

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

- My fellow MC authors, especially S.Gieseke, K.Hamilton, L.Lonnblad, F.Maltoni, M.Mangano, P.Richardson, M.Seymour, T.Sjostrand, B.Webber.
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Menu of lecture 4

- Hadronisation models
- Beyond factorisation: Underlying event

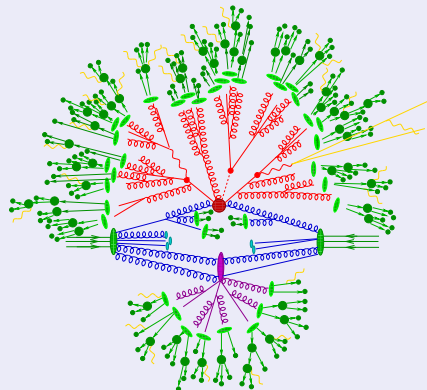
Prelude: Orientation

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

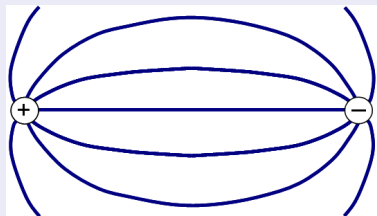


Hadronisation

Confinement

- Consider dipoles in QED and QCD

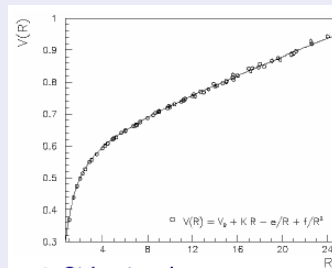
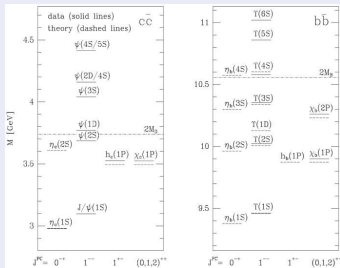
QED:



QCD:

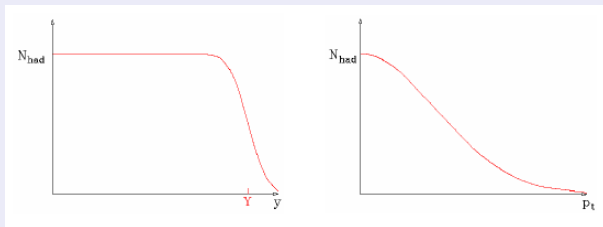


Linear QCD potential in Quarkonia



Some experimental facts $\rightarrow$ naive parameterisations

- In $e^+e^- \rightarrow$ 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:

$$E = \int_0^Y dy d p_{\perp}^2 \rho(p_{\perp}^2) p_{\perp} \cosh y = \lambda \sinh Y$$

$$P = \int_0^Y dy d p_{\perp}^2 \rho(p_{\perp}^2) p_{\perp} \sinh y = \lambda (\cosh Y - 1) \approx E - \lambda$$

$$\lambda = \int d p_{\perp}^2 \rho(p_{\perp}^2) p_{\perp} = \langle p_{\perp} \rangle .$$

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

Implementation of naive parameterisations

- Feynman-Field independent fragmentation.

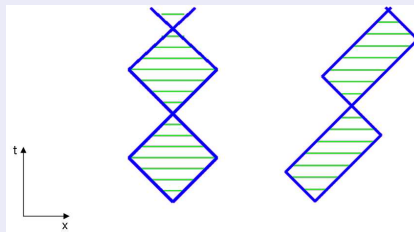
R.D.Field and R.P.Feynman, Nucl. Phys. B **136** (1978) 1

- Recursively fragment $q \rightarrow q' + \text{had}$, 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.

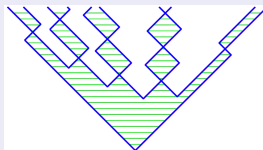
- Light quarks connected by string: area law $m^2 \propto \text{area}$.
- $L=0$ mesons only have 'yo-yo' modes:



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

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

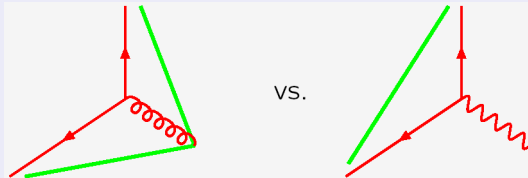
- Ignoring gluon radiation: Point-like source of string.
- Intense chromomagnetic field within string:
More $q\bar{q}$ pairs created by tunnelling.
- Analogy with QED (Schwinger mechanism):
 $d\mathcal{P} \sim dxdt \exp(-\pi m_q^2/\kappa)$, $\kappa =$ “string tension”.



Gluons in strings = kinks

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

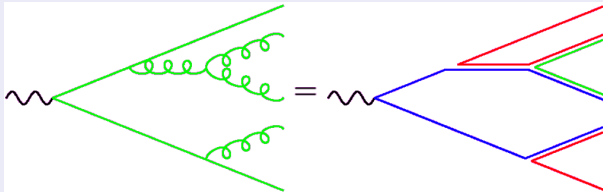
- String model = well motivated model, constraints on fragmentation
(Lorentz-invariance, left-right symmetry, ...)
- Gluon = kinks on string? Check by “string-effect”



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

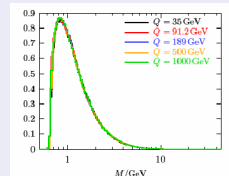
Preconfinement

- 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 (" $\approx$ excited hadrons) decay into hadrons



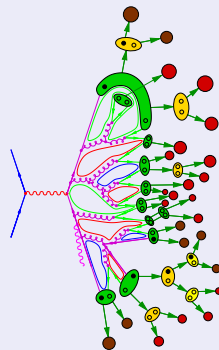
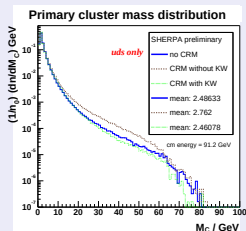
Cluster model

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

- Split gluons into $q\bar{q}$ pairs, form singlet clusters:
 $\implies$ 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 $\rightarrow$ hadrons.
- Naively: spin information washed out, decay determined through phase space only $\rightarrow$ heavy hadrons suppressed (baryon/strangeness suppression).

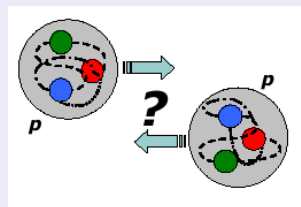
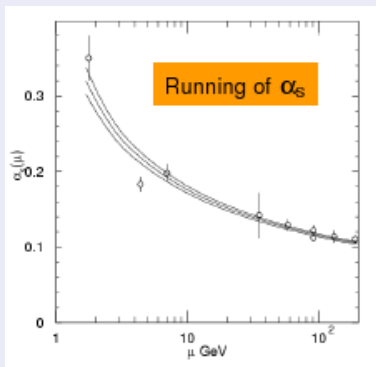
Colour reconnections in the cluster model

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



Underlying Event

Multiple parton scattering?

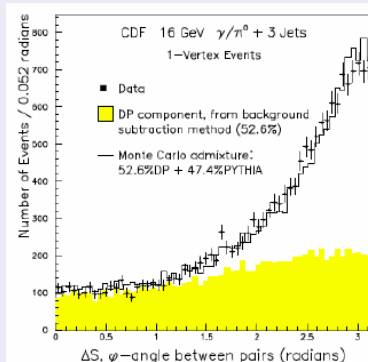


- Hadrons = extended objects!
- No guarantee for one scattering only.
- Running of α_s
 $\Rightarrow$ preference for soft scattering.

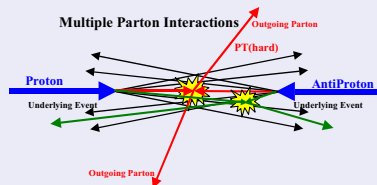
Evidence for multiple parton scattering

- 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;
- $\sigma_{\text{DPS}} = \frac{\sigma_{\gamma j} \sigma_{jj}}{\sigma_{\text{eff}}}$,
 $\sigma_{\text{eff}} \approx 14 \pm 4$ 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

$$\sigma_{\text{hard}}(p_{\perp,\text{min}}) = \int_{p_{\perp,\text{min}}^2}^{s/4} dp_{\perp}^2 \frac{d\sigma(p_{\perp}^2)}{dp_{\perp}^2} > \sigma_{pp,\text{total}}$$

for low $p_{\perp,\text{min}}$. Here: $\frac{d\sigma(p_{\perp}^2)}{dp_{\perp}^2} = \int_0^1 dx_1 dx_2 d\hat{t} f(x_1, q^2) f(x_2, q^2) \frac{d\hat{\sigma}_{2 \rightarrow 2}}{dp_{\perp}^2} \delta\left(1 - \frac{\hat{t}\hat{u}}{\hat{s}}\right)$
 ($f(x, q^2)$ = PDF, $\hat{\sigma}_{2 \rightarrow 2}$ = parton-parton x-sec)

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

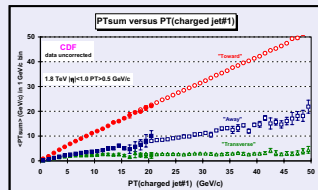
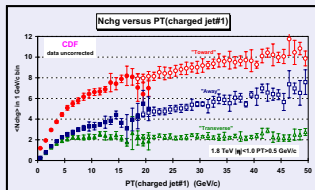
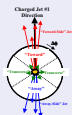
Old Pythia model: Algorithm, simplified

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

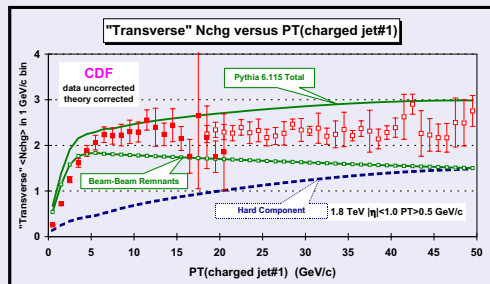
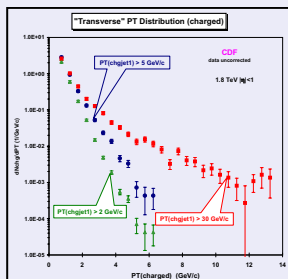
- Start with hard interaction, at scale Q_{hard}^2 .
- Select a new scale $p_{\perp}^2$
(according to $f = \frac{d\sigma_{2\rightarrow 2}(p_{\perp}^2)}{dp_{\perp}^2}$ with $p_{\perp}^2 \in [p_{\perp,\text{min}}^2, Q^2]$)
- Rescale proton momentum ("proton-parton = proton with reduced energy").
- Repeat until below $p_{\perp,\text{min}}^2$.
- May add impact-parameter dependence, showers, etc..
- Treat intrinsic $k_{\perp}$ of partons ($\rightarrow$ parameter)
- Model proton remnants ($\rightarrow$ parameter)

Observables

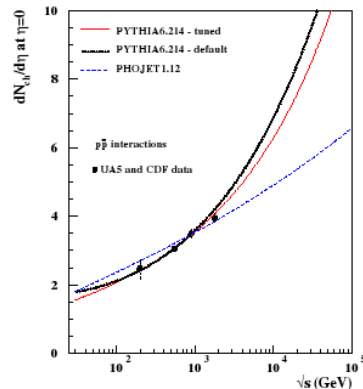
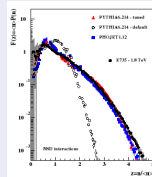
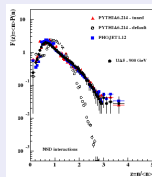
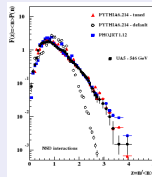
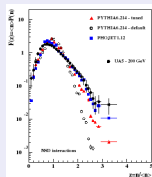
In the following: Data from CDF, PRD 65 (2002) 092002, plots partially from C. Buttar



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:
 $d\sigma/dp_{\perp} \propto p_{\perp}^{4-8} \implies$ strong dependence on cut-off $p_{\perp}^{\min}$.
- “Regularisation”: $d\sigma/dp_{\perp} \propto (p_{\perp}^2 + p_0^2)^{2-4}$, 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.