Gauge Boson Pair Production at the LHC

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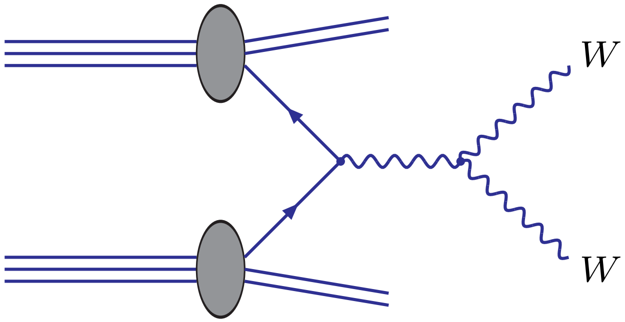
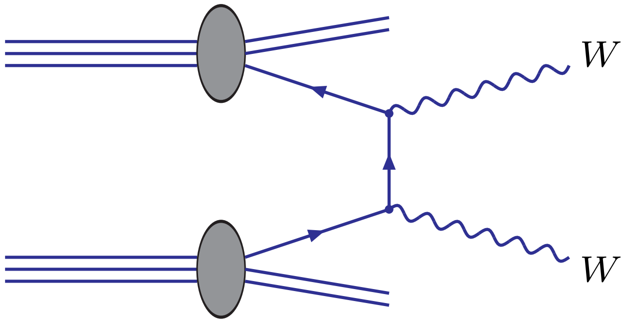
I. Introduction

II. QCD and Electroweak Corrections

III. Conclusion

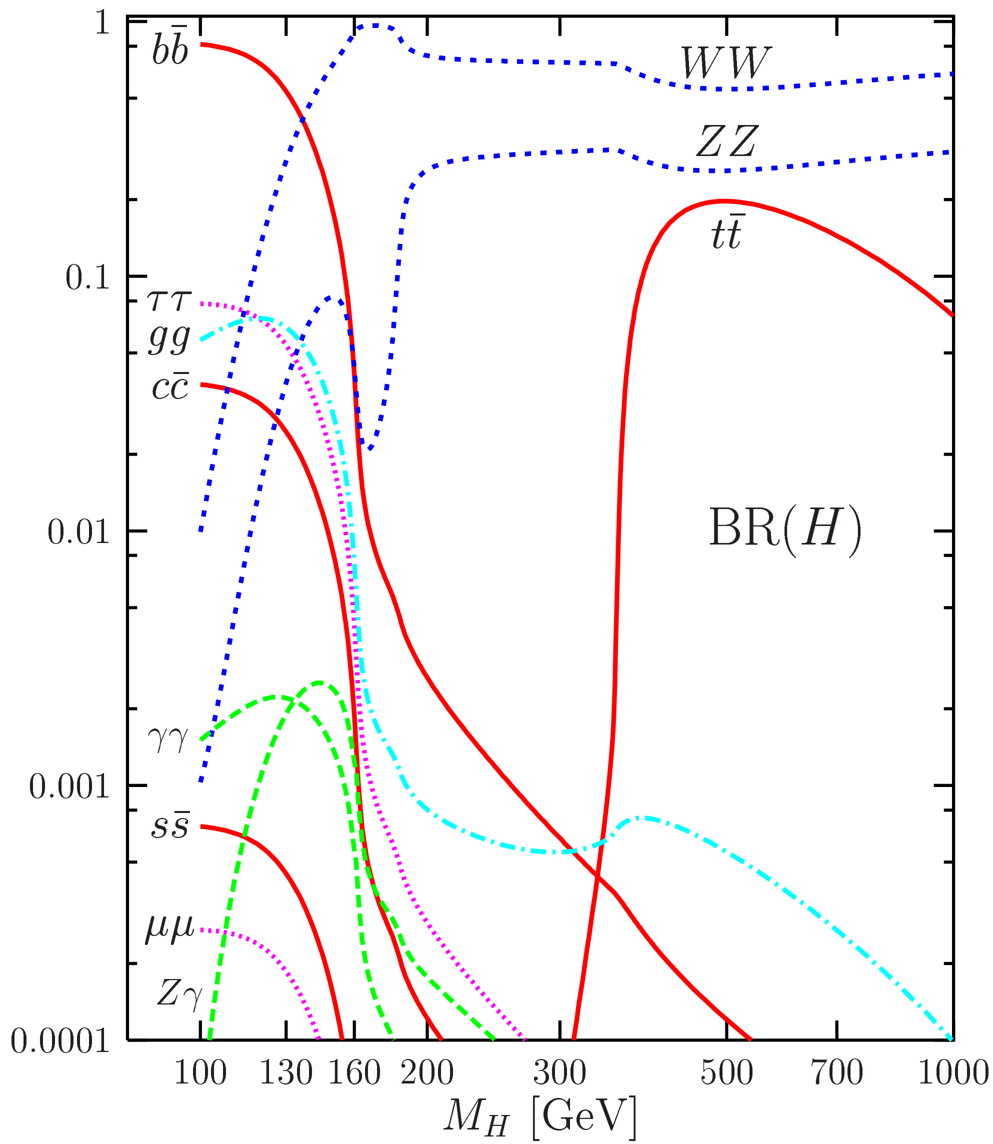




I. Introduction

Gauge boson pair production

is an important irreducible background to SM Higgs boson production in intermediate and high mass region.



- **H → WW, ZZ:**

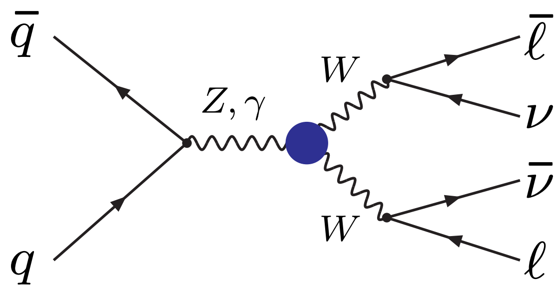
  Discovery channels for heavy Higgs (exclusion).

- H → $\gamma\gamma$:

  Rare process but very clean signature and low background. Discovery process for the light Higgs.

Gauge boson pair production provides:

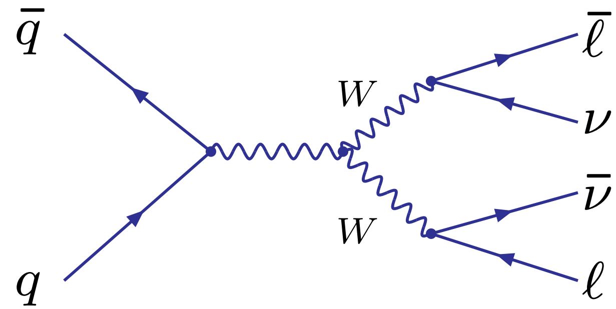
- an excellent opportunity to test the non-abelian structure of triple gauge boson couplings of the SM at high energies.
  $\hookrightarrow$ constraint on non-standard γWW, ZWW-couplings.

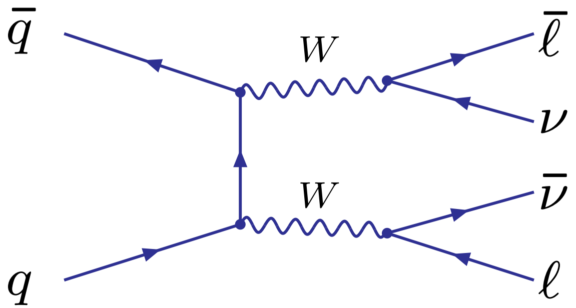


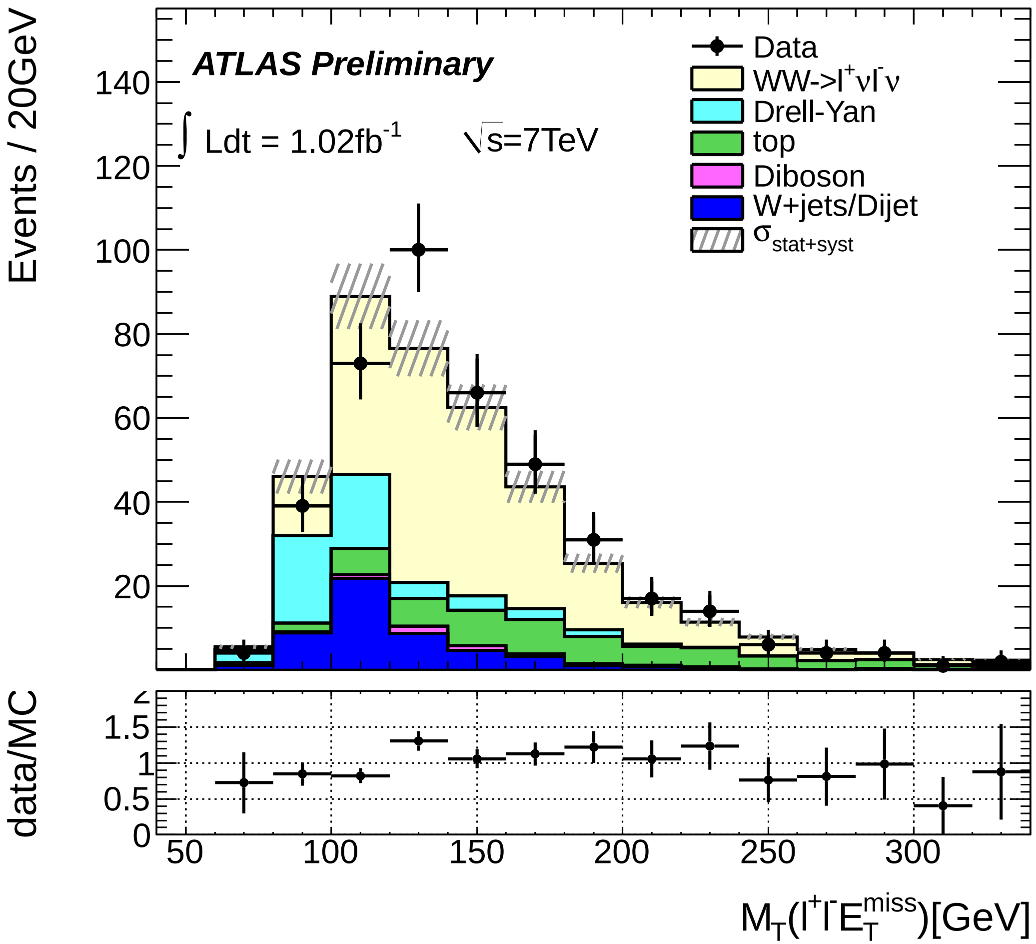
- Search for anomalous triple and quartic couplings.

- Backgrounds to new physics searches,
  i.e. leptons $+\not{E}_T$ signatures.
  $\hookrightarrow$ Pair production of supersymmetric particles.

Vector-Boson Pair Production: $pp \to VV' \to 4\ell$

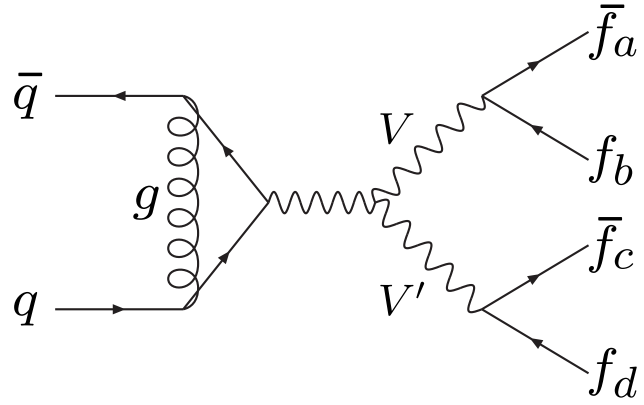


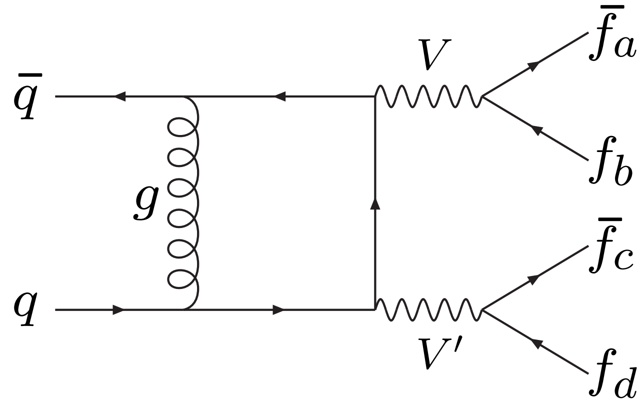




II. QCD and Electroweak Corrections to Gauge Boson Pair Production

QCD Corrections to VV'-pair production:





NLO QCD corrections are available for full process including leptonic decays.

Dixon, Kunszt, Signer '99; Campbell, Ellis '99
De Florian, Signer '00

Results matched with parton showers and combined with soft-gluon resummation.

S. Frixione, B.R. Weber '06
P. Nason, G. Redolfi '06

Weak-boson pair production dominated by tree-level $q\bar{q}$ annihilation channels. Significant contributions of the channels $gg \to VV' \sim 10\%$ to LO, although formally at $\mathcal{O}(\alpha_s^2)$.

Dührssen et.al. '05
Glover, van der Bij '89; Kao, Dicus'91

By considering event selection for Higgs searches corrections of 30% can even be obtained.

Binoth et. al. '06

Overview: EW corrections to gauge-boson production:

- Complete $\mathcal{O}(\alpha)$ corrections known to $pp \to W\gamma \to \ell\bar{\nu}\gamma + X$ in single pole approximation.
  Accomando, Denner, Pozzorini '01
  Accomando, Denner, Meier '05
- Complete $\mathcal{O}(\alpha)$ corrections for on-shell Z bosons $pp \to Z\gamma$.
  Hollik, Meier '04
- Complete $\mathcal{O}(\alpha)$ corrections for $pp \to Z\gamma \to \ell\ell\gamma + X$ in a single pole approximation.
  Accomando, Denner, Meier '05
- Complete $\mathcal{O}(\alpha)$ corrections for $pp \to WW, ZZ, WZ \to 4\ell + X$ in high energy and pole-approximations.
  $\longrightarrow$ Large negative EW corrections for large energy scale.
  Accomando, Denner, Pozzorini '01
  Accomando, Denner, Kaiser '04
- NNLL effects at two loop calculation for WW channel.
  Kühn, Metzler, Penin, Uccirati '11

EW Corrections at High Energies: **Sudakov Logarithms:**

High-energy limit:

$$s \sim |t| \sim |u| \gg M^2 := M_\mathsf{W}^2 \simeq M_\mathsf{Z}^2 \sim M_\mathsf{H}^2 \sim M_\mathsf{t}^2 \gg m_f^2 \gg \underbrace{M_\gamma^2}_{\text{IR-regulator}}$$

$\hookrightarrow$ bosons produced at large p_T

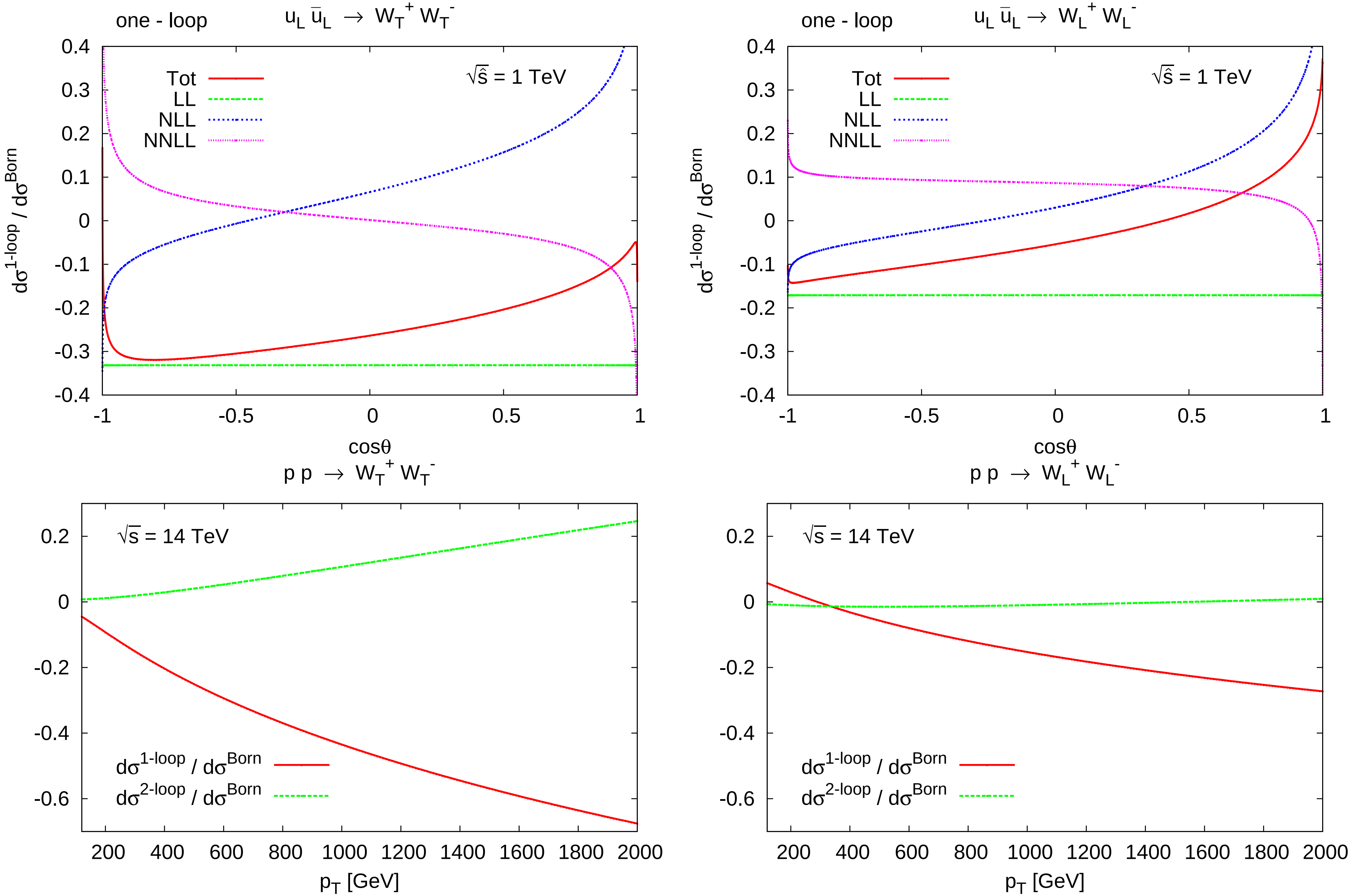
- $\mathcal{O}(\alpha^L)$ EW corrections are enhanced by large logarithms that originate from mass singularities $\mathsf{Log}(s/M^2)$ and grow with energy:

$$\underbrace{\alpha^L\,\mathsf{Log}^{2L}(s/M^2)}_{\mathsf{LL}}, \quad \underbrace{\alpha^L\,\mathsf{Log}^{2L-1}(s/M^2)}_{\mathsf{NLL}}, \; \ldots$$

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

Note: Change of sign going from LL to NLL (to NNLL etc.)

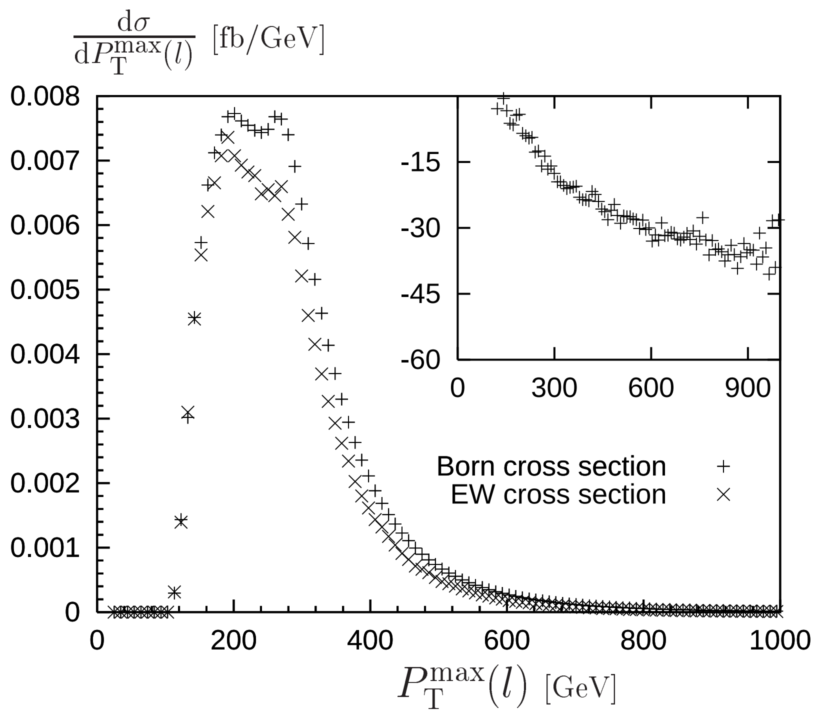
$\hookrightarrow$ **partial cancellations are possible!**



Kühn, Metzler, Penin, Uccirati 2011

- Standard LHC event selection cuts applied to final-state leptons and missing transverse momentum; additionally $M_{e^+\mu^-} > 500$ GeV and $|\Delta\, y(\ell\bar{\ell}')| < 3$ required
- Large negative corrections at large transverse momenta
- Substantial negative corrections to inclusive observables
- Error due to double-pole approximation (DPA) about 10% in the relative corrections
- **EW corrections significantly larger than experimental error throughout the whole energy range (for $L \sim 30$ fb^{-1})**

$pp \to WW \to \ell\bar{\nu}_\ell \nu_{\ell'} \bar{\ell}'$



Accomando, Denner, Kaiser '04

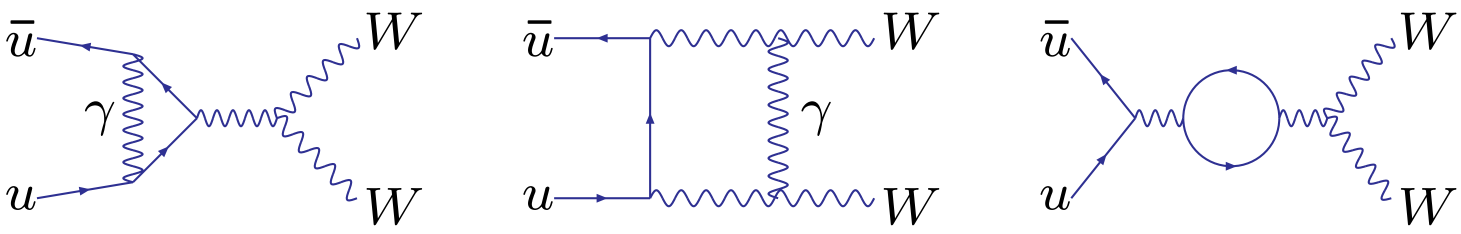
Theoretical Issues . . .

Higher-order effects due to electroweak interactions at $\mathcal{O}(\alpha^3)$:

Virtual corrections:

$\longrightarrow$ Ultraviolet (UV) divergences

$\longrightarrow$ Infrared (IR) divergences (soft and collinear singularities)



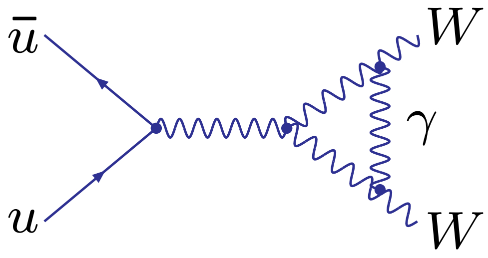
$+$ many more...

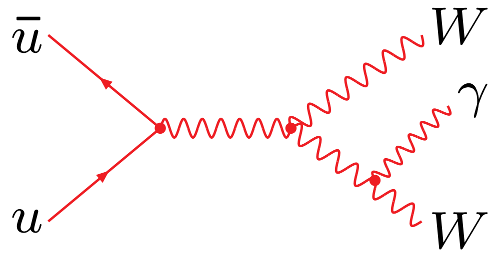
$\hookrightarrow$ UV singularities arise from self energies and vertex corrections in loop integrals $\Longrightarrow$ **renormalization** required!

- Field and mass renormalization in the *on-shell* (OS) scheme
- Renormalization of mixing angle and charge in the OS- or $\overline{\text{MS}}$-scheme
- $V_{ij}^{\text{CKM}} = \delta_{ij} \Longrightarrow$ no renormalization of V_{ij}^{CKM} is required

Add counter-term diagrams $\Longrightarrow$ result is **UV finite** but **not IR-finite!**

Virtual corrections and real radiation cannot be discussed separately.
↪ **Soft singularities** arise where on-shell particles exchange (or emit) a photon ($M_\gamma = 0$ and $E_\gamma \to 0$)



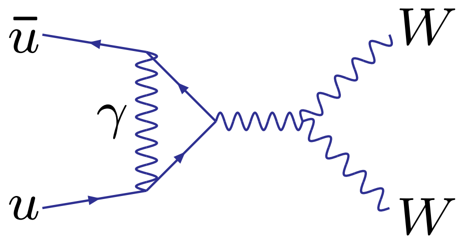


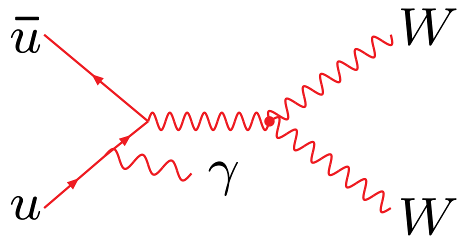
divergent for $M_\gamma = 0$ and $E_\gamma \to 0$!

KLN-theorem: cancellation between **virtual** and **real** corrections leads to IR-finite results.

- introduce photon mass $M_\gamma \neq 0$ as IR-regulator
  $\Longrightarrow$ divergences appear as logarithms Log(M_γ);
- add soft real photon contributions to virtual corrections
  $\Longrightarrow$ **cancellation of logarithms Log**(M_γ).

$\hookrightarrow$ When massless initial-state quarks ($m_q = 0$) emit real or virtual photon, **collinear singularities** appear:





divergent for $m_q = 0$ and $\Theta_{q\gamma} \to 0$!

- keep small quark mass $m_q \neq 0$ as IR-regulator
  $\Longrightarrow$ divergences appear as logarithms $\mathrm{Log}(m_q)$.
- Sudakov double logarithms ($\mathrm{Log}^2(s/m_q^2)$) cancel in the sum of virtual and real corrections.
- Remaining single logarithms have to be absorbed in parton densities
  $\longrightarrow$ renormalization of PDFs.

$$f_q(x, \mu_{\text{fac}}) = f_q(x) + (\text{divergent part of } \int_0^{\mu_{\text{fac}}^2} \mathrm{d}k_T^2)$$

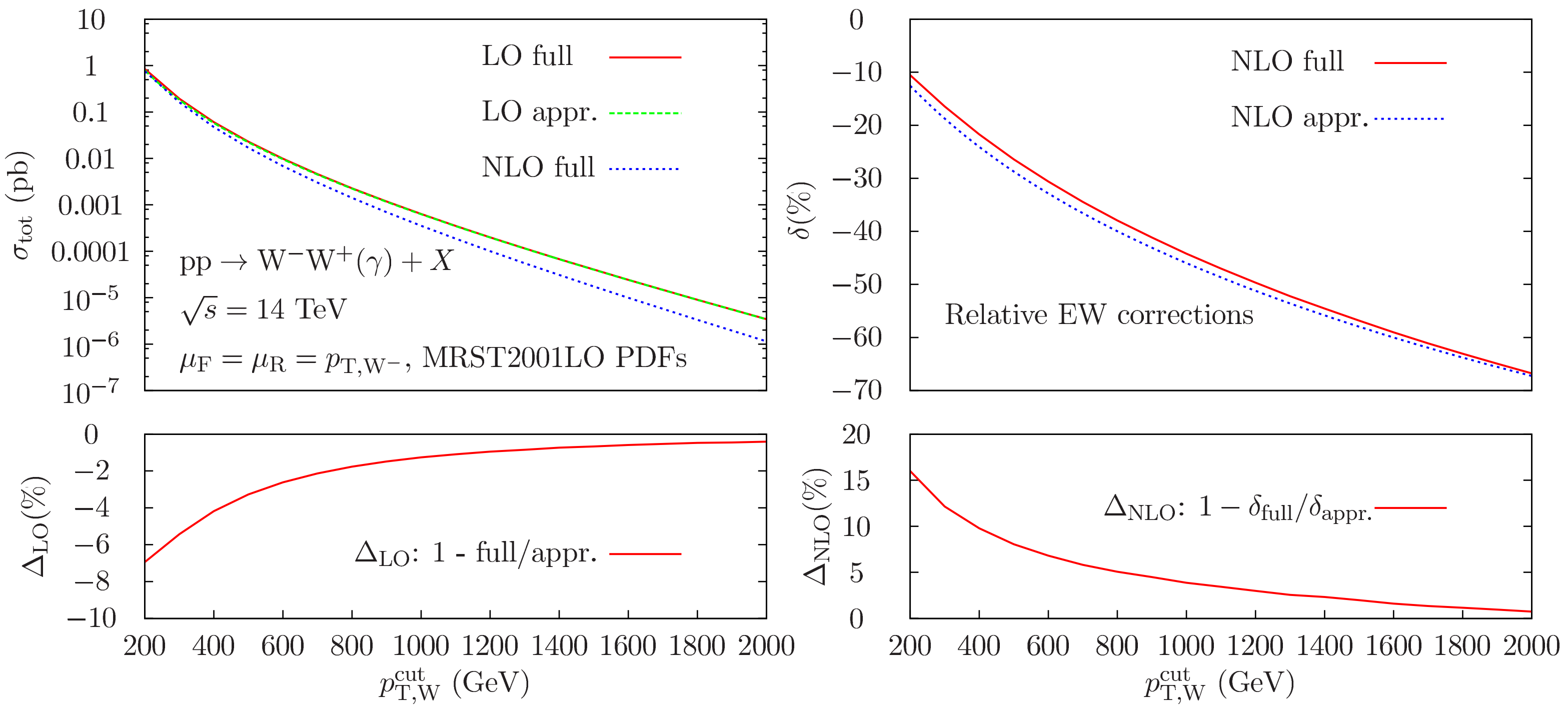
$\Longrightarrow$ Result is independent of m_q, but depends on factorization scale μ_{fac}.

Numerical Results:

Full Electroweak Corrections

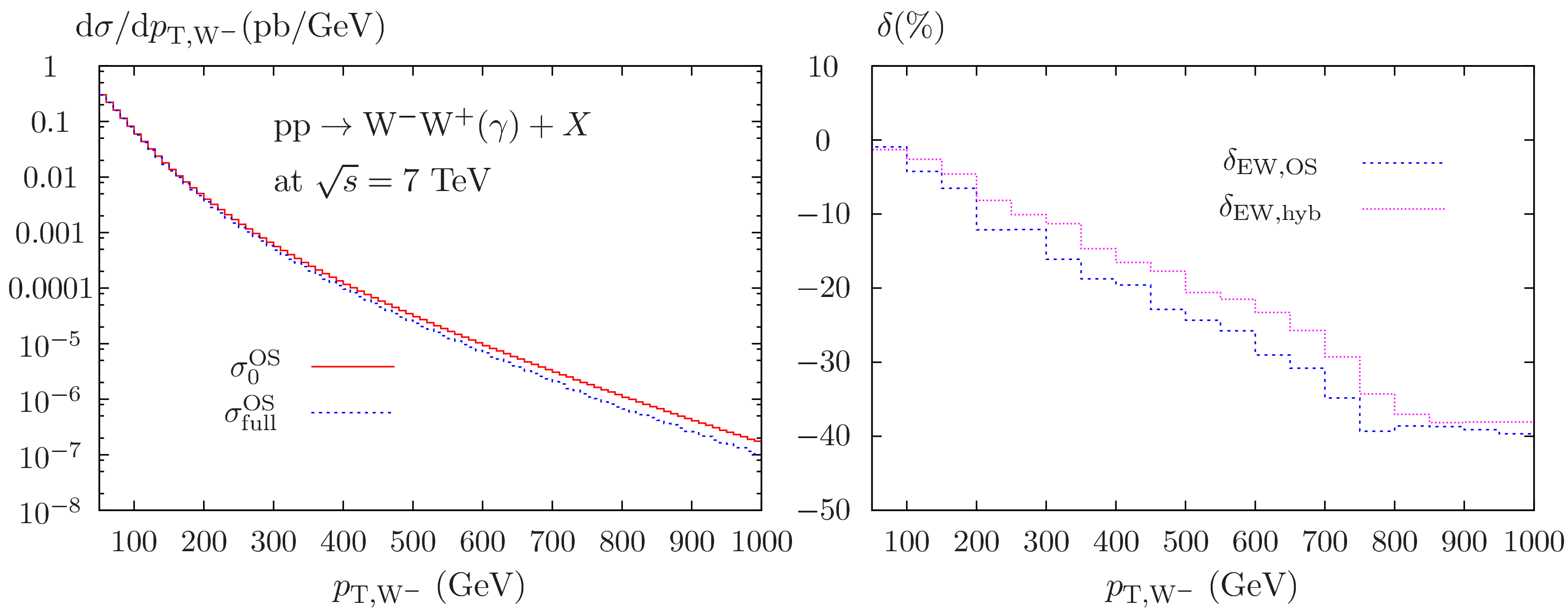
Comparison with Kühn et. al.: arXiv:1101.2563 for WW production (NNLL accuracy at NLO):

- Renormalization of mixing angle and charge in $\overline{\text{MS}}$-scheme.
- Field and mass renormalization in OS-scheme (**"Hybrid Scheme"**).



- High-energy approximation for total cross section becomes crude below 1 TeV.
- Relative corrections described well by approximate prediction.

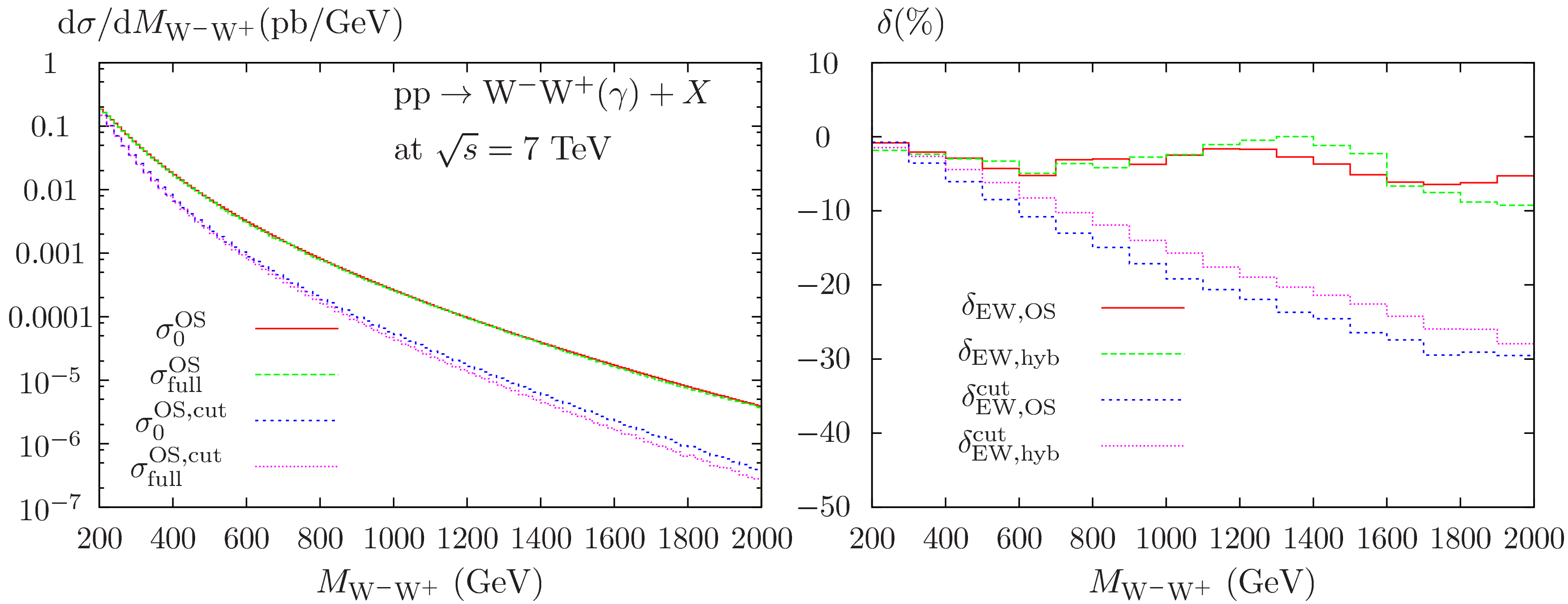
Differential distribution of the W^- transverse momentum at the LHC (MSTW2008 PDFs Martin et al. 2009; Scale choice: $\mu_F = \mu_R = M_{WW}$)



- Rapid decrease of the cross section over several orders of magnitude for increasing p_T
- Typical increasing negative relative corrections due to EW Sudakov logarithms (moderate scheme dependence)

Differential distribution of the W^-W^+ invariant mass M_{WW} at the LHC

(MSTW2008 PDFs Martin et al. 2009; Scale choice: $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \langle M_{\mathrm{T,W}} \rangle$)



- Apply cut on scattering angle $\theta > 30^\circ$
- Logarithmic corrections dominate
- Cross section significantly decreased for high invariant masses
  $\Rightarrow$ majority of events not described by Sudakov kinematics

III. Conclusion

Conclusion:

- Understanding of gauge boson pair production processes crucial at the LHC:
  - $\longrightarrow$ Understand Standard Model at high energies
  - $\longrightarrow$ Understand background to Higgs- and BSM-physics searches
- We have computed the full EW corrections to W-pair production at the LHC:
  - $\longrightarrow$ small corrections to the total cross section
  - $\longrightarrow$ But: sizable negative corrections in the high energy limit
  - $\longrightarrow$ Good agreement with former approximate results
- Future work:
  - $\longrightarrow$ Include leptonic decays of the W bosons
  - $\longrightarrow$ Consider WZ and ZZ production.