Electroweak corrections for LHC physics

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IPPP, Durham University

Overview

1. Introduction
   - Why and where are EW corrections important?
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

Why and where are EW corrections important?

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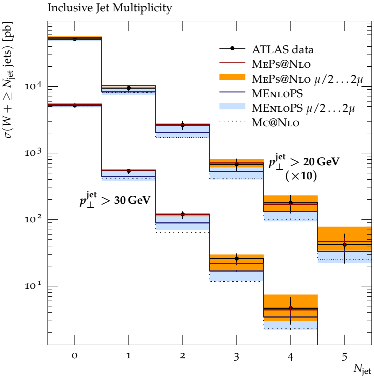
Available and needed precision

Höche, Krauss, MS, Siegert '12



start of the LHC:

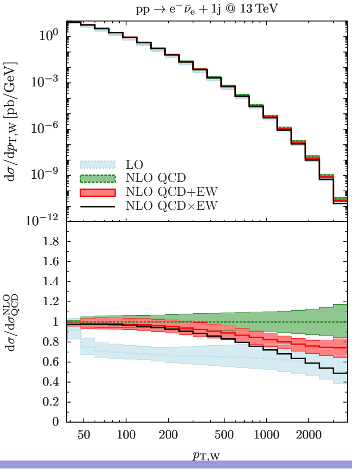
- QCD the great unknown
  - NLO QCD automated ✓
  - NLO QCD multijet merging baseline MC for the LHC ✓
  - NNLO QCD where required ✓

LHC Run II and beyond:

- emergence of EW corrections
  - precision measurements (sub)percent accuracy ✗
  - high-p_{T} distributions tens of percent corrections ✗

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

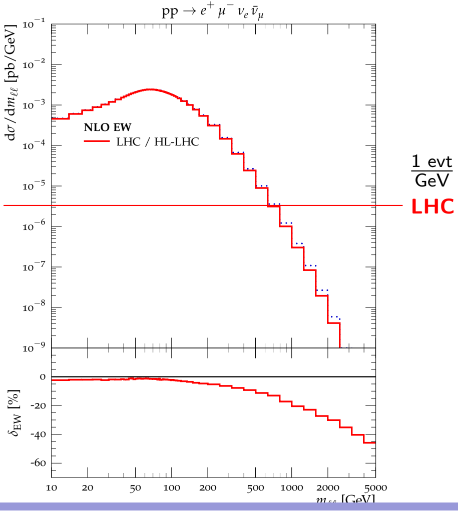
Electroweak corrections are of $\mathcal{O}(\alpha)$, thus generally of $\mathcal{O}(1\%)$. Roughly, their size can be gauged by $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$.

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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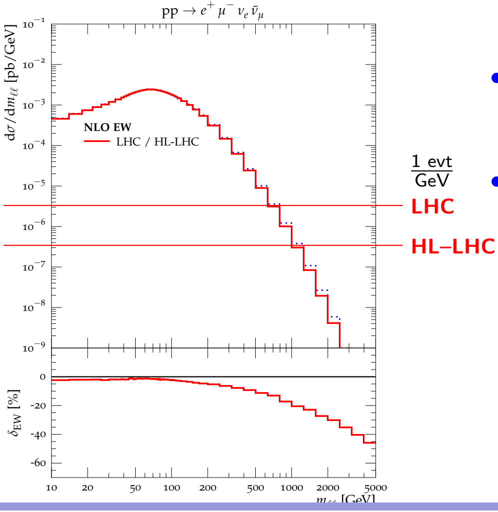

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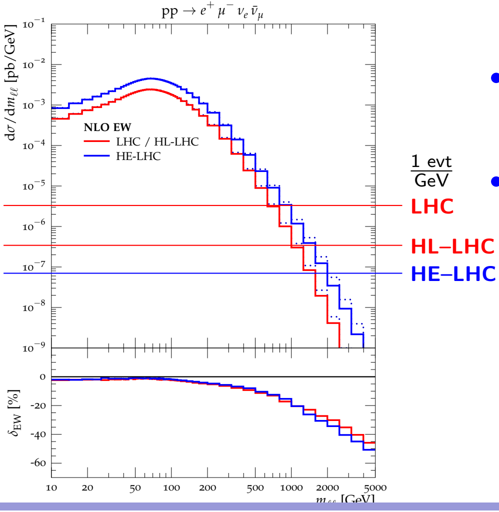

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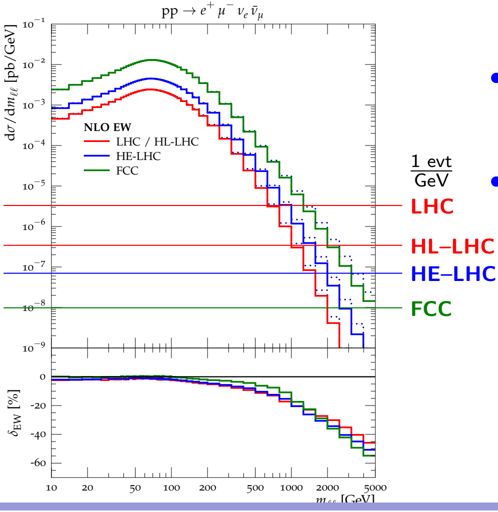

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Electroweak corrections

Electroweak correction can often be separated in QED and genuine weak corrections.

Virtual weak 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 weak 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.

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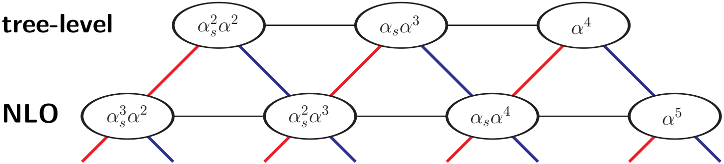
Higher order corrections

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 ↔ jets)
  - introduce similar concepts in EW sector for photons and leptons

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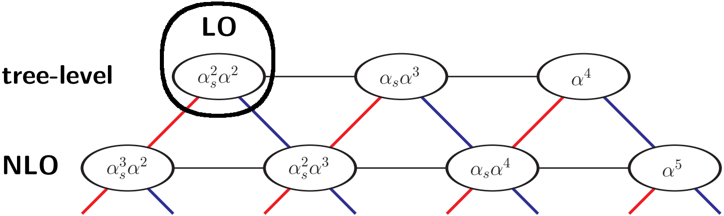

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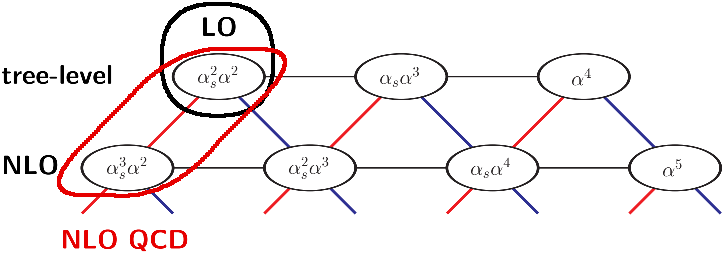

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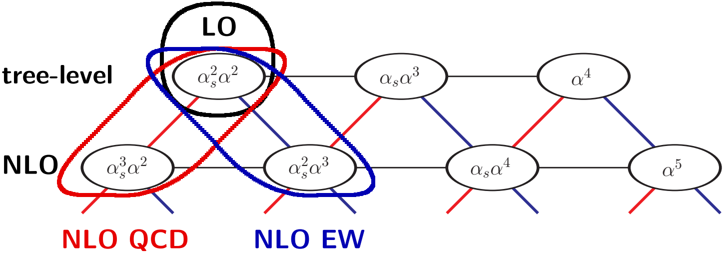

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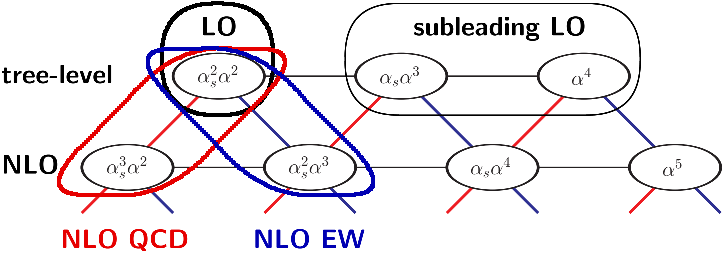

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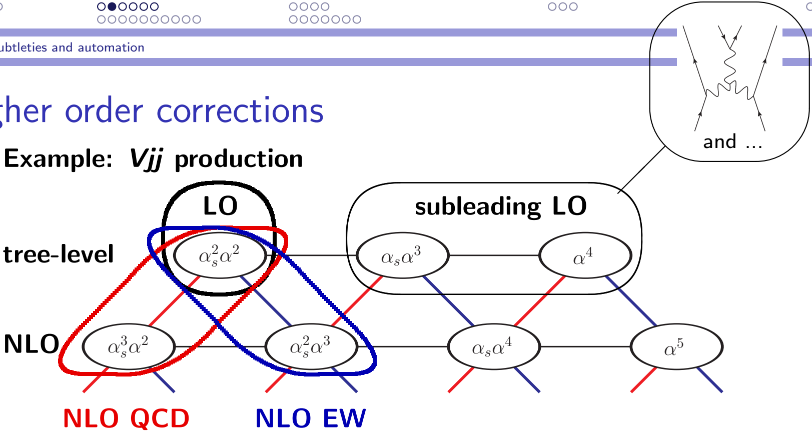

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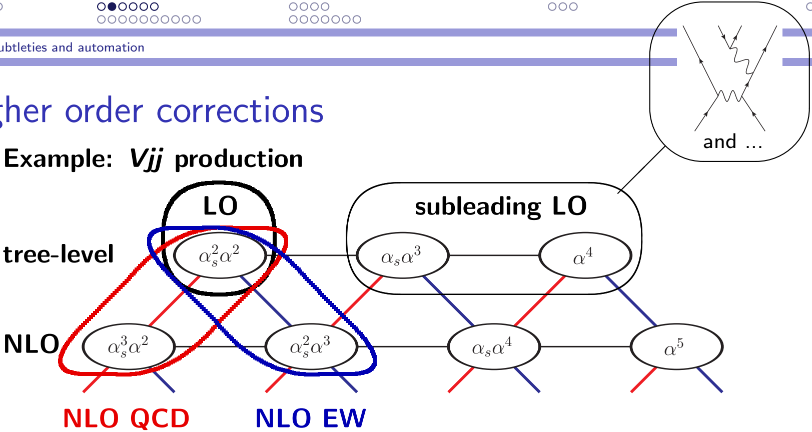

LO

subleading LO

tree-level $\alpha_s^2\alpha^2$ $\alpha_s\alpha^3$ α^4

NLO $\alpha_s^3\alpha^2$ $\alpha_s^2\alpha^3$ $\alpha_s\alpha^4$ α^5

NLO QCD **NLO EW**

and ...

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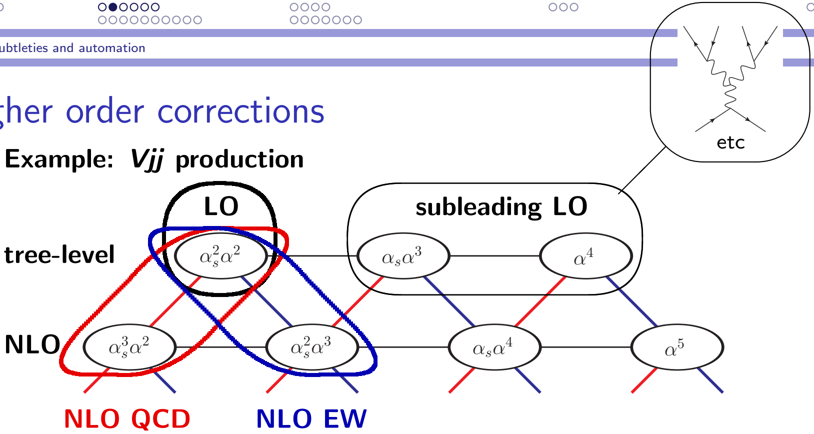

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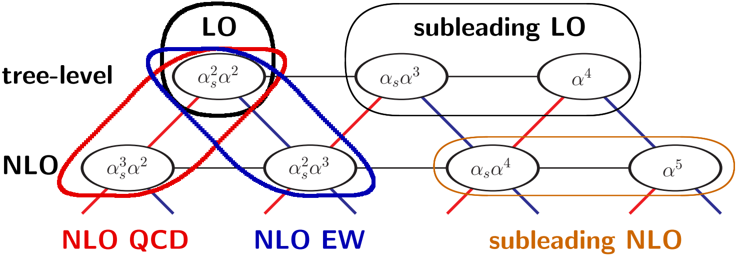

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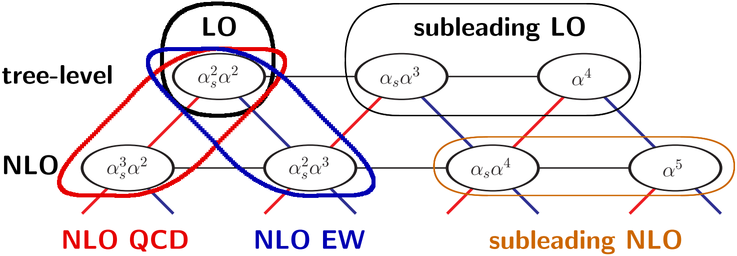

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Definition of physical objects

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

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

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

What is a lepton?

- simplified as leptons not gauge bosons
- dressed lepton: masseless 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:
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ jets — FCC report, EW report, LH'15; Kallweit, Lindert, Maierhöfer, Pozzorini, MS '14, '15; Lindert et.al. '17
  - $pp \to Vh$ — FCC report '16
  - $pp \to 2\ell 2\nu$ — Kallweit, Lindert, Pozzorini, MS '17
  - $pp \to t\bar{t}/t\bar{t}j$ — Gütschow, Lindert, MS '18
  - $pp \to t\bar{t}h$ — LH'15
- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets — Chiesa et.al. '17
  - $pp \to \gamma\gamma\gamma\,/\,\gamma\gamma\ell\nu\,/\,\gamma\gamma\ell\ell$ — Greiner, MS '17
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. '17
  - $pp \to 3\ell 3\nu$ — MS '18
  - $pp \to jj/jjj$ — Reyer, MS, Schumann '19
  - $pp \to 2\ell 2\nu + 0, 1$ j — to appear

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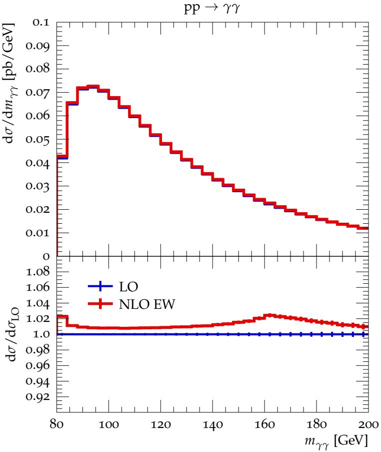
General setup

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

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

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

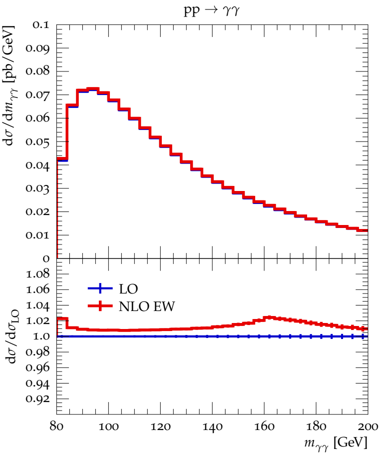
Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

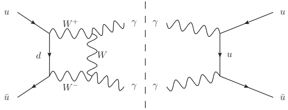
- peak-like enhancement around $m_{\gamma\gamma} \approx 160\,\text{GeV}$
- induced by W-box creating pseudo-resonant structures
- should be accounted for in data-driven background fits in diphoton resonance searches

Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

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



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

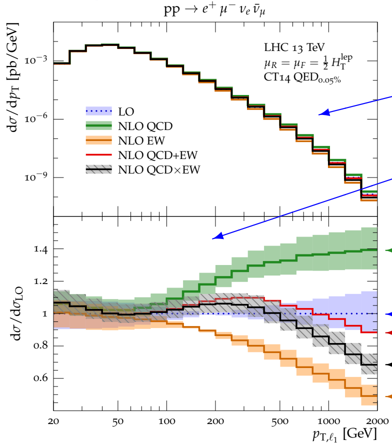
Kallweit, Lindert, Pozzorini, MS '17

- 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, ($p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$), $|\eta_\ell| < 2.5$),
  $n_f = 4$ 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



absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

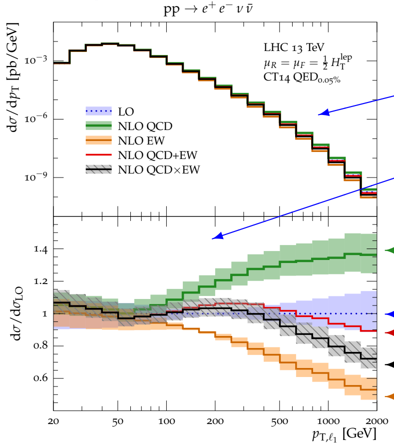
NLO QCD+EW

NLO QCD×EW

NLO EW

- large pos. NLO QCD, large neg. NLO EW
  → NLO QCD+EW and NLO QCD⊗EW differ significantly

Diboson production – $2\ell2\nu$ – SF



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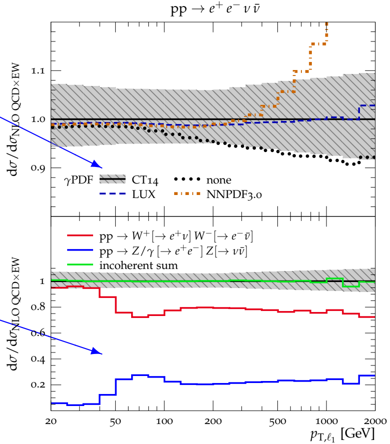
Diboson production – $2\ell 2\nu$ – SF

relative importance of γ-induced channels wrt. NLO QCD×EW

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed

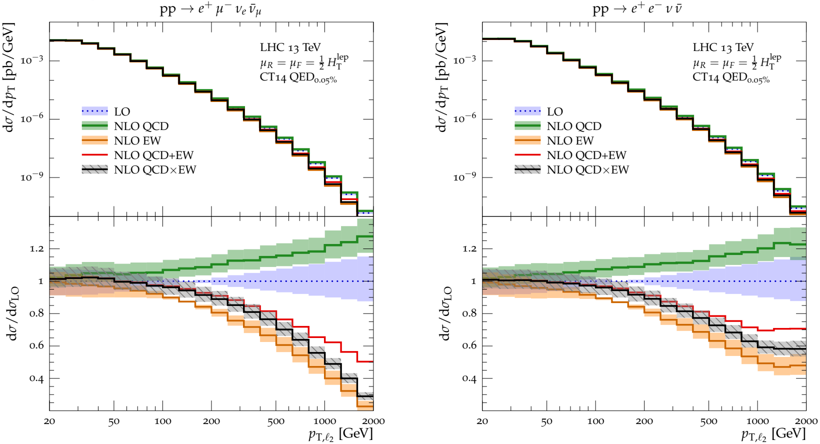
rel. contribs of WW and ZZ subtops

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



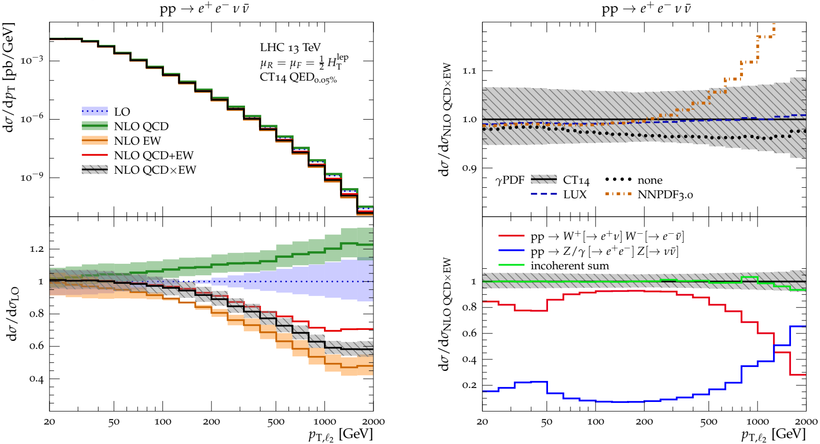
- WW dominant throughout, ZZ only contribs 10-20%
  → overall very similar to DF case

Diboson production – $2\ell2\nu$ – DF and SF



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

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



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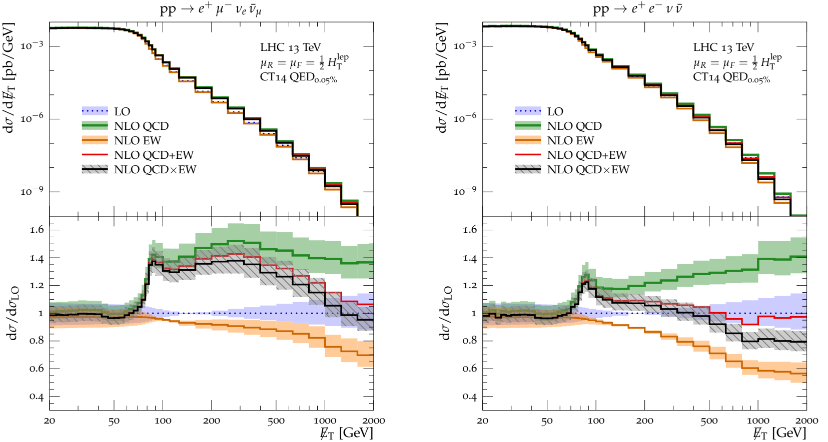
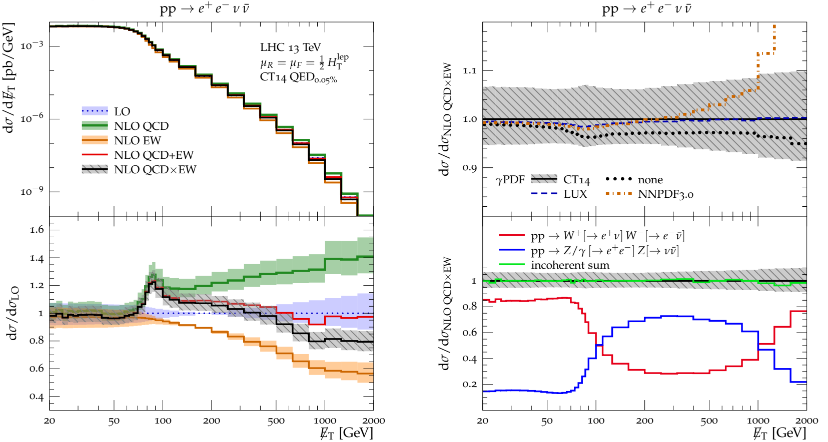
Diboson production – $2\ell 2\nu$ – DF and SF



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

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



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

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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:

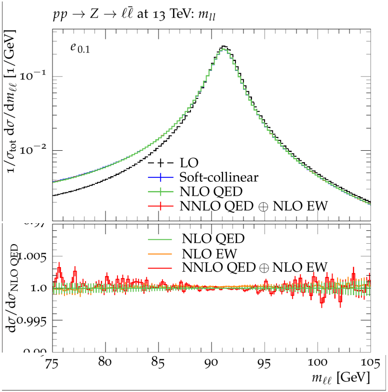
- $W - m_W$
- $Z - \sin\theta_w^{\text{eff}}$, A_{FB}, $A_0 \ldots A_8$

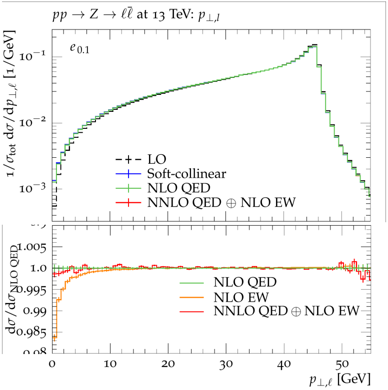
To reach the desired theoretical accuracy, many different aspects need to be controled:

- 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 $Z \to \ell\ell$ kinematics

Determination of the strong coupling α_s

Typically, α_s at hadron colliders extracted from ratio of three-jet production to two-jet production.
Necessitates precise predictions over large kinemtatic ranges, from a few tens of GeV to the multi-TeV regime.

Dijet production

- NNLO QCD — Currie et.al. '17
- NLO QCD — Ellis, Kunszt, Soper '92; Giele, Glover, Kosower '93
- NLO EW and all subl. corrections — Moretti, Nolten, Ross '06; Dittmaier, Huss, Speckner '12; Frederix et.al. '16

Three-jet production

- NLO QCD — Nagy '01
- NLO EW and all subl. corrections — Reyer, MS, Schumann '19

Three-jet production – contributions

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

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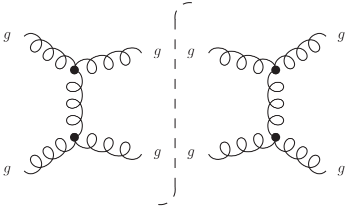
$\mathcal{O}(\alpha_s^2)$



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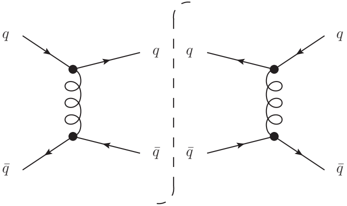

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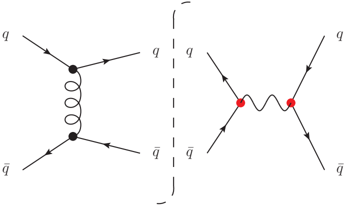
$\mathcal{O}(\alpha_s\alpha)$



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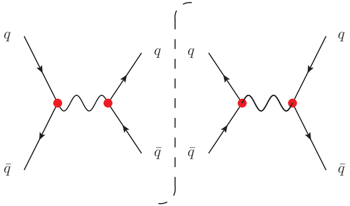
$\mathcal{O}(\alpha^2)$



hadronic DY

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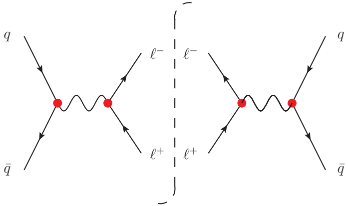

leptonic DY

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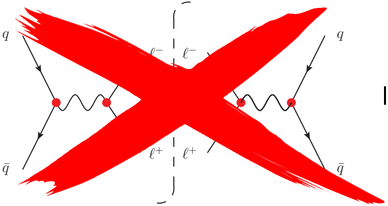

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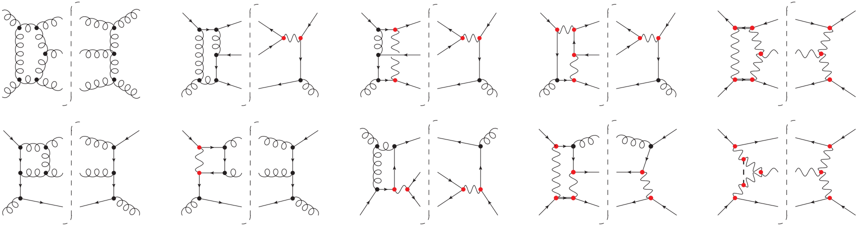
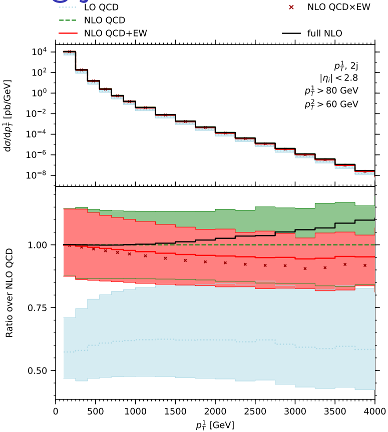
Contributions at NLO

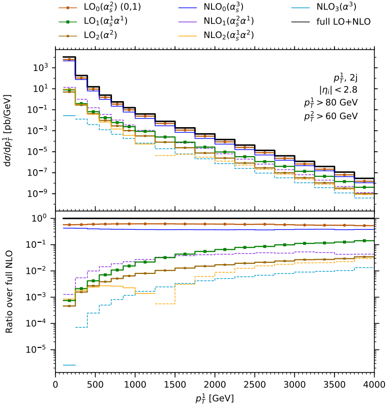


$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell\nu qg$, $\ell\ell qg$, $\ell\ell\ell\ell$, $\ell\ell\ell\nu$ final states

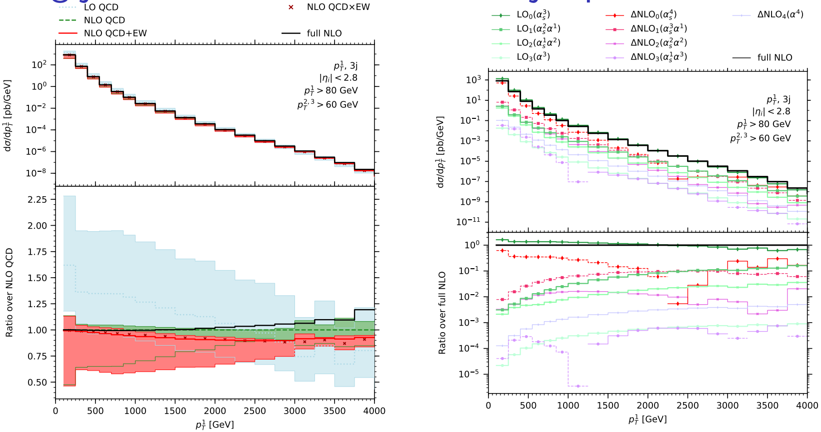
Leading jet transverse momenta in dijet production





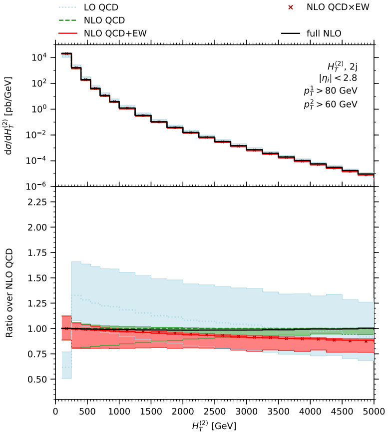
- moderate EW corrections
- overcompensated by subleading orders

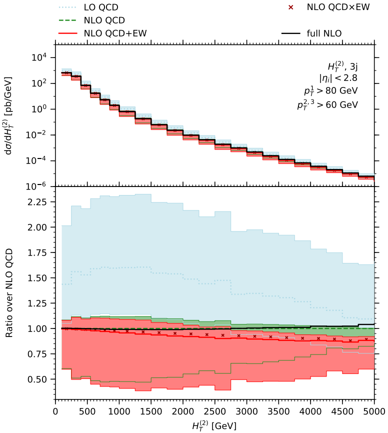
Leading jet transverse momenta in 3-jet production



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

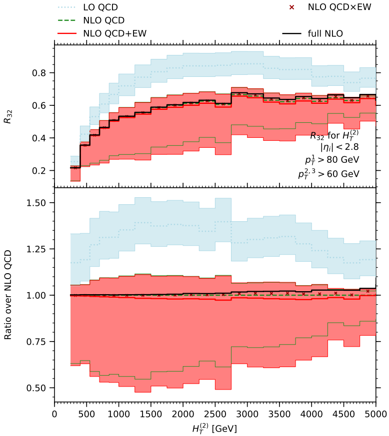
$H_{\mathrm{T}}^{(2)}$





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

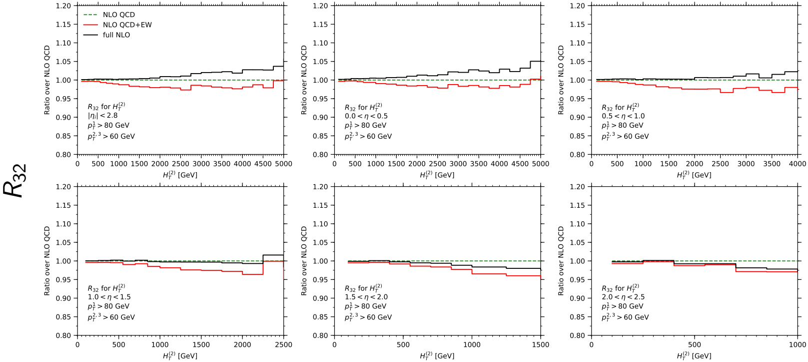
R_{32}



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

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

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 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 in particle-level event generation

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

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

- 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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exact virtual contribution

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optionally include subleading Born

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exact virtual contribution

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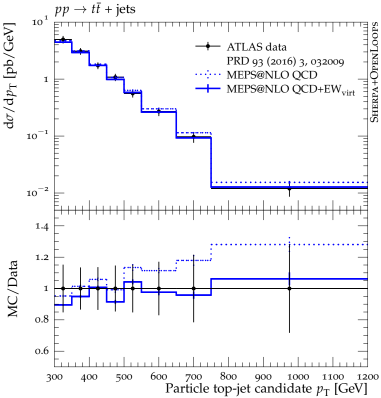
Results: $pp \to t\bar{t} + \text{jets}$

Gütschow, Lindert, MS in '18



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

  Höche, Krauss, MS, Siegert '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
- can be incorporated in multijet merging to improve description in those regions
  ⇒ 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)

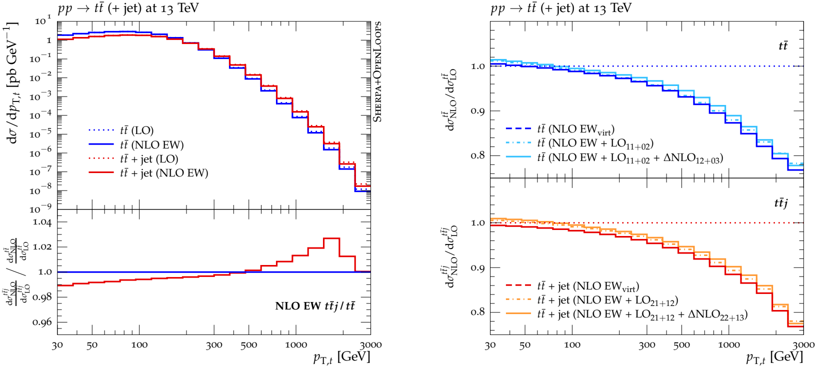
http://sherpa.hepforge.org

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

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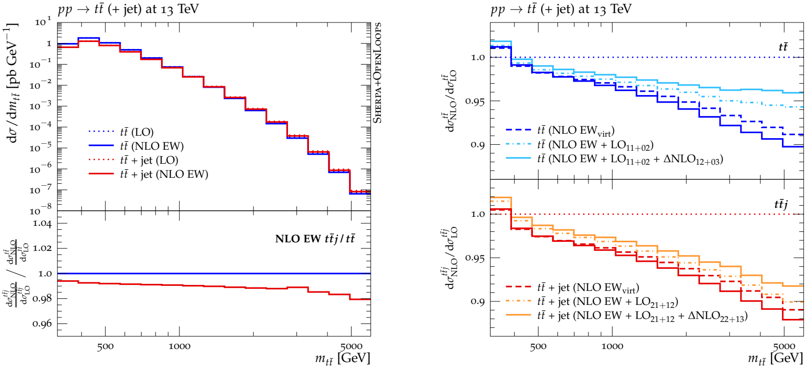
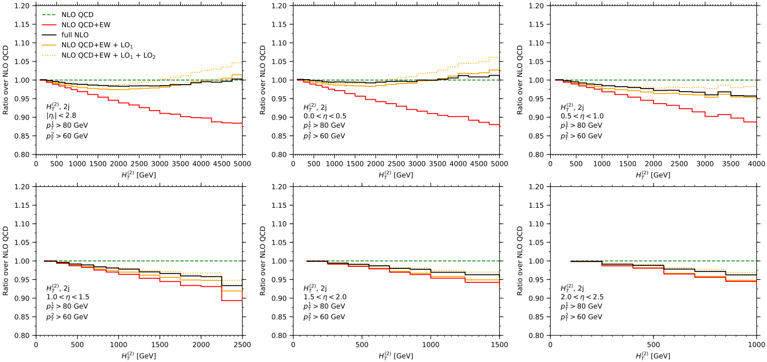


Observation: subleading orders important

R_{32} in different Δy-slices

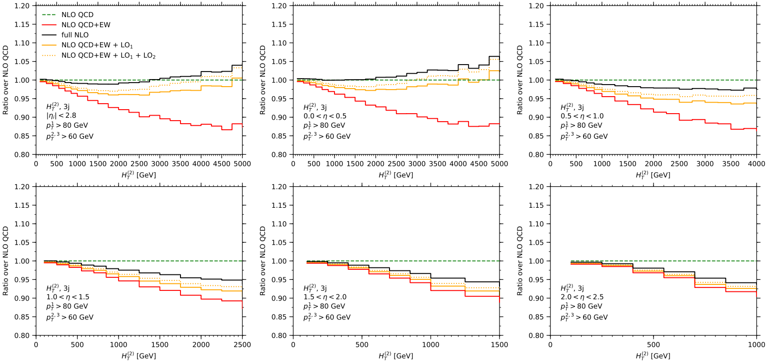
dijet production



- effects already seen in Dittmaier, Huss, Speckner '12

R_{32} in different Δy-slices

three jet production



- slightly different in 3-jet production