TeV4LHC Workshop
Fermilab
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A new model for parton showers and the underlying event.

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Based on:

- TS+PS, “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”, hep-ph/0408302.
- TS+PS, “Multiple Interactions and the Structure of Beam Remnants”, JHEP 0403 (2004) 053.

Overview

- Introduction:
  - Parton Showers and the Underlying Event.
  - Why develop a new model?
- The new framework.
  - $p_\perp$–ordered showers: FSR and ISR.
  - Interleaved multiple interactions.
  - Model tests.
- Outlook.

Basic Philosophy — Parton Showers

1 hadron collision =

$(2 \to 2 \oplus \underbrace{\text{ISR} \oplus \text{FSR}} \oplus \text{UE}) \otimes$ hadronisation etc.

Eff. resum. of multiple (semi-)soft gluon emission effects

- $2 \to 2$: 'hard subprocess' (on–shell).
- ISR: Initial–State Radiation (spacelike).
- FSR: Final–State Radiation (timelike).
- UE: Underlying Event – any additional (perturbative) activity.

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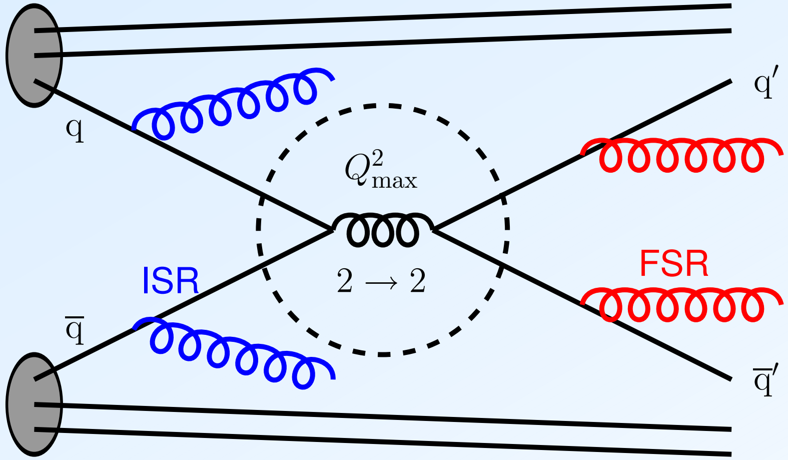
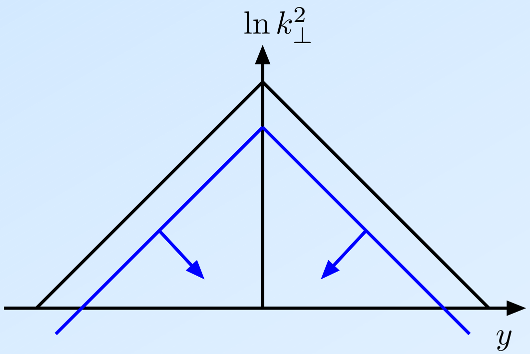


NB: no doublecounting!

⇒ For QCD: the hard $2 \to 2 \equiv$ most virtual ∼ shortest distance, everything else is softer.

Existing Showers: Pros and Cons

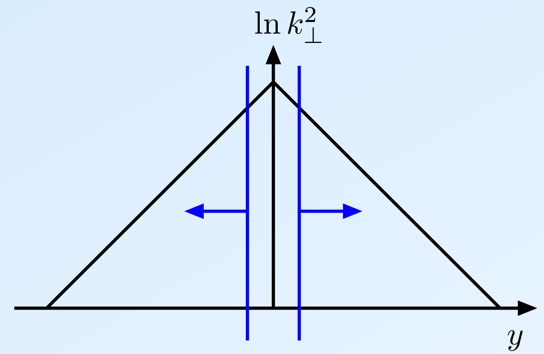
- Essential difference: ordering variables.
  consider e.g. gluon emission off a $q_1\overline{q}_2$ system.



PYTHIA/JETSET

m^2 ($-m^2$ for ISR)

High–virtuality ems. first.
(may be at ‘small’ angles.)



HERWIG

$\sim E^2\theta^2$

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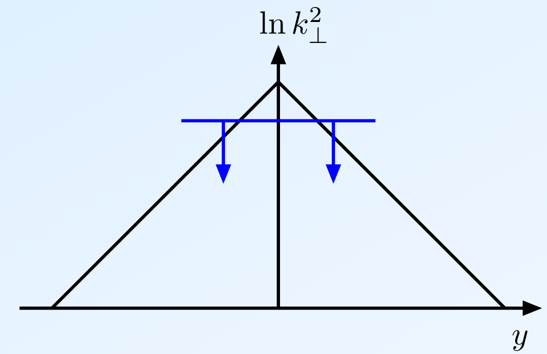

ARIADNE

$p_\perp^2$

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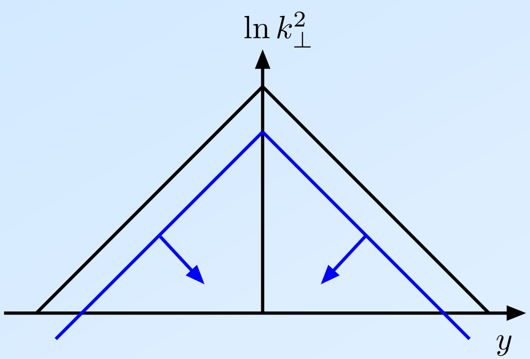

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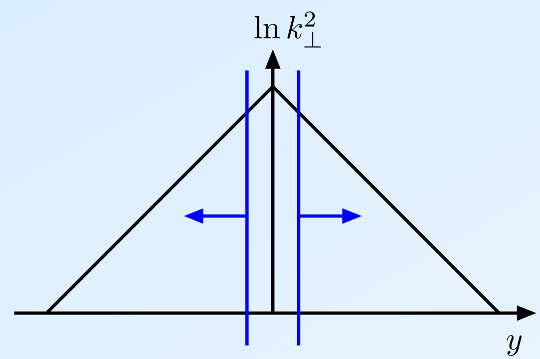

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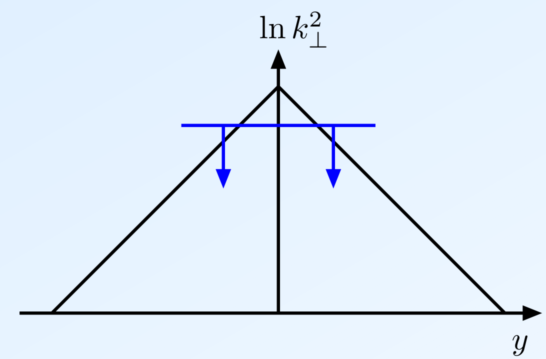


ARIADNE

$p_\perp^2$

Large–$p_\perp$ ems. first.

- Another important difference is the way recoils are assigned, i.e. how the on–shell kinematics prior to the branching is reinterpreted to include the virtual (branching) leg.

Existing Showers: Pros and Cons

- HERWIG: $Q^2 \approx E^2(1-\cos\theta) \approx E^2\theta^2/2$

  $+$ angular ordering $\Rightarrow$ coherence inherent

  $-$ emissions not ordered in hardness

  $-$ emissions do not cover full phase space (messy kinematics)

  $-$ kinematics constructed at the very end

- PYTHIA: $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

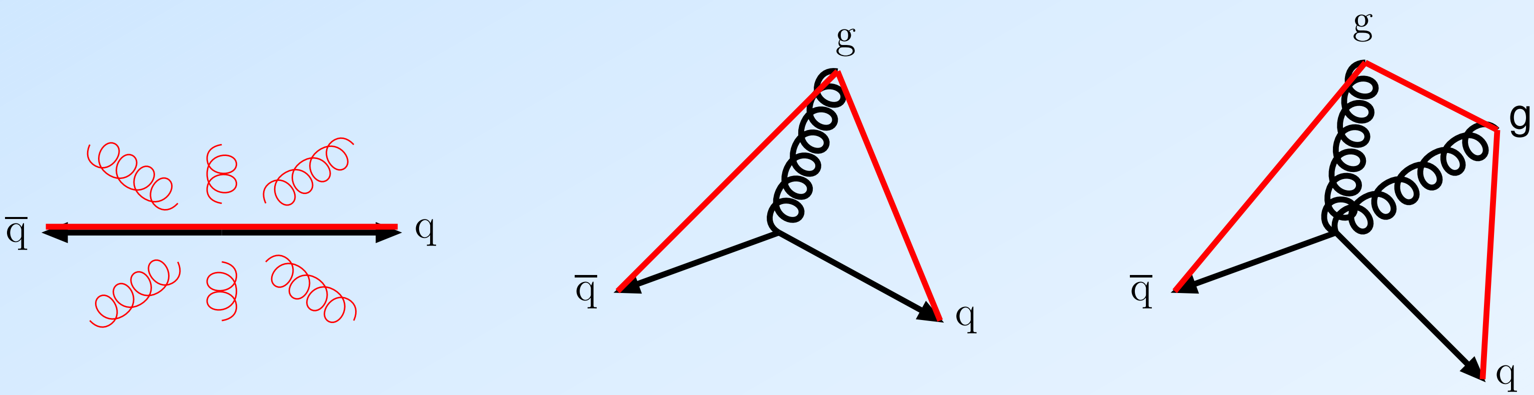
  $+$ convenient merging with ME

  $\pm$ emissions ordered in (some measure of) hardness

  $-$ coherence by brute force $\Rightarrow$ approximate

  $-$ kinematics constructed when daughter masses known

Existing Showers: Pros and Cons



- ARIADNE: $Q^2 = p_\perp^2$, (final-state) dipole emission
  - $+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent
  - $+$ Lorentz invariant
  - $+$ emissions ordered in hardness
  - $+$ kinematics constructed after each branching (partons explicitly on-shell until they branch)
  - $+$ showers can be stopped and restarted at any $p_\perp$ scale. $\Rightarrow$ good for ME/PS matching (L-CKKW, real+fictitious showers)

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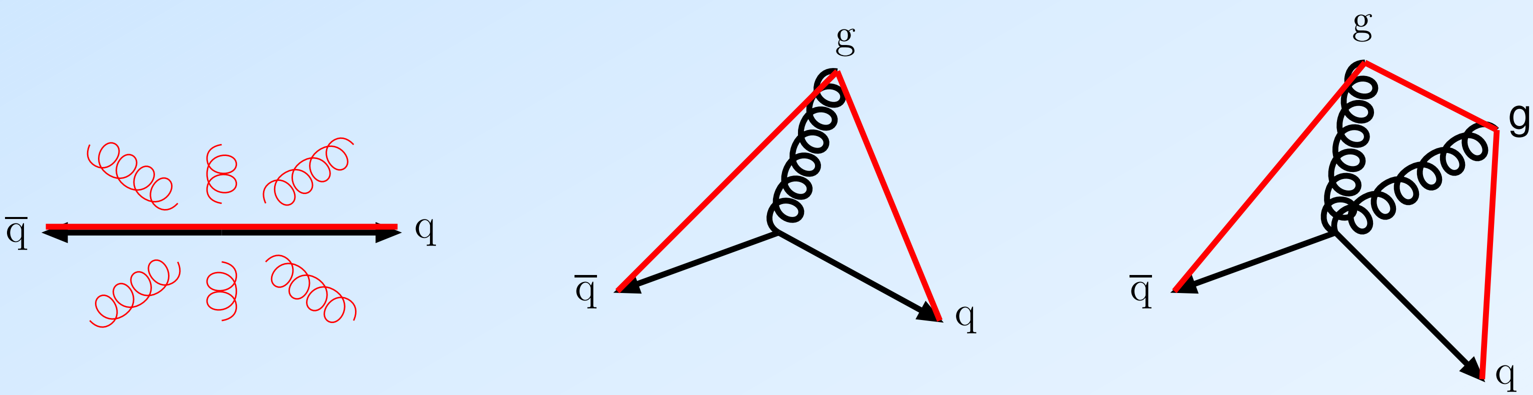

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  - $-$ $\mathrm{g} \rightarrow \mathrm{q}\overline{\mathrm{q}}$ artificial
  - $-$ not so suited for pp on its own: ISR is primitive in ARIADNE.

Why Develop a New Shower?

- **Incorporate several of the good points of the dipole formalism within the shower approach**

  $\pm$ explore alternative $p_\perp$ definitions

  $+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent

  $+$ ME merging works as before
  (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)

  $+$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ natural

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$+$ allows to combine $p_\perp$ evolutions of showers and multiple interactions $\to$ *common* (competing) evolution of ISR, FSR, and MI!

$\equiv$ 'Interleaved Multiple Interactions'

Basic Philosophy — Multiple Interactions

Consider perturbative QCD $2 \to 2$ scattering:

(dominated by t-channel gluon exchange – IR divergent: $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{1}{p_\perp^4}$)

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

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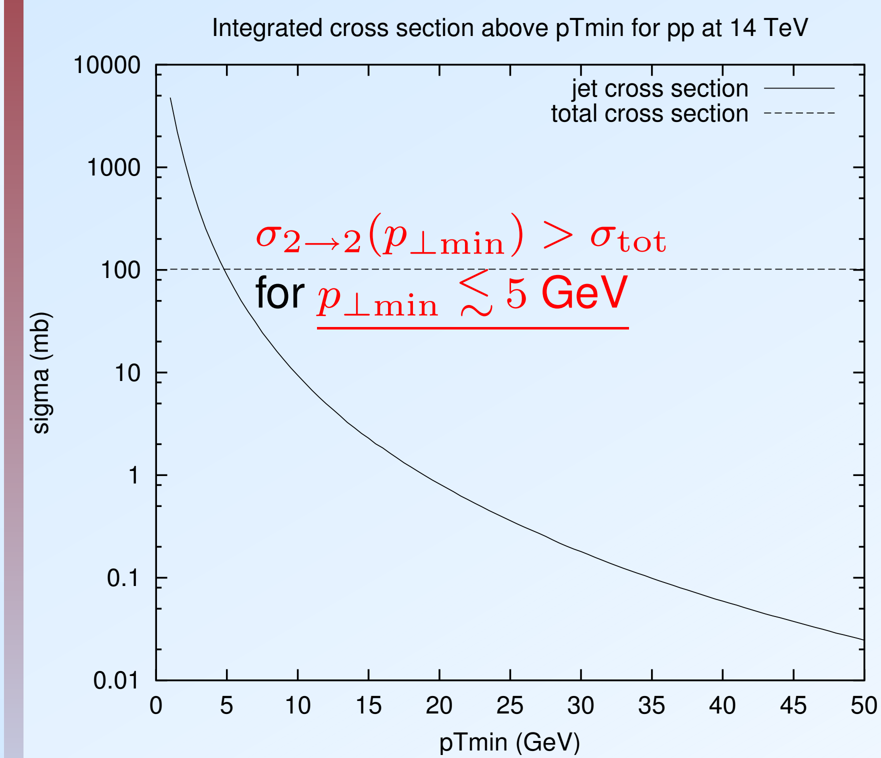
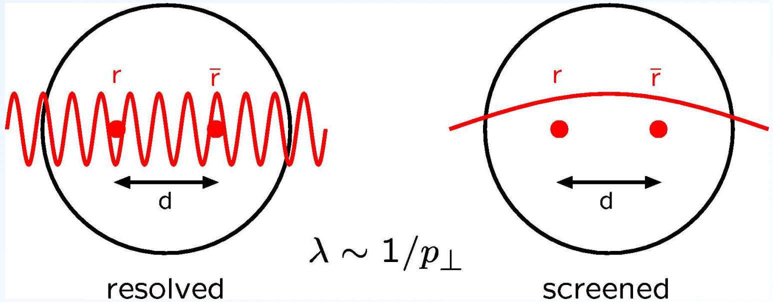


1. **Multiple interactions (MI)!**
   - Must exist (hadrons are composite!)
   - σ_{tot}: hadron-hadron collisions.
     $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
   - $\sigma_{2\to 2}$: parton–parton collisions.
     $\sigma_{2\to 2} = \sum_{n=0}^{\infty} n\,\sigma_n$
   - $\sigma_{2\to 2} > \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1$

2. **Breakdown of pQCD, colour screening.**

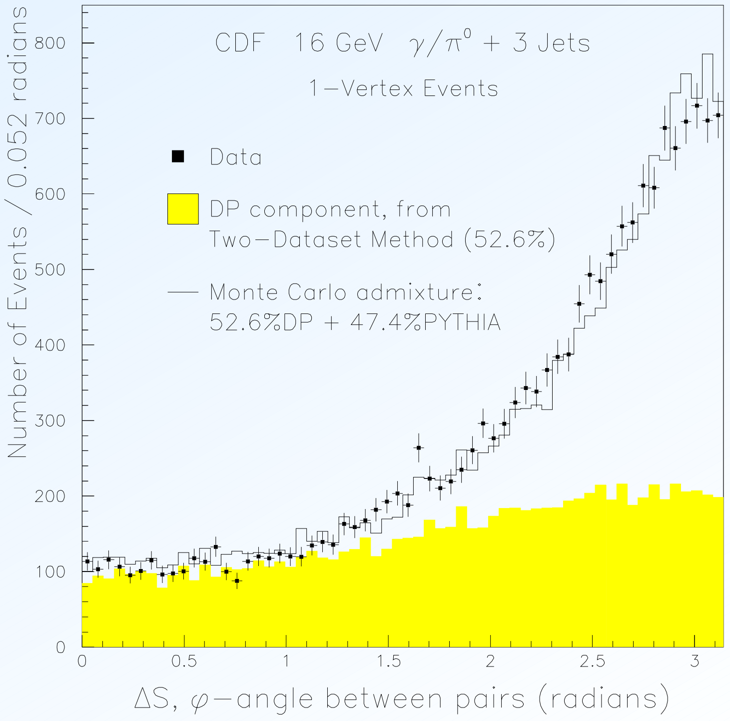


$p_{\perp 0} \sim 2$ GeV

Multiple Interactions — Evidence

Basic idea : expect four 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, $I = p_{\perp 1}^2 + p_{\perp 2}^2$. Excess of events with small I.
- **CDF**: Extraction by comparing double parton scattering (DPS) to a mix of two separate scatterings. Sample: 14000 $\gamma/\pi^0 + 3j$ events. Strong signal observed, 53% DPS
- **+ Indirect**: KNO violation, pedestal effect, Fwd–Bwd asymmetry, ...

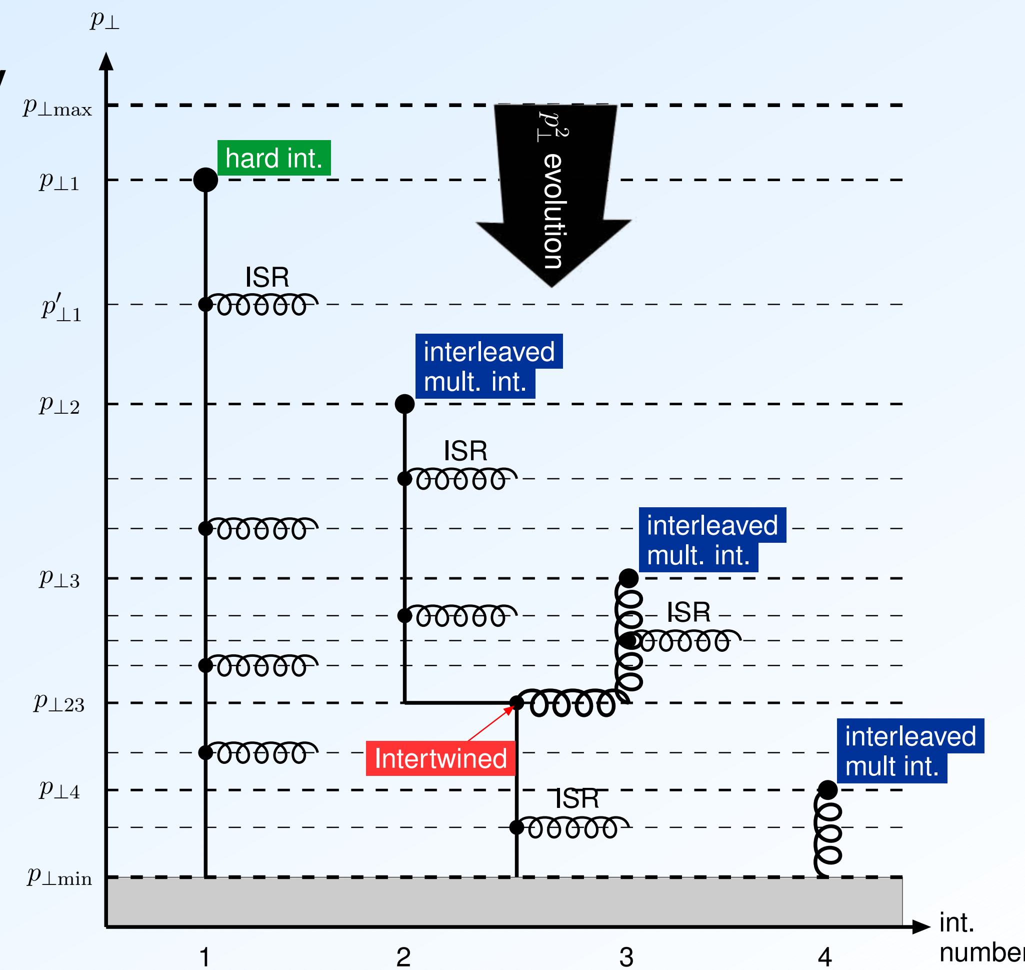


Why Develop a New UE Model?

- Need to understand correlations and fluctuations. From QCD point of view:
  many interesting questions remain unanswered.
- Any reliable extrapolation to LHC energies will require a good understanding of the physics mechanisms.
  Simple parametrizations not sufficient.
- 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:
  $\longrightarrow$ great topic for phenomenology right now!

The New Framework

- This led us to develop a new sophisticated model for UE (and min–bias) $\rightarrow$ JHEP 0403 (2004) 053.
- But still each interaction was considered separately, with *its* set of ISR and FSR.
- That's probably not the way it happens in real life...
- The new picture: start at the most inclusive level, $2 \rightarrow 2$. Add exclusivity progressively by evolving *everything* downwards in *one* common sequence: $\rightarrow$ Interleaved evolution
- ($\rightarrow$ also possible to have interactions *intertwined* by the ISR activity?)



The New Framework

The building blocks:

- $p_\perp$–ordered initial–state parton showers. ✔
- $p_\perp$–ordered final–state parton showers. ✔
- $p_\perp$–ordered multiple interactions. ✔
- $p_\perp$ used as scale in α_s and in PDF's. ✔
- (Model for) correlated multi–parton densities. ✔
- Beam remnant hadronization model. ✔
- Model for initial state colour correlations. (✔ — but far from perfect!)
- Other phenomena? (e.g. colour reconnections (✔), ...)
- Realistic tunes to data (not yet!)

Multiple Interactions: Some Details

Correlated PDF's:

- Momentum and Energy in parent hadron conserved.
- Sum rules for valence quarks respected.
  (Can't kick the same quark out twice!)
- Sea quarks knocked out $\rightarrow$ 'companion quarks'.

Hadronization:

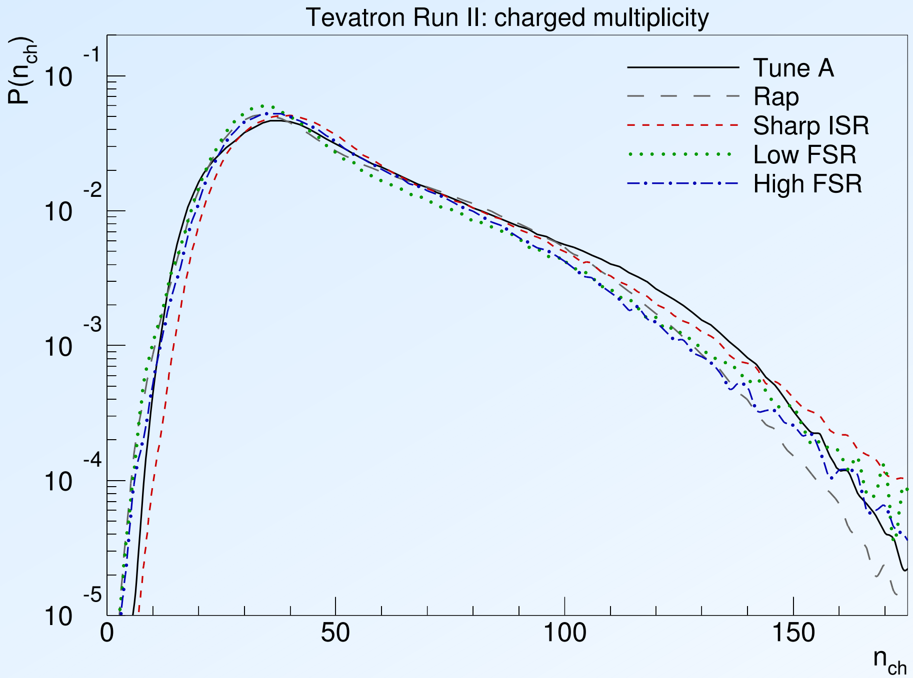
- Possible to have composite objects in the beam remnants, e.g. diquarks.
- Addressing 'baryonic' colour topologies $\rightarrow$ 'string junctions' in the colour confinement field.

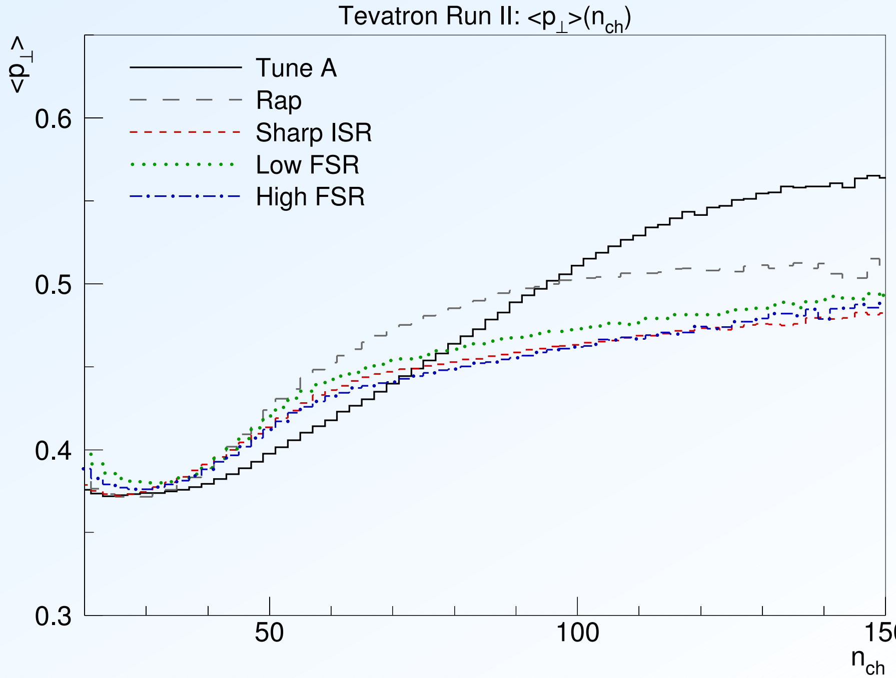
Colour Correlations:

- The big question! Seems Nature likes a *very* high degree of correlation (cf. 'Tune A' of old model!).
- Several possibilities investigated, so far without success.

Model Tests

- Whole framework.
  - Produced a few rough tunes to ‘Tune A’ at the Tevatron, using charged multiplicity distribution and $\langle p_\perp \rangle (n_{\mathrm{ch}})$, the latter being highly sensitive to the colour correlations.
  - Similar overall results are achieved (not shown here), but $\langle p_\perp \rangle (n_{\mathrm{ch}})$ still difficult.
  - Anyway, these were only *rough* tunes...





Outlook

- New sophisticated framework for $p_\perp$–ordered *interleaved* parton showers and multiple interactions has been developed.
- Good overall performance, still only primitive studies carried out, except for FSR.
- Colour correlations still a headache. We thought perhaps *intertwined* showers would yield a more correlated colour flow, but preliminary studies do not indicate intertwining at perturbative energies to be a frequent phenomenon.

Outlook

- New sophisticated framework for $p_\perp$–ordered *interleaved* parton showers and multiple in


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

- G ... itive st
- C ... th ... uld yi ... pr ... in ... e a fr
- But nobody said hadron collisions were easy...

Model Tests: FSR

FSR algorithm.

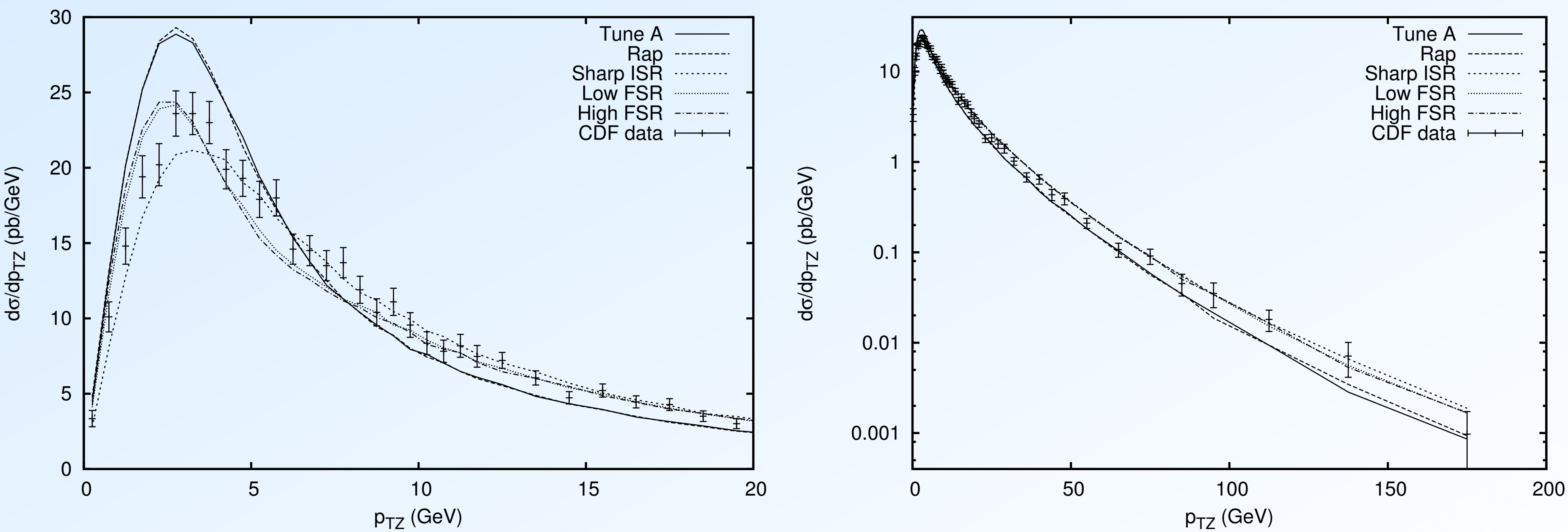
- Tested on ALEPH data (G. Rudolph).

Distribution of	nb.of interv.	$\sum \chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
$1-$Thrust	21	60	8
Thrust$_{\mathrm{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\mathrm{cm}}$	46	207	151
$p_{\perp \mathrm{in}}$	25	99	170
$p_{\perp \mathrm{out}} < 0.7$ GeV	7	29	24
$p_{\perp \mathrm{out}}$	(19)	(590)	(1560)
x(B)	19	20	68
sum $N_{\mathrm{dof}} =$	190	497	765

- (Also, generator is not perfect. Adding 1% to errors $\Rightarrow$ $\sum \chi^2 = 234$. i.e. generator is 'correct' to $\sim$1%)

Model Tests: ISR

- ISR algorithm.
  - Less easy to test. We looked at $p_\perp$ of Z^0 at Tevatron.
  - Compared “Tune A” with an ‘intermediate scenario’ (“Rap”), and three rough tunes of the new framework.
  - Description is improved (but there is still a need for a large primordial $k_\perp$).



MI — Indirect Verifications

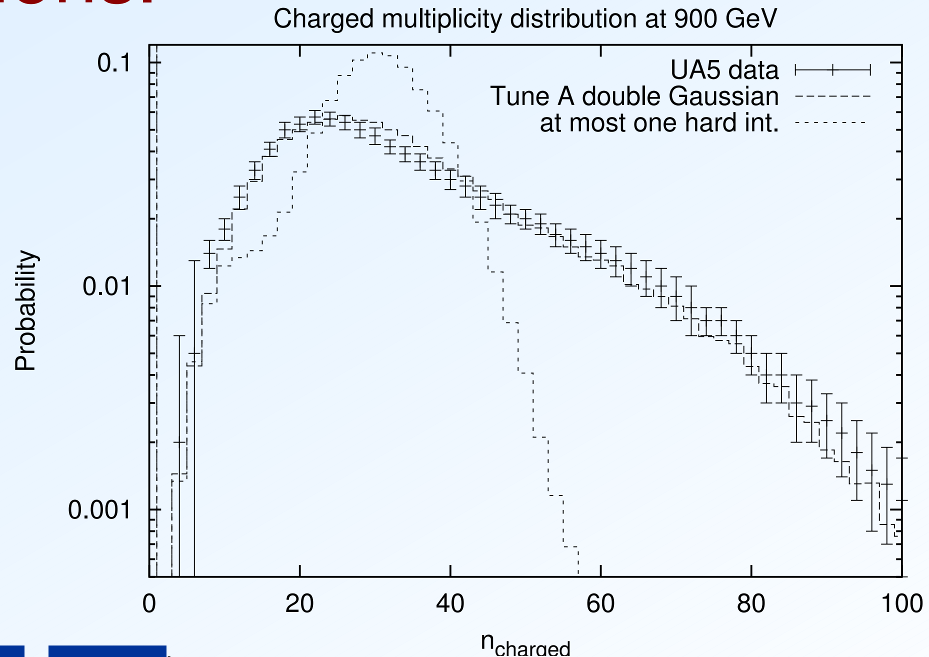
Basic idea :

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

UA5: (900 GeV)

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

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



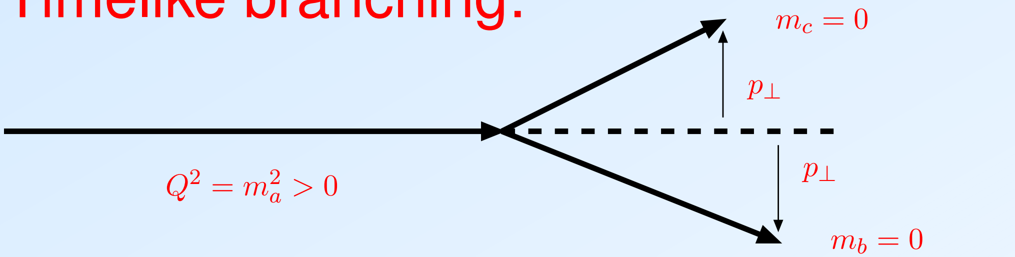
- + forward–backward correlations (**UA5**, **E735**)
- + pedestal effect (**UA1**, **CDF**, **H1**), ...

$p_\perp$–ordered showers: Simple Kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^\pm = E \pm p_z$

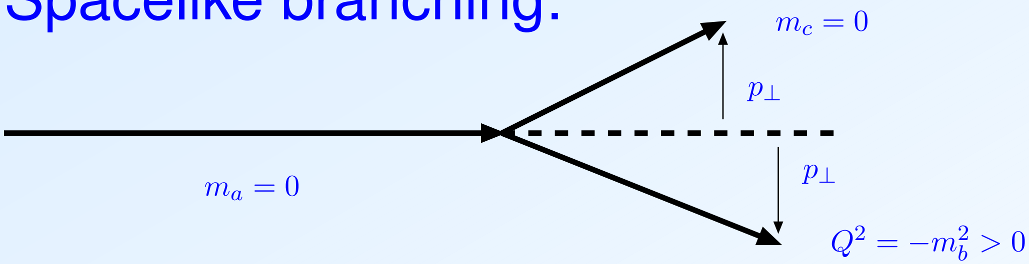
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



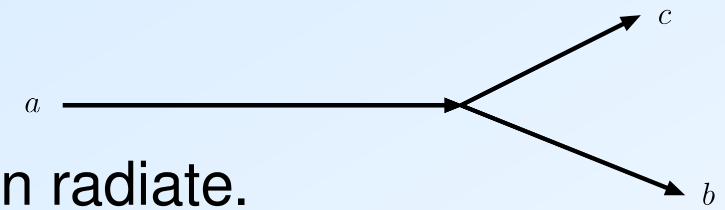
$$p_\perp^2 = (1-z)Q^2$$

Guideline, not final $p_\perp$!

$p_\perp$–ordered showers: General Strategy (1)

1) *Define* $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)Q^2$ for FSR

$\mathrm{p}^2_{\perp\mathrm{evol}} = (1-z)Q^2$ for ISR



2) Find list of *radiators* = partons that can radiate.
Evolve them all *downwards* in $\mathrm{p}_{\perp\mathrm{evol}}$ from common $p_{\perp\mathrm{max}}$

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}\mathrm{p}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_{\mathrm{s}}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z \, \exp\left(-\int_{\mathrm{p}^2_{\perp\mathrm{evol}}}^{p^2_{\perp\mathrm{max}}} \cdots\right)$$

$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}\mathrm{p}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_{\mathrm{s}}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} \frac{x' f_a(x', \mathrm{p}^2_{\perp\mathrm{evol}})}{x f_b(x, \mathrm{p}^2_{\perp\mathrm{evol}})} P_{a\to bc}(z)\,\mathrm{d}z \, \exp\left(-\cdots\right)$$

Pick the one with *largest* $\mathrm{p}_{\perp\mathrm{evol}}$ to undergo branching; also gives z.

3) *Derive* $Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/z(1-z)$ for FSR

$Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/(1-z)$ for ISR

$p_\perp$–ordered showers: General Strategy (2)

4) Find *recoiler* = parton to take recoil when radiator is pushed off-shell

usually nearest colour neighbour for FSR

incoming parton on other side of event for ISR

5) Interpret z as *energy fraction* (not lightcone)

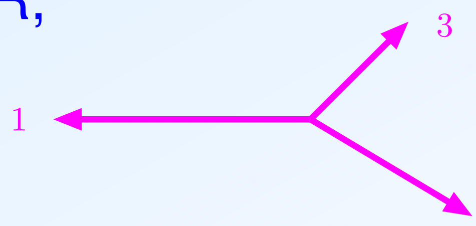
in radiator+recoiler rest frame for FSR,

in mother-of-radiator+recoiler rest frame for ISR,

so that *Lorentz invariant*

$(2E_i/E_{\mathrm{cm}} = 1 - m_{jk}^2/E_{\mathrm{cm}}^2)$

and straightforward match to matrix elements



6) Do *kinematics* based on Q^2 and z,

a) assuming yet unbranched partons on-shell

b) shuffling energy–momentum from recoiler as required

7) Continue evolution of all radiators from recently picked $\mathrm{p}_{\perp\mathrm{evol}}$.

Iterate until no branching above $p_{\perp\mathrm{min}}$.

$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

$p_\perp$–ordered showers: Some Details

FSR Evolution:

- Massive quarks: $\mathrm{p}_{\perp\mathrm{evol}}^2 = z(1-z)(m^2 - m_Q^2)$
  $\Rightarrow m^2 \to m_Q^2$ when $\mathrm{p}_{\perp\mathrm{evol}}^2 \to 0$.
- Special treatment of narrow resonances (e.g. top).

ISR Evolution:

- Massive quarks: $\mathrm{p}_{\perp\mathrm{evol}}^2 = (1-z)(Q^2 + m_Q^2) = m_Q^2 + \mathrm{p}_{\perp\mathrm{LC}}^2$
  $\Rightarrow$ Light–Cone $\mathrm{p}_{\perp\mathrm{LC}}^2 \to 0$ when $\mathrm{p}_{\perp\mathrm{evol}}^2 \to m_Q^2$.
- Backwards evolution uses correlated pdf's at scales where more than 1 interaction is resolved.

Both ISR and FSR:

- ME merging by veto for many SM+MSSM processes.
- Gluon polarization $\to$ asymmetric φ distribution.

Correlated PDF's in flavour and x_i

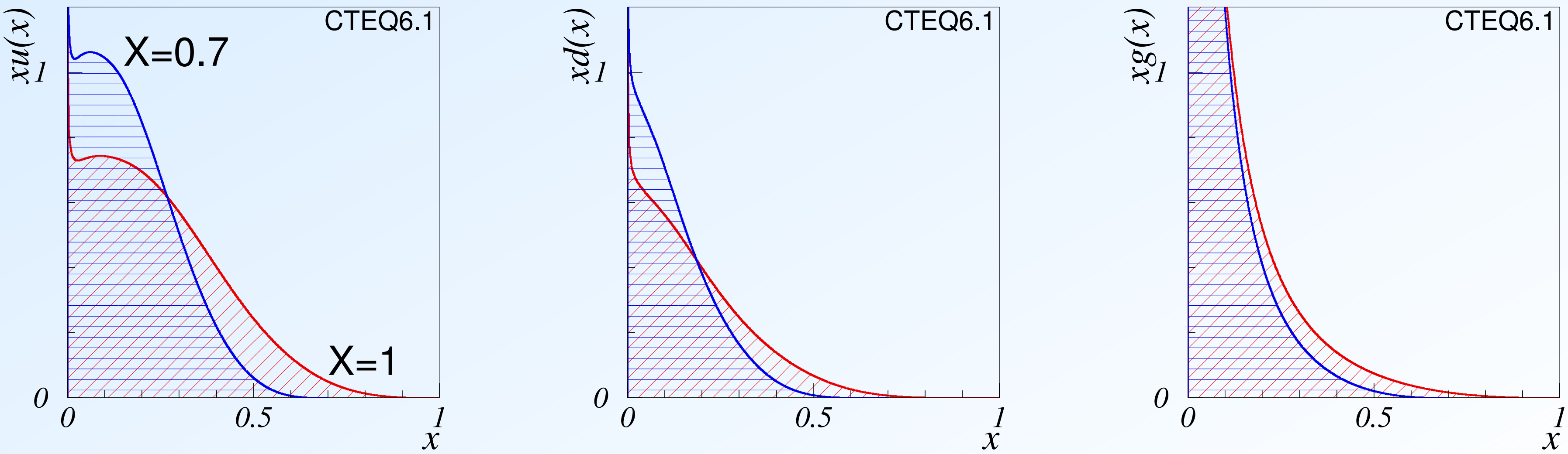
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

1. Overall momentum conservation (old):

Starting point: simple scaling ansatz in x.

For the n'th scattering:

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



Correlated PDF's 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:

✧ If valence quark knocked out.

→ 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.

→ 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:

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

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

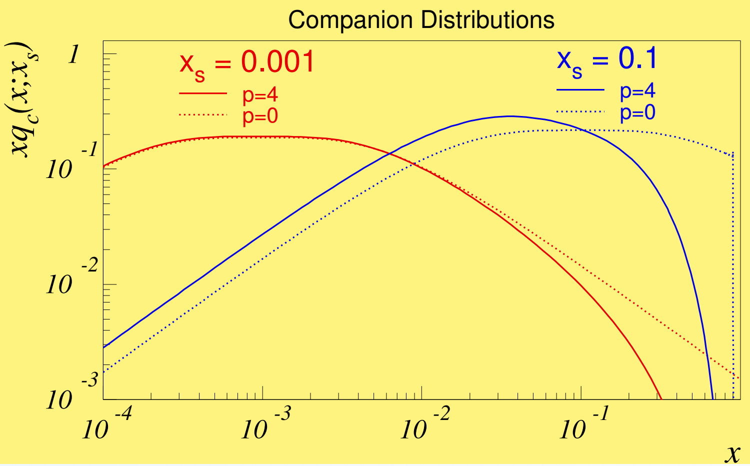
Remnant PDFs

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

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

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

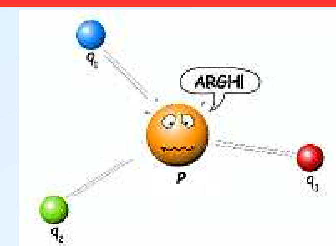
$$a = \frac{1 - \sum_f N^{\mathrm{val}}_{fn}\langle x^{\mathrm{val}}_{f0}\rangle - \sum_{f,j}\langle x^{\mathrm{cmp}_j}_{f0}\rangle}{1 - \sum_f N^{\mathrm{val}}_{f0}\langle x^{\mathrm{val}}_{f0}\rangle}$$

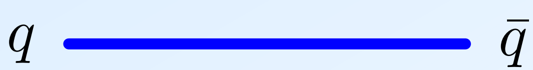


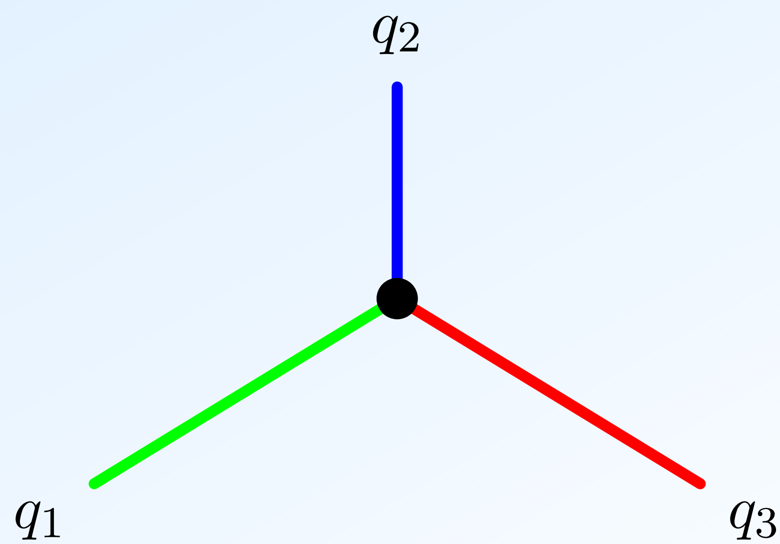
Used to select $p_\perp$-ordered $2 \to 2$ scatterings, and to perform backwards DGLAP shower evolution.

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

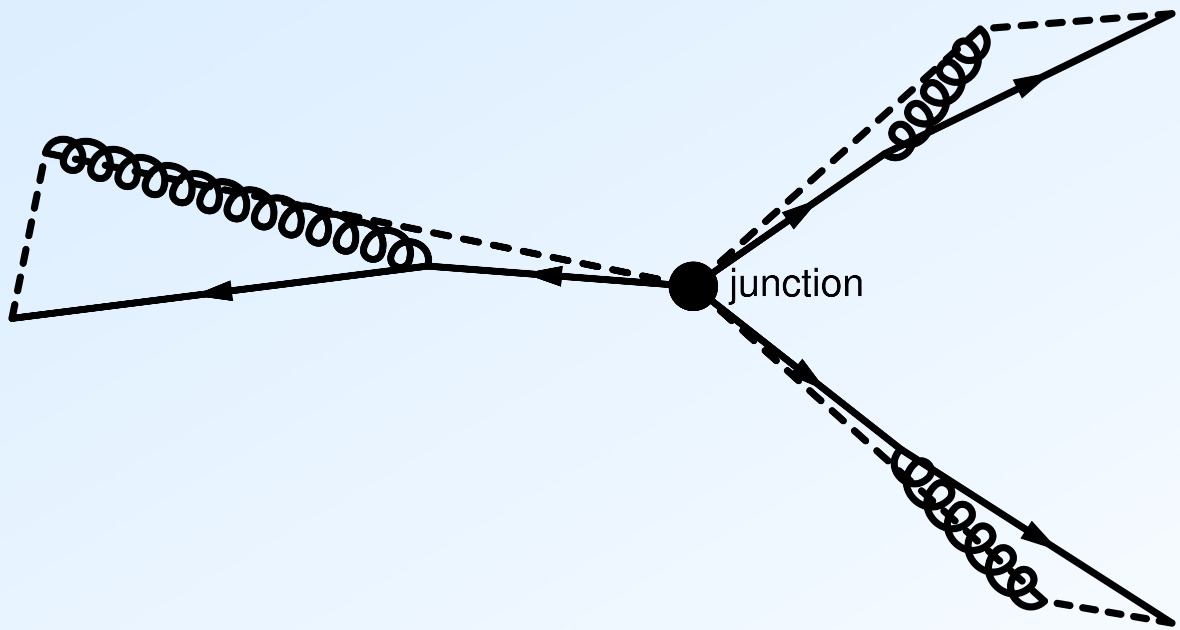




- Need to extend string model to handle baryonic topology.

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?

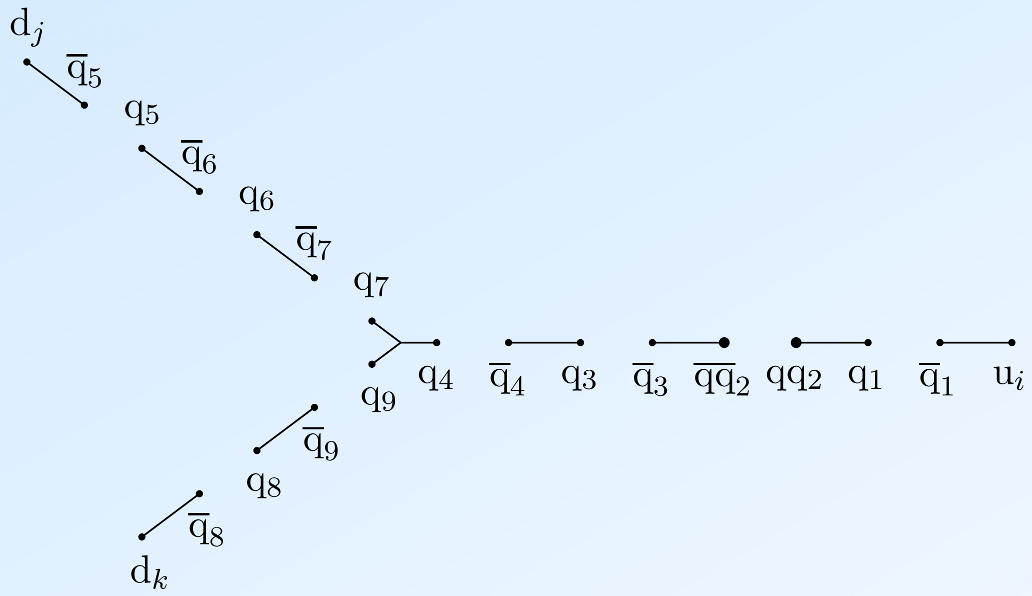
- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at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

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

  (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).