# Higgs Production at LHC

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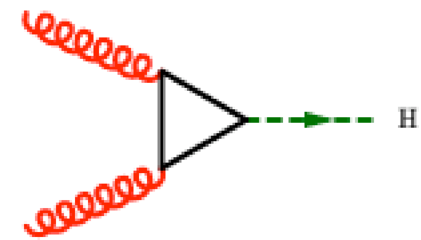
Roma 21 ottobre 2004

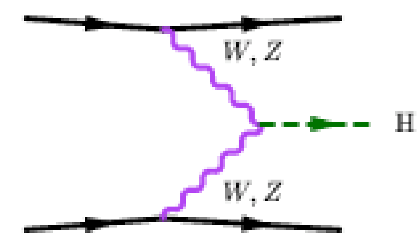
# Higgs Production Modes at LHC

In proton collisions at 14 TeV, and for $M_H > 100 \text{ GeV}$ the Higgs is produced mostly via

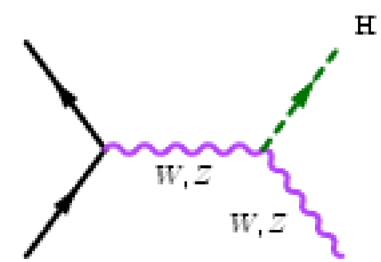
- gluon fusion $gg \rightarrow H$
  - largest rate for all $M_H$
  - proportional to the top Yukawa coupling $y_t$



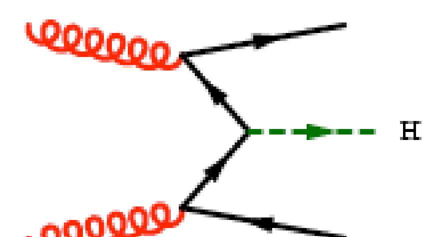

- weak-boson fusion (WBF) $qq \rightarrow qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



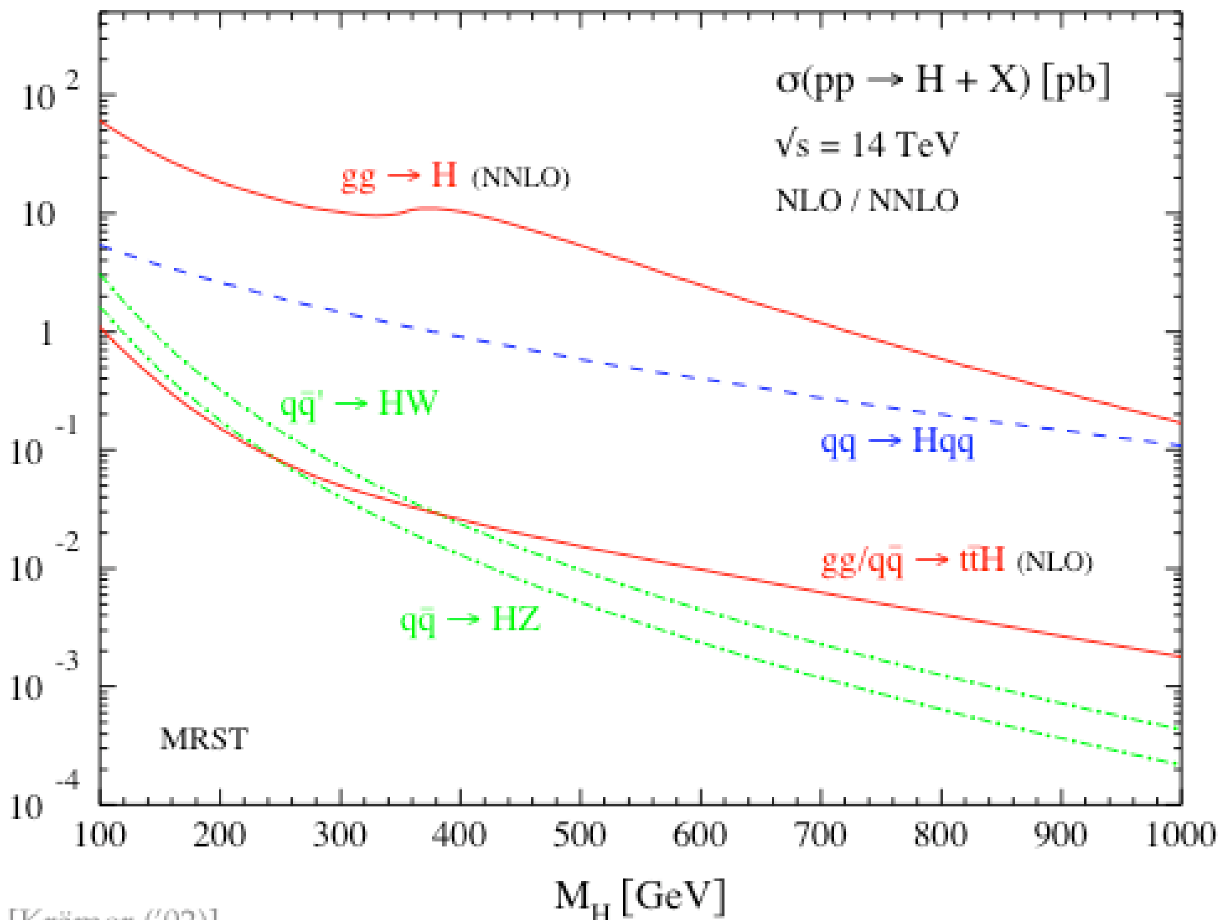

- Higgs-strahlung $q\bar{q} \rightarrow W(Z)H$
  - third largest rate
  - same coupling as in WBF




- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher $x$ range
  - proportional to the heavy-quark Yukawa coupling $y_Q$



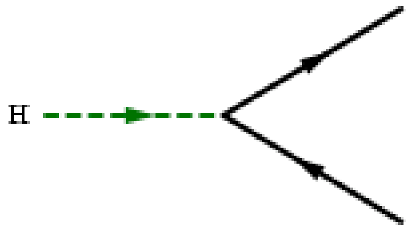
# HIGGS PRODUCTION AT LHC



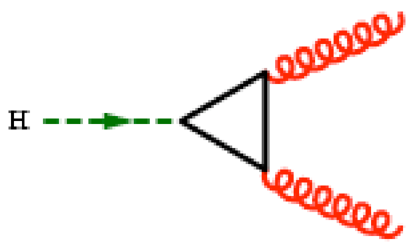

[Krämer ('02)]

- in the intermediate Higgs mass range $M_H \sim 100 - 200$ GeV
  - gluon fusion cross section is $\sim 20 - 60$ pb
  - WBF cross section is $\sim 3 - 5$ pb
  - $WH, ZH, t\bar{t}H$ yield cross sections of $\sim 0.2 - 3$ pb

# Higgs Decay Modes at LHC

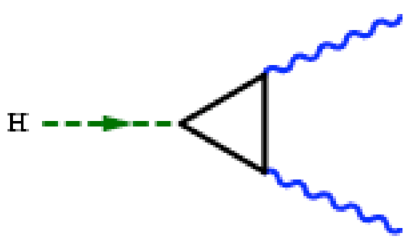


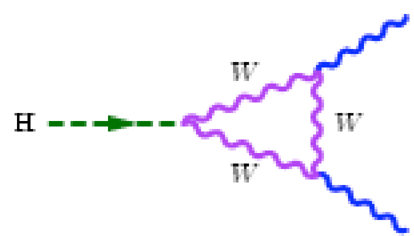

proportional to the Yukawa coupling squared, and thus to $m_f^2$



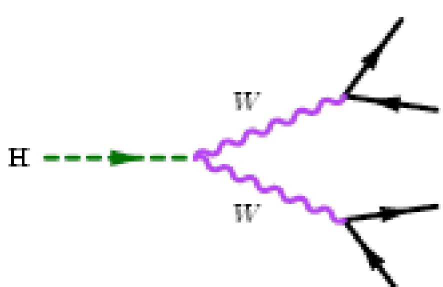

proportional to $m_f^4/m_H^4$

but dominated by top quark Yukawa coupling



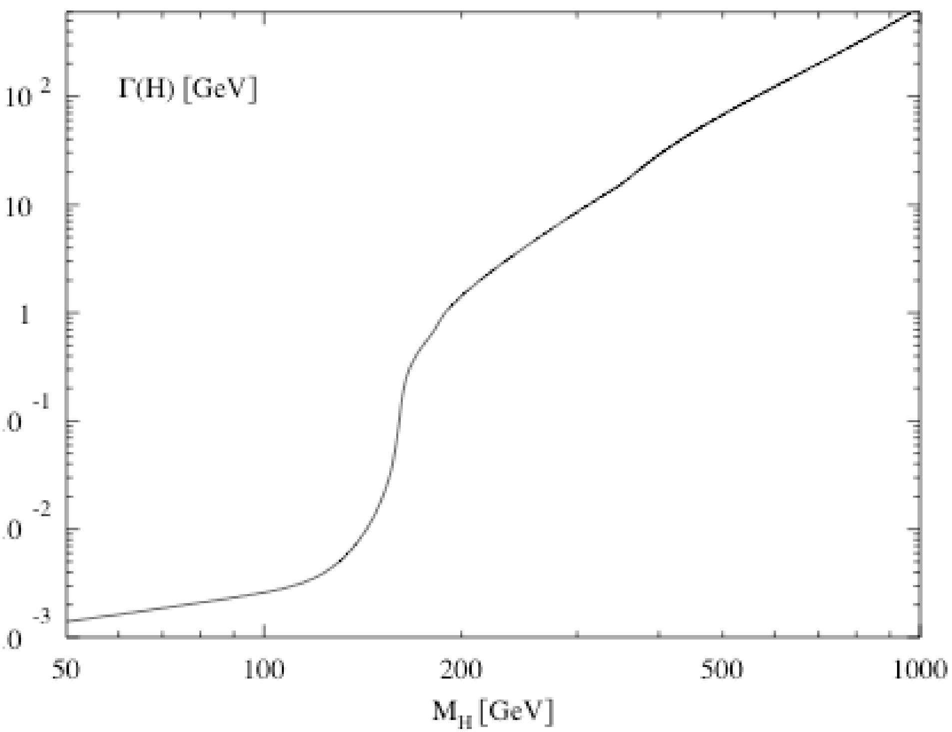

dominated by EW coupling

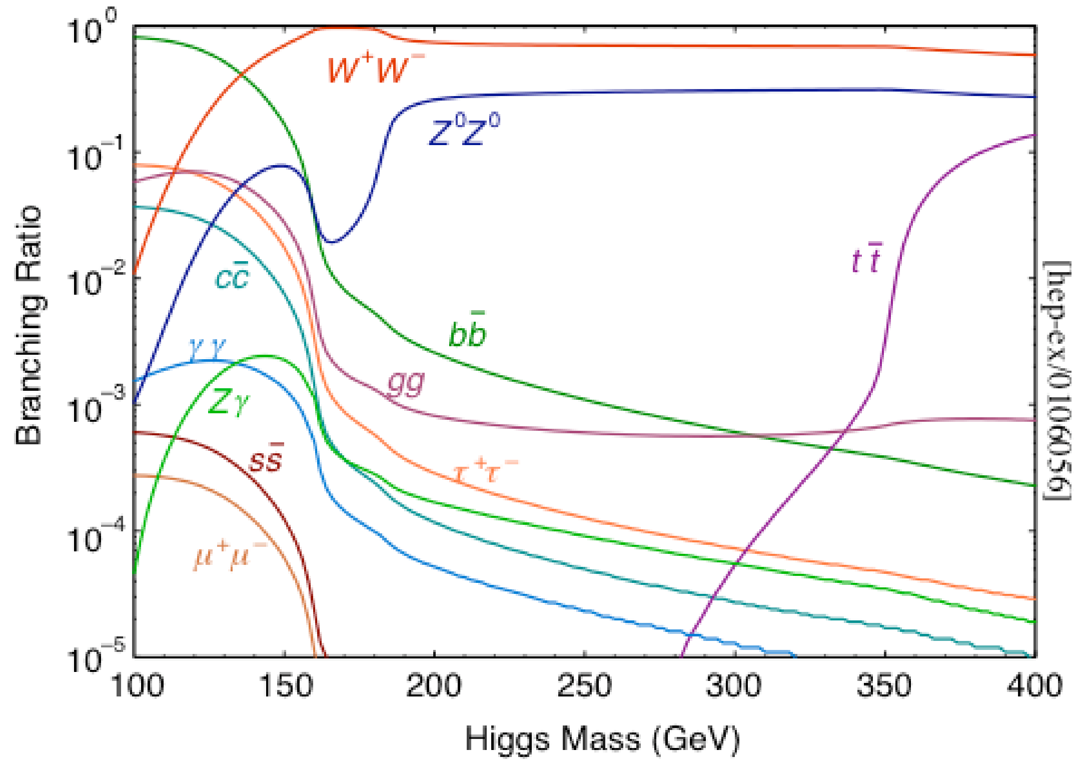



proportional to $\alpha_W$

Decay width into $W^*W^*$ plays a significant role

# HIGGS DECAY AT LHC

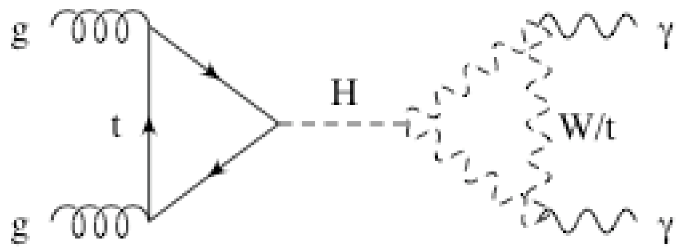


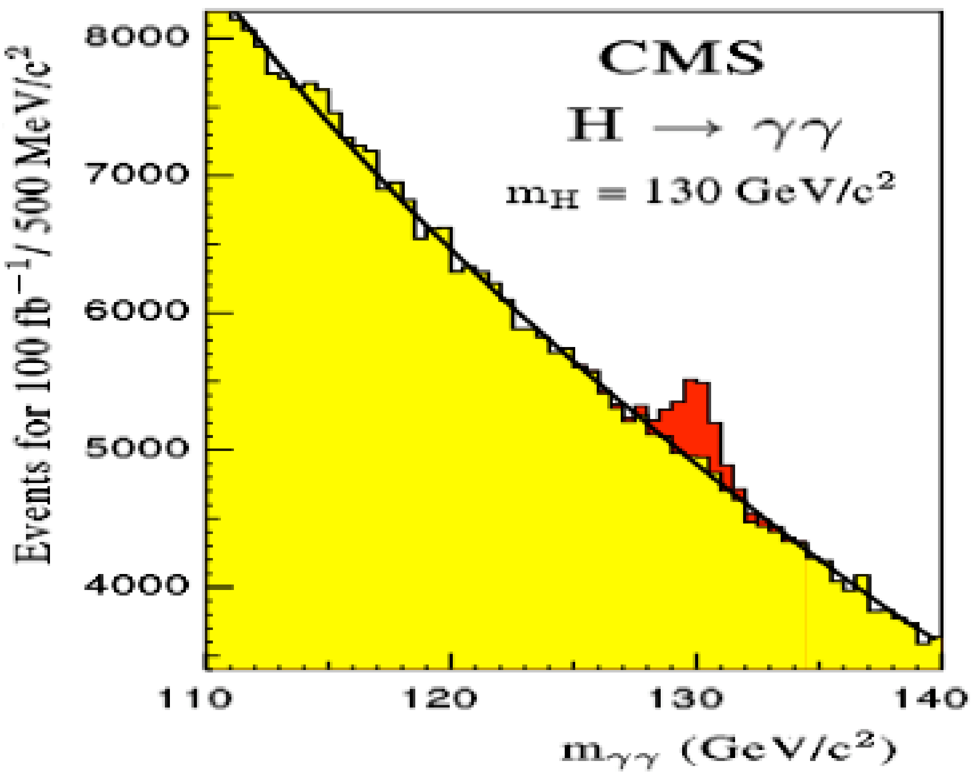




total width

branching fractions

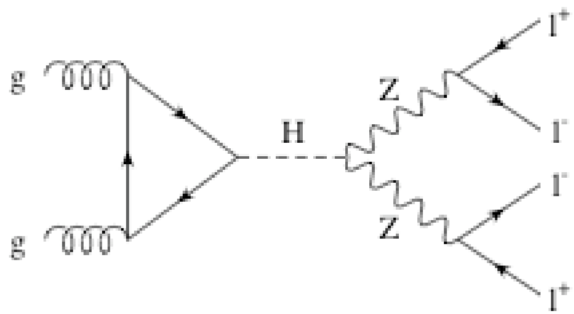
# INCLUSIVE SEARCHES: $H \to \gamma\gamma$

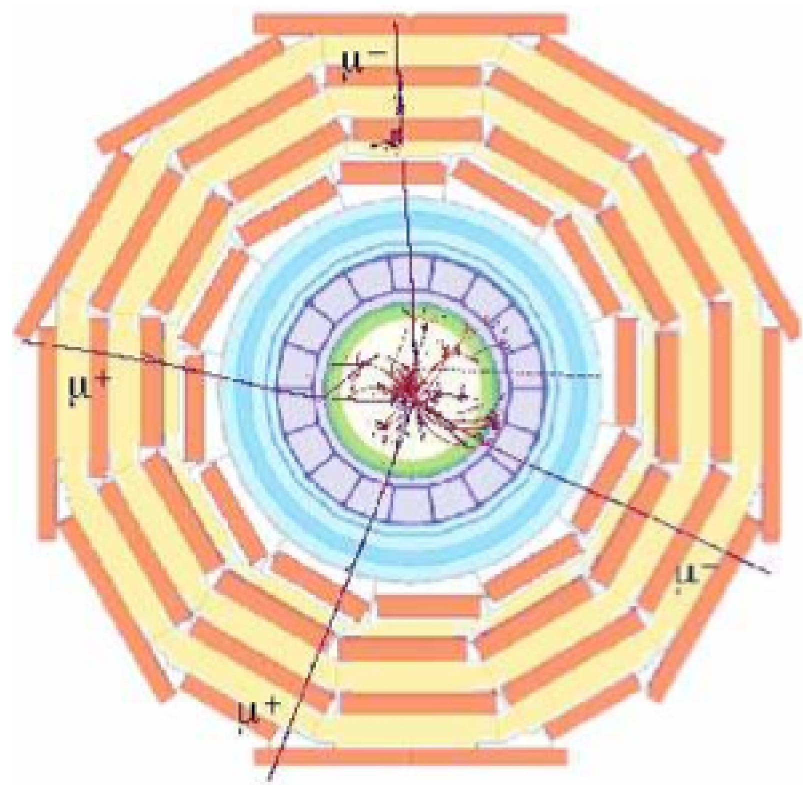



- Small BR: $\approx 10^{-3}$
- Large backgrounds from $pp \to \gamma\gamma$
- CMS and ATLAS have very good photon-energy resolution: $\mathcal{O}(1\%)$
- Search for a narrow $\gamma\gamma$ invariant mass peak, with $m_H < 150$ GeV
- Background is smooth: extrapolate it into the signal region from the sidebands

# Inclusive searches: $H \to ZZ \to l^+l^-l^+l^-$

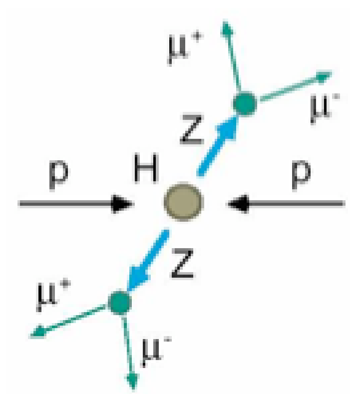


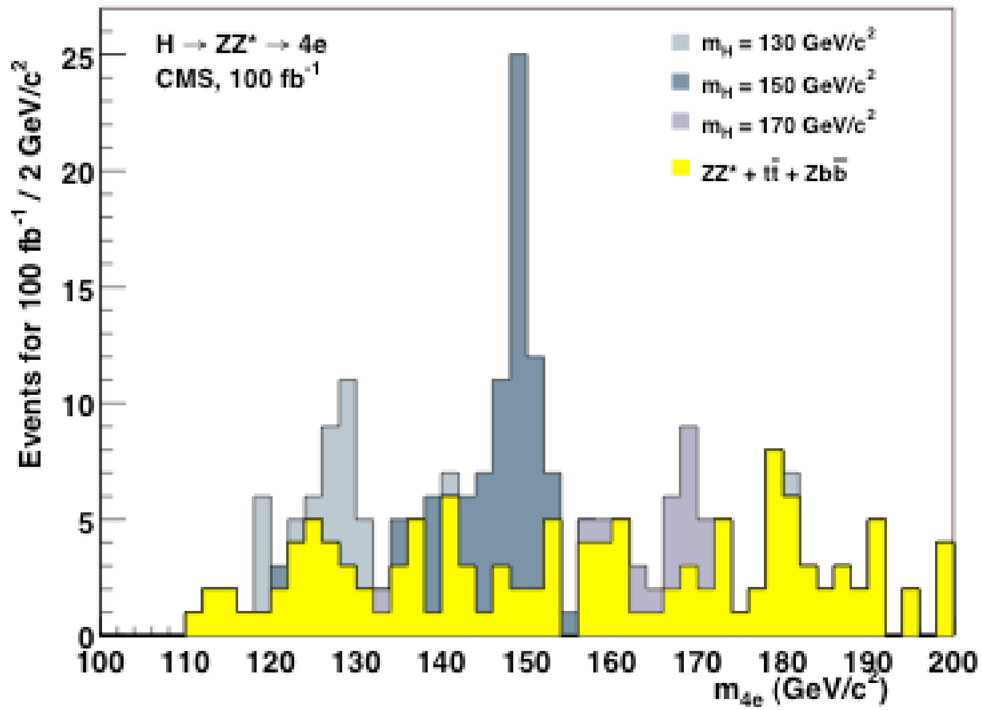




- Gold-plated mode: cleanest mode for $2m_Z < m_H < 600$ GeV
- Smooth, irreducible background from $pp \to ZZ$
- Small BR: $\mathrm{BR}(H \to ZZ)$ is a few $\%$ at threshold

# INCLUSIVE SEARCHES: $H \to ZZ \to l^+l^-l^+l^-$

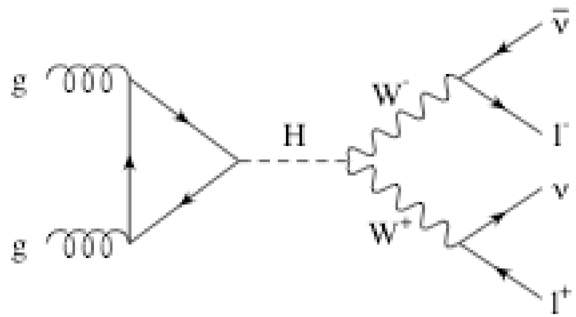
- Fully reconstructed invariant mass of the leptons



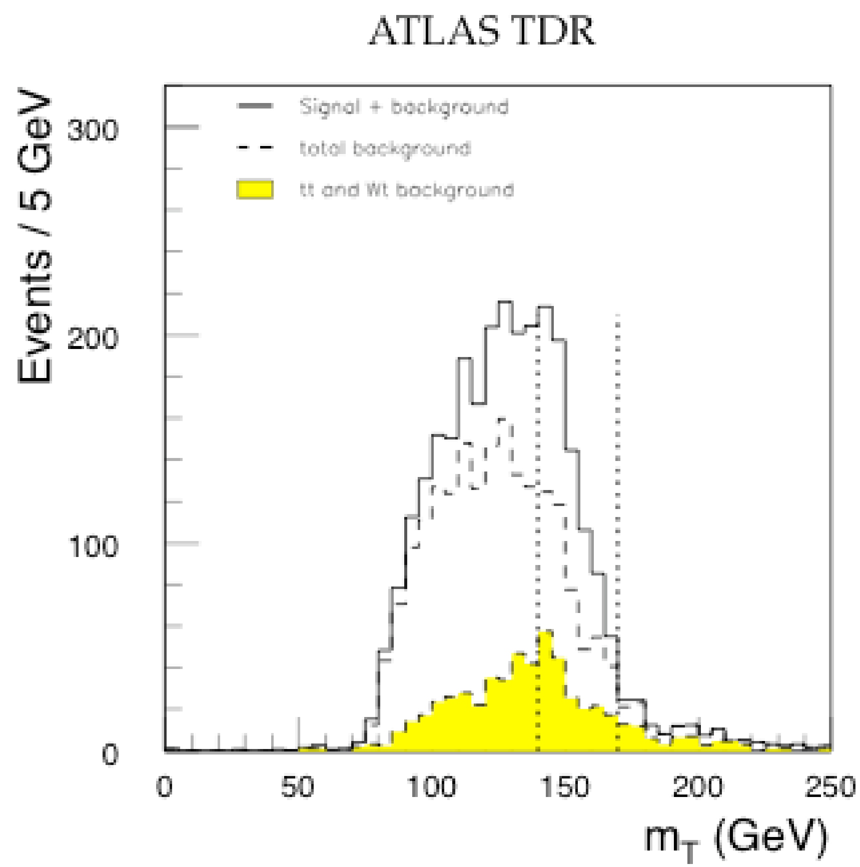

- Silver-plated mode $H \to ZZ \to l^+l^-\nu\bar{\nu}$ useful for $m_H \approx 0.8 - 1$ TeV

# INCLUSIVE SEARCHES: $H \to WW \to l^+\nu l^-\bar{\nu}$




- Exploit $l^+l^-$ angular correlations

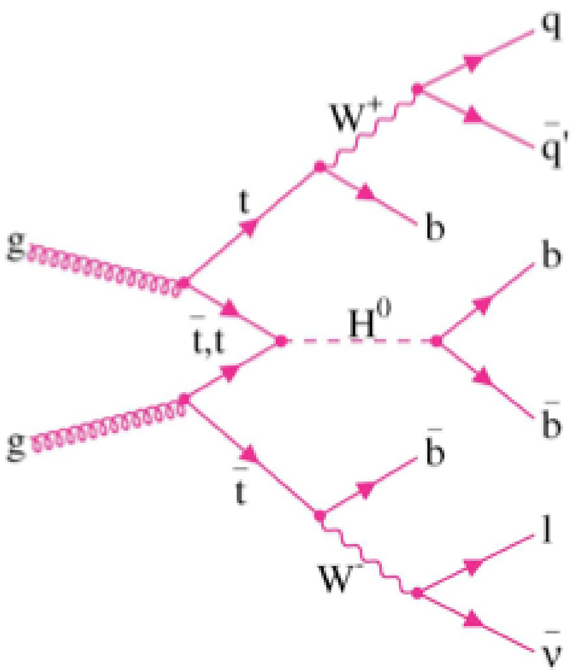
- Signal and background have similar shapes: must know background normalisation well

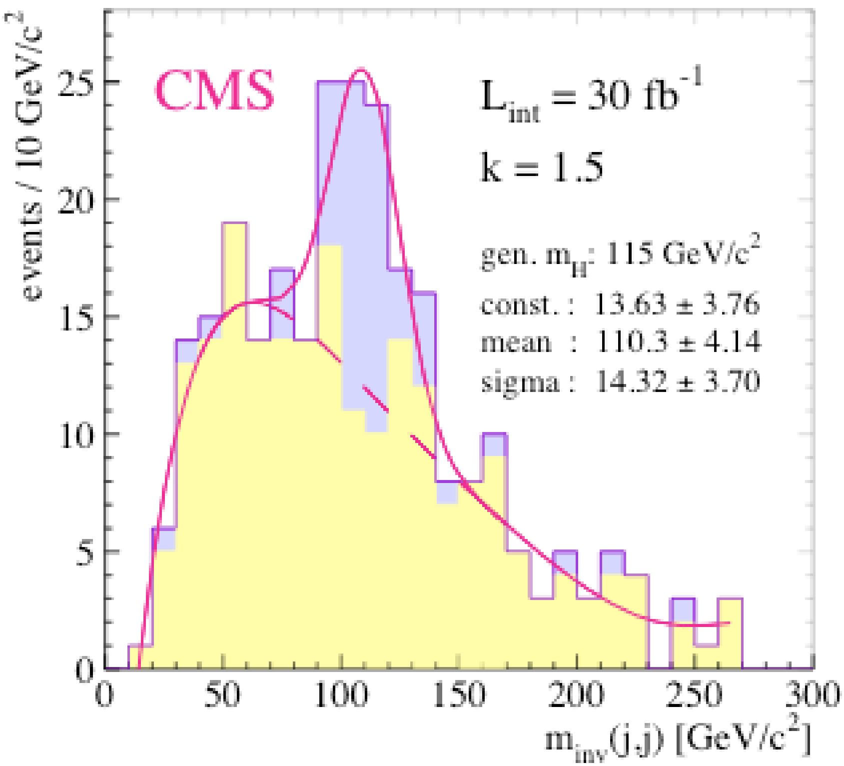



$m_H = 170\ \text{GeV}$

integrated luminosity: $20\ \text{fb}^{-1}$

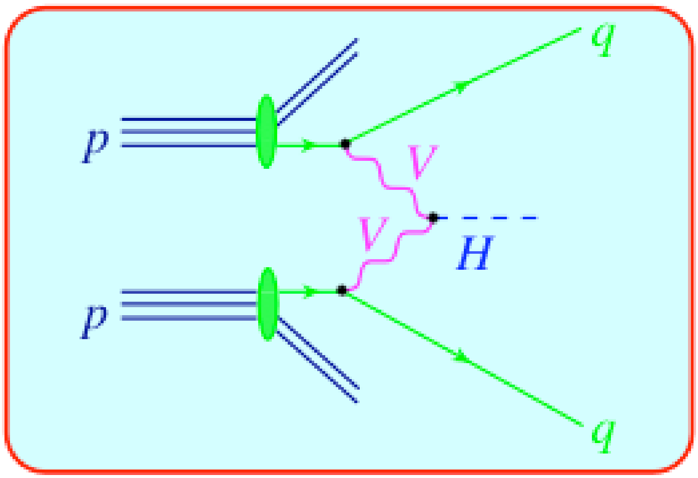
# ASSOCIATED PRODUCTION: $Ht\bar{t} \to t\bar{t}b\bar{b}$

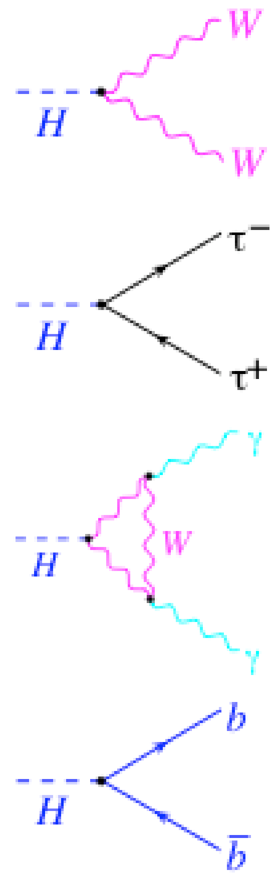



- Search channel for $m_H = 120 - 130$ GeV
- Measure $h_t^2$ BR$(H \to b\bar{b})$ with $h_t = Ht\bar{t}$ Yukawa coupling
- must know background normalisation well

# WEAK BOSON FUSION: $qq \longrightarrow qqH$




$m_H > 120$ GeV

$m_H < 140$ GeV

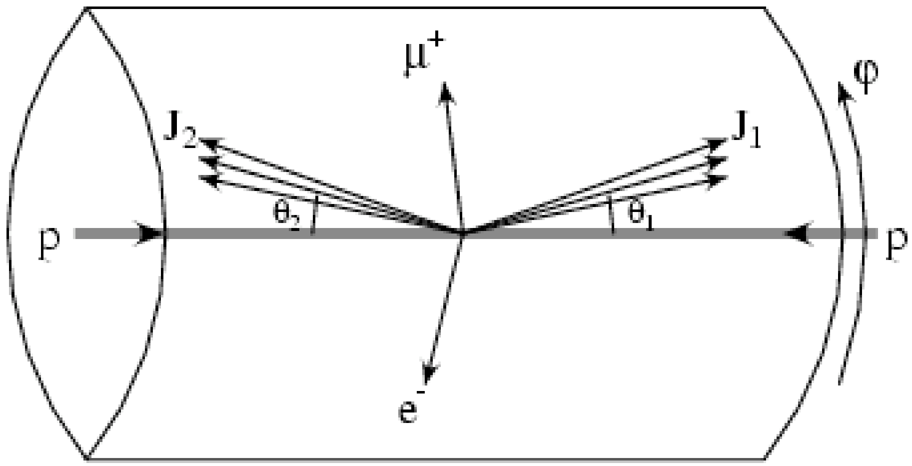
$m_H < 150$ GeV

$m_H < 140$ GeV

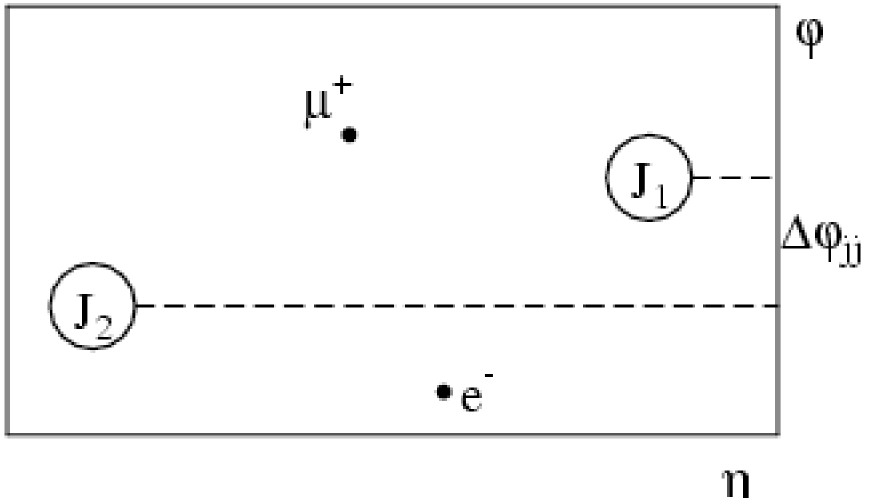
- WBF can be measured with good statistical accuracy: $\sigma \times \mathrm{BR} \approx \mathcal{O}(10\%)$

# Weak Boson Fusion

A WBF event




Lego plot

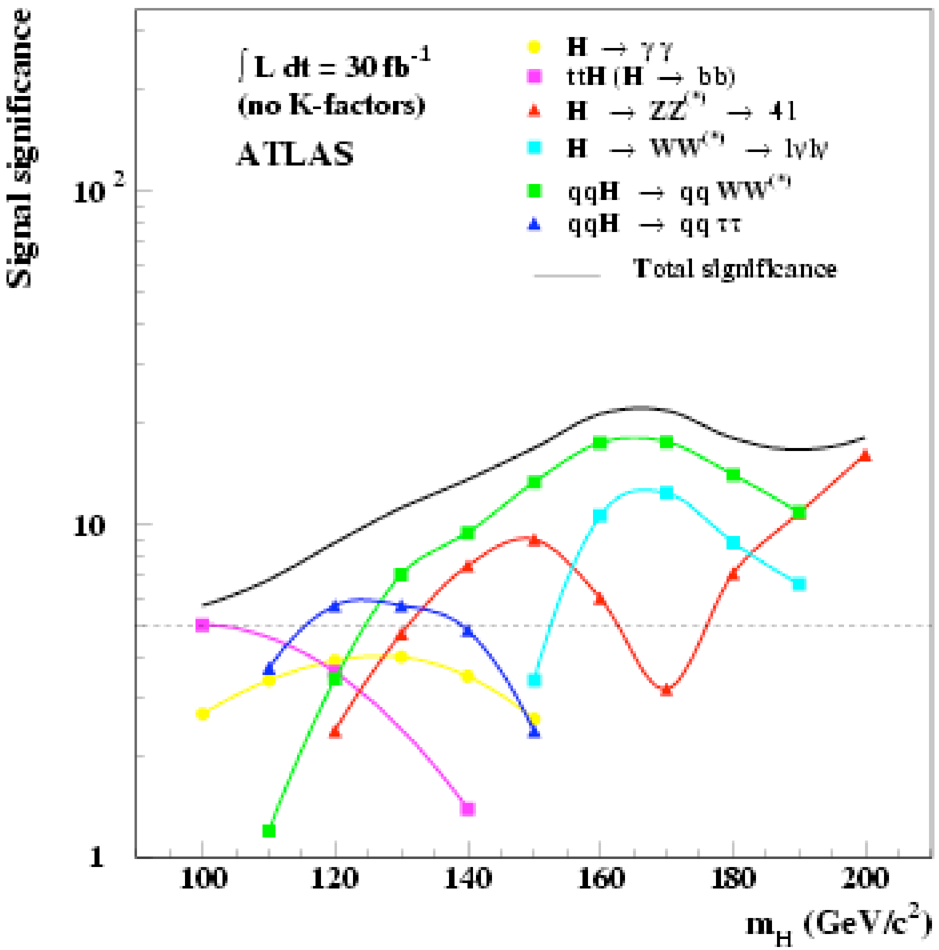



$$\eta = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}$$

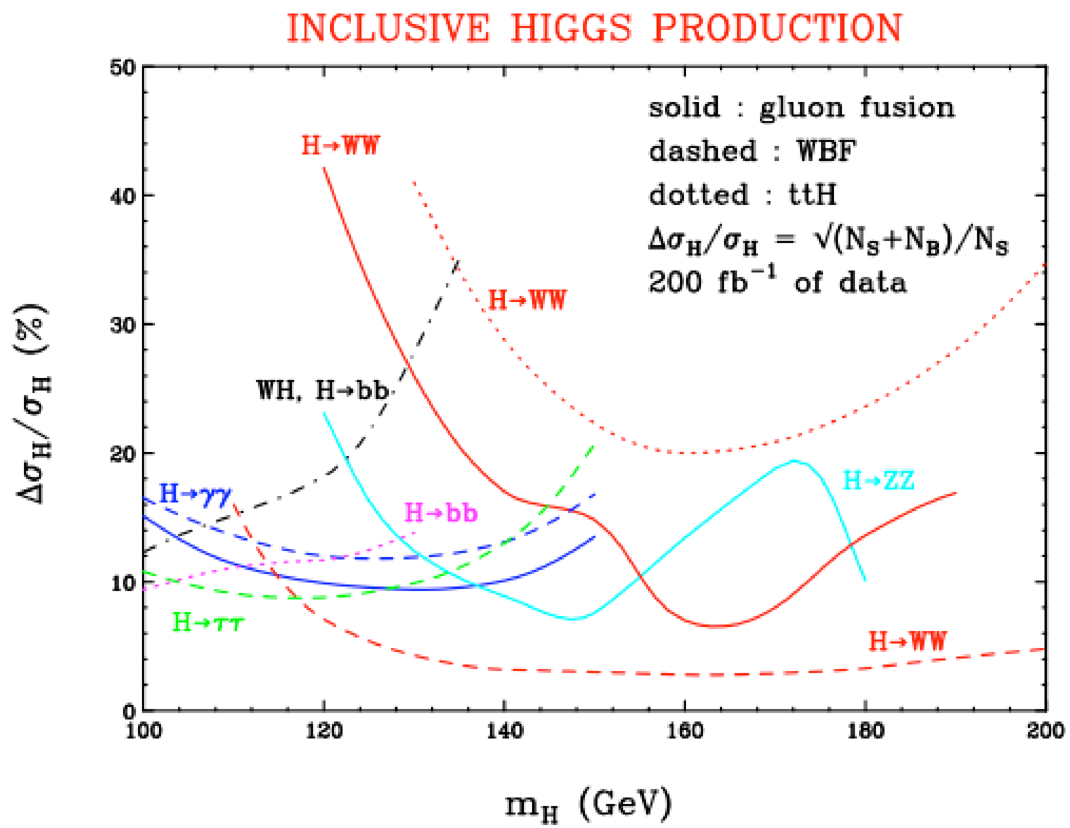
- WBF features
  - energetic jets in the forward and backward directions
  - Higgs decay products between the tagging jets
  - sparse gluon radiation in the central-rapidity region, due to colourless $W/Z$ exchange
  - NLO corrections increase the WBF production rate by about $10\,\%$, and thus are small and under control

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003

# Signal significance and (stat + syst) error




hep-ph/0402254




hep-ph/0203187

Statistical significance: $\frac{N_S}{\sqrt{N_S + N_B}}$

QCD/p.d.f. uncertainties:

$\mathcal{O}(5\%)$ for WBF

$\mathcal{O}(20\%)$ for gluon fusion

luminosity uncertainties: $\mathcal{O}(5\%)$

# Higgs Couplings and Quantum Numbers

The properties of the Higgs-like resonance are its

- couplings: gauge, Yukawa, self-couplings
- quantum numbers: charge, colour, spin, CP

assuming $W/Z$-universality, WBF and gluon-fusion rates yield measurements of combinations of partial widths

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma} \quad \text{from} \quad qq \to qqH, \; H \to \gamma\gamma$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma} \quad \text{from} \quad qq \to qqH, \; H \to \tau\tau$$

$$X_W = \frac{\Gamma_W^2}{\Gamma} \quad \text{from} \quad qq \to qqH, \; H \to WW^*$$

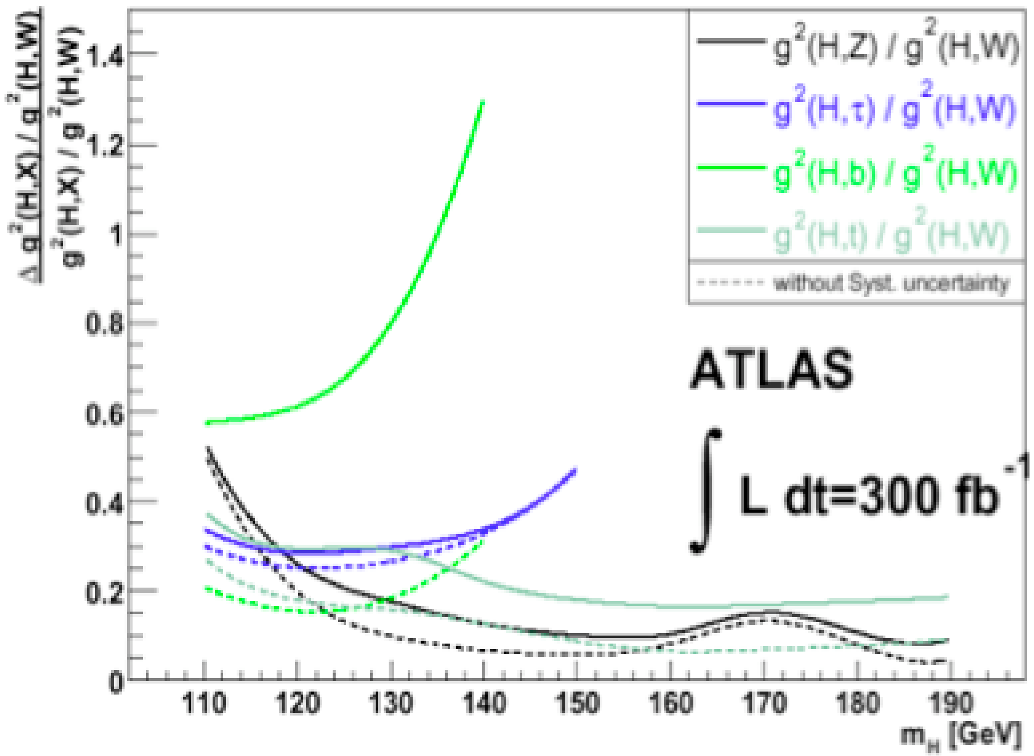
$$Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma} \quad \text{from} \quad gg \to H \to \gamma\gamma$$

$$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma} \quad \text{from} \quad gg \to H \to ZZ^*$$

$$Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma} \quad \text{from} \quad gg \to H \to WW^*$$

# HIGGS COUPLINGS AND QUANTUM NUMBERS

Ratios of Y/X cancel uncertainties on initial state luminosities and p.d.f.'s, and allow for the determination of the ratio of the Yukawa/gauge coupling



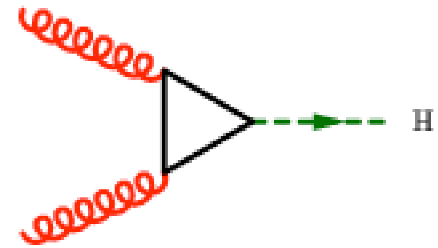

Zeppenfeld et al. hep-ph/0002036

The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events (more on this later)

# Higgs Production via Gluon Fusion

## Leading Order

$\mathcal{O}(\alpha_s^2)$ $\quad gg \to H$

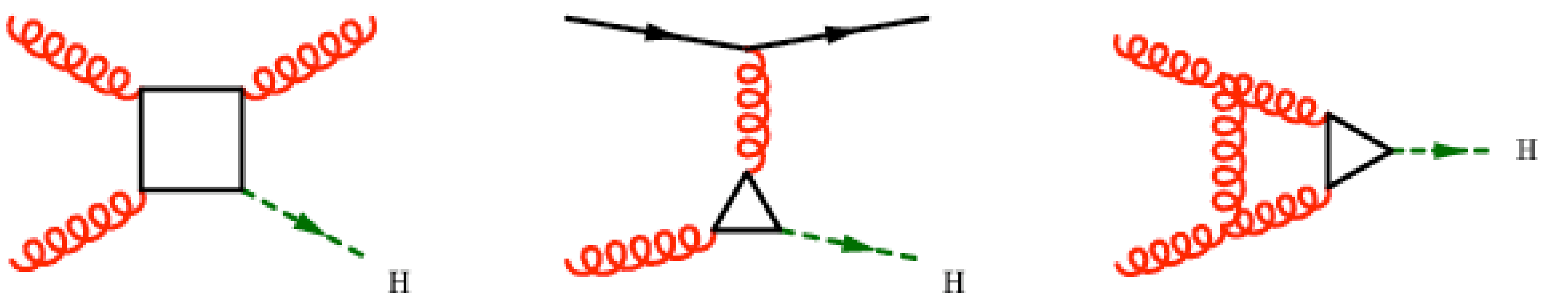



☛ energy scales: $\hat{s} = M_{\rm H}^2$ and $M_t^2$

## NLO corrections

$\mathcal{O}(\alpha_s^3)$

- 2-loop $\quad gg \to H$
- 1-loop $\quad gg \to gH \quad qg \to qH \quad +$ crossings

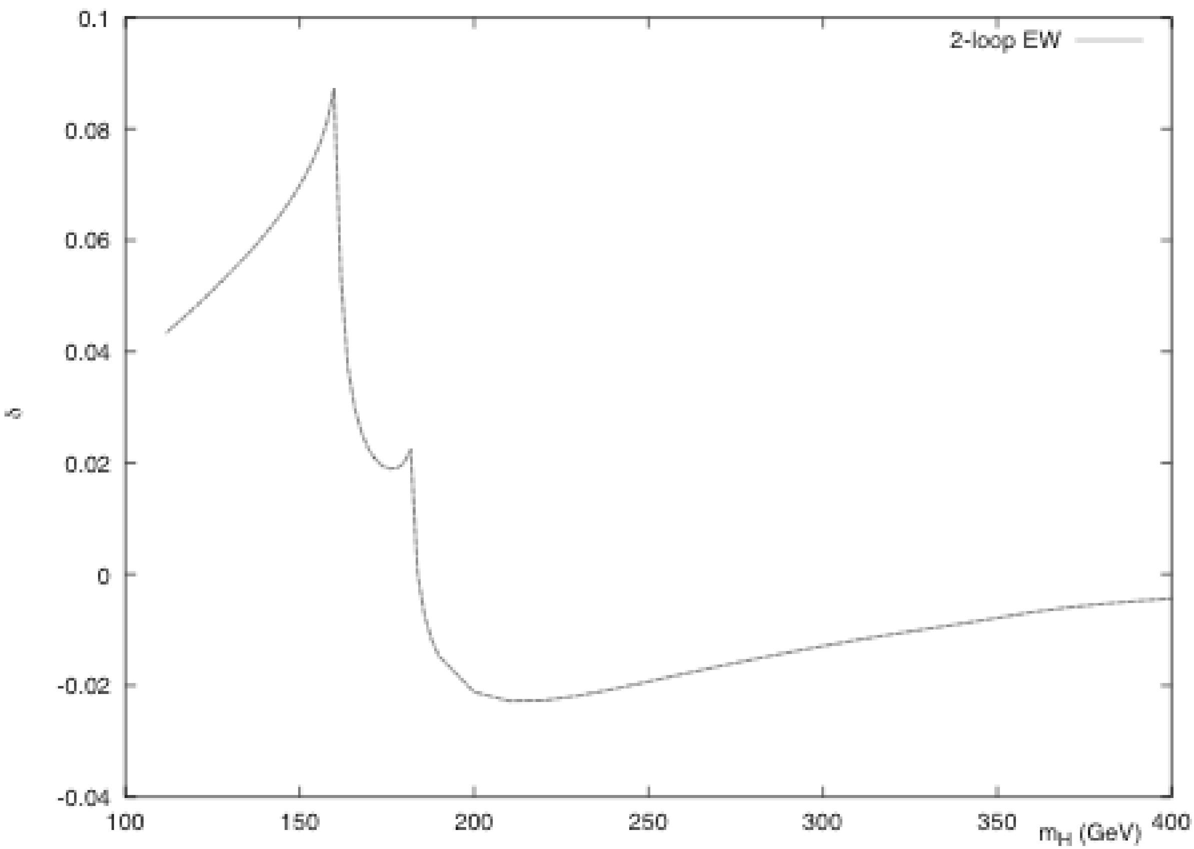


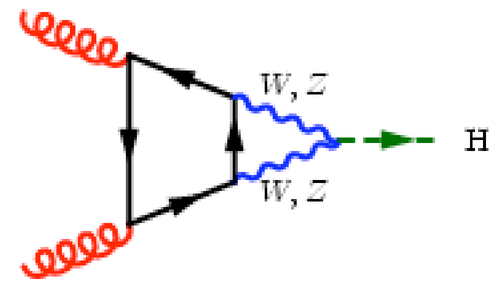

Djouadi, Graudenz, Spira, Zerwas, '93-'95

☛ large $K$ factor: $\sigma^{\rm NLO} = K^{\rm NLO}\, \sigma^{\rm LO}$ $\qquad \mathcal{O}(40 - 100\%)$

# EW CORRECTIONS

a QCD loop + an EW loop $\mathcal{O}(\alpha_S^2 \alpha_W^2)$



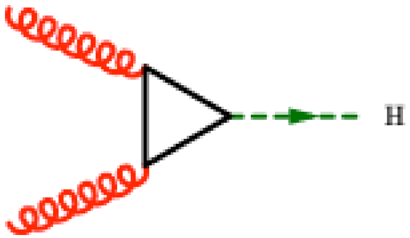




Aglietti Bonciani Degrassi Vicini 04
(light fermion loop)

Degrassi Maltoni 04
(heavy fermion loop)

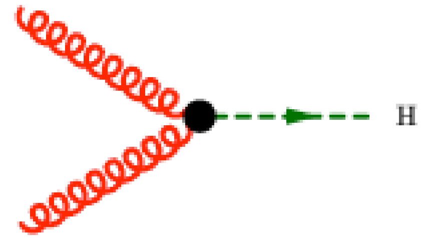
- Relative corrections to production and decay through gluon fusion (with light fermion loop)
- For $115\,\mathrm{GeV} \leq M_H \leq 2M_W$ the total electroweak corrections are 5 to 8 % of leading order

# The Large Top-mass Limit

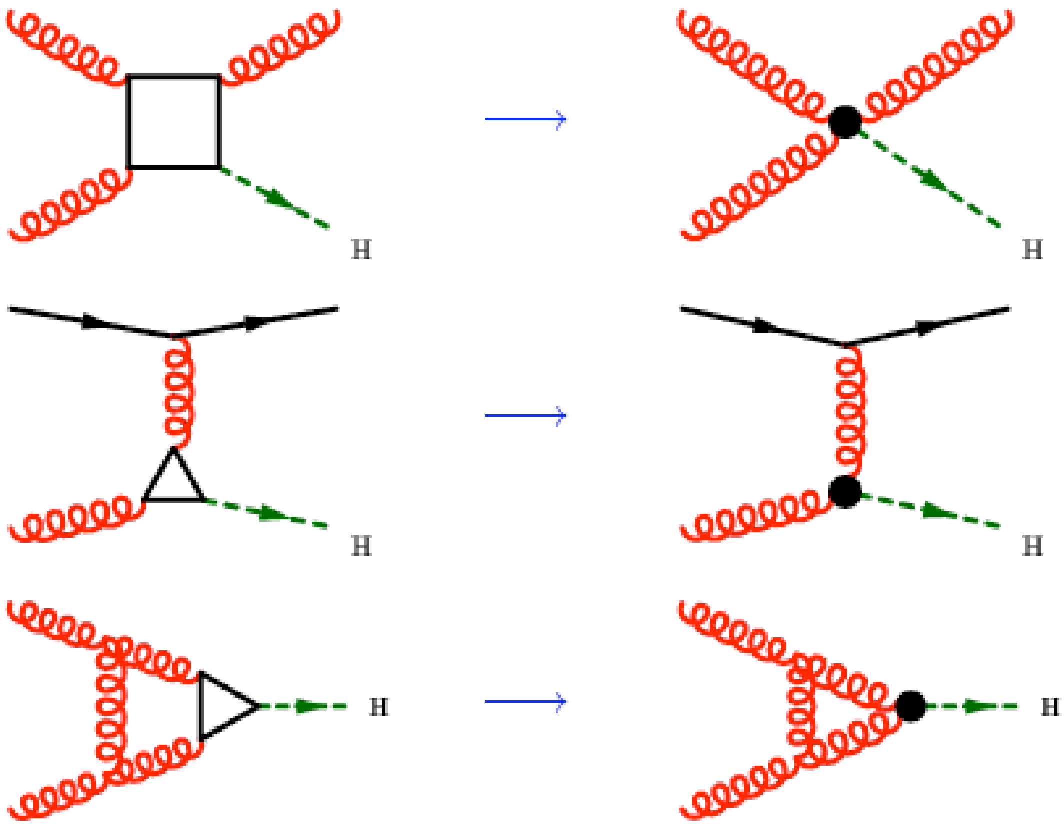



$M_H \ll 2M_t$

$\longrightarrow$




## NLO corrections




$K$ factor in the large $M_t$ limit

$$K_\infty = \lim_{M_t \to \infty} K$$

NLO rate in the large $M_t$ limit

$$\sigma_\infty^{\rm NLO} = K_\infty^{\rm NLO}\, \sigma^{\rm LO}$$

$\sigma_\infty^{\rm NLO}$ is within 10% of $\sigma^{\rm NLO}$ for $M_H \lesssim 1$ TeV

# $gg \to H$ IN THE LARGE $M_t$ LIMIT

## NNLO CORRECTIONS

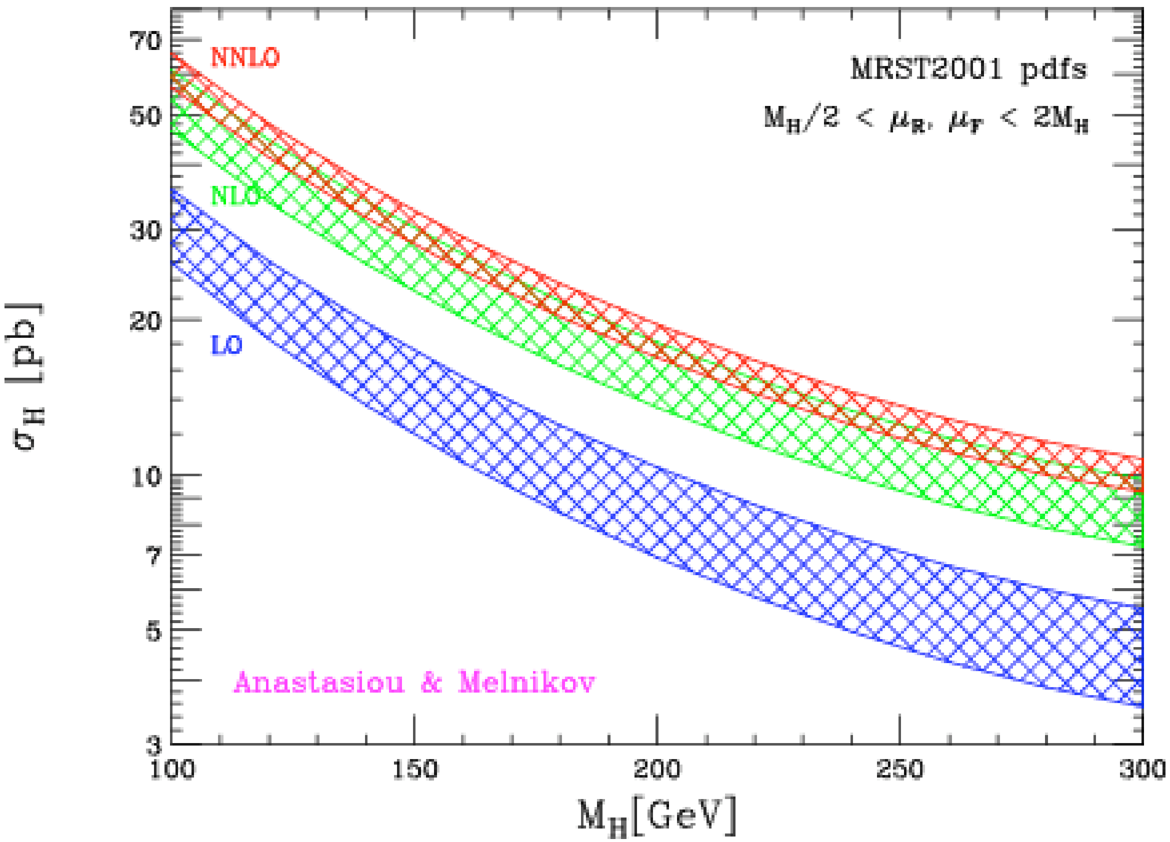
$\mathcal{O}(\alpha_S^4)$

2-loop $gg \to H$

1-loop $gg \to gH \quad qg \to qH \quad +$ crossings

tree $gg \to ggH \quad qg \to qgH \quad qQ \to qQH \quad +$ crossings

R. Harlander hep-ph/0007289




total cross section for inclusive Higgs production at LHC

Harlander Kilgore 02
Anastasiou Melnikov 02
Ravindran Smith van Neerven 03

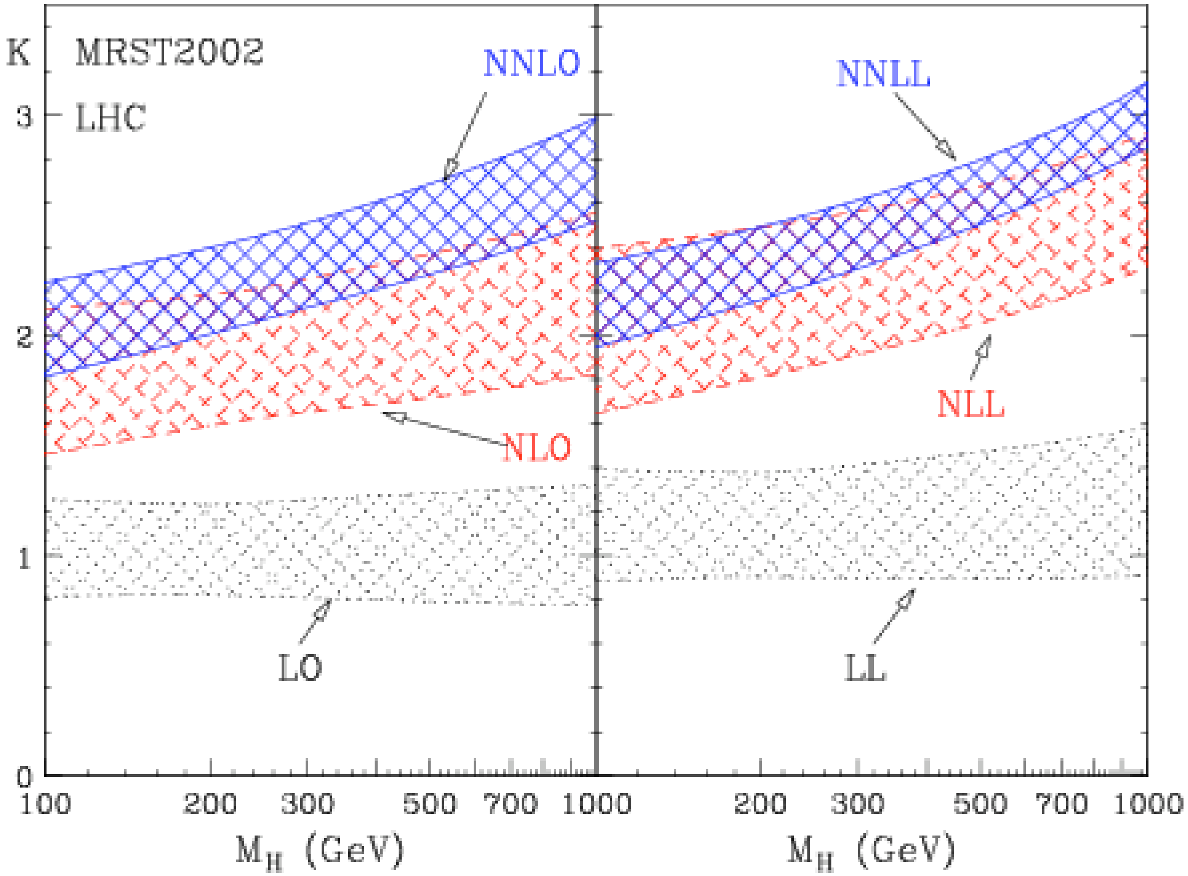
The band contours are

lower $\mu_R = 2M_H \quad \mu_F = M_H/2$

upper $\mu_R = M_H/2 \quad \mu_F = 2M_H$

# NNLO CORRECTIONS + NNLL RESUMMATION

☛ Threshold resummation of soft gluon radiation




Catani, de Florian
Grazzini, Nason
hep-ph/0306211

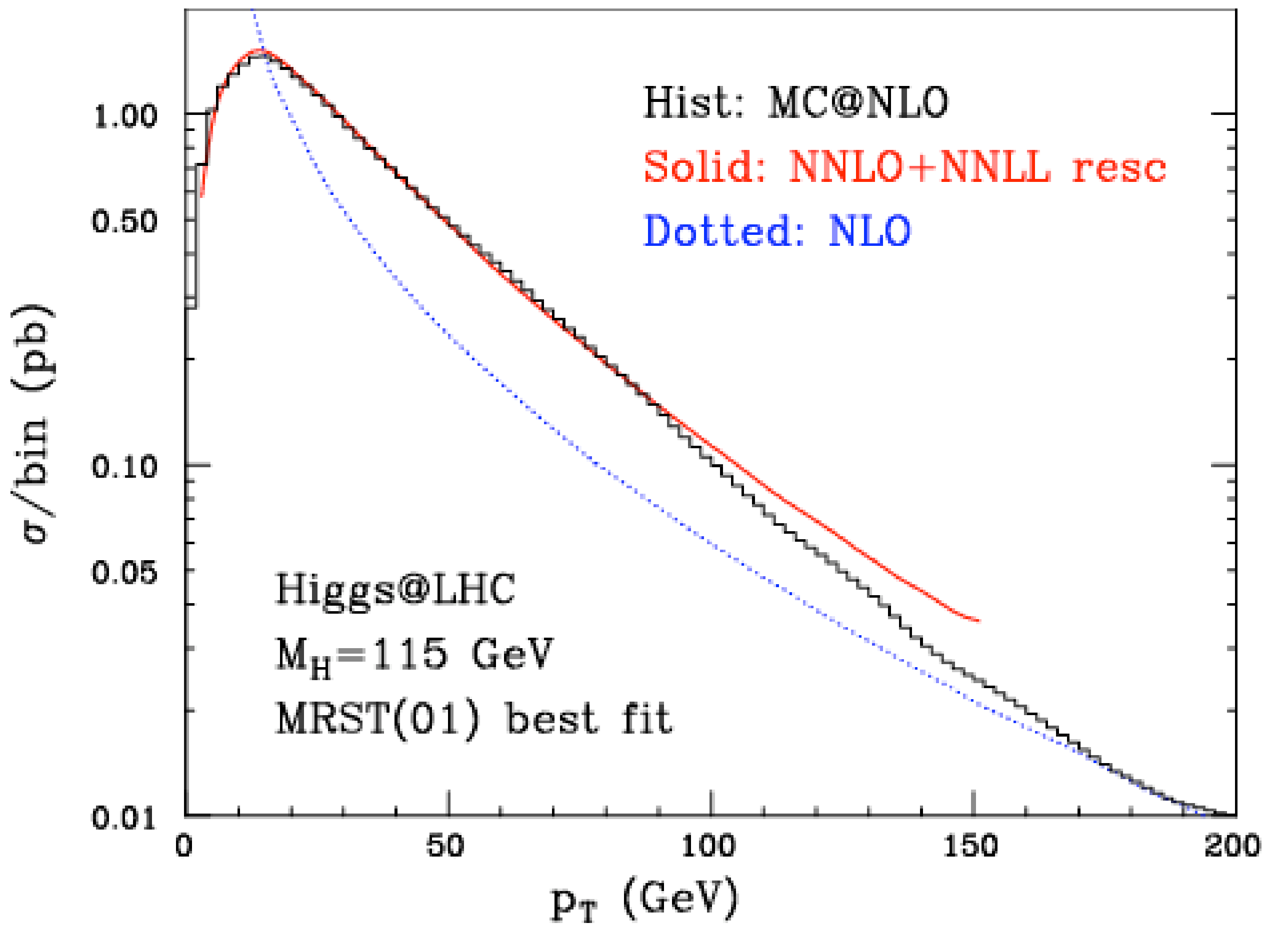
☛ $K$ factor is computed wrt to $\sigma^{\mathrm{LO}}$ at $\mu_R = \mu_F = M_{\mathrm{H}}$
band contours have $\mu_{R(F)} = \chi_{R(F)} M_{\mathrm{H}}$ and $1/2 \leq \chi_{R(F)} \leq 2$ but $1/2 \leq \chi_R/\chi_F \leq 2$

☛ NNLL increases NNLO by about 6%

☛ scale uncertainty at NNLL of about 8% (at NNLO of about 10%)

# NNLO + NNLL versus MC@NLO

Higgs $p_T$ distribution



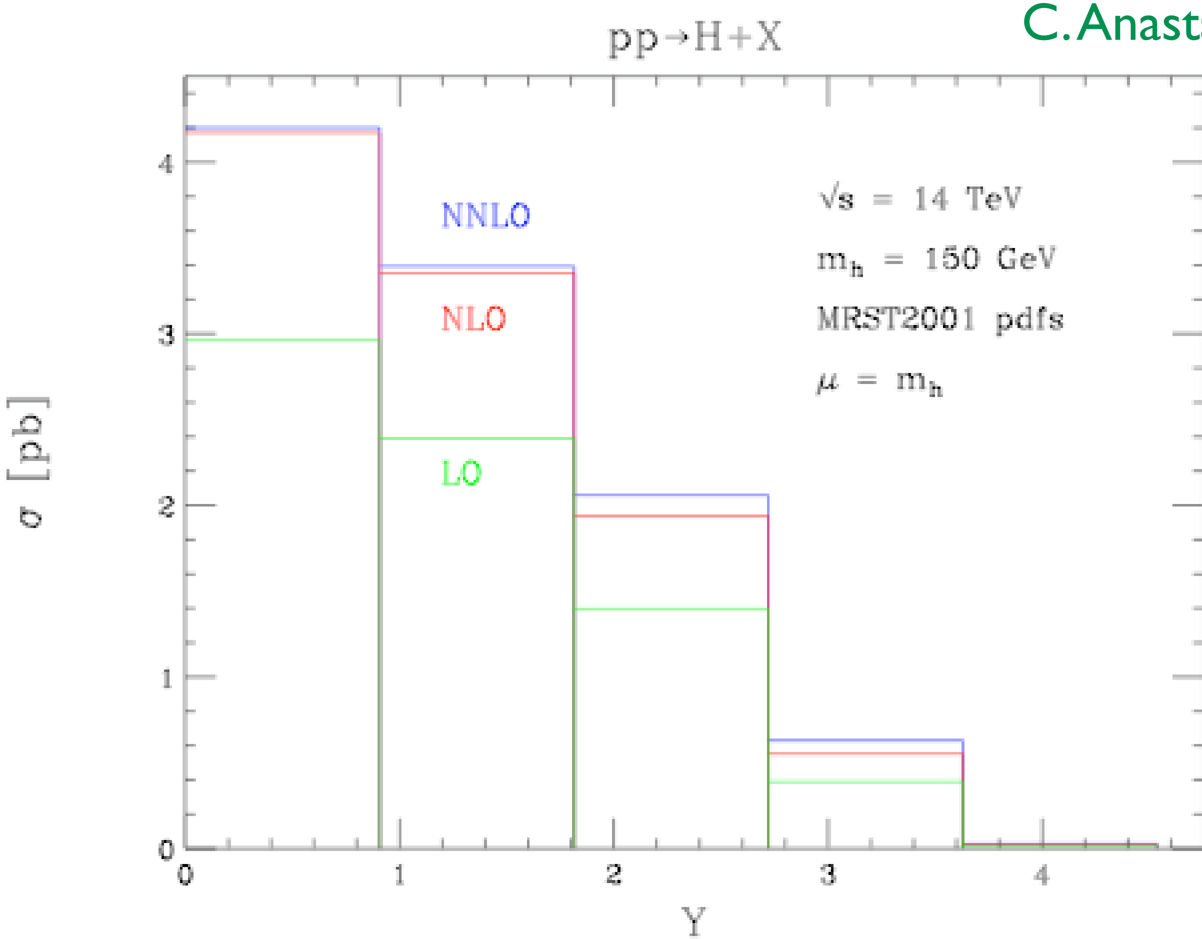

difference at large $p_T$ is due to different default $\mu = \mu_R = \mu_F$ scale
$\mu^2 = M_H^2$ for NNLO + NNLL, $\mu^2 = M_H^2 + p_T^2$ for MC@NLO

S. Frixione hadron collider wksp MSU 2004

# NNLO CORRECTIONS

a fully differential cross section:
bin-integrated rapidity distribution, with a jet veto

C. Anastasiou K. Melnikov F. Petriello 2004




jet veto: require

$R = 0.4$

$|\mathbf{p}_T^j| < p_T^{veto} = 40\ \mathrm{GeV}$

for 2 partons

$R_{12}^2 = (\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2$

if $R_{12} > R$

$|\mathbf{p}_T^1|, |\mathbf{p}_T^2| < p_T^{veto}$

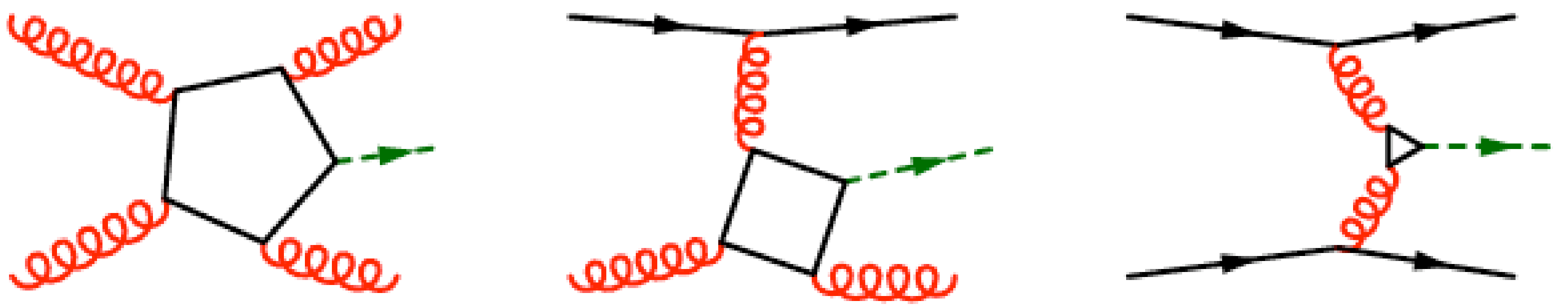
if $R_{12} < R$

$|\mathbf{p}_T^1 + \mathbf{p}_T^2| < p_T^{veto}$

- $M_H = 150\ \mathrm{GeV}$ (jet veto relevant in the $H \to W^+W^-$ decay channel)
- K factor is much smaller for the vetoed x-sect than for the inclusive one: average $|\mathbf{p}_T^j|$ increases from NLO to NNLO: less x-sect passes the veto

# Higgs + 2 Jets via Gluon Fusion

## Leading Order $\mathcal{O}(\alpha_s^4)$

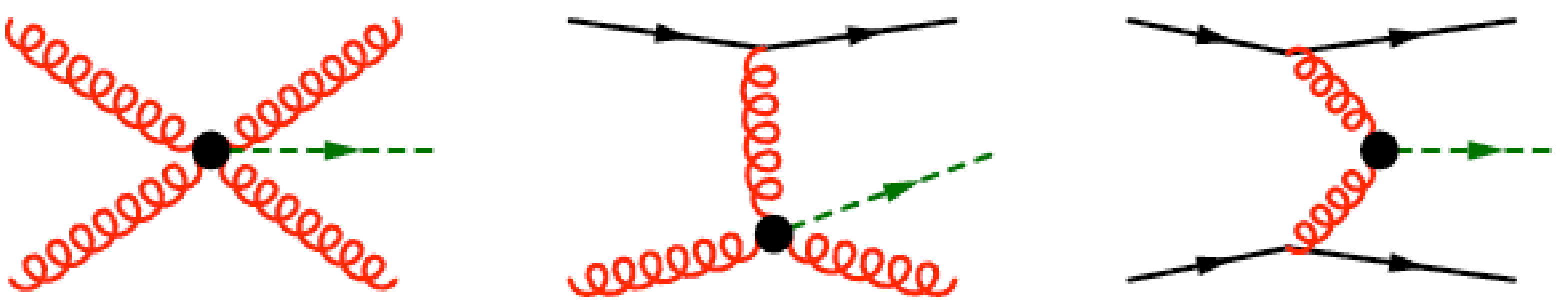


- tree $gg \to ggH$ $qg \to qgH$ $qQ \to qQH$ + crossings
- energy scales: $\hat{s}\,, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}}, s_{j_1 j_2}, M_{\mathrm{H}}^2, M_t^2$, with $\hat{s} = s_{j_1 j_2} + s_{j_1 \mathrm{H}} + s_{j_2 \mathrm{H}} - M_{\mathrm{H}}^2$

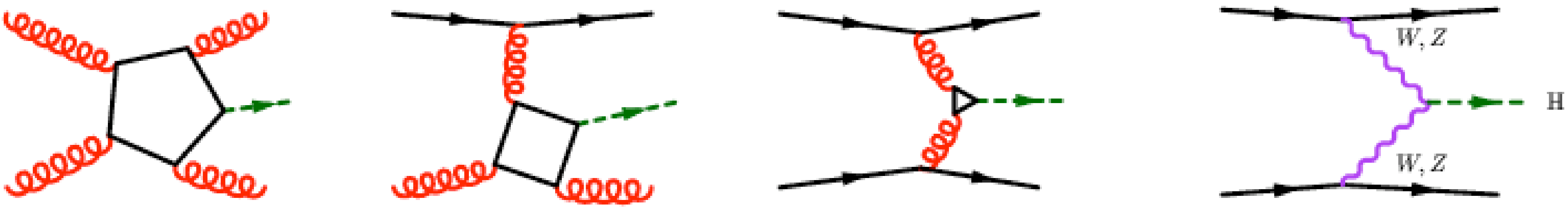
## Large $M_t$ limit

is accurate if $M_{\mathrm{H}} \ll 2M_t$ and $p_{j_1 \perp}, p_{j_2 \perp}, p_{\mathrm{H}\perp} \ll M_t$

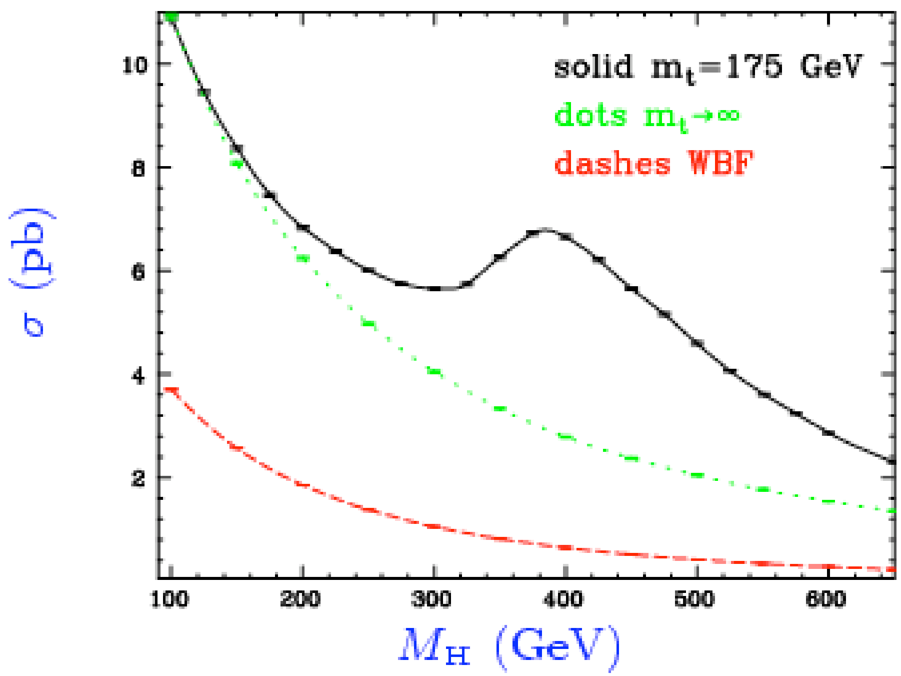
is valid even when $s_{j_1 j_2}, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}} \gg M_t^2$

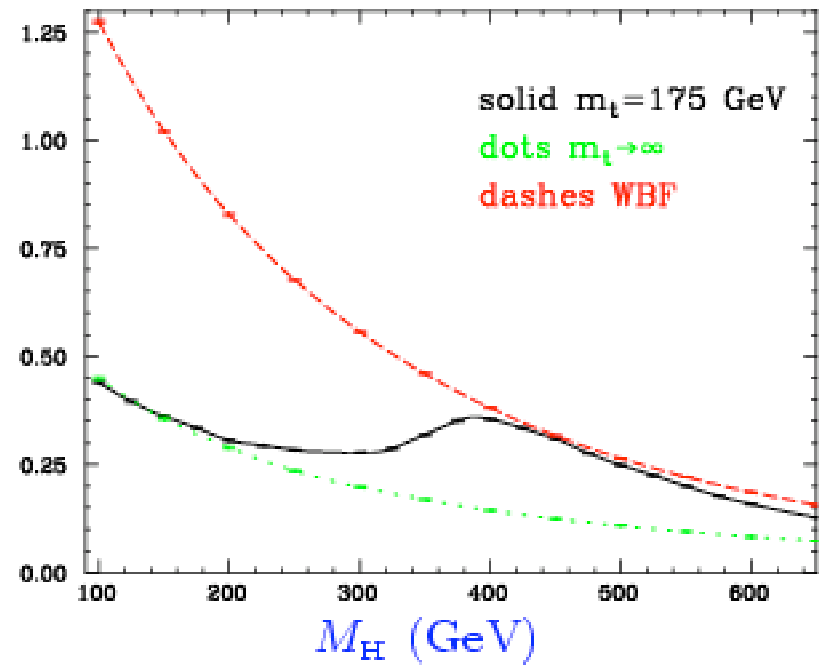


## $H+$ 2 JETS RATE as a function of $M_H$




$\mu_F = \sqrt{p_{j_1\perp} p_{j_2\perp}}\,, \mu_R = M_Z$ Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0105129



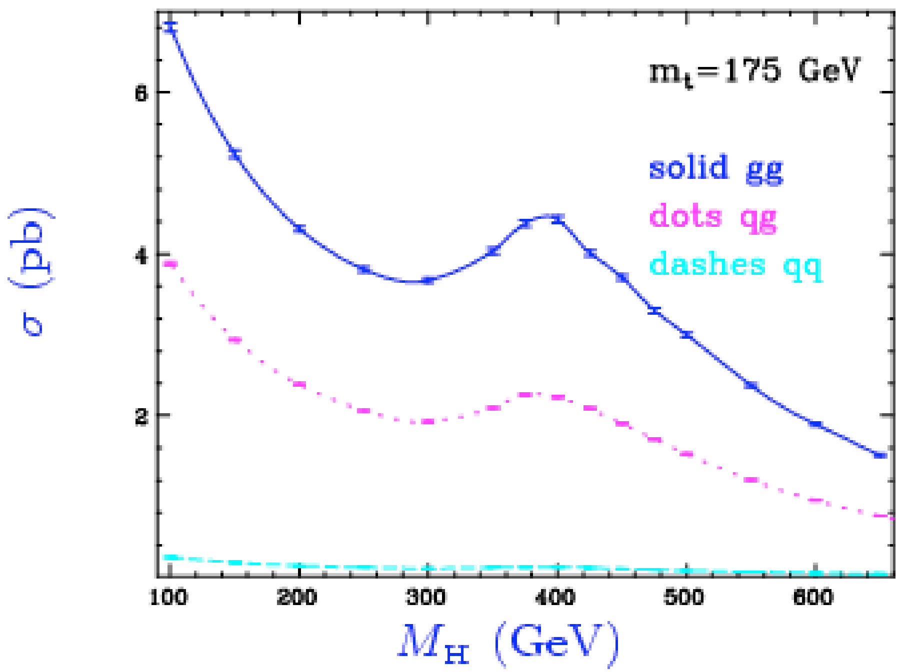

inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

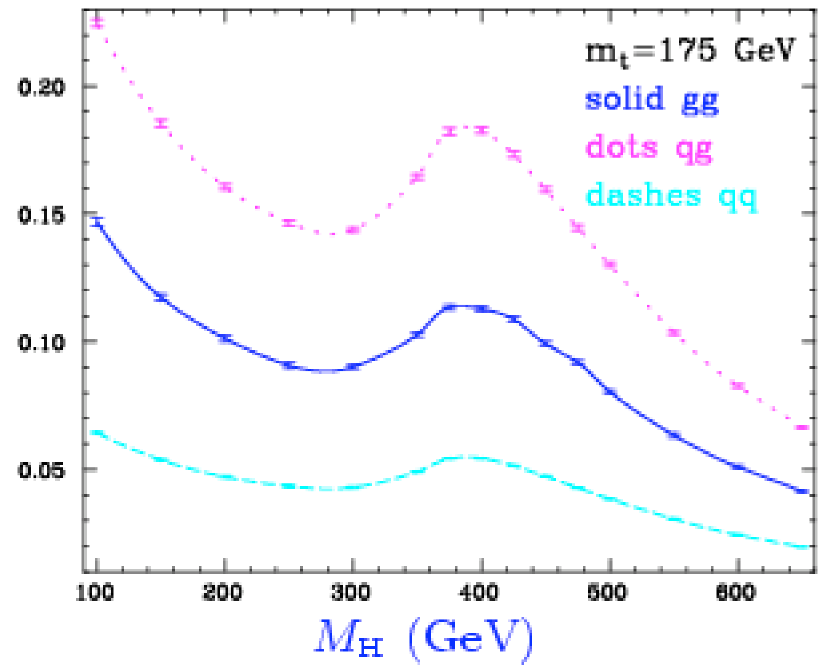
WBF cuts: incl. + $\begin{cases} |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{cases}$

☛ WBF cuts enhance WBF wrt gluon fusion by a factor 10

# $H+$ 2 JETS VIA GLUON FUSION by sub-process

$$\mu_F = \sqrt{p_{j_1\perp} p_{j_2\perp}}\,, \mu_R = M_Z$$




inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

WBF cuts: incl. + $\begin{cases} |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{cases}$

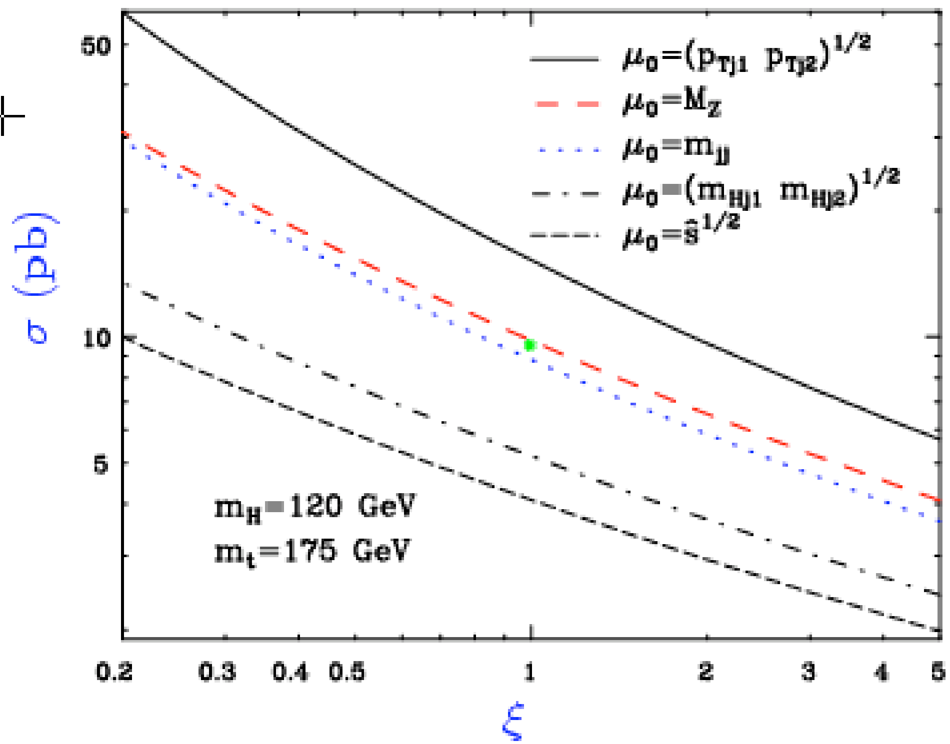
☛ WBF cuts enhance $qg$ wrt $gg$, and make $qq$ non-negligible

# SCALE DEPENDENCE

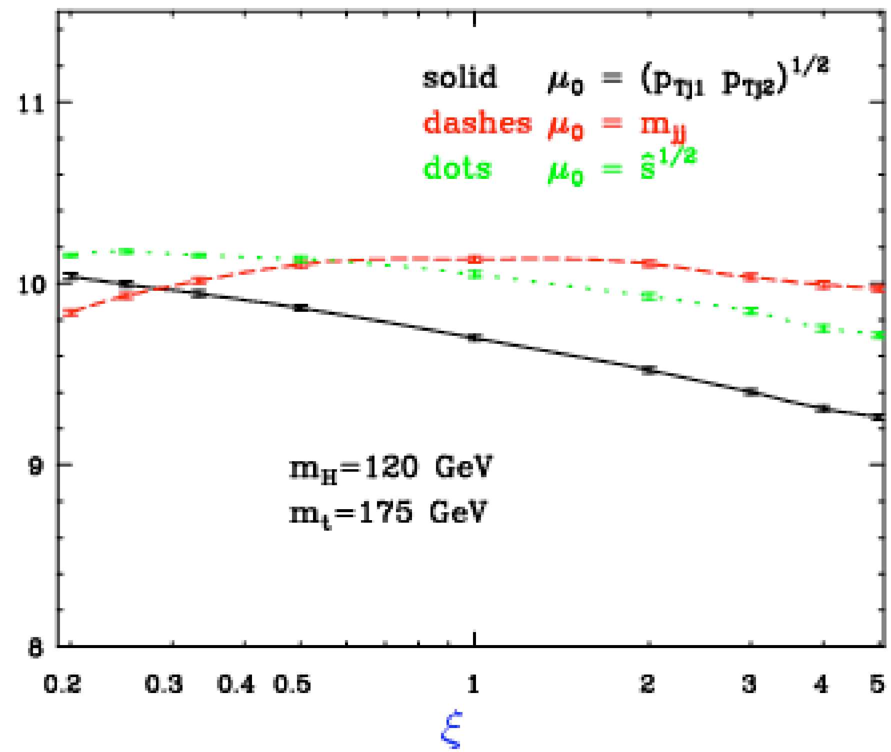
renormalisation $\mu_R$ & factorisation $\mu_F$ scales

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0108030

$\mu_R = \xi\mu_0,\ \mu_F = \sqrt{p_{j_1\perp}p_{j_2\perp}}$




$\mu_F = \xi\mu_0,\ \mu_R = M_Z$

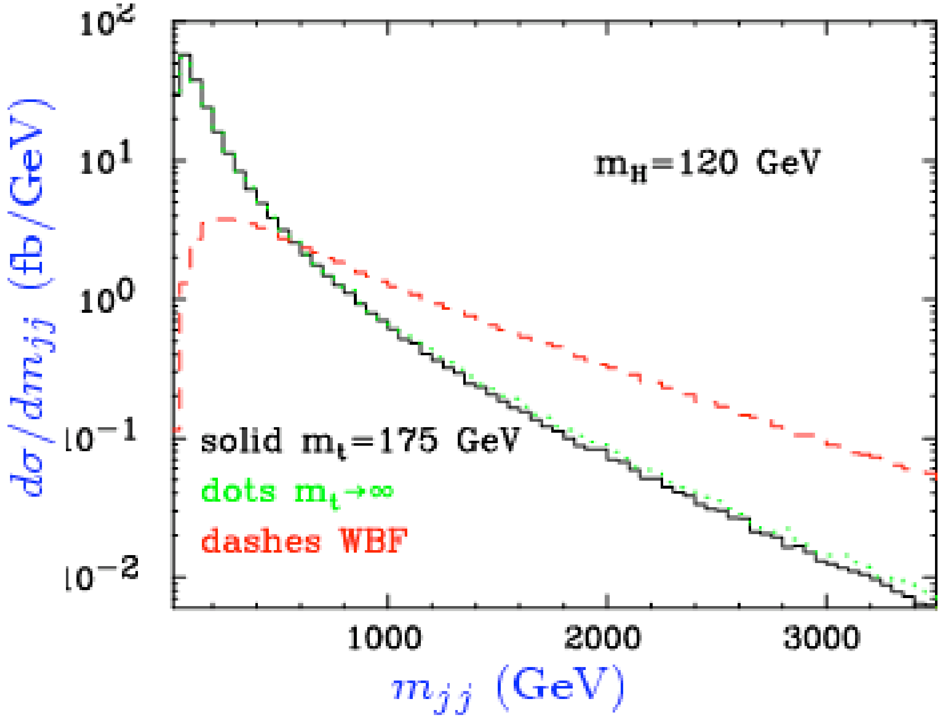


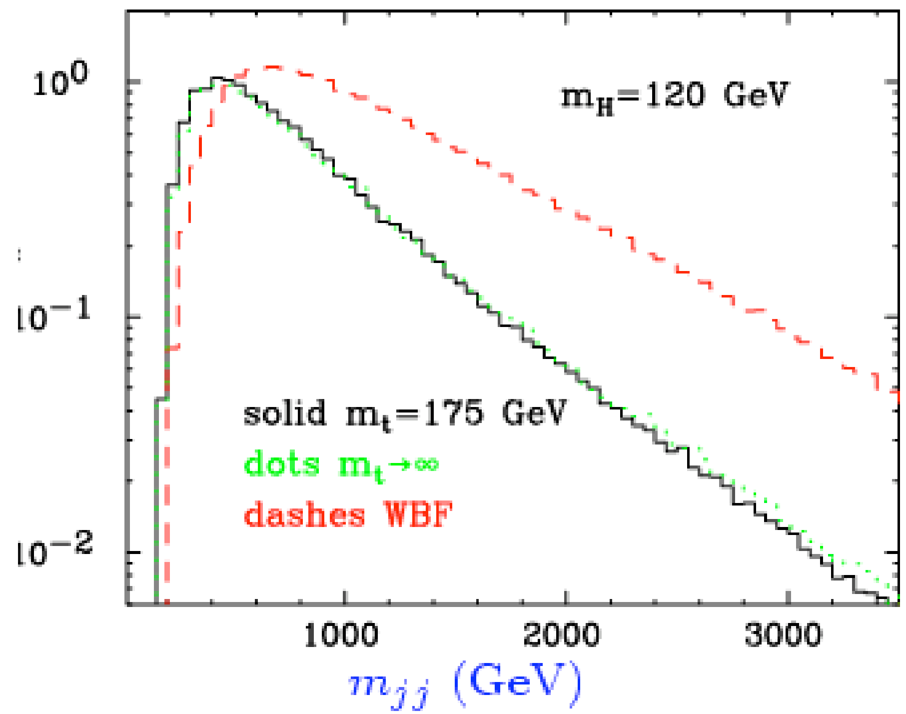

- strong $\mu_R$ dependence: the calculation is LO and $\mathcal{O}(\alpha_s^4)$
  - a natural scale for $\alpha_s$ ?

    high energy limit suggests $\alpha_s^4 \to \alpha_s(p_{j_1\perp})\alpha_s(p_{j_1\perp})\alpha_s^2(M_H)$
    - $\sigma$ varies by a factor 2.5 for $\mu_0/2 < \mu_R < 2\mu_0$
- mild $\mu_F$ dependence: $\mathcal{O}(10\%)$ over the $\mu_0/5 < \mu_R < 5\mu_0$ range

# DIJET MASS DISTRIBUTIONS

$\sqrt{s_{jj}} \equiv m_{jj}$: dijet invariant mass



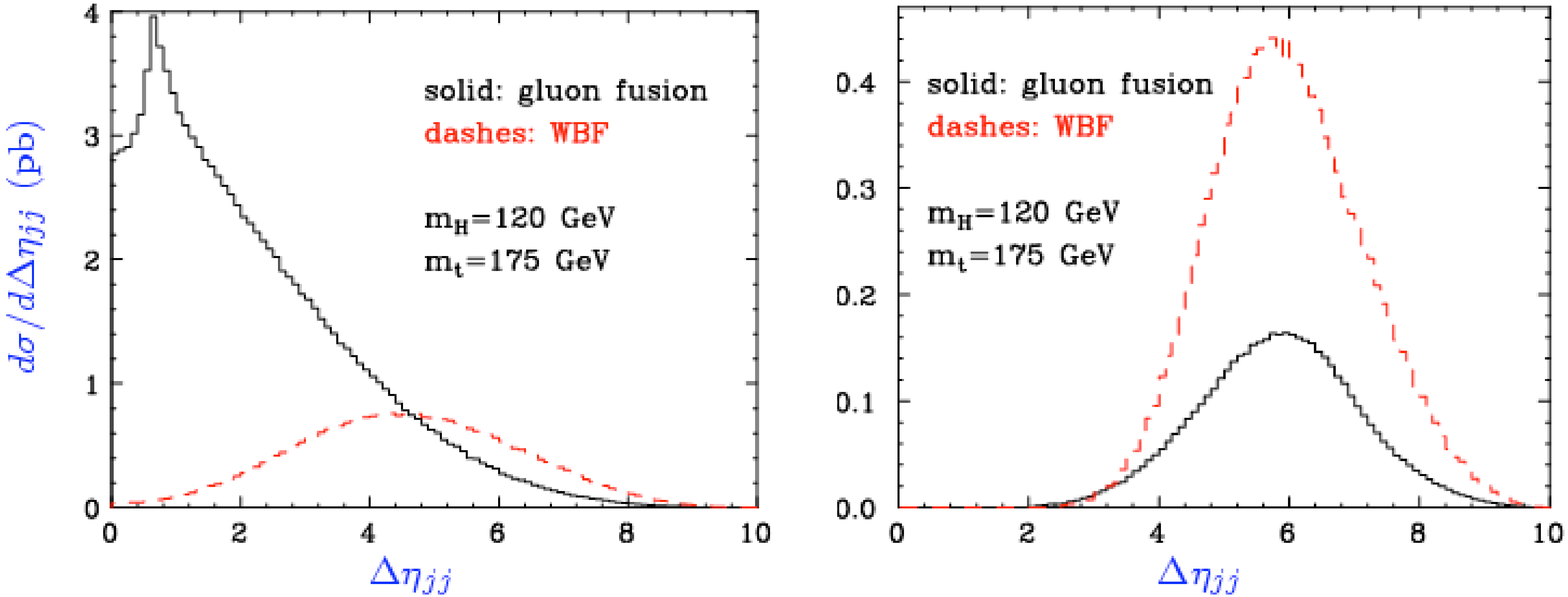

inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

WBF cuts: incl. + $\begin{cases} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \end{cases}$

- high dijet mass region ($m_{jj} \gtrsim 1$ TeV) is dominated by WBF
- large dijet masses do not invalidate the large $M_t$ limit (as long as $p_{j_1\perp}, p_{j_2\perp} \ll M_t$)

# RAPIDITY DISTRIBUTIONS

+ $\Delta\eta_{jj}$: rapidity difference between the two jets




inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

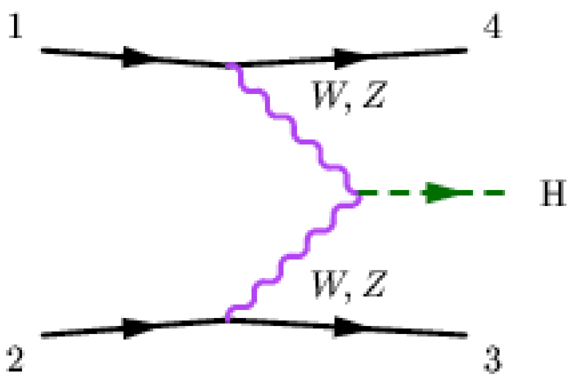
WBF cuts: incl. + $\begin{cases} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{cases}$

☛ WBF events spontaneously have a large $\Delta\eta_{jj}$

☛ dip in gluon fusion at low $\Delta\eta_{jj}$ is unphysical: $R_{jj} = \sqrt{\Delta\eta_{jj} + \Delta\phi_{jj}} > 0.6$

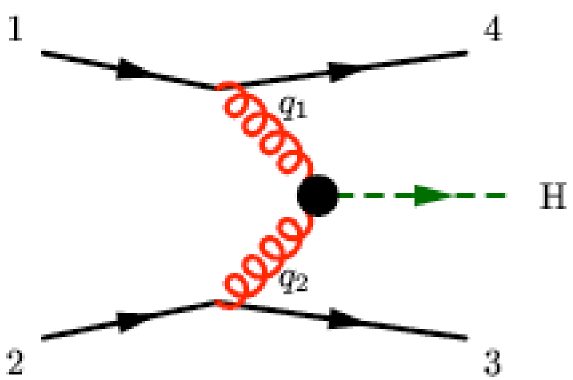
# Azimuthal angle correlations

$\Delta\phi_{jj} \equiv$ the azimuthal angle between the two jets




$$\mathcal{A}_{WBF} \sim \frac{1}{2p_1 \cdot p_4 - M_W^2} \frac{1}{2p_2 \cdot p_3 - M_W^2} \hat{s} m_{jj}^2$$

➥ a flat $\Delta\phi_{jj}$ distribution




gluon fusion in the large $M_t$ limit

$\mathcal{L}_{eff} = \frac{1}{4} A \; H \; G^a_{\mu\nu} G^{a\,\mu\nu} \quad A = \dfrac{\alpha_s}{3\pi v}$

$\mathcal{A}_{gluon} \sim J_1^\mu (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu$

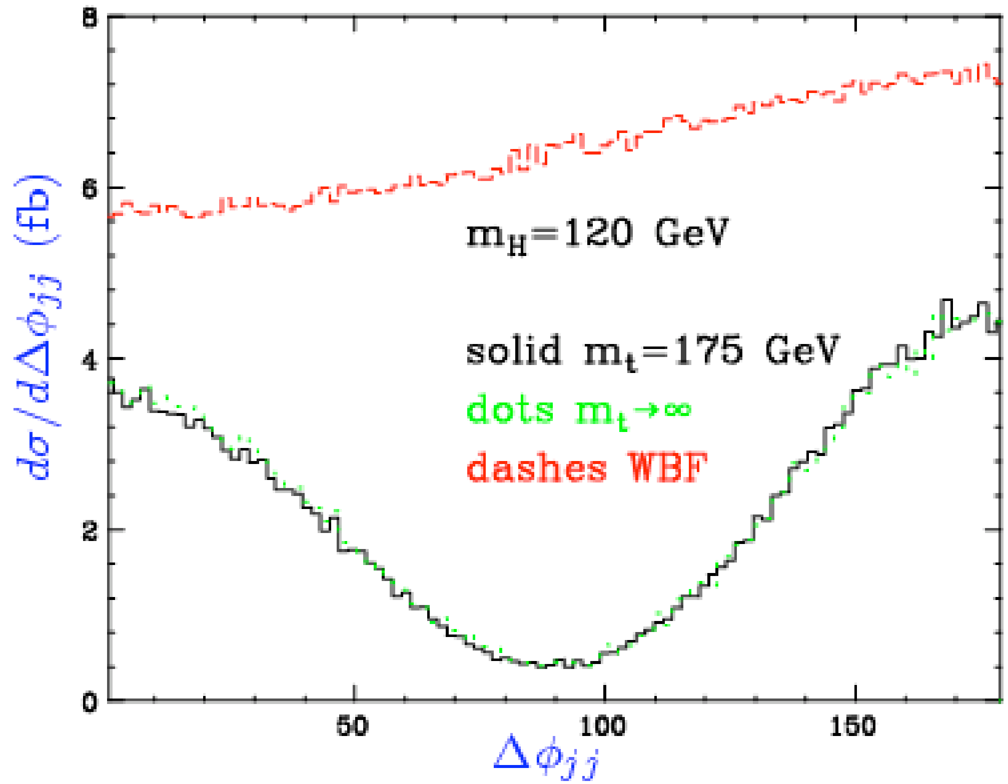
$J^\mu \equiv$ quark-gluon current

for $|p_i{}^z| \gg |p_i{}^{x,y}| \quad i = 3, 4$: forward jets

$\mathcal{A}_{gluon} \sim (J_1^0 J_2^0 - J_1^3 J_2^3) \; p_{3\perp} \cdot p_{4\perp}$

➥ zero at $\Delta\phi_{jj} = \dfrac{\pi}{2}$

# AZIMUTHAL ANGLE DISTRIBUTION



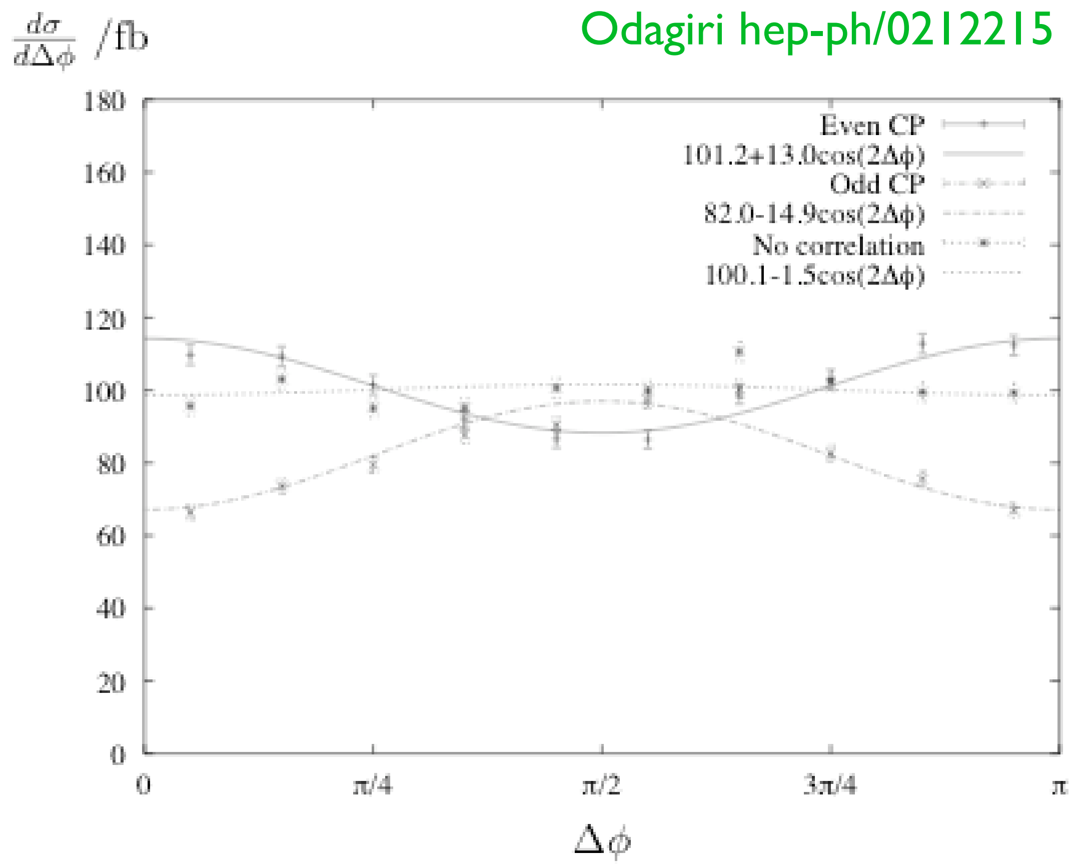

$$\text{WBF cuts:} \quad \left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right. \quad + \quad \left\{ \begin{array}{l} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ m_{jj} > 600 \text{ GeV} \end{array} \right.$$

- the azimuthal angle distribution discriminates between WBF and gluon fusion
- note that the large $M_t$ limit curve approximates very well the exact curve

# Caveat

Including parton showers and hadronisation through HERWIG, Odagiri finds much less correlation between the jets, but the plot has been obtained by generating also the jets through the showers

Odagiri hep-ph/0212215




A better analysis would require the generation of the basic final-state topology (i.e. Higgs + 2 jets) through the exact matrix elements, and the additional radiation through showers and hadronisation

ALPGEN Collab & VDD, in progress

# WWH Coupling

- the azimuthal angle $\Delta\phi_{jj}$ between the jets can be used as a tool to investigate the tensor structure of the WWH coupling

  Plehn, Rainwater, Zeppenfeld hep-ph/0105325

- take a gauge-invariant effective Lagrangian with dim. 6 operators (CP even and CP odd) describing an anomalous WWH coupling

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda^2_{e,6}} \left(\Phi^\dagger\Phi\right) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda^2_{o,6}} \left(\Phi^\dagger\Phi\right) \widetilde{V}_{\mu\nu} V^{\mu\nu}$$

- expand $\Phi$ about the vev (get dim. 5 (D5) operators)

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}}\, H\, W^+_{\mu\nu} W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}}\, H\, \widetilde{W}^+_{\mu\nu} W^{-\mu\nu} \quad \text{with} \quad \frac{1}{\Lambda_5} = \frac{g^2 v}{\Lambda^2_6}$$

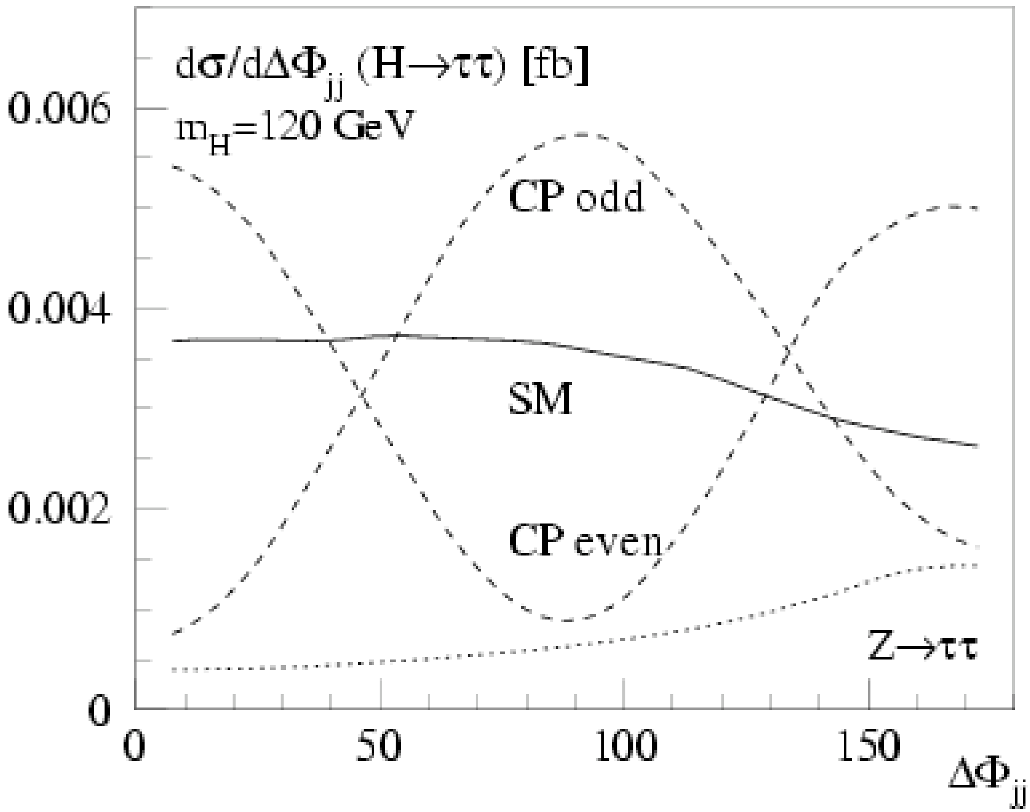
- CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling
  - ➥ zero at $\Delta\phi_{jj} = 0, \pi$

- CP even D5 operator is like the effective $ggH$ coupling

$$\mathcal{A}_{\text{CP even}} \sim \frac{1}{\Lambda_{e,5}} J_1^\mu \left(q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2\right) J_2^\nu \qquad \Rightarrow \qquad \text{zero at } \Delta\phi_{jj} = \frac{\pi}{2}$$

# Azimuthal angle distribution for WWH couplings

- assume a Higgs-like scalar signal is found at LHC at the SM rate (for D5 operators: $\Lambda_5 \sim 500$ GeV)




WBF cuts:

$p_{j\perp} > 20$ GeV

$|\eta_j| < 5$

$R_{jj} > 0.6$

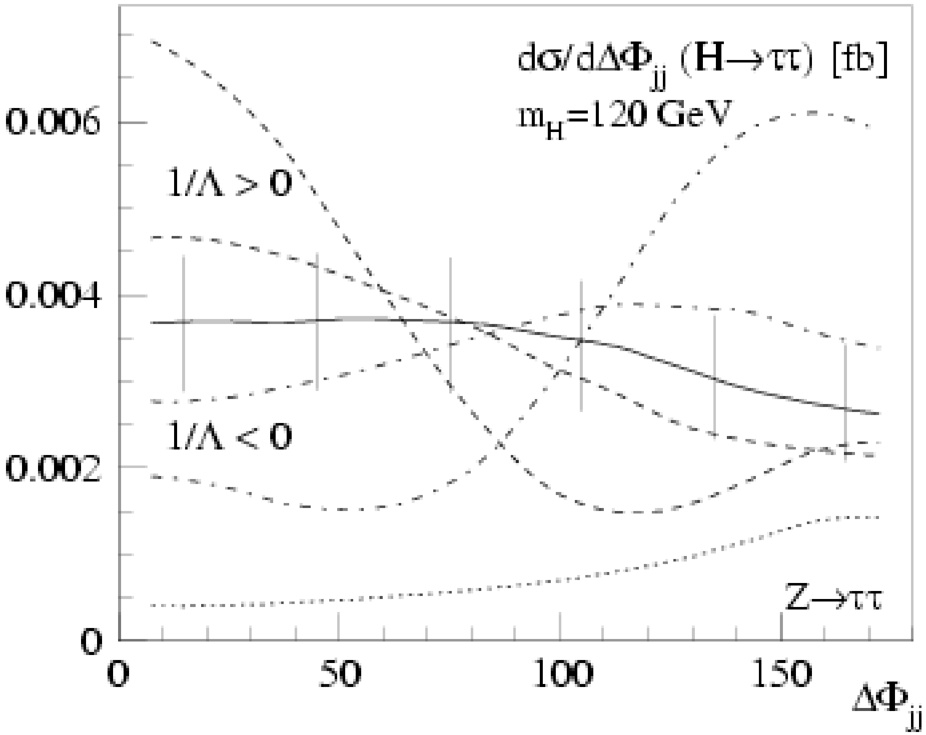
$\eta_{j_1} \cdot \eta_{j_2} < 0$

$|\eta_{j_1} - \eta_{j_2}| > 4.2$

- the $\Delta\phi_{jj}$ distribution
  - ☛ discriminates between different WWH couplings
  - ☛ is independent of the particular decay channel and the Higgs mass range

# Interference effects in the $\Delta\phi_{jj}$ distribution

- assume a Higgs candidate is found at LHC with a predominantly SM $g^{\mu\nu}$ coupling. How sensitive are experiments to any D5 terms ?
- no interference between SM and CP odd D5 operator




$\Delta\phi_{jj}$ distribution for the SM and interference with a CP even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{SM} = 0.04, 1.0$. Error bars correspond to an integrated luminosity of 100 $fb^{-1}$ per experiment, distributed over 6 bins, and are statistical only

- interference between SM and CP even D5 operator: $|\mathcal{A}|^2 = |\mathcal{A}_{SM} + \mathcal{A}_{e,5}|^2$
  - all terms, but $|\mathcal{A}_{SM}|^2$, have an approximate zero at $\Delta\phi_{jj} = \pi/2$
  - systematic uncertainty induced by $H + 2$ jet rate from gluon fusion
    - $HG_{\mu\nu}G^{\mu\nu}$ is a CP even D5 operator

# The Central Jet Veto

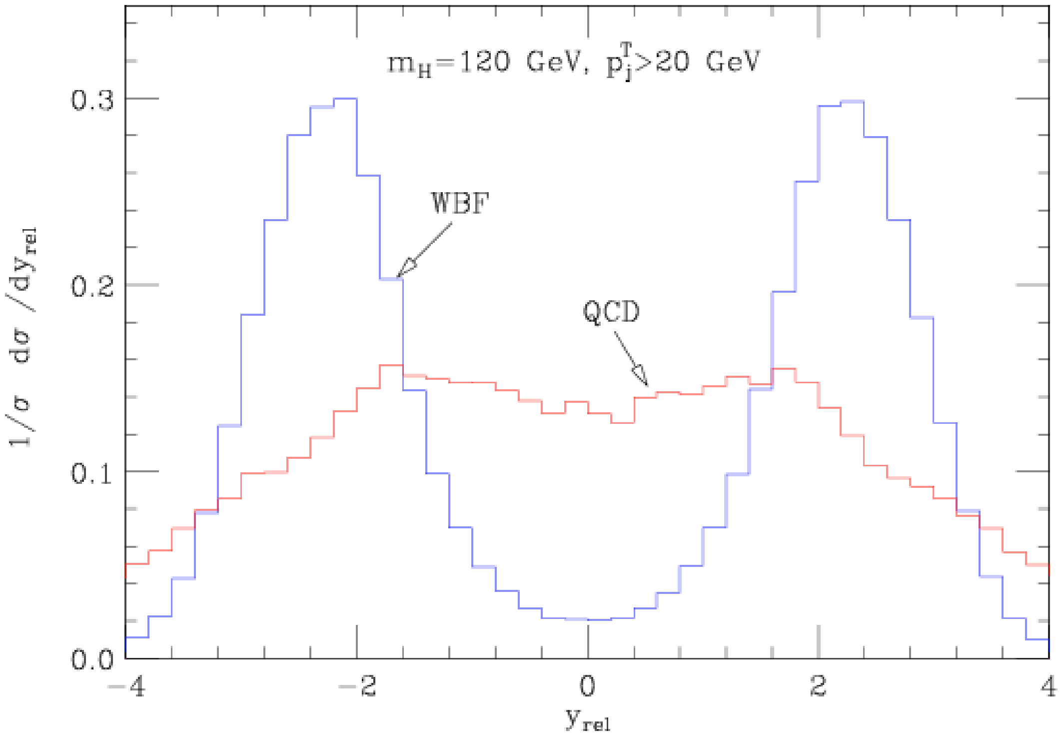
- In WBF no colour is exchanged in the $t$ channel

- The central-jet veto is based on the different radiation pattern expected for WBF versus its major backgrounds, i.e. $t\bar{t}$ production and WW + 2 jet production

  Barger, Phillips & Zeppenfeld hep-ph/9412276

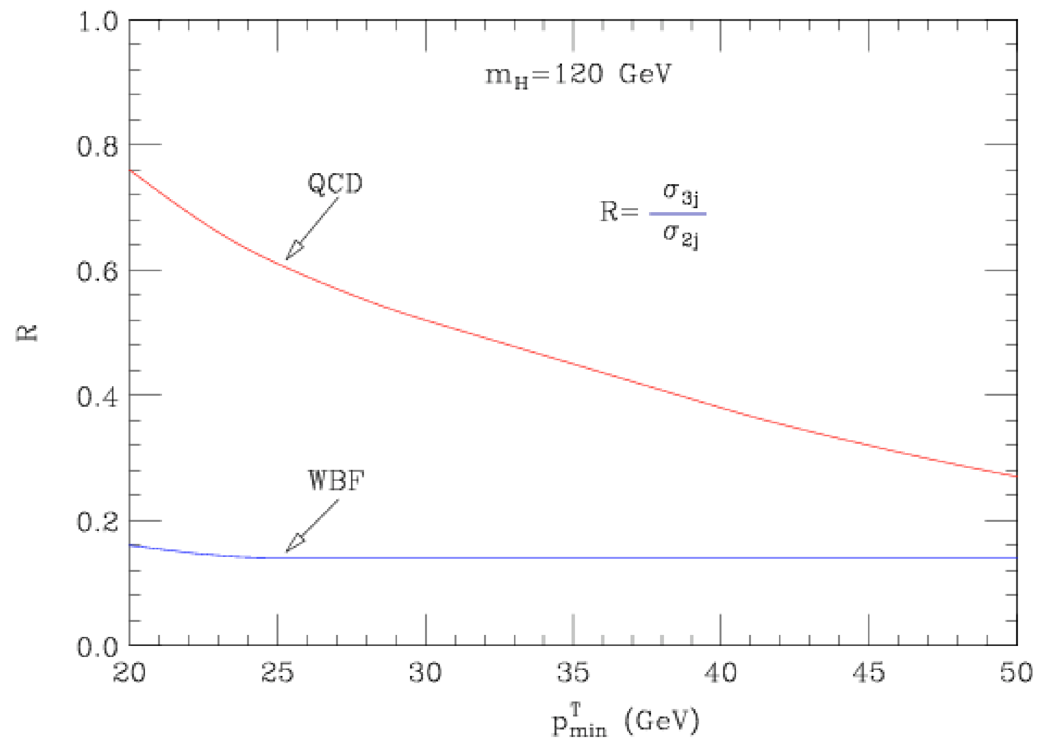
- The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF

Frizzo, Maltoni, VDD hep-ph/0404013




Distribution in rapidity of the third jet wrt to the rapidity average of the tagging jets

Ratio of Higgs + 3 jet to Higgs + 2 jet production as a function of $p^T_{min}$



# Conclusions

- In Higgs + 2 jets, the azimuthal angle correlation between the two jets can be used as a tool to distinguish between WBF and gluon fusion, and to investigate the tensor structure of the WWH coupling
- Higgs + 2 jets via gluon fusion is known at leading order, including the top mass dependence
  - it has a strong renormalisation scale dependence
  - the large $M_t$ limit is accurate if $M_H \ll 2M_t$ and $p_T \ll M_t$, and is valid even when the dijet, or jet-Higgs, invariant masses are much larger than $M_t$
- Higgs + 2 jets via WBF is known at NLO, which increases the WBF production rate by about $10\,\%$
- Large-rapidity (WBF) cuts can be used to deplete gluon fusion wrt WBF
- A central-jet veto can be used to further deplete gluon fusion wrt WBF; a study of the veto can be performed through Higgs + 3 jets, which has been computed at leading order in the large $M_t$ limit