

# Electroweak corrections for LHC physics

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## Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

Virtual electroweak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing with  $p_{\perp}$ .

Real electroweak corrections usually constitute a separate process. However, largest BR of  $W/Z$  bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

Beware of subleading orders.

# Outline

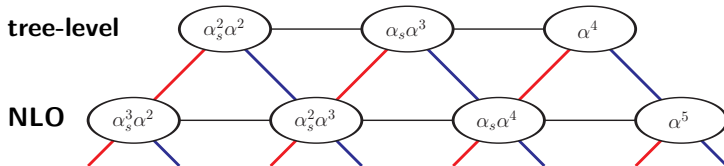
- 1 Next-to-leading order electroweak corrections
  - Setup, subtleties and automation
  - Selected results
- 2 Electroweak corrections in MCs
  - Approximate inclusion in NLO QCD multijet merging
  - Selected results
- 3 Real boson radiation
  - Resummation via EW parton showers
  - Case study: Finding  $W$  bosons inside jets
- 4 Conclusions

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# Higher order corrections

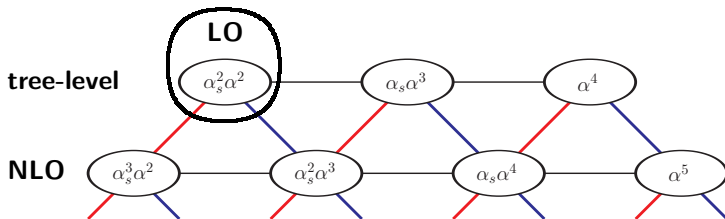
## Example: $Vjj$ production



- 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
- in general particle identification only through fragmentation fns., effective definitions for certain process classes exist

# Higher order corrections

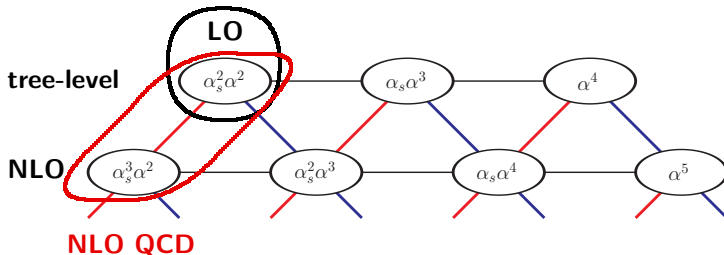
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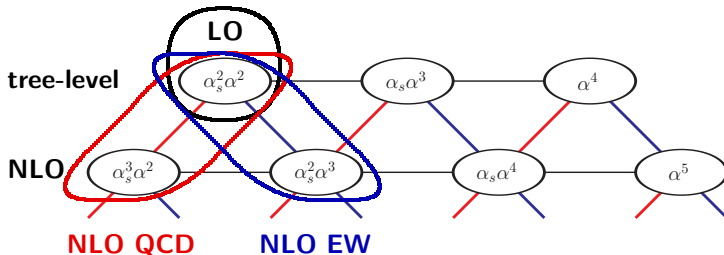
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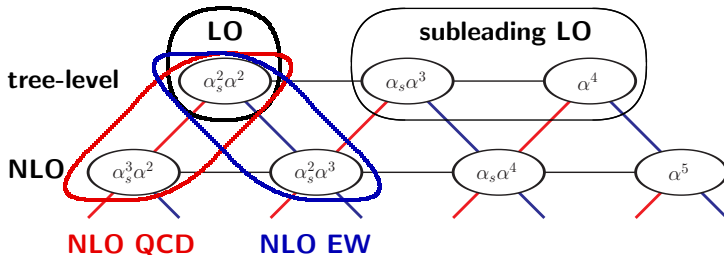
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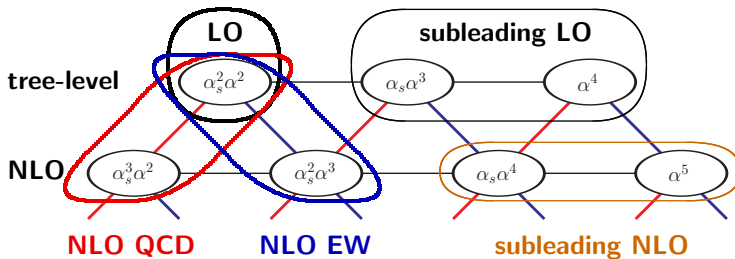
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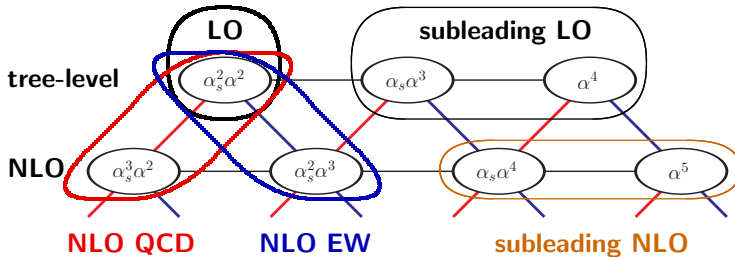
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# Automation

- ⇒ emergence of automated frameworks for NLO EW computations along the principles of NLO QCD automation
- Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
  - SHERPA [MS arXiv:1712.07975](#)
  - MADGRAPH [Frederix et.al. arXiv:1804.10017](#)
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GOSAM [Chiesa et.al. arXiv:1507.08579](#)
  - MADLOOP [Frixione et.al. arXiv:1407.0823](#)
  - OPENLOOPS [Kallweit et.al. arXiv:1412.5157](#)
  - RECOLA [Actis et.al. arXiv:1211.6316](#)
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

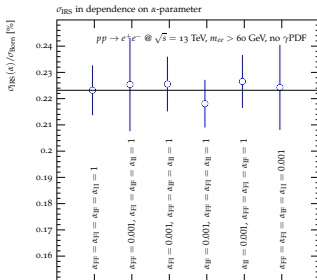
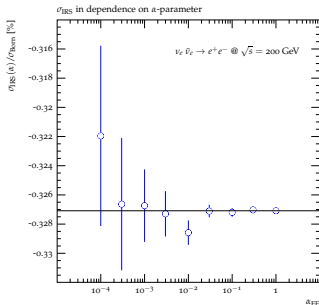


# NLO EW subtraction in SHERPA

MS arXiv:1712.07975

- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)  
Catani, Dittmaier, Seymour, Trocsanyi Nucl.Phys.B627(2002)189-265

- replacements:  $\alpha_s \rightarrow \alpha$ ,  $C_F \rightarrow Q_f^2$ ,  $C_A \rightarrow 0$ ,  
 $T_R \rightarrow N_{c,f} Q_f^2$ ,  $n_f T_R \rightarrow \sum_f N_{c,f} Q_f^2$ ,  
 $\frac{\mathbf{T}_{ij} \cdot \mathbf{T}_k}{\mathbf{T}_{ij}^2} \rightarrow \frac{Q_{ij} Q_k}{Q_{ij}^2}$



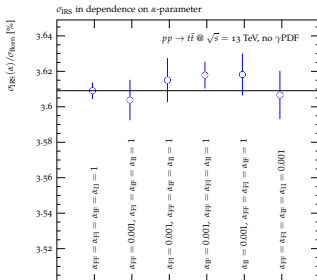
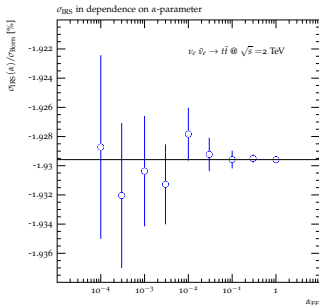


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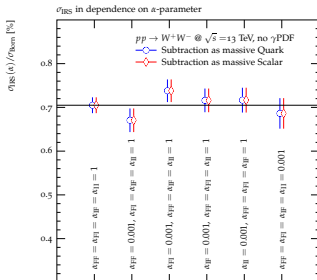
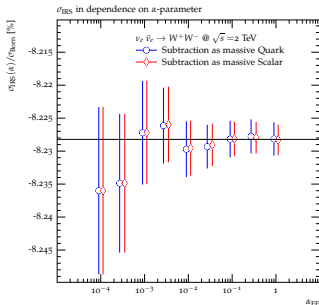


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## NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:

- $pp \rightarrow V + 0, 1, 2(, 3) \text{ jets}$  FCC report, EW report, LH'15  
Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1412.5157, arXiv:1511.08692
- $pp \rightarrow Zj/pp \rightarrow \gamma j$  ratio LH'15 arXiv:1605.04692  
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- $pp \rightarrow \gamma/\ell\ell/\ell\nu/\nu\nu + j$  Lindert et.al arXiv:1705.04664
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- SHERPA+GOSAM

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- $pp \rightarrow \gamma\gamma\gamma / \gamma\gamma\ell\nu / \gamma\gamma\ell\ell$  Greiner, MS arXiv:1710.11514
- $pp \rightarrow \gamma\gamma b\bar{b}$  Greiner, MS in prep.

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- $pp \rightarrow V + 0, 1, 2 j, pp \rightarrow 4\ell, pp \rightarrow t\bar{t}h$  Biedermann et.al. arXiv:1704.05783
- $pp \rightarrow 3\ell 3\nu$  MS arXiv:1806.00307



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## General setup

- work with dressed leptons with  $\Delta R_{\text{dress}} = 0.1$
- input parameters for the following calculations

$$\begin{aligned}
 G_\mu &= 1.16637 \times 10^{-5} \text{ GeV}^2 \\
 m_W &= 80.385 \text{ GeV} & \Gamma_W &= 2.0897 \text{ GeV} \\
 m_Z &= 91.1876 \text{ GeV} & \Gamma_Z &= 2.4955 \text{ GeV} \\
 m_h &= 125.0 \text{ GeV} & \Gamma_h &= 0.00407 \text{ GeV} \\
 m_t &= 173.2 \text{ GeV} & \Gamma_t &= 1.3394 \text{ GeV} .
 \end{aligned}$$

- EW parameter renormalisation in  $G_\mu$ -scheme
- photon induced processes considered where relevant



## Diboson production – $2\ell 2\nu$ – DF and SF

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

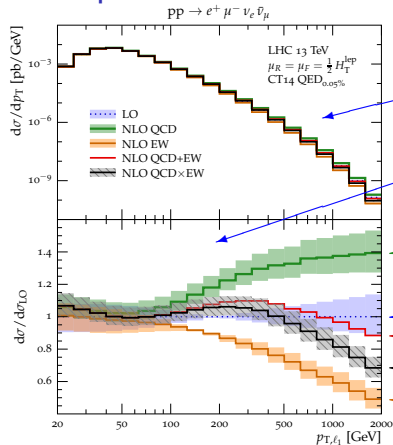
- study  $e^+ \mu^- \nu \bar{\nu}$  (DF) and  $e^+ e^- \nu \bar{\nu}$  (SF) production

DF	$e^+ \mu^- \nu_e \bar{\nu}_\mu$	$WW$
SF	$e^+ e^- \nu_e \bar{\nu}_e$	$WW + ZZ$
	$e^+ e^- \nu_{\mu/\tau} \bar{\nu}_{\mu/\tau}$	$ZZ$

- SHERPA for Born, real em., subtraction and phase space integration, MUNICH (MEs from OPENLOOPS) for subtraction and p. s. int.
- OPENLOOPS for virtual corrections using COLLIER for tensor integrals
- incl. event selection w/ standard lepton acceptance cuts,  $n_f = 4$  and mild jet veto to suppress large NLO QCD corr.



## Selected results

Diboson production –  $2\ell 2\nu$  – DF

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD $\times$ EW

NLO EW

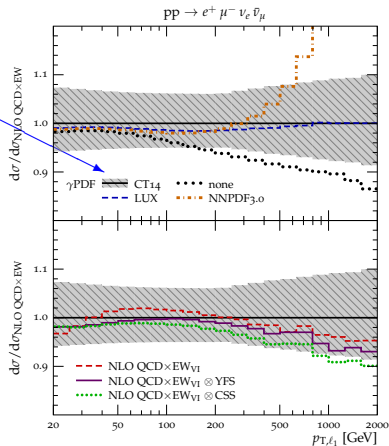
- large pos. NLO QCD, large neg. NLO EW  
 $\rightarrow$  NLO QCD+EW and NLO QCD $\otimes$ EW differ significantly

# Diboson production – $2\ell 2\nu$ – DF

relative importance of  $\gamma$ -induced channels wrt. NLO  $\text{QCD} \times \text{EW}$

CT14qed (baseline)  
LUXqed

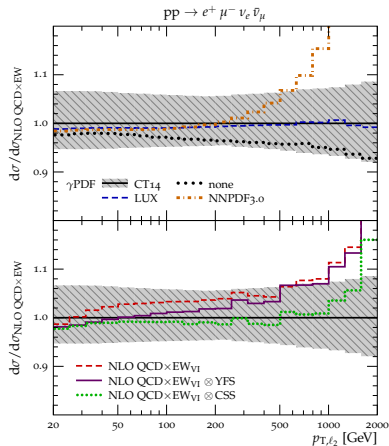
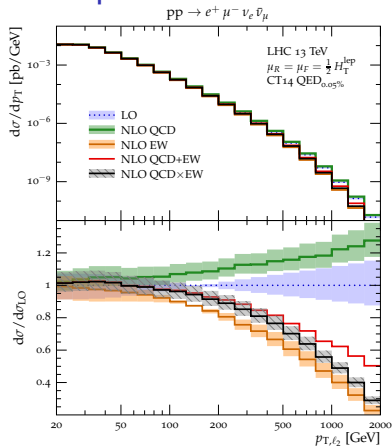
no  $\gamma$ PDF  
NNPDF3.0qed



- all  $\gamma$ PDF agree that  $\gamma$ -ind.  $> 10\%$  for  $p_T > 500$  GeV
- very good agreement between CT14qed and LUXqed



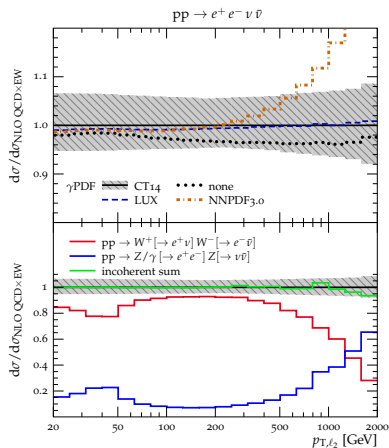
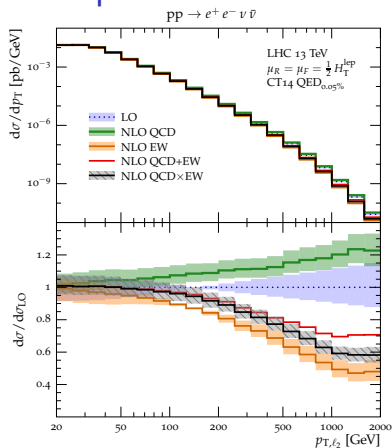
## Diboson production – $2\ell 2\nu$ – DF



- ZZ dominant at very large  $p_T$   
 → different EW corrections, take care when extrapolating

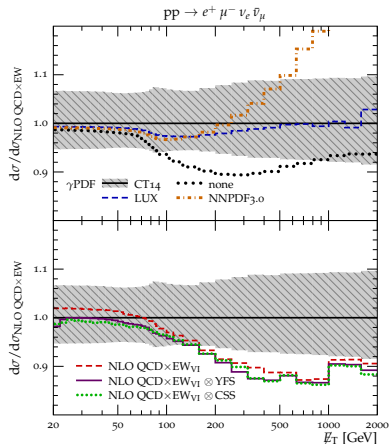
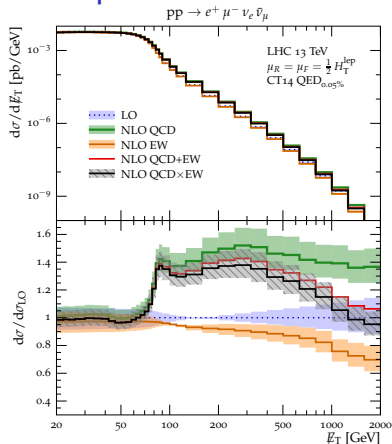


## Selected results

Diboson production –  $2\ell 2\nu$  – SF

- $ZZ$  dominant at very large  $p_T$   
 $\rightarrow$  different EW corrections, take care when extrapolating

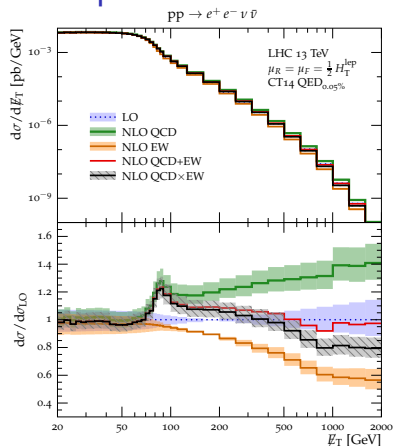
# Diboson production – $2\ell 2\nu$ – DF



- kinematic suppression for  $p_T^{\nu\nu}$  at LO, unlocked at NLO QCD  
not present in  $\gamma$ -induced  $\Rightarrow$  large contrib



## Selected results

Diboson production –  $2\ell 2\nu$  – SF

- kinematic suppression for  $p_T^{\nu\nu}$  for  $WW$ , but not  $ZZ$   
 $ZZ$  dominates for  $\text{MET} > 100$  GeV with large EW corr.

# Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

MS arXiv:1806.00307

- contributes from 0 SFOS ( $e^- \mu^+ \mu^+ \bar{\nu} \nu \nu$ ), 1 SFOS ( $e^- e^+ \mu^+ \bar{\nu} \nu \nu$ ) and 2 SFOS ( $e^- e^+ e^+ \bar{\nu} \nu \nu$ ) processes, and  $e \leftrightarrow \mu$

0 SFOS	$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	WWW	WZ [ $\rightarrow 2\ell 2\nu$ ]	Wh
1 SFOS	$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	WWW + WZZ	WZ [ $\rightarrow 2\ell 2\nu$ ]	Wh
	$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	WZZ	WZ [ $\rightarrow 2\ell 2\nu$ ]	Wh
	$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	WZZ	WZ [ $\rightarrow 2\ell 2\nu$ ]	Wh
2 SFOS	$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	WWW + WZZ	WZ [ $\rightarrow 2\ell 2\nu$ ]	Wh
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# NLO EW corrections in off-shell trilepton production

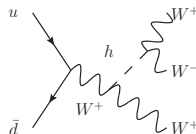
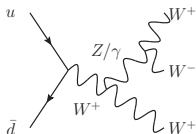
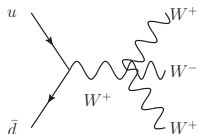
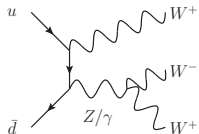
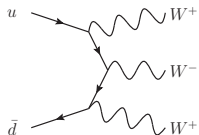
MS arXiv:1806.00307

Selection	Cut	Value	
general	$p_T(\ell)$	$[20 \text{ GeV}, \infty)$	lepton acceptance
	$y(\ell)$	$[-2.5, 2.5]$	
	$\Delta R(\ell, \ell)$	$[0.2, \infty)$	
$\cancel{p}_T > 20 \text{ GeV}$	$\Delta\phi(\cancel{p}_T, \ell\ell\ell)$	$[\frac{5}{6}\pi, \pi]$	jet veto
1, 2 SFOS	$\cancel{p}_T$	$[50 \text{ GeV}, \infty)$	WZ veto
	$m_{\ell\ell}^{\text{SFOS}}$	$[0, 70 \text{ GeV}] \wedge [100 \text{ GeV}, \infty)$	

- minimise  $t\bar{t}W$ ,  $tWW$ ,  $WZ$  backgrounds
- scale choice:  $\mu = \sum m_{T,i}^W$ ; ambiguous in all channels, EW corrections largely scale independent: choose  $\mu_R = \mu_F = 3 m_W$
- use NNPDF31\_nlo\_as\_0118\_luxqed for reliable  $\gamma$ PDF

# On-shell vs. off-shell triboson production

## On-shell production

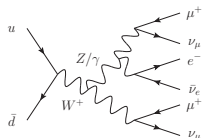
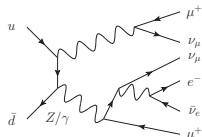
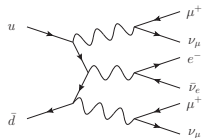


- only triple res. dgrms, threshold at  $3 m_W$
- strong interference between diagrams in which different numbers of gauge bosons couple to quark line
- some kinematic width effects recoverable through BW-shape improved spin-correlated decays
- NLO QCD+EW

Dittmaier, Huss, Knippen arXiv:1705.03722

# On-shell vs. off-shell triboson production

## Off-shell production

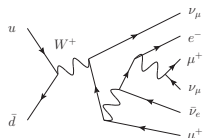
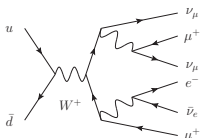


- triple, double and single res. diagrams, importance of single/double resonant topologies as in  $WW$

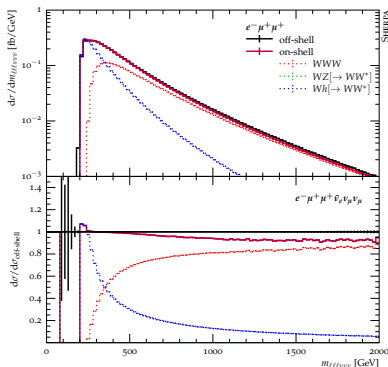
Biedermann et.al. [arXiv:1605.03419](https://arxiv.org/abs/1605.03419)

- includes on-shell  $WWW$  production,  $WZ$  production with  $Z \rightarrow 2\ell 2\nu$ ,  $Wh$  production with  $h \rightarrow WW^*/ZZ^*$
- thresholds given by acceptance cuts
- NLO QCD

Campanario et.al. [arXiv:0809.0790](https://arxiv.org/abs/0809.0790)



# On-shell vs. off-shell triboson production



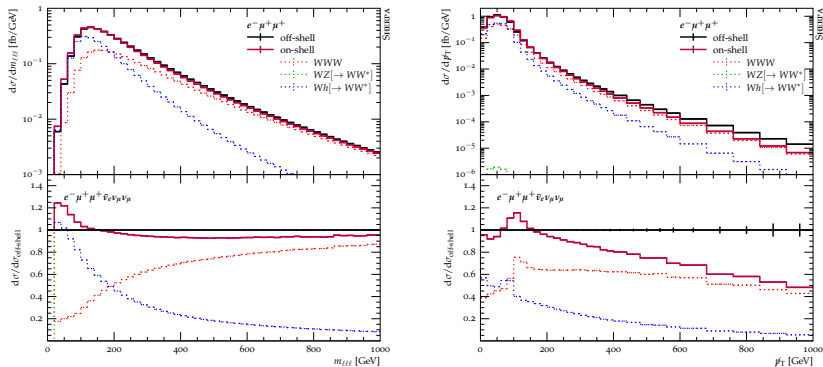
$$m_{ll\nu\nu} = m_{WWW}$$

- no unique  $W$  identification possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- on-shell  $WWW$  not dominating for incl. xsec
- large cross section from  $Wh$ ,  $WZ$  negligible
- at larger  $m_{WWW}$  contribs from double (single) resonant

→ cross checked with off-shell calculation projected on triple  $W$  resonant subset of diagrams

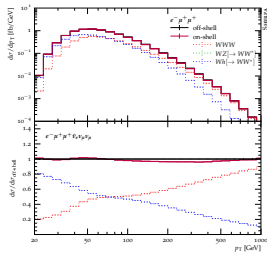


## On-shell vs. off-shell triboson production

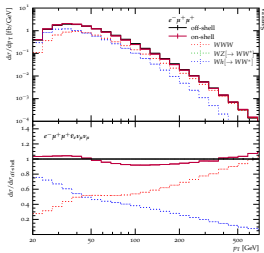


- on-shell approximation reasonable for  $m_{\ell\ell}$
- large single and double resonant contris for MET

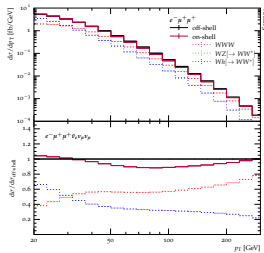
# On-shell vs. off-shell triboson production



1st lepton



2nd lepton



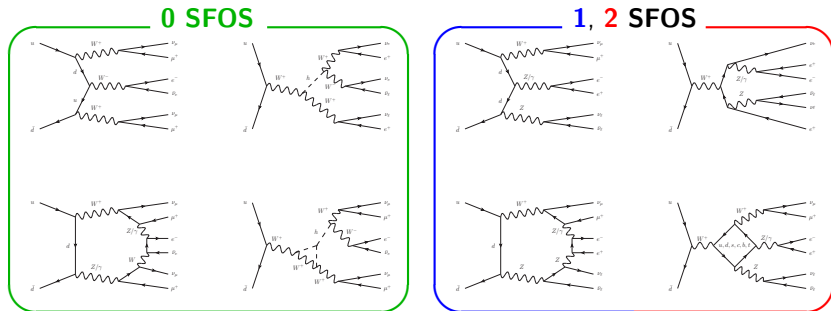
3rd lepton

- on-shell approximation reasonable for lepton  $p_T$
- moderate impact of double (single) resonant contris



# NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307



- at LO: triple and quartic gauge boson self-interactions
- at NLO EW: appearance of octagons, closed fermion loops, Higgs self-interactions, Yukawa couplings, etc
- genuine NLO EW  $2 \rightarrow 6$  calculation with 3 resonances



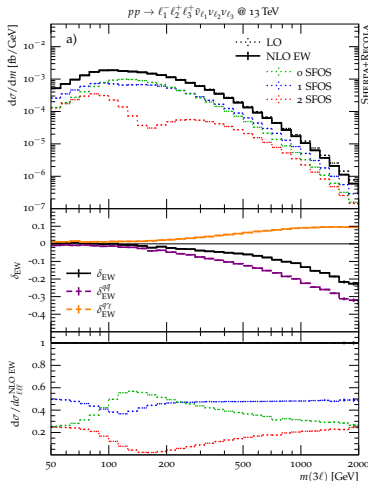
# Triboson production

MS arXiv:1806.00307

- off-shell  $W^+W^+W^-$  production
- includes 0, 1, 2 SFOS processes ( $WWW$  and  $WZZ$  structures)
- EW correction (incl.  $\gamma$ -induced) important
- accidental cancellations of EW corr. in  $q\bar{q}$  and  $q\gamma/\bar{q}\gamma$  channels

Dittmaier, Huss, Knippen  
arXiv:1705.03722

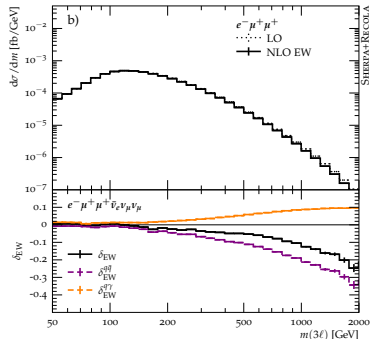
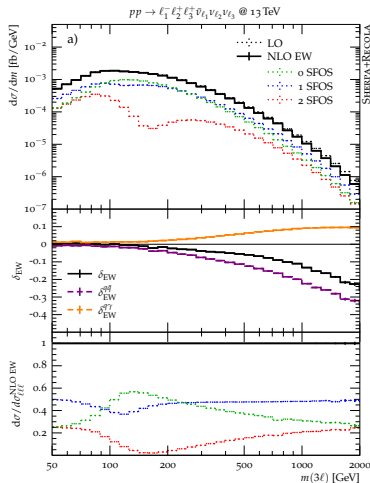
but highly obs. dependent





# Triboson production – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307

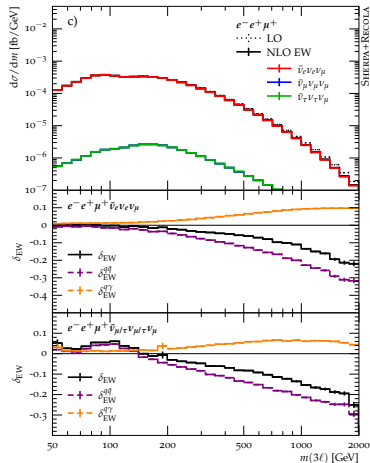
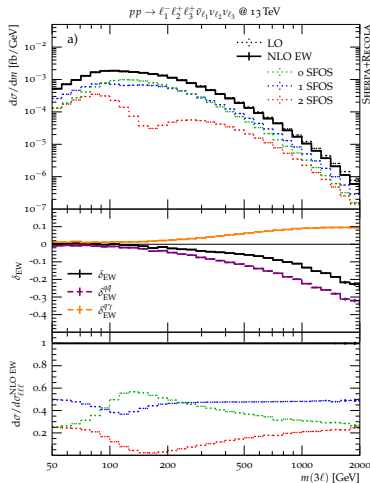




Selected results

# Triboson production – 0, 1, 2 SFOS decomposition

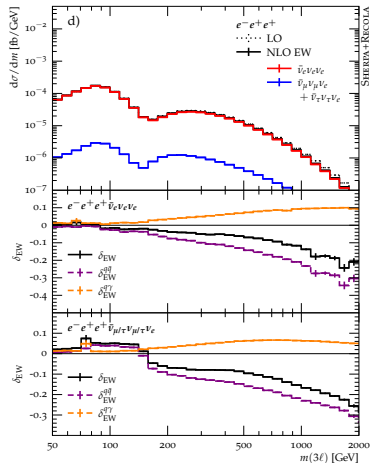
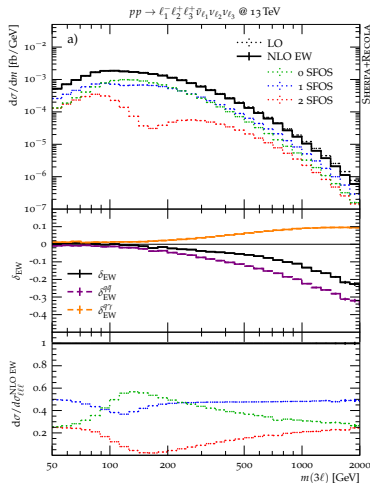
MS arXiv:1806.00307





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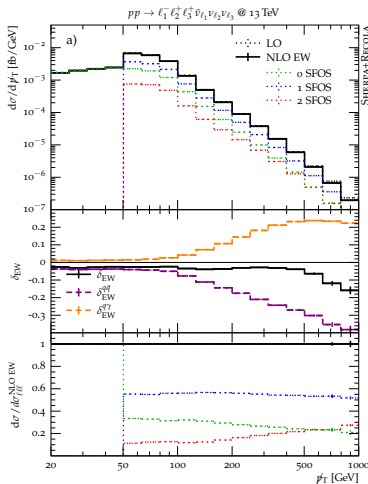
MS arXiv:1806.00307



# Triboson production

MS arXiv:1806.00307

- 1, 2 SFOS: req.  $p_T > 50$  GeV to suppress WZ background
- substantial  $\gamma$ -induced contributions
- accidental cancellations

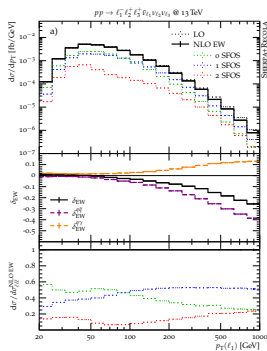




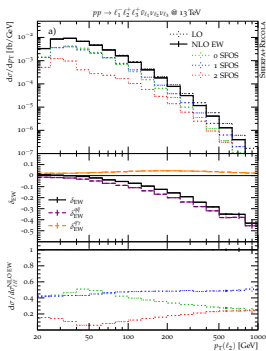
Selected results

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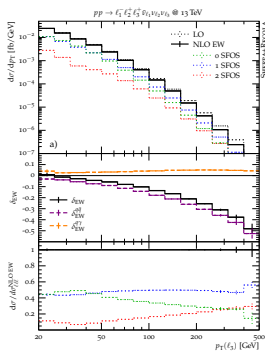
MS arXiv:1806.00307



1st lepton



2nd lepton



3rd lepton

# Electroweak corrections for LHC physics

- 1 Next-to-leading order electroweak corrections
  - Setup, subtleties and automation
  - Selected results
- 2 Electroweak corrections in MCs
  - Approximate inclusion in NLO QCD multijet merging
  - Selected results
- 3 Real boson radiation
  - Resummation via EW parton showers
  - Case study: Finding  $W$  bosons inside jets
- 4 Conclusions

## Electroweak corrections in particle-level event generation

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

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

- 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

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optionally include subleading Born

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exact virtual contribution

approximate integrated real contribution

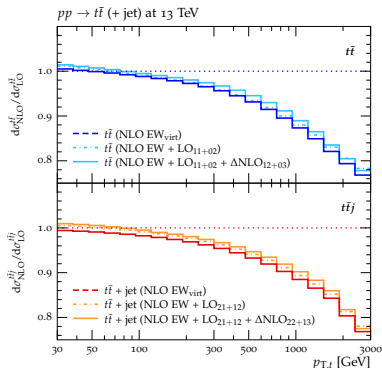
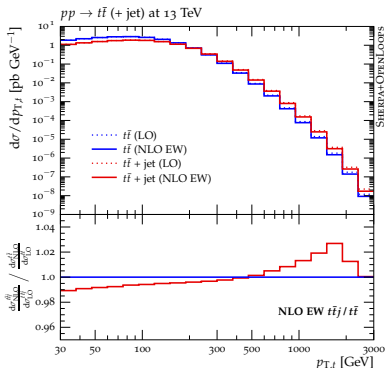
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## Selected results

## Top pair production in association with jets

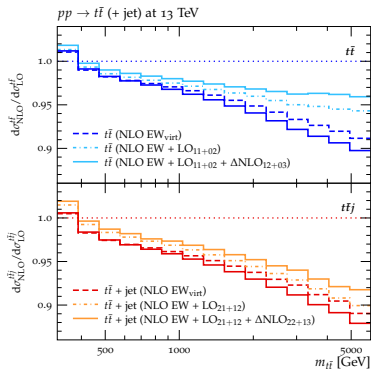
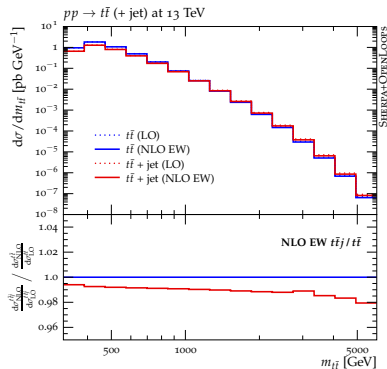
Gütschow, Lindert, MS in arXiv:1803.00950



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

# Top pair production in association with jets

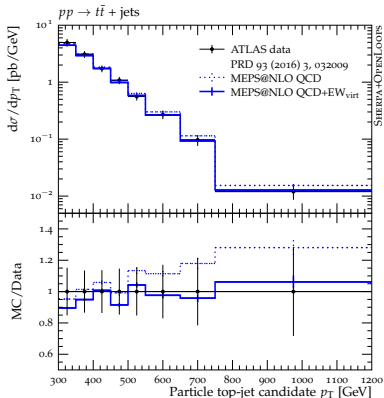
Gütschow, Lindert, MS in arXiv:1803.00950



Observation: subleading orders important



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



Gütschow, Lindert, MS in arXiv:1803.00950

- $pp \rightarrow t\bar{t} + 0, 1j@NLO$   
+ 2, 3, 4j@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential  $K$ -factor

Höche, Krauss, MS, Siegart  
arXiv:1009.1127

- improved description of data

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## Collinear limit with $E \gg m$

- QED parton showers well known and available in every major shower
- approximation to collinear (vector) boson emission in limit  $E \gg m$ , in dipole language (splitter-spectator pairs):  $f(s) \rightarrow f^{(\prime)}V(s)$

$$d\sigma_{n+V} = d\sigma_n \sum_f \sum_s^{n_{\text{spec}}} dt dz \frac{d\phi}{2\pi} \frac{1}{n_{\text{spec}}} J(t, z) \mathcal{K}_{f(s) \rightarrow f^{(\prime)}V(s)}(t, z)$$

- emitter fermion  $f$ , suitable spectator  $s$
- flavour change  $f \rightarrow f'$  in case of  $W$  emissions
- IS kernels contain ratio of PDFs (change in  $x, Q, \text{flavour}$ )
- similar ansatz with diff. kernels in [Christiansen, Sjöstrand JHEP04\(2014\)115](#)
- new developments [Chen, Han, Tweedie arXiv:1611.00788](#)  
[Bauer, Ferland, Webber JHEP08\(2017\)036](#)

# Splitting kernels

Denner, Hebenstreit unpublished

- use Denner-Hebenstreit expressions modified into CDST form

$$\mathcal{K}_{f(s) \rightarrow f' W(s)}(t, z) = \frac{\alpha}{2\pi t} \left[ f_W c_{\perp}^W \tilde{V}_{f(s) \rightarrow f' b(s)}^{\text{CDST}}(t, z) + f_h c_L^W \frac{1}{2} (1 - z) \right]$$

$$\mathcal{K}_{f(s) \rightarrow f Z(s)}(t, z) = \frac{\alpha}{2\pi t} \left[ f_Z c_{\perp}^Z \tilde{V}_{f(s) \rightarrow f b(s)}^{\text{CDST}}(t, z) + f_h c_L^Z \frac{1}{2} (1 - z) \right]$$

with

$$c_{\perp}^W = s_{\text{eff}} \frac{1}{2s_W^2} |V_{ff'}|^2, \quad c_{\perp}^Z = s_{\text{eff}} \frac{s_W^2}{c_W^2} Q_f^2 + (1 - s_{\text{eff}}) \frac{(I_f^3 - s_W^2 Q_f^2)^2}{s_W^2 c_W^2},$$

$$c_L^W = \frac{1}{2s_W^2} |V_{ff'}|^2 \left[ s_{\text{eff}} \frac{m_f^2}{m_W^2} + (1 - s_{\text{eff}}) \frac{m_f^2}{m_W^2} \right], \quad c_L^Z = \frac{I_f^3}{s_W^2} \frac{m_f^2}{m_W^2},$$

- couplings  $ff^{(\prime)} V$  depend on spin of  $f$ , but standard parton showers are spin averaged (no spin information)
- process dependent average spin of fermion line  $s_{\text{eff}}$   
 $\Rightarrow pp \rightarrow jj: s_{\text{eff}} = \frac{1}{2}, pp \rightarrow W: s_{\text{eff}} = 1$ , undefined in general
- factors  $f_W, f_Z, f_h$  modify couplings to test sensitivity

Krauss, Petrov, MS, Spannowsky Phys.Rev.D89(2014)114006

## Can we see radiated $W$ bosons inside jets at the LHC (14 TeV)?

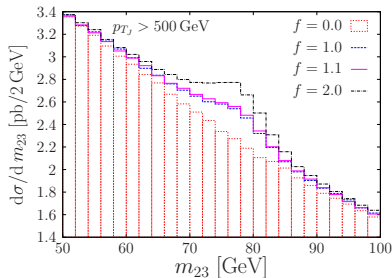
- need high- $p_{\perp}$  jets to produce real  $W$  bosons at sufficient rate
- need high- $p_{\perp}$  jets to satisfy assumption  $E \gg m$

### Boosted analysis:

- find jets (anti- $k_{\perp}$ ,  $R = 1.5$ ,  $p_{\perp} > 200$  GeV)
- no isolated leptons ( $p_{\perp} > 25$  GeV,  $|\eta| < 2.5$ ,  
 $E_{\text{had}} < 0.1 E_{\ell}$  in  $\Delta R = 0.2$ )
- require further two jets with  $p_{\perp} > 500, 750, 1000$  GeV to drive  $W$  radiation into collinear region

## Hadronic analysis

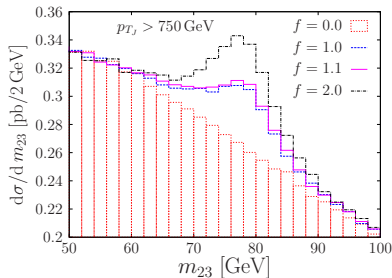
- recluster fat jets into C/A ( $R = 0.3$ ,  $p_{\perp} > 20$  GeV) microjets
  - discard leading microjet as likely from leading quark
  - use  $m_{23}$  as gluon em. tends to be softer than decay prod. of  $W$  em.
  - accept candidate if  $m_{23} \in [70, 86]$  GeV
- ⇒ large, but continuous QCD background, clear signal shape
- ⇒ more  $W$  emissions with high  $p_{\perp}$ , but peak shifts





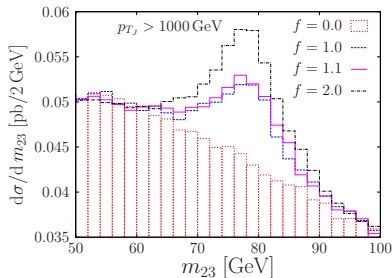
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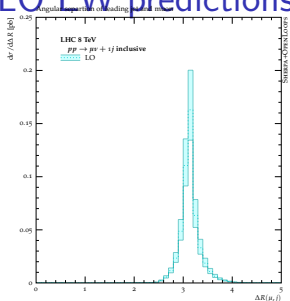
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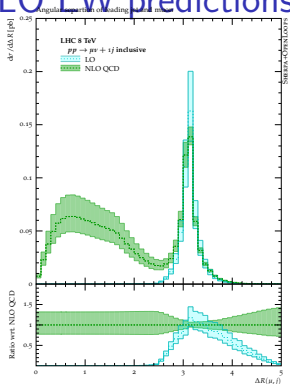


Case study: Finding  $W$  bosons inside jetsNLO EW predictions for  $\Delta R(\mu, j_1)$ 

Measure coll.  $W$  emissions, simplified from  
 Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

LHC@8TeV,  $p_{\perp}^{j_1} > 500$  GeV, central  $\mu$  and jet

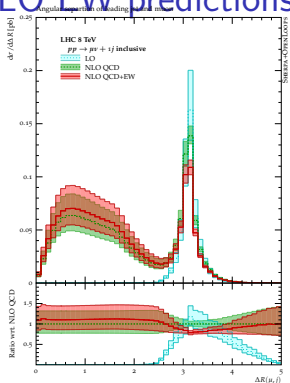
- LO  $pp \rightarrow Wj$  with  $\Delta\phi(\mu, j) \approx \pi$ 
  - NLO corrections neg. in peak
  - large  $pp \rightarrow Wjj$  component opening PS
  - subleading Born ( $\gamma$ PDF) imp. at large  $\Delta R$
  - restrict to exactly  $1j$ , no  $p_{\perp}^{j_2} > 100$  GeV
  - describe  $pp \rightarrow Wjj$  @ NLO,  $p_{\perp}^{j_2} > 100$  GeV
  - pos. NLO QCD,  $\Delta R(\mu, j) \sim \text{flat}$
  - subleading Born contribs positive
  - sub<sup>2</sup>leading Born (diboson etc) conts. pos.  
 → possible double counting with BG
  - merge using exclusive sums

Case study: Finding  $W$  bosons inside jetsNLO EW predictions for  $\Delta R(\mu, j_1)$ 

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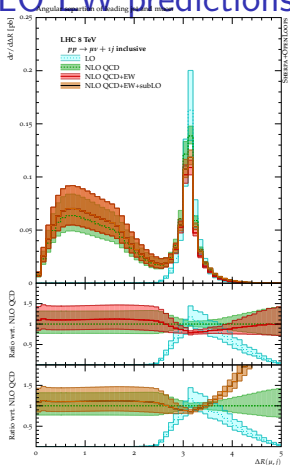
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- pos. NLO QCD,  $\frac{d\sigma}{d\Delta R} \sim \text{flat}$
- subleading Born contris positive
- sub<sup>2</sup>leading Born (diboson etc) contrs. pos.  
 → possible double counting with BG
- merge using exclusive sums

Case study: Finding  $W$  bosons inside jetsNLO EW predictions for  $\Delta R(\mu, j_1)$ 

Measure coll.  $W$  emissions, simplified from  
 Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

LHC@8TeV,  $p_{\perp}^{j_1} > 500$  GeV, central  $\mu$  and jet

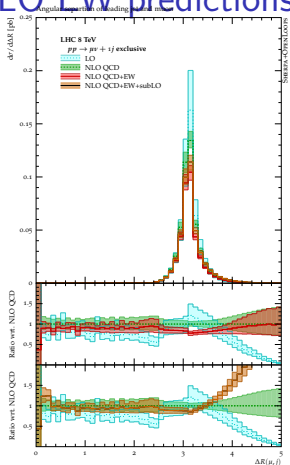
- LO  $pp \rightarrow Wj$  with  $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak  
 large  $pp \rightarrow Wjj$  component opening PS
- subleading Born ( $\gamma$ PDF) imp. at large  $\Delta R$
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- pos. NLO QCD,  $\sim$  flat
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- subleading Born ( $\gamma$ PDF) imp. at large  $\Delta R$ 
  - restrict to exactly  $1j$ , no  $p_{\perp}^b > 100$  GeV
  - describe  $pp \rightarrow Wjj$  @ NLO,  $p_{\perp}^b > 100$  GeV
  - pos. NLO QCD,  $\Delta R > 3$ ,  $\Delta\phi(\mu, j) \sim \text{flat}$
  - subleading Born contribs positive
  - sub<sup>2</sup>leading Born (diboson etc) conts. pos.  
 → possible double counting with BG
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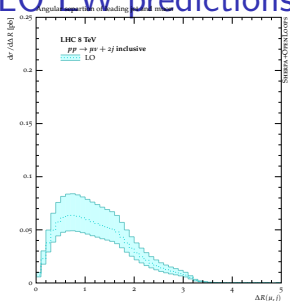
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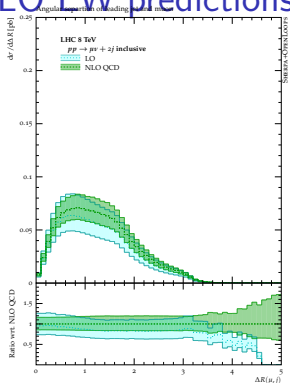
# NLO EW predictions for $\Delta R(\mu, j_1)$



Measure coll.  $W$  emissions, simplified from  
[Krauss, Petrov, MS, Spannowsky PRD89\(2014\)114006](#)

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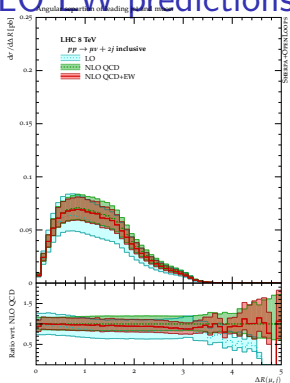
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- describe  $pp \rightarrow Wjj$  @ NLO,  $p_{\perp}^{j_2} > 100$  GeV
  - pos. NLO QCD,  $\Delta R \sim 1$ ,  $\Delta\phi \sim \text{flat}$
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  - sub<sup>2</sup>leading Born (diboson etc) conts. pos.  
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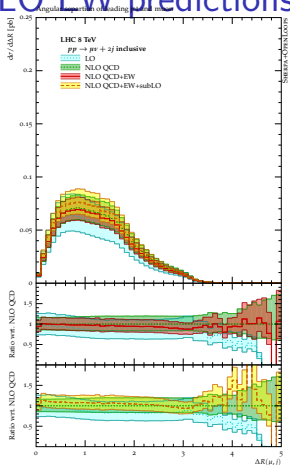
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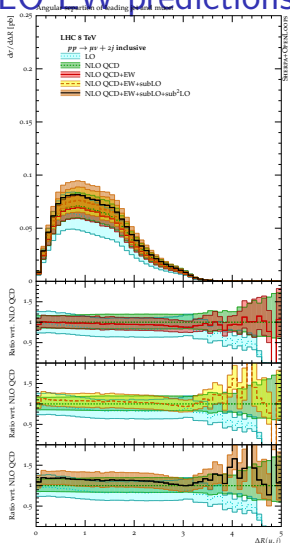
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Case study: Finding  $W$  bosons inside jets

# NLO EW predictions for $\Delta R(\mu, j_1)$

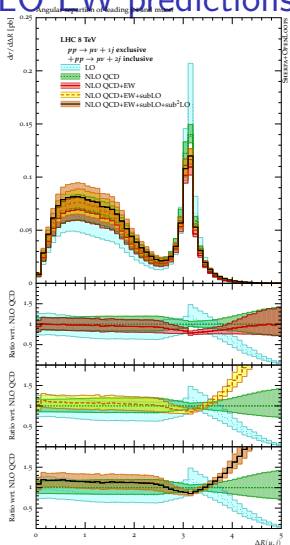


Measure coll.  $W$  emissions, simplified from  
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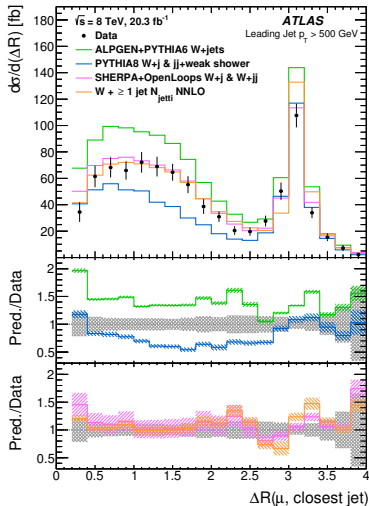
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Case study: Finding  $W$  bosons inside jetsNLO EW predictions for  $\Delta R(\mu, j_1)$ 

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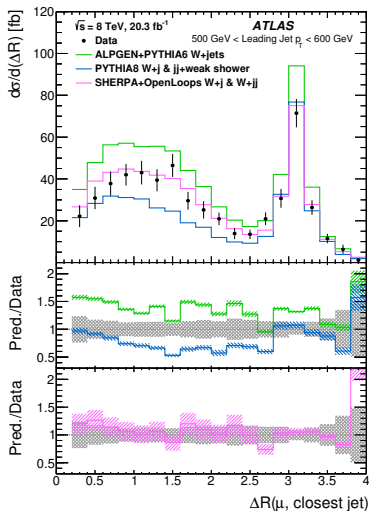
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## Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

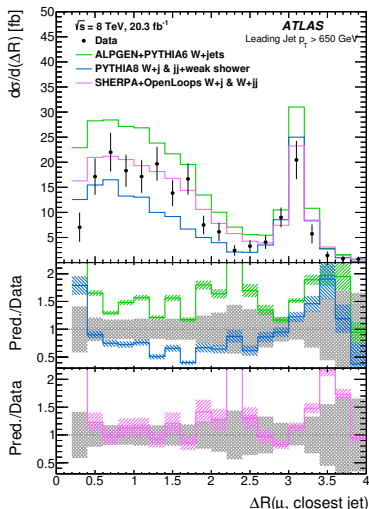
- ALPGEN+PYTHIA  
 $pp \rightarrow W + \text{jets}$  MLM merged  
 Mangano et.al. JHEP07(2003)001
- PYTHIA 8  
 $pp \rightarrow Wj + \text{QCD shower}$   
 $pp \rightarrow jj + \text{QCD+EW shower}$   
 Christiansen, Prestel EPJC76(2016)39
- SHERPA+OPENLOOPS  
 NLO QCD+EW+subLO  
 $pp \rightarrow Wj/Wjj$  excl. sum  
 Kallweit, Lindert, Maierhöfer,  
 Pozzorini, MS JHEP04(2016)021
- NNLO QCD  $pp \rightarrow Wj$   
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## Conclusions

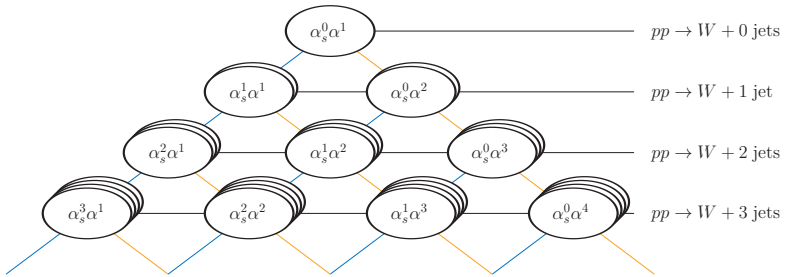
- electroweak effects are important at LHC, HE-LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet merging to improve description in those regions
  - ⇒ included since SHERPA-2.2.1 (now SHERPA-2.2.5)
- automation of NLO EW follows on the heels of NLO QCD
  - much more care with consistent schemes and order counting
  - very rich phenomenology
  - includes many more pitfalls than NLO QCD
  - ⇒ included in next major SHERPA release
- EW parton showers suffer from strong spin dependence of  $W/Z$  emission as parton showers are usually do not have spin information
  - ⇒ not included in SHERPA public release

Thank you for your attention!

# Backup

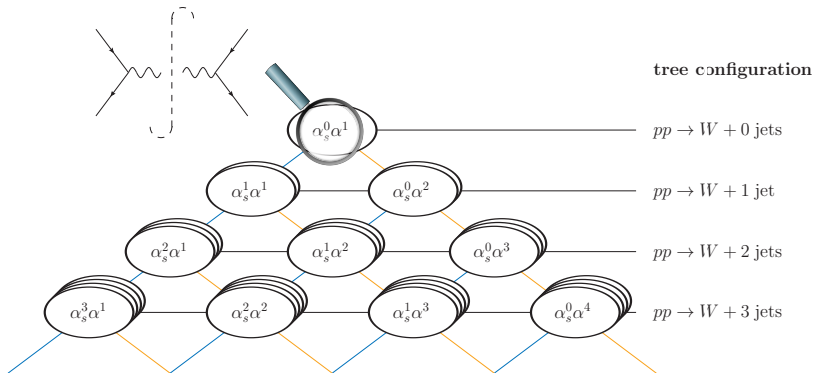
# Consistent setup: counting orders and defining signatures

tree configuration



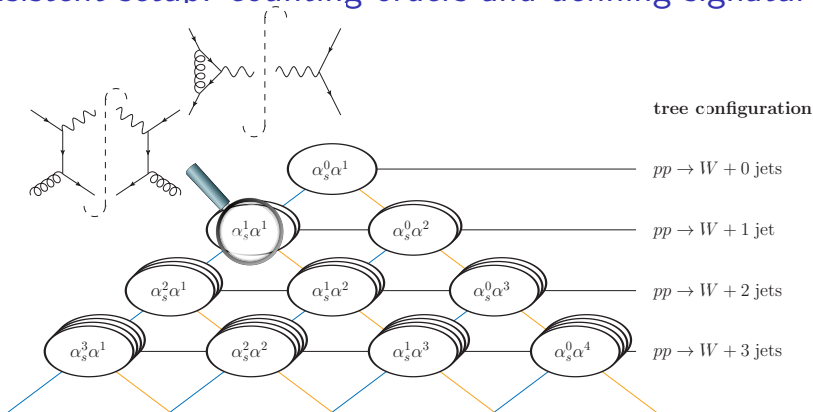
- NLO QCD:  $\alpha_s^1 = 1$  parton, only MEs from squared diagrams
- NLO EW:  $\alpha^1 = 1$  photon

# Consistent setup: counting orders and defining signatures



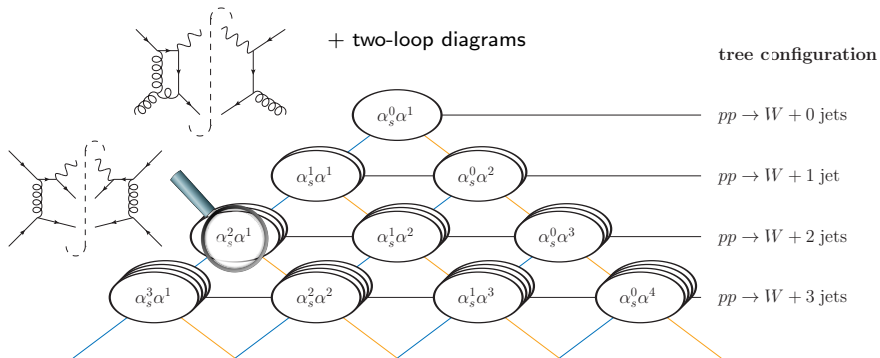
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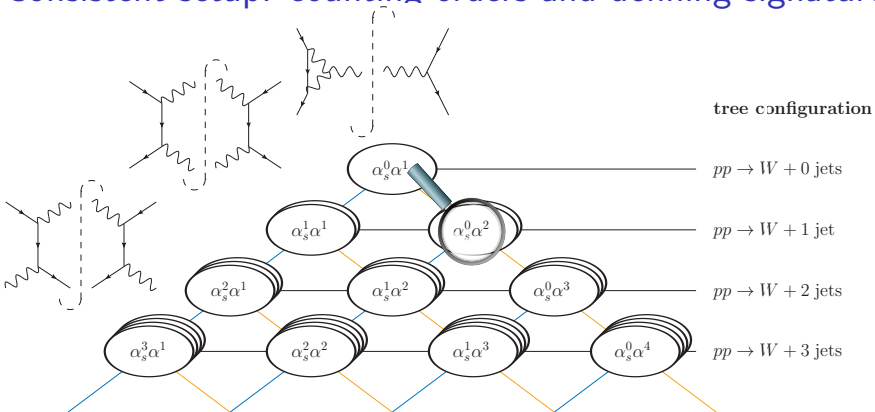
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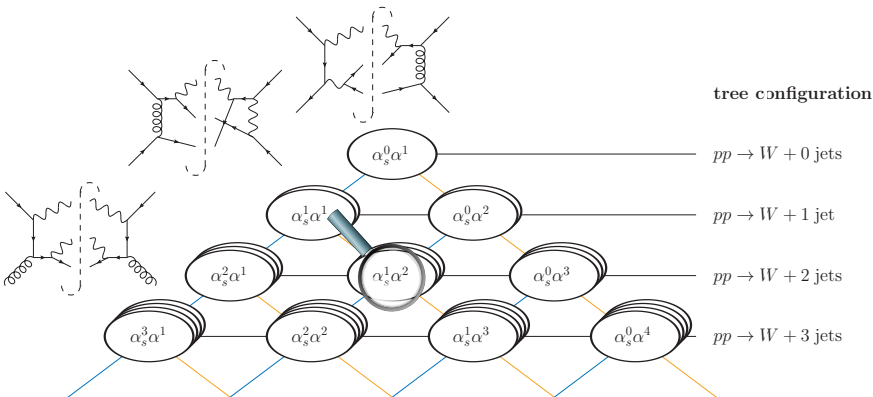
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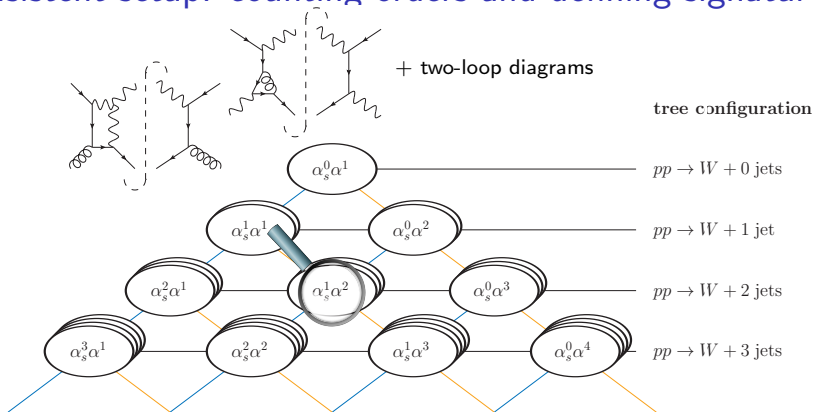
- NLO QCD:  $\alpha_s^1 = 1$  parton, only MEs from squared diagrams
- NLO EW:  $\alpha^1 = 1$  photon or 1 parton  
also MEs from interfering  $\mathcal{O}(g_s^{n\pm 1} e^{m\mp 1})$  diagrams, resonances

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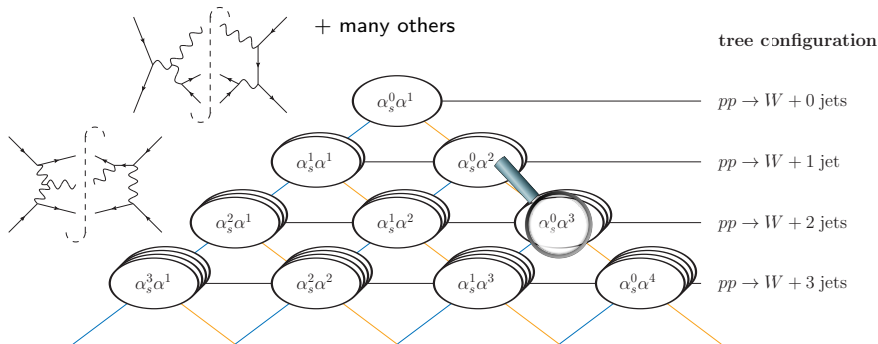
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## Subtleties: photons in initial state

Harland-Lang et.al. arXiv:1605.04935, Kallweit et.al. arxiv:1705.00598

### NLO EW for photon initiated processes

- initial state photons are not resolved, should be treated as any other parton
  - multiple sources: elastic (proton remains intact)  
inelastic (proton broken up)
  - both elastic and inelastic photons evolve according to DGLAP  
→ splittings  $\gamma \rightarrow \gamma$ ,  $\gamma \rightarrow q\bar{q}$ ,  $q \rightarrow q\gamma$   
→ can be combined into a single PDF as long as one is not concerned with what happens to the proton
  - the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section
- ⇒ renormalisation in short-distance scheme ( $G_\mu$ ,  $\alpha(m_Z)$ ,  $\overline{\text{MS}}$ , ...)

## Subtleties: photons in final state

### What is a jet?

- photons must be part of a jet, but to what extent?
- **democratic:**
  - + straight forward, close to experiment for many procs
  - more subtractions (Born configs with FS photons)
  - single photons constitute a jet

- **anti-tagging jets with too large photon content:**

dress quarks for collinear safety,

discard jets if  $E_\gamma > z_{\text{thr}} E_{\text{jet}}$  (e.g.  $z_{\text{thr}} = 0.5$ )

- + fewer contributions
- difference to experimental jet definition (usually subpercent)
- ill-defined at lower order NLO correction (w/  $\gamma \rightarrow q\bar{q}$  splittings)
- single photons do not constitute a jet

general anti-tagging must proceed through fragmentation functions

## Subtleties: photons in final state

### What is a photon?

- differentiate: short-distance photon (photon as parton), long-distance photon (identified, measurable photon)
  - a) treat as identified particle, renormalise on-shell ( $\alpha(0)$ ), no  $\gamma \rightarrow ff$ 
    - renormalisation contains IR poles
    - problematic if both identified and unresolved photons in Born
  - b) treat democratically (just another parton), renormalise in short distance scheme ( $G_\mu$ ,  $\alpha(m_Z)$ ,  $\overline{MS}$ , ...), include  $\gamma \rightarrow ff$  splittings
    - pure UV renormalisation
    - if needed, identify photon through frag. function  $D_\gamma^p(z, \mu)$ 
      - i.e.  $D_\gamma^q(z, \mu) = \frac{\alpha(0)}{\alpha_{sd}} \delta(1-z) + \mathcal{O}(\alpha^2)$
      - all others  $D_\gamma^q(z, \mu) = \mathcal{O}(\alpha)$ ,  $D_\gamma^g(z, \mu) = \mathcal{O}(\alpha_s \alpha)$
- identical at NLO EW, if fragmentation  $D_\gamma^q$  on Born is negligible

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- identical at NLO EW, if fragmentation  $D_\gamma^q$  on Born is negligible

## Subtleties: photons in final state

### What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

$$D_{\ell}^{\ell}(z, \mu) = \delta(1 - z) + \text{QED bremsstrahlung}$$

$$D_{\ell}^{\gamma}(z, \mu) = \mathcal{O}(\alpha) \text{ problematic in processes with } \ell \text{ and unresolved photons in Born}$$

$$\text{all other } D_{\ell}^q(z, \mu) = \mathcal{O}(\alpha^2), D_{\ell}^g(z, \mu) = \mathcal{O}(\alpha_s \alpha^2)$$

- **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

## Combination of NLO QCD and EW correction

- additive – strict fixed order expansion

$$d\sigma_{\text{QCD}+\text{EW}}^{\text{NLO}} = d\sigma^{\text{LO}} (1 + \delta_{\text{QCD}} + \delta_{\text{EW}})$$

- multiplicative – contains terms of  $\mathcal{O}(\alpha_s\alpha)$

$$d\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} = d\sigma^{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW}})$$

this construction is expected to well approximate the true  $\mathcal{O}(\alpha_s\alpha)$  in the Sudakov limit where QCD and EW corrections factorise

- ⇒ in general, difference between additive and multiplicative combination can be used to assign higher-order uncertainty