

# Electroweak corrections for LHC physics

Marek Schönherr

IPPP, Durham University



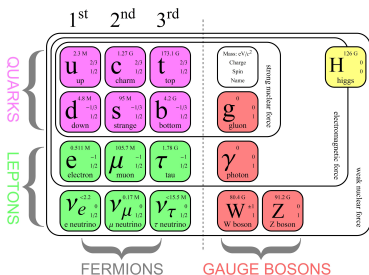
## Overview

- 1 The future of the LHC  
The Large Hadron Collider  
The need for precision calculations
- 2 Electroweak corrections for New Physics searches  
Setup, subtleties and automation  
Selected results
- 3 Electroweak corrections for precision measurements  
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Three-jet production and  $R_{32}$
- 4 Electroweak corrections in MCs  
Approximate inclusion in NLO QCD multijet merging
- 5 Conclusions

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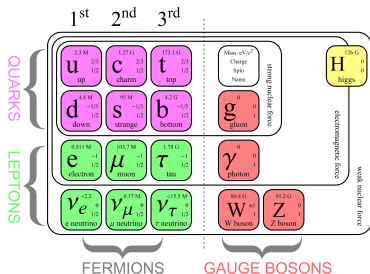
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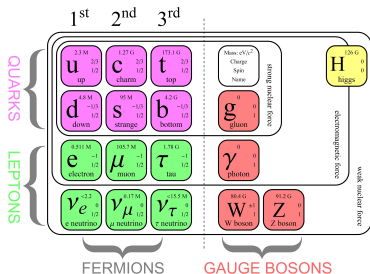
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QCD

unbroken gauge group

$\alpha_s$

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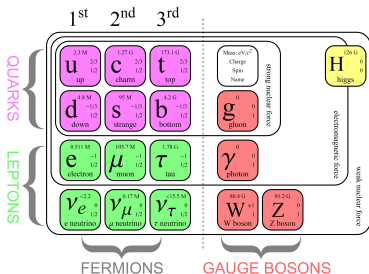
$\alpha_s$

EW theory

spontaneously broken gauge group  
massive W/Z bosons,  $U(1)_{\text{QED}}$  remains

$\alpha$

# The Standard Model of Particle Physics

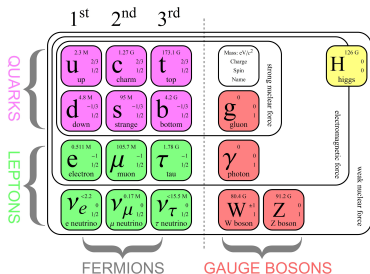


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All fields have been observed.  
**Higgs boson discovery at the LHC in 2012.**  
 But not all interactions.

But it is incomplete, as it includes neither dark matter, neutrino masses nor gravity. Signs of new physics are sought beyond the currently accessible data.

# The Standard Model of Particle Physics

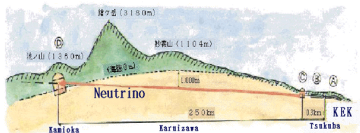
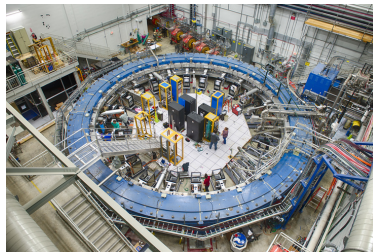
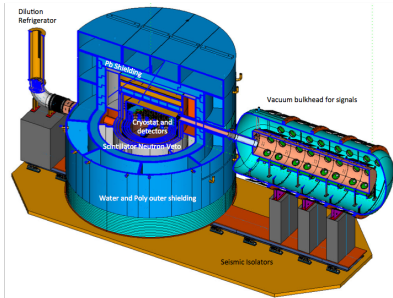


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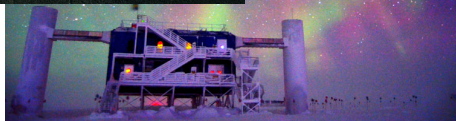
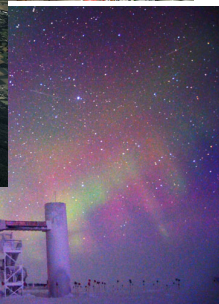
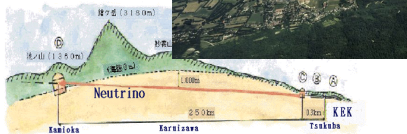
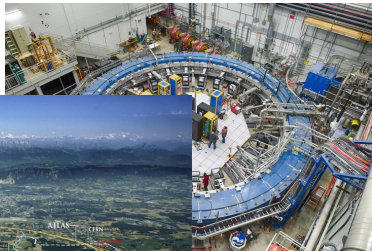
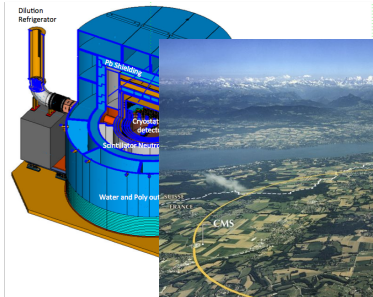
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# Experimental tests



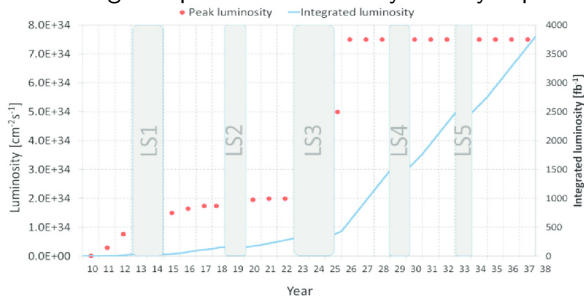


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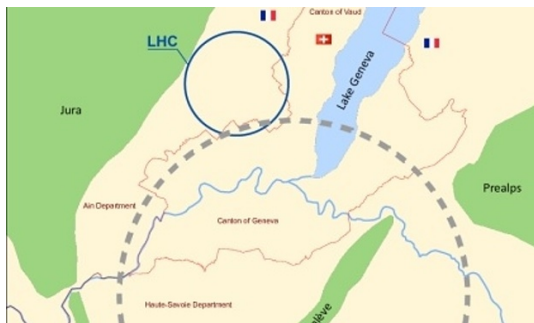
# The LHC physics programme

- Run-I (7 & 8 TeV) and Run-II (13 TeV) completed
- many important measurements (Higgs discovery,  $W$  mass), but no signal of new physics yet
  - increasing luminosity crucial for new physics searches
  - theoretical accuracy of Monte-Carlo predictions must keep pace with envisaged experimental accuracy to fully exploit the data



# The LHC and beyond

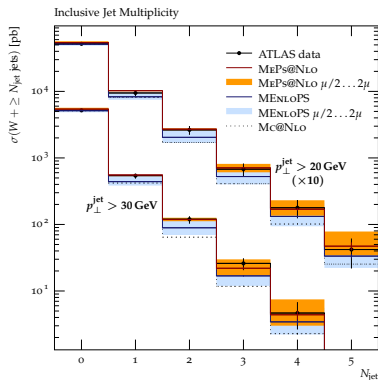
LHC	13 TeV	0.3 $\text{ab}^{-1}$	} <b>increase in both collision energy and statistical reach</b>
HL-LHC	14 TeV	3 $\text{ab}^{-1}$	
HE-LHC	27 TeV	15 $\text{ab}^{-1}$	
FCC	100 TeV	25-100 $\text{ab}^{-1}$	





# Available and needed precision

Höche, Krauss, MS, Siegart '12



## start of the LHC:

- QCD the great unknown
  - NLO QCD automated ✓
  - NLO QCD multijet merging baseline MC for the LHC ✓
  - NNLO QCD where required ✓

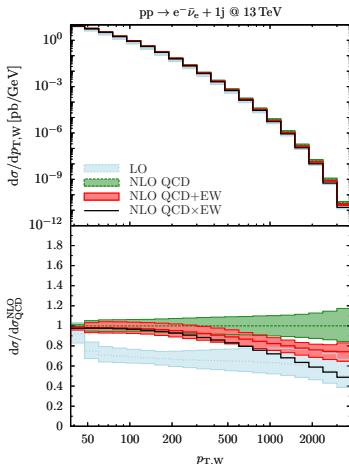
## LHC Run II and beyond:

- emergence of EW corrections
  - precision measurements (sub)percent accuracy ✗
  - high- $p_T$  distributions tens of percent corrections ✗



# Available and needed precision

Kallweit, Lindert, Maierhöfer, Pozzorini, MS '14  
MS '17



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## Electroweak corrections

### Precision measurements

Measurement that aim for subpercent experimental accuracy.

→ theoretical predictions must keep pace

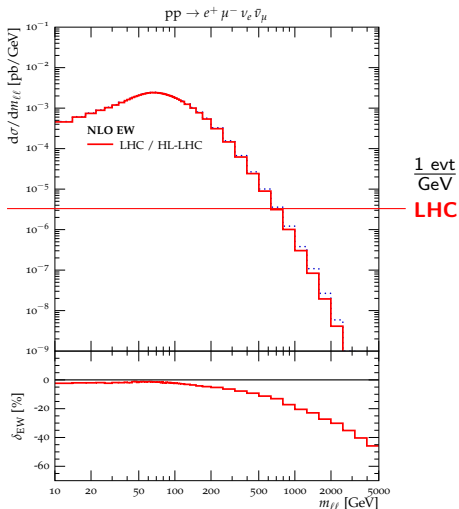
Electroweak corrections are of  $\mathcal{O}(\alpha)$ , thus generally of  $\mathcal{O}(1\%)$ . Roughly, their size can be gauged by  $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$ .

### New physics searches

Search for excesses over SM background in TeV-scale observables that we could not probe until now.

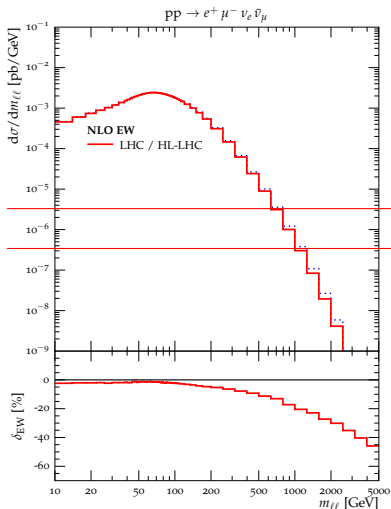
Incomplete infrared cancellations due to broken structure of the EW gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces corrections which are negative and logarithmically growing with the size of the kinematic invariants, e.g.  $p_T$ . Thus,  $\mathcal{O}(20\%)$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

## Why care about the tails of distributions?



- new physics searches look for deviations in shape in high- $p_T$  tails or large invariant masses
- EW corrections increase in these tails to tens of percent
  - the level of **accuracy determines achievable discovery potential** and exclusion bounds
  - otherwise precision data cannot be fully exploited

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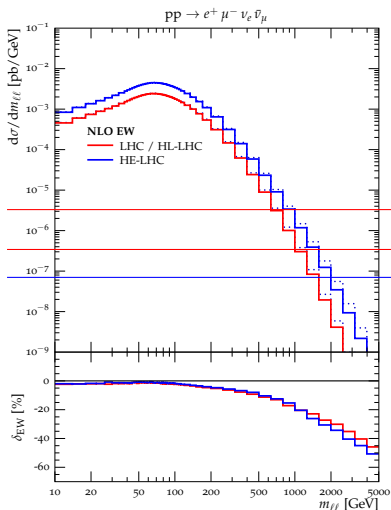
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LHC

HL-LHC

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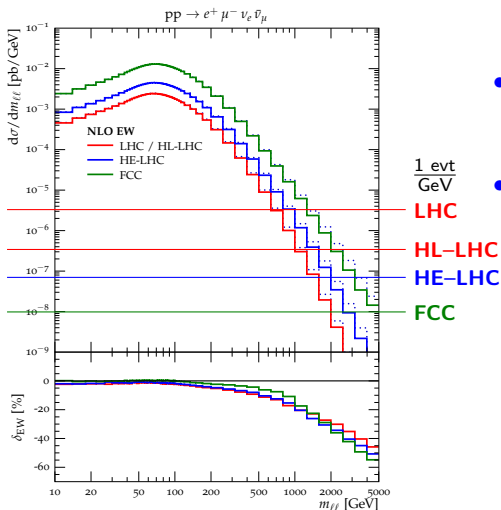
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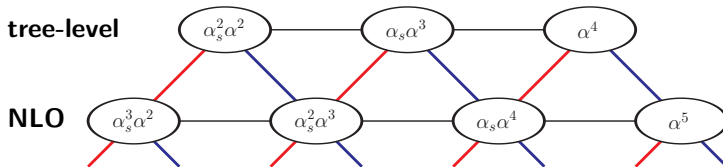
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## Higher order corrections

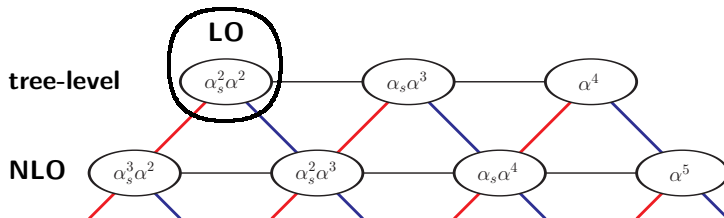
### Example: $Vjj$ production



- 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

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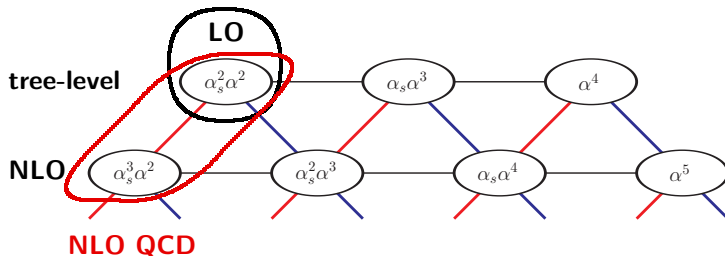
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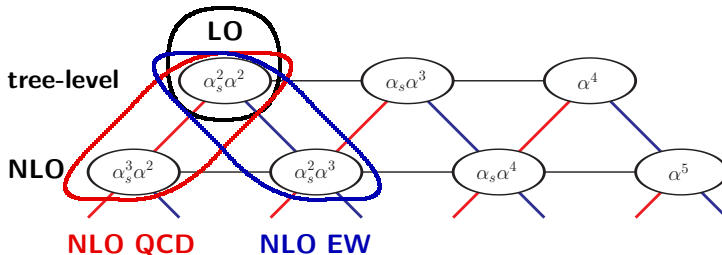
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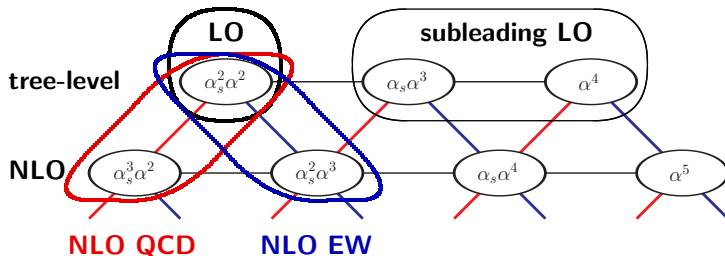
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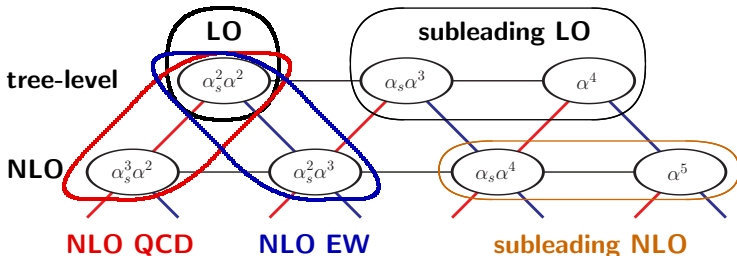
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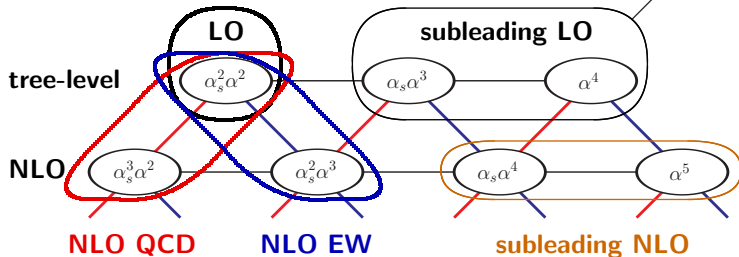
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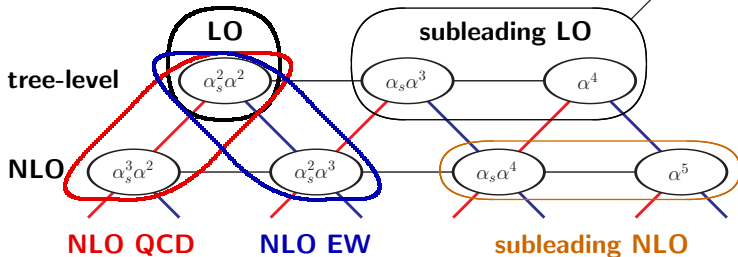
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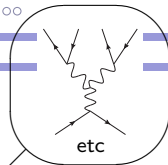
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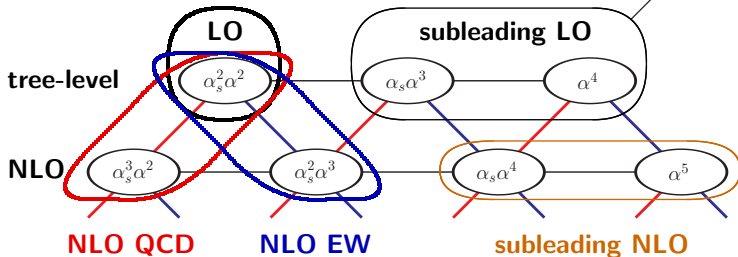


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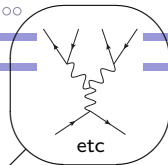


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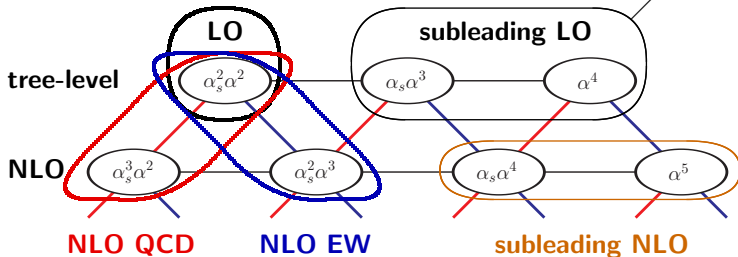


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# Definition of physical objects

## 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

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

⇒ 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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# 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 '17
    - MADGRAPH Frederix et.al. '18
  - virtual corrections (EW one-loop matrix elements, renormalisation)
    - GOSAM Chiesa et.al. '15
    - MADLOOP Frixione et.al. '14
    - OPENLOOPS Kallweit et.al. '14
    - RECOLA Actis et.al. '12
  - currently generally limited to fixed-order
  - a number of dedicated calculations and private codes

## NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:

- $pp \rightarrow \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2, (3) \text{ jets}$  FCC report, EW report, LH'15  
Kallweit, Lindert, Maierhöfer, Pozzorini, MS '14, '15  
Lindert et.al. '17
- $pp \rightarrow Vh$  FCC report '16
- $pp \rightarrow 2\ell 2\nu$  Kallweit, Lindert, Pozzorini, MS '17
- $pp \rightarrow t\bar{t}/t\bar{t}j$  Gütschow, Lindert, MS '18
- $pp \rightarrow t\bar{t}h$  LH'15

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- $pp \rightarrow \gamma\gamma\gamma / \gamma\gamma\ell\nu / \gamma\gamma\ell\ell$  Greiner, MS '17

- SHERPA+RECOLA

- $pp \rightarrow V + 0, 1, 2 \text{ j}, pp \rightarrow 4\ell, pp \rightarrow t\bar{t}h$  Biedermann et.al. '17
- $pp \rightarrow 3\ell 3\nu$  MS '18
- $pp \rightarrow jj/jjj$  Reyer, MS, Schumann '19

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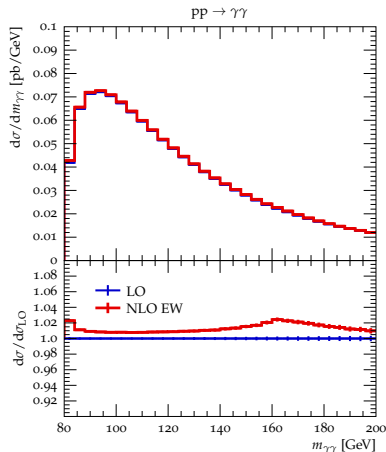
## General setup

- 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 throughout

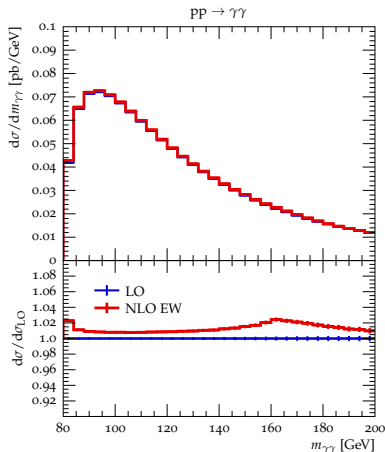
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## NLO EW corrections to diphoton production

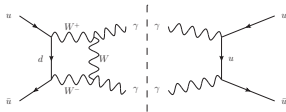
- peak-like enhancement around  $m_{\gamma\gamma} \approx 160$  GeV
- induced by  $W$ -box creating pseudo-resonant structures
- should be accounted for in data-driven background fits in diphoton resonance searches

# Diphoton production – $\gamma\gamma$



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- peak-like enhancement around  $m_{\gamma\gamma} = 2 m_W$
- induced by  $W$ -box creating pseudo-resonant structures



- should be accounted for in data-driven background fits in diphoton resonance searches

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

Kallweit, Lindert, Pozzorini, MS '17

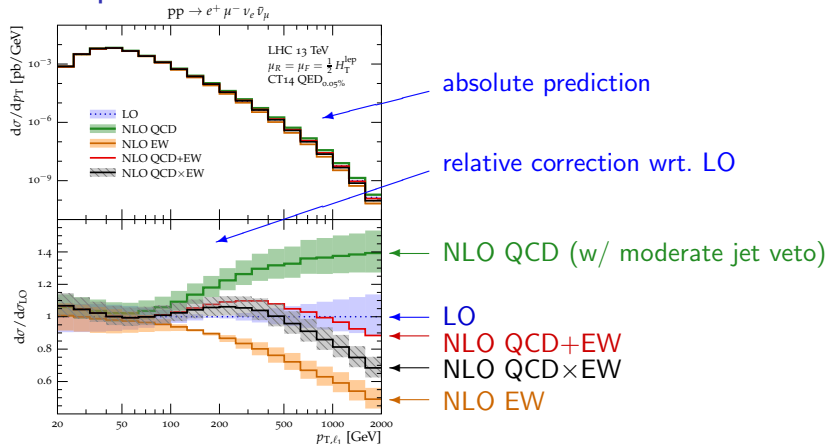
- study  $e^+ \mu^- \nu \bar{\nu}$  (DF) and  $e^+ e^- \nu \bar{\nu}$  (SF) production, and  $e \leftrightarrow \mu$

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

- incl. event selection w/ standard lepton acceptance cuts, ( $p_{T,\ell} > 20 \text{ GeV}$ ),  $|\eta_\ell| < 2.5$ ),  $n_f = 4$  and mild jet veto to suppress large NLO QCD corr.
- similar intricate interplay between different “on-shell” in  $3\ell 3\nu$  production at NLO EW

MS '18

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



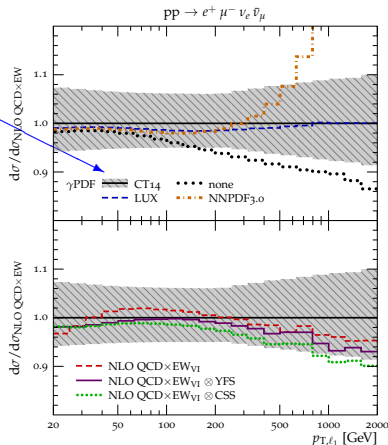
- large pos. NLO QCD, large neg. NLO EW  
 → NLO QCD+EW and NLO QCD $\otimes$ EW differ significantly

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

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

CT14qed (baseline)  
LUXqed

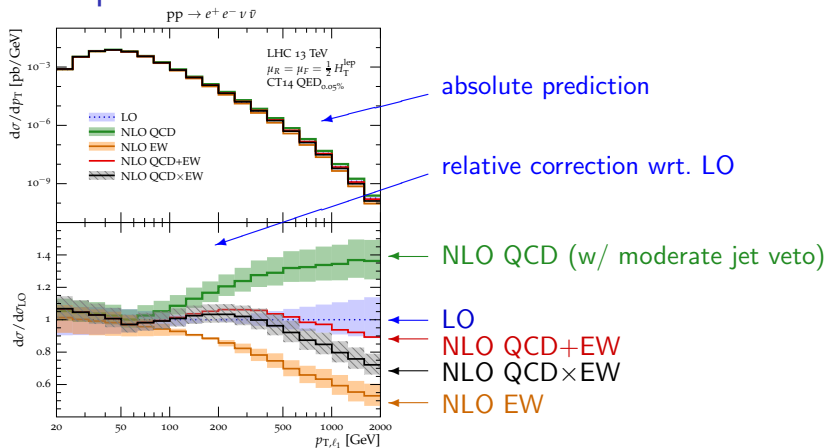
no  $\gamma$ PDF  
NNPDF3.0qed



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



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



- large pos. NLO QCD, large neg. NLO EW  
 → NLO QCD+EW and NLO QCD $\times$ EW differ significantly

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

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

CT14qed (baseline)  
LUXqed

no  $\gamma$ PDF  
NNPDF3.0qed

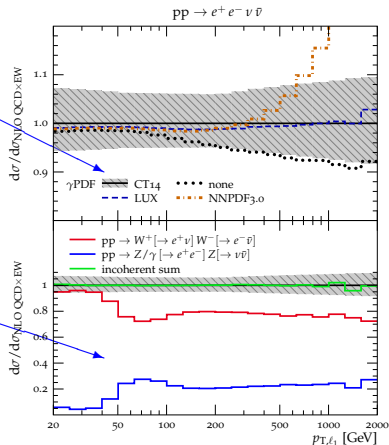
rel. contribs of  $WW$  and  $ZZ$  subtops

coherent  $|WW + ZZ|^2$

incoherent  $|WW|^2 + |ZZ|^2$

only  $|WW|^2$

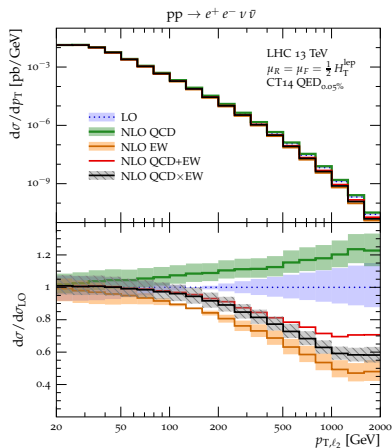
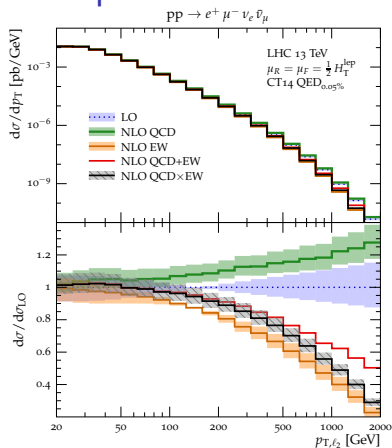
only  $|ZZ|^2$



- $WW$  dominant throughout,  $ZZ$  only contribs 10-20%  
→ overall very similar to DF case

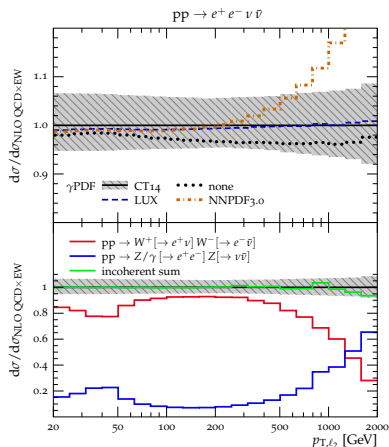
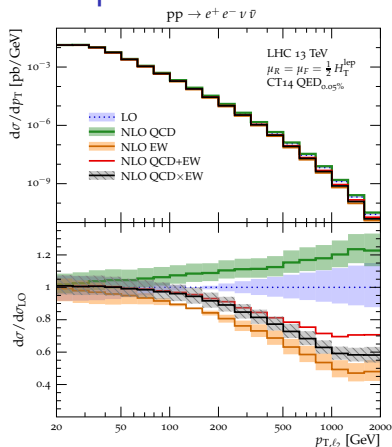


## Selected results

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

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

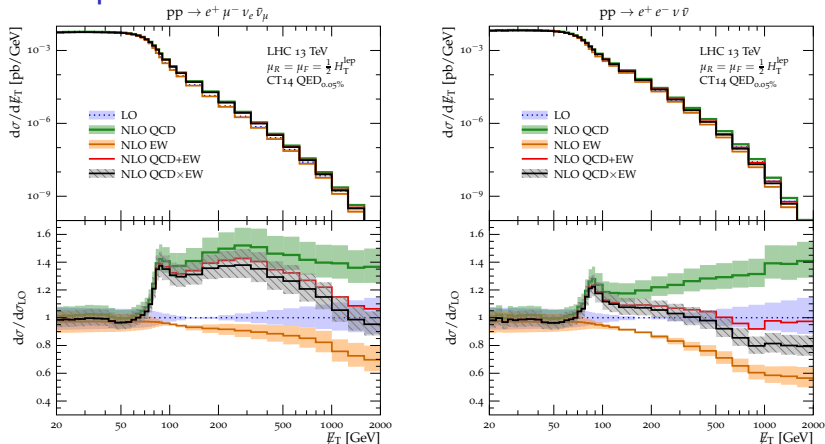
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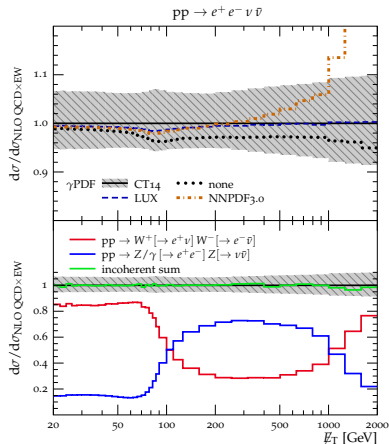
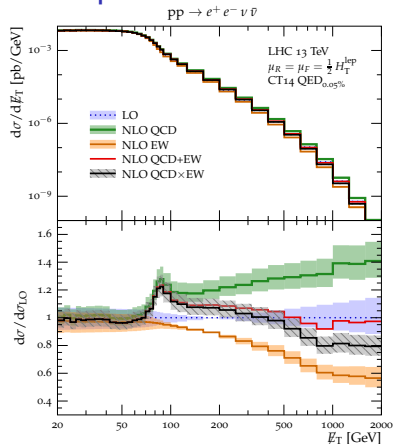
## Selected results

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

- 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.

# Electroweak corrections for precision measurements

- ① The future of the LHC
  - The Large Hadron Collider
  - The need for precision calculations
- ② Electroweak corrections for New Physics searches
  - Setup, subtleties and automation
  - Selected results
- ③ Electroweak corrections for precision measurements
  - Electroweak corrections for precision measurements
  - Three-jet production and  $R_{32}$
- ④ Electroweak corrections in MCs
  - Approximate inclusion in NLO QCD multijet merging
- ⑤ Conclusions

## Electroweak corrections for precision measurements

$W$ ,  $Z$  bosons produced with large cross section, and their decay into leptons offers a clear signature.

Large data sets, complemented by additional small data sets in low pile-up environment to control systematic uncertainties, allow for permille level accuracy in the experimental measurement.

Typical precision observables:

$$W - m_W$$

$$Z - \sin \theta_w^{\text{eff}}, A_{\text{FB}}, A_0 \dots A_8$$

To reach the desired theoretical accuracy, many different aspects need to be controlled:

QCD corrections to  $W/Z$  production processes

EW (mostly QED) corrections to decay kinematics

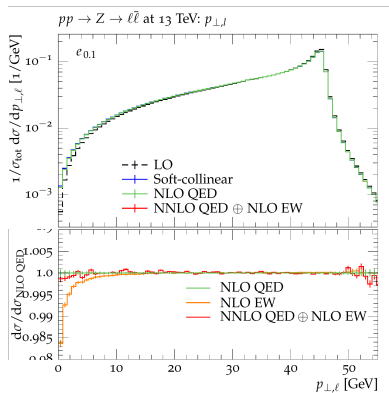
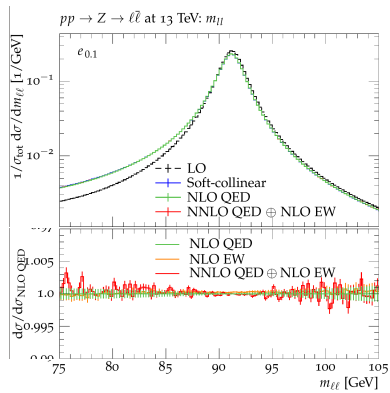
parton distributions in the proton

...



# Electroweak corrections for precision measurements

Krauss, Lindert, Linten, MS '18



- soft photon resummation matched to NNLO QED + NLO EW
- permille accuracy in the description of the  $Z \rightarrow \ell\bar{\ell}$  kinematics

## Determination of the strong coupling $\alpha_s$

Typically,  $\alpha_s$  at hadron colliders extracted from ratio of three-jet production to two-jet production.

Necessitates precise predictions over large kinematic ranges, from a few tens of GeV to the multi-TeV regime.

### Dijet production

- NNLO QCD
- NLO QCD
- NLO EW and all subl. corrections

Currie et.al. '17

Ellis, Kunszt, Soper '92  
Giele, Glover, Kosower '93

Moretti, Nolten, Ross '06  
Dittmaier, Huss, Speckner '12  
Frederix et.al. '16

### Three-jet production

- NLO QCD
- NLO EW and all subl. corrections

Nagy '01

Reyer, MS, Schumann '19

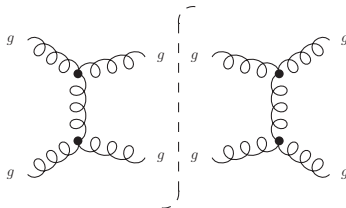
## Three-jet production – contributions

- **define jets completely democratically,**  
 incl. all massless visible particles of the SM ( $q, g, \gamma, \ell$ )  
 $p_T(j_1) > 80 \text{ GeV}, p_T(j_i) > 60 \text{ GeV} (i > 1)$
- anti-tag jets against leptons  
 exclude jets with net lepton number within lepton acceptance  
 care: jet acceptance and lepton acceptance may differ  
 here:  $|\eta(j)| < 2.8, |\eta(\ell)| < 2.5$

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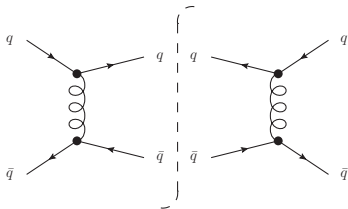
$\mathcal{O}(\alpha_s^2)$



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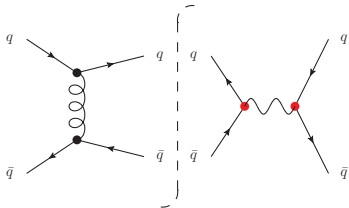
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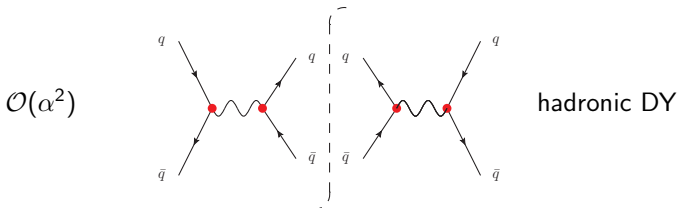
$\mathcal{O}(\alpha_s \alpha)$



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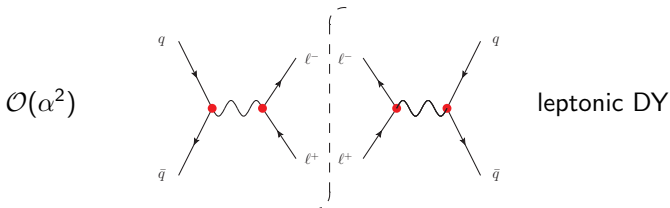
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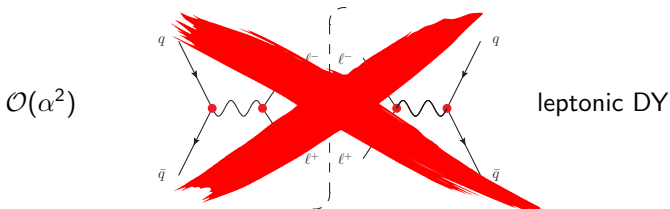
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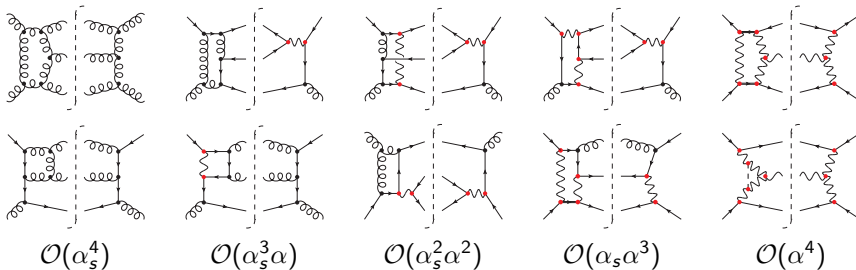
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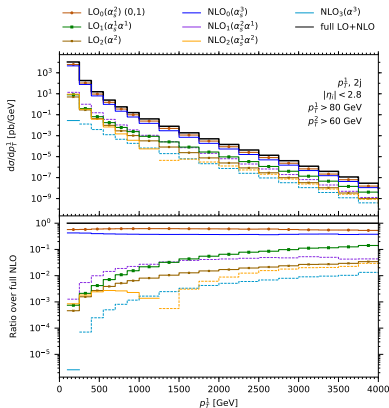
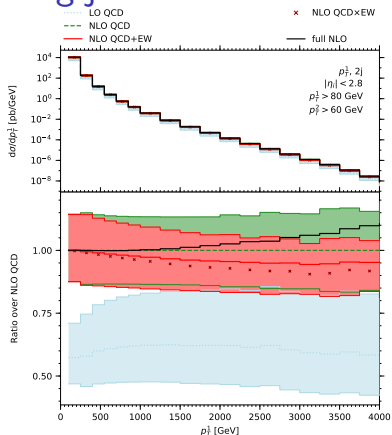
## Contributions at NLO



- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include:  $lvqg$ ,  $llqg$ ,  $llll$ ,  $lllv$  final states

Three-jet production and  $R_{32}$ 

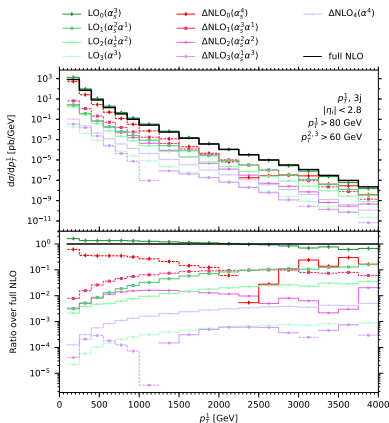
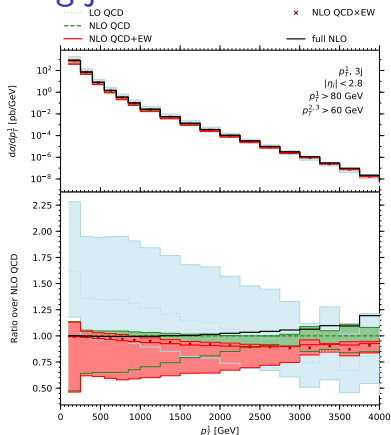
## Leading jet transverse momenta in dijet production



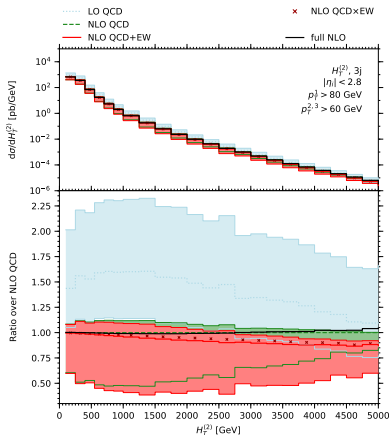
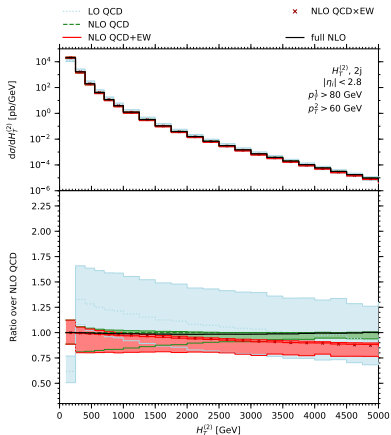
- moderate EW corrections
- overcompensated by subleading orders

Three-jet production and  $R_{32}$ 

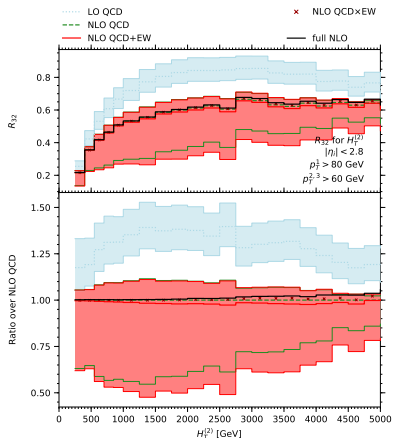
## Leading jet transverse momenta in 3-jet production



- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

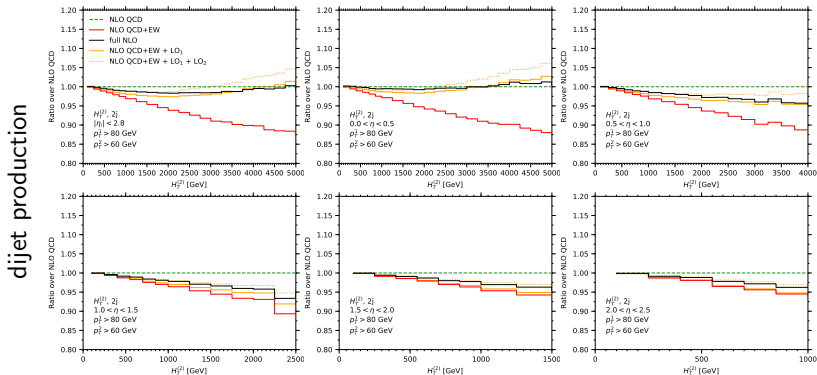
Three-jet production and  $R_{32}$ 
 $H_T^{(2)}$ 


- NLO EW reduces x-sec. by  $\approx 15\%$  at  $H_T^{(2)} = 2 \text{ TeV}$
- again, large accidental compensations between NLO EW and subleading orders

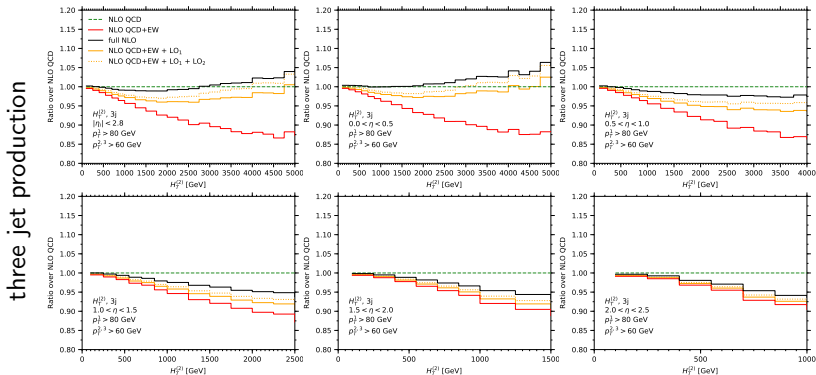
Three-jet production and  $R_{32}$  $R_{32}$ 

- NLO EW and subleading order contributes very similar between  $2j$  and  $3j$   
 $\Rightarrow R_{32}$  largely unaffected
- supports factorisation of NLO QCD and NLO EW correction at large  $H_T^{(2)}$
- scale uncertainty by synchronous scale variation

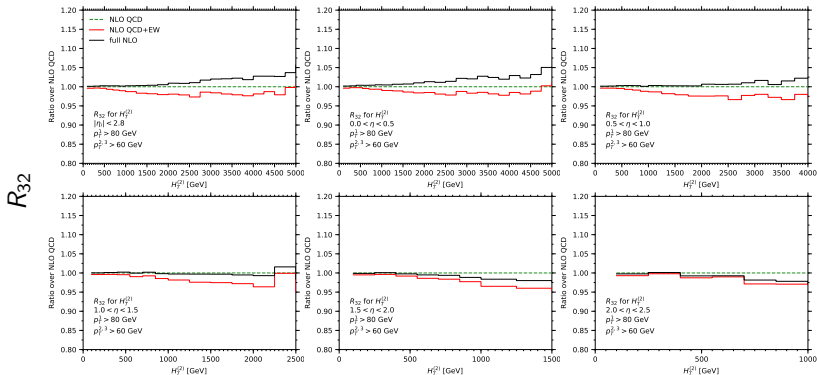
$\Rightarrow$  safe to use  $R_{32}$  with NLO QCD MCs for  $\alpha_s$  extraction

Three-jet production and  $R_{32}$  $R_{32}$  in different  $\Delta y$ -slices

- effects already seen in [Dittmaier, Huss, Speckner '12](#)

Three-jet production and  $R_{32}$  $R_{32}$  in different  $\Delta y$ -slices

- slightly different in 3-jet production

Three-jet production and  $R_{32}$  $R_{32}$  in different  $\Delta y$ -slices

- different net effects in different rapidity slices

# Electroweak corrections for LHC physics

- 1 The future of the LHC
  - The Large Hadron Collider
  - The need for precision calculations
- 2 Electroweak corrections for New Physics searches
  - Setup, subtleties and automation
  - Selected results
- 3 Electroweak corrections for precision measurements
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  - Three-jet production and  $R_{32}$
- 4 Electroweak corrections in MCs
  - Approximate inclusion in NLO QCD multijet merging
- 5 Conclusions

## Electroweak corrections in particle-level event generation

- 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  $\overline{B}$ -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

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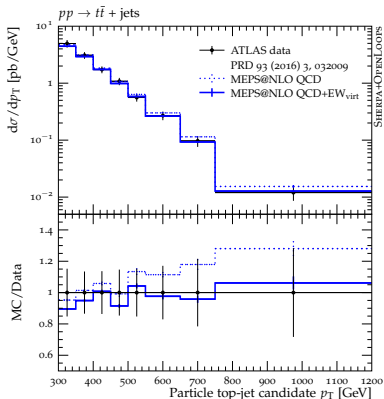
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Approximate inclusion in NLO QCD multijet merging

# 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  
Höche, Krauss, MS, Siebert '10
- improved description of data

## Conclusions

- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- NLO EW often not enough, need also subleading contribs
- precise definition of physics objects needed
  - ⇒ differentiate short-distance parton and long-distance measurable object
- can be incorporated in multijet-merged particle-level calculations to improve description in those regions
  - currently tailored to TeV-scale physics
- automation of NLO EW follows on the heels of NLO QCD
  - much more care with consistent schemes and order counting
  - very rich phenomenology
  - can induce peaks, edges or kinks in distributions
  - includes many more pitfalls than NLO QCD

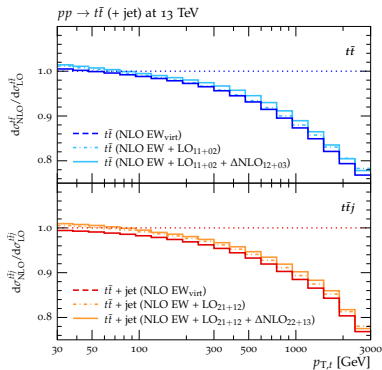
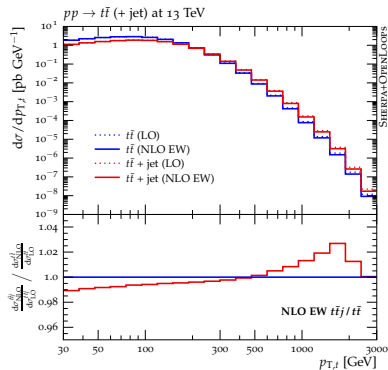
Thank you!

# Backup



# Top pair production in association with jets

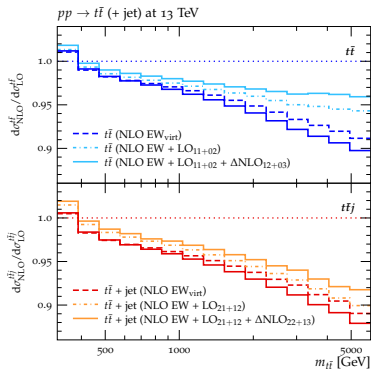
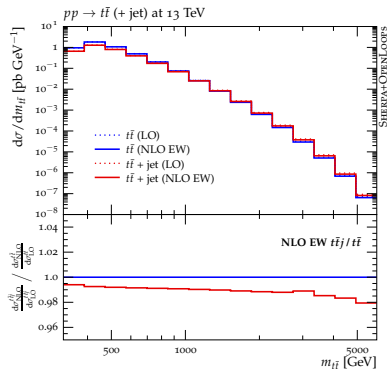
Gütschow, Lindert, MS in '18



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

# Top pair production in association with jets

Gütschow, Lindert, MS in '18



Observation: subleading orders important