Parton Shower Event Generators

Keith Hamilton
University College London
Parton Shower Event Generators

- PS MCs generate hard scattering events according to fixed order perturbation theory, characterised by mom. transfers in the region of 10’s to 1000’s of GeV ...
Parton Shower Event Generators

- dressing them with increasingly soft, real & virtual, resummed radiative corrections, accounting for the structure of events at ever smaller scales
Parton Shower Event Generators

- down to the scale where hadrons form $O(1)$ GeV
leaving us with a fully realistic description of events...
NLO + Parton Shower Event Generators

- Incisive new theory c. 2004 — AMC@NLO and POWHEG — showed how to fuse PSMC consistently with NLO perturbation theory, in generality and in practice
NLO + Parton Shower Event Generators

- NLOPS codes for basically all SM processes of interest can be freely obtained from a number of teams: HERWIG7, AMC@NLO, SHERPA, POWHEG-BOX
Does it matter?

- % of ATLAS+CMS+LHCb Higgs papers citing a given article Jan ‘14 → last week

- PS / NLOPS MC is truly ubiquitous in Higgs analysis
- PYTHIA features prominently in 93% of papers, POWHEG 83%, AMC@NLO 66%

w.o. self-citations
~ 221 published articles
**VH \& H \rightarrow b\bar{b}**

- Observation of Higgs decay to bottom quarks \& VH production

![Dijet Mass Analysis](image)

- NLOPS simulating ~14 signal \& background processes in each analysis
- SHERPA, POWHEG and MG5/AMC@NLO with PYTHIA
- Theoretical modelling a substantial uncertainty here even with state-of-the-art MC
NLOPS

- Selected strands of recent development relevant for Higgs (& much more)
  - NLO Electroweak Corrections
  - Heavy flavour backgrounds [M.Zaro — Tues]
  - Finite $m_{\text{top}}$ effects at NLO [L.Scyboz — Weds]
  - Comparing NLOPS and NNLO

Other strong work on NLO Higgs MC is omitted for sake of time, e.g. important works by HEJ & SHERPA
NLOPS HV and MiNLO HV+jet

- Builds on HVJ MiNLO code used for HV & H → b̅b observation in ATLAS & CMS

- EW corrⁿs depress inclusive xsecⁿs ~5-10% level depending on kinematic regime
- Give rise to sizeable shape changes in transverse momentum distⁿs at high p_T
- MiNLO HV+jet doubly NLO : for inclusive HV quantities it agrees with NLO HV
- Public code available with facility to modify trilinear Higgs coupling in input file
In this paper, we have studied a number of topics relevant to the perturbative computations slightly up to \( \alpha^2 \) Afterwards, and reaching a value of about 30\% for higher orders. LO terms.

In order to exemplify the procedure adopted to subtract the infrared singularities in \( \alpha_s \) mixings, we have explicitly extended the relevant formulae of the FKS subtraction scheme to the QCD+QED case. We have also shown how to re-formulate the FKS subtraction scheme for mixed-coupling capabilities in MadGraph5-aMC@NLO, which allows one to formulate the code, but loaded dynamically into it as part of a model that is fully under the user's control. One example not related to EW corrections has been presented in ref. [1], and NLO corrections to the Hardest jet transverse momentum were discussed.

Conclusions

- Public tour-de-force framework for automatic fixed order NLO QCD+EW calculations
- FKS NLO subtraction extended to EW sector, implemented, automated
- Finite width effects in automated complex mass scheme at tree & 1-loop level
- QED shower counterterms done, public release of NLOPS part pending further study

Impressive progress in this direction also by SHERPA+OpenLoops and SHERPA+RECOLA groups
NLOPS HH & HJ production with full top mass dependence

- Pioneering 2 → 2 two-loop calculations with internal and external mass scales
- NLO corrns to HH with finite \( m_t \) are large and not captured by \( m_t \rightarrow \infty \) K-factor
- NLOOPS simulations implemented; variable \( \lambda_{HHH} \) recently added in POWHEG
- NLO corrns to HJ with finite \( m_t \) are large but are captured by \( m_t \rightarrow \infty \) K-factor
Les Houches study NNLO vs NLOPS for HJ [also ZJ & JJ]

- Many advanced TH calcns, jet radii, scales, physics effects, carefully compared
- Answers important qs about state-of-the-art predictns, builds significant confidence
NNLOPS

- NNLO matched to PS firmly established its usefulness & reliability in ggF
- Three groups work to deliver NNLO matched to PS for other processes
  - NNLOPS method within POWHEG framework
  - GENEVA project based on SCET
  - SHERPA project based on `UNLOPS`
NNLOPS accurate predictions for WW production

- Resummation/multiple emission effects pop up all the time: NNLO → NNLOPS
- LHS: jet veto xsec in WW MiNLO [grey] & NNLOPS [blue] physical down to $p_T=0$
- RHS: fixed order diverges @ $p_{T,\text{miss}}>20$ GeV cut, NNLOPS resums → physical
- Similar-ish issue for $p_{T,\text{ll}} \gtrsim M_W$; pure LO cuts out → region filled by higher orders
NNLO+NNLL' HZ and HW matched parton shower simulation

- NNLO matched to SCET resummed NNLL' beam thrust matched to PS
- Sub-percent level agreement with NNLO calcns for incl observables
- Typical good resummation effects found going from NNLO → NNLO+PS
- And PS has negligible effects on inclusive quantities
- Including sizeable loop induced gg →ZH leads to enhanced PS sensitivity [not unexpectedly]
Parton showers

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w.o. self-citations
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Part of goal to extend DIRE to an ‘NLO shower’ adding in higher order corr$n$s
- Include double soft ‘splitting f$n$’ & 1-loop corr$n$ to single soft ‘splitting f$n$’
- Essentially do shower as an ‘MC@NLO’ for every parton shower emission
- Strong reduction in uncertainty estimates
- Open question as to the accuracy but v. interesting & impressive development
Parton Showers: Logarithmic accuracy of parton showers: a fixed order study

- Study looks at new showers based on evolving events as collections of colour dipoles
- Finds colour coherence not reflected in handling of recoil, or colour charge, when these PS emit gluons
- Gluons far apart in angle affect each other when the physics says they're meant to be independent
- Gluon #1 kicked by gluon #2 too often
- Leads to erroneous LL subleading $N_c$ & NLL leading $N_c$ contributions
- Study was $\alpha_s^2$: what about all-orders?
Summary

- **NLOPS**
  - NLO EW: the fixed order is automated, NLOPS including NLO EW in progress
  - Heavy flavours: good progress made but still a source of large uncertainty
  - Finite $m_{top}$ effects at NLO: public codes for HH & HJ including exact 2-loop virtuals
  - Understanding NLOPS: LH NNLO vs NLOPS study gives confidence & useful insights

- **NNLOPS**
  - Handful of public NNLOPS codes by now developed by Re, Zanderighi and friends
  - GENEVA team completed NNLO+NNLL’ matched to Pythia for DY & HW/Z

- **Parton showers**
  - Improvements re inclusion of spin & colour correlations though effects look small
  - Work towards ‘NLO showers’ by DIRE
  - Nuts+bolts analysis of dipole showers w.r.t resummation initiated [Dasgupta & Co]
Cuts
Computing worries

- Complex high precision simulations (NLOPS for complex processes) quickly go through CPU (e.g. NLO-merging)
- Typically a step up in precision for some process or methodology is accompanied by a severe CPU penalty
- CPU requirements of HL-LHC already can’t be met by MC generation on the GRID (with optimistic assumptions)
- Any further step-change to higher precision may be of limited use/impact
- Established methods may want [need?] rethinking, recoding, and/or new ideas, as well as priorities in the TH community
Observation of the Higgs boson decay to a pair of $\tau$ leptons in CMS

Challenging analysis: several (non-trivial) event categories and channels

Several background processes and a fair amount of shape in them

NLO+PS used extensively: POWHEG & MG5/AMC@NLO with PYTHIA
Differential xsecs

- For colour singlet processes NLOPS has been promoted to NNLOPS via MiNLO

- Finite top and bottom quark mass effects in gluon fusion included to NLO
- Tuned to reproduce NNLL Higgs $p_T$ & simultaneously gives NNLL jet veto effy
- Subject to wide-ranging validation studies and, so far, accurately describes data
Key background for ttH

- New POWHEG $t\bar{t}b\bar{b}$ generator in 4FS [massive b’s]; public code `near future`
- LO here is $O(\alpha_s^4)$ & multiscale $\rightarrow$ NLO vital but hard
- NLOPS scale uncertainties $\sim$halved w.r.t LOPS & a lot more stable w.r.t PS
- Follow-up work proposed to study more advanced scale setting procedures
Remarkable agreement shown in a variety of contexts between TH tools
[agreement between different MC event generators is quite striking]

- NNLO R-dependence agrees v.well with resummed NLOPS MC for broad range of R
- NNLO/NLOPS ‘global’ K-factor corrects $p_{T,H}$ and $p_{T,Jet}$ spectra pretty nicely
- Prescriptions for more robust determinations of NNLO scale uncertainties constructed
**NNLOPS for HW and HZ production**

- **Left:** lead jet $p_T$ affected by dynamical scale choice at high $p_T$, while Sudakov logs [MiNLO], parton shower and hadronization felt at low $p_T$
- **Right:** differences amplified when selecting violent underlying HW events w. high Higgs $p_T$ with jet vetoes [left 3 bins] or demanding jets [right 3 bins]
Including NNLO corrections into MiNLO

- Identify spurious NNLO terms in MiNLO’ [messy] replace by known true ones
- Differences of resulting MiNNLO w.r.t conventional NNLO formally higher order
- An interesting revision to the MiNLO’ approach to NNLOPS
- Still a lot more room for new ideas on how to best match NNLO and PS
MiNLO’ for H+2 jets: a door onto HJ-NNLOPS

- $p_{T,j1}$: NNLOPS is NLO, $HJj$-MiNLO is LO $\rightarrow HJj$-MiNLO* on top of NNLOPS
- $p_{T,j2}$: NNLOPS is LO, $HJj$-MiNLO is NLO $\rightarrow HJj$-MiNLO* on top of $HJj$-MiNLO

$HJj$-MiNLO* simultaneously NLO for $Hj$ & $HJj$ without NLO merging
nNLOPS: MINLO t-channel single-top plus jet

- Multiscale Improved NLO, aka MiNLO, method extended to MiNLO’ for colour singlet+jet production HJ / VJ / HVJ / WWJ
- MiNLO’ means above calcns become simultaneously NLO for H / V / HV / WW
- Extended to complex process [HJJ] in proof-of-concept work [Frederix, KH]
- Proof-of-concept refined into public code for MiNLO’ single-top+jet [ STJ* ]

Stefano Carrazza, Rikkert Frederix, Keith Hamilton, Giulia Zanderighi
Spin correl\textsuperscript{n}s implemented between parton shower splittings in HERWIG\textsuperscript{7}

- Effect of these azimuthal correl\textsuperscript{n}s in shower evol\textsuperscript{n} is typically v.small
- Most important spin correl\textsuperscript{n} effects already carried by MEs [prod\textsuperscript{n} → decays]
- Spurious azimuthal correl\textsuperscript{n} effect induced by recoil found in dipole shower
Parton Showers: Colour matrix element corrections

- Generally PS operate in the large-$N_{\text{colours}}$ approx\(^n\): $C_F \rightarrow \frac{1}{2}C_A$ etc.
- Beyond large-$N_{\text{colours}}$ approx\(^n\) is fierce: interfering colour flows imply computing & exponentiating larger & larger colour mixing matrices.
- Plätzer, Sjodahl, Thorén improve PS real radial dist\(^n\) to $N_{\text{colours}} = 3$ for first 2/3 emissions; virtual effects on colour flow & subleading $N_{\text{colours}}$ in Sudakov neglected.
- Generally small differences $\sim$few %; how much can MEPS/NLOPS already get us?

Nagy & Soper also recently proposed a practical recipe for systematic improvement toward $N_{\text{colours}} = 3$