Parton shower matching and merging

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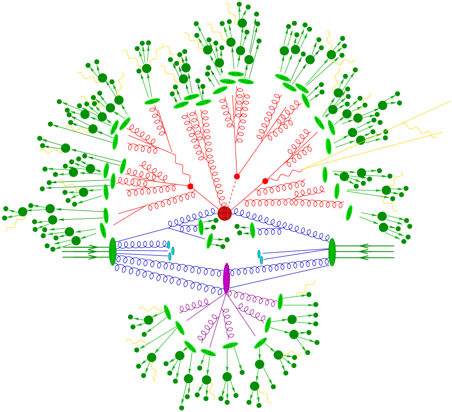
Universität Zürich

Tools 2017, Corfu

The SHERPA event generator framework

JHEP02(2009)007

- hard interaction (ME)
- parton evolution (PS)
- multiple interactions
- hadronisation
- hadron decays



Matching and merging aims at improving the perturbative description of the event description (ME+PS)

Outline

1. Matching (N)NLO matrix elements to parton showers
2. Multijet merging
3. NLO corrections in PS
4. Conclusions

Matching (N)NLO matrix elements to parton showers

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Matching (N)NLO matrix elements to parton showers

NLOPS

- well established and standard tools
  - MC@NLO Frixione, Webber JHEP06(2002)029
  - POWHEG Frixione, Nason, Oleari, Ridolfi JHEP11(2007)070
  - variants thereof Höche, Krauss, MS, Siegert JHEP09(2012)049
Plätzer, Gieseke EPJC72(2012)2187
- available for all processes of interest

⇒ **NLO for production ME**
emission properties described at LOPS accuracy only

NNLOPS

- only exist for singlet production
  - MiNLO-based Hamilton, Nason, Re, Zanderighi JHEP10(2013)222
  - UN^{2}LOPS Höche, Li, Prestel Phys.Rev.D91(2015)074015
  - GENEVA Alioli et.al. Phys.Rev.D92(2015)094020

⇒ **NNLO for production ME**
emission properties described at NLOPS accuracy

NLOPS: How does it work?

Höche, Krauss, MS, Siegert JHEP09(2012)049

Aim: Keep NLO accuracy in expansion of α_S
Keep full logarithmic accuracy of parton shower resummation

Both MC@NLO and POWHEG follow the same paradigm

- parton shower's resummation kernels used for IR subtraction
- define resummation region

$$\langle O\rangle^{\text{NLOPS}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B} + \mathrm{V} + \mathrm{I_K}\Big](\Phi_B)\,\Big[\Delta_{\mathrm{D_K}}(\mu_Q^2, t_c)\,O(\Phi_B) + \int \mathrm{d}t'\,\frac{\mathrm{D_K}}{\mathrm{B}}\,\Delta_{\mathrm{D_K}}(\mu^2, t')\,\mathrm{PS}_R(t', O)\Big] + \int \mathrm{d}\Phi_R\,\Big[\mathrm{R} - \mathrm{D_K}\Big](\Phi_R)\,\mathrm{PS}_R(t_R, O)$$

- schemes differ in choices for form of kernels $\mathrm{D_K}$ and resummation region (limited by μ_Q)
- variants address various problems inherent in both approaches

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$$+ \int \mathrm{d}\Phi_R\, \mathrm{H}\,(\Phi_R)\, \mathrm{PS}_R(t_R, O)$$

- schemes differ in choices for form of kernels $\mathrm{D_K}$ and resummation region (limited by μ_Q)
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POWHEG/MC@NLO

Description of emission spectrum:

$$\langle O_{\text{em}}\rangle^{\text{NLOPS}} = \int \mathrm{d}\Phi_B \mathrm{d}\Phi_1\, \overline{\mathrm{B}}(\Phi_B)\, \frac{\mathrm{D_K}(\Phi_B\cdot\Phi_1)}{\mathrm{B}(\Phi_B)}\, O(\Phi_R) + \int \mathrm{d}\Phi_R \left[\mathrm{R}-\mathrm{D_K}\right](\Phi_R)\, O(\Phi_R)$$

In the resummation region $\mathrm{D_K} \approx \mathrm{R}$

→ the emission spectrum is enhanced with $\overline{\mathrm{B}}/\mathrm{B}$

	MC@NLO	POWHEG
$\mathrm{D_K}$	$\mathrm{B}\cdot\widetilde{\mathrm{K}}_{\mathrm{PS}}$	R
μ_Q^2	μ_F^2	S_{had}

Powheg:

split $\mathrm{R} = \mathrm{R}_{\text{soft}} + \mathrm{R}_{\text{hard}}$

with

$$\mathrm{R}_{\text{soft}} = \frac{h^2}{p_\perp^2 + h^2}\,\mathrm{R}$$

and $\mathrm{D_K} = \mathrm{R}_{\text{soft}}$

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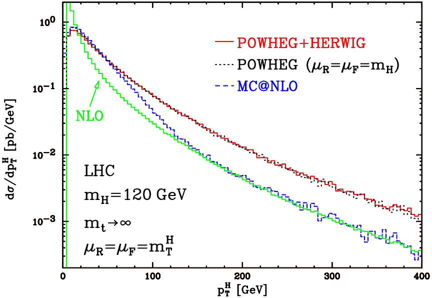

Alioli, Nason, Oleari, Re JHEP04(2009)002

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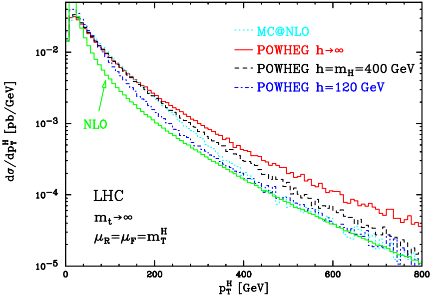
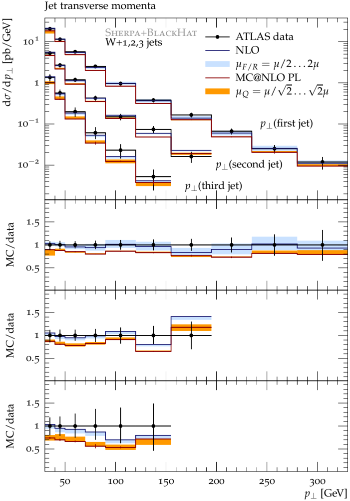


Alioli, Nason, Oleari, Re JHEP04(2009)002

NLOPS

Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001



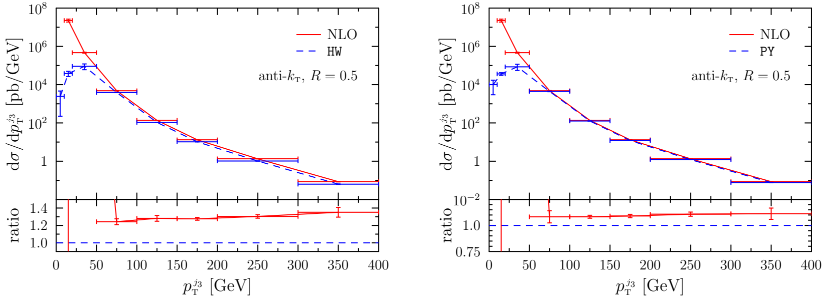
$pp \to W + 1, 2, 3$ jets

- 3 separate samples/calculations
- NLO accuracy for inclusive observables of respective jet multiplicity
- resummation of softest/LO jet, i.e. 4th jet in $pp \to W + 3$ jets
- no resummation of sample-defining jet multiplicity, i.e. first 3 jets in $pp \to W + 3$ jets

ATLAS data Phys.Rev.D85(2012)092002

NLOPS

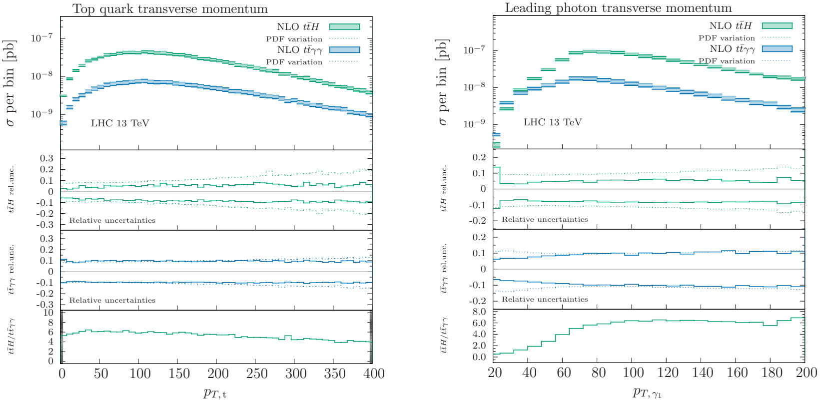
Kardos, Nason, Oleari JHEP04(2014)043



- $pp \to 3j$ production

NLOPS

van Deurzen et.al. Eur.Phys.J.C76 (2016) no.4, 221



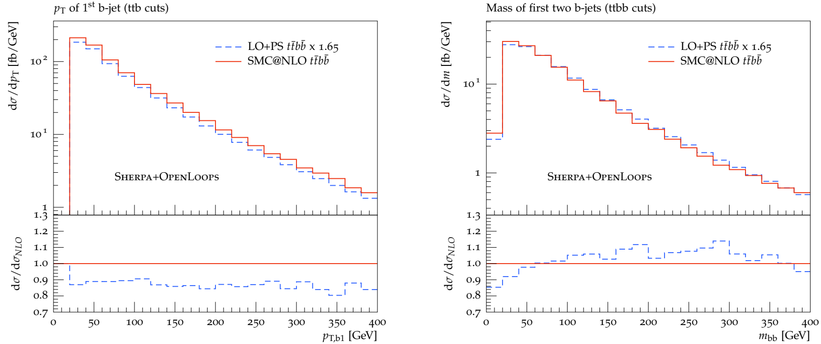
- $pp \to t\bar{t}\,h[\to\gamma\gamma]$ vs. $pp \to t\bar{t}\gamma\gamma$

aMC@NLO + GOSAM

NLOPS

- for complicated processes small event selection efficiencies can render increased running time of NLOPS prohibative
- detailed validation studies needed to use LOPS as proxy

Moretti, Petrov, Pozzorini, Spannowsky Phys.Rev. D93 (2016) 014019



NLOPS for resonant processes

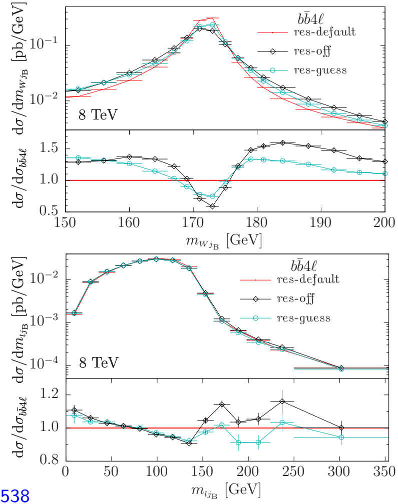
Processes with resonances

- standard IR subtractions do not preserve shape of resonances
- standard parton showers do not preserve shape of resonances

⇒ schemes for resonance identification

⇒ modify recoil in parton shower

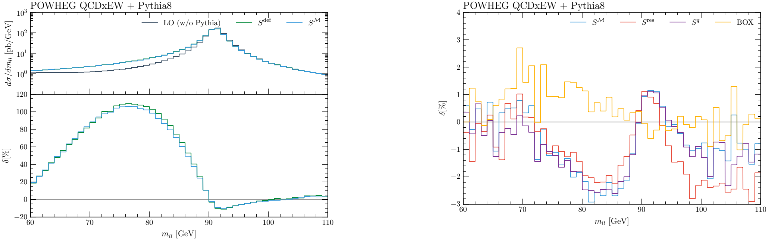
⇒ consistency in matching



arXiv:1509.09071, arXiv:1603.01178, arXiv:1607.04538

NLOPS for EW corrections

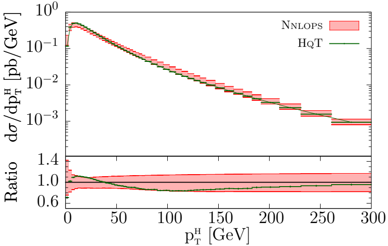
Bernaciak, Wackeroth Phys.Rev.D85(2012)093003
Barze, Montagna, Nason, Nicrosini, Piccinini, Vicini Eur.Phys.J.C73(2013)no.6, 2474
Mück, Oymanns JHEP05(2017)090



- first process specific solutions for NLOPS for EW corrections
- results very dependent on specifics of resonance treatment
- plenty of development still needed

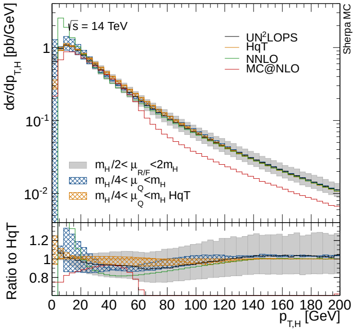
NNLOPS

- available only for production of colourless final states
- inclusive observables at NNLO accuracy
- emission sensitive observables only at NLOPS



Hamilton, Nason, Re, Zanderighi

arXiv:1309.0017



Höche, Li, Prestel arXiv:1407.3773

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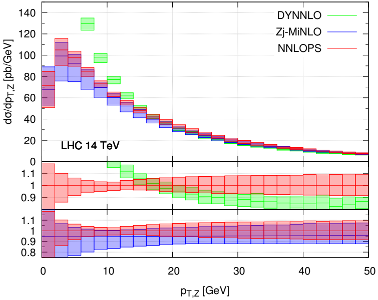
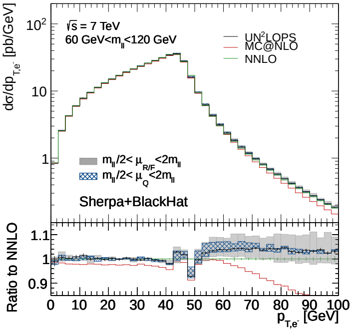


Karlberg, Re, Zanderighi

arXiv:1407.2940



Höche, Li, Prestel arXiv:1405.3607

(N)NLOPS

Available tools

- aMC@NLO + HERWIG/PYTHIA
  MC@NLO
- POWHEG-BOX + HERWIG/PYTHIA
  POWHEG / NNLOPS
- MADGRAPH/LOOPPROVIDER+HERWIG7
  MC@NLO/ POWHEG variant / KRKNLO
- SHERPA+LOOPPROVIDER
  MC@NLO variant / NNLOPS
- GENEVA + PYTHIA
  NNLOPS

Multijet merging

1. Matching (N)NLO matrix elements to parton showers
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Multijet merging

LOPS, NLOPS and NNLOPS describe observables dominated by topologies of a single multiplicity very well.

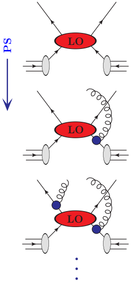
Goal: Describe observables that receive contributions from many final state multiplicities consistently at the higherst available precision.

Examples: H_T, $p_\perp$, $\Delta\phi$ etc.
NLOPS, for example, will describe the low end at NLO accuracy, an intermediate region at LO accuracy, and the high end at PS accuracy only

⇒ **multijet merging**

At the same time, multijet merged samples provide the LHC experiments with largest freedom of projecting these samples onto observables without the loss of accuracy.

Multijet merging at LO

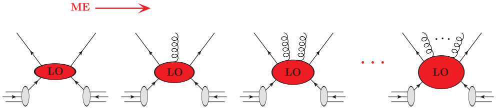


Parton showers

resummation of (soft-)coll. limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space, separate by Q_{cut}
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS

Multijet merging at LO



Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

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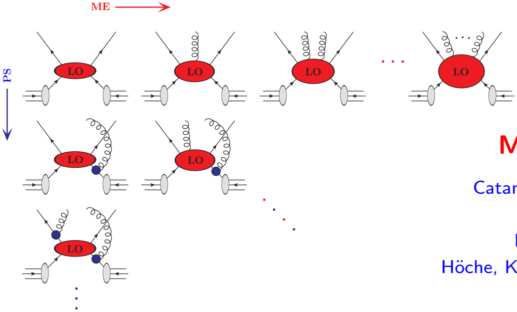

MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Mangano, Moretti, Pittau NPB632(2002)343
Höche, Krauss, Schumann, Siegert JHEP05(2009)053
Lönnblad, Prestel JHEP03(2012)019
Plätzer JHEP08(2013)114

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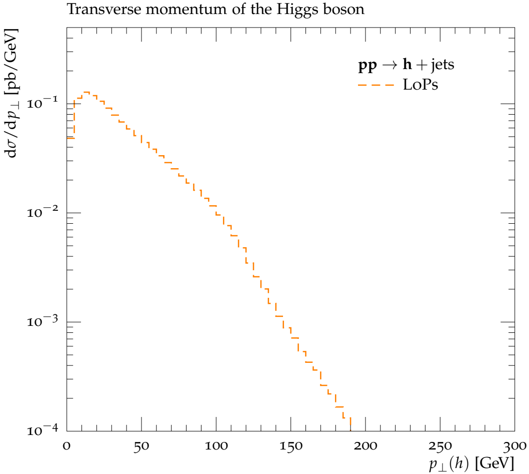

- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LoPs $pp \to h +$ jet for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h +$ jet to $Q_{n+2} < Q_{\text{cut}}$
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- sum all contributions

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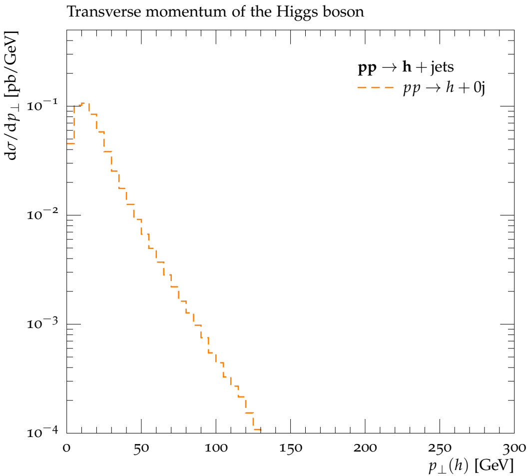

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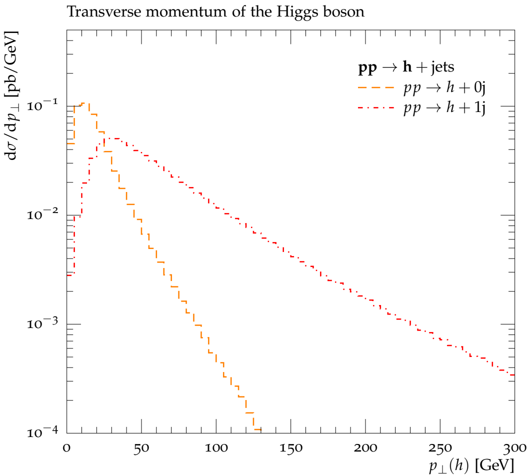

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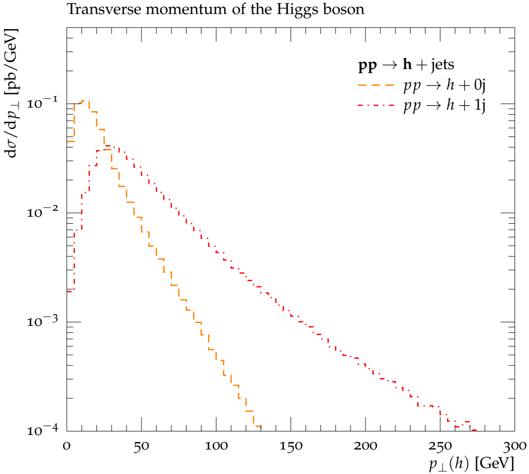

Transverse momentum of the Higgs boson

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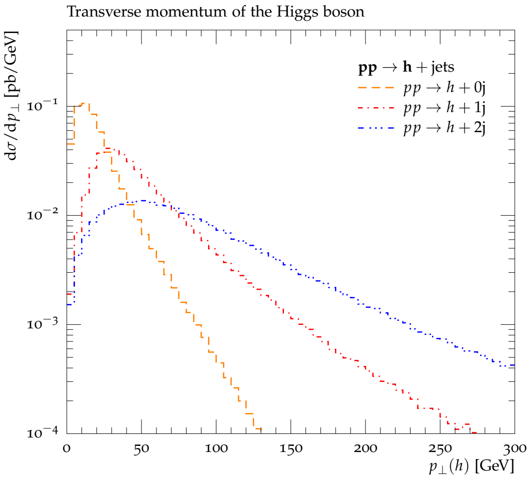

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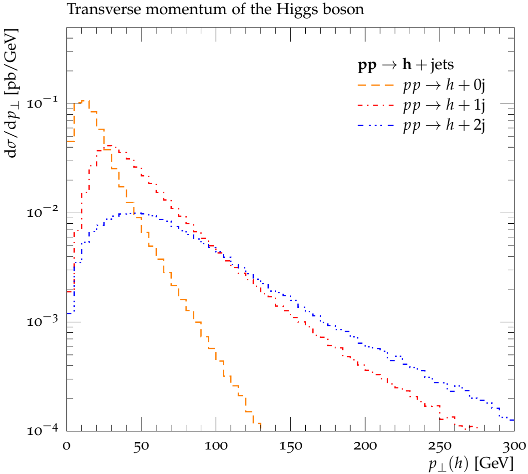

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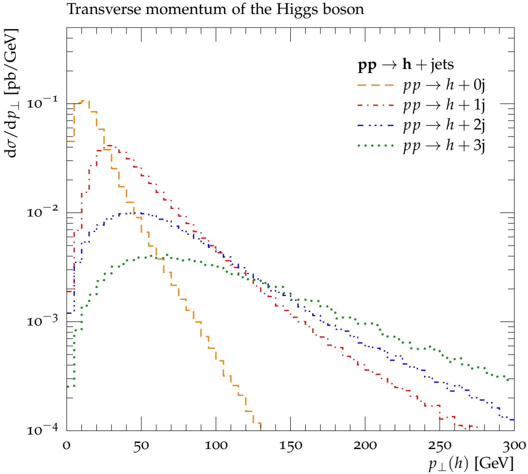

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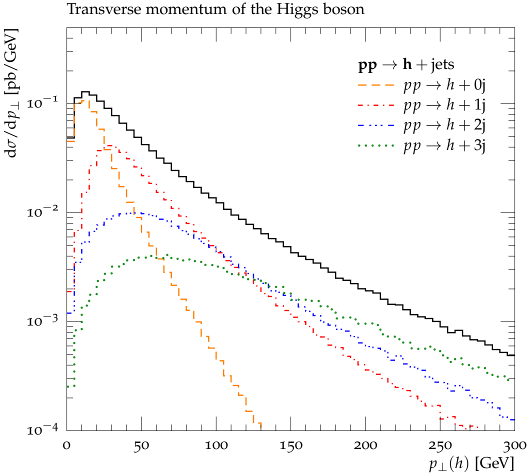

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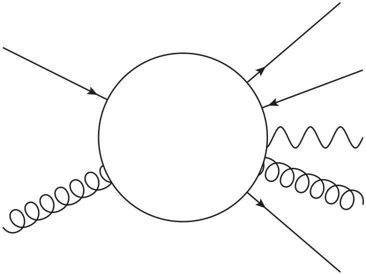
Resummation properties in ME region

Multiply with Sudakov factors according to reconstructed history

Example: Drell-Yan production in association with jets



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- often use k_t-algorithm as simple approximation
- identify a shower history (probabilistically), determine scale t_i up to predefined t_I
- apply $\prod_{i=1}^{n} \Delta(t_i, t_{i-1})$ and $\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^{n} \alpha_s(t_i)$

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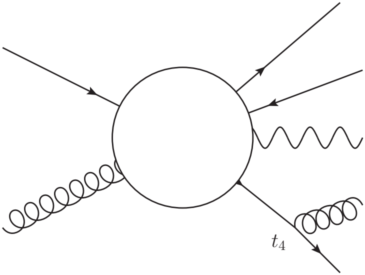

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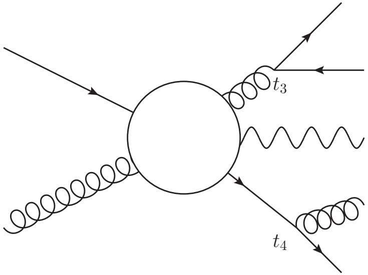
Example: Drell-Yan production in association with jets



- cluster external particles using inverse parton shower → flavour conscious, initial state aware, probabilistic jet algorithm
- often use k_t-algorithm as simple approximation
- identify a shower history (probabilistically), determine scale t_i up to predefined t_I
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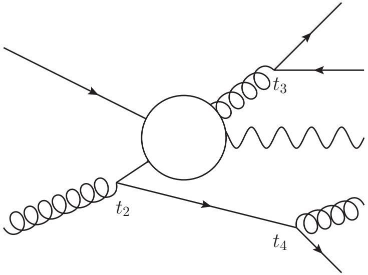

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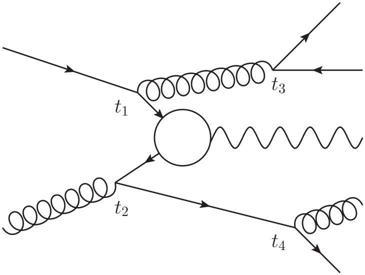

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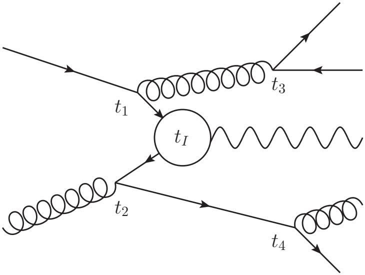

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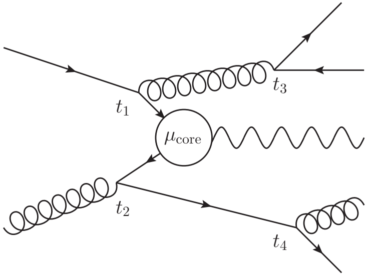

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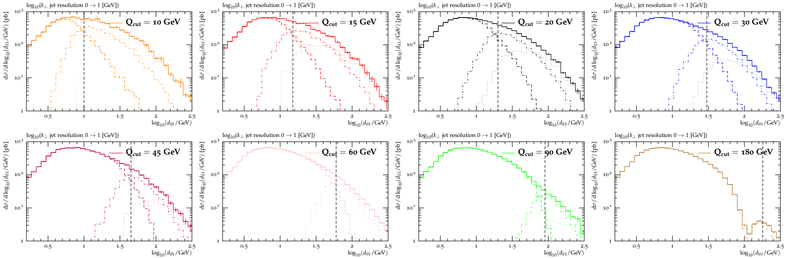
Merging systematics

Merging cut Q_{cut} dependence in $pp \to Z + \text{jets}$:



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- changes the region where higher accuracy is used for calculation
  → part of the uncertainty is due to degraded accuracy for large Q_{cut}
- all samples are identical for $Q < Q_{\text{cut}}^{\text{smallest}}$ and $Q > Q_{\text{cut}}^{\text{largest}}$ by construction

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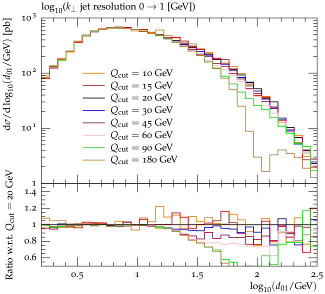

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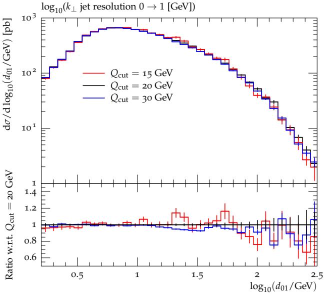

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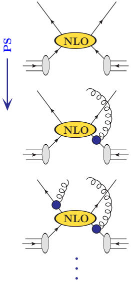
Multijet merging at NLO

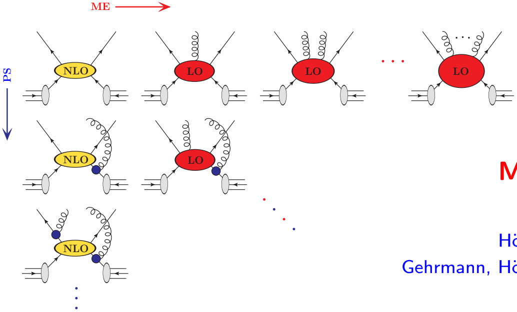


NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- Multijet merging at LO combines multiple LOPS
- NLOPS elevate LOPS to NLO accuracy
- First steo supplements core NLOPS with higher multiplicities LOPS
- **Multijet merging at NLO combines multiple NLOPS**

Multijet merging at NLO



Multijet merging

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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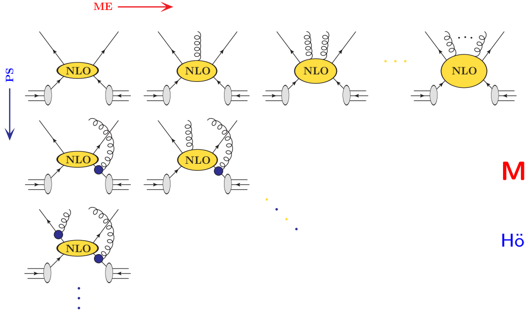

Multijet merging at NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Fredrerix, Frixione JHEP12(2012)061
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114

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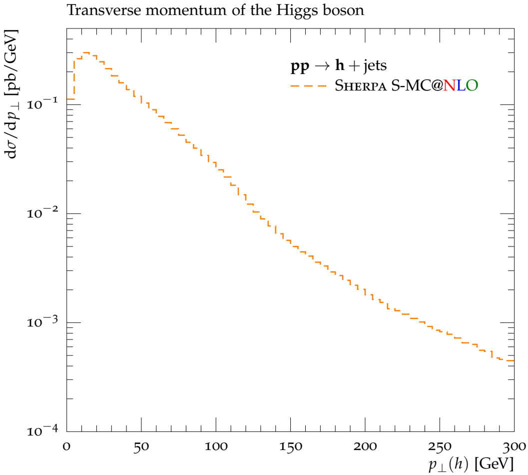

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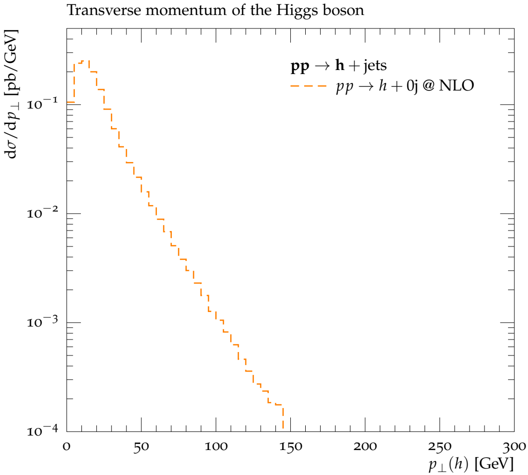

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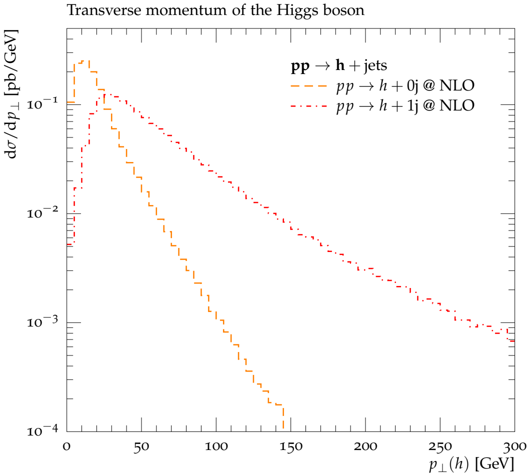

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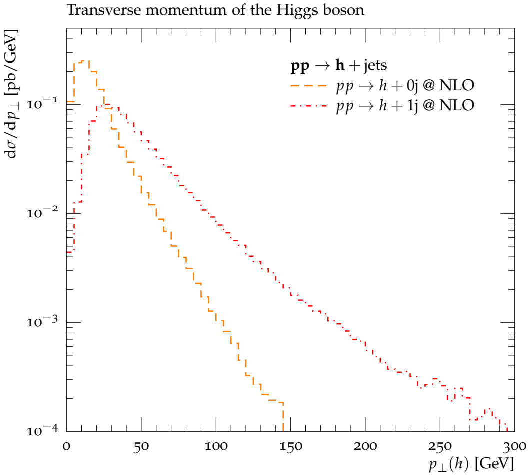

Transverse momentum of the Higgs boson

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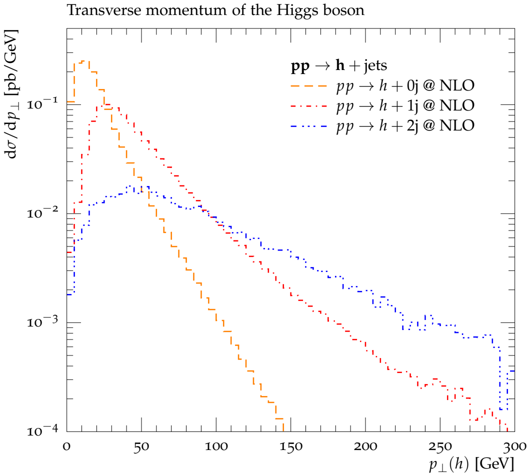

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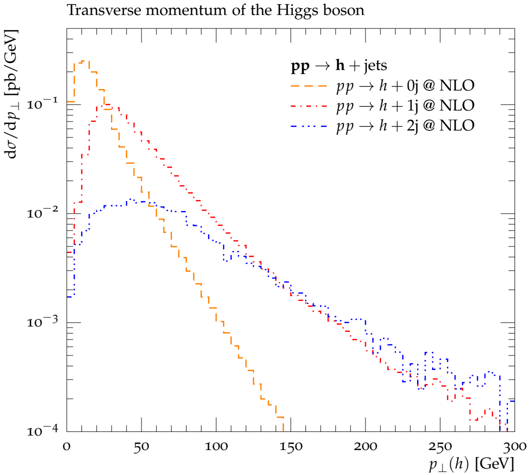

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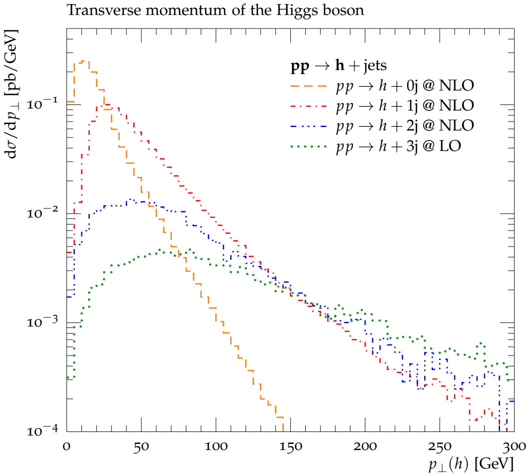

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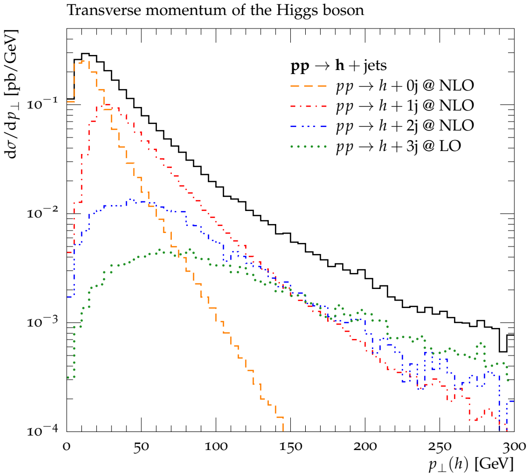

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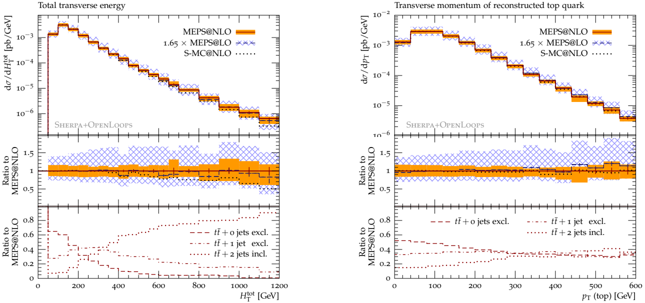
Multijet merging

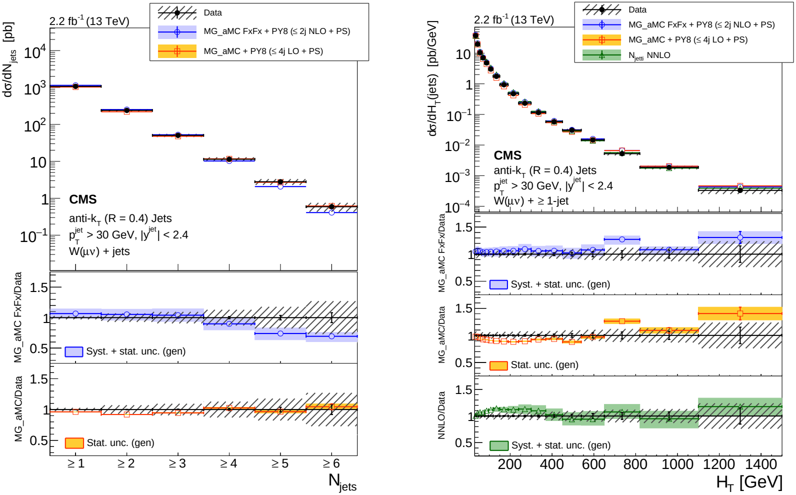
- multijet merging replaces emission spectrum of (N)LOPS above some merging scale by higher order calculation
  → MEPS/MEPS@NLO, MLM/FXFX, UMEPS/UNLOPS
- can be thought of as improving splitting functions of (N)LOPS by higher order and beyond-logarithmic corrections above merging scale
- does not improve resummation properties

Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert in PLB748(2015)74-78



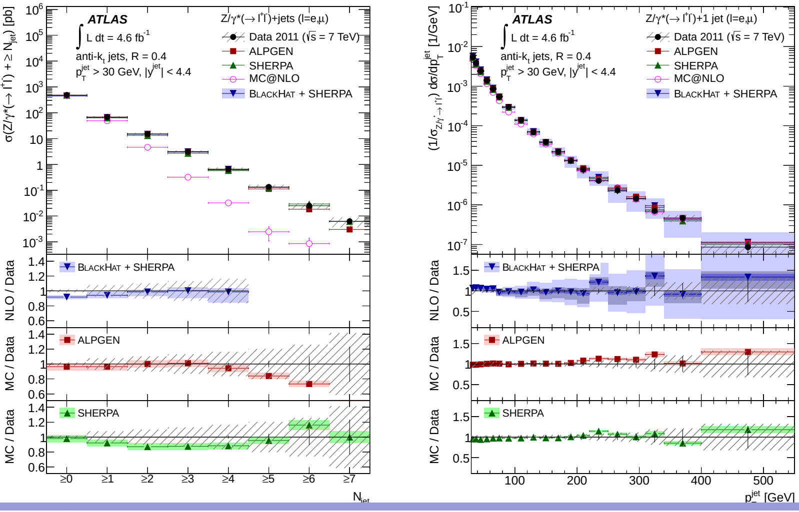
Multijet merging at NLO

lepton + MET production



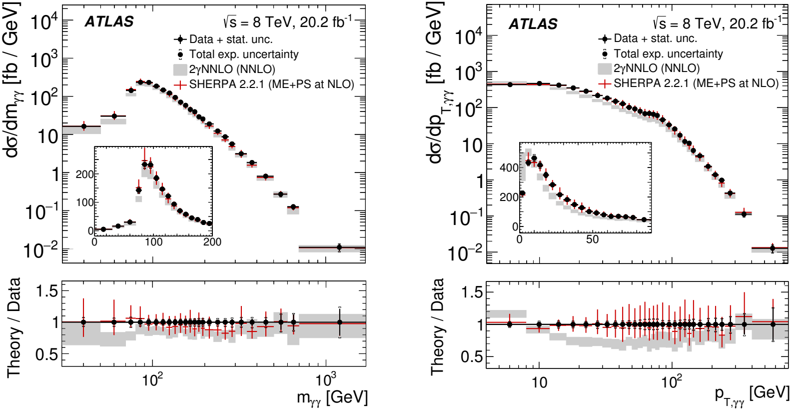
Multijet merging at NLO

lepton pair production



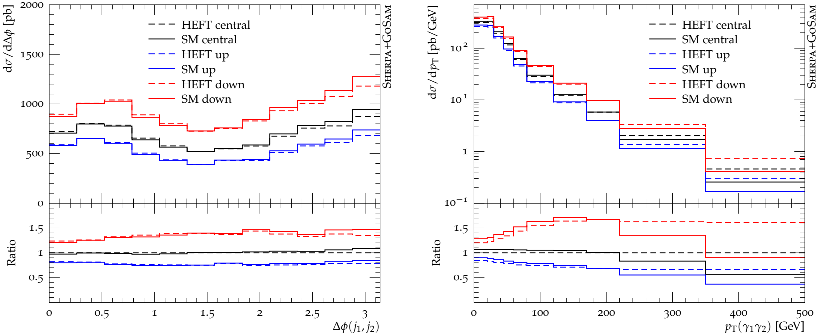
Multijet merging at NLO

diphoton production



Multijet merging at NLO

Higgs production

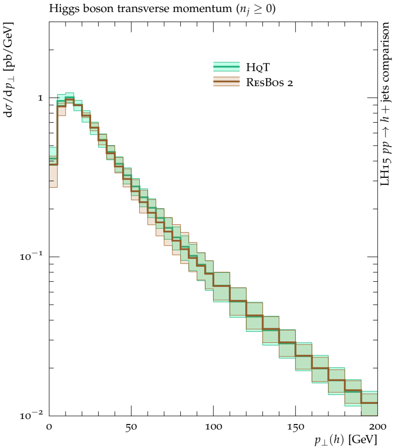


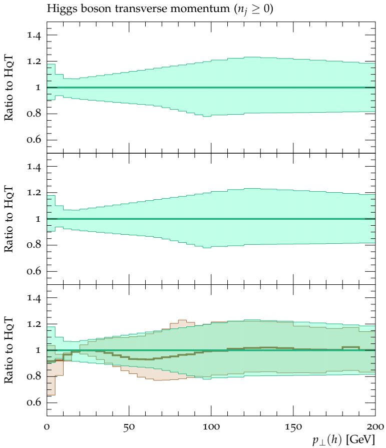
- $pp \to h + 0, 1, 2, 3j$ @ NLO including top mass effects

à la Buschmann, Goncalves, Kuttimalai, MS, Krauss, Plehn JHEP02(2015)038

State-of-the-art

Les Houches 2015

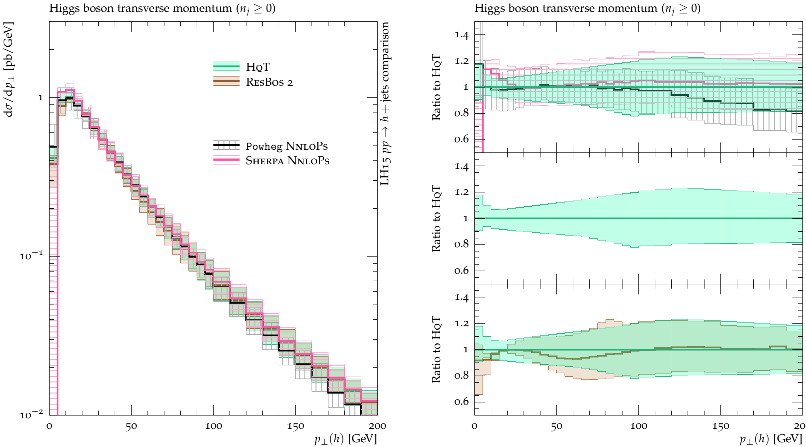




- observable specific calculations, NNLOPs, NLO multijet merging

State-of-the-art

Les Houches 2015



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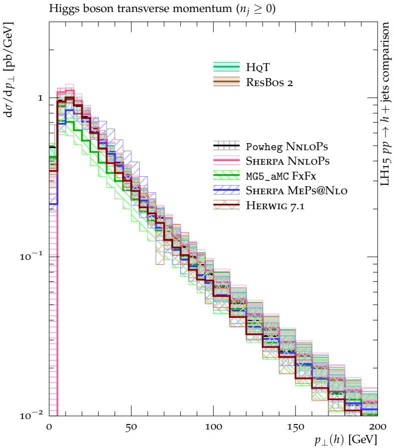
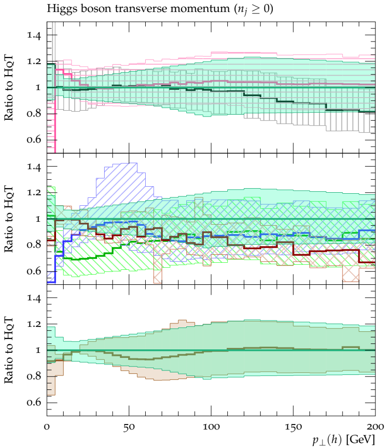




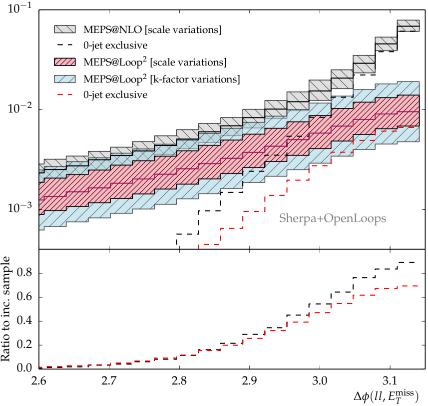
- observable specific calculations, NnloPs, NLO multijet merging

Multijet merging of loop induced processes

Goncalves et.al. PRD94(2016)no.5,053014

Loop induced processes

- LOOP^2 production of $X + 0, 1, \ldots$ jets
- works schematically as merging at LO
- contribution of LOOP^2 often depends on observable



Multijet merging at NLO

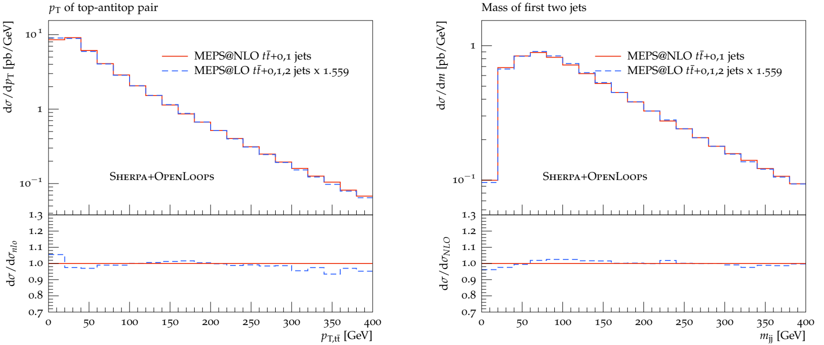
Available implementations

- ALPGEN+HERWIG/PYTHIA
  MLM (LO)
- MADGRAPH/LOOPPROVIDER+HERWIG7
  UNLOPS (NLO), UMEPS (LO)
- MADGRAPH+PYTHIA
  FXFX (NLO), UNLOPS (NLO), MLM (LO), UMEPS (LO), MLM@LOOP^2 (LO)
- SHERPA+LOOPPROVIDER
  MEPS@NLO (NLO), MEPS (LO), MEPS@LOOP^2 (LO)

Multijet merging at NLO

- complicated processes and small event selection efficiencies can render increased running time of NLO multijet merging prohibative
- detailed validation studies needed to use LO merging as proxy

Moretti, Petrov, Pozzorini, Spannowsky Phys.Rev. D93 (2016) 014019



Electroweak corrections in particle-level event generation

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2016)021

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathsf{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathsf{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathsf{EW}}(\Phi_n) + \mathrm{I}_{n,\mathsf{EW}}(\Phi_n) + \mathrm{B}_{n,\mathsf{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging

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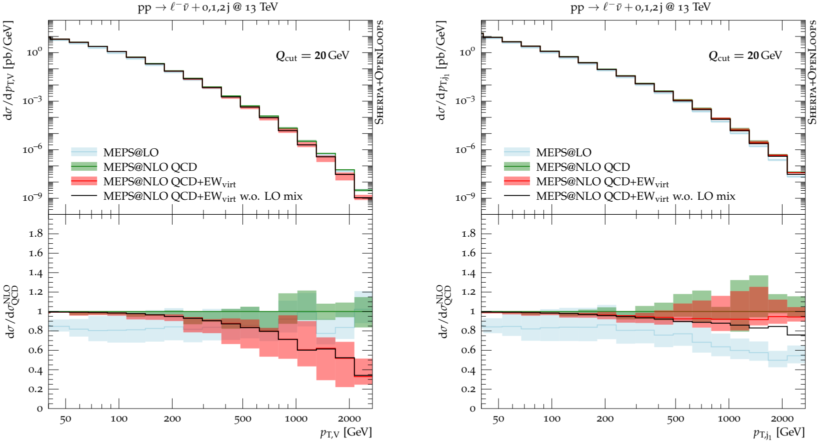
$pp \to \ell^- \bar{\nu} + \text{jets}$

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2016)021



⇒ particle level events including dominant EW corrections

NLO corrections in parton showers

1. Matching (N)NLO matrix elements to parton showers
2. Multijet merging
3. NLO corrections in PS
4. Conclusions

NLO corrections in parton showers

Höche, Krauss, Prestel arXiv:1705.00982

- LO parton showers already include terms $\propto 1/(1-z) \times \Gamma(2)$

  Catani, Marchesini, Webber Nucl.Phys. B349, 635 (1991)
- include NLO corrections in DGLAP evolution
  use NLO collinear splitting functions

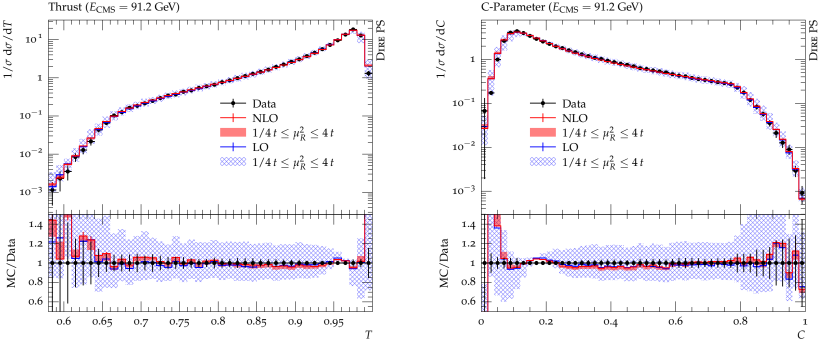
$$P_{ab}(z) = P_{ab}^{(0)}(z) + \frac{\alpha_S}{2\pi}\,P_{ab}^{(1)}(z)$$

Curci, Furmanski, Petronzio Nucl.Phys. B175, 27 (1980)
Furmanski, Petronzio Phys.Lett. B97, 437 (1980)

- includes triple-collinear splitting functions Höche, Prestel arXiv:1705.00742
- contains flavour changes $q \to q'$ and $q \to \bar{q}$
- does not include higher order corrections to soft evolution yet
- include also soft terms $\propto 1/(1-z) \times \Gamma(3)$
- still leading colour, as no exponentiation of off-diagonal colour MEs
- **this is generally not the same as achieving a higher logarithmic accuracy, not even for the PS evolution variable**

NLO corrections in parton showers

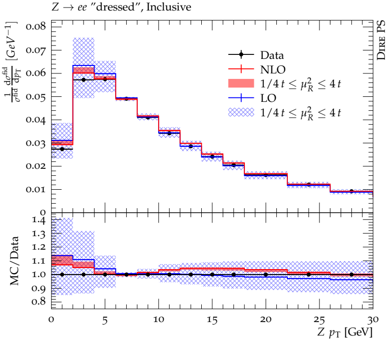
Höche, Krauss, Prestel arXiv:1705.00982

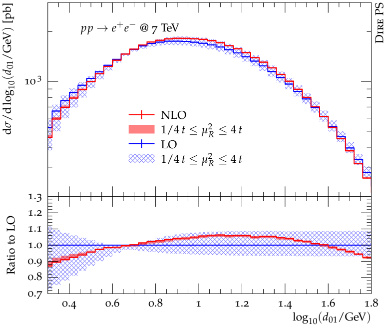


- small effects in event shapes at e^+e^-
- reduced scale uncertainty (commonly not assessed in LO parton showers)

NLO corrections in parton showers

Höche, Krauss, Prestel arXiv:1705.00982

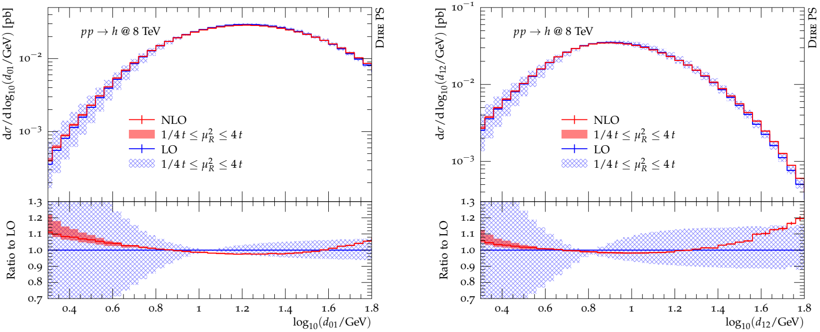




- larger effects in Sudakov shapes in *pp*
- reduced scale uncertainty (commonly not assessed in LO parton showers)

NLO corrections in parton showers

Höche, Krauss, Prestel arXiv:1705.00982



- larger effects in Sudakov shapes in *pp*
- reduced scale uncertainty (commonly not assessed in LO parton showers)

Conclusions

- NLOPS are the commonly used tools
- NNLOPS available for key processes
  $\rightarrow$ parton shower improvements necessary for $V + j$ NNLOPS
- multijet merging improves relative description of multi-emission kinematics and is the highest available precision at the moment
  $\rightarrow$ feasible for up to 3j at NLO, 6j at LO
  $\rightarrow$ approximate EW corrections can be incorporated
- first developments to include higher order corrections to the splitting functions in parton showers
  $\rightarrow$ NLO collinear DGLAP evolution
  $\rightarrow$ PS does not yet contain full logarithmic structure for matching to NNLO

Thank you for your attention!