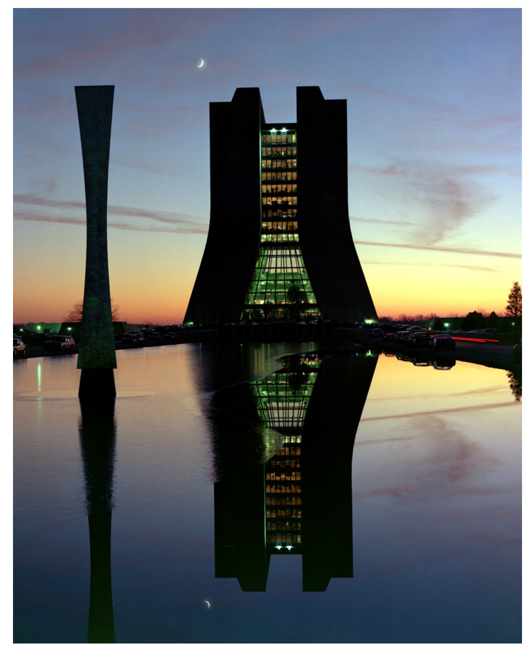
Tevatron Combination

Gavin Davies
On behalf of the CDF and DØ Collaborations



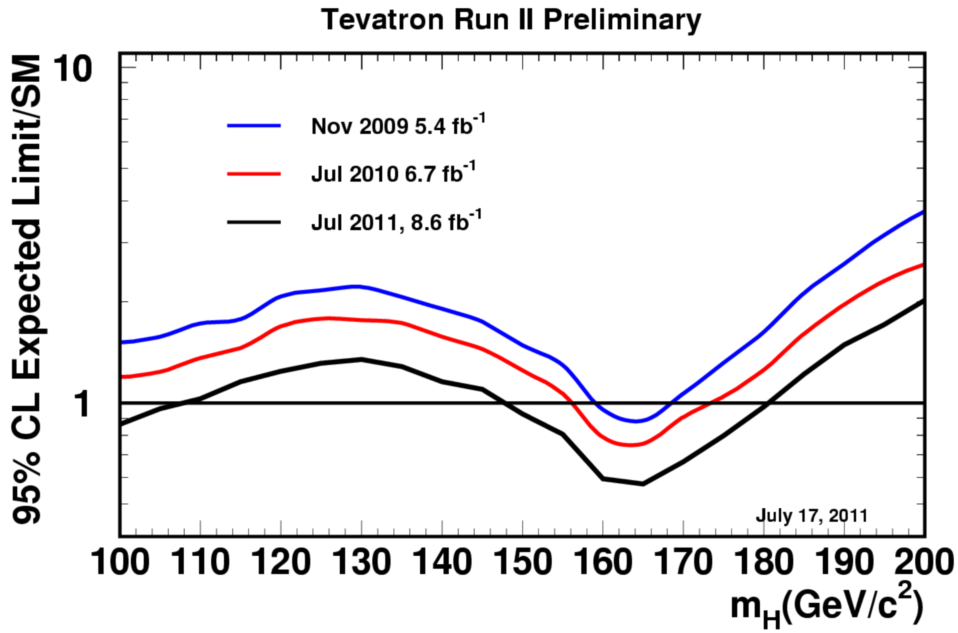
Outline

- Introduction
- Inputs
  - See previous talks
- Techniques
- Results
- Conclusions
- Future prospects
  - See Ben's talk

[Thanks to all Tevatron colleagues]

Introduction

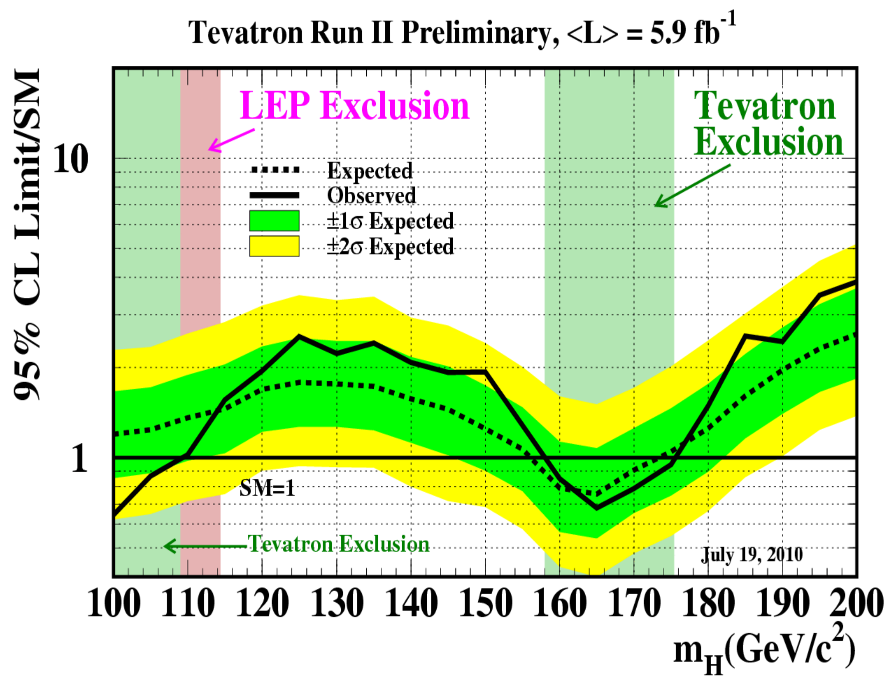
- Higgs Hunting – a huge, worldwide enterprise
- Still ongoing – after decades



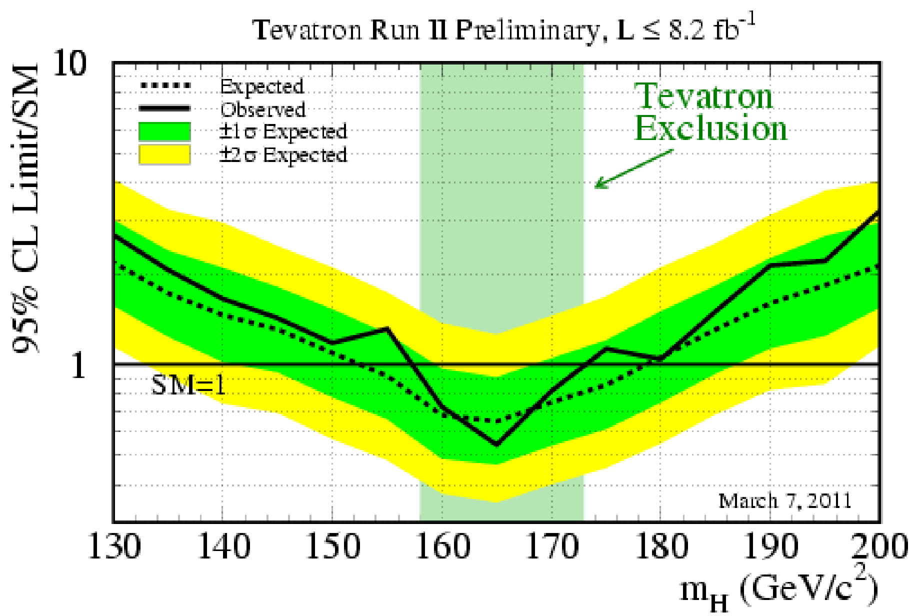
- Tevatron approach
  - Leave no stone unturned
    - Improve existing analyses
    - Include new channels
  - Combine across channels & experiments

Previous Limits

Summer 2010



Spring 2011



SM excluded:

$158 < m_H < 175$ GeV obs

$156 < m_H < 173$ GeV exp

SM excluded:

$158 < m_H < 173$ GeV obs

$153 < m_H < 179$ GeV exp

Inputs - I

- Total: 165 mutually exclusive 'sub-channels'
  - 71 from CDF, 94 from DØ

CDF

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu bb$ 2-jet channels	4×(TDT,LDT,ST,LDTX)	7.5	100-150
$WH \to \ell\nu b\bar{b}$ 3-jet channels	2×(TDT,LDT,ST)	5.6	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$	(TDT,LDT,ST)	7.8	100-150
$ZH \to \ell^+\ell^- b\bar{b}$	2×(TDT,LDT,ST)	7.7	100-150
$H \to W^+W^-$	2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	8.2	110-200
$WH \to WW^+W^-$	(same-sign leptons)+(tri-leptons)	8.2	110-200
$ZH \to ZW^+W^-$	(tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	8.2	110-200
		8.2	110-200
$H + X \to \tau^+\tau^-$	(1 jet)+(2 jets)	6.0	100-150
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$	(ℓ-ℓ-τ_{had})+(e-μ-τ_{had})+(ℓ-τ_{had}-τ_{had})	6.2	110-150
$WH + ZH \to jjb\bar{b}$	(GF,VBF)×(TDT,LDT)	4.0	100-150
$H \to \gamma\gamma$	(CC,CP,CC-Conv,CP-Conv)	7.0	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton)	(4jet,5jet)×(TTT,TTL,TLL,TDT,LDT)	6.3	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton)	(low met,high met)×(2 tags,3 or more tags)	5.7	100-150

Inputs - II

DØ

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \rightarrow \ell\nu b b$ (LST,LDT,2,3 jet)	8.5	100-150
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ (LST,LDT)	8.4	100-150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ (TST,TLDT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	8.6	100-150
$H+X \rightarrow \ell^{\pm}\tau^{\mp}_{had}jj$	4.3	105-200
$VH \rightarrow \ell^{\pm}\ell^{\pm} + X$	5.3	115-200
$H \rightarrow W^+W^- \rightarrow \ell^{\pm}\nu\ell^{\mp}\nu$ (0,1,2+ jet)	8.1	115-200
$H \rightarrow W^+W^- \rightarrow \mu\nu\tau_{had}\nu$	7.3	115-200
$H \rightarrow W^+W^- \rightarrow \ell\bar{\nu}jj$	5.4	130-200
$H \rightarrow \gamma\gamma$	8.2	100-150

Techniques

- Two statistical approaches used
  - Better than 10% agreement over whole mass range (~2% on average)
- Bayesian
  - Flat signal prior, credibility intervals
- Modified frequentist
  - Log-likelihood test statistic, $CL_s = CL_{s+b}/CL_b$
- Operate on binned, final discriminants
  - Poisson statistics assumed for each bin
- Systematics introduced as nuisance parameters
  - Impact of these mitigated with constraints from data

Systematics

- Unconstrained uncertainties can be as large as signal
- Included using a Bayesian formalism
  - Gaussian prior
- Consider both rate and shape errors
- Correlations included where appropriate
  - e.g. Across experiments
    - Mainly theoretical uncertainties, component of luminosity uncertainty
  - e.g. Across channels
    - Theoretical & experimental e.g. Within an experiment: Lepton / jet efficiencies, b-tagging, jet energy scale
  - Included in constraints from data

Theoretical Uncertainties - I

- Focus here on gg $\rightarrow$ H process
  - Cross-section: NNLO with soft resummation to NNLL (& EW corrections)
    - D. de Florian and M. Grazzini, arXiv:0901.2427 [hep-ph]
    - C. Anastasiou, R. Boughezal and F. Petriello, arXiv:0811.3458 [hep-ph]
  - Use MSTW08 PDF set as recommended by PDF4LHC

- Have included different errors for different jet bins for a while, but some changes this time

- Channels that don't split by number of jets
  - PDF+α_s: Use PDF4LHC prescription
  - Scale: Vary factorisation + renormalization errors by factor of 2 together
  - PDF+α_s and scale treated as uncorrelated

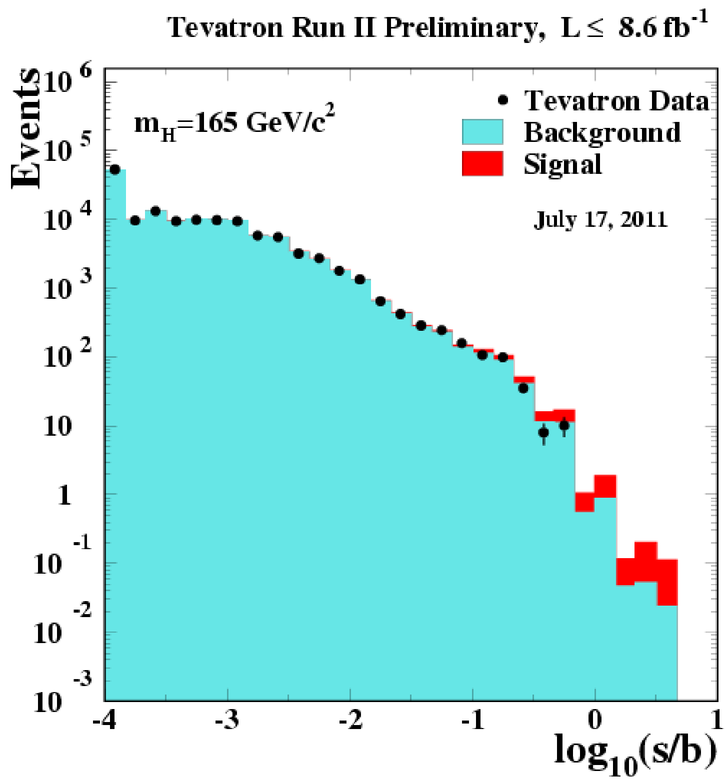
Theoretical Uncertainties - II

- Channels that split by number of jets
  - Different PDF+α_s and scale errors for each bin as before but
  - Treat scale uncertainty of NNLO+NNLL inclusive, NLO-1-or-more & NLO-2-or-more-jets as uncorrelated a la BNL
    - Berger et al., arXiv:1012.4480 [hep-ph]
    - Stewart and Tackmann, arXiv:1107.2217 [hep-ph]
  - From these calculate exclusive H+0jet, H+1jet, H+2jet-or-more scale uncertainties

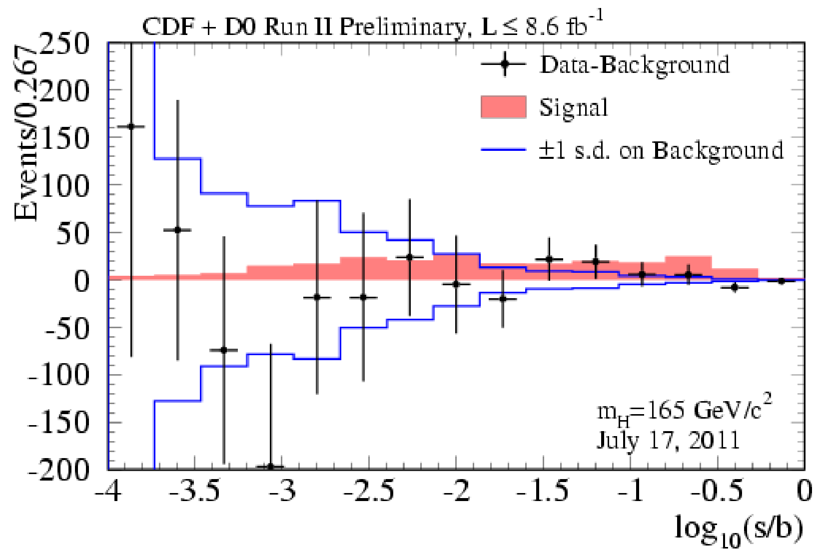
Jet bin	s0	s1	s2
0 jet	13.4%	-23.0%	0
1 jet	0	35%	-12.7%
>= 2 jets	0	0	33%

  - PDF errors from Anastasiou et al., JHEP 0908, 099 (2009) as before

Results



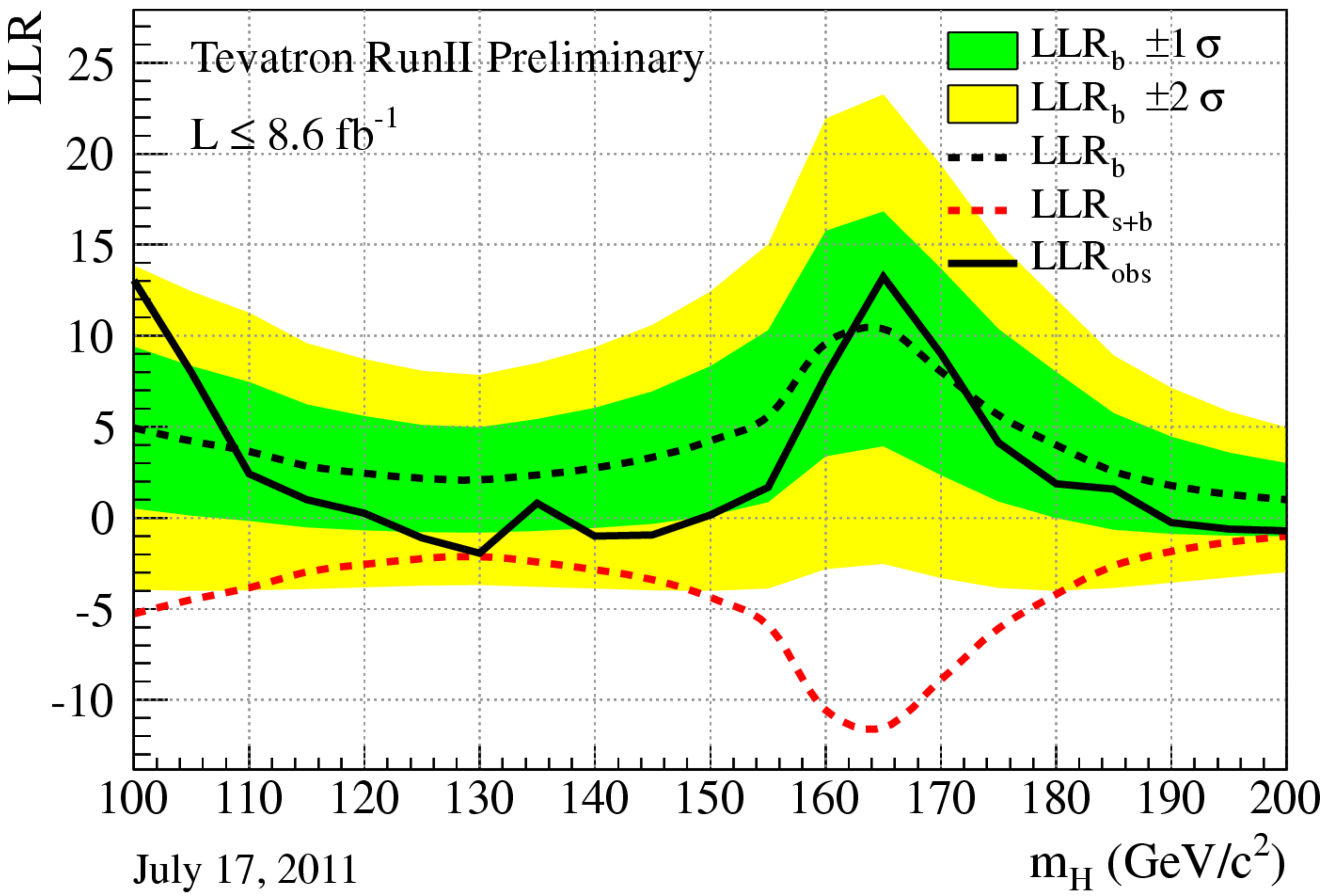
With background subtraction



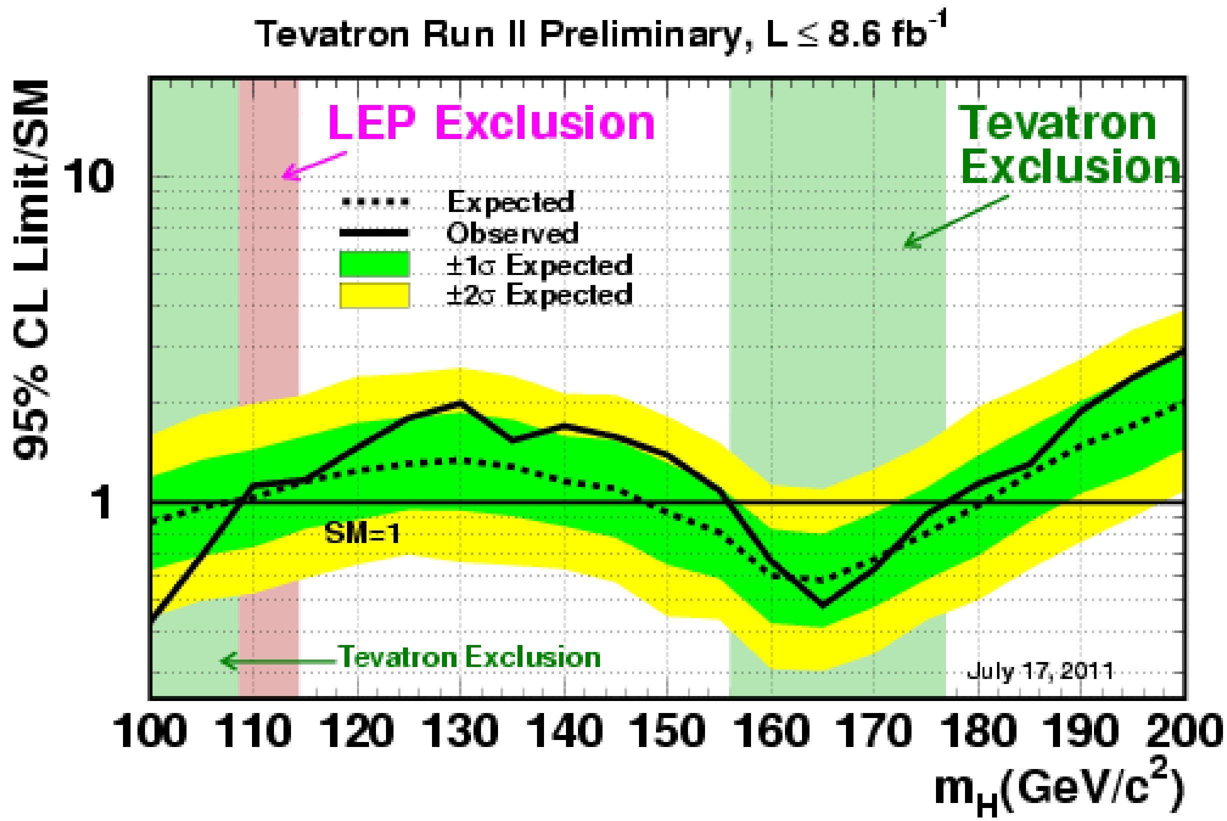
Agreement between background model and data very good

Log-likelihood ratio (LLR)

LLR = -2lnQ where Q = L_{s+b}/L_b



Exclusion



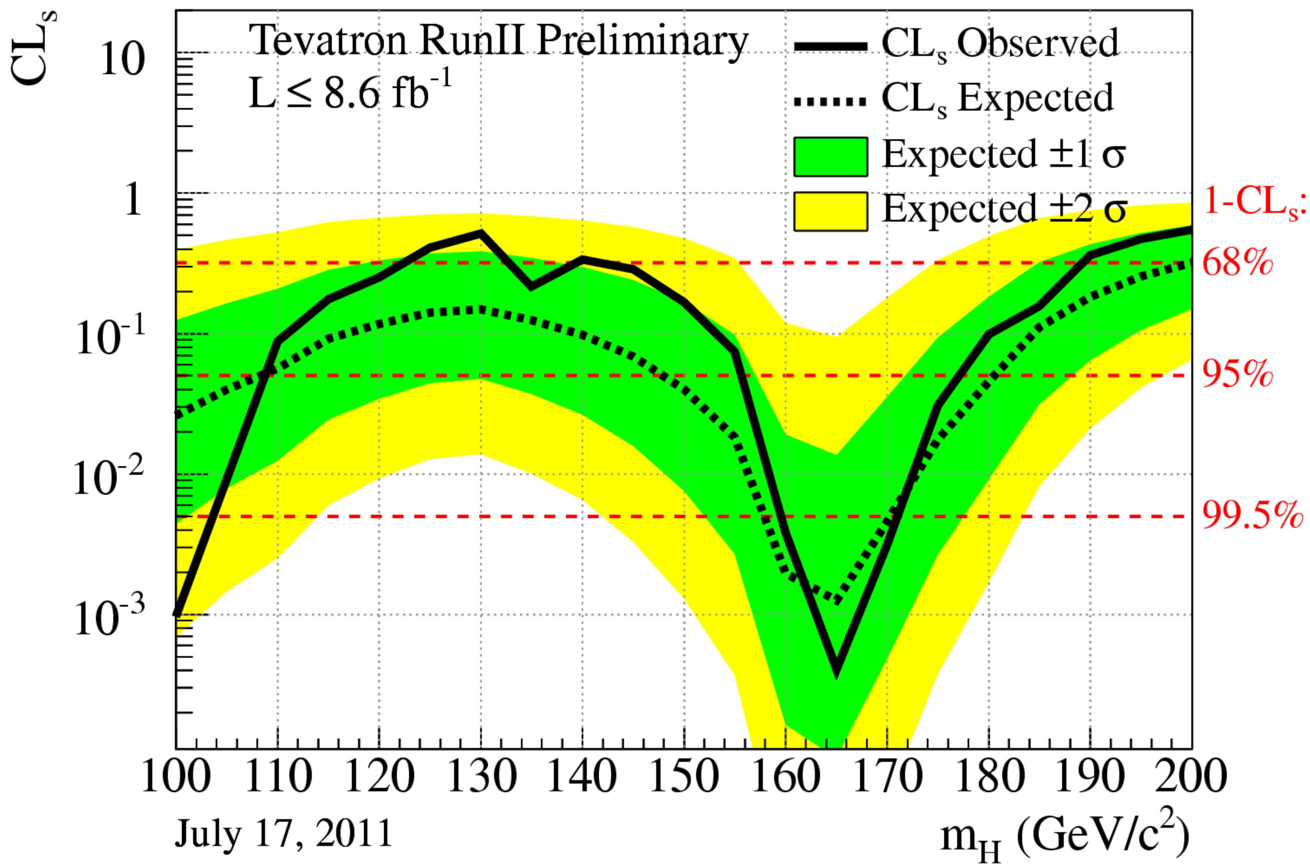
SM Higgs excluded @ 95% C.L.

$156 < m_H < 177$ GeV obs ($148 < m_H < 180$ GeV exp)

$100 < m_H < 108$ GeV obs ($100 < m_H < 109$ GeV exp)

Exclusion: CLs

$CL_s = CL_{s+b}/CL_b$



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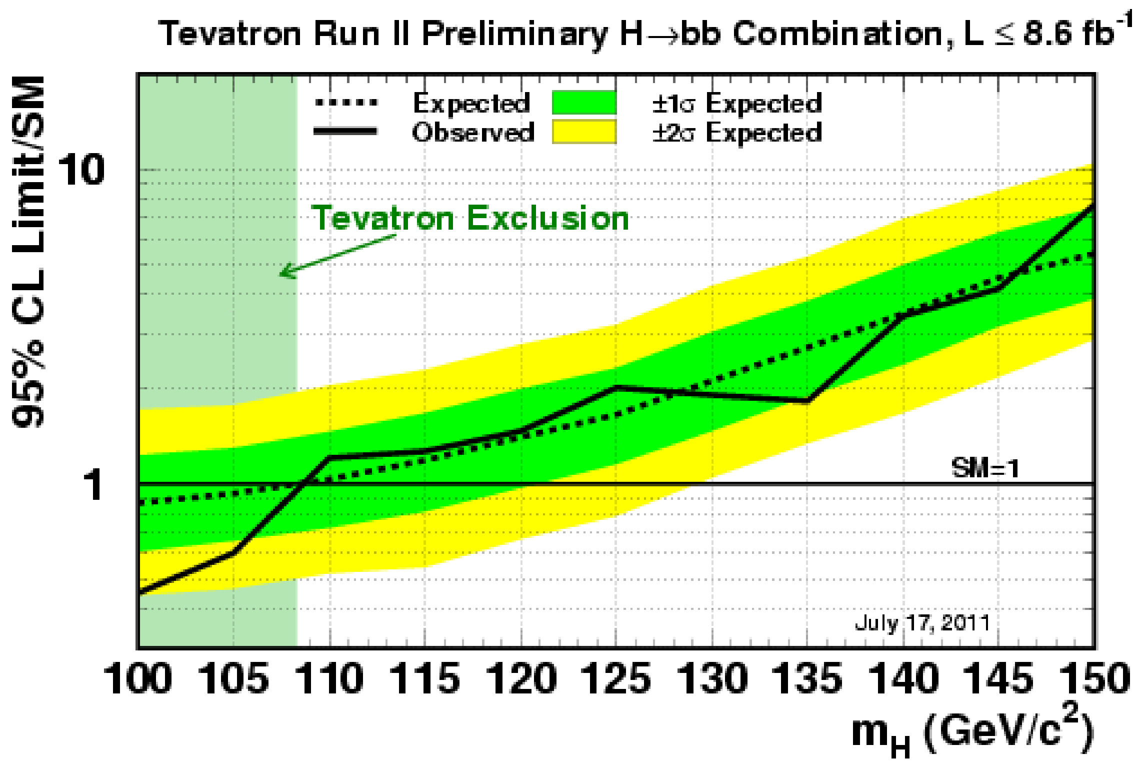
Other Combinations

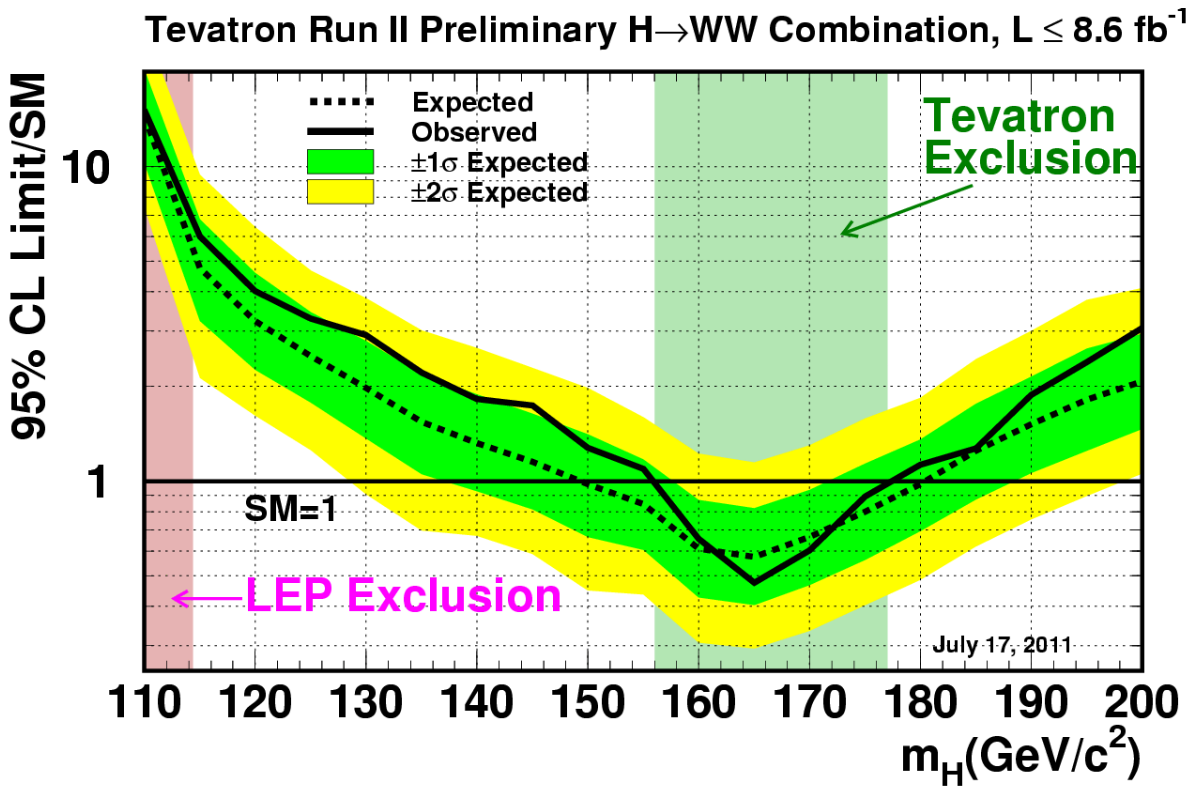
- Look at associated production & $H \rightarrow bb$ decay



- Expected and observed in good agreement

Other Combinations

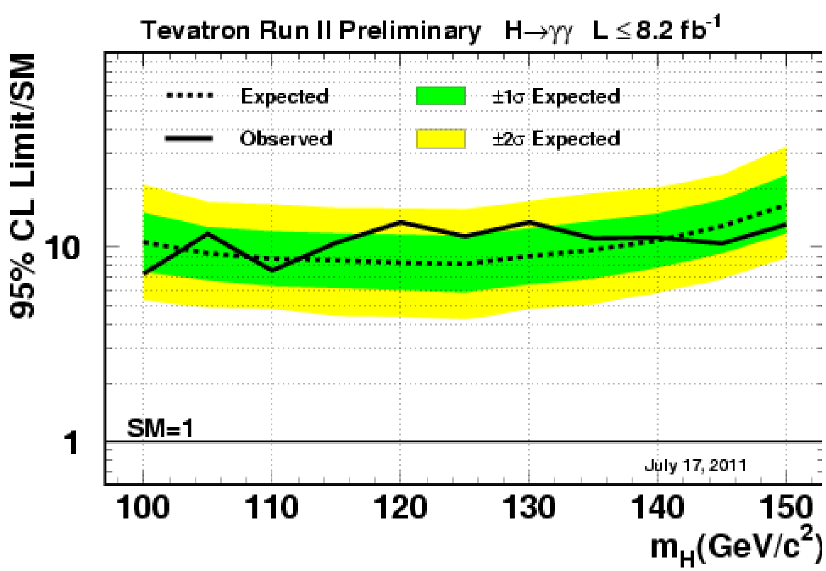
- Channels targeting $H \to WW$ decay



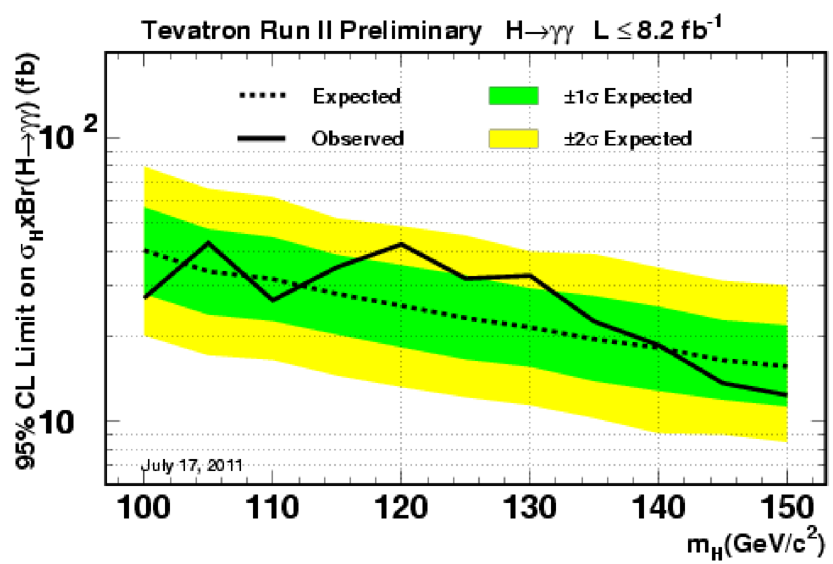
Other combinations

- Look at $H \rightarrow \gamma\gamma$

Ratio to SM production



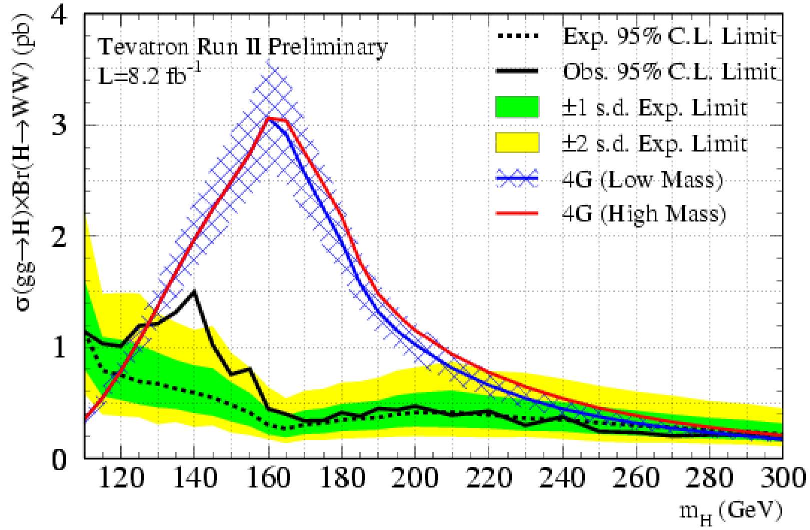
Cross section x BR

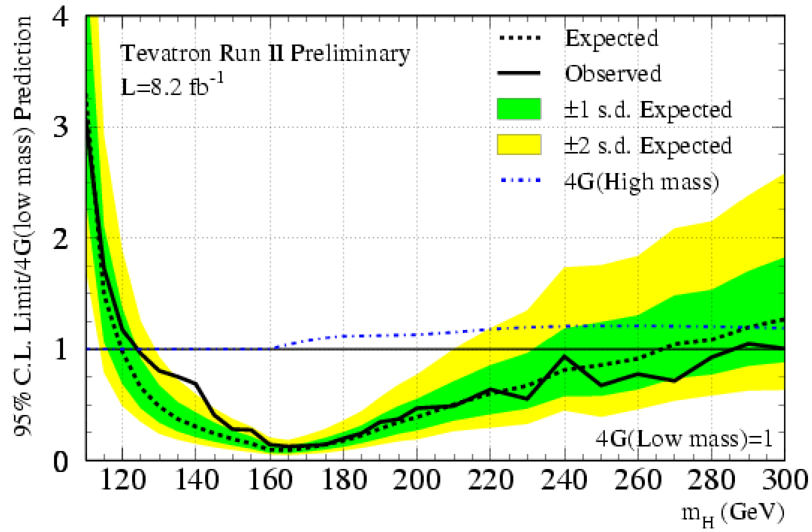


- Fermiophobic combination soon
  - Eg CDF alone m_{hf} < 114.8GeV

Fourth Generation

- Include only gg → H production
  - Enhanced by a factor 9
- Look at H → WW/ZZ decays
- Set limits on cross section x Br
- Set limits on 4G model
  - Exclude
    $124 < m_H < 286$ GeV obs
    ($120 < m_H < 267$ GeV exp)



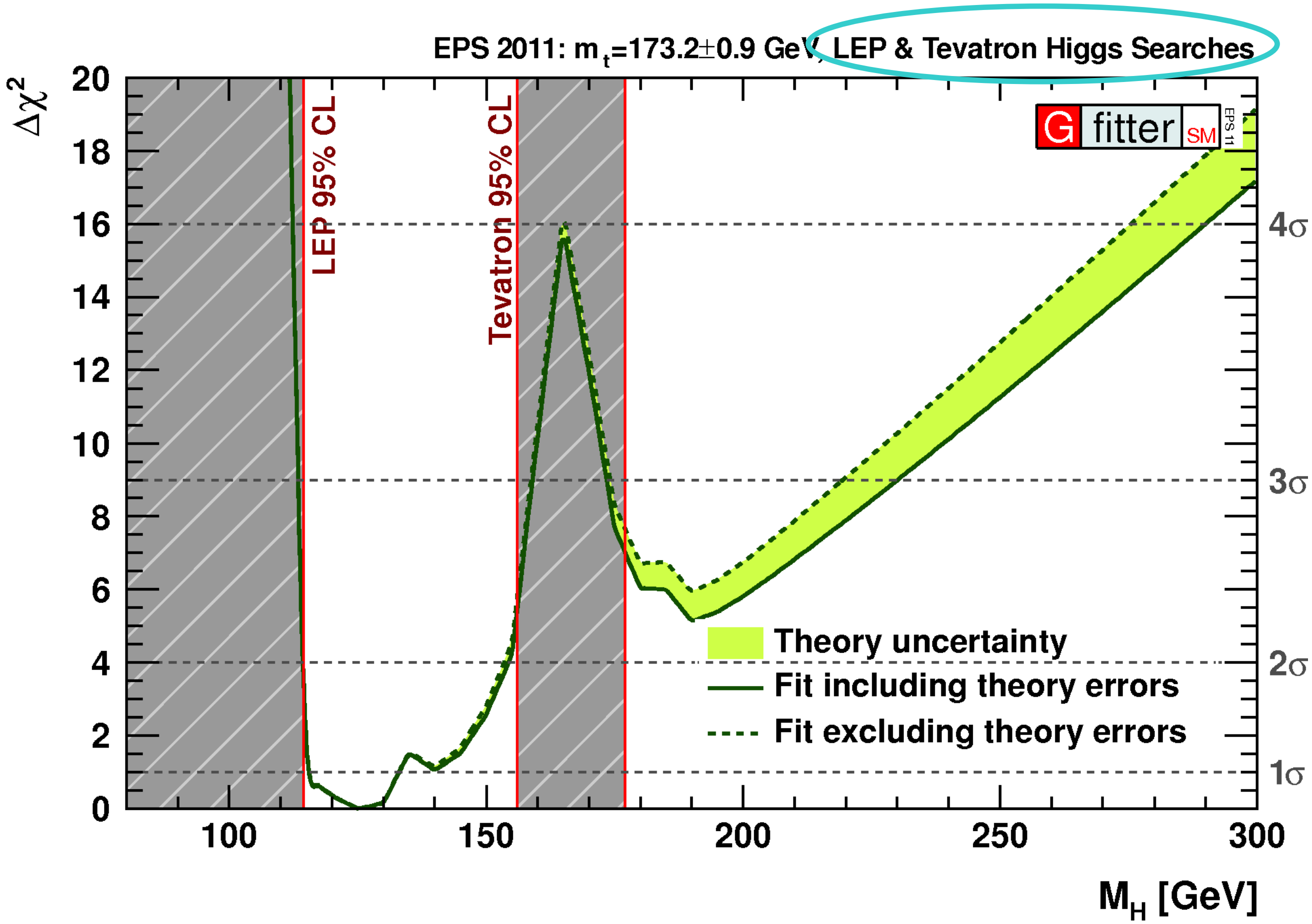


Conclusions

- New combination of SM Higgs boson searches at Tevatron
- High mass:
  - Observed exclusion: $156 < m_H < 177$ GeV
  - Expected exclusion: $148 < m_H < 180$ GeV
- Elsewhere:
  - Expected sensitivity: within 1.4 of SM prediction from 100-185 GeV
  - Exclusion for $100 < m_H < 108$ GeV
  - Slight excess over range 125-155 GeV
- Expect well over $10 fb^{-1}$ by end of Run
- More analysis improvements in the pipeline
- Exciting times ahead
  - See http://tevnphwg.fnal.gov/ for further details

Backup slides

Updated Global EW Fit



M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Ludwig, K. Moenig, M. Schott, and J. Stelzer, arXiv:1107.0975v1

New njet dependent scale error

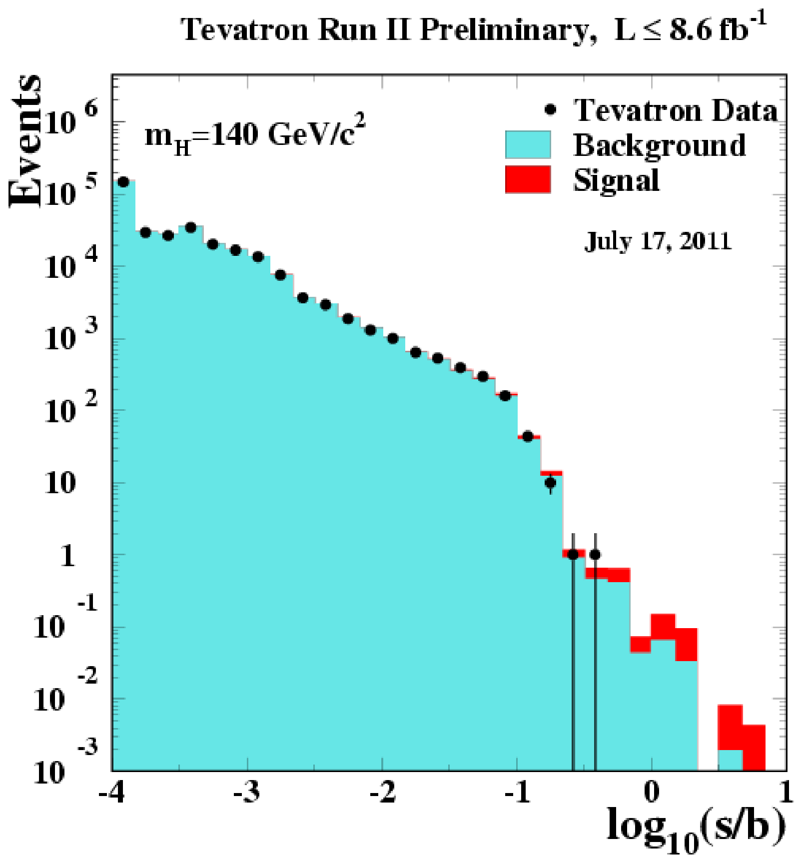
- 3 scales – Tackmann et al., arXiv:1107.2217 [hep-ph] → 3 nuisance parameters
  - S0 – scale uncertainty on x0, S1 – scale uncertainty on x1, S2 – scale uncertainty on x2

- X0: Inclusive cross section: Florian & Grazzini, Phys. Lett. B 674, 291 (2009)
- X1: H+1-or-more-jets: MCFM
- x2: H+2-or-more-jets: Campbell, Ellis & Williams, arXiv:1001.4495 [hep-ph]

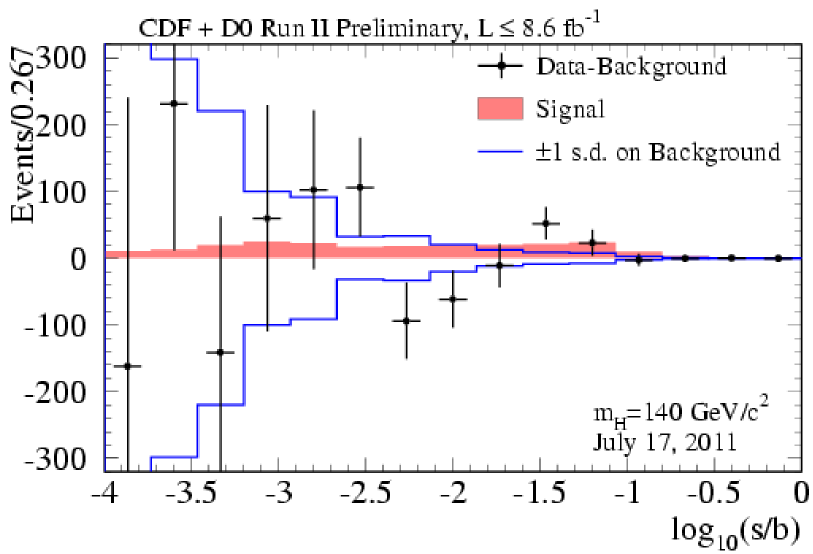
Signal Category	S0	S1	S2
0-jet	S0x(x0/(x0-x1))	-S1x(x1/(x0-x1))	0
1-jet	0	S1x(x1/(x1-x2))	-S2x(x2/x1-x2))
2-jet	0	0	S2

Signal Category	S0	S1	S2
0-jet	0.13	-0.23	0
1-jet	0	0.35	-0.13
2-jet	0	0	0.33

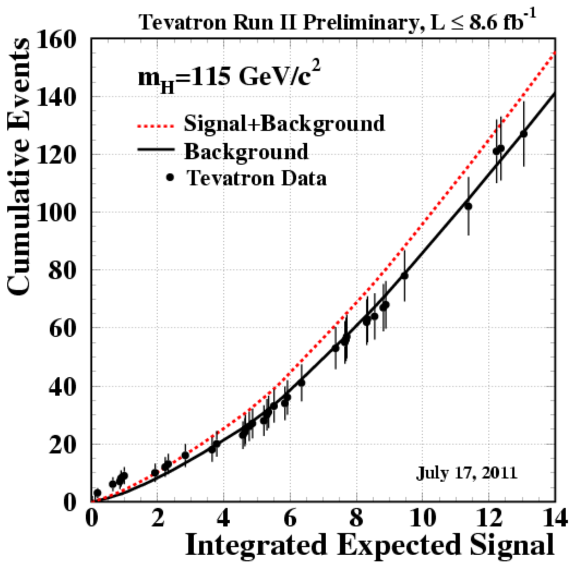
Results - 140GeV

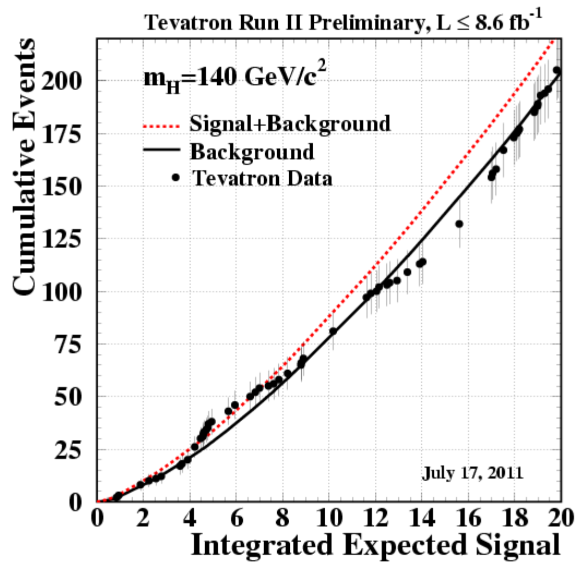


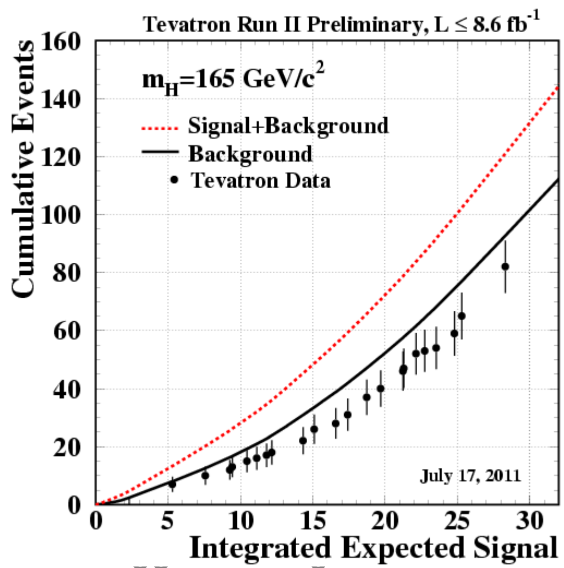
With background subtraction



Integrated s/b distributions







Start integrating from high s/b side

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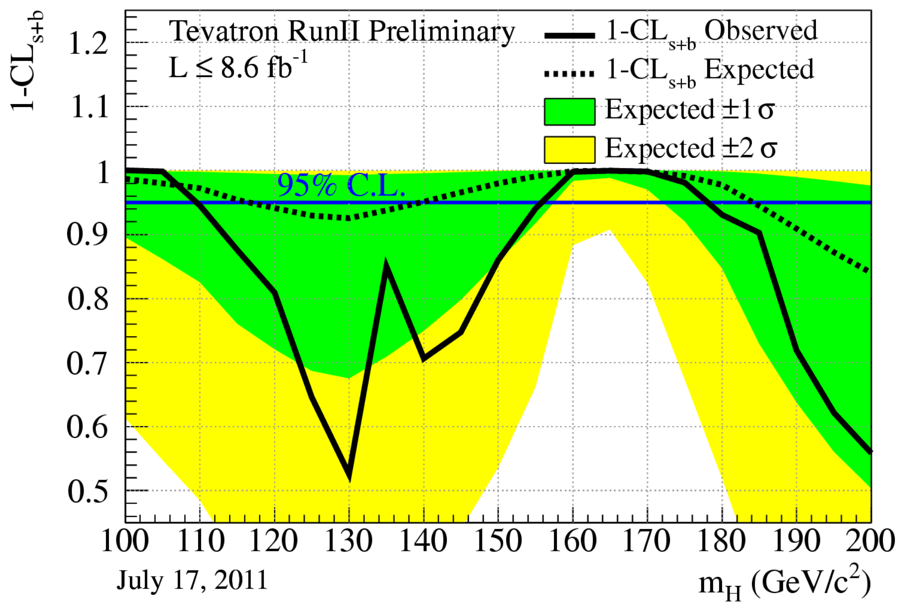
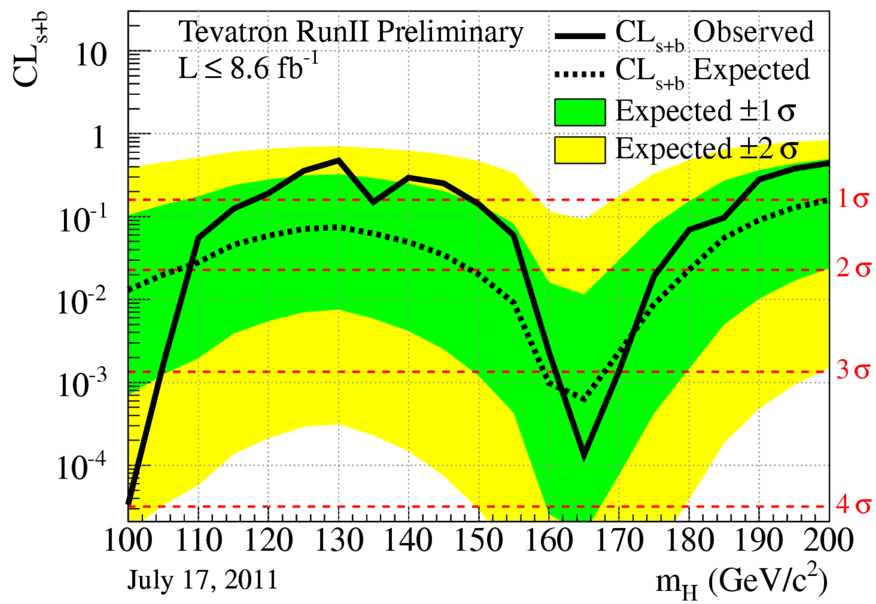
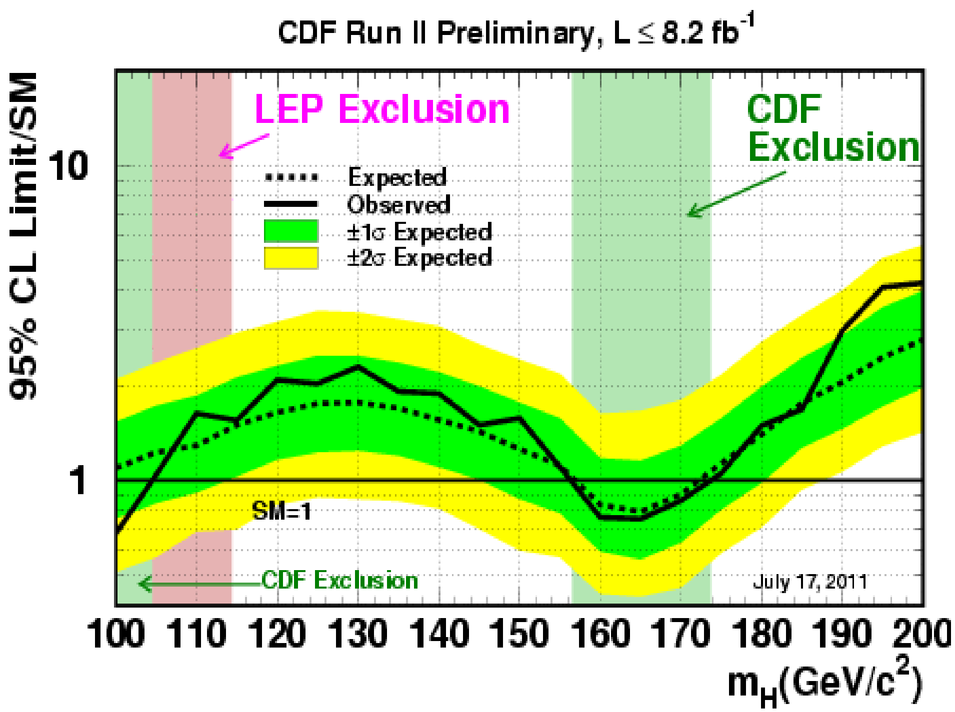
CL_{s+b}

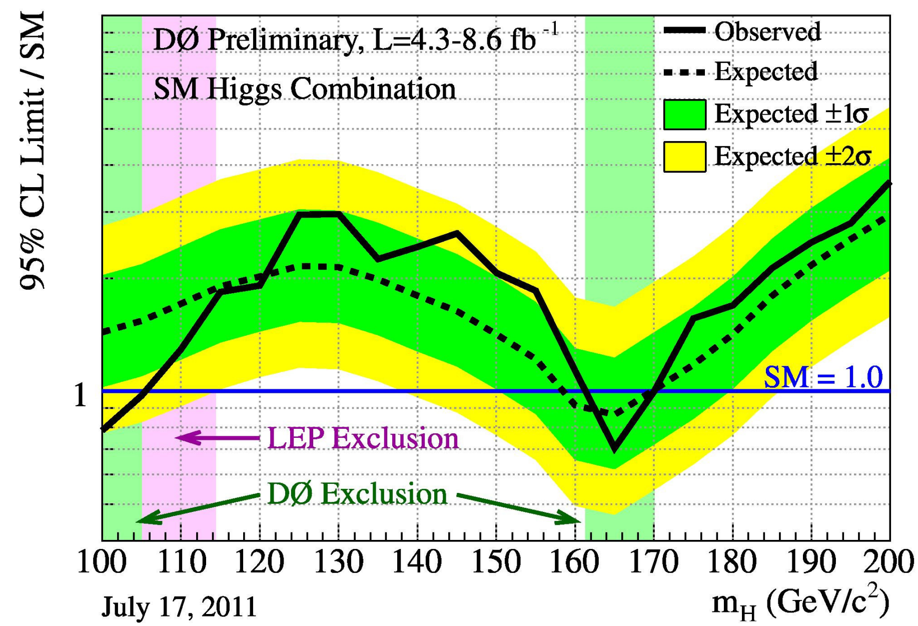




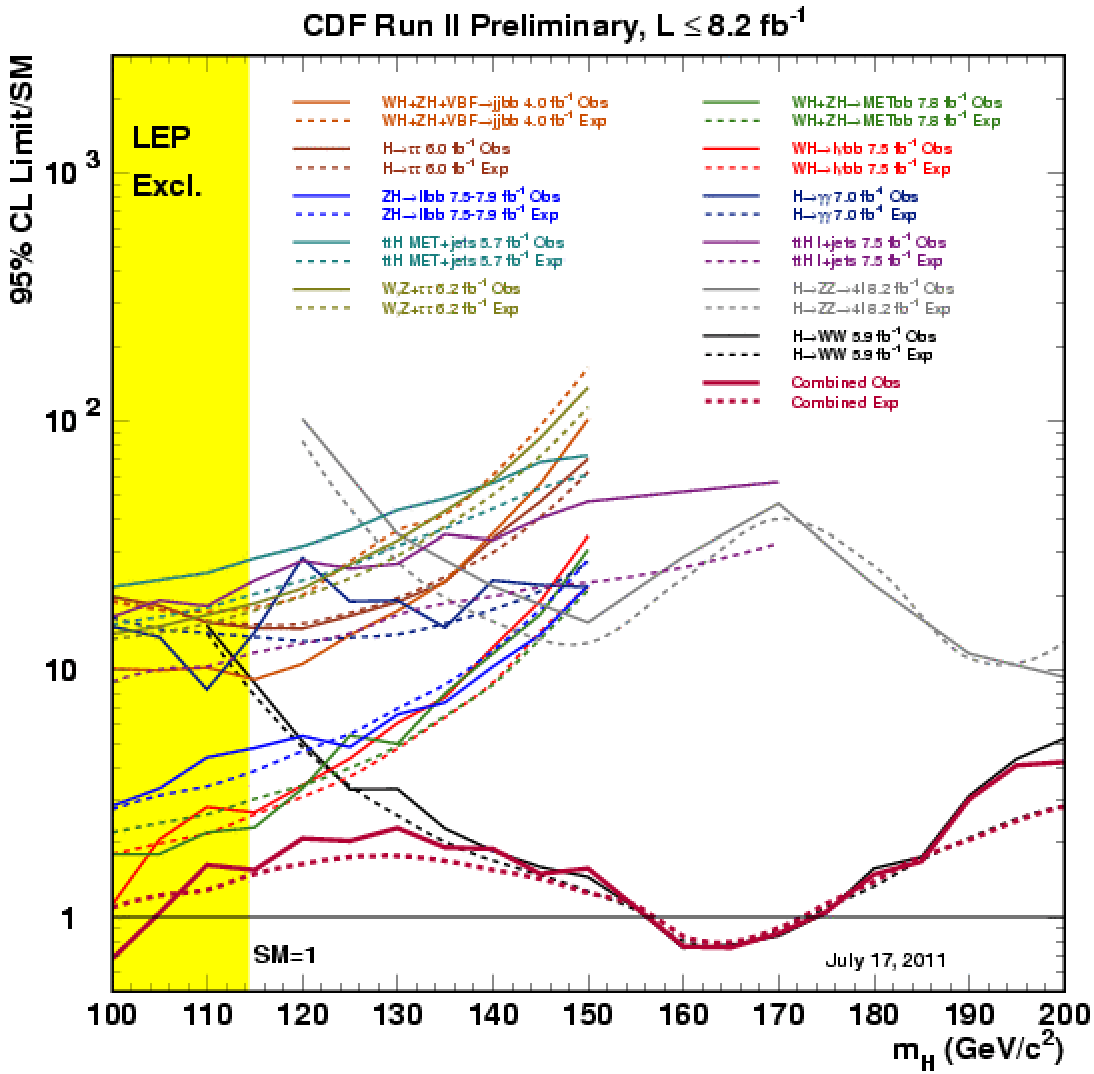
An alternate approach – similar to power constrained limit from ATLAS

By experiment

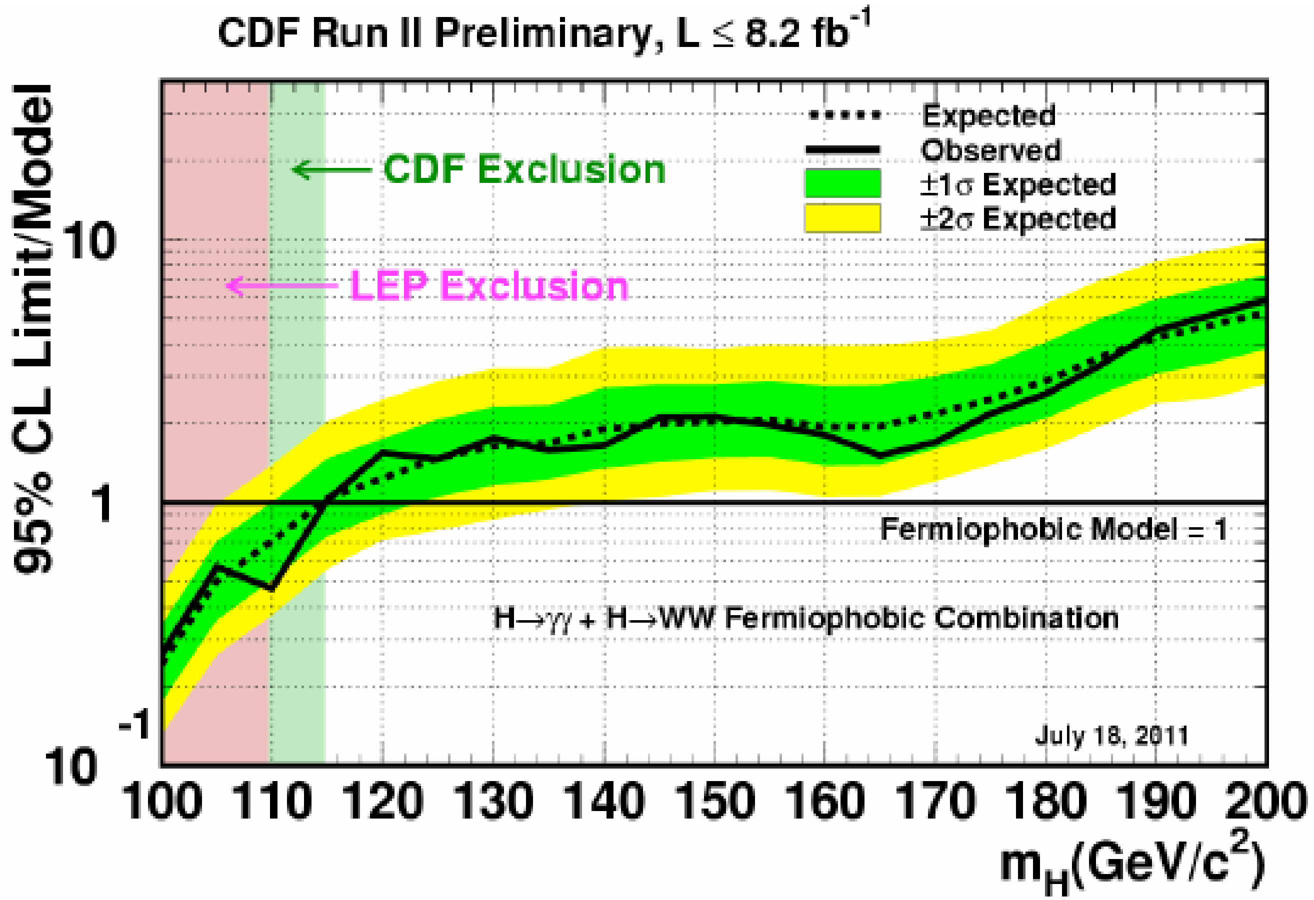




By channel


CDF Run II Preliminary, L ≤ 8.2 fb^{-1}
95% CL Limit/SM
LEP
Excl.
WH+ZH+VBF→jjbb 4.0 fb^{-1} Obs
WH+ZH+VBF→jjbb 4.0 fb^{-1} Exp
H→ττ 6.0 fb^{-1} Obs
H→ττ 6.0 fb^{-1} Exp
ZH→llbb 7.5-7.9 fb^{-1} Obs
ZH→llbb 7.5-7.9 fb^{-1} Exp
ttH MET+jets 5.7 fb^{-1} Obs
ttH MET+jets 5.7 fb^{-1} Exp
W,Z+ττ 6.2 fb^{-1} Obs
W,Z+ττ 6.2 fb^{-1} Exp
WH+ZH→METbb 7.8 fb^{-1} Obs
WH+ZH→METbb 7.8 fb^{-1} Exp
WH→lνbb 7.5 fb^{-1} Obs
WH→lνbb 7.5 fb^{-1} Exp
H→γγ 7.0 fb^{-1} Obs
H→γγ 7.0 fb^{-1} Exp
ttH l+jets 7.5 fb^{-1} Obs
ttH l+jets 7.5 fb^{-1} Exp
H→ZZ→4l 8.2 fb^{-1} Obs
H→ZZ→4l 8.2 fb^{-1} Exp
H→WW 5.9 fb^{-1} Obs
H→WW 5.9 fb^{-1} Exp
Combined Obs
Combined Exp
10^3
10^2
10
1
SM=1
July 17, 2011
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c^2)

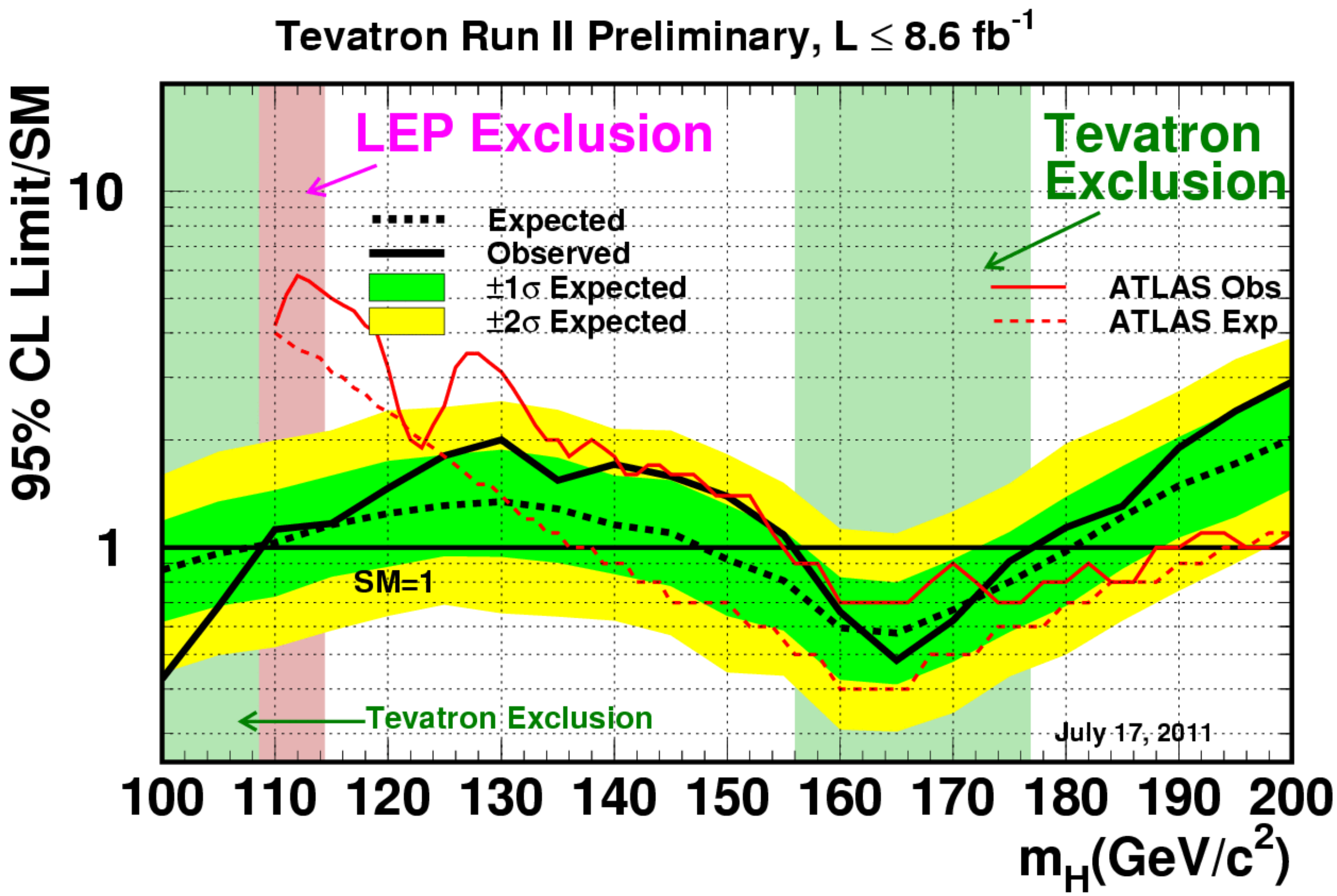
CDF Fermiophobic



Expected Exclusion: m_H < 114.4 GeV

Observed Exclusion: m_H < 114.8 GeV

Comparison with ATLAS result



CLs

Need to define test statistic & treatment of nuisance parameters

Table 10: Comparison of $\mathrm{CL_s}$ definitions as used at LEP, Tevatron, and adopted for summer 2011 Higgs combination at LHC.

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2\ln\frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2\ln\frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$q_\mu = -2\ln\frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|\hat{\mu},\hat{\theta})}$	yes $(0 \le \hat{\mu} \le \mu)$	frequentist

From: ATLAS Collaboration, CMS Collaboration, and LHC Higgs Combination Group, "Procedure for the LHC Higgs boson search combination in summer 2011", (July, 2011)