Higgs Production at LHC

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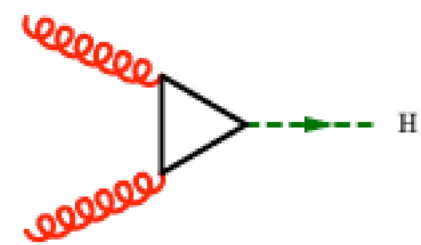
Roma 21 ottobre 2004

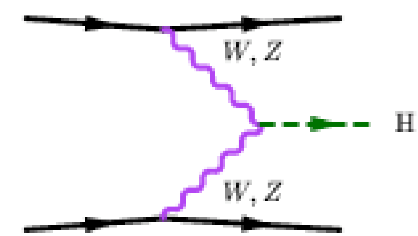
Higgs Production Modes at LHC

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

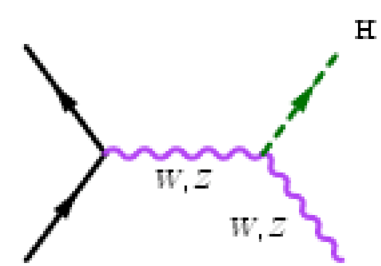
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



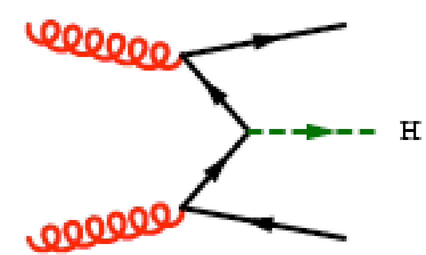
- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



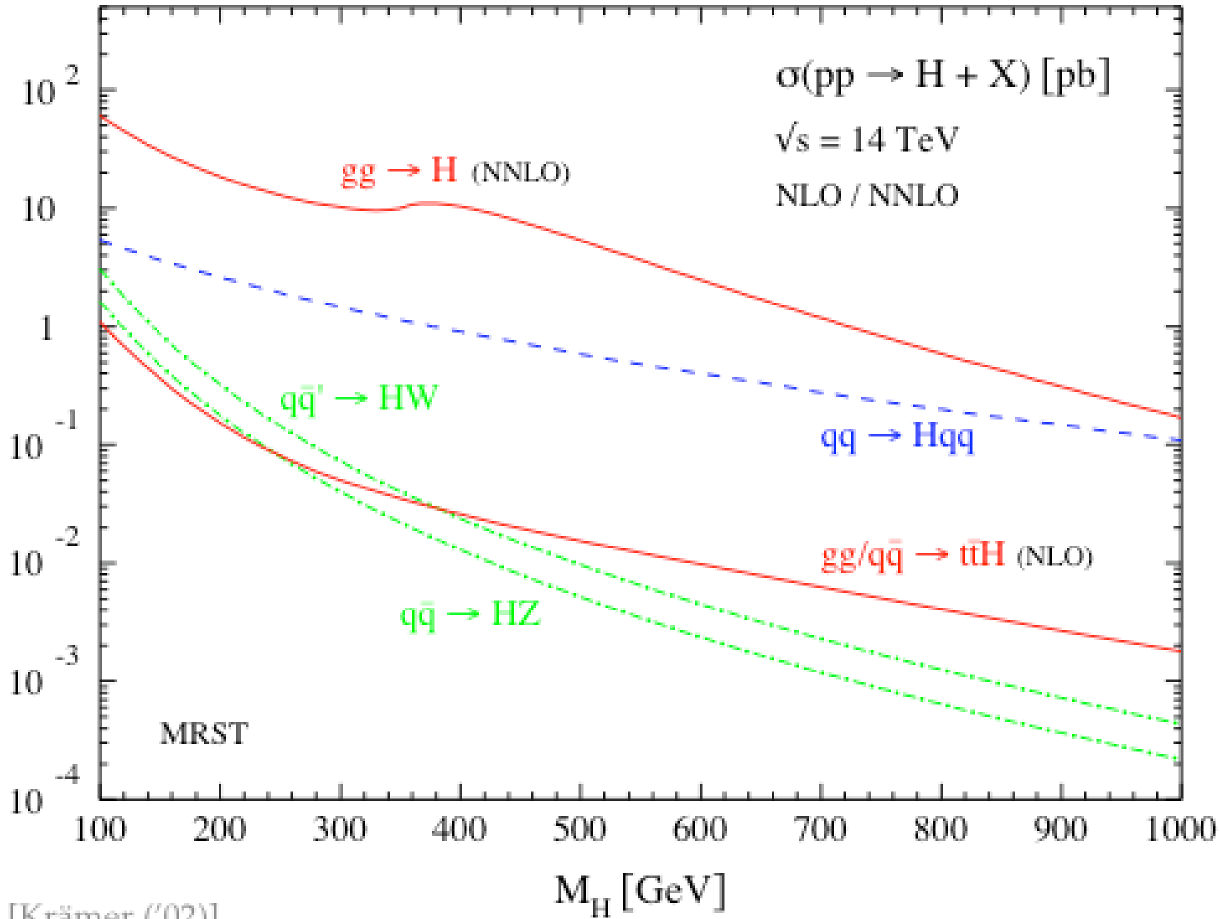
- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in WBF



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



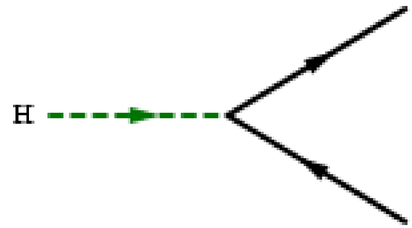
HIGGS PRODUCTION AT LHC



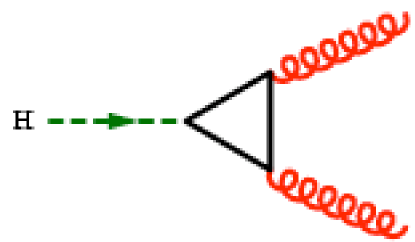
[Krämer ('02)]

- 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

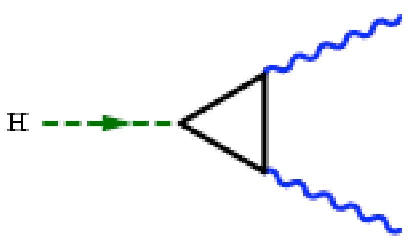


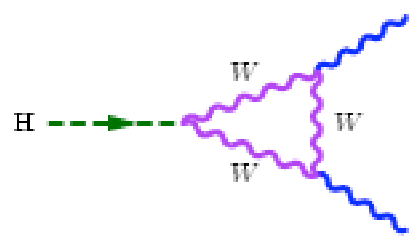
proportional to the Yukawa coupling squared, and thus to m_f^2



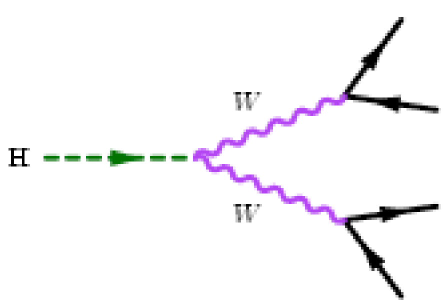
proportional to m_f^4/m_H^4

but dominated by top quark Yukawa coupling





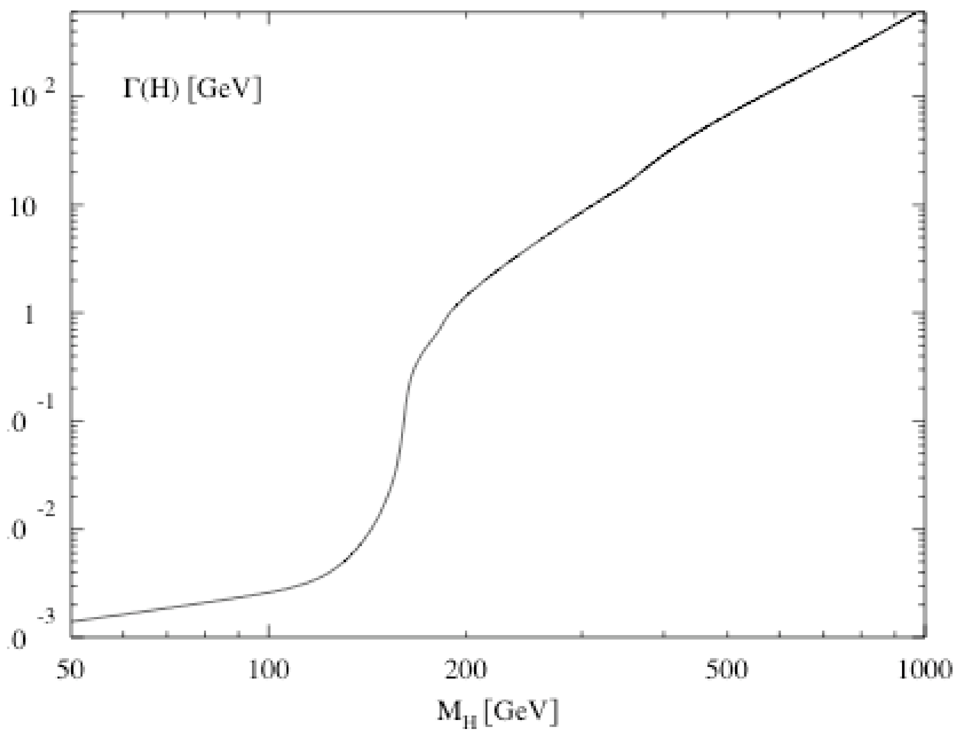
dominated by EW coupling



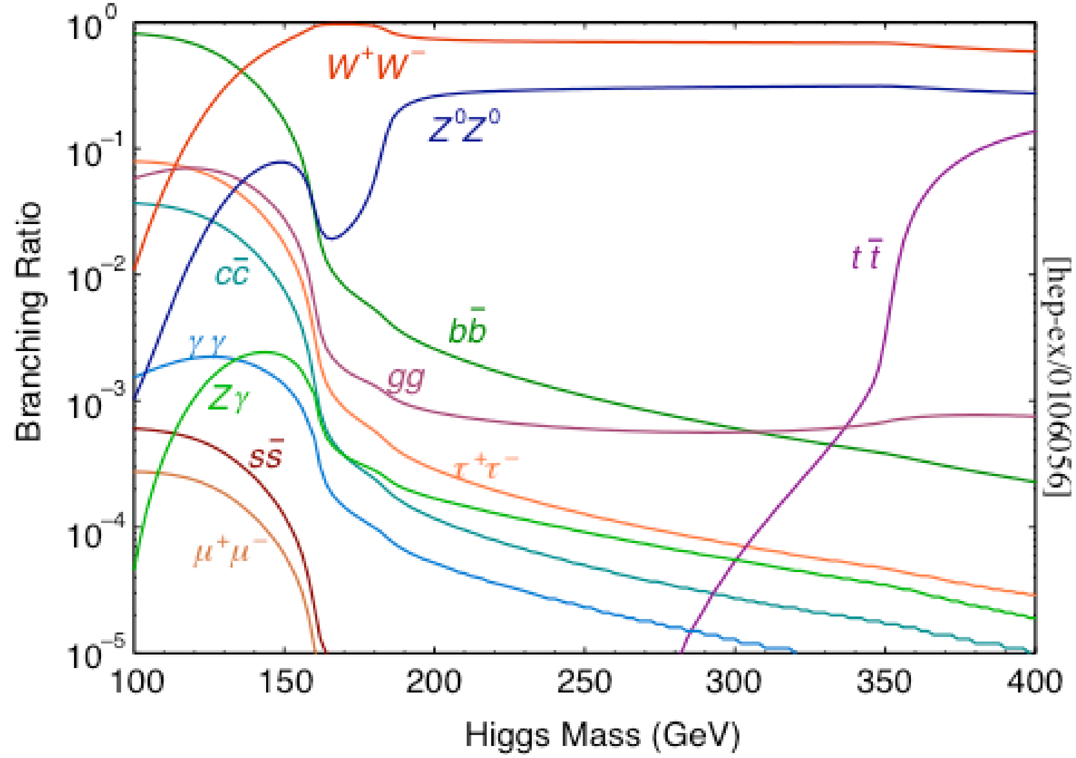
proportional to α_W

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

Higgs Decay at LHC

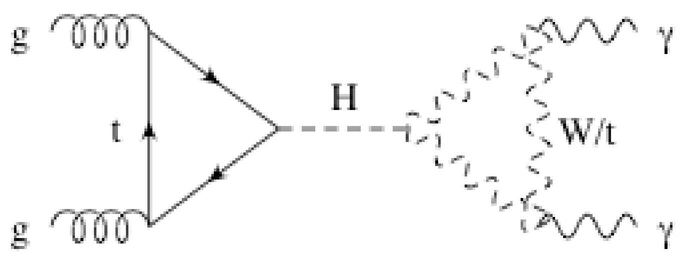


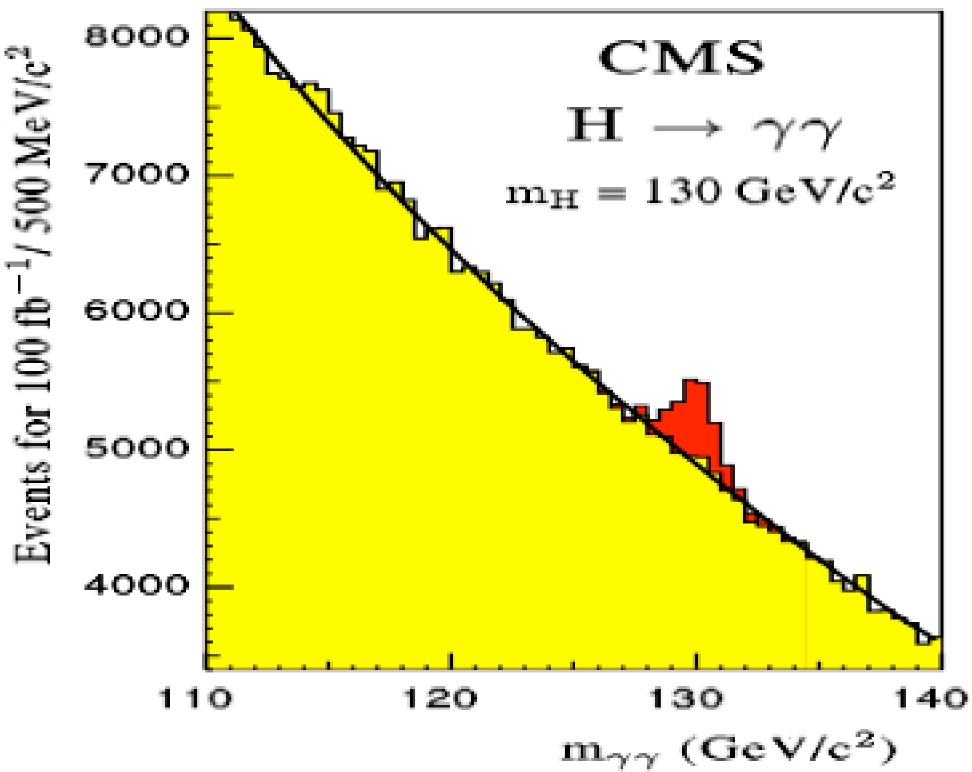
total width



branching fractions

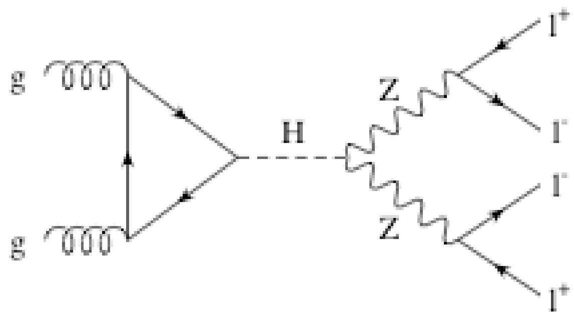
Inclusive searches: $H \to \gamma\gamma$

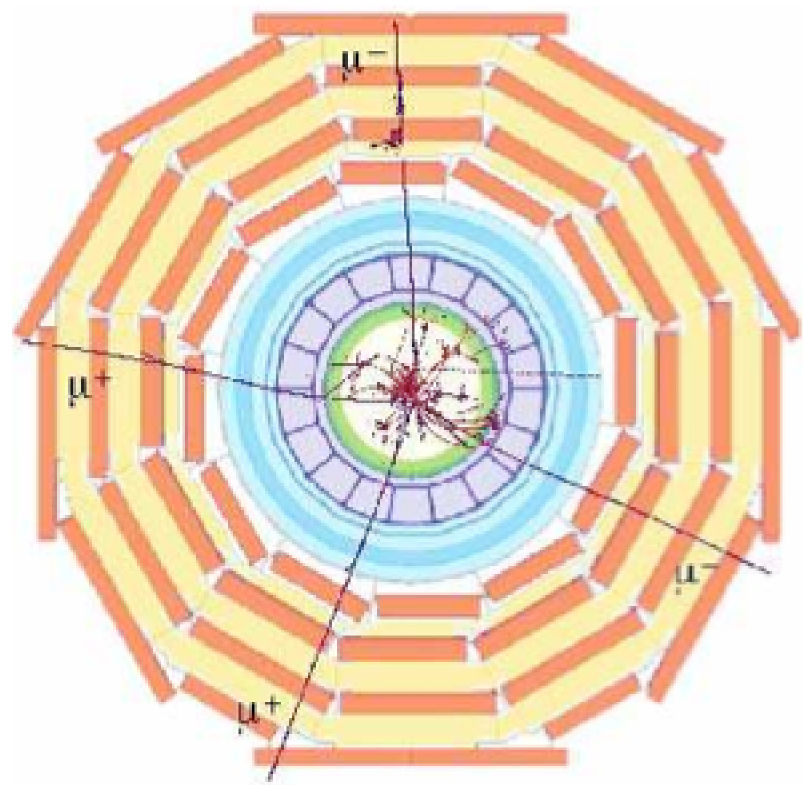




- Small BR: $\approx 10^{-3}$
- Large backgrounds from $pp \to \gamma\gamma$
- CMS and ATLAS have very good photon-energy resolution: $\mathcal{O}(1\%)$
- Search for a narrow $\gamma\gamma$ invariant mass peak, with $m_H < 150$ GeV
- Background is smooth: extrapolate it into the signal region from the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

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

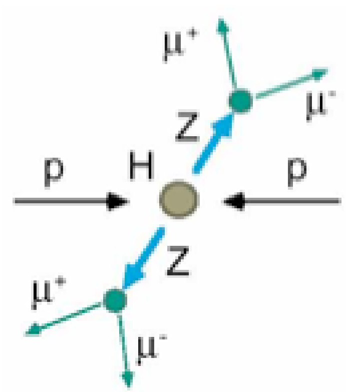


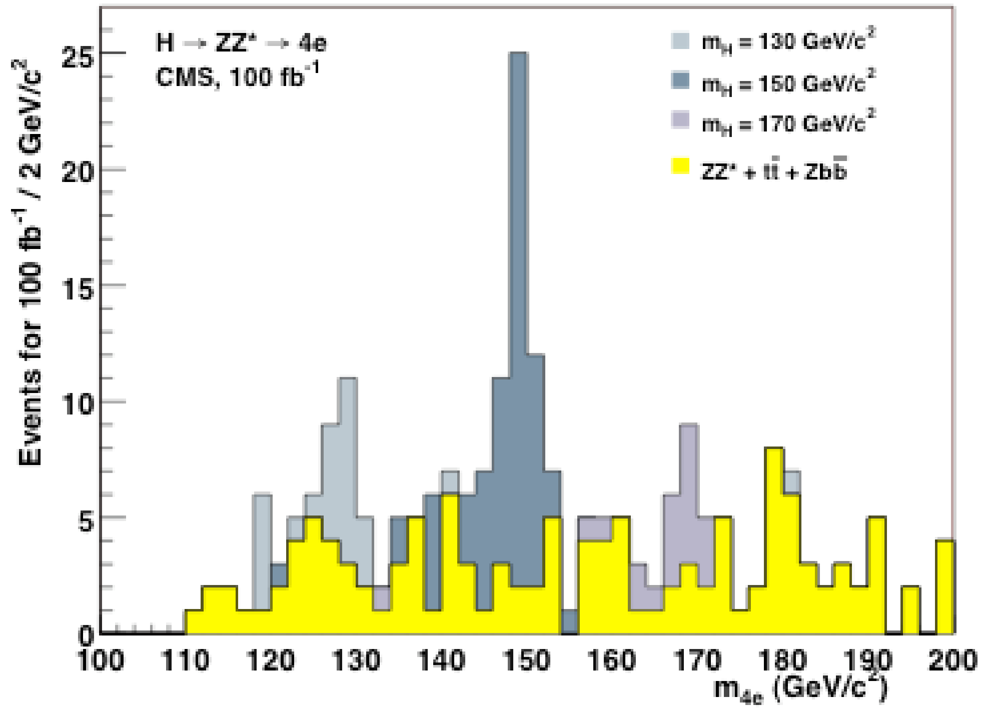


- Gold-plated mode: cleanest mode for $2m_Z < m_H < 600\ \mathrm{GeV}$
- Smooth, irreducible background from $pp \to ZZ$
- Small BR: $\mathrm{BR}(H \to ZZ)$ is a few $\%$ at threshold

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

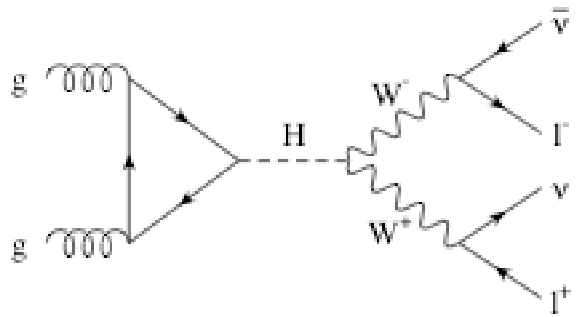
- Fully reconstructed invariant mass of the leptons



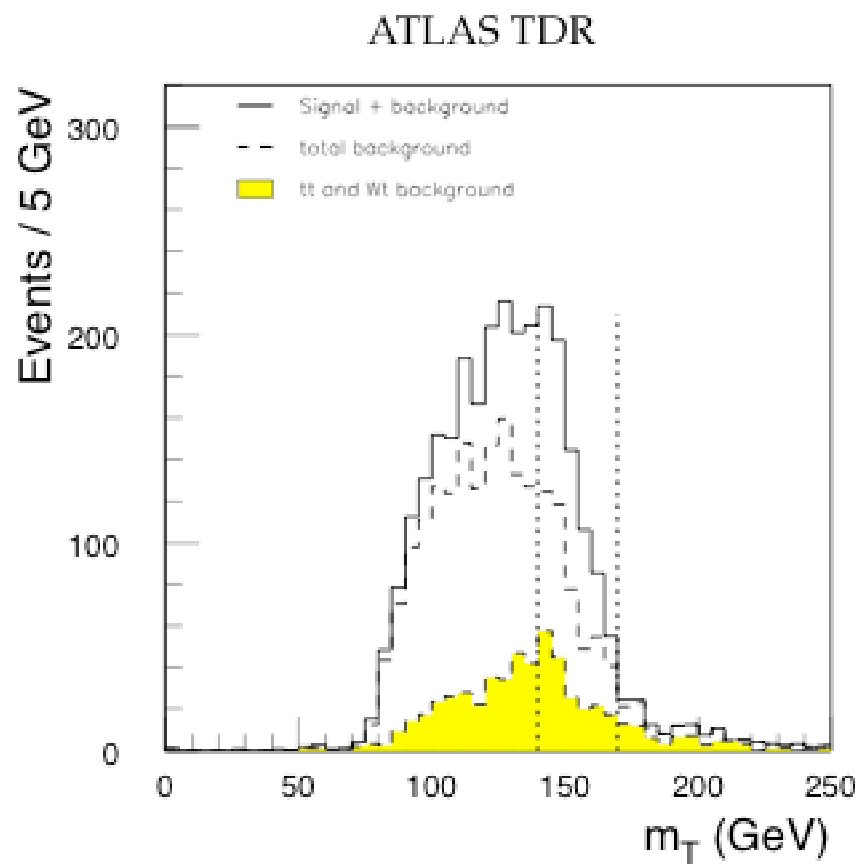


- Silver-plated mode $H \to ZZ \to l^+l^-\nu\bar{\nu}$ useful for $m_H \approx 0.8 - 1\ \mathrm{TeV}$

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



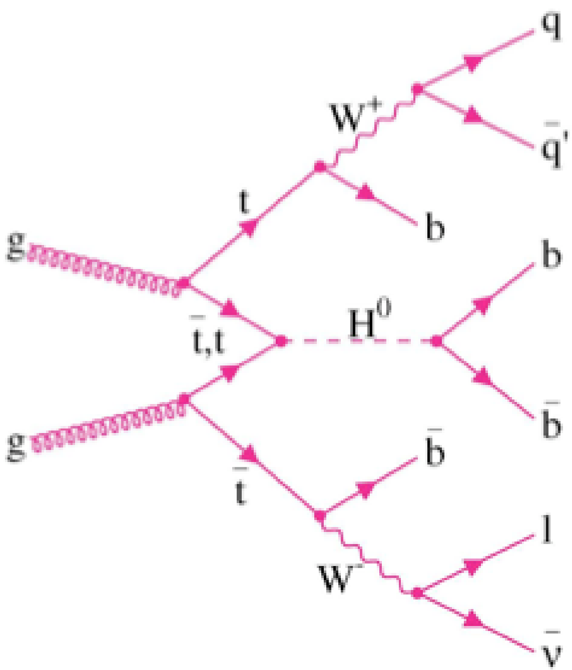
- Exploit l^+l^- angular correlations
- Signal and background have similar shapes: must know background normalisation well

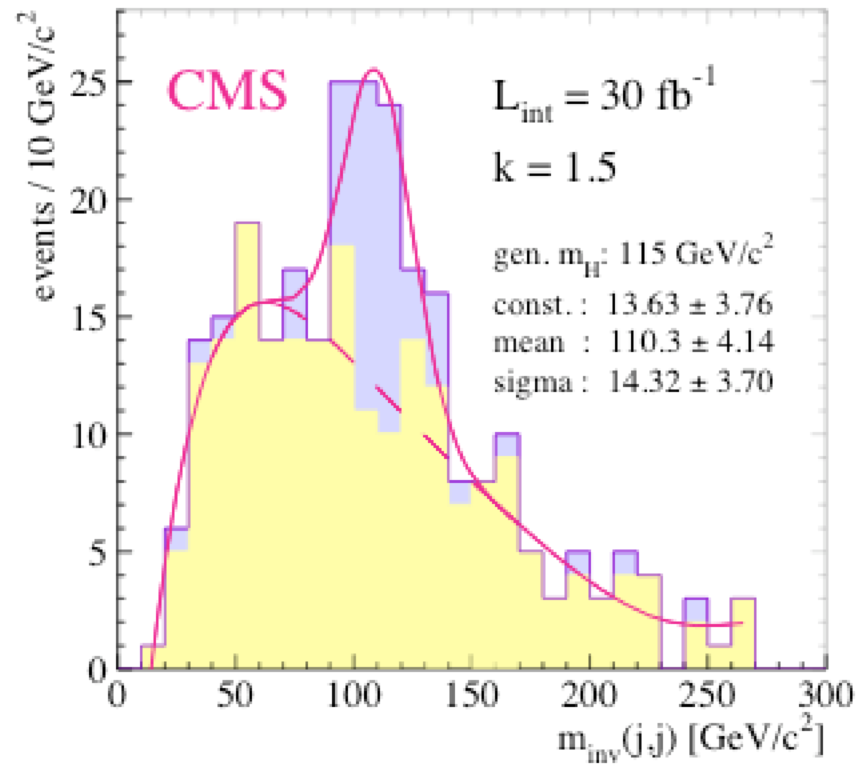


$m_H = 170$ GeV

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

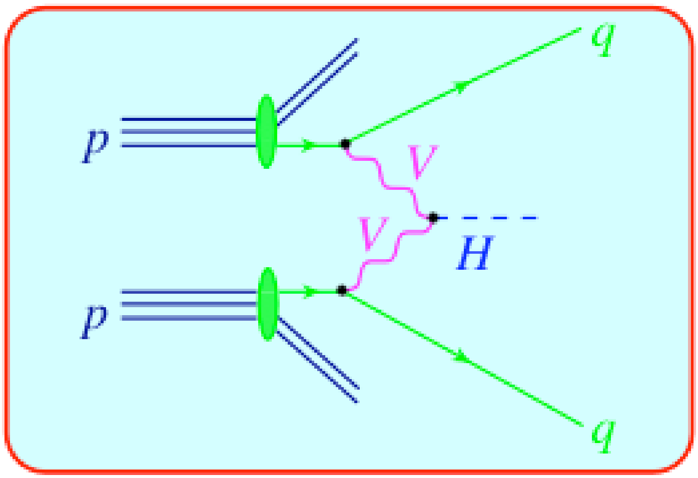
ASSOCIATED PRODUCTION: $Ht\bar{t} \longrightarrow t\bar{t}b\bar{b}$

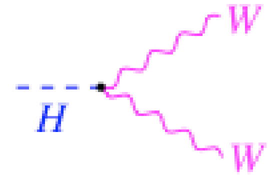




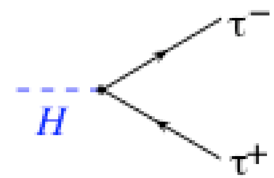
- Search channel for $m_H = 120 - 130$ GeV
- Measure h_t^2 BR$(H \rightarrow b\bar{b})$ with $h_t = Ht\bar{t}$ Yukawa coupling
- must know background normalisation well

WEAK BOSON FUSION: $qq \longrightarrow qqH$

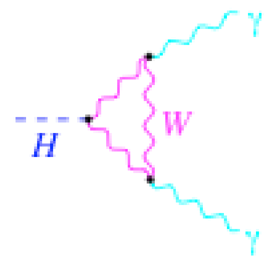




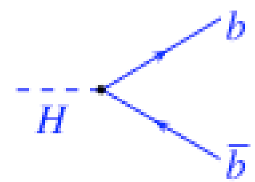
$m_H > 120$ GeV



$m_H < 140$ GeV



$m_H < 150$ GeV

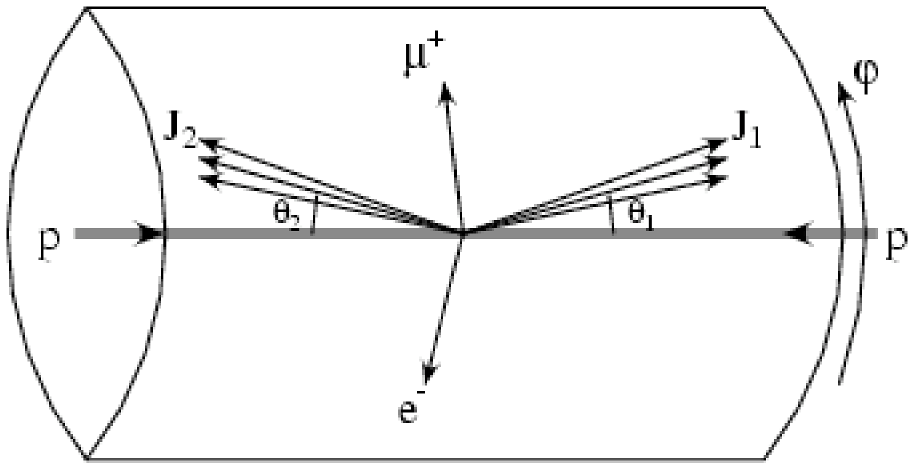


$m_H < 140$ GeV

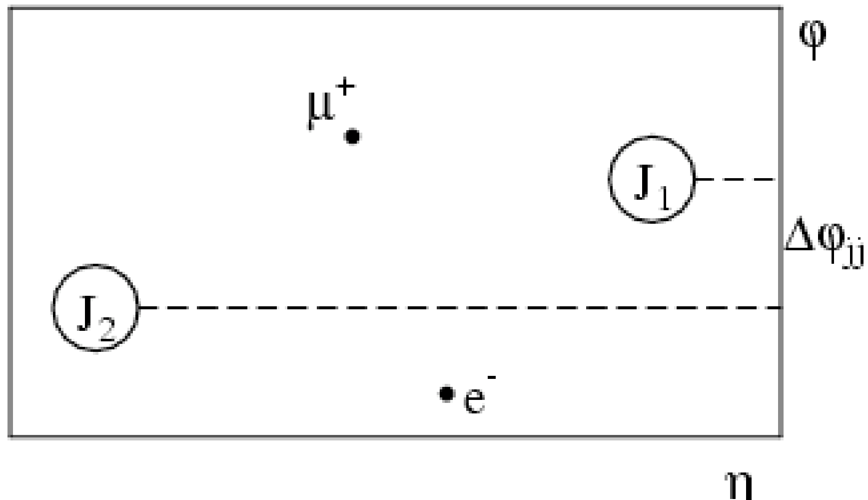
- WBF can be measured with good statistical accuracy: $\sigma \times \mathrm{BR} \approx \mathcal{O}(10\%)$

Weak Boson Fusion

A WBF event



Lego plot

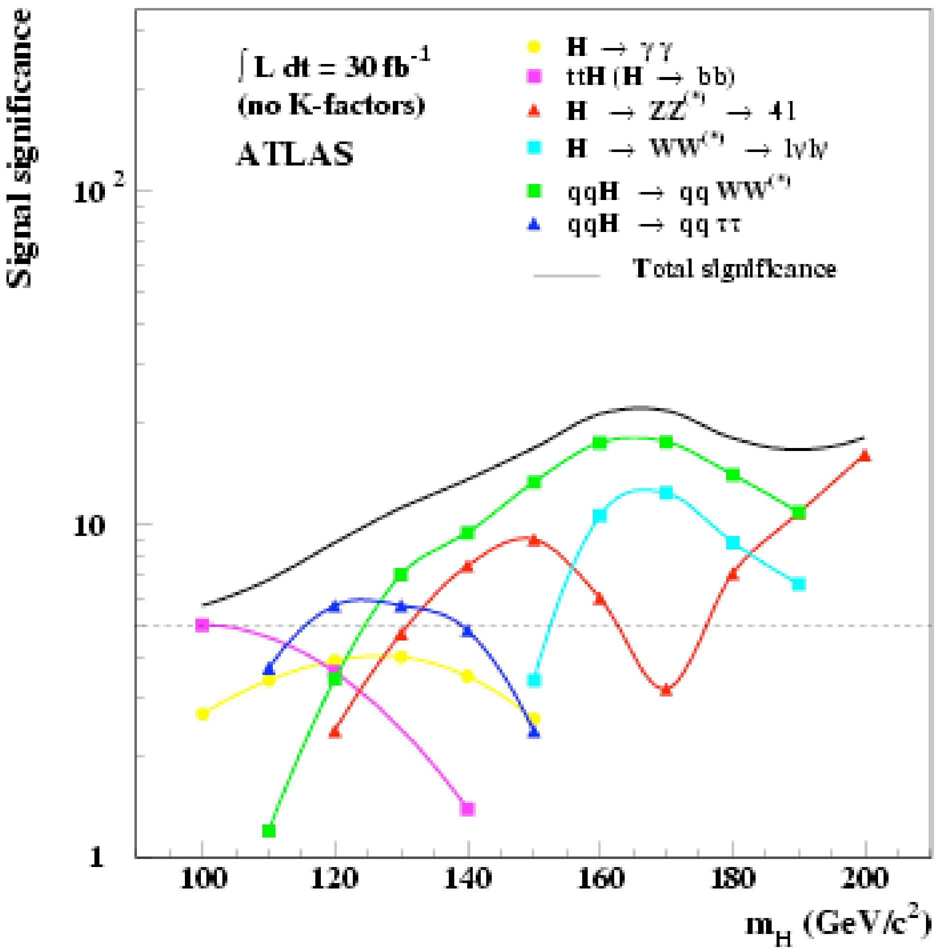


$$\eta = \frac{1}{2} \ln \frac{1+\cos\theta}{1-\cos\theta}$$

- 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

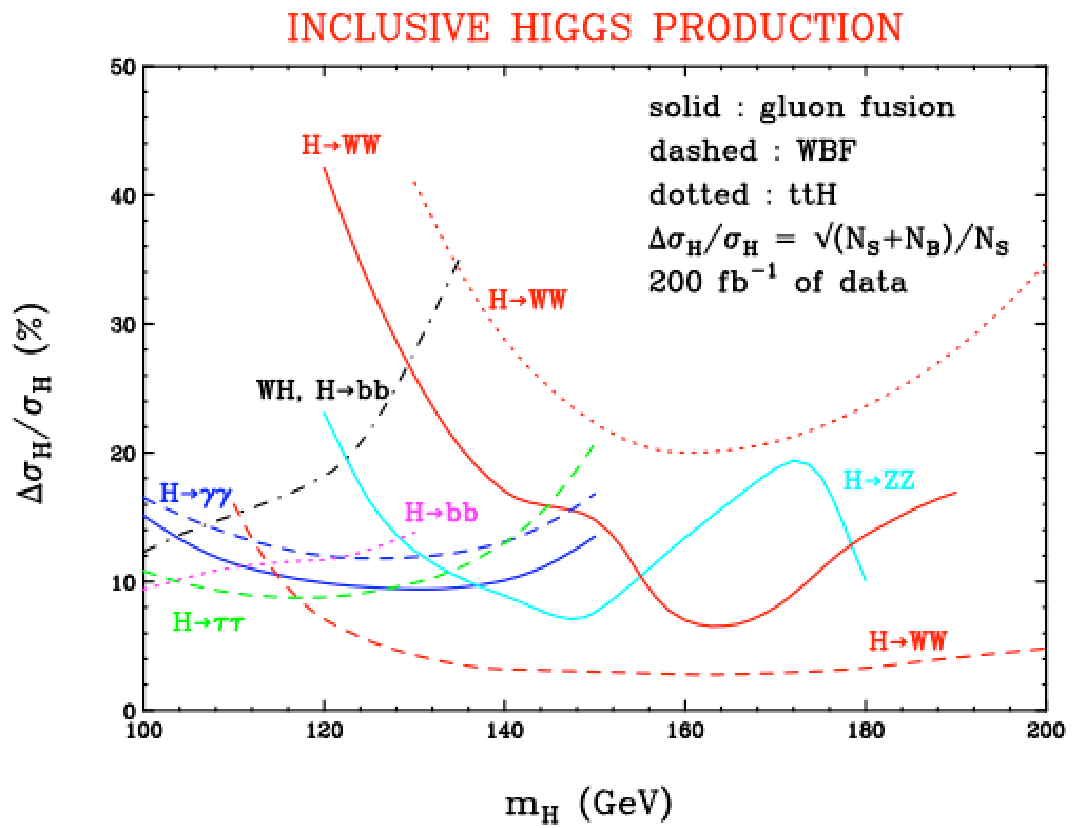
Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003

SIGNAL SIGNIFICANCE AND (STAT + SYST) ERROR



hep-ph/0402254

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



hep-ph/0203187

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

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

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

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

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

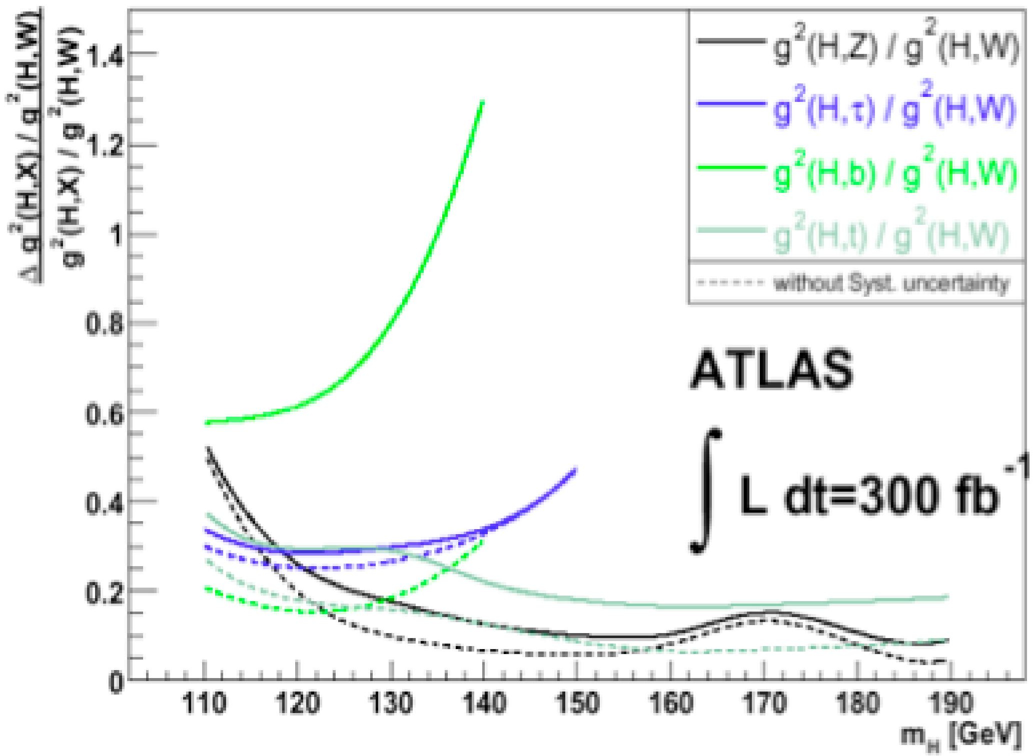
$$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma} \quad \text{from} \quad gg \to H \to ZZ^*$$

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

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

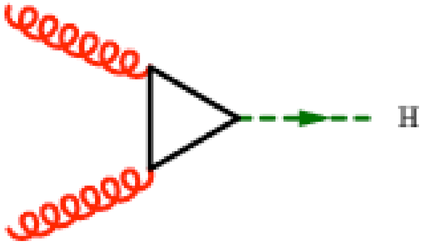


The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events (more on this later)

Higgs Production via Gluon Fusion

Leading Order

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

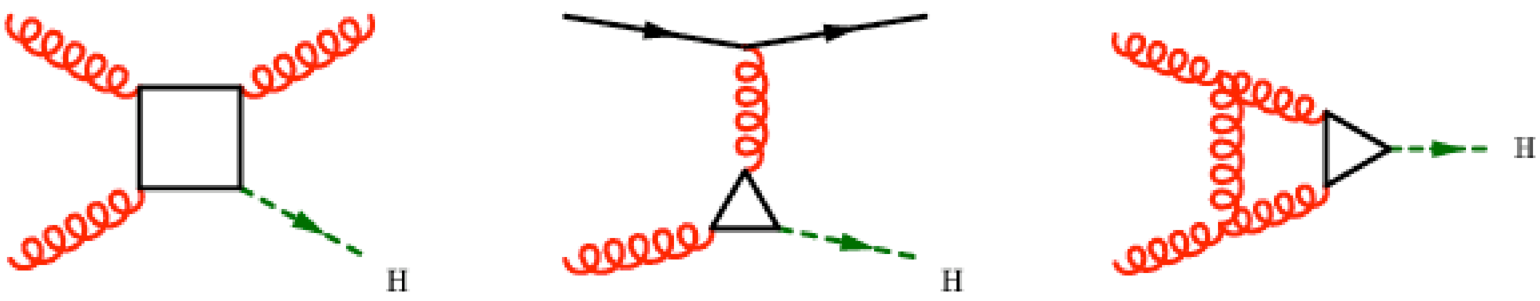


☛ energy scales: $\hat{s} = M_H^2$ and M_t^2

NLO corrections

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

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

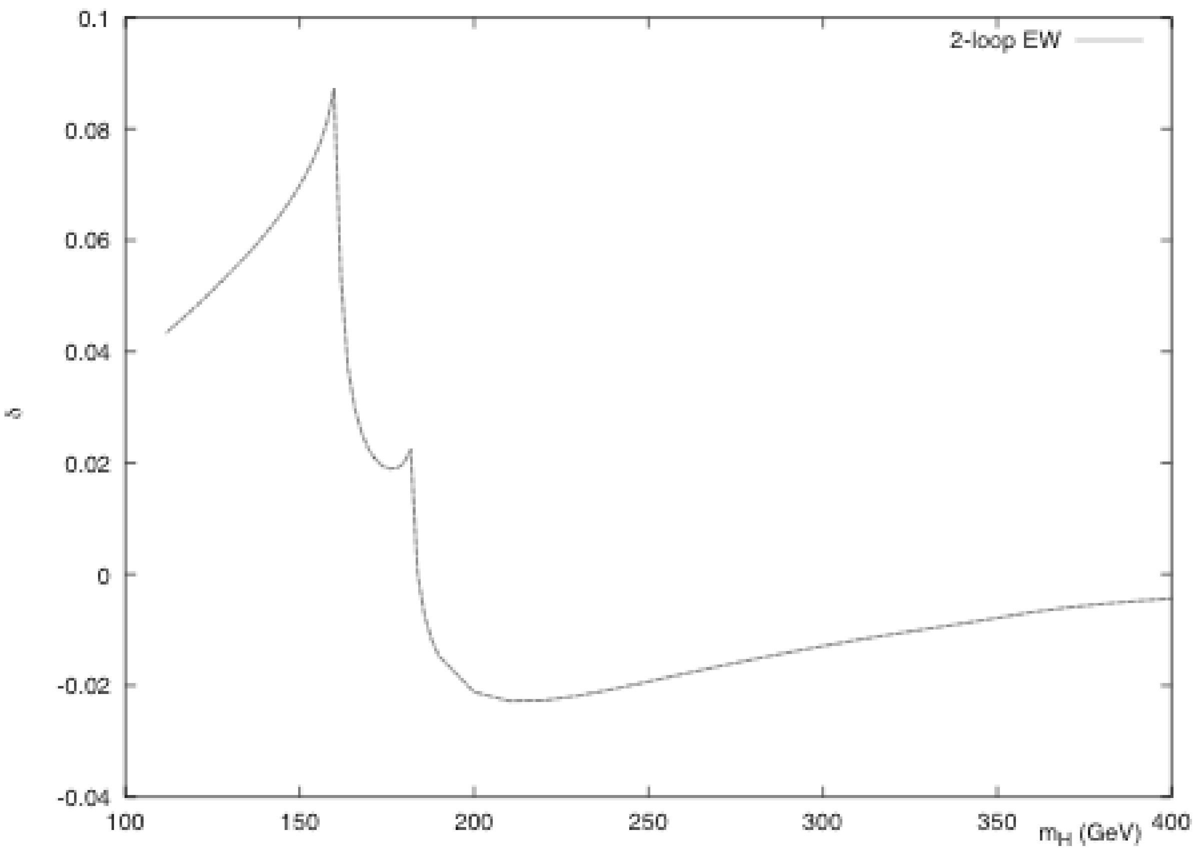


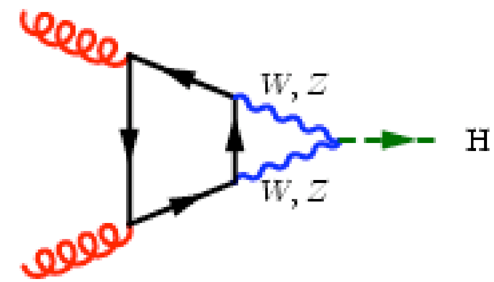
Djouadi, Graudenz, Spira, Zerwas, '93-'95

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

EW CORRECTIONS

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



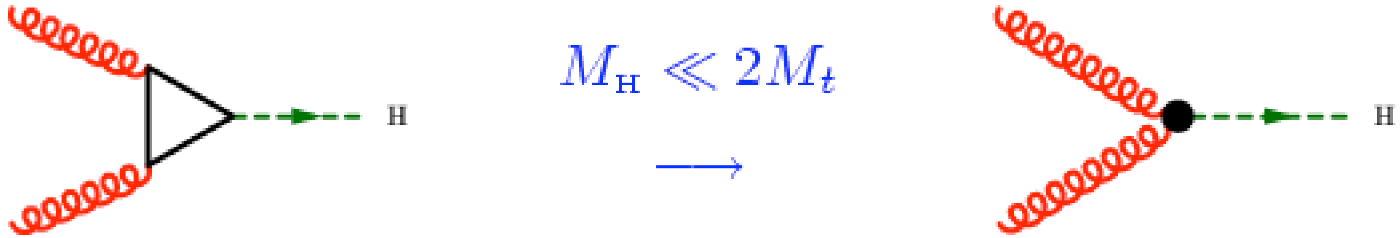


Aglietti Bonciani Degrassi Vicini 04
(light fermion loop)

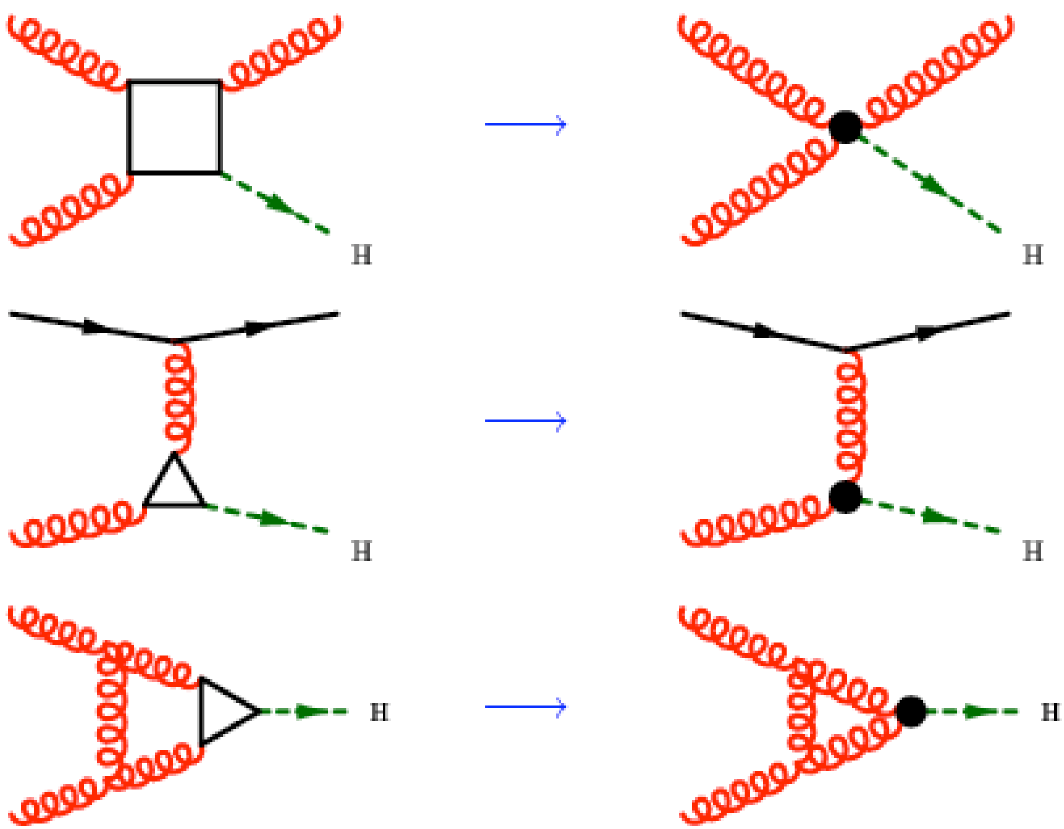
Degrassi Maltoni 04
(heavy fermion loop)

- 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



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

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

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

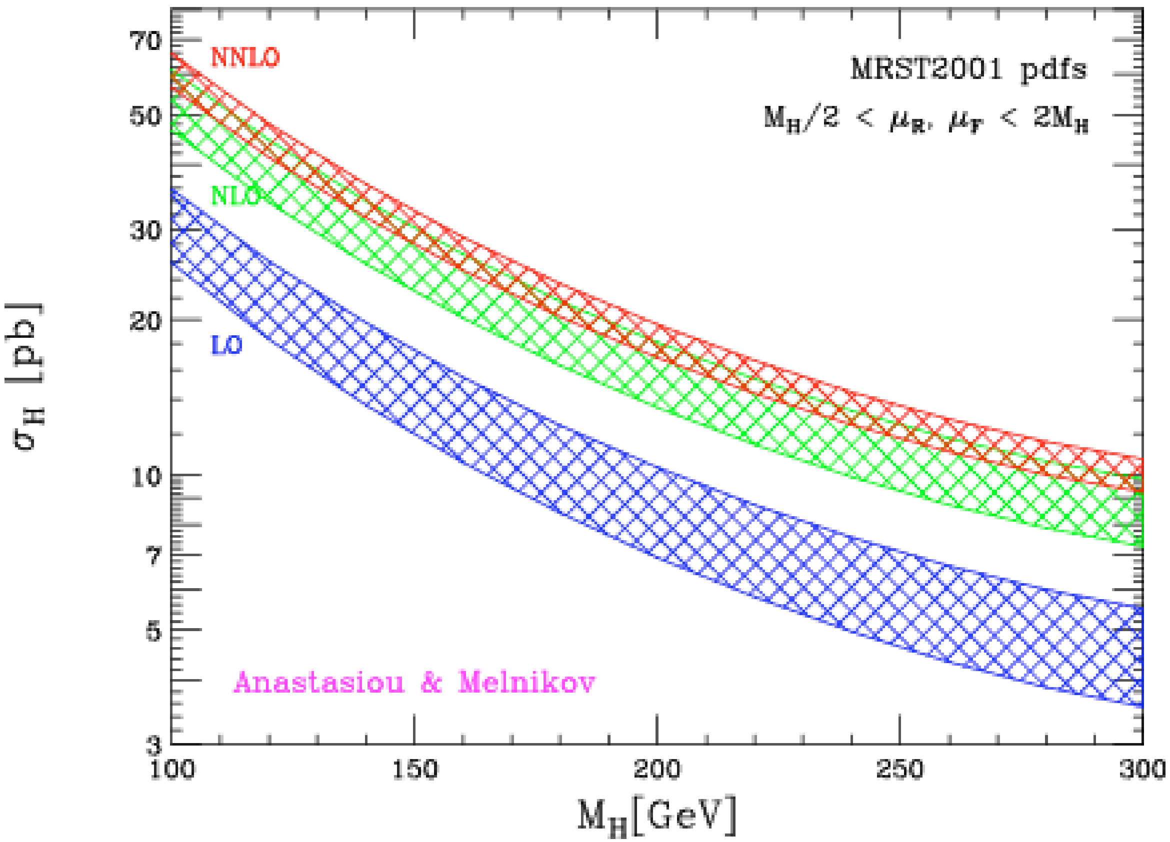
$gg \to H$ IN THE LARGE M_t LIMIT

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

2-loop $gg \to H$ R. Harlander hep-ph/0007289

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

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



total cross section for inclusive Higgs production at LHC

Harlander Kilgore 02
Anastasiou Melnikov 02
Ravindran Smith van Neerven 03

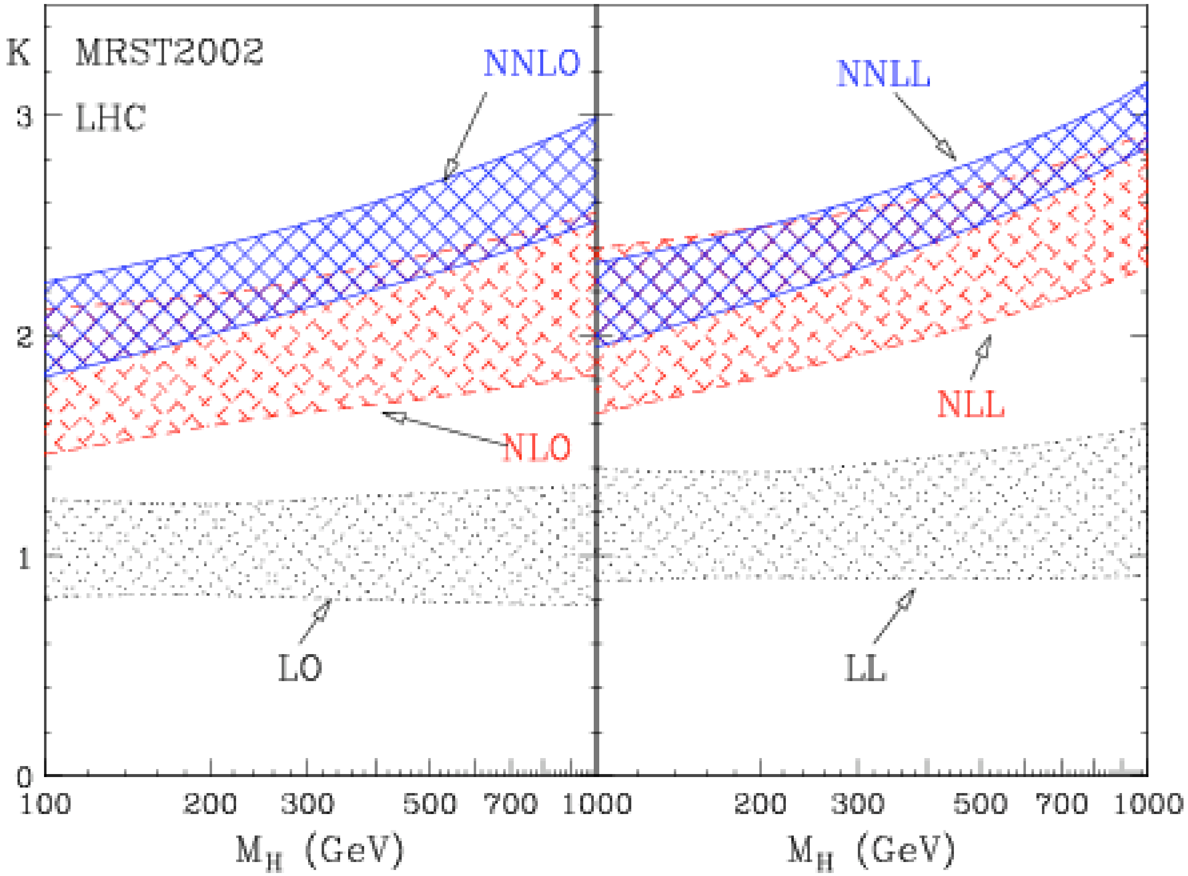
The band contours are

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

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

NNLO CORRECTIONS + NNLL RESUMMATION

- Threshold resummation of soft gluon radiation

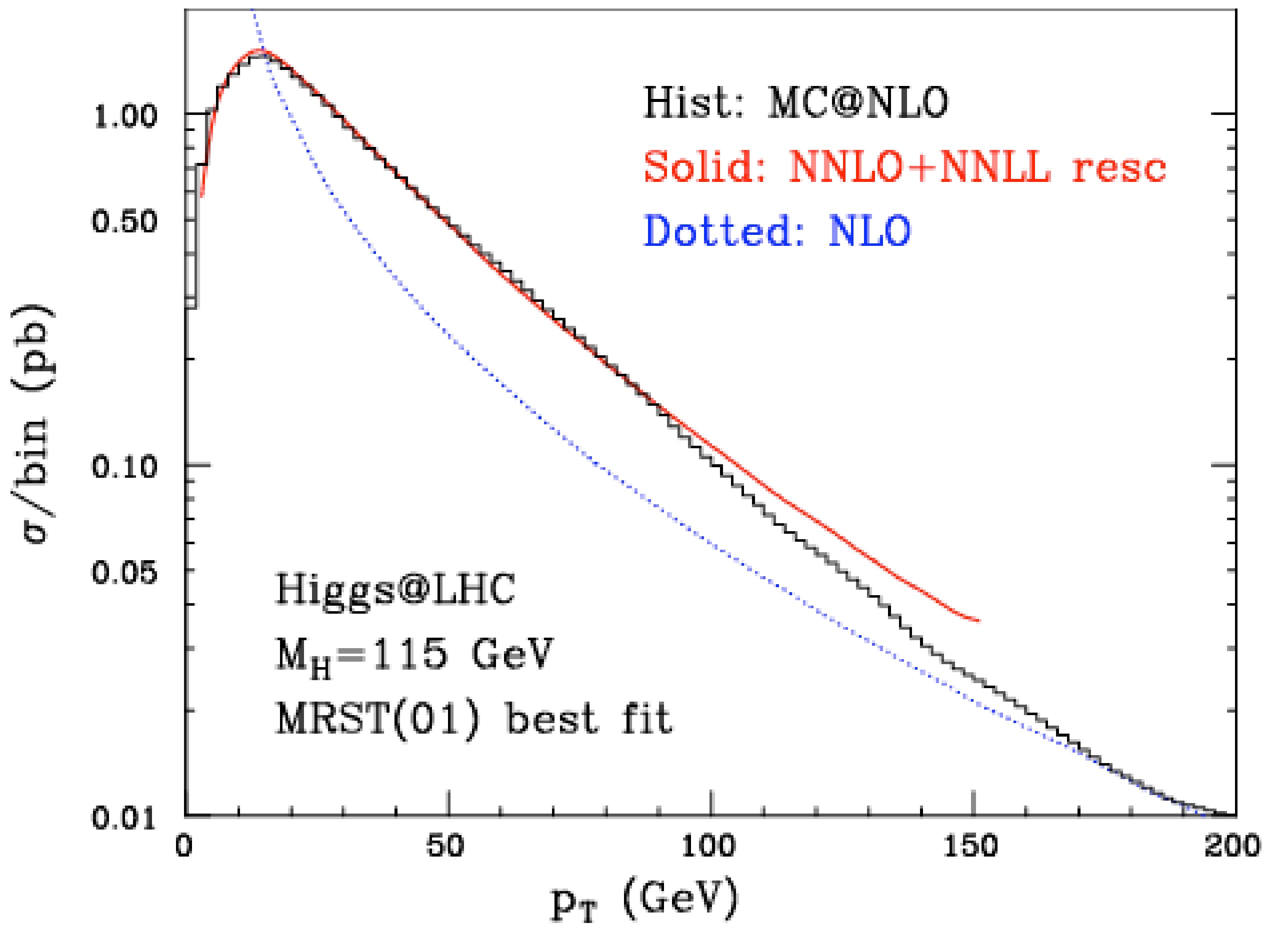


Catani, de Florian
Grazzini, Nason
hep-ph/0306211

- K factor is computed wrt to σ^{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



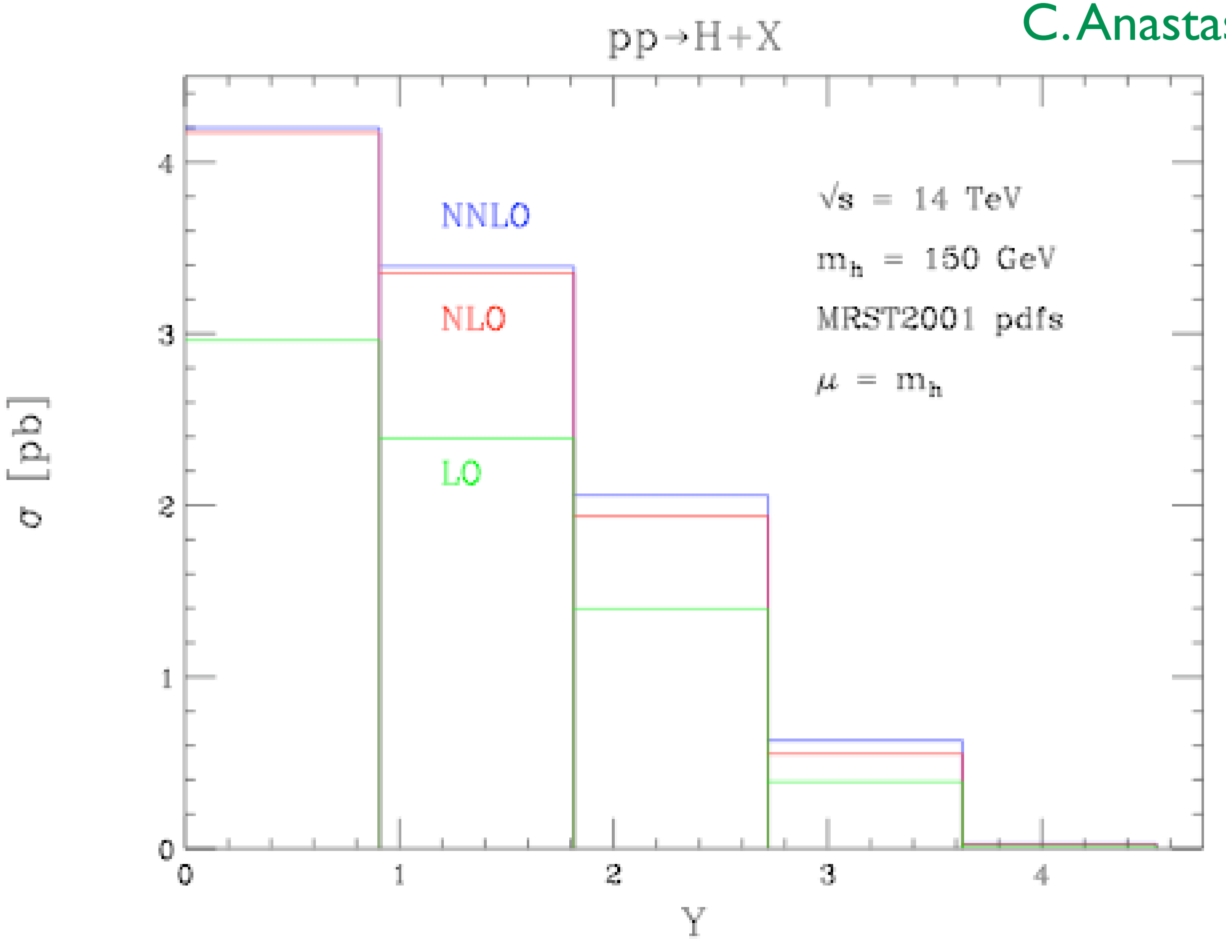
difference at large p_T is due to different default $\mu = \mu_R = \mu_F$ scale
$\mu^2 = M_H^2$ for NNLO + NNLL, $\mu^2 = M_H^2 + p_T^2$ for MC@NLO

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 $R_{12} > R$

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

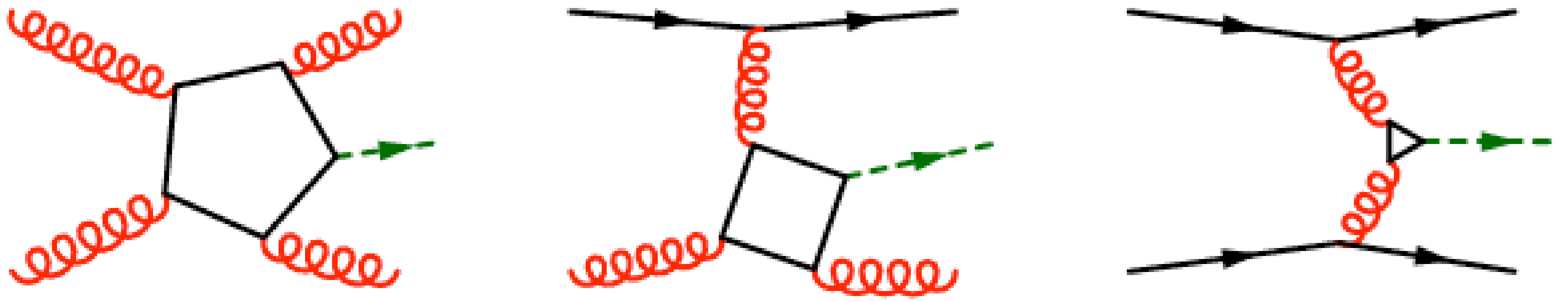
if $R_{12} < R$

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

- $M_H = 150\ \mathrm{GeV}$ (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 $\mathcal{O}(\alpha_s^4)$

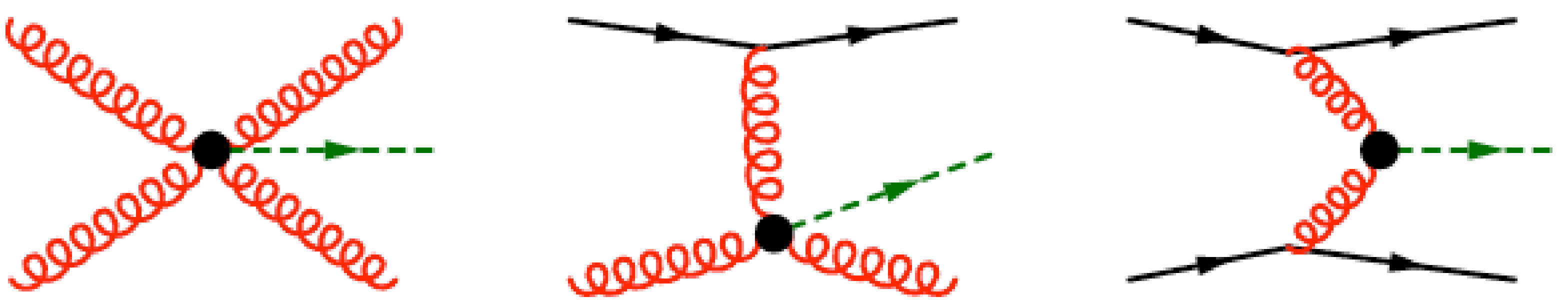


- tree $gg \to ggH \quad qg \to qgH \quad qQ \to qQH \quad + \quad$ crossings
- energy scales: $\hat{s}\,, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}}, s_{j_1 j_2}, M_{\mathrm{H}}^2, M_t^2$, with $\hat{s} = s_{j_1 j_2} + s_{j_1 \mathrm{H}} + s_{j_2 \mathrm{H}} - M_{\mathrm{H}}^2$

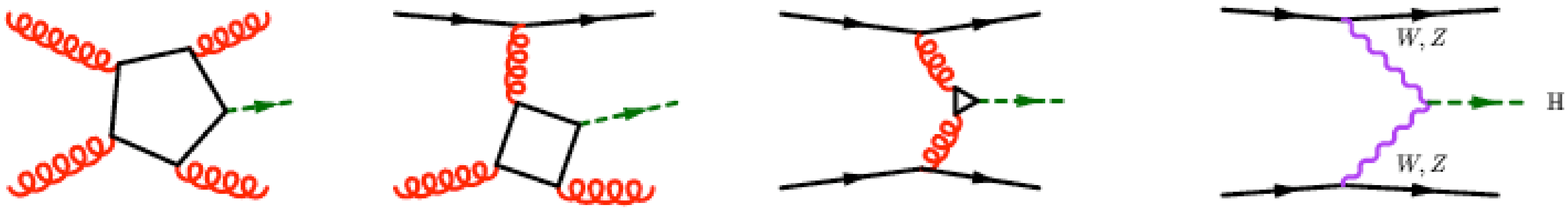
LARGE M_t LIMIT

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

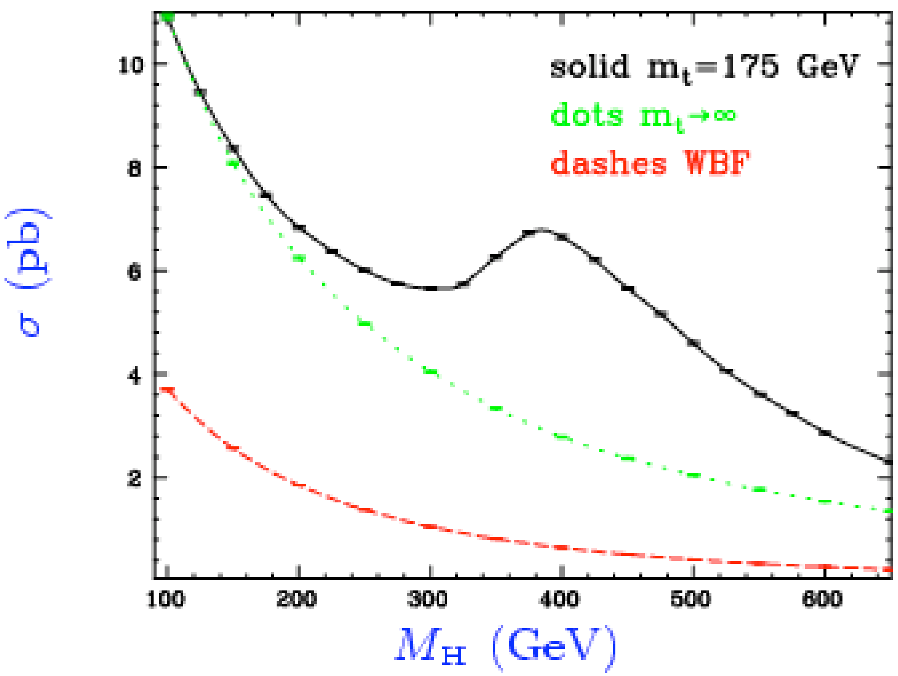
is valid even when $s_{j_1 j_2}\,, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}} \gg M_t^2$

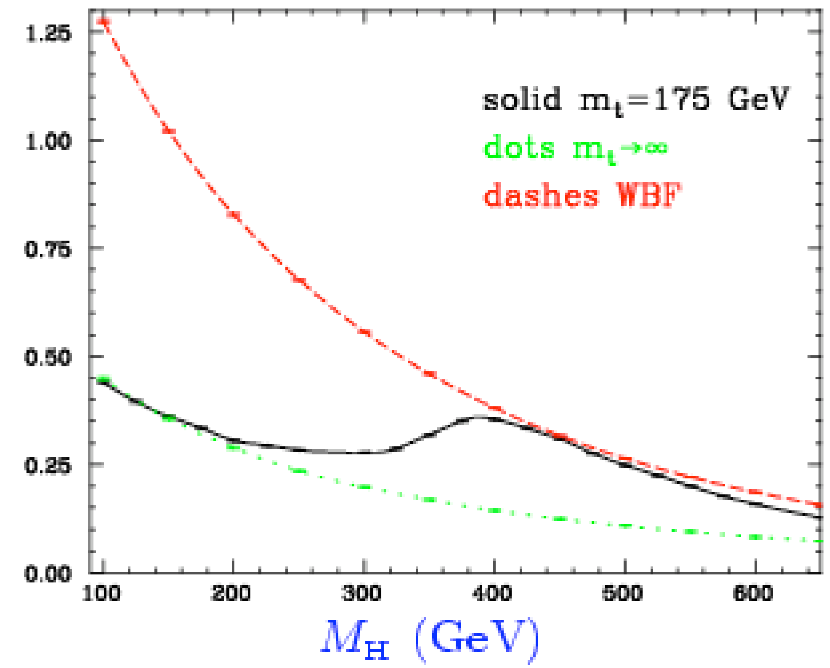


$H+$ 2 JETS RATE as a function of M_H



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



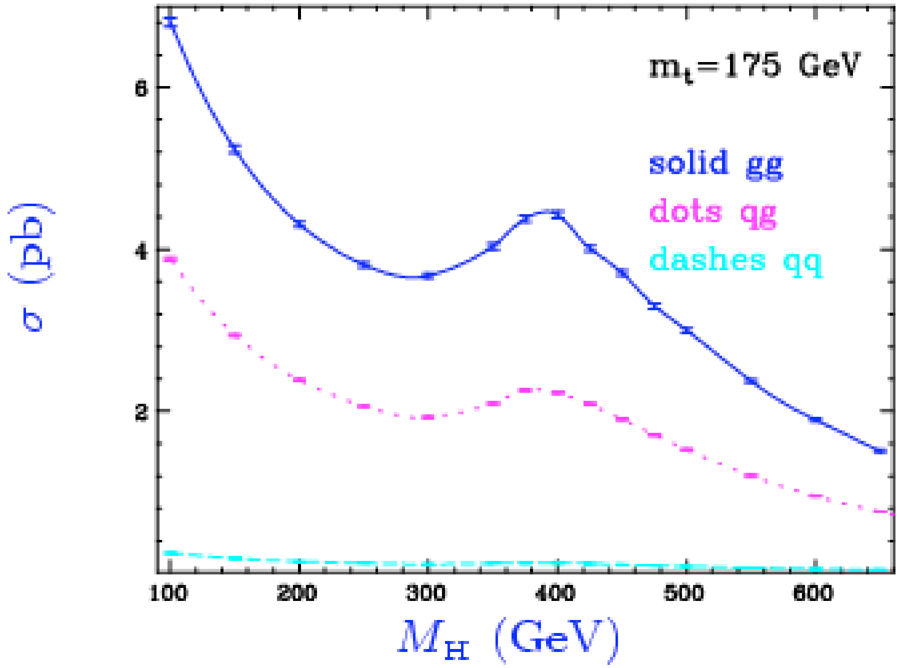


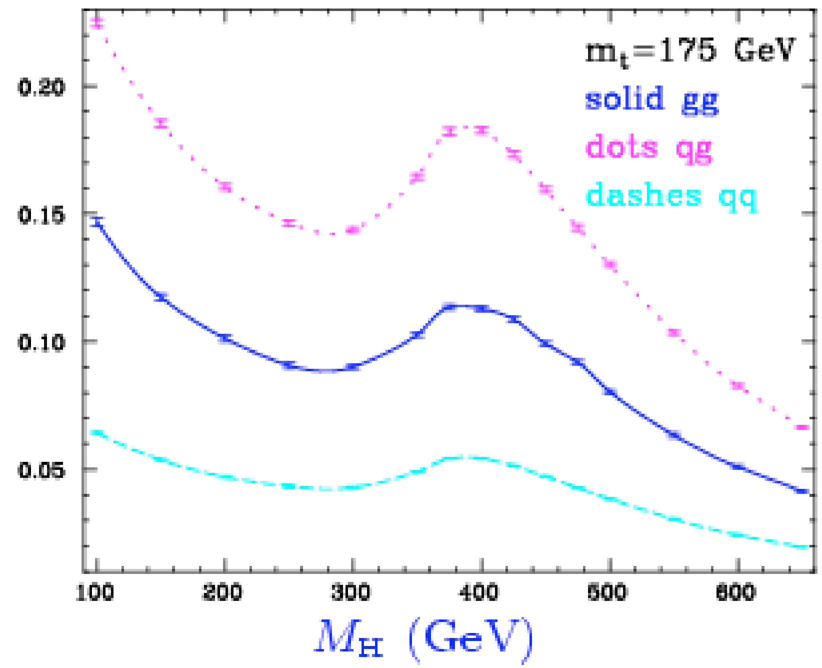
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$ WBF cuts: incl. $+ \begin{cases} |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{cases}$

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

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

$\mu_F = \sqrt{p_{j1\perp} p_{j2\perp}}, \mu_R = M_Z$





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

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

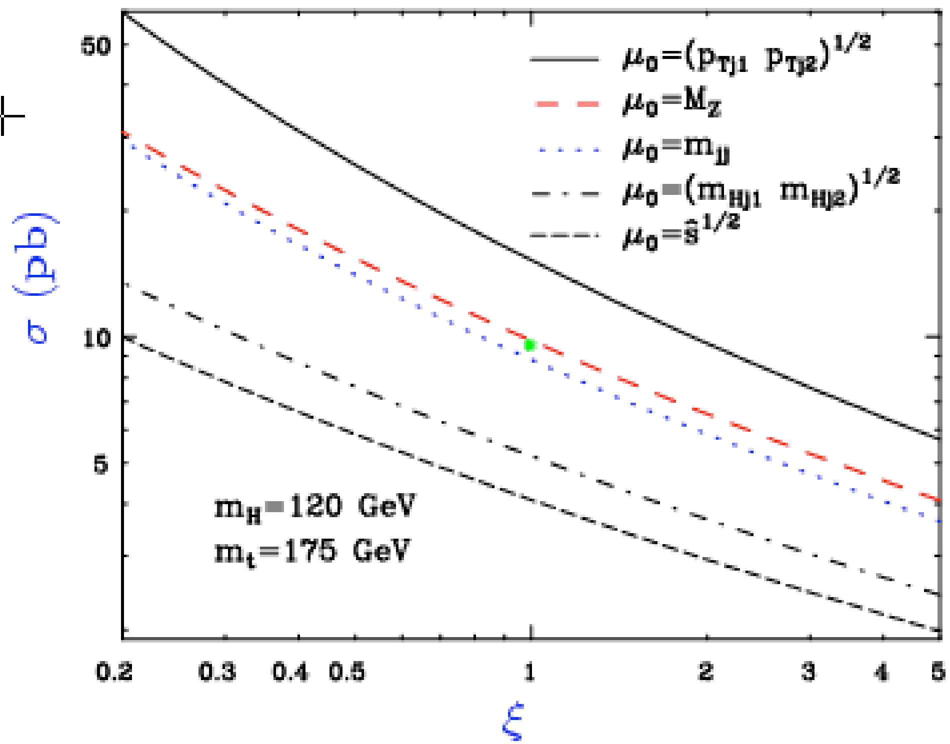
☛ WBF cuts enhance qg wrt gg, and make qq non-negligible

SCALE DEPENDENCE

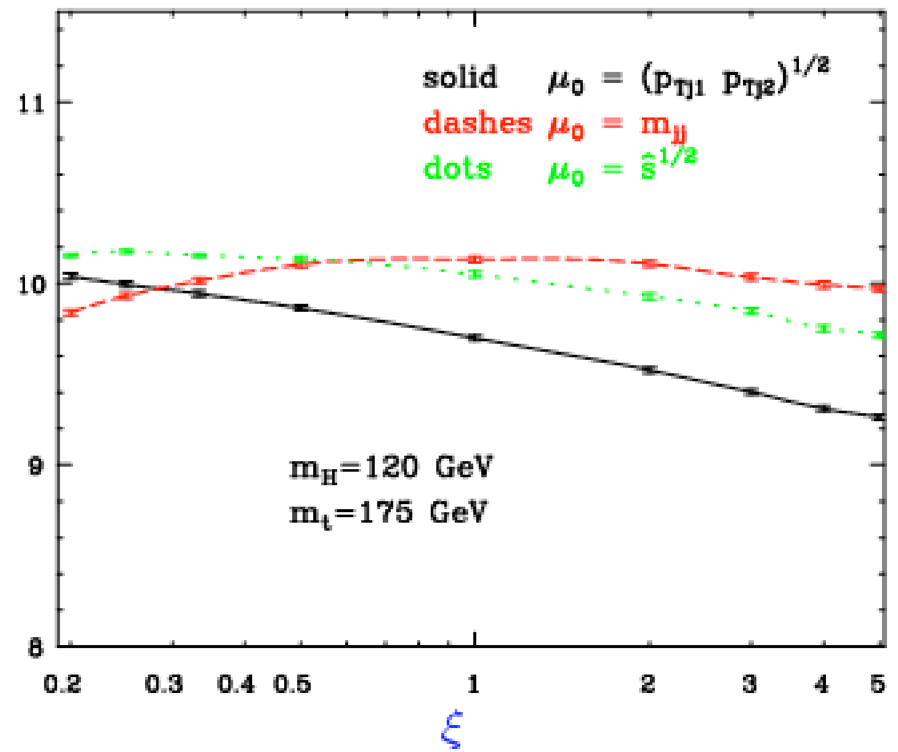
renormalisation μ_R & factorisation μ_F scales

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

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



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

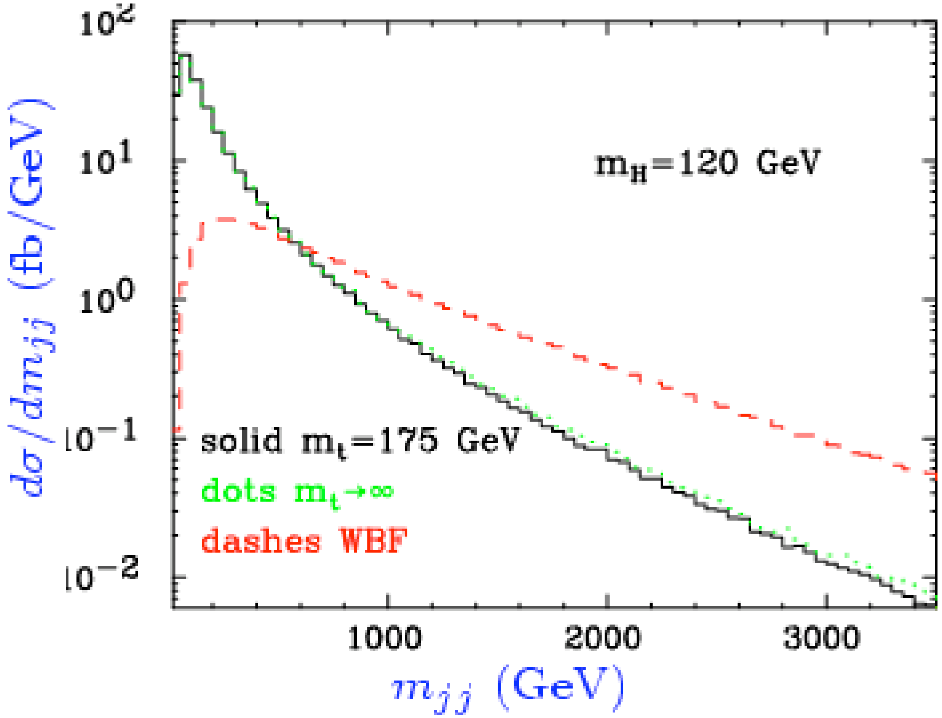


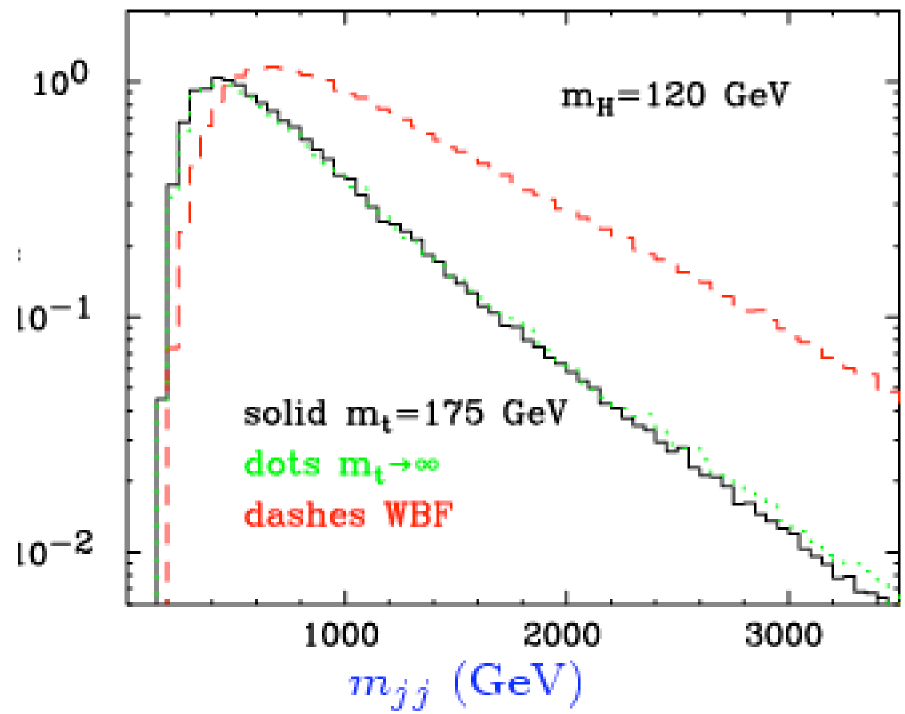
- strong μ_R dependence: the calculation is LO and $\mathcal{O}(\alpha_S^4)$
  - a natural scale for α_S ?

    high energy limit suggests $\alpha_S^4 \to \alpha_S(p_{j_1\perp})\alpha_S(p_{j_1\perp})\alpha_S^2(M_H)$
    - σ varies by a factor 2.5 for $\mu_0/2 < \mu_R < 2\mu_0$
- mild μ_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





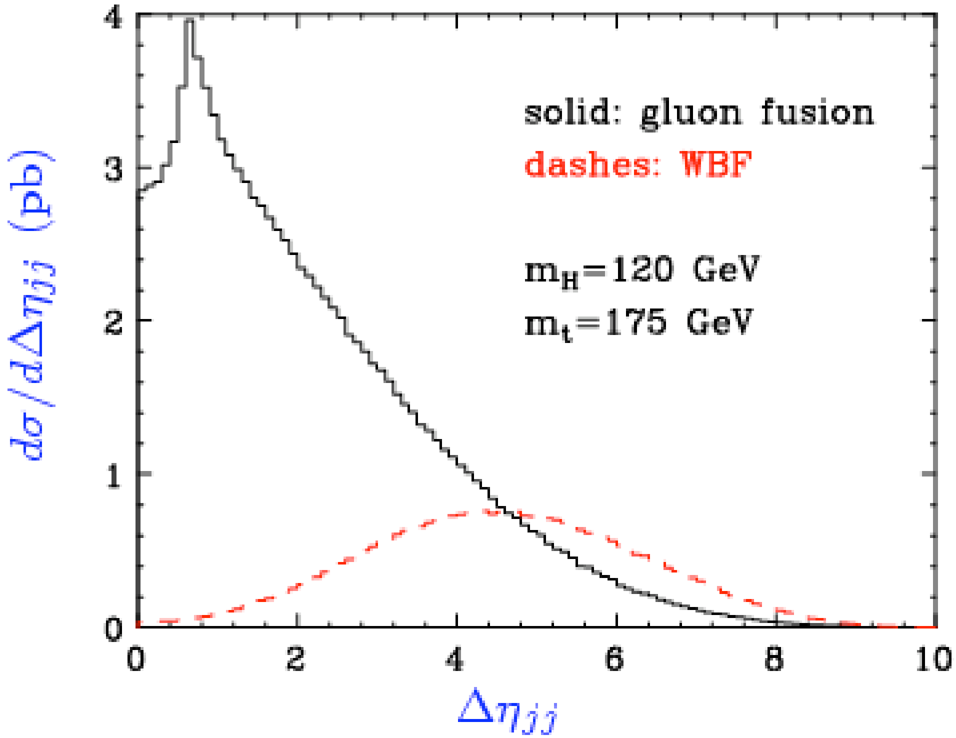
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

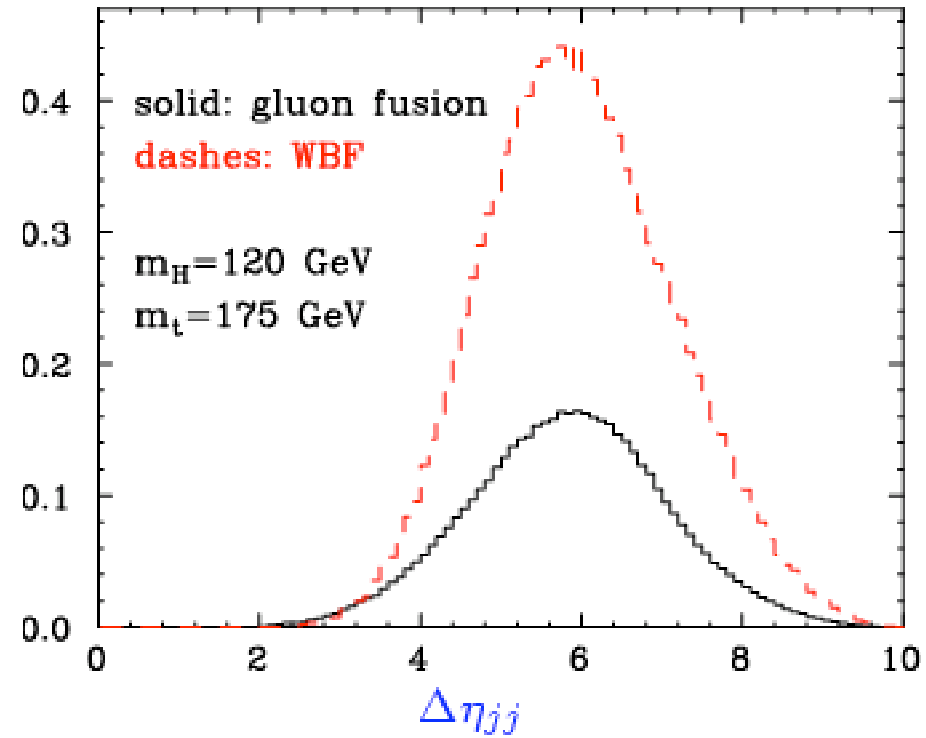
WBF cuts: incl. + $\begin{cases} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \end{cases}$

- 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





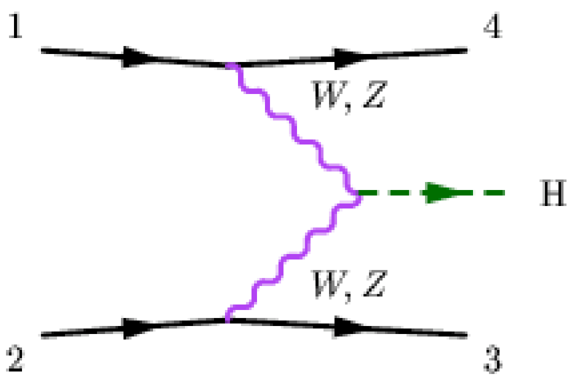
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

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: $R_{jj} = \sqrt{\Delta\eta_{jj} + \Delta\phi_{jj}} > 0.6$

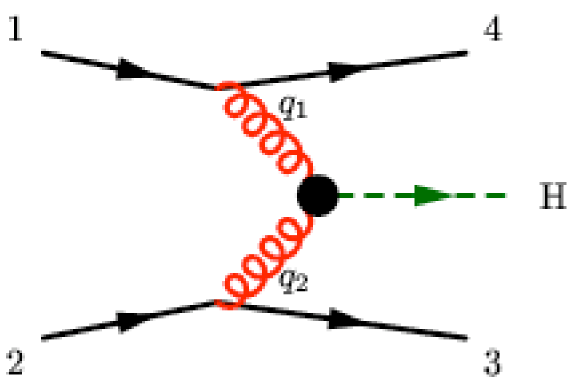
Azimuthal angle correlations

$\Delta\phi_{jj} \equiv$ 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

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

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

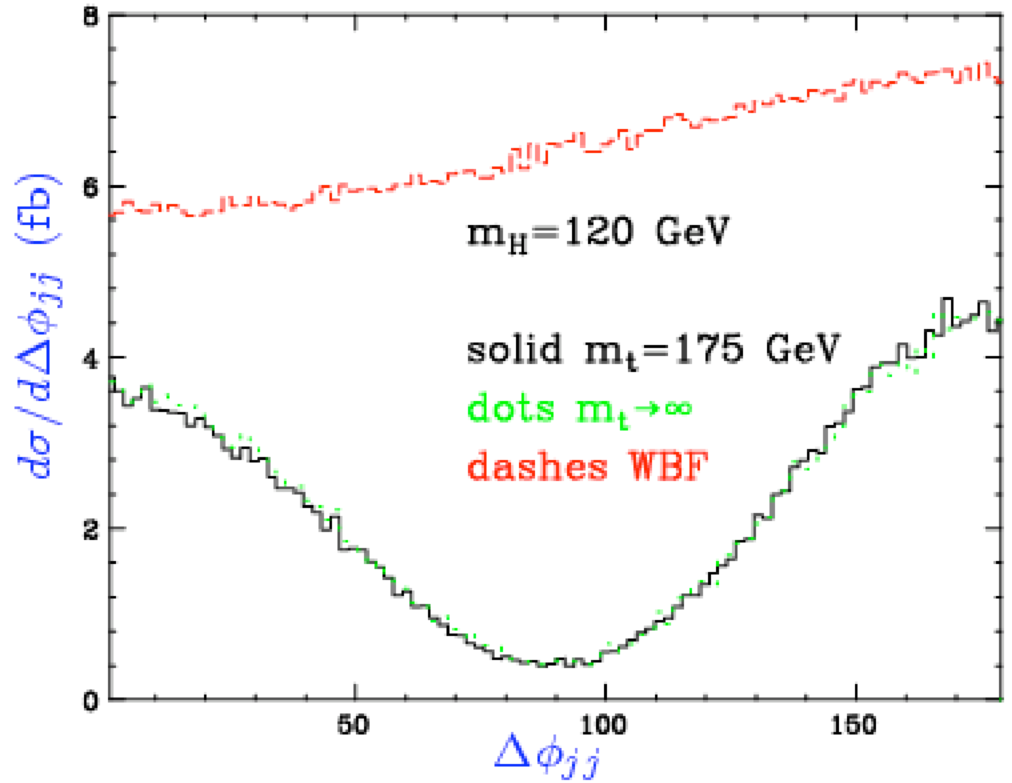
$J^\mu \equiv$ quark-gluon current

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 $\Delta\phi_{jj} = \frac{\pi}{2}$

Azimuthal angle distribution



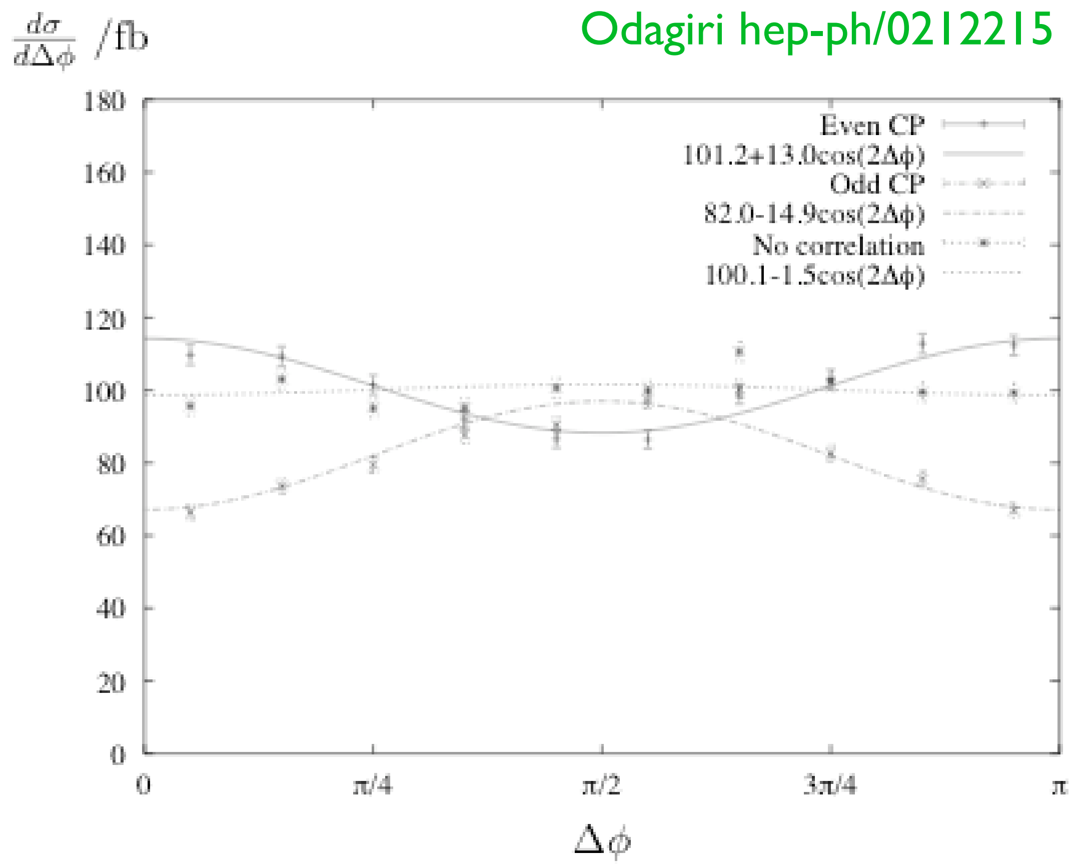
WBF cuts: $\left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right. + \left\{ \begin{array}{l} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ m_{jj} > 600 \text{ GeV} \end{array} \right.$

- 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

Odagiri hep-ph/0212215

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



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

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 Φ about the vev (get dim. 5 (D5) operators)

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H\, W^+_{\mu\nu} W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}} H\, \widetilde{W}^+_{\mu\nu} W^{-\mu\nu} \quad \text{with} \quad \frac{1}{\Lambda_5} = \frac{g^2 v}{\Lambda_6^2}$$

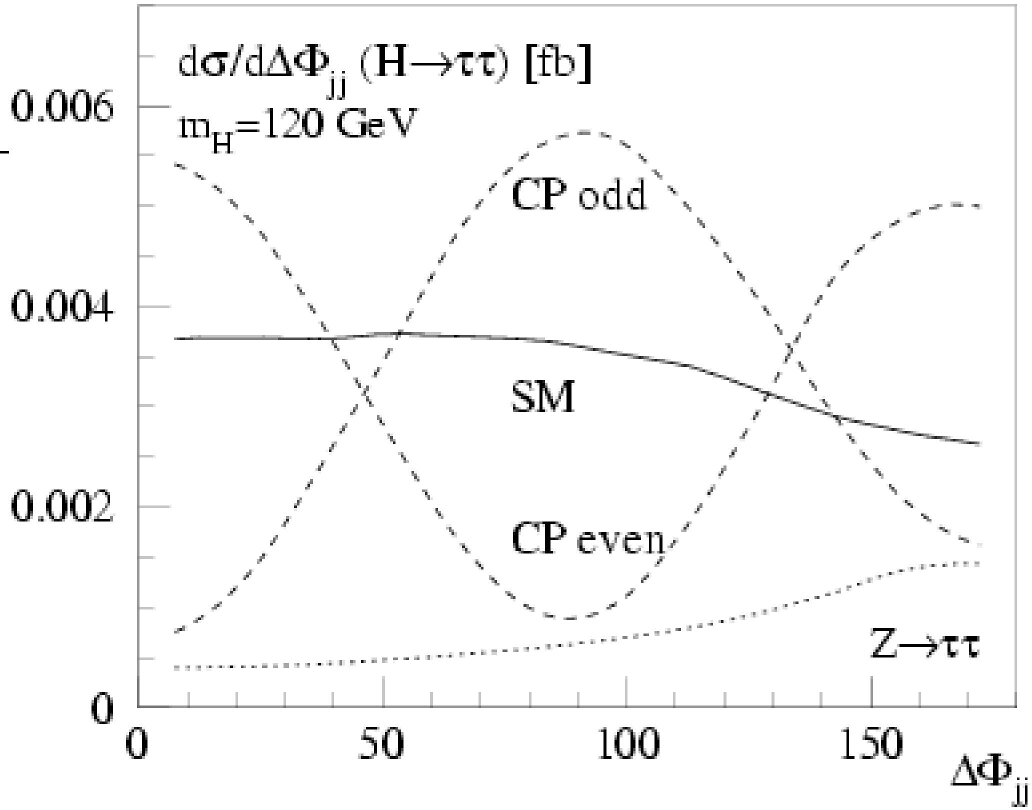
- CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling
  - ➥ zero at $\Delta\phi_{jj} = 0, \pi$

- 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

$|\eta_j| < 5$

$R_{jj} > 0.6$

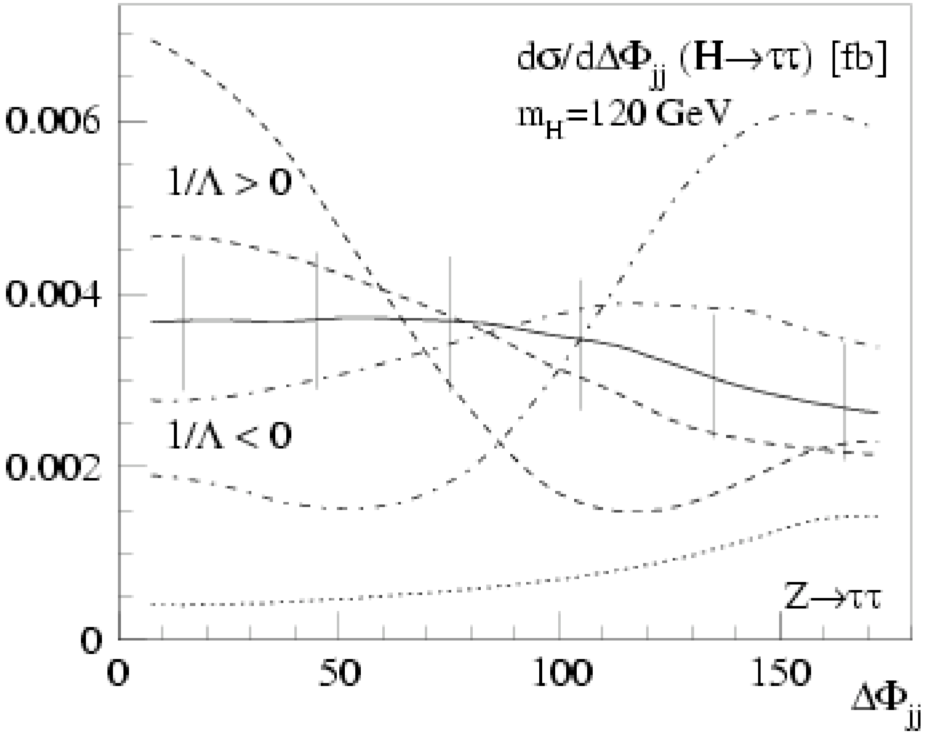
$\eta_{j_1} \cdot \eta_{j_2} < 0$

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

- 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 $\sigma/\sigma_{\rm SM} = 0.04, 1.0$. 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: $|\mathcal{A}|^2 = |\mathcal{A}_{\rm SM} + \mathcal{A}_{e,5}|^2$
  - ☛ all terms, but $|\mathcal{A}_{\rm SM}|^2$, have an approximate zero at $\Delta\phi_{\rm jj} = \pi/2$
  - ☛ systematic uncertainty induced by $H + 2$ jet rate from gluon fusion
    - ➥ $HG_{\mu\nu}G^{\mu\nu}$ is a CP even D5 operator

Higgs + 3 Jets

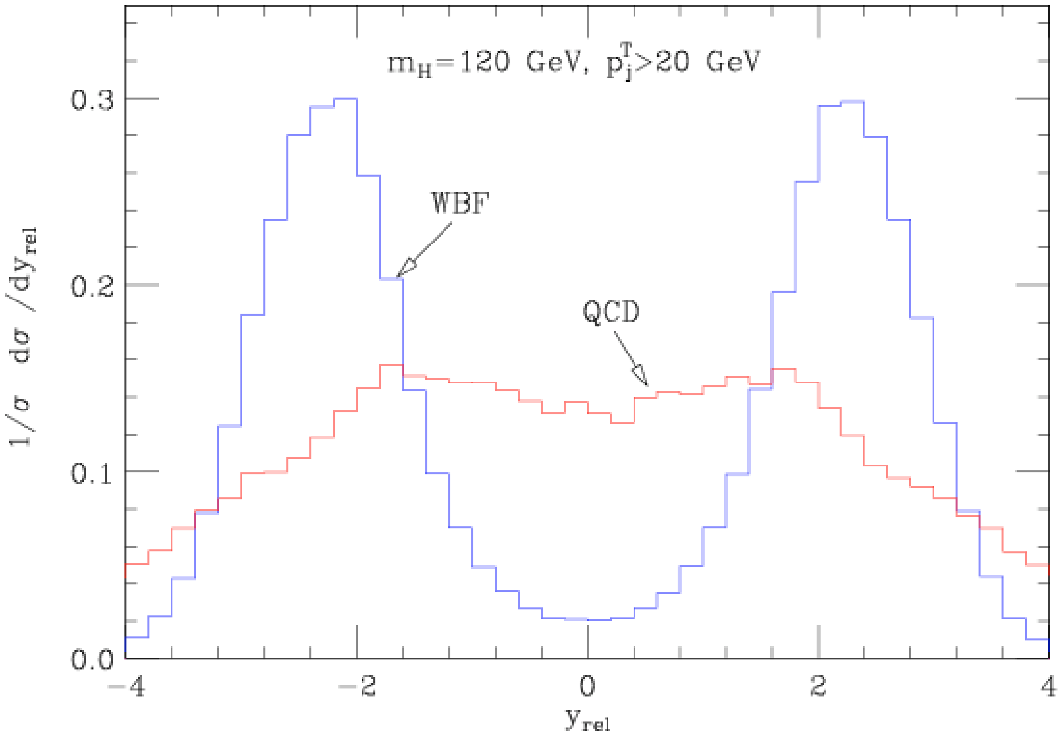
- In WBF no colour is exchanged in the t channel

- 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

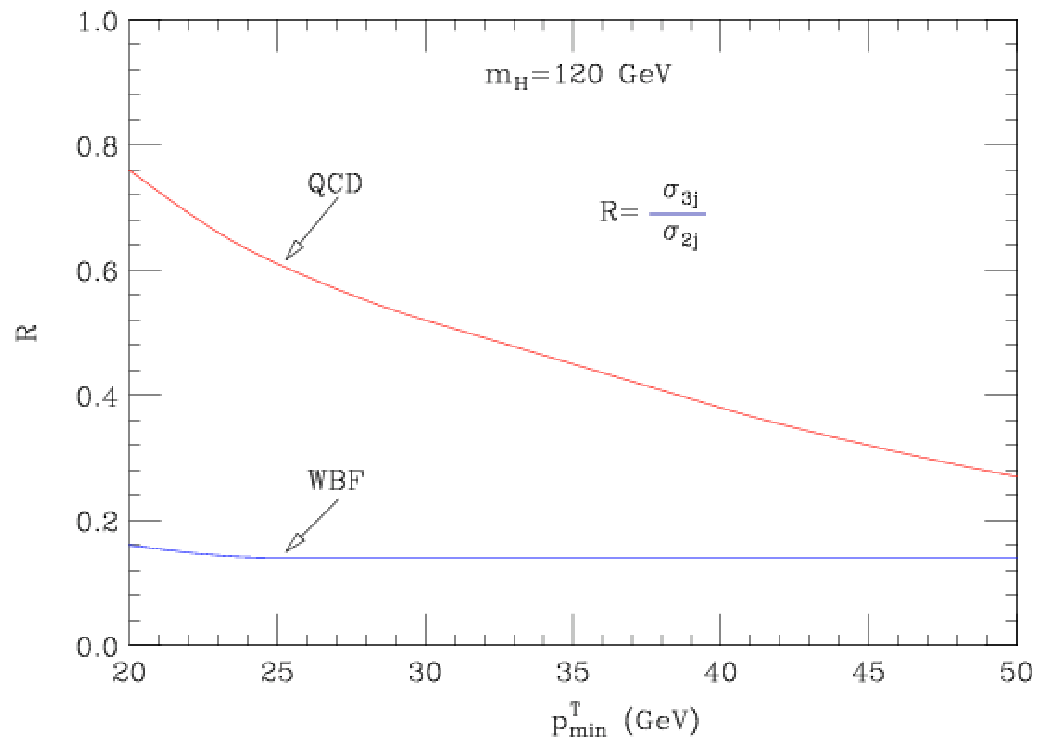
- The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF

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