ELECTROWEAK PHYSICS AT THE LHC

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für Bildung
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- EW precision tests
- Weak boson pair production
- QCD corrections to VVV production
- Conclusions

EW precision data

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

Summary of electroweak precision measurements (status winter 2012) as given on LEP-EWWG page:
http://lepewwg.web.cern.ch/LEPEWWG/

Important new measurements:

- Tevatron: $m_W = 80.385 \pm 0.015$ GeV
- Tevatron: $m_t = 173.20 \pm 0.90$ GeV
- LHC Higgs constraints:
  $117.5 < m_H < 127.5$ GeV
  (as used by GFitter group)

Compatibility of precision data and mass determinations

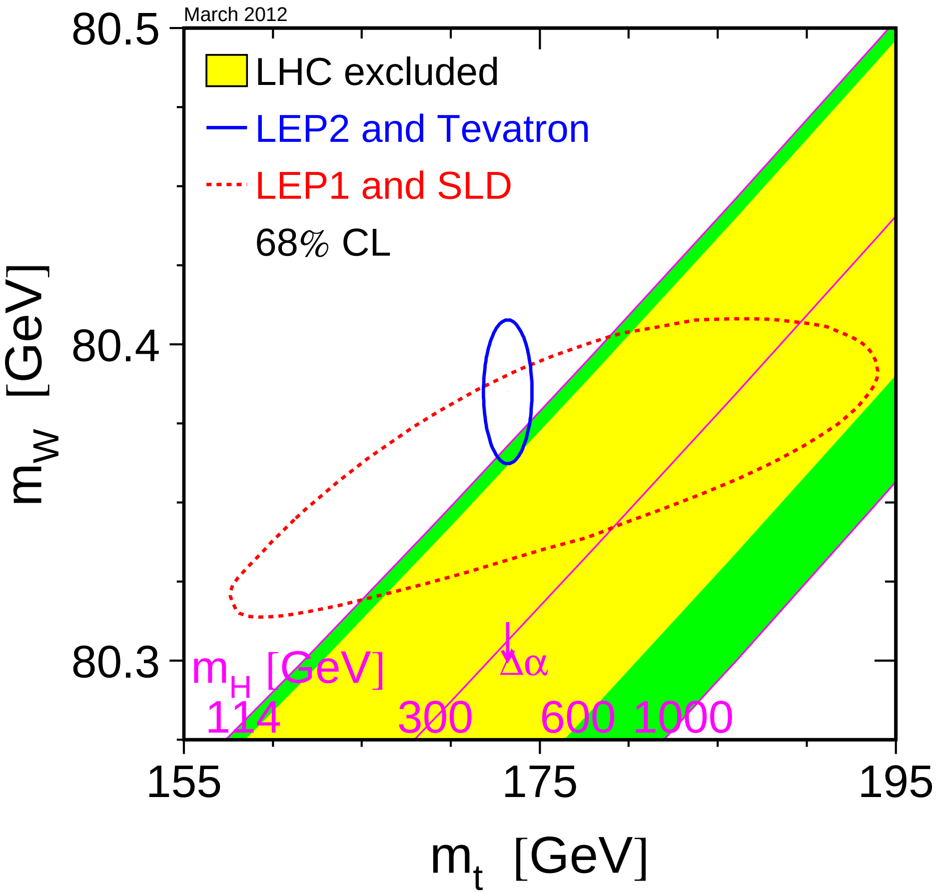
Indirect measurements of m_W and m_t (dotted line)

Direct measurements of m_W and m_t (solid line)

$m_t = 173.2 \pm 0.9$ GeV

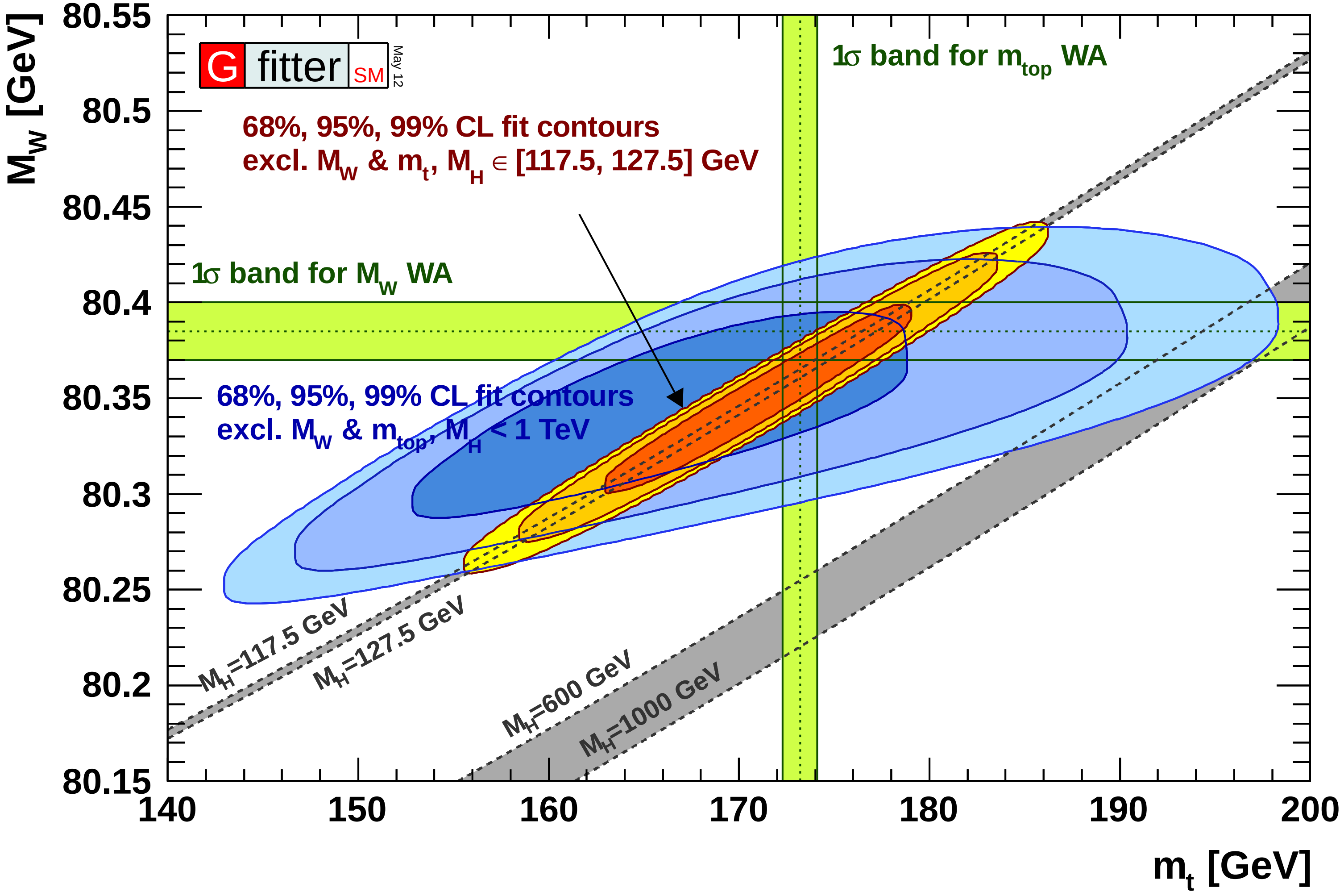
$m_W = 80.385 \pm 0.015$ GeV

both shown as one-standard-deviation regions.



Taking into account the Higgs search results

Dörthe Kennedy, LoopFest 2012



SM Higgs mass fit to EW precision data

Dörthe Kennedy, LoopFest 2012

$$m_H = 94^{+29}_{-24}\ \text{GeV}$$

Including theory uncertainty

$$m_H < 152\ \text{GeV} \quad (95\%\ \text{CL})$$

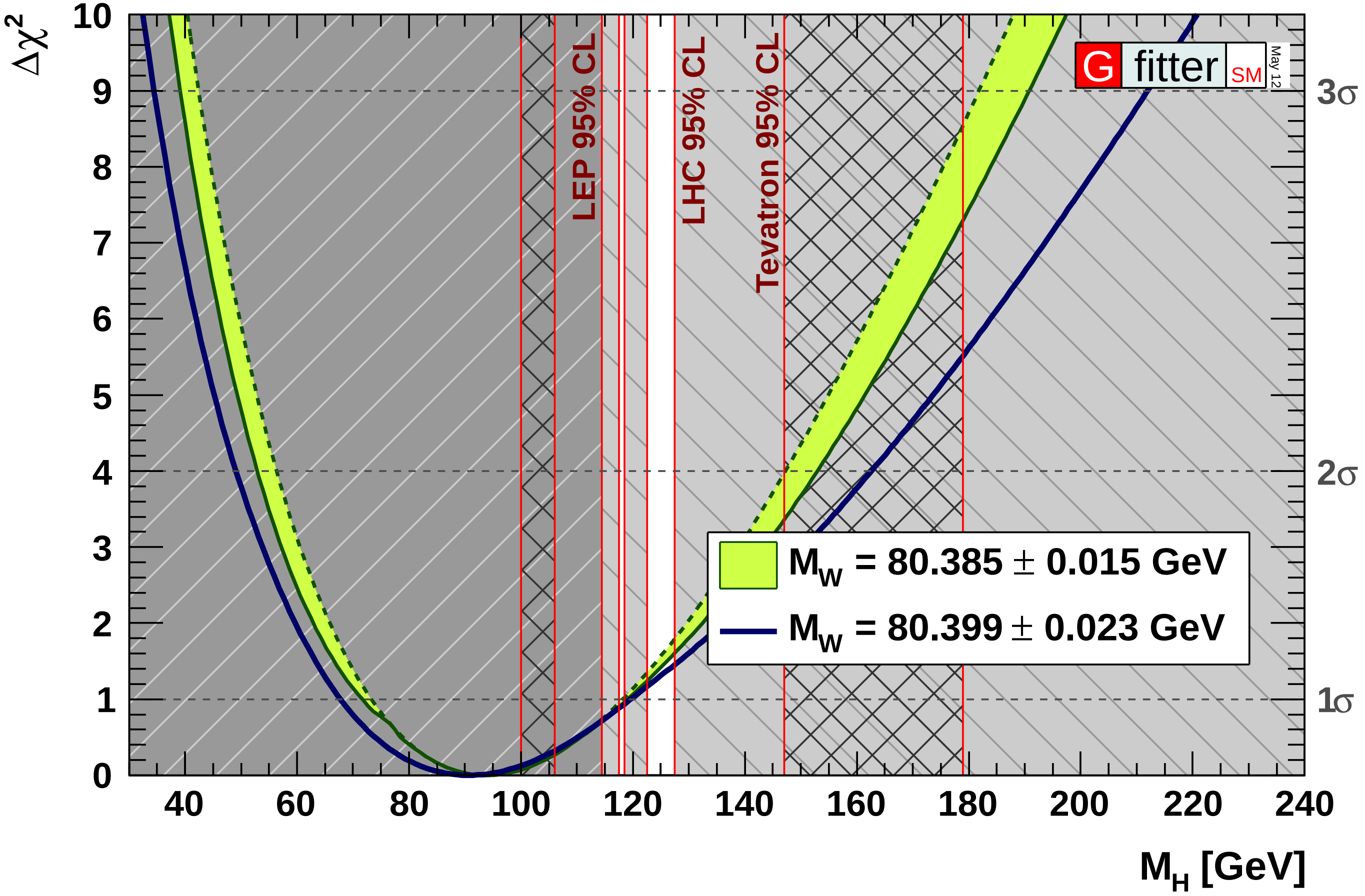
Does not include

Direct search limit from LEP

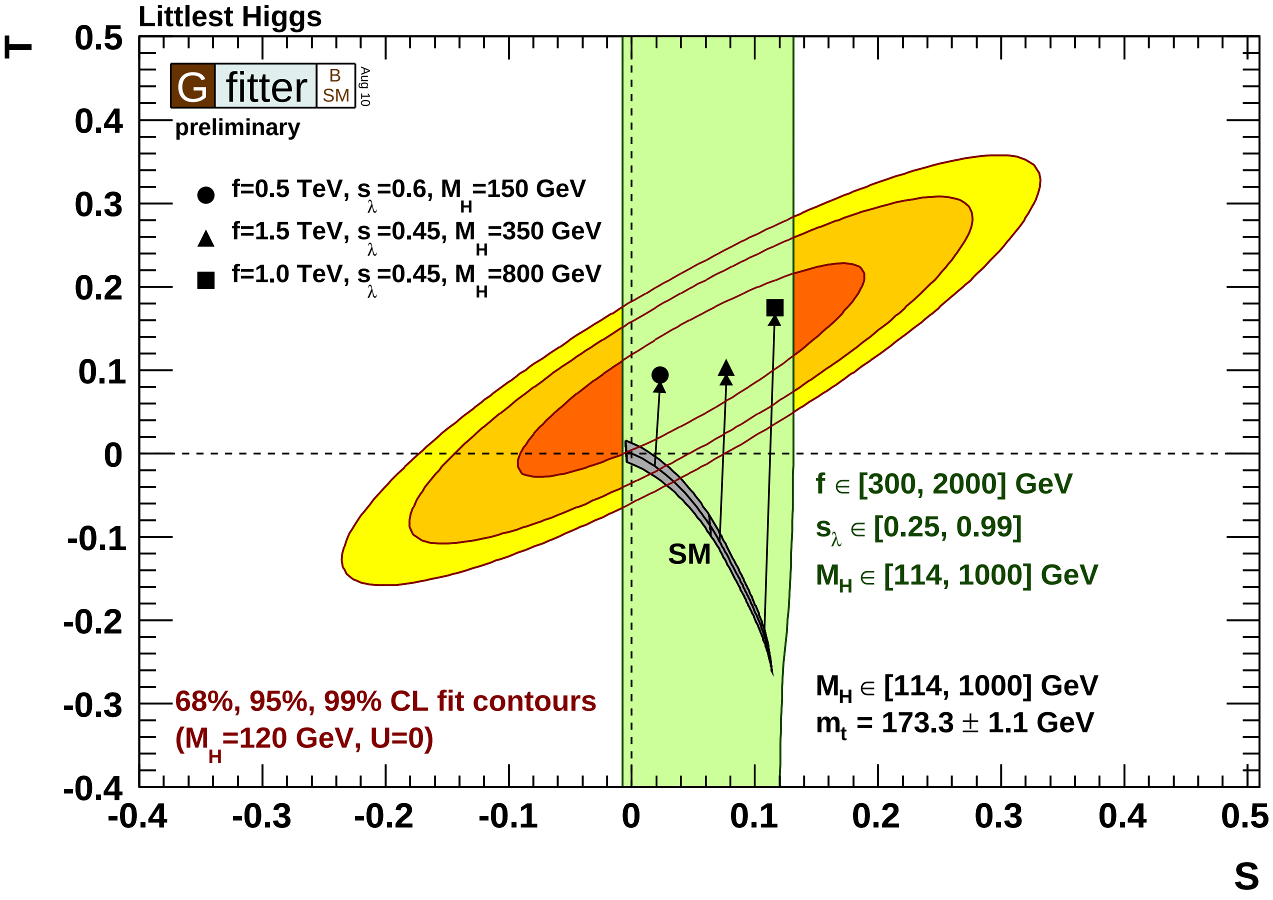
$$m_H > 114\ \text{GeV} \quad (95\%\ \text{CL})$$

Renormalize probability for $m_H > 114$ GeV to 100%:

$$m_H < 171\ \text{GeV} \quad (95\%\ \text{CL})$$

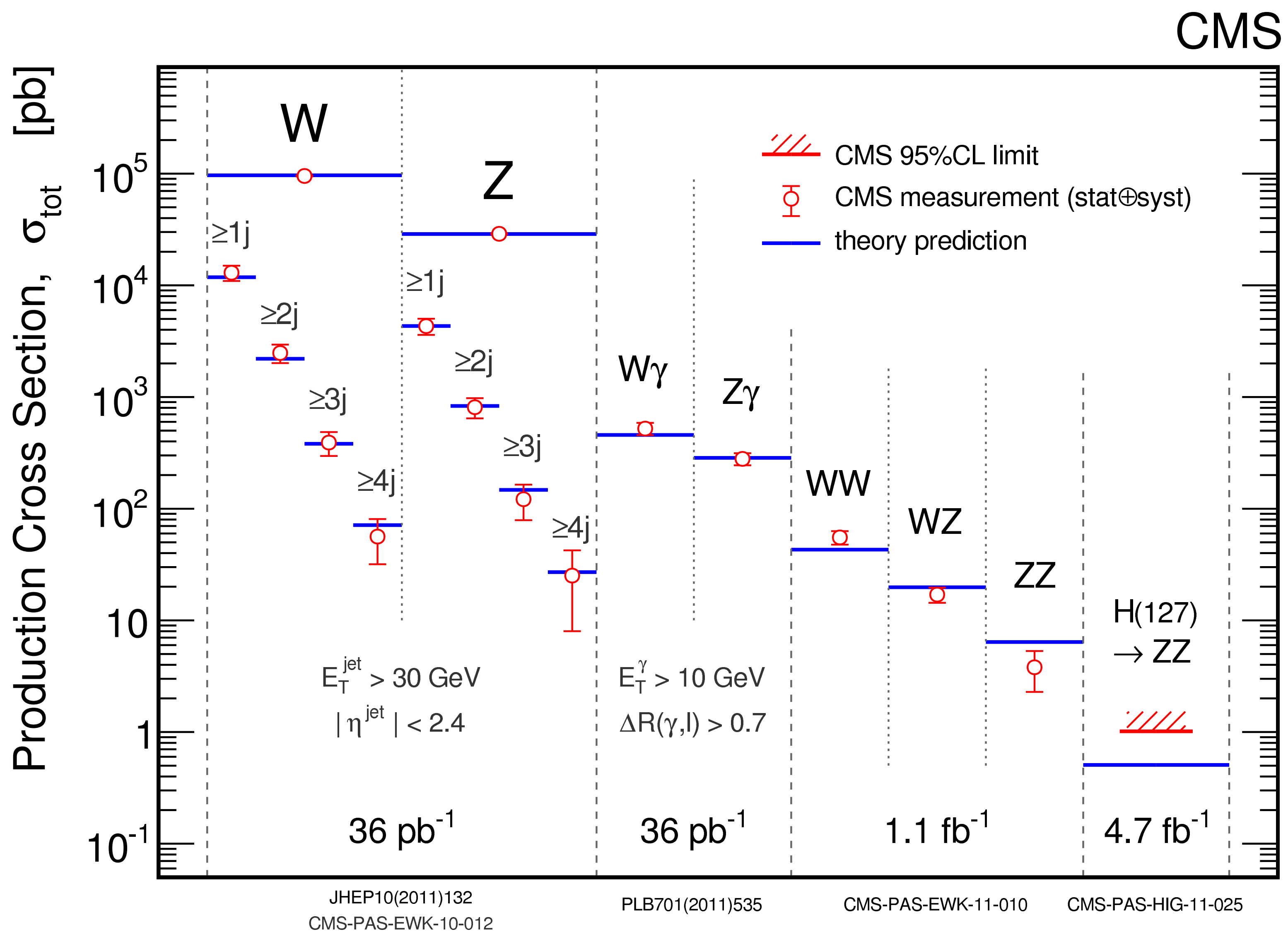


Electroweak precision data and heavy Higgs

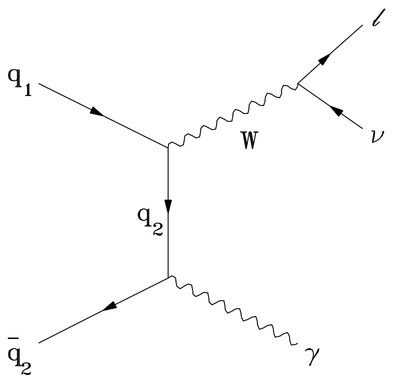


A heavy Higgs boson is compatible with EW precision data provided new physics effects contribute to quantum corrections in loop integrals (Example: Littlest Higgs model)

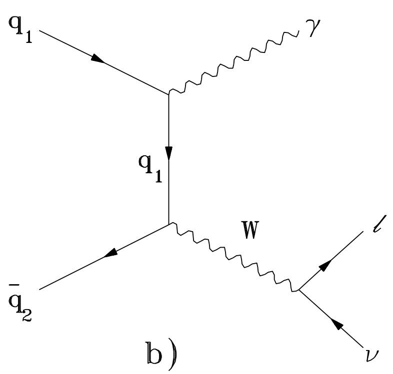
Weak boson cross sections at the LHC



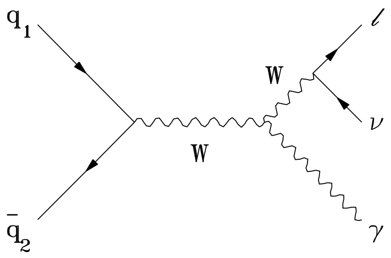
EW boson pair production: $q\bar{q} \longrightarrow W^+W^-$, $W\gamma$ etc.



a)



b)



c)

- Test non-abelian structure of SM
- Repeat studies of $e^+e^- \longrightarrow W^+W^-$ and $q\bar{q} \longrightarrow V_1V_2$ of LEP and Tevatron

Parameterize WWV couplings by effective Lagrangian

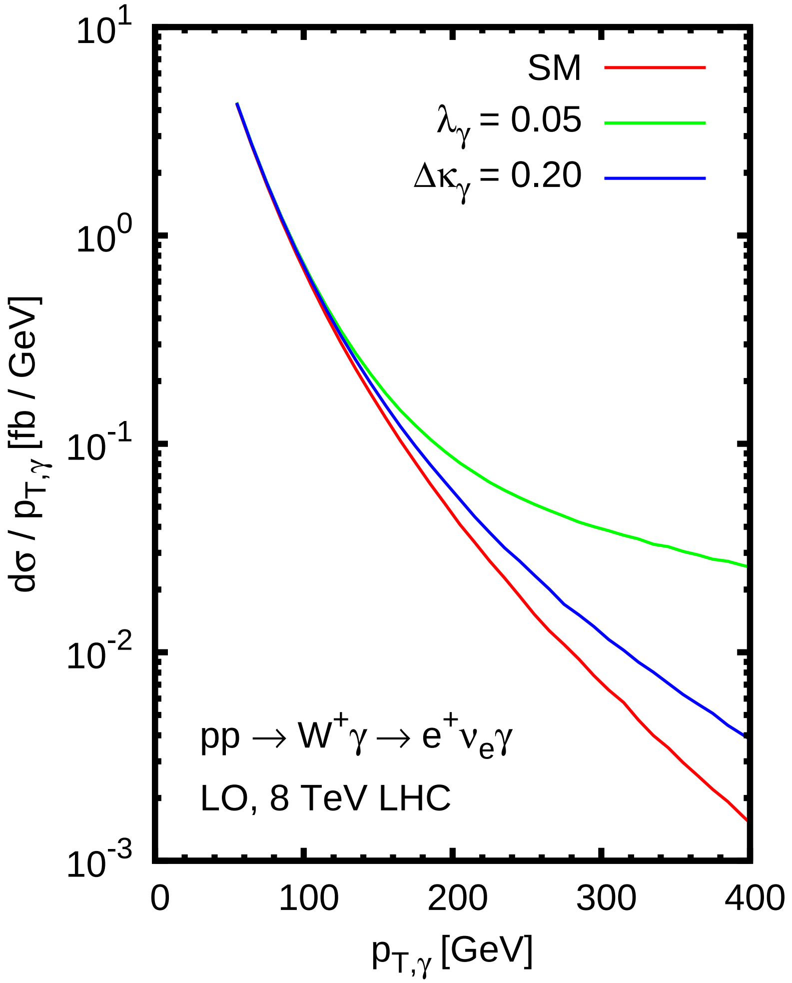
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

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

$$\Delta g_1^V = g_1^V - 1\,, \quad \Delta\kappa_V = g_1^V - 1\,, \quad \lambda_V$$

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

Effects of anomalous couplings



- Anomalous couplings lead to enhanced production of hard events with $J = 1$
  $\Longrightarrow$ mostly central events
- Anomalous couplings are produced by loop-effects of heavy particles with new interactions
  $\Longrightarrow$ form-factor effects
- $\sqrt{\hat{s}}$-dependence of form factors unknown
  $\Longrightarrow$ shape of $\sqrt{\hat{s}}$- or p_T-distributions is ambiguous
- loop effects typically produce small to modest deviations
  $\Longrightarrow$ form-factor effects expected to strongly reduce enhancements at high p_T

Effects of NLO QCD corrections

Baur, Han, Ohnemus (1993)

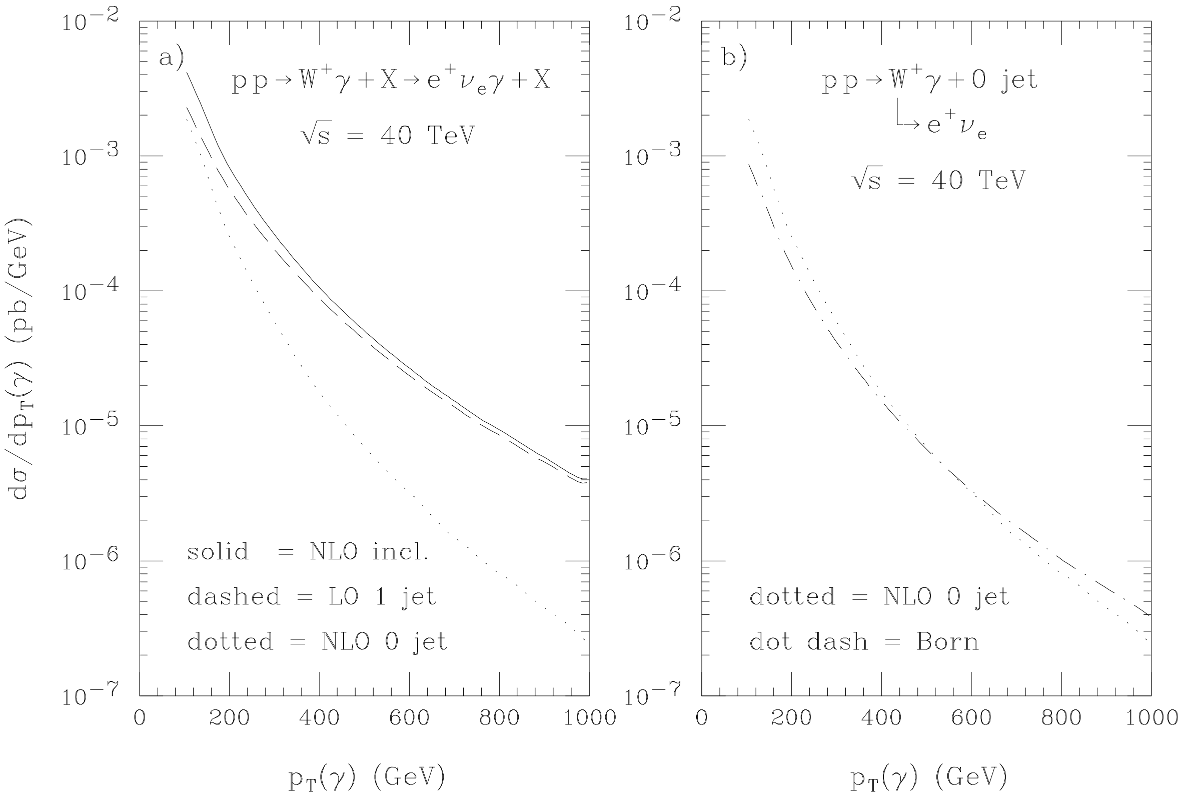


Figure 14

Central jet veto against radiation:
Baur (1993)

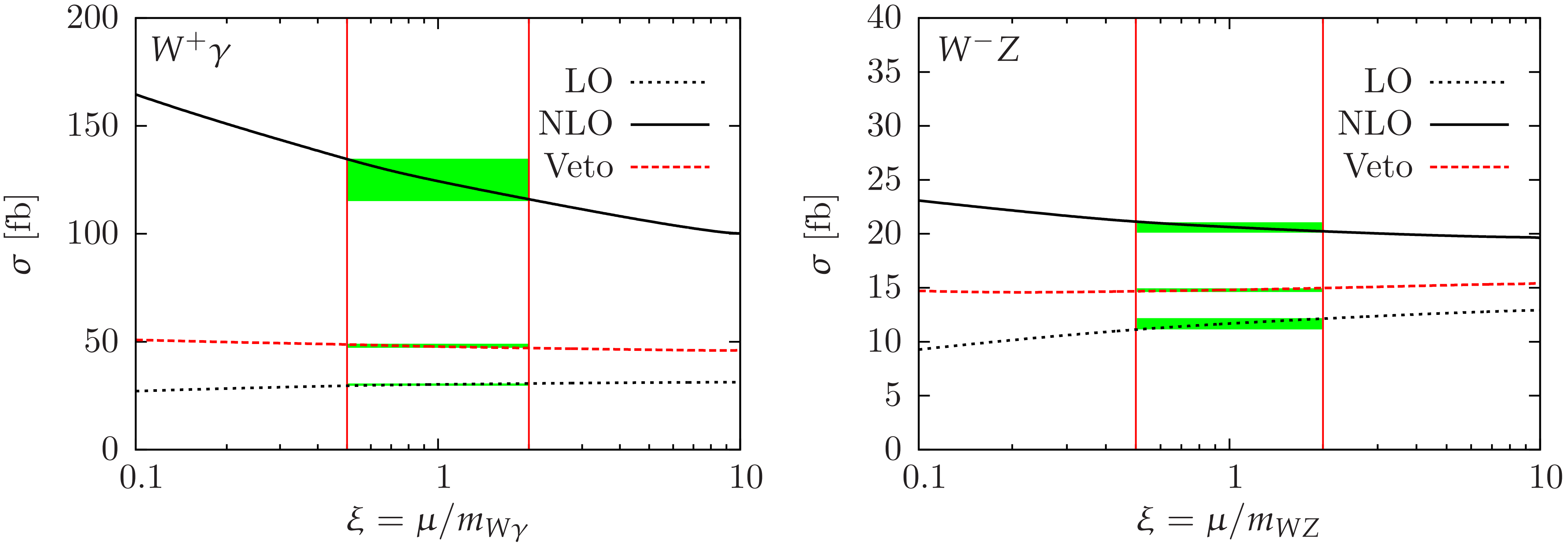
- Anomalous couplings and QCD corrections lead to enhanced production of hard events
- Hard QCD jets recoil against photon: hard γj event with soft W radiation
- Jet veto (no jet with $p_T(j) > 50$ GeV in event) restores LO expectations

Theory uncertainty from scale variation

Beneficial side effect: reduced scale variation of vetoed NLO cross section

$\Longrightarrow$ apparent reduction of theoretical uncertainties

LHC14: $E^T_\gamma > 100$ GeV, $p^T_\ell > 15$ GeV, $|\eta_{\ell,\gamma}| < 2.5$, $\Delta R_{\ell\gamma} > 0.7$, $E^T_{miss} > 30$ GeV, $M^T(\ell\gamma,\nu) > 90$ GeV



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

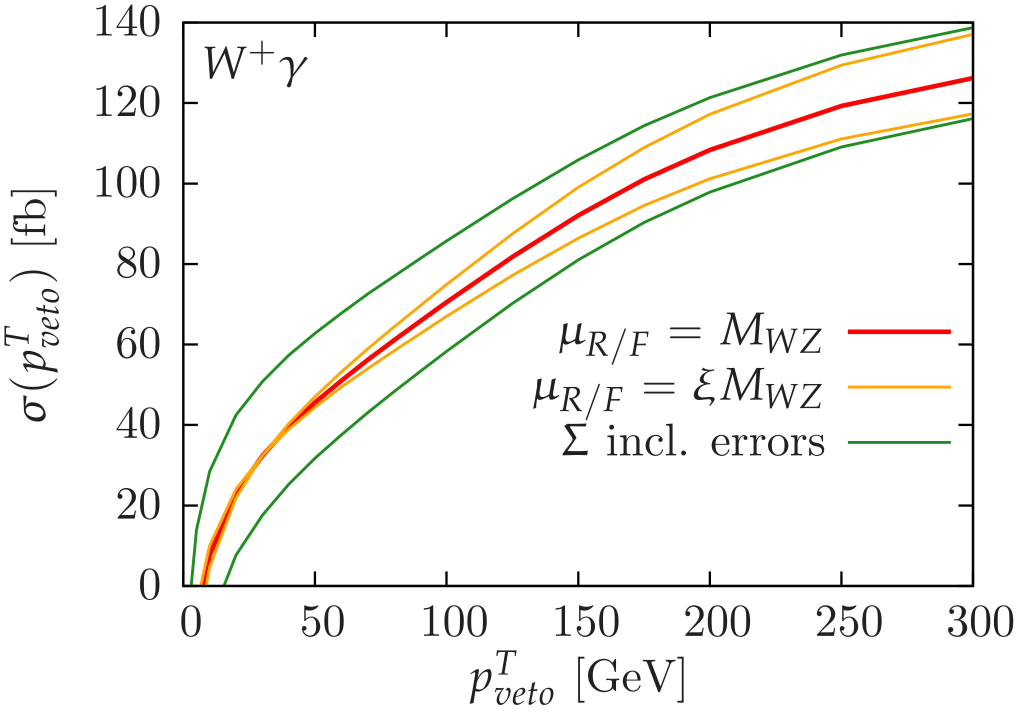
Theory uncertainty from scale variation?

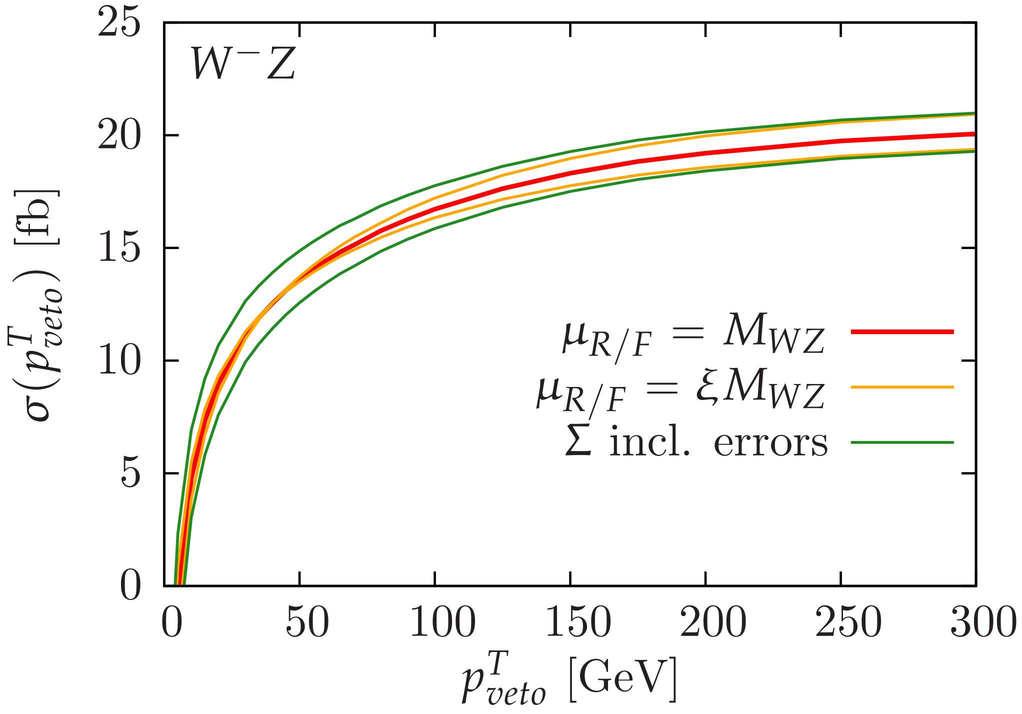
Borrow error estimate from Higgs + n-jet cross section:

$$\sigma^{NLO}_{excl.} = \sigma^{NLO}_{\geq 0\; jet} - \sigma^{LO}_{1\; jet}$$

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

add their scale uncertainties in quadrature





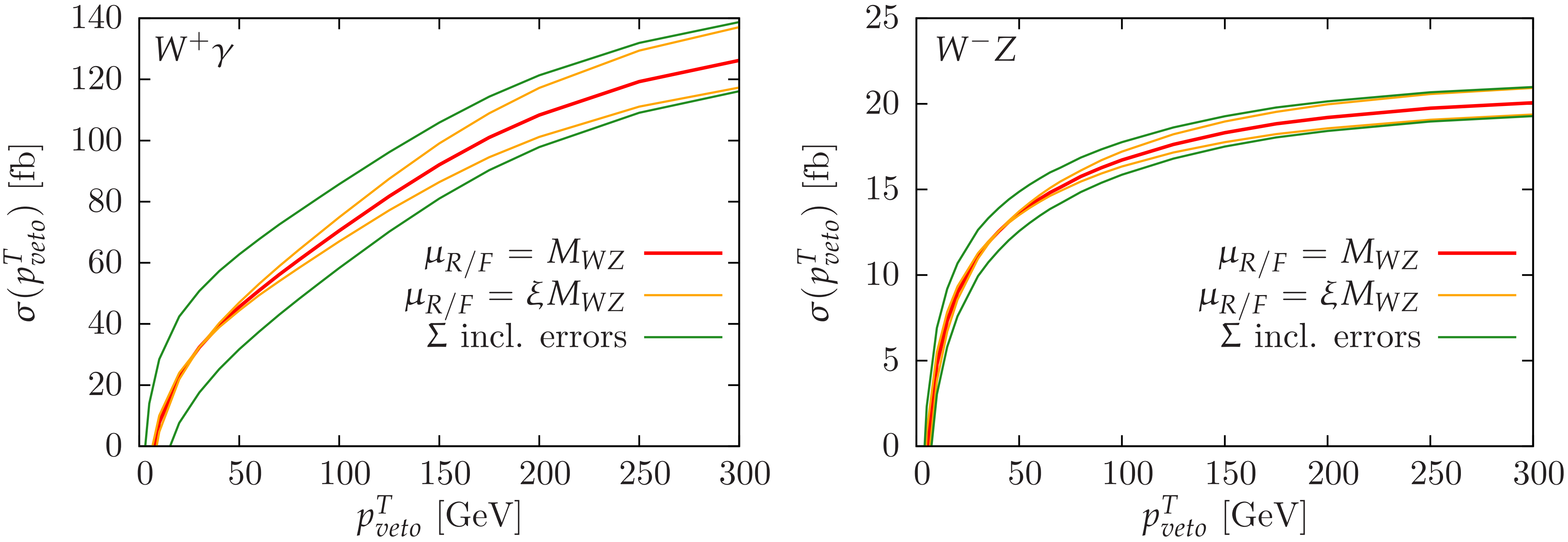
Theory uncertainty from scale variation?

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

$$\sigma^{NLO}_{excl.} \quad = \quad \sigma^{NLO}_{\geq 0\ jet} - \sigma^{LO}_{1\ jet} \quad = \quad \sigma^{LO}_{0\ jet}\left(1 + \alpha_s(\mu_R)\, g(p^T_{veto})\right)$$

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

add their scale uncertainties in quadrature



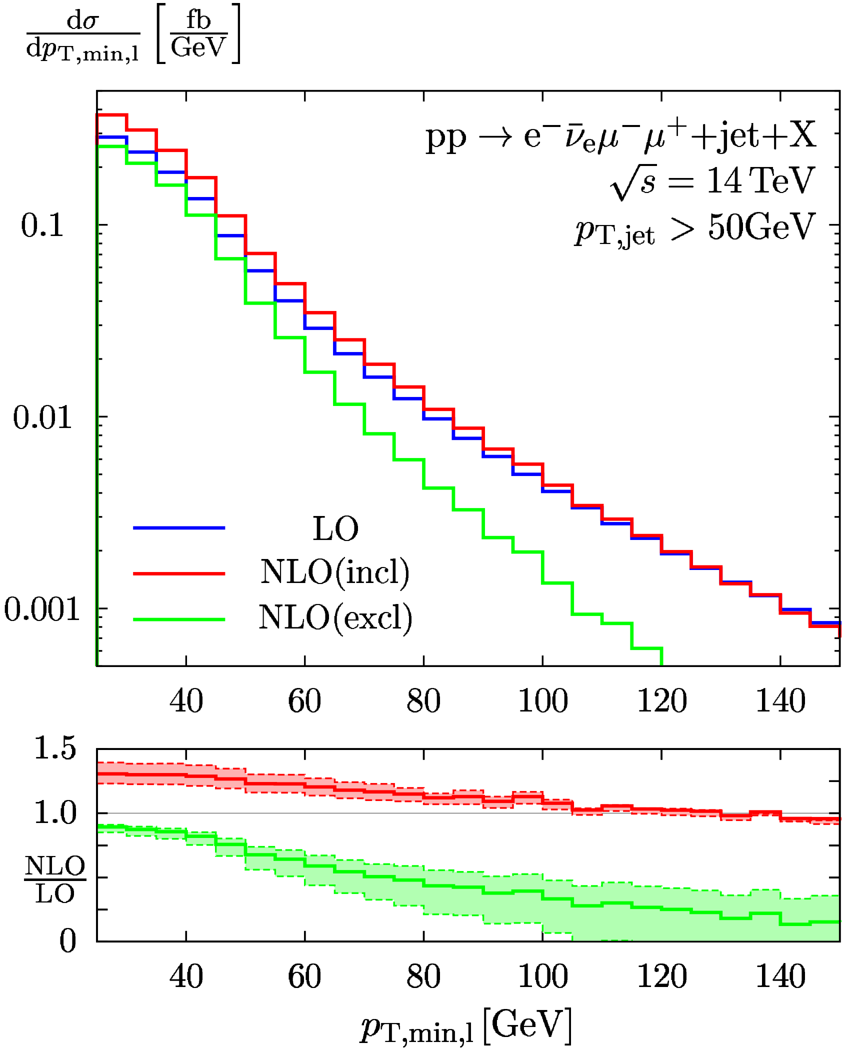
Reason for small scale dependence: $g(p^T_{veto})$ vanishes near $p^T_{veto} = 50$ GeV

Scale variation of p_T-distributions

Jet veto induces potentially large logarithms: $\log(p_{T,jet}^2/Q^2)$

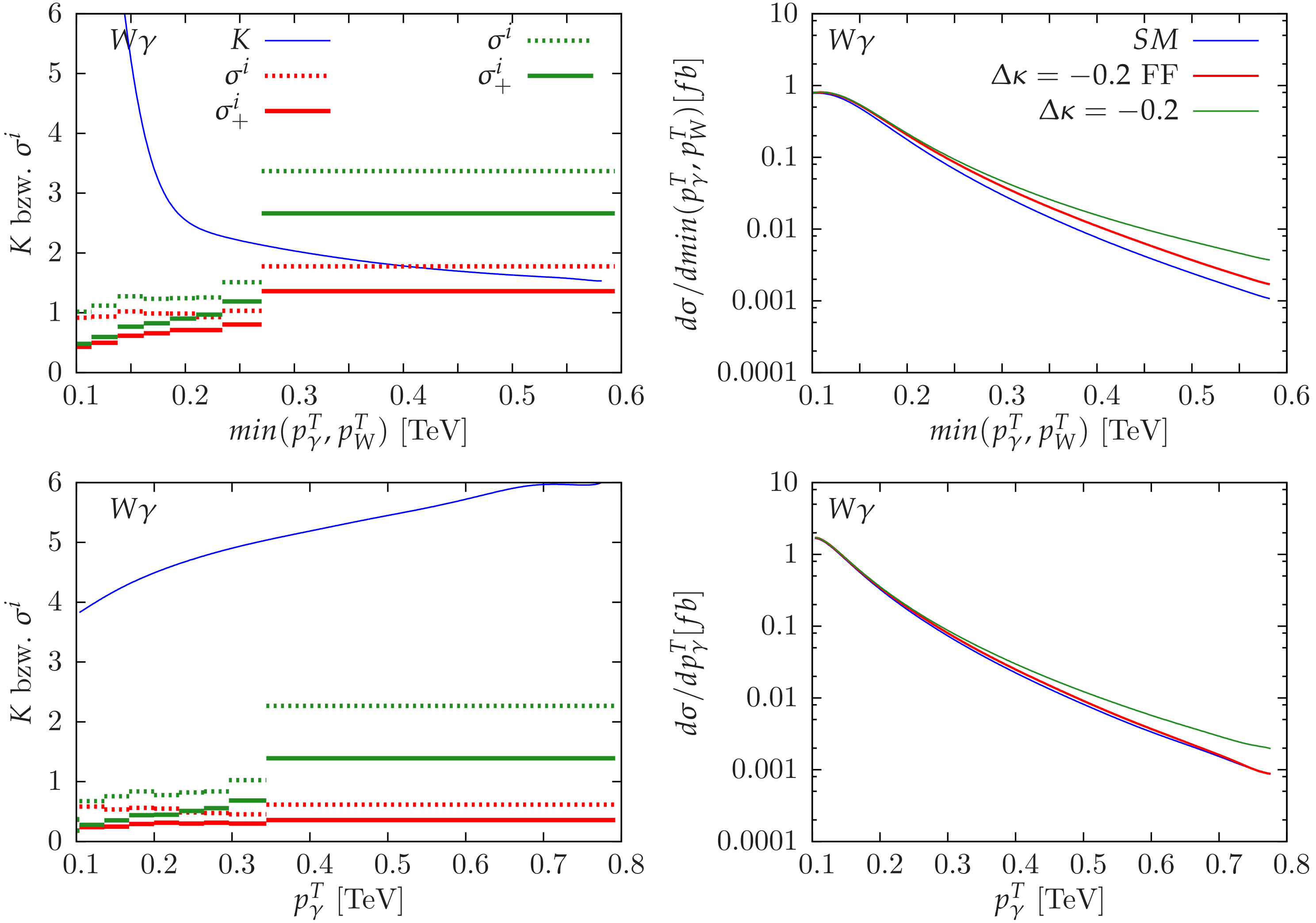
- Substantial increase of theory error due to jet veto
- Inclusive event selection has smaller theory uncertainty
- Use variables for aTGC analysis which are more inclusive

Problem: must avoid sensitivity degradation at high p_T due to dominating events configuration of hard γj event with soft W radiation



Alternative variables

$min\{p_\gamma^T,\ p_W^T\}$ is better behaved under scale variations of inclusive distributions than p_γ^T



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

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

- Ideally, experiments should extract functions $\Delta\kappa(\hat{s})$, $\lambda(\hat{s})$ etc.
- Unitarity requires $\lambda(\hat{s})\hat{s} < const.$ and similar for $\Delta\kappa$ and Δg_1
- In the past an ad hoc ansatz for these form factors has been used, such as

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

  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

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

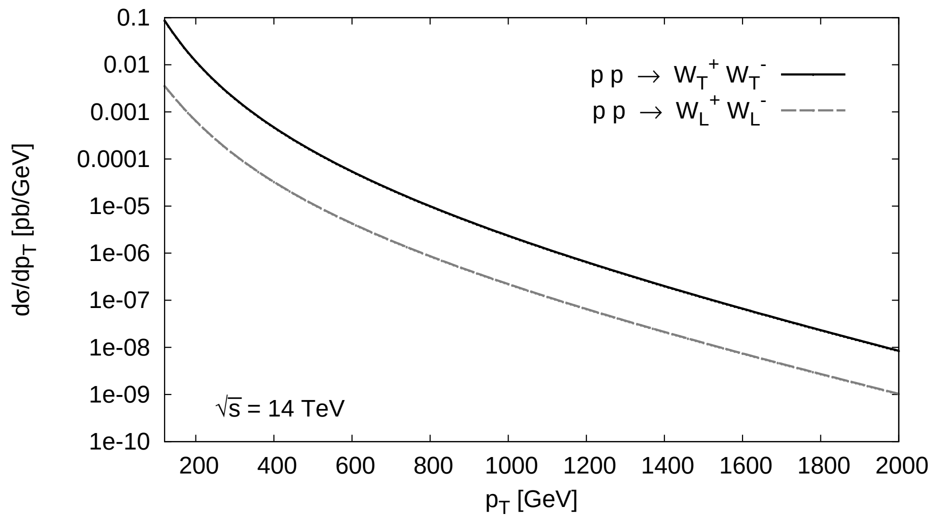
  where M_i must be small enough to satisfy the unitarity constraints

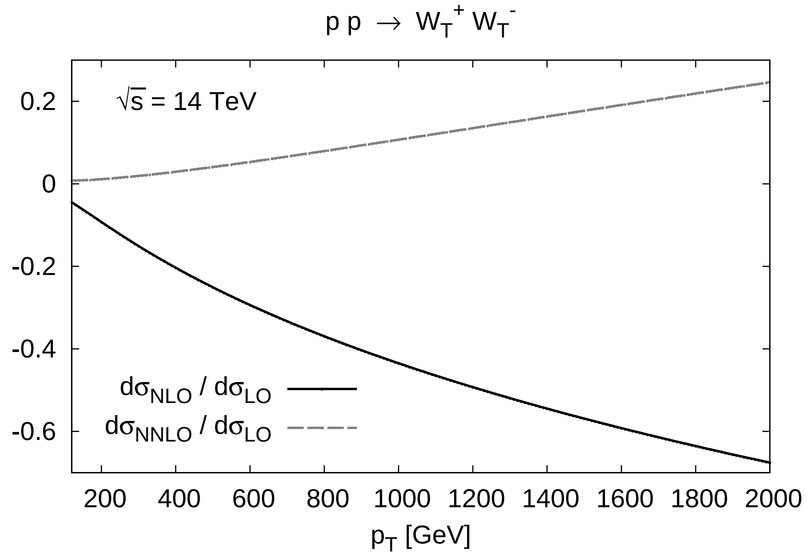
- Small M_i: small deviations from large SM cross section at modest p_T or $\hat{s}$
  Large M_i: strong enhancement over small SM cross section at large p_T or $\hat{s}$

Electroweak Corrections and Sudakov Suppression

Electroweak corrections to VV production become very import at high energy: corrections can be 50% or more

Kühn, Metzler, Penin, Uccirati arXiv:1101.2563



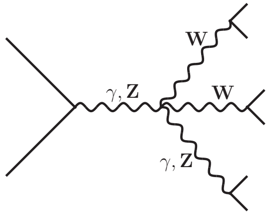


Reason for large (negative) corrections: Sudakov suppression for production of exactly two weak bosons: radiation of an additional W or Z becomes a soft correction

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 + $\not p_T$ signature
- Possibility to obtain information about quartic electroweak couplings.

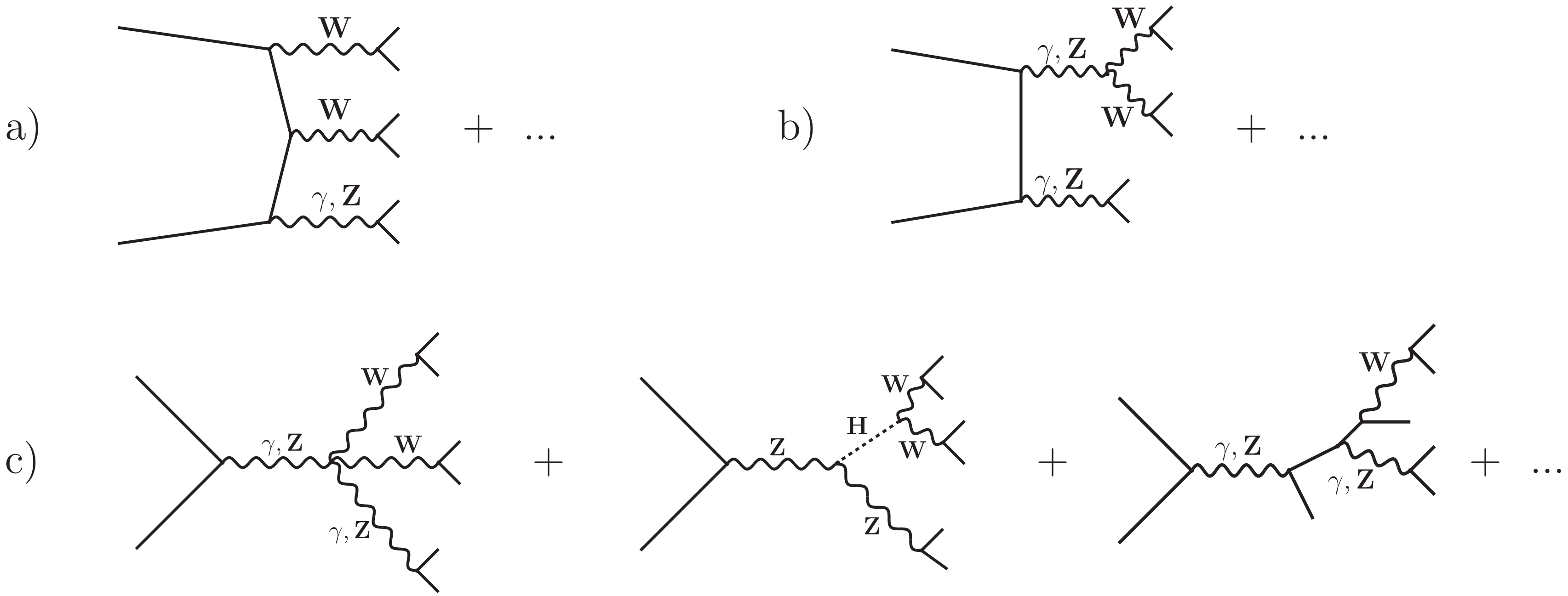


QCD corrections to all VVV production processes have been calculated within the past 5 years

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

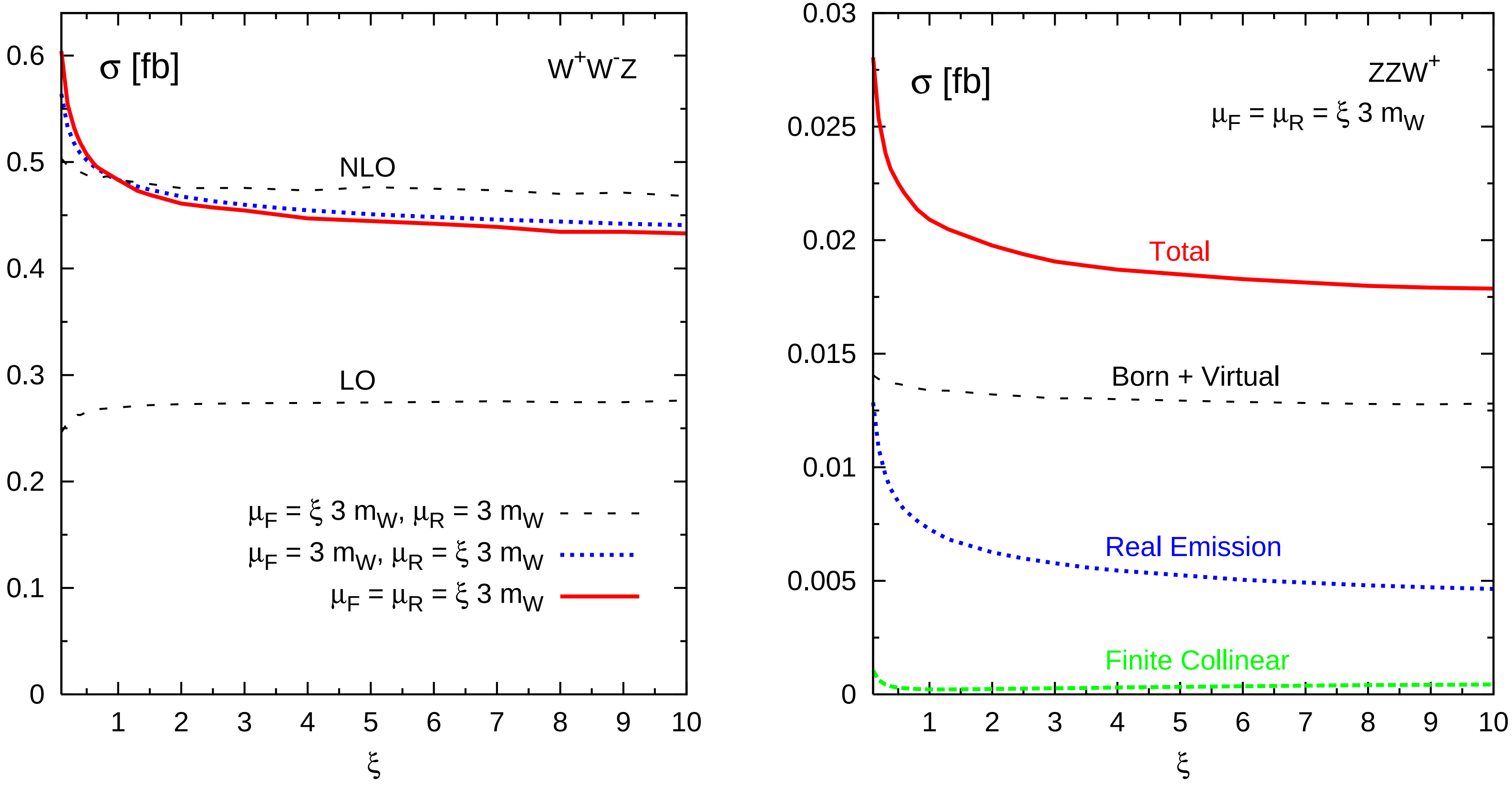
Code of VBFNLO release is available at
http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb

Example: Contributions to WWZ production



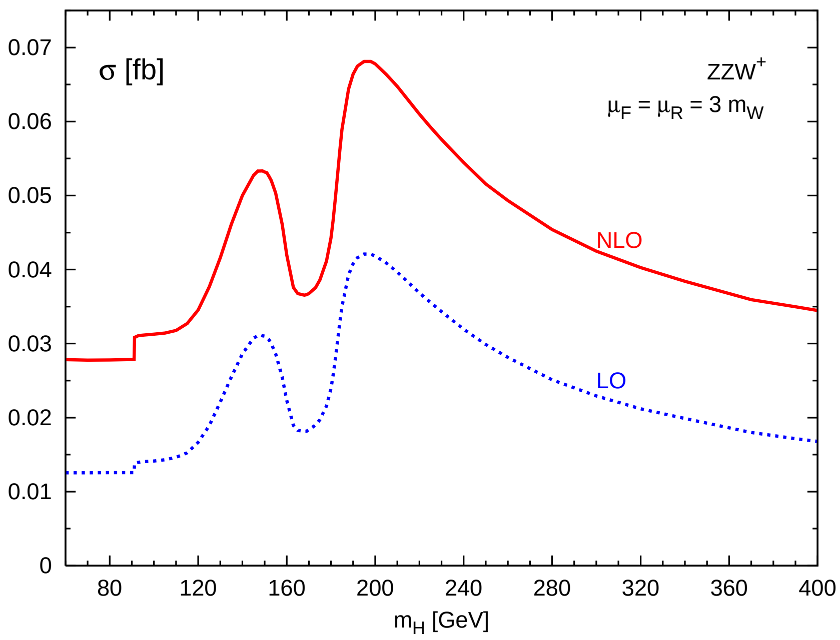
- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)

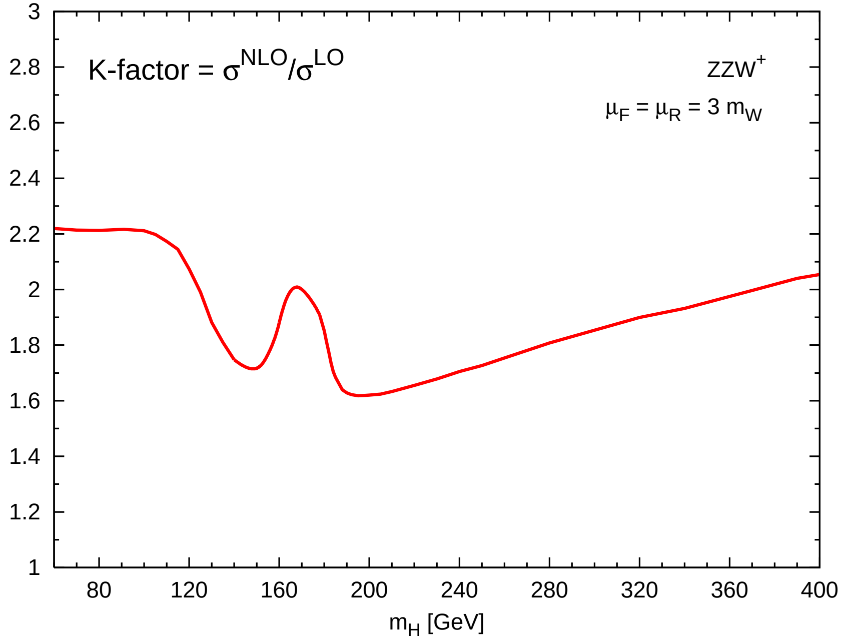
Scale Dependence

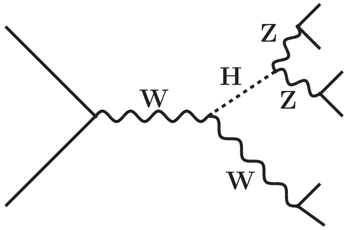


- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Higgs mass dependence

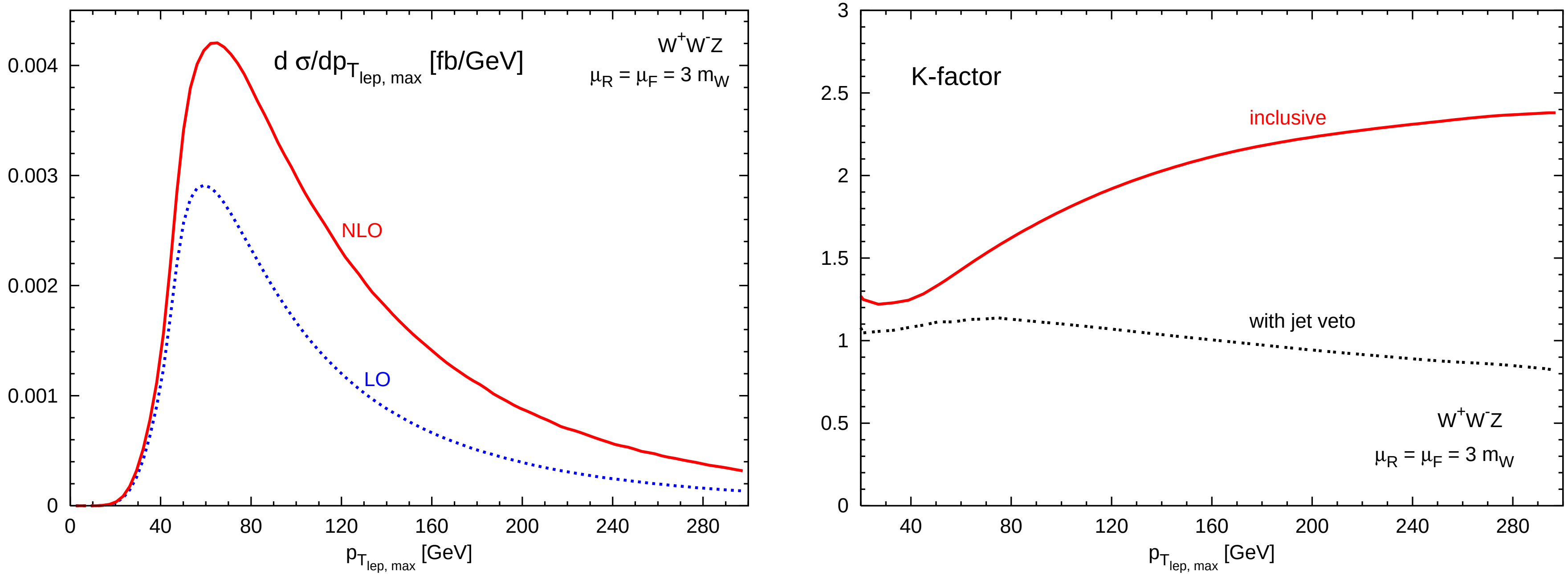






- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to ZH$ production is about K = 1.3
  $\Longrightarrow$ Different K-factor for resonance production

Differential cross section and K-factor for the highest-p_T-lepton



- 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