

# Electroweak corrections in SHERPA

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THE  
ROYAL  
SOCIETY

# Electroweak corrections

Electroweak sector of the Standard Model is described by a broken  $SU(2)_L \times U(1)_Y$  gauge group resulting in  $U(1)_{\text{QED}}$  and massive weak gauge bosons ( $W^\pm, Z$ ).

## Precision physics, inclusive NLO EW corrections

Electroweak corrections are of  $\mathcal{O}(\alpha)$ , thus generally of  $\mathcal{O}(1\%)$ . Roughly, their size can be gauged by  $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$ .

## High momentum transfer physics, EW Sudakov corrections

Incomplete infrared cancellations due to broken structure of the EW gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces corrections which are negative and logarithmically growing with the size of the kinematic invariants, e.g.  $p_T$ . [EW Sudakovs](#). Thus,  $\mathcal{O}(20\%)$  corrections possible in the TeV range.

# Electroweak corrections

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## QED radiation, photon PDFs

Accelerated charges radiate. Every interaction that changes the momentum of a charged particle receives higher-order QED corrections.

Traditionally addressed through QED FSR, but leads also to photon PDFs.

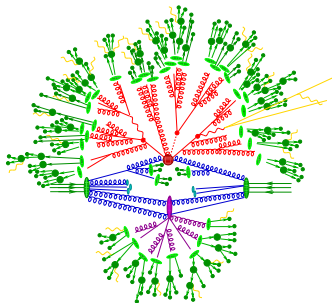
## Weak boson radiation, weak boson PDFs

Similarly, accelerated weak charges radiate weak bosons (at high enough energies). These splittings are suppressed by the boson mass and depend on the chirality of the emitting particle, e.g.  $u_L \rightarrow d_L W^-$  but no  $u_R \rightarrow d_R W^-$ .

# Electroweak corrections in SHERPA

## SHERPA-2.2.11

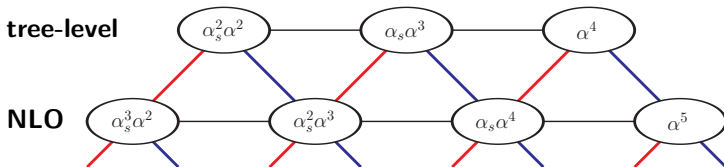
- two matrix element generators
- two parton showers
- soft-photon resummation
- multi-parton interactions
- hadronisation
- hadron decays



Type of correction	Availability in SHERPA-2.2.11 (event generation)
<b>inclusive NLO EW corrections</b>	(✓)
<b>EW Sudakov corrections</b>	✓
<b>QED FSR / QED PDFs</b>	✓ / ✓
<b>Weak boson radiation / PDFs</b>	(✓) / ✗

## Higher order corrections

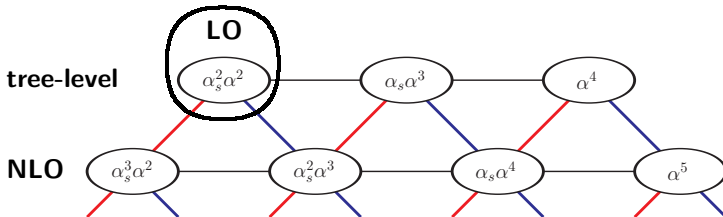
### Example: $Vjj$ production



- strictly defined only through order counting
- in principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
  - well known in QCD (quarks, gluons  $\leftrightarrow$  jets)
  - introduce similar concepts in EW sector for photons and leptons

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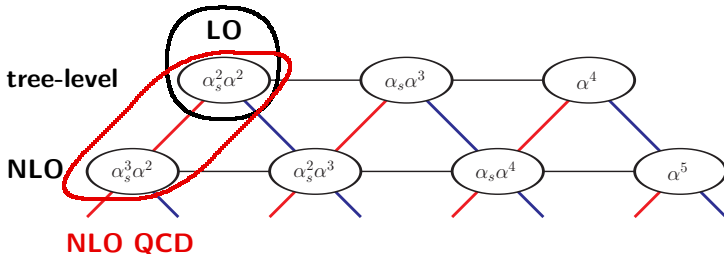
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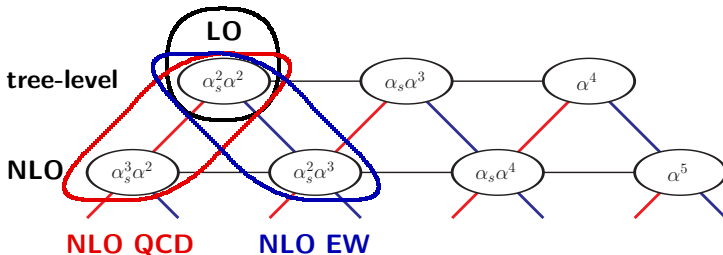
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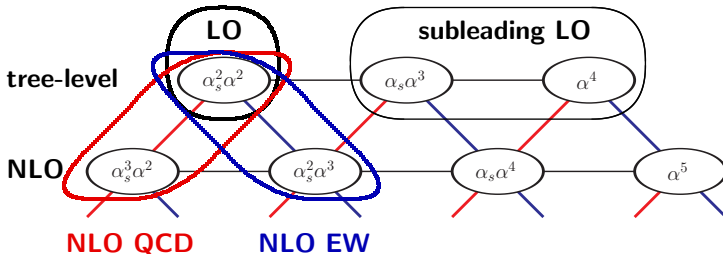
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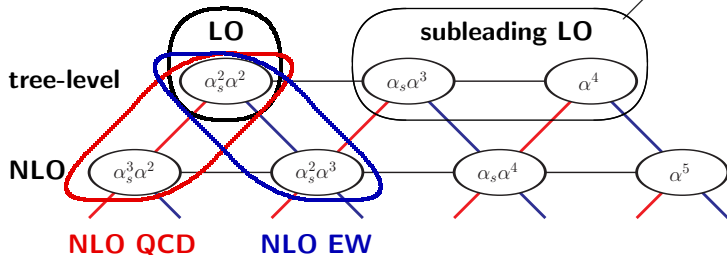
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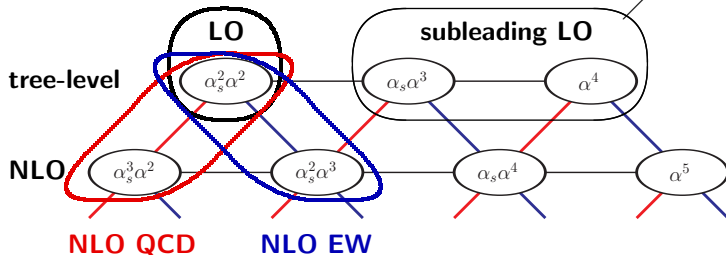
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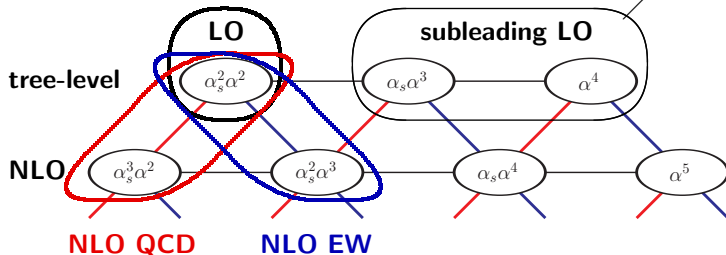
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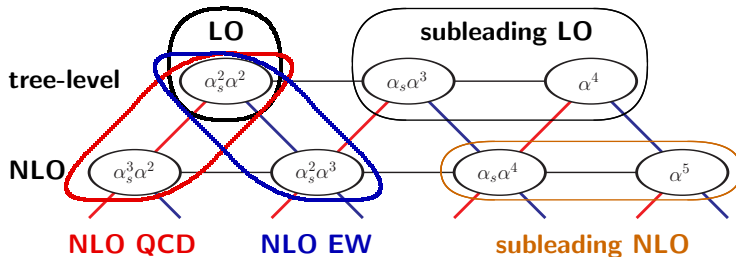
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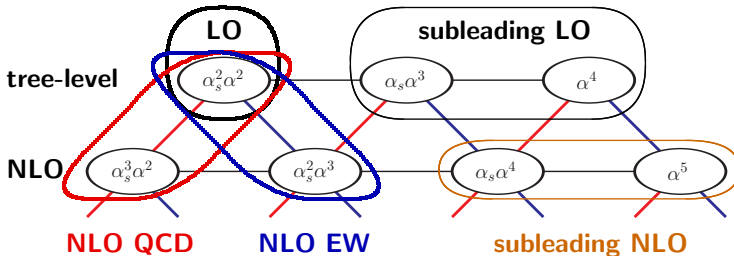
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# Definition of physical objects

## What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- **democratic:**
  - + straight forward, always well defined
  - many contributions
  - single photons constitute a jet
  - single leptons constitute a jet
- **anti-tagging jets with certain flavour content:**
  - + fewer contributions
  - needs a lot of care to be well-defined at all contributing orders
  - anti-tag jets with too large photon content
  - anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

# Definition of physical objects

## What is a photon?

- differentiate: short-distance photon (photon as parton),  
long-distance photon (identified, measurable photon)
- identify through fragmentation function

$$D_\gamma^z(z, \mu) = \frac{\alpha(0)}{\alpha_{\text{sd}}} \delta(1-z) + \mathcal{O}(\alpha^2)$$

⇒ leads to  $\alpha(0)$ -scheme for identified photons

## What is a lepton?

- simplified as leptons not gauge bosons
- dressed lepton: massless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

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# EW corrections

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

## Approximate EW corrections / EW<sub>virt</sub> approximation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- tailored to large- $p_T$  regions where EW corrections dominated by virtual  $W/Z$  exchange and RG running
- modify MC@NLO  $\bar{B}$ -function to include NLO EW virtual corrections

optionally include subleading Born

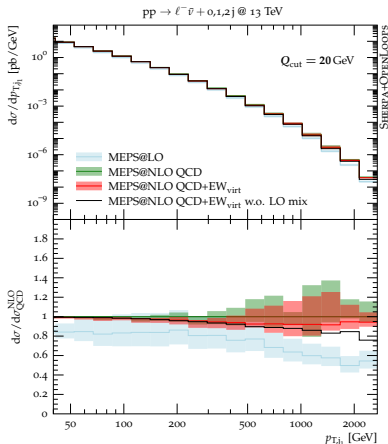
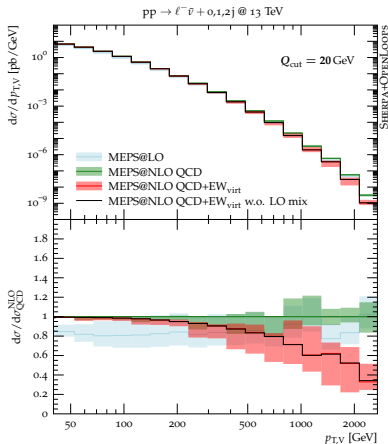
$$\bar{B}_{n,\text{QCD}+\text{EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{sub}}(\Phi_n)$$

exact virtual contribution

approximate integrated real contribution

- real QED radiation can be recovered through YFS resummation
- simple stand-in for proper QCD+EW matching and merging

# EW corrections



⇒ particle level events including dominant EW corrections

## EW corrections

- approx. EW corrections in  $EW_{\text{virt}}$  scheme available as alternative event weights (same as scale and PDF variations)
  - separately for EW, EW+subLO, EW+subLO+subLO2, ...
- calculated in three schemes
  - additive

$$\overline{B}_n^{\text{QCD+EW}} = \overline{B}_n^{\text{QCD}} + B_n \delta_{\text{EW}}^{\text{approx}} + B_n^{\text{sub}}$$

- multiplicative

$$\overline{B}_n^{\text{QCD} \times \text{EW}} = \overline{B}_n^{\text{QCD}} (1 + \delta_{\text{EW}}^{\text{approx}}) + B_n^{\text{sub}}$$

- exponentiated (caution: only Sudakov logs exponentiate, not complete  $EW_{\text{virt}}$ )

$$\overline{B}_n^{\text{QCD} \times \text{EW exp}} = \overline{B}_n^{\text{QCD}} \exp(\delta_{\text{EW}}^{\text{approx}}) + B_n^{\text{sub}}$$



**not the same as fixed-order multiplicative scheme**

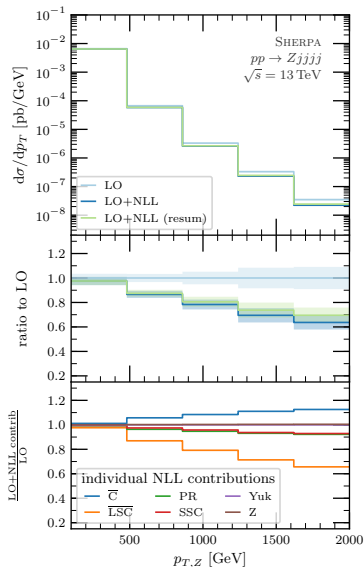


# EW corrections

## Upcoming in SHERPA-3.0.0

- fixed-order NLO EW  
[MS arXiv:1712.07975](#)
- EW Sudakov approximation for parton showered event generation

[Bothmann, Napoletano arXiv:2006.14635](#)



## EW clustering

In the interpretation of a  $Z + \text{jets}$  configuration allow for the possibility that this signature was produced by dijet configuration radiating a  $Z$  boson.

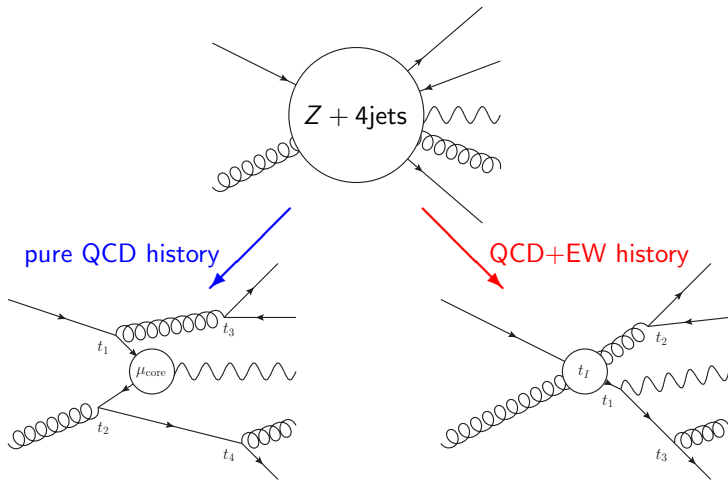
- identify parton shower history to determine CKKW scales and calculate intermediate Sudakov factors

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^n \alpha_s(t_i)$$

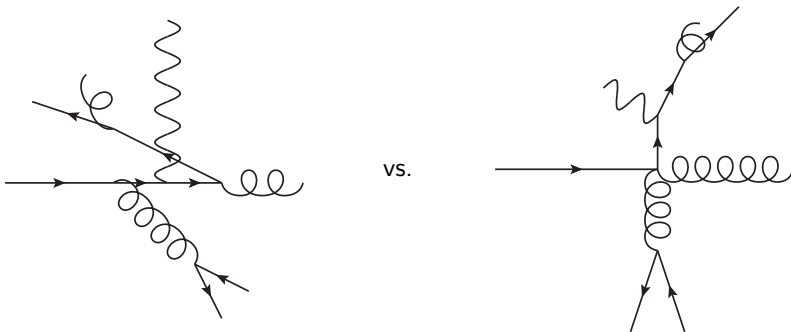
- identifying an EW splitting will “simply skip a step”,  $\alpha$  taken as constant (as in ME), no EW Sudakov applied
- use spin averaged EW splitting functions in  $E \gg m$  limit

**This affects scale choices, no higher-order EW corrs. introduced.**

# Multijet merging – identifying a history

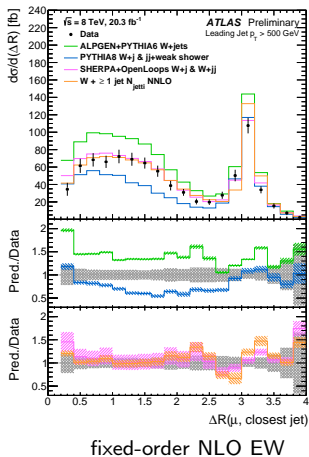
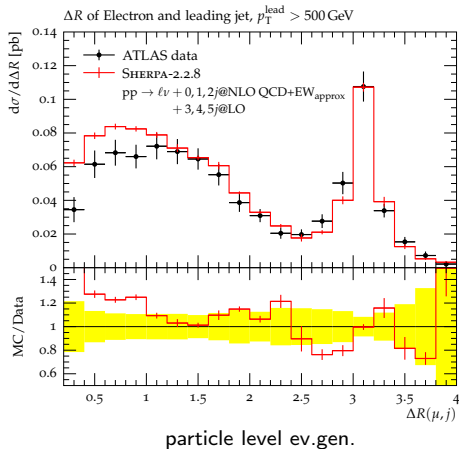


# QCD multijet merging – identifying a history



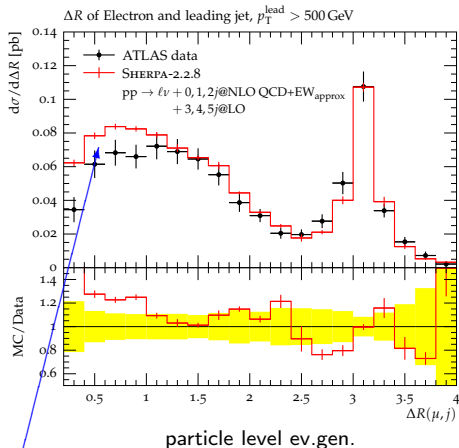
## EW clustering

ATLAS arXiv:1609.07045

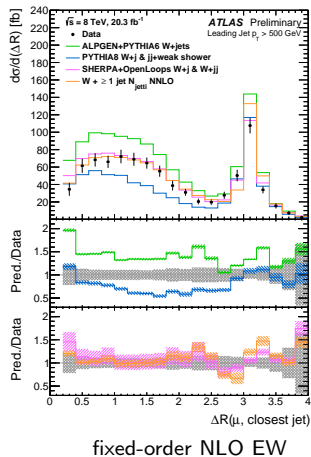


## EW clustering

ATLAS arXiv:1609.07045



improved in SHERPA-2.2.11 through improved handling of non-hierarchical histories



# Electroweak input schemes

- |   |               |   |                                      |
|---|---------------|---|--------------------------------------|
| 1 | $\alpha(0)$   | input $(\alpha(0), m_Z, \Gamma_Z, m_W, \Gamma_W)$ ,   | derived $(\sin \theta, vev)$         |
| 2 | $\alpha(m_Z)$ | input $(\alpha(m_Z), m_Z, \Gamma_Z, m_W, \Gamma_W)$ , | derived $(\sin \theta, vev)$         |
| 3 | $G_\mu$       | input $(G_F, m_Z, \Gamma_Z, m_W, \Gamma_W)$ ,         | derived $(\alpha, \sin \theta, vev)$ |

Dependence on EW input/renormalisation scheme equivalent to  $\mu_R$  dependence in QCD.

**Example:**  $pp \rightarrow 4\mu$

Gütschow, MS arXiv:2007.15360

$\mu^+ \mu^- \mu^+ \mu^-$	fiducial cross-section [fb]		
scheme	LO	NLO EW	$\delta_{EW}^{NLO}$
$G_\mu$	8.99	8.56	-4.78%
$\alpha(m_Z)$	8.11	8.33	+2.71%
rel. difference	10.85%	2.76%	

## Electroweak input schemes

**Historically** often used inconsistent EW input scheme, having both  $m_W$ ,  $m_Z$  and  $\sin \theta$  at their measured values.

Fine at LO EW, impossible if higher-order EW effects are to be included as they are related through  $\sin^2 \theta = 1 - \frac{m_W^2}{m_Z^2}$ .

$G_\mu$  and  $\alpha(m_Z)$  schemes have  $m_W$  &  $m_Z$  as input, but value of  $\sin \theta$  is off.

**New** input schemes with  $m_Z$  and  $\sin \theta$  implemented since SHERPA-2.2.10, as required for precision DY simulation.

21 input ( $G_F, m_Z, \Gamma_Z, \sin \theta$ ), derived ( $\alpha, m_W, \Gamma_W, \text{vev}$ )

22 input ( $\alpha(m_Z), m_Z, \Gamma_Z, \sin \theta$ ), derived ( $m_W, \Gamma_W, \text{vev}$ )

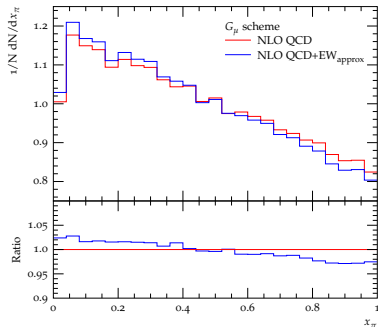
Schemes 21 and 22 also implemented by OPENLOOPS including appropriate renormalisation

[Chiesa, Piccinini, Vicini arXiv:1906.11569](#)

## Impact of EW parameters – $\tau$ polarisation

In a consistent setup, having  $\sin\theta$  as a dependent parameter may have unintended consequences, eg.  $\tau$  asymmetries, angular coefficients and spin correlations in  $Z \rightarrow \tau\tau$  events.

Problem not apparent when using Tool11 for ME, Tool12 for PS, Tool13 for  $\tau$  decays as EW parameters typically not synchronised.



Using scheme with  $\sin\theta$  as input fixes this issue.

## Conclusions

- SHERPA-2.2.11 state-of-the-art all-round sample including
  - NLO QCD multijet merging
  - approx. EW corrections tailored to TeV regime (no accuracy for incl. observables)
  - parton shower QCD resummation
  - YFS soft-photon resummation w/ NLO QED corrections
  - suitable EW input schemes for DY precision observables
- currently most higher-order EW corrections included targeted to TeV scale physics, with the exception of soft-photon resummation
- many other features: elastic photon-induced procs. in EPA, ...
- additional features in upcoming SHERPA-3.0.0

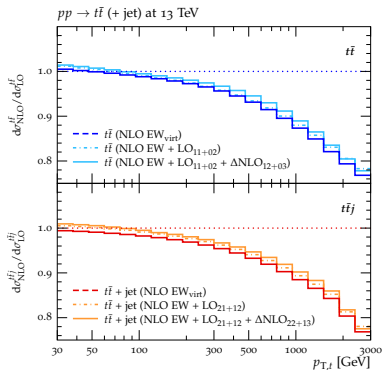
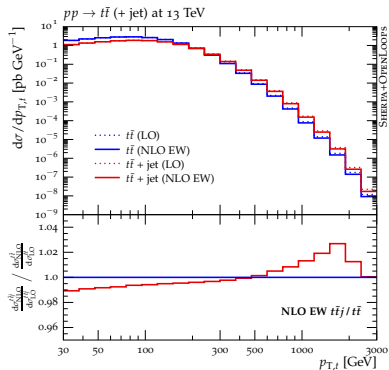
<https://sherpa-team.gitlab.io>

Thank you!

# Backup

# Top pair production in association with jets

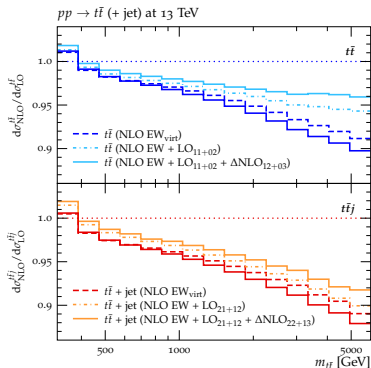
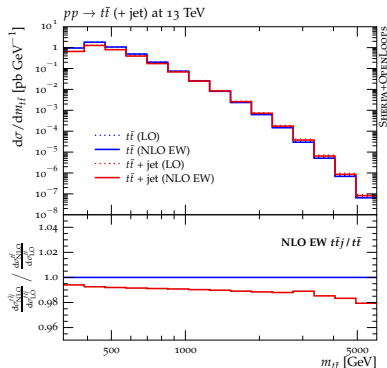
Gütschow, Lindert, MS in '18



Observation: NLO EW factorises from additional jet activity when rather inclusive on jet definition

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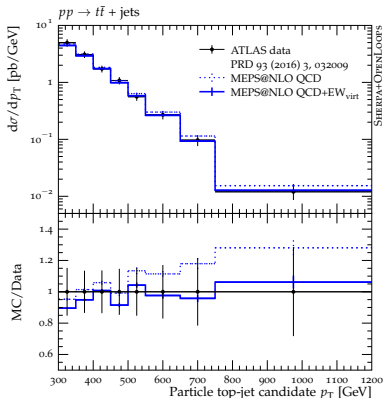
Gütschow, Lindert, MS in '18



Observation: subleading orders important

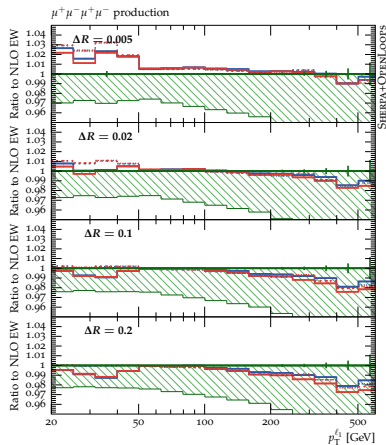
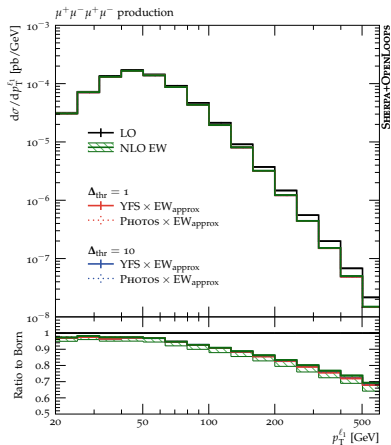
# Results: $pp \rightarrow t\bar{t} + \text{jets}$

Gütschow, Lindert, MS in '18



- $pp \rightarrow t\bar{t} + 0, 1j@NLO$   
+ 2, 3, 4j@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential  $K$ -factor  
Höhe, Krauss, MS, Siegert '10
- improved description of data

# EW virtual approximation in $4\ell$ production



# EW virtual approximation in $4\ell$ production

