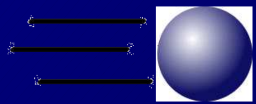
# Unifying parton showers and underlying events

Peter Skands, Fermilab



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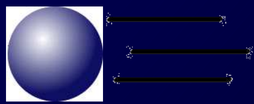


- A new model for the Underlying Event
- New $p_\perp$–ordered (ISR and FSR) parton showers
- A unified description of UE and PS
- A new model for beam remnants and hadronization

# Underlying Event: the basics

*Why multiple perturbative interactions?*

Consider perturbative QCD $2 \to 2$ scattering:

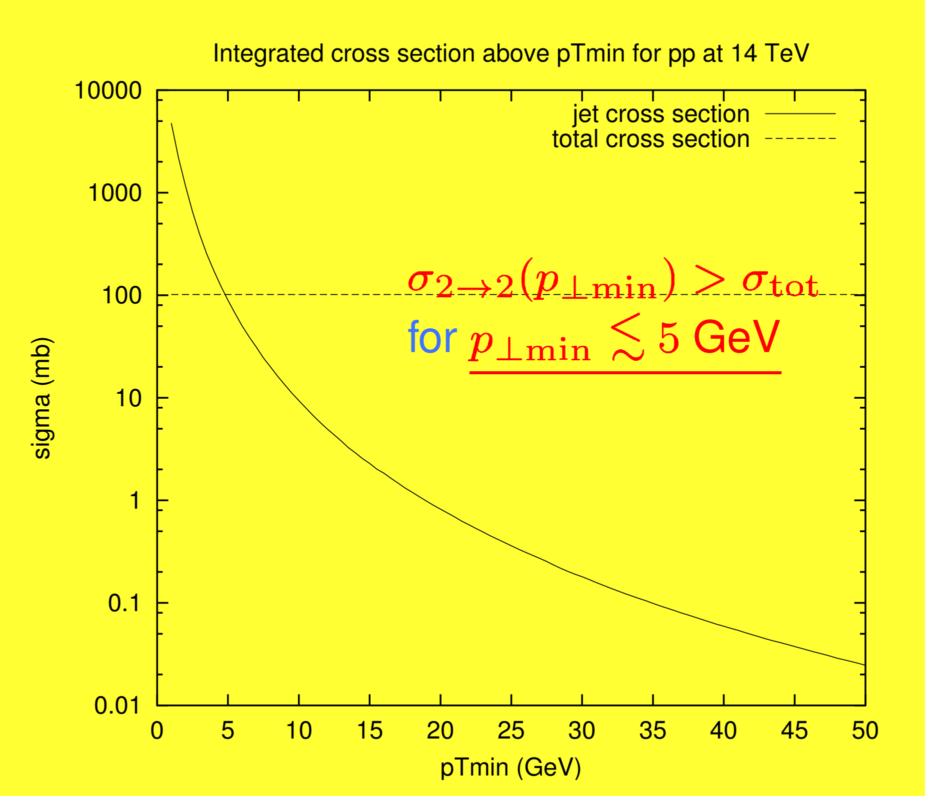
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{1}{t^2} \sim \frac{1}{p_\perp^4}$$

$\Longrightarrow$ '2-jet' cross sect

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

while total pp cross sect:

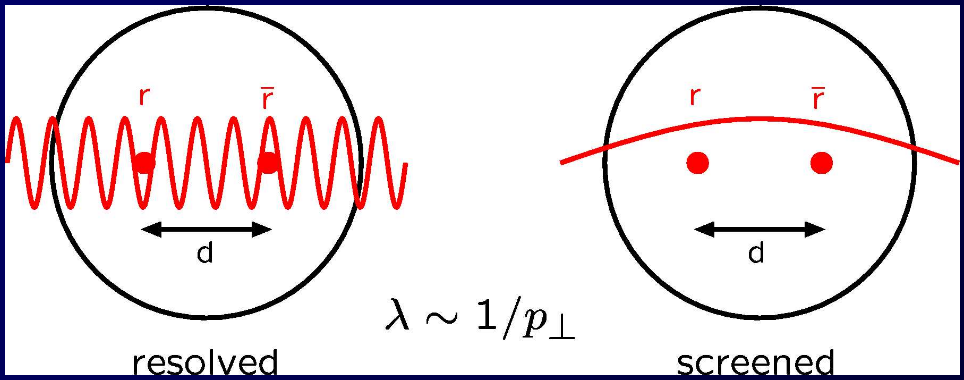
$$\sigma_{\mathrm{pp}} \propto s^{0.08}$$



# What's going on?

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

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

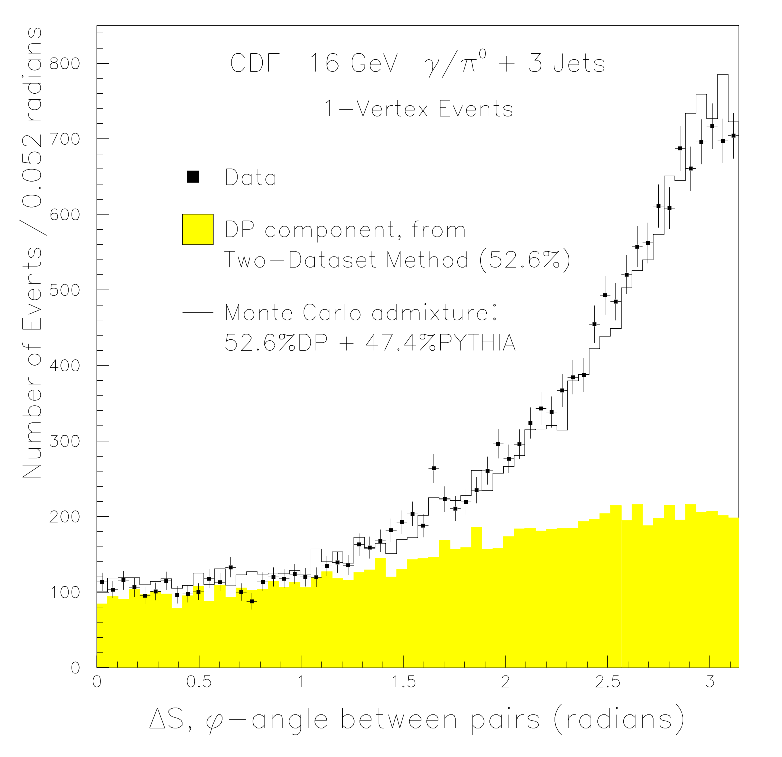



$p_{\perp 0} \sim 2$ GeV

# (Multiple Interactions — Direct 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 $\eta$. 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
- (Note: only plot made was comparison to PYTHIA with MI switched *off*!)



# (Multiple Interactions — Indirect Verifications)

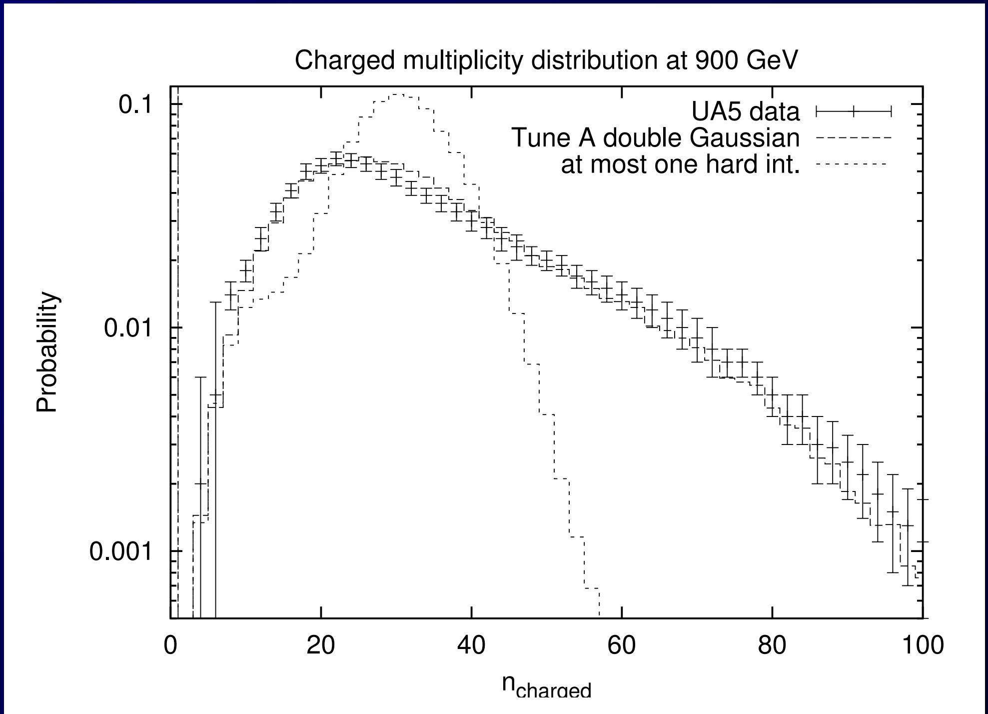
**Basic idea :**

- **Hadronization alone produces roughly Poissonian fluctuations in multiplicity.**
- **Additional soft interactions + $b$ dependence $\rightarrow$ 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 ), R. Field's studies ( CDF ), ...**

# UE: Present Status

Available tools:

- Soft UE model (min-bias) (HERWIG)
- Soft+semi-hard UE (DTU) (ISAJET, DTUJET)
- Multiple Interactions (PYTHIA, JIMMY)

Of these, the PYTHIA model (from 1987) is probably the most sophisticated, with tunes like 'Tune A' being capable of simultaneously reproducing a large part of Tevatron min–bias and UE data, as well as data from other colliders.

[T. Sjöstrand, M. van Zijl, "A Multiple Interaction Model For The Event Structure In Hadron Collisions", Phys. Rev. D 36 (1987) 2019.]

[R.D. Field, presentations available at `www.phys.ufl.edu/~rfield/cdf/`]

# New UE Model: Why Bother?

- QCD point of view: hadron collisions are complex. Present models are not. More detail $\rightarrow$ hopefully more insight.
- LHC point of view: reliable extrapolations require such insight. Simple parametrizations are not sufficient.
- New Physics and precision point of view: random and systematic fluctuations in the underlying activity will impact cuts/measurements: More reliable understanding is needed.
- Practical point of view: Tevatron (and RHIC, HERA?) data is (will be?) available to test new developments: a great topic for phenomenology right now!

# Parton Showers: the basics

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- Today, basically 2 approaches to showers:
  Parton Showers (e.g. HERWIG, PYTHIA)
  and Dipole Showers (e.g. ARIADNE).

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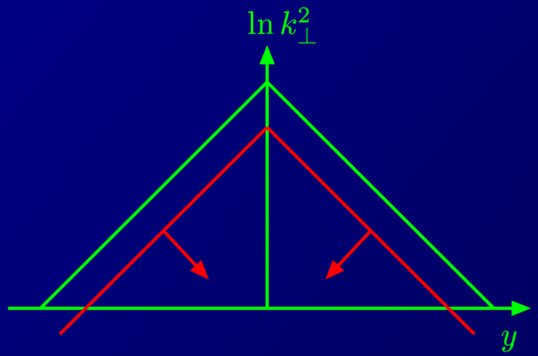
  and Dipole Showers (e.g. ARIADNE).

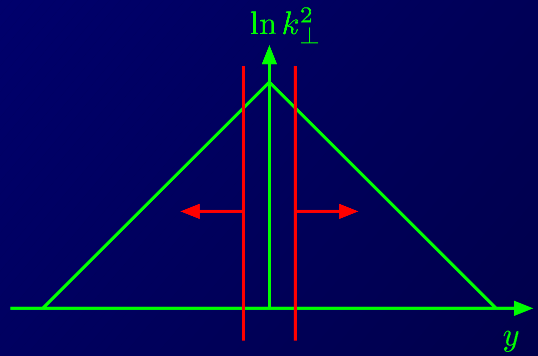
- Essential difference: ordering variables.
  consider e.g. gluon emission off a $q_1\bar{q}_2$ system.




PYTHIA/JETSET

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

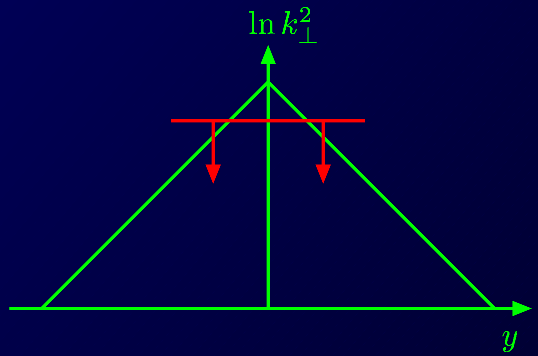
High–virtuality ems. first.




HERWIG

$\sim E^2\theta^2$

Large–angle ems. first.




ARIADNE

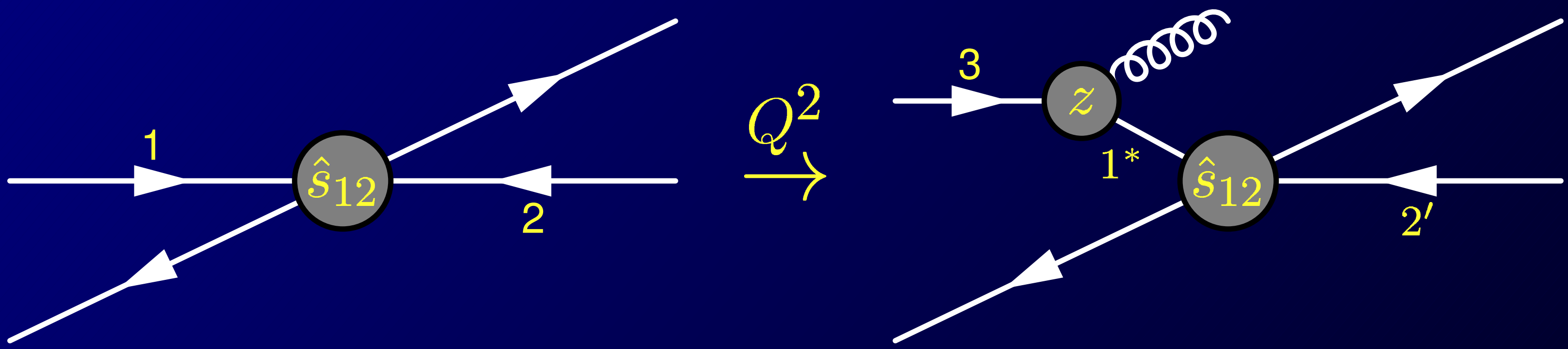
$p_\perp^2$

Large–$p_\perp$ ems. first.

# Parton Showers: the basics

- Today, basically 2 approaches to showers:
  Parton Showers (e.g. HERWIG, PYTHIA)
  and Dipole Showers (e.g. ARIADNE).

- 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.
  e.g. ISR:




| $2 \to 2$ Matrix Element | (1st) Correction |
|---|---|
| 1 and 2 on shell | 3 and 2' now on shell |
| $E^2_{cm} = \hat{s}_{12} = x_1 x_2 s$ | $E^2_{cm} = x_3 x_2 s = \frac{x_1}{z} x_2 s$ |

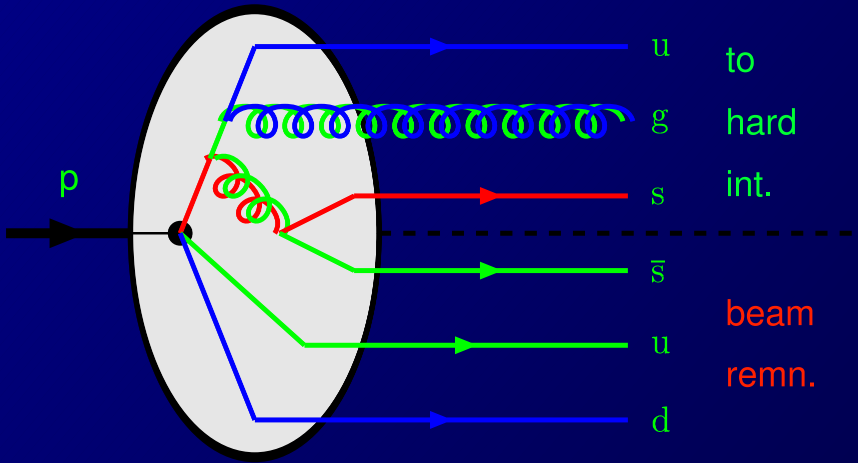
# New Parton Showers: Why Bother?

- Today, basically 2 approaches to showers:
  Parton Showers (e.g. HERWIG, PYTHIA)
  and Dipole Showers (e.g. ARIADNE).

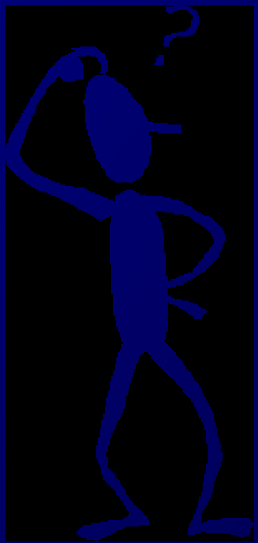
- Each has pros and cons, e.g.:
  - In PYTHIA, ME merging is easy, and emissions are ordered in some measure of (Lorentz invariant) hardness, but angular ordering has to be imposed by hand, and kinematics are somewhat messy.
  - HERWIG has inherent angular ordering, but also has the (in)famous “dead zone” problem, is not Lorentz invariant and has quite messy kinematics.
  - ARIADNE has inherent angular ordering, simple kinematics, and is ordered in a (Lorentz Invariant) measure of hardness, but is primarily a tool for FSR, with somewhat primitive modeling of ISR and hadron collisions, and $g \to q\bar{q}$ is 'artificial' in dipole formalism.
  - Finally, while all of these describe LEP data very well, none are perfect.

- Possible to combine the virtues of each of these approaches while avoiding the vices?

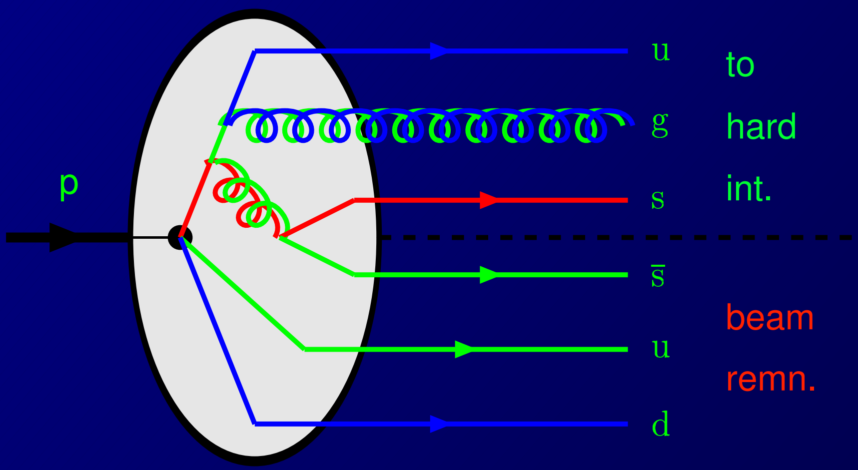
# Completing the picture




How are the hard scattering initiators and beam remnant partons correlated:



# Completing the picture

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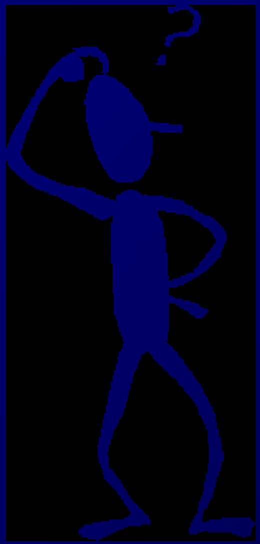


- ☞ In impact parameter?
- ☞ In flavour?
- ☞ In longitudinal momentum?
- ☞ In colour?
- ☞ In (primordial) transverse momentum?
- ☞ What does the beam remnant look like?
- ☞ (How) are the showers correlated / intertwined?

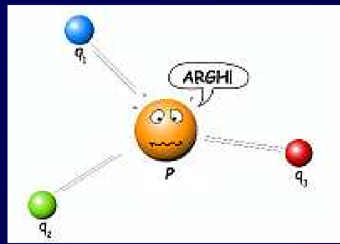
# $(\ldots) \otimes$ Hadronization.

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

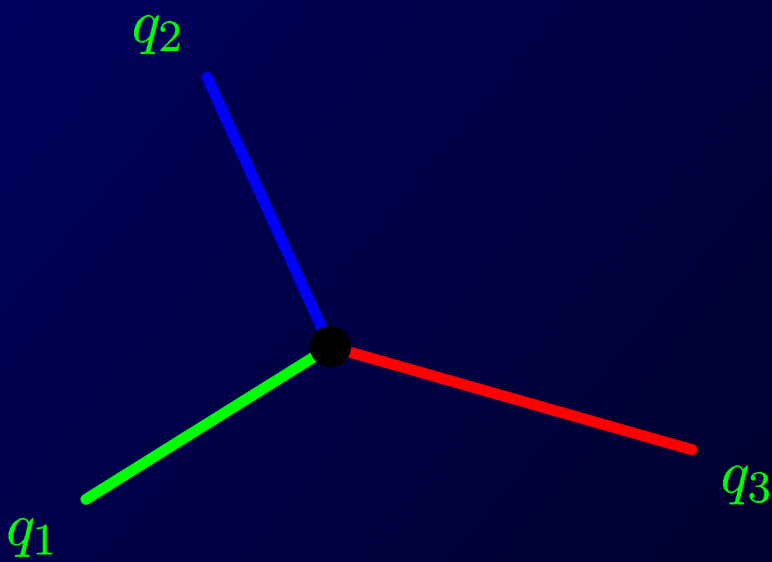
'Ordinary' colour topology

'Baryonic' colour topology

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

(e.g. 

):

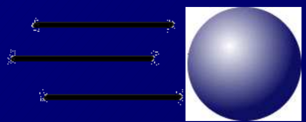

- How does such a system fragment? How to draw the strings?

# So...

All this was just to argue:

There is no such thing as ‘a simple hadron collision’!

or: If a model is simple, it is wrong.



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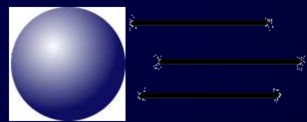


We therefore proceeded to complicate matters...

# News in PYTHIA 6.3

PYTHIA 6.3 includes a new model for multiple parton–parton interactions, including correlations in $b$, flavour, $x$, colour, and $k_T$,+ beam remnants, + string hadronization (extended to baryonic string topologies).

It also contains new ISR and FSR parton showers, based on a $p_\perp$-ordered sequence of $1 \to 2$ parton splittings inside dipoles.

Further, the description of parton showers and the underlying event has been unified in a common $p_\perp$-ordered 'interleaved evolution' of the event as a whole.

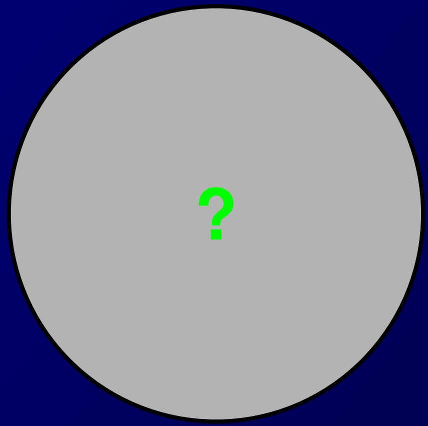
(The old PYTHIA shower and underlying-event framework remains in `PYEVNT`, while the new options are obtained by using `PYEVNW` instead.)

# THE NEW FRAMEWORK


Multiple Interactions

# Correlations in flavour and $\mathbf{x}_i$

Consider a hadron:




Generally, should be described by pdf's giving probablity for finding flavours $i_1 \dots i_n$ with momenta $x_1 \dots x_n$ in a hadron $H$ probed at scales $Q_1 \dots Q_n$ :

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

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

OK, so we make a theoretical cocktail...

# Correlated PDF's in flavour and $\mathbf{x}_i$

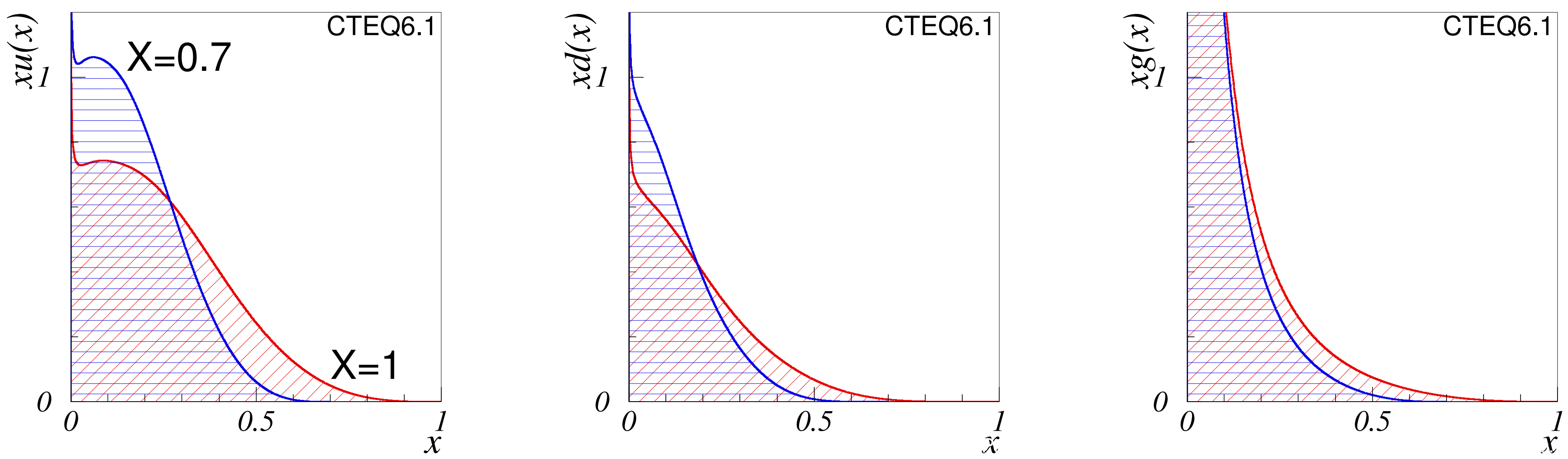
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

## 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 $\mathbf{x}_i$

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.
  - $\rightarrow$ Impose valence counting rule: $\int_0^X q_{fn}^{\text{val}}(x, Q^2)\,\mathrm{d}x = N_{fn}^{\text{val}}$.
- If sea quark knocked out.
  - $\rightarrow$ Postulate "companion antiquark": $\int_0^{1-x_s} q_f^{\text{cmp}}(x; x_s)\,\mathrm{d}x = 1$.

# Correlated PDF's in flavour and $\mathbf{x}_i$

**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.

# Correlated PDF's in flavour and $\mathbf{x}_i$

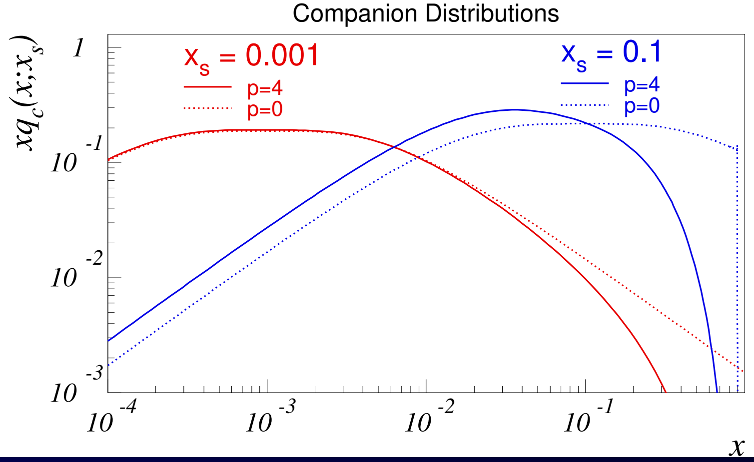
## Remnant PDFs

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

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

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

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




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

# THE NEW FRAMEWORK

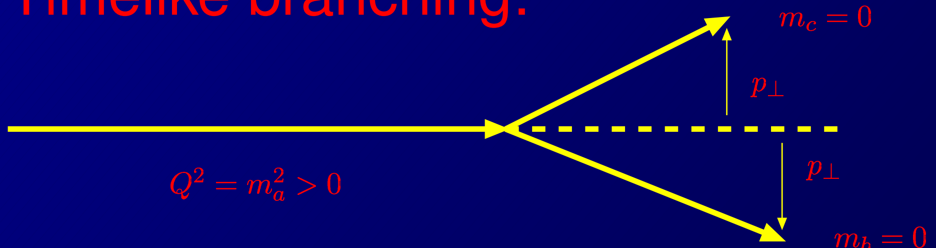
+ showers

# $p_\perp$–ordered showers: Simple Kinematics

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

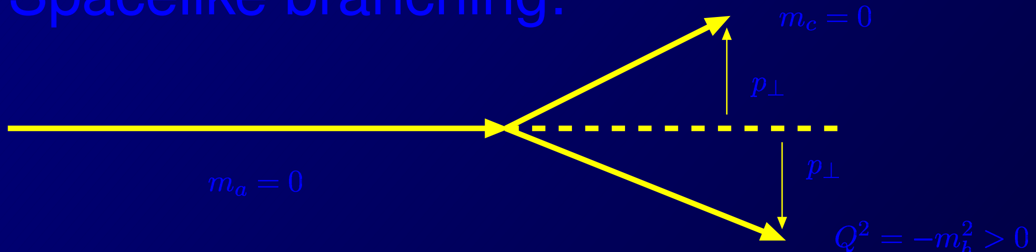
$$\left.\begin{aligned} p_b^+ &= z p_a^+ \\ p_c^+ &= (1-z) p_a^+ \\ p^- &\ \text{conservation} \end{aligned}\right\} \implies m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:




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

Spacelike branching:



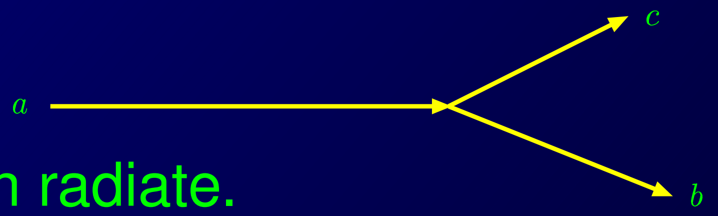

$$p_\perp^2 = (1-z)Q^2$$

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 $p_{\perp\mathrm{max}}$

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

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

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

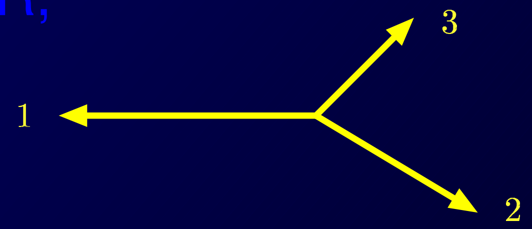
3) *Derive* $Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/z(1-z)$ for FSR

$Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/(1-z)$ 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*
   - $(2E_i/E_{\rm cm} = 1 - m_{jk}^2/E_{\rm cm}^2)$
   - 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: $p^2_{\perp\mathrm{evol}} = z(1-z)(m^2 - m_Q^2)$
  $\Rightarrow m^2 \to m_Q^2$ when $p^2_{\perp\mathrm{evol}} \to 0$.
- Special treatment of narrow resonances (e.g. top).

## ISR Evolution:

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

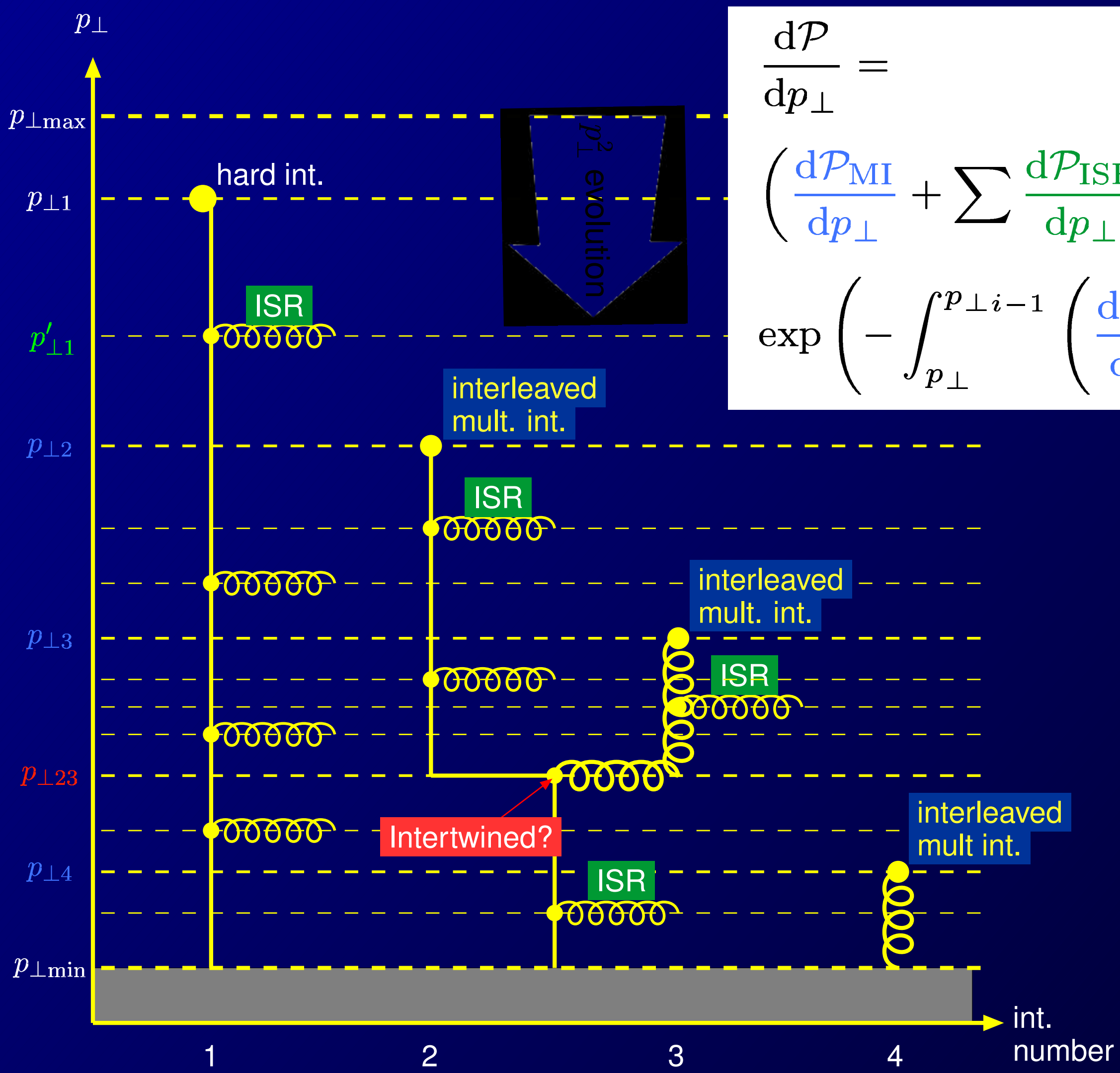
## Both ISR and FSR:

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

# Unifying PS and UE: Interleaved Evolution

The new picture: start at the most inclusive level, $2 \to 2$.

Add exclusivity progressively by evolving *everything* downwards.




$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p_\perp}\right) \times \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)$$

# THE NEW FRAMEWORK


+ remnants
+ (string) hadronization

# Confinement, primordial $\mathbf{k}_\perp$, and $\mathbf{x}_{\rm rem}$ sharing.

- Confined wavefunctions $\to k_\perp = \hbar/r_{\rm p} \sim \Lambda_{\rm QCD}$.
  Empirically, one notes a need for larger values.
  $$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x \mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)}$$
  $\sigma(1\ \mathrm{GeV}) \approx 0.36\ \mathrm{GeV}\ (hadr.)$
  $\sigma(10\ \mathrm{GeV}) \approx 1\ \mathrm{GeV}\ (EMC)$
  $\sigma(m_Z) \approx 2\ \mathrm{GeV}\ (Tevatron)$
  $\to$ Fitted approx. shape $\sigma(Q) = 2.1Q/(7+Q)$GeV
- Recoils : along colour neighbours (or chain of neighbours) or onto all initiators and beam remnant partons equally. ($k_z$ rescaled to maintain energy conservation.)
- Lightcone fractions $x_{j,k}$ in remnants: use remnant pdf's and fragmentation functions (with $(E,p)$ conserved).
- Composite BR systems possible (diquarks, mesons, w. pion/gluon clouds?) $\to$ larger $x$?

# Intermezzo: now it gets tougher

**We have arrived at:**

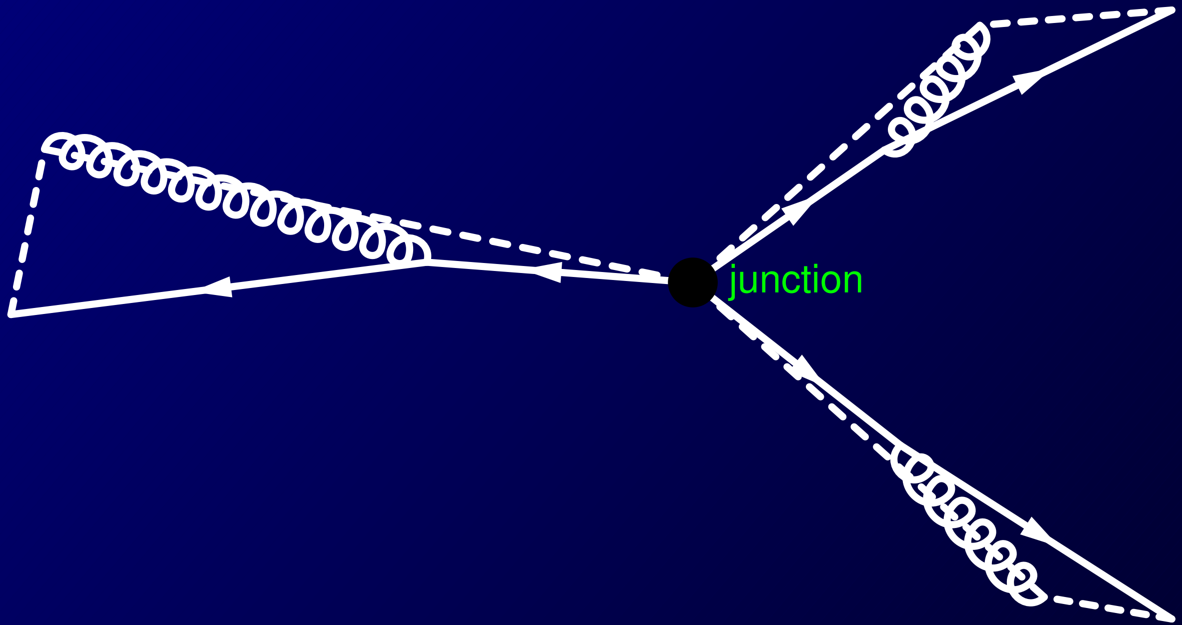
- A set of $p_\perp$-ordered interactions, with showers, taking into account non-zero primordial $k_\perp$ effects.
- A set of partons (possibly diquarks etc) left behind in the beam remnants, whose flavours are known and whose kinematics have been worked out (i.e. $x$ and $\vec{k}_\perp$).

**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: 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°:

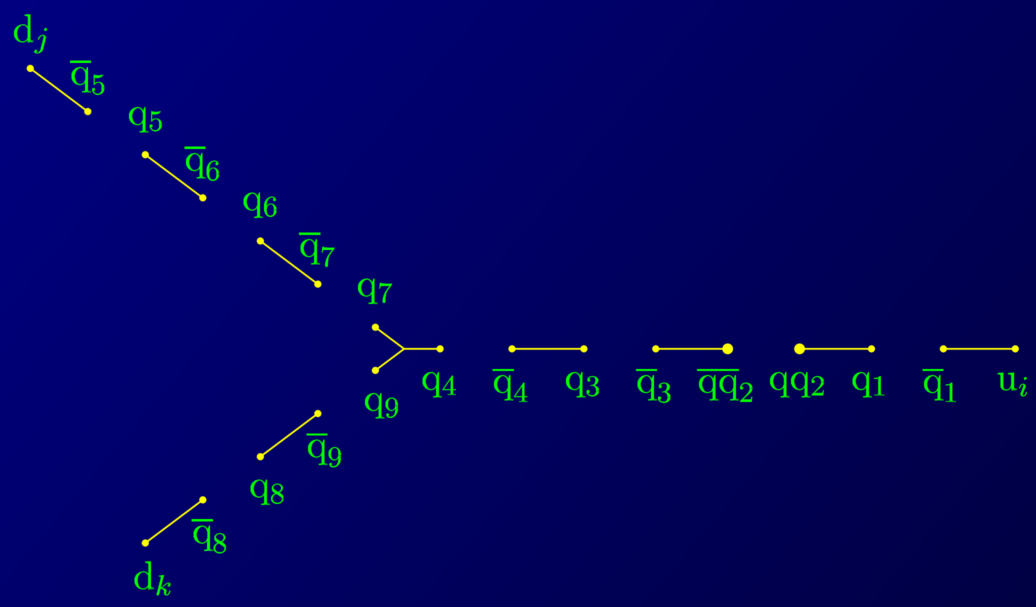
$$p^\mu_{\mathrm{pull}} = \sum_{i=1,N} p^\mu_i e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

(since soft gluons 'eaten' by string)

- Note: the junction motion also determines the baryon number flow!)

# Junction Fragmentation

## How does the system fragment?




- NB: Other topologies also possible (junction–junction strings, junction–junction annihilation).

# Colour Correlations:

Currently, this is the biggest question.

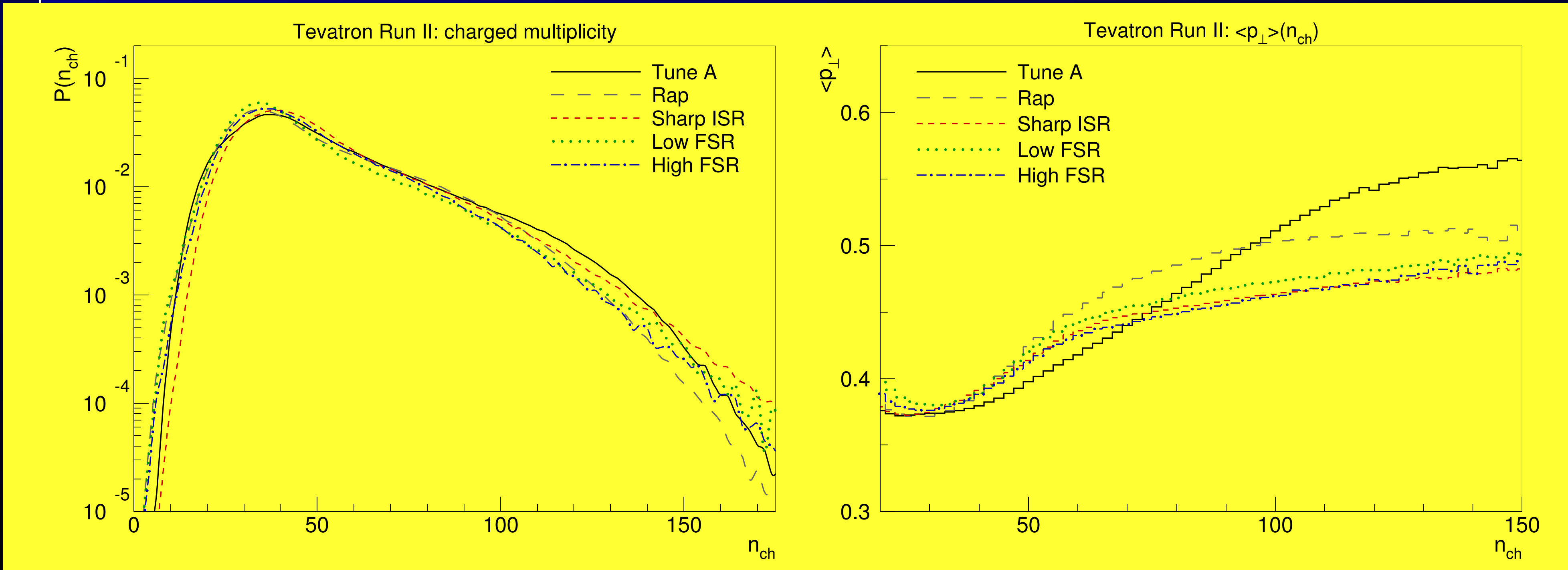
- Tune A depends on VERY high degree of (brute force) colour correlation in the final state.
- Several physical possibilities for colour flow ordering investigated with new model. So far it has not been possible to obtain similarly extreme correlations.
- This may be telling us interesting things!

More studies are still needed... in progress.

- Fortunately, this is not a showstopper. Even with less correlated colours than Tune A, we are getting interesting results out of the new framework.

# Model Tests

- Whole framework.
  - The rough tunes were made 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...



# Model Tests: FSR Algorithm

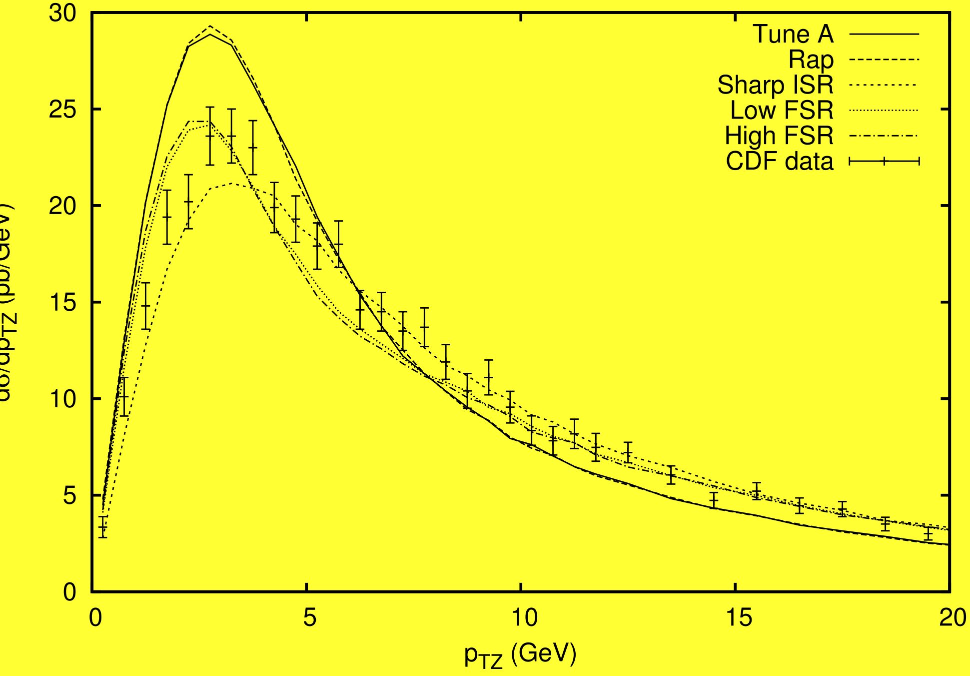
- Tested on ALEPH data (courtesy G. Rudolph).

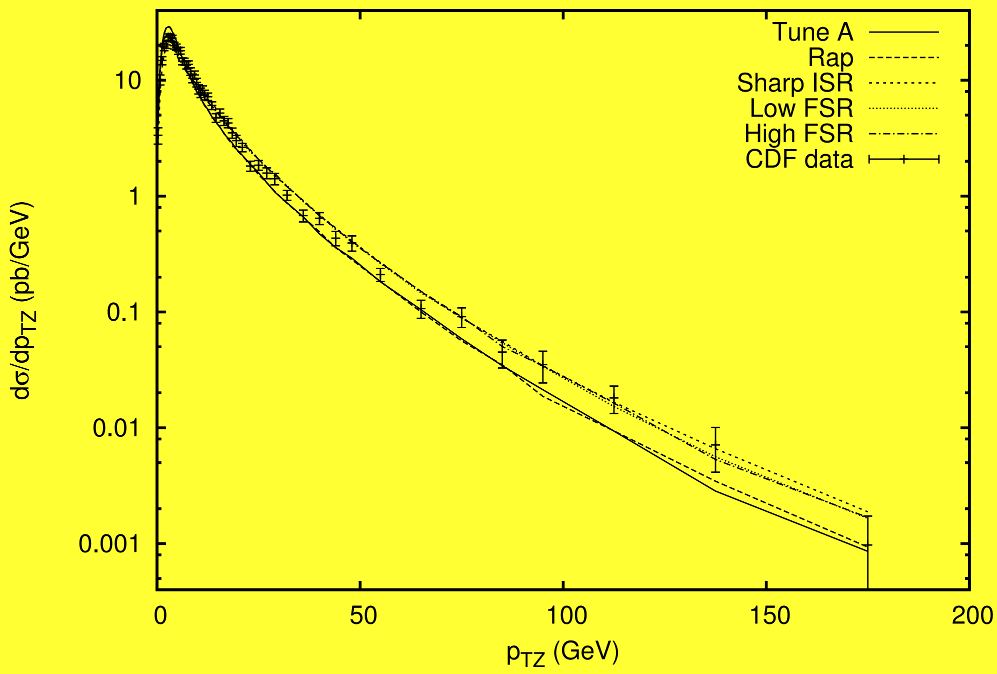
| | | $\sum \chi^2$ of model | |
|---|---|---|---|
| Distribution of | nb.of interv. | PY6.3 $p_\perp$-ord. | PY6.1 mass-ord. |
| Sphericity | 23 | 25 | 16 |
| Aplanarity | 16 | 23 | 168 |
| $1-$Thrust | 21 | 60 | 8 |
| Thrust$_{\mathrm{minor}}$ | 18 | 26 | 139 |
| jet res. $y_3$(D) | 20 | 10 | 22 |
| $x = 2p/E_{\mathrm{cm}}$ | 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 Algorithm

- Less easy to test. We looked at $p_\perp$ of $\mathrm{Z}^0$ 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 $k_\perp$).




$\rightarrow$ More studies ongoing (e.g. looking at $p_\perp$ of $\mathrm{t\bar{t}}$)...

# Outlook

- New complete framework for hadron collisions.
- Includes $p_\perp$–ordered *interleaved* parton showers and multiple interactions, correlated remnant parton distributions, impact parameter–dependence, extended (junction) string fragmentation model, etc.
- It's all in PYTHIA 6.316 (24 Nov 2004).
- Good overall performance, though still only primitive studies/tunes carried out, except for FSR.
- Colour correlations still a headache. Still unclear what role *intertwining* may play.

# Outlook

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

- Conclusion: our picture of hadron collisions <u>is</u> becoming more complex...

# PYTHIA 6.3

# OVERVIEW OF RELEVANT PARAMETERS

# PYTHIA 6.3 Parameter Overview: Switches

| | |
|---|---|
| MSTP(61) | Master switch for initial–state radiation. Default is on. |
| MSTP(71) | Master switch for final–state radiation. Default is on. |
| MSTP(81) | Master switch for multiple interactions and beam remnant framework. |
| MSTP(70) | Selects regularization scheme for ISR when $p_\perp \to 0$. Default is sharp cutoff at the regularization scale used for MI. |
| MSTP(72) | Selects maximum scale for radiation off FSR dipoles stretched between ISR partons. Default is $p_\perp$ scale of radiating parton. |
| MSTP(82) | Selects which functional form to assume for the impact-parameter dependence of the matter overlap between two beam particles. |
| MSTP(84) | Selects whether initial–state radiation is turned on or off for subsequent interactions (i.e. interactions after the main one). Default is on. |
| MSTP(85) | Selects whether final–state radiation is turned on or off for subsequent interactions (i.e. interactions after the main one). Default is on. |
| MSTP(89) | Controls how initial–state parton shower initiators are colour–connected to each other. Default is to assume a rapidity ordering. |
| MSTP(95) | Selects whether colour reconnections are allowed or not. Default is on. |

# PYTHIA 6.3 Parameter Overview: Parameters

| | |
|---|---|
| `PARP(82)` | Regularization scale, $p_{\perp 0}$, for multiple interactions, at reference energy `PARP(89)`. Default is 2 GeV. |
| `PARP(89)` | Reference energy for energy rescaling of $p_{\perp 0}$ cutoff, i.e. the energy scale at which $p_{\perp 0}$ is equal to `PARP(82)`. Default is 1800 GeV. |
| `PARP(90)` | Power of energy rescaling used to determine the value of $p_{\perp 0}$ at scales different from the reference scale `PARP(89)`. |
| `PARP(83:84)` | Shape parameters, controlling the assumed matter distribution or overlap profile, as applicable (i.e. depending on `MSTP(82)`). |
| `PARP(78)` | Controls the amount of colour reconnection in the final state. |
| `PARP(79)` | Enhancement factor for $x$ values of composite systems (e.g. diquarks) in the beam remnant. |
| `PARP(80)` | Suppression factor for initial–state colour connections that would break up the beam remnant. |

# More information on PYTHIA 6.3

- The PYTHIA 6.3 manual: hep-ph/0308153
- “Notes on using PYTHIA 6.3”: on my homepage:
  `http://home.fnal.gov/~skands/`
- Physics descriptions of the new ISR/FSR/MI framework:
  - TS+PS, “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”, hep-ph/0408302.
  - TS, “New Showers with transverse-momentum-ordering”, hep-ph/0401061.
  - TS+PS, “Multiple Interactions and the Structure of Beam Remnants”, JHEP 0403 (2004) 053.
- + Slides like these.
  (See “Slides/Talks” on my homepage for a complete list)