Non-diffractive and diffractive event generation from dipoles

Christoffer Flensburg

Department of Theoretical Physics
Lund University

Copenhagen 11 April

Work done with Gösta Gustafson and Leif Lönnblad.

Contents

- Introduction: low-x
- A dipole solution
  - Inclusive observables: total cross sections
  - Exclusive non-diffractive observables: event generator
- NEW: diffractive final states
  - Event generator for diffractive excitation!

Problems in low-x and BFKL

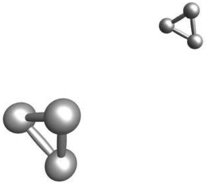
- NLL BFKL is significant.
  - Next to leading order calculations are very involved.
- Saturation important at high energy: MPI. BFKL linear equation. Many different saturation models.
  - BK best known approach, but only partially solves the problem.
  - Infrared difficulties.
- Soft effects and running α_s important at low Q^2.
- Exclusive observables very hard to get to.
- Some approaches can address some of the problems, but not all at once.

A dipole approach from Lund

- Colour dipoles in transverse space, evolved in rapidity.
- Solves the problems:
  - Includes most of NLL, and collinear resumation. (about 10% error)
  - Saturation: naturally includes MPI, and saturates the cascade through dipole swing.
  - Use effective gluon mass for confinement at soft limit.
  - Exclusive observables possible, even an event generator called DIPSY.

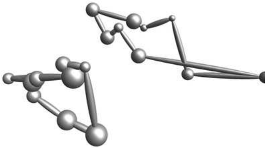
The general idea: Inclusive

- Model incoming particles with colour dipoles in transverse space and rapidity (eg γ^* = single dipole, proton = )
- BFKL evolution in rapidity until they meet.
- Collide at interaction rapidity y_0. BFKL interaction amplitudes. Gives inclusive cross sections.



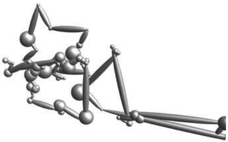
The general idea: Inclusive

- Model incoming particles with colour dipoles in transverse space and rapidity (eg $\gamma^* =$ single dipole, proton = )
- BFKL evolution in rapidity until they meet.
- Collide at interaction rapidity y_0. BFKL interaction amplitudes. Gives inclusive cross sections.



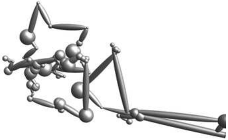
The general idea: Inclusive

- Model incoming particles with colour dipoles in transverse space and rapidity (eg γ^* = single dipole, proton = )
- BFKL evolution in rapidity until they meet.
- Collide at interaction rapidity y_0. BFKL interaction amplitudes. Gives inclusive cross sections.



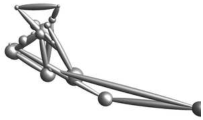
The general idea: Exclusive

- Select which dipoles interact.
- Separate real gluons from virtual ones by backtracing the interactions.
- Add final state radiation: ARIADNE.
- Hadronise: PYTHIA.



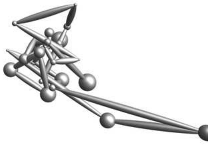
The general idea: Exclusive

- Select which dipoles interact.
- Separate real gluons from virtual ones by backtracing the interactions.
- Add final state radiation: ARIADNE.
- Hadronise: PYTHIA.



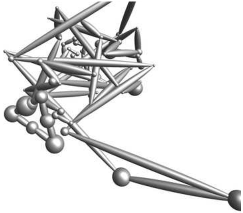
The general idea: Exclusive

- Select which dipoles interact.
- Separate real gluons from virtual ones by backtracing the interactions.
- Add final state radiation: ARIADNE.
- Hadronise: PYTHIA.



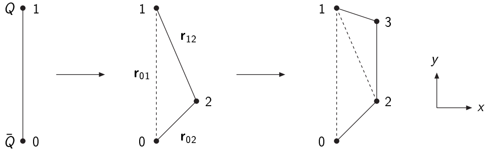
The general idea: Exclusive

- Select which dipoles interact.
- Separate real gluons from virtual ones by backtracing the interactions.
- Add final state radiation: ARIADNE.
- Hadronise: PYTHIA.

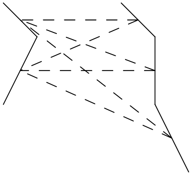


Leading Logarithm BFKL amplitudes

- Dipole emission: $\frac{d\mathcal{P}}{dy} = \frac{\bar{\alpha}}{2\pi} d^2\mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2\, r_{12}^2}$



- Dipole-dipole interaction amplitude $f_{ij} = \frac{\alpha_s^2}{2} \ln^2\left(\frac{r_{12}\, r_{24}}{r_{14}\, r_{23}}\right)$.
  Sum over dipole pairs $F = \sum_{ij} f_{ij}$.



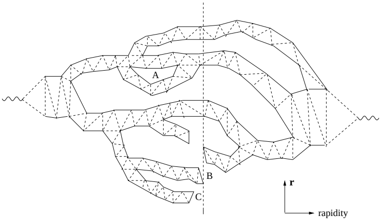
Corrections

- NLL effects
  - p_+ and p_- ordering: dynamic cutoff for small and large dipoles.
  - running α_s from dipole size.
- Confinement from a gluon mass. Suppresses emissions at large transverse distance. Fullfills Froissart bound.
- Saturation, dipole swing:
  (N_C^2 suppressed)

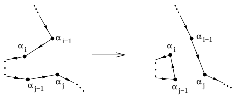
  - Each dipole has colour index, only dipoles of same colour can swing: quadrupoles.
  - Swings happen often between emission, but favours smaller dipoles over larger dipoles.
  - Dynamic. Depends on the cascade in this event.

The Dipole Swing: motivation.

- Multiple interactions forms loops.
  - But that can not create loop in the cascade!

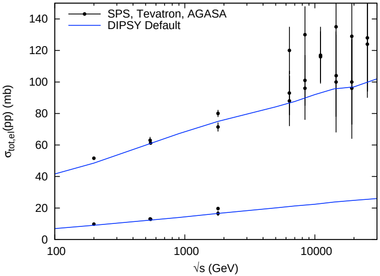


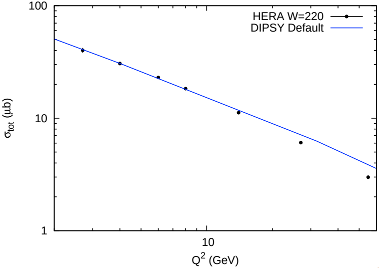
- Add the Dipole Swing:



- Amplitude to mimic multiple interaction.
- **Multiple interactions + frame independence $\rightarrow$ Dipole Swing.**

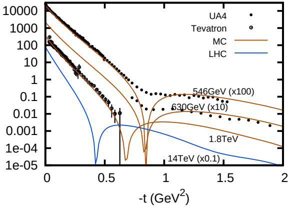
Some inclusive cross sections.



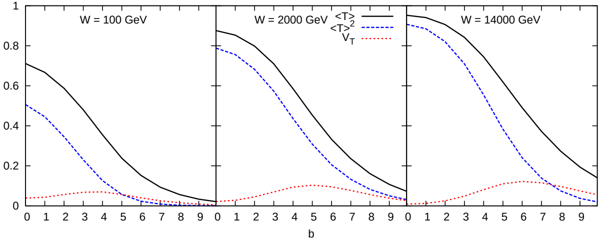


Total and elastic $\sigma_{pp}(\sqrt{s})$ (left) and total $\sigma_{\gamma^* p}(Q^2)$ (right).

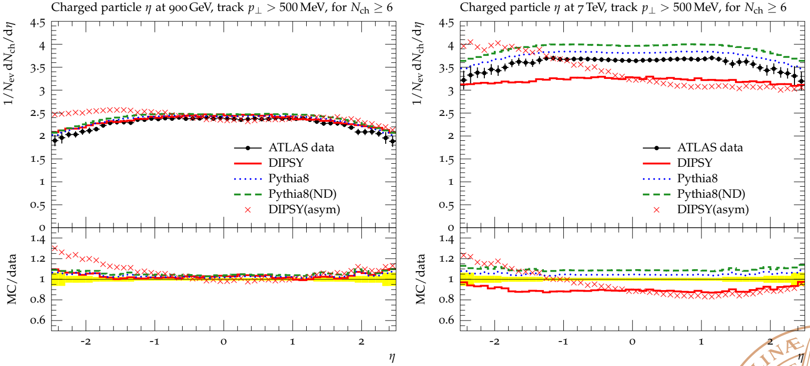
Some inclusive cross sections.



Elastic $\sigma_{pp}(t)$ for some different $\sqrt{s}$ (left). Impact parameter profile for total, elastic and diffractive $\sigma_{pp}(B)$ (down) at different $\sqrt{s}$.

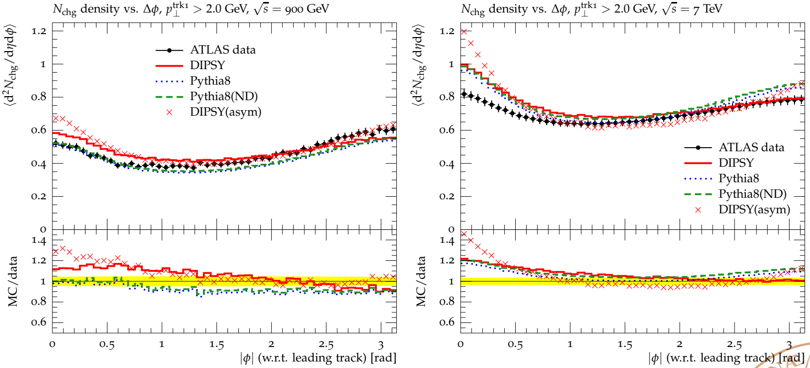


ATLAS exclusive data



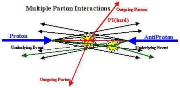
Pseudorapidity distributions of charged particles at 0.9 and 7 TeV.

ATLAS exclusive data



Multiplicity as function of azimutal angle w.r.t. a leading charged particle of at least 2 GeV at 0.9 and 7 TeV.

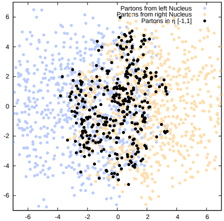
Comparing to Pythia

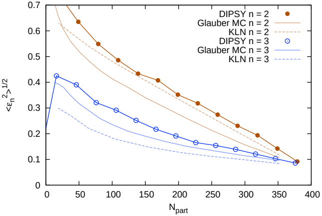


- Pythia, and all other pp event generators use DGLAP + PDFs
  - DGLAP does initial state radiation in large Q^2 approximation.
  - Start with a hard interaction, then does backwards evolution.
  - Uses Parton Distribution Functions.
    - Does not naturally include multiple interaction correlations.
  - Works well for new physics searches and hard jets, minimum bias is pushing the limit of the approximations.
- DIPSY uses BFKL.
  - BFKL builds gluon chains in low x limit, ie not too large Q^2.
  - Forward evolution in $x_\perp$ makes it easy to include saturation and multiple interaction.
  - DIPSY does not need PDFs.
  - Hard physics is currently out of reach for this approach. (Need matrix element corrections.) Minimum bias works well.

(Heavy ions)

- 1 proton (1 triangle) -> A nucleons (A triangles).
- Distributed with Wood-Saxon + hard core.
- Then run Program as normal!
  - Interactions between nucleons happen naturally from the Swing.
- Big news for heavy ions, but not subject of this talk.





Exclusive diffractive excitation: Hard!

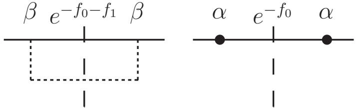
$$\sigma_{\mathrm{ND}} = \int d^2b \langle 1 - e^{-2F} \rangle$$

$$\sigma_{\mathrm{diff\ ex}} = \int d^2b \left(\langle \left(1 - e^{-F}\right)^2 \rangle - \langle 1 - e^{-F} \rangle^2 \right)$$

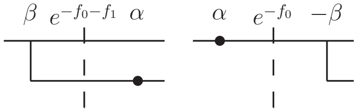
- Amplitude does not factorise into probabilities of final states. Harder to make a Monte Carlo implementation.
- Origin of diffractive excitation is fluctuations in interaction amplitude between different cascades.
  - Can not calculate the amplitude from a single final state.
- Strong interference at amplitude level: canceling contributions.

Exclusive diffractive excitation: Toy model

- Incoming state (mass eigenstate) $|0\rangle$
- Can emit gluon (β) or not (α). Unitary: $\alpha^2 + \beta^2 = 1$.
- Absorbed into non-diffractive states when scattering. Interaction eigenstates with eigenvalues $1 - e^{-\sum f_i}$.
- Can emit/absorb (inverse rotation) gluon also after scattering.
- $A_{\text{Elastic}} = \beta^2 e^{-f_0 - f_1} + \alpha^2 e^{-f_0}$.



- $A_{\text{Diff ex}} = \alpha\beta(e^{-f_0 - f_1} - e^{-f_0})$.

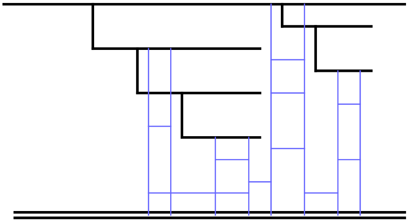


Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.

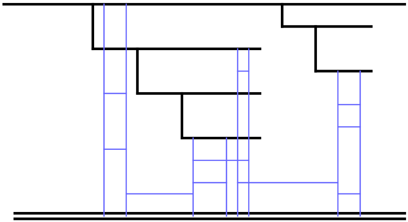
Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.



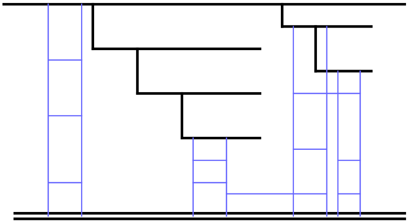
Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.



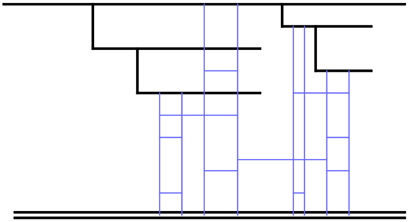
Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.



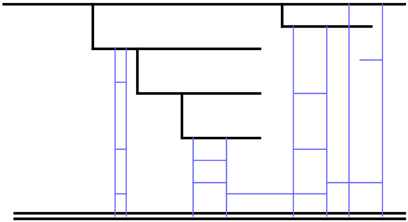
Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.

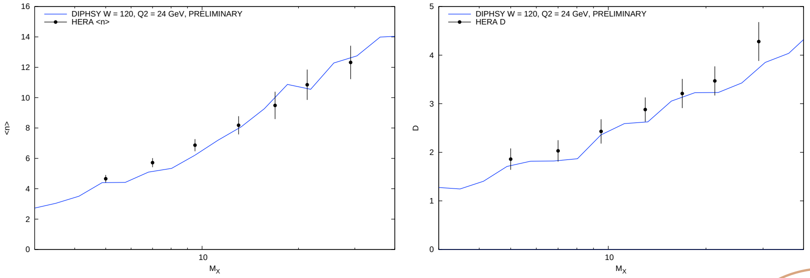


Exclusive diffractive excitation: Solved!

- A single real final state cascade is collided with a large number of virtual cascades.
  - Takes time, but can do calculations at amplitude level.
- Collide several similar real final states, to calculate fluctuations.
  - Takes even more time, but necessary.
- No extra parameters! Exclusive diffractive excitation event generator as prediction from inclusive and non-diffractive minimum bias.

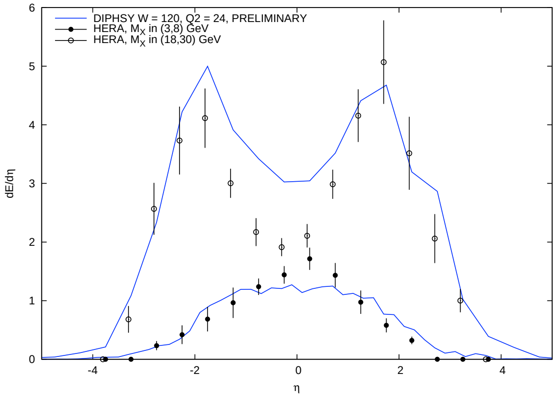


Preliminary Results: HERA Single Diffraction



Multiplicity and fluctuations in multiplicity as function of M_X.

Preliminary Results: HERA Single Diffraction



Energy flow as function of pseudorapidity in bins of M_X.

Conclusions

- BFKL-based dipole model in transverse space, evolved in rapidity.
  - Includes saturation, confinement and most of NLL.
- Does exclusive non-diffractive observables and now full event generator.
  - Monte Carlo implementation: DIPSY `arXiv:1103:4321`.
- Now also exclusive diffractive excitation.
  - Calculates fluctuations at amplitude level.
  - No extra parameters, all prediciton!
  - Agrees very well with Hera data.

Non-diffractive interaction probability

- Non-diffractive interaction probability is total - diffractive:

$$2(1-e^{-F}) - (1-e^{-F})^2 = 1 - e^{-2F}$$

- The non-interaction probability factorise ($F = \sum f_{ij}$)

$$1 - e^{-2\sum f_{ij}} = 1 - \prod e^{-2f_{ij}}$$

- assuming independent interactions, the non-diffractive dipole-dipole interaction probability between dipole i and j is $1 - e^{-2fij}$.
- This can be used to determine the interacting dipoles in our Monte Carlo implementation: DIPSY.

Details on extracting Final State...

- There are plenty of subtleties where perturbative QCD gives little guidance, but that still affects observables. See `arXiv:1103:4321` for further details.
  - reweighting of some $k_\perp$-max in evolution.
  - deciding what parents to put on shell.
  - formulation of ordering and coherence.
  - and more.
- These are first decided by self consistency (frame independence) and tuning to inclusive observables.
- Last freedom in model-space is left to be tuned to exclusive obervables such as charged particle distributions.

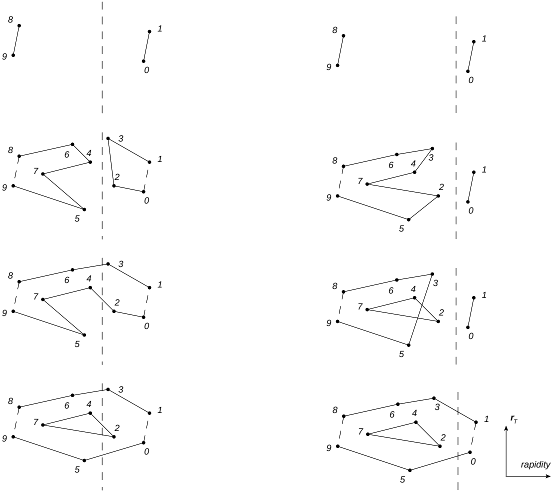
Final State radiation and Hadronisation

- FSR fills up the remaining phase space (emissions that are unordered in $p_\pm$).
- FSR with the ARIADNE Monte Carlo, based on the Linked Dipole Chain model.
- Hadronisation with the Lund String Model using PYTHIA 8.

More possibilities

- DIS final states.
  - Inclusive and semi-inclusive data is well described.
  - Current version can generate $\gamma^* p$ final states, but have not yet been compared to data.
- $\gamma^* A$ inclusive and exclusive observables.
  - By first tuning AA, pA and $\gamma^* p$ to data, it should be reliable.
- Diffractive final states.
  - Tricky (interactions are not independent), but underway.
  - Hope to return soon with results.

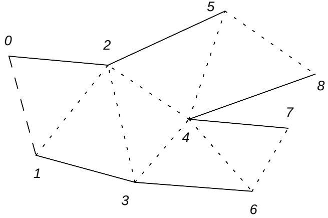
Swing motivated by frame independence

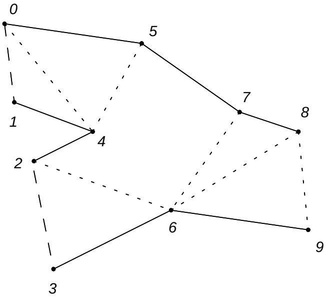


Swing motivated by frame independence

- Same state created with different interaction frames y_0, marked by dashed vertical line.
- the cascades and interaction described in 4 steps going from up to down.
- What is a multiple interaction ((23) interacting with (64), and (02) with (57)) in the left scenario, is a swing ((34) with (25)) and a single interaction ((35) with (01)) in the right scenario.

Swing giving 2 → 1 merging

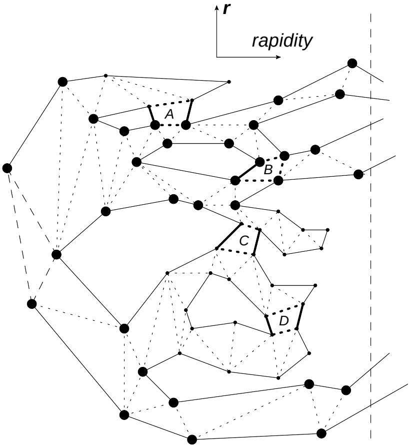




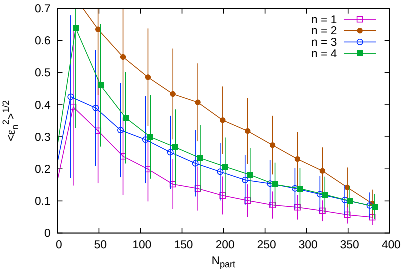
Dipole evolving from left to right.

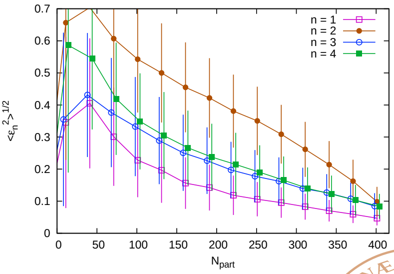
left: 1 → 2 chain splitting. right: swing induced 2 → 1 merging. dipole (26) swings with (45).

Swing giving 2 → 1 merging

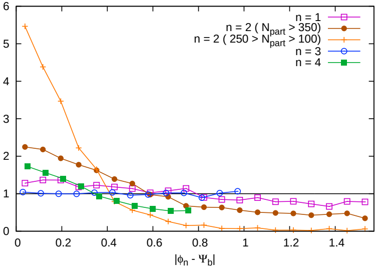


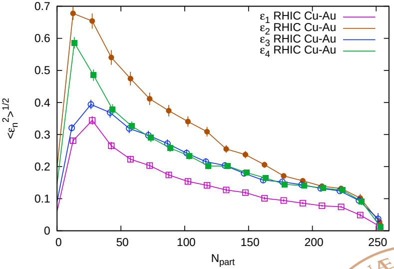
ε_n at RHIC and LHC



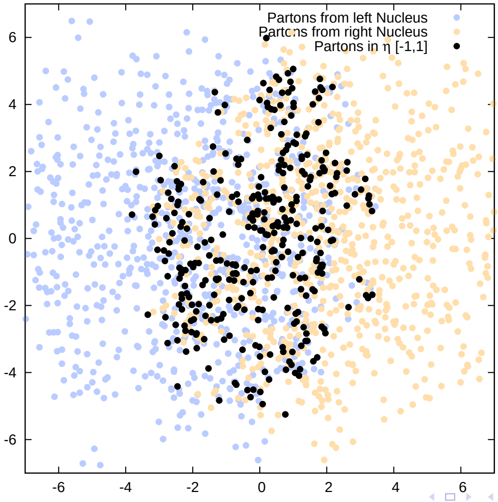


$\phi_n - \Psi_B$ at RHIC and ε_n for CuAu

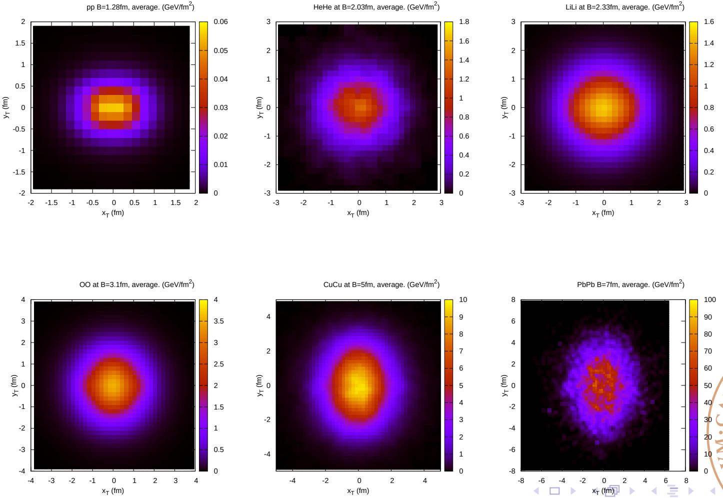




AA

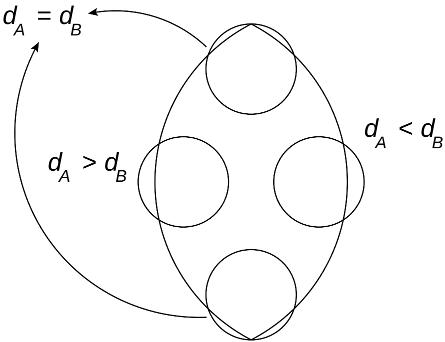

Partons from left Nucleus
Partons from right Nucleus
Partons in η [-1,1]
6
4
2
0
-2
-4
-6
-6
-4
-2
0
2
4
6

average E dens. at fix $B = (0.8R, 0\text{fm})$, central η



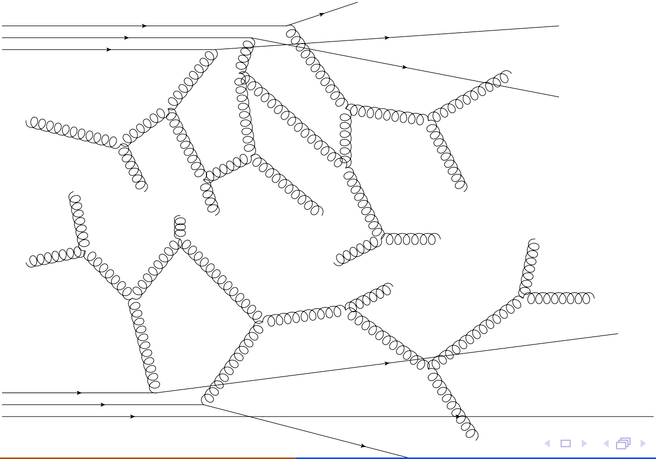
Interpretating ε_2

- Glauber: central η density $\sim N_{\text{part }A}(x_\perp) + N_{\text{part }B}(x_\perp)$.
- KLN: central η density $\sim \min(N_{\text{part }A}(x_\perp), N_{\text{part }B}(x_\perp))$.
- DIPSY: central η density $\sim N_{\text{part }A}(x_\perp) N_{\text{part }B}(x_\perp) S_{\text{sat}}(x_\perp, \ldots)$.
- Glauber MC underestimates ε_2.



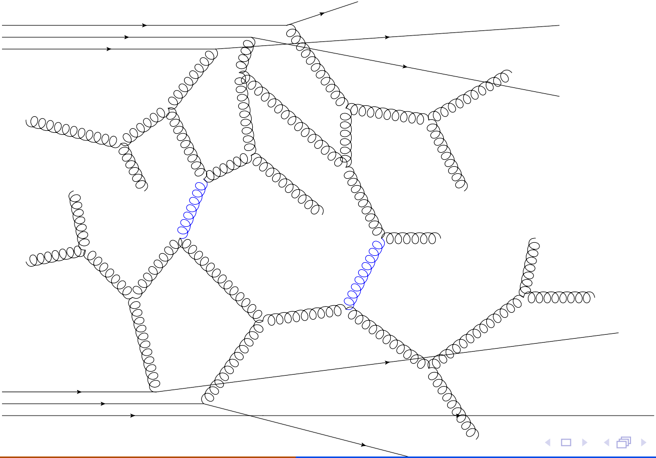
Virtual vs Real gluons

- The interacting gluons (and their parents) are saved, the others are reabsorbed.



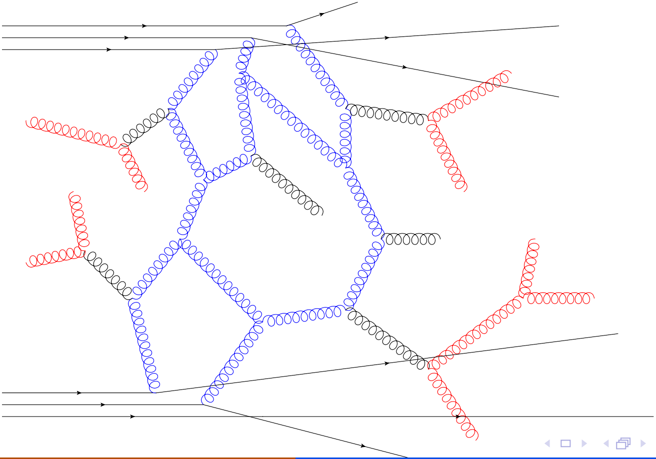
Virtual vs Real gluons

- The interacting gluons (and their parents) are saved, the others are reabsorbed.



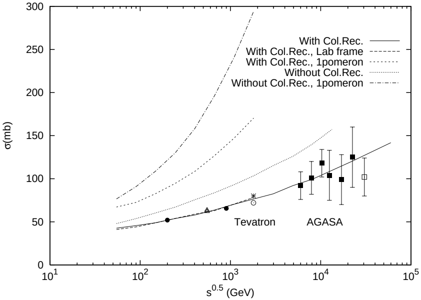
Virtual vs Real gluons

- The interacting gluons (and their parents) are saved, the others are reabsorbed.

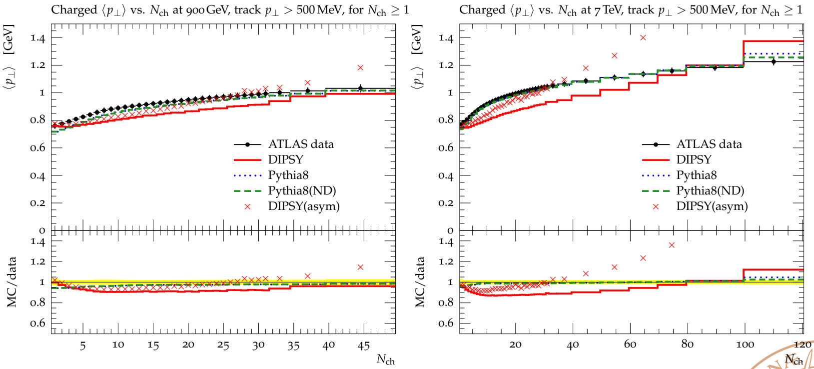


The Dipole Swing: Saturation.

- Turns large dipoles into small dipoles.
  - Dynamically generates a saturation scale Q_s from local gluon density.
- Small dipoles have smaller interaction probability $\rightarrow$ saturation.

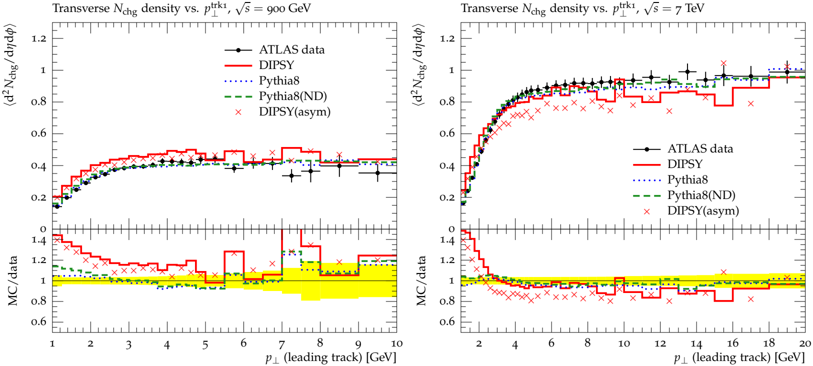


ATLAS exclusive data



Average transverse momentum as function of charged multiplicity at 0.9 and 7 TeV.

ATLAS exclusive data



The multiplicity of charged particles in the transverse region as function of the transverse momentum of the leading charged particle at 0.9 and 7 TeV. More plots at `http://home.thep.lu.se/~leif/DIPSY.html`.