Status of automated NLO calculations

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The art of collaboration

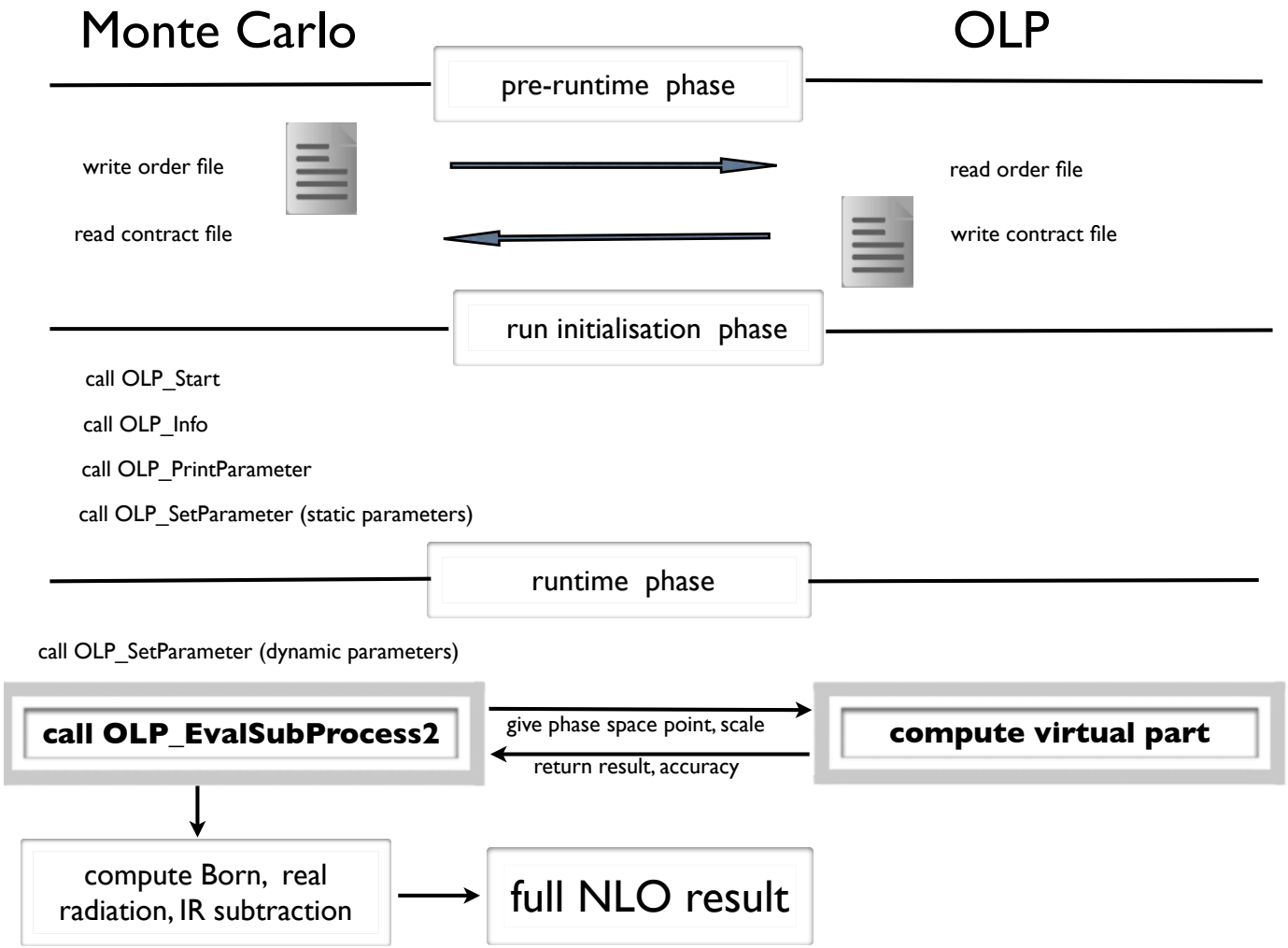
Share the workload

$$\sigma_{\mathrm{NLO}} = \int \mathrm{d}\Phi_{\mathrm{B}} \sum \left(\mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I}\right) + \int \mathrm{d}\Phi_{R} \sum \left(\mathrm{R} - \mathrm{S}\right)$$

- One-Loop Engines (OLEs) provide virtual piece
- ME generator takes care of Born, real emission, subtraction phase-space integration and event generation

The art of collaboration

[Binoth et al.] arXiv:1001.1307, [Alioli et al.] arXiv:1308.3462



Born, real radiation and subtraction terms

Tree-level tools

- **Feynman diagrams**
  - AMEGIC++ [Gleisberg,Krauss,Kuhn,Schumann] hep-ph/0109036
  - CompHEP [Boos et al.] hep-ph/0403113
  - MADGRAPH [Alwall,Herquet,Maltoni,Mattelaer,Stelzer] arXiv:1106.0522
- **Recursive relations**
  - ALPGEN [Mangano,Moretti,Piccinini,Pittau,Polosa] hep-ph/0206293
  - Comix [Gleisberg,SH] arXiv:0808.3674
  - HELAC [Kanaki,Papadopoulos] hep-ph/0002082
  - O'Mega [Moretti,Ohl,Reuter] hep-ph/0102195

IR subtraction schemes & tools

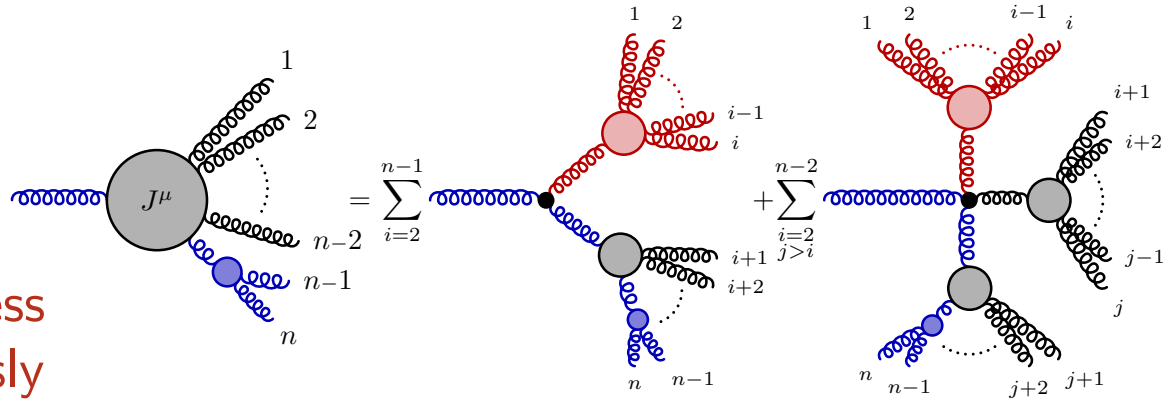
- **Dipoles** [Catani,Seymour] hep-ph/9605323
  [Catani,Dittmaier,Seymour,Trocsanyi] hep-ph/0201036, implemented in
  - AMEGIC++ [Gleisberg,Krauss] arXiv:0709.2881, Comix [SH] colorful
  - HELAC/PHEGAS [Czakon,Papadopoulos,Worek] arXiv:0905.0883 polarized
  - MADDIPOLE [Frederix,Gehrmann,Greiner] arXiv:0808.2128, arXiv:1004.2905
- **FKS** [Frixione,Kunszt,Signer] hep-ph/9512328, implemented in
  - MADFKS [Frederix,Frixione,Maltoni,Stelzer] arXiv:0908.4272

Born, real radiation and subtraction terms

One-Loop codes capable of computing very high multiplicity processes
$\rightarrow$ need to compute real-radiation & infrared subtraction terms efficiently

- Naively computational effort in dipole subtraction method grows like N^3 with number of external QCD particles
- Can be reduced by recursive computation similar to Berends-Giele technique at LO

- Fix spectator parton as "final" leg in amplitude
- Recycle subamplitudes from real-radiation process and dipoles simultaneously



- Implemented in ME generator Comix [Gleisberg,SH] arXiv:0808.3674

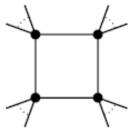
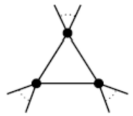
Virtual contribution

Plethora of (semi-)automated programs to compute virtual correction
Rough classification based on technique to evaluate loop integrals

- **Tensor reduction** [Denner,Dittmaier] hep-ph/0509141
  [Binoth,Guillet,Pilon,Heinrich,Schubert] hep-ph/0504267
  - Golem95 [Binoth,Cullen,Greiner,Guffanti,Guillet,Heinrich,Karg,Kauer,Reiter,Reuter]
  - MadGolem [Binoth,Goncalves Netto,Lopez-Val,Mawatari,Plehn,Wigmore]
  - NLOX [Reina,Schutzmeier]
  - OpenLoops [Cascioli,Maierhöfer,Pozzorini]
- **Generalized unitarity** [Bern,Dixon,Dunbar,Kosower] hep-ph/9409265 hep-ph/9708239
  [Ossola,Papadopoulos,Pittau] hep-ph/0609007, [Forde] arXiv:0704.1835
  - BlackHat [Bern,Dixon,Febres-Cordero,Ita,Kosower,LoPresti,Maître,Ozeren,SH]
  - GoSam [Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
  - HelacNLO [Bevilacqua,Czakon,Garzelli,vanHameren,Kardos,Papadopoulos,Pittau,Worek]
  - MadLoop [Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau]
  - NJet [Badger,Biedermann,Uwer,Yundin]
  - OpenLoops [Cascioli,Maierhöfer,Pozzorini]
  - Rocket [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- **Numerical integration** [Becker,Goetz,Reuschle,Schwan,Weinzierl] arXiv:1111.1733

Generalized unitarity and the NLO revolution

- Basic ideas [Bern,Dixon,Dunbar,Kosower] hep-ph/9409265 hep-ph/9708239
- Cut-constructible part of virtual amplitudes
  can be reduced to scalar integrals at integrand level
  [Ossola,Papadopoulos,Pittau] hep-ph/0609007, [Forde] arxiv:0704.1835

$$A_{loop} = \sum d_i \; \text{  } + \sum c_i \; \text{  } + \sum b_i \; \text{  } + R + \mathcal{O}(\epsilon)$$

- Determine coefficients from tree amplitudes [Ellis,Giele,Kunszt] arXiv:0708.2398
- Computation of both cut-constructible and rational parts
  using D-dimensional unitarity cuts [Giele,Kunszt,Melnikov] arXiv:0801.2237

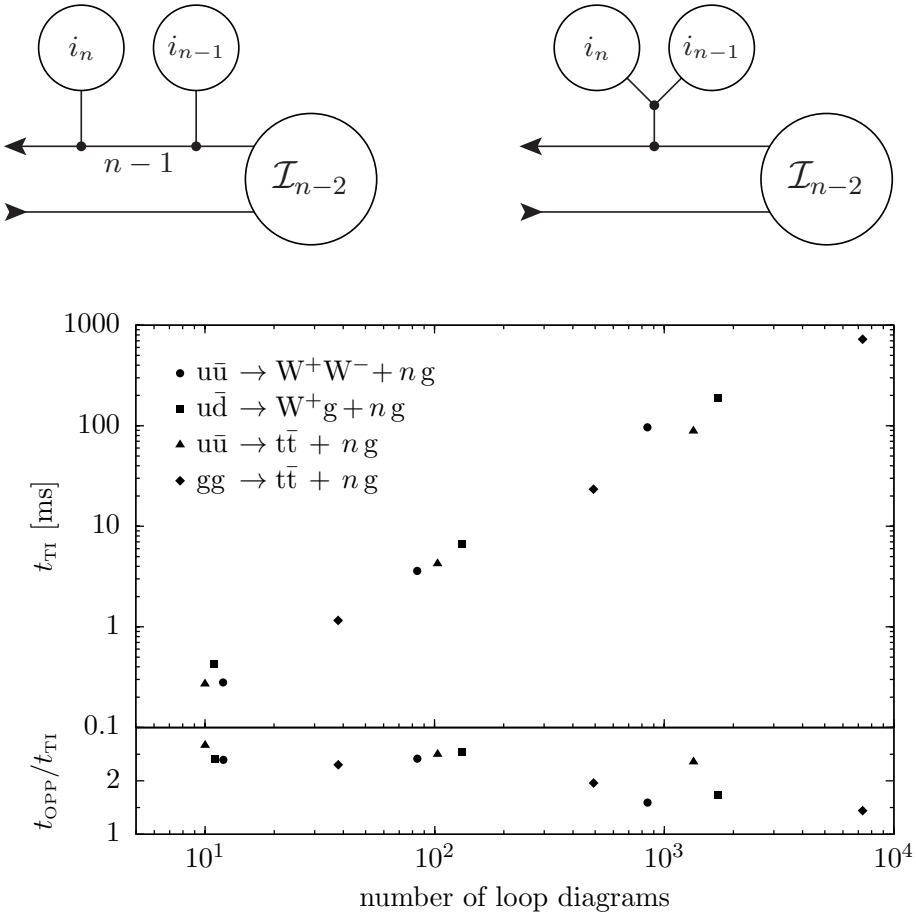
Recursive techniques for the integrand

[OpenLoops] arXiv:1111.5206

- Tree algorithm promoted to loop-momentum polynomials $\rightarrow$ open loops
- Can be combined with tensor-integral and OPP reduction method
- Generic, fast and stable

- Already used for 4 lepton (+jet) predictions matched to parton shower

  [Cascioli et al.] arXiv:1309.0500



Status of the NLO wishlist

Process ($V \in \{Z, W, \gamma\}$)	Status
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
$pp \to 4/5$ jets	Blackhat+Sherpa/NJets

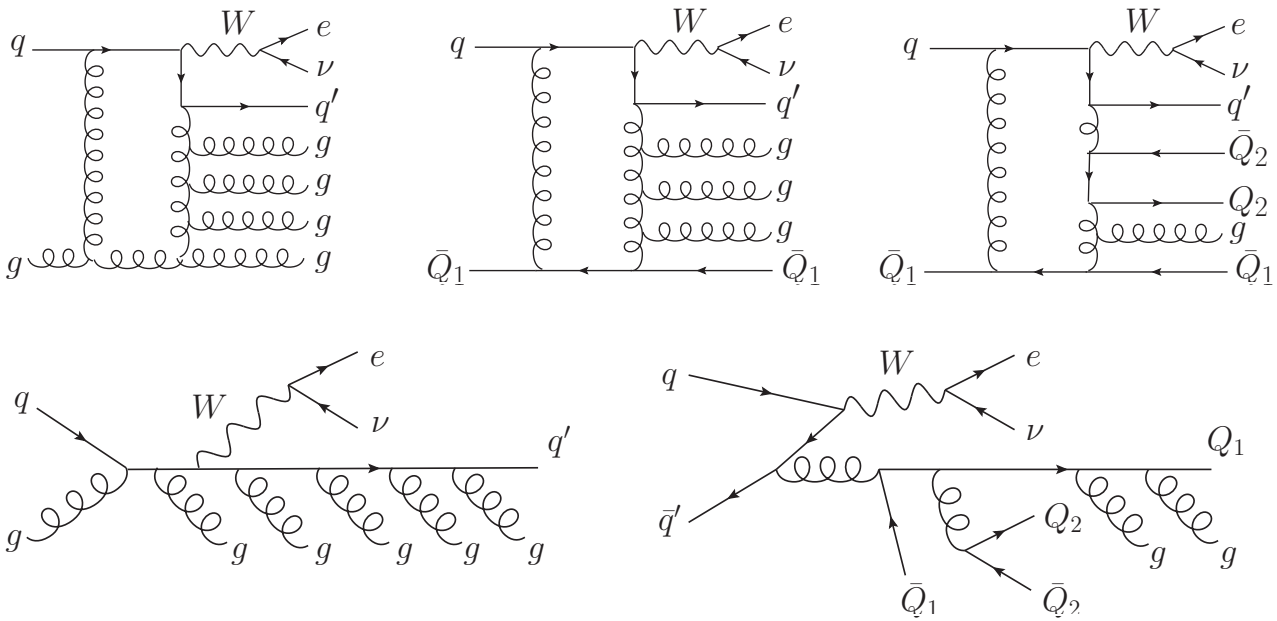
Closed

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

Recent progress: W+5jets at the LHC

[BlackHat] arXiv:1304.1253

- First $2 \to 6$ NLO calculation (plus decay $W \to l\nu$)
- Will be measured with good precision at LHC $\to$ test of SM
- Can be used to understand jet scaling patterns $\to$ BSM searches

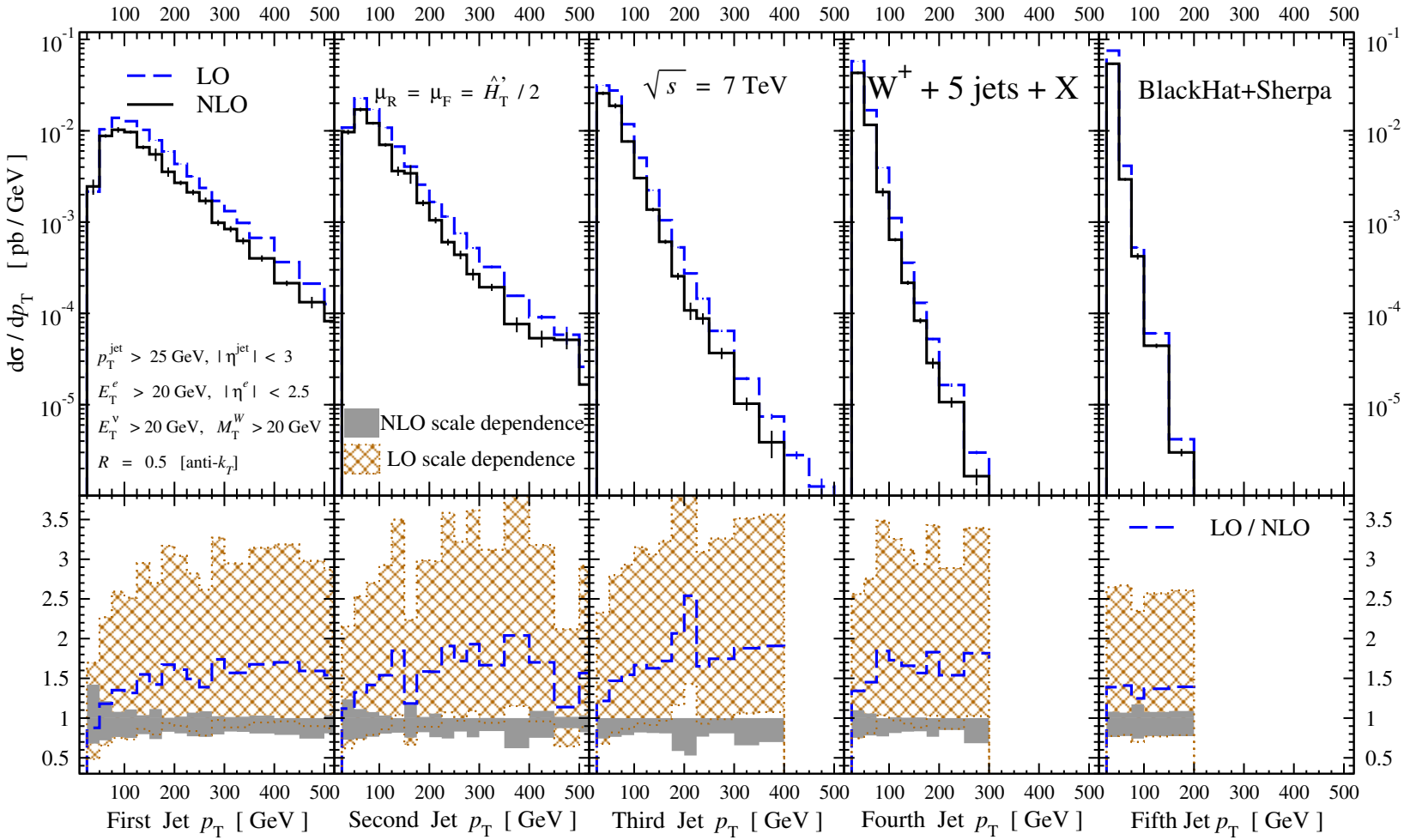


Approximations:

- Leading color in virtual piece (estimated $< 3\%$ correction)
- No real corrections with 8 quark lines ($< 1\%$ correction)

Recent progress: W+5jets at the LHC

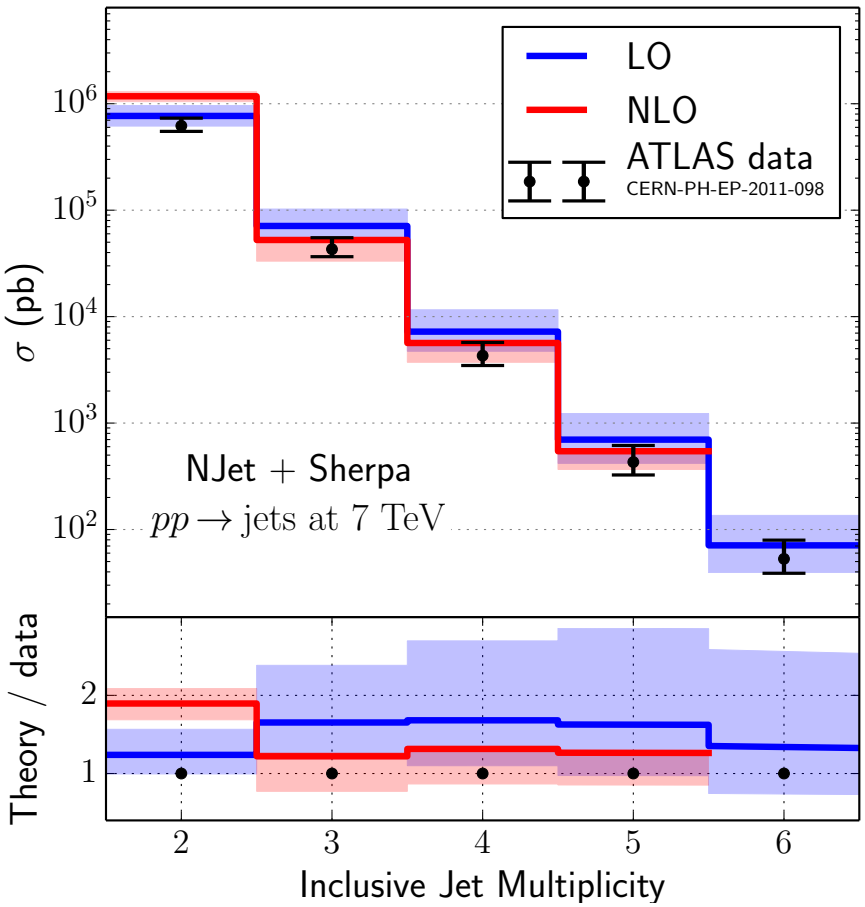
[BlackHat] arXiv:1304.1253

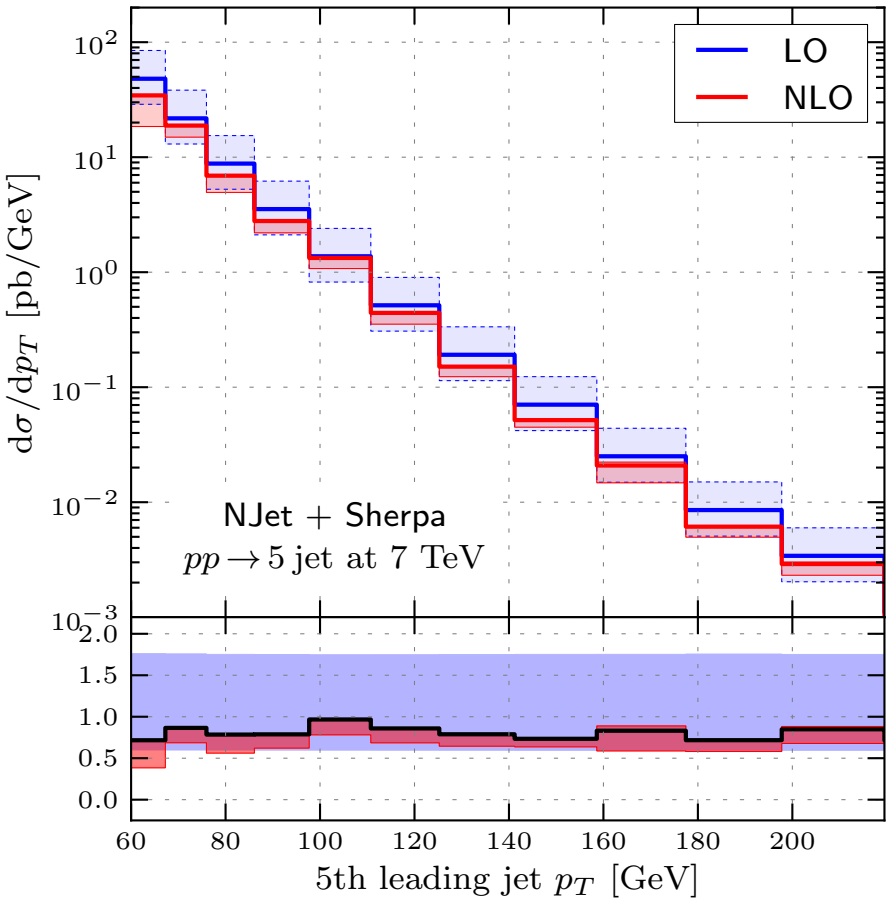


Recent progress: 5jets at the LHC

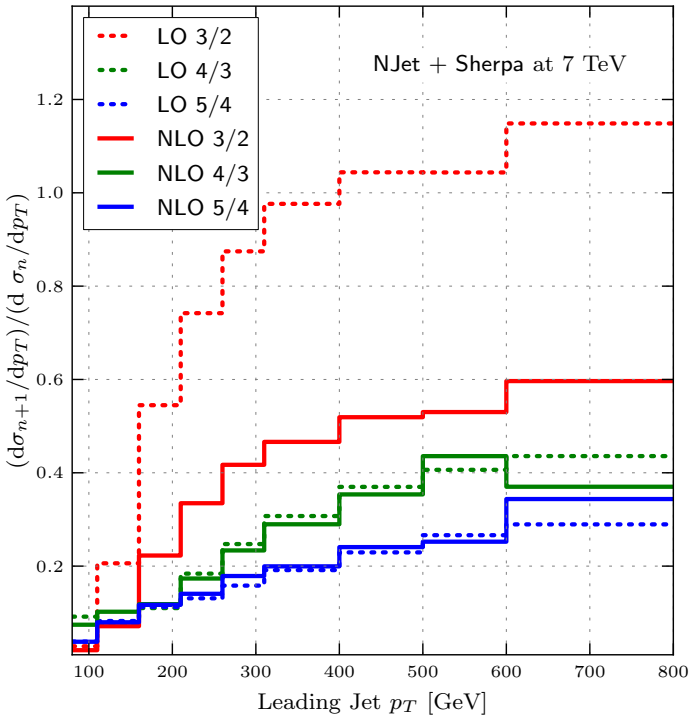
[NJet] arXiv:1309.6585

- Can help constrain PDFs with LHC data
- Can be used to understand jet scaling patterns → BSM searches
- Full colour calculation, using D-dimensional unitarity and BG recursion

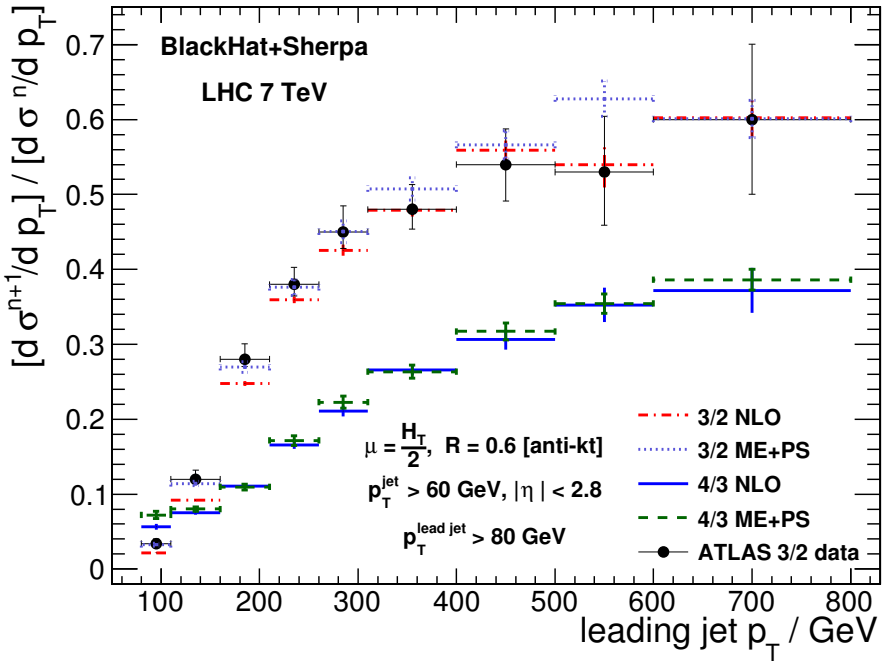




Recent progress: 5jets at the LHC



[NJet] arXiv:1309.6585

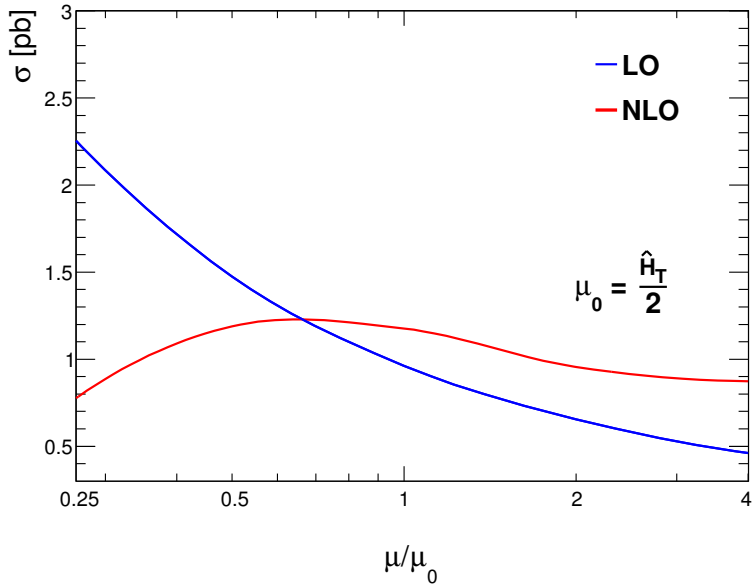


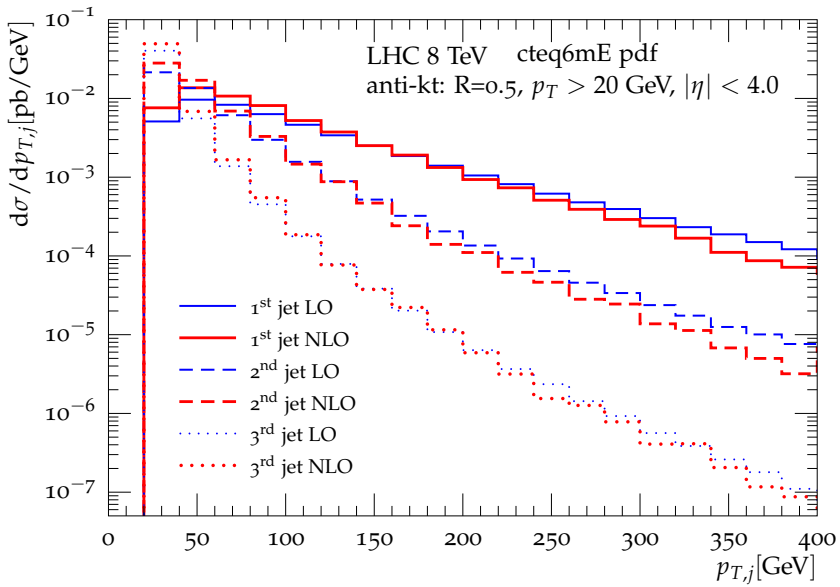
[BlackHat] arXiv:1112.3940

- Good perturbative convergence of 4/3- and 5/4-jet ratios
- Previous 4/3-jet calculation by BlackHat+Sherpa also showed good agreement with ME+PS and ATLAS data

Recent progress: Higgs+3 jets

[GoSam] arXiv:1307.4737





- Can be used to improve prediction of exclusive $H + 2$jets production
- Combination of GoSam, Sherpa and MadEvent

Automation, automation, automation ...

[MadLoop] arXiv:1103.0621

Computation of NLO cross sections in any model through MadGraph

- Feynman rules from `FeynRules` [Christensen,Duhr] arXiv:0806.4194
  interfaced through UFO [Degrande et al.] arXiv:1108.2040
- Generation of helicity amplitudes by ALOHA [deAquino et al.] arXiv:1108.2041
- Subtraction by MadFKS [Frederix et al.] arXiv:0908.4272
- Loop amplitudes from MadLoop [Hirschi et al.] arXiv:1103.0621

	Process	μ	n_{lf}	LO	NLO
a.1	$pp \to t\bar{t}$	m_t	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_t	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_t	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_t/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_t/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^- j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^- jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
...					

So what is left to be done?

- NLO calculations now in a state where tree-level was $\sim$10 years ago
- Many OLP projects, often specializing on a unique market
  (apologies for not being able to cover all in this talk)
- Several MC generators to provide tree-level parts & integration
- Goals for OLPs
  - Scalability
  - Flexibility
- Goals for MCs
  - Speed
  - Efficiency
- NLO calculations to supersede tree-level predictions
  in particle-level MC simulations ($\nearrow$ yesterday's talks)