MCnet

Monte Carlo net

MANCHESTER 1824

The University of Manchester

Monte Carlo Event Generators

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Corfu Summer Institute 2010

Week 1 : Standard Model and Beyond – Cosmology

August 29th – September 5th

EISA

European Institute for Sciences and Their Applications

http://www.montecarlonet.org/

MCnet

Monte Carlo net

- About the network
- Monte Carlo schools
  - Durham 2007
  - CTEQ 2008
  - Lund 2009
  - Karlsruhe 2010
- Short-term studentships
- The projects
- The teams
- Meetings
- Publications
- Contact info

Monte Carlo Schools

Throughout the course of the network we will run one high level school a year aimed at advanced doctoral students and young postdocs. These schools will be closely modeled on the highly successful national schools organized by proponents of this network in Durham in 2005 and in Dresden in 2006.

The schools will be organized by individual teams in, or close to, their universities. They will typically be held in early summer, with precise dates to be set with input from the user community concerning experimental collaboration meetings and other schools and workshops.

In order to attract students and postdocs from as wide a variety of backgrounds as possible, we will fully fund all local costs for the schools. We will also make a significant contribution towards the travel costs in the form of bursaries. These will be automatically awarded for participants from Less-Favoured Regions and New Member States and on a case-by-case basis according to need elsewhere.

Direct links to the home pages of the different schools:

- Durham 2007
- CTEQ 2008
- Lund 2009
- Karlsruhe 2010

Overview and Motivation

Babar's observation of η_b

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Overview and Motivation

D0’s observation of ZZ production

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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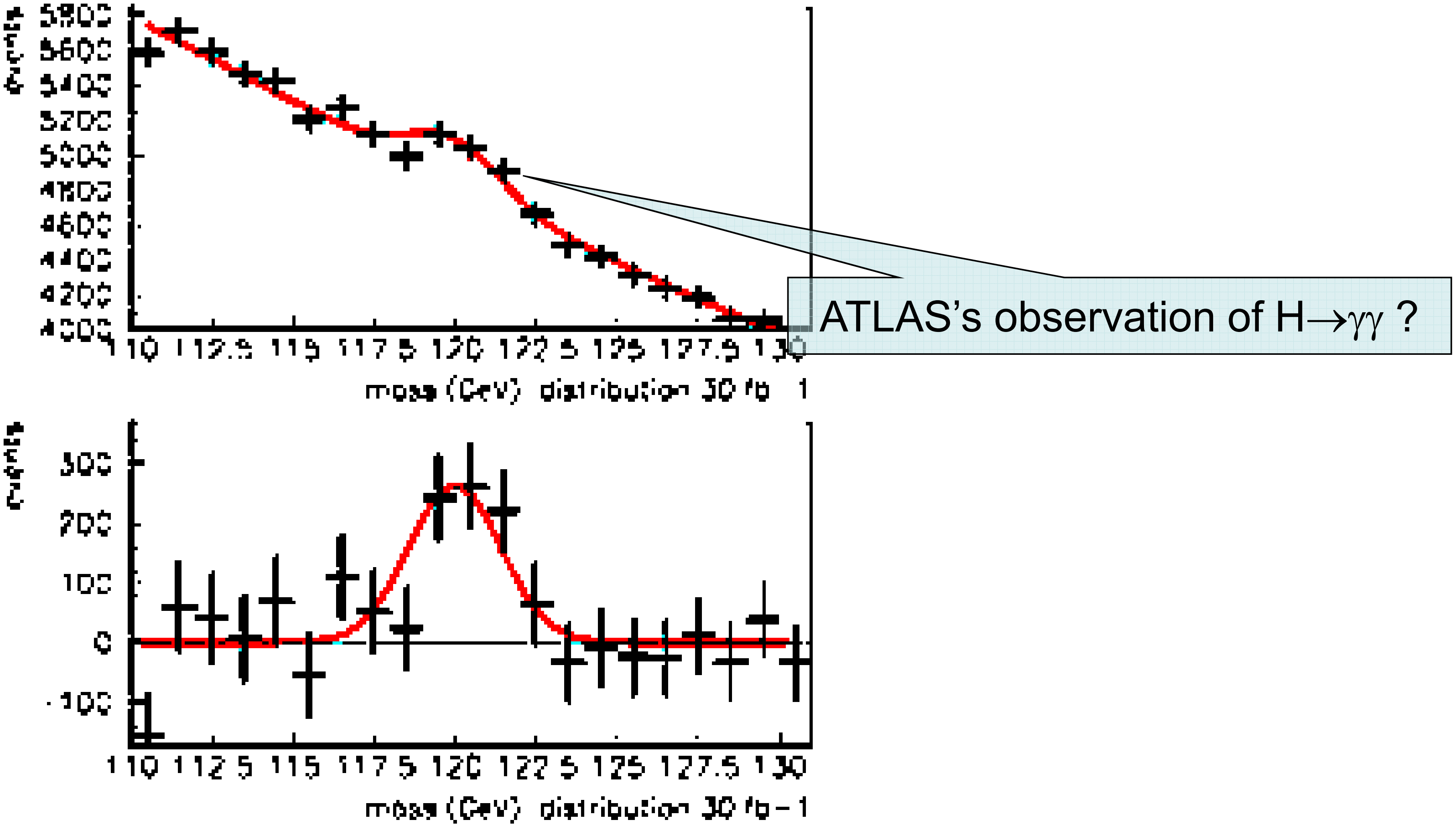
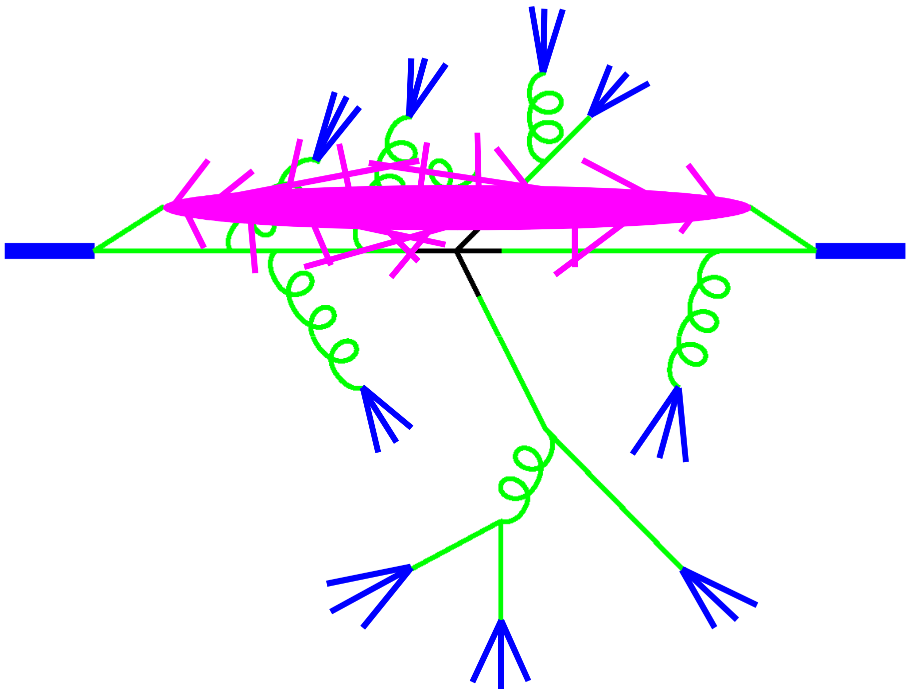
Overview and Motivation



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
- GRACE
- COMPHEP
- AMAGIC++ (SHERPA)
- ALPGEN

Matrix elements squared positive definite ⇒ simple Monte Carlo implementation

Next-to-leading order starting to be automated…

- MCFM
- NLOJET++
- MC@NLO

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

Introduction to Parton Showers

QED: accelerated charges radiate.

QCD identical: accelerated colours radiate.

gluons also charged.

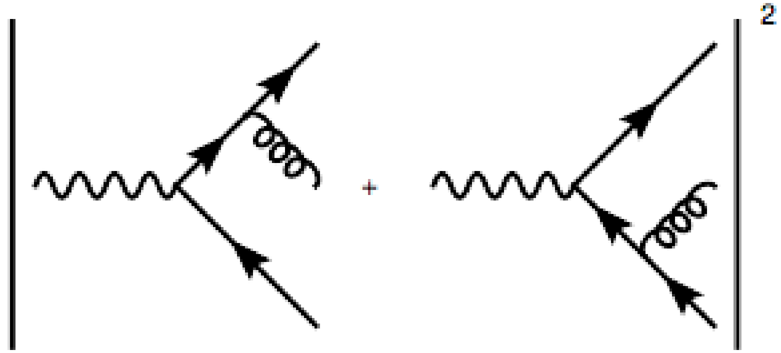
→ cascade of partons.

= parton shower.

1. QCD emission matrix elements diverge
2. The collinear limit
3. The soft limit
4. Initial-state radiation
5. Hard scattering

QCD emission matrix elements diverge

e.g. $e^+e^- \to$ 3 partons:



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}z_g} \sim \sigma_0\, C_F\, \frac{\alpha_s}{2\pi}\, \frac{2}{\sin^2\theta}\, \frac{1+(1-z_g)^2}{z_g}$$

$E_g/E_{g,max}$

$e^+e^- \to$ 2 partons

"quark charge squared"

QCD running coupling ~ 0.1

Divergent in collinear limit $\theta \to 0,\pi$ (for massless quarks)

and soft limit $z_g \to 0$

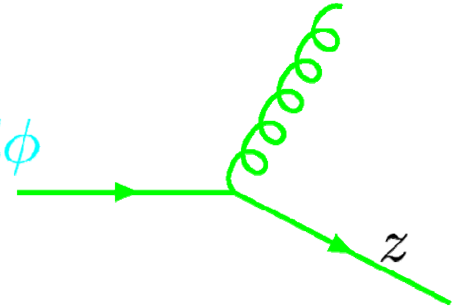
Collinear Limit

Universal:

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

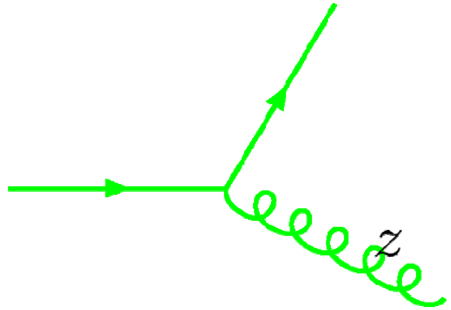
$P(z, \phi) =$

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



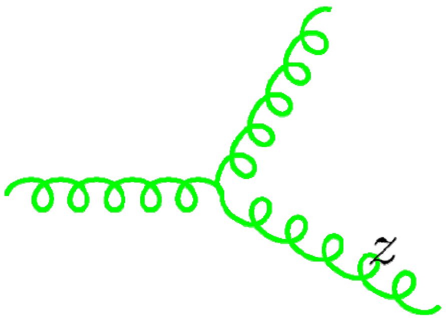
$q \to qg$

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



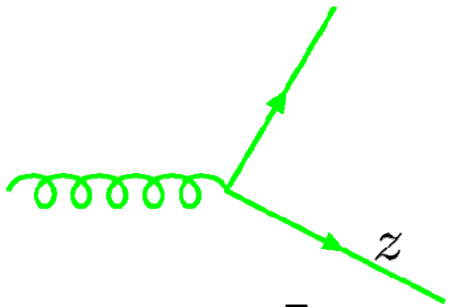
$q \to gq$

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



$g \to gg$

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



$g \to q\bar{q}$

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

Multiple Collinear Emission

Formulated as evolution in

- opening angle θ^2
- virtuality $q^2 \sim z(1-z)E^2\,\theta^2$
- transverse momentum $k_\perp{}^2 \sim z^2(1-z)^2E^2\,\theta^2$

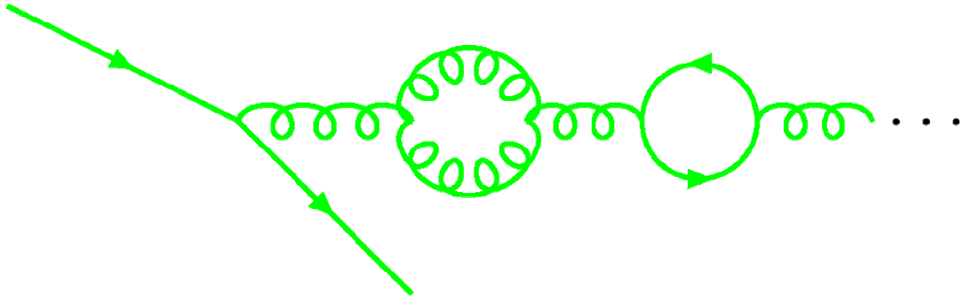
Sums leading logarithms $(\alpha_s \log(Q/Q_0))^n$ to all orders

where Q_0 is parton resolution criterion i.e. infrared cutoff

"Leading log parton shower algorithm"

Running coupling

Effect of summing up higher orders:



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

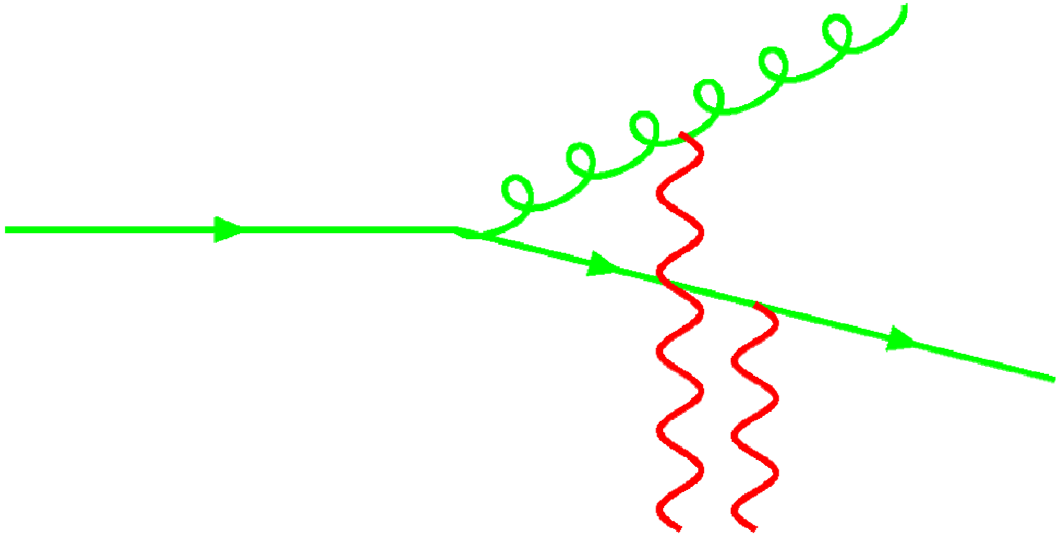
Much faster parton multiplication – phase space fills with soft gluons.

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…



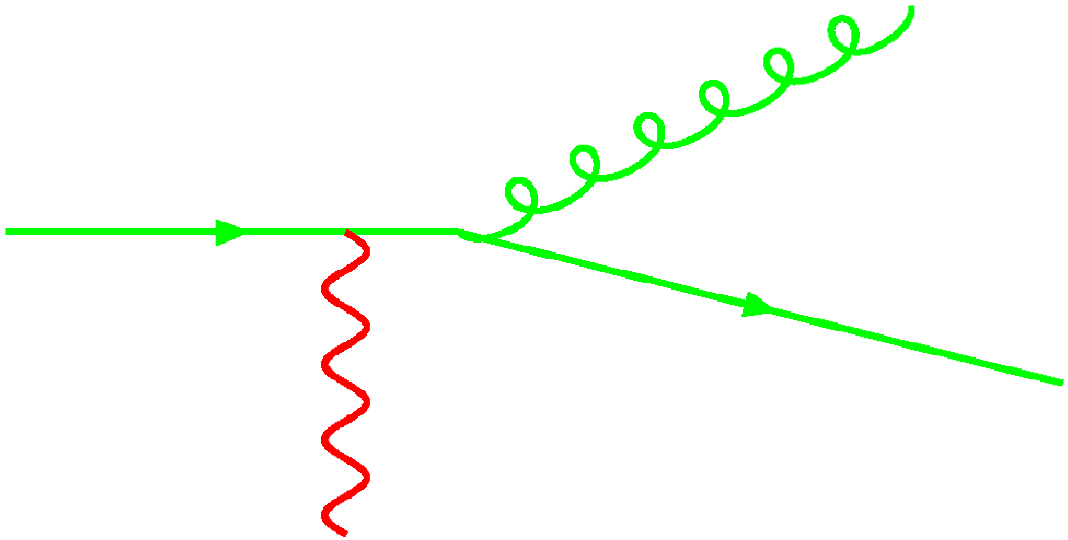
soft gluon comes from everywhere in event.

→ Quantum interference.

Spoils independent evolution picture?

Angular ordering

NO:



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

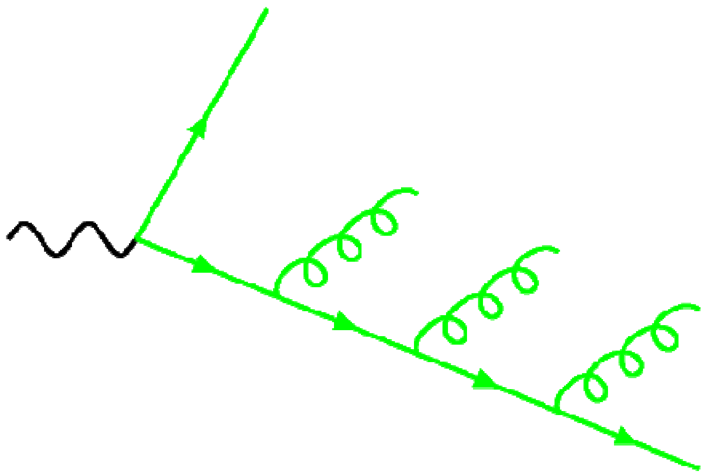
Soft gluon effects fully incorporated by using θ^2 as evolution variable: angular ordering

First gluon not necessarily hardest!

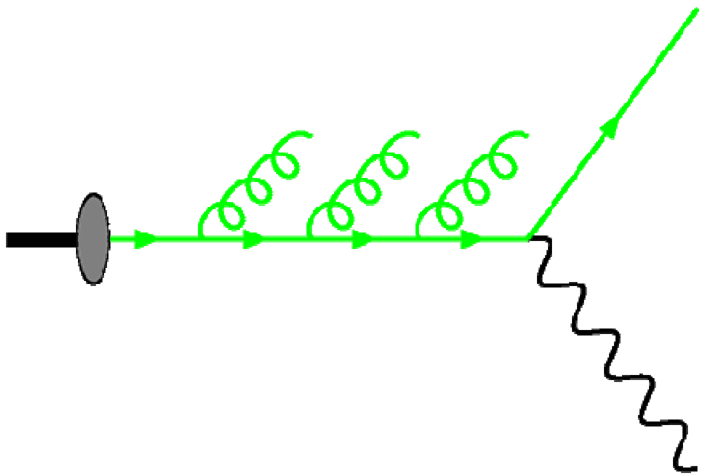
Initial state radiation

In principle identical to final state (for not too small x)

In practice different because both ends of evolution fixed:



vs.



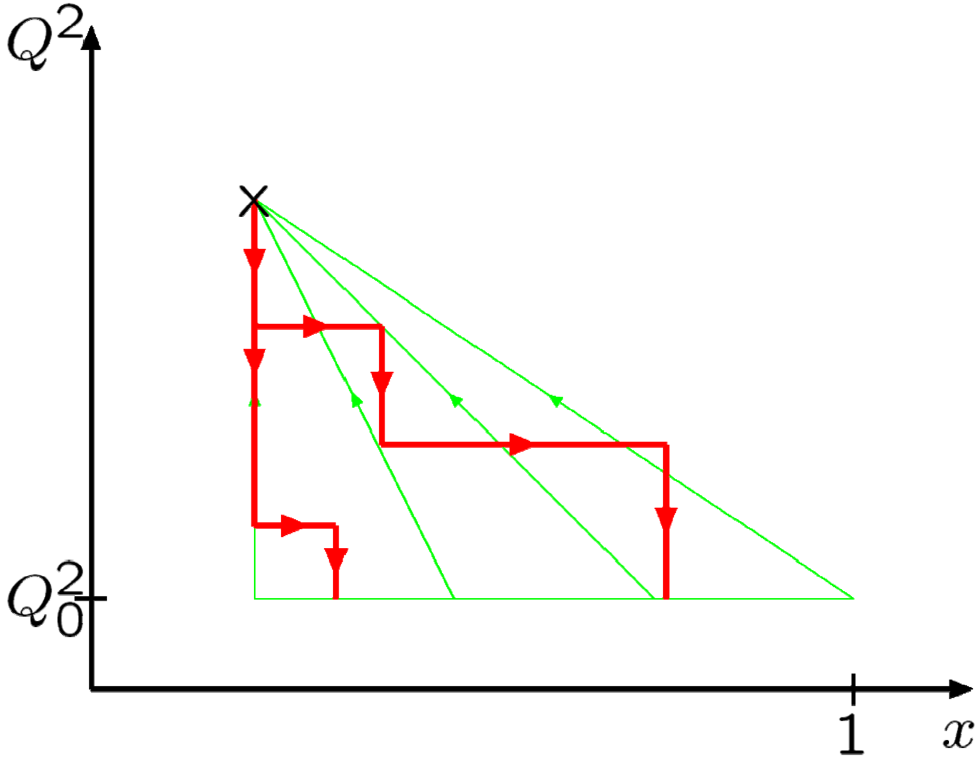
Use approach based on evolution equations…

Backward evolution

DGLAP evolution: pdfs at (x, Q^2) as function of pdfs at $(> x, Q_0^2)$:

Evolution paths sum over all possible events.

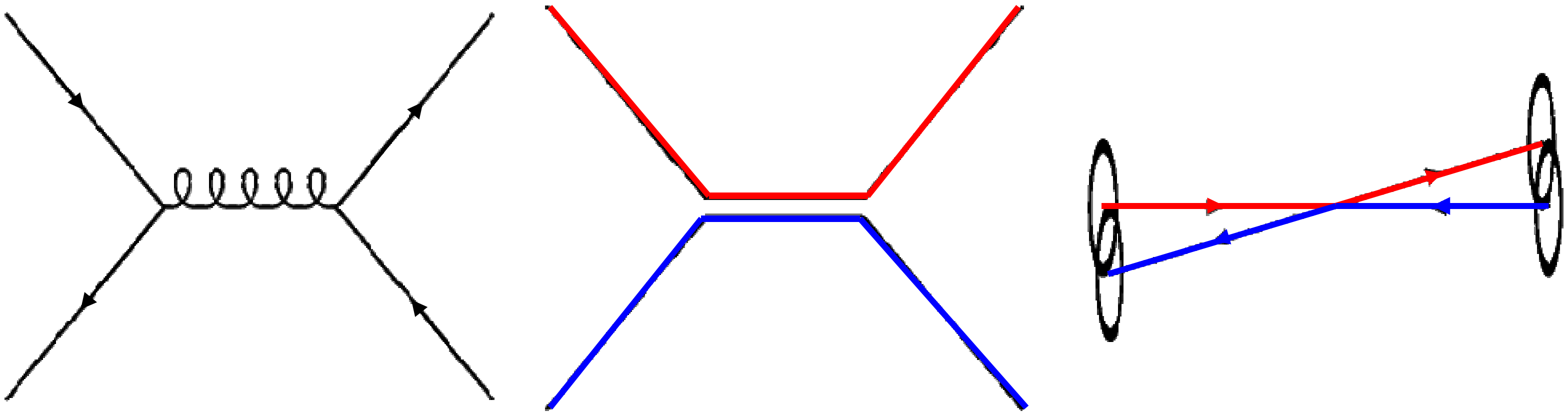
Formulate as backward evolution: start from hard scattering and work down in q^2, up in x towards incoming hadron.



Hard Scattering

Sets up initial conditions for parton showers.

Colour coherence important here too.

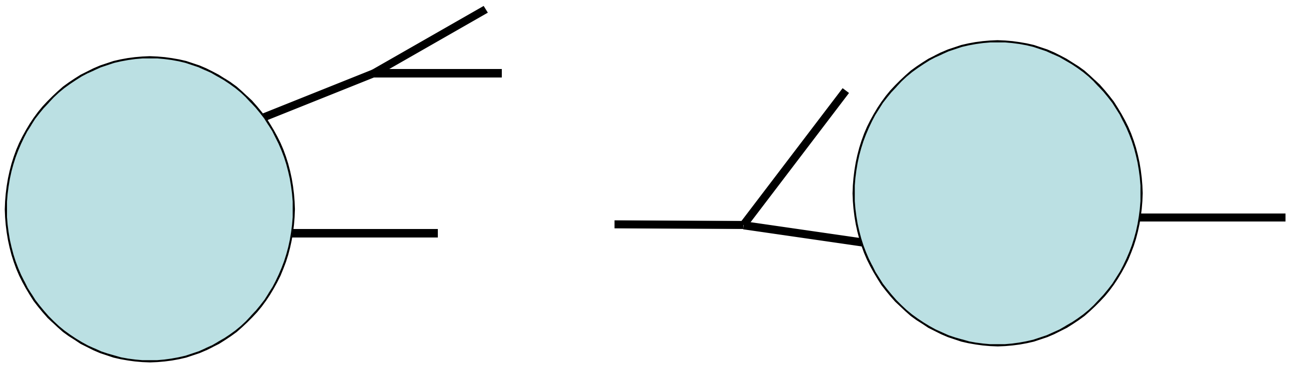


Emission from each parton confined to cone stretching to its colour partner

Essential to fit Tevatron data…

Dipole Cascades

- Recent progress: several dipole cascade algorithms:
  - Catani & MHS (1997)
  - Kosower (1998)
  - Nagy & Soper (May 2007)
  - Giele, Kosower & Skands (July 2007) VINCIA
  - Dinsdale, Ternick & Weinzierl (Sept 2007)
  - Schumann & Krauss (Sept 2007) SHERPA
  - Winter & Krauss (Dec 2007) SHERPA



Structure of LHC Events

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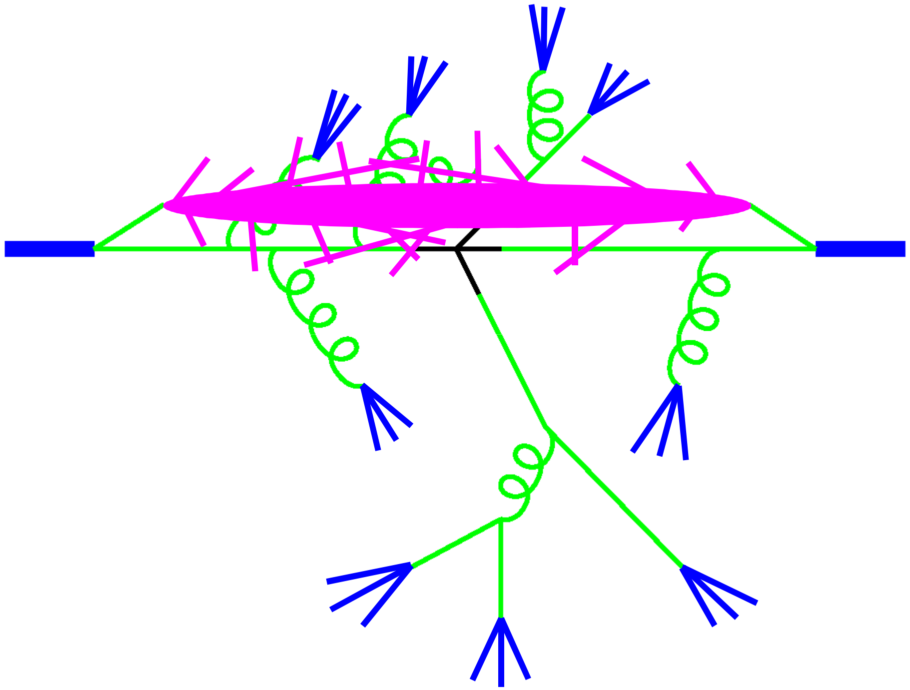


Hadronization: Introduction

Partons are not physical particles: they cannot freely propagate.

Hadrons are.

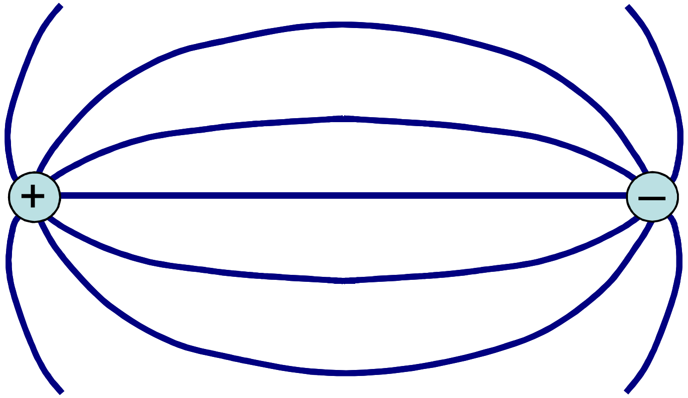
Need a model of partons' confinement into hadrons: hadronization.

1. Confinement
2. The string model
3. Preconfinement
4. The cluster model
5. Underlying event models

Confinement

Asymptotic freedom: $Q\bar{Q}$ becomes increasingly QED-like at short distances.

QED:



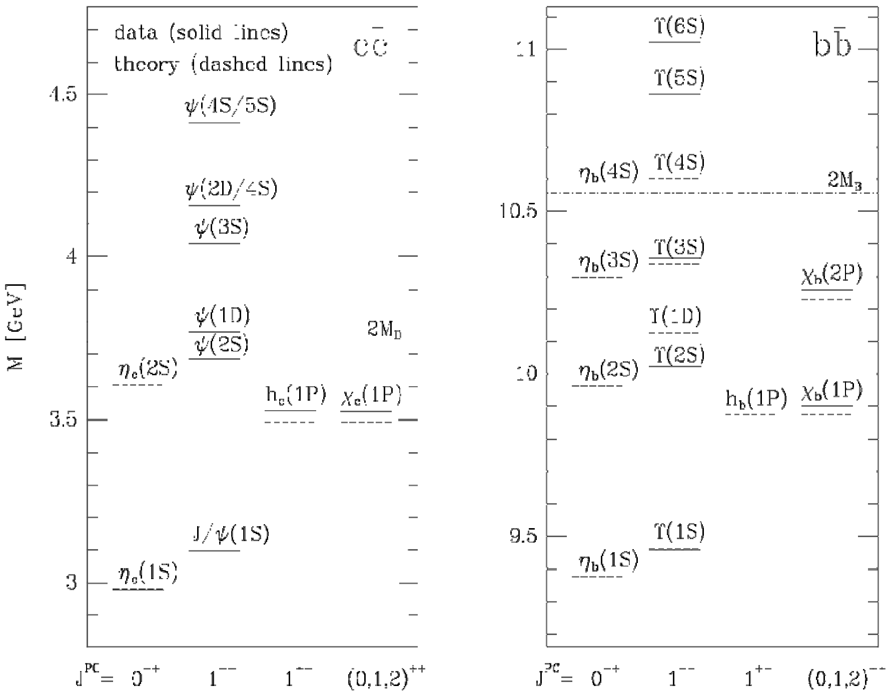
but at long distances, gluon self-interaction makes field lines attract each other:

QCD:

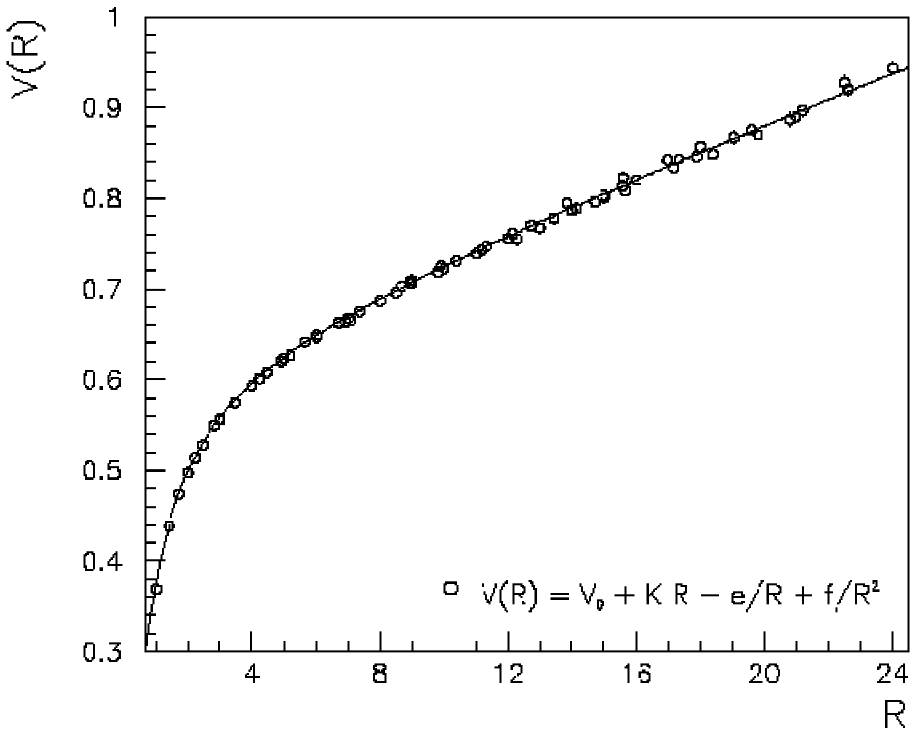
→linear potential → confinement

Interquark potential

Can measure from
quarkonia spectra:



or from lattice QCD:



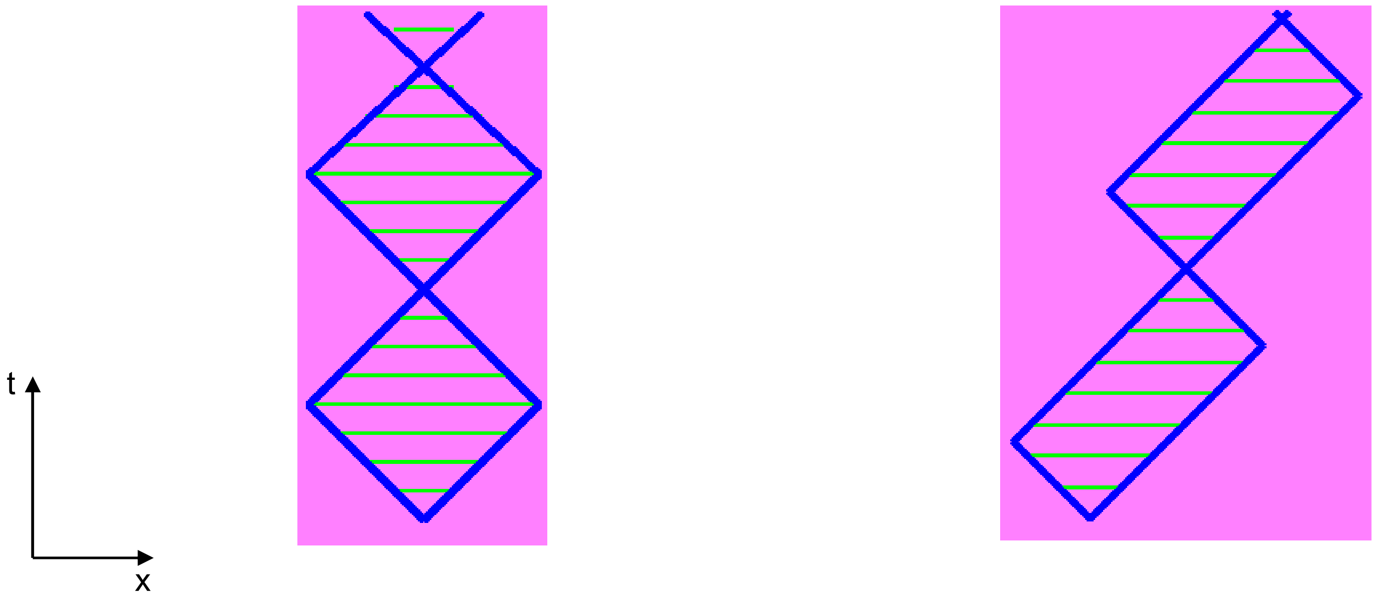
→ String tension

$$\kappa \approx 1\ \mathrm{GeV/fm}.$$

String Model of Mesons

Light quarks connected by string.

L=0 mesons only have ‘yo-yo’ modes:



Obeys area law: $m^2 = 2\kappa^2 \text{ area}$

The Lund String Model

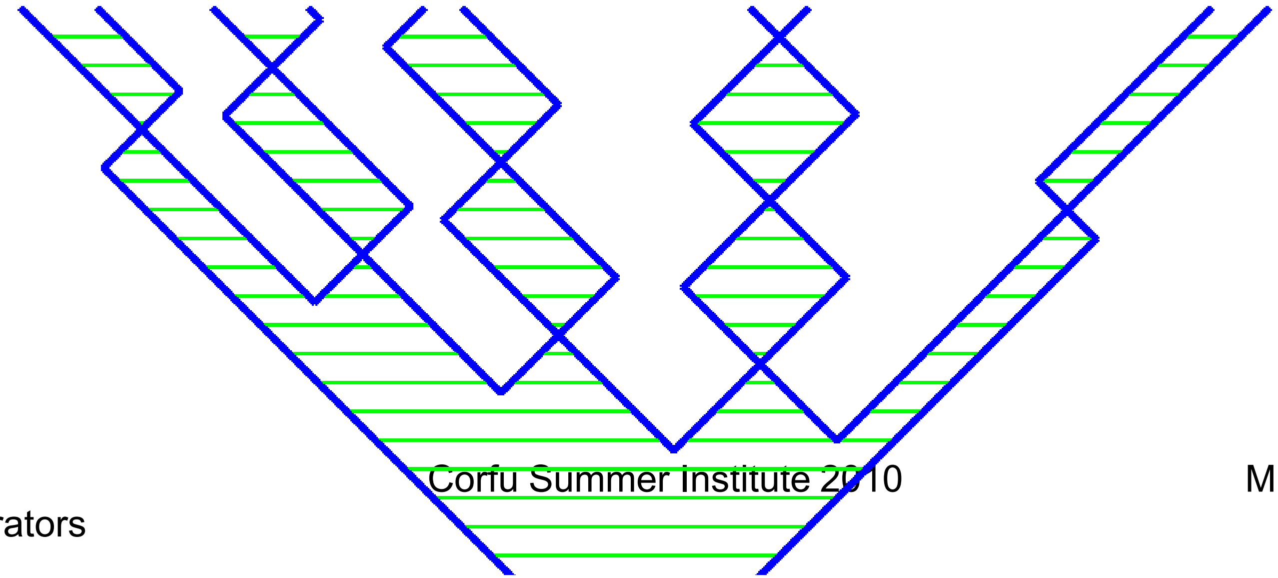
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string → $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

Expanding string breaks into mesons long before yo-yo point.

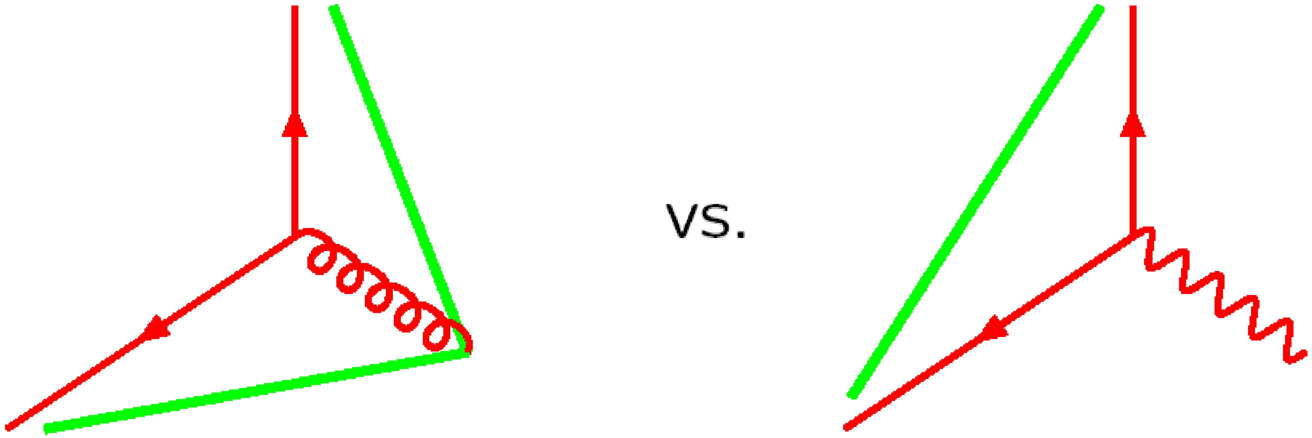


Three-jet Events

So far: string model = motivated, constrained independent fragmentation!

New feature: universal

Gluon = kink on string → the string effect

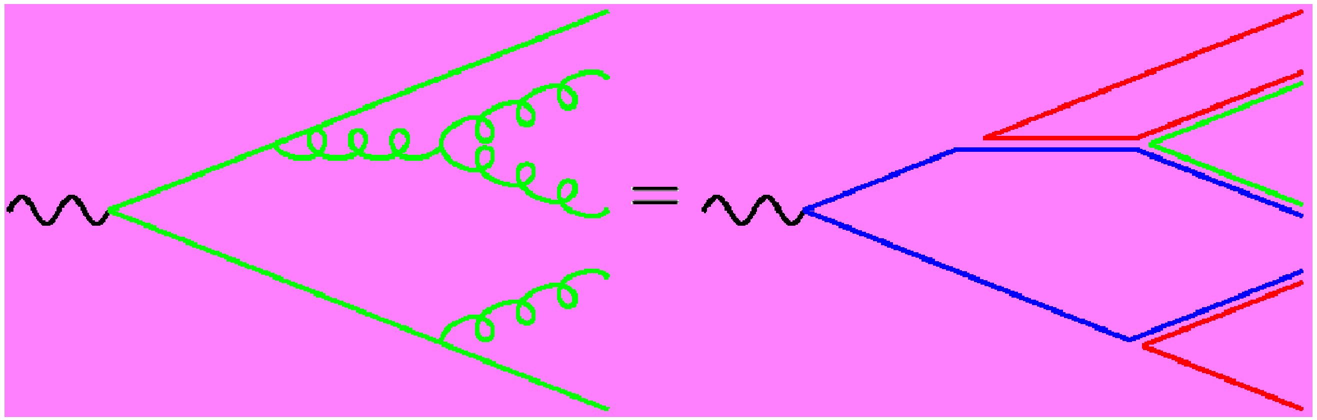


Infrared safe matching with parton shower: gluons with $k_\perp <$ inverse string width irrelevant.

Preconfinement

Planar approximation: gluon = colour—anticolour pair.

Follow colour structure of parton shower: colour-singlet pairs end up close in phase space

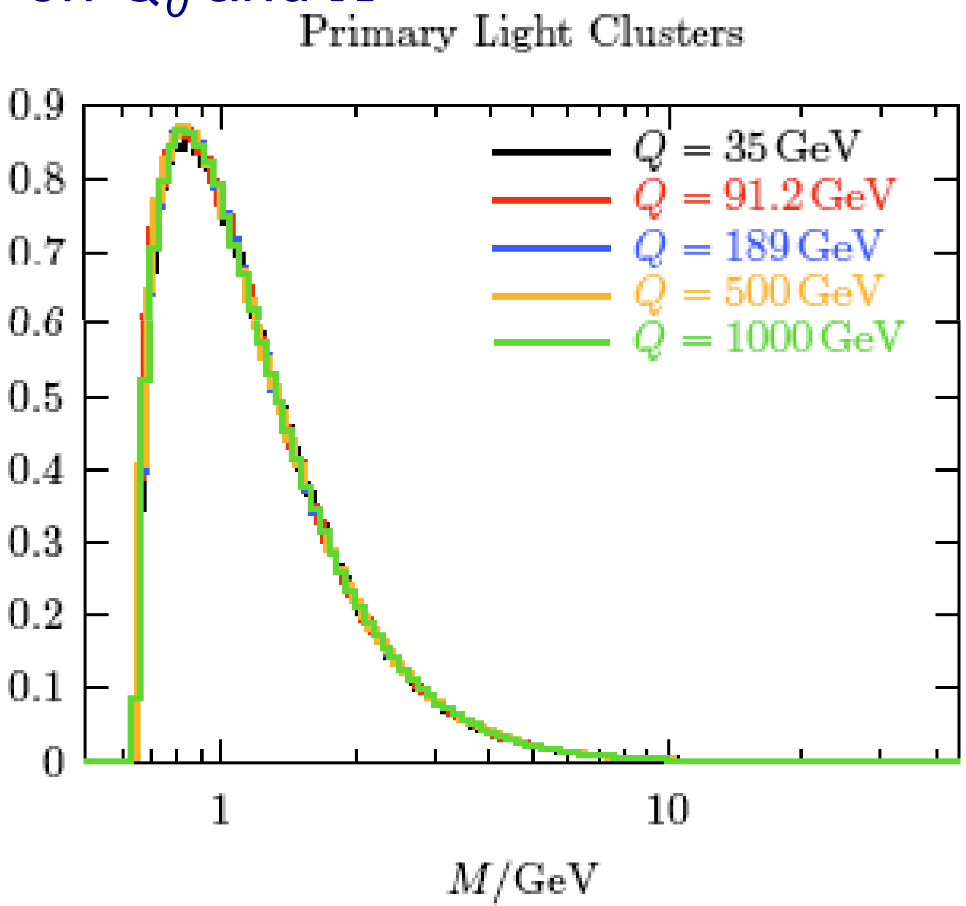


Mass spectrum of colour-singlet pairs asymptotically independent of energy, production mechanism, …

Peaked at low mass $\sim Q_0$.

Cluster mass distribution

- Independent of shower scale Q
  - depends on Q_0 and Λ



The Cluster Model

Project colour singlets onto continuum of high-mass mesonic resonances (=clusters). Decay to lighter well-known resonances and stable hadrons.

Assume spin information washed out:

decay = pure phase space.

→ heavier hadrons suppressed

→ baryon & strangeness suppression 'for free' (i.e. untuneable).

Hadron-level properties fully determined by cluster mass spectrum, i.e. by perturbative parameters.

Q_0 crucial parameter of model.

Strings

"Hadrons are produced by hadronization: you must get the non-perturbative dynamics right"

Improving data has meant successively refining perturbative phase of evolution…

Clusters

"Get the perturbative phase right and any old hadronization model will be good enough"

Improving data has meant successively making non-perturbative phase more string-like…

???

Structure of LHC Events

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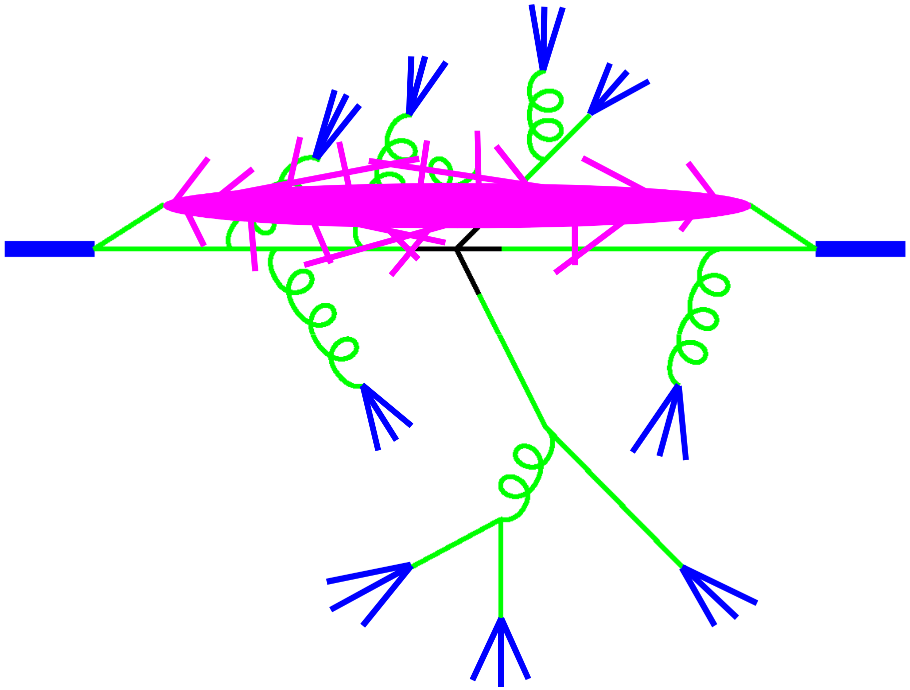
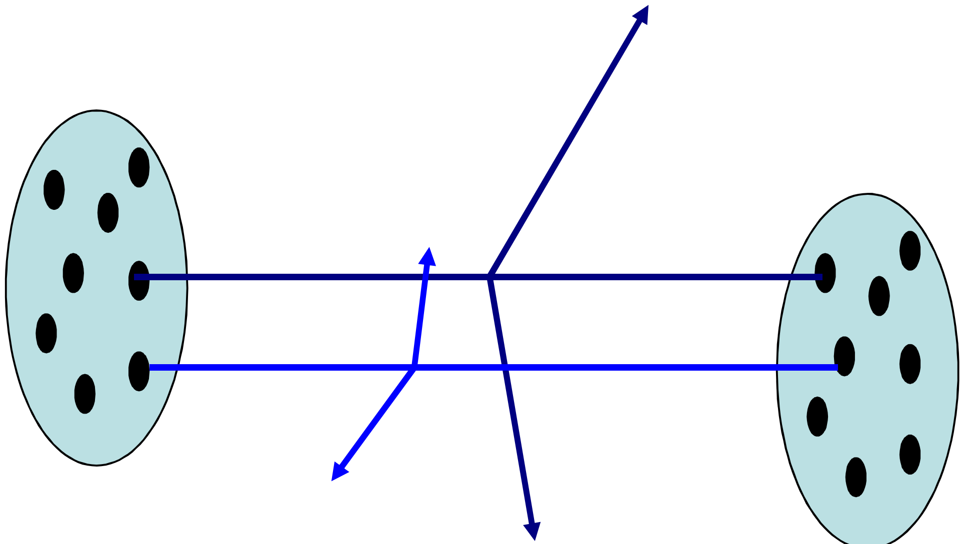


The Underlying Event

- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?



Two models:

- Non-perturbative: Soft parton—parton cross section is so large that the remnants always undergo a soft collision.
- Perturbative: 'Hard' parton—parton cross section huge at low p_t, high energy, dominates inelastic cross section and is calculable.

Matrix Element Matching

Parton shower built on approximations to QCD matrix elements valid in **collinear** and **soft** approximations

→ describe bulk of radiation well → hadronic final state

→ but …

- searches for new physics
- top mass measurement
- *n* jet cross sections
- …

→ hard, well-separated jets

- described better by fixed ("leading") order matrix element
- would also like next-to-leading order normalization

→ need matrix element matching

Multi-jet matching: CKKW

(Catani, Krauss, Kuhn, Webber hep-ph/0109231)

- Impose a matching scale μ
- Generate n-parton matrix elements (for all n) with all parton $p_t > \mu$
- Use jet algorithm to find most likely history
- Reweight by probability of no harder emission
- Parton shower with $p_t < \mu$ to avoid double-counting

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

NLO matching: MC@NLO

(Frixione, Webber hep-ph/0204244)

- Can we supplement parton shower so its normalization is NLO cross section, and hardest emission is exact ?
- Yes: use parton shower as subtraction cross section for NLO calculation in the subtraction scheme – solves double-counting problem
- Downsides:
  - Sub-process cross sections not positive definite
  - Very complicated subtraction term construction
- Used in practice for top, Higgs, W/Z… processes

NLO matching: POWHEG

- Use NLO cross section as hardest emission of a parton shower (Nason, hep-ph/0409146)
- Positive definite
- Needs modified parton (“truncated”) shower (similar to CKKW implementation)
- Implemented for many processes in recent Herwig++ versions

The future: NLO multijet matching ?

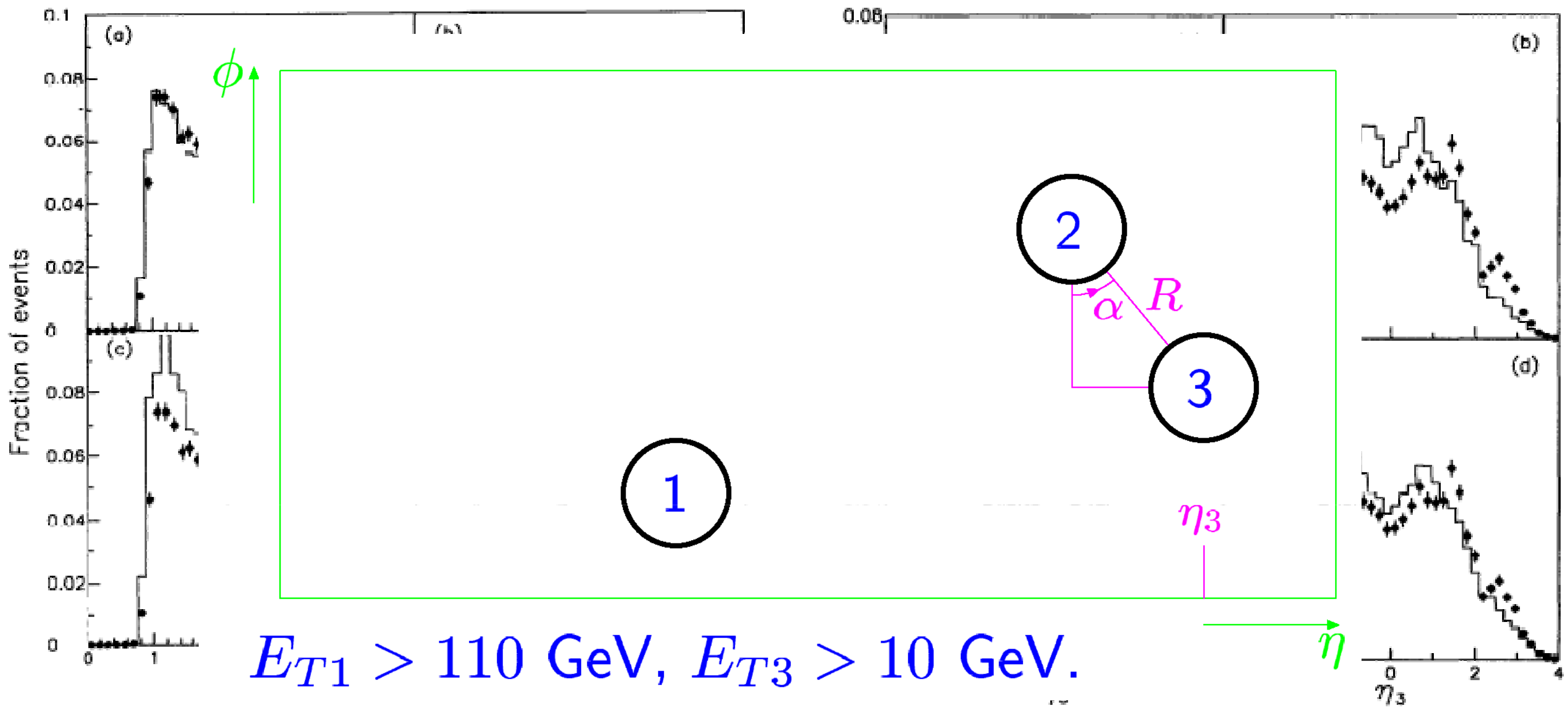
- Nagy & Soper (hep-ph/0503053) showed in principle how to extend CKKW idea to NLO, producing a sample of multijet events matched with NLO matrix element, where available, LO matrix element, where available, fully parton showered
- Needs a much deeper understanding of parton shower algorithm itself beyond leading log
- Practical implementation ?

Summary

- Monte Carlo event generators are needed for nearly every LHC analysis
- Hard process is a direct implementation of perturbation theory
- Parton shower is an approximation to P.T. summing largest contributions to all orders
- Hadronization models are not predictive from first principles, but universal $\Rightarrow$ predictive after tuning
- Matrix element matching: using fixed orders of P.T. to improve all-orders approximation solvable in principle, but theoretically challenging

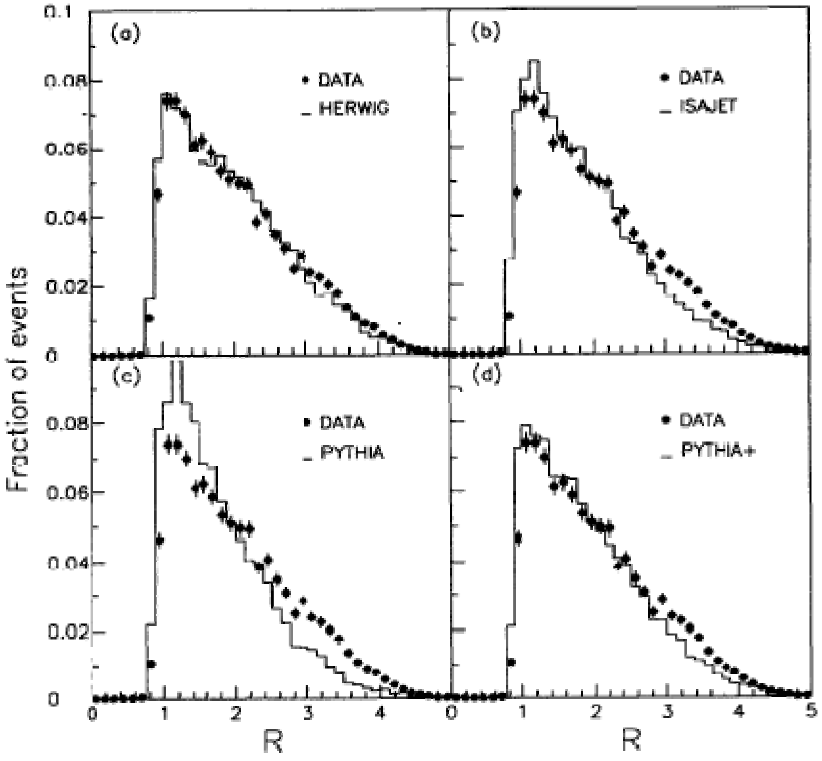
Back-up slides

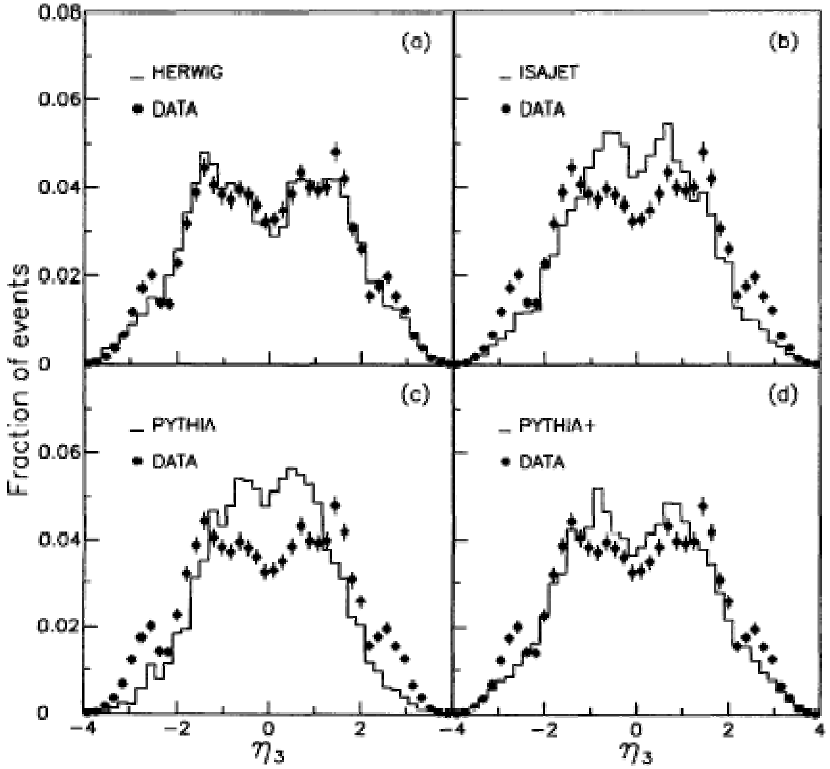
Colour coherence in hard process



$E_{T1} > 110$ GeV, $E_{T3} > 10$ GeV.

Distributions of third-hardest jet in multi-jet events





Distributions of third-hardest jet in multi-jet events

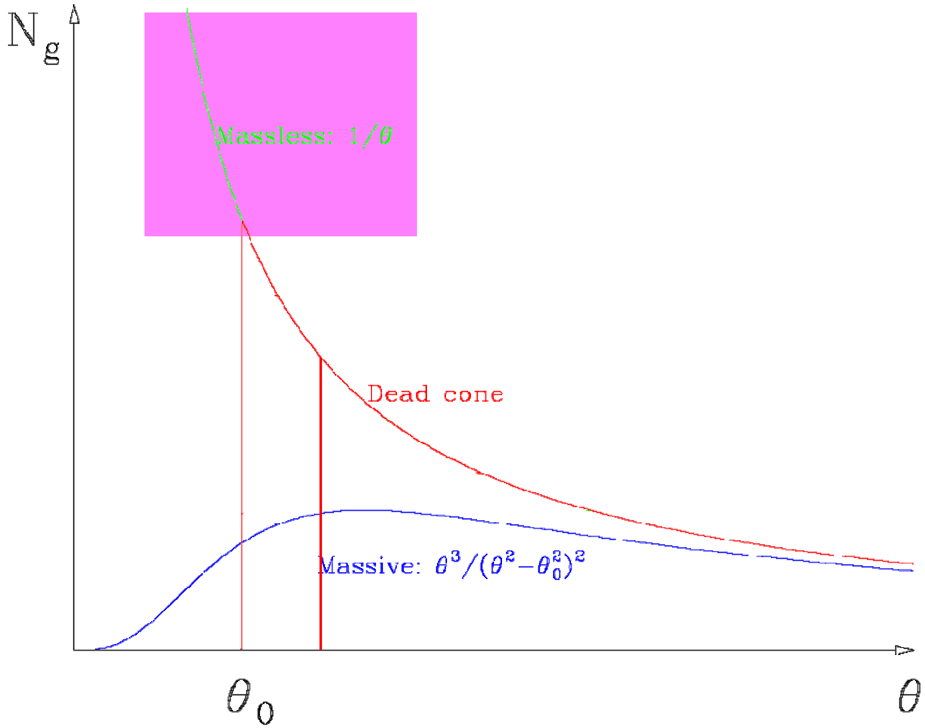
HERWIG has complete treatment of colour coherence, PYTHIA+ has partial

Back-up slides

Masses in parton showers

Heavy Quarks/Spartons

look like light quarks at large angles, sterile at small angles:



approximated as energy-dependent cutoff: $\theta > \theta_0 = \frac{m_q}{E_q}$.

The ‘dead cone’. Too extreme?

Heavy Quarks/Spartons

More properly treated using quasi-collinear splitting:

$$\mathrm{d}\mathcal{P}_{\widetilde{ij}\to ij} = \frac{\alpha_S}{2\pi}\frac{\mathrm{d}\tilde{q}^2}{\tilde{q}^2}\,\mathrm{d}z\,P_{\widetilde{ij}\to ij}\left(z,\tilde{q}\right),$$

$$\begin{aligned}
P_{q\to qg} &= \frac{C_F}{1-z}\left[1+z^2-\frac{2m_q^2}{z\tilde{q}^2}\right], \\
P_{g\to gg} &= C_A\left[\frac{z}{1-z}+\frac{1-z}{z}+z\left(1-z\right)\right], \\
P_{g\to q\bar{q}} &= T_R\left[1-2z\left(1-z\right)+\frac{2m_q^2}{z\left(1-z\right)\tilde{q}^2}\right], \\
P_{\tilde{g}\to\tilde{g}g} &= \frac{C_A}{1-z}\left[1+z^2-\frac{2m_{\tilde{g}}^2}{z\tilde{q}^2}\right], \\
P_{\tilde{q}\to\tilde{q}g} &= \frac{2C_F}{1-z}\left[z-\frac{m_{\tilde{q}}}{z\tilde{q}^2}\right],
\end{aligned}$$

→ smooth suppression in forward region

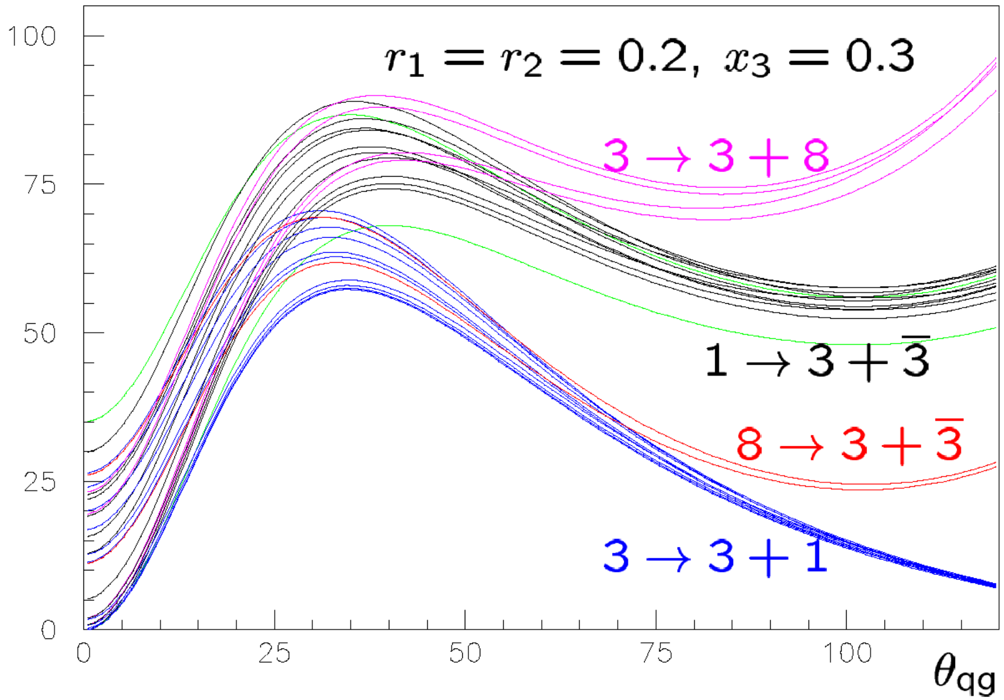
Heavy Quarks/Spartons

- Dead cone only exact for
  - emission from spin-0 particle, or
  - infinitely soft emitted gluon

- In general, depends on
  - energy of gluon
  - colours and spins of emitting particle and colour partner

→ process-dependent mass corrections

colour	spin	γ_5	example
$1 \to 3 + \bar{3}$	—	—	(eikonal)
$1 \to 3 + \bar{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3 + \bar{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$
$1 \to 3 + \bar{3}$	$1 \to 0 + 0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3 + \bar{3}$	$0 \to 0 + 0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$

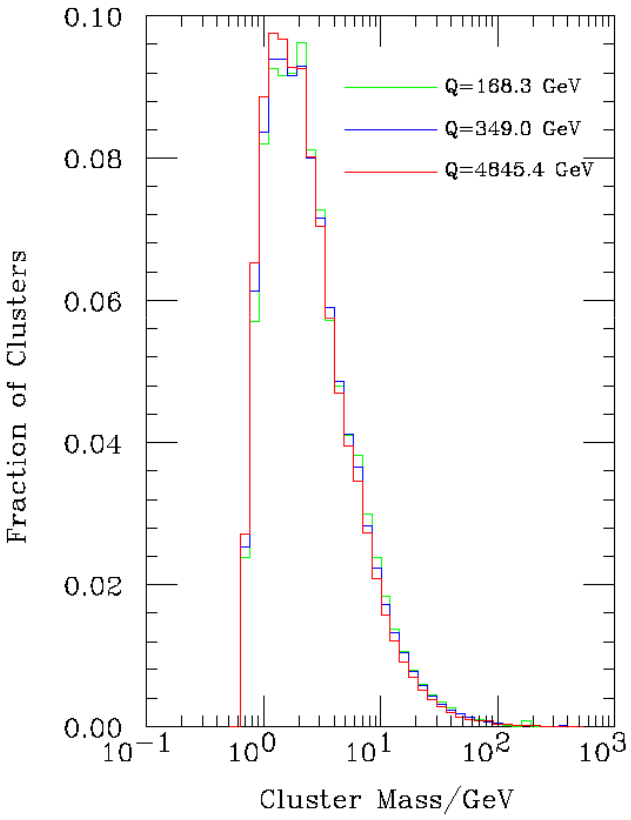


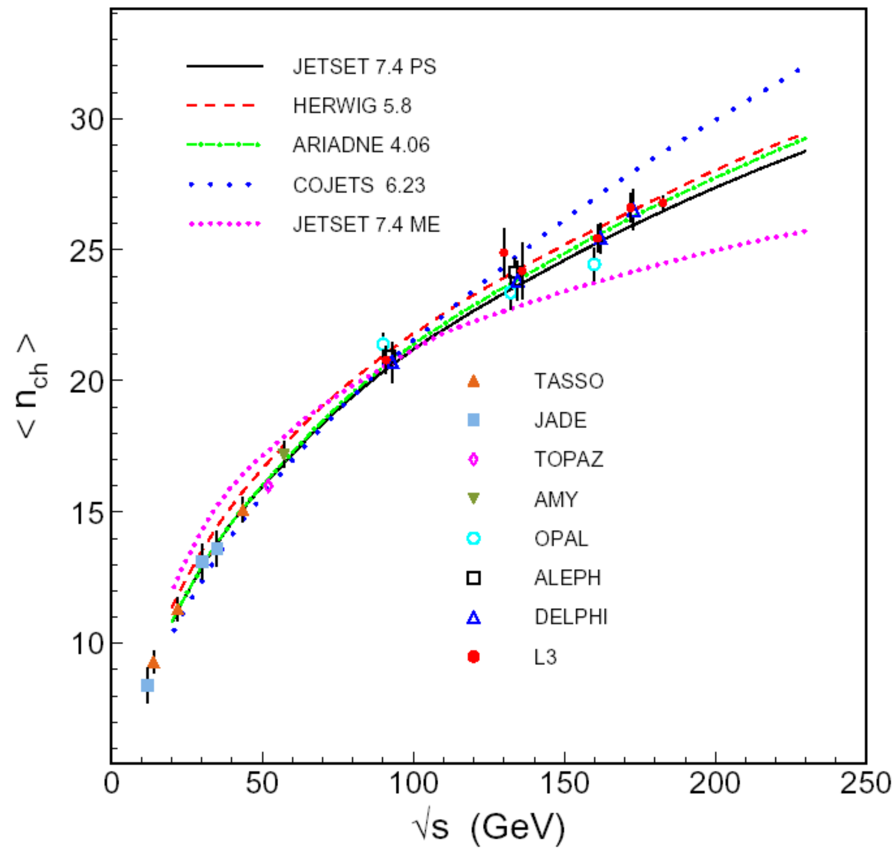
Back-up slides

Universality of hadronization models

Universality of Hadronization Parameters

- Is guaranteed by preconfinement: do not need to retune at each energy





→ Only tune what's new in hadron—hadron collisions