Underlying-Event Models in Herwig and Pythia

Low-x Meeting, July 2008, Crete

Peter Skands
Theoretical Physics, CERN / Fermilab

Why study UE/Min-Bias?

Disclaimer: no “theory” of UE. All I can do is show which features are in currently used MC models (Herwig/Pythia).

See also talks by E. Avsar and L. Lönnblad

► Why study Min-Bias and Underlying Event?

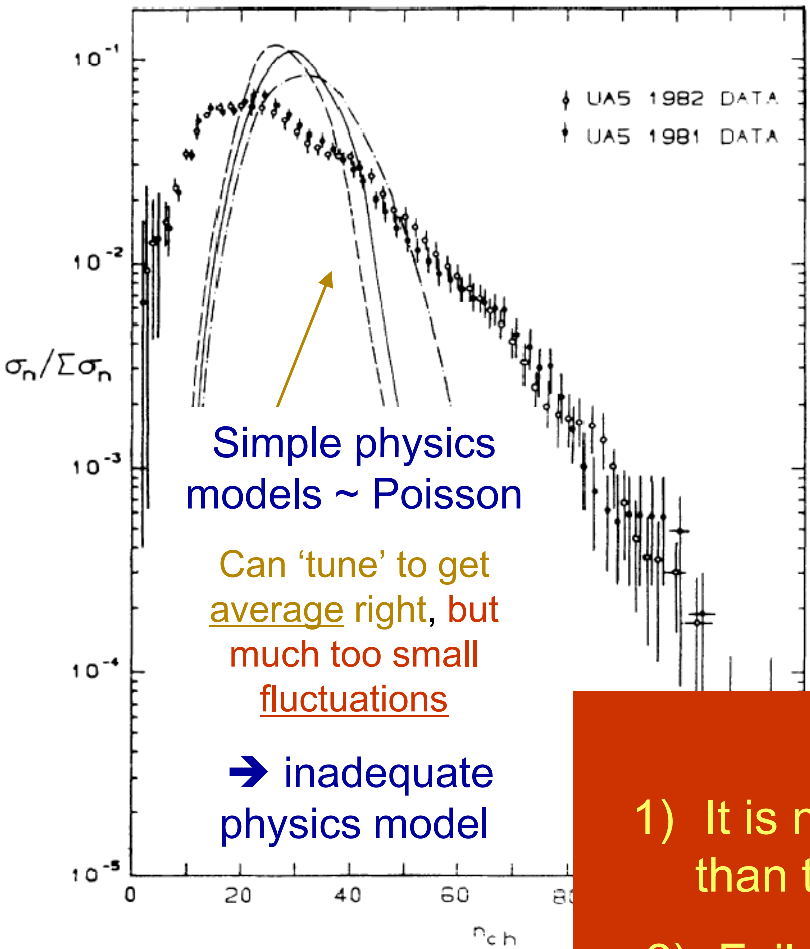
- Solving QCD requires compromise
- Construct and constrain models (~ sets of compromises)
- → precision knowledge + constrained pheno models

► Feedback to high-p_T physics

- Reliable correction procedures
- Without reliable models, reliable extrapolations are hard to hope for

Classic Example: Number of tracks

UA5 @ 540 GeV, single pp, charged multiplicity in minimum-bias events

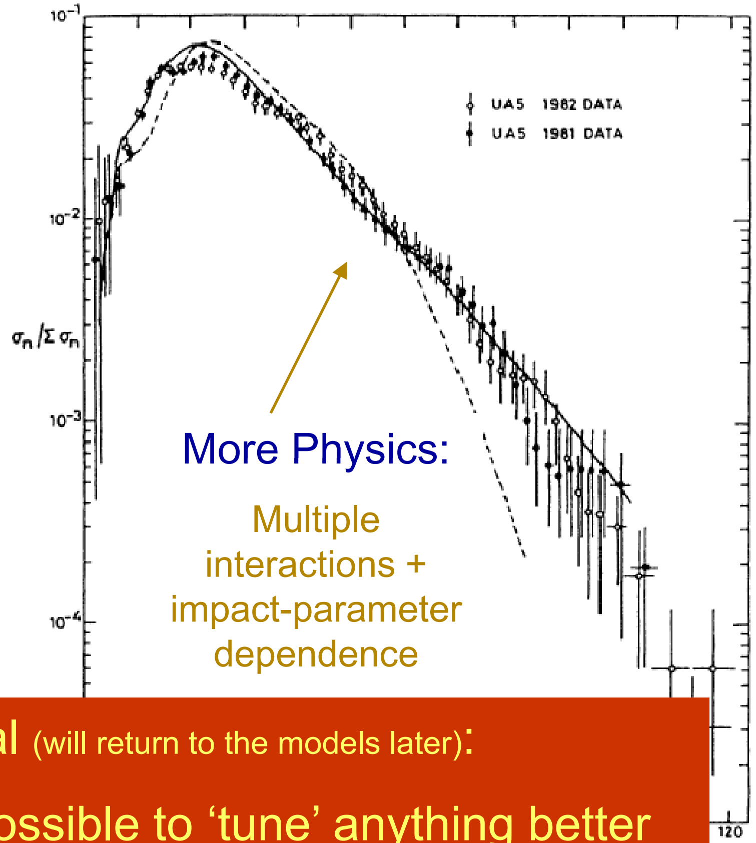


Simple physics models ~ Poisson

Can 'tune' to get average right, but much too small fluctuations

➔ inadequate physics model

FIG. 3. Charged-multiplicity distribution
results (Ref. 32) vs simple models: dashed
cluding hard scatterings, dash-dotted also in
final-state radiation.



More Physics:

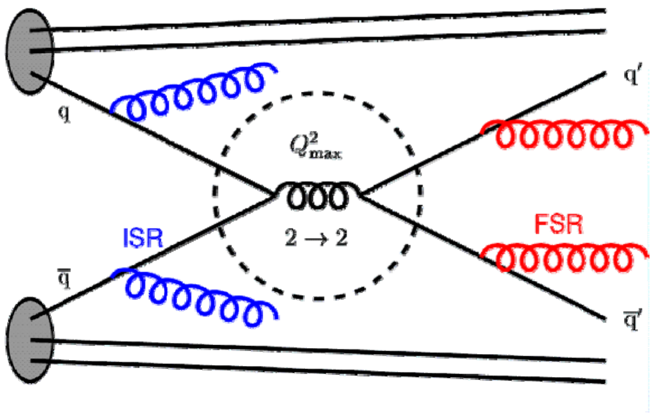
Multiple interactions + impact-parameter dependence

eV, UA5
riable im-
tribution;
dashed line, with fix impact parameter [i.e., $O_0(b)$].

Moral (will return to the models later):

1) It is not possible to 'tune' anything better than the underlying physics model allows
2) Failure of a physically motivated model usually points to more, interesting physics

Traditional Event Generators



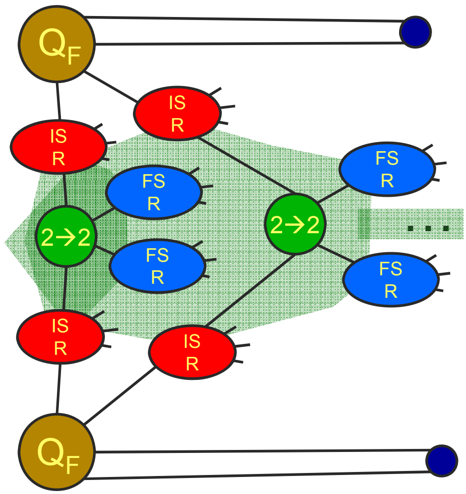
- Basic aim: improve lowest order perturbation theory by including leading corrections → exclusive event samples
  1. sequential resonance decays
  2. bremsstrahlung
  3. **underlying event**
  4. **hadronization**
  5. hadron (and τ) decays

Additional Sources of Particle Production

► Domain of fixed order and parton shower calculations:

- hard parton-parton scattering
  - (normally 2→2 in MC)

+ bremsstrahlung associated with it
  → 2→n



► But hadrons are not elementary

► + QCD diverges at low p_T

► → multiple perturbative parton-parton collisions should occur

e.g. 4→4, 3→ 3, 3→2

► Normally omitted in fixed-order / parton shower expansions (~ higher twists / powers)

Note:

Can take

$Q_F >> \Lambda_{QCD}$

Additional Sources of Particle Production

- Domain of fixed order and parton shower calculations:
  - hard parton-parton scattering
    - (normally 2→2 in MC)
  - \+ bremsstrahlung associated with it
    - → 2→n

+

Stuff at

$Q_F \sim \Lambda_{QCD}$

- \+ Remnants from the incoming beams
- \+ additional (non-perturbative / collective) phenomena?
  - Bose-Einstein Correlations
  - Non-perturbative gluon exchanges / colour reconnections ?
  - String-string interactions / collective multi-string effects ?
  - Interactions with “background” vacuum / with remnants / with active medium?

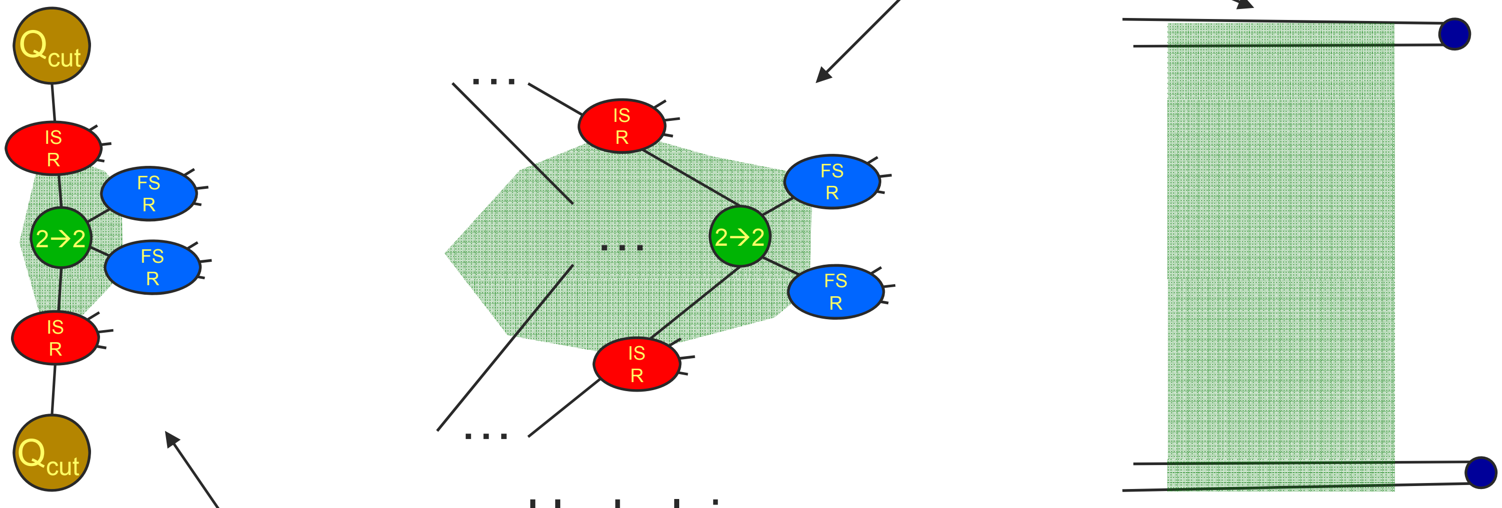
These are need-to-know issues for infrared sensitive quantities (e.g., multiplicity)

Naming Conventions

See also **Tevatron-for-LHC Report of the QCD Working Group, hep-ph/0610012**

- ► Many nomenclatures being used.
  - Not without ambiguity. I use:

Some freedom in how much particle production is ascribed to each: “hard” vs “soft” models



Primary Interaction (~ trigger)

Underlying Event

Beam Remnants

Note: each is colored ➔ Not possible to separate clearly at hadron level

Inelastic, non-diffractive

Why Perturbative MPI?

► Analogue: Resummation of multiple bremsstrahlung emissions

- Divergent σ for one emission (X + jet, fixed-order)

➔Finite σ for divergent number of jets (X + jets, infinite-order)

  - N(jets) rendered finite by finite perturbative resolution = parton shower cutoff

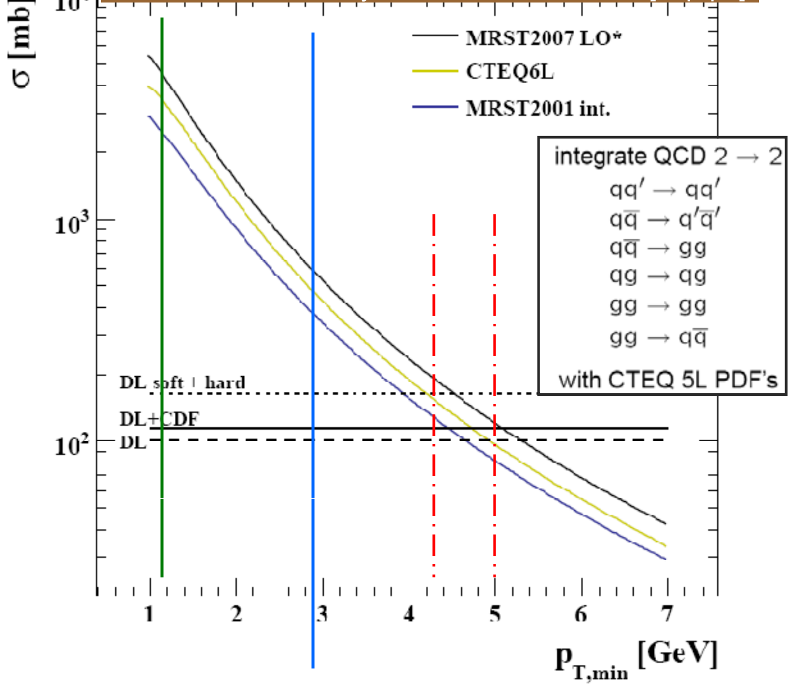
►(Resummation of) Multiple Perturbative Interactions

•Divergent σ for one interaction (fixed-order)

➔Finite σ for divergent number of interactions (infinite-order)

- N(jets) rendered finite by finite perturbative resolution = color-screening cutoff (E_{cm}-dependent, but large uncert)

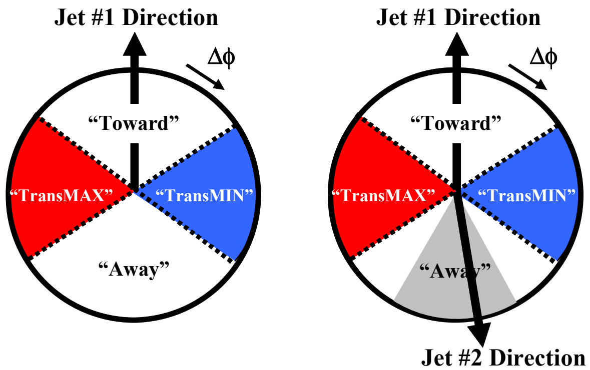
Bahr, Butterworth, Seymour: arXiv:0806.2949 [hep-ph]



Saturation? Current models need MPI IR cutoff > PS IR cutoff

Why Perturbative MPI?

- + Experimental investigations (AFS, CDF)
  - Find pairwise balanced minijets,
  - Evidence for "lumpy" components in "transverse" regions
  - But that overview should be given by an experimentalist



- Here will focus on
  - Given that these are the models used by Tevatron and LHC experiments (and for pp at RHIC), what are their properties?
  - What are they missing?
- Especially in low-x context
  - → discussion session

NB: Herwig: no MPI.

Here will talk about Jimmy/Herwig++

How many?

- The interaction cross section

$$\frac{d\sigma_{2j}}{dp_\perp^2} = \sum_{i,j,k} \int dx_1 \int dx_2 \int d\hat{t}\; f_i(x_1,\mu_F^2)\, f_j(x_2,\mu_F^2)\, \frac{d\hat{\sigma}_{ij\to kl}}{d\hat{t}}\, \delta\!\left(p_\perp^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) \propto \frac{1}{p_{\perp\min}^2}$$

With constant α_s, neglecting x integrals

- … is an inclusive number.

- … so an event with n interactions …
  - … counts n times in σ_{2j} but only once in σ_{tot}

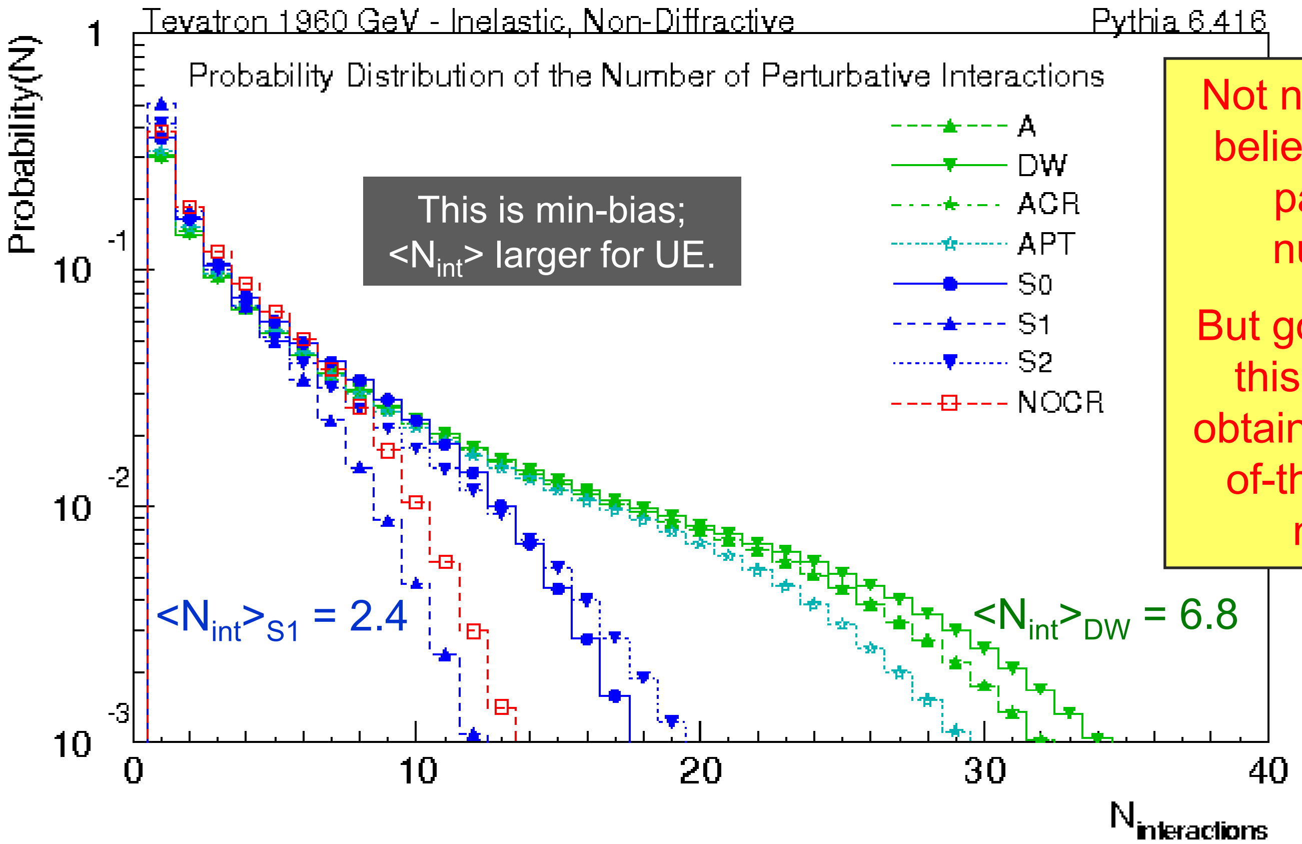
$$\langle n\rangle(p_{\perp\min}) = \frac{\sigma_{2j}(p_{\perp\min})}{\sigma_{tot}} \quad \Longleftrightarrow \quad \mathcal{P}_n(p_{\perp\min}) = [\langle n\rangle(p_{\perp\min})]^n \frac{\exp\left[-\langle n\rangle(p_{\perp\min})\right]}{n!}$$

•Poisson only exact if the individual interactions are completely independent, so will be modified in real life

- **Herwig** starts directly from Poisson → n, but includes vetos if (E,p) violated.
- **Pythia** uses a transverse-momentum ordered Sudakov formalism, interleaved with the shower evolution ~ resummation. (E,p) explicitly conserved at each step.

How many?

► Probability distribution of the number of Multiple Interactions



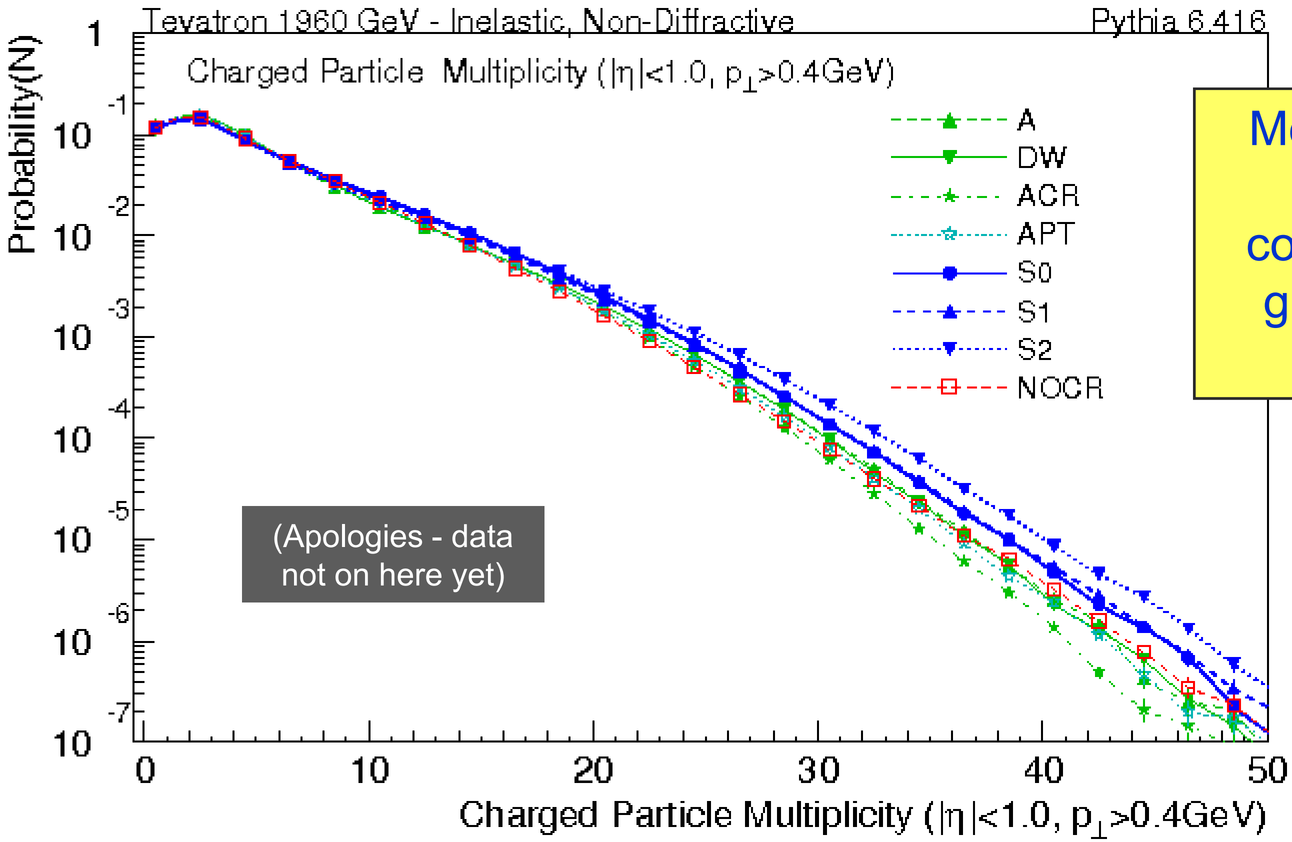
Not necessary to believe in these particular numbers.

But good to know this is what is obtained with out-of-the-box MC models

Buttar et al., Les Houches SMH Proceedings (2007) **arXiv:0803.0678** [hep-ph]
More plots collected at `http://home.fnal.gov/~skands/leshouches-plots/`

Different Cocktails?

- Observed charged particle multiplicity



Moral: vastly different cocktails can give similar answers

(Apologies - data not on here yet)

Buttar et al., Les Houches SMH Proceedings (2007) **arXiv:0803.0678** [hep-ph]
More plots collected at `http://home.fnal.gov/~skands/leshouches-plots/`

Impact Parameter

- Impact parameter: central vs. peripheral collisions

All models currently assume f(x,b) = f(x) g(b)

  - Obviously not the final word.

- Large fluctuations → g(b) needs to be "lumpy"

Large difference between peripheral and central

"No" UE in peripheral collisions (low multiplicity)

"Jet pedestal" effect

"Saturated" UE in central collisions (high multiplicity)

Pythia: default: double gaussian: "hard core" (valence lumps?)

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left\{-\frac{r^2}{a_1^2}\right\} + \frac{\beta}{a_2^3} \exp\left\{-\frac{r^2}{a_2^2}\right\}$$

Core size $a_2/a_1 = 0.5$
Contains fraction $\beta = 0.4$

Herwig: EM form factor, but width rescaled to smaller radius

$$G_{\bar{p}}(\mathrm{b}) = G_p(\mathrm{b}) = \int \frac{d^2\mathrm{k}}{2\pi} \frac{e^{i\mathrm{k}\cdot\mathrm{b}}}{(1+\mathrm{k}^2/\mu^2)^2}$$

$\mu_{ep} = 0.7\ \mathrm{GeV}^2 \rightarrow \mu = 1.5\ \mathrm{GeV}^2$

Multi-parton pdfs

Herwig

Snapshot of proton: re-use 1-parton inclusive f(x)

Subsequently impose (E,p) cons by vetoing events that violate it.

Pythia

1-parton inclusive f(x) = pdf for “trigger” scattering

Multi-parton pdfs explicitly constructed, respecting flavour and momentum sum rules

quarks

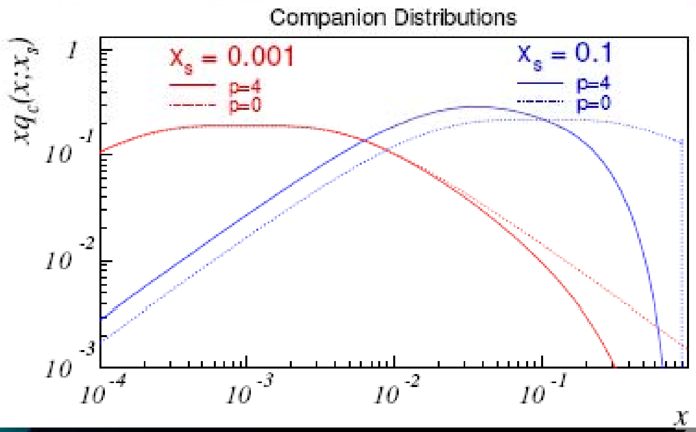
$$q_{fn}(x) = \frac{1}{X}\left[\frac{N^{\mathrm{val}}_{fn}}{N^{\mathrm{val}}_{f0}}\, q^{\mathrm{val}}_{f0}\left(\frac{x}{X},Q^2\right) + a\, q^{\mathrm{sea}}_{f0}\left(\frac{x}{X},Q^2\right) + \sum_j q^{\mathrm{cmp}_j}_{f0}\left(\frac{x}{X};x_{s_j}\right)\right]$$

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

gluons

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

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



Interleaved Evolution

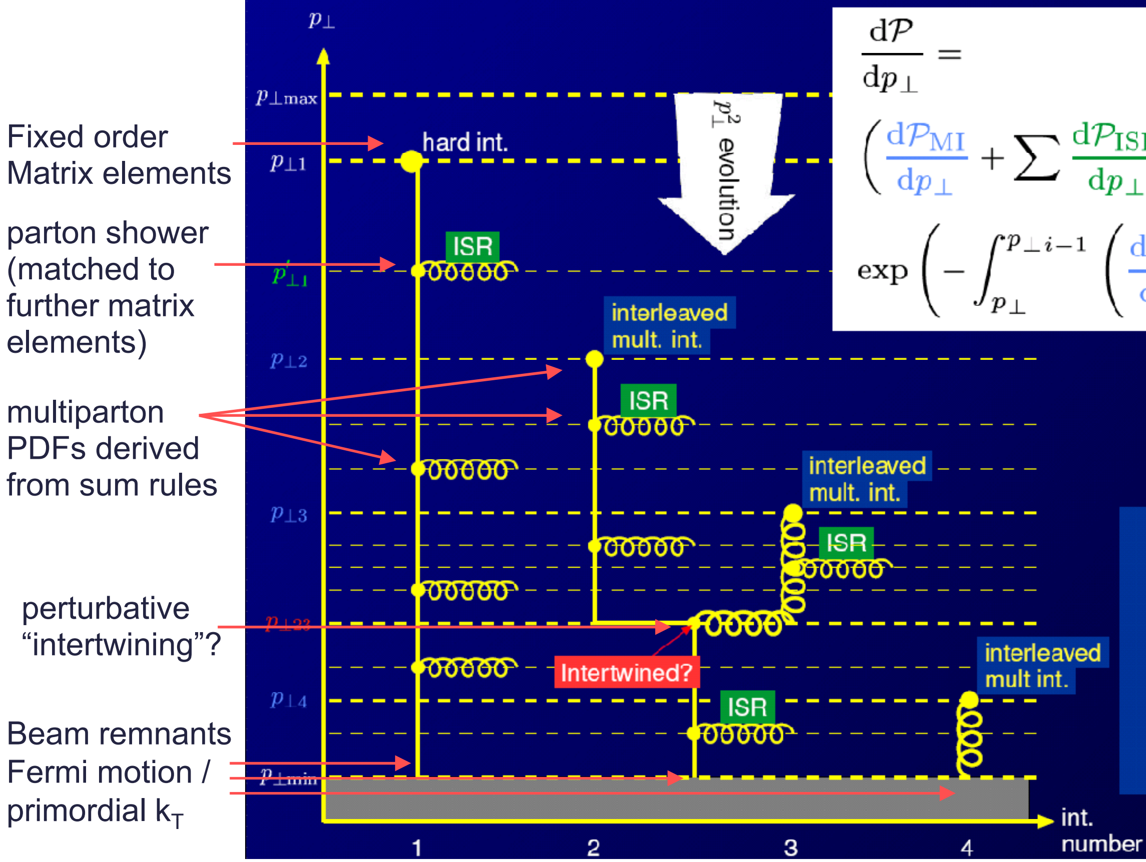
Sjöstrand, PS; JHEP03(2004)053, EPJC39(2005)129

Pythia

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

Add exclusivity progressively by evolving *everything* downwards.

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



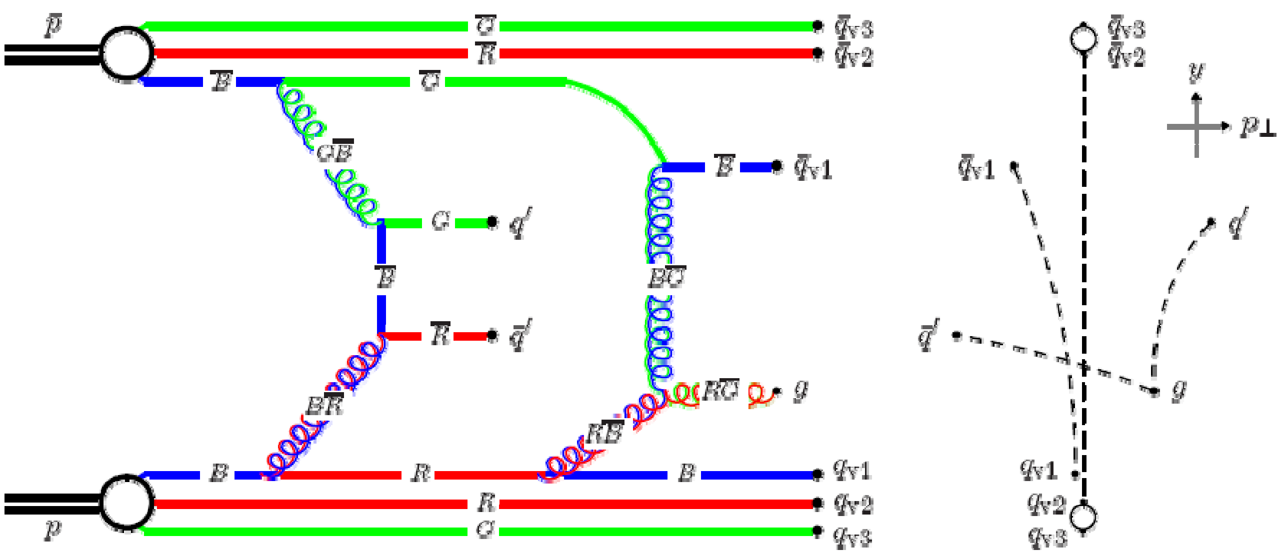
~ "Finegraining"

→ correlations between all perturbative activity at successively smaller scales

The Underlying Event and Colour

► The colour flow determines the hadronizing string topology

- Each MPI, even when soft, is a color spark
- Final distributions <u>crucially</u> depend on color space



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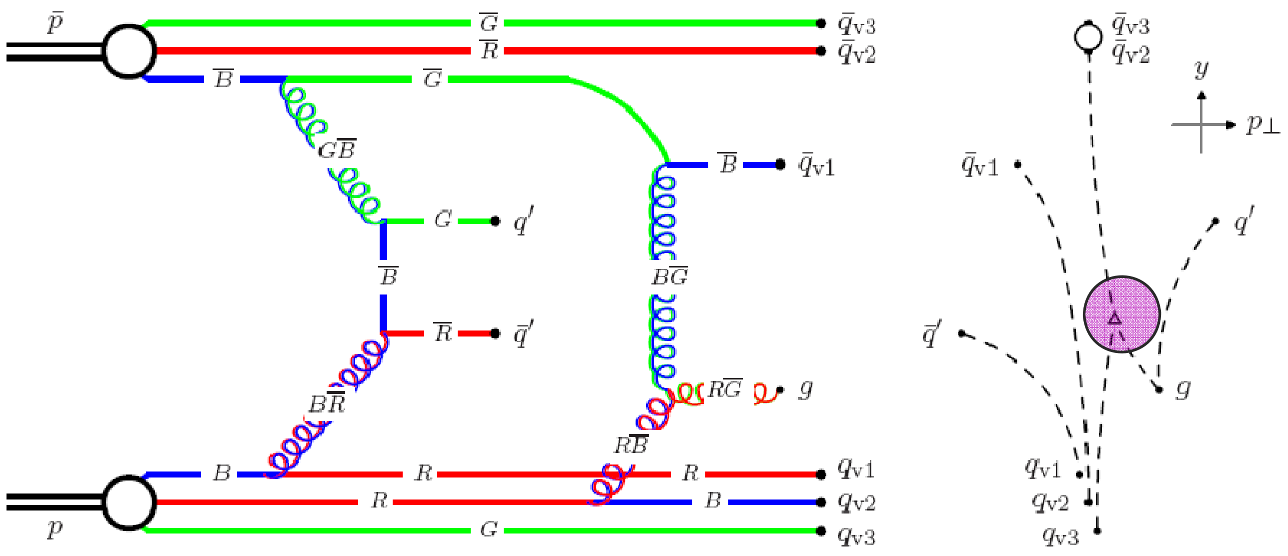
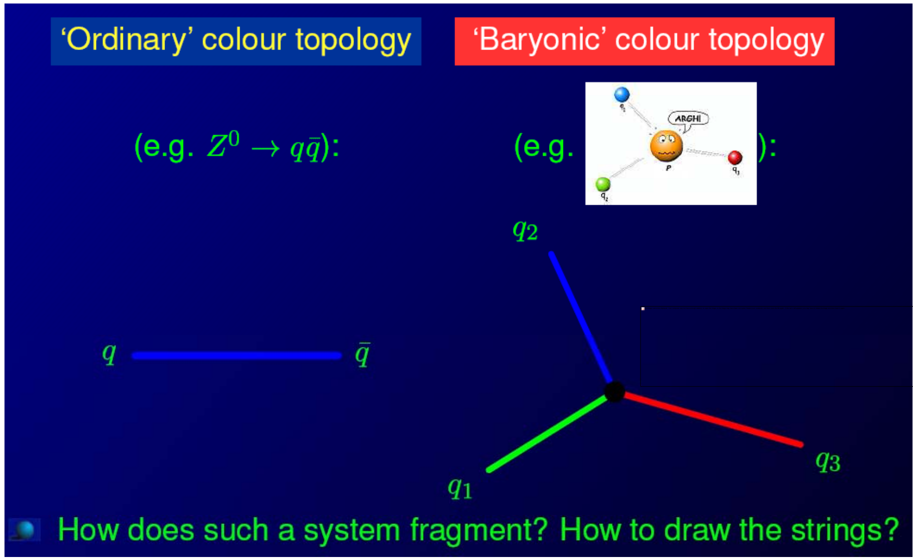


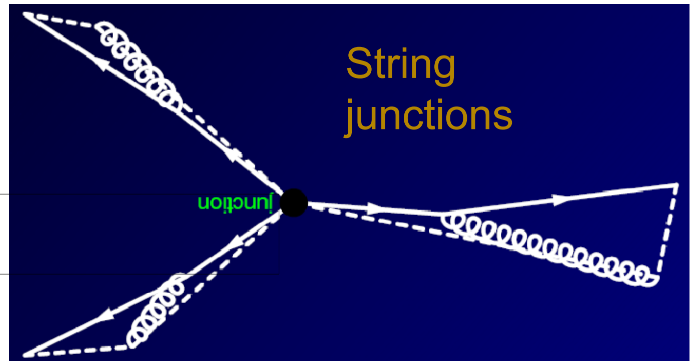
Baryonic String Topologies

- ▶ Original Lund string: leading-color (triplet-antitriplet) connections

Pythia

  - → "Mesonic" description
  - Baryon number violation (or a resolved baryon number in your beam) ➔ explicit epsilon tensor in color space. Then what?





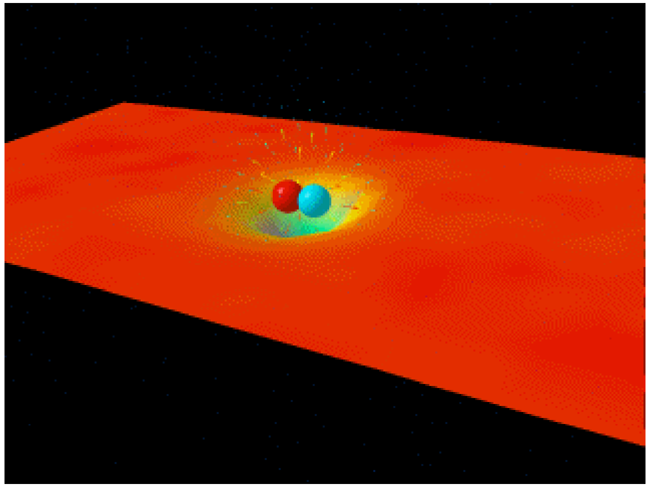
Sjöstrand & PS : Nucl.Phys.B659(2003)243, JHEP03(2004)053

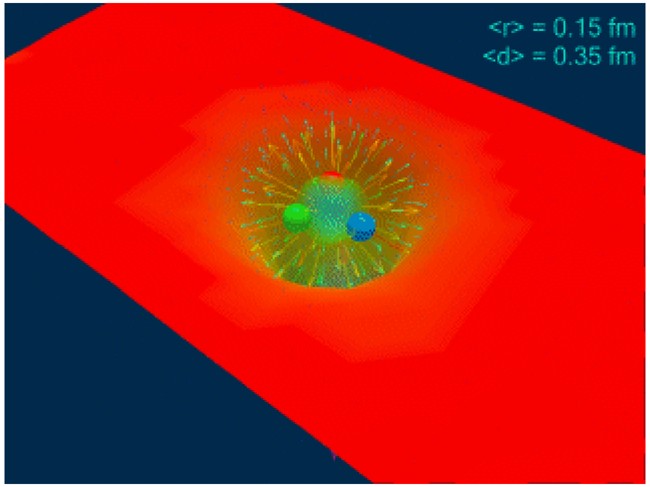
- ▶ Perturbative Triplets → String endpoints
- ▶ Perturbative Octets → Transverse kinks
- ▶ Perturbative Epsilon tensors → String junctions

Baryonic String Topologies

► Lattice simulation of mesonic and baryonic configurations

Simulation from
D. B. Leinweber, hep-lat/0004025



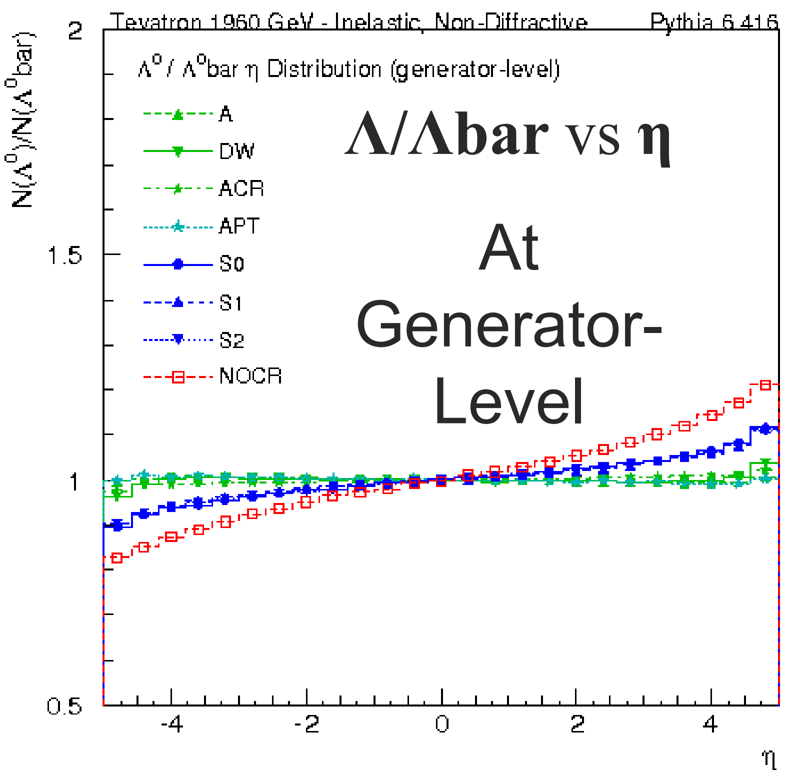


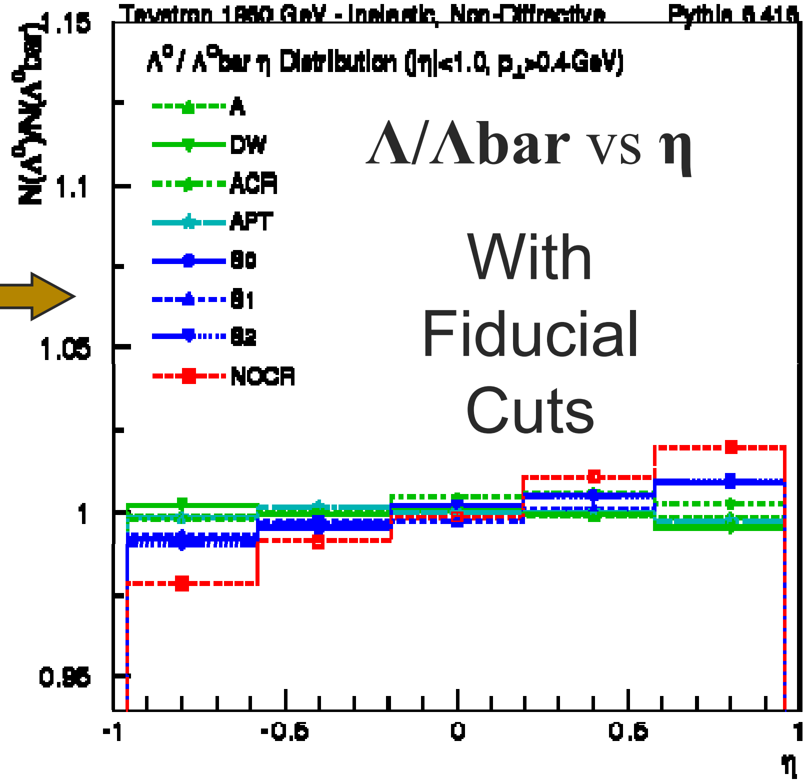
The manner in which QCD vacuum fluctuations are expelled from the interior region of a baryon […]. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quarks. The vector field illustrates the gradient of this reduction. The positions in space where the vacuum action is maximally expelled from the interior of the proton are also illustrated, exposing the presence of flux tubes. A key point of interest is the distance at which the flux-tube formation occurs. […] indicates that the transition to flux-tube formation occurs when the distance of the quarks from the centre of the triangle (< r >) is greater than 0.5 fm. The average inter-quark distance (< d >) is also indicated. Again, the diameter of the flux tubes remains approximately constant as the quarks move to large separations. As it costs energy to expel the vacuum field fluctuations, a linear confinement potential is felt between quarks in baryons as well as mesons.

[from http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/]

➔ Baryon Number Transport

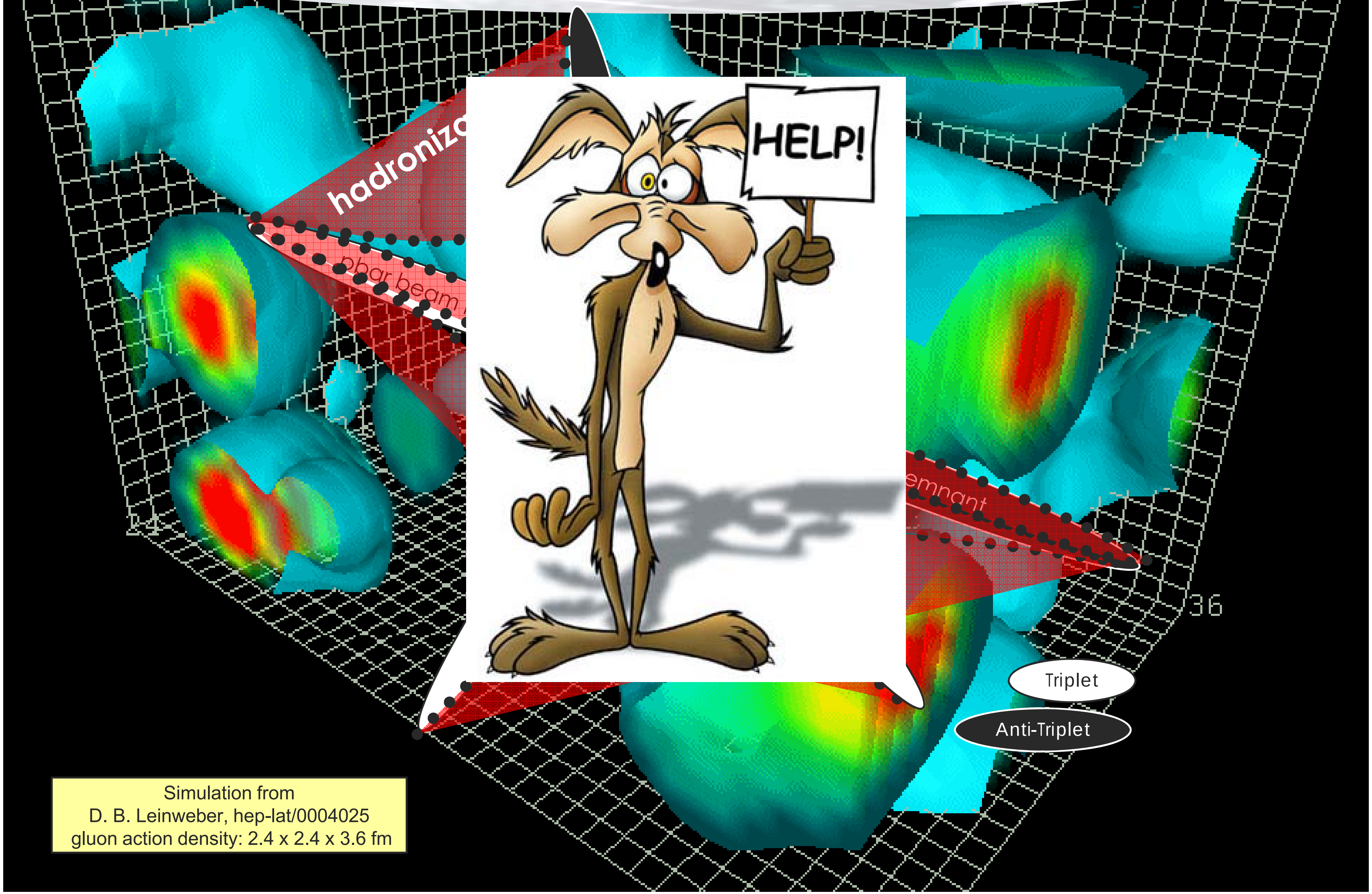
▶ Observable consequence





plots collected at `http://home.fnal.gov/~skands/leshouches-plots/`

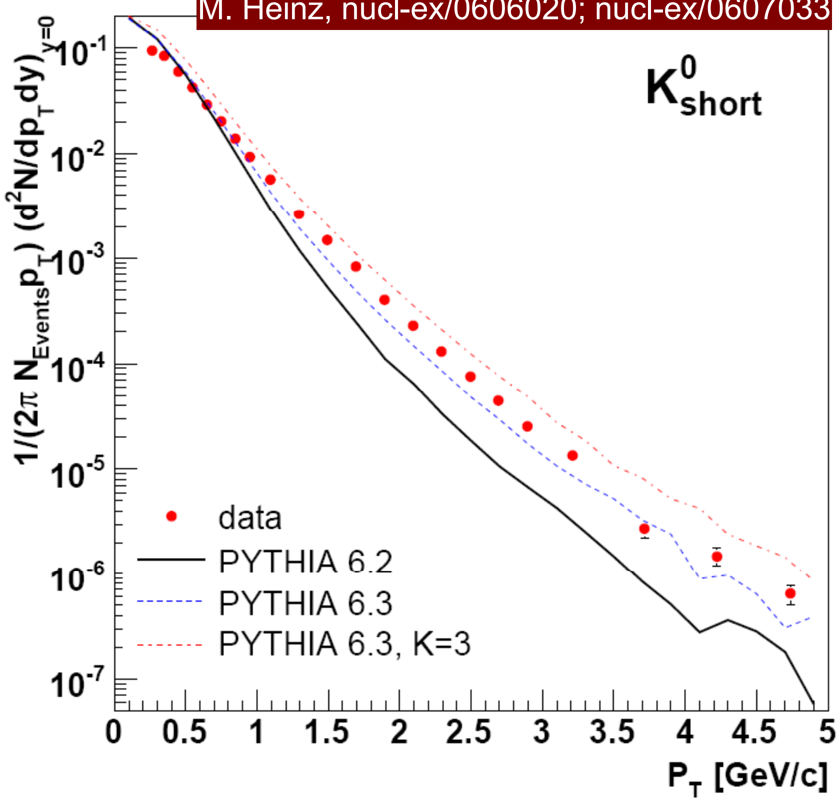
Now Hadronize This



Underlying Event and Colour

- Not much was known about the colour correlations, so some "theoretically sensible" default values were chosen
  - Rick Field (CDF) noted that the default model produced too soft charged-particle spectra.
  - The same is seen at RHIC:
  - For 'Tune A' etc, Rick noted that <p_T> increased when he increased the colour correlation parameters
  - But needed ~ 100% correlation. So far not explained
  - Virtually all 'tunes' now used by the Tevatron and LHC experiments employ these more 'extreme' correlations
  - What is their origin? Why are they needed?

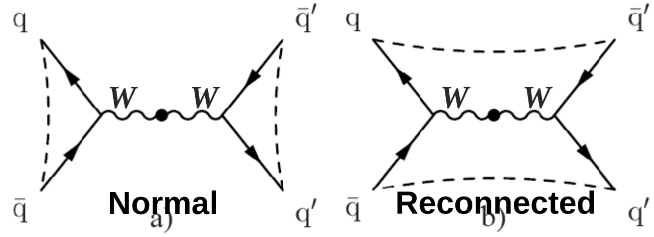
M. Heinz, nucl-ex/0606020; nucl-ex/0607033



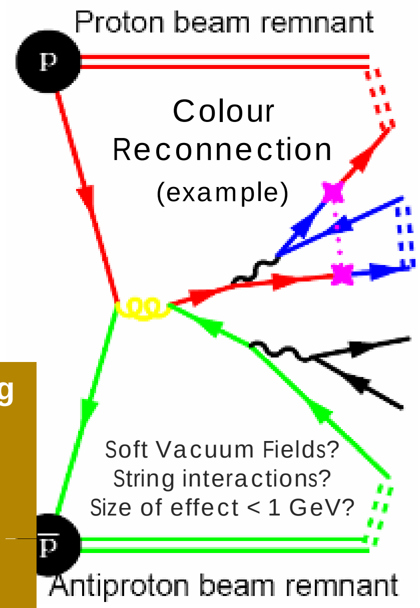
Color Reconnections

Sjöstrand, Khoze, Phys.Rev.Lett.72(1994)28 & Z. Phys.C62(1994)281 + more …
OPAL, Phys.Lett.B453(1999)153 & **OPAL**, hep-ex0508062

- ► Searched for at LEP
  - Major source of W mass uncertainty
  - Most aggressive scenarios excluded
  - But effect still largely uncertain $P_{reconnect} \sim 10\%$



- ► Prompted by CDF data and Rick Field's studies to reconsider.
  What do we know?
  - Non-trivial initial QCD vacuum
  - A lot more colour flowing around, not least in the UE
  - String-string interactions? String coalescence?
  - Collective hadronization effects?
  - More prominent in hadron-hadron collisions?
  - What (else) is RHIC, Tevatron telling us?
  - *Implications for precision measurements:Top mass? LHC?*



Existing models only for WW ➔ a new toy model for all final states: **colour annealing**
Attempts to minimize total area of strings in space-time (similar to Uppsala GAL)
• Improves description of minimum-bias collisions
PS, Wicke EPJC52(2007)133 ;
Preliminary finding Delta(mtop) ~ 0.5 GeV
Now being studied by Tevatron top mass groups

Colour Annealing

- Toy model of (non-perturbative) color reconnections, applicable to any final state
  - at hadronisation time, each string piece has a probability to interact with the vacuum / other strings:

$$P_{reconnect} = 1 - (1-\chi)^n$$

    - χ = strength parameter: fundamental reconnection probability (free parameter)
    - n = # of multiple interactions in current event (~ counts # of possible interactions)

- For the interacting string pieces:
  - New string topology determined by annealing-like minimization of 'Lambda measure'
    - Similar to area law for fundamental strings: Lambda ~ potential energy ~ string length ~ log(m) ~ N

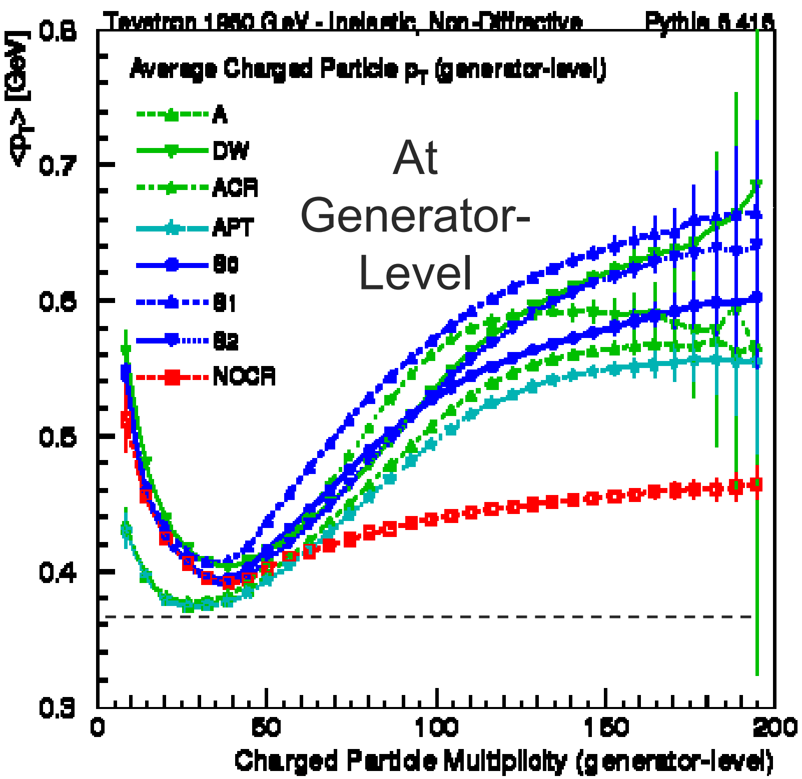
- → good enough for order-of-magnitude

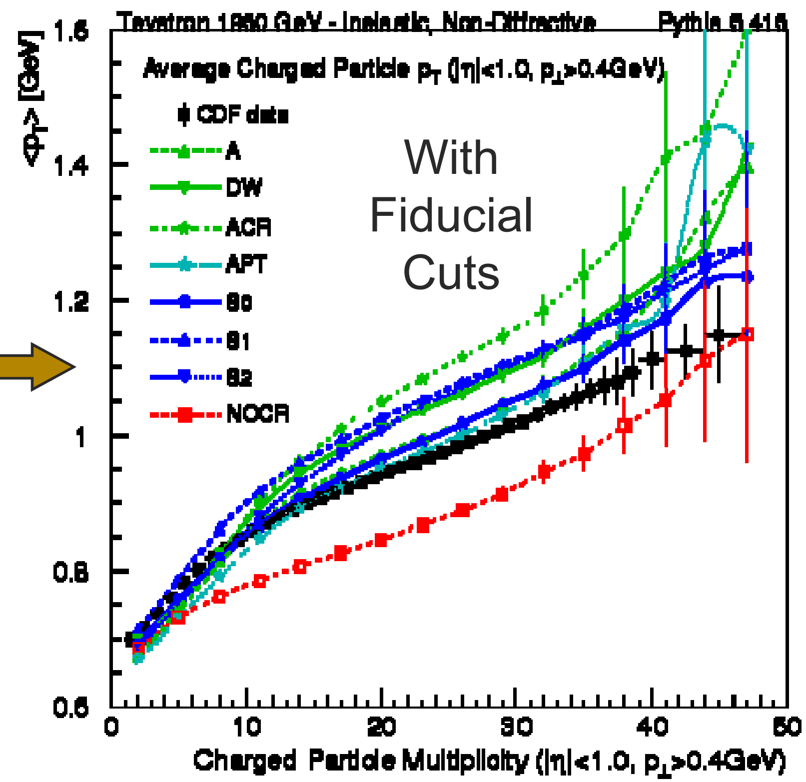
Sandhoff + PS, in Les Houches '05 SMH Proceedings, hep-ph/0604120

Evidence for String Interactions?

- Tevatron min-bias

Pythia Only the models which include *some* minimization mechanism for the string potential give good fits

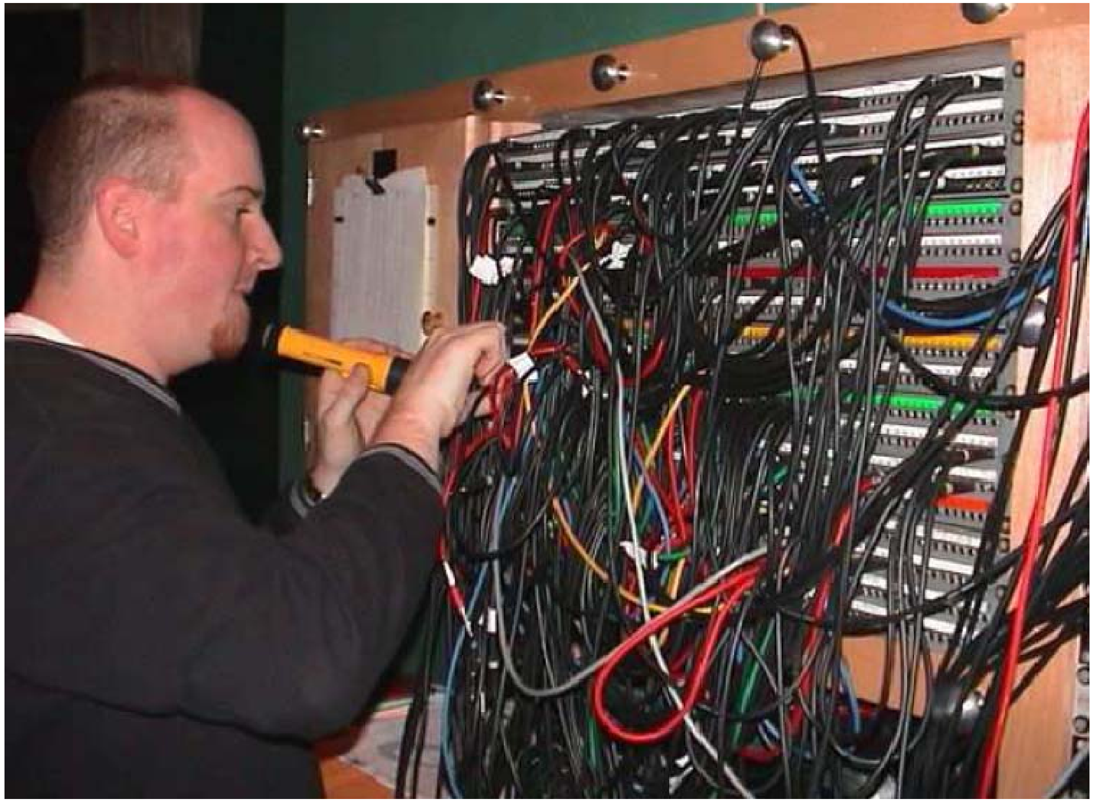




plots collected at `http://home.fnal.gov/~skands/leshouches-plots/`

Conclusion

► A Lot of Work remains …



Questions

- ► Transverse hadron structure
  - How important is the assumption f(x,b) = f(x) g(b)
  - What observables could be used to improve transverse structure?
- ► How important are flavour correlations?
  - Companion quarks, etc. Does it really matter?
  - Experimental constraints on multi-parton pdfs?
  - What are the analytical properties of interleaved evolution?
  - Factorization?
- ► "Primordial kT"
  - (~ 2 GeV of pT needed at start of DGLAP to reproduce Drell-Yan)
  - Is it just a fudge parameter?
  - Is this a low-x issue? Is it perturbative? Non-perturbative?

More Questions

- ► Correlations in the initial state
  - Underlying event: small p_T, small x (although x/X can be large)
  - Infrared regulation of MPI (+ISR) evolution connected to saturation?
  - Additional low-x / saturation physics required to describe final state?
  - Diffractive topologies?
- ► Colour correlations in the final state
  - MPI → color sparks → naïvely lots of strings spanning central region
  - What does this colour field do?
  - Collapse to string configuration dominated by colour flow from the "perturbative era"? or by "optimal" string configuration?
  - Are (area-law-minimizing) string interactions important?
  - Is this relevant to model (part of) diffractive topologies?
  - What about baryon number transport?
    - Connections to heavy-ion programme

Multiple Interactions → Balancing Minijets

- Look for additional balancing jet pairs "under" the hard interaction.
- Several studies performed, most recently by Rick Field at CDF → 'lumpiness' in the underlying event.

(Run 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

angle between 2 'best-balancing' pairs