

# Electroweak radiative corrections for the LHC

## Lecture II

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## Lecture I

### Relevance and calculational techniques

- Relevance of electroweak (EW) corrections at LHC
- Calculational techniques for virtual corrections
- Calculational techniques for real corrections

## Lecture II

### Unstable particles and results for specific LHC processes

- Unstable particles
- Higgs production in vector-boson fusion
- Single gauge-boson production
- Gauge-boson pair production
- Higgs production in gluon fusion

# Unstable particles

# Relevance of unstable particles

Almost all interesting elementary particles are unstable:

- known: leptons  $\mu, \tau$ , heavy quarks  $b, t$ , massive gauge bosons  $W, Z$
- Higgs bosons  $H_{\text{SM}}$ ,  $\{h, H, A, \tilde{H}\}_{\text{MSSM}}$
- new particles, e.g. in SUSY:  $\tilde{l}, \tilde{q}, \tilde{g}, \tilde{\chi}$

lifetimes  $\tau$  too short for detection (e.g.  $\tau_{Z,W} \sim 10^{-25} \text{ s} \rightarrow \Delta l = c\Delta t \sim 10^{-16} \text{ m}$ )

→ experiments detect only decay products  
unstable particles appear as resonances in certain distributions

interesting reactions at the LHC involving unstable particles:

$pp \rightarrow W/Z(+\text{jets}) \rightarrow 2l(+\text{jets}), \quad pp \rightarrow H + 2q \rightarrow ZZ + 2q \rightarrow 4l + 2\text{jets},$   
 $pp \rightarrow t\bar{t} \rightarrow b\bar{b}WW \rightarrow 2l + 2\text{jets} + E_T, \dots$

Need consistent treatment of unstable particles  
in perturbative evaluation of gauge theories  
with spontaneous symmetry breaking

# Mass and width of unstable particles

Dyson series and propagator poles

propagator near resonance: (scalar example)

$$\bullet - \circlearrowleft - \bullet = \bullet - \overbrace{\phantom{----}}^{\text{---}} - \bullet + \bullet - \overbrace{\bullet - \bullet}^{\text{---}} - \bullet + \bullet - \overbrace{\bullet - \bullet - \bullet}^{\text{---}} - \bullet + \dots$$

$$G^{\phi\phi}(p) = \frac{i}{p^2 - m^2} + \frac{i}{p^2 - m^2} i\Sigma(p^2) \frac{i}{p^2 - m^2} + \dots = \frac{i}{p^2 - m^2 + \Sigma(p^2)}$$

$\Sigma(p^2)$  = renormalized self-energy,  $m$  = ren. mass

stable particle:  $\text{Im}\{\Sigma(p^2)\} = 0$  at  $p^2 \sim m^2$

→ propagator pole for real value of  $p^2$ ,  
renormalization condition for physical mass  $m$ :  $\Sigma(m^2) = 0$   
**physical mass = pole of propagator**

unstable particle:  $\text{Im}\{\Sigma(p^2)\} \neq 0$  at  $p^2 \sim m^2$

→ propagator pole shifted into complex  $p^2$  plane,  
**definition of mass and width non-trivial**

# Commonly used mass/width definitions

- “on-shell mass/width”  $M_{\text{OS}}/\Gamma_{\text{OS}}$ :  $M_{\text{OS}}^2 - m^2 + \text{Re}\{\Sigma(M_{\text{OS}}^2)\} \stackrel{!}{=} 0$   
 $\hookrightarrow G^{\phi\phi}(p) \underset{p^2 \rightarrow M_{\text{OS}}^2}{\sim} \frac{1}{(p^2 - M_{\text{OS}}^2)(1 + \text{Re}\{\Sigma'(M_{\text{OS}}^2)\}) + i\text{Im}\{\Sigma(M_{\text{OS}}^2)\}}$

comparison with form of Breit–Wigner resonance  $\frac{R_{\text{OS}}}{p^2 - m^2 + im\Gamma}$

yields:  $M_{\text{OS}}\Gamma_{\text{OS}} \equiv \text{Im}\{\Sigma(M_{\text{OS}}^2)\} / (1 + \text{Re}\{\Sigma'(M_{\text{OS}}^2)\}), \quad \Sigma'(p^2) \equiv \frac{\partial\Sigma(p^2)}{\partial p^2}$

- “pole mass/width”  $M/\Gamma$ :  $\mu^2 - m^2 + \Sigma(\mu^2) \stackrel{!}{=} 0$

complex pole position:  $\mu^2 \equiv M^2 - iM\Gamma$

$$\hookrightarrow G^{\phi\phi}(p) \underset{p^2 \rightarrow \mu^2}{\sim} \frac{1}{(p^2 - \mu^2)[1 + \Sigma'(\mu^2)]} = \frac{R}{p^2 - M^2 + iM\Gamma}$$

note:  $\mu$  = gauge independent for any particle (pole location is property of  $S$ -matrix)

$M_{\text{OS}}$  = gauge dependent at 2-loop order

Sirlin '91; Stuart '91;  
Gambino, Grassi '99;  
Grassi, Kniehl, Sirlin '01

# Relation between “on-shell” and “pole” definitions

Subtraction of defining equations yields:

$$M_{\text{OS}}^2 + \text{Re}\{\Sigma(M_{\text{OS}}^2)\} = M^2 - iM\Gamma + \Sigma(M^2 - iM\Gamma)$$

Taylor expand self-energies about  $M^2$

use counting in  $\alpha$ :  $M_{\text{OS}}, M = \mathcal{O}(\alpha^0)$ ,  $\Gamma_{\text{OS}}, \Gamma, \Sigma(p^2) = \mathcal{O}(\alpha^1)$

$$(M^2 - M_{\text{OS}}^2)(1 - \text{Re}\{\Sigma'(M^2)\}) = -M\Gamma \text{Im}\{\Sigma'(M^2)\} + \mathcal{O}(\alpha^3)$$

$$M\Gamma(1 + \text{Re}\{\Sigma'(M^2)\}) = \text{Im}\{\Sigma(M^2)\} - \frac{1}{2}(M\Gamma)^2 \text{Im}\{\Sigma''(M^2)\} + \mathcal{O}(\alpha^4)$$

eliminate  $M\Gamma$

$$M_{\text{OS}}^2 = M^2 + \text{Im}\{\Sigma(M^2)\} \text{Im}\{\Sigma'(M^2)\} + \mathcal{O}(\alpha^3)$$

use formula for on-shell width and expand

$$\begin{aligned} M_{\text{OS}}\Gamma_{\text{OS}} &= M\Gamma + \text{Im}\{\Sigma(M^2)\} \text{Im}\{\Sigma'(M^2)\}^2 \\ &\quad + \frac{1}{2} \text{Im}\{\Sigma(M^2)\}^2 \text{Im}\{\Sigma''(M^2)\} + \mathcal{O}(\alpha^4) \end{aligned}$$

final result:  $\{M_{\text{OS}}, \Gamma_{\text{OS}}\} = \{M, \Gamma\} + \text{gauge-dependent 2-loop corrections}$

# Important examples: W and Z bosons

In good approximation:  $W \rightarrow f\bar{f}', \quad Z \rightarrow f\bar{f}$  with masses fermions  $f, f'$

$$\text{so that: } \text{Im}\{\Sigma_T^V(p^2)\} = p^2 \times \frac{\Gamma_V}{M_V} \theta(p^2), \quad V = W, Z$$

$$\hookrightarrow M_{\text{OS}}^2 = M^2 + \Gamma^2 + \mathcal{O}(\alpha^3) \quad M_{\text{OS}}\Gamma_{\text{OS}} = M\Gamma + \frac{\Gamma^3}{M} + \mathcal{O}(\alpha^4)$$

in terms of measured numbers:

$$W \text{ boson: } M_W \approx 80 \text{ GeV}, \quad \Gamma_W \approx 2.1 \text{ GeV}$$

$$\hookrightarrow M_{W,\text{OS}} - M_{W,\text{pole}} \approx 28 \text{ MeV}$$

$$Z \text{ boson: } M_Z \approx 91 \text{ GeV}, \quad \Gamma_Z \approx 2.5 \text{ GeV}$$

$$\hookrightarrow M_{Z,\text{OS}} - M_{Z,\text{pole}} \approx 34 \text{ MeV}$$

$$\text{exp. accuracy: } \Delta M_{W,\text{exp}} = 25 \text{ MeV}, \quad \Delta M_{Z,\text{exp}} = 2.1 \text{ MeV}$$

$\hookrightarrow$  difference in definitions phenomenologically important !

# A closer look into resonance shapes

- “on-shell mass/width”  $M_{\text{OS}}/\Gamma_{\text{OS}}$ :  $M_{\text{OS}}^2 - m^2 + \text{Re}\{\Sigma(M_{\text{OS}}^2)\} \stackrel{!}{=} 0$

$$\begin{aligned}
 G^{\phi\phi}(p) &= \frac{1}{p^2 - M_{\text{OS}}^2 + \Sigma(p^2) - \text{Re}\{\Sigma(M_{\text{OS}}^2)\}} \\
 &\stackrel{p^2 \rightarrow M_{\text{OS}}^2}{=} \frac{1}{(p^2 - M_{\text{OS}}^2)[1 + \text{Re}\{\Sigma'(M_{\text{OS}}^2)\}] + i \text{Im}\{\Sigma(p^2)\} + \mathcal{O}[(p^2 - M_{\text{OS}}^2)^2]} \\
 &= \frac{R_{\text{OS}}}{p^2 - M_{\text{OS}}^2 + i M_{\text{OS}} \Gamma_{\text{OS}}(p^2) + \mathcal{O}[(p^2 - M_{\text{OS}}^2)^2]}
 \end{aligned}$$

with the “running on-shell width”  $\Gamma_{\text{OS}}(p^2) = \frac{\text{Im}\{\Sigma(\textcolor{red}{p}^2)\}}{M_{\text{OS}}[1 + \text{Re}\{\Sigma'(M_{\text{OS}}^2)\}]}$

- “pole mass/width”  $M/\Gamma$ :  $\mu^2 - m^2 + \Sigma(\mu^2) \stackrel{!}{=} 0$

$$\begin{aligned}
 G^{\phi\phi}(p) &= \frac{1}{p^2 - \mu^2 + \Sigma(p^2) - \Sigma(\mu^2)} \\
 &\stackrel{p^2 \rightarrow \mu^2}{=} \frac{1}{(p^2 - \mu^2)[1 + \Sigma'(\mu^2)] + \mathcal{O}[(p^2 - \mu^2)^2]} = \frac{R}{(p^2 - \mu^2) + \mathcal{O}[(p^2 - \mu^2)^2]}
 \end{aligned}$$

# Example of W and Z bosons continued

Approximation of massless decay fermions:

$$\Gamma_{V,\text{OS}}(p^2) = \Gamma_{V,\text{OS}} \times \frac{p^2}{M_{V,\text{OS}}^2} \theta(p^2), \quad V = W, Z$$

fit of W/Z resonance shapes to experimental data:

- ansatz  $\left| \frac{R'}{p^2 - m'^2 + i\gamma' p^2/m'} \right|^2$  yields:  $m' = M_{V,\text{OS}}$ ,  $\gamma' = \Gamma_{V,\text{OS}}$
- ansatz  $\left| \frac{R}{p^2 - m^2 + i\gamma m} \right|^2$  yields:  $m = M_{V,\text{pole}}$ ,  $\gamma = \Gamma_{V,\text{pole}}$

note: the two forms are equivalent:

$$R = \frac{R'}{1 + i\gamma'/m'}, \quad m^2 = \frac{m'^2}{1 + \gamma'^2/m'^2}, \quad m\gamma = \frac{m'\gamma'}{1 + \gamma'^2/m'^2}$$

↪ consistent with relation between “on-shell” and “pole” definitions !

# Unstable particles and gauge invariance

Gauge invariance implies...

- Slavnov–Taylor or Ward identities
  - = algebraic relations between Greens functions
  - ↪ crucial for proof of unitarity of  $S$ -matrix,  
guarantee cancellation of unitarity-violating terms
- compensation of gauge-fixing artifacts
  - = 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 !

but: resonances require Dyson summation of resonant propagators

- ↪ perturbative orders mixed
- ↪ gauge invariance jeopardised !

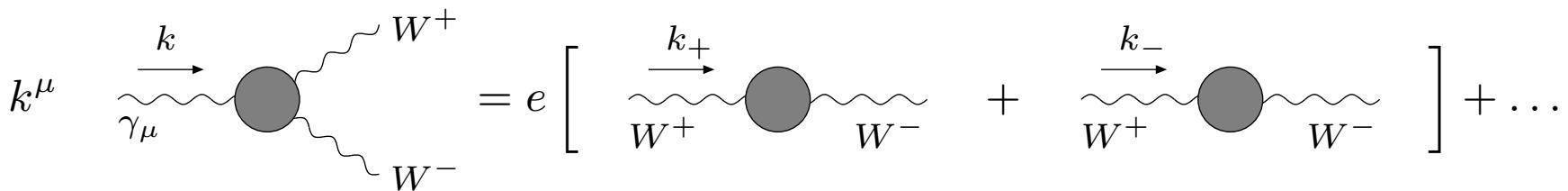
note: gauge-invariance-violating terms are formally of higher order,  
but can be dramatically enhanced

# Violation of Ward identities by Dyson summation

Dyson summation in general violates Ward identities

example: electromagnetic Ward identity for photon–W-boson vertex

$$-k^\mu V_{\mu\nu\rho}^{\gamma W^+ W^-}(k, k_+, k_-) = e \left[ \left( P^{W^+ W^-} \right)^{-1}_{\nu\rho}(k_+) - \left( P^{W^+ W^-} \right)^{-1}_{\nu\rho}(k_-) \right] + \text{unphysical terms}$$



valid for lowest order or complete higher orders

violated for Dyson-resummed propagators:

$$k_+^2 - k_-^2 \neq \left[ k_+^2 - M_W^2 + \Sigma(k_+^2) \right] - \left[ k_-^2 - M_W^2 + \Sigma(k_-^2) \right] = k_+^2 - k_-^2 + \Sigma(k_+^2) - \Sigma(k_-^2)$$

unless  $\Sigma(k_+^2) = \Sigma(k_-^2)$  or if also  $V_{\mu\nu\rho}^{\gamma W^+ W^-}(k, k_+, k_-)$  is changed

violation may lead to large unphysical contributions to *S*-matrix elements

# Elmg. U(1) gauge invariance

$$k^\mu \gamma_\mu = 0 \quad \text{for any on-shell fields } F_l$$

↪ identity becomes crucial for collinear light fermions:

for fermion momenta  $p_1 \sim c p_2$ :

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

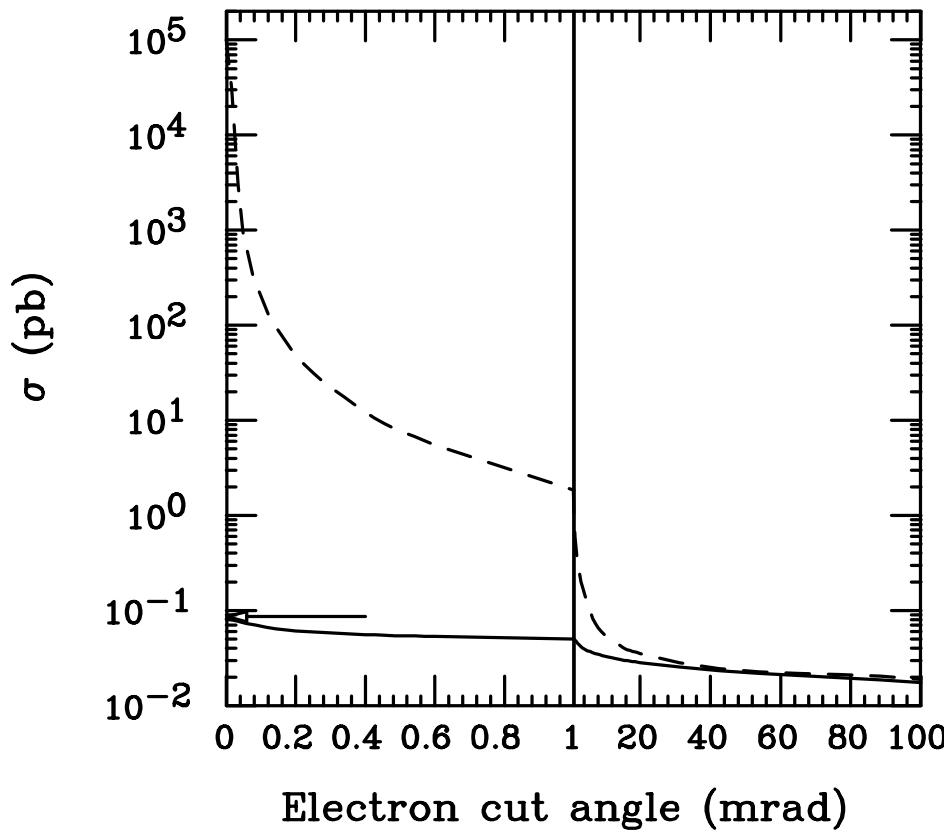
typical situation: quasi-real space-like photons

$$e \rightarrow e \gamma \rightarrow e \quad \sim \frac{1}{k^2} k^\mu T_\mu^\gamma \quad \text{for } k^2 \rightarrow (m_e^2) \ll E^2$$

identity  $k^\mu T_\mu^\gamma = 0$  needed to cancel  $1/k^2$ ,

otherwise gauge-invariance-breaking terms enhanced by  $E^2/m_e^2$  ( $\sim 10^{10}$  for LEP2)

# An example: $e^-e^+ \rightarrow e^-\bar{\nu}_e u\bar{d}$



Kurihara, Perret-Gallix, Shimizu '95

$\sqrt{s} = 180$  GeV

cross section as a function of the cut on the electron scattering angle

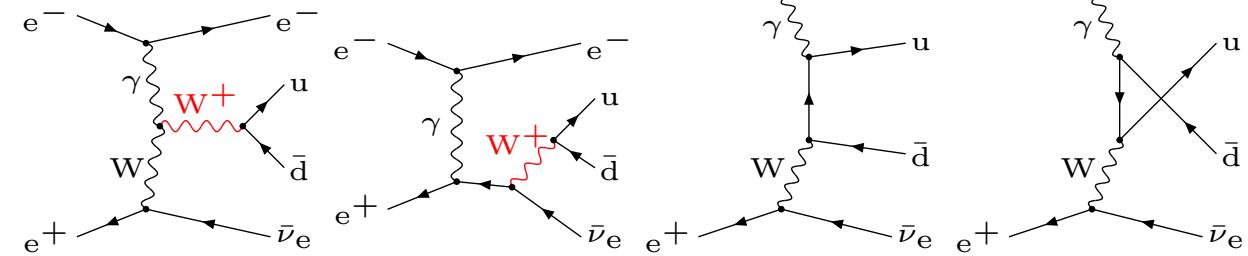
solid: gauge-invariant  
(fudge factor) scheme

dashed: constant width  
only in resonant propagator

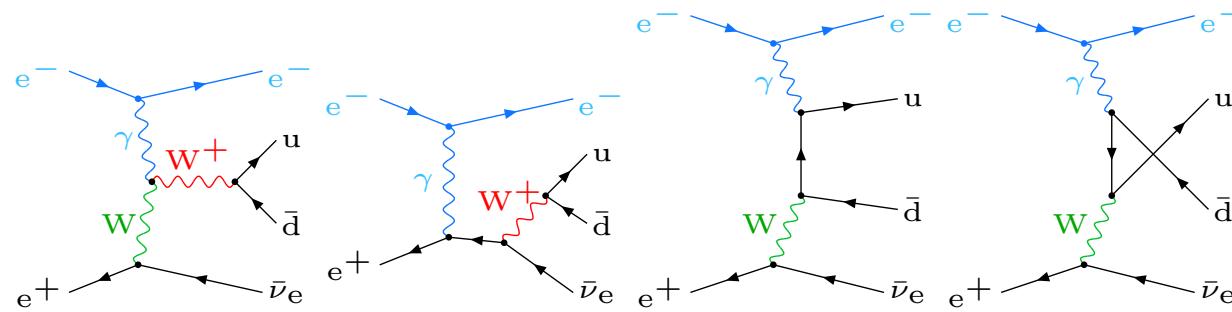
→ crude U(1) gauge-invariance violation

dominant diagrams:

nearly real photon !



# Example $e^-e^+ \rightarrow e^-\bar{\nu}_e u\bar{d}$ continued



partial amplitude from above “photon diagrams”:

$$\mathcal{M}_\gamma = Q_{ee} \bar{u}_e(k_e) \gamma^\mu u_e(p_e) \frac{1}{k_\gamma^2} T_\mu^\gamma$$

for  $k_e \sim cp_e \Rightarrow \bar{u}_e(k_e) \gamma^\mu u_e(p_e) \propto k_\gamma^\mu$

elmg. Ward identity (crucial to soften  $1/k_\gamma^2$  pole):

$$0 \stackrel{!}{=} k_\gamma^\mu T_\mu^\gamma \propto (p_+^2 - p_-^2) Q_W P_w(p_+^2) P_w(p_-^2) + Q_e P_w(p_+^2) - (Q_d - Q_u) P_w(p_-^2)$$

with  $Q_W = Q_e = Q_d - Q_u$  and  $P_w(p^2) = [p^2 - M_W^2 + iM_W\Gamma_W(p^2)]^{-1}$

one obtains:  $\Gamma_W(p_+^2) \stackrel{!}{=} \Gamma_W(p_-^2)$

→ elmg. gauge invariance demands common width for all propagators

⇒ "fixed width scheme"

# Electroweak SU(2) gauge invariance

$$\begin{array}{ccc}
 k^\mu \begin{array}{c} \text{---} \\ Z_\mu \end{array} & = & iM_Z \quad \begin{array}{c} \text{---} \\ \chi \end{array} \\
 \begin{array}{c} F_1 \\ \vdots \\ F_n \end{array} & & \begin{array}{c} F_1 \\ \vdots \\ F_n \end{array} \\
 k^\mu \begin{array}{c} \text{---} \\ W_\mu^\pm \end{array} & = & \pm M_W \quad \begin{array}{c} \text{---} \\ \phi^\pm \end{array} \\
 \begin{array}{c} F_1 \\ \vdots \\ F_n \end{array} & & \begin{array}{c} F_1 \\ \vdots \\ F_n \end{array}
 \end{array}$$

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

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

↪ fermion current attached to  $V(k)$  again  $\propto k^\mu$

$$\sim \frac{1}{k^2 - M_V^2} k^\mu T_\mu^V \quad \text{for } k^0 \gg M_V$$

identity  $k^\mu T_\mu^V = c_V M_V T^S$  needed to cancel factor  $k^0$

otherwise gauge-invariance/unitarity-breaking terms enhanced by  $k^0/M_V$

# Consistent implementation of unstable particles

- Gauge independence

use pole mass and width from complex pole (gauge independent)

instead of full or more complete Dyson summation  $\Rightarrow$  no running width

- Ward identities

- QED and QCD

Ward identities depend only on masses and strong/elmg. coupling constants

$\Rightarrow$  Ward identities hold after replacing of real by complex masses

use complex pole masses in all propagators  $\Rightarrow$  fixed width scheme

QED and QCD corrections: complex masses are independent parameters

$\Rightarrow$  no further complications

- Electroweak theory

couplings are related to masses via weak mixing angle  $c_w = M_W/M_Z$

Ward identities require use of complex masses also in couplings

$\Rightarrow$  complex weak mixing angle  $\Rightarrow$  complex-mass scheme

Electroweak corrections

corrections included in electroweak widths must be subtracted

mass renormalization must be done for complex pole

# The complex-mass scheme at tree level

Denner, Dittmaier, Roth, Wackeroth '99

**Basic idea:** mass<sup>2</sup> = location of propagator pole in complex  $p^2$  plane  
 ↵ consistent use of complex masses everywhere !

application to gauge-boson resonances:

- replace  $M_W^2 \rightarrow \mu_W^2 = M_W^2 - iM_W\Gamma_W$ ,  $M_Z^2 \rightarrow \mu_Z^2 = M_Z^2 - iM_Z\Gamma_Z$   
 and define (complex) weak mixing angle via  $\cos^2 \theta_w \equiv c_w^2 = 1 - s_w^2 = \frac{\mu_W^2}{\mu_Z^2}$
- virtue: gauge-invariant result !  
 all algebraic relations remain valid: Ward identities, Slavnov–Taylor identities  
 ↵ gauge-parameter independence, unitarity cancellations !
- drawbacks: spurious terms of  $\mathcal{O}(\Gamma/M) = \mathcal{O}(\alpha)$   
 (from  $\Gamma$  in  $t$ -channel/off-shell propagators and complex mixing angle)  
 ↵ but these terms are beyond tree-level accuracy !

# Complex-mass scheme at one-loop level

Denner, Dittmaier, Roth, Wieders '05

(renormalized mass)<sup>2</sup> = location of propagator pole in complex  $p^2$  plane

→ complex mass renormalization:

$$\underbrace{M_{W,0}^2}_{\text{bare mass}} = \mu_W^2 + \underbrace{\delta\mu_W^2}_{\text{ren. constant}}, \quad \text{etc.}$$

→ Feynman rules with complex masses and counterterms

## virtues

- perturbative calculations as usual
- no double counting (bare Lagrangian unchanged !)

## drawbacks

- loop integrals with complex masses
- spurious  $\mathcal{O}(\alpha^2)$  terms in one-loop amplitudes  
(spoil unitarity of  $S$  matrix at  $\mathcal{O}(\alpha^2)$ )

# Complex renormalization: W-boson as example

Direct generalization of on-shell renormalization scheme

Aoki et al. '81; Denner '93; Denner, Dittmaier, Weiglein '94

⇒ complex field renormalization

$$\underbrace{W_0^\pm}_{\text{bare field}} = \left(1 + \frac{1}{2} \underbrace{\delta \mathcal{Z}_W}_{\text{ren. constant}}\right) W^\pm, \quad \text{etc.}$$

- complex  $\delta \mathcal{Z}_W$  applies to both  $W^+$  and  $W^- \Rightarrow (W^+)^{\dagger} \neq W^-$
- $\delta \mathcal{Z}_W$  drops out in *S*-matrix elements without external W-bosons

on-shell renormalization conditions for W-boson self-energy

$$\hat{\Sigma}_T^W(\mu_W^2) = 0, \quad \hat{\Sigma}'_T^W(\mu_W^2) = 0$$

↪  $\mu_W^2$  is location of propagator pole, and residue = 1

solutions of renormalization conditions

$$\delta \mu_W^2 = \Sigma_T^W(\mu_W^2), \quad \delta \mathcal{Z}_W = -\Sigma'_T^W(\mu_W^2)$$

require self-energy for complex squared momenta ( $p^2 = \mu_W^2$ )

↪ analytic continuation of the 2-point functions to unphysical Riemann sheet

# Expansion of counterterms about real momenta

Way around: appropriate expansions about real arguments

$$\Sigma_T^W(\mu_W^2) = \Sigma_T^W(M_W^2) + (\mu_W^2 - M_W^2)\Sigma'_T^W(M_W^2) + \underbrace{\mathcal{O}(\alpha^3)}_{\text{beyond } \mathcal{O}(\alpha) \text{ and UV-finite}}$$

modified counterterms

$$\delta\mu_W^2 = \Sigma_T^W(M_W^2) + (\mu_W^2 - M_W^2)\Sigma'_T^W(M_W^2), \quad \delta\mathcal{Z}_W = -\Sigma'_T^W(M_W^2)$$

⇒ renormalized self-energy

$$\hat{\Sigma}_T^W(k^2) = \Sigma_T^W(k^2) - \delta M_W^2 + (k^2 - M_W^2)\delta Z_W$$

with

$$\delta M_W^2 = \Sigma_T^W(M_W^2), \quad \delta Z_W = -\Sigma'_T^W(M_W^2)$$

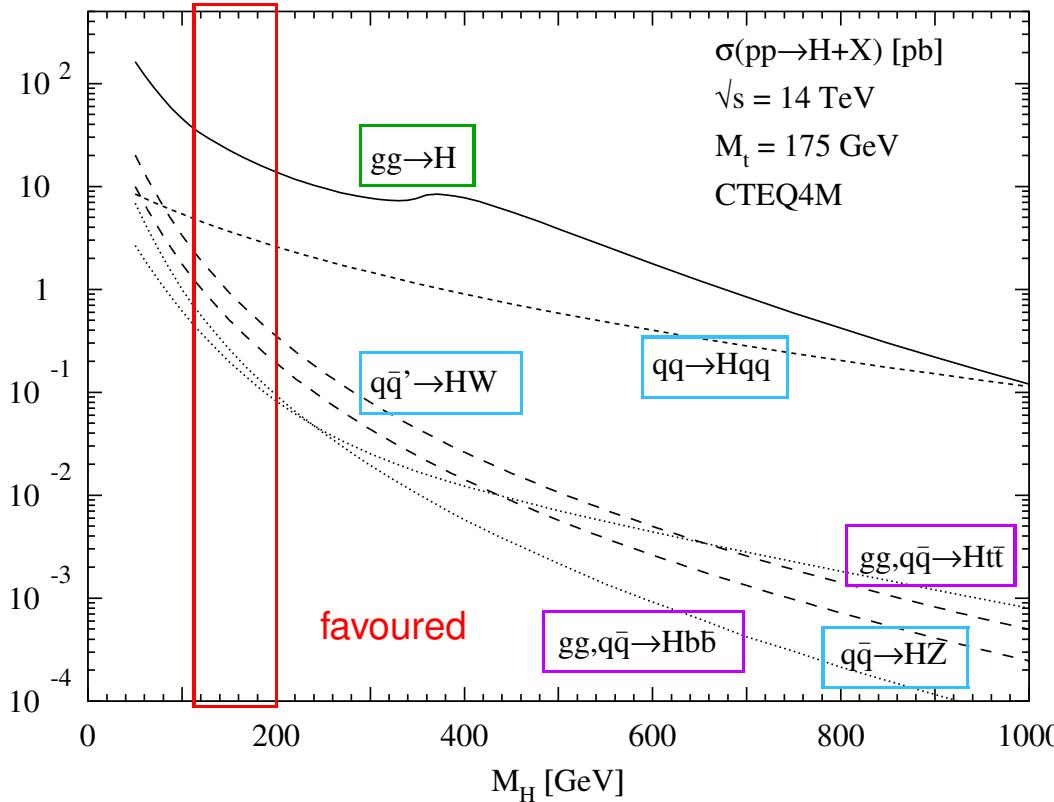
exactly the form of the renormalized self-energies in usual on-shell scheme

- but
- no real parts are taken from  $\Sigma^W$
  - $\Sigma^W$  depends on complex masses and complex mixing angle

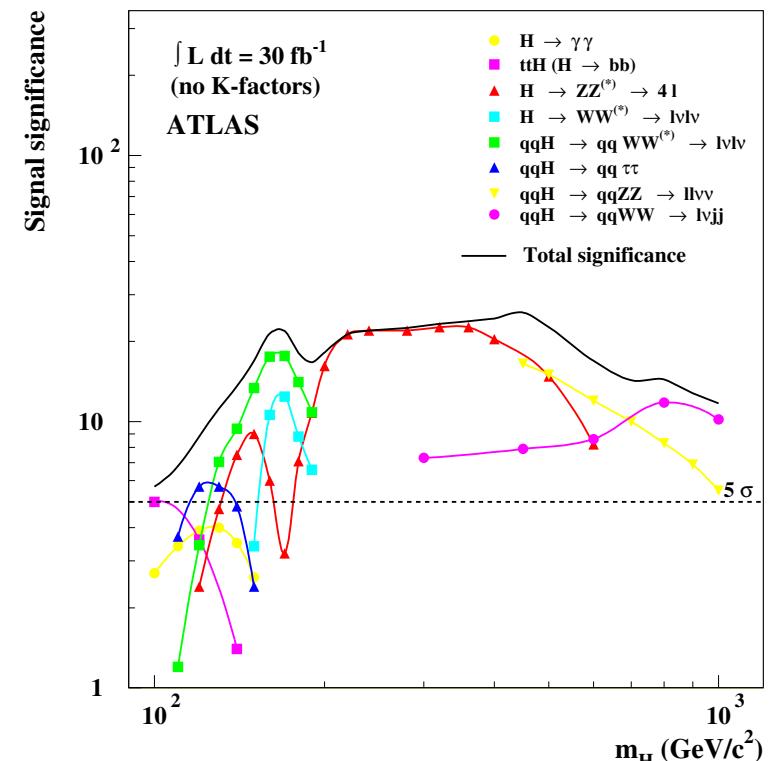
$$pp \rightarrow H + 2\text{jets} + X$$

# Significance of Higgs signal at LHC

Spira et al. '98



ATLAS

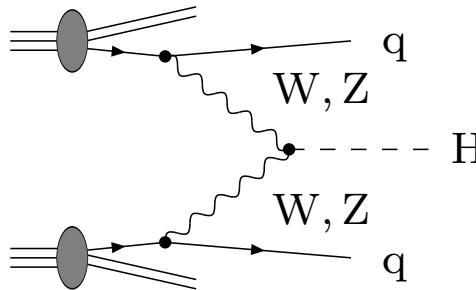


**Importance of vector-boson fusion (VBF)  $pp \rightarrow H + 2\text{jets} + X$ :**

- important Higgs-production process for  $100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}$  and large Higgs boson masses
- measurement of HVV couplings

**expected statistical uncertainty for  $\sigma \times B$ :** 5–10%      Zeppenfeld et al. '00

# Process topology of Higgs production via VBF



process dominated by  $t$ - and  $u$ -channel diagrams  
 $\Rightarrow t$ -channel approximation  
dominant contribution has two forward jets

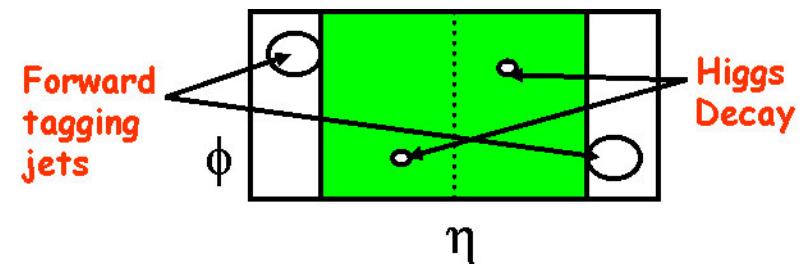
## VBF cuts and background suppression:

- 2 hard “tagging” jets demanded:  
 $p_{Tj} > 20 \text{ GeV}, \quad |y_j| < 4.5$
- tagging jets forward–backward directed:  
 $\Delta y_{jj} > 4, \quad y_{j1} \cdot y_{j2} < 0$

→ suppression of background

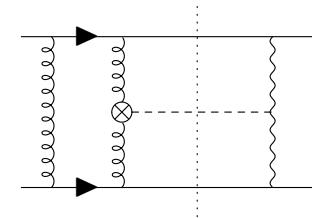
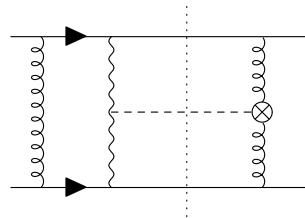
- from other (non-Higgs) processes,  
such as  $t\bar{t}$  or  $WW$  production      Zeppenfeld et al. '94–'99
- induced by Higgs production via gluon fusion,  
such as  $gg \rightarrow ggH$       Del Duca et al. '06; Campbell et al. '06

signature = Higgs + 2 jets



# Results on Higgs+2 jets production in NLO

- NLO QCD corrections to VBF in “*t*-channel approximation” (vertex corrections)  
colour exchange between quark lines suppressed  $\Rightarrow$  small QCD corrections
  - ▶ total cross section Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00  
 $\hookrightarrow$  corrections  $\sim 5\text{--}10\%$ , residual scale dependence: few per cent
  - ▶ realistic cuts, distributions Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04  
 $\hookrightarrow$  corrections  $\sim 10\text{--}20\%$ , strongly phase-space dependent
- NLO QCD corrections to gluon-initiated channels Campbell, R.K.Ellis, Zanderighi '06  
(effective  $Hgg$  coupling)  $\Rightarrow$  contribution to VBF  $\sim 5\%$  Nikitenko, Vazquez '07
- complete NLO QCD+EW corrections to VBF Ciccolini, Denner, Dittmaier '07  
 $\hookrightarrow$  NLO QCD  $\sim$  NLO EW  $\sim 5\text{--}10\%$
- QCD loop-induced interferences between VBF and gluon-initiated channels



Andersen, Binoth, Heinrich, Smillie '07  
Bredenstein, Hagiwara, Jäger '08

$\rightarrow$  impact  $\lesssim 10^{-3}\%$  (negligible!)

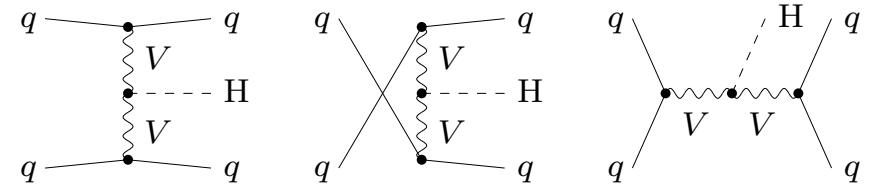
- SUSY QCD+EW corrections Hollik, Plehn, Rauch, Rzezhak '08

$\hookrightarrow |MSSM - SM| \lesssim 1\%$  for SPS points (2–4% for low SUSY scales)

# Details of the NLO calculation for H + 2jets

## EW production of Higgs+2 jets in LO

- many subcontributions from  $qq$ ,  $q\bar{q}$ , and  $\bar{q}\bar{q}$  channels
- each channel receives contributions from one or two topologies (" $t$ ,  $u$ ,  $s$ "):



different channels related by crossing

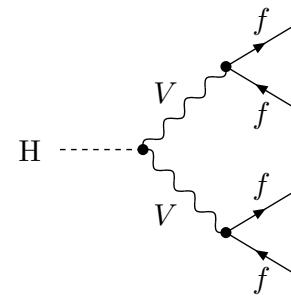
all contributions and interferences taken into account in LO and NLO

## EW production of Higgs+2 jets in NLO

- partonic channels for
  - one-loop diagrams:  $qq$ ,  $q\bar{q}$ ,  $\bar{q}\bar{q}$
  - real QCD corrections  $qq$ ,  $q\bar{q}$ ,  $\bar{q}\bar{q}$  (gluon emission),  $qg$ ,  $\bar{q}g$  (gluon induced)
  - real QED corrections  $qq$ ,  $q\bar{q}$ ,  $\bar{q}\bar{q}$  (photon emission),  $q\gamma$ ,  $\bar{q}\gamma$  (**photon induced**)
- collinear initial-state singularities from QCD and QED splittings
  - factorization and PDF redefinition for QCD and QED singularities

# Survey of Feynman diagrams for H + 2jets

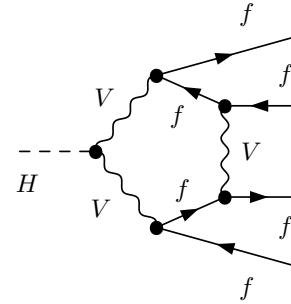
Lowest order:



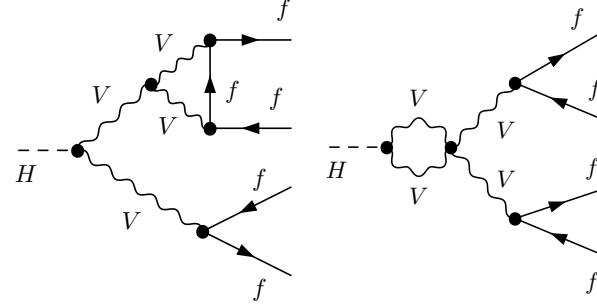
$$V = W, Z$$

typical one-loop diagrams:

6/8 pentagons

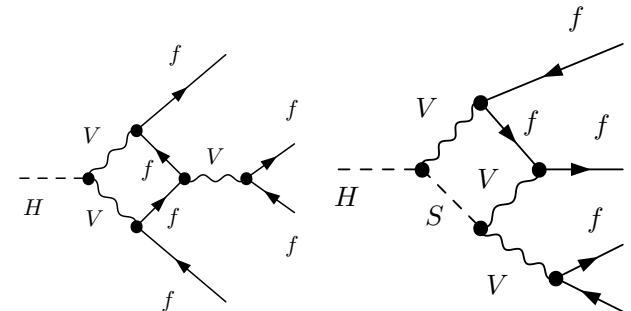


vertices

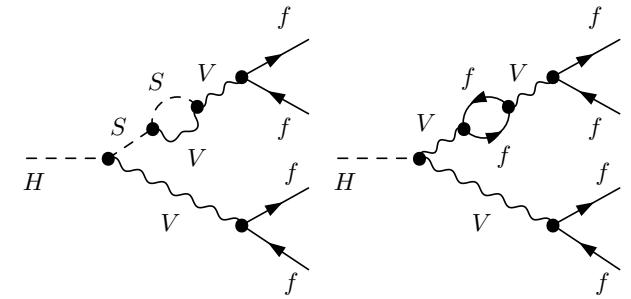


$$\# \text{ diagrams} = \mathcal{O}(200) \text{ per tree diagram}$$

14/24 boxes



self-energies



+ tree graphs with real photons and gluons

Tools: crucial methods already developed for  $e^+e^- \rightarrow 4f$

Denner, Dittmaier, Roth, Wieders '05

- generation of Feynman diagrams with FeynArts version 1 and 3

Küblbeck, Böhm, Denner, Eck '90,'92; Hahn '01

- algebraic simplifications using two independent in-house programs implemented in *Mathematica*, one building upon FORMCALC

Hahn, Perez-Victoria '99, Hahn '00

- reduction of tensor integrals according to

Denner, Dittmaier, NPB658 (2003)175 [hep-ph/0212259], NPB734 (2006) 62 [hep-ph/0509141]

→ numerically stable results

- scalar integrals: evaluated with standard techniques and analytic continuation for complex masses

## contributions

- complete NLO QCD and electroweak corrections

- leading two-loop corrections  $\propto G_\mu^2 M_H^4$  to VVH vertex in large  $M_H$  limit

Ghinculov '95; Frink et al. '96

# SMEs for $pp \rightarrow H + 2\text{jets} + X$

Decomposition of amplitude for  $\bar{f}_a(k_a, \sigma) \bar{f}_c(k_c, \tau) \rightarrow \bar{f}_b(k_b, \sigma) \bar{f}_d(k_d, \tau) H(k_H)$

$$\mathcal{M}^{abcd, \sigma\tau} = \sum_{i=1}^{13} F_i^{abcd, \sigma\tau} \hat{\mathcal{M}}_i^{abcd, \sigma\tau}$$

with

$$\hat{\mathcal{M}}_{\{1,2\}}^{abcd, \sigma\tau} = \Gamma_{\alpha}^{ab, \sigma} \Gamma^{cd, \tau, \{\alpha, \alpha k_a k_b\}},$$

$$\hat{\mathcal{M}}_{\{5,6\}}^{abcd, \sigma\tau} = \Gamma_{k_c}^{ab, \sigma} \Gamma^{cd, \tau, \{k_a, k_b\}},$$

$$\hat{\mathcal{M}}_{\{9,10\}}^{abcd, \sigma\tau} = \Gamma_{\alpha\beta k_c}^{ab, \sigma} \Gamma^{cd, \tau, \{\alpha\beta k_a, \alpha\beta k_b\}},$$

$$\hat{\mathcal{M}}_{13}^{abcd, \sigma\tau} = \Gamma_{\alpha\beta\gamma}^{ab, \sigma} \Gamma^{cd, \tau, \alpha\beta\gamma}$$

$$\hat{\mathcal{M}}_{\{3,4\}}^{abcd, \sigma\tau} = \Gamma_{\alpha k_c k_d}^{ab, \sigma} \Gamma^{cd, \tau, \{\alpha, \alpha k_a k_b\}}$$

$$\hat{\mathcal{M}}_{\{7,8\}}^{abcd, \sigma\tau} = \Gamma_{k_d}^{ab, \sigma} \Gamma^{cd, \tau, \{k_a, k_b\}}$$

$$\hat{\mathcal{M}}_{\{11,12\}}^{abcd, \sigma\tau} = \Gamma_{\alpha\beta k_d}^{ab, \sigma} \Gamma^{cd, \tau, \{\alpha\beta k_a, \alpha\beta k_b\}}$$

and

$$\Gamma_{\{\alpha, \alpha\beta\gamma\}}^{ab, \sigma} = \bar{v}_{\bar{f}_a}(k_a) \{\gamma_\alpha, \gamma_\alpha\gamma_\beta\gamma_\gamma\} \omega_\sigma v_{\bar{f}_b}(k_b)$$

$$\Gamma_{\{\alpha, \alpha\beta\gamma\}}^{cd, \tau} = \bar{v}_{\bar{f}_c}(k_c) \{\gamma_\alpha, \gamma_\alpha\gamma_\beta\gamma_\gamma\} \omega_\tau v_{\bar{f}_d}(k_d)$$

other channels obtained via crossing

in 4 dimensions 13 SME for each helicity amplitude can be reduced to one

Denner, Dittmaier, Roth, Weber '03

# Algebraic reduction of tensor integrals

For details see Denner, Dittmaier NPB734 (2006) 62 [hep-ph/0509141]

- **1- and 2-point integrals:** numerically stable direct calculation
- **3-point and 4-point integrals:** Passarino–Veltman reduction
  - inverse Gram determinants of up to three momenta
  - serious numerical instabilities where  $\det G \rightarrow 0$   
 (at phase-space boundary, but also within phase space!)

two hybrid methods

- (i) Passarino–Veltman  $\oplus$  expansions in small Gram and other kinematical determinants (see also R.K.Ellis et al. '05)
  - (ii) Passarino–Veltman  $\oplus$  analytical special cases
    - $\oplus$  semi-numerical method (in this calculation for checks only)  
 (numerical calculation of logarithmic Feynman-parameter integral and algebraic reduction to this basis integral) (see also Binoth et al. '05; Ferroglia et al. '02)
- **5-point integrals** → five 4-point integrals Melrose '65; Denner, Dittmaier '02, '05
  - **6-point integrals** → six 5-point integrals (see also Binoth et al. '05)
- without inverse Gram determinants and simultaneous reduction of rank by one

# Real corrections for $pp \rightarrow H + 2\text{jets} + X$

## Matrix elements

- Weyl-van der Waerden spinor technique Dittmaier '98  $\Rightarrow$  compact expressions

soft and collinear singularities:

- regularized with infinitesimal photon/gluon and quark masses
- dipole subtraction formalism Catani, Seymour '96; Dittmaier '99; Diener, Dittmaier, Hollik '05

$$\int d\sigma_{2 \rightarrow 4} = \int \left[ d\sigma_{2 \rightarrow 4} - \sum_{\substack{i,j=1 \\ i \neq j}}^4 d\sigma_{2 \rightarrow 4}^{\text{dipole},ij} \right] + \sum_{\substack{i,j=1 \\ i \neq j}}^4 \mathcal{F}_{ij} \otimes d\sigma_{2 \rightarrow 3}$$

numerically stable/efficient, but 12 subtraction terms

- phase-space slicing Giele,Glover '92; Giele et al. '93; Keller,Laenen '98; Harris,Owens '01

$$\int d\sigma_{2 \rightarrow 4} = \int_{\substack{E > \delta_s \sqrt{\hat{s}}/2 \\ \cos \theta < 1 - \delta_c}} d\sigma_{2 \rightarrow 4} + F(\delta_s, \delta_c) \otimes d\sigma_{2 \rightarrow 3}$$

numerical cancellations/CPU-consuming, but “simple” and important check

## phase-space integration

- multi-channel Monte Carlo integration with adaptive optimization Berends, Kleiss, Pittau '94; Kleiss, Pittau '94  
 $\sim 250$  channels to map peaks from all propagators and dipoles in all partonic channels

# Checks on the calculation for $pp \rightarrow H + 2\text{jets} + X$

- **UV structure** of virtual corrections
  - independence of reference mass  $\mu$  of dimensional regularization
- **IR structure** of virtual + soft-gluon/photon corrections
  - independence of  $\ln m_\gamma$  ( $m_\gamma$  = infinitesimal photon mass)
- **mass singularities** of virtual + collinear gluon/photon corrections
  - independence of  $\ln m_{f_i}$  ( $m_{f_i}$  = small masses of external fermions)
- **gauge invariance** of amplitudes with  $\Gamma_W, \Gamma_Z \neq 0$ 
  - identical results in 't Hooft–Feynman and background-field gauge  
Denner, Dittmaier, Weiglein '94
- **real corrections**
  - squared amplitudes compared with MADGRAPH      Stelzer, Long '94
- **combination of virtual and real corrections**
  - identical results with two-cutoff slicing and dipole subtraction
- **two completely independent calculations of all ingredients!**

# Set-up for numerical calculation of H + 2jets

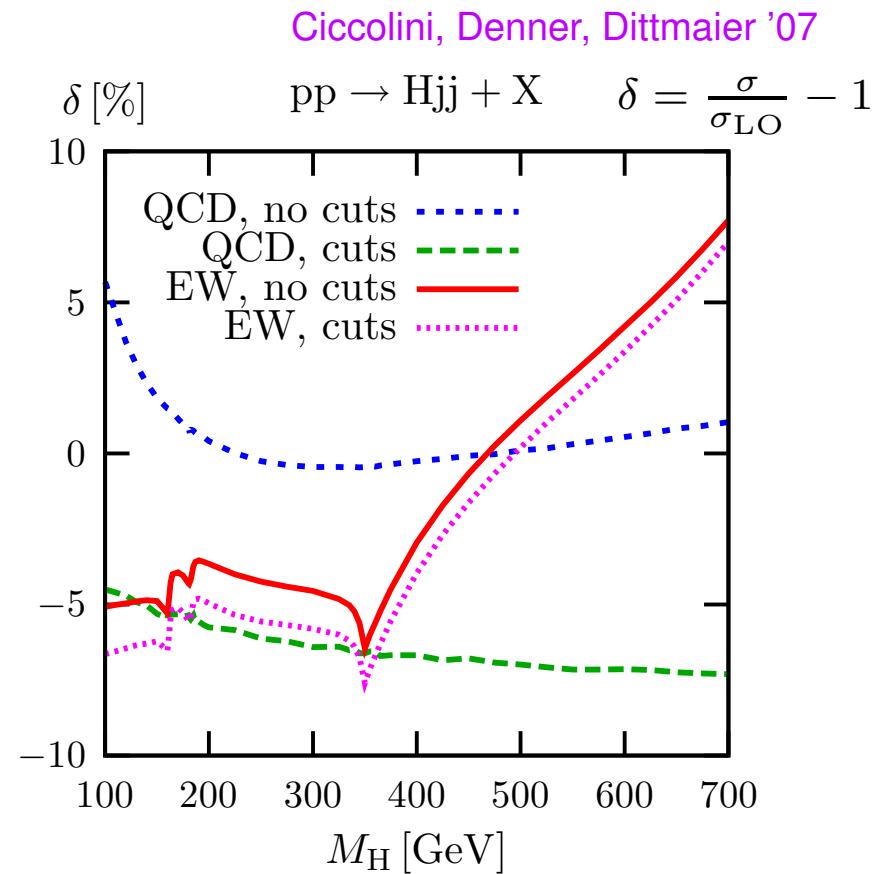
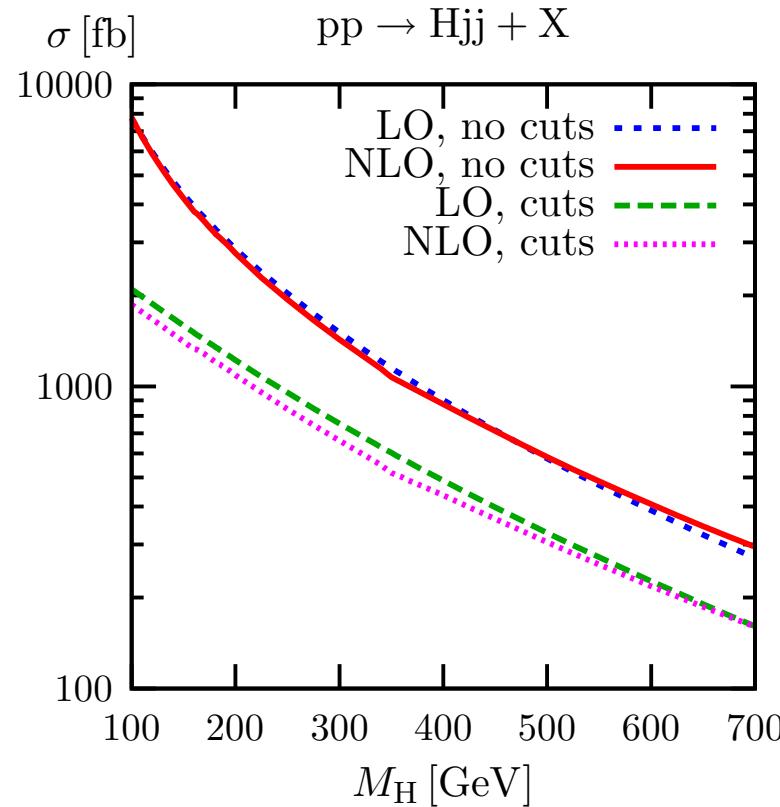
## Definition of observables

- jet definition:  $k_T$  algorithm as used at Tevatron run II      Blazey et al. '00  
 ↵ clusters partons with  $|\eta| < 5$  into jets with jet resolution  $D = 0.8$   
 photons included in clustering
- VBF cuts: following Figy, Zeppenfeld '04
  - ▶ 2 hard “tagging” jets demanded:  $p_{Tj_1} > p_{Tj_2} > 20 \text{ GeV}$ ,  $|y_{j_{1,2}}| < 4.5$
  - ▶ tagging jets forward–backward directed:  $|y_{j_1} - y_{j_2}| > 4$ ,  $y_{j_1} \cdot y_{j_2} < 0$
  - ▶ no cuts on Higgs momentum (should be adjusted to specific decays)

## NLO settings:

- central scales:  $\mu_R = \mu_F = M_W$
- PDFs: MRST2004QED which includes QED corrections and  $\gamma$  PDF  
 with  $\alpha_S(M_Z) = 0.1187$
- $\alpha_s(\mu_R)$  with 5 active flavours (top-quark decoupled) and two-loop running
- $\alpha$  defined in  $G_\mu$  scheme:  $\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2(1 - M_W^2/M_Z^2)/\pi$   
 ↵ absorbs running of  $\alpha$  from  $Q = 0$  to EW scale and  $\Delta\rho$  in  $Wq\bar{q}'$  coupling

# Total cross section for $pp \rightarrow H + 2\text{jets} + X$



- QCD and EW corrections are of same generic size ( $\sim 5\%$ )
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at  $M_H \sim 700$  GeV:  $\underbrace{G_\mu M_H^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_H^2)^2}_{\text{2-loop}} \sim 4\%$   
→ breakdown of perturbation theory
- scale uncertainty  $\sim 2\text{--}3\%$  within  $M_W/2 < \mu_{R/F} < 2M_W$  in NLO ( $\sim 10\%$  in LO)

# Corrections and subcontributions to cross sections

Ciccolini, Denner, Dittmaier '07

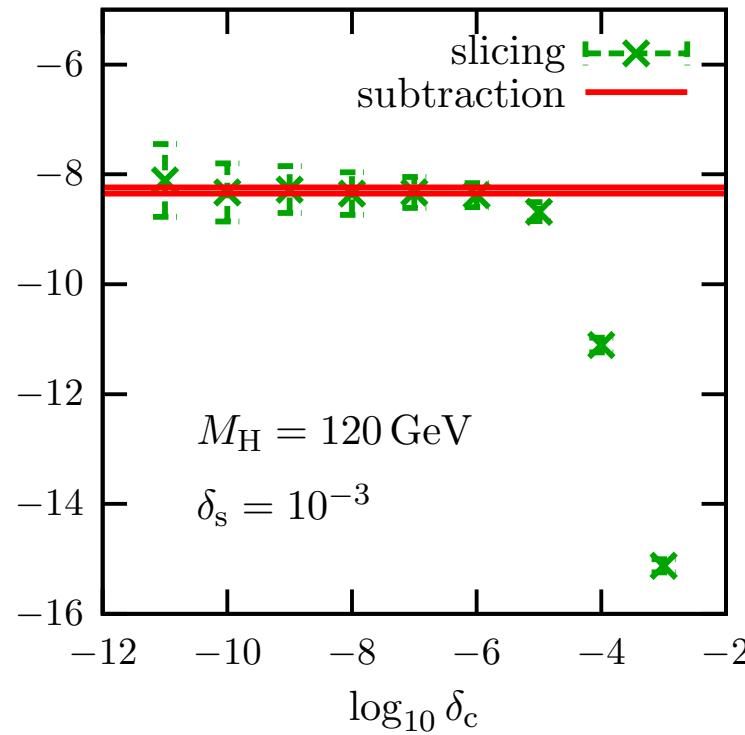
$M_H$ [GeV]	no cuts		VBF cuts		$\mathcal{O}(5-10\%)$
	120–200	700	120–200	700	
<b>various corrections</b>					
$\delta_{QCD}$ [%]	4–0.5	+1	≈ –5	–7	$\mathcal{O}(5-10\%)$
$\delta_{EW,qq}$ [%]	≈ –5	+6	≈ –7	+5	$\mathcal{O}(5-10\%)$
$\delta_{EW,q\gamma}$ [%]	≈ +1	+2	≈ +1	+2	$\mathcal{O}(1\%)$
$\delta_{G_\mu^2 M_H^4}$ [%]	< 0.1	+4	< 0.1	+4	negligible for $M_H < 400$ GeV
<b>specific contributions</b>					
$\Delta_{s\text{-channel}}$ [%]	30–10	1	< 0.6	< 0.1	negligible with VBF cuts
$\Delta_{t/u\text{-interference}}$ [%]	< 0.5	< 0.1	< 0.1	< 0.1	negligible
$\Delta_{b\text{-quarks}}$ [%]	≈ 4	1	≈ 2	1	

# Comparison between subtraction and slicing methods

VBF cuts

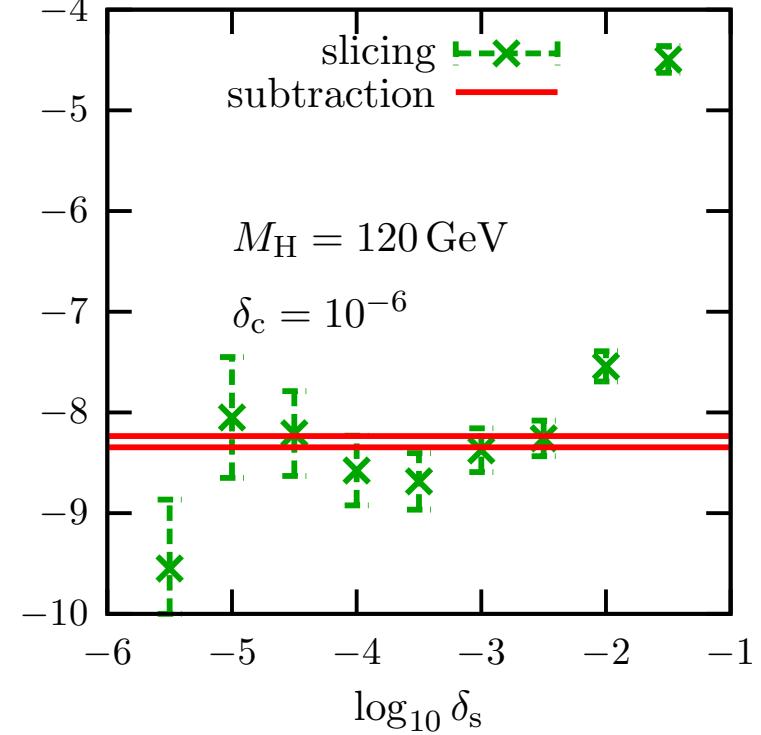
$$\mu_F = \mu_R = M_H$$

$$\frac{d\sigma}{d\sigma_{LO}} - 1 [\%] \quad pp \rightarrow Hjj + X$$



Ciccolini, Denner, Dittmaier '07

$$\frac{d\sigma}{d\sigma_{LO}} - 1 [\%] \quad pp \rightarrow Hjj + X$$



- slicing cuts in partonic CM frame:

$$\text{soft region: } E_{\gamma,g} < \delta_s \frac{\sqrt{\hat{s}}}{2}, \quad \text{collinear cone: } 1 - \cos(\theta_{\{\gamma,g\}q}) < \delta_c$$

- slicing:  $10^9$  events, 144 CPU h

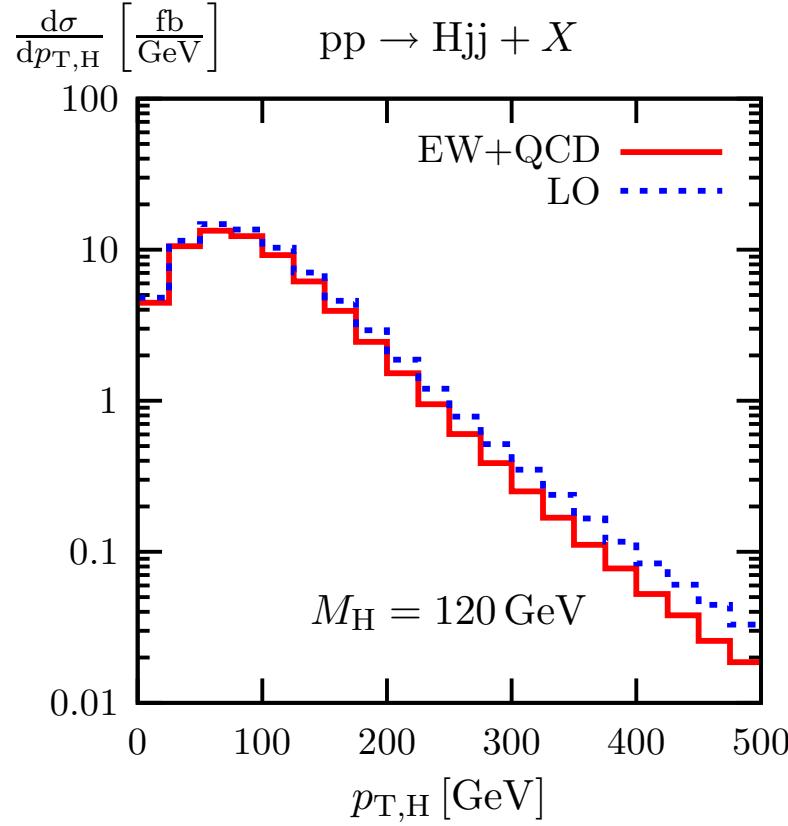
$$\Delta\sigma/\sigma_{LO} = 0.2\%$$

- subtraction:  $10^8$  events, 64 CPU h

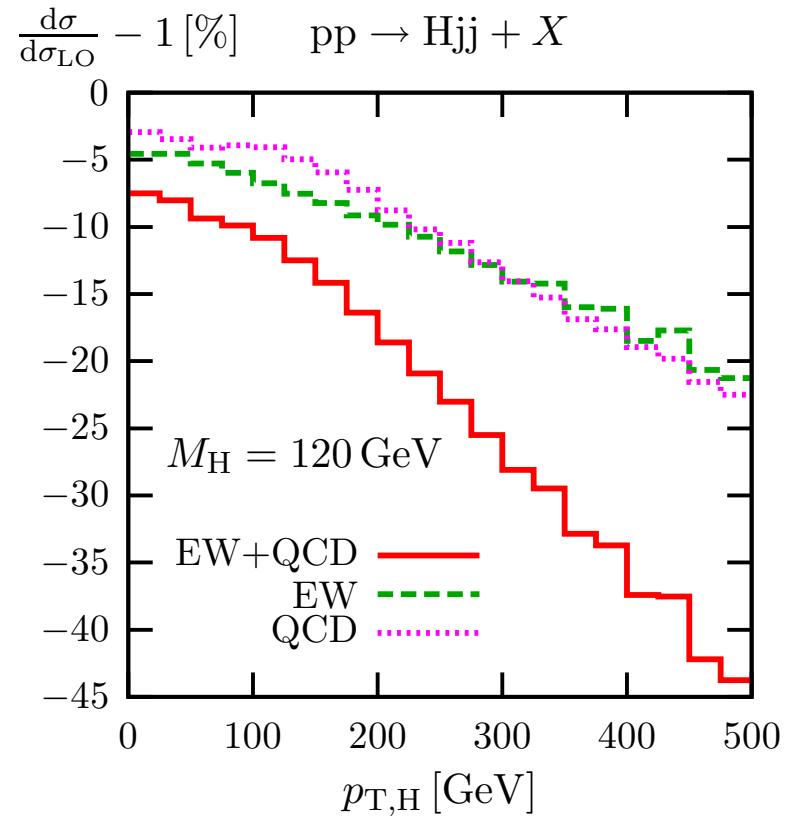
$$\Delta\sigma/\sigma_{LO} = 0.06\%$$

# Distribution in transverse momentum of Higgs boson

## VBF cuts



Ciccolini, Denner, Dittmaier '07

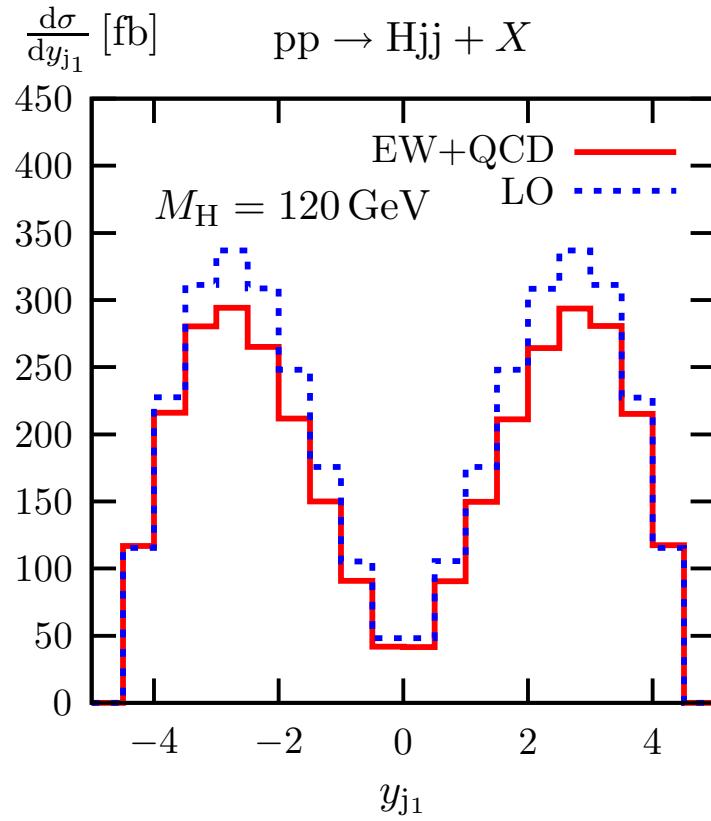


EW and QCD corrections similar

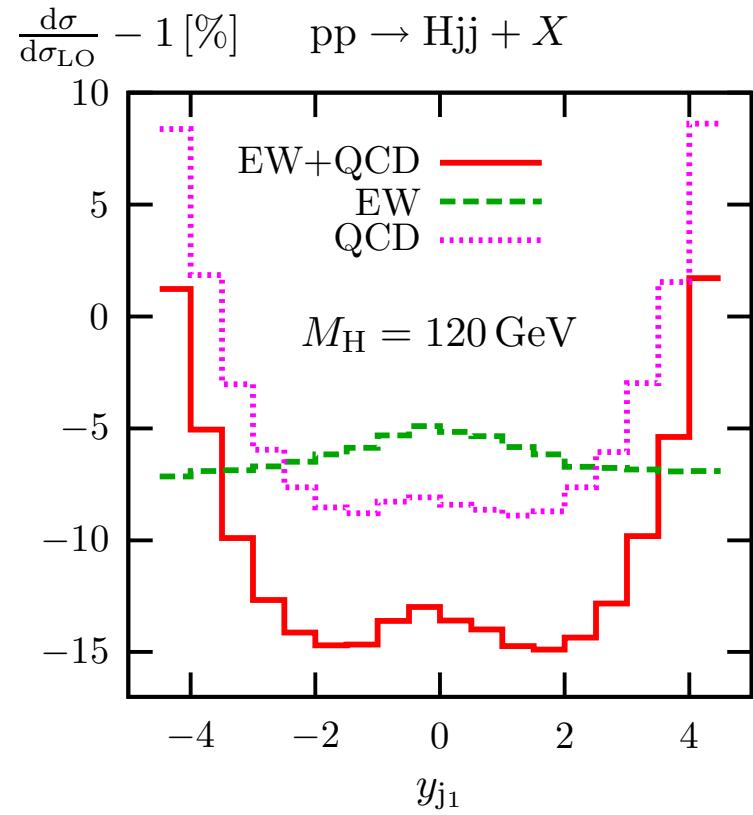
EW corrections  $-20\%$  at  $p_{T,H} = 500 \text{ GeV}$

# Distribution in the rapidity of the harder tagging jet

## VBF cuts



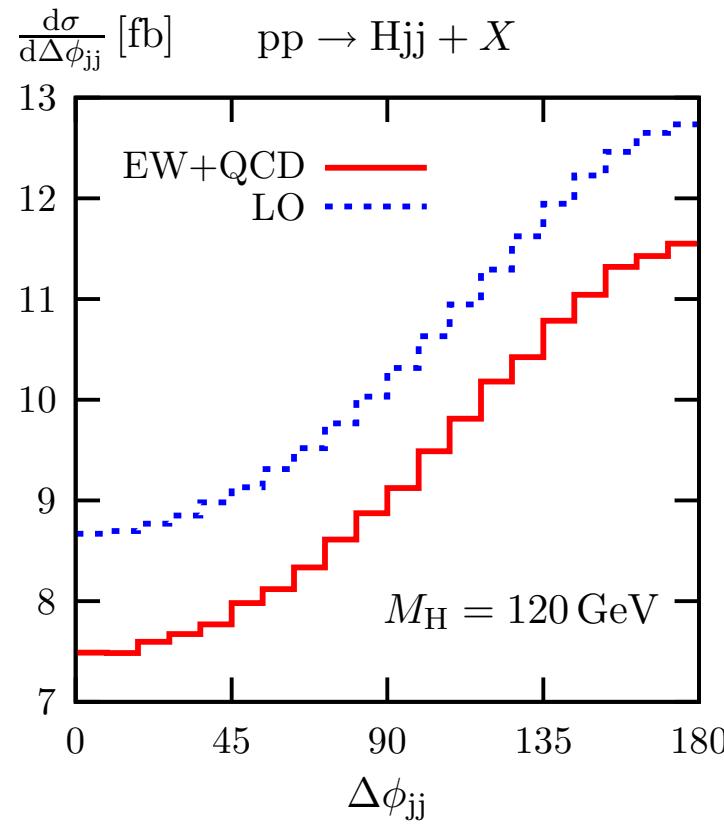
Ciccolini, Denner, Dittmaier '07



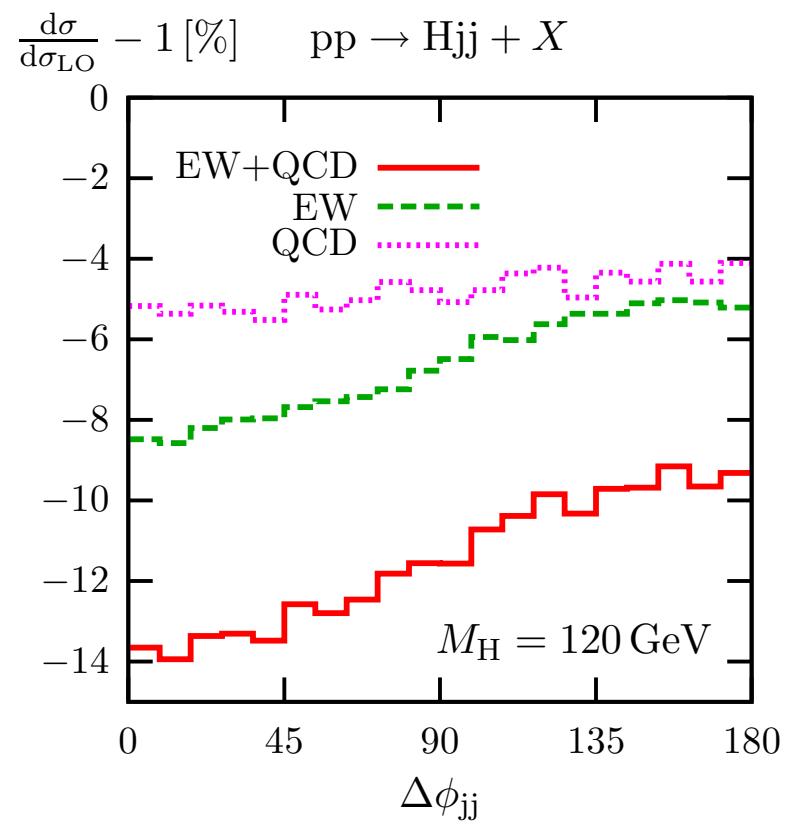
- tagging jets forward–backward
- QCD corrections distort shape significantly
- EW corrections depend only weakly on rapidity  $y_{j_1}$  ( $-4\% -- 7\%$ )

# Distribution in azimuthal angle separation of tagging jets

VBF cuts



Ciccolini, Denner, Dittmaier '07

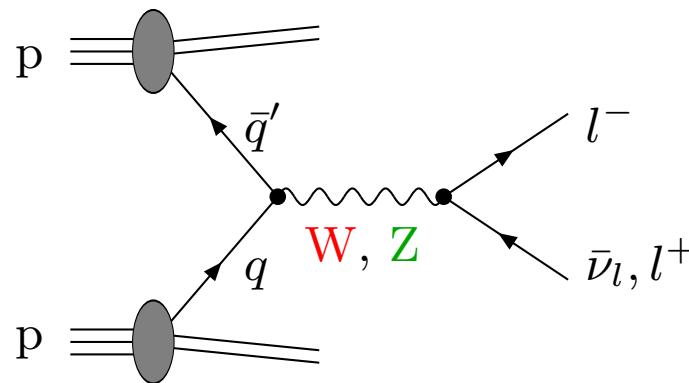


distribution in  $\Delta\phi_{jj}$  sensitive to non-standard HVV couplings Figy, Zeppenfeld '04

EW corrections yield distortion of distribution by 4%

# Single gauge-boson prod.

# Drell–Yan-like W and Z production



**large cross sections:**  $\sigma(W) = 30 \text{ nb}$   
 $\sigma(Z) = 3.5 \text{ nb}$

## Physics goals:

- $M_Z$  → detector calibration by comparing with LEP1 result
- $\sin^2 \theta_{\text{eff}}^{\text{lept}}$  with  $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}} \sim 0.00014$  → comparison with results of LEP1 and SLC
- $M_W$  → improvement to  $\Delta M_W \sim 15 \text{ MeV}$ , strengthen EW precision tests
- decay widths  $\Gamma_Z$  and  $\Gamma_W$  from  $M_{ll}$  or  $M_{T,l\nu_l}$  tails ( $\Delta \Gamma_W \sim 30 \text{ MeV}$ )
- search for  $Z'$  and  $W'$  at high  $M_{ll}$  or  $M_{T,l\nu_l}$
- information on PDFs, determination of collider luminosity

# Known corrections to W/Z production

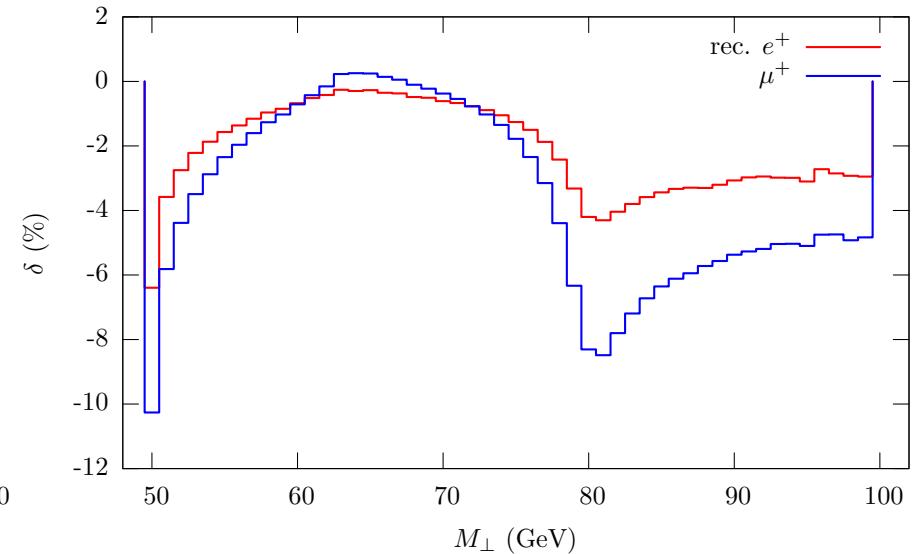
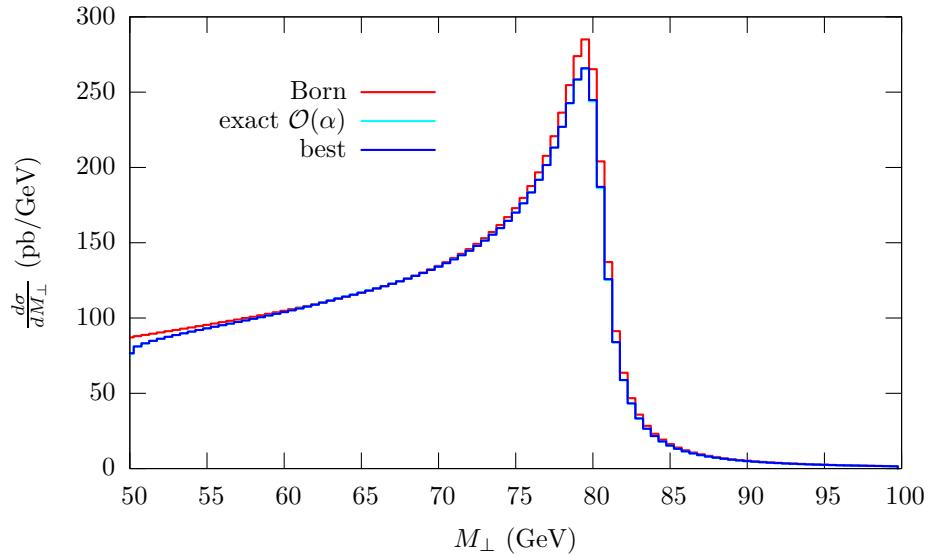
- NLO EW correction to W production  
Baur, Keller, Wackerloth '98; Zykunov '01;  
Dittmaier, Krämer '02; Baur, Wackerloth '04  
Arbuzov et al. '06; Carloni Calame et al. '06
- NLO EW correction to Z production  
Baur, Keller, Sakumoto '97; Baur, Wackerloth '99  
Brein, Hollik, Schappacher '99; Baur et al. '02  
Zykunov '07; Arbuzov et al. '07  
Carloni Calame et al. '07
- multi-photon radiation via leading logs  
Baur, Stelzer '99; Carloni Calame et al. '03, '05  
Placzek, Jadach '03; Brensing et al. '07
- photon-induced processes  
Dittmaier, Krämer '06; Arbusov, Sadykov '07  
Brensing et al. '07
- MSSM NLO corrections to W production  
Brensing et al. '07
- NLO QCD corrections merged with QCD parton showers  
MC@NLO, POWHEG  
Frixione, Webber '02; Frixione, Nason, Oleari '07
- NNLO QCD corrections  
total cross section  
distributions  
residual scale dependence below 1%  
Hamberg, v.Neerven, Matsuura '91;  
v.Neerven, Zijlstra '92; Harlander, Kilgore '02  
Anastasiou et al. '03; Melnikov, Petriello '06  
Catani et al. '09
- soft gluon resummation  
Balazs, Yuan '97; Ellis, Veseli '98  
Landry et al. '02; Cao, Yuan '04

# W transverse mass distribution

transverse mass  $M_{W,T} = \sqrt{2p_\perp^l p_\perp^\nu (1 - \cos \phi_{l\nu})}$

- Jacobian peak at W mass relatively insensitive to QCD ISR

Carloni Calame et al. '06



- final-state photon radiation distorts Breit–Wigner resonance  
logarithmic corrections  $\propto (\alpha/\pi) \log(M_W^2/m_l^2)$   
 $\Rightarrow$  shift in extracted W mass:  $\delta M_W \sim -170(60)$  MeV for  $W \rightarrow \mu\nu(e\nu)$   
partial KLN cancellation for recombined electrons
- full EW  $\mathcal{O}(\alpha)$  corrections:  $\delta M_W \sim 10$  MeV    Baur, Keller, Wackerlo. '99
- multiple final-state photon radiation:  $\delta M_W \sim 10(2)$  MeV    Carloni Calame et al. '04

# Combination of electroweak and QCD corrections

No proper combination of QCD  $\oplus$  EW corrections yet !

- first attempt: combination of soft-gluon resummation with final state QED corrections Cao, Yuan '04 (ResBos-A)
- additive combination of QCD and EW correction Balossini et al. '07, '09

$$d\sigma_{QCD \oplus EW} = d\sigma_{QCD} + \{d\sigma_{EW} - d\sigma_{Born}\}_{HERWIGPS}$$

QCD = MC@NLO Frixione, Webber '02

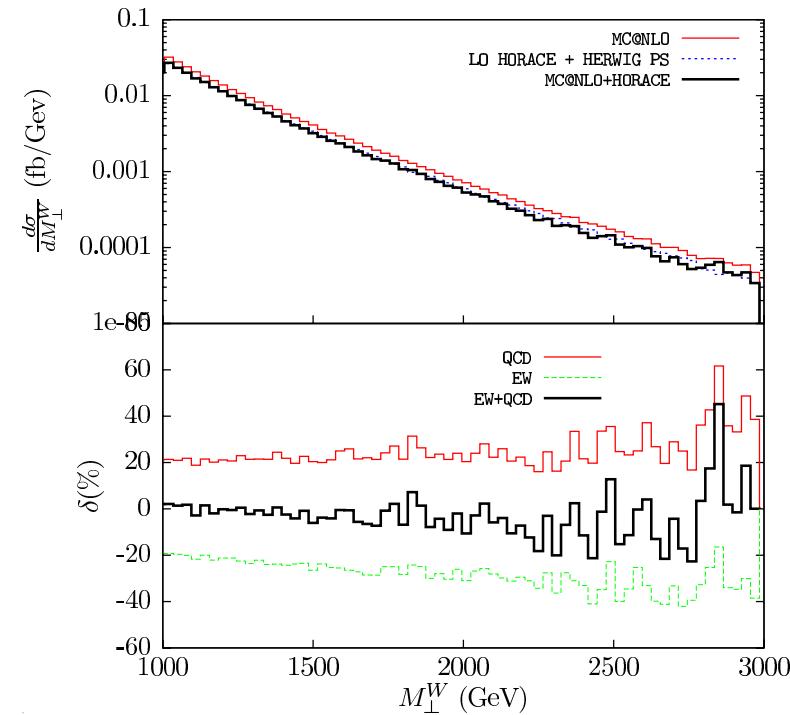
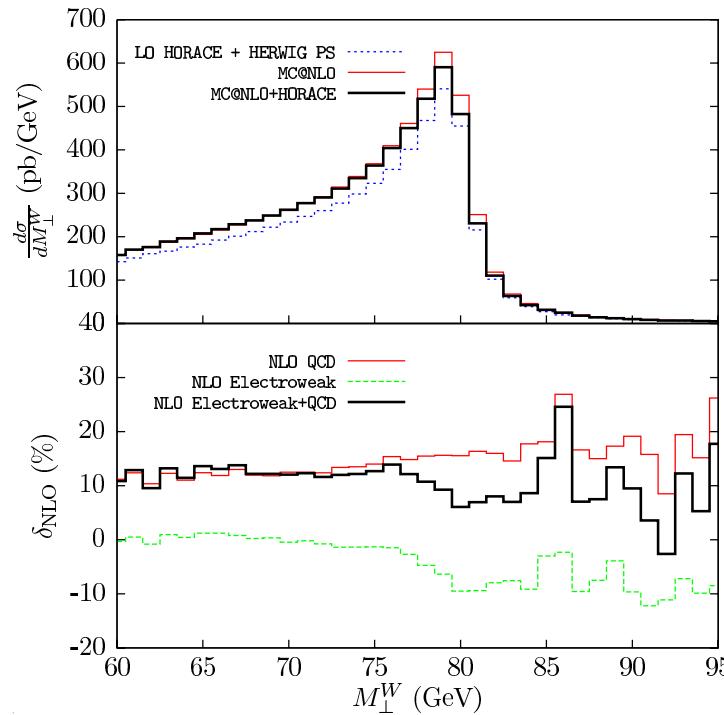
EW = HORACE interfaced with HERWIG QCD PS

$\Rightarrow$  inclusion of some logarithmically enhanced  $\mathcal{O}(\alpha\alpha_s)$  terms  
no hard non-collinear radiation corrections to EW cross section  
no electromagnetic corrections to QCD cross section

- beyond additive approximation full two-loop  $\mathcal{O}(\alpha\alpha_s)$  analysis needed  
virtual  $\mathcal{O}(\alpha\alpha_s)$  for Z production exist Kotikov, Kühn, Veretin '07

# Transverse W-mass distribution

Balossini et al. '08

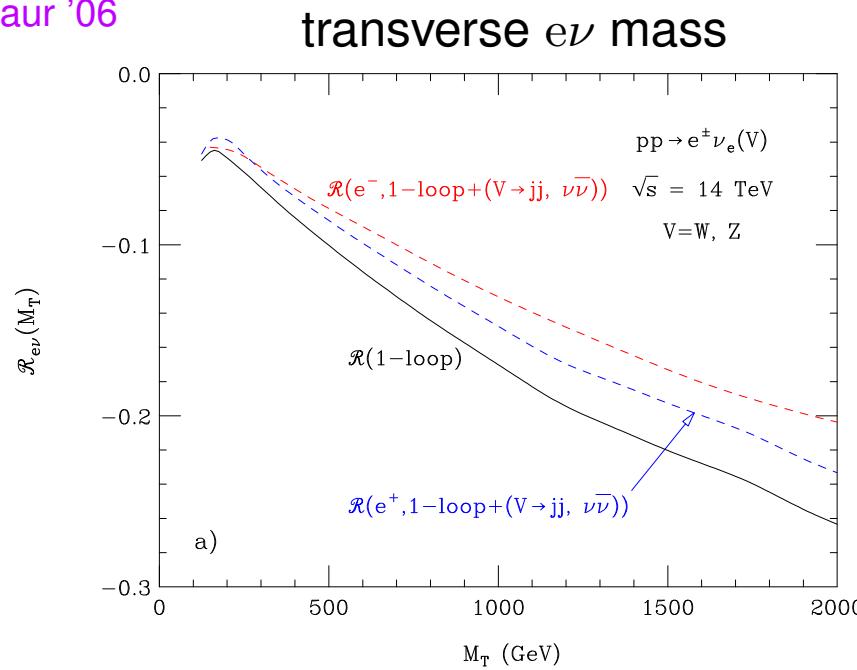


- corrections relative to LO+PS
- $M_{W,T} \sim M_W$ : negative EW corrections compensate positive QCD corrections  
**EW corrections mandatory around Jacobian peak ( $-10\%$ )**
- $M_{W,T} \gg M_W$ : **large negative EW corrections** (Sudakov logarithms)  
cancel positive QCD corrections

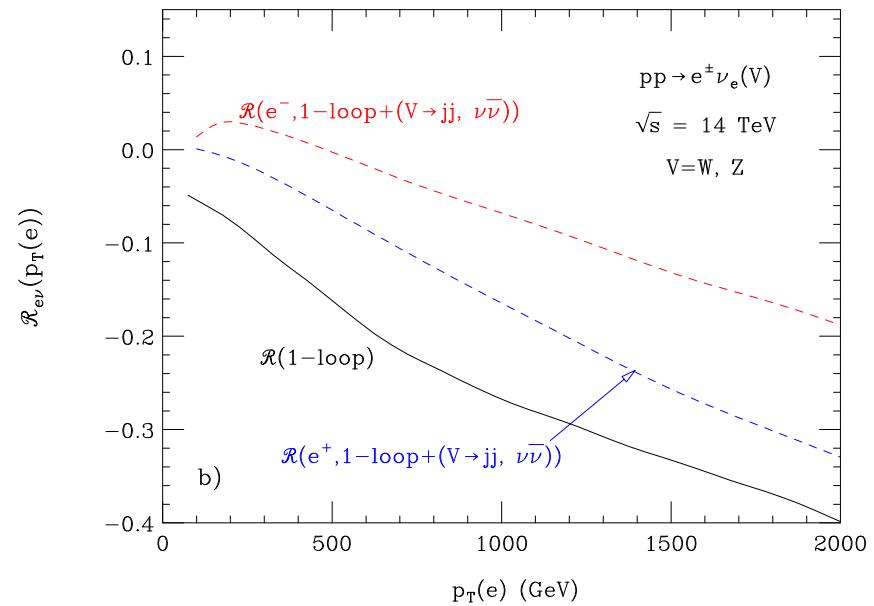
# Effects of real weak-boson radiation

- Virtual EW corrections enhanced by large logarithms at high energy scales
- for realistic cuts real massive gauge-boson radiation partially cancels virtual EW corrections

Baur '06



transverse electron momentum



- $M_T(e\nu) = 2$  TeV: reduction of corrections from  $-26\%$  to  $-23\%/-22\%$
- $p_T(e) = 1$  TeV: reduction of corrections from  $-28\%$  to  $-17\%/-7\%$

# Gauge-boson + jet production

## EW corrections

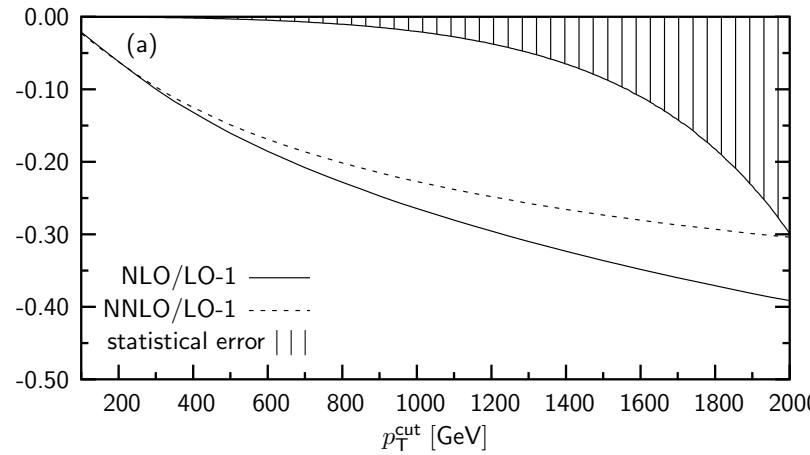
- $\text{pp} \rightarrow V + \text{jet} + X$  ( $V = \gamma, Z$ )

► weak  $\mathcal{O}(\alpha)$  correction Maina, Moretti, Ross '04

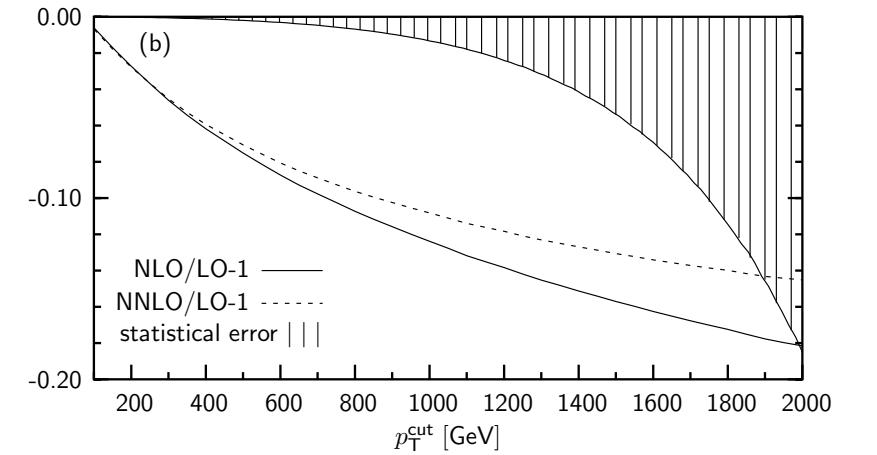
$$\delta_{\text{weak}} \sim -(5-15)\% \text{ for } p_T \lesssim 500 \text{ GeV}$$

► (NLO + NNLL) EW corrections Kühn, Kulesza, Pozzorini, Schulze '04, '05

$$\text{pp} \rightarrow Z + \text{jet} + X$$



$$\text{pp} \rightarrow \gamma + \text{jet} + X$$



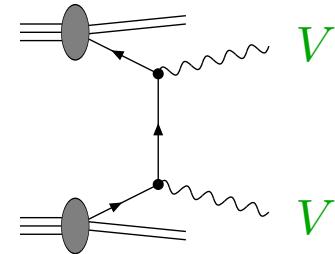
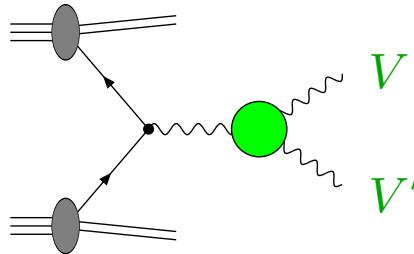
- $\text{pp} \rightarrow W + \text{jet} + X$  Kühn et al. '07; Hollik, Kasprzik, Kniehl '07

$$\delta_{\text{weak}} \sim -30\% \text{ for } p_T \sim 2000 \text{ GeV}$$

photo production appreciably contributes to relative corrections (+10%) Hollik et al.

# Gauge-boson pair prod.

# Gauge-boson pair production



$$V, V' = \gamma, Z, W^\pm$$

$$\sigma(WW) \sim 100 \text{ fb}$$

$$\sigma(W^\pm Z) \sim 30/20 \text{ fb}$$

$$\sigma(ZZ) \sim 15 \text{ fb}$$

## Physics issues:

- triple-gauge-boson couplings at high momentum transfer
- dynamics of longitudinal massive gauge bosons at high energies  
 $W_L, Z_L \sim$  Goldstone bosons  $\rightarrow$  scalar sector  
 strongly interacting longitudinal  $W/Z$  bosons if no Higgs exists  
 $\hookrightarrow$  unitarity requires resonances
- important class of background processes to many searches  
 (e.g.  $H \rightarrow VV \rightarrow 4f$ , supersymmetry)

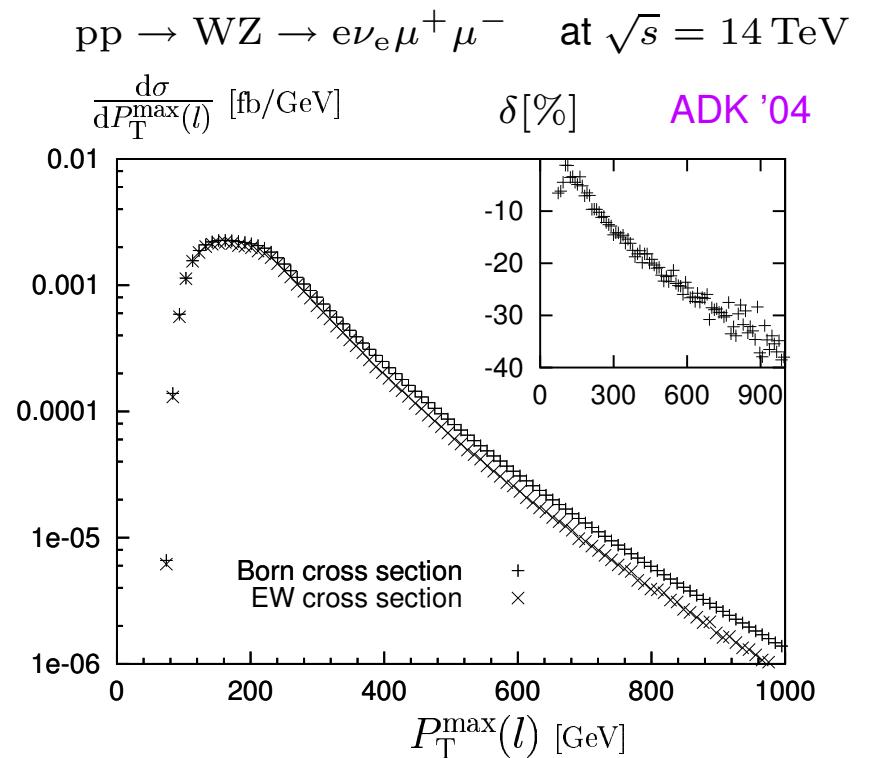
NLO QCD corrections available for full process including leptonic decays

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

# EW corrections to gauge-boson pair production

- $pp(\rightarrow W\gamma) \rightarrow l\bar{\nu}\gamma + X$  Accomando, Denner, Pozzorini '01; Accomando, Denner, Meier '05  
 $\mathcal{O}(\alpha)$  correction in pole approximation  
 $\hookrightarrow \delta \sim -10\% (-27\%)$  for  $p_{T,\gamma} \gtrsim 250 \text{ GeV}$  ( $700 \text{ GeV}$ )
- $pp \rightarrow Z\gamma + X$  Hollik, Meier '04 and  $pp(\rightarrow Z\gamma) \rightarrow ll\gamma + X$  Accomando, Denner, Meier '05  
complete  $\mathcal{O}(\alpha)$  correction for on-shell Z bosons / in pole approximation  
 $\hookrightarrow \delta \sim -10\%$  for  $M_{\gamma Z}$  distribution
- $pp(\rightarrow WW, WZ, ZZ) \rightarrow 4 \text{ leptons} + X$   
Accomando, Denner, Pozzorini '01  
Accomando, Denner, Kaiser '04  
 $\mathcal{O}(\alpha)$  correction in high-energy and pole approximations

large negative EW corrections  
(Sudakov logarithms)  
for large energy scales



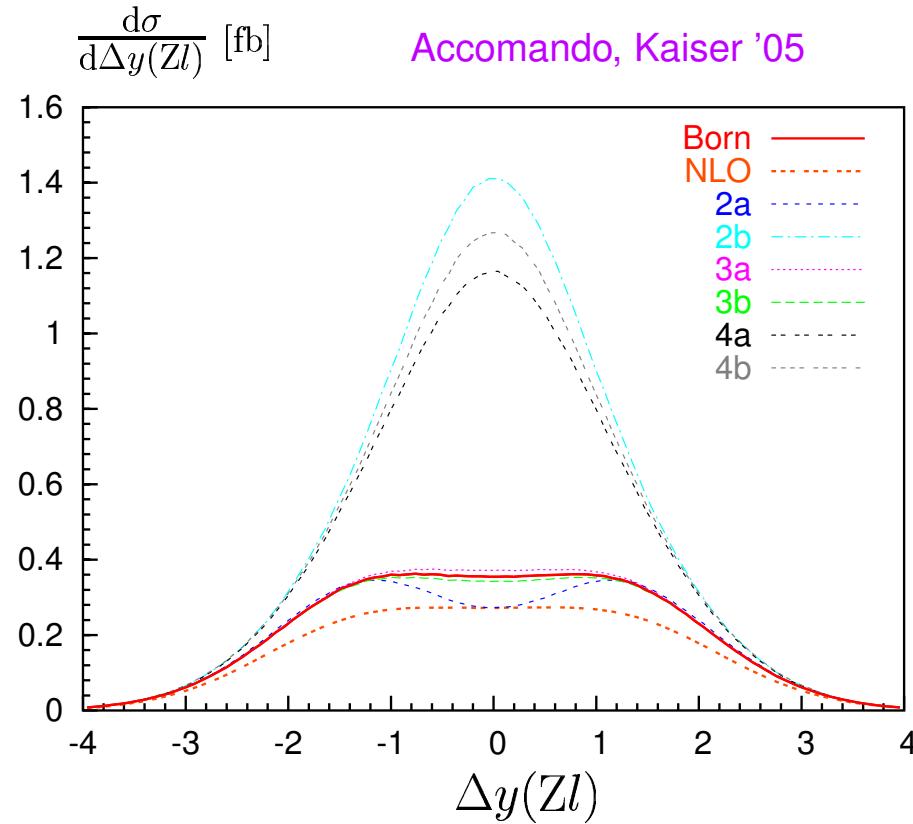
# Electroweak corrections vs anomalous couplings

$pp \rightarrow WZ \rightarrow l\nu_l l'\bar{l}'$ :

distribution in rapidity difference of Z boson and lepton from W decay  $\Delta y(Zl)$

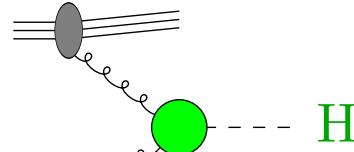
NLO = NLO electroweak:  $\sim -20\%$

2a/2b:  $\Delta g_1^Z = \pm 0.02$ , 3a/3b:  $\Delta \kappa_\gamma = \pm 0.04$ , 4a/4b:  $\lambda = \pm 0.02$

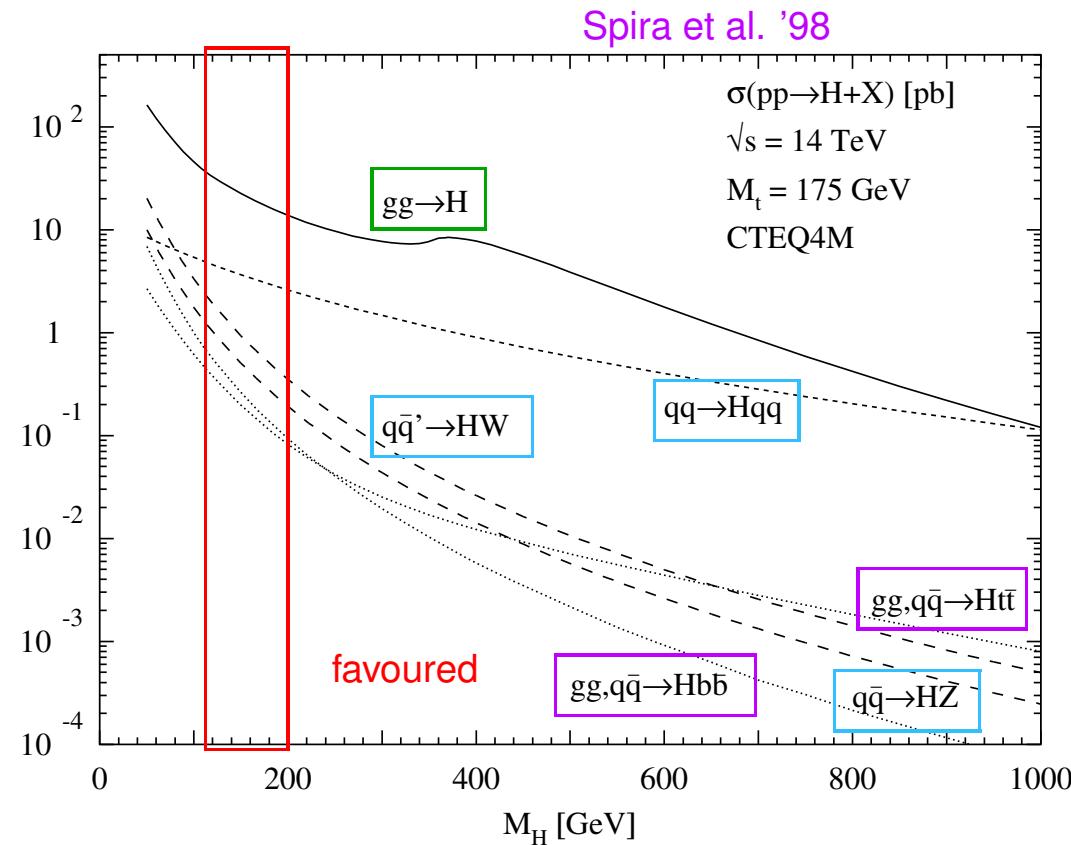
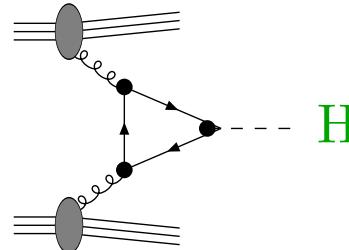


# Higgs prod. in gluon fusion

# Higgs production in gluon fusion



leading diagram



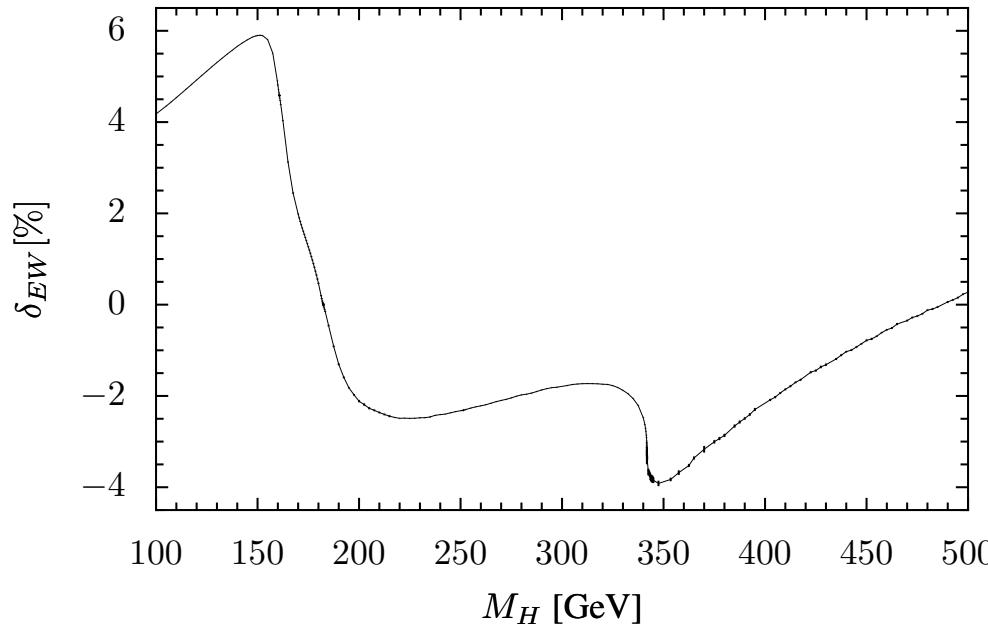
- most important Higgs-production process at LHC
- NLO QCD corrections 80–100% Dawson '91; Djouadi, Spira, Zerwas '91; Spira et al. '95
- NNLO QCD corrections  $\sim 20\%$  Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03

# Two-loop EW corrections to $pp(gg) \rightarrow H$

Actis, Passarino, Sturm, Uccirati '09

- complete set of fermionic and bosonic two-loop diagrams
- exact dependence on  $M_W, M_Z, M_H, m_t$   
previous results based on expansions in  $M_H/M_W$   
Aglietti et al '04, '06; Degrassi Maltoni '04
- consistent description of WW, ZZ and tt thresholds  
based on complex-mass scheme

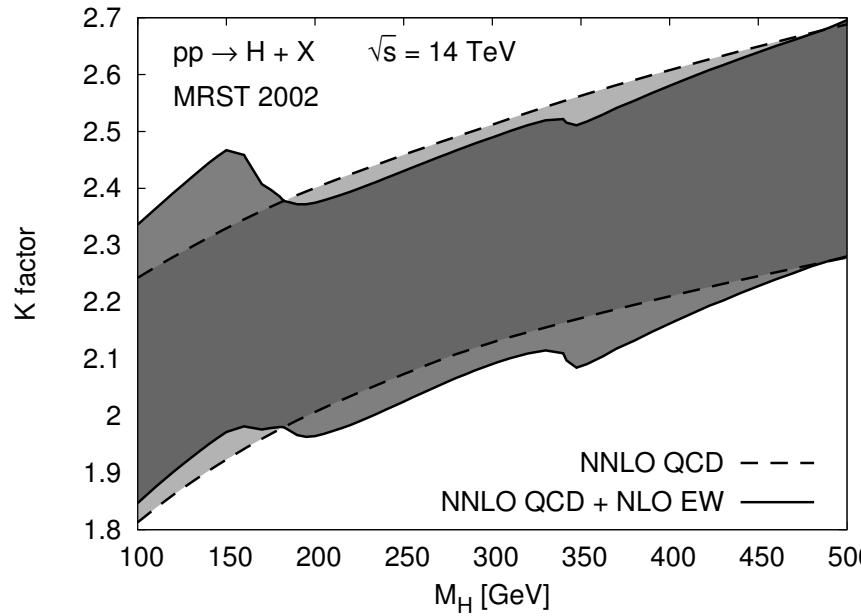
NLO EW corrections to partonic cross section  $\sigma(gg \rightarrow H)$



# Numerical results

NNLO plus two-loop EW result for LHC

- combined with HIGGSNNLO code (NNLO QCD) Catani, Grazzini '07-'08
- NNLO predictions shifted by  $[-3\%, +6\%]$
- largest effect around WW threshold



# Conclusions

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## Electroweak radiative corrections

- typically at level of few % to 10%  
→ important for precision measurements:  $M_W$ ,  $\Gamma_W$ ,  $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ , PDFs, luminosity
- in some kinematic regions NLO EW corrections strongly enhanced
  - ▶ real photon bremsstrahlung distorts leptonic distributions [ $\ln(m_l^2/M_W^2)$ ]
  - ▶ virtual W and Z exchange distorts tail of  $p_T$  distributions [ $\ln(p_T^2/M_W^2)$ ]
- in some cases even NNLO EW corrections relevant

## theoretical status

- methods for multiparticle processes exist
- further improvements desireable/needed
- many results available, more are needed
- combination of QCD and EW corrections required