

Electroweak corrections for LHC physics

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IPPP, Durham University



THE
ROYAL
SOCIETY

Overview

1 Introduction

Why and where are EW corrections important?

2 Electroweak corrections at fixed-order NLO

Setup, subtleties and automation

Selected results

3 Electroweak corrections in Event Generators

Soft-photon resummation

EW virtual approximation

4 Conclusions

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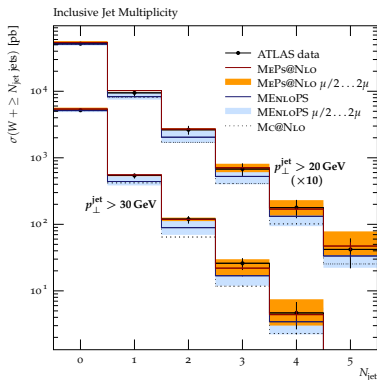
Soft-photon resummation

EW virtual approximation

4 Conclusions

Available and needed precision

Höche, Krauss, MS, Siegert '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:

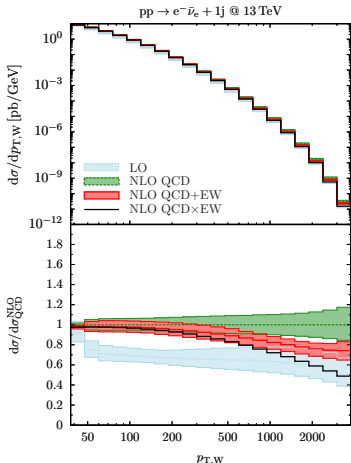
- emergence of EW corrections
 - precision measurements (sub)percent accuracy ✗
 - high- p_T distributions tens of percent corrections ✗

Why and where are EW corrections important?

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 $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$.

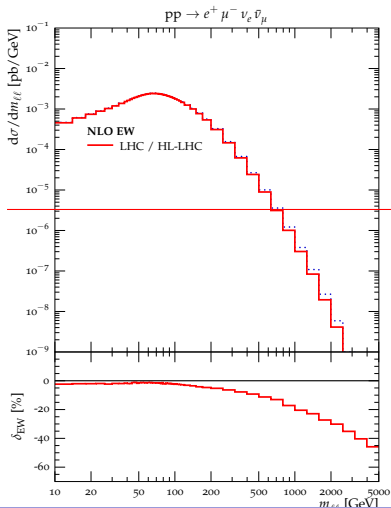
New physics searches

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 . **EW Sudakovs**. Thus, $\mathcal{O}(20\%)$ corrections possible already for LHC range.

Why and where are EW corrections important?

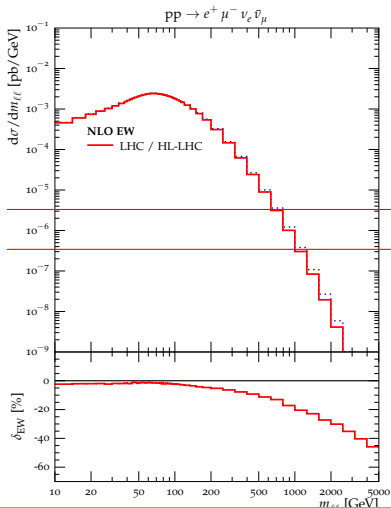
Why care about the tails of distributions?



- 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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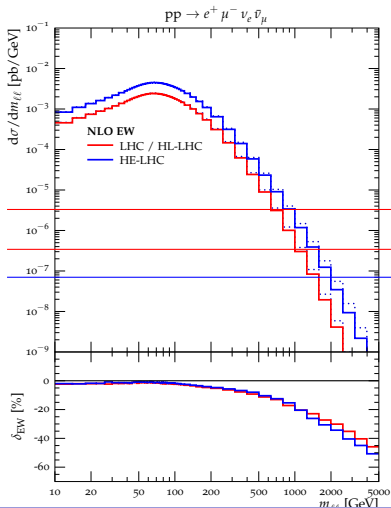
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$\frac{1 \text{ evt}}{\text{GeV}}$

LHC

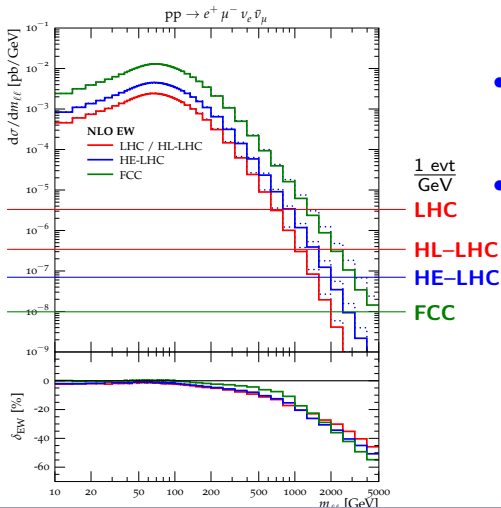
HL-LHC

HE-LHC

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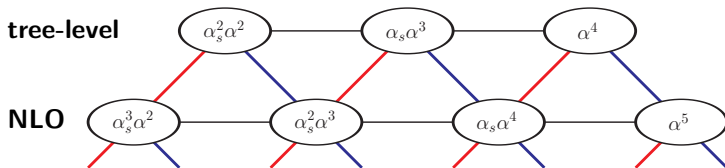
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Higher order corrections

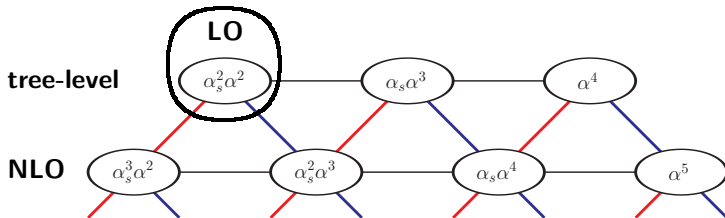
Example: Vjj production



- 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

Higher order corrections

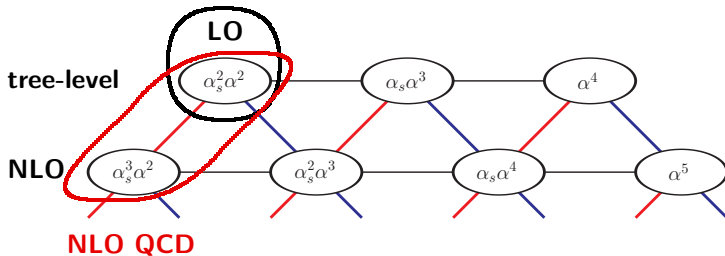
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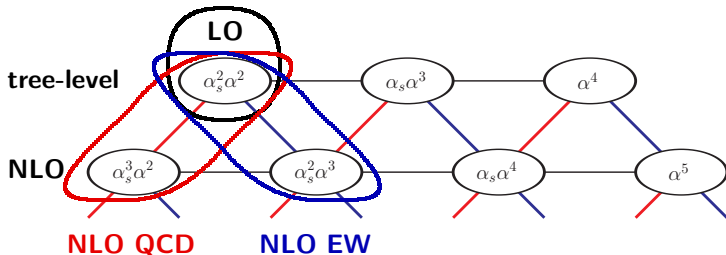
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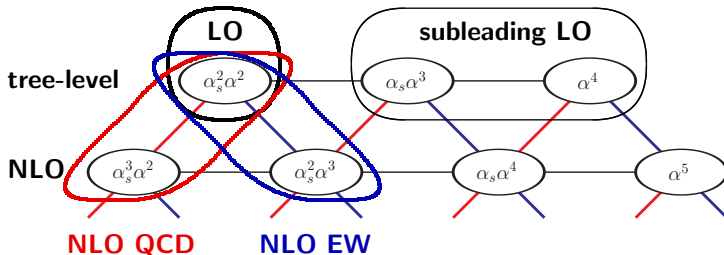
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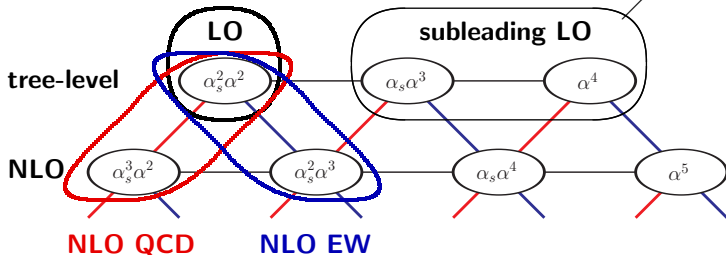
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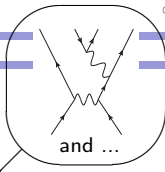
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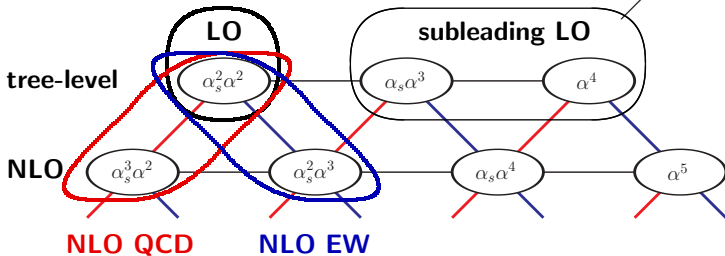


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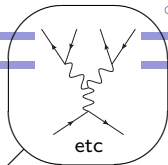


Higher order corrections

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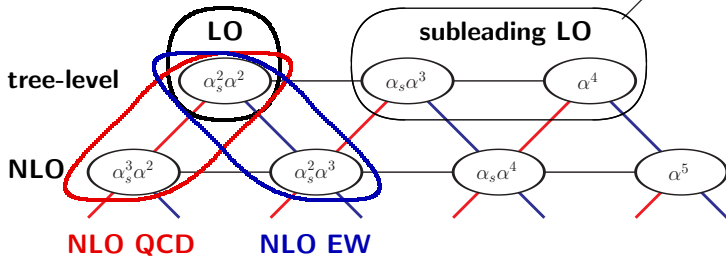


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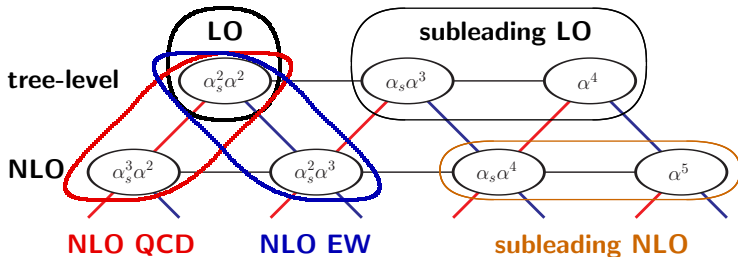
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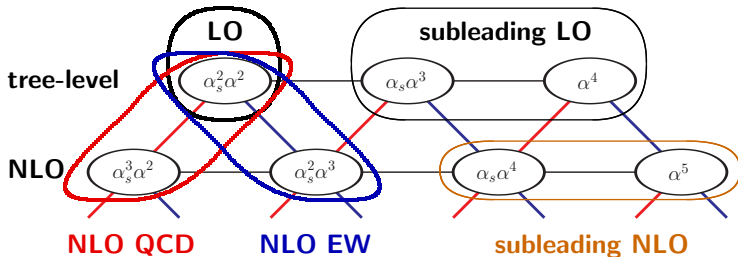
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Definition of physical objects

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

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

⇒ 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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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
- $pp \rightarrow 2\ell 2\nu, 4\ell$ Kallweit, Lindert, Pozzorini, MS '17, Gütschow, MS '20
- $pp \rightarrow t\bar{t}/t\bar{t}j$ Gütschow, Lindert, MS '18
- $pp \rightarrow t\bar{t}h$ LH'15

- SHERPA+GOSAM

- $pp \rightarrow \gamma\gamma + 0, 1, 2 \text{ jets}$ Chiesa et.al. '17
- $pp \rightarrow \gamma\gamma/\gamma\ell\nu/\gamma\ell\ell$ 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
- $pp \rightarrow 2\ell 2\nu + 0, 1 \text{ j}$ Bräuer, Denner, Pellen, MS, Schumann '20

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General setup

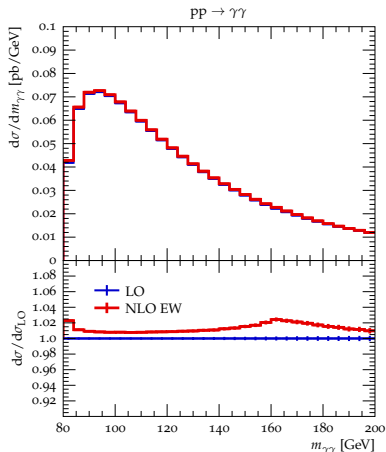
- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$
- input parameters for the following calculations

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

- EW parameter renormalisation in G_μ -scheme
- photon induced processes considered throughout

Diphoton production – $\gamma\gamma$

Chiesa, Greiner, MS, Tramontano '17

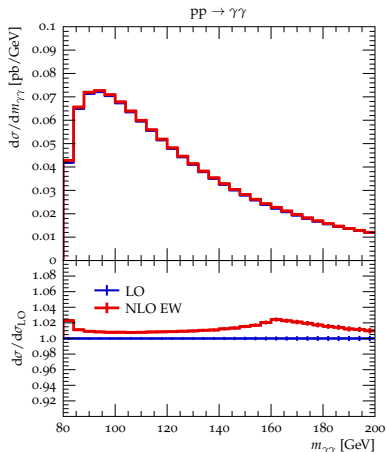


NLO EW corrections to diphoton production

- 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

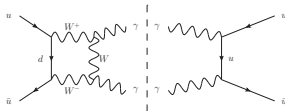
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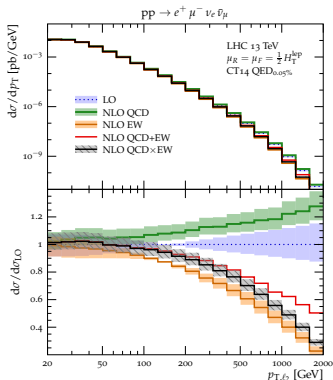
- peak-like enhancement around $m_{\gamma\gamma} = 2 m_W$
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Diboson production – $2\ell 2\nu$ – DF and SF

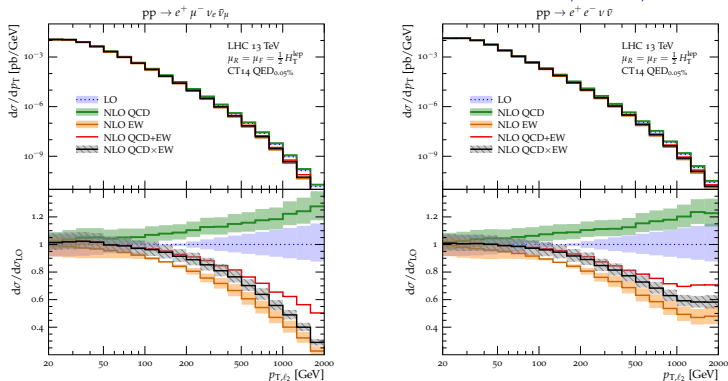
Kallweit, Lindert, Pozzorini, MS '17



- EW Sudakovs – logarithmic suppression at large momentum transfer
- ZZ dominant at very large p_T in SF
→ different EW corrections, take care when extrapolating

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R_{32} – Three-jet production

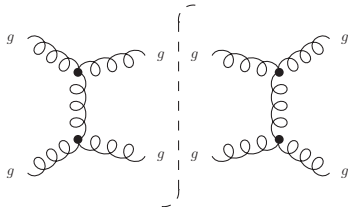
- **define jets completely democratically,**
incl. all massless visible particles of the SM (q, g, γ, ℓ)
 $p_T(j_1) > 80 \text{ GeV}, p_T(j_i) > 60 \text{ GeV} (i > 1)$

- **anti-tag jets against leptons**
exclude jets with net lepton number within lepton acceptance
care: jet acceptance and lepton acceptance may differ
here: $|\eta(j)| < 2.8, |\eta(\ell)| < 2.5$

Three-jet production – contributing configurations

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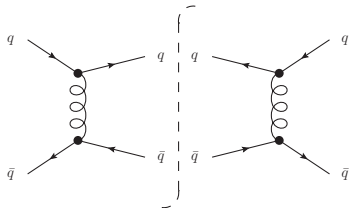
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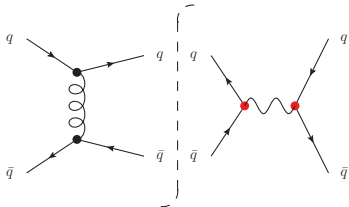
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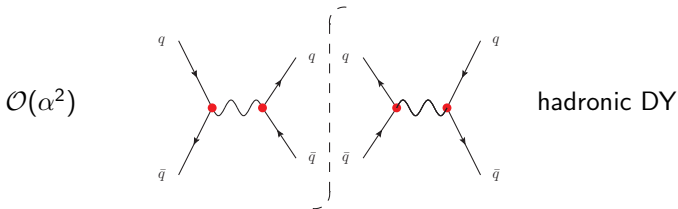
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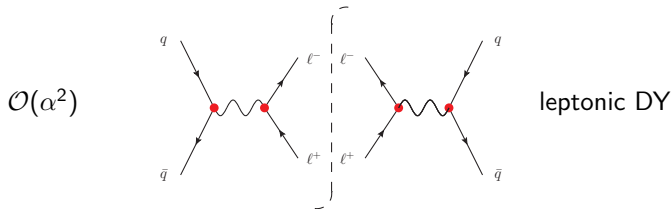
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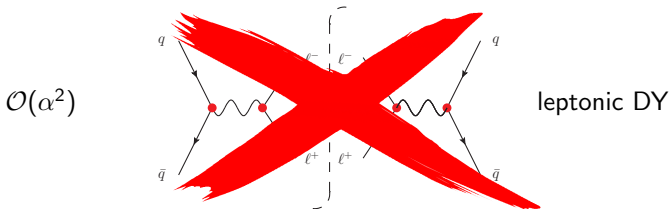
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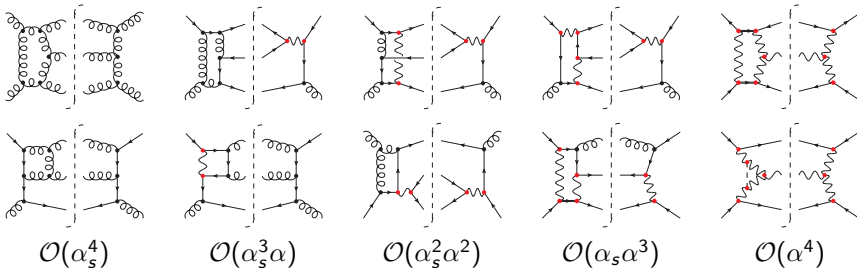
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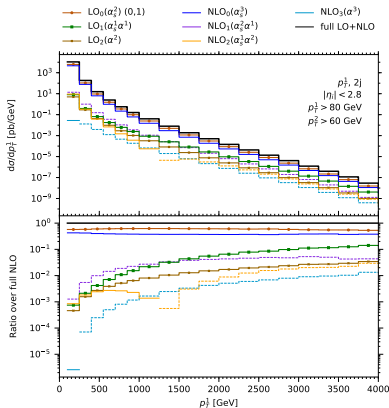
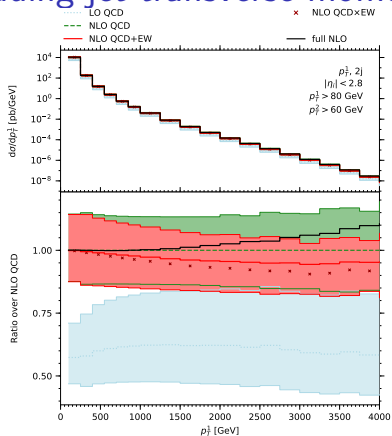
Contributions at NLO



- 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

Selected results

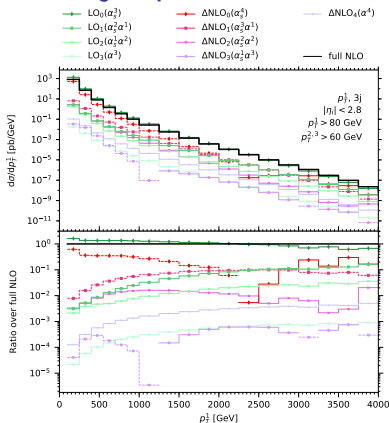
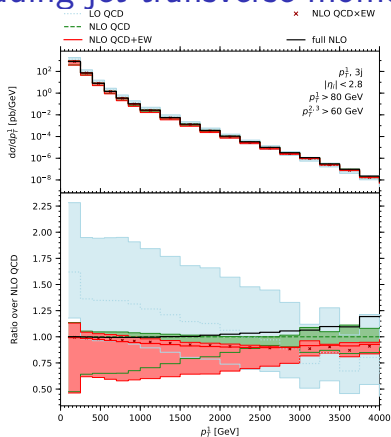
Leading jet transverse momenta in dijet production



- moderate EW corrections
- overcompensated by subleading orders

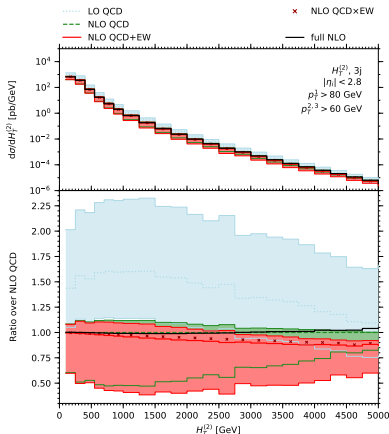
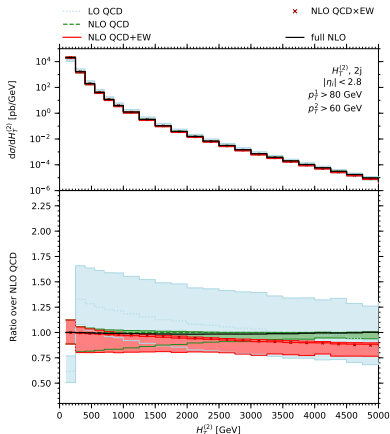
Selected results

Leading jet transverse momenta in 3-jet production

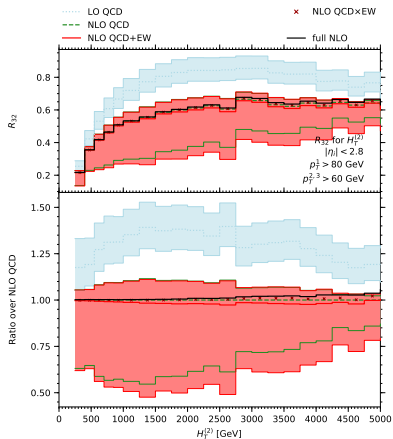


- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

Selected results

 $H_T^{(2)}$ 

- 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

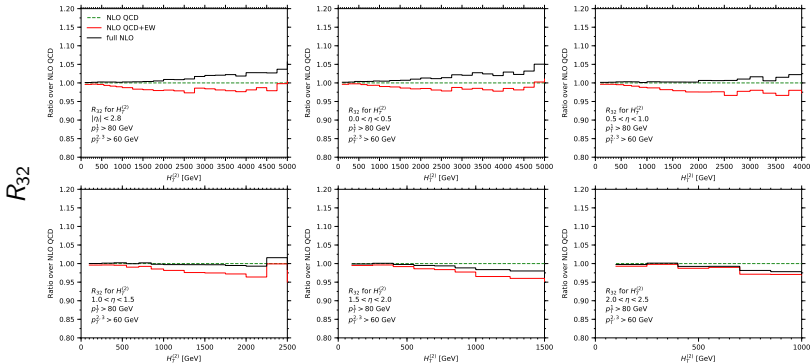
R_{32} 

- NLO EW and subleading order contribs 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 α_s extraction

Selected results

R_{32} in different Δy -slices



- different net effects in different rapidity slices

Electroweak corrections for LHC physics

1 Introduction

Why and where are EW corrections important?

2 Electroweak corrections at fixed-order NLO

Setup, subtleties and automation
Selected results

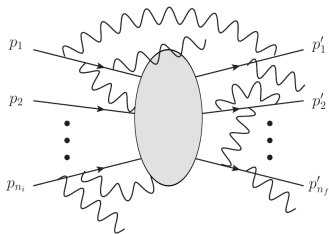
3 Electroweak corrections in Event Generators

Soft-photon resummation
EW virtual approximation

4 Conclusions

Soft-photon resummation

- universal soft-photon limit of all-order QED amplitudes
(Abelian nature and fermion masses/absence of divergent photon splittings essential) Yennie, Frautschi, Suura '61

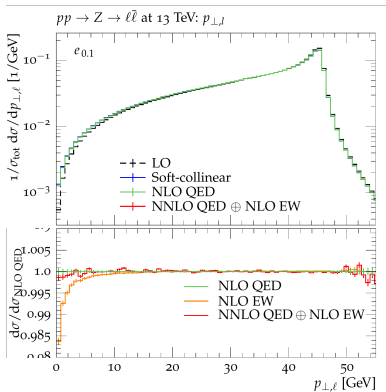
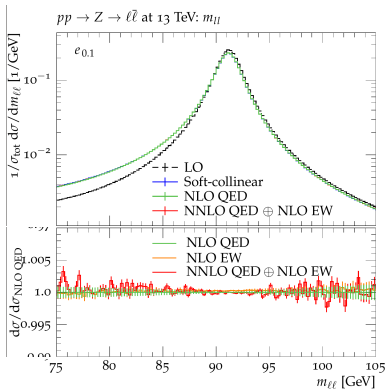


$$d\sigma^{\text{YFS}} = \sum_{n_\gamma} \frac{1}{n_\gamma!} d\Phi e^Y \prod_{i=1}^{n_\gamma} [d\Phi_{k_i} \cdot \alpha \tilde{S}(k_i)] \left[\tilde{\beta}_0 + \sum_{i=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_i)}{\tilde{S}(k_i)} + \dots \right]$$

- coherent multiple soft-photon emission from Eikonals \tilde{S}
- re-orders perturbative series in terms of hard-remainders $\tilde{\beta}_i$ defined on reduced phase spaces in multiphoton configurations

Soft-photon resummation

MS, Krauss '08; Krauss, Lindert, Linten, MS '18



- implementation in SHERPA: matched to NNLO QED + NLO EW
- permille accuracy in the description of the $Z \rightarrow \ell\bar{\ell}$ kinematics

EW virtual approximation

Kallweit, Lindert, Maierhöfer, Pozzorini, MS '15

- ultimate goal: incorporate EW corrections in standard/established parton showered event generation
- construct approximation that only reweights a Born configuration

$$\delta_{EW}^{\text{approx}}(\Phi_n) = \frac{V_n^{\text{EW}}(\Phi_n) + I_n^{\text{EW}}(\Phi_n)}{B_n(\Phi_n)}$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)

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approximate integrated real contribution

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EW virtual approximation

Recovering real photon emission corrections

- important for any lepton distribution, inv. masses in particular $\mathcal{O}(1)$ effects below resonance peaks or on-shell thresholds
- YFS soft-photon resummation

Yennie, Frautschi, Suura '61
MS, Krauss '08

$$d\Gamma^{\text{YFS}} = d\Gamma_0 \cdot e^{\alpha Y(\omega_{\text{cut}})} \cdot \sum_{n_\gamma} \frac{1}{n_\gamma!} \left[\prod_{i=1}^{n_\gamma} d\Phi_{k_i} \cdot \alpha \tilde{S}(k_i) \Theta(k_i^0 - \omega_{\text{cut}}) \cdot \mathcal{C} \right]$$

- other popular options among experiments: PHOTOS

Resonance identification

- internal resonance structure of event must be preserved, identify lepton pair if $(f_j = \ell, \nu)$, treat separately in NWA

$$\Delta = |m_{f_1 f_2} - m_{\text{res}}| / \Gamma_{\text{res}} < \Delta_{\text{thr}}$$

EW virtual approximation

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EW virtual approximation in 4ℓ production

Gütschow, MS '20

- investigate quality of approximation in 4ℓ production, using exact NLO EW as reference (G_μ vs. $\alpha(m_Z)$ as uncertainty estimate)
- use fiducial phase space of ATLAS analysis ATLAS '19
 - $p_T(\ell_1, \ell_2, \ell_3, \ell_4) > (20, 15, 10, 7)$ GeV
 - sliding window for subleading $m_{\ell\ell}$ in dependence on $m_{4\ell}$
- investigate different systematic uncertainty
 - dependence on ΔR_{dress} : [0.005, 0.02, 0.1, 0.2]
 - resonance identification Δ_{thr} : [1, 10]
 - QED FSR resummation: [YFS, PHOTOS]

EW virtual approximation in 4ℓ production

scheme	fiducial cross-section [fb]					
	LO	NLO EW	NLO EW _{approx} × YFS		NLO EW _{approx} × PHOTOS	
			$\Delta_{\text{thr}} = 1$	$\Delta_{\text{thr}} = 10$	$\Delta_{\text{thr}} = 1$	$\Delta_{\text{thr}} = 10$
$\mu^+ \mu^- \mu^+ \mu^-$						
$\alpha_{G\mu}^4 \cdot \alpha(0)$	8.99	8.56	8.54	8.54	8.55	8.55
$\alpha^4(m_Z) \cdot \alpha(0)$	8.11	8.33	8.34	8.34	8.36	8.36

scheme	fiducial cross-section [fb]		
	LO	NLO EW	NLO EW _{approx} × YFS
$\mu^+ \nu_\mu e^- \bar{\nu}_e$			
$\alpha_{G\mu}^5$	319.7	310.8	313.3

- good agreement for inclusive cross section accidental, approximation not constructed for this limit

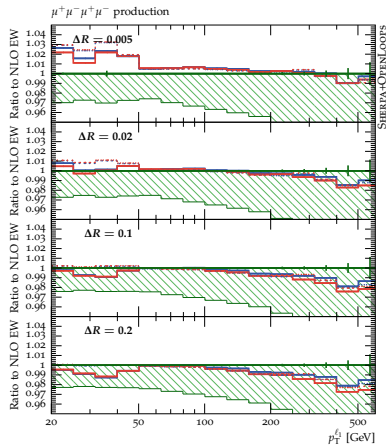
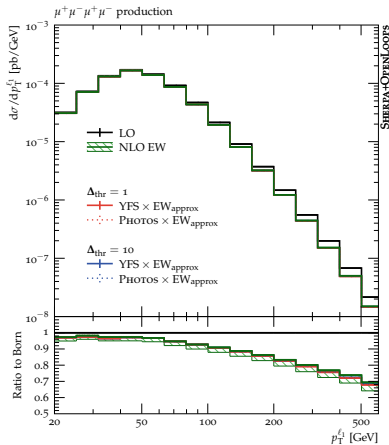
EW virtual approximation in 4ℓ production

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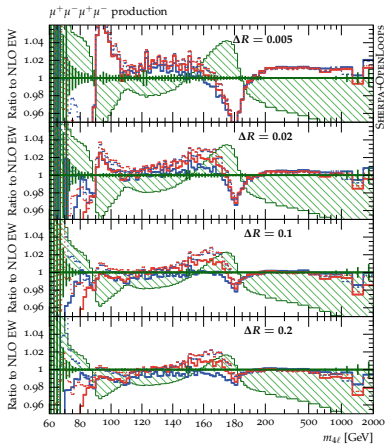
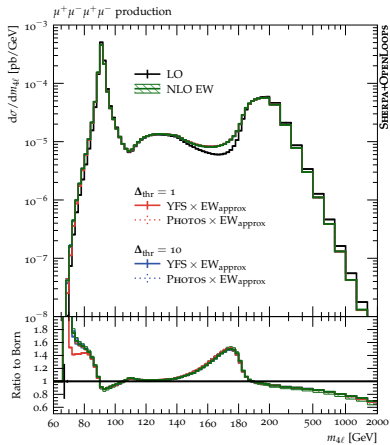
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EW virtual approximation in 4ℓ production



EW virtual approximation in 4ℓ production



EW virtual approximation in multijet merging

Kallweit, Lindert, Maierhöfer, Pozzorini, MS '15

- 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 and integrated approx. real corrections

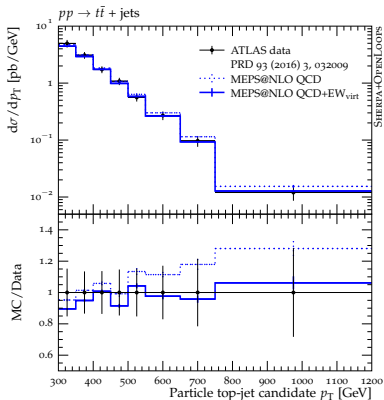
$$\bar{B}_{n,\text{QCD}+\text{EW}_{\text{approx}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + B_n(\Phi_n) \delta_{\text{EW}}^{\text{approx}} + B_{n,\text{mix}}(\Phi_n)$$

$$\bar{B}_{n,\text{QCD}\times\text{EW}_{\text{approx}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) (1 + \delta_{\text{EW}}^{\text{approx}}) + B_{n,\text{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging

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

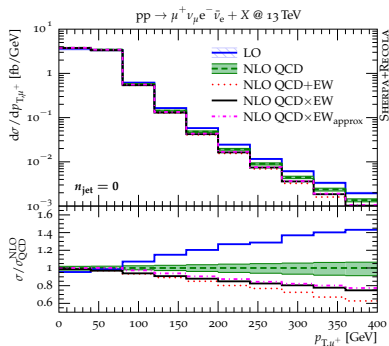
Gütschow, Lindert, MS in '18



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

Höhe, Krauss, MS, Siegert '10

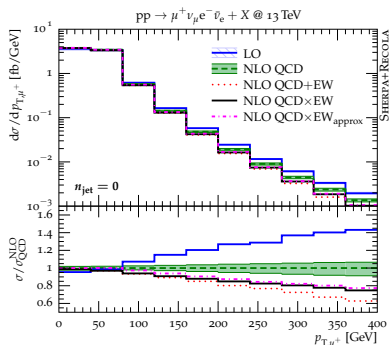
$2\ell 2\nu$ production



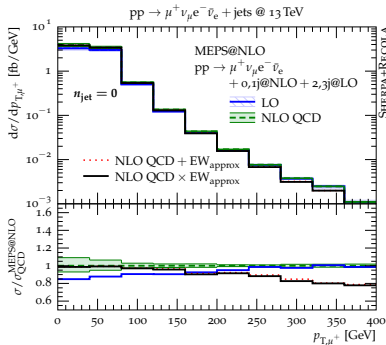
Bräuer, Denner, Pellen, MS, Schumann '20

- investigate EW_{virt} approximation in exclusive jet bins
- use W^+W^- as relevant for Higgs measurements
- include in multijet merging
pp $\rightarrow \mu^+ \nu_\mu e^- \bar{\nu}_e$
+ 0, 1j@NLO + 2, 3j@LO

$2l2\nu$ production – $n_{\text{jet}} = 0$ selection



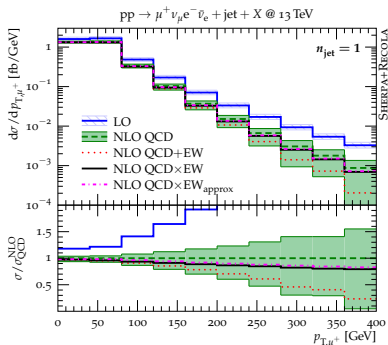
fixed-order



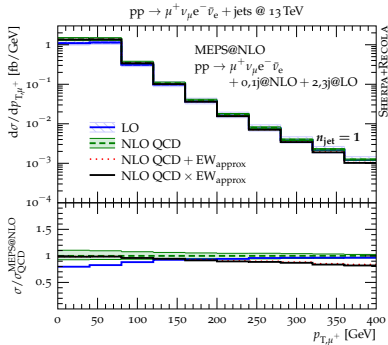
multijet merged

- EW corrections well reproduced at large momentum transfer
- parton shower resummation stabilises results

$2\ell 2\nu$ production – $n_{\text{jet}} = 1$ selection



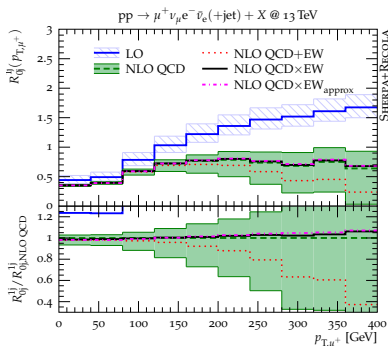
fixed-order



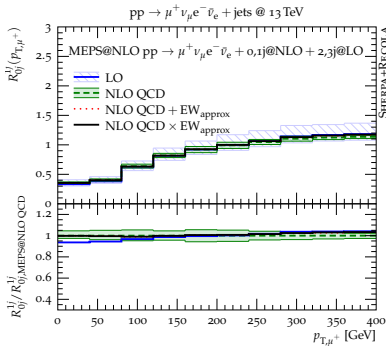
multijet merged

- fixed-order results pathological due to jet-veto logarithms
- parton shower resummation stabilises results

$2\ell 2\nu$ production – $(n_{\text{jet}} = 1)/(n_{\text{jet}} = 0)$ ratio



fixed-order



multijet merged

- fixed-order results pathological due to jet-veto logarithms
- parton shower resummation stabilises results

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 (and beyond)
 - ⇒ included since SHERPA-2.2.1
(since SHERPA-2.2.9 both in add. and mult. scheme)
- 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 (SHERPA-3.0)

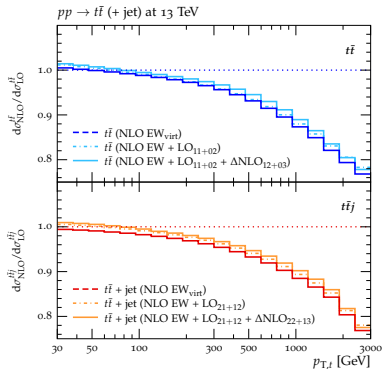
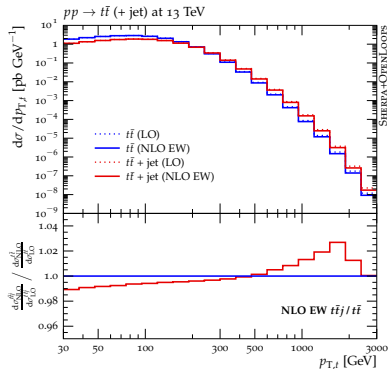
<http://sherpa.hepforge.org>

Thank you!

Backup

Top pair production in association with jets

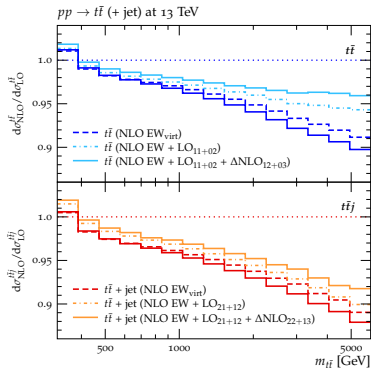
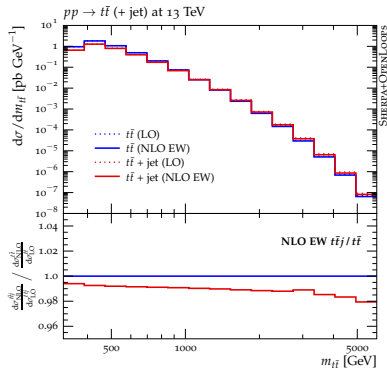
Gütschow, Lindert, MS in '18



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

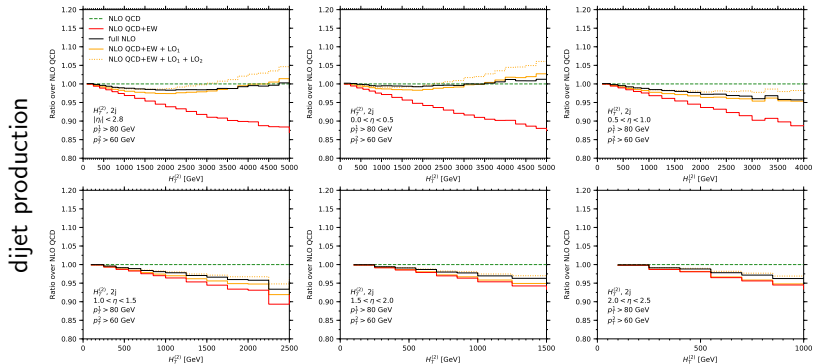
Top pair production in association with jets

Gütschow, Lindert, MS in '18



Observation: subleading orders important

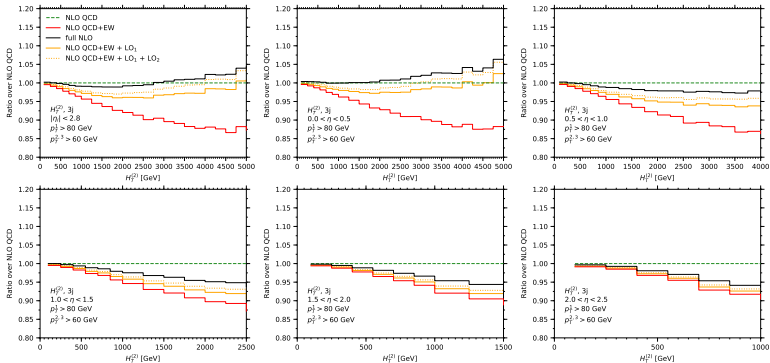
R_{32} in different Δy -slices



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

R_{32} in different Δy -slices

three jet production



- slightly different in 3-jet production