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**SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"**
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# *Higgs bosons searches at LHC*
# *Part II*

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# The Higgs at the LHC

**Abdelhak DJOUADI ( LPT Orsay)**

- **The Higgs boson in the Standard Model**
- **<u>The SM Higgs at the LHC</u>**

**1. Generalities on Higgs production in pp**

**2. Higgs production and detection channels**

**3. Measurement of Higgs properties**

- **The Higgs boson in SUSY theories**
- **The SUSY Higgs bosons at the LHC**

# 1. Generalities on Higgs production in pp

**LHC: pp collider** $\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV
$\mathcal{L} \sim 10\,\mathrm{fb}^{-1}$ first years and 100 $\mathrm{fb}^{-1}$ later

- **Huge cross sections for QCD processes.**
- **Small cross sections for EW Higgs signal.**

  **S/B** $\gtrsim 10^{10} \Rightarrow$ **a needle in a haystack!**
- **Need some strong selection criteria:**

**Trigger: get rid of uninteresting events...**

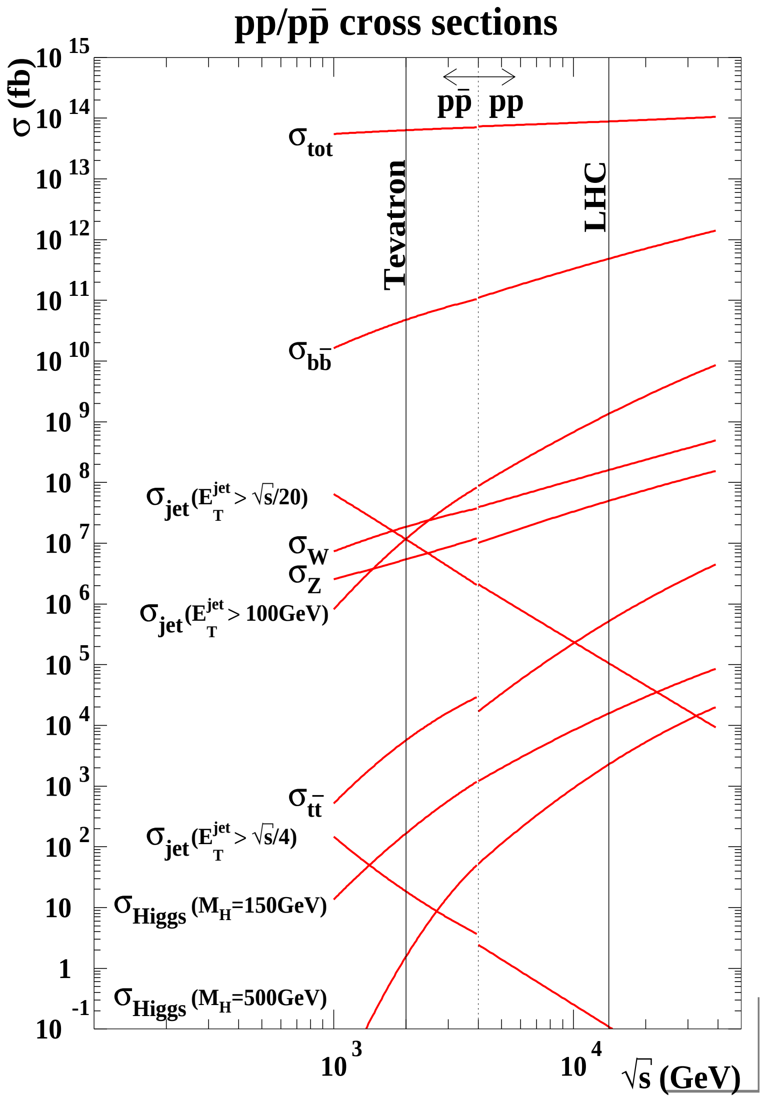
**Select clean channels:** $H \to \gamma\gamma, VV \to \ell$

**Use different kinematic features for Higgs**

**Combine different decay/production channels**

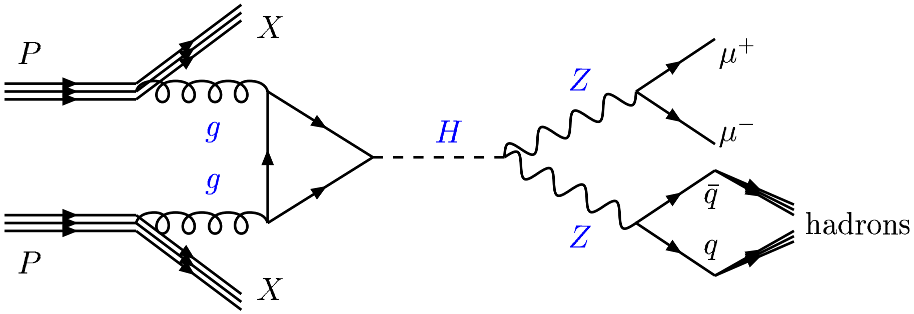
**Have a precise knowledge of S and B rates.**

- **Gigantic experimental (+theoretical) efforts!**



# 1. Generalities: example of process in pp

**An example of process at pp colliders to see how things work.**




$$N_{ev} = \mathcal{L} \times P(g/p) \times \hat{\sigma}(gg \to H) \times B(H \to ZZ) \times B(Z \to \mu\mu) \times BR(Z \to qq)$$

**For a large number of events, all these numbers should be large!**

**Two ingredients: hard process ($\sigma$, B) and soft process (PDF, hadr).**

**Factorization theorem! Here discuss production process (BR done).**

**The partonic cross section of the subprocess, $gg \to H$, is:**

$$\hat{\sigma}(gg \to H) = \int \frac{1}{2\hat{s}} \times \frac{1}{2\cdot 8} \times \frac{1}{2\cdot 8} |\mathcal{M}_{Hgg}|^2 \frac{d^3 p_H}{(2\pi)^3 2E_H} (2\pi^4) \delta^4 (q - p_H)$$

**Flux factor, color/spin average, matrix element squared, phase space.**

**Convolute with gluon densities to obtain total hadronic cross section**

$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2 \frac{\pi^2 M_H}{8\hat{s}} \Gamma(H \to gg) g(x_1) g(x_2) \delta(\hat{s} - M_H^2)$$

# 1. Generalities: example of process in pp

**The calculation of $\sigma_{\rm born}$ is not enough in general at pp colliders:**

need to include higher order radiative corrections which introduce terms of order $\alpha_{\bf s}^{\bf n} \log^{\bf m}({\bf Q}/{\bf M_H})$ where Q is either large or small...

- Since $\alpha_s$ is large, these corrections are in general very important.
- Choose a (natural scale) which absorbs/resums the large logs.

Since we truncate pert. series: only NLO/NNLO corrections available.

- The (hopefully) not known HO corrections induce a theoretical error.
- The scale variation is a (naive) measure of the HO: must be small.

Also, precise knowledge of $\sigma$ is not enough: need to calculate some kinematical distributions (e.g. ${\bf p_T}, \eta, \frac{{\bf d}\sigma}{\bf dM}$) to distinguish S from B.

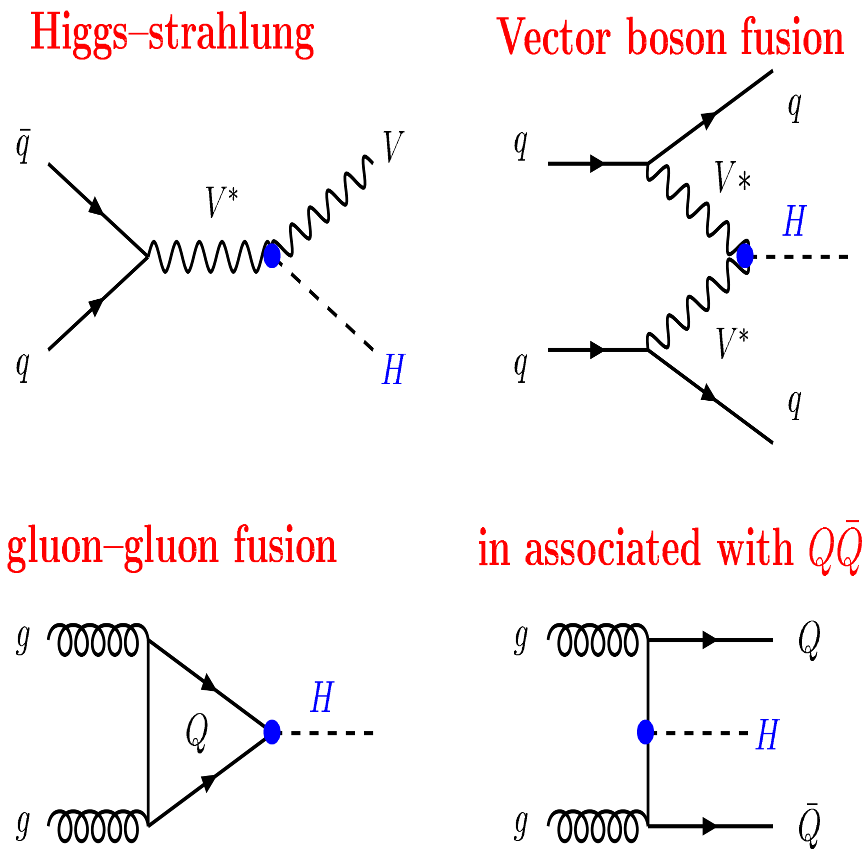
In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{\rm N_S}{\sqrt{\rm N_{bjg}}}$

**$\Rightarrow$ a lot of theoretical work is needed!**

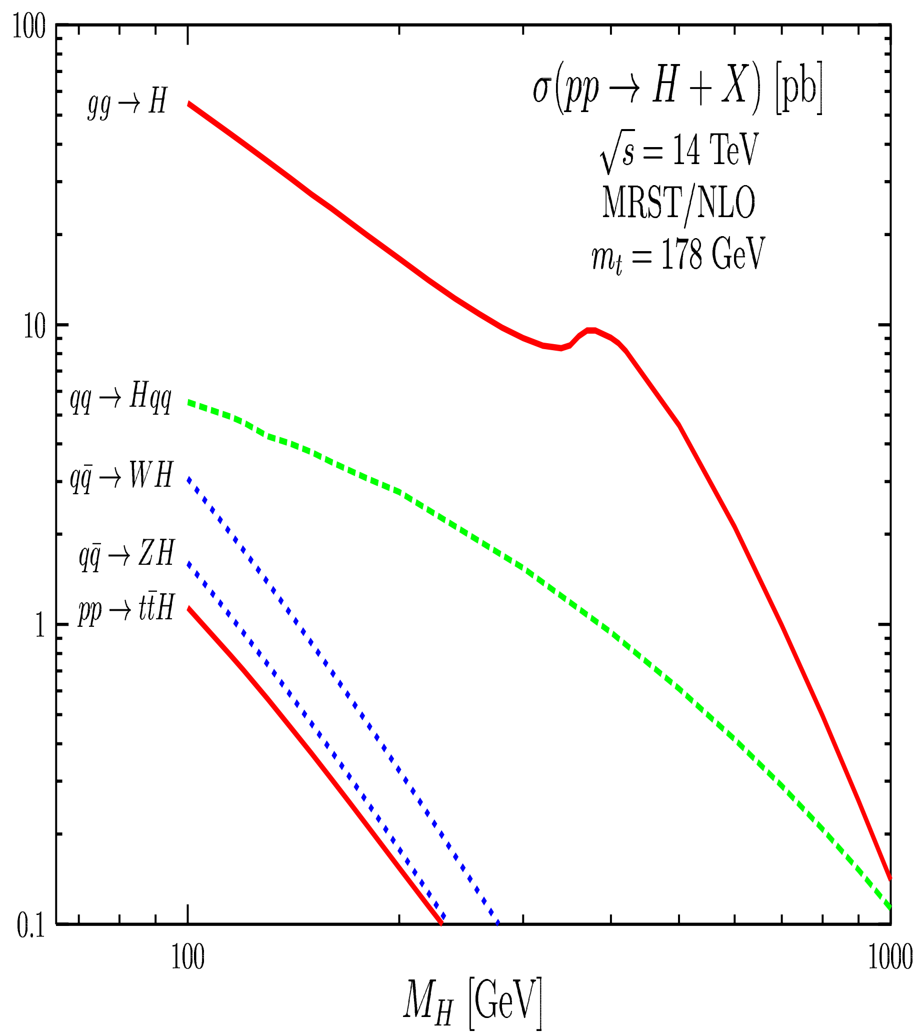
But most complicated thing is to actually see the signal for S/B$\ll$1!

# 1. Generalities: Higgs production in pp

## Production mechanisms




## Cross sections at the LHC

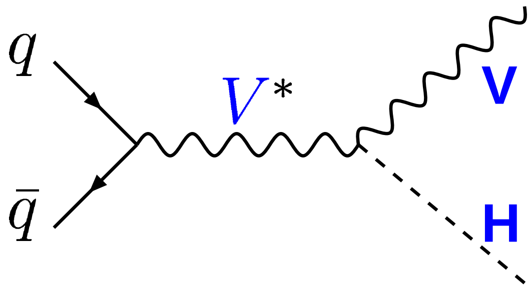



**There are also subleading processes, $gg \to HH$, etc...**

# 2. SM Higgs production

**Let us look at all the main Higgs production channels at the LHC:**

**The associated HV production:**




$$\hat{\sigma}_{\rm LO}(\mathbf{q\bar{q}} \to \mathbf{VH}) = \frac{\mathbf{G_\mu^2 M_V^4}}{\mathbf{288\pi \hat{s}}} \times (\mathbf{\hat{v}_q^2} + \mathbf{\hat{a}_q^2}) \lambda^{1/2} \frac{\lambda + \mathbf{12 M_V^2/\hat{s}}}{(\mathbf{1 - M_V^2/\hat{s}})^2}$$

**Similar to $e^+e^- \to \mathbf{HZ}$ process used for Higgs searches at LEP2.**

**Cross section $\propto \hat{s}^{-1}$ sizable only for low $M_H \lesssim 200$ GeV values.**

**Cross section for $W^\pm H$ approximately 2 times larger than $ZH$.**

**In fact, simply Drell–Yan production of virtual boson with $\mathbf{q^2} \neq \mathbf{M_V^2}$**

$$\hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{HV}) = \hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{V^*}) \times \frac{d\Gamma}{d\mathbf{q^2}}(\mathbf{V^*} \to \mathbf{HV})$$

**$\Rightarrow$ radiative corrections are mainly those of the known DY process**

**(at 2-loop, need to consider also $gg \to \mathbf{HZ}$ through box which is $\neq$).**

# 2. SM Higgs production: associated HV

**Radiative corrections needed:**

**– for precise determination of $\sigma$**

**– stability against scale variation**

**HO also needed to fix scales:**

**– renormalization $\mu_R$ for $\alpha_s$**

**– factorization $\mu_F$ for matching.**

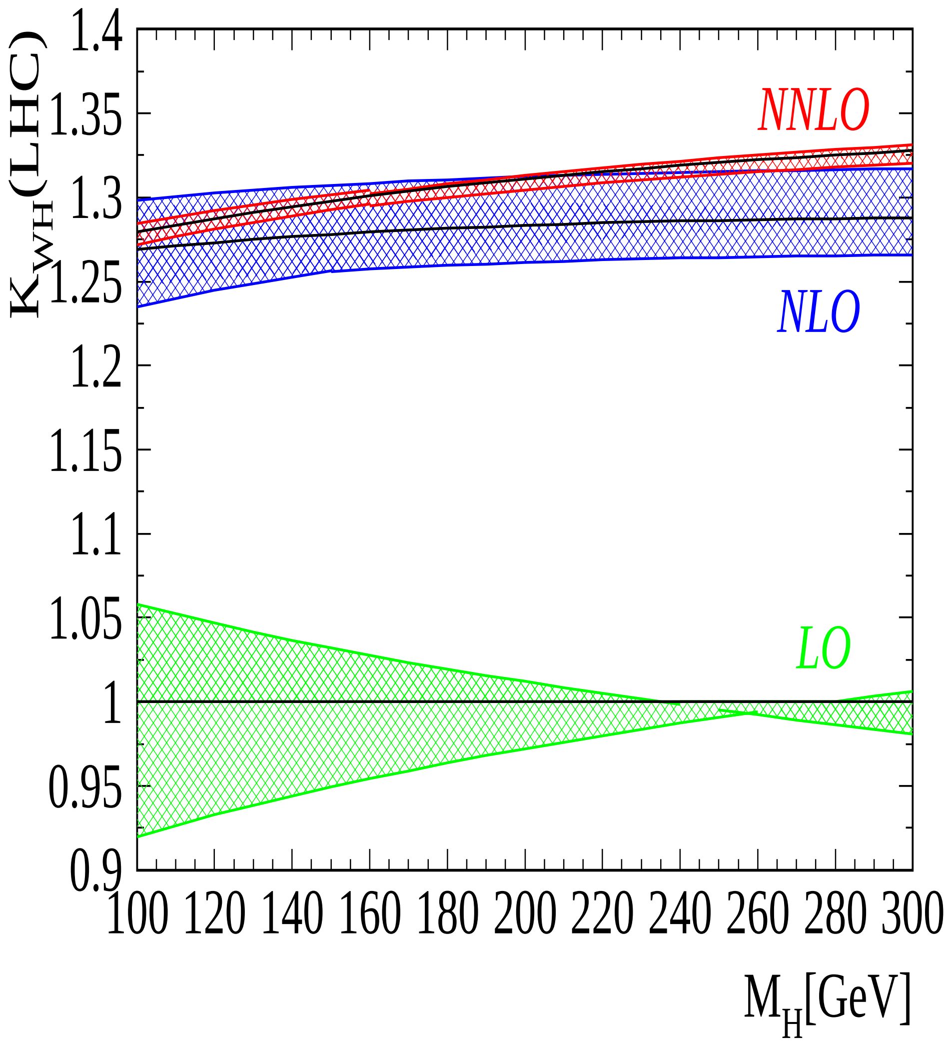
**RC parameterized by K–factor:**

$$\mathbf{K} = \frac{\sigma_{\rm HO}(\mathbf{pp \to H+X})}{\sigma_{\rm LO}(\mathbf{pp \to H+X})}$$

**Can also define K-factor at LO.**

**QCD RC known up to NNLO.**

**EW RC known at $\mathcal{O}(\alpha)$: small.**



# 2. SM Higgs production: associated HV

Up-to-now, it only plays a marginal role at the LHC (small rates etc...).

Interesting final states are: $\mathbf{WH} \to \gamma\gamma\ell, \mathbf{b\bar{b}}\ell, \mathbf{3}\ell$ and $\mathbf{ZH} \to \mathbf{q\bar{q}}\nu\nu$.

Analyses by ATLAS+CMS: 5$\sigma$ discovery possible with $\mathcal{L} \gtrsim 100$ fb.

But very clean channel when normalized to $\mathrm{pp} \to \mathbf{Z}$. Measurements!

**However**:

WH channel is the most important at Tevatron:

$M_H \lesssim 130$ GeV: H$\to$ bb:

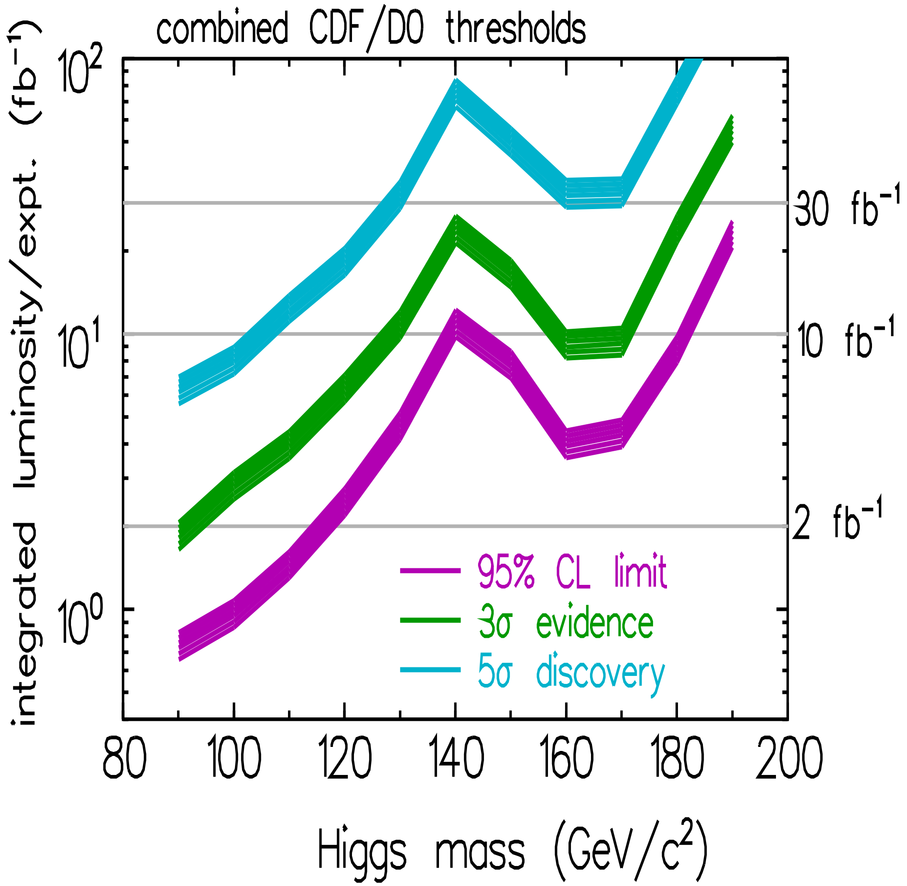
$\Rightarrow \ell\nu b\bar{b},\ \nu\bar{\nu}b\bar{b},\ \ell^+\ell^- b\bar{b}$

$M_H \gtrsim 130$ GeV: H$\to$ WW*

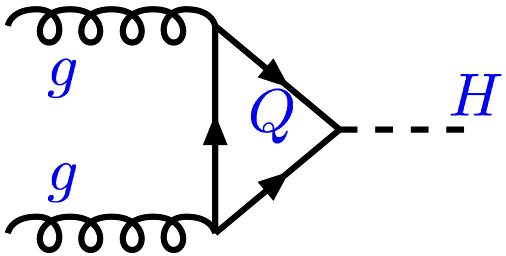
$\Rightarrow \ell^\pm\ell^\pm jj,\ 3\ell^\pm$

Possible discovery!!

(Report Tevatron HWG)



# 2. SM Higgs production: gg fusion




$$\hat{\sigma}_{\rm LO}(\mathbf{gg \to H}) = \frac{\pi^2}{8\mathbf{M_H}}\Gamma_{\rm LO}(\mathbf{H \to gg})\delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

$$\sigma_0^{\mathbf{H}} = \frac{\mathbf{G}_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q \mathbf{A}_{1/2}^{\mathbf{H}}(\tau_Q) \right|^2$$

**Related to the Higgs decay width into gluons discussed previously.**

- **In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.**
- **For $\mathbf{m_Q} \to \infty, \tau_Q \sim 0 \Rightarrow \mathbf{A}_{1/2} = \frac{4}{3}$ = constant and $\hat{\sigma}$ finite.**
- **Approximation $\mathbf{m_Q} \to \infty$ valid for $\mathbf{M_H} \lesssim 2\mathbf{m_t} = 350$ GeV.**

**Gluon luminosities large at high energy+strong QCD and Htt couplings**

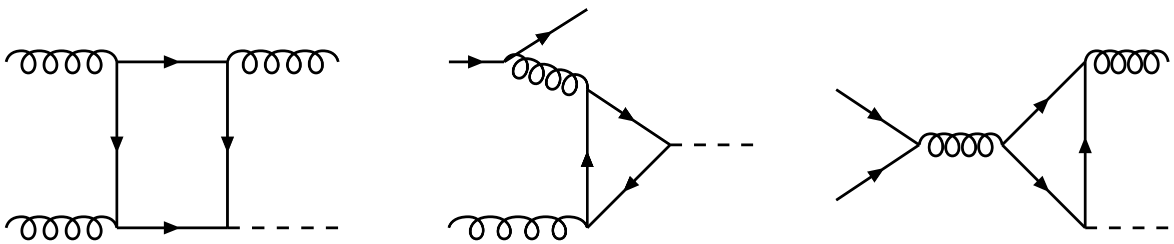
**$gg \to H$ is the leading production process at the LHC.**

- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs $\mathbf{P_T}$ is zero at LO, must generated at NLO.**

# 2. SM Higgs production: gg fusion

## QCD radiative corrections to $gg \to H$: NLO case

**Typical diagrams for virtual and real QCD corrections to $gg \to H$ at NLO:**



- **Regularization of UV divergences from virtual and IR+collinear divergences from real corrections in dimensional regularization.**
- **UV divergences cancelled by corresponding counterterms.**
- **IR divergences cancel in sum of virtual+real corrections.**
- **Collinear singularities are left: absorbed in PDF renormalization.**

# 2. SM Higgs production: gg fusion

- **Corrections known exactly, i.e. for finite $\mathbf{m_t}$ and $\mathbf{M_H}$, at NLO:**

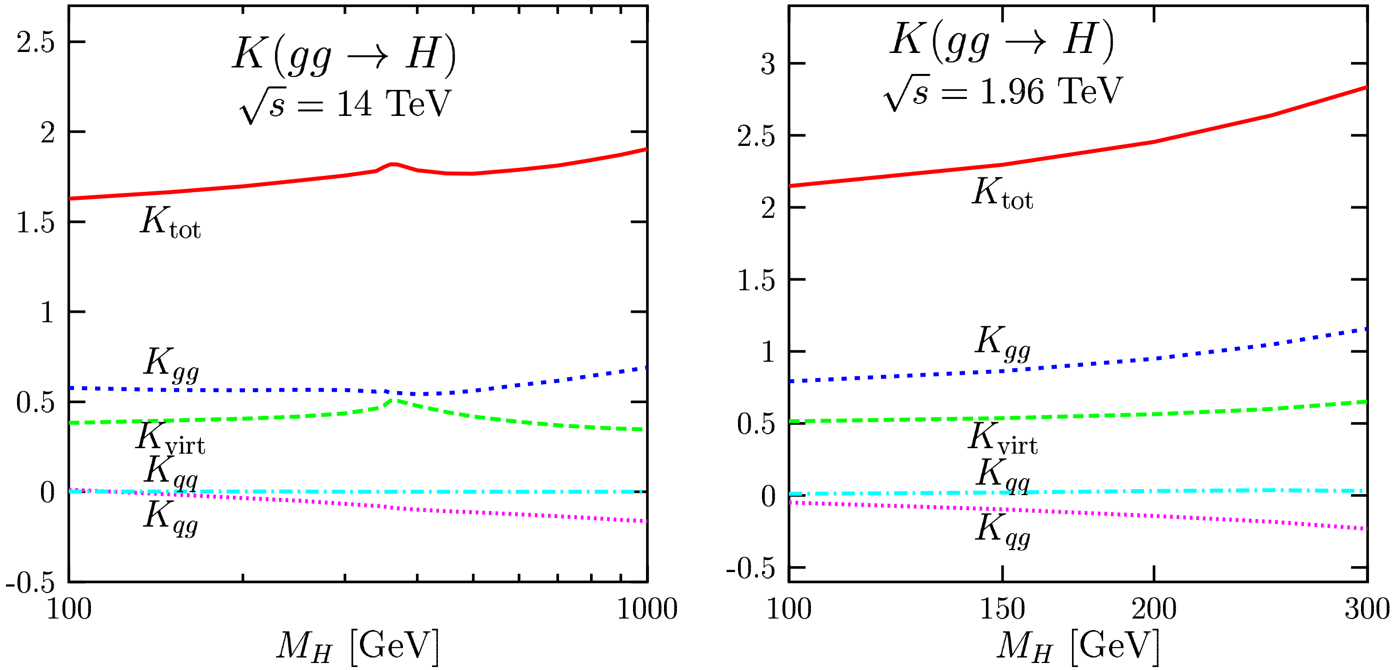
**– quark mass effects are important for $\mathbf{M_H \gtrsim 2m_t}$.**

**– $\mathbf{m_t \to \infty}$ is still a good approximation for masses below 300 GeV.**

**– corrections are large, increase cross section by a factor 1.6–1.9.**

**Note 1: NLO corrections to $P_T, \eta$ distributions are also known.**

**Note 2: NLO EW corrections are also available, they are rather small.**



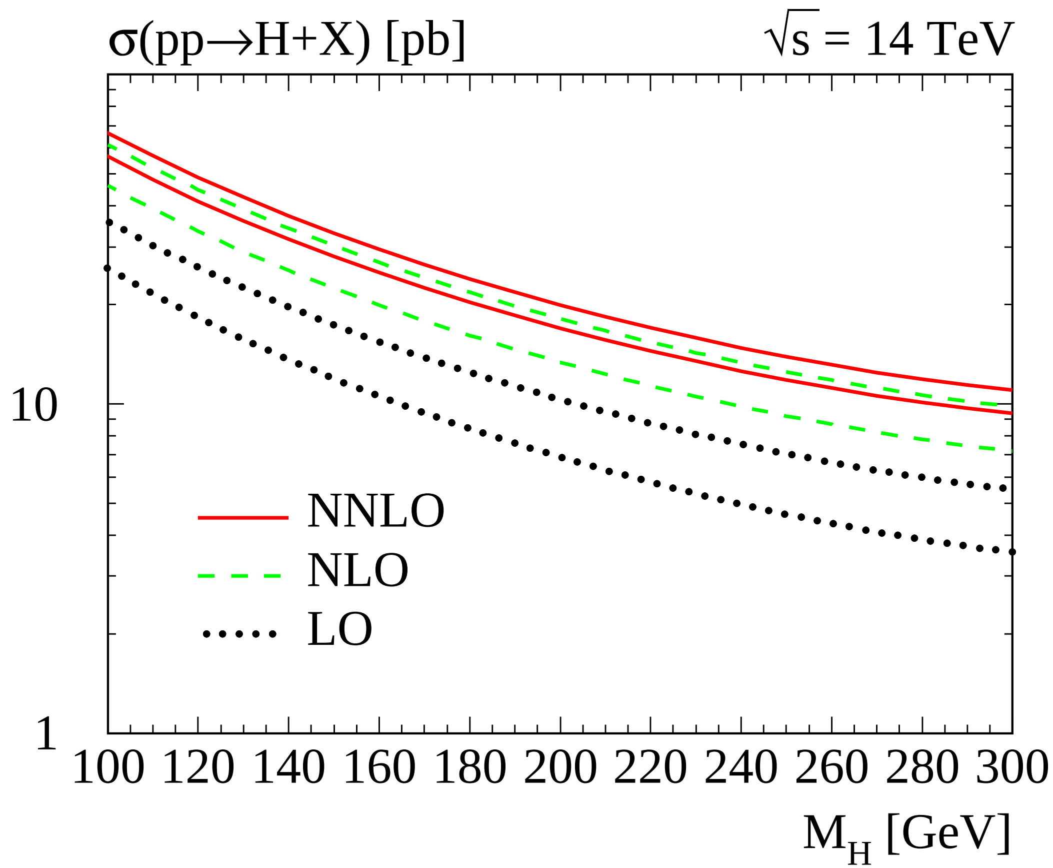
# 2. SM Higgs production: gg fusion

- **Corrections have been calculated in $m_t \to \infty$ limit at NNLO.**

**– moderate increase of cross section by 30% (good behavior of PT!).**

**– large stabilization with renormalization and factorization scales.**

**– soft–gluon resummation performed up to NNLL: $\sim 5\%$ effects.**



# 2. SM Higgs production: gg fusion

**Relevant detection signals**

- $\mathbf{H \to b\bar{b}, \tau^+\tau^-, t\bar{t}}$: **hopeless.**
- $\mathbf{H \to \gamma\gamma}$ **for** $\mathbf{M_H \lesssim 150}$ **GeV:**

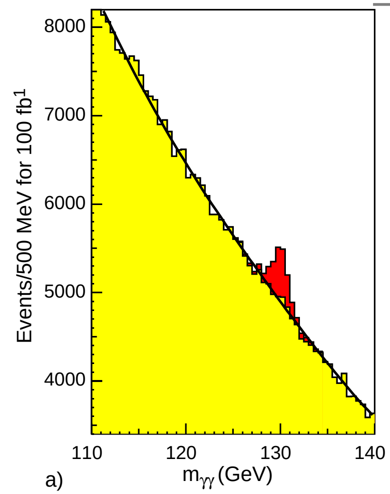
– **large** $\sigma$ **and small BR: many events left.**

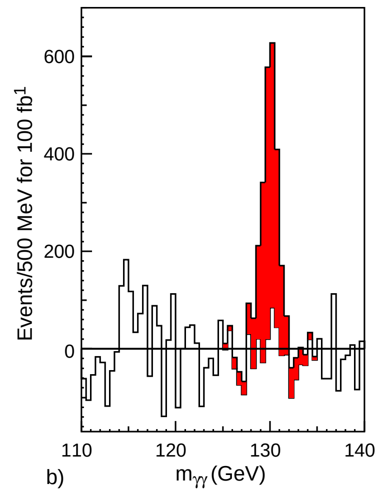
– **huge irreducibe bkgs from jets:** $10^6$ **rejection.**

– **large physics bkg from** $\mathbf{q\bar{q}/gg \to \gamma\gamma + X}$**.**

– **measure** $\mathbf{d\sigma/dM_{\gamma\gamma}}$ **on both sides of peak.**

– $\mathbf{S/B = 1/30}$ **for** $\mathbf{M_{\gamma\gamma} \sim 2}$ **GeV (good** $\gamma\gamma$ **res.).**




- $\mathbf{H \to WW \to \ell\ell\nu\nu}$ **for** $\mathbf{M_H}$ **∼130–200 GeV:**

– **large** $\sigma \times \mathrm{BR}$ **in this range but no** $\mathbf{M_H^{recons}}$

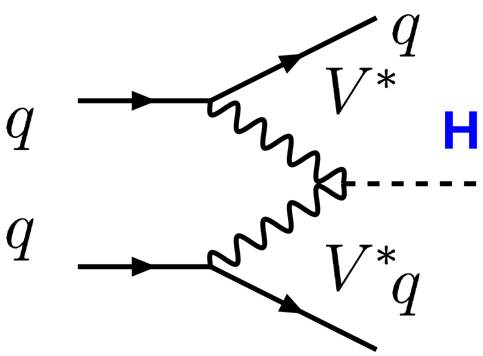
– **large bkg from WW/tt but use spin-correlations!**

- $\mathbf{H \to ZZ \to 4\ell^\pm}$ **for** $\mathbf{M_H \gtrsim}$ **180–500 GeV:**

– **gold plated mode, clean and small/measurable ZZ bkg.**

- $\mathbf{H \to ZZ \to \ell\ell jj, \ell\ell\nu\nu, WW \to \ell\nu jj}$ **for** $\mathbf{M_H}$**=0.5–1 TeV.**

# 2. SM Higgs production: WW fusion




$$\hat{\sigma}_{\rm LO} = \frac{\mathbf{16\pi^2}}{\mathbf{M_H^3}}\Gamma(\mathbf{H} \to \mathbf{V_L V_L})\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}} \sim \frac{\alpha}{\mathbf{4\pi^3}}(\mathbf{v_q^2} + \mathbf{a_q^2})^{\mathbf{2}} \log\left(\frac{\hat{\mathbf{s}}}{\mathbf{M_H^2}}\right)$$

**Three–body final state: analytical expression rather complicated...**

**Simple form in LVBA: $\sigma$ related to $\Gamma(\mathbf{H} \to \mathbf{VV})$ and $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}|_{V_L V_L/qq}$**

**Not too bad approximation at $\sqrt{\hat{\rm s}} \gg \rm M_H$: a factor 2 accurate.**

**Large cross section: in particular for small $\rm M_H$ and large c.m. energy:**

**$\Rightarrow$ most important process at the LHC after $\rm gg \to H$.**

**QCD radiative corrections small: order 10% (also for distributions).**

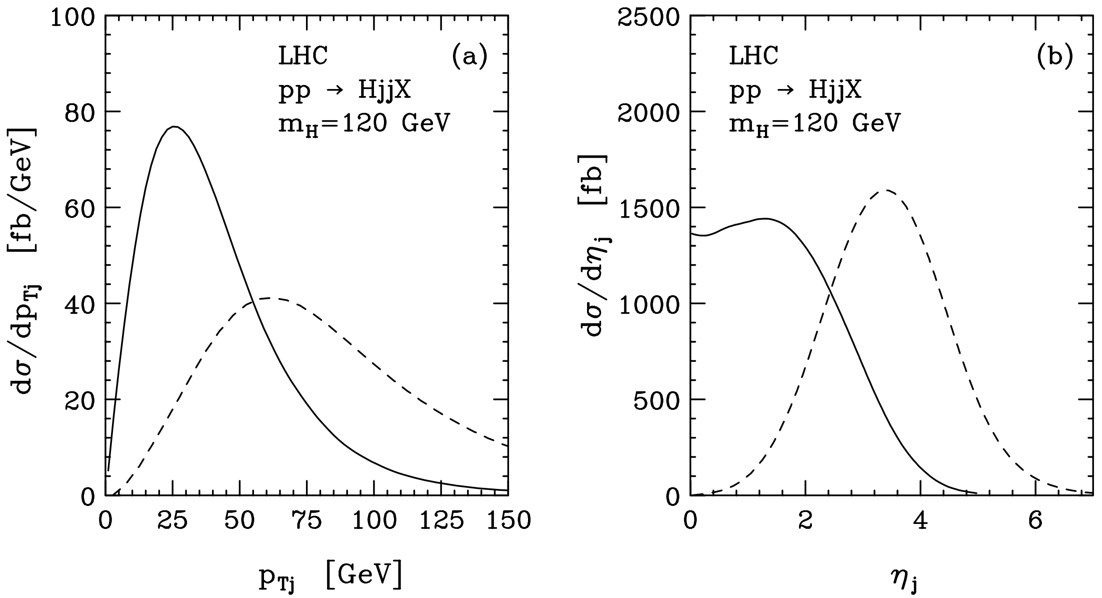
**In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks: QCD corrections only consist of known corrections to the PDFs!**

# 2. SM Higgs production: WW fusion

**Kinematics of the process: a very specific kinematics indeed....**

- **Forward jet tagging: the two final jets are very forward peaked.**
- **They have large energies of $\mathcal{O}$(1 TeV) and sizeable $P_T$ of $\mathcal{O}(\mathrm{M_V})$.**
- **Central jet vetoing: Higgs decay products are central and isotropic.**
- **Small hadronic activity in the central region no QCD (trigger uppon).**

**Allow to suppress the background to the level of H signal: $\mathrm{S/B} \sim 1$.**




**——— lowest/central jet    – – – – highest/central jet**

# 2. SM Higgs production: WW fusion

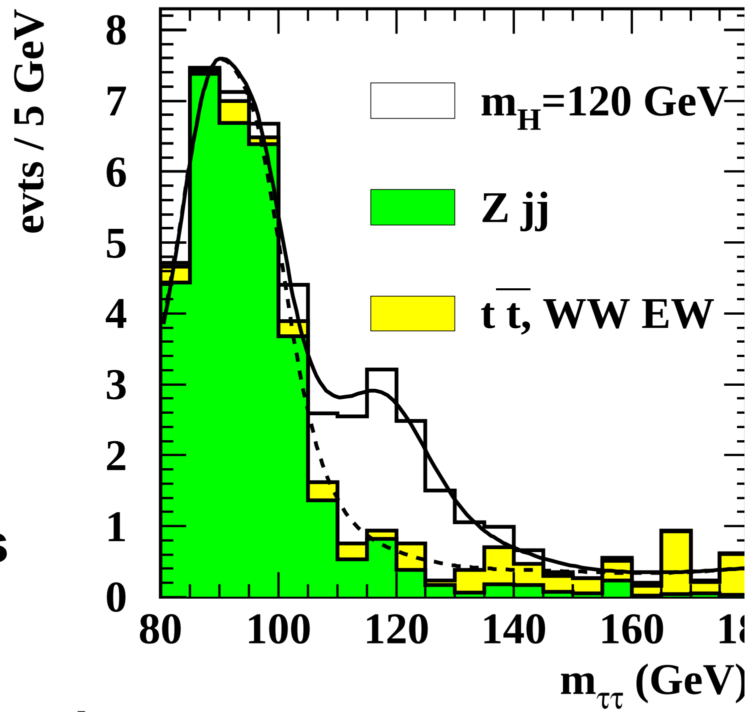
**Relevant detection signals**

- $\mathrm{H} \to \tau^+\tau^-$ for $\mathrm{M_H} \lesssim 150$ GeV:

first to be established: needs $\mathcal{L} \sim 30\mathrm{fb}^{-1}$

$\mathrm{M}^{\mathrm{recons.}}_{\tau^+\tau^-}$ against WW/tt/Zjj bkg.

$\tau$ polarization usefull against $\mathrm{Z} \to \tau^+\tau^-$




- $\mathrm{H} \to \gamma\gamma$ for $\mathrm{M_H} \lesssim 150$ GeV:

very clean with small/measurable bkgs

rare/needs $\mathcal{L}$+combine with other channels

- $\mathrm{H} \to \mathrm{WW} \to \ell\ell\nu\nu$

very difficult as you need to know background.

but feasible at low $\mathrm{M_H}$ and efficient at high $\mathrm{M_H}$.

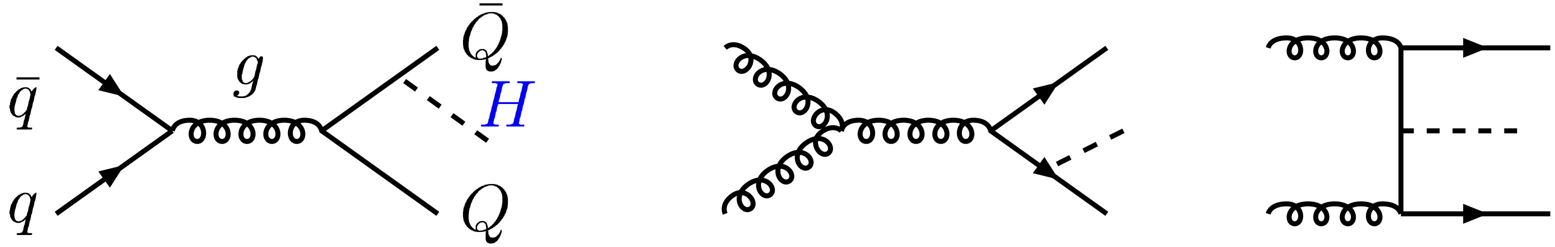
- $\mathrm{H} \to \mathrm{ZZ} \to \ell\ell\nu\nu, \ell\ell\mathrm{jj}$: have large bkg

need high $\mathcal{L}$, usefull at high masses in combination.

- $\mathrm{H} \to \mathrm{b\bar{b}}, \mathrm{t\bar{t}}$ very difficult and $\mathrm{H} \to \mu^+\mu^-$ needs high $\mathcal{L}$.

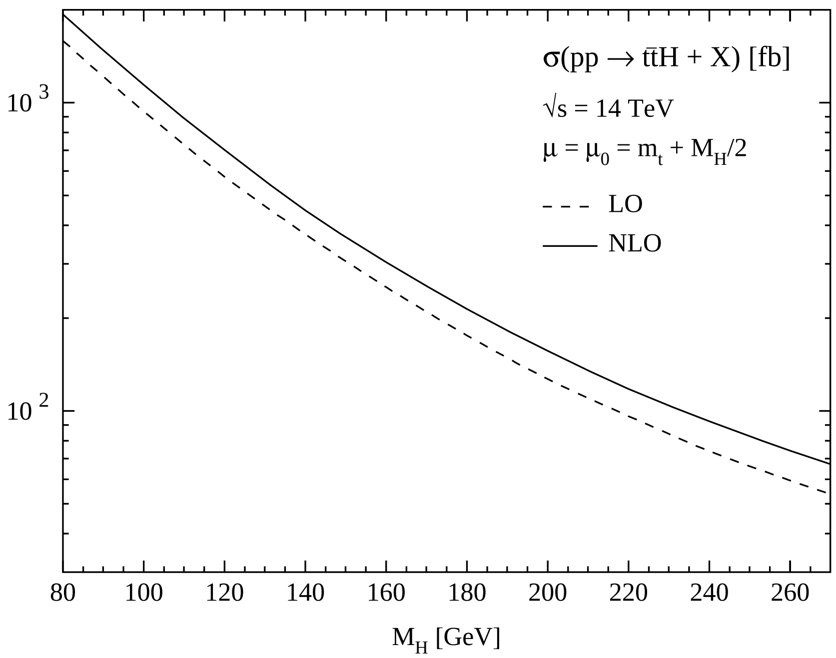
# 2. SM Higgs production: Htt production

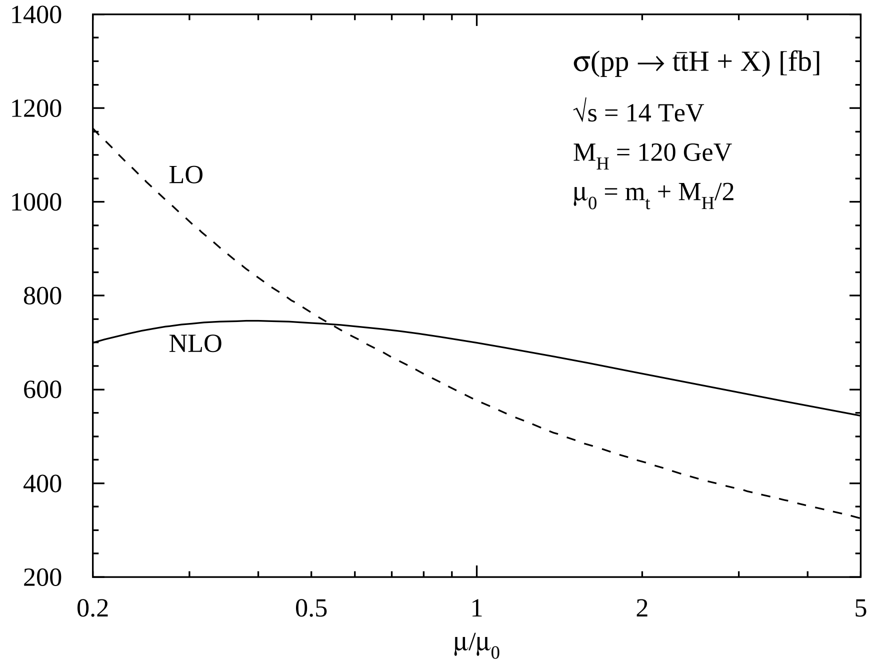
**Most complicated process for Higgs production in pp: many channels:**




**NLO corrections recently calculated (Zerwas et al., Dawson et al.):**

**small K–factors $(\sim 1.2)$ but strong reduction of scale variation!**



# 2. SM Higgs production: Htt production

**Small corrections to kinematical distributions (e.g: $p_T^{top}, P_T^H$), etc...**

- **Rather tiny uncertainties from higher orders, PDFs.**
- **Other possible processes involving heavy quarks work only in BSM:**

**– Single top+Higgs production: $pp \to tH + X$.**

**– Associated production with bottom quarks: $pp \to bbH$.**

**Interesting signals at the LHC for this process are:**

- $pp \to Htt \to \gamma\gamma\ell^{\pm}$**: clean but rather small rates.**
- $pp \to Htt \to b\bar{b}\ell^{\pm}$**: needs efficent b tagging.**
- $pp \to Htt \to \ell^{\mp}\ell^{\pm}\nu\nu$**: large bckgs from ttWjj, etc...**

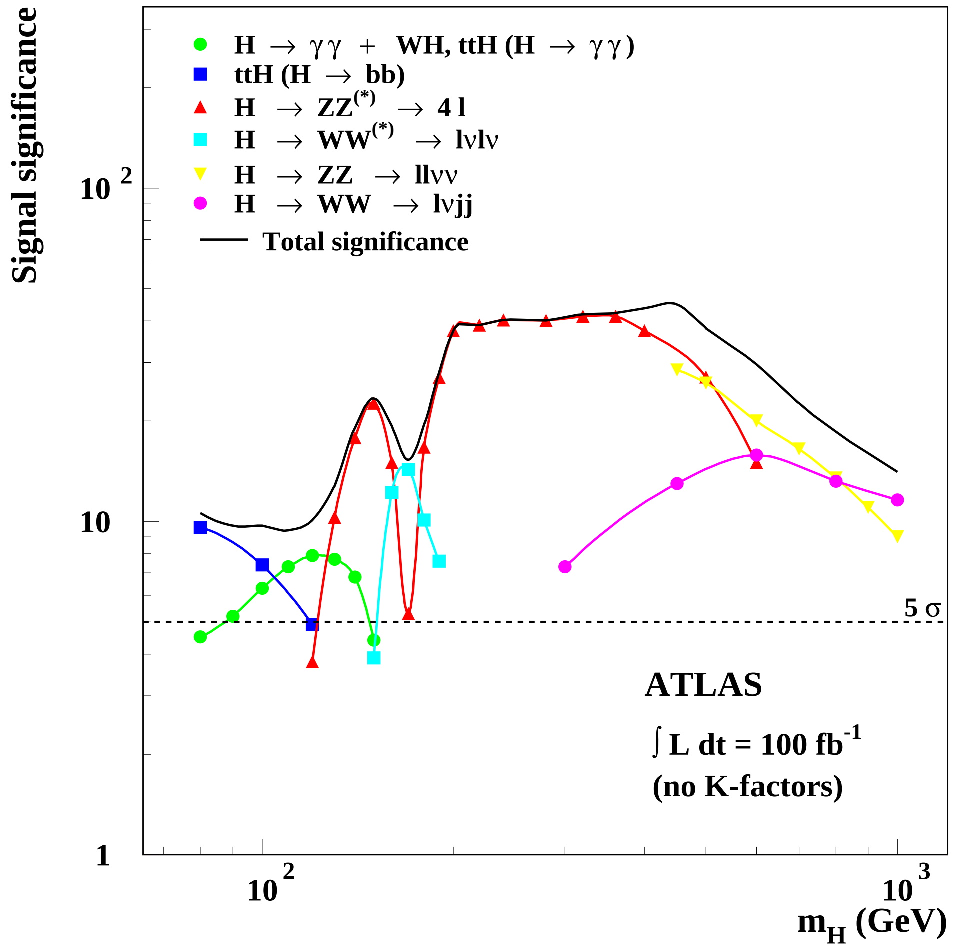
**Possibility for a 3–5 signal at $M_H \lesssim 140$ GeV with high luminosity.**

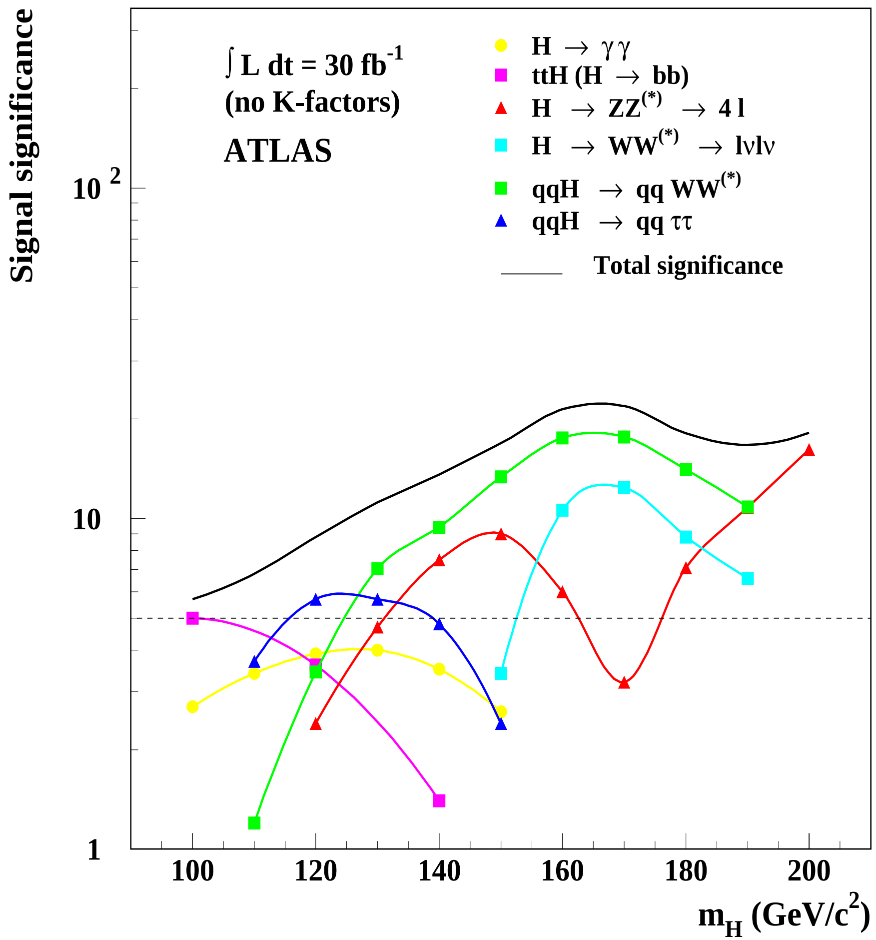
**Needs to be combined with similar channels and topologies (eg:**
**$pp \to WH \to \ell\gamma\gamma, \ell b\bar{b}$) to increase total signal significance.**

**But process very important for measurement of Htt Yukawa coupling!**

# 2. SM Higgs production: summary

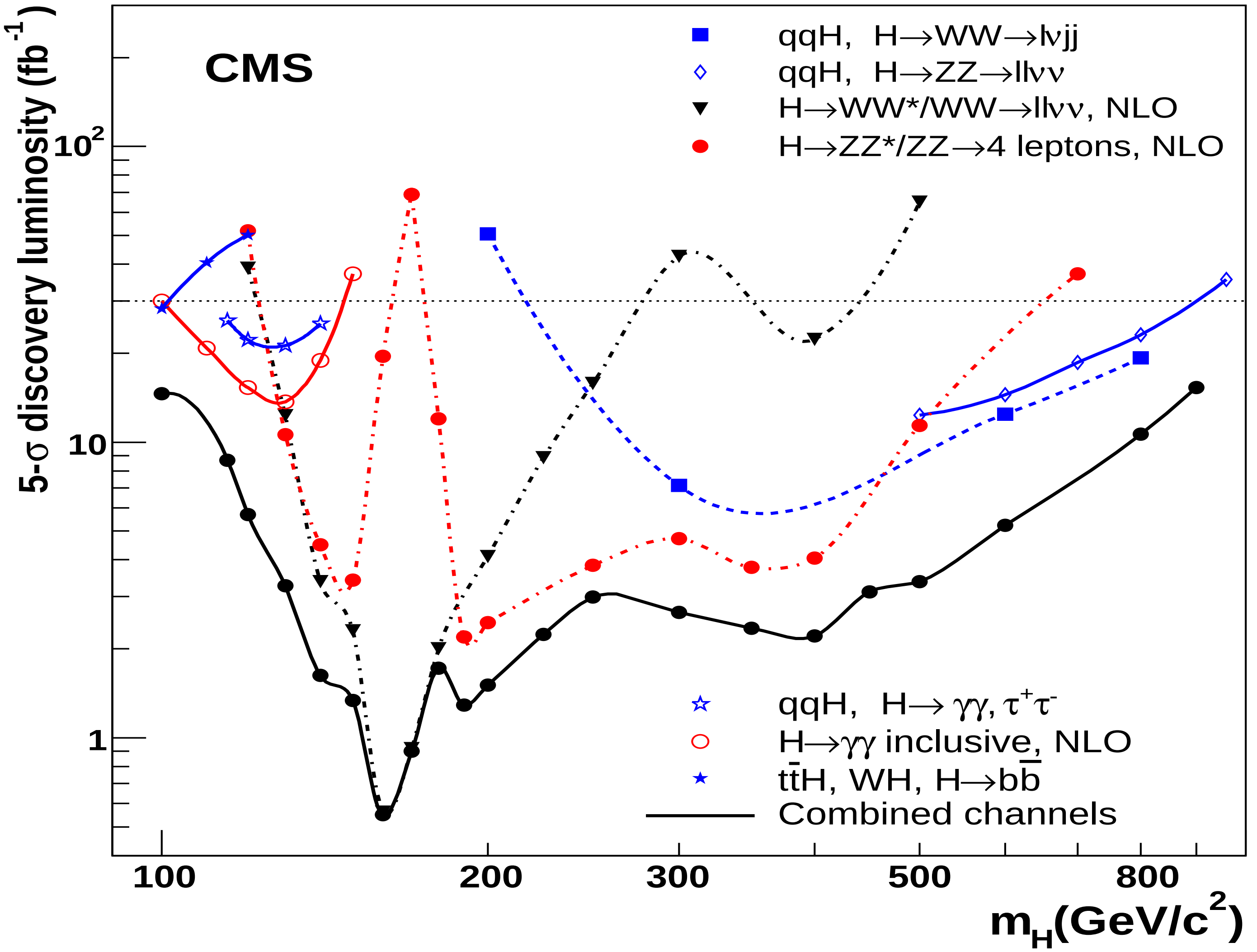
**All in all, when you do the hard experimental work, you will get:**



# 2. SM Higgs production: summary

**Another way too summarize the expections: in terms of luminosity**



# 3. Measurement of Higgs properties

**So in 2-3 years from now we will find the Higgs (and maybe nothing else):**

**we celebrate, shake hands, drink champagne, take care of our bets, ...**

**and should we declare Particle Physics closed and go home or fishing?**

**No! We need to check that it is indeed responsible of spontaneous EWSB**

**Measure its fundamental properties in the most precise way:**

- **its mass and total decay width,**
- **its spin–parity quantum numbers and chek $J^{PC} = 0^{++}$,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential $V_H$ that makes EWSB.**

**A very ambitious and challenging program!**

**which is even more difficult to achieve than the Higgs discovery itself...**

# 3. Higgs properties: mass and width

**Higgs boson mass from:**

– $H \to \gamma\gamma$ **for** $M_H \lesssim 130$ **GeV**

– $H \to ZZ \to 4\ell^\pm$ **beyond**

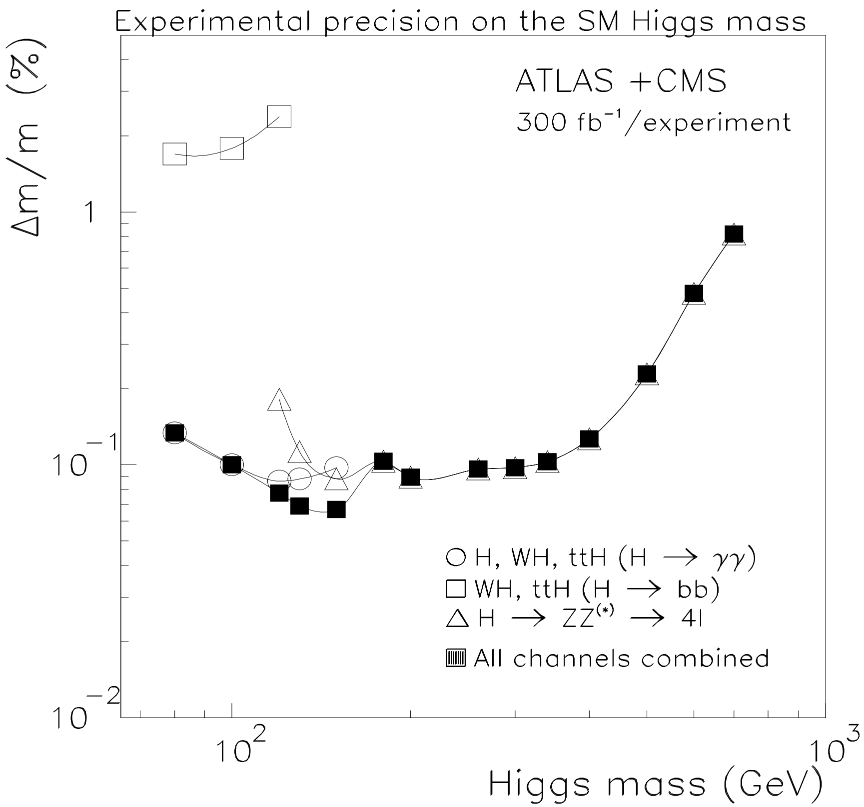
**Final** $\Delta M_H/M_H \sim 0.1\%$ to $1\%$.

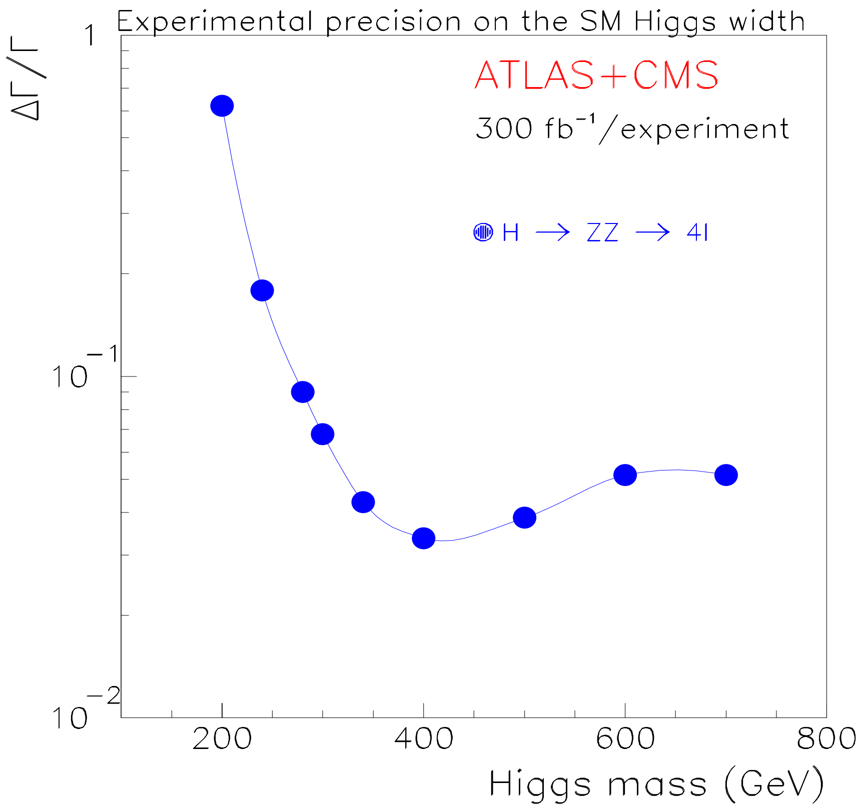
**Higgs boson total width:**

– **Too small for** $M_H \lesssim 2M_Z$

– $H \to ZZ \to 4\ell^\pm$ **beyond**

**Final** $\Delta\Gamma_H/\Gamma_H \sim$ **a few %**




**However: for large $M_H$ effects from large width are important!**

# 3. Higgs properties: $J^{PC}$ numbers

- **Higgs spin:**

**Higgs can be observed in $H \to \gamma\gamma$ decays: rules out J=1 and fixes C=+,**

**– argument not generalizable to $H \leftrightarrow gg$ since no g/q distinction,**

**– other particle spin–assignements might be possible J=2 (radion), etc.**

- **Higgs parity:**

**– Higgs can be observed in $H \to ZZ \to 4\ell^{\pm}$ rules out CP–odd state.**

**– Higgs spin–correlations in $gg \to H \to WW^*$ also useful here...**

**But we need to check that H is pure CP–even with no CP–odd mixture:**

**– it becomes then a challenging high–precision measurement,**

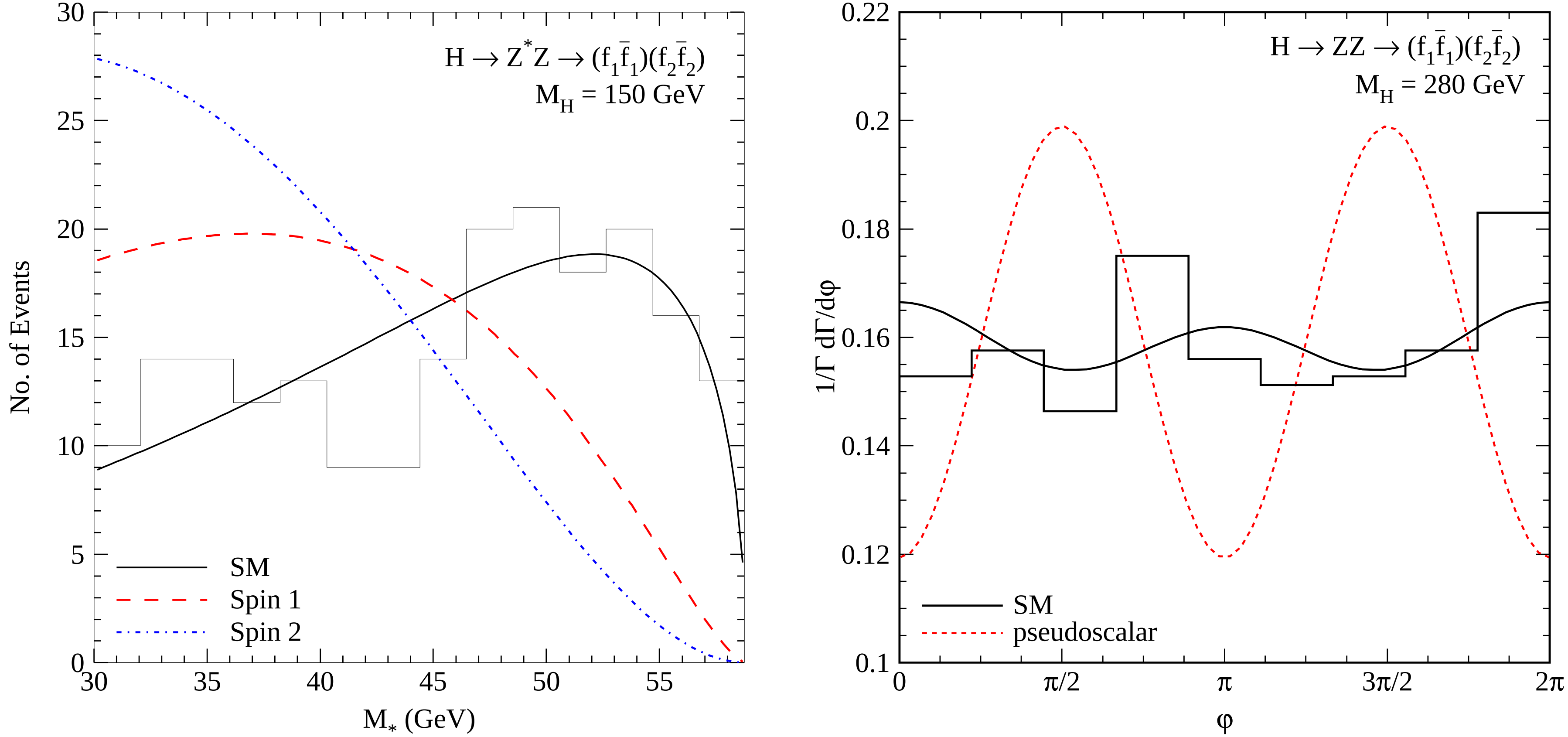
**– can be done roughly by looking at correlations in $H \to ZZ, WW$.**

**Drawback: If H is mostly CP–even, rates for $A \to VV$ too small...**

**More convincing to look at more democratic Higgs-fermion couplings.**

**Possible channels: $H \to \tau^+\tau^-$ or $pp \to t\bar{t}H$: very challenging!!**

# 3. Higgs properties: $J^{PC}$ numbers




**left: threshold behavior of $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ}^*)/\mathrm{dM}_*$ distribution for J=0,1,2**

**right: azimuthal distributions $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ})/\mathrm{d}\phi$ for SM and CP-odd A**

**ATLAS simulation including bkgs with $\int \mathcal{L}\mathrm{dt} = 300\,\mathrm{fb}^{-1}$ at the LHC**

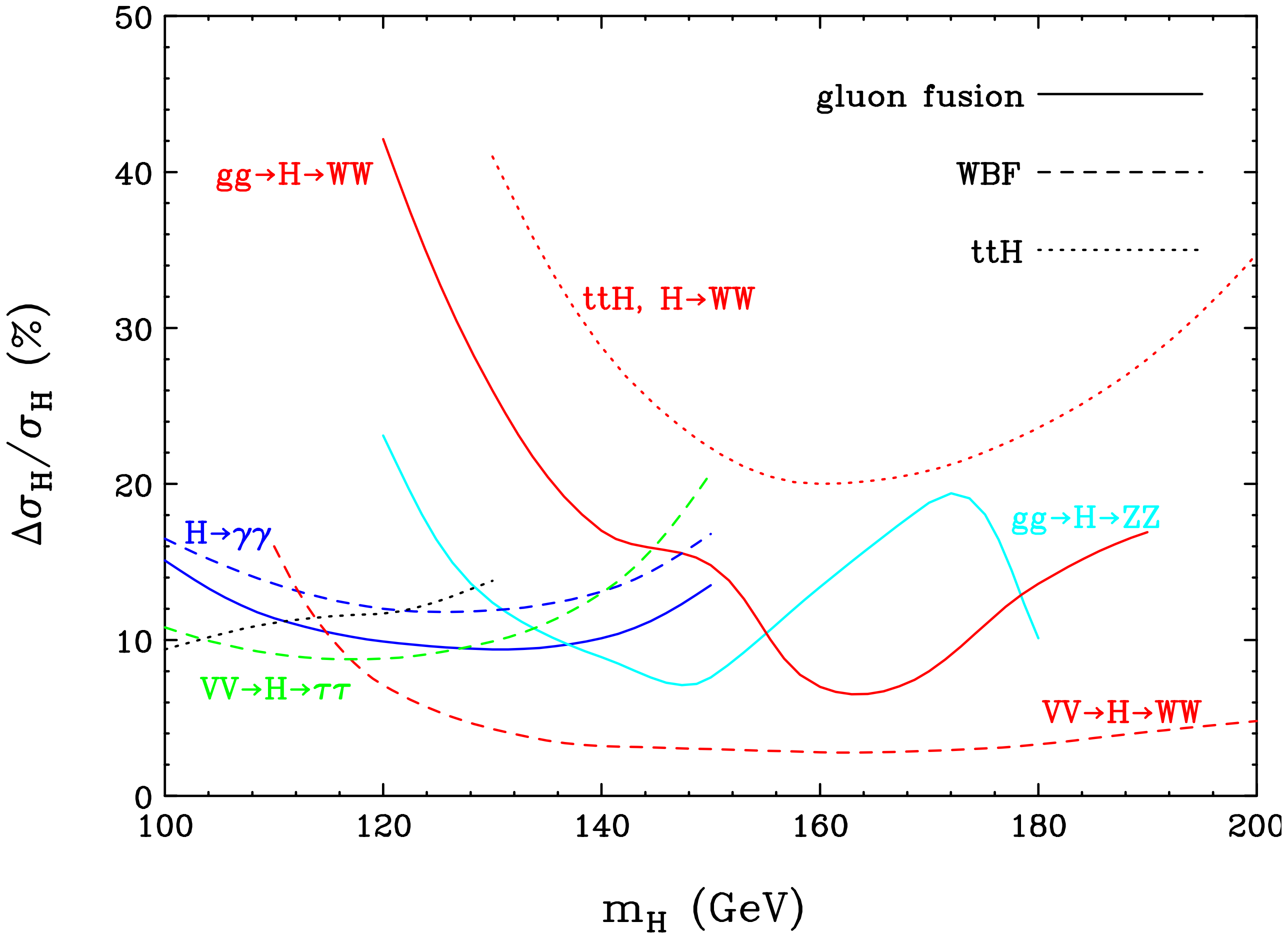
# 3. Higgs properties: Higgs couplings

**Higgs couplings can be determined by looking at various Higgs production and decay channels and measuring $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$.**

**LHC with $\mathcal{L} = 300$fb$^{-1}$.**

**Only statistical errors.**

**D. Zeppenfeld et al.**



# 3. Higgs properties: Higgs couplings

**The errors are in general rather large unfortunately:**

- **experimental errors: statistics, systematics, parton luminosity,...**
- **theoretical errors: PDFs, HO+scale variation, model dependence...**

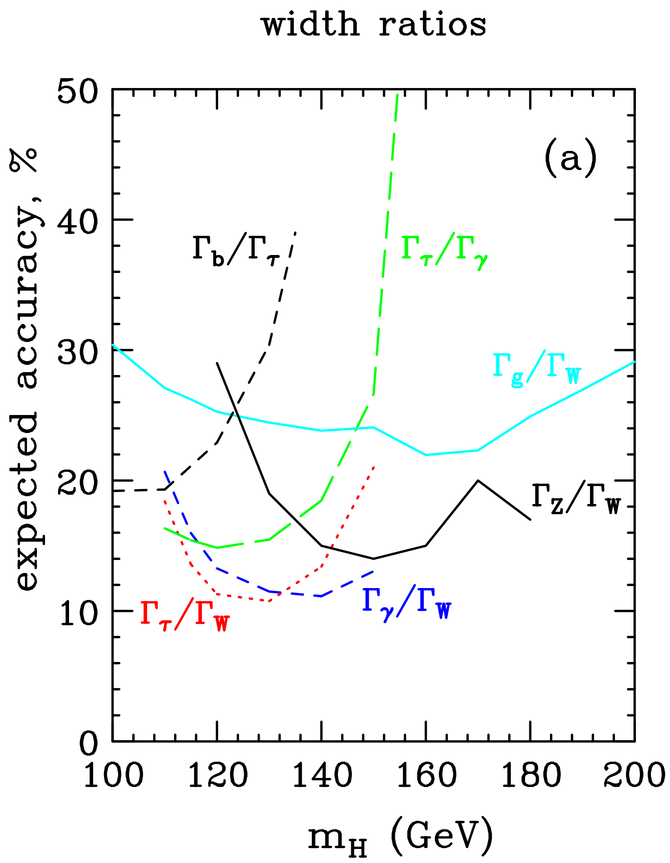
$\Rightarrow$ **ratios of $\sigma \times \mathrm{BR}$: many errors drop out!**

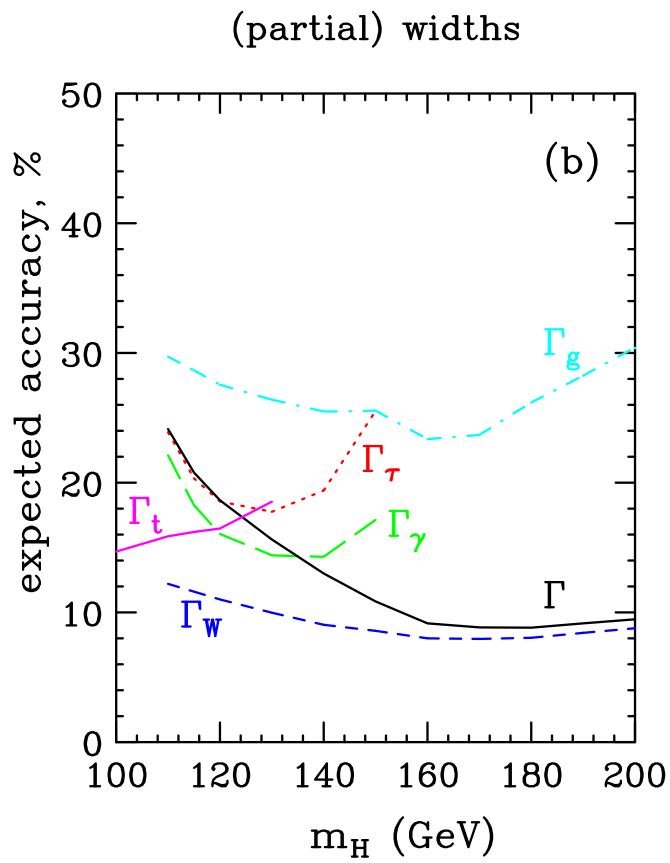
| Process | Measurement quantity | Error | Mass range |
|---|---|---|---|
| $\frac{(t\bar{t}H+WH)\to\gamma\gamma+X}{(t\bar{t}H+WH)\to b\bar{b}+X}$ | $\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to b\bar{b})}$ | $\sim 15\%$ | $80-120$ GeV |
| $\frac{H\to\gamma\gamma}{H\to 4\ell^+}$ | $\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^*)}$ | $\sim 7\%$ | $120-150$ GeV |
| $\frac{t\bar{t}H\to\gamma\gamma,b\bar{b}}{WH\to\gamma\gamma,b\bar{b}}$ | $(g_{Htt}/g_{HWW})^2$ | $\sim 15\%$ | $80-120$ GeV |
| $\frac{H\to ZZ^*\to 4\ell^+}{H\to WW^*\to 2\ell^\pm 2\nu}$ | $(g_{HZZ}/g_{HWW})^2$ | $\sim 10\%$ | $130-190$ GeV |

**Note: for $\mathrm{M_H} \gtrsim 2\mathrm{M_Z}$ only few processes accessible: $\mathbf{H \to WW/ZZ}$.**
**while $\sigma(\mathrm{gg}\to\mathrm{H})$ provides $\mathrm{g_{Htt}}$ but indirectly since loop mediated.**

# 3. Higgs properties: Higgs couplings

- **Then translate into partial widths $\propto$ Higgs coupling squared.**
- **Precision on coupling measurement is:** $\Delta g_{HXX} = \frac{1}{2}\frac{(\Delta^{exp}\Gamma + \Delta^{th}\Gamma)}{\Gamma}$
- **Some theoretical assumptions (no invisible, SU(2) invariance, some couplings are known, etc..) allow to extract additional couplings....**



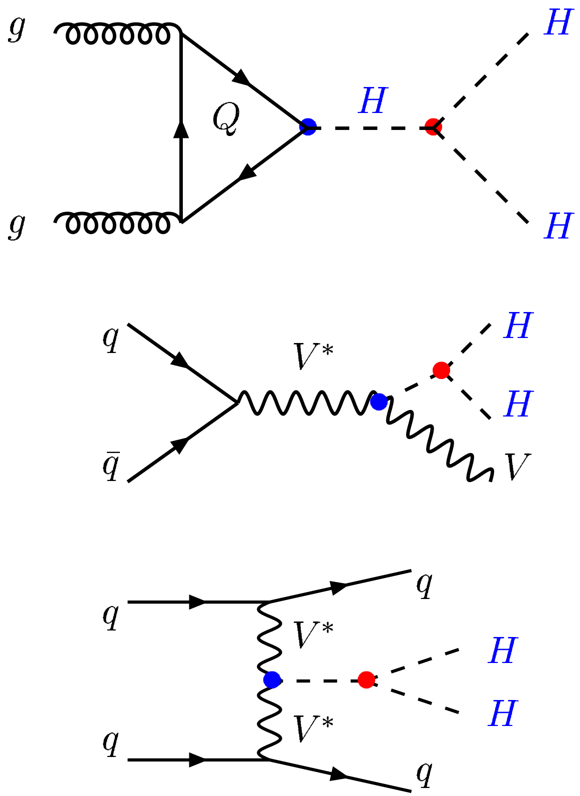



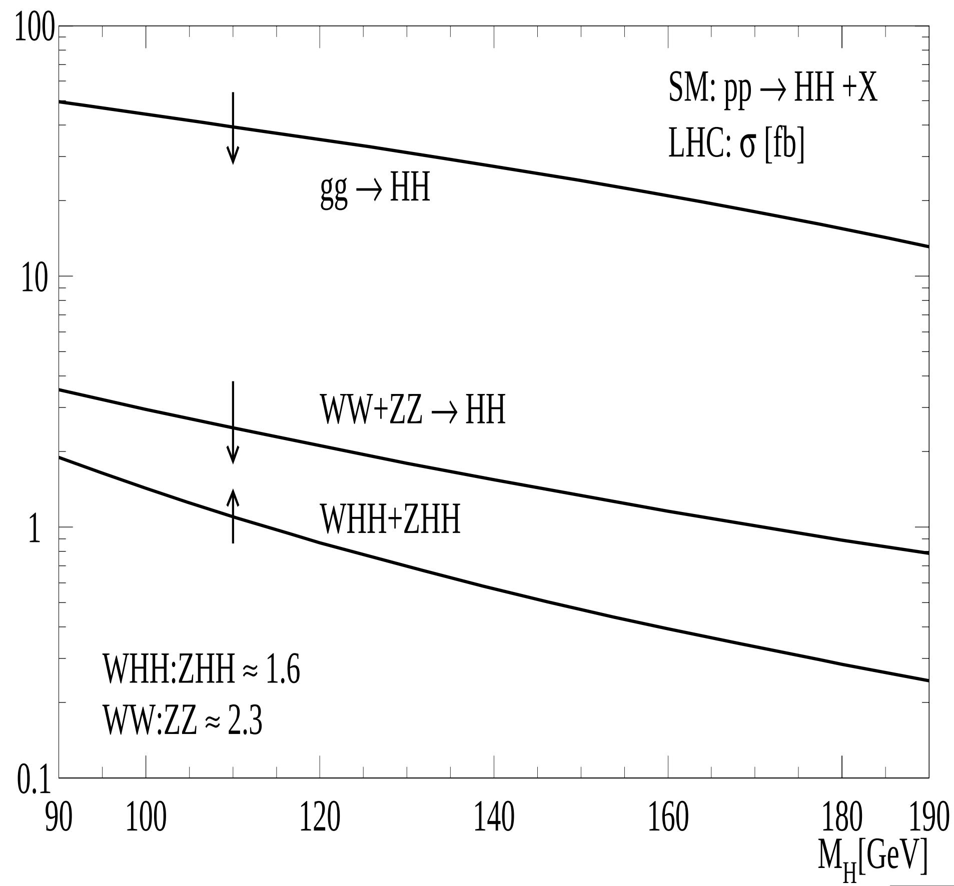
# 3. Higgs properties: Higgs self-couplings

**Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to $V_H$.**

- $g_{H^3}$ **is accessible in double Higgs production:** $pp \to HH + X$
- $g_{H^4}$ **is hopeless to measure, needs pp→HHH+X with too low rates.**

**Relevant processes for HH prod:**



# 3. Higgs properties: Higgs self-couplings

**Cross sections small, except maybe for gg→HH at $M_H \lesssim 200$ GeV:**

- $\mathrm{H} \to \gamma\gamma$ **decay too rare,**
- $\mathrm{H} \to \mathrm{b\bar{b}}$ **decay not clean**
- $\mathrm{H} \to \mathrm{WW}$ **at low $\mathrm{M_H}$?**

**Yes, it has been tried:**

**– parton level analysis...**

**– look for $2\ell^\pm, 3\ell^\pm + \nu$+jets+**

**– look at IM distributions**

**– use large luminosity.**

**Some hope to set limits....**

**Needs to go to SLHC...**

**U. Baur et al.**