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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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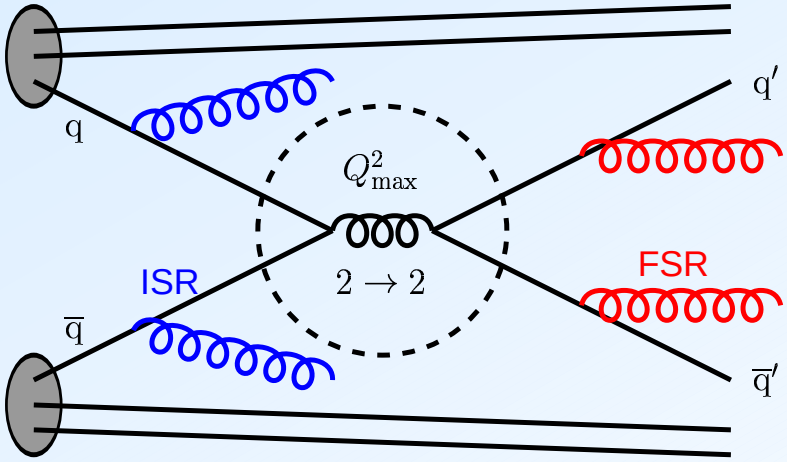

NB: no doublecounting!

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

Why Develop a New Shower?

- **Incorporate several of the good points of the dipole formalism (Ariadne) within the shower approach**
  - $-$ "old" shower in Q^2, whereas UE ordered in $p_\perp$
  - $-$ "old" UE model had no shower development in MIs
  - $\pm$ 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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  - $+$ $\mathrm{g} \to \mathrm{q\overline{q}}$ natural
  - $+$ 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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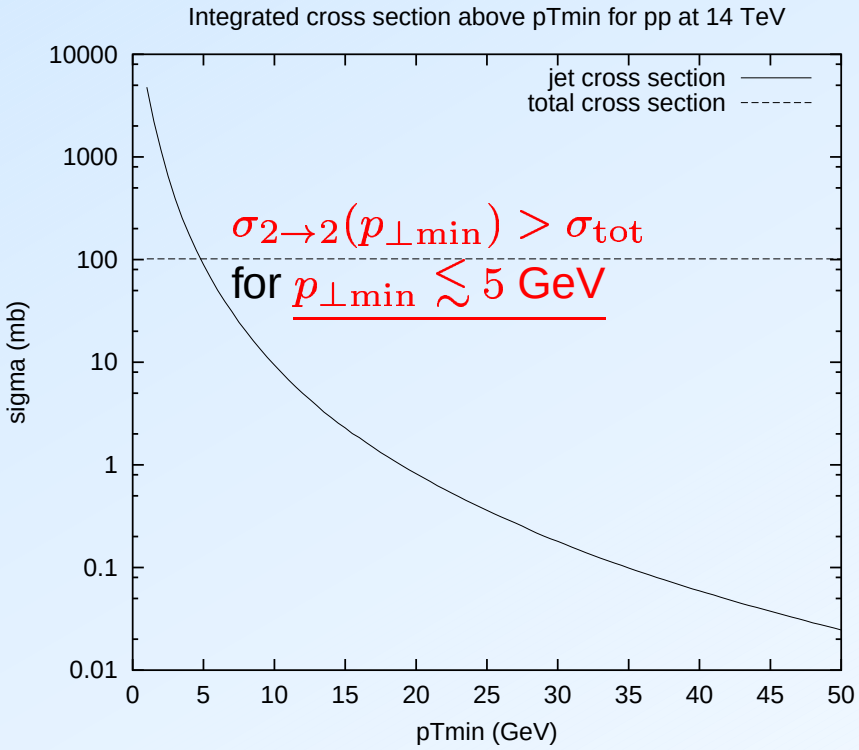
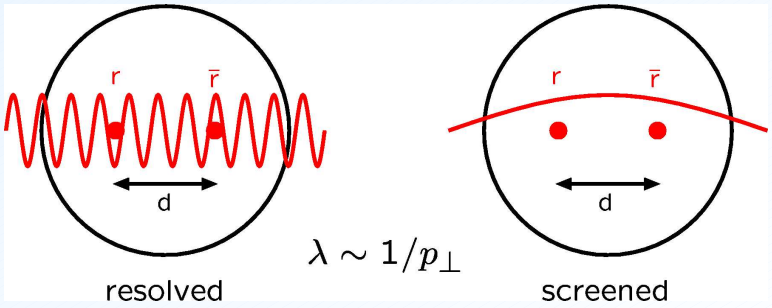


1. **Multiple interactions (MI)!**
   - Must exist (hadrons are composite!)
   - σ_{tot}: hadron-hadron collisions.
     $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
   - $\sigma_{2\to2}$: parton–parton collisions.
     $\sigma_{2\to2} = \sum_{n=0}^{\infty} n\,\sigma_n$
   - $\sigma_{2\to2}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

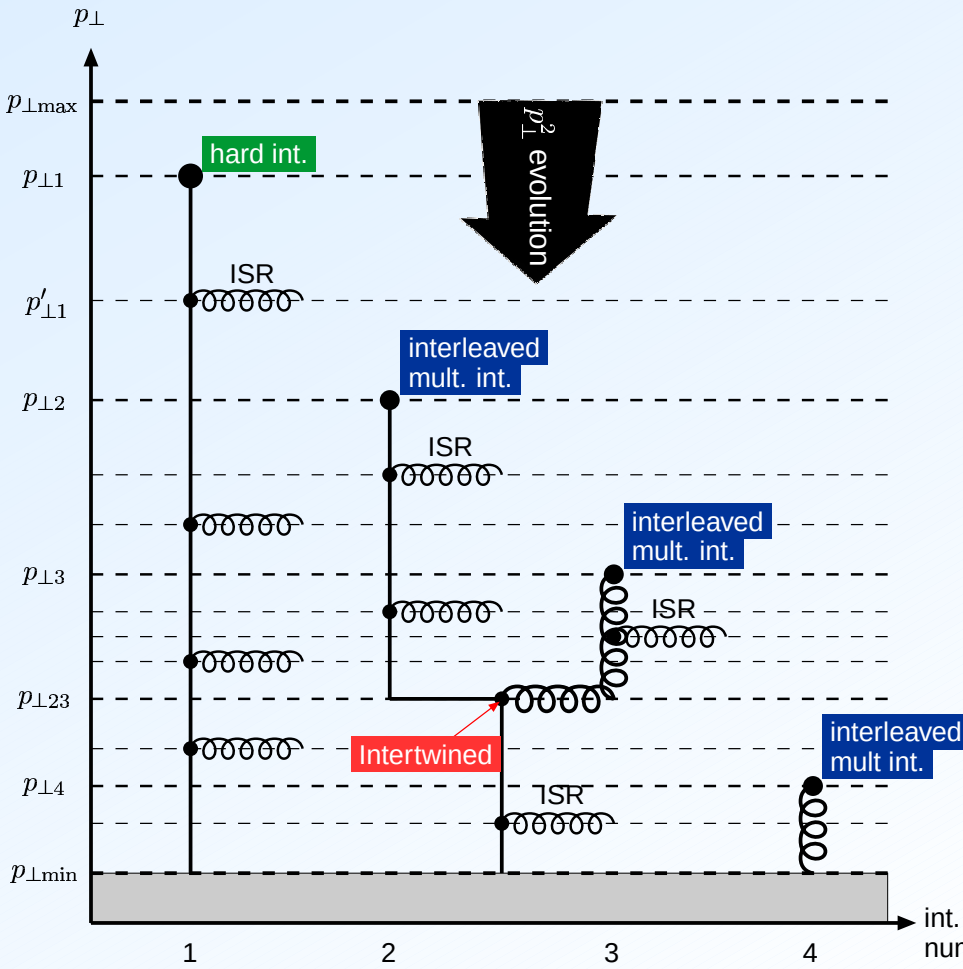
2. **Breakdown of pQCD, color screening.**



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

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:

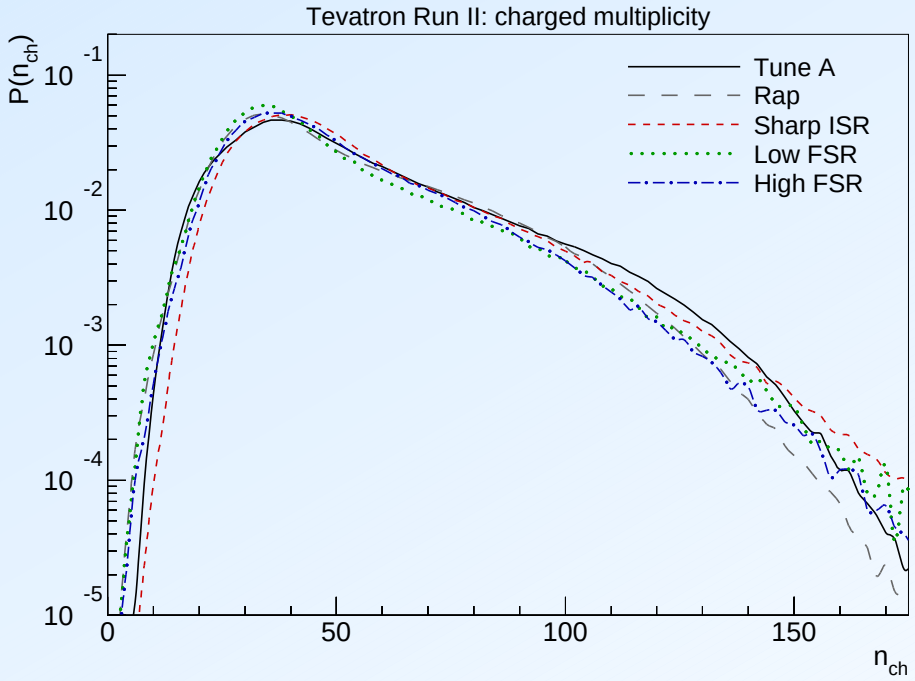
- $p_\perp$–ordered initial–state parton showers.
- $p_\perp$–ordered final–state parton showers.
- $p_\perp$–ordered multiple interactions.
- $p_\perp$ used as scale in α_s and in PDF's.
- (Model for) correlated multi–parton densities.
- Beam remnant hadronization model.
- Model for initial state color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

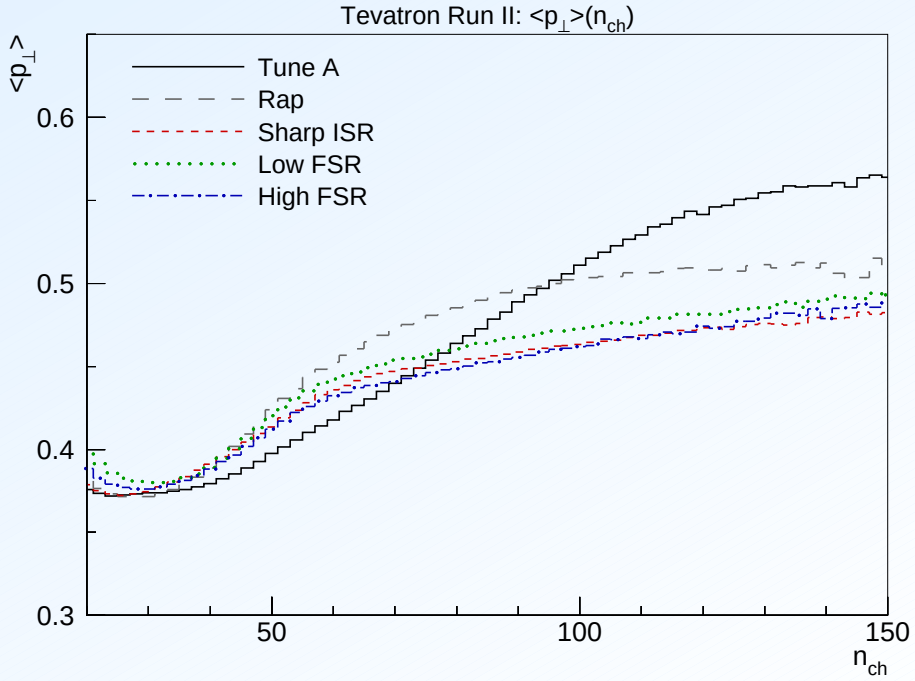
Multiple Interactions: Some Details

- **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' color topologies $\rightarrow$ 'string junctions' in the color confinement field.
- **Color 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

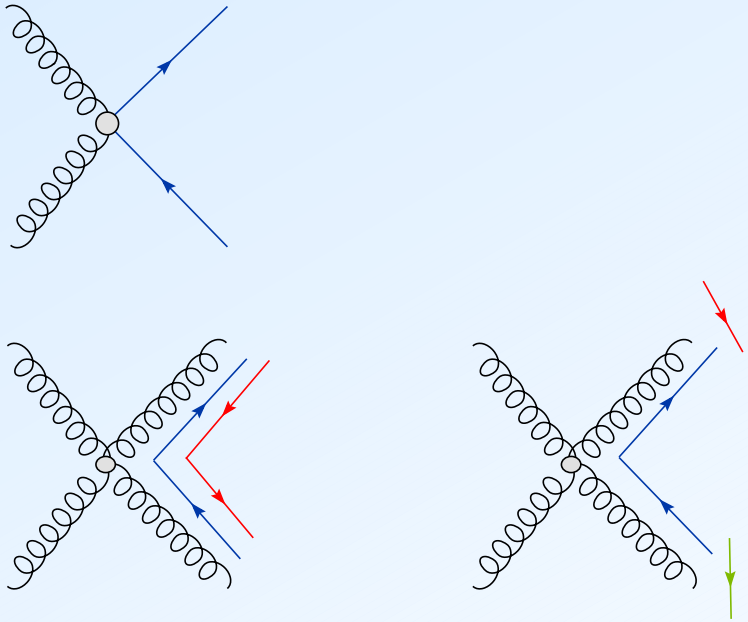
- Whole framework.
  - Produced a few rough tunes to ‘Tune A’ at the Tevatron, using charged multiplicity distribution and $\langle p_\perp \rangle (n_{\mathrm{ch}})$, the latter being highly sensitive to the color correlations.
  - Similar overall results are achieved (not shown here), but $\langle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





The Voodoo of Tune A

The multiple interactions are simply there to add the non-perturbative objects used to turn partons into hadrons. In `Pythia`, this is the string.



Tune A favors the last configuration, but how does this happen?

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.
- Color correlations still a headache. We thought perhaps *intertwined* showers would yield a more correlated color 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 int
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Butch Cassidy and the Sundance Kid. Copyright: Twentieth Century Fox Films Inc.

- But nobody said hadron collisions were easy...

Model Tests: FSR

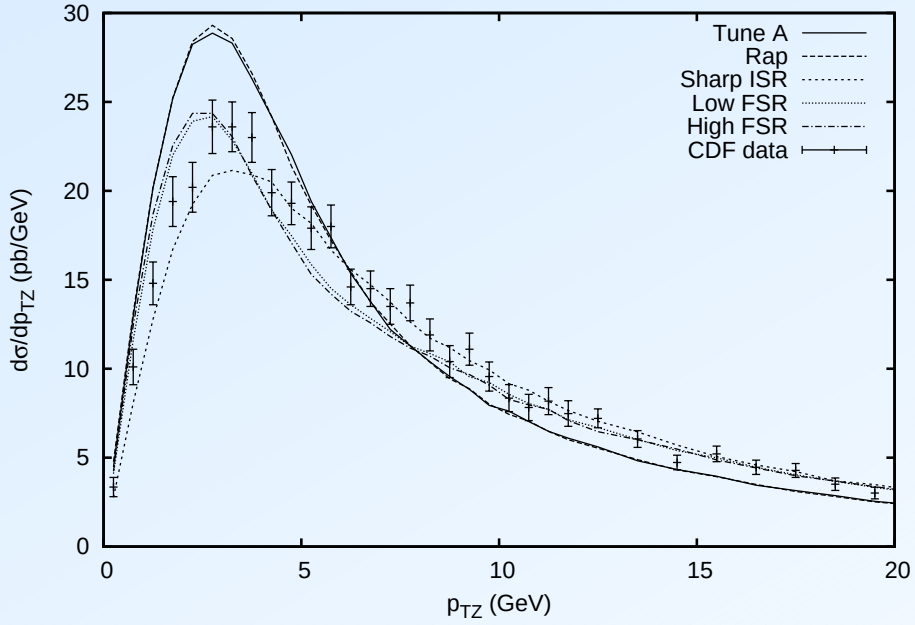
- FSR algorithm.
  - Tested on ALEPH data (G. Rudolph).

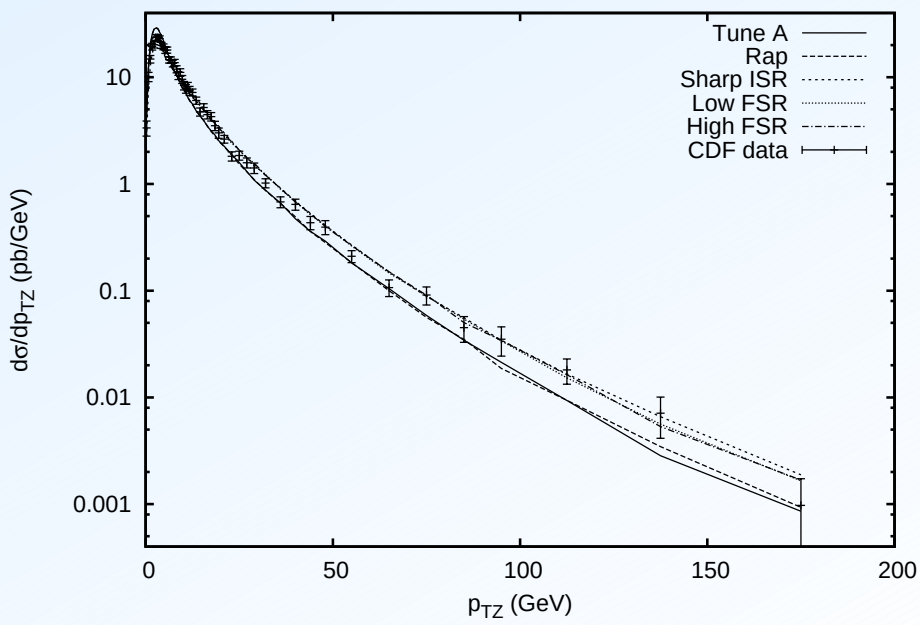
Distribution of	nb.of interv.	$\sum\chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
$1-$Thrust	21	60	8
$\text{Thrust}_{\text{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\text{cm}}$	46	207	151
$p_{\perp\text{in}}$	25	99	170
$p_{\perp\text{out}}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





MI — Indirect Verifications

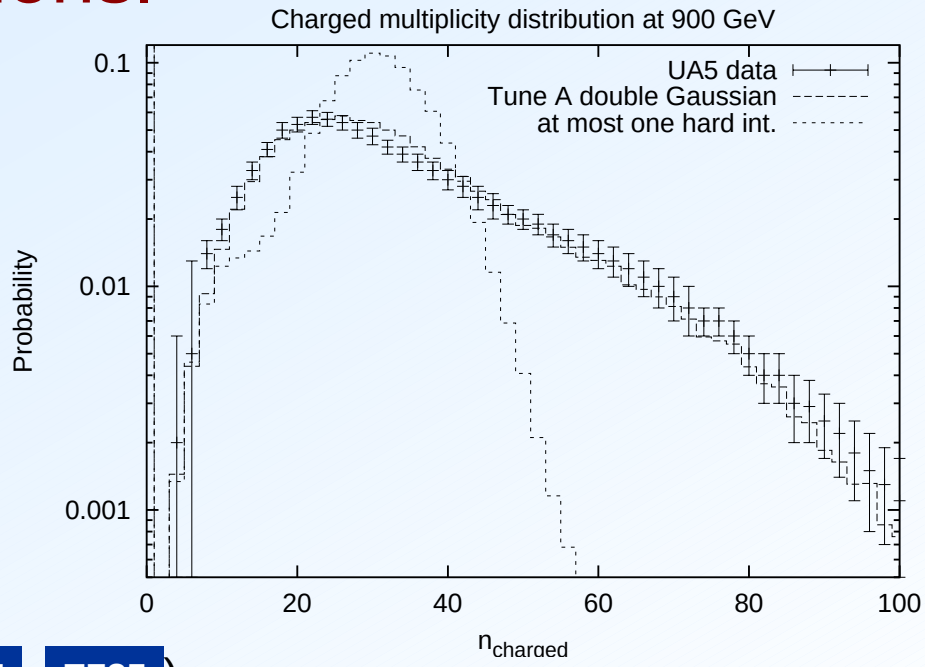
Basic idea :

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

UA5: (900 GeV)

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

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



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

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

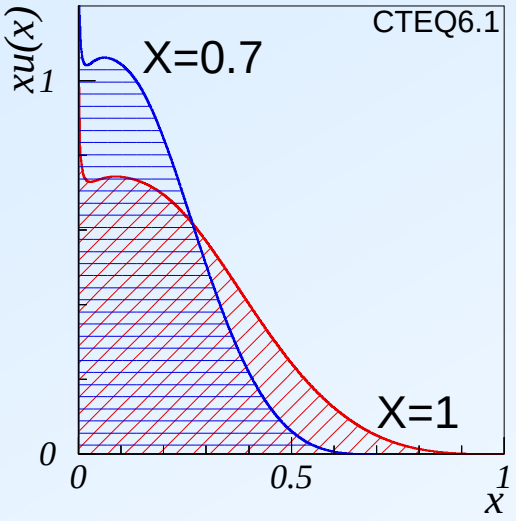
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

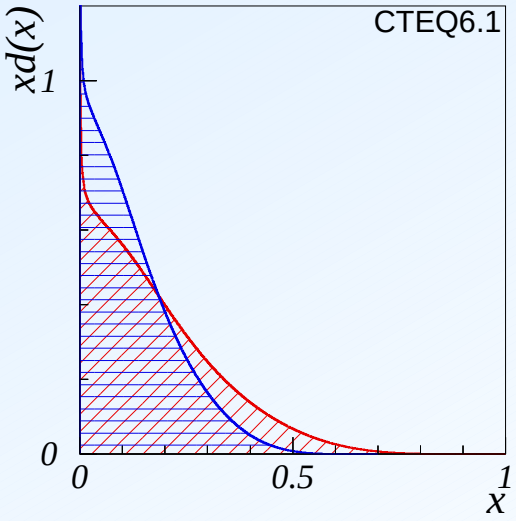
1. Overall momentum conservation (old):

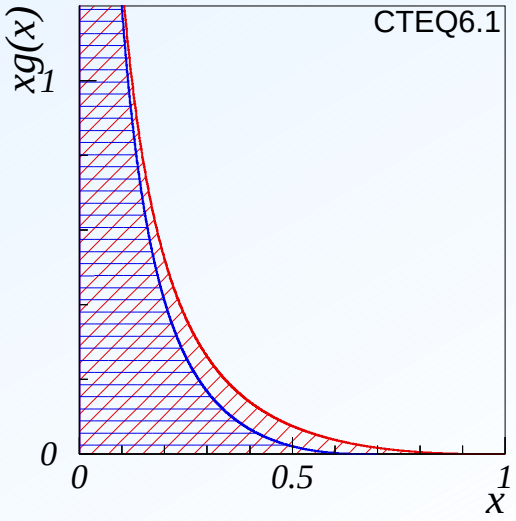
Starting point: simple scaling ansatz in x.

For the n'th scattering:

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







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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 x_i

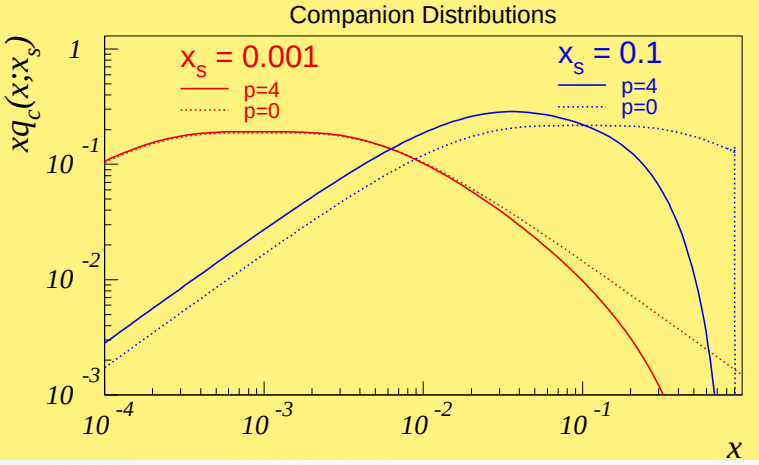
Remnant PDFs

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

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

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

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



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