Precision QCD at the LHC

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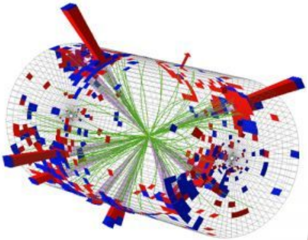
APS Meeting

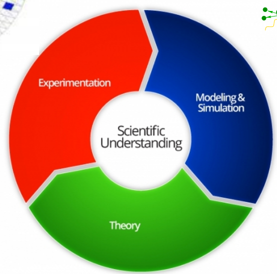
April 13, 2015

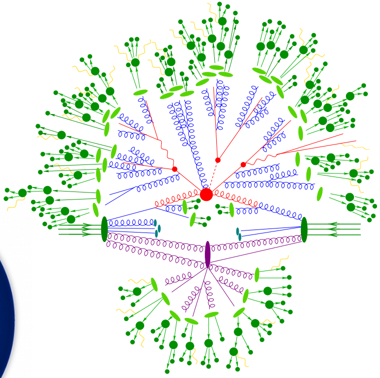
U.S. DEPARTMENT OF ENERGY
Office of Science

NATIONAL ACCELERATOR LABORATORY

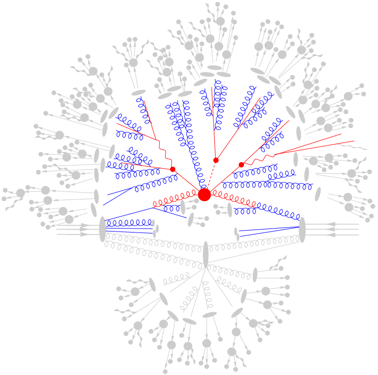
QCD at the LHC







$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$



Aspects of the theory

- Perturbative regime
  - Hard processes
  - Radiative corrections
- Non-perturbative regime
  - Hadronization
  - Particle decays

Divide et Impera

- Quantity of interest: Total interaction rate
- Convolution of short & long distance physics

$$\sigma_{p_1 p_2 \to X} = \sum_{i,j \in \{q,g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{f_{p_1,i}(x_1,\mu_F^2) f_{p_2,j}(x_2,\mu_F^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij \to X}(x_1 x_2, \mu_F^2)}_{\text{short distance}}$$

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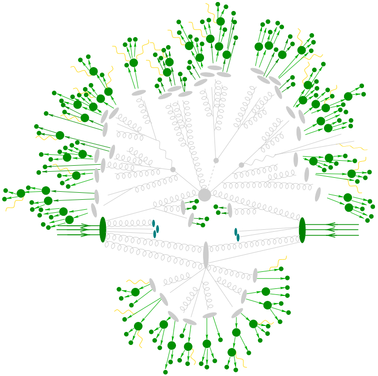

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QCD at the LHC

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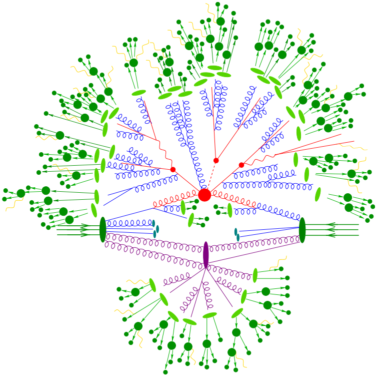

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Toolkit inventory

All processes of interest

- Parton shower Monte Carlo (Herwig,Pythia,Sherpa,...)
- Automated tree-level calculations & merging with PS (Alpgen,CompHEP,Helac,MadGraph,Sherpa,...)
- Automated NLO virtual corrections (BlackHat,GoSam,Helac,MadLoop,MadGolem,NJet,OpenLoops,...)
- Matching to parton shower (aMC@NLO,Herwig,POWHEG Box,Sherpa,...)
- Merging at LO & NLO (Alpgen,aMC@NLO,Helac,Pythia,Sherpa,...)

Selected processes

- Inclusive NNNLO (gg$\to$H)
- Inclusive NNLO ($t\bar{t}$,jets,H+jet,W+jet,single top)
- Differential NNLO (W,Z,gg$\to$H,Vγ,VV,VH)
- NNLO+N^{x}LL resummation ($e^+e^- \to$2/3 jets, gg$\to$H)
- NNLO+PS (W,Z,gg$\to$H)

Automated NLO calculations

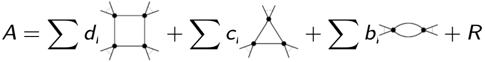
- General approach: subtraction methods

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

- Universal infrared behavior 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]

Automated NLO calculations

- 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: BlackHat, GoSam, HelacNLO, MadLoop, MadGolem, NJet, OpenLoops, ...

  [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,...]

W+5jets at NLO and jet scaling

[Bern,Dixon,Febres Cordero,SH,Ita,Kosower,Maître,Ozeren 2014]

- W+jets at 7 TeV, $E_T^e > 20$ GeV , $|\eta^e| < 2.5$, $\not{E}_T > 20$ GeV
  $p_T^j > 25$ GeV , $|\eta^j| < 3$, $M_T^W > 20$ 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 gives (for $n \geq 2$)

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

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

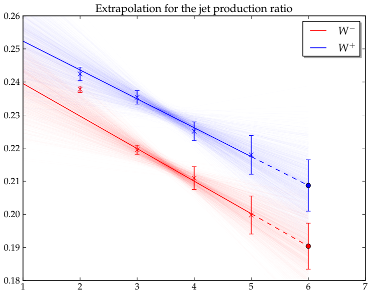
- Extrapolate to six jets

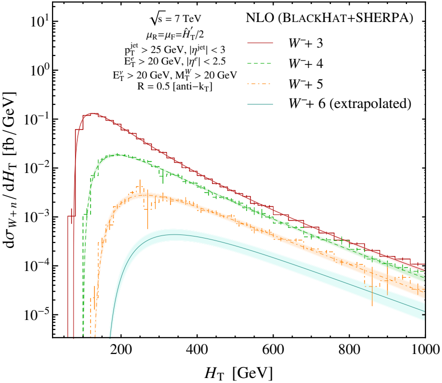
  $W^- + 6$ jets : 0.15 ± 0.01 pb

  $W^+ + 6$ jets : 0.30 ± 0.03 pb

W+5jets at NLO and jet scaling

[Bern,Dixon,Febres Cordero,SH,Ita,Kosower,Maître 2015]

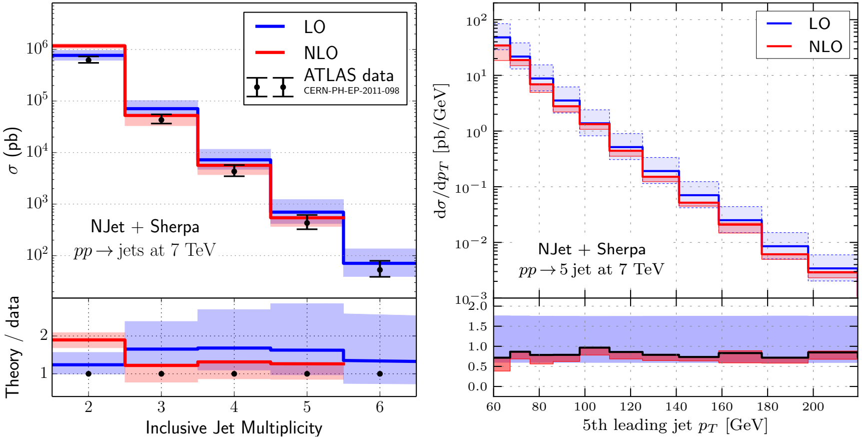




- Extrapolation of jet rate ratio and H_T spectrum
- Scaling proven by jet calculus [Gerwick,Gripaios,Schumann,Webber 2013]

5jets at NLO

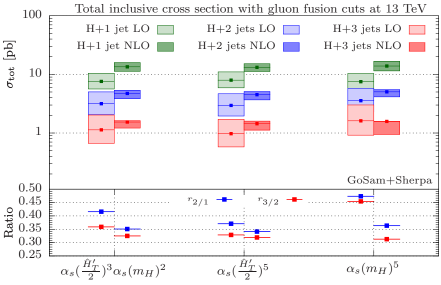
[Badger, Biedermann, Uwer, Yundin 2013]

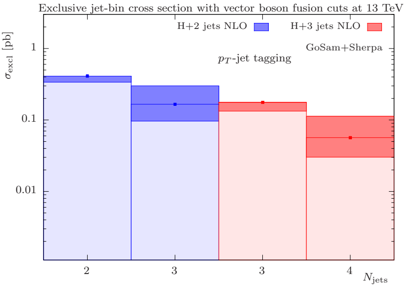


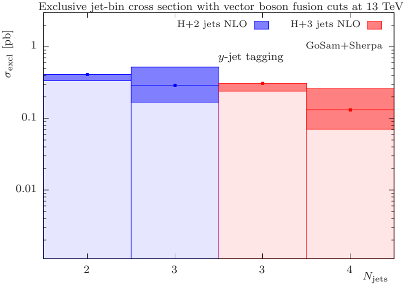
- Used to understand jet scaling in BSM searches
- Helps constrain PDFs with LHC data

Higgs+3 jets at NLO and VBF backgrounds

[Greiner,SH,Luisoni,Schönherr,Winter,Yundin 2015]







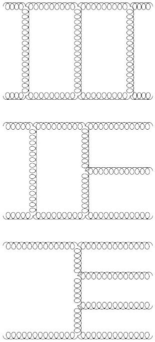
- $H + 2$jets through gluon fusion is irreducible background to VBF $\rightarrow$ get handle on jet veto efficiency through $H + 3$jets at NLO
- Jet scaling in process with topology similar to Drell-Yan

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 implicit poles from real emission
  - Tree-level matrix elements
    implicit poles from real emissions
- Challenge: Construction of subtraction methods for RR and RV contribution

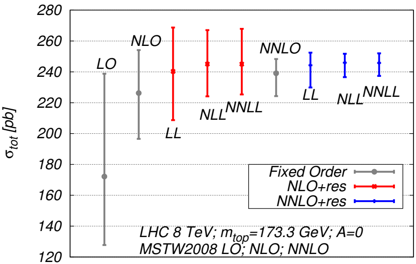


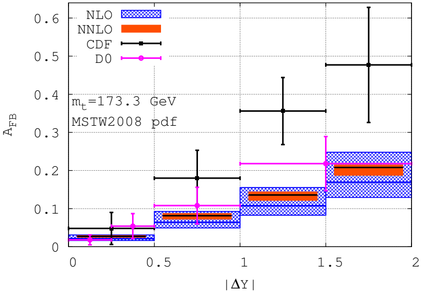
Methods for real radiation at NNLO

- Sector decomposition [Binoth,Heinrich 2004;Anastasiou,Melnikov,Petriello 2004]
  - $pp \to H$, $pp \to V$ [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]
- Cutoff method based on N-jettiness [Boughezal,Focke,Liu,Petriello 2015]
  - $pp \to W$+jet [Boughezal,Focke,Liu,Petriello]

Top-quark pair production

[Bärnreuther,Czakon,Fiedler,Mitov 2013-2014]





- Fully differential calculation in sector-improved subtraction scheme
- Constrains gluon PDF at large x (unc. reduction 15-25%)

T-channel single top production

[Brucherseifer,Caola,Melnikov 2014]

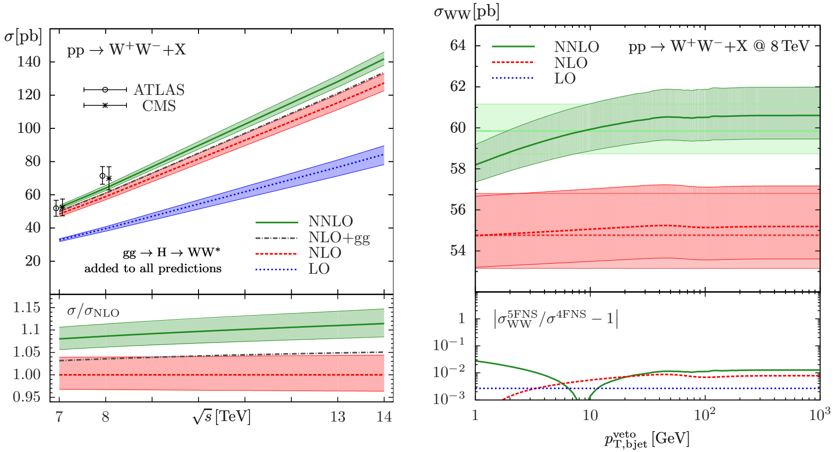
$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$	$19.1^{+0.3}_{+0.1}$	$+11.7\%$	$19.3^{-0.2}_{+0.1}$	$+1.0\%$
60 GeV	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

- Calculation performed in structure function approximation
- Fully differential using sector-improved subtraction
- Confirms NLO results at much higher theoretical accuracy

WW production

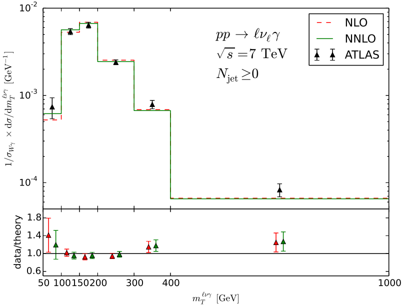
[Gehrmann,Grazzini,Kallweit,Maierhöfer,von Manteuffel,Pozzorini,Rathlev,Tancredi 2014]

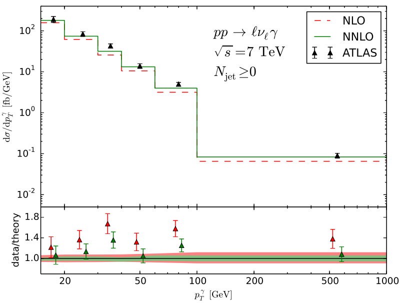


- Total cross section enhanced by 9(12)% at 7(14) TeV
- Top-subtracted 5FNS result agrees with 4FNS at 1(2)% for 7(14) TeV

$V\gamma$ production

[Grazzini,Kallweit,Rathlev 2015]

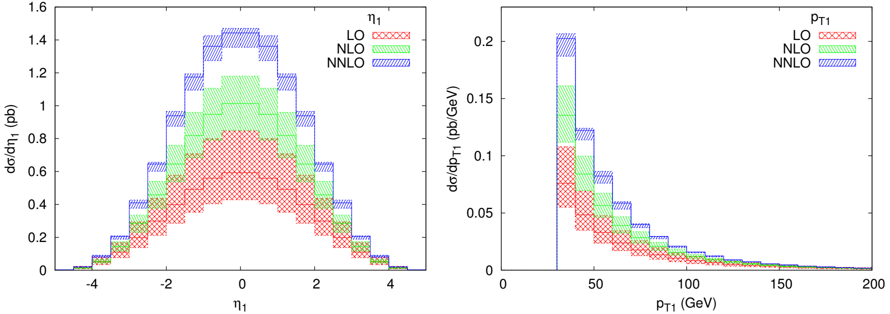




- Calculation performed using q_T-subtraction method
- $W\gamma \to$ NNLO effects important: 19% to 26%, depending on cuts
- $Z\gamma \to$ NNLO corrections 8% to 18%, depending on cuts

Higgs+jet production

[Chen,Gehrmann,Glover,Jaquier 2014]



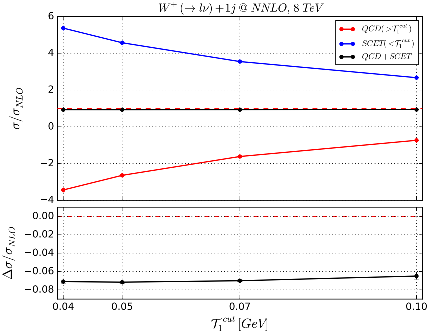
- Parton-level event generator, based on antenna subtraction
- Large rate change in inclusive result:

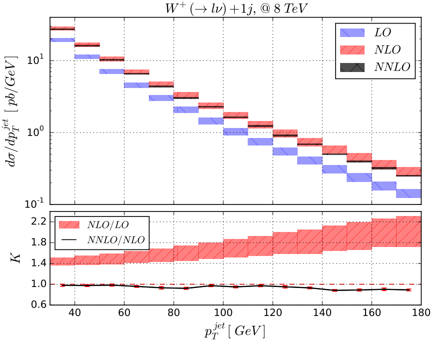
$$\sigma_{NLO} = 4.38^{+0.76}_{-0.74} pb \rightarrow \sigma_{NNLO} = 6.34^{+0.28}_{-0.49} pb \text{ at } p_{Tj} > 30 \text{ GeV}$$

- Residual theory uncertainty on p_T-spectra 5-16%
- Independent calculation by [Boughezal,Caola,Melnikov,Petriello,Schulze 2013]

W+jet production

[Boughezal,Focke,Liu,Petriello 2015]





- New cutoff method based on N-jettiness (needed NNLL soft function)
- Techniques also applicable to Higgs-boson plus jet production

Higgs-boson production through gluon fusion

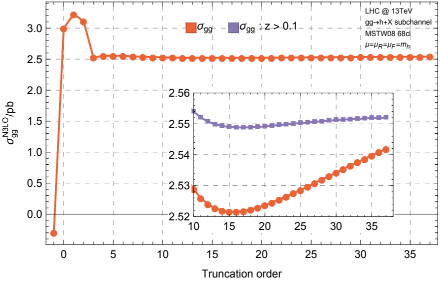
- Gluon fusion is dominant Higgs production mode at the LHC
- In large m_t limit described by effective Lagrangian

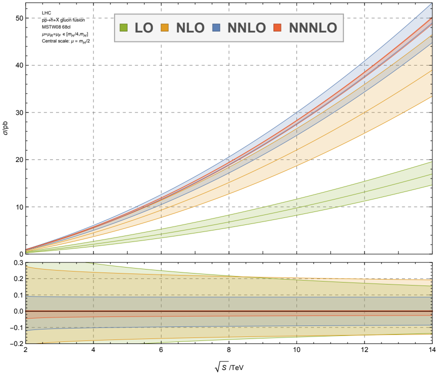
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{QCD}} - \frac{C}{4}\, H\, G^{a}_{\mu\nu}\, G_{a}^{\mu\nu}$$

- C known to N^{4}LO [Chetyrkin,Kniehl,Steinhauser 1998], [Schröder,Steinhauser 2006], [Chetyrkin,Kühn,Sturm 2006]
- Inclusive and fully differential NNLO known [Anastasiou,Melnikov 2002], [Harlander,Kilgore 2002], [Anastasiou,Melnikov,Petriello 2005], [Catani,Grazzini 2007]
- Mixed QCD+EW corrections known [Anastasiou,Boughezal,Petriello 2009], [Actis,Passarino,Sturm,Uccirati 2008]
- NNLO scale uncertainty still $\mathcal{O}(10\%)$
  Comparable to experimental uncertainty in Run I

Higgs-boson production through gluon fusion

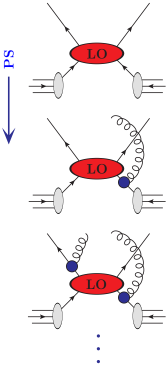
[Anastasiou,Duhr,Dulat,Herzog,Mistlberger 2015]





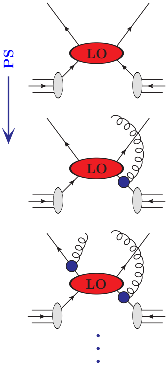
- First complete N^{3}LO calculation at a hadron collider
- Total scale variation 3%, reducing theory uncertainty by factor 3
- Calculation performed using reverse unitarity and threshold expansion

- Parton showers



$\sigma_{2\to 2}^{\rm incl}\,\mathcal{F}_{\rm MC}(Q^2)$

- Parton showers



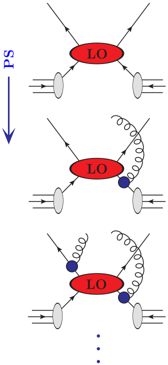
$$\sigma_{2\to 2}^{\text{incl}}\Bigg[\Delta(t_c,Q^2)$$

$$+\int\limits_{t_c}^{Q^2}\frac{\mathrm{d}t}{t}\int\mathrm{d}z\frac{\alpha_s}{2\pi}P(z)\,\Delta(t,Q^2)$$

$$+\frac{1}{2}\Bigg(\int\limits_{t_c}^{Q^2}\frac{\mathrm{d}t}{t}\int\mathrm{d}z\frac{\alpha_s}{2\pi}P(z)\Bigg)^2\Delta(t,Q^2)$$

$$+\dots$$

- Parton showers



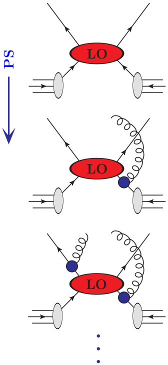
$$\sigma_{2\to 2}^{\rm incl}\Bigg[\,\Delta(\tau_c)$$

$$+\int_{\tau_c}^{1}\frac{{\rm d}\tau}{\tau}\int{\rm d}z\,\frac{\alpha_s}{2\pi}P(z)\,\Delta(\tau)$$

$$+\,\frac{1}{2}\left(\int_{\tau_c}^{1}\frac{{\rm d}\tau}{\tau}\int{\rm d}z\,\frac{\alpha_s}{2\pi}P(z)\right)^2\Delta(\tau)$$

$$+\ldots$$

- Parton showers



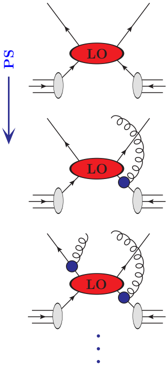
$$\sigma_{2\to2}^{\rm incl}\Bigg[\,\Delta(\tau_c)$$

$$+\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\,\big(A\log\tau+B\big)\,\Delta(\tau)$$

$$+\frac{1}{2}\Bigg(\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\,\big(A\log\tau+B\big)\Bigg)^2\Delta(\tau)$$

$$+\ldots$$

- Parton showers



$$\sigma_{2\to2}^{\rm incl}\left[\,\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\left(A\log\tau'+B\right)\right\}\right.$$

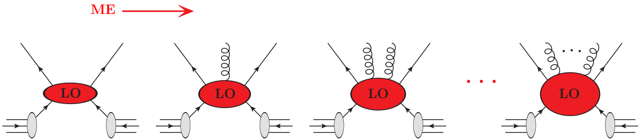
$$+\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\left(A\log\tau+B\right)\,\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\left(A\log\tau'+B\right)\right\}$$

$$+\frac{1}{2}\left(\int_{\tau_c}^{1}{\rm d}\tau\,\frac{\alpha_s}{\tau}\left(A\log\tau+B\right)\right)^2\exp\left\{-\int_{\tau_c}^{1}{\rm d}\tau'\,\frac{\alpha_s}{\tau'}\left(A\log\tau'+B\right)\right\}$$

$$+\ldots$$

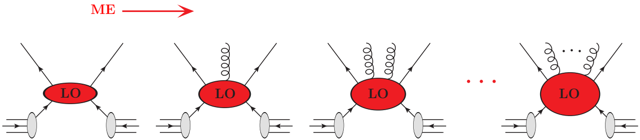
Parton shower resummation and combination with N^xLO

- Matrix elements



$\sigma^{\text{incl}}_{2\to2}$ $\sigma^{\text{incl}}_{2\to3}$ $\sigma^{\text{incl}}_{2\to4}$ $\ldots$ $\sigma^{\text{incl}}_{2\to\text{N}}$

- Matrix elements

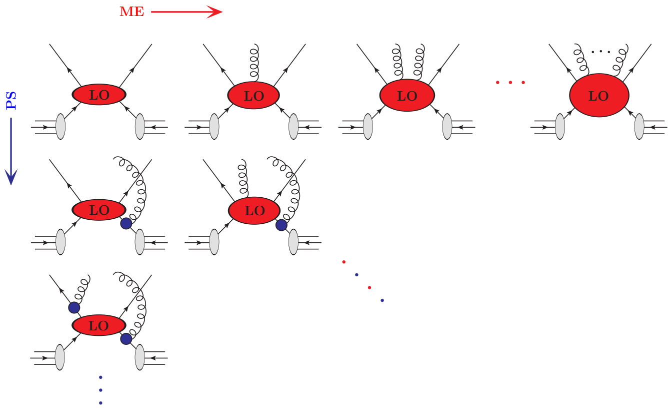


$\sigma^{\rm incl}_{2\to2}$ $\quad\sigma^{\rm incl}_{2\to3}$ $\quad\sigma^{\rm incl}_{2\to4}$ $\quad\ldots$

$$\sigma^{\rm incl}_{2\to4} \approx \sigma^{\rm incl}_{2\to2}\,\frac{\alpha_s}{\tau}\big(A\log\tau+B\big)\int_\tau^1 {\rm d}\tau'\,\frac{\alpha_s}{\tau'}\big(A\log\tau'+B\big)$$

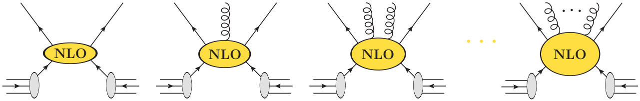
$$\sigma^{\rm incl}_{2\to3} \approx \sigma^{\rm incl}_{2\to2}\,\frac{\alpha_s}{\tau}\big(A\log\tau+B\big)$$

- Matrix element - parton shower merging (MEPS)



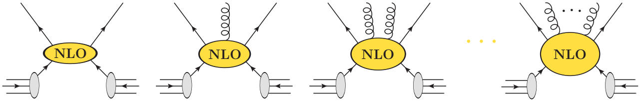
Parton shower resummation and combination with $\mathrm{N}^x\mathrm{LO}$

- NLO calculations



$\sigma_{2\to 2}^{\text{incl, NLO}}$ $\sigma_{2\to 3}^{\text{incl, NLO}}$ $\sigma_{2\to 4}^{\text{incl, NLO}}$ $\ldots$ $\sigma_{2\to \mathrm{N}}^{\text{incl, NLO}}$

- NLO calculations



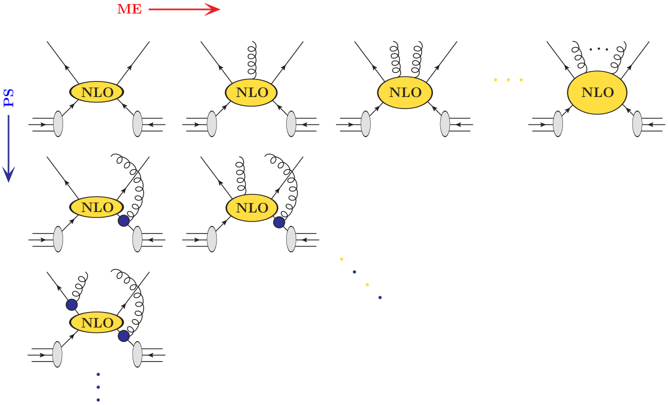
$$\sigma^{\text{incl, NLO}}_{2\to 2} \qquad \sigma^{\text{incl, NLO}}_{2\to 3} \qquad \ldots$$

$$\approx \sigma^{\text{incl}}_{2\to 2}\left(\frac{\alpha_s}{\tau}\left(A\log\tau + B\right)\left[1+\frac{\alpha_s}{2\pi}C_1+\frac{\alpha_s}{2\pi}\beta_0\log\tau - \int_\tau^1 \mathrm{d}\tau'\,\frac{\alpha_s}{\tau'}\left(A\log\tau'+B\right)+\ldots\right]+\frac{\alpha_s}{\tau}\frac{\alpha_s}{2\pi}K_g\,A\log\tau\right)+\ldots$$

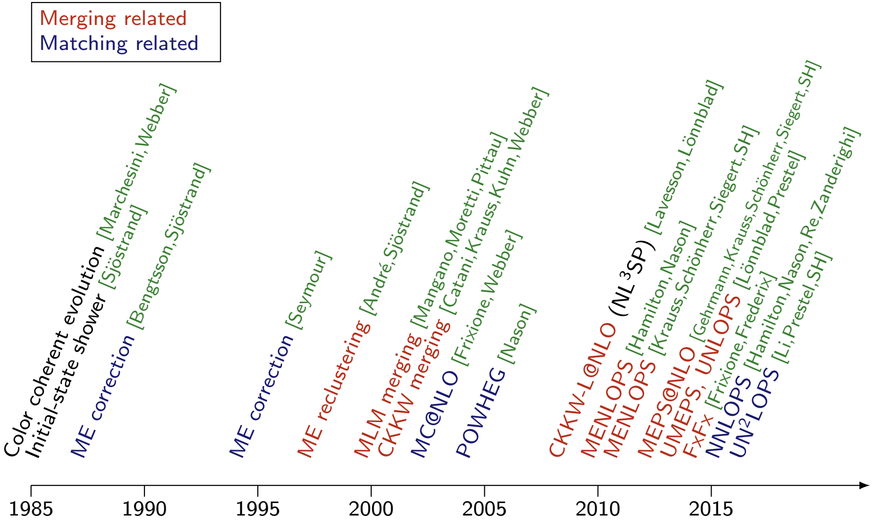
$$\sigma^{\text{incl}}_{2\to 2}\left[1+\frac{\alpha_s}{2\pi}C_1\right]$$

Parton shower resummation and combination with N^xLO

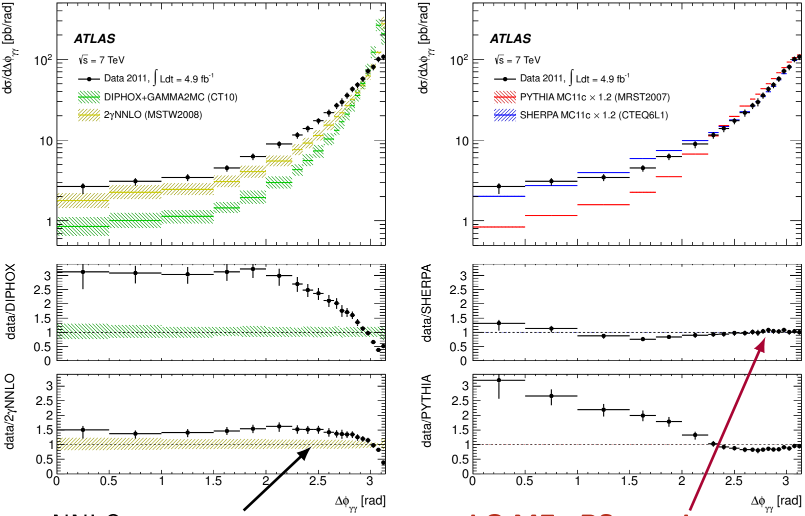
- Matrix element - parton shower merging at NLO (MEPS@NLO)



Parton shower resummation and combination with N^{x}LO



Parton shower resummation and combination with N^{x}LO

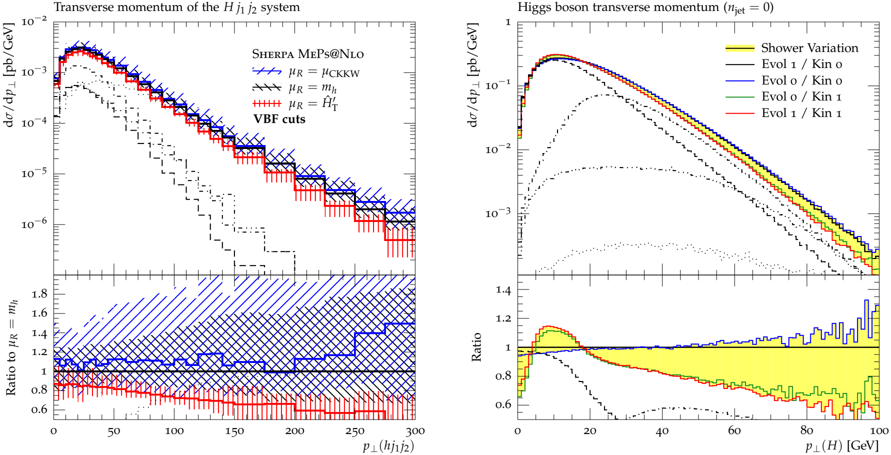


NNLO $pp \to \gamma\gamma$

LO ME+PS merging

Higgs-Boson production at NLO+PS

[Krauss,Schönherr,SH 2014]

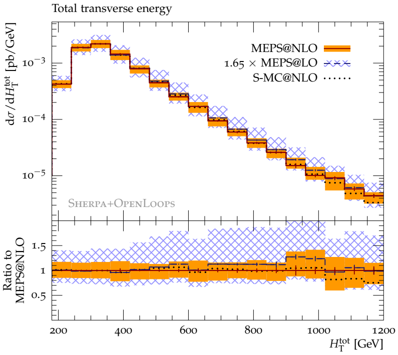


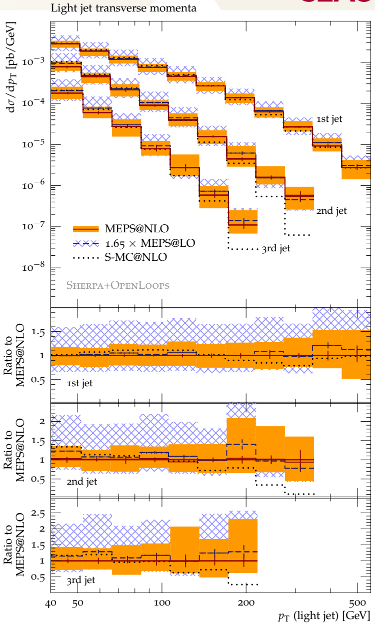
- Combines NLO QCD calculations for $pp \to h + 0, 1\&2$-jet plus 3-jet at LO
- Resummation uncertainty remains large in vetoed region relevant for VBF

Top-quark pair production at NLO+PS

[Krauss,Maierhöfer,Pozzorini,Schönherr,Siegert,SH 2014]

- First matched/merged sim for $t\bar{t}$+2j full result has $t\bar{t}$+0,1,2j@NLO, 3j@LO
- Largely reduced theory uncertainty for both for measurement (p_T, $N_{\rm jet}$) and BSM search (H_T) observables

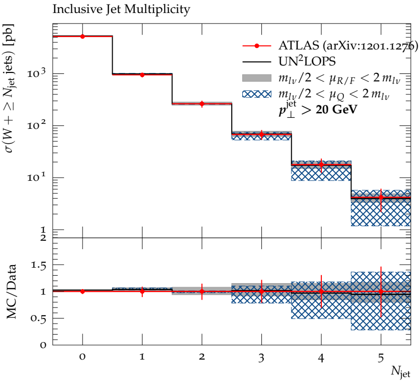


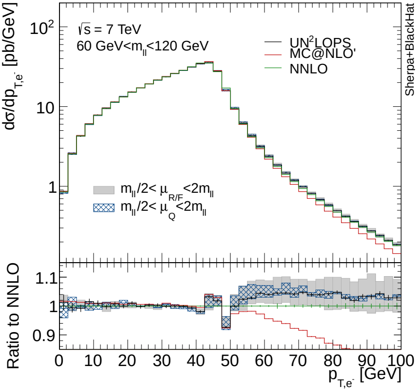


W/Z-production at NNLO+PS

[Li,Prestel,SH 2014]

- Matching scheme based on unitarized merging method [Lönnblad,Prestel 2012]
- First NNLO+PS event generator for Drell-Yan type processes
  Includes dominant electroweak (QED) effects

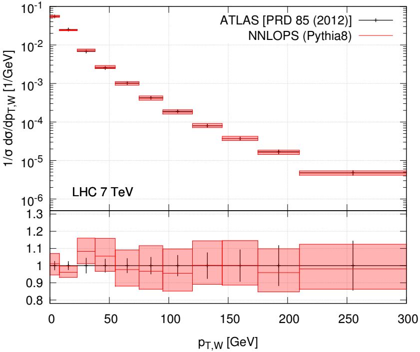


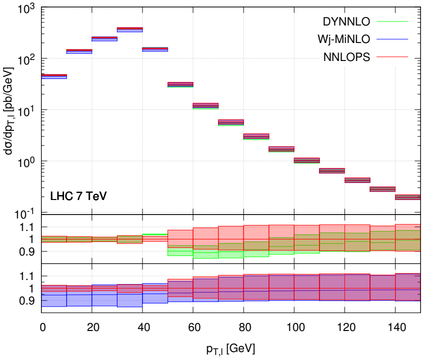


W/Z-production at NNLO+PS

[Karlberg,Re,Zanderighi 2014]

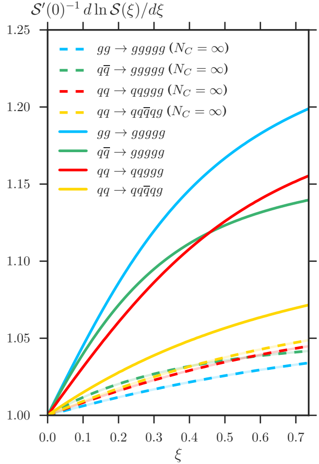
- Matching scheme based on MiNLO method [Hamilton,Nason,Re,Zanderighi 2013]
- NNLO rate obtained by reweighting with fully differential K-factor

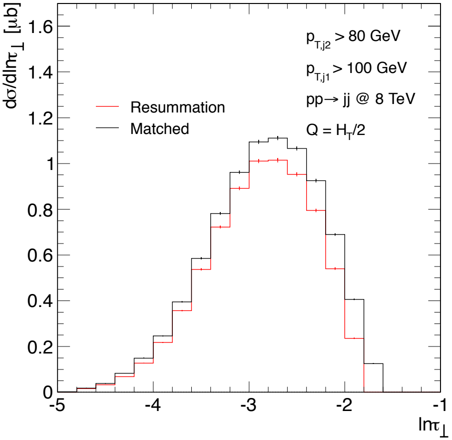




High-multiplicity NLL resummation & matching

[Gerwick,SH,Marzani,Schumann 2014]





- Automated calculation of hard matrix and soft anomalous dimension
- Automated matching of spectrum at LO, based on dipole subtraction

Summary

SLAC

- Precision QCD at hadron colliders is a reality
- NLO calculations, even at high multiplicity, are the standard
- Matching to parton showers extends NLO precision to the particle level
- NNLO calculations now become available for processes with light jets
- The first NNNLO result at a hadron collider was just computed
- Many higher-order results are implemented in event generators