

High-precision Standard Model physics with SHERPA

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THE
ROYAL
SOCIETY

Disclaimer

This talk will focus on the physics capabilities of **SHERPA-2.2.6**.

There are many more advanced developments in the pipeline for **SHERPA-3.0.0**, but I will only marginally touch upon them in this talk today.

Contents

- 1 Overview
- 2 Precision in $V + \text{jets}$ processes
- 3 Precision in top processes
- 4 Precision in multi-boson processes
- 5 Precision in Higgs processes
- 6 Conclusions

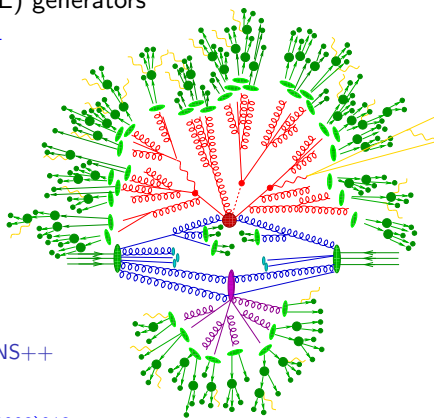
Overview

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The SHERPA event generator framework

JHEP02(2009)007

- Two multi-purpose Matrix Element (ME) generators
 AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
 COMIX JHEP12(2008)039, PRL109(2012)042001
- Two Parton Shower (PS) generators
 CSSHOWER JHEP03(2008)038
 DIRE EPJC75(2015)461
- A multiple interaction simulation
 à la PYTHIA AMISIC++ hep-ph/0601012
- A cluster fragmentation module
 AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using
 YFS-resummation PHOTONS++ JHEP12(2008)018



Sherpa's traditional strength is the perturbative part of the event
 LO, NLO, NNLO, LoPs, NLOPs, NNLOPs, MEs, MENLOs, MEs@NLO

Acronyms and nomenclature

Fixed order calculations

- matrix elements only, implies fixed multiplicities
- no parton shower, no non-perturbative physics, no particle level

⇒ LO, NLO, NNLO

Parton shower matched calculations

- combination of fixed order calculation and parton shower for one multiplicity
- particle level predictions, no multijet observables

⇒ LOPs, NLOPs, NNLOPs

Multijet merged calculations

- combination of parton shower matched calculations for increasing final state multiplicities (mostly jets)
- particle level predictions, multijet observables

⇒ MEPS(@LO), MEPS@NLO (special case MENLOPs)

SHERPA-2.2.6

- SHERPA-2.2.6 released Jan '19
 - contains bugfixes for all known bugs of SHERPA-2.2.5
 - UFO support for BSM physics
 - two parton showers: CSSHOWER (default), DIRE
 - **on-the-fly scale and PDF variations** for ME part in
 - LO, NLO
 - LOPs, NLOPs (S-Mc@NLO)
 - MEPS, MENLOPs, MEPS@NLO
- also for** incorporation of assoc. **approx. EW corr.** and sub-LO
→ use named weights in HEPMC (av. since HEPMC-2.06)
- full scale & PDF variations including correlated with parton shower and for NNLO/NNLOPs in SHERPA-3.0.0
 - allow to force HEPMC event record into pure tree structure, lost information available through disconnected vertices
 - default PDF: NNPDF30_nnlo_as_0118

$V + \text{jets}$ processes

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SHERPA for p_T^Z and p_T^W

Fixed order:

- NNLO QCD and NLO EW for inclusive W and Z production
- NLO QCD and NLO EW for $p_T^{W/Z}$

Matched to parton shower:

- NNLOPS for inclusive W and Z production
- NLOPS (S-Mc@NLO) for $p_T^{W/Z}$

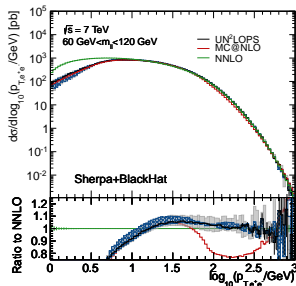
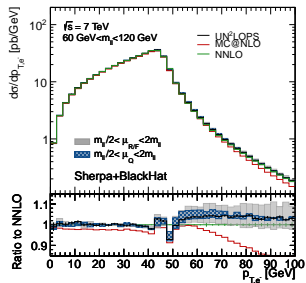
Multijet merged:

- MEPS@NLO
 - inclusive and for low $p_T (< Q_{\text{cut}})$ same as incl. NLOPS
 - for high- p_T benefit from NLO accuracy for multijet processes

NNLOPS for p_T^W and p_T^Z

Höche, Li, Prestel arXiv:1405.3607

- NNLOPS matching in UN²LOPS scheme
- scheme constructed to minimise uncontrolled higher order terms
- no reweighting, generated directly
- NLOPS accuracy as $p_T^{W/Z} \rightarrow 0$
- QED corrections through YFS soft-photon res.

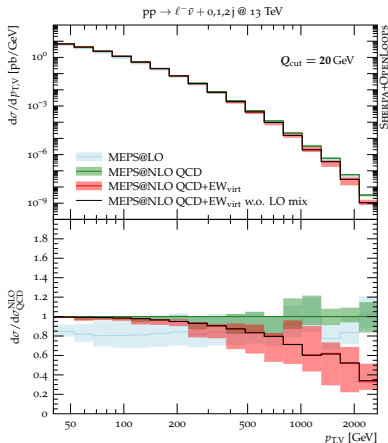


Large p_T^W and p_T^Z

Lindert, Kallweit, Maierhöfer, Pozzorini, MS arXiv:1511.08692

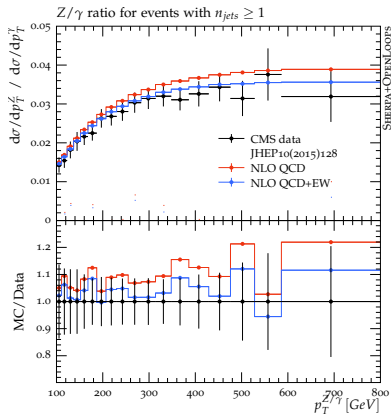
MEPS@NLO QCD+EW_{virt}

- incorporate approximate NLO EW corrections
 \approx EW Sudakov approx.
 \rightarrow but also includes many non-logarithmic terms that render the result closer to NLO EW
 \rightarrow **recover large EW corr. at large p_T**
- also include large subleading orders
- QED FSR through YFS soft-photon resummation



NLO EW corrections

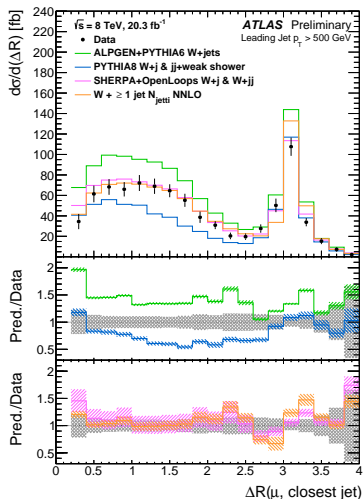
LH'15 arXiv:1605.04692



important to describe Z/γ ratio

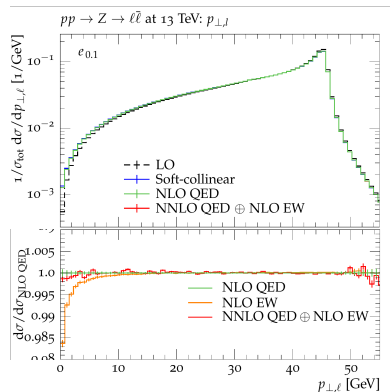
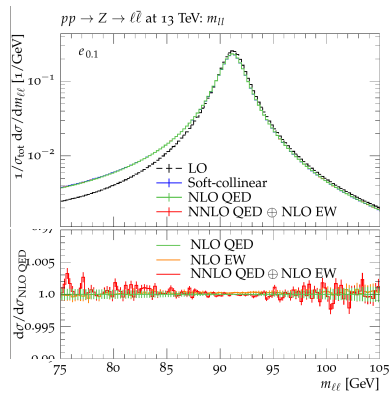
⇒ **preview to SHERPA-3.0.0**

ATLAS arXiv:1609.0745



Soft-photon resummation

Krauss, Lindert, Linten, MS arXiv:1809.10650



2.2.6: YFS formalism, matched to NLO QED for $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\bar{\ell}$

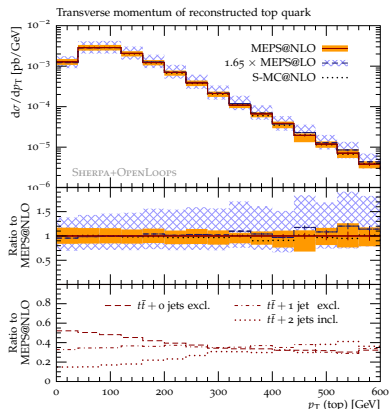
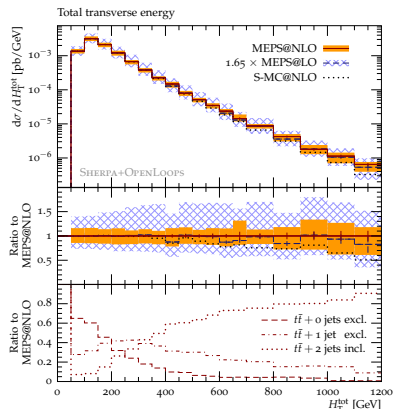
3.0.0: YFS formalism, matched to NNLO QED + NLO EW

Top processes

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$t\bar{t}$ + jets production

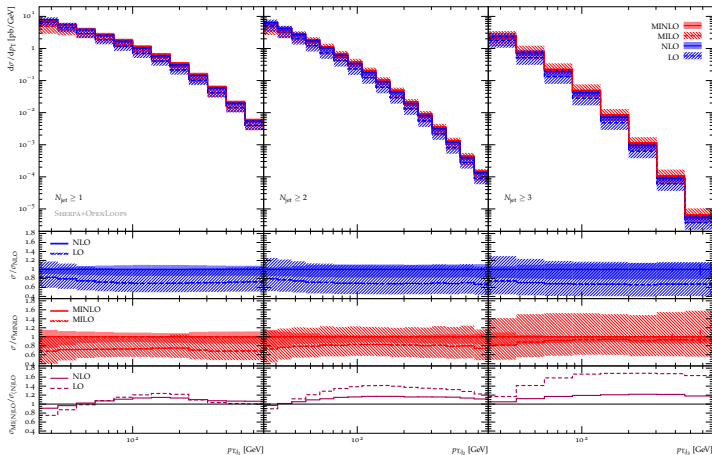
Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert arXiv:1401.7971



- $t\bar{t}$ + 0, 1, 2j@NLO QCD
- shapes very similar, normalisation and uncertainty improvements

$pp \rightarrow t\bar{t} + 3\text{jets}$ @ NLO QCD (no parton shower)

Höche, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1607.06934

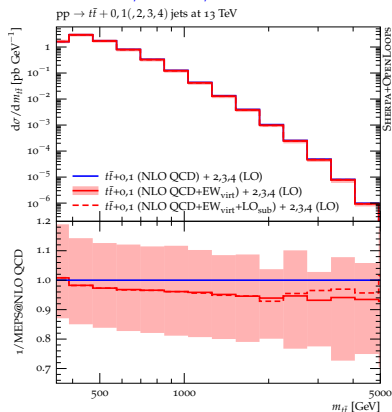
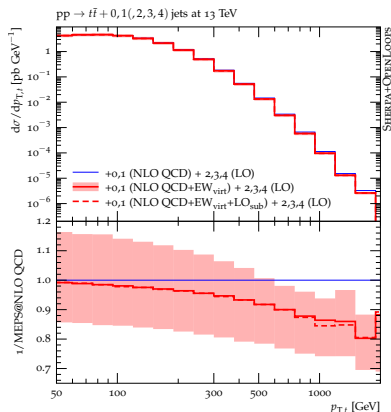


leading jet p_T

- exist as public NTUPLE to be studied

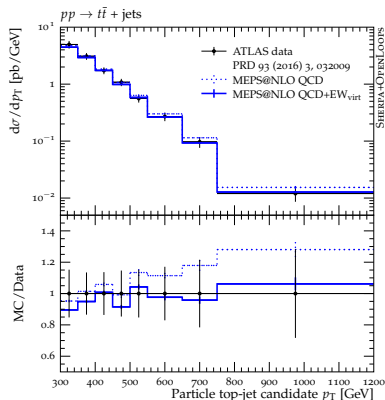
$t\bar{t}$ + jets production incl. approx. electroweak corrections

Gütschow, Lindert, MS arXiv:1803.00950



$t\bar{t} + 0, 1j @ \text{NLO QCD} + \text{EW}_{\text{virt}} + 2, 3, 4j @ \text{LO}$
 reproduces well the corrections seen at fixed-order

$t\bar{t}$ + jets production incl. approx. electroweak corrections



Gütschow, Lindert, MS arXiv:1803.00950

- $t\bar{t} + 0, 1j @ \text{NLO QCD} + \text{EW}_{\text{virt}}$
+ 2, 3, 4j @ LO
- include approx. virtual corrections
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential K -factor

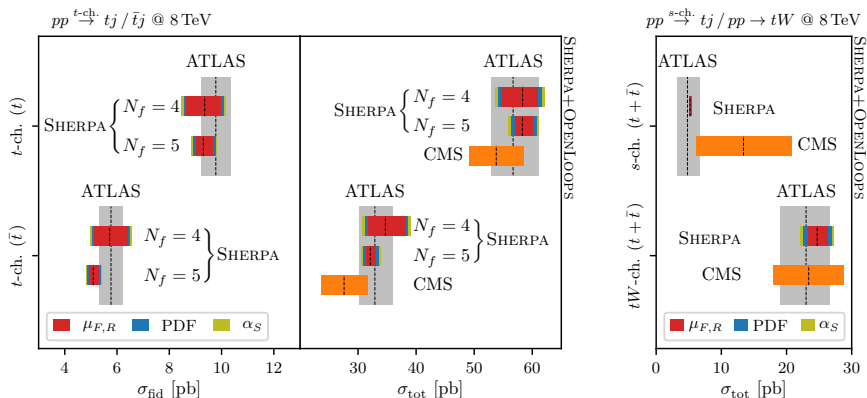
Höche, Krauss, MS, Siegert

arXiv:1009.1127

- improved description of data

Single-top production

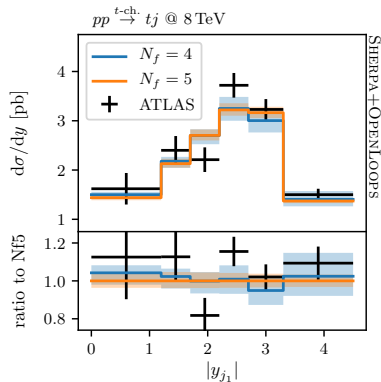
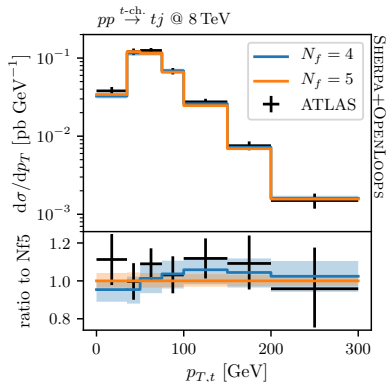
Bothmann, Krauss, MS arXiv:1711.02568



- S-MC@NLO t - and s -channel production in $N_f = 4$ and $N_f = 5$
- S-MC@NLO tW -channel in $N_f = 5$ with DR to separate from $t\bar{t}$

Single-top production

Bothmann, Krauss, MS arXiv:1711.02568



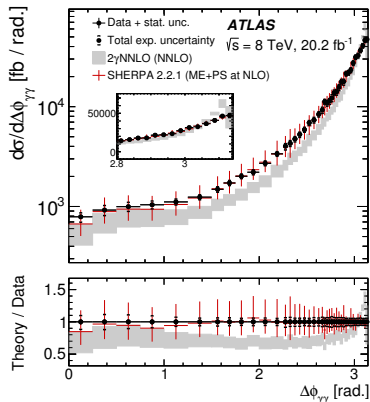
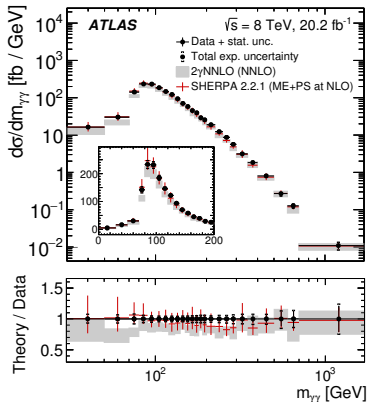
- good description of incl. and fiducial xsec with $N_f = 4$ and $N_f = 5$
- parton shower uncertainty studies will be possible in SHERPA-2.2.7

Multibosons

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Diphoton

ATLAS arXiv:1704.03839

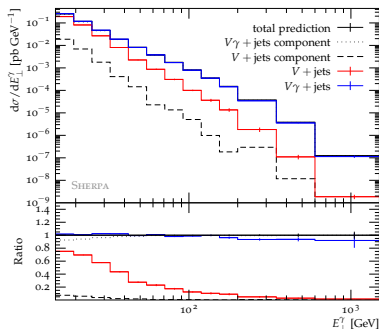


$\gamma\gamma + 0, 1j @ \text{NLO QCD} + 3, 4L0$

V + photon

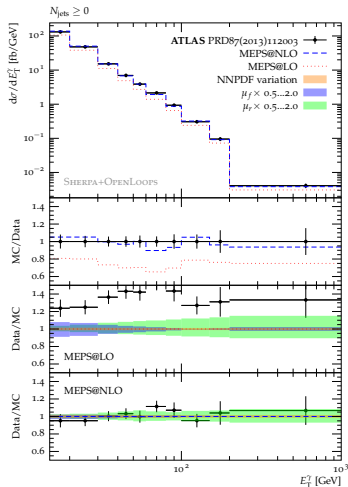
Siegert, Krause arXiv:1708.06283

- $Z\gamma + 0, 1j$ NLO QCD
- overlap of $Z + \text{jets} + \gamma$ FSR and $Z\gamma + \text{jets}$
- photons from decay of Z better described with YFS resummation matched to higher order QED corrections (FSR)
- else better described through NLO QCD for $Z\gamma$
- overlap removal at particle level
→ custom cuts available
- well reproduces data



V + photon

Siegert, Krause arXiv:1708.06283



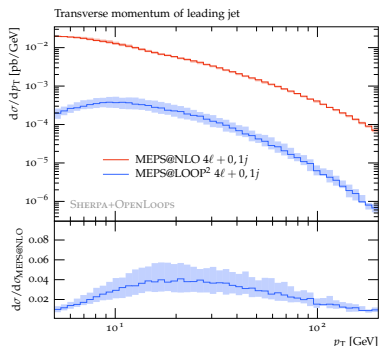
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Diboson

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.0500

Incorporate both NLO merging for $q\bar{q}$ channels and LO merging for loop-induced gg channels

- MEPS@NLO
 $4\ell + 0, 1j$ @NLO QCD
- MEPS@LOOP²
 $4\ell + 0, 1j$ @LO

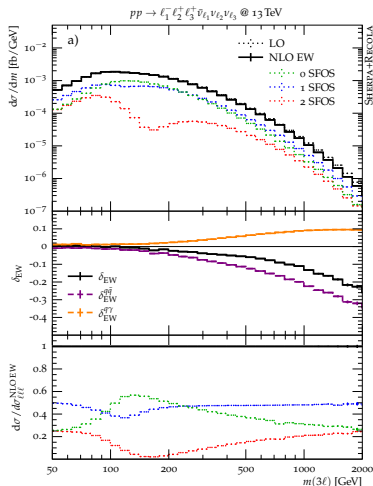


consistent incorporation of loop-induced processes

Triboson

- off-shell $W^+ W^+ W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ -induced) important
- cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels highly observable dependent
- **NLO EW available in SHERPA-3.0.0**

MS arXiv:1806.00307



Higgs processes

- 1 Overview
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Higgs production in gluon fusion

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

Kuttimalai, Krauss, Maierhöfer, MS LH'15 arXiv:1605.04692

Kuttimalai, Krauss, Maierhöfer, MS for YR4

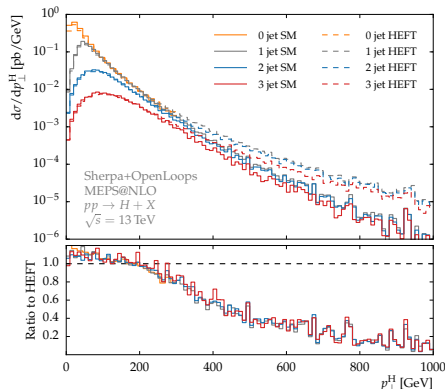
$pp \rightarrow H + \text{jets}$ production (ggF)

- correction factor/weight

$$r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \rightarrow \infty)|^2}$$

- loops from OPENLOOPS
- construct MEPS@NLO from reweighted S-MC@NLO
- factorised approach for unknown top mass dependence in V_n , otherwise exact NLO mass dependence

$$d\sigma_n = d\Phi_n r_t^{(n)} \left[B_n + V_n + \int d\Phi_1 D_n \right] \widetilde{\text{PS}}_n + d\Phi_{n+1} \left[r_t^{(n+1)} R_n - r_t^{(n)} D_n \right]$$



Higgs production in gluon fusion

Kuttimalai, Krauss, Maierhöfer, MS LH'15, LHC HXSWG YR4

$pp \rightarrow H + \text{jets}$ production (ggF)

- no reweighted MEPS@NLO for m_b -dep components as

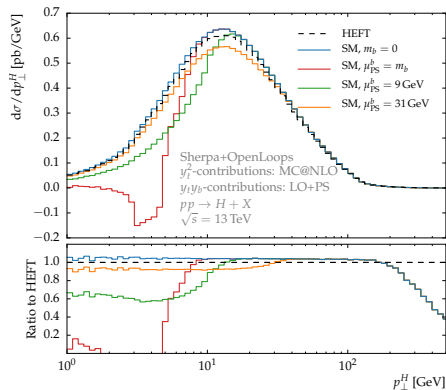
$$V = \frac{B}{B_{\text{HEFT}}} V_{\text{HEFT}}$$

not a good approximation

- LOPS leads to huge variation when varying starting scale as argued in the literature

Bagnaschi et.al. JHEP01(2016)090

- MEPS allows to leave starting scale, resummation scale at high value when setting the $Q_{\text{cut}} \sim m_b \Rightarrow$ **small variation**



Higgs production in gluon fusion

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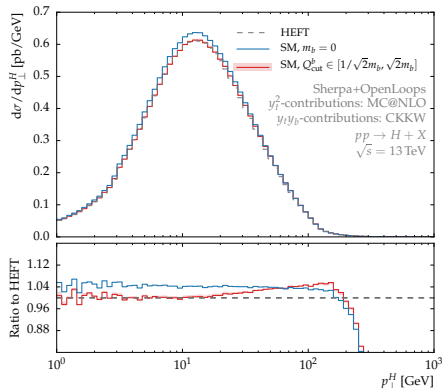
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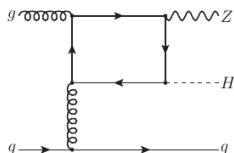


Higgs bosons in associated production

Goncalves,Krauss,Kuttimalai,Maierhöfer PRD92(2015)7,073006

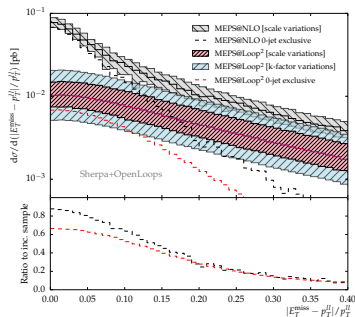
$pp \rightarrow ZH + \text{jets production}$

- MEPS@NLO for $q\bar{q}$
MEPS@LOOP² for gg
- care for $qg \rightarrow ZHq$:



→ part of NLO ZHj
→ in loop-induced as gauge
inv. subset of NNLO ZHj

- loops from OPENLOOPS



$pp \rightarrow Z[\rightarrow \ell\ell]H[\rightarrow \text{inv}] + \text{jets}$

BSM physics

[Höche, Kuttimalai, Schumann, Siebert EPJC75\(2015\)3,135](#)

- full support for UFO model [Degrande et.al. CPC183\(2012\)1201](#)
- Lorentz and colour structures automatically built for COMIX
- automatic identification of all $1 \rightarrow 2$ and $1 \rightarrow 3$ decay channels of every unstable particle in the model
→ calculation of all decay widths (LO)
- per default all decay channel used
→ inclusive production
→ mechanism to select individual channels,
cross section optionally adjusted accordingly
- spin-correlated decay chains of arbitrary length
using spin density matrices [Richardson JHEP11\(2001\)029](#),
[Knowles CPC58\(1990\)271](#)

⇒ see **Davide's talk**

SHERPA-2.2.6

- a new parton shower DIRE
- vastly extended support for UFO BSM format
- multijet merging for loop induced processes further tested, use as:
 - MEPS@LOOP²
 - reweight MEPS@NLO Higgs production in HEFT with top mass dependence (approximate in virtual corrections only)
- on-the-fly variations of μ_R , μ_F , α_s and PDF for
 - LO, NLO
 - LOPs, NLOPs (S-MC@NLO)
 - MEPS, MENLOPs, MEPS@NLO
- incorporation of approx. NLO EW corrs in existing NLO QCD MEPS@NLO
- default PDF: NNPDF30_nnlo_as_0118 including tune of non-perturbative parameters
- SHERPA-2.2.7 will be out soon (PS var for single-top, HEPMC 3)
- **coming in SHERPA-3.0.0:** full NLO EW, NLO for loop-induced processes, DIRE@NLO, ...

Thank you for your attention!

Backup