NLO EW corrections for the LHC

(with a small detour into mixed corrections)

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Gargnano, 16 Sep. 2018

Outline

Coupling structure of SM processes (I)

Distinguish three cases:

- In QCD, the terms "LO" and "NLO" have unambiguous meanings:

$$\langle O\rangle = \underbrace{\mathcal{O}(\alpha_s^n)}_{\text{LO}} + \underbrace{\mathcal{O}(\alpha_s^{n+1})}_{\text{NLO corr.}} + \underbrace{\mathcal{O}(\alpha_s^{n+2})}_{\text{NNLO corr.}} + \dots$$

  where n is uniquely defined by the process under consideration.

- However, in the SM we have two couplings, α_s and α. Many (but not all) processes still have an unambigiguos LO and two higher-orders:

$$\langle O\rangle = \underbrace{\mathcal{O}(\alpha^m\alpha_s^n)}_{\text{LO}} + \underbrace{\mathcal{O}(\alpha^m\alpha_s^{n+1})}_{\text{QCD corr.}} + \underbrace{\mathcal{O}(\alpha^{m+1}\alpha_s^n)}_{\text{EW corr.}} + \dots$$

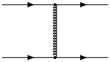
  For example: pp $\to \gamma\gamma + \mathrm{X}$

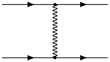
- Finally, the can be more than one leading order

Coupling structure of SM processes (II)

→ number of quark lines determines possible order(s), because quarks couple both with gluons and EW bosons.

- In general, at Born level and for each $2 \to n$ scattering process with
  n_g gluons and
  n_q quarks (including anti-quarks),
  the coupling order(s) are
  $$\mathcal{O}(\alpha^a \alpha_s^b)$$
  where $a + b = n$ and
  $$\min(n_g, n) \leq b \leq n_g + n_q - 2.$$
- first non-trivial case: $n_q = 4$, e.g. dijets, where
  - $\mathcal{O}(\alpha^0 \alpha_s^2)$, strong production: $\left|\mathcal{M}^2_{\text{QCD}}\right|^2$,
  - $\mathcal{O}(\alpha^1 \alpha_s^1)$, interference: $2\,\text{Re}\left\{\mathcal{M}^*_{\text{QCD}}\mathcal{M}_{\text{EW}}\right\}$,
  - $\mathcal{O}(\alpha^2 \alpha_s^0)$, electroweak productio: $\left|\mathcal{M}^2_{\text{EW}}\right|^2$

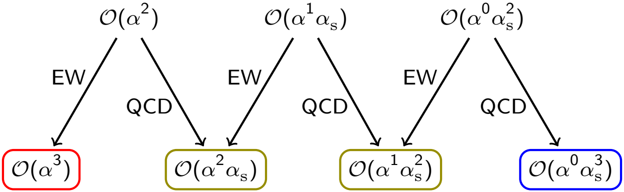
$\mathcal{M}_{\text{QCD}} =$  $+ \ldots$

$\mathcal{M}_{\text{EW}} =$  $+ \ldots$

- then: $n_q = 6$, e.g. $\text{pp} \to \mu^+ \nu_\mu \text{b}\bar{\text{b}}\text{jj} + \text{X}$, "top-pair" production, decaying semileptonically:
  $$\mathcal{O}(\alpha^2 \alpha_s^4), \quad \mathcal{O}(\alpha^3 \alpha_s^3), \quad \mathcal{O}(\alpha^4 \alpha_s^2), \quad \mathcal{O}(\alpha^5 \alpha_s^1), \quad \mathcal{O}(\alpha^6 \alpha_s^0)$$

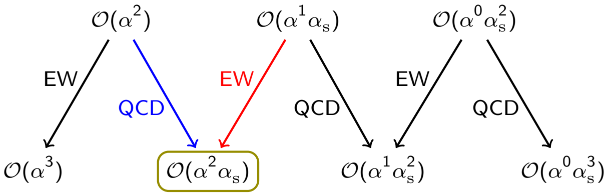
Coupling structure of SM processes (III)

At NLO, we perform EW and QCD corrections:

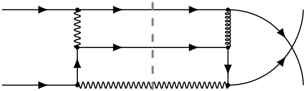


- One EW correction, one QCD correction, two mixed corrections
- Sometimes possible to approx. mixed corrections by neglecting EW part (or vice versa)
  - Borns have different color structures → different gauge invariant sets of diagrams
  - EW and QCD infrared singularities must not mix (Example later)

Mixing of IR singularities (see also [R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H.S. Shao, M. Zaro])

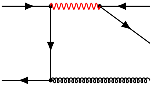


$$2\,\mathrm{Re}\left\{\mathcal{M}^{\mathrm{QCD},*}\mathcal{M}^{\mathrm{EW}}_{\mathrm{real}}\right\} \ni$$



$+\dots$

$$\left|\mathcal{M}^{\mathrm{QCD}}_{\mathrm{real}}\right|^2 \ni$$



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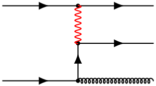


$+\dots$

- "QCD"-correction has both QCD and EW singularities
- EW singularities cancel against collinear counterterm and EW virtuals

→ "mixing" of EW and QCD singularities, "inherently" mixed

→ infrared-safe jet definition requires the inclusion of $\gamma \to q\bar{q}$

Outline

EW corrections: A few technical differences (I)

- Amplitudes: Broken symmetry $\rightarrow$ More particles (more diagrams), more parameters, less symmetry: No easy recursion relations as e.g. in QCD
- But amplitude generators are available now, e.g. OPENLOOPS [F. Cascioli, P. Maierhöfer, S. Pozzorini], RECOLA [S. Actis, A. Denner, L. Hofer, J.-N. Lang, A. Scharf, S. Uccirati], and MADGRAPH5_AMC@NLO [R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro] for EW corrections
- Massive, unstable particles: $\mathrm{W}^{\pm}$, Z
  - Rather than the unstable particles itself (e.g. pp $\rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$) we prefer their decay products (pp $\rightarrow \mathrm{e}^{+}\nu_{\mathrm{e}}\mu^{-}\overline{\nu}_{\mu}$)
  - Dominant PS regions are $k_{\mathrm{V}}^2 - M_{\mathrm{V}}^2 \approx 0 \rightarrow$ large propagators. Regularization?

  $\rightarrow$ Resummation of the propagators, so that

$$M_{\mathrm{V}}^2 \rightarrow M_{\mathrm{V}}^2 + \mathrm{i} M_{\mathrm{V}} \Gamma_{\mathrm{V}}$$

  everywhere (gauge-invariance, parameter relations); leads to complex parameters, in particular

$$\cos^2\theta_w = \frac{M_{\mathrm{W}}^2 + \mathrm{i} M_{\mathrm{W}} \Gamma_{\mathrm{W}}}{M_{\mathrm{Z}}^2 + \mathrm{i} M_{\mathrm{Z}} \Gamma_{\mathrm{Z}}}$$

  and one-loop functions evaluated with complex masses (implemented e.g. COLLIER [A. Denner, S. Dittmaier, L. Hofer]) in the complex mass scheme [A. Denner, S. Dittmaier, M. Roth, D. Wackeroth] [A. Denner, S. Dittmaier, M. Roth, L.H. Wieders]

EW corrections: A few technical differences (II)

- Instead of $\overline{\text{MS}}$, on-shell scheme is chosen with a non-running coupling in the G_μ scheme, where

$$\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_\text{W}^2 \left(1 - \frac{M_\text{W}^2}{M_\text{Z}^2}\right)$$

  with G_μ determined from μ-decay; absorbs some higher-order corrections in α_{G_μ}.
- Observables are *usually* defined such that real corrections are processes with an extra photon
- Additionally one can include extra Z, and/or W-bosons [U. Baur] [G. Bell, J.H. Kuhn, J. Rittinger]
- Recombination of photons e.g. done with an anti-k_R algorithm and $R = 0.1$
- Regularization of infrared singularities (from extra photons): Replace

$$C_A \to 0, \quad C_F \to Q_f^2, \quad T_R \to N_{C,f} Q_f^2, \quad T_R N_f \to \sum_f N_{C,f} Q_f^2$$

  in your favorite QCD subtraction method
- EW corrections exhibit initial state collinear singularities → photon PDFs

EW corrections: Size

- $\alpha \approx \alpha_s^2 \rightarrow$ NLO EW corrections expected to be as large as NNLO QCD corrections
- Naive estimate not always true: large EW (Sudakov) logarithms

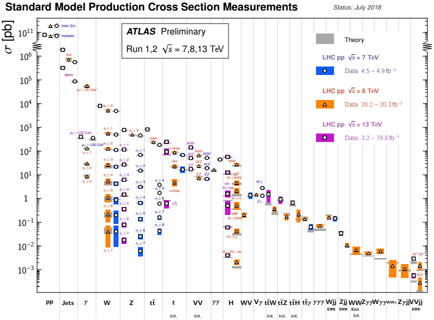
$$\frac{\alpha}{\pi} \log^2 \left(\frac{s}{M_\mathrm{V}} \right)$$

  remnants of uncancelled quasi-soft/collinear singularities (if no W- or Z-radiation is considered)

$\rightarrow$ usually small effect on integrated cross sections, large corrections in tails of distributions

- But there are also processes with large EW corrections on the integrated cross section $\rightarrow$ VBS

EW corrections: LHC @ 13/14 TeV overview



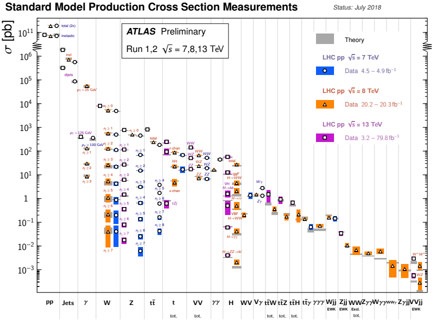

-plot from: [ATLAS collaboration]

picture from [animalsake.com]

Full EW off-shell (with decays) calculations:

- Drell–Yan
  - $\mu^+\nu_\mu$ [S. Dittmaier, M. Krämer]
  - $\mu^+\mu^-$ [U. Baur, O. Brein, W. Hollik, C. Schappacher, D. Wackeroth]
- Top-pair
  - $\mu^-\overline{\nu}_\mu e^-\overline{\nu}_e b\overline{b}$ @ $\mathcal{O}(\alpha^5\alpha_s^2)$ [A. Denner, M. Pellen]
- Diboson
  - $\mu^+\nu_\mu e^-\overline{\nu}_e$ [B. Biedermann, M. Billoni, A. Denner, S. Dittmaier, L. Hofer, B. Jäger, L. Salfelder]
  - $\mu^+\mu^-e^+\nu_e$ [B. Biedermann, A. Denner, L. Hofer]
  - $\mu^+\mu^-e^+e^-$ [B. Biedermann, A. Denner, S. Dittmaier, L. Hofer, B. Jäger]
  - $\mu^+\nu_\mu\gamma$ [A. Denner, S. Dittmaier, M. Hecht, C. Pasold]
  - $\mu^+\mu^-\gamma$ [A. Denner, S. Dittmaier, M. Hecht, C. Pasold]
  - $\gamma\gamma$ [A. Bierweiler, T. Kasprzik, J. H. Kühn]
- $t\bar{t}H$
  - $\mu^-\overline{\nu}_\mu e^+\overline{\nu}_e b\overline{b}H$ @ $\mathcal{O}(\alpha^5\alpha_s^2)$ [A. Denner, J.-N. Lang, M. Pellen, S. Uccirati]

EW corrections: LHC @ 13/14 TeV overview



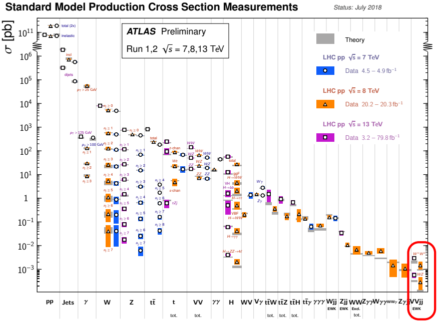
-plot from: [ATLAS collaboration]

picture from [animalsake.com]

Full EW off-shell (with decays) calculations:

- Drell–Yan
  - $\mu^+\nu_\mu$: -1.8%
  - $\mu^+\mu^-$: -1.2%
- Top-pair
  - $\mu^-\overline{\nu}_\mu e^-\overline{\nu}_e b\bar{b}$ @ $\mathcal{O}(\alpha^5\alpha_s^2)$: +0.38%
- Diboson
  - $\mu^+\nu_\mu e^-\overline{\nu}_e$: -3.1%
  - $\mu^+\mu^- e^+\nu_e$: -1.1%
  - $\mu^+\mu^- e^+ e^-$: -5.1%
  - $\mu^+\nu_\mu\gamma$: > -1%
  - $\mu^+\mu^-\gamma$: -3.2%
  - $\gamma\gamma$: 0.2%
- $t\bar{t}H$
  - $\mu^-\overline{\nu}_\mu e^+\overline{\nu}_e b\bar{b}H$ @ $\mathcal{O}(\alpha^5\alpha_s^2)$: +0.2%

EW corrections: LHC @ 13/14 TeV overview



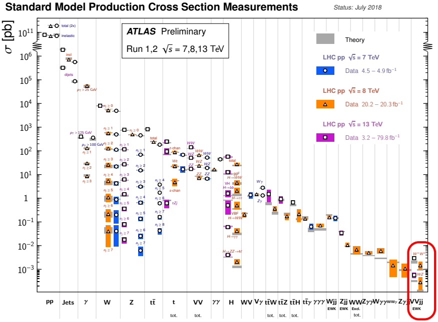
-plot from: [ATLAS collaboration]

picture from [animalsake.com]

Full EW off-shell (with decays) calculations:

- Vjj
  - $\mu^+\nu_\mu$jj @ $\mathcal{O}(\alpha^3\alpha_s^2)$ [M. Chiesa, N. Greiner, F. Tramontano]
  - $\mu^+\mu^-$jj @ $\mathcal{O}(\alpha^3\alpha_s^2)$ [A. Denner, L. Hofer, A. Scharf, S. Uccirati]
- VVjj
  - $\mu^+\nu_\mu e^+\nu_e$jj @ $\mathcal{O}(\alpha^7)$ [B. Biedermann, A. Denner, M. Pellen]
  - $\mu^+\mu^- e^+\nu_e$jj @ $\mathcal{O}(\alpha^7)$ → later in this talk
- Triboson
  - $e^-\overline{\nu}_e\gamma\gamma$ [N. Greiner, M. Schönherr]
  - $e^+e^-\gamma\gamma$ [N. Greiner, M. Schönherr]
  - $\gamma\gamma\gamma$ [N. Greiner, M. Schönherr]
  - $e^-\overline{\nu}_e\mu^+\nu_\mu\mu^+\nu_\mu$ [M. Schönherr]
  - $e^-\overline{\nu}_e\mu^+\nu_\mu e^+\nu_e$ [M. Schönherr]
  - $e^-\overline{\nu}_e e^+\nu_e e^+\nu_e$ [M. Schönherr]

EW corrections: LHC @ 13/14 TeV overview

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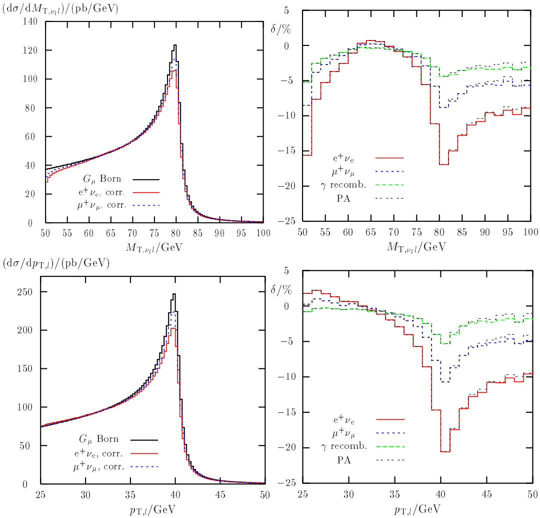
picture from [animalsake.com]

Full EW off-shell (with decays) calculations:

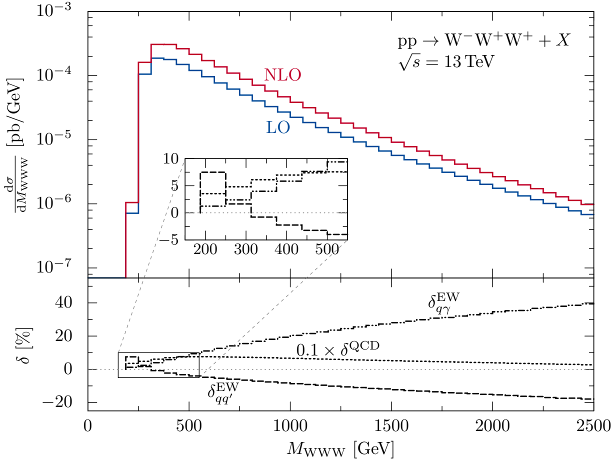
- Vjj
  - $\mu^+\nu_\mu$jj @ $\mathcal{O}(\alpha^3\alpha_s^2)$: -0.8%
  - $\mu^+\mu^-$jj @ $\mathcal{O}(\alpha^3\alpha_s^2)$: -2.5%
- VVjj
  - $\mu^+\nu_\mu e^+\nu_e$jj @ $\mathcal{O}(\alpha^7)$: -16%
  - $\mu^+\mu^- e^+\nu_e$jj @ $\mathcal{O}(\alpha^7)$ $\rightarrow$ later in this talk
- Triboson
  - $e^-\overline{\nu}_e\gamma\gamma$: -1.8%
  - $e^+e^-\gamma\gamma$: -4.4%
  - $\gamma\gamma\gamma$: 0.6%
  - $e^-\overline{\nu}_e\mu^+\nu_\mu\mu^+\nu_\mu$: -2.2%
  - $e^-\overline{\nu}_e\mu^+\nu_\mu e^+\nu_e$: -1.4%
  - $e^-\overline{\nu}_e e^+\nu_e e^+\nu_e$: -3.4%

Drell–Yan ($pp \to \ell^+\nu_\ell + X$) [S. Dittmaier, M. Krämer]



- Extraction of M_W
- "γ recomb.": photons recombined with the leptons inside $\Delta R_{\ell\gamma} < 0.1$
- $e^+\overline{\nu}_e$, $\mu^+\nu_\mu$: photons not recombined with the leptons (collinear unsafe), diff. due to fermion masses
- PA: pole approximation for virtuals

Triple-gauge production ($pp \to W^+W^+W^- + X$) [S. Dittmaier, A. Huss, G. Knippen]

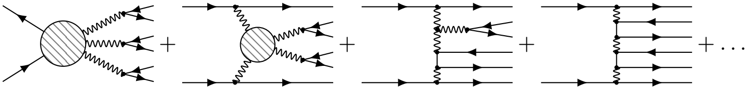


- QCD corrections much larger than EW corrections
- Photon-initiated contributions dominate over other EW contributions
- At threshold: Coulomb singularity for each $W^+W^\mp$-pair: $\delta \sim \pm\frac{\alpha\pi}{2\beta_W}$

Vector-boson scattering ($pp \to e^+\nu_e\mu^+\mu^- jj + X$) (I)

with A. Denner, S. Dittmaier, P. Maierhöfer, M. Pellen

$\mathcal{M}_{\mathrm{LO}} =$

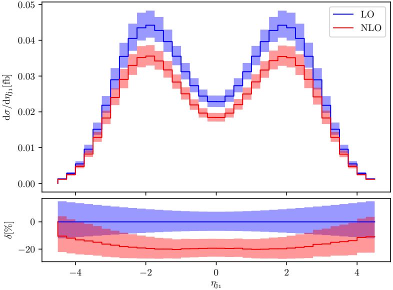


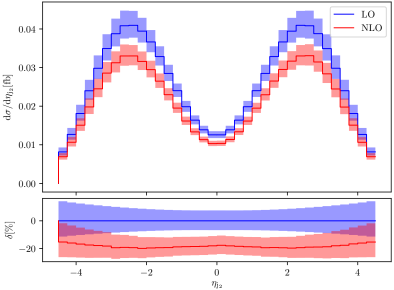
Integrated xs for $pp \to e^+\nu_e\,\mu^+\mu^- jj + X$ @ $\sqrt{s} = 13\,\mathrm{TeV}$ for the fiducial PS volume:

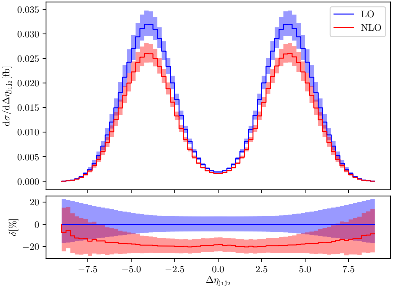
LO [fb]	NLO [fb]	$\delta = \frac{\mathcal{O}(\alpha^7)}{\mathcal{O}(\alpha^6)}$ [%]
$0.2362^{+9.433\%}_{-8.022\%}$	$0.1899^{+8.356\%}_{-7.575\%}$	-19.6%

- Uncertainty is the range given by varying $\mu_F = M_W$ by (1/2,2)
- No dep. on $\alpha_s \to$ no dep. on μ_R
- Huge correction on the integrated cross section, larger than even like-sign W-scattering (-16%)
- corrections are even larger in specific regions of p_T distributions

Vector-boson scattering ($pp \to e^+\nu_e\mu^+\mu^- jj + X$) (II)



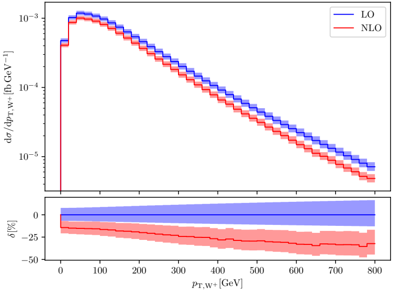


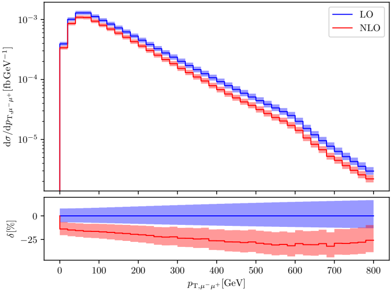


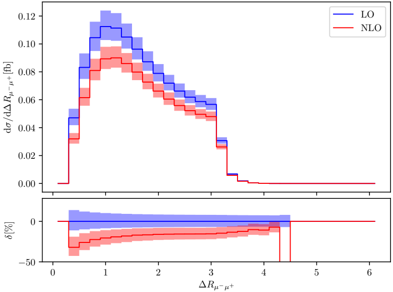
- EW corrections flat in most PS regions
- Bands: large dependence on μ_F
- $\Delta\eta_{j_1j_2} \approx 0$ suppressed because of $M_{j_1j_2} > 500\,\text{GeV}$ cut:

$$\cosh \Delta\eta_{j_1j_2} \approx \frac{M_{j_1j_2}}{2p_{T,j_1} \cdot p_{T,j_2}} + \cos \Delta\phi_{j_1j_2}$$

Vector-boson scattering ($pp \to e^+\nu_e\mu^+\mu^-jj + X$) (III)







$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- In $p_{\mathrm{T,W^+}}$ Sudakov logs further increase EW corrections
- $\Delta R_{\mu\bar{\mu}}$ is limited from above because $M_{\mu\bar{\mu}} \approx M_{\mathrm{Z}}$ cut limits $\Delta\eta_{\mu\bar{\mu}} < 3.3$
- Kink in $p_{\mathrm{T},\mu\bar{\mu}}$ caused by $\Delta R_{\ell\ell}$ cut at $p_{\mathrm{T}} \approx 2M_{\mathrm{Z}}/\Delta R_{\ell\ell}$

Summary

- Introduction into EW calculations: unstable particles, complex mass scheme, . . .
- Overview of EW corrections at the LHC; size typically order few percent
- Large corrections in high-energy tails, up to several ten percent
- Mixed-corrections: Inherently mixed corrections, infrared safety and jet definition

Fiducial phase space volume for pp $\to e^+\nu_e\mu^+\mu^-jj + X$

Cuts chosen similar to the ATLAS 8 TeV-analysis [CERN-EP-2016-017]:

- At least two $R = 0.4$ anti-k_t jets with $p_T > 30$ GeV, $|\eta| < 4.5$, and $\Delta R_{j\ell} > 0.3$
- $M_{j_1 j_2} > 500$ GeV, no $\Delta\eta_{j_1 j_2}$ cut[1]
- $p_{T,\ell} > 20$ GeV and $|y_\ell| < 2.5$
- $p_{T,\text{miss}} > 30$ GeV
- $|M_{\mu\bar{\mu}} - M_Z| < 10$ GeV
- $\Delta R_{\ell\ell} > 0.3$

Other:

- Photons recombined with charged particles using anti-k_t algorithm with $R = 0.1$
- PDFs: `NNPDF30_nlo_as_0118_qed`
- $\sqrt{s} = 13$ TeV

Complex mass scheme [Denner, Dittmaier, Roth, Wackeroth][Denner, Dittmaier, Roth, Wieders], input parameters:

- $G_\mu = 1.663\,787 \times 10^{-5}\ \text{GeV}^{-2}$
- $M_W = 80.357\,97$ GeV, $\Gamma_W = 2.084\,30$ GeV
- $M_Z = 91.153\,48$ GeV, $\Gamma_Z = 2.494\,27$ GeV
- $M_H = 125.0$ GeV, $\Gamma_H = 4.07 \times 10^{-3}$ GeV

with coupling calculated as:

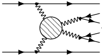
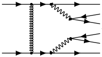
$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Scale choice: $\mu_F = (1/2, 1, 2) \cdot M_W$
$\to$ No dependence on μ_R, since processes do not depend on α_s!

[1] Unused in the ATLAS 8 TeV-analysis, but used both in the ATLAS and CMS 13 TeV analyses

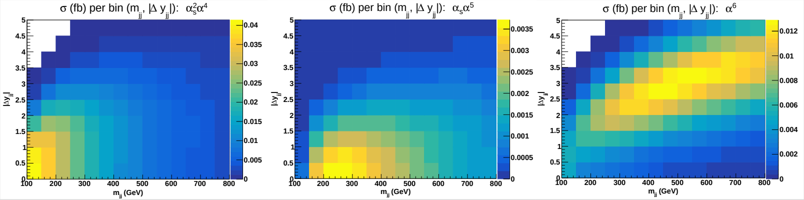
Discriminating between EW and QCD production

→ At LO, three different coupling orders:

$\mathcal{M}_{\text{EW}} =$  $+\dots$ $\quad \mathcal{M}_{\text{QCD}} =$  $+\dots$ →

- $\mathcal{O}(\alpha^4 \alpha_s^2)$: $|\mathcal{M}_{\text{QCD}}|^2$
- $\mathcal{O}(\alpha^5 \alpha_s^1)$: $2\mathfrak{Re}\left\{\mathcal{M}^*_{\text{QCD}}\mathcal{M}_{\text{EW}}\right\}$
- $\mathcal{O}(\alpha^6 \alpha_s^0)$: $|\mathcal{M}_{\text{EW}}|^2$

How to maximize the EW production ("signal")? $(\text{pp} \to \text{e}^+\nu_{\text{e}}\,\mu^+\nu_\mu \text{jj} + \text{X})$



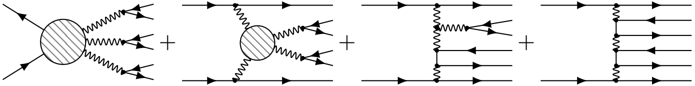
(plots from VBSCAN WG1 report [Ballestrero, et. al.])

→ Observables $M_{\text{j}_1\text{j}_2}$ and $\Delta y_{\text{j}_1\text{j}_2}$ are used to discrimate the QCD from the EW production

→ In the fiducial PS region, EW > QCD for like-sign scattering, for W^+ Z-scattering vice-versa

Feynman diagrams and partonic channels

$\mathcal{M}_{\mathrm{LO}} =$



$+ \ldots$

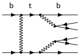
Borns and Born-like:

- $\mathrm{uu} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{du}$ (~47% XS),
- $\mathrm{du} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{dd}$ (~18% XS),
- $\ldots +$ 38 more: bottleneck are virtuals

Not included, small or negligable:

- $\gamma\gamma \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- (\mathrm{d\bar{u}}/\mathrm{s\bar{c}})$, and
- $\mathrm{bu} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{db}$,
- $\ldots +$ 7 more, with resonant top-quarks:

$\mathcal{M}_{\text{b-quarks}} =$



$+ \ldots$

Reals:

- $\mathrm{uu} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{du}\gamma$,
- $\mathrm{du} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{dd}\gamma$,
- $\ldots +$ 38 more,

Reals not yet calculated, expected to be small:

- $\gamma\mathrm{u} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{du\bar{u}}$,
- $\ldots +$ 27 more,
- $\gamma\gamma \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{d\bar{u}}\gamma$, and
- $\gamma\gamma \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{d\bar{u}}\gamma$.

Validation and checks

We performed two independent calculations of the $\mathcal{O}(\alpha^7)$:

"Freiburg"

- MEs from OpenLoops [Cascioli, Maierhöfer, Pozzorini]
- Loops evaluated with DD (COLI fallback) from COLLIER [Denner, Dittmaier, Hofer]
- General purpose Monte Carlo [CS]
- Dipole subtraction [Catani, Seymour] to regularize IR singularities
- PDFs from LHAPDF 6 [Buckley, et. al.]

"Würzburg"

- MEs from RECOLA [Actis, Denner, Hofer, Scharf, Uccirati]
- Loops evaluated with COLI (and DD) from COLLIER
- MoCaNLO [Feger] used by M. Pellen
- CS dipole subtraction with α-dependent dipoles [Nagy]
- PDFs from LHAPDF 6

Checks:

- NLO virtuals checked against each other for 1000 PS points passing the cuts
- integrated cross sections
- 23 differential distributions, each bin