Parton Shower Approaches

from protons to nuclei

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3D structure of the nucleon
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Outline

- Conventional Parton shower models and MPI.
- The DIPSY model
- Nucleon vs. nuclei collisions.

Parton shower generators

≈ PYTHIA

Start out with few-parton matrix elements.

Evolve incoming legs backwards (undoing the PDF evolution).

Evolve outgoing legs forward to get exclusive partonic states

Smack on hadronization of choice (i.e. strings).

Decay unstable partons.

Done.

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Undoing the evolution of PDFs means explicitly constructing the full kinematics of all the parton splittings leading up to the parton entering the hard interaction.

Reconstructing the transverse momentum dependence of the $k_\perp$-integrated PDFs a-postiori.

But only leading-log DGLAP.
No small-x resummation (see Hannes talk).

Multiple Interactions

Starting Point:

$$\frac{d\sigma_H}{dk_\perp^2} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{Hij}}{dk_\perp^2}$$

The perturbative QCD $2 \to 2$ cross section is divergent. $\int_{k_{\perp c}^2} d\sigma_H$ will exceed the total *pp* cross section at the LHC for $k_{\perp c} \lesssim 10$ GeV.

There are more than one partonic interaction per *pp*-collision

$$\langle n \rangle (k_{\perp c}) = \frac{\int_{k_{\perp c}^2} d\sigma_H}{\sigma_{tot}}$$

The trick in PYTHIA is to treat everything as if it is perturbative.

$$\frac{d\hat{\sigma}_{Hij}}{dk_\perp^2} \rightarrow \frac{d\hat{\sigma}_{Hij}}{dk_\perp^2} \times \left(\frac{\alpha_S(k_\perp^2 + k_{\perp 0}^2)}{\alpha_S(k_\perp^2)} \cdot \frac{k_\perp^2}{k_\perp^2 + k_{\perp 0}^2} \right)^2$$

Where $k_{\perp 0}^2$ is motivated by colour screening and is dependent on collision energy.

$$k_{\perp 0}(E_{\mathrm{CM}}) = k_{\perp 0}(E_{\mathrm{CM}}^{\mathrm{ref}}) \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^\epsilon$$

with $\epsilon \sim 0.16$ with some handwaving about the the rise of the total cross section.

The total and non-diffractive cross section is put in by hand (or with a Donnachie—Landshoff parameterization).

- Pick a hardest scattering according to $d\sigma_H/\sigma_{\mathrm{ND}}$ (for small $k_\perp$, add a Sudakov-like form factor).
- Pick an impact parameter, b, from the overlap function (high $k_\perp$ gives bias for small b).
- Generate additional scatterings with decreasing $k_\perp$ according to $d\sigma_H(b)/\sigma_{\mathrm{ND}}$

Hadronic matter distributions

We assume that we have factorization

$$\mathcal{L}_{ij}(x_1, x_2, b, \mu_F^2) = \mathcal{O}(b) f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)$$

$$\mathcal{O}(b) = \int dt \int dxdydz \rho(x, y, z) \rho(x + b, y, z + t)$$

Where ρ is the matter distribution in the proton
(note: general width determined by $\sigma_{\rm ND}$)

- A simple Gaussian (too flat)
- Double Gaussian (hot-spot)
- x-dependent Gaussian (New Model)

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x-dependent overlap

Small-x partons are more spread out

$$\rho(r, x) \propto \exp\left(-\frac{r^2}{a^2(x)}\right)$$

with $a(x) = a_0(1 + a_1 \log 1/x)$

Note that high $k_\perp$ generally means higher x and more narrow overlap distribution.

Energy–momentum conservation

Each scattering consumes momentum from the proton, and eventually we will run out of energy.

- Continue generating MI's with decreasing $k_\perp$, until we run out of energy.
- Or rescale the PDF's after each additional MI. (Taking into account flavour conservation).

Note that also initial-state showers take away momentum from the proton.

Interleaved showers

When do we shower?

- First generate all MI's, then shower each?
- Generate shower after each MI?

Is it reasonable that a low-$k_\perp$ MI prevents a high-$k_\perp$ shower emission? Or vice versa?

- Include MI's in the shower evolution

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After the primary scattering we can have

- Initial-state shower splitting, P_{ISR}
- Final-state shower splitting, P_{ISR}
- Additional scattering, P_{MI}
- Rescattering of final-state partons, P_{RS}

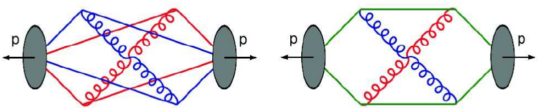
Let them compete

$$\frac{d\mathcal{P}_a}{dk_\perp^2} = \frac{dP_a}{dk_\perp^2} \times \exp - \left(\int_{k_\perp^2} (dP_{\mathrm{ISR}} + dP_{\mathrm{FSR}} + dP_{\mathrm{MI}} + dP_{\mathrm{RS}}) \right)$$

Colour Connections

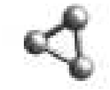
Every MI will stretch out new colour-strings.

Evidently not all of them can stretch all the way back to the proton remnants.

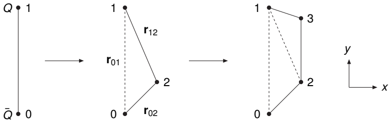


To be able to describe observables such as $\langle p_{\perp} \rangle (n_{\text{ch}})$ we need a lot of colour (re-)connections.

DIPSY (with E. Avsar, C. Bierlich, 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)

The interaction

- Dipole–dipole interaction:
  $F = \sum_{ij} f_{ij} \qquad f_{(12)(34)} \propto \alpha_s^2 \ln^2 \left(\frac{r_{13} r_{24}}{r_{14} r_{23}} \right)$
- Unitarize to get saturation effects (pomeron loops):
  $F \rightarrow 1 - e^{-F}$
- 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.

The Swing

- The unitarized interaction probability gives pomeron loops only in the interaction frame.
- To be Lorentz invariant we want them also in the evolution
- Accomplished by the *Swing* (colour reconnection)
- Two dipoles with the same colour may reconnect.
- Does not reduce the number of dipoles, but smaller dipoles are favoured, and these have weaker interactions.
- In the end we get saturation in both evolution and interaction

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

- pp and ep-DIS total cross section OK
- pp and ep-DIS (quasi) elastic cross section OK including t-dependence
- pp and ep-DIS diffraction OK
- Double parton scattering at the LHC — interesting predictions
  (σ_{eff} depends more on jet $p_{\perp}$ than on x and rapidity, arXiv:1103.4320 [hep-ph])

Going further to produce fully exclusive final states is quite complicated.

Real gluons

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.

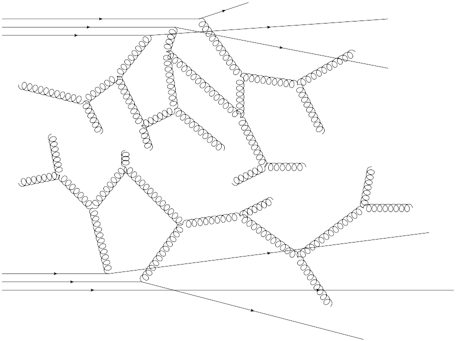
In the momentum picture all gluons in the proton with large p_+ will be off-shell with a negative p_- component.

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

Virtual vs Real gluons

Once the interactions are in place, it is easy to see the interacting gluon chains.

Emissions not on interacting chains are emitted as final state radiation by ARIADNE, removed in DIPSY to not double count.



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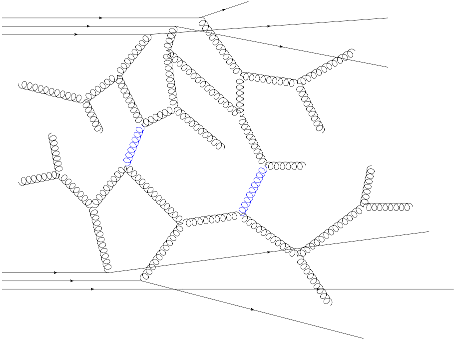

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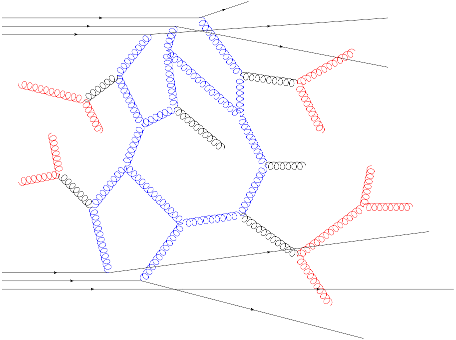


But... energy–momentum conservation effects were taken into account assuming all gluons were real. When some are reabsorbed the kinematics will change.

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 will completely dominate the cross section.

- Choose which dipoles interact: $1 - e^{-F_{ij}}$
- Take away non-interacting gluons
- Take away kinematically impossible interactions/gluons
- Take away wrongly distributed sub-scatterings
- Take away non-ordered gluons

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:

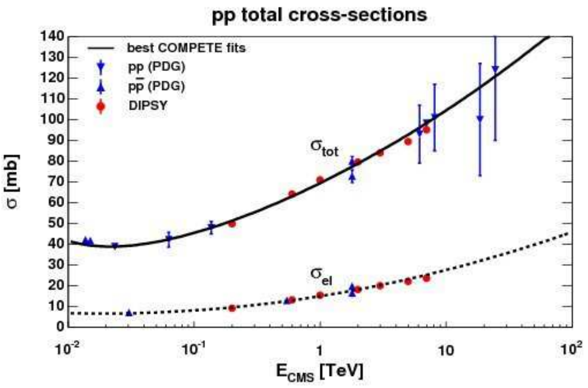
- $R_{\rm max}$: Non-perturbative regularization
- R_p: Proton size ($\approx R_{\rm max}$)
- w_p: Fluctuations in the initial proton size (small)
- $\Lambda_{\rm QCD}$: in the running $\alpha_{\rm s}$
- λ_r: Swing parameter (saturated)

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.

Inclusive cross sections.



Final-state observables

Can be found on

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

In general the description of data is worse than for e.g. PYTHIA8 (Tune 4c), but better than many other generators/tunes (c.f. `mcplots.cern.ch`).

One main problem is the naive valence configuration used: we may get very high energy gluons interacting and giving too hard jets in the forward region.

Other issues:

- Frame dependence
- Final state swing
- Hadronization of dense string configurations

The DIPSY model in unique in its treatment of correlations and fluctuations in the colliding protons, and even if it does not describe final states as well as PYTHIA8 it is still interesting.

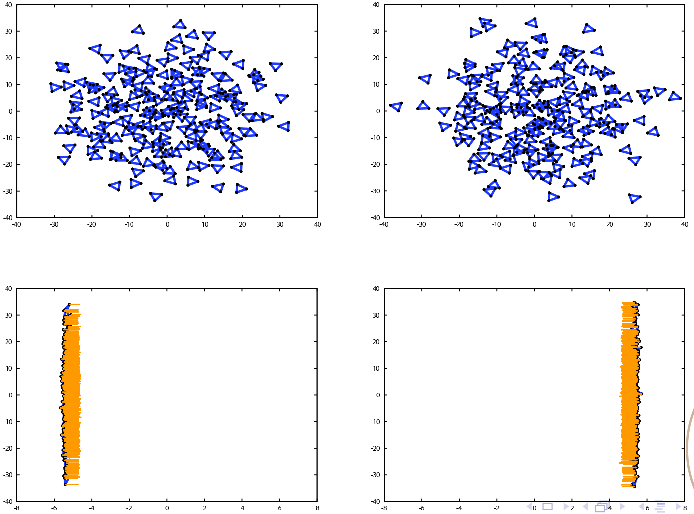
Especially for understanding multiple interactions and minimum bias.

And the extention to also model heavy-ion collisions is “trivial”

Heavy Ions

- An ion starts as *A* nucleons (dipole triangles) distributed in transverse space.
  - Wood-Saxon with hard core.
- The swings, within and between nucleons, describe the saturation in the evolution.
- Get a full partonic picture with both momentum and transverse position.
- Dynamically describes all fluctuations and correlations.
- No new model dependence! (only nucleon distribution) Everything tuned from *pp* and $\gamma^* p$.
- (DIPSY is a bit too slow right now, ∼30 min for a PbPb-event at LHC)

Sample Au-Au event



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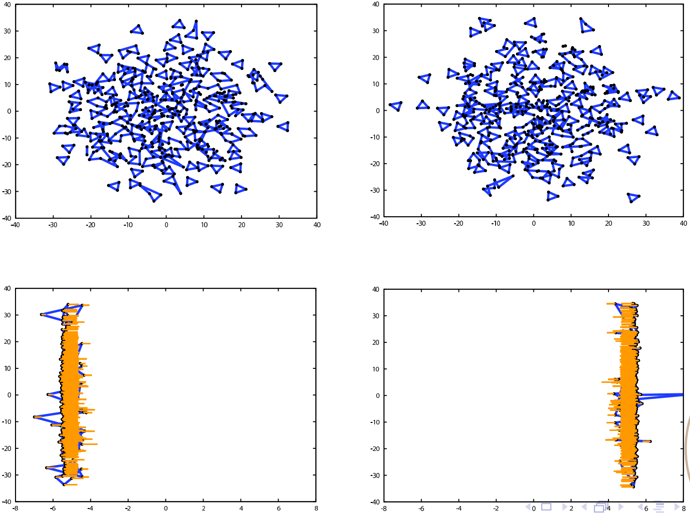

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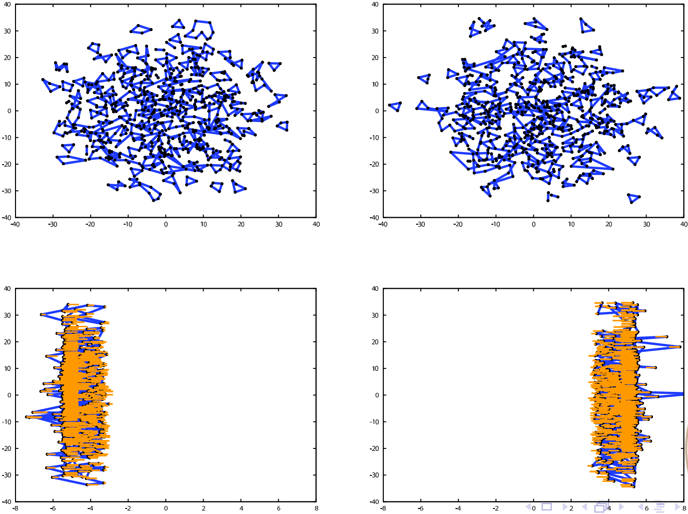

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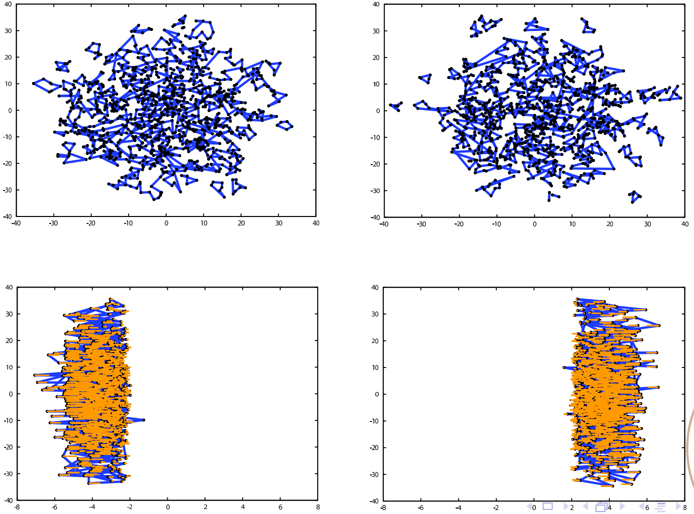

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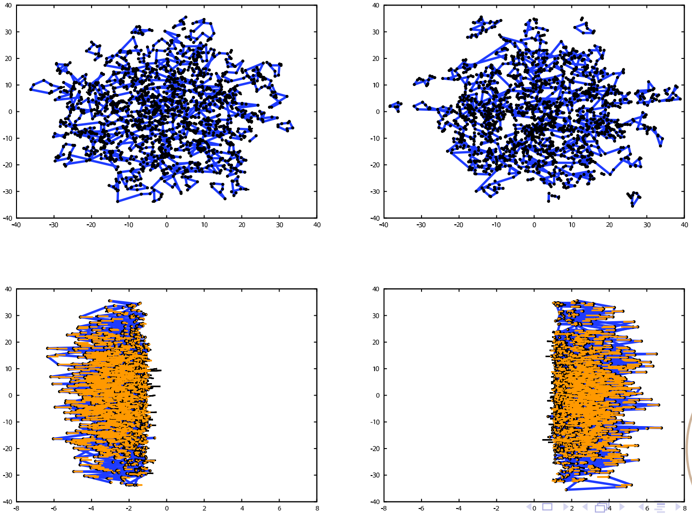

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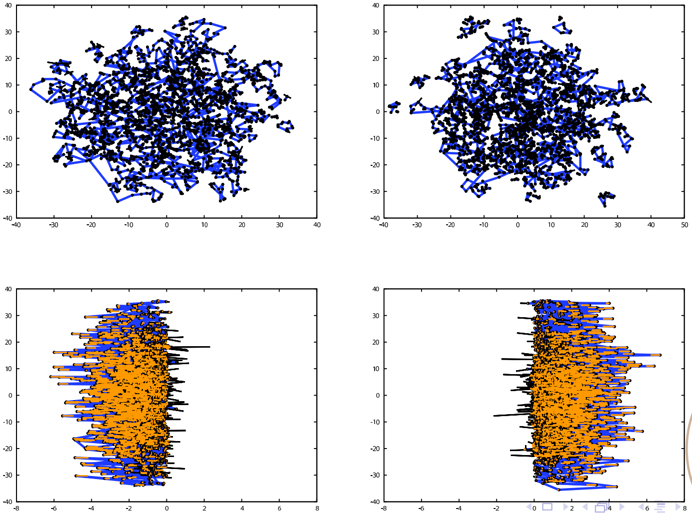

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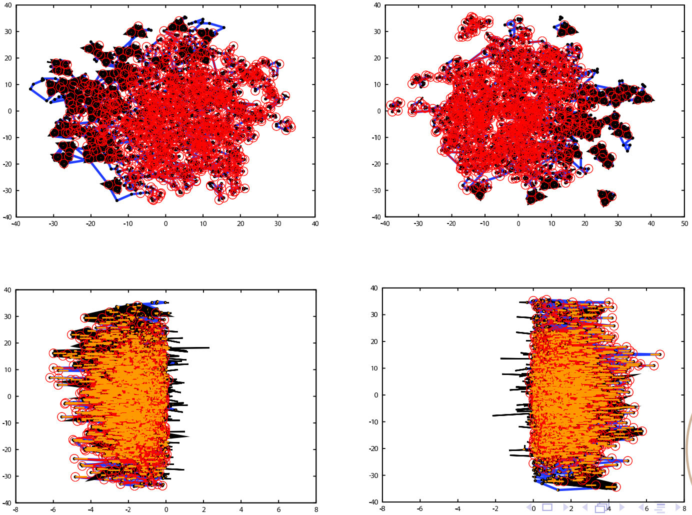

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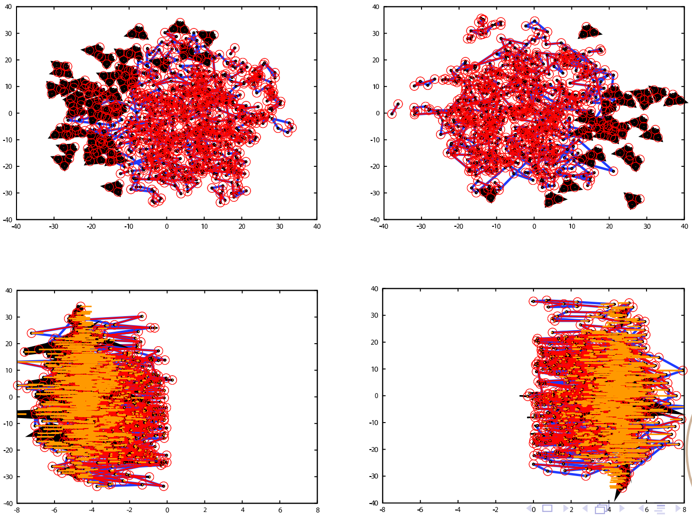

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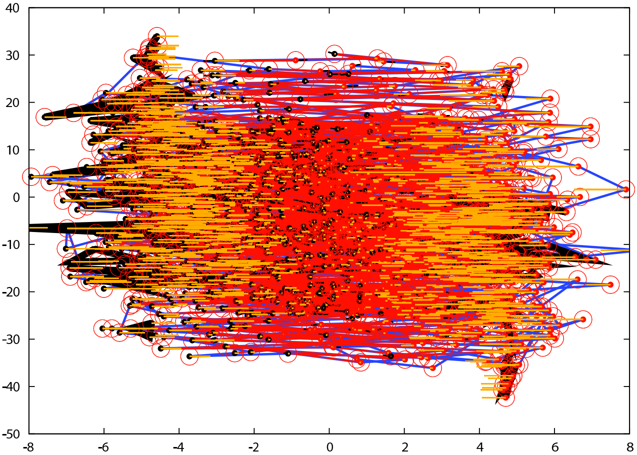

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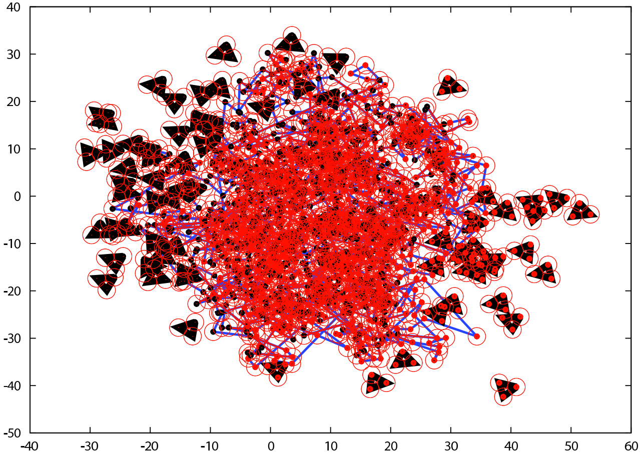
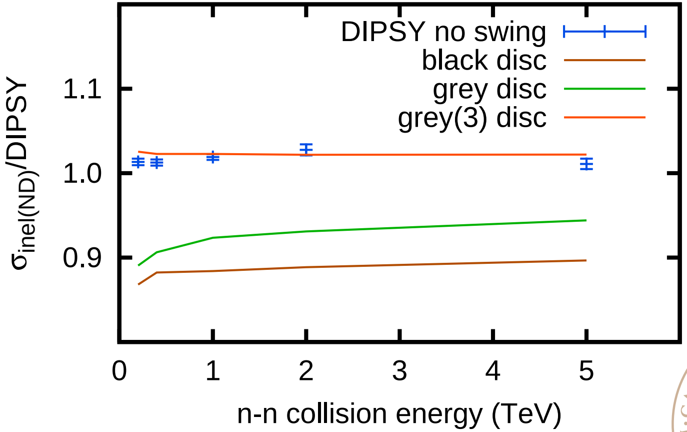


p-Cu inelastic non-diffractive cross section



The final states are extremely messy. We have to think very carefully of how to hadronize strings in this very *colourful* environment.

The transverse size of a (Lund) string is rather large.

What will happen if several strings overlap in impact-parameter space?

Strings $\rightarrow$ Ropes

Take the simplest case of two simple, un-correlated, completely overlapping strings, with opposite colour flow.

$$\begin{array}{ccc} q & \longleftarrow & \bar{q} \\ \bar{q}' & \longrightarrow & q' \end{array}$$

- 1/9: A colour-singlet
- 8/9: A colour-octet

The string tension is proportional to the Casimir operator $C_2^{(8)} = \frac{9}{4} C_2^{(3)}$.

A toy model for rope-fragmentation

The singlet case is dealt with by introducing a final-state swing.

The octet case is approximated by normal fragmentation of two strings but with increased string tension

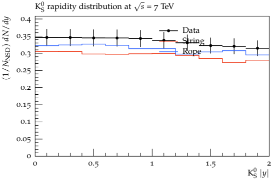
$$\kappa_{\mathrm{eff}} = \frac{C_2^{(8)}}{2C_2^{(3)}}\kappa_0$$

The higher string tension affects several fragmentation parameters in a non-trivial way, basically increasing the probability to create heavy quarks or di-quarks in string break-ups.

Generalize to several and partly overlapping strings.

Prel. results from toy model implementation. Data from CMS

K $dn/d\eta$



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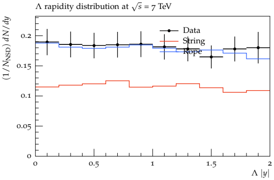

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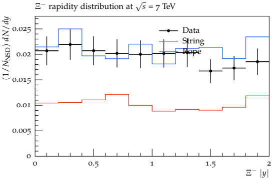
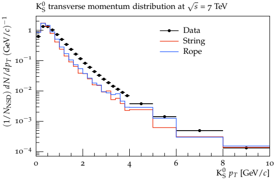


K $dn/dp_\perp$



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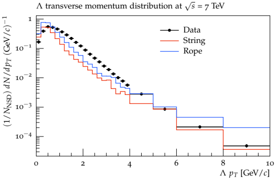

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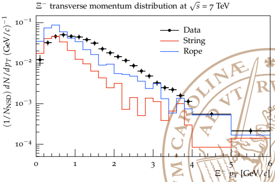

Summary

- Conventional event generators are not very 3D, and mainly models average properties of partons in nucleon.
- Still, most observables in high-energy collisions are well described.
- With DIPSY we have a detailed partonic 3D-picture of the nucleon, including fluctuations and correlations.
- So far there are a lot of short comings:
  - only gluons (small-x)
  - only leading-log x (+ some NLL corrections)
  - no ME-corrections (difficulties with hard jets)
  - ...
- but also possibilities (eg. Heavy Ion)