Looking Inside Hadron Collisions

Peter Skands (Fermilab)

Looking Inside...

- Matrix Elements and Parton showers
- The Underlying Event
- Beam Remnants and Hadronization

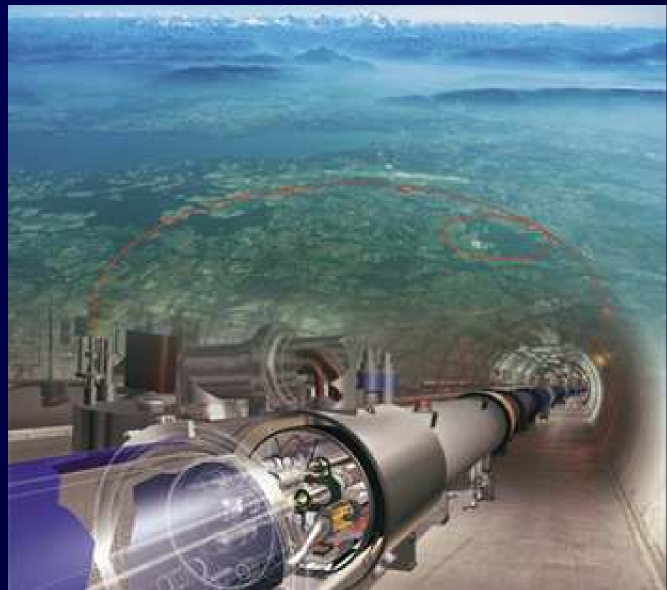
Why Study Supernovae?

- They are the highest energy explosions in the universe
- They give us clues to other physics
  - Type Ia = large-distance standard candles
    $\to$ distance/redshift relation
    $\to$ Λ problem
  - SN1987a
    $\to$ neutrino physics,
    Cooling $\to$ limits on light/weak particles
    + much much more ...

Price: <u>extremely</u> complicated dynamics $\leftrightarrow$ they are now *almost* making them explode in simulations...

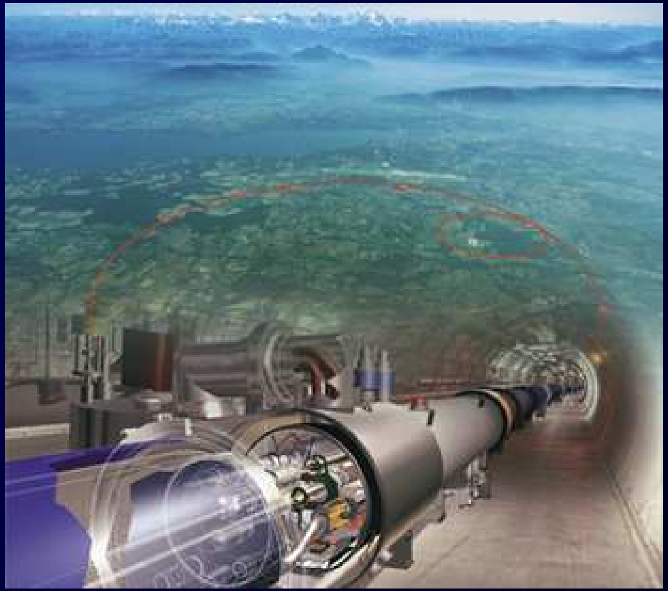
Much can be done even in complex environments.
More if the complex dynamics can be understood and modeled

The Near (Accelerator) Future is Hadron Collisions



The Near (Accelerator) Future is Hadron Collisions

- Tevatron
  - expect 2 – 10 fb^{-1} by LHC turn-on $\rightarrow$ Large W, Z, and $\mathrm{t\bar{t}}$ samples (including hard tails !)
  - Reduction of t and W mass uncertainties by $\sim 50\%$
  - Potential discoveries...



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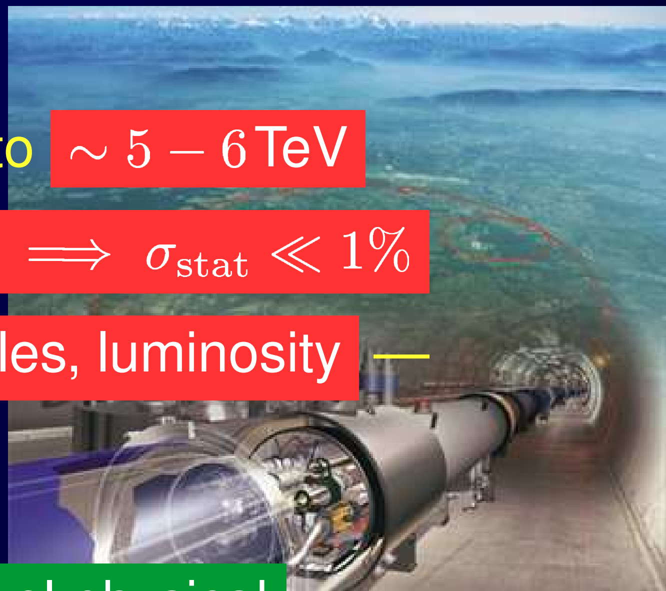
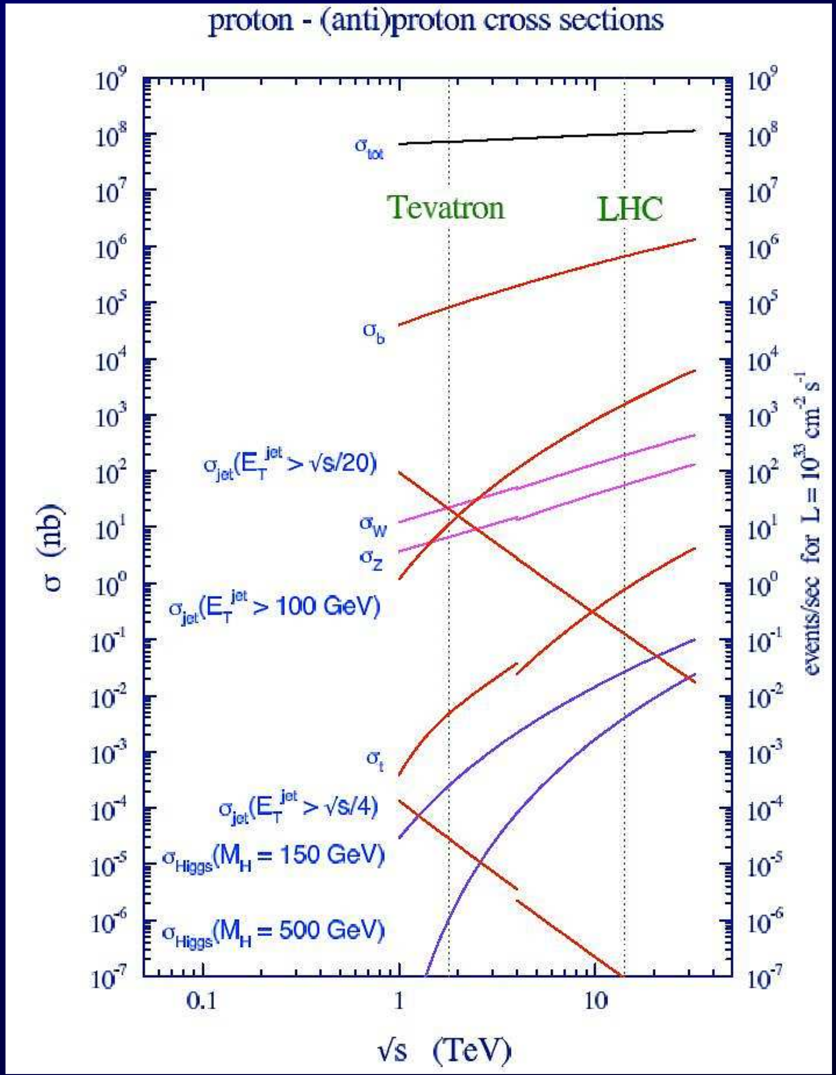


- **LHC**
  - Explore EWSB / Probe New Physics up to $\sim 5 - 6$ TeV
  - 1 year $\rightarrow$ more than 10^7 W, Z, $\mathrm{t\bar{t}}$ events $\Longrightarrow \sigma_{\mathrm{stat}} \ll 1\%$
  - Improved Systematics — jet energy scales, luminosity — from high–statistics ’standard candles’

- $\Longrightarrow$ Large discovery potential + percent level physics!

But Hadrons Grant Nothing Witout Hard Work

- Not all discovery channels produce dramatic signatures $\rightarrow$ Need theoretical control of shapes, backgrounds, uncertainties, ...
- Scattering at LHC $\neq$ "rescaled" scattering at Tevatron. (smaller x, more intensive BGs, UE,...)
- Aiming for percent level measurements, PDFs, luminosities, jets etc $\implies$ solid understanding of QCD in hadron collisions, both perturbative and non–perturbative, is crucial
- State-of-the art is wide range of FO, PS, Res, hadr, ... results & tools.



Matrix Elements and Parton Showers

- **Matrix Elements — Fast Forward**

  $+$ FO α: Exact (interference, helicity, loops, ...)

  $-$ Limited Applicability: LEP $\rightarrow$ multiple soft gluons significant in building full event structure

  $-$ Phase space for soft gluons larger at HE

  $+$ PT expansion better behaved at HE (α_s smaller)

  $+$ Few, well–separated partons in final state

  $\pm$ For full event structure, need to go beyond FO.

- **Parton Showers — Fast Forward**

  $-$ Approximate in wide–angle hard region

  $+$ Universal

  $+$ exponentiate $\rightarrow$ arbitrary number of FS partons

  $+$ Match to hadronization

- **Marriage desireable** $\rightarrow$ (L)CKKW, MLM, MC@NLO, ...

What I am Talking About

- Focus of this talk:
  - Parton Showers & Underlying Events
  - Beam Remnants & Hadronization
- Not the focus of this talk:
  - Resummation approaches
  - Fixed–Order approaches
  - Parton Shower / (born-level) Matrix Element matching & merging
  - Parton Shower / NLO Matrix Element matching & merging

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).

  Basic formalism: Sudakov (DGLAP) evolution:

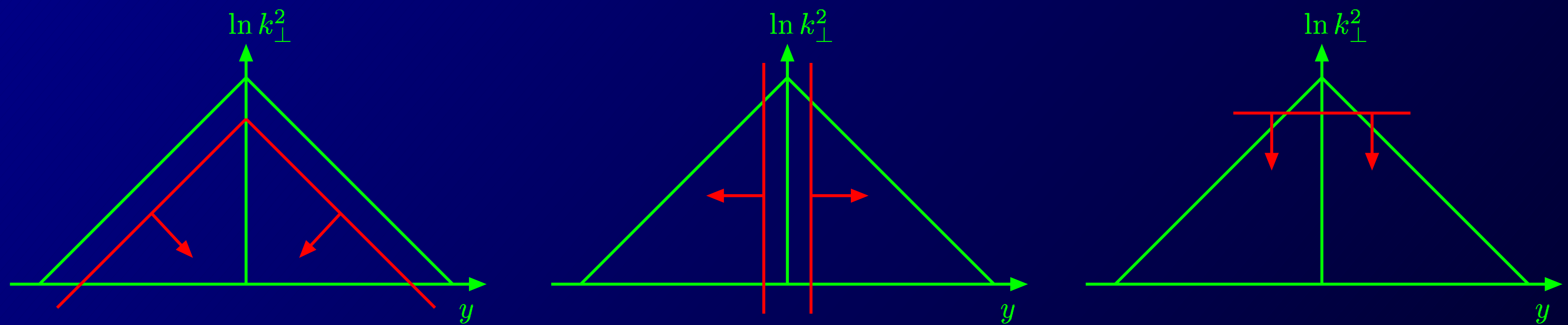
$$\mathrm{FSR}: \; \mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}X^2}{X^2} \frac{\alpha_\mathrm{s}(X^2)}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z \,\exp\left(-\int_X^{X_\mathrm{max}} \cdots\right)$$

  - X: some measure of 'resolution', z: energy sharing
  - $P_{a\to bc}(z)$: collinear limit ($t \to 0$) of ME (can include $m \neq 0$ effects).
  - Correctly resums Leading Logs + some NLL effects (momentum conservation, running α_s etc).
  - Big boon: universal and amenable to iteration $\to$ algorithm can give you fully exclusive (='resolved') final states $\to$ match to hadronization

Parton Showers: the basics

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

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

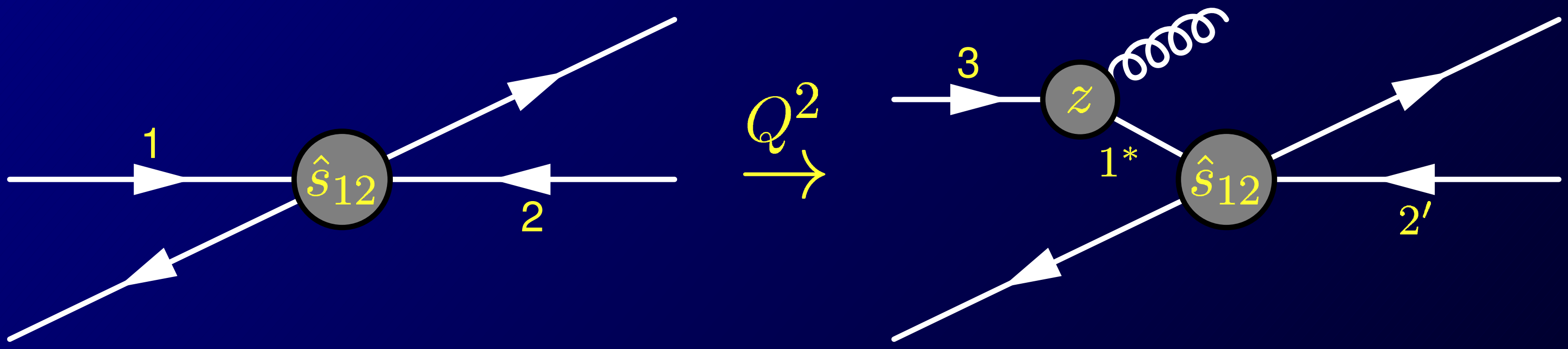


PYTHIA/JETSET	HERWIG	ARIADNE
m^2 ($-m^2$ for ISR)	$\sim E^2\theta^2$	$p_\perp^2$
High–virtuality ems. first.	Large–angle ems. first.	Large–$p_\perp$ ems. first.

Parton Showers:

- 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
1 and 2 on shell
$E^2_{cm} = \hat{s}_{12} = x_1 x_2 s$

(1st) Correction
3 and 2' now on shell
$E^2_{cm} = x_3 x_2 s = \frac{x_1}{z} x_2 s$

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?

Underlying Event: the basics

Why *multiple perturbative interactions*?

Consider perturbative QCD $2 \to 2$ scattering:

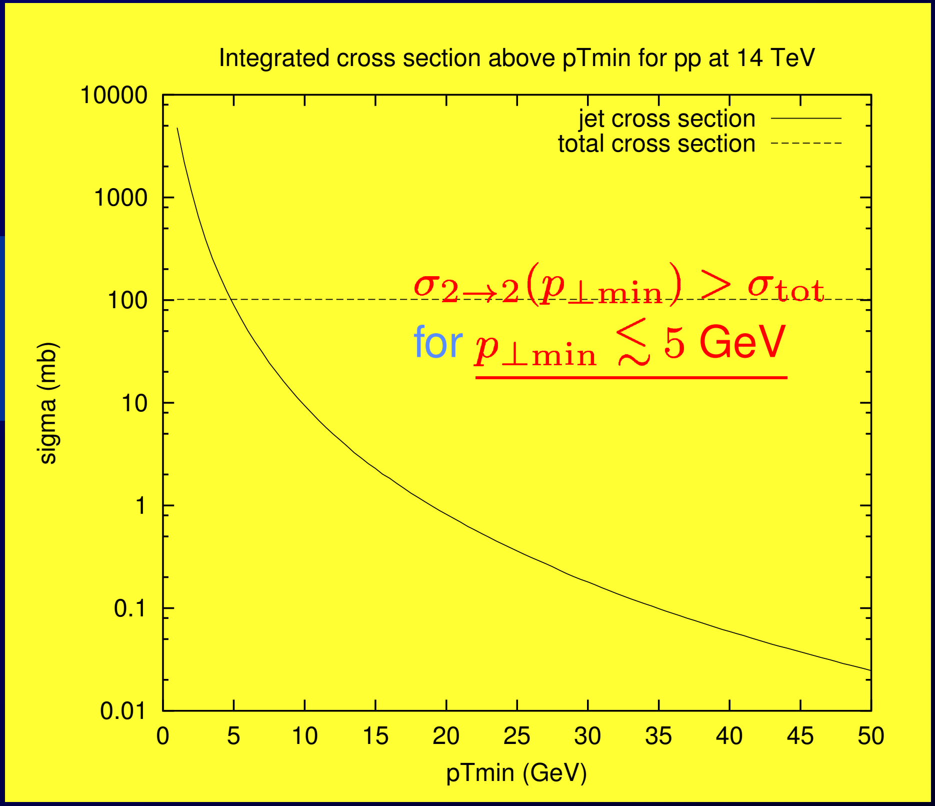
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{1}{t^2} \sim \frac{1}{p_\perp^4}$$

$\Longrightarrow$ '2-jet' cross sect

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

while total pp cross sect:

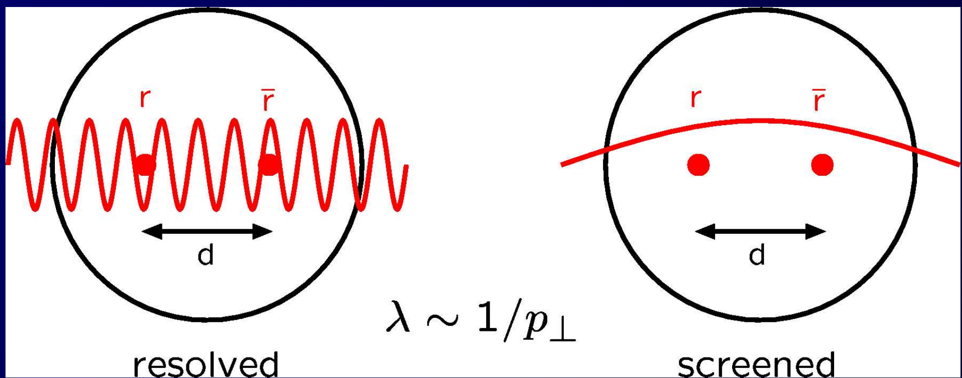
$$\sigma_{\mathrm{pp}} \propto s^{0.08}$$



What's going on?

1. **Multiple interactions (MI)!**
   - Must exist (hadrons are composite!)
   - σ_{tot}: hadron-hadron collisions. $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
   - $\sigma_{2\to2}$: parton–parton collisions. $\sigma_{2\to2} = \sum_{n=0}^{\infty} n\,\sigma_n$
   - $\sigma_{2\to2} > \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1$

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

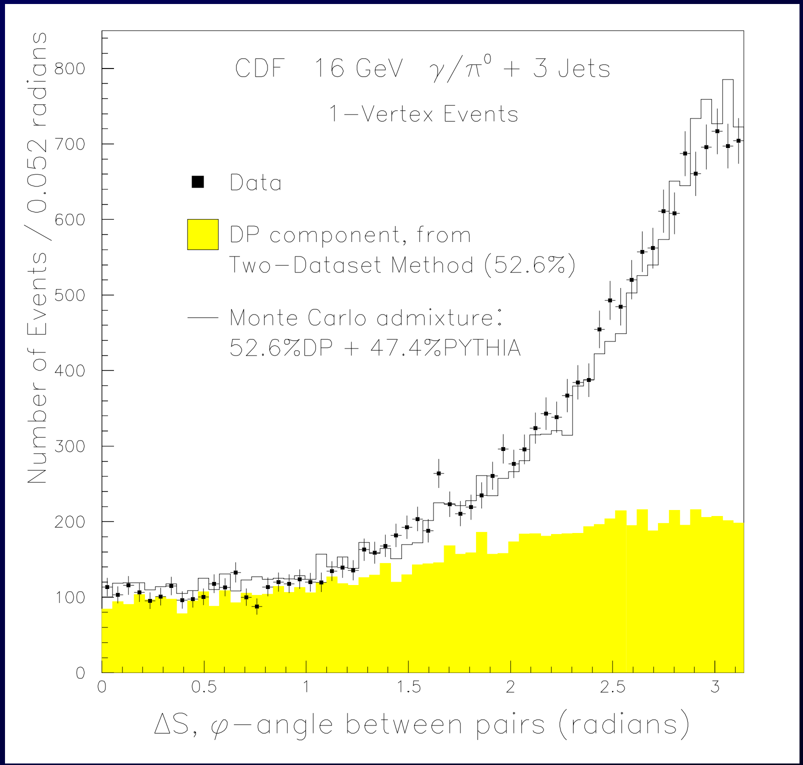


$p_{\perp 0} \sim 2$ GeV

(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 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. Sample: 14000 $\gamma/\pi^0 + 3j$ events. Strong signal observed, 53% DPS



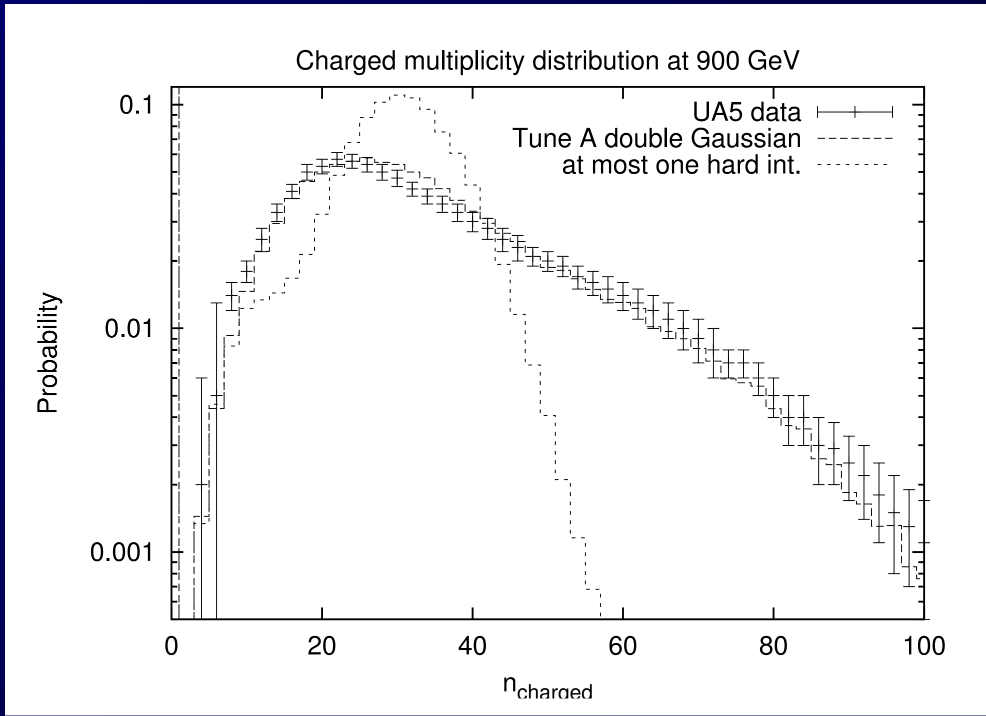
- (Note: only plot made was comparison to PYTHIA with MI switched *off*!)

(Multiple Interactions — Indirect Verifications)

Basic idea :

- **Hadronization alone produces roughly Poissonian fluctuations in multiplicity.**
- **Additional soft interactions + b dependence $\to$ 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) was probably the most sophisticated; tunes like 'Tune A' can simultaneously reproduce a large part of Tevatron min–bias and UE data, as well as data from other colliders.

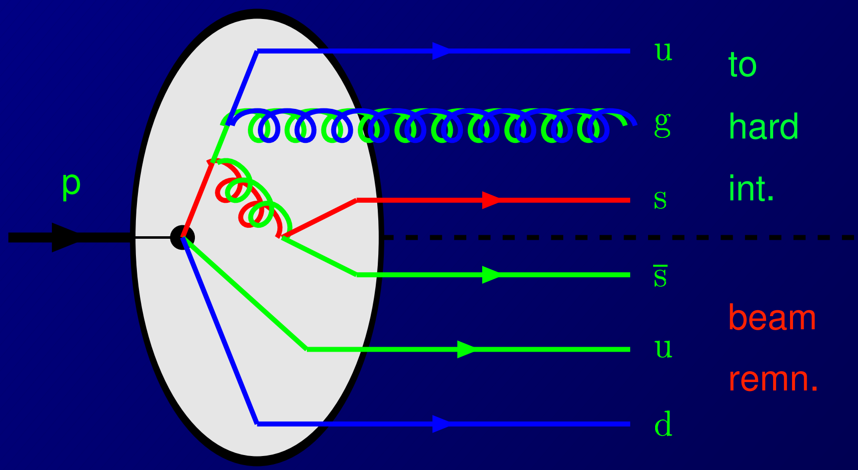
[T. Sjöstrand, M. van Zijl, "A Multiple Interaction Model For The Event Structure In Hadron Collisions", Phys. Rev. D 36 (1987) 2019.]

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

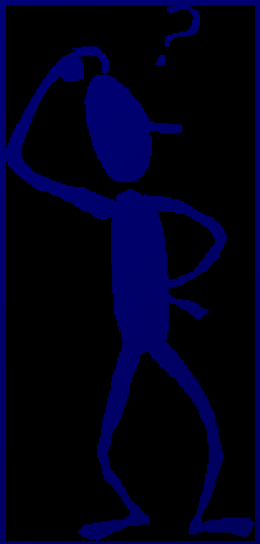
New UE Model: Why Bother?

- QCD point of view: hadron collisions are complex. Present models are not.
  More detail $\rightarrow$ more insight $\rightarrow$ more precision
- 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!

Completing the picture



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



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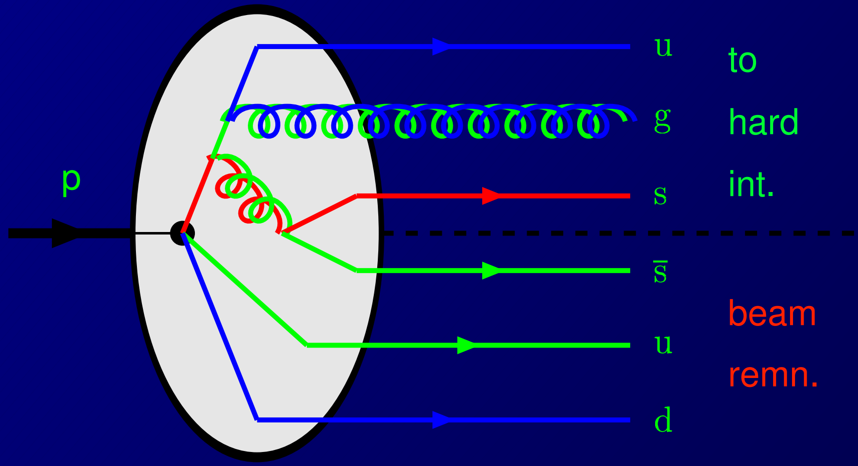

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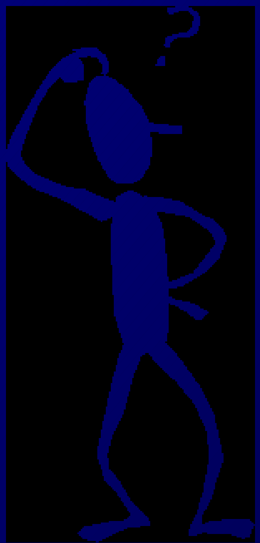
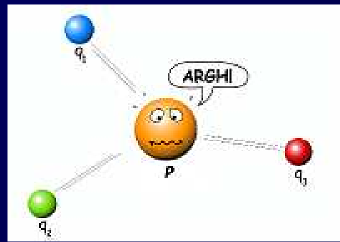
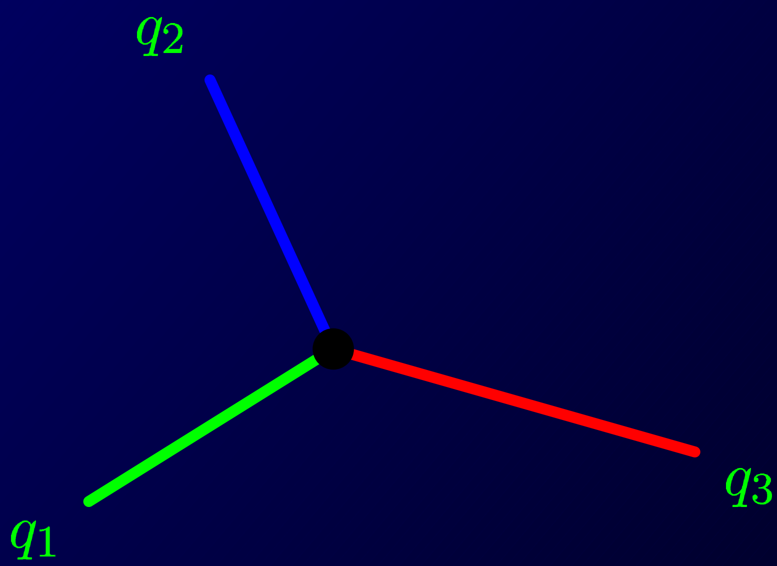


- In impact parameter?
- In flavour?
- In longitudinal momentum?
- In colour?
- In (primordial) transverse momentum?
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

(...) $\otimes$ 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.

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.

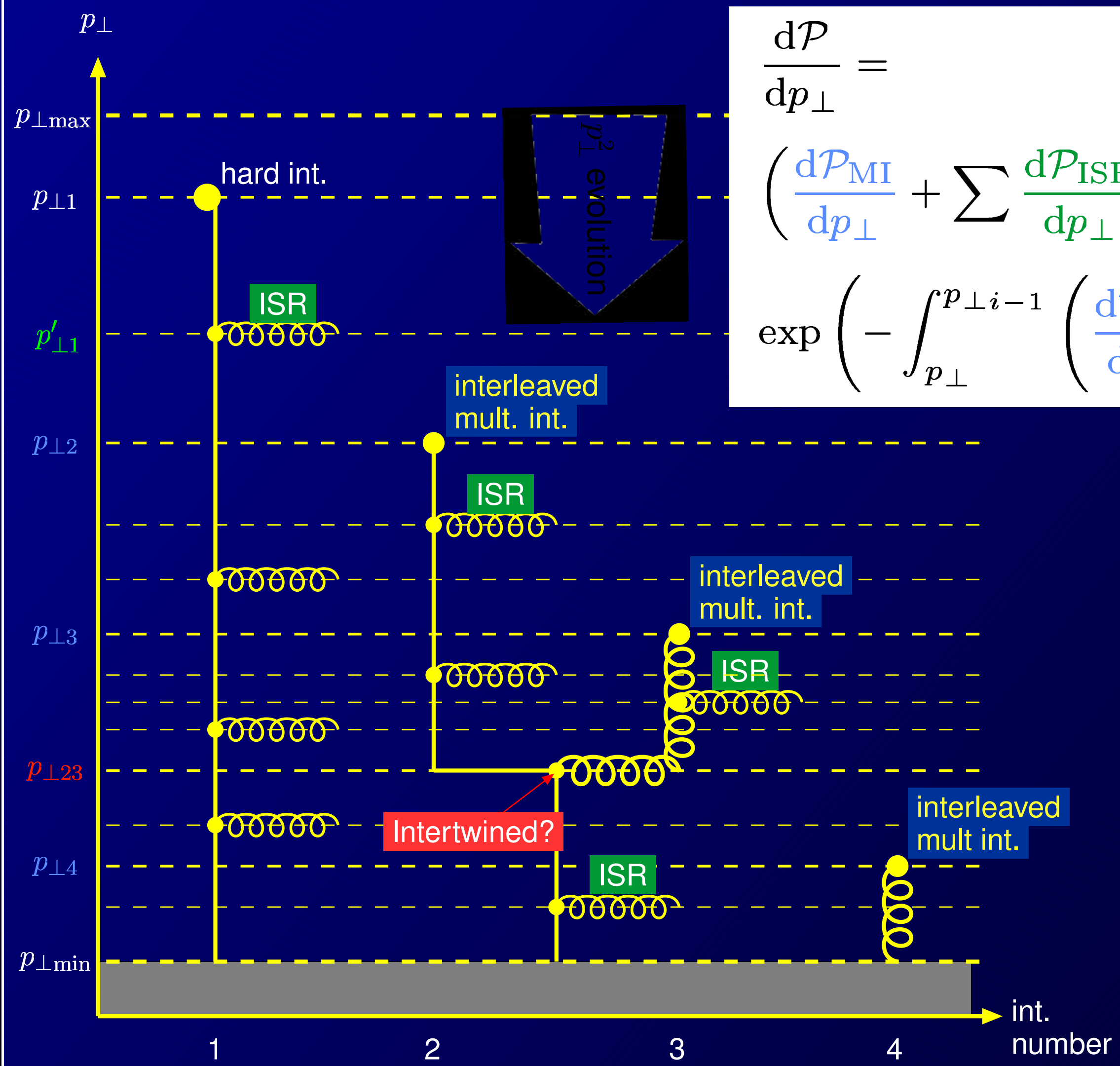
Further, the description of parton showers and the underlying event has been unified in a common $p_\perp$-ordered 'interleaved evolution' of the event as a whole.

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

Unifying PS and UE: Interleaved Evolution

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

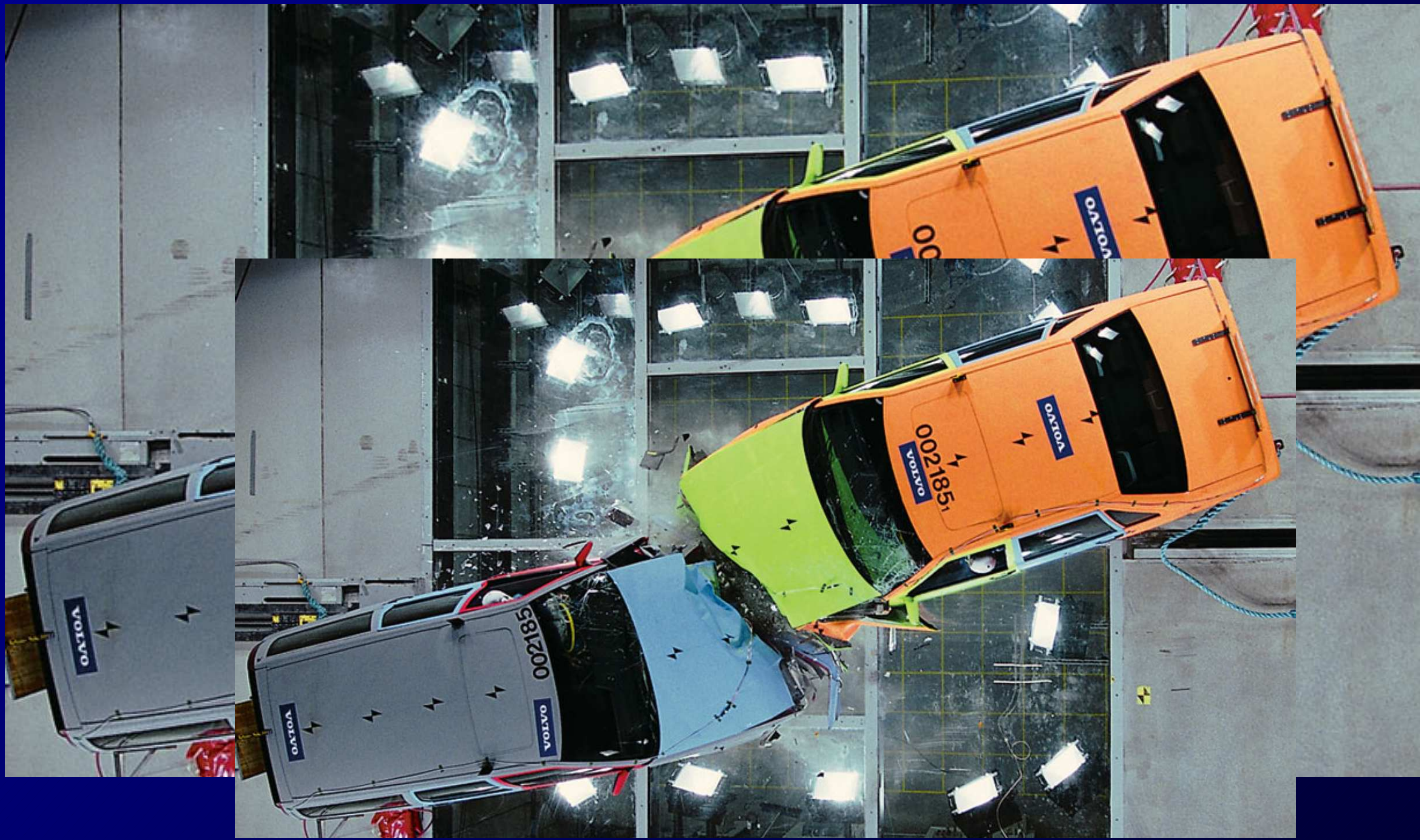
Add exclusivity progressively by evolving *everything* downwards.



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

$\sim$ "Finegraining"

THE NEW FRAMEWORK

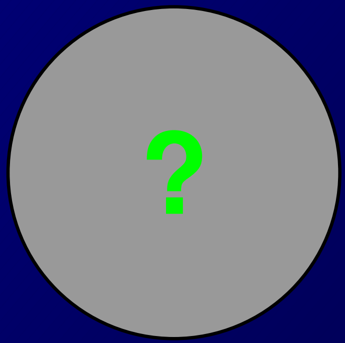


Multiple Interactions

T. Sjöstrand+PS, JHEP 0403 (2004) 053
T.Sjöstrand+PS, EPJ C39 (2005) 129

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

Consider a hadron, H:



MI context: need PDFs for finding partons $i_1 \ldots i_n$ with momenta $x_1 \ldots x_n$ in 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 $n = 1$.

Global fits:	CTEQ	MRST	
DIS fits:	Alekhin	H1	ZEUS
Other PDF:	GRV	...	

$\rightarrow f_{i_1/H}(x_1, Q_1^2)$

So we make a theoretical cocktail...

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

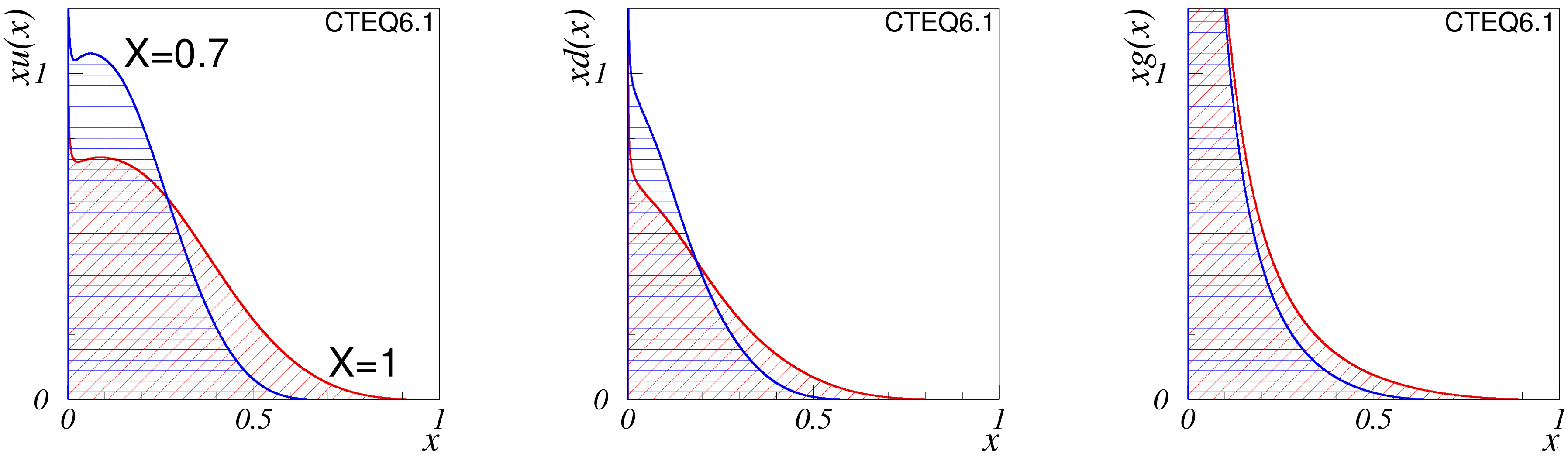
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

1. Overall momentum conservation ('trivial'):

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

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- 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 would be 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.

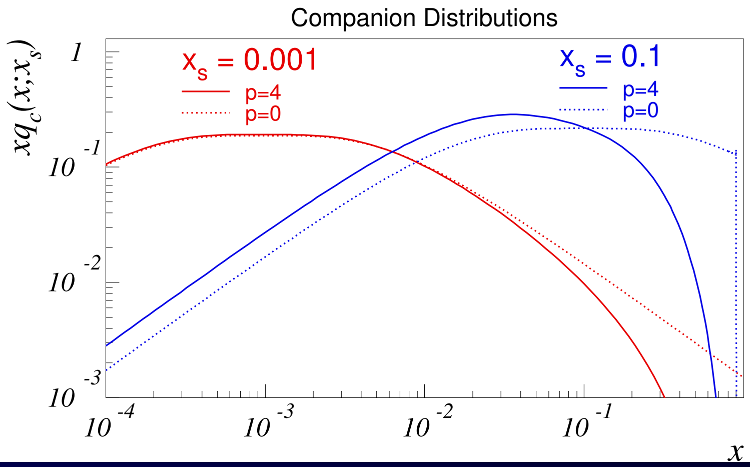
Remnant PDFs

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

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

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

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



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

THE NEW FRAMEWORK

+ showers

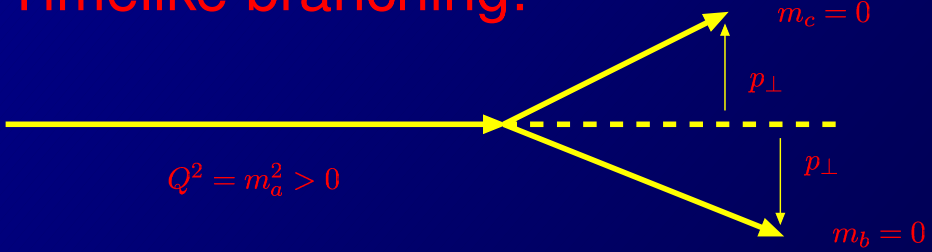
T.Sjöstrand+PS, EPJ C39 (2005) 129
T.Sjöstrand, hep-ph/0401061.

$p_\perp$–ordered showers: Simple Kinematics

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

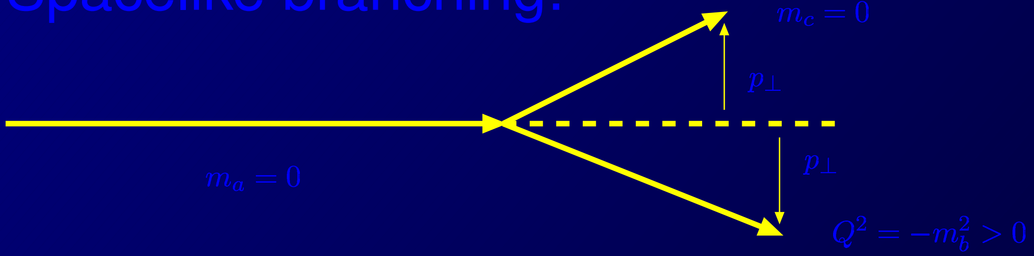
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



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

Spacelike branching:



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

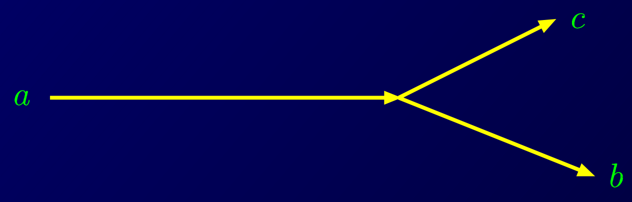
Guideline, not final $p_\perp$!

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

1) *Define*

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

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



2) Evolve all radiators *downwards* in $p_{\perp\mathrm{evol}}$ from common $p_{\perp\max}$

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

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

3) Then *Derive* Q^2

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

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

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

4) Interpret z as *Lorentz invariant energy fraction* (not lightcone)
$(2E_i/E_{\mathrm{cm}} = 1 - m_{jk}^2/E_{\mathrm{cm}}^2)$
$\rightarrow$ straightforward match to matrix elements by reweighting!

5) Construct exclusive *kinematics* based on Q^2 and z, assuming yet unbranched partons on-shell

6) Continue summing those logs...
$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$

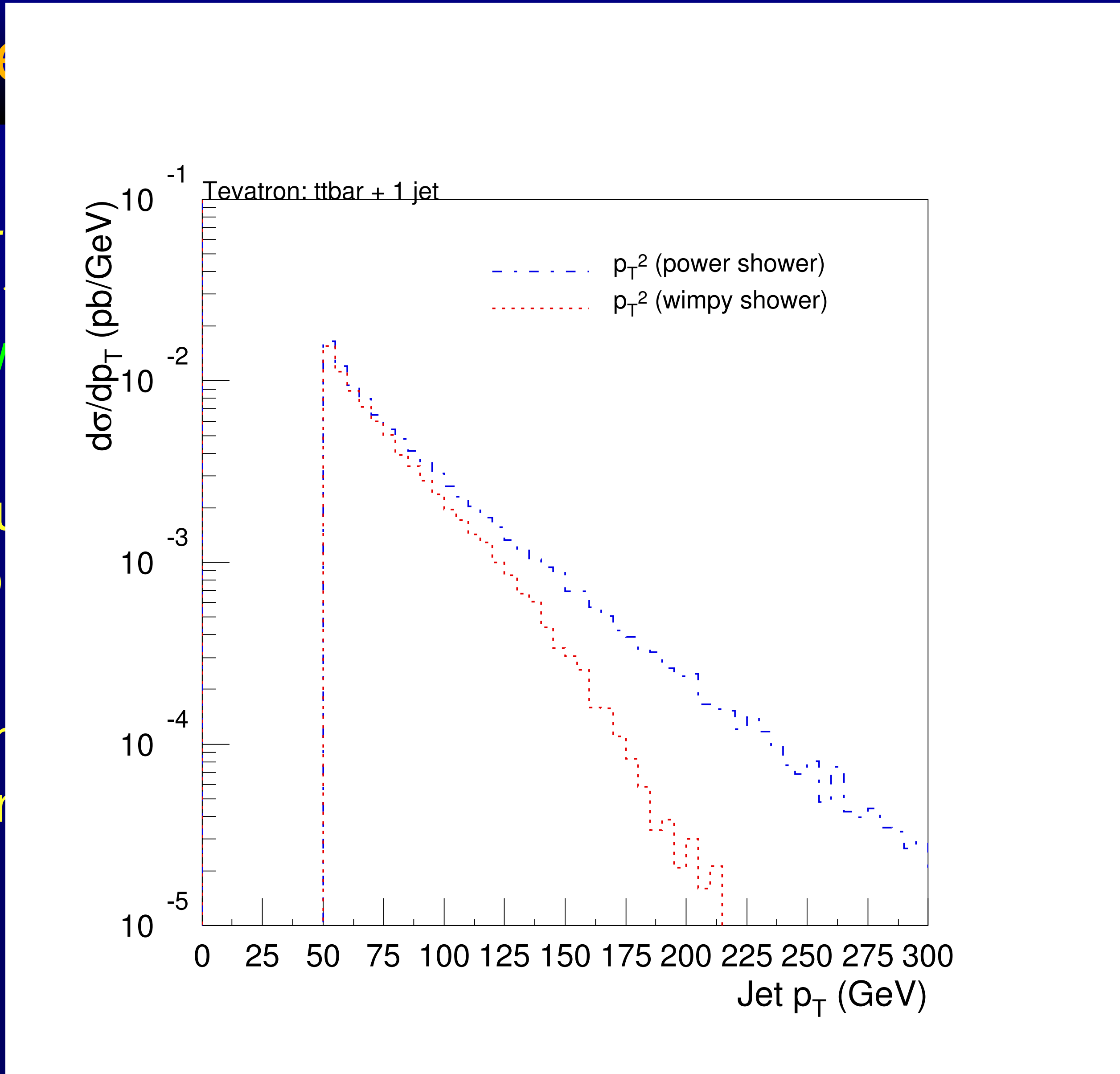
NB: Choice of $p_{\perp\mathrm{max}}$ non-trivial and *very* important for hard jet tail
$\leftrightarrow$ wimpy vs power showers...

$p_\perp$–ordere

4) Interpret z as L
$(2E_i/E_{\mathrm{cm}} = 1$
$\rightarrow$ straightforw

5) Construct exclu ... yet
unbranched parto

6) Continue summ
$\Rightarrow$ One combir



NB: Choice of $p_{\perp\mathrm{max}}$ non-trivial and *very* important for hard jet tail
$\leftrightarrow$ wimpy vs power showers...

($p_\perp$–ordered showers: Some Details)

- **FSR Evolution:**
  - Massive quarks: $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)(m^2 - m_Q^2)$
    $\Rightarrow m^2 \to m_Q^2$ when $\mathrm{p}^2_{\perp\mathrm{evol}} \to 0$.
  - Special treatment of narrow resonances (e.g. top).
- **ISR Evolution:**
  - Massive quarks: $\mathrm{p}^2_{\perp\mathrm{evol}} = (1-z)(Q^2 + m_Q^2) = m_Q^2 + \mathrm{p}^2_{\perp\mathrm{LC}}$
    $\Rightarrow$ Light–Cone $\mathrm{p}^2_{\perp\mathrm{LC}} \to 0$ when $\mathrm{p}^2_{\perp\mathrm{evol}} \to m_Q^2$.
  - 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 φ distribution.

THE NEW FRAMEWORK

+ remnants
+ (string) hadronization

T. Sjöstrand+PS, NPB 659 (2003) 243
T. Sjöstrand+PS, JHEP 0403 (2004) 053

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

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

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

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

  $\to$ 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:

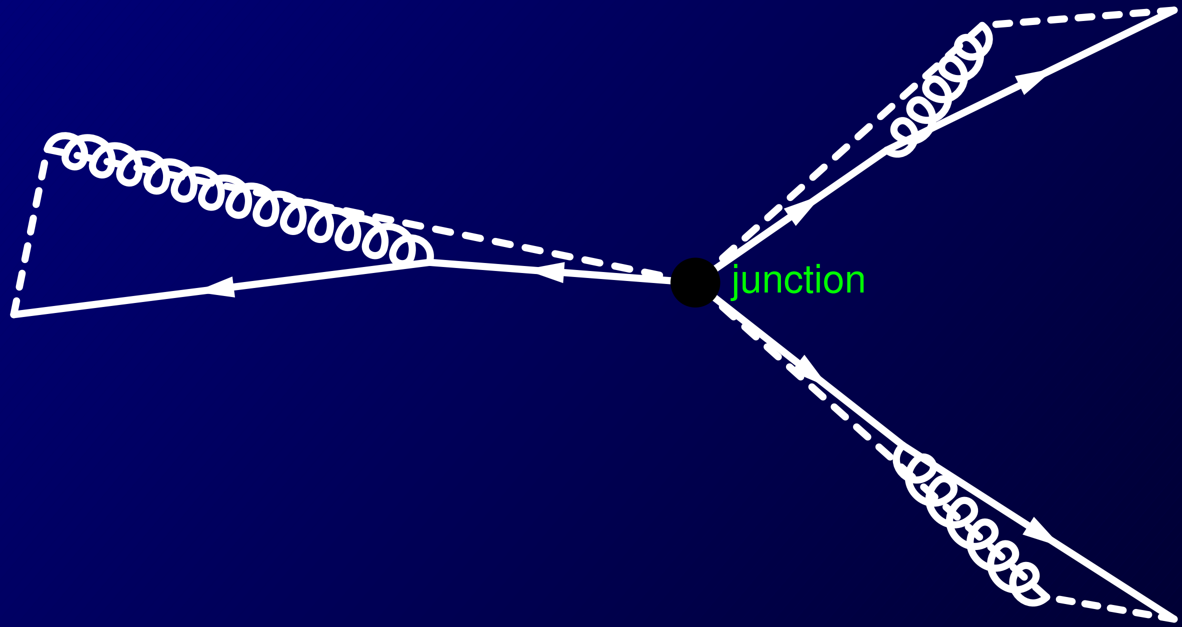
- A set of $p_\perp$-ordered interactions, with showers, taking into account non-zero primordial $k_\perp$ effects.
- A set of partons (possibly diquarks etc) left behind in the beam remnants, whose flavours are known and whose kinematics have been worked out (i.e. x and $\vec{k}_\perp$).

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?

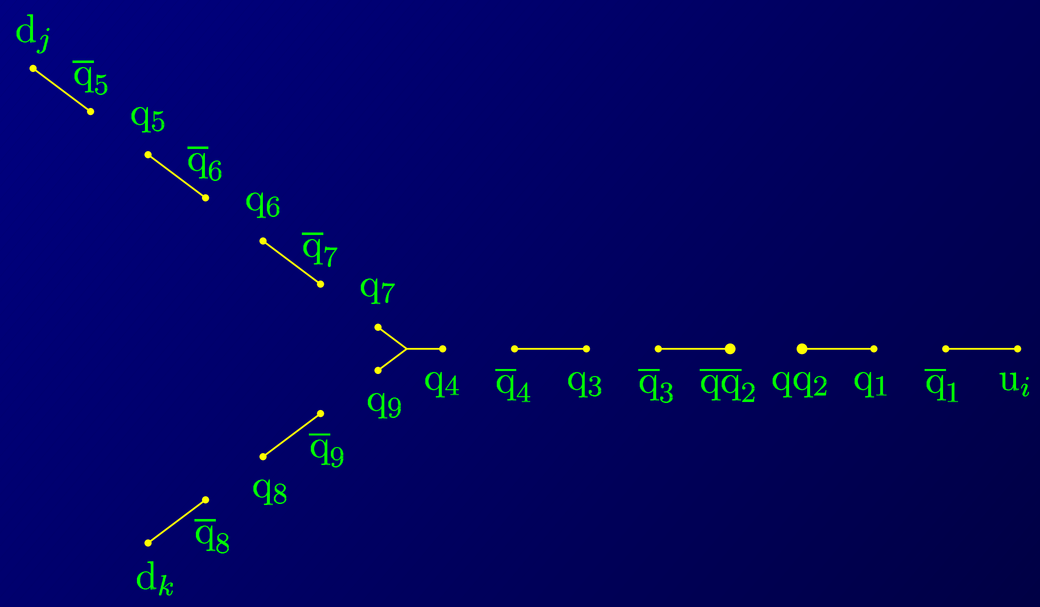
- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at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

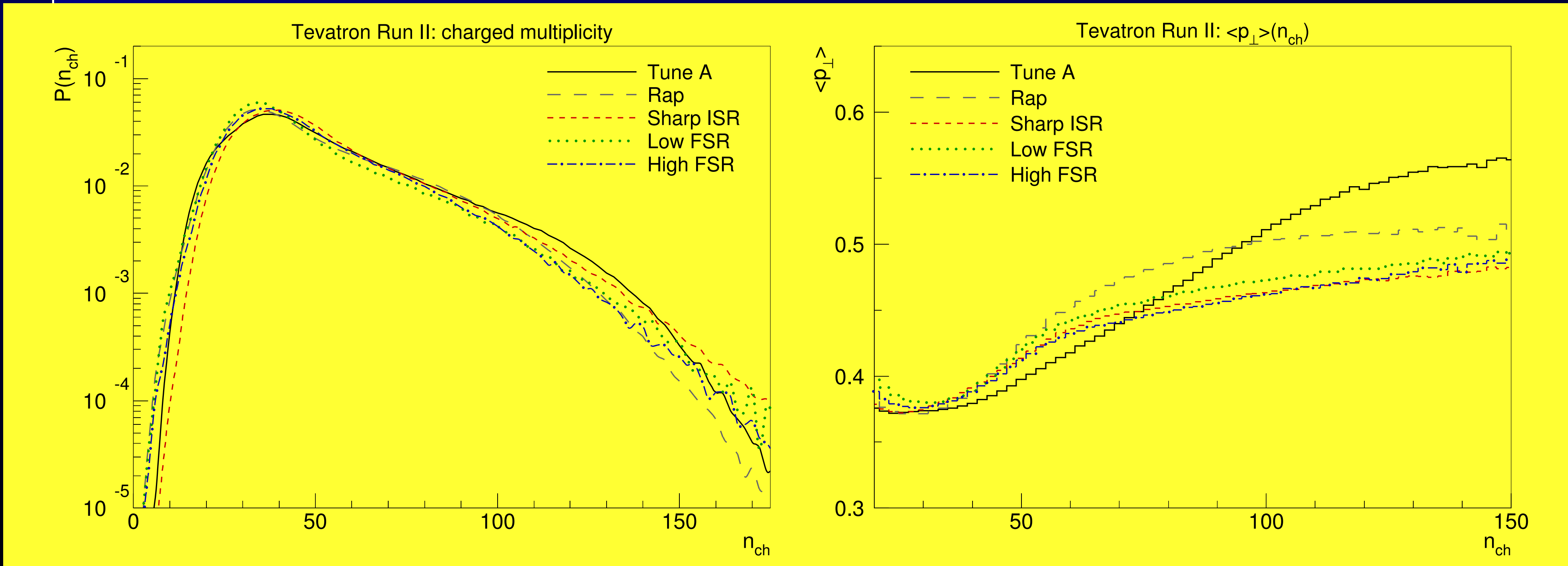
- Tune A depends on VERY high degree of (brute force) colour correlation in the final state.
- Several physical possibilities for colour flow ordering investigated with new model. So far it has not been possible to obtain similarly extreme correlations.
- This may be telling us interesting things!

More studies are still needed... in progress.

- Fortunately, this is not a showstopper. Mostly relevant for soft details (parton $\leftrightarrow$ hadron multiplicity etc).

Model Tests

- Whole framework.
  - 3 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

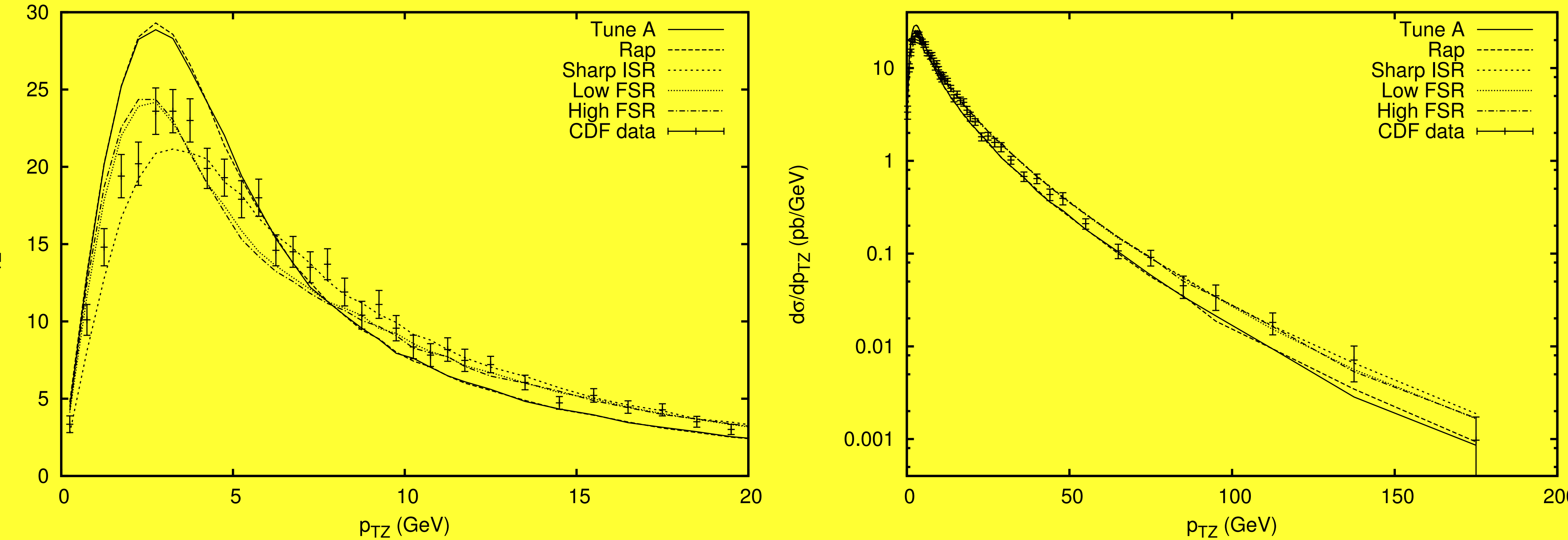
- Tested on ALEPH data (courtesy G. Rudolph).

		$\sum \chi^2$ 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 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

- To fully exploit expected experimental precision, need good understanding of (all aspects of) hadron collisions.
- We've developed a new UE/PS model including:
  $p_\perp$–ordered *interleaved* parton showers and multiple interactions, correlated remnant parton distributions, impact parameter dependence, extended (junction) string fragmentation model, etc.
- We even made it available! → PYTHIA 6.3
- Good overall performance, though still only primitive studies/tunes carried out (except for FSR).
- Colour correlations still a headache.

Outlook

- ed

- ons,

  etc.

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

- **Conclusion: still a long way to go for LHC.**
- But hey, we're still way ahead of the Supernova crowd!

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)