Vector-Boson Production at the LHC: QCD and Electroweak effects

Tobias Kasprzik

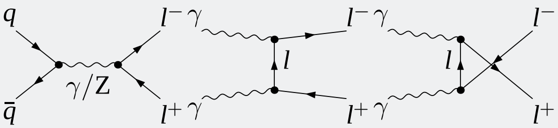
Karlsruhe Institute of Technology (KIT),
Institut für Theoretische Teilchenphysik (TTP)

22nd July 2011, EPS HEP 2011, Grenoble

Outline

Introduction – The Drell–Yan Process at the LHC

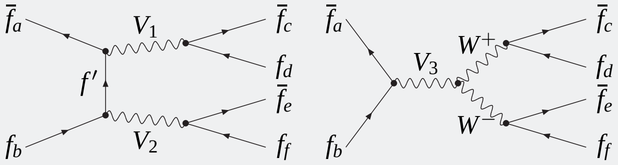
The Drell–Yan process: pp $\longrightarrow$ W/Z $\longrightarrow l\nu_l/l\bar{l}$



Large production cross sections!

- **Z-boson production:**
  - Clean signature
    $\longrightarrow$ Detector calibration, luminosity monitoring
  - Measure forward-backward asymmetries A_{FB}
    $\longrightarrow$ effective weak mixing angle accessible at the LHC
- **W-boson production:**
  - Determination of M_W and Γ_W by fitting $M_{\mathrm{T},ll}$ and $p_{\mathrm{T},l}$ to the data
  - Constrain PDFs by studying $R_\mp = \frac{\mathrm{d}\sigma(\mathrm{W}^-)}{\mathrm{d}\sigma(\mathrm{W}^+)}$, W-boson charge asymmetry, . . .

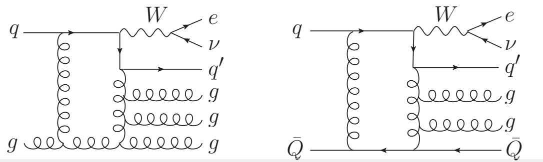
Vector-boson pair production: pp $\longrightarrow$ WW/ZZ/WZ $\longrightarrow$ $4l$



- ZZ/WW production important irreducible background to inclusive SM Higgs-boson production in the intermediate mass range
- Probe non-abelian structure of the Standard Model (SM) at high energies
- Search for anomalous trilinear and quartic couplings
- Backgrounds to new-physics searches, i.e. leptons + $\not{E}_T$ signatures
  $\longrightarrow$ SUSY-particle pair production

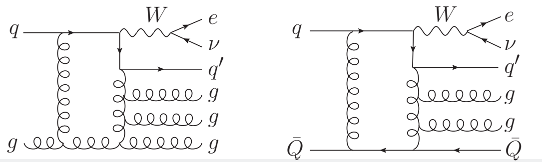
Introduction – W/Z + Jets at the LHC

V + jets production: pp $\longrightarrow$ W/Z + n jets



- Proper understanding of SM physics
- Study jet dynamics in QCD
- Backgrounds to various signatures (leptons + jets + $\not\!\!E_{\mathrm{T}}$) predicted by new-physics models
  - SUSY-particle pair production
  - Single-graviton production (1 jet + $\not\!\!E_{\mathrm{T}}$)

V + jets production: pp $\longrightarrow$ W/Z + n jets



- Proper understanding of SM physics
- Study jet dynamics in QCD
- Backgrounds to various signatures (leptons + jets + $\not{E}_{\mathrm{T}}$) predicted by new-physics models
  - SUSY-particle pair production
  - Single-graviton production (1 jet + $\not{E}_{\mathrm{T}}$)

High-precision theoretical predictions necessary!

QCD Corrections to the Drell–Yan Process

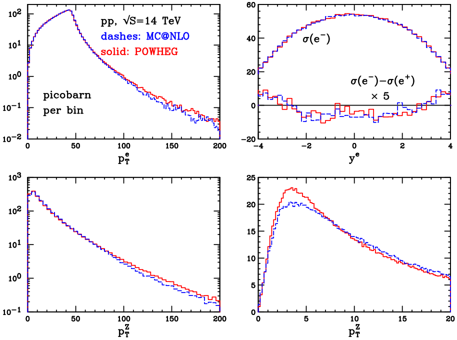
QCD corrections crucial at the LHC:

At least NLO QCD predictions necessary to understand electroweak (EW) physics properly

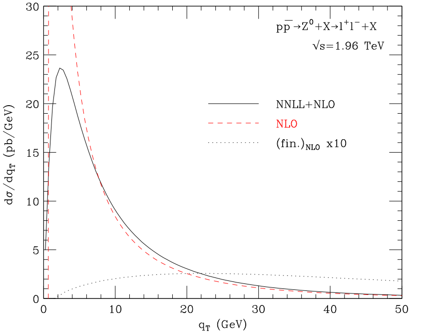
- Normalization of cross sections
- Reduction of scale dependence
- Shapes of differential cross sections

NLO (one-loop) corrections:

- combined with soft gluon resummation (resum large contributions $\propto \alpha_s^n \ln^m(M_V^2/q_T^2)$) [Bozzi et al. 2008/2010; Berge, Nadolsky, Olness 2006; . . .]
  $\longrightarrow$ accurate theoretical predictions for low-p_T jets/bosons
- matched with parton showers (e.g. `MC@NLO` [Frixione, Webber 2006], `POWHEG` [Frixione, Nason, Oleari 2007; Alioli, Nason, Oleari, Re 2008])



[Alioli et al.: arXiv:0805.4802 [hep-ph]]



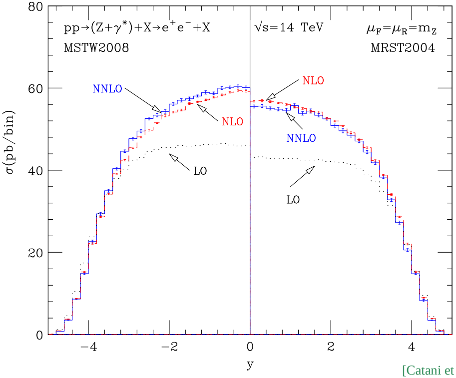
[Bozzi et al.: arXiv:1007.2351v2 [hep-ph]]

QCD Corrections to the Drell–Yan Process (II)

Higher-order corrections:

- NNLO (two-loop) corrections known fully differentially [Catani, Ferrera, Grazzini 2010; Catani, Cieri, Ferrera, de Florian, Grazzini 2009; Melnikov, Petriello 2006; Anastasiou, Dixon, Melnikow, Petriello 2004]
- N^3LO corrections known in the soft-plus-virtual approximation [Ravindran, Smith 2007,. . .]
  $\rightarrow$ theoretical error due to perturbative QCD $\sim$ 1% for integrated cross sections

Z-BOSON RAPIDITY:

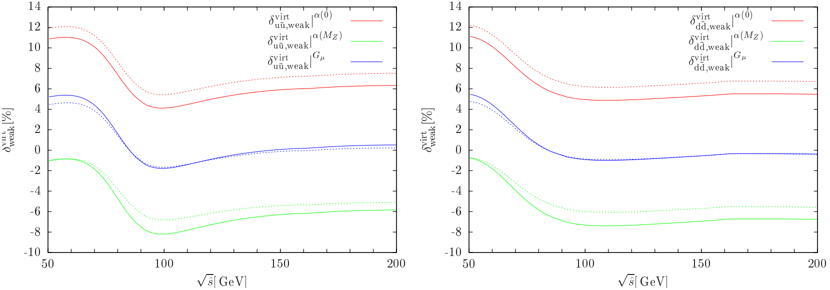


[Catani et al.: arXiv:0903.2120 [hep-ph]]

EW Corrections to the Drell–Yan Process

- NLO corrections to $l\bar{l}$ (NC) and $\nu_l l$ (CC) production known [(NC): Dittmaier, Huber 2009; Arbuzov et al. 2008; Carloni Calame, Montagna, Nicrosini, Vicini 2007; Zykunov 2007; Baur et al. 2002; Baur, Keller, Sakumoto 1998, (CC): Brensing et al. 2008, Carloni Calame et al. 2006; Arbuzov et al. 2006; Baur et al. 1999/2004, . . .]
  - Tuned comparisons of independent implementations [Buttar et al. 2006/2008; Gerber et al. 2007]
    $\longrightarrow$ reliable theoretical predictions
- Universal leading two-loop Sudakov effects included
- Predictions for different input schemes: $\alpha(0)$, $\alpha(M_Z)$, and α_{G_μ}
  $\longrightarrow$ higher-order correcions to $\Delta\alpha$ and $\Delta\rho$ absorbed in effective couplings

[Dittmaier, Huber: arXiv:0911.2329v2 [hep-ph]]

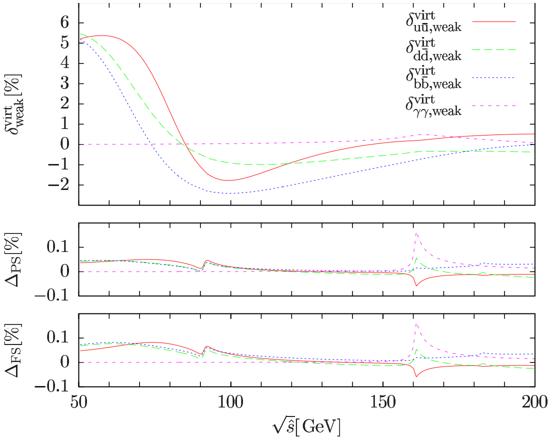


Different theoretical treatment of the Z-boson resonance:

- Pole scheme (PS)
- Complex-mass scheme (CMS)
- Factorization scheme (FC)

Deviations from CMS $\sim$ 0.1%

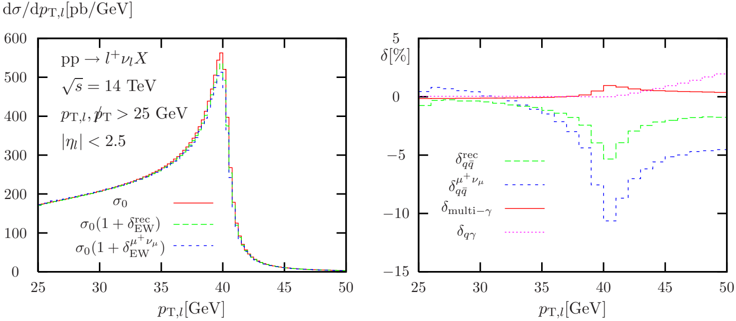
[Dittmaier, Huber: arXiv:0911.2329v2 [hep-ph]]



EW Corrections to the Drell–Yan Process (III)

- Significant enhancement of corrections due to non-collinear-safe photon radiation off muons in the final state → determination of M_W (CC)
- Multi-photon radiation included within the structure-function approach [Dittmaier, Huber 2009; Carloni Calame et al. 2004; Placzek, Jadach 2003], matched to $\mathcal{O}(\alpha)$ corrections within HORACE [Carloni Calame et al. 2006(CC)/07(NC)] → corrections of up to a few % in the resonance region
- Small phase-space dependent corrections due to photon-induced processes

W-BOSON PRODUCTION, LEPTON p_T:

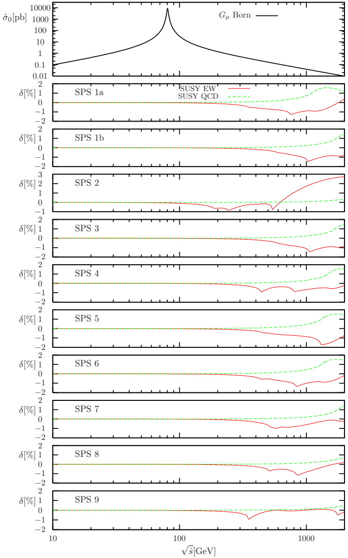


[Brensing et al.: arXiv:0710.3309v2 [hep-ph]]

EW Corrections to the Drell–Yan Process (IV)

- Tiny effects of virtual contributions of MSSM particles (in the resonance region)
  $\rightarrow$ **Drell–Yan physics well-described by SM physics**
- First steps taken towards combined QCD $\otimes$ EW (two-loop) analysis to push EW accuracy to the level of 1%

  [Kotikov, Kühn, Veretin 2008; Balossini et al. 2008, Viccini et al. 2007; Ward et al. 2007/05; Cao et al. 2004]

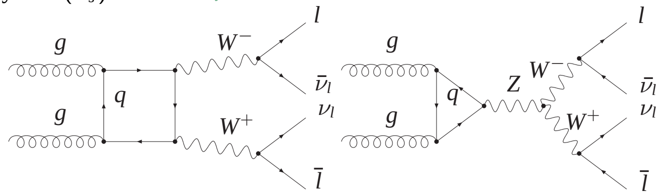


[Brensing et al.: arXiv:0710.3309v2 [hep-ph]]

Vector-Boson Pair Production – QCD Effects

Extensive study of production of WW, WZ, ZZ, Wγ, Zγ, $\gamma\gamma$ at NLO QCD [Campbell, Ellis, Williams 2011; Campbell, Ellis 1999, Dixon, Kunszt, Signer 1999,. . .]

- Results matched with parton showers $\oplus$ combined with soft gluon resummation [Frixione, Webber 2006]
- On-shell leptonic decays of the vector bosons taken into account (narrow-width approximation) retaining all spin information
- Weak-boson pair production dominated by tree-level $q\bar{q}$ annihilation channels
  - Significant contributions of the channels $gg \to V_1V_2$ ~ 10 % to LO, although formally at $\mathcal{O}(\alpha_s^2)$ [Glover, van der Bij 1989; Kao, Dicus 1991; Duhrssen et al. 2005]



  - Even larger corrections of 30% if event selection for Higgs searches is applied [Binoth et al. 2006]

EW Corrections to Vector-Boson Pair Production

Sudakov Logarithms

EW corrections at high energies dominated by universal large logarithms

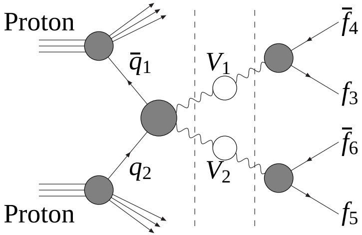
$$\propto \alpha^L \ln^{2L}(M_V/\sqrt{s}) \quad (\mathrm{LL})\,, \quad \propto \alpha^L \ln^{2L-1}(M_V/\sqrt{s}) \quad (\mathrm{NLL})\,, \ldots$$

at the *L*-loop level

- Corrections of $\sim -40\%$ at $\sqrt{s} = 2\,\mathrm{TeV}$ (process-dependent!)

EW Corrections to Vector-Boson Pair Production

- $\mathcal{O}(\alpha)$ high-energy approximation known for all channels, vector bosons treated in pole-approximation $\rightarrow$ final-state leptons phenomenologically accessible
  [Accomando et al. 2002–2006]

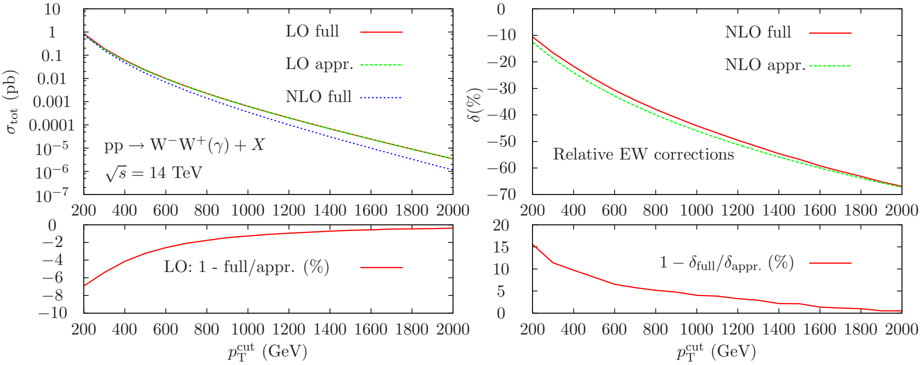


- Full $\mathcal{O}(\alpha)$ corrections known to Wγ and Zγ production in single-pole approximation (real corrections complete) [Accomando, Denner, Maier 2005]
- We have calculated full one-loop corrections to on-shell WW production at the LHC [Bierweiler, TK, Kühn, Uccirati]
  $\rightarrow$ reasonable agreement with former high-energy approximations
- NNLL effects at two loops published recently for the WW channel [Kühn, Metzler, Uccirati, Penin 2011]

EW Corrections to pp → $W^-W^+ + X$ – Numerical results (Preliminary)

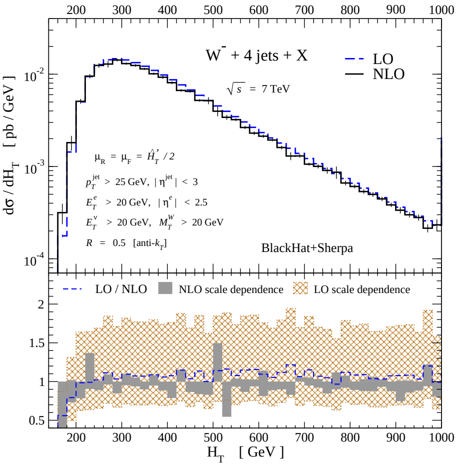
Comparison with [Kühn et al.: arXiv:1101.2563] (NLO at NNLL accuracy):

- $\overline{\text{MS}}$ renormalization of weak mixing angle and coupling α, on-shell renormalization of masses
- **Scale choice:** $\mu_F = \mu_R = p_{T,W^-}$
- Adopt MRST2001LO PDFs [Martin et al. 2002]



W/Z + *n* jets multi-leg processes, high jet multiplicity
→ demanding calculations, high computational effort

- NLO corrections matched with parton showers for W/Z + jet production [Alioli et al. 2010]
- NLO corrections to W/Z + jet / W/Z + 2jet production known, e.g. included in `MCFM` [Campbell, Ellis]
- NLO W/Z + 3jet results computed with `BlackHat` + `SHERPA` [Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maître 2009, 2010], `Rocket` + `MCFM` [Ellis, Giele, Melnikov, Kunszt, Zanderighi]
- W + 4jets known at NLO, Z + 4jets within reach [Berger et al. 2011]
  → First 2 → 5 NLO prediction for hadron colliders!

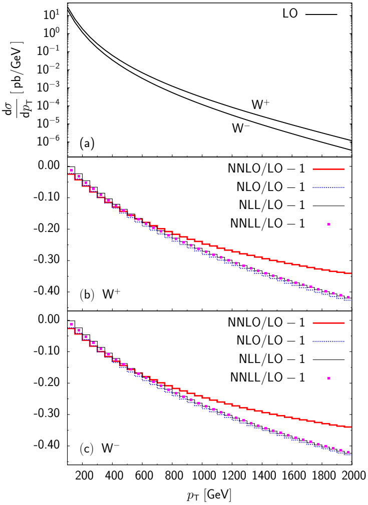


[Berger et al.: arXiv:1009.2338 [hep-ph]]

On-Shell W/Z production with one QCD jet:

- Purely weak corrections to on-shell Z + jet production known, including NLL and NNLL approximations at one loop [Kühn, Kulesza, Pozzorini, Schulze 2005]
- Full $\mathcal{O}(\alpha)$ corrections known for on-shell W + jet production [Kühn, Kulesza, Pozzorini, Schulze 2007/08; Hollik, TK, Kniehl 2008]
  - NNLO = NLO + 2-loop NLL
  - NLL and NNLL considered at one loop

W + JET PRODUCTION:

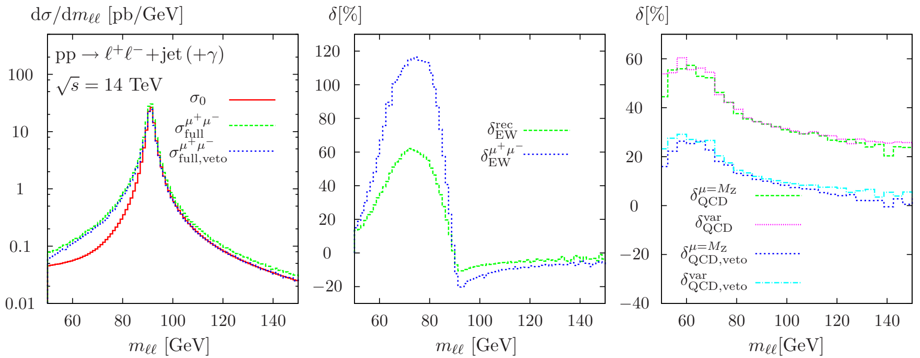


[Kühn et al.: arXiv:0708.0476 [hep-ph]]

Inclusion of leptonic decays / off-shell effects:

- Full NLO corrections to $\nu_l l$ + jet and $l\bar{l}$ + jet production [Denner, Dittmaier, TK, Mück 2009/11]
- Reasonable agreement with on-shell approximation at high energies

Z+JET-PRODUCTION CROSS SECTION:



- Huge positive corrections to the invariant-mass distributions below the on-shell peak, especially for bare muons
- Important ingredient of a combined QCD $\otimes$ EW analysis at $\mathcal{O}(\alpha\alpha_s)$

Summary & Conclusions

Precise theoretical predictions for Drell–Yan, vector-boson pair production and V + jet(s) available

- Both fixed-order and resummed EW and QCD contributions considered
- **Drell–Yan:**
  - Most accurate determination of M_{W} possible at the LHC:

$$\delta_{M_{\mathrm{W}}} = 15\ \mathrm{MeV}$$

  - Precise determination of EW precision observables at the LHC:

$$\delta_{\sin^2\theta_{\mathrm{eff}}} = 0.00014$$

    (expected at 100 fb^{-1}; better than LEP accuracy!)
- **V-pair production and V + jets:**
  - Reliable predictions for SM backgrounds to BSM-physics signatures
  - Important background to SM Higgs signals
- Accurate knowledge of weak-boson physics necessary to reduce PDF uncertainties

Summary & Conclusions

Precise theoretical predictions for Drell–Yan, vector-boson pair production and V + jet(s) available

- Both fixed-order and resummed EW and QCD contributions considered
- **Drell–Yan:**
  - Most accurate determination of M_W possible at the LHC:

$$\delta_{M_\mathrm{W}} = 15\ \mathrm{MeV}$$

  - Precise determination of EW precision observables at the LHC:

$$\delta_{\sin^2\theta_\mathrm{eff}} = 0.00014$$

  (expected at 100 fb^{-1}; better than LEP accuracy!)
- **V-pair production and V + jets:**
  - Reliable predictions for SM backgrounds to BSM-physics signatures
  - Important background to SM Higgs signals
- Accurate knowledge of weak-boson physics necessary to reduce PDF uncertainties

Thank You!

NLO Electroweak Corrections – IR-Safe Observables

Infrared Singularities

- Occur in real bremsstrahlung corrections as well as in loop diagrams
- Have to be regularized to make them calculable!
- **Mass regularization** for IR singularities: include small fermion masses m_ℓ, m_q and an infinitesimal photon mass λ (**Neglect regulator masses in non-singular parts of the calculation!**)
  - combine virtual and real corrections $\rightarrow \ln(\lambda)$ dependence drops out.
  - Initial-state collinear singularities absorbed into PDFs
  - Final-state collinear singularities give rise to $\ln(m_\ell)$ and $\ln(m_q)$ terms in the cross section.

Important: Proper definition of observables!

NLO Electroweak Corrections – IR-Safe Observables

Important: Proper definition of observables!

Collinear photon-quark pair:

- Photon-quark recombination to get rid of unphysical $\ln(m_q)$ terms
- Photon-gluon recombination will lead to soft gluon pole!
- **Way out:** Distinguish Z+jet from Z+γ events $\rightarrow$ discard events with $z_\gamma = \frac{E_\gamma}{E_q + E_\gamma} > 0.7$ $\rightarrow$ residual logs absorbed in **renormalized photon fragmentation function** [Buskulic et al. 1996; Glover, Morgan 1994; Denner, Dittmaier, Gehrmann, Kurz 2010]

$$D_{q\rightarrow\gamma}(z_\gamma) = \frac{\alpha Q_q^2}{2\pi} P_{q\rightarrow\gamma}(z_\gamma)\left(\ln\frac{m_q^2}{\mu_\mathrm{F}^2} + 2\ln z_\gamma + 1\right) + D_{q\rightarrow\gamma}^{\mathrm{ALEPH},\overline{\mathrm{MS}}}(z_\gamma, \mu_\mathrm{F})$$

- Non-perturbative part $D_{q\rightarrow\gamma}^{\mathrm{ALEPH},\overline{\mathrm{MS}}}(z_\gamma, \mu_\mathrm{F})$ determined by the ALEPH experiment at CERN

NLO Electroweak Corrections – IR-Safe Observables

Important: Proper definition of observables!

A collinear $e^{\pm} + \gamma$ pair cannot be distinguished experimentally
$\rightarrow$ recombination necessary
$\rightarrow$ $\ln(m_e)$ drops out (KLN theorem)

collinear-safe observable

A collinear $\mu^{\pm} + \gamma$ pair can be distinguished experimentally
$\rightarrow$ no recombination necessary
$\rightarrow$ $\ln(m_\mu)$ survives
$\rightarrow$ physical contributions!
$\rightarrow$ **enhanced corrections!**

non-collinear-safe observable

We have worked out the **dipole subtraction formalism** for non-collinear-safe observables and various QED splittings. [Dittmaier, Kabelschacht, TK 2008]

The Complex-Mass Scheme (CMS) [Denner, Dittmaier, Roth, Wieders 2005]

A problem with unstable particles

Naive implementation of finite width in gauge-boson propagator:

$$\frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}\epsilon} \to \frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}}$$

Γ_W includes Dyson summation of self energies, mixing of perturbative orders
$\to$ **might destroy gauge invariance (even at leading order!)**

The Complex-Mass Scheme (CMS) [Denner, Dittmaier, Roth, Wieders 2005]

A problem with unstable particles

Naive implementation of finite width in gauge-boson propagator:

$$\frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}\epsilon} \to \frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}}$$

Γ_W includes Dyson summation of self energies, mixing of perturbative orders
$\rightarrow$ **might destroy gauge invariance (even at leading order!)**

$\rightarrow$ **CMS universal solution that**

- respects gauge invariance
- is valid in all phase-space regions

Straightforward implementation:

- **LO:** $M_\mathrm{V}^2 \to \mu_\mathrm{V}^2 = M_\mathrm{V}^2 - \mathrm{i}M_\mathrm{V}\Gamma_\mathrm{V}, \quad \cos^2\Theta_\mathrm{W} = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}, \quad \mathrm{V} = \mathrm{W}, \mathrm{Z}$
- **NLO:**
  - Complex renormalization: $\mathcal{L}_0 \to \mathcal{L} + \delta\mathcal{L}$, **bare (real) Lagrangian unchanged!**
  - Evaluate loop integrals with complex masses

EW Input Schemes

- $\alpha(0)$: On-shell definition in the Thomson-limit (zero momentum transfer)

$$\bar{u}(p)\Gamma^{Ae\bar{e}}_{\mu}(p,p)u(p)\Big|_{p^2=m_e^2} = e(0)\bar{u}(p)\gamma_\mu u(p)\,,\alpha(0) = e(0)^2/4\pi$$

- $\alpha(M_Z)$ obtained via renormalization-group running from 0 to weak scale M_Z

$$\alpha(M_Z) = \frac{\alpha(0)}{1-\Delta\alpha(M_Z)}\,, \quad \Delta\alpha = \Pi^{AA}_{f\neq t}(0) - \mathrm{Re}\,\Pi^{AA}_{f\neq t}(M_Z^2)$$

- α_{G_μ} defined through the Fermi constant related to the muon lifetime

$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_W^2 s_w^2}{\pi} = \frac{\alpha(0)}{1-\Delta r}$$

  Δr includes corrections to muon lifetime not contained in QED-improved Fermi model

- light-fermion mass logs resummed in effective couplings $\alpha(M_Z)$ and α_{G_μ}