Introduction to Monte Carlo Event Generation
Lecture 2: Parton Showers

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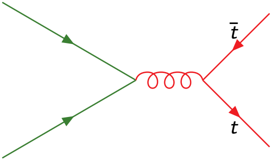
Introduction

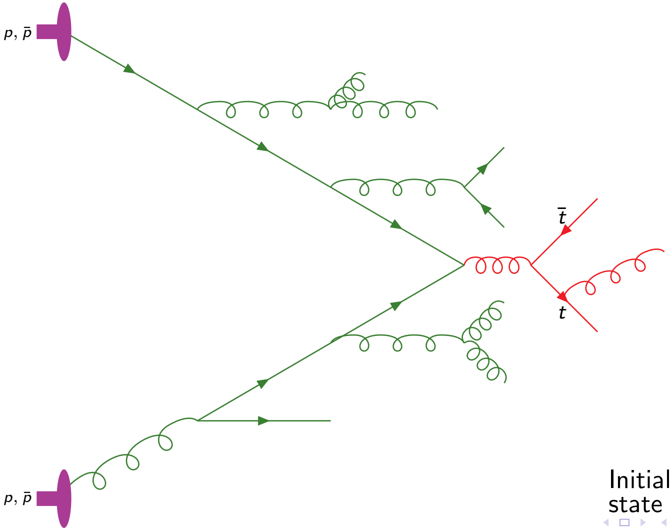
- In classical and quantum electrodynamics accelerated charges radiate.
- Similarly in QCD accelerated colour charges radiate.
- This gives a cascade of quarks and gluons, the parton shower

A Monte Carlo Event



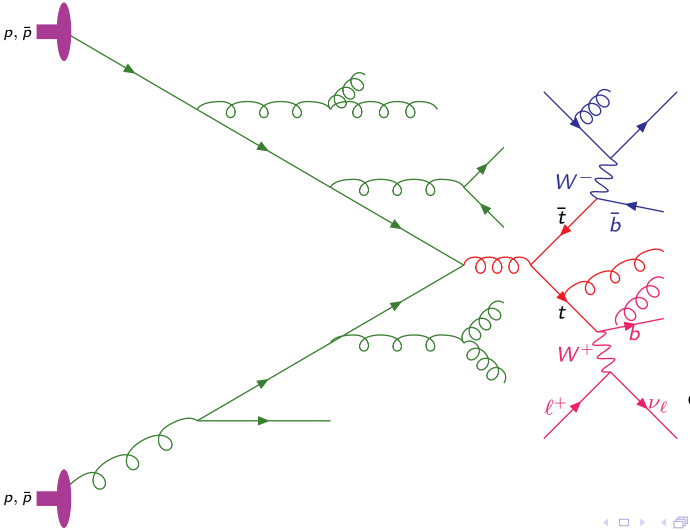
Hard Process, usually calculated at leading order

A Monte Carlo Event



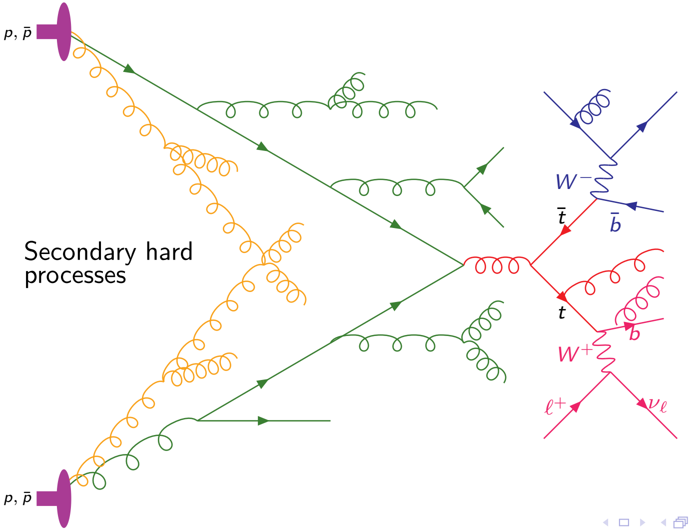
Initial- and final-state parton shower

A Monte Carlo Event

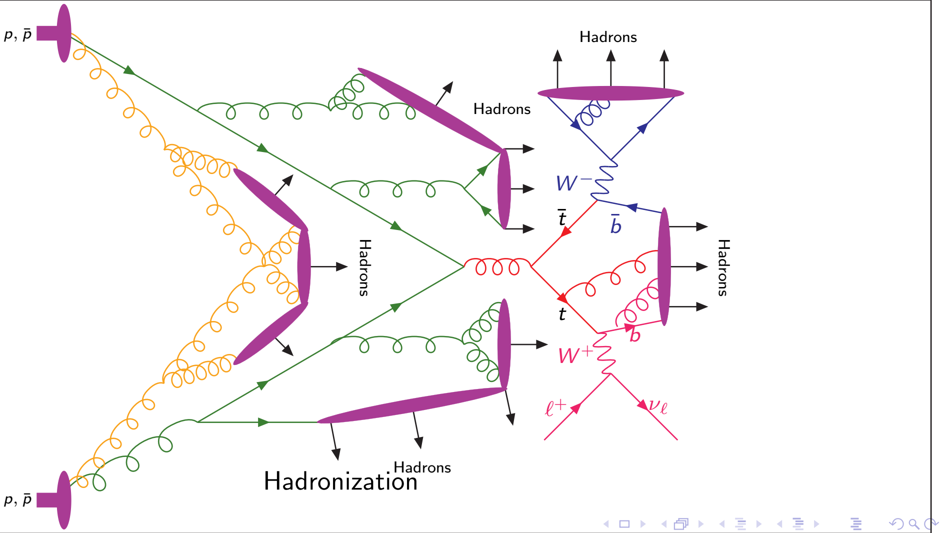


Perturbative decays of heavy particles

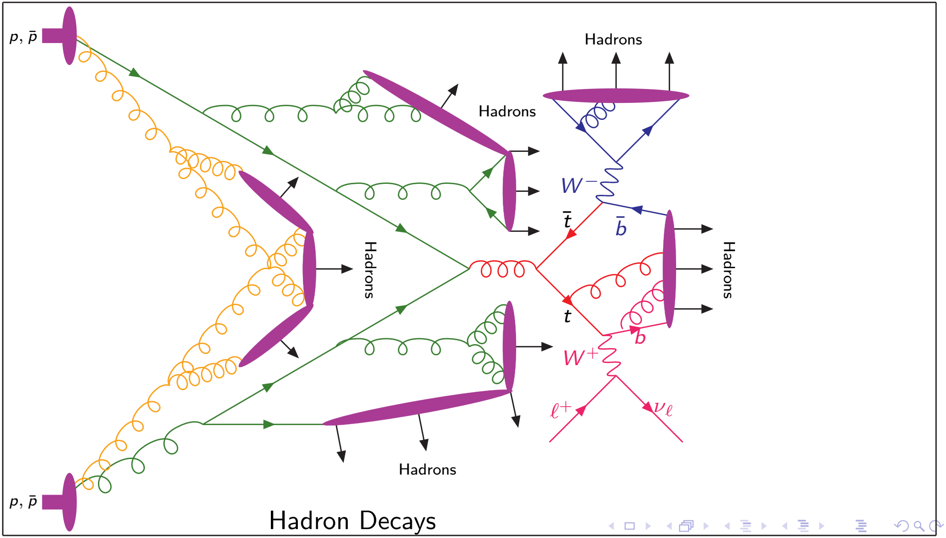
A Monte Carlo Event



A Monte Carlo Event



A Monte Carlo Event



Plan

- Infrared divergences.
- Colinear Emission.
- Sudakov Form Factors.
- Soft emission and colour coherence.
- Initial-State radiation.
- Heavy quarks.
- Dipole cascades.
- Intrinsic $p_\perp$

Gluon Emission

- Let's start with the simplest possible gluon emission process, *i.e.* $e^+e^- \to q\bar{q}g$.

- The total cross section is

$$\sigma(e^+e^- \to q\bar{q}g) \quad = \quad \sigma_0 C_F \frac{\alpha_S}{2\pi} \int \mathrm{d}x_1 \mathrm{d}x_2 \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)},$$

where $x_i \equiv 2p_i/\sqrt{s}$ and $\sigma_0 = \sigma(e^+e^- \to q\bar{q})$.

- Divergent at the edge of phase space as $x_{1,2} \to 1$ so that the total cross section is $\sigma = \infty$!

Gluon Emission

- Common feature of all perturbative QCD calculations.
- Configurations which are indistinguishable from the leading-order result are divergent.
- Physically there are two regions where this happens
  1. Colinear limit: $x_1 \to 1$ at fixed x_2 or $x_2 \to 1$ at fixed x_1

$$2p_2{\cdot}k = \frac{sx_2x_3}{2}(1-\cos\theta_{23}) = s(1-x_1) \Rightarrow (1-\cos\theta_{23}) = \frac{2(1-x_1)}{x_2x_3} \to 0.$$

  2. Soft limit: $x_{1,2} \to 1$ at fixed $\frac{1-x_1}{1-x_2}$

$$E_g = \frac{\sqrt{s}}{2}x_3 = \frac{\sqrt{s}}{2}(1-x_1+1-x_2) \to 0.$$

- Both universal features of QCD matrix elements.

Colinear Limit

- If we take k parallel to p_2 $(\theta_{23} = 0)$ we can define

$$p_2 = (1-z)\bar{p}_2, \qquad k = z\bar{p}_2, \qquad \text{with} \quad \bar{p}_2^2 = 0.$$

- In this limit the matrix element factorizes

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 \times \frac{g_s^2}{p_2 \cdot k} \times C_F \frac{1+(1-z)^2}{z}.$$

- As does the phase space

$$\mathrm{d}x_1 \mathrm{d}x_2 \longrightarrow \frac{1}{4} z(1-z)\mathrm{d}z\mathrm{d}\theta_{23}^2.$$

Colinear Limit

- Putting this together

$$\sigma = \sigma_0 \int \frac{\mathrm{d}\theta_{23}^2}{\theta_{23}^2} dz C_F \frac{\alpha_S}{2\pi} \frac{1+(1-z)^2}{z}.$$

- The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi splitting function is a universal probability distribution for the radiation of a colinear gluon in any process producing a quark.
- Exactly same form for anything proportional to θ^2, *e.g.*
  - transverse momentum $k_\perp^2 = z^2(1-z)^2\theta^2$;
  - invariant mass $q^2 = z(1-z)\theta^2 E^2$.

such that

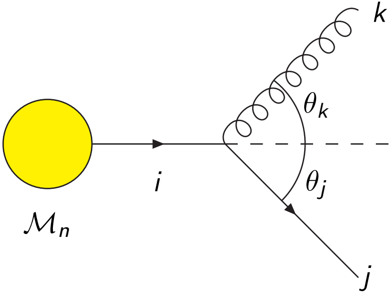
$$\frac{\mathrm{d}\theta^2}{\theta^2} = \frac{\mathrm{d}k_\perp^2}{k_\perp^2} = \frac{\mathrm{d}q^2}{q^2}$$

Parton Shower

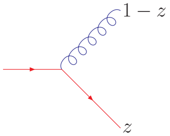
- The simulation of QCD radiation is based this factorization, *i.e*

$$d\sigma_{n+1} = d\sigma_n \frac{d\theta^2}{\theta^2} dz \frac{\alpha_S}{2\pi} P_{ji}(z)$$

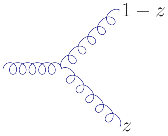
where the splitting function only depends on the spin and flavour of the partons.



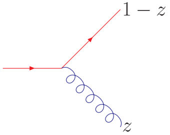
Splitting Functions



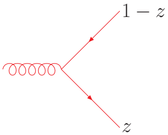
$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$$



$$P_{g\to gg}(z) = C_A \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right]$$



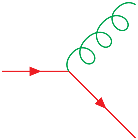
$$P_{q\to gq}(z) = C_F \frac{1+(1-z)^2}{z}$$



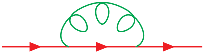
$$P_{g\to q\bar{q}}(z) = T_R \left[z^2 + (1-z)^2\right]$$

Parton Shower

- This expression is singular as $\theta \to 0$.
- What is a parton? (or what is the difference between a colinear pair and a parton).
- Introduce a resolution criterion, e.g. $k_\perp > Q_0$.
- Combine the virtual corrections and unresolvable emission



Resolvable Emission
Finite



Unresolvable Emission
Finite

- Unitarity: Unresolved + Resolved $=1$

Sudakov Form Factor

- We can then exponentiate the real emission piece

$$
\begin{aligned}
\mathcal{P}(\mathrm{unresolved}) &= 1-\mathcal{P}(\mathrm{resolved}), \\
&= 1-\int_{q^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}}\mathrm{d}z\frac{\alpha_S}{2\pi}P(z), \\
&= \exp\left(-\int_{q^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}}\mathrm{d}z\frac{\alpha_S}{2\pi}P(z)\right).
\end{aligned}
$$

- The Sudakov form factor which is the probability of evolving between two scales and emitting no radiation.
- More strictly it is the probability of evolving from a high scale to the cut-off with no resolvable emission.

Sudakov Form Factor

- More formally, the probability of emission between $\mathrm{d}q^2$ and $q^2+\mathrm{d}q^2$ is

$$\mathrm{d}\mathcal{P} = \frac{\mathrm{d}q^2}{q^2}\int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}} \mathrm{d}z \frac{\alpha_S}{2\pi}P(z)$$

- We can then write a differential equation for the evolution of the probability of no-emission between Q^2 and q^2, $\Delta(Q^2,q^2)$

$$\mathrm{d}\Delta(Q^2,q^2) = \Delta(Q^2,q^2)\mathrm{d}\mathcal{P} \;\Rightarrow\; \frac{\mathrm{d}\Delta(Q^2,q^2)}{\Delta(Q^2,q^2)} = \frac{\mathrm{d}q^2}{q^2}\int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}} \mathrm{d}z \frac{\alpha_S}{2\pi}P(z)$$

giving

$$\Delta(Q^2,q^2) = \exp\left(-\int_{q^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}} \mathrm{d}z \frac{\alpha_S}{2\pi}P(z)\right)$$

Numerical Procedure

Radioactive Decay

- Start with an isotope.
- Work out when it decays by generating a random number $R\exists[0,1]$ and solving

$$R = \exp\left[-\frac{t}{\tau}\right],$$

  where τ is its lifetime.
- Generate another random number and use the branching ratios to find the decay mode.
- Generate the decay using the masses of the decay products and phase space.
- Repeat the process for any unstable decay products.
- This algorithm is actually used in Monte Carlo event generators to simulate particle decays.

Parton Shower

- Start with a parton at a high virtuality, Q, typical of the hard collision.
- Work out the scale of the next branching by generating a random number $R\exists[0,1]$ and solving

$$R = \Delta(Q^2, q^2),$$

  where q is the scale of the next branching.
- If there's no solution for $q > Q_0$ then stop.
- Otherwise workout the type of branching.
- Generate the momenta of the decay products using the splitting functions.
- Repeat the process for the partons produced in the branching.

Veto Algorithm

- Usually we cannot easily solve $\Delta(Q^2, q^2) = \mathcal{R}$.
- Instead we start by picking an overestimate $P_{\rm over}(z) \geq P(z)$ which is easily invertible, *i.e.* we can calculate $H(z) = \int P_{\rm over}(z){\rm d}z$ and $H^{-1}(z)$.
- Also overestimate of the integration region $z^{\rm over}_{\rm min} \leq z_{\rm min}$ and $z^{\rm over}_{\rm max} \geq z_{\rm max}$, and the maximum value of α_S, $\alpha^{\rm over}_S \geq \alpha_S(p_\perp(q^2, z)) \;\forall\; z, q^2$.
- We now have an overestimate of the integrand of the Sudakov form factor, *i.e.*

$$F(k^2) = \frac{1}{k^2}\int_{z_{\rm min}}^{z_{\rm max}} {\rm d}z \frac{\alpha_S}{2\pi} P_(z) \;\; \rightarrow \;\; G(k^2) = \frac{1}{k^2}\int_{z^{\rm over}_{\rm min}}^{z^{\rm over}_{\rm max}} {\rm d}z \frac{\alpha^{\rm over}_S}{2\pi} P_{\rm over}(z)$$

Veto Algorithm

- We can solve this to get a first trial value of q^2

$$\ln\mathcal{R} = -\int_{q^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\int_{z_{\min}^{\mathrm{over}}}^{z_{\max}^{\mathrm{over}}}\mathrm{d}z\frac{\alpha_S^{\mathrm{over}}}{2\pi}P_{\mathrm{over}}(z) \Rightarrow \quad q^2 = Q^2\exp\left(\frac{\ln\mathcal{R}}{\int_{z_{\min}^{\mathrm{over}}}^{z_{\max}^{\mathrm{over}}}\mathrm{d}z\frac{\alpha_S^{\mathrm{over}}}{2\pi}P_{\mathrm{over}}(z)}\right)$$

- However we cannot do simple accept/reject
- Instead generate a value of z using

$$z = H^{-1}\left[H(z_{\min}^{\mathrm{over}}) + \mathcal{R}(H(z_{\max}^{\mathrm{over}}) - H(z_{\min}^{\mathrm{over}}))\right]$$

- We reject the emission if z is outside the true limits or with probability

$$\frac{F(q^2)}{G(q^2)} = \frac{\frac{\alpha_S}{2\pi}P(z)}{\frac{\alpha_S^{\mathrm{over}}}{2\pi}P_{\mathrm{over}}(z)} \geq \mathcal{R}$$

if z is inside the true limits but if the try is rejected start again with $Q^2 = q^2$ and generate another try.

Veto Algorithm

If we define $\mathcal{P}_n(q^2)$ to be probability we accept q^2 after rejecting n attempts then the probability of generating q^2 is $\sum_{n=0}^{\infty} \mathcal{P}_n(t)$, where

$$\mathcal{P}_0(q^2) = G(q^2)\Delta^{\rm over}(Q^2,q^2)\frac{F(q^2)}{G(q^2)} = \Delta^{\rm over}(Q^2,q^2)F(q^2)$$

$$\mathcal{P}_1(q^2) = \int_{q'^2}^{Q^2} {\rm d}q'^2 G(q'^2)\Delta^{\rm over}(Q^2,q'^2)\left[1-\frac{F(q'^2)}{G(q'^2)}\right] G(q^2)\Delta^{\rm over}(q'^2,q^2)\frac{F(q^2)}{G(q^2)}$$

$$= F(q^2)\Delta^{\rm over}(Q^2,q^2)\int_{q^2}^{Q^2} {\rm d}q'^2 \left(G(q'^2)-F(q'^2)\right)$$

$$\ldots$$

$$\mathcal{P}_n(q^2) = \frac{1}{n!}F(q^2)\Delta^{\rm over}(Q^2,q^2)\left[\int_{q^2}^{Q^2} {\rm d}q'^2 \left(G(q'^2)-F(q'^2)\right)\right]^n$$

Veto Algorithm

- Summing

$$\sum_{n=0}^{\infty}\mathcal{P}_n(t) = F(q^2)\Delta^{\rm over}(Q^2,q^2)\sum_{n=0}^{\infty}\left[\int_{q^2}^{Q^2}\mathrm{d}q'^2\left(G(q'^2)-F(q'^2)\right)\right]^n$$
$$= F(q^2)\Delta^{\rm over}(Q^2,q^2)\exp\left[\int_{q^2}^{Q^2}\mathrm{d}q'^2\left(G(q'^2)-F(q'^2)\right)\right]$$
$$= F(q^2)\exp\left[-\int_{q^2}^{Q^2}\mathrm{d}q'^2\,G(q'^2)\right]\exp\left[\int_{q^2}^{Q^2}\mathrm{d}q'^2\left(G(q'^2)-F(q'^2)\right)\right]$$
$$= F(q^2)\Delta^{\rm over}(Q^2,q^2)$$

as required.

Monte Carlo Procedure

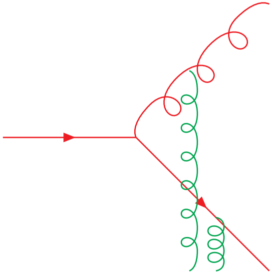
The key difference between the different Monte Carlo simulations is in the choice of the evolution variable.

- Evolution Scale
  - Virtuality, q^2
  - Transverse Momentum, $k_\perp$
  - Angle, θ
- Energy fraction, z
  - Energy fraction
  - Light-cone momentum fraction
  - ...

Are all the same in the colinear limit.

Soft Emission

- We have only considered colinear emission. What about soft emission?
- Soft gluons come from all over the event.
- There is quantum interference
- Does this spoil the parton shower picture?



Soft Limit

- In the limit that $E_g \to 0$ the matrix element for the $e^+e^- \to q\bar{g}$ factorizes

$$\mathcal{M}_{q\bar{q}g} = \mathcal{M}_{q\bar{q}} g_s t^a_{ij} \left(\frac{p_1}{p_1 \cdot k} - \frac{p_2}{p_2 \cdot k} \right) \cdot \epsilon_A(k).$$

- Called the Eikonal Current.
- The matrix element squared therefore factorizes in this case

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 g_s^2 C_F \frac{2p_1 \cdot p_2}{p_1 \cdot k p_2 \cdot k}.$$

- In this case the phase space is

$$\mathrm{d}x_1 \mathrm{d}x_2 \longrightarrow \frac{2}{s} E_g \mathrm{d}E_g \mathrm{d}\cos\theta.$$

Soft Limit

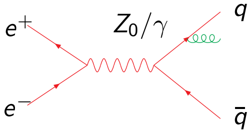
- So in the soft limit

$$\sigma = \sigma_0 \int C_F \frac{\alpha_S}{2\pi} \frac{\mathrm{d}E_g}{E_g} \mathrm{d}\cos\theta \frac{2(1-\cos\theta_{qq})}{(1-\cos\theta_{qg})(1-\cos\theta_{\bar{q}g})}.$$

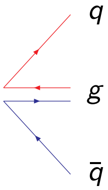
- Gives the Dipole Radiation pattern.
- Universal probability distribution to emit a soft gluon from any colour-connected pair of partons.
- Only universal at the amplitude level

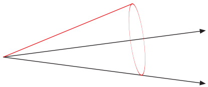
Angular Ordering

- In the soft limit the matrix element factorizes but at the amplitude level.
- The remarkable result is that if we take the large number of colours limit much of the interference is destructive.
- In particular if we consider the colour flow in an event.
- QCD radiation only occurs in a cone up to the direction of the colour partner.
- The best choice of evolution variable is therefore an angular one

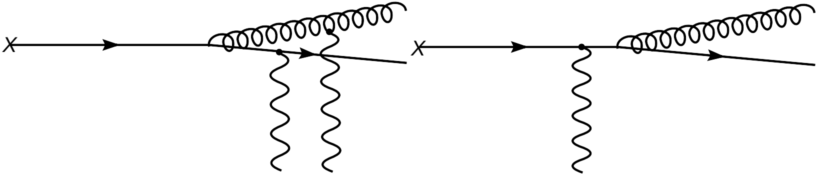


Feynman Diagram





Colour Coherence



- Wide angle soft gluons cannot resolve the difference between a gluon and "colinear" quark and gluon with the same quantum numbers.
- Called Colour Coherence
- Angular ordering is one way of including this physics, but there are others.

Accuracy of Parton Shower simulations

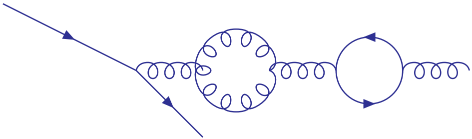
- Formally the parton shower is accurate to leading log.

$$\Delta(Q^2, Q_0^2) \approx \exp\left[-C_F \frac{\alpha_S}{2\pi} \ln^2\left(\frac{Q^2}{Q_0^2}\right)\right]$$

- However Monte Carlo simulations include a number of subleading effects.
- The most important is the conservation of energy and momentum.
- Others include the choice of the scale for α_S.

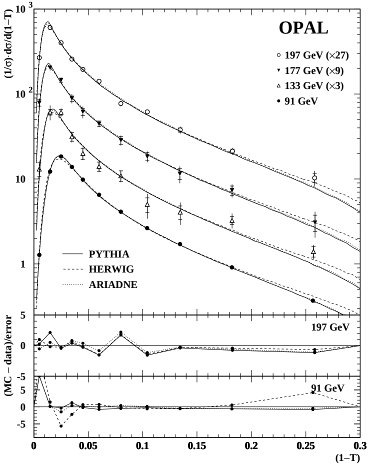
Running Coupling

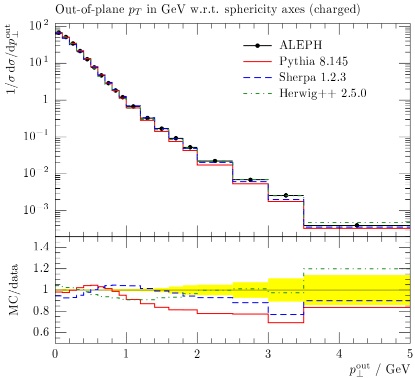
- Some of the higher order effects are included by



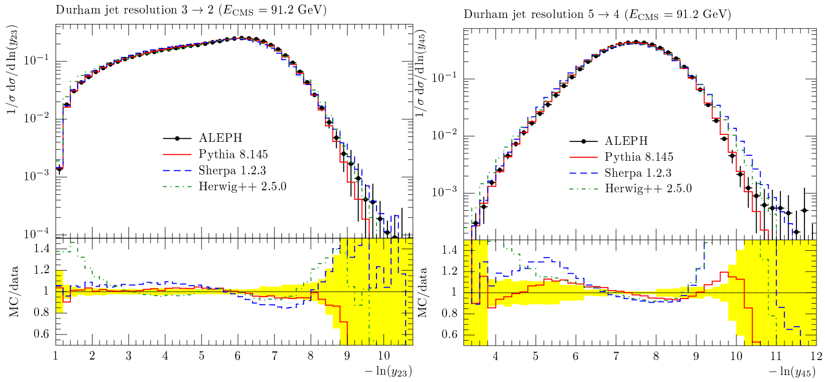
  replacing $\alpha_S \rightarrow \alpha_S(k_\perp^2)$
- Gives more emission as $k^2 \rightarrow Q_0^2$. The phase space fills with soft gluons.
- Must avoid the Landau pole $K_\perp^2 \gg \Lambda^2$ so that Q_0^2 becomes a physical parameter.

LEP Event Shapes

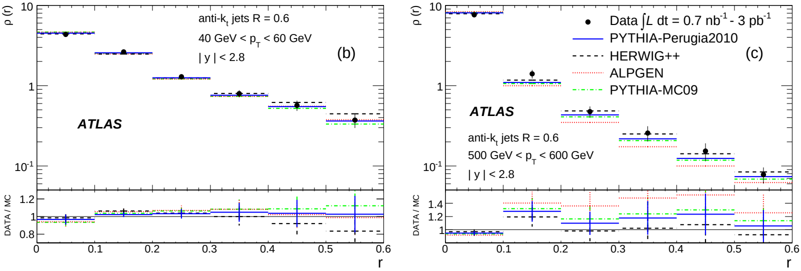




LEP Jet Resolution



Jet Shapes



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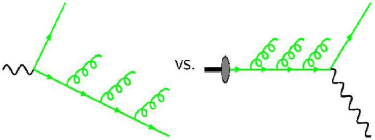
Hadron–Hadron Simulations

- In order to simulate hadron collisions we also need to simulate initial-state radiation.
- In principle this is similar to final-state radiation, but in practice there is a complication.
- For final-state radiation: One end of the evolution fixed, the scale of the hard collision.
- For initial-state radiation: Both ends of the evolution fixed, the hard collision and the incoming hadron.



- Use a different approach based on the evolution equations.

Initial-State Radiation

There are two options for the initial-state shower:

- Forward Evolution
  - Start at the hadron with the distribution of partons given by the PDF.
  - Use the parton shower to evolve to the hard collision.
  - Reproduces the PDF by a Monte Carlo procedure.
  - Unlikely to give an interesting event at the end, so highly inefficient.
- Backward Evolution
  - Start at the hard collision and evolve backwards to the proton guided by the PDF.
  - Much more efficient in practice.

Initial-State Radiation

- The evolution equation for the PDF can be written as

$$t\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a\left(\frac{x}{z},Q^2\right)\frac{\alpha_S}{2\pi}P_{a\to bc}(z) \quad \text{where} \quad t=\ln\left(\frac{Q^2}{\Lambda^2}\right)$$

or

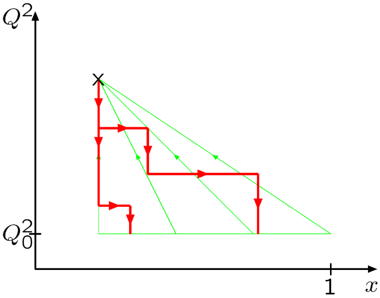
$$\frac{\mathrm{d}f_b(x,Q^2)}{f_b(x,Q^2)} = \frac{\mathrm{d}t}{t}\sum_a \int_x^1 \frac{\mathrm{d}z}{z}\frac{x' f_a\left(x',Q^2\right)}{x f_b(x,Q^2)}\frac{\alpha_S}{2\pi}P_{a\to bc}(z) \quad \text{where} \quad x'=\frac{x}{z}$$

- This can be written as a Sudakov form-factor for evolving backwards in time, i.e from the hard collision at high Q^2 to lower with

$$\Delta = \exp\left(-\frac{\mathrm{d}t}{t}\sum_a \int_x^1 \frac{\mathrm{d}z}{z}\frac{x' f_a\left(x',Q^2\right)}{x f_b(x,Q^2)}\frac{\alpha_S}{2\pi}P_{a\to bc}(z)\right).$$

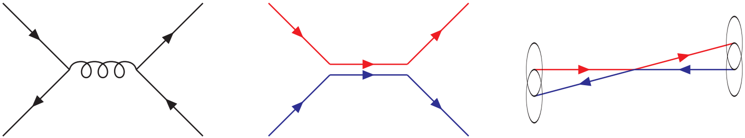
Backward Evolution

- The evolution equations give the PDFs at (x, Q^2) as a function of those at $(> x, < Q^2)$
- Backward evolution starts from the hard scattering at (x, Q^2) and work $\downarrow q^2$ and $\uparrow x$ towards the incoming hadron.



Hadron Collisions

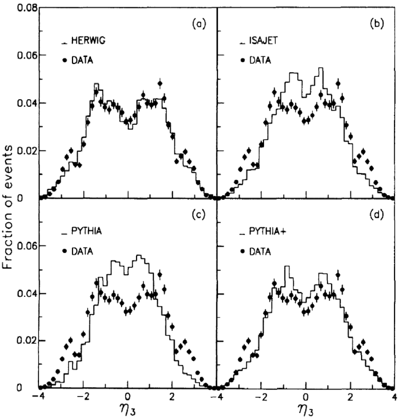
- The hard scattering sets up the initial conditions for the parton shower.
- Colour coherence is important here too.
- Each parton can only emit in a cone stretching to its colour partner.



- Essential to fit the Tevatron data.

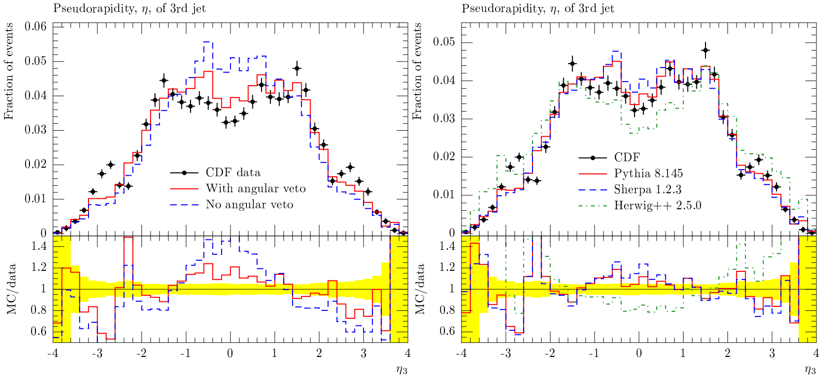
Colour Coherence

- Distributions of the pseudorapidity of the third jet.
- At the time only described by HERWIG which has complete treatment of colour coherence.
- PYTHIA+ had partial.
- Modern generators now all include coherence in some manner.



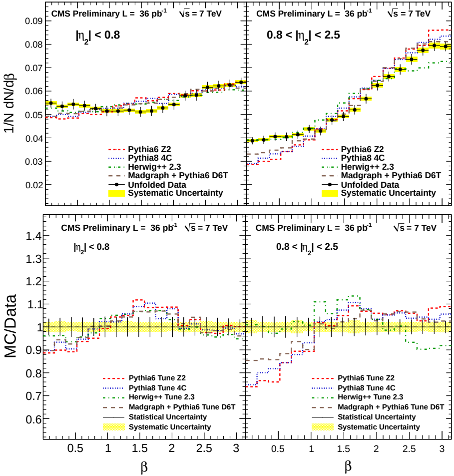
PRD50, 5562, CDF (1994)

Colour Coherence



PRD50, 5562, CDF (1994)

Colour Coherence



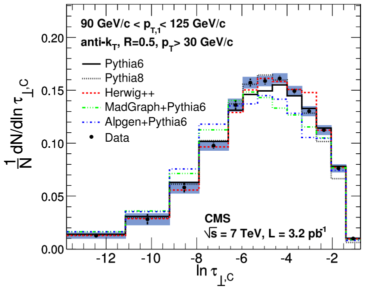
CMS-PAS-SMP-12-010 CMS (2013)

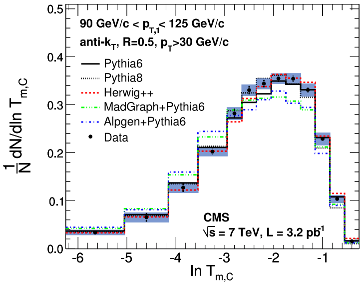
Hadronic Event Shapes

- In hadron collisions we can't use the same event shapes as e^+e^- collisions due to radiation along the beam direction.
- There are however a range of event shapes using transverse quantities, for example

$$\tau_{\perp,\mathcal{C}} = 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}.$$

Hadronic Event Shapes





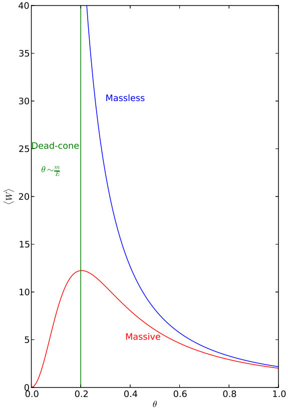
CMS Phys. Lett. B699 (2011) 48-67

Heavy Quarks

- The colinear singularity is regulated by the quark mass.

$$
\begin{aligned}
2p_2 \cdot k &= 2E_g(E_q - |p_q|\cos\theta_{23}) \\
&= 2E_g|p_q|\left(\sqrt{1+\frac{m^2}{|p_q|^2}} - \cos\theta_{23}\right)
\end{aligned}
$$

- Taking the azimuthal average of the soft radiation function gives a smooth suppression of radiation as $\theta \to 0$ starting from $\theta \sim \frac{m}{E}$.
- Historically implemented as a cut-off.



Heavy Quarks

- Better treatment involves the use of the quasi-colinear splitting functions Catani et.al Phys.Lett. B500 149-160 (2001)

$$\mathrm{d}\mathcal{P} = \frac{\alpha_S}{2\pi}\frac{\mathrm{d}q^2}{q^2-m^2}P_{\tilde{ij}\to ij}(z,q^2)$$

where

$$P_{q\to qg} = \frac{C_F}{1-z}\left[1+z^2-\frac{2(1-z)m_q^2}{q^2-m_q^2}\right], P_{g\to q\bar{q}} = T_R\left[1-2z(1-z)+\frac{2m_q^2}{q^2-m_q^2}\right],$$

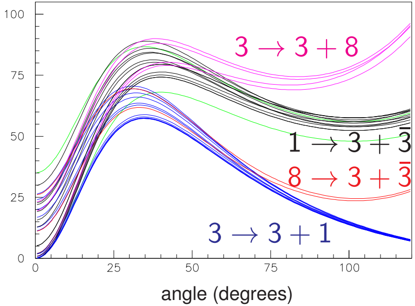
$$P_{\tilde{g}\to \tilde{g}g} = \frac{C_A}{1-z}\left[1+z^2-\frac{2(1-z)m_{\tilde{g}}^2}{q^2-m_{\tilde{g}}^2}\right], P_{\tilde{q}\to \tilde{q}g} = \frac{2C_F}{1-z}\left[z-\frac{(1-z)m_{\tilde{q}}}{q^2-m_{\tilde{q}}^2}\right].$$

- Gives a smooth suppression as $\theta \to 0$.

Heavy Quarks

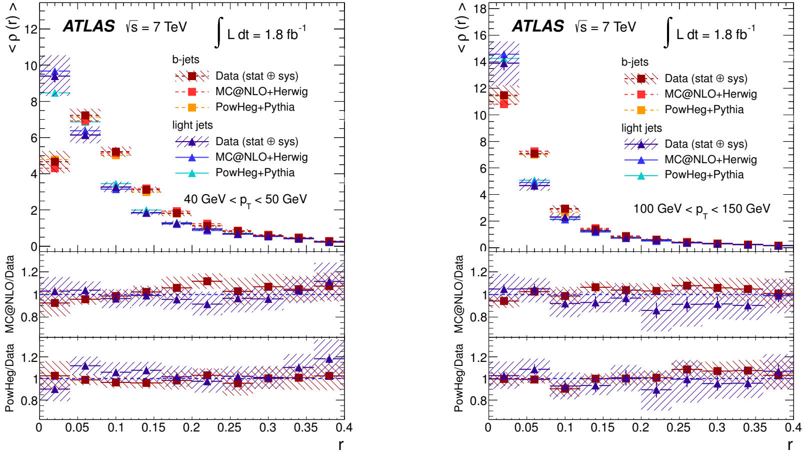
- Only exact for either:
  - soft emission $E_{\rm gluon} \to 0$;
  - radiation from scalars.
- In general the radiation depends on:
  - Gluon energy;
  - spins of radiating particles and colour partner;
  - colours of the particles;

  i.e. process-dependent mass corrections.



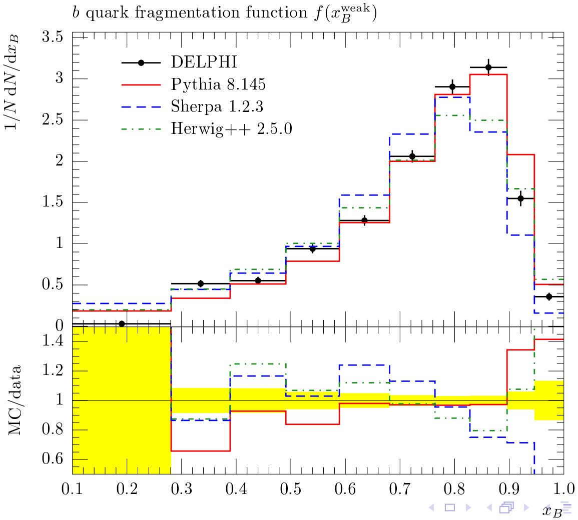
Nucl.Phys. B603 297-342 Norrbin & Sjostrand (2001)

Jet Shapes for bottom quark jets



arXiv:1307.5749 ATLAS (2013)

b-fragmentation function



The Colour Dipole Model

- Conventional parton showers: start from colinear limit, modify to incorporate soft gluon coherence
- Colour Dipole Model: start from soft limit Emission of soft gluons from colour-anticolour dipole universal (and classical):

$$\mathrm{d}\sigma \sim \sigma_0 \frac{1}{2} C_A \frac{\alpha_S(k_\perp)}{2\pi} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \mathrm{d}y,$$

  where $y =$ is the rapidity of the emitted particle.
- After emitting a gluon, colour dipole is split:

The Colour Dipole Model

- Subsequent dipoles continue to split.
- Conventional parton-showers $1 \to 2$ parton splittings.
- CDM one dipole to two dipoles, $2 \to 3$ partons.
- Problems with the treatment of initial=-state radiation.
- The hadronic remnant forms a dipole with scattered quark.
- But as the remnant is an extended object there is a suppression.

Dipole Cascades

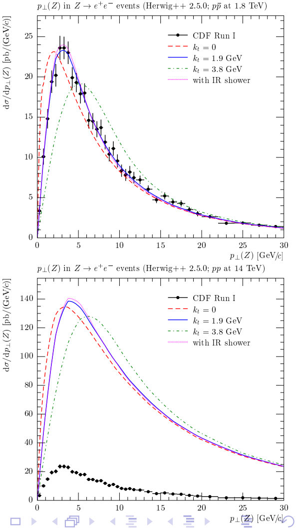
- Most new shower algorithms are based on a dipole picture.
- However most split the dipole into two pieces, one for radiation from each of the partons forming it, as in Catani-Seymour subtraction.
- The partner is used to absorb recoil and define the radiation pattern.

Dipole Vinica, ARIADNE

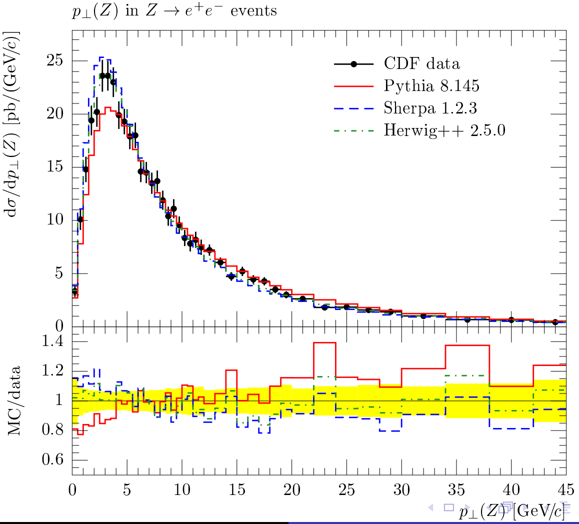
Split PYTHIA6.3, PYTHIA8, Sherpa and Herwig++ dipole showers

Primordial $p_\perp$

- The partons inside the proton have some motion with $p_\perp \sim \frac{1}{1\,\mathrm{fm}}$.
- Intrinsic $p_\perp$ is essential to describe the low $p_\perp$ behaviour of Drell-Yan.
- Particularly important at the Tevatron as no perturbative radiation in some events.
- Less important at the LHC, *pp* and higher energy.



Primordial $p_\perp$



Older Programs

- PYTHIA 6: two showers
  - q^2 ordering with veto of non-ordered final state emission and partial implementation of angular ordering in initial state;
  - $p_\perp$ -ordered parton showers, interleaved with multi-parton interactions and dipole-style recoil.

  Matrix element for first emission in many processes and a large range of hard processes.
- HERWIG6: complete implementation of colour coherence; NLO evolution for large x; smaller range of hard processes.
- ARIADNE: complete implementation of colour dipole model; best fit to HERA data; interfaced to PYTHIA for hard processes.

Modern Programs

- PYTHIA8: new program with many of the same features as PYTHIA6, many obsolete features removed.
- SHERPA: new program built from scratch; either older q^2 or newer $p_\perp$-ordered dipole showers; multi-jet matching scheme (CKKW) and NLO built in.
- Herwig++: new program with similar parton shower to HERWIG (angular ordered) plus quasi-colinear limit and recoil strategy based on colour flow; spin correlations.

Summary

- Accelerated colour charges radiate gluons.
- As the gluon is also coloured this leads to a cascade of gluons.
- Modern parton shower algorithms are sophisticated implementations of perturbative QCD.
- Allows us to evolve from the scale of the hard collision to the hadronization scale.
- However we then need non-perturbative hadronization models.