Applications of Higher Order QCD

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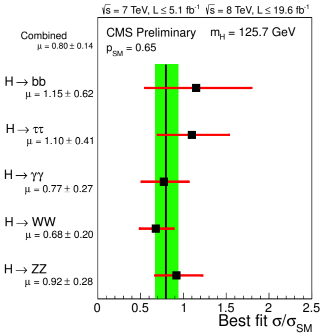
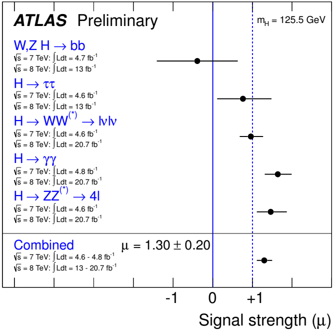
SLAC

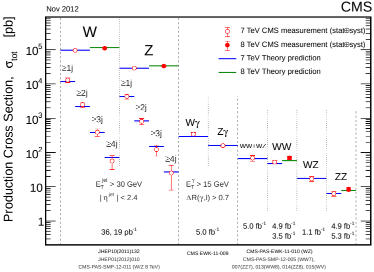
Physics In Collision 2013

Beijing, 09/04/13

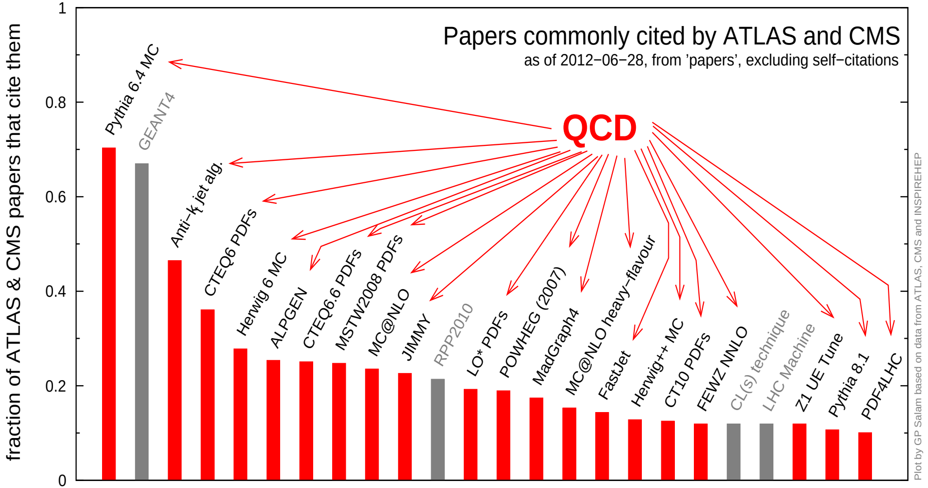




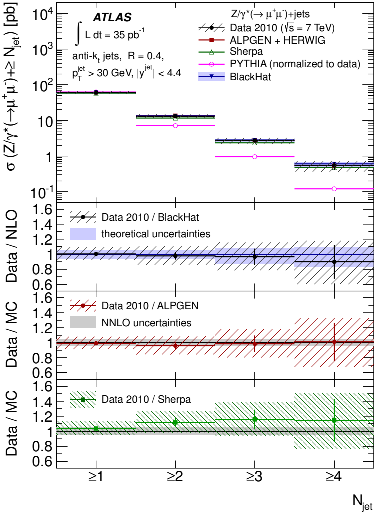
- 2013 → Higgs physics has moved from discovery to precision stage
- Improved theoretical predictions required to search for (small) deviations from Standard Model
- Great success of SM so far, but should keep looking everywhere



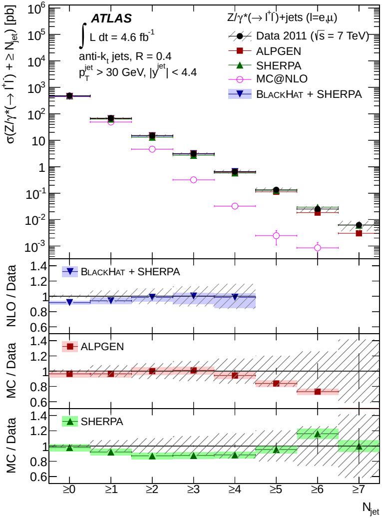
G.P. Salam, La Thuile 2012



- Any event at the LHC involves QCD, and so does most of our work



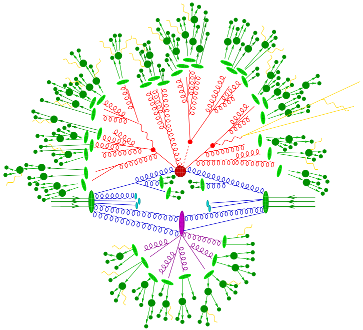
1 year! →



- 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

$$\sigma_{h_1 h_2 \to X} = \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{f_{h_1,i}(x_1,\mu_F^2) f_{h_2,j}(x_2,\mu_F^2)}_{\text{PDFs}} \underbrace{\hat{\sigma}_{ij\to X}(x_1 x_2 S,\mu_F^2)}_{\text{partonic cross section}} + \underbrace{\mathcal{O}(\Lambda_{QCD}/Q)^n}_{\text{power corrections}}$$

- PDFs inherently non-perturbative, but evolution with μ_F calculable
  Universality → 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 ($2\to4,5,6$)
  - 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$\to$H,$t\bar{t}$,jets,H+jet)
  - Fully differential NNLO (FEHiP,FEWZ,HNNLO)
  - NNLO+N^{x}LL resummation ($e^+e^- \to 2/3$ jets, $pp \to H$)

Automated NLO calculations

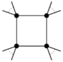
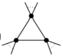
- NLO subtraction methods

$$\mathrm{d}\hat{\sigma}_{\mathrm{NLO}} = \int_{\Phi_n} \Big(\mathrm{d}\hat{\sigma}^{\mathrm{B}} + \underbrace{\mathrm{d}\hat{\sigma}^{\mathrm{V}} + \mathrm{d}\hat{\sigma}^{\mathrm{MF}} + \int_{\Phi_1} \mathrm{d}\hat{\sigma}^{\mathrm{S}}}_{\text{finite, compute with MC}} \Big) + \int_{\Phi_{n+1}} \underbrace{\Big(\mathrm{d}\hat{\sigma}^{\mathrm{R}} - \mathrm{d}\hat{\sigma}^{\mathrm{S}} \Big)}_{\text{finite, compute with MC}}$$

- 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,vanHameren,Heinrich,Hirschi,Ita,Kardos,Karg,Kauer,Kosower,Lopez-Val,Kunszt, Luisoni,Maierhöfer,Maître,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. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti WZ jet, $W\gamma$ jet completed by Campanario et al.
2. $pp \to$ 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. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld see also Binoth/Ossola/Papadopoulos/Pittau VBFNLOmeanwhile also contains WWW, ZZW, ZZZ, $WW\gamma$, $ZZ\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$, $W\gamma\gamma j$
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa and Rocket collaborations Z+3jets by Blackhat/Sherpa
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al.Bevilacqua et al.
8. $pp \to VV$+2jets	W^+W^++2jets, W^+W^-+2jets, relevant for VBF $H \to VV$ VBF contributions by (Bozzi/)Jäger/Oleari/Zeppenfeld
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al.
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets, Z+4jets see also HEJfor $W+n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures, Bevilacqua/Worek
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld
$pp \to 4$ jets	Blackhat/Sherpa

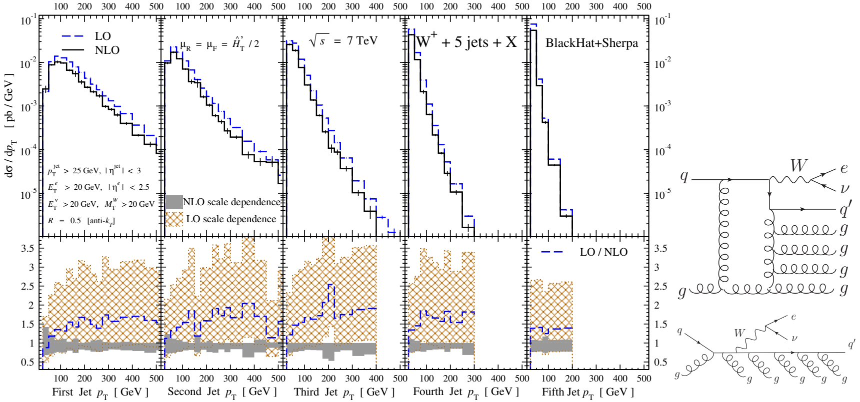
closed

Experimenter's NLO wishlist

- Started Les Houches 2005
- Item 9 added in 2007, 10-12 in 2009
- Finally retired in 2012

NLO highlights: $pp \to W + 5$ jets

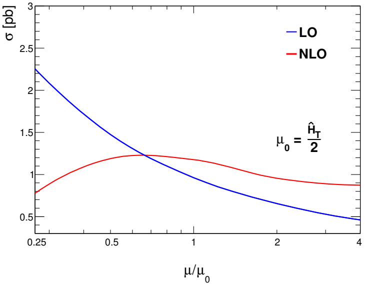
Bern, Dixon, Febres Cordero, SH, Ita, Kosower, Maître, Ozeren 2013

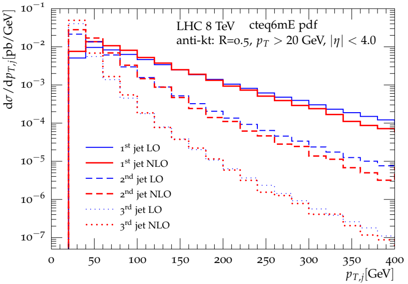


- First $2 \to 6$ NLO calculation for hadron colliders
- Allows extrapolation of jet rates to higher multiplicity (scaling)
- Flat K-factor for 5$^{\mathrm{th}}$jet with suitable scale $\hat{H}'_T = \sum p_{T,j} + E_{T,W}$

NLO highlights: Higgs+3 jets

Cullen,vanDeurzen,Greiner,Luisoni,Mastrolia,Mirabella,Ossola,Peraro,Tramontano 2013





- Largely reduced scale dependence
- Can be used to improve prediction of exclusive $H+2$jets production

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

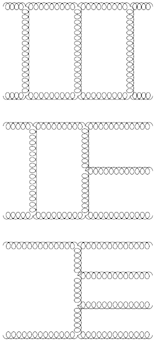
- Combination of One Loop program (GoSam) and MC (Sherpa, MadEvent) Using Binoth LesHouches accord Binoth et al. 2010; Alioli et al. 2013

The NNLO frontier

- Structure of the calculation

$$\mathrm{d}\hat{\sigma}_{\mathrm{NNLO}} = \int_{\Phi_{n+2}} \left(\mathrm{d}\hat{\sigma}^{RR} - \mathrm{d}\hat{\sigma}^{S}\right) + \int_{\Phi_{n+1}} \left(\mathrm{d}\hat{\sigma}^{RV} - \mathrm{d}\hat{\sigma}^{VS} + \mathrm{d}\hat{\sigma}^{MF,1}\right)$$
$$+ \int_{\Phi_{n}} \left(\mathrm{d}\hat{\sigma}^{VV} + \mathrm{d}\hat{\sigma}^{MF,2}\right) + \int_{\Phi_{n+1}} \mathrm{d}\hat{\sigma}^{VS} + \int_{\Phi_{n+2}} \mathrm{d}\hat{\sigma}^{S}$$

- Require three principal ingredients
  - Two-loop matrix elements
    explicit poles from loop integrals
  - One-loop matrix elements
    explicit poles from loop integral
    and implict poles from real emission
  - Tree-level matrix elements
    implicit poles from real emissions
- Challenge: Construction of subtraction methods for RR and RV contribution



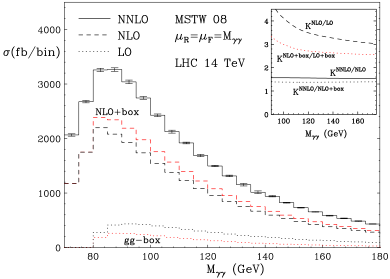
Methods for real radiation at NNLO

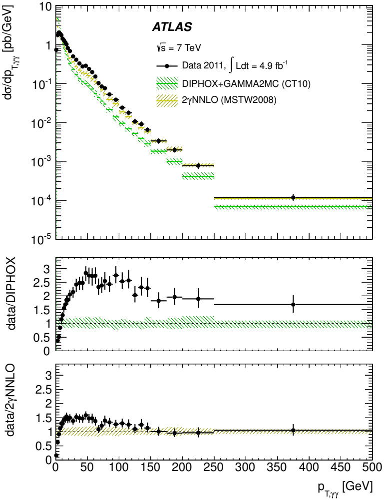
- Sector decomposition Binoth,Heinrich 2004;Anastasiou,Melnikov,Petriello 2004
  - $pp \to H$, $pp \to V$ Anastasiou,Melnikov,Petriello; Bühler,Herzog,Lazopoulos,Müller
- Antenna subtraction Gehrmann,Gehrmann-DeRidder,Glover
  - $e^+e^- \to$ 3jets Gehrmann,Gehrmann-DeRidder,Glover,Heinrich,Weinzierl
  - $pp \to$ 2jets Gehrmann,Gehrmann-DeRidder,Glover,Pires
- q_T subtraction Catani,Grazzini 2007
  - $pp \to H$, $pp \to V$, $pp \to VH$, $pp \to \gamma\gamma$ Catani,Cieri,DeFlorian,Ferrera,Grazzini,Tramontano
- Sector-improved subtraction Czakon 2010;Boughezal,Melnikov,Petriello 2011
  - $pp \to t\bar{t}$ Czakon,Fiedler,Mitov
  - $pp \to H$+jet Boughezal,Caola,Melnikov,Petriello,Schulze

Diphoton production at NNLO

Catani,Cieri,deFlorian,Ferrera,Grazzini 2011

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

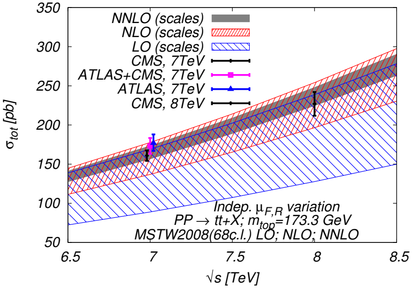


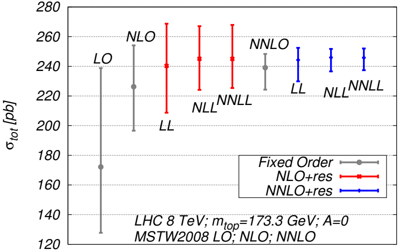


Top pair production at NNLO

$q\bar{q} \rightarrow t\bar{t}$ Bärnreuther,Czakon,Mitov 2012
$gg \rightarrow t\bar{t}$ 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, α_s, m_t) are all of same size
- Already used to constrain PDFs Czakon,Mangano,Mitov,Rojo 2013

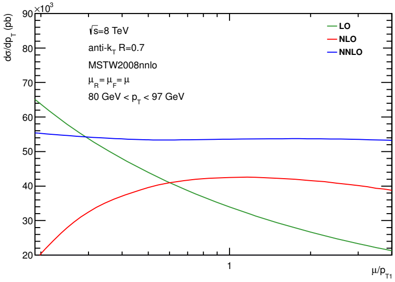


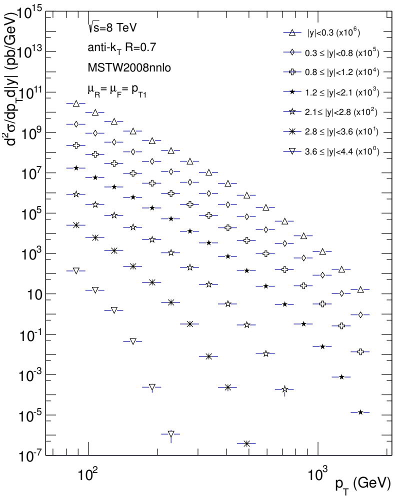


Jet production at NNLO

$pp \to 2$ 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

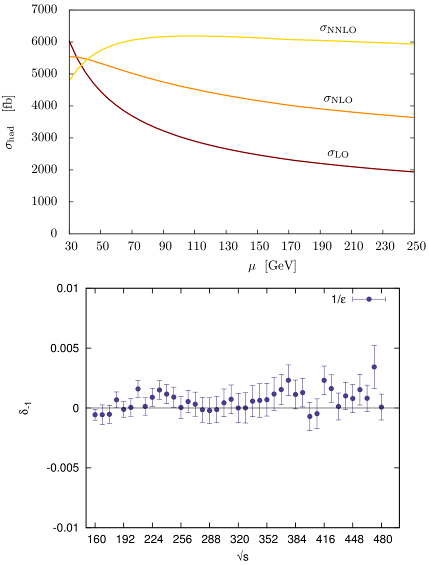




Higgs+jet production at NNLO

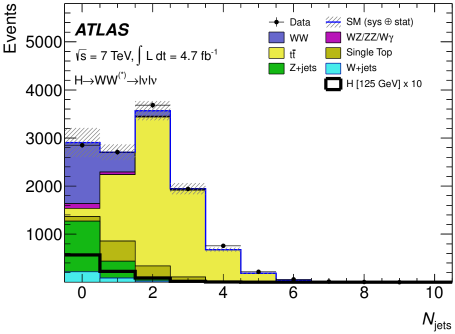
Boughezal,Caola,Melnikov,
Petriello,Schulze 2013

- 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 $\to$ 5% at NNLO



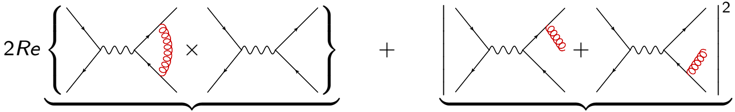
The importance of exclusive calculations

- 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



Why are exclusive calculations difficult?

- NLO corrections include virtual and real-emission part



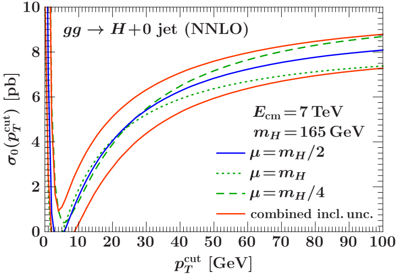
$$-1/\varepsilon_{IR}^2 + \dots \qquad +1/\varepsilon_{IR}^2 - C\,\log^2(Q/p_{T,\mathrm{cut}}) + \dots$$

- In inclusive case, finite correction remains
- In exclusive case, logarithmic dependence on $p_{T,\mathrm{cut}}$

- Higgs production in gluon fusion:

$$-6\frac{\alpha_s}{\pi}\log^2\frac{m_h}{p_{T,\mathrm{cut}}} \;\to \text{large!}$$

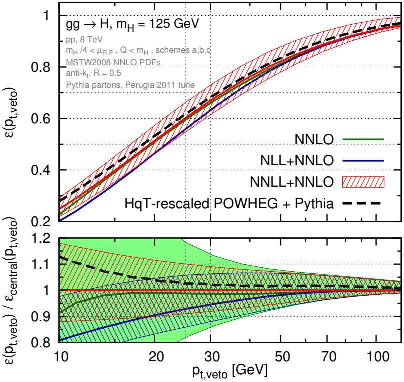
- Negative correction leads to pinch point in scale variation
- Uncertainty estimate requires resummation of log corrections

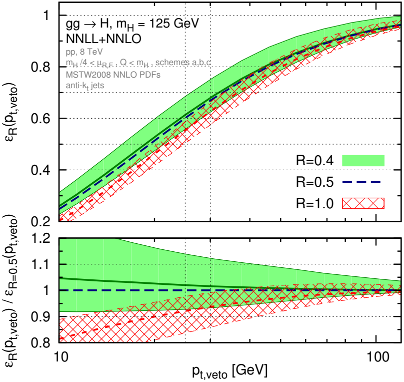


Higgs production with a jet veto

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%)

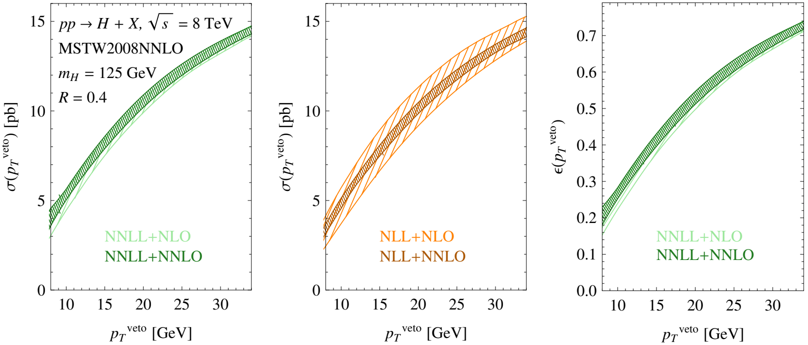




Higgs production with a jet veto

Becher,Neubert 2012

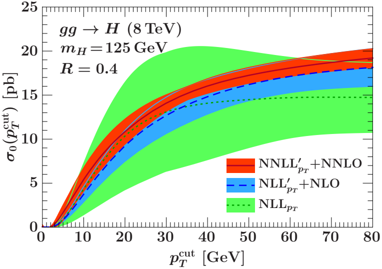
- First all-order factorization theorem for Higgs production with a jet veto
- Resummation now being performed at N^{3}LL Becher,Neubert,Rothen

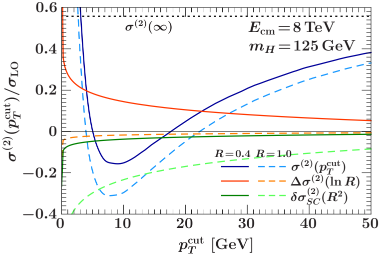


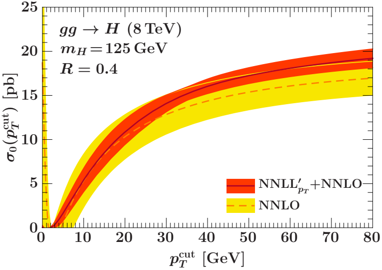
Higgs production with a jet veto

Tackmann,Walsh,Zuberi 2013

- Large fixed-order uncertainty $\Delta^2_{\rm incl} + \Delta^2_{\geq 1}$ Stewart,Tackmann 2011 reduced by SCET NNLL'+NNLO
- Full NNLO calculation of soft function for H_T veto + clustering corrections Tackmann,Walsh,Zuberi 2012



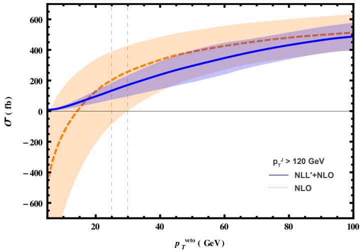


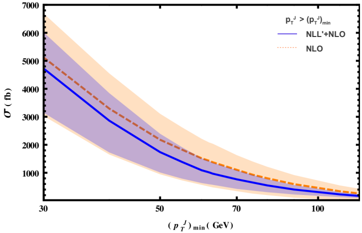


Higgs+jet production with a jet veto

Liu,Petriello 2013

- Leading jet with transverse momentum of $\mathcal{O}(m_H)$ not uncommon
- Fixed-order uncertainty $\Delta^2 = \Delta^2_{\geq 1} + \Delta^2_{\geq 2}$ large at small $p_{T,\mathrm{veto}}$ 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

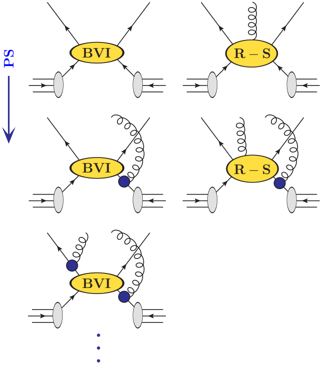
New concepts

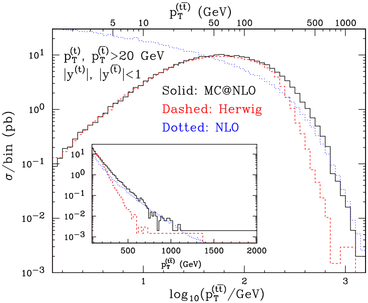
- Sector showers
  Larkoski,Peskin
- Antenna showers
  Giele,Gehrmann-DeRidder, Hartgring,Kosower,Laenen,Lopez-Villarejo,Ritzmann,Skands

Extension of older methods

- Dipole showers
  Gieseke,Plätzer
- Full color showers
  Höche,Krauss,Plätzer, Schönherr,Siegert,Sjödahl

Matching NLO calculations and parton showers



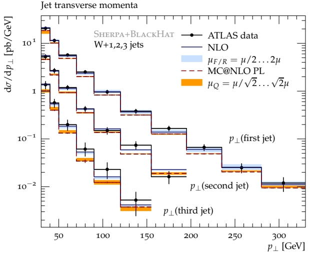


- Fixed-order corrections improve high-p_T region
- Parton-shower resums logarithmic corrections at small p_T
- Generate particle-level events from NLO calculations

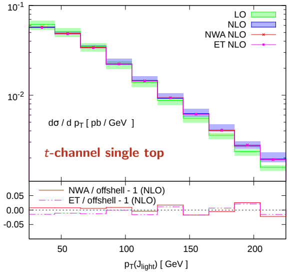
Automated NLO+PS Matching

- 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 $\to$ full automation using MadLoop/MadDipole/MadFKS Frederix, Frixione,Hirschi,Maltoni,Pittau,Torrielli 2011
- Most challenging processes so far:

  $W + 3$jets, $Z + 2$jets,
  $t\bar{t} + 1$jet, $t\bar{t} + h/W/Z$
  $pp \to 2$jets

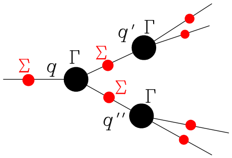


SH,Krauss,Siegert,Schönherr 2012



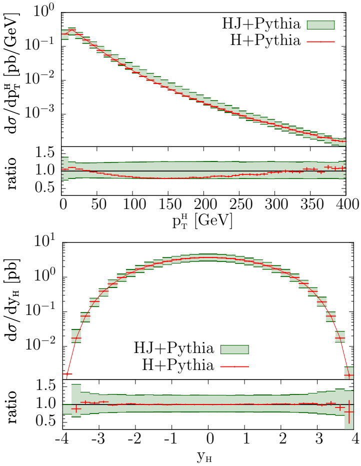
Papanastasiou,Frederix,Frixione, Hirschi,Maltoni 2013

Multi-scale improved NLO (MINLO)



Hamilton, Nason, Zanderighi 2012

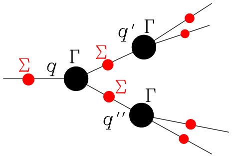
- Interpret NLO event in terms of QCD branchings, much like a parton-shower
- Assign transverse momentum scales q to splittings, evaluate α_s at these scales
- Multiply with Sudakov factors, but subtract first-order expansion (already included in NLO calculation)



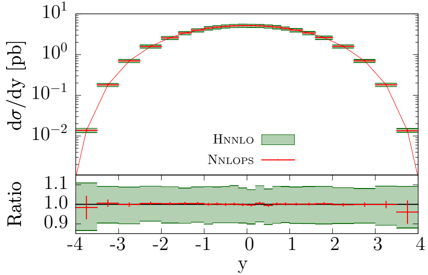
Hamilton, Nason, Oleari, Zanderighi 2012

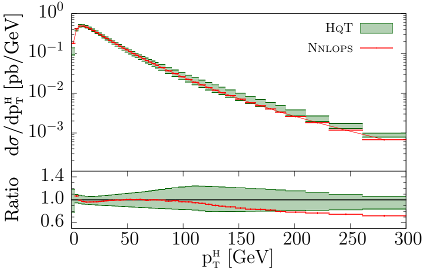
NNLO+PS matching

Hamilton,Nason,Re,Zanderighi 2013

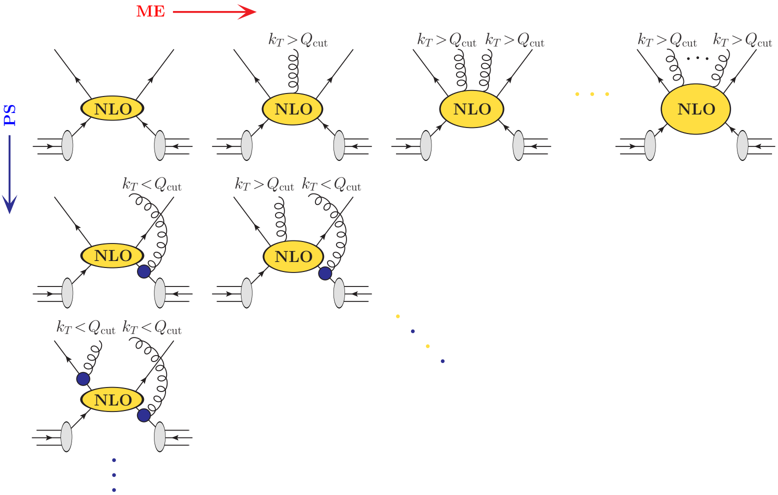


- Supplement MINLO with known NLL coefficients in Sudakovs
- Can perform NLO calculation for h+jet in region where $p_{Tj} \to 0$
- Reweight with NNLO prediction $\to$ NNLO+PS matched result

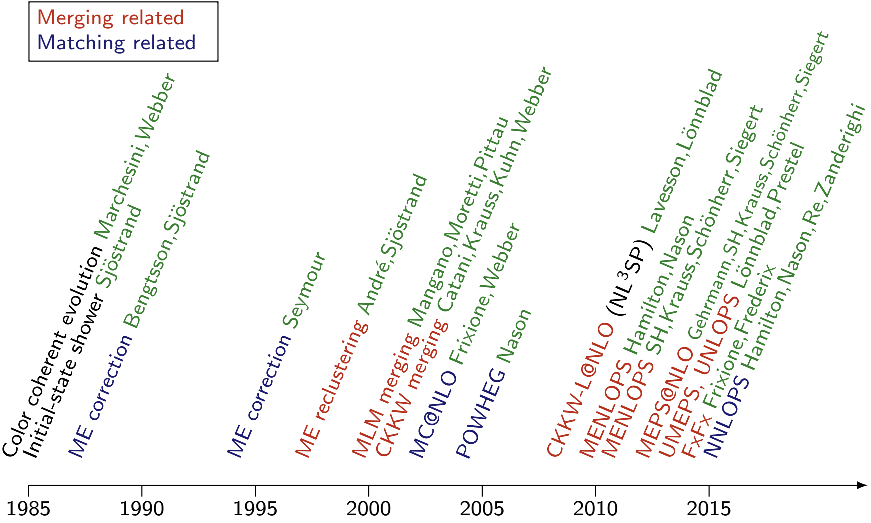




Multi-jet merging at next-to-leading order

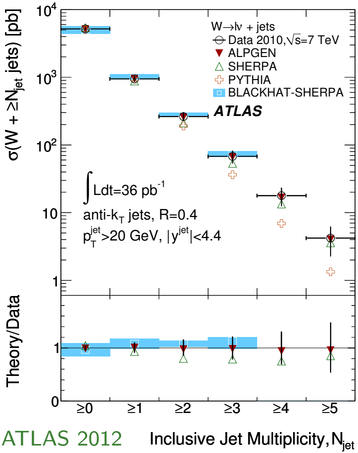


Evolution of matching and merging methods

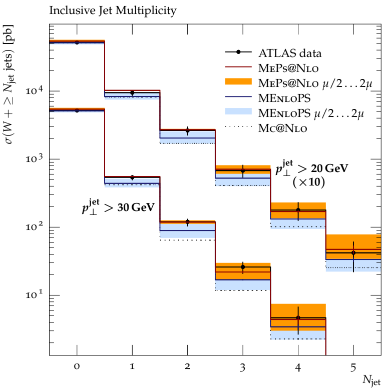


Multi-jet merging at next-to-leading order

- 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



ATLAS 2012

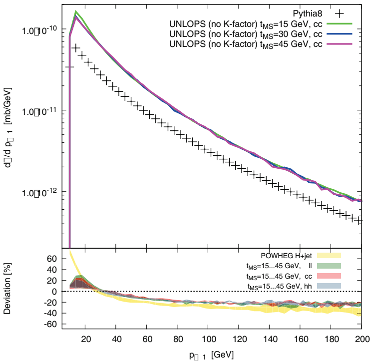


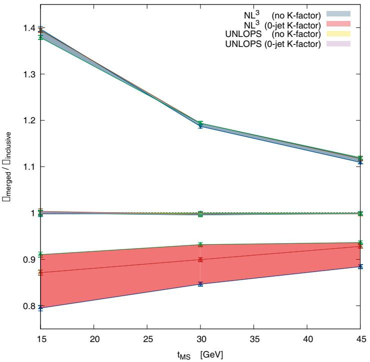
SH,Krauss,Schönherr,Siegert 2012

Multi-jet merging at next-to-leading order

Lönnblad,Prestel 2013

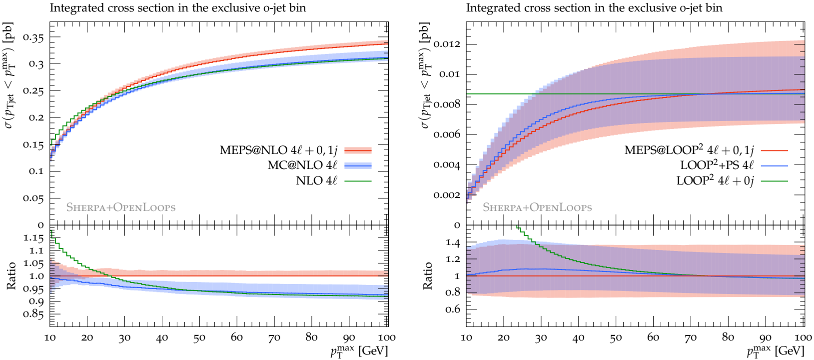
- Merging of different NLO processes introduces higher-order corrections
- Typically changes overall cross section → "Unitarity violation"
- Can be avoided using explicit subtraction of excess → UNLOPS





Higgs backgrounds in jet bins with ME+PS@NLO

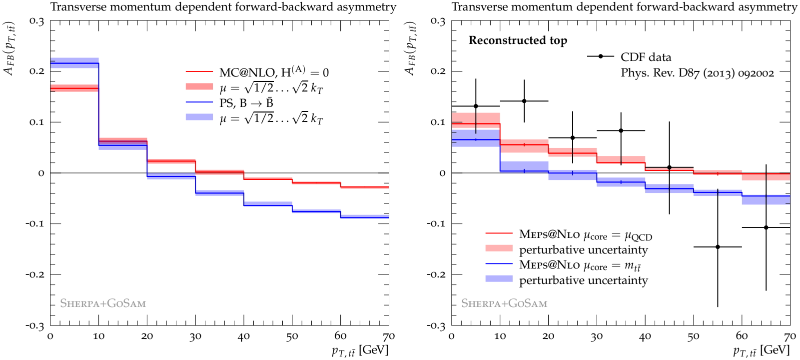
Cascioli,SH,Krauss,Maierhöfer,Pozzorini,Siegert 2013



- $pp \to 4l + 0, 1$jet at NLO with OpenLoops Cascioli,Maierhöfer,Pozzorini 2012
  Including squared quark-loop contributions up to one extra jet
- Matched to Sherpa PS and merged (first merging of loop^2 contribution)
- Sensible perturbative uncertainties in jet bins due to PS resummation

Top quark forward-backward asymmetry

SH,Huang,Luisoni,Schönherr,Winter 2013



- 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

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

$\sim$ 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**:

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

- First predicted for W/Z+jets
  Berends,Giele,Kuijf 1989
- Induced by democratic jet cuts

- **Poisson Scaling**:

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

- Independent emission picture
  (like soft γ 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+jets at 7 TeV, $E_T^e > 20\ \mathrm{GeV}\ , \quad |\eta^e| < 2.5\ , \quad \not{E}_T > 20\ \mathrm{GeV}$
  $p_T^j > 25\ \mathrm{GeV}\ , \quad |\eta^j| < 3\ , \quad M_T^W > 20\ \mathrm{GeV}$

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 $(n \geq 2)$

$$R_{n/(n-1)}^{\mathrm{NLO},\ W^-} = 0.248 \pm 0.008 - (0.009 \pm 0.002)\, n$$

$$R_{n/(n-1)}^{\mathrm{NLO},\ W^+} = 0.263 \pm 0.009 - (0.009 \pm 0.003)\, n$$

- Extrapolation to six jets

$W^- + 6$ jets : $\quad 0.15 \pm 0.01$ pb

$W^+ + 6$ jets : $\quad 0.30 \pm 0.03$ 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
  ($pp \to t\bar{t}$, $pp \to$jets, $pp \to H+$jet at parton level)
- NNLO+NNLL resummation for exclusive observables
  ($pp \to H + 0$jets, also $pp \to H + 1$jets at NLO+NLL)
- NNLO+PS matching on the horizon