Sherpa – future developments

Frank Krauss
(IPPP)

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www.ippp.dur.ac.uk

Outline

- Introduction
- Some formalism
  - Eikonals and multiple interactions
  - The KMR model in a nutshell
  - Inclusive observables
- Monte Carlo realization
  - Primary ladders, initialisation and further emissions
  - Rescattering
  - Example results

Motivation

- Why Minimum Bias? Why another model?
  - Most complete view of physics (at LHC and any other experiment)
  - Intimate connection to underlying event & multi-parton scattering
  - First day physics at LHC, with impact on searches for the Higgs boson, especially when relying on occurrence on rapidity gaps
  - Intellectual challenge: Up to now no first-principles model, connecting total xsec, elastic scattering, diffraction and various distributions describing particle production on the same footing
  - Aim: Model embedding hard, semi-hard and soft physics on the same footing, interpolating between the different regions.
  - Also: Minimal number of parameters.

Eikonals and multiple interactions
in (simple) Monte Carlo models

S-Channel Unitarity & Cross Sections

- Optical theorem relates total cross section with elastic forward scattering amplitude $\mathcal{A}$(s,t)

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

- Rewrite amplitude in impact parameter space

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

- Write cross sections as

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

Parametrisations of cross sections

- “Good old strong scattering theory”: Sum over exchanges of Regge poles
- Assuming leading pole (pomeron) yields

$$\sigma_{\rm tot} = \sigma_0 \left(\frac{s}{s_0}\right)^{\alpha_P - 1}$$

- Various fits for parameters σ_0, s_0, and pomeron intercept $\alpha_P = 1 + \Delta$
  - Donnachie-Landshoff & CDF fit find $\Delta = 0.0808$
- Can go more elaborate: two-pomeron fits, etc..
- Predictions for total cross sections from pomeron fits:

$$\sigma_{\rm tot}(14{\rm TeV}) = \begin{cases} 101.5\,{\rm mb} & ({\rm DL}) \\ 114.0{\rm mb} & ({\rm CDF}) \\ 164.4{\rm mb} & (\text{two-pom}) \end{cases}$$

Eikonals

- Common problem to all Regge/pomeron fits: Violation of unitarity
- Solution: use parametrisation for the eikonal rather than for the cross section
- In other words: Rewrite forward amplitude through eikonal Ω as

$$a(s,\, \vec{b}_\perp) = \frac{e^{-\Omega(s,\vec{b}_\perp)} - 1}{2i}$$

- N.B.: For Reggeon parametrisation, have $\Omega = (s/s_0)^{\alpha-1}$
- Cross sections then read

$$\begin{aligned}
\sigma_{\rm tot}(s) &= 2\int \mathrm{d}^2 b_\perp [1 - e^{-\Omega(s,\vec{b}_\perp)}] \\
\sigma_{\rm el}(s) &= \int \mathrm{d}^2 b_\perp [1 - e^{-\Omega(s,\vec{b}_\perp)}]^2 \\
\sigma_{\rm inel}(s) &= \int \mathrm{d}^2 b_\perp [1 - e^{-2\Omega(s,\vec{b}_\perp)}]
\end{aligned}$$

Simple multiple-interaction models

- For example Herwig++ (Pythia can be reduced to similar ideas)
- Write eikonal as sum of a perturbative and a non-perturbative part (in Pythia use a modification of the perturbative bit by adding a regulator)

$$\Omega(s, \vec{b}_\perp) = \Omega_S(s, \vec{b}_\perp) + \Omega_{\rm QCD}(s, \vec{b}_\perp)$$

- Use QCD 2→2 matrix elements + PDFs in collinear factorisation, assume complete factorisation of kinematics and impact parameter space,

$$\Omega_{\rm QCD}(s, \vec{b}_\perp) = \frac{1}{2} A(\vec{b}_\perp)\, \sigma_{2\to 2}(s)$$

- Model form factors A(b), add parton showers & hadronisation
- In Herwig++: Assume a cut-off t_0 such that QCD xsec < total xsec and fill with soft eikonal = constant.
- N.B.: Can naively generate diffraction by colour reshuffling.

MC-Algorithm in a nutshell

- Fix impact parameter from inelastic scattering
- Assume independent scatters: generate h hard and s soft scatters, both h and s distributed according to Poissonians

$$P_{h,s} = \frac{[2\Omega_{\mathrm{QCD}}(\vec{b}_\perp)]^h}{h!} \frac{[2\Omega_S(\vec{b}_\perp)]^s}{s!} \exp[-2\Omega(\vec{b}_\perp)]$$

- Select flavours and kinematics of hard scatters according to parton-level cross sections, shower and hadronise
- For soft part, assume gluon-gluon scattering, distribute transverse momenta according to Gaussian, do not shower.
- Recent addition: Diffraction, see Herwig++ talk for details (hopefully)

Multichannel eikonal models
&
the Khoze-Martin-Ryskin model

Multichannel eikonals

- Problem with simple single-channel eikonals:
  cannot describe low-mass single or double diffraction.
- Reason: This process can be understood as ("quasi-") elastic excitation of the nucleon into, say, a N(1440).
- Such processes are due to the internal structure of the hadrons.
- For description: go to high-energy limit, Fock states of nucleons are "frozen", and diffraction = separate elastic scattering of such states, destroying the coherence of the colliding hadrons.
- Naively: Two-channel eikonals, realised by two Good-Walker states

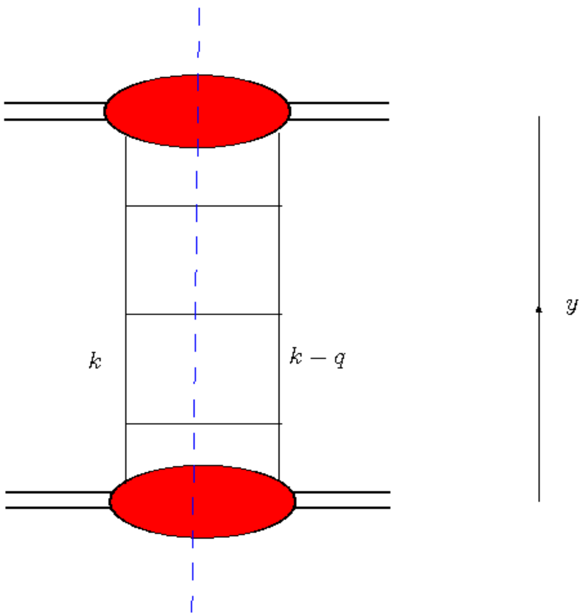
$$|p\rangle = \sum_i a_i|\phi_i\rangle, \text{ where } \langle\phi_i|\phi_k\rangle = \delta_{ik} \text{ and } \sum_i |a_i|^2 = 1$$

- And wave functions of p, N(1440) are given by

$$|p,\ N^*\rangle = \frac{1}{\sqrt{2}}\left[|\phi_1\rangle \pm |\phi_2\rangle\right]$$

Towards a partonic picture

- Basic idea: Regge physics rules
  - define amplitudes/eikonals through pomeron exchange
  - must sum over all possible exchanges and topologies – hard to do in a MC, only approximate solutions will be possible
  - Simplified picture: start from a simple ladder
  - Treat as amplitude for the production of N particles, homogeneously distributed in rapidity in [-Y/s, Y/s], where $Y = \log s/m_p^s$
  - $\sigma_{2\to N} = |A_{2\to N}|^2$
  - Will connect to pomeron on next slide



Ladders and pomerons

- The amplitude (scalar particles) then reads

$$A(Y) = \sum_n \frac{1}{n!} \prod_{i=1}^{N} \int_{-Y/2}^{Y/2} \mathrm{d}y_i \alpha = \sum_n \frac{(\alpha Y)^n}{n!} = e^{\alpha Y} = s^{\alpha}$$

- where the kernel is given by

$$\alpha(q_\perp^2) = \frac{g^2}{16\pi^2} \int \frac{\mathrm{d}^2 k_\perp}{[k_\perp^2 - m^2][(k_\perp - q_\perp)^2 - m^2]}$$

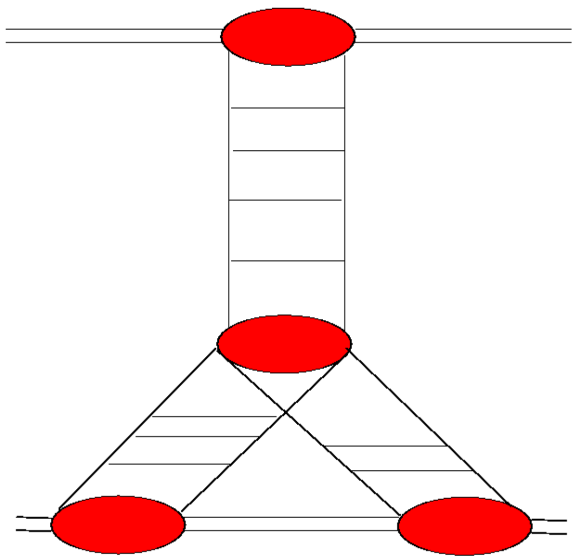
- This allows to rewrite the amplitude as evolution equation,

$$\frac{\mathrm{d}A(y)}{\mathrm{d}y} = \alpha A(y)$$

- write, as before, $\alpha_P = 1 + \Delta$, with the perturbative pomeron intercept $\Delta = 0.3$
- Note: also understood as evolution equation for parton densities f(y).

Rescattering

- In high-density, strong-coupling regime rescattering becomes important
- In Regge language this is driven by the triple-pomeron vertex.
- Visible physical effect: high-mass dissociation
- Also: softening of total cross section (rescattering as "fusion" of two partons)
- Note: also more complicated cuts than example
- Can resum "fan" diagrams (Schwimmer model):



$$\frac{\mathrm{d}f(y)}{\mathrm{d}y} = \Delta f(y) - g_{3P} f(y)$$

- But total cross section becomes too low, must resum all fans

$$\frac{\mathrm{d}f(y)}{\mathrm{d}y} = \exp[-\lambda f(y)] \Delta f(y)$$

Khoze-Martin-Ryskin model

- Eikonal as convolution of two" parton densities"

$$\Omega(\vec{b}_\perp) = \frac{1}{2\beta_0^2}\int \mathrm{d}^2 b_\perp^{(1)} \mathrm{d}^2 b_\perp^{(2)} \delta^2(\vec{b}_\perp - \vec{b}_\perp^{(1)} - \vec{b}_\perp^{(2)}) \cdot \Omega_{i(k)}(\vec{b}_\perp^{(1)}, \vec{b}_\perp^{(2)}, y) \Omega_{(i)k}(\vec{b}_\perp^{(1)}, \vec{b}_\perp^{(2)}, y)$$

- Two channel eikonal, with two evolution equations

$$\frac{\mathrm{d}\ln\Omega_{i(k)}(y)}{\mathrm{d}y} = +\exp\left\{-\frac{\lambda}{2}\left[\Omega_{i(k)}(y) + \Omega_{(i)k}(y)\right]\right\}\Delta$$

$$\frac{\mathrm{d}\ln\Omega_{(i)k}(y)}{\mathrm{d}y} = -\exp\left\{-\frac{\lambda}{2}\left[\Omega_{i(k)}(y) + \Omega_{(i)k}(y)\right]\right\}\Delta$$

Khoze-Martin-Ryskin model (cont'd)

- Boundary conditions involve form factors

$$\Omega_{i(k)}(\vec{b}_\perp^{(1)}, \vec{b}_\perp^{(2)}, -Y/2) = F_i(b_\perp(1)^2)$$

$$\Omega_{(i)k}(\vec{b}_\perp^{(1)}, \vec{b}_\perp^{(2)}, +Y/2) = F_k(b_\perp(2)^2)$$

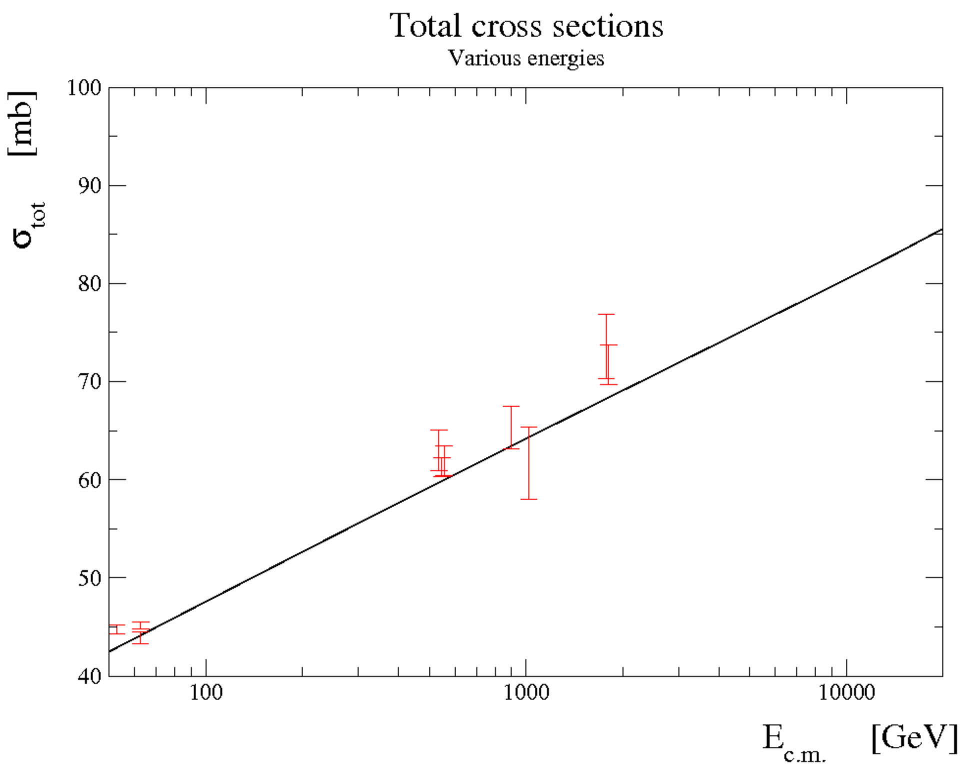
- Form factor as Fourier transforms of (dipole form with extra dampening)

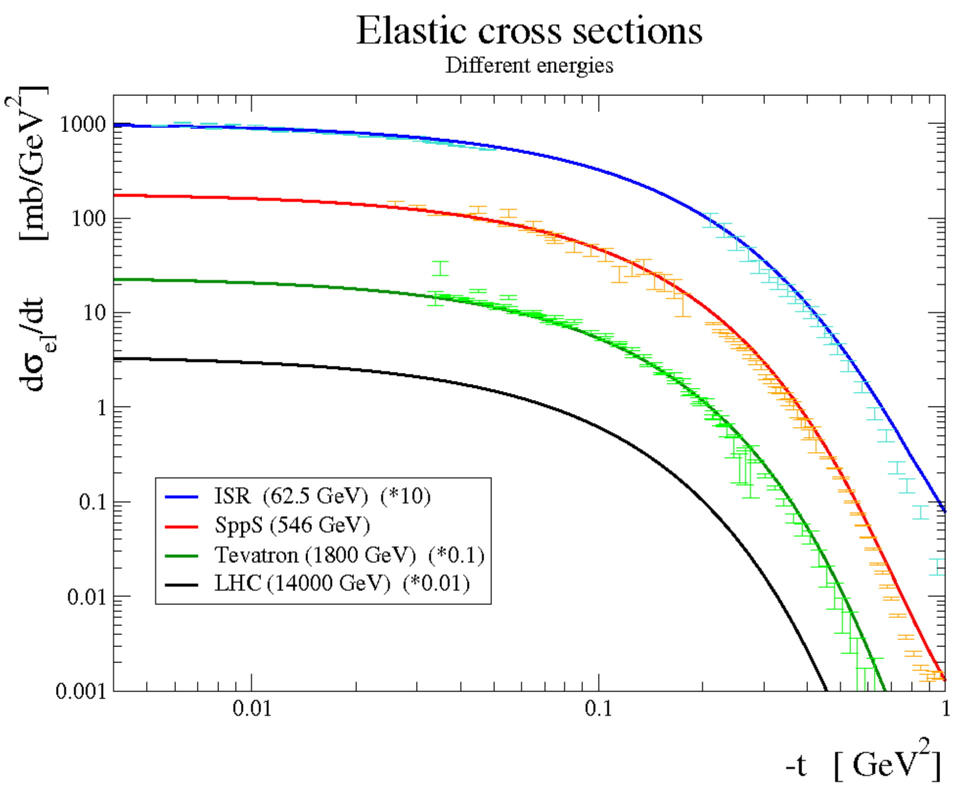
$$F_{1,2}(q_\perp) = \beta_0^2(1 \pm \kappa)\frac{\exp\left[-\frac{(1\pm\kappa)\xi q_\perp^2}{\Lambda^2}\right]}{\left[1 + \frac{(1\pm\kappa)q_\perp^2}{\Lambda^2}\right]^2}$$

- Parameters: $\Delta = 0.3$, $\lambda = 0.25$, $\beta_0^2 = 30$ mb, $\kappa = 0.5$, $\Lambda^2 = 1.5\ \mathrm{GeV}^2$, $\xi = 0.225$

Inclusive results

- Total and elastic cross sections vs. data at various energies





MC model for Minimum Bias

based on the KMR model

(will be part of Sherpa)

Selecting the mode

- Select the mode according to cross sections:

$$\sigma^{pp}_{\text{tot}} = 2\int \mathrm{d}^2 b_\perp \sum_{i,k=1}^{S} \left\{ |a_i|^2 |a_k|^2 \left[1 - e^{-\Omega_{ik}(b_\perp)}\right] \right\}$$

$$\sigma^{pp}_{\text{inel}} = \int \mathrm{d}^2 b_\perp \sum_{i,k=1}^{S} \left\{ |a_i|^2 |a_k|^2 \left[1 - e^{-2\Omega_{ik}(b_\perp)}\right] \right\}$$

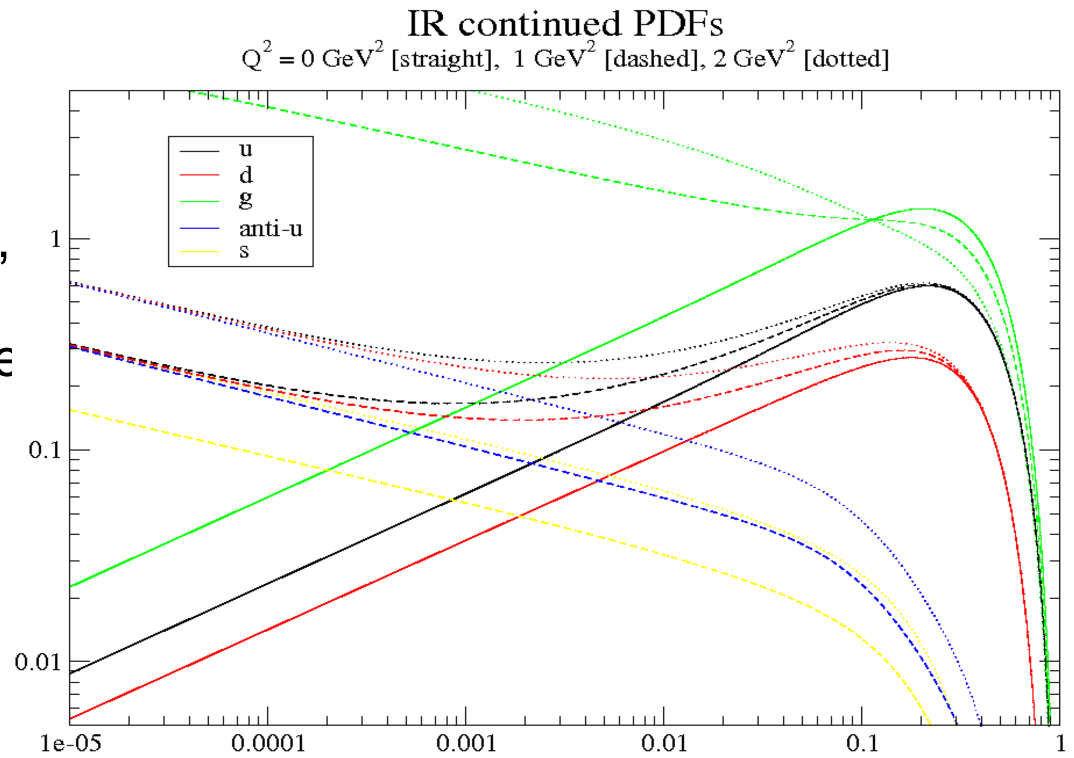
$$\sigma^{pp}_{\text{el}} = \int \mathrm{d}^2 b_\perp \left\{ \sum_{i,k=1}^{S} \left[|a_i|^2 |a_k|^2 \left(1 - e^{-\Omega_{ik}(b_\perp)}\right)\right] \right\}^2$$

- Formula for single/double diffractive modes (low mass) pretty similar, will yield N(1440) in the final state(s) + subsequent decays.
- If elastic is chosen, select momentum transfer according to FT
- If inelastic is chosen, select Good-Walker states i and k and impact parameter according to contributions in integrand.

Inelastic scattering in the model

Initialising the (primary) ladders

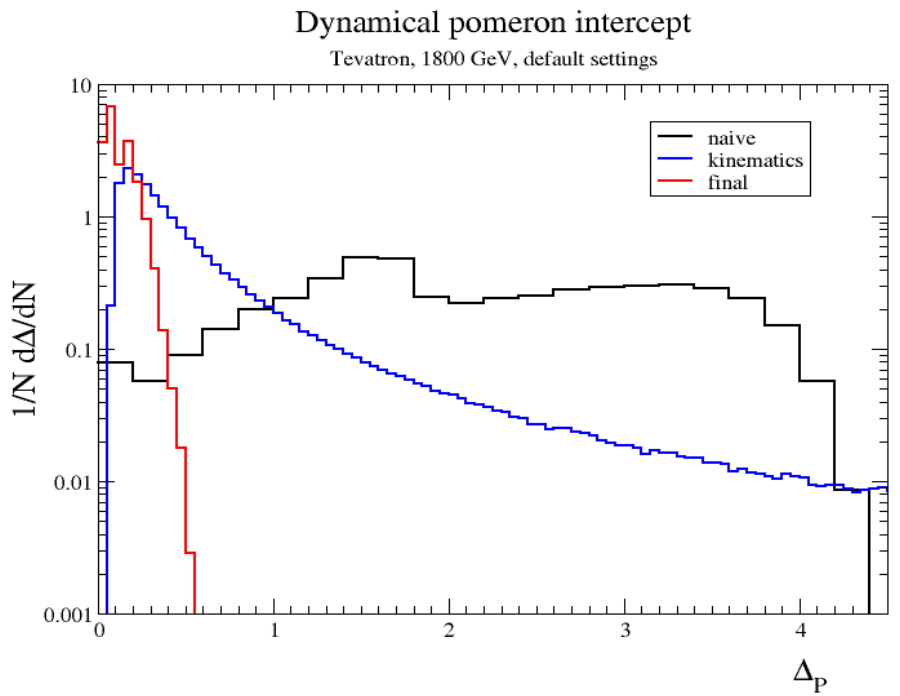
- Select flavours and (collinear) momenta according to IR-continued PDFs and Regge-motivated cross-section $(s/s_0)^{1+\eta}$, where
  - s_0 is fixed to reproduce inelastic cross section in this channel ik, $s>s_0$
  - Exponent $\eta = \Delta \exp[-\lambda/2(\Omega_{ik}(b,0)+\Omega_{ki}(b,0))]$ = "effective intercept"
- IR-continued PDFs:
  - assume f(x,0) = valence only
  - keep norm of valence quarks, renormalise "valence" gluons to satisfy momentum sum rule
  - switch off sea with Q
- Weight = Regge expression



Filling the ladders

- Generate emissions in between, according to “Sudakov form factor”

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



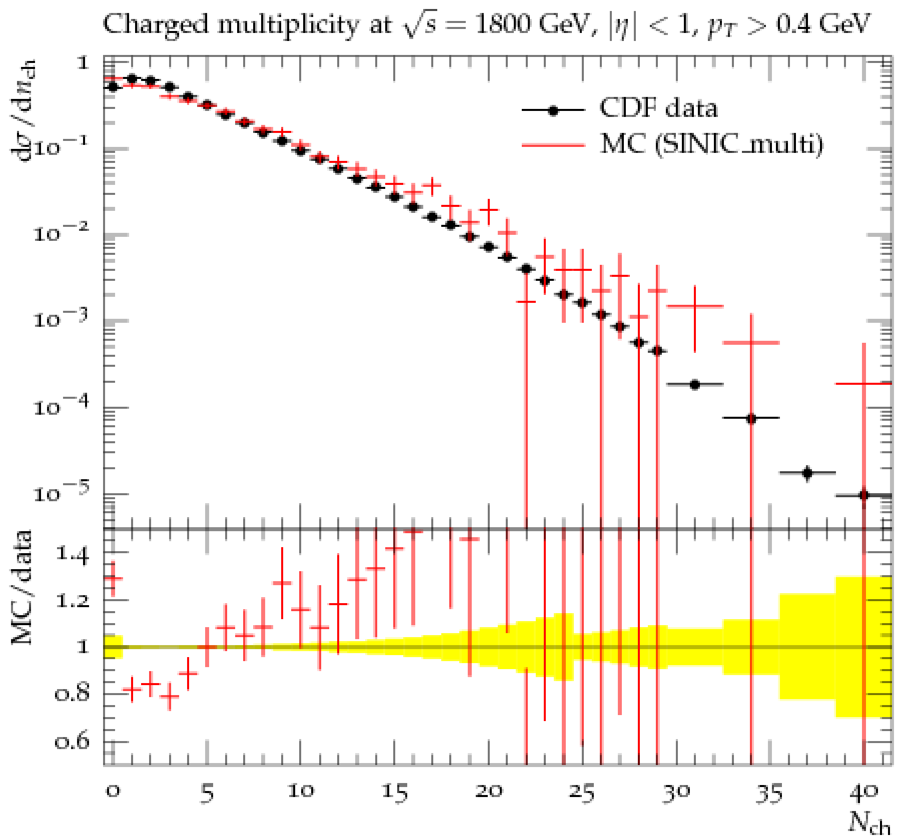
- dynamical pomeron intercept
- Reweight ladder with ME for hardest emission

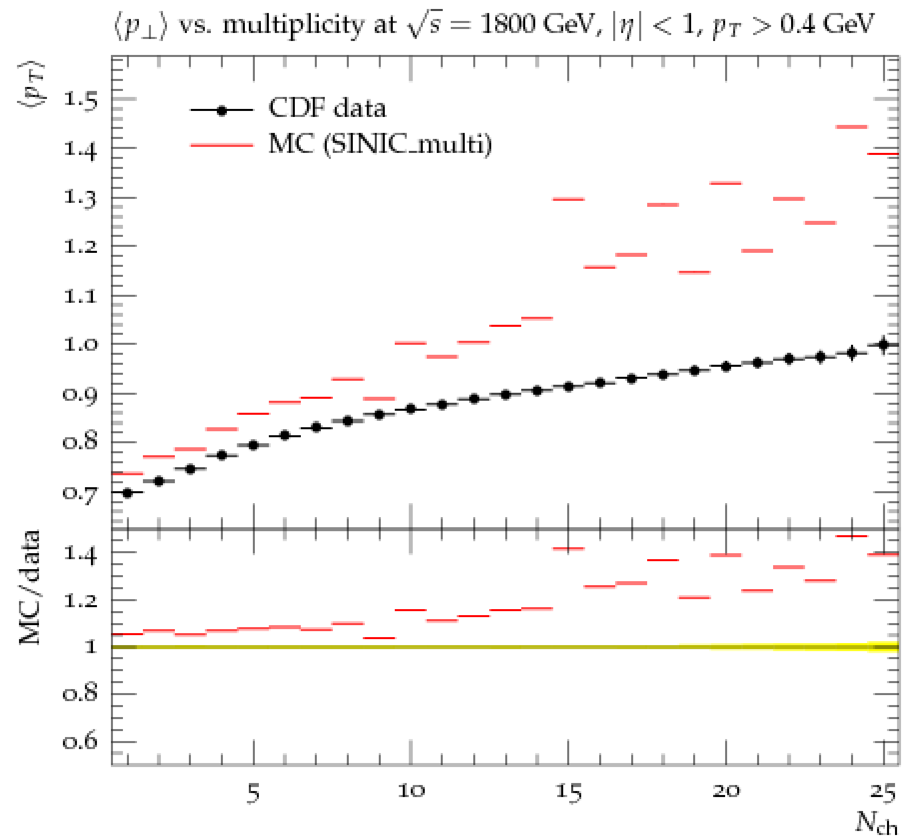
Rescattering & colours

- Rescattering:
  - After production of ladder, invoke parton shower
  - Rescatter probability for each pair [y,Y]: $1-\exp[-(\Omega_{ik}(Y)-\Omega_{ik}(y)/\Omega_{ik}(Y))]$
  - Continue rescattering until all options exhausted
  - Fill and reweight each rescatter ladder as before
- Colours:
  - Before filling the ladder, decide whether singlet exchange
  - Prob for singlet in [y,Y]: $\{1-\exp[-(\Omega_{ik}(Y)-\Omega_{ik}(y)/(2\ \Omega_{ik}(Y))]\}^2$
  - After each emission check in both intervals, whether singlet
  - Try to minimize colours and colour connections in beam remnants (essentially singlets consisting of one quark/diquark + gluons)

Snapshot: Example results

(all Tevatron, Run I, untuned)





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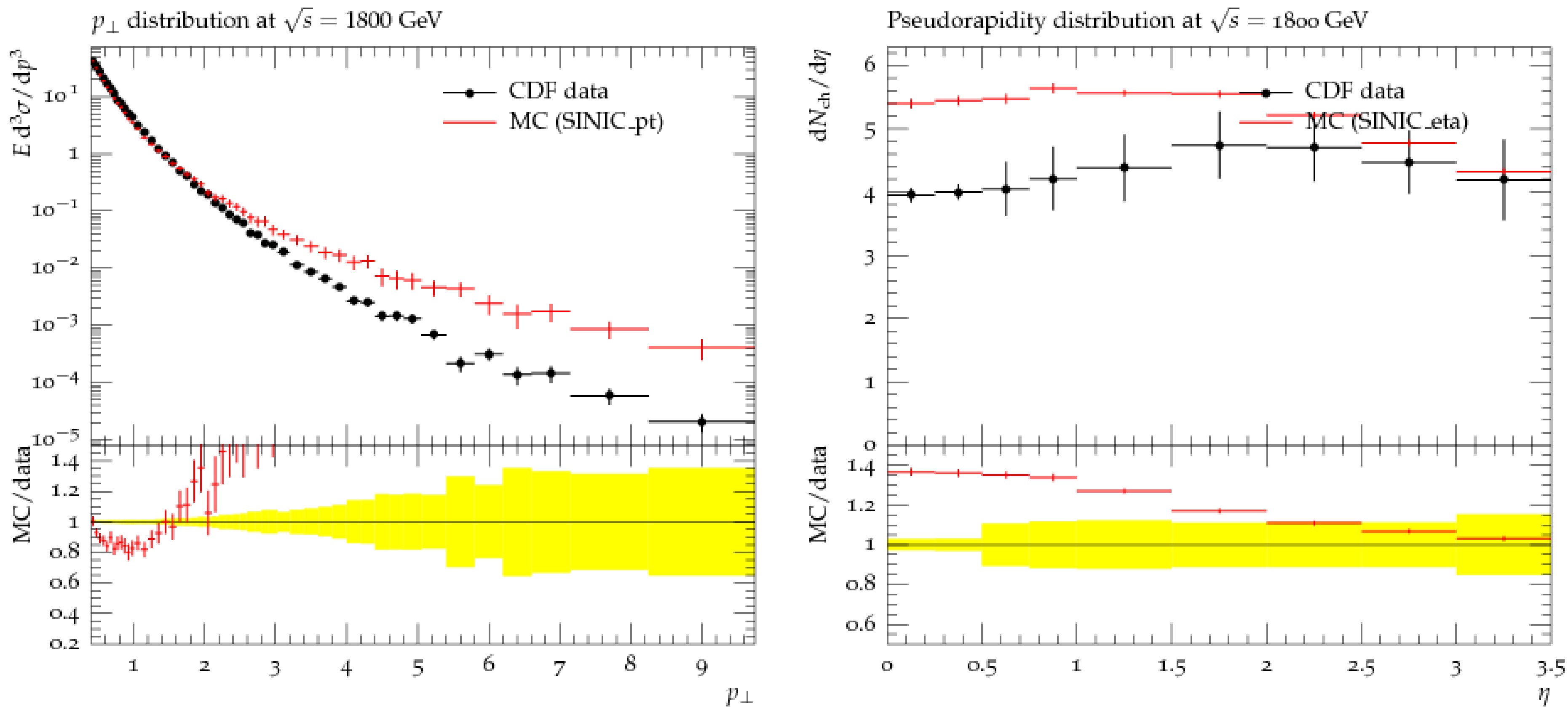

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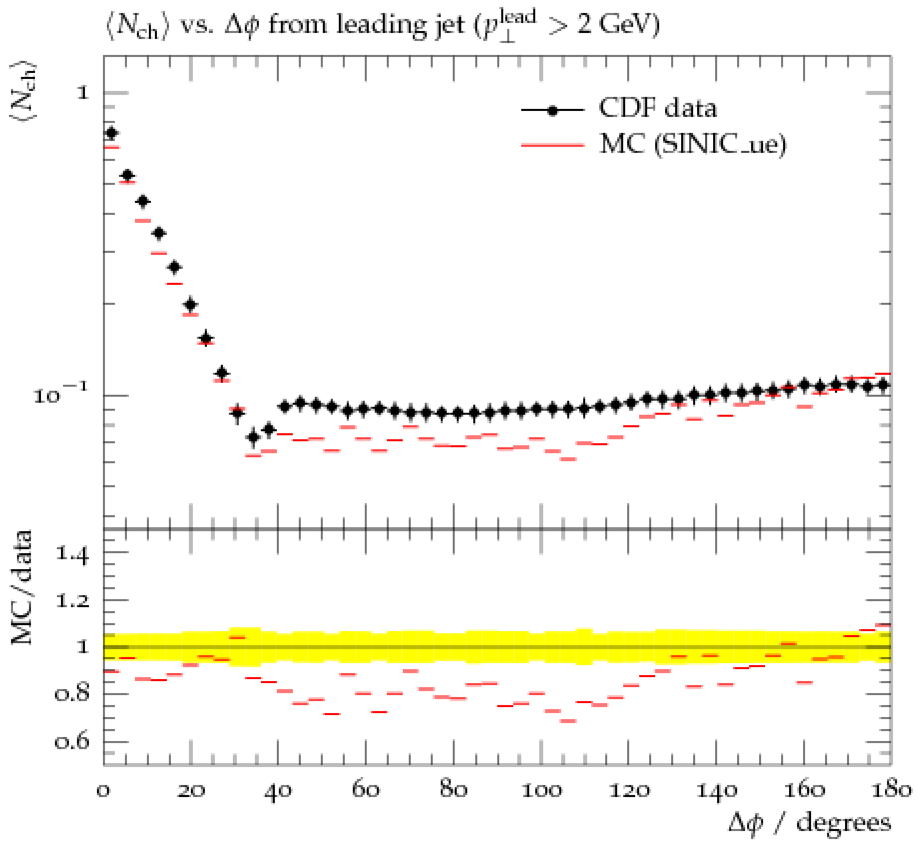

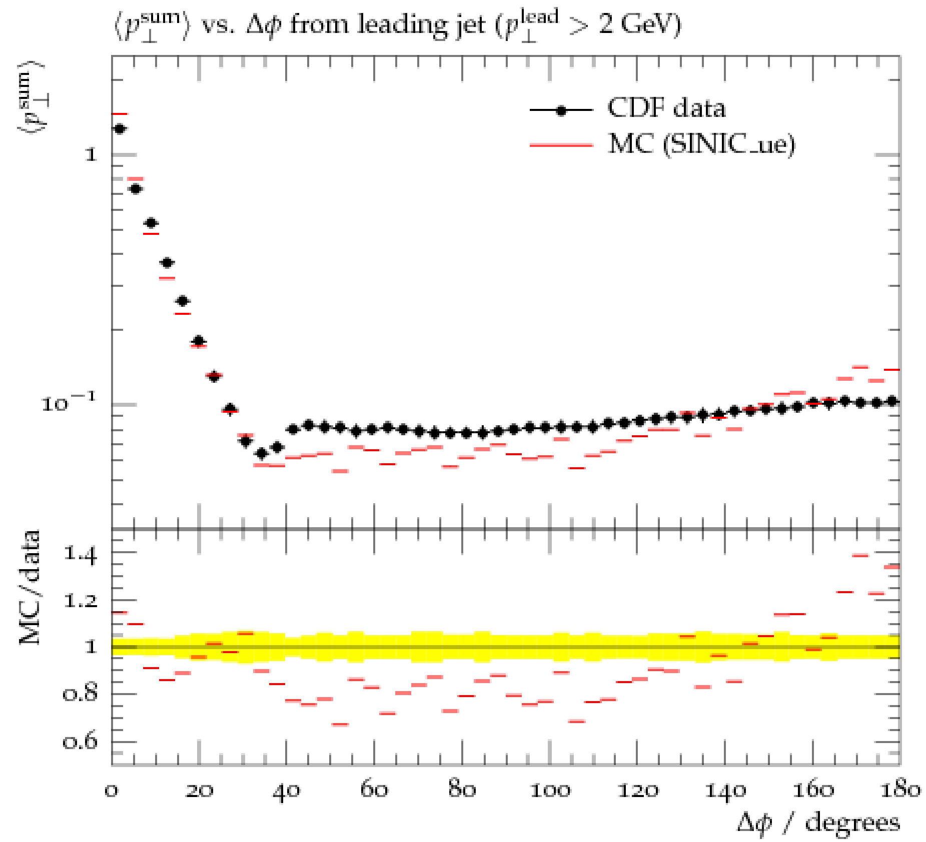

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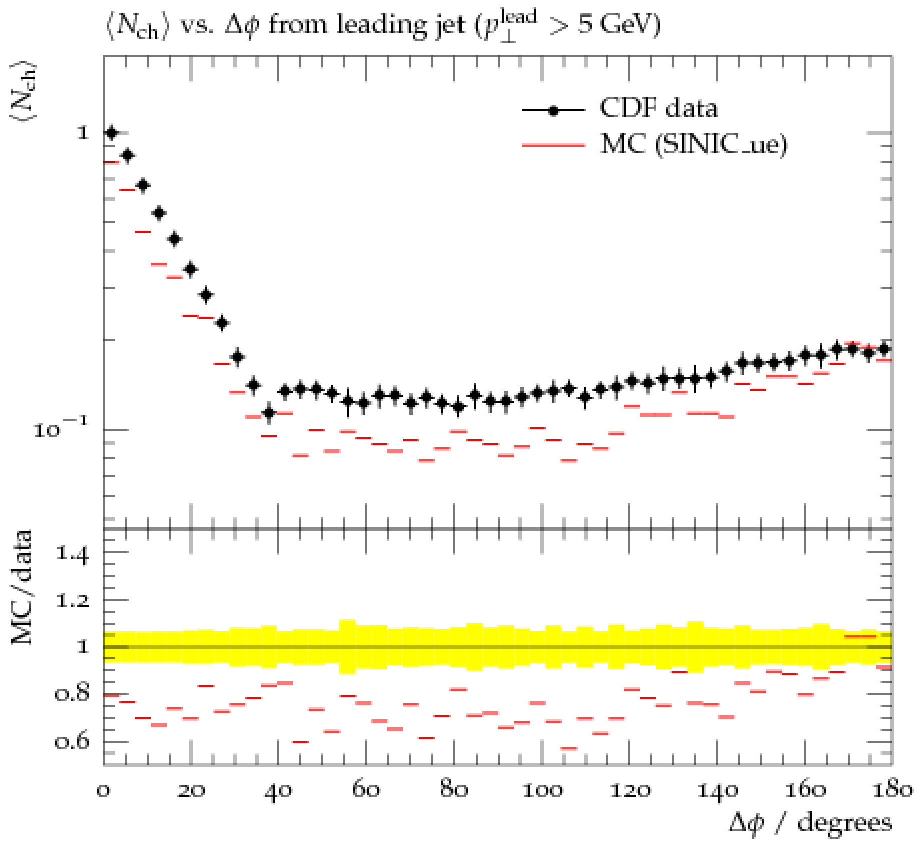

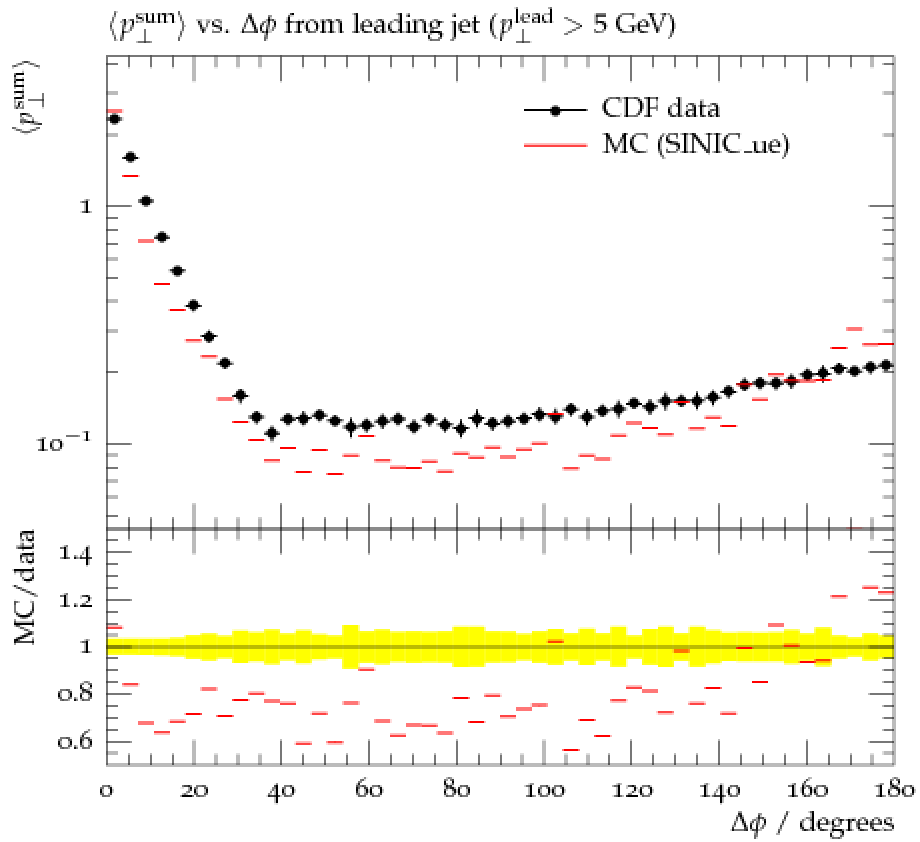

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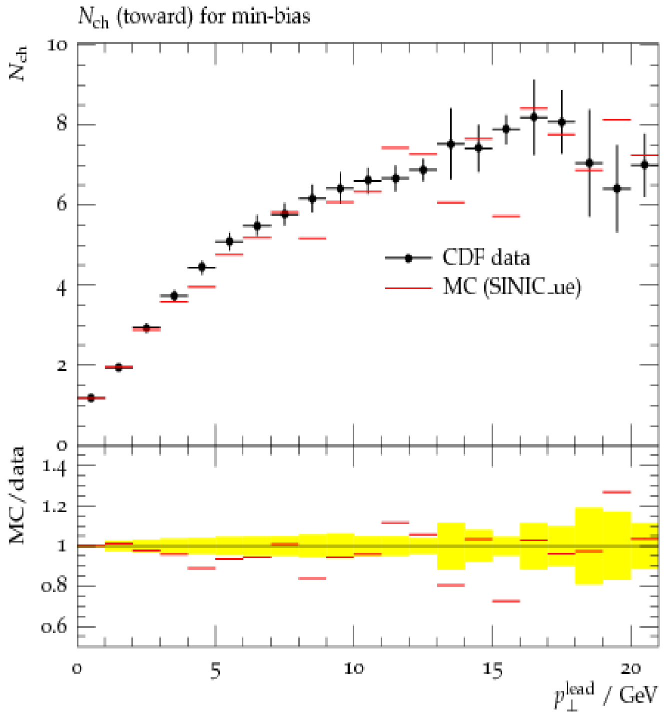

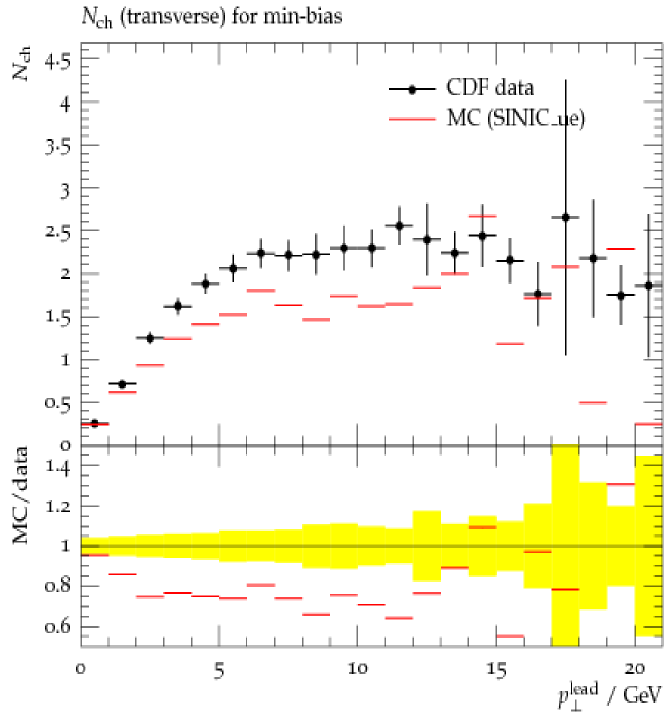

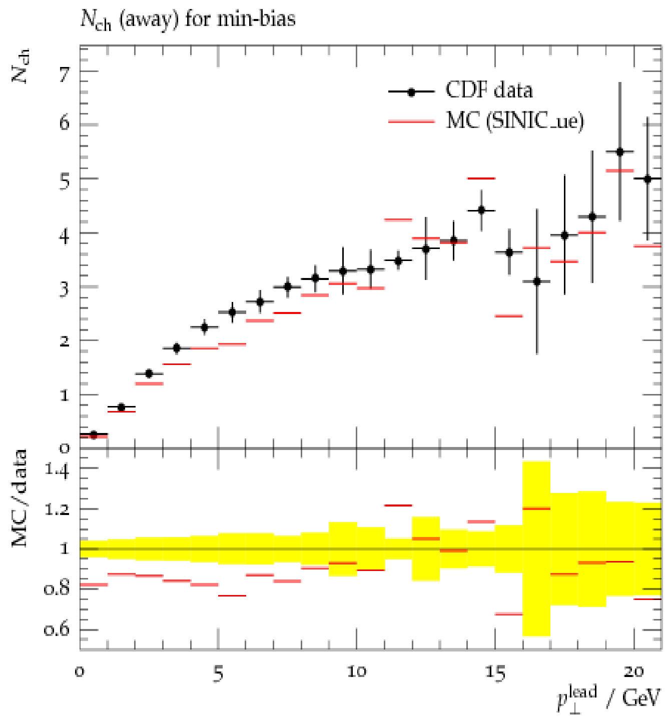

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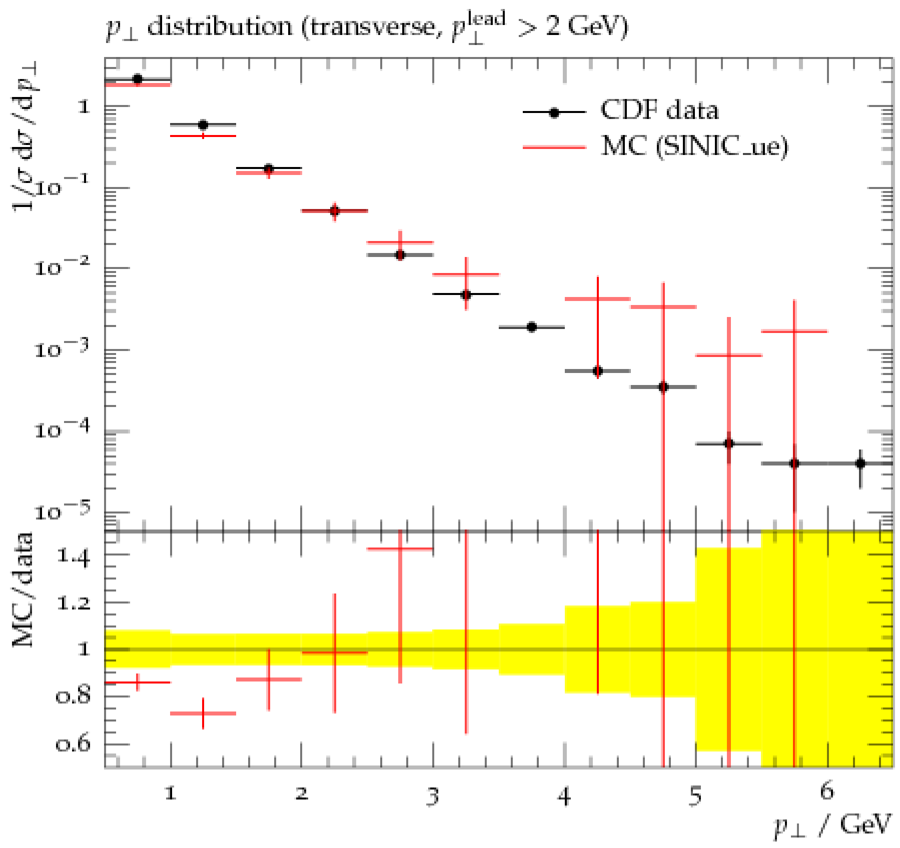

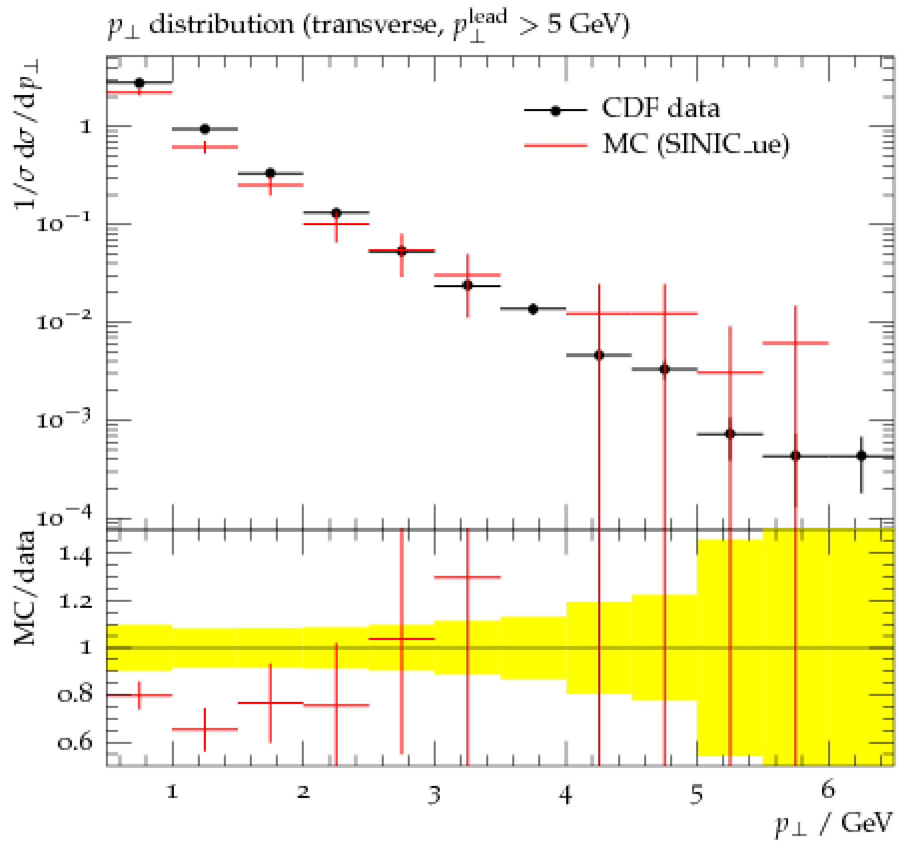

Outlook

- Interesting model with many attractive features – only very few parameters
  - Essentially FF's, IR regulator, pomeron intercept, triple pomeron vertex
- Finalise the model/solve remaining issues (especially pt shape of particles)
  - May have to produce more involved colour treatment, little changes there have huge effects
  - Must tune the model and validate at varying energies
- Model will become Sherpa's default UE/MinBias model
  - Up to now, there's a Sjostrand-van der Zijl-inspired model, essentially a cheap version of Pythia's UE model