MPI vs. small-x vs. Matching

Leif Lönnblad

Department of Astronomy
and Theoretical Physics
Lund University

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Outline

- Introduction
- MPI vs. small-x (DIPSY)
- Small-x vs. matching (HEJ)
- Matching vs. MPI (UMEPS, UNLOPS)

One-slide bottom line

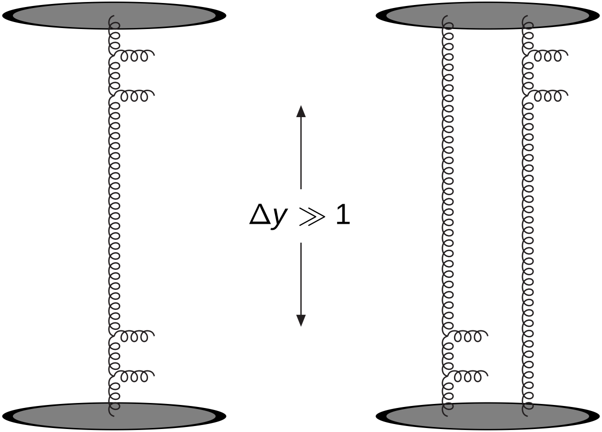
PYTHIA8

Although the PYTHIA8 MPI model describes almost all data on MB and UE, it is not quite satisfactory.

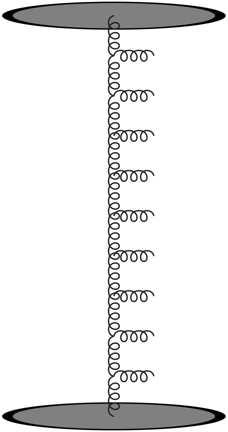
- Using DGLAP very low scales and small x
- Needs phenomenological assumptions
- Total cross section put in by hand
- Diffraction put in by hand
- At best motivated by small-x theory

(HERWIG++ and (old) SHERPA MPI are similar)

Can we tell PYTHIA MPI and true small-x evolution apart?



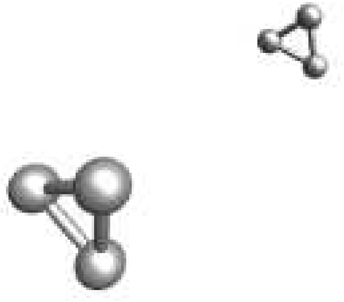
How many (mini-) jets are there



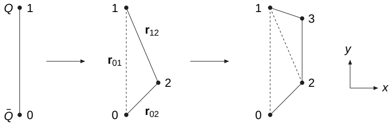
- Huge phase space for jet production
- In a typical BFKL-like calculations there are $\sim$ 1 gluon per unit rapidity
- ALPGEN can now do up to 9 jets
- Do we need small-x resummation?
- How do we combine high-multiplicity ME with MPI

DIPSY

(with C. Flensburg, G. Gustafson)



The virtual cascade



- Muellers formulation of BFKL
- $\frac{dP}{dy} = \frac{\bar{\alpha}}{2\pi} d^2 r_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2}$
- Dipoles in impact parameter space, evolved in rapidity
- Builds up virtual Fock-states of the proton

Non-leading effects

- Running α_s
- Introduce $k_\perp \sim 1/r$ to get energy–momentum conservation.
  (Ordering in p_+ and p_- gives a dynamic cutoff)
- Non-perturbative regularization with small gluon mass (confinement effects)
- Add dipole *Swing* to get colour-suppressed effects (saturation)

The interaction

- Dipole–dipole interaction:
  $F = \sum_{ij} f_{ij} \qquad f_{(12)(34)} \propto \alpha_s^2 \ln^2 \left(\frac{r_{13} r_{24}}{r_{14} r_{23}} \right)$
- Without energy conservation we get exponential growth of small dipoles which do not interact
- Non-perturbative regularization with small gluon mass
- Rederive Mueller's expression above in transverse momentum space for final states.
- Unitarize to get saturation effects (pomeron loops):
  $F \to 1 - e^{-F}$
- Together with the saturation from the Swing we should have a Lorentz-invariant description.

Final-states

We have generated the gluonic Fock-states of the colliding protons.

Most of the gluons in this state are simply virtual fluctuations, which will not make it to the final state.

In the momentum picture all gluons in the proton with large p_+ will be off-shell with a negative p_- component.

Only those gluons which actually collides (or have children that collides) with gluons from the proton with large p_- will be able to come on-shell. All others must be reabsorbed.

But... energy–momentum conservation effects were taken into account assuming all gluons were real. When some are reabsorbed the kinematics will change.

Also some sequences of emissions in the evolution will correspond to local hard scatterings in some frame, and these will not get the proper $\sim 1/q_{\perp}^{4}$ behavior.

In the end we want to just have *primary* (a.k.a. backbone) gluons left, which are ordered in both q_{+} and q_{-} (and hence also in rapidity).

These are the ones we know gives the non-vanishing contributions to the cross section.

Final state radiation and hadronization

The primary gluons are now sent to ARIADNE for final-state showering.

This is a unitary procedure and only emissions which are *unordered* in q_+ and q_- w.r.t. the primary gluons are allowed.

Then we send everything to PYTHIA8 for hadronization.

Frame-independence

We have quite a lot of parameters:

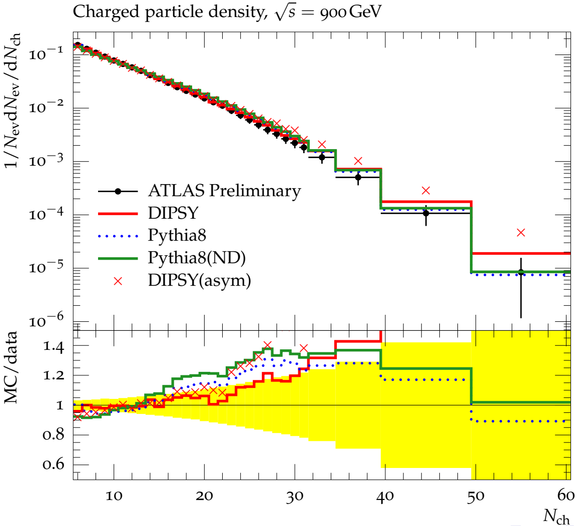
- R_{max}: Non-perturbative regularization
- R_p: Proton size ($\approx R_{\text{max}}$)
- w_p: Fluctuations in the initial proton size (small)
- Λ_{QCD}: in the running α_s
- λ_r: Swing parameter (saturated)

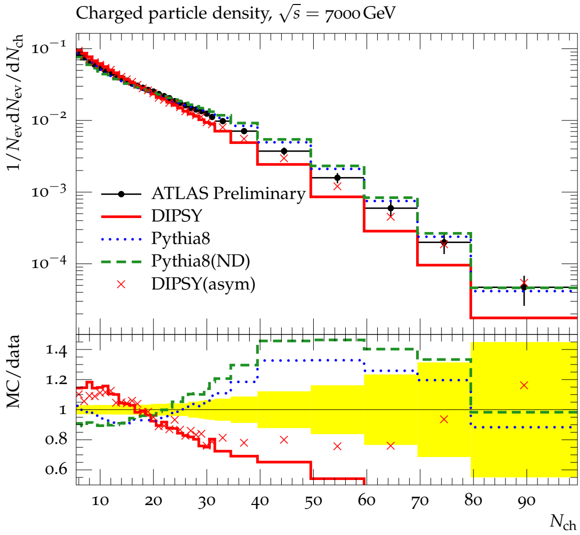
Most of these can be fit to the total and elastic cross sections.

But there are also a lot of choices made for which no guidance can be found in perturbative QCD, especially for the selection of the real gluons.

Most of these can be fixed by requiring frame-independence.

Minimum-Bias Observables





More plots on `http://home.thep.lu.se/~leif/DIPSY.html`

We now have a single model for inclusive and semi-exclusive and fully exclusive observables, which includes explicit modeling of fluctuations in the initial state

- pp and ep-DIS total cross section
- pp and ep-DIS (quasi) elastic cross section including *t*-dependence
- pp and ep-DIS diffraction
- Double parton scattering at the LHC — interesting predictions
  (σ_{eff} depends more on jet $p_{\perp}$ than on x and rapidity, arXiv:1103.4320)
- Fully exclusive final states (arxiv:1103.4321)
  (also in diffraction, arXiv:1210.2407)
- Also for *pA* and *AA* (but slow)

Outlook

DIPSY is working, but there are things to do:

- NLL effects (quarks, non-singular terms)
- ME-corrections for high-$p_\perp$
- Improved valence structure (fuzzy valence)
- Final-state swing (re-tune)
- Other final state effects in HI
  (quenching? hydro? rescatterings?)

manpower is a problem. . .

Multi-jet ME/PS matching

Even with improvements, can we get a small-x based generator with enough precision to beat PYTHIA?

Maybe it is better to try to improve PYTHIA . . .

Large logarithms comes from integration over real emissions.

Small x means large phase space, means many jets.

Maybe matching to multi-jet ME generators is the way forward.

Standard CKKL-like matching schemes adds resummation to multi-jet ME's, but not proper small-x resummation.

HEJ - High Energy Jets

(J. Andersen, J. Smillie, et al.)

HEJ is basically a Matrix Element generator (à la MadEvent) with a perturbative approximation of jet production to any order of α_s.

The predictions are exact in the limit of large invariant mass between all partons (BFKL).

Is matched to MadGraph for low parton multiplicities.

The typical process: $f_1 f_2 \to f_1 g \cdots g f_2$

$$\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2} \sum_{n=2}^{\infty} \prod_{i=1}^{n} \left(\int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty} \frac{\mathrm{d}^2 \mathbf{p}_{i\perp}}{(2\pi)^3} \int \frac{\mathrm{d}y_i}{2} \right) \frac{\overline{|\mathcal{M}_{\text{HEJ}}^{f_1 f_2 \to f_1 g \cdots g f_2}(\{p_i\})|}^2}{\hat{s}^2}$$
$$\times \sum_m \mathcal{O}_{mj}^e(\{p_i\})\, w_{m-\text{jet}}$$
$$\times \quad x_a f_{A,f_1}(x_a, Q_a)\, x_2 f_{B,f_2}(x_b, Q_b)\, (2\pi)^4\, \delta^2\!\left(\sum_{i=1}^{n} \mathbf{p}_{i\perp} \right) \; \mathcal{O}_{2j}(\{p_i\})$$

Resum to all-orders the leading logarithmic virtual corrections to the *t*-channel poles.

Matching to a collinear shower

As with all matrix element generators, we want to add parton showers and hadronization to get fully simulated final states. And we must be careful not to double count!

How do we do that here, where HEJ already resums some towers of logarithms?

- Parton Shower: soft and collinear resummation
- HEJ: soft resummation (better than the PS).

We will simply send the partonic state generated by HEJ to ARIADNE and start the shower.

For each emission, we send back the new state to HEJ and ask, *Hej! How would you have done this emission?*

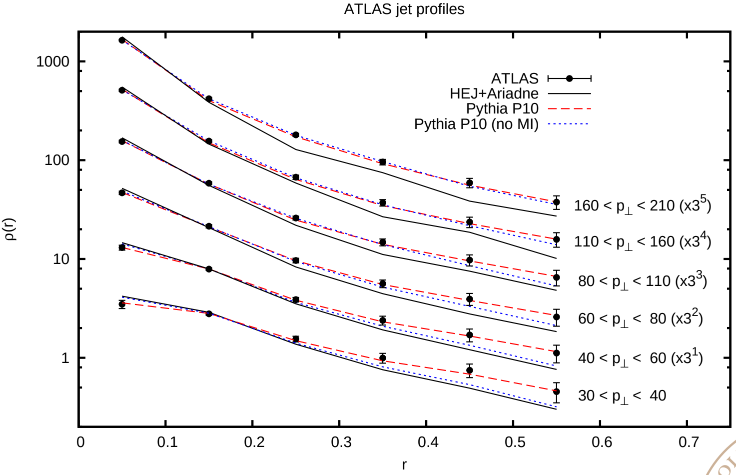
The dipole splitting function in ARIADNE is an approximation to the ratio of matrix elements

$$D^{\mathrm{Ari}}(p_\perp^2, y) \approx \frac{z}{16\pi^2}\frac{|\mathcal{M}_{n+1}|^2}{|\mathcal{M}_n|^2}.$$

From this we simply subtract the corresponding HEJ calculation

$$D^{\mathrm{HEJ}}(p_\perp^2, y) = \frac{z}{16\pi^2}\frac{\left|\mathcal{M}_{n+1}^{\mathrm{HEJ}}\right|^2}{\left|\mathcal{M}_n^{\mathrm{HEJ}}\right|^2}.$$

Easily included in the Sudakov-veto algorithm to get the correct exponentiation.



Clearly MPI’s are needed. . .
And proper CKKW-L type matching

UMEPS and UNLOPS

Brand new ME/PS merging algorithms. Implemented in PYTHIA8.

Combines the interleaved (with MPI) shower with multi-jet ME. Tree-level **and** NLO.

Based on unitarity. The NLO correctness of a given multiplicity is not affected by including higher multiplicities.

Stabilizes the merging-scale dependence. The merging scale can in principle be taken arbitrarily small.

(with S. Prestel arXiv:1211.4827, arXiv:1211.7278)

Still uses the Pythia8 shower for resummation, but improves it by resumming the full ME in the leading order(s).

Also resums (some) $k_\perp$-unordered emissions.

Far from full small-x resummation, though…

Needs to be investigated more. Especially together with MPI.

Matching and MPI

MPI is interleaved with the shower in the PYTHIA8 matching.

However, only proper shower emissions are vetoed above the merging scale. MPI's are not.

Important to allow MPI all over phase space in a consistent way.

This is taken care of in UMEPS and UNLOPS.

This will screw up your NLO calculation. But don't blame the messenger — Nature screws up your NLO calculation!

Conclusions

- MPI are small-x processes and need proper small-x resummation.
- BFKL-based models exist for final states, but are often very crude and lack precision.
- High-multiplicity matrix elements may give us more insight. But need to be properly matched, using both small-x resummation and MPI.
- Still, we need small-x models to understand saturation and diffraction.