

Rope Hadronisation

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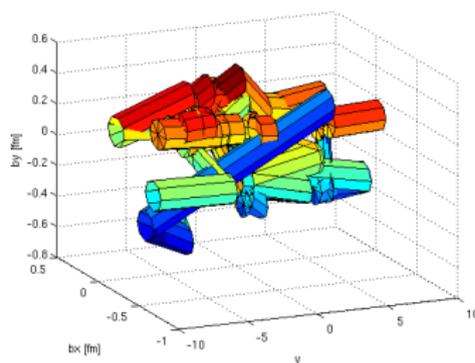
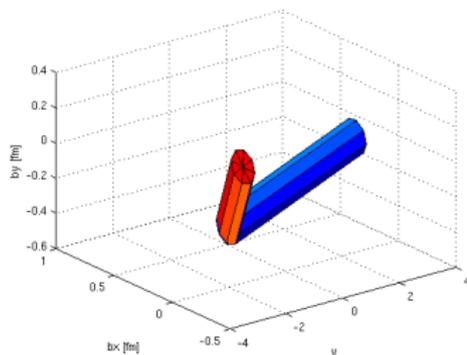
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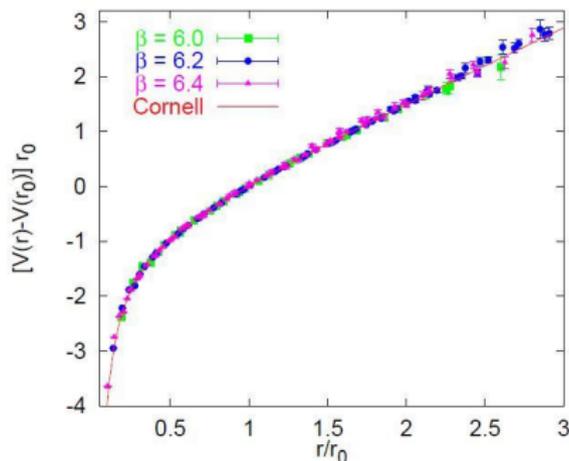
Introduction

- The Lund String model provides a strong picture for hadronization.
- Developed for LEP – Busy LHC events are a challenge.
- Rope Model: Corrections based on string overlaps
- Framework: DIPSY event generator, part of ARIADNE.
- DIPSY provides a space time picture of events.



String Hadronisation [Sjöstrand et al. hep-ph/0603175, 2006]

- Linear confinement potential $V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm.
- Valid for large distances – for small distances perturbation theory should be valid.



- Confirmed by lattice calculations Figure from: [Bali, G, hep-ph/0001312, 2000].
- Realized in a 1+1 dimensional string with tension κ .

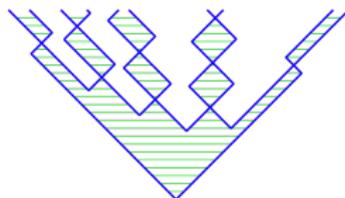
String Hadronisation II [Andersson et al. Z. Phys. C20 317, 1983]

- Repeated *breaking* with $\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp}^2}{\kappa}\right)$ [Schwinger, J. Phys. Rev. 82 664, 1951].
- Left-right symmetry in the breaking gives:

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_{\perp}^2}{z}\right)$$

- a and b related to total multiplicity.
- Strange and baryon suppression determined by Schwinger mechanism (tuned):

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

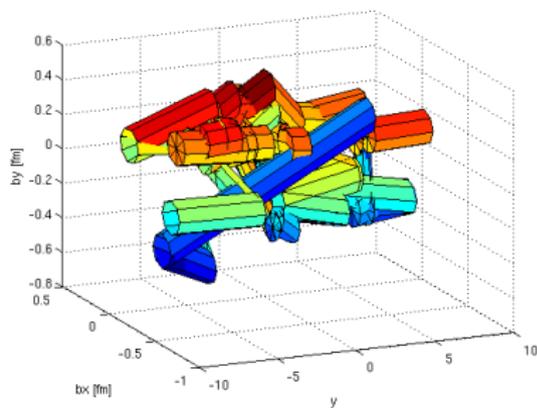
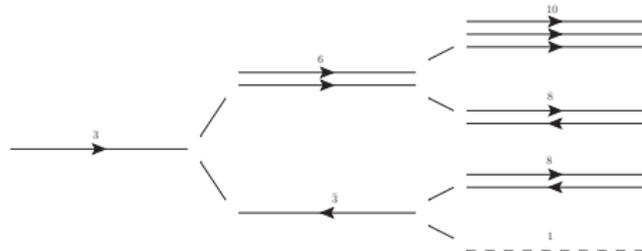


Rest of this talk

- 1 String overlap?
- 2 The rope model
- 3 Effect on junctions and string tension
- 4 Tuning and results
- 5 Heavy ion

String overlap?

- So what *can* happen when strings overlap?
- Expectation: Stronger field \Rightarrow More strange quarks and diquarks.
- $\rho = \exp\left(-\frac{\pi(m_s^2 - m_{ud}^2)}{\kappa}\right)$ for some enhanced κ [Sorge, H et al, Phys. Lett. B, 289 6-11, 1992 and many others]
- Deal with effects, let Pythia 8 hadronize.



- Three options (random walk) [Biro et al., Nu cl. Phys. B 245, 449-468, 1984]

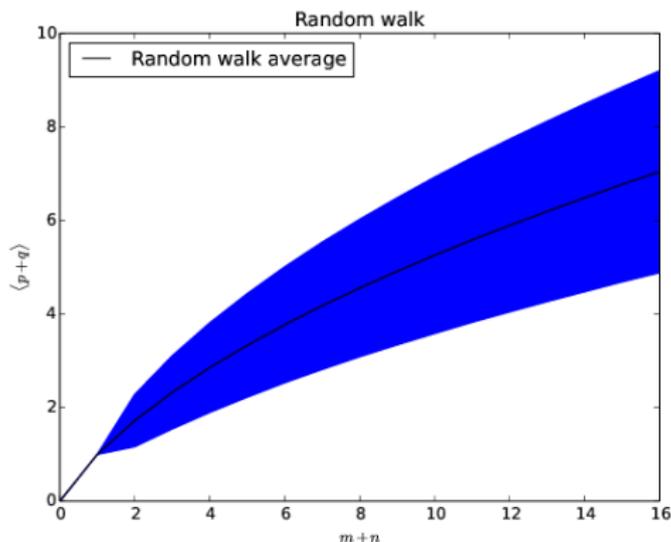
- 1 Highest multiplet.
- 2 Junction structure.
- 3 Singlet.

The random walk

- Derive recursion relations for adding (anti-)triplets to general $\{p, q\}$ multiplets:

$$\{p, q\} \otimes \{1, 0\} = \{p, q - 1\} \oplus \{p - 1, q + 1\} \oplus \{p + 1, q\}.$$

$$\{p, q\} \otimes \{0, 1\} = \{p - 1, q\} \oplus \{p, q + 1\} \oplus \{p + 1, q - 1\}.$$



Singlet: The colour swing

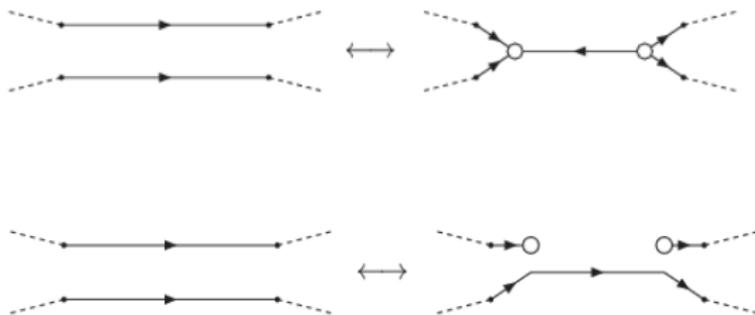
- The singlet is taken care of by the Ariadne colour reconnection model: The final state swing.
- Idea: Let dipoles, which are colour compatible, reconnect.



- Exactly the singlet in $3 \otimes \bar{3} = 8 \oplus 1$.
- Also kinematic effect: Low p_{\perp} hadrons \Rightarrow high p_{\perp} hadrons.

Junction handling

- Pythia 8 does not (yet, see talk by J. R. Christiansen) handle all junctions.
- Very simplistic (popcorn-inspired) handling: keep potential baryons ($\mathcal{P} = 1 - \beta$), ignore reversed colour flow.



Enhancement of κ

- Idea: String tension scales like $C2$ of the multiplet [Ambjörn, J et al. Nucl. Phys. B 240, 533, 1984] and [Bali, G. S, hep-lat/0006022, 2000].
- Averaged over $N = p + q$ partial breakups: $\tilde{\kappa}/\kappa = \frac{1}{4}(N + 3 - \frac{pq}{N})$
- Given the dipole mapping, local p, q are calculated.
- Effective fragmentation parameters for *each hadronisation step*.
- Pythia 8 hadronizes, need to know where we are on dipole:
 - 1 Hard for gluon loops, use average value.
 - 2 Invariant mass of produced hadrons tells us *which* dipole.
 - 3 The fraction:

$$\frac{m_{had} - m_n}{m_{n+1} - m_n}$$

can tell us *where* on that dipole

Short summary

- The process of handling string interaction can be summarized:
 - 1 Dipoles are allowed to "swing" during the fs shower.
 - 2 All strings are split into dipoles, with other dipoles overlapping.
 - 3 Dipoles are subjected to a random walk to determine a multiplet.
 - 4 Junction dipoles are broken into quark or diquark pairs.
 - 5 Leftover dipoles are hadronized with effective parameters in each hadronization step.

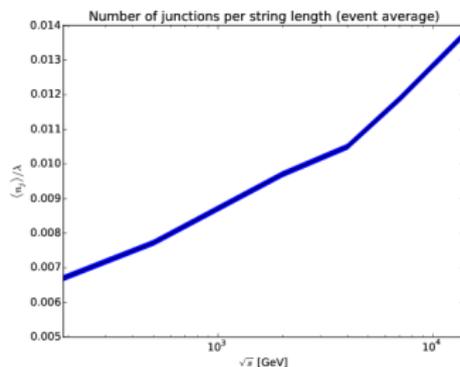
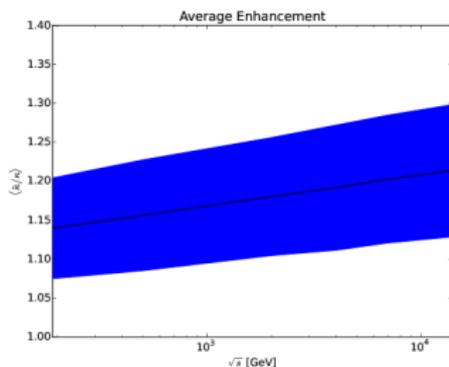
Effect

- Average increased string tension, increases w. energy (sum over dipoles).

$$\langle \tilde{\kappa}/\kappa \rangle = \frac{\sum_i \lambda_i \kappa_i}{\sum_i \lambda_i}, \lambda_i = \ln \left(\frac{m_i^2}{m_0^2} \right)$$

- Number of junctions per string length.

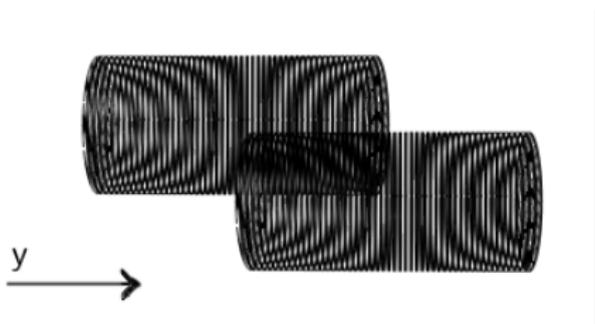
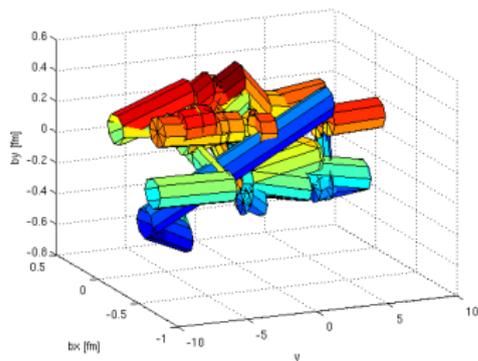
$$n_j = \frac{\sum_i n_{junctions,i}}{\sum_i \lambda_i}$$



Sanity check: a pipe based approach

- Dipoles and junction handling introduces much complexity.
- Crude approximation: Draw pipes around each string, calculate volume overlap of the pipes:

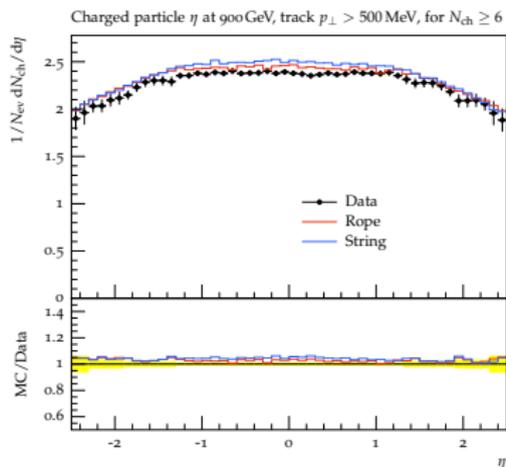
$$\langle N \rangle_{\text{total}} = \langle N \rangle_{\text{self}} + \sum_{i \neq \text{self}} \frac{V_{o,i}}{V_i} \langle N \rangle_i$$



- Would like to see the crude estimate improved by dipoles.

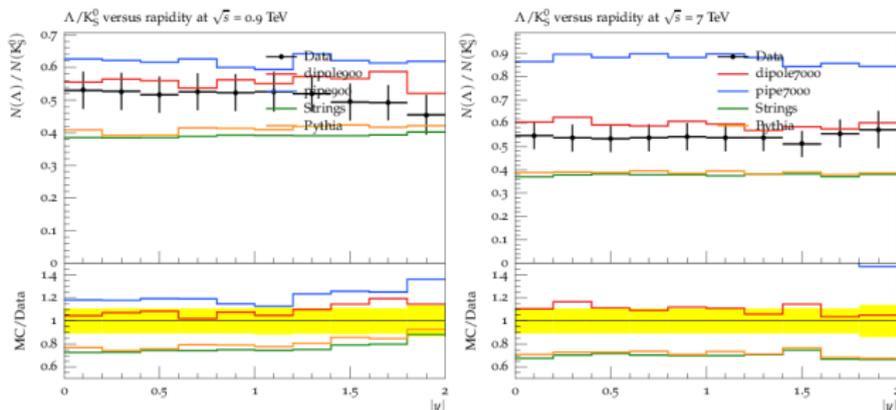
Tuning [ATLAS, 1012.5104 [hep-ex], 2010]

- Since multiplicity is altered, we must retune.
- Retune fragmentation parameters (LEP) with fs swing (change a).
- Retune DIPSY cascade with all rope effects.



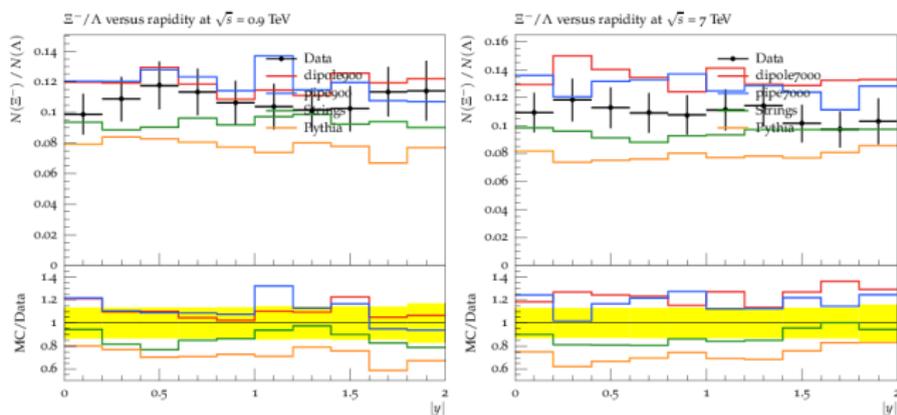
Comparison to data (CMS) [CMS, 1102.4282 [hep-ex], 2011]

- Vanilla DIPSY/ARIADNE 5 (string hadronisation) suffers from similar problem.
- Content improves ($r_0 = 1.1$ fm, $\beta = 0.22$).



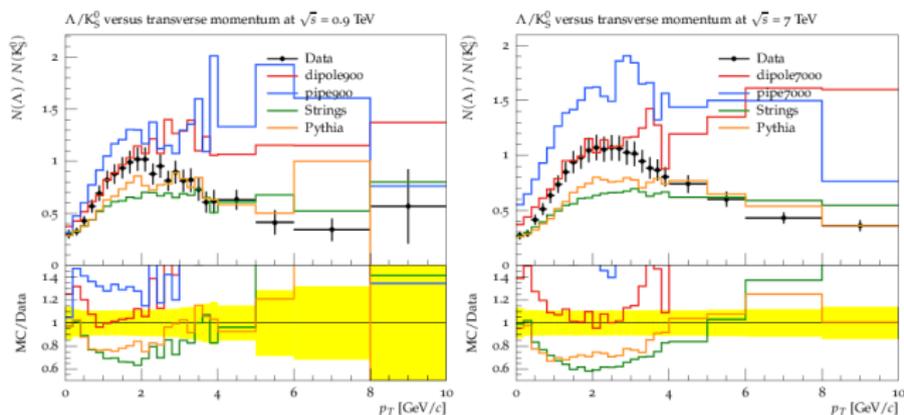
Comparison to data (CMS) II

- Two diquarks, Cascade has two s -quarks.



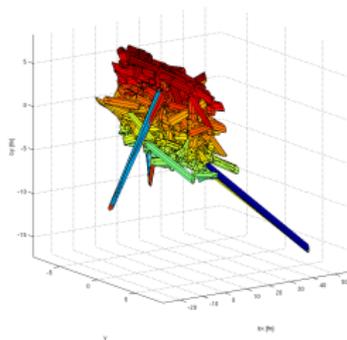
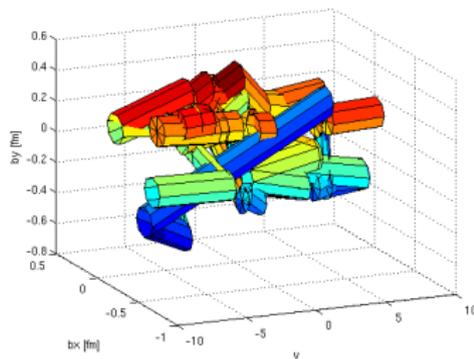
Comparison to data (CMS) III

- Kinematics. Inherent problem with large p_{\perp} tails.



Heavy Ion (preliminary)

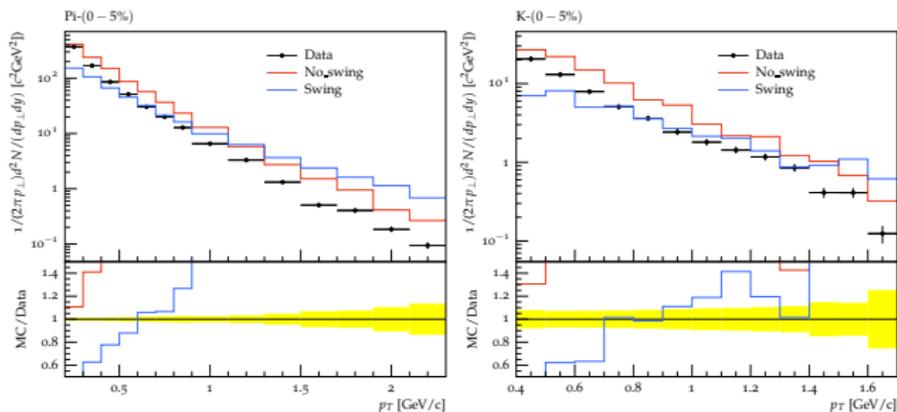
- Heavy ion events (AuAu at 130 GeV, RHIC) are way more stringy!



- It is absolutely necessary to deal with coherence effects.

Comparison to data (PHENIX) [PHENIX, 2002, arXiv:nucl-ex/0112006]

- Swing effect dominates over rope, perhaps not entirely understood.
- Even more pronounced for higher p_{\perp} (eg. ALICE PbPb).



Outlook and conclusions

- The string model needs corrections in dense environments.
- Spatially overlapping strings enhance string tension.
- Implemented in context of DIPSY/Ariadne 5.
- Ropes formed by colour charges acting coherently gets strange/baryonic content right in pp .
- Effects should increase for higher LHC energies/SLHC.
- Promise for Heavy Ion events, colour reconnection by swing is a work in progress.

The End

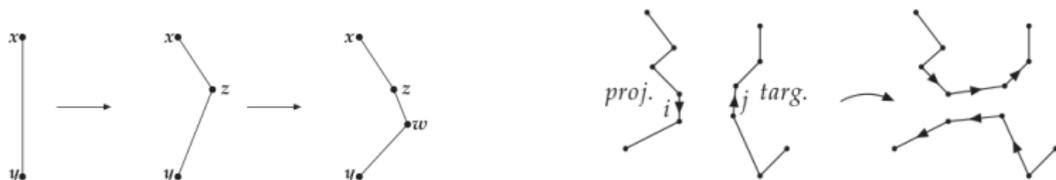
Bonus slides

The DIPSY event generator [Flensburg et al. arXiv:1103.4321 [hep-ph], 2011]

- A Monte Carlo implementation of the Mueller Dipole Cascade (with corrections).
- Builds up virtual Fock states of proton, colliding dipoles interact via gluon exchange.
- A dipole (\vec{x}, \vec{y}) can emit a gluon at position \vec{z} with probability (P) per unit rapidity (Y) ; dipoles i and j interact with probability $2f_{ij}$:

$$\frac{dP}{dY} = \frac{\bar{\alpha}}{2\pi} d^2\vec{z} \frac{(\vec{x} - \vec{y})^2}{(\vec{x} - \vec{z})^2(\vec{z} - \vec{y})^2}$$

$$f_{ij} = \frac{\alpha_s^2}{8} \left[\log \left(\frac{(\vec{x}_i - \vec{y}_j)^2(\vec{y}_i - \vec{x}_j)^2}{(\vec{x}_i - \vec{x}_j)^2(\vec{y}_i - \vec{y}_j)^2} \right) \right]^2$$

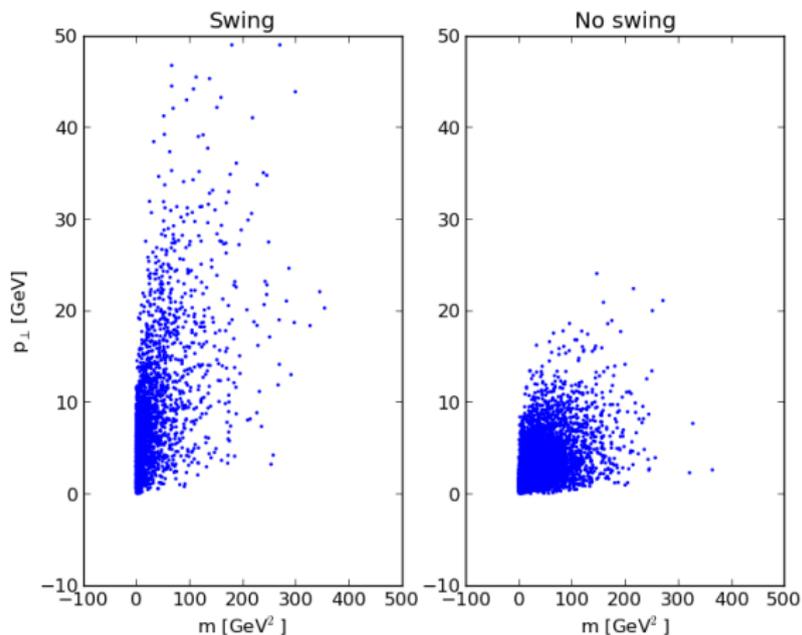


Monte Carlo event generation

- Many corrections beyond Muellers model – see reference on previous page.
- Rough sketch of MC generation of an event:
 - 1 Generate projective and target cascades;
 - 2 Determine which dipoles interact;
 - 3 Reabsorption of non-interacting chains (dipole loops);
 - 4 Final state radiation (ARIADNE 5);
 - 5 Hadronisation;

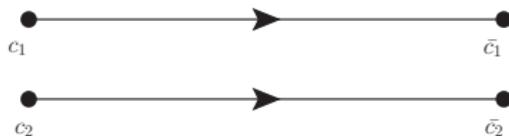
Effect of swing

- Swing transforms low p_{\perp} particles to high p_{\perp} particles.
- Seems to be right for pp , but overshooting the effect in HI collisions.

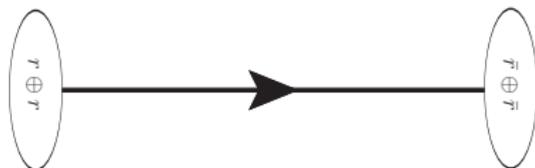


Rope model – example 1

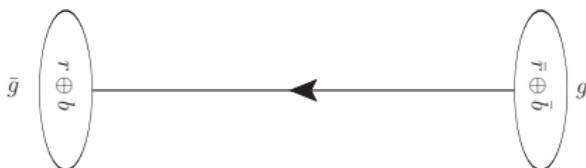
- The simplest example: Two $q\bar{q}$ pairs act coherently, colour flow in same direction:



Case (a), $c_1 = c_2$:

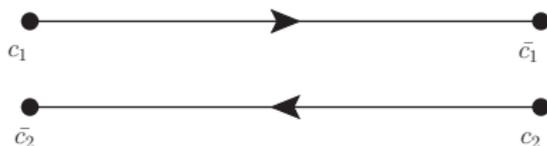


Case (b), $c_1 \neq c_2$:



Rope model – example 2

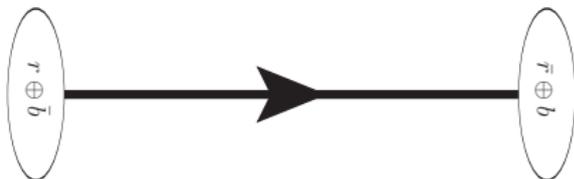
- Next-to-simplest: Two $q\bar{q}$ pairs act coherently, having oppositely directed colour flow:



Case (a), $c_1 = c_2$:

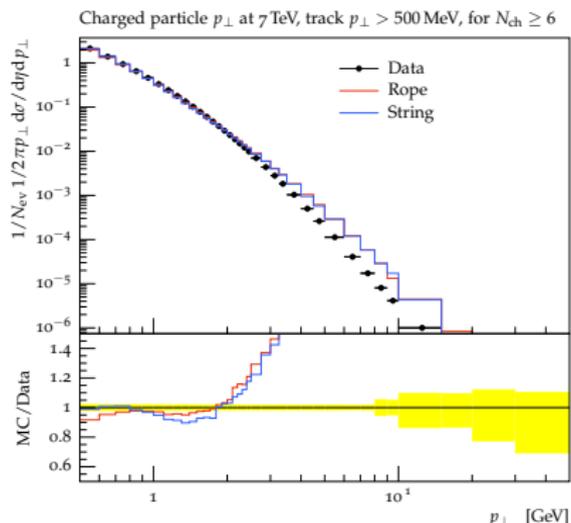
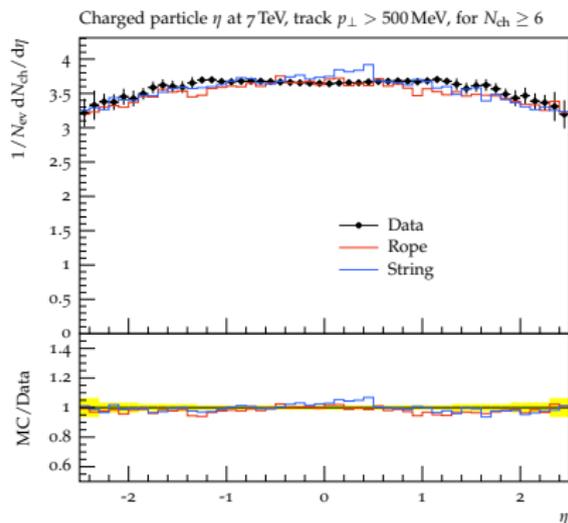


Case (b), $c_1 \neq c_2$:



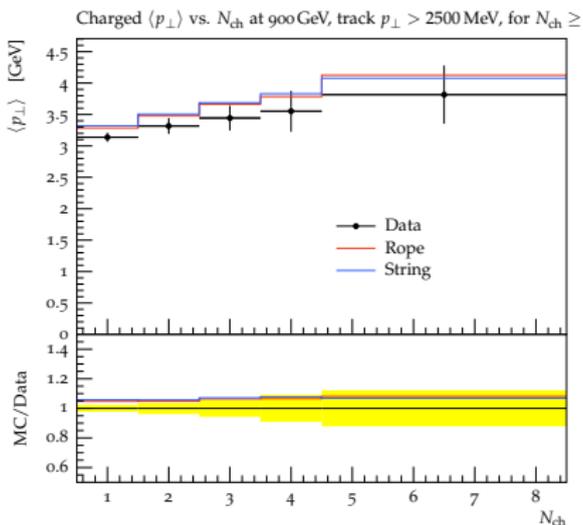
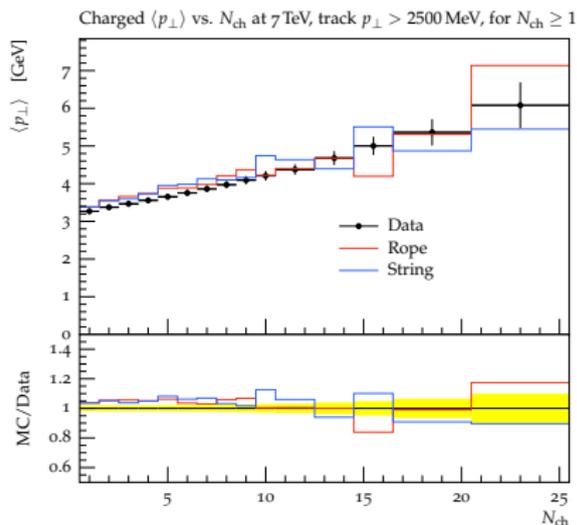
Effect on total multiplicity [ATLAS, Phys. Lett. B688, 21-42, 2010]

- Must not destroy total multiplicity, which is so carefully tuned...



Effect on $\langle p_{\perp} \rangle$ [ATLAS, Phys. Lett. B688, 21-42, 2010]

- The mean p_{\perp} is also an interesting observable.
- We see that it is not destroyed by neither swing nor ropes.



Recursion relations etc.

- All multiplets are given by pairs of fundamental quantum numbers $\{p, q\}$.
- We can choose another set of fundamental quantum numbers, eg.:

$$N = \frac{1}{2}(p+1)(q+1)(p+q+2),$$

$$C_2(\{p, q\})/C_2(\{1, 0\}) = \frac{1}{4}(p^2 + q^2 + pq + 3(p+q))$$

- Related to Young tableaux as: $q = \lambda_2$ and $p+q = \lambda_1$ so eg:

$$\{2, 3\} = \begin{array}{|c|c|c|c|} \hline \square & \square & \square & \square \\ \hline \square & \square & & \\ \hline \end{array}$$

- Following the usual rules we have:

$$\{1, 0\} \otimes \{1, 0\} = \square \otimes \square = \begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{|c|} \hline \square \\ \hline \end{array} = \{2, 0\} \oplus \{0, 1\},$$

$$\{1, 0\} \otimes \{0, 1\} = \square \otimes \begin{array}{|c|} \hline \square \\ \hline \end{array} = \begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} \oplus I = \{1, 1\} \oplus \{0, 0\}.$$

Recursion relations cont'd

- Directly generalizable:

$$\{p, q\} \otimes \{1, 0\} = \underbrace{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}_q \dots \underbrace{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}_p \otimes \square =$$

$$\{p, q-1\} \oplus \{p-1, q+1\} \oplus \{p+1, q\}.$$

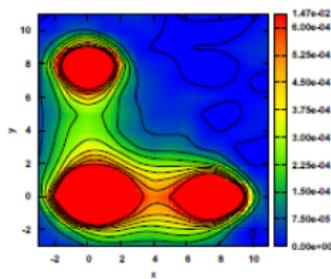
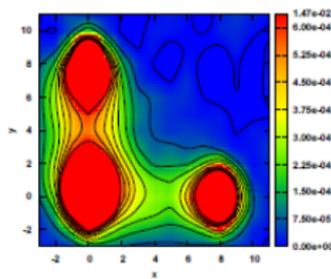
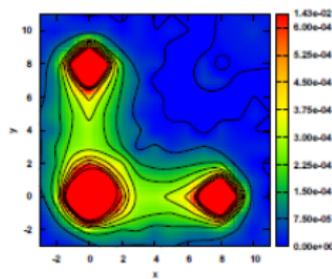
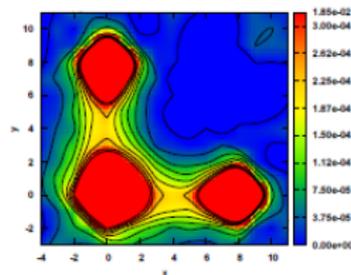
- and:

$$\{p, q\} \otimes \{0, 1\} = \underbrace{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}_q \dots \underbrace{\begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}}_p \otimes \begin{array}{|c|} \hline \square \\ \hline \end{array} =$$

$$\{p-1, q\} \oplus \{p, q+1\} \oplus \{p+1, q-1\}.$$

Lattice confirmation

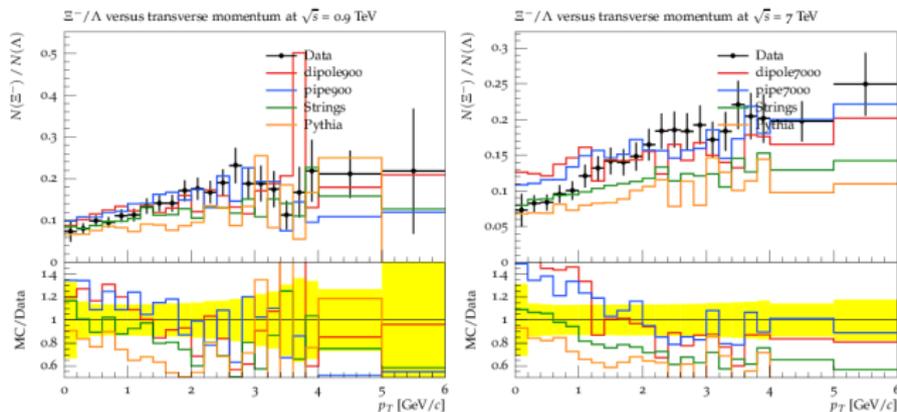
- $\kappa \propto C2(\text{multiplet})$ confirmed on the lattice.
- See [Ambjörn, J et al. Nucl. Phys. B 240, 533, 1984] and [Bali, G. S, hep-lat/0006022, 2000] and nice pictures from [Cardoso, M et al, hep-lat/0912.3181, 2012].

(a) $\langle E_x^2 \rangle$ (b) $\langle E_y^2 \rangle$ (c) $\langle E_z^2 \rangle$ 

(d) Energy Density

Comparison to data (CMS) IV

- Two diquarks, Cascade has two s -quarks.



Diffractive events

- DIPSY cannot produce diffractive events – need particle ratios.
- Demonstration using Pythia8 model for diffraction.

