PYTHIA Showering in 6.3

Based on:

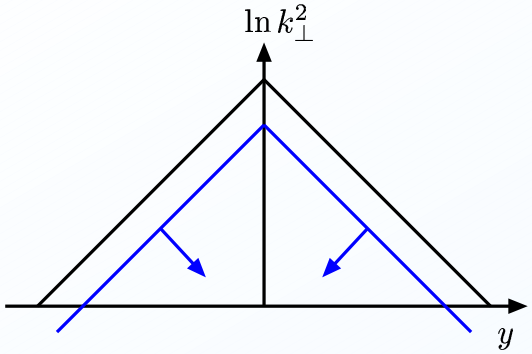
- T. Sjöstrand + PS, “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”, hep-ph/0408302 (in print, EPJC).
- T. Sjöstrand + PS, “Multiple Interactions and the Structure of Beam Remnants”, JHEP 0403 (2004) 053.

PARTON SHOWERS

Showers: Existing Approaches

Essential difference: ordering variables.

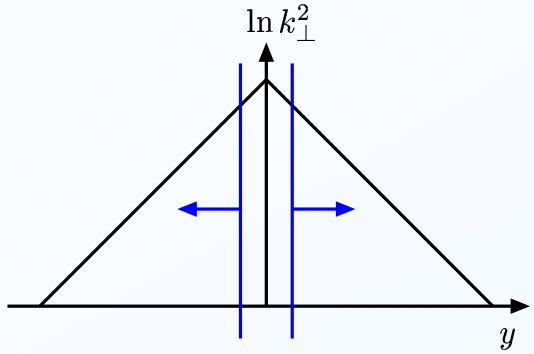
consider e.g. gluon emission off a $\mathrm{q}_1\overline{\mathrm{q}}_2$ system.



PYTHIA/JETSET

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

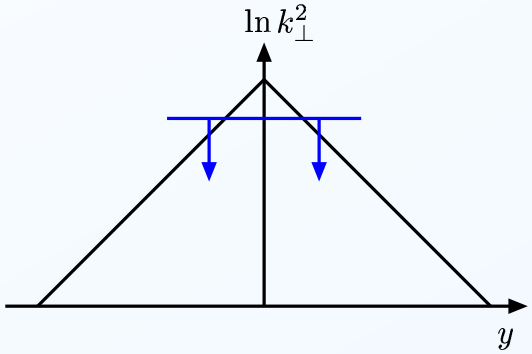
High–virtuality ems. first.



HERWIG

$\sim E^2\theta^2$

Large–angle ems. first.



ARIADNE

$p_\perp^2$

Large–$p_\perp$ ems. first.

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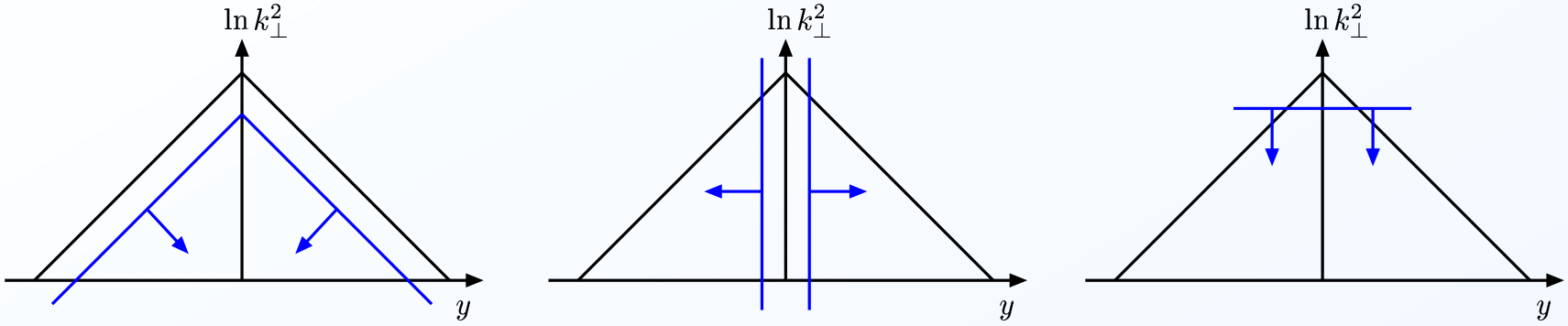
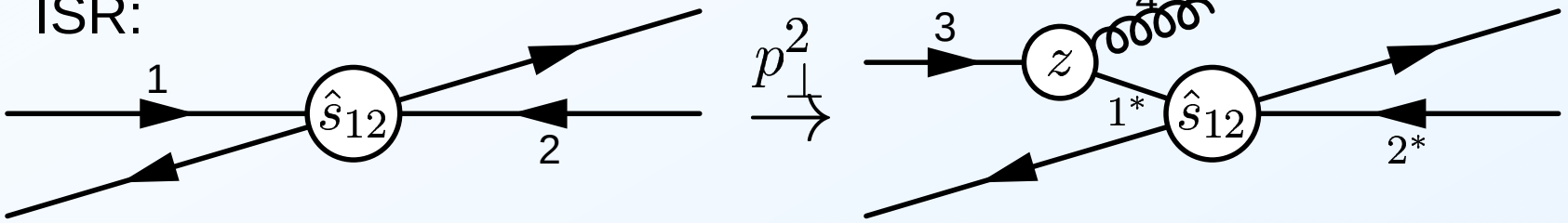


PYTHIA/JETSET	HERWIG	ARIADNE
m^2 ($-m^2$ for ISR)	$\sim E^2\theta^2$	$p_\perp^2$
High–virtuality ems. first.	Large–angle ems. first.	Large–$p_\perp$ ems. first.

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.

ISR:

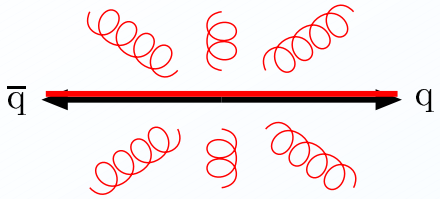


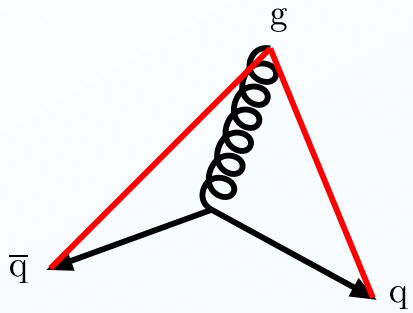
Existing Showers: Pros and Cons

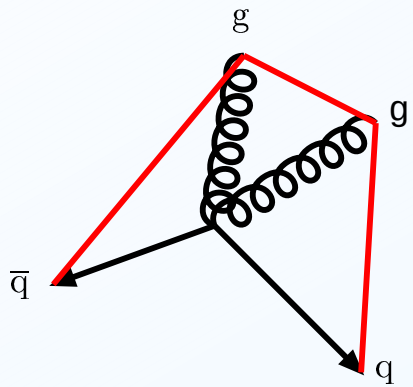
- HERWIG: $Q^2 \approx E^2(1-\cos\theta) \approx E^2\theta^2/2$
  - $+$ angular ordering $\Rightarrow$ coherence inherent
  - $-$ emissions not ordered in hardness
  - $-$ emissions do not cover full phase space (dead zone)
  - $-$ kinematics constructed at the very end

- 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
  - $+$ 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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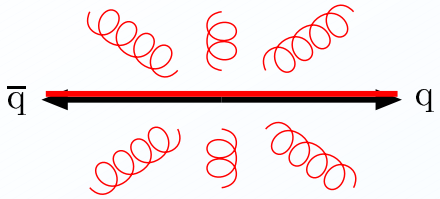

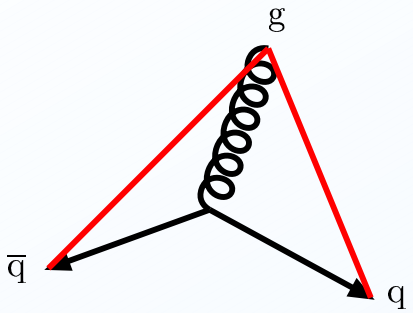

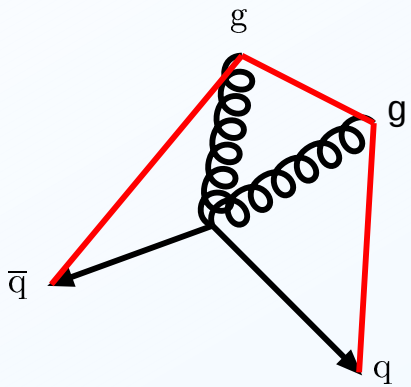

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    $\Rightarrow$ good for ME/PS matching (L-CKKW, real+fictitious showers)
  - $-$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ artificial
  - $-$ not so suited for pp on its own: ISR is primitive in ARIADNE.

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
- $+$ Merging with Matrix Elements unproblematic
  (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)
- $+$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ natural
- $+$ kinematics constructed after each branching
  (partons explicitly on-shell until they branch)
- $+$ showers can be stopped and restarted at any $p_\perp$ scale
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  (not yet worked-out for ISR+FSR)

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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'**

THE NEW MODEL

Interactions

+ showers

+ remnants

WHY BOTHER?

- QCD point of view: hadron collisions are highly complex, while present descriptions are not.

  Should be possible to gain further physics insight.

- Any reliable extrapolation to LHC energies will require such insight.

  Simple parametrizations are not sufficient.

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

  More reliable understanding is needed.

- Lots of fresh data from Tevatron :

  Great topic for phenomenology right now

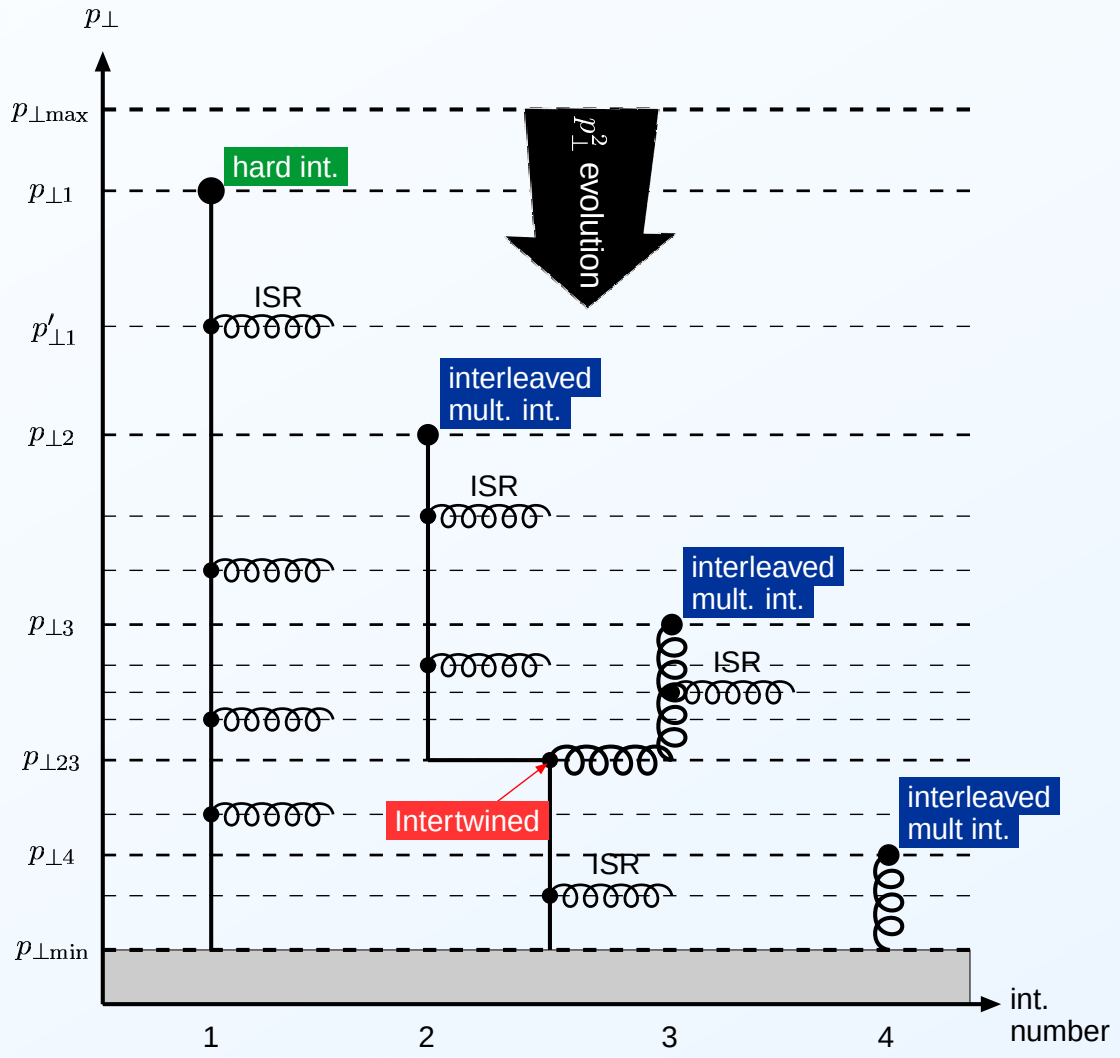
The New Framework

- This led us to develop a new sophisticated model for Underlying Event (and min–bias) $\rightarrow$ 'intermediate model' (PYTHIA 6.305).
- 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 Framework

The new picture: start at the most inclusive level, $2 \to 2$. Add exclusivity progressively by evolving *everything* downwards in *one* common sequence:

→ Interleaved evolution



(→ also possible to have interactions *intertwined* by the ISR activity?)

The New Framework

The building blocks:

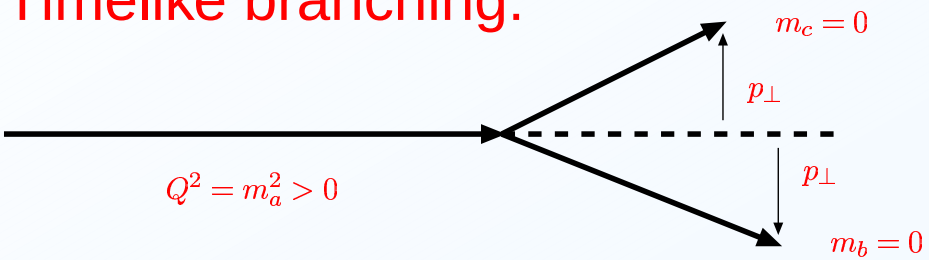
- $p_\perp$–ordered multiple interactions. ✔
- $p_\perp$–ordered initial–state parton showers. ✔
- $p_\perp$–ordered final–state parton showers. ✔
- $p_\perp$ used as scale in α_s and in PDF's. ✔
- (Model for) correlated multi–parton densities. ✔
- Beam remnant hadronization model. ✔
- Model for initial state colour correlations. (✔ — but far from perfect!)
- Other phenomena? (e.g. colour reconnections (✔), ...)
- Realistic tunes to data (so far only for FSR...)

$p_\perp$–ordered showers: Simple Kinematics

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

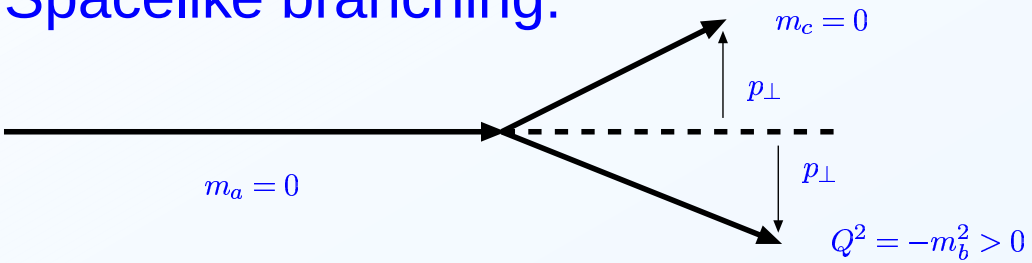
$$\left.\begin{aligned} p_b^+ &= z p_a^+ \\ p_c^+ &= (1-z) p_a^+ \\ p^- &\text{ conservation} \end{aligned}\right\} \Longrightarrow \quad m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



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

Spacelike branching:



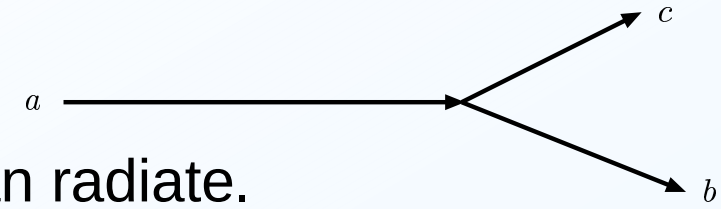
$$p_\perp^2 = (1-z)Q^2$$

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.

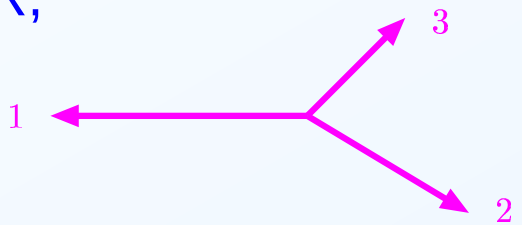
3) *Derive* $Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/z(1-z)$ for FSR

$Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/(1-z)$ 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*
   $(2E_i/E_{\rm cm} = 1 - m^2_{jk}/E^2_{\rm cm})$
   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 $\rm p_{\perp evol}$.
   Iterate until no branching above $p_{\perp\rm min}$.
   $\Rightarrow$ One combined sequence $p_{\perp\rm max} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\rm min}$.

$p_\perp$–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.

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: FSR

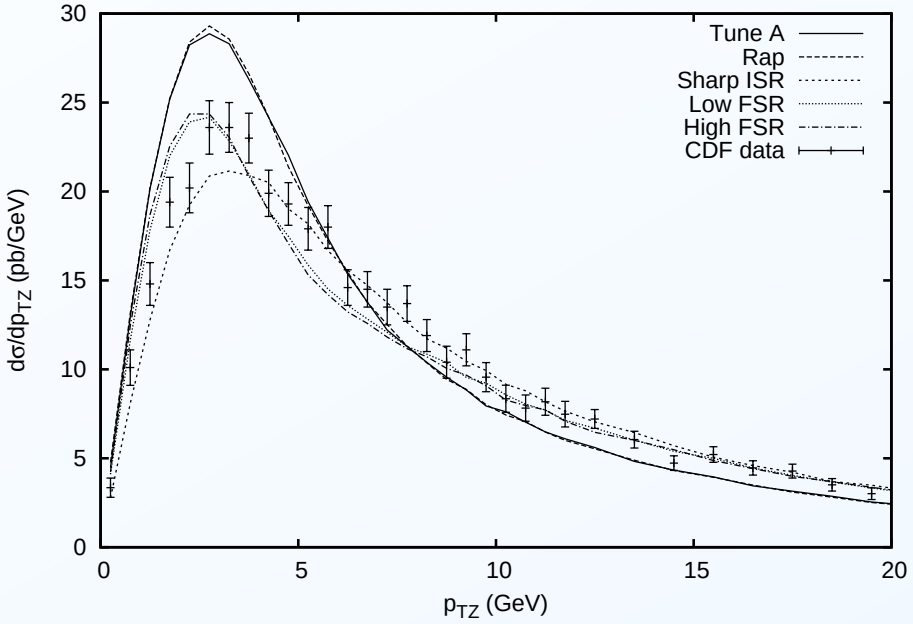
- FSR algorithm.
  - Tested on ALEPH data (G. Rudolph).

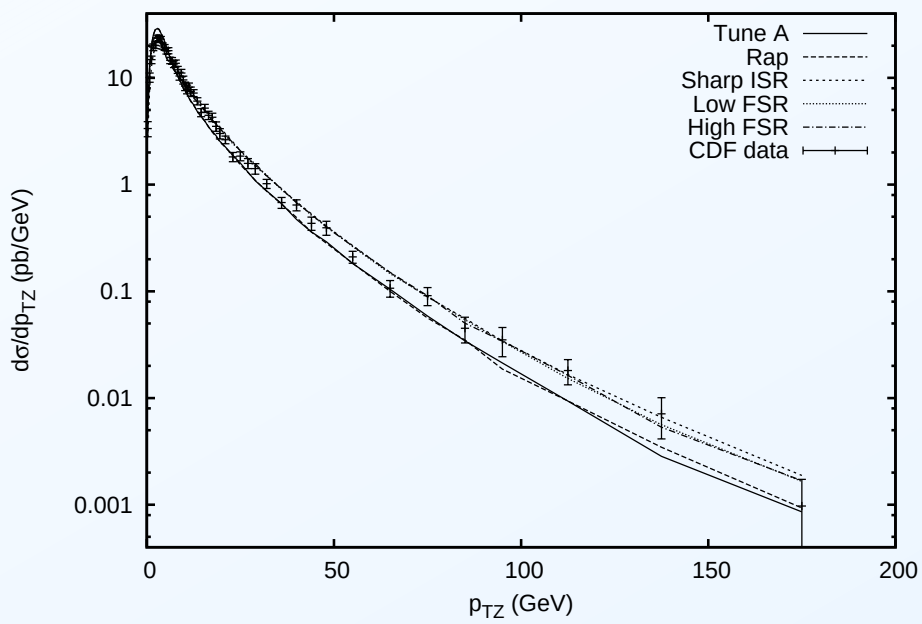
Distribution of	nb.of interv.	$\sum\chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
$1-$Thrust	21	60	8
$\text{Thrust}_{\text{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\text{cm}}$	46	207	151
$p_{\perp\text{in}}$	25	99	170
$p_{\perp\text{out}}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

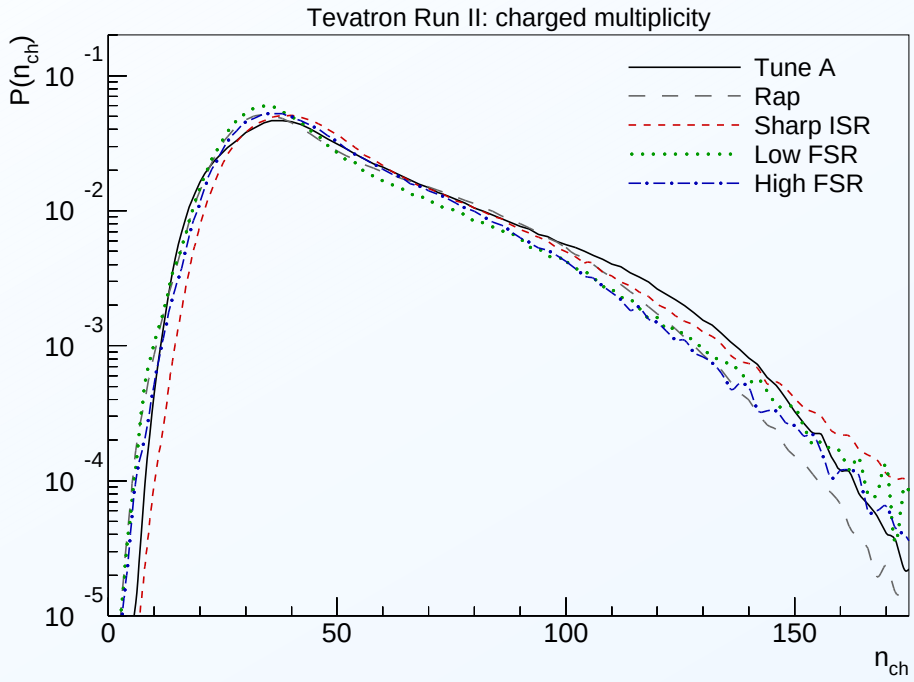
- ISR algorithm.
  - Less easy to test. We looked at $p_\perp$ of Z^0 at Tevatron.
  - Compared “Tune A” with an ‘intermediate scenario’ (“Rap”), and three rough tunes of the new framework.
  - Description is improved (but there is still a need for a large primordial $k_\perp$).

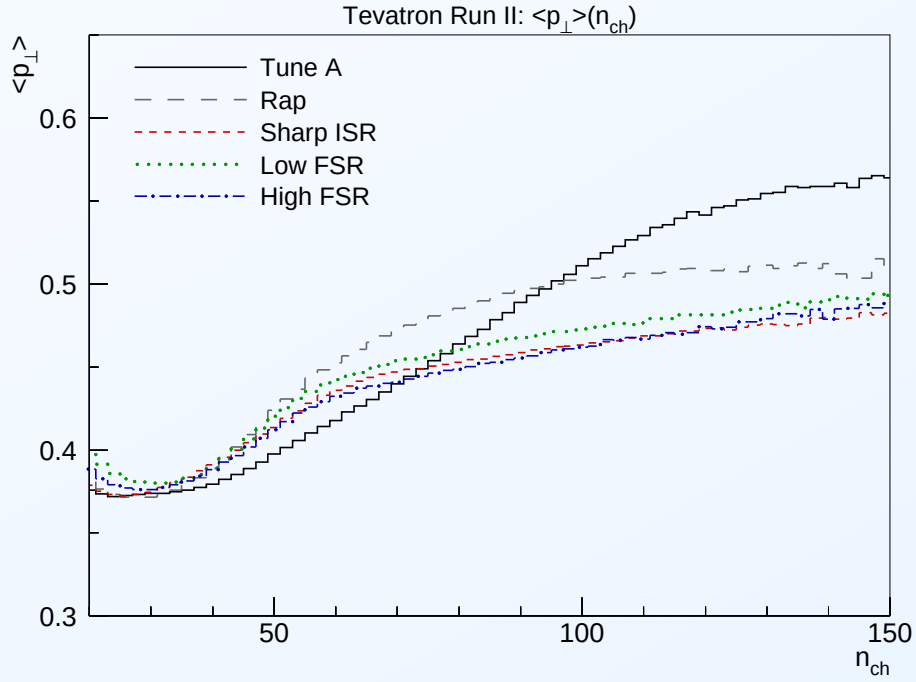




Model Tests

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





The Next Step (ultra-brief summary)

- Tune A depends HEAVILY on high degree of colour correlation in the final state. So far impossible to reproduce with more 'physical' model (i.e. based on perturbation theory).
- Strangeness and baryon production anomalies at HERA $\rightarrow$ indications of similar phenomena?

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What will be done next is:

- Last 'desperate' attempt with P.T. at the MAX to get most highly correlated colour flow *without* reconnections. Continued failure would be interesting!
- $\rightarrow$ develop physical principles for collapse of colour wavefunction at hadronization and construct practical implementation. (Some ideas already.)

Outlook

- New complete framework for hadron collisions has been developed. 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 6.315 (20 Oct 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.
- Are jets universal or not?

Outlook

- New complete framework for hadron collisions has
- hat
- Are jets universal or not?
- But nobody said hadron collisions were easy...

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