Exploiting the Weak Boson Fusion at LHC

- Measuring Higgs couplings at LHC
- Weak Boson Fusion in the
  $qq \to qqH \to qqWW$ search
- Selection:
  Forward Jet Tagging, lepton isolation...
- No Higgs scenario?
  Strongly interacting Vector Bosons!
- Conclusions and Outlook

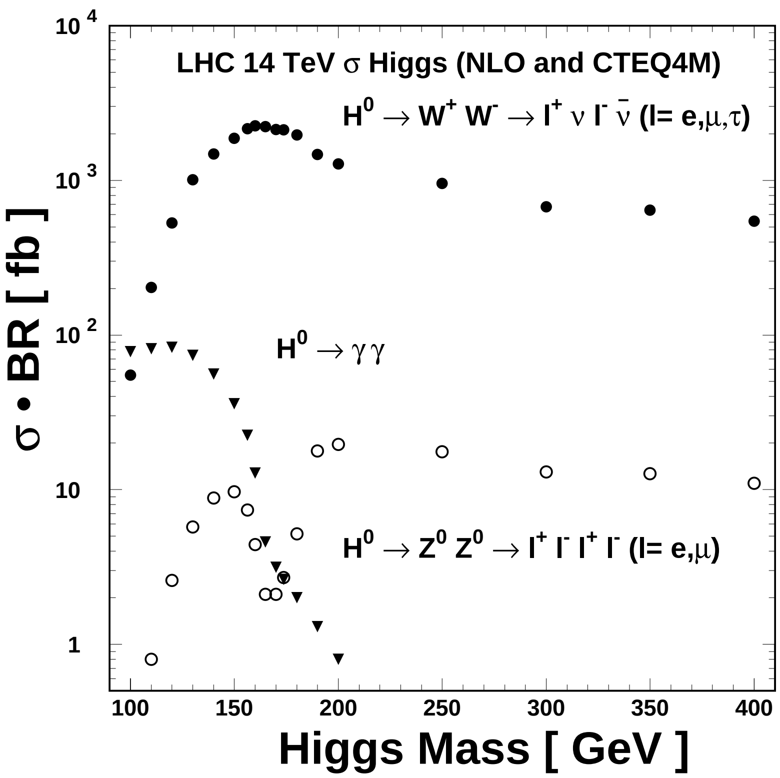
Dario Zürcher, PSI / ETH Zürich
Doktorandenseminar , Oct. 5th 2000

Measuring Higgs boson couplings at LHC

▶ **Main goal:**
assure Higgs discovery for the entire mass range

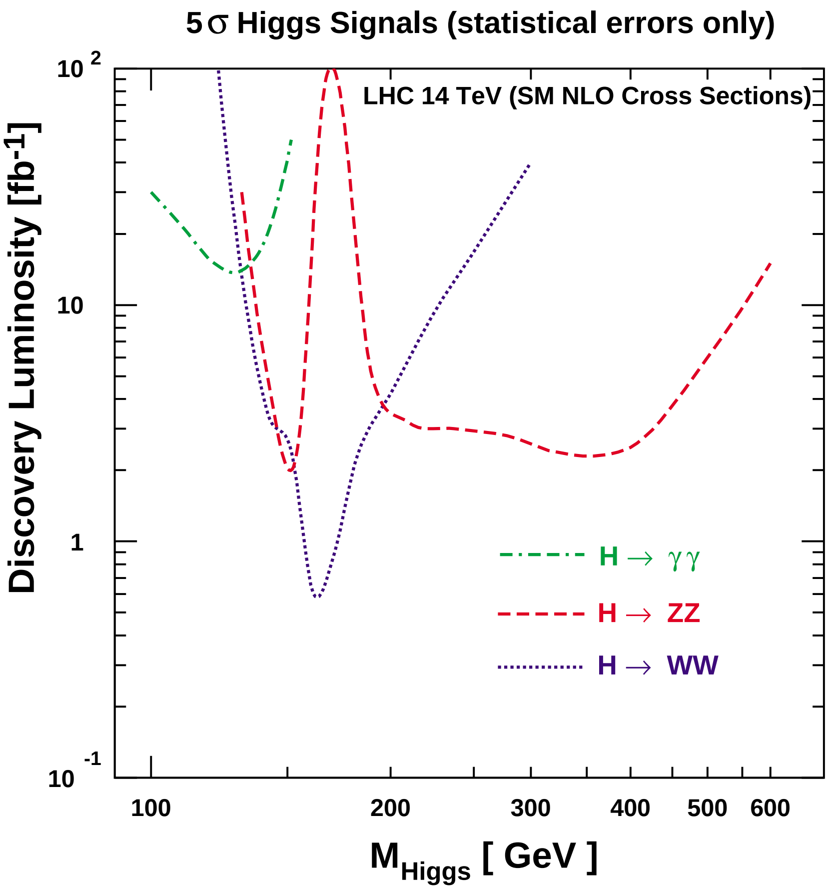
⇒ **Find the observable modes which have the maximal $\sigma \times$BR within the different mass regions.**

For a SM scenario:



⇒ **First studies to optimize the visibility of the signal**

Required Luminosity for a 5 σ Higgs discovery (SM):



Well known:

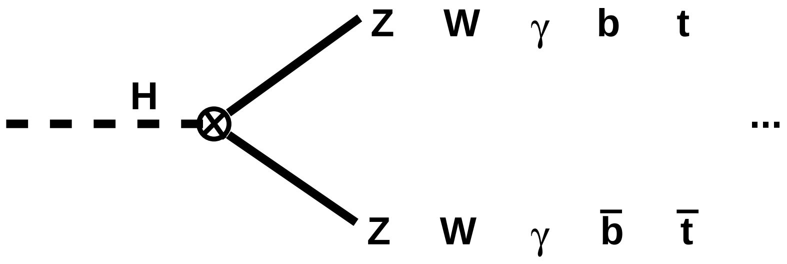
only few accessible search channels for any given boson mass. Possible scenarios, depending on m$_H$:

$pp \to H \to \gamma\gamma$	**m$_H \lesssim$ 150 GeV**
$pp \to H \to ZZ^* \to 4l$	**m$_H \gtrsim$ 130 GeV**
$pp \to H \to WW^* \to l\bar{\nu}\bar{l}\nu$	**m$_H \gtrsim$ 150 GeV**
$pp \to H \to WW \to l\nu q\bar{q}$	**m$_H \gtrsim$ 300 GeV**

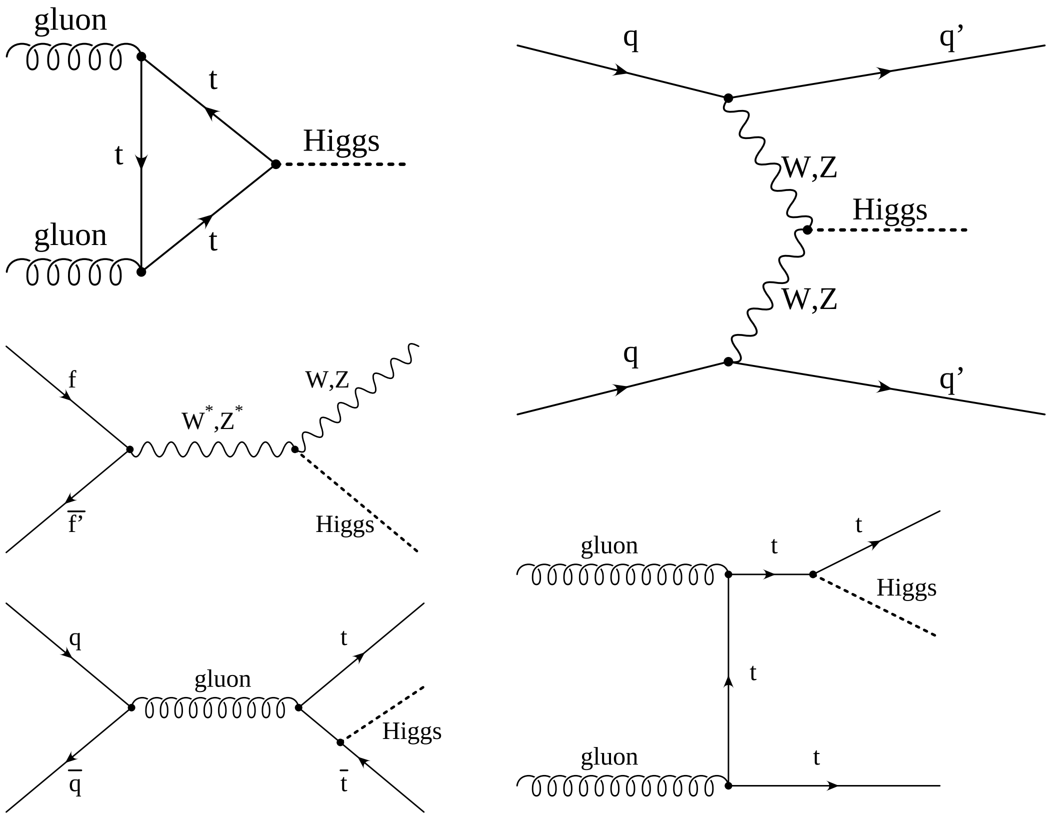
▶ What's next?

Systematic investigation of Higgs boson properties!

⇒ Determination of the couplings to fermions and gauge bosons:



Higgs Production Modes at LHC:



Z. Kunszt, S. Moretti, W.J. Stirling: *Higgs Production at the LHC*

(Published in Z.Phys.C74:479-491,1997)

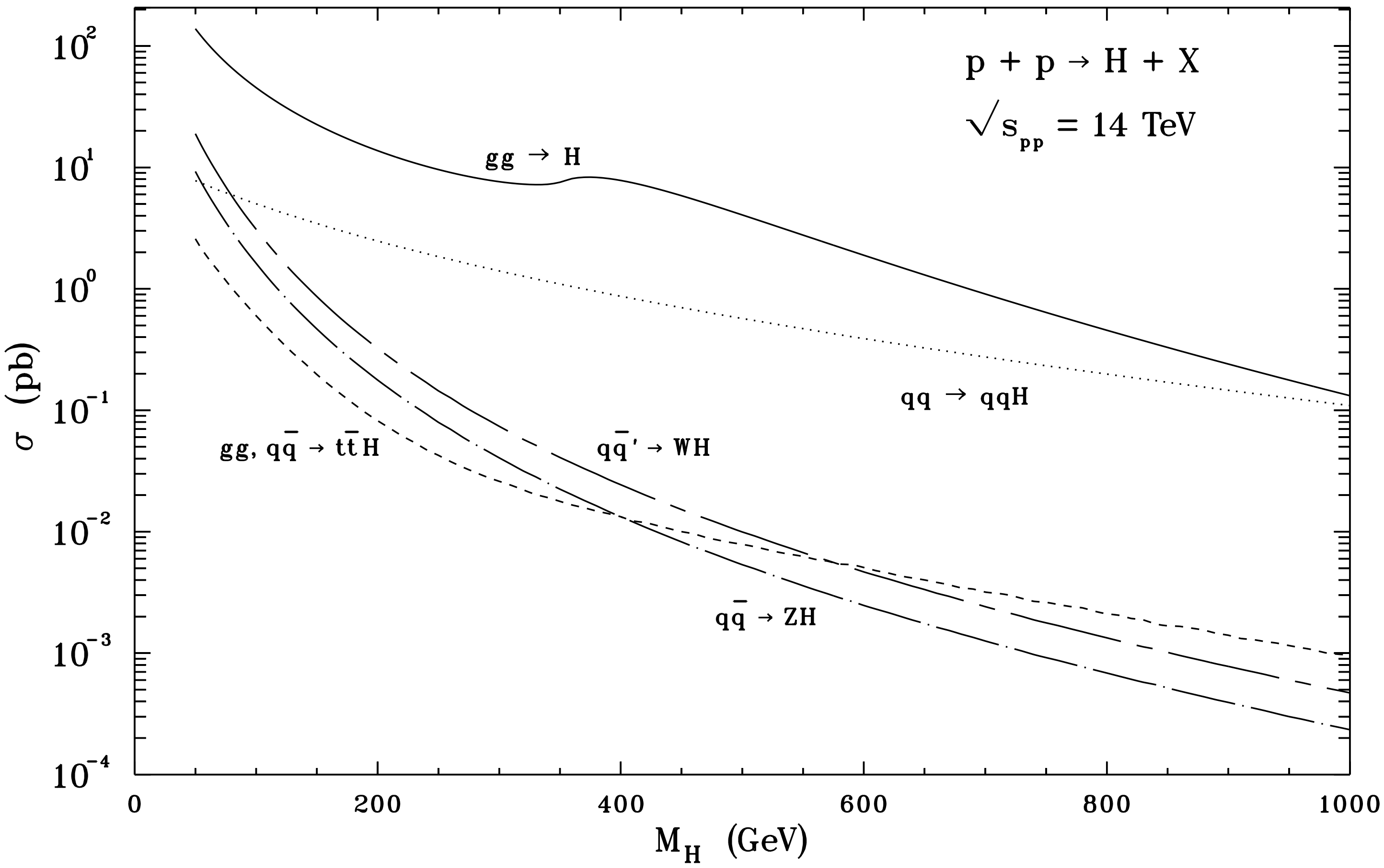


Fig. 5b

NOW (1999):

New studies show: Weak Boson Fusion is a promising Higgs production channel also in the intermediate mass range!!

$qq \to qqH \to jj\gamma\gamma$	$\mathbf{m}_H \lesssim$ **150 GeV**
$qq \to qqH \to jj\tau\tau$	$\mathbf{m}_H \lesssim$ **140 GeV**
$qq \to qqH \to qqWW^* \to jje^{\pm}\mu^{\mp}\ \not{p}_T$	$\mathbf{m}_H \gtrsim$ **120 GeV**

$\Rightarrow$ **Possibility to observe several Higgs production and decay channels, over the entire intermediate mass range**

$\Rightarrow$ **Informations about Higgs couplings to bosons and fermions (ratios of different production channels with same decays):**

$$\frac{\sigma_{f\bar{f}\to H}}{\sigma_{VV\to H}} \sim \frac{\sigma_{gg\to H\to WW\to l\nu l\nu}}{\sigma_{qq\to H\to WW\to l\nu l\nu}}$$

More precisely:

$$\Gamma_f = \Gamma(H \to \bar{f}f) = c_f \frac{g^2_{Hff}}{8\pi}\left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} m_H$$

Ratios of Partial widths $\Rightarrow$ ratios of couplings

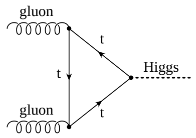
$\frac{\Delta\sigma}{\sigma}(qq \to qqH)\cdot$**BR**$(H \to WW, ZZ, \gamma\gamma)$
$\frac{\Delta\sigma}{\sigma}(gg \to H)\cdot$**BR**$(H \to WW, ZZ, \gamma\gamma)$ } **Statistical Error: 2 - 15 %**

(200 fb^{-1}, $m_H =$ 100-200 GeV)

How can we translate:

MEASURED σ_H $\hookrightarrow$ HIGGS COUPLINGS ?

Partial Widths: $\Gamma_f \equiv \Gamma(H \to \bar{f}f) = c_f \frac{g^2_{Hff}}{8\pi}\left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} m_H$

$\left[\Gamma_g \equiv \Gamma(H \to gg) \cong \Gamma(H \to \bar{t}t)\right.$  $\left.\right]$

Production σ_H:

$$\sigma(gg \to H) = \Gamma_g \frac{\pi^2}{8m_H^3}\tau \int_\tau^1 \frac{dx}{x} g(x, m_H^2) g(\tfrac{\tau}{x}, m_H^2) \qquad \tau = \frac{m_H^2}{s}$$

to be multiplied with the branching fractions for final state j:

BR$(H \to j)$ = $\frac{\Gamma_j}{\Gamma}$ $[\Gamma \equiv$ **total Higgs width**$]$

$\Rightarrow$ **Cross Section measurement** $\sim \frac{\Gamma_i \Gamma_j}{\Gamma}$

Theoretical uncertainties

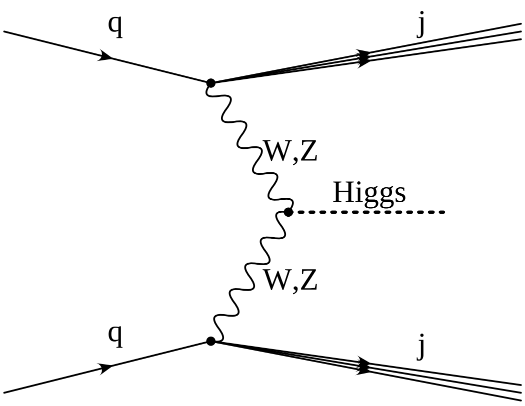
$$\begin{cases} \frac{\Delta\sigma}{\sigma}(gg \to H)^{NLO} & \sim 20\% \\ \frac{\Delta\sigma}{\sigma}(qq \to qqH)^{NLO} & \sim 5\% \end{cases}$$

$\Rightarrow$ **Take Ratios!** $\Rightarrow$ **QCD, PDF, Luminosity uncertainties cancel!**

$$qq \rightarrow qqH \rightarrow jjW^{(*)}W^{(*)} \rightarrow jjl^{\pm}l^{\mp} \not{p}_T$$

"Observing $H \rightarrow W^{(*)}W^{(*)} \rightarrow e^{\pm}\mu^{\mp} \not{p}_T$ in weak boson fusion with dual forward jet tagging at the CERN LHC",
D. Rainwater, D. Zeppenfeld $Phys.Rev.$ D**60** (1999)

Weak Boson Fusion: main features



- **Two very energetic forward jets**
- **Color coherence between initial and final state quarks**
  - $\Rightarrow$ **Suppressed hadron production in the central region**

$\Rightarrow$ **Should allow a large suppression of background processes**

Goal of this new analysis (m_H = 160 GeV):

check the parton-level analysis of Rainwater & Zeppenfeld at Pythia-level (with detector acceptance)

- **Forward Jets Reconstruction**
- **Lepton Isolation**
- **Tau Rejection**

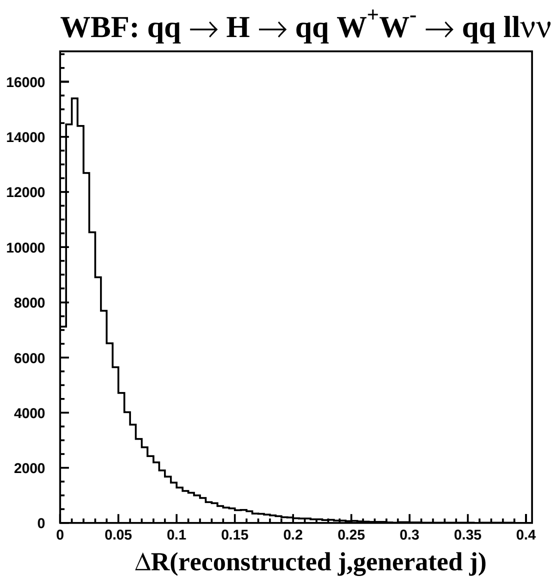
...

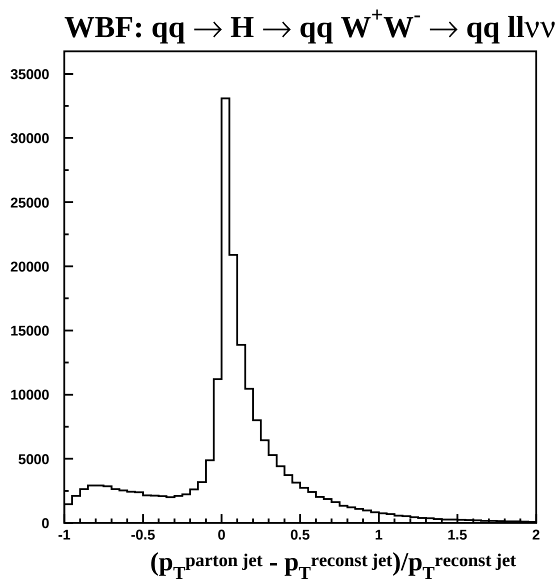
Possible Backgrounds?

Process	Comments
$t\bar{t} \rightarrow WWb\bar{b}$	large σ (BR(t $\rightarrow$ Wb) $\sim$ 100%)
QCD WW + jj	Not included in Pythia!
QED WW + jj	Kinematically similar to the signal
$\tau\bar{\tau}jj$	Tau rejection?

Jet reconstruction

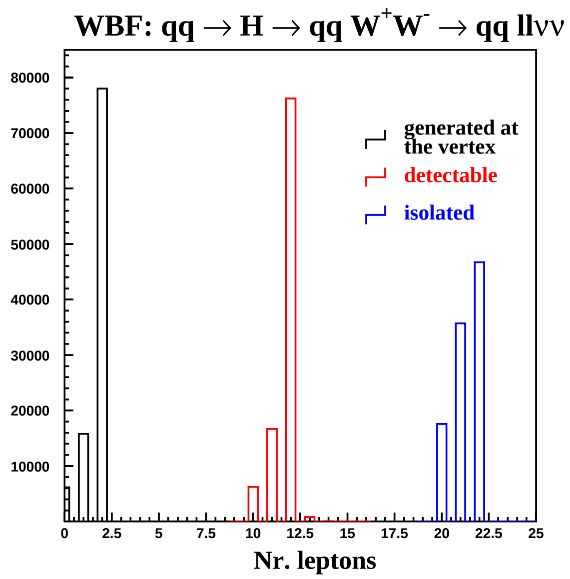
- **Only "detectable" particles are selected:** $|\eta| < 4.5,\ p_T > 0.5$ **GeV**
- **Jets are reconstructed within a cone of R$<$0.6, starting from the particle ($p_T > 5$ GeV) with more "neighbours"**
- **Jets/Taus are selected/rejected depending on the energy shape, charge multiplicity**
- $p_T^{jets} > 20$ **GeV,** $|\eta_{jets}| < 4.5$

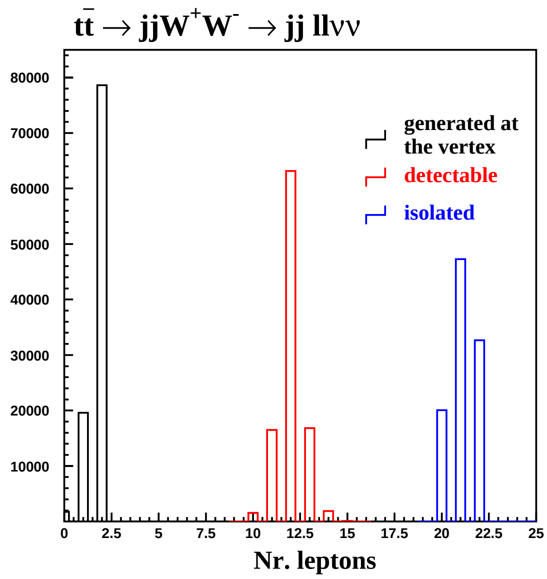




Lepton Isolation

- **Only leptons with** $|\eta| < 2.5,\ p_T > 20$ **GeV**
- **No other particle (except other leptons) close to the candidate**
- $m_{\rm cone} < 2$ **GeV**
- $E_l > 90\% \cdot E_{tot}$ **in a cone with R $<$ 0.5**





Jet-Lepton & Jet-Jet separation

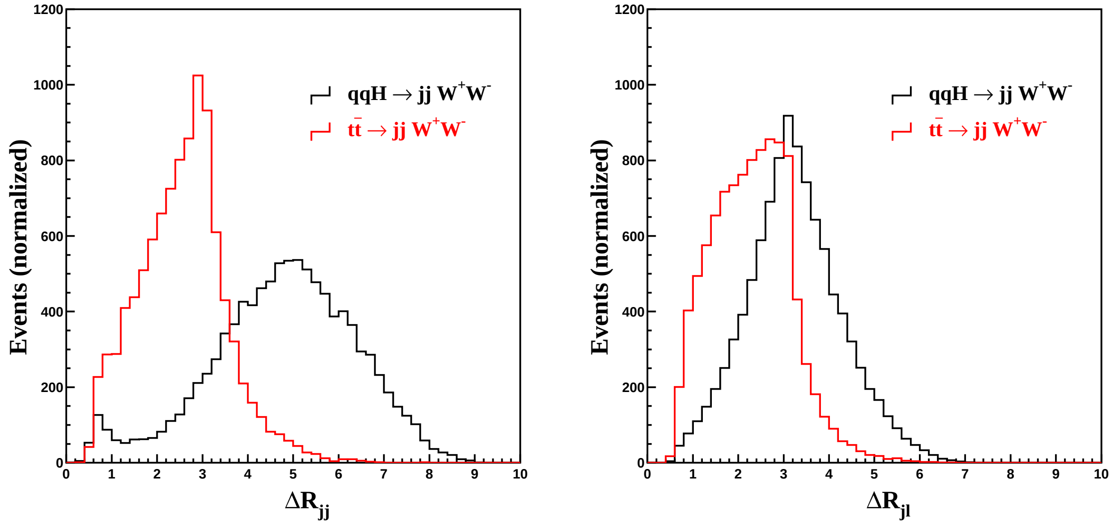
▶ **QCD WWjj:**

weak boson bremsstrahlung occurs at small angles relative to parent quarks

$$\Rightarrow \quad \eta_{j,min} + 0.7 < \eta_{l_{1,2}} < \eta_{j,max} - 0.7 \quad , \quad \eta_{j1} \cdot \eta_{j2} < 0$$

▶ **Wide separation between tagging jets:**

$$\Rightarrow \quad \Delta\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4$$



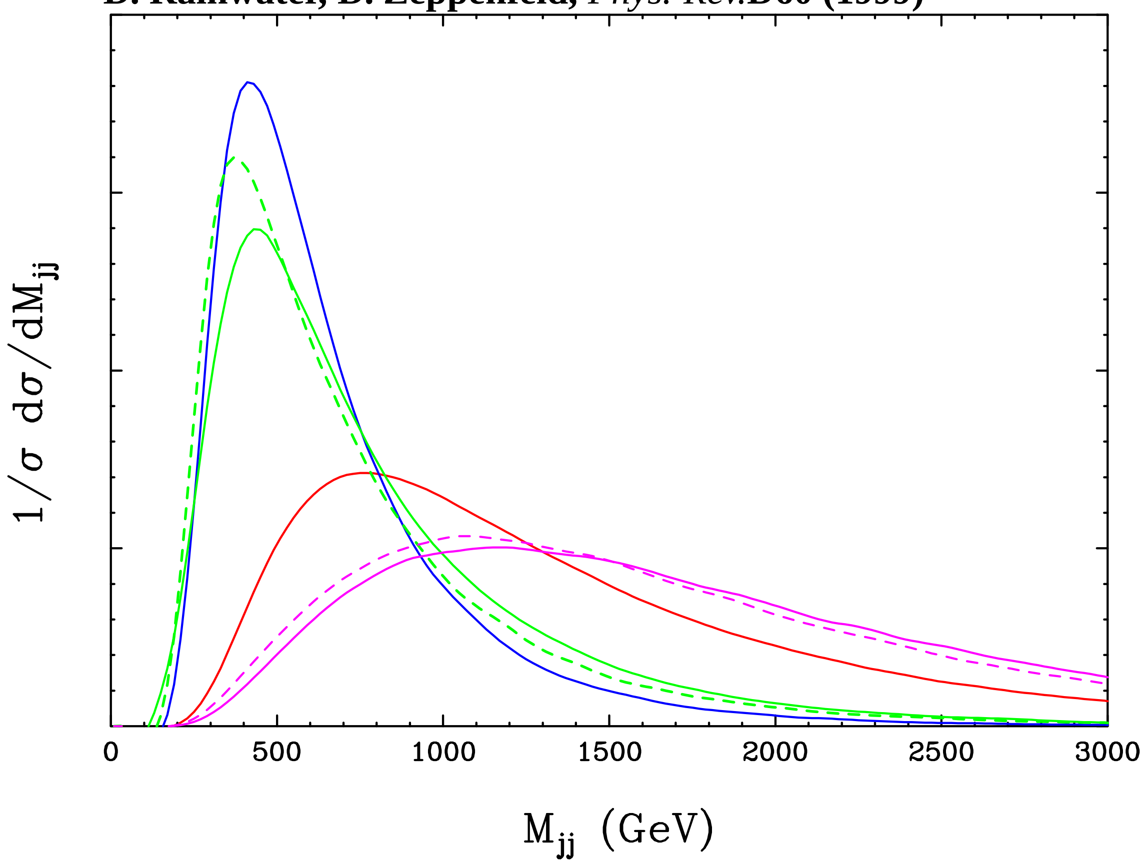
▶ **Suppress most of the $t\bar{t}$-background by vetoing events with other jets between the tagging ones**

▶ **Dominance of low-x gluons within the protons**

$\Rightarrow$ **QCD processes occur at smaller invarant masses than EW processes**

$\Rightarrow$ **Lower bound on m$_{jj}$:** $m_{jj} > 650$ **GeV**

D. Rainwater, D. Zeppenfeld, *Phys. Rev.* **D60 (1999)**



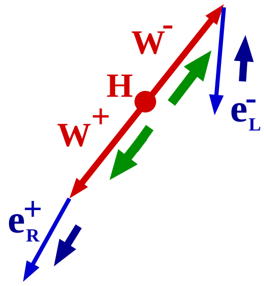
— Signal — $t\bar{t} + jets$ — QCD $WWjj$

— EW $WWjj$ - - QCD $\tau\tau + jj$ - - EW $\tau\tau + jj$

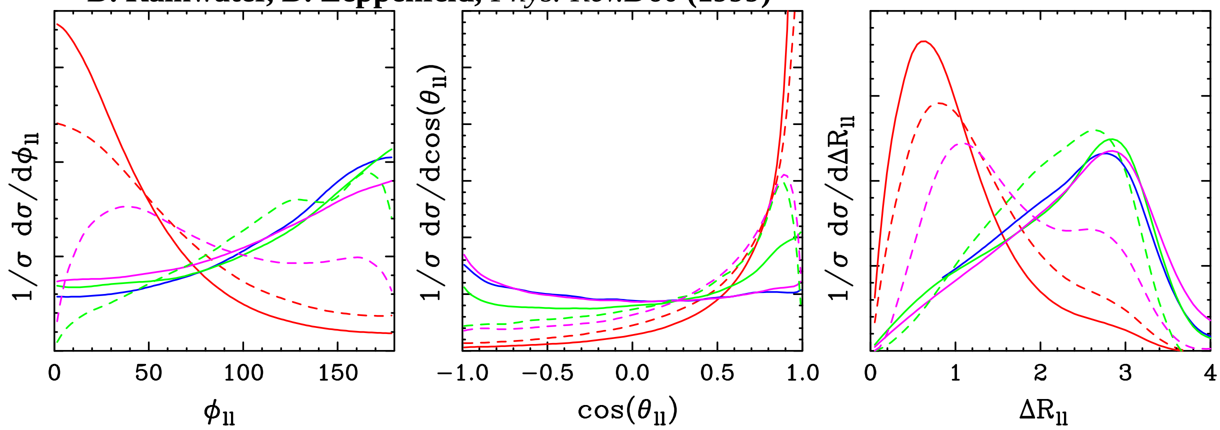
- W^+W^- **spin correlations and V-A structure of the W-decays**

  $\Rightarrow$ **leptons preferentially emitted in same direction:**

  $\phi_{ll} < 105^o \;,\; cos\theta_{ll} > 0.2 \;,\; \Delta R_{ll} < 2.2$



D. Rainwater, D. Zeppenfeld, *Phys. Rev.***D60 (1999)**

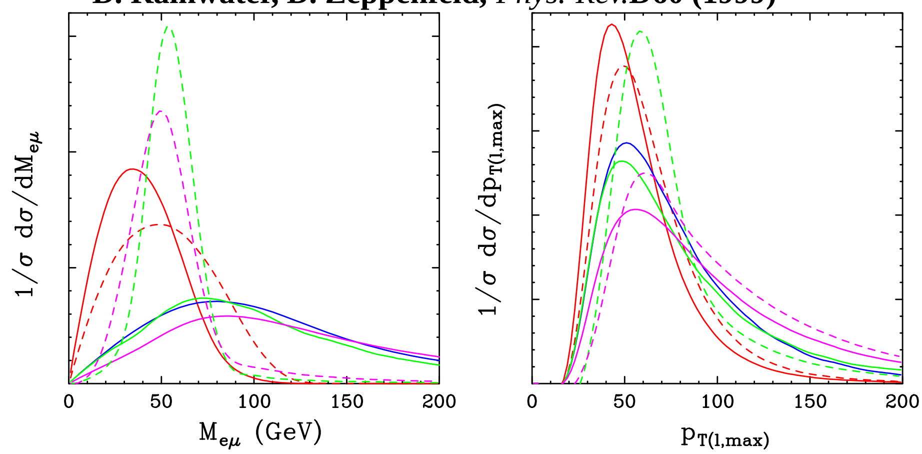


- p_T **and** m **cuts on lepton-pairs:**

  $m_{ll} < 110$ **GeV** $\;,\; p_{T_{ll}} <$**120 GeV**

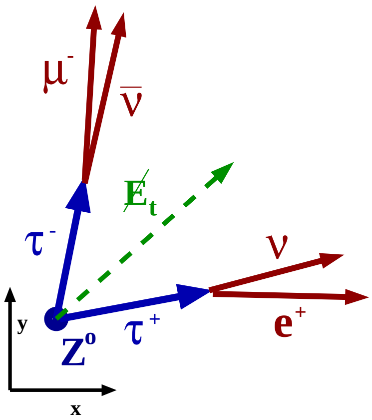
(QCD and EW background prefer significantly higher values)

D. Rainwater, D. Zeppenfeld, *Phys. Rev.***D60 (1999)**



▶ **QCD and EW $Z/\gamma \to \tau\tau jj$ background:**

<u>Z or γ with high-p_T</u>

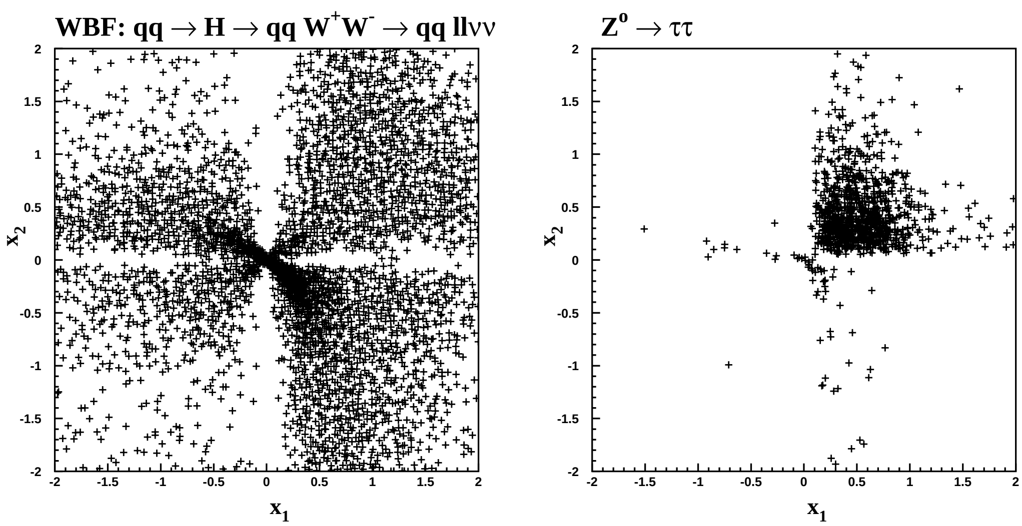


> **⇒ large τ boost**
> **⇒ τ decay products nearly collinear**

Fractions of τ energy carried by each lepton:

$$x_{\tau_1} = \frac{p_x^{l_1} \cdot p_y^{l_2} - p_x^{l_2} \cdot p_y^{l_1}}{p_y^{jets} \cdot p_x^{l_2} - p_x^{jets} \cdot p_y^{l_2}} \;,\; x_{\tau_2} = \frac{p_x^{l_2} \cdot p_y^{l_1} - p_x^{l_1} \cdot p_y^{l_2}}{p_y^{jets} \cdot p_x^{l_1} - p_x^{jets} \cdot p_y^{l_1}}$$

Real τ decays: $\not{p}_T$ vector lies between the 2 leptons
⇒reconstruction yields $0 < x_{\tau_1}, x_{\tau_2} < 1$



⇒ Suppress background by vetoing events with:

$x_{\tau_1}, x_{\tau_2} > 0$ **,** $m_Z - 25$ **GeV** $< m_{\tau\tau} < m_Z + 25$ **GeV**

Signal rates

	Rainwater & Zeppenfeld (fb)	Pythia (Parton Level) (fb)	Pythia (Full showering) (fb)	$t\bar{t} + jets$ Background (fb)
$\sigma \times$BR	$\sim$125	140.4	140.4	-
2 Isolated leptons + $\geq$2 jets	-	-	65	-
forward tagging	17.1	16.8	7.7	1080
m_{jj} and angular cuts (V-A)	11.8	11.7	4.9	5.5
real τ rejection	11.4	11.3	4.6	5.1
tag ID efficiency +no minijet	7.5	-	-	1.1

▶ **Expected events and significance for 5 fb^{-1}:**

m_H (GeV)	130	160	180	200
N_{events}	8.8	37.5	29.9	16.3
σ_{Gauss}	2.6	9.0	7.5	4.5

Higher masses regions: Strongly Interacting Vector Bosons?

- **No light Higgs found?**

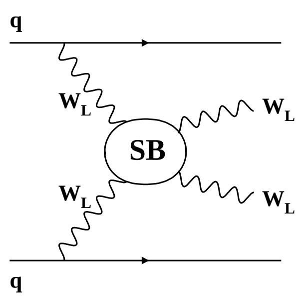
  $\Rightarrow$ **Something should happen before the $\sim$ TeV scale (Unitarity!)**

- **Longitudinally polarized Weak Bosons are a direct consequence of the Higgs Mechanism**

  $\Rightarrow$ **If $m_H \gg 2m_W$: $V_L V_L$ scattering becomes strong!**
  ($H \rightarrow V_L V_L$ dominates over $H \rightarrow V_T V_T$)

- **Any deviation from the predicted SM cross section**

  $\Rightarrow$ **important informations on the nature of symmetry breaking and new physics!**
  (if the Higgs particle is not found)

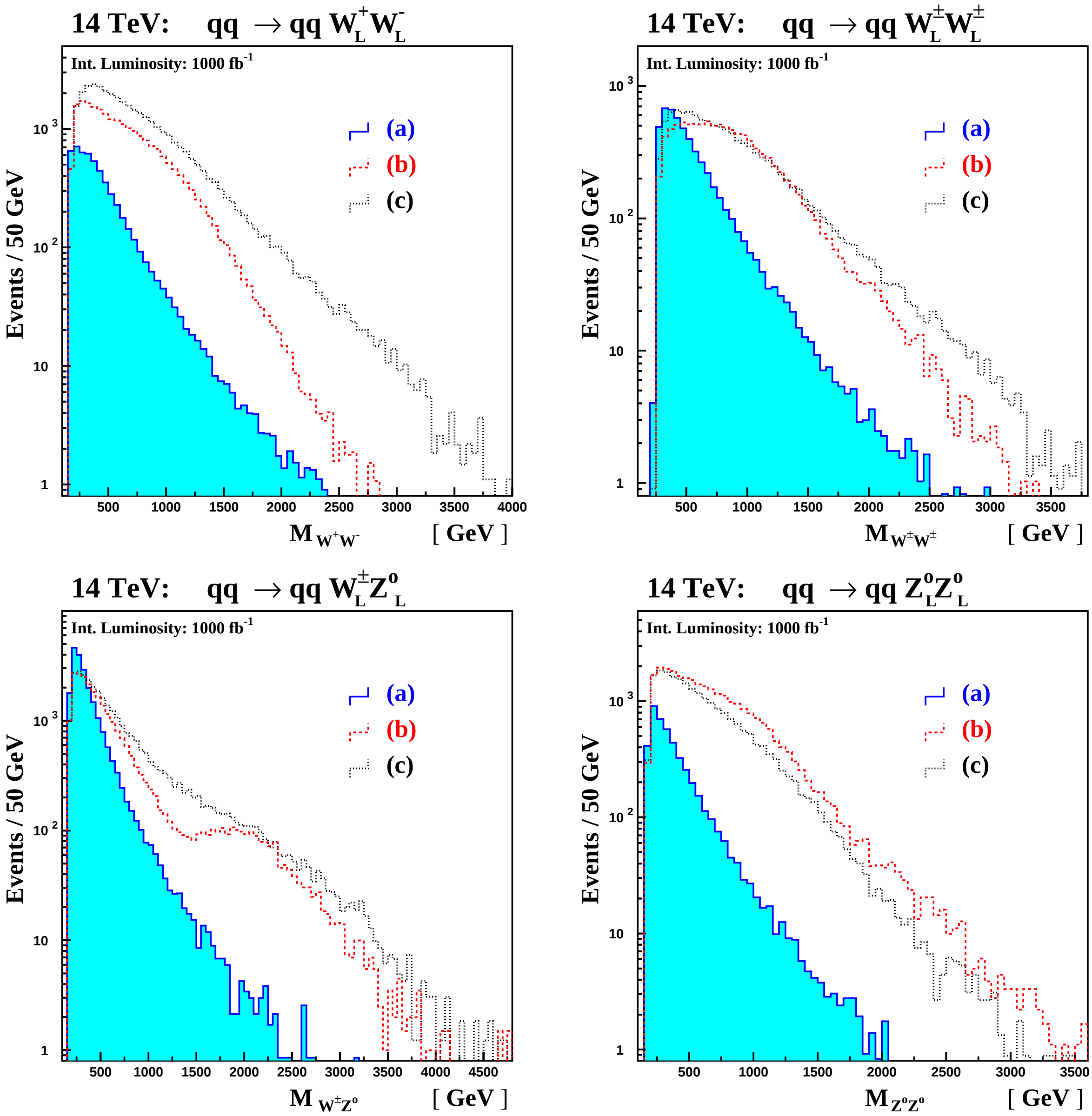


$$\sqrt{s} \longrightarrow \infty$$

$$\sigma \longrightarrow \infty$$

$\Rightarrow$ Exploit the Forward Jet Tagging!

No light Higgs?
Strong VV scattering...



(a) SM scenario with light Higgs (m_H=170 GeV)

(b) non Higgs scenario (resonant) [Dobado, Herrero, Terron]

(c) non Higgs scenario (non-resonant) [Dobado, Herrero et al.]

SUMMARY AND OUTLOOK

- **After Higgs discovery:**

  Weak Boson Fusion will provide new channels for the study of the Higgs couplings

- **Particularily:**

  the qqH **with** $H \to WW \to e^{\pm}\mu^{\mp}\ \not{p}_T$**, for** m_H**=130-200 GeV, has a virtually background-free environement, thanks to the powerful suppression allowed by the very energetic forward jets**

- **The ability to measure strong WW scattering confers a no-loose capability to establish mass scale and strenght of symmetry breaking**