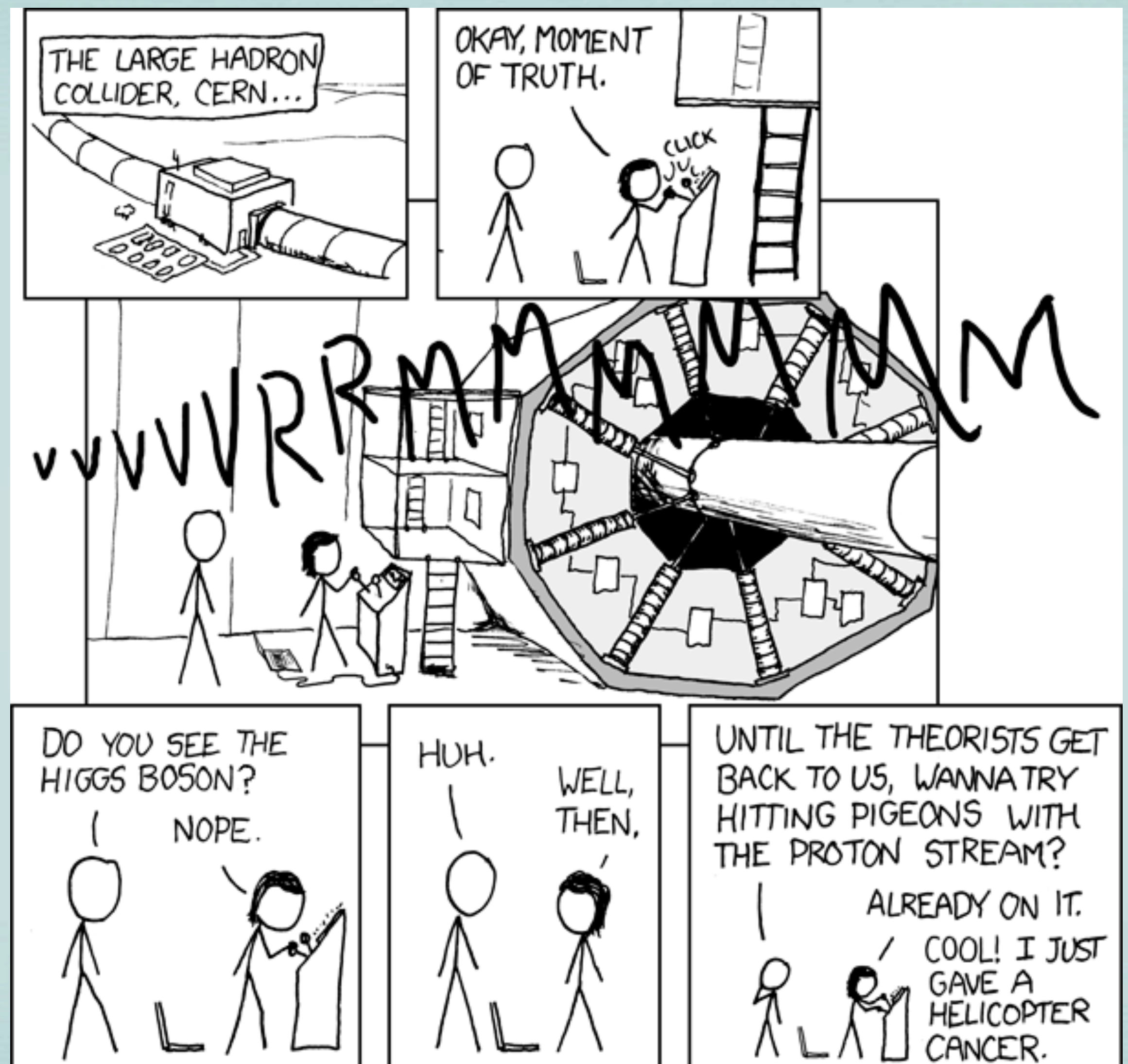
SEARCHING FOR THE HIGGS BOSON



xkcd.com

2009 CTEQ Summer School
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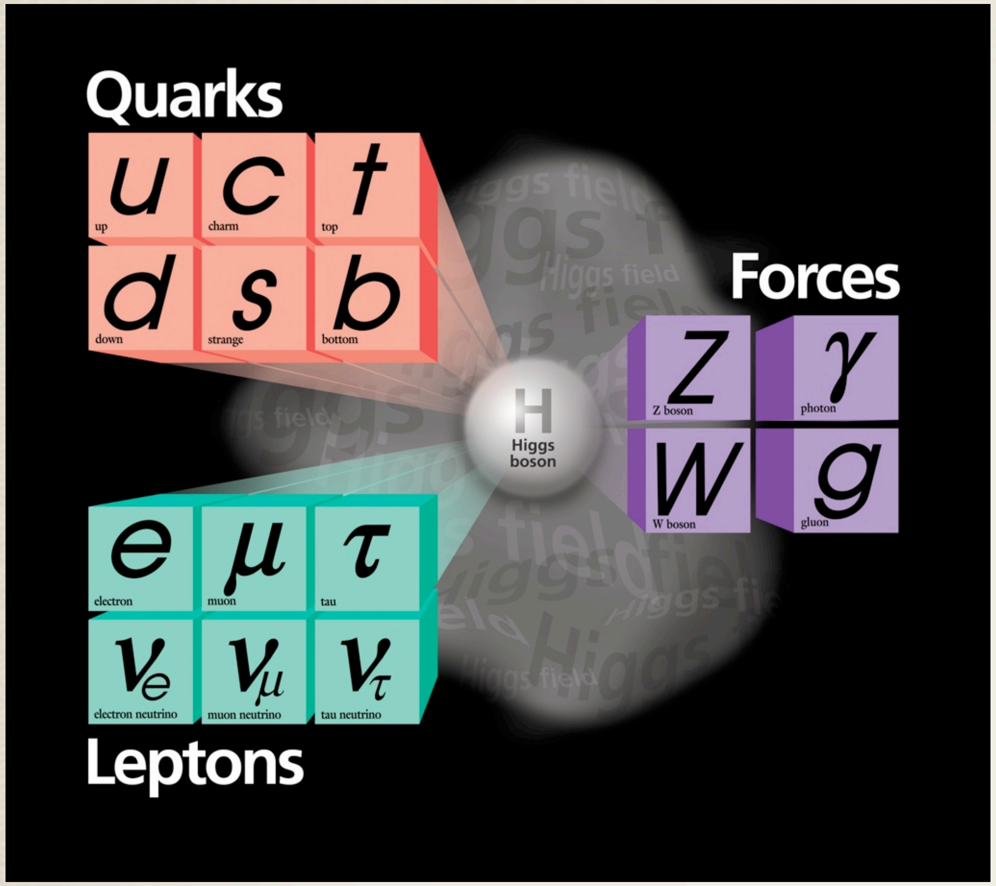
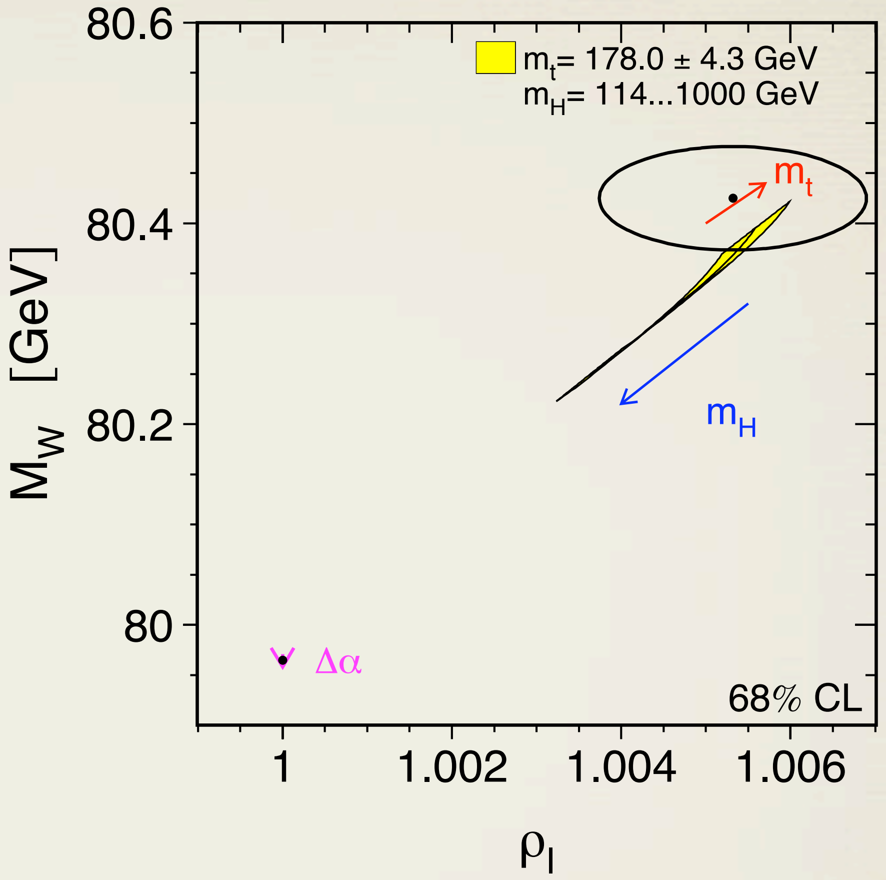
Outline

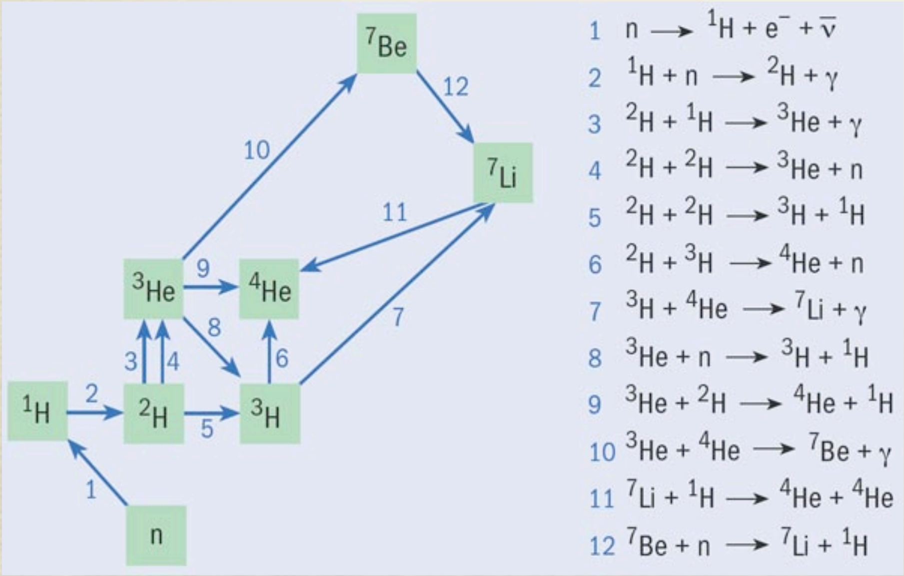
* Quick review of the SM and the Higgs mechanism
* Constraining the Higgs: theoretical constraints and electroweak precision
* A phenomenological profile: decays of the Higgs boson
* Production mechanisms at e^+e^- and hadron colliders
* A case study in QCD: gluon-fusion production
* Searches at the Tevatron and the LHC

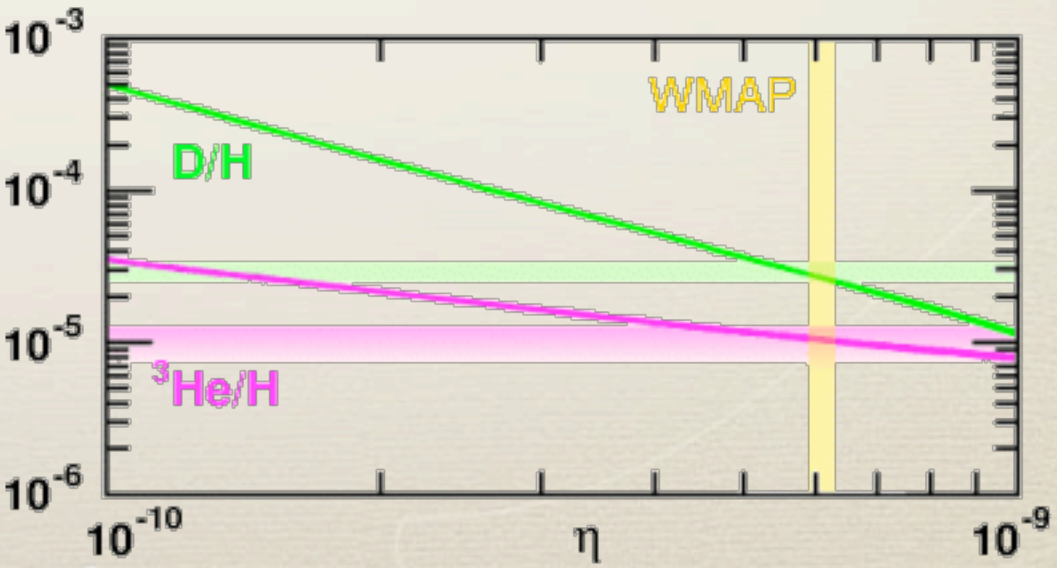
Mostly SM, but will try to mention possible deviations

Success of the Standard Model









Building a gauge theory

* Guiding principle in construction of SM is *gauge symmetry*
* Pick a gauge group
* Assign matter fields (fermions, scalars) to a *representation* of the gauge group, e.g., the *fundamental* N-component vector for SU(N)
* To make the matter Lagrangian gauge invariant, replace $\partial_\mu \to D_\mu$

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + \mathcal{L}_{matter}\left(\Psi, D_\mu\Psi\right)$$

gives Feynman rules for gauge self-interactions

governs gauge-matter interactions

The Standard Model

- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$ (8 gluons; eventually photon, $W^{\pm}$,Z)
- Three generations of fermionic matter

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$:	3	2	1/6
u_R :	3	1	2/3
d_R :	3	1	−1/3
$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$:	1	2	−1/2
e_R :	1	1	−1

- Electric charge: $Q=T_3+Y$

Problems with mass

* The Lagrangian of the SM:

$$\mathcal{L}_{gauge+ferm} = -\frac{1}{4}\overbrace{B_{\mu\nu}B^{\mu\nu}}^{U(1)_Y} - \frac{1}{4}\overbrace{W^a_{\mu\nu}W_a^{\mu\nu}}^{SU(2)_L} - \frac{1}{4}\overbrace{G^a_{\mu\nu}G_a^{\mu\nu}}^{SU(3)_C} + \underbrace{\sum_f i\bar{f}\,\not{D}f}_{f=Q_L,u_R,d_R,L_L,e_R}$$

* We know the $W^\pm$, Z bosons have mass, but this is not allowed by gauge symmetry

$$\mathcal{L}^{SU(2)}_{mass} = \frac{1}{2}m^2 W^a_\mu W_a^\mu \Rightarrow \Delta\mathcal{L}^{SU(2)}_{mass} \neq 0 \text{ under G.T.}$$

* Similarly, fermion mass terms are not allowed by $SU(2)_L$ or $U(1)_Y$

$$\mathcal{L}^{ferm}_{mass} = -m\,\underbrace{\left[\bar{f}_R f_L + \bar{f}_L f_R\right]}_{\text{transforms as } SU(2)_L \text{ doublet, } \sum Y \neq 0}$$

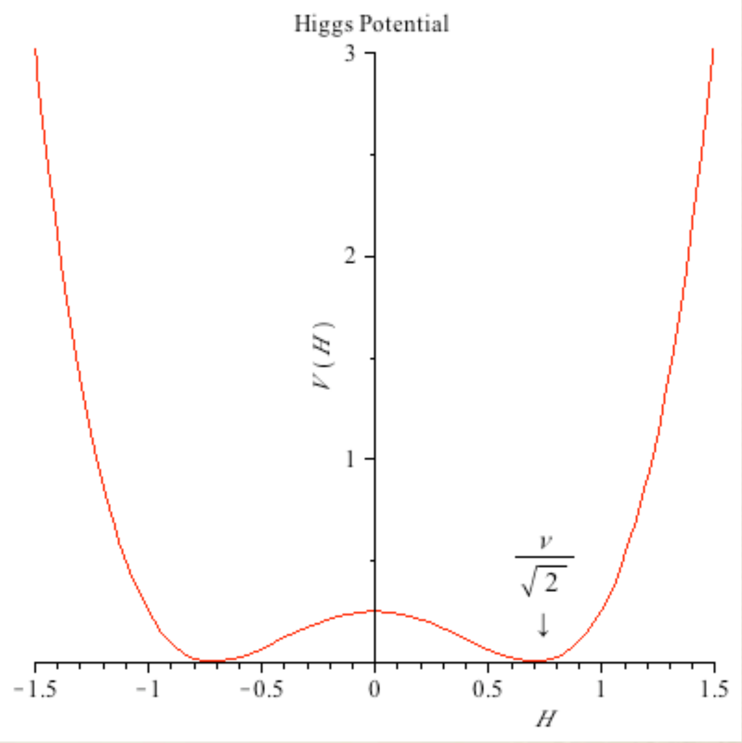
Spontaneous symmetry breaking

- The solution: Lagrangian is symmetric, ground state isn't ⇒ *spontaneous symmetry breaking*
- Complex scalar transforming as (1,2,1/2) under $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{Higgs} = (D_\mu H)^\dagger D^\mu H - \overbrace{\lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2}^{V(H)}$$

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

$$D^\mu = \partial^\mu - igW_a^\mu \frac{\sigma^a}{2} - ig' B^\mu \frac{1}{2}$$



$$\text{Vacuum expectation value: } \langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$\text{Expand around vev: } H = \begin{pmatrix} \phi^+ \\ \frac{v + h + i\chi}{\sqrt{2}} \end{pmatrix}$$

(φ^+,χ can be removed by G.T., set to zero)

The Higgs mechanism

- Work out the kinetic part of Higgs Lagrangian

$$D_\mu H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} - \frac{i}{2}\left[\frac{v+h}{\sqrt{2}}\right]\begin{pmatrix} \sqrt{2} g W_\mu^+ \\ \sqrt{g^2+g'^2} Z_\mu \end{pmatrix}$$

$$(D^\mu H)^\dagger D_\mu H = \frac{1}{2}\partial_\mu h \partial^\mu h + \left(1+\frac{h}{v}\right)^2 \left(\underbrace{\frac{g^2 v^2}{4}}_{M_W^2} W^{\mu +} W_\mu^- + \frac{1}{2} \underbrace{\frac{(g^2+g'^2)v^2}{4}}_{M_Z^2} Z_\mu Z^\mu \right)$$

$$Z_\mu = c_W W_\mu^3 - s_W B_\mu, \; A_\mu = s_W W_\mu^3 + c_W B_\mu, \quad W_\mu^\pm = \frac{W_\mu^1 \mp i W_\mu^2}{\sqrt{2}}$$

$$c_W = \frac{g}{\sqrt{g^2+g'^2}}, \quad s_W = \frac{g'}{\sqrt{g^2+g'^2}}$$

- $W^\pm$, Z acquire mass by "eating" φ^+,χ

Prediction: $\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1$

(tree-level; more later)

Fermion masses

- Yukawa interactions with Higgs doublets give fermions mass

$$\mathcal{L}_{Yuk} = -\lambda_d \bar{Q}_L H d_R - \lambda_u \bar{Q}_L (i\sigma_2 H^*) u_R - \lambda_e \bar{L}_L H e_R + \text{h.c.}$$
$$\Rightarrow -\left(1+\frac{h}{v}\right) \sum_{f=u,d,e} m_f \bar{f} f \quad \text{with} \quad m_f = \frac{\lambda_f v}{\sqrt{2}}$$

(matrix in generation space, implicitly diagonalized at price of V_{CKM} in charged currents)

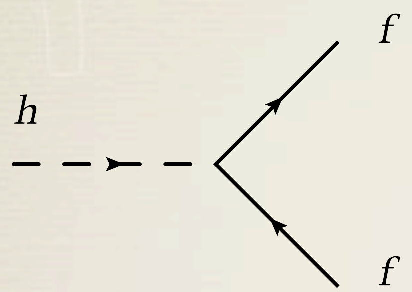
- Sum of all pieces so far give the SM Lagrangian:

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge+ferm} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yuk}$$

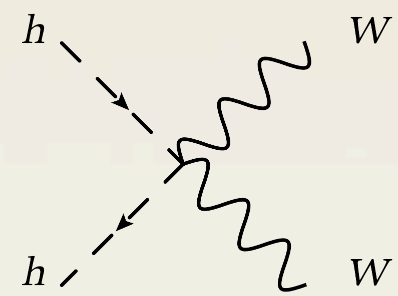
- The single Higgs doublet is just the simplest way to break $SU(2)_L \times U(1)_Y \to U(1)_{EM}$; EWSB could be more intricate.
But this is the benchmark to compare other theories against.

Feynman rules

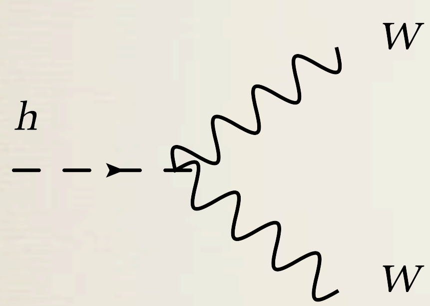
* Work out the experimental predictions with Feynman rules:



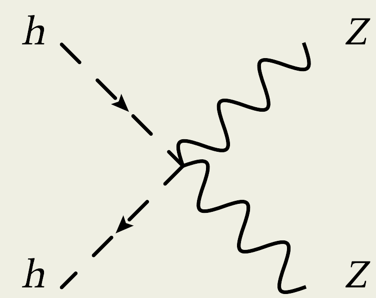
$$= -i\frac{m_f}{v}$$



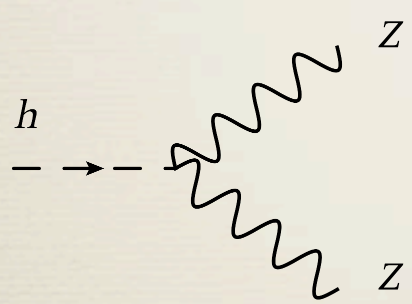
$$= 2i\frac{M_W^2}{v^2}g_{\mu\nu}$$



$$= 2i\frac{M_W^2}{v}g_{\mu\nu}$$



$$= 2i\frac{M_W^2}{v^2}g_{\mu\nu}$$



$$= 2i\frac{M_Z^2}{v}g_{\mu\nu}$$

From muon decay,
$v^2 = 1/(G_F\sqrt{2}) \Rightarrow v \approx 246$ GeV

* Only scalars with vevs have linear HVV couplings

Test the consequences of the Higgs mechanism

Unitarity of S-matrix

- Conservation of probability in QFT:

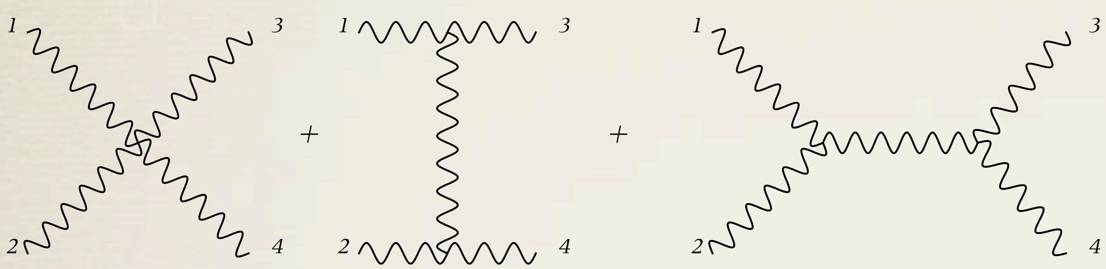
$$S^\dagger S = 1 \;\Rightarrow\; \sigma = \frac{1}{s}\mathrm{Im}\underbrace{\{\mathcal{M}(\theta=0)\}}_{\text{forward scattering}}$$

- Decompose into Legendre polynomials

$$\begin{aligned}
\mathcal{M} &= 16\pi \sum_{l=0}^{\infty}(2l+1)P_l(c_\theta)a_l \\
a_l &= \frac{1}{32\pi}\int_{-1}^{1} dc_\theta\, P_l(c_\theta)\mathcal{M} \\
\Rightarrow \sigma &= \frac{16}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2 \\
&\Rightarrow\; |a_L|^2 = \mathrm{Im}(a_l) \\
&\Rightarrow\; \mathrm{Re}(a_l) \le 1/2
\end{aligned}$$

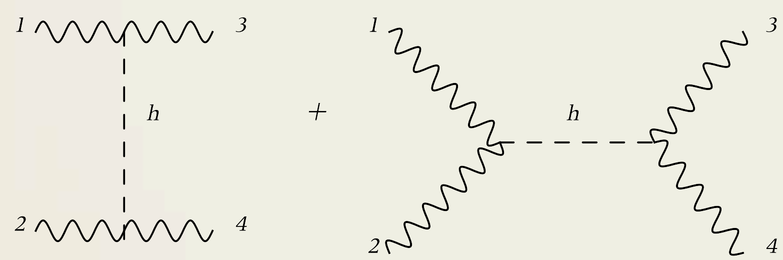
WW scattering

- Longitudinal modes: $\varepsilon_L = (p/M, 0 , 0, E/M)$ (boost from (0,0,0,1))



$$a_0(W_L W_L \to W_L W_L) \to -\frac{s}{32\pi v^2}$$

+

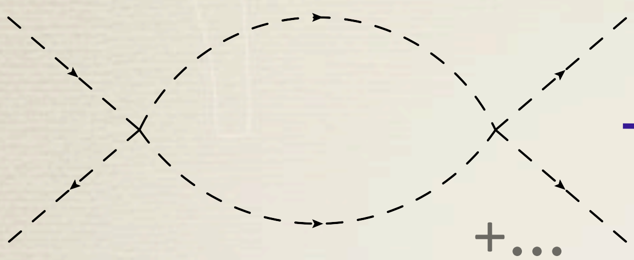


$$a_0(W_L W_L \to W_L W_L) \to -\frac{M_H^2}{8\pi v^2}$$

- Probability not conserved without Higgs; with, M_H<900 GeV (perturbative argument)

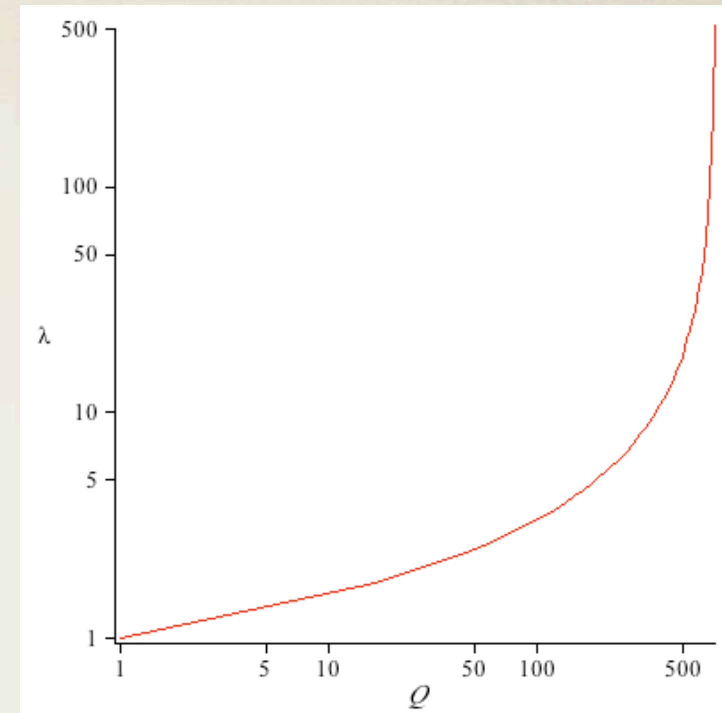
Theoretical constraints

- Landau pole of λh^4 coupling



$$\lambda(Q) = \frac{M_H^2}{2v^2}\,\frac{1}{1-\frac{3}{4\pi^2}\frac{M_H^2}{v^2}\ln\frac{Q}{v}}$$

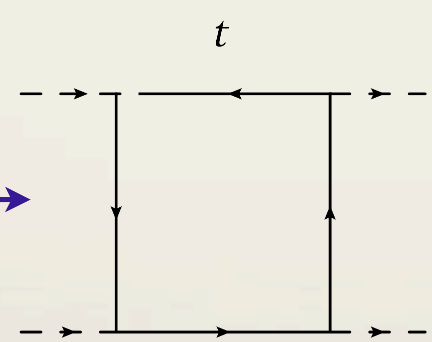
(large λ limit)



Breaks down at some Q
For validity up to Q=Λ (λ<∞),
upper bound on M_H

- Shape of Higgs potential: λ>0 ⇒ lower bound on M_H

top quark drives
coupling negative

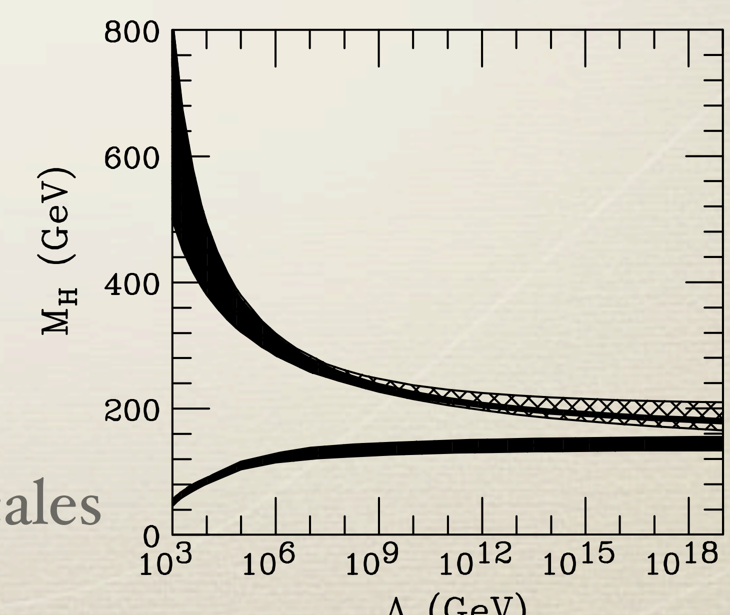


+...

$$\lambda(Q) = \lambda_0 - \frac{\frac{3y_t^4}{8\pi^2}\ln\frac{Q}{Q_0}}{1-\frac{9y_t^2}{16\pi^2}\ln\frac{Q}{Q_0}}$$

(small λ limit)

Validity of SM to high scales
restricts allowed M_H



Electroweak precision

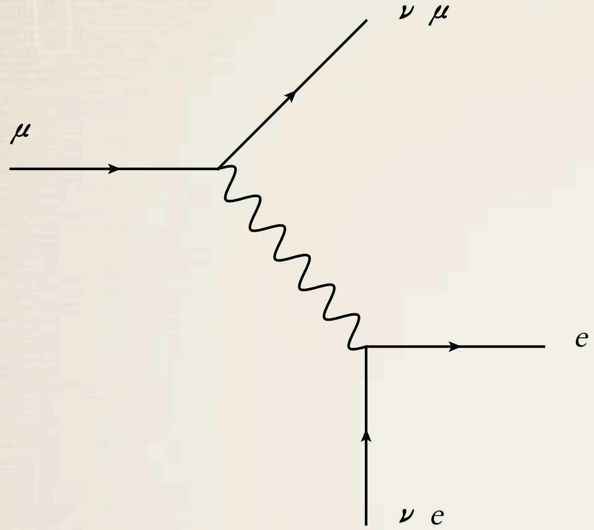
* Can experimentally probe properties of the Higgs directly (try to produce at a collider) or indirectly (through quantum effects)
* LEP+SLC: millions of $e^+e^- \to Z \to f\bar{f}$, high-precision measurements of SM electroweak parameters ⇒ effect of Higgs?
* Study one-loop predictions of SM
* Basic idea in renormalizable theory: fix most precisely known quantities, calculation others in terms of them

$$
\begin{aligned}
G_F &= 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2} \quad \text{(muon decay)} \\
\alpha^{-1} &= 137.035999679(94) \quad \text{(low-energy experiments)} \\
M_Z &= 91.1875(21) \quad \text{(LEP)}
\end{aligned}
$$

* Example: we'll outline prediction for M_W

Muon decay

- Muon-decay at tree-level:



$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2} \quad (m_{e,\mu} = 0)$$

$$s_W^2 = 1 - \frac{M_W^2}{M_Z^2} \quad \text{(on-shell scheme)}$$

$$\Rightarrow \frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\,(1 - M_W^2/M_Z^2)}$$

$$\Rightarrow M_W^2 = \frac{M_Z^2}{2}\left\{1 + \left[1 - \frac{2\sqrt{2}\pi\alpha}{G_F M_Z^2}\right]^{1/2}\right\}$$

$$\approx 80.94 \text{ GeV}$$

$\Rightarrow$ experiment gets 80.4 GeV!

- Keep only leading corrections (m_t, M_H, running of α; others defined as 'small')

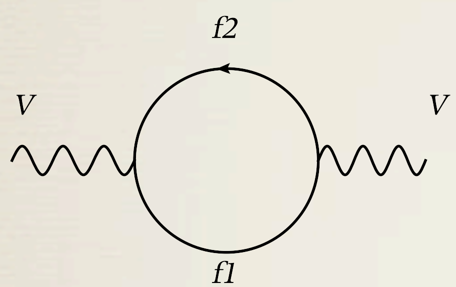
$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1 + \Delta r)$$

$$\Rightarrow M_W^2 = \frac{M_Z^2}{2}\left\{1 + \left[1 - \frac{2\sqrt{2}\pi\alpha\,(1 + \Delta r)}{G_F M_Z^2}\right]^{1/2}\right\}$$

Δρ and non-decoupling

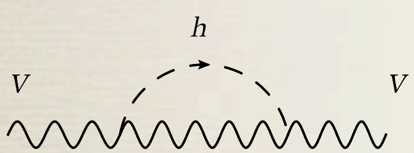
Δr receives important contribution from gauge-boson self-energies

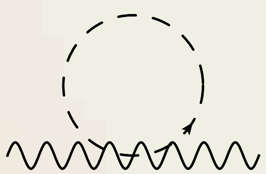
$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho$$
$$\Delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$



$$\Delta\rho_{ferm} = \overbrace{\frac{3G_F m_t^2}{8\pi^2\sqrt{2}}}^{\text{quadratic in } m_t} + \text{subleading terms}$$

Exercise: Derive these





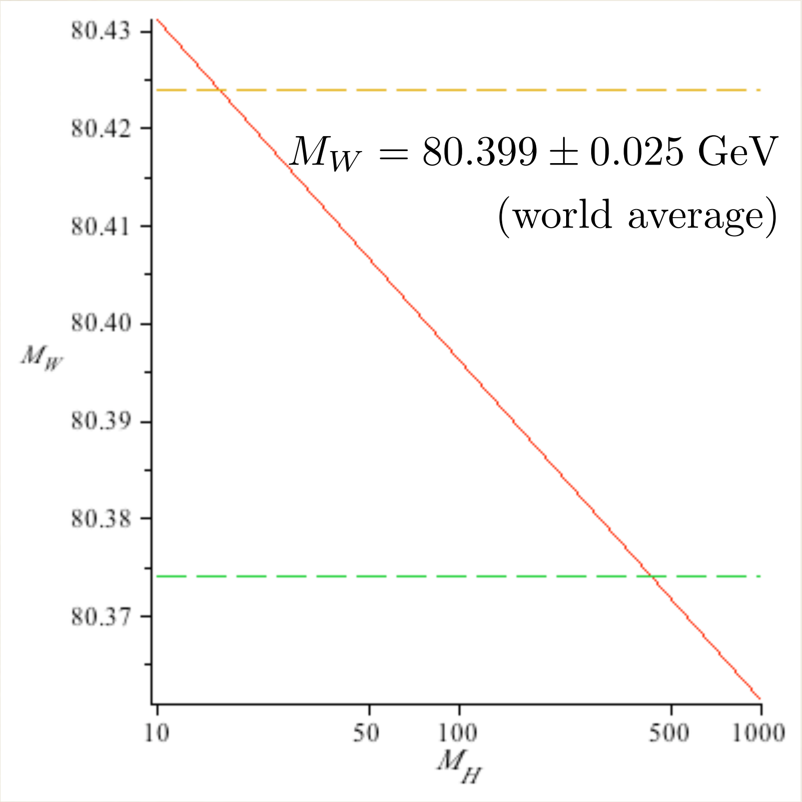
$$\Delta\rho_{Higgs} = -\frac{3G_F M_Z^2 s_W^2}{4\pi^2\sqrt{2}} \underbrace{\ln\frac{M_H}{M_Z}}_{\text{logarithmic in } M_H} + \text{subleading terms}$$

Decoupling theorem holds only if dimensionful parameters made large

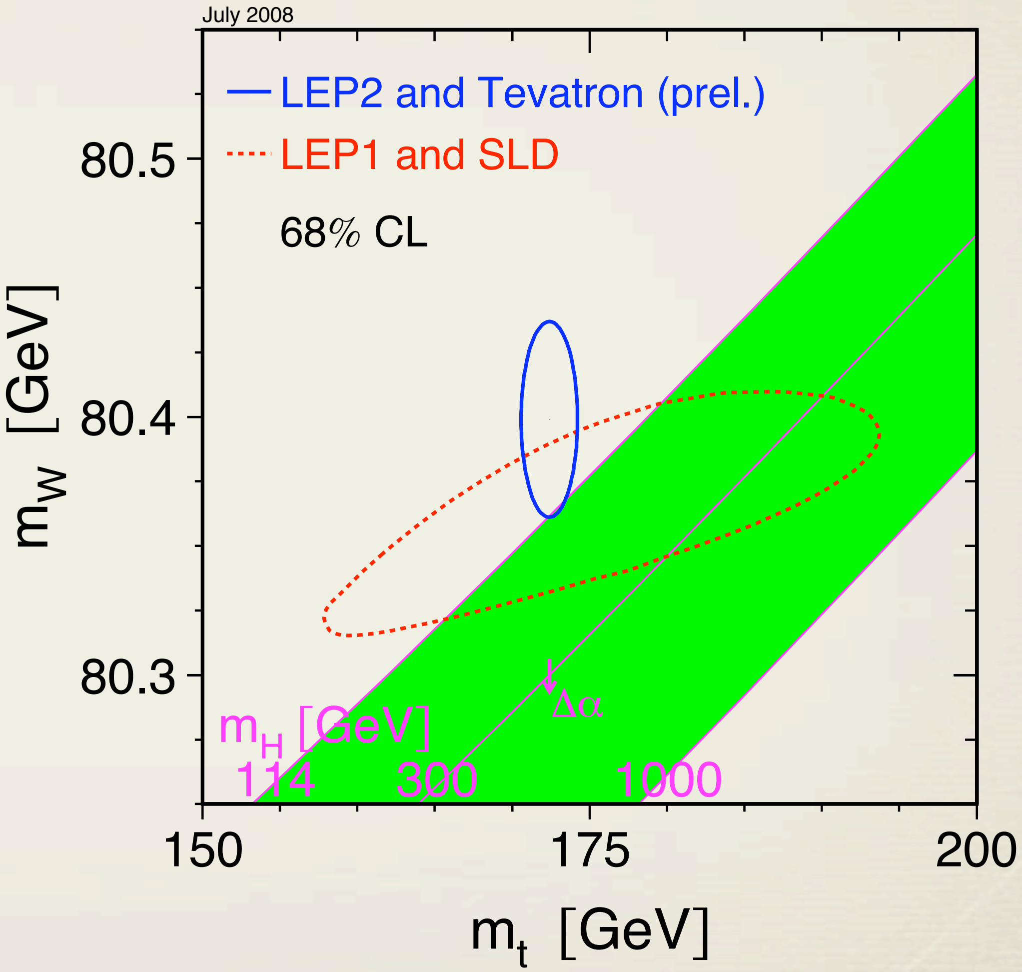
$$m_t = \frac{\lambda_t v}{\sqrt{2}} \quad \Rightarrow \quad m_t \to \infty, \ \ v \text{ fixed} \Rightarrow \lambda_t \to \infty$$
$$M_H^2 = 2\lambda v^2 \quad \Rightarrow M_H \to \infty, \ \ v \text{ fixed} \Rightarrow \lambda \to \infty$$

Bounding the Higgs mass

- Logarithmic dependence on M_H allows M_W to bound it (but very sensitive to the top-quark mass)



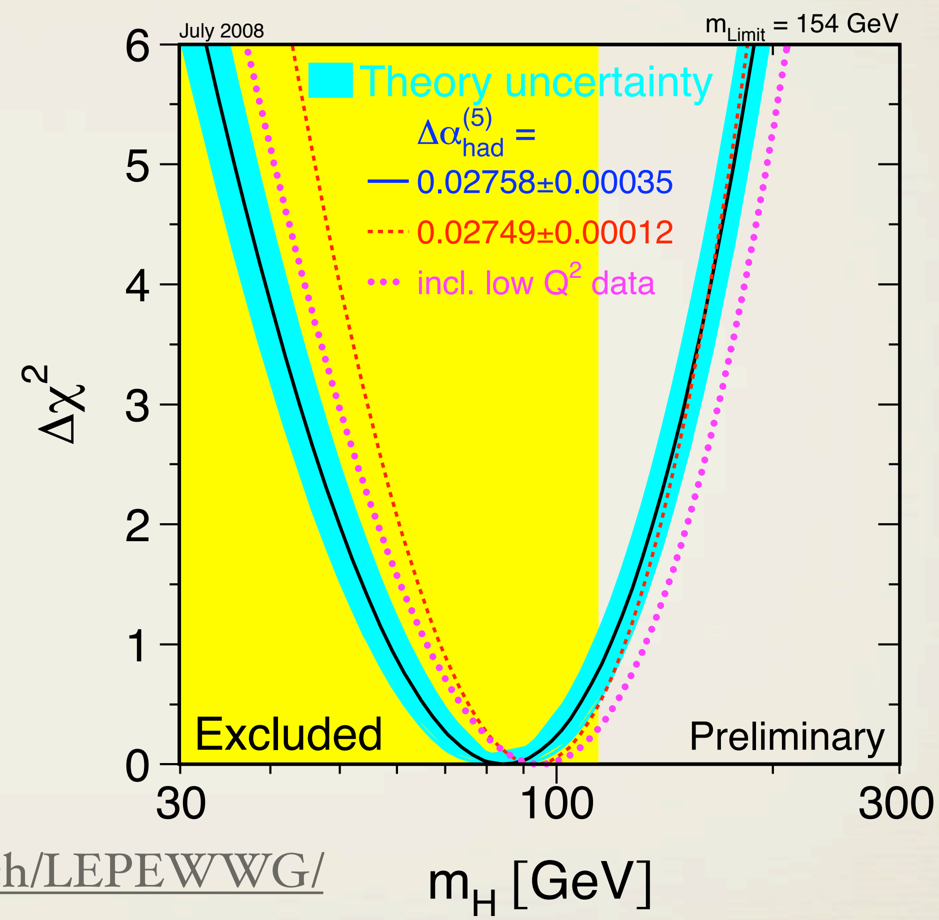
(Refinements needed for real comparison to data; important $\ln(m_t)$ and other terms; see PDG and refs within)



$$M_W^{tree} = 80.94 \text{ GeV} \Rightarrow M_W^{1-loop} = 80.39 \text{ GeV} \ (M_H = 120 \text{ GeV})$$

Global EW fit

- Do the same for large set of LEP-SLC measurements



http://lepewwg.web.cern.ch/LEPEWWG/

SM Higgs mass: M_H<~160 GeV from EW precision measurements

S, T, and hiding a heavy Higgs

- How robust are these bounds? Consider corrections that are *oblique:* affect only gauge boson propagators

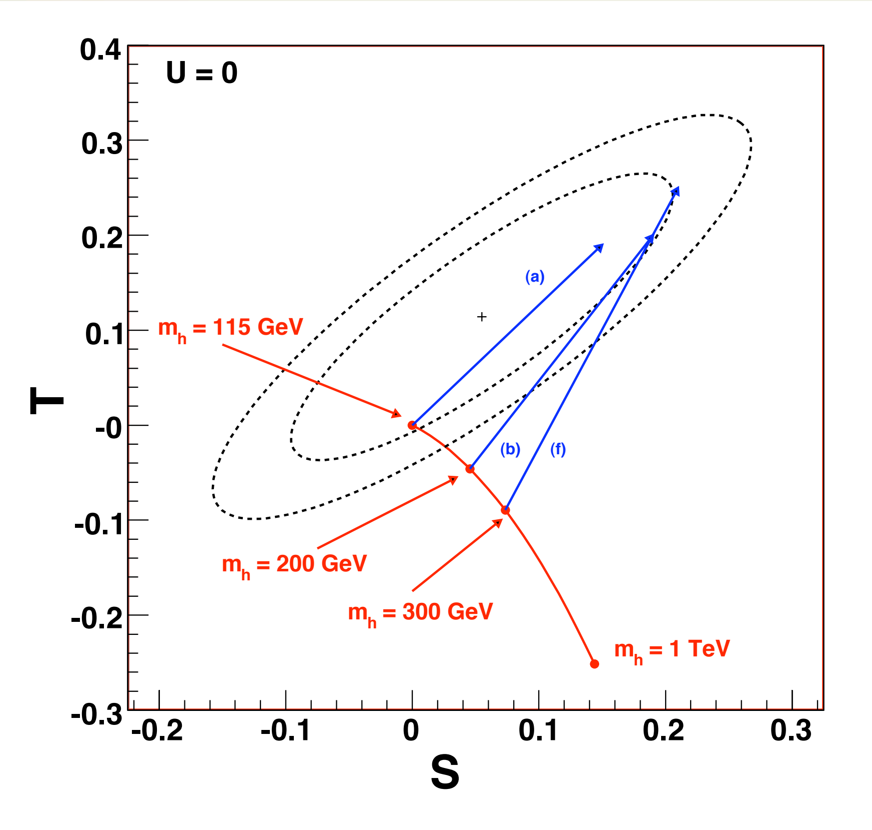
$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \Delta\rho$$

$$\frac{\alpha}{4 s_W^2 c_W^2} S = \frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

(Not a complete basis, but these are often the most important ones)

- Calculate for reference M_H, propagate through all EW parameters

Example: 4th generation (Kribs et al., 0706.3718)



$$\Delta\rho_{new} = \frac{3G_F \overbrace{\Delta m^2_{ferm}}^{\text{doublet mass splitting}}}{8\pi^2\sqrt{2}} - \frac{3G_F M_Z^2 s_W^2}{4\pi^2\sqrt{2}} \ln \frac{M_H}{M_H^{ref}}$$

$\Rightarrow$ increase M_H, cancel with Δm

Need direct searches!

Decays of the Higgs boson

Higgs decays

- Since $g_{Hxx} \sim m_x$, Higgs tends to decay to heaviest kinematically accessible states (with many important caveats...)
- Tree-level decays to various massive final states:

$$\Gamma_{qq} = N_c \frac{G_F}{4\sqrt{2}\pi} M_H m_f^2 \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2} \quad , \quad \Gamma_{ll} = \frac{G_f}{4\sqrt{2}\pi} M_H m_f^3 \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$$\Gamma_{VV} = \frac{G_F}{8\sqrt{2}\pi n_V} M_H^3 \left(1-4x\right)^{1/2} \left(1 - 4x + 12x^3\right) \text{ with } x = \frac{M_V^2}{M_H^2}, n_W = 1, n_Z = 2$$

- Threshold structure depends on spin, CP (3/2→1/2 for CP-odd A)
- Note $\Gamma_{ff} \sim M_H$, while $\Gamma_{VV} \sim (M_H)^3 \Rightarrow$ when W, Z channels open, Higgs becomes very broad
- For light Higgs ($M_H \leq 130$ GeV), expect bb, ττ, cc to be important

Equivalence theorem

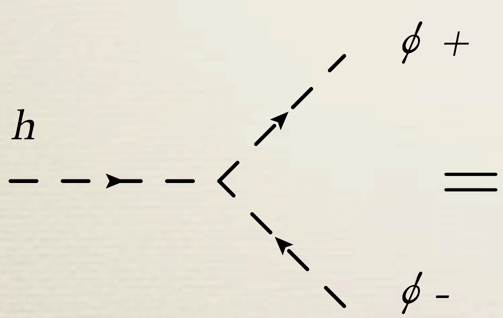
- Growth of VV width comes from longitudinal gauge modes

$$\mathcal{A}(h \to W_L^+ W_L^-) = 2\frac{M_W^2}{v}\epsilon_L^+ \cdot \epsilon_L^-, \quad \epsilon_L^\pm = \frac{E}{M_W}\left(\pm\beta_W, \vec{0}, 1\right)$$

$$\mathcal{A}(h \to W_L^+ W_L^-) \to -\frac{M_H^2}{v} + \mathcal{O}\left(\frac{M_V^2}{M_H^2}\right)$$

$$\Gamma_{WW} = \frac{1}{16\pi M_H}|\mathcal{A}|^2 \to \frac{G_F M_H^3}{8\pi\sqrt{2}} + \mathcal{O}\left(\frac{M_V^2}{M_H^2}\right)$$

- In the high energy limit, longitudinal mode interactions equivalent to those of eaten scalar $\Rightarrow$ *Goldstone boson equivalence theorem*

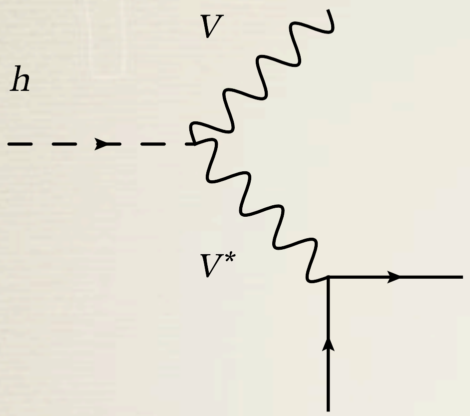


$$= -i\frac{M_H^2}{v} \qquad \mathcal{A}(h \to \phi^+\phi^-) = -\frac{M_H^2}{v}$$

Exercise: Work out from L_{Higgs}

Three-body decays

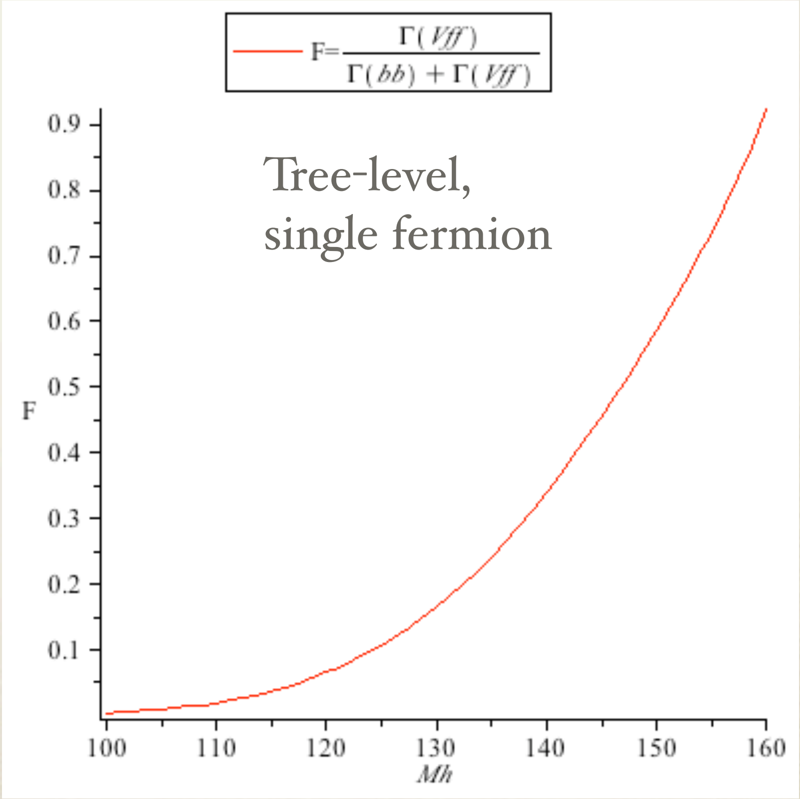
* Since $M_{W,Z} >> m_{b,c,\tau}$, $H \to VV^* \to Vf\bar{f}$ important for $M_H < 2M_{W,Z}$



$$\Gamma_{W\bar{f}f} = \frac{3G_F^2 M_W^4}{16\pi^3} M_H \left\{ \frac{3(1-8x+20x^2)}{\sqrt{4x-1}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)\ln x \right\}$$

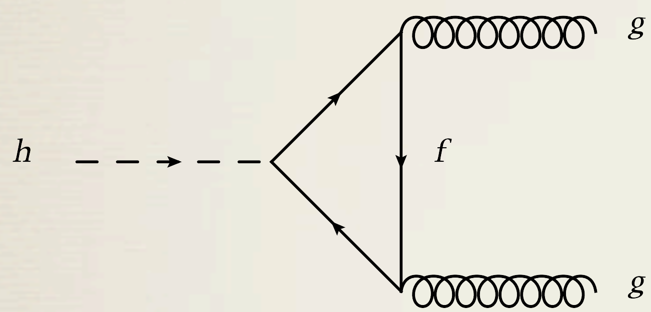
$$x = M_W^2/M_H^2$$

* Important mode even down at $M_H \approx 130$ GeV since f=e,μ



Loop-induced H→gg

- Can we leverage the large Htt, HVV couplings at low M_H?
- Two important cases: h→gg (production more important), h→γγ



$+$ *crossed diagram*

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 M_H^3}{36\pi^3\sqrt{2}} \left| \frac{3}{4} \sum_Q \mathcal{F}_{1/2}(\tau_Q) \right|^2 \quad \text{with } \tau_Q = \frac{M_H^2}{4m_Q^2}$$

$$\mathcal{F}_{1/2}(\tau) = \frac{2}{\tau^2}\left[\tau + (\tau - 1) f(\tau)\right]$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \leq 1 \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

$$\tau \to 0 \quad \Rightarrow \quad \mathcal{F}_{1/2} \to \frac{4}{3}$$

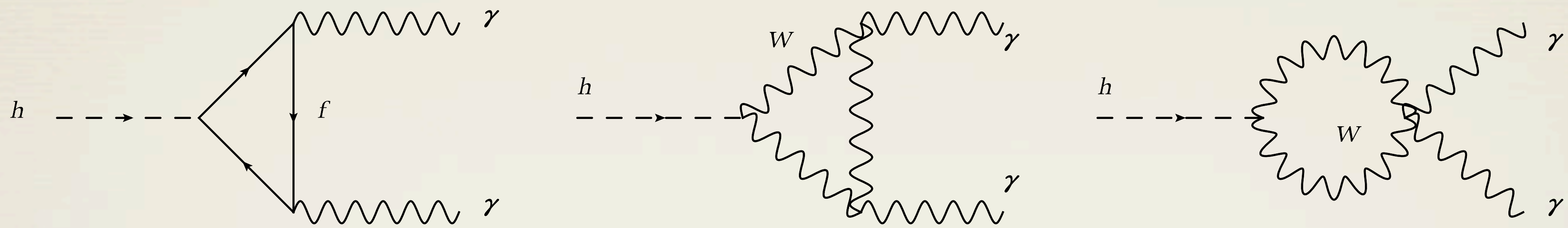
$$\tau \to \infty \quad \Rightarrow \quad \mathcal{F}_{1/2} \to -\frac{2m_Q^2}{M_H^2} \ln \frac{M_H^2}{m_Q^2}$$

- Independent of m_f when $m_f \to \infty$ ⇒ true for *any* heavy fermion that gets its mass from Higgs

Exercise: Derive $m_t \to \infty$ result from direct integration

Loop-induced H→γγ

- Crucial for low-mass Higgs search at LHC



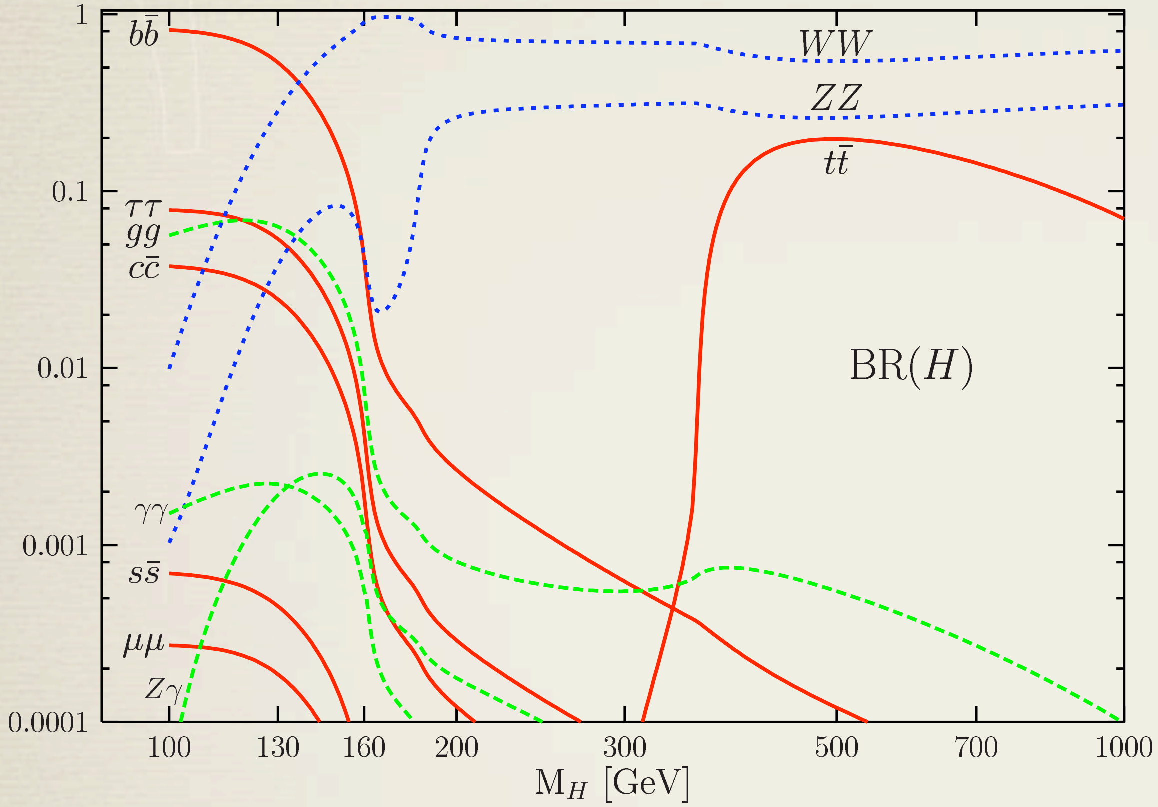
$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 M_H^3}{128\pi^3\sqrt{2}} \left| \sum_f N_c Q_f^2 \mathcal{F}_{1/2}(\tau_f) + \mathcal{F}_1(\tau_W) \right|^2$$

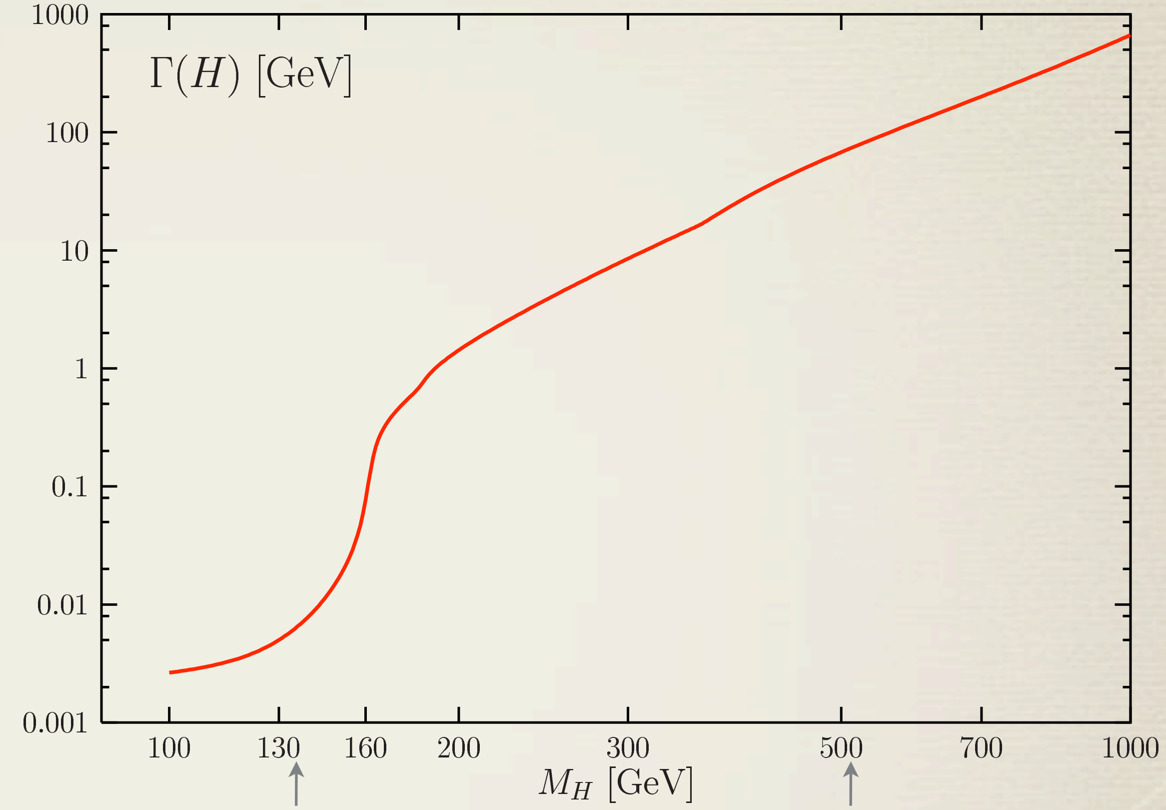
$$\mathcal{F}_1(\tau) = -\frac{1}{\tau^2}\left[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)\right]$$

$\tau \to 0 \Rightarrow \mathcal{F}_1 \to -7$

W contribution larger than top-quark, they interfere destructively

Putting it all together





$\Gamma/M \sim 10^{-5}$ $\Gamma/M \sim 0.2$

Most important channels:

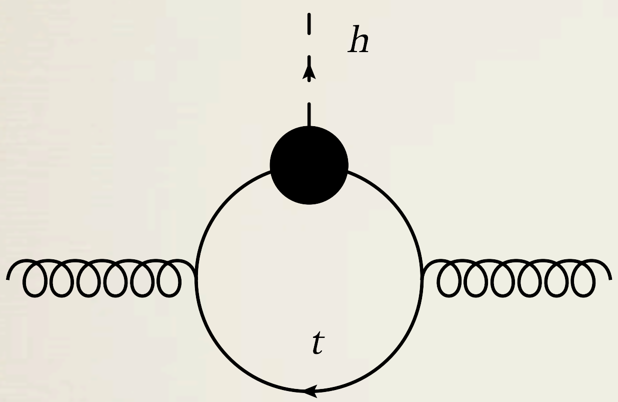
$M_H \leq 130$ GeV: bb, ττ, γγ (clean signature)

$M_H \geq 130$ GeV: WW, ZZ

(boundaries are rough)

Refinement: low-energy theorems

- Can exactly calculate QCD corrections to h→gg, γγ (two-loop diagrams plus real radiation for gg decay) Djouadi, Spira, Zerwas early 1990s
- Useful, illuminating alternative approach for $2m_t > M_H$



$$\frac{i}{\not{k} - m_t} \quad \rightarrow \quad \frac{i}{\not{k} - m_t} \frac{-im_t}{v} \frac{i}{\not{k} - m_t} = i\frac{m_t}{v}\left(\frac{1}{\not{k} - m_t}\right)^2$$

$$= \frac{m_t}{v}\frac{\partial}{\partial m_t}\frac{i}{\not{k} - m_t}$$

Generates both diagrams in the $M_H \rightarrow 0$ limit

- Diagrammatically, clear that Higgs interaction comes from derivatives of the top part of the gluon self-energy:

$$\mathcal{M}(hgg) \underbrace{=}_{p_H \rightarrow 0} \frac{m_t}{v}\frac{\partial}{\partial m_t}\mathcal{M}(gg)$$

Effective Lagrangian

* Integrate out top quark to produce effective Lagrangian

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \mathcal{L}_{top}$$

$$\Rightarrow \underbrace{G^{a\prime}_{\mu}}_{\text{EFT field}} = \zeta_3 \underbrace{G^a_\mu}_{\text{full QCD}}$$

$$\Rightarrow \mathcal{L}_{EFT} = -\frac{\zeta_3}{4} G^{a\prime}_{\mu\nu} G^{\mu\nu\prime}_a$$

Equate propagators in full QCD and EFT

$$-\frac{i g_{\mu\nu}}{p^2}\zeta_3 = -\frac{i g_{\mu\nu}}{p^2} \underbrace{[1+\Pi_t(0)]}_{m_t^2 \gg p^2}$$

$$\Rightarrow \zeta_3 = 1 + \Pi_t(0)$$

$$\Rightarrow \mathcal{L}_{EFT} = -\frac{[1+\Pi_t(0)]}{4} G^{a\prime}_{\mu\nu} G^{\mu\nu\prime}_a$$

* Can generate hgg amplitudes from derivatives of gg amplitudes:

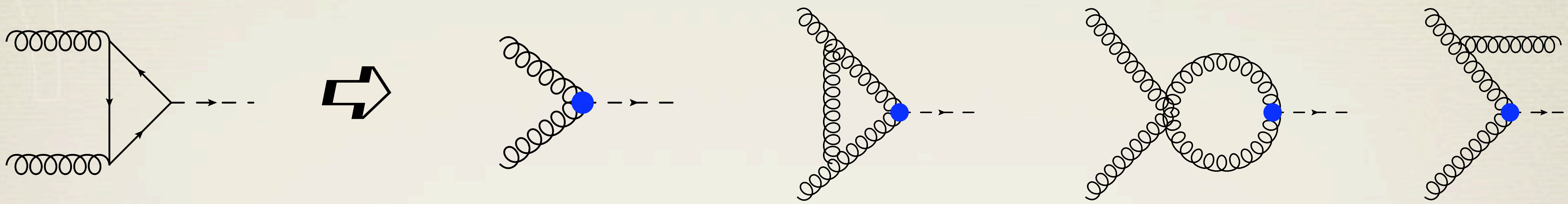
$$\mathcal{L}^{hgg}_{EFT} = -\frac{m_t}{4v}\left(\frac{\partial}{\partial m_t}\Pi_t(0)\right) h\, G^{a\prime}_{\mu\nu} G^{\mu\nu\prime}_a$$

$$\Rightarrow \Pi_t(0) = \frac{\alpha_s}{6\pi}\left[\frac{\bar{\mu}^2}{m_t^2}\right]^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon}$$

$$\Rightarrow \mathcal{L}^{hgg}_{EFT} = \frac{\alpha_s}{12\pi}\frac{h}{v} G^{a\prime}_{\mu\nu} G^{\mu\nu\prime}_a$$

Decay in the EFT

* Reduces 2-loop calculation ⇒ 1-loop; separates m_t dependence



* Systematically improvable to all orders in α_s

$$\mathcal{L}_{EFT}^{hgg} = -C_1 \frac{h}{v} G^{a\prime}_{\mu\nu} G^{\mu\nu\prime}_{a}$$

$$C_1 = -\frac{1}{12}\frac{\alpha_s}{\pi}\left\{1 + \frac{\alpha_s}{\pi}\left(\frac{11}{4} - \frac{1}{6}\ln\frac{\mu^2}{m_t^2}\right) + \ldots\right\}$$

Correction to h→light hadrons:
(must include qq at higher orders)

$$K = 1 + 17.9167\, a'_s + 152.5(a'_s)^2 + 381.5(a'_s)^3$$
$$= 1 + 0.65038 + 0.20095 + 0.01825.$$

Large!

Baikov, Chetyrkin
hep-ph/0604194

* Can do same for h→γγ decay, for W contribution also

For references and subtleties, see Chetyrkin et al. hep-ph/9708255, Kniehl, Spira hep-ph/9504378

Decays beyond the SM

- NMSSM: decays to light CP-odd scalar can produce final states h→aa→bbττ,ττττ,ττγγ,...
- Extended scalar sectors: decays to stable scalars (dark matter) can make Higgs invisible decaying

m_{h_1}/m_{a_1} (GeV)	Branching Ratios $h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau\bar{\tau}$	$n_{\rm obs}/n_{\rm exp}$ units of 1σ	$s95$	N_{SD}^{LHC}
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2

Dermisek, Gunion hep-ph/0510322

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!}S^4$$

h→SS decays can dominate

Burgess, Pospelov, ter Veldhuis NPB 619 (2001); Davoudiasl et al. hep-ph/0405097

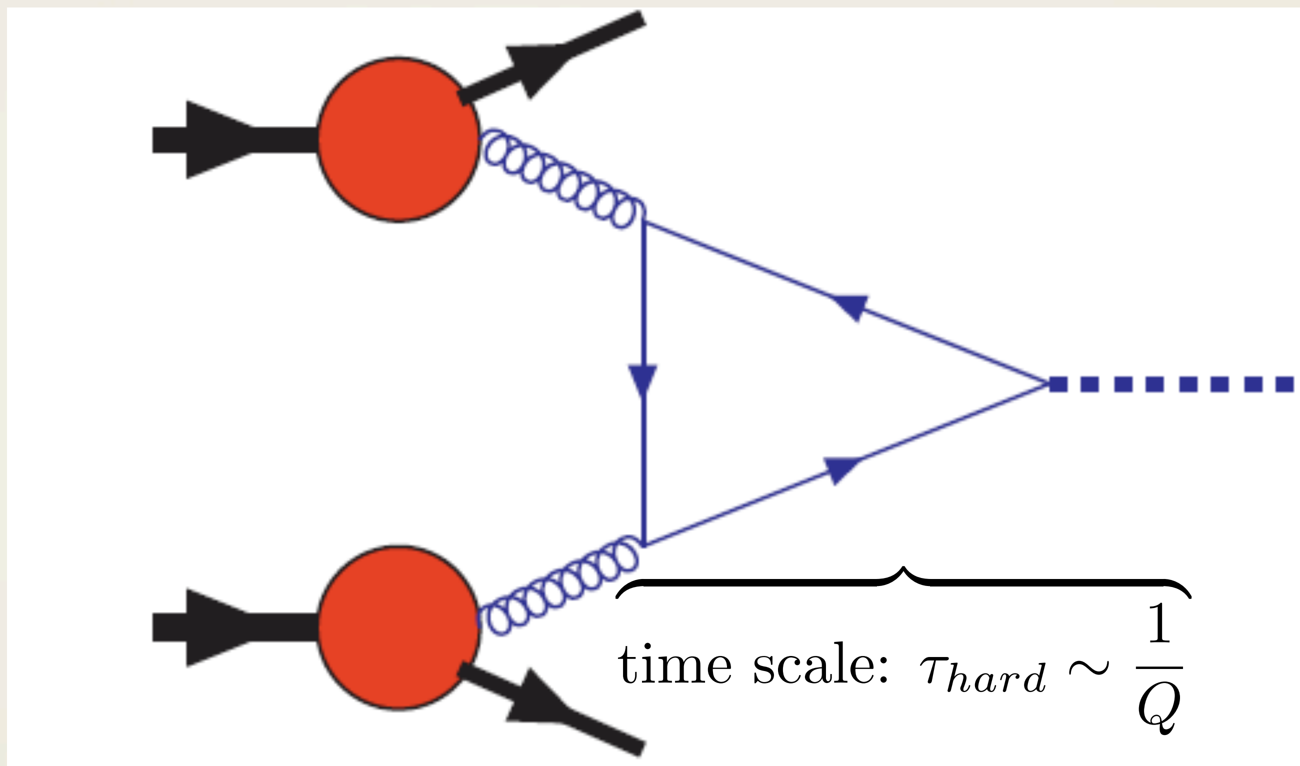
Many deviations, some drastic, from SM predictions possible!

Producing the Higgs boson

Hadron collider basics

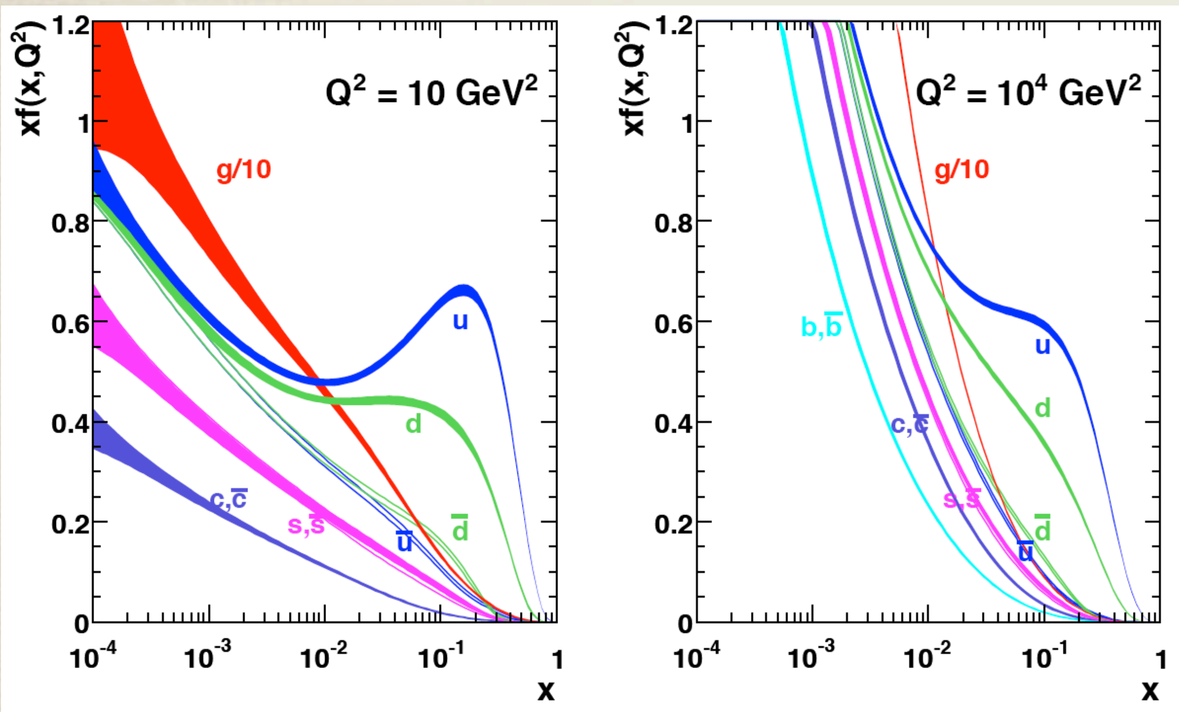
* The basic picture of hadronic collisions: factorize long and short time processes

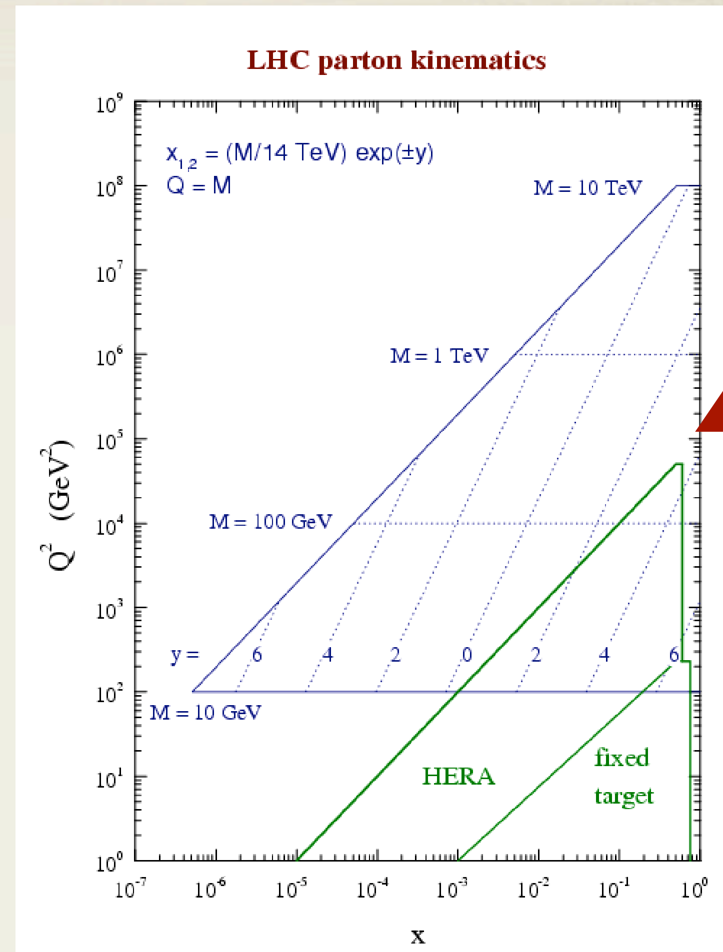
$$\underbrace{\text{time scale: } \tau_{proton} \sim \frac{1}{\Lambda_{QCD}}}$$



$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \, \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij\to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

Parton distribution functions





DGLAP

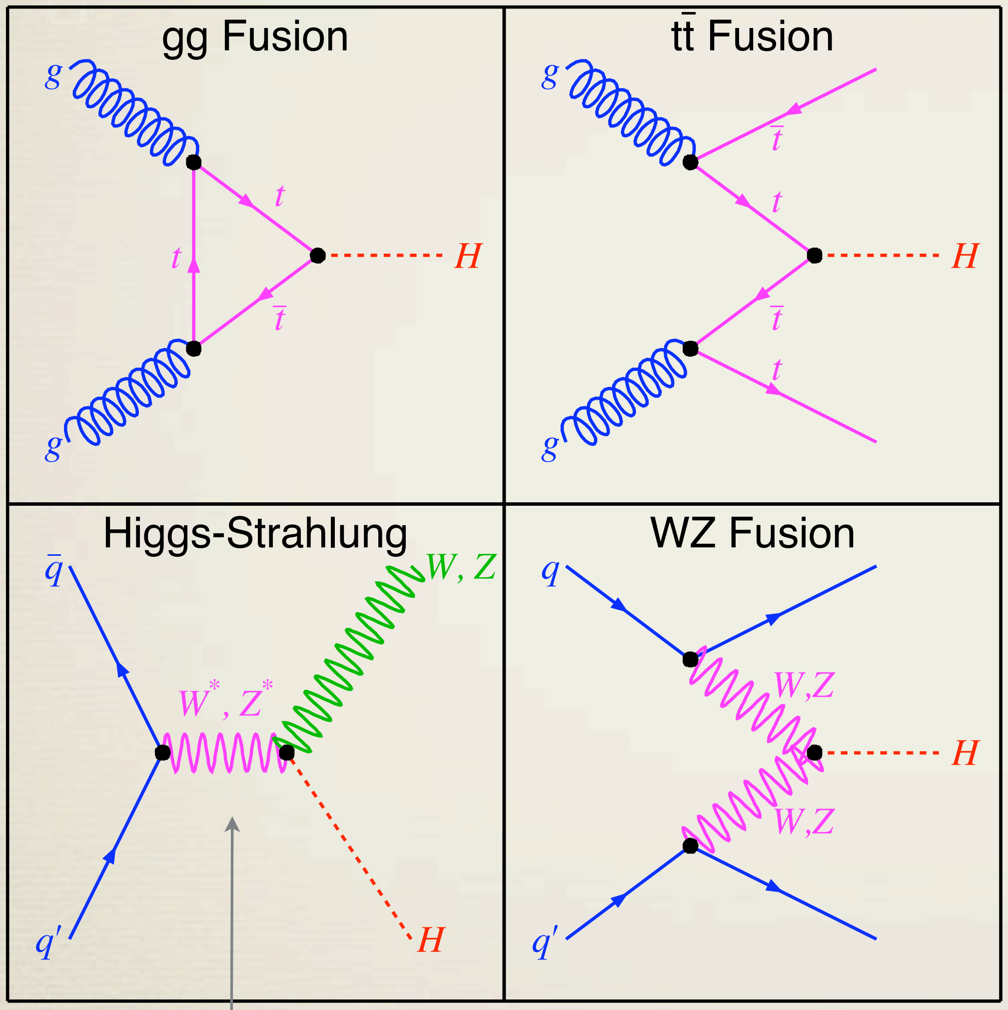
$x \sim M_H/\sqrt{s}$

LHC Tevatron

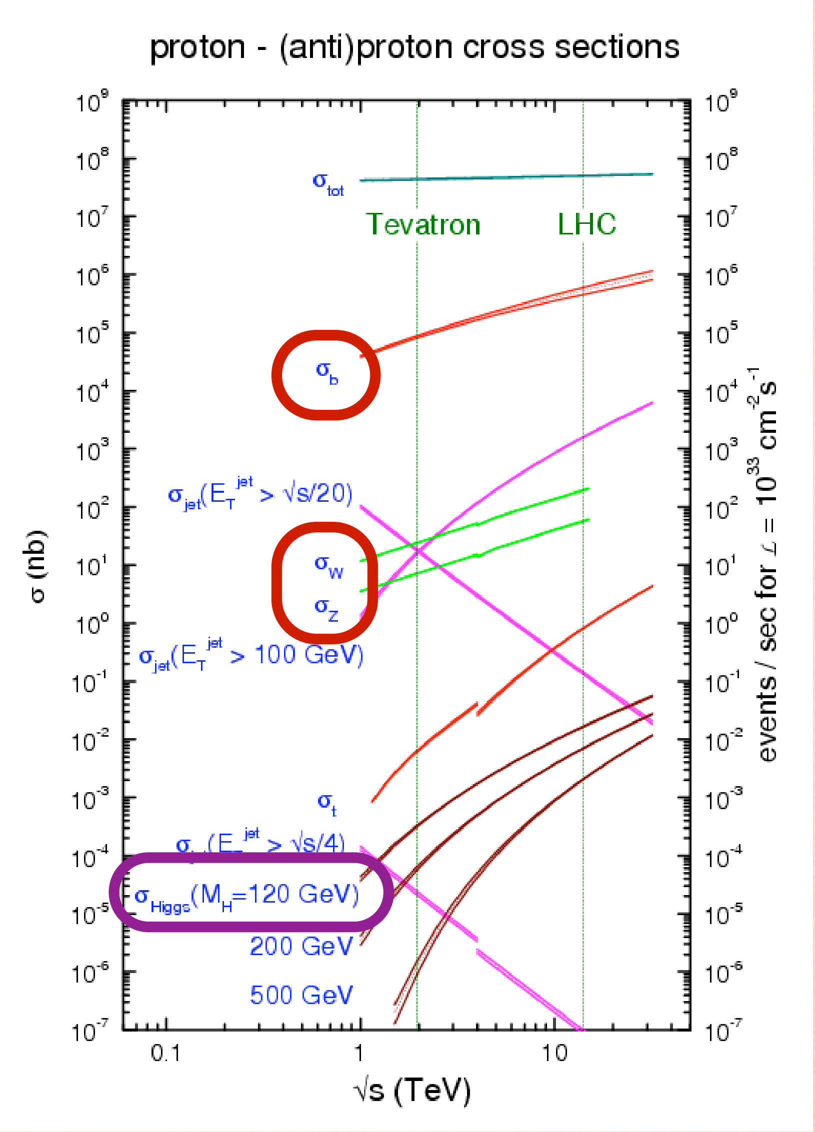
Lots of gluons, at LHC especially

Higgs at hadron colliders

- Clearly want to use large gluon luminosity; W, Z assisted production another option



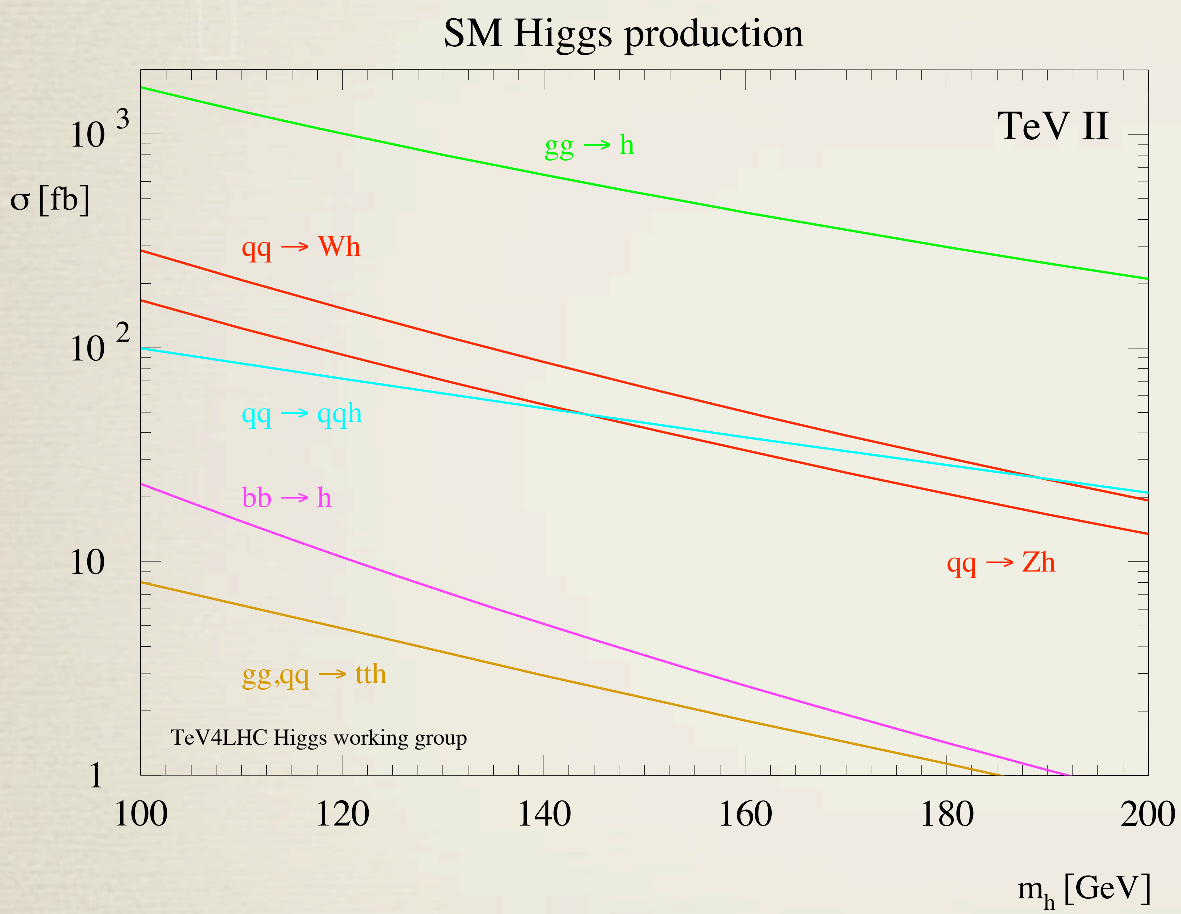
Can't do LEP search, √s not fixed at hadron machine

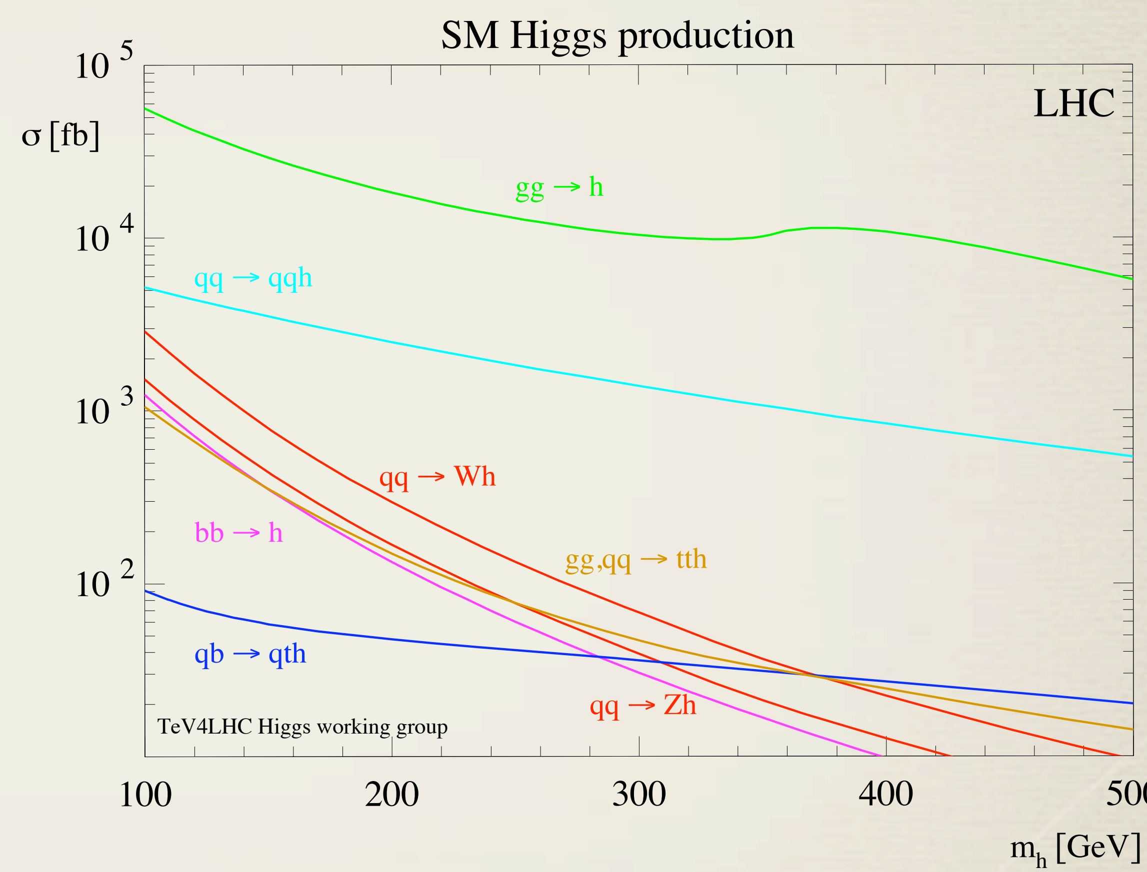


Any hadron collider search must confront backgrounds

Overview of Higgs cross sections

- Gluon-fusion dominant at both colliders; WH next at Tevatron, WBF at LHC

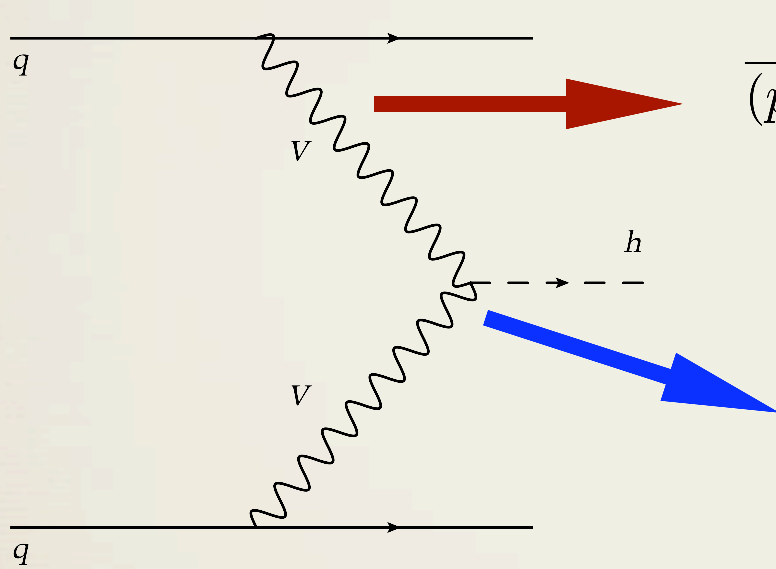




- SUSY: $g_{bbh} \sim \tan^2\beta$; becomes dominant at tan β ~ 10
- Plan: discuss WBF and gluon-fusion properties (some tricky/ interesting aspects), then move on to searches at Tevatron/LHC

Weak boson fusion: effective W/Z

- Important throughout large region of Higgs mass and in many decay modes; forward jets give experimental handle
- First approximation: inclusive cross section for $M_H >> M_{W,Z}$



$$\frac{1}{(p_1 - p_3)^2 - M_V^2} \quad \Rightarrow \quad \text{peaked at } p_1 \cdot p_3 = 0$$

$$\Rightarrow \tau_{q \to V} \quad \sim \quad 1/M_V$$

$$\tau_{VV \to h} \sim 1/M_H \ll \tau_{q \to V}$$

- Should be able to factorize, think of V as a parton in q

$$\sigma_{qq \to VV \to h} = \int dz_1 dz_2 \, f_{q/V_1}(z_1) f_{q/V_2}(z_2) \, \sigma_{VV \to h}$$

WBF + the equivalence theorem

* Can derive when $M_V << \sqrt{s}$ (small angle scattering dominated)

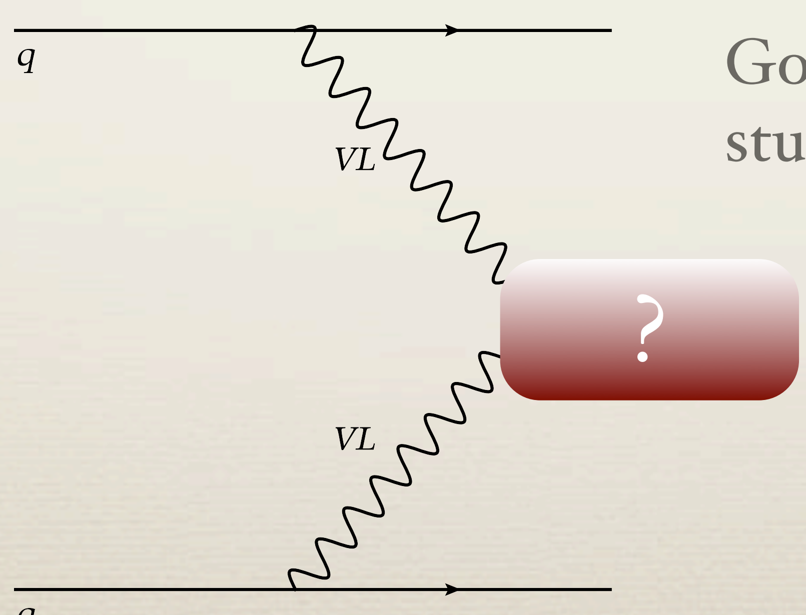
$$\sigma_{q_1 q_2 \to VV \to h} = \int_{2M_V/\sqrt{\hat{s}}}^{1} dz_1 \int_{2M_V/\sqrt{\hat{s}}}^{1} dz_2\, f_{q/V_L}(z_1) f_{q/V_L}(z_2)\, \sigma_{V_L V_L \to h}(z_1 z_2 \hat{s})$$

$$\sigma_{V_L V_L \to h}(x) = \frac{\pi}{36}\, g_{HVV}^2 \frac{x}{M_V^2} \delta(x - M_H^2)$$

$$f_{q/V_L}(z) = \frac{g_v^2 + g_a^2}{4\pi^2} \frac{1-z}{z}$$

Exercise: Derive this

* Angular momentum cons. prevents emission of transverse boson with forward quark: $\bar{u}^{\pm}(p\hat{z})\, \not{\epsilon}\, u^{\pm}(p'\hat{z}) \Rightarrow$ Set $\not{\epsilon} = \gamma^{1,2} \Rightarrow \xi_{\pm}^{\dagger} \sigma^{1,2} \xi_{\pm} = 0$

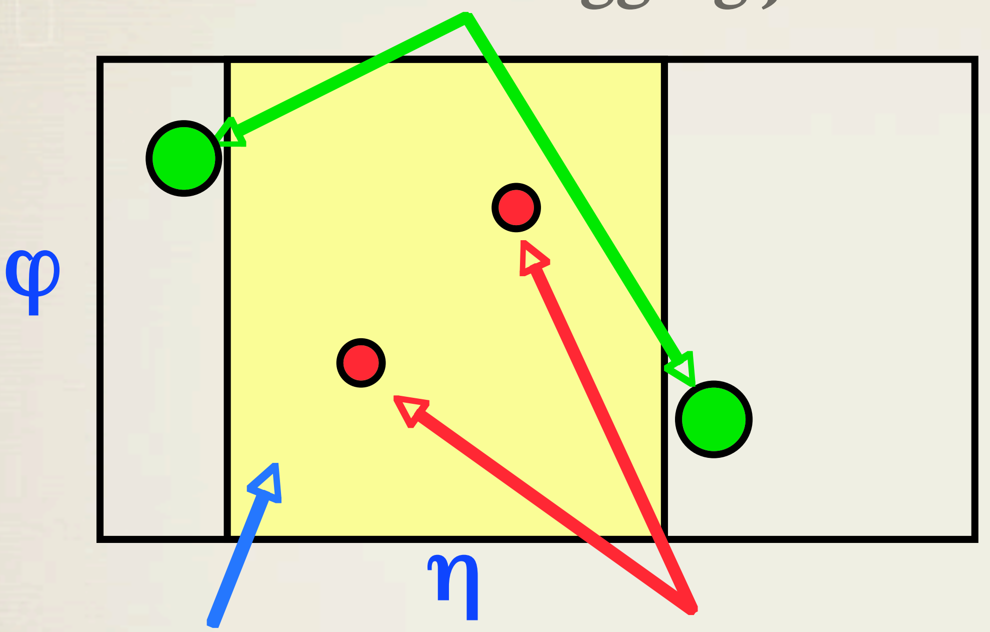


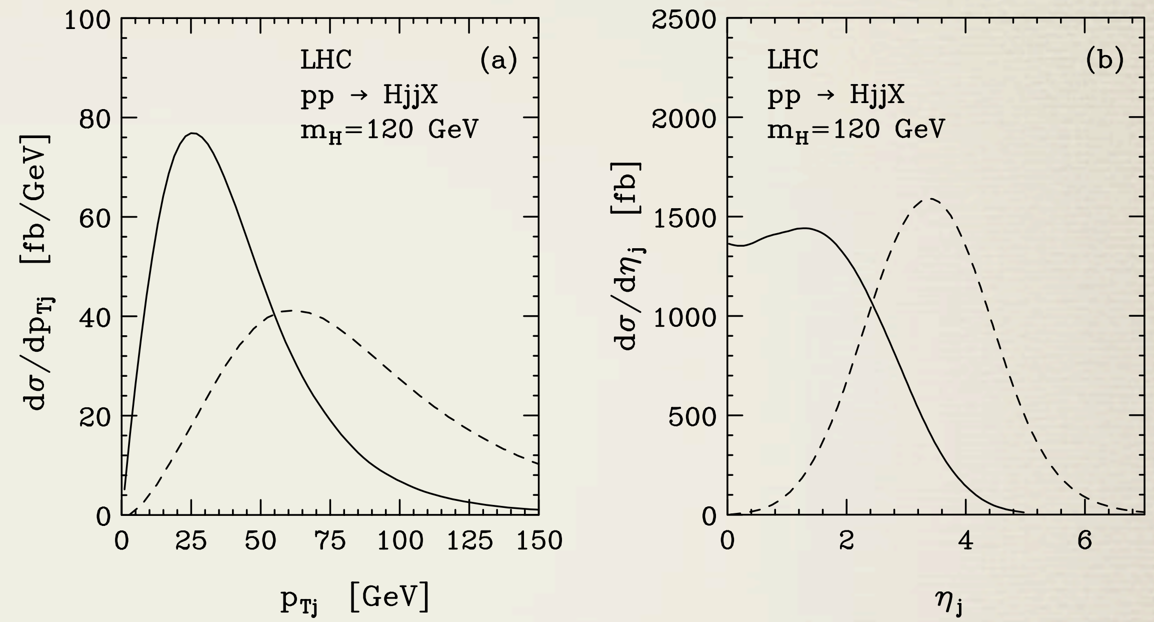
Good channel to study strong EWSB

Dawson 1984; Chanowitz, Gaillard 1985

Kinematics of WBF

- Two energetic (p_T~40 GeV) jets with large rapidity separation





Rainwater, Zeppenfeld hep-ph/9906218
and many others... check refs+citations

- Extra gluon emission suppressed; impose central jet veto

$$\mathcal{M}(q_1 q_2 \to q_3 q_4 h + g) \quad \propto \quad \mathcal{M}(q_1 q_2 \to q_3 q_4 h)\, T^a \left\{ \frac{p_3 \cdot \epsilon_g^a}{p_3 \cdot p_g} + \frac{p_4 \cdot \epsilon_g^a}{p_4 \cdot p_g} - \frac{p_1 \cdot \epsilon_g^a}{p_1 \cdot p_g} - \frac{p_2 \cdot \epsilon_g^a}{p_2 \cdot p_g} \right\}$$

$$\to \quad 0 \;\; \text{since} \;\; p_1 \parallel p_3, \quad p_2 \parallel p_4$$

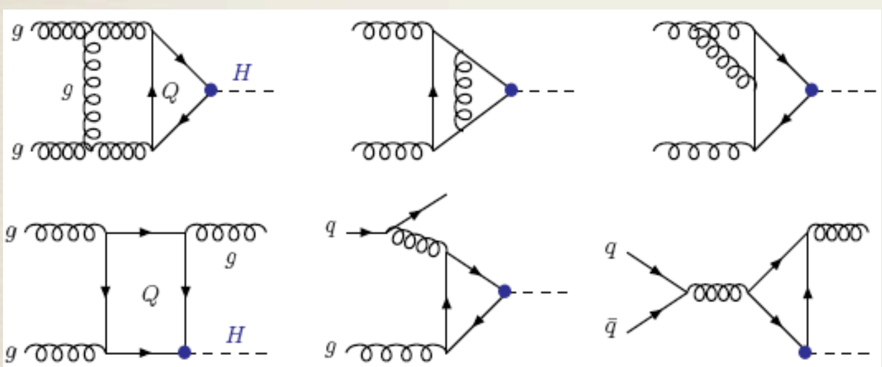
Exercise: Derive this

Gluon fusion production

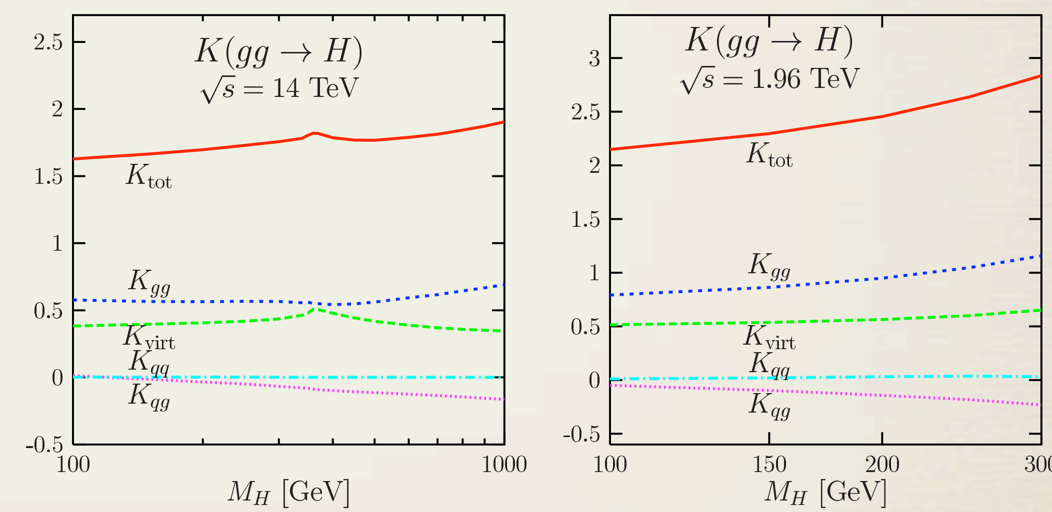
* Largest mode at Tevatron and LHC; through top-quark loops

$$\sigma^{LO}_{gg\to h} = \frac{G_F \alpha_s^2}{288\pi\sqrt{2}} \left| \frac{3}{4} \sum_Q \mathcal{F}_{1/2}(\tau_Q) \right|^2 \delta(1-z), \quad \tau_Q = \frac{M_H^2}{4m_Q^2}. \quad z = \frac{M_H^2}{\hat{s}}$$

* NLO QCD corrections require 2-loop virtual, 1-loop real-virtual



Djouadi, Graudenz, Spira, Zerwas PLB 264 (1991), hep-ph/9504378

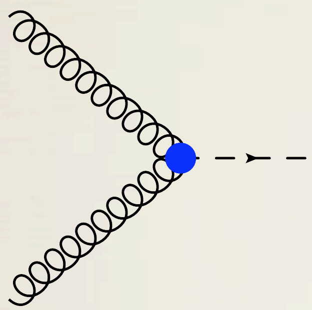


* Can reach $K_{NLO}=\sigma_{NLO}/\sigma_{LO}\approx 2$ at LHC, 3 at Tevatron; why so large?

EFT gluon-fusion

- Study carefully in the EFT with Hgg vertex

$$\sigma_{ij} \quad = \quad \sigma_0 \left\{ G^{(0)}_{ij} + \frac{\alpha_s}{\pi} G^{(1)}_{ij} + \mathcal{O}(\alpha_s^2) \right\} \qquad \mathcal{L}_{EFT} = \frac{1}{12}\frac{\alpha_s}{\pi}\left[1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$



$$G^{(0)}_{ij} \quad = \quad \delta(1-z)\delta_{ig}\delta_{jg}$$ (Overall factors in σ_0)

($z=M^2/x_1/x_2/s$; integral over PDFs ⇒ integral over z)

- NLO receives contributions from 5 pieces: virtual diagrams, real-radiation, ultraviolet renormalization, PDF renormalization correction to EFT coefficient

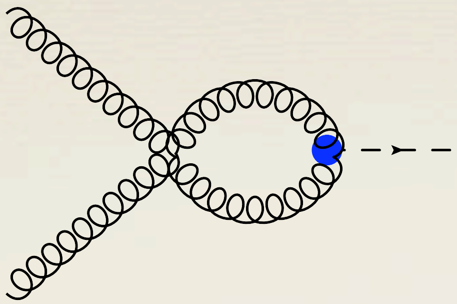
<u>Notes</u>:

- Everything in $d=4-2\varepsilon$ dimensions; gluon has d-2 polarization states
- Scaleless integrals vanish ⟶ $\int d^d k \frac{1}{k^2} \sim \frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}} \to 0$
- Coupling constant gets dimensions: $g \to g\mu^\varepsilon$
- Feynman gauge
- Only gg initial-state (others smaller, simpler)

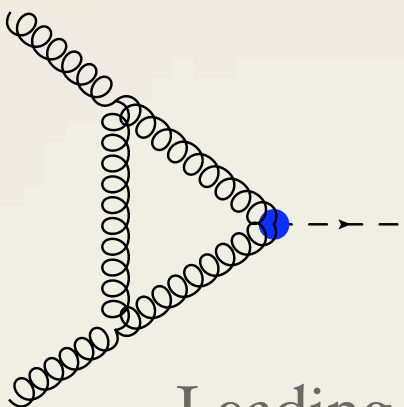
J. Collins, *Renormalization*

Gluon-fusion: virtual

* Virtual:



$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\left(\frac{\mu^2}{\hat{s}}\right)^{\epsilon}\left\{-\frac{13}{4\epsilon}-\frac{83}{12}\right\}\delta(1-z)$$



$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\left(\frac{\mu^2}{\hat{s}}\right)^{\epsilon}\left\{-\frac{3}{\epsilon^2}+\frac{1}{4\epsilon}+\frac{47}{12}+2\pi^2\right\}\delta(1-z)$$

Leading soft+collinear singularity; emitting gluons from gluons gives color factor C_A=3

* UV renormalization: counterterm for α_s at leading order

Full d-dimensional LO

First term in beta-function

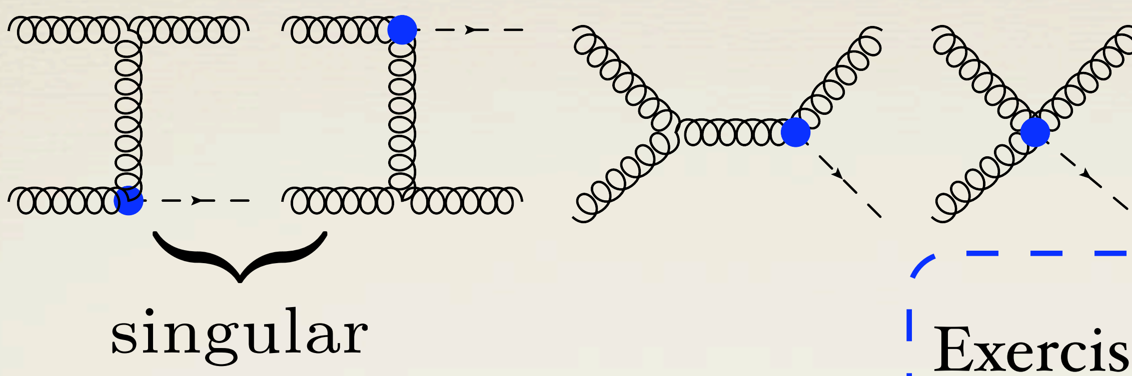
$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\frac{1}{\epsilon}G_{gg}^{(0),d}\{-2\,b_0\}$$

$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\left\{-\frac{11}{2}+\frac{N_F}{3}\right\}\left[\frac{1}{\epsilon}+1\right]\delta(1-z)$$

Number of light fermions

Gluon-fusion: real radiation

* Real:



Exercise: Derive the phase space

Phase space :
$$\frac{1}{2\hat{s}}\int \frac{d^d p_g}{(2\pi)^d}\frac{d^d p_H}{(2\pi)^d}\,(2\pi)\delta(p_g^2)\,(2\pi)\delta(p_H^2 - M_H^2)\,(2\pi)^d\delta^{(d)}(p_1 + p_1 - p_g - p_H)$$

$$= \frac{1}{16\pi\hat{s}}\frac{s^{-\epsilon}}{(4\pi)^{-\epsilon}\Gamma(1-e)}(1-z)^{1-2\epsilon}\int_0^1 d\lambda\,\lambda^{-\epsilon}(1-\lambda)^{-\epsilon}$$

$$\Rightarrow\ \hat{t} = (p_1 - p_g)^2 = -\hat{s}(1-z)\lambda,\quad \hat{u} = (p_2 - p_g)^2 = -\hat{s}(1-z)(1-\lambda)$$

$$|\bar{\mathcal{M}}|^2 = 48\,\alpha_s\left\{\frac{(1-2\epsilon)}{(1-\epsilon)^2}\frac{M_H^8 + \hat{s}^4 + \hat{t}^4 + \hat{u}^4}{\hat{s}\hat{t}\hat{u}} + \frac{\epsilon}{2(1-\epsilon)^2}\frac{\left(M_H^4 + \hat{s}^2 + \hat{t}^2 + \hat{u}^2\right)^2}{\hat{s}\hat{t}\hat{u}}\right\}$$

$$\Rightarrow (1-z)^{-1-2\epsilon}\lambda^{-1-\epsilon}(1-\lambda)^{-1-\epsilon}$$

singular   regulator

λ: collinear
z: soft

Real radiation and plus dists.

- Extract singularities using plus distribution expansion

$$\lambda^{-1-\epsilon} = -\frac{1}{\epsilon}\delta(\lambda) + \frac{1}{[\lambda]_+} - \epsilon\left[\frac{\ln\lambda}{\lambda}\right]_+ + \mathcal{O}(\epsilon^2), \quad \text{etc.}$$

$$\int_0^1 dx f(x)[g(x)]_+ = \int_0^1 dx\,[f(x) - f(0)]\,g(x)$$

$$\Rightarrow \quad \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\left(\frac{\mu^2}{\hat{s}}\right)^{\epsilon}\left\{\overbrace{\left[\frac{3}{\epsilon^2} + \frac{3}{\epsilon}\right]\delta(1-z)}^{\text{cancels virtual poles}} - \frac{6}{\epsilon}\frac{1}{[1-z]_+} + \frac{6z(z^2-z+2)}{\epsilon}\right.$$

$$+ \quad (3-\pi^2)\,\delta(1-z) - \frac{6}{[1-z]_+} + 12\left[\frac{\ln\,(1-z)}{1-z}\right]_+ - \frac{6(z^2-z+1)^2\ln\,z}{1-z}$$

$$\left. - \quad 12z(z^2-z+2)\ln(1-z) - \frac{11}{2} + \frac{57z}{2} - \frac{45z^2}{2} + \frac{23z^3}{2}\right\}$$

Remaining terms

* PDF renormalization: counterterm for initial-state collinear sings.

$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\frac{1}{\epsilon}G^{(0),d}_{gg} P_{gg}(z) \longrightarrow \text{Altarelli-Parisi splitting function}$$

$$= \frac{\alpha_s}{\pi}\frac{\Gamma(1+\epsilon)}{(4\pi)^{-\epsilon}}\left\{\underbrace{\left(\frac{11}{2}-\frac{N_F}{3}\right)\delta(1-z)}_{\text{cancels UV counterterm}}+\underbrace{\frac{6}{[1-z]_+}-6z(z^2-z+2)}_{\text{cancels real radiation}}\right\}\left[\frac{1}{\epsilon}+1\right]$$

* Coefficient correction: $= \frac{\alpha_s}{\pi}\frac{11}{2}\delta(1-z)$

* Can check that $(\mu^2/s)^\varepsilon$ terms give $\ln(\mu^2/s)$ upon expansion ⇒ combined with scale dependence of α_s (implicit so far) and PDFs give estimate of theoretical uncertainty (can also get these logs from renormalization group considerations)

Final result

- Final result for NLO correction:

$$G_{gg}^{(1)} = \left(\frac{11}{2} + \pi^2\right)\delta(1-z) + 12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z)$$
$$-6\frac{(z^2+1-z)^2}{1-z}\ln(z) - \frac{11}{2}(1-z)^3$$

($M^2/s \leq z \leq 1$)

(integrate over PDFs, removes singularity)

- What is the source of the π^2? Since $1/\varepsilon^2$ poles cancel, can change that $\Gamma(1+\varepsilon)$ normalizing the real, virtual can be exchanged for something that differs at $O(\varepsilon^2)$ ⇒ shuffles terms between R, V

$$\Gamma(1+\epsilon) \to \underbrace{\frac{1}{\Gamma^2(1-\epsilon)\Gamma(1+\epsilon)}}_{\mathcal{N}} \Gamma^2(1-\epsilon)\Gamma^2(1+\epsilon) = \mathcal{N}\left(1 + \frac{\pi^2}{3}\epsilon^2 + \mathcal{O}(\epsilon^4)\right)$$

Real: $\mathcal{N}\left(1+\frac{\pi^2}{3}\epsilon^2\right)\left(\frac{3}{\epsilon^2} - \pi^2 + \ldots\right)\delta(1-z) = \mathcal{N}\left(\frac{3}{\epsilon^2} + \ldots\right)$

Virtual: $\mathcal{N}\left(1+\frac{\pi^2}{3}\epsilon^2\right)\left(-\frac{3}{\epsilon^2} + 2\pi^2 + \ldots\right)\delta(1-z) = \mathcal{N}\left(-\frac{3}{\epsilon^2} + \pi^2 + \ldots\right)$

Completely from analytic continuation: $6(-\mu^2/s)^\varepsilon = (\mu^2/s)^\varepsilon \times (6 + \pi^2 + \text{imaginary parts} + \ldots)$

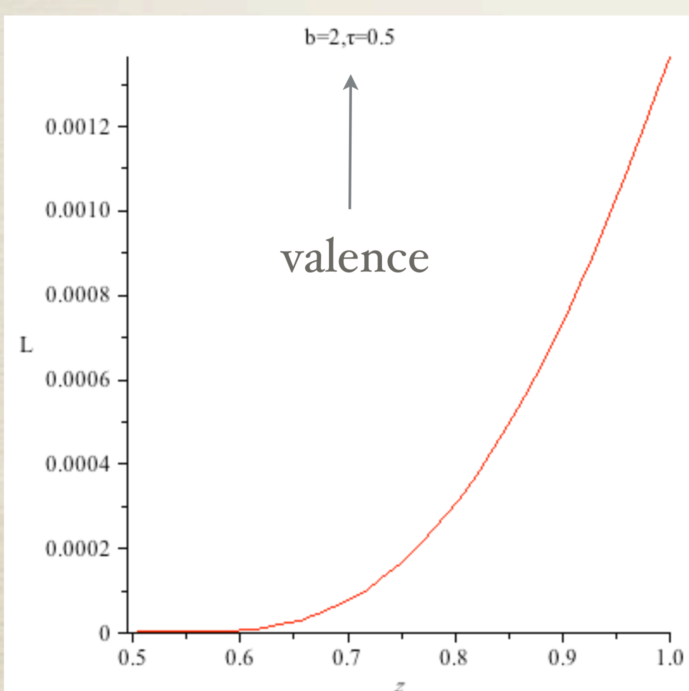
From $C_A=3$ color, $2\times\mathrm{Re}(M_0 M_1^*)$

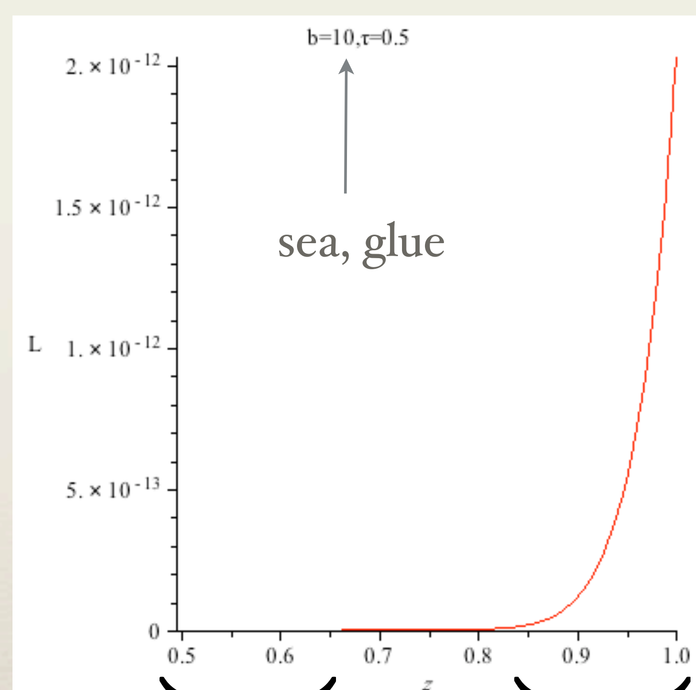
Threshold logs and PDFs

- Logarithm is associated with soft radiation; is $z \to 1$ region enhanced?
- Begin with hadronic cross section in following form ($\tau = M^2/s$, $z = M^2/x_1 x_2 s$)

$$\sigma_{had} = \tau \int_\tau^1 dz \, \frac{\sigma(z)}{z} \, \mathcal{L}\left(\frac{\tau}{z}\right), \quad \overbrace{\mathcal{L}(y) = \int_y^1 dx \, \frac{y}{x} \, f_1(x) f_2(y/x)}^{\text{partonic luminosity}}$$

Assume $f_i \sim x^a(1-x)^b$; plot L for various τ, b ('a' less important)
Look for peak near $z \approx 1$





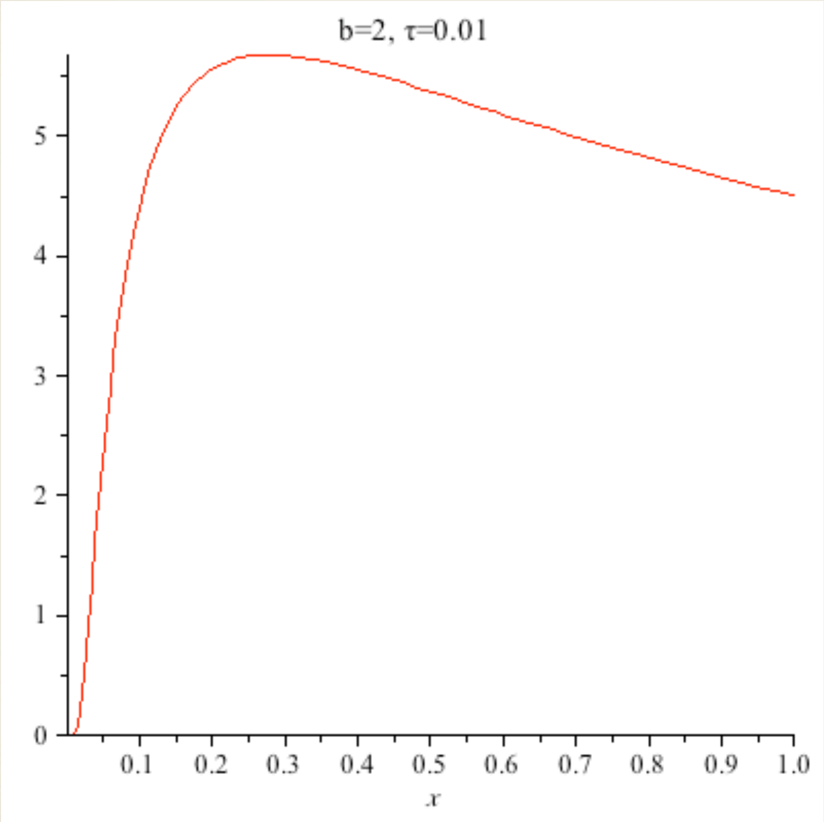
Hard emissions **Threshold**

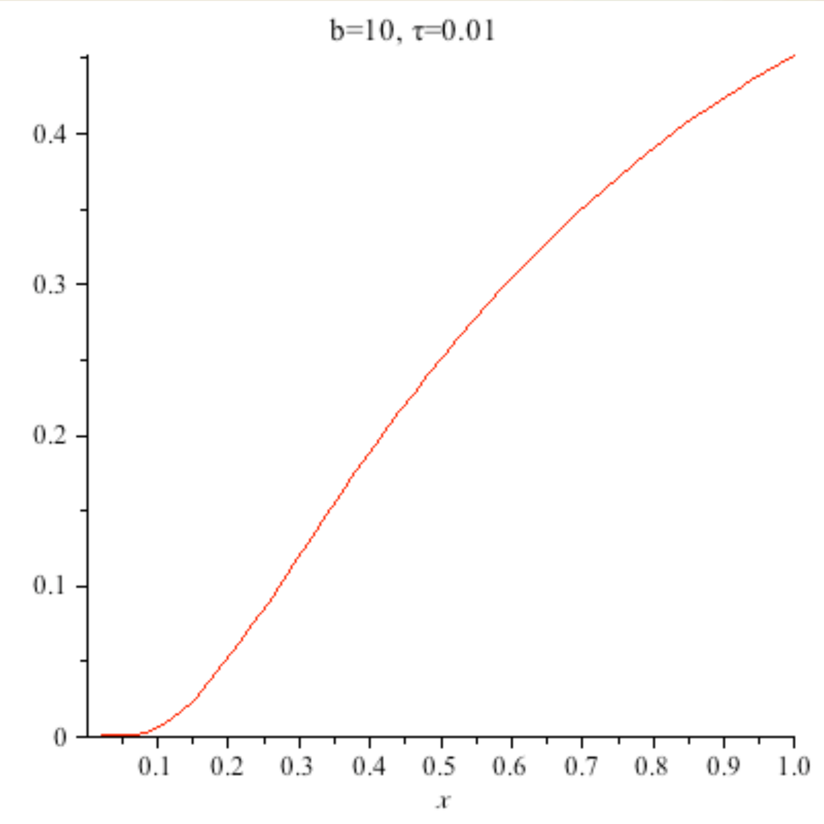
Clear importance for $\tau \approx 1$; rapid fall-off of large-z PDFs

$$\int_0^1 dx \left[\frac{\ln^n(1-x)}{1-x}\right]_+ \overbrace{\theta(x - x_{cut})}^{\text{approximate } \mathcal{L}/x} = -\frac{1}{n+1} \ln^{n+1}(1 - x_{cut})$$

Threshold logs and PDFs

* Shape of PDFs near 1 important for small τ; large exponents in $(1-z)^b$ can enhance region where logs are large





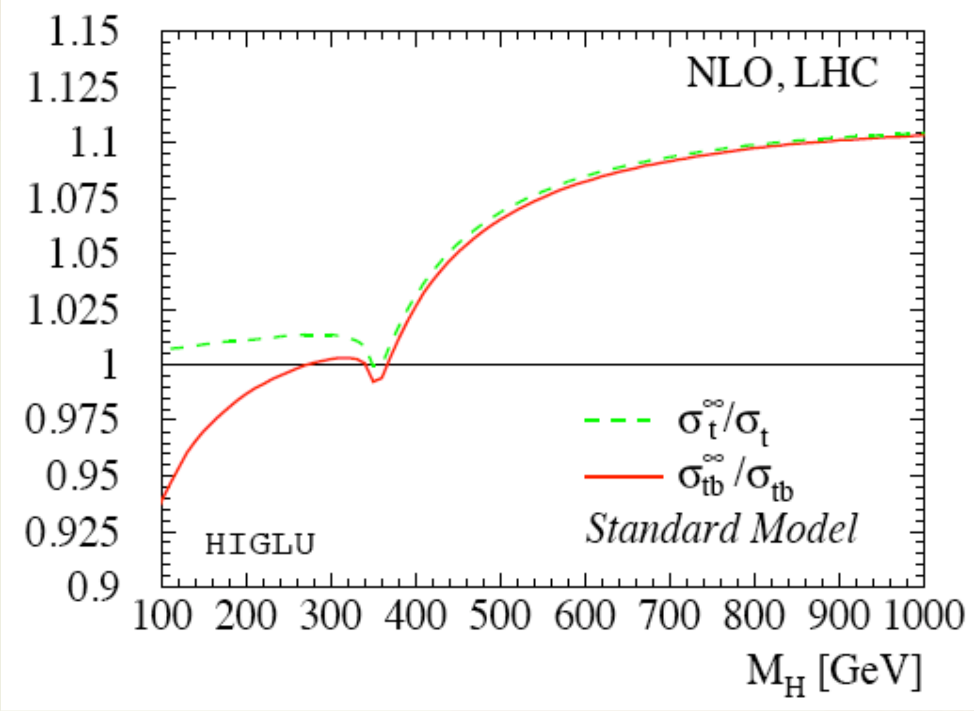
* A numerical question regarding how dominant the logarithmic terms are in the perturbative expansion; for Higgs, both plus dist. and $\delta(1-z)$ give large corrections
(discussions in Kramer, Laenen, Spira hep-ph/9611272, Catani et al. hep-ph/0306211, Ahrens, Becher, Neubert, Yang 0809.4283)

Effective theory validity

- Clearly want to go beyond NLO, but the 3-loop massive computations in the full theory are intractable

$$\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}}\right)\sigma_{LO}^{QCD}$$

%-level or better for $M_H<2m_t$, even gets >90% of correction above



Harlander, 2009 Zurich Higgs workshop

Soft, collinear gluons do not resolve top-quark loop (e.g., soft gluons are eikonal×tree)

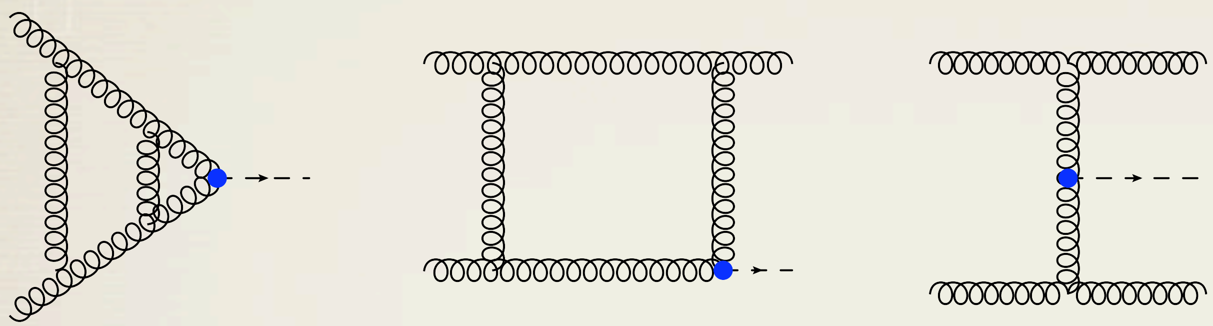
Kramer, Laenen, Spira; Marzani et al. 0801.2544

- Use EFT to go to NNLO

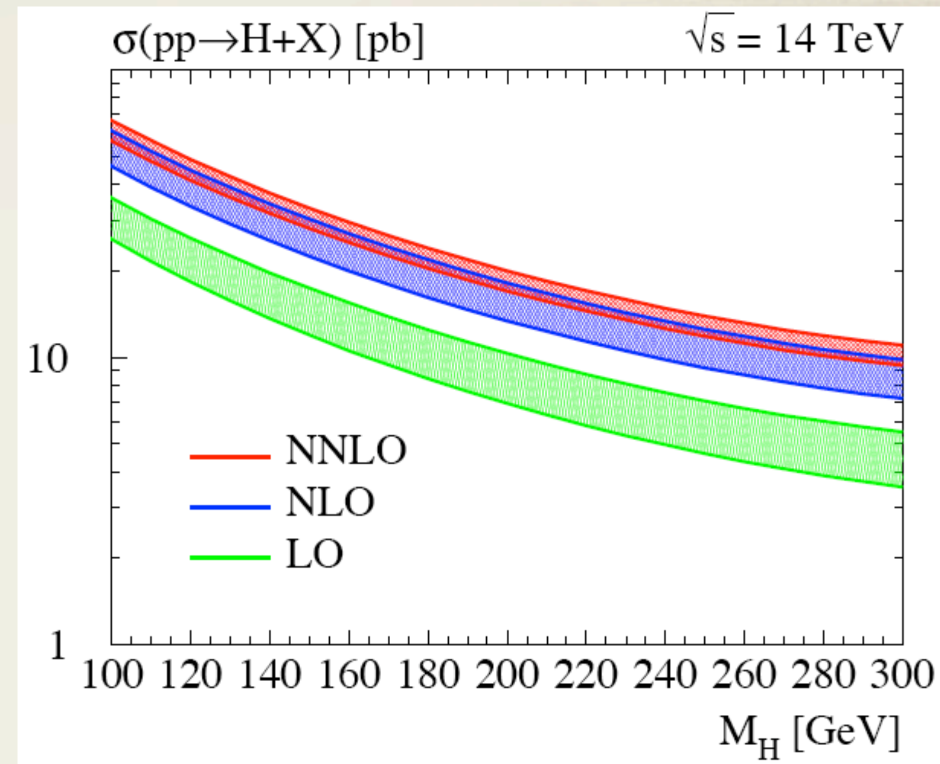
$$\sigma_{NNLO}^{approx} = \left(\frac{\sigma_{NNLO}^{EFT}}{\sigma_{LO}^{EFT}}\right)\sigma_{LO}^{QCD}$$

Inclusive Higgs at NNLO

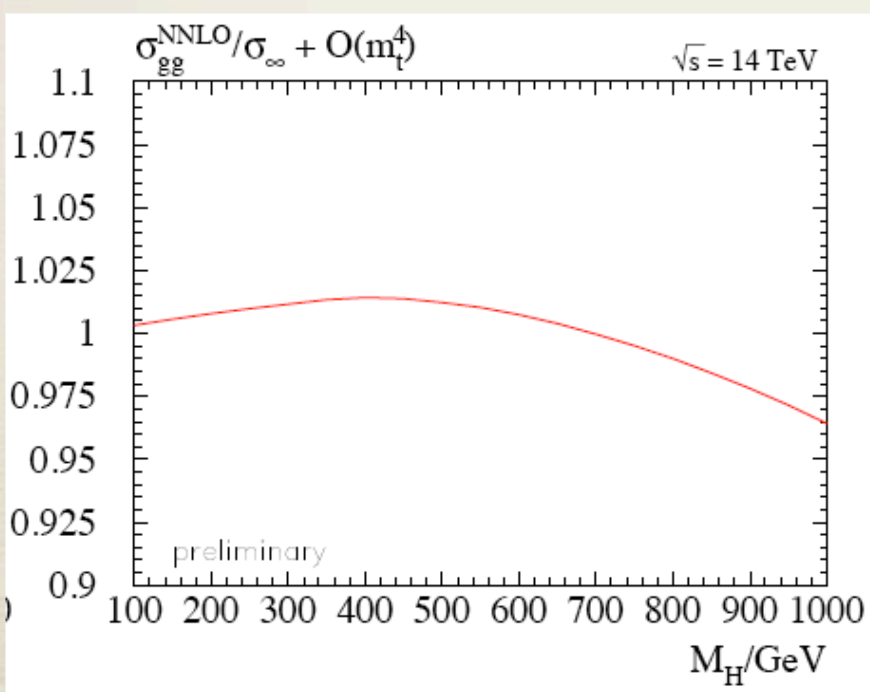
- Full calculation at NNLO in the EFT and resummation of logarithms



virtual-virtual **real-virtual** **real-real**



Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith van Neerven '03



K. Ozeren (w/ R. Harlander), LoopFest 2009

Recent asymptotic expansion of sub-leading $1/m_t$ terms at NNLO indicates they are small

Low-p_T resummation

* One more issue with result; go back and look at real radiation

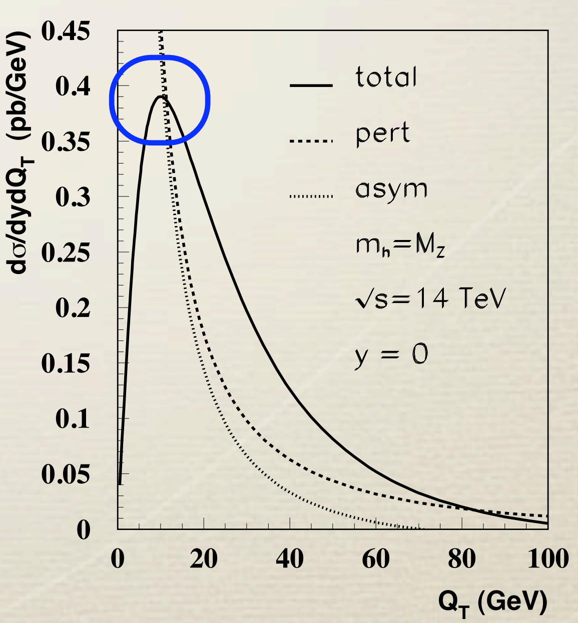
$$p_T^2 = \frac{\hat{t}\hat{u}}{\hat{s}} = \hat{s}(1-z)^2\lambda(1-\lambda)$$
$$\Rightarrow |\bar{\mathcal{M}}|^2 \times PS \sim (p_T^2)^{-1-\epsilon}$$

Fine if p_T integrated, but what if experiment selects low p_T?

$$\int_0^{p_T^{max}} (p_T^2)^{-1-\epsilon} \to \ln \frac{M_H}{p_T^{max}} \gg 1 \text{ for } M_H \gg p_T^{max}$$

* If low p_T selected, need resummation of $\ln(M_H/p_T)$ terms
(Collins, Soper, Sterman '85; Berger, Qiu hep-ph/0210135; Bozzi et al. hep-ph/0302104; Balazs, Yuan and others)

Can show
$$\frac{d\sigma}{dY\,dp_T^2} \approx \left(\frac{d\sigma}{dY}\right)_{LO} \exp\left(-\frac{3\,\alpha_s}{2\pi}\ln^2 s/p_T^2\right)$$
(J. Owens, CTEQ SS 2000)

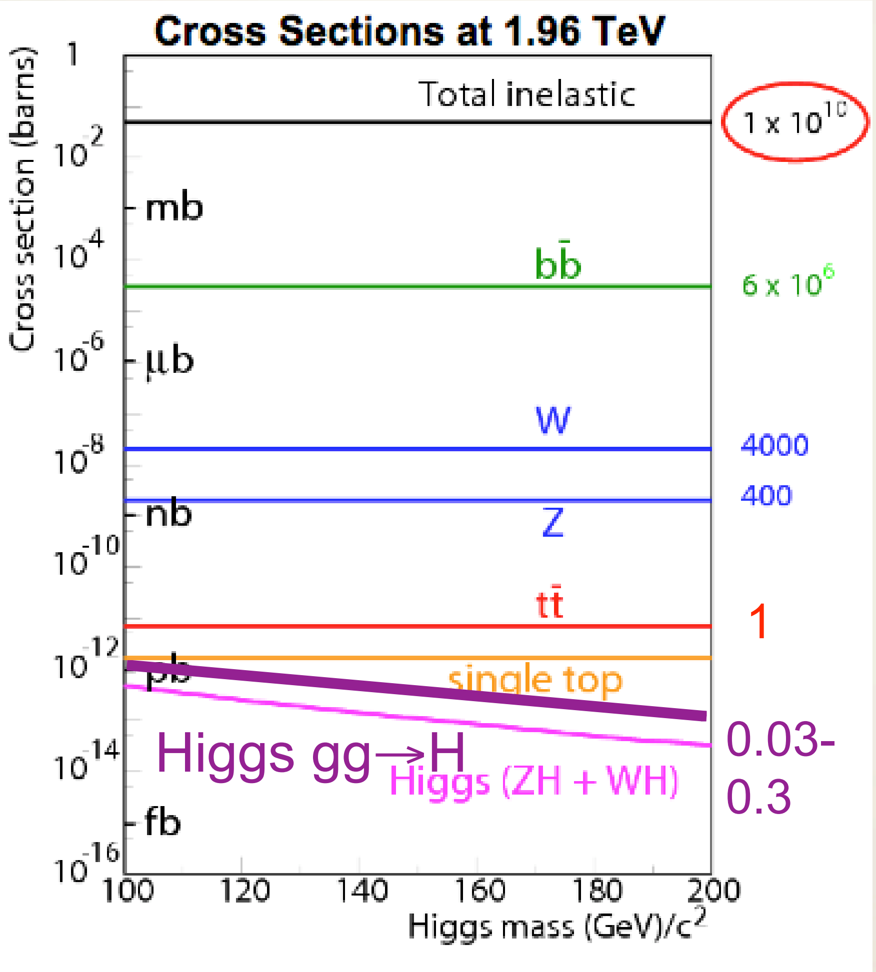


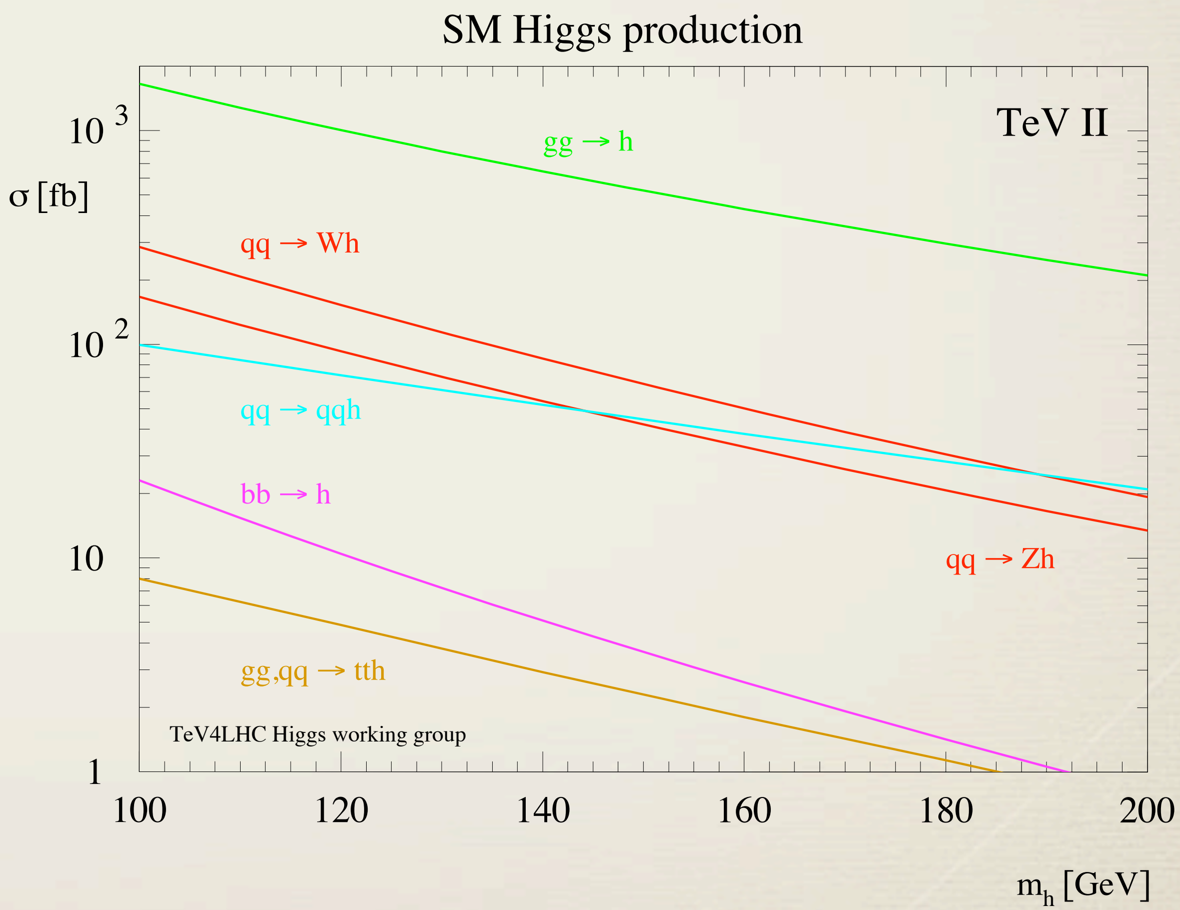
Systematically improvable beyond this leading approximation

Searches at the Tevatron and LHC

Tevatron analysis overview

* Inclusive gg→h→bb not feasible at low masses
* WBF only slightly adds to analyses designed for other channels

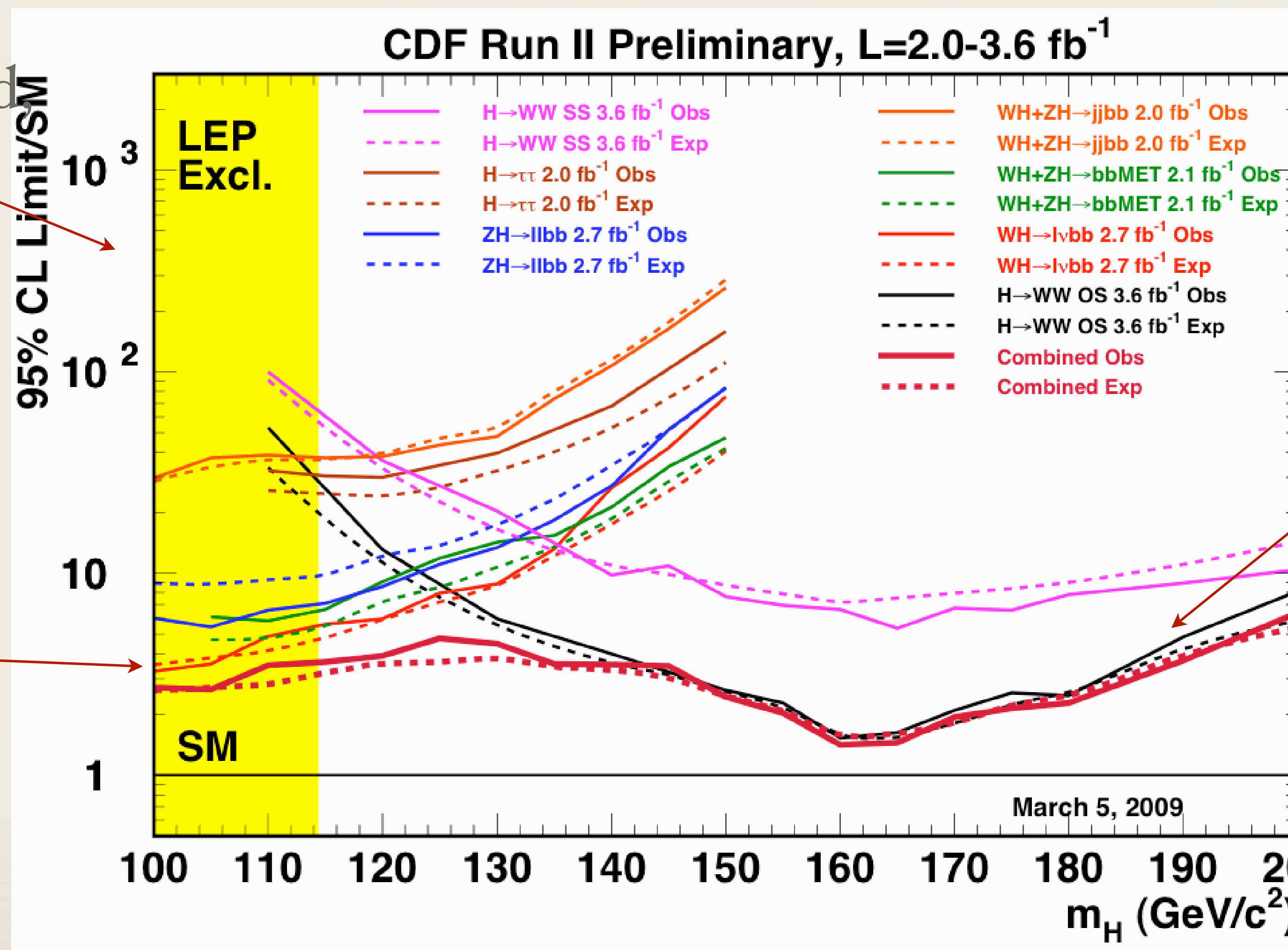




Combined exclusion limit

- No observation, so collaborations report 95% C.L. exclusion by combining many possible channels

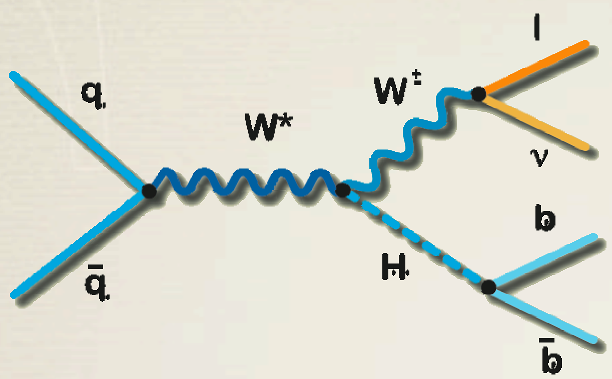
Cross section excluded normalized to SM



Most sensitive: Wh→lνbb

At high mass, all sensitivity from H→WW

Wh→lνbb analysis



Basic acceptance cuts :

- $p_T^l > 20$ GeV
- $\not{E}_T > 20$ GeV
- 2-3 jets, 1-2 b-tags
- $p_T^j > 20$ GeV

Process	1 tag	2 tags
All Pretag Cands.	50644.0 ± 0.0	57174.0 ± 0.0
WW	56.2 ± 6.2	0.4 ± 0.1
WZ	23.0 ± 1.7	4.8 ± 0.5
ZZ	0.8 ± 0.1	0.2 ± 0.0
TopLJ	121.3 ± 17.1	23.8 ± 3.9
TopDil	48.8 ± 6.8	14.1 ± 2.3
STopT	64.0 ± 9.3	1.8 ± 0.3
STopS	40.6 ± 5.7	12.8 ± 2.1
Z+jets	37.4 ± 5.5	2.1 ± 0.3
Total MC	392.0 ± 35.0	59.9 ± 7.5
Wbb	538.7 ± 162.5	70.3 ± 22.5
Wcc/Wc	489.1 ± 150.9	6.8 ± 2.3
Total HF	1027.8 ± 312.3	77.1 ± 24.7
Mistags	458.0 ± 57.9	2.2 ± 0.6
Non-W	135.5 ± 54.2	9.0 ± 3.6
Total Prediction	2013.3 ± 324.1	148.2 ± 26.1
WH100	9.5 ± 0.8	2.9 ± 0.3
WH105	8.6 ± 0.7	2.7 ± 0.3
WH110	7.6 ± 0.6	2.4 ± 0.3
WH115	6.3 ± 0.5	2.0 ± 0.2
WH120	4.9 ± 0.4	1.6 ± 0.2
WH125	4.0 ± 0.3	1.3 ± 0.2
WH130	3.1 ± 0.3	1.0 ± 0.1
WH135	2.3 ± 0.2	0.7 ± 0.1
WH140	1.5 ± 0.1	0.5 ± 0.1
WH145	1.0 ± 0.1	0.3 ± 0.0
WH150	0.7 ± 0.1	0.2 ± 0.0
Observed	1998.0 ± 0.0	156.0 ± 0.0

From CDF, after event selection

``Estimating the background contribution after applying the event selection to the WH candidate sample is an elaborate process"

W+jets: normalization from data; heavy-flavor fraction from ALPGEN for shape (tree-level)+data for norm.; Do also uses NLO to check

Combined theory +experiment error

CDF Note 9463; PRL 100 041801 (2008); Do Note 5828-CONF; PRL 102 051803 (2009)

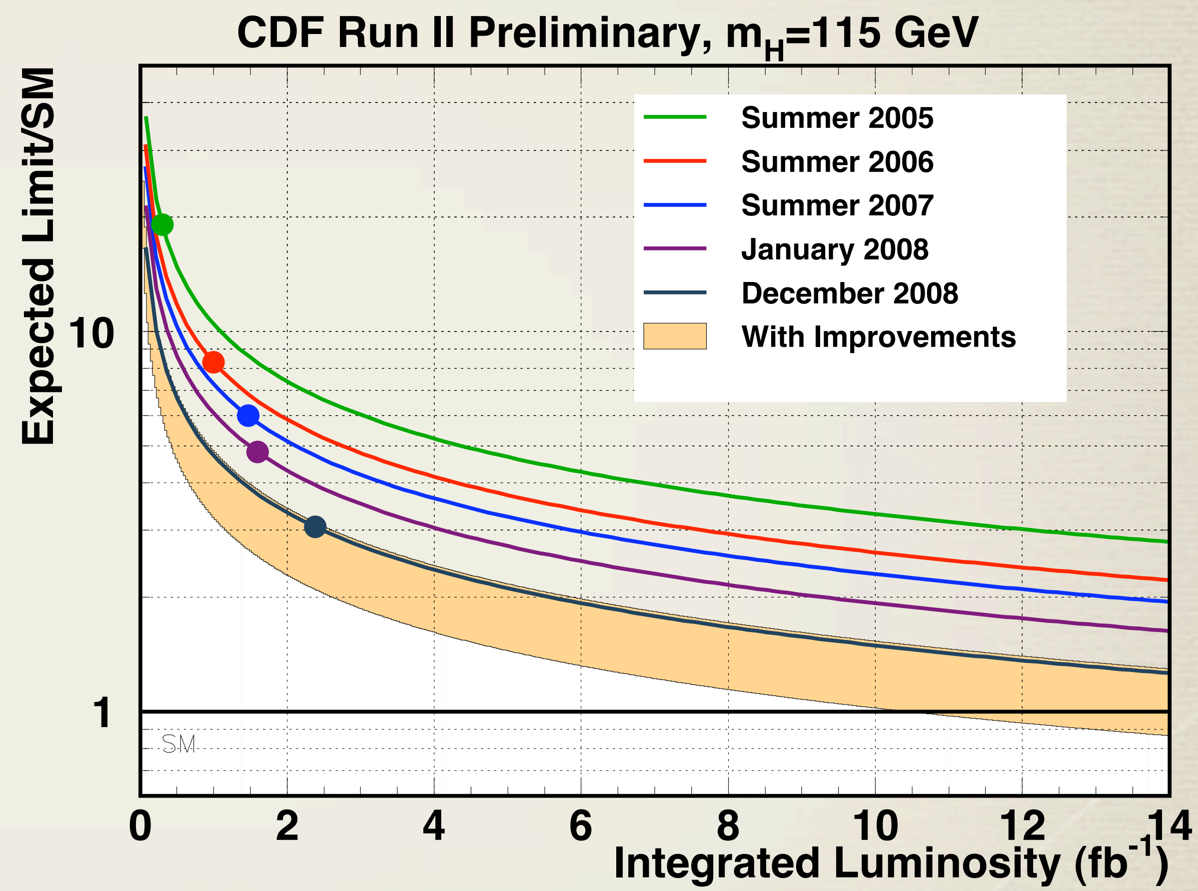
Low-mass limits and projections

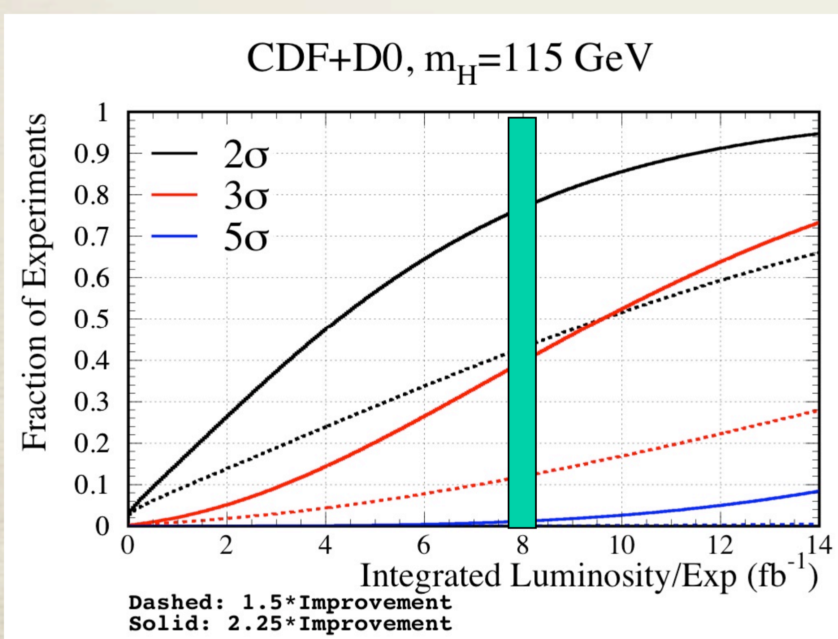
* Analysis improvements expected: better dijet mass resolution, increased acceptance

Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN+ME+BDT	2.7	8.4	4.8	5.8
DØ ME+NN new	2.7	13.3	6.7	6.4

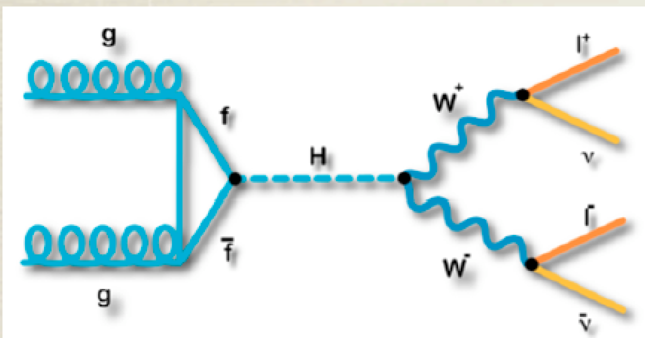
from M. Herndon, LoopFest 2009





Likely to have exclusion, possibility of 3σ at low mass (depends on Nature...)

h→WW→lνlν



Basic acceptance cuts (CDF) :

- $p_T^{l1} > 20$ GeV
- $p_T^{l2} > 10$ GeV
- $\not{E}_T > 15 - 25$ GeV

  (for various final states)
- Look separately at 0,1,2+ jet bins

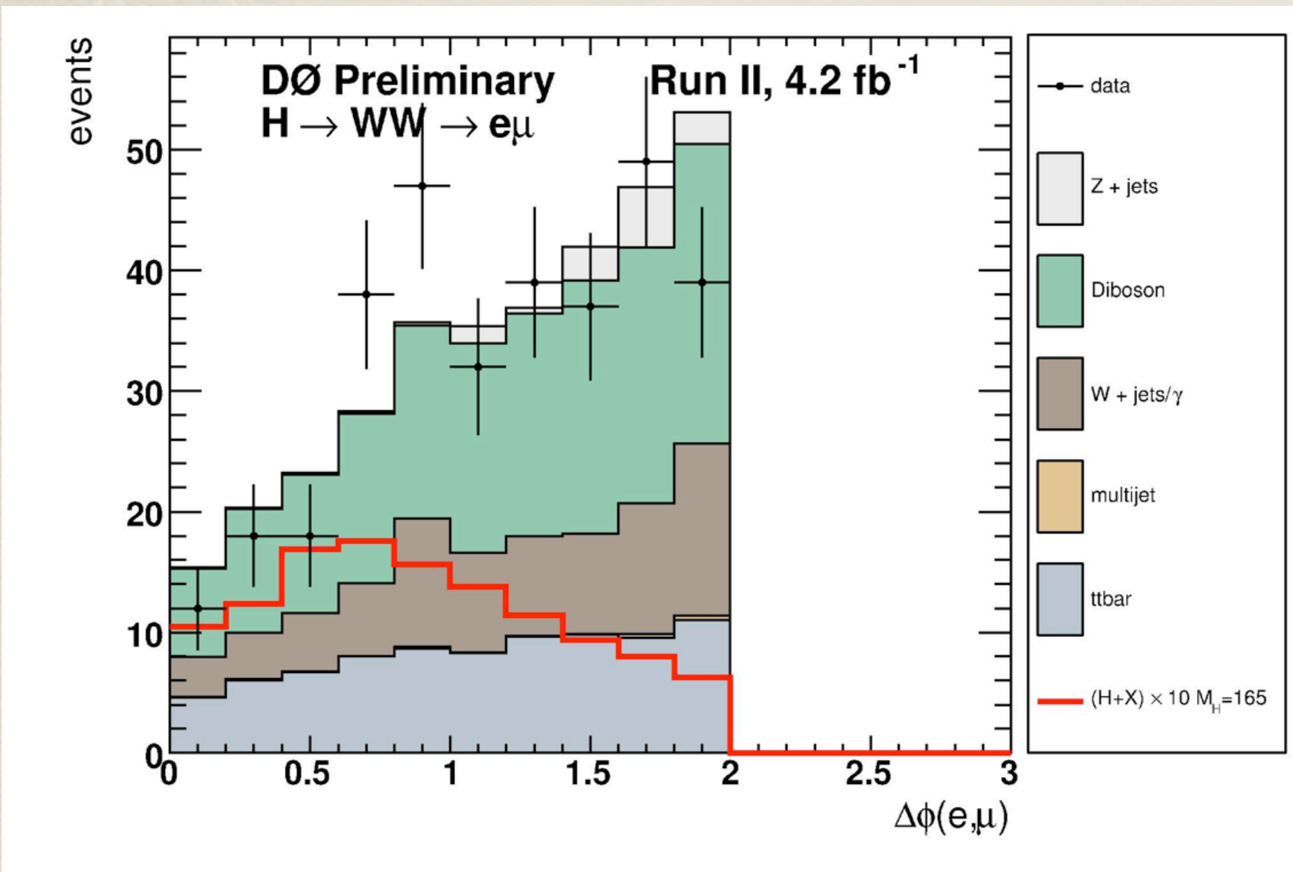
from D0

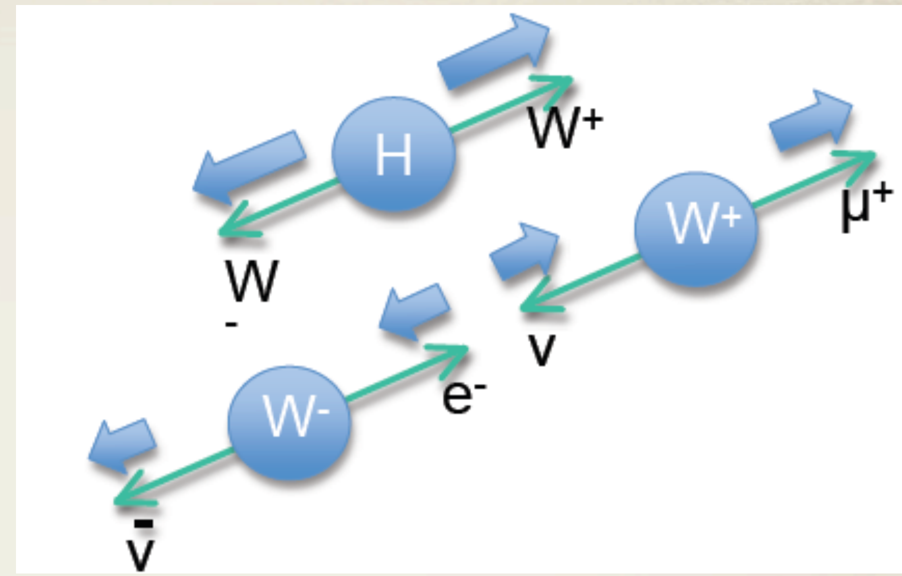
	ee pre-selection	ee final	$e\mu$ pre-selection	$e\mu$ final
$Z \to ee$	218695 ± 704	108 ± 14	280.6 ± 3.3	$0.0^{+0.1}_{-0.0}$
$Z \to \mu\mu$	–	–	274.6 ± 0.9	5.8 ± 0.1
$Z \to \tau\tau$	1135 ± 16	1.4 ± 0.5	3260 ± 3	7.3 ± 0.1
$t\bar{t}$	131.4 ± 1.4	39.9 ± 0.8	272.0 ± 0.3	82.5 ± 0.2
W+jets	241 ± 5	98 ± 3	183 ± 4	78.6 ± 2.8
WW	172.2 ± 2.6	66.8 ± 1.6	421.2 ± 0.1	154.7 ± 0.1
WZ	112.5 ± 0.2	9.68 ± 0.05	20.5 ± 0.1	6.6 ± 0.1
ZZ	98.2 ± 0.2	7.68 ± 0.07	5.3 ± 0.1	0.60 ± 0.01
Multijet	1351 ± 55	$1.7^{+2.0}_{-1.7}$	279 ± 168	$1.1^{+9.6}_{-1.1}$
Signal ($M_H = 165$ GeV)	9.45 ± 0.01	6.13 ± 0.01	17.1 ± 0.01	12.2 ± 0.1
Total Background	221937 ± 707	332 ± 15	4995 ± 168	337 ± 10
Data	221530	336	4995	329

tt: affects 2-jet bin; taken from NLO calculations
W+jets: jet fakes lepton; from data-driven methods
WW: taken from NLO calculation

CDF Note 9764; D0 Note 5871-CONF

Kinematic discriminants

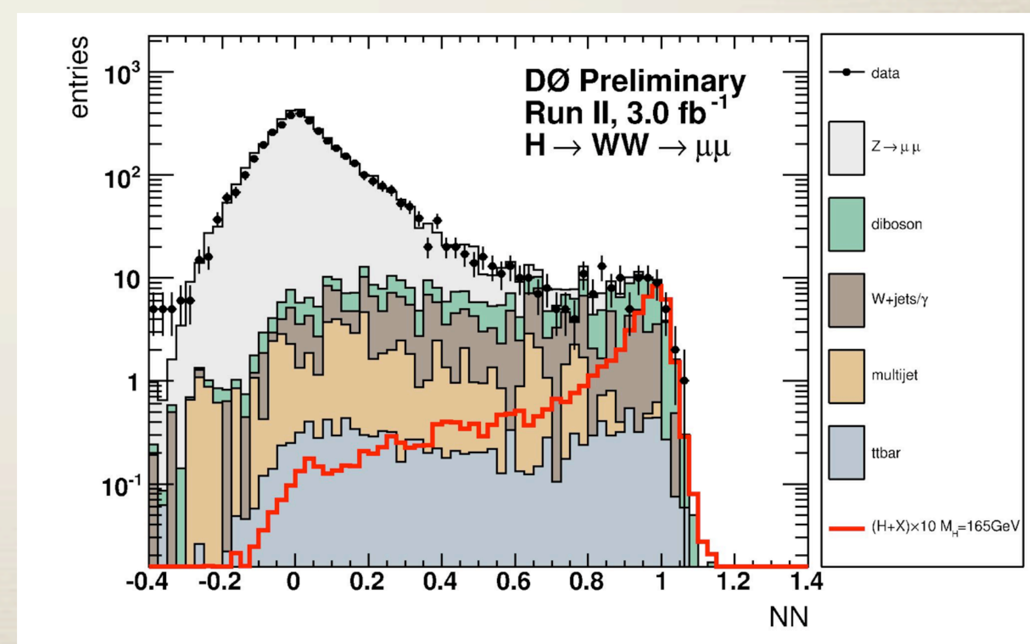




A primary handle for 0-jet bin: $\Delta\varphi_{ll}$

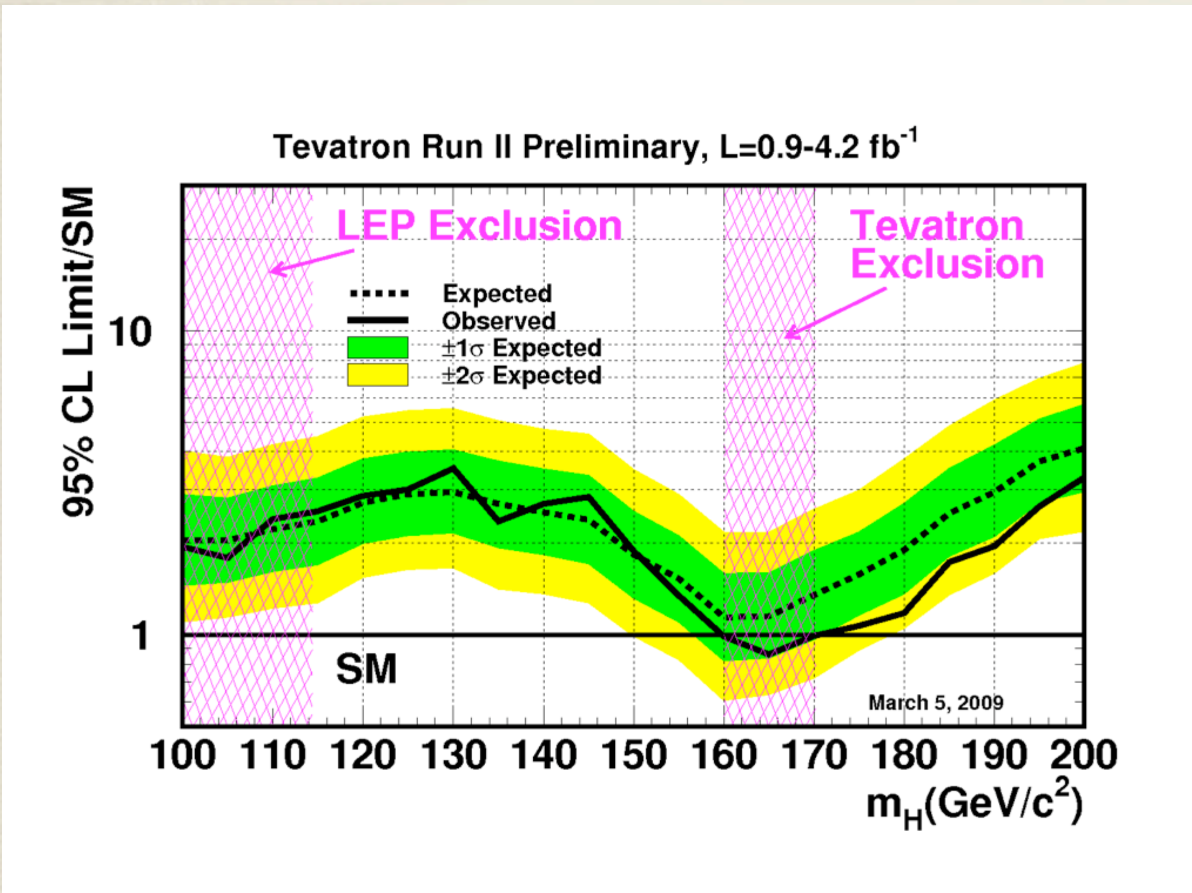
Spin correlation: leptons in same direction

NN Analysis Variables	
p_T of leading lepton	$p_T(\ell_1)$
p_T of trailing lepton	$p_T(\ell_2)$
Minimum of both lepton qualities	$\min(q_{\ell 1}, q_{\ell 2})$
Vector sum of the transverse momenta of the leptons:	$p_T(\ell_1) + p_T(\ell_2)$
Scalar sum of the transverse momenta of the jets:	$H_T = \sum_i \lvert p_T(\text{jet}_i)\rvert$
Invariant mass of both leptons	$M_{\text{inv}}(\ell_1, \ell_2)$
Minimal transverse mass of one lepton and $\not\!\!E_T$	M_T^{min}
Missing transverse energy	$\not\!\!E_T$
Scalar transverse energy	E_T^{scalar}
Azimuthal angle between selected leptons	$\Delta\phi(\ell_1, \ell_2)$
Solid angle between selected leptons ($e\mu$ only)	$\Delta\Theta(\ell_1, \ell_2)$
ΔR between selected leptons ($e\mu$ only)	$\Delta R(\ell_1, \ell_2)$
Azimuthal angle between leading lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_1)$
Azimuthal angle between trailing lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_2)$



High-mass exclusion

- Combine CDF+D0 exclusion limits: $160 \leq M_H \leq 170$ GeV at 95% CL



95%CL Limits/SM

M Higgs(GeV)	155	160	165	170	175
Method 1: Exp	1.5	1.1	1.1	1.4	1.6
Method 1: Obs	1.4	0.99	0.86	0.99	1.1
Method 2: Exp	1.5	1.1	1.1	1.3	1.6
Method 2: Obs	1.3	0.95	0.81	0.92	1.1

Solidly exclude SM at 165 GeV

0 Jet Uncertainties	$gg \to H$
Cross Section	
Scale	10.9%
PDF Model	5.1%
Total	12.0%

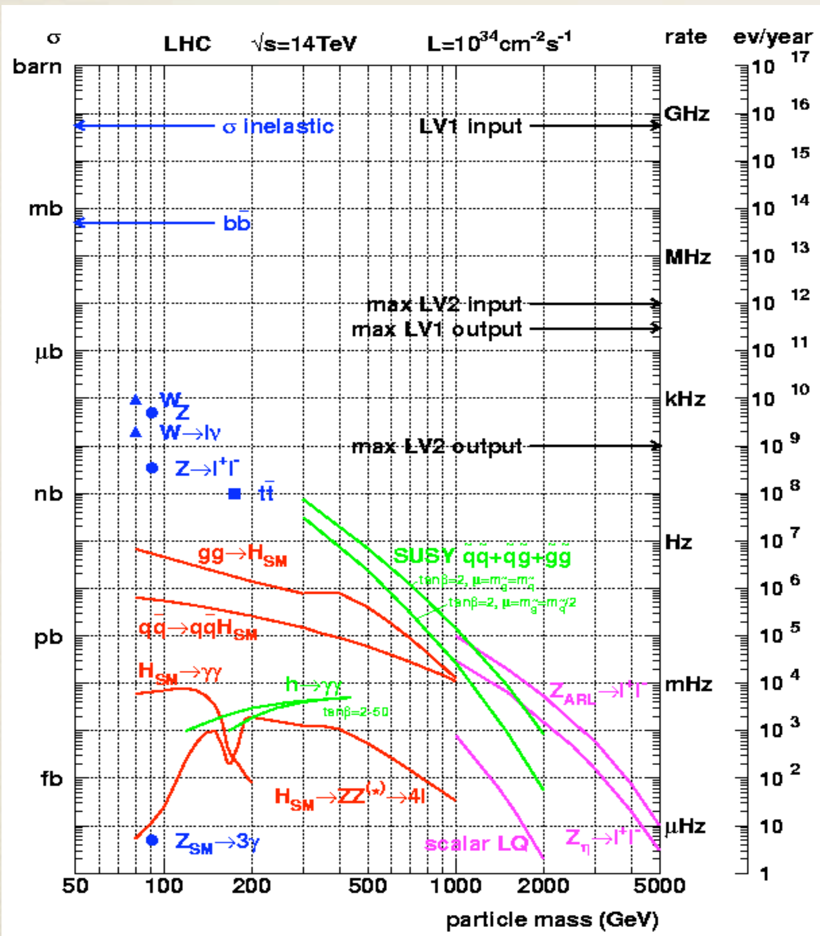
→ These are some of the largest systematics in the analysis; detailed QCD study crucial to perform this search!

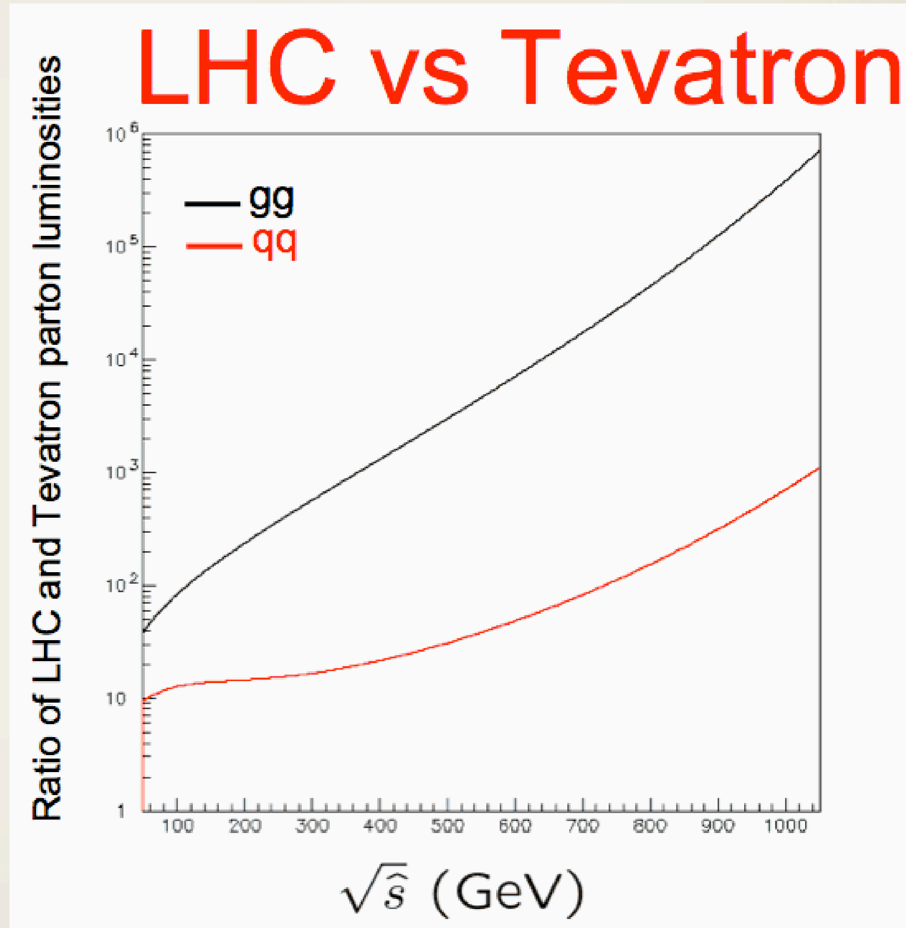
LHC physics overview

- Qualitative change; gluons now overwhelm scattering rate

Background

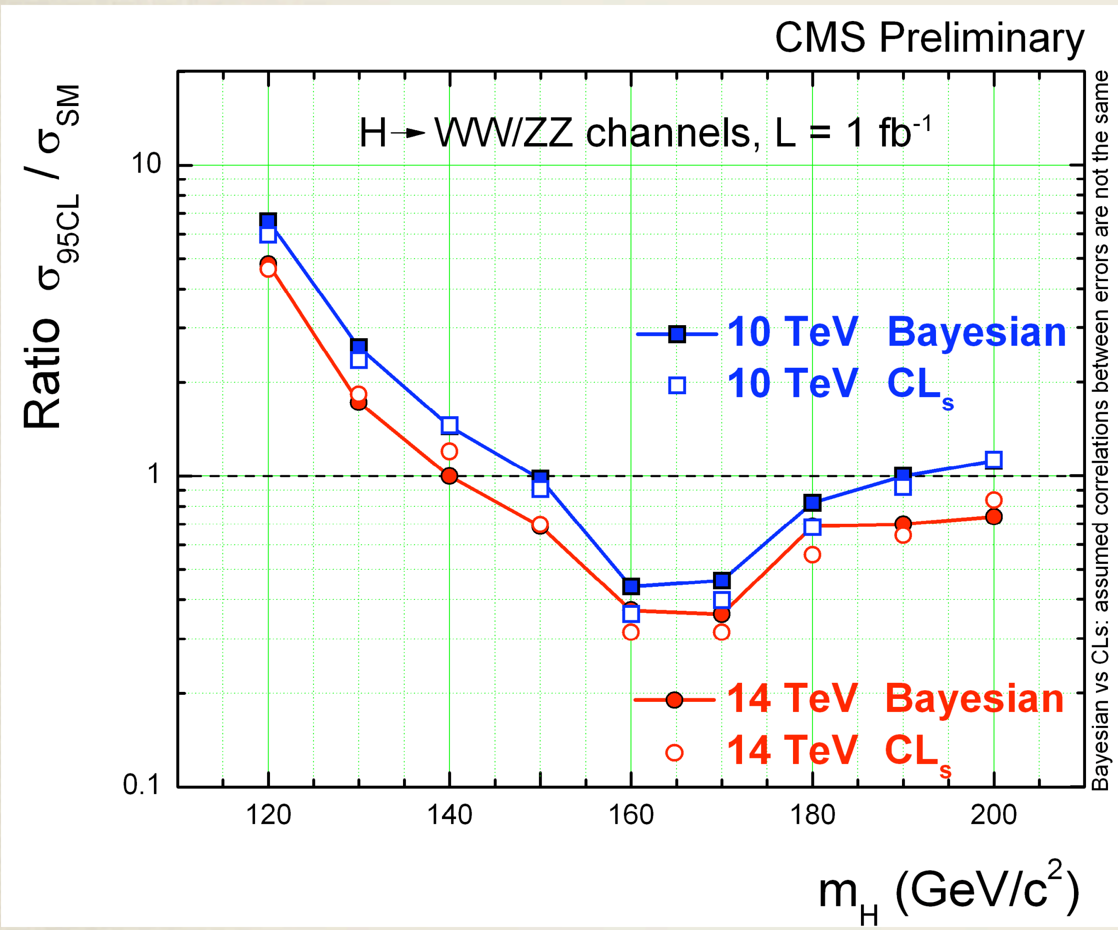
Higgs

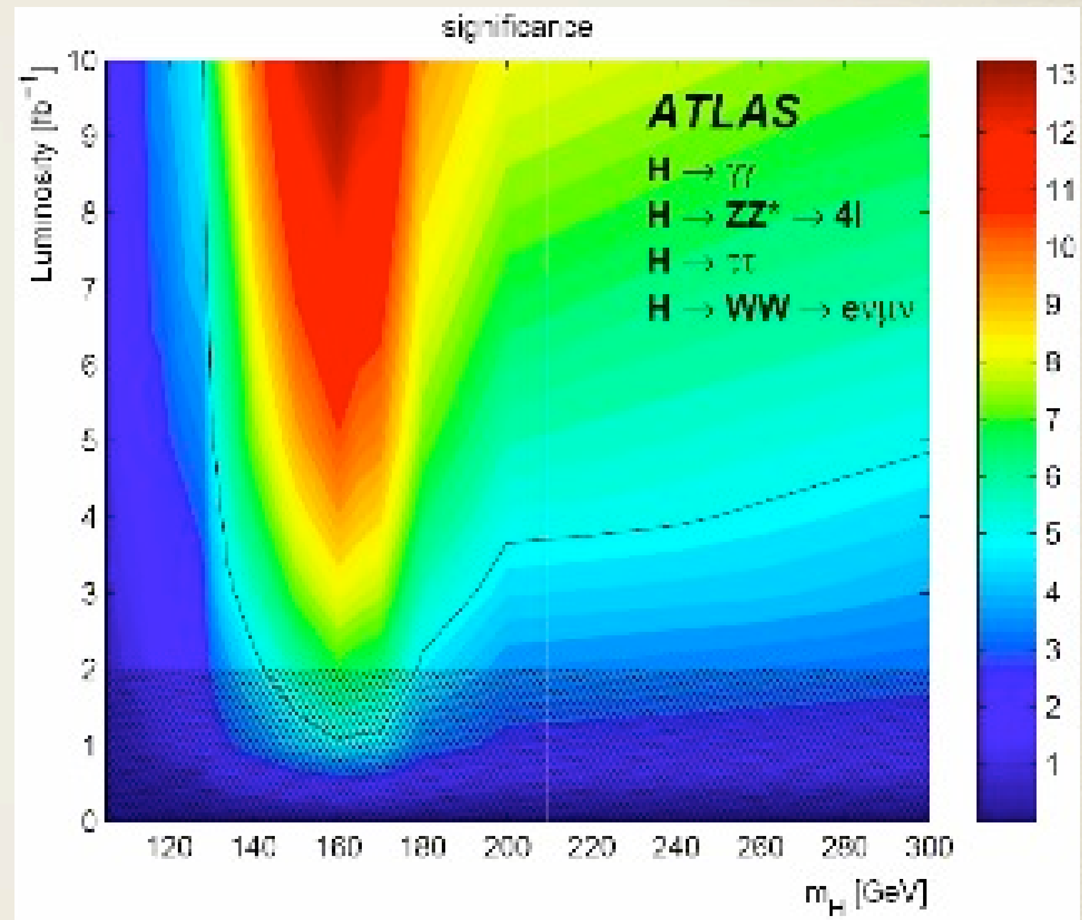




LHC summary: low fb^{-1}

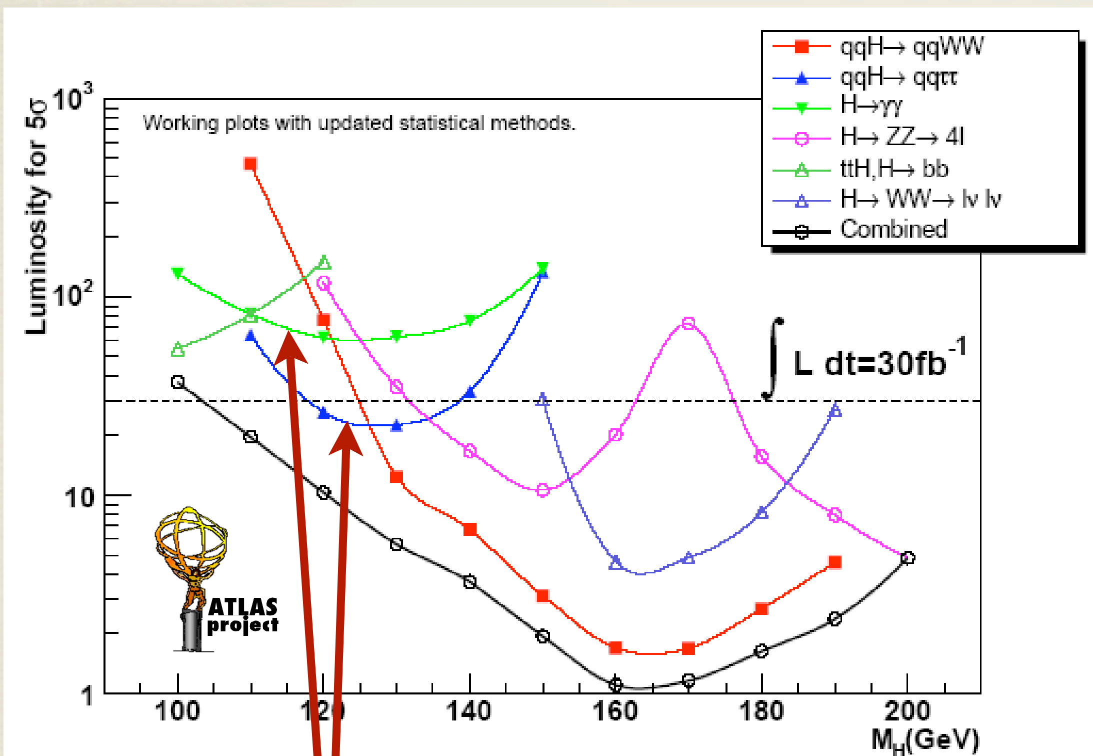
- Will reproduce expected Tevatron exclusion with 1 fb^{-1}

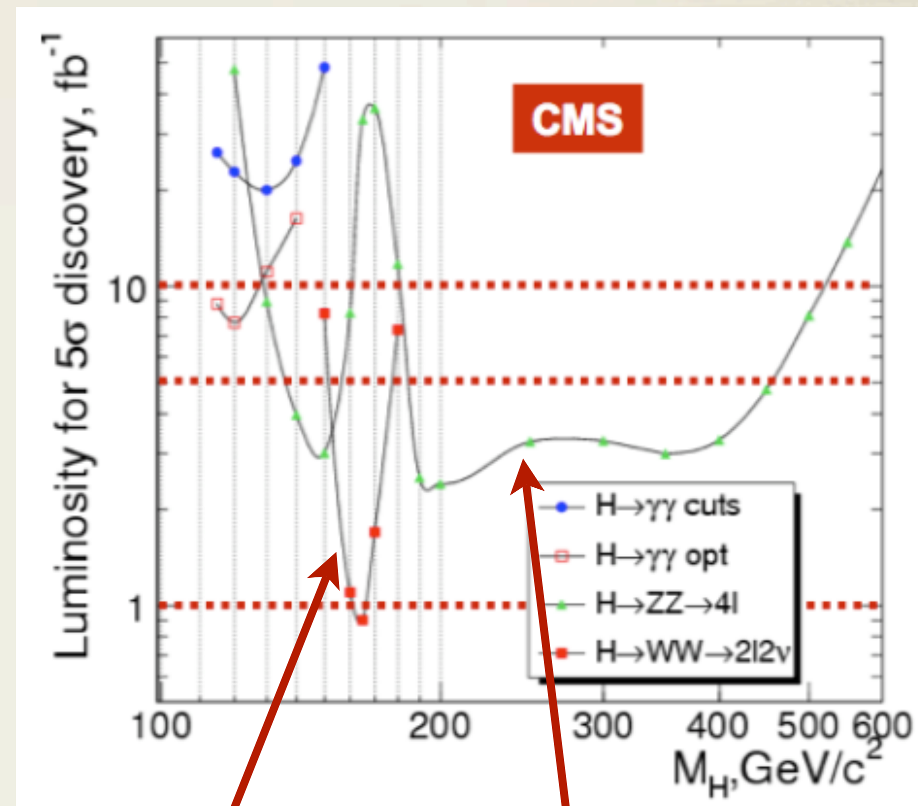




LHC summary: high fb^{-1}

* Entire mass range covered, much with multiple modes





h→γγ, WBF h→ττ cover low mass range

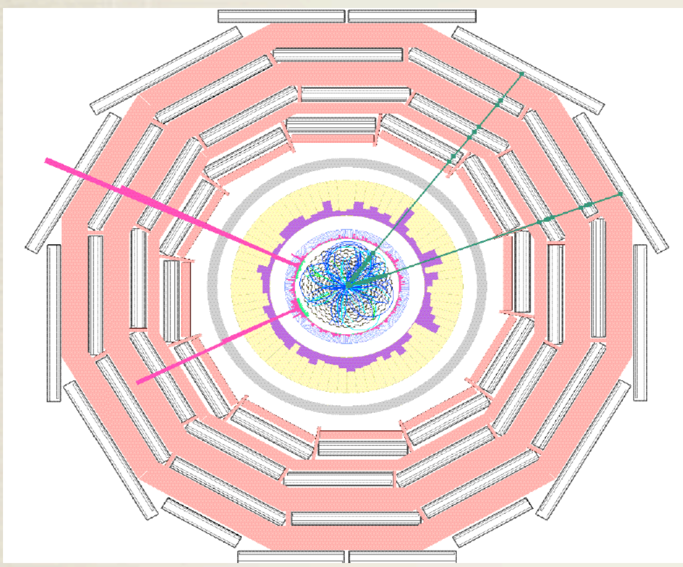
h→ZZ→4l assures discovery over entire high-mass range

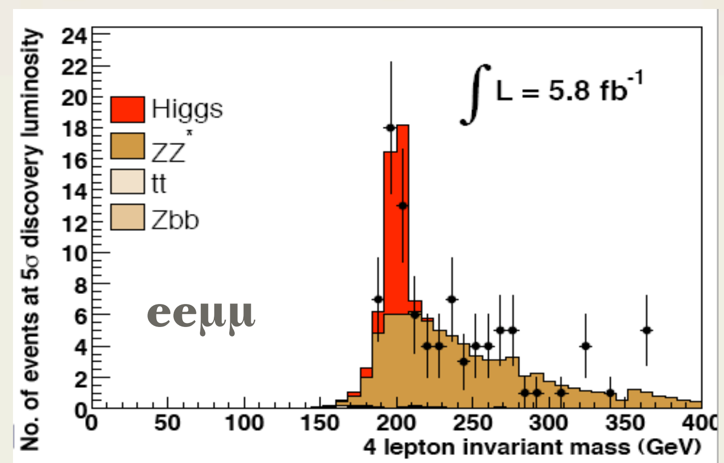
M_H>200 GeV: only few fb^{-1}
M_H<120 GeV: 20-30 fb^{-1}

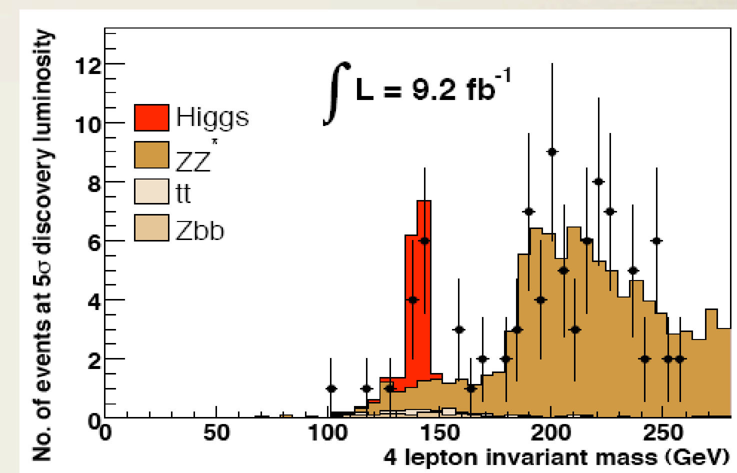
h→WW→lνlν again important at LHC

$h \to ZZ \to l_1 l_1 l_2 l_2$

* Trigger: one p_T>20-25 GeV or two p_T>10-15 GeV leptons
Reconstruct: at least one Z→ll decay

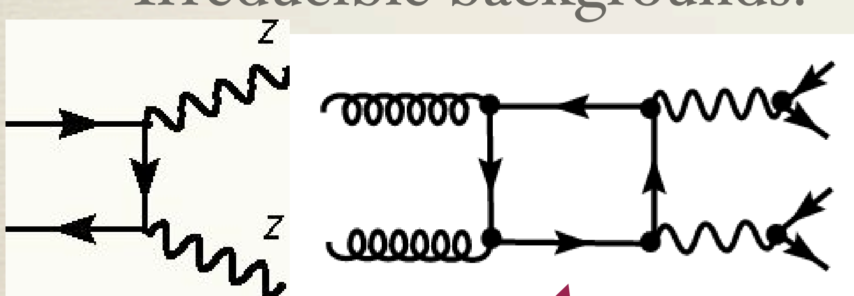




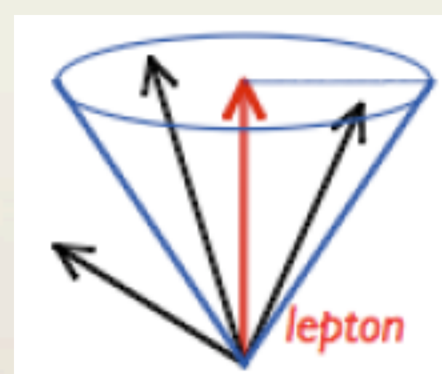


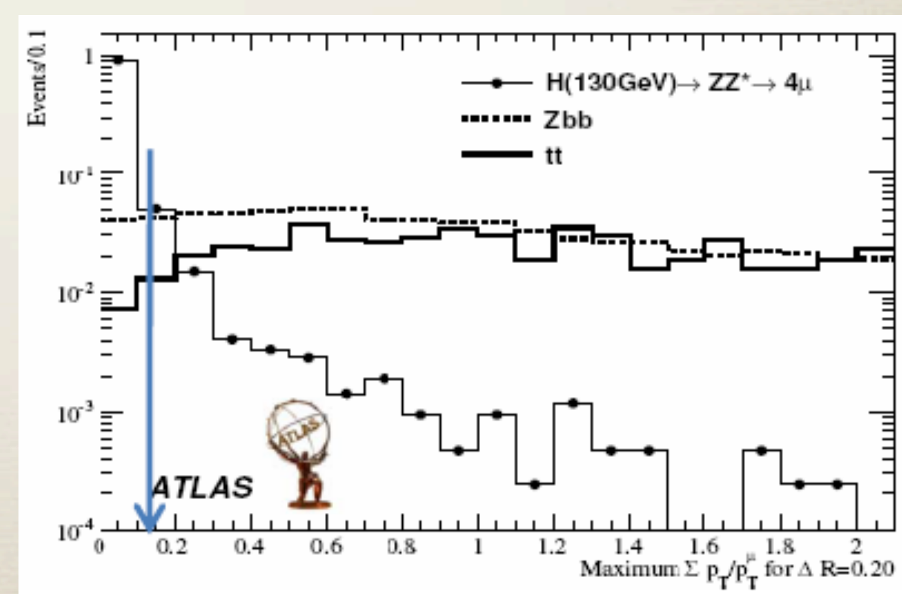
Reducible: tt->llννbb, Zbb with semi-leptonic b-decay

Irreducible backgrounds:



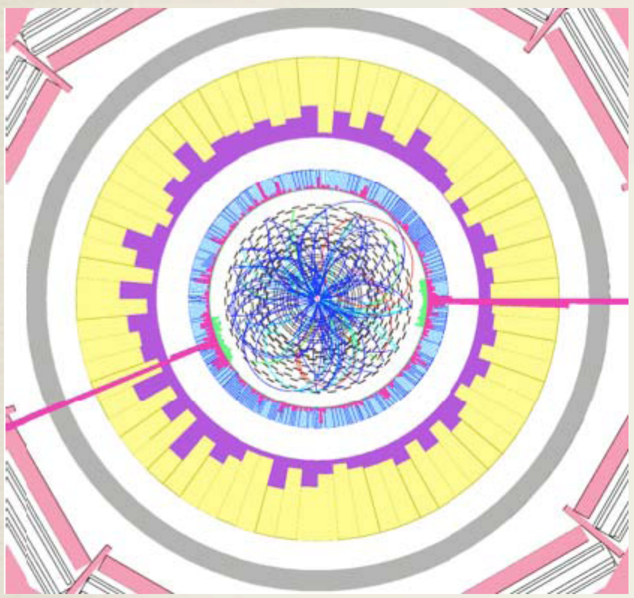
Formally NNLO, but enhanced by gg luminosity

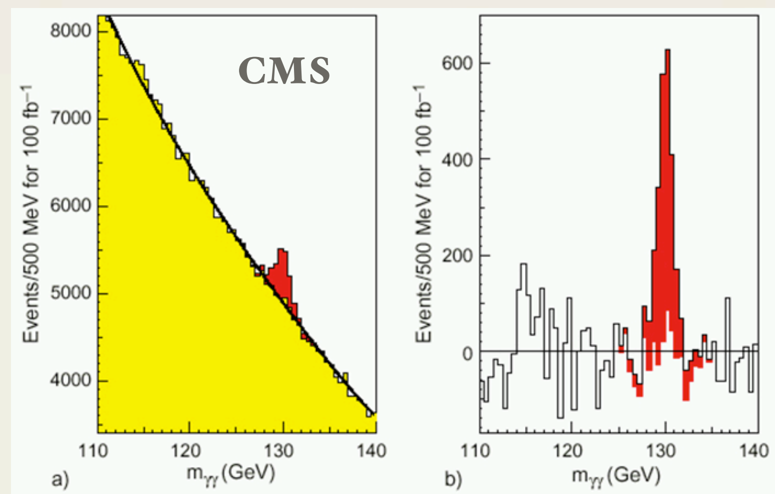




h→γγ

* Trigger: 1-2 photons; Reconstruct: p_T>40 GeV, p_T>25 GeV
  Excellent EM calorimeter resolution; calibrate with Z→ee

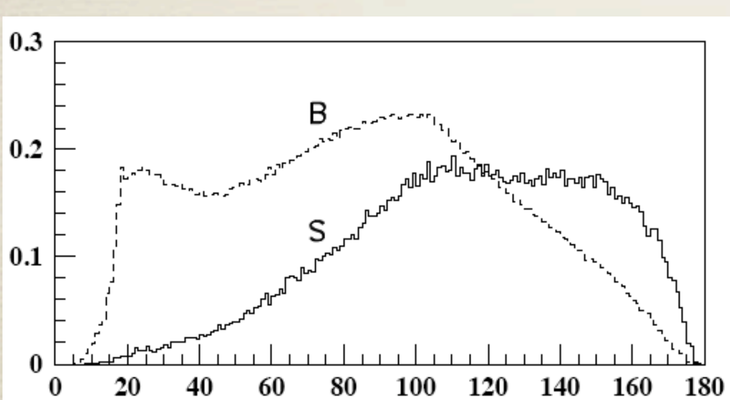




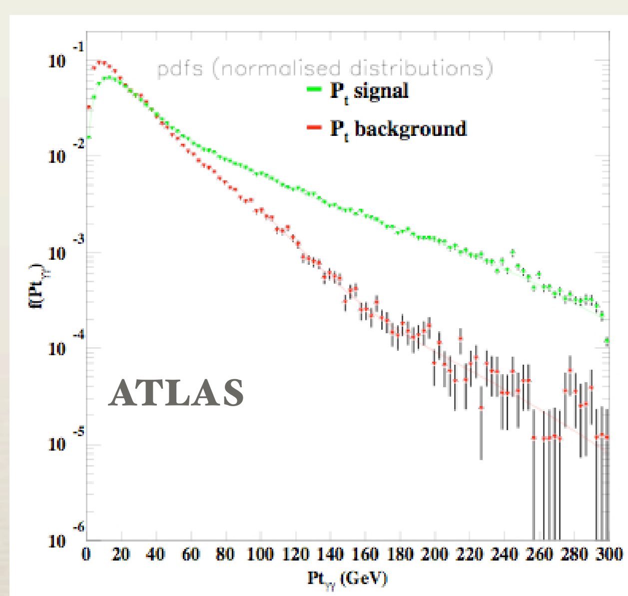
Huge π^0→γγ background; measure from sideband

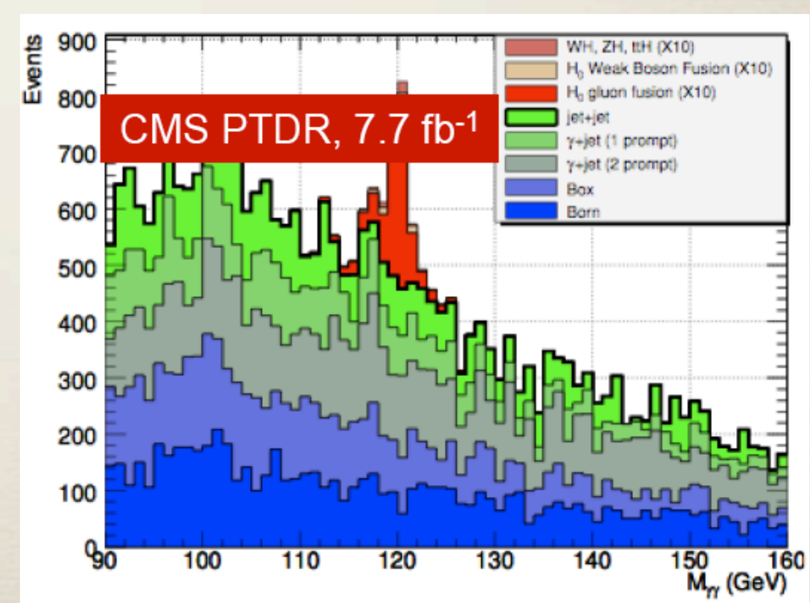
5σ: 20-30 fb^{-1} for M_H<140 GeV

Additional handles with jets; consider γγ+j,2j



Abdullin et al., hep-ph/9805341 $\theta^*_{\gamma j}$

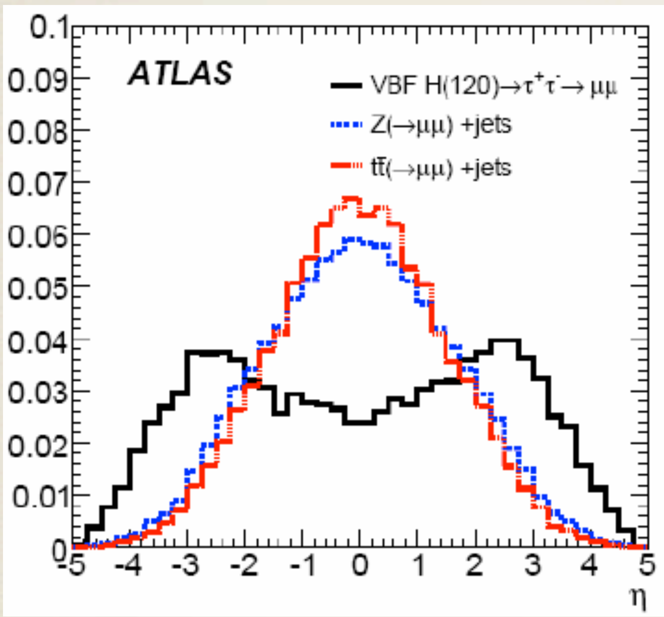


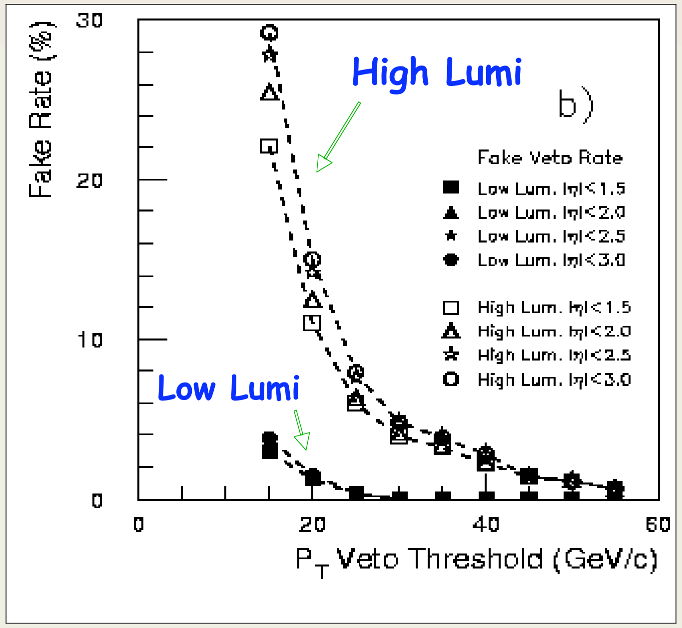


Nisati, KITP '08

WBF $h \to \tau\tau$

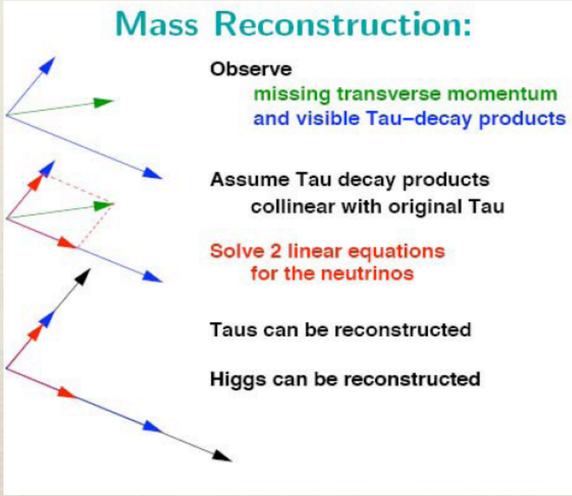
- Two tagging jets: $E_T > 40$ GeV, $\eta_{jj} > 4$, $M_{jj} > 500\text{-}1000$ GeV
  Higgs decay products between tagging jets; central-jet veto
  $\tau\tau \to ll$, lh modes possible



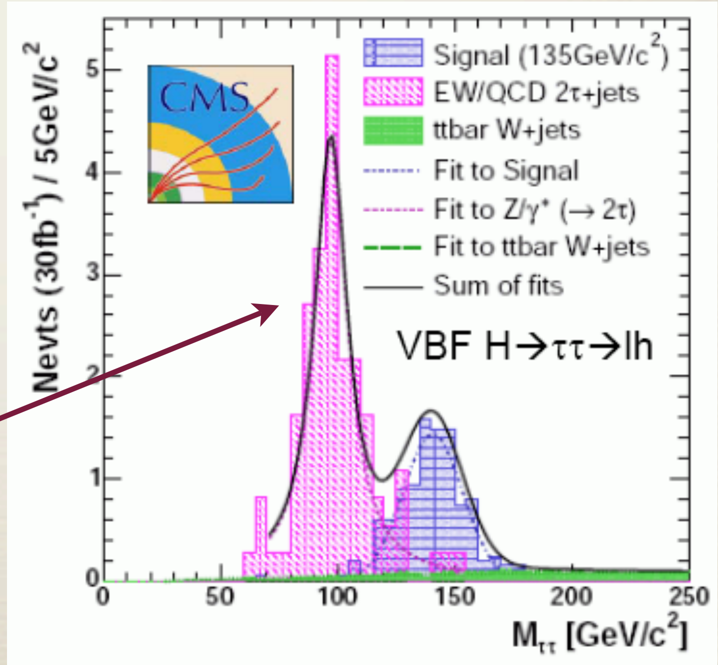


Central-jet veto a concern at high luminosities

Collinear approximation for τ's (highly boosted):



Data-driven techniques to control $Z \to \tau\tau$ line-shape



Mellado, CTEQ summer school '07

Global analysis of couplings

- Observe Higgs in many modes: gluon-fusion, WBF, W/Z+h (not discovery at LHC, but after M_H known Butterworth et al., 0802.2470

$$\sigma_p \times BR(h \to xx) = \underbrace{\left(\frac{\sigma_p}{\Gamma_p}\right)_{SM}}_{\text{NP effects cancel, calculate}} \times \underbrace{\frac{\Gamma_p \Gamma_x}{\Gamma}}_{\text{measure}}$$

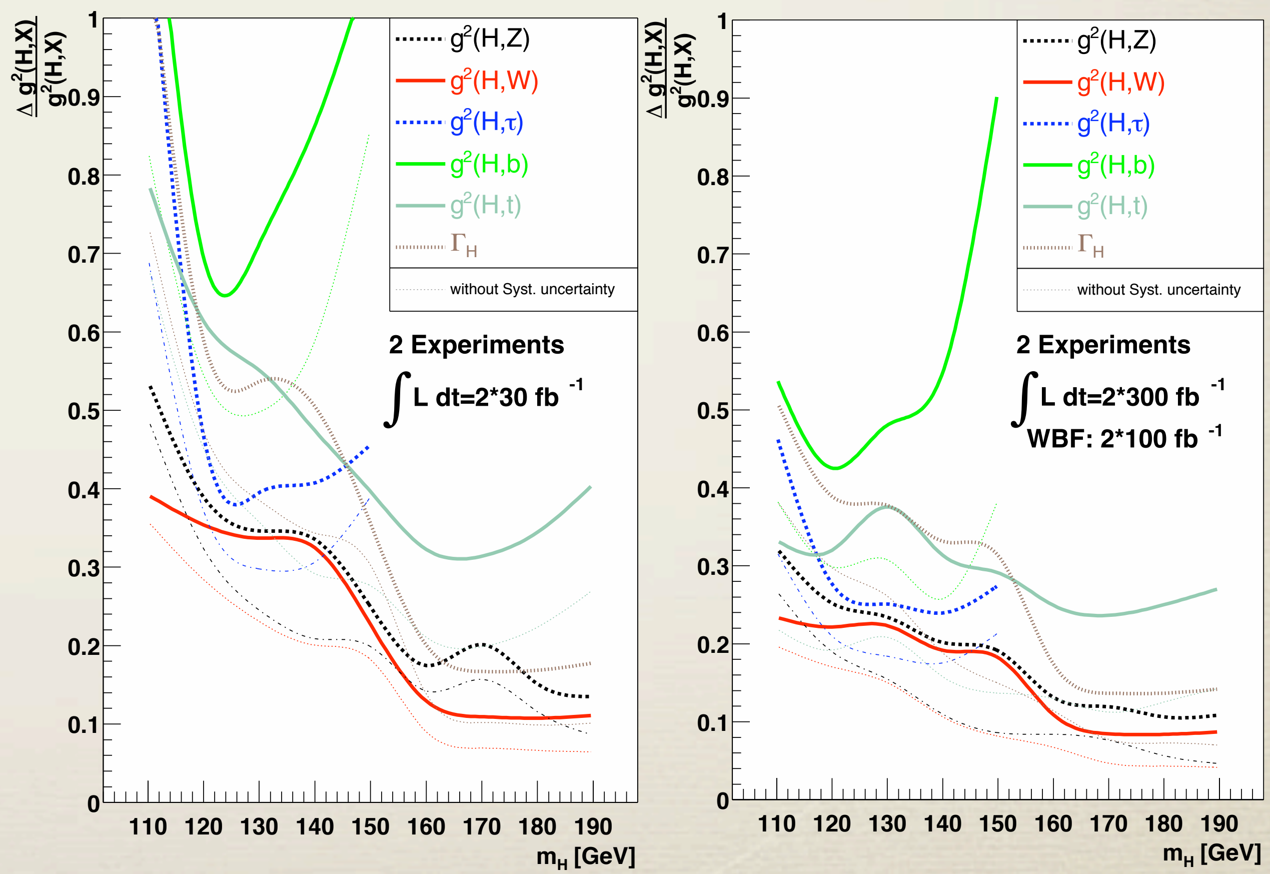
Scaling degeneracy if total width unknown:

$$\Gamma_i \to f\,\Gamma_i, \Gamma \to f^2\,\Gamma$$

Mild assumption: $g^2_{hVV} < 1.05 \times g^2_{hVV,SM}$

Allows any # of scalar doublets, new particles in loops, small contributions of scalar triplets

⇒Assumption+VBF measurement of $(\Gamma_V)^2/\Gamma$ breaks degeneracy



Duhrssen et al. hep-ph/0406323, Lafaye et al. 0904.3866

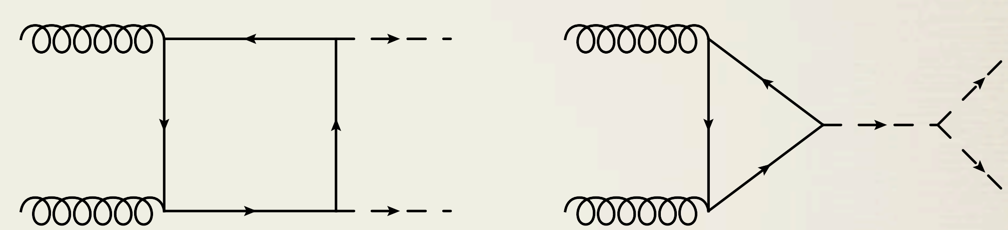
Measuring the Higgs potential

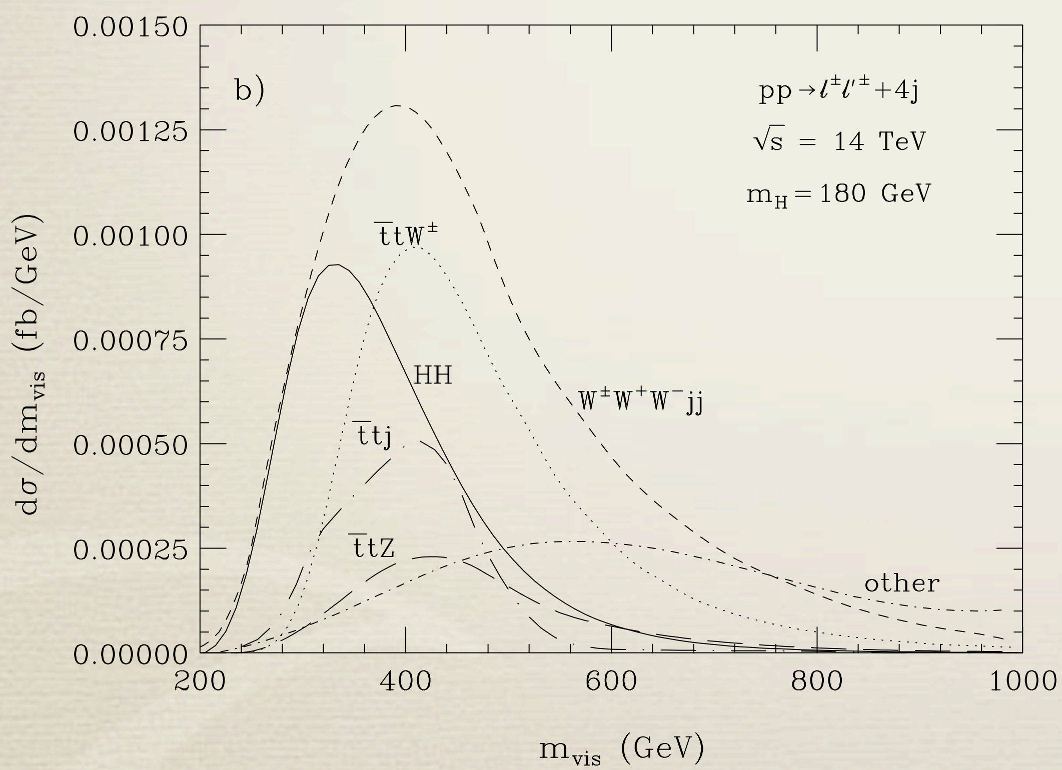
* Form of SM Higgs potential makes definite predictions

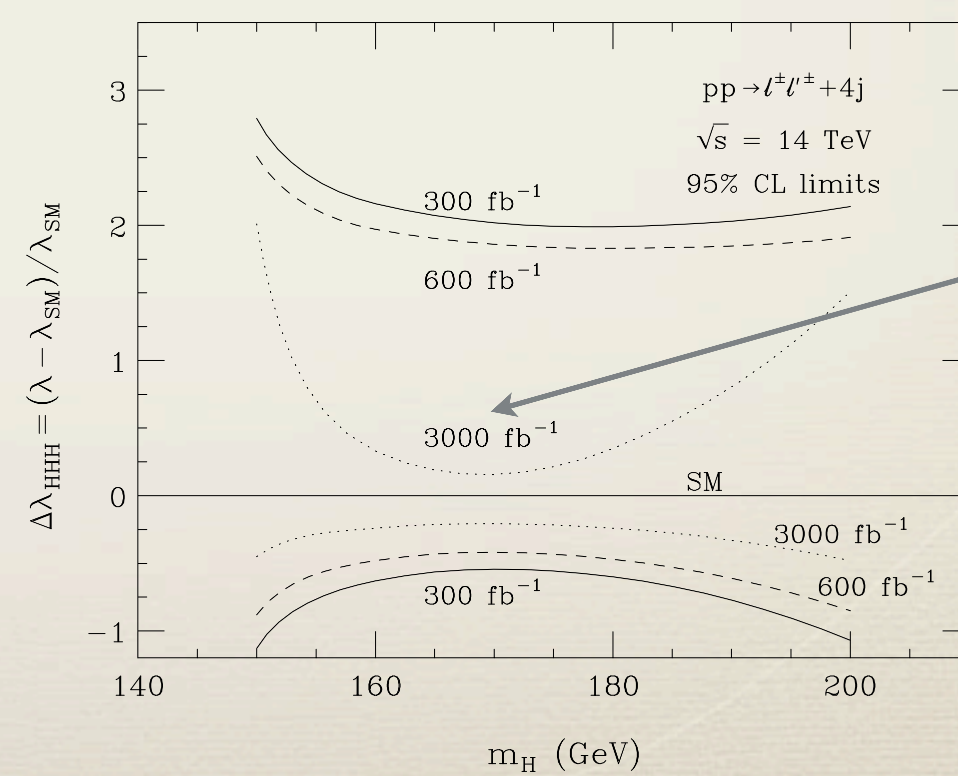
$$V(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

$$\Rightarrow g_{hhh} = 3M_H^2/v$$

Probe in $gg \to hh \to W^+W^-W^+W^- \to l^+l'^+ + 4j + \text{missing } p_T$ (one possible final state)







super-LHC luminosity upgrade required

Baur, Plehn, Rainwater hep-ph/0211224

Conclusions

* We must find a Higgs boson or something else which consistently breaks EW symmetry
* Phenomenology of Higgs intricate and highly dependent on its mass; detailed experimental program needed to find it
* Very sensitive to quantum effects; better have a good handle on QCD!
* Tevatron beginning to reach into allowed SM mass region; LHC will pick up the search later this year
* Potential to determine whether the Higgs is SM or not with LHC measurements