Event Generation

A Brief & Vague description

Components

1. Parton Shower
    - (FSR) Final State Radiation
    - (ISR) Initial State Radiation
2. Multiple Parton Interactions
3. Matrix Elements
    - Coherence
    - Matching
4. Hadronization
    - String Fragmentation
    - Color Reconnection
5. Generators

Parton Shower

- Simplest Model: Splitting comes from a specific parton and does not include coherent interference.
- Tree Level QCD: Interactions are taken from the Lagrangian.
  - q⇒g q & q-bar⇒g q-bar (co-linear divergence & angular interference)
  - g⇒gg (co-linear divergence & angular interference)
  - g⇒q q-bar (flavor dependency)
  - g⇒g g g (ignored in shower, since coupling is α_S^2 rather than α_S)
- Co-linear gauge boson emission has an infrared divergence.
  - The divergence is interpreted as the gauge field surrounding the parton.
  - Applying a cutoff is analogous to including the surrounding field.
- Partons departing from an interaction have E >> p_T and shower back to E ~ p_T. ("Timelike" shower yielding Final State Radiation)
- Partons arriving at an interaction have p_T >> E and shower back to E ~ p_T. ("Spacelike" shower yielding Initial State Radiation.)

Parton Shower

- Given one off-shell parton the goal is to calculate the collection of near-shell partons into which it will shower.
- Calculate the 1→2 splitting as a function of:
  - Energy partitioning (z)
  - Spin orientations (s)
  - Color flow (c)
  - Energy scale (off-shell measure)
  - Opening angle
- Sum over configuration parameters (s, c, z, split type...) to find the splitting probability.
- Except for a single parameter t with respect to which the shower is generated. (Random Step)

$$dP_{a\to bc}(t,z,s,c) = \frac{dt}{t}\frac{\alpha_S(t)}{2\pi}\rho_{a\to bc}(t,z,s,c)dz$$

Parton Shower: FSR

- Sudakov Factor $P_{a\to a}(t_1,t_2)$: Probability to evolve from t_1 to t_2 without splitting.

$$dP_{a\to a}(t) = (1 - \int_{bc,s,c,z} dP_{a\to bc}(t,s,c,z)) \Rightarrow P_{a\to a}(t_1,t_2) = e^{-\int_t^{[t_1,t_2]} \int_{bc,s,c,z} dP_{a\to bc}(t,s,c,z)}$$

$$P_{a\to a}(t_1,t_2) = \frac{P_{a\to a}(t_0,t_2)}{P_{a\to a}(t_0,t_1)} = R \in [0,1]$$

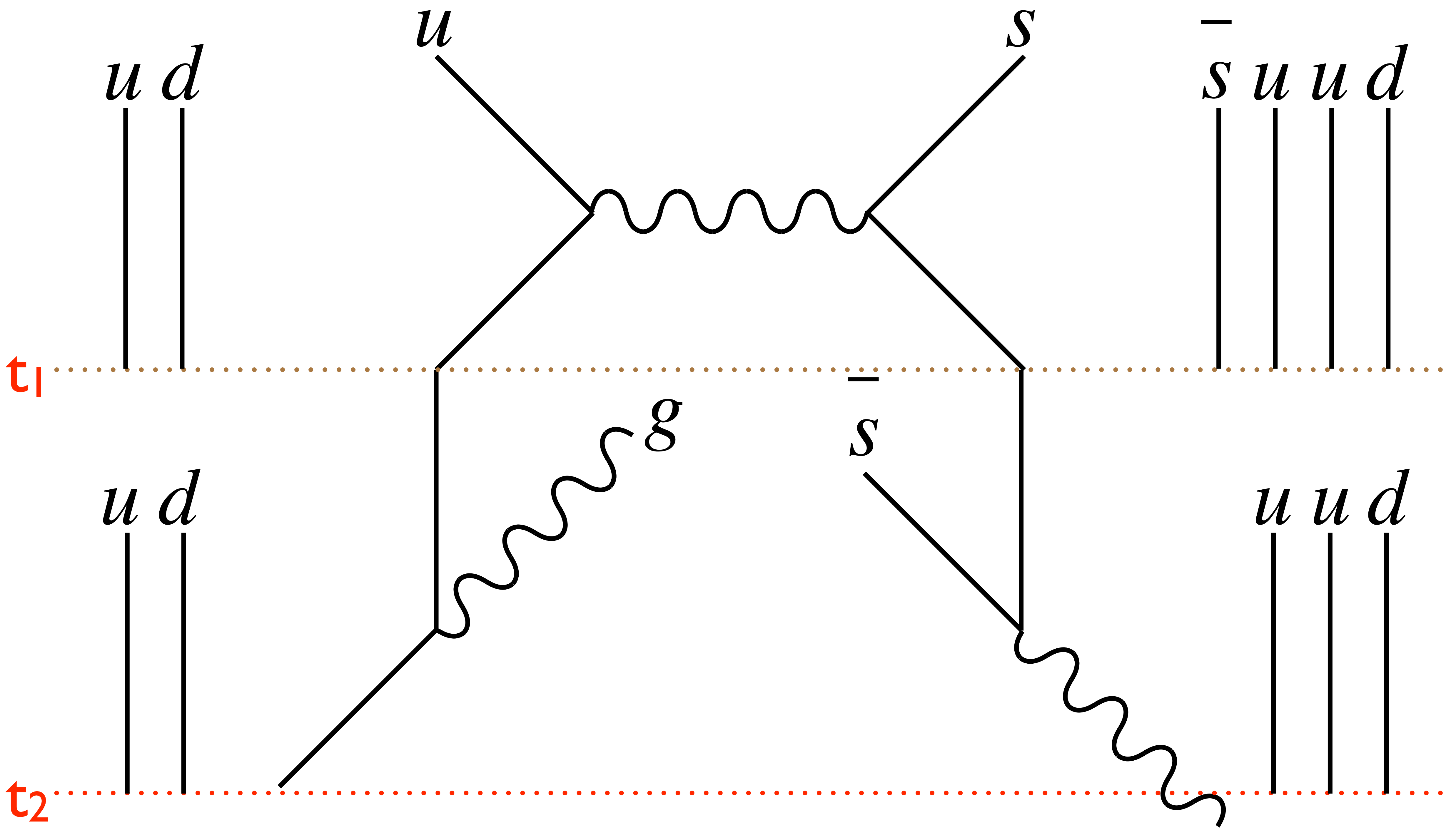
- Random Step: At t_1 Choose R and solve for t_2.
- Cutoff at Λ_{QCD}.
  - Analogous to IR cutoff for QED
  - String formation (hadronization) cutoff for QCD, independent of IR cutoff.
- Coherent Effects:
  - Herwig: A first approximation is that a g emitted following a q q-bar or g g split must have a smaller opening angle.
  - Pythia: Optionally apply a veto to enforce opening angle ordering.
  - Ariadne: A more accurate method is to consider the shower to be a succession of dipoles. However g → q q-bar does not involve interference.

Parton Shower: ISR

- Sudakov Factor: calculated from the probability that the incoming parton actually came from ...
  - Requires knowing the distribution of a reservoir of partons at a given scale t.
- If a parton's parent was of a different type then the reservoir distribution must be updated accordingly.
- DGLAP: Evolve the modified collection of partons to a lower energy.

$$t\frac{\partial}{\partial t}f_a(x,t)=\sum_{b,c}\int_{z}^{[x,1]}\frac{1}{z}\frac{\alpha_S}{2\pi}P_{a\to bc}(z,t)f_b(\frac{x}{z},t)$$

- Result: Ladder of partons connecting the proton PDF to the hard scatter.
- FSR showers can originate from ISR partons.


u
s
u d
s̄ u u d
t1
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Multiple Parton Interactions

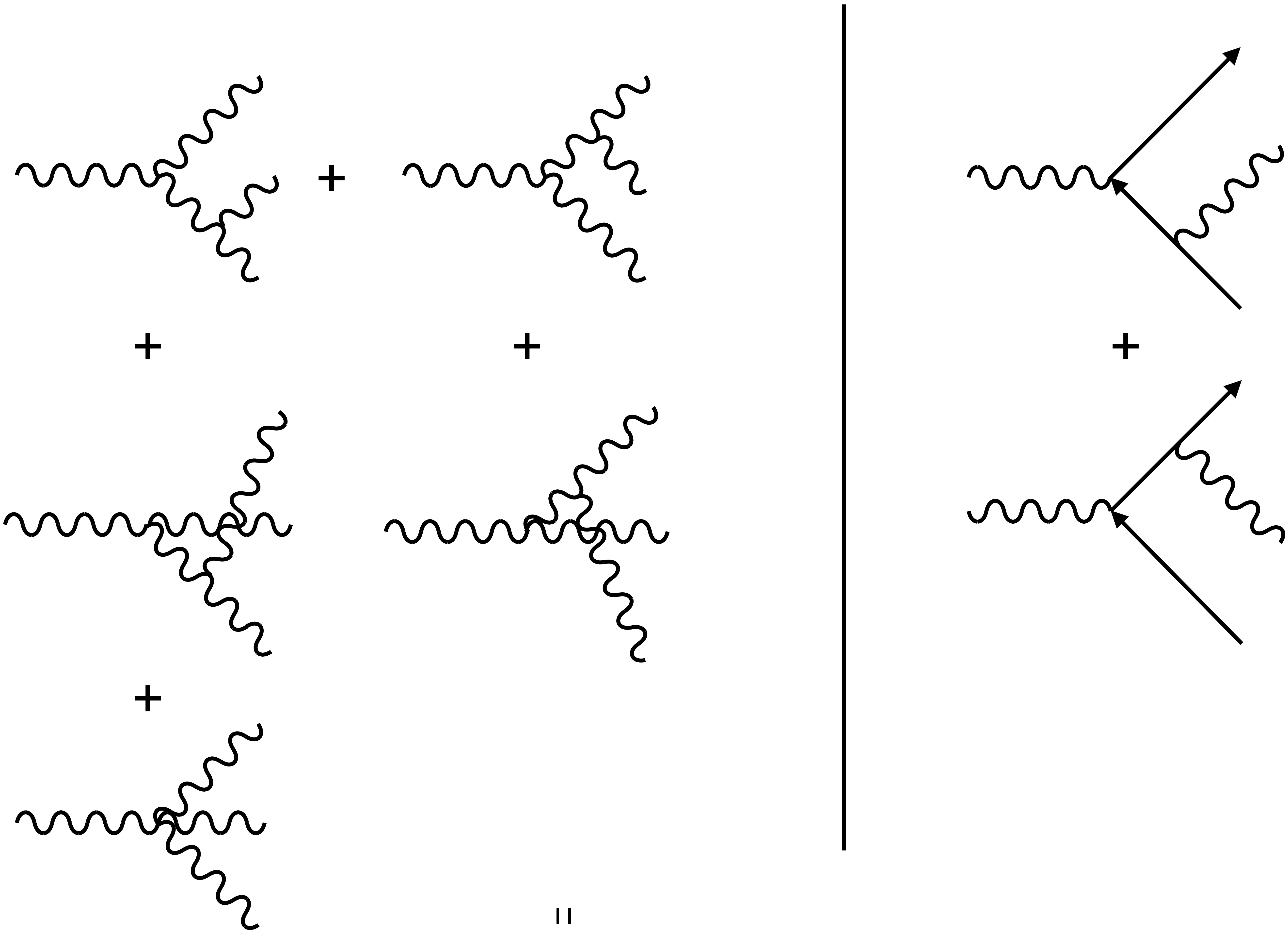
- Minimum Bias Observations:
- Low Energy: Independent Production
  - ➡ Poisson distribution.
  - ➡ Probably from fragmentation.
- Middle Energy: Memoryless Production
  - ➡ Negative Binomial Distribution.
  - ➡ More exponential implies shower contribution.
- High Energy: Correlated Production
  - ➡ An above average number of particles in a partial count is correlated to an above average number of particles in the remaining count.
  - ➡ Each interaction implies an increased probability of further interactions.

Multiple Parton Interactions

- Jimmy Model: Independent Interactions - Highest LHC prediction
    - Poisson distribution for a given:
        - Collision energy: FIXED
        - Impact parameter: VARIABLE ⇒ CORRELATION
- Pythia Model: Interleaved MPI & ISR - Middle LHC prediction
    - Interactions draw from the ISR modified PDF and likewise modify the particle content.
    - All interactions can be sources of ISR.
    - Interaction probability depends on:
        - PDF at the ISR scale, which is set by the hard scatter, which has a collision energy dependent cross-section.
        - Collision impact parameter. Current data are fit by a double gaussian.
- PhoJet Model: Cut Reggeons & Pomerons - Lowest LHC prediction
    - Interaction probability is set by elastic & diffractive scattering.
    - Pomeron exchange dominates at high energies ⇒ p p-bar and p p will have similar soft backgrounds.
    - A cut Reggeon yields one string, while a cut Pomeron yields two strings.

Matrix Elements

- A high energy q q → q q interaction has a distribution of final states that includes coherent interference and exchange rules.
- Higher order interactions will include loops and higher numbers of partons in the final state.
- Running coupling & spin effects can be included explicitly in the splitting distribution.
- Coherence can be included in the shower (Ariadne, Photos)
- Next order: Include the (gauge invariance required) $(\alpha_S)^2$ 4 gluon vertex.
- Next order: radiated gluon exchange follows boson rules.



Matrix Elements: Matching

- Problem: Given a 2 → 2 interaction with FSR, one can reinterpret the diagram as a different 2 → 2 interaction with ISR.
  - Resolution: With respect to the shower parameters (t, x), the matrix element is the maximum value in the shower.
- Problem: Given a matrix element to order $(\alpha_S)^4$ that yields a 2 → 2 interaction there was also a probability for a 2 → 4 interaction.
  - FSR beginning from the 2 → 2 interaction could yield a state identical to that reached by the 2 → 3 interaction.
  - Solution: MLM requires that hard scatter partons be matched to distinct jets, otherwise a veto is applied to the whole event. (Implies wide angle matrix elements and narrow showers.)
  - Solution: CKKM requires that a shower back to a 2 → 2 interaction inferred from a final state configuration have a suitably high probability.
  - Pythia: Re-weight the first emission from an interaction (say W production) in order to match the full matrix element.
  - Herwig: An angular ordered shower comes with a dead zone, which is populated using the matrix element. In addition the highest energy interaction (not known until the entire shower is generated) is corrected using a reweighting.

Matrix Elements: Matching

- General method (the GenEvA framework):
  - In General: It is necessary to choose a projection from the phase space of a higher number partons to those with a lower number of partons.
  - Solution: This is precisely what the jet finding cluster algorithms do! (This is the basis for both the MLM and CKKW schemes.)
    - ★ P_T ordered shower ~ k_T projection ~ DGLAP higher energy
    - ★ Angular ordered shower ~ Cambridge/Aachen projection ~ BFKL middle energy
    - ★ Boost ordered fragmentation ~ Anti-k_T projection ~ Topological expansion low energy
  - Warning: This is NOT a reconstruction. A projection applied to a shower with ISR & MPI will infer a single shower.
  - Warning: A parton pair might have no candidate parent particle, or might not have a unique parent.
  - In the case of a $2 \rightarrow 3$ interaction the projection artificially associates the 3 parton states with unique preceding 2 parton states.
  - A shower parameter starting cut applied to the $2 \rightarrow 3$ matrix element projects back to a shower starting cut for the $2 \rightarrow 2$ states.

Hadronization

- Concept: a color-neutral q q-bar pair are connected by a “string” so that the field energy increases linearly with separation.
  - Loop calculation of static field when all quark masses are > Λ_{QCD}.
  - Topological expansion for low energy non-Abelian fields.
- Fragmentation: string energy is used to create q q-bar pairs.
  - The naïve probability distribution is constrained by the requirement of causal-independence.
  - This must be modified by the requirement that the string fragments consist of on-shell hadrons.
- Baryons: A diquark has anti-quark color, and can be a string end, or a q q-bar can be inserted along a string.
- Gluons are associated with “kinks” in the string.
  - Gluons from the shower are assigned to various strings. These can be associated with jets having a characteristically broader shape.
  - The background of soft gluons are incorporated as a distribution of momentum transverse to the string. This is associated with the standard jet constituent distribution.
- Clusters: Force all gluons to split to q q-bar pairs in the shower. Instead of “strings” one is left with clustered q q-bar pairs.
  - This method is used by Herwig, where there is the advantage of having no prior energy assignment.

Hadronization: Color Reconnection

- Motive: Randomly generating the color of partons based on the shower structure yields a distribution of hadrons that are too numerous at lower p_T.
- Observation: If the strings were shorter the same energy would be shared by fewer hadrons, yielding the observed distributions.
  - This observation is made by looking at the dN / dp_T spectrum above some minimum trackable p_T.
  - The mean p_T of partons is sensitive to color reconnection tuning.
- Resolution: introduce a probability of swapping colors to a configuration with shorter strings.
  - This can be justified by noting that soft gluon exchange becomes increasingly likely, and will preferentially minimize string lengths.

Generators

- Pythia
  - FSR, ISR and MPI are all p_T ordered.
  - MPI uses double gaussian impact parameterization.
  - Matrix Element Matching by re-weighting.
  - Hadronization by Lund string fragmentation.
- Herwig
  - FSR, ISR are angle ordered.
    - MPI added as background distribution, with negative binomial parameterization.
  - Matrix Element Matching by re-weighting.
  - Hadronization by cluster fragmentation.
- Shower Alternatives:
  - Ariadne & LDC (for Pythia): QCD Dipole radiation of FSR & ISR respectively.
  - Photos (takes HEPEVT input): Coherent showering for QED & EW production.

Generators

- MPI Alternatives:
  - PhoJet (for Pythia): Pomeron & Reggeon cuts.
  - Jimmy (for Herwig): Independent MPI with impact parameter correlation.
- Matrix Elements
  - MadGraph (yields LesHouches description): Tree level matrix element calculation.
  - AcerMC (for Pythia, Herwig, Ariadne): library of MadGraph matrix elements.
  - AlpGen (for Pythia, Herwig): library of standard model matrix elements.
- Decays
  - Tauola (for Photos): Tau decays.
  - Horace (for Photos): EW decays to one loop.
  - EvtGen (takes STDHEP input): Beauty decays.
- Higher Orders
  - MC@NLO (for Herwig): Matrix element matching with negative weights.
  - Sherpa (for Pythia): Takes matrix elements (AMEGIC) and matches to parton showers (APACIC) using CKKW.
  - GenEvA: It doesn't exist yet.

Generators

- Diffraction:
  - PhoJet (for Pythia): Pomeron & Reggeon exchange, using the same parameterization as for inelastic collisions.
  - ExHuMe (for Pythia): Gluon fusion with possible Higgs production.
  - DPEMC (for Herwig): Double pomeron exchange with possible Higgs production.
- Site Specific Overlays
  - BeamHaloGen
  - CavernBkgGenerator
  - CosmicForAtlas
- Heavy Ion Collisions
  - HIJinG: Heavy Ion Collisions
  - Nexus3: Heavy Ion Fragmentation fluid model followed by string fragmentation.
- Beyond the Standard Model... if you want it then you find it!