}(y) \right\}$$

QCD; Regge weight; absorption/rescattering weight

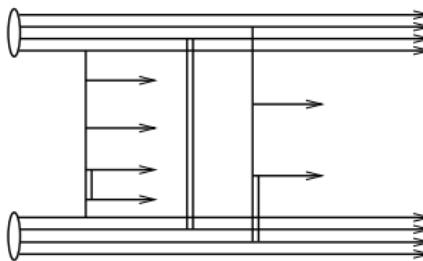
- ▶ infra-red continuation with dynamical regulator $Q_0^2(y)$
- ▶ generates dynamical Δ

Generating emissions

- ▶ t -channel propagators can be colour **singlets** or **octets**

$$\mathcal{P}_1(y_1, y_2) = \left[1 - \exp \left(-\frac{\Delta_\omega}{2} \right) \right]^2 \quad \text{and} \quad \mathcal{P}_8(y_1, y_2) = 1 - \exp(-\Delta_\omega)$$

with $\Delta_\omega = \lambda^2 \frac{|\omega_{i(k)}(y_1) - \omega_{i(k)}(y_2)|}{\min(\omega_{i(k)}(y_1), \omega_{i(k)}(y_2))}$



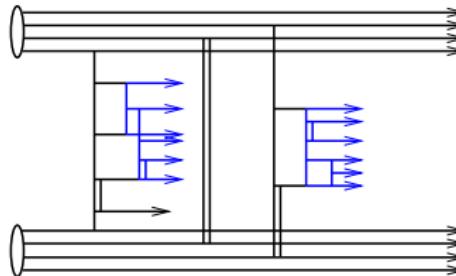
- ▶ correct **hardest** emission to pQCD MEs & add parton shower

Rescattering: generating secondary ladders

- ▶ partons may exchange **rescatter ladders**
- ▶ rescatters of rescatters of rescatters...
- ▶ rescattering probability:

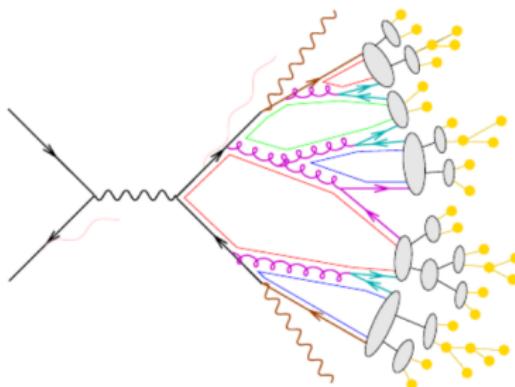
$$\mathcal{P}_{\text{resc}} = \frac{1}{N_{\text{resc}}!} \mathcal{P}_8 \left[\frac{\hat{s}_{ab}}{\max(\hat{s}_{ab}, s_{\min})} \right]^{1+\eta_{ik}},$$

- ▶ rescattering over singlet propagators is forbidden

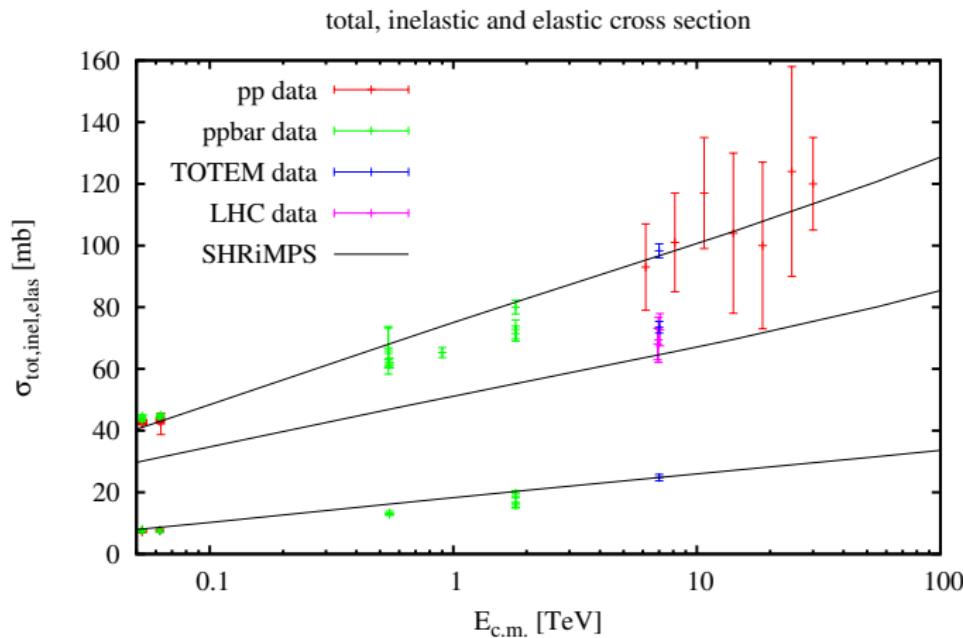


Hadronisation

- ▶ colour reconnections
- ▶ probability for colour swap decreases with distance
similar to PYTHIA model
- ▶ hadronisation with SHERPA's cluster hadronisation

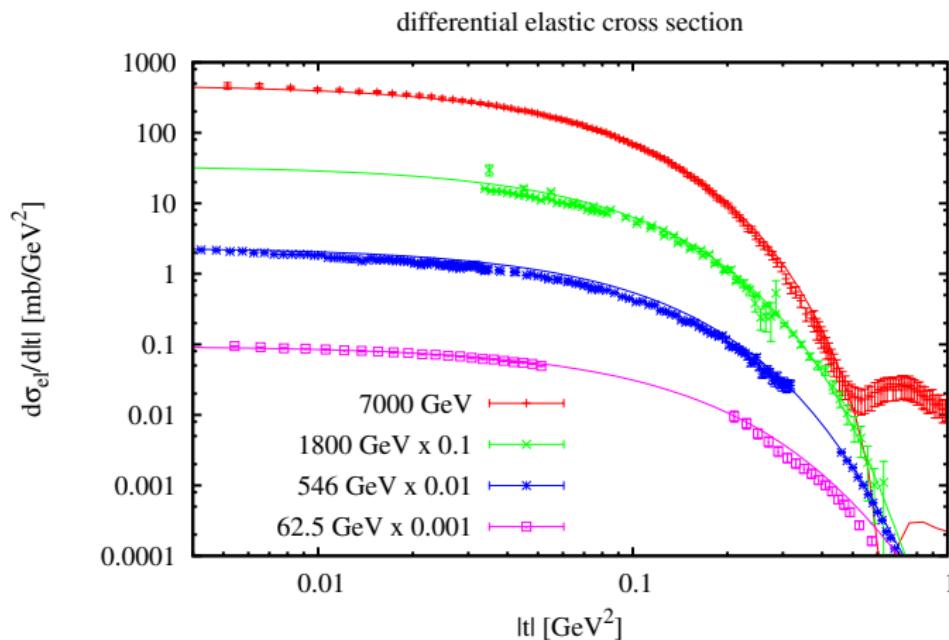


Cross Sections



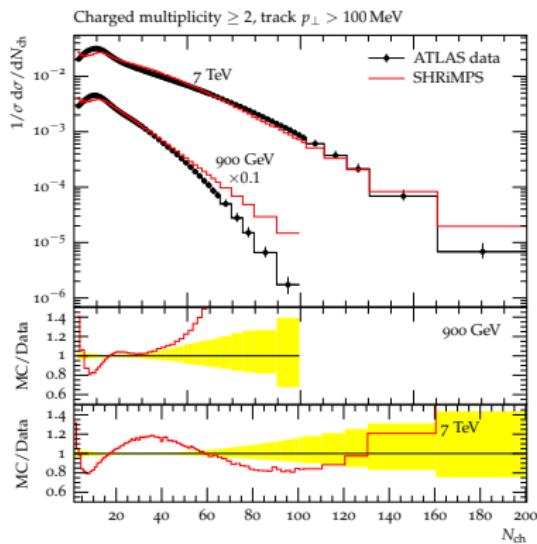
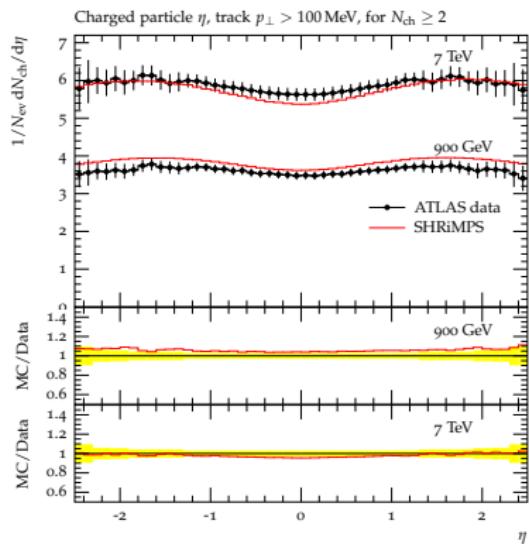
$$\Delta = 0.25, \lambda = 0.35, \beta_0^2 = 25 \text{ mb}$$

Differential Elastic Cross Section



Comparison to data

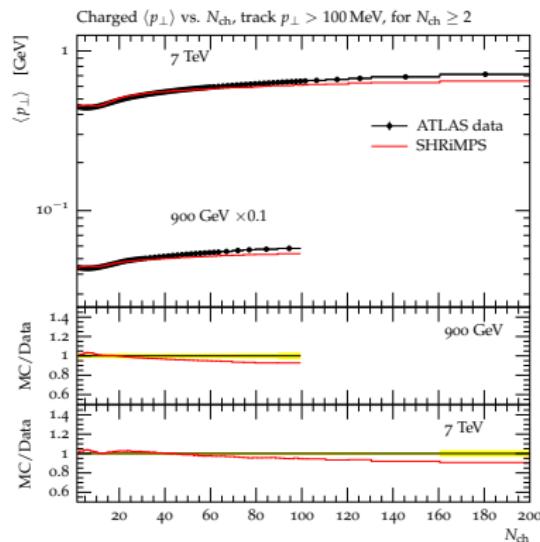
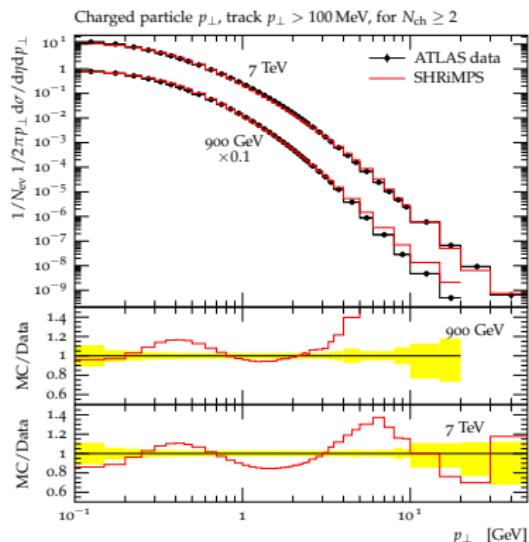
Minimum Bias @900 GeV & 7 TeV



ATLAS, New J. Phys. 13 (2011) 053033

Comparison to data

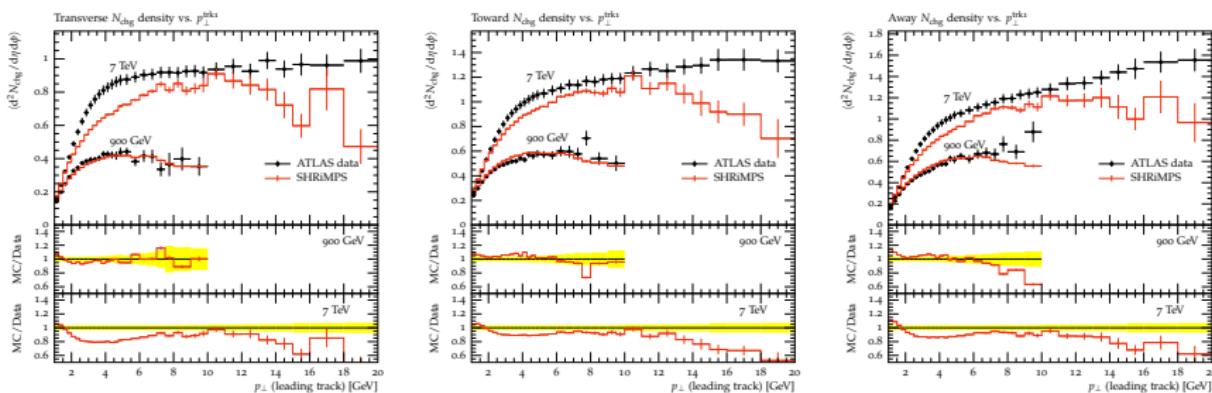
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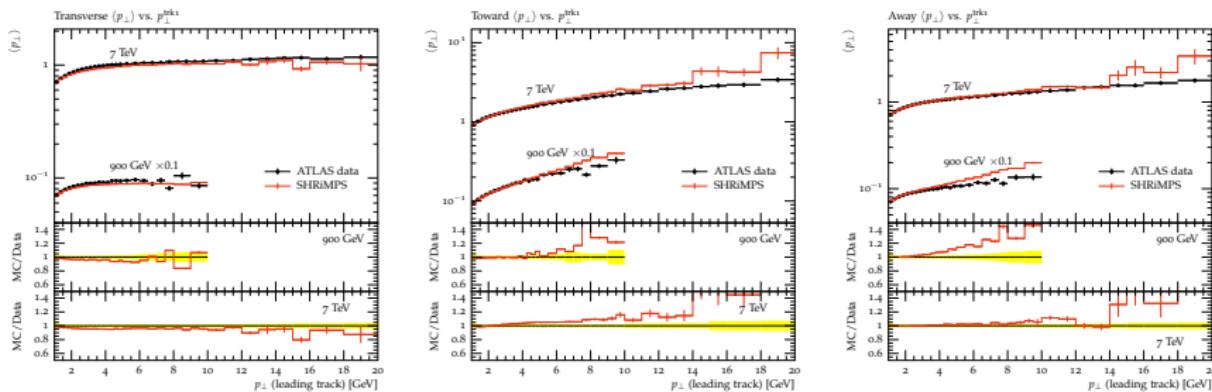
Comparison to data

Underlying Event @900 GeV & 7 TeV



ATLAS, Phys. Rev. D 83 (2011) 112001

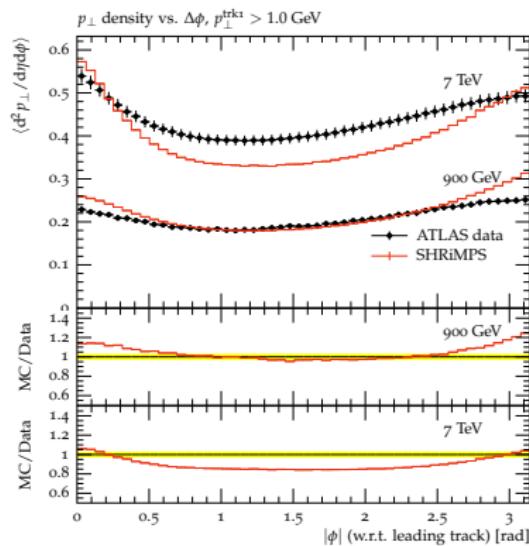
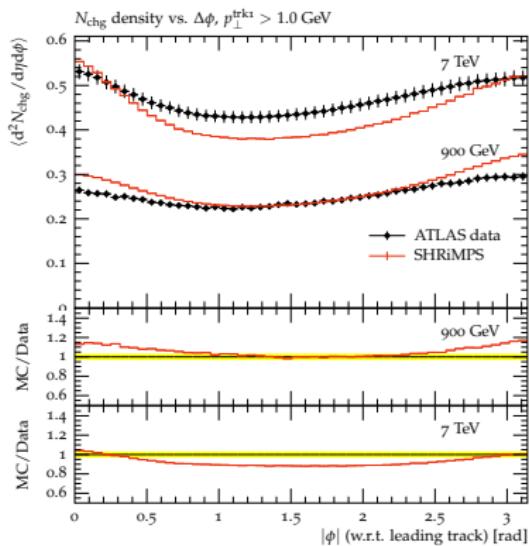
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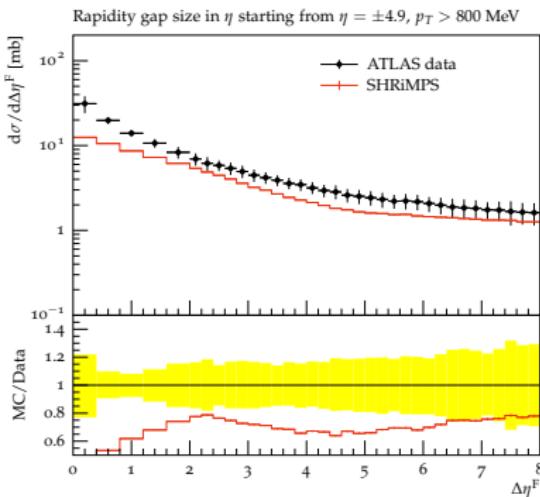
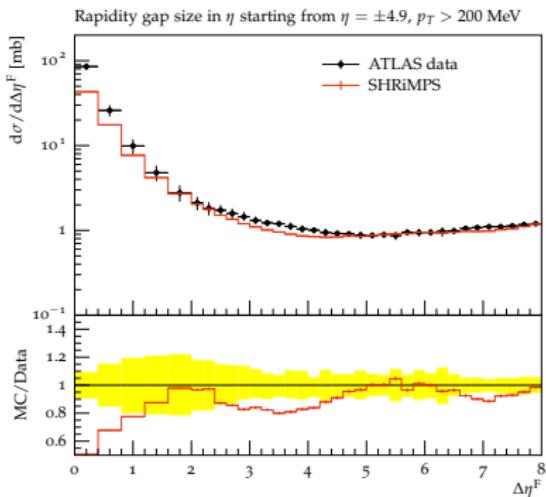
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Underlying Event @900 GeV & 7 TeV



ATLAS, Phys. Rev. D 83 (2011) 112001

Rapidity Gap Cross Section @7 TeV



ATLAS, Eur. Phys. J. C 72 (2012) 1926

What to remember

- ▶ SHERPA: multi-purpose event generator
- ▶ focus on precision in hard processes
- ▶ SHRiMPS: soft QCD model in SHERPA
- ▶ models **all** soft QCD processes in one framework
 - elastic, low mass diffraction, high mass diffraction, inelastic
- ▶ based on Khoze-Martin-Ryskin model for inclusive processes
- ▶ multi-channel eikonal model of elastic amplitude
 - exploit optical theorem to simulate scattering cross sections
- ▶ SHRiMPS: fully exclusive final states
- ▶ SHRiMPS available in SHERPA release, but under further development and untuned
 - stay tuned