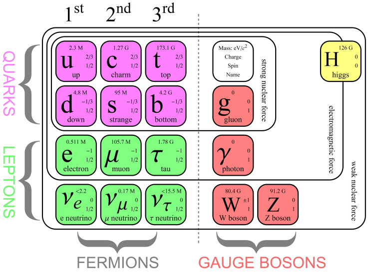
The electroweak sector of the Standard Model and precision calculations for the LHC

Marek Schönherr

IPPP, Durham University

Overview

The Standard Model of Particle Physics



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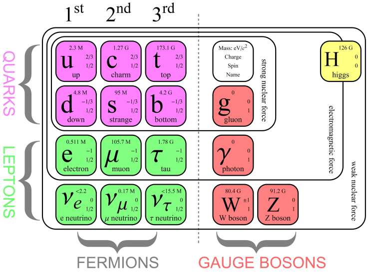

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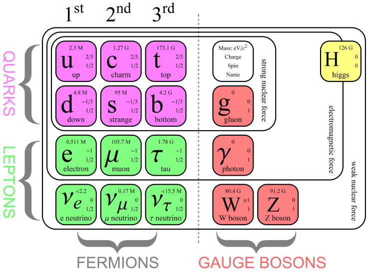

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QCD

unbroken gauge group

α_s

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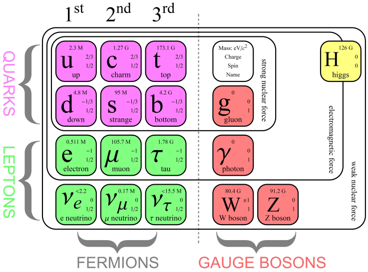

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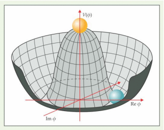


$$\underbrace{SU(3)_c}\times\underbrace{SU(2)_L\times U(1)_Y}$$

QCD

unbroken gauge group

α_s

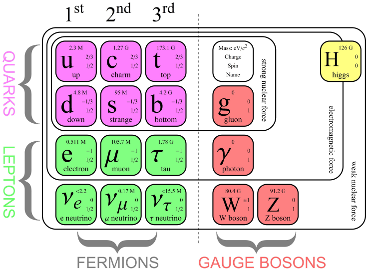
EW theory

spontaneously broken gauge group

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

α

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.

We know the Standard Model is incomplete.
It includes neither dark matter nor neutrino masses.
No even speaking or gravity.
Signs of new physics are sought beyond the currently accessible data.

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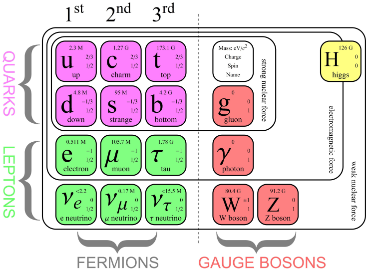

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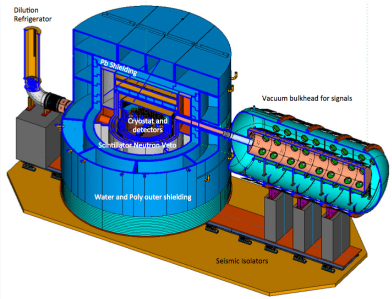
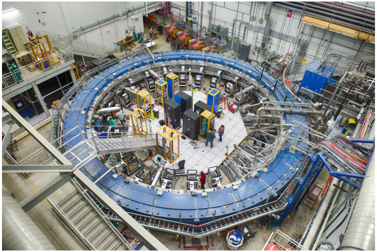
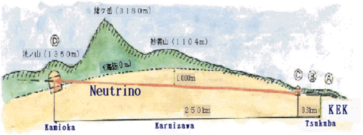
Experimental tests







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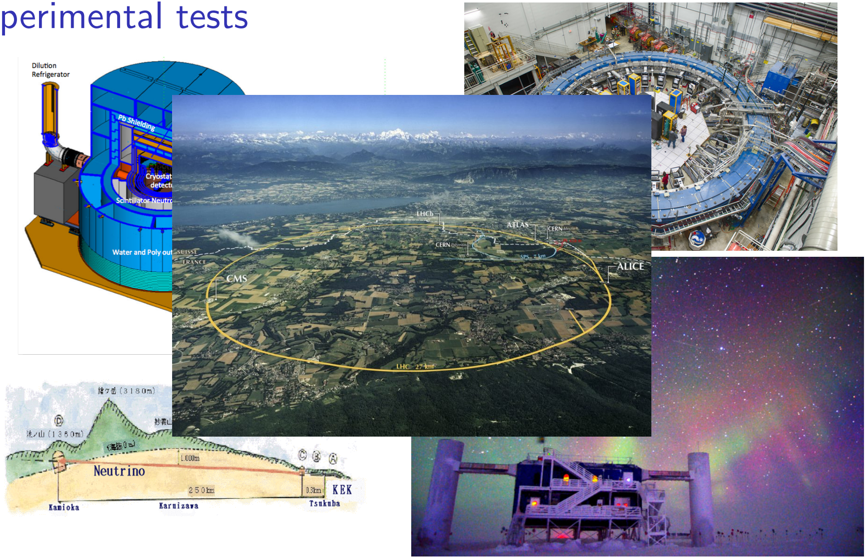
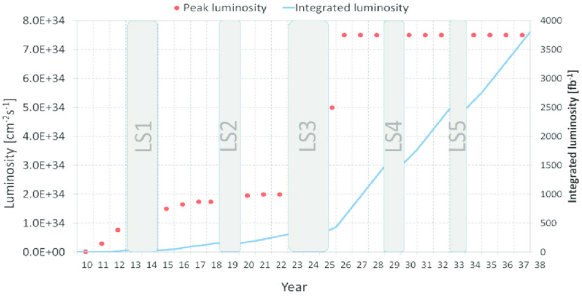


The LHC physics programme

- 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

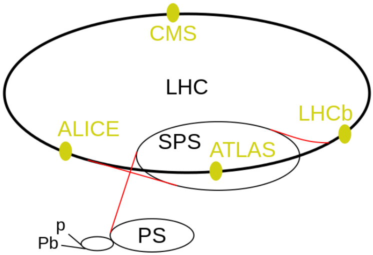


The LHC and beyond

LHC	13 TeV	0.3 ab^{-1}
HL-LHC	14 TeV	3 ab^{-1}
HE-LHC	27 TeV	15 ab^{-1}
FCC	100 TeV	25-100 ab^{-1}

increase in both collision energy and statistical reach

The Large Hadron Collider

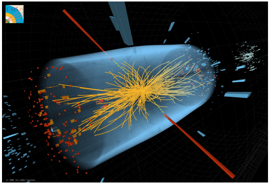


4 LHC experiments

ATLAS, CMS – general purpose
LHCb – B physics, forward physics
ALICE – heavy ion physics, quark-gluon plasma

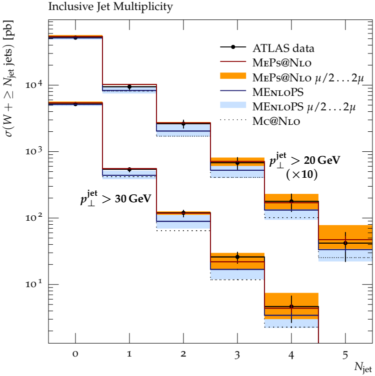
Collider experiments test the Standard Model at various energy scales.

Monte-Carlo Event Generators connect theoretical predictions to data.
HERWIG, PYTHIA, SHERPA



Available and needed precision

Höche, Krauss, MS, Siegert '12



start of the LHC:

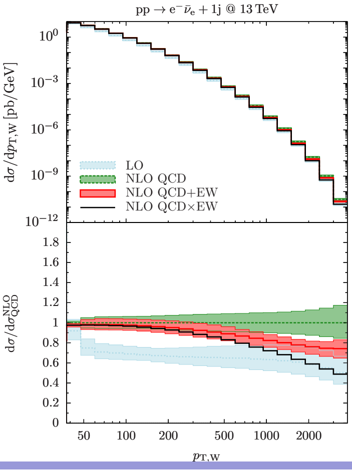
- QCD the great unknown
  - NLO QCD automated ✓
  - NLO QCD multijet merging baseline MC for the LHC ✓
  - NNLO QCD where required ✓

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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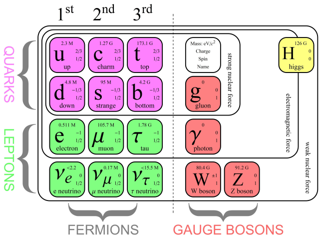
Electroweak corrections for LHC physics

Electroweak corrections

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

Masses, mass separations and hierarchies ($W^\pm$, Z, h, t) are an essential part of the phenomenology.

The remaining $U(1)_\mathrm{QED}$ is non-confining, ie. leptons and photons are observable degrees of freedom.



Asymptotic physical states (p, $e^\pm$) not isospin neutral.

Electroweak corrections

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

Because of the gauge boson masses, weak virtual and real corrections can be separated.

- **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.

Electroweak corrections at large momentum transfers

Denner, Pozzorini Eur.Phys.J. C18 (2001) 461-480, Eur.Phys.J. C21 (2001) 63-79

Typically only virtual corrections due to $W^\pm$ and Z exchange considered. At large momentum transfer gives rise to corrections of the structure

$$-|\widetilde{\mathcal{M}}_{\mathrm{Born}}|^2 \cdot \frac{\alpha}{4\pi \sin^2\theta_{\mathrm{w}}} \log^2 \frac{s}{m_W^2} \,.$$

Not compensated by the corresponding $W^\pm$ and Z boson real emissions because of

- multitude of gauge boson decay channels leading to experimentally distinguishable signatures
- initial state (p, $e^\pm$) has definite isospin

preventing a complete summing over all states of isospin doublet.

Electroweak corrections

Precision measurements
Measurement that aim for subpercent experimental accuracy.
$\rightarrow$ 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 $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$.

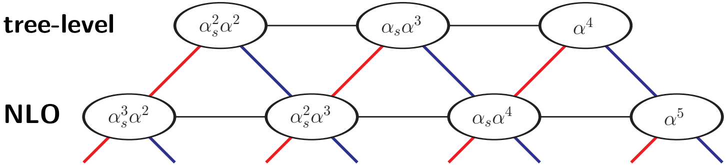
New physics searches
Search for excesses over SM background in TeV-scale observables that we could not probe until now.

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.

Higher order corrections

- strictly defined only through order counting

Example: *Vjj* production



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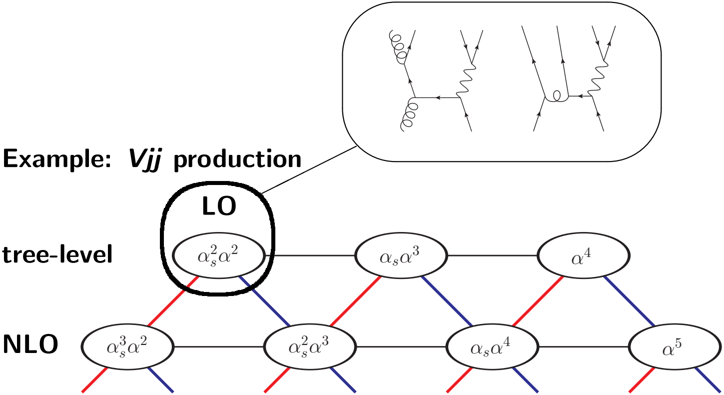

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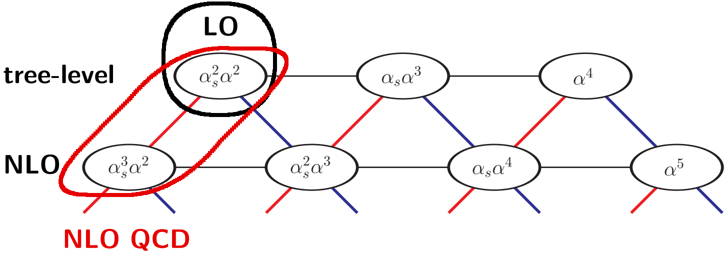

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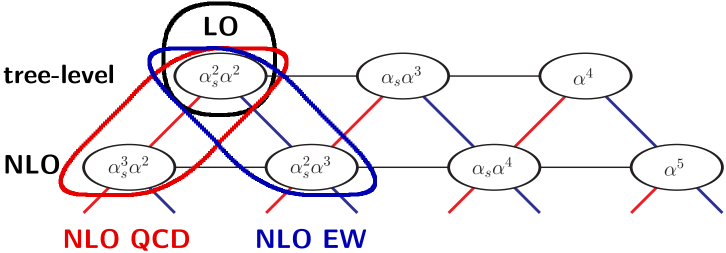

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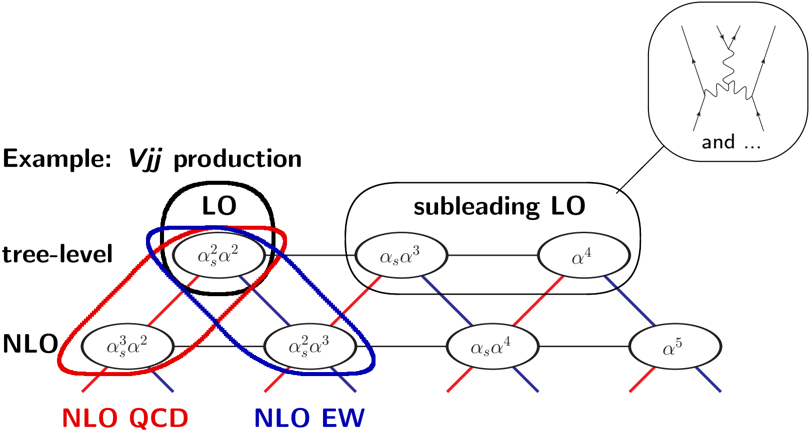

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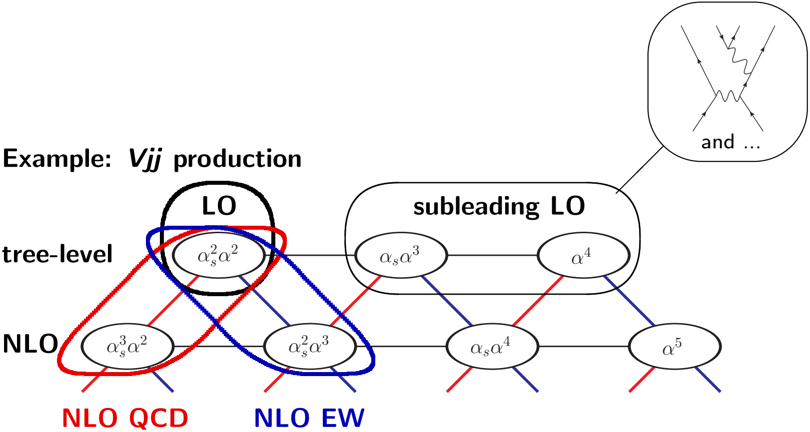

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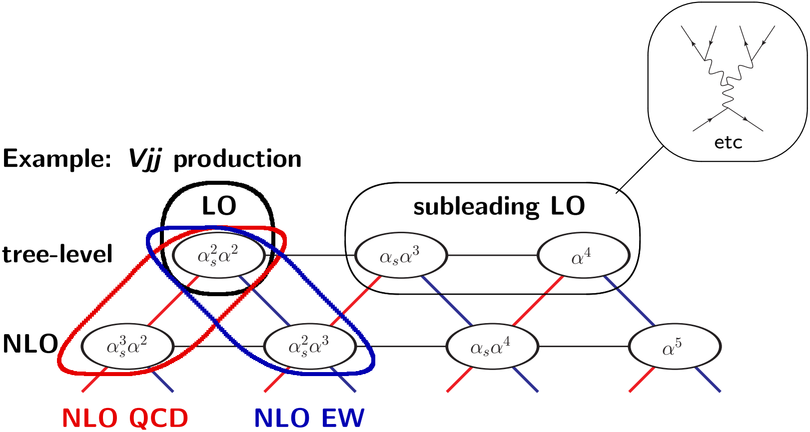

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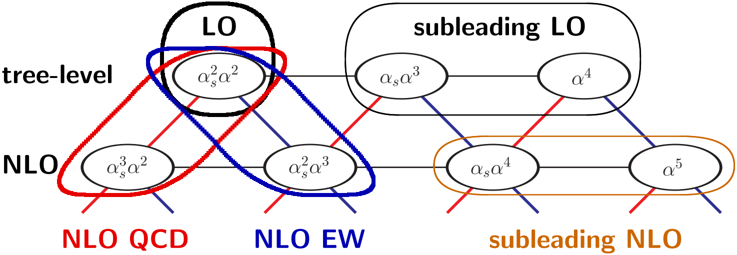
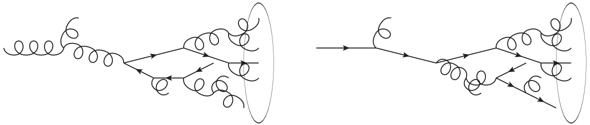


Definition of physical objects

In principle one must differentiate between short-distance objects (partons) and long distance objects (observable objects)

What is a jet?

- in QCD, this problem was solved decades ago
- define through jet algorithm which clusters quarks and gluons

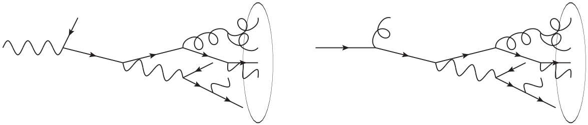


- capture IR divergence structure of QCD splitting functions P_{ab}

Definition of physical objects

What is a jet?

- in the EW sector, photons and leptons must also be part of a jet (due to addition of $P_{q\gamma}$, $P_{\gamma\ell}$, etc), but to what extent?



- **democratic:**
  - \+ straight forward, always well defined
  - − all particle identified as jets and only jets
- **anti-tagging jets with certain flavour content:**
  - \+ allows for realistic flavour identification/rejection
  - − needs fragmentation functions
- which approach is closer to experiment depends on analysis

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

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

What is a lepton?

- simplified as leptons not gauge bosons
- dressed lepton: 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:
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ 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

Phenomenological implications

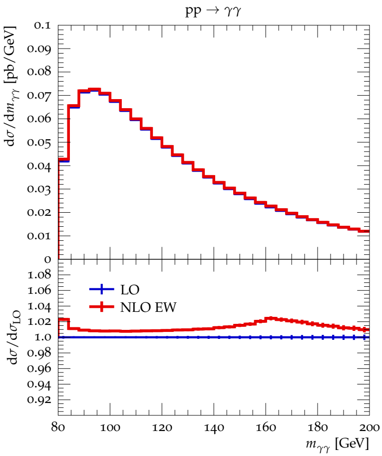
General setup

- 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

Effects due to internal masses



NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} \approx 160\,\mathrm{GeV}$
- 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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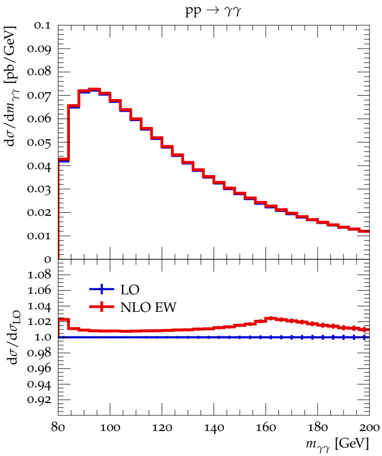

NLO EW corrections to diphoton production

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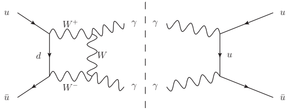

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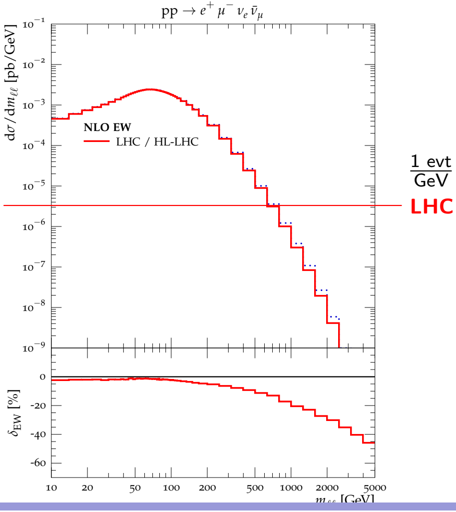
Effects at large momentum transfers



- 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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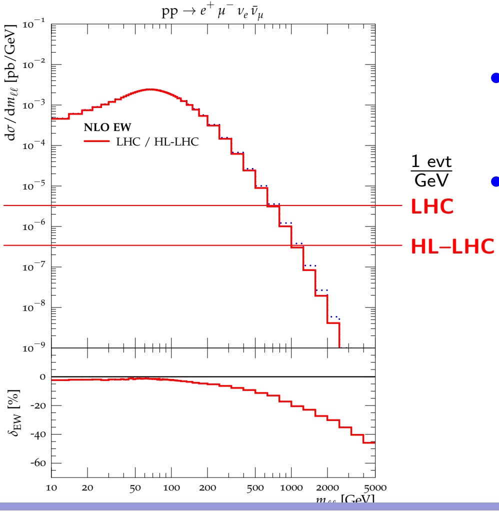

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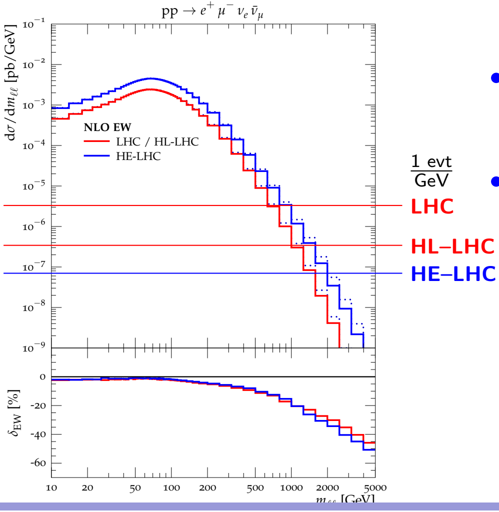

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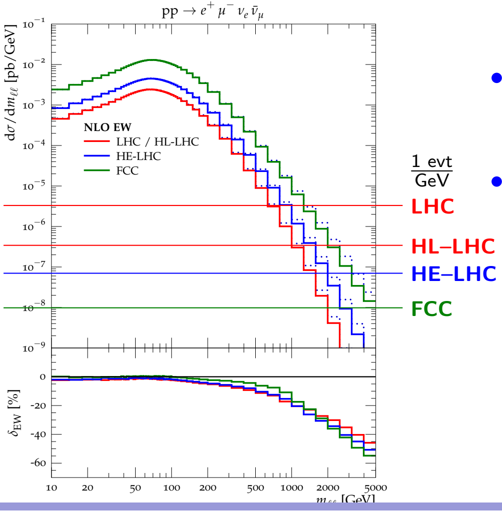

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Determination of the strong coupling α_s

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)
  $p_{\mathrm{T}}(j_1) > 80$ GeV, $p_{\mathrm{T}}(j_i) > 60$ 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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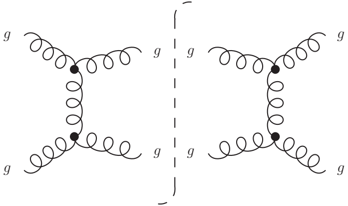

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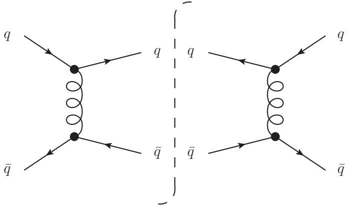

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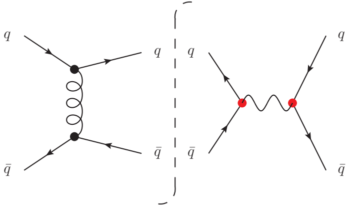
$\mathcal{O}(\alpha_s\alpha)$



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

Three-jet production – contributions

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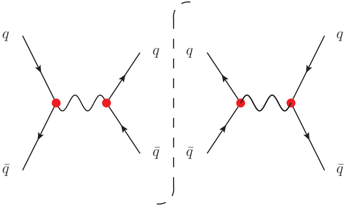

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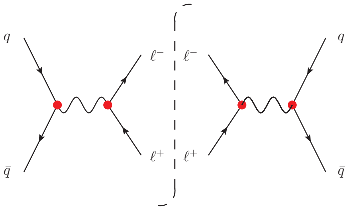

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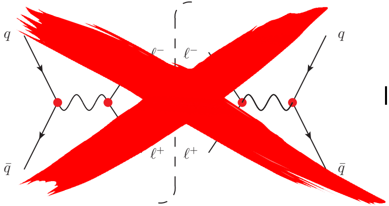

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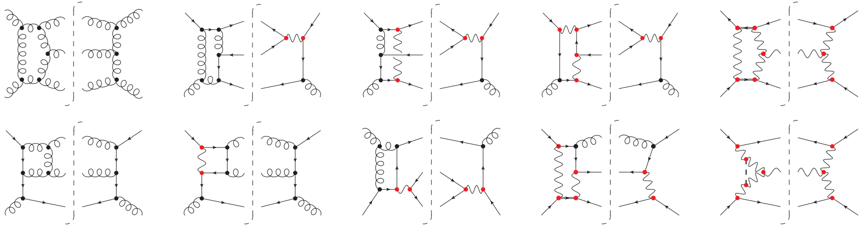
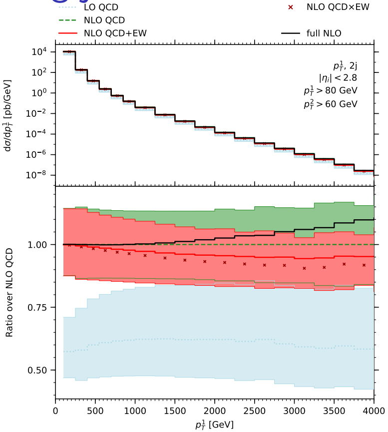
Contributions at NLO

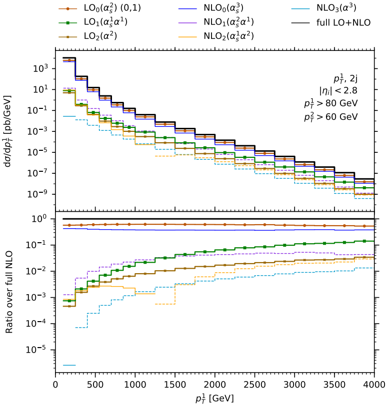


$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

- 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

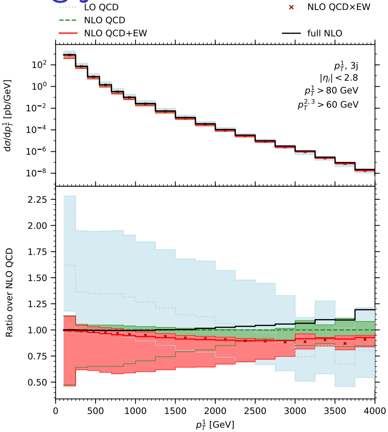
Leading jet transverse momenta in dijet production

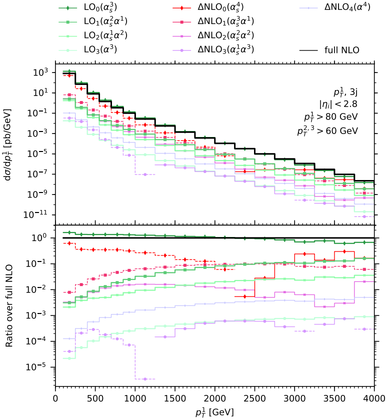




- moderate EW corrections
- overcompensated by subleading orders

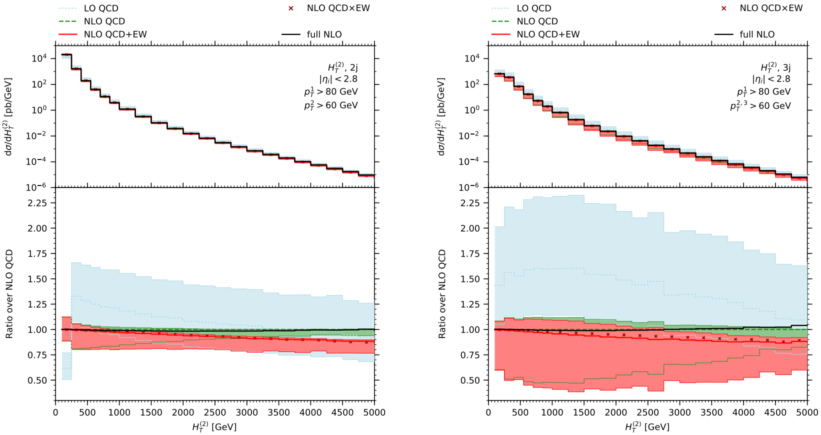
Leading jet transverse momenta in 3-jet production





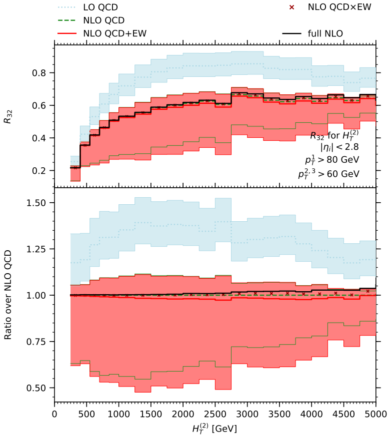
- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

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



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

R_{32}

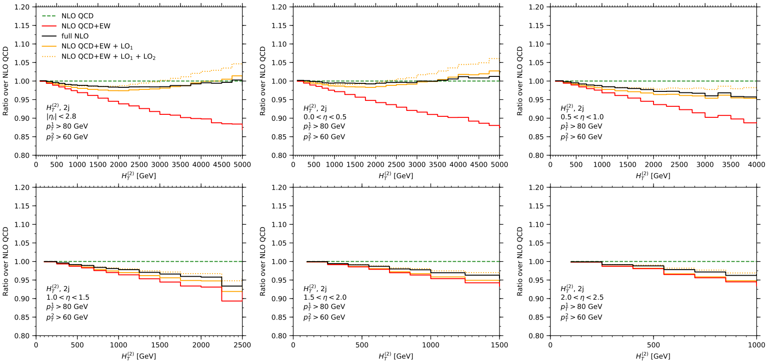


- NLO EW and subleading order contribs very similar between 2j and 3j
  $\Rightarrow$ R_{32} largely uneffected
- supports factorisation of NLO QCD and NLO EW correction at large $H_\mathrm{T}^{(2)}$
- scale uncertainty by synchronous scale variation

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

R_{32} in different Δy-slices

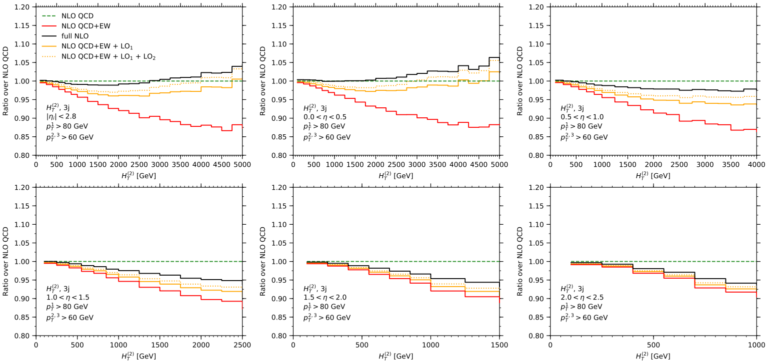
dijet production



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

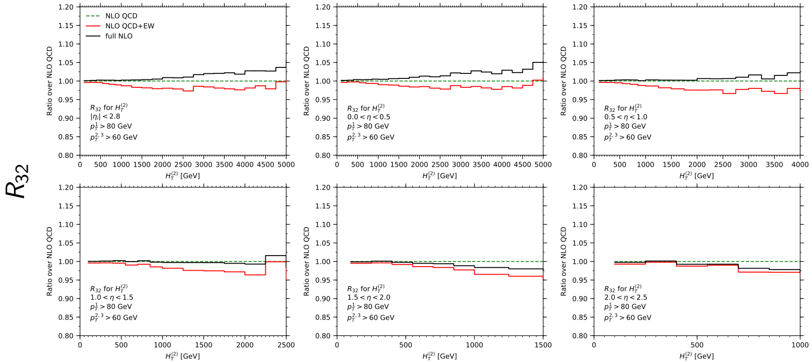
R_{32} in different Δy-slices

three jet production



- slightly different in 3-jet production

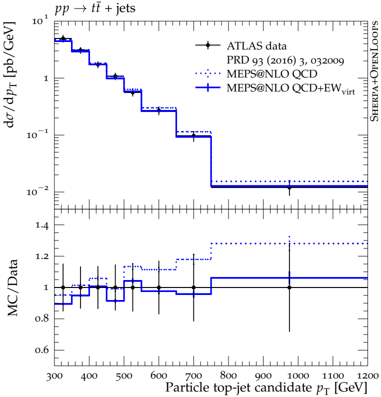
R_{32} in different Δy-slices



- different net effects in different rapidity slices

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

Gütschow, Lindert, MS in '18



LHC 8 TeV
boosted top quark analysis

- $pp \to t\bar{t} + 0, 1j$@NLO $+ 2, 3, 4j$@LO
- include approx. EW corrections in event generation
- improved description of data

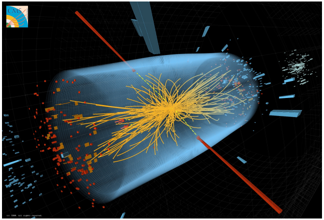
Conclusions

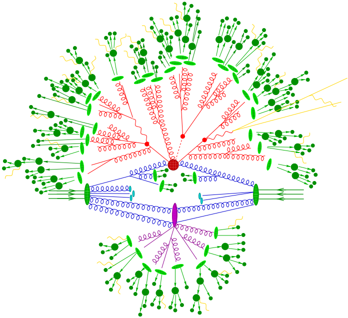
- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- precise definition of physics objects needed
  $\Rightarrow$ differentiate short-distance parton and
  long-distance measurable object
- approximate NLO corrections incorporated in SHERPA event generator
  $\rightarrow$ currently tailored to TeV-scale physics
- automation of NLO EW follows on the heels of NLO QCD
  $\rightarrow$ much more care with consistent schemes and order counting
  $\rightarrow$ very rich phenomenology
  $\rightarrow$ can induce peaks, edges or kinks in distributions
  $\rightarrow$ includes many more pitfalls than NLO QCD

Thank you!

Backup

Event generators





Factorise event into processes at different characteristic scales

hard partonic scatter – fixed-order expansion of pert. series in α and α_s
$\rightarrow$ only able to calculate idealised observables

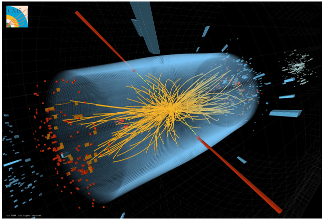
parton shower – resummation of scale hierarchies

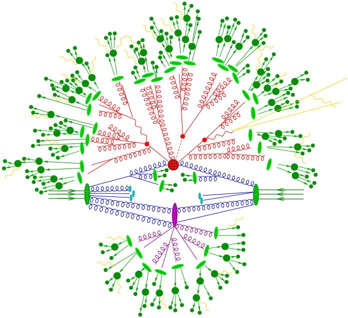
soft/non-perturbative physics:
multiple parton interactions, hadronisation, hadron decays

QED corrections

$\Rightarrow$ **Fully differential description of event kinematics**

Event generators





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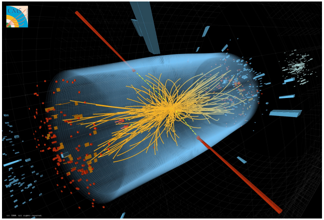

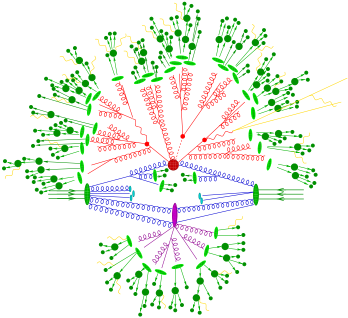

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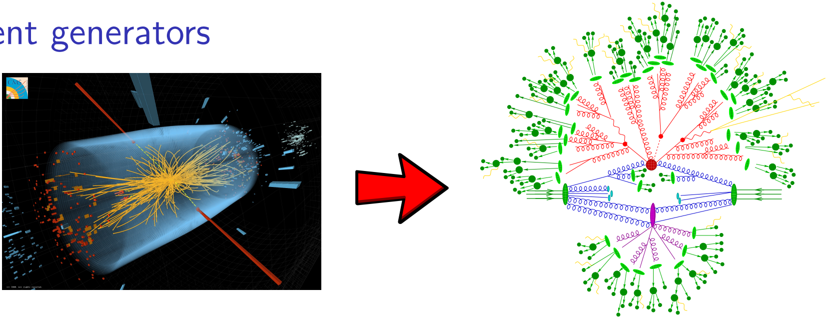

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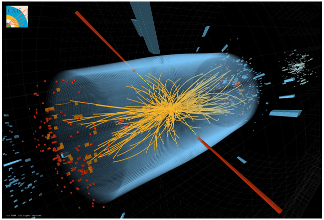

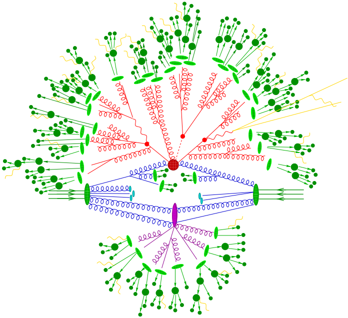

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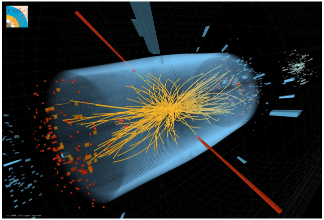

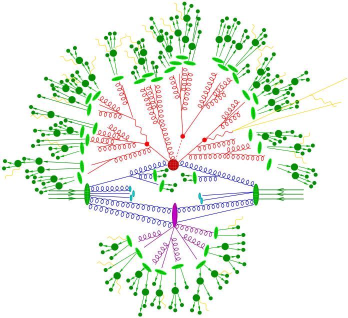

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Electroweak corrections in particle-level event generation

- 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

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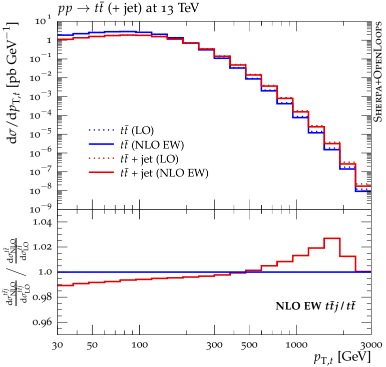
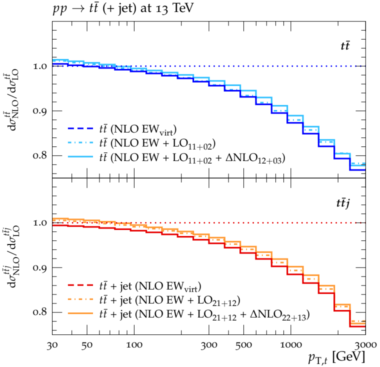
Top pair production in association with jets

Gütschow, Lindert, MS in '18





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

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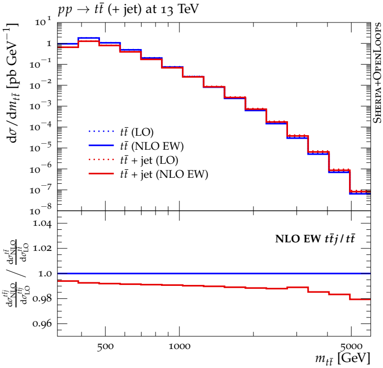

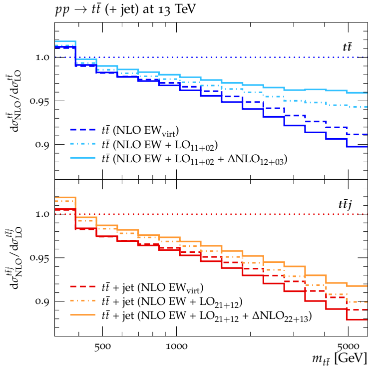

Observation: subleading orders important