Parton Shower Monte Carlo Event Generators

Mike Seymour

University of Manchester

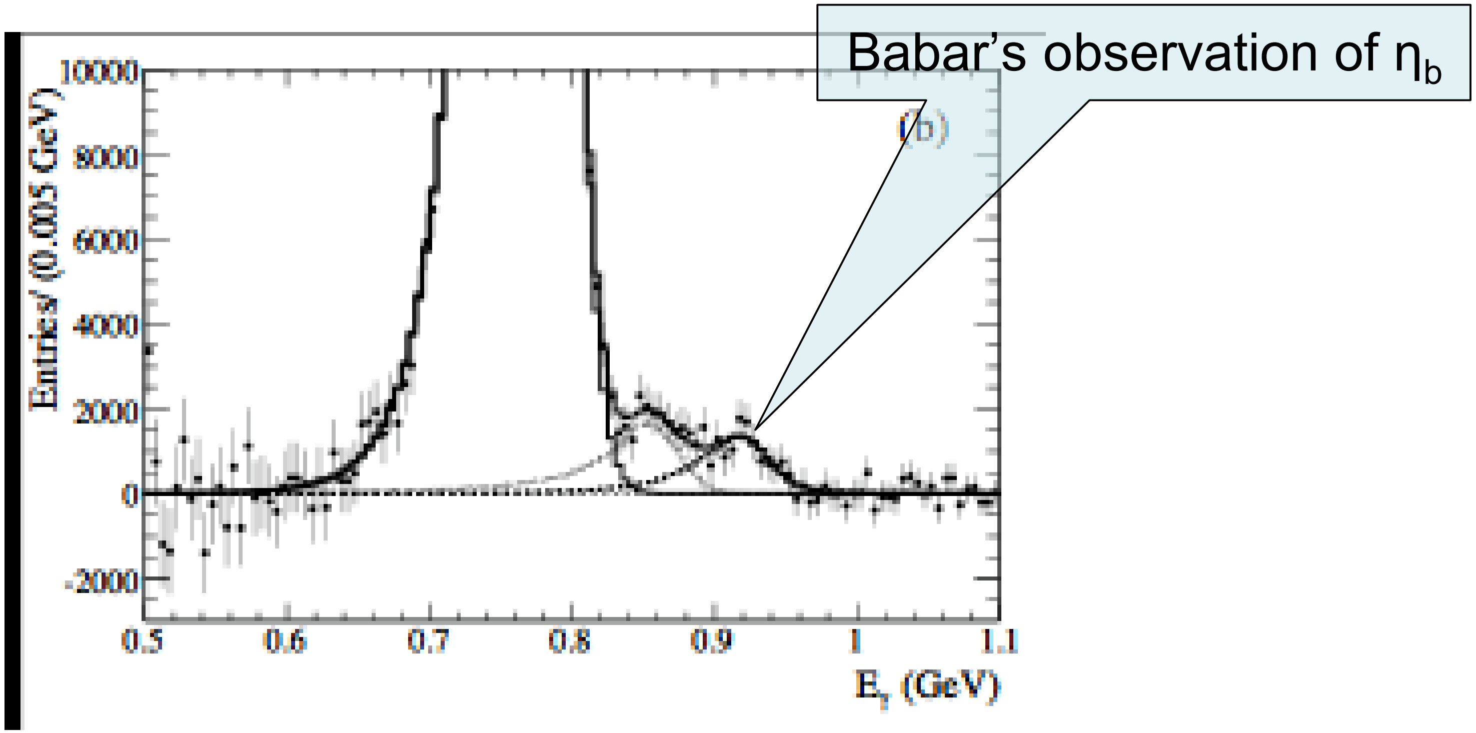
& CERN

MC4LHC EU Networks' Training Event

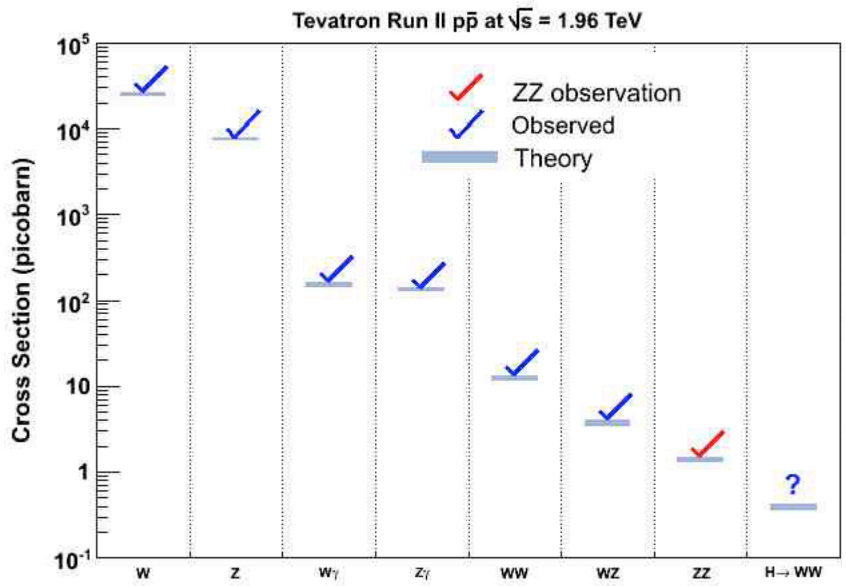
May 4th – 8th 2009

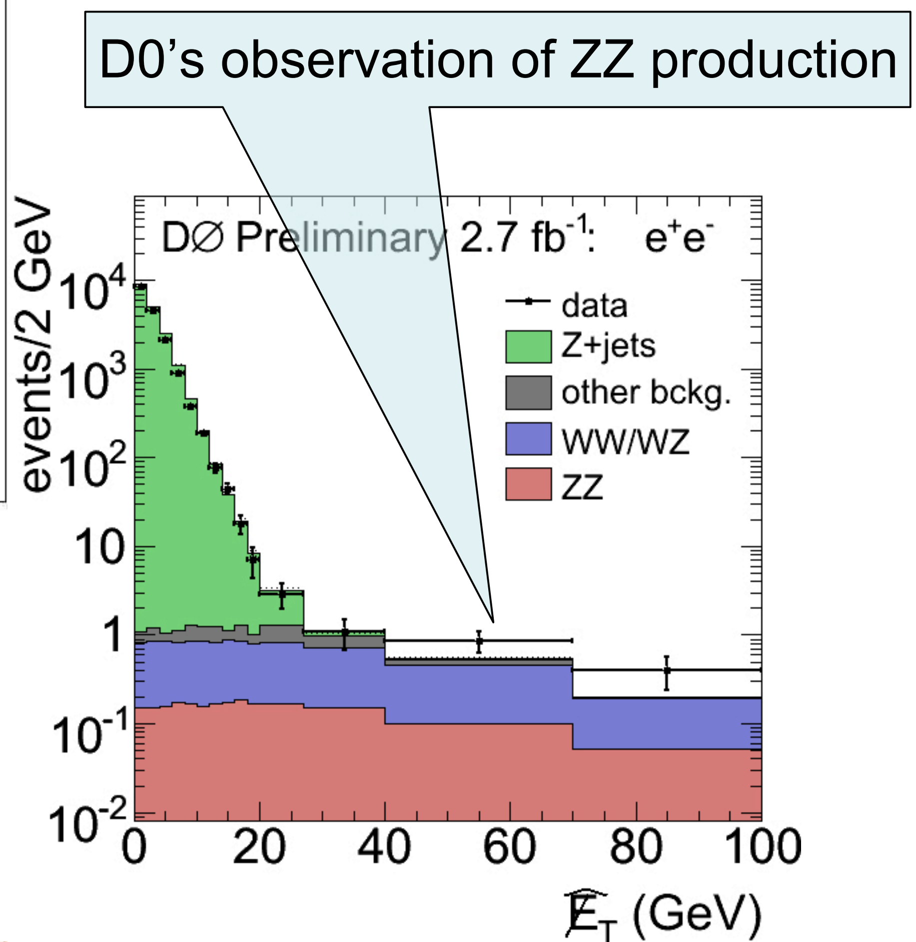
http://www.montecarlonet.org/

Overview and Motivation

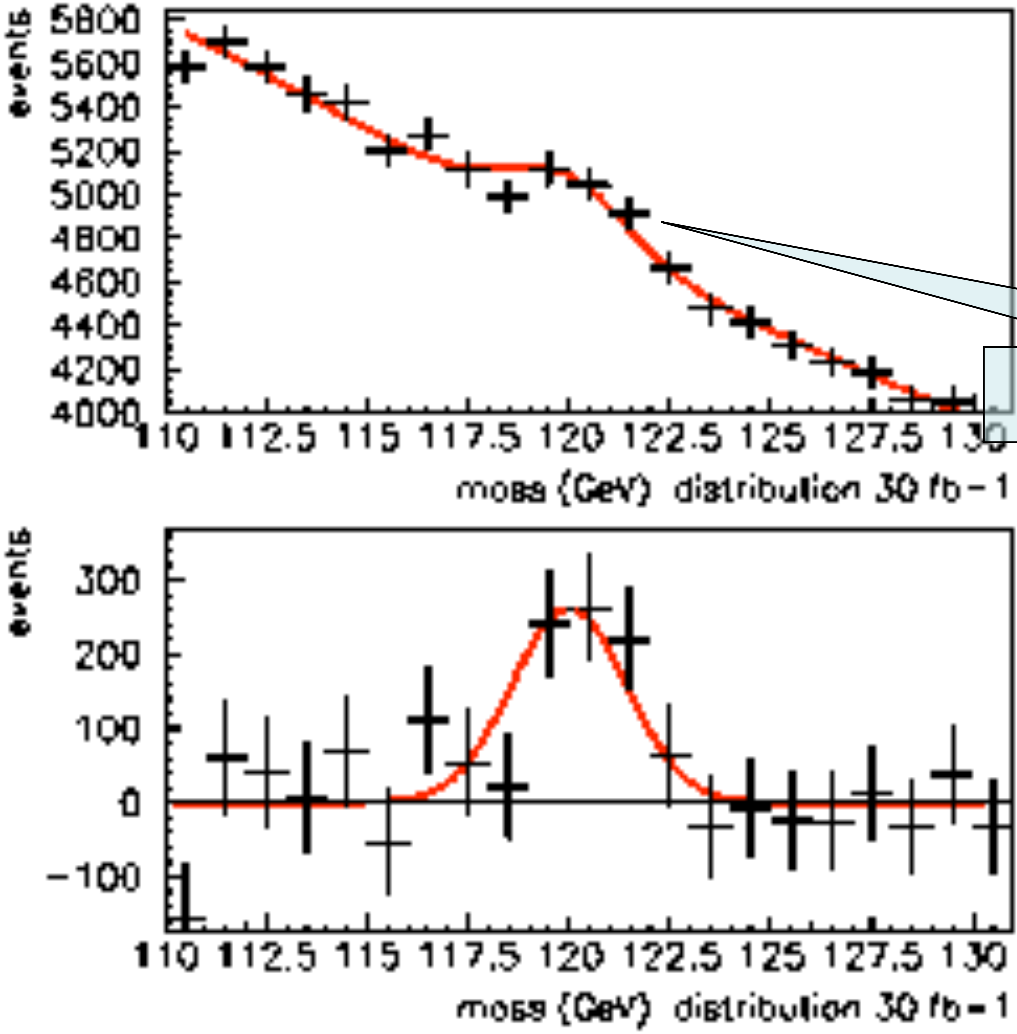


Overview and Motivation





Overview and Motivation



ATLAS's observation of $H \to \gamma\gamma$?

- Marie Curie Research Training Network
- for Monte Carlo event generator
  - development
  - validation and tuning
- Approved for four years from 1st Jan 2007

MCnet

CERN

Mike Seymour
Alberto Ribon
Peter Skands

Lars Sonnenschein
Alex Flossdorf
Michal Deak
Andrzej Siodmok

Durham
(incl. Cambridge)

Peter Richardson
Frank Krauss
Bryan Webber
David Grellscheid
Seyi Latunde-Dada
Sasha Sherstnev
Jonathan Tully
Tanju Gleisberg

Stefan Hoeche
Steffen Schumann
Jan Winter
Martyn Gigg
Keith Hamilton
Frank Siegert
Marek Schoenherr
Jonathan Ferland
Jennifer Archibald
Andreas Papaefstathiou

Userlink

Andy Buckley
James Monk
Mark Sutton
Manuel Baehr
Noam Hod
Piergiulio Lenzi
Alex Richards
Beate Heinemann
Filip Moortgat
Steve Mrenna
Paolo Nason

Jon Butterworth
Emily Nurse
Robert Thorne
Ben Waugh
Mike Whalley
Matthew Wing

Lund

Leif Lönnblad
Torbjörn Sjöstrand
Hendrik Hoeth
Nils Lavesson
Richard Corke
Christopher Flensburg
Florian Bechtel

Karlsruhe
(incl. Krakow)

Stefan Gieseke
Simon Plaetzer
Manuel Baehr
Luca D'Errico
Christoph Hackstein

External Advisors

Mark Gibbs
Paolo Nason
Beate Heinemann
Filip Moortgat
Andreas Morsch
Gloria Corti

MCnet

CEDAR

Jon Butterworth
Emily Nurse
Ben Waugh
Mike Whalley
Lars Sonnenschein
Hendrik Hoeth
Frank Siegert
Andy Buckley
James Monk
Piergiulio Lenzi
Alex Richards

Herwig

Peter Richardson
Bryan Webber
Mike Seymour
Alberto Ribon
Stefan Gieseke
Andrzej Siodmok
Martyn Gigg
David Grellscheid
Keith Hamilton
Seyi Latunde-Dada
Sasha Sherstnev
Jonathan Tully
Simon Plaetzer
Manuel Baehr
Luca D'Errico
Michal Deak
Andreas Papaefstathiou

PYTHIA

Torbjörn Sjöstrand
Steve Mrenna
Peter Skands
Richard Corke
Hendrik Hoeth
Florian Bechtel
Noam Hod

ThePEG Ariadne

Leif Lönnblad
Nils Lavesson
Christopher Flensburg

SHERPA

Frank Krauss
Tanju Gleisberg
Stefan Hoeche
Steffen Schumann
Jan Winter
Frank Siegert
Marek Schoenherr

MCnet objectives

Training:

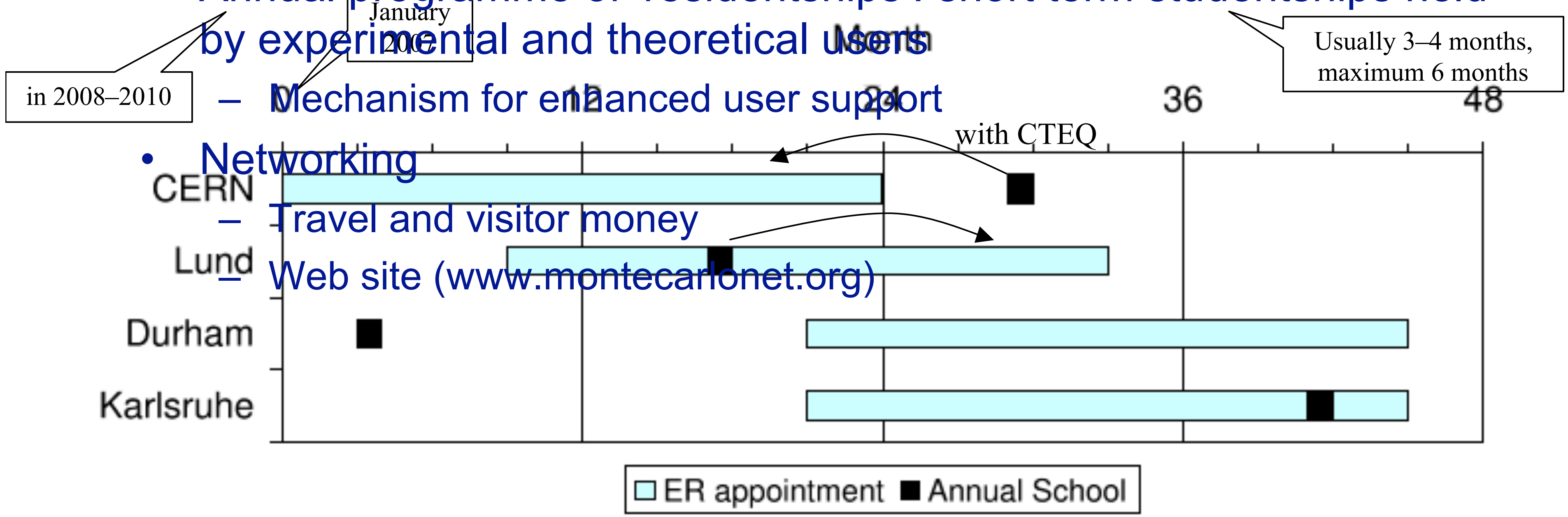
- To train a large section of the user base in the physics and techniques of event generators
- To train the next generation of event generator developers

Through Research:

- To develop the next generation of event generators intended for use throughout the lifetimes of the LHC and ILC experiments
- To play a central role in the analysis of early LHC data and the discovery of new particles and interactions there
- To extract the maximum potential from existing data to constrain the modeling of the data from the LHC and other future experiments.

MCnet main activities

- Four postdoc positions
- Two joint studentships (Karlsruhe–Durham, Durham–UCL)
- Annual School
- Two annual meetings (Januarys @ CERN, summer with school)
- Annual programme of 'residentships': short term studentships held by experimental and theoretical users
  - Mechanism for enhanced user support
- Networking
  - Travel and visitor money
  - Web site (www.montecarlonet.org)



MCnet opportunities 2009:

- MC4LHC (with Heptools and Artemis)
- MCnet school (→ May 1st)
- Short-term studentships:

for th. and exptl. students to spend 3-6 months with MC authors in:

- CERN
- Durham/Cambridge
- Karlsruhe
- Lund
- UCL

on a project of their choice

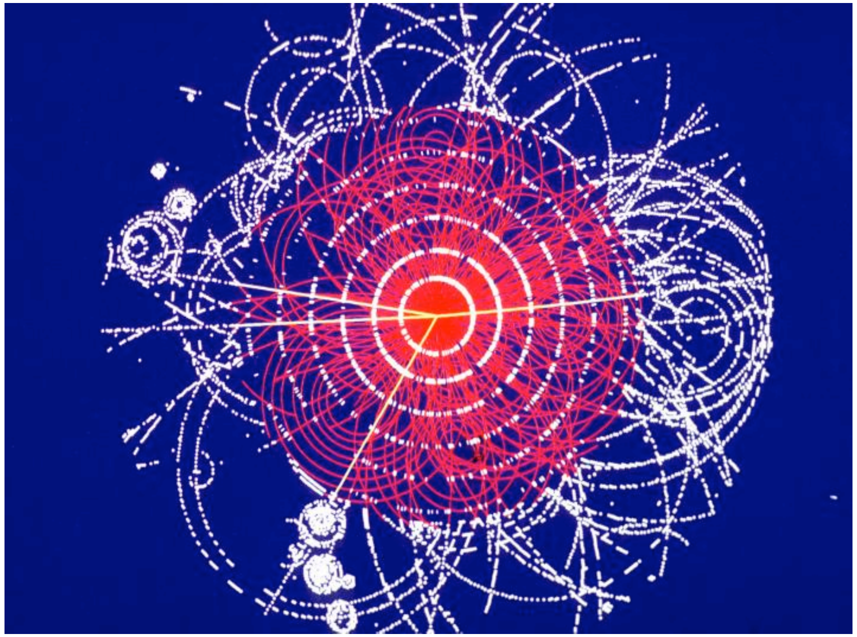
- Next closing dates:
  - May 4th
  - August 3rd

Monte Carlo net

Mike Seymour

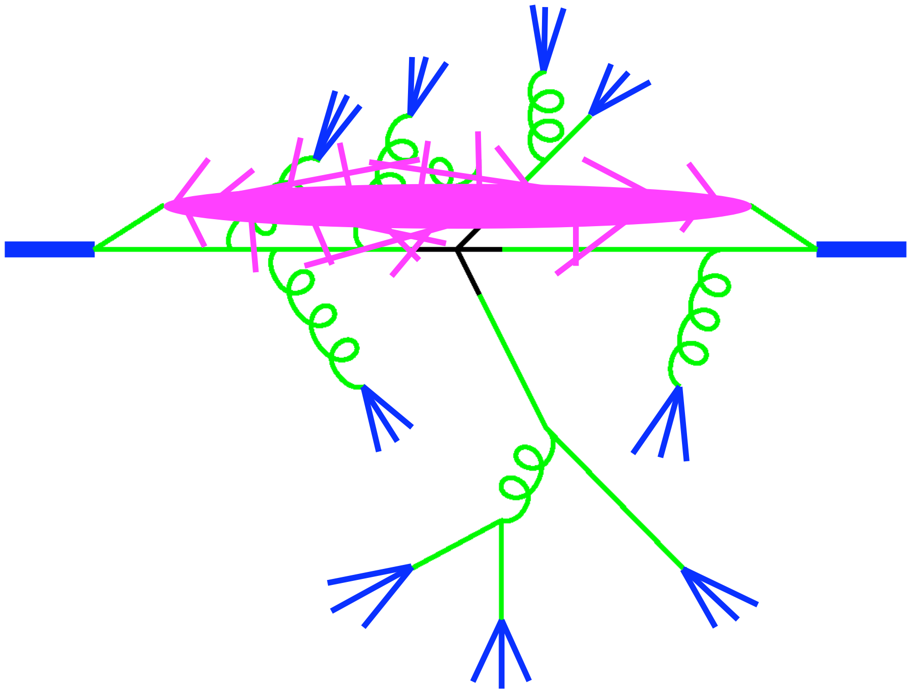
Introduction to Parton Shower Monte Carlo Event Generators

- Basic principles
- LHC event generation
- Parton showers
- Hadronization
- Underlying Events
- Practicalities



Structure of LHC Event Simulations

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event



Hard Process Simulation

Typically use fixed-order perturbative matrix elements

Leading order can be largely automated…

- MADGRAPH/MADEVENT
- GRACE
- COMPHEP
- AMAGIC++ (SHERPA)
- ALPGEN
- HELAC

Matrix elements squared positive definite ➞ simple Monte Carlo implementation

Next-to-leading order getting there…

- MCFM
- NLOJET++
- MC@NLO
- … …

Real and virtual contributions have equal and opposite divergences ➞ naïve Monte Carlo fails

Hard Process Simulation

Typically use fixed-order perturbative matrix elements

Leading order can be largely automated…

- MADGRAPH/MADEVENT
- GRACE
- COMPHEP
- AMAGIC++ (SHERPA)
- ALPGEN
- HELAC

Matrix elements squared positive definite → simple Monte Carlo implementation

But…

- Fixed parton/jet multiplicity
- No control of large logs
- Parton level

→ Need hadron level event generators

Intro to Monte Carlo Generators

1. Basic principles
2. Parton showers
3. Hadronization
4. Introduction to the MCnet Monte Carlo Event Generator projects

Parton Showers: Introduction

QED: accelerated charges radiate.

QCD identical: accelerated colours radiate.

gluons also charged.

→ cascade of partons.

= parton shower.

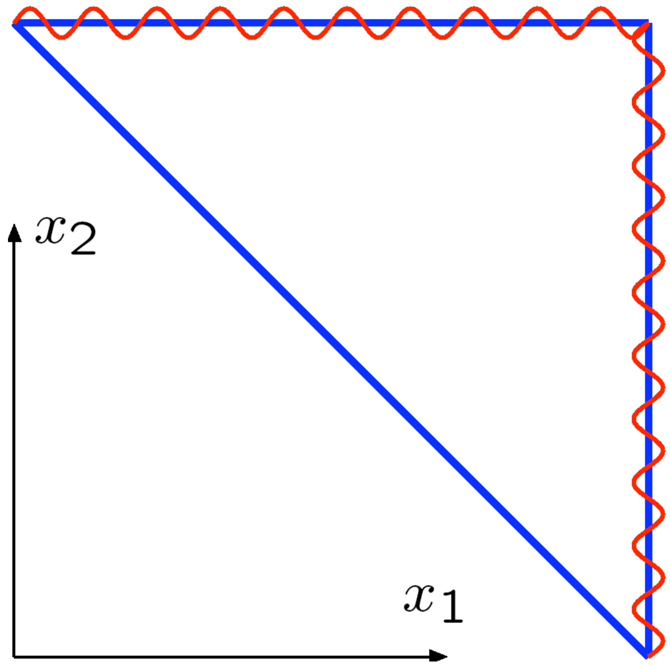
1. e^+e^-annihilation to jets.
2. Universality of collinear emission.
3. Sudakov form factors.
4. Universality of soft emission.
5. Angular ordering.
6. Initial-state radiation.
7. Hard scattering.
8. Heavy quarks.
9. Dipole cascades.
10. Matrix element matching

e^+e^- annihilation to jets

Three-jet cross section:

$$\frac{d\sigma}{dx_1 dx_2} = \sigma_0\, C_F \frac{\alpha_s}{2\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

singular as $x_{1,2} \to 1$



Rewrite in terms of quark-gluon opening angle θ and gluon energy fraction x_3:

$$\frac{d\sigma}{d\cos\theta\, dx_3} = \sigma_0\, C_F \frac{\alpha_s}{2\pi} \left\{ \frac{2}{\sin^2\theta} \frac{1+(1-x_3)^2}{x_3} - x_3 \right\}$$

Singular as $\sin\theta \to 0$ and $x_3 \to 0$.

can separate into two independent jets:

$$\frac{2\, d\cos\theta}{\sin^2\theta} = \frac{d\cos\theta}{1-\cos\theta} + \frac{d\cos\theta}{1+\cos\theta}$$
$$= \frac{d\cos\theta}{1-\cos\theta} + \frac{d\cos\bar{\theta}}{1-\cos\bar{\theta}}$$
$$\approx \frac{d\theta^2}{\theta^2} + \frac{d\bar{\theta}^2}{\bar{\theta}^2}$$

jets evolve independently

$$d\sigma = \sigma_0 \sum_{\text{jets}} C_F \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2}\, dz \frac{1+(1-z)^2}{z}$$

Exactly same form for anything $\propto \theta^2$

eg transverse momentum: $k_\perp^2 = z^2(1-z)^2\,\theta^2\,E^2$

invariant mass: $q^2 = z(1-z)\,\theta^2\,E^2$

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

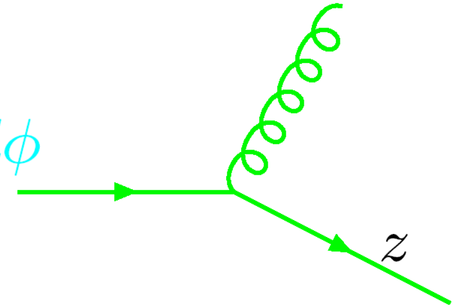
Collinear Limit

Universal:

$$d\sigma = \sigma_0 \, \frac{\alpha_s}{2\pi} \, \frac{d\theta^2}{\theta^2} \, dz \, P(z, \phi) d\phi$$

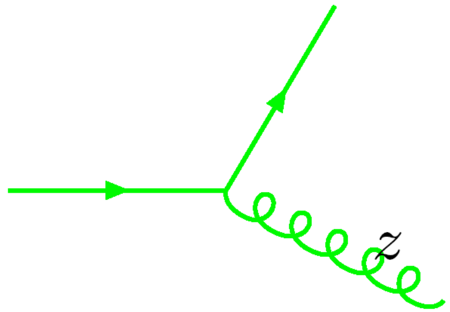
$$P(z, \phi) =$$

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi splitting kernel: dependent on flavour and spin



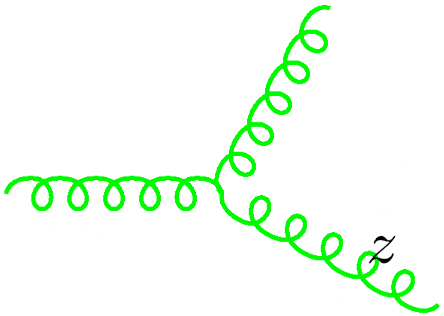
$q \to qg$

$$C_F \frac{1+z^2}{1-z}$$



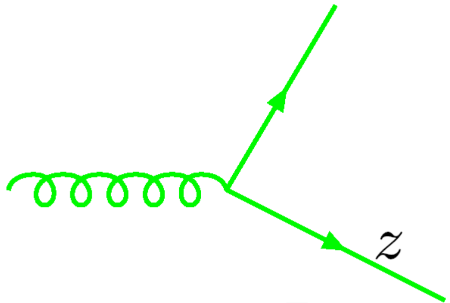
$q \to gq$

$$C_F \frac{1+(1-z)^2}{z}$$



$g \to gg$

$$C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$$



$g \to q\bar{q}$

$$T_R \left(z^2 + (1-z)^2\right)$$

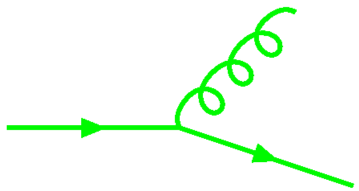
Resolvable partons

What is a parton?

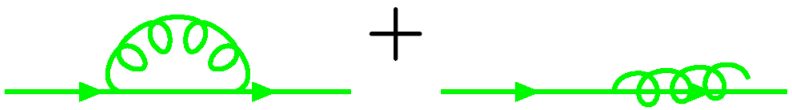
Collinear parton pair $\longleftrightarrow$ single parton

Introduce resolution criterion, eg $k_\perp > Q_0$.

Virtual corrections must be combined with unresolvable real emission



Resolvable emission
Finite



Virtual + Unresolvable emission
Finite

Unitarity: P(resolved) + P(unresolved) = 1

Sudakov form factor

Probability(emission between q^2 and $q^2 + dq^2$)

$$d\mathcal{P} = \frac{\alpha_s}{2\pi} \frac{dq^2}{q^2} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz \; P(z) \equiv \frac{dq^2}{q^2} \bar{P}(q^2).$$

Define probability(no emission between Q^2 and q^2) to be $\Delta(Q^2, q^2)$. Gives evolution equation

$$\frac{d\Delta(Q^2, q^2)}{dq^2} = \Delta(Q^2, q^2) \frac{d\mathcal{P}}{dq^2}$$

$$\Rightarrow \Delta(Q^2, q^2) = \exp - \int_{q^2}^{Q^2} \frac{dk^2}{k^2} \bar{P}(k^2).$$

c.f. radioactive decay

atom has probability λ per unit time to decay.

Probability(no decay after time T) = $\exp - \int^T dt \, \lambda$

Sudakov form factor

Probability(emission between q^2 and $q^2 + dq^2$)

$$d\mathcal{P} = \frac{\alpha_s}{2\pi}\frac{dq^2}{q^2}\int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz\ P(z) \equiv \frac{dq^2}{q^2}\bar{P}(q^2).$$

Define probability(no emission between Q^2 and q^2) to be $\Delta(Q^2, q^2)$. Gives evolution equation

$$\frac{d\Delta(Q^2,q^2)}{dq^2} = \Delta(Q^2,q^2)\frac{d\mathcal{P}}{dq^2}$$

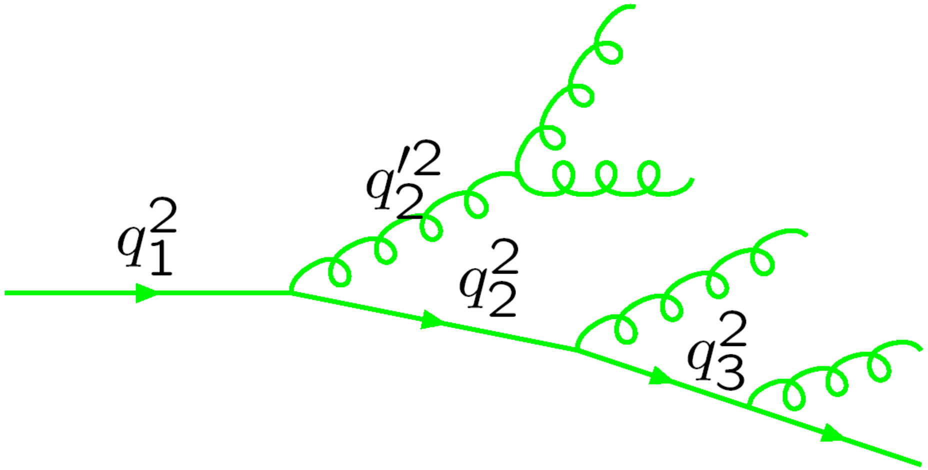
$$\Rightarrow \Delta(Q^2,q^2) = \exp - \int_{q^2}^{Q^2}\frac{dk^2}{k^2}\bar{P}(k^2).$$

$\Delta(Q^2, Q_0^2) \equiv \Delta(Q^2)$ Sudakov form factor

=Probability(emitting no resolvable radiation)

$$\Delta_q(Q^2) \sim \exp - C_F \frac{\alpha_s}{2\pi}\log^2\frac{Q^2}{Q_0^2}$$

Multiple emission



$$q_1^2 > q_2^2 > q_3^2 > \ldots$$
$$q_1^2 > q_2'^2 \ldots$$

But initial condition? $q_1^2 < ???$

Process dependent

Monte Carlo implementation

Can generate branching according to

$$d\mathcal{P} = \frac{dq^2}{q^2} \bar{P}(q^2)\, \Delta(Q^2, q^2)$$

By choosing $0 < \rho < 1$ uniformly:

If $\rho < \Delta(Q^2)$ no resolvable radiation, evolution stops.

Otherwise, solve $\rho = \Delta(Q^2, q^2)$

for q^2=emission scale

Considerable freedom:

Evolution scale: $q^2/k_\perp^2/\theta^2$?

z: Energy? Light-cone momentum?

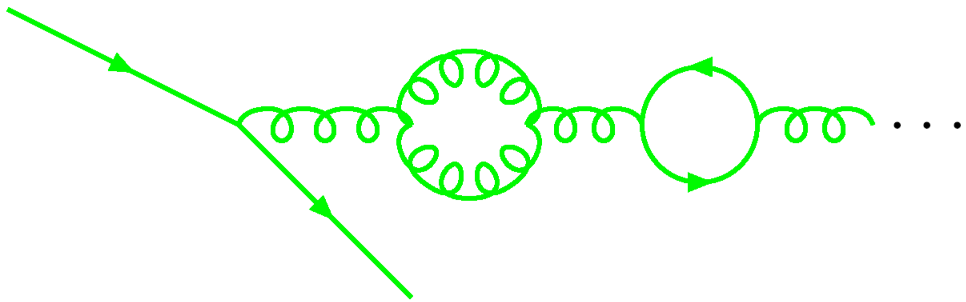
Massless partons become massive. How?

Upper limit for q^2?

All formally free choices, but can be very important numerically

Running coupling

Effect of summing up higher orders:



absorbed by replacing α_s by $\alpha_s(k_\perp^2)$.

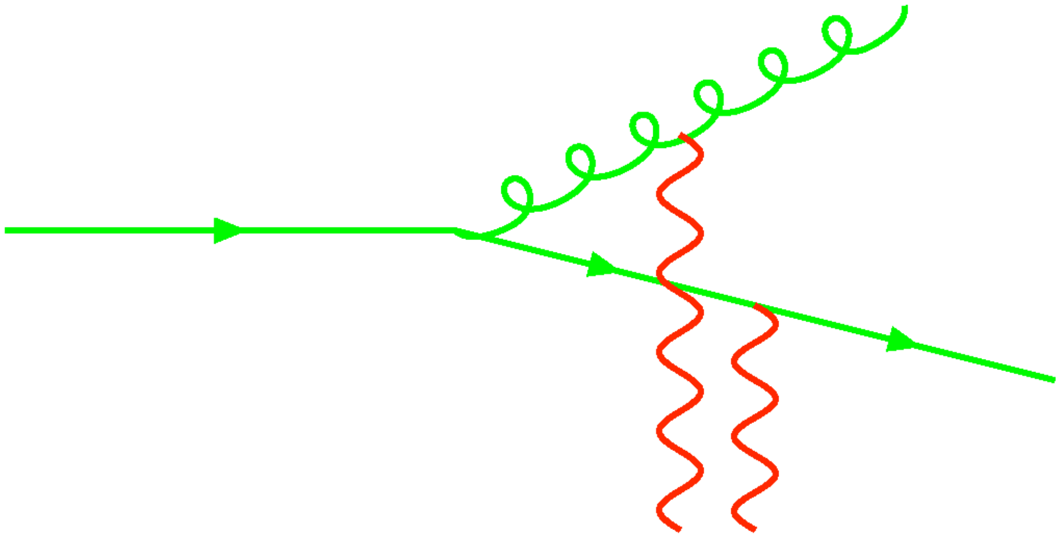
Much faster parton multiplication – phase space fills with soft gluons.

Must then avoid Landau pole: $k_\perp^2 \gg \Lambda^2$.

Q_0 now becomes physical parameter!

Soft limit

Also universal. But at amplitude level…



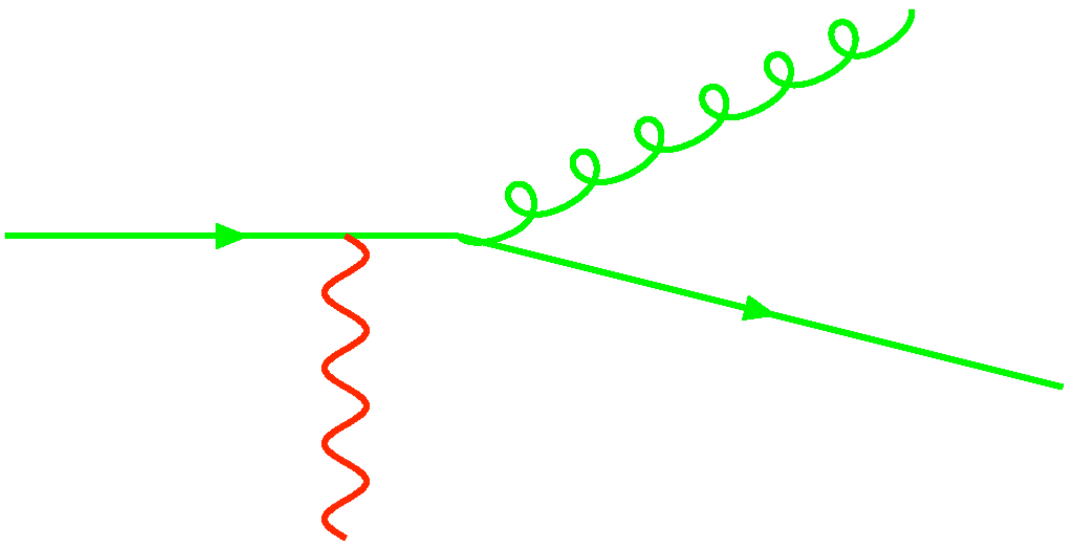
soft gluon comes from everywhere in event.

→ Quantum interference.

Spoils independent evolution picture?

Angular ordering

NO:



outside angular ordered cones, soft gluons sum coherently: only see colour charge of whole jet.

Soft gluon effects fully incorporated by using θ^2 as evolution variable: angular ordering

First gluon not necessarily hardest!