MC Overview

Peter Skands
(CERN-TH)
Count what is Countable

**Measure what is Measurable**

*(and keep working up the beam)*

Theory

Feedback Loop

Experiment

Amplitudes
Monte Carlo
Resummation
Strings
...

Theory worked out to **Hadron Level**
with acceptance cuts
(\sim detector-independent)

Measurements corrected to **Hadron Level**
with acceptance cuts
(\sim model-independent)

Hits
0100110
GEANT
B-Field
....
\[ \mathcal{L} = \bar{\psi}_q^i (i \gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F_{\mu \nu}^a F^{a \mu \nu} \]

+ quark masses and value of \( \alpha_s \)
\[ \mathcal{L} = \bar{\psi}_q (i \gamma^\mu) (D_\mu)_{ij} \psi_q - m_q \bar{\psi}_q^i \psi_q^j - \frac{1}{4} F_{\mu \nu}^a F^{a \mu \nu} \]

“Nothing”

Gluon action density: 2.4x2.4x3.6 fm

QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025
"Nothing"

Gluon action density: 2.4x2.4x3.6 fm

QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025
Perturbation Theory
Perturbation Theory

Reality is more complicated
The Way of the Chicken

► Who needs QCD? I’ll use leptons
  • Sum inclusively over all QCD
    ▪ Leptons almost IR safe by definition
    ▪ WIMP-type DM, Z’, EWSB → may get some leptons
Who needs QCD? I’ll use leptons

- Sum inclusively over all QCD
  - Leptons almost IR safe by definition
  - WIMP-type DM, Z’, EWSB → may get some leptons
- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - At least need well-understood PDFs
  - High precision = higher orders → enter QCD (and more QED)
- Isolation → indirect sensitivity to QCD
- Fakes → indirect sensitivity to QCD
Who needs QCD? I’ll use leptons

- Sum inclusively over all QCD
  - Leptons almost IR safe by definition
  - WIMP-type DM, $Z'$, EWSB $\rightarrow$ may get some leptons

- Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  - At least need well-understood PDFs
  - High precision $\rightarrow$ higher orders $\rightarrow$ enter QCD (and more QED)

- Isolation $\rightarrow$ indirect sensitivity to QCD
- Fakes $\rightarrow$ indirect sensitivity to QCD
- Not everything gives leptons
  - Need to be a lucky chicken …
The Way of the Chicken

► Who needs QCD? I’ll use leptons
  • Sum inclusively over all QCD
    ▪ Leptons almost IR safe by definition
    ▪ WIMP-type DM, Z’, EWSB → may get some leptons
  • Beams = hadrons for next decade (RHIC / Tevatron / LHC)
    ▪ At least need well-understood PDFs
    ▪ High precision = higher orders → enter QCD (and more QED)
  • Isolation → indirect sensitivity to QCD
  • Fakes → indirect sensitivity to QCD
  • Not everything gives leptons
    ▪ Need to be a lucky chicken …

► The unlucky chicken
  • Put all its eggs in one basket and didn’t solve QCD
The Way of the Chicken

► Who needs QCD? I’ll use leptons

• Sum inclusively over all QCD
  ▪ Leptons almost IR safe by definition
  ▪ WIMP-type DM, Z’, EWSB → may get some leptons

• Beams = hadrons for next decade (RHIC / Tevatron / LHC)
  ▪ At least need well-understood PDFs
  ▪ High precision = higher orders → enter QCD (and more QED)

• Isolation → indirect sensitivity to QCD
• Fakes → indirect sensitivity to QCD
• Not everything gives leptons
  ▪ Need to be a lucky chicken …

► The unlucky chicken

• Put all its eggs in one basket and didn’t solve QCD
Monte Carlo Generators

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

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

Calculate Everything $\approx$ solve 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, ...)
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
- PYTHIA-like MPI model + HERWIG-like hadronization model
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
- PYTHIA-like MPI model + HERWIG-like hadronization model

+ WHIZARD (OMEGA): emerging serious tool with focus on BSM
Bremsstrahlung
Bremsstrahlung

Charges
Stopped
Bremsstrahlung

Charges Stopped

Associated field (fluctuations) continues
Bremsstrahlung

Charges Stopped

Associated field (fluctuations) continues
Bremsstrahlung

The harder they stop, the harder the fluctuations that continue to become strahlung
Bremsstrahlung

**Conformal QCD** (a.k.a. Bjorken scaling)

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

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

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

Soft/Collinear enhancements DIVERGENT for $p_T \ll m_X$

See, e.g.,

Plehn, Tait: 0810.2919 [hep-ph]
Alwall, de Visscher, Maltoni: JHEP 0902(2009)017
1. Fixed-order QCD

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

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

→ All resolved scales $\gg \Lambda_{\text{QCD}}$ AND no large hierarchies
Fixed-Order QCD

All resolved scales $\gg \Lambda_{\text{QCD}}$ 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

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

All resolved scales $\gg \Lambda_{\text{QCD}}$ 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

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

$\rightarrow$ Initial-State Showers in MC $\quad$ $\rightarrow$ Final-State Showers (+ hadronization) in MC
Resummed QCD

Trivially untrue for QCD

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

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

PDFs: needed to compute inclusive cross sections
→ Initial-State Showers in MC

FFs: needed to compute (semi-)exclusive cross sections
→ Final-State Showers (+ hadronization) in MC
Resummed QCD

All resolved scales $\gg \Lambda_{\text{QCD}}$ 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
→ Initial-State Showers in MC

FFs: needed to compute (semi-)exclusive cross sections
→ Final-State Showers (+ hadronization) in MC

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

\[ d\sigma_X = \ldots \]
Bremsstrahlung

d\sigma_X = \ldots

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

\[ d\sigma_X = \ldots \]

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

\[ d\sigma_X = \ldots \]

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

\[ d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2} \; ds_{2b}}{s_{a2} \; s_{2b}} \]
Bremsstrahlung

\[ d\sigma_X = \ldots \]

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

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

\[ d\sigma_X = \ldots \]

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

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

\[ d\sigma_{X+3} \sim 2g^2d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}} \]
Bremsstrahlung

\[ d\sigma_X = \ldots \]

\[ d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{d\sigma_{a_1}}{s_{a_1}} \frac{d\sigma_{s_1b}}{s_{s_1b}} \]

\[ d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{d\sigma_{a_2}}{s_{a_2}} \frac{d\sigma_{s_2b}}{s_{s_2b}} \]

\[ d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{d\sigma_{a_3}}{s_{a_3}} \frac{d\sigma_{s_3b}}{s_{s_3b}} \]

This gives an approximation to infinite-order tree-level cross sections (here “DLA”)
Bremsstrahlung

\[ d\sigma_X = \ldots \]
\[ d\sigma_{X+1} \sim 2g^2d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}} \]
\[ d\sigma_{X+2} \sim 2g^2d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}} \]
\[ d\sigma_{X+3} \sim 2g^2d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}} \]

This gives an approximation to infinite-order tree-level cross sections (here “DLA”)

But something is not right …

Total cross section would be infinite …
Loops and Legs

Summation

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)} ...

The Virtual corrections are missing

Universality (scaling)

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

\[ d\sigma_X = \ldots \]

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

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

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

Unitarity

KLN:

\[ \text{Virt} = - \text{Int(Tree)} + F \]

In LL showers: neglect \( F \)

Imposed by Event evolution:

When \((X)\) branches to \((X+1)\):

Gain one \((X+1)\). Loose one \((X)\).

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

\[ \rightarrow \text{includes both real and virtual corrections (in LL approx)} \]
Bootstrapped pQCD

Resummation

Born + Shower

Loops

Legs

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

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

\[ \text{Born} \rightarrow X+1^{(0)} \rightarrow X+2^{(0)} \rightarrow X+3^{(0)} \rightarrow \ldots \]

Unitarity

Exponentiation

Universality (scaling)

Jet-within-a-jet-within-a-jet-...
Bootstrapped pQCD

Resummation

Born + Shower

Loops

Legs

Unitarity

Universality (scaling)

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

Exponentiation
Matching

A (Complete Idiot’s) Solution – Combine

1. \([X]_{ME} +\text{ showering}\)
2. \([X + 1\text{ jet}]_{ME} +\text{ showering}\)
3. ...

Run generator for \(X\) (+ shower)
Run generator for \(X+1\) (+ shower)
Run generator for … (+ shower)
Combine everything into one sample
Matching

► A (Complete Idiot’s) Solution – Combine
1. $[X]_{\text{ME}}$ + showering
2. $(X + 1 \text{ jet})_{\text{ME}}$ + showering
3. ...

► Doesn’t work

- $[X]$ + shower is inclusive
- $(X+1]$ + shower is also inclusive

Run generator for $X$ (+ shower)
Run generator for $X+1$ (+ shower)
Run generator for … (+ shower)
Combine everything into one sample

What you get

\[ X \text{ inclusive} \]
\[ X+1 \text{ inclusive} \]
\[ X+2 \text{ inclusive} \]

Overlapping “bins”

What you want

\[ X \text{ exclusive} \]
\[ X+1 \text{ exclusive} \]
\[ X+2 \text{ inclusive} \]

One sample
The Matching Game

Shower off $X$ already contains LL part of all $X+n$

$V^d_1 \rightarrow 2g^2 d\sigma \frac{ds_1}{s_1}$

Adding back full ME for $X+n$ would be overkill
The Matching Game

- Shower off $X$ already contains LL part of all $X+n$
- Adding back full ME for $X+n$ would be overkill

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

**Solution 1:** “Additive” (most widespread)

**Add** event samples, with modified weights

\[
w_X = |M_X|^2 + \text{Shower} \\
w_{X+1} = |M_{X+1}|^2 - \text{Shower}\{w_X\} + \text{Shower} \\
w_{X+n} = |M_{X+n}|^2 - \text{Shower}\{w_X, w_{X+1}, \ldots, w_{X+n-1}\} + \text{Shower}
\]

**HERWIG:** for $X+1 @ LO$ (Shower = 0 in dead zone of angular-ordered shower)

**MC@NLO:** for $X+1 @ LO$ and $X @ NLO$ (note: correction can be negative)

**CKKW & MLM:** for all $X+n @ LO$ (force Shower = 0 above “matching scale” and add ME there)

SHERPA (CKKW), ALPGEN (MLM + HW/PY), MADGRAPH (MLM + HW/PY), PYTHIA8 (CKKW-L from LHE files), …

Seymour, CPC90(1995)95 + many more recent…

Only CKKW and MLM
Shower off $X$ already contains LL part of all $X+n$

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

Adding back full ME for $X+n$ would be overkill
The Matching Game

Solution 2: “Multiplicative”

One event sample

\[ w_X = |M_X|^2 \] + Shower

Make a “course correction” to the shower at each order

\[ R_{X+1} = |M_{X+1}|^2/\text{Shower}\{w_X\} \] + Shower

\[ R_{X+n} = |M_{X+n}|^2/\text{Shower}\{w_{X+n-1}\} \] + Shower

PYTHIA: for \( X+1 \) @ LO (for color-singlet production and \( \sim \) all SM and BSM decay processes)

POWHEG: for \( X+1 \) @ LO and \( X \) @ NLO (note: positive weights)

VINCIJA: for all \( X+n \) @ LO and \( X \) @ NLO (only worked out for decay processes so far)
## MS/EVENT

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>Strategy</th>
<th>$Z \rightarrow 3$</th>
<th>$Z \rightarrow 4$</th>
<th>$Z \rightarrow 5$</th>
<th>$Z \rightarrow 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pythia 8</strong>&lt;br&gt;$\text{Initialization time} \sim 0$</td>
<td>TS</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vincia (sector, }Q_{\text{match}} = 5 \text{ GeV)</strong>&lt;br&gt;$\text{Initialization time} \sim 0$</td>
<td>GKS</td>
<td>0.26</td>
<td>0.50</td>
<td>1.40</td>
<td>6.70</td>
</tr>
<tr>
<td><strong>Sherpa (}Q_{\text{match}} = 5 \text{ GeV)</strong>&lt;br&gt;$\text{Initialization time} = $</td>
<td>CKKW</td>
<td>5.15*</td>
<td>53.00*</td>
<td>220.00*</td>
<td>400.00*</td>
</tr>
<tr>
<td>(expect similar scaling for MLM)</td>
<td></td>
<td>1.5 minutes</td>
<td>7 minutes</td>
<td>22 minutes</td>
<td>2.2 hours</td>
</tr>
</tbody>
</table>

*Matched and unweighted. Hadronization off gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory*

--

**Efficient Matching with Sector Showers**<br>J. Lopez-Villarejo & PS : JHEP 1111 (2011) 150

---

Generator Versions: Pythia 6.425 (Perugia 2011 tune), Pythia 8.150, Sherpa 1.3.0, Vincia 1.026 (without uncertainty bands, NLL/NLC=OFF)
Additional Sources of Particle Production

\[ Q_F \gg \Lambda_{QCD} \]

\( \text{ME+ISR/FSR} \)

\(+\) perturbative MPI

\[ Q_F \sim \Lambda_{QCD} \]

Multiple (perturbative) parton-parton Interactions occurring in each single hadron-hadron collision

→ underlying event

(distinct from pile-up caused by high lumi)
Additional Sources of Particle Production

\[ Q_F \gg \Lambda_{QCD} \]
ME+ISR/FSR
+ perturbative MPI

\[ Q_F \sim \Lambda_{QCD} \]

Stuff at

Multiple (perturbative) parton-parton Interactions occurring in each single hadron-hadron collision → underlying event
(distinct from pile-up caused by high lumi)

Need-to-know issues for IR sensitive quantities (e.g., N\text{\text{ch}})

22
Hadronization
Hadronization

The problem:

- Given a set of partons resolved at a scale of \( \sim 1 \) GeV (the shower + MPI cutoff), need a "mapping" from this set onto a set of on-shell colour-singlet hadronic states.
- I.e., a fully exclusive fragmentation function defined at \( Q_{\text{Had}} \sim 1 \) GeV
Hadronization

The problem:

• Given a set of partons resolved at a scale of ~ 1 GeV (the shower + MPI cutoff), need a “mapping” from this set onto a set of on-shell colour-singlet hadronic states.

• I.e., a fully exclusive fragmentation function defined at $Q_{\text{Had}} \sim 1$ GeV

MC models do this in three steps

1. Map partons onto continuum of highly excited hadronic states (called ‘strings’ or ‘clusters’)

2. Iteratively map strings/clusters onto discrete set of primary hadrons (string breaks / cluster splittings / cluster decays)

3. Sequential decays into secondary hadrons (e.g., $\rho > \pi\pi$, $\Lambda > n\pi0$, $\pi0 > \gamma\gamma$, ...)
The problem:

- Given a set of partons resolved at a scale of ~ 1 GeV (the shower + MPI cutoff), need a “mapping” from this set onto a set of on-shell colour-singlet hadronic states.
- I.e., a fully exclusive fragmentation function defined at $Q_{\text{Had}} \sim 1$ GeV

**MC models** do this in three steps

1. Map partons onto **continuum of highly excited hadronic states** (called ‘strings’ or ‘clusters’)
2. Iteratively map strings/clusters onto **discrete set of primary hadrons** (string breaks / cluster splittings / cluster decays)
3. Sequential decays into **secondary hadrons** (e.g., rho $\rightarrow$ pi pi, Lambda $\rightarrow$ n pi0, pi0 $\rightarrow$ gamma gamma, ...)

Hadronization
From Partons to Strings

Short Distances ~ pQCD

Long Distances ~ Linear Confinement

Partons

Strings (Flux Tubes), Hadrons

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]
From Partons to Strings

- Motivates a model:
  - Separation of transverse and longitudinal degrees of freedom
  - Simple description as 1+1 dimensional worldsheet – string – with Lorentz invariant formalism

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \iff V(r) \approx \kappa r \]
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
Details of string breaks more complicated
Conclusions

• **QCD Phenomenology** is witnessing a rapid evolution: LO & NLO matching, better showers, tuning, interfaces ...
  - Driven by demand for high precision in complex LHC environment with huge phase space

• BSM Physics
  - Generally relies on chains of tools (MC4BSM)
  - Sufficient to reach O(10%) accuracy, with hard work, though must be careful with scale hierarchies, width effects, decay distributions, …
  - Next machine is a long way off → must strive to build capacity for yet higher precision, to get max from LHC data.

• **Ultimate limit set by solutions to pQCD** (getting better) and then the **really** hard stuff
  - Like Hadronization, Underlying Event, Diffraction, … (& BSM equivalents?)
  - For which fundamentally new ideas may be needed

For more, see the *MCnet Review: General-purpose event generators for LHC physics* : arXiv:1101.2599