Review of recent theoretical developments in Higgs Physics

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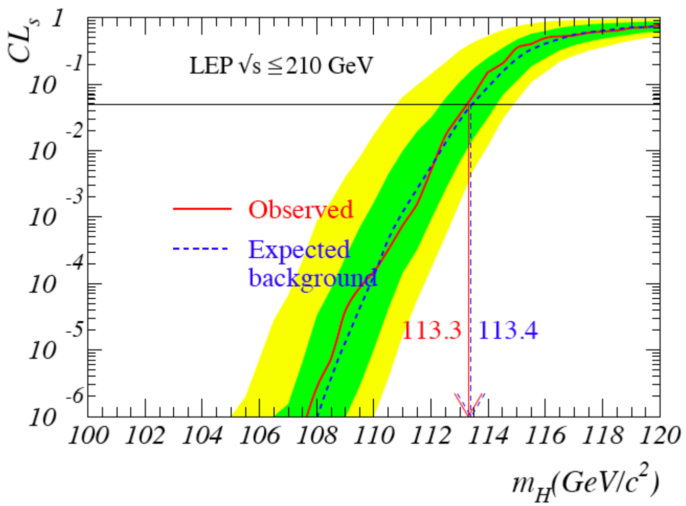
Argonne NATIONAL LABORATORY

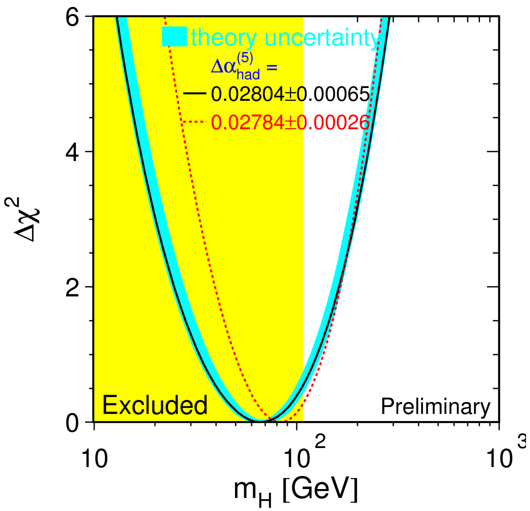
DPF meeting, August 2011, Brown University, Providence

The SM Higgs Journey from LEP to LHC

- **Where we were beginning of 2000….**

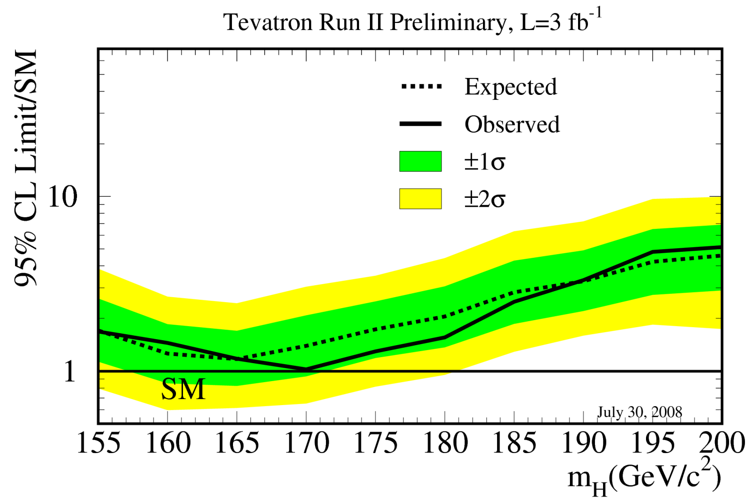


MH < 113.4 GeV excluded @ 95% CL



MH < 170 GeV @ 95% CL

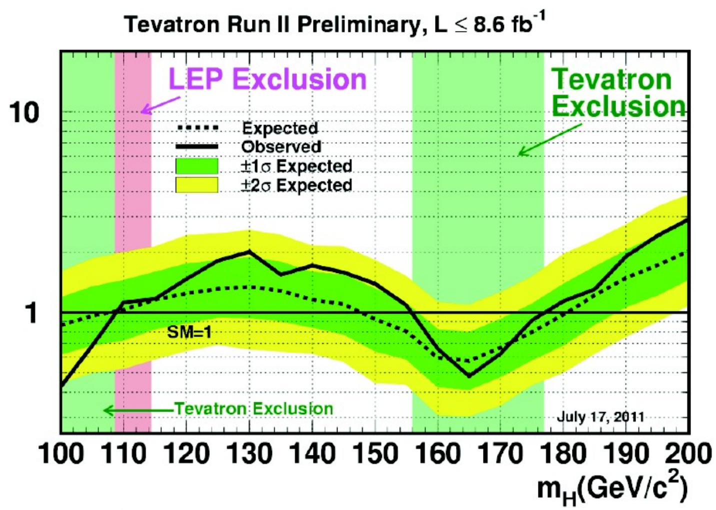
- **2008: First direct exclusion of a SM Higgs mass above 114 GeV by Tevatron**



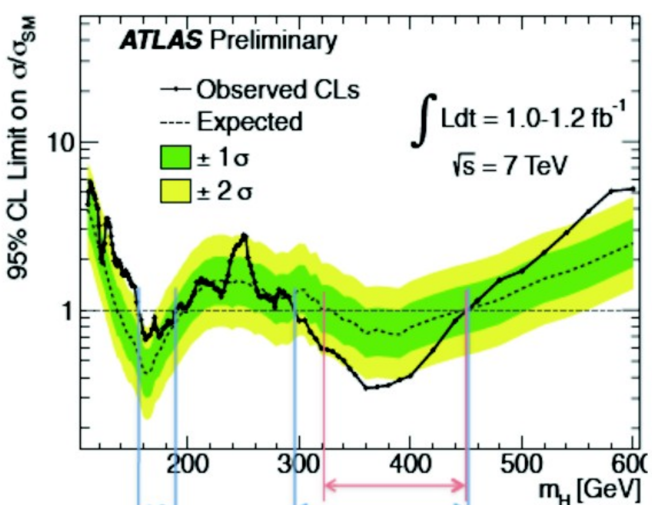
MH = 170 GeV is excluded at 95% CL

The SM Higgs Journey from LEP to LHC

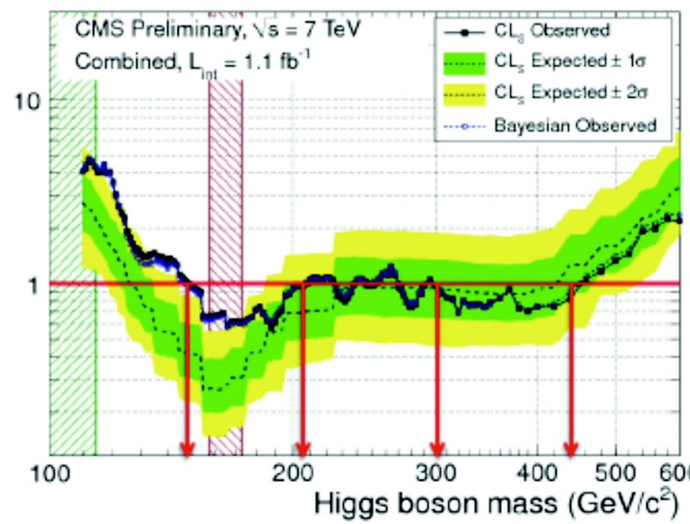
- Where we are now….



156 < MH < 177 GeV
@ 95% CL



155<M_H<190 and 295 <M_H< 450 GeV/c²
excluded at @ 95% CL



Excluded (GeV)
[149-206] … [300-440]
and 3 short segments
in between

The SM Higgs Journey from LEP to LHC

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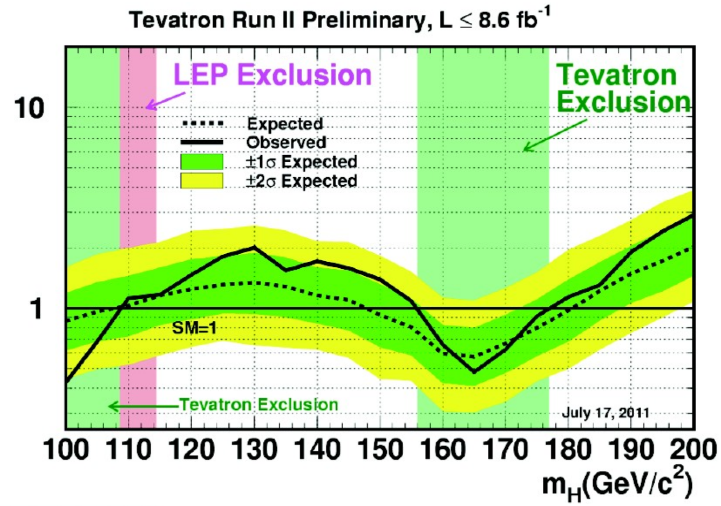

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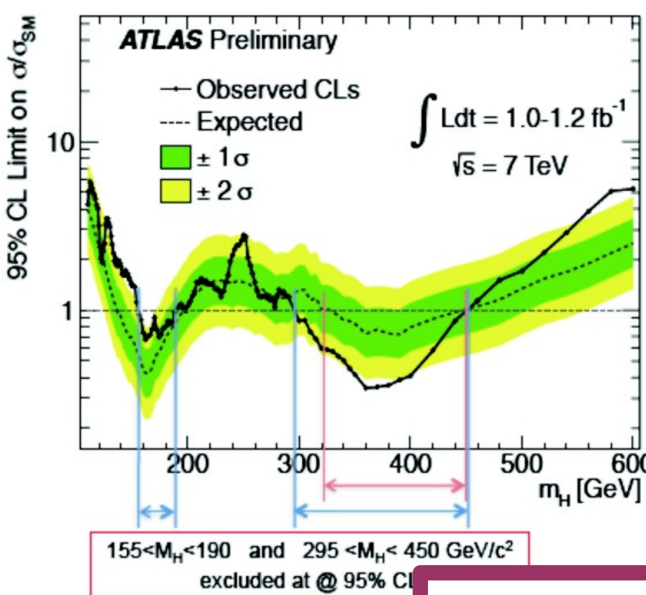
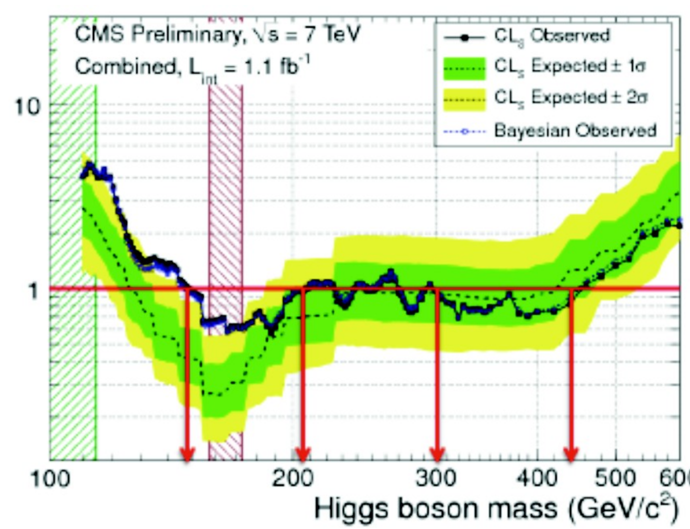




Excluded (GeV)
[149-206] … [300-440]
and 3 short segments
in between

Closing in on the SM Higgs

Higgs Discovery

$\sqrt{s}=7$ TeV

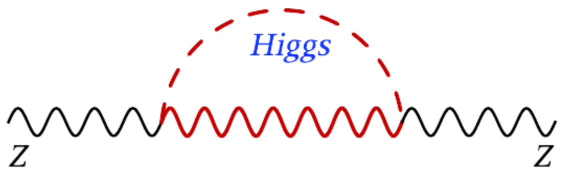
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity	
1 fb^{-1}	120 - 530	135 - 475	152 - 175	
2 fb^{-1}	114 - 585	120 - 545	140 - 200	
5 fb^{-1}	114 - 600	114 - 600	128 - 482	2011
10 fb^{-1}	114 - 600	114 - 600	117 - 535	2012

We will know soon if the SM Higgs exists

Outline

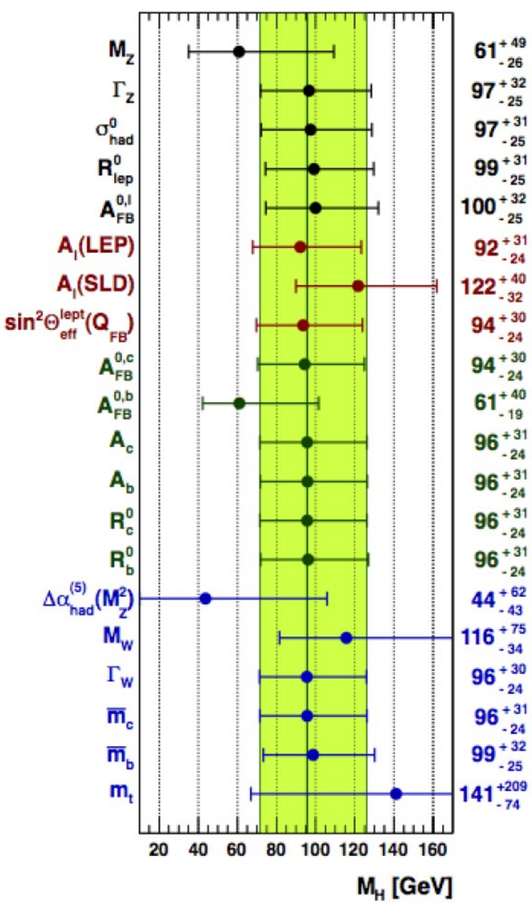
- Review of the SM Higgs
- Recent developments in gluon fusion:
    - PDFs and the Higgs
    - The jet veto in gluon fusion
    - Higgs as a window on BSM
- Other production modes:
    - Vector boson fusion and associated VH production
- Conclusions

Indirect Searches



$$\Delta M^2_Z \sim M^2_Z \ln M_{Higgs}/M_Z$$

Higgs searched for via indirect influence through quantum effects



$\Delta\chi^2$ estimator for the standard and complete fits versus M_H

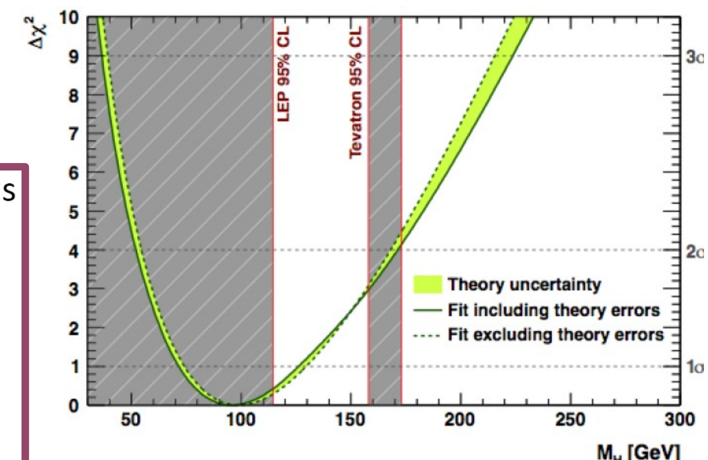
$$M_H = \begin{cases} 96^{+31}_{-24}\ \text{GeV} & \text{(standard fit)} \\ 120^{+12}_{-5}\ \text{GeV} & \text{(complete fit)} \end{cases}$$

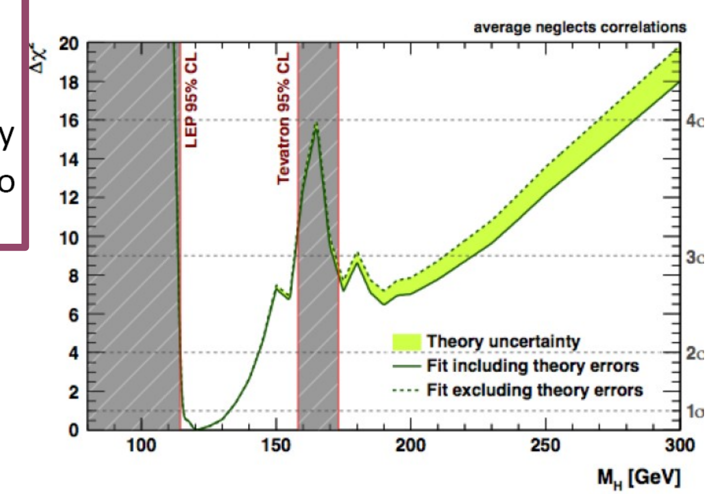
with the 95% (99%) upper bounds of

- 169GeV (200 GeV) for the standard fit
- 143GeV (149 GeV) for the complete fit

The errors and limits include the various theory uncertainties that taken together amount to approximately 8 GeV on M_H .

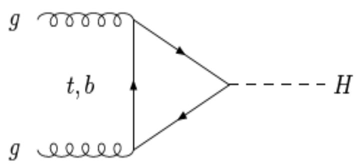
G fitter



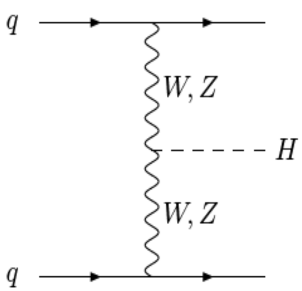


M. Schott

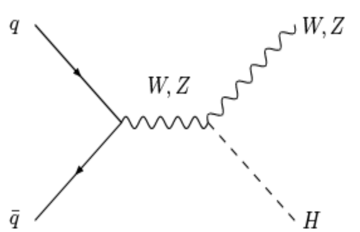
Phenomenological Profile



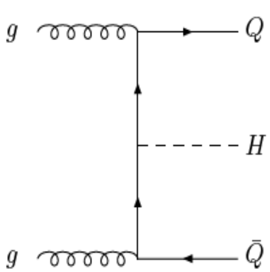
gg fusion



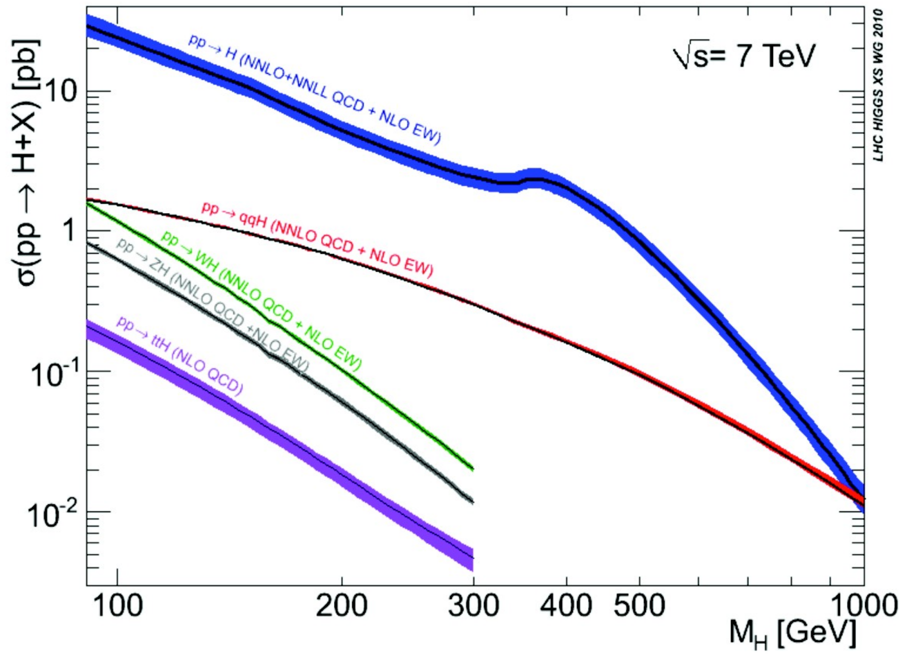
vector boson fusion

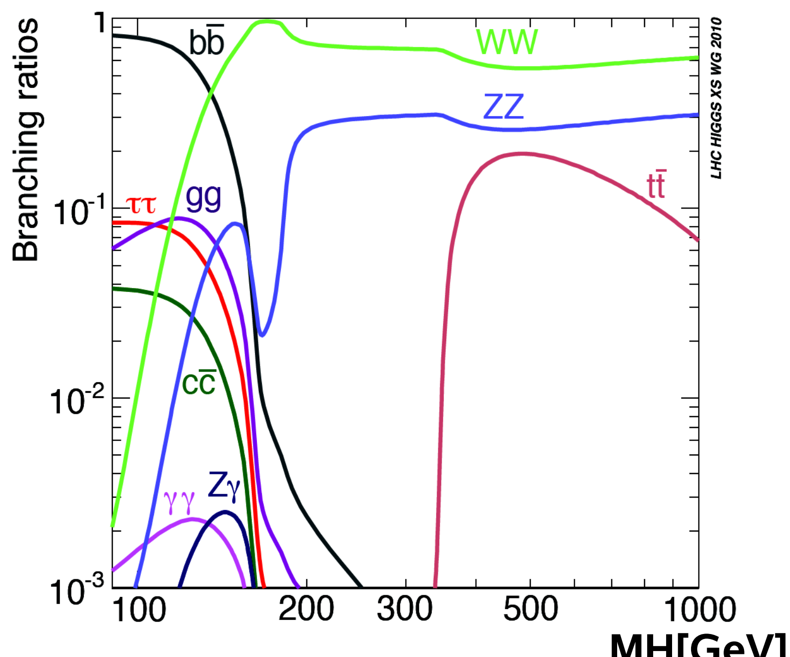


associated production with W, Z



associated production with $Q\bar{Q}$

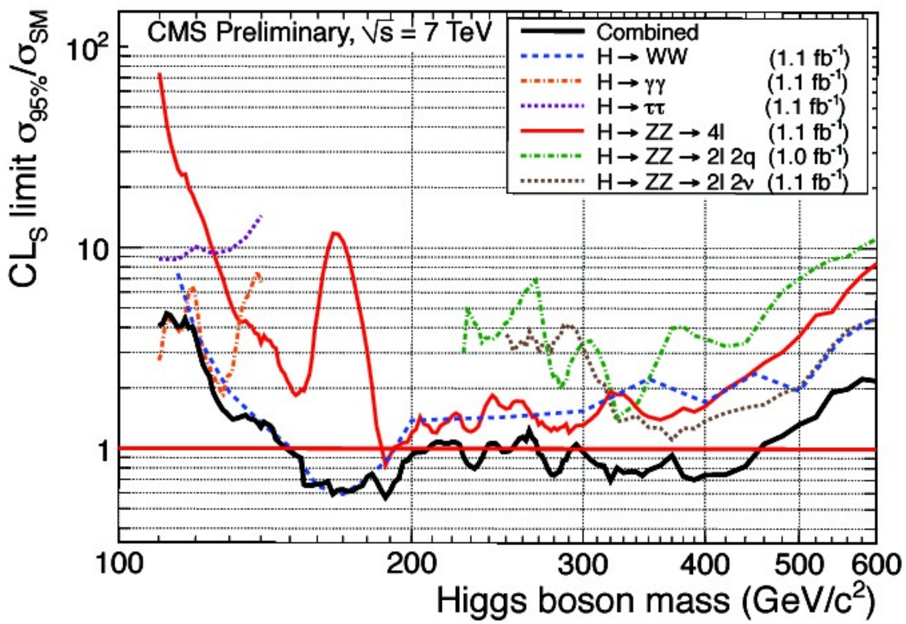


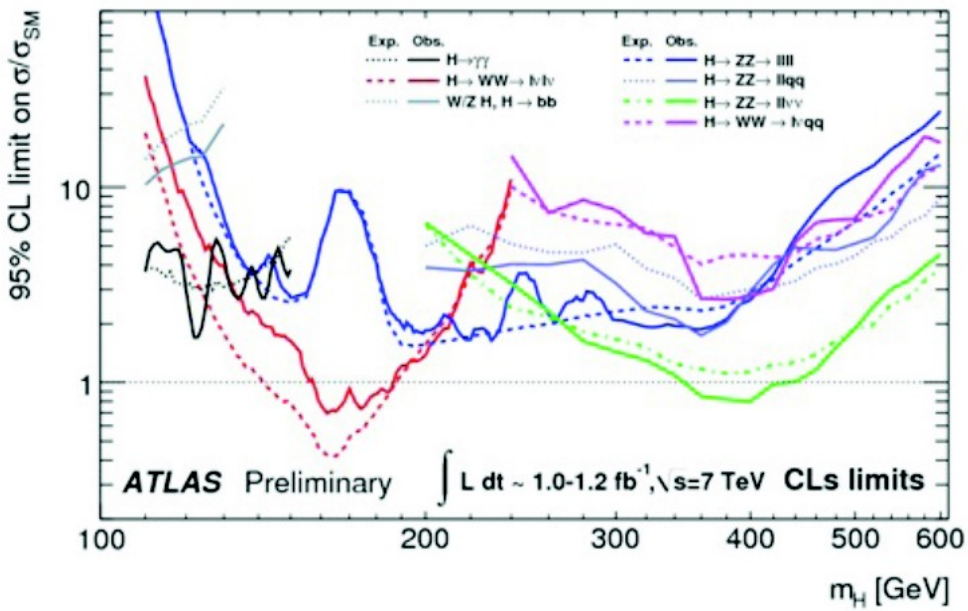


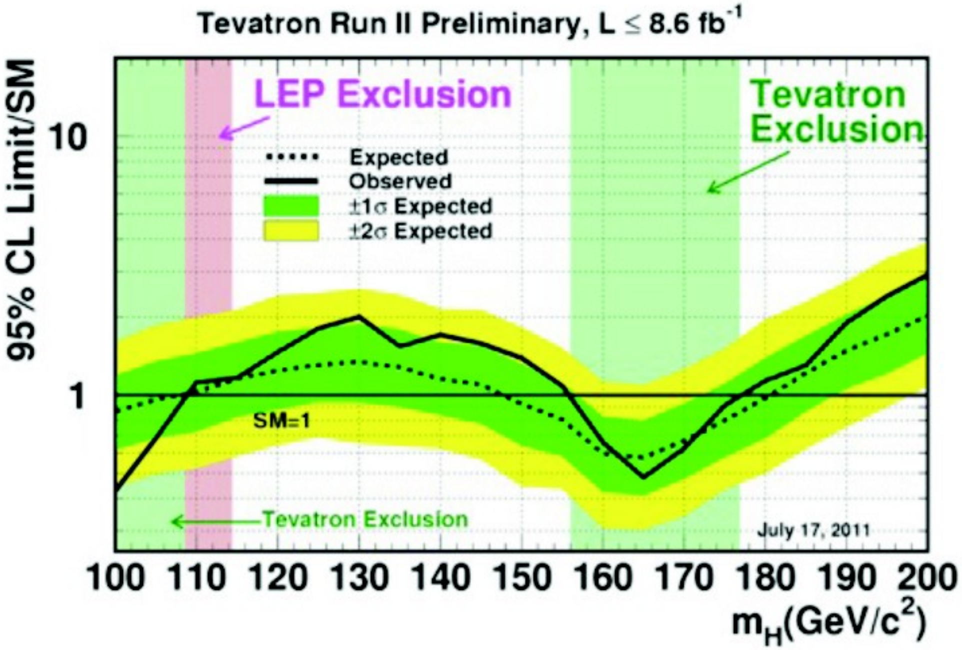
From CMS:

Mode	Mass	L (fb^{-1})	Doc
γγ	110-140	1.1	HIG-11-010
ττ	110-140	1.1	HIG-11-009
ZZ(2ℓ2n)	250-600	1.1	HIG-11-007
ZZ(2ℓ2j)	226-600	1.0	HIG-11-006
ZZ(4ℓ)	110-600	1.1	HIG-11-004
WW(2ℓ2ν)	110-600	1.1	HIG-11-001

Experimental Summary





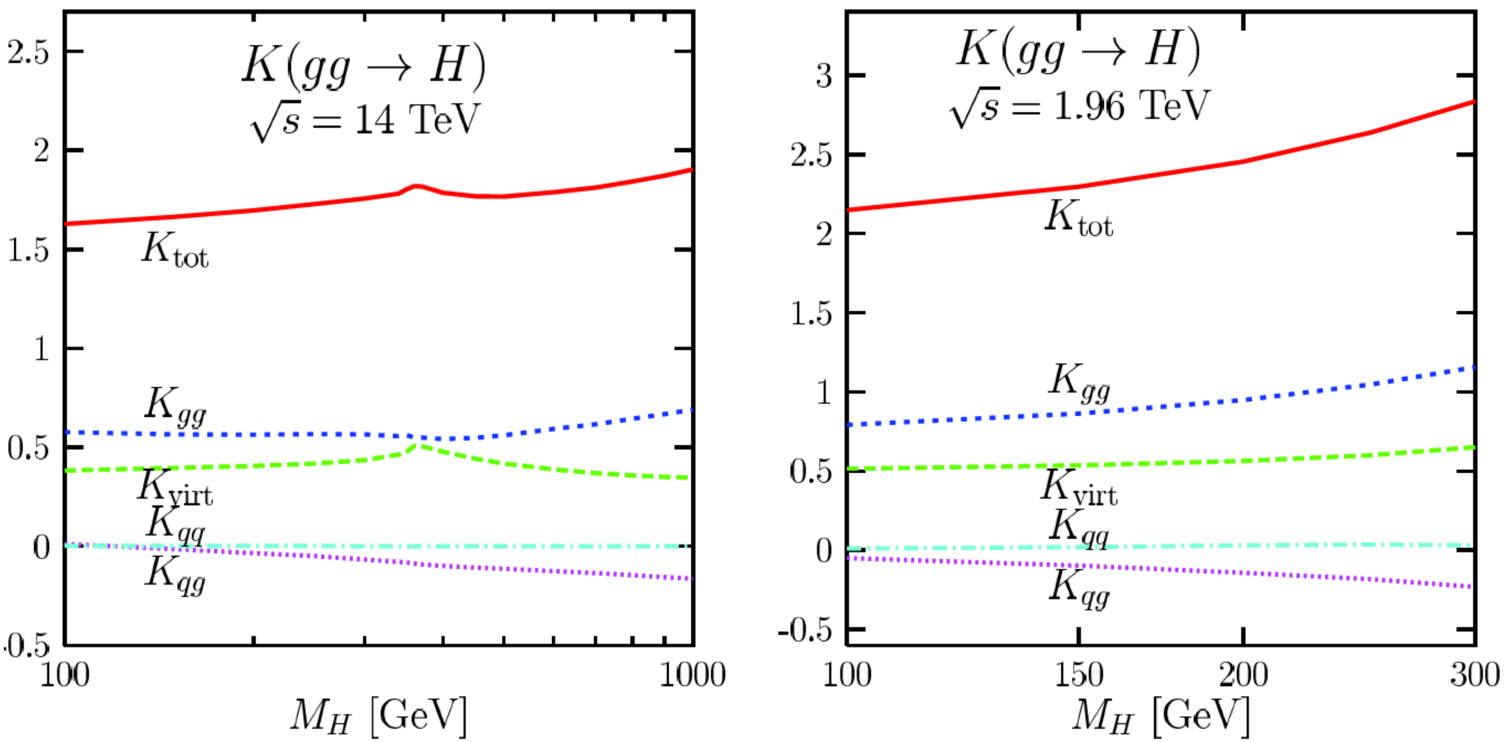


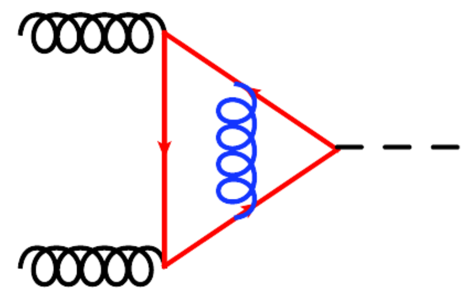
- What theory goes into these studies?
- Current limits come almost entirely from gg→h; focus first on this mode

Review of Gluon Fusion

Gluon-fusion

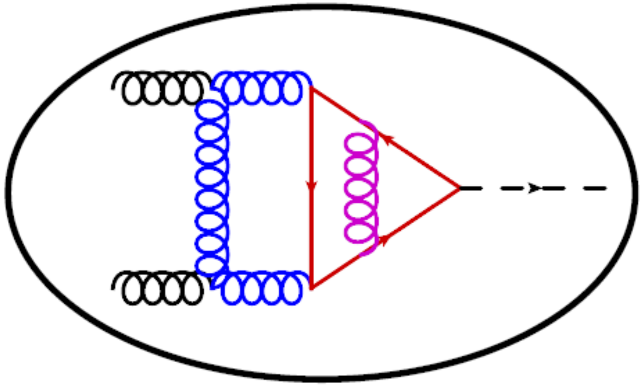
- Famously sensitive to large QCD corrections; difficult to calculate to requisite order in perturbation theory





Dawson; Djouadi, Graudenz, Spira, Zerwas, 1991, 1995

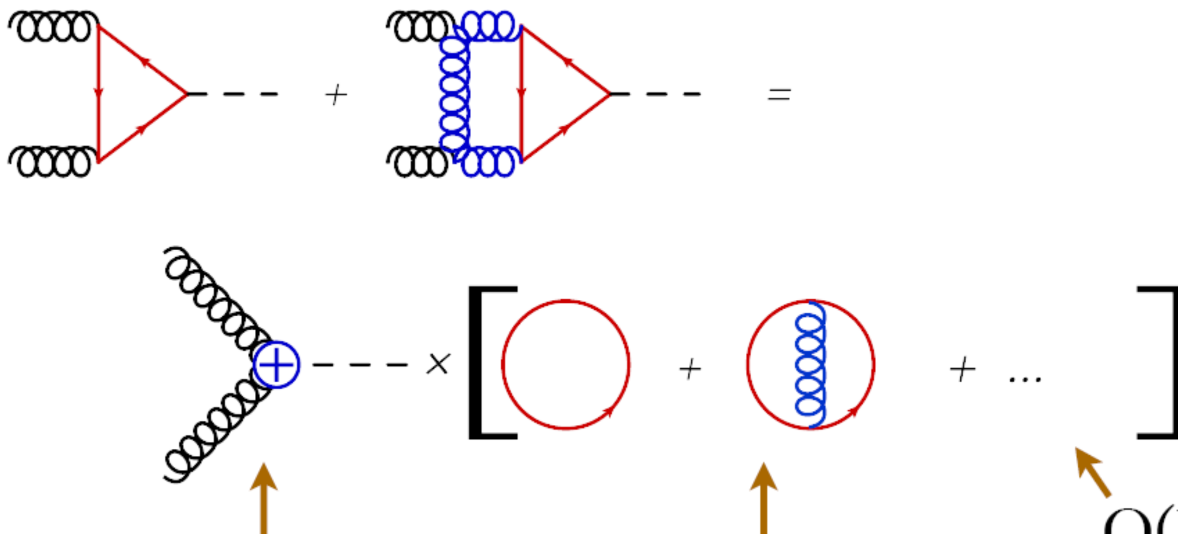
Effective Interactions



Getting the next terms requires new techniques

Effective field theory: exploit heavy mass of virtual particles

Two scales:
M_{Higgs}, m_{top}



Only M_{Higgs}

Only m_{top}

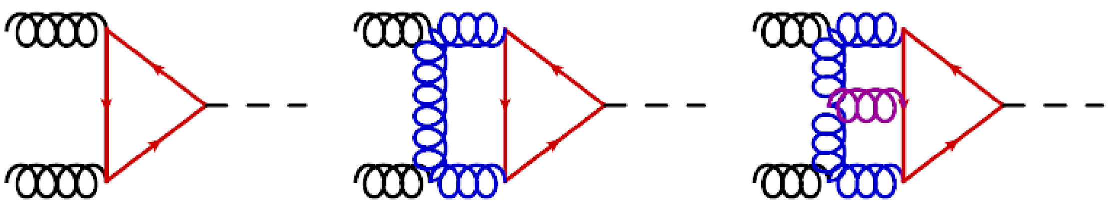
$O(M^2_{Higgs}/4m^2_{top})$

The Higgs Lagrangian

Summarized in an "effective Lagrangian" for Higgs-gluon interactions

$$\mathcal{L}_{eff} = \alpha_s \frac{C_1}{4v} H\, G^a_{\mu\nu} G^{\mu\nu}_a$$

$$C_1 = -\frac{1}{3\pi}\left\{1 + \alpha_s C_{1t} + \alpha_s^2 C_{2t} + \lambda_{EW}\left[1 + C_{1w}\right]\right\}$$



Inami, Kubota, Okada 1982

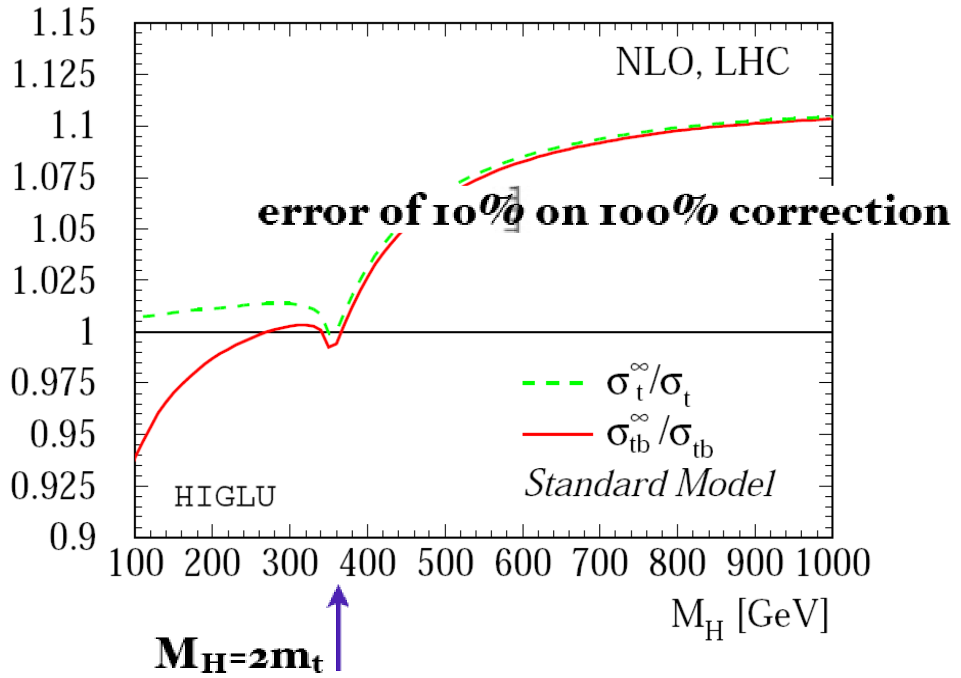
Chetyrkin, Kniehl, Steinhauser 1997

EW terms: Actis et al 2008; Anastasiou, R. B. , Petriello 2009

Unreasonably Effective EFT

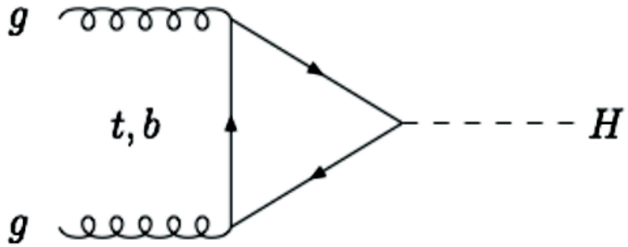
$$\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}} \right) \sigma_{LO}^{QCD}$$

NNLO study of $1/m_t$ suppressed operators, matched to large s-hat limit, large indicates this persists
Harlander, Mantler, Marzani, Ozeren; Pak, Rogal, Steinhauser 2009



Gluon-fusion: inclusive

- Focus on the dominant gluon-fusion mode, which dominates production in WW, ZZ, γγ final states. Enormous effort devoted to understanding effects all the way down to the 5-10% level



The Higgs coupling is proportional to the quark mass → top-loop dominates

QCD corrections to the total rate computed more than 15 years ago and found to be large

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas; S. Dawson (1991)

They increase the LO result by about 80-100 % !

Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit

R.Harlander, W. Kilgore (2001,2002)

C.Anastasiou, K. Melnikov (2002)

V. Ravindran, J. Smith, W.L.Van Neerven (2003)

Large-m_{top} approximation works extremely well up to m_H=300 GeV (differences of the order of 0.5 % !)

R.Harlander et al. (2009,2010)

M.Steinhauser et al. (2009)

Gluon-fusion: inclusive

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

S. Catani, D. De Florian, P. Nason, Grazzini (2003)

Moch, Vogt (2005)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach

Anastasiou, R. B. , Petriello (2008)

EW effects for real radiation (effect O(1%))

W. Keung, F. Petriello (2009)

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After 20 years of work we now understand the SM Higgs precisely

Recent Results

PDFs and the Higgs

- Recent controversy regarding large variation of Higgs cross section with PDF sets

Example: ABM + JR @ Tevatron

ABM vs MSTW at 160 GeV

-30% (>5 sigma)

Cross section in picobarns

M_H (GeV)	ABM10 [8]	ABKM09 [9]	JR [10]	MSTW08 [11]	HERAPDF [12]
100	1.438 ± 0.066	1.380 ± 0.076	1.593 ± 0.091	1.682 ± 0.046	1.417
110	1.051 ± 0.052	1.022 ± 0.061	1.209 ± 0.078	1.265 ± 0.038	1.055
115	0.904 ± 0.047	0.885 ± 0.055	1.060 ± 0.072	1.104 ± 0.034	0.917
120	0.781 ± 0.042	0.770 ± 0.050	0.933 ± 0.067	0.968 ± 0.031	0.800
125	0.677 ± 0.038	0.672 ± 0.045	0.823 ± 0.062	0.851 ± 0.029	0.700
130	0.588 ± 0.034	0.589 ± 0.041	0.729 ± 0.058	0.752 ± 0.026	0.615
135	0.513 ± 0.031	0.518 ± 0.037	0.647 ± 0.054	0.666 ± 0.024	0.541
140	0.449 ± 0.028	0.456 ± 0.034	0.576 ± 0.050	0.591 ± 0.022	0.479
145	0.394 ± 0.025	0.403 ± 0.031	0.514 ± 0.047	0.527 ± 0.020	0.424
150	0.347 ± 0.023	0.358 ± 0.028	0.461 ± 0.044	0.471 ± 0.018	0.377
155	0.306 ± 0.020	0.318 ± 0.026	0.413 ± 0.041	0.421 ± 0.017	0.336
160	0.271 ± 0.019	0.283 ± 0.024	0.371 ± 0.039	0.378 ± 0.016	0.300
165	0.240 ± 0.017	0.253 ± 0.022	0.335 ± 0.036	0.341 ± 0.014	0.269
170	0.213 ± 0.015	0.226 ± 0.020	0.302 ± 0.034	0.307 ± 0.013	0.241
175	0.190 ± 0.014	0.203 ± 0.019	0.274 ± 0.032	0.278 ± 0.012	0.217
180	0.169 ± 0.013	0.182 ± 0.017	0.248 ± 0.030	0.251 ± 0.012	0.195
185	0.151 ± 0.012	0.164 ± 0.016	0.225 ± 0.028	0.228 ± 0.011	0.176
190	0.136 ± 0.011	0.148 ± 0.015	0.205 ± 0.027	0.207 ± 0.010	0.159
200	0.109 ± 0.009	0.121 ± 0.013	0.170 ± 0.024	0.172 ± 0.009	0.131

Such differences may affect Higgs exclusion limits

Why so different Higgs cross sections?

ABM: Alekhin, Blumlein, Moch; JR: Jimenez-Delgado, Reya

NMC Data

ABM claim other groups treat NMC data incorrectly, leading to the discrepancy

NMC: $Q^2 < 40$ GeV^2 muon-nucleon scattering

$$\frac{d^2\sigma(x,Q^2)}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left\{1-y-xy\frac{M^2}{s}+\left(1-\frac{2m_l^2}{Q^2}\right)\left(1+4x^2\frac{M^2}{Q^2}\right)\frac{y^2}{2(1+R(x,Q^2))}\right\}F_2(x,Q^2)$$

- NMC gives both $d\sigma$ and F_2; fit to which?
- F_2 was extracted before QCD corrections to R known
- MSTW uses F_2; ABKM (lowest σ_H) uses $d\sigma$

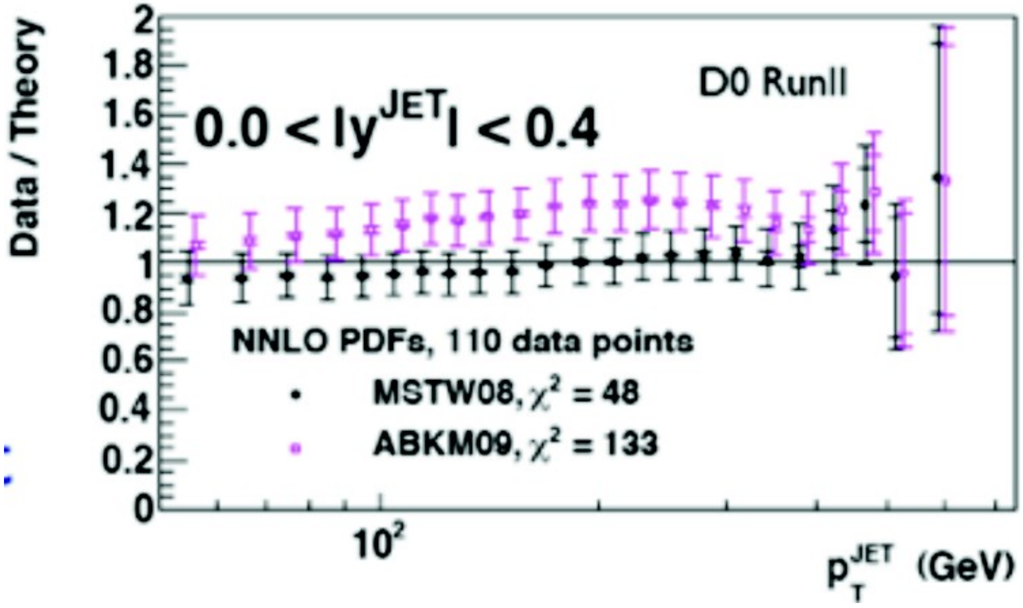
- R. Thorne & G. Watt (TW) tried using different versions of NMC data and find small effect for gluon and coupling

- NNPDF finds also very small effect

Tevatron Jet Data

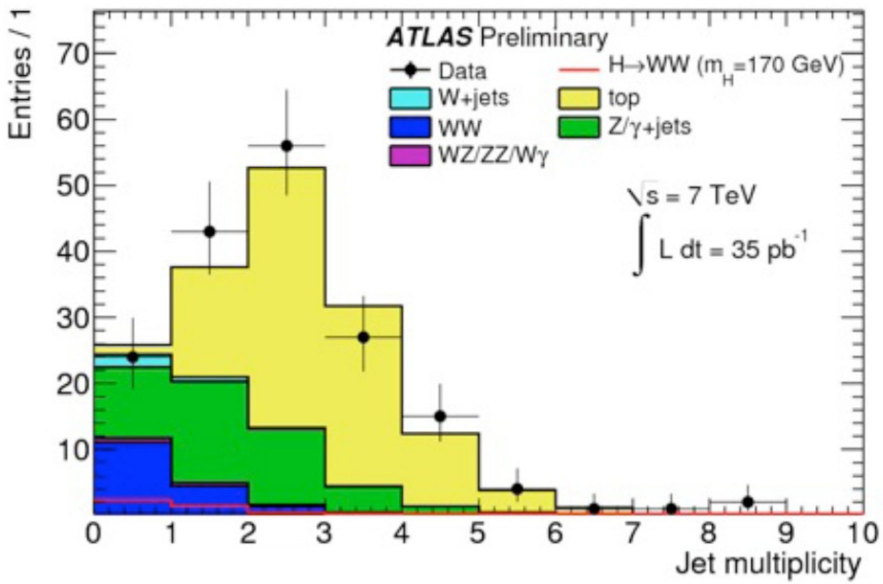
• Interesting exercise by Thorne and Watt (2011)

➡ Check how well PDFs reproduce Tevatron jet data

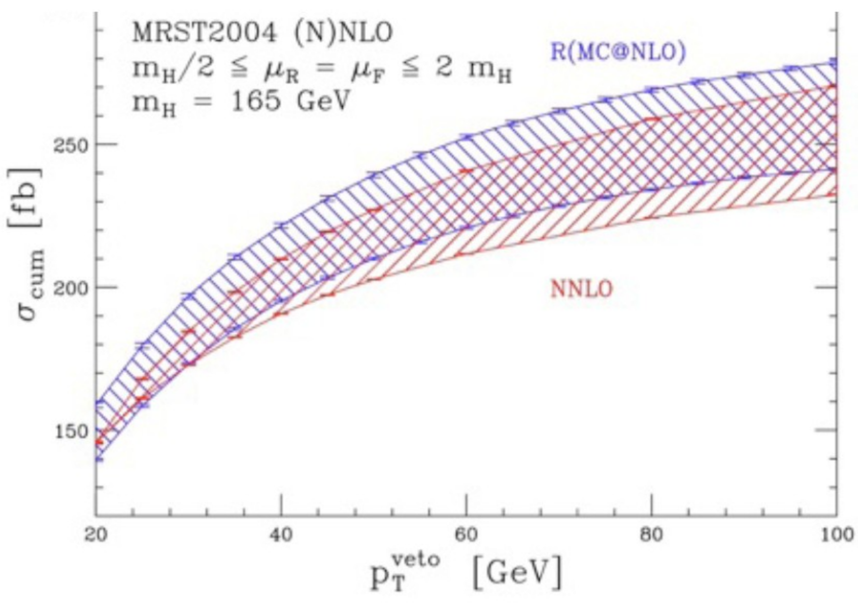


Message from Thorne and Watt: only global analysis provide accurate distributions and uncertainties. No acceptable description of jet data from non-global sets

The Jet Veto in Gluon Fusion



- Toughest cut from theoretical perspective is the jet veto
- Required in WW channel due to background composition
- 25-30 GeV jet cut envisioned; restriction of radiation leads to large logs



Anastasiou, Dissertori, Stoeckli 2007

- Inclusive scale variation 10%; with a 25 GeV jet veto, 5-6%!
- Having $\Delta\sigma_{veto} < \Delta\sigma_{tot}$ doesn't seem correct; σ_{veto} has a more complicated structure and a larger expansion parameter, $\alpha_S \ln^2(m_H/p_{T,cut})$ rather than α_S

The BNL Accord

- **Better solution pointed out in course of SCET study** Stewart, Tackmann (2011)

- In the limit of $\ln(m_H/p_{T,cut})$ large, σ_{tot} and $\sigma_{\geq 1}$ have independent expansions
- Gives expected result, that $\Delta\sigma_{veto} > \Delta\sigma_{tot}$
- Agreed to as the procedure for LHC error treatment at 2011 BNL workshop

First consider *inclusive* jet cross sections

$$\sigma_{\rm total},\ \sigma_{\geq 1},\ \sigma_{\geq 2} \quad \Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} & 0 & 0 \\ 0 & \Delta^2_{\geq 1} & 0 \\ 0 & 0 & \Delta^2_{\geq 2} \end{pmatrix}$$

Transform to *exclusive* jet cross sections

$$\sigma_0 = \sigma_{\rm total} - \sigma_{\geq 1}\,, \qquad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}\,, \qquad \sigma_{\geq 2}$$

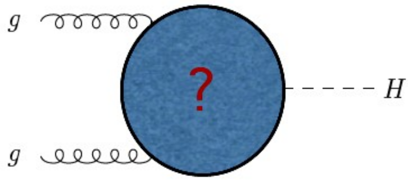
$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ -\Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 2} & \Delta^2_{\geq 2} \end{pmatrix}$$

cut	$\frac{\Delta\sigma_{\rm total}}{\sigma_{\rm total}}$	$\frac{\Delta\sigma_{\geq 1}}{\sigma_{\geq 1}}$	$\frac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$	$\frac{\Delta\sigma_0}{\sigma_0}$	$\frac{\Delta\sigma_1}{\sigma_1}$
$p_T^{\rm cut} = 30\,{\rm GeV},\ \eta^{\rm cut} = 3$	10%	21%	45%	17%	29%

Higgs as a window on BSM

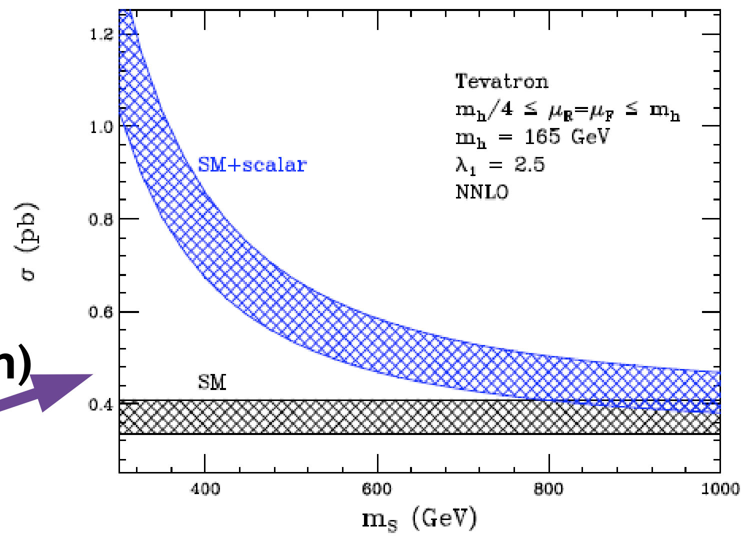
Looking beyond the SM with the Higgs

• New states can significantly modify the properties of the Higgs



- squark/gluino loops

Anastasiou, Beerli, Daleo (2008); Muehlleitner, Rzehak, Spira (2008)

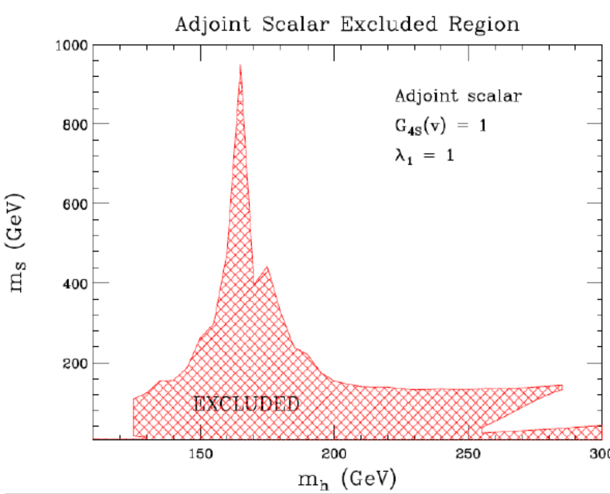


- Extra heavy quark families (eg. 4th generation)

(Anastasiou, R. B., Furlan 2010)

- Color octet scalars

(R. B., Petriello 2010)



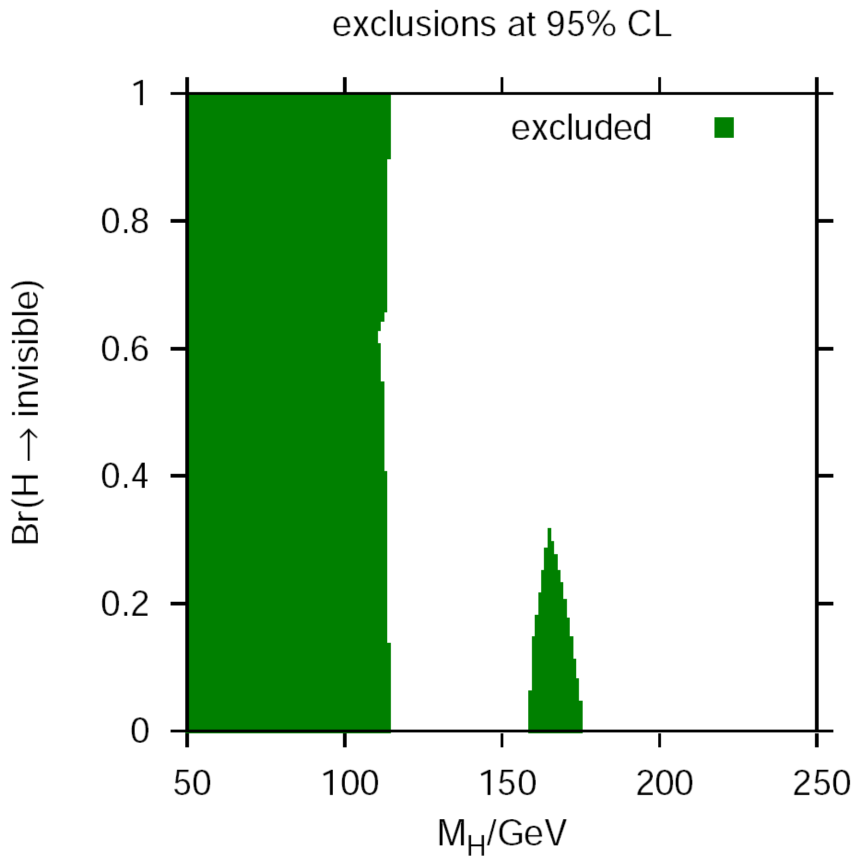
- Using the calculated signal and branching ratio in the presence of new states and the Tevatron bounds on $\sigma(g\,g \to H) \times Br(H \to WW)$ strong bounds on the parameter space of new physics can be obtained (R. B. 2011)

R. B.

Looking beyond the SM with the Higgs

- **HiggsBounds 2.0.0: a tool that tests nutral and charged Higgs sectors of arbitrary models against the current exclusion bounds from Higgs searches at LEP and Tevatron** **Bechtle, Brein, Heinemeyer, Weiglein, Wiliams 2011**

Example exculsion of the parameter space of a toy model where the Higgs decays invisibly. Higgs production cross sections and all other Higgs decay widths take SM values.



Many Alternatives to SM Higgs

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

NMSSM

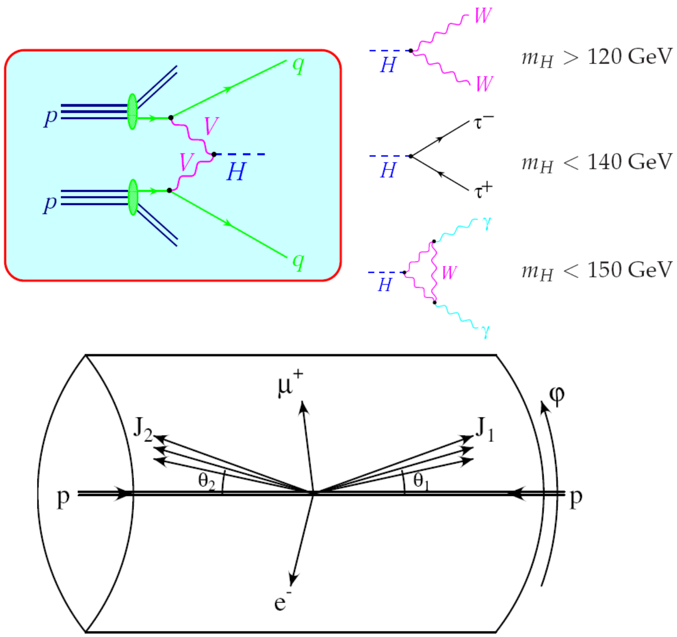
MSSM

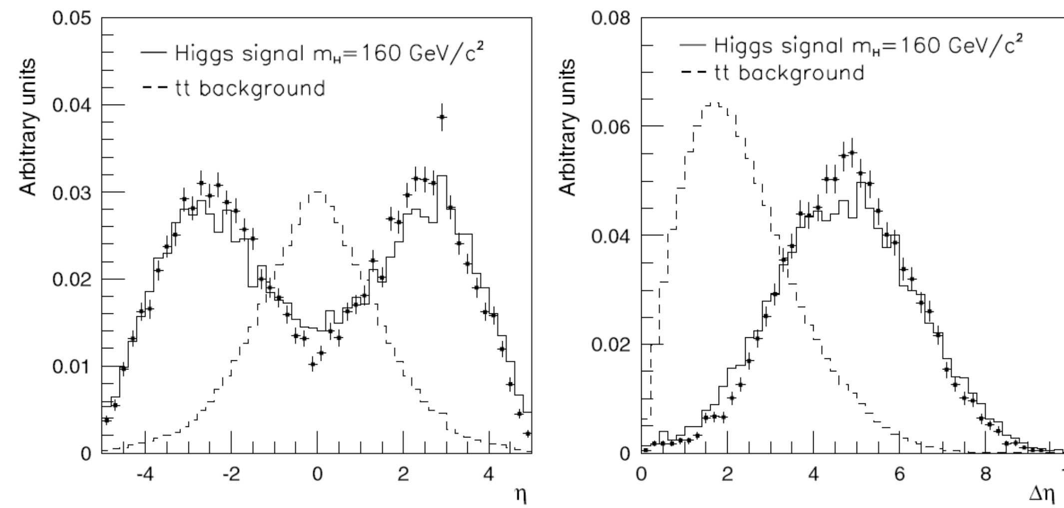
Require dedicated talks ...

Vector Boson Fusion

Vector Boson Fusion

- Attractive channel for discovery (distinctive signature) and measurement of Higgs coupling at LHC





signature

- Energetic jets in the forward and backward directions (PT > 20GeV)
- Large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products typically between tagging jets
- Little jet activity in central-rapidity region due to the colorless exchanged W/Z
- Applied cuts to achieve a clear separation from background are:

$$P_{T\ j} > 20\text{GeV}\ ,\ |\eta_j| \le 4-5,\ \Delta\ \eta \equiv |\eta_1 - \eta_2| \ge 4,\ \eta_1 \cdot \eta_2 < 0$$

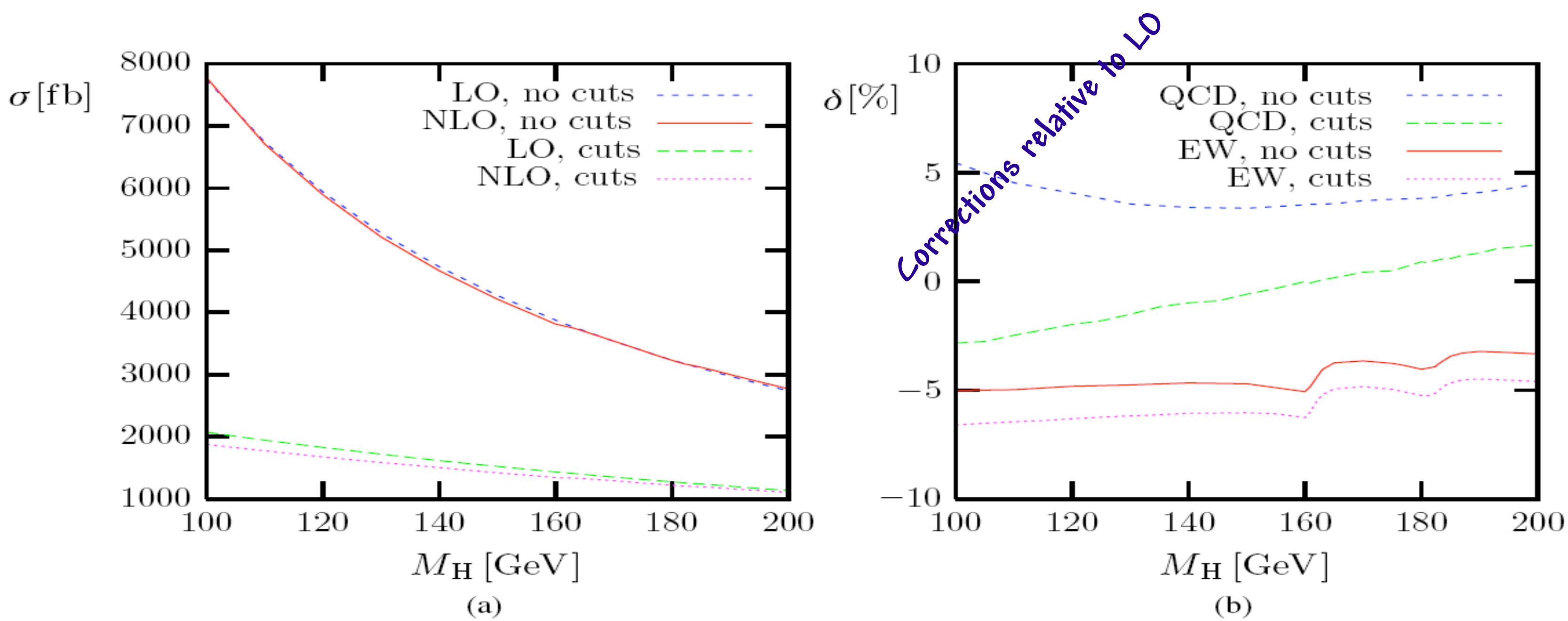
Vector Boson Fusion

- NLO QCD Corrections to total xsection (5-10%): Han, Valencia, Willenbrock (1992)
- Distributions at NLO are implimented in VBFNLO:

Figy, Oleari, Zeppenfeld (2003); Figy, Zeppenfeld (2004); Campbell, Ellis (2003); Arnold et al (2008)

- EW+QCD: Ciccolini, Denner, Dittmaier (2007)

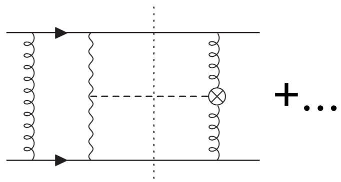
implimented in a flexible parton level generator HAWK



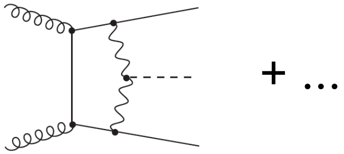
Vector Boson Fusion

- **Mixed QCD/EW** Bredenstein, Hagiwara, Jaeger (2008)

- **Gluon fusion/VBF interference** Anderesen, Binoth, Heinrich, Smillie (2007)

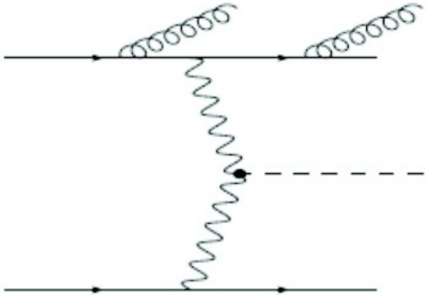


- **Gluon induced VBF** Harlander, Vollinga, Webber (2008)
  (effect below 1%)



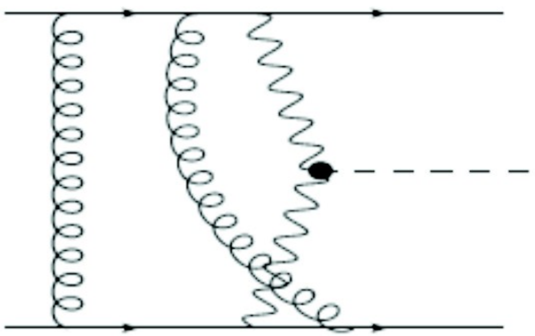
- **DIS like NNLO contributions computed within the structure function approach**

  Bolzoni, Maltoni, Moch, Zaro (2010)



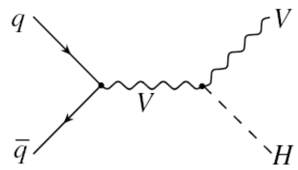
→ Scale uncertainty reduced to 2%

still missing :
(but kinematically
and parametrically
suppressed)



Associated VH Production

Higgs Strahlung



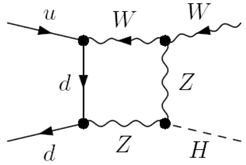
- pp→ VH + X (V=W/Z):
  - Most important channel for low mass at Tevatron: leptons provide the necessary background rejection
  - considered not important at LHC due to small cross section and large background
  - Resurrected through boosted analysis Butterworth et al (2008)

NLO QCD corrections: increase xsection by 30% Han, Willenbrock (1991)

NNLO QCD corrections: increase xsection by 5-10% Brein, Djouadi, Harlander (2004)

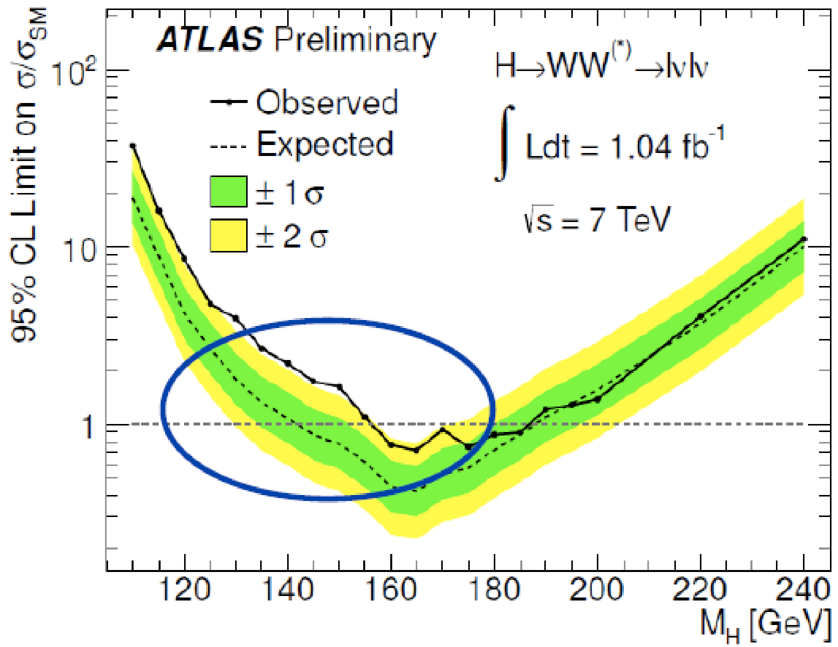
⇒ reduction of scale uncertainty from 10% (LO) to 5%(NLO) to 2% (NNLO)

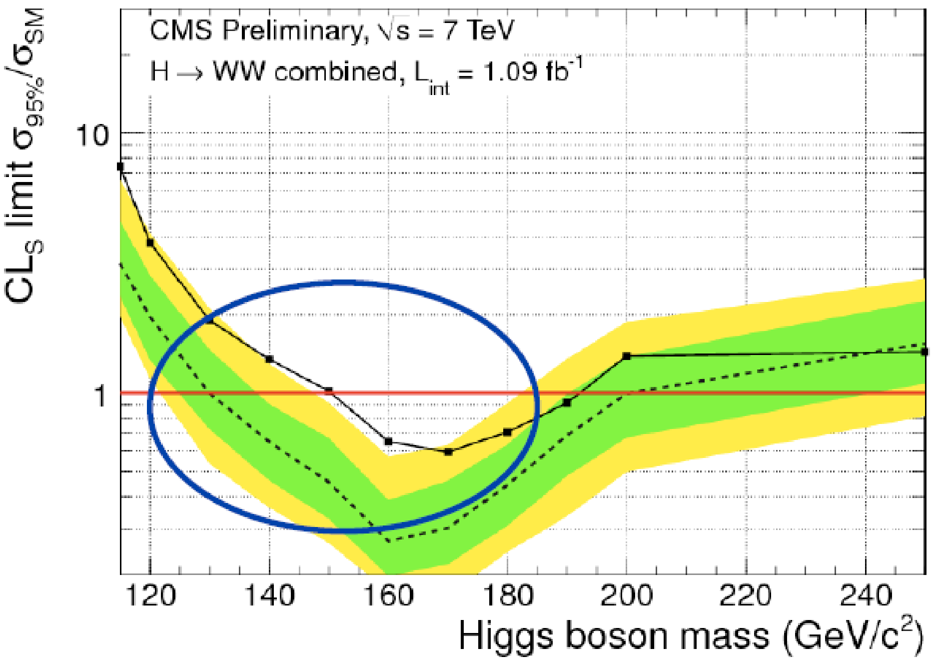
$O(\alpha)$ EW corrections: -5% to -10% Ciccolini, Dittmaier, Kramer (2003)



+…

Conclusions





Deviations between expected and observed limits possibly consistent with the presence of a Higgs signal...

We're all excited to see what happens next!