Theory status of V+jets at the LHC
ELECTROWEAK PRECISION

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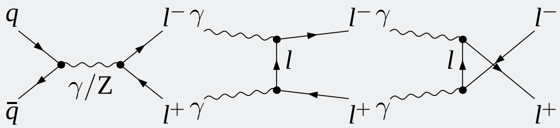
Outline

1. The Drell–Yan Process
   - Overview of QCD and Electroweak Effects
2. W/Z + Jets at the LHC
   - Review of QCD Predictions
   - Electroweak Corrections to Off-Shell V+jet Production
3. Summary & Conclusions

Introduction – The Drell–Yan Process at the LHC

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



Large production cross sections!

- **Z-boson production:**
  - Clean signature
    $\rightarrow$ Detector calibration, luminosity monitoring
  - Measure forward-backward asymmetries A_{FB}
    $\rightarrow$ 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, ...

QCD Corrections to the Drell–Yan Process

- LHC is a hadron collider
  ⇒ **All measurements carried out in a QCD-dominated environment**

QCD corrections crucial at the LHC:

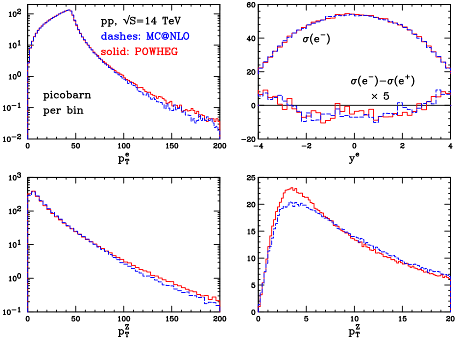
At least NLO QCD predictions necessary to understand electroweak (EW) physics properly

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

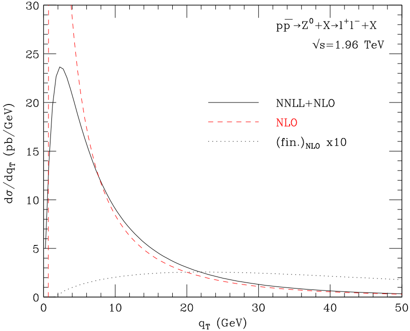
QCD Corrections to the Drell–Yan Process

NLO (one-loop) corrections:

- combined with soft-gluon resummation (resum large contributions $\propto \alpha_s^n \ln^m(M_V^2/q_\mathrm{T}^2)$) [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, Re 2007; Alioli, Nason, Oleari, Re 2008])

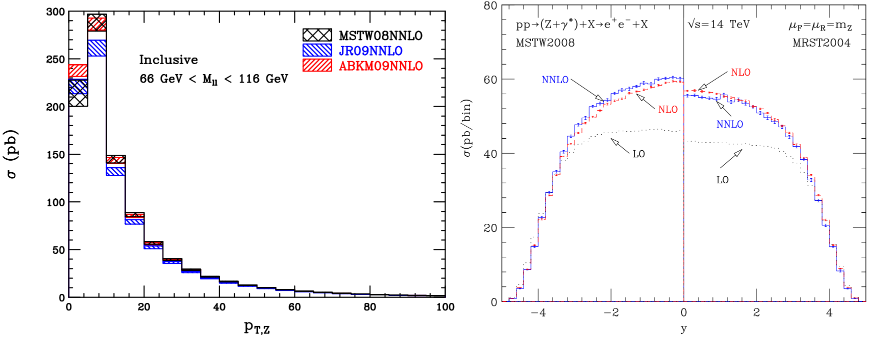


[Alioli et al.: arXiv:0805.4802 [hep-ph]]



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

QCD Corrections to the Drell–Yan Process (II)



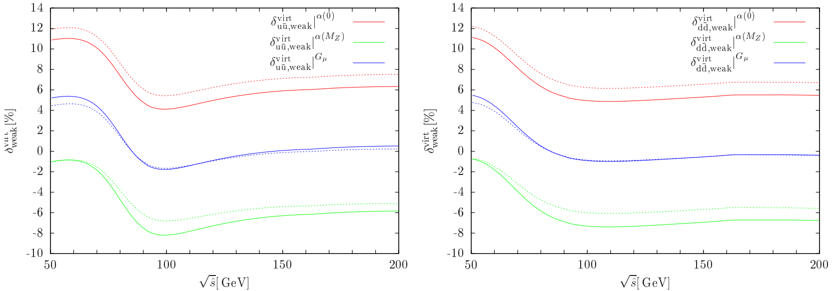
[Gavin et al.: arXiv:1011.3540] [Catani et al: arXiv:0903.2120 [hep-ph]]

- NNLO (two-loop) corrections known fully differentially [Catani, Cieri, Ferrera, de Florian, Grazzini 2009; Melnikov, Petriello 2006; Anastasiou, Dixon, Melnikow, Petriello 2004], implemented in Monte Carlo programs (`FEWZ` [Gavin et al. 2010], `DYNNLO` [Catani et al. 2009])
- N^3LO corrections known in the soft-plus-virtual approximation [Ravindran, Smith 2007,. . .]
  → theoretical error due to perturbative QCD ∼ 1% for integrated cross sections

EW Corrections to the Drell–Yan Process

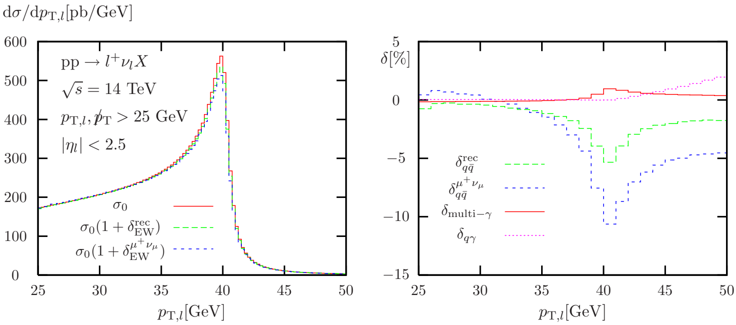
- NLO corrections to $l\bar{l}$ (NC) and $\nu_l l$ (CC) production known [(NC): Dittmaier, Huber 2009; Arbuzov et al. 2008; Carloni Calame, Montagna, Nicrosini, Vicini 2007; Zykunov 2007; Baur et al. 2002; Baur, Keller, Sakumoto 1998, (CC): Brensing et al. 2008, Carloni Calame et al. 2006; Arbuzov et al. 2006; Baur et al. 1999/2004, . . .]
  - Tuned comparisons of independent implementations [Buttar et al. 2006/08; 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 corrections due to $\Delta\alpha$ and $\Delta\rho$ absorbed in effective couplings

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



EW Corrections to the Drell–Yan Process (II)

- 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], 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 by photon-induced processes

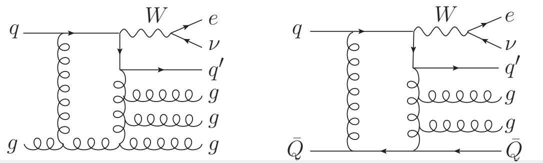


[Brensing et al.: arXiv:0710.3309v2 [hep-ph]]

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 + $\not{E}_{\mathrm{T}}$) predicted by new-physics models
  - SUSY-particle pair production
  - Single-graviton production (1 jet + $\not{E}_{\mathrm{T}}$)

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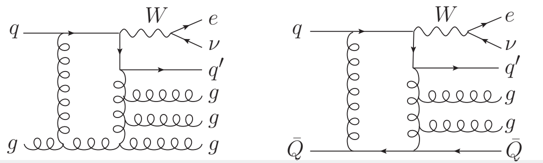

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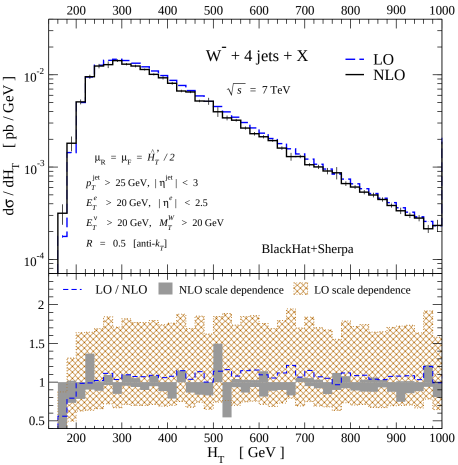
High-precision theoretical predictions necessary!

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 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!**

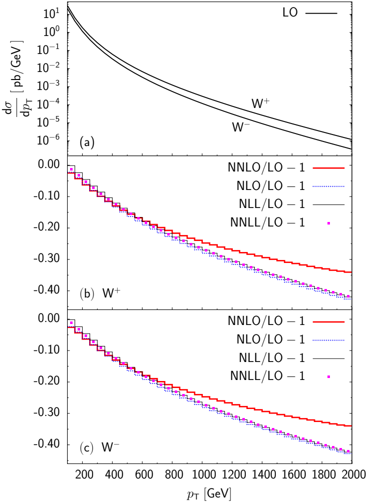


[Berger et al.: arXiv:1009.2338 [hep-ph]]

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 $\mathcal{O}(\alpha)$ 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%



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

EW Corrections to V + jet Production (II)

Next step:

Compute full NLO EW corrections to

$$\begin{aligned} \mathrm{pp} &\rightarrow \mathrm{W} + \mathrm{jet} \rightarrow \nu_\ell \ell + \mathrm{jet}\,, \\ \mathrm{pp} &\rightarrow \mathrm{Z}/\gamma + \mathrm{jet} \rightarrow \ell\bar{\ell} + \mathrm{jet} \end{aligned}$$

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:

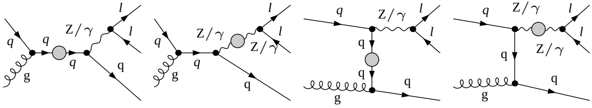
- ✓ Investigate distribution of $m_{\ell\ell}$ (NC) and $m_{\mathrm{T},\ell\ell}$ (CC)
  → Search for new resonances in the off-shell tails (→ CDF W+dijet anomaly)

Challenges:

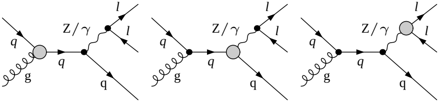
⟹ Consistent treatment of finite gauge-boson width!

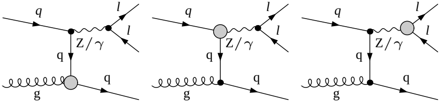
⟹ Demanding $2 \rightarrow 3$ computation in the full SM (many scales, pentagon diagrams, infrared singularities, ...)

Self-energy insertions:

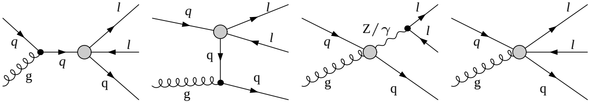


Triangle insertions:





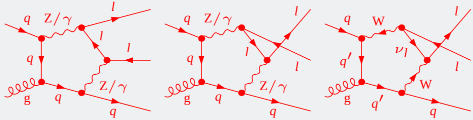
Box and pentagon insertions:



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

Some details

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

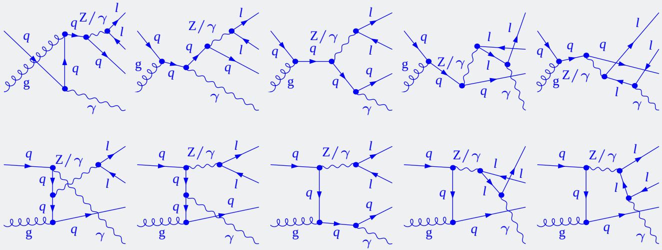


- We use the G_μ scheme to calculate the loop corrections:

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

- 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 complex scalar one-loop 4-point integrals [Denner, Dittmaier 2010]

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

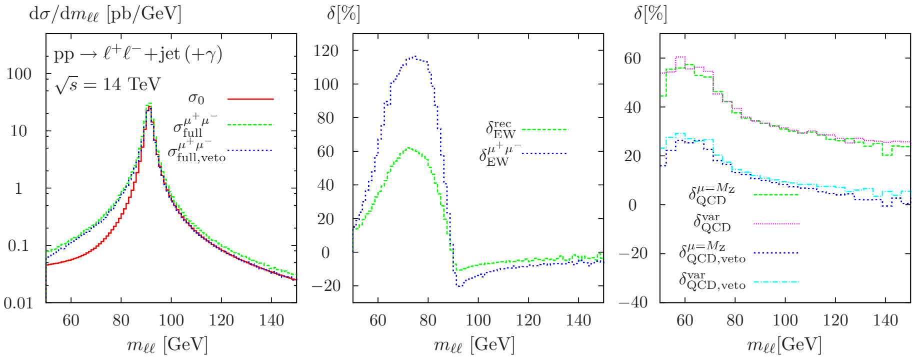


- **Soft singularities** due to soft photons
- **Initial-state** collinear singularities due to collinear photon radiation off initial-state quarks $\longrightarrow$ renormalization of PDFs
- **Final-state** collinear singularities due to photon-radiation off final-state leptons and quarks

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

Numerical Results at the LHC

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

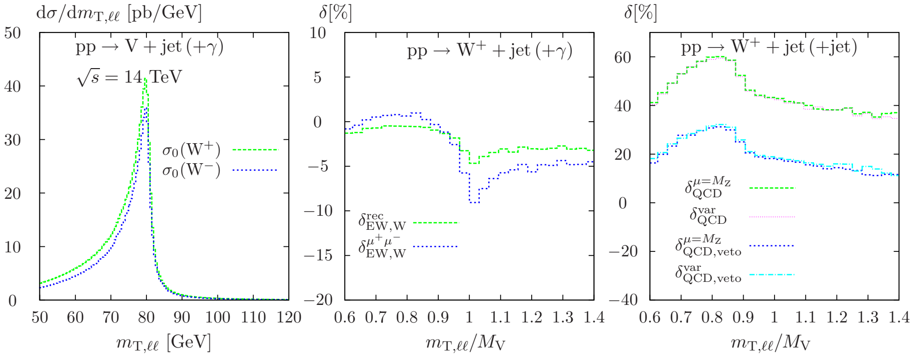


- Typical Breit–Wigner shape of the LO distribution
- Final-state photon radiation systematically shifts events to smaller $m_{\ell\ell}$ → huge positive corrections; **corrections to total cross section still small (-5%)!**
- **Note:** QCD corrections uniform and of expected size

Numerical Results – Compare Z and W Cross Sections

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

W-PRODUCTION CROSS SECTION:



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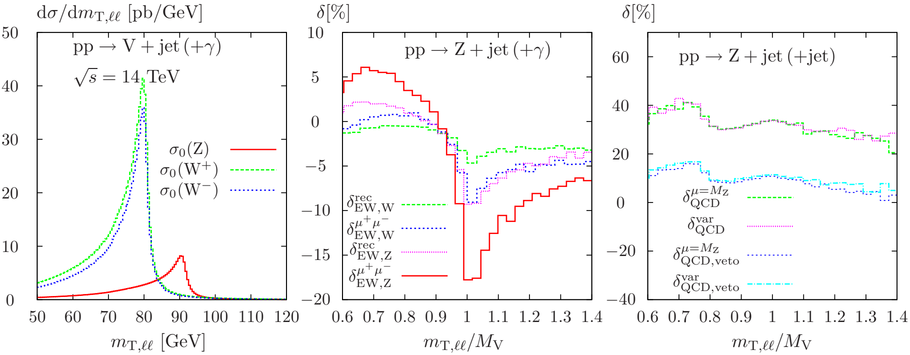

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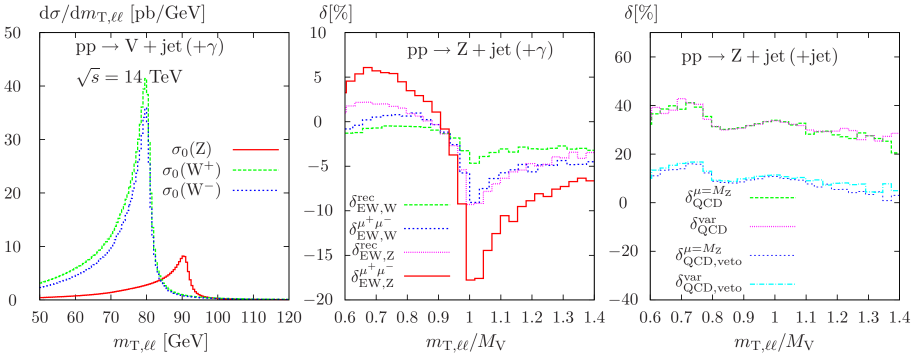

- $\sigma(W^+)/\sigma(Z) \sim 5$
- Phase-space-dependent EW corrections 100% bigger in Z-boson production
- QCD corrections of similar size for W and Z production

Summary & Conclusions

✓ Precise theoretical predictions for Drell–Yan and V + jet(s) production

✓ Both fixed-order and resummed EW and QCD effects have been considered

- **EW corrections:**
  - inclusive observables dominated by final-state photon radiation
  - corrections at high energies described well by logarithmic approximations
- **Drell–Yan:**
  - Most accurate determination of M_W and EW precision observables (e.g. $\sin^2\theta_{eff}$) may be possible at the LHC.
  - Accurate knowledge of Drell–Yan physics necessary to reduce PDF uncertainties
- **Vector-bosons + jets:**
  - Understand EW physics in hadron collider environment
  - Reliable predictions for SM backgrounds to new-physics searches

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Thank You!

EW Corrections to the Drell–Yan Process (III)

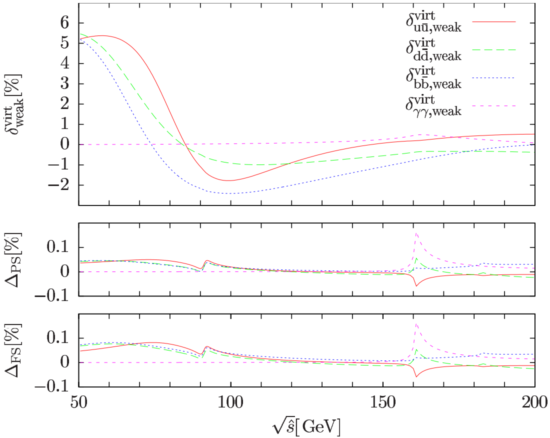
Miscellaneous theoretical treatment of the Z-boson resonance

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

⇒ **agreement within** $\sim 0.1\%$

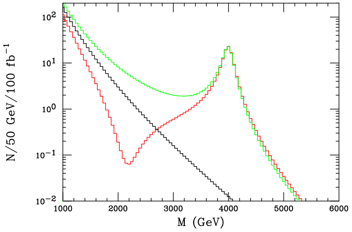
Drell–Yan process insenstitive to theoretical treatment of vector-boson resonance

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



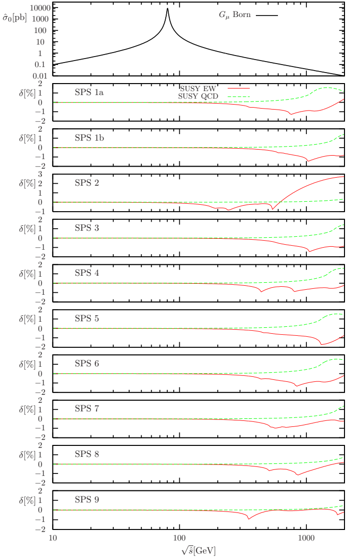
New Physics in the Drell–Yan Signal?

- Tiny effects of virtual contributions of MSSM particles
  $\rightarrow$ **Drell–Yan physics well-described by Standard Model**
- Search for heavy resonances (Z'/W' or Kaluza–Klein excitations) at high invariant masses



black: SM prediction; red, green: Kaluza–Klein excitations

[Rizzo: arXiv:hep-ph/0109179]



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

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]

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

- 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-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)

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!)**

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

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}**

High-energy limit

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

$\longrightarrow$ **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 . . .)
  $\longrightarrow$ **substantial cancellations possible!**