SHERPA

–

High-precision physics

in the

Standard Model and beyond

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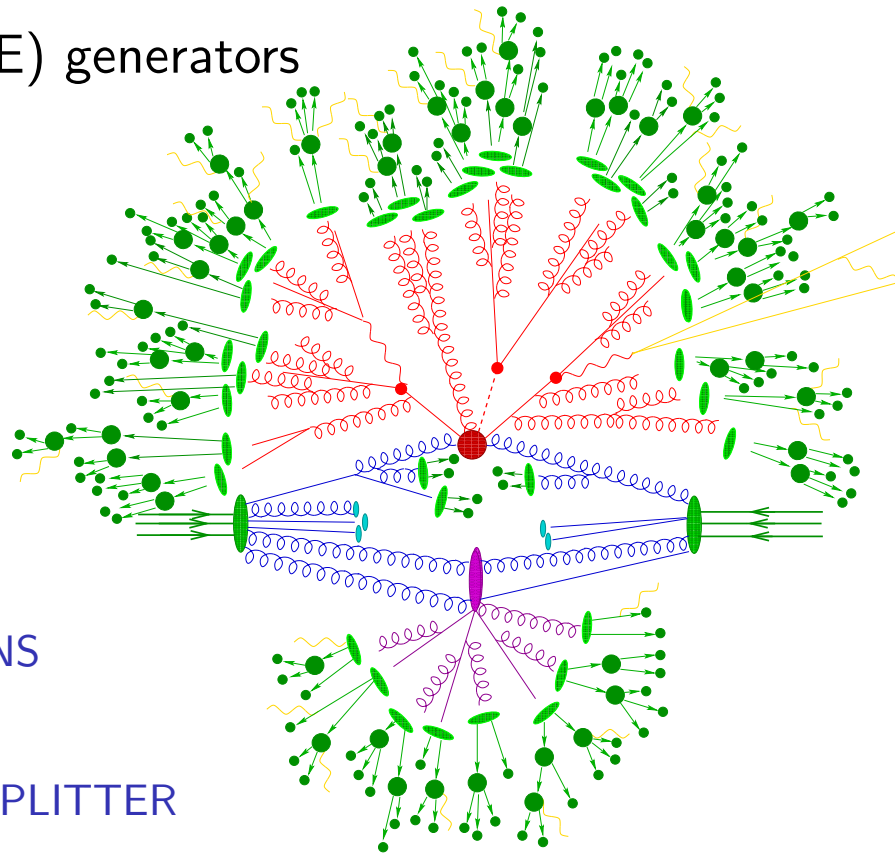
Contents

Overview

The SHERPA event generator framework

Sherpa coll., arXiv:1905.09127

- Two multi-purpose Matrix Element (ME) generators AMEGIC, COMIX
- Three Parton Shower (PS) generators CSSHOWER, DIRE, ALARIC
- A multiple interaction simulation à la PYTHIA AMISIC
- A cluster fragmentation module AHADIC EPJC36(2004)381
- A hadron and τ decay package HADRONS
- A higher order QED generator using YFS-resummation PHOTONS, PHOTONSPLITTER



Sherpa's traditional strength is the perturbative part of the event

LO, NLO, NNLO, LOPS, NLOPS, NNLOPS, MEPS, MENLOPS, MEPS@NLO

Acronyms and nomenclature

Fixed order calculations

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

$\Rightarrow$ LO, NLO, NNLO

Parton shower matched calculations

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

$\Rightarrow$ LOPS, NLOPS, NNLOPS

Multijet merged calculations

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

$\Rightarrow$ MEPS(@LO), MEPS@NLO (special case MENLOPS)

SHERPA-2.2.15

- SHERPA-2.2.15 released Mar '23
- contains bugfixes for all known bugs of SHERPA-2.2.14
- **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 corrs.** and sub-LO
  $\rightarrow$ use named weights in HEPMC (av. since HEPMC-2.06)
- full scale & PDF variations including correlated with parton shower
- performance improvements using simplified pilot runs
- default PDF: `NNPDF30_nnlo_as_0118`
- `UFO` support for BSM physics

V + jets processes

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 $p_{\mathrm{T}}^{W/Z}$

Matched to parton shower:

- NNLOPS for inclusive W and Z production
- NLOPS (S-MC@NLO) for $p_{\mathrm{T}}^{W/Z}$

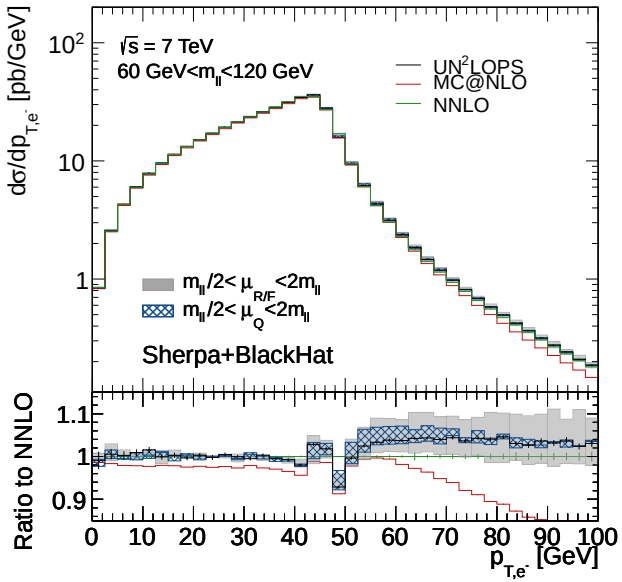
Multijet merged:

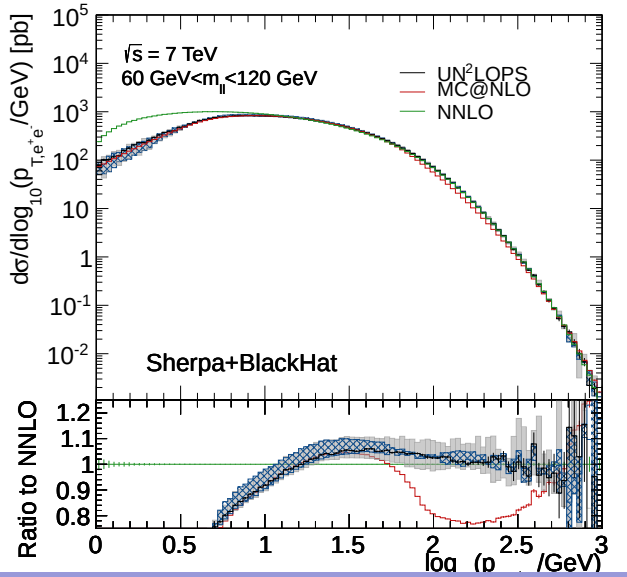
- MEPS@NLO
  $\rightarrow$ inclusive and for low $p_{\mathrm{T}}(< Q_{\mathrm{cut}})$ same as incl. NLOPS
  $\rightarrow$ for high-p_{T} benefit from NLO accuracy for multijet processes

NNLOPS for p_T^W and p_T^Z

Höche, Li, Prestel arXiv:1405.3607

- NNLOPS matching in UN^{2}LOPS scheme
- scheme constructed to minimise uncontroled higher order terms
- no reweighting, generated directly
- NLOPS accuracy as $p_T^{W/Z} \to 0$
- QED corrections through YFS soft-photon res.



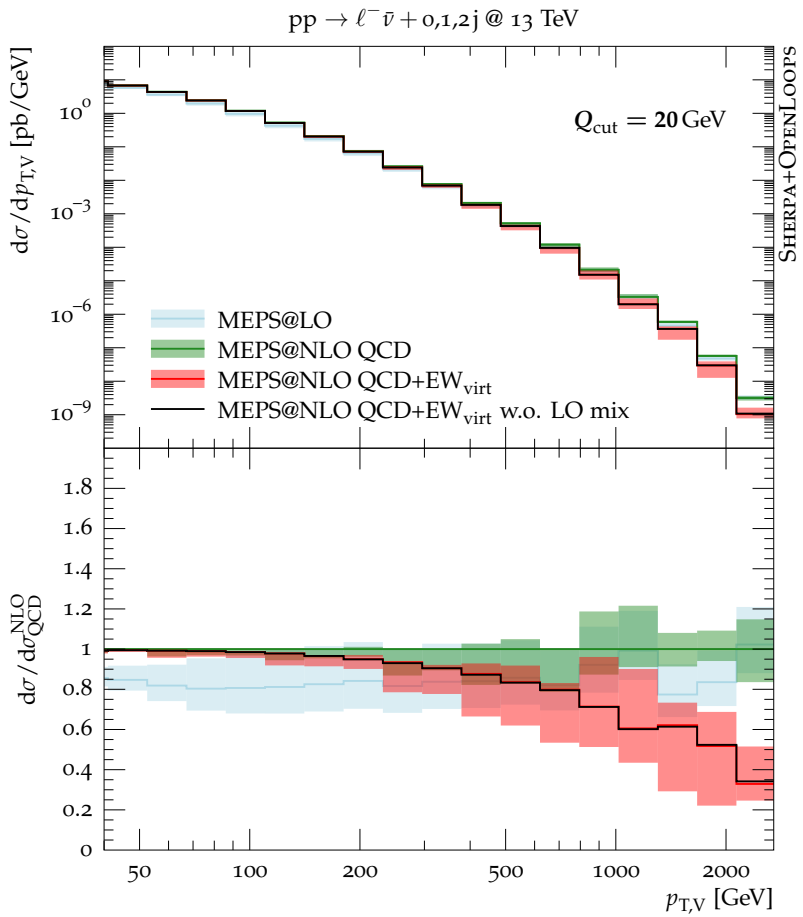


Large p_{T}^{W} and p_{T}^{Z}

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

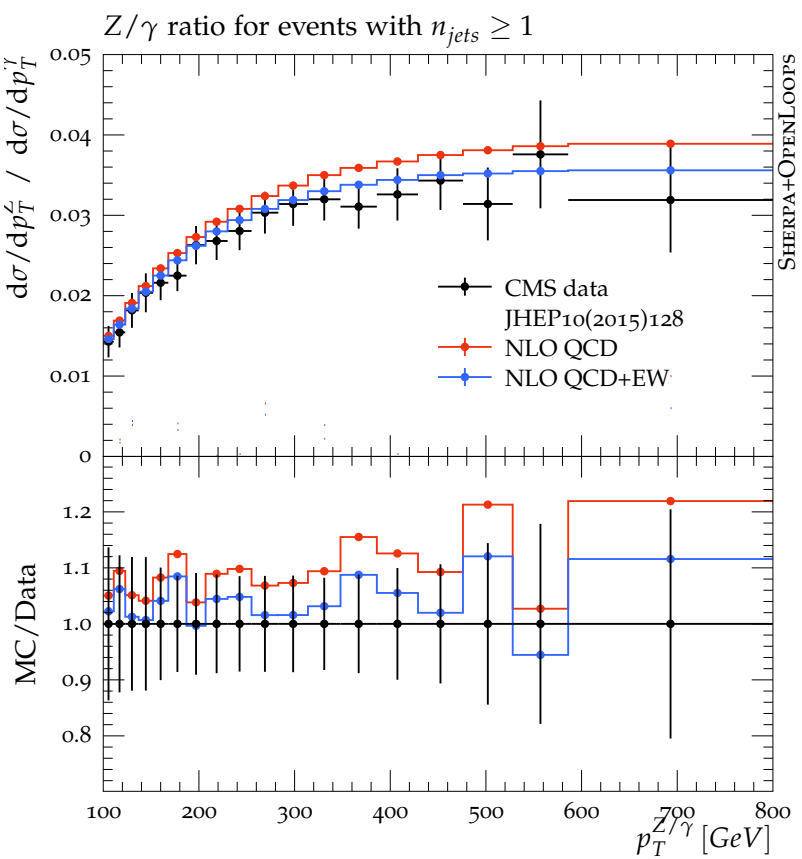
MEPS@NLO QCD+EW$_{\mathrm{virt}}$

- 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



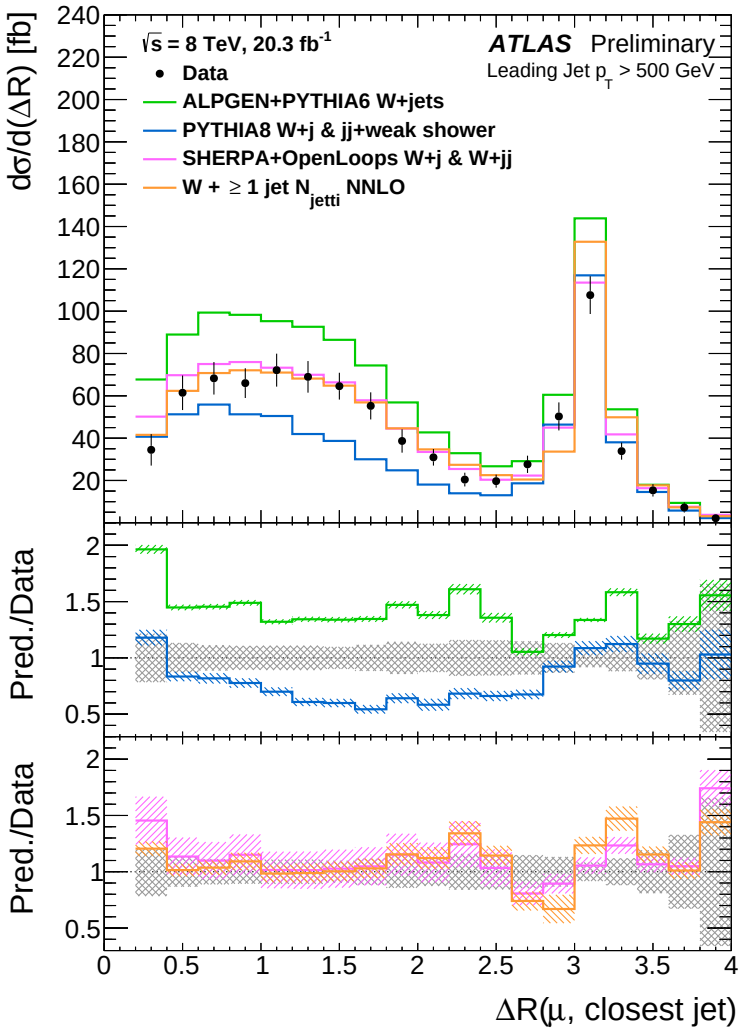
NLO EW corrections

LH'15 arXiv:1605.04692



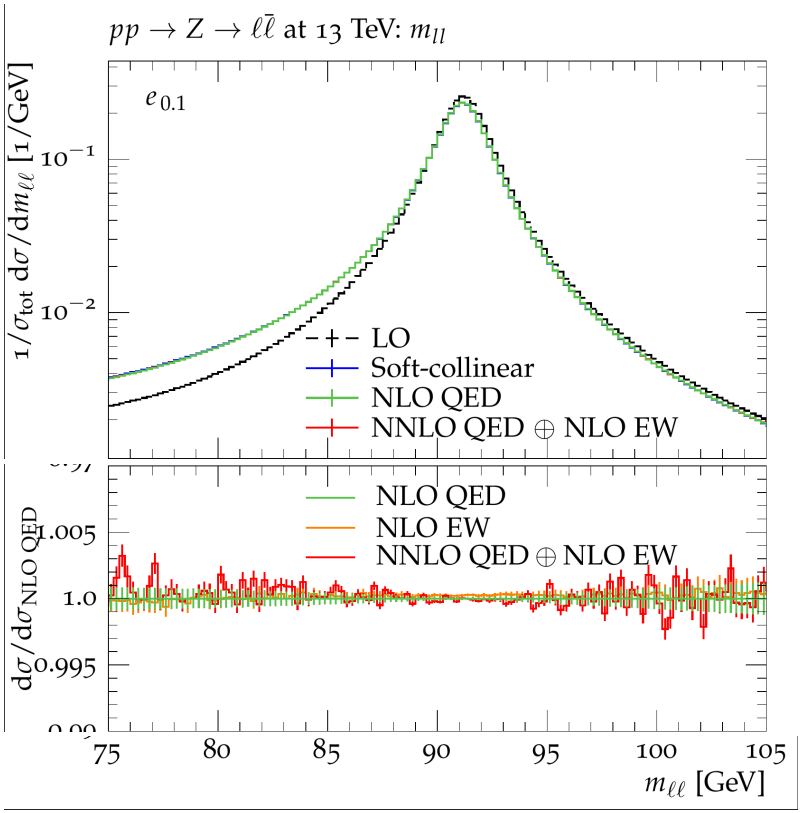
important to describt Z/γ ratio

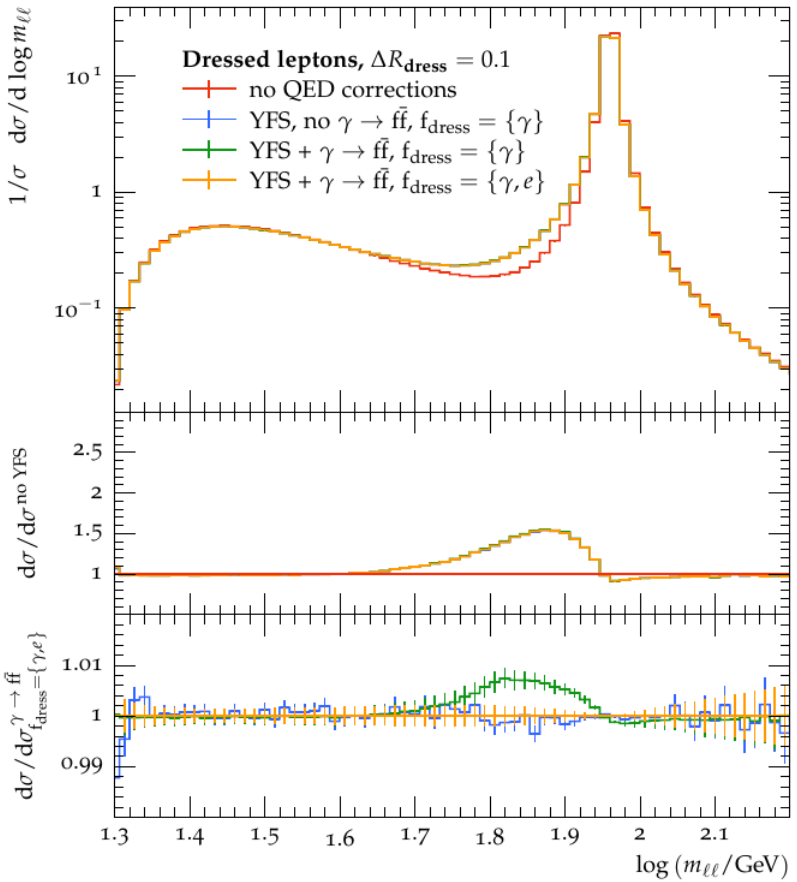
ATLAS arXiv:1609.0745



Soft-photon resummation

Krauss, Lindert, Linten, MS arXiv:1809.10650, Flower, MS arXiv:2210.07007



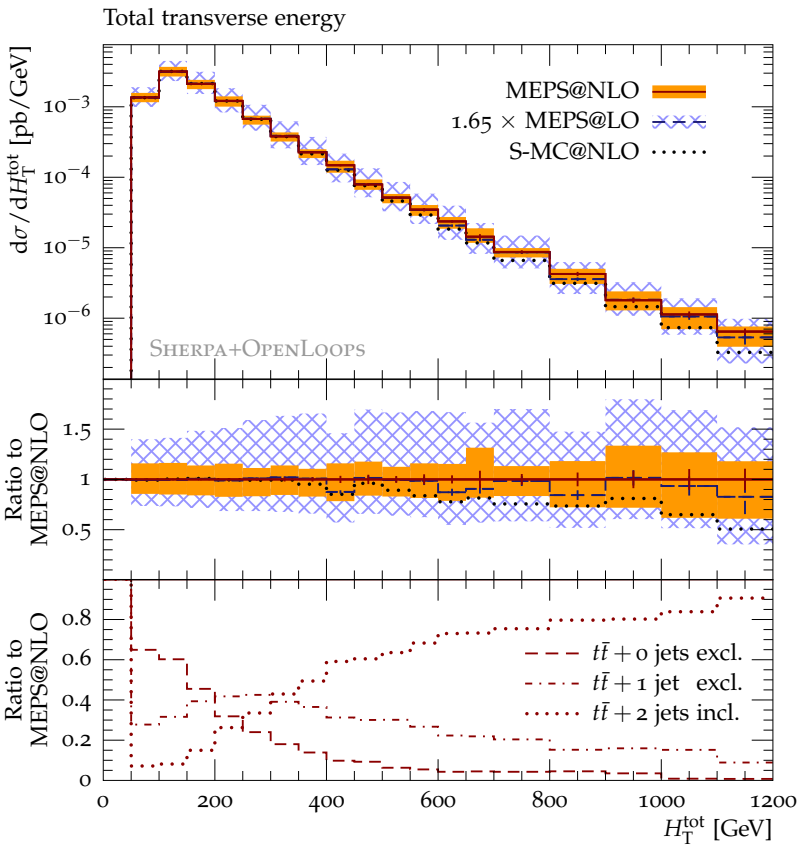


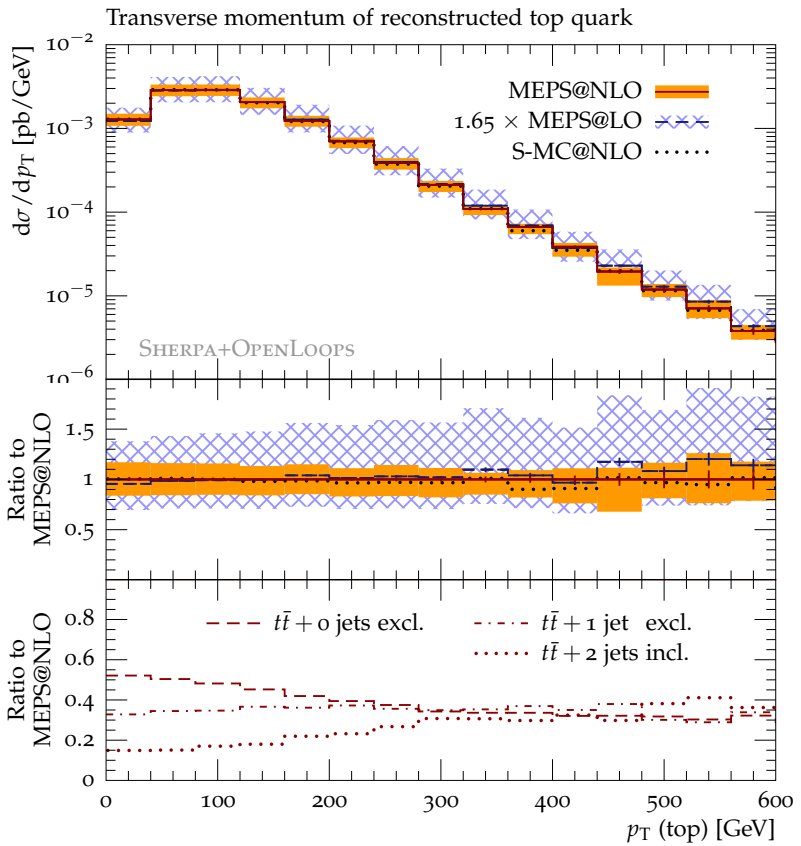
YFS formalism, matched to NNLO QED + NLO EW, including $\gamma \to f\bar{f}$

Top processes

$t\bar{t}$ + jets production

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

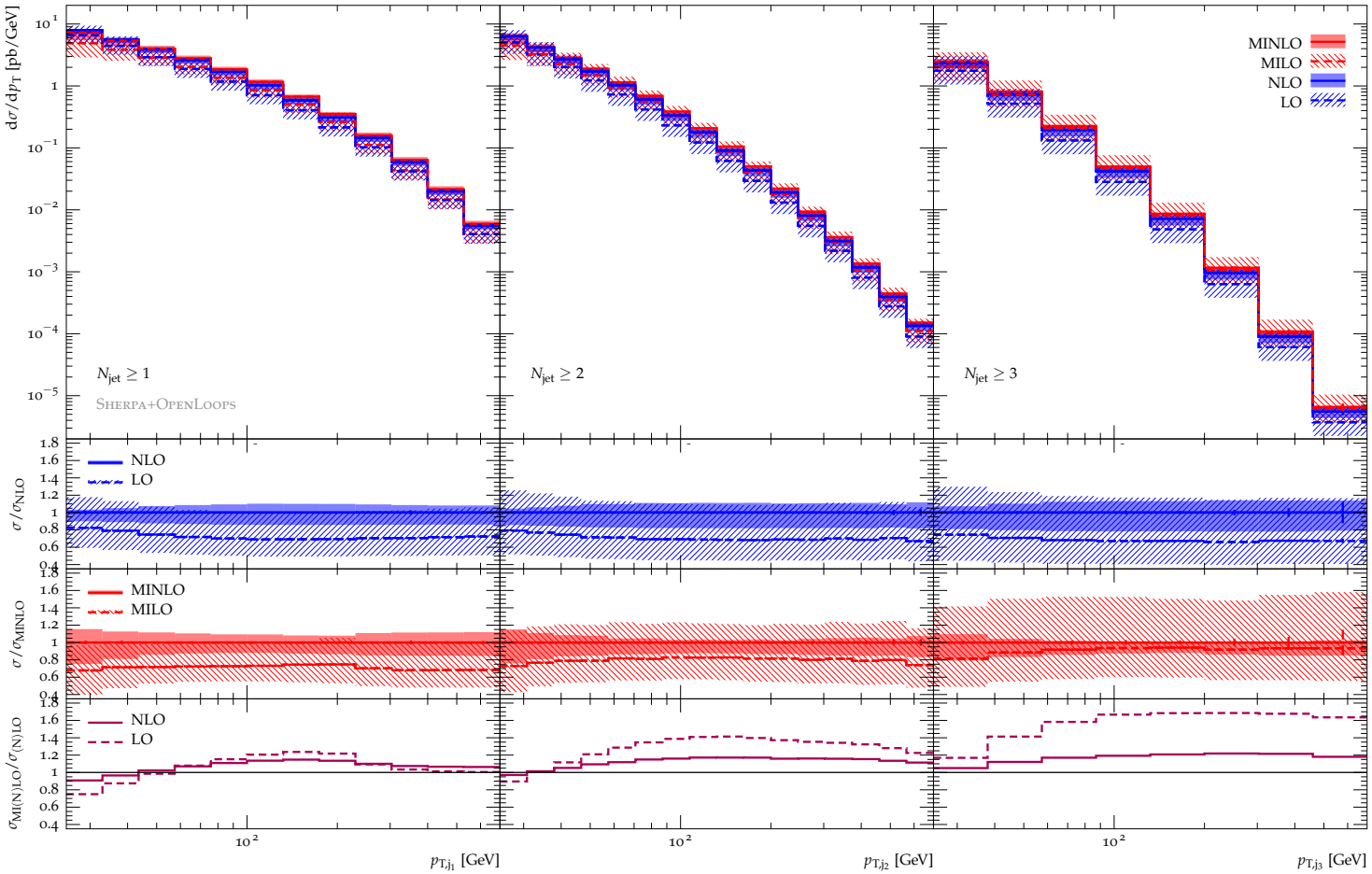




- $t\bar{t} + 0, 1, 2j$@NLO QCD
- shapes very similar, normalisation and uncertainty improvements

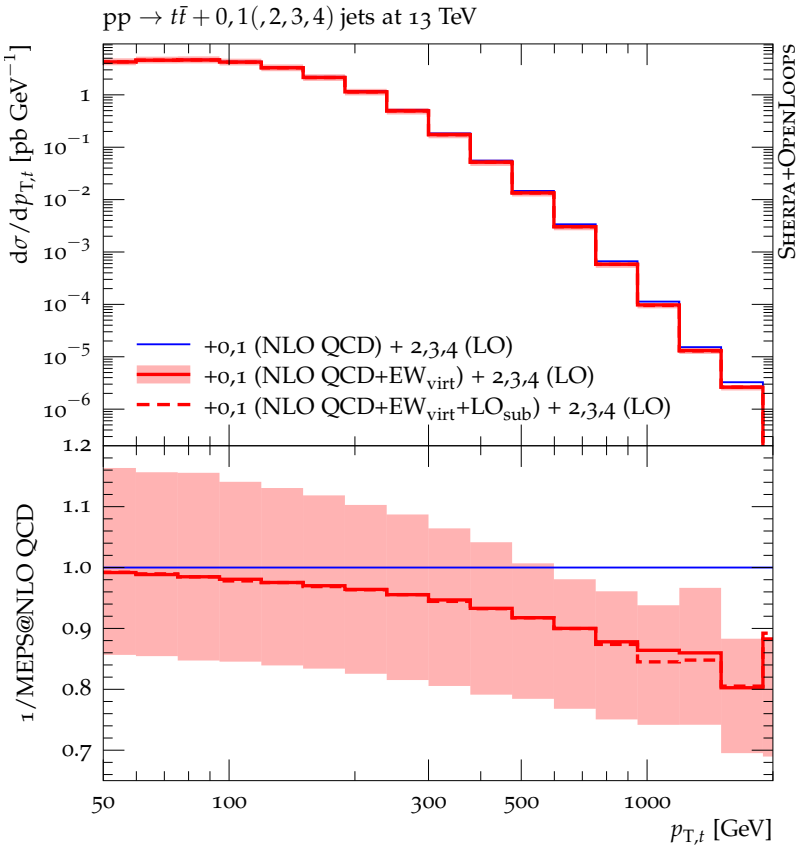
$pp \to t\bar{t}$ + 3jets @ NLO QCD (no parton shower)

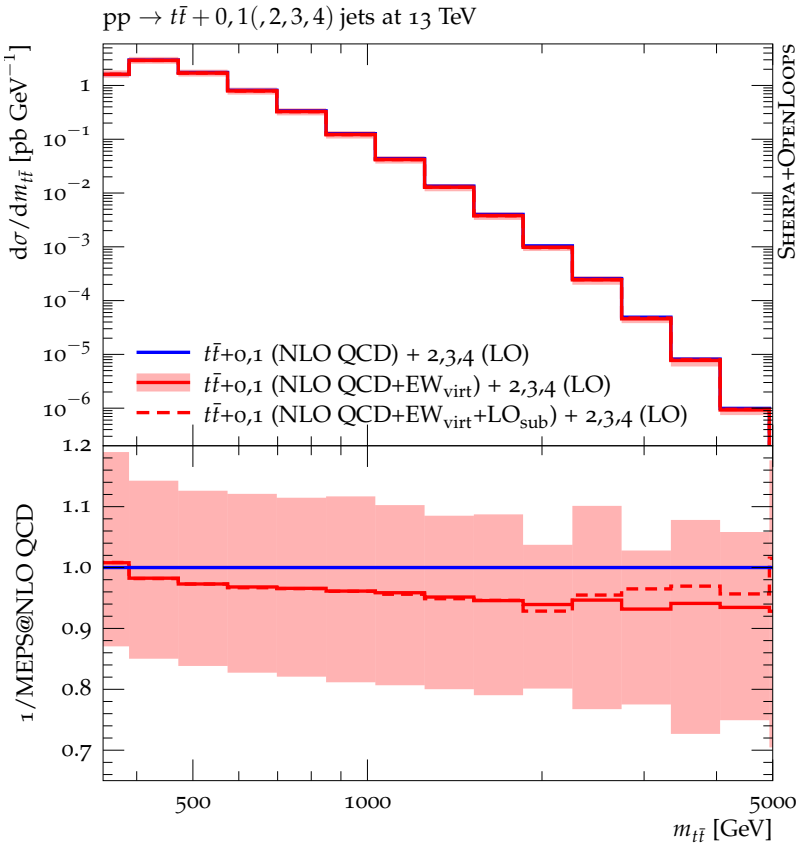
Höche, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1607.06934



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

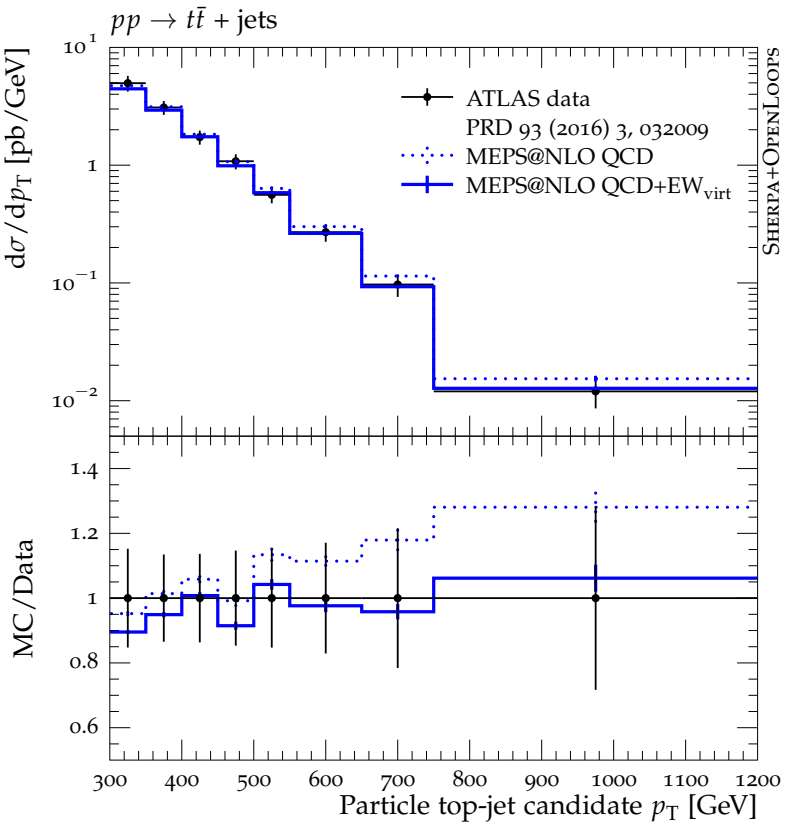
Gütschow, Lindert, MS arXiv:1803.00950





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

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



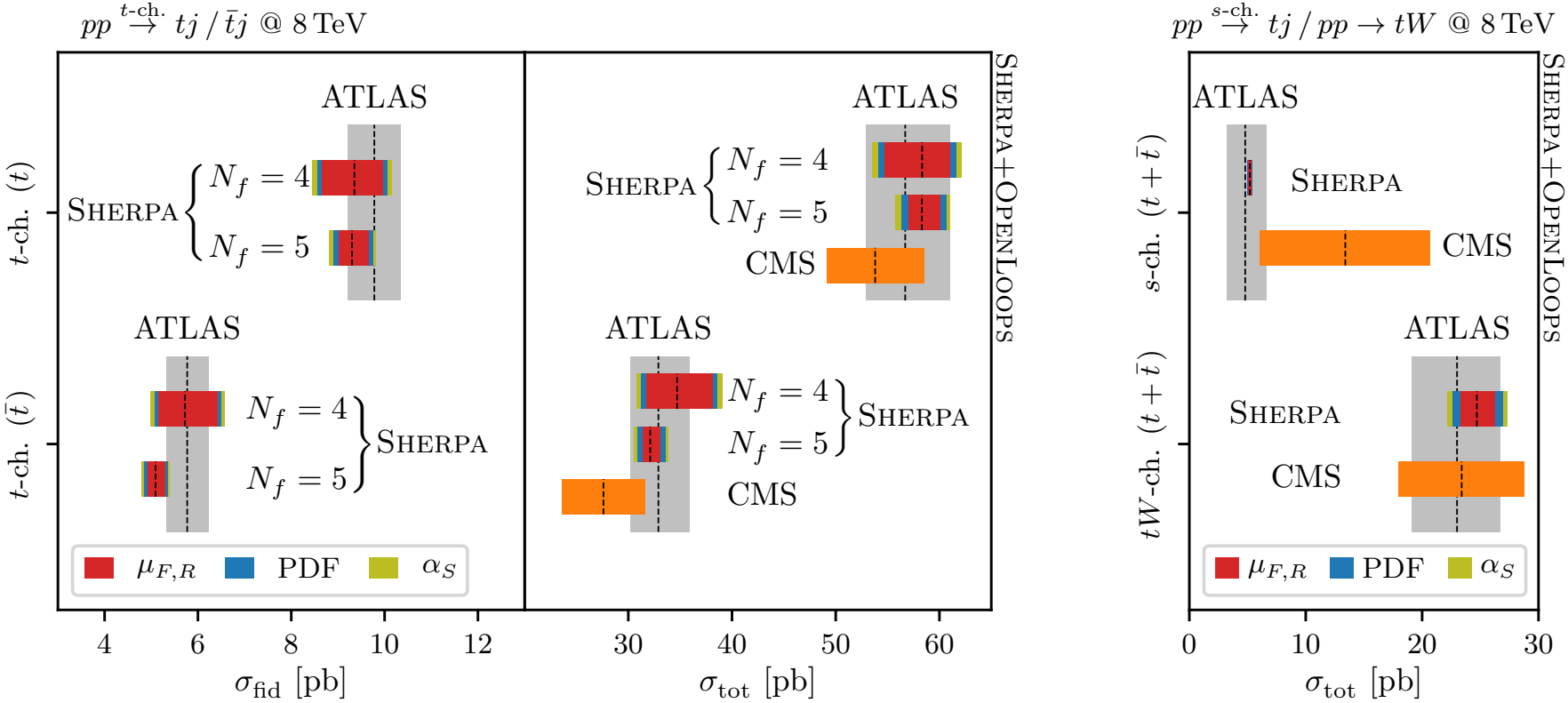
Gütschow, Lindert, MS arXiv:1803.00950

- $t\bar{t} + 0, 1j$@NLO QCD+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

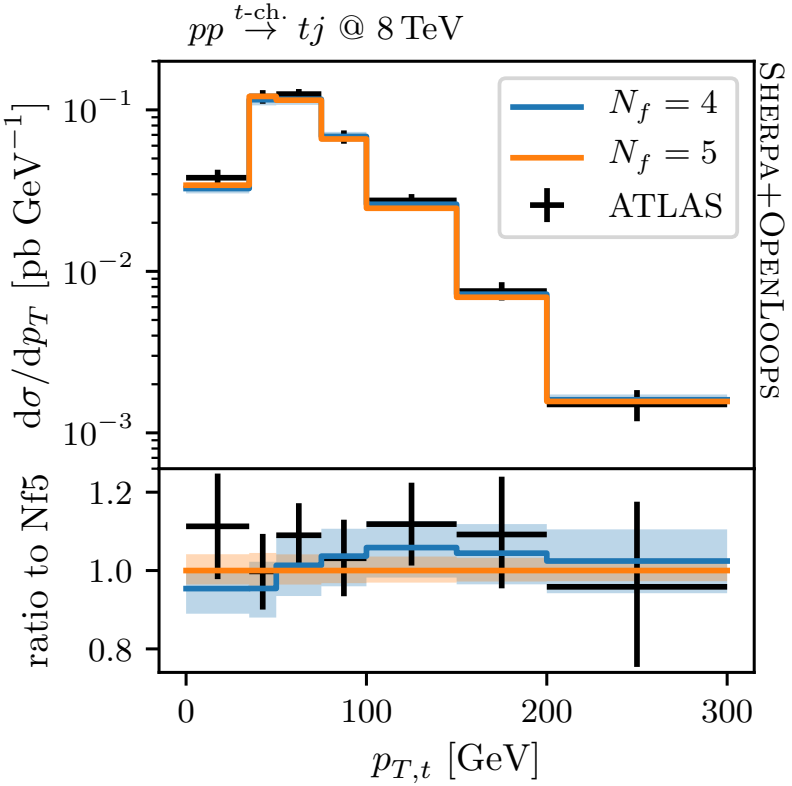
Bothmann, Krauss, MS arXiv:1711.02568

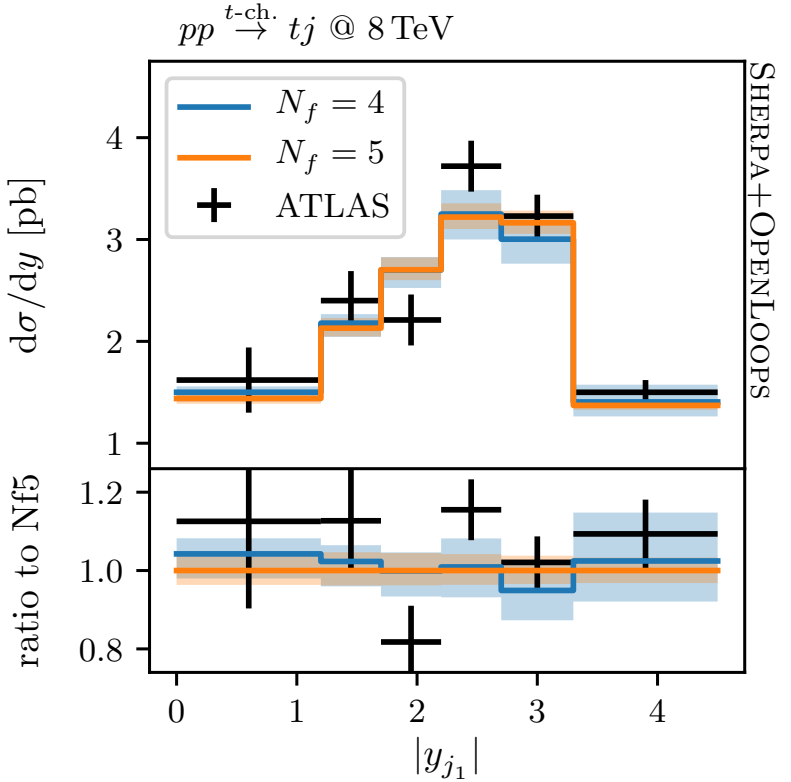


- S-MC@NLO t- and s-channel production in $N_f = 4$ and $N_f = 5$
- S-MC@NLO tW-channel in $N_f = 5$ with DR to separate from $t\bar{t}$

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

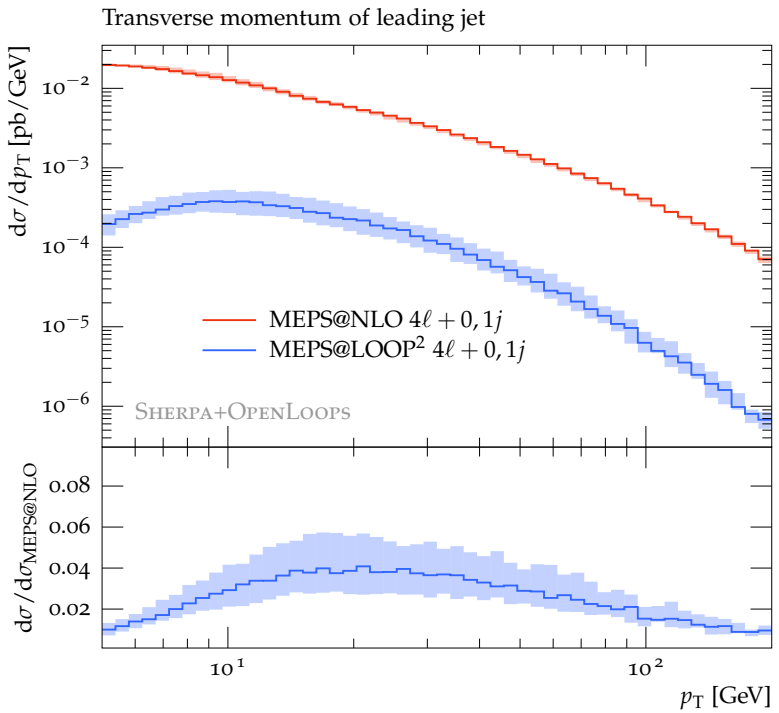
Multibosons

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

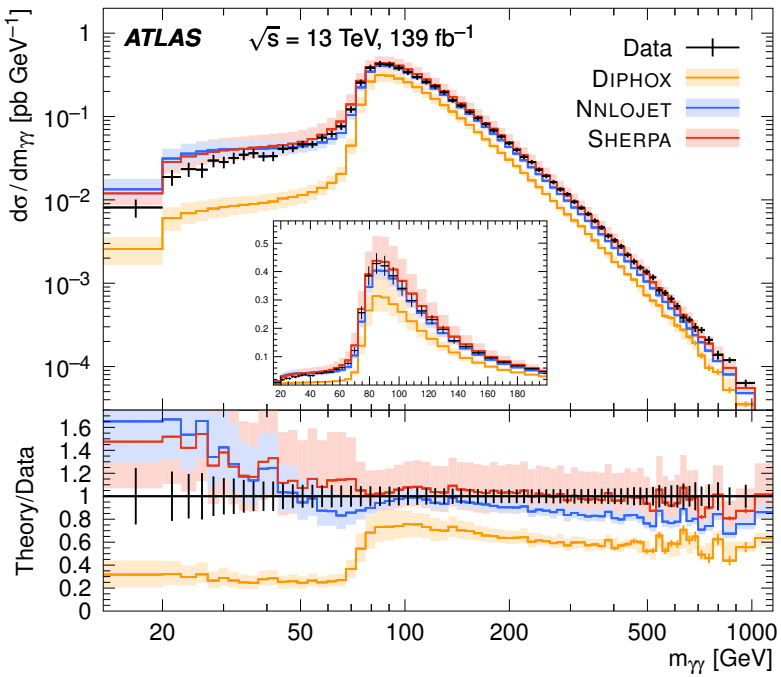
- MEPS@NLO
  $4\ell + 0, 1j$@NLO QCD
- MEPS@LOOP^2
  $4\ell + 0, 1j$@LO

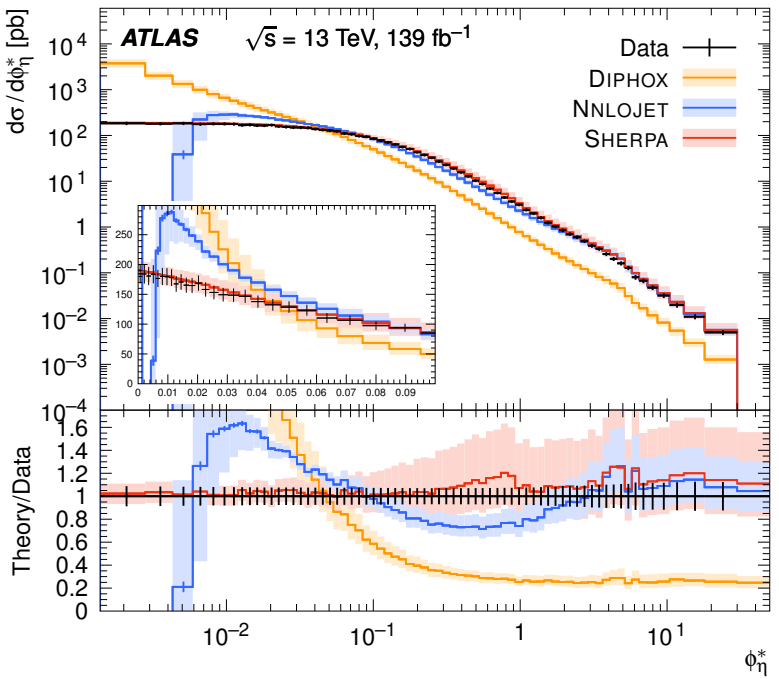


consistent incorporation of loop-induced processes

Diphoton

ATLAS arXiv:2107.09330





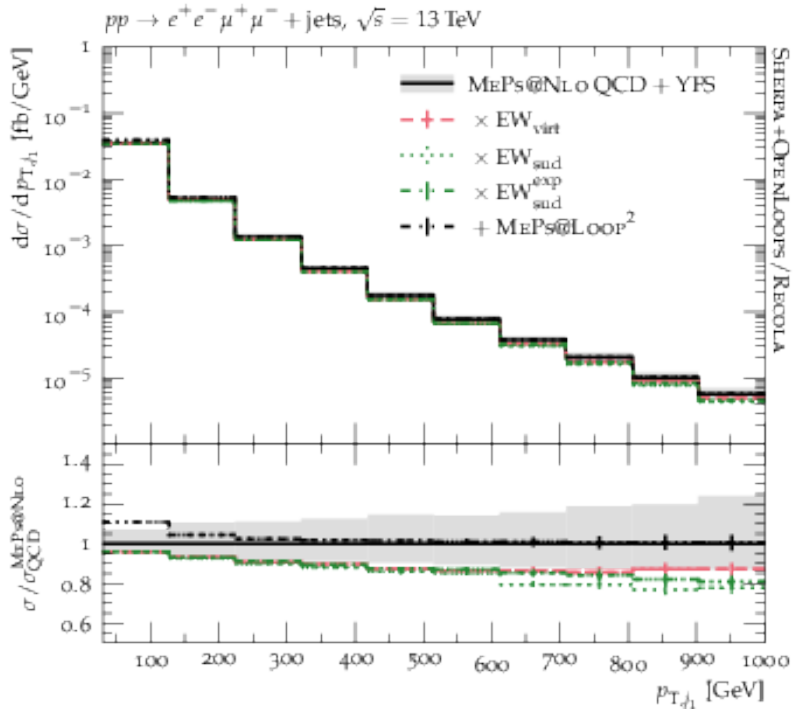
$\gamma\gamma + 0, 1j$@NLO QCD $+ 2, 3$LO

Diboson

Bräuer et.al. arXiv:2005.12128, Bothmann et.al. arXiv:2111.13453

MEPS@NLO for VV and VVj
pp$\to 0,1j$@NLO $+ 2,3j$@LO

- NLO QCD and EW corrs.
  EW_{virt} for $\mathbb{S}$-events,
  EW_{sud} for $\mathbb{H}$- and LO events
- consistent YFS for QED FSR



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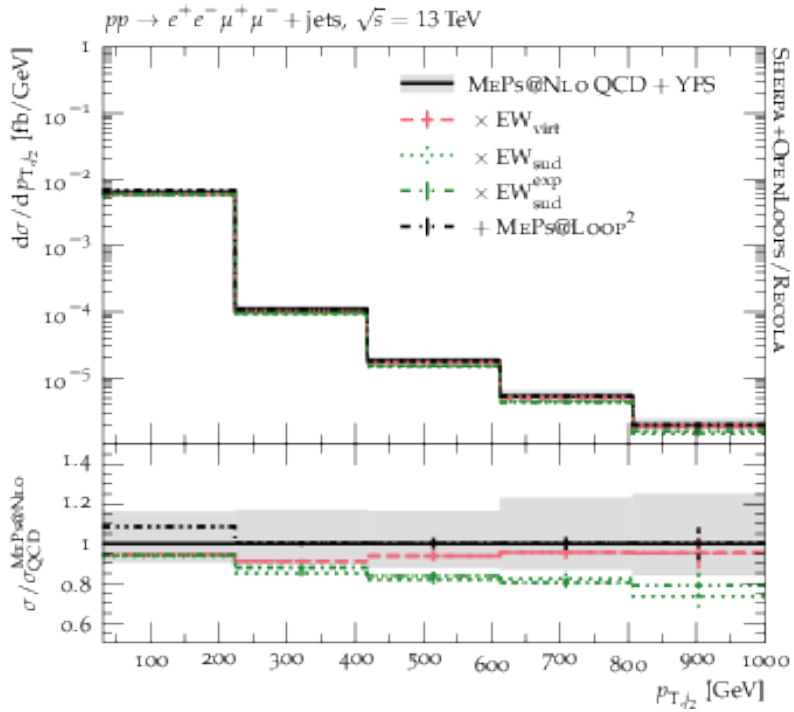


Higgs processes

Higgs production in gluon fusion

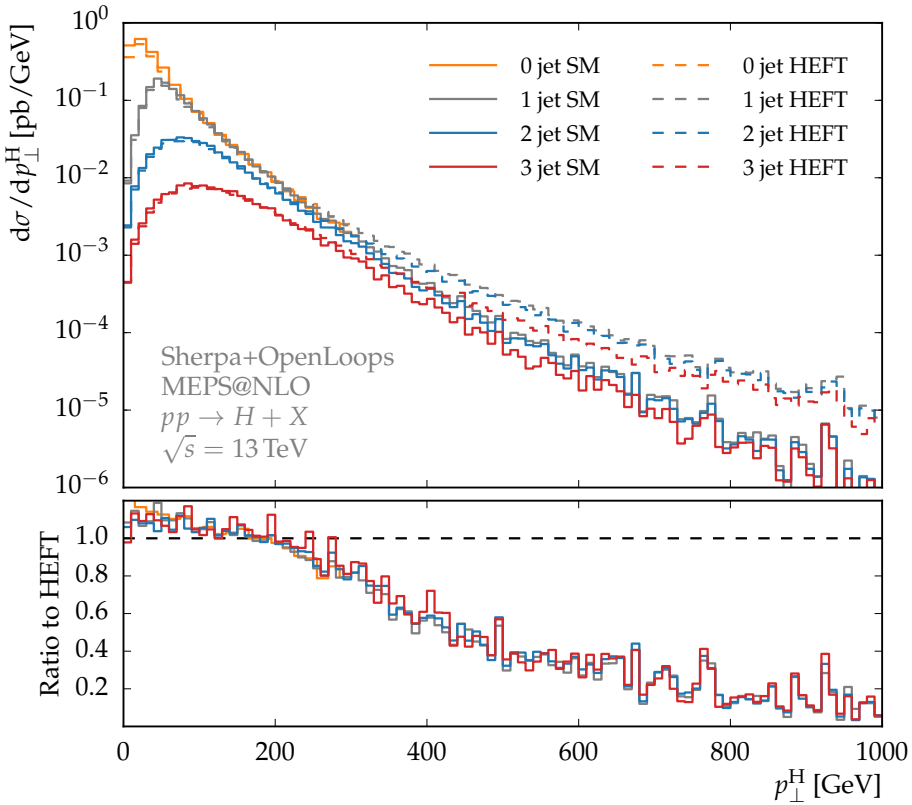
Buschmann,Goncalves,Kuttimalai,MS,Krauss,Plehn arXiv:1410.5806
Kuttimalai,Krauss,Maierhöfer,MS LH'15 arXiv:1605.04692
Kuttimalai,Krauss,Maierhöfer,MS for YR4

$pp \to H +$ jets production (ggF)

- correction factor/weight

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

- 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



Higgs production in gluon fusion

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

$pp \to H +$ jets production (ggF)

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

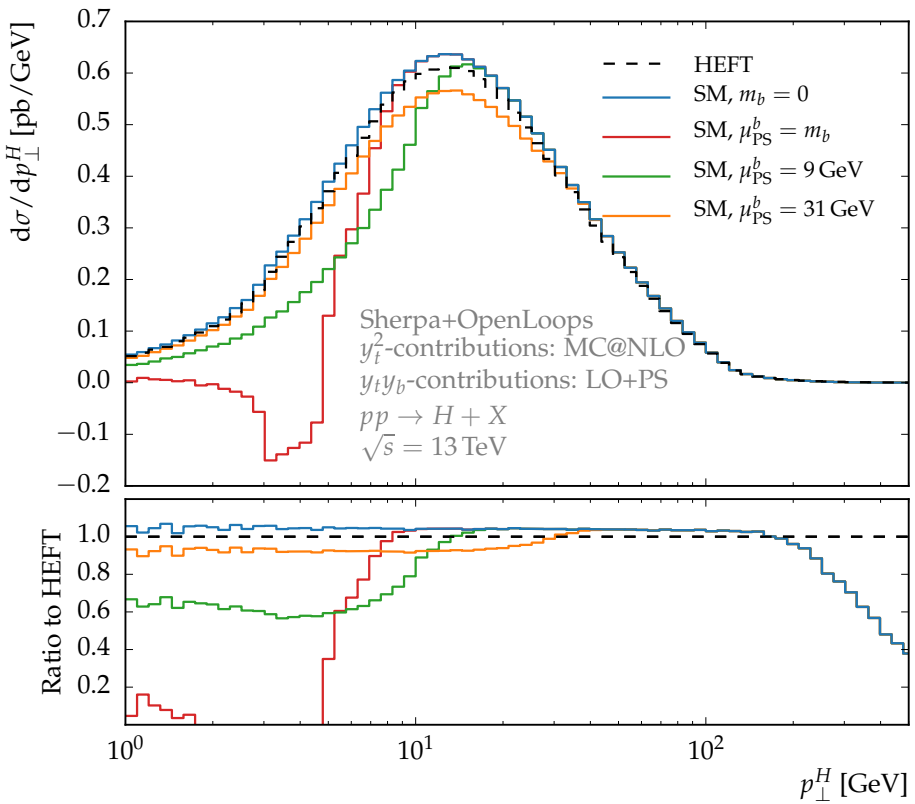
$$\mathrm{V} = \frac{\mathrm{B}}{\mathrm{B}_{\mathrm{HEFT}}} \mathrm{V}_{\mathrm{HEFT}}$$

  not a good approximation

- LOPS leeds 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 $Q_{\mathrm{cut}} \sim m_b \Rightarrow$ **small variation**



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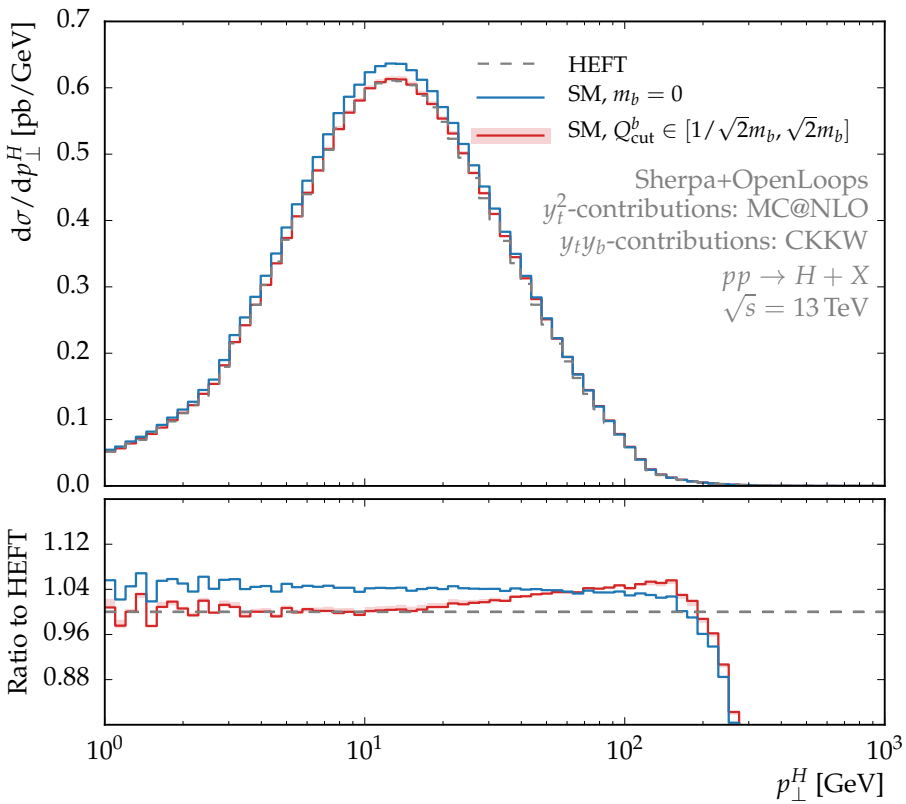
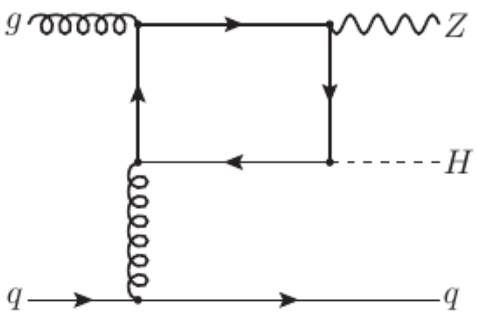


Higgs bosons in associated production

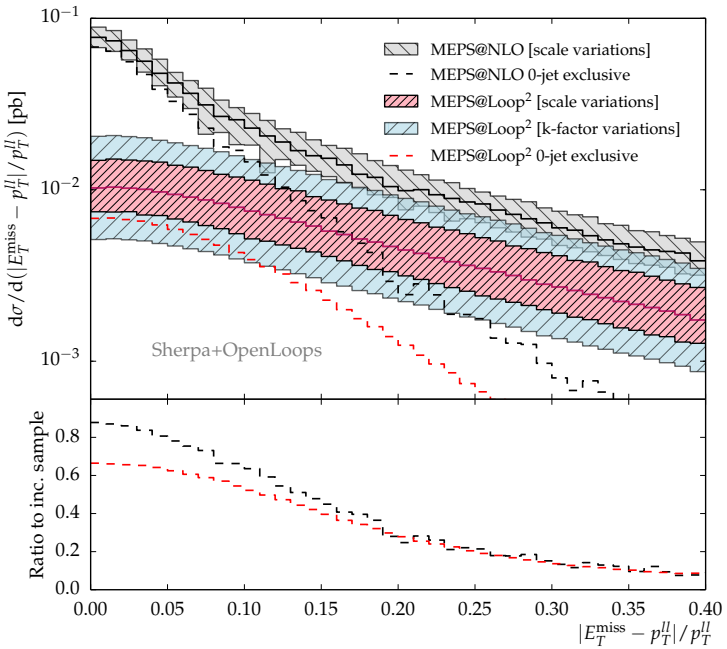
Goncalves,Krauss,Kuttimalai,Maierhöfer PRD92(2015)7,073006

$pp \to Z\,H$ + jets production

- MEPS@NLO for $q\bar{q}$
  MEPS@LOOP^2 for gg
- care for $qg \to ZHq$:



  $\to$ part of NLO ZHj
  $\to$ in loop-induced as gauge inv. subset of NNLO ZHj
- loops from OPENLOOPS



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

BSM processes

BSM physics

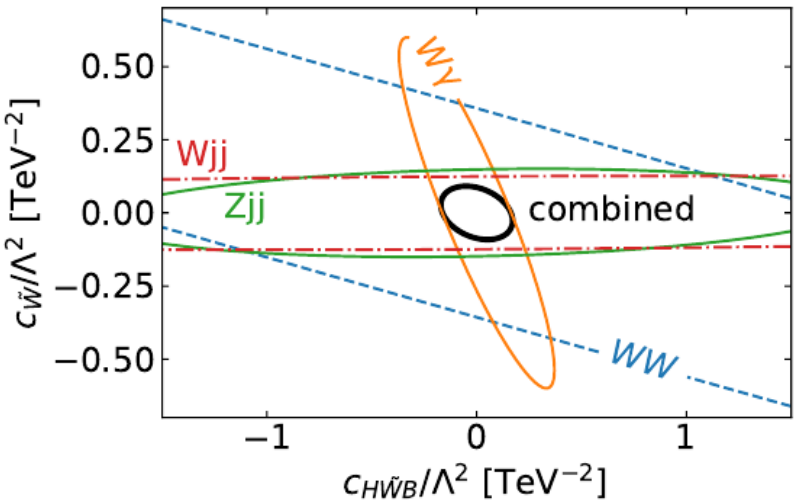
Höche,Kuttimalai,Schumann,Siegert EPJC75(2015)3,135

- full support for UFO model Degrande et.al. CPC183(2012)1201
  UFO2 ongoing Darmé et.al. arXiv:2304.09883
- Lorentz and colour structures automatically built for COMIX
- automatic inclusion in hard decay module
  - identification of all $1\to2$ and $1\to3$ decay channels of every unstable particle in the model
    $\to$ calculation of all decay widths (LO)
  - by default all decay channel used
    $\to$ inclusive production
    $\to$ 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

BSM limits using UFO

- LO multileg with SMEFT, model defined through UFO
- use public ATLAS and CMS SM measurements to constrain SMEFT parameters

Biekötter, Gregg, Krauss, MS arXiv:2102.01115



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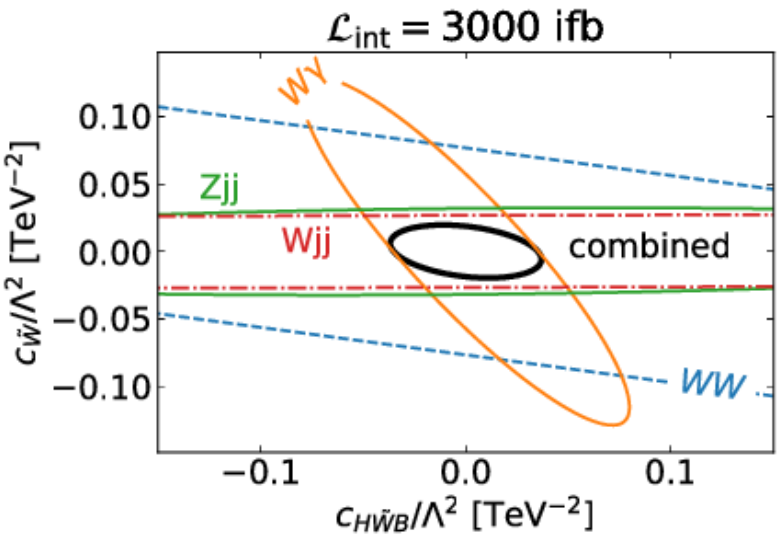
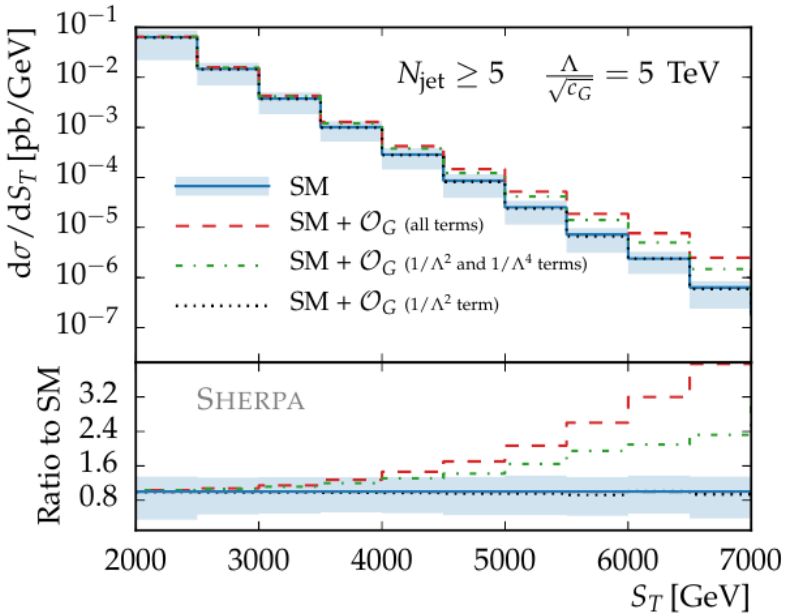
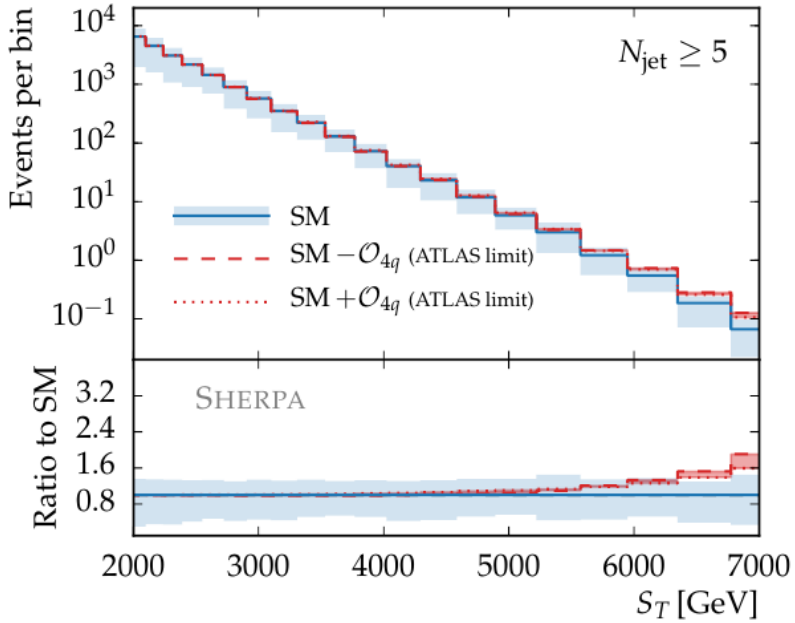


BSM limits using UFO

Krauss, Kuttimalai, Plehn et.al. arXiv:1611.00767





- multijet-merged predictions for multijet production with the inclusion of anomalous gluon and quark contact interactions

SHERPA-2.2.15 / SHERPA-3.0.0

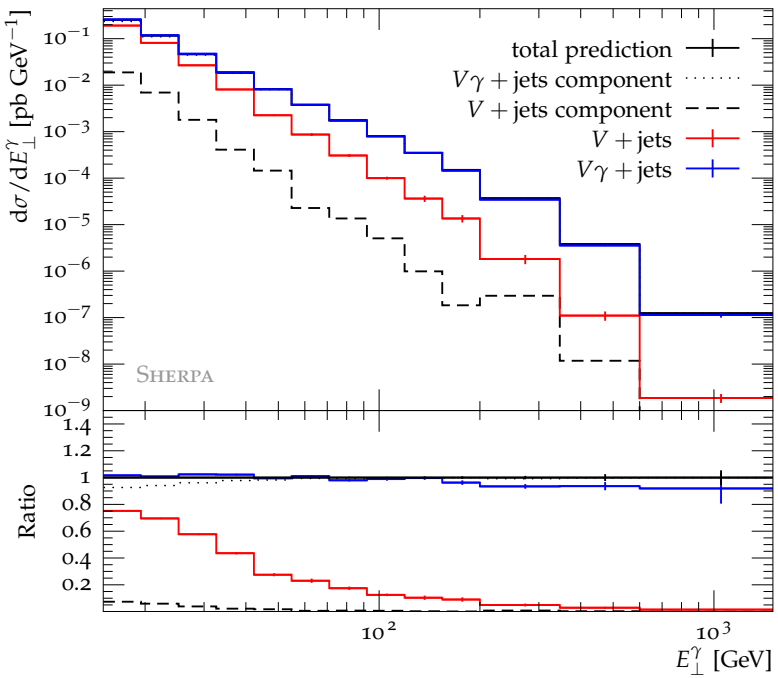
- vastly extended support for UFO BSM format
- multijet merging for loop induced processes further tested, use as:
  - MEPS@LOOP^2
  - reweight MEPS@NLO Higgs production in HEFT with top mass dependence (approximate in virtual corrections only)
- on-the-fly variations of μ_R, μ_F, α_s and PDF for
  - 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

http://sherpa.hepforge.org

Thank you for your attention!

Backup

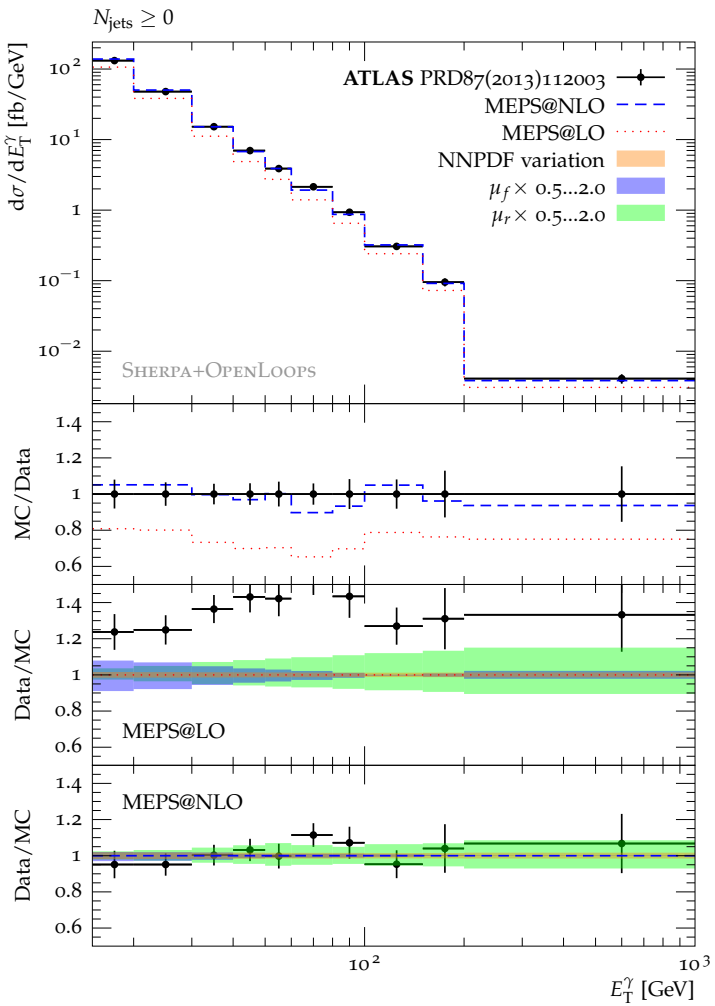
V+photon



Siegert, Krause arXiv:1708.06283

- $Z\gamma + 0, 1j$NLO QCD
- overlap of Z + jets + γFSR and $Z\gamma$ + 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
  $\rightarrow$ custom cuts available
- well reproduces data

V+photon



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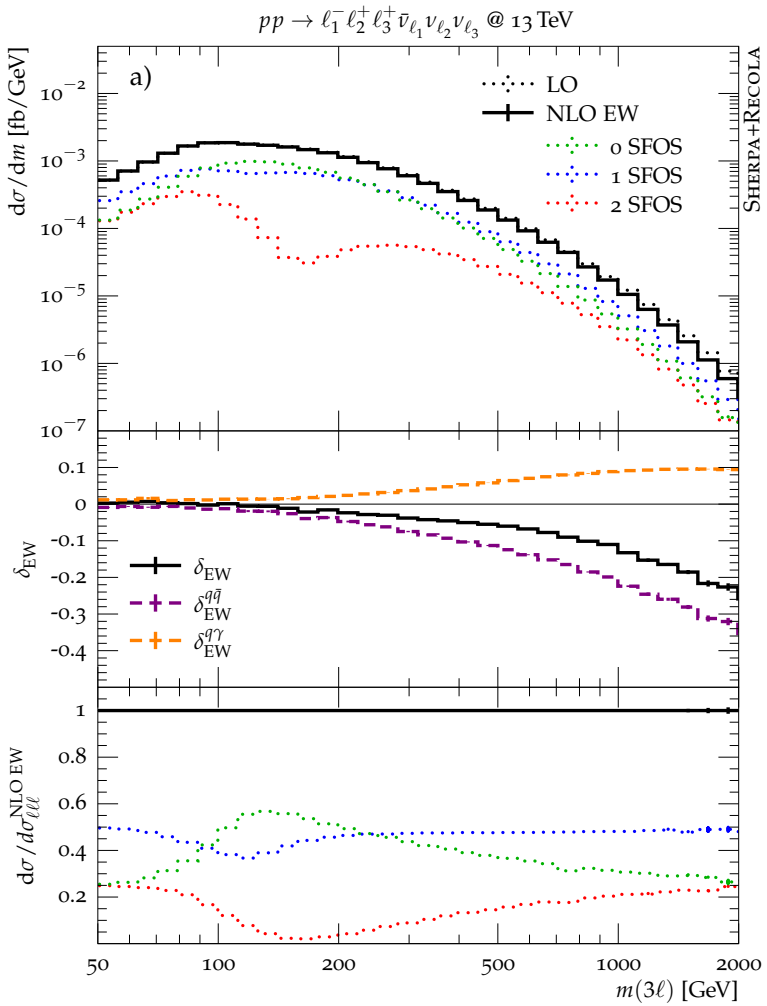
Triboson

MS arXiv:1806.00307

- 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**



Approximate electroweak corrections for high p_{T} physics

- 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

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

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
  $\rightarrow$ validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ (on δ_{EW}) for observables not driven by real radiation

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