Monte Carlo Generators
P. Skands (CERN TH)
Count what is Countable

**Measure what is Measurable**  
(and keep working on the beam)

---

### Theory
- Theory worked out to **Hadron Level** with acceptance cuts (~ detector-independent)

### Experiment
- Measurements corrected to **Hadron Level** with acceptance cuts (~ model-independent)

---

If not worked out to hadron level: data must be unfolded with someone else’s hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined ‘MC Truth’ or ‘parton level’)

---

**MC Generators**
- Amplitudes
- Monte Carlo
- Resummation
- Strings

**Detector Unfolding**
- Hits
- 0100110
- GEANT
- B-Field

---

**Feedback Loop**
From Partons ...

- Main Tool
  - Lowest-Order Matrix Elements calculated in a fixed-order perturbative expansion → parton-parton scattering cross sections

\[ L = \ldots \]

\[ q q' \to q q' : \frac{d\sigma}{d\hat{t}} = \frac{\pi}{s^2} \frac{4}{9} \alpha_s^2 \frac{s^2 + \hat{u}^2}{\hat{t}^2} \]

\[ \hat{s} = (p_1 + p_2)^2 \]
\[ \hat{t} = (p_1 - p_3)^2 = -\hat{s}(1 - \cos \hat{\theta})/2 \]
\[ \hat{u} = (p_1 - p_4)^2 = -\hat{s}(1 + \cos \hat{\theta})/2 \]

\[ L \to \text{FeynRules/LanHEP} \to \text{AlpGen/MadGraph/CalcHEP/CompHEP/…} \to \text{partons} \]
Reality is more complicated...

... to Pions

Reality is more complicated
Monte Carlo Generators

Calculate Everything $\approx$ solving QCD $\rightarrow$ requires compromise!

Improve Born-level perturbation theory, by including the ‘most significant’ corrections
$\rightarrow$ complete events $\rightarrow$ any observable you want

1. Parton Showers
2. Matching
3. Hadronisation
4. The Underlying Event

1. Soft/Collinear Logarithms
2. Finite Terms, “K”-factors
3. Power Corrections (more if not IR safe)
4. ?

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, ...)

roughly
Want to generate events
In as much detail as Mother Nature
Get average and fluctuations right
Make random choices ≈ as in nature

$$\frac{d\sigma}{dX} = \sum_{a,b} \sum_f \int_{\hat{X}_f} \hat{f}_a(x_a, Q_i^2) \hat{f}_b(x_b, Q_i^2) \frac{d\hat{\sigma}_{ab\rightarrow f}(x_a, x_b, f, Q_i^2, Q_f^2)}{d\hat{X}_f} \hat{D}(\hat{X}_f \rightarrow X, Q_i^2, Q_f^2)$$

$$\sigma_{\text{final state}} = \sigma_{\text{hard process}} P_{\text{tot, hard process} \rightarrow \text{final state}}$$

where $P_{\text{tot}} = P_{\text{res}} P_{\text{ISR}} P_{\text{FSR}} P_{\text{MI}} P_{\text{remnants}} P_{\text{hadronization}} P_{\text{decays}}$

with $P_i = \prod_j P_{ij} = \prod_j \prod_k P_{ijk} = \ldots$ in its turn

$\implies$ divide and conquer
Main Workhorses

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):
- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

HERWIG (successor to EARWIG, begun in 1984):
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):
- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- leans on PYTHIA for MPI and hadronization
Hard Processes

Wide spectrum from “general-purpose” to “one-issue”, see e.g. [http://www.cedar.ac.uk/hepcode/](http://www.cedar.ac.uk/hepcode/)

Free for all as long as Les-Houches-compliant output.

I) General-purpose, leading-order:
- MadGraph/MadEvent (amplitude-based, \( \leq 7 \) outgoing partons):
- CompHEP/CalcHEP (matrix-elements-based, \( \sim \leq 4 \) outgoing partons)
- Comix: part of SHERPA (Behrends-Giele recursion)
- HELAC–PHEGAS (Dyson-Schwinger)

II) Special processes, leading-order:
- ALPGEN: \( W/Z^+ \leq 6j, nW + mZ + kH^+ \leq 3j, \ldots \)
- AcerMC: \( t\bar{t}b\bar{b}, \ldots \)
- VECBOS: \( W/Z^+ \leq 4j \)

III) Special processes, next-to-leading-order:
- MCFM: NLO \( W/Z^+ \leq 2j, WZ, WH, H^+ \leq 1j \)
- GRACE+Bases/Spring

Note: NLO codes not yet generally interfaced to shower MCs
Distribution of observable: $O$

In production of $X +$ anything

Fixed Order (all orders)

\[ \left. \frac{d\sigma}{dO} \right|_{\text{ME}} = \sum_{k=0} \int d\Phi_{X+k} \left| \sum_{\ell=0} M_{X+k}^{(\ell)} \right|^2 \delta(O - O(p)_{X+k}) \]

Cross Section differentially in $O$

Phase Space

Sum over identical amplitudes, then square

Matrix Elements for $X+k$ at $(l)$ loops

Momentum configuration

Evaluate observable $\rightarrow$ differential in $O$

Truncate at $k=0$, $l=0$

$\rightarrow$ Born Level = First Term

Lowest order at which $X$ happens
QCD at Fixed Order

Distribution of observable: \( O \)

In production of \( X + \text{anything} \)

\[
\left. \frac{d\sigma}{dO} \right|_{\text{ME}} = \sum_{k=0} \int d\Phi_{X+k} \left| \sum_{\ell=0} M_{X+k}^{(\ell)} \right|^2 \delta(O - O(\{p\}X+k))
\]

Fixed Order (all orders)

Cross Section differentially in \( O \)

Phase Space

Sum over identical amplitudes, then square

Matrix Elements for \( X+k \) at (l) loops

Momentum configuration

Evaluate observable \( \rightarrow \) differential in \( O \)

Truncate at \( k=n, l=0 \)

\( \rightarrow \) Leading Order for \( X + n \)

Lowest order at which \( X + n \) happens
QCD at Fixed Order

Distribution of observable: $O$

In production of $X +$ anything

Fixed Order (all orders)

$$\frac{d\sigma}{dO} \bigg|_{\text{ME}} = \sum_{k=0}^{\infty} \int d\Phi_{X+k} \left| \sum_{\ell=0} M_{X+k}^{(\ell)} \right|^2 \delta(O - O(\{p\}_{X+k}))$$

- Cross Section differentially in $O$
- Sum over "anything" = legs
- Phase Space
- Matrix Elements for $X+k$ at ($l$) loops
- Evaluate observable $\rightarrow$ differential in $O$
- Sum over identical amplitudes, then square

Momentum configuration

Truncate at $k+l \leq n$

$\rightarrow N^nLO$ for $X$

Includes $N^{n-1}LO$ for $X+1$, $N^{n-2}LO$ for $X+2$, ...
### Loops and Legs

#### Another representation

<table>
<thead>
<tr>
<th>Loops</th>
<th>Legs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^{(2)}$</td>
<td>$X+1^{(2)}$</td>
</tr>
<tr>
<td>$X^{(1)}$</td>
<td>$X+1^{(1)}$ $X+2^{(1)}$ $X+3^{(1)}$ ...</td>
</tr>
<tr>
<td>Born</td>
<td>$X+1^{(0)}$ $X+2^{(0)}$ $X+3^{(0)}$ ...</td>
</tr>
</tbody>
</table>
Loops and Legs

Another representation

Loops

\[ X^{(2)} \quad X+1^{(2)} \quad \ldots \]

\[ X^{(1)} \quad X+1^{(1)} \quad X+2^{(1)} \quad X+3^{(1)} \quad \ldots \]

Born

Legs

\[ X+1^{(0)} \quad X+2^{(0)} \quad X+3^{(0)} \quad \ldots \]

M. Born
(1882-1970)
Nobel 1954
Loops and Legs

Another representation

Loops:

- $X^{(2)}$
- $X+1^{(2)}$
- ...

- $X^{(1)}$
- $X+1^{(1)}$
- $X+2^{(1)}$
- $X+3^{(1)}$
- ...

- Born
- $X+1^{(0)}$
- $X+2^{(0)}$
- $X+3^{(0)}$
- ...

Legs:

Note: $\sigma \to \infty$ if jet not resolved
Loops and Legs

Another representation

X^{(2)} X^{(2)+1} ... 

X^{(1)} X^{(1)+1} X^{(1)+2} X^{(1)+3} ... 

Born X^{(0)+1} X^{(0)+2} X^{(0)+3} ... 

X @ NLO
(includes X+1 @ LO)

Note: X+1 jet observables only correct at LO
Loops and Legs

Another representation

\[
\begin{array}{c}
\text{Loops} \\
X^{(2)} & X+1^{(2)} & \cdots \\
X^{(1)} & X+1^{(1)} & X+2^{(1)} & X+3^{(1)} & \cdots \\
\text{Born} & X+1^{(0)} & X+2^{(0)} & X+3^{(0)} & \cdots \\
\end{array}
\]

\[X+1 \text{ @ NLO} \]
(includes \(X+2 \text{ @ LO}\))

Note: \(\sigma \rightarrow \infty\) if no jet resolved

Note: \(X+2\) jet observables only correct at LO
Fixed-Order QCD

What kind of observables can we evaluate this way?

Perturbation theory valid → $\alpha_s$ must be small
→ All $Q_i \gg \Lambda_{QCD}$

Multi-scale: absence of enhancements from soft/collinear singular (conformal) dynamics
→ All $Q_i/Q_j \approx 1$

All resolved scales $>> \Lambda_{QCD}$ AND no large hierarchies*

*)At “leading twist” (not counting underlying event)
Trivially untrue for QCD

We’re colliding, and observing, hadrons $\rightarrow$ small scales
We want to consider high-scale processes $\rightarrow$ large scale differences

$\rightarrow$ A Priori, no perturbatively calculable observables in hadron-hadron collisions

All resolved scales $\gg \Lambda_{QCD}$ AND no large hierarchies*

*At “leading twist” (not counting underlying event)
Resummed QCD

All resolved scales $\gg \Lambda_{QCD}$ AND no large hierarchies

Trivially untrue for QCD

We’re colliding, and observing, hadrons $\rightarrow$ small scales
We want to consider high-scale processes $\rightarrow$ large scale differences

\[
\frac{d\sigma}{dX} = \sum_{a,b} \sum_{f} \int_{\hat{X}_f} f_a(x_a, Q_i^2) f_b(x_b, Q_i^2) \frac{d\hat{\sigma}_{ab\rightarrow f}(x_a, x_b, f, Q_i^2, Q_f^2)}{d\hat{X}_f} D(\hat{X}_f \rightarrow X, Q_i^2, Q_f^2)
\]

PDFs: needed to compute inclusive cross sections
FFs: needed to compute (semi-)exclusive cross sections

All resolved scales $\gg \Lambda_{QCD}$ AND $X$ Infrared Safe

*) At “leading twist” (not counting underlying event)
Parton Showers
≈ Exclusive Resummation
Conformal QCD

**Bremsstrahlung**

Rate of bremsstrahlung jets mainly depends on the RATIO of the jet $p_T$ to the “hard scale”

![Diagram](image)

\[
\sigma_X (j \geq 5 \text{ GeV}) \approx \sigma_X (j \geq 50 \text{ GeV})
\]

Rate of 5-GeV jets in $X$ production

Rate of 50-GeV jets in production of 10$X$

See, e.g.,

- Plehn, Tait: 0810.2919 [hep-ph]
- Alwall, de Visscher, Maltoni: JHEP 0902(2009)017
Bremsstrahlung

\[ d\sigma_X = \ldots \]

\[
\begin{align*}
    d\sigma_{X+1} &\sim 2g^2d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}} \\
    d\sigma_{X+2} &\sim 2g^2d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}} \\
    d\sigma_{X+3} &\sim 2g^2d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}}
\end{align*}
\]

Interpretation: the structure evolves

This is an approximation to infinite-order tree-level cross sections

But something’s not right…

Total cross section would be infinite …
Loops and Legs

Summation

Loops

$X^{(2)} \quad X+1^{(2)} \quad \ldots$

$X^{(1)} \quad X+1^{(1)} \quad X+2^{(1)} \quad X+3^{(1)} \quad \ldots$

Born $X+1^{(0)} \quad X+2^{(0)} \quad X+3^{(0)} \quad \ldots$

The Virtual corrections are missing

Conformal/Bjorken Scaling

Jet-within-a-jet-within-a-jet-…
Resummation

Interpretation: the structure evolves! (example: $X = 2$-jets)

- Take a jet algorithm, with resolution measure “$Q$”, apply it to your events
- At a very crude resolution, you find that everything is 2-jets

$$d\sigma_X = \cdots$$

$$d\sigma_{X+1} \sim 2g^2d\sigma_X \frac{ds_{a1} ds_{1b}}{s_{a1} s_{1b}}$$

$$d\sigma_{X+2} \sim 2g^2d\sigma_{X+1} \frac{ds_{a2} ds_{2b}}{s_{a2} s_{2b}}$$

$$d\sigma_{X+3} \sim 2g^2d\sigma_{X+2} \frac{ds_{a3} ds_{3b}}{s_{a3} s_{3b}}$$
Resummation

\[ \sigma_{X+1}(Q) = \sigma_{X;\text{incl}} - \sigma_{X;\text{excl}}(Q) \]

Interpretation: the structure evolves

This includes both real and virtual corrections

\[ + \text{ UNITARITY:} \]
\[ \text{Virt} = - \text{Int(Tree)} + F \]
(or: given a jet definition, an event has either 0, 1, 2, or \( n \) jets)

\[ \sigma_{X;\text{excl}} = \sigma_X - \sigma_{X+1} = \sigma_X - \sigma_{X+1;\text{excl}} - \sigma_{X+2;\text{excl}} - \ldots \]
Loops and Legs

Resummation

Loops

Born

X(2) → X+1(2) → X+2(2) → X+3(2) → ...

X(1) → X+1(1) → X+2(1) → X+3(1) → ...

Born+Res

Legs

X(0) → X+1(0) → X+2(0) → X+3(0) → ...

Unitarity

... Conformal/Bjorken Scaling

Jet-within-a-jet-within-a-jet-...

... Exponentiation
Born to Shower

\[ \frac{d\sigma}{d\hat{O}} \bigg|_{\text{Born}} = \int d\Phi_X \ w_X^{(0)} \delta(\hat{O} - \hat{O}(\{p\}_X)) \]

\( w_X^{(0)} \propto \text{PDFs} \times |M_X^{(0)}|^2 \)

But instead of evaluating \( O \) directly on the Born final state, first insert a showering operator

\[ \frac{d\sigma}{d\hat{O}} \bigg|_{\text{PS}} = \int d\Phi_X \ w_X^{(0)} \ S(\{p\}_X, \hat{O}) \]

\( S(\{p\}_X, \hat{O}) = \delta(\hat{O} - \hat{O}(\{p\}_X)) + \mathcal{O}(\alpha_s) \)

To first order, \( S \) does nothing
The Shower Operator

**To Lowest Order**

\[ S({p}_X, \mathcal{O}) = \delta(\mathcal{O} - \mathcal{O}(\{p\}_X)) \]

**To First Order**

\[ S({p}_X, \mathcal{O}) = \left( 1 - \int_{t_{\text{start}}}^{t_{\text{had}}} dt \frac{d\mathcal{P}}{dt} \right) \delta(\mathcal{O} - \mathcal{O}(\{p\}_X)) \]

\[ + \int_{t_{\text{start}}}^{t_{\text{had}}} dt X+1 \frac{d\mathcal{P}}{dt X+1} \delta(\mathcal{O} - \mathcal{O}(\{p\}_X+1)) \]

**Splitting Operator**

\[ \mathcal{P} = \int \frac{d\Phi_{X+1}}{d\Phi_X} \frac{w_{X+1}}{w_X} \bigg|_{\text{PS}} \]

= Shower approximation of \( X \rightarrow X+1 \)
The Shower Operator

To ALL Orders

\[
S(\{p\}_x, \mathcal{O}) = \Delta(t_{\text{start}}, t_{\text{had}}) \delta(\mathcal{O} - \mathcal{O}(\{p\}_x))
\]

“Nothing Happens” \to “Evaluate Observable”

\[
- \int_{t_{\text{start}}}^{t_{\text{had}}} dt \frac{d\Delta(t_{\text{start}}, t)}{dt} S(\{p\}_{x+1}, \mathcal{O})
\]

“Something Happens” \to “Continue Shower”

All-orders Probability that nothing happens

\[
\Delta(t_1, t_2) = \exp \left( - \int_{t_1}^{t_2} dt \frac{d\mathcal{P}}{dt} \right)
\]

(Exponentiation)

Analogous to nuclear decay

\[
N(t) \approx N(0) \exp(-ct)
\]
Splitting Functions

\[ S \left( \left\{ p \right\}_X, O \right) = \delta (O - O \left( \left\{ p \right\}_X \right)) \]

\[ S \left( \left\{ p \right\}_X, O \right) = \left( 1 - \int_{t_{\text{start}}}^{t_{\text{had}}} dt \right) \delta (O - O \left( \left\{ p \right\}_X \right)) + \int_{t_{\text{had}}}^{t_{\text{start}}} dt \ X \left( 1 + \int_{t_{\text{had}}}^{t_{\text{start}}} dt \right) \delta (O - O \left( \left\{ p \right\}_X + 1 \right)) \]

\[ S \left( \left\{ p \right\}_X, O \right) = \Delta (t_{\text{start}}, t_{\text{had}}) \delta (O - O \left( \left\{ p \right\}_X \right)) - \int_{t_{\text{had}}}^{t_{\text{start}}} dt \Delta (t_{\text{start}}, t_{\text{had}}) \]

\[ \Delta (t_{\text{start}}, t_{\text{had}}) \]

\[ P = \int \frac{dQ^2}{Q^2} dz P_i(z) \]

\[ P_{\text{DGLAP}} = \sum_i \int \frac{dQ^2}{Q^2} dz P_i(z) \]

\[ P_{\text{Antenna}} = \int \frac{d s_{ij} d s_{jk}}{16 \pi^2 s} \left| M_3(s_{ij}, s_{jk}, s) \right|^2 \]

\[ \left| M_2(s) \right|^2 \]

Splitting Operator

Examples

\[ \frac{\alpha s_{ab}}{s_{ai} s_{ib}} \]

\[ \alpha s_{ab} \]

\[ \alpha s_{ab} \]

\[ \alpha s_{ab} \]
## Splitting Functions

### DGLAP

(E.g., HERWIG, PYTHIA)

\[
d\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a\to bc}(z) \, dt \, dz .
\]

- \[ P_{q\to qg}(z) = C_F \frac{1 + z^2}{1 - z} , \]
- \[ P_{g\to gg}(z) = N_C \frac{(1 - z(1 - z))^2}{z(1 - z)} , \]
- \[ P_{g\to q\overline{q}}(z) = T_R (z^2 + (1 - z)^2) , \]
- \[ P_{q\to q\gamma}(z) = e_q^2 \frac{1 + z^2}{1 - z} , \]
- \[ P_{\ell\to \ell\gamma}(z) = e_\ell^2 \frac{1 + z^2}{1 - z} , \]

### Dipole-Antennae

(E.g., ARIADNE, VINCIA)

\[
d\mathcal{P}_{IK\to ijk} = \frac{ds_{ij}ds_{jk}}{16\pi^2s} a(s_{ij}, s_{jk})
\]

- \[ a_{qq\to qq\overline{q}} = \frac{2C_F}{s_{ij}s_{jk}} (2s_{ik}s + s_{ij}^2 + s_{jk}^2) \]
- \[ a_{qq\to qg} = \frac{C_A}{s_{ij}s_{jk}} (2s_{ik}s + s_{ij}^2 + s_{jk}^2 - s_{ij}^3) \]
- \[ a_{gg\to qg} = \frac{C_A}{s_{ij}s_{jk}} (2s_{ik}s + s_{ij}^2 + s_{jk}^2 - s_{ij}^3 - s_{jk}^3) \]
- \[ a_{qq\to q\overline{q}'q'} = \frac{T_R}{s_{jk}} (s - 2s_{ij} + 2s_{ij}^2) \]
- \[ a_{gg\to q\overline{q}'q'} = a_{qq\to q\overline{q}'q'} \]

... + non-singular terms

**NB:** Also others, e.g., Catani–Seymour (SHERPA), Sector Antennae, ....
Coherence

QED: Chudakov effect (mid-fifties)

\[ \text{cosmic ray } \gamma \text{ atom} \]

\[
\begin{array}{c}
\text{emulsion plate} \\
\text{reduced ionization} \\
\text{normal ionization}
\end{array}
\]

QCD: colour coherence for soft gluon emission

Approximations to Coherence:

Angular Ordering (HERWIG)
Angular Vetos (PYTHIA)
Coherent Dipoles/Antennae (ARIADNE, CS, VINCIA)

Illustrations by T. Sjöstrand
The Initial State

Parton Densities and Initial-State Showers
Parton Densities for MC

**LO**

- Consistent with LO matrix elements in LO generators
- Effectively ‘tuned’ to absorb missing NLO contributions
- But they give quite bad fits compared to NLO ...

**NLO**

- Formally consistent with NLO matrix elements
- Effectively ‘tuned’ with NLO theory
- → badly tuned for LO matrix elements (not enough low-x glue)?
- Suggest to only use for NLO generators?

**LO*, MC pdfs, ...**

- Best of both worlds?
  - PDF has always had an impact on generator tuning
  - But now we are going the other way: tune the PDF!
  - Still gaining experience. Proceed with caution & sanity checks
PDF Uncertainties

Much debate recently on PDF errors

Try to propagate experimental errors properly → 68% CL

But "tensions" between different badly compatible data sets → ... ?

→ 90%, something else?

+ unknown uncertainty from starting parametrization at low $Q^2$

Still, good to $\approx 10\%$ even for LO gluon in $10^{-6} < x < 10^{-1}$ (bigger errors at lower $Q^2$)
Initial-State Evolution
= Spacelike (backwards) Evolution

FSR:
Virtualities are Timelike: \( p^2 > 0 \)
Start at \( Q^2 = Q_f^2 \)
Unconstrained forwards evolution

ISR:
Virtualities are Spacelike: \( p^2 < 0 \)
Start at \( Q^2 = Q_i^2 \)
Constrained backwards evolution towards boundary condition = proton

+ Look Out! (Especially Tricky): ISR-FSR interference! FSR off ISR!
Small strings → clusters, Large clusters → strings

<table>
<thead>
<tr>
<th>Program Model</th>
<th>PYTHIA String</th>
<th>HERWIG (&amp;SHERPA) Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy–Momentum Picture</td>
<td>Powerful Predictive Few</td>
<td>Simple Unpredictive Many</td>
</tr>
<tr>
<td>Parameters</td>
<td>Messy Unpredictive Many</td>
<td>Simple In-Between Few</td>
</tr>
</tbody>
</table>

Illustrations by T. Sjöstrand
Independent Fragmentation?

\[ \sim \text{Local Parton-Hadron Duality (LPHD)} \]

Universal fragmentation of a parton into hadrons

This is awfully wrong!

The point of confinement is that partons are colored.

Hadronization = the process of color neutralization.

I.e, the one question NOT addressed by LPHD or I.F.

My opinion: despite some success at describing inclusive quantities, it is fundamentally misguided to think about independent fragmentation of individual partons.
The (Lund) String Model

Map:

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break constant per unit area → **AREA LAW**

Gluon = kink on string, carrying energy and momentum

Simple space-time picture + no separate params for g jets
Details of string breaks more complicated …
Underlying Event:
Multiple Parton-Parton Interactions

Underlying Event (note: interactions correlated in colour: hadronization not independent)

→ Underlying Event
～ “Finegraining”

Main parameter: $p_{\perp\text{min}}$ (perturbative cutoff)

Generators - Summary

• Allow to connect theory ↔ experiment
  • On PHYSICAL OBSERVABLES
  • Precision is a function of Model & Constraints

• Random Numbers to Simulate Quantum Behaviour
  • Fixed-Order pQCD supplemented with showers, hadronization, decays, underlying event, matching, ...

• No single program does it all
  • + Variations needed for uncertainty estimates!
  • Rapid evolution of theory/models/constraints/tunes/…
  • Emphasis on interfaces, interoperability
(Some) Possible Discussion Topics

- What’s the difference (relation?) between zero bias, minimum-bias, and underlying event?
  - What’s (the role of) diffraction?

- How does resummation get around the problem of infinities at fixed order? Where do the infinities go?

- Where does the motivation for the string model come from? How much can we “know” about non-perturbative physics?
  - How do strings break?

- Multiple interactions: perturbative or a non-perturbative component? Beam remnants and PDFs? Is it a theory or a model?

- Factorization