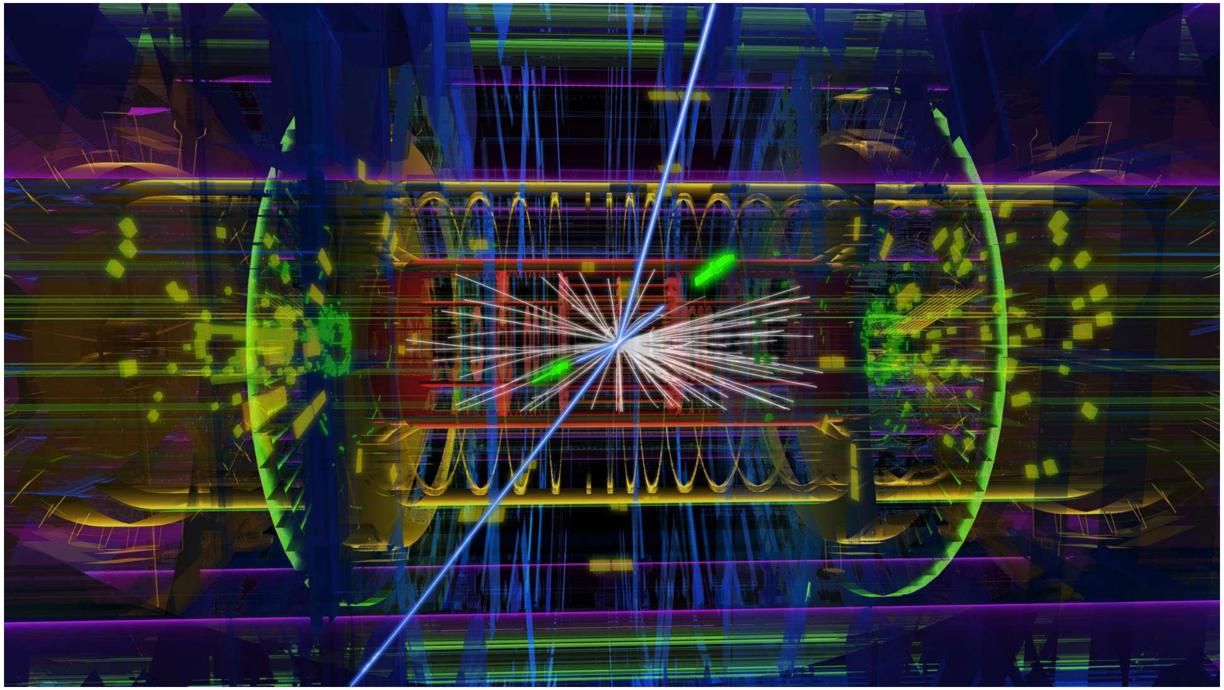
Electroweak Di-boson Production at the LHC



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(based on collaboration with B.Biedermann, M.Billoni, A.Denner, M.Hecht, L.Hofer, B.Jäger, C.Pasold, L.Salfelder, C.Speckner)

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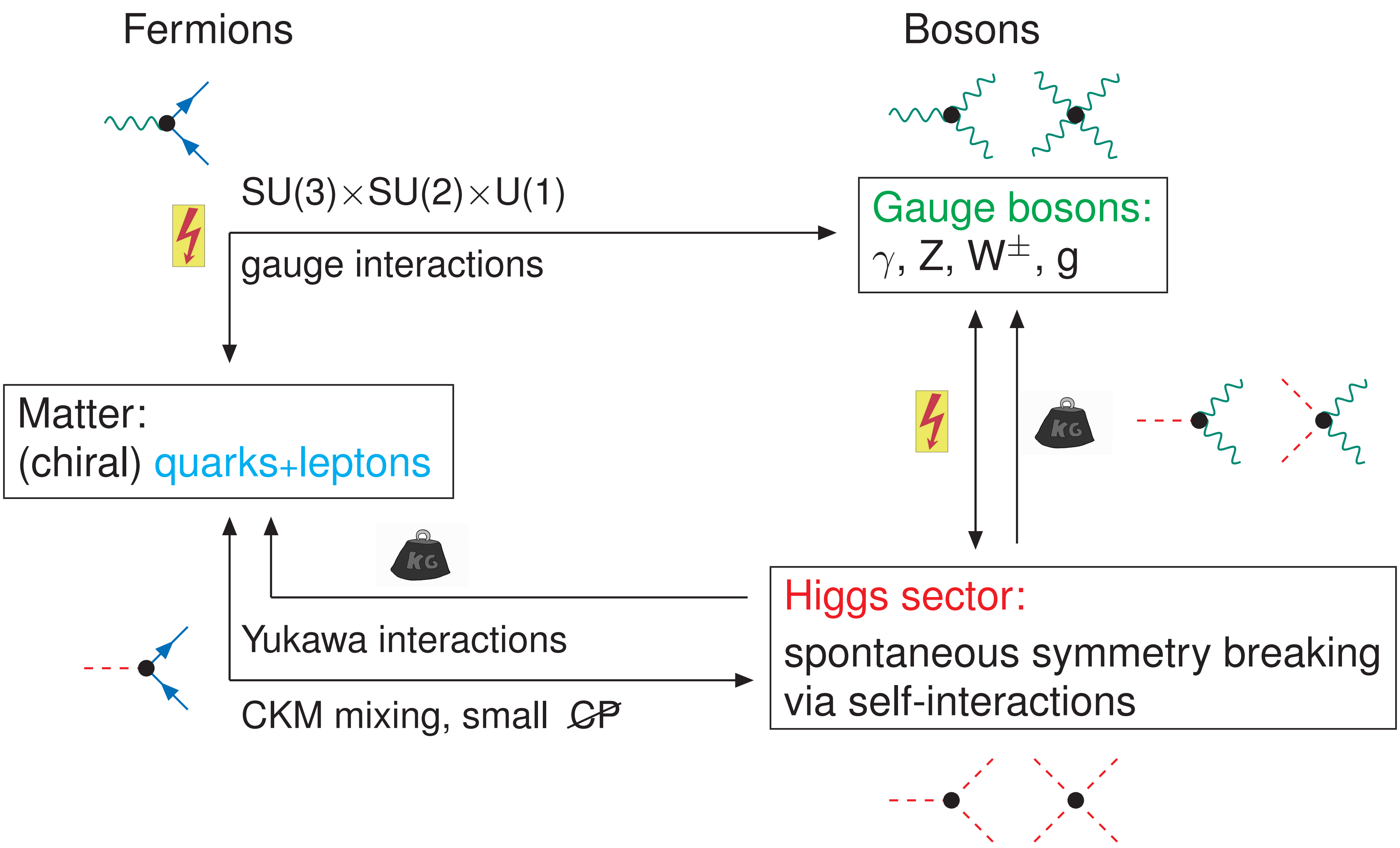

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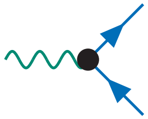
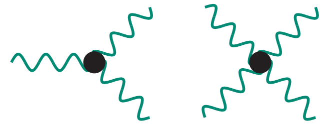
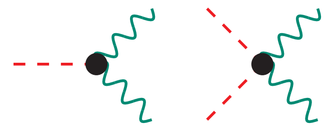


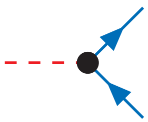


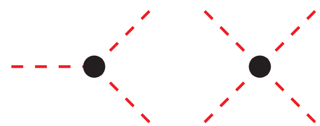
Test of the model

$\Leftrightarrow$ Exp. reconstruction of the elementary couplings

Feynman rules







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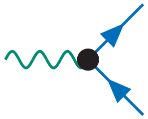

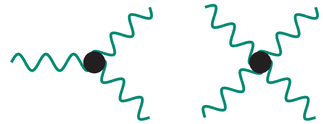

Test of the model
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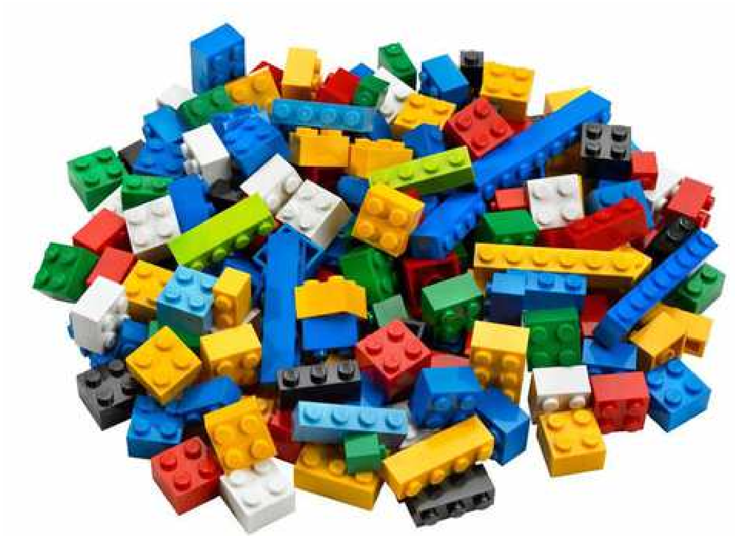
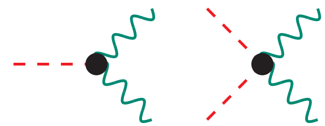
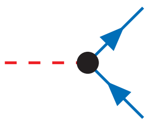
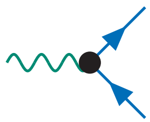
Building blocks for particle reactions

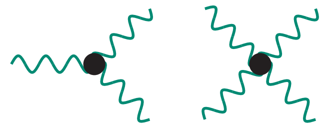






Structure and elementary interactions of the Standard Model





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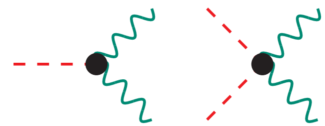
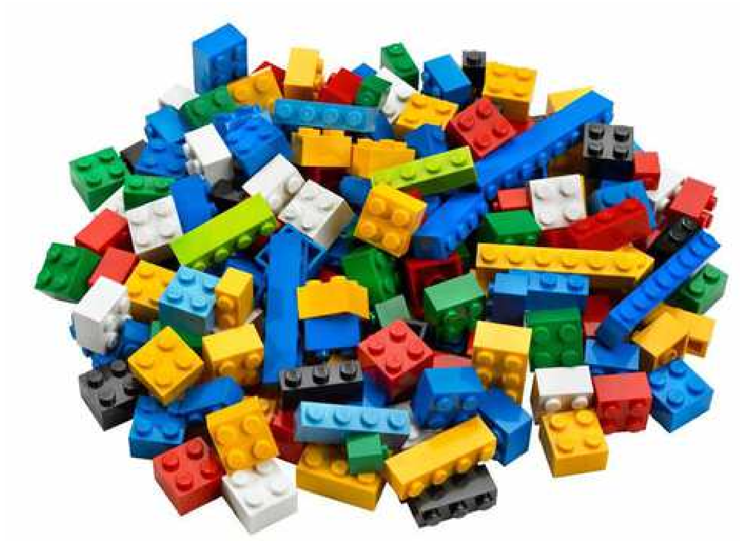
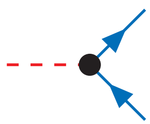
Building blocks for particle reactions







Standard Model extensions $\rightarrow$ more fields, more particles, more interactions, ...

Feynman rules derived from SM Lagrangian:

$\hookrightarrow$ Recapitulate EW gauge interactions !

Gauge-boson self-interactions

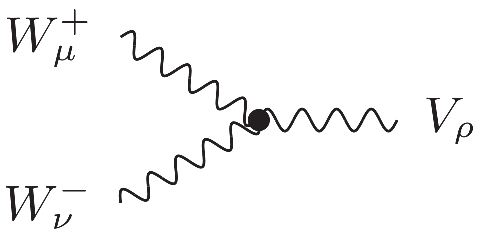
$\hookrightarrow$ induced by gauge-invariant Yang–Mills Lagrangian

$$\mathcal{L}_{\mathrm{YM}} = -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu},$$

with the field-strength tensors

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu, \qquad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

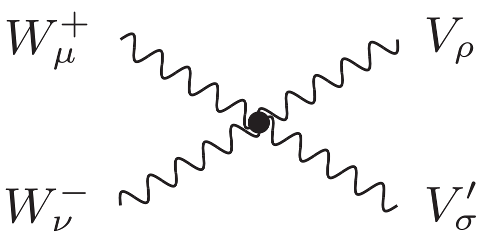
$\Rightarrow$ Feynman rules for gauge-boson self-interactions: (fields and momenta incoming)



$$\mathrm{i}e C_{WWV} \Big[g_{\mu\nu}(k_+ - k_-)_\rho + g_{\nu\rho}(k_- - k_V)_\mu + g_{\rho\mu}(k_V - k_+)_\nu \Big]$$

with $C_{WW\gamma} = 1, \quad C_{WWZ} = -\frac{c_{\mathrm{W}}}{s_{\mathrm{W}}}$

$\rightarrow$ testable in di-boson production $\mathrm{ee/pp} \rightarrow VV$



$$\mathrm{i}e^2 C_{WWVV'} \Big[2 g_{\mu\nu} g_{\rho\sigma} - g_{\mu\rho} g_{\sigma\nu} - g_{\mu\sigma} g_{\nu\rho} \Big]$$

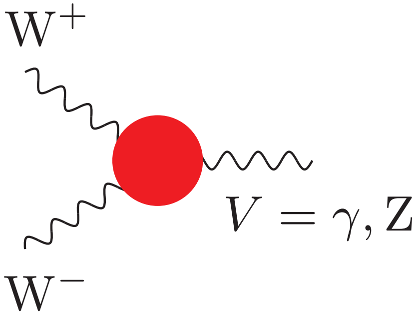
with $C_{W^2\gamma^2} = -1, C_{W^2\gamma Z} = \frac{c_{\mathrm{W}}}{s_{\mathrm{W}}}, C_{W^2 Z^2} = -\frac{c^2_{\mathrm{W}}}{s^2_{\mathrm{W}}}, C_{W^4} = \frac{1}{s^2_{\mathrm{W}}}$

$\rightarrow$ testable in tri-boson production $\mathrm{ee/pp} \rightarrow VVV$
and vector-boson scattering $\mathrm{pp}(VV \rightarrow VV) \rightarrow VV + 2\mathrm{jets}$

(Non-)standard TGCs

Gaemers, Gounaris '79; Hagiwara, Hikasa, Peccei, Zeppenfeld '87; Bilenky, Kneur, Renard, Schildknecht '93; etc.

General parametrization (C- and P-conserving):



$$\mathcal{L}_{VWW} = -\mathrm{i}eg_{VWW}\Big\{ g_1^{\mathrm{V}}\left(W^+_{\mu\nu}W^{-,\mu}V^\nu - W^{-,\mu\nu}W^+_\mu V_\nu\right) + \kappa_{\mathrm{V}} W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_{\mathrm{V}}}{M_{\mathrm{W}}^2} W^+_{\rho\mu} W^{-,\mu}_{\ \ \nu} V^{\nu\rho}\Big\}$$

Meaning for static W^+ bosons:

$$Q_{\mathrm{W}} = eg_1^\gamma = \text{electric charge } (= e \text{ by charge conservation})$$

$$\mu_{\mathrm{W}} = \frac{e}{2M_{\mathrm{W}}}\left(g_1^\gamma + \kappa_\gamma + \lambda_\gamma\right) = \text{magnetic dipole moment}$$

$$q_{\mathrm{W}} = -\frac{e}{M_{\mathrm{W}}^2}\left(\kappa_\gamma - \lambda_\gamma\right) = \text{electric quadrupole moment}$$

Standard Model values:

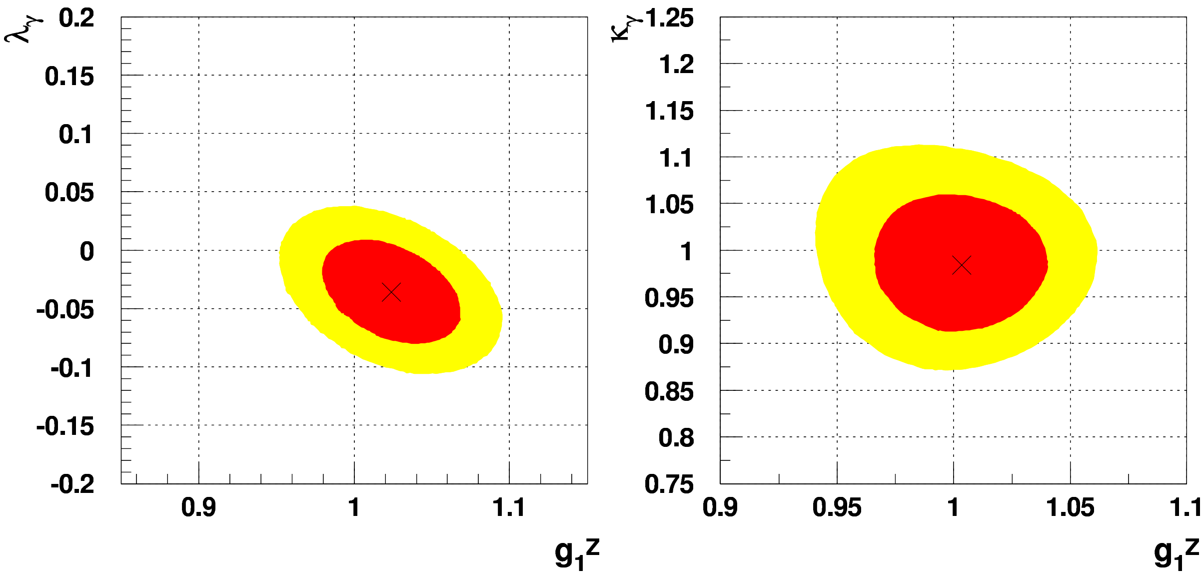
$$g_1^{\mathrm{V}} = \kappa_{\mathrm{V}} = 1, \qquad \lambda_{\mathrm{V}} = 0$$

Restriction to SU(2)×U(1)-symmetric dim-6 operators:

$$\kappa_{\mathrm{Z}} = g_1^{\mathrm{Z}} - (\kappa_\gamma - 1)\tan^2\theta_{\mathrm{W}}, \qquad \lambda_{\mathrm{Z}} = \lambda_\gamma$$

LEP2 constraints on charged TGCs from $e^+e^- \to WW \to 4f$

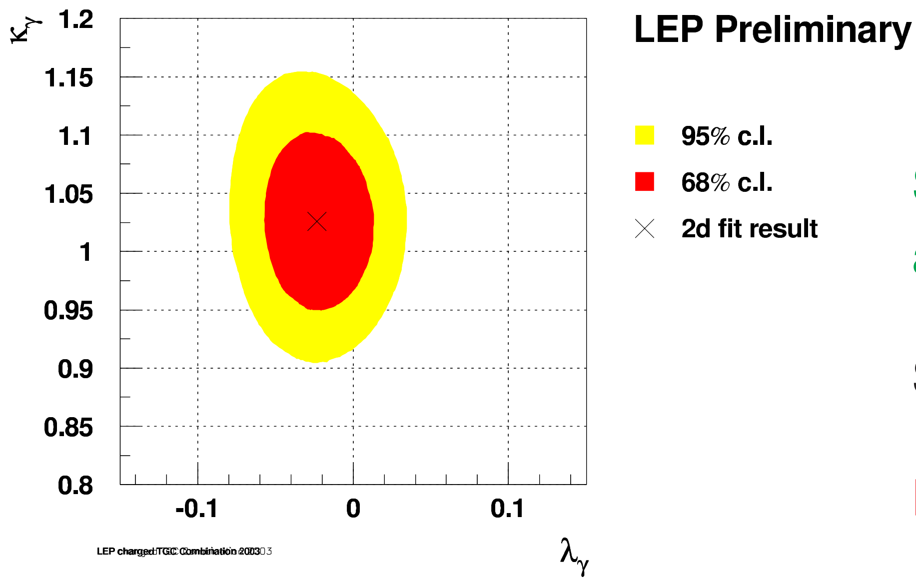
LEPEWWG '04



$$\Delta g_1^Z = -0.009^{+0.022}_{-0.021}$$

$$\Delta \kappa_\gamma = -0.016^{+0.042}_{-0.047}$$

$$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$$

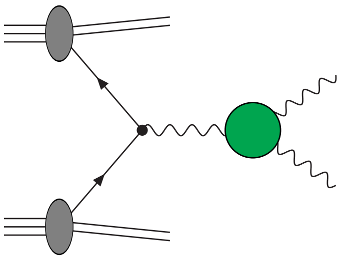


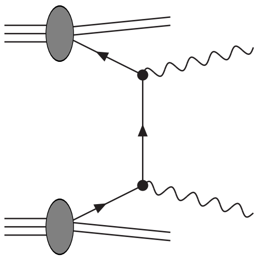
Standard Model values verified at the level of 2–4%

Similar results from Tevatron and LHC Run 1

LHC will tighten limits further !

EW di-boson production at the LHC





$\mathrm{V}, \mathrm{V}' = \gamma, \mathrm{Z}, \mathrm{W}^{\pm}$

Physics issues:

- triple-gauge-boson couplings, especially at high momentum transfer
  - ◇ EW corrections significant
  - ◇ anomalous TGC: "formfactor approach" to switch off unitarity violation
    $\hookrightarrow$ element of arbitrariness, avoid when possible
- important background processes
  - ◇ to Higgs production, $\mathrm{H} \to \mathrm{WW}^*/\mathrm{ZZ}^* \to 4f$
    $\hookrightarrow$ invariant masses below VV thresholds,
    proper description of off-shell $V^*V^* \to 4f$ production required !
  - ◇ to searches at high invariant masses
    $\hookrightarrow$ EW corrections

State-of-the-art predictions

$W\gamma/Z\gamma$ (with leptonic decays)

- NNLO QCD Grazzini, Kallweit, Rathlev '14,'15
- NLO EW Denner, S.D., Hecht, Pasold '14,'15

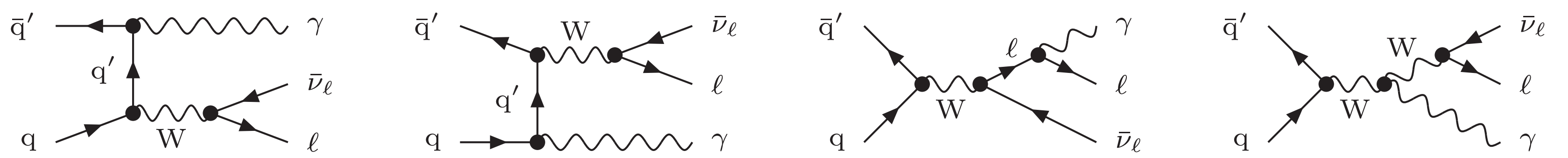
WW, WZ, ZZ

- NNLO QCD
  - ◇ ZZ (on-shell and off-shell) Cascioli et al. '14; Grazzini, Kallweit, Rathlev '15
  - ◇ WW (on-shell) Gehrmann et al. '14
  - ◇ $gg \to VV \to 4$ leptons Binoth et al. '05,'06

    + NLO corrections for on-shell V's Caola et al. '15
- NLO EW
  - ◇ stable W/Z bosons Bierweiler, Kasprzik, Kühn '12/'13 Baglio, Le, Weber '13
  - ◇ $pp \to WW \to 4$ leptons in DPA Billoni, S.D., Jäger, Speckner '13
  - ◇ approximative inclusion in HERWIG++ Gieseke, Kasprzik, Kühn '14
  - ◇ full off-shell calculations in progress ($pp \to \mu^+\mu^-e^+e^-$ completed) Biedermann et al. '16

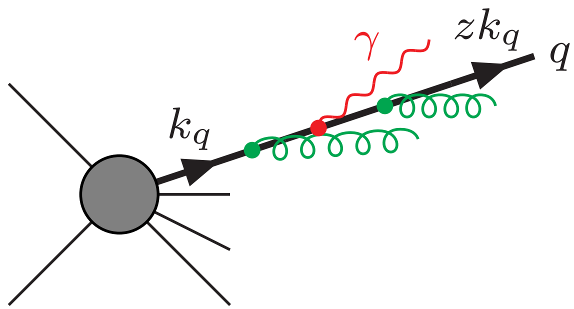
$W\gamma$ / $Z\gamma$ production

Example of $\mathrm{W}\gamma$ production

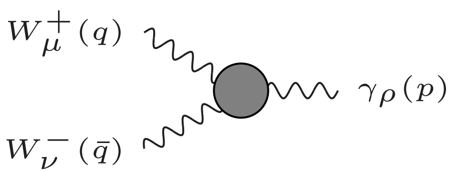


Issues / physics goals:

- clean photon–jet separation
  $\hookrightarrow$ quark-to-photon fragmentation function Glover, Morgan '94
  or Frixione isolation Frixione '98



- stronger bounds on anomalous $\mathrm{WW}\gamma$ coupling:

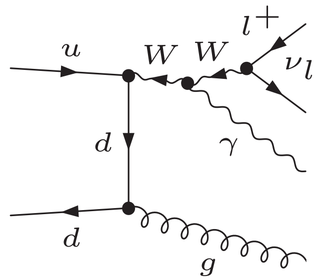


$$= e\left\{\bar{q}^\mu g^{\nu\rho}\left(\Delta\kappa^\gamma + \lambda^\gamma \frac{q^2}{M_\mathrm{W}^2}\right) - q^\nu g^{\mu\rho}\left(\Delta\kappa^\gamma + \lambda^\gamma \frac{\bar{q}^2}{M_\mathrm{W}^2}\right) + (\bar{q}^\rho - q^\rho)\frac{\lambda^\gamma}{M_\mathrm{W}^2}\left(p^\mu p^\nu - \frac{1}{2} g^{\mu\nu} p^2\right)\right\} \times \left(1 + \frac{M_{\mathrm{W}\gamma}^2}{\Lambda^2}\right)^2$$

ATLAS limits '12: $\Delta\kappa^\gamma = 0.41, \quad \lambda^\gamma = 0.074$ for $\Lambda = 2\,\mathrm{TeV}$

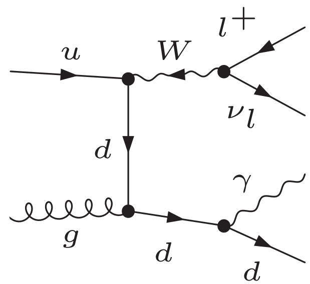
Photon–jet separation via photon fragmentation function $D_{q\to\gamma}$ Glover, Morgan '94

Why?



- QCD radiation cannot be suppressed by cuts

  $\hookrightarrow$ treat at least soft/collinear jets inclusively



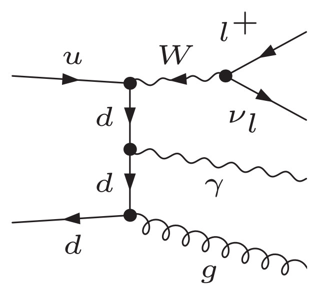
- separation of collinear quarks and photons leads to IR-unstable corrections $\propto \ln(m_q^2/Q^2)$

  $\hookrightarrow$ recombine collinear quarks and photons

- quark and gluon jets cannot be distinguished event by event

  $\hookrightarrow$ common recombination required for quarks/gluons with photons

  $\Rightarrow$ $\underbrace{(g_{\rm hard} + \gamma_{\rm soft})}_{\text{EW corr. to X+jet}}$ and $\underbrace{(g_{\rm soft} + \gamma_{\rm hard})}_{\text{QCD corr. to X+}\gamma}$ both appear as 1 jet



Problem: signatures of X+jet and X+γ overlap !

Photon–jet separation via photon fragmentation function $D_{q\to\gamma}$ Glover, Morgan '94

Solution:

- idea: declare photon/jet systems as photon or jet according to energy share

- determine photon energy fraction $z_\gamma = \dfrac{E_\gamma}{E_{\mathrm{jet}} + E_\gamma}$ of photon/jet system

  $\hookrightarrow$ event selection:

  $z_\gamma > z_0$: photon

  $z_\gamma < z_0$: jet (typical value $z_0 = 0.7$)

- but: cut on z_γ destroys inclusiveness needed for KLN theorem

  $\hookrightarrow$ collinear singularity $\propto \alpha \ln m_q$ remains (but are universal!)

- absorb universal collinear singularity in "fragmentation function" $D_{q\to\gamma}(z_\gamma)$

  $\hookrightarrow$ subtract convolution of LO cross section with

$$D^{\overline{\mathrm{MS}}}_{q\to\gamma}(z_\gamma, \mu_{\mathrm{fact}})\Big|_{\mathrm{mass.reg.}} = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma) \left[\ln\frac{m_q^2}{\mu_{\mathrm{fact}}^2} + 2\ln z_\gamma + 1\right] \quad \leftarrow \text{cancels coll. singularities}$$

$$+ \; D^{\mathrm{ALEPH}}_{q\to\gamma}(z_\gamma, \mu_{\mathrm{fact}}) \quad \leftarrow \text{non-perturbative part fitted to ALEPH data}$$

where $P_{q\to\gamma}(z_\gamma) = \frac{1+(1-z_\gamma)^2}{z_\gamma}$ = quark-to-photon splitting function

Alternative: photon–jet separation via Frixione isolation

Frixione '98

Idea: suppress jets inside collinear cone around photons:

$$p_{\mathrm{T,jet}} < \varepsilon\, p_{\mathrm{T},\gamma} \left(\frac{1-\cos R_{\gamma\mathrm{jet}}}{1-\cos R_0} \right) \qquad (R_0 = \text{fixed cone size})$$

- photon and jet collinear ($R_{\gamma\mathrm{jet}} \to 0$) $\to$ event discarded
- photon soft or collinear to beams ($p_{\mathrm{T},\gamma} \to 0$) $\to$ event discarded
- jet soft or collinear beams ($p_{\mathrm{T,jet}} \to 0$) $\to$ event kept $\Rightarrow$ IR safety

Comments:

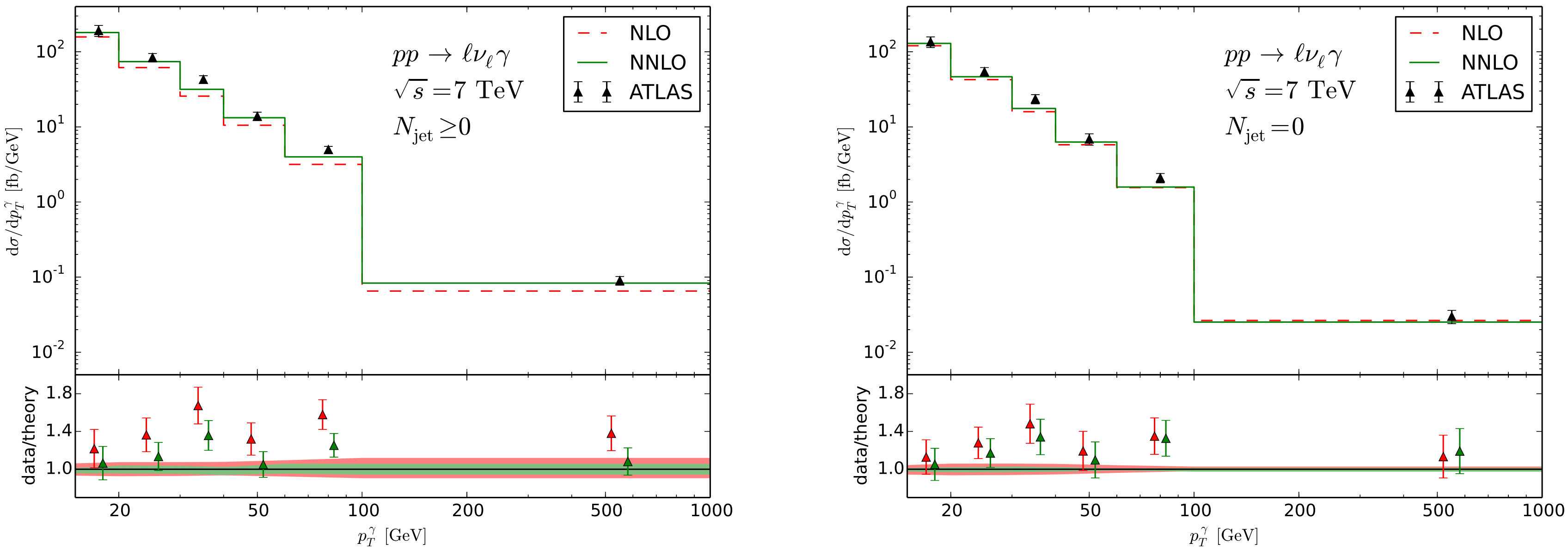
- Frixione isolation simple to implement theoretically, but problematic experimentally
- cleaner isolation of non-perturbative effects by fragmentation function
- approximate relation between the two methods:

$$z_\gamma \sim \frac{p_{\mathrm{T},\gamma}}{p_{\mathrm{T},\gamma}+p_{\mathrm{T,jet}}} > \frac{1}{1+\varepsilon\frac{1-\cos R_{\gamma\mathrm{jet}}}{1-\cos R_0}} \sim \frac{1}{1+\varepsilon} \quad \text{for } R_{\gamma\mathrm{jet}} \sim R_0$$

$\hookrightarrow$ methods yield quite similar results for $z_0 \sim \frac{1}{1+\varepsilon}$

Wγ production – QCD theory versus experiment

Grazzini, Kallweit, Rathlev '15

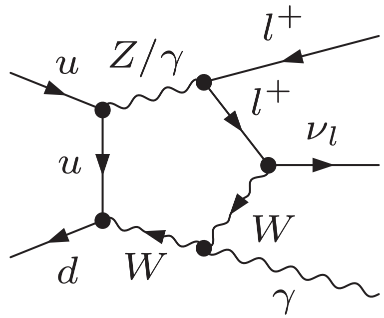


- good agreement of experimental results with NNLO QCD
  (no EW corrections included)
- QCD uncertainties: (for small/moderate $p_{\mathrm{T},\gamma}$)
  scale: $4{-}5\%$, PDF: $1{-}2\%$ (increasing with $p_{\mathrm{T},\gamma}$)
- LHC run 2: higher energy reach & higher statistics
  $\hookrightarrow$ EW corrections important

Wγ production – EW corrections

Denner, S.D., Hecht, Pasold '14

- NLO EW corrections calculated with full W off-shell/decay effects
  (complex-mass scheme)
  $\hookrightarrow$ more + more complicated diagrams than in QCD

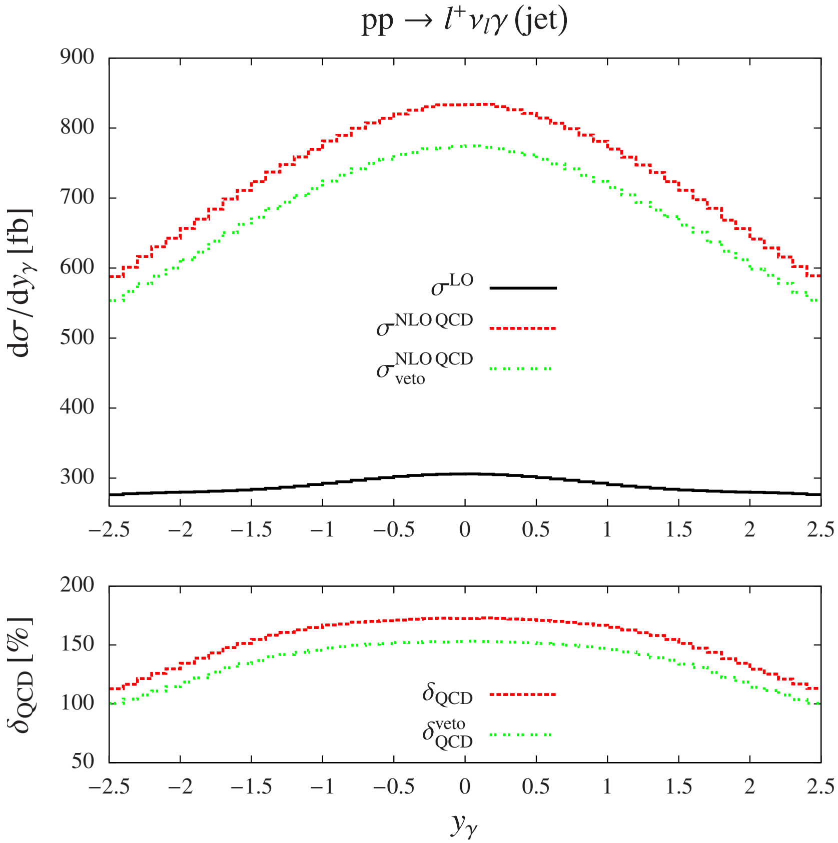


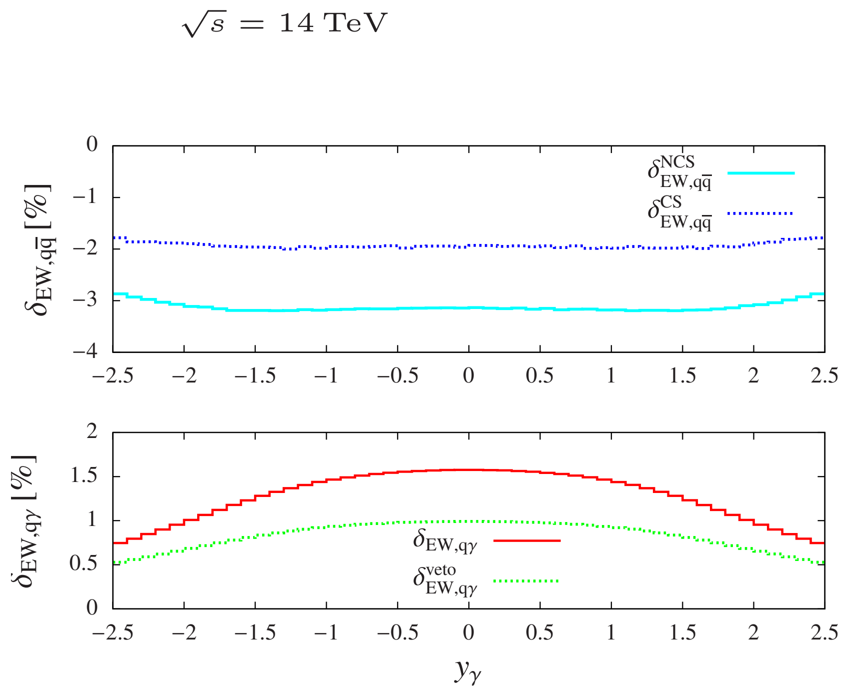
etc.

- particular focus on:
  - ◇ high energies (e.g. large p_{T}):
    large EW corrections $\leftrightarrow$ sensitivity to anomalous couplings
    $\hookrightarrow$ missing corrections could fake anomalous couplings
  - ◇ photon-induced contributions

Rapidity distributions in $\mathrm{W}\gamma$ production

Denner, S.D., Hecht, Pasold ’14

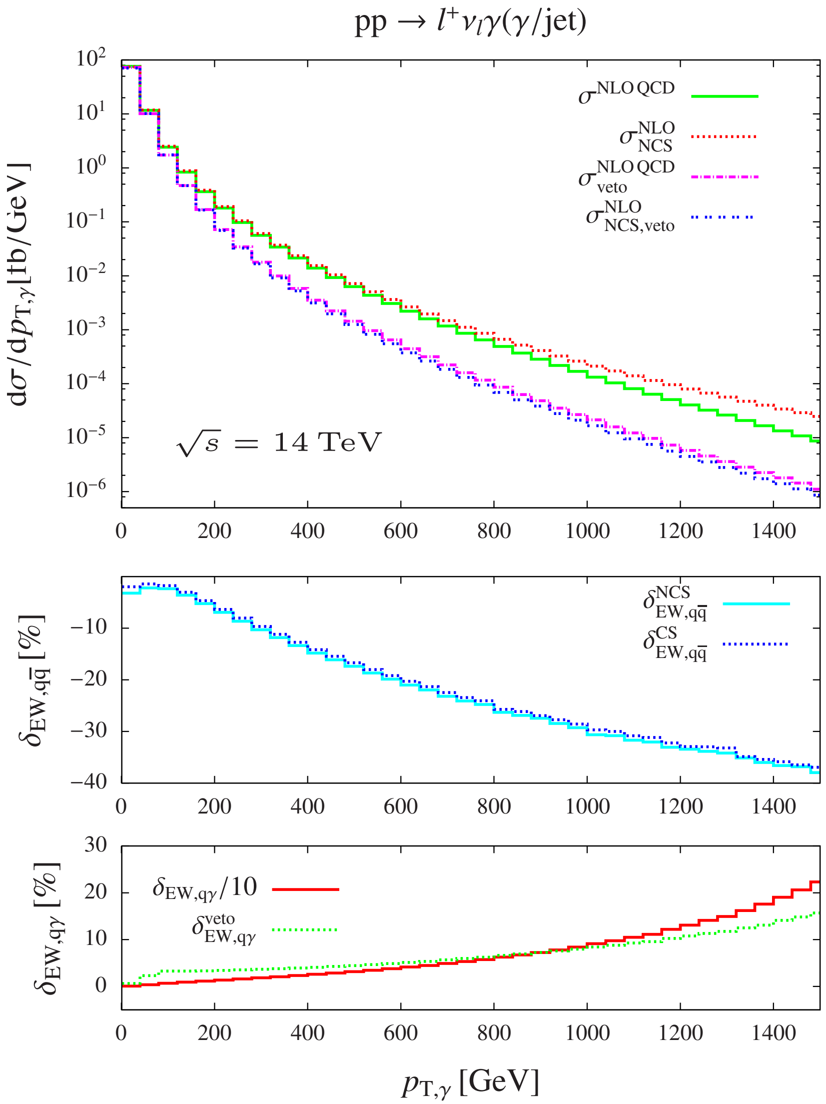


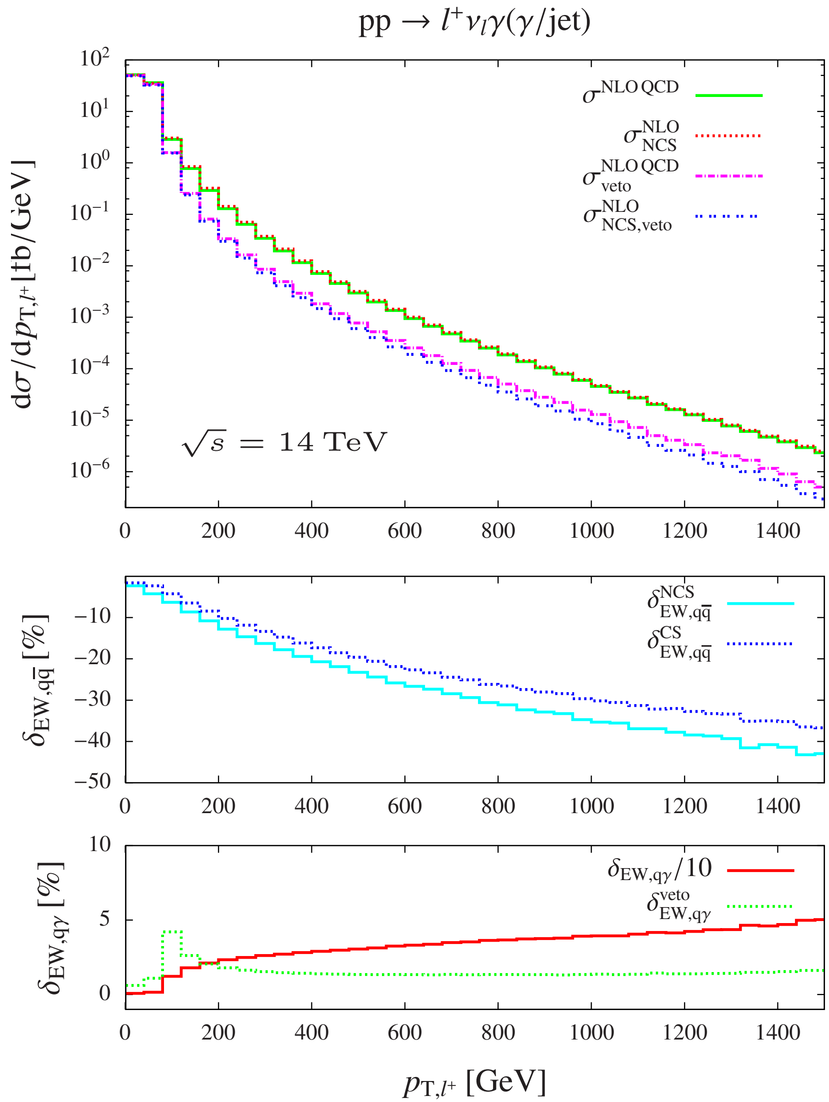


- huge QCD corrections ($\sim 100\%$), only mildly reduced by jet veto $p_{\mathrm{T,jet}} < 100\,\mathrm{GeV}$
- EW corrections and $q\gamma$ channels (few $\%$) small and flat (CS=collinear-safe, NCS=non-collinear-safe)
  $\hookrightarrow$ resemble corrections to integrated cross section

p_{T} distributions in $\mathrm{W}\gamma$ production – EW corrections

Denner, S.D., Hecht, Pasold '14

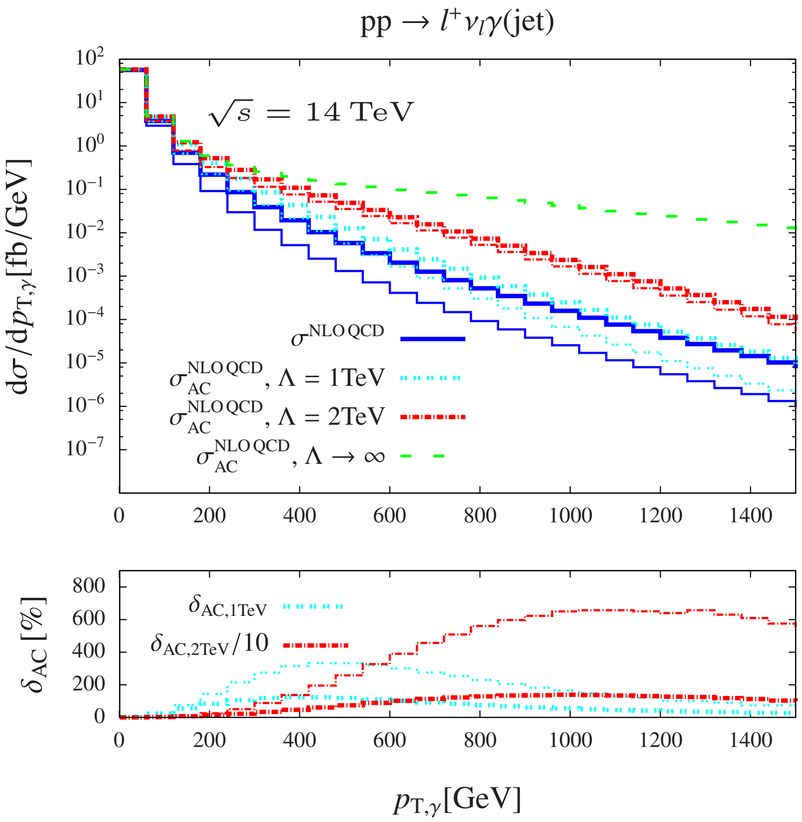


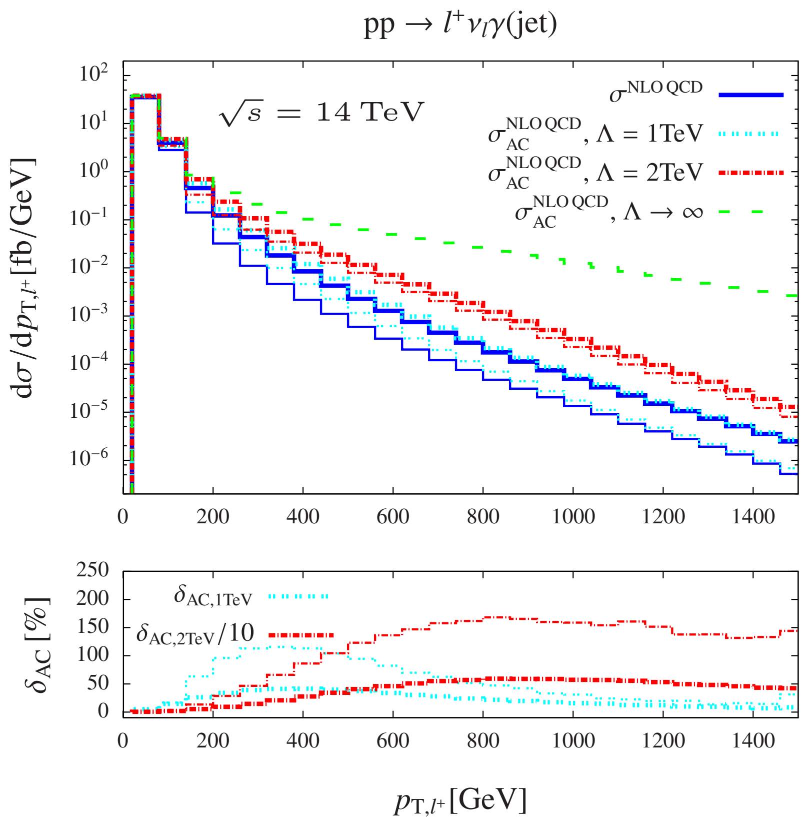


- EW corrections $\sim -30\%$ in TeV range (CS=collinear-safe, NCS=non-collinear-safe)
- γ-induced corrections non-negligible in TeV range (even with jet veto)
  $\hookrightarrow$ reduction of γ PDF uncertainties mandatory !

$W\gamma$ production – anomalous couplings

Denner, S.D., Hecht, Pasold ’14





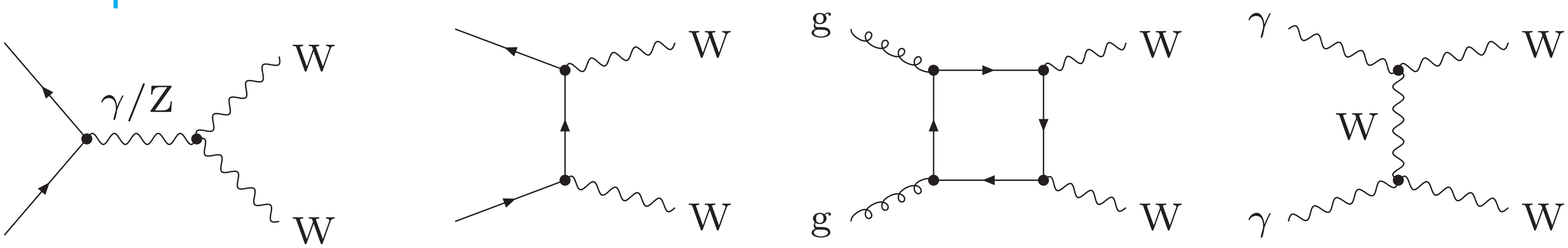
- results shown without and with jet veto on $p_{T,jet} > 100\,\mathrm{GeV}$
- ATLAS values of 2012 used: $\Delta\kappa^\gamma = 0.41$, $\lambda^\gamma = 0.074$

  $\hookrightarrow$ much tighter limits expected at LHC run 2

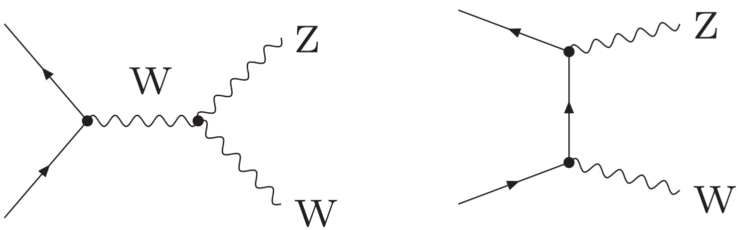
WW / WZ / ZZ production

Complementarity in WW / WZ / ZZ production

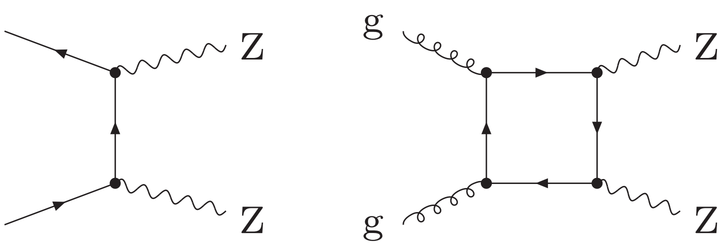
WW production:



WZ production:

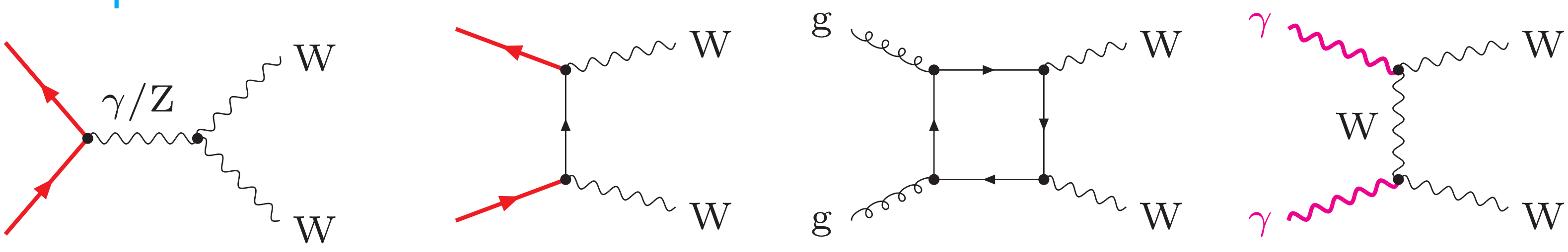


ZZ production:

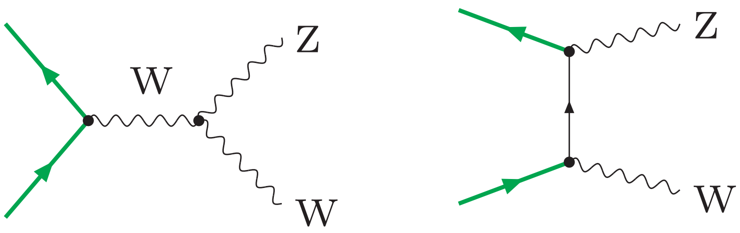


Complementarity in WW / WZ / ZZ production

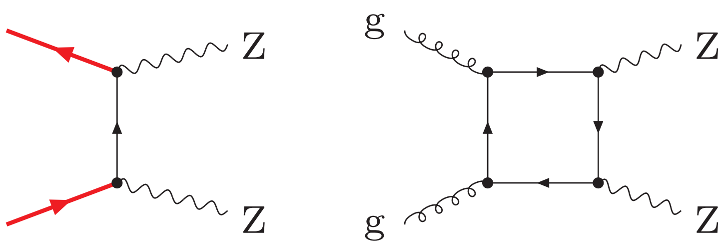
WW production:



WZ production:



ZZ production:

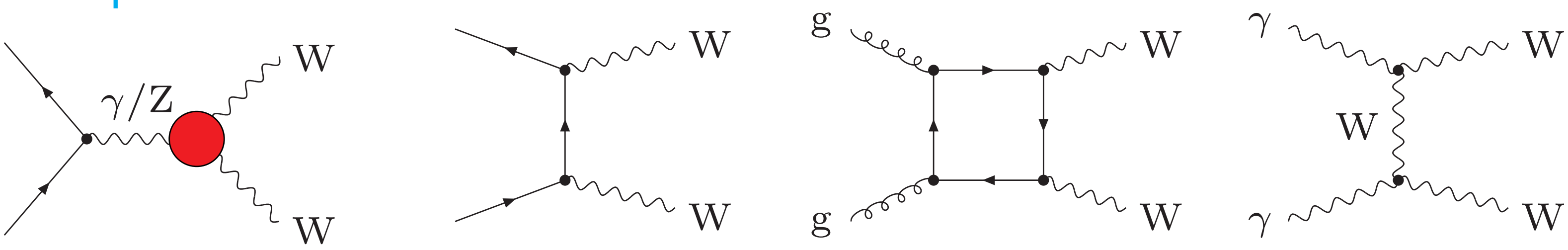


Sensitivity to different PDF combinations:

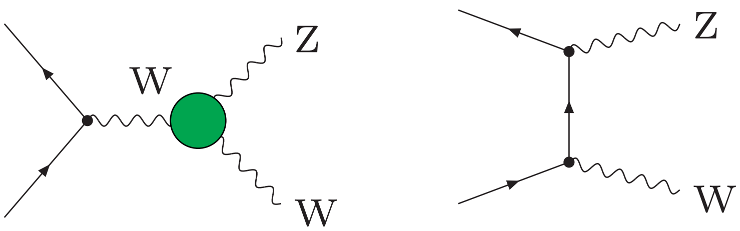
- $q\bar{q}$ in WW/ZZ
- $u\bar{d}/d\bar{u}$ in $\mathrm{W}^{+}\mathrm{Z}/\mathrm{W}^{-}\mathrm{Z}$
- $\gamma\gamma$ in WW

Complementarity in WW / WZ / ZZ production

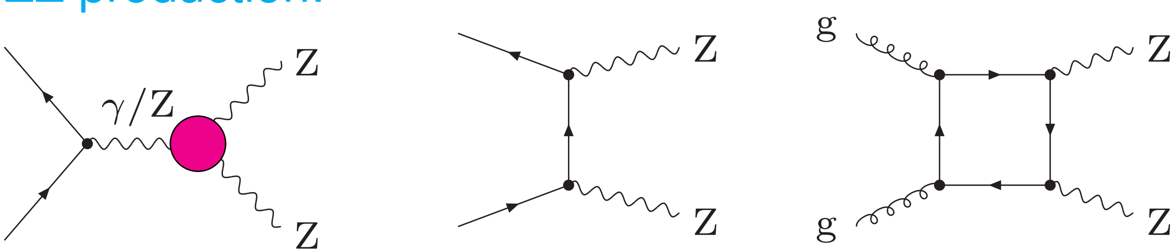
WW production:



WZ production:



ZZ production:

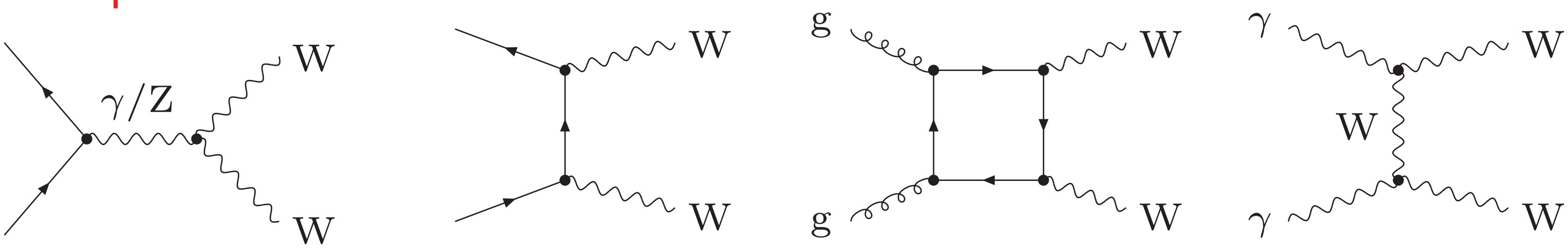


Sensitivity to different anomalous TGCs:

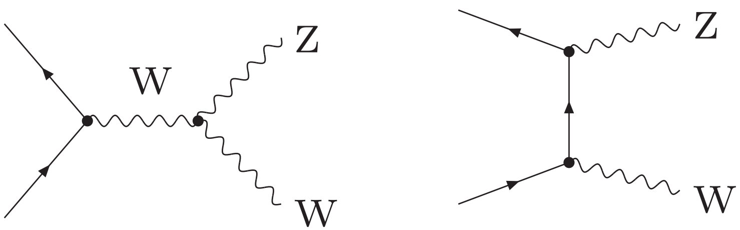
- overlay of $\gamma\mathrm{WW}/\mathrm{ZWW}$ in WW
- only ZWW in WZ
- $\gamma\mathrm{ZZ}/\mathrm{ZZZ}$ in ZZ

Complementarity in WW / WZ / ZZ production

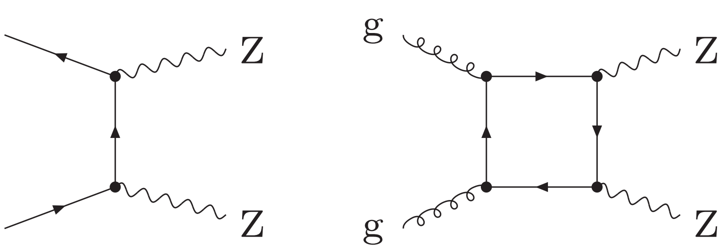
WW production:



WZ production:

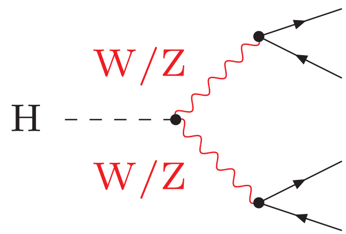


ZZ production:



Background to Higgs production
in channel $\mathrm{H} \to \mathrm{WW}^*/\mathrm{ZZ}^* \to 4f$

$\hookrightarrow$ off-shell calculation
particularly important for WW/ZZ !

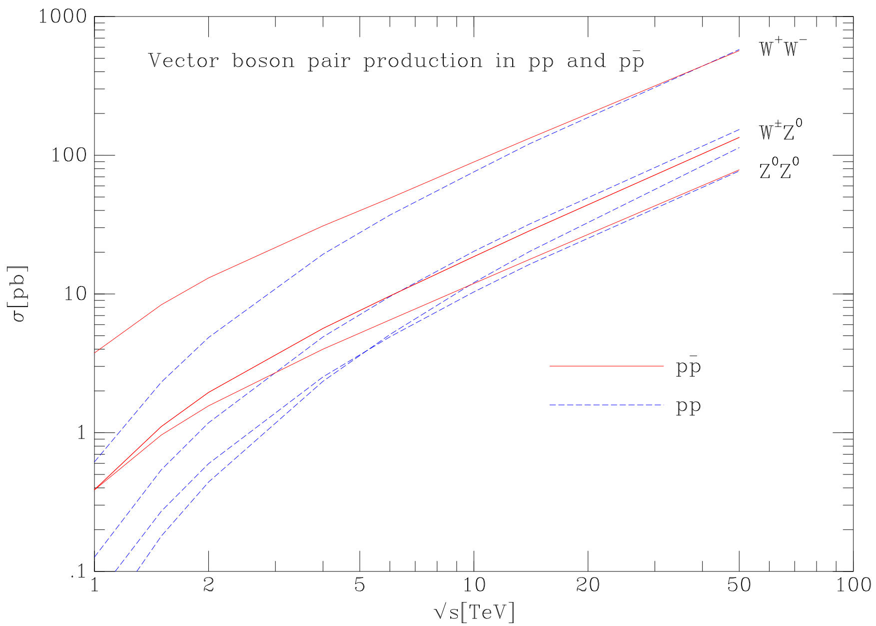


QCD corrections to $\mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}, \mathrm{W}\gamma, \mathrm{Z}\gamma$ production

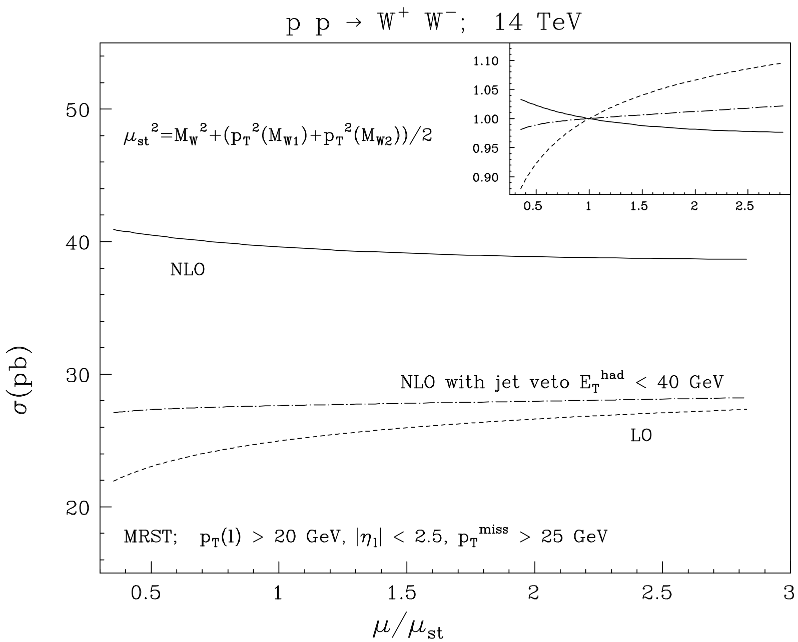
NLO QCD calculated (including leptonic W/Z decays)

Baur, Han, Ohnemus '93-'98
Dixon, Kunszt, Signer '99
Campbell, R.K.Ellis '99
DeFlorian, Signer '00

Campbell, R.K.Ellis et al. '99



Haywood et al. '00

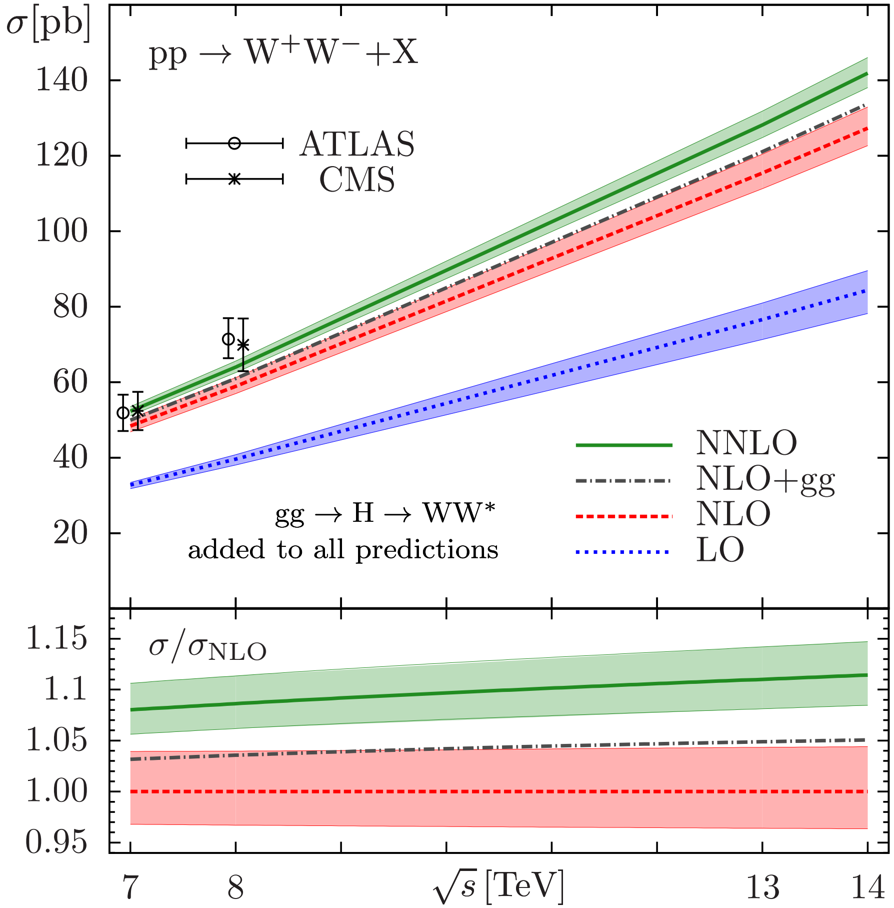


Large positive corrections due to jet radiation, i.e. $VV + \mathrm{jet}$ production

- reduction of corrections and scale dependence by jet veto: $p_{\mathrm{T,jet}} < \mathrm{cut}$?
  $\hookrightarrow$ include QCD resummation for veto
- NNLO QCD corrections important

WW production – NNLO QCD theory versus experiment

Gehrmann et al. '14



Subtlety:

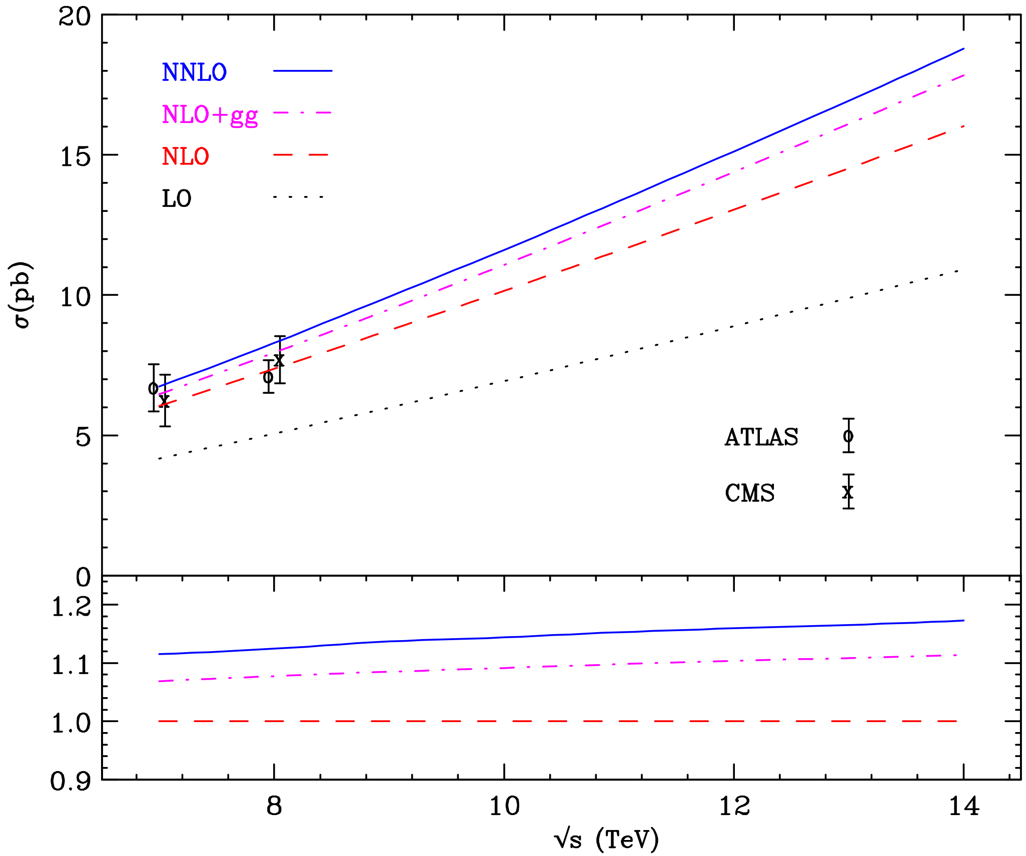
Separation of single-t and $t\bar{t}$ contributions @ NNLO QCD

$\hookrightarrow$ b-jet veto, etc.

- good agreement of experimental results with NNLO QCD
- NNLO QCD correction $\sim 7(12)\%$ @ $8(13)$ TeV, scale uncertainty $\lesssim 3\%$
- gg contribution $\sim 7(8)\%$ @ $8(13)$ TeV
- LHC run 2: higher energy & higher statistics $\rightarrow$ EW corrections important

ZZ production – NNLO QCD theory versus experiment

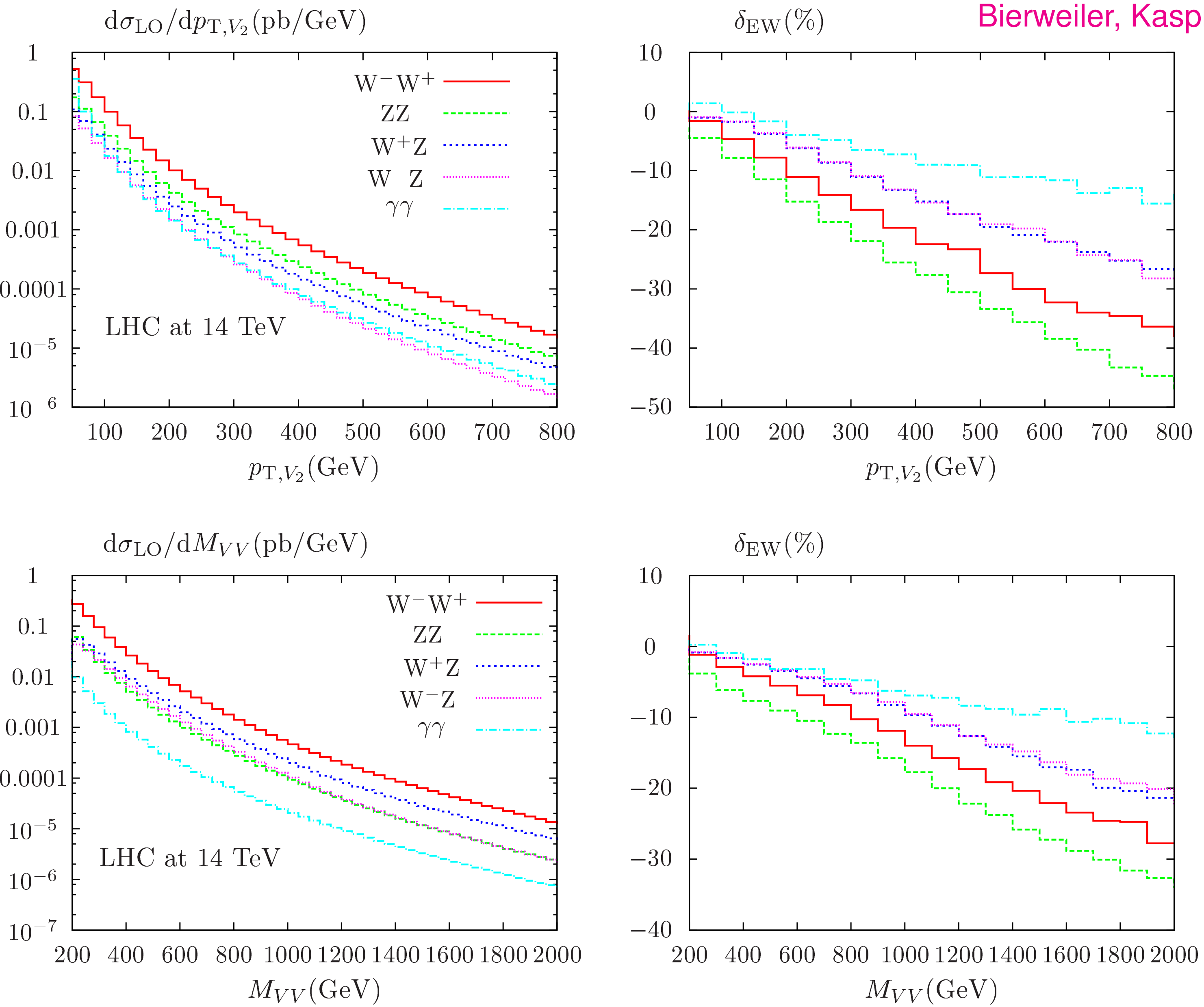
Cascioli et al. '14



- good agreement of experimental results with NNLO QCD
- NNLO QCD correction $\sim 12(17)\%$ @ $8(13)\,\mathrm{TeV}$, scale uncertainty $\lesssim 3\%$
- gg contribution $\sim 7(10)\%$ @ $8(13)\,\mathrm{TeV}$
- LHC run 2: higher energy & higher statistics $\rightarrow$ EW corrections important

EW corrections to massive di-boson production

Bierweiler, Kasprzik, Kühn '13



EW corrections

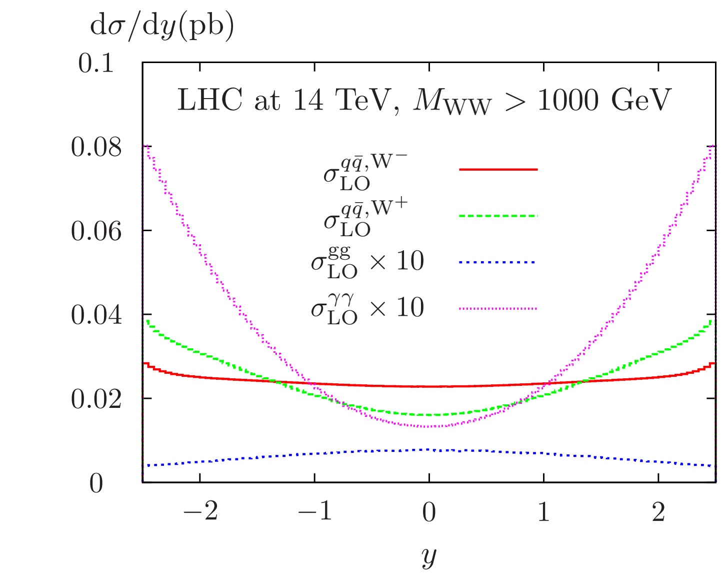
- small for integrated XS
- growing in distributions for larger scales

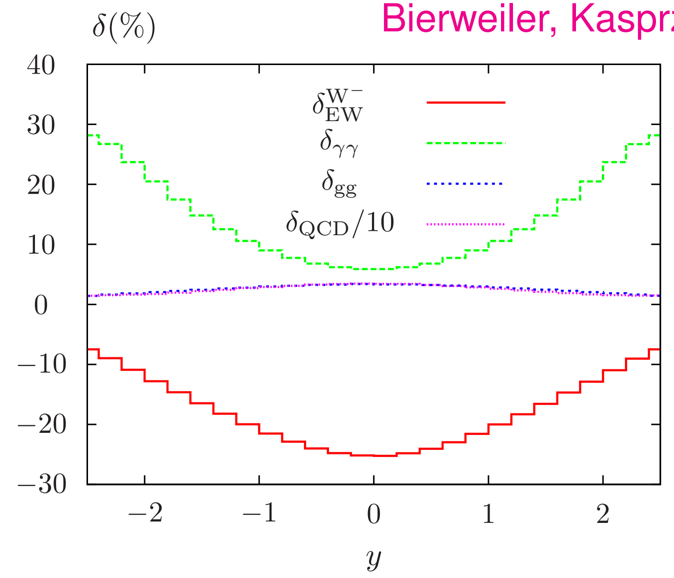
Note:

- M_{VV} not accessible for W final states
- on-shell approximation not applicable for $M_{VV} < M_{V_1} + M_{V_2}$

Survey of corrections to WW production (stable/on-shell W bosons)

Bierweiler, Kasprzik, Kühn '12

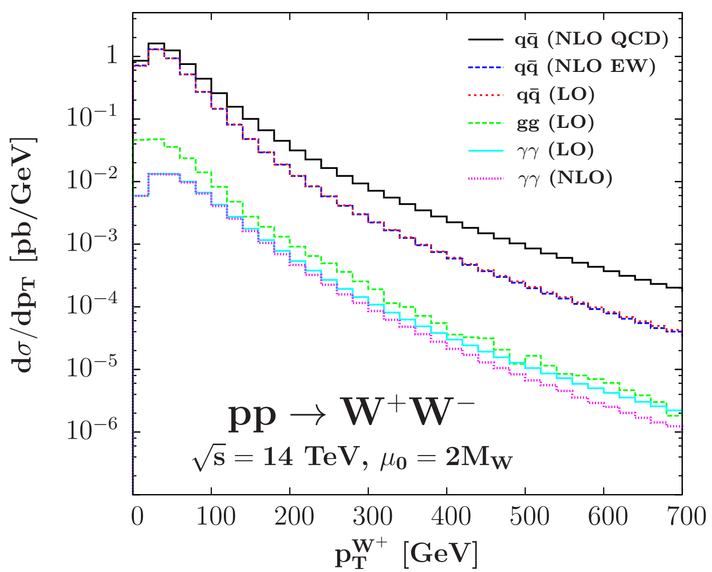


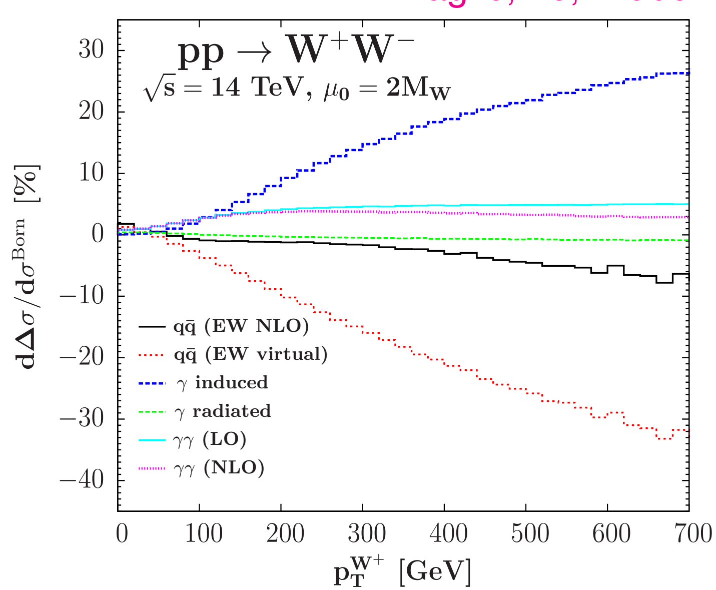


Note:

large contribution by $\gamma\gamma$ channel for high invariant WW masses !

Baglio, Le, Weber '13

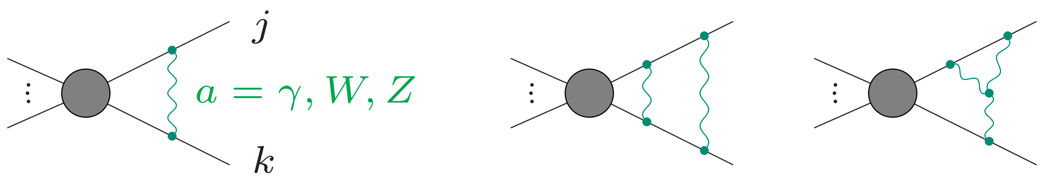




Large impact of $q\gamma$ collisions ?

Electroweak corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



etc.

+ sub-leading logarithms from collinear singularities

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta_{\mathrm{LL}}^{1-\mathrm{loop}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2}\ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta_{\mathrm{NLL}}^{1-\mathrm{loop}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2}\ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

$$\delta_{\mathrm{LL}}^{2-\mathrm{loop}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4}\ln^4\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 3.5\%, \qquad \delta_{\mathrm{NLL}}^{2-\mathrm{loop}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4}\ln^3\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -4.2\%$$

$\Rightarrow$ Corrections still relevant at 2-loop level

Note: differences to QED / QCD where Sudakov log's cancel

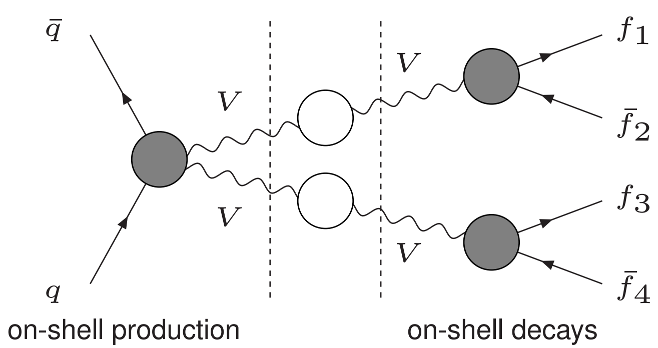
- massive gauge bosons W, Z can be reconstructed
  $\hookrightarrow$ no need to add "real W, Z radiation"
- non-Abelian charges of W, Z are "open" $\to$ Bloch–Nordsieck theorem not applicable

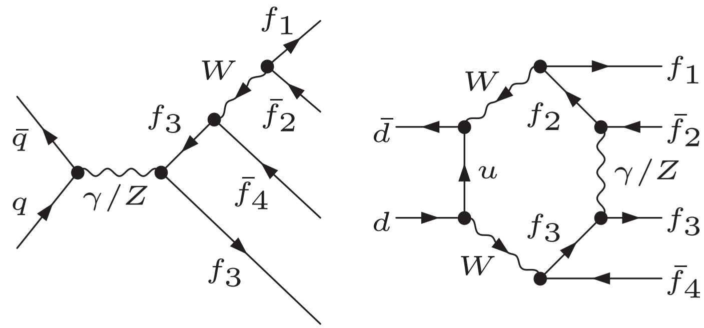
Extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations

Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner, Pozzorini; Fadin et al.; Hori et al.; Melles; Kühn et al., Denner et al., Manohar et al. '00–

EW corrections with leptonic W/Z decays

Double-pole approximation (DPA) vs. Full off-shell $q\bar{q} \to 4f$ calculation





Double-pole approximation (DPA)

- expansion about resonance poles
  $\hookrightarrow$ factorizable & non-factorizable corrs.
- not many diagrams ($2 \to 2$ production)

\+ numerically fast

– validity only for $\sqrt{\hat{s}} > 2M_V + \mathcal{O}(\Gamma_V)$

- error estimate for $\sqrt{\hat{s}} \lesssim 0.5\text{–}1\,\mathrm{TeV}$:
  $\Delta \sim \frac{\alpha}{\pi}\frac{\Gamma_V}{M_V}\log(\ldots) \sim 0.5\text{–}2\%$

Full off-shell $q\bar{q} \to 4f$ calculation

- off-shell calculation with complex-mass scheme
- many off-shell diagrams ($\sim 10^3$/channel)

– very CPU intensive

\+ NLO accuracy everywhere

- global error estimate:
  $\Delta \sim \delta_{\mathrm{NNLO\,EW}} \sim \delta^2_{\mathrm{NLO\,EW}}$

Approaches compared for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ Denner, S.D., Roth, Wieders '05

New: $\mathrm{pp} \to \mathrm{WW} \to 4f$ Biedermann et al. (in preparation)

Collier is hosted by Hepforge, IPPP Durham

COLLIER

A Complex One-Loop LIbrary with Extended Regularizations

To be released soon!

Authors
Ansgar Denner *Universität Würzburg, Germany*
Stefan Dittmaier *Universität Freiburg, Germany*
Lars Hofer *Universitat de Barcelona, Spain*

Features of the library

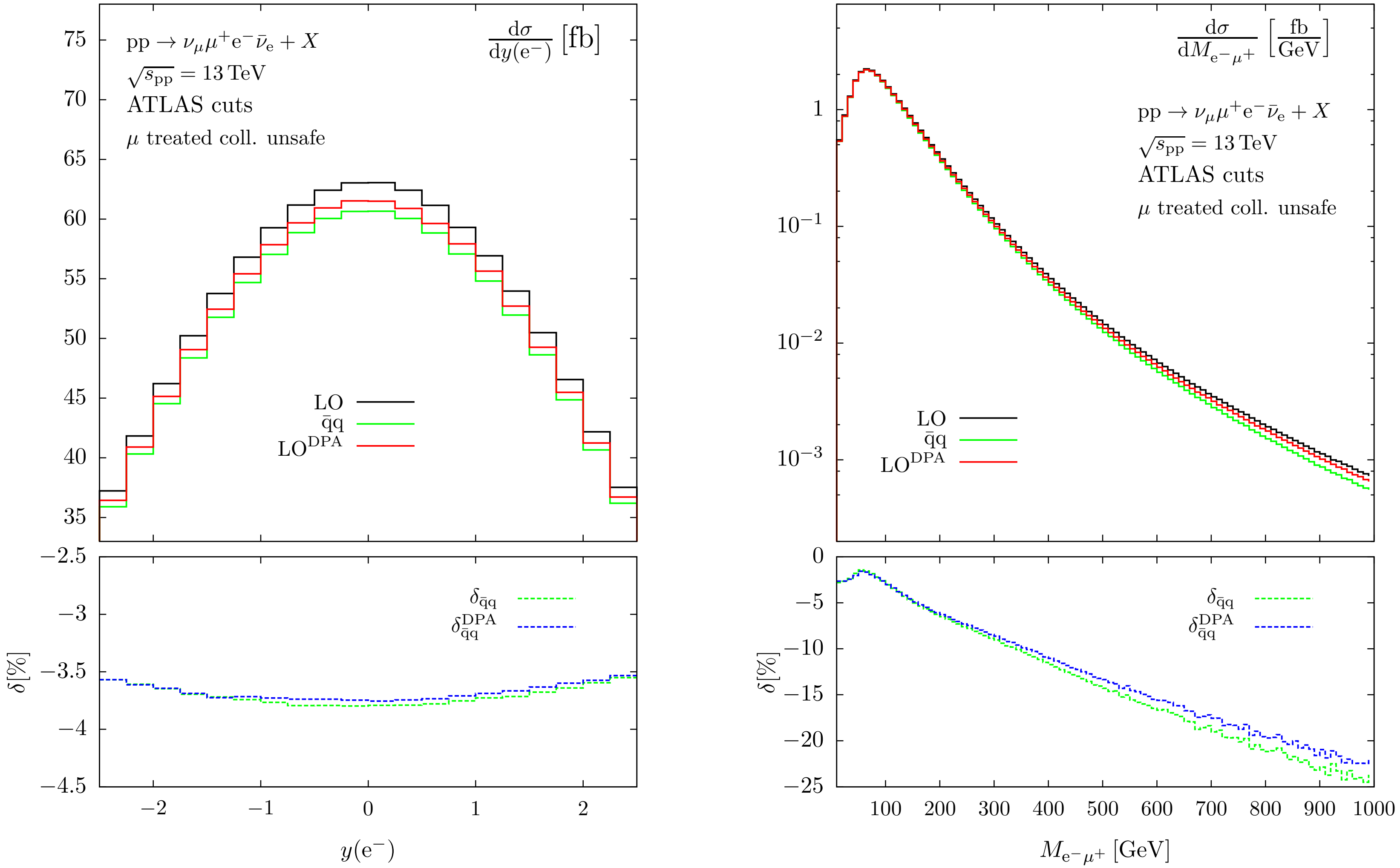
COLLIER is a fortran library for the numerical evaluation of one-loop scalar and tensor integrals appearing in perturbative relativistic quantum field theory with the following features:

- scalar and tensor integrals for high particle multiplicities
- dimensional regularization for ultraviolet divergences
- dimensional regularization for soft infrared divergences (mass regularization for abelian soft divergences is supported as well)
- dimensional regularization or mass regularization for collinear mass singularities
- complex internal masses (for unstable particles) fully supported (external momenta and virtualities are expected to be real)
- numerically dangerous regions (small Gram or other kinematical determinants) cured by dedicated expansions
- two independent implementations of all basic building blocks allow for internal cross-checks
- cache system to speed up calculations

If you use Collier for a publication, please cite all the references listed here!

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

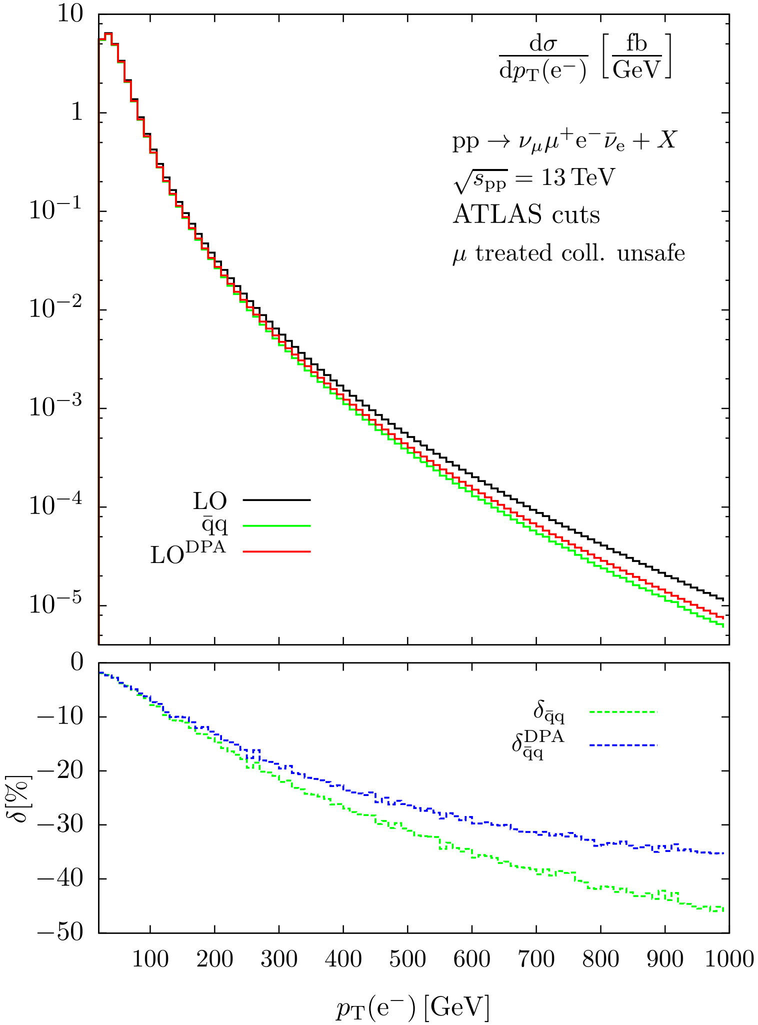
Rapidity and invariant-mass distributions **Preliminary!**

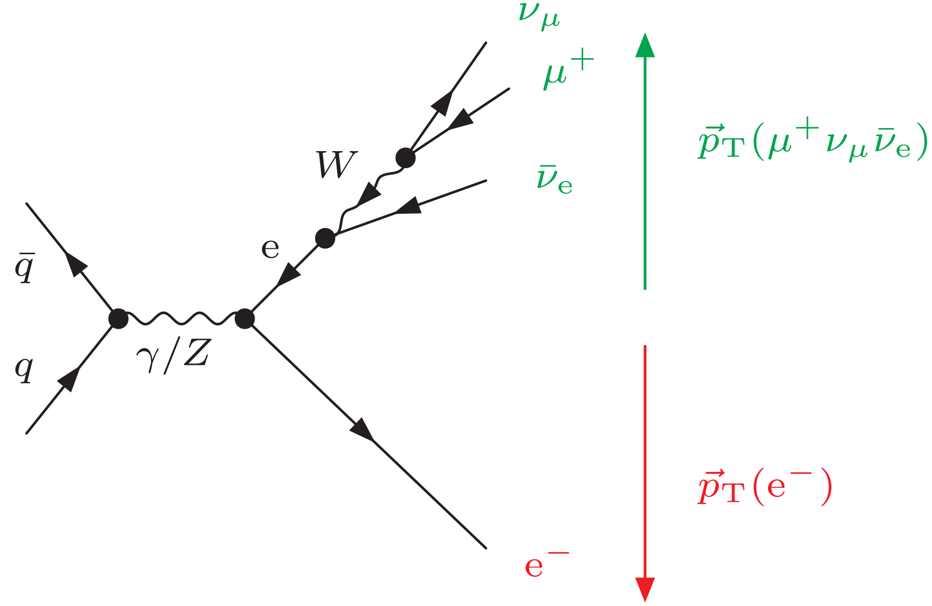


Level of agreement as expected (dominance of doubly-resonant diagrams)

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

Transverse-momentum distribution of a single lepton **Preliminary!**



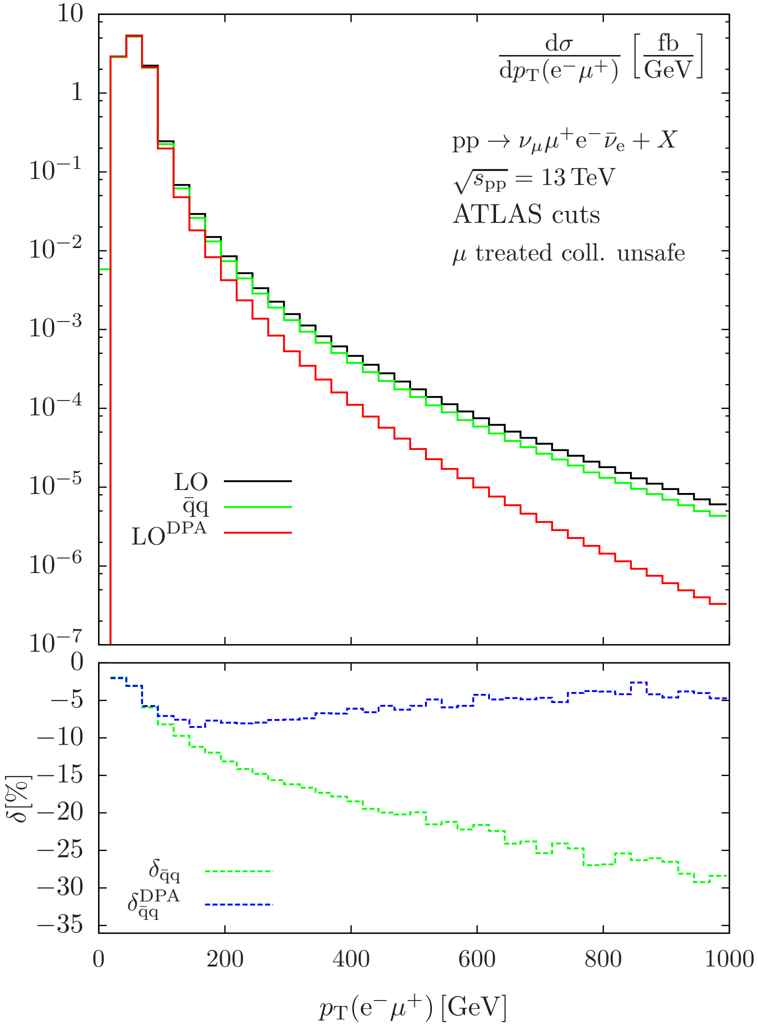


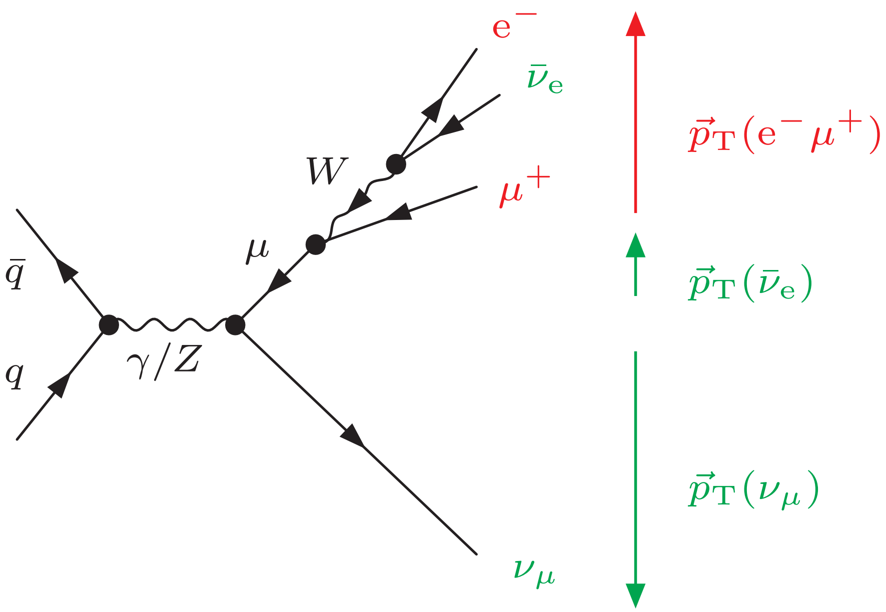
Impact of singly-resonant diagrams where e^- takes recoil from $(\mu^+ \nu_\mu \bar{\nu}_\mathrm{e})$

Agreement degrades for $p_\mathrm{T} \gtrsim 300\,\mathrm{GeV}$, since off-shell diagrams get enhanced

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

Transverse-momentum distribution of the charged lepton pair **Preliminary!**





Dominance of singly-resonant diagrams where $(\mathrm{e}^-\mu^+)$ recoil against $(\nu_\mu\bar{\nu}_\mathrm{e})$

DPA fails for $p_\mathrm{T} \gtrsim 200\,\mathrm{GeV}$, since off-shell production dominates!

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Setup (inspired by ATLAS)

$$p_{\mathrm{T}}(\ell_i) > 6\,\mathrm{GeV}, \quad |y(\ell_i)| < 2.5, \quad \Delta R(\ell_i,\ell_j) = \sqrt{(y_i-y_j)^2+(\phi_i-\phi_j)^2} > 0.2$$

$$40\,\mathrm{GeV} < M_{\ell_1^+\ell_1^-} < 120\,\mathrm{GeV}, \qquad 12\,\mathrm{GeV} < M_{\ell_2^+\ell_2^-} < 120\,\mathrm{GeV}$$

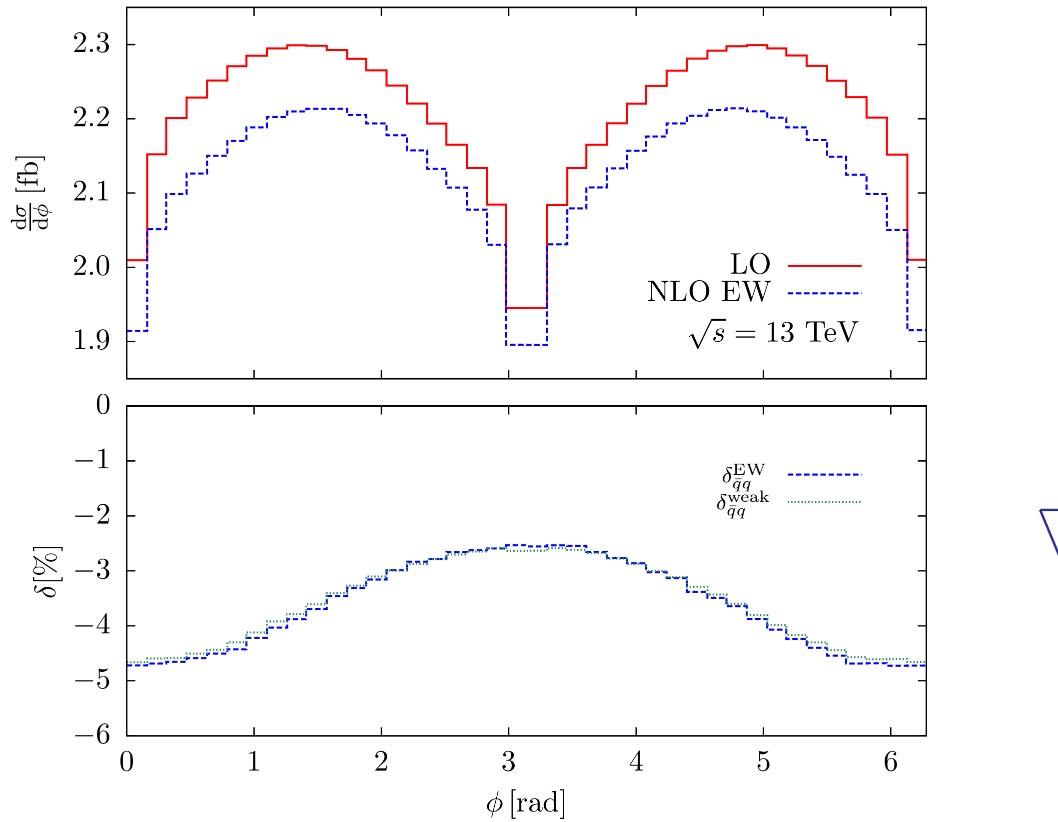
Integrated cross section

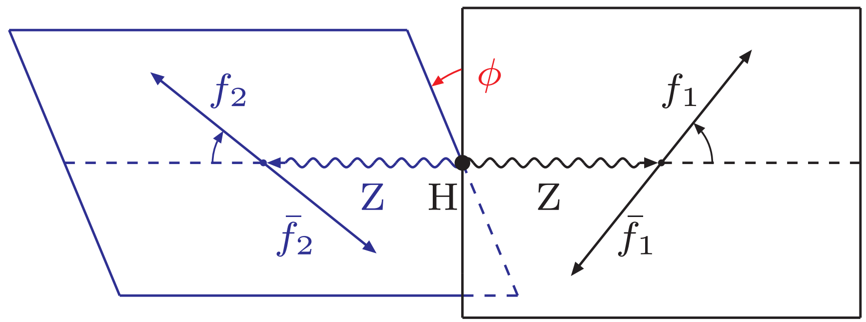
$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{EW}}_{\bar{q}q}$ [%]	$\delta^{\mathrm{weak}}_{\bar{q}q}$ [%]
7	7.3293(4)	−3.4	−3.3
8	8.4704(2)	−3.5	−3.4
13	13.8598(3)	−3.6	−3.6
14	14.8943(8)	−3.6	−3.6

- weak corrections moderate
- photonic corrections negligible
  (due to inclusiveness of the event selection)
- deviation of δ from on-shell ZZ calculation $\sim 1\%$

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Distribution in the angle between decay planes

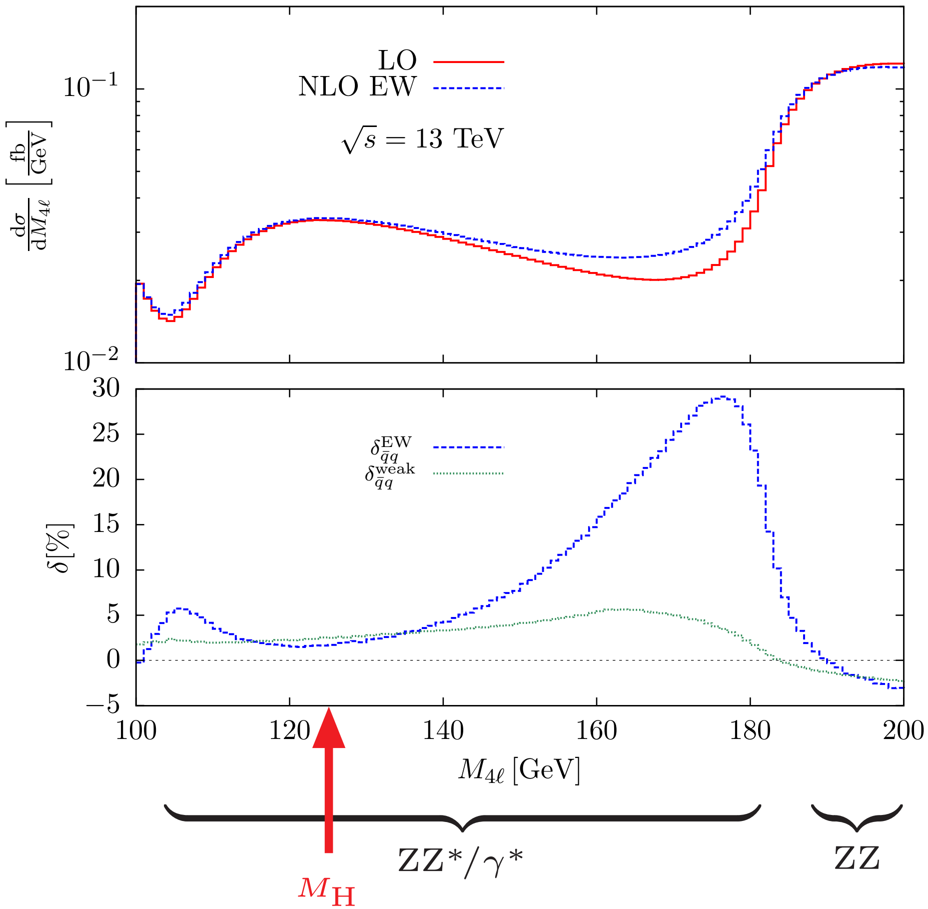




- observable dominated by resonant ZZ production
- corrections mostly resemble corrections to the integrated cross section
- photonic corrections extremely suppressed
  (insensitivity of ϕ to collinear photon emission off leptons)

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Distribution in the 4-lepton invariant mass



- large radiative tails in photonic corrections below thresholds (known effect ...)
- weak corrections $\sim \mathcal{O}(5\%)$
  with sign change in transition from on-shell ZZ to off-shell ZZ^*/γ^* region

Conclusions

Di-boson production at the LHC

- sensitive to non-Abelian gauge-boson self-interactions
  $\hookrightarrow$ LHC will tighten constraints on anomalous triple-gauge-boson couplings
- important background
  - ◇ to new-physics searches and
  - ◇ to precision Higgs analyses in $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

$\Rightarrow$ Precise predictions with QCD and EW corrections required

Recent progress at the precision frontier

- NNLO QCD corrections to direct VV' production (Vs partially off-shell)
- NLO QCD corrections to loop-induced channels $\mathrm{gg} \to VV$ (on-shell)
- NLO EW corrections to direct VV' production with off-shell Vs
  $\hookrightarrow$ particularly important at the TeV scale
- QCD resummations, QCD parton-shower matching (not discussed here)

$\Rightarrow$ SM predictions in good shape!

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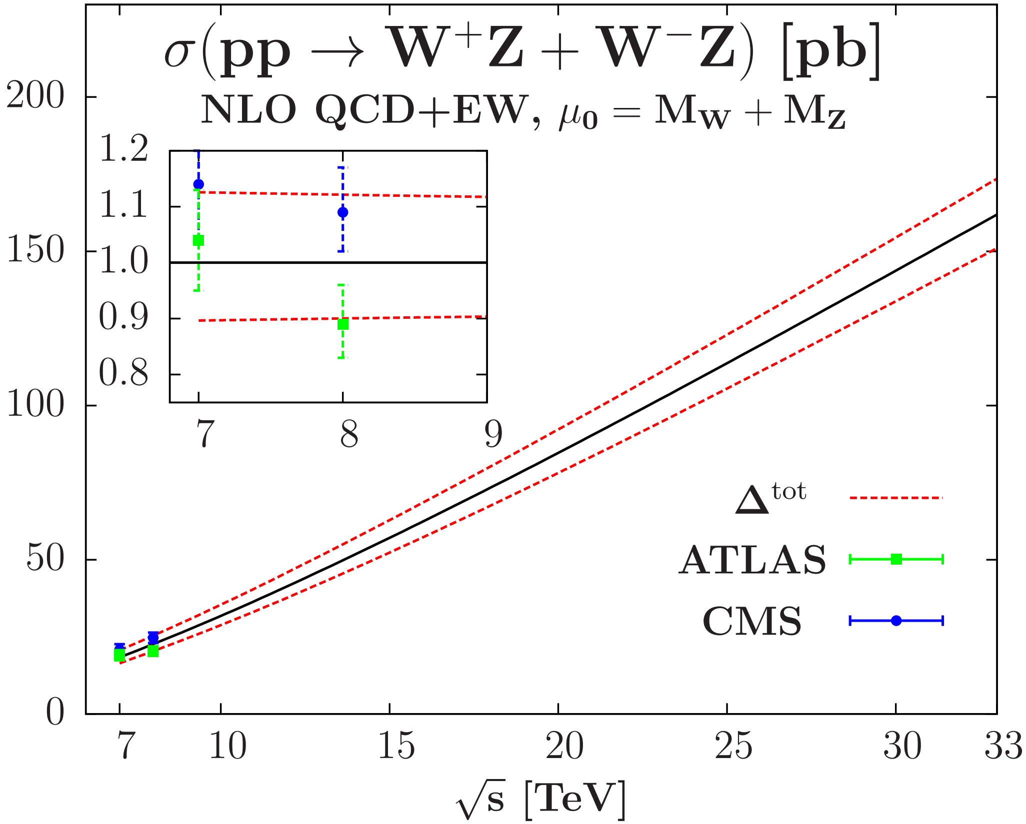
⇒ SM predictions in good shape!

"In ~~football as in watchmaking~~ *particle theory*, talent and elegance mean nothing without rigour and precision."
[Lionel Messi]

Backup slides

WZ production – NLO QCD theory versus experiment

Baglio, Le, Weber et al. '13



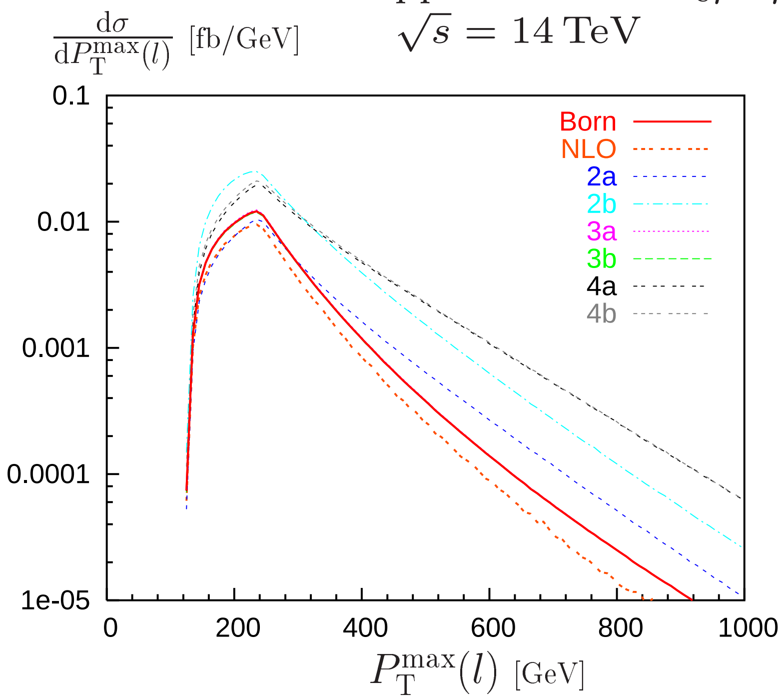
- good agreement of experimental results with NLO QCD
- NLO QCD scale uncertainty $\sim 3\%$, $\Delta_{\mathrm{PDF}+\alpha_s} \sim 4\%$
- LHC run 2: higher energy & higher statistics
  ↪ NNLO QCD and NLO EW corrections important

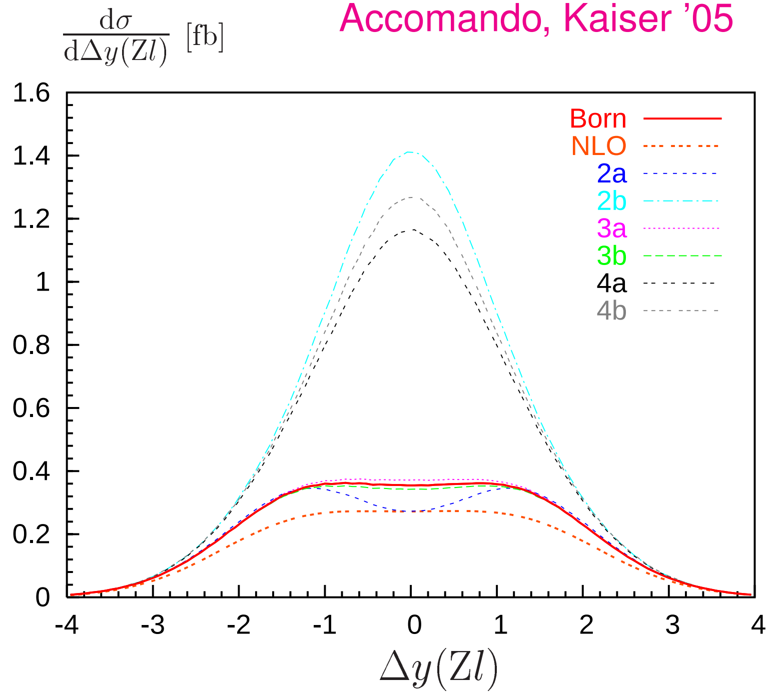
EW corrections vs. anomalous TGCs in gauge-boson pair production

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_\mathrm{e}\mu^+\mu^-$

$\sqrt{s} = 14\,\mathrm{TeV}$

Accomando, Kaiser '05





Scenario	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
Born	0	0	0
2a/2b	± 0.02	0	0
3a/3b	0	± 0.04	0
4a/4b	0	0	± 0.02

$$\lambda_\mathrm{Z} = \lambda_\gamma, \quad \Delta\kappa_\mathrm{Z} = \Delta g_1^\mathrm{Z} - \tan^2\theta_\mathrm{W}\Delta\kappa_\gamma$$

formfactor rescaling ($\Lambda = 1\,\mathrm{TeV}$):

$$\Delta Y \to \frac{\Delta Y}{(1+\hat{s}/\Lambda^2)^2}, \quad \Delta Y = \Delta g_1^\mathrm{Z}, \Delta\kappa_\gamma, \lambda_\gamma$$

Note:

- EW corrections and anomalous couplings distort distributions
- neglect of EW corrections can mimick anomalous couplings

Gauge-invariance issues

in EW multi-boson production

Gauge invariance implies...

- Slavnov–Taylor or Ward identites
  = algebraic relations of or between Greens functions

  $\hookrightarrow$ guarantee cancellation of unitarity-violating terms,
  crucial for proof of unitarity of S-matrix
- Nielsen identities (compensation of gauge-fixing artefacts)

  $\hookrightarrow$ gauge-parameter independence of S-matrix

  although Greens function (e.g. self-energies) are gauge dependent

Both statements hold order by order in standard perturbation theory !

Implications:

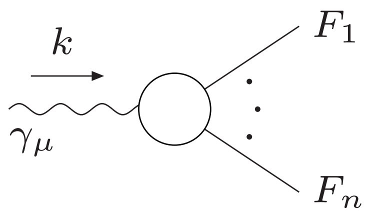
- Resonances require Dyson summation of resonant propagators

  $\hookrightarrow$ perturbative orders mixed $\rightarrow$ gauge invariance jeopardized !

  Gauge-invariance-violating terms $\propto \Gamma$ are formally of higher order,
  but can be dramatically enhanced if unitarity cancellations disturbed
- Anomalous couplings potentially enhanced
  if effective operator not gauge invariant

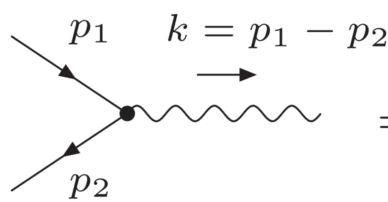
Important Ward identities for processes with EW gauge bosons:

Elmg. U(1) gauge invariance implies

k^μ 

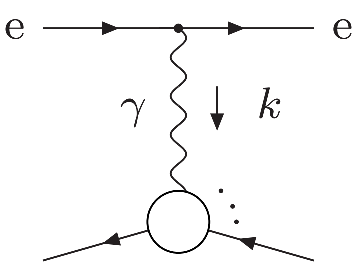
$= 0$ for any on-shell fields F_l

$\hookrightarrow$ Identity becomes crucial for collinear light fermions:

for fermion momenta $p_1 \sim c\,p_2$: 

$= \bar{u}_2(p_2)\gamma^\mu u_1(p_1) \propto k^\mu$

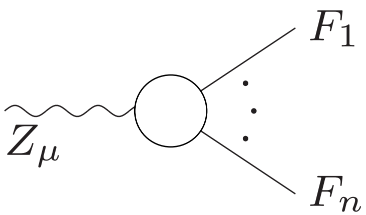
A typical situation: quasi-real space-like photons

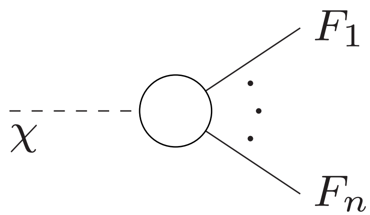


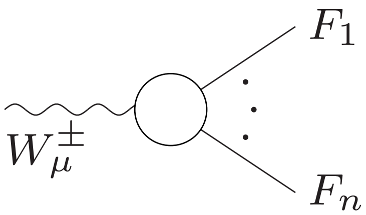
$\sim \dfrac{1}{k^2}\, k^\mu\, T^\gamma_\mu$ for $k^2 \to \mathcal{O}(m_\mathrm{e}^2) \ll E^2$

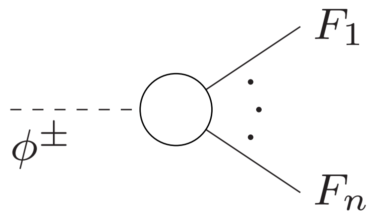
Identity $k^\mu\, T^\gamma_\mu = 0$ needed to cancel $1/k^2$,
otherwise gauge-invariance-breaking terms enhanced by E^2/m_e^2 ($\sim 10^{10}$ for LEP2)

Electroweak SU(2) gauge invariance implies

k^μ 

$= \; \mathrm{i} M_\mathrm{Z}$ 

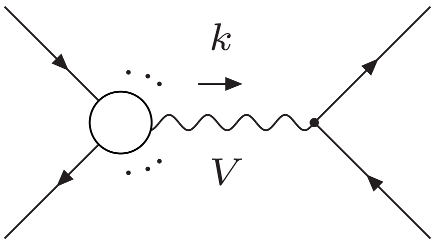
k^μ 

$= \; \pm M_\mathrm{W}$ 

F_l = on-shell fields
$\chi, \phi^\pm$ = would-be Goldstone fields

A typical situation: high-energetic quasi-real longitudinal vector bosons

$\hookrightarrow$ fermion current attached to $\mathrm{V}(k)$ again $\propto k^\mu$



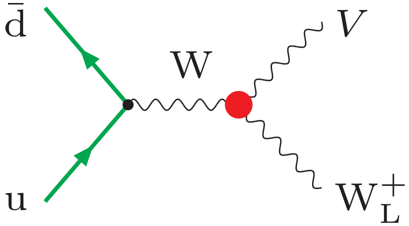
$$\sim \frac{1}{k^2 - M_\mathrm{V}^2} \, k^\mu \, T^V_\mu \qquad \text{for } k^0 \gg M_\mathrm{V}$$

Identity $k^\mu T^V_\mu = c_V \, M_\mathrm{V} T^S$ needed to cancel factor k^0,
otherwise gauge-invariance/unitarity-breaking terms enhanced by k^0/M_V

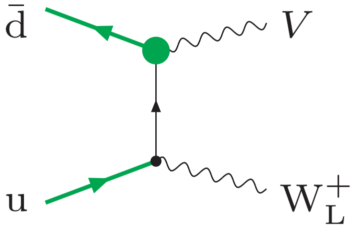
For on-shell V: $\quad \varepsilon^\mu_{V_\mathrm{L}}(k) = \dfrac{k^\mu}{M_V} + \mathcal{O}(M_V/k^0)$

Illustration of unitarity cancellations for $\mathrm{W}V$ production ($V=\mathrm{Z}/\gamma$)

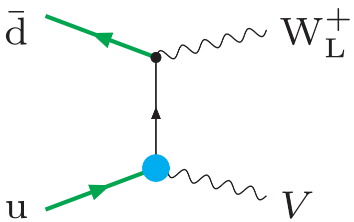
Leading behaviour of amplitudes with $\varepsilon^{\mu}_{\mathrm{W}^+_\mathrm{L}}(k) = \dfrac{k^\mu}{M_V} + \ldots$ for $k^0 \gg M_\mathrm{W}$:



$$\sim \frac{-\mathrm{i}e^2 g_{VWW}}{2\sqrt{2} s_\mathrm{W} M_\mathrm{W}} \left[\bar{v}_{\bar{\mathrm{d}}}\gamma_\mu \omega_- u_\mathrm{u}\right] \left\{ g_1^V \left[\varepsilon_V^{*\mu} - k^\mu \frac{\varepsilon_V^* \cdot k}{s}\right] + \kappa_V \left[\varepsilon_V^{*\mu} + k^\mu \frac{\varepsilon_V^* \cdot k}{s}\right]\right\}$$



$$\sim \frac{\mathrm{i}e^2 g^{-}_{Vdd}}{\sqrt{2} s_\mathrm{W} M_\mathrm{W}} \left[\bar{v}_{\bar{\mathrm{d}}} \not\varepsilon_V^* \omega_- u_\mathrm{u}\right], \qquad g^{-}_{Zdd} = -\frac{s_\mathrm{W}}{c_\mathrm{W}} Q_\mathrm{d} - \frac{1}{2 s_\mathrm{W} c_\mathrm{W}}, \qquad g^{-}_{\gamma dd} = -Q_\mathrm{d}$$



$$\sim \frac{-\mathrm{i}e^2 g^{-}_{Vuu}}{\sqrt{2} s_\mathrm{W} M_\mathrm{W}} \left[\bar{v}_{\bar{\mathrm{d}}} \not\varepsilon_V^* \omega_- u_\mathrm{u}\right], \qquad g^{-}_{Zuu} = -\frac{s_\mathrm{W}}{c_\mathrm{W}} Q_\mathrm{u} + \frac{1}{2 s_\mathrm{W} c_\mathrm{W}}, \qquad g^{-}_{\gamma uu} = -Q_\mathrm{u}$$

Cancellation (unitarity!) of sum demands:

$$g^{-}_{Vdd} - g^{-}_{Vuu} - \frac{g_{VWW}}{2}\left(g_1^V + \kappa_V\right) \overset{!}{=} 0, \qquad g_1^V \overset{!}{=} \kappa_V$$

$\hookrightarrow$ SM provides unique solution: $\quad g_1^\mathrm{Z} = \kappa_\mathrm{Z} = g_1^\gamma = \kappa_\gamma = 1$

Note: no constraint on coupling λ_V, since effective operator gauge invariant !

Width schemes for LO calculations and gauge invariance

Naive propagator substitutions in full tree-level amplitudes:

$$\frac{1}{k^2 - m^2} \to \frac{1}{k^2 - m^2 + \mathrm{i}m\Gamma(k^2)} \qquad \text{in all propagators}$$

- constant width $\Gamma(k^2) = \text{const.}$ $\to$ U(1) respected, SU(2) "mildly" violated
- running width $\Gamma(k^2) \neq \text{const.}$ $\to$ U(1) and SU(2) violated

  $\hookrightarrow$ results can be totally wrong !

Fudge factor approaches:

Multiply full amplitudes without widths with

factors $\dfrac{p^2 - m^2}{p^2 - m^2 + \mathrm{i}m\Gamma}$ for each potentially resonant propagator

$\hookrightarrow$ gauge invariant, but spurious factors of $\mathcal{O}(\Gamma/m)$

Complex-mass scheme: (see lecture 1)

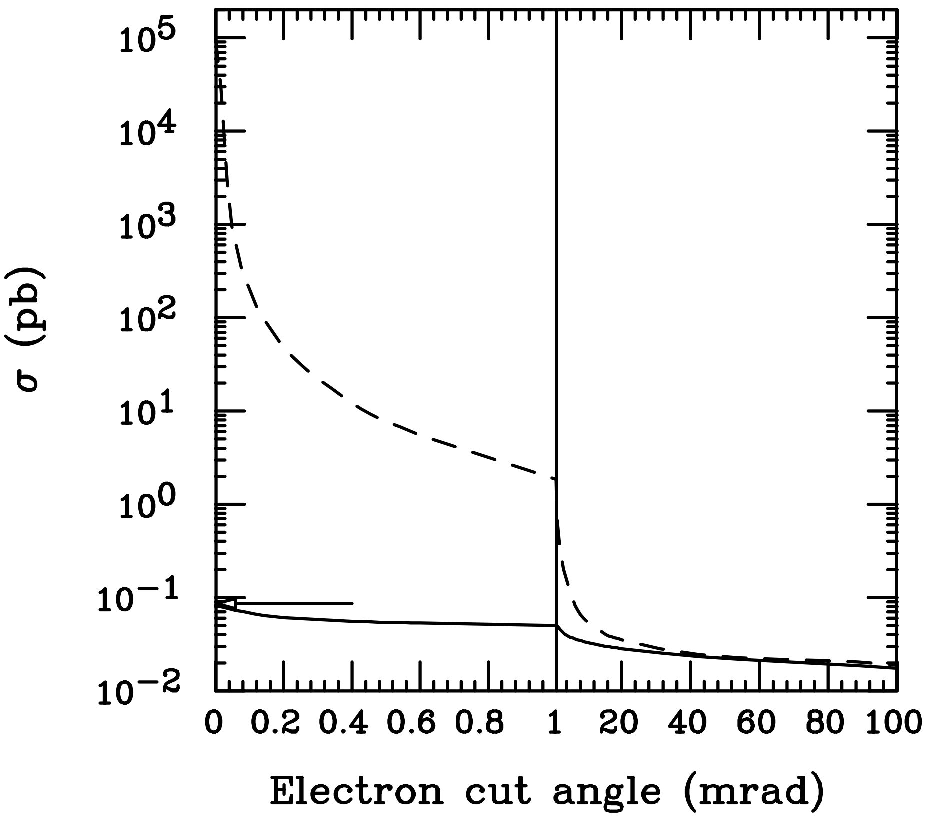
Consistent use of complex masses everywhere (including couplings)

For W/Z bosons: $M_V^2 \to \mu_V^2 = M_V^2 - \mathrm{i}M_V\Gamma_V, \quad V = \mathrm{W,Z}$

complex weak mixing angle: $c_\mathrm{W}^2 = 1 - s_\mathrm{W}^2 = \dfrac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

$\hookrightarrow$ gauge invariance fully respected

An example: $e^-e^+ \to e^-\bar{\nu}_e u\bar{d}$ result of Kurihara, Perret-Gallix, Shimizu '95



$\sqrt{s} = 180\,\mathrm{GeV}$

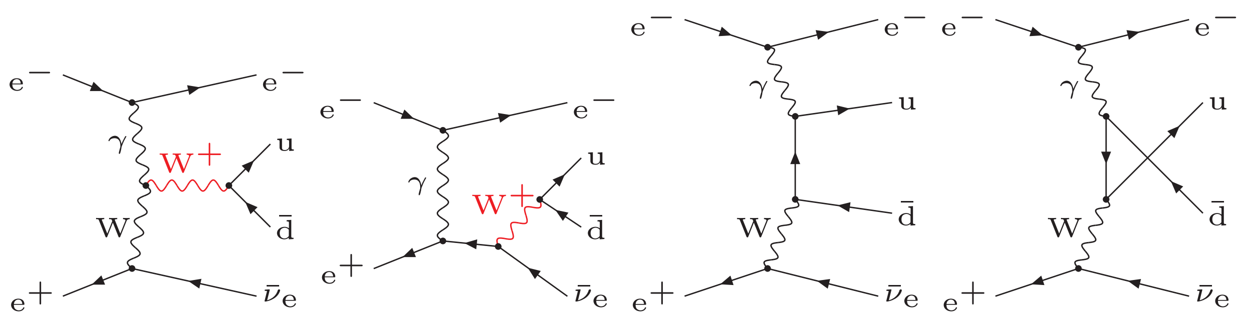
solid: gauge-invariant (fudge factor) scheme

dashed: constant width only in resonant propagator

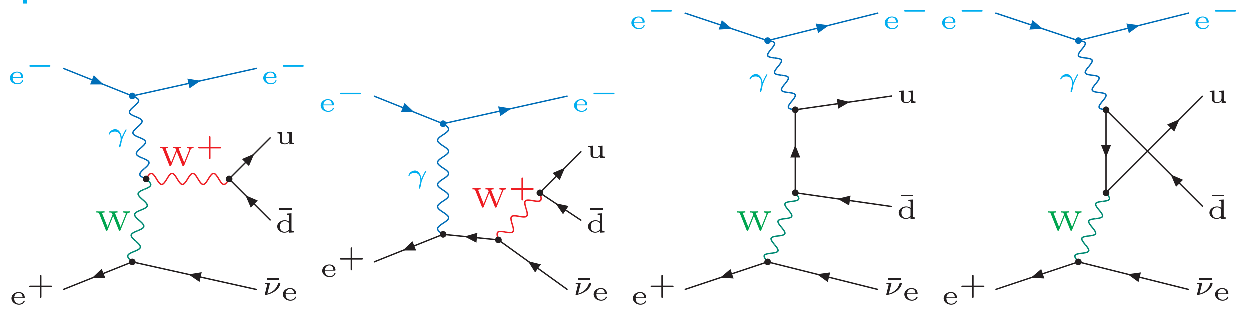
$\hookrightarrow$ crude U(1) gauge-invariance violation

Dominant diagrams:

nearly real photon !



Example continued:



Partial amplitude from above "photon diagrams":

$$\mathcal{M}_\gamma = Q_\mathrm{e} e\, \bar{u}_\mathrm{e}(k_\mathrm{e})\gamma^\mu u_\mathrm{e}(p_\mathrm{e})\, \frac{1}{k_\gamma^2}\, T_\mu^\gamma$$

Elmg. Ward identity:

$$0 \overset{!}{=} k_\gamma^\mu T_\mu^\gamma \propto (p_+^2 - p_-^2) Q_\mathrm{W} P_\mathrm{W}(p_+^2) P_\mathrm{W}(p_-^2) + Q_\mathrm{e} P_\mathrm{W}(p_+^2) - (Q_\mathrm{d} - Q_\mathrm{u}) P_\mathrm{W}(p_-^2)$$

With $Q_\mathrm{W} = Q_\mathrm{e} = Q_\mathrm{d} - Q_\mathrm{u}$ and $P_\mathrm{W}(p^2) = [p^2 - M_\mathrm{W}^2 + \mathrm{i} M_\mathrm{W} \Gamma_\mathrm{W}(p^2)]^{-1}$

one obtains: $\Gamma_\mathrm{W}(p_+^2) \overset{!}{=} \Gamma_\mathrm{W}(p_-^2)$

$\hookrightarrow$ Elmg. gauge invariance demands
common width on s- and t-channel propagators in "naive fixed width scheme"

Examples from e^+e^- physics: RacoonWW (Denner et al. '99-'01) and Lusifer (S.D.,Roth '02)

- σ[fb] for $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu$

$\sqrt{s}$	189 GeV	500 GeV	2 TeV	10 TeV
constant width	703.5(3)	237.4(1)	13.99(2)	0.624(3)
running width	703.4(3)	238.9(1)	34.39(3)	498.8(1)
complex mass	703.1(3)	237.3(1)	13.98(2)	0.624(3)

- σ[fb] for $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu + \gamma$ (separation cuts for "visible" γ: $E_\gamma, \theta_{\gamma f} >$ cut)

$\sqrt{s} =$	189 GeV	500 GeV	2 TeV	10 TeV
constant width	224.0(4)	83.4(3)	6.98(5)	0.457(6)
running width	224.6(4)	84.2(3)	19.2(1)	368(6)
complex mass	223.9(4)	83.3(3)	6.98(5)	0.460(6)

- σ[fb] for $e^+e^- \to \nu_e\bar{\nu}_e\mu^-\bar{\nu}_\mu u\bar{d}$ (phase-space cuts applied)

$\sqrt{s}$	500 GeV	800 GeV	2 TeV	10 TeV
constant width	1.633(1)	4.105(4)	11.74(2)	26.38(6)
running width	1.640(1)	4.132(4)	12.88(1)	12965(12)
complex mass	1.633(1)	4.104(3)	11.73(1)	26.39(6)

Gauge-invariant width schemes @ NLO

Problem much more complicated than at LO ! (would fill own lectures)

Complex-Mass Scheme (CMS) Denner, S.D., Roth, Wieders '05

- complex, but straightforward renormalization
- NLO everywhere in phase space
- loop integrals with complex masses

Pole Approximation (PA) (= leading term of pole expansion)

- corrections decomposed into two types
  - ◇ factorizable: corrections to on-shell production / decay
  - ◇ non-factorizable: soft photon/gluon exchange between production / decays
- NLO in neighbourhood of resonances
- PA involves less diagrams than CMS $\to$ higher multiplicities possible

Effective Field Theories Beneke et al. '03,'04; Hoang,Reisser '04

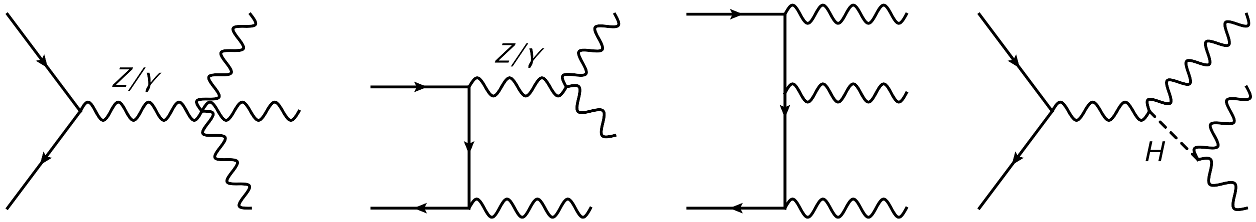
- involves pole expansions $\to$ NLO in neighbourhood of resonances
- formal elegance $\to$ e.g. combination with resummations

$\hookrightarrow$ **For details & examples see literature ...**

Outlook to electroweak tri-boson production

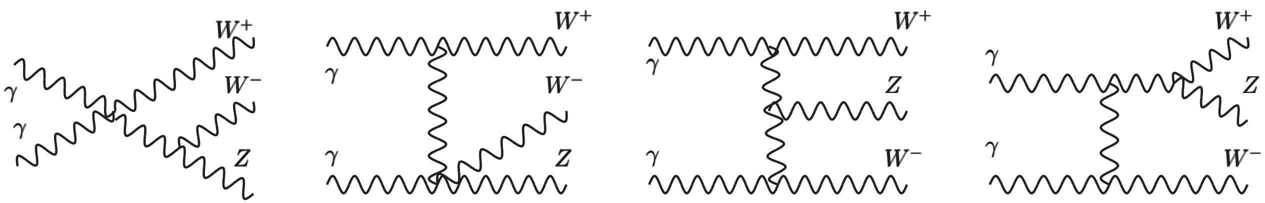
Electroweak tri-boson production – overview

Typical LO diagrams (example of WWZ production):



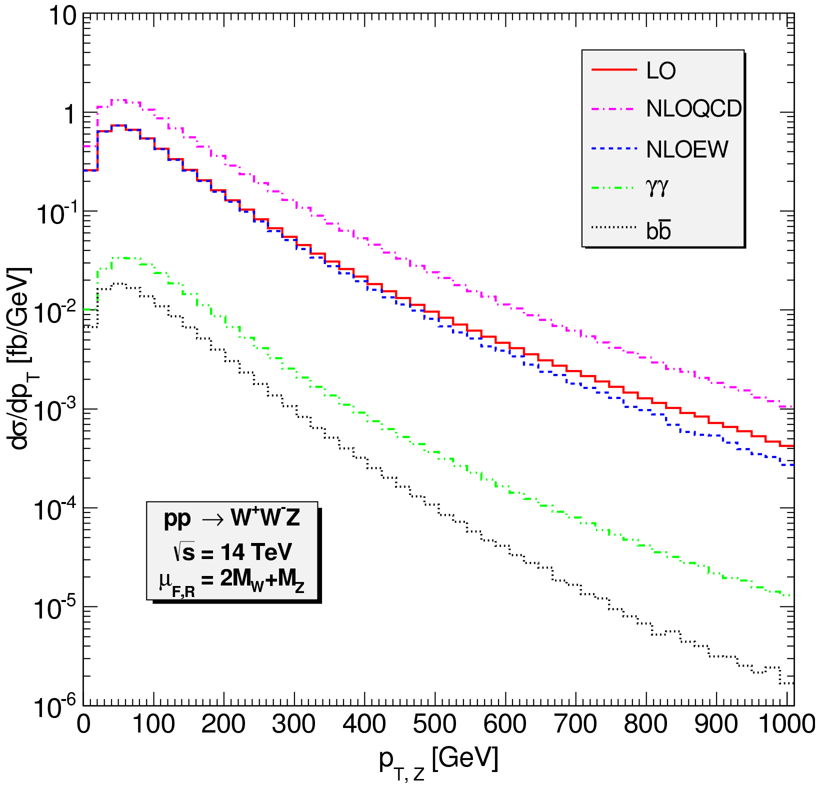
- similiarity/complementarity to vector-boson scattering (crossed kinematics)
  - sensitivity to quartic gauge couplings
  - sensitivity to electroweak symmetry breaking
- background to WH/ZH production with $\mathrm{H} \to VV^*$ (if accessible)

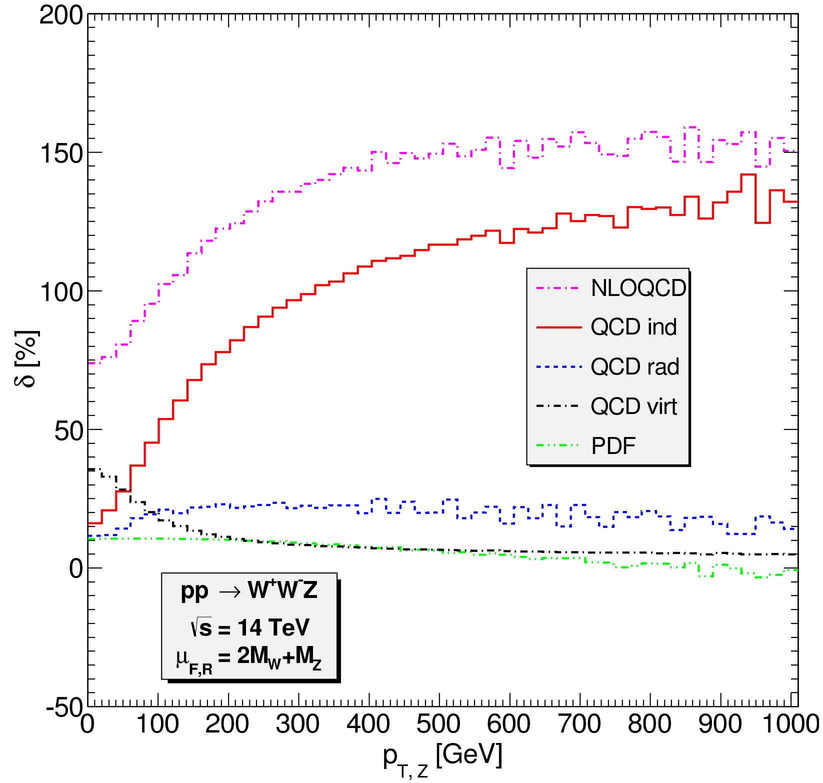
$\gamma\gamma$ channel for WWZ/γ production:



QCD corrections to WWZ production

Nhung, Le, Weber '13

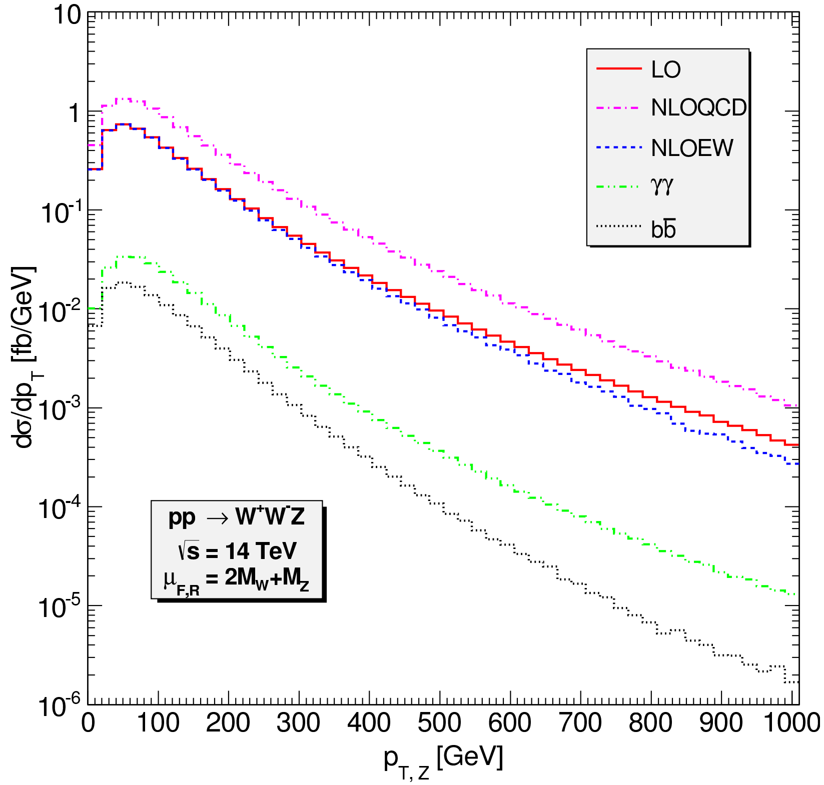


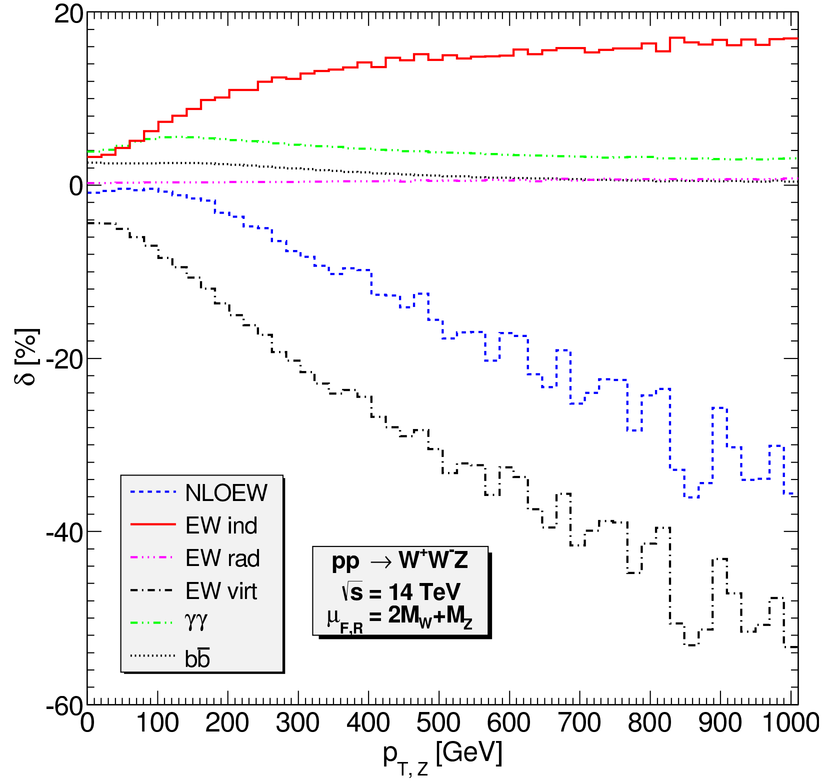


- inclusive cross section $\sim 200\,\mathrm{fb}$ @ $\sqrt{s} = 14\,\mathrm{TeV}$
- QCD corrections $\sim 100\%$
  - other final states WWW, WZZ, etc. known to NLO QCD as well
    Lazopoulos, et al. '07; Hankele/Zeppenfeld '07; Binoth et al. '08; Nhung et al. '13
  - analyze possible jet vetoes
  - $\mathrm{W/Z}$ decays partially included in NWA

EW corrections to WWZ production

Nhung, Le, Weber '13





- sizeable EW corrections in TeV range (as expected from di-boson case)
- EW corrections only known for on-shell (stable) WWZ production

  $\hookrightarrow$ homework for theorists to ...
  - ◇ consider the other cases WWW, WZZ, etc. as well
  - ◇ include W/Z decays
  - ◇ combine NLO QCD (known) and EW corrections