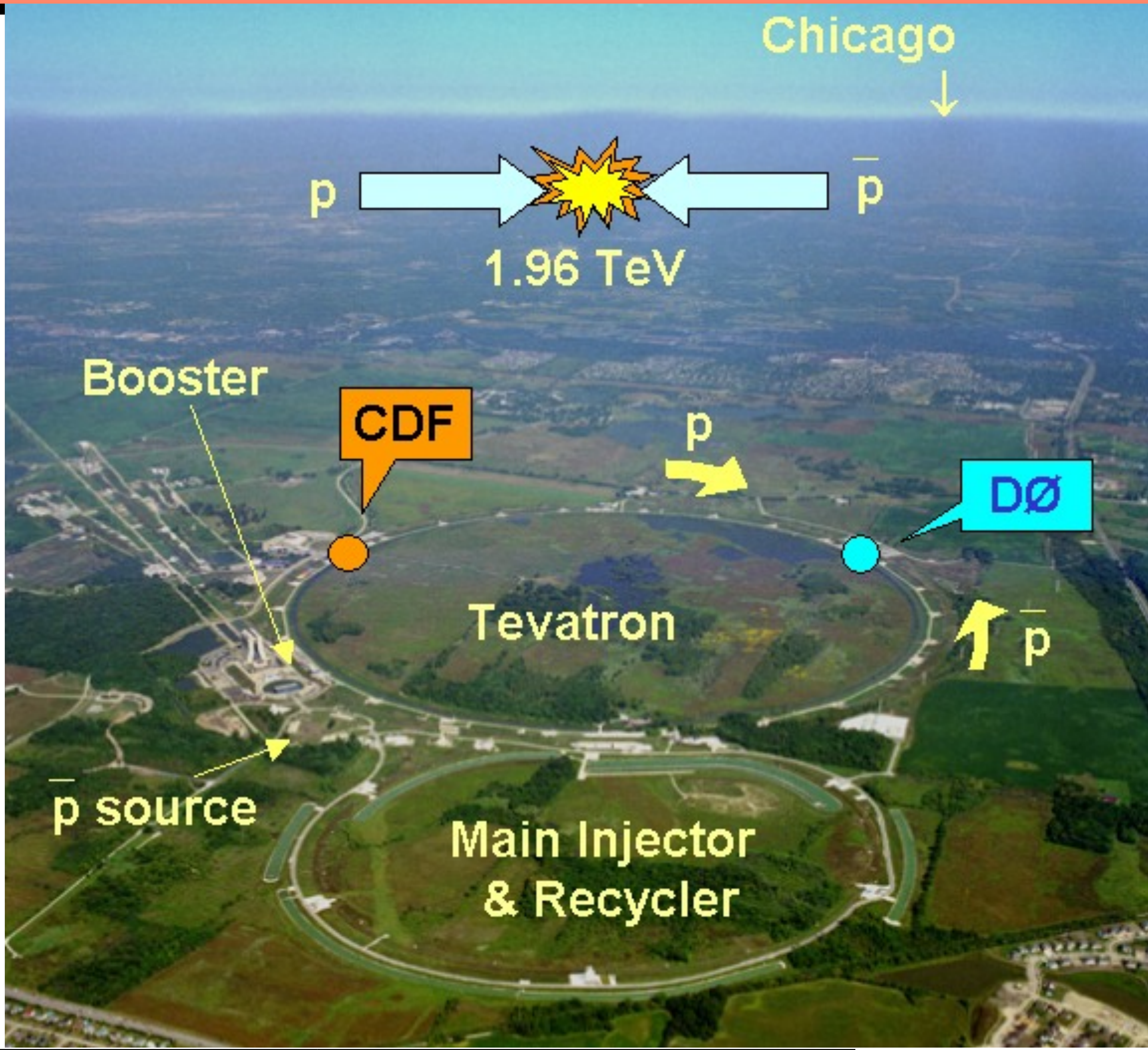
Richard E. Hughes
The Ohio State University
for
The CDF and D0 Collaborations

Tevatron Higgs Combination

1

Tevatron and Experiments



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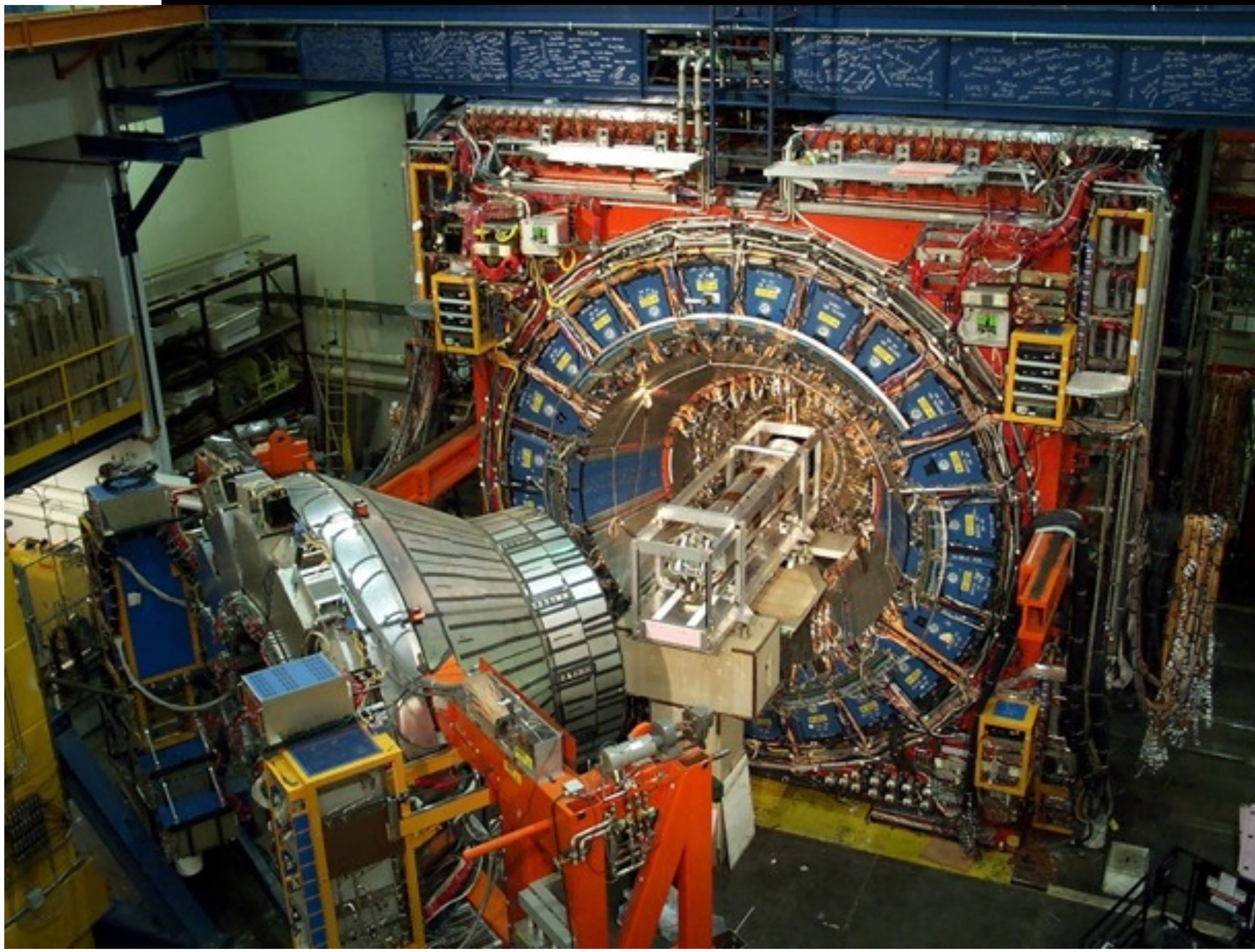

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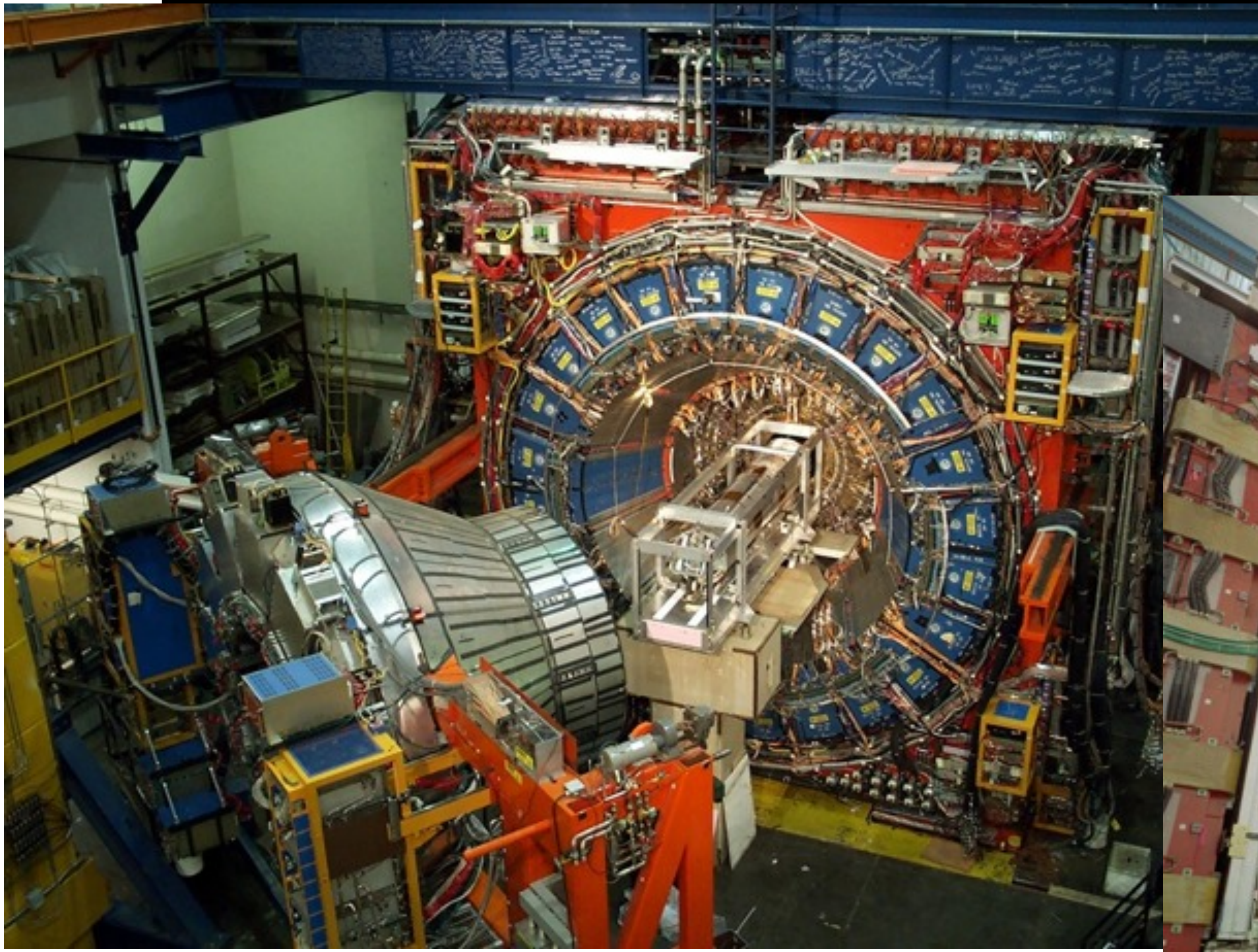

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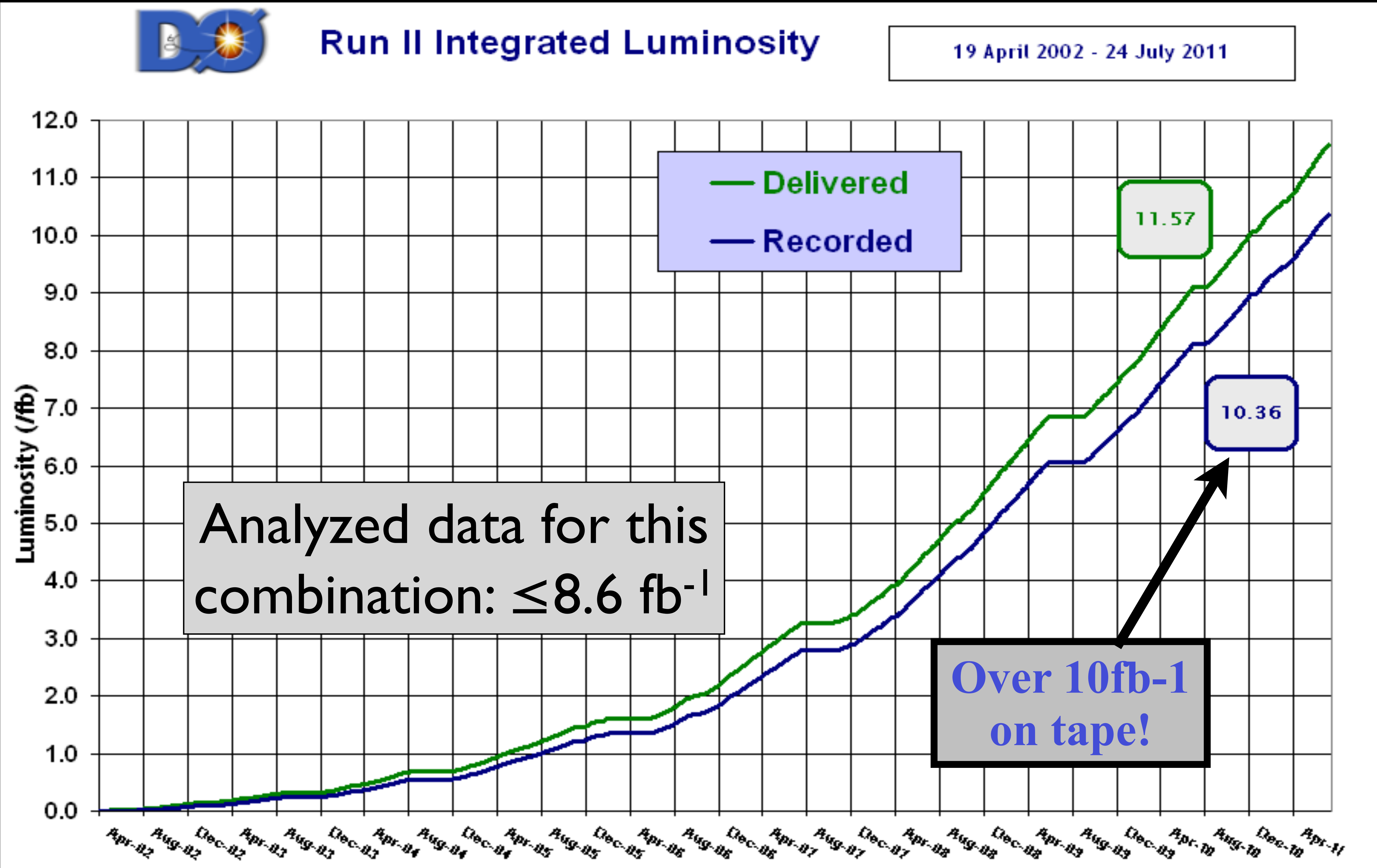
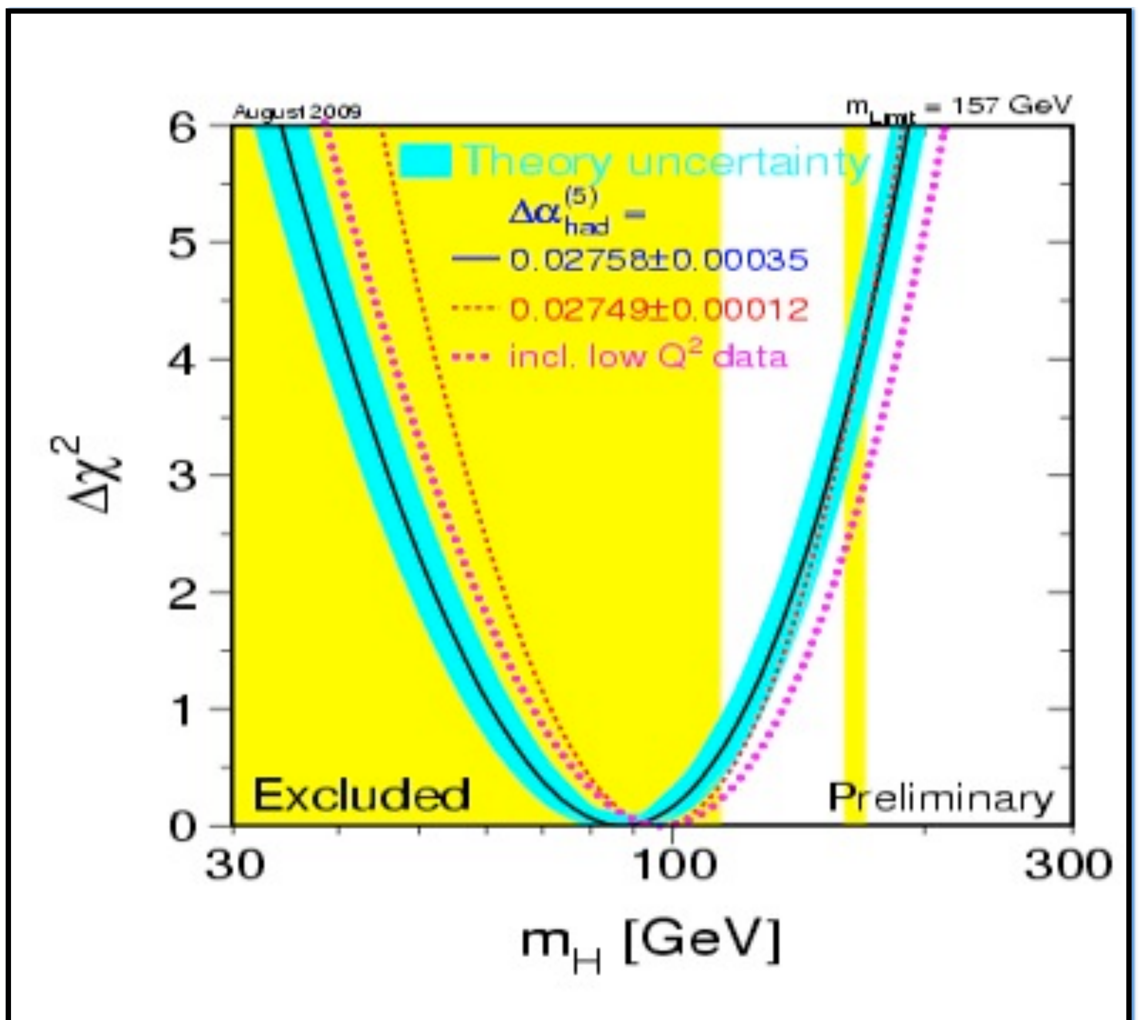
Tevatron and Experiments

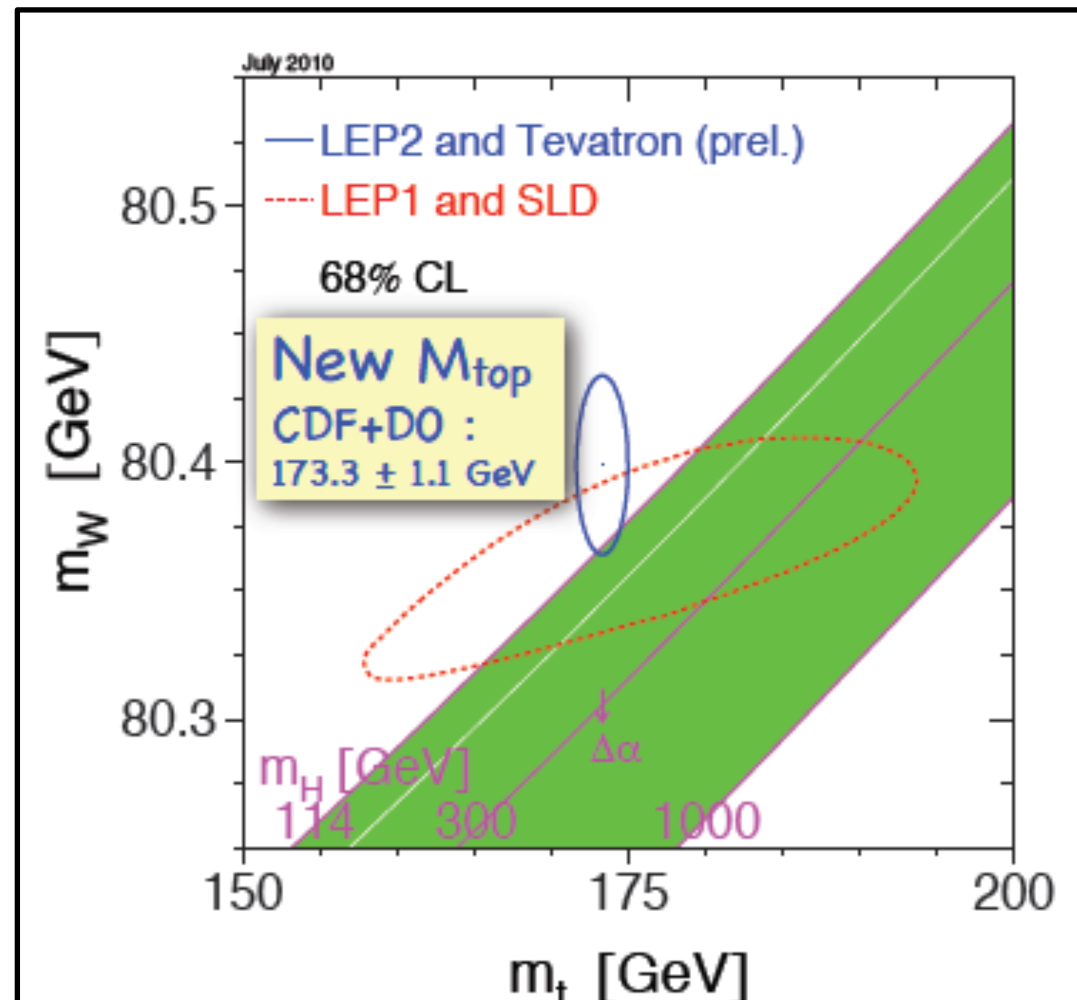


Constraints on the SM Higgs Boson

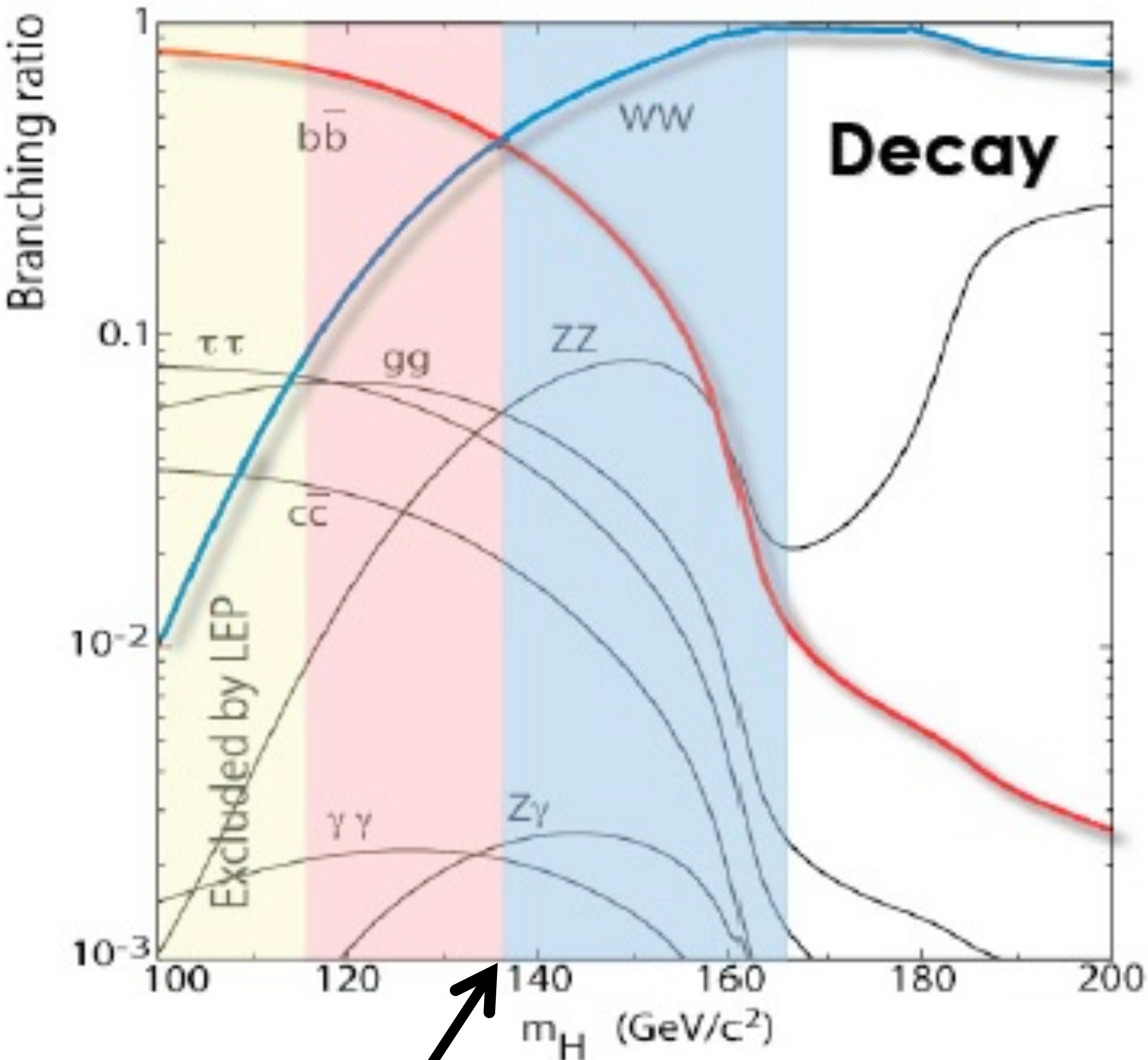
What we know:

- **Direct search at LEPII:**
  Mh > 114 GeV/c2 @95% CL
- **Precision EWK meaurements (top mass, W mass, etc):**
  $M_h = 89.0^{+35}_{-26}$ GeV/c^2
  $M_h < 158$ GeV/c^2 @95% CL





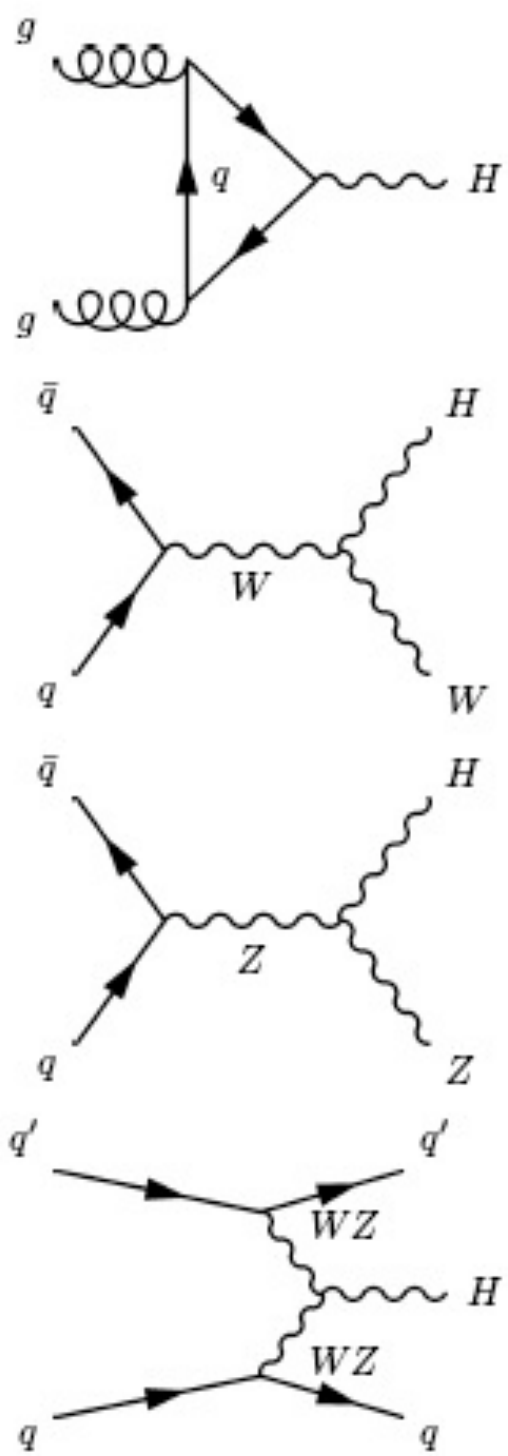
Higgs Decay

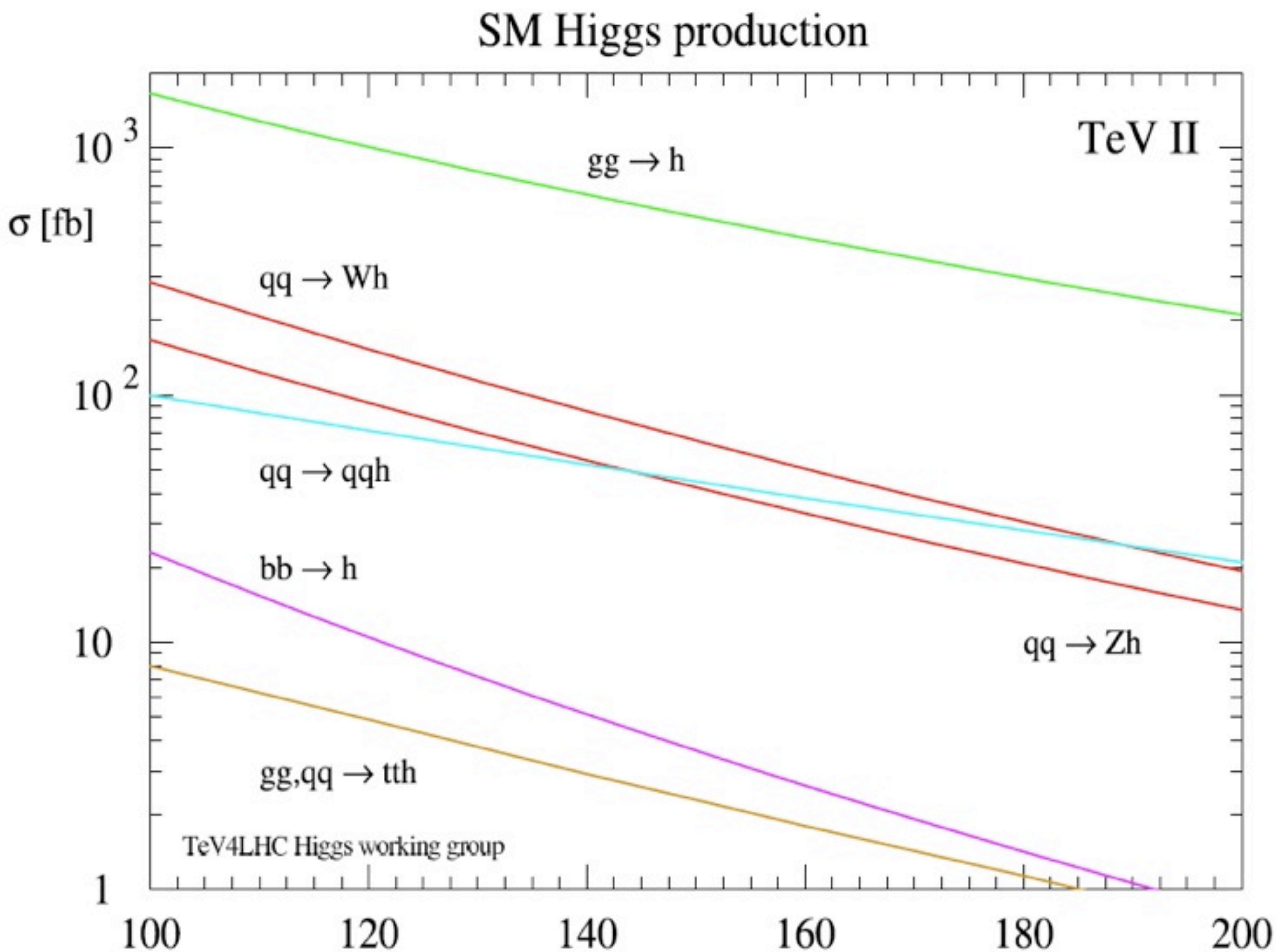


Cross-Over Point
(m_H ~ 135 GeV)

- Low Mass
  - Focus on H→bb
  - Also H→ττ and H→γγ
- High Mass
  - Focus on H→WW
  - Also H→ZZ

Higgs Production at Tevatron





Higgs Search Challenges

Expected number of events per fb^{-1} per experiment

Higgs Mass (GeV/c^2)	$WH \rightarrow l\nu bb$	$ZH \rightarrow \nu\nu bb$	$ZH \rightarrow llbb$	$H \rightarrow WW \rightarrow l\nu l\nu$
120	25	12	4	13
135	10	5	2	26
150	3	2	1	32

reconstruction/selection/tagging efficiencies ~ 10% in $H \rightarrow bb$ channels and ~25% in $H \rightarrow WW$ channels

Combining Channels

- Our goal: "No Higgs events left behind"
- Best sensitivity is obtained through the combination of many independent search channels

$WH \rightarrow l\nu bb$
$ZH \rightarrow \nu\nu bb$
$ZH \rightarrow llbb$
$WH/ZH \rightarrow jjbb$

$ttH \rightarrow WbWbbb$
$H \rightarrow \gamma\gamma$
$H \rightarrow \tau\tau$
$WH \rightarrow l\nu\tau\tau$ / $ZH \rightarrow ll\tau\tau$

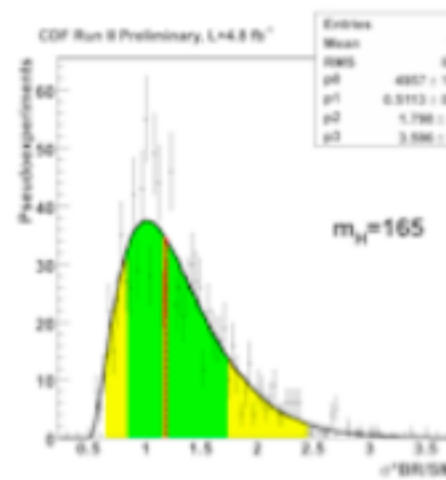
$H \rightarrow WW \rightarrow l\nu l\nu$
$H \rightarrow WW \rightarrow l\nu jj$
$WH \rightarrow WWW$ / $ZH \rightarrow ZWW$
$H \rightarrow ZZ$

Combination Methods

- Two statistical approaches used
  - ✦ Bayesian: Flat signal prior, credibility intervals
  - ✦ Modified frequentist: Log-likelihood test statistic, CLs = CLs+b/CLb
- Better than 10% agreement over whole mass range (~2% on average)
- Operate on binned, final discriminants
  - ✦ Poisson statistics assumed for each bin

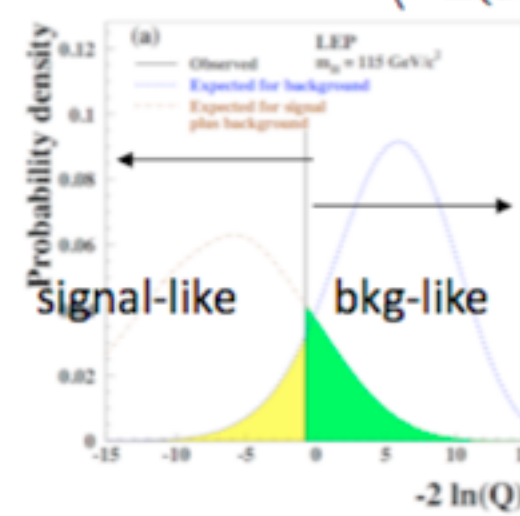
Bayesian (used by CDF)

$$0.95 = \frac{\int_0^{R_{\lim}} L'(data\,|\,R)\pi(R)dR}{\int_0^{\infty} L'(data\,|\,R)\pi(R)dR}$$



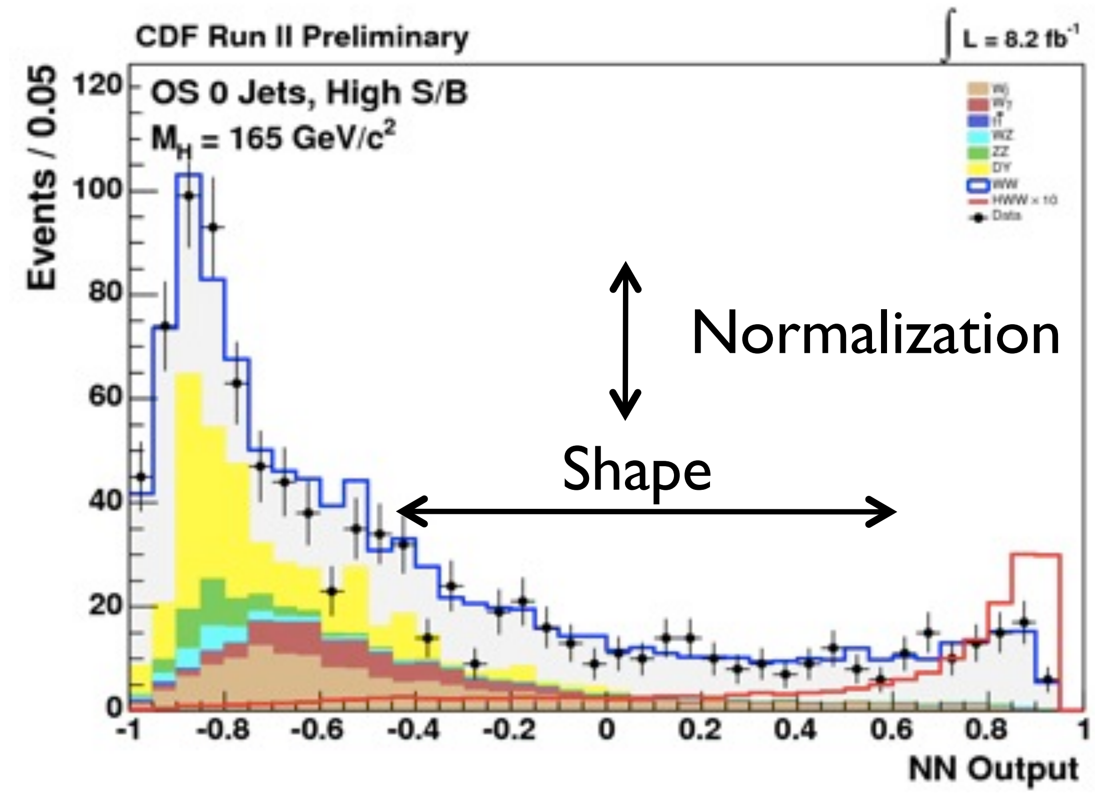
CL_s (used by D0)

$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,s+b,\hat{\theta})}{L(\text{data}\,|\,b,\hat{\hat{\theta}})}\right)$$



Systematic Uncertainties

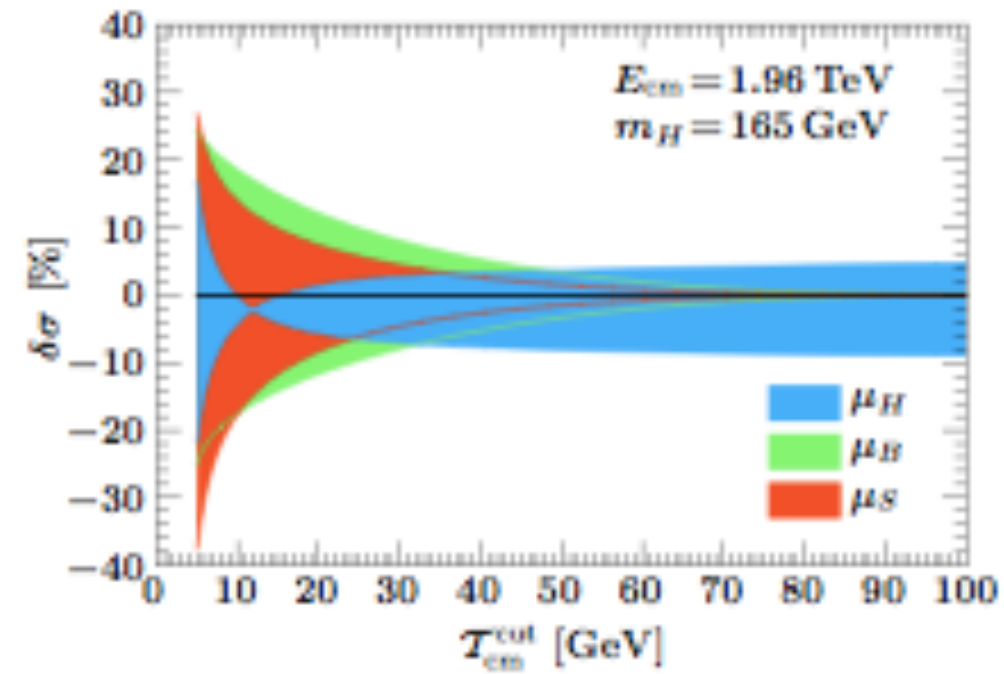
- Include systematic uncertainties on both signal and background
  - Normalization
  - Shape of final discriminations
- Systematics are incorporated in limit setting procedure as nuisance parameters
  - Correlations between different channels is taken into account



In this way, backgrounds can be further constrained by using information from different channels

Theoretical Uncertainties

- Since we combine searches focusing on different Higgs production and decay modes, cross section limits are given with respect to nominal SM predictions
- This forces us to incorporate theoretical predictions and uncertainties for signal cross sections and branching ratios
- Changed in each iteration to reflect recent theoretical developments



Berger et al., arXiv:1012.4480v2

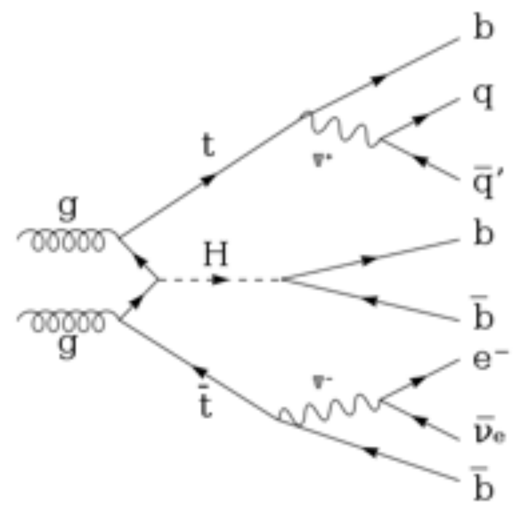
channel	scale 0	scale 1	scale 2
0 jet	13.4%	-23.0%	-
1 jet	-	35.0%	-12.7%
2+ jets	-	-	33.0%

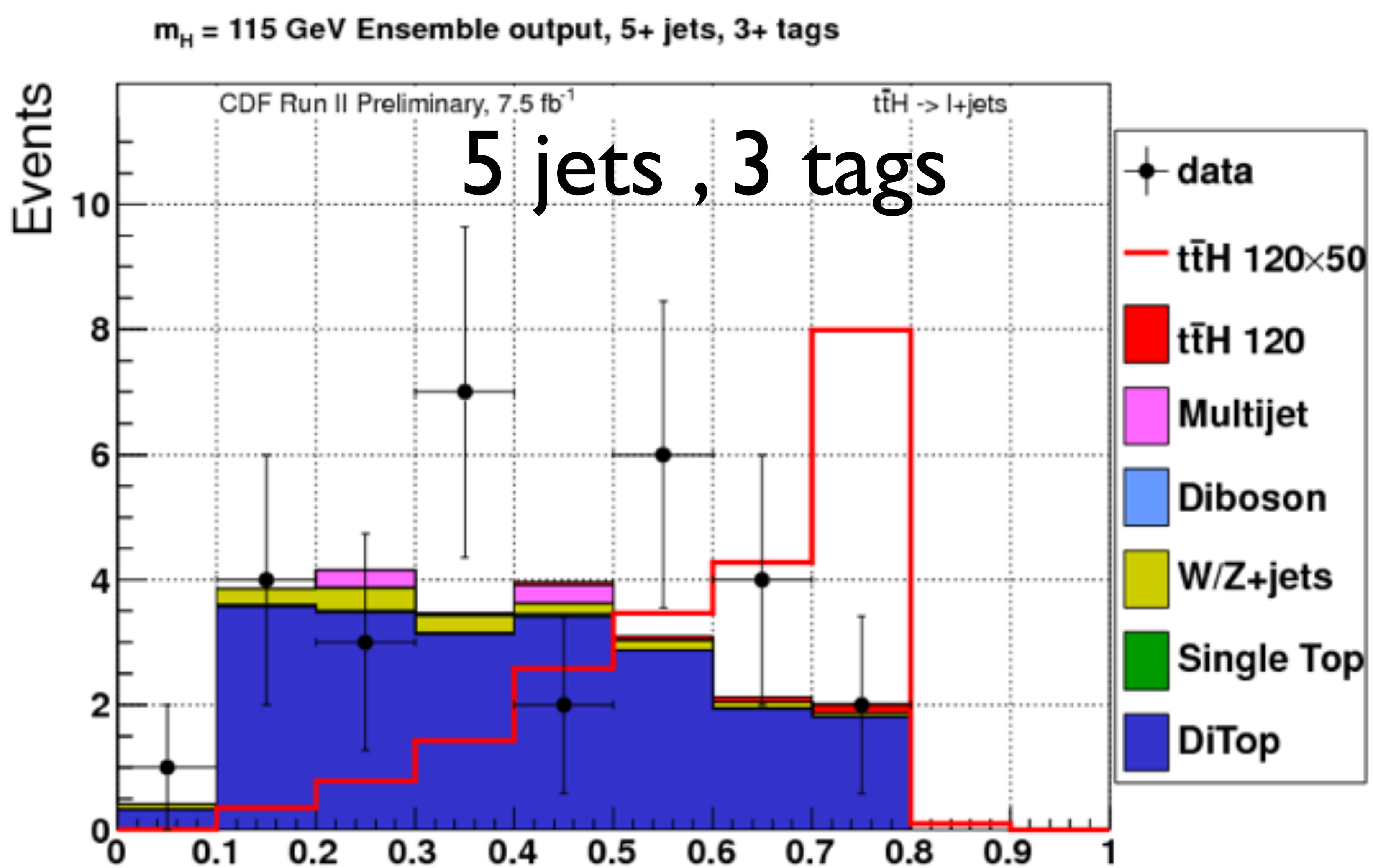
Stewart and Tackmann, arXiv:1107.2117v1

Example Single Channel Result: ttH

- Search for events that are t-tbar like, but with higher jet multiplicity (>=4 jets) and more b-tags (>= 2 b-tags)

- search for a Higgs boson in the range: 100 GeV/c^2 - 170 GeV/c^2, using neural networks optimized for each mass point independently.





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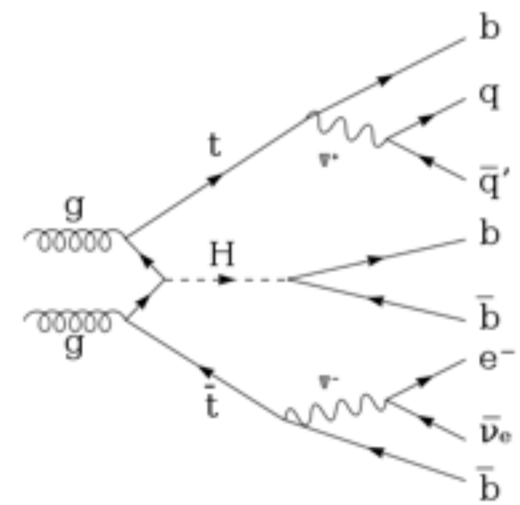
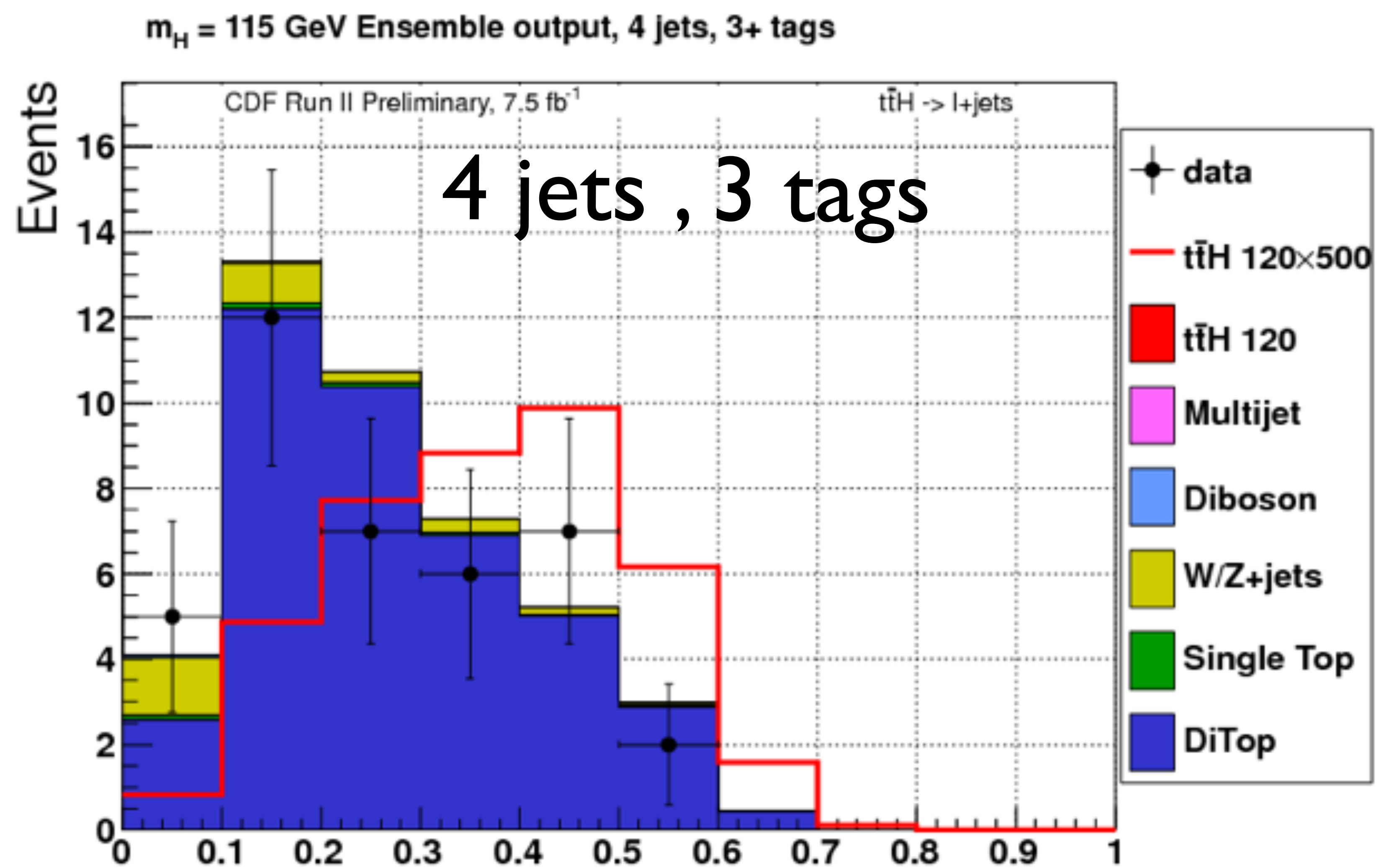




Example Systematics: CDF ttH

Systematics

5 jets	STSTST	
	$t\bar{t}$	$t\bar{t}H$
XS_ttH	0	10
XS_ttbar	10	0
LUMI	3.8	3.8
CDFLUMI	4.4	4.4
BTAGSF	$^{+11}_{-16}$	$^{+9.9}_{-13}$
CDFMISTAG	$^{+8.1}_{-3.4}$	$^{+1.3}_{-0.5}$
CDFJES	$^{+15}_{-15}$	$^{-2.7}_{-8.1}$
ISRFSR	$^{+14}_{-2.0}$	$^{-1.9}_{+1.9}$

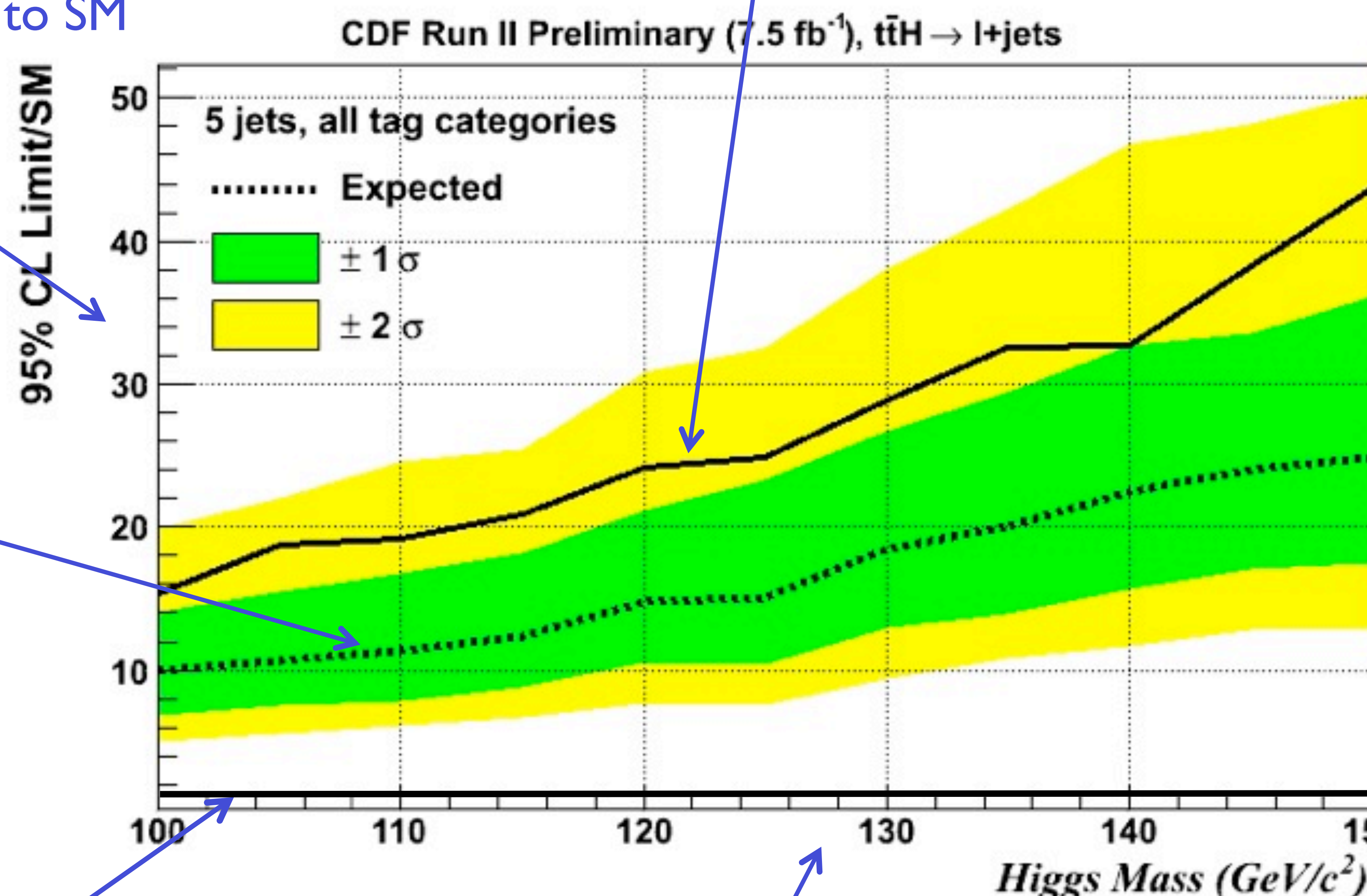
Systematics which can be correlated across the two experiments: signal/background cross sections, luminosity

Systematics which can be correlated within one experiment: portion of luminosity, b-tagging, jet energy scale, etc.

Example Limit Plot: CDF ttH

Observed limit (solid line) from data

Upper cross section limit for Higgs production relative to SM prediction



Median expected limit (dot-dashed line) and predicted 1σ/ 2σ (green/yellow bands) excursions from background only pseudo-experiments

SM Prediction

Analysis repeated using different signal templates for each m_H between 100 and 200 GeV in 5 GeV steps

Combination Inputs

Channel	CDF	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

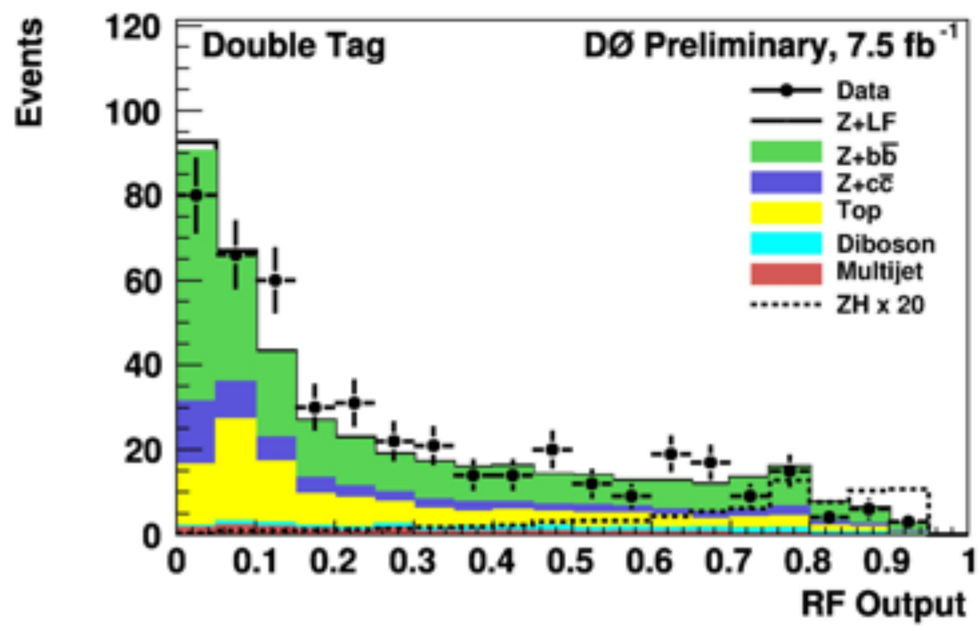
71 exclusive sub-channels

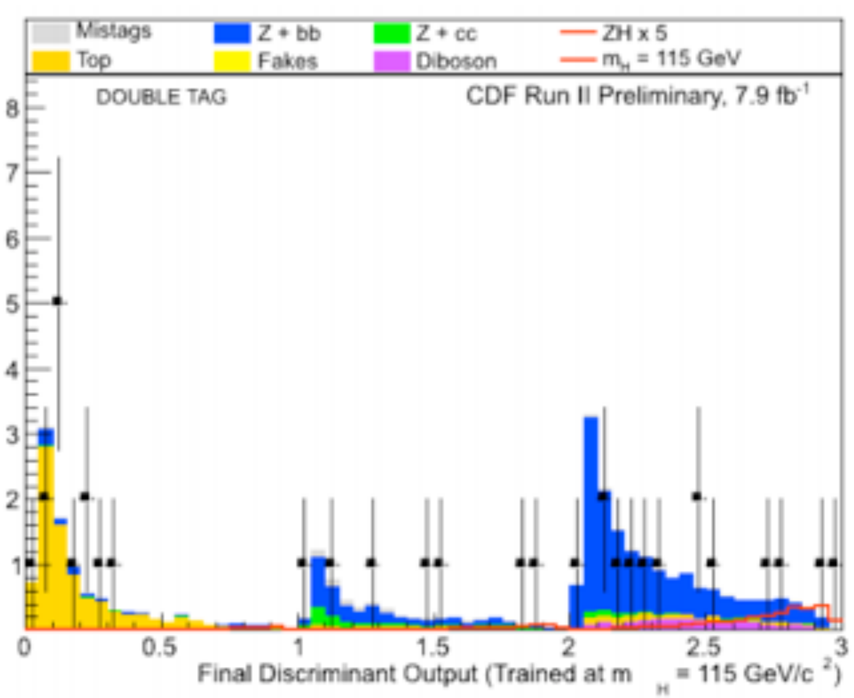
Channel	DØ	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu bb$	(LST,LDT,2,3 jet)	8.5	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$	(LST,LDT)	8.4	100-150
$ZH \to \ell^+\ell^- b\bar{b}$	(TST,TLDT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{had}jj$		4.3	105-200
$VH \to \ell^\pm\ell^\pm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

94 exclusive sub-channels

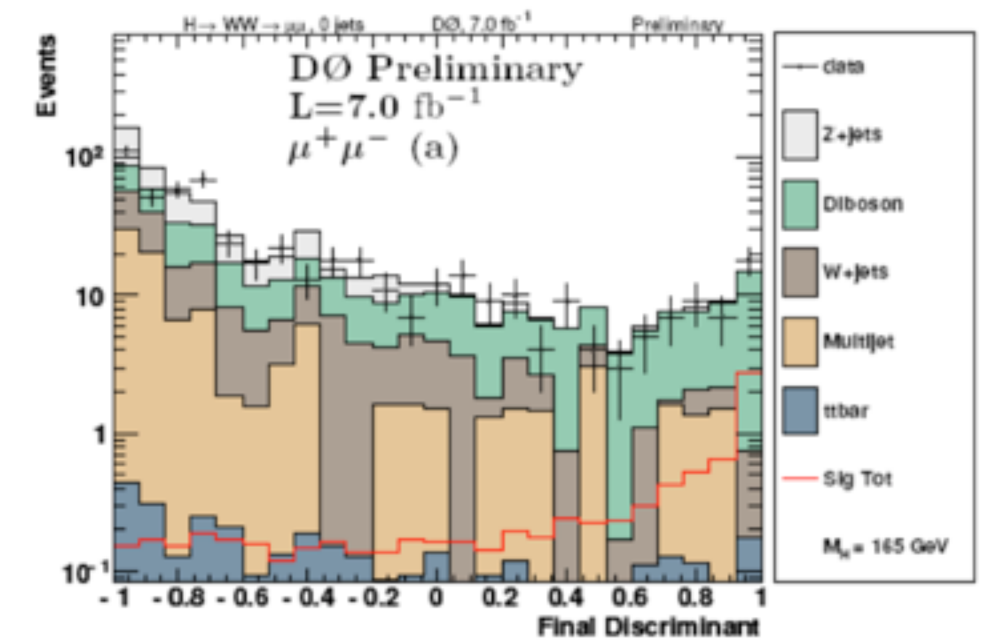
Example Channels

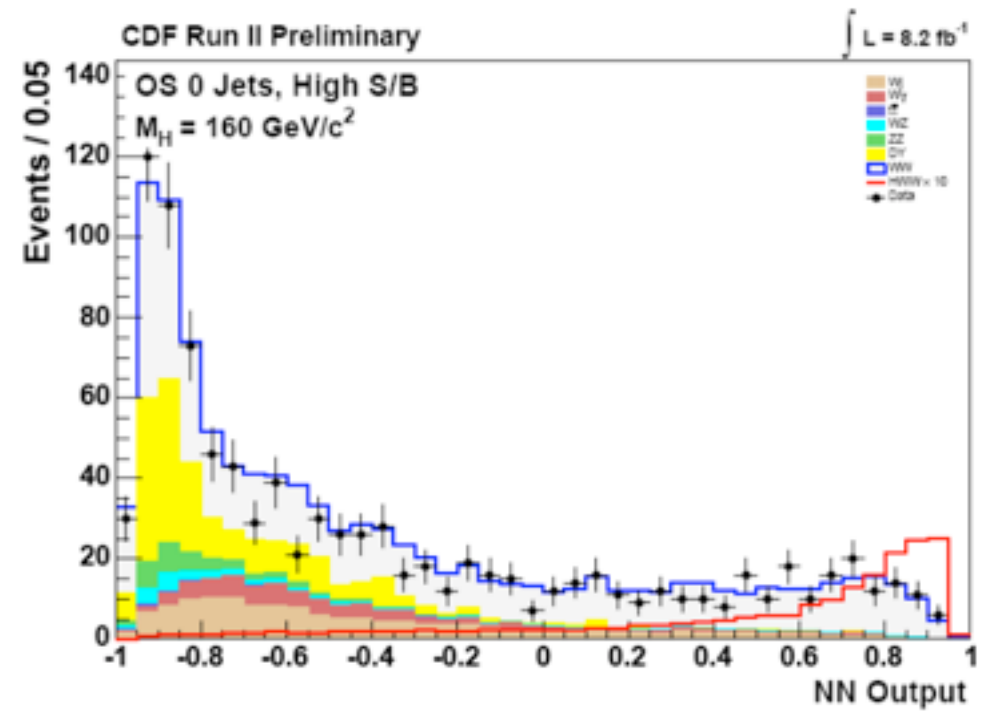
ZH→l⁺l⁻bb
(see M. Kirby's talk Friday)





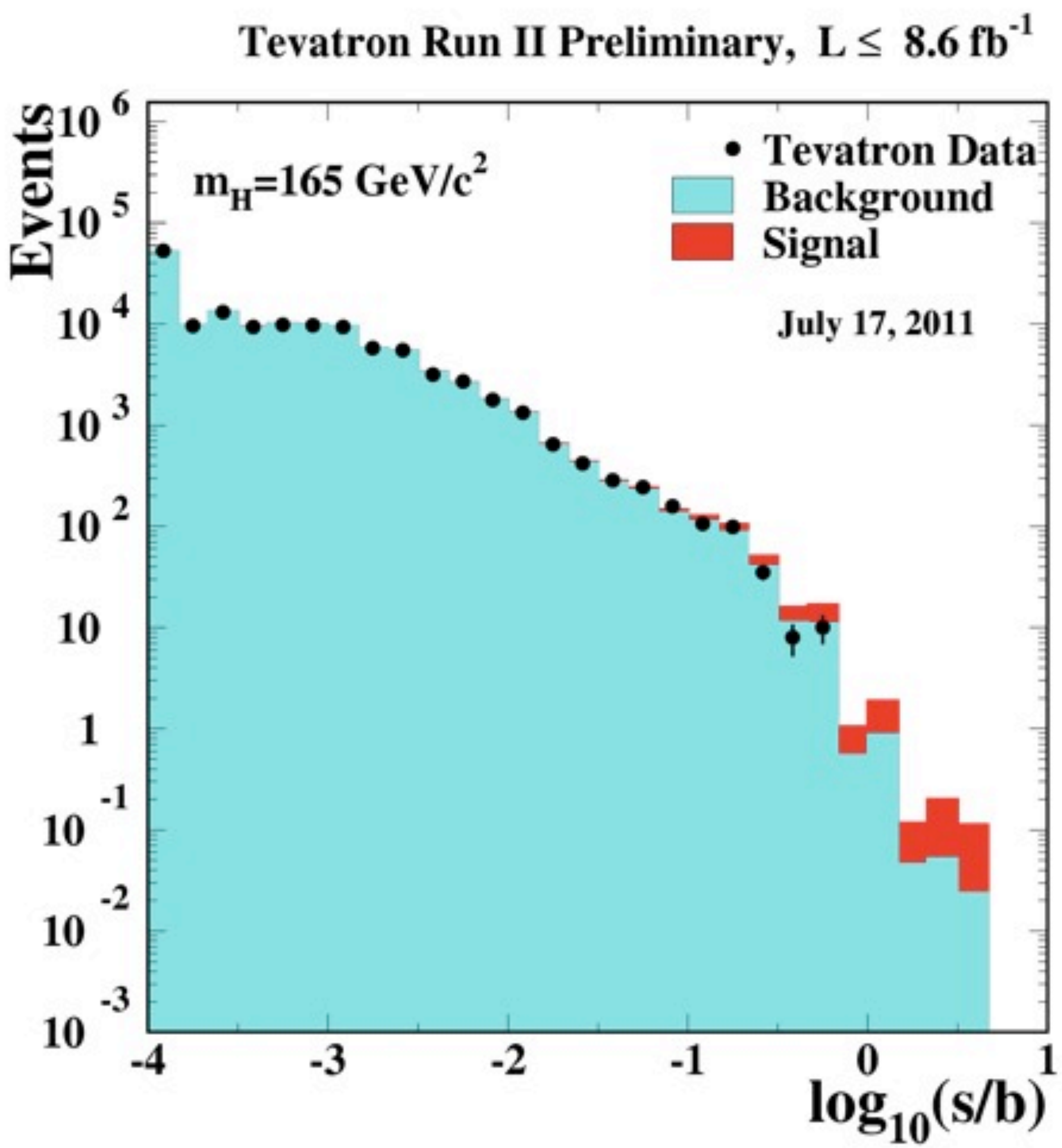
H→W⁺W⁻
(see B. Carls' talk Wednesday)

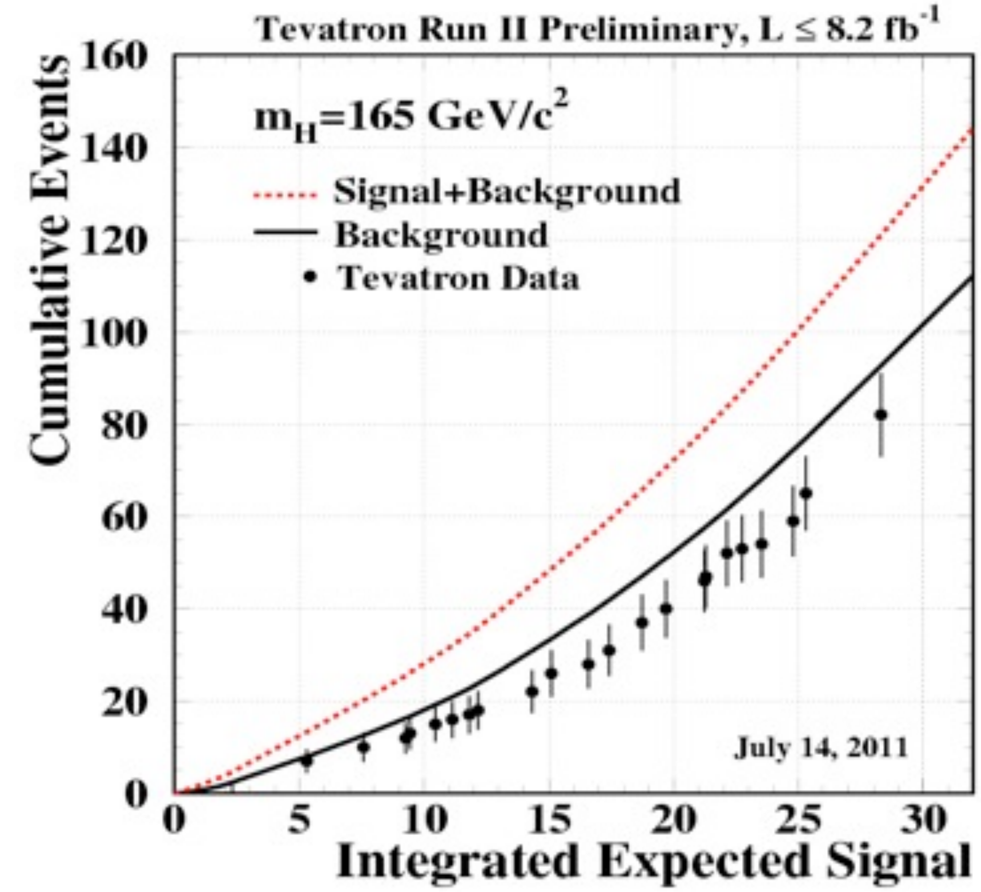


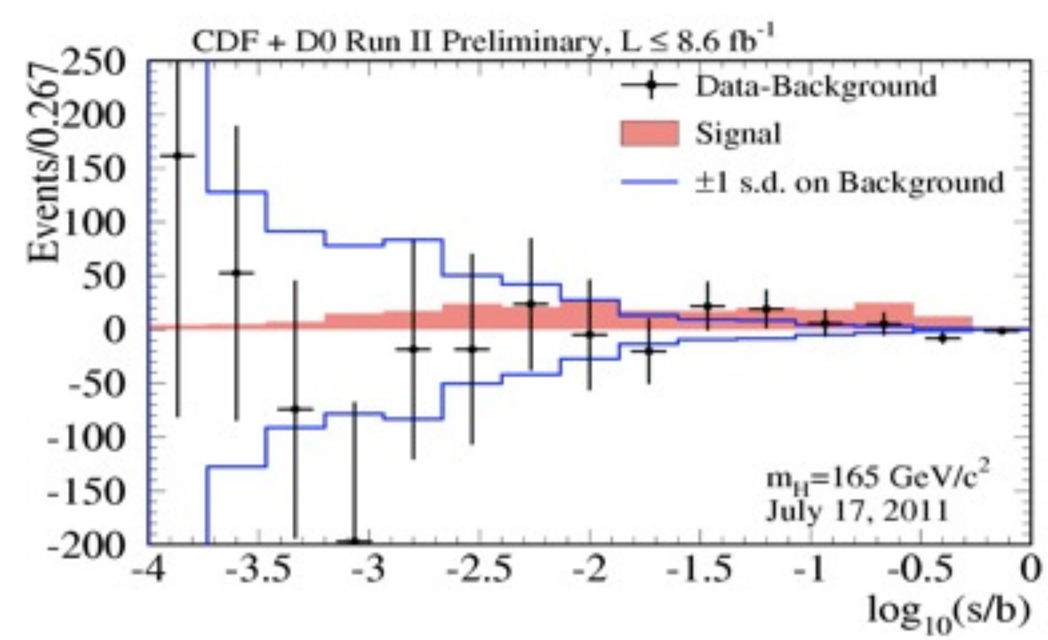


Combining Regions of Similar s/b

$m_H = 165\ GeV/c^2$

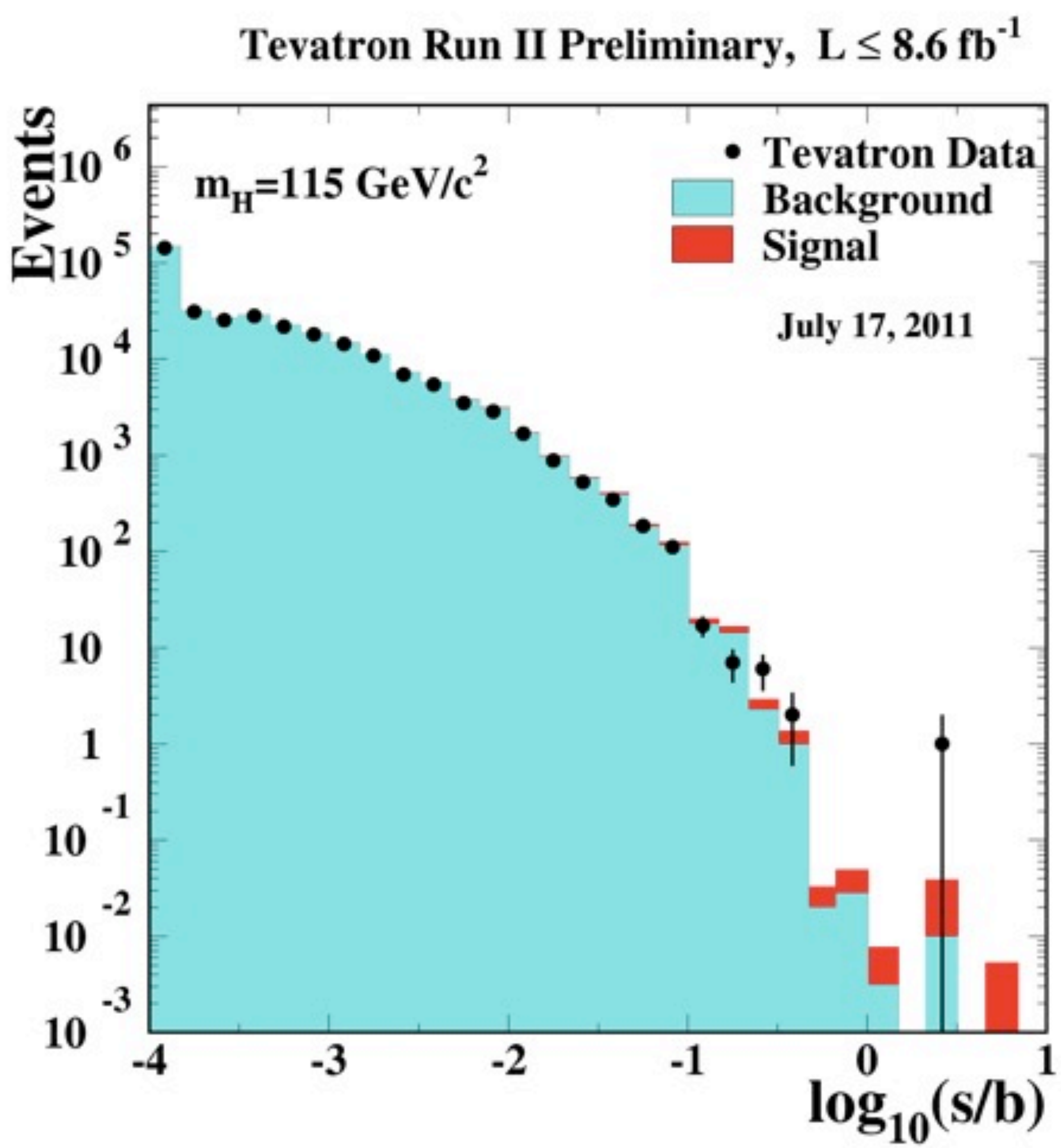


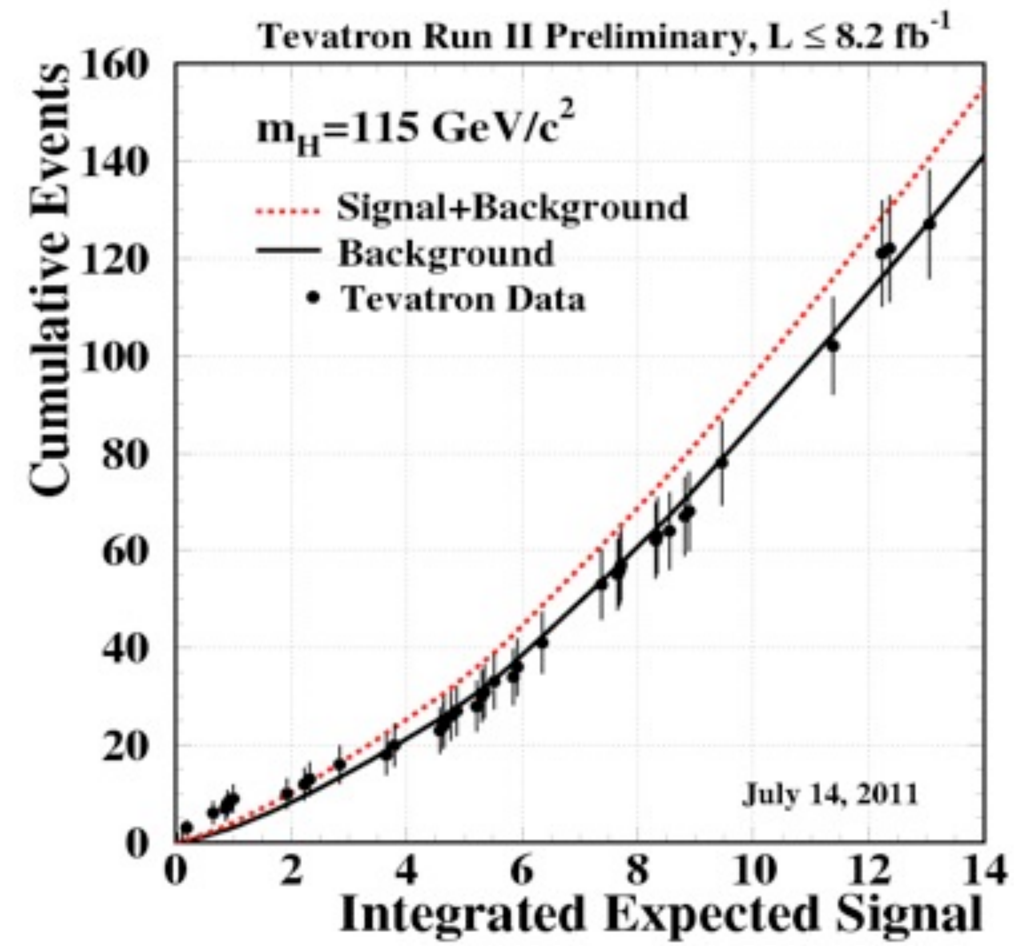


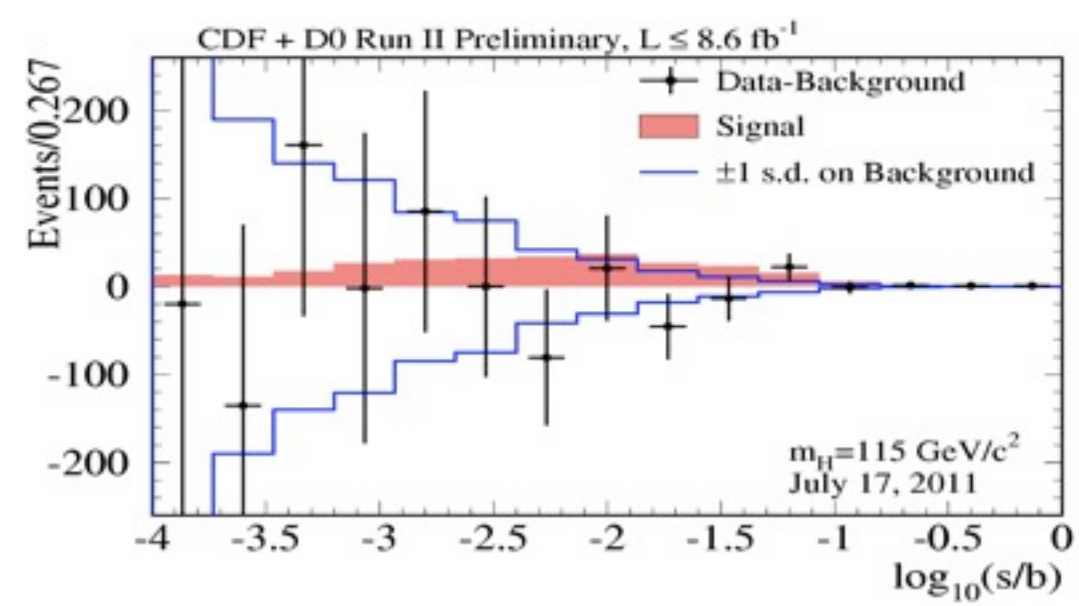


Combined Discriminants

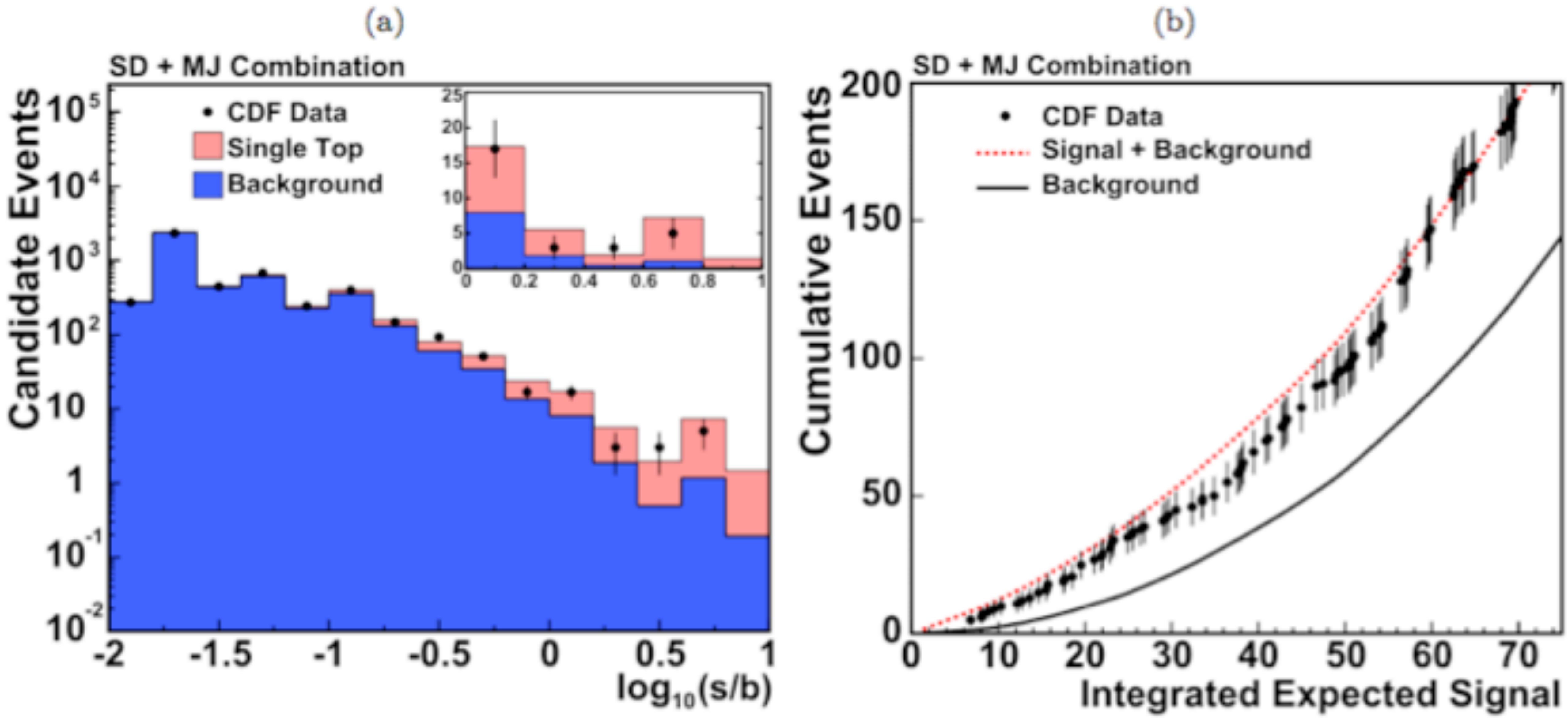
$m_H = 115\ GeV/c^2$







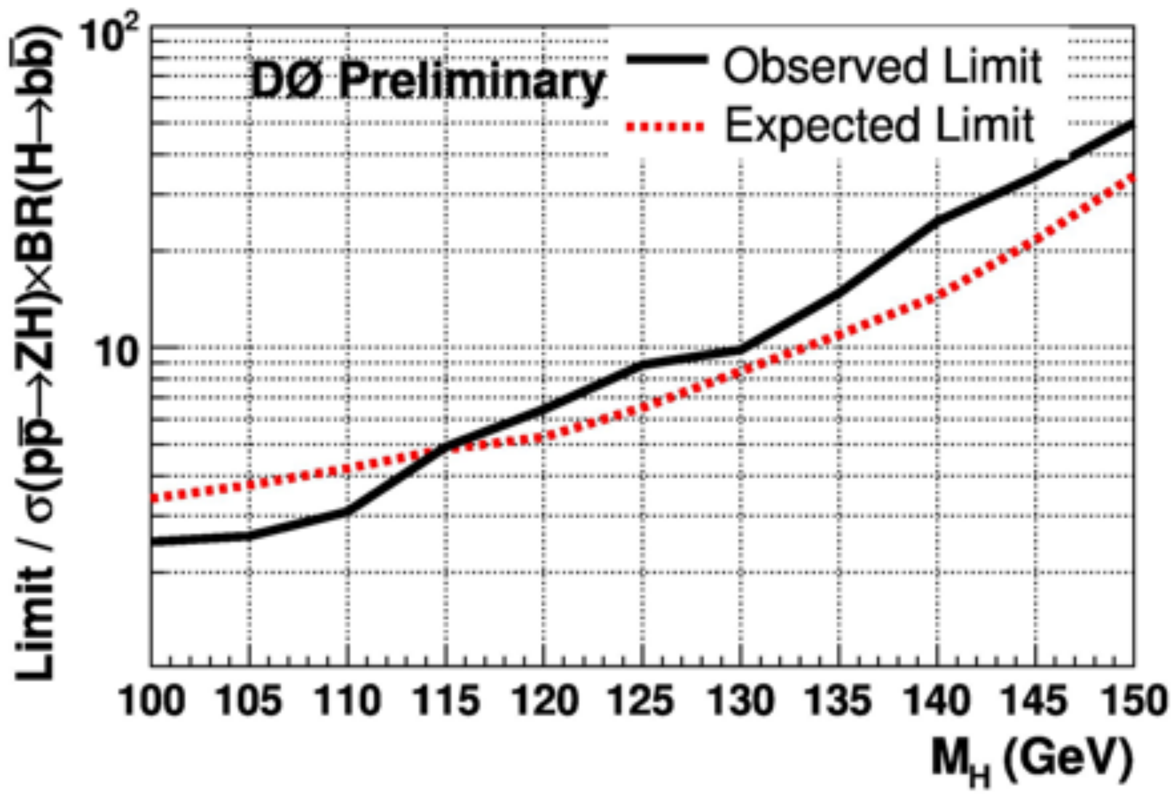
What a 5σ Observation Looks Like

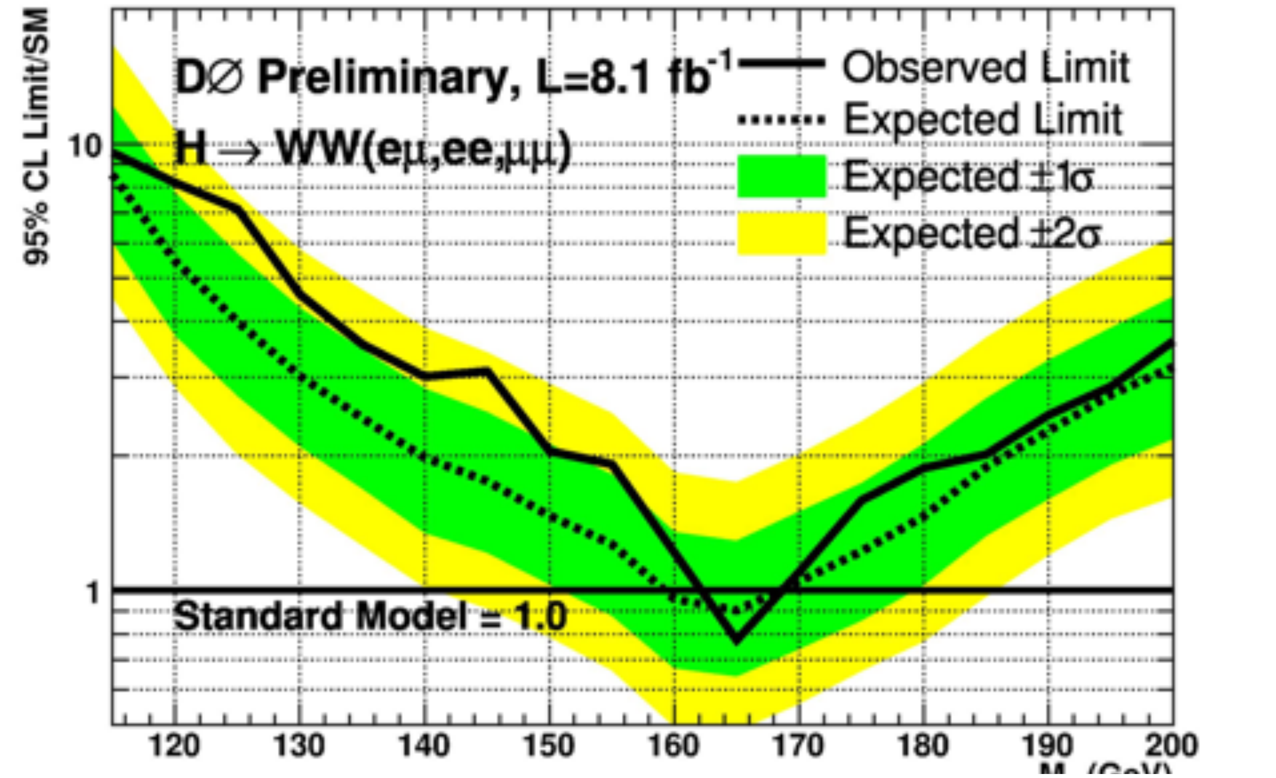


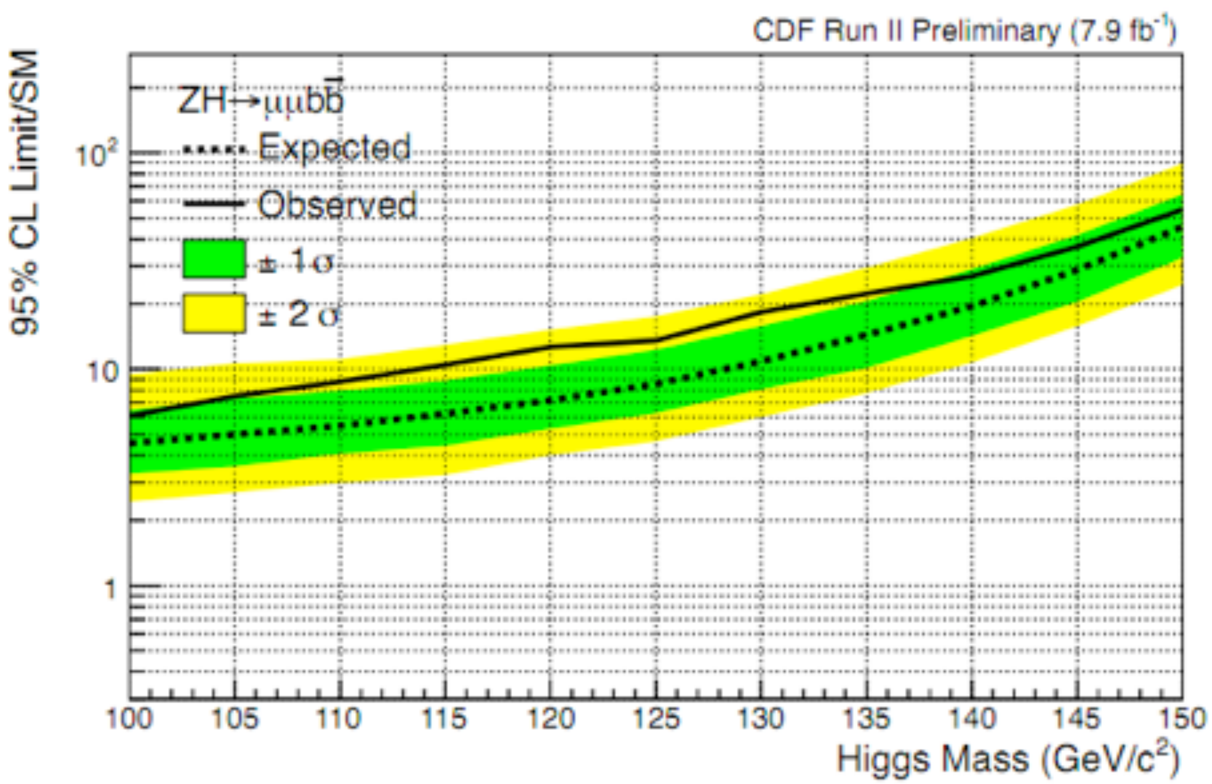
arXiv:1004.1181 Accepted by PRD

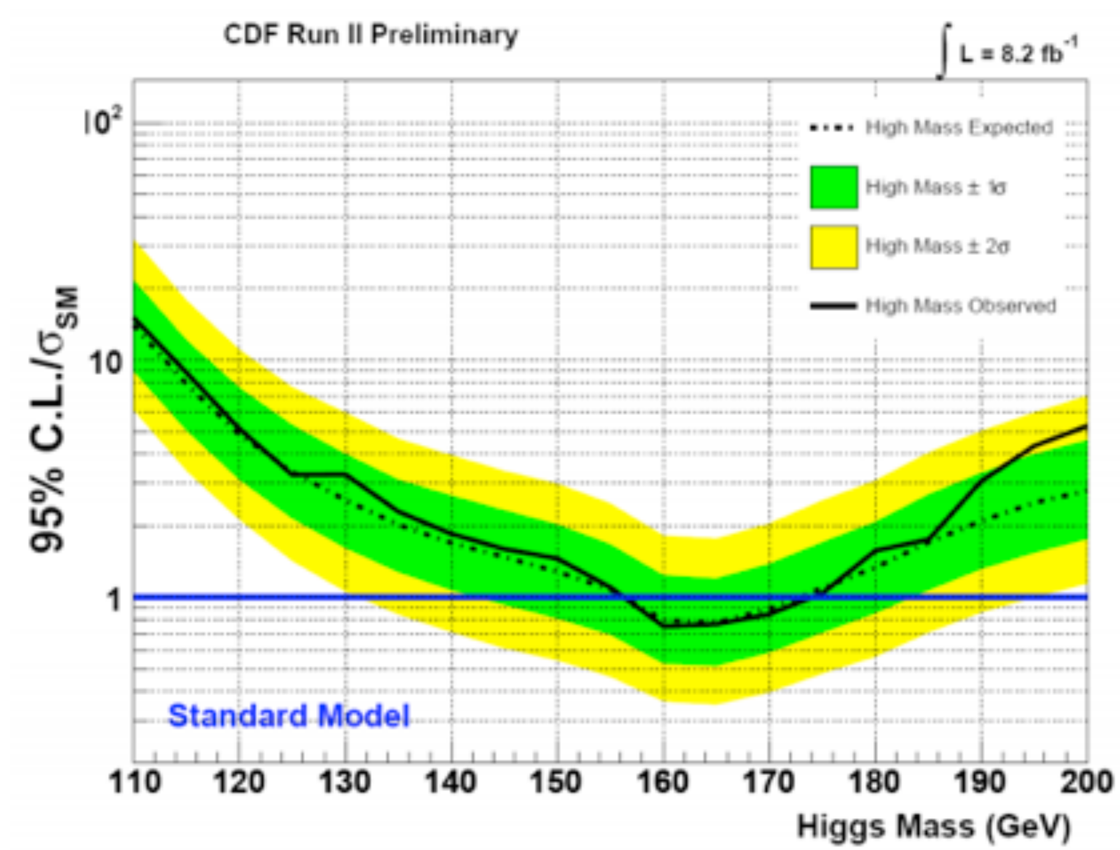
CDF Single Top, 3.2 fb^{-1}

Example Individual Channel Limits

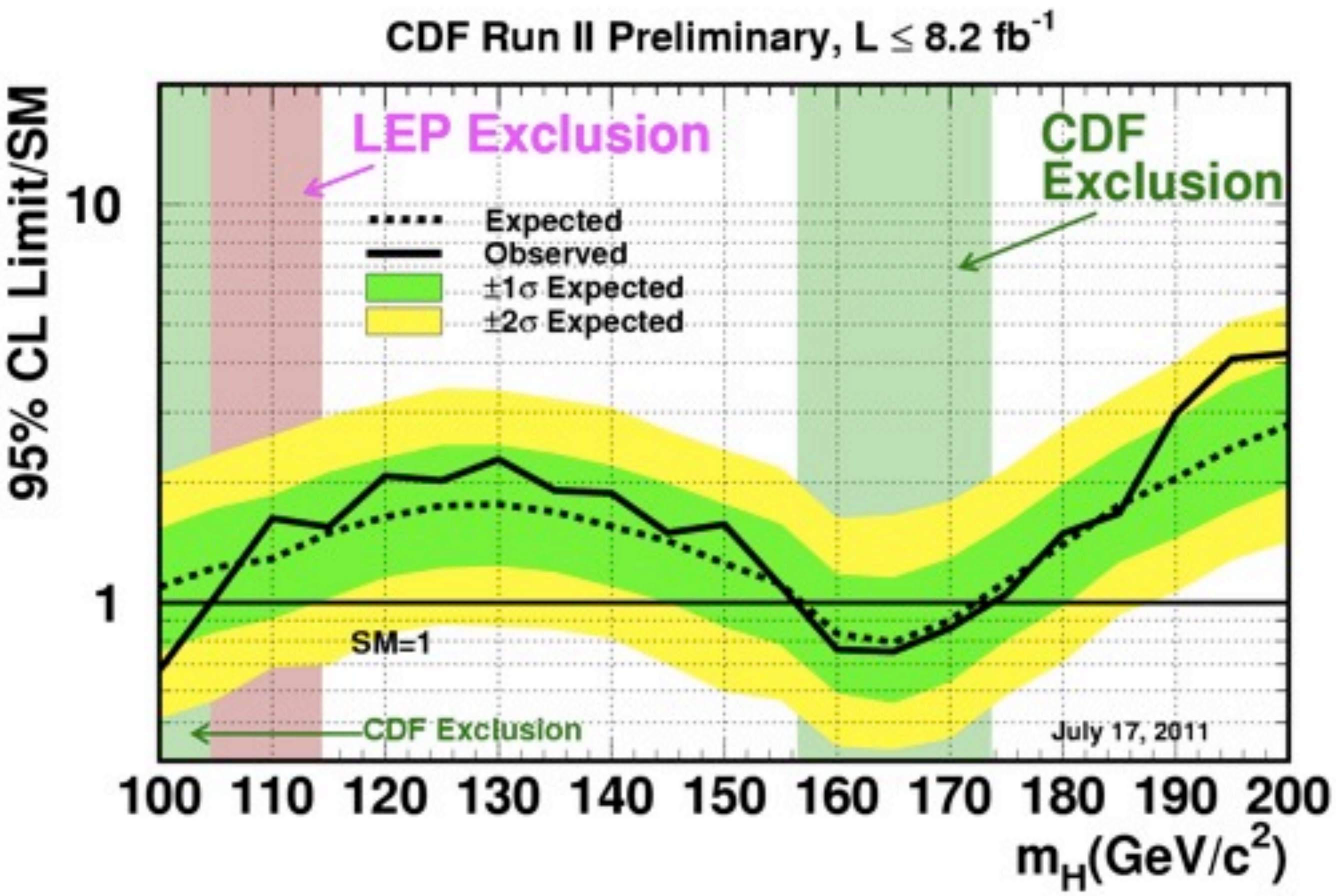


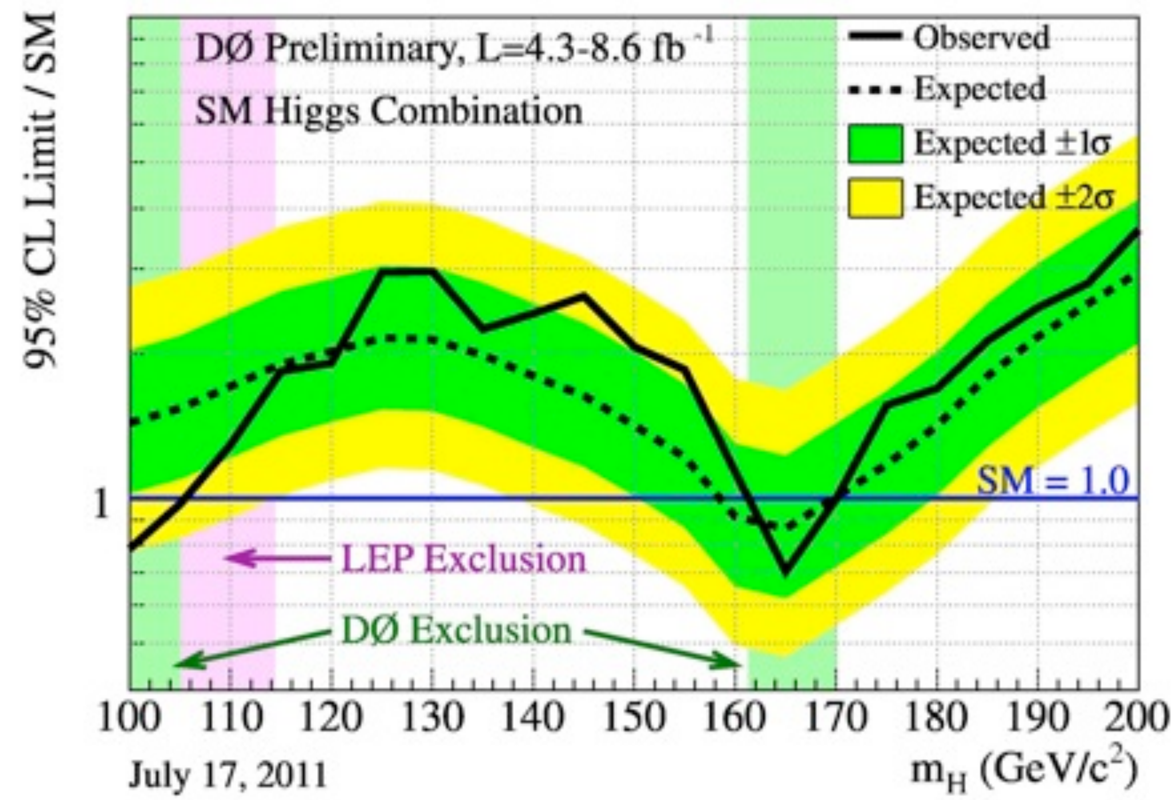






CDF/D0 Combined Limits

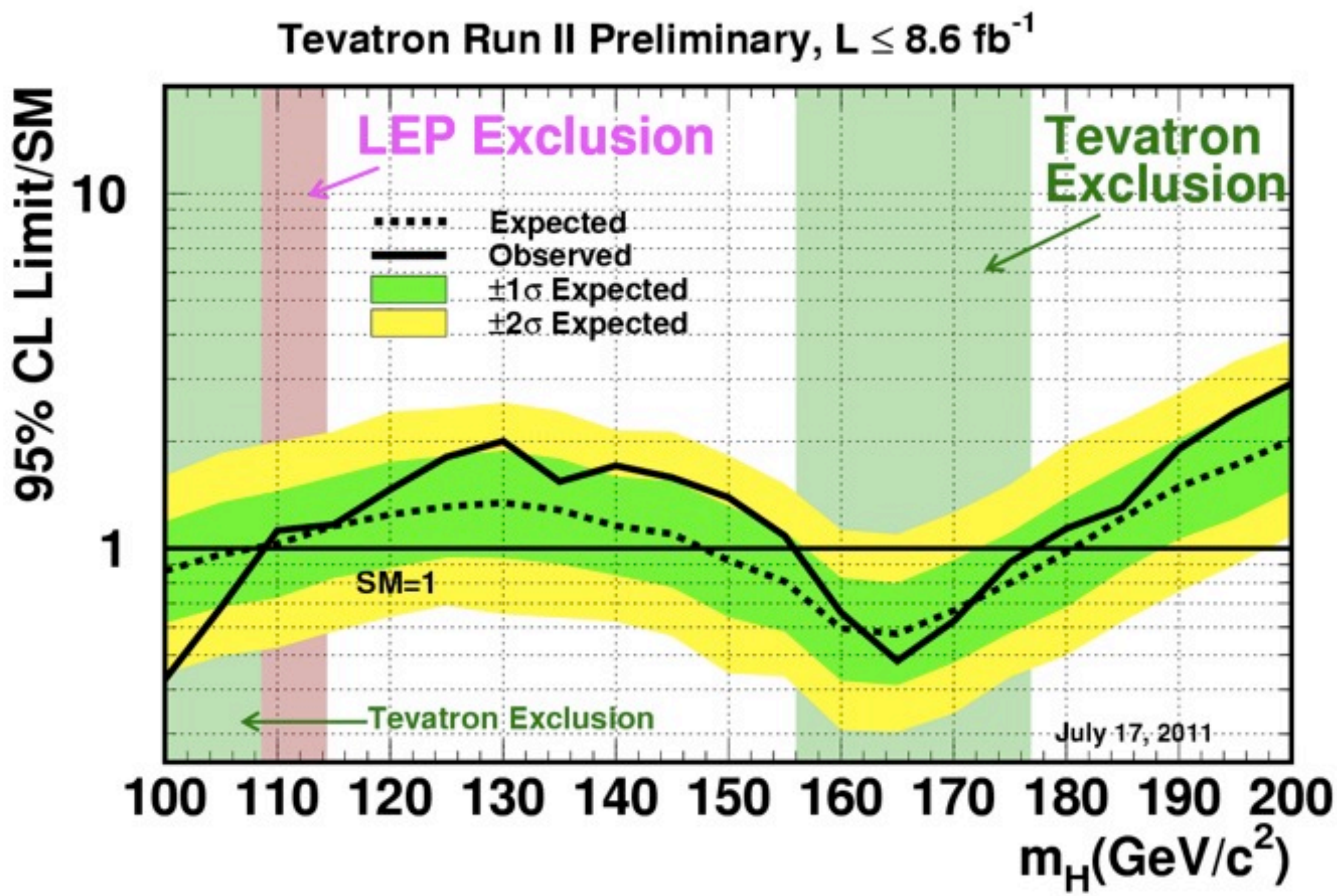




CDF-only combination

D0-only Combination

New Tevatron Combination

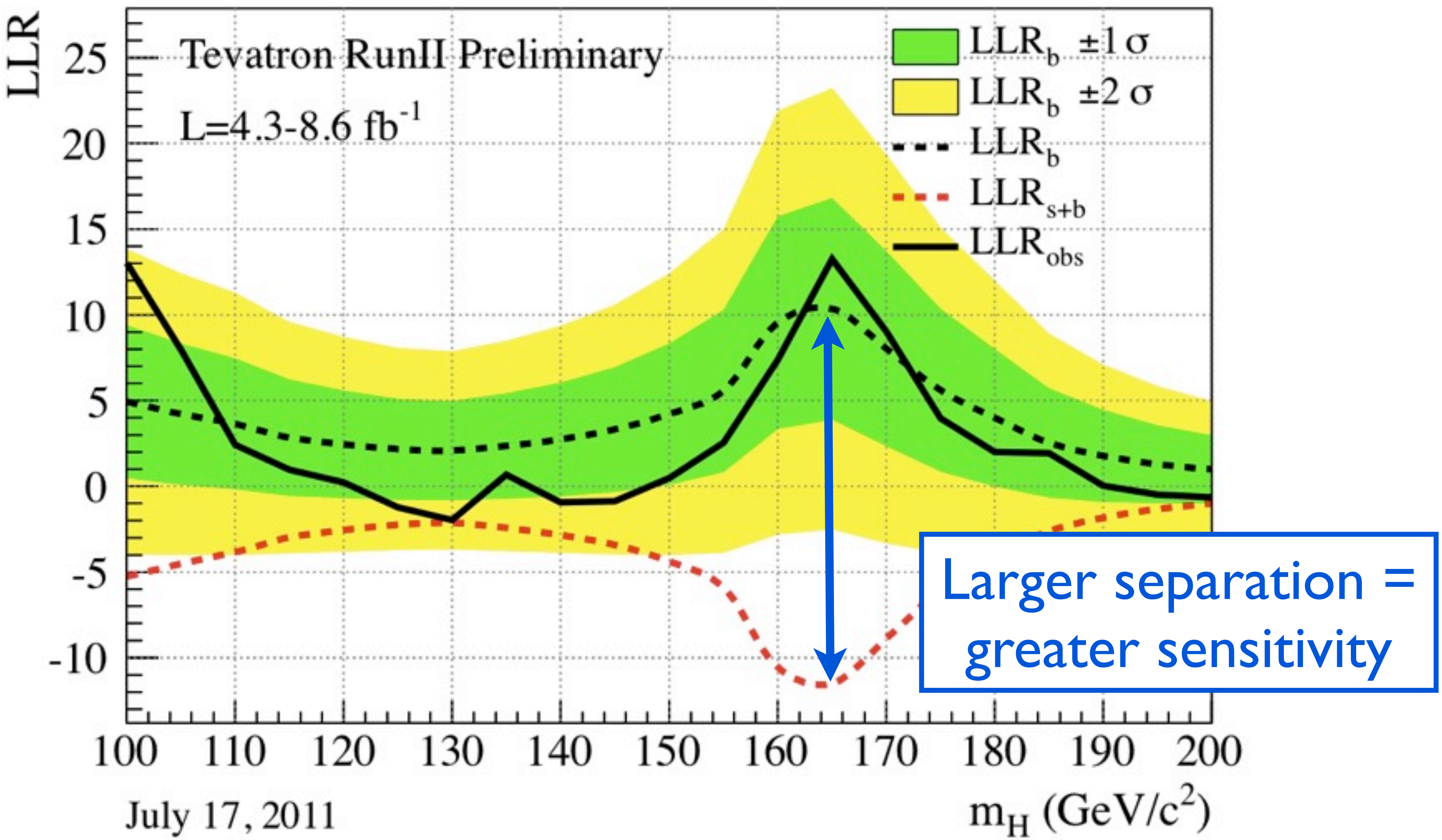


Observed Exclusion : 100-109 and 156-177 GeV/c^2

Expected Exclusion : 100-108 and 148-181 GeV/c^2

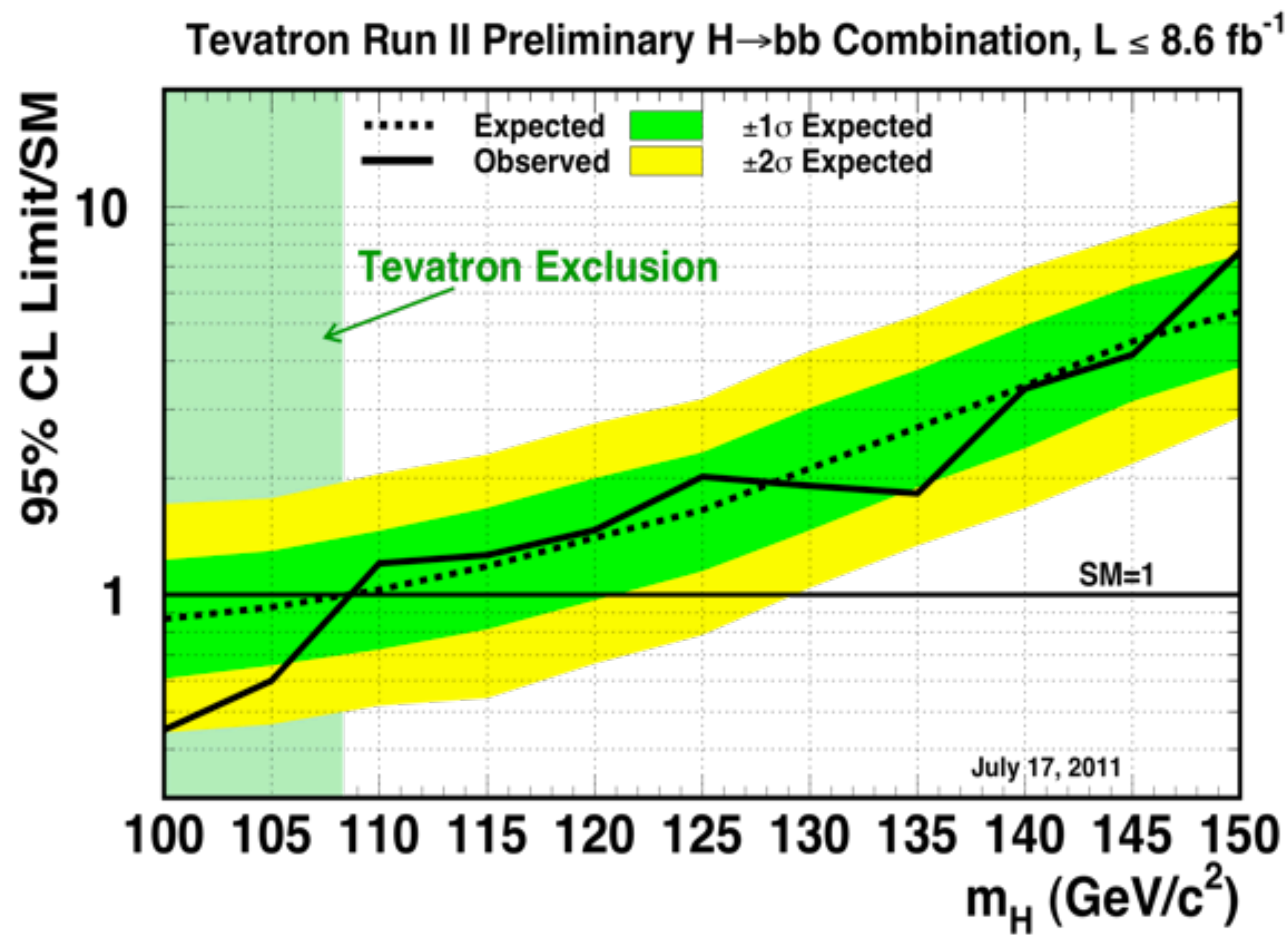
S+B versus B-only Hypotheses

$$LLR = -2\ln Q \text{ where } Q = L_{s+b}/L_b$$



Other combinations: H→bb

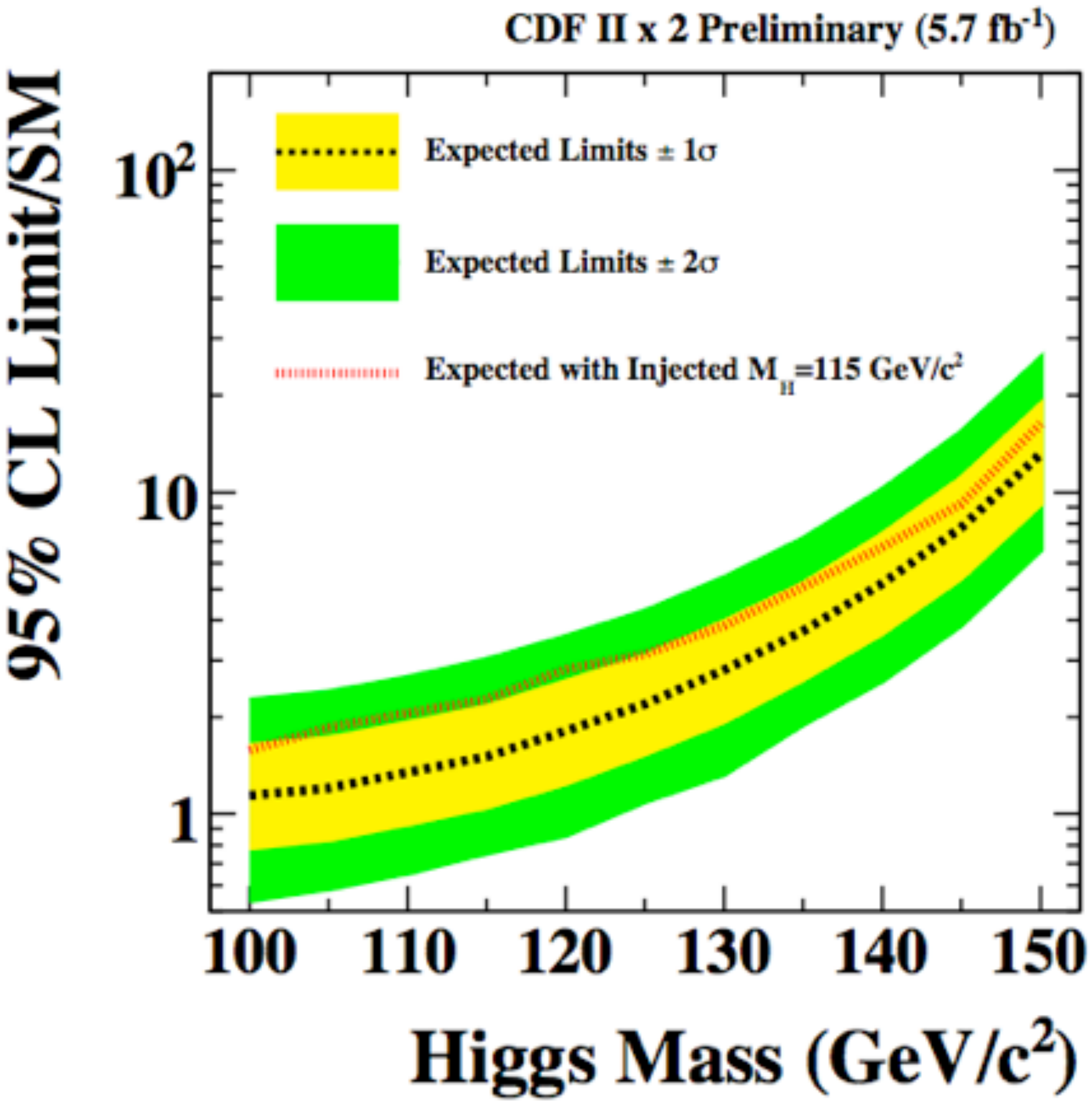
- Look at associated production & H → bb decay
- These channels provide best sensitivity in the mass region just above the LEP bounds
- Observation of this decay mode is important for establishing that a Higgs-like signal found in other channels is in fact the SM Higgs

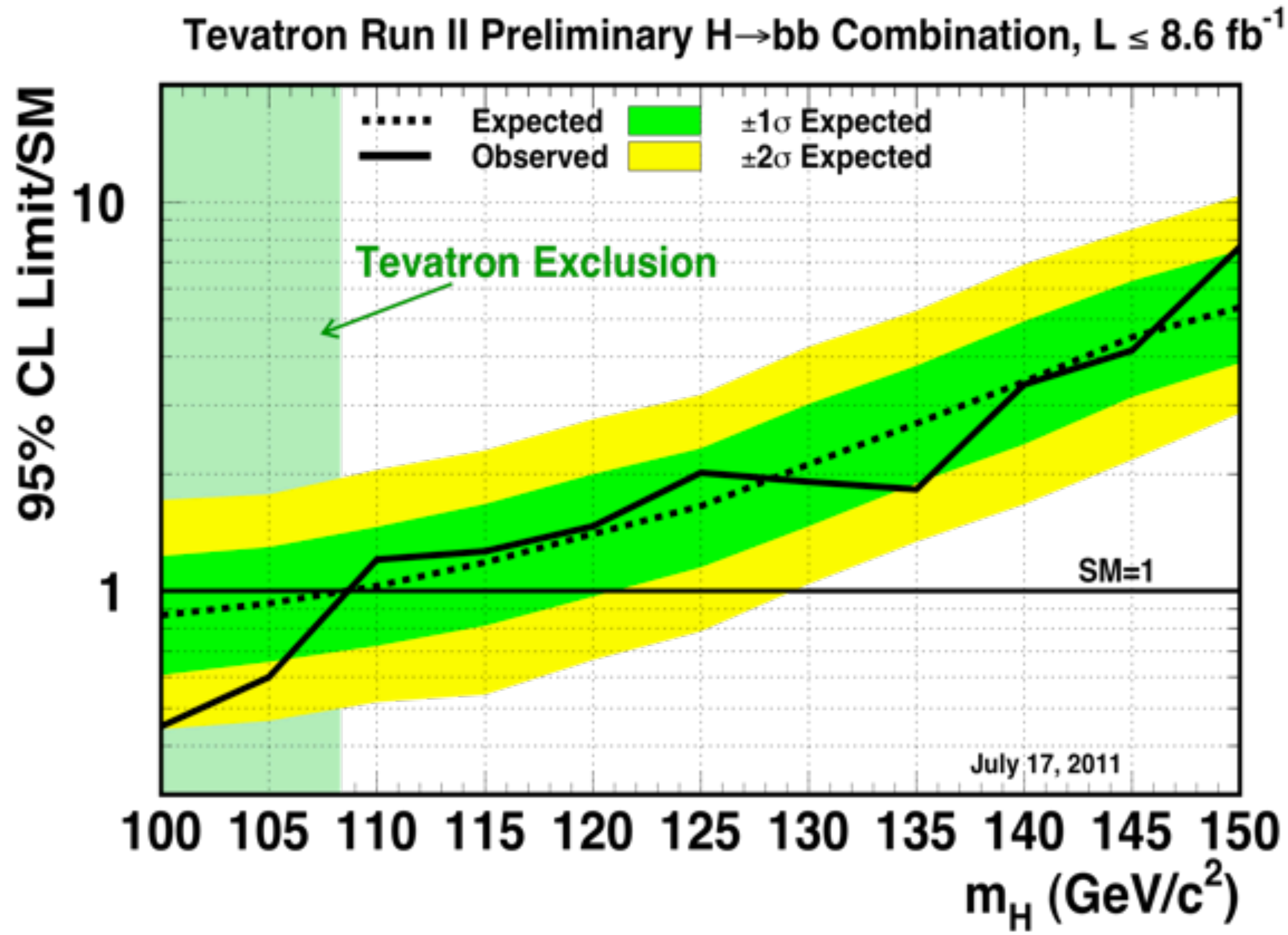


Observed and expected in good agreement

H→bb Compared to Expectations

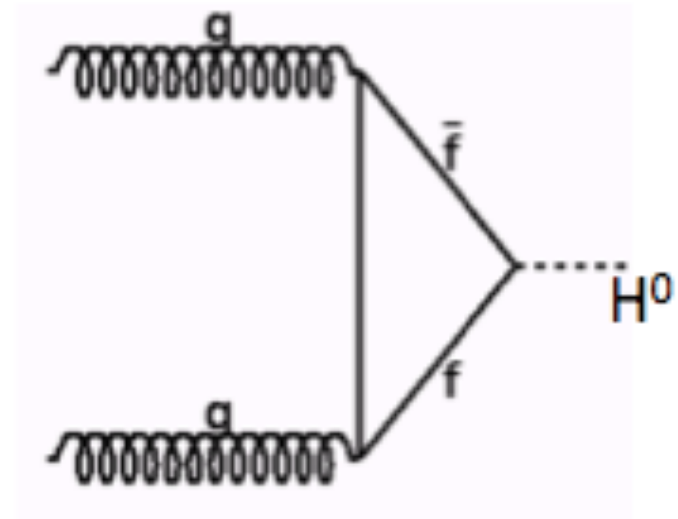
Observed vs Expected with Injection of Higgs

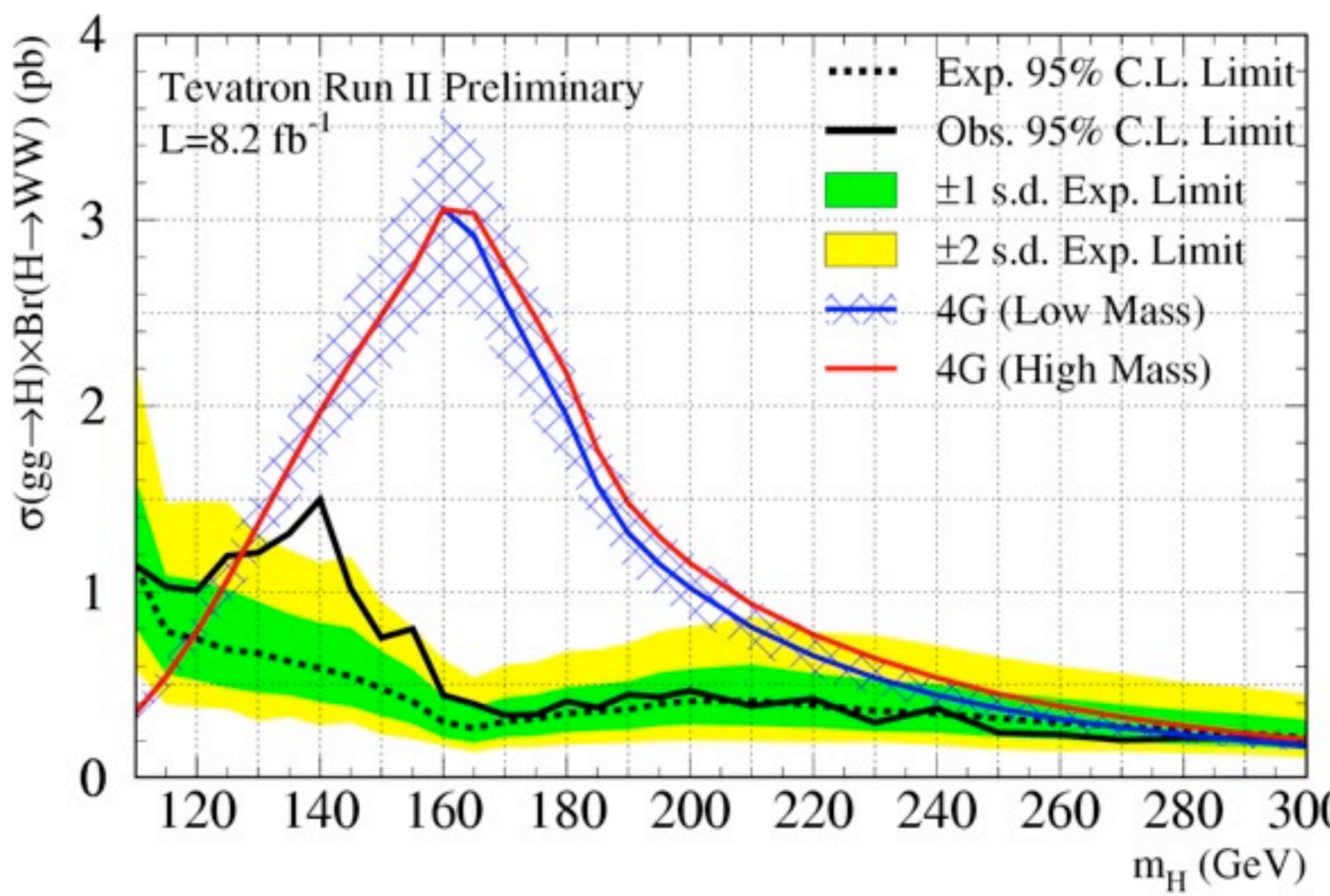




Fourth Generation Interpretation

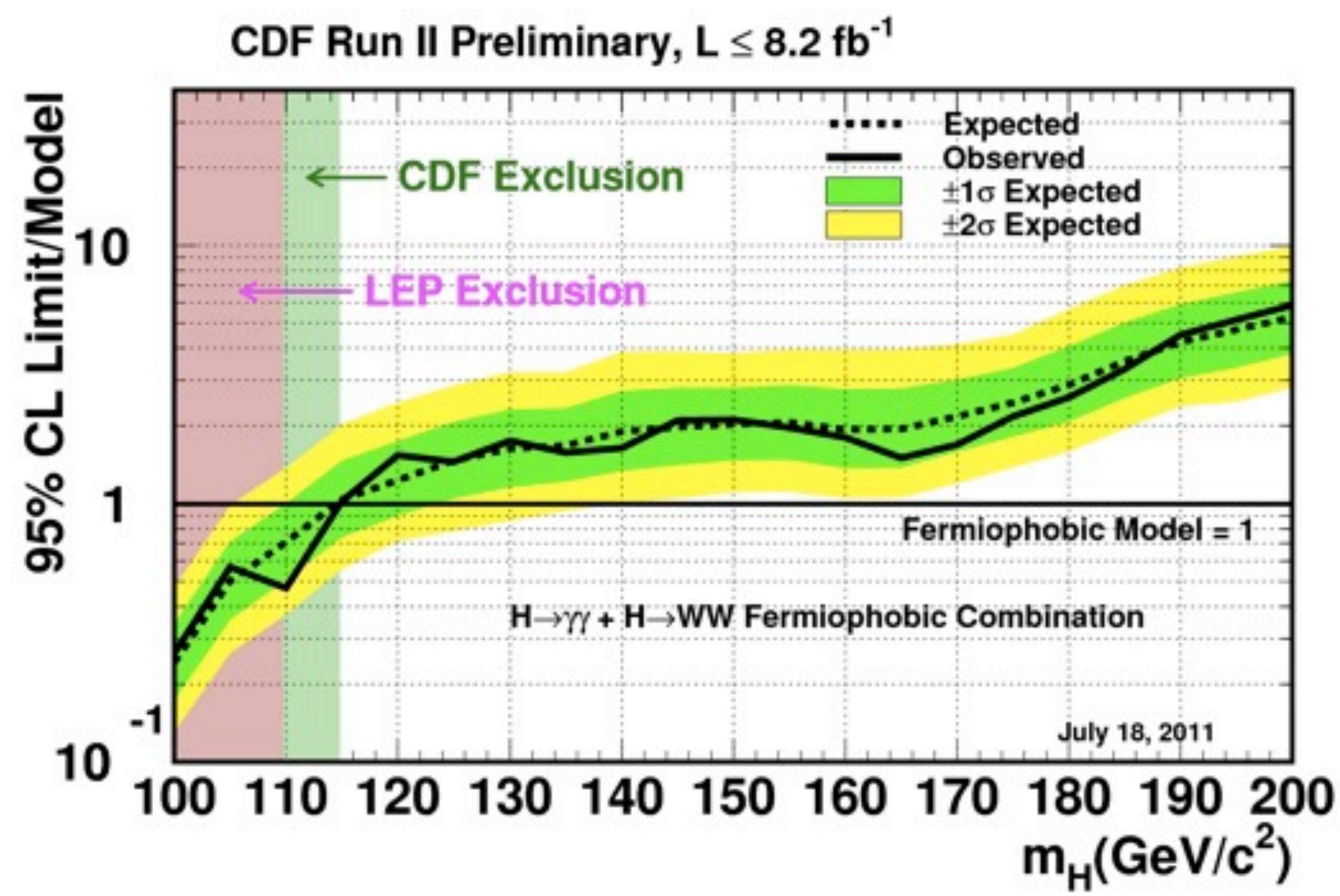
- We also interpret our high mass search results in terms of a fourth generation model
- Presence of additional quarks enhances gg→H production by as much as a factor of nine - also modifies Higgs branching ratios
- Look at H → WW/ZZ decays • Set limits on cross section x Br
- Observed exclusion : 124 < m_H < 286 GeV





Fermiophobic Higgs

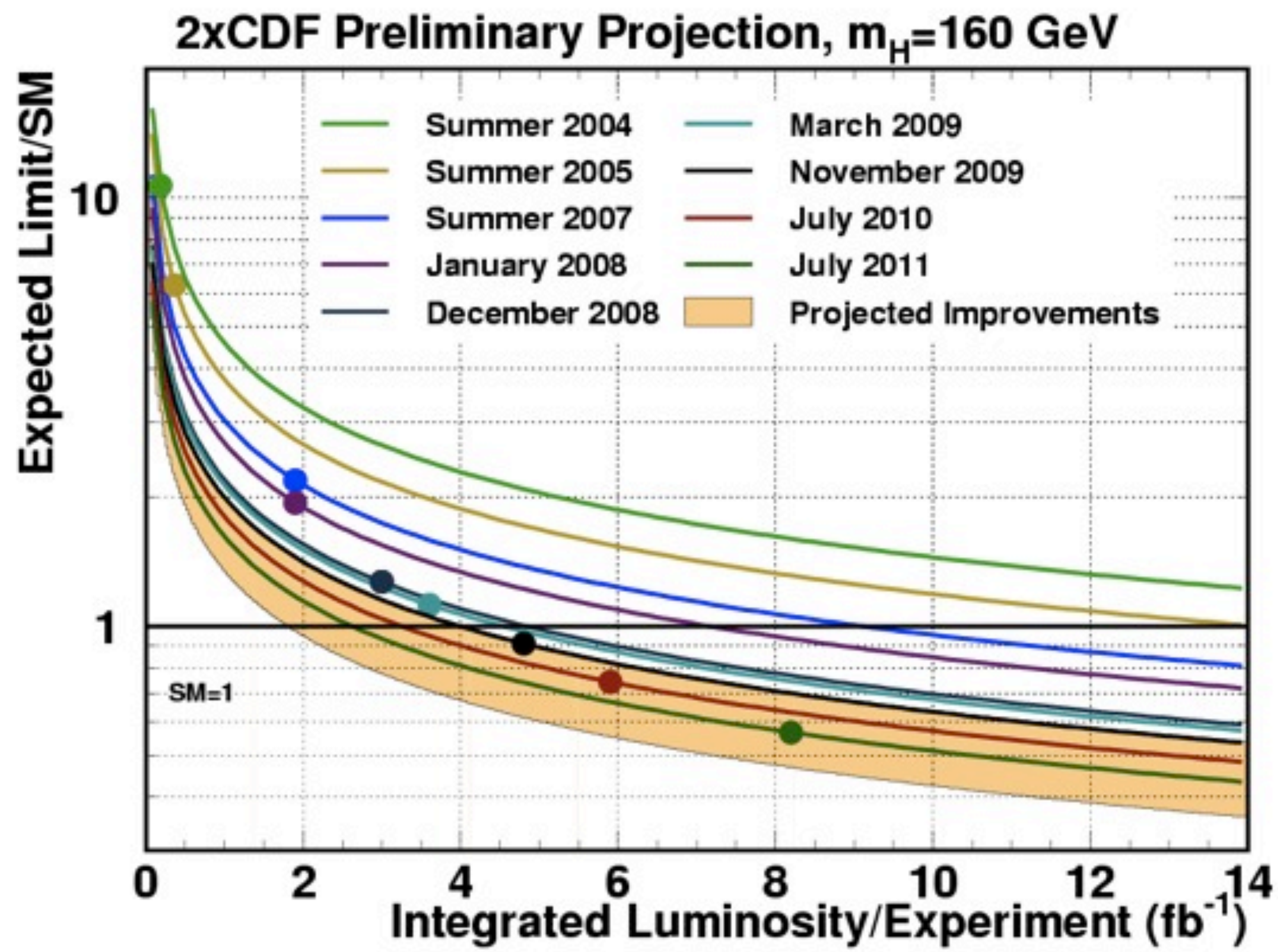
- “benchmark” Fermiophobic model
- No Higgs coupling to fermions
- SM Higgs coupling to bosons
- Br(h→bb) suppressed by $m_b = m^2_W$
- Br(h→ϒϒ)high for low mass (Mh < 110 GeV/c^2)
- Only WH, WZ, and VBF production (no gg → h)
- SM production cross section assumed



$m_H > 114.8$ GeV/c^2

Final Steps

- We continue to obtain large improvements in search sensitivity beyond that expected from simply adding more data
- Tevatron is on track to deliver Higgs search results next spring based on the full $10 fb^{-1}$ datasets that achieve our expected sensitivity goals



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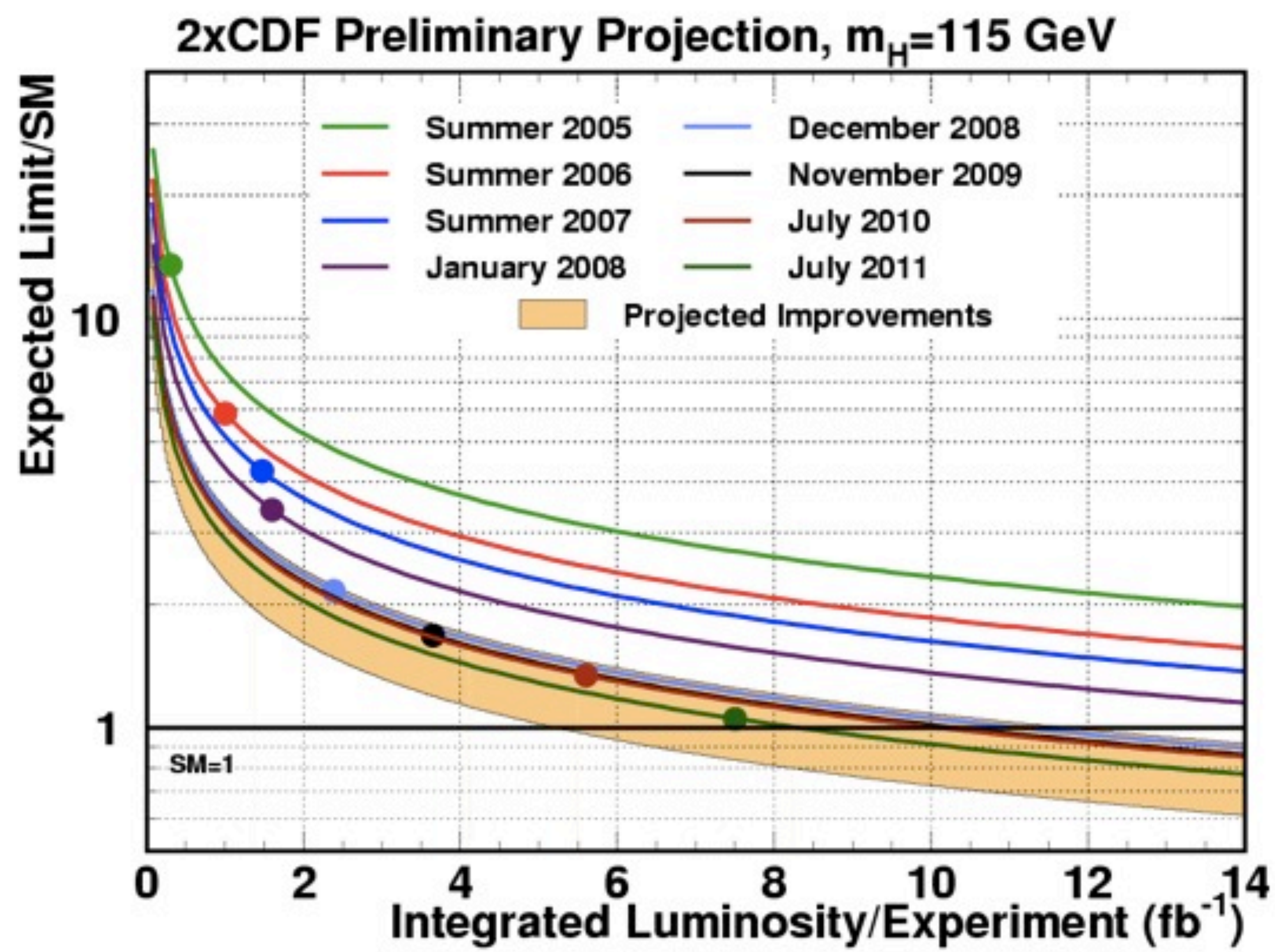
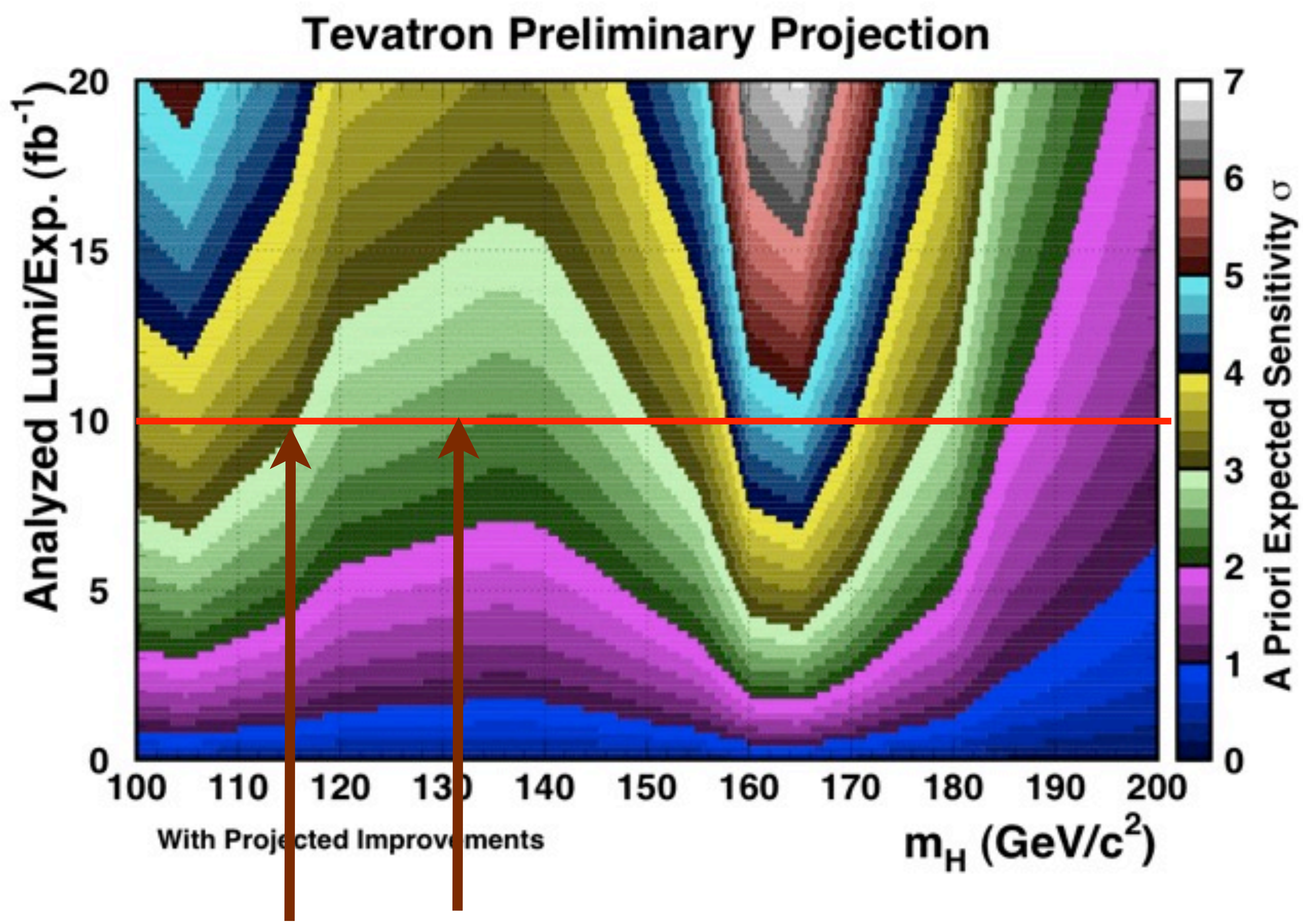


Final Steps

Implies Tevatron 95% C.L. exclusion sensitivity over the entire Higgs mass range between 100 and 185 GeV/c^2 for next spring

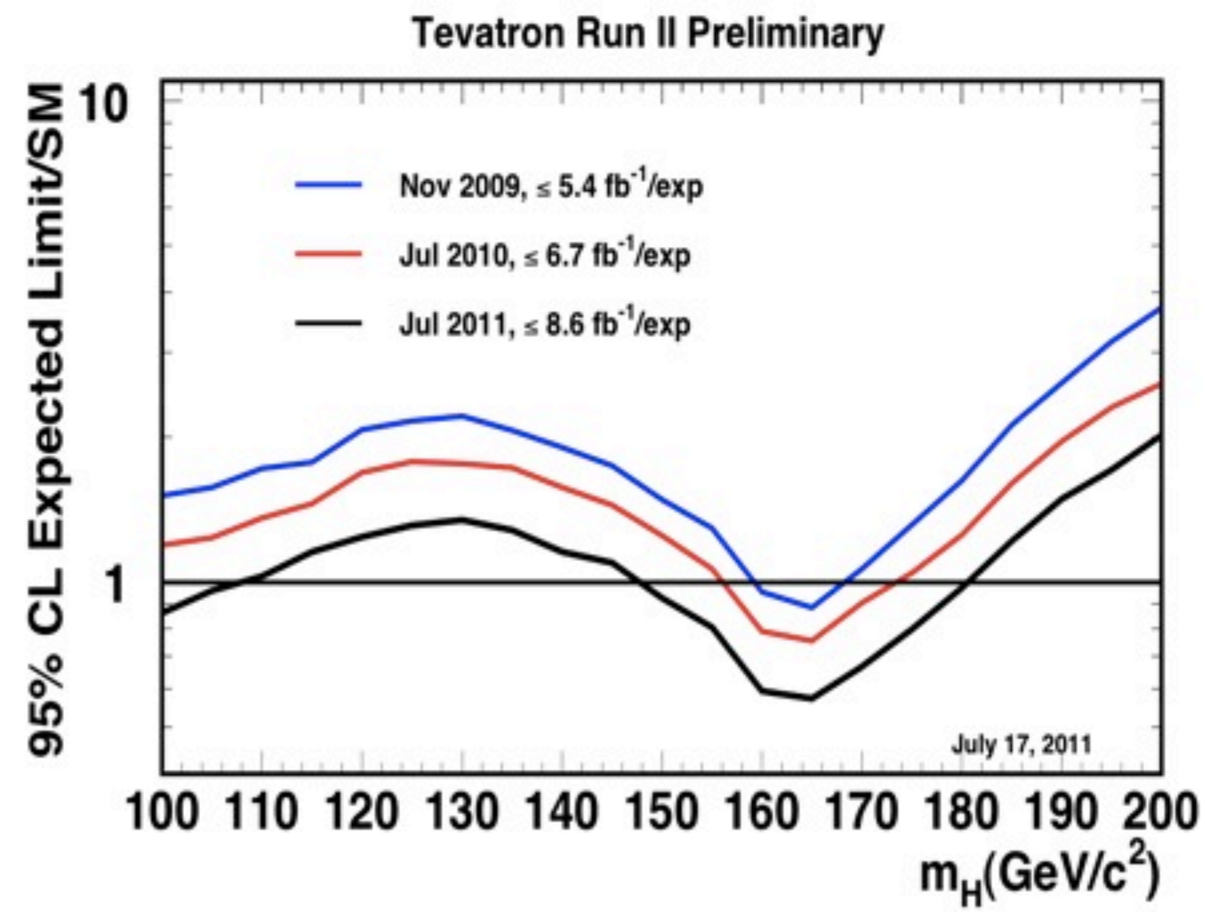


Better than 3σ for m_H=115 GeV/c^2

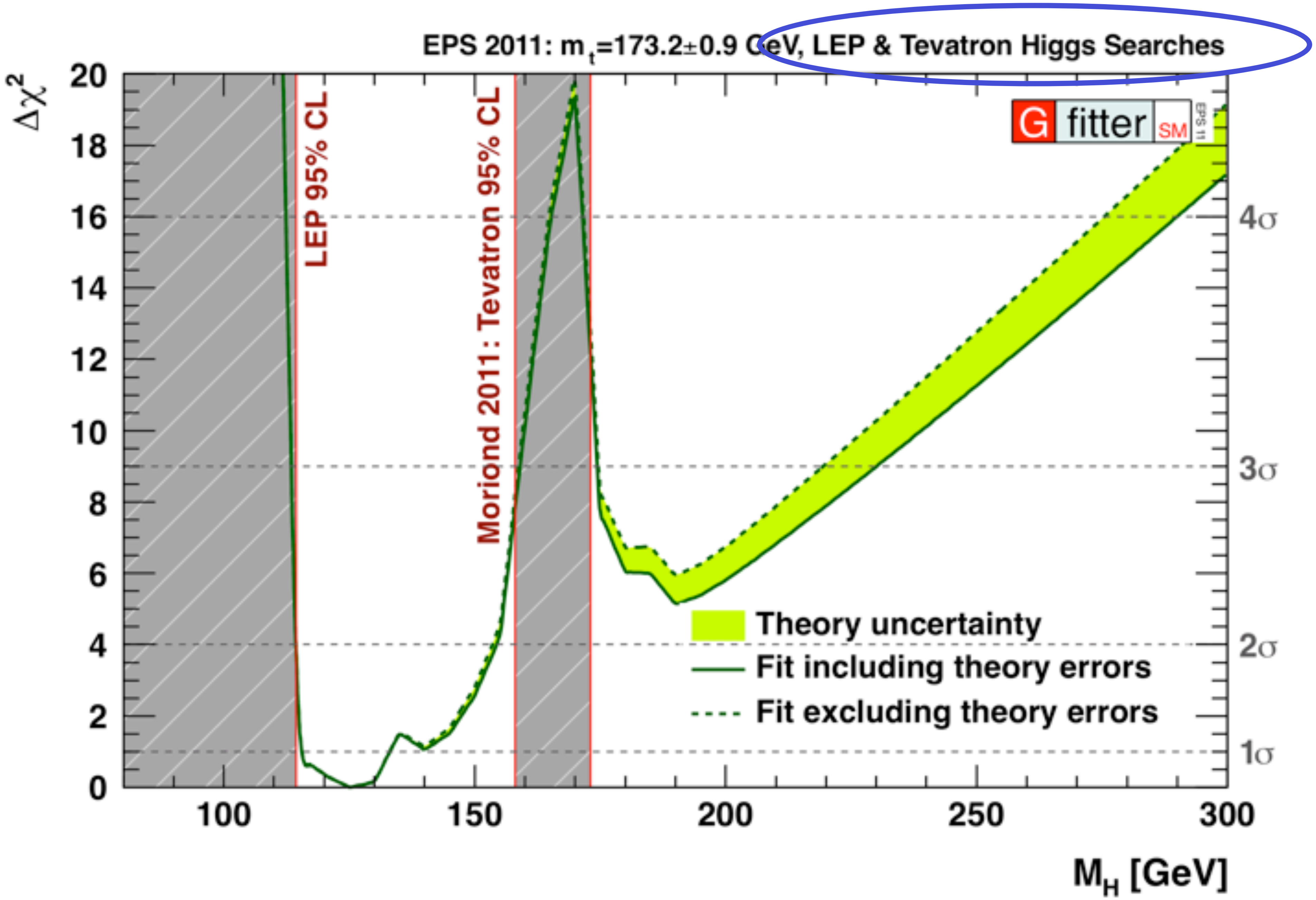
Only 2.4σ for m_H=130 GeV/c^2

Conclusions and Outlook

- Expect to collect over 10 fb^{-1} of analyzable data by the end of September 2011
- On track to reach 95% C.L. exclusion sensitivity over entire m_H range from 100 to 185 GeV/c^2 by next spring
- Best current sensitivity to bb Higgs decay mode
- We continue to improve our analyses: 5 new channels this summer, substantial improvement in existing channels



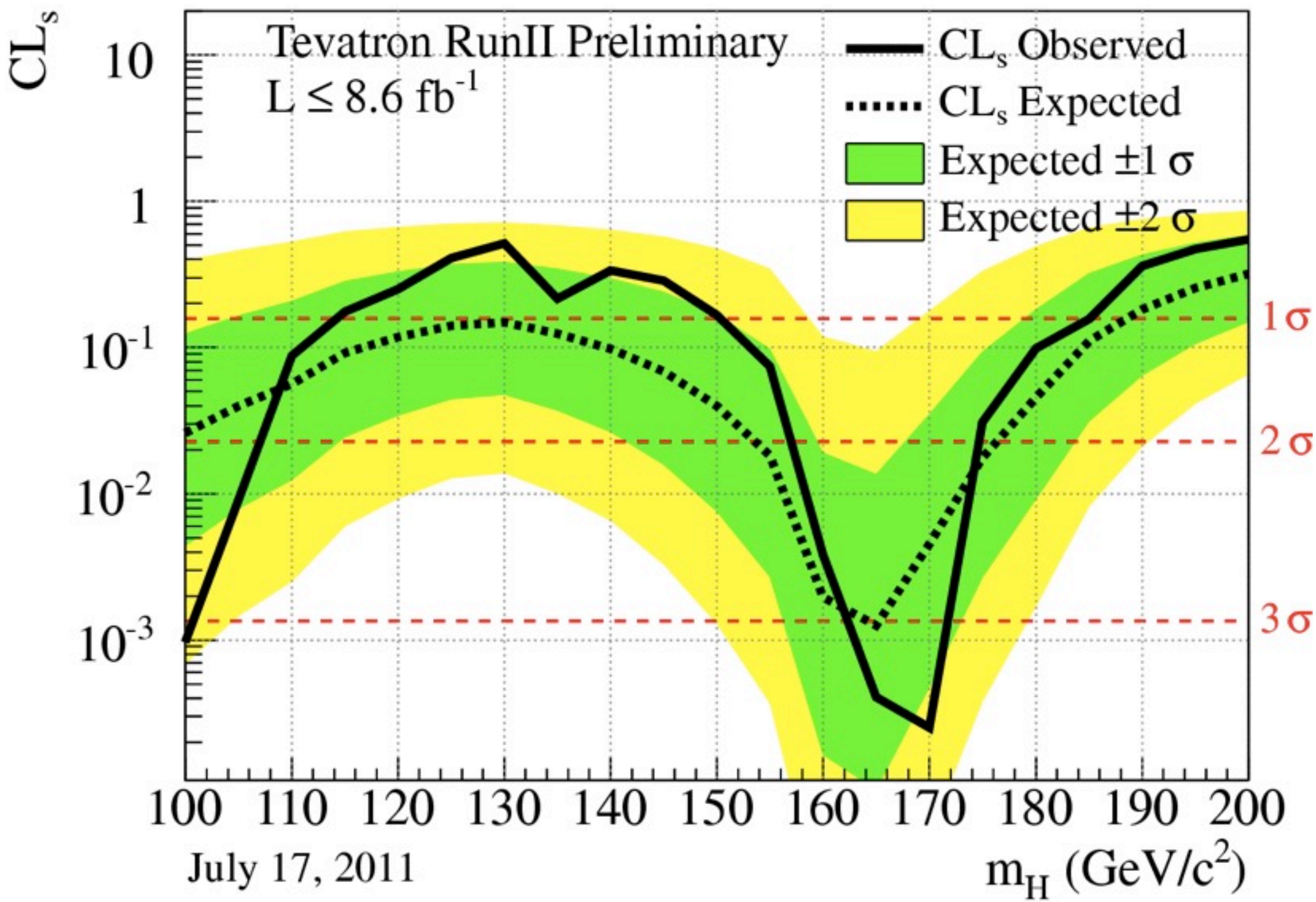
Updated Global EWK Fit



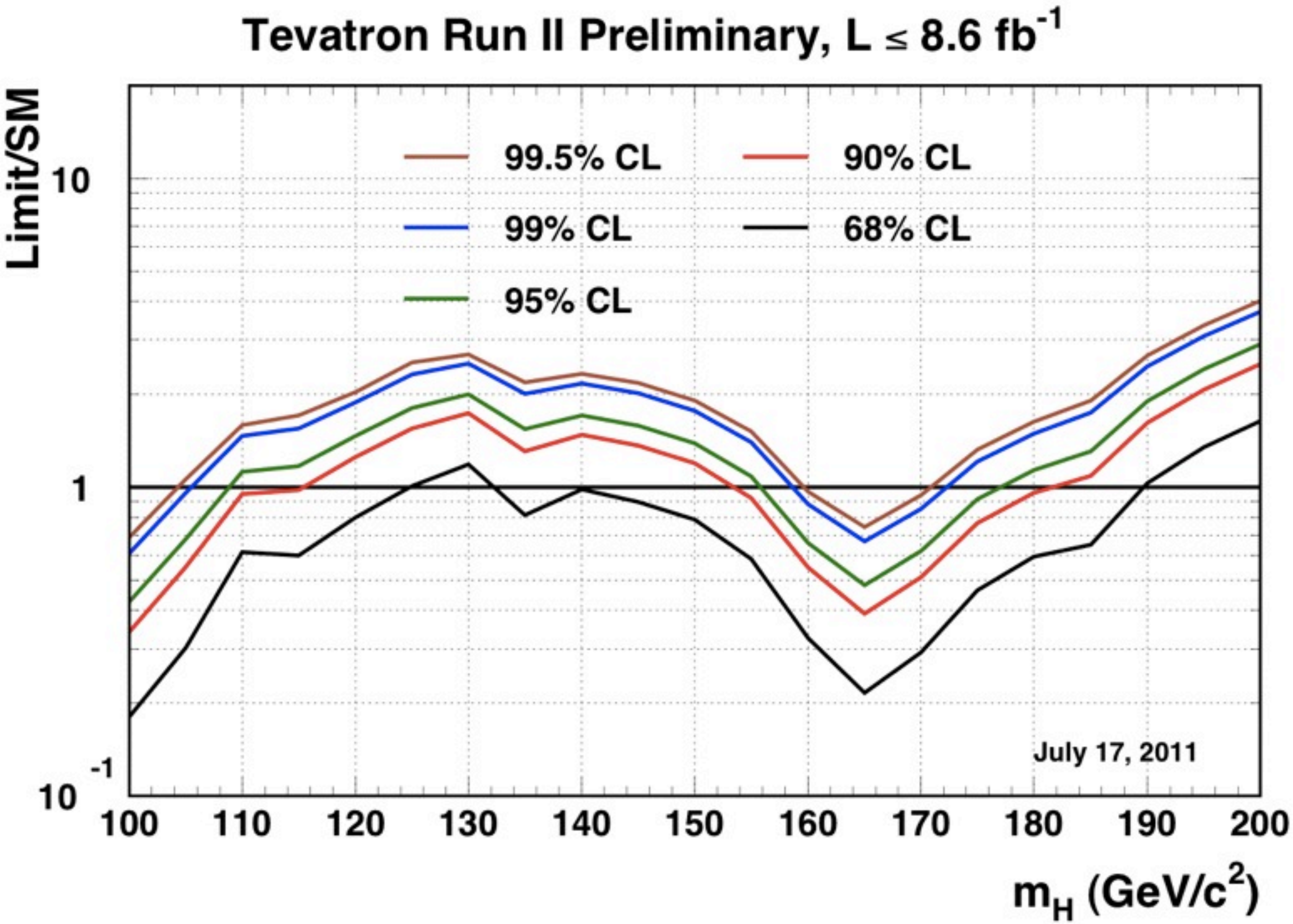
M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Ludwig, K. Moenig, M. Schott, and J. Stelzer, arXiv:1107.0975v1

CL_S Plot

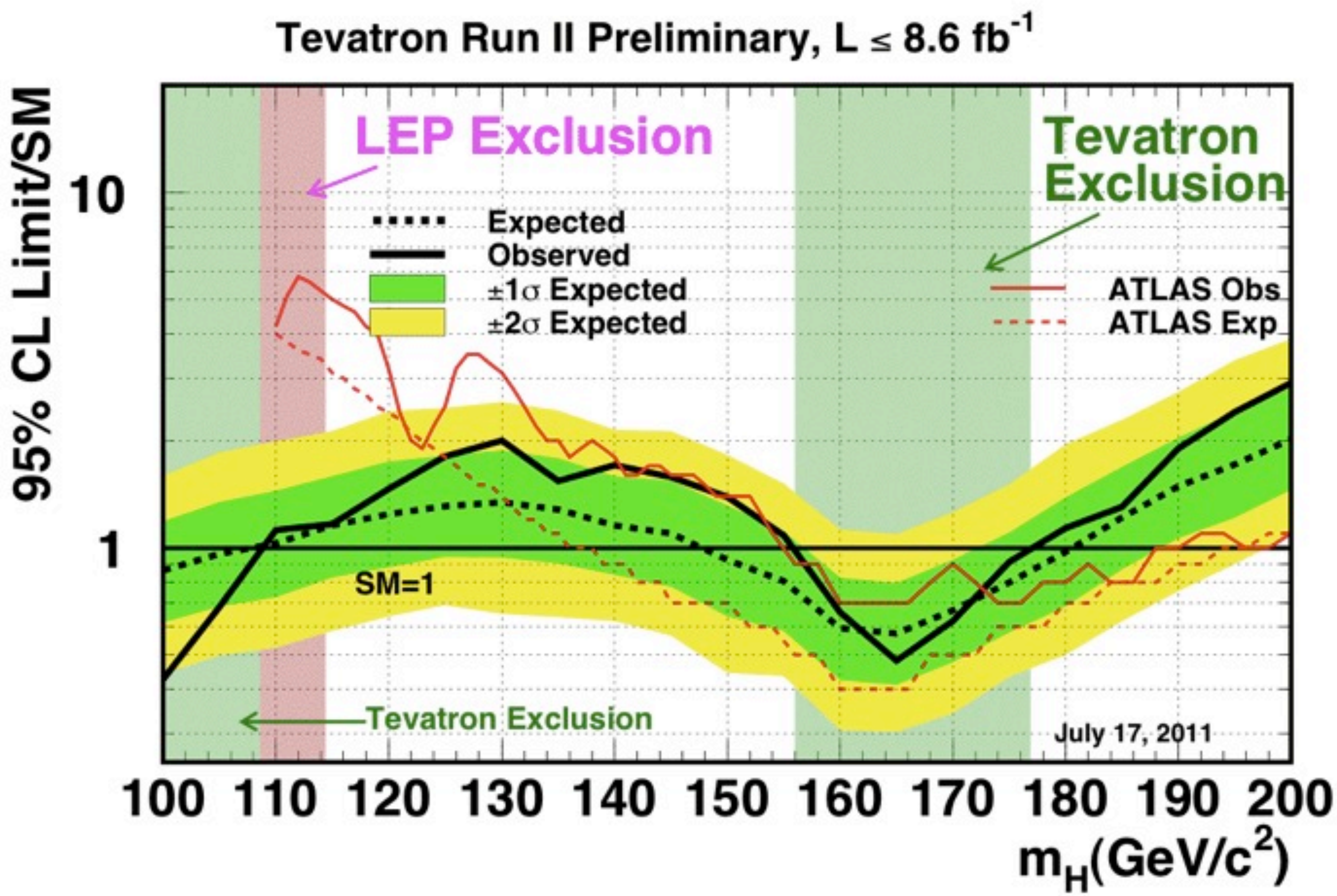
$CL_s = CL_{s+b}/CL_b$



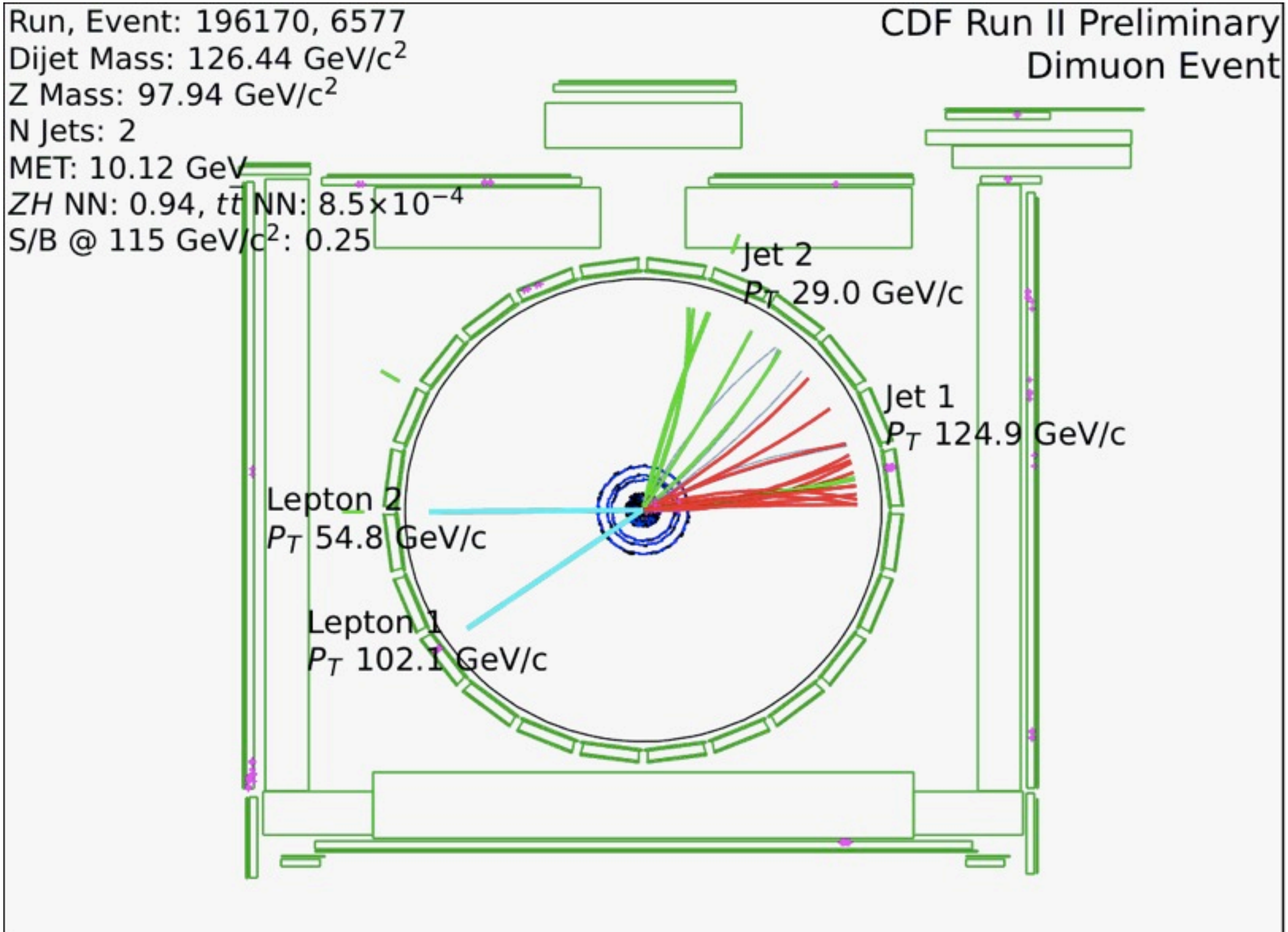
Confidence Levels



Comparison with ATLAS

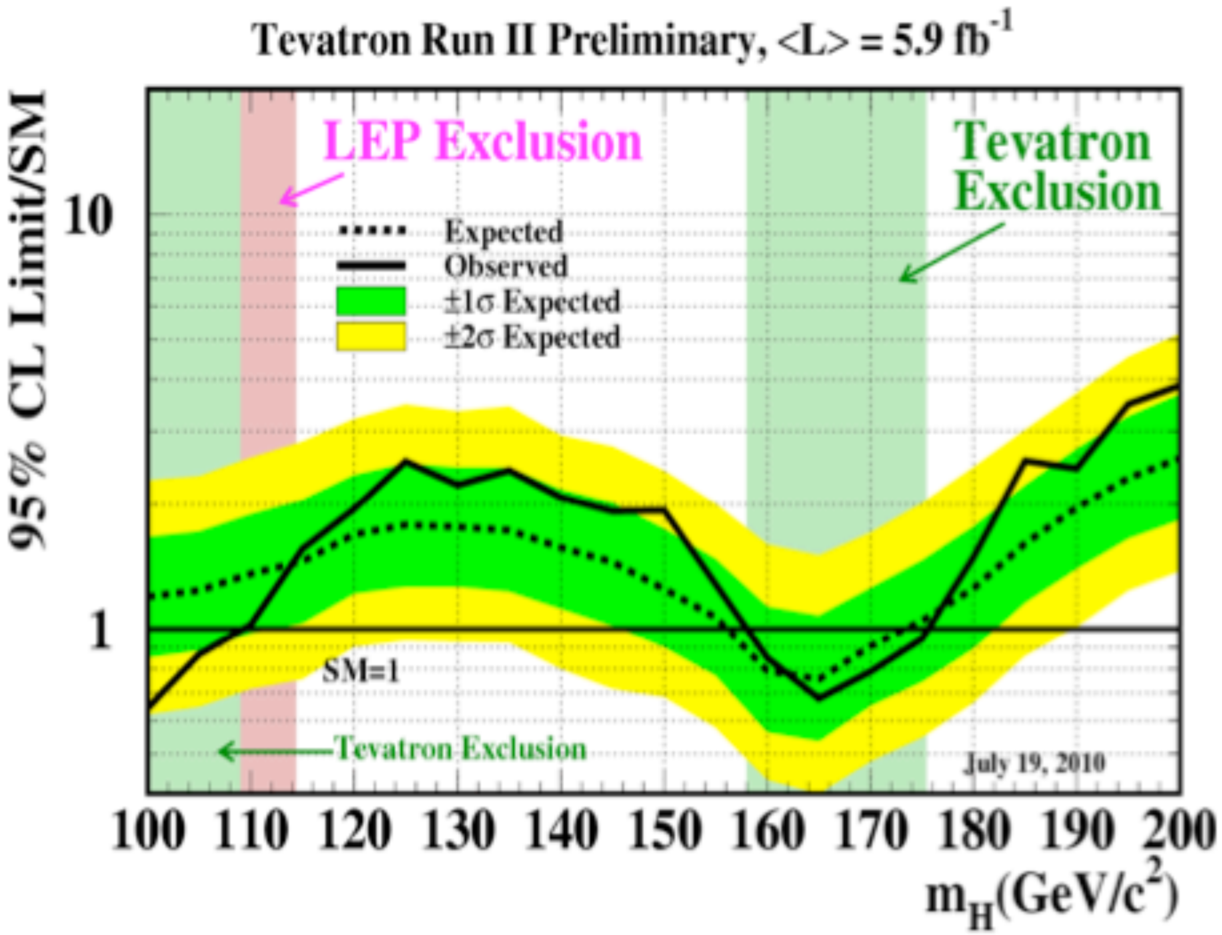


Event Display

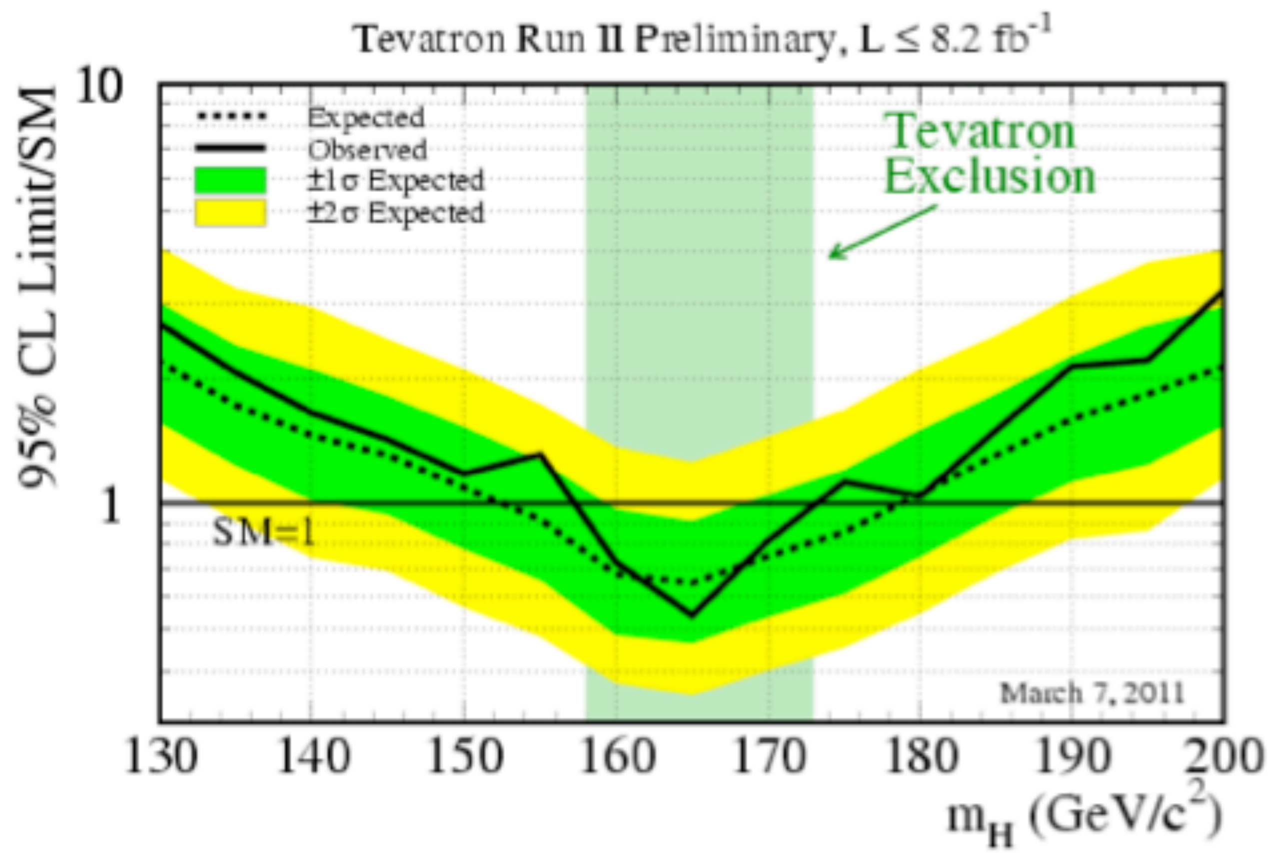


Recent History

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