Perturbative QCD for collider physics

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Foreword

- QCD is a well-established theory that describes the real world.
- Strongly coupled field theory at work.
- Large body of beautiful theoretical and experimental results, that are classical by now.
- Many non-perturbative aspects are still only vaguely understood.
- QCD as a service subject.
- Focus of this talk: aspects of QCD relevant for the LHC.
Outline

• Introduction
  ○ Challenges at the LHC

• Leading order matrix elements and parton showers
  ○ Showers vs. exact LO matrix elements
  ○ CKKW procedure and examples

• NLO
  ○ successes and problems
  ○ examples
  ○ MC@NLO

• NNLO
  ○ PDFs
  ○ $Z, W$ production
  ○ Higgs production at the LHC

• Conclusions
Introduction: challenges

• **High luminosity and high energy** of the LHC lead to large rates for multijet processes not explored at the Tevatron and elsewhere.

• Multijet processes at the LHC are backgrounds to New Physics; their understanding is essential for the successful LHC physics program.

• Accurate description of strong interactions is the goal of pQCD.

• Various approaches:
  - parton shower event generators (PYTHIA, HERWIG, etc.);
  - resummations (RESBOS);
  - fixed order computations (LO, NLO, NNLO);
  - combinations of the above (CKKW, MC@NLO).

• Different domains of applicability:
  - parton showers (resummations) are valid at the edges of phase-space;
  - fixed order computations in the bulk of the phase-space;

• They differ in “user-friendliness”:
  - compare all-purpose, easy-to-use shower event generators to fixed order computations performed case-by-case.
Introduction: challenges

- The user-friendliness of event generators makes them the default choice for many analysis (experimental; New Physics backgrounds estimates).

- Significant part of recent research in pQCD for collider physics is devoted to understanding regions of applicability of various approaches.

- This is done by
  - tuning parameters in parton showers and/or merging them with LO and NLO computations;
  - comparing LO and NLO computations to data;

- Other important topics in pQCD for collider physics:
  - extraction of parton distribution functions (CTEQ, MRST, Alekhin);
  - NLO computations for higher multiplicity processes;
  - NNLO computations: general algorithms and phenomenology.
Introduction: jumping to conclusions

- Shower event generators should not be used beyond their region of applicability.
- LO + shower approach (CKKW) works quite well for the Tevatron data. The approach is parametric; every reason to believe that it will be successful for the LHC.
- NLO works. We need better methods to deal with NLO QCD for high multiplicity processes. We need better qualitative understanding of NLO effects: when are they large? when do they change kinematic distributions?
- Realistic NNLO phenomenology is emerging.
- For central rapidities and typical mass scales $M \sim 100$ GeV, we have reliable PDFs. Many new measurements from the Tevatron will further constrain them.
- In the rest of the talk, I will discuss those points and elaborate on them.
- I will not discuss (so far) pure theoretical developments in pQCD. For this reason, no twistor-based or twistor-inspired methods for tree-level and loop computations; no SCET applications for collider physics; no general techniques for NNLO computations.
Parton showers and exact LO matrix elements

- All-purpose shower event generators such as PYTHIA and HERWIG are default choices for many studies. Are these studies reliable?
- Parton showers are based on collinear emissions.
- Collinear emissions are independent $\Rightarrow$ probabilistic description.
- Showers are good for processes dominated by soft/collinear radiation; typically this occurs at the phase-space boundaries.
- Showers generate large transverse momenta by emissions of many jets with moderate $p_{\perp} \Rightarrow \alpha_s$ suppression of high $p_{\perp}$ radiation.
- Showers do not change normalizations of total cross-sections
  \[
  \int d\sigma_{\text{LO}} \times \text{PS} = \sigma_{\text{LO}}.
  \]
- An alternative: exact LO matrix elements. LO matrix elements should be a reasonable description in the bulk of phase-space, away from kinematic boundaries. Exact kinematics; good for high $p_{\perp}$ physics.
Parton showers and exact LO matrix elements

\[ M_{\text{eff}} = \sum_{\text{jets}} p_{\perp} + E_{\perp}^{\text{miss}} \]

- ALPGEN: exact LO matrix elements; correct hard emissions built in.
- PYTHIA: emulates hard emissions by producing large number of softer jets.
- PYTHIA underestimates the background significantly.
Parton showers and exact ME: isolated photons in DIS

- Production of isolated photons in $e^\pm p$ collisions was studied by ZEUS collaboration.
  
  
  \[ \begin{align*}
  &e^\pm p \rightarrow q\gamma \rightarrow \gamma p \\
  &e^\pm p \rightarrow q\gamma \rightarrow \gamma q
  \end{align*} \]

- HERWIG (PYTHIA) cross-section is smaller than experimental result by factor 7.9 (2.3).
- PYTHIA lacks photon emission off leptons; HERWIG lacks photon emissions off quarks.
- Simple LO computation gets both effects and leads to the correct description of data.

Gehrmann, Gehrmann-de Ridder, Poulsen
Combining showers and LO matrix elements

• An $N+1$-jet event is obtained from an $N$-jet event either by 
  
  large angle hard emission or shower.

• Event generators can do a better job for multi-jet processes if both mechanisms are taken into account.

• Catani-Krauss-Kuhn-Webber (CKKW) procedure:
  
  ◦ calculate $pp \to m$ HARD jets, with $m < N$. Determine probability of an event with $m$ hard jets using the cross-section values, 

  \[
  P_m = \frac{\sigma_m}{\sigma_0 + \sigma_1 + \sigma_2 + ... + \sigma_N}, \quad \sigma_m = \sigma_m(y_{\text{cut}}).
  \]

  ◦ Generate hard jet configuration according to the probability distribution; shower it.
  ◦ Requires introduction of a measure to distinguish between hard jet and shower jet.

• This procedure has been recently implemented in major shower event generators, such as PYTHIA and HERWIG.

• CKKW and similar procedures seem to be rather successful in describing data.
ME + shower test: $Z/\gamma + \text{jets}$ production Run II

- A test case study: $Z/\gamma + n\ \text{jets}$ Tevatron, Run II  
- D0 collaboration.

- Comparison of MCFM, PYTHIA and ME-PS (PYTHIA with CKKW-like prescription).

- MCFM and ME-PS describe data well, including kinematic distributions.

- PYTHIA predicts too few jets, as can expected on general grounds.
ME + shower: azimuthal correlations in Higgs + 2 jets

- One can study CP properties of the Higgs boson by looking at the azimuthal angular correlations of the two jets in $pp \rightarrow H + 2j$.
  
  Plehn, Rainwater, Zeppenfeld

- LO result: CP-even $\leftrightarrow$ minimum at $\Delta \phi = \pi/2$; CP-odd $\leftrightarrow$ maximum at $\Delta \phi = \pi/2$.

- Does this result survive soft/collinear gluon emissions?

  Odagiri

- If two hardest jets are generated by HERWIG, the azimuthal angle distribution is more flat than in ALPGEN + HERWIG analysis.

  Del Duca et al.
LO uncertainties and NLO qualitative features

- Any leading order prediction has the renormalization and factorization scales uncertainty.
- Example: $pp \rightarrow \nu\bar{\nu} + N \text{ jets}, p_T^\perp > 80 \text{ GeV}, |\eta| < 2.5$, $\mu = \sqrt{M_Z^2 + \sum_{\text{jets}} p_T^2}$.

<table>
<thead>
<tr>
<th>N</th>
<th>$\sigma(2\mu)\text{ pb}$</th>
<th>$\sigma(\mu/2)\text{ pb}$</th>
<th>variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6.47</td>
<td>13.52</td>
<td>70%</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
<td>2.48</td>
<td>93%</td>
</tr>
</tbody>
</table>

- Large scale dependence $\Rightarrow$ large NLO corrections.
- Typical NLO corrections are $10 - 30\%$ for quark-initiated processes and $50 - 100\%$ for gluon-initiated.
- NLO effects may be large because:
  - $\pi^2$ factors, typical for time-like processes;
  - new channels open up at NLO $\leftrightarrow$ gluon density is very large at small $x$;
  - color factors: the expansion parameter is $N_c\alpha_s/\pi \sim \alpha_s$, for $N_c = 3$. 
Next-to-leading order computations

- Typical background processes at the LHC are complex: \((t\bar{t})^n (WZ)^m \text{ jets}^l, n, m, l > 0\).
- NLO approximation is more reliable because of
  1. controllable normalization;
  2. (more) realistic final states (jet = 1 or 2 partons);
  3. reduced dependence on unphysical parameters (factorization/renormalization).
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- Current state of the art is \(2 \rightarrow 3\) processes. Established programs
  - NLOJET++ \(pp \rightarrow (2, 3)j, \ e^+e^- \rightarrow 3, 4j, \gamma^*p \rightarrow (2, 3)j\) Nagy;
  - AYLEN/EMILIA \(pp \rightarrow (W, Z) + (W, Z, \gamma)\) de Florian, Dixon, Kunszt, Signer;
  - MCFM \(pp \rightarrow (W, Z) + (0, 1, 2)j, \ pp \rightarrow (W, Z) + b\bar{b}\) Campbell, Ellis;
  - DIPHOX/EPHOX \(pp \rightarrow \gamma + 1j, \ pp \rightarrow \gamma\gamma, \gamma^*p \rightarrow \gamma + 1j\) Aurinche et. al;
  - VBFNLO \(pp \rightarrow (W, Z, H) + 2j\) Figy, Zeppenfeld, Oleari.
Next-to-leading order computations

• Typical background processes at the LHC are complex: $(t\bar{t})^n (WZ)^m \text{jets}^l$, $n, m, l > 0$.

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• ... and recent progress:
  ◦ $pp \rightarrow t \rightarrow Wb$, Ellis, Campbell;
  ◦ $pp \rightarrow H\bar{b}b, Ht\bar{t}$, Dawson, Jackson, Wackeroth, Reina, Spira, Krämer;
  ◦ $pp \rightarrow H \rightarrow 2 \text{jets}$, Zanderighi, Campbell, Ellis;
  ◦ $pp \rightarrow W + \bar{b}b, m_b \neq 0$, Wackeroth, Reina;
  ◦ $pp \rightarrow t\bar{t} + j$, Uwer, Dittmaier

• First complete $2 \rightarrow 4$ computation: $e^+e^- \rightarrow 4 \text{fermions}$, Denner, Dittmaier et al.
Next-to-leading order

- Traditional analytic methods turned out to be not very successful for multijet processes.
- Fully numerical approaches become the focus.
- The problem is in combining numerical techniques developed for extracting soft/collinear singularities with numerical techniques developed to deal with branch point singularities of Feynman diagrams.
- Many new approaches
  1. Mellin-Barnes transform
  2. IBP’s, sector decompozition, numerics
  3. Numerical solutions of IBP’s
  4. Unitarity/twistor based methods
  5. Contour deformation
  6. Residues

Anastasiou, Daleo; Binoth, Heinrich; Glover, Giele; C. Berger, Dixon, Bern, Kosower Soper, Nagy; Catani,
Next-to-leading order: Higgs in WBF

- Higgs production in WBF checks $HW^+W^-$ and $HZZ$ couplings, but $H + 2j$ is a background. Zeppenfeld, Oleari, Figi, Berger, Cambpell

- Separation of the signal and the background: two forward tagging jets that are well separated in rapidity. Specifically:

  $p_j^\perp > 40 \text{ GeV}, \ |\eta_j| < 4.5, \ R_{jj} > 0.8, \ |\eta_{j1} - \eta_{j2}| > 4.2, \ \eta_{j1}\eta_{j2} < 0.$

- $pp \rightarrow H$ in WBF is known through NLO; QCD effects are small but the background estimates (LO) are uncertain.
Next-to-leading order: Higgs in WBF

- QCD corrections to $H + 2j$ were recently computed. Campbell, Ellis, Zanderighi
- Full cross-sections (pb) for $m_H = 115$ GeV with/without WBF cuts:
  \[ \sigma_{LO} = 0.271/3.50, \quad \sigma_{NLO} = 0.346/4.03, \quad \sigma_{WBF} = 0.911/1.77. \]
- QCD corrections to $H + 2j$ are almost independent of the kinematics.
  \[ L_{eff} = \frac{\alpha_s}{12\pi\nu} C H G^{\alpha\mu} G_{\alpha\mu}, \quad C = 1 + \frac{11}{4} \frac{\alpha_s}{\pi}, \quad \sigma_{NLO}/\sigma_{LO} = 1.15 - 1.25 \approx C^2. \]
- Could the kinematics-independence have been guessed?
NLO: azimuthal de-correlations in inclusive jet events

- D0 collaboration measured the relative azimuthal angle distribution between two hardest jets in $p\bar{p} \rightarrow$ jets in Run II, Tevatron.
- At LO, two jets are back-to-back, $\Delta \phi = \pi$, but additional QCD radiation reduces this correlation.
- NLOJET++ computes up to $p\bar{p} \rightarrow 3$ jets at NLO.

- NLO essential for the correct description of the shape. HERWIG does fine; default PYTHIA does not do a good job.
NLO: bottom production

- Bottom production in hadron collisions: $p\bar{p} \rightarrow B + X$ was a long-standing problem for pQCD with discrepancy often quoted as a factor 2-4.
- New Physics explanations, e.g. light gluinos, sbbottoms.

NLO QCD prediction for $p_B^\perp$ is non-trivial:
  - $b \rightarrow B$ fragmentation function;
  - uncertainties due to PDFs;
  - dependence on the $b$-quark mass;
  - large NLO QCD corrections;
  - $\sigma_{tot}$ is dominated by $p_\perp \sim m_b$.

Cacciari, Nason
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Cacciari, Nason

- Excellent agreement of the total cross-sections

\[
\sigma_{J/\psi}^{\text{CDF}} = 19.9^{+3.8}_{-3.2} \text{ nb}, \quad \sigma_{J/\psi}^{\text{pQCD}} = 18.3^{+8.1}_{-5.7} \text{ nb}.
\]

Cacciari et al.

- Large ±50% theory uncertainty remains.
Event generators and higher orders

- Shower event generators and perturbative calculations are complimentary:
  - Showers: universal, realistic jets, automatic resummations, hadronization;
  - PT: correct rates, correct description of hard emissions, improvable errors.
- Combining parton showers and perturbative computations is a good (old) idea. Dobbs
- The most advanced implementation is called MC@NLO (based on HERWIG shower):
  \[ MC@NLO = MC (1 + \alpha_s [NLO - MC\alpha_s]) . \]

Features:
- outputs unweighted events;
- no double counting;
- total rates are accurate through NLO.

Processes included:
- \( H, W, Z, VV, HZ, t\bar{t}, b\bar{b} \) and single top.

Alternative implementations would be most useful Krämer, Nagy, Soper, Giele, Skands
**NNLO**

- NNLO calculations are desirable for:
  - processes where good estimate of the uncertainty is required;
  - processes with large NLO corrections.

- This leaves us with $H, W, Z, 2$ jets, heavy quarks.

- What is known through NNLO for hadron colliders:
  - $W, Z, gg \rightarrow H, gg \rightarrow A, b\bar{b} \rightarrow H$ production; total cross-sections; 
    van Neerven, Matsuura, Kilgore, Harlander, Anastasiou, K.M., Ravindran, Smith
  - $W, Z, \gamma^*$ rapidity distribution; 
    Anastasiou, Dixon, K.M., Petriello
  - $gg \rightarrow H, Z, W$ production, fully differential with spin correlations; 
    Anastasiou, K.M., Petriello

- Generalization to $2 \rightarrow 2$ processes (jets, heavy quarks) is highly non-trivial.
**NNLO: PDFs**

- A consistent implementation of NNLO calculations requires NNLO PDFs and NNLO evolution kernels.
- NNLO Altarelli-Parisi splitting kernels known. \( \text{Vermaseren, Moch, Vogt} \)
- NNLO PDFs extractions exist. \( \text{MRST, Alekhin} \)
- Broad measure of PDFs fits reliability:

\[
\alpha_s^{\text{Alekhin}}(M_Z) = 0.114(1), \quad \alpha_s^T(M_Z) = 0.121(1).
\]

**NNLO effects increase the disagreement.**

- For hard processes at the LHC, PDF uncertainty is

\[
\frac{\delta \sigma}{\sigma} \approx 5\%, \quad M \sim 100 \text{ GeV}, \quad |Y| < 2.
\]

- For larger \(|Y|\), \(\ln(1/x)\) terms may require resummations (BFKL, saturation)
NNLO: $Z$ and $W$ rapidity distributions

- Use the $Z, W$ production to measure $L$.

- Partonic luminosities $\leftrightarrow$ rapidity of gauge bosons

$$\frac{d\sigma}{dMdy} \sim q_1(x_1)q_2(x_2), \quad x_{1,2} = \frac{M}{\sqrt{S}} e^{\pm Y}.$$  

- NNLO results: scale stability and PDF sensitivity

Dittmar et al.

Anastasiou, Dixon, Petriello, K.M.
NNLO: \( Z \) and \( W \) production, fully exclusive

- Exclusive NNLO QCD computation of \( Z \rightarrow l^+l^- \) and \( W \rightarrow l + \bar{\nu}_l \) is available.

- Fully realistic:
  - cuts on the charged lepton and/or missing energy.
  - spin correlations;
  - finite widths effects;
  - \( Z-\gamma \) mixing for the neutral current.

- Realistic acceptances for \( Z, W \) production at the Tevatron and the LHC.

- Example: \( pp \rightarrow W^- \) central/forward cross-sections ratio (CDF, preliminary).
  
  Central: \( |\eta| < 1.2, \ E_\perp > 25 \text{ GeV}, \ E_{\text{miss}}^\perp > 25 \text{ GeV} \).

  Forward: \( 1.2 < |\eta| < 2.8, \ E_\perp > 20 \text{ GeV}, \ E_{\text{miss}}^\perp > 25 \text{ GeV} \).

- Observable is potentially useful to constrain shapes of PDFs

\[ R_{c/f}^{\text{CDF}} = 0.925(33), \quad R_{c/f}^{\text{NLO}} = 0.940(12), \quad R_{c/f}^{\text{NNLO}} = 0.9266(19), \]
NNLO: Higgs boson signal at the LHC

- QCD effects increase the inclusive $gg \rightarrow H$ production cross-section by a factor two.

- For $H \rightarrow \gamma\gamma$, the following cuts on the final photons are imposed (ATLAS,CMS):
  
  - $p^{(1)}_\perp \geq 25$ GeV, $p^{(2)}_\perp \geq 40$ GeV, $|\eta_{1,2}| \leq 2.5$.
  
  - Isolation cuts, e.g. $E_{T,\text{hadr}} \leq 15$ GeV, $\delta R = \sqrt{\delta \eta^2 + \delta \phi^2} < 0.4$.

- Do the conclusions based on inclusive calculations change when those cuts are imposed?

C. Anastasiou, K.M., F. Petriello

Re-weighting MC@NLO and PYTHIA to double differential distribution in Higgs $p_\perp$ and rapidity. [Davatz et al.]
Conclusions

• Good understanding of pQCD is very important for the successful LHC physics program.

• Recent developments include
  ◦ showers become more realistic (CKKW, MC@NLO);
  ◦ large-scale NLO computations;
  ◦ emerging NNLO phenomenology (computations, NNLO PDF fits).

• We would like to see further progress in
  ◦ alternatives to MC@NLO;
  ◦ numerical techniques for NLO computations;
  ◦ PDF determinations (uncertainties);
  ◦ NNLO techniques (2 → 2 processes).

• There are interesting challenges, room for new ideas and unorthodox approaches.

• We will benefit from significant progress that occurred in pQCD in the last few years once the LHC turns on.