Z+jet Production at the LHC: ELECTROWEAK RADIATIVE CORRECTIONS

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Outline

1. Motivation and introduction: The Drell–Yan process
2. Overview: Z+jet production at higher oders
3. Details of our calculation
4. Numerical results (Preliminary)
5. Summary & outlook

Motivation – Importance of the Drell–Yan Process

- **LHC:** Z bosons produced with large cross section ($\sim 2 \times 10^7$ events/year), lepton pair easy to reconstruct
  $\longrightarrow$ Drell–Yan-like processes important **"standard candles"** at the LHC!
  - Monitor and calibrate the LHC's luminosity
  - Determine lepton energy scale, detector resolution, linearity of detector response
    $\longrightarrow$ Important impact on precision of W-boson mass measurement!
  - Ratio $R_{\mathrm{Z/W}} = \sigma_{\mathrm{Z}}/\sigma_{\mathrm{W}}$ important to reduce error on measurement of Γ_{W}
  - Measure $\sin^2 \Theta_{\mathrm{eff}}^{\mathrm{lep}}$ at the LHC by investigating A_{FB}
  - **Constrain PDFs** by studying appropriate observables

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  $\longrightarrow$ Z′-signatures in tail of $m_{\ell\ell}$ distribution
  $\longrightarrow$ $\mathbf{Z + jet \longrightarrow \nu\bar{\nu} + jet}$: Mono-jet event, same signature as for graviton production in certain Extra-Dimension models

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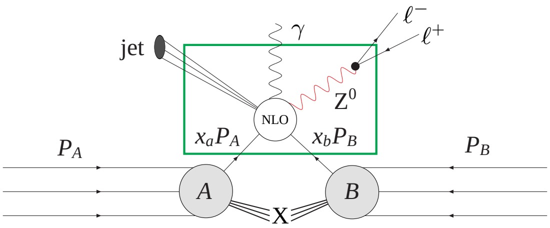
High-precision theoretical predictions necessary!

Reminder: Calculation of Hadronic Cross Sections

Schematic illustration for
$pp/p\bar{p} \rightarrow$
$Z^0 + \text{jet} + (\text{jet}/\gamma) \rightarrow$
$\ell^-\ell^+ + \text{jet} + (\text{jet}/\gamma)$



Hadronic cross sections

$$
\begin{aligned}
d\sigma_{AB}(p_A, p_B) \quad &= \quad \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b \, f_{a/A}(x_a, \mu_F)\, f_{b/B}(x_b, \mu_F)\, d\hat{\sigma}_{ab}^{\text{NLO}}(p_a, p_b, \mu_F, \mu_R) \\
&\times \mathcal{F}^{(\ell^-\ell^+ + \text{jet} + (\text{jet}/\gamma))}(\{\mathcal{O}_{\text{FS}}\}) \,, \qquad p_{a,b}^{\mu} = x_{a,b} P_{A,B}^{\mu}
\end{aligned}
$$

- Dependence on μ_R, μ_F reduced by inclusion of higher perturbative orders
- $\mathcal{F}^{(\ell^-\ell^+ + \text{jet} + (\text{jet}/\gamma))}$ incorporates definition of observables $\{\mathcal{O}_{\text{FS}}\}$ $\oplus$ phase-space cuts

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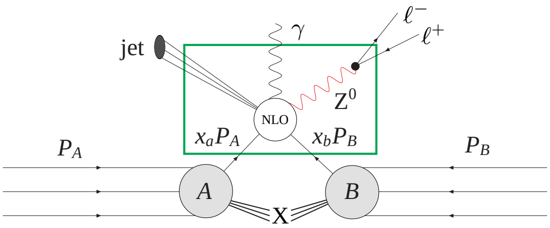

Hadronic cross sections

$$\mathrm{d}\sigma_{AB}(p_A, p_B) = \sum_{a,b} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a/A}(x_a, \mu_\mathrm{F}) \, f_{b/B}(x_b, \mu_\mathrm{F}) \, \mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ab}(p_a, p_b, \mu_\mathrm{F}, \mu_\mathrm{R})$$
$$\times \mathcal{F}^{(\ell^-\ell^+ + \mathrm{jet} + (\mathrm{jet}/\gamma))}(\{\mathcal{O}_{\mathrm{FS}}\}), \qquad p^\mu_{a,b} = x_{a,b} P^\mu_{A,B}$$

NLO partonic cross section:

$$\hat{\sigma}^{\mathrm{NLO}}_{ab} = \hat{\sigma}^{\mathrm{LO}}_{ab} + \hat{\sigma}^{\mathrm{virt}}_{ab} + \hat{\sigma}^{\mathrm{real}}_{ab}$$

Importance of Higher-Order Corrections – QCD

Fixed-order QCD corrections

- NLO corrections can be huge
- Mandatory for reduction of renormalization- and factorization-scale dependence

What we know already:

- NLO (1-loop) corrections to single-Z production
  - matched with parton showers [Frixione, Webber 2006; Alioli, Nason, Oleari, Re 2008]
  - combined with soft-gluon resummation [Bozzi et al. 2008; Berge, Nadolsky, Olness 2006; . . .]
- NNLO (2-loop) corrections to the Drell–Yan process known fully differentially [Catani, Cieri, Ferrera, de Florian, Grazzini 2009; Melnikov, Petriello 2006; Anastasiou, Dixon, Melnikow, Petriello 2004]
- NLO corrections to Z+jet / Z+2jet production known, e.g. included in `MCFM` [Campbell, Ellis], NLO V+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]

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Calculate NLO EW corrections,
because $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$

Higher-Order Corrections (II) – EW Contributions

EW Corrections (A summary)

- NLO EW corrections known for off-shell single-Z production [Dittmaier, Huber 2009; Arbuzov et al. 2008; Carloni Calame, Montagna, Nicrosini, Vicini 2007; Zykunov 2007; Baur et al. 2002; Baur, Keller, Sakumoto 1998]

$$\mathrm{pp} \to \ell^- \ell^+ \, (+\gamma) + \mathrm{X}$$

- Virtual EW corrections known for on-shell Z+jet production, including NLL and NNLL approximations [Kühn, Kulesza, Pozzorini, Schulze 2005]

$$\mathrm{pp} \to \mathrm{Z}^0 + \mathrm{jet} + \mathrm{X}$$

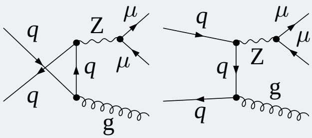
Important improvement: Do calculation for intermediate Z boson (physical final state), include γ-emission!

$$\mathrm{pp} \;\to\; \mathrm{Z}^0 + \mathrm{jet}\,(+\gamma) + \mathrm{X} \;\to\; \ell^- \ell^+ + \mathrm{jet}\,(+\gamma) + \mathrm{X}$$

- Use same setup as for W+jet calculation [Denner, Dittmaier, TK, Mück 2009]
- Study off-shell effects, allow for a realistic event definiton!
- Photon radiation off final-state leptons **(absent in on-shell approx.!)**
  $\to$ Relevant deviations in the shape of differential cross sections for leptonic FS

LO Contributions

Partonic LO contributions, $\mathcal{O}(\alpha_s \alpha^2)$



- **LO contributions:** 3 partonic channels, related by crossing symmetry

$$\begin{aligned} q_i\ \bar{q}_i &\rightarrow \mathrm{Z}^0\ \mathrm{g}, \quad q = \mathrm{u}, \mathrm{d}, \\ q_i\ \mathrm{g} &\rightarrow \mathrm{Z}^0\ q_i, \\ \mathrm{g}\ \bar{q}_i &\rightarrow \mathrm{Z}^0\ \bar{q}_i \end{aligned}$$

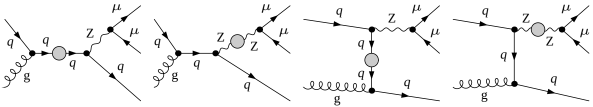
- **Sum over quark flavors** (Example: $q\,\bar{q} \rightarrow \mathrm{Z}^0\,\mathrm{g}$)

$$\sigma^{\mathrm{LO}}_{\mathrm{pp}(q\bar{q})} = \int \mathrm{d}x_a \mathrm{d}x_b \sum_{q=\mathrm{u},\mathrm{d}} \sum_{i=1}^{f_q} f_{q_i/\mathrm{p}}(x_a)\, f_{\bar{q}_i/\mathrm{p}}(x_b)\ \hat{\sigma}^{\mathrm{LO}}_{q_i\bar{q}_i \rightarrow \mathrm{Z}^0\mathrm{g}}$$

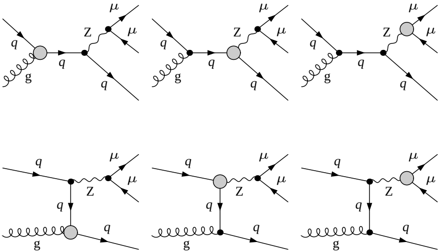
- **Partonic LO cross section**

$$\hat{\sigma}^{\mathrm{LO}}_{ab} = \frac{1}{2\hat{s}} \int_{\ell^- \ell^+ \mathrm{jet}} \mathrm{dPS} |\mathcal{M}_{\mathrm{LO}}|^2, \qquad \hat{s} = (p_a + p_b)^2$$

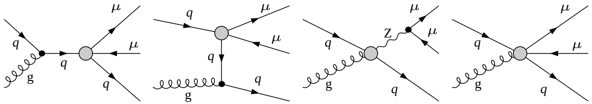
Self-energy insertions:



Triangle insertions:



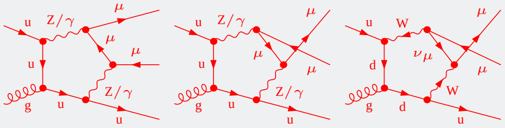
Box and pentagon insertions:



New: Virtual EW Corrections (II)

Some details

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



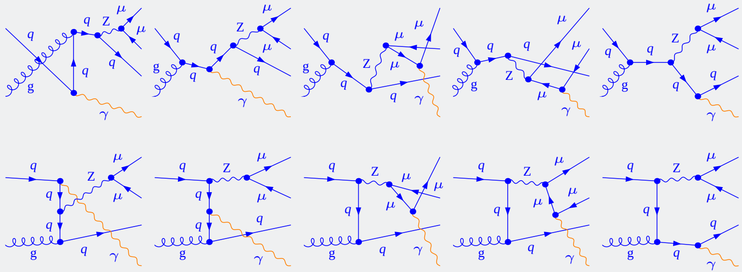
- We use the G_μ scheme to calculate the loop corrections:

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

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

New: Real EW Corrections

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



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

$\longrightarrow$ **Dipole subtraction for photon radiation off fermions** [Dittmaier 1999]

NLO Electroweak Corrections – IR Singularities

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 Singularities

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 $\longrightarrow$ discard events with $z_\gamma = \frac{E_\gamma}{E_q + E_\gamma} > 0.7$ $\longrightarrow$ residual logs absorbed in **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

NLO Electroweak Corrections – IR Singularities

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!**

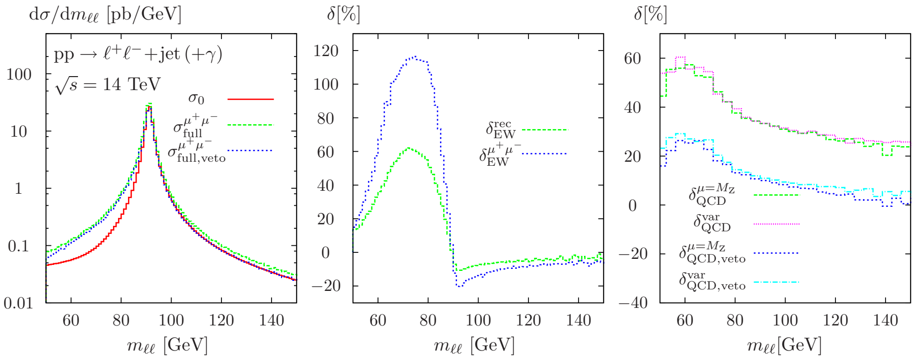
non-collinear-safe observable

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

Numerical Results at the LHC – Preliminary

(Physical setup → backup slide)

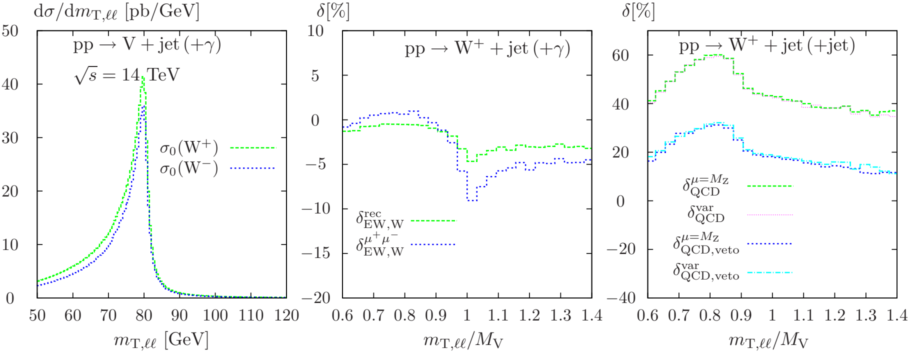
Distribution of the invariant mass $m_{\ell\ell} = \sqrt{(p_{\ell^+} + p_{\ell^-})^2}$



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

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:



Numerical Results – Compare Z and W Cross Sections
Preliminary

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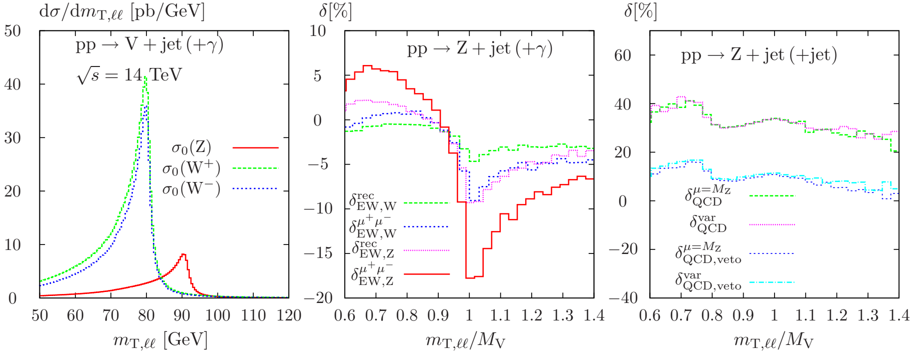

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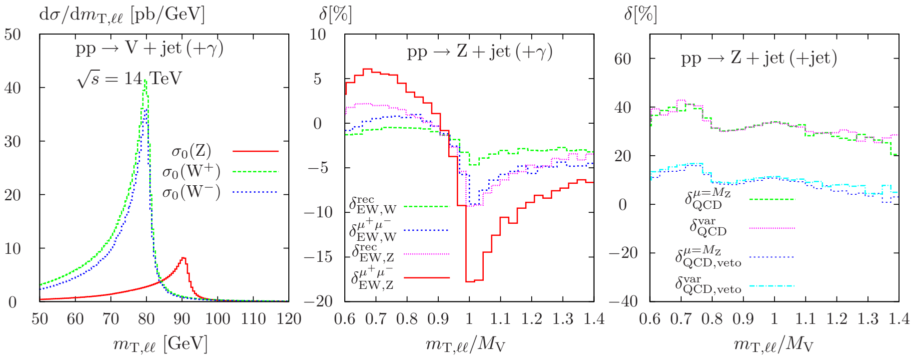

- $\sigma(\mathrm{W}^+)/\sigma(\mathrm{Z}) \sim 5$
- Phase-space-dependent EW corrections 100% bigger in Z-boson production
- QCD corrections of similar size for W and Z production

Summary & Outlook

- We have calculated the full NLO EW corrections to off-shell Z+jet production at the LHC/Tevatron:
  - Consistent treatment of the Z-boson resonance (Complex-Mass Scheme!)
  - All off-shell effects included
  - Non-collinear-safe treatment of final-state γ radiation from leptons
- Calculation fully differential $\longrightarrow$ We can apply any (sensible) phase-space cuts and calculate any differential cross section that might be of interest.
- We have two independent implementations of the calculation $\longrightarrow$ reliable check of the results!
- EW corrections are sizeable in certain phase-space regions $\longrightarrow$ should be taken into account in an analysis of experimental data
- **Future plans:**
  - Include final-state multi-photon radiation?
  - Investigate phenomenological impact on relevant observables as $R_{\mp}$, $R_{Z/W}$, A_{FB}, . . .

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Thank You!

The Complex-Mass Scheme (CMS) for Unstable Particles

[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!)**

$\to$ **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

Physical Setup – Definition of Observables

Definition of the physical final state:

1. Recombination of photon and nearest lepton if $R_{\gamma,\ell} < 0.1 \rightarrow \tilde{p}_\ell = p_\ell + k_\gamma$
2. Recombination of photon and jet (q, g) if $R_{\gamma,\mathrm{jet}} < 0.5$
3. **NLO QCD:** Recombination of two QCD partons to one jet if $R_{1,2} < 0.5$

Leptonic cuts

- Require $|y_\ell| < 2.5$ and $p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}$ for each final-state lepton
- Require $m_{\ell\ell} > 50\,\mathrm{GeV}$

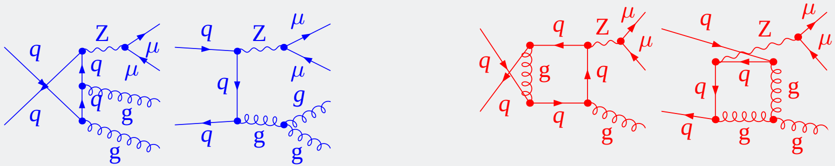
Jet observables in NLO QCD

- Require at least one hard jet with $|y_{\mathrm{jet}}| < 2.5$, $p_{\mathrm{T,jet}} > 25\,\mathrm{GeV}$
- **Two-jet veto:** Discard events with two back-to-back jets, require $p_{\mathrm{T},2} < p_{\mathrm{T},1}/2$ $\rightarrow$ reduction of (sizeable) tree-level Z + 2 jet contributions
- **Variable scale choice:** constant scale $\mu_\mathrm{R} = \mu_\mathrm{F} = M_\mathrm{Z}$, variable scale $\mu_\mathrm{R} = \mu_\mathrm{F} = \sqrt{m_{\ell\ell}^2 + p_{\mathrm{T,had}}^2} \rightarrow$ adjust scale to kinematics

Lepton-jet separation: Discard event if $R_{\ell,\mathrm{jet}} < 0.5$

One-Loop QCD Corrections – Review

NLO QCD contributions at $\mathcal{O}(\alpha_s^2\alpha^2)$ (sample diagrams)



- **Real corrections:** 3 generic processes, crossing and 5 active quark flavors lead to $\sim$ 100 different partonic channels

$$\begin{aligned} q_i\ \bar{q}_i &\rightarrow \mathrm{Z}^0\ \mathrm{g}\ \mathrm{g}, \qquad q = \mathrm{u}, \mathrm{d}, \\ \mathrm{u}_i\ \bar{\mathrm{u}}_i &\rightarrow \mathrm{Z}^0\ \mathrm{d}_j\ \bar{\mathrm{d}}_j, \\ q_i\ \bar{q}_j &\rightarrow \mathrm{Z}^0\ q_k\ \bar{q}_l \end{aligned}$$

- **Virtual corrections:** Self-energies, triangles, box diagrams
- **Cross section contributions:**

$$\hat{\sigma}^{\mathrm{virt}} + \hat{\sigma}^{\mathrm{real}} = \frac{1}{2\hat{s}} \int_4 \mathrm{dPS}\ |\mathcal{M}_{\mathrm{real}}|^2 + \frac{1}{2\hat{s}} \int_3 \mathrm{dPS}\ 2\mathrm{Re}[\mathcal{M}_{\mathrm{virt}}\mathcal{M}^*_{\mathrm{LO}}]$$