ELECTROWEAK PHYSICS AT THE LHC

Dieter Zeppenfeld
Karlsruhe Institute of Technology

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- EW precision tests
- Weak boson pair production
- QCD corrections to VVV production
- Conclusions
Summary of electroweak precision measurements (status winter 2012) as given on LEP-EWWG page:
http://lepewwg.web.cern.ch/LEPEWWG/

Important new measurements:
- Tevatron: $m_W = 80.385 \pm 0.015 \text{ GeV}$
- Tevatron: $m_t = 173.20 \pm 0.90 \text{ GeV}$
- LHC Higgs constraints:
  \[ 117.5 < m_H < 127.5 \text{ GeV} \]  
  (as used by GFitter group)
Compatibility of precision data and mass determinations

Indirect measurements of $m_W$ and $m_t$
(dotted line)

Direct measurements of $m_W$ and $m_t$
(solid line)
$m_t = 173.2 \pm 0.9$ GeV
$m_W = 80.385 \pm 0.015$ GeV

both shown as one-standard-deviation regions.
Taking into account the Higgs search results

Dörthe Kennedy, LoopFest 2012

68%, 95%, 99% CL fit contours excl. $M_W$ & $m_t$, $M_H \in [117.5, 127.5]$ GeV

68%, 95%, 99% CL fit contours excl. $M_W$ & $m_{top}$, $M_H < 1$ TeV
$m_H = 94^{+29}_{-24}$ GeV

Including theory uncertainty

$m_H < 152$ GeV (95% CL)

Does not include

Direct search limit from LEP

$m_H > 114$ GeV (95% CL)

Renormalize probability for

$m_H > 114$ GeV to 100%:

$m_H < 171$ GeV (95% CL)
A heavy Higgs boson is compatible with EW precision data provided new physics effects contribute to quantum corrections in loop integrals (Example: Littlest Higgs model)
Weak boson cross sections at the LHC

W
\[ \geq 1j \]
\[ \geq 2j \]
\[ \geq 3j \]
\[ \geq 4j \]

Z
\[ \geq 1j \]
\[ \geq 2j \]
\[ \geq 3j \]
\[ \geq 4j \]

Production Cross Section, \( \sigma_{\text{tot}} \)

[pb]

CMS 95\% CL limit
CMS measurement (stat@syst)
theory prediction

E_{T} > 30 \text{ GeV}
|\eta_{j}| < 2.4

E_{T} > 10 \text{ GeV}
\Delta R(\gamma,j) > 0.7

36 pb^{-1}
36 pb^{-1}
1.1 fb^{-1}
4.7 fb^{-1}

JHEP10(2011)132
CMS-PAS-EWK-10-012
PLB701(2011)535
CMS-PAS-EWK-11-010
CMS-PAS-HIG-11-025
EW boson pair production: $q\bar{q} \rightarrow W^+ W^-, W\gamma$ etc.

Parameterize $WWV$ couplings by effective Lagrangian

$$\mathcal{L}_{WWV} = \frac{g_{WWV}}{g_{WWV}} \left( i g^V_1 (W^\dagger_{\mu\nu} W^{\mu\nu} V - W^\dagger_{\mu} V_{\nu} W^{\mu\nu}) + i\kappa_{V} W^\dagger_{\mu} W_{\nu} V^{\mu\nu} + \frac{i\lambda_{V}}{m_{W}^2} W^\dagger_{\lambda\mu} W^{\mu\nu} V^{\nu\lambda} \right)$$

Deviations from SM values (anomalous triple gauge couplings, aTGC)

$$\Delta g^V_1 = g^V_1 - 1, \quad \Delta \kappa_{V} = g^V_1 - 1, \quad \lambda_{V}$$

must be form factors to preserve unitarity at high energy, $\sqrt{s}$

- Test non-abelian structure of SM
- Repeat studies of $e^+ e^- \rightarrow W^+ W^-$ and $q\bar{q} \rightarrow V_1 V_2$ of LEP and Tevatron
Effects of anomalous couplings

- Anomalous couplings lead to enhanced production of hard events with $J = 1$  
  $\Rightarrow$ mostly central events

- Anomalous couplings are produced by loop-effects of heavy particles with new interactions  
  $\Rightarrow$ form-factor effects

- $\sqrt{s}$-dependence of form factors unknown  
  $\Rightarrow$ shape of $\sqrt{s}$- or $p_T$-distributions is ambiguous

- loop effects typically produce small to modest deviations  
  $\Rightarrow$ form-factor effects expected to strongly reduce enhancements at high $p_T$
Central jet veto against radiation: Baur (1993)

- Anomalous couplings and QCD corrections lead to enhanced production of hard events
- Hard QCD jets recoil against photon: hard $\gamma j$ event with soft $W$ radiation
- Jet veto (no jet with $p_T(j) > 50$ GeV in event) restores LO expectations
Beneficial side effect: reduced scale variation of vetoed NLO cross section

⇒ apparent reduction of theoretical uncertainties

\[ E_T^{\gamma} > 100 \text{ GeV}, \, p_T^{\ell} > 15 \text{ GeV}, \, |\eta_{\ell, \gamma}| < 2.5, \, \Delta R_{\ell, \gamma} > 0.7, \, E_T^{\text{miss}} > 30 \text{ GeV}, \, M_T(\ell \gamma, \nu) > 90 \text{ GeV} \]

Problem: NLO scale variation of vetoed cross section does underestimate theory error from missing higher orders (just like LO variation of factorization scale)
Theory uncertainty from scale variation?

Borrow error estimate from Higgs + n-jet cross section:

\[ \sigma_{\text{excl.}}^{\text{NLO}} = \sigma_{\geq 0 \ jet}^{\text{NLO}} - \sigma_{1 \ jet}^{\text{LO}} \]

smallest theory error for individual inclusive n-jet cross sections which are uncorrelated
add their scale uncertainties in quadrature

\[ \Sigma \text{ incl. errors} \]
Theory uncertainty from scale variation?

Borrow error estimate from Higgs + n-jet cross section:

\[ \sigma_{\text{excl.}}^{NLO} = \sigma_{\geq 0 \text{ jet}}^{NLO} - \sigma_{1 \text{ jet}}^{LO} = \sigma_{0 \text{ jet}}^{LO} \left( 1 + \alpha_s(\mu_R) g(p_T^{\text{veto}}) \right) \]

smallest theory error for individual inclusive n-jet cross sections which are uncorrelated

add their scale uncertainties in quadrature

Reason for small scale dependence: \( g(p_T^{\text{veto}}) \) vanishes near \( p_T^{\text{veto}} = 50 \text{ GeV} \)
Jet veto induces potentially large logarithms: \( \log(p_{T,jet}^2/Q^2) \)
- Substantial increase of theory error due to jet veto
- Inclusive event selection has smaller theory uncertainty
- Use variables for aTGC analysis which are more inclusive

Problem: must avoid sensitivity degradation at high \( p_T \) due to dominating events configuration of hard \( \gamma j \) event with soft W radiation
Alternative variables

\( \min\{p^T_\gamma, p^T_W\} \) is better behaved under scale variations of inclusive distributions than \( p^T_\gamma \)
Analysis of anomalous TGC with form factors

- For production of on-shell weak bosons $V_1(q_1) \rightarrow V_2(q_2)V_3(q_3)$ the aTGC are form-factors

$$\Delta \kappa = \Delta \kappa(q_1^2) = \Delta \kappa(\hat{s}), \text{ etc.}$$

- Ideally, experiments should extract functions $\Delta \kappa(\hat{s})$, $\lambda(\hat{s})$ etc.

- Unitarity requires $\lambda(\hat{s}) < \text{const.}$ and similar for $\Delta \kappa$ and $\Delta g_1$

- In the past an ad hoc ansatz for these form factors has been used, such as

$$\lambda(\hat{s}) = \lambda_0 \frac{M^4}{\hat{s} + M^2}$$

which is not well motivated by specific models

- **Alternative proposal**: Derive bounds on constant low energy aTGC for a sequence of step function form factors, parameterized by cut-off scale $M_i$, such as

$$\lambda(\hat{s}) = \lambda_i \theta(M_i^2 - \hat{s})$$

where $M_i$ must be small enough to satisfy the unitarity constraints

- **Small $M_i$**: small deviations from large SM cross section at modest $p_T$ or $\hat{s}$

- **Large $M_i$**: strong enhancement over small SM cross section at large $p_T$ or $\hat{s}$
Electroweak corrections to $VV$ production become very important at high energy: corrections can be 50% or more

Reason for large (negative) corrections: Sudakov suppression for production of exactly two weak bosons: radiation of an additional $W$ or $Z$ becomes a soft correction

Structure of weak boson pair production has very interesting QCD and EW effects
VVV Production: Motivation and QCD corrections

- Standard Model background for SUSY processes with multi-lepton + $p_T$ signature

- Possibility to obtain information about quartic electroweak couplings.

QCD corrections to all VVV production processes have been calculated within the past 5 years

- ZZZ production: Lazopoulos, Melnikov, Petriello (2007)
- All VVV production processes for $V = W, Z, \gamma$: VBFNLO collaboration (2008-2011)
  includes Higgs contributions, anomalous triple and quartic gauge couplings and more

Code of VBFNLO release is available at
http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb
Example: Contributions to $WWZ$ production

- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)
- At LO only small $\mu_F$-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.
Cross section reflects behavior of $BR(H \rightarrow ZZ)$

K-factor is reduced by Higgs contribution.

K-factor for $pp \rightarrow ZH$ production is about $K = 1.3$

$\implies$ Different $K$-factor for resonance production
- K-factor increases with transverse momentum ($p_T$) by almost a factor of 2.
- Strong phase space dependence due to events with high $p_T$ jets recoiling against the leptons.
- Veto on jets with $p_T > 50$ GeV leads to fairly flat K-factor, but also to same problems as discussed for $VV$ production.
Conclusions

- LHC will revolutionize our knowledge of electroweak interactions: we are already probing the origins of electroweak symmetry breaking
- Vector boson pair and $VVV$ production are intriguing processes to be studied at LHC
- Rich interplay of QCD and EW loop effects for $VV$ and $VVV$ production which wait to be studied