HIGGS AT LHC

Higgs production and search strategy

Lecture 9

DIPARTIMENTO DI FISICA

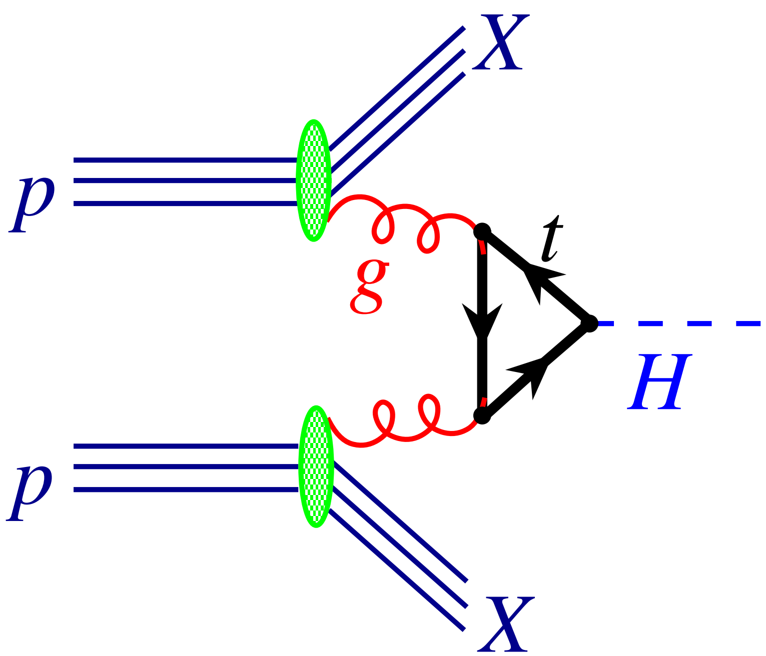
SAPIENZA
UNIVERSITÀ DI ROMA

Shahram Rahatlou

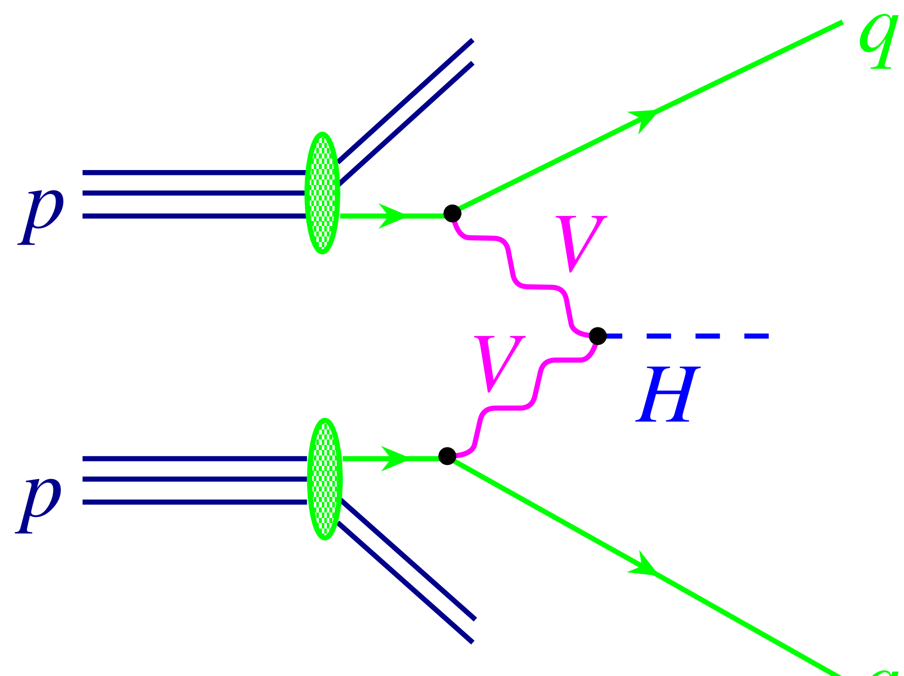
Fisica delle Particelle Elementari, Anno Accademico 2015-16

http://www.roma1.infn.it/people/rahatlou/particelle/

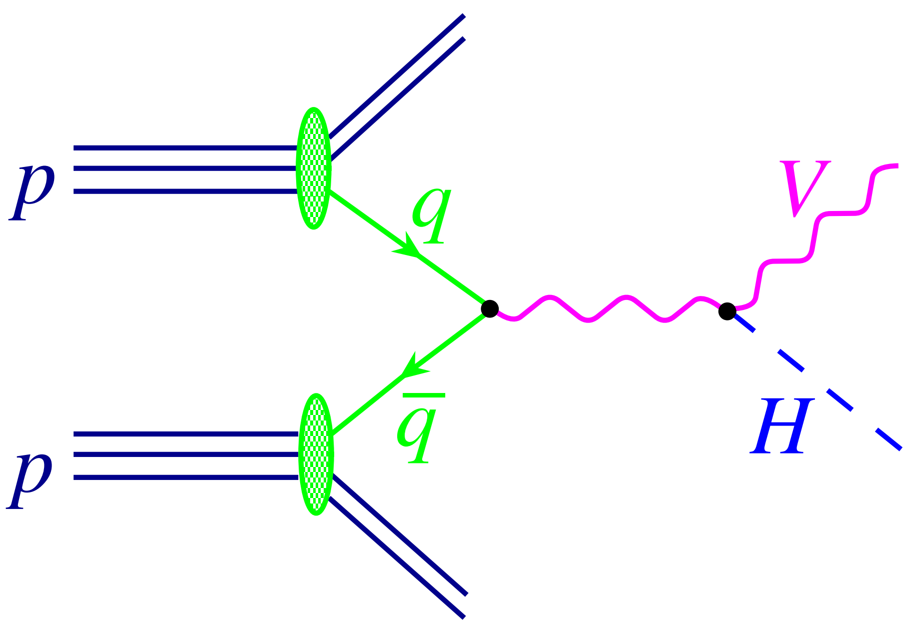
Higgs Production at Hadron Colliders



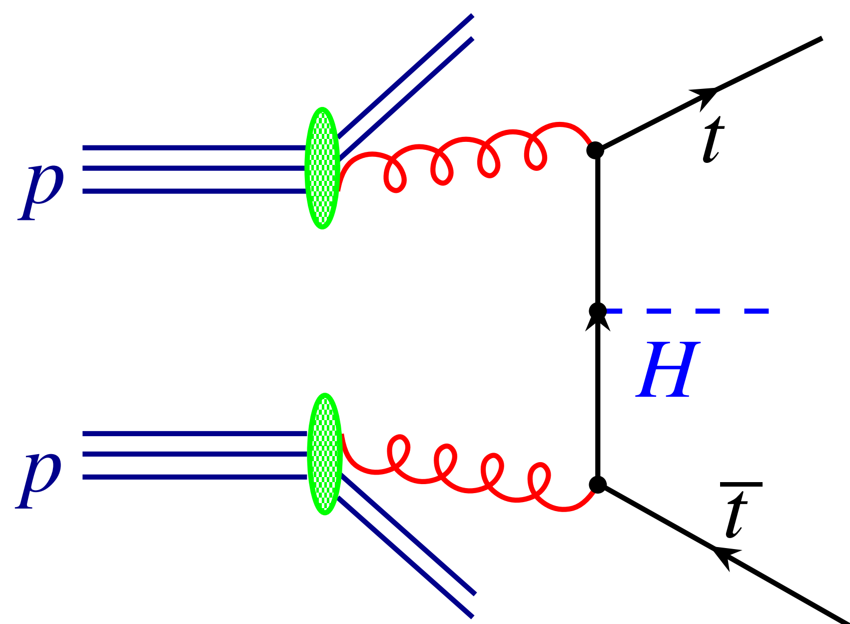
Gluon fusion



Weak-Boson Fusion

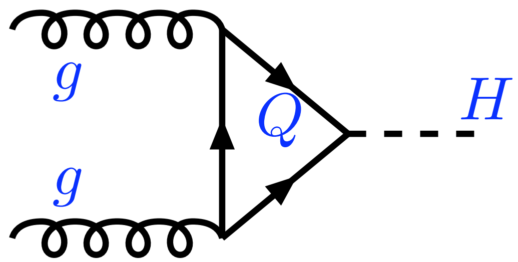


Higgs Strahlung



$t\bar{t}H$

GLUON-GLUON FUSION



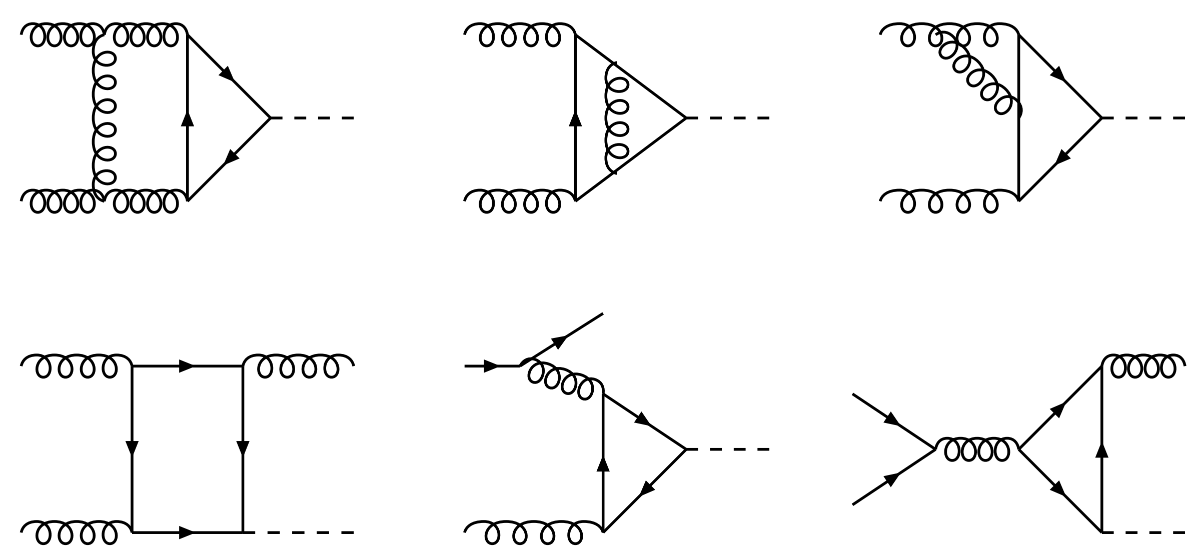
$$\hat{\sigma}_{LO}(gg \to H) = \frac{\pi^2}{8M_H}\Gamma_{LO}(H \to gg)\delta(\hat{s} - M_H^2)$$

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

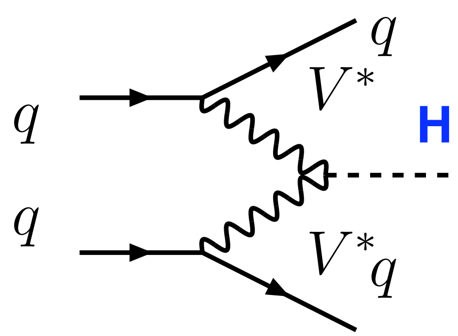
$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$f(\tau) = \arcsin^2\sqrt{\tau}\ \text{for}\ \tau = M_H^2/4m_Q^2 \le 1$$

- Leading production mechanism at LHC
  - Recall: parton luminosity highest for gluons
- In Standard Model only top quark matters
  - b quark contribution ~5%
  - In models beyond SM other particles could enter the loop
    - modification to expected cross section
- Cross section known with uncertainty at the level of 5%
  - many additional radiative terms included



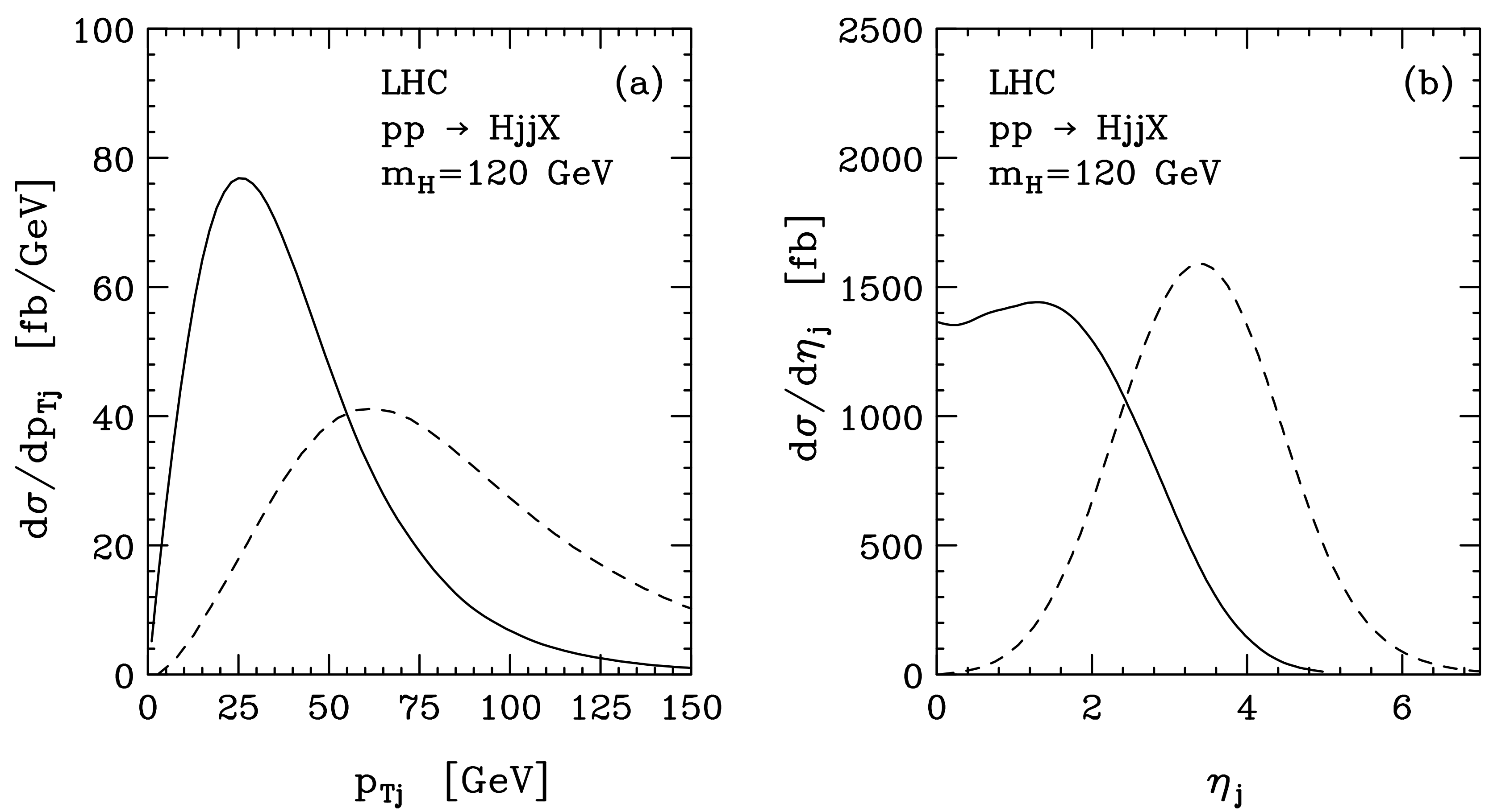
VECTOR BOSON FUSION



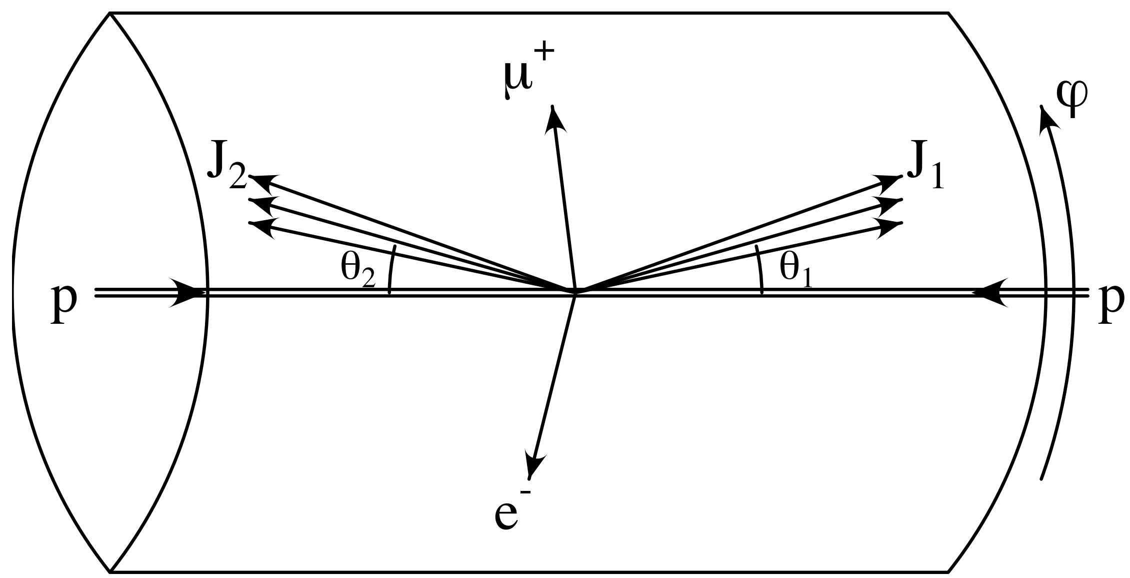
$$\hat{\sigma}_{\mathrm{LO}} = \frac{\mathbf{16\pi^2}}{\mathbf{M_H^3}}\mathbf{\Gamma(H \to V_L V_L)}\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}}$$

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

- Cross section grows with center-of-mass energy
- Process becomes more important at higher energy and for lighter Higgs
- Radiative corrections relatively small at 10% level
- Distinctive kinematic signature: forward jets with high transverse momentum

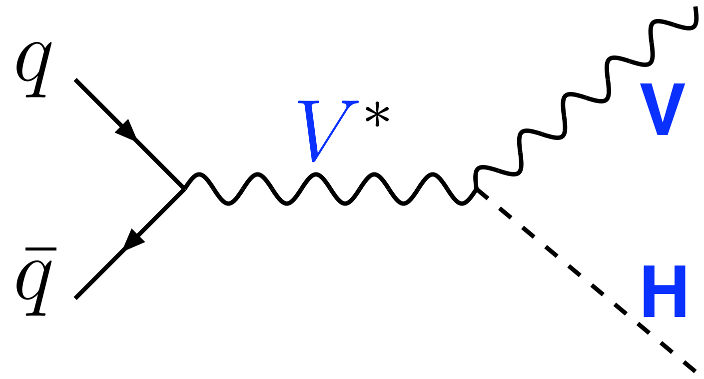


Kinematics of VBF



- Energetic jets in forward and backward regions (p_T > 20 GeV)
  - tagging jets
- Large rapidity separation between two leading jets which leads to high invariant mass
  - rapidity gap
- Higgs and its decay products typically produce in rapidity gap between jets
  - more isolation for Higgs products except for underlying event
- Little gluon radiation in central rapidity region since W/Z exchange is colorless
  - require no jets in central region between two tagging jets

HIGGS-STRAHLUNG



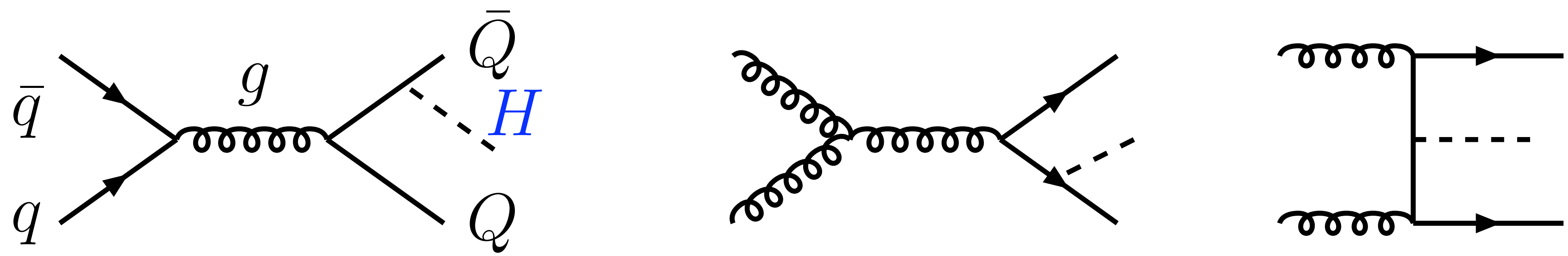
$$\hat{\sigma}_{\rm LO}(\mathbf{q\bar{q}} \to \mathbf{VH}) = \frac{\mathbf{G_\mu^2 M_V^4}}{\mathbf{288}\pi\hat{\mathbf{s}}} \times (\hat{\mathbf{v}}_\mathbf{q}^\mathbf{2} + \hat{\mathbf{a}}_\mathbf{q}^\mathbf{2})\lambda^{1/2}\frac{\lambda + \mathbf{12M_V^2}/\hat{\mathrm{s}}}{(\mathbf{1} - \mathbf{M_V^2}/\hat{\mathrm{s}})^\mathbf{2}}$$

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

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

- Minor role at LHC because of parton luminosity
  - anti-quark from sea
- Cross section favored mostly in low mass region where WW and ZZ final states are still small
- Important production mechanism at Tevatron
  - valence anti-quarks in anti-proton

Associated Production



- Higgs production associated with pair of fermions in final state
  - useful experimental signature to recognize (tag) events
- top dominates because of its much larger coupling to Higgs
  - b quark also contributes
- different diagrams imply different kinematics
  - recall: VBF very different from gluon-gluon fusion
- top decays require dedicated or at least b- tagging
- Non-leptonic Higgs decays rather challenging when combined with two top quarks

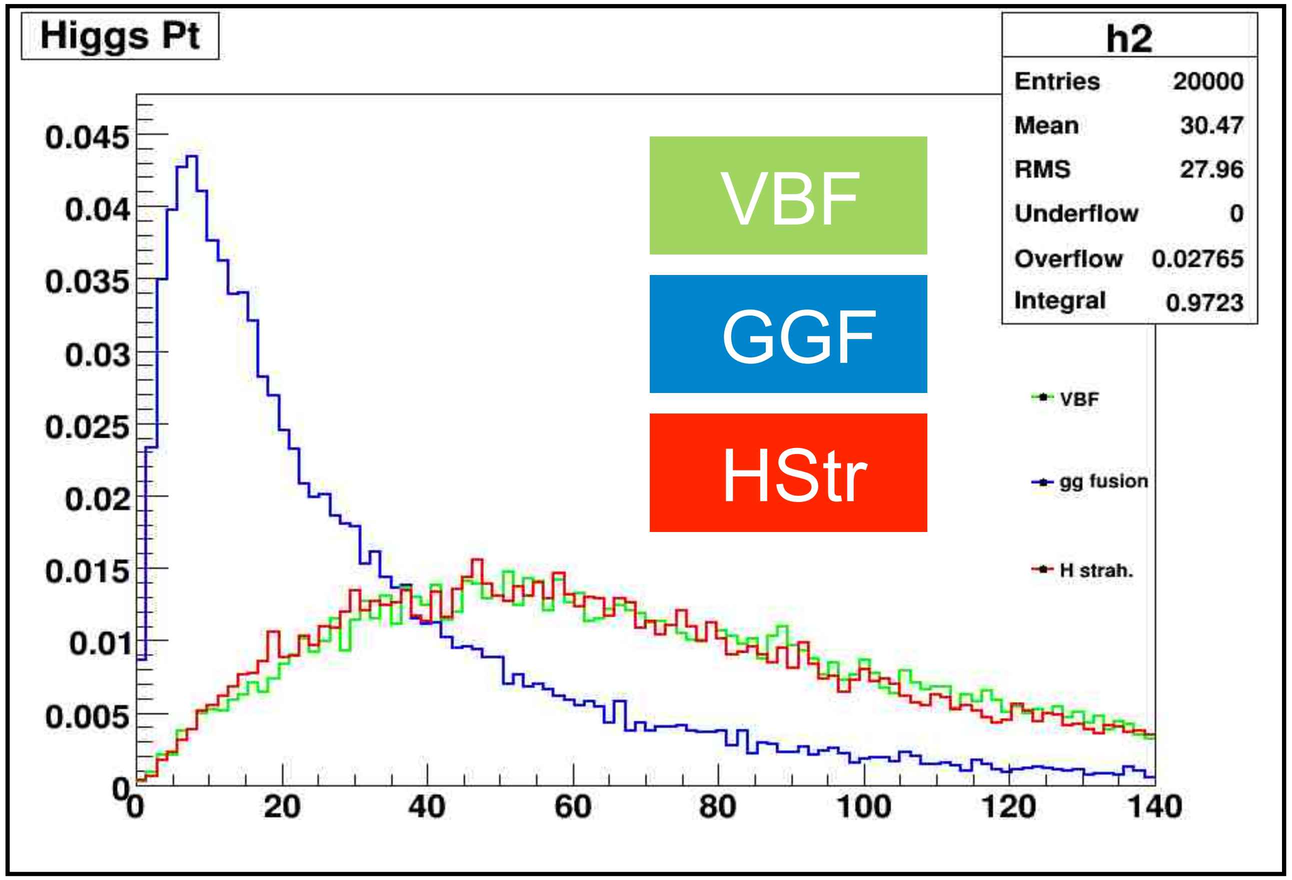
Comparison between Processes

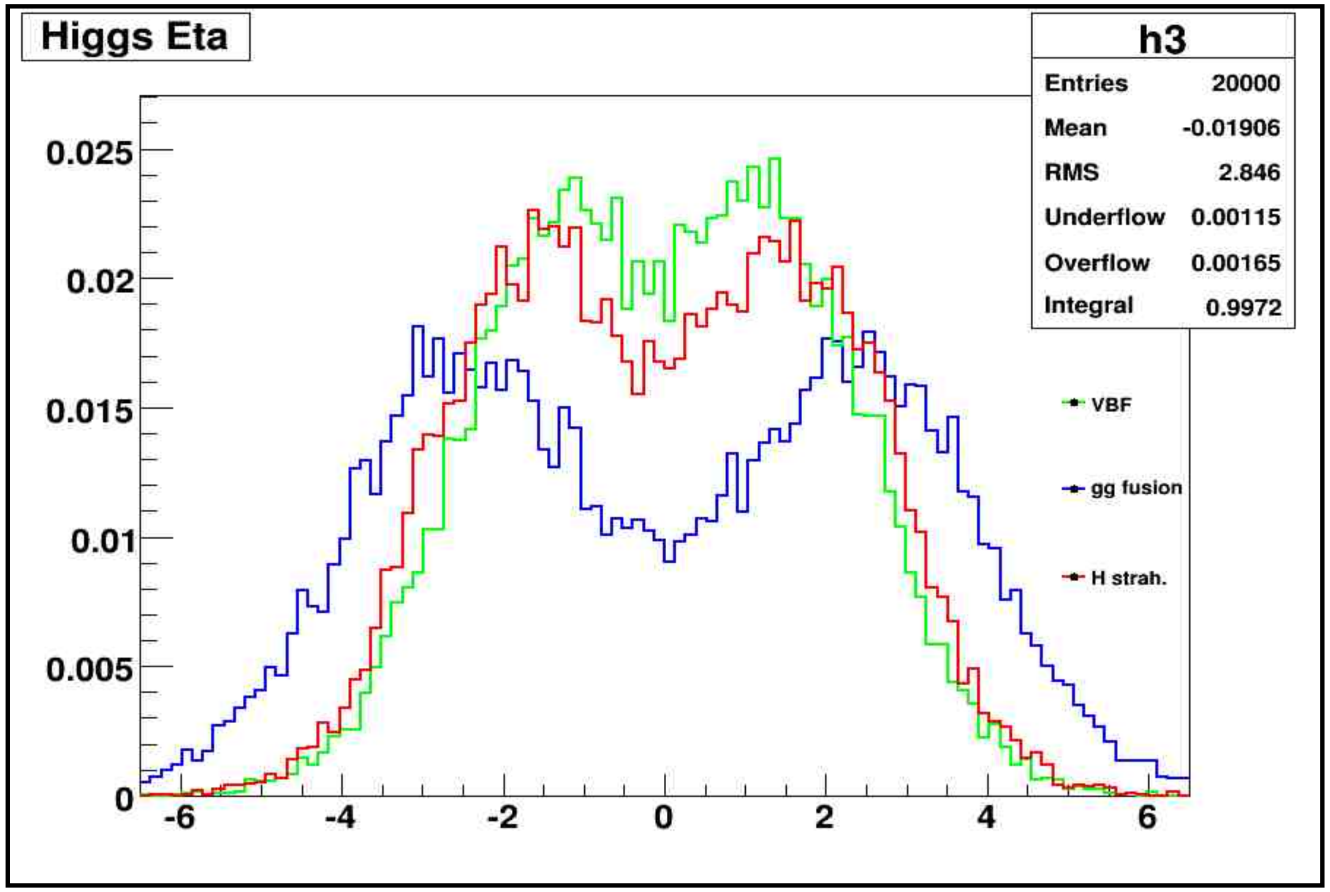
- gluon-gluon fusion relevant for any Higgs mass and hence relevant for all decay channels

- Vector boson fusion most important for mid-high Higgs mass
  - distinctive kinematic signature with accompanying forward-backward jets
  - beneficial for WW final state that suffers from more background because of missing particles in final state

- Higgs-strahlung most important for low mass region

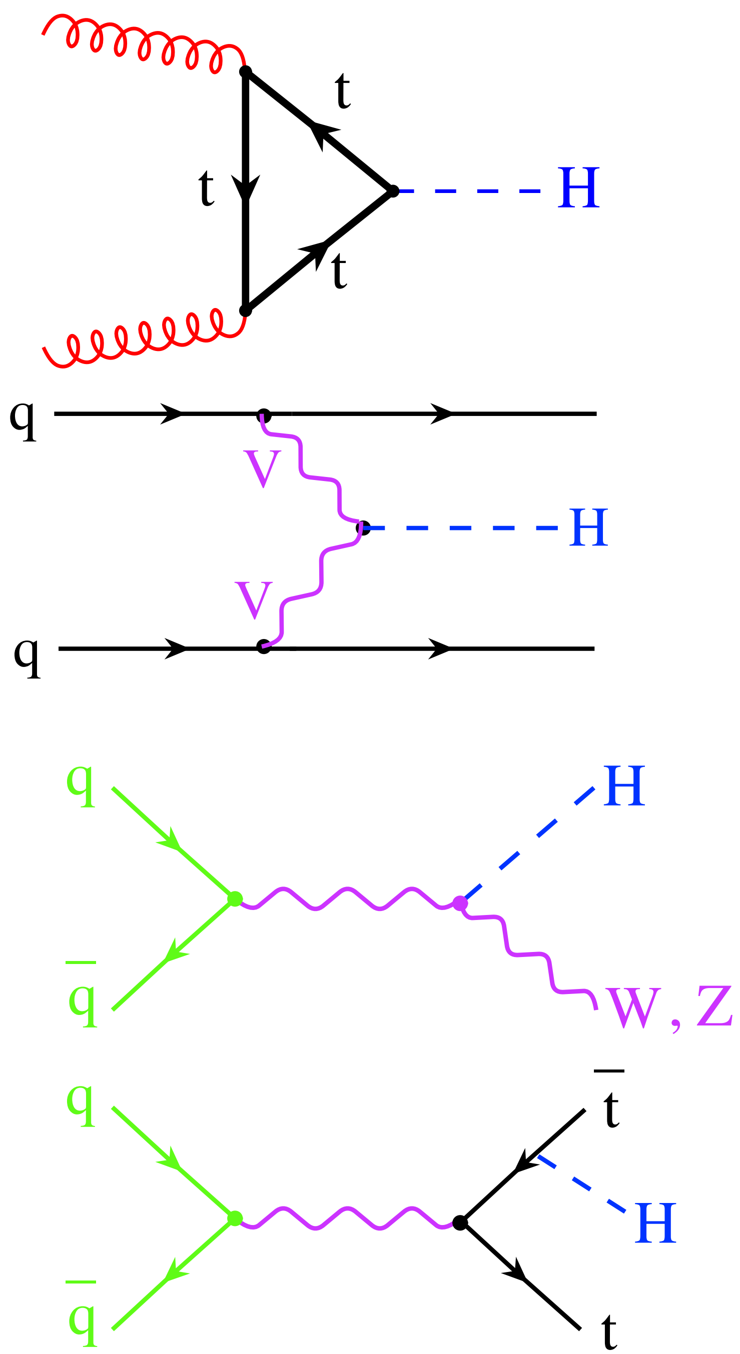
HIGGS KINEMATICS

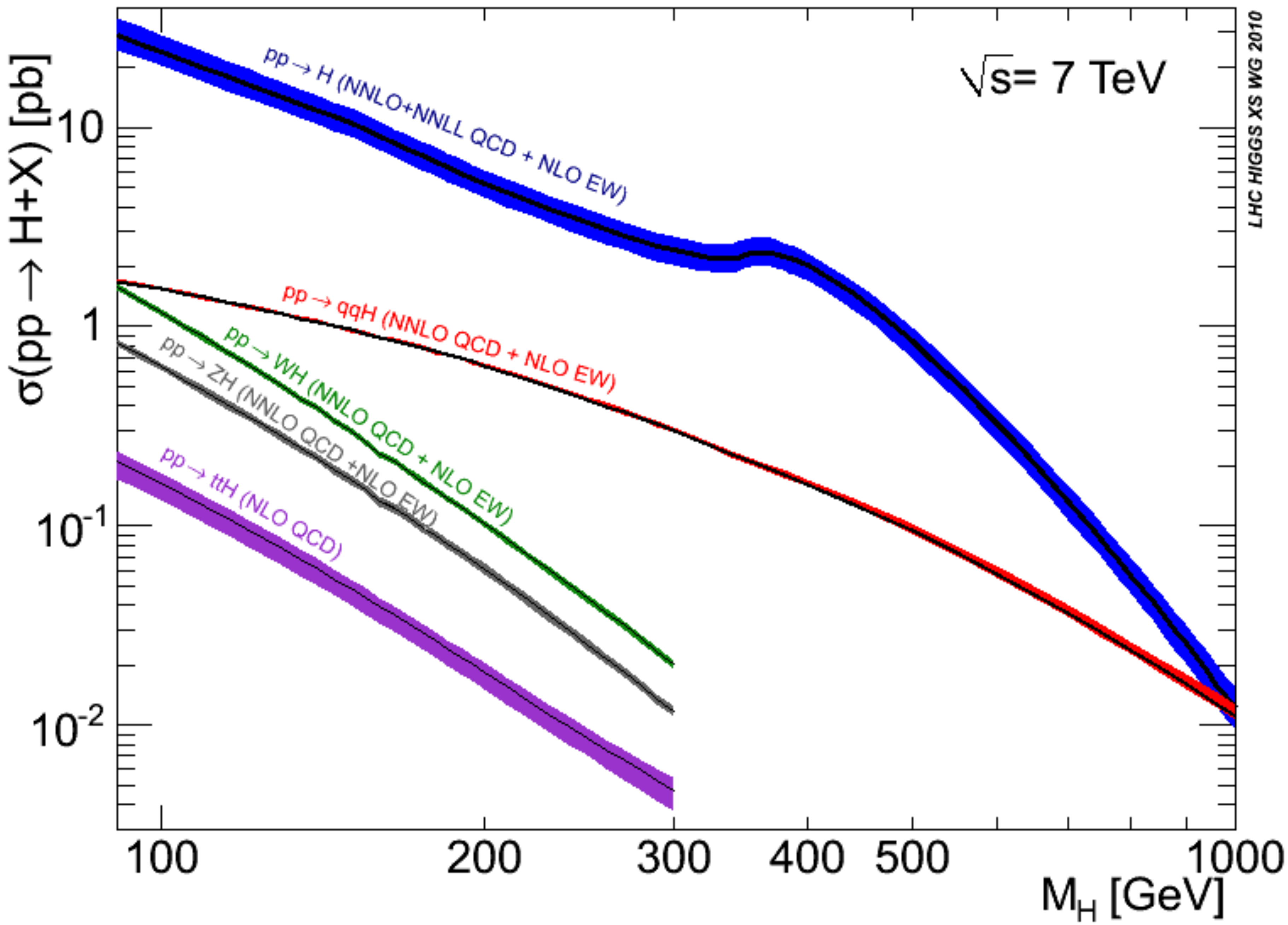




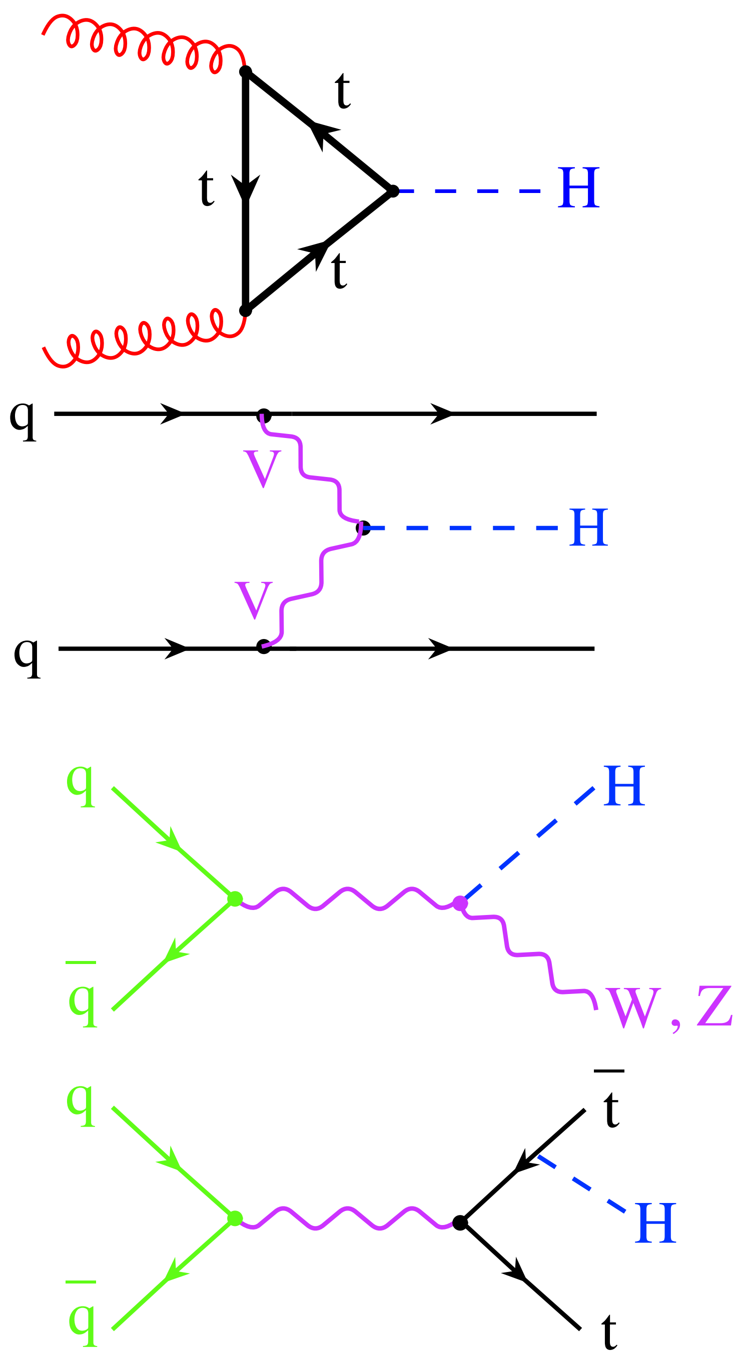
- Very little transverse boost in gluon-gluon fusion
- More particles produced at high rapidity in g-g fusion hence reducing background
  - luckily this is also the favorite production mode

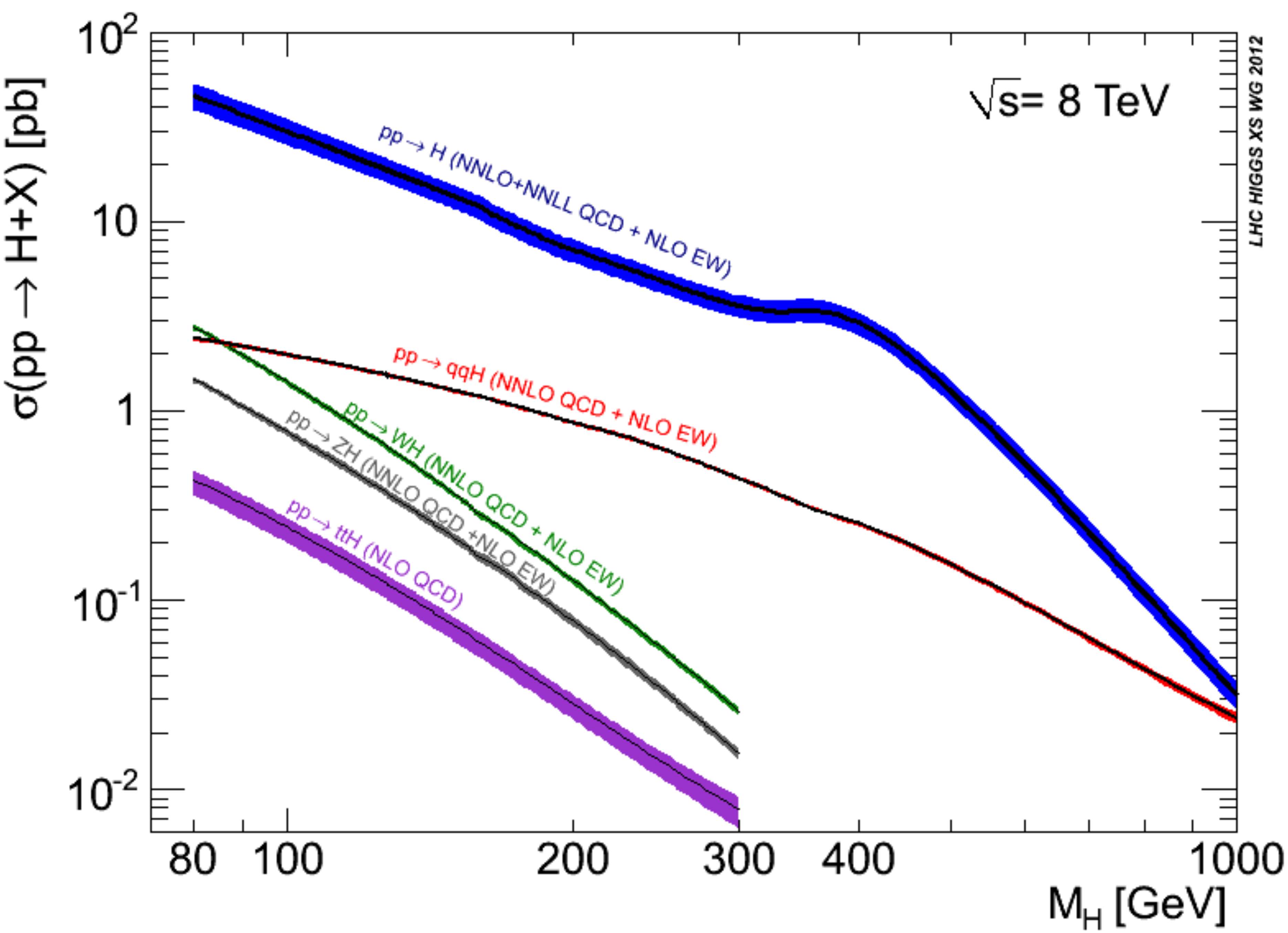
HIGGS PRODUCTION CROSS SECTION @ 7 TEV



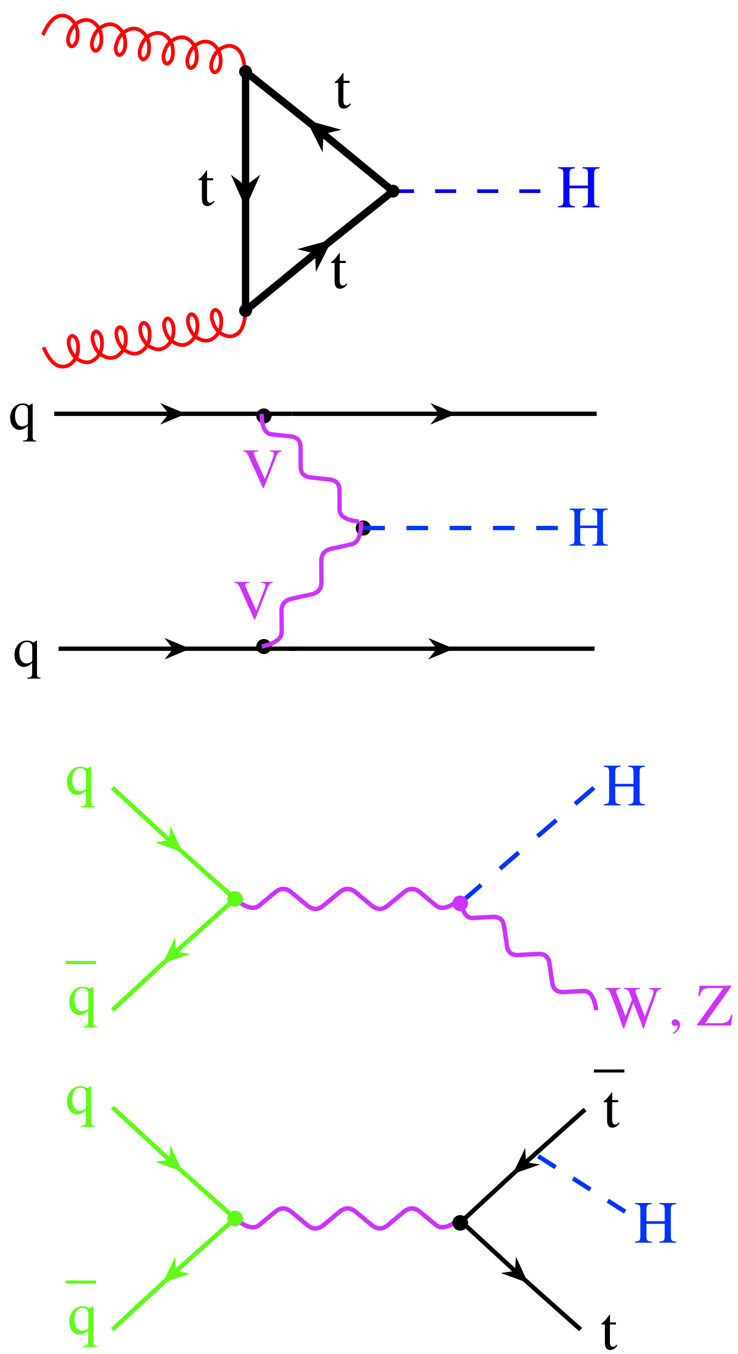


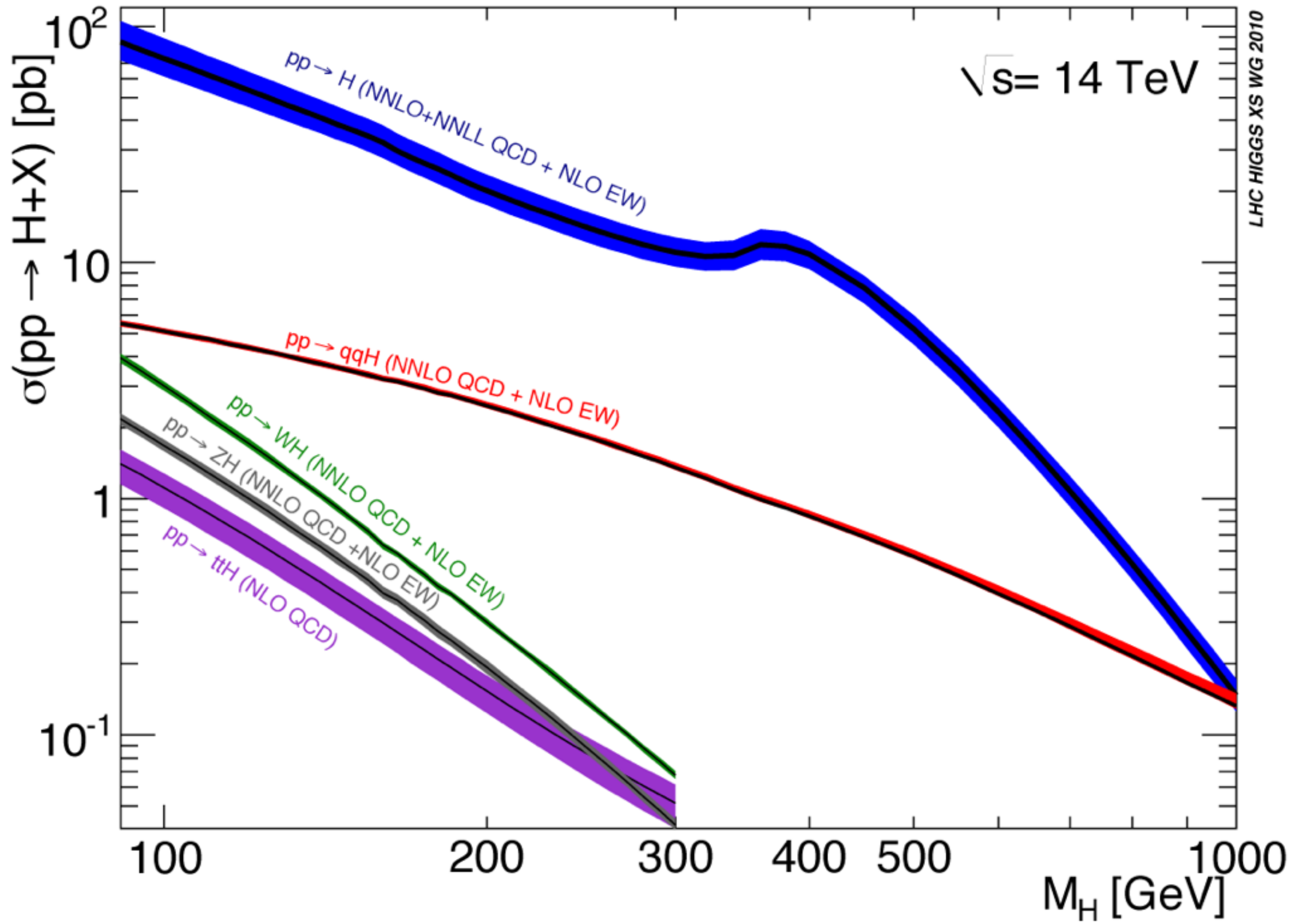
HIGGS PRODUCTION CROSS SECTION @ 8 TEV



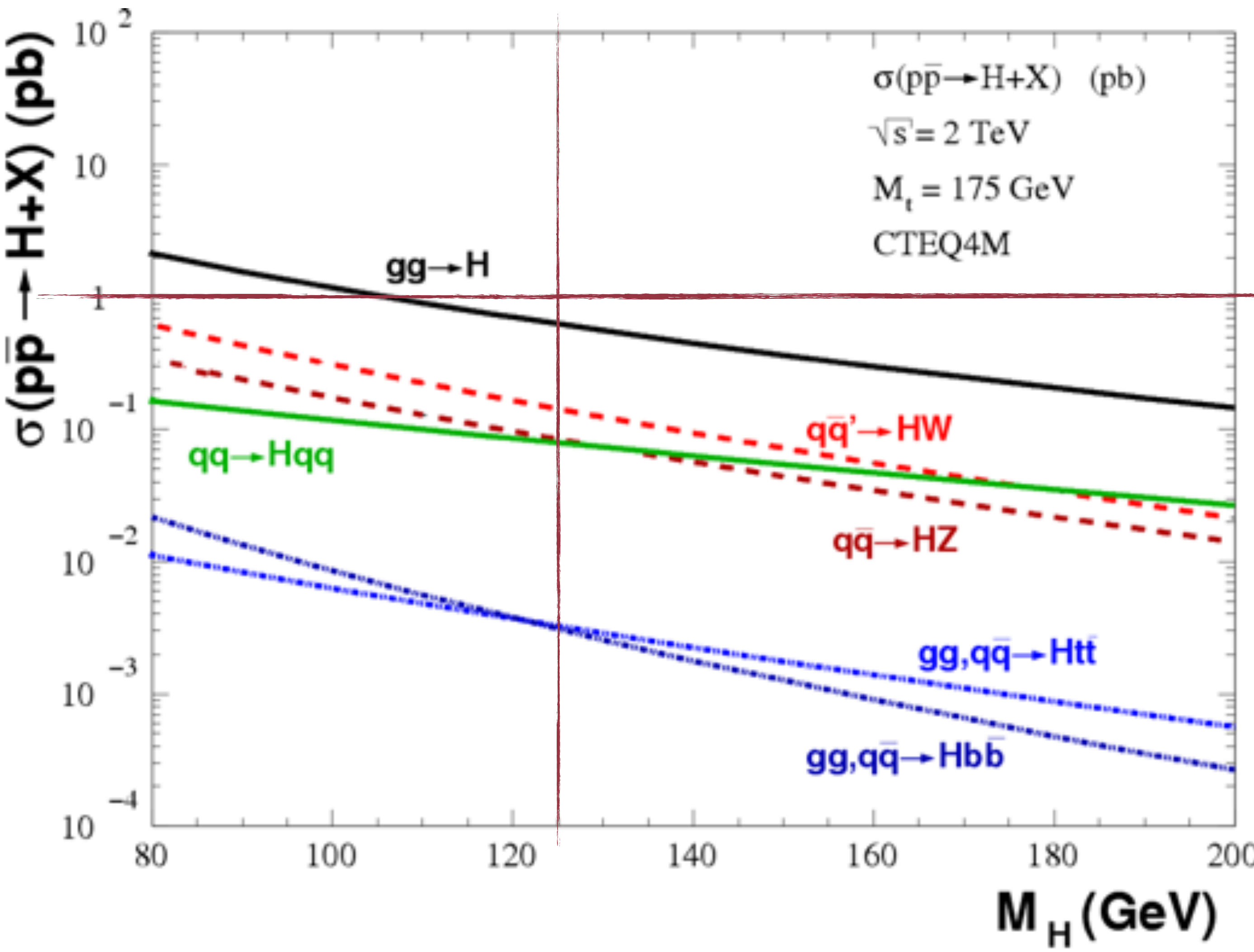


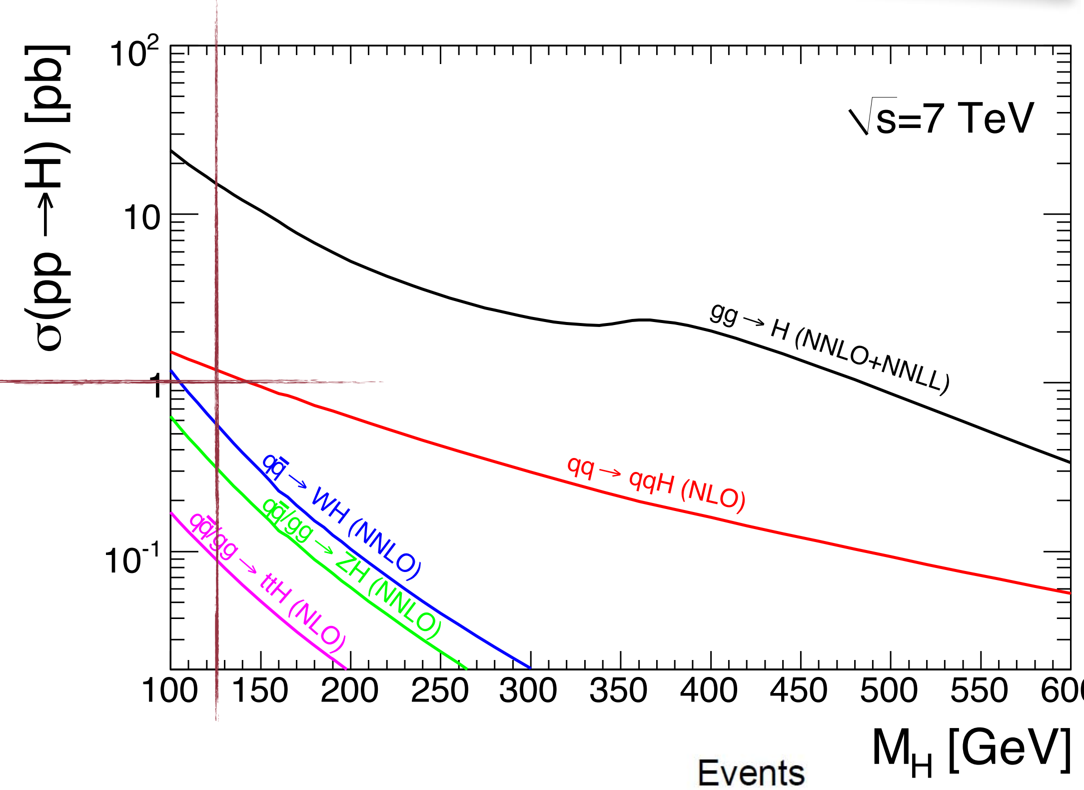
HIGGS PRODUCTION CROSS SECTION @ 14 TEV

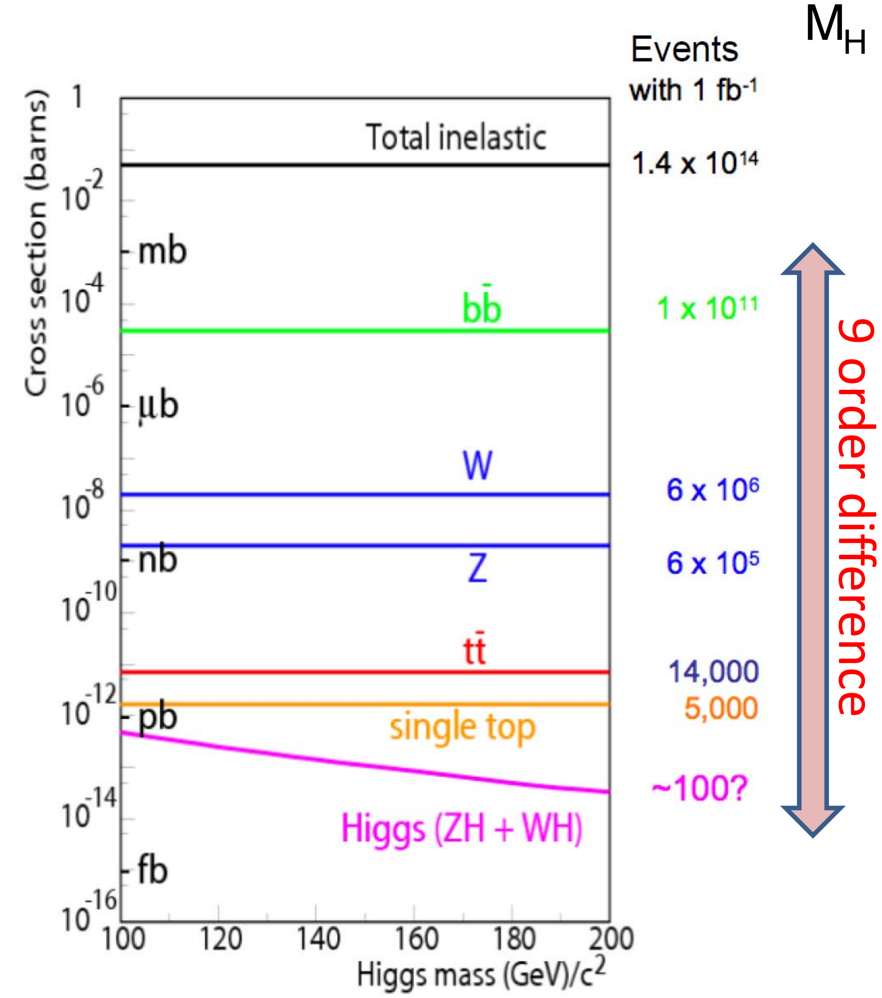




Cross Section at Tevatron

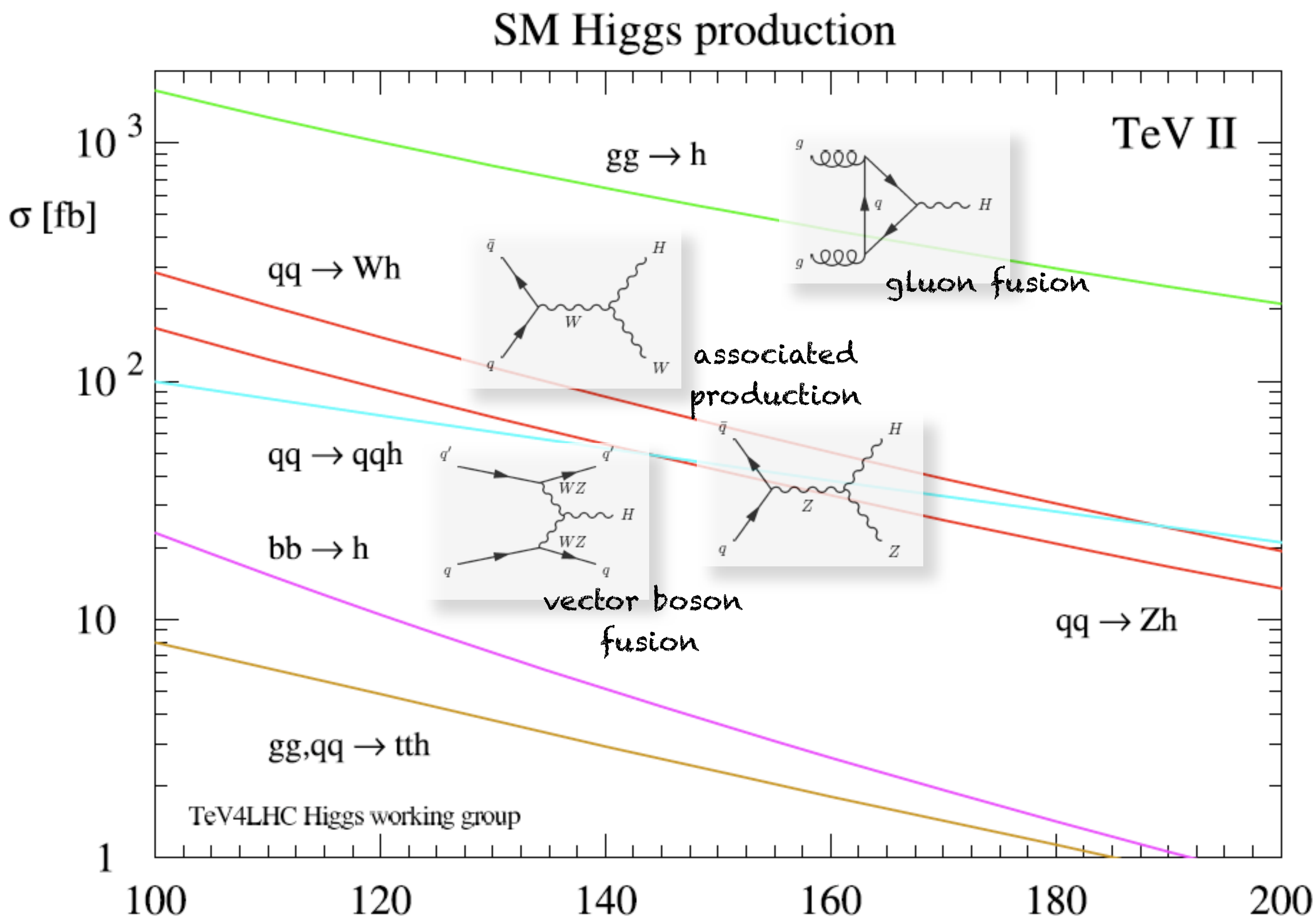


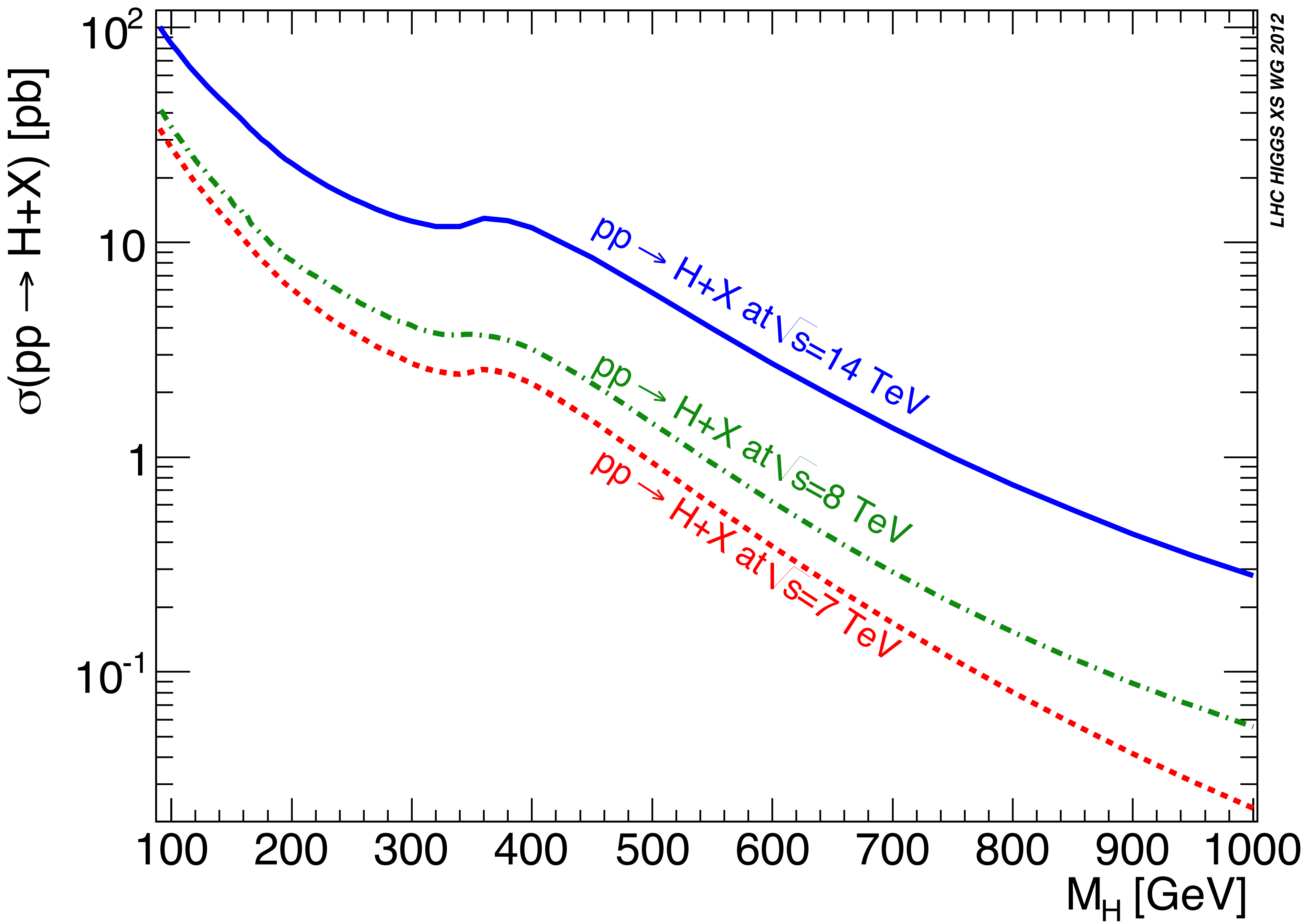




- almost x10 difference between Tevatron and LHC in some mass regions
- In addition signal efficiency and acceptance also different between experiments

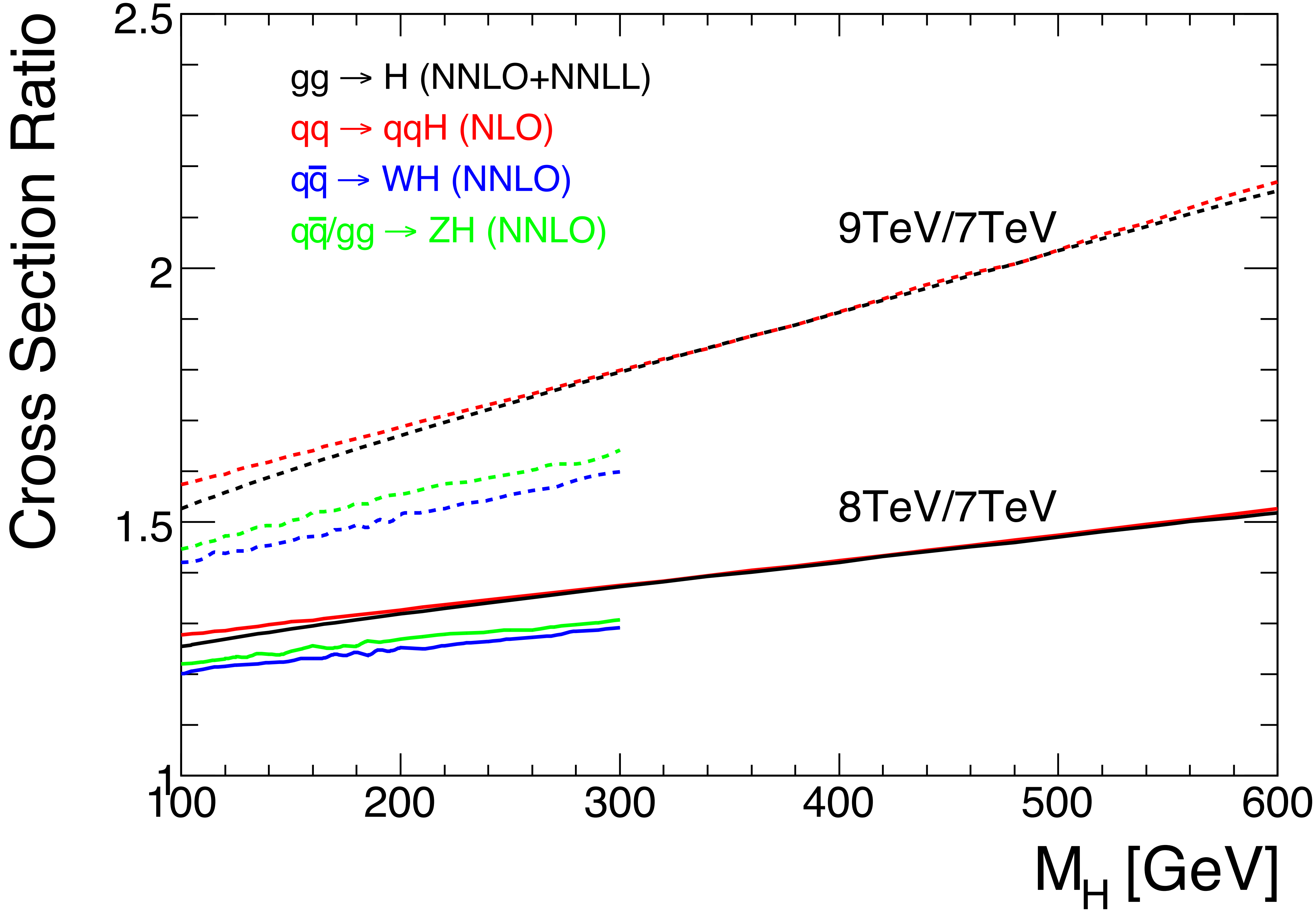
HIGGS PRODUCTION AT TEVATRON





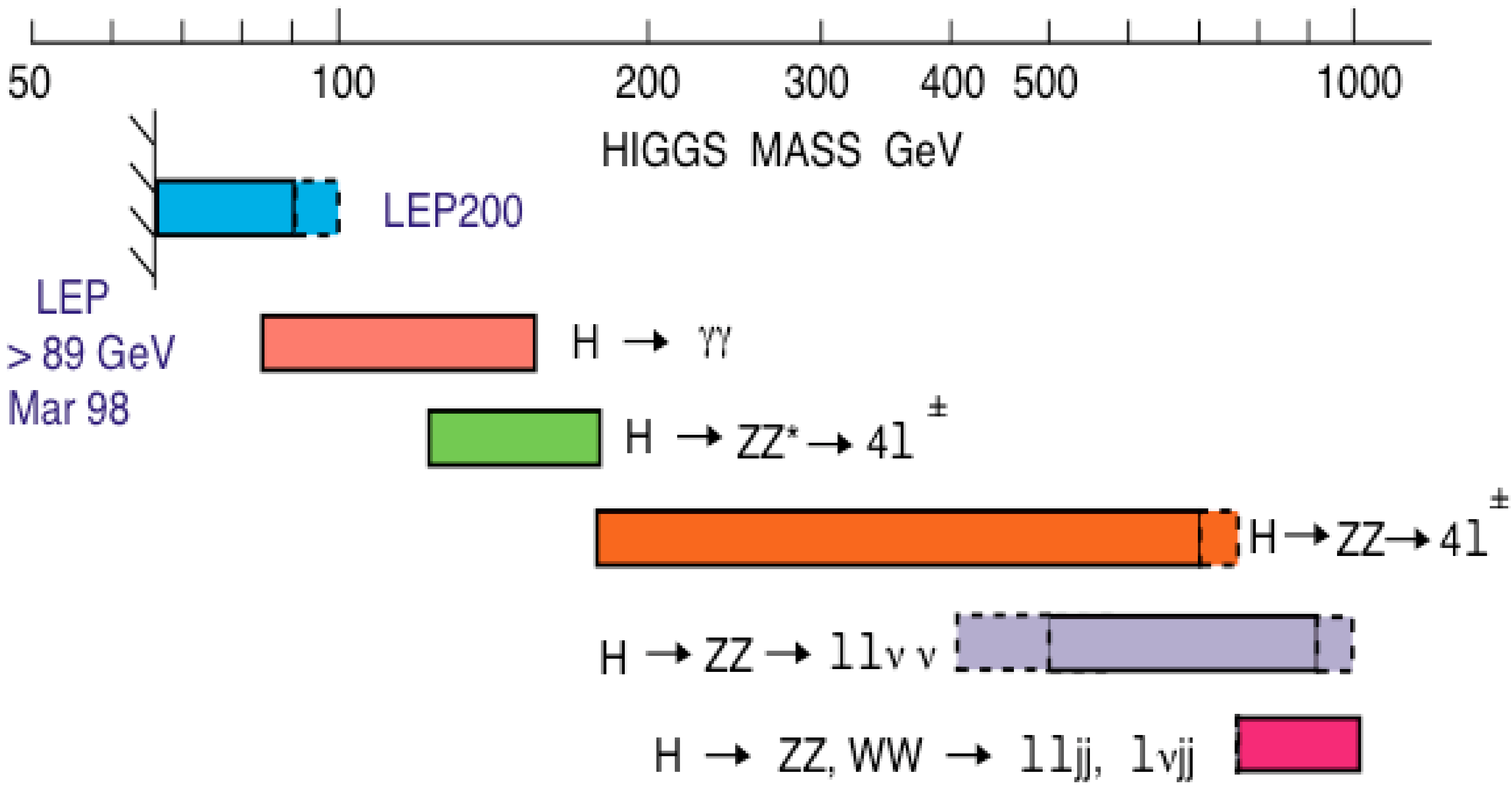
$\sigma(pp \to H+X)$ [pb]
10^2
10
1
10^{-1}
100
200
300
400
500
600
700
800
900
1000
M_H [GeV]
$pp \to H+X$ at $\sqrt{s}$=14 TeV
$pp \to H+X$ at $\sqrt{s}$=8 TeV
$pp \to H+X$ at $\sqrt{s}$=7 TeV
LHC HIGGS XS WG 2012

IMPACT OF HIGHER ENERGY



- 25% higher cross section at 8 TeV
  - 25% more data compared to running at 7 TeV
  - or 25% less running time to have same sensitivity

HIGGS DISCOVERY CHANNELS

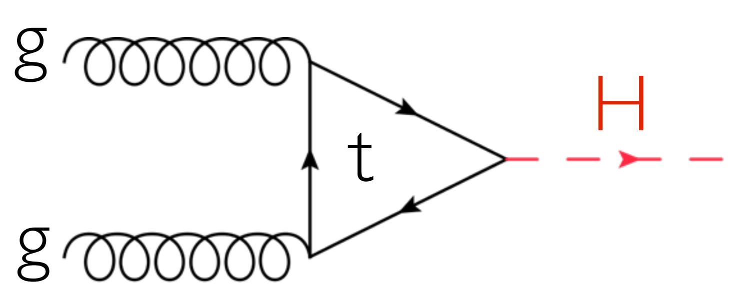


Inclusive or Exclusive?

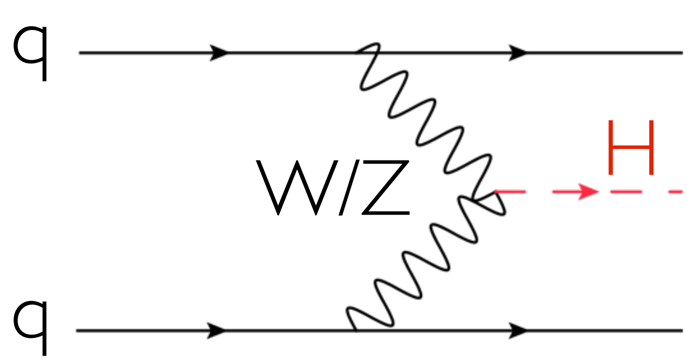
- Inclusive: no distinction between production mechanism
  - Look for a given decay mode (final state)
  - Advantages:
    - simpler analysis strategy focused mostly on identifying Higgs products
  - Disadvantage:
    - cannot benefit from features of production mechanism (e.g. vector boson fusion)
    - background of gluon-gluon could be much larger than in VBF (or vice versa)
    - different physics backgrounds can be specific to only one production mode
- Exclusive: separate each production mode
  - VBF is relatively easy, gluon-gluon not so much!
  - some efficiency loss looking for forward jets
  - Advantage:
    - Significantly improve S/B ratio in WW with VBF
  - Disadvantage:
    - VBF suppressed by almost x10 compared to gluon-gluon fusion

WHY IDENTIFY EACH PRODUCTION MODE?

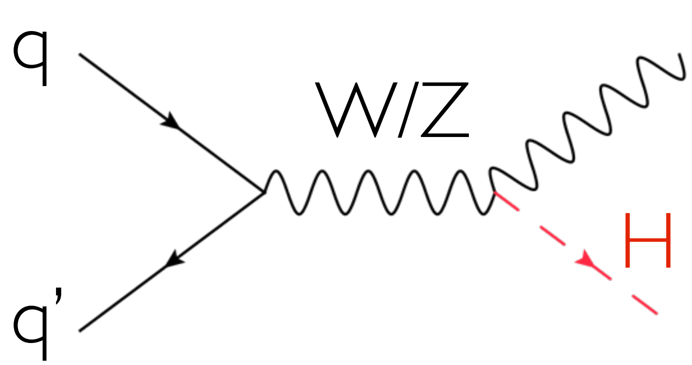
- Each production mode proportional to different Higgs coupling



Gluon-gluon Fusion
Cross section: 19.5 pb
Final state: Higgs alone



Vector Boson Fusion
Cross section: 1.56 pb
Final state: two forward jets



Associated Production
Cross section: 1.09 pb
Final state: W/Z boson

HIGGS COUPLING

- Generic Lagrangian for a light Higgs-like boson

$$\mathcal{L} = -V(h) + \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \dots$$

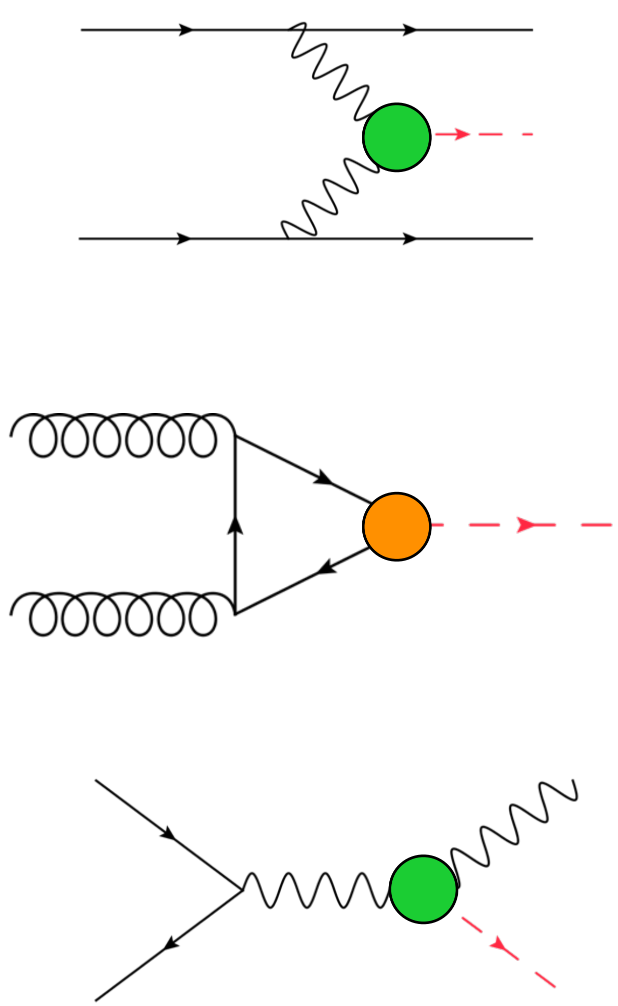
where $\mathcal{L}^{(n)}$ includes the terms with n derivatives and $V(h)$ is the potential for h

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\frac{h}{v} + c_{2u}\frac{h^2}{v^2} + \cdots\right) + h.c.$$
$$- \frac{v}{\sqrt{2}}\lambda^d_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(0, d^{(i)}_R\right)^T\left(1 + c_d\frac{h}{v} + c_{2d}\frac{h^2}{v^2} + \cdots\right) + h.c.$$
$$- \frac{v}{\sqrt{2}}\lambda^l_{ij}\left(\bar{\nu}^{(i)}_L, \bar{l}^{(i)}_L\right)\Sigma\left(0, l^{(i)}_R\right)^T\left(1 + c_l\frac{h}{v} + c_{2l}\frac{h^2}{v^2} + \cdots\right) + h.c.$$

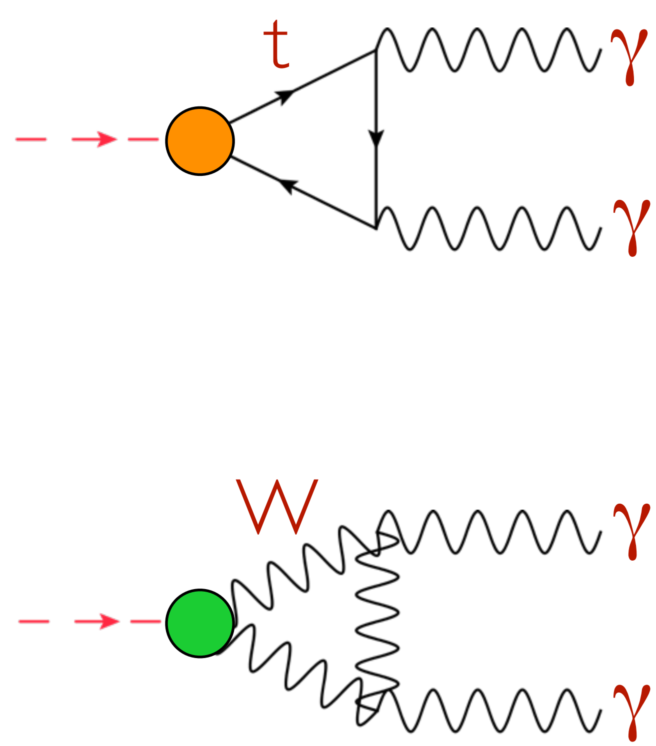
If a = c_x = 1 ➔ Lagrangian describes Standard Model Higgs

Measuring Higgs Couplings

Higgs Production



Higgs Decay



Number of Events

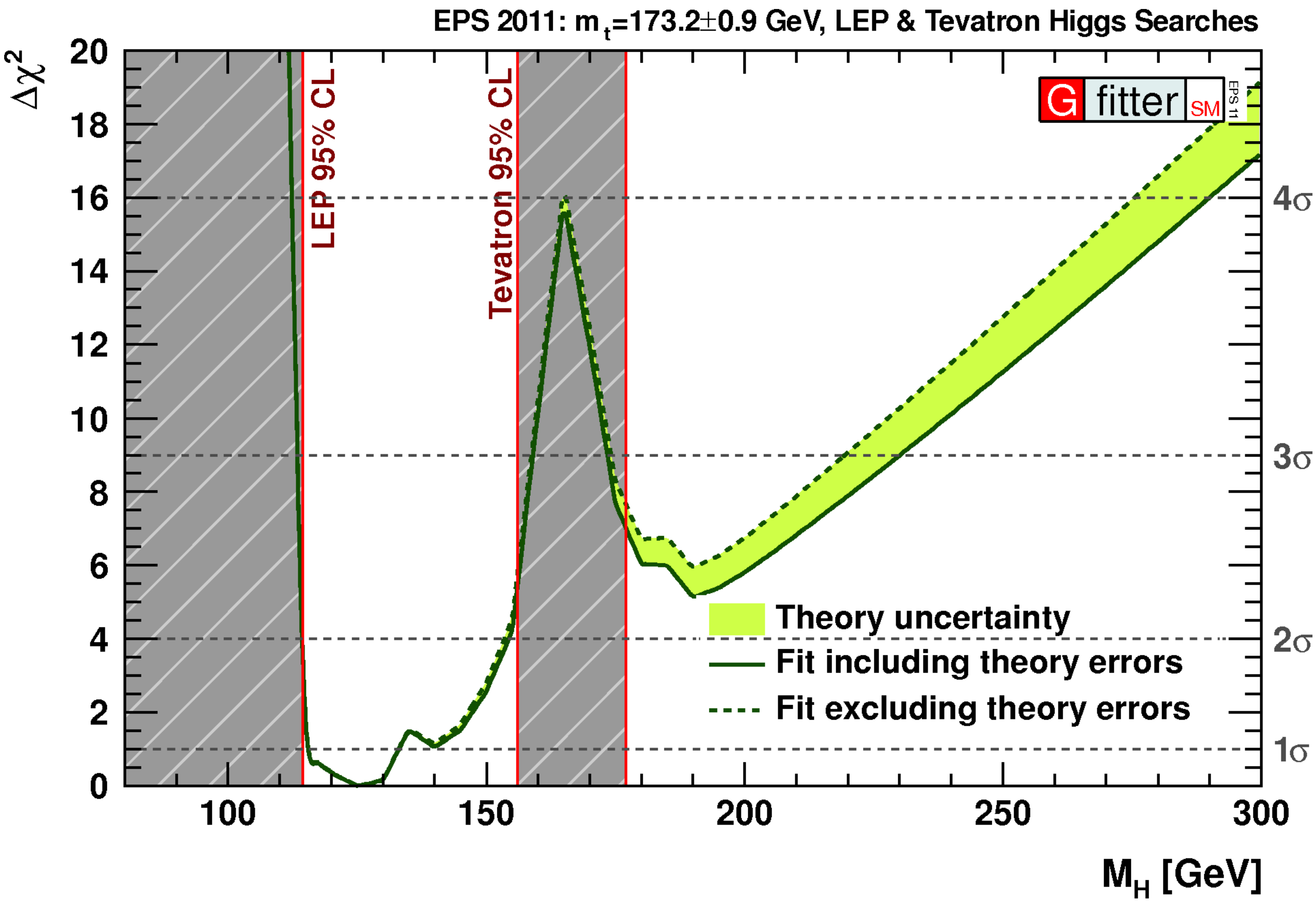
$$N \sim c_V^2 \frac{(4.5\, c_V^2 - c_F^2)}{c_F^2}$$

$$N \sim c_F^2 \frac{(4.5\, c_V^2 - c_F^2)}{c_F^2}$$

: coupling Higgs - bosons (c_V)

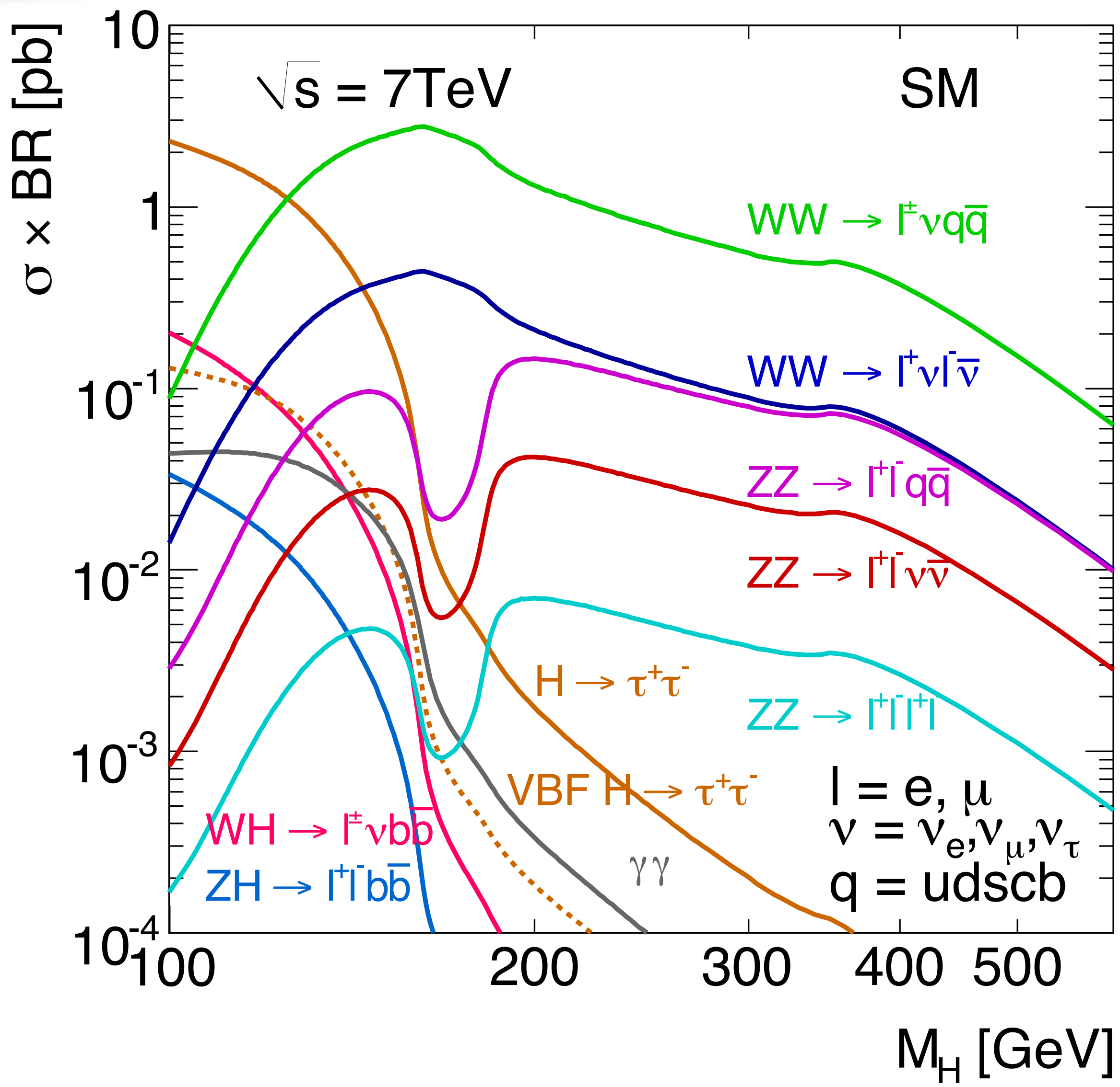
: coupling Higgs - fermions (c_F)

HIGGS SEARCHES BEFORE LHC @ SUMMER 2011



http://arxiv.org/abs/1107.0975

Higgs Search Strategy At LHC

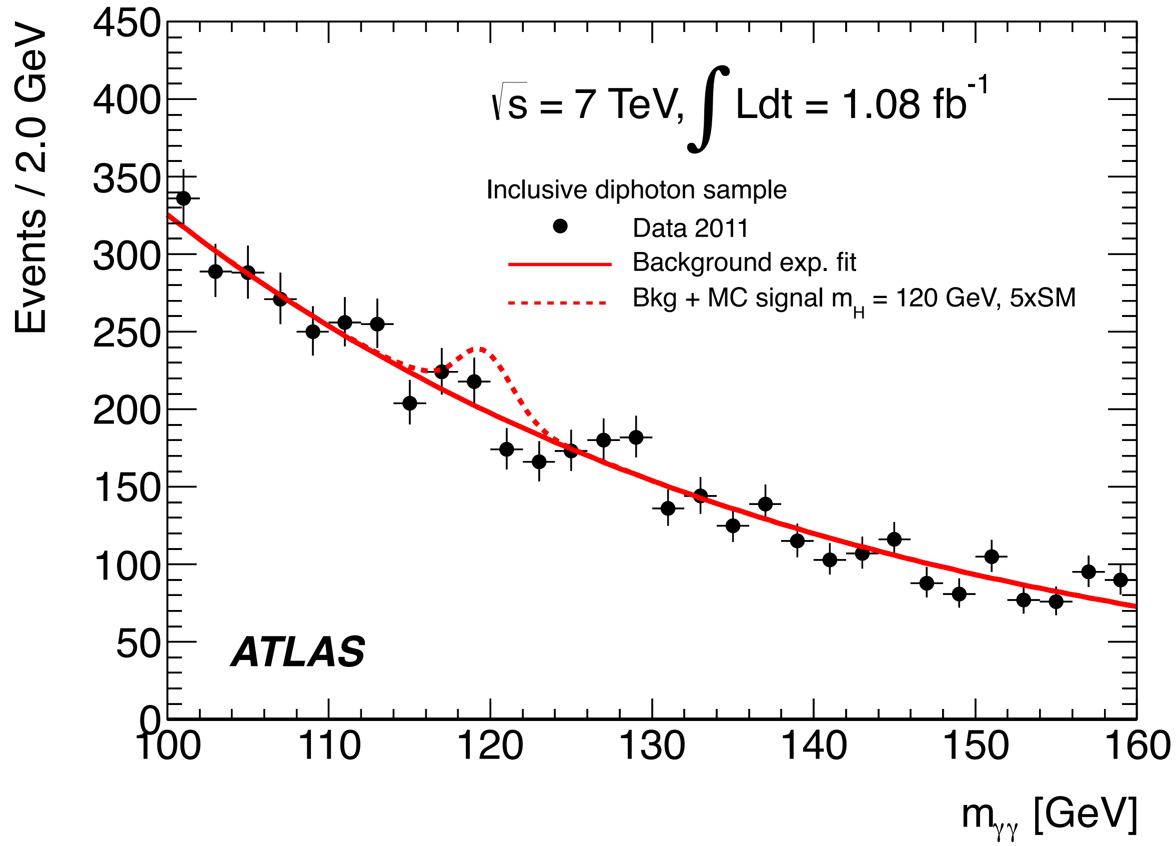


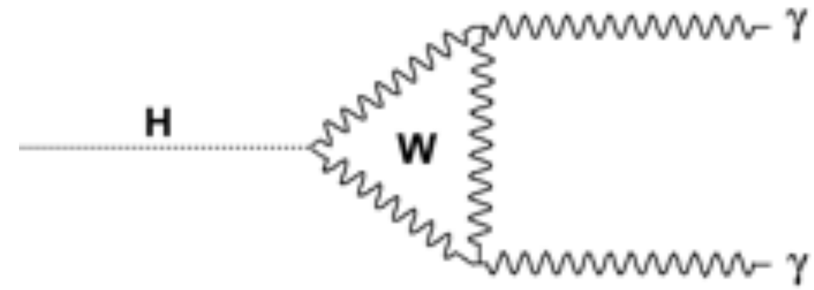
Events produced in 1 fb^{-1}

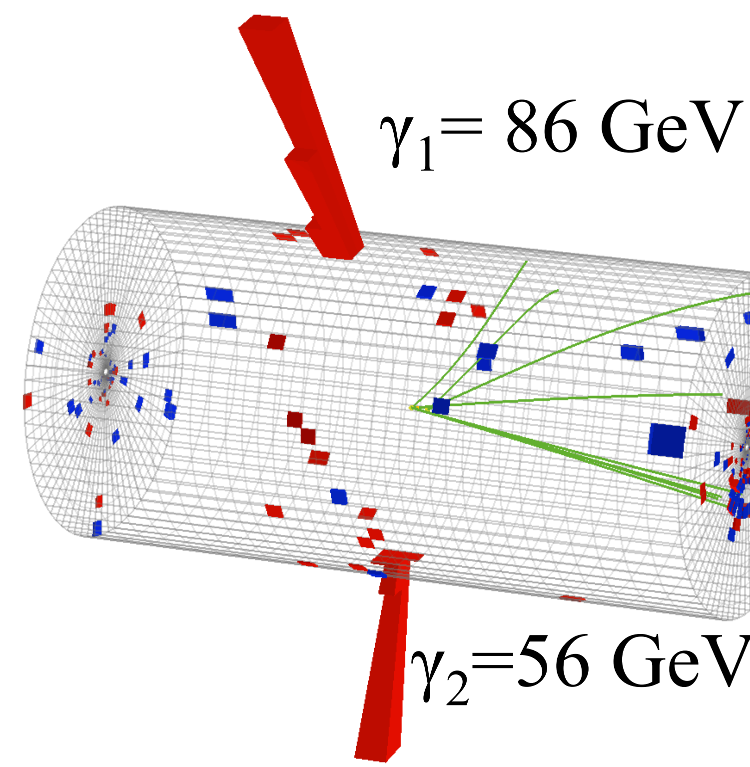
m_H, GeV	WW→2l2ν	ZZ→4l	γγ
120	127	1,5	43
150	390	4,6	16
300	89	3,8	0,04

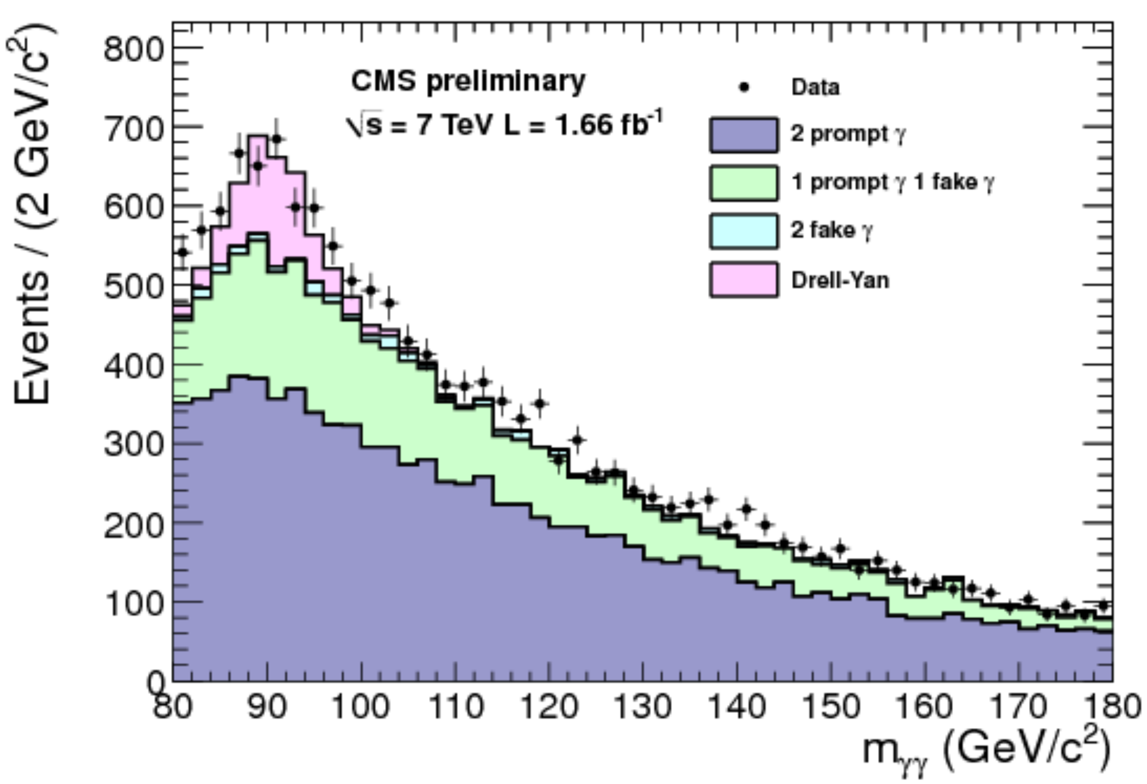
- H→WW→2l2ν sensitive in a wide region up to low m_H (no mass reconstruction)
- Also H→ZZ→4l sensitive in a wide range (mass reco but small BR)
- At low m_H (<150) also:
  - H→γγ, H→ττ, VH→bb
- At high m_H include also W/Z decays in qq and invisible Z decay

H→γγ Early 2011



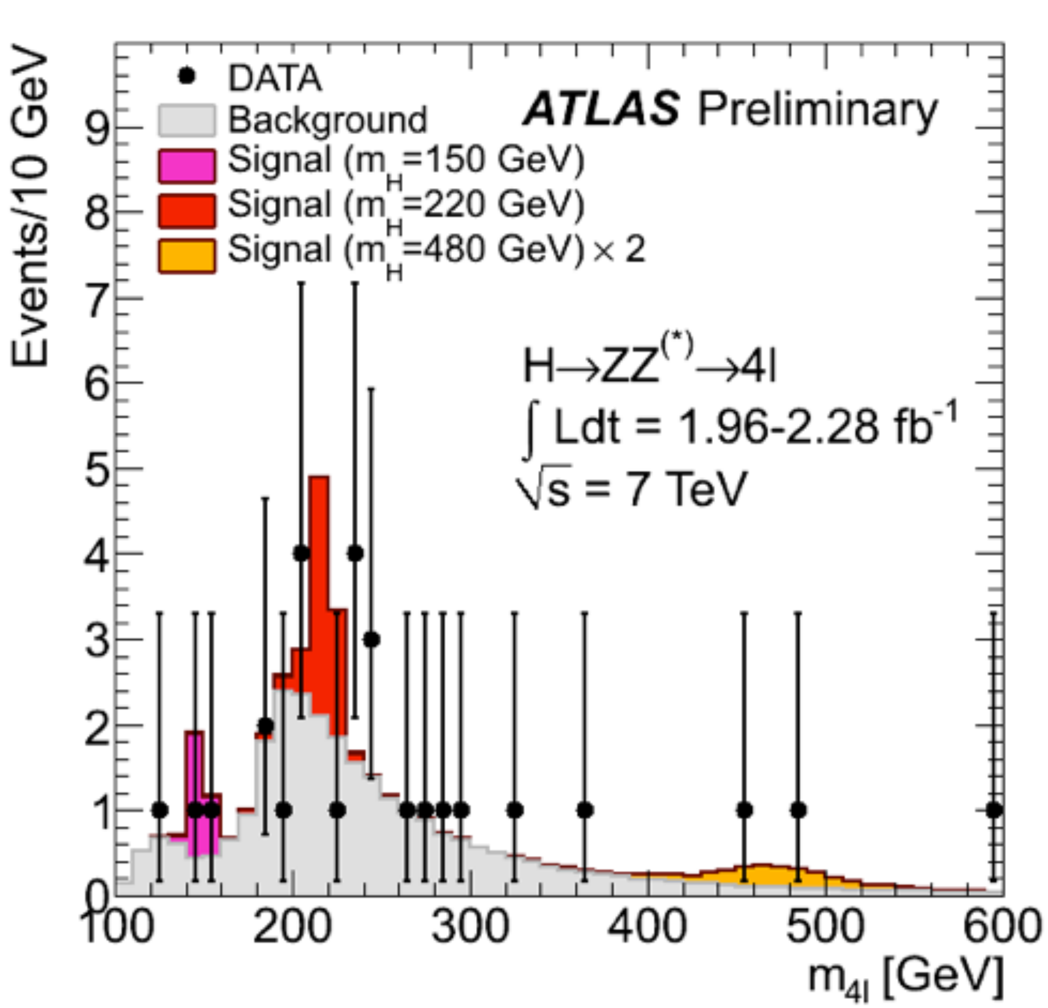


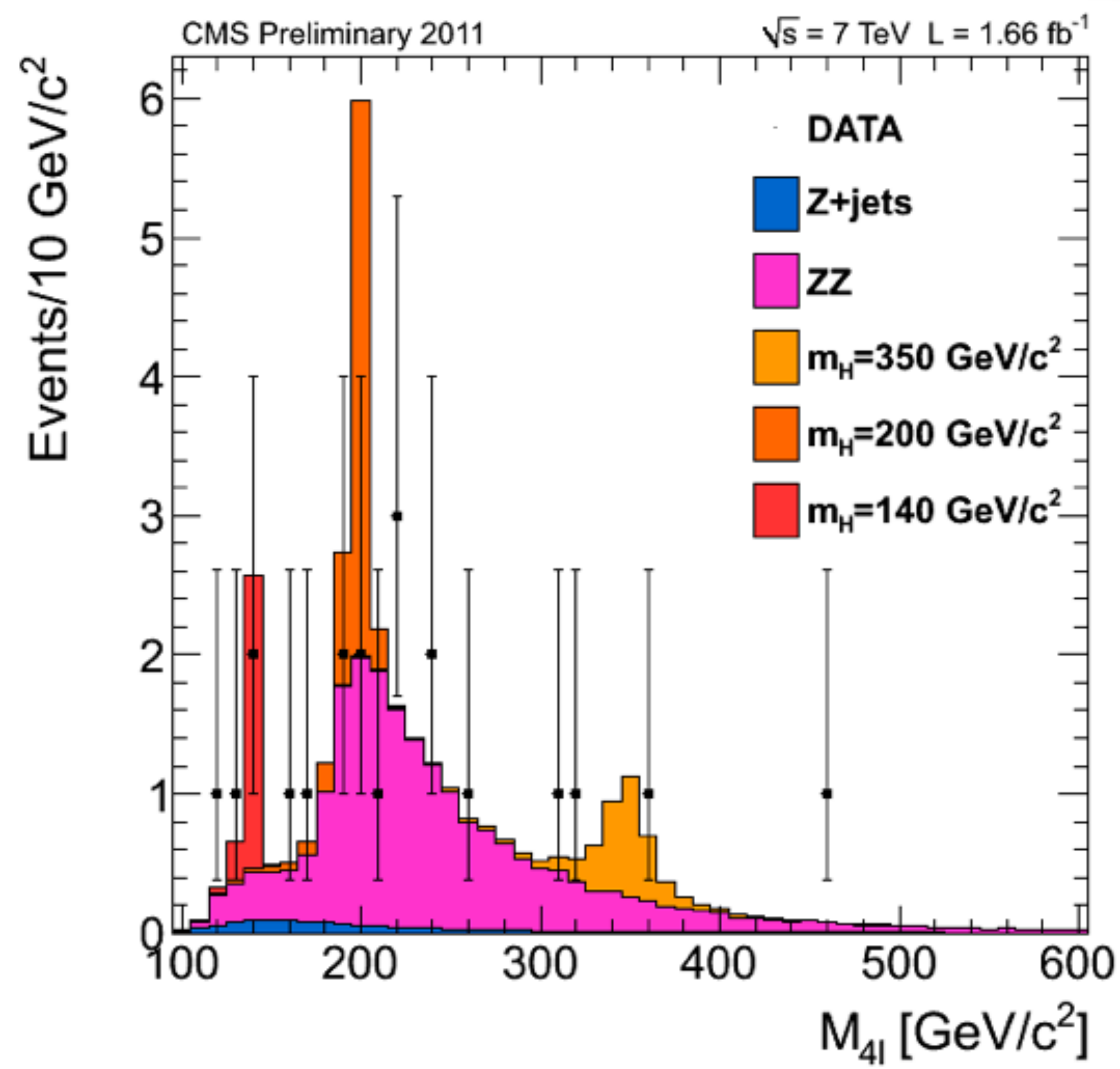




- No sign of Standard Model Higgs yet

H → ZZ → 4l Early 2011

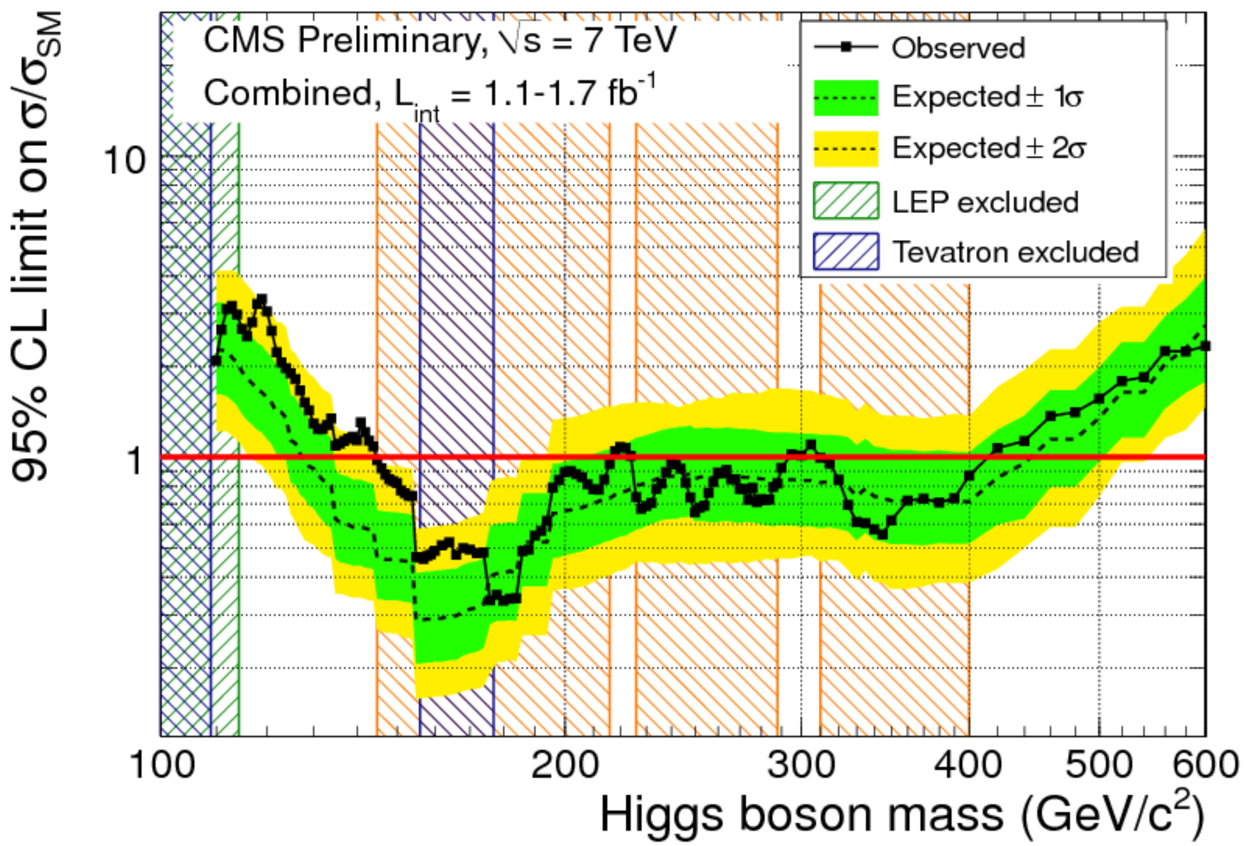


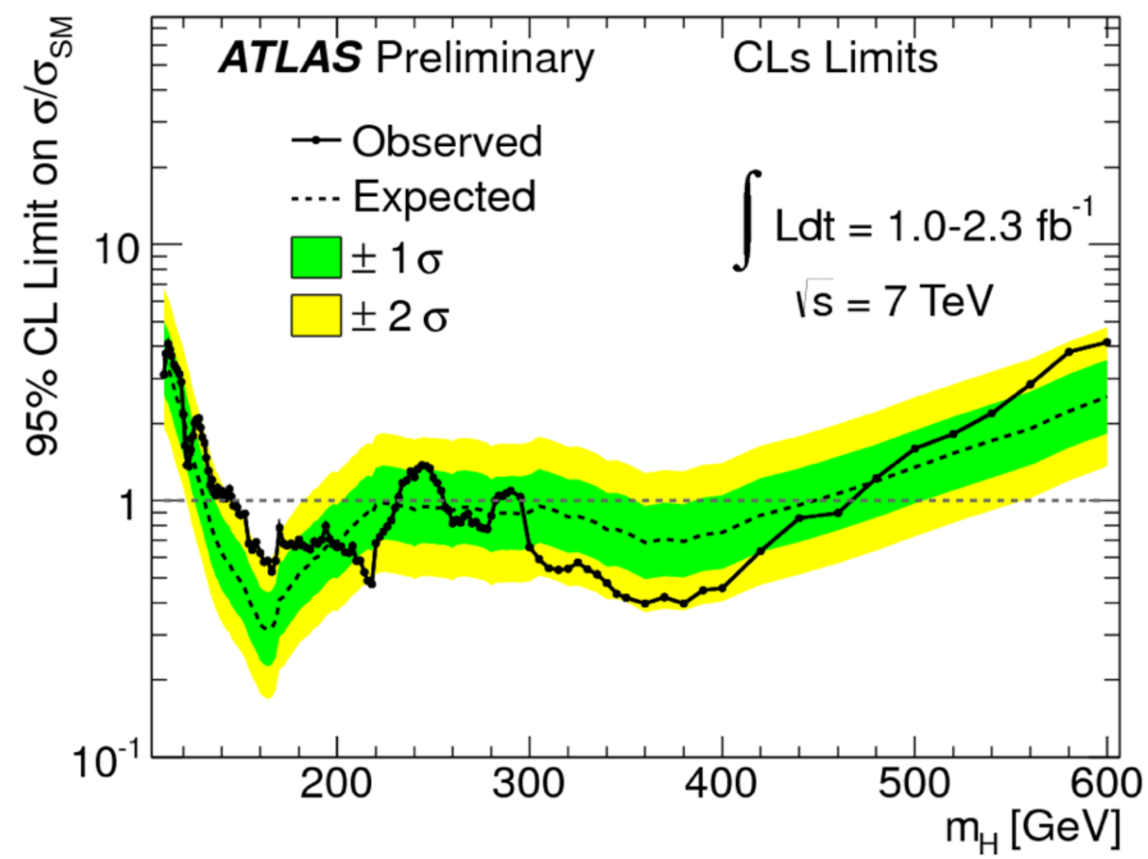


- Total of 27 events are selected in data: 6 (4e), 9 (2e2μ), 12 (4μ)
- Expected: 28±4

	baseline		
	$4e$	4μ	$2e2\mu$
ZZ	4.05 ± 0.26	6.02 ± 0.40	9.87 ± 0.66
Z+jet	0.48 ± 0.08	0.09 ± 0.02	0.61 ± 0.11
$Zb\bar{b}/c\bar{c}, t\bar{t}$	0.01 ± 0.01	0.05 ± 0.01	0.06 ± 0.01
WZ	0.009 ± 0.009	0.009 ± 0.009	0.04 ± 0.02
All background	4.54 ± 0.27	6.12 ± 0.40	10.52 ± 0.67
$m_H = 140\,\mathrm{GeV}/c^2$	0.45	0.82	1.19
$m_H = 200\,\mathrm{GeV}/c^2$	1.20	1.71	2.80
$m_H = 350\,\mathrm{GeV}/c^2$	0.70	0.93	1.63
Observed	5	10	6

HIGGS SEARCHES, SUMMER 2011





- 1/fb of data collected at LHC in 2011 at 7 TeV excluded very large mass regions

Higgs @ December 2011