Introduction to Event Generators

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Topics of the lectures

1. Lecture 1: *The Monte Carlo Principle*
2. Lecture 2: *Parton level event generation*
3. Lecture 3: *Dressing the Partons*
4. Lecture 4: *Modelling beyond Perturbation Theory*

Thanks to

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Menu of lecture 4

- Hadronisation models
- Beyond factorisation: Underlying event

Prelude: Orientation

Event generator paradigm

Divide event into stages, separated by different scales.

- Signal/background:

  Exact matrix elements.

- QCD-Bremsstrahlung:

  Parton showers (also in initial state).

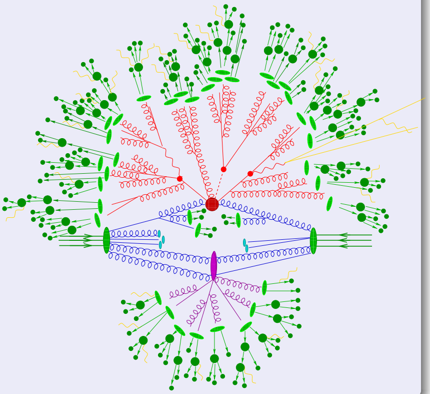
- Multiple interactions:

  Beyond factorisation: Modelling.

- Hadronisation:

  Non-perturbative QCD: Modelling.

Sketch of an event

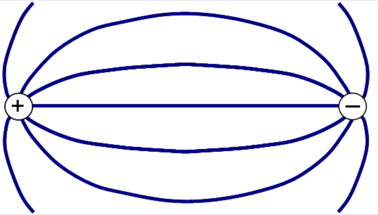


Hadronisation

Confinement

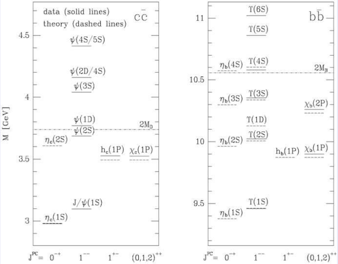
- Consider dipoles in QED and QCD

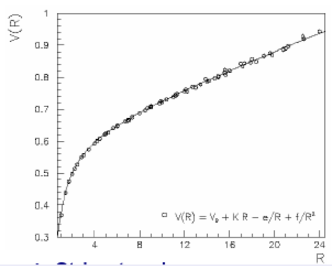
QED:



QCD:

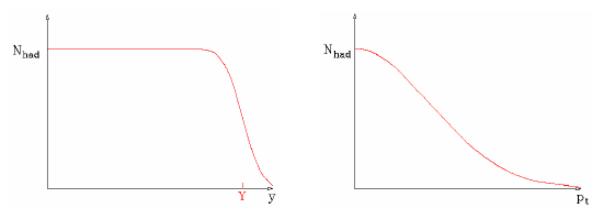
Linear QCD potential in Quarkonia





Some experimental facts → naive parameterisations

- In $e^+e^- \to$ hadrons: Limits $p_\perp$, flat plateau in y.



- Try "smearing": $\rho(p_\perp^2) \sim \exp(-p_\perp^2/\sigma^2)$

Effect of naive parameterisations

- Use parameterisation to "guesstimate" hadronisation effects:

$$
\begin{aligned}
E &= \int_0^Y \mathrm{d}y \mathrm{d}p_\perp^2 \, \rho(p_\perp^2) p_\perp \cosh y = \lambda \sinh Y \\
P &= \int_0^Y \mathrm{d}y \mathrm{d}p_\perp^2 \, \rho(p_\perp^2) p_\perp \sinh y = \lambda(\cosh Y - 1) \approx E - \lambda \\
\lambda &= \int \mathrm{d}p_\perp^2 \, \rho(p_\perp^2) p_\perp = \langle p_\perp \rangle \,.
\end{aligned}
$$

- Estimate $\lambda \sim 1/R_{\mathrm{had}} \approx m_{\mathrm{had}}$, with m_{had} 0.1-1 GeV.
- Effect: Jet acquire non-perturbative mass $\sim 2\lambda E$ ($\mathcal{O}(10\mathrm{GeV})$ for jets with energy $\mathcal{O}(100\mathrm{GeV})$).

Implementation of naive parameterisations

- Feynman-Field independent fragmentation.

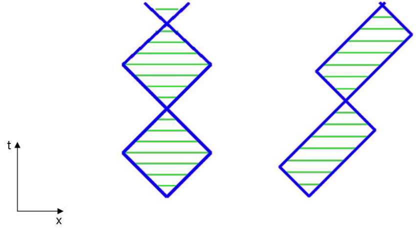
R.D.Field and R.P.Feynman, Nucl. Phys. B **136** (1978) 1

- Recursively fragment $q \to q' +$ had, where
  - Transverse momentum from (fitted) Gaussian;
  - longitudinal momentum arbitrary (hence from measurements);
  - flavour from symmetry arguments + measurements.
- Problems: frame dependent, “last quark”, infrared safety, no direct link to perturbation theory, ...

Yoyo-strings as model of mesons

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

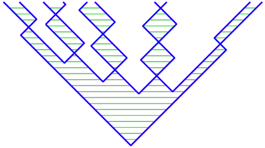
- Light quarks connected by string: area law $m^2 \propto$area.
- L=0 mesons only have 'yo-yo' modes:



Dynamical strings in $e^+e^- \to q\bar{q}$

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

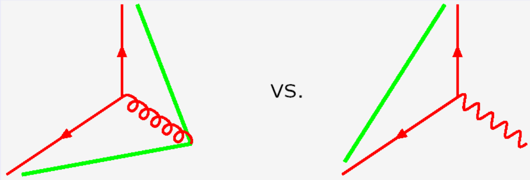
- Ignoring gluon radiation: Point-like source of string.
- Intense chromomagnetic field within string:
  More $q\bar{q}$ pairs created by tunnelling.
- Analogy with QED (Schwinger mechanism):
  $\mathrm{d}\mathcal{P} \sim \mathrm{d}x\mathrm{d}t \exp\left(-\pi m_q^2/\kappa\right)$, $\kappa =$ "string tension".



Gluons in strings = kinks

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

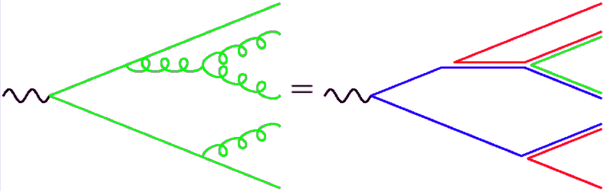
- String model = well motivated model, constraints on fragmentation (Lorentz-invariance, left-right symmetry, ...)
- Gluon = kinks on string? Check by "string-effect"



- Infrared-safe, advantage: smooth matching with PS.

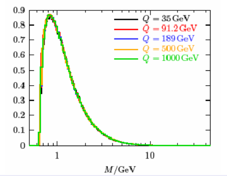
Preconfinement

- Underlying: Large N_c-limit (planar graphs).
- Follows evolution of colour in parton showers: at the end of shower colour singlets close in phase space.
- Mass of singlets: peaked at low scales $\approx Q_0^2$.



Primordial cluster mass distribution

- Starting point: Preconfinement;
- split gluons into $q\bar{q}$-pairs;
- adjacent pairs colour connected, form colourless (white) clusters.
- Clusters ("≈ excited hadrons) decay into hadrons



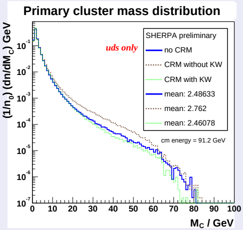
Cluster model

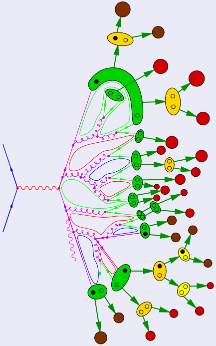
B.R.Webber, Nucl. Phys. B **238** (1984) 492.

- Split gluons into $q\bar{q}$ pairs, form singlet clusters:
  $\Longrightarrow$ continuum of meson resonances.
- Decay heavy clusters into lighter ones;
  (here, many improvements to ensure leading hadron spectrum hard enough, overall effect: cluster model becomes more string-like);
- if light enough, clusters $\to$ hadrons.
- Naively: spin information washed out, decay determined through phase space only $\to$ heavy hadrons suppressed (baryon/strangeness suppression).

Colour reconnections in the cluster model

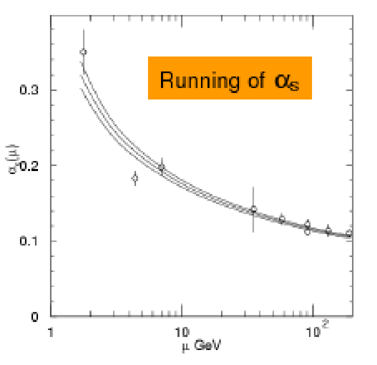
- Maybe toy with phenomenological models of non-perturbative colour reconnection?

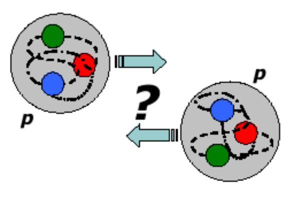




Underlying Event

Multiple parton scattering?



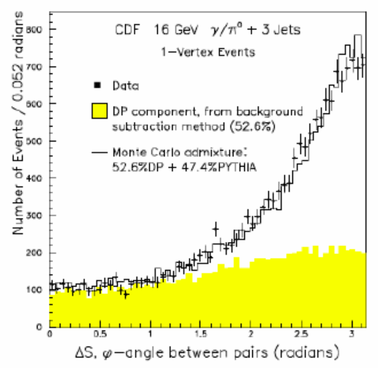


- Hadrons = extended objects!
- No guarantee for one scattering only.
- Running of α_S
  $\Longrightarrow$ preference for soft scattering.

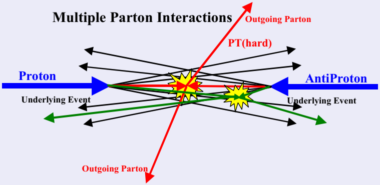
Evidence for multiple parton scattering

- Events with $\gamma + 3$ jets:
  - Cone jets, $R = 0.7$, $E_T > 5$ GeV; $|\eta_j| <1.3$;
  - "clean sample": two softest jets with $E_T < 7$ GeV;
- $\sigma_{\rm DPS} = \frac{\sigma_{\gamma j}\sigma_{jj}}{\sigma_{\rm eff}}$, $\sigma_{\rm eff} \approx 14 \pm 4$ mb.

CDF collaboration, Phys. Rev. **D56** (1997) 3811.



Definition(s)



1. Everything apart from the hard interaction including IS showers, FS showers, remnant hadronisation.
2. Remnant-remnant interactions, soft and/or hard.
3. Lesson: hard to define

Model: Multiple parton interactions

- To understand the origin of MPS, realism that

$$\sigma_{\rm hard}(p_{\perp,\rm min}) = \int\limits_{p^2_{\perp,\rm min}}^{s/4} {\rm d}p_\perp^2 \frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} > \sigma_{pp,\rm total}$$

for low $p_{\perp,\rm min}$. Here: $\frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} = \int\limits_0^1 {\rm d}x_1{\rm d}x_2{\rm d}\hat{t} f(x_1,\,q^2)f(x_2,\,q^2)\frac{{\rm d}\hat{\sigma}_{2\to 2}}{{\rm d}p_\perp^2}\delta\left(1-\frac{\hat{t}\hat{u}}{\hat{s}}\right)$

($f(x,\,q^2)$ =PDF, $\hat{\sigma}_{2\to 2}$ =parton-parton x-sec)

- $\langle\sigma_{\rm hard}(p_{\perp,\rm min})/\sigma_{pp,\rm total}\rangle \geq 1$
- Depends strongly on cut-off $p_{\perp,\rm min}$ (Energy-dependent)!

Old Pythia model: Algorithm, simplified

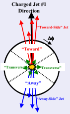
T.Sjostrand and M.van Zijl, Phys. Rev. D **36** (1987) 2019.

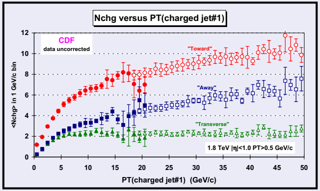
- Start with hard interaction, at scale $Q^2_{\rm hard}$.
- Select a new scale $p_\perp^2$

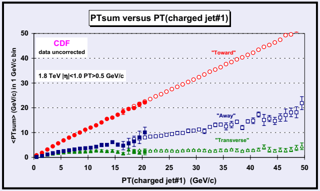
  (according to $f = \frac{\mathrm{d}\sigma_{2\to 2}(p_\perp^2)}{\mathrm{d}p_\perp^2}$ with $p_\perp^2 \in [p^2_{\perp,\rm min},\, Q^2]$)
- Rescale proton momentum ("proton-parton = proton with reduced energy").
- Repeat until below $p^2_{\perp,\rm min}$.
- May add impact-parameter dependence, showers, etc..
- Treat intrinsic $k_\perp$ of partons ($\longrightarrow$ parameter)
- Model proton remnants ($\longrightarrow$ parameter)

Observables

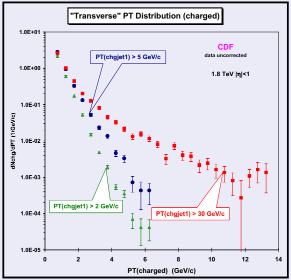
In the following: Data from CDF, PRD 65 (2002) 092002, plots partially from C.Buttar

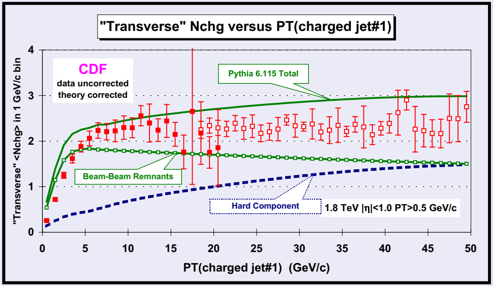




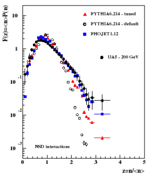


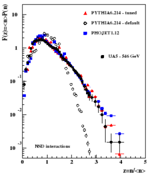
Hard component in transverse region

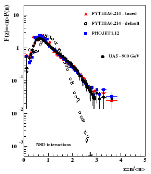


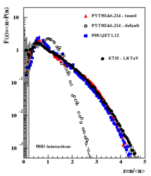


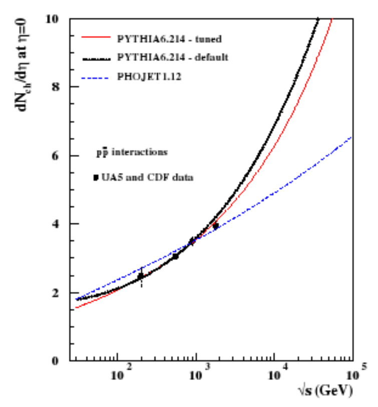
Energy extrapolation











General facts on current models

- No first-principles approach for underlying event:

  Multiple-parton interactions: beyond factorisation

  Factorisation (simplified) = no process-dependence in use of PDFs.

- Models usually based on xsecs in collinear factorisation: $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto p_\perp^{4-8} \implies$ strong dependence on cut-off $p_\perp^{\min}$.
- "Regularisation": $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto (p_\perp^2 + p_0^2)^{2-4}$, also in α_S.
- Model for scaling behaviour of $p_\perp^{\min}(s) \propto p_\perp^{\min}(s_0)(s/s_0)^\lambda$, $\lambda =?$

  Two Pythia tunes: $\lambda = 0.16$, $\lambda = 0.25$.

- Herwig model similar to old Pythia and SHERPA
- New Pythia model: Correlate parton interactions with showers, more parameters.

Summary of lecture 4

- Hadronisation
  - Various phenomenological models;
  - tuned to LEP data, overall agreement satisfying;
  - validity for hadron data not quite clear.

(beam remnant fragmentation not in LEP.)

- Underlying event
  - Theoretically not understood;
  - models typically based on collinear factorisation and semi-independent multi-parton scattering;
  - models highly parameter-dependent, leading to large differences in predictions;
  - even unclear: good observables to distinguish models.