QCD & Monte Carlo Tools

Frank Krauss

Institute for Particle Physics Phenomenology
Durham University

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Topics of the lectures

1. Lecture 1: *The Monte Carlo Principle*
   - Monte Carlo as integration method
   - Hard physics simulation: Parton Level event generation
2. Lecture 2: *Dressing the Partons*
   - Hard physics simulation, cont'd: Parton Showers
3. Lecture 3: *Modelling beyond Perturbation Theory*
   - Hadronic initial states: PDFs
   - Soft physics simulation: Hadronization
   - Beyond factorization: Underlying Event
4. Lecture 4: *Higher Orders in Monte Carlos*
   - Some nomenclature: Anatomy of HO calculations
   - Merging vs. Matching

Thanks to

- the other Sherpas: T.Gleisberg, S.Höche, S.Schumann, F.Siegert, M.Schönherr, J.Winter;
- other MC authors: S.Gieseke, K.Hamilton, L.Lonnblad, F.Maltoni, M.Mangano, P.Richardson, M.Seymour, T.Sjostrand, B.Webber, ...

Simulation's paradigm

Basic strategy

Divide event into stages, separated by different scales.

- Signal/background:

  Exact matrix elements.

- QCD-Bremsstrahlung:

  Parton showers (also in initial state).

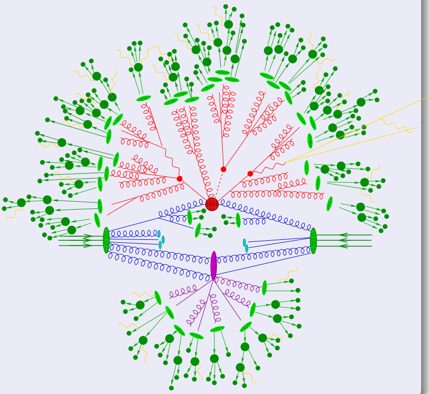
- Multiple interactions:

  Beyond factorization: Modeling.

- Hadronization:

  Non-perturbative QCD: Modeling.

Sketch of an event



Outline of today's lecture

- PDFs and factorization
- Hadronization models
- Beyond factorization: Underlying event

PDFs and factorization

Parton picture

- Parton picture: Hadrons made from partons.
- Distribution(s) of partons in hadrons not from first principles, only from measurements.
- First idea: probability to find parton a in hadron h only dependent on Bjorken-x ($x = E_a/E_h$ or similar) $\mathcal{P}(a|h) = f_a^h(x)$ (LO interpretation of PDF).
- But QCD: Partons in partons in partons
  $\Longrightarrow$ scaling behavior of PDFs: $f = f(x, Q^2)$.
- Still: PDFs must be measured, but scaling in Q^2 from theory (DGLAP, resums large logs of Q^2)

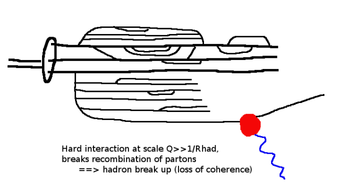
PDFs and factorization

Space-time picture of hard interactions

Partons "collinear" with hadron: $k_\perp \ll 1/R_{\rm had}$.

Lifetime of partons $\tau \sim 1/x$, $r \sim 1/Q$.

Hard interaction at scales $Q_{\rm hard} \gg 1/R_{\rm had}$.



- Too "fast" for color field - only one parton takes part.
- Other partons feel absence only when trying to recombine.
- Universality (process-independence) of PDFs.
- Collinear factorization.

PDFs and factorization

Determination of PDFs: Strategy in a nutshell

- Ansatz $g(x)$ for PDFs at some fixed value of $Q_0^2 = Q^2 \approx 1\mathrm{GeV}^2$.
  For example, MRST (personal bias):

$$
\begin{aligned}
xu_v &= A_u x^{\eta_1}(1-x)^{\eta_2}(1+\varepsilon_u\sqrt{x}+\gamma_u x)\\
xu_v &= A_d x^{\eta_2}(1-x)^{\eta_4}(1+\varepsilon_d\sqrt{x}+\gamma_d x)\\
xu_v &= A_S x^{-\lambda_S}(1-x)^{\eta_S}(1+\varepsilon_S\sqrt{x}+\gamma_S x)\\
xu_v &= A_g x^{-\lambda_g}(1-x)^{\eta_g}(1+\varepsilon_g\sqrt{x}+\gamma_g x)
\end{aligned}
$$

- Collect data at various x, Q^2, use DGLAP equation to evolve down to Q_0^2 and fit parameters (including α_S).
- Ensure sum rules (Gottfried, momentum, ...).

PDFs and factorization

Determination of PDFs: Data input

Example: MSTW parameterization and their effect:

New data included.

NuTeV and Chorus data on $F_2^{\nu,\bar{\nu}}(x,Q^2)$ and $F_3^{\nu,\bar{\nu}}(x,Q^2)$ replacing CCFR.

NuTeV and CCFR dimuon data included directly. Leads to a direct constraint on $s(x,Q^2)+\bar{s}(x,Q^2)$ and on $s(x,Q^2)-\bar{s}(x,Q^2)$. Affects other partons.

CDFII lepton asymmetry data in two different E_T bins – $25\text{GeV} < E_T < 35\text{GeV}$ and $35\text{GeV} < E_T < 45\text{GeV}$.

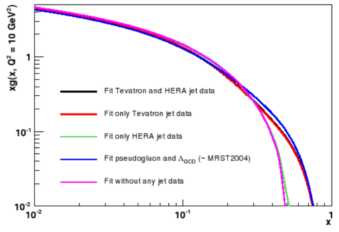
HERA inclusive jet data (in DIS).

New CDFII high-E_T jet data.

Direct high-x data on $F_L(x,Q^2)$.

Update to include all recent charm structure function data.

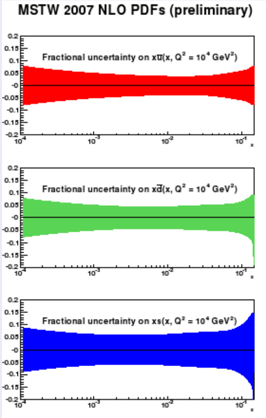
Look at dependence of fit on m_c – defined as pole mass.

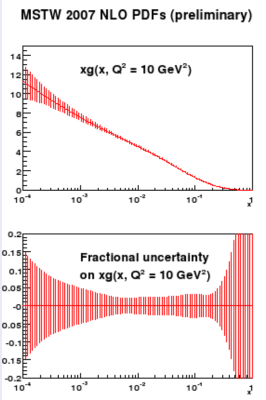


(From R.Thorne's talk at DIS 2007)

PDFs and factorization

Uncertainties of global PDFs



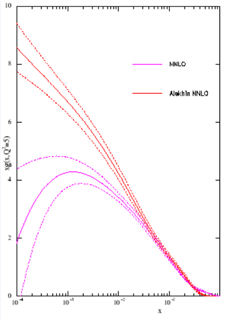


(From R.Thorne's talk at DIS 2007)

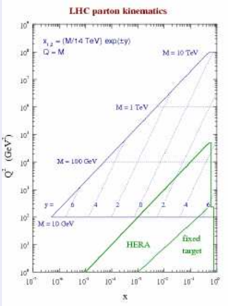
PDFs and factorization

Effect of different input: DIS only vs. global

MSTW vs. Alekhin's NNLO parameterization



Compare with kinematical coverage



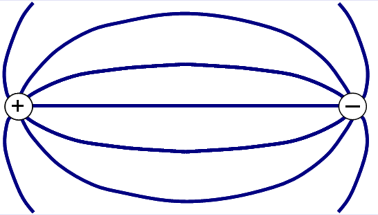
(From R.Thorne's talk at DIS 2007)

Hadronization

Confinement

- Consider dipoles in QED and QCD

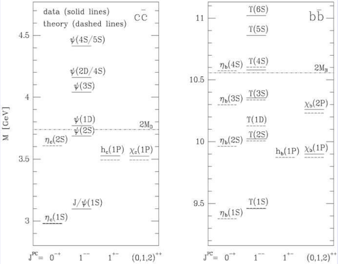
QED:

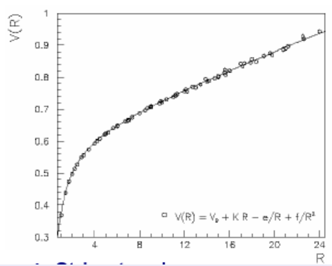


QCD:

Hadronization

Linear QCD potential in quarkonia

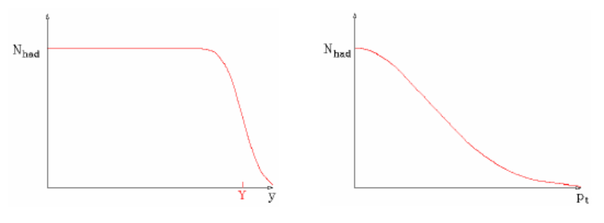




Hadronization

Some experimental facts $\longrightarrow$ naive parameterizations

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



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

Hadronization

Effect of naive parameterizations

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

Hadronization

Implementation of naive parameterizations

- Feynman-Field independent fragmentation.

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

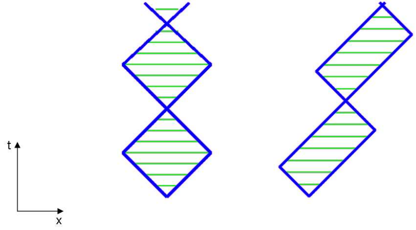
- Recursively fragment $q \to q' +$ had, where
  - Transverse momentum from (fitted) Gaussian;
  - longitudinal momentum arbitrary (hence from measurements);
  - flavor from symmetry arguments + measurements.
- Problems: frame dependent, "last quark", infrared safety, no direct link to perturbation theory,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

Hadronization

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:

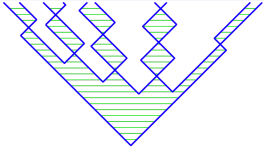


Hadronization

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".

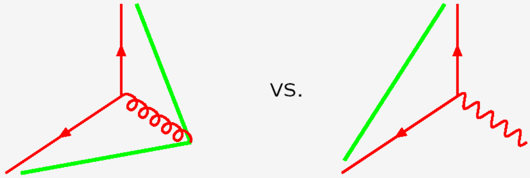


Hadronization

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"

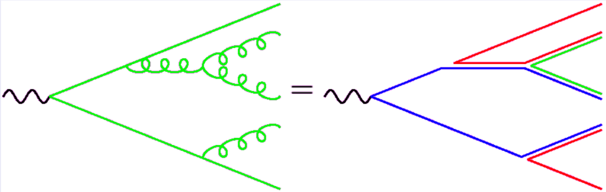


- Infrared-safe, advantage: smooth matching with PS.

Hadronization

Preconfinement

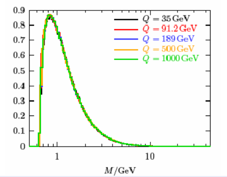
- Underlying: Large N_c-limit (planar graphs).
- Follows evolution of color in parton showers: at the end of shower color singlets close in phase space.
- Mass of singlets: peaked at low scales $\approx Q_0^2$.



Hadronization

Primordial cluster mass distribution

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



Hadronization

Cluster model

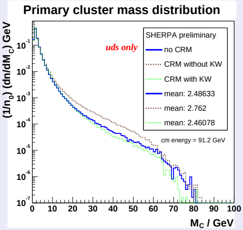
B.R.Webber, Nucl. Phys. B **238** (1984) 492.

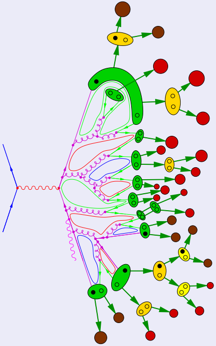
- Split gluons into $q\bar{q}$ pairs, form singlet clusters:
  $\Longrightarrow$ continuum of meson resonances.
- Decay heavy clusters into lighter ones;
  (here, many improvements to ensure leading hadron spectrum hard enough, overall effect: cluster model becomes more string-like);
- if light enough,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

Hadronization

Color reconnections in the cluster model

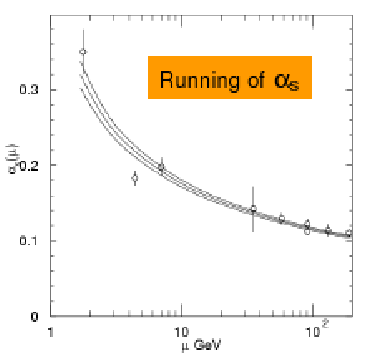
- Maybe toy with phenomenological models of non-perturbative color reconnection?

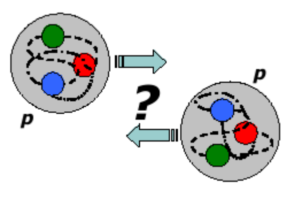




Underlying Event

Multiple parton scattering?





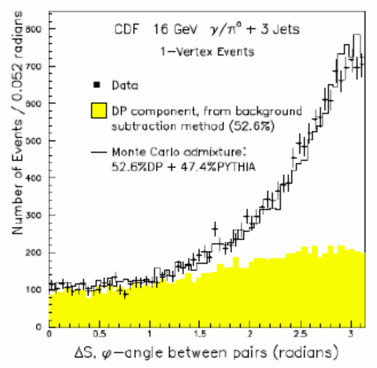
- Hadrons = extended objects!
- No guarantee for one scattering only.
- Running of α_S
  $\Longrightarrow$ preference for soft scattering.

Underlying Event

Evidence for multiple parton scattering

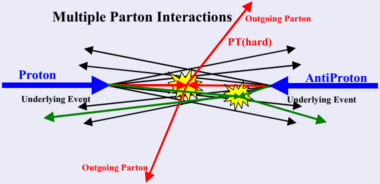
- Events with $\gamma + 3$ jets:
  - Cone jets, $R = 0.7$, $E_T > 5$ GeV; $|\eta_j| < 1.3$;
  - "clean sample": two softest jets with $E_T < 7$ GeV;
- $\sigma_{\rm DPS} = \frac{\sigma_{\gamma j}\sigma_{jj}}{\sigma_{\rm eff}}$, $\sigma_{\rm eff} \approx 14 \pm 4$ mb.

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



Underlying Event

Definition(s)



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

Underlying event

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: $\frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} = \int\limits_0^1 {\rm d}x_1{\rm d}x_2{\rm d}\hat{t} f(x_1,\, q^2) f(x_2,\, q^2) \frac{{\rm d}\hat{\sigma}_{2\to2}}{{\rm d}p_\perp^2}\delta\left(1 - \frac{\hat{t}\hat{u}}{\hat{s}}\right)$

($f(x,q^2)$ =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)!

Underlying event

Old Pythia model: Algorithm, simplified

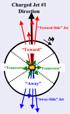
T.Sjostrand and M.van Zijl, Phys. Rev. D **36** (1987) 2019.

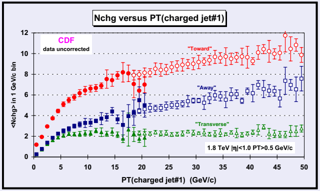
- Start with hard interaction, at scale $Q^2_{\rm hard}$.
- Select a new scale $p_\perp^2$
  (according to $f = \frac{{\rm d}\sigma_{2\to 2}(p_\perp^2)}{{\rm d}p_\perp^2}$ with $p_\perp^2 \in [p^2_{\perp,\rm min},\, Q^2]$)
- Rescale proton momentum ("proton-parton = proton with reduced energy").
- Repeat 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)

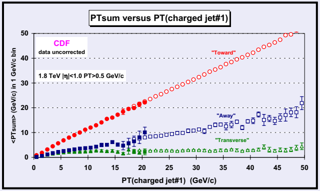
Underlying Event

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

Observables

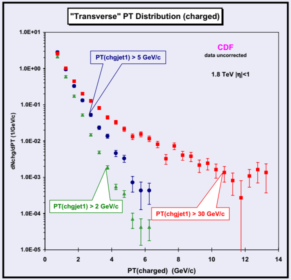


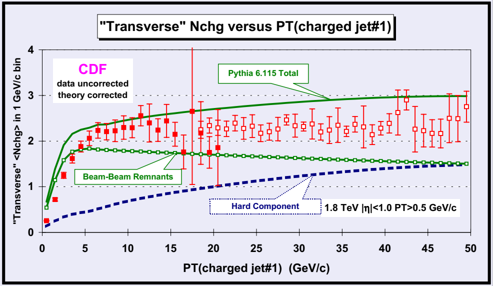




Underlying event

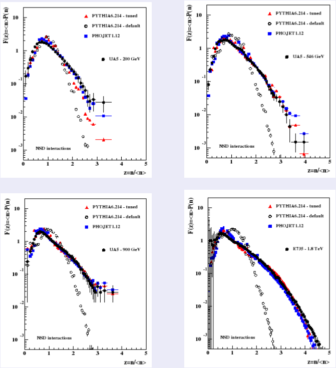
Hard component in transverse region

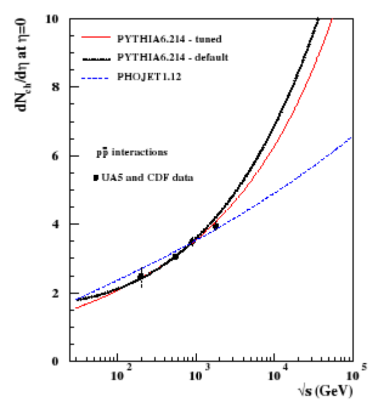




Underlying event

Energy extrapolation





Underlying event

General facts on current models

- No first-principles approach for underlying event:

  Multiple-parton interactions: beyond factorization

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

- Models usually based on xsecs in collinear factorization: $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto p_\perp^{4-8} \implies$ strong dependence on cut-off $p_\perp^{\min}$.
- "Regularization": $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto (p_\perp^2 + p_0^2)^{2-4}$, also in α_S.
- Model for scaling behavior 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 so far

1. Hard MEs:
   - Theoretically very well understood, realm of perturbation theory.
   - Fully automated tools at tree-level available, $2 \to 6$ no problem at all.
   - Obstacle for higher multiplicities: factorial growth, phase space integration.
   - NLO calculations much more involved, no fully automated tool, only libraries for specific processes (MCFM, NLOJET++), typically up to $2 \to 3$.
   - NNLO only for a small number of processes.

Summary so far

1. Parton showers:
   - Theoretically well understood, still in realm of perturbation theory, but beyond fixed order.
   - Consistent treatment of leading logs in soft/collinear limit, formally equivalent formulations lead to different results because of non-trivial choices (evolution parameter, etc.).

Summary so far

1. PDFs
   - Important input for cross section calculations at hadron colliders;
   - scaling behavior theoretically well understood, but input data needed;
   - selection of input data and cuts crucial - leads to significant differences.
   - Kinematical coverage of LHC and HERA quite different; may lead to extrapolation errors.

Summary so far

1. Hadronization
   - Various phenomenological models;
   - different levels of sophistication, different number of parameters;
   - tuned to LEP data, overall agreement satisfying;
   - validity for hadron data not quite clear - differences possible (beam remnant fragmentation not in LEP).

Summary so far

1. Underlying event
   - Various definitions for this phenomenon.
   - Theoretically not understood, in fact: beyond theory understanding (breaks factorization);
   - models typically based on collinear factorization and semi-independent multi-parton scattering
     $\Longrightarrow$ very naive;
   - models highly parameter-dependent, leading to large differences in predictions;
   - connection to minimum bias, diffraction etc.?
   - even unclear: good observables to distinguish models.