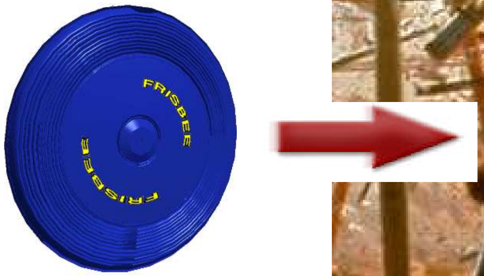
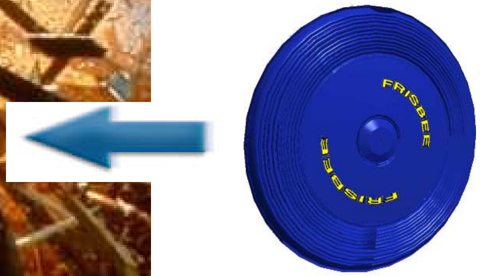
THE UNDERLYING EVENT

A new model for multiple parton scattering



Butch Cassidy and the Sundance Kid. Copyright: Twentieth Century Fox Films Inc.



P. Skands & T. Sjöstrand (Lund University).

Based on hep-ph/0402078, hep-ph/0310315, hep-ph/0308153.

THE UNDERLYING EVENT

1. Basic Phenomenology:

   Multiple Interactions — Lightning Review.

2. A New Model $\to$ PYTHIA 6.3:

   Flavour and Momentum Correlations.

   Beam Remnants.

   Colour Correlations and String Topologies.

3. Outlook.

The Underlying Event

- Need to understand correlations and fluctuations. Simple parametrizations not sufficient. From QCD point of view: many interesting questions remain unanswered.

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  more reliable understanding is needed.

The Underlying Event

- ✧Need to understand correlations and fluctuations. Simple parametrizations not sufficient. From QCD point of view:

  many interesting questions remain unanswered.

- ✧Random and systematic fluctuations in the underlying activity can impact precision measurements as well as New Physics searches:

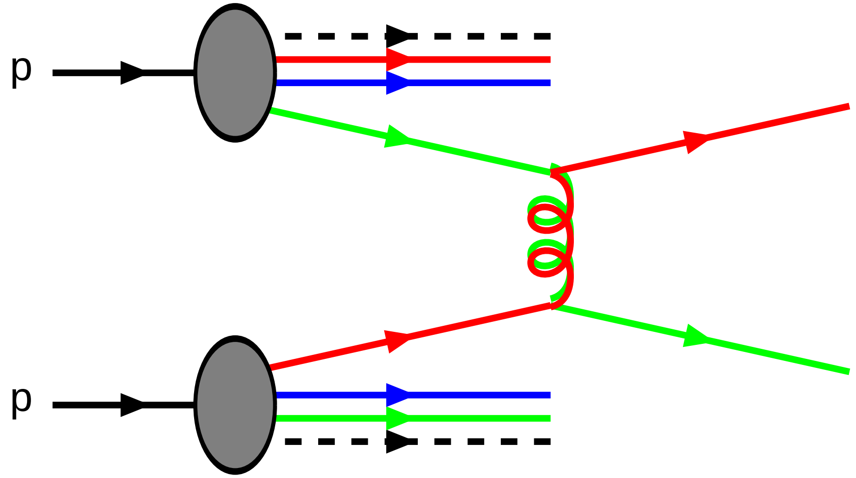
  more reliable understanding is needed.

- ✧Lots of fresh data from Tevatron:

  $\rightarrow$ great topic for phenomenology right now!

Multiple Interactions — Lightning Review

Consider just perturbative QCD $2 \to 2$ scattering:



$$\mathrm{qq}' \to \mathrm{qq}'$$
$$\mathrm{q}\bar{\mathrm{q}} \to \mathrm{q}'\bar{\mathrm{q}}'$$
$$\mathrm{q}\bar{\mathrm{q}} \to \mathrm{gg}$$
$$\mathrm{qg} \to \mathrm{qg}$$
$$\mathrm{gg} \to \mathrm{gg}$$
$$\mathrm{gg} \to \mathrm{q}\bar{\mathrm{q}}$$

✧ dominated by t-chanel gluon exchange: $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{1}{p_\perp^4}$

Cross Section is Infrared Divergent:

$$\sigma_{2\to2}(p_{\perp\min}) = \int_{p_{\perp\min}}^{\sqrt{s}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}\mathrm{d}p_\perp \propto \frac{1}{p_{\perp\min}^2}$$

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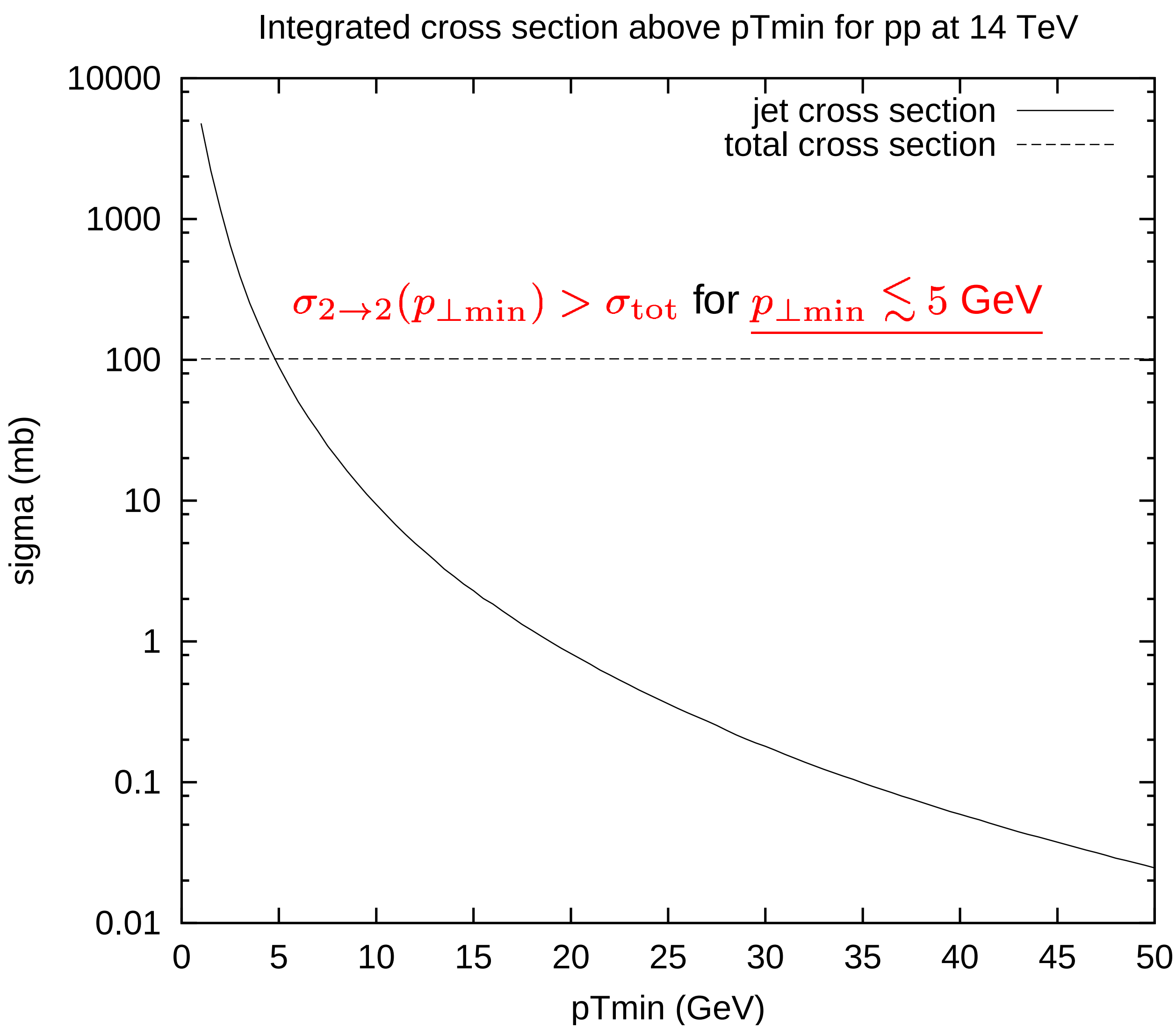
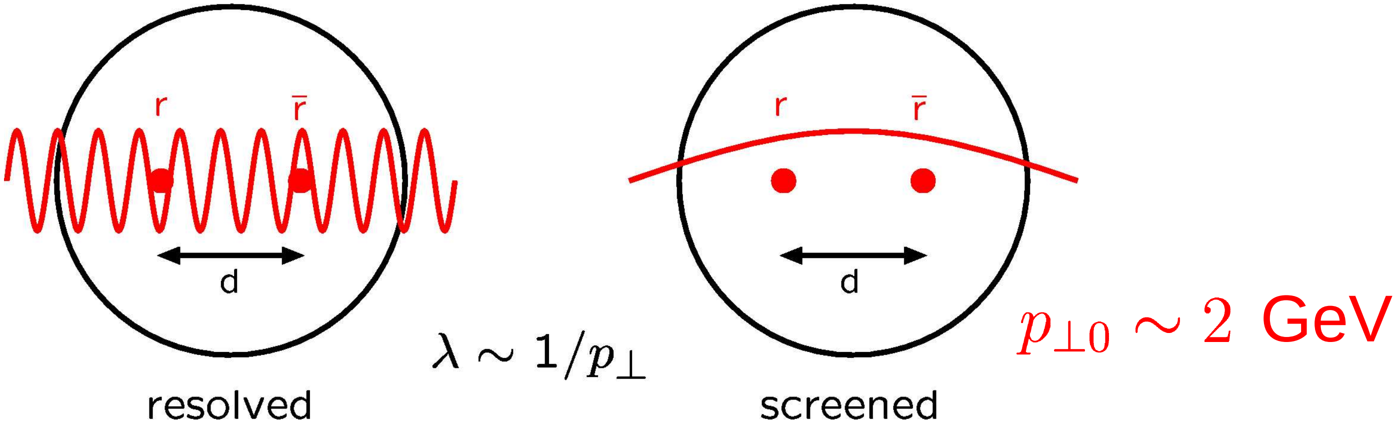


2 Reasons...

1. **Multiple interactions!**
   - Simple consequence of composite nature of hadrons. *Must* exist!
   - σ_{tot}: hadron-hadron collisions. $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
   - $\sigma_{2\to 2}$: parton–parton collisions. $\sigma_{2\to 2} = \sum_{n=0}^{\infty} n\, \sigma_n$
   - $\sigma_{2\to 2} > \sigma_{\mathrm{tot}} \iff$ Many interactions / event: $\langle n \rangle > 1$

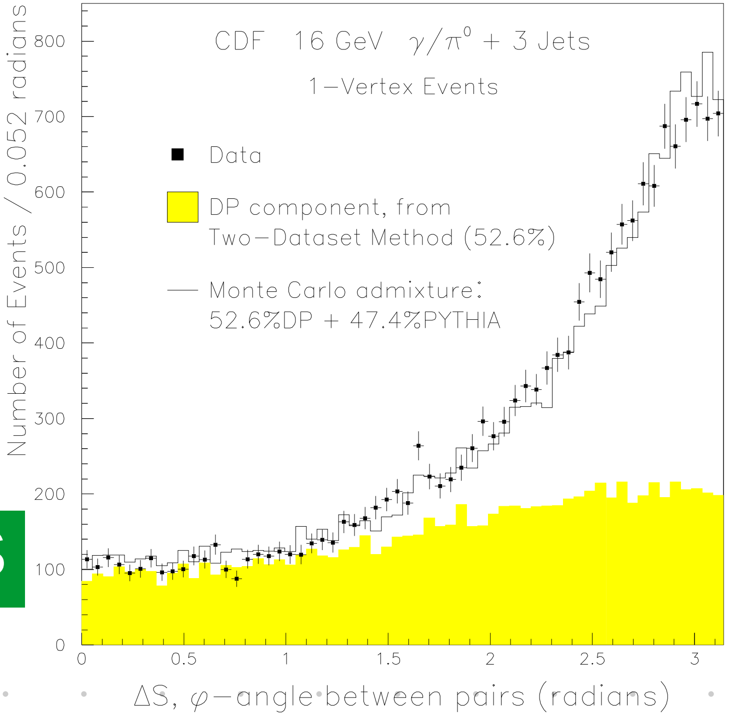
2. **Breakdown of perturbative QCD, colour screening.**



Direct Verifications

Basic idea: expect two pair-wise balancing jets in double parton scattering (DPS) but not in double bremsstrahlung emission.

- **AFS**: 4-jet events at $E_\perp > 4$GeV in 1.8 units of η. Project out 2 pairs of jets and study imbalancing variable, $I = p^2_{\perp 1} + p^2_{\perp 2}$. **Excess of events with small I**.
- **CDF**: Extraction by comparing double parton scattering (DPS) to a mix of two separate scatterings. Event sample: 14000 $\mathrm{p\bar{p}} \to \gamma/\pi^0 + 3j$ events. **Strong signal observed, 53% DPS**



Indirect Verifications

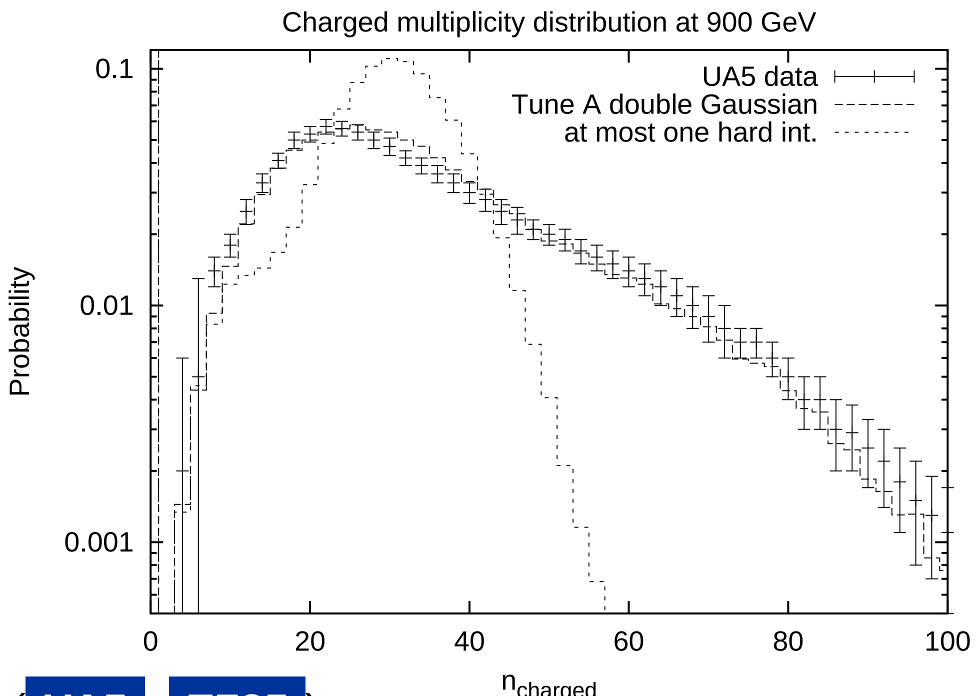
Basic idea:

- Hadronization alone produces roughly Poissonian fluctuations in multiplicity.
- Additional soft interactions can 'mess up' colour flow $\rightarrow$ larger fluctuations.

UA5: (900 GeV)

$\langle n_{\mathrm{ch}} \rangle = 35.6$,

$\sigma_{n_{\mathrm{ch}}} = 19.6$.



- + forward–backward correlations (**UA5**, **E735**)
- + pedestal effect (**UA1**, **CDF**, **H1**), ...

Why care?

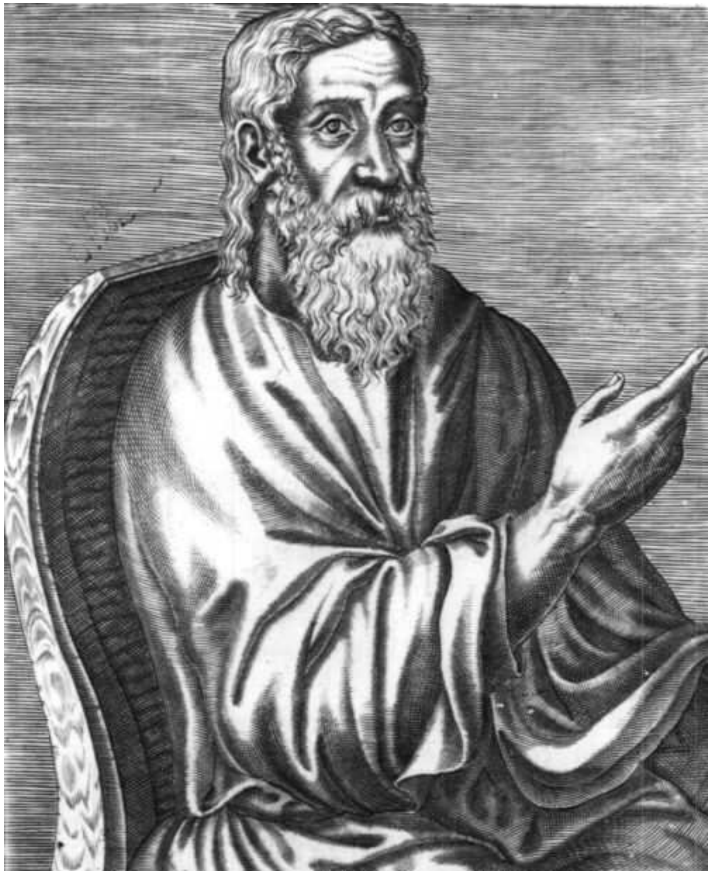
Multiple Interactions:

- are guaranteed to exist (+ AFS, UA1, UA5, E735, H1, CDF).
- lead to correlations and fluctuations in activity for which no detailed physics model yet exists.
- even when soft, they can have drastic consequences, by affecting the colour flow.
- when (semi)hard they produce multiple (mini)jets.
- affect jet profiles and jet pedestals.
- give random as well as systematic shifts in jet energies.

$\Longrightarrow$ precision physics involving jets or underlying events impossible without good understanding of multiple interactions.

A New Model

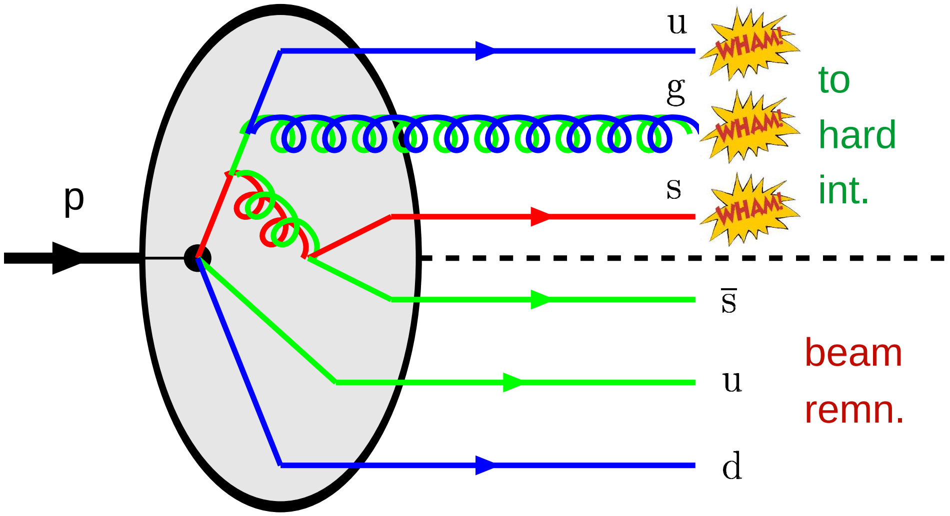
✧ This talk is about PYTHIA 6.3



"A solemn Hellenic assembly had met at Pytho, to celebrate the death of the Pythic serpent (v. 6.2), when Eunomos sang the reptile's epitaph. Whether his ode was a hymn in praise of the serpent, or a dirge, I am not able to say."

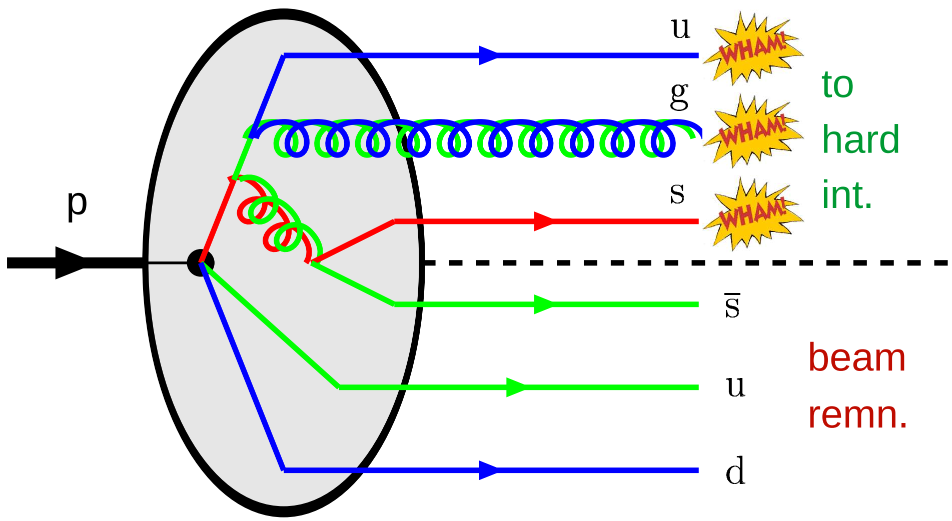
[Clement of Alexandria ($\sim$ 200 AD): "Exhortation to the Heathen"]

Towards a realistic model



- How are the hard scattering initiators and beam remnant partons correlated?

Towards a realistic model



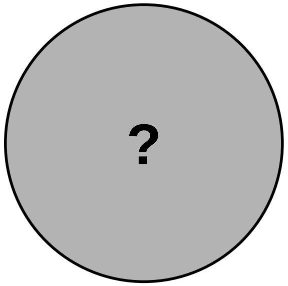
- How are the hard scattering initiators and beam remnant partons correlated?

☞ In impact parameter?
☞ In flavour?
☞ In longitudinal momentum?
☞ In colour?
☞ In (primordial) transverse momentum?

- (How) are the showers correlated / intertwined?

Correlations in flavour and x_i

Consider a hadron:



PDF for finding flavours $i_1 \ldots i_n$ with momenta $x_1 \ldots x_n$ in a hadron H probed at scales $Q_1 \ldots Q_n$:

$$f_{i_1 \ldots i_n / H}(x_1 \ldots x_n, Q_1^2 \ldots Q_n^2)$$

But experimentally, all we got is $n = 1$.

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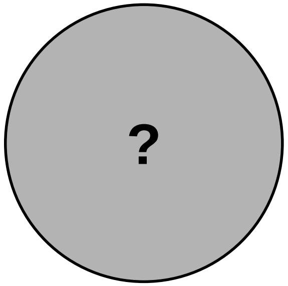

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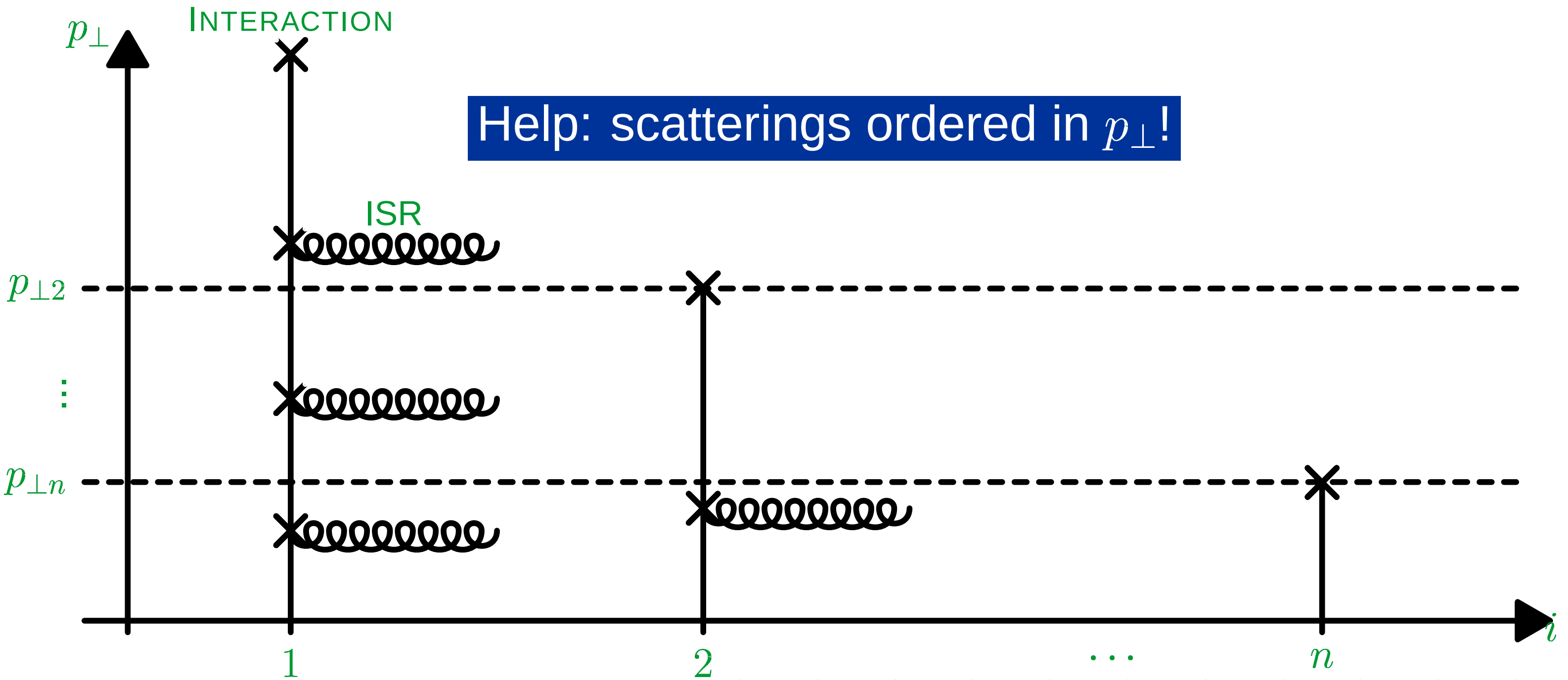


Correlations in flavour and x_i

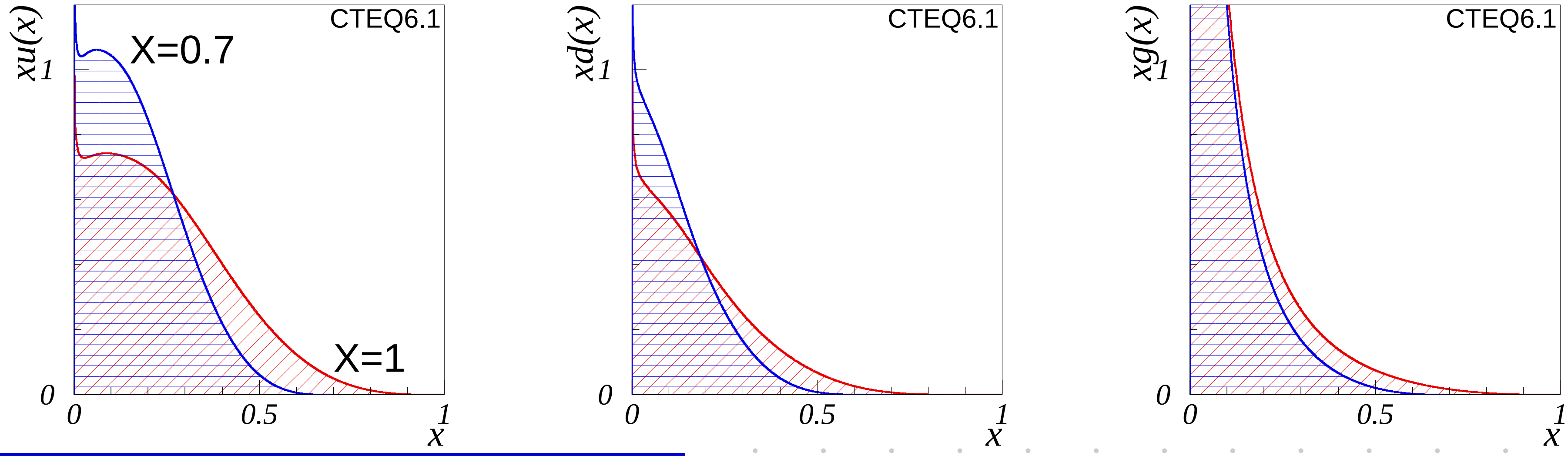
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

1. Overall momentum conservation (old):

Starting point: simple scaling ansatz in x.

For the n'th scattering:

$$x \in [0, X] \;\; ; \; X = 1 - \sum_{i}^{n-1} x_i \implies f_n(x) \sim \frac{1}{X} f_0\left(\frac{x}{X}\right)$$



Correlations in flavour and x_i

Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

——— Normalization and shape NEW!: ———

- If valence quark knocked out.

  $\rightarrow$ Impose valence counting rule: $\int_0^X q_{fn}^{\mathrm{val}}(x, Q^2)\,\mathrm{d}x = N_{fn}^{\mathrm{val}}$.

- If sea quark knocked out.

  $\rightarrow$ Postulate "companion antiquark": $\int_0^{1-x_s} q_f^{\mathrm{cmp}}(x; x_s)\,\mathrm{d}x = 1$.

- But then momentum sum rule is violated:

$$\int_0^X x\Big(\sum_f q_{fn}(x, Q^2) + g_n(x, Q^2)\Big)\mathrm{d}x \neq X$$

$\rightarrow$ Assume sea+gluon fluctuates up when a valence quark is removed and down when a companion quark is added.

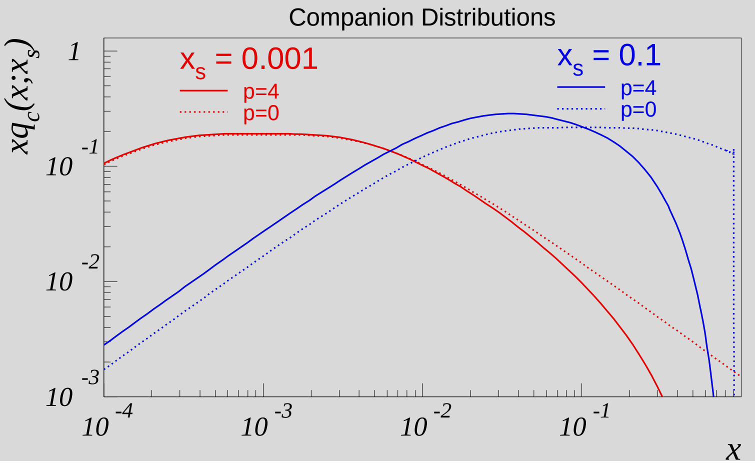
Remnant PDFs

$$\text{quarks}: \quad q_{fn}(x) = \frac{1}{X}\left[\frac{N^{\text{val}}_{fn}}{N^{\text{val}}_{f0}} q^{\text{val}}_{f0}\left(\frac{x}{X}, Q^2\right) + a\, q^{\text{sea}}_{f0}\left(\frac{x}{X}, Q^2\right) + \sum_j q^{\text{cmp}_j}_{f0}\left(\frac{x}{X}; x_{s_j}\right)\right]$$

$$q^{\text{cmp}}_{f0}(x; x_s) = C\,\frac{\tilde{g}(x+x_s)}{x+x_s} P_{g\to q_f\bar{q}_f}\left(\frac{x_s}{x+x_s}\right) \quad ; \quad \left(\int_0^{1-x_s} q^{\text{cmp}}_{f0}(x; x_s)\,\mathrm{d}x = 1\right)$$

$$\text{gluons}: \quad g_n(x) = \frac{a}{X} g_0\left(\frac{x}{X}, Q^2\right)$$

$$a = \frac{1 - \sum_f N^{\text{val}}_{fn}\langle x^{\text{val}}_{f0}\rangle - \sum_{f,j}\langle x^{\text{cmp}_j}_{f0}\rangle}{1 - \sum_f N^{\text{val}}_{f0}\langle x^{\text{val}}_{f0}\rangle}$$



Used to select a $p_\perp$-ordered sequence of hard $2 \to 2$ scatterings, and to perform backwards DGLAP shower evolution.

Intermezzo 1: exit perturbation theory

Perturbation theory got us:

- A set of interactions, with showers, starting from $k_\perp = 0$ initiator partons.
- A set of partons left behind in the beam remnants, with only flavours known at this point (by flavour conservation).
- A total $1 - X$ of longitudinal momentum has been removed from each beam remnant.

Hurdles remaining:

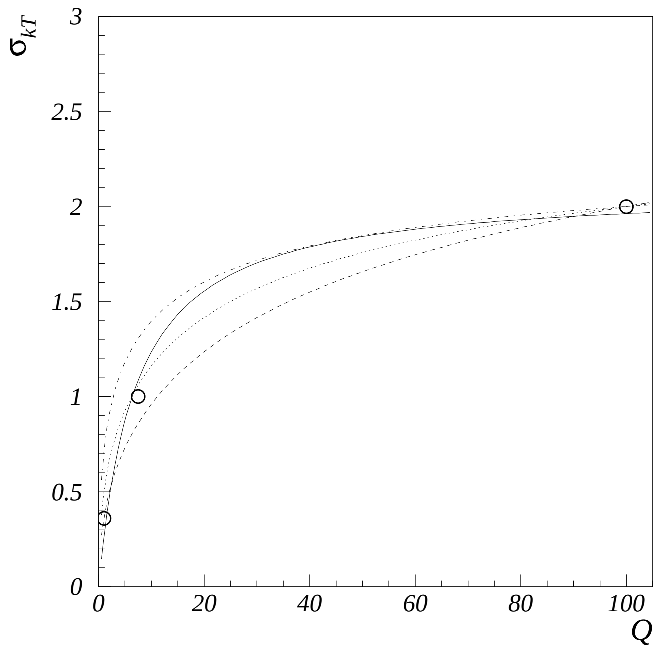
- Confinement effects $\to$ primordial $k_\perp$. How much? Recoils?
- What is the momentum sharing in the remnants?
- How are initiator and remnant partons correlated in colour?
- How do the remnant systems hadronize?

Confinement and primordial $k_\perp$

- Confined wavefunctions $\to k_\perp = \hbar / r_\mathrm{p} \sim \Lambda_\mathrm{QCD}$.
- Empirically, one notes a need for larger values.

$$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x\,\mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)}$$

$$\sigma(1\ \mathrm{GeV}) \approx 0.36\ \mathrm{GeV}\ (hadr.)$$
$$\sigma(10\ \mathrm{GeV}) \approx 1\ \mathrm{GeV}\ (EMC)$$
$$\sigma(m_Z) \approx 2\ \mathrm{GeV}\ (Tevatron)$$



Solid: $\dfrac{2.1Q}{7+Q}$ (hardcoded default)

Dashed: $\dfrac{4\sqrt{Q}}{10+\sqrt{Q}}$

Dotted: $\dfrac{3\sqrt{Q}}{5+\sqrt{Q}}$

Dot-dashed: $\dfrac{2.5\sqrt{Q}}{2.5+\sqrt{Q}}$

- **Recoils**: along colour neighbours (or chain of neighbours) or onto all initiators and beam remnant partons equally. (k_z rescaled to maintain energy conservation.)

Sharing of x_{rem} in beam remnant

Each hard scattering subsystem has light-cone momenta:

$$\begin{aligned} p_+ &= \gamma(E_1^{CM(z)} + E_2^{CM(z)}) + \gamma\beta(E_1^{CMz} + E_2^{CMz}) \\ &= \sqrt{\tfrac{1+\beta}{1-\beta}\left(\hat{s} + (\vec{p}_\perp^{(1)} + \vec{p}_\perp^{(2)})^2\right)} \\ &= \sqrt{\tfrac{x_1}{x_2}}\sqrt{\hat{s}_\perp} \\ p_- &= \gamma(1-\beta)(E_1^{CM(z)} + E_2^{CM(z)}) = \sqrt{\tfrac{x_2}{x_1}}\sqrt{\hat{s}_\perp} \end{aligned}$$

Remaining light-cone momenta available for BR:

$$p_{rem}^+ = \sqrt{s} - \sum_i \sqrt{\tfrac{x_i^{(+)}}{x_i^{(-)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)} \;\; ; \;\; p_{rem}^- = \sqrt{s} - \sum_i \sqrt{\tfrac{x_i^{(-)}}{x_i^{(+)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)}$$

Def:"$\pm$" side BR partons have fractions $x_{j/k}$ of $p_{rem}^{\pm}$.

- Assume $x_{j,k}$ distributed according to 'remnant' pdf's and fragmentation functions (with (E,p) conserved).
- NB: composite BR systems (w. pion/gluon clouds?) $\rightarrow$ larger x?

Intermezzo 2: now it gets tougher

We have arrived at:

- A set of $p_\perp$-ordered interactions, with showers, taking into account non-zero primordial $k_\perp$ effects.
- A set of partons left behind in the beam remnants, whose flavours are known and whose kinematics have been worked out (i.e. x and $\vec{k}_\perp$).

But life grants nothing to us mortals without hard work

- How are initiator and remnant partons correlated in colour?
- How do remnant systems hadronize?

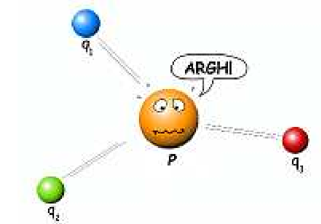
Hadronization of Remnant Systems

- Imagine placing a stick o' dynamite inside a proton, imparting the 3 valence quarks with large momenta relative to each other.

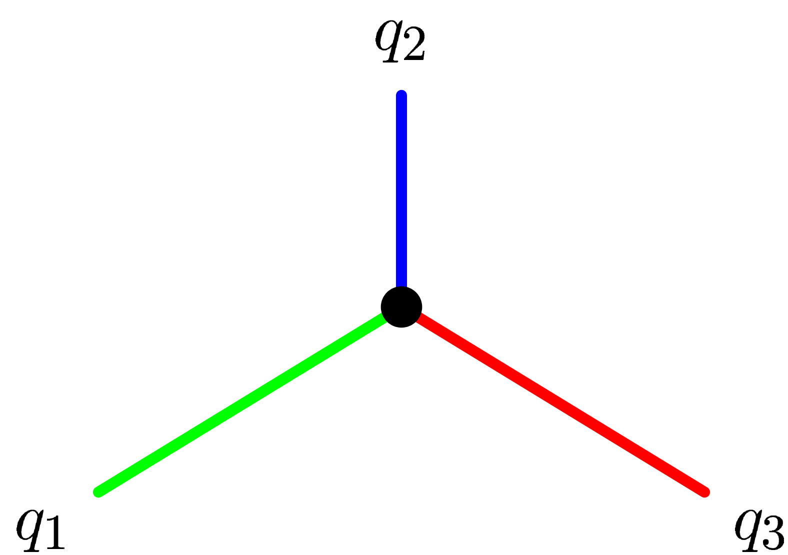
'Ordinary' colour topology

(e.g. $Z^0 \to q\bar{q}$):

'Baryonic' colour topology

(e.g. 

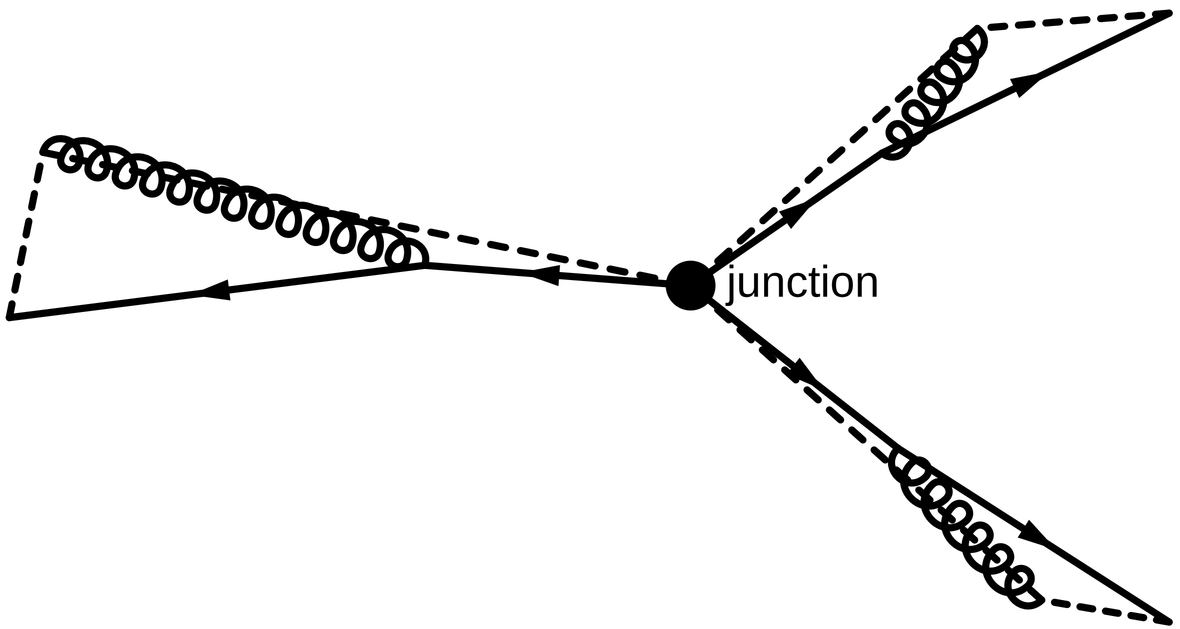
):



- Need to extend string model to handle baryonic topology.

String Junctions

- Fundamental properties of QCD vacuum suggest string picture still applicable.
- Baryon wavefunction building and string energy minimization $\Longrightarrow$ picture of 3 string pieces meeting at a 'string junction'.



(Warning: This picture was drawn in a "pedagogical projection" where distances close to the center are greatly exaggerated!)

Junction Fragmentation

How does the junction move?

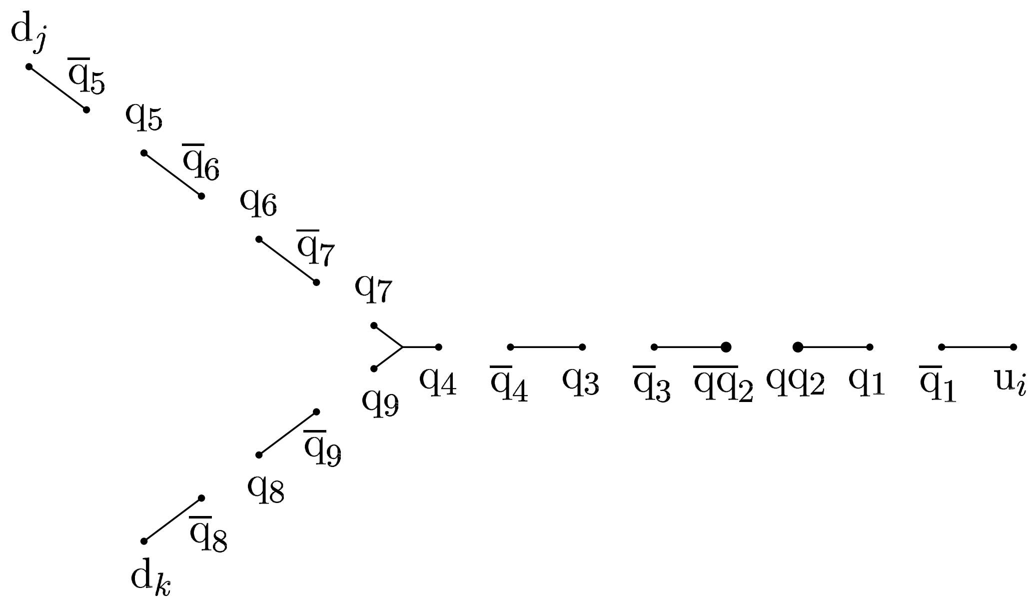
- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at 120°:

  $$p^\mu_{\mathrm{pull}} = \sum_{i=1,N} p^\mu_i e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

  (since soft gluons 'eaten' by string)
- Note: the junction motion also determines the baryon number flow!)

Junction Fragmentation

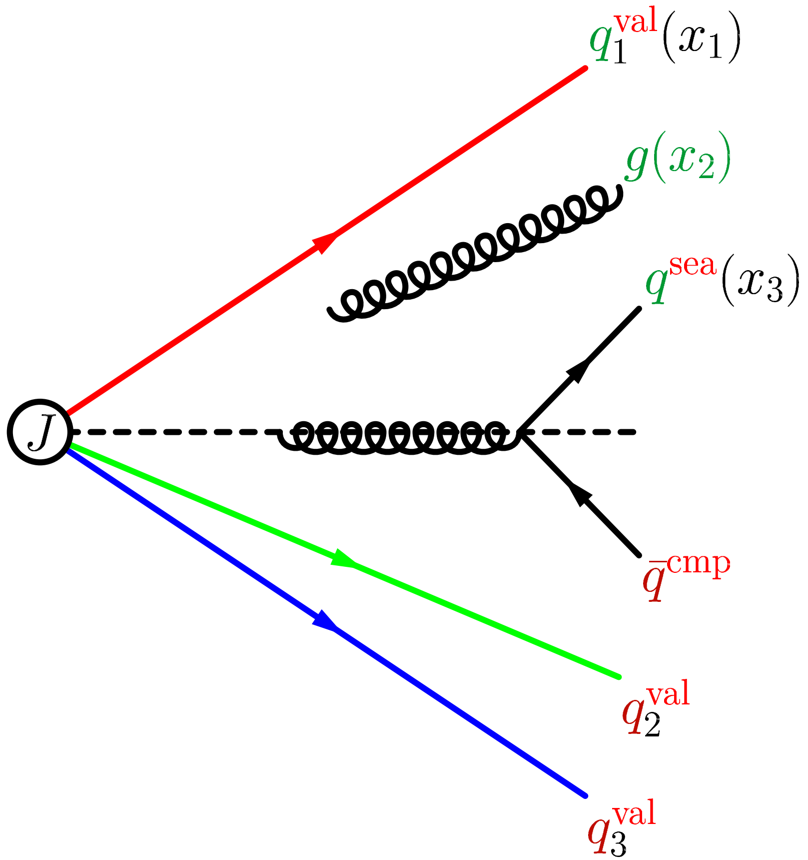
How does the system fragment?



- First 2 pieces fragmented outwards–in, junction baryon formed around junction, last string piece fragmented as ordinary $q\overline{q}$ string.
- NB: Other topologies also possible (junction–junction strings, junction–junction annihilation).

Colour Correlations and String Topologies

- But how to draw the strings? How are initiator and beam remnant partons colour connected to each other?



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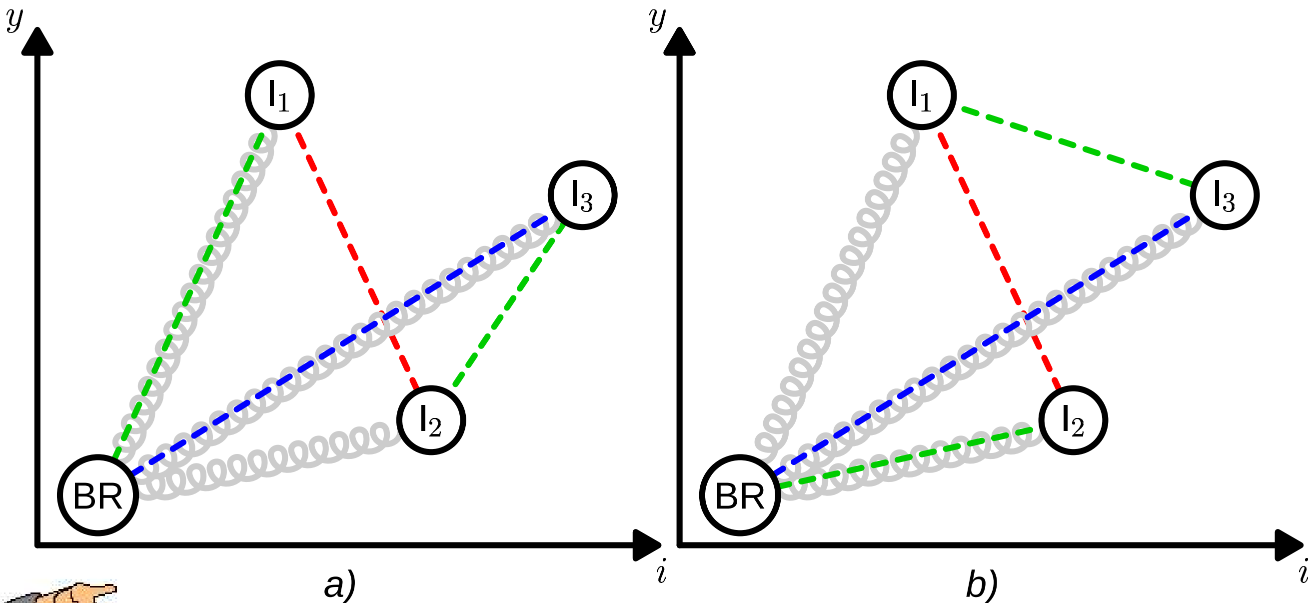


What is the colour flow?

What is the Colour Flow?

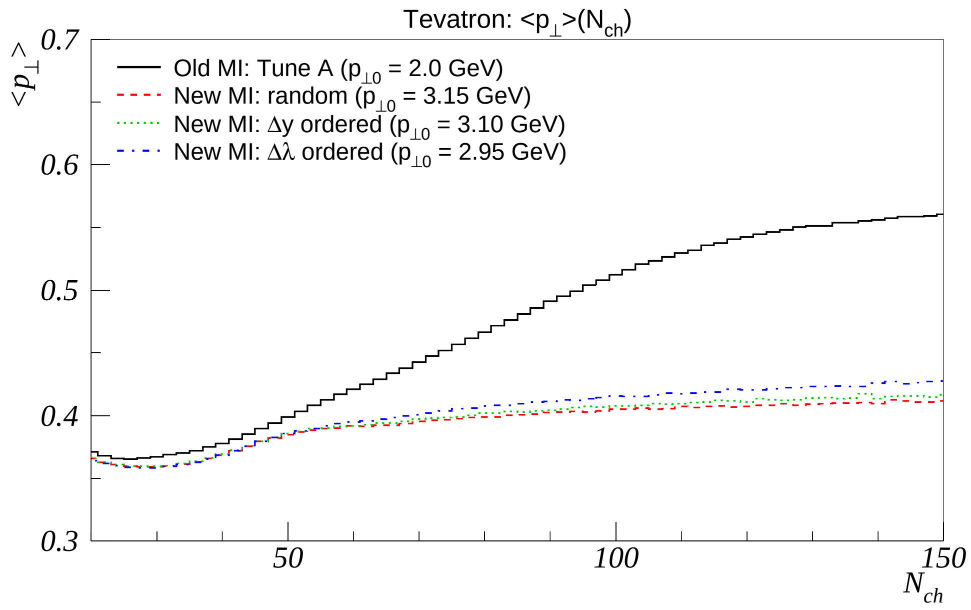
Possible ordering mechanisms:

- Always require physical colour flow (e.g. no singlet g).
- Simplest ordering is random, but gives *very* large multiplicity increase per interaction *and* large baryon number stopping.
- Tune A indicates that nature favours small increases in string length over large ones $\rightarrow$ try 'smarter' ways of connecting initial state colours.

1. Random (but with suppression of remnant breakups)
2. Ordering of connections by rapidity, Δy.
3. Ordering by approximate string length, $\Delta\lambda$.

Testing the Colour Correlations

- A variable that we have found to be very sensitive is the average transverse momentum (per charged particle) as a function of n_{ch}, $\boxed{\langle p_\perp \rangle (n_{\mathrm{ch}})}$.
- At present, we cannot describe it



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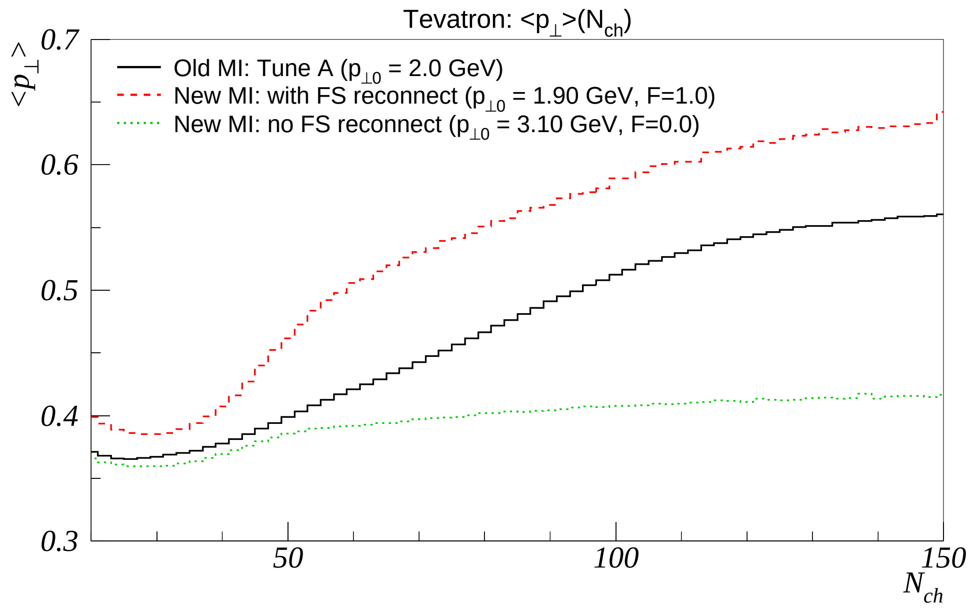

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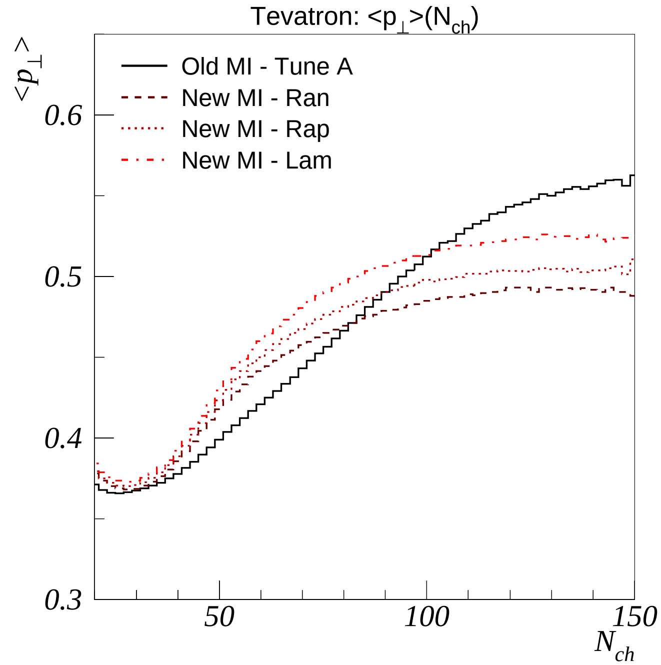

- $\rightarrow$ intertwined showers and/or FS reconnections?

Summary & Outlook — Multiple Interactions

☞ Overwhelming amount of data confirms basic idea.
(AFS, UA1, UA5, E735, H1, CDF)

Much remains uncertain!

- ★ $p_{\perp\mathrm{min}}/p_{\perp 0}$ cutoff.
- ★ Impact parameter dependence.
- ★ Energy dependence.
- ★ Multiparton densities in incoming hadrons.
- ★ Colour correlations and colour reconnections.
- ★ Interferences between showers.

☞ Important to understand for hadronic collisions.
(+ extensions to diffractive topologies, baryon flow in heavy ion collisions, and to meson/photon beams are imaginable.)

☞ A new physical model for detailed studies has been developed; available in PYTHIA 6.3. Right now, we're concentrating on figuring out how to hook up those colour strings...

Summary & Outlook — Multiple Interactions

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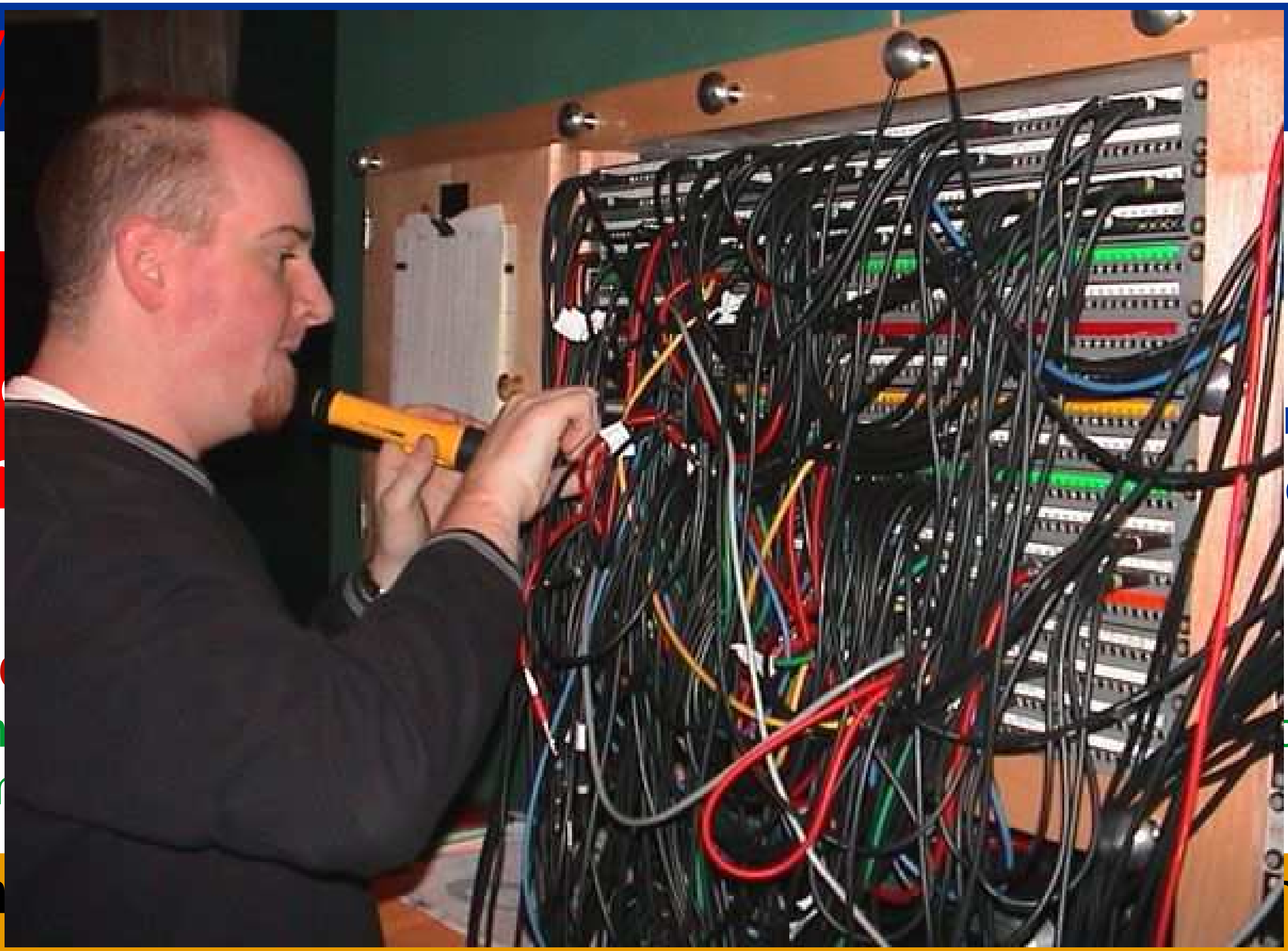

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