V + jet production at the LHC:
ELECTROWEAK PRECISION

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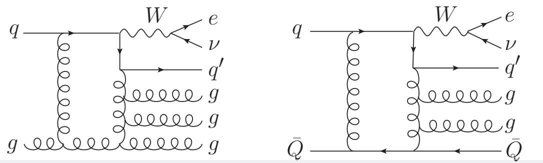
Outline

1. Introduction
2. Status of Theory Predictions
   - QCD Corrections
   - Electroweak Corrections
3. Details of the Calculations
   - Virtual Corrections
   - Real Corrections
4. Numerical Results
5. Combination of QCD and EW Corrections
6. Summary & Conclusions

Introduction – W/Z + Jets at the LHC

Vector bosons almost always produced together with additional QCD radiation

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 + $\not{E}_T$) predicted by new-physics models
    - SUSY-particle pair production
    - Single-graviton production (1 jet + $\not{p}_T$) $\longrightarrow$ $\nu_\ell \bar{\nu}_\ell$ + jet

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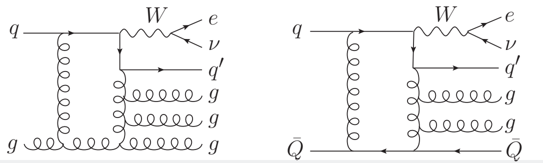

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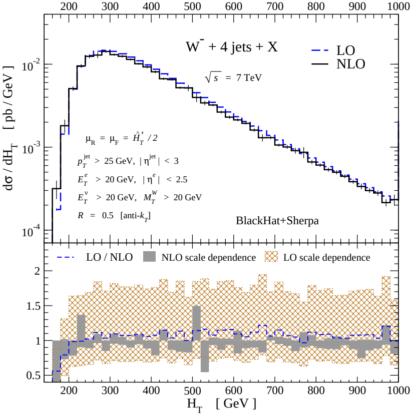
High-precision theoretical predictions necessary!

W/Z + jet(s) at the LHC – QCD Corrections

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 [Alioli et al. 2010] and W + 1/2/3 jets production [Sherpa+MC@NLO: Hoeche, Krauss, Schönherr, Siegert 2012]
- Resummation effects known for V-boson production at small [Bozzi et al. 2008; Berge, Nadolsky, Olness 2006; . . .] and large p_T [Becher, Lorentzen, Schwartz 2012, . . .]
- NLO corrections to W + 1/2/3/4(/5) jets and Z + 1/2/3/4 jets known [BlackHat+Sherpa, Rocket+MCFM, many others . . .]

  → **W + 5 jets: First 2 → 6 NLO prediction for hadron colliders!**
- Automation of NLO computations [OpenLoops, GoSam, HELAC-NLO, MadLoop/aMC@NLO, . . .]



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

V + jet Production at High Energies

Sudakov Logarithms

High-energy limit

$$s, |t|, |u| \gg M_V^2 \,, \quad s \sim |t| \sim |u|$$

→ **bosons have to be produced at large p_{T}**

- EW corrections at high energies dominated by universal large logarithms

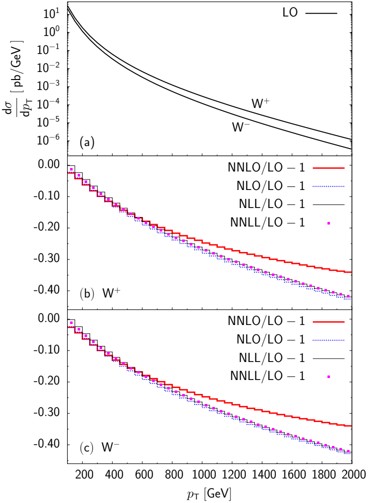
$$\begin{aligned} &\propto \quad \alpha^L \ln^{2L}(M_V/\sqrt{s}) \quad (\mathrm{LL})\,, \\ &\propto \quad \alpha^L \ln^{2L-1}(M_V/\sqrt{s}) \quad (\mathrm{NLL})\,, \ldots \end{aligned}$$

  at the *L*-loop level
- Sizable negative corrections at NLO at large p_{T}
- Change of sign going from LL to NLL (to NNLL . . .)
  → **substantial cancellations possible!**

EW Corrections to V + jet Production

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 $\mathcal{O}(\alpha)$ + leading 2-loop 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
  - Typical negative one-loop Sudakov logs
  - NLL two-loop corrections lead to a shift of $\sim$ 10% at highest p_T



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

EW Corrections to V + jet Production (II)

Next step:

Compute full NLO EW corrections to

$$\begin{aligned} \mathrm{pp} &\to \mathrm{W} + \mathrm{jet} \to \nu_\ell \ell + \mathrm{jet}\,, \\ \mathrm{pp} &\to \mathrm{Z}/\gamma^* + \mathrm{jet} \to \ell^+\ell^- / \nu_\ell \bar{\nu}_\ell + \mathrm{jet} \end{aligned}$$

in the SM **[Denner, Dittmaier, TK, Mück 2009/11]**

Include leptonic decays:

- ✓ Final-state leptons phenomenologically accessible
- ✓ Investigate effects due to final-state photon radiation

Include off-shell effects:

- ✓ Investigate distribution of $m_{\ell\ell}$ (NC) and $m_{\mathrm{T},\ell\ell}$ (CC)
  → Search for new resonances in the off-shell tails

Challenges:

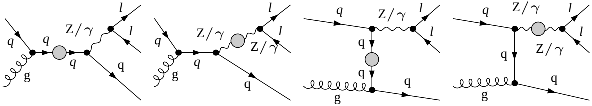
$\Longrightarrow$ Consistent treatment of finite gauge-boson width!

$\Longrightarrow$ Demanding $2 \to 3$ computation in the full SM (many scales, pentagon diagrams, infrared singularities, . . .)

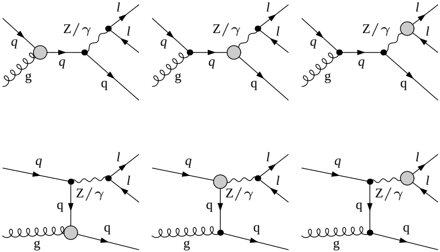
Virtual EW Corrections to pp $\rightarrow \ell\bar{\ell} + \mathrm{jet}$

Overview – 1PI Insertions

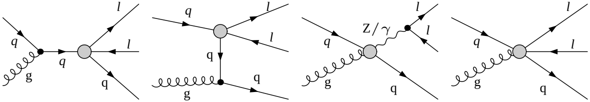
Self-energy insertions:



Triangle insertions:



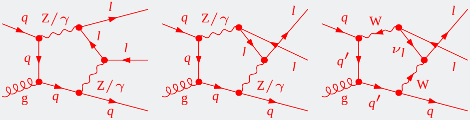
Box and pentagon insertions:



Virtual EW Corrections pp $\to \ell\bar{\ell}$ + jet (II)

Some details

Pentagon Contributions at $\mathcal{O}(\alpha^3\alpha_s)$



- The fine-structure constant is defined in the G_μ scheme:

$$\boxed{\alpha(0) \to \alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_\mathrm{W}^2}{\pi}\left(1-\frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right), \quad \delta\mathcal{Z}_e \to \delta\mathcal{Z}_e - \frac{1}{2}\Delta r}$$

- Loops calculated using **Complex-Mass Scheme** [Denner, Dittmaier, Roth, Wieders 2005]
- Reduction of pentagons directly to boxes avoiding small Gram determinants [Denner, Dittmaier 2003, 2005]
- Need to calculate scalar one-loop 4-point integrals with complex masses [Denner, Dittmaier 2010]

The Complex-Mass Scheme (CMS)

A problem with unstable particles

Naive implementation of finite width in gauge-boson propagator:

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

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

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

→ **CMS universal solution that**
- respects gauge invariance
- is valid in all phase-space regions

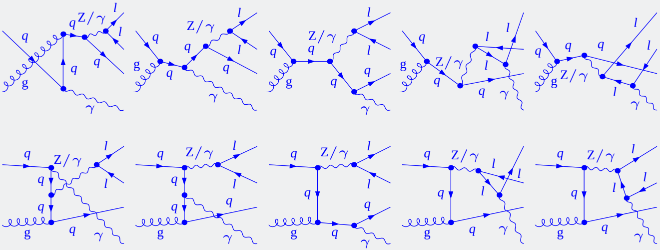
Straightforward implementation:

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

Real EW Corrections to pp $\longrightarrow \ell\bar{\ell} + \text{jet}$

Infrared Singularities

Real photon radiation at $\mathcal{O}(\alpha_s\alpha^3)$: $q\ \mathrm{g} \to \ell^-\ell^+ + q + \gamma$



- **Soft singularities** due to soft photons
- **Initial-state** collinear singularities due to collinear photon radiation off initial-state quarks ⟶ renormalization of PDFs
- **Final-state** collinear singularities due to photon-radiation off final-state leptons and quarks

⟶ **Dipole subtraction for photon radiation off fermions** [Dittmaier 1999]

Final-State Radiation

We allow for fully exclusive treatment of FS photon radiation:

- **dressed electrons (rec.):** recombination of collinear electron–photon configurations
  → large $\ln m_e$ terms cancel
- **bare muons:** exclusive treatment of collinear muon–photon configurations
  → enhancement of corrections due to large $\ln m_\mu$ terms

- **quark → photon fragmentation:** exclusive treatment of collinear parton(q, g)–photon configurations to separate V + jet from V + photon
  → residual $\ln m_q$ terms absorbed in the perturbative part of a renormalized photon fragmentation function [Buskulic et al. 1996; Glover, Morgan 1994; Denner, Dittmaier, Gehrmann, Kurz 2010]

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

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

Technical Framework

Tools for numerical evaluation: Two completely different implementations!

SD (Freiburg), TK (Karlsruhe)

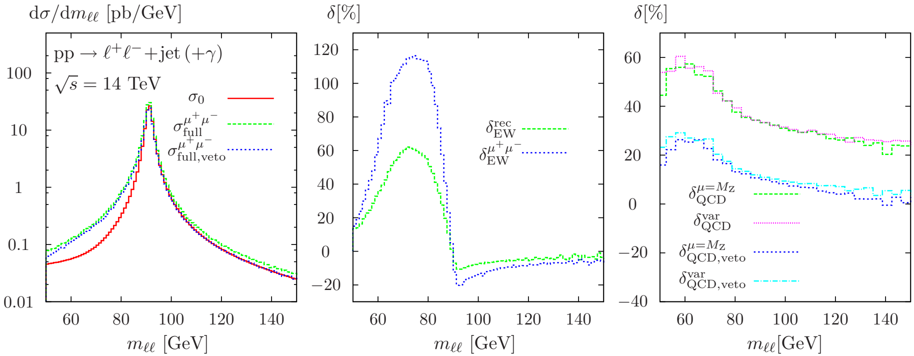
- **Virtuals:** `FeynArts-1.0` [Küblbeck, Böhm, Denner],
- **Algebraical reduction:** in-house `Mathematica` routines
- **Real emission:** amplitudes worked out by hand
- **Numerical integration:** `Vegas` [Lepage]

AD (Würzburg), AM (Aachen)

- **Virtuals & real emission:** `FeynArts-3.2/FormCalc-3.1` [Hahn]
- `Fortran` code generated automatically by `Pole` [Meier, Mück]
- **Numerical integration:** `Pole` interface to `Lusifer` [Dittmaier, Roth] (`Vegas`-improved)

Numerical Results (I) – Z + jet production

Distribution of the invariant mass $m_{\ell\ell} = \sqrt{(p_{\ell^+} + p_{\ell^-})^2}$

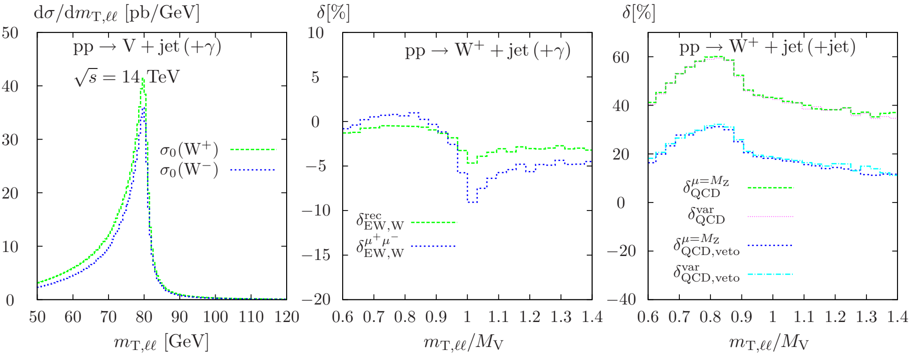


- Typical Breit–Wigner shape of the LO distribution
- Final-state photon radiation systematically shifts events to smaller $m_{\ell\ell}$
  $\longrightarrow$ huge positive corrections
  corrections to total cross section still small (−5%)
- **Note:** QCD corrections uniform and of expected size

Numerical Results (II) – Compare Z and W Cross Sections

Distribution of the transverse mass $m_{\mathrm{T},\ell\ell} = \sqrt{2p_{\mathrm{T},\ell^+}p_{\mathrm{T},\ell^-}(1-\cos\phi_{\ell\ell})}$

W-PRODUCTION CROSS SECTION:



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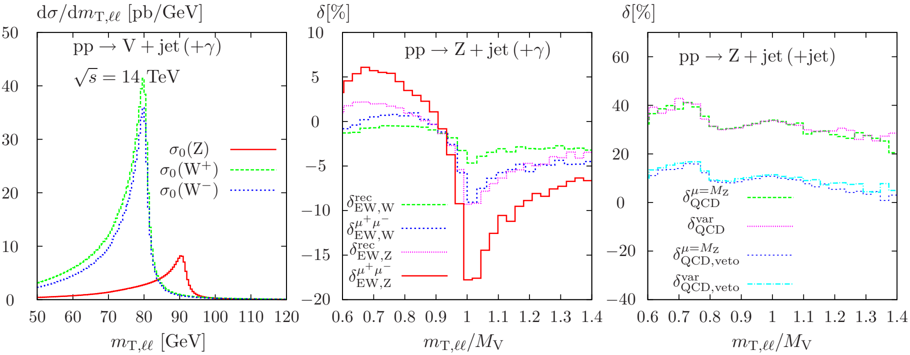

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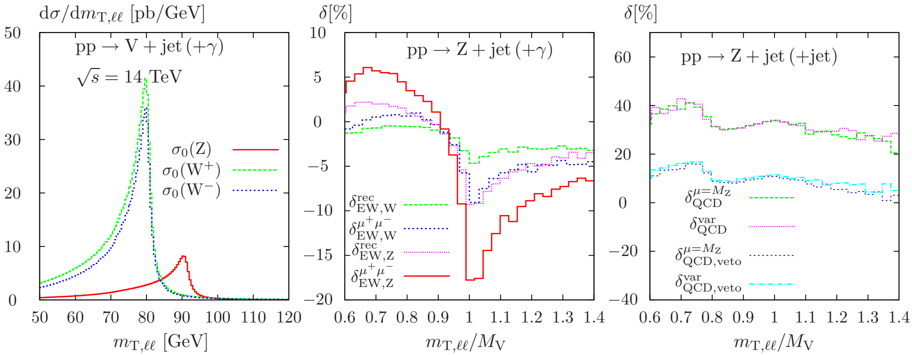
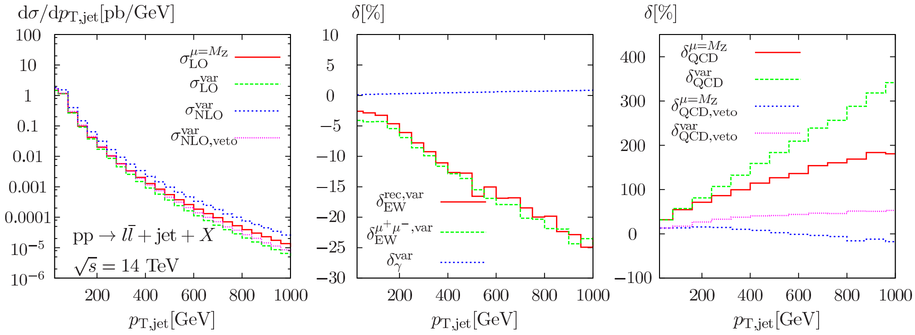


- $\sigma(\mathrm{W}^+)/\sigma(\mathrm{Z}) \sim 5$
- Phase-space-dependent EW corrections 100% bigger in Z-boson production (two leptons in the final state!)
- QCD corrections of similar size for W and Z production

Numerical Results (III): Z + jet production

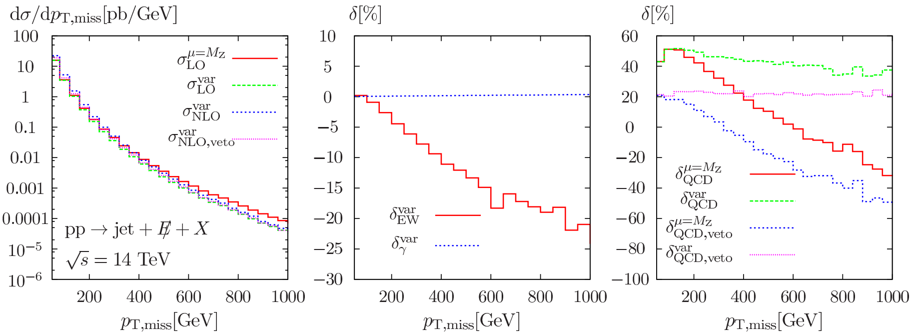
Z+jet production, leading-jet transverse momentum



- Huge QCD corrections at high $p_{T,jet}$
  → events at NLO dominated by tree-level Z + 2 jets production
- Jet veto stabilizes corrections; reduction of scale dependence
- Large negative EW corrections at high $p_{T,jet}$ due to universal Sudakov logs

Numerical Results (IV) – Single-Jet Production

Monojet production, missing transverse momentum



- Moderate QCD corrections, constant *K*-factor for variable scale choice
  → jet veto leads to a moderate shift (-20%), no distortion of process signature
- Assume factorization of EW corrections for this particular observable

Combination of QCD and EW Corrections

Task: Include EW corrections in comparison with experimental data

(**DY:** Additive combination of NLO EW + NNLO QCD in `FEWZ` [Li, Petriello 2012])

Challenge

How to combine our NLO EW corrections with a “state-of-the-art” QCD Monte Carlo (N(N)LO, parton-shower, resummation, hadronization, . . .)

- Compute mixed QCD×EW corrections
  ⇒ difficult, requires involved 2-loop computations
- EW corrections dominated by Sudakov logs attributed to hard process, QCD corrections dominated by soft and collinear radiation
  ⇒ factorized ansatz may be well justified

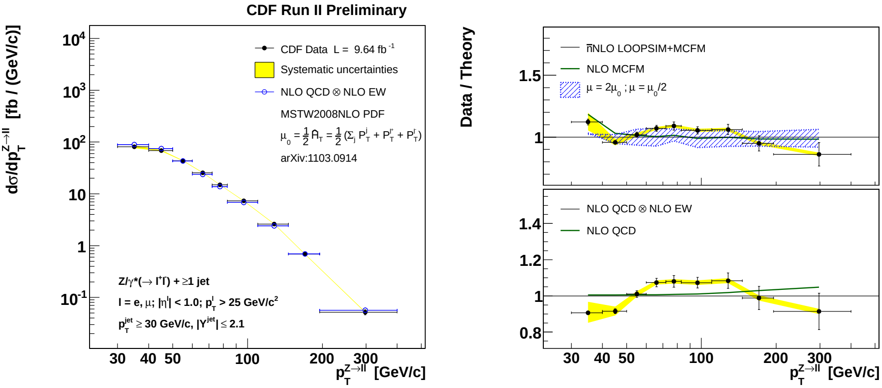
$$\frac{\mathrm{d}\sigma^{\mathrm{best}}_{\mathrm{QCD}\times\mathrm{EW}}}{\mathrm{d}p_{\mathrm{T,Z}}} = (1+\delta_{\mathrm{EW}}(p_{\mathrm{T,Z}}))\,\frac{\mathrm{d}\sigma^{\mathrm{best}}_{\mathrm{QCD}}}{\mathrm{d}p_{\mathrm{T,Z}}}$$

Caveat: Factorized ansatz will fail for observables which are dominated by hard QCD radiation (Z + 2 jets at LO)!
⇒ veto hard back-to-back jets

EW Corrections at the Tevatron

Our predictions have been included in the analysis of Tevatron data

[http://www-cdf.fnal.gov/physics/new/qcd/QCD.html]



- $\delta_{\text{EW}} \sim 5\%$ at $p_{\text{T,Z}} = 300$ GeV
- Onset of Sudakov logs visible at the Tevatron
- EW corrections crucial at the LHC

Summary & Conclusions

We have calculated the full NLO EW corrections to off-shell V+jet production and single-jet production at the LHC:

- Consistent treatment of the vector-boson resonance using the Complex-Mass Scheme
- All off-shell effects included
- Non-collinear-safe treatment of final-state photon radiation from leptons possible
- Calculation fully differential
- Predictions for Z+jet production implemented in CDF analysis: `http://www-cdf.fnal.gov/physics/new/qcd/QCD.html`

Future Work:

- Publish monojet results!
- Combination of EW and QCD corrections
- Compare our results to LHC data

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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 → discard events with $z_\gamma = \frac{E_\gamma}{E_q+E_\gamma} > 0.7$ → residual logs absorbed in **renormalized photon fragmentation function** [Buskulic et al. 1996; Glover, Morgan 1994; Denner, Dittmaier, Gehrmann, Kurz 2010]

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

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NLO Electroweak Corrections – IR-Safe Observables

Important: Proper definition of observables!

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

collinear-safe observable

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

EW Input Schemes – Definition of α

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

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

- $\alpha(M_\mathrm{Z})$ obtained via renormalization-group running from 0 to weak scale M_Z

$$\alpha(M_\mathrm{Z}) = \frac{\alpha(0)}{1-\Delta\alpha(M_\mathrm{Z})}\,, \quad \Delta\alpha(M_\mathrm{Z}) = \Pi_{f\neq t}^{AA}(0) - \mathrm{Re}\,\Pi_{f\neq t}^{AA}(M_\mathrm{Z}^2)$$

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

$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_\mathrm{W}^2 s_\mathrm{w}^2}{\pi} = \frac{\alpha(0)}{1-\Delta r}$$

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

- **light-fermion mass logs contained in $\Pi_{f\neq t}^{AA}(0)$ resummed in effective couplings $\alpha(M_\mathrm{Z})$ and α_{G_μ}**