Meeting on Hadronization, RAL, May 30 2008

Monte Carlos and Hadronization Models and Questions

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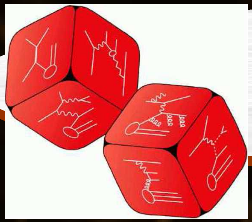
Overview

- What are we here for?
  - Not to calculate anything
  - I think: to ponder, what is the next step in hadronization?
  - Different from other “next steps” in phenomenology
    - In pQCD, calculating higher orders is hard, but at least you know what the question is, what it is you want to compute
    - Here, the question is more basic. We don’t even know what the “next order” of hadronization models really is, or means
- Monte Carlo Hadronization Models
- Simple Questions
- Tough Questions



The Monte Carlo Method

- External input: $\sigma_{\text{hard process}}$
- Then set up Markov chain to compute $P_{\text{tot, hard process} \to \text{final state}}$

$$\sigma_{\text{final state}} = \sigma_{\text{hard process}} \, P_{\text{tot, hard process} \to \text{final state}}$$

where $P_{\text{tot}} = P_{\text{res}} \, P_{\text{ISR}} \, P_{\text{FSR}} \, P_{\text{MI}} \, P_{\text{Remnants}} \, P_{\text{Hadronization}} \, P_{\text{decays}}$

- In general, this chain is ordered
  - "short-distance" phenomena occur "before" long-distance (~ time of formation / fluctation time)

With $P_i = \Pi_j P_{ij} = \Pi_j \Pi_k P_{ijk} =$ …in its turn

➔ Divide and conquer

➔ Evolution

Everything happens at a characteristic length/energy scale

Hard Part

Up to E_{cm}

$\sigma_{\text{hard process}}, P_{\text{res}}$

Parton Showers + Multiple Interactions

> 1 GeV

$P_{\text{ISR}}, P_{\text{FSR}}, P_{\text{MI}}$

Hadronization + Remnants

~ 1 GeV ~ 10^{-15} m

$P_{\text{remnants}}, P_{\text{hadronization}}$

Hadron Deca

P_{decays}

Components of Markov Chain

- Resonance decays (not discussed here)
- Perturbative radiation (quark and gluon bremsstrahlung):
  - Iterative application of approximations to $|M_{n+1}|^2/|M_n|^2$
  - Restrict to phase space region to where non-perturbative corrections "small" → hadronization cutoff
  - Result: semi-inclusive calculation,
    - All brems activity "above" hadronization scale explicitly resolved (exclusive)
    - All activity "below" hadronization scale inclusively summed over
    - I.e., defined at a factorization scale of order the hadronization cutoff.
- Hadronization
  - Add last step of exclusivity to semi-inclusive calculation above
  - Iterative application of ???
- More stuff in pp (will get back to later)

Central point: MC hadronization models ≠ FO fragmentation functions. Job in MC is only to do last step from $Q_F \sim 1$ GeV → $Q_F \sim 0$

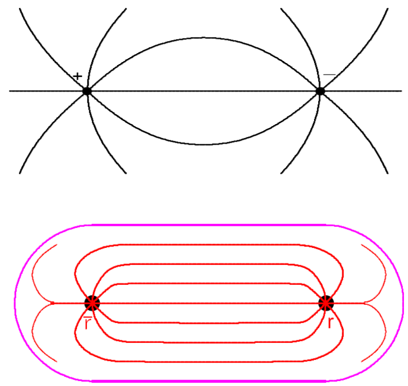
MC Hadronization Models

- The problem
  - Given a set of partons resolved at a scale of ~ 1 GeV, need a "mapping" from this set onto a set of colour-singlet hadronic states.

  - MC models do this in several steps
    - First map partons onto string or cluster states
      - "Representing continuum of highly excited hadronic states"
    - Then map strings/clusters onto discrete set of primary hadrons
    - Then allow primary hadrons to decay into secondary ones
      - (e.g., rho → pi pi)

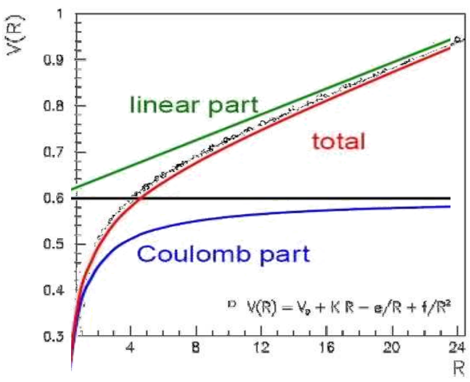
From Partons to Strings

- QCD : gluon self-interaction
  - → vacuum state contains quark (and gluon) Cooper pairs
  - → at large distances field lines compressed into vortex lines
- Linear confinement, string tension

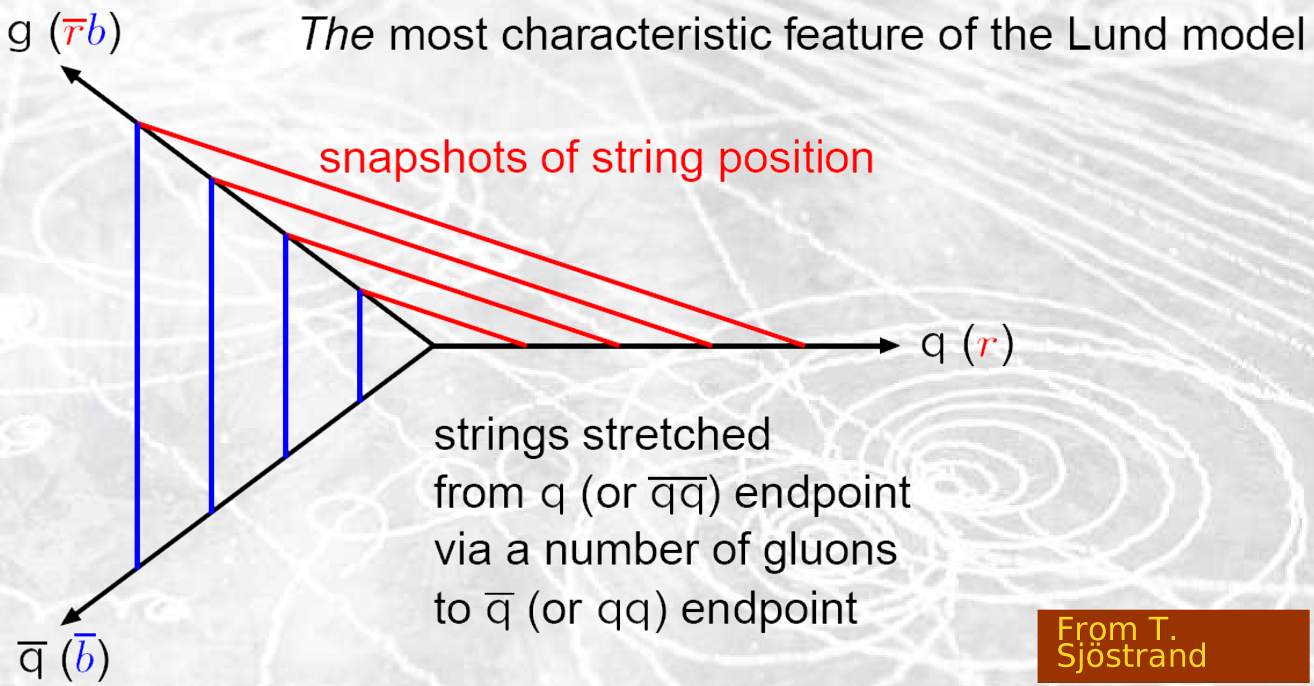


$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \iff V(r) \approx \kappa r$$

→ Motivates a model:
  - Separation of transverse and longitudinal degrees of freedom
  - → simple description as 1+1 dimensional worldsheet – string – with Lorentz invariant formalism



Gluons → Transverse Excitations



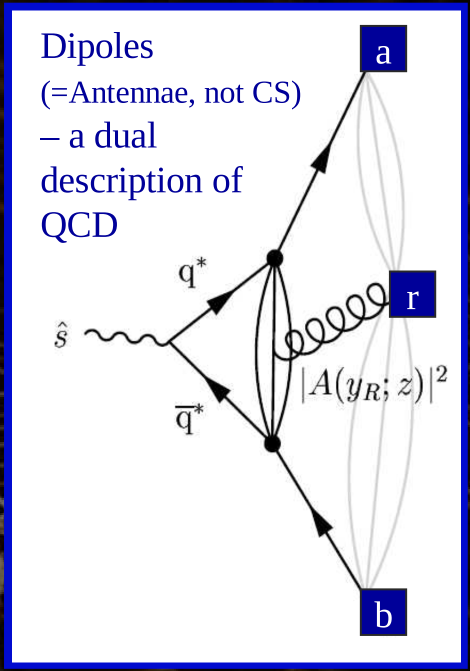
From T. Sjöstrand

Gluon = kink on string, carrying energy and momentum

- → Transverse structure
  - In the Lund model, this completes the parton → string mapping.
  - Physics now in terms of strings, with kinks, evolving in spacetime
  - Very simple space-time picture, few parameters (mess comes later)

Same picture from pQCD

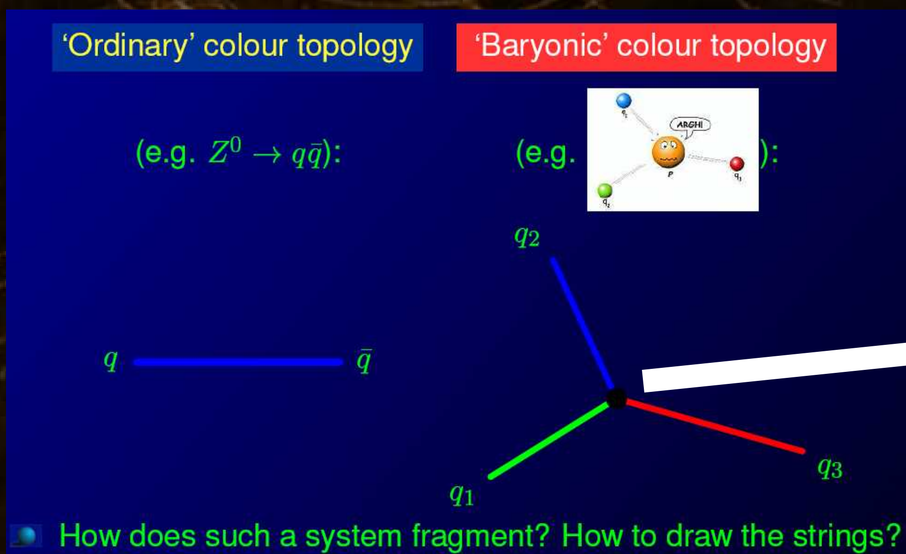
- Dual description of QCD: dipole-antennae
  - Can recast a system of radiating partons as chain of dipoles
  - Gives same LL approximation to QCD as parton showers, with better NLL properties
  - The Lund string can then be interpreted as the non-perturbative limit of such antennae

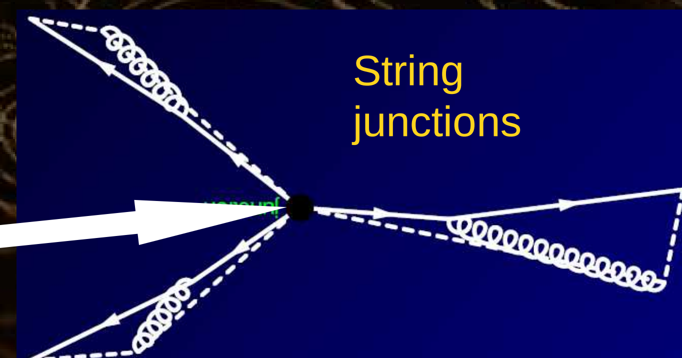


- Is Lund string *derivable as the "leading order" in some expansion representing this non-perturbative limit?*
  - *If so, could we access higher orders systematically?*
    - *E.g., Fatness? String interactions? String decay? Non-continuum effects? Subleading Colour? Coulomb part? …*
  - *Even if basic picture correct, next order may be very hard …*

One example of a "Next-Order" complication

- Original Lund string: leading-color (triplet-antitriplet) connections
  - → "Mesonic" description
  - Baryon number violation (or a resolved baryon number in your beam) → explicit epsilon tensor in color space. Then what?



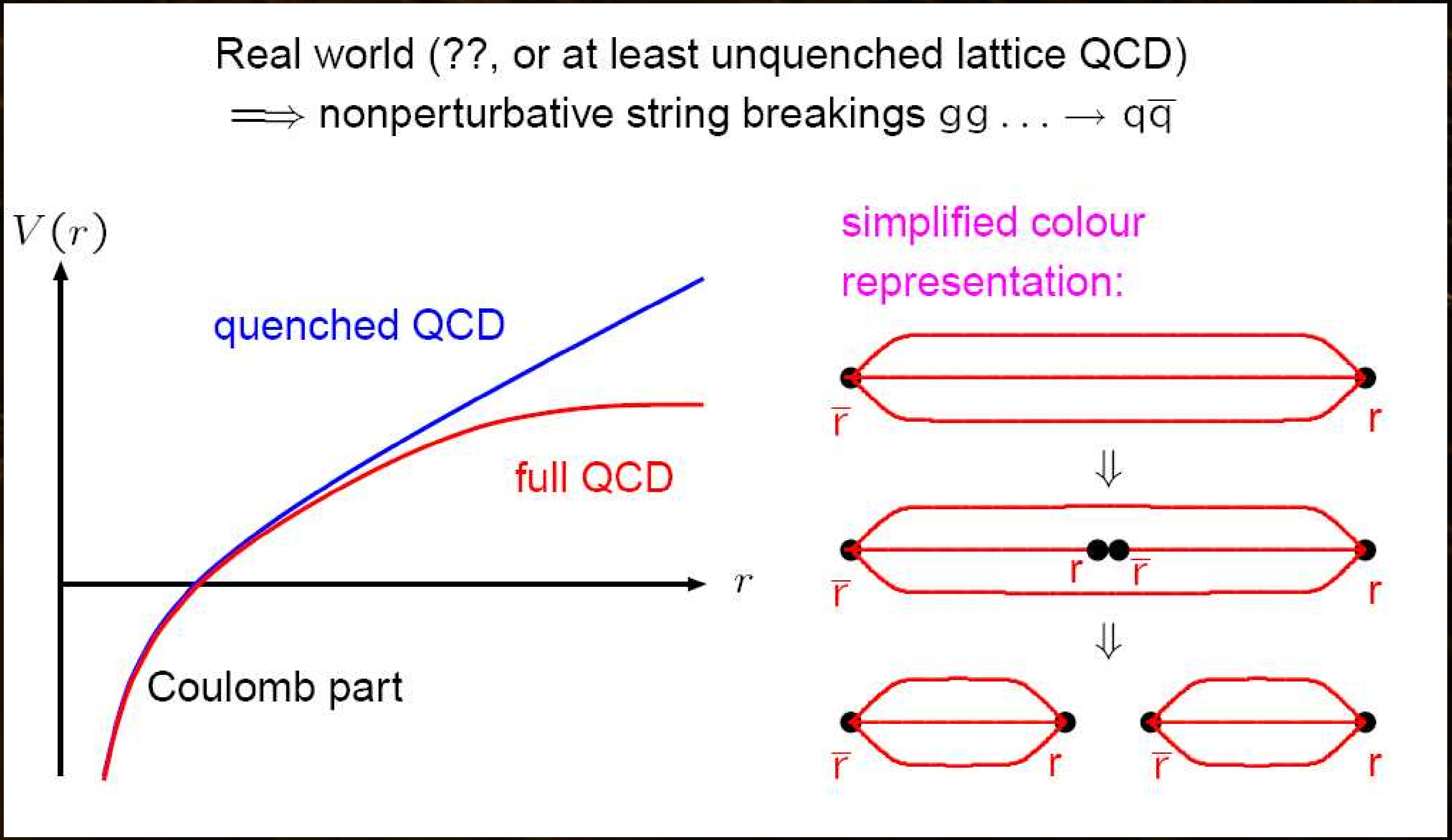


Sjöstrand & PS : Nucl.Phys.B659(2003)243, JHEP03(2004)053

- Perturbative Triplets → String endpoints
- Perturbative Octets → Transverse kinks
- Perturbative Epsilon tensors → String junctions

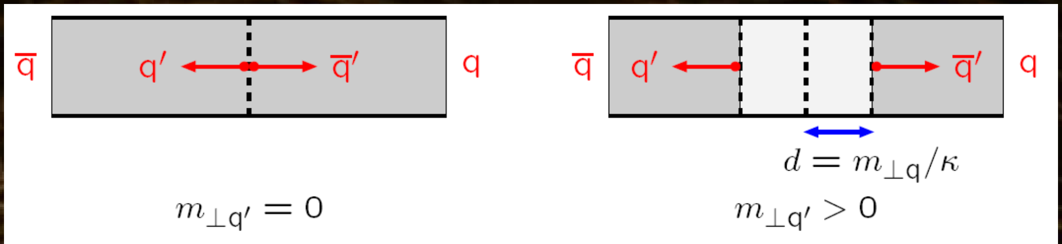
Real World : Strings Break

- Quantum fluctuations in string field →real if energy is to be gained



Strings → Hadrons

- Hadron production arises from string breaks



- String breaks modeled by tunneling

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{q}^2}{\kappa}\right)$$

1) common Gaussian $p_\perp$ spectrum

2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

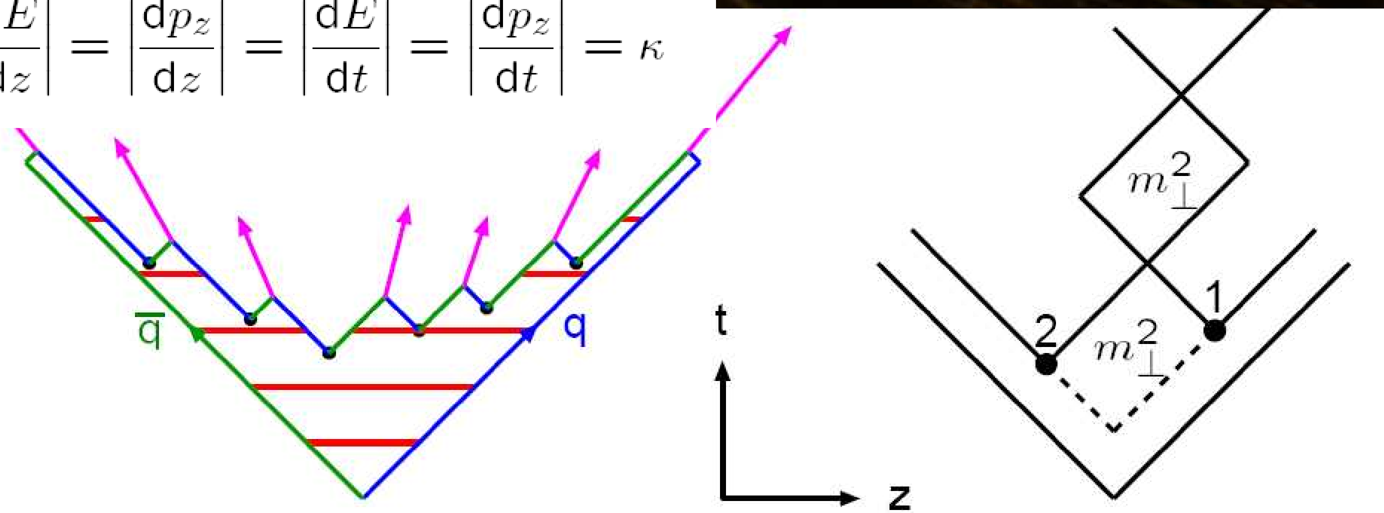
→ + Probability of string break constant per unit area → area law!

- But also depends on spins, hadronic wave functions, phase space, baryon production, … → (much) more complicated → many parameters

Strings → Hadrons

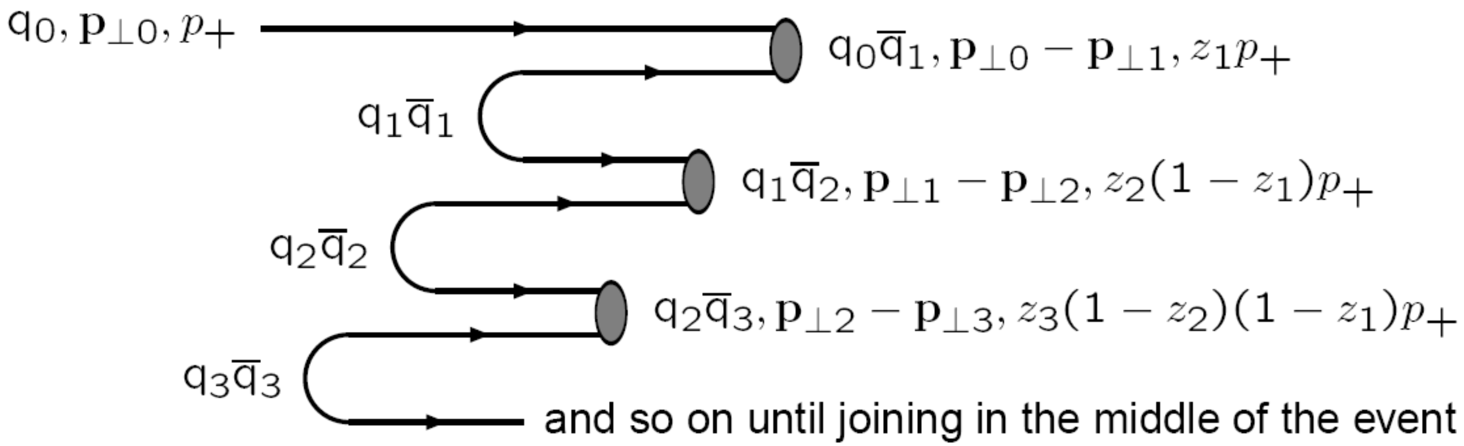
Repeat for large system ⇒ *Lund model*
which neglects Coulomb part:

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

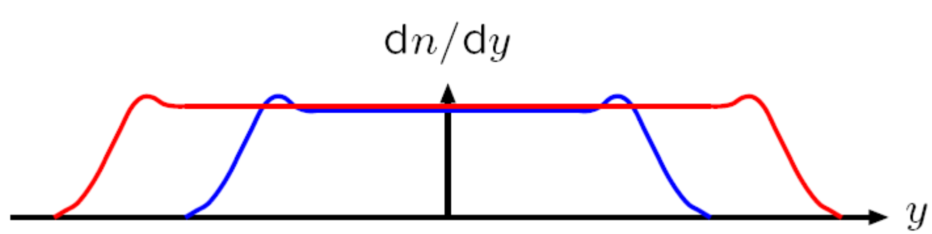


- Most fundamental : **THE AREA LAW**
  - Probability to get a specific configuration proportional to exp(-kA)
- String breaks causally disconnected → can proceed in arbitrary order (left-right, right-left, in-out, …) → iterative ansatz

The Iterative Ansatz



Scaling in lightcone $p_\pm = E \pm p_z$ (for $q\overline{q}$ system along z axis) implies flat central rapidity plateau + some endpoint effects:



$\langle n_{\mathrm{ch}} \rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, $\sim$ Poissonian multiplicity distribution

From T. Sjöstrand

Simple Questions

- Can current models be perceived as “first term” in some systematic expansion?
  - Could some parameters be calculable / constrained ?
  - Concerning space-time evolution? Concerning string breaks?
  - Can we say anything about further terms in such an expansion that could be modeled / calculated?
- It seems “clear”, phenomenologically, that
  - Hadrons (LPHD?) ~ resonant limit
  - Clusters ~ small-mass continuum “limit”
  - Strings ~ large-mass continuum limit

- Is there a unified model?
  - Can / should one “match” these models? (effectively what is already done)
  - Can / should one improve matching to pQCD?
- Which of these questions is most relevant?

Bottom Line So Far

- For applied phenomenology:
  - Current models adequate at LEP, possibly excepting baryon production.
  - To reach even higher precision, need data-driven methods.
- For theoretical phenomenology
  - Successes and failures of models have elucidated the structure of non-pert. QCD
  - Simple ideas have evolved to complex models, with many “non-trivial” effects included (massive quarks, junctions, baryon production, Bose-Einstein, …)
  - But not clear how to systematically go further.
- Life grants nothing to us mortals without hard work
  - Enter LHC

Additional Sources of Particle Production

- Domain of fixed order and parton shower calculations: hard partonic scattering, and bremsstrahlung associated with it.

- But hadrons are not elementary
- + QCD diverges at low p_T
- → multiple perturbative parton-parton collisions should occur → pairwise balancing minijets ('lumpiness') in the underlying event

e.g. 4→4, 3→ 3, 3→2

- Normally omitted in explicit perturbative expansion
- + Remnants from the incoming beams
- + additional (non-perturbative / collective) phenomena?
  - Bose-Einstein Correlations
  - Non-perturbative gluon exchanges / colour reconnections ?
  - String-string interactions / collective multi-string effects ?
  - Interactions with "background" vacuum / with remnants / with active medium?

Interleaved Evolution

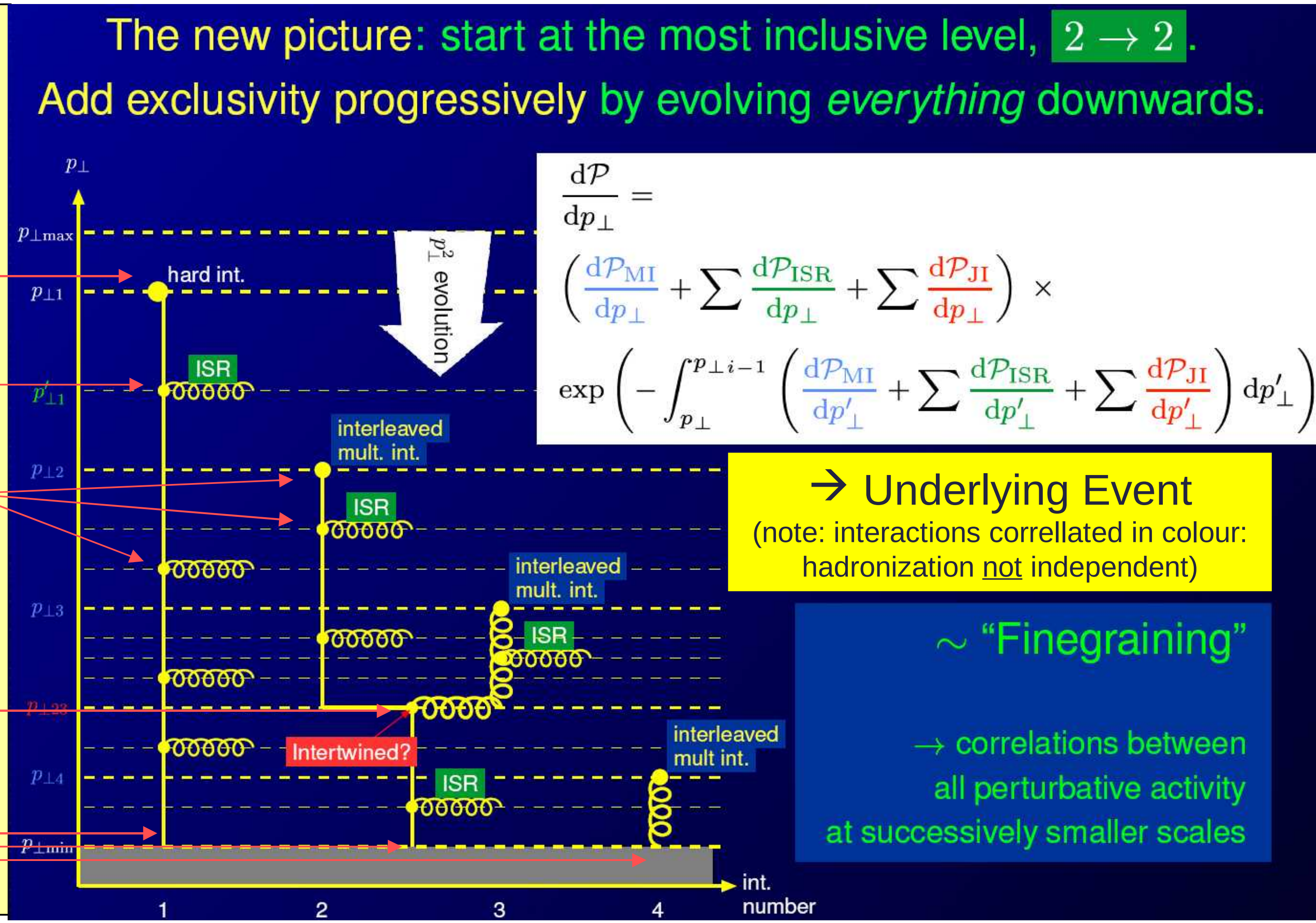
Fixed order matrix elements

Parton Showers matched to further matrix elements

multiparton PDFs derived from sum rules

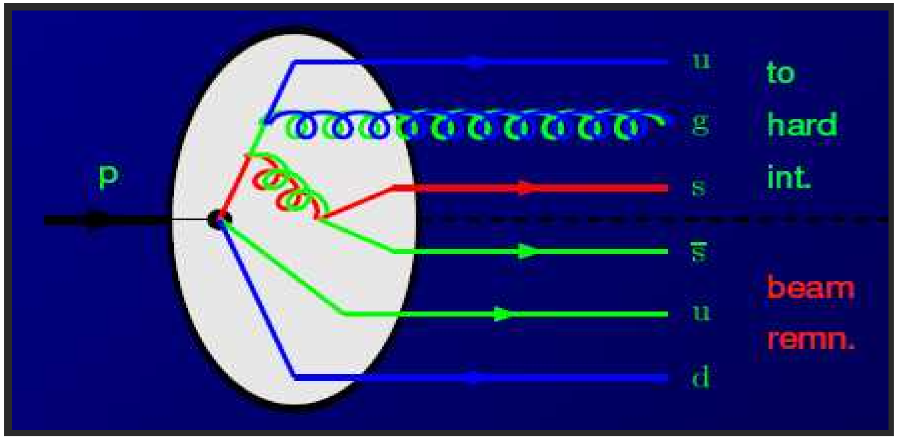
perturbative “intertwining”?

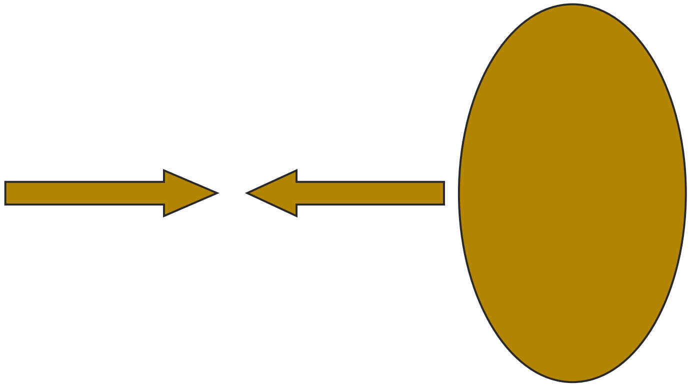
Beam remnants Fermi motion / primordial k_T



Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

What's the problem?

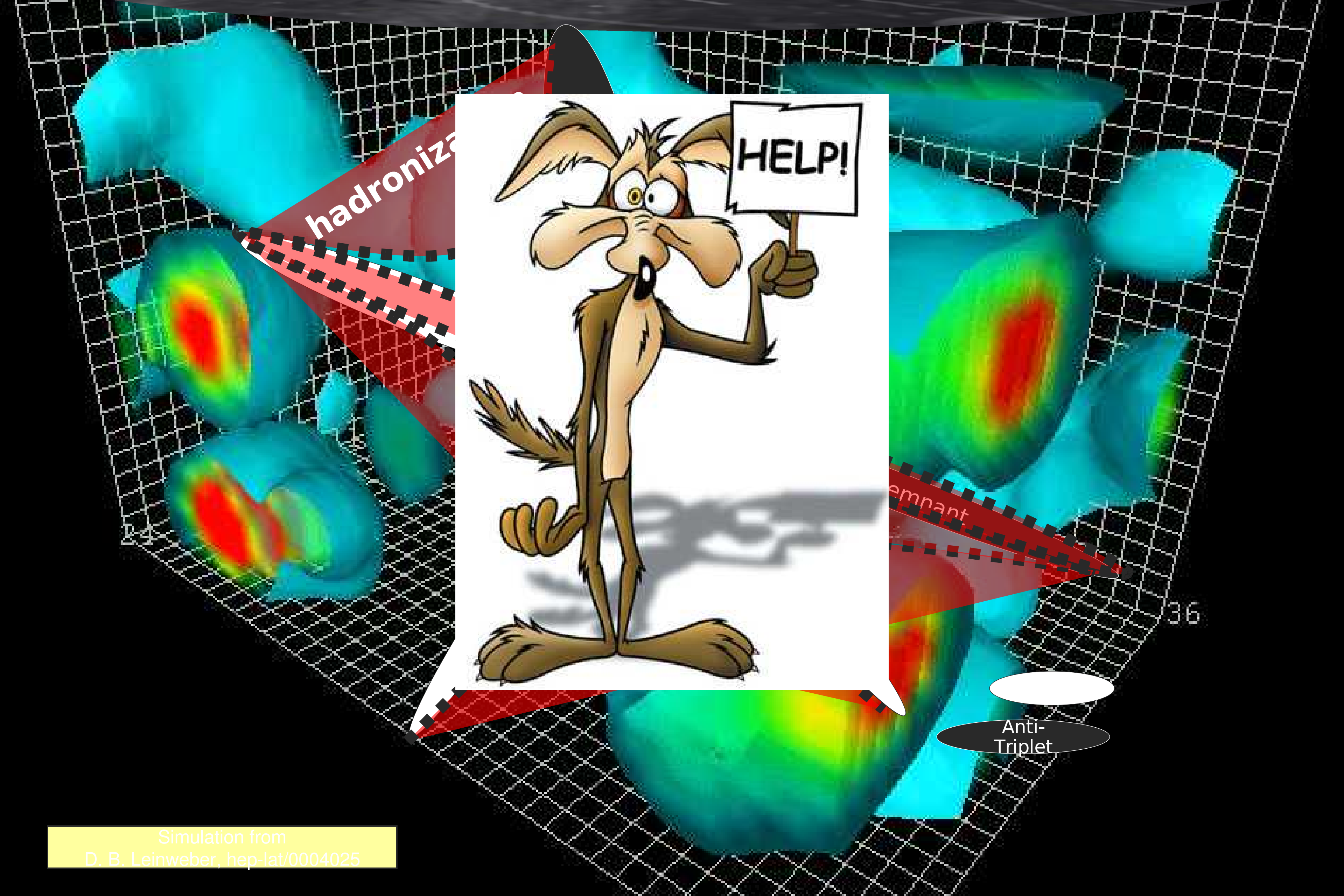




How are the initiators and remnant partons correllated?

- in impact parameter?
- in flavour?
- in x (longitudinal momentum)?
- in k_T (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

Now Hadronize This!

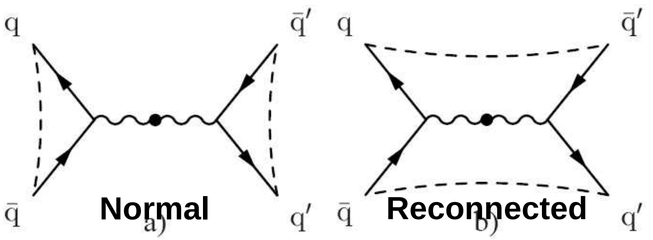


Simulation from
D. B. Leinweber, hep-lat/0004025

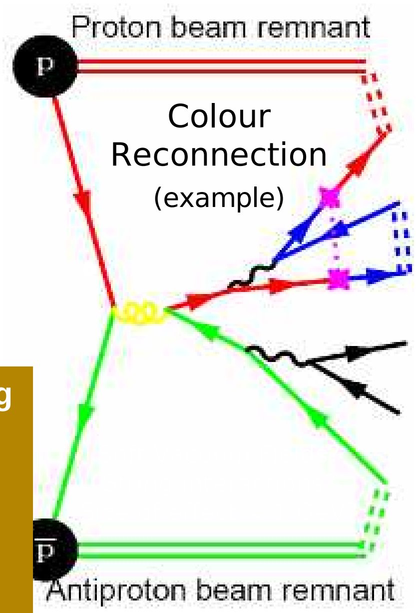
Color Reconnections

Sjöstrand, Khoze, Phys.Rev.Lett.72(1994)28 & Z. Phys.C62(1994)281 + more …
OPAL, Phys.Lett.B453(1999)153 & **OPAL**, hep-ex0508062

- Searched for at LEP
  - Major source of W mass uncertainty
  - Most aggressive scenarios excluded
  - But effect still largely uncertain $P_{reconnect} \sim 10\%$



- Prompted by CDF data and Rick Field’s studies to reconsider.
  What do we know?
  - Non-trivial initial QCD vacuum
  - A lot more colour flowing around, not least in the UE
  - String-string interactions? String coalescence?
  - Collective hadronization effects?
  - More prominent in hadron-hadron collisions?
  - What (else) is RHIC, Tevatron telling us?
  - *Implications for precision measurements:Top mass? LHC?*



Existing models only for WW ➔ a new toy model for all final states: **colour annealing**
Attempts to minimize total area of strings in space-time
• Improves description of minimum-bias collisions
Skands, Wicke EPJC52(2007)133 ;
Preliminary finding Delta(mtop) ~ 0.5 GeV
Now being studied by Tevatron top mass groups

Summary

- I find hadronization interesting because
  - It’s a field where more than just calculations rema
  - Real possibilities for real surprises, both in experi theory (color reconnections just one example)

- To go beyond current models does appear quite challenging. Several goals possible?
  - Hard line: I want a systematic approach to hadronization which is both connected to first principles and which beats current models. Useful for everyone.
  - Pheno line: Give up formal connection to first principles. Combine new first-principles information with better model building. Useful for pheno/experiment.
  - Fomal line: Give up beating current models (at least to begin with, see hard line above for later). Explore connection with first principles and hope for further spoils later. Useful for theory.

AdS Hadronization