Applications of Higher Order QCD

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SLAC

Physics In Collision 2013

Beijing, 09/04/13
→ 2013 → Higgs physics has moved from discovery to precision stage

- Improved theoretical predictions required to search for (small) deviations from Standard Model

- Great success of SM so far, but should keep looking everywhere

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**CMS Preliminary**

$m_{\text{H}} = 125.7 \text{ GeV}$

$\mathbf{P}_{\text{SM}} = 0.65$

- $\mathbf{H} \rightarrow \mathbf{bb}$
  - $\mu = 1.15 \pm 0.62$

- $\mathbf{H} \rightarrow \mathbf{\tau\tau}$
  - $\mu = 1.10 \pm 0.41$

- $\mathbf{H} \rightarrow \mathbf{\gamma\gamma}$
  - $\mu = 0.77 \pm 0.27$

- $\mathbf{H} \rightarrow \mathbf{WW}$
  - $\mu = 0.68 \pm 0.20$

- $\mathbf{H} \rightarrow \mathbf{ZZ}$
  - $\mu = 0.92 \pm 0.28$

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**ATLAS Preliminary**

$m_{\text{H}} = 125.5 \text{ GeV}$

$\mathbf{P}_{\text{SM}} = 0.65$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{bb}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 1.30 \pm 0.20}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{\tau\tau}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 1.04 \pm 0.48}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{\gamma\gamma}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 0.79 \pm 0.27}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{WW}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 0.63 \pm 0.21}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{ZZ}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 0.92 \pm 0.28}$

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**Nov 2012**

**Production Cross Section, $\sigma_{\text{tot}}$**

- $\mathbf{W} \rightarrow \mathbf{\ell\nu}\mathbf{\mathbf{\ell\nu}}$
  - $36.19 \text{ fb}^{-1}$

- $\mathbf{Z} \rightarrow \mathbf{\ell\ell}$
  - $5.0 \text{ fb}^{-1}$

- $\mathbf{WZ} \rightarrow \mathbf{\ell\nu\ell\nu}$
  - $4.9 \text{ fb}^{-1}$

- $\mathbf{ZZ} \rightarrow \mathbf{\ell\ell\ell\ell}$
  - $4.9 \text{ fb}^{-1}$

**7 TeV Theory prediction**

- $\mathbf{W}$
  - $3.7 \times 10^{-5}$

- $\mathbf{Z}$
  - $5.0 \times 10^{-5}$

**8 TeV Theory prediction**

- $\mathbf{W}$
  - $3.7 \times 10^{-5}$

- $\mathbf{Z}$
  - $5.0 \times 10^{-5}$

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**ATLAS**

**Preliminary**

$\mathbf{m_{\gamma}} = 125.5 \text{ GeV}$

$\mathbf{P}_{\text{SM}} = 0.65$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{bb}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 1.30 \pm 0.20}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{\tau\tau}$
  - $\mathbf{\mathbf{\mu}} \mathbf{= 1.04 \pm 0.48}$

- $\mathbf{WZ} \mathbf{H} \rightarrow \mathbf{\gamma\gamma}$
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**Stefan Höche**

**Applications of Higher Order QCD**
Any event at the LHC involves QCD, and so does most of our work.
- QCD theory needs to keep up with incredible pace of LHC experiments
Event structure at hadron colliders

- How to make predictions for complex events?
- Must account for multiple physics effects at widely different scales

- Key strategy: Factorization of hard and soft QCD effects

\[
\sigma_{h_1 h_2 \rightarrow \chi} = \int dx_1 dx_2 \frac{f_{h_1, i}(x_1, \mu_F^2) f_{h_2, j}(x_2, \mu_F^2)}{\hat{\sigma}_{ij \rightarrow \chi}(x_1 x_2 S, \mu_F^2) + \mathcal{O}(\Lambda_{QCD}/Q)^n}
\]

- PDFs inherently non-perturbative, but evolution with $\mu_F$ calculable
  Universality $\rightarrow$ Measured in DIS & fixed-target and applied to LHC
- Focus of this talk will be calculation of partonic cross sections
Toolkit inventory

- All processes of interest
  - Parton shower Monte Carlo (Herwig, Pythia, Sherpa, ...)
  - Automated tree-level calculations & merging with PS (Alpgen, CompHEP, Helac, MadGraph, Sherpa, ...)
- Available for increasingly complex final states (2→4, 5, 6)
  - Automated NLO (BlackHat, GoSam, Helac, MadLoop, MadGolem, NJet, OpenLoops, Rocket, ...)
  - Matching to parton shower (aMC@NLO, Herwig, POWHEG Box, Sherpa, ...)
  - Merging at NLO (aMC@NLO, Pythia, Sherpa, ...)
- Available for some processes
  - Inclusive NNLO (W, Z, gg→H, t¯t, jets, H+jet)
  - Fully differential NNLO (FEHiP, FEWZ, HNNLO)
  - NNLO+N^xLL resummation (e^+e^-→2/3 jets, pp→H)
Automated NLO calculations

- NLO subtraction methods

\[ d\hat{\sigma}_{\text{NLO}} = \int_{\Phi_n} \left( d\hat{\sigma}^B + d\hat{\sigma}^V + d\hat{\sigma}^{\text{MF}} + \int_{\Phi_1} d\hat{\sigma}^S \right) + \int_{\Phi_{n+1}} \left( d\hat{\sigma}^R - d\hat{\sigma}^S \right) \]

finite, compute with MC

- Universal infrared behaviour of amplitudes
  - FKS subtraction Frixione, Kunszt, Signer 1995
  - Dipole subtraction Catani, Seymour 1996 + Dittmaier, Trocsanyi 2002
  - Antenna subtraction Kosower 1997

- Realized in tree-level ME generators & stand-alone codes
  - Sherpa Gleisberg, Krauss 2007
  - MadDipole Frederix, Greiner, Gehrmann 2008
  - Helac Czakon, Papadopoulos, Worek 2009
  - TeVJet Seymour, Tevlin 2008
  - AutoDipole Hasegawa, Moch, Uwer 2008
  - MadFKS Frederix, Frixione, Maltoni, Stelzer 2009
The NLO revolution

- One-loop amplitudes evaluated by extracting coefficients of box/triangle/bubble/tadpole master integrals

\[ A = \sum d_i + \sum c_i + \sum b_i + R \]

- “Feynmanian” approach → Improved decomposition & reduction
  Denner, Dittmaier 2005 Binoth, Guillet, Pilon, Heinrich, Schubert 2005

- “Unitarian” approach → Multi-particle cuts & complex momenta
  Bern, Dixon, Dunbar, Kosower 1994 Britto, Cachazo, Feng 2004
  Ossola, Papadopoulos, Pittau 2006 Forde 2007 Ellis, Giele, Kunszt, Melnikov 2008

- Plethora of (semi-)automated programs emerged: BlackHat, GoSam, HelacNLO, MadLoop, MadGolem, NJet, OpenLoops, Rocket, . . .
  Badger, Bern, Bevilacqua, Biedermann, Binoth, Cascioli, Cullen, Czakon, Dixon, Ellis, Febres Cordero, Frederix, Frixione, Garzelli, Giele, Goncalves Netto, Greiner, Guffanti, Guillet, van Hameren, Heinrich, Hirschi, Ita, Kardos, Karg, Kauer, Kosower, Lopez-Val, Kunszt, Luisoni, Maierhöfer, Maitre, Maltoni, Mastrolia, Mawatari, Melnikov, Ossola, Ozeren, Papadopoulos, Pittau, Plehn, Pozzorini, Reiter, Reuter, Tramontano, Uwer, Wigmore, Worek, Yundin, Zanderighi, Zeppenfeld, . . .
### Making wishes come true

| Process $(V \in \{Z, W, \gamma\})$ | Comments |
|----------------------------------|----------|
| 1. $pp \rightarrow VV$ jet       | $WW$ jet completed by Dittmaier/Kallweit/Uwer; $ZZ$ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti $WZ$ jet, $W\gamma$ jet completed by Campanario et al. |
| 2. $pp \rightarrow$ Higgs+2 jets | NLO QCD to the $gg$ channel completed by Campbell/Ellis/Zanderighi NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier Interference QCD-EW in VBF channel |
| 3. $pp \rightarrow VVV$ ZZZ       | $ZZZ$ completed by Lazopoulos/Melnikov/Petriello and $WWZ$ by Hankele/Zeppenfeld see also Binoth/Ossola/Papadopoulos/Pittau VBFNLO meanwhile also contains $WWW, ZZW, ZZZ, W W, ZZ, WZ, W\gamma, Z\gamma, \gamma\gamma, W\gamma j$ |
| 4. $pp \rightarrow t\bar{t}b\bar{b}$ | relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek |
| 5. $pp \rightarrow V+3$ jets      | $W+3$ jets calculated by the Blackhat/Sherpa and Rocket collaborations $Z+3$ jets by Blackhat/Sherpa |
| 6. $pp \rightarrow t\bar{t}+2$ jets | relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek |
| 7. $pp \rightarrow VVb\bar{b},$  | Pozzorini et al.Bevilacqua et al. |
| 8. $pp \rightarrow VV+2$ jets    | $W^+W^-+2$ jets,$W^+W^-+2$ jets, relevant for VBF $H \rightarrow VV$ VBF contributions by (Bozzi/)Jäger/Oleari/Zeppenfeld |
| 9. $pp \rightarrow b\bar{b}b\bar{b}$ | Binoth et al. |
| 10. $pp \rightarrow V+4$ jets   | top pair production, various new physics signatures Blackhat/Sherpa: $W+4$ jets,$Z+4$ jets see also HEJ for $W+n$ jets |
| 11. $pp \rightarrow Wb\bar{b}j$  | top, new physics signatures, Reina/Schutzmeier various new physics signatures, Bevilacqua/Worek |
| 12. $pp \rightarrow t\bar{t}t\bar{t}$ | |

$pp \rightarrow W\gamma\gamma$ jet
$pp \rightarrow 4$ jets
Campanario/Englert/Rauch/Zeppenfeld
Blackhat/Sherpa

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Experimenter’s NLO wishlist

- Started Les Houches 2005
- Item 9 added in 2007, 10-12 in 2009
- Finally retired in 2012
NLO highlights: $pp \rightarrow W + 5$ jets

Bern, Dixon, Febres Cordero, SH, Ita, Kosower, Maître, Ozeren 2013

- First 2 → 6 NLO calculation for hadron colliders
- Allows extrapolation of jet rates to higher multiplicity (scaling)
- Flat $K$-factor for $5^{th}$ jet with suitable scale $\hat{H}_T' = \sum p_{T,j} + E_{T,W}$
NLO highlights: Higgs+3 jets

Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano 2013

**Largely reduced scale dependence**

**Can be used to improve prediction of exclusive \( H + 2 \text{jets} \) production**

\[
\sigma_{2j,\text{excl}} = \sigma_{2j,\text{incl}} - \sigma_{3j,\text{incl}}
\]

**Combination of One Loop program (GoSam) and MC (Sherpa, MadEvent)**

Using Binoth LesHouches accord Binoth et al. 2010; Alioli et al. 2013
The NNLO frontier

- Structure of the calculation

\[ d\hat{\sigma}_{\text{NNLO}} = \int_{\Phi_{n+2}} (d\hat{\sigma}^{RR} - d\hat{\sigma}^{S}) + \int_{\Phi_{n+1}} (d\hat{\sigma}^{RV} - d\hat{\sigma}^{VS} + d\hat{\sigma}^{MF,1}) \]

\[ + \int_{\Phi_{n}} (d\hat{\sigma}^{VV} + d\hat{\sigma}^{MF,2}) + \int_{\Phi_{n+1}} d\hat{\sigma}^{VS} + \int_{\Phi_{n+2}} d\hat{\sigma}^{S} \]

- Require three principal ingredients
  - Two-loop matrix elements
    explicit poles from loop integrals
  - One-loop matrix elements
    explicit poles from loop integrals and implicit poles from real emission
  - Tree-level matrix elements
    implicit poles from real emissions

- Challenge: Construction of subtraction methods for RR and RV contribution
Methods for real radiation at NNLO

- **Sector decomposition** Binoth, Heinrich 2004; Anastasiou, Melnikov, Petriello 2004
  - $pp \rightarrow H$, $pp \rightarrow V$ Anastasiou, Melnikov, Petriello; Bühler, Herzog, Lazopoulos, Müller

- **Antenna subtraction** Gehrmann, Gehrmann-DeRidder, Glover
  - $e^+ e^- \rightarrow 3\text{jets}$ Gehrmann, Gehrmann-DeRidder, Glover, Heinrich, Weinzierl
  - $pp \rightarrow 2\text{jets}$ Gehrmann, Gehrmann-DeRidder, Glover, Pires

- **$q_T$ subtraction** Catani, Grazzini 2007
  - $pp \rightarrow H$, $pp \rightarrow V$, $pp \rightarrow VH$, $pp \rightarrow \gamma \gamma$
    Catani, Cieri, DeFlorian, Ferrera, Grazzini, Tramontano

- **Sector-improved subtraction** Czakon 2010; Boughezal, Melnikov, Petriello 2011
  - $pp \rightarrow t\bar{t}$ Czakon, Fiedler, Mitov
  - $pp \rightarrow H + \text{jet}$ Boughezal, Caola, Melnikov, Petriello, Schulze
Diphoton production at NNLO

Catani, Cieri, de Florian, Ferrera, Grazzini 2011

- Frixione photon isolation criterion
- $q_T$ subtraction for real corrections
- First fully consistent inclusion of box contribution

\[
\frac{d\sigma}{dp_T^{\gamma\gamma}} \simeq 10^{-5} \text{ pb/GeV}
\]

\[
\sigma = 4.9 \text{ fb} \quad \int \text{Data 2011, DIPHOX+GAMMA2MC (CT10) NNLO (MSTW2008)}
\]

\[
\gamma^2 \quad ATLAS = 7 \text{ TeV}
\]

\[
\frac{\text{data}}{2} \quad \text{NNLO}
\]

\[
\frac{\text{data/DIPHOX}}{\text{ATLAS}} \quad \frac{\text{data/2NNLO}}{\text{ATLAS}}
\]
Top pair production at NNLO

\[ q\bar{q} \rightarrow t\bar{t} \quad \text{Bärnreuther, Czakon, Mitov 2012} \]
\[ gg \rightarrow t\bar{t} \quad \text{Czakon, Fiedler, Mitov 2013} \]

- Sector-improved subtraction for double real contribution
- First hadron collider calculation at NNLO with more than 2 colored partons
- First NNLO hadron collider calculation with massive fermions
- Point of saturation reached, where uncertainties (scale, PDF, \(\alpha_s\), \(m_t\)) are all of same size
- Already used to constrain PDFs
  Czakon, Mangano, Mitov, Rojo 2013
Jet production at NNLO

\[ pp \rightarrow 2 \text{ jets} \] Gehrmann, Gehrmann-DeRidder, Glover, Pires 2013

- Antenna subtraction in double real and real-virtual contribution
- Calculation implemented in a parton-level event generator
- Leading colour, gluons only very small scale dependence
Higgs+jet production at NNLO

Boughezal, Caola, Melnikov, Petriello, Schulze 2013

- Two independent calculations
- Sector-improved subtraction for double real contribution
- Large $K$-factor, 30% enhancement w.r.t. NLO for $\mu = m_H$
- Gluonic contribution only very small scale dependence 20% at NLO $\rightarrow$ 5% at NNLO
The importance of exclusive calculations

- Higgs measurements in $WW$ channel binned in number of jets to reduce background (top veto)
- Also used to separate gluon fusion from VBF
- Different uncertainties in different jet bins

\[
\begin{align*}
\text{Events} &\quad 1000 &\quad 2000 &\quad 3000 &\quad 4000 &\quad 5000 \\
\text{Data} &\quad &\quad &\quad &\quad &\quad \\
\text{SM (sys + stat)} &\quad &\quad &\quad &\quad &\quad \\
\text{WW} &\quad &\quad &\quad &\quad &\quad \\
\text{WZ/ZZ/W} &\quad &\quad &\quad &\quad &\quad \\
\text{t\bar{t}} &\quad &\quad &\quad &\quad &\quad \\
\text{Single Top} &\quad &\quad &\quad &\quad &\quad \\
\text{Z+jets} &\quad &\quad &\quad &\quad &\quad \\
\text{W+jets} &\quad &\quad &\quad &\quad &\quad \\
\text{H [125 GeV] x 10} &\quad &\quad &\quad &\quad &\quad \\
\end{align*}
\]
Why are exclusive calculations difficult?

- NLO corrections include virtual and real-emission part

\[
2 \text{Re} \left\{ \begin{array}{c}
\times \\
-1/\varepsilon^2_{IR} + \ldots
\end{array} \right\} + \begin{array}{c} \\
1/\varepsilon^2_{IR} - C \log^2(Q/p_{T,\text{cut}}) + \ldots
\end{array}
\]

- In inclusive case, finite correction remains
- In exclusive case, logarithmic dependence on \( p_{T,\text{cut}} \)
- Higgs production in gluon fusion:

\[
-6 \frac{\alpha_s}{\pi} \log^2 \frac{m_h}{p_{T,\text{cut}}} \rightarrow \text{large!}
\]
- Negative correction leads to pinch point in scale variation
- Uncertainty estimate requires resummation of log corrections
Higgs production with a jet veto

NLL Banfi,Salam,Zanderighi 2012, NNLL Banfi,Monni,Salam,Zanderighi 2012

- Automated NLL resummation (CESAR)
- Continued to NNLL+NNLO using $q_T$ resummation
- Hadronization and UE corrections found to be small (<1%)
Higgs production with a jet veto

Becher, Neubert 2012

- First all-order factorization theorem for Higgs production with a jet veto
- Resummation now being performed at $N^3\mathrm{LL}$ Becher, Neubert, Rothen

\[ pp \to H + X, \sqrt{s} = 8 \text{ TeV} \]

\[ \text{MSTW2008NNLO} \]

\[ \text{NNLL}/\text{PluΣNLO} \]

\[ \text{NNLL}/\text{PluΣNNLO} \]

\[ p_T^{\text{veto}} [\text{GeV}] \]

\[ \sigma(p_T^{\text{veto}}) [\text{pb}] \]

\[ \epsilon(p_T^{\text{veto}}) \]
Higgs production with a jet veto

Tackmann,Walsh,Zuberi 2013

- Large fixed-order uncertainty
\[ \Delta_{\text{incl}}^2 + \Delta_{\geq 1}^2 \]
Stewart,Tackmann 2011
reduced by SCET NNLL’+NNLO

- Full NNLO calculation of soft function for \( H_T \) veto + clustering corrections
Tackmann,Walsh,Zuberi 2012

\[
\sigma_0(p_{\text{cut}}^T) \quad \text{[pb]}
\]

\( m_H = 125 \text{ GeV} \)
\( gg \rightarrow H \) (8 TeV)
\( R = 0.4 \)

\( p_T \) +NNLO

LO

\[ \text{Large fixed-order uncertainty} \]
\[ \Delta_{\text{incl}}^2 + \Delta_{\geq 1}^2 \]

Stewart,Tackmann 2011

reduced by SCET NNLL’+NNLO

\[ \Delta \]

Inclusion

\[ \delta \sigma_{\text{SC}}(R^2) \]

\[ \Delta \sigma_{2}(\ln R) \]

\[ \sigma_{2}(p_{\text{cut}}^T) \]

\[ \sigma_{2}(\infty) \]

\[ E_{\text{cm}} = 8 \text{ TeV} \]
\[ m_H = 125 \text{ GeV} \]

\( p_{\text{cut}}^T \) [GeV]

\( \sigma_0(p_{\text{cut}}^T) \quad \text{[pb]} \)

\( m_H = 125 \text{ GeV} \)
\( gg \rightarrow H \) (8 TeV)
\( R = 0.4 \)

\( p_{\text{cut}}^T \) [GeV]
Higgs+jet production with a jet veto

Liu, Petriello 2013

- Leading jet with transverse momentum of $\mathcal{O}(m_H)$ not uncommon

- Fixed-order uncertainty $\Delta^2 = \Delta_{\geq 1}^2 + \Delta_{\geq 2}^2$ large at small $p_T, \text{veto}$ Stewart, Tackmann 2011

- Significant reduction by NLL' SCET resummation matched to NLO
Parton shower event generators

- PS provides resummation to (N)LL accuracy and realistic final states
- Matching allows for NLO precision in all aspects of experimental analysis

New concepts

- Sector showers
  Larkoski, Peskin

- Antenna showers
  Giele, Gehrmann-DeRidder, Hartgring, Kosower, Laenen, Lopez-Villarejo, Ritzmann, Skands

Extension of older methods

- Dipole showers
  Gieseke, Plätzer

- Full color showers
  Höche, Krauss, Plätzer, Schönherr, Siegert, Sjödahl
Matching NLO calculations and parton showers

- Fixed-order corrections improve high-$p_T$ region
- Parton-shower resums logarithmic corrections at small $p_T$
- Generate particle-level events from NLO calculations
Automated NLO+PS Matching

- Methods: MC@NLO Frixione, Webber 2002 and POWHEG Nason 2004
- Public frameworks: POWHEG Box Alioli, Nason, Oleari, Re 2010 and Sherpa SH, Krauss, Schönherr, Siegert 2012
- aMC@NLO → full automation using MadLoop/MadDipole/MadFKS Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli 2011

- Most challenging processes so far:
  \( W + 3\text{jets}, \ Z + 2\text{jets}, \ t\bar{t} + 1\text{jet}, \ t\bar{t} + h/W/Z \)
  \( pp \rightarrow 2\text{jets} \)
Multi-scale improved NLO (MINLO)

- Interpret NLO event in terms of QCD branchings, much like a parton-shower
- Assign transverse momentum scales $q$ to splittings, evaluate $\alpha_s$ at these scales
- Multiply with Sudakov factors, but subtract first-order expansion (already included in NLO calculation)
NNLO+PS matching

- Supplement MINLO with known NLL coefficients in Sudakovs
- Can perform NLO calculation for $h+\text{jet}$ in region where $p_{Tj} \to 0$
- Reweight with NNLO prediction $\to$ NNLO+PS matched result

![Graphs showing dσ/dy and dσ/dp_T ratios for H and H_T](image)
Multi-jet merging at next-to-leading order

\[ k_T > Q_{\text{cut}} \]

\[ k_T > Q_{\text{cut}} \]

\[ k_T > Q_{\text{cut}} \]

\[ k_T > Q_{\text{cut}} \]

\[ k_T < Q_{\text{cut}} \]

\[ k_T < Q_{\text{cut}} \]

\[ k_T < Q_{\text{cut}} \]

\[ k_T < Q_{\text{cut}} \]
Evolution of matching and merging methods

- Color coherent evolution: Marchesini, Webber
- Initial-state shower: Sjöstrand
- ME correction: Bengtsson, Sjöstrand
- ME reclustering: André, Sjöstrand
- MLM merging: M. Moretti, Pittau
- MEPS@NLO: Gehrmann, Schönherr, Siegert
- CKKW merging: Catani, Krauss, Kuhn, Webber
- MC@NLO: Frixione, Webber
- CKKW-L@NLO (NL^3SP): Lavesson, Lonnblad
- MENLOPS: Hamilton, Nason
- MEPS@NLO: Gehrmann, Schönherr, Siegert
- MNLOPS: Hamilton, Lonnblad, Prester

Matching related

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Multi-jet merging at next-to-leading order

- Three different methods, implemented in Pythia, Sherpa and aMC@NLO
  - Lavesson, Lönnblad 2008
  - Lönnblad, Prestel 2012,
  - Gehrmann, SH, Krauss, Schönherr, Siegert 2012
  - Frixione, Frederix 2012
- Allows inclusive particle-level predictions with uncertainty estimates

\[
\sigma(W + \geq N_{\text{jet}} \text{ jets}) \text{ [pb]}
\]

- Data 2010, \(\sqrt{s} = 7 \text{ TeV}\)
- ALPGEN
- SHERPA
- PYTHIA
- BLACKHAT-SHERPA

ATLAS

- \(\int L dt = 36 \text{ pb}^{-1}\)
- anti-\(k_T\) jets, \(R = 0.4\)
- \(p_T^{\text{jet}} > 20 \text{ GeV, } |y^{\text{jet}}| < 4.4\)

Inclusive Jet Multiplicity

- ATLAS data
- MePs@Nlo
- MePs@Nlo \(\mu / 2 \ldots 2\mu\)
- MEnloPS
- MEnloPS \(\mu / 2 \ldots 2\mu\)
- Mc@Nlo

\(p_T^{\text{jet}} > 20 \text{ GeV}\)
\(p_T^{\text{jet}} > 30 \text{ GeV}\)

SH, Krauss, Schönherr, Siegert 2012
Multi-jet merging at next-to-leading order

- Merging of different NLO processes introduces higher-order corrections
- Typically changes overall cross section → “Unitarity violation”
- Can be avoided using explicit subtraction of excess → UNLOPS

![Graph showing the deviation of multijet cross sections](chart.png)

**Lönnblad, Prestel 2013**

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Higgs backgrounds in jet bins with ME+PS@NLO

Cascioli, SH, Krauss, Maierhöfer, Pozzorini, Siegert 2013

Integrating cross section in the exclusive 0-jet bin

\[ \sigma(p_{T_{\text{jet}}} < p_{T_{\text{max}}}) \text{ [pb]} \]

\begin{align*}
\text{Ratio} & \quad \text{pp} \rightarrow 4\ell + 0,1\text{jet at NLO with OpenLoops} \quad \text{Cascioli, Maierhöfer, Pozzorini 2012} \\
& \begin{aligned}
\text{Including squared quark-loop contributions up to one extra jet} \\
\text{Matched to Sherpa PS and merged (first merging of loop}^2 \text{ contribution)} \\
\text{Sensible perturbative uncertainties in jet bins due to PS resummation}
\end{aligned}
\end{align*}
Combined 0+1-jet NLO prediction with merging cut at 7GeV

- Large effect of color coherent emission in MC@NLO
- Large dependence on functional form of scale
- NLO-accurate prediction of $A_{FB}(p_T)$ except for first bin
Jet ratio scaling patterns

- Consider cross section ratios in $X + n$ jets

$$R_{(n+1)/n} = \frac{\sigma_{n+1}^{\text{excl}}}{\sigma_n^{\text{excl}}}$$

$\sim$ stable against QCD corrections Gerwick,Plehn,Schumann,Schichtel 2012

Can be computed using NLL jet rates Gerwick,Schumann,Gripaios,Webber 2012

Helpful to determine many-jet backgrounds in searches

- **Staircase Scaling:**

$$R_{(n+1)/n} = \text{const} \left( \sigma_n = \sigma_0 R^n \right)$$

- First predicted for $W/Z+$jets
  Berends,Giele,Kuijf 1989

- Induced by democratic jet cuts

- **Poisson Scaling:**

$$R_{(n+1)/n} = \frac{\bar{n}}{n+1} \left( \sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!} \right)$$

- Independent emission picture (like soft $\gamma$ radiation in QED)

- Driven by large emission probability

- Induced by presence of hard jet
Testing scaling with NLO calculations

Bern, Dixon, Febres Cordero, SH, Ita, Kosower, Maître, Ozeren 2013

- \( W^{\pm} + \text{jets} \) at 7 TeV,
  - \( E_T^e > 20 \text{ GeV} \), \( |\eta^e| < 2.5 \), \( E_T^j > 20 \text{ GeV} \)
  - \( p_T^j > 25 \text{ GeV} \), \( |\eta^j| < 3 \), \( M_T^W > 20 \text{ GeV} \)

| Jets | \( \frac{W^{-} + (n+1)}{W^{-} + n} \) | \( \frac{W^{+} + (n+1)}{W^{+} + n} \) |
|------|-----------------|-----------------|
|      | LO NLO          | LO NLO          |
| 1    | 0.2949(0.0003)  | 0.238(0.001)    | 0.3119(0.0005) | 0.242(0.002) |
| 2    | 0.2511(0.0005)  | 0.220(0.001)    | 0.2671(0.0004) | 0.235(0.002) |
| 3    | 0.2345(0.0008)  | 0.211(0.003)    | 0.2490(0.0005) | 0.225(0.003) |
| 4    | 0.218(0.001)    | 0.200(0.006)    | 0.2319(0.0008) | 0.218(0.006) |

- Fit to straight line for \( W + n \) jets gives \( n \geq 2 \)
  \[
  R^{\text{NLO}, W^{-}}_{n/(n-1)} = 0.248 \pm 0.008 - (0.009 \pm 0.002) n
  \]
  \[
  R^{\text{NLO}, W^{+}}_{n/(n-1)} = 0.263 \pm 0.009 - (0.009 \pm 0.003) n
  \]

- Extrapolation to six jets
  - \( W^{-} + 6 \) jets : \( 0.15 \pm 0.01 \) pb
  - \( W^{+} + 6 \) jets : \( 0.30 \pm 0.03 \) pb
Summary

- QCD NLO calculations fully automated
  Limited only by final-state multiplicity
- NLO precision for multiple jets in event generators
  Meaningful uncertainty bands for the first time
- NNLO is the new frontier, with lots of progress
  \( pp \rightarrow t\bar{t}, \ pp \rightarrow \text{jets}, \ pp \rightarrow H+\text{jet} \) at parton level
- NNLO+NNLL resummation for exclusive observables
  \( pp \rightarrow H + 0\text{jets}, \text{ also } pp \rightarrow H + 1\text{jets} \) at NLO+NLL)
- NNLO+PS matching on the horizon