

# SHERPA: overview and recent developments

Marek Schönherr

Universität Zürich

QCD@LHC 23 Aug 2016



Universität  
Zürich<sup>UZH</sup>

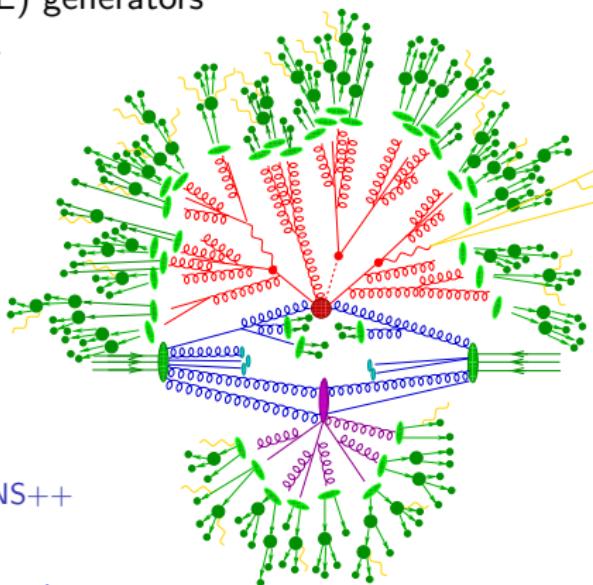


FONDS NATIONAL SUISSE  
SCHWEIZERISCHER NATIONALFONDS  
FONDO NAZIONALE SVIZZERO  
SWISS NATIONAL SCIENCE FOUNDATION

# 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  
`CSSHOWE` [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  $\tau$  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, MEps, MENLoPs, MEps@NLO

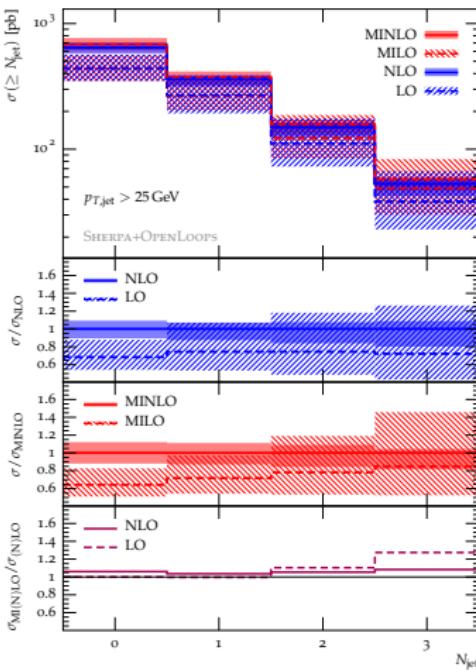
## SHERPA-2.2.1

- SHERPA-2.2.1 released Jul '16
- contains bugfixes for all known bugs of SHERPA-2.2.0
- UFO support for BSM physics
- new parton shower DIRE in addition to CSSOWER
- on-the-fly scale and PDF variations for ME part in
  - LO, NLO
  - LoPs, NLoPs (S-MC@NLO)
  - MEPs, MENLoPs, MEPs@NLO
- use named weights in HEPMC (av. since HEPMC-2.06)
- full scale & PDF variations including parton shower and for NNLO/NNLoPs in SHERPA-2.3.0
- allow to force HEPMC event record into pure tree structure, lost information available through disconnected vertices
- new default PDF: NNPDF30\_nnlo\_as\_0118 → new tune

# NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

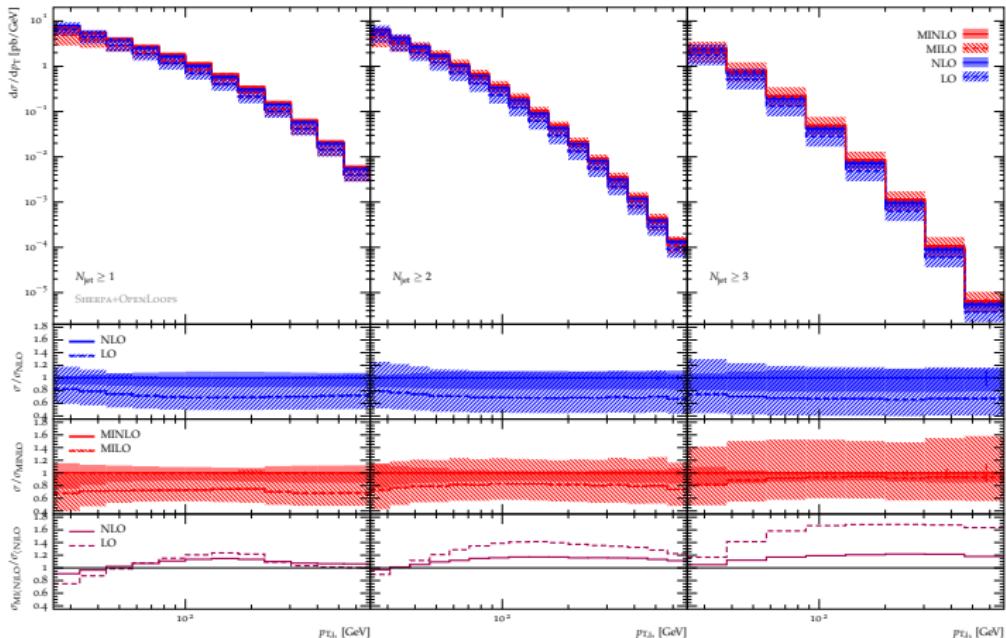
Höche, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1607.06934

- First computation of  $t\bar{t}+3$  jets at NLO / MiNLO accuracy
- Sherpa NLO MC framework using Comix Gleisberg, Höche arXiv:0808.3674 combined with OpenLoops Cascioli, Maierhöfer, Pozzorini arXiv:1111.5206
- Public results in NTuple format à la BlackHat collaboration arXiv:1310.7439 for easy analysis & recycling available at NERSC (login req'd)
- Scale dependence studied using  $H_{T,m} = \sum m_\perp$  and MiNLO Hamilton, Nason, Zanderighi arXiv:1206.3572 extended to massive partons



# NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

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



- Inclusive jet- $p_T$  spectra

# Parton showers – DIRE

Höche, Prestel EPJC75(2015)461

- combination of parton and dipole shower picture  
→ partial fractioning soft eikonal      Catani,Seymour Nucl.Phys.B485(1997)291

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j} \frac{p_i p_k}{(p_i + p_k)p_j} + \frac{1}{p_k p_j} \frac{p_i p_k}{(p_i + p_k)p_j}$$

- capture dominant coherence effects (3-parton correlations)

$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2 + \kappa^2} \quad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

- preserve collinear anomalous dimensions & sum rules  
→ splitting functions fixed

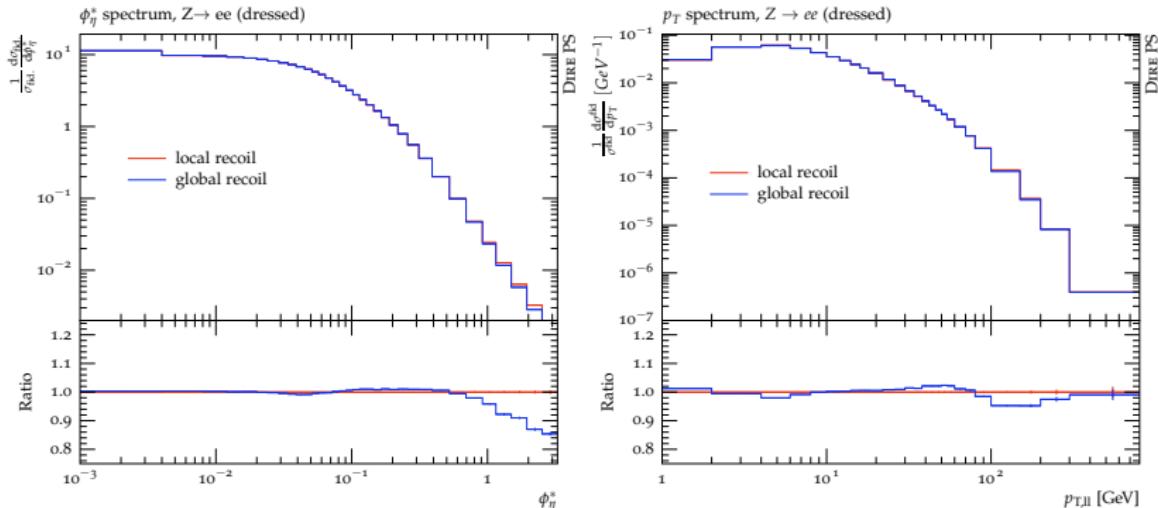
$$P_{qq}(z, \kappa^2) = 2 C_F \left[ \left( \frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ - \frac{1+z}{2} \right] + \gamma_q \delta(1-z)$$

$$P_{gg}(z, \kappa^2) = 2 C_A \left[ \left( \frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ + \frac{z}{z^2 + \kappa^2} - 2 + z(1-z) \right] + \gamma_g \delta(1-z)$$

$$P_{qg}(z, \kappa^2) = 2 C_F \left[ \frac{z}{z^2 + \kappa^2} - \frac{2-z}{2} \right] \quad P_{gq}(z, \kappa^2) = T_R \left[ z^2 + (1-z)^2 \right]$$

# Parton showers – DIRE

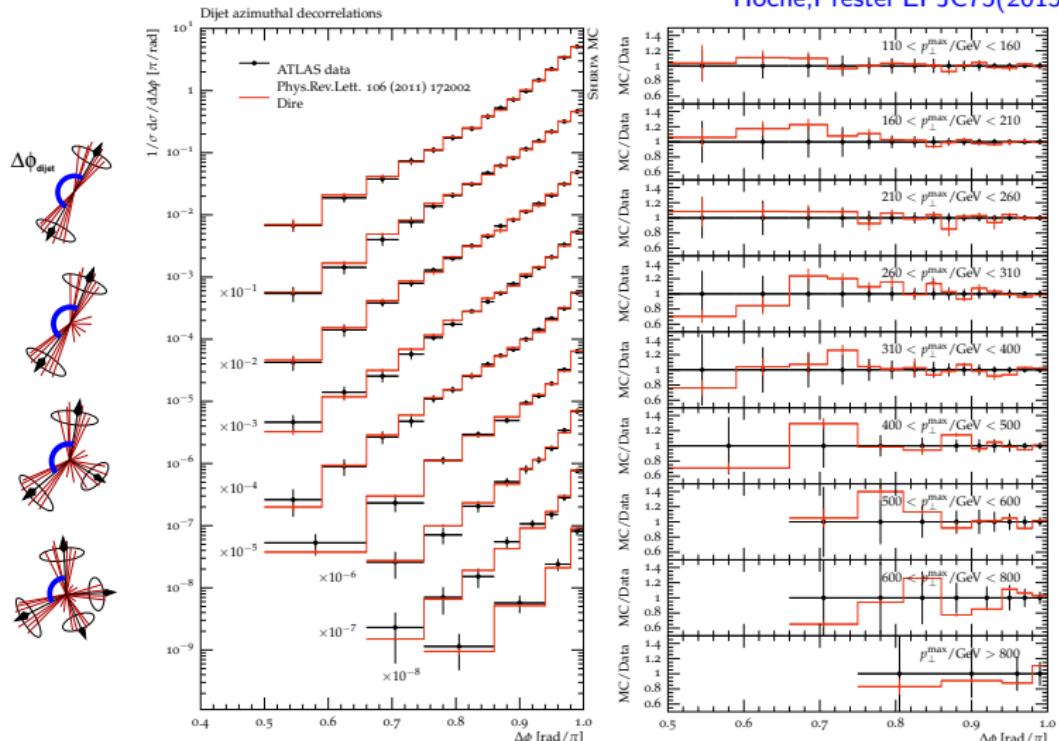
Höche,Prestel EPJC75(2015)461



- Two mapping schemes for IF dipoles
  - local [Catani,Seymour Nucl.Phys.B485\(1997\)291](#)
  - global [Plätzer,Gieseke JHEP01\(2011\)024](#), [Höche,Schumann,Sieger PRD81\(2010\)034026](#)
- Negligible impact on  $q_T$ -spectrum in low- $q_T$  range  
(spectrum dominated by singlet evolution at LHC energies)

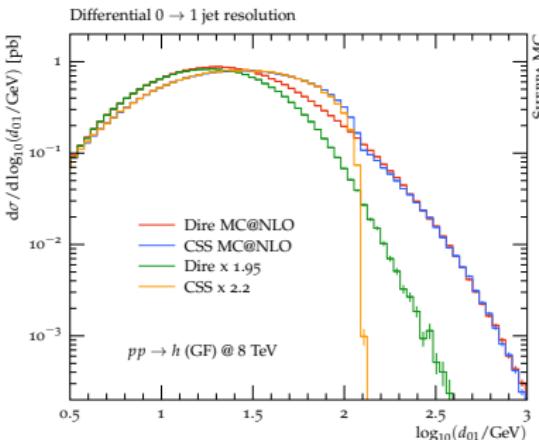
# Parton showers – DIRE

Höche,Prestel EPJC75(2015)461



# Parton showers – DIRE

- New shower kernels can be used as modified CS subtraction
- Sherpa S-Mc@NLO based on exponentiation of CS dipole subtraction terms  
 Höche,Krauss,Sieger,MS  
[JHEP09\(2012\)049](#), [PRD86\(2012\)094042](#)
- Dire modified CS subtraction automatically available for S-Mc@NLO matching
- Interesting differences due to evolution variables and kernels



# Higgs physics |

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

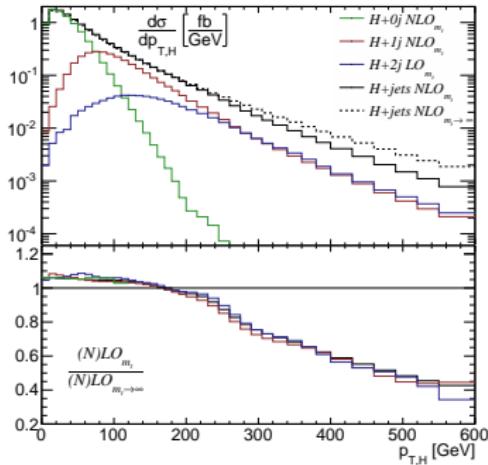
$pp \rightarrow H + \text{jets}$  production (ggF)

- 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

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

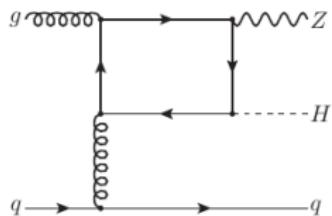


# Higgs physics II

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

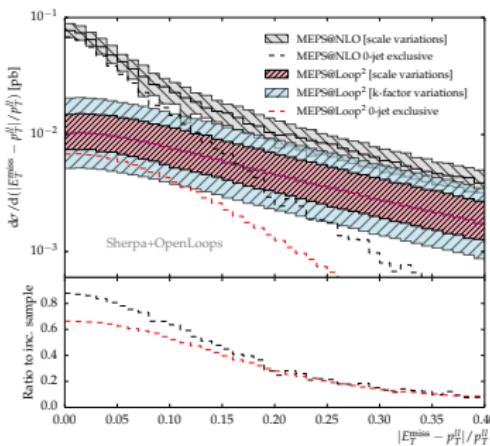
$pp \rightarrow Z H + \text{jets}$  production

- MEPS@NLO for  $q\bar{q}$
- MEPS@LOOP<sup>2</sup> for  $gg$
- care for  $qg \rightarrow ZHq$ :



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

- loops from OPENLOOPSS



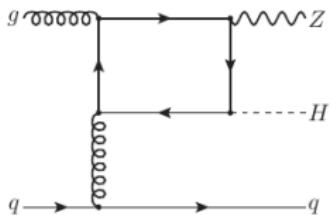
$pp \rightarrow Z[\rightarrow \ell\ell]H[\rightarrow \text{inv}] + \text{jets}$

Higgs physics II

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

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

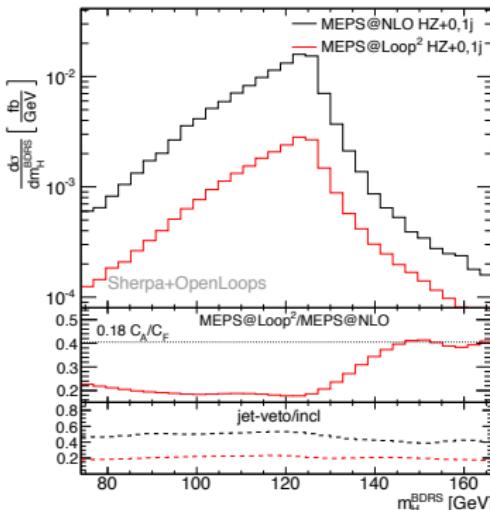
- MEPS@NLO for  $q\bar{q}$   
MEPS@LOOP<sup>2</sup> for  $gg$
  - care for  $qg \rightarrow ZHq$ :



→ part of NLO  $ZHj$

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

- loops from OPENLOOPS



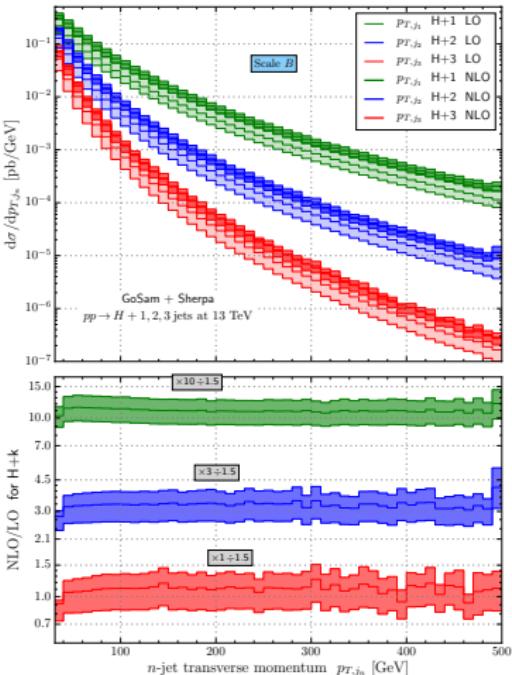
$$pp \rightarrow Z[\rightarrow \ell\ell] H[\rightarrow b\bar{b}] + \text{jets}$$

# Higgs physics III

Greiner,Höche,

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

- public NTuples for h1j, h2j, h3j @ NLO  
→ fixed-order analysis  
GoSAM interfaced for virtuals
- MEPS@NLO preliminary  
 $pp \rightarrow h + 0, 1, 2, 3j$  @ NLO,  
 $4, 5j$  @ LO  
produced for Les Houches '15  
detailed comparison

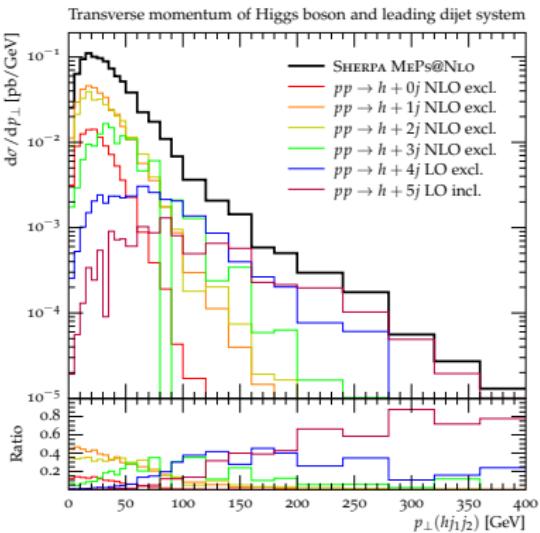


# Higgs physics III

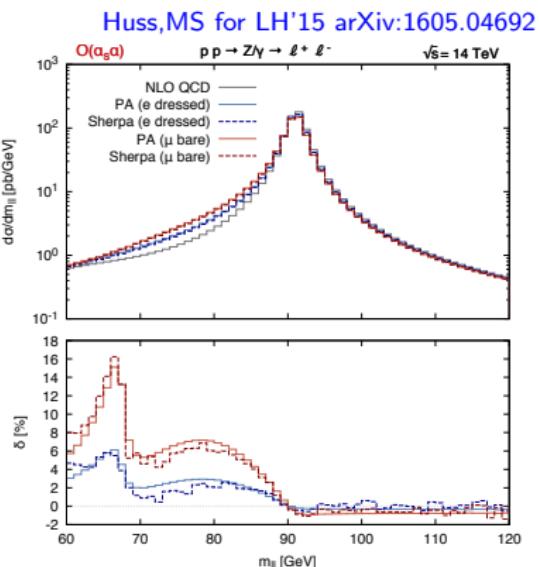
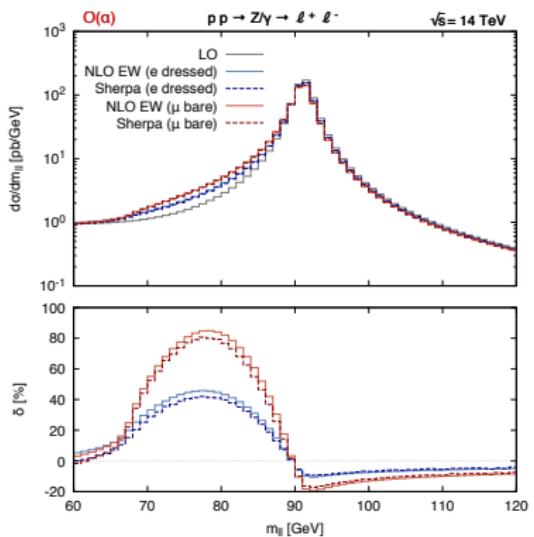
Greiner,Höche,Luisoni,MS,Winter,Yundin JHEP01(2016)169

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

- public NTuples for  $h1j, h2j, h3j$  @ NLO  
→ fixed-order analysis  
GoSAM interfaced for virtuals
- MEPS@NLO preliminary  
 $pp \rightarrow h + 0, 1, 2, 3j$  @ NLO,  
 $4, 5j$  @ LO  
produced for Les Houches '15  
detailed comparison



# YFS – comparison against dedicated calculations



- compare against pole approximation NNLO  $\mathcal{O}(\alpha_s\alpha)$   
Dittmaier,Huss,Schwinn Nucl.Phys.B904(2016)216
- very good reproduction of  $\mathcal{O}(\alpha)$  and  $\mathcal{O}(\alpha_s\alpha)$
- major differences traced to multi-photon emissions in YFS

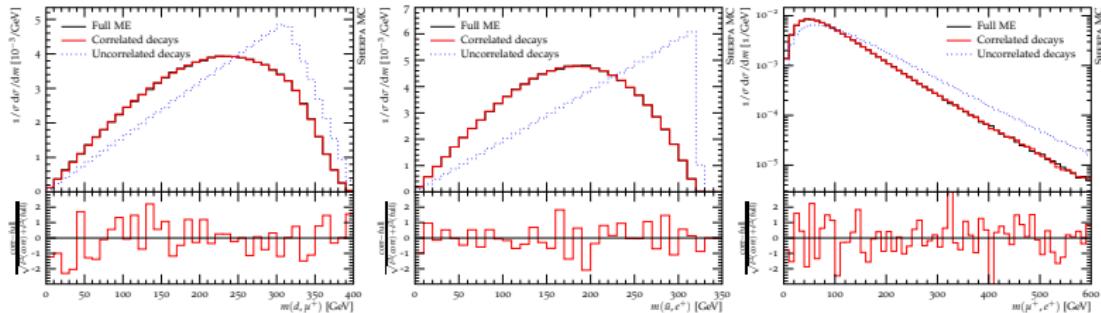
# BSM physics

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

- full support for UFO model [Degrande et.al. CPC183\(2012\)1201](#)
- Lorentz structures automatically built,  
colour structures mapped on SM/MSSM-like
- 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](#)

# BSM physics

Höche,Kuttmalai,Schumann,Siegrist EPJC75(2015)3,135



- simple three-step example:  

$$pp \rightarrow \tilde{u}[\rightarrow d\chi_1^+[\rightarrow \chi_1^0 W^+[\rightarrow \mu^+ \nu_\mu]]] \tilde{u}^*[\rightarrow \bar{u}\chi_2^0[\rightarrow e^+ \tilde{e}^-[\rightarrow e^- \chi_1^0]]]$$
- use truncated showers for QCD radiation off intermediate particles
- QED correction for each decay in YFS soft-photon resummation

# Reweighting

## Parameters

**parametric** e.g.  $\alpha_s(m_Z)$ ,  $m_t$ , PDF

**perturbative** e.g. NLO, NLL, leading- $N_c \rightarrow \mu_R, \mu_F$

**algorithmic** e.g. evolution variable, recoil schemes, matching scheme

## Explicit variations

- can be done for any scale or PDF dependence
- functional form can be changed
- separate run (independent calculation) for every variation

## On-the-fly variations

Bothmann,MS,Schumann arXiv:1606.08753

- can be done for  $\mu_R, \mu_F, \alpha_s$  & PDF dependence of ME & PS
- functional form can currently not be changed
- full syntax, cf. Manual

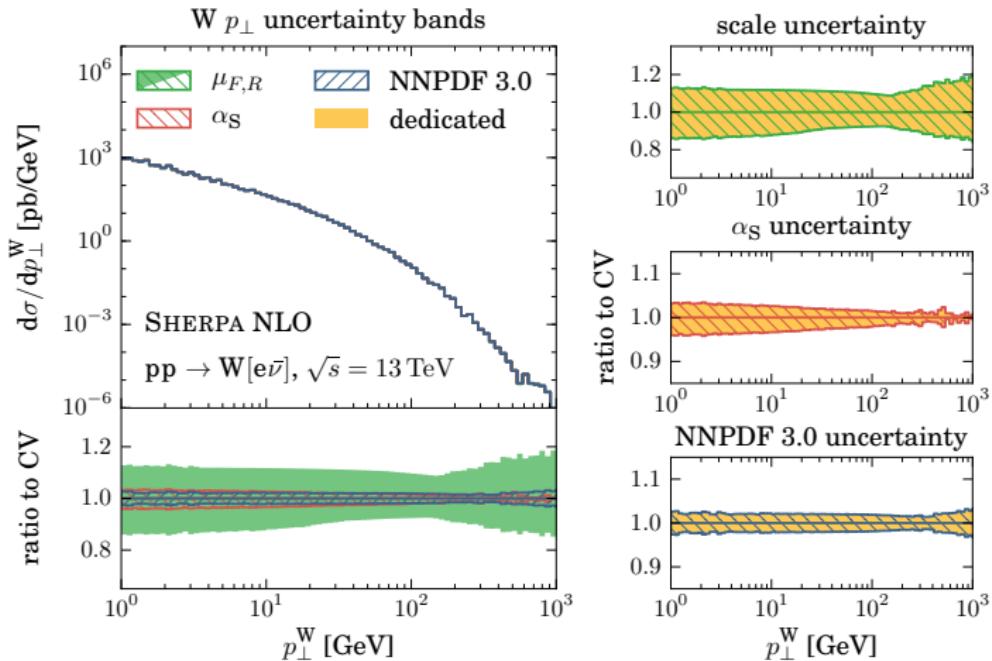
VARIATIONS 0.25,0.25 4.,4.

VARIATIONS NNPDF30\_nnlo\_as\_0118[all]

- store in HEPMC weight container using LH'13 naming convention

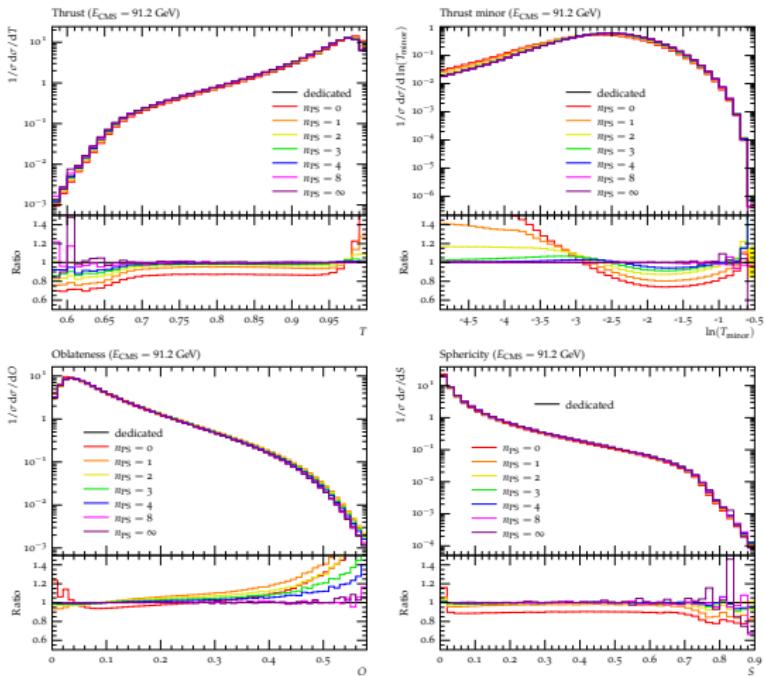
# Reweighting – closure test – NLO

Bothmann, MS, Schumann arXiv:1606.08753



# Reweighting – closure test – LoPs

Bothmann,MS,Schumann arXiv:1606.08753



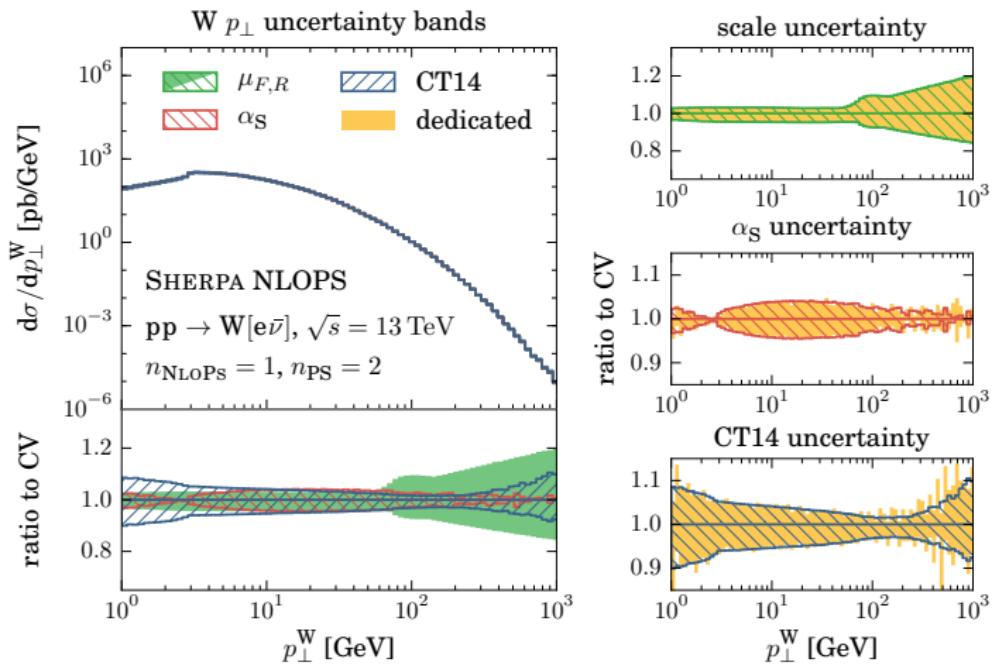
$e^+ e^- \rightarrow \text{hadrons}$

**closure test with  
 $n_{\text{PS}} = 0, 1, 2, 3, 4, 8, \infty$**

- $\alpha_s(m_Z) = 0.120$ 
  - ↓
  - $\tilde{\alpha}_s(m_Z) = 0.128$
- $n_{\text{PS}}$  needed obs. dependent

# Reweighting – closure test – NLOPs

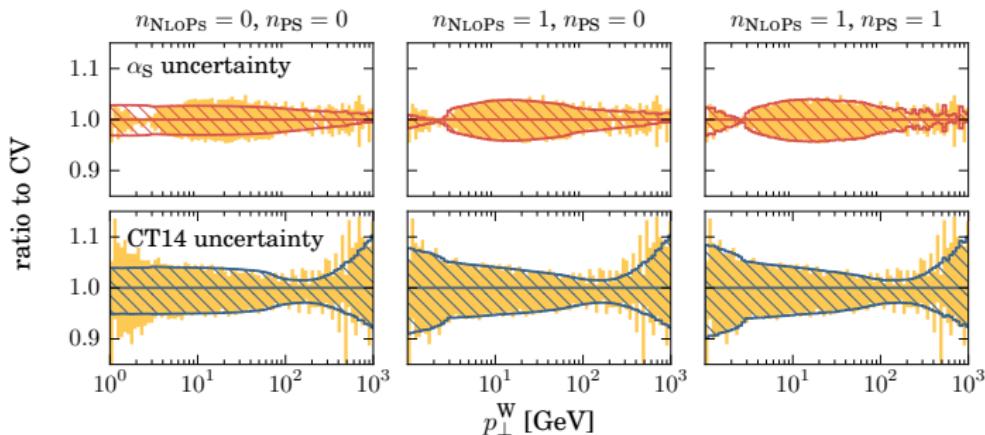
Bothmann,MS,Schumann arXiv:1606.08753



# Reweighting – closure test – NLOPs

Bothmann,MS,Schumann arXiv:1606.08753

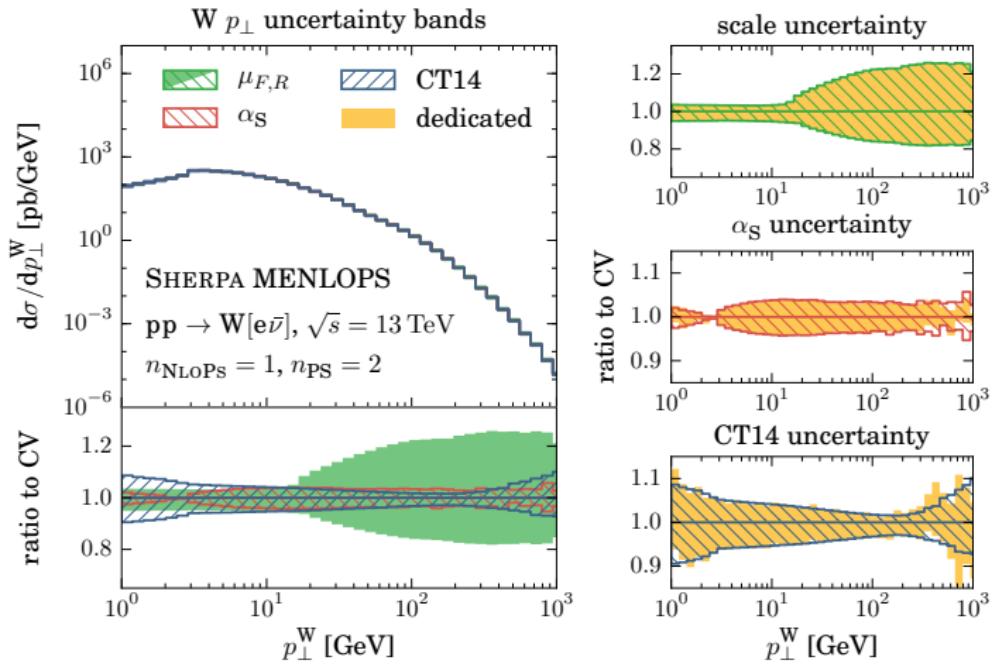
other maximum numbers of reweighted emissions  $n_{\text{NLOPs}}, n_{\text{PS}}$



→ reweighting two emission sufficient for this observable

# Reweighting – closure test – MEPS@NLO

Bothmann,MS,Schumann arXiv:1606.08753



# NLO EW corrections

Kallweit,Lindert,Maierhöfer,Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021

- fixed-order next-to-leading order electroweak corrections
- use one-loop matrix element from OPENLOOPS
- already studied a range of processes:
  - $pp \rightarrow V + 0, 1, 2(, 3)$  jets

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2015)012, JHEP04(2016)021

EW report arXiv:1606.02330

- $pp \rightarrow t\bar{t}h$
- $pp \rightarrow Zj / pp \rightarrow \gamma j$  ratio

Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704

LH'15 arXiv:1605.04692

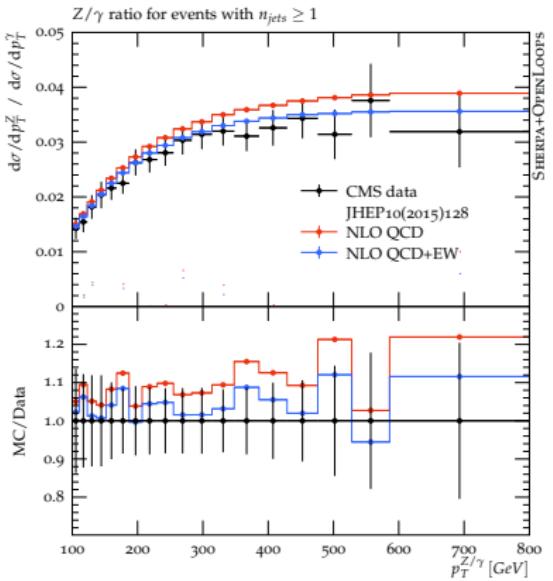
- $pp \rightarrow Vh$

FCC report, arXiv:1607.01831

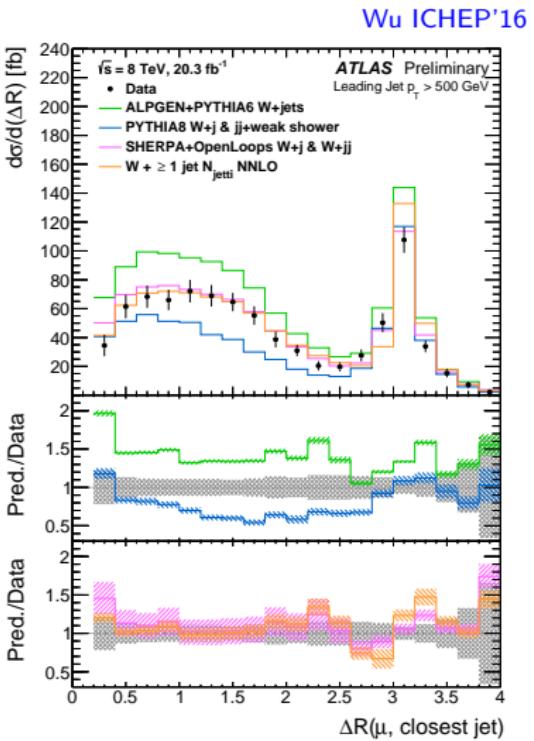
- dedicated comparisons in LH'15 against RECOLA ( $Z + 2j$ ) and MADGRAPH ( $tth$ ) showed agreement

# NLO EW corrections

LH'15 arXiv:1605.04692



important to describe  $Z/\gamma$  ratio



## Electroweak corrections in particle-level event generation

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

$$\bar{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

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

## Electroweak corrections in particle-level event generation

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

$$\bar{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

exact virtual contribution



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

## Electroweak corrections in particle-level event generation

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

$$\bar{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

exact virtual contribution      approximate integrated real contribution

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

# Electroweak corrections in particle-level event generation

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

optionally include subleading Born

$$\bar{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

exact virtual contribution      approximate integrated real contribution

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

# Electroweak corrections in particle-level event generation

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

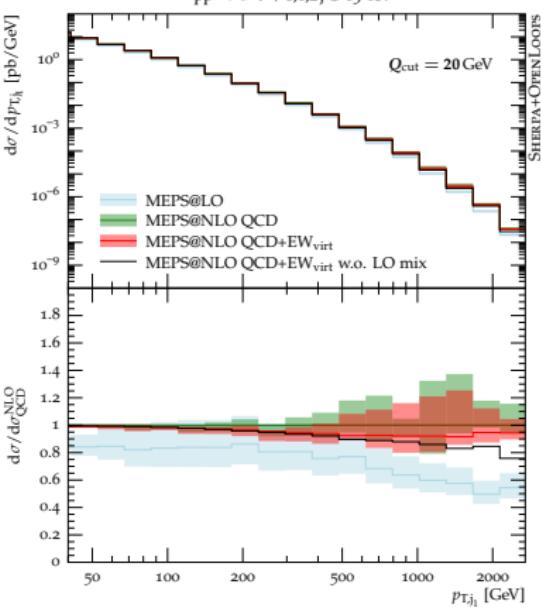
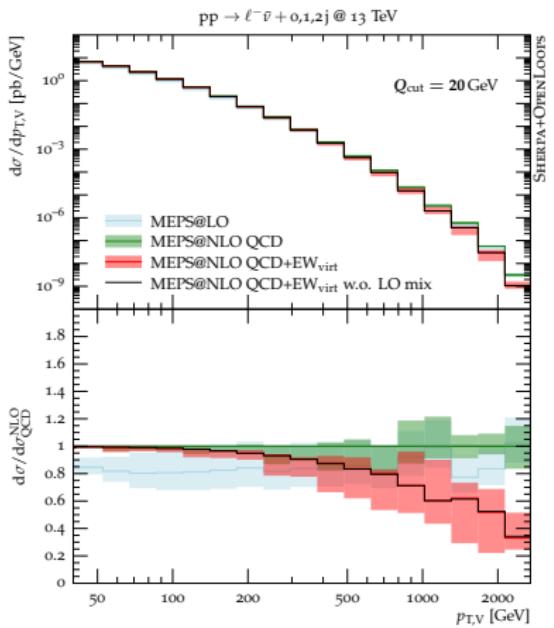
$$\bar{B}_{n,\text{QCD+EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

exact virtual contribution                              approximate integrated real contribution

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

# Results: $pp \rightarrow \ell^-\bar{\nu} + \text{jets}$

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



→ particle level events including dominant EW corrections

## SHERPA-2.2.1

- a new parton shower DIRE
- vastly extended support for UFO BSM format
- multijet merging for loop induced processes further tested, use as:
  - MEPS@LOOP<sup>2</sup>
  - reweight MEPS@NLO Higgs production in HEFT with top mass dependence (approximate in virtual corrections only)
- on-the-fly variations of  $\mu_R$ ,  $\mu_F$ ,  $\alpha_s$  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
- **coming in SHERPA-2.3.0:** PS reweighting, full NLO EW

<http://sherpa.hepforge.org>

Thank you for your attention!