Perturbative QCD for collider physics

Kirill Melnikov

University of Hawaii

November 2006

Joint DPF/JPS meeting, Honolulu, HI, 2006

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 $M \sim 100\ \mathrm{GeV}$, 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.

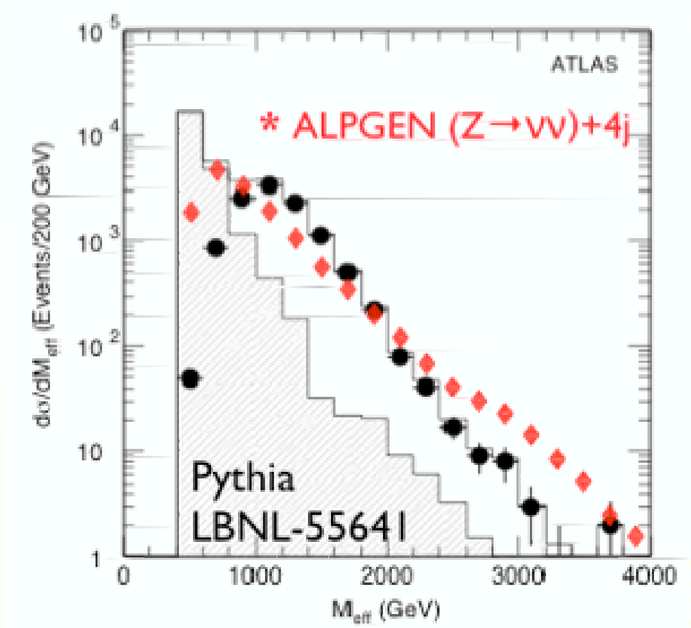
Parton showers and exact LO matrix elements

- 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 $p_\perp$ $\Rightarrow$ α_s suppression of high $\boldsymbol{p}_\perp$ radiation.
- Showers do not change normalizations of total cross-sections

$$\int d\sigma_{\mathrm{LO}} \times \mathrm{PS} = \sigma_{\mathrm{LO}}.$$

- 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



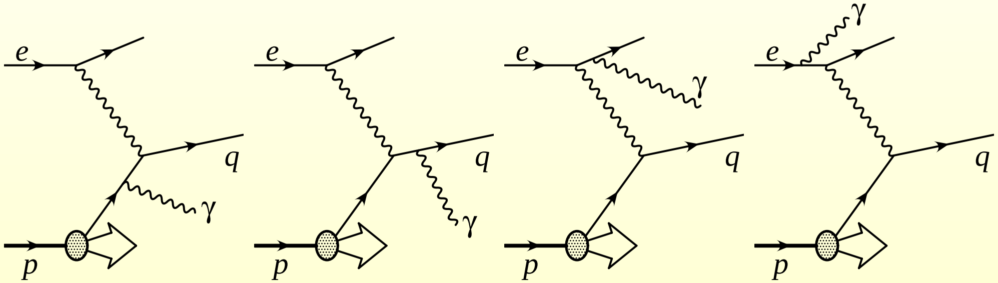
$$M_{\text{eff}} = \sum_{\text{jets}} p_{\perp} + E_{\perp}^{\text{miss}}$$

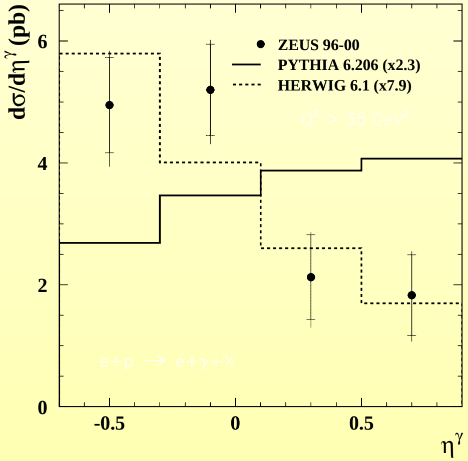
Mangano

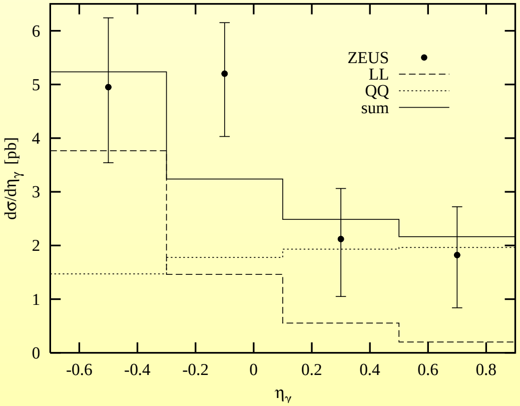
- ALPGEN: exact LO matrix elements; correct hard emissions built in.
- PYTHIA: emulates hard emissions by producing large number of softer jets.
- PYTHIA underestimates the background significantly.

Parton showers and exact ME: isolated photons in DIS

- Production of isolated photons in $e^{\pm}p$ collisions was studied by ZEUS collaboration.







- 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.

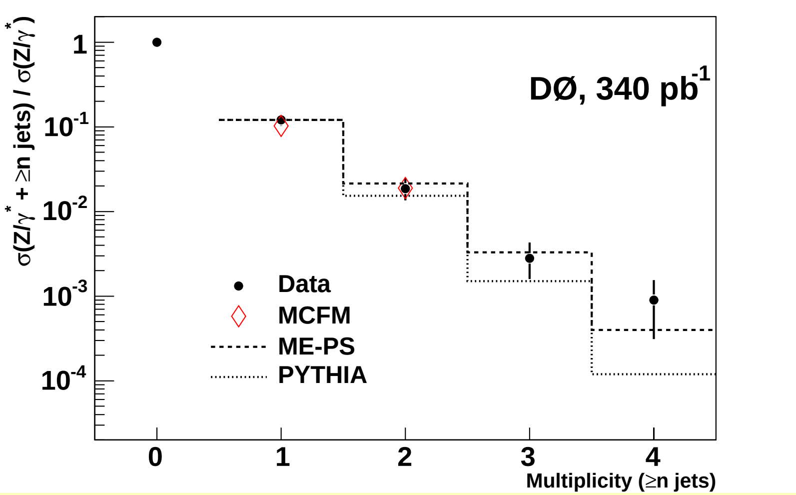
- Event generators can do a better job for multi-jet processes if both mechanisms are taken into account.
- Catani-Krauss-Kuhn-Webber (CKKW) procedure:
  - calculate $pp \to m$ HARD jets, with $m < N$. Determine probability of an event with m hard jets using the cross-section values,

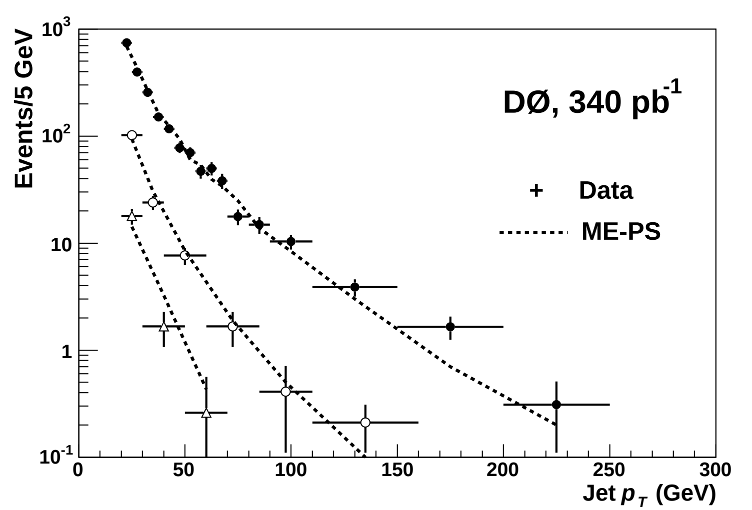
$$P_m = \frac{\sigma_m}{\sigma_0 + \sigma_1 + \sigma_2 + \ldots\sigma_N}, \qquad \sigma_m = \sigma_m(y_{\mathrm{cut}}).$$

  - 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. Mrenna, Richardson
- 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: $Z/\gamma + n$ jets Tevatron, Run II D0 collaboration.
- Comparison of MCFM, PYTHIA and ME-PS (PYTHIA with CKKW-like prescription).

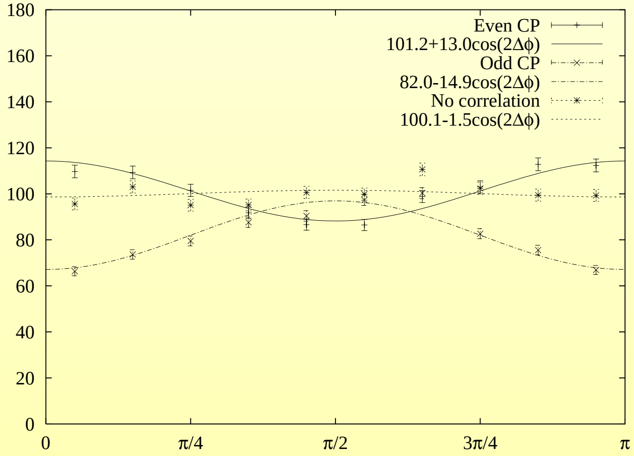




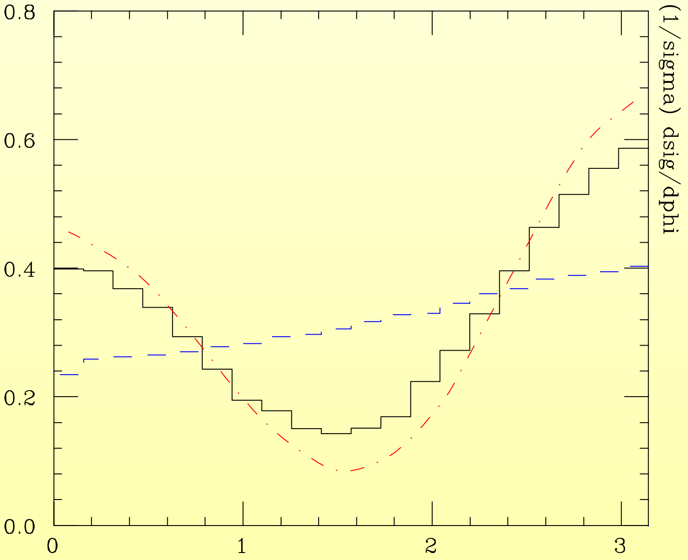
- MCFM and ME-PS describe data well, including kinematic distributions.
- PYTHIA predicts too few jets, as can expected on general grounds.

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 $pp \to H + 2j$. Plehn, Rainwater, Zeppenfeld
- LO result: CP-even ↔ minimum at $\Delta\phi = \pi/2$; CP-odd ↔ maximum at $\Delta\phi = \pi/2$.
- Does this result survive soft/collinear gluon emissions?



Odagiri



Del Duca *et al.*

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

LO uncertainties and NLO qualitative features

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

N	$\sigma(2\mu)$pb	$\sigma(\mu/2)$pb	variation
3	6.47	13.52	70%
4	0.90	2.48	93%

- 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:
  - π^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: $(t\bar{t})^n\ (WZ)^m\ \mathrm{jets}^l, n, m, l > 0$.
- 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).

Next-to-leading order computations

- Typical background processes at the LHC are complex: $(t\bar{t})^n \; (WZ)^m \; \mathrm{jets}^l, n, m, l > 0$.
- 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).
- Current state of the art is $2 \longrightarrow 3$ processes. Established programs
  - NLOJET++ $pp \to (2,3)j, \;\; ep \to 3j, \;\; e^+e^- \to 3, 4j, \gamma^* p \to (2,3)j$ Nagy ;
  - AYLEN/EMILIA $pp \to (W, Z) + (W, Z, \gamma)$ de Florian, Dixon, Kunszt, Signer ;
  - MCFM $pp \to (W, Z) + (0, 1, 2)j, pp \to (W, Z) + b\bar{b}$ Campbell, Ellis ;
  - DIPHOX/EPHOX $pp \to \gamma + 1j, pp \to \gamma\gamma, \gamma^* p \to \gamma + 1j$ Aurinche et. al ;
  - VBFNLO $pp \to (W, Z, H) + 2j$ Figy, Zeppenfeld, Oleari .

Next-to-leading order computations

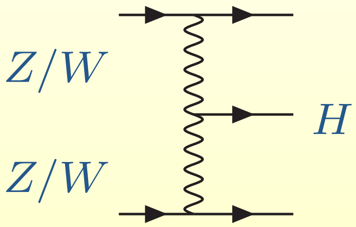
- Typical background processes at the LHC are complex: $(t\bar{t})^n\ (WZ)^m$ jets^l, $n, m, l > 0$.
- NLO approximation is more reliable because of
  1. controllable normalization;
  2. (more) realistic final states (jet = 1 or 2 partons);
  3. reduced dependence on unphysical parameters (factorization/renormalization).
- ... and recent progress :
  - ○ $pp \longrightarrow t \longrightarrow Wb$, Ellis, Campbell;
  - ○ $pp \longrightarrow Hb\bar{b}, Ht\bar{t}$, Dawson, Jackson, Wackeroth, Reina, Spira, Krämer;
  - ○ $pp \longrightarrow W^+W^-(ZZ) + 2j$, [VBF] Jäger, Oleari, Zeppenfeld.
  - ○ $pp \longrightarrow H \longrightarrow 2$ jets, Zanderighi, Campbell, Ellis;
  - ○ $pp \longrightarrow W + b\bar{b}$, $m_b \neq 0$, Wackeroth, Reina;
  - ○ $pp \longrightarrow t\bar{t} + j$, Uwer, Dittmaier
- First complete $2 \longrightarrow 4$ computation: $e^+e^- \longrightarrow 4$ fermions, Denner, Dittmaier et al.

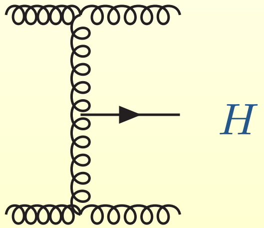
Next-to-leading order

- 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 Anastasiou, Daleo;
  2. IBP’s, sector decompozition, numerics Binoth, Heinrich;
  3. Numerical solutions of IBP’s Glover, Giele;
  4. Unitarity/twistor based methods C. Berger, Dixon, Bern, Kosower
  5. Contour deformation Soper, Nagy;
  6. Residues 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

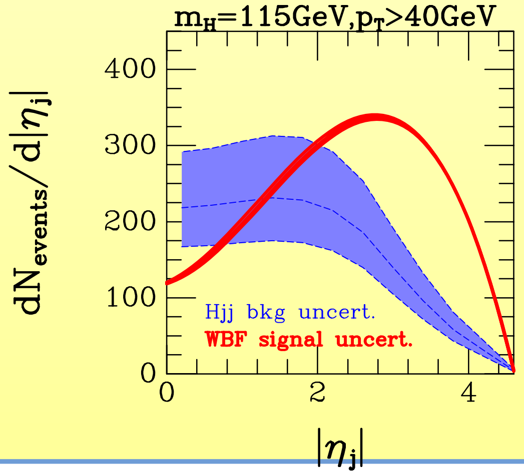




- Separation of the signal and the background: two forward tagging jets that are well separated in rapidity. Specifically:

$$p_\perp^j > 40 \text{ GeV}, \quad |\eta_j| < 4.5, \quad R_{jj} > 0.8, \quad |\eta_{j_1} - \eta_{j_2}| > 4.2, \quad \eta_{j_1}\eta_{j_2} < 0.$$

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



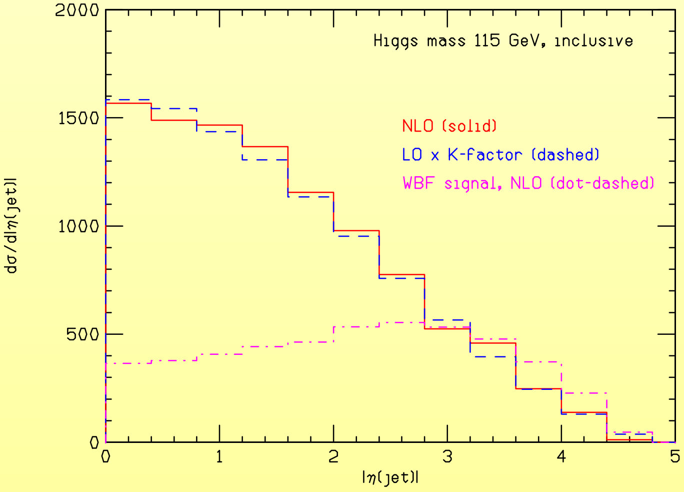
Next-to-leading order: Higgs in WBF

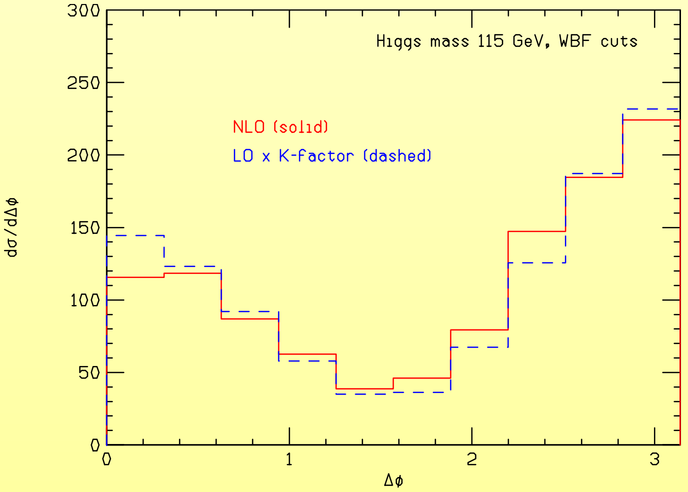
- QCD corrections to $H + 2j$ were recently computed. Campbell, Ellis, Zanderighi
- Full cross-sections (pb) for $m_H = 115$ GeV with/without WBF cuts:

$$\sigma_{\rm LO} = 0.271/3.50, \quad \sigma_{\rm NLO} = 0.346/4.03, \quad \sigma_{\rm WBF} = 0.911/1.77.$$

- QCD corrections to $H + 2j$ are almost independent of the kinematics.

$$L_{\rm eff} = \frac{\alpha_s}{12\pi v} C H G^a_{\mu\nu} G^{a,\mu\nu}, \quad C = 1 + \frac{11}{4}\frac{\alpha_s}{\pi}, \quad \sigma_{\rm NLO}/\sigma_{\rm LO} = 1.15 - 1.25 \approx C^2.$$



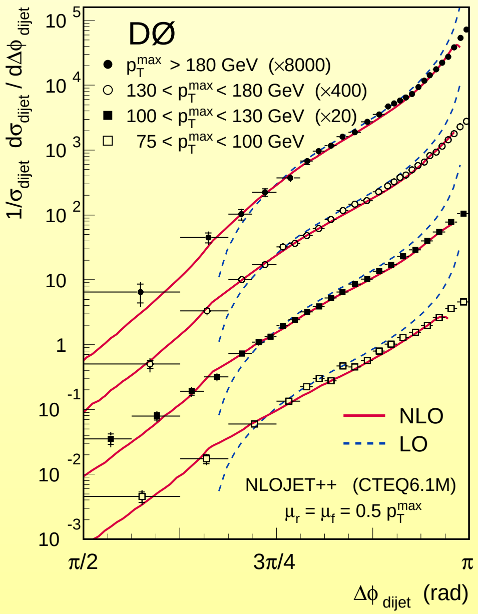


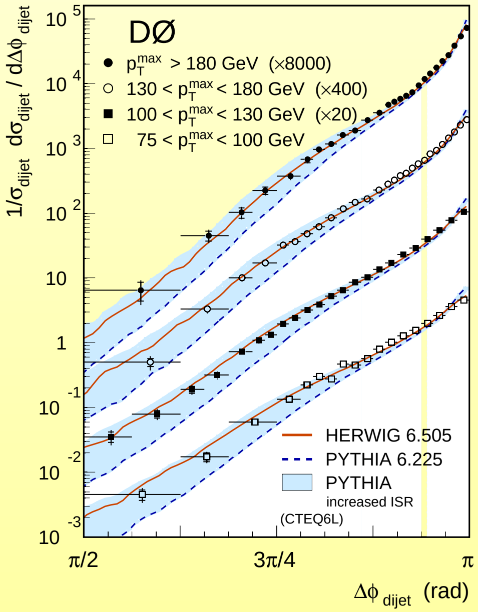
- Could the kinematics-independence have been guessed?

NLO: azimuthal de-correlations in inclusive jet events

- D0 collaboration measured the relative azimuthal angle distribution between two hardest jets in $p\bar{p} \longrightarrow$ 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 $p\bar{p} \longrightarrow 3$ jets at NLO.

Nagy





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

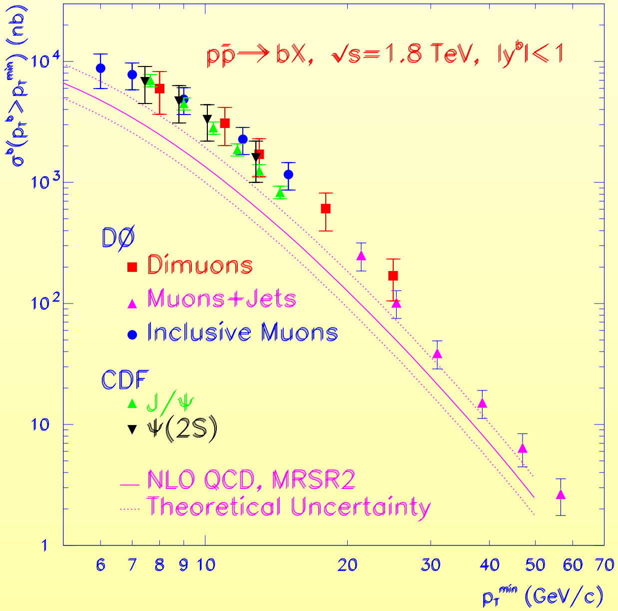
NLO: bottom production

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

NLO QCD prediction for $p_\perp^B$ is non-trivial:

- $b \longrightarrow B$ fragmentation function;
- uncertainties due to PDFs;
- dependence on the b-quark mass;
- large NLO QCD corrections;
- $\sigma_{\rm tot}$ is dominated by $p_\perp \sim m_b$.

Cacciari, Nason



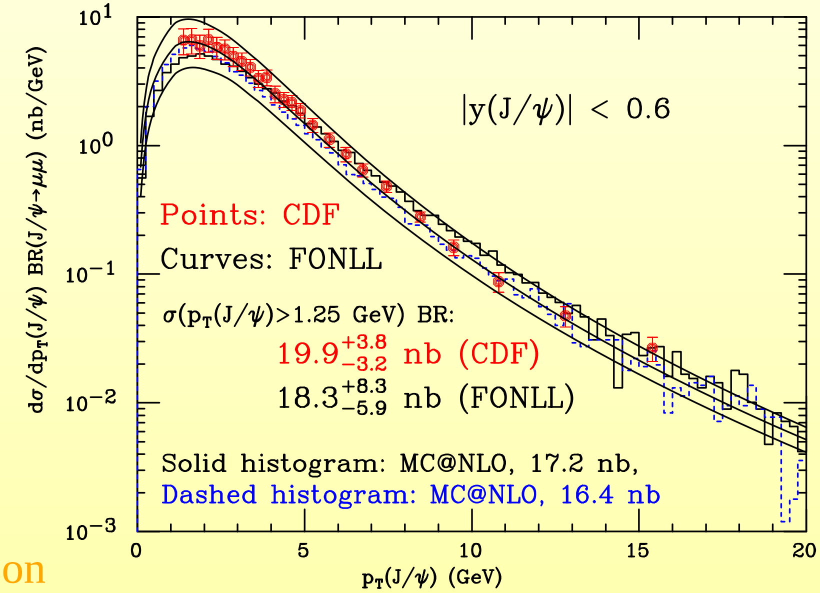
NLO: bottom production

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

NLO QCD prediction for $p_\perp^B$ is non-trivial:

- $b \longrightarrow B$ fragmentation function;
- uncertainties due to PDFs;
- dependence on the b-quark mass;
- large NLO QCD corrections;
- $\sigma_{\rm tot}$ is dominated by $p_\perp \sim m_b$.

Cacciari, Nason



- Excellent agreement of the total cross-sections

Cacciari et al.

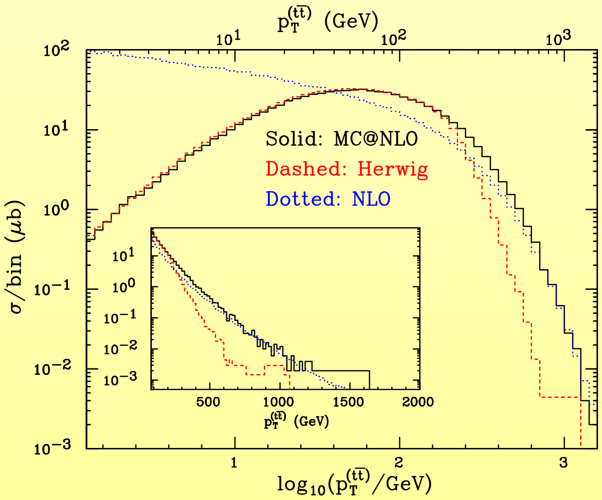
$$\sigma_{J/\psi}^{\rm CDF} = 19.9^{+3.8}_{-3.2}\ {\rm nb}, \quad \sigma_{J/\psi}^{\rm pQCD} = 18.3^{+8.1}_{-5.7}\ {\rm nb}.$$

- 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): Frixione, Webber

$$\mathrm{MC@NLO} = \mathrm{MC}\left(1+\alpha_s[\mathrm{NLO}-\mathrm{MC}_{\alpha_s}]\right).$$



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 $H, W, Z, 2\ \mathrm{jets}$, heavy quarks.
- What is known through NNLO for hadron colliders:
  - $W, Z, gg \to H, gg \to A, b\bar{b} \to H$ production; total cross-sections;

    van Neerven, Matsuura, Kilgore, Harlander, Anastasiou, K.M., Ravindran, Smith
  - W, Z, γ^* rapidity distribution;

    Anastasiou, Dixon, K.M., Petriello
  - $gg \to H, Z, W$ production, fully differential with spin correlations;

    Anastasiou, K.M., Petriello
- Generalization to $2 \to 2$ 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. Vermaseren,Moch,Vogt
- NNLO PDFs extractions exist. MRST, Alekhin.
- Broad measure of PDFs fits reliability:

$$\alpha_s^{\text{Alekhin}}(M_Z) = 0.114(1), \quad \alpha_s^{\tau}(M_Z) = 0.121(1).$$

NNLO effects increase the disagreement.

- For hard processes at the LHC, PDF uncertainty is

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

- For larger $|Y|$, $\ln(1/x)$ terms may require resummations (BFKL, saturation)

NNLO: Z and W rapidity distributions

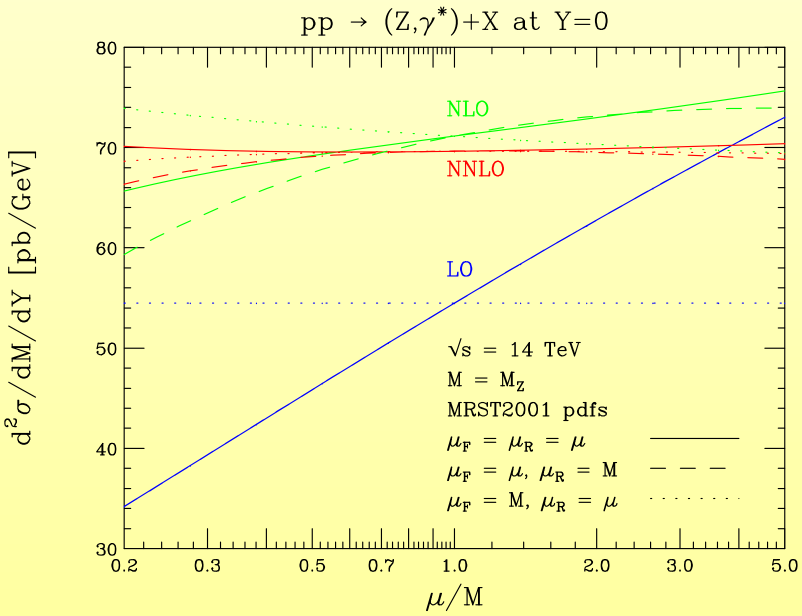
- Use the Z, W production to measure L.

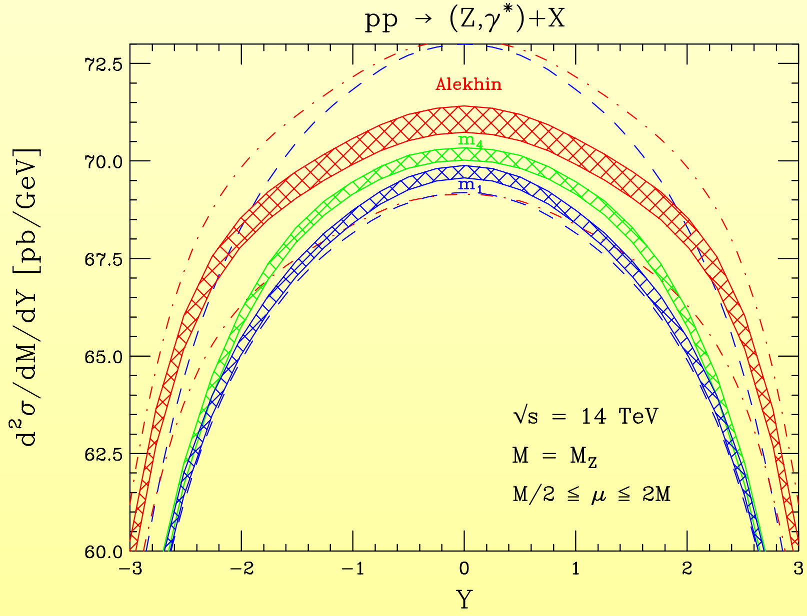
Dittmar et al.

- Partonic luminosities ↔ rapidity of gauge bosons

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

- NNLO results: scale stability and PDF sensitivity





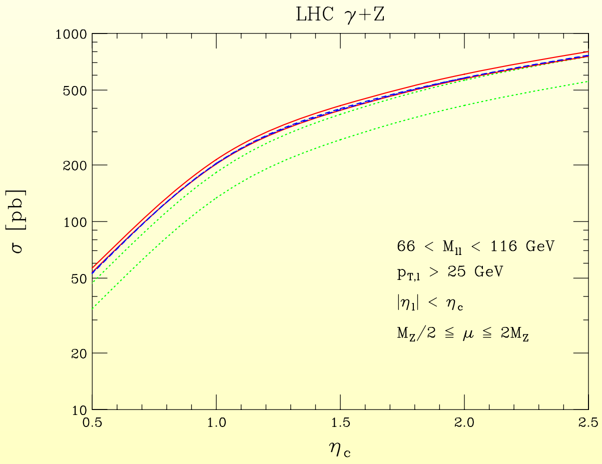
Anastasiou, Dixon, Petriello, K.M.

NNLO: Z and W production, fully exclusive

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

Petriello, K.M.

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



- Realistic acceptances for Z, W production at the Tevatron and the LHC.
- Example: $pp \to W^-$ central/forward cross-sections ratio (CDF, preliminary).

$$\text{Central}: \quad |\eta| < 1.2, \quad E_\perp > 25\,\text{GeV}, \quad E_\perp^{\text{miss}} > 25\,\text{GeV}.$$

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

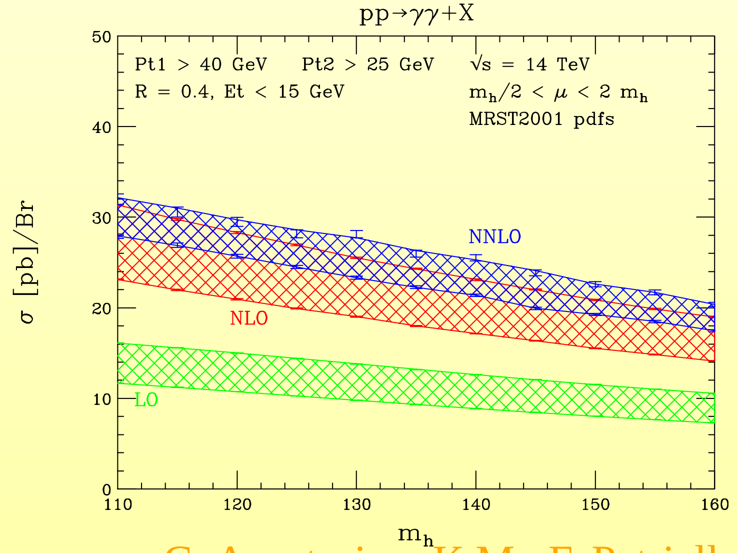
- Observable is potentially useful to constrain shapes of PDFs

Lancaster

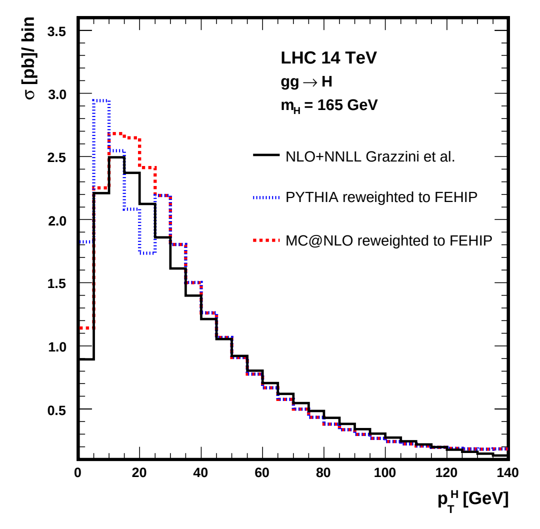
$$R_{c/f}^{\text{CDF}} = 0.925(33), \quad R_{c/f}^{\text{NLO}} = 0.940(12), \quad R_{c/f}^{\text{NNLO}} = 0.9266(19),$$

NNLO: Higgs boson signal at the LHC

- QCD effects increase the inclusive $gg \to H$ production cross-section by a factor two.
- For $H \to \gamma\gamma$, the following cuts on the final photons are imposed (ATLAS,CMS):
  - $p_\perp^{(1)} \geq 25$ GeV, $p_\perp^{(2)} \geq 40$ GeV, $|\eta_{1,2}| \leq 2.5$.
  - Isolation cuts, e.g. $E_{\mathrm{T,hadr}} \leq 15$ 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 ($2 \longrightarrow 2$ 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.