The impact of mixed QCD-EW corrections on the W-mass measurement

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Drell-Yan production and W-mass measurement

- Drell-Yan production $pp \to \ell\bar{\ell}$ is a keystone process at hadron colliders:
  - Calibration; measurements of $m_W, \sin\theta_W, \ldots$; determination of pdfs; searches for BSM physics at high energies, …
- W mass is a fundamental property of an elementary particle.
- Linked to EWSB:

$$\sin^2\theta_W = 1 - m_W^2/m_Z^2 = e^2/g^2$$

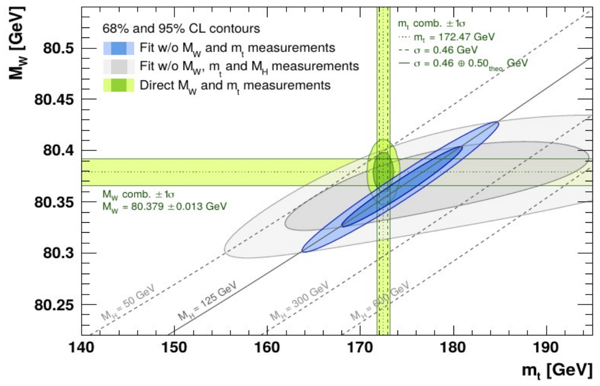
→ Connection between masses and couplings.

- Radiative corrections:

$$m_W^2(1 - m_W^2/m_Z^2) = (\pi\alpha)/(\sqrt{2}G_F)(1+\Delta r)$$

[Awramik, Czakon, Freitas, Weiglein ('03)]

→
- Test self-consistency of SM.
- Probe potential BSM effects.



Global fits and direct measurements

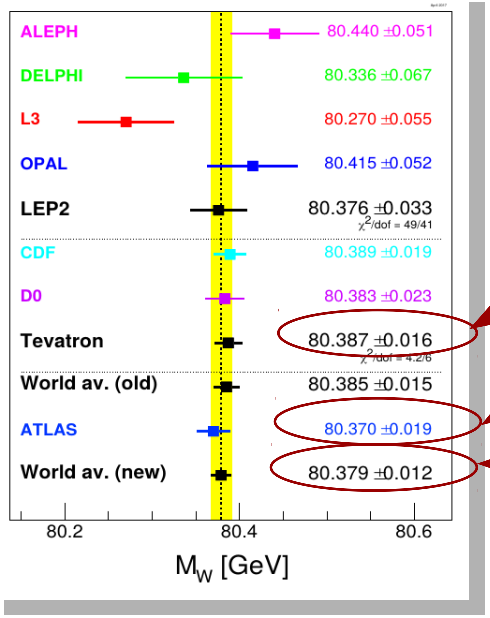
- Theory prediction from global EW fits
  $m_W = 80.354 \pm 0.007\ \text{GeV}$
  - sets target precision for direct measurements.

[Gfitter Group: Haller *et al.* (‘18)]

- Direct measurements in $pp \to W \to \ell\nu$
- Template fits: simulations for different values of W-mass and fit to data.
- Strongest pull from $p_{T,\ell}$, also most sensitive to theoretical corrections.

  [Carloni Calame *et al.* (‘16)]

- Direct measurements consistent with theory prediction, but higher precision desirable.
- Uncertainty dominated by physics modelling.



[PDG (’19)]

Tevatron average

ATLAS (2017)

World average

Theoretical calculations for Drell-Yan production

Substantial theoretical effort in calculating higher-order corrections:

$$\hat{\sigma}ij = \hat{\sigma}_{ij}^{(0,0)} + \alpha_s \hat{\sigma}_{ij}^{(1,0)} + \alpha_s^2 \hat{\sigma}_{ij}^{(2,0)} + \alpha_s^3 \hat{\sigma}_{ij}^{(3,0)} + \ldots + \alpha \, \hat{\sigma}_{ij}^{(0,1)} + \alpha_s \alpha \, \hat{\sigma}_{ij}^{(1,1)} + \ldots$$

Recent advances:

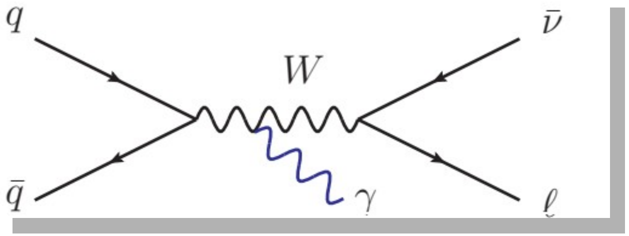
- N3LO QCD corrections to:
  - cross section [Dulat, Duhr, Mistlberger ('20)].
  - rapidity distributions [Chen, Gehrmann, Glover, Huss, Yang ('21)].
- Mixed QCD-EW $\mathcal{O}(\alpha\alpha_s)$ corrections:

  [Bonciani, Buccioni, Mondini, Vicini ('17); De Florian, Der, Fabre ('18); Delto, Jaquier, Melnikov, R.R. ('19); Bonciani, Buccioni, Rana, Triscari, Vicini ('19); Buccioni *et al.* ('20); Cieri, De Florian, Der, Mazzitelli ('20); Bonciani, Buccioni, Rana, Vicini ('20); Behring *et al.* ('20); Buonocore, Grazzini, Kallweit, Savoini, Tramontano ('21); Bonciani *et al.* ('21)]

  - Expected corrections to cross sections at permille level.
  - Enhanced impact at high energies – searches for BSM physics.
  - Relevant for ultra-high precision physics – e.g. measurement of W-mass.

W-mass measurements

- Direct measurements rely crucially on excellent experimental control of $pp \to Z \to \ell\bar{\ell}$ to calibrate detector response, tune generators, and verify results.
- Implicit assumption: higher-order corrections to W and Z production strongly correlated.
- Reasonable for QCD corrections:
  - Minor differences: pdfs, masses, helicity structures, …
- EW corrections: qualitatively different – *W* charged, can radiate:



- Mixed QCD-EW corrections potentially decorrelated.
- Possible impact on W-mass measurements at desired precision.

Mixed QCD-EW corrections

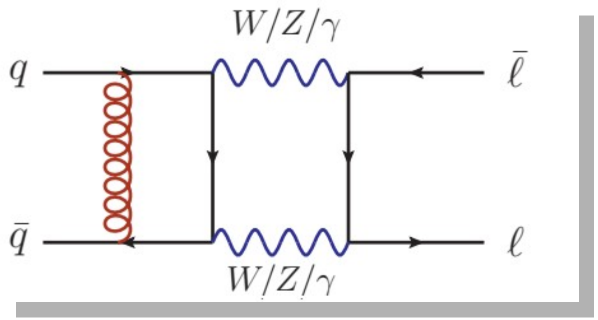
Two challenges in computing mixed QCD-EW corrections to $pp \to \ell\bar{\ell}$

1. Two-loop amplitudes:

- Several energy scales – very demanding!
- Recent computations:

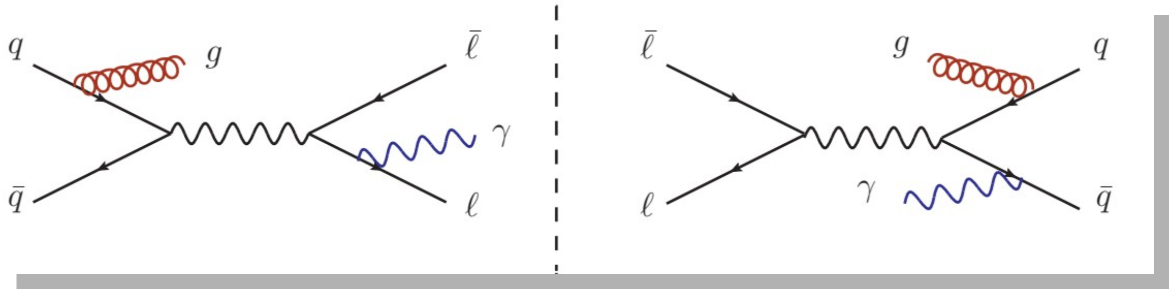
  [Heller, von Manteuffel, Schabinger, Spiesberger ('20)]

  [Bonciani *et al.* ('21)]



2. QCD and EW singularities:

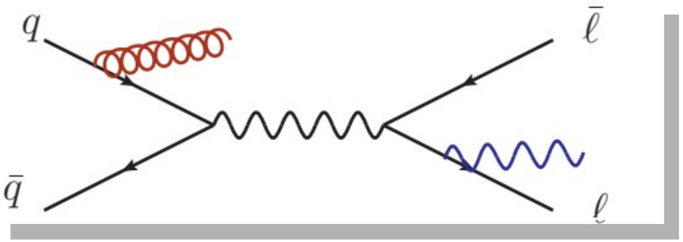
- Infrared singularities arising from radiated and virtual partons and photons.



QCD-EW corrections to onshell vector boson production

Simplification: consider onshell vector bosons $pp \to V \to \ell\bar{\ell}$ [Dittmaier, Huss, Schwinn, (‘14, ‘15)]

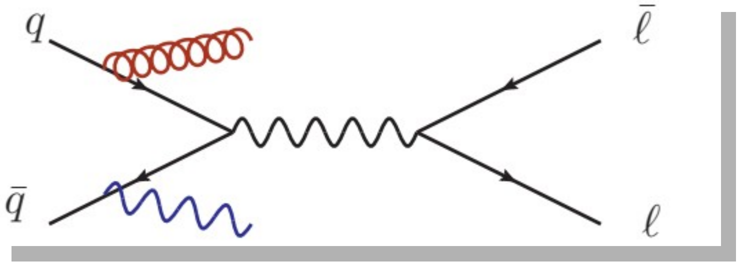
- QCD (production) x EW (decay)



- ➢ Corrections known.

  [Dittmaier, Huss, Schwinn, (‘14, ‘15)]
- ➢ Impact on W-mass measurements ~ 14 MeV.

- QCD x EW (production)



- ➢ Two-loop amplitudes → much simpler form factors.
- ➢ Major challenge: treating simultaneous QCD and EW IR singularities.
- ➢ Insight from NNLO QCD: treatment of IR singularities from double emissions.

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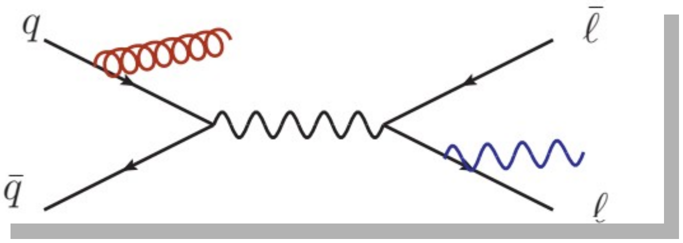

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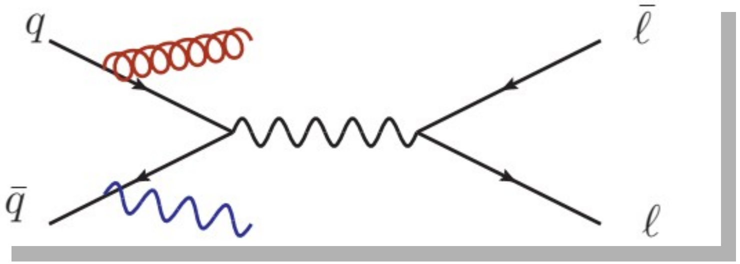

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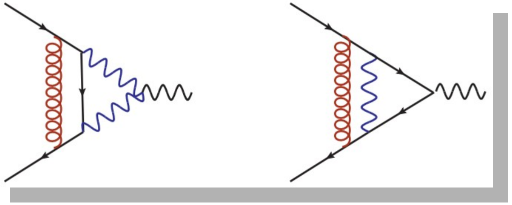
Treating Infrared Singularities in QCD-EW corrections

- Nested soft-collinear subtraction method developed for NNLO QCD singularities.

  [Caola, Melnikov, R.R. (‘17, ‘19); Delto, Frellesvig, Caola, Melnikov (‘18); Delto, Melnikov (‘19); Asteriadis, Caola, Melnikov, R.R. (‘19)]

- Flexible: straightforward modifications → QCD-EW corrections to $pp \to V \to \ell\bar{\ell}$
- Loop amplitudes:

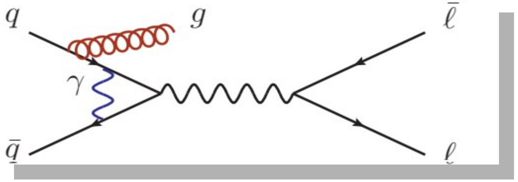
✔ Two-loop



Computed:

- Verified known results for Z production. [Kotikov, Kühn, Veretin (‘08)]
- First computation for W production.

✔ Real-virtual



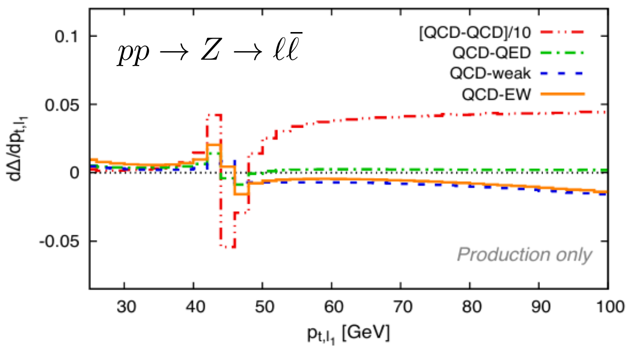
→ OpenLoops [Cascioli, Maierhöfer, Pozzorini (‘12); Buccioni, Pozzorini, Zoller (‘18); Buccioni *et al.* (‘19)]

Mixed QCD-EW corrections to vector boson production

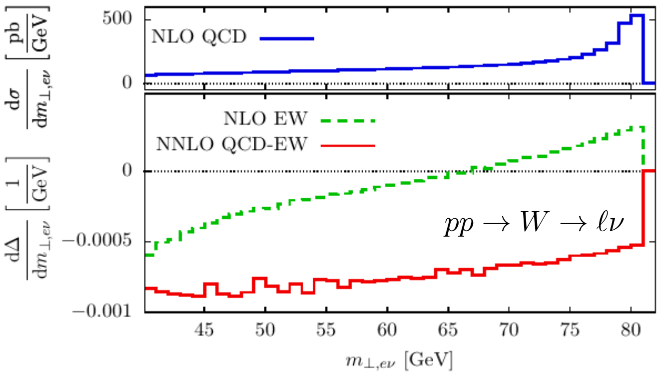
Fully differential mixed QCD-EW corrections to $pp \to Z \to \ell\bar{\ell}$ and $pp \to W \to \ell\nu$

- Corrections in production only

  [QCD (production) x EW (decay) known] [Dittmaier, Huss, Schwinn, ('14, '15)]



[Buccioni et al., ('20)]



[Behring et al., ('20)]

- Z production: QCD-weak corrections usually larger than QCD-QED corrections.
- G_μ scheme suppresses NLO EW corrections → smaller than QCD-EW corrections.

W mass determination

- ***Estimate*** effect of QCD-EW corrections on W mass measurement.
- Decorrelated corrections between *Z* and *W* production.
- Correlation between average transverse momentum of leptons and mass of boson:

$$\frac{m_W}{m_Z} = \frac{\langle p_{T,l}^W \rangle}{\langle p_{T,l}^Z \rangle} \Rightarrow m_W^{\text{meas.}} = m_Z \frac{\langle p_{T,l}^{W,\text{meas.}} \rangle}{\langle p_{T,l}^{Z,\text{meas.}} \rangle} C_{\text{th.}}$$

- Theoretical correction: assume input masses, compute W-mass, and compare with input W-mass.

$$\Rightarrow C_{\text{th.}} = \frac{m_W^{\text{in}}}{m_Z^{\text{in}}} \frac{\langle p_{T,l}^{Z,\text{th.}} \rangle}{\langle p_{T,l}^{W,\text{th.}} \rangle}$$

→ estimate impact of decorrelations in *W* and *Z* spectra from higher order corrections:

$$\frac{\delta m_W^{\text{meas.}}}{m_W^{\text{meas.}}} = \frac{\delta C_{\text{th.}}}{C_{\text{th.}}} = \frac{\delta \langle p_{T,l}^{Z,\text{th.}} \rangle}{\langle p_{T,l}^{Z,\text{th.}} \rangle} - \frac{\delta \langle p_{T,l}^{W,\text{th.}} \rangle}{\langle p_{T,l}^{W,\text{th.}} \rangle}$$

Impact on W mass determination

Shifts in W-mass: inclusive setup

- NLO EW: $\Delta m_W = 1 \text{ MeV}$
- QCD-EW: $\Delta m_W = -7 \text{ MeV}$

➔ Impact of QCD-EW corrections larger than NLO EW:

- NLO EW corrections suppressed in G_μ scheme.
- NLO EW corrections more correlated between *W* and *Z* production.
- Consider QCD-EW corrections to *W* production only:
  - NLO EW: $\Delta m_W = -31 \text{ MeV}$
  - QCD-EW: $\Delta m_W = 54 \text{ MeV}$

$\sqrt{s} = 13 \text{ TeV}$

G_μ scheme

$m_Z = 91.1876 \text{ GeV}$

$m_W = 80.398 \text{ GeV}$

$m_t = 173.2 \text{ GeV}$

$m_H = 125 \text{ GeV}$

$G_F = 1.16339 \cdot 10^{-5} \text{ GeV}^{-2}$

NNPDF31_luxQED

$\mu_R = \mu_F = m_V/2$

Impact on W mass determination

Shifts in W-mass: fiducial setup

- Inclusive setup: $\Delta m_W = -7 \text{ MeV}$
- "ATLAS" cuts: $\Delta m_W = -17 \text{ MeV}$
- "Tuned" cuts: $\Delta m_W = -1 \text{ MeV}$

➔ Cuts can have dramatic impact: shifts vary by factor of ~20.

- ➢ "ATLAS" cuts have stronger cuts on leptons from (lighter) *W* than from *Z* → decorrelation.

➔ QCD-EW shifts potentially relevant for target precision of 8 MeV.

$p^{Z}_{T,\ell} > 25 \text{ GeV}; |\eta^{Z}_{\ell}| < 2.4$

"ATLAS" cuts: $\mathrm{p}^{W}_{T,\ell} > 30 \text{ GeV}; \mathrm{p}^{\mathrm{W}}_{\mathrm{T,miss}} > 30 \text{ GeV}; |\eta^{\mathrm{W}}_{\ell}| < 2.4.$

"Tuned" cuts: $\mathrm{p}^{W}_{T,\ell} > 25.44 \text{ GeV}; \mathrm{p}^{\mathrm{W}}_{\mathrm{T,miss}} > 25.44 \text{ GeV}; |\eta^{\mathrm{W}}_{\ell}| < 2.4.$

Interpretation

- These results are **estimates** of impact of QCD-EW corrections on W-mass measurements at the LHC.
- Indicate that QCD-EW corrections could be relevant for 0.1 permille precision on W-mass measurements.
- Further investigations are essential:
  - What is the impact when using the full transverse momentum spectrum?
  - What is the impact on other observables?
  - How well are these captured with standard experimental simulation tools?
  - How reliable are these results – do we need to include parton showers to handle Sudakov shoulder?
  - ...

Summary

- Performed first fully differential calculation of mixed QCD-EW corrections to onshell *W* and *Z* boson production.
- IR singularities treated using modified nested soft-collinear subtractions.
- Mixed QCD-EW corrections generally comparable in magnitude to NLO EW corrections in G_μ scheme, but with different shapes.
- Estimated impact on measurement of W-mass at LHC ~ 10 MeV.
  - Strongly cut-dependent.
  - Potentially relevant for target uncertainty of 0.1 per mille.
  - Further investigations needed.

Thank you for your attention