Finding the Higgs

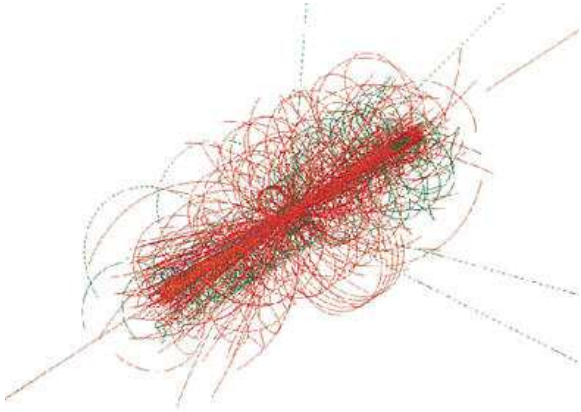
Robert Harlander

Institute for Theoretical Particle Physics

University of Karlsruhe

YETI'05, January 5–8, 2005

Guidelines



What are we looking for?

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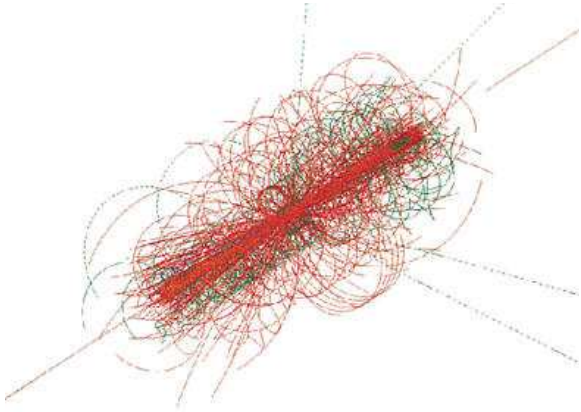

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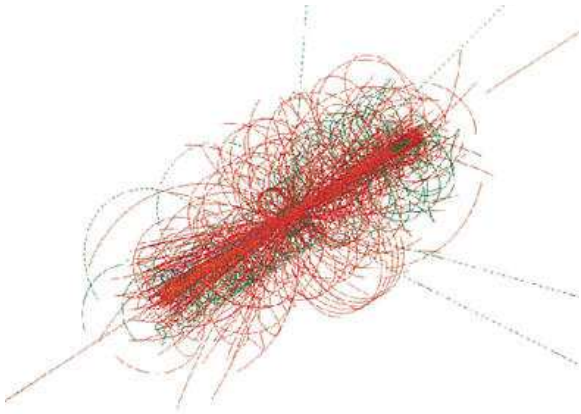

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  - spin = 0
  - electric charge = 0
  - mass = ?
  - couples to mass!

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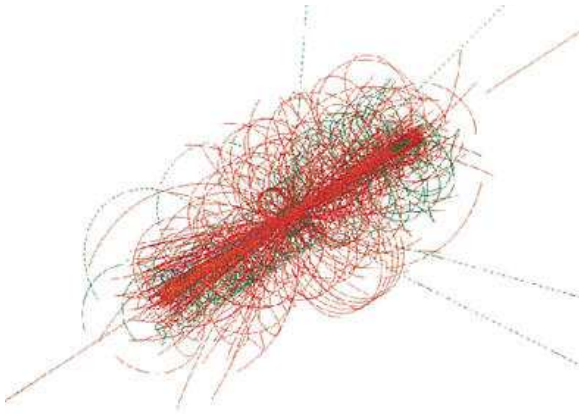

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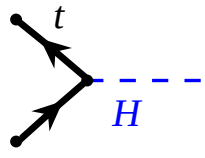
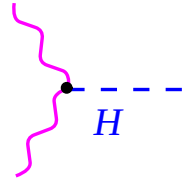


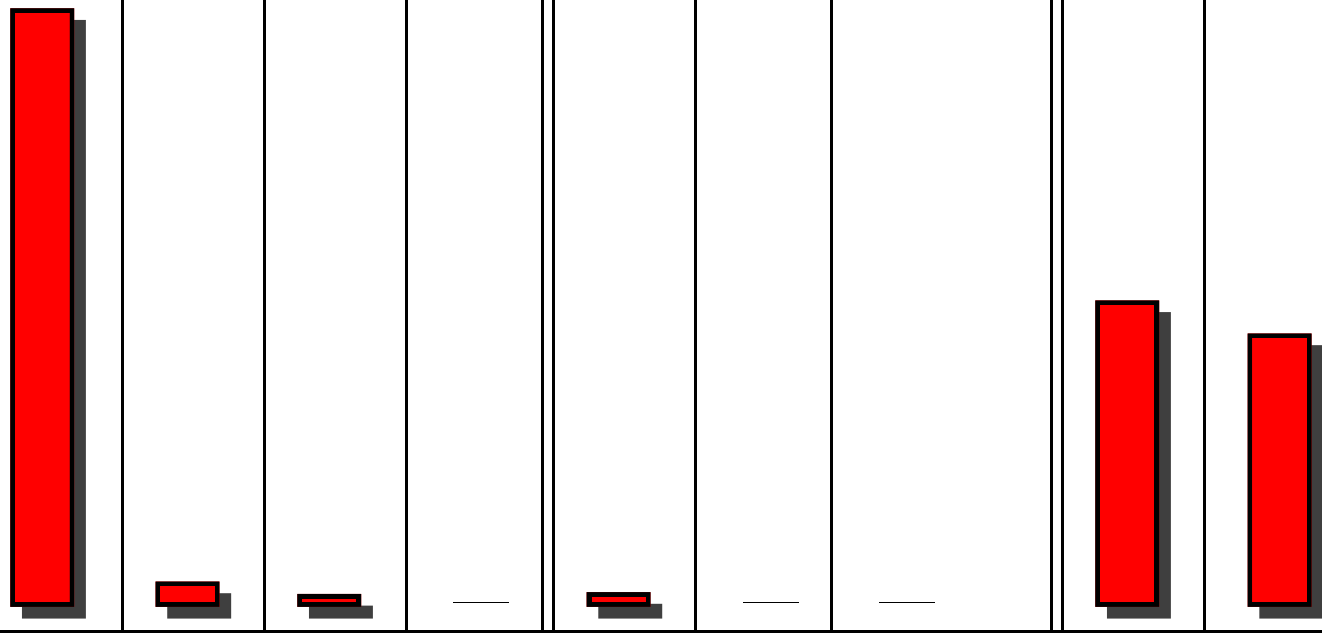
$$= \frac{m_t}{v}\,,$$



$$= 2\frac{M_V^2}{v}$$

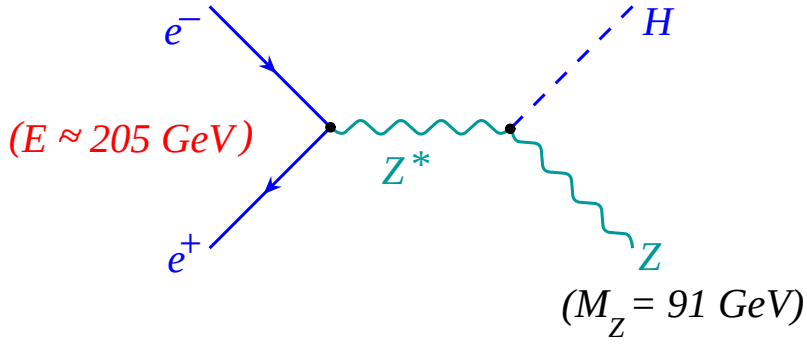
Particle masses

t	b	c	s	τ	μ	e	Z	$W^{\pm}$	H
178	5	1.3	0.1	1.8	0.1	0.0005	91	80	



Higgs search at LEP

- direct:



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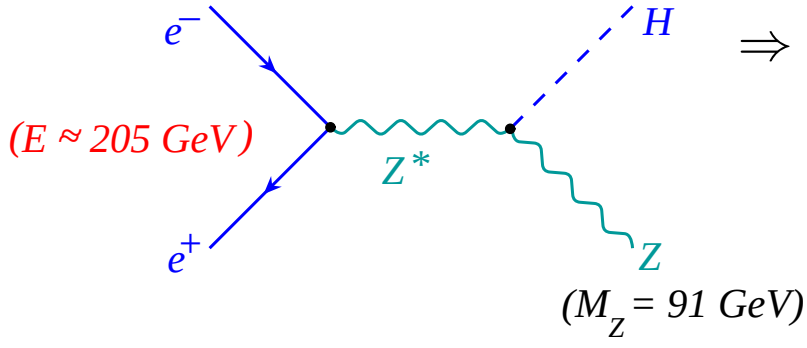

$\Rightarrow$ $M_H \gtrsim 114.4\,\text{GeV}$

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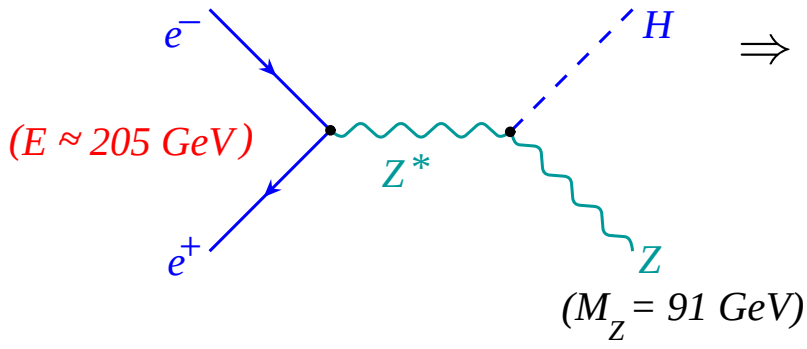

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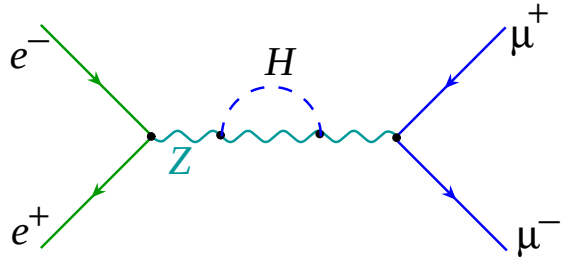

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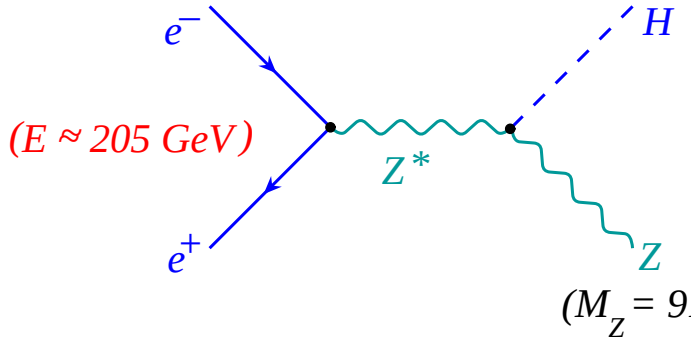

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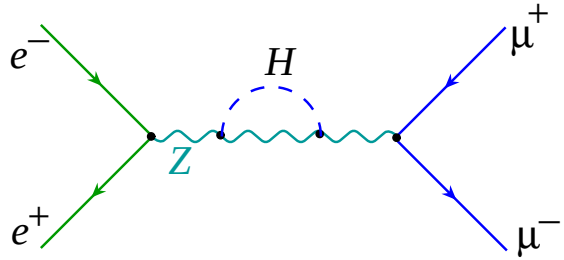

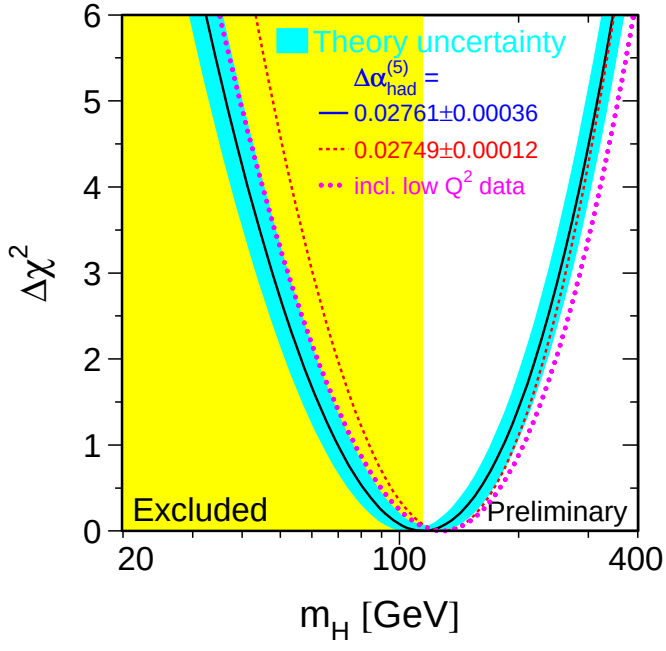

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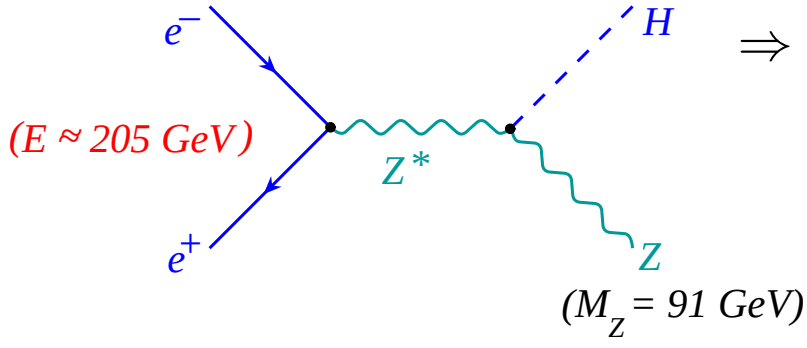

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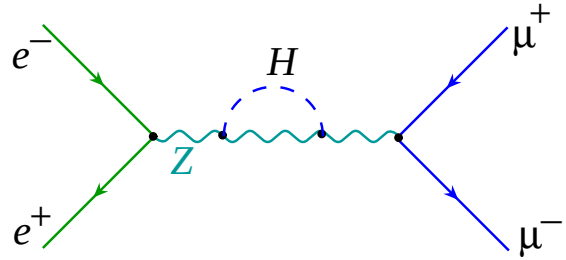
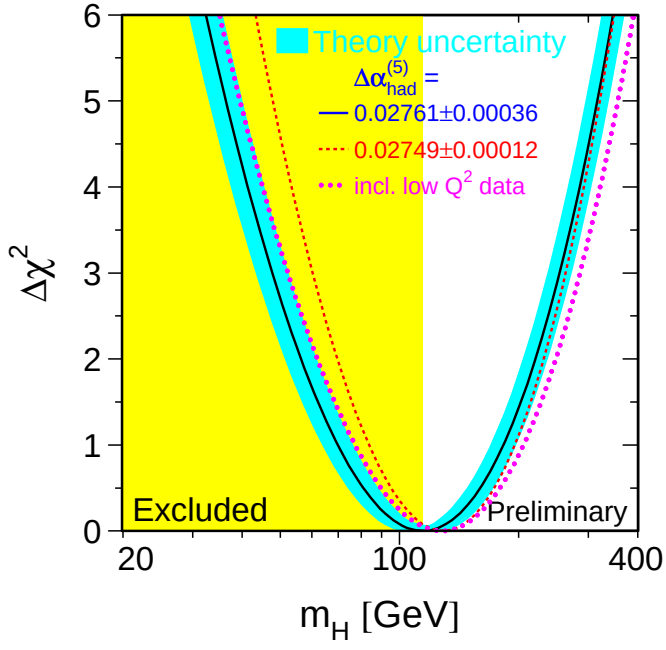


$\Rightarrow \quad M_H = 114^{+69}_{-45}\,\text{GeV}$

$M_H < 260\,\text{GeV}$



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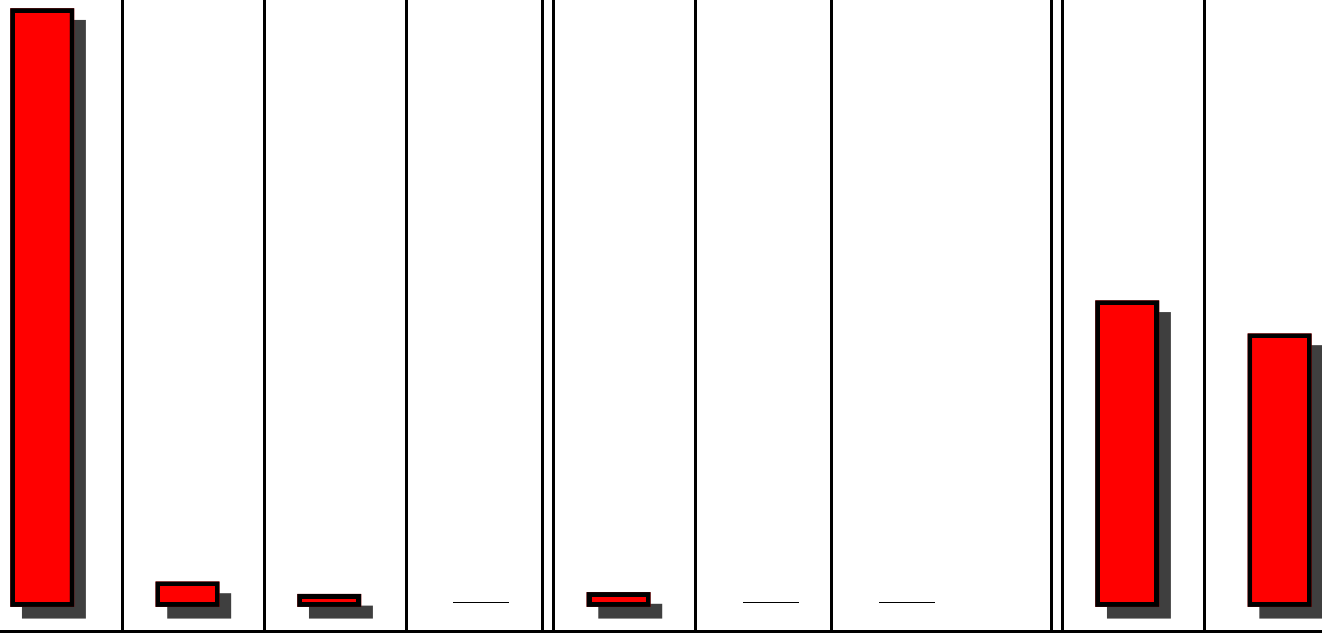

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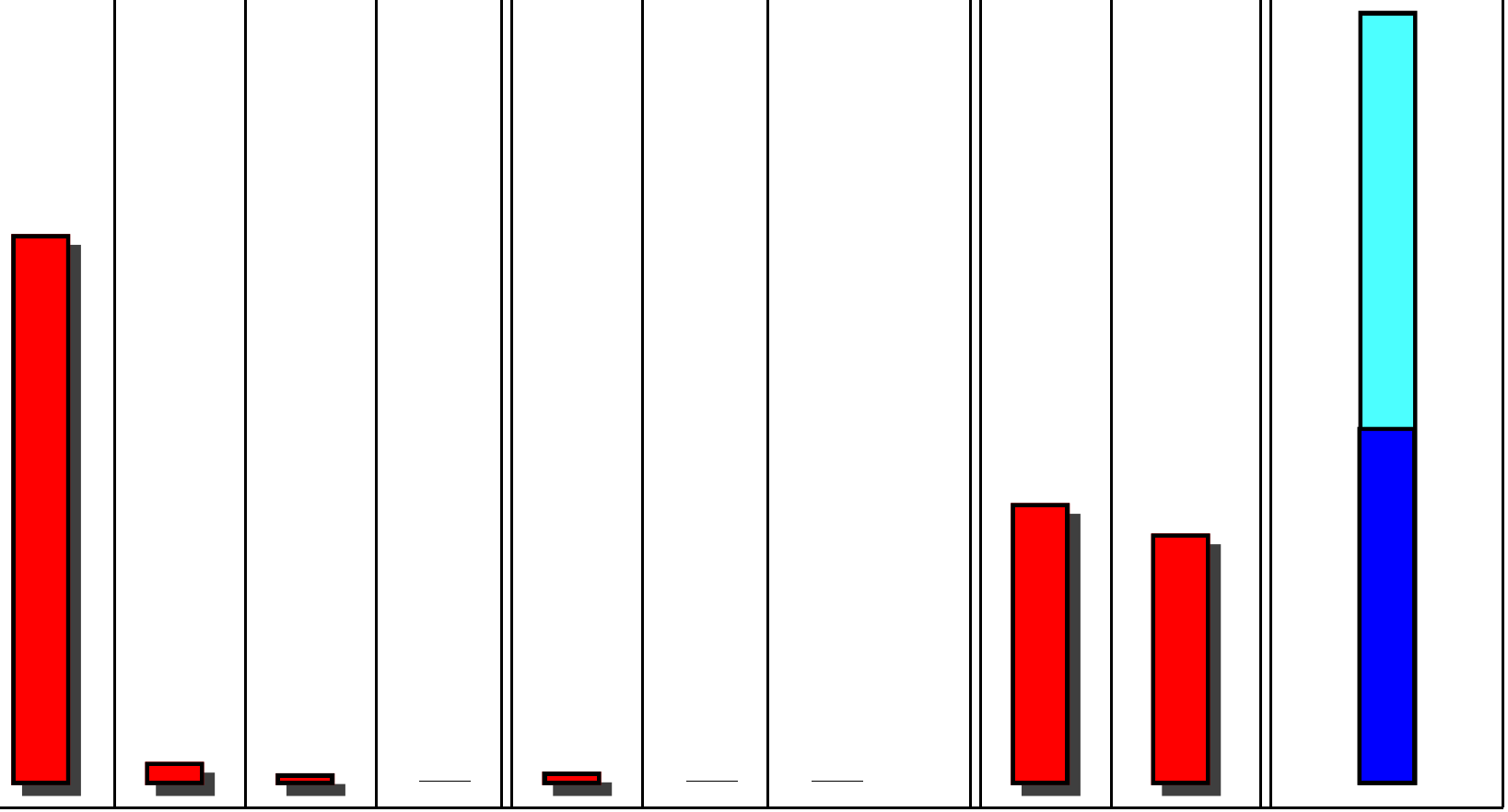
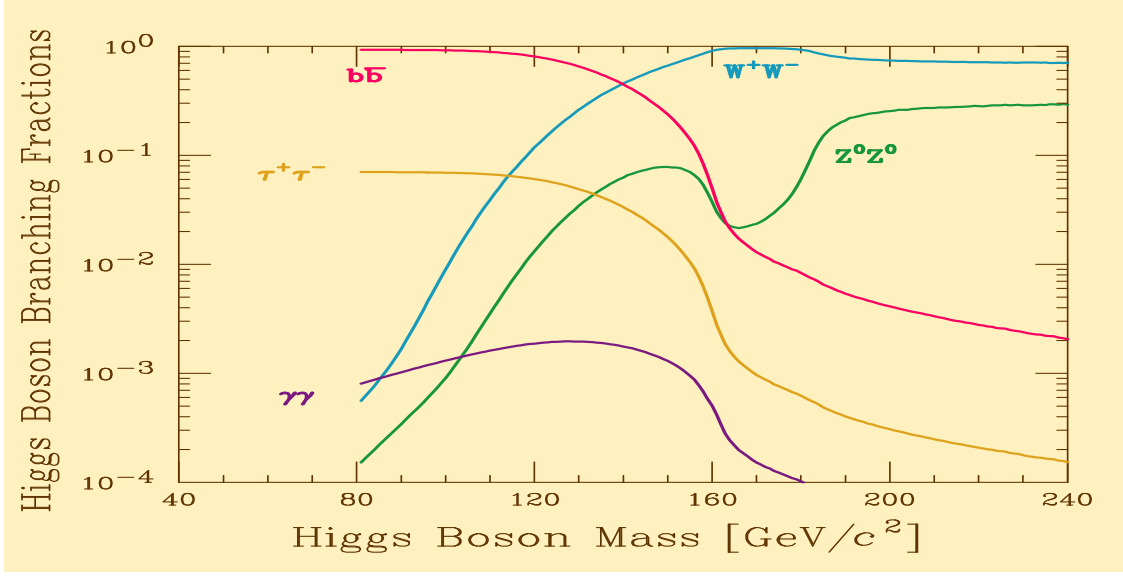
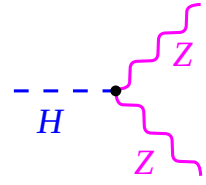
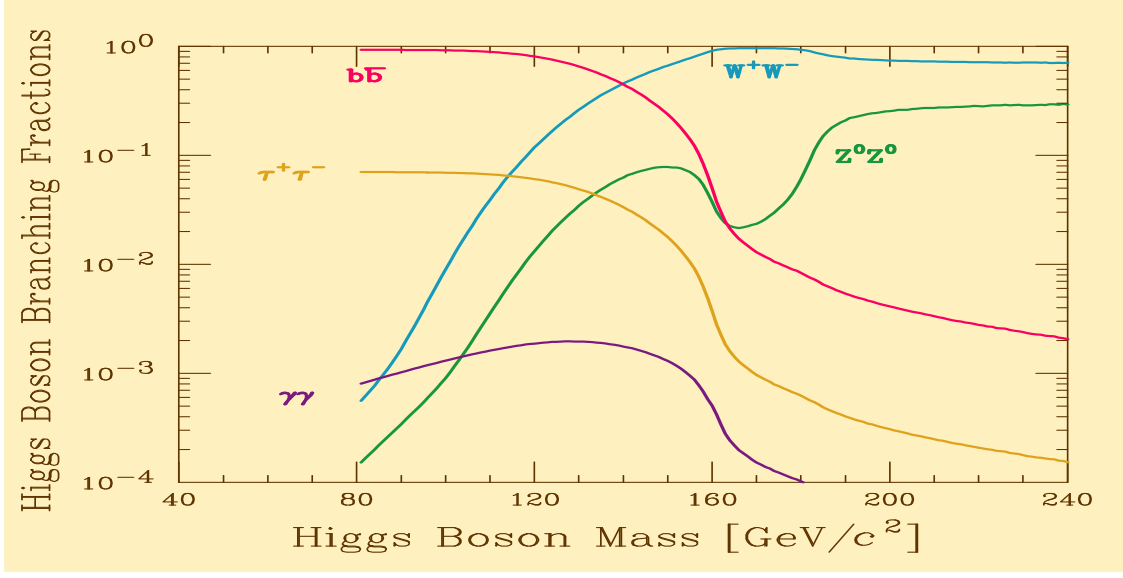


Higgs Decay


Higgs Boson Branching Fractions
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
W^+W^-
Z^0Z^0
$\tau^+\tau^-$
$\gamma\gamma$
40
80
120
160
200
240
Higgs Boson Mass [GeV/c^2]


Z
H
Z

Higgs Decay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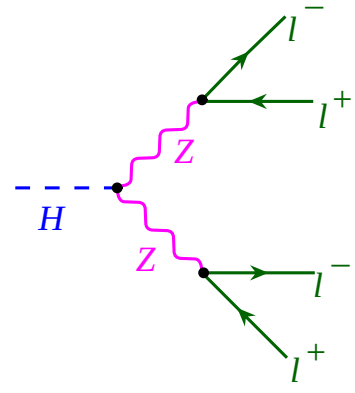
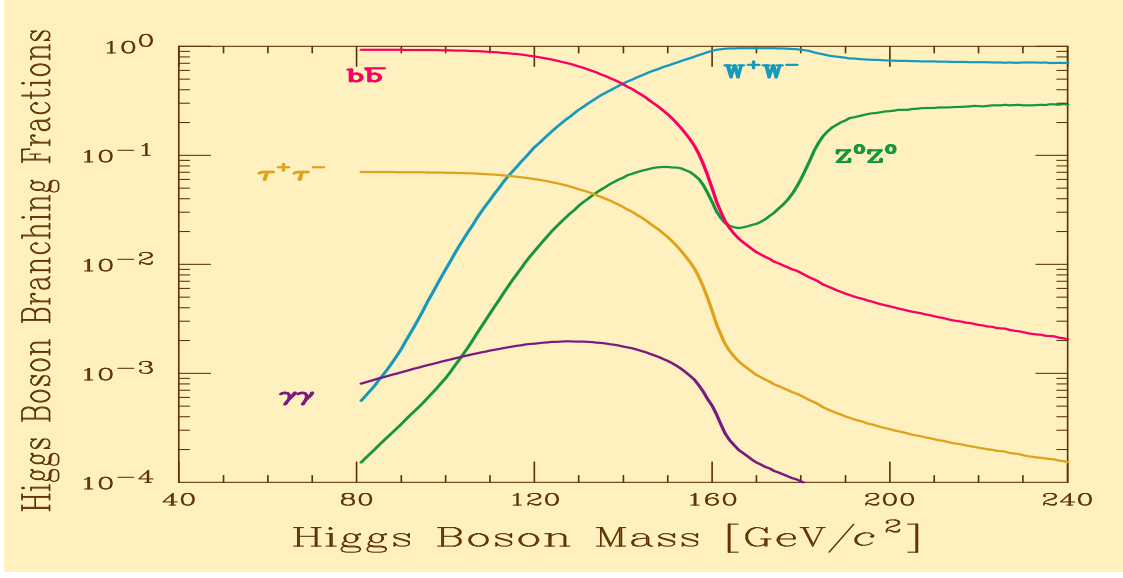

l^-
l^+
Z
H
Z
l^-
l^+

Higgs Decay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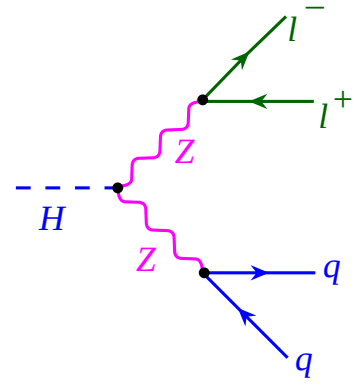
l^-
l^+
Z
H
Z
q
q

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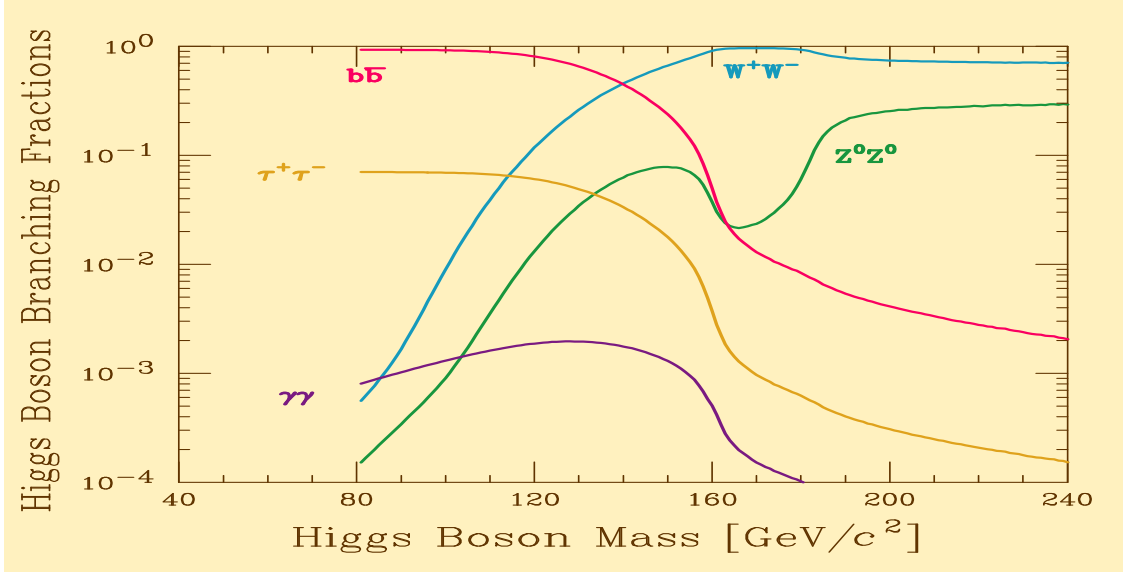
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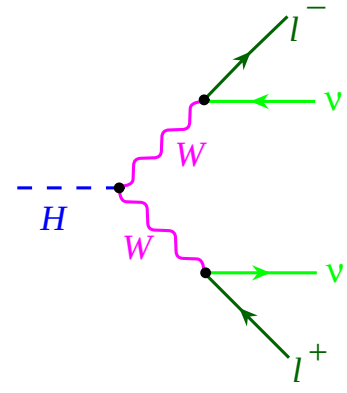
l^-
ν
W
H
W
ν
l^+

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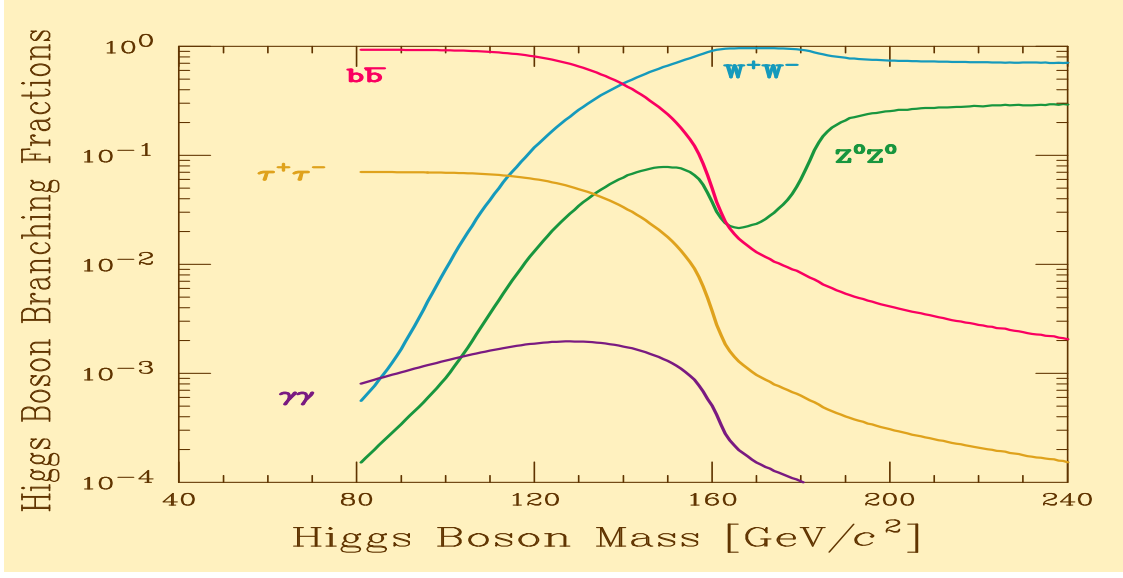
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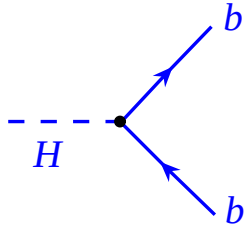
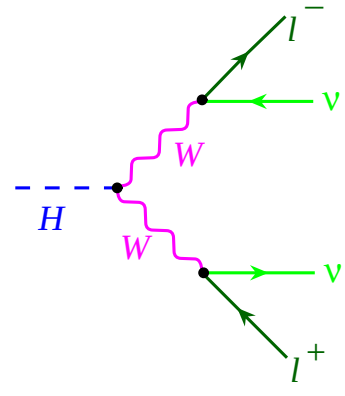

b
H
b


l^-
ν
W
H
W
ν
l^+

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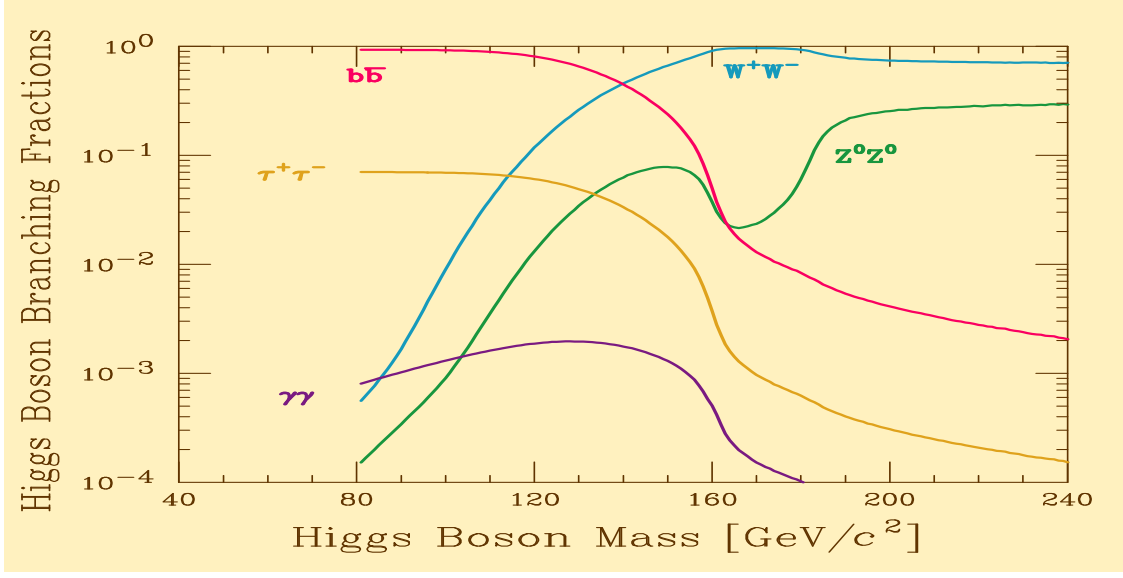
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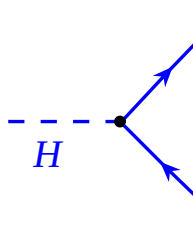
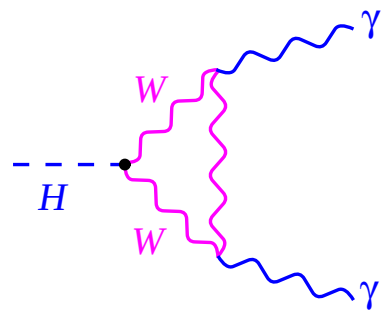
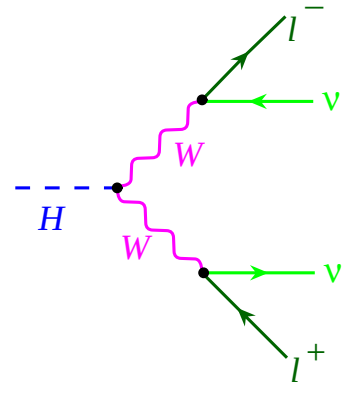
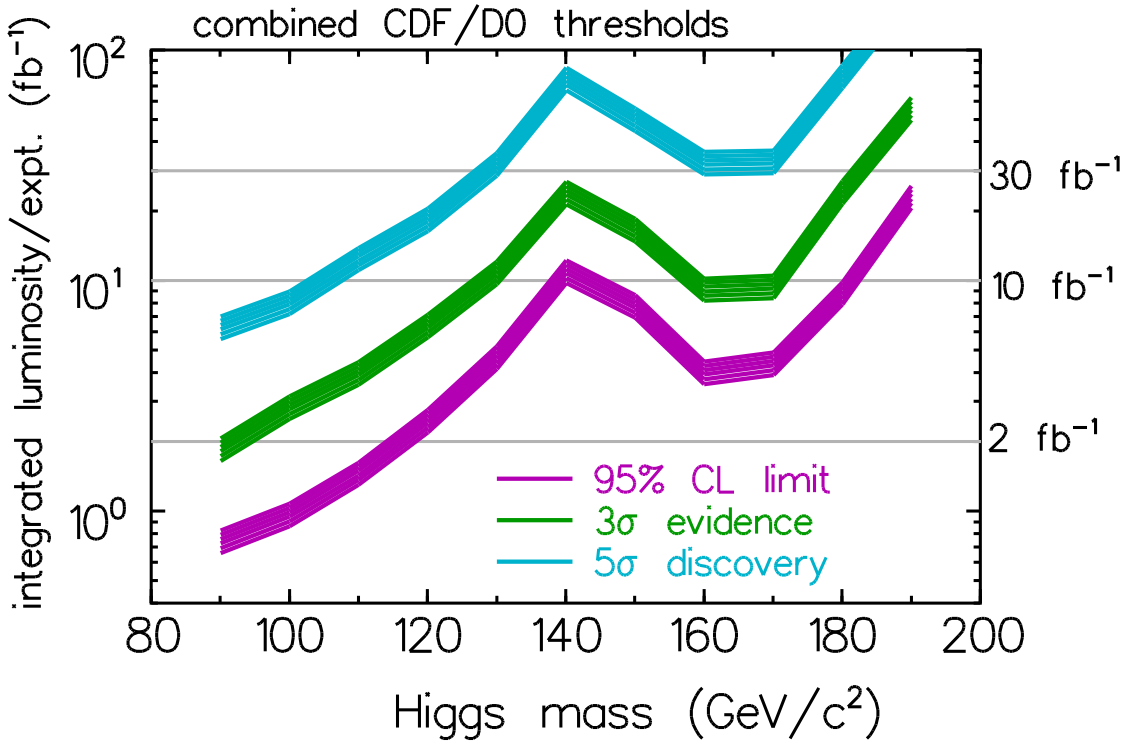

H
b
b


H
W
W
γ
γ

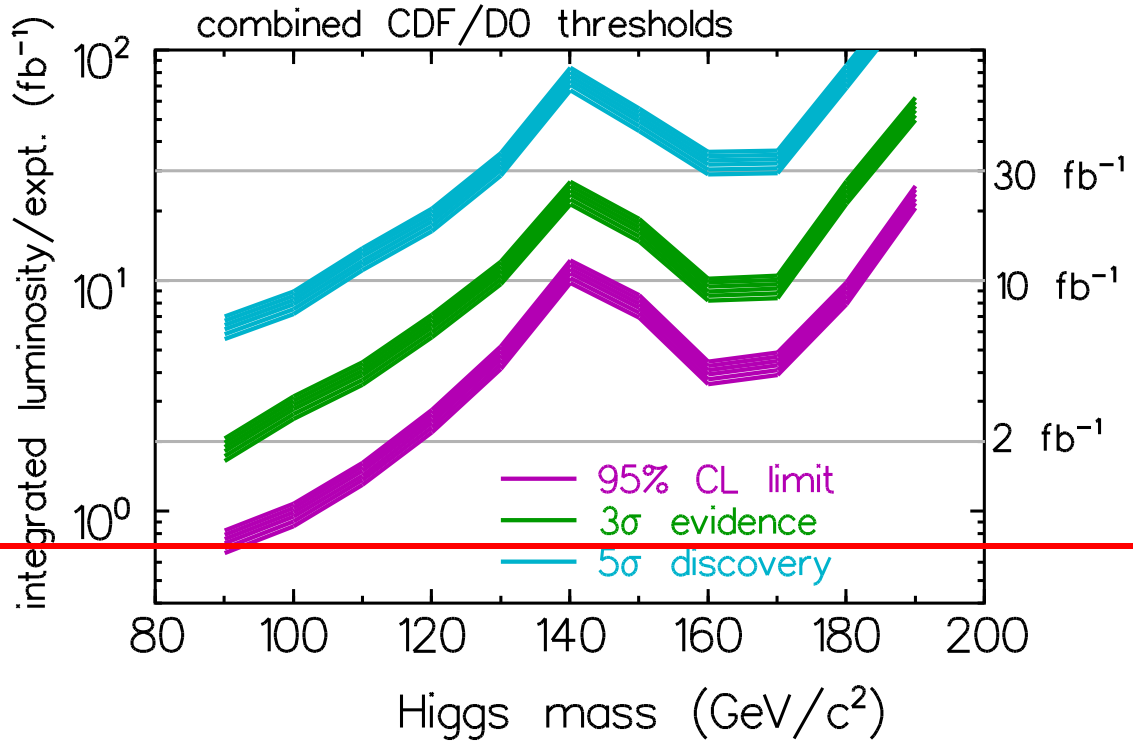

H
W
W
l^-
ν
ν
l^+

Tevatron Discovery Potential



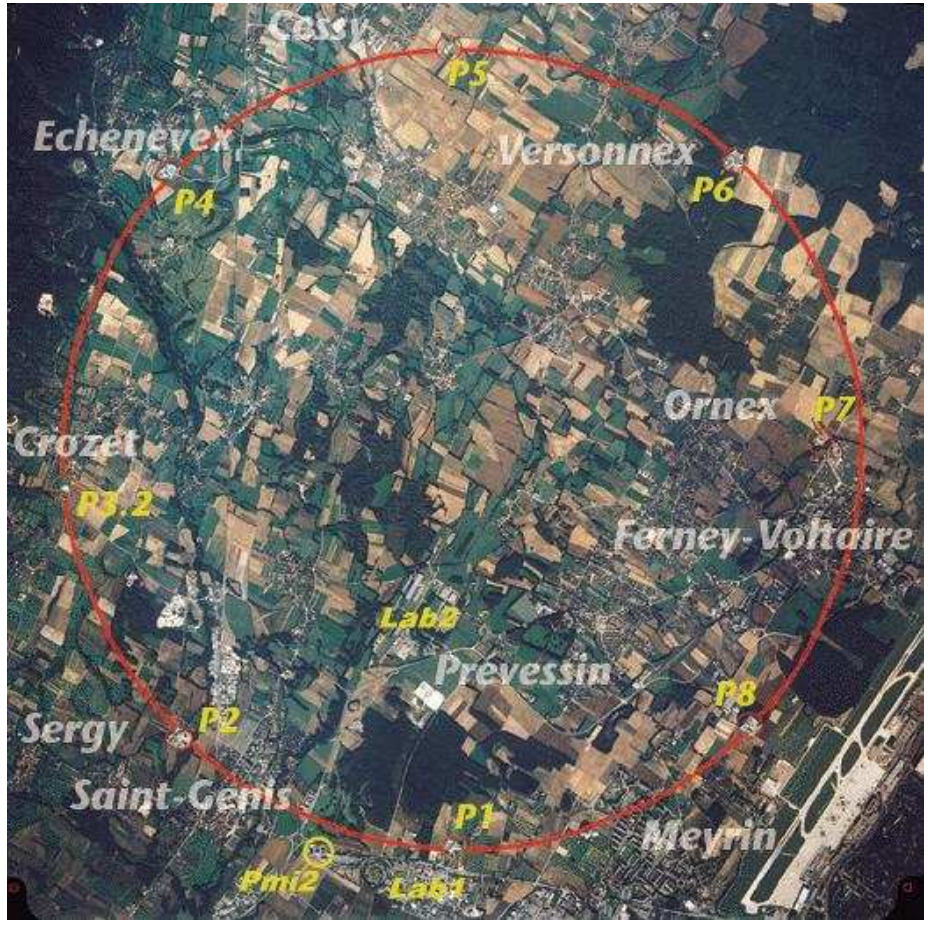
Tevatron Discovery Potential

currently:



Higgs search at the LHC

proton – proton collider



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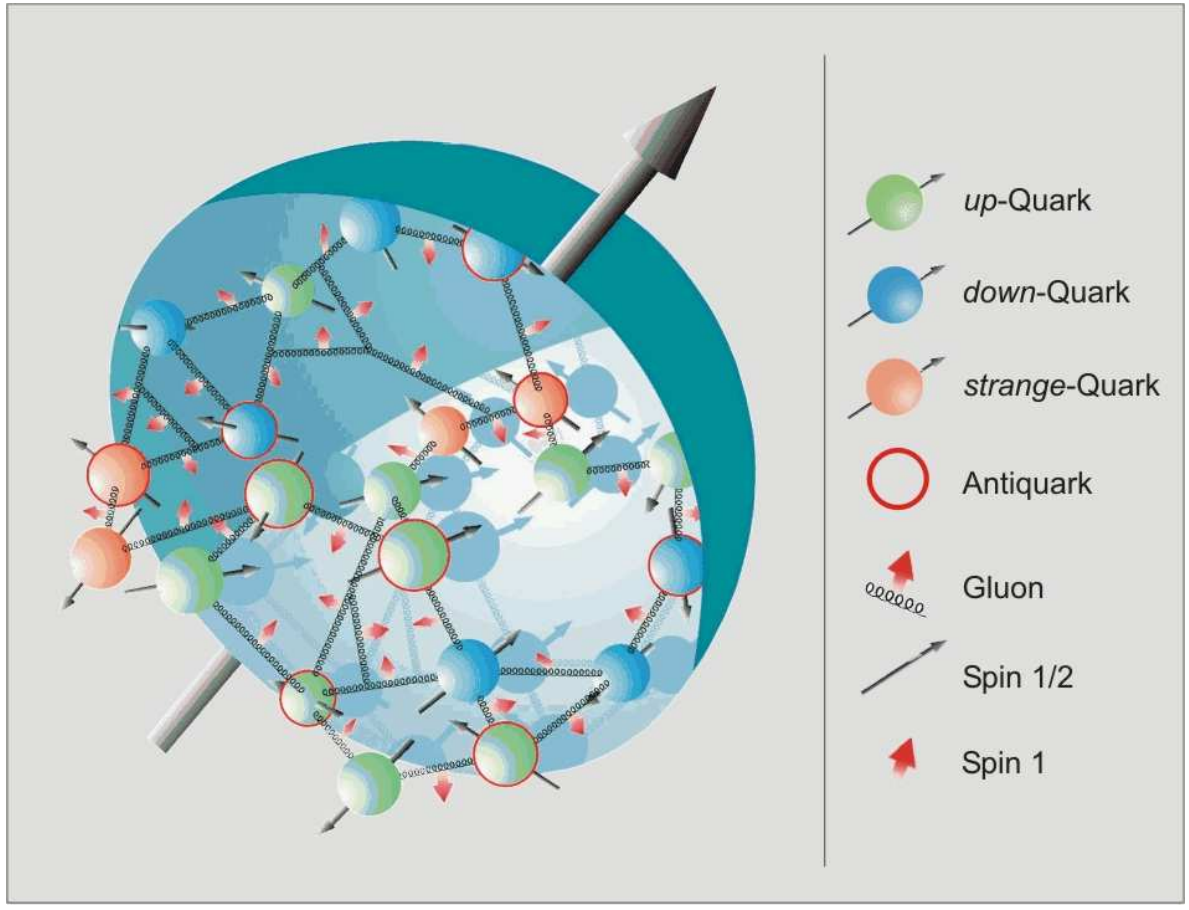

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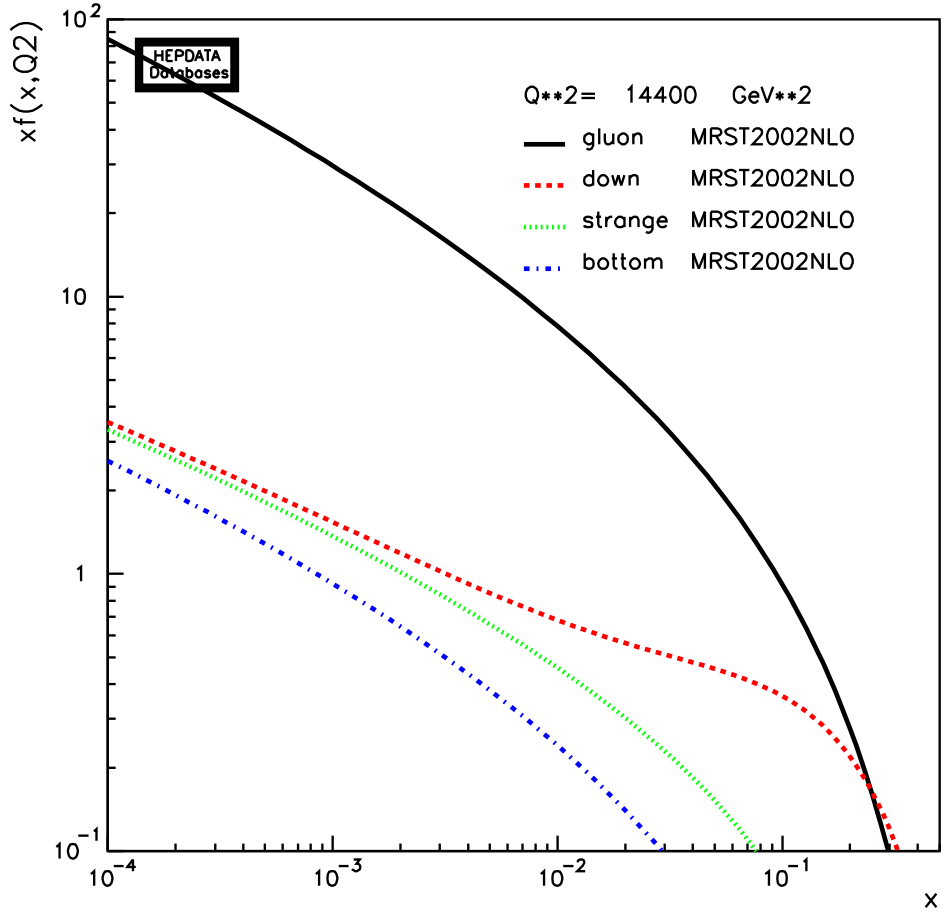

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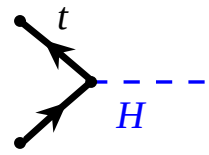

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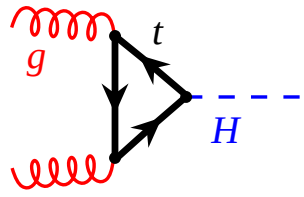

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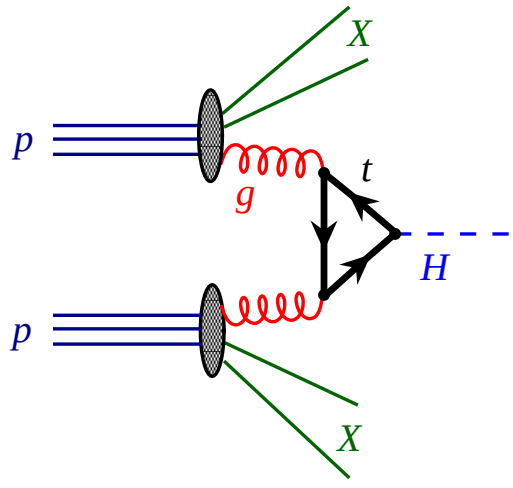
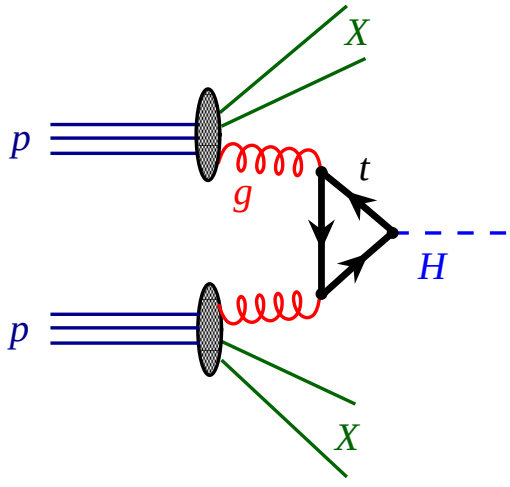
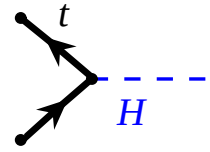


gluon fusion

Higgs search at the LHC





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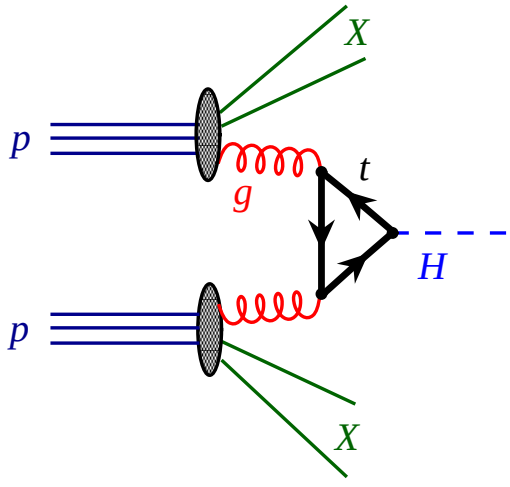

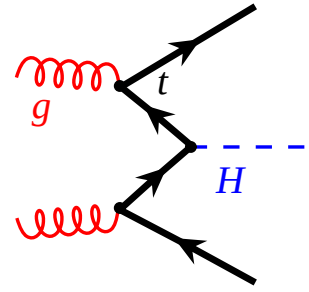

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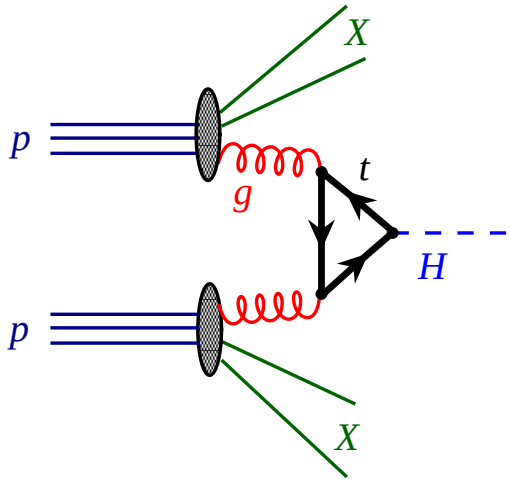

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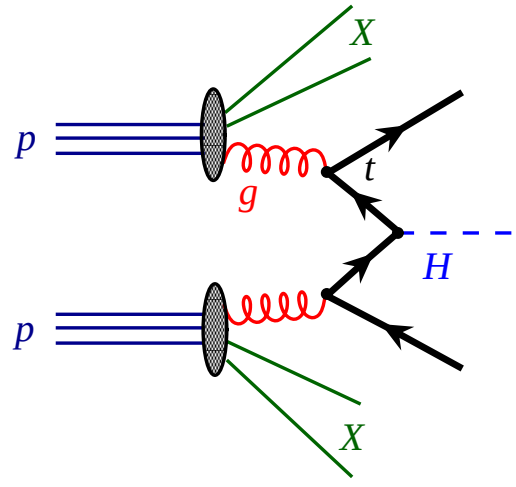

$t\bar{t}H$

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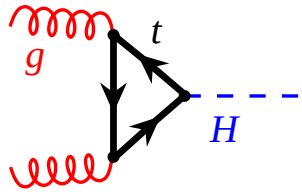

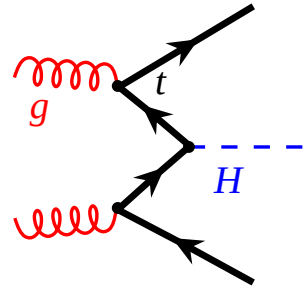

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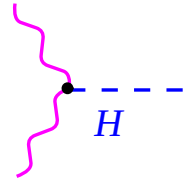
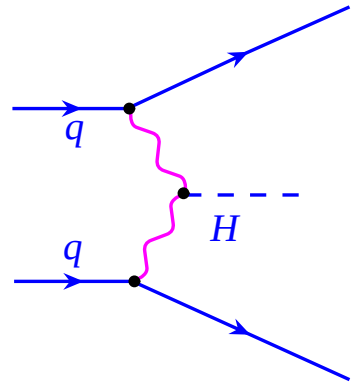
$t\bar{t}H$

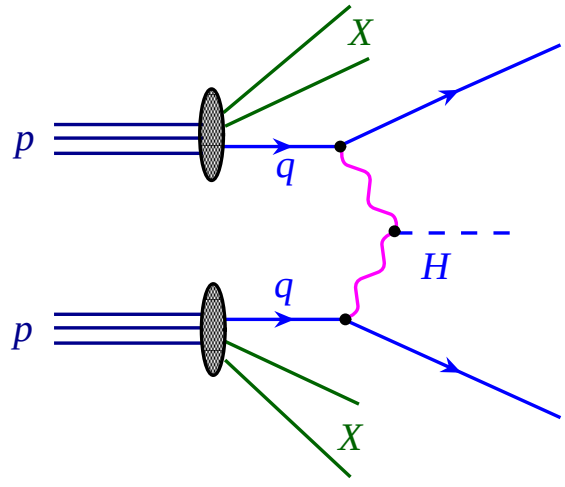
Higgs search at the LHC



Higgs search at the LHC

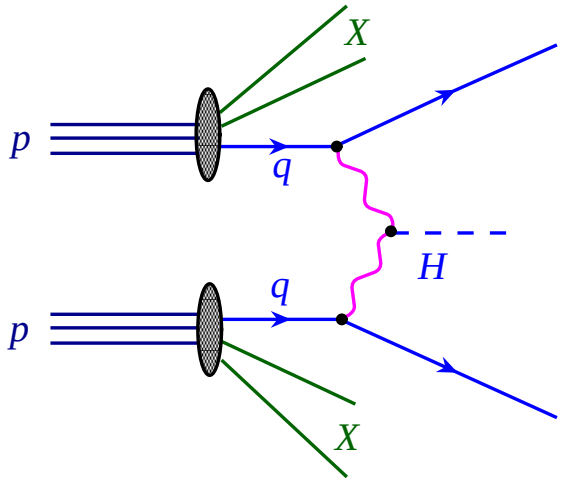


Higgs search at the LHC

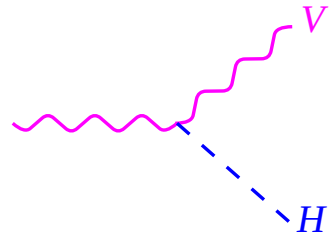


VBF

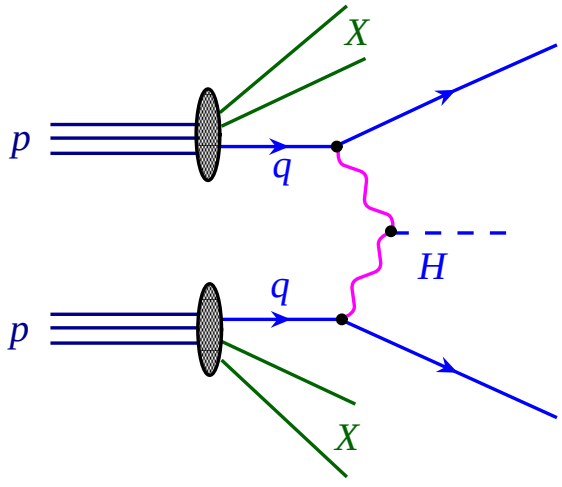
Higgs search at the LHC



VBF



Higgs search at the LHC



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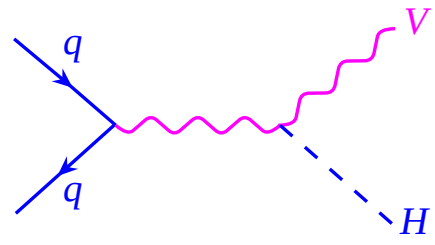
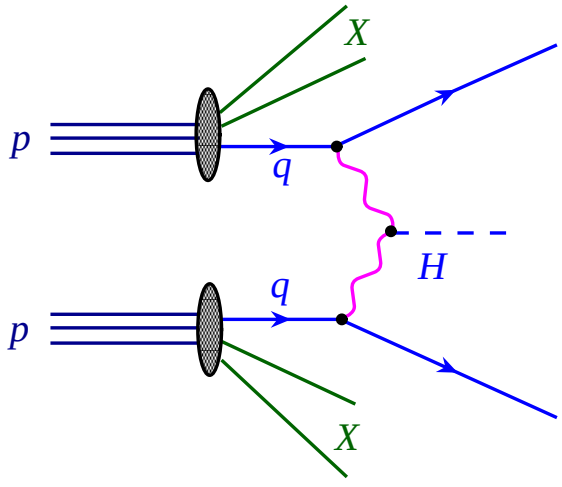


Higgs search at the LHC



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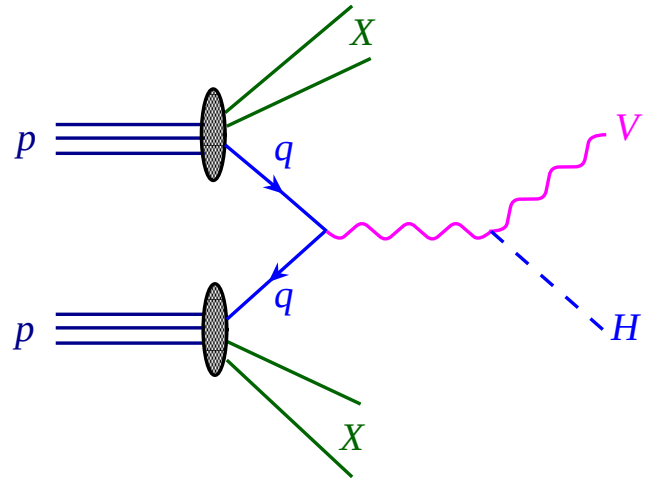
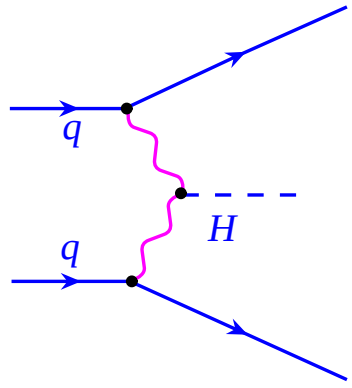
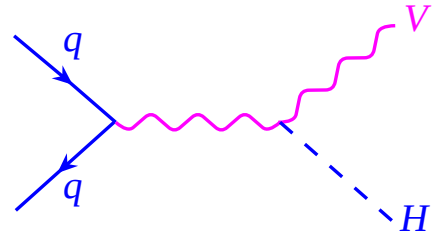


Higgs Strahlung

Higgs search at the LHC

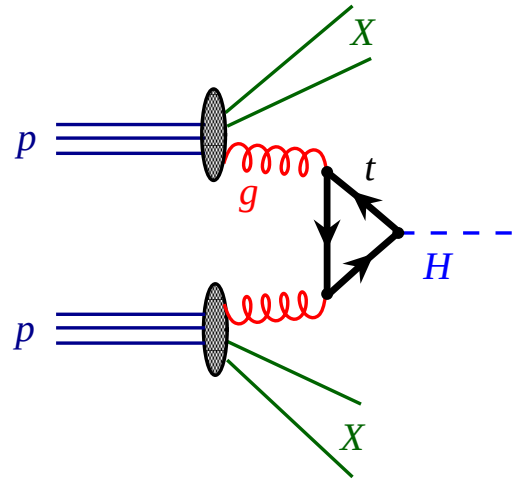


VBF

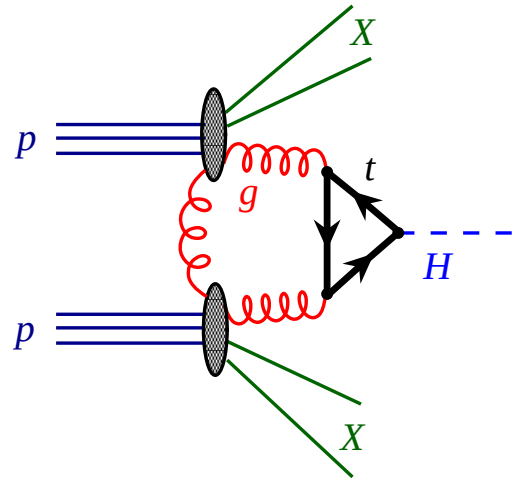


Higgs Strahlung

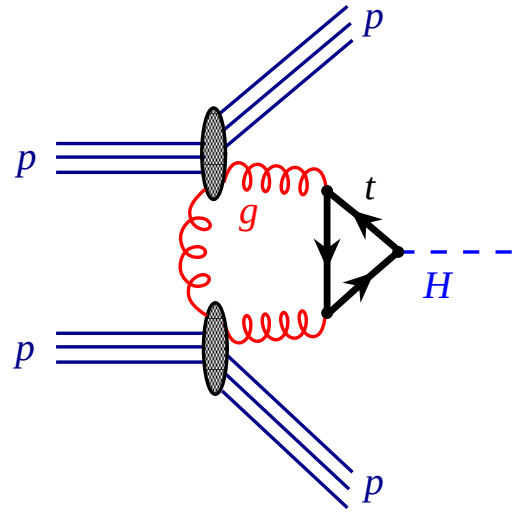
Diffractive Higgs Production



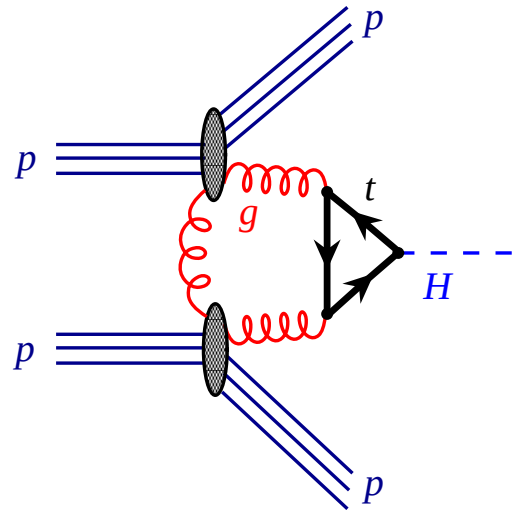
Diffractive Higgs Production



Diffractive Higgs Production



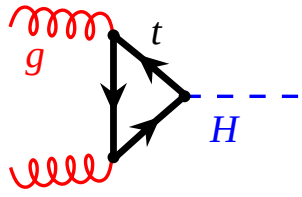
Diffractive Higgs Production



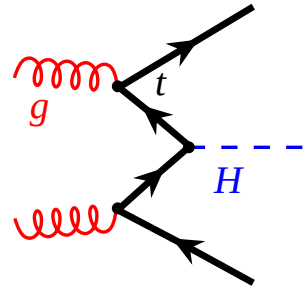
- signature: $p \oplus H \oplus p$ ($\oplus$ = rapidity gap)

  [Khoze, Martin, Ryskin]
  [Boonekamp, de Roeck, Peschanski, Royon], ...

Gluon Fusion vs. $t\bar{t}H$

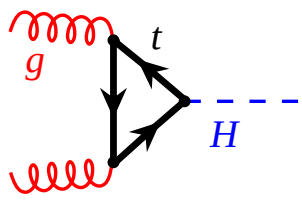


gluon fusion



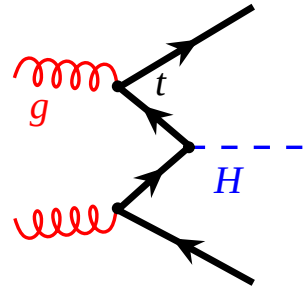
$t\bar{t}H$

Gluon Fusion vs. $t\bar{t}H$



gluon fusion

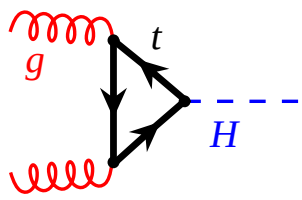
$\hat{s} \geq M_H$



$t\bar{t}H$

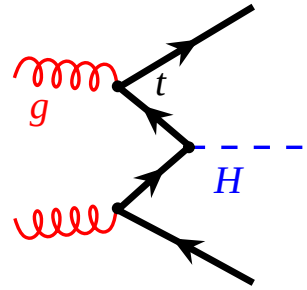
$\hat{s} \geq 2m_t + M_H$

Gluon Fusion vs. $t\bar{t}H$



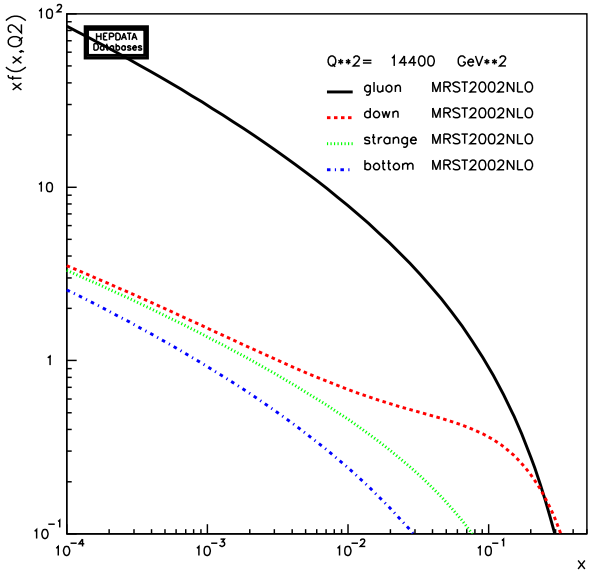
gluon fusion

$\hat{s} \geq M_H$



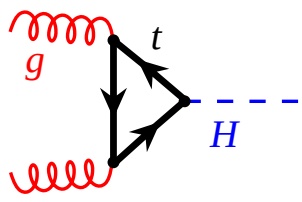
$t\bar{t}H$

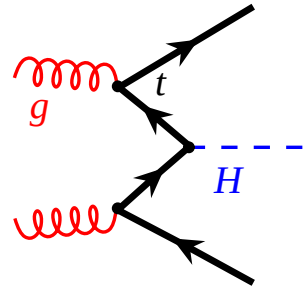
$\hat{s} \geq 2m_t + M_H$



$$\hat{s} = x_1\, x_2 s \sim x^2\, s$$

Gluon Fusion vs. $t\bar{t}H$





gluon fusion

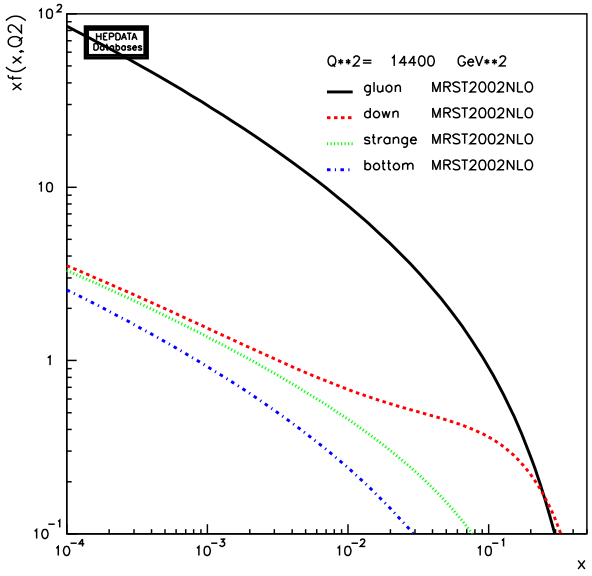
$\hat{s} \geq M_H$

$x \geq 0.8 \cdot 10^{-2}$

$t\bar{t}H$

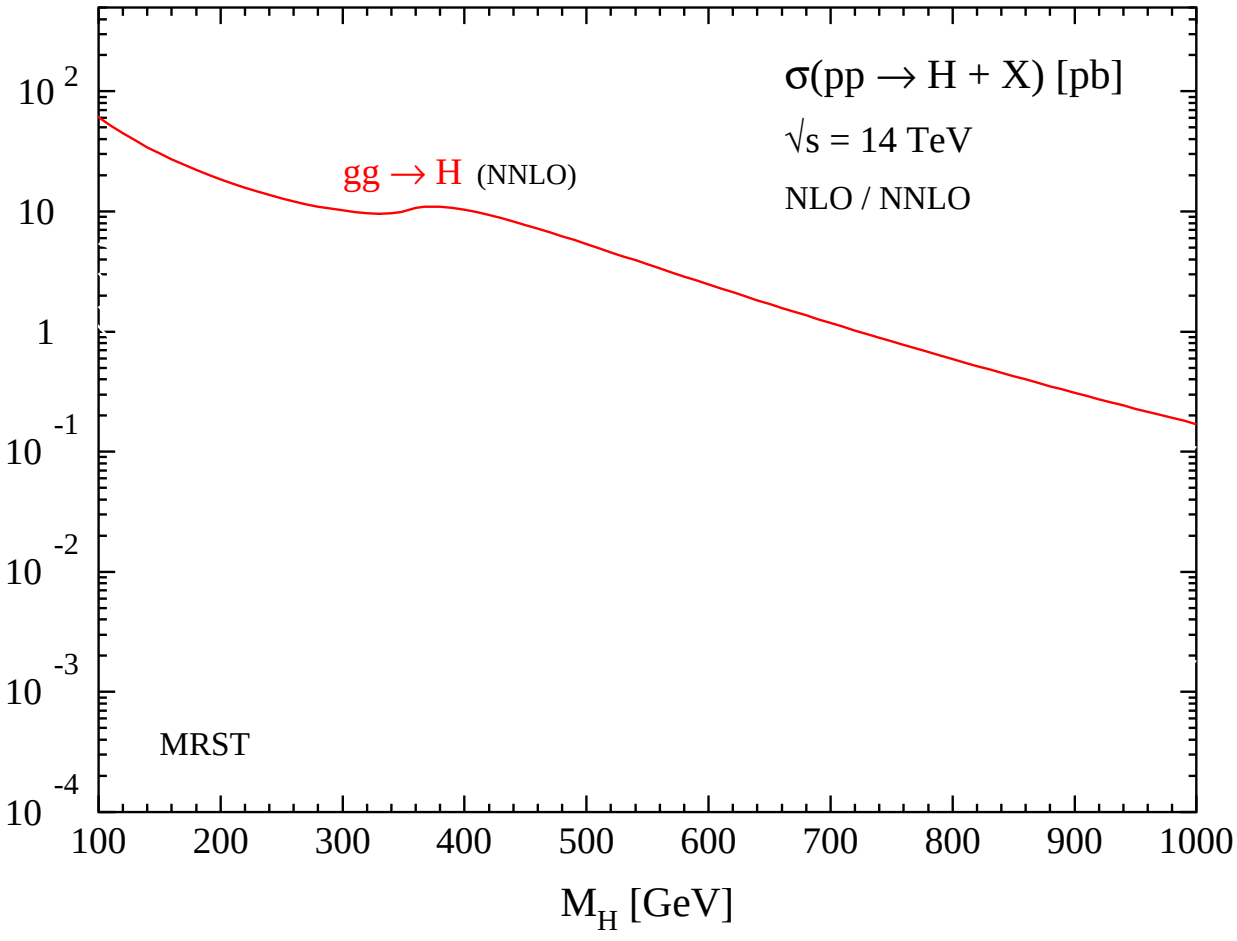
$\hat{s} \geq 2m_t + M_H$

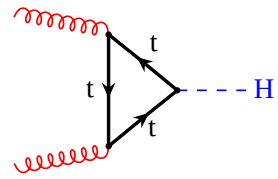
$x \geq 3.3 \cdot 10^{-2}$



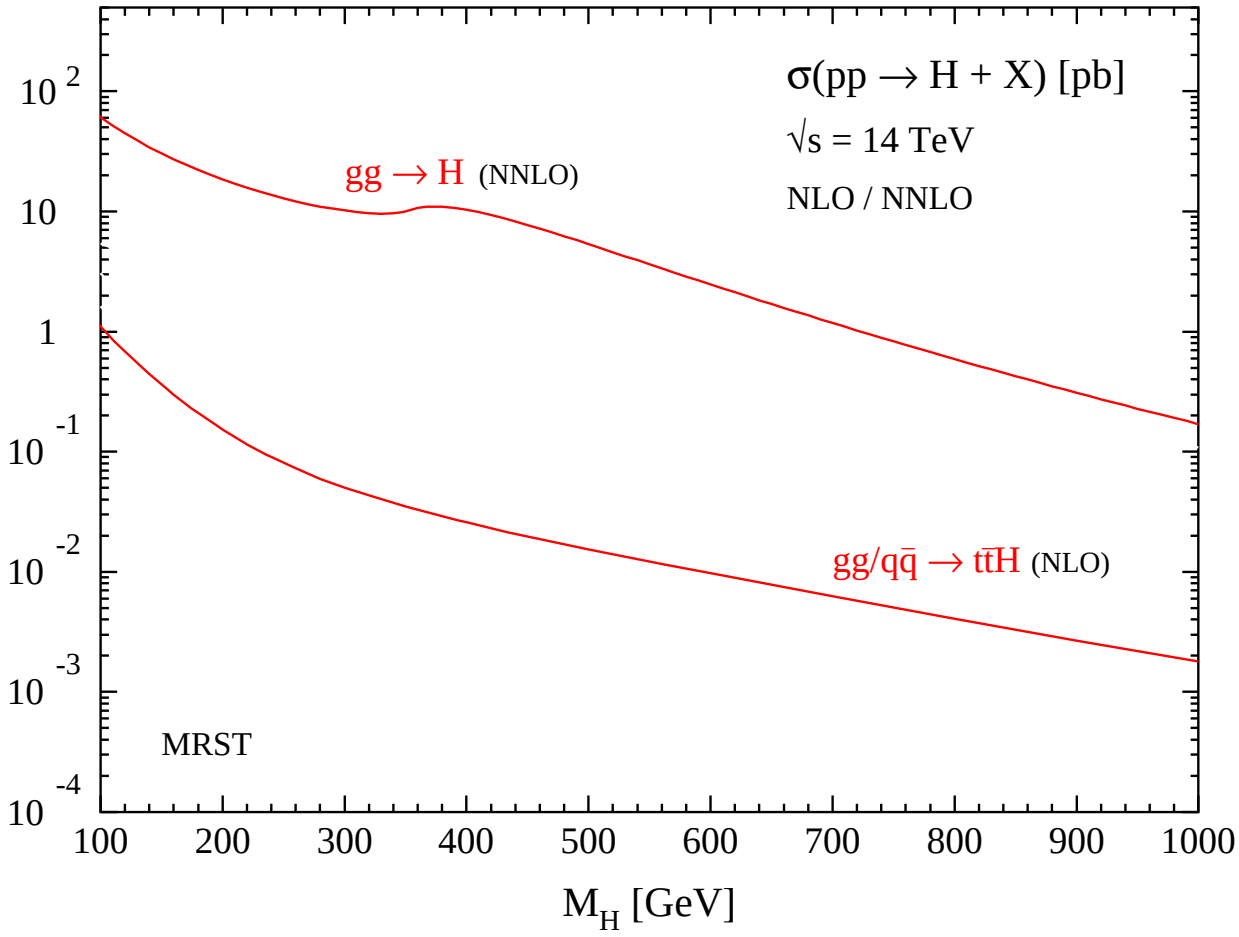
$\hat{s} = x_1\, x_2 s \sim x^2\, s$

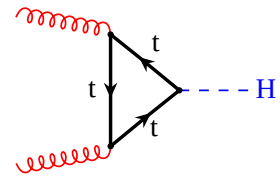
Cross sections

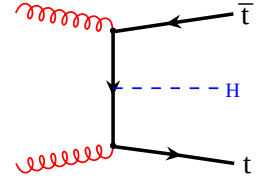




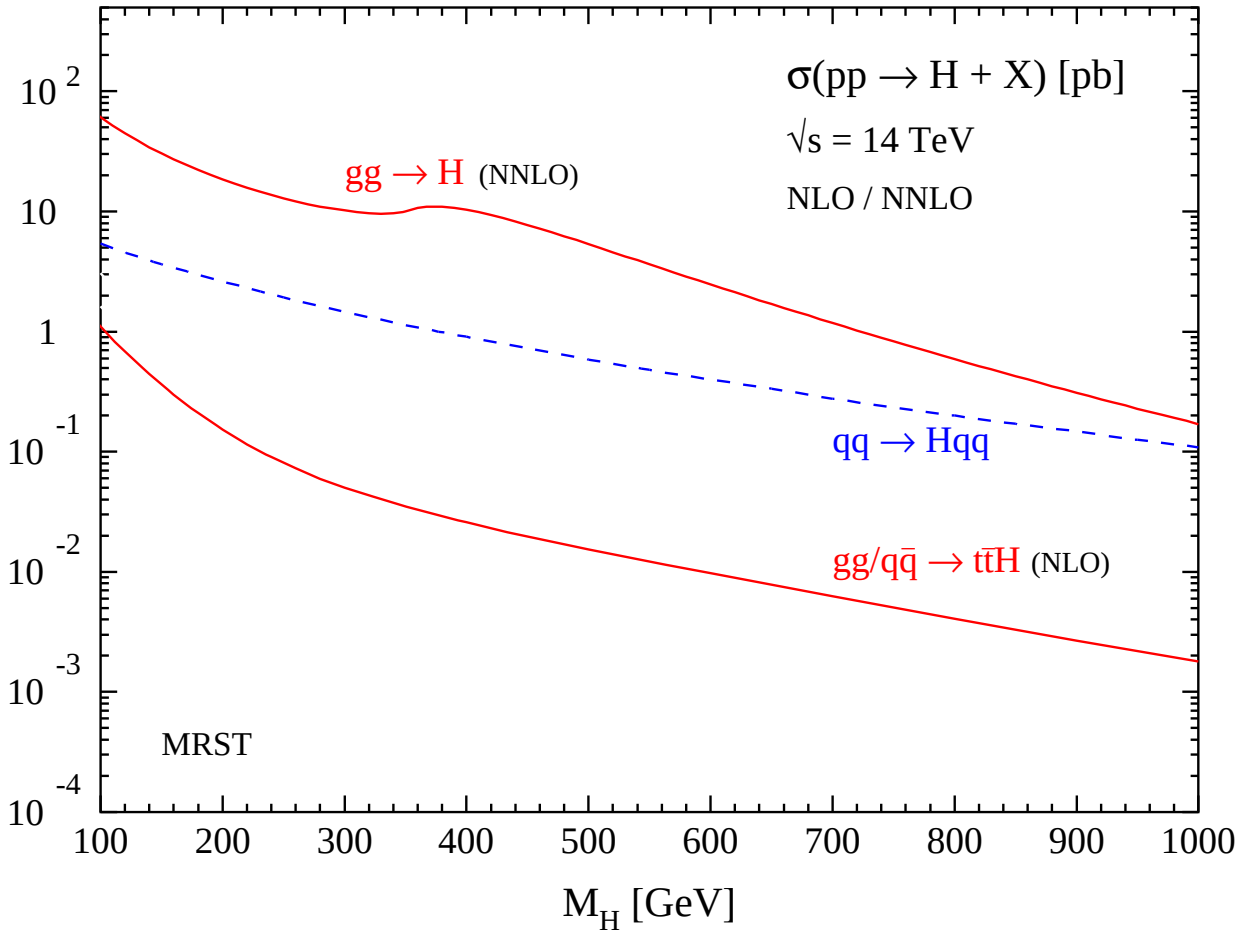
Cross sections

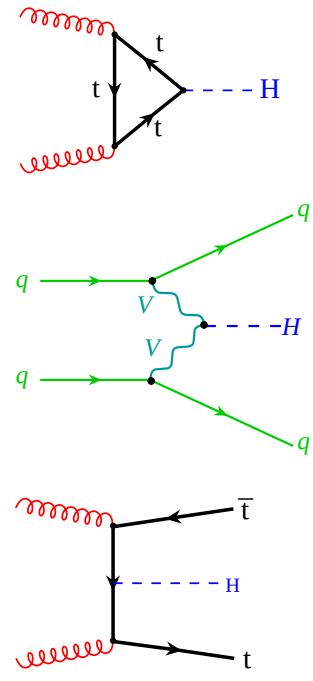




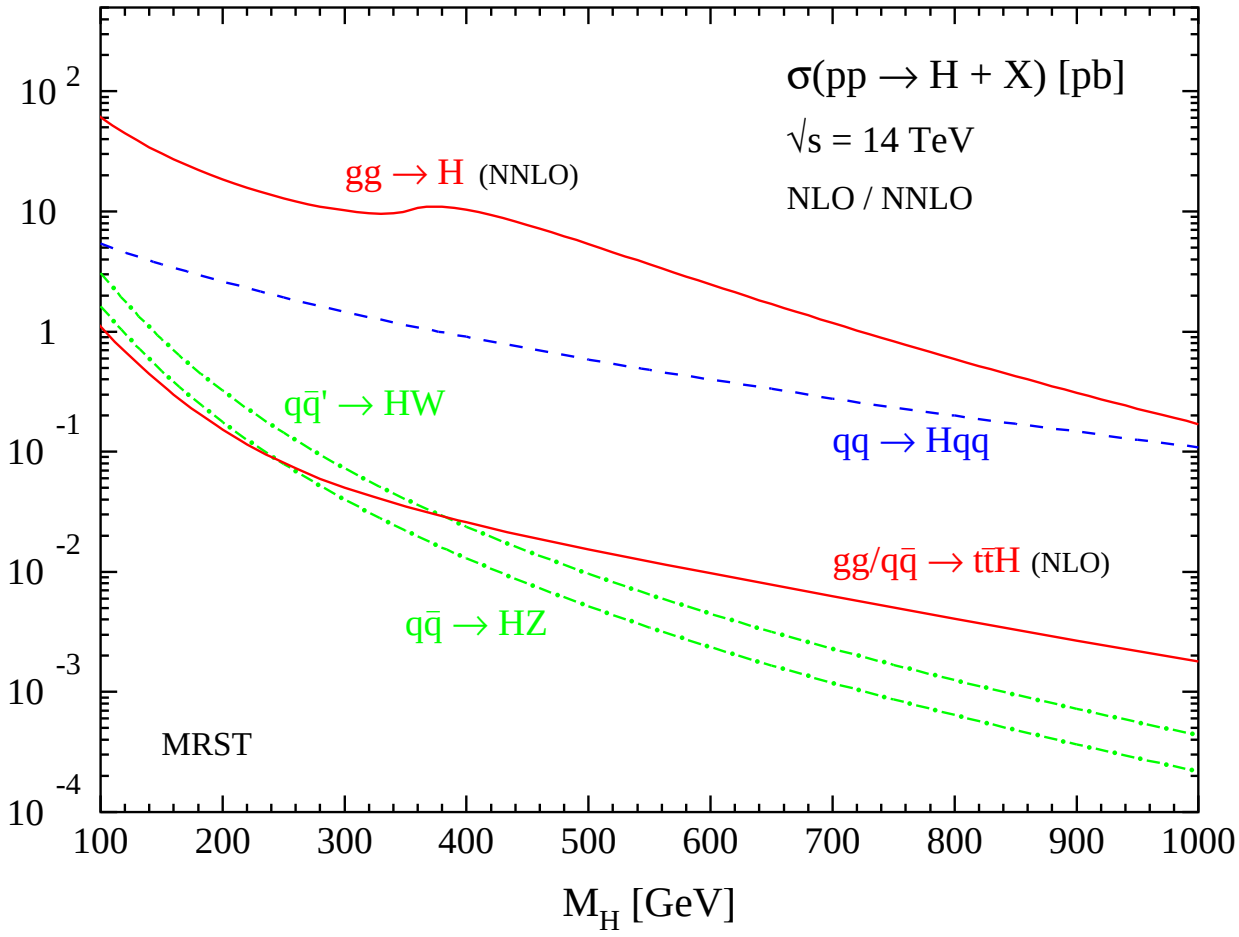


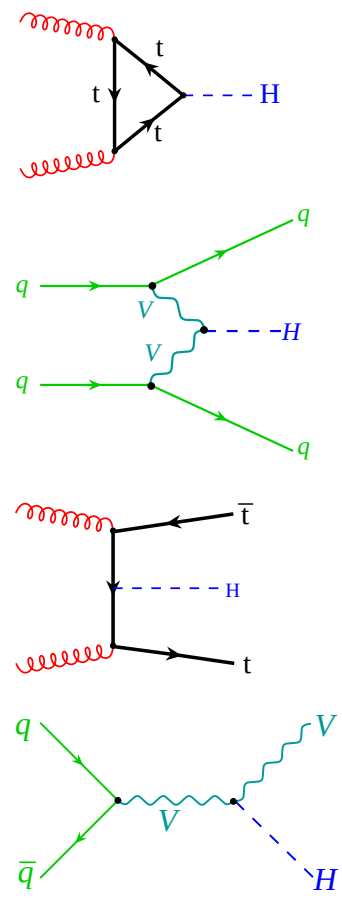
Cross sections



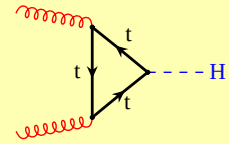


Cross sections



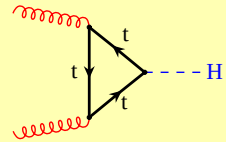


Gluon fusion:

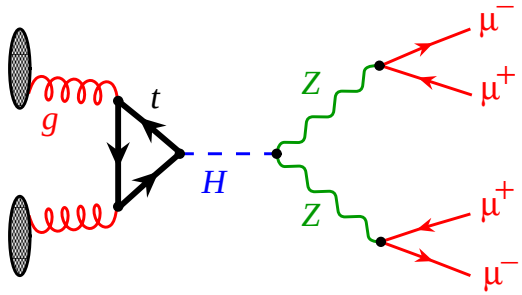


- largest cross section

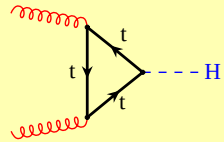
Gluon fusion:



- largest cross section
- $gg \to H \to ZZ \to 4\mu$: gold plated mode for $M_H \gtrsim 135\,\text{GeV}$



Gluon fusion:



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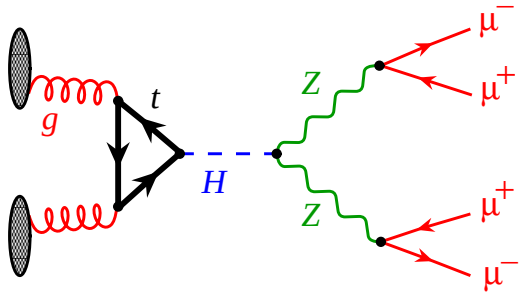
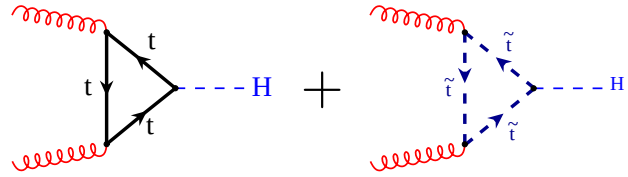
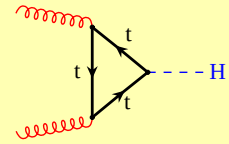


- sensitive to
  - new particles, e.g. supersymmetry:



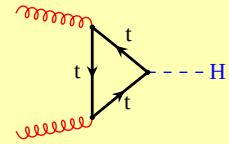
  - top Yukawa coupling

Gluon fusion:



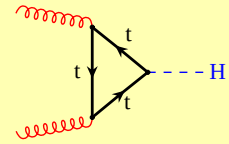
- but:

Gluon fusion:

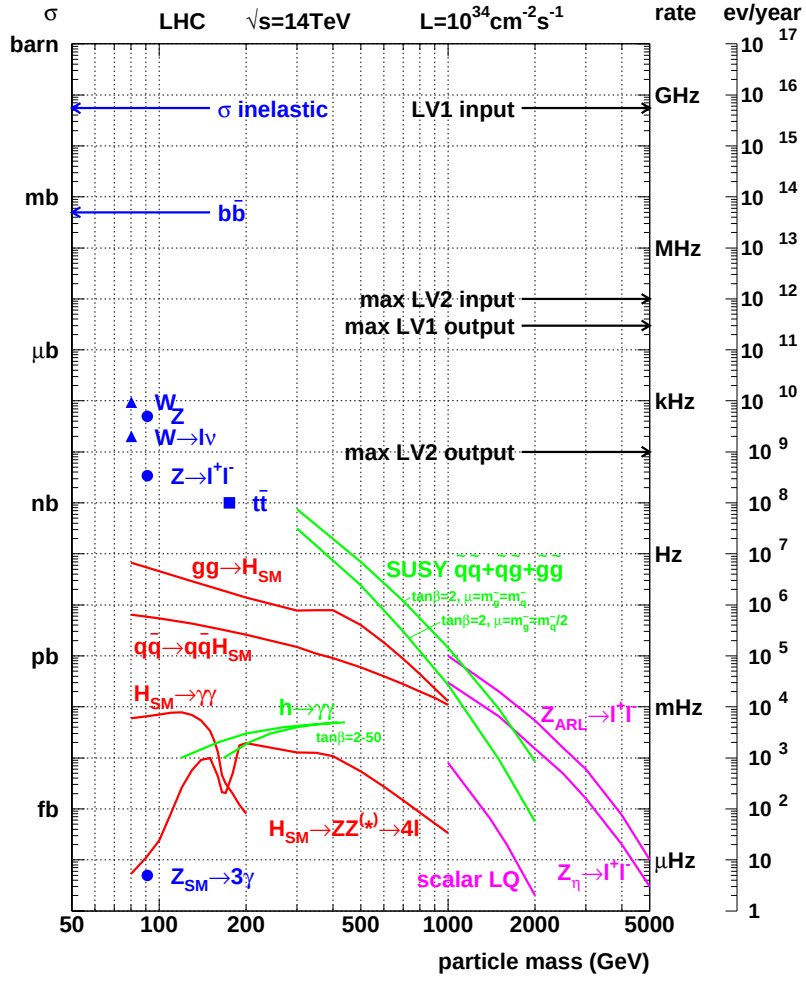


- but: $gg \to H \to b\bar{b}$ not useful!

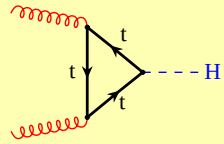
Gluon fusion:



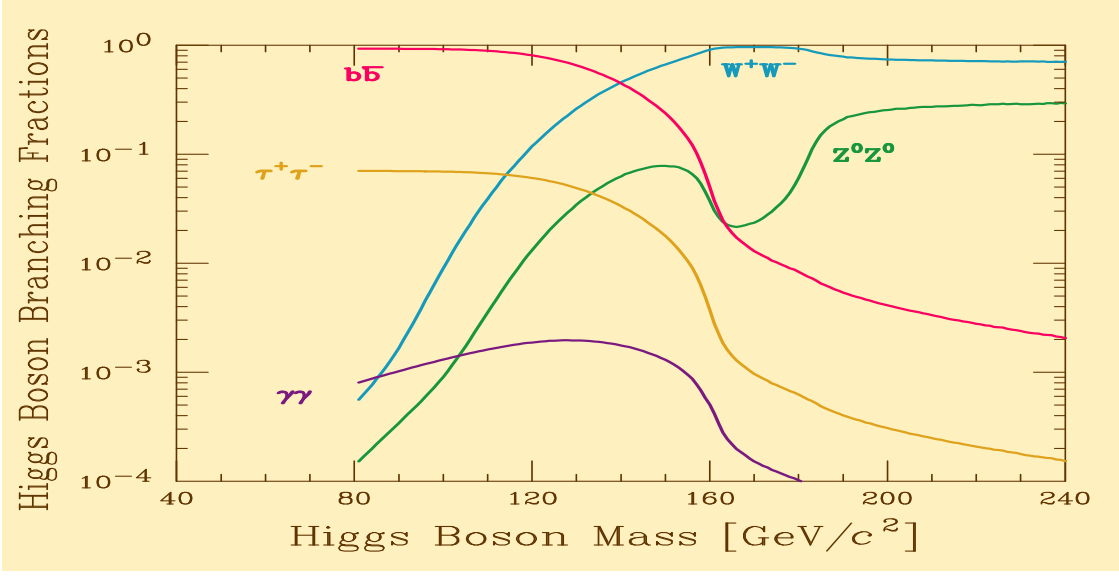
- but: $gg \longrightarrow H \longrightarrow b\bar{b}$ not useful!



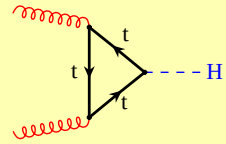
Gluon fusion:



- but: $gg \to H \to b\bar{b}$ not useful!
- need to rely on $gg \to H \to \gamma\gamma$ at $M_H \lesssim 135\,\text{GeV}$



Gluon fusion:



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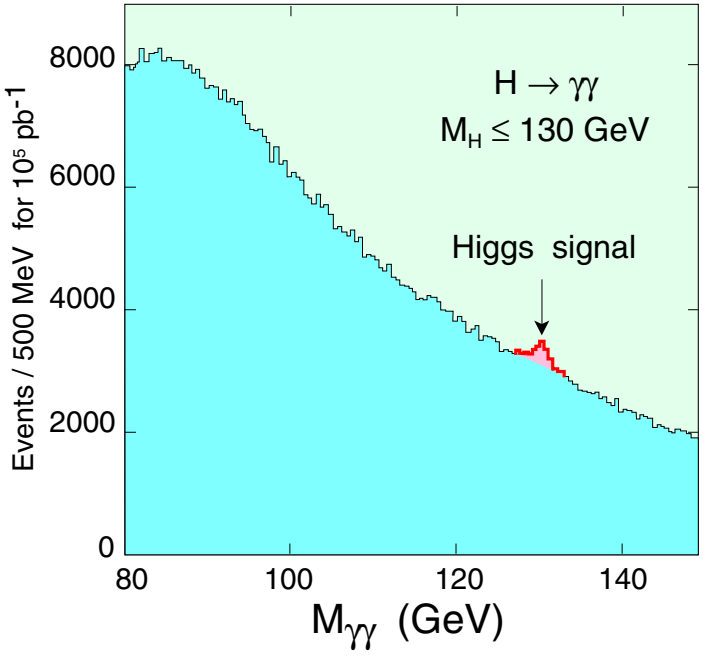
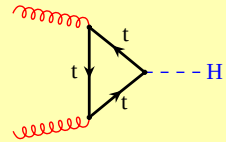
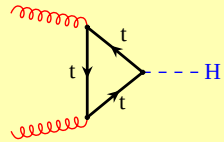


Gluon fusion:



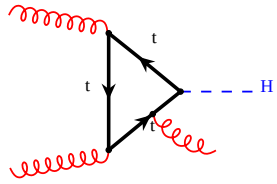
- but: $gg \to H \to b\bar{b}$ not useful!
- need to rely on $gg \to H \to \gamma\gamma$ at $M_H \lesssim 135\,\text{GeV}$
- phase space is a single point: $\hat{s} \equiv M_H^2$

Gluon fusion:



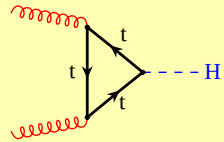
- but: $gg \to H \to b\bar{b}$ not useful!
- need to rely on $gg \to H \to \gamma\gamma$ at $M_H \lesssim 135\,\text{GeV}$
- phase space is a single point: $\hat{s} \equiv M_H^2$

NLO:



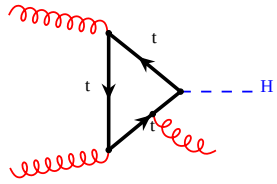
$\Rightarrow$ phase space opens: $\hat{s} \geq M_H^2$!

Gluon fusion:



- but: $gg \to H \to b\bar{b}$ not useful!
- need to rely on $gg \to H \to \gamma\gamma$ at $M_H \lesssim 135\,\text{GeV}$
- phase space is a single point: $\hat{s} \equiv M_H^2$

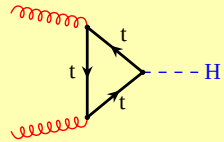
NLO:



$\Rightarrow$ phase space opens: $\hat{s} \geq M_H^2$!

$\Rightarrow$ large radiative corrections expected

Gluon fusion:



- but: $gg \to H \to b\bar{b}$ not useful!
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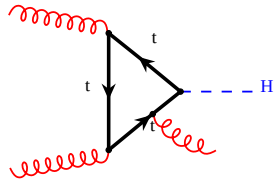
- phase space is a single point: $\hat{s} \equiv M_H^2$

NLO:

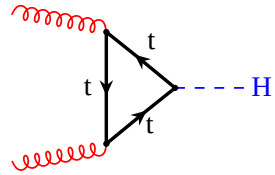


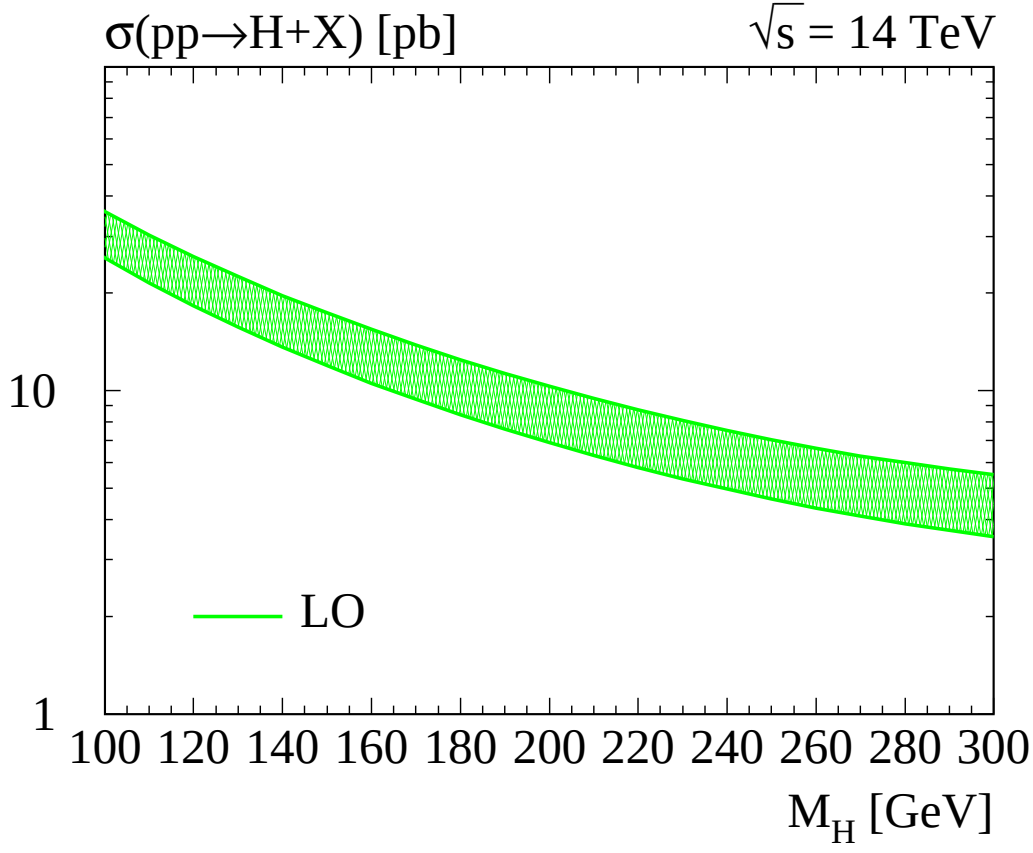
$\Rightarrow$ phase space opens: $\hat{s} \geq M_H^2$!

$\Rightarrow$ large radiative corrections expected

$\to$ reliable result requires NNLO

Gluon fusion: theory prediction





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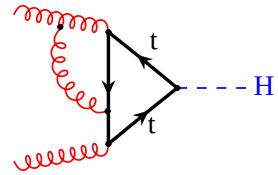

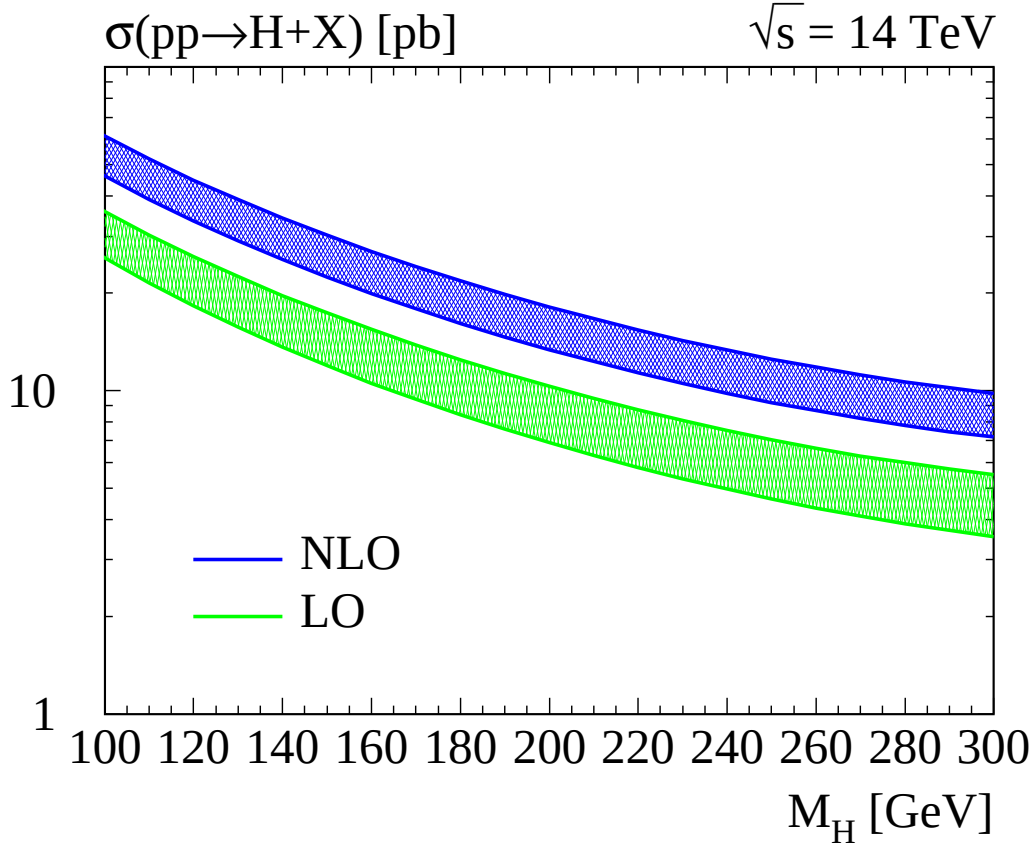

[Spira, Djouadi, Graudenz, Zerwas '91/'93]

[Dawson '91]

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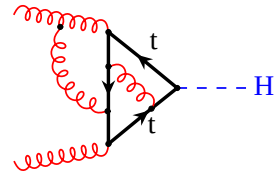
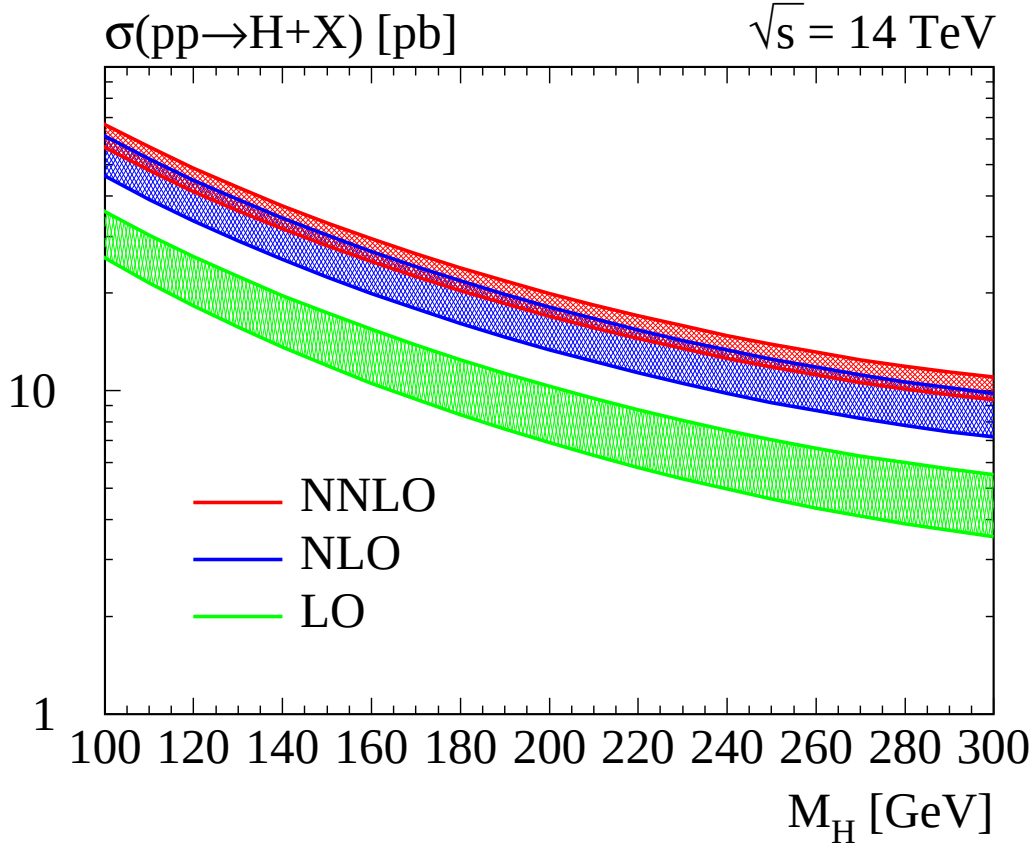




[R.H., Kilgore ’02]

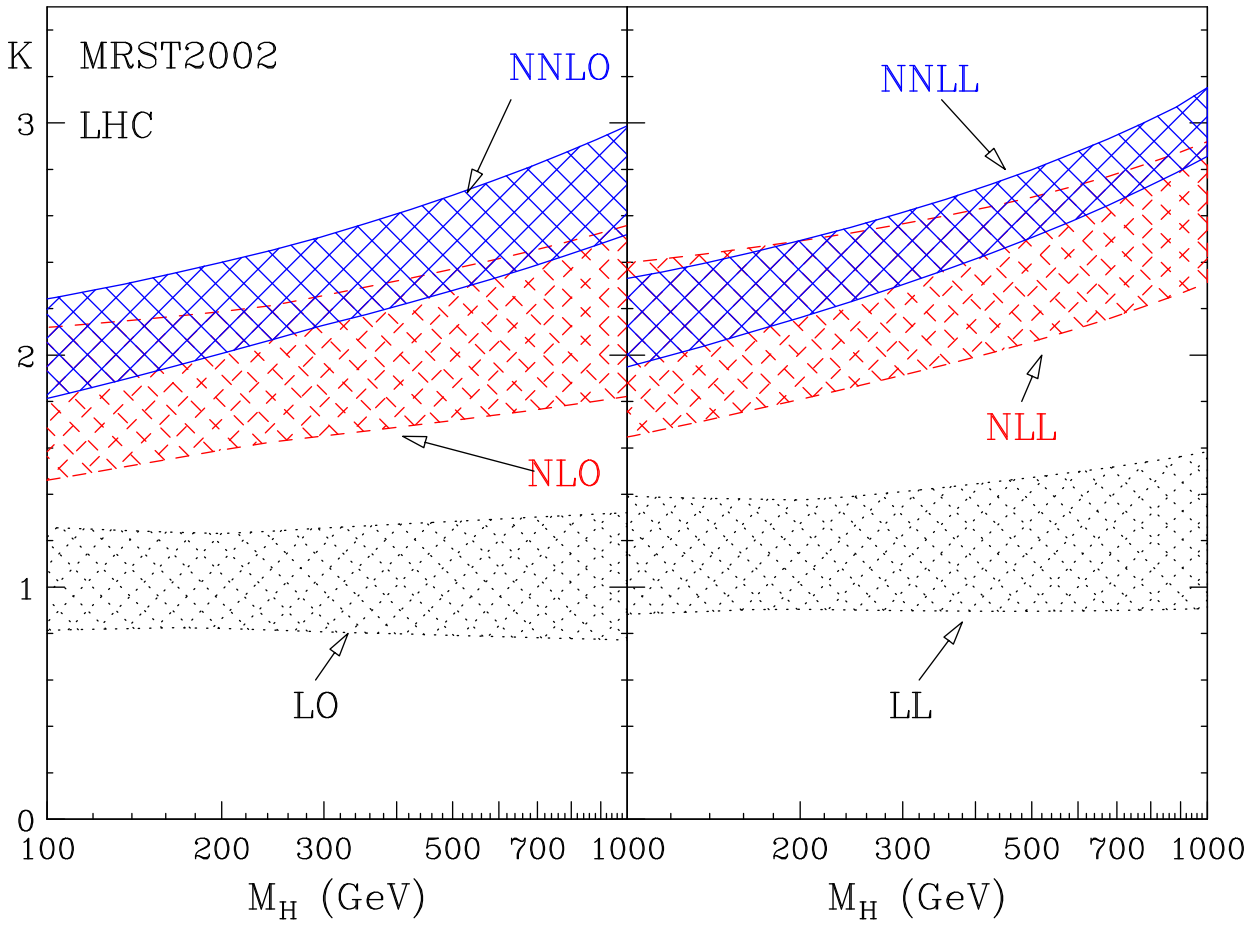
[Anastasiou, Melnikov ’02]

[Ravindran, Smith, v. Neerven ’03]

[Spira, Djouadi, Graudenz, Zerwas ’91/’93]

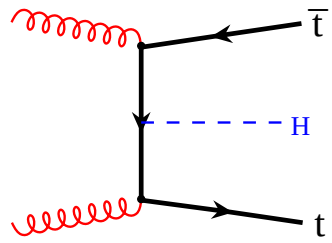
[Dawson ’91]

Resummation



[Catani, de Florian, Grazzini, Nason ('03)]

$t\bar{t}H$



- clear signature: $b\bar{b}b\bar{b}W^+W^-$

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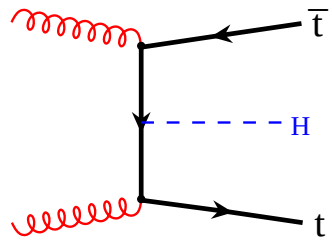

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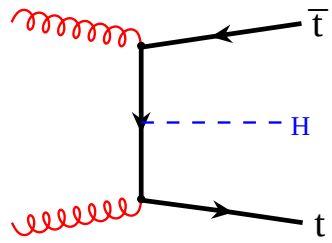

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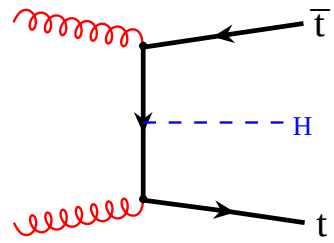

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- increased by QCD corrections?

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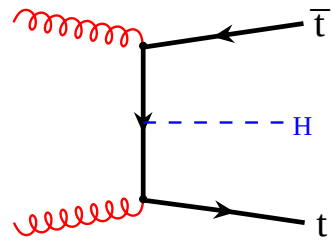
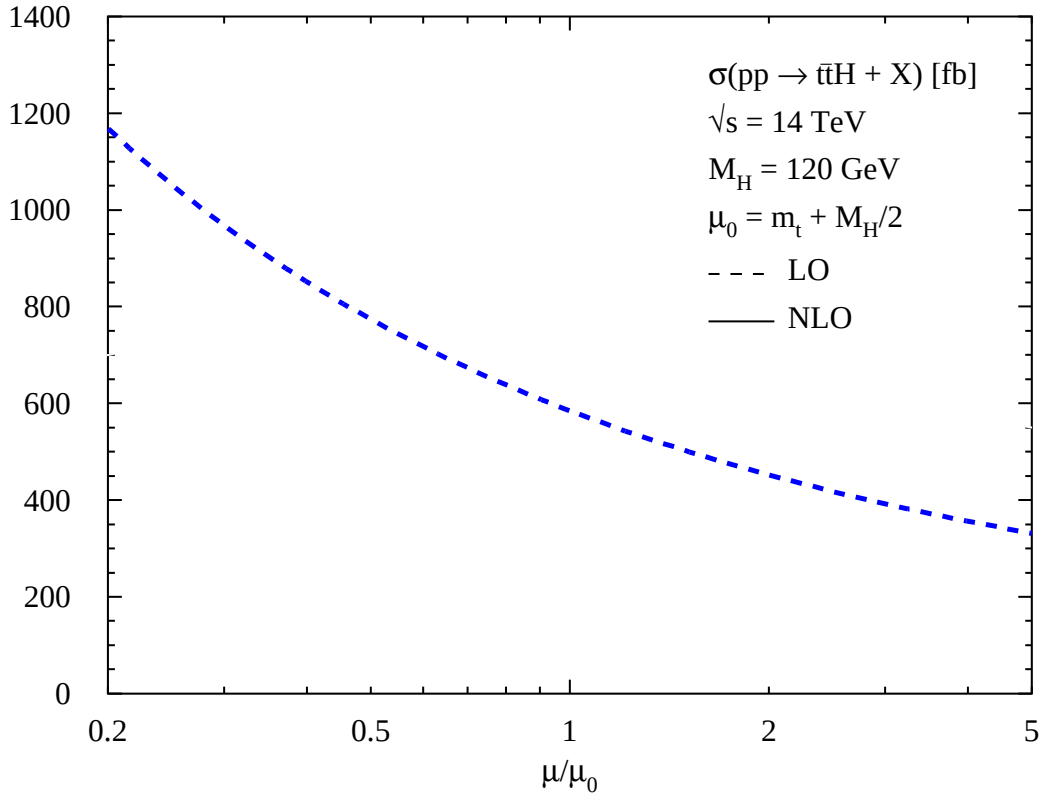
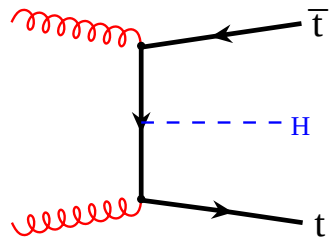
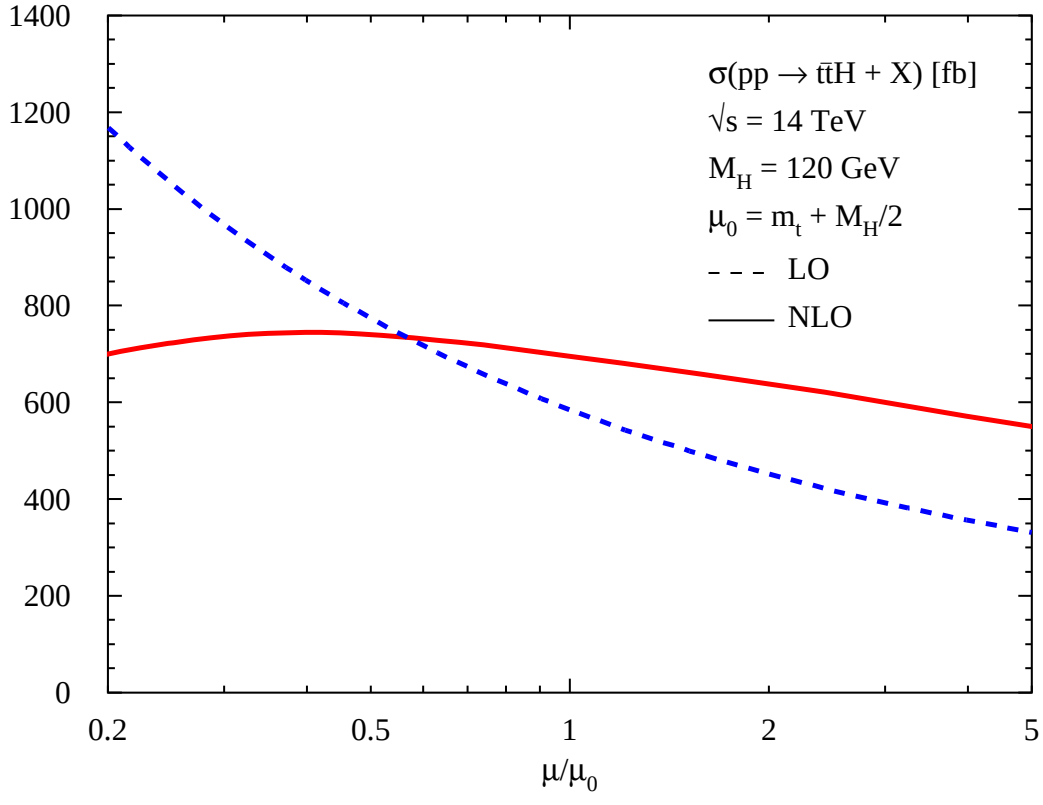

t̄
H
t


σ(pp → t̄tH + X) [fb]
√s = 14 TeV
M_H = 120 GeV
μ_0 = m_t + M_H/2
LO
NLO
1400
1200
1000
800
600
400
200
0
0.2
0.5
1
2
5
μ/μ_0

$t\bar{t}H$

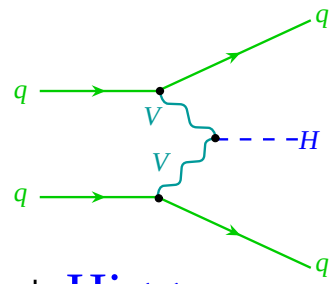




[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

[Dawson, Reina, Wackeroth, Orr, Jackson '01-'03]

Vector Boson Fusion



- signature: two forward jets + Higgs

  $H \to \gamma\gamma, \quad H \to \tau^+\tau^-, \quad H \to WW, \quad H \to b\bar{b}$

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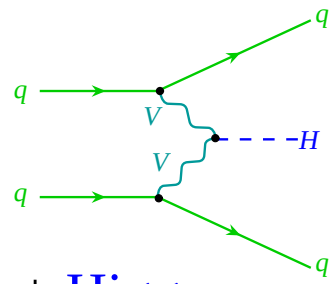

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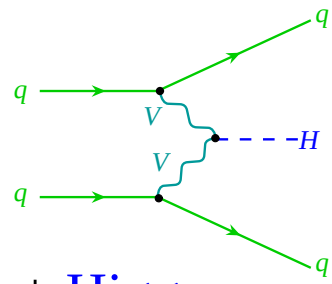

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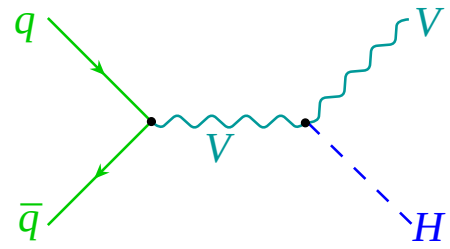
  and study (e.g. couplings [Zeppenfeld *et al.*], [Dührssen *et al.*])

- QCD corrections under control (and small)

  [Han, Willenbrock '91], [Figy, Oleari, Zeppenfeld '03]

Higgs Strahlung



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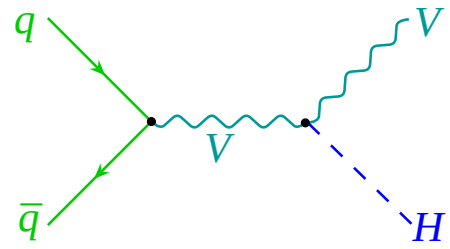

- most important mode at Tevatron!

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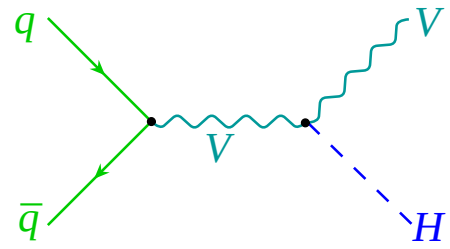
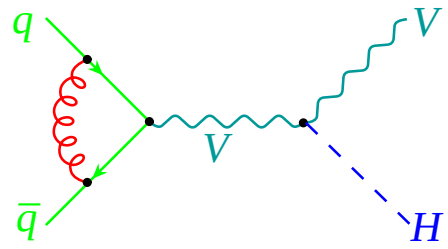
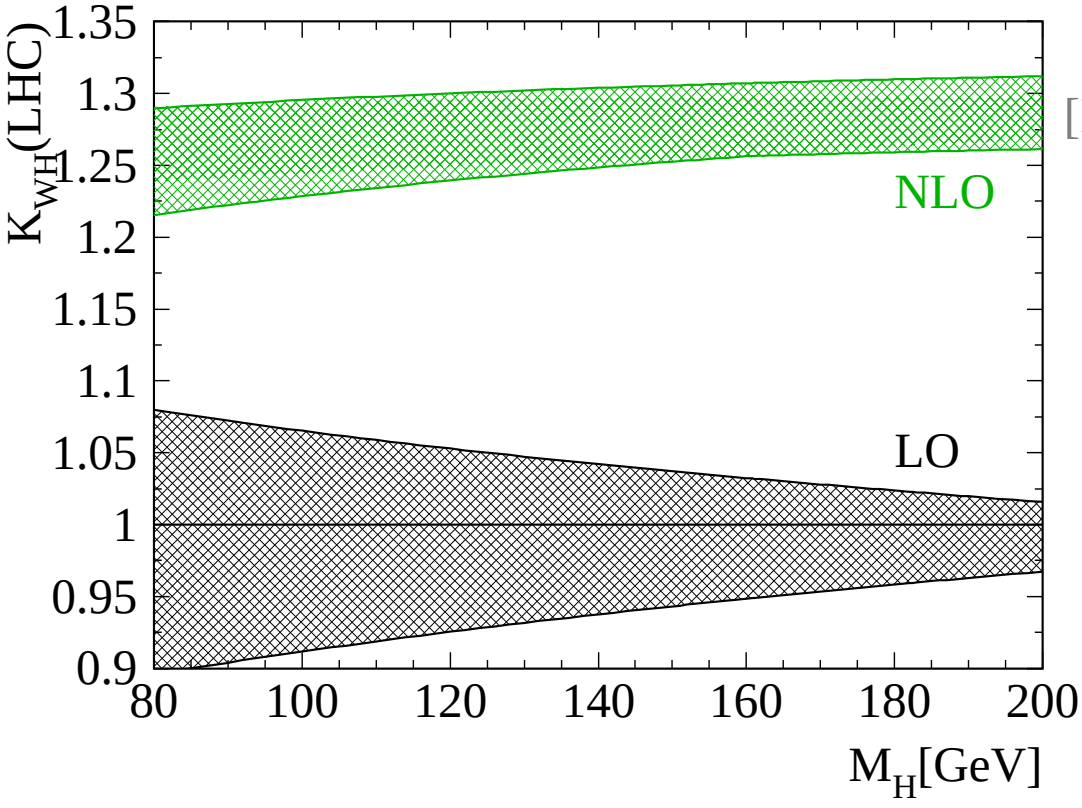


- most important mode at Tevatron!
- . . . but only marginal importance at LHC

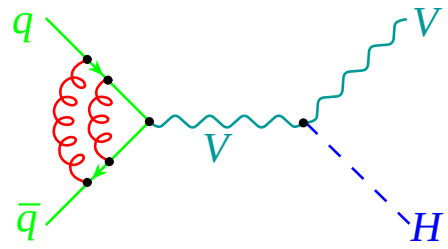
Higgs Strahlung

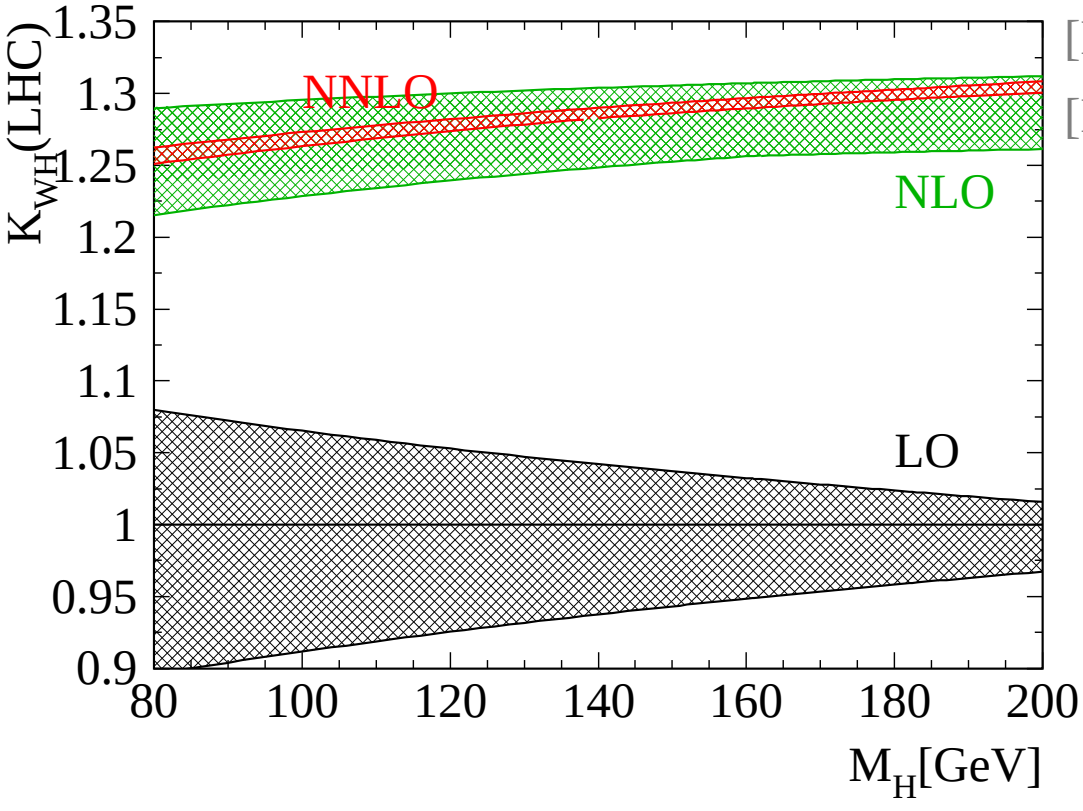




[Han, Willenbrock '90]

Higgs Strahlung





[Brein, Djouadi, R.H. ’03]

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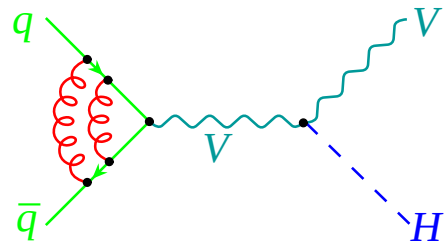

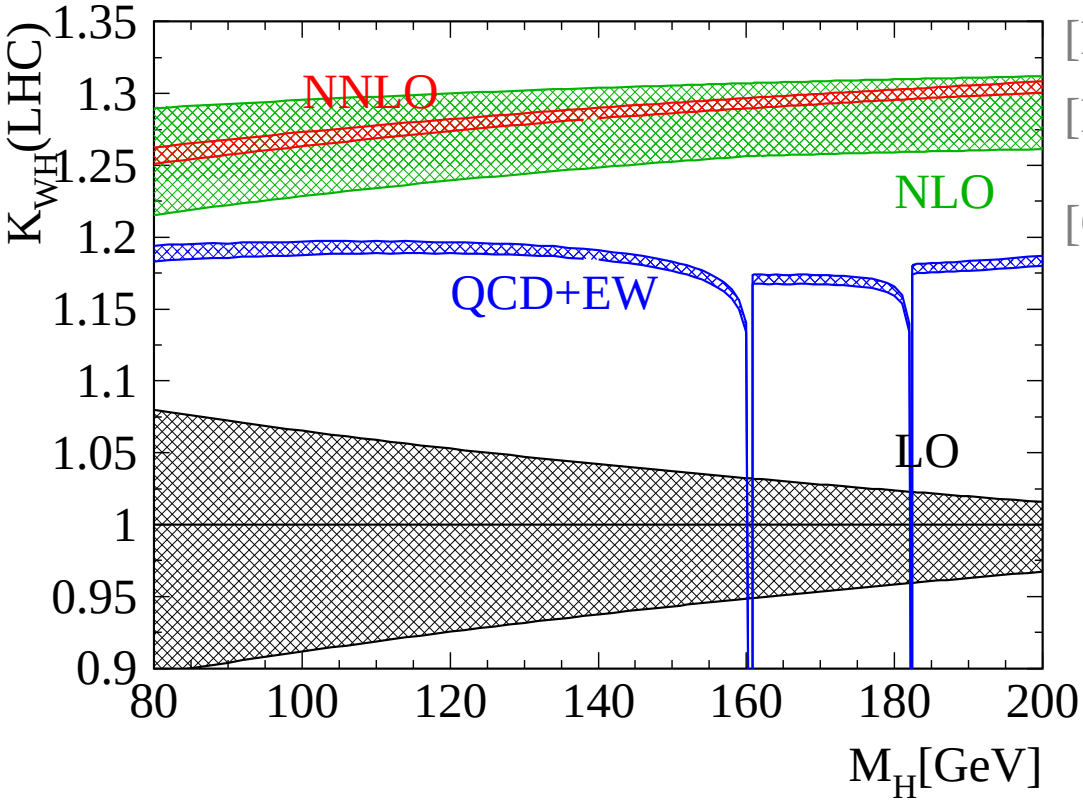

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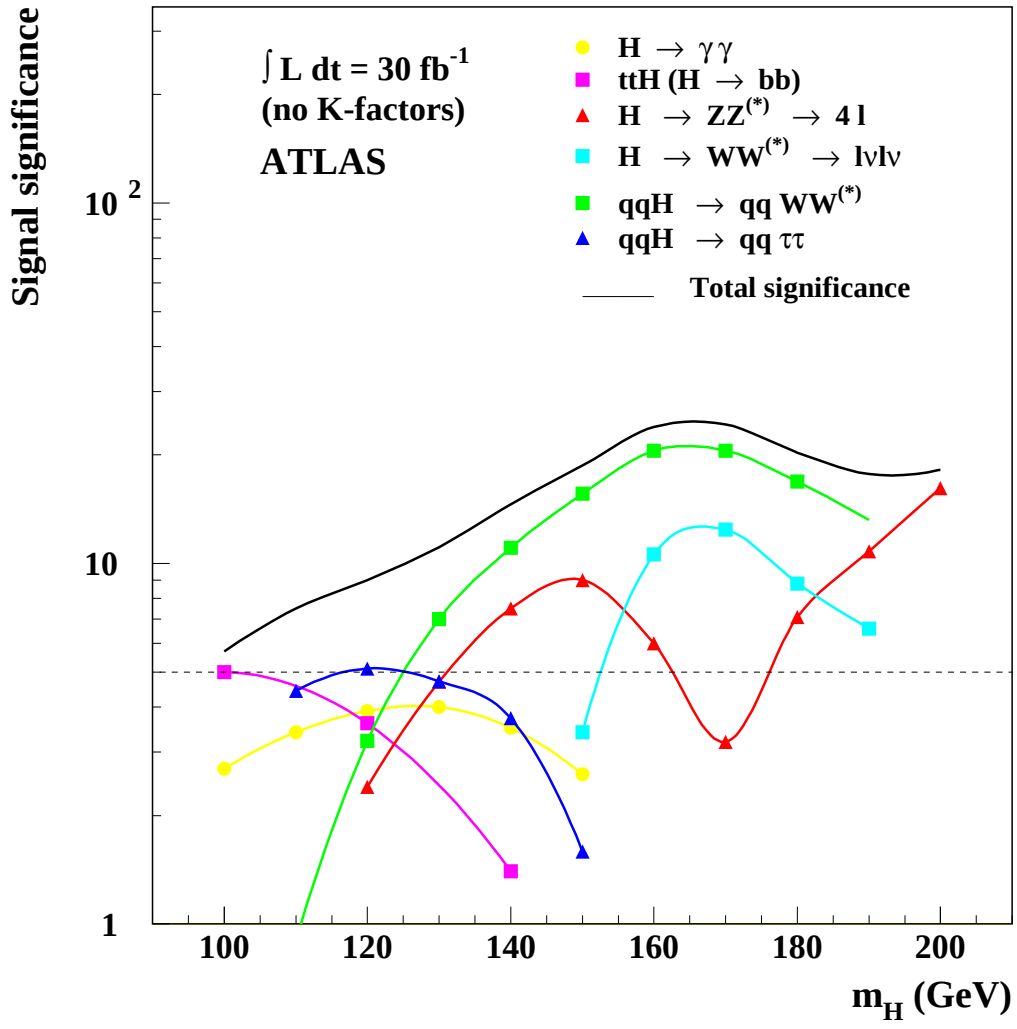
[Han, Willenbrock ’90]

[Ciccolini, Dittmaier, Krämer ’03]

Discovery Potential



Higgs sector in SUSY

$$H \quad \leftrightarrow \quad h^0, H^0, A, H^+, H^-$$

- $M_{h^0} \lesssim 130\,\text{GeV}$
- modified couplings to SM particles ($\tan\beta$!)

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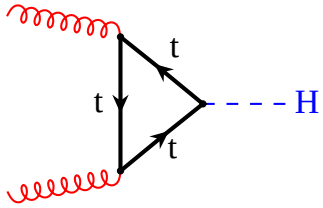
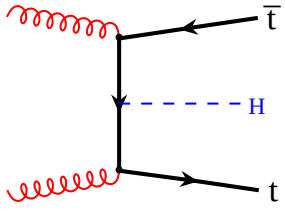
  - 

  - 

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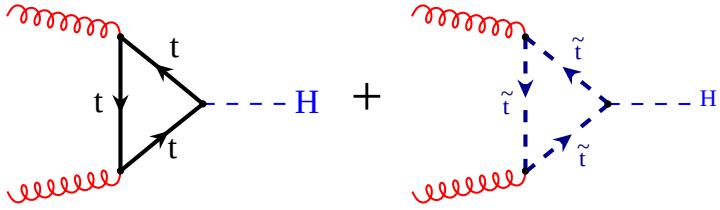
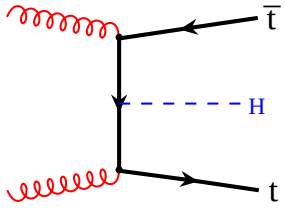
  - 

  - 

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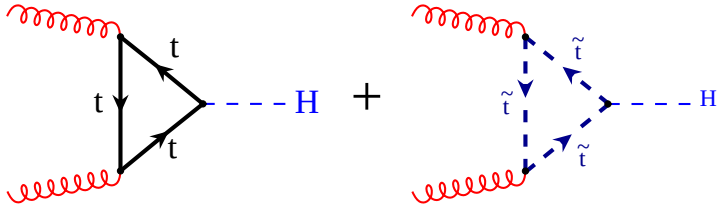
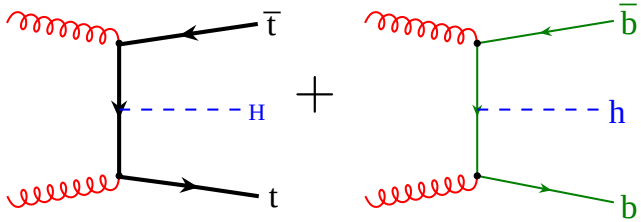
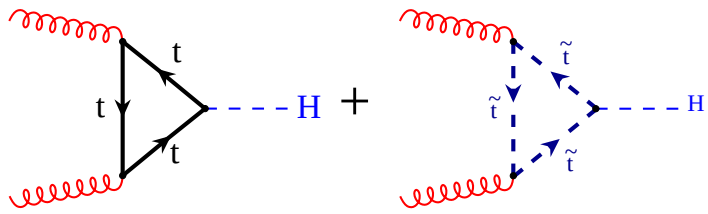
  - 

  - 

Example: “gluophobic Higgs”

[Djouadi ’98], [Carena *et al.* ’99]



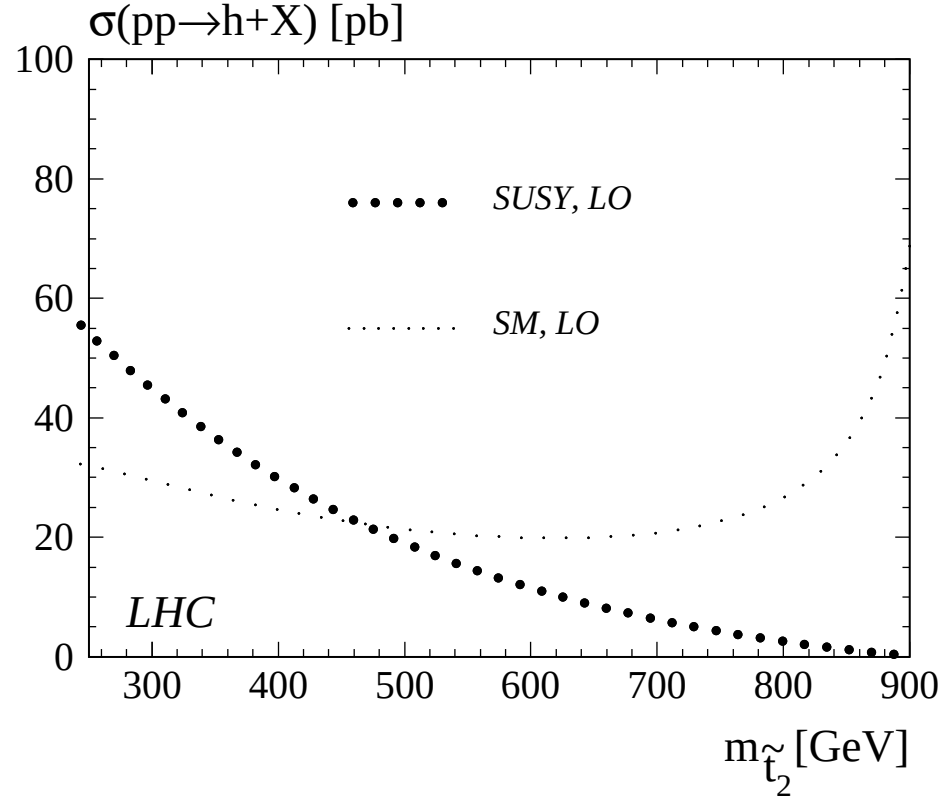
interfere destructively!

$m_{\tilde{t}_1} = 200\,\text{GeV}$

$m_{\tilde{g}} = 1\,\text{TeV}$

$\tan\beta = 10\,, \quad \alpha = 0\,,$

$\theta_t = \frac{\pi}{4}$



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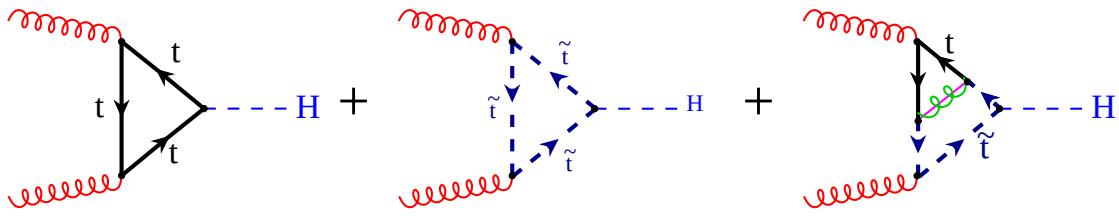

[R.H., Steinhauser ’04]

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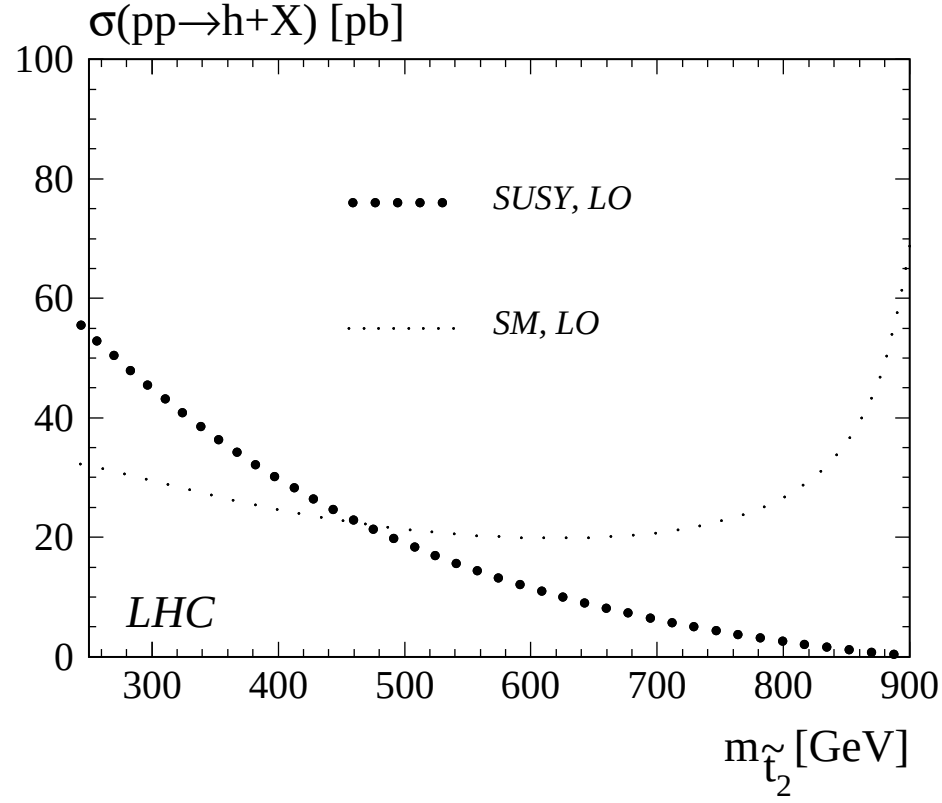

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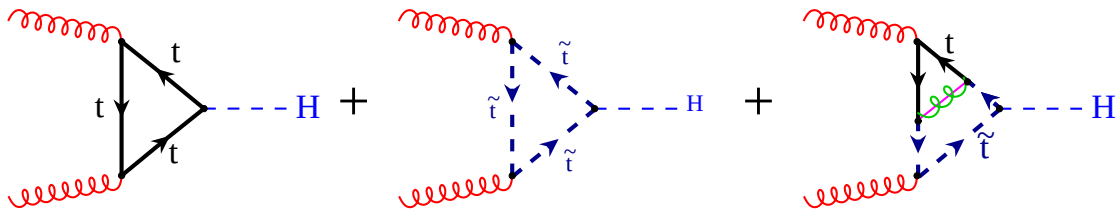

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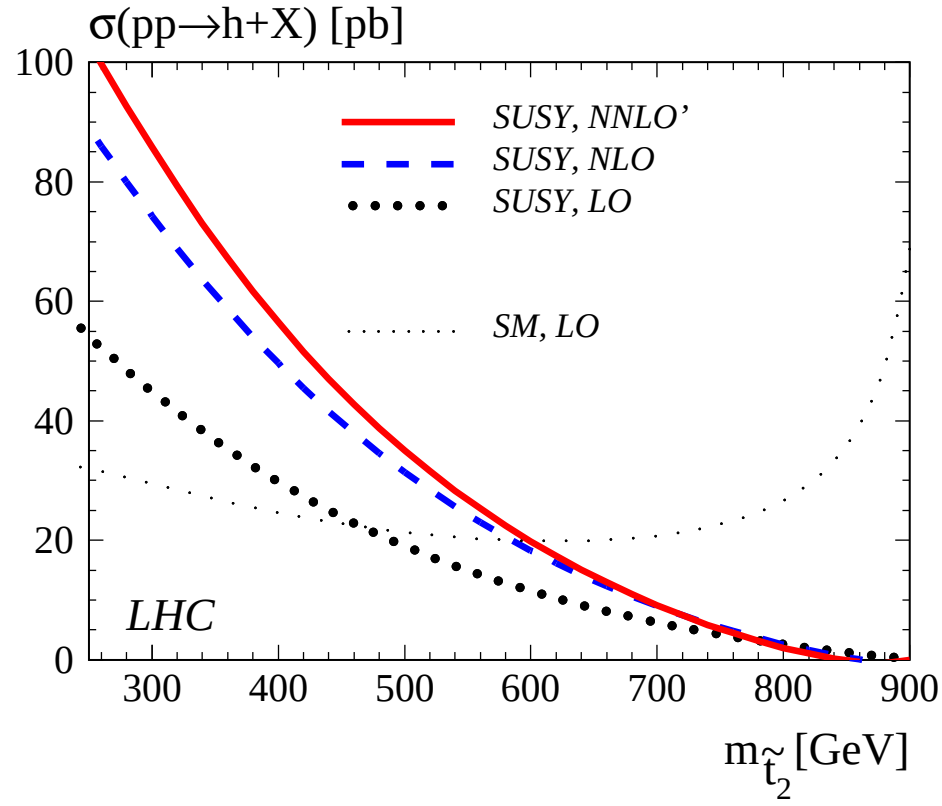
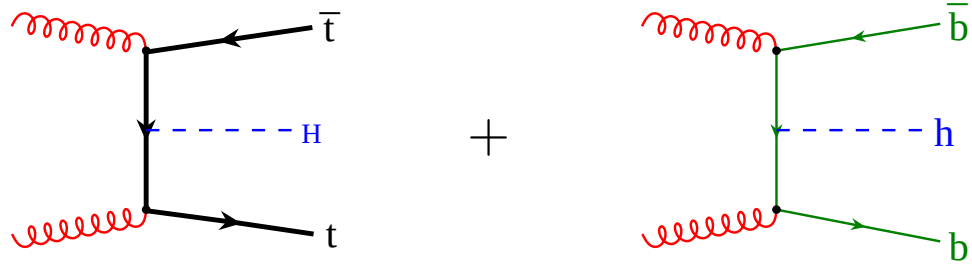


$b\bar{b} \to H$ in SUSY

- modified Yukawa couplings in SUSY:

$$\frac{\lambda_b}{\lambda_t} = \frac{m_b}{m_t} \cdot \frac{v_u}{v_d} = \frac{m_b}{m_t} \cdot \tan\beta$$



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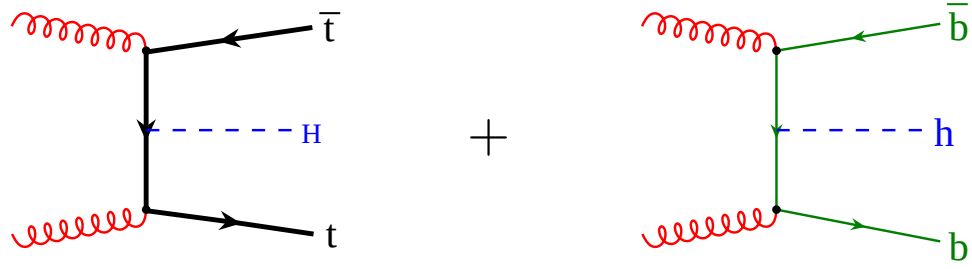

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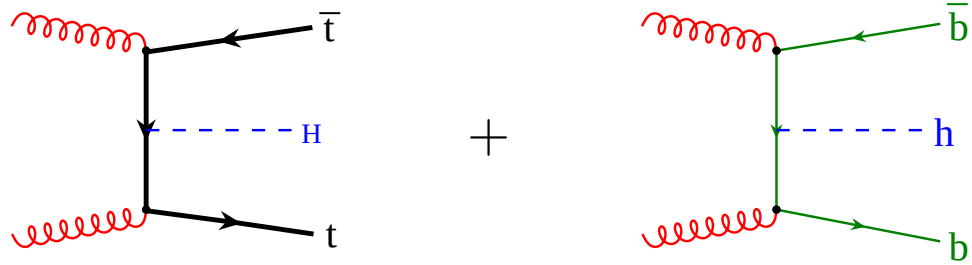

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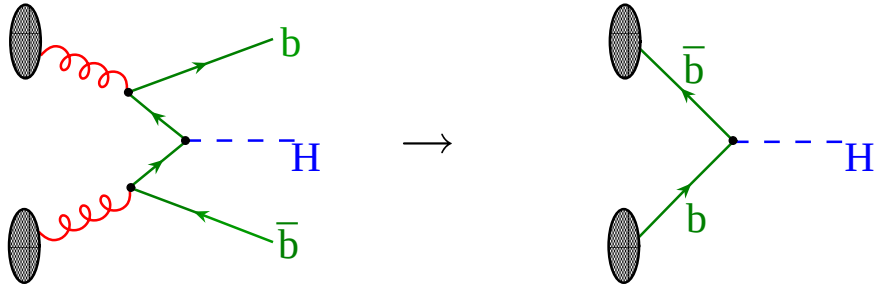
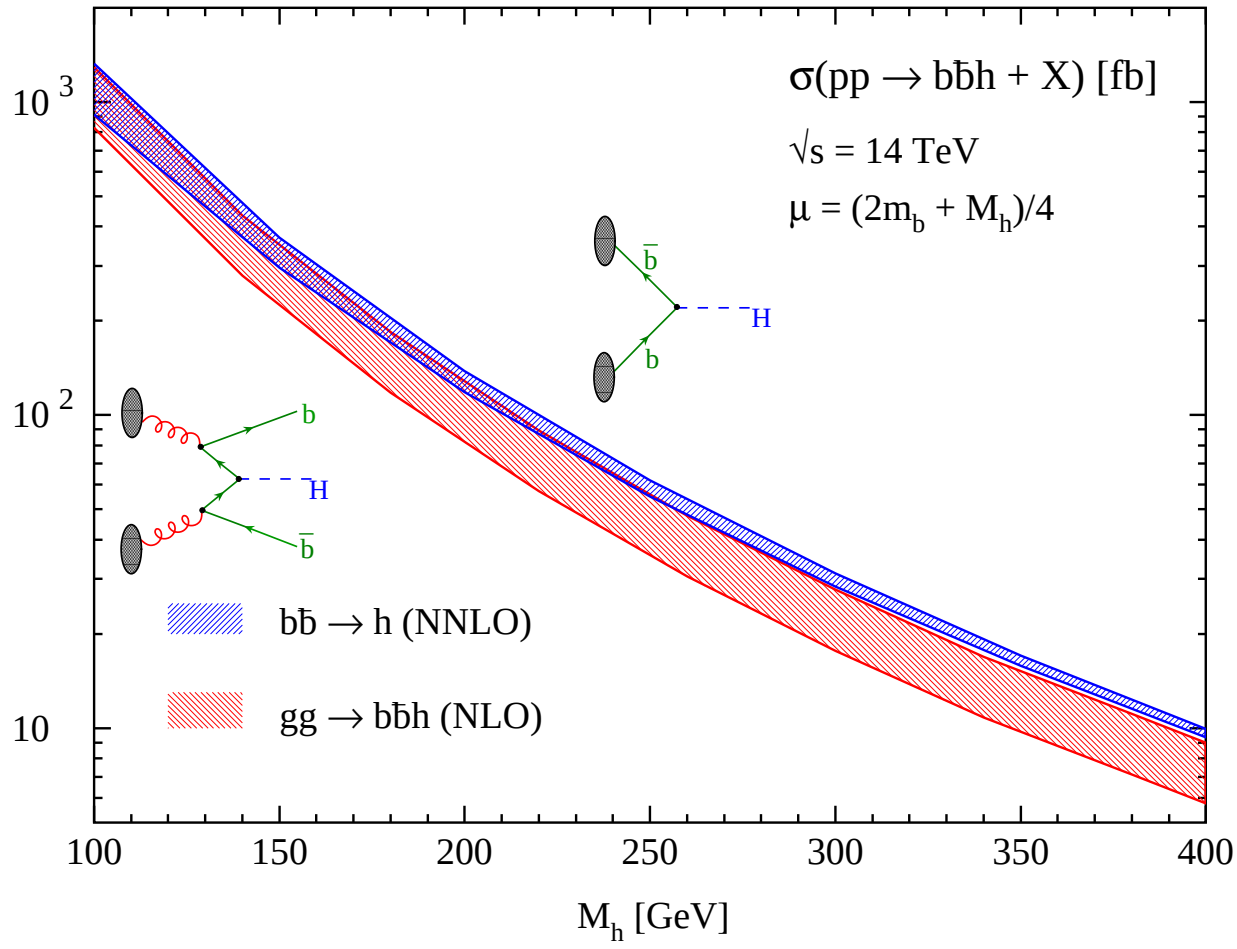


$pp \to H + b\bar{b}$



- $b\bar{b} \to H$: [R.H., Kilgore '03]
- $gg \to b\bar{b}H$: [Dawson *et al.* '04], [Dittmaier *et al.* '04]

What I could not talk about. . .

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- backgrounds

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- backgrounds
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- backgrounds
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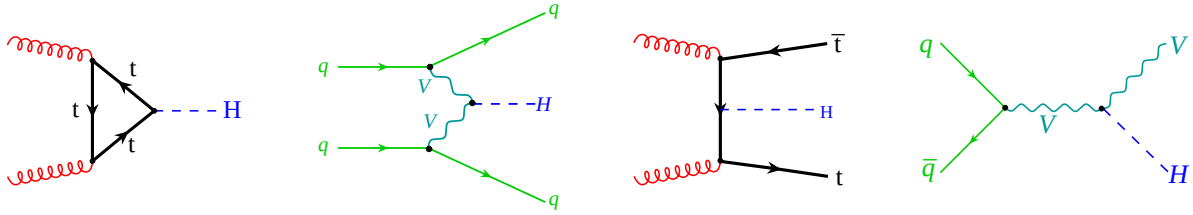

(+ diffractive)

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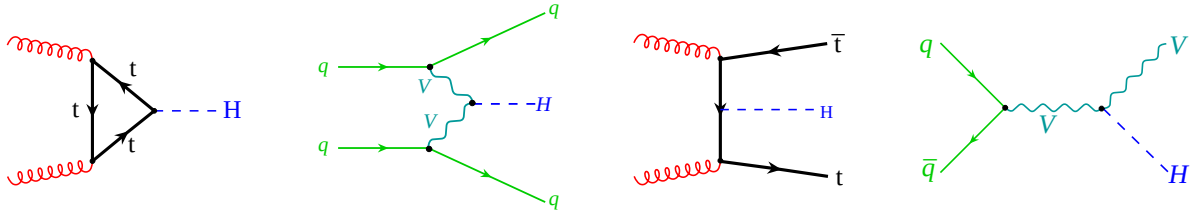

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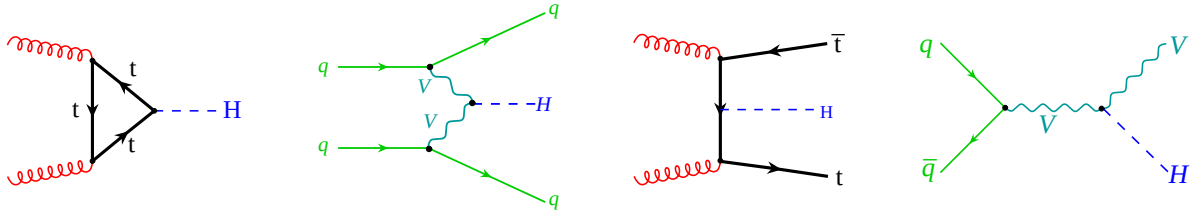

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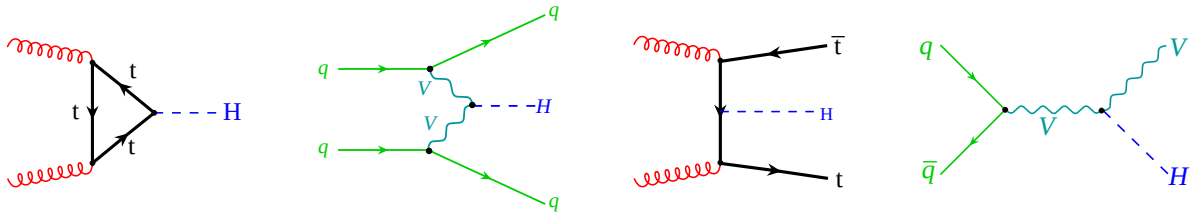

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- combination necessary for Higgs studies
- theory predictions under good control

  $\rightarrow$ triggered many important technical developments
- supersymmetry: much wider field,

  but many results remain valid