Rope Hadronisation

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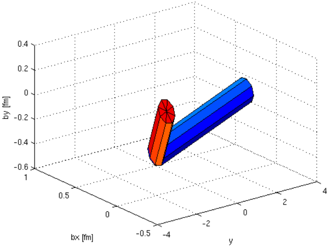
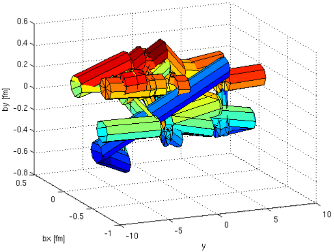
Introduction

- The *string model* is the primary hadronization workhorse for the Lund family of Monte Carlo EG.
- The string model is developed for the very clean LEP environment...
- ...while *pp* min. bias or Heavy Ion is more messy
- Corrections based on *coherence effects* or *rope hadronisation*.
- Part of the DIPSY/Ariadne 5 Monte Carlo EG.



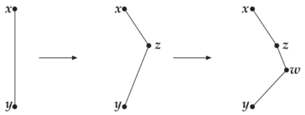


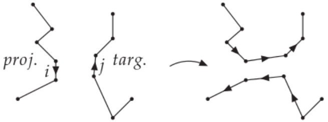
The DIPSY event generator [Flensburg et al. arXiv:1103.4321 [hep-ph], 2011]

- A Monte Carlo implementation of the Mueller Dipole Cascade (with corrections) [see talks this morning or G. Gustafson, proceedings 2011].
- 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 interacts 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

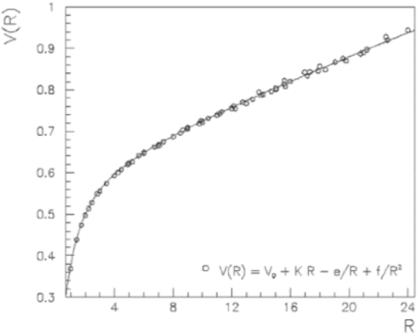
- Many corrections beyond Muellers model – se reference on previous page.
- Rough sketch of MC generation of an event:
  1. Generate projective and target cascades;
  2. Detemine which dipoles interact;
  3. Reabsorption of non-interacting chains (dipole loops);
  4. Final state radiation (ARIADNE 5);
  5. Hadronisation;
- The rest of this talk will concentrate on the last part!

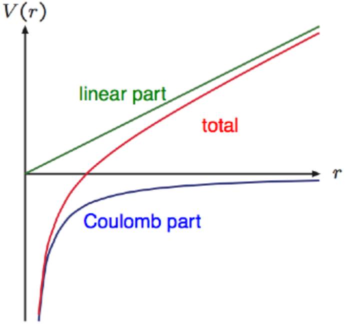
Rest of this talk

1. Ordinary string hadronisation
2. Rope model
3. Results for *pp*
4. Prospects
5. Outlook and conclusion

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.

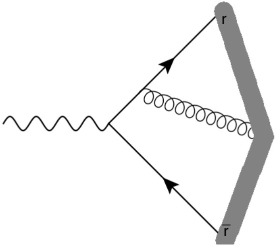




- Realized in a 1+1 dimensional string with tension κ.

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

- Repeated *breaking* with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.
- Left-right symmetry in the breaking gives $f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right)$.



- a and b related to total multiplicity.
- Flavours determined by relative probabilities:

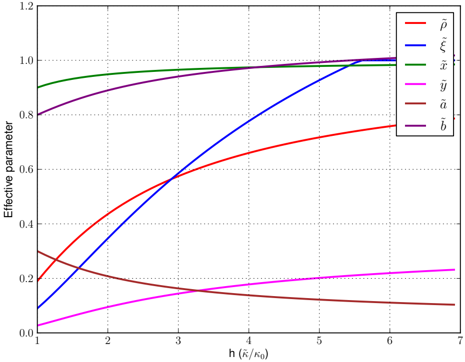
$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

$$x = \frac{\mathcal{P}_{\text{strange diquark}}}{\mathcal{P}_{\text{diquark}}}, y = \frac{\mathcal{P}_{\text{spin 1 diquark}}}{\mathcal{P}_{\text{spin 0 diquark}}}$$

- Notice that probabilities are related to κ via tunneling equation.

Change of string tension

- All parameters related through string tension.
- Used to produce a set of *effective parameters*.



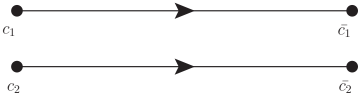
- Let $\kappa \mapsto \tilde{\kappa} = h\kappa$.
- All effective parameters calculable from the two governing equations.
- Parameters ρ and ξ are very sensitive to change in κ.
- Can this be connected to overlapping strings?

The Rope Model at a glance

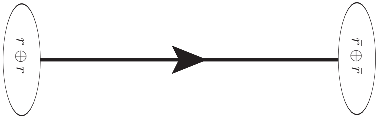
- The *Rope Model*:
    1. Let charges act coherently to form a rope.
    2. The rope is an SU(3) multiplet, with $\kappa \propto C_2$.
    3. All ropes described by two quantum numbers $\{p, q\}$.
    4. Rope breaks in steps, one strand at a time.
- Must still map colour configuration to $\{p, q\}$ for individual strands.
- Hadronisation of strands by Pythia 8, using effective parameters.
- *Input:* Colour connected output from DIPSY/Ariadne 5 shower.
- *Output:* Individual strands with an associated set of effective parameters.

Rope model – example 1

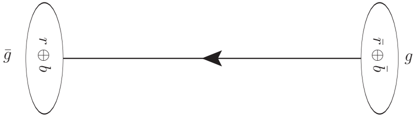
- The simplest example: Two $q\bar{q}$ pairs act coherently, colour flow in same direction:



Case (a), $c_1 = c_2$:

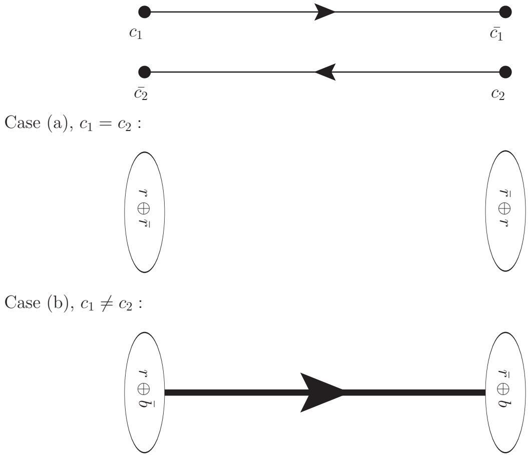


Case (b), $c_1 \neq c_2$:



Rope model – example 2

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

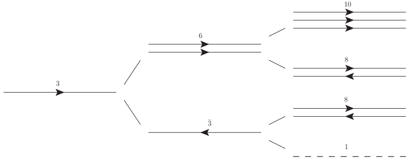


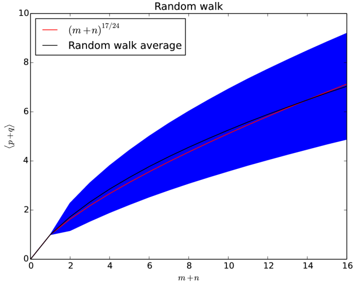
Generalization – The Ropewalk

- Generalizable to arbitrarily many triplets and anti triplets $\{m, n\}$.
- The procedure is iterative, adding one (anti)-triplet at a time.
- This is similar to a random walk in colour space Biro et al., Nucl. Phys. B 245, 449-468, 1984.
- Below: A forming machine at the end of a *ropewalk* (reeperbahn).

The Ropewalk II

- Random walk carried out to form multiplets, using recursion relations.

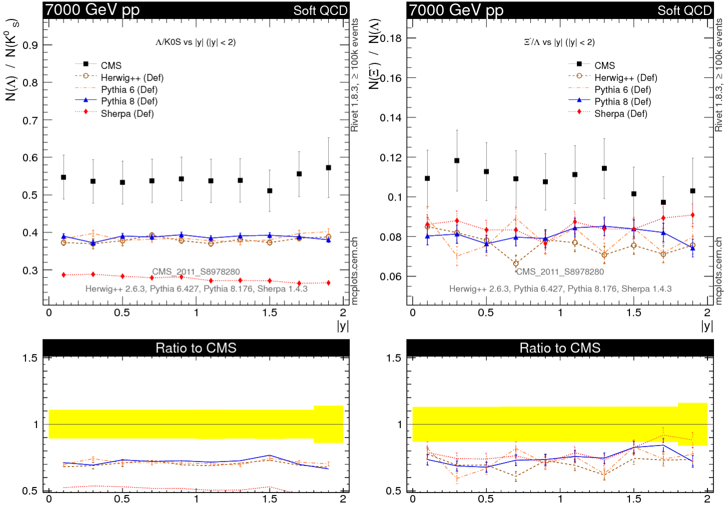




- Rope tension equivalent to 2nd Casimir operator [Ambjörn, J et al. Nucl. Phys. B 240, 533, 1984] and [Bali, G. S, hep-lat/0006022, 2000].
- Averaged over $N = p + q$ partial breakups: $\tilde{\kappa}/\kappa = \frac{1}{4}(N + 3 - \frac{pq}{N})$

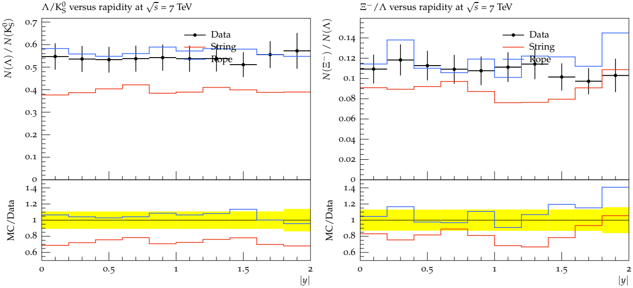
Comparison to data (CMS)

- From MCplots, comparison to CMS data [CMS, arXiv:1102.4282 [hep-ex], 2012]:



Comparison to data (CMS)

- Vanilla DIPSY/ARIADNE 5 (string hadronisation) suffers from similar problem.
- Including rope effects improves the picture.

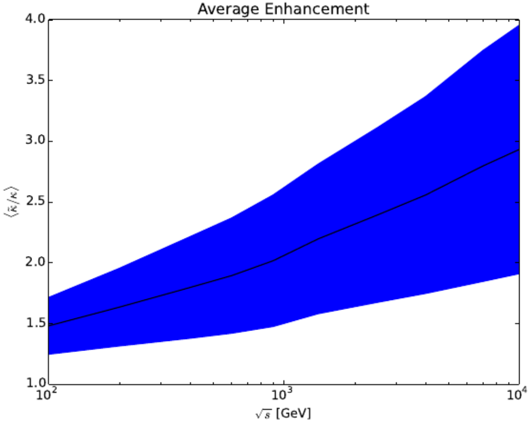


Two prospects

- Two future prospects:
- Higher energy (trivial)
- Heavy Ions

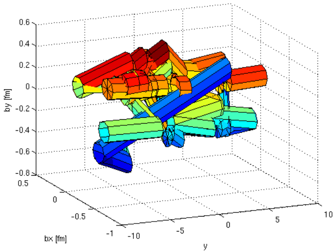
Increased energy

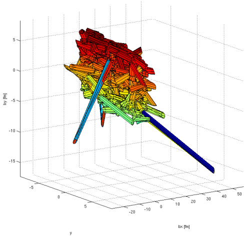
- Increased energy results in more strings.
- With more overlap comes a larger effect!



Heavy Ion (very preliminary!)

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

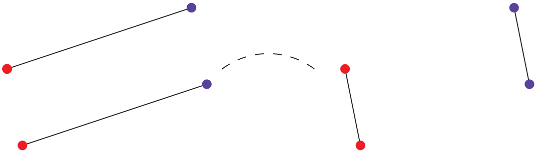




- It is absolutely neccesary to deal with coherence effects.

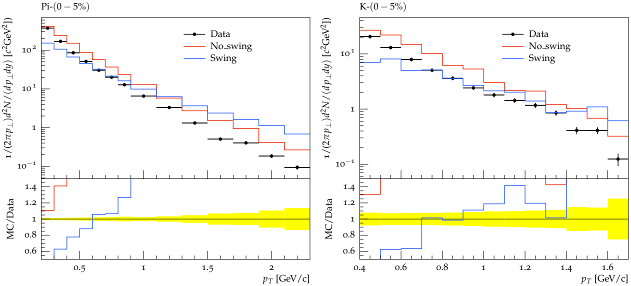
The Colour Swing

- We deal with the simple case $3 \otimes \bar{3} \to 1$ using a colour swing mechanism (also in pp).
- Let nearby dipoles »swing« if compatible.
- Far reaching consequences for kinematics!



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

- Hard tail from the swing, rope effect not visible.
- Even more pronounced for higher $p_\perp$ (eg. ALICE PbPb).



Outlook and conclusions

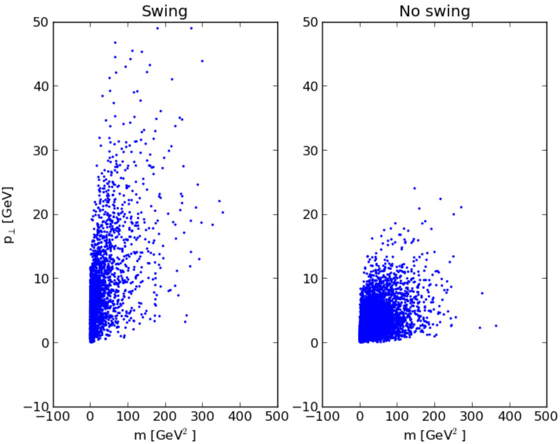
- The string model needs corrections in dense environments.
- Spatially overlapping strings enhance string tension.
- Implemented in context of DIPSY/Ariadne 5.
- Ropes formed by colour charges acting coherently gets strange/baryonic content right in *pp*.
- Effects should increase for higher LHC energies/SLHC.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

The End

Bonus slides

Effect of swing

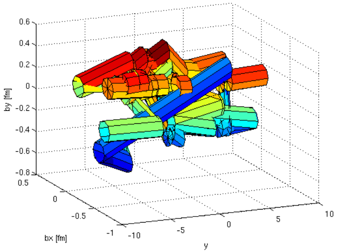
- Swing transforms low $p_\perp$ particles to high $p_\perp$ particles.
- Seems to be right for *pp*, but overshooting the effect in HI collisions.

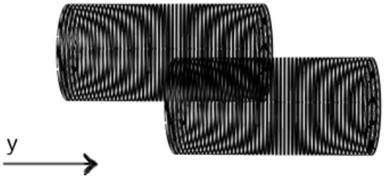


Calculation of $\{m, n\}$

- Finding the $\{m, n\}$ strings producing a rope is not an entirely trivial matter.
- Must deal with partial overlaps.
- Crude approximation: Draw cylinders around each string, calculate volume overlap of cylinders:

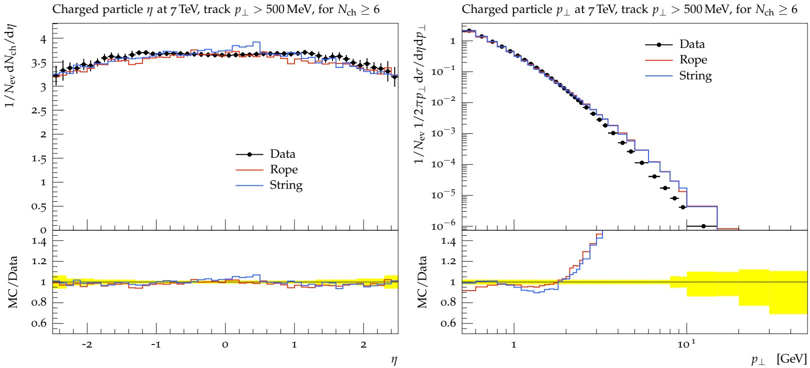
$$\langle N \rangle_{\text{total}} = \langle N \rangle_{\text{self}} + \sum_{i \neq \text{self}} \frac{V_{o,i}}{V_i} \langle N \rangle_i$$





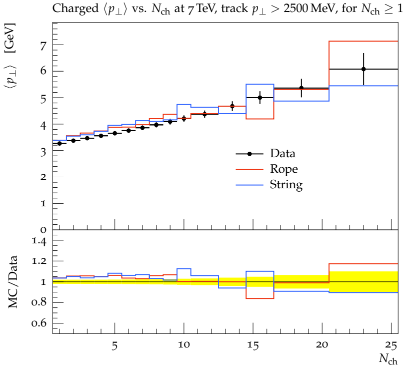
Effect on total multiplicity [ATLAS, Phys. Lett. B688, 21-42, 2010]

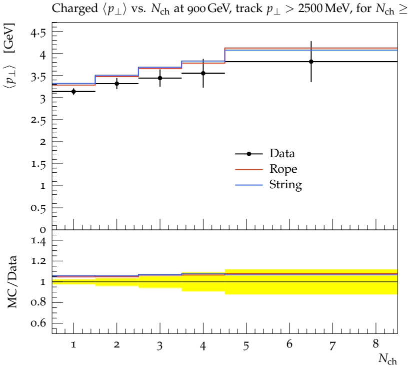
- Must not destroy total multiplicity, which is so carefully tuned...



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:

$$\{2,3\} = \yng(5,3)$$

- Following the usual rules we have:

$$\{1,0\} \otimes \{1,0\} = \square \otimes \square = \yng(2) \oplus \yng(1,1) = \{2,0\} \oplus \{0,1\},$$

$$\{1,0\} \otimes \{0,1\} = \square \otimes \yng(1,1) = \yng(2,1) \oplus I = \{1,1\} \oplus \{0,0\}.$$

Recursion relations cont'd

- Directly generalizable:

$$\{p,q\} \otimes \{1,0\} = \underbrace{\begin{smallmatrix}\Box\Box\cdots\Box\\ \Box\Box\cdots\Box\end{smallmatrix}}_{q}\underbrace{\Box\Box\cdots\Box}_{p} \otimes \Box =$$

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

- and:

$$\{p,q\} \otimes \{0,1\} = \underbrace{\begin{smallmatrix}\Box\Box\cdots\Box\\ \Box\Box\cdots\Box\end{smallmatrix}}_{q}\underbrace{\Box\Box\cdots\Box}_{p} \otimes \begin{smallmatrix}\Box\\ \Box\end{smallmatrix} =$$

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