QCD at Colliders: Theoretical Results

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SLAC

Lepton-Photon 2013

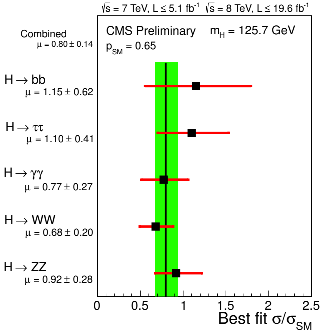
San Francisco, 06/25/13

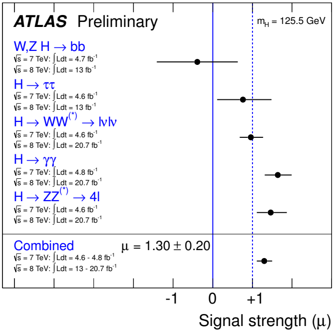
Outline

- NLO
- NNLO
- Resummation
- Event generators

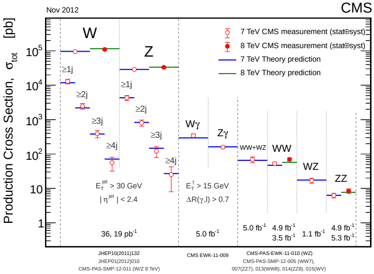
Disclaimer: 99% of recent interesting QCD results not covered.

Apologies to all whose work was omitted because of time constraints!





- 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



Toolkit inventory

- All processes of interest
  - Parton shower Monte Carlo (Herwig,Pythia,Sherpa,...)
  - Automated tree-level calculations & merging with PS (Alpgen,CompHEP,Helac,MadGraph,Pythia,Sherpa,...)
- Available for increasingly complex final states ($2 \to 4,5,6$)
  - Automated NLO (BlackHat,GoSam,Helac,MadGolem,MadLoop,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

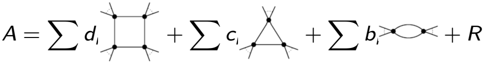
- General approach: subtraction methods

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

- 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



- "Feynmanian" approach → Improved decomposition & reduction

  Denner,Dittmaier 2005; Binoth,Guillet,Pilon,Heinrich,Schubert 2005

- "Unitarian" approach → Use 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,...

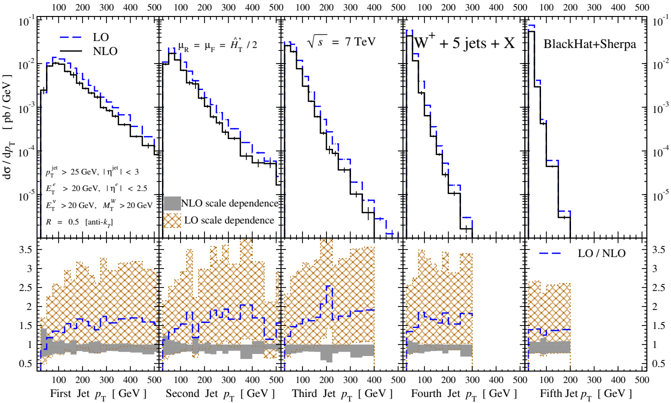
... making wishes come true

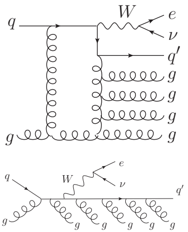
Process ($V \in \{Z, W, \gamma\}$)	Comments
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti WZ jet, $W\gamma$ jet completed by Campanario et al.
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed 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

Experimenter's NLO wishlist

- Started Les Houches 2005
- Item 9 added in 2007, 10-12 in 2009
- Finally retired in 2012
- Now to be replaced by NNLO wishlist?

First process from the (much longer) 2001 wishlist





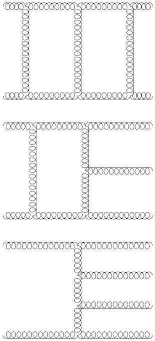
- $pp \to W + 5$ jets Bern,Dixon,Febres Cordero,SH,Ita,Kosower,Maître,Ozeren 2013
- Qualitatively very similar to $pp \to W + 4$ jets
- Allows extrapolation of jet rates to higher multiplicity

The NNLO frontier

- Structure of the calculation

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

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



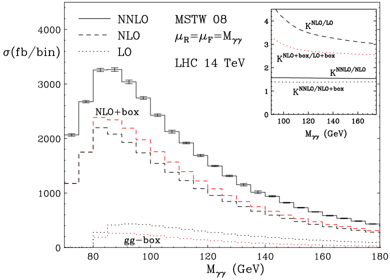
Methods for real radiation at NNLO

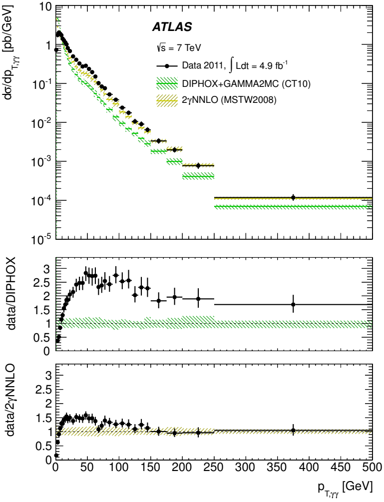
- Sector decomposition Binoth,Heinrich 2004;Anastasiou,Melnikov,Petriello 2004
  - $pp \to H$, $pp \to V$ Anastasiou,Melnikov,Petriello Bühler,Herzog,Lazopoulos,Müller
- Antenna subtraction Gehrmann,Gehrmann-DeRidder,Glover
  - $e^+e^- \to$ 3jets Gehrmann,Gehrmann-DeRidder,Glover,Heinrich,Weinzierl
  - $pp \to$ 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

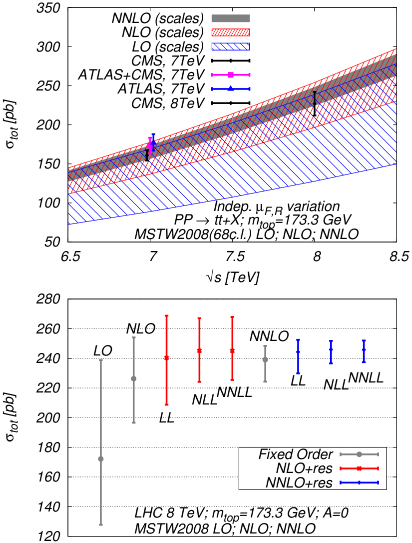




Top pair production at NNLO

$q\bar{q} \to t\bar{t}$ Bärnreuther,Czakon,Mitov 2012
$gg \to t\bar{t}$ Czakon,Fiedler,Mitov 2013

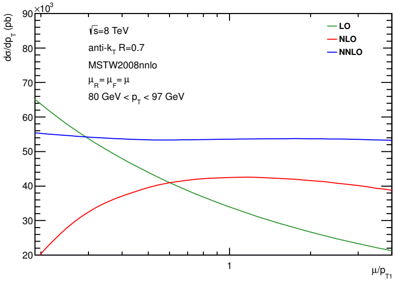
- Sector-improved subtraction for double real contribution
- First hadron collider calculation at NNLO with more than 2 colored partons
- First NNLO hadron collider calculation with massive fermions
- Point of saturation reached, where uncertainties (scale, PDF, α_s, m_t) are all of same size
- Already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

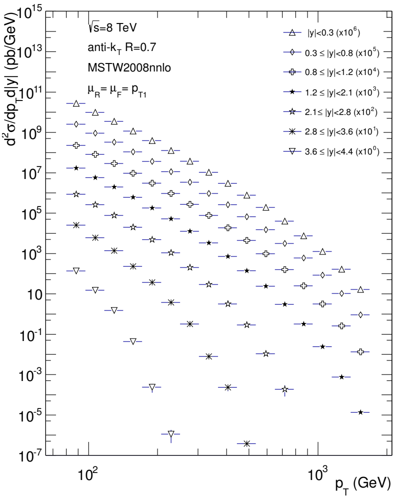


Jet production at NNLO

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 but very small scale dependence

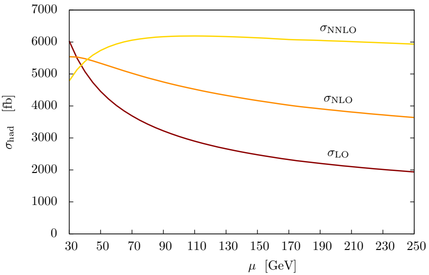


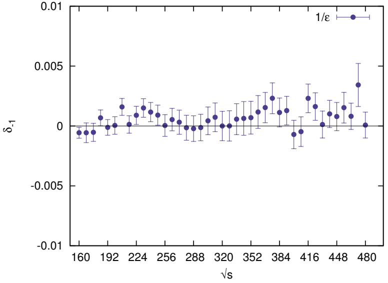


Higgs+jet production at NNLO

Boughezal,Caola,Melnikov,
Petriello,Schulze 2013

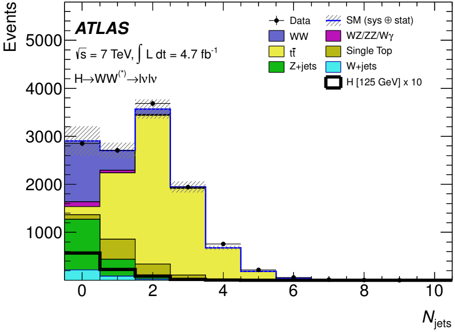
- Two independent calculations
- Sector-improved subtraction for double real contribution
- Large K-factor, 30% enhancement w.r.t. NLO for $\mu = m_H$
- Gluonic contribution only, but very small scale dependence 20% at NLO $\rightarrow$ 5% at NNLO
- Excellent numerical stability





Importance of exclusive calculations

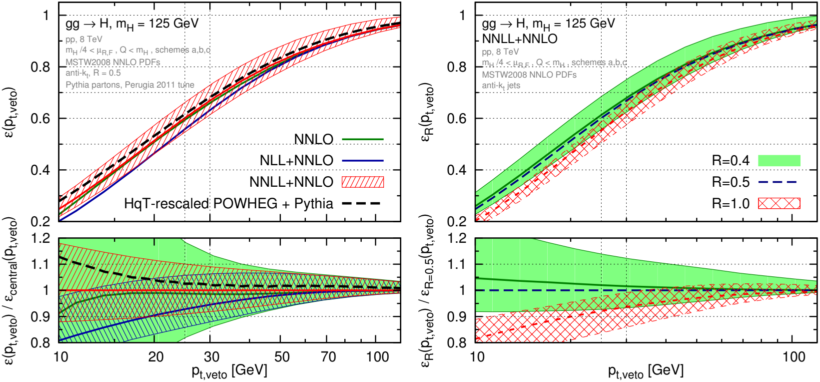
- Higgs measurements in *WW* channel binned in number of jets to reduce background (top veto)
- Also used to separate gluon fusion from VBF
- Different uncertainties in different jet bins



Higgs production with a jet veto

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

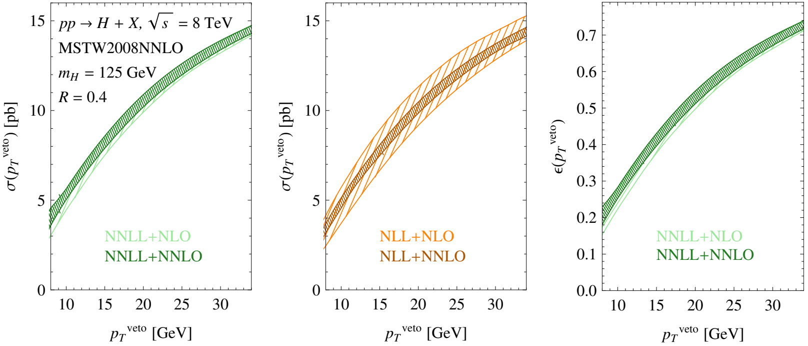
- Automated NLL resummation (CESAR)
- Continued to NNLL+NNLO using q_T resummation
- Hadronization and UE corrections have small impact (<1%)



Higgs production with a jet veto

Becher,Neubert 2012

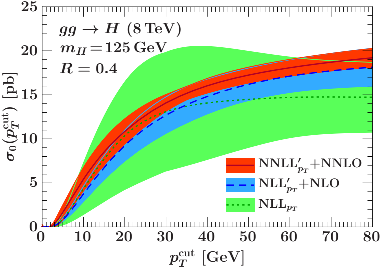
- First all-order factorization theorem for Higgs production with a jet veto
- K_T-type jet algorithm separates soft & collinear modes for intermediate R
- Resummation at NNLL, now working on N^{3}LL Becher,Neubert,Rothen

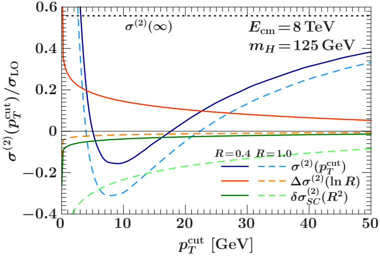


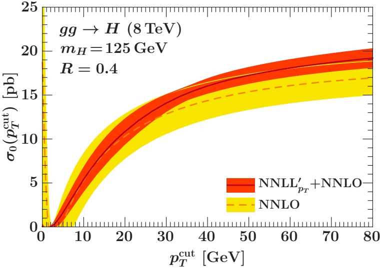
Higgs production with a jet veto

Tackmann,Walsh,Zuberi 2013

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



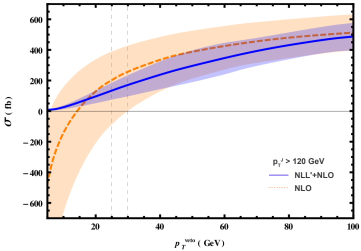


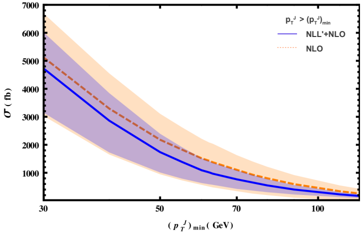


Higgs+jet production with a jet veto

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

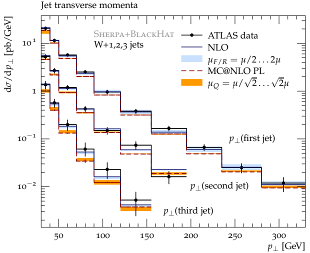
- Sector showers
  Larkoski,Peskin
- Antenna showers
  Giele,Gehrmann-DeRidder, Hartgring,Kosower,Laenen,Lopez-Villarejo,Ritzmann,Skands

Extension of older methods

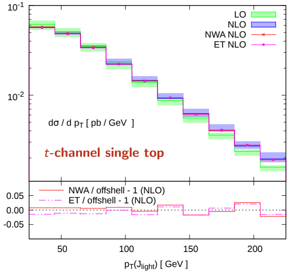
- Dipole showers
  Gieseke,Plätzer
- Full color showers
  SH,Krauss,Plätzer, Schönherr,Siegert,Sjödahl

NLO + Parton Shower Matching

- NLO calculation provides normalization and exact description of first hard emission, PS resums jet rates at (N)LL and allows to generate particle-level events
- Methods: MC@NLO Frixione,Webber 2002 and POWHEG Nason 2004
- Public (automated) frameworks: POWHEG Box Alioli,Nason,Oleari,Re 2010 and Sherpa SH,Krauss,Schönherr,Siegert 2012
- aMC@NLO → full NLO automation using MadLoop/MadDipole/MadFKS Frederix, Frixione,Hirschi,Maltoni,Pittau,Torrielli 2011



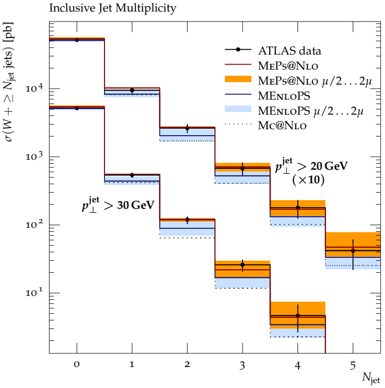
SH,Krauss,Siegert,Schönherr 2012



Papanastasiou,Frederix,Frixione, Hirschi,Maltoni 2013

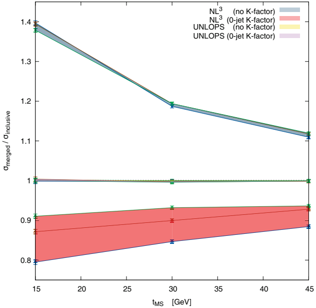
Combination of NLO+PS matched calculations

- ME+PS merging promoted to NLO accuracy Lavesson,Lönnblad 2008; Lönnblad, Prestel 2012; Gehrmann,SH,Krauss,Schönherr,Siegert 2012; Frixione,Frederix 2012
- Three different methods, implemented in Pythia, Sherpa and aMC@NLO
- Allows inclusive predictions with uncertainties from event generators



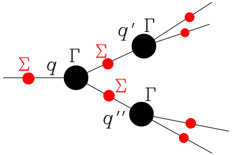
SH,Krauss,Schönherr,Siegert 2012

- Unitarization built into Pythia implementation



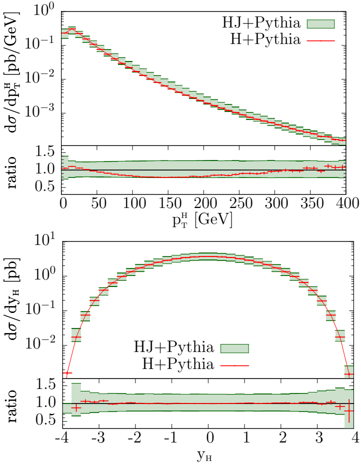
Lönnblad,Prestel 2012

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)
- Can be used to perform NLO calculation for X+jet in region where $p_{Tj} \to 0$



Hamilton,Nason,Oleari, Zanderighi 2012

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 BSM 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
  Computed for $W+ \leq 5$jet
  Bern,Dixon,Febres Cordero,SH, Ita,Kosower,Maître,Ozeren 2013
- 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

Conclusions

- QCD NLO calculations fully automated
  Corrections can be computed in arbitrary models soon
  Alwall,Degrande,Duhr,Fuks,Maltoni,Mattelaer,Stelzer,...
- 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)
- NNLO+NNLL resummation results for $pp \to H + 0$jets
- First results for $pp \to H$ at N^{3}LO
  Anastasiou,Bühler,Duhr,Dulat,Herzog,Mistlberger