Combination of Standard Model Higgs Boson Searches at the Tevatron

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Introduction

- Tevatron is closing in on SM Higgs boson
- Extract as much as possible out of dataset
  - Cover as many possible production and decay channels as possible (see P. Totaro and K. Petridis talks)
    - Use multi-variate analysis methods
  - Combine these channels
  - Double dataset by combining CDF and D0

- Combination covers m_H=100 GeV/c^2 to 200 GeV/c^2
  - "Low mass": all channels, m_H < 150 GeV/c^2
    - Last updated summer 2010
  - "High mass": primarily $H \rightarrow WW$, m_H>130 GeV/c^2
    - **New** for this conference

Channels considered: Summer 2010

CDF

56 mutually exclusive final states

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu bb$ 2-jet channels 4×(TDT,LDT,ST,LDTX)	5.7	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)	5.7	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 4×(TDT,LDT,ST)	5.7	100-150
$H \to W^+W^-$ 2×(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	5.9	110-200
$WH \to WW^+W^-$ (same-sign leptons 1+ jets)+(tri-leptons)	5.9	110-200
$ZH \to ZW^+W^-$ (tri-leptons 1 jet)+(tri-leptons 2+ jets)	5.9	110-200
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	2.3	100-150
$WH + ZH \to jjb\bar{b}$ 2×(TDT,LDT)	4.0	100-150
$H \to \gamma\gamma$	5.4	100-150

D0

73 mutually exclusive final states

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu bb$ (ST,DT,2,3 jet)	5.3	100-150
$VH \to \tau^+\tau^- b\bar{b}/q\bar{q}\tau^+\tau^-$	4.9	105-145
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2-6.4	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ (ST,DT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	4.2-6.2	100-150
$VH \to \ell^\pm\ell^\pm + X$	5.3	115-200
$H \to W^+W^- \to e^\pm\nu e^\mp\nu, \mu^\pm\nu\mu^\mp\nu$	5.4	115-200
$H \to W^+W^- \to e^\pm\nu\mu^\mp\nu$ (0,1,2+ jet)	6.7	115-200
$H \to W^+W^- \to \ell\bar{\nu}jj$	5.4	130-200
$H \to \gamma\gamma$	4.2	100-150
$t\bar{t}H \to t\bar{t}b\bar{b}$ (ST,DT,TT,4,5+ jets)	2.1	105-155

Channels considered: New (high mass)

CDF

12 mutually exclusive final states

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$H \to W^+W^-$	2×(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	7.1	110-200
$WH \to WW^+W^-$	(same-sign leptons 1+ jets)+(tri-leptons)	7.1	110-200
$ZH \to ZW^+W^-$	(tri-leptons 1 jet)+(tri-leptons 2+ jets)	7.1	110-200

D0

35 mutually exclusive final states

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$H \to W^+W^- \to l^\pm \nu l^\mp \nu$ (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	115-200
$VH \to \ell^\pm\ell^\pm + X$	5.3	115-200
$VH \to \tau^+\tau^- b\bar{b}/q\bar{q}\tau^+\tau^-$	5.3	105-200
$H \to \gamma\gamma$	8.2	100-150

Combining

- Perform combination using two techniques
  - Require agreement within 5% at each m_H and 2% on average
- Both methods
  - Use distribution of final discriminants
  - Poisson statistics in all bins
  - Systematics as nuisance parameters (133 in all!), determined from fit to data
- Method 1: Bayesian method
  - Based on credibility, using flat prior
- Method 2: Modified frequentist method
  - Uses CL_s method- compare b only and s+b hypotheses
  - Based on coverage

Systematics

- Systematics on signal and background estimates in two categories
  - Rate: affects overall normalization (*e.g.* tag uncertainty)
  - Shape: affects distribution (*e.g.* jet energy scale)
- Correlated between CDF and D0
  - Integrated luminosity (4% correlated, ~6% total)
  - Theoretical cross sections for signal and background (5-20%)
- Correlated amongst analyses of a single experiment
  - b-quark tagging efficiency uncertainty
  - Lepton selection efficiency
  - Jet energy scale
  - QCD ISR/FSR
  - Jet/missing E_T modeling
  - Background modeling

Cooperation, not competition

- Prior Run 2 CDF+D0 combinations (e.g. m_{top}) performed after analyses complete and approved separately
- Higgs combinations approved in parallel with analyses
- Inputs shared when still "confidential"!
- We hope this spirit continues in the LHC era

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Combination of Tevatron Searches for the Standard Model Higgs Boson in the W^+W^- Decay Mode

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Barria,[44,42,*] J. F. Bartlett,[89,†] P. Bartos,[65,*] U. Bassler,[21,†] D. Bauer,[74,†] G. Bauer,[108,*] S. Beale,[7,†] A. Bean,[100,†] P.-H. Beauchemin,[6,*] F. Bedeschi,[42,*] D. Beecher,[75,*] M. Begalli,[3,†] M. Begel,[124,†] S. Behari,[103,*] C. Belanger-Champagne,[69,†] L. Bellantoni,[89,†] G. Bellettini,[43,42,*] J. Bellinger,[141,*] J. A. Benitez,[113,†] D. Benjamin,[125,*] A. Beretvas,[89,*] S. B. Beri,[33,†] G. Bernardi,[20,†] R. Bernhard,[26,†] I. Bertram,[72,†] M. Besançon,[21,†] R. Beuselinck,[74,†] V. A. Bezzubov,[63,†] P. C. Bhat,[89,†] V. Bhatnagar,[33,†] A. Bhatti,[121,*] M. Binkley,[89,*,a] D. Bisello,[41,40,*] I. Bizjak,[75,*,ff] R. E. Blair,[88,*] G. Blazey,[92,†] S. Blessing,[87,†] C. Blocker,[110,*] K. Bloom,[115,†] B. Blumenfeld,[103,*] A. Bocci,[125,*] A. Bodek,[122,*] A. Boehnlein,[89,†] V. Boisvert,[122,*] D. Boline,[105,†] T. A. Bolton,[101,†] E. E. Boos,[62,†] G. Borissov,[72,†] D. Bortoletto,[98,*] T. Bose,[105,†] J. Boudreau,[132,*] A. Boveia,[84,*] A. Brandt,[134,†] B. Brau,[84,*,b] A. Bridgeman,[94,*] L. Brigliadori,[38,37,*] R. Brock,[113,†] C. Bromberg,[113,*] G. Brooijmans,[120,†] A. Bross,[89,†] D. Brown,[22,†] E. Brubaker,[90,*] X. B. Bu,[8,†] D. Buchholz,[93,†] J. Budagov,[60,*] H. S. Budd,[122,*] S. Budd,[94,*] M. Buehler,[139,†] V. Buescher,[29,†] V. Bunichev,[62,†] S. Burdin,[72,†,hh] K. Burkett,[89,*] T. H. Burnett,[140,†] G. Busetto,[41,40,*] P. Bussey,[71,*] C. P. Buszello,[74,†] A. Buzatu,[6,*] K. L. Byrum,[88,*] S. Cabrera,[125,*,aa] C. Calancha,[67,*] P. Calfayan,[30,†] B. Calpas,[18,†] S. Calvet,[19,†] E. Camacho-Pérez,[57,†] S. Camarda,[66,*] J. Cammin,[122,†] M. Campanelli,[75,*] M. Campbell,[111,*] F. Canelli,[89,90,*] A. Canepa,[130,*] B. Carls,[94,*] D. Carlsmith,[141,*] R. Carosi,[42,*] M. A. Carrasco-Lizarraga,[57,†] E. Carrera,[87,†] S. Carrillo,[86,*,o] S. Carron,[89,*] B. Casal,[68,*] M. Casarsa,[89,*] B. C. K. Casey,[89,†] H. Castilla-Valdez,[57,†] A. Castro,[38,37,*] P. Catastini,[44,42,*] D. Cauz,[48,*] V. Cavaliere,[44,42,*] M. Cavalli-Sforza,[66,*] A. Cerri,[79,*] L. Cerrito,[75,*,s] S. Chakrabarti,[123,†] D. Chakraborty,[92,†] K. M. Chan,[97,†] A. Chandra,[95,†] S. H. Chang,[54,*] Y. C. Chen,[9,*] M. Chertok,[80,*] E. Cheu,[78,†] S. Chevalier-Théry,[21,†] G. Chiarelli,[42,*] G. Chlachidze,[89,*] F. Chlebana,[89,*] K. Cho,[54,*] D. K. Cho,[105,†] S. W. Cho,[55,†] S. Choi,[56,†] D. Chokheli,[60,*] J. P. Chou,[107,*] B. Choudhary,[34,†] T. Christoudias,[74,†] K. Chung,[89,*,p] W. H. Chung,[141,*] Y. S. Chung,[122,*] T. Chwalek,[28,*] S. Cihangir,[89,†] C. I. Ciobanu,[20,*] M. A. Ciocci,[44,42,*] D. Claes,[115,†] A. Clark,[70,*] D. Clark,[110,*] J. Clutter,[100,†] G. Compostella,[40,*] M. E. Convery,[89,*] J. Conway,[80,*] M. Cooke,[89,†] W. E. Cooper,[89,†] M. Corbo,[20,*] M. Corcoran,[137,†] M. Cordelli,[39,*] F. Couderc,[21,†] M.-C. Cousinou,[18,†] C. A. Cox,[80,*] D. J. Cox,[80,*] F. Crescioli,[43,42,*] C. Cuenca Almenar,[85,*] J. Cuevas,[68,*,y] R. Culbertson,[89,*] J. C. Cully,[111,*] D. Cutts,[133,†] M. Ćwiok,[36,†] D. Dagenhart,[89,*] N. d'Ascenzo,[20,*,x] A. Das,[78,†] M. Datta,[89,*] G. Davies,[74,†] T. Davies,[71,*] K. De,[134,†] P. de Barbaro,[122,*] S. De Cecco,[46,*] A. Deisher,[79,*] S. J. de Jong,[59,†] E. De La Cruz-Burelo,[57,†] F. Déliot,[21,†] M. Dell'Orso,[43,42,*] G. De Lorenzo,[66,*] C. Deluca,[66,*] M. Demarteau,[89,†] R. Demina,[122,†] L. Demortier,[121,*] J. Deng,[125,*,g] M. Deninno,[37,*] D. Denisov,[89,†] S. P. Denisov,[63,†] M. d'Errico,[41,40,*] S. Desai,[89,†] K. DeVaughan,[115,†] A. Di Canto,[43,42,*] H. T. Diehl,[89,†] M. Diesburg,[89,†] B. Di Ruzza,[42,*] J. R. Dittmann,[138,*] A. Dominguez,[115,†] S. Donati,[43,42,*] P. Dong,[89,*] M. D'Onofrio,[66,*] T. Dorigo,[40,*] T. Dorland,[140,†] S. Dube,[116,*] A. Dubey,[34,†] L. V. Dudko,[62,†] L. Duflot,[19,†] D. Duggan,[116,†] A. Duperrin,[18,†] S. Dutt,[33,†] A. Dyshkant,[92,†] M. Eads,[115,†] K. Ebina,[53,*] D. Edmunds,[113,†] A. Elagin,[135,*] J. Ellison,[83,†] V. D. Elvira,[89,†] Y. Enari,[20,†] S. Eno,[104,†] R. … N. Ershaidat,[20,*,ee] R. Eusebi,[135,*] H. Evans,[95,†] A. Evdokimov,[124,†] V. N. E… S. Farrington,[77,*] W. T. Fedorko,[90,*] R. G. Feild,[85,*] M. Feindt,[28,*] A… J. P. Fernandez,[67,*] C. Ferrazza,[45,42,*] F. Fiedler,[29,†] R. Field,[86,*] F. Fil… G. Flanagan,[98,*,u] R. Forrest,[80,*] M. Fortner,[92,†] H. Fox,[72,†] M. J. Frank,… S. Fuess,[89,†] I. Furic,[86,*] T. Gadfort,[124,†] C. F. Galea,[59,†] M. Gallinaro,… J. E. Garcia,[70,*] A. Garcia-Bellido,[122,†] A. F. Garfinkel,[98,*] P. Garosi,[44,42,… W. Geng,[18,113,†] D. Gerbaudo,[117,†] C. E. Gerber,[91,†] H. Gerberich,[94,*] D. G… S. Giagu,[47,46,*] V. Giakoumopoulou,[32,*] P. Giannetti,[42,*] K. Gibson,… C. M. Ginsburg,[89,*] G. Ginther,[89,122,†] N. Giokaris,[32,*] M. Giordani,[49,48,*] P. …

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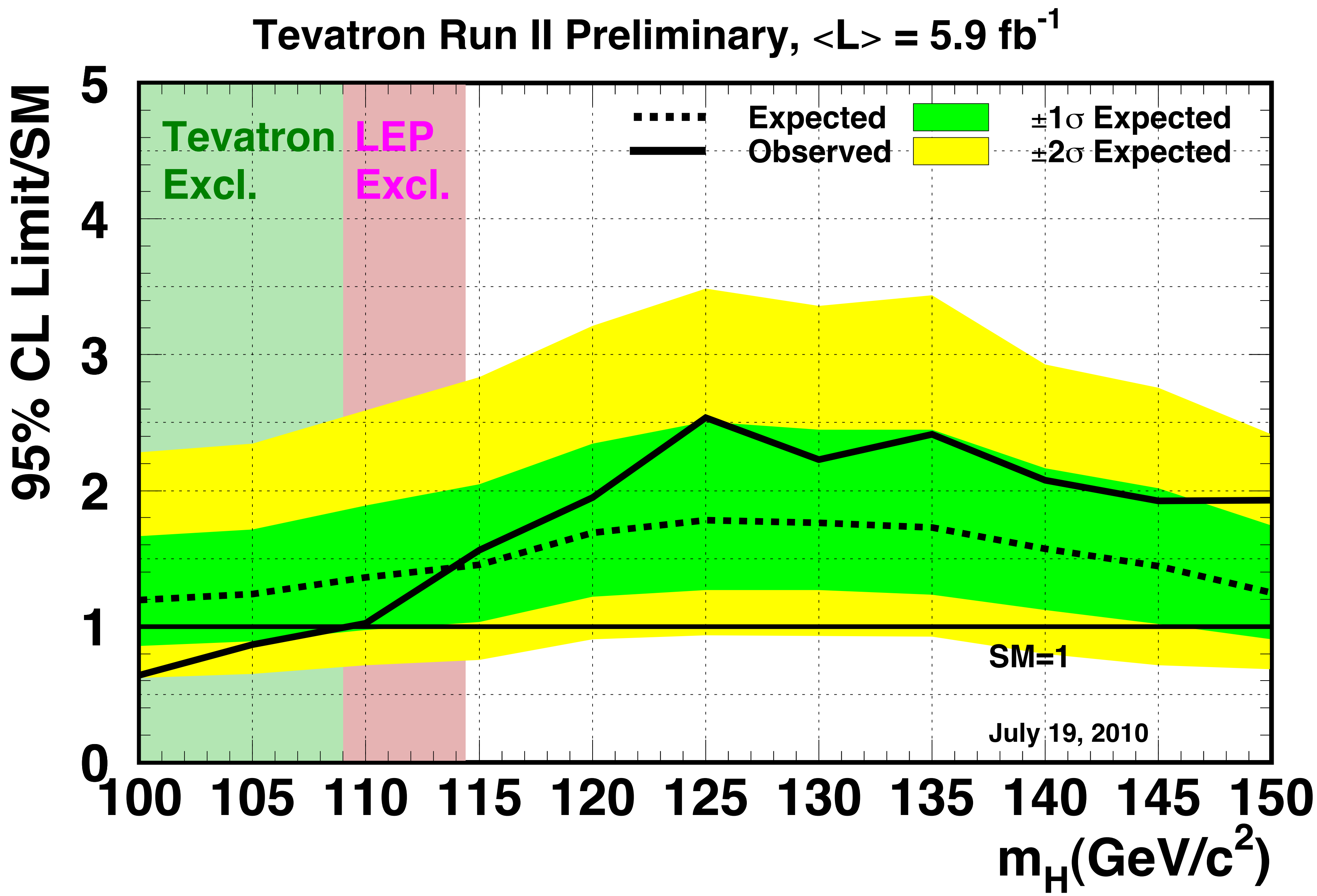
First CDF+DØ publication in Run II

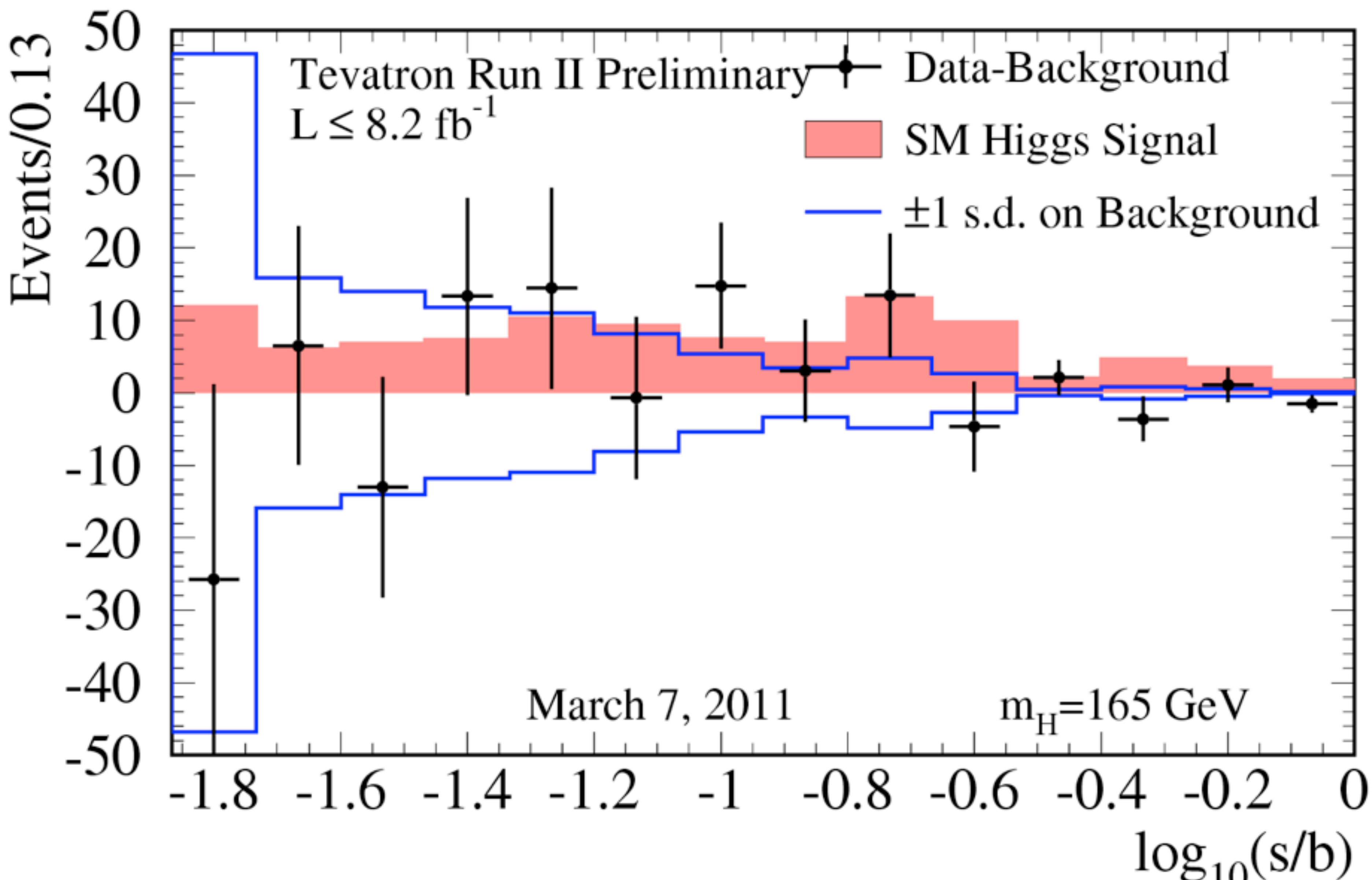
Low mass result



- Upper limit for m_H=115 GeV/c^2 of 1.56×σ_{SM} @95% CL
- Tevatron-only exclusion at 95% CL of 100 < m_H < 109 GeV/c^2

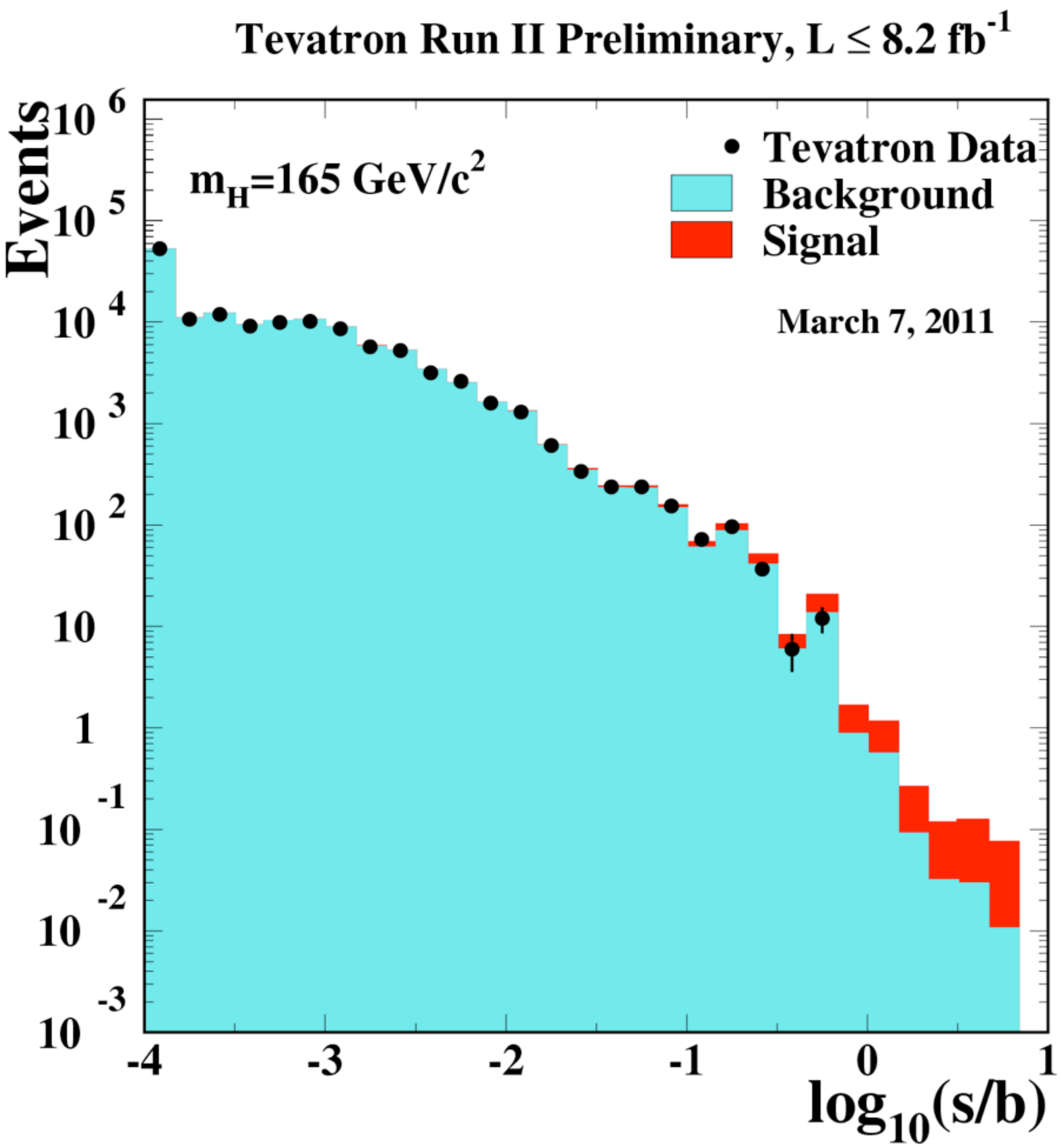
Background subtracted data

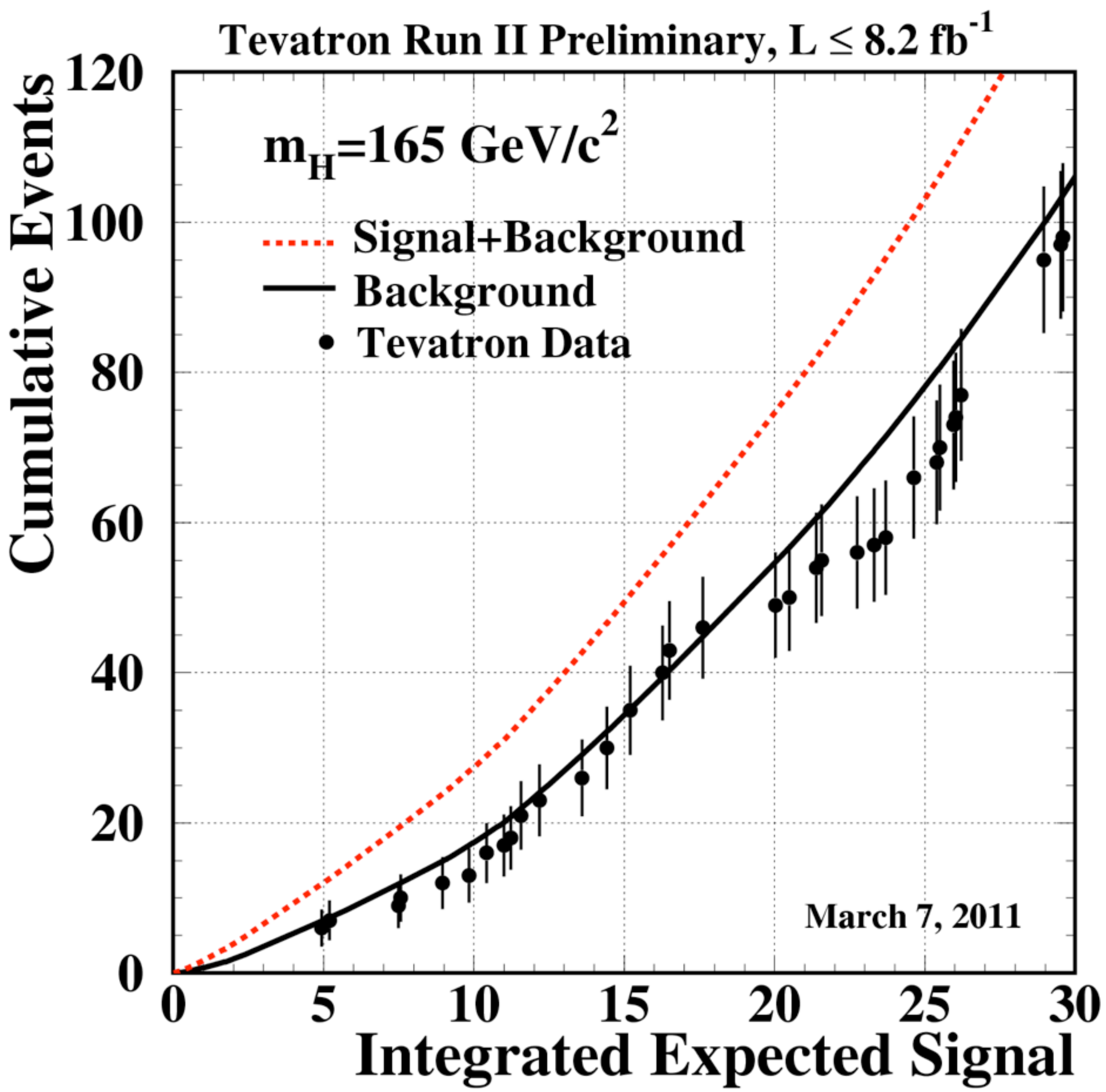
- Subtract background model that has been fit to data
  - Independent of any assumed Higgs cross section
- **No excess** above background observed
  - Proceed to set a limit



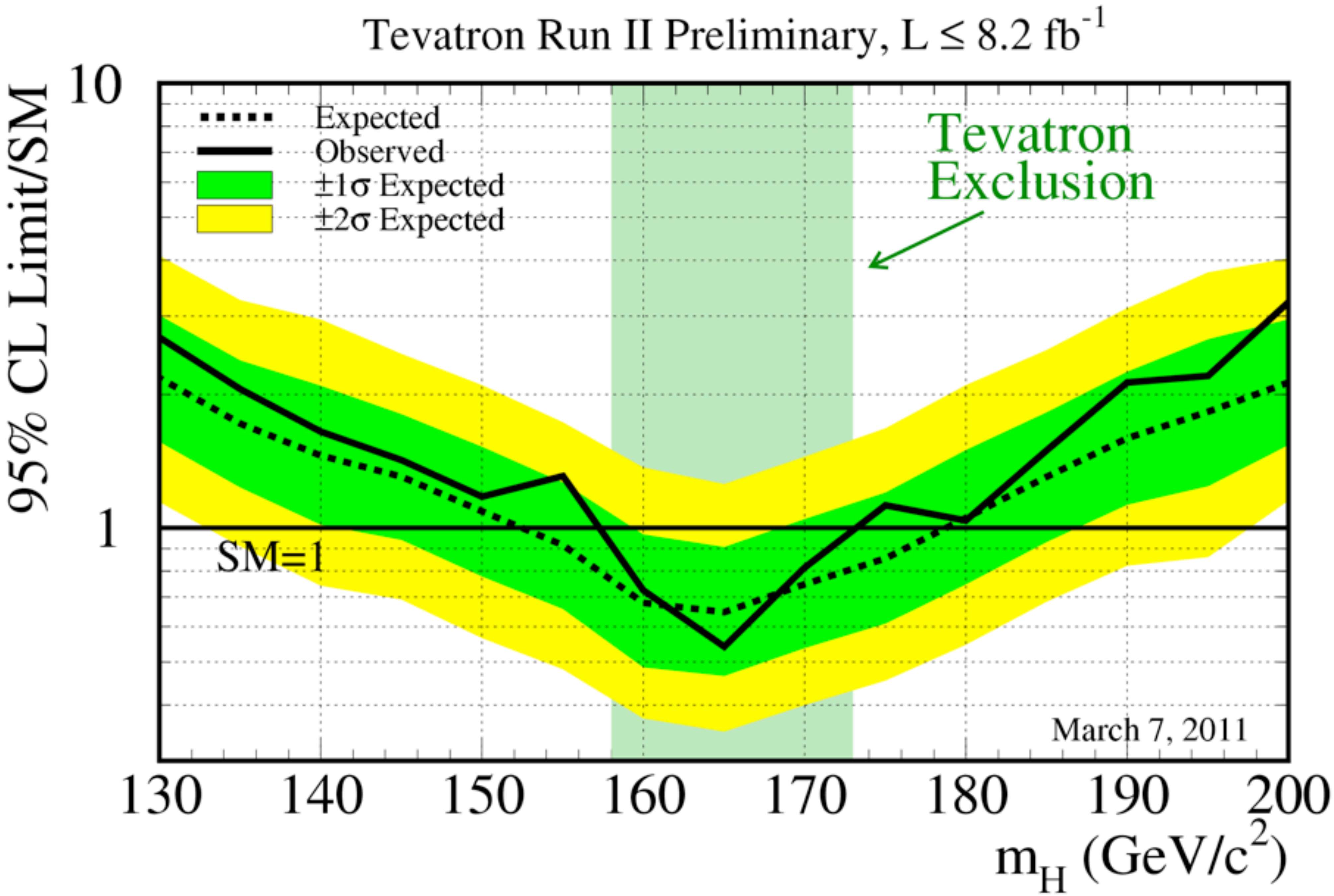
Data distributions

- Rebin histograms of final discriminants for all channels in log(S/B)



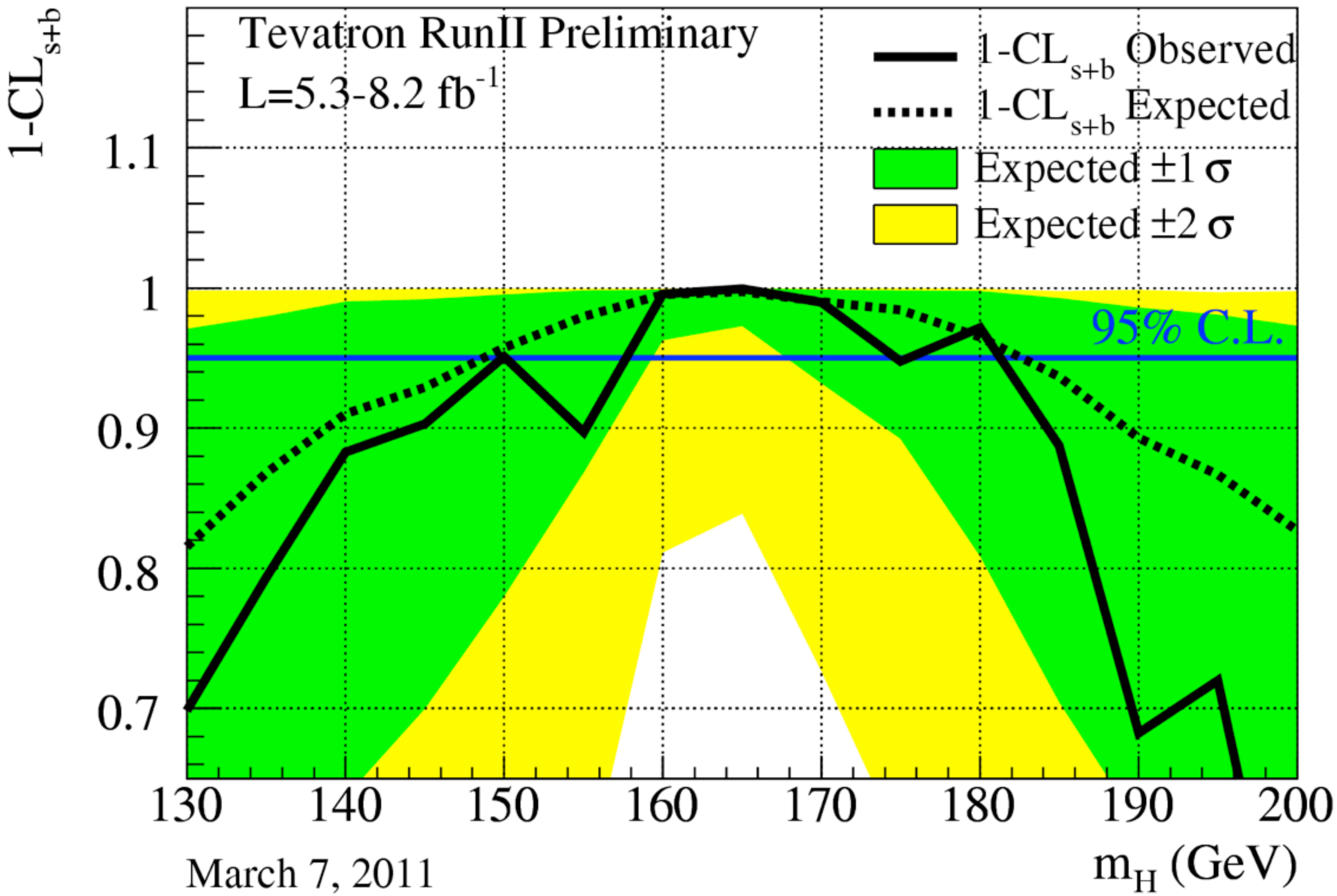


New Tevatron Higgs Limits



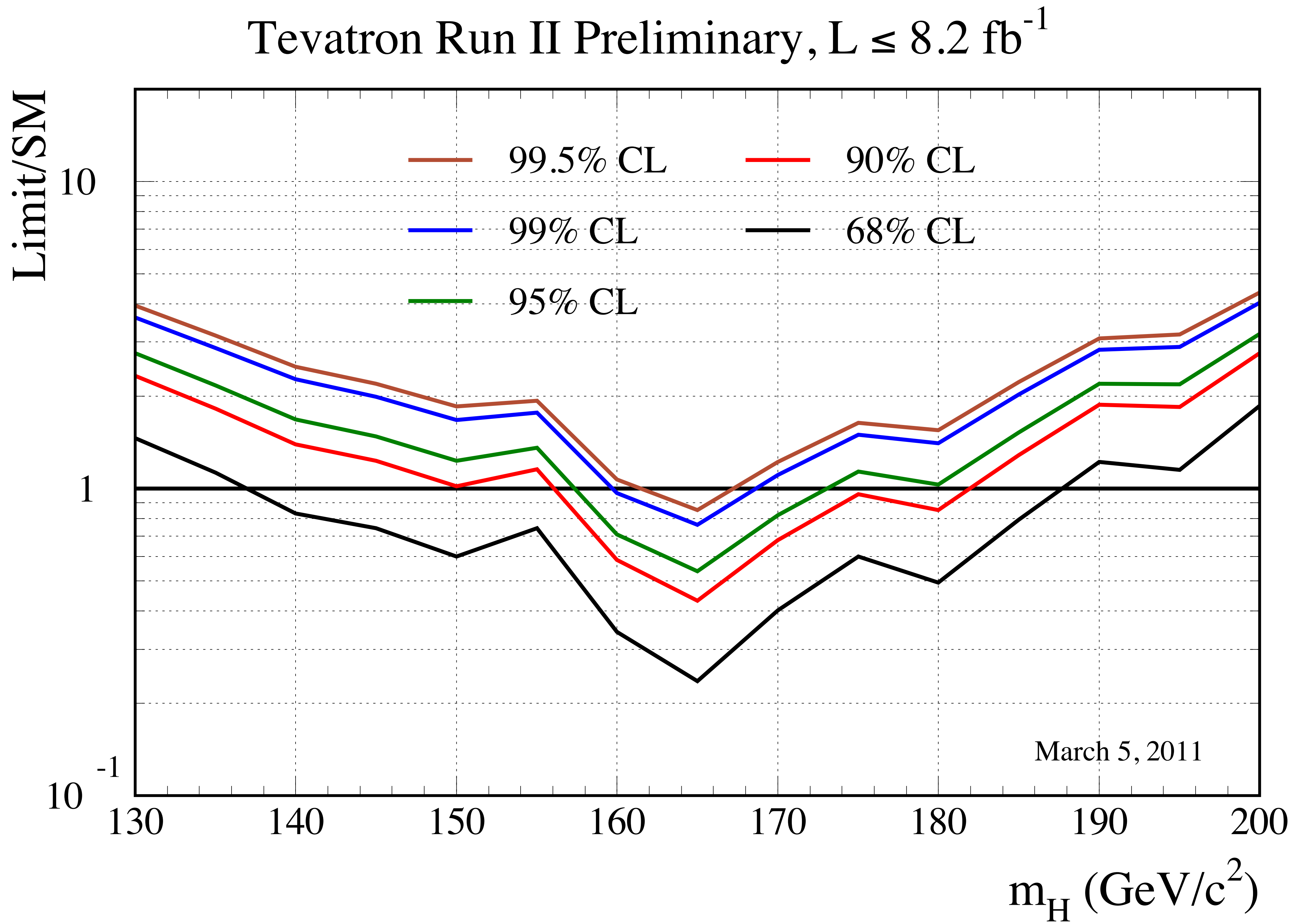
- SM Higgs boson **excluded** at 95% CL for **158 < m_H < 173 GeV**
- Expected exclusion at 95% CL for **153 < m_H < 179 GeV**
  - Compare to summer 2010 expected exclusion of 156 < m_H < 173 GeV

Another approach: CL_{s+b}



- Roughly comparable to Power constrained CL_{s+b} approach used by ATLAS

Just how excluded is it?



- SM Higgs of $162 < m_H < 166$ GeV excluded **@99.5% CL**

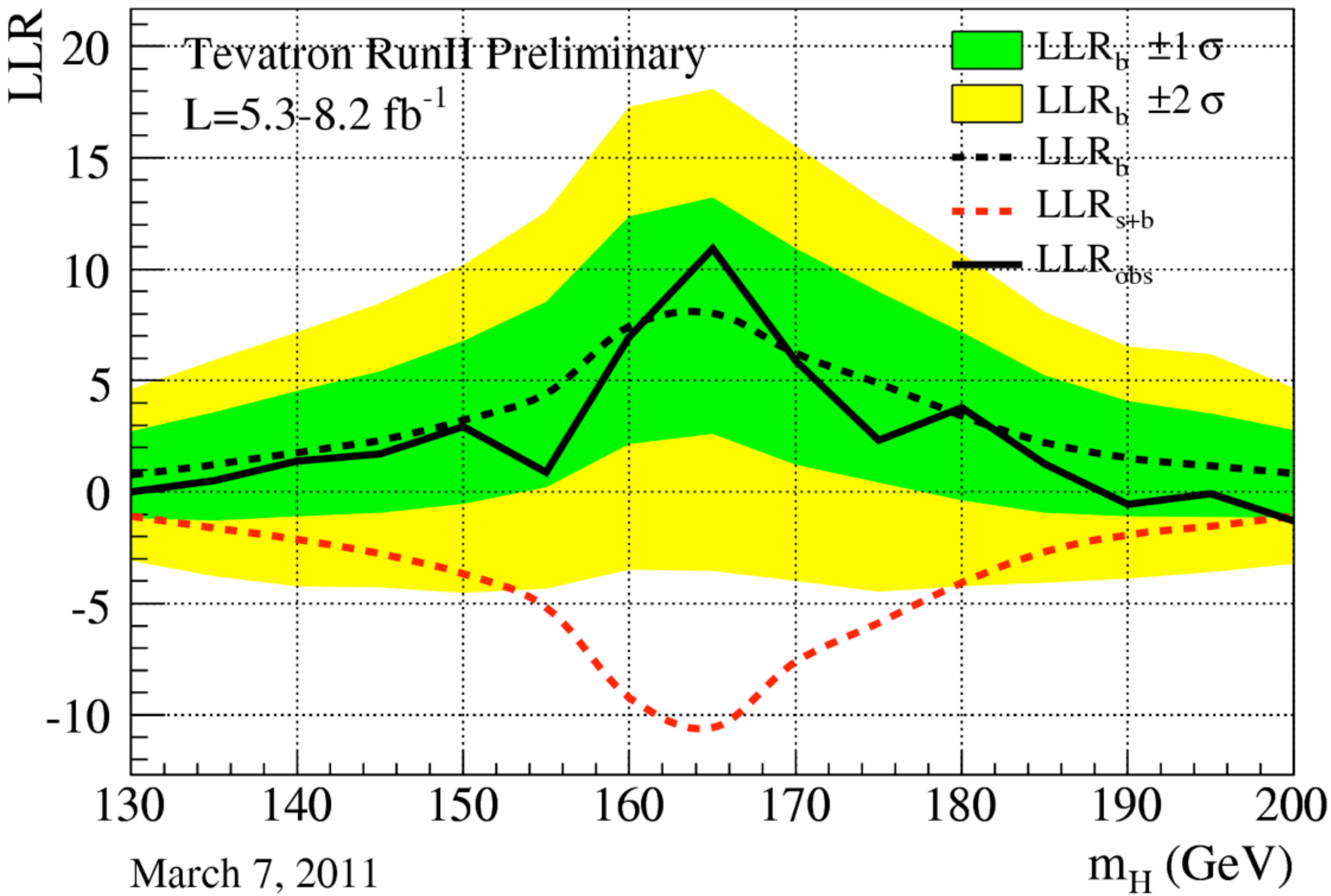
Conclusion

- Combination of all Tevatron searches has been performed
  - Up to 5.9 fb^{-1} of data for $100 < m_H < 130$ GeV
  - Up to 8.2 fb^{-1} of data for $130 < m_H < 200$ GeV
- Tevatron results **exclude** at **95% CL**
  - $100 < m_H < 109$ GeV
  - $158 < m_H < 173$ GeV
- Expected exclusion of $153 < m_H < 179$ GeV
  - Up from $156 < m_H < 173$ GeV
- Individual experiment exclusions now from both CDF and D0
- Tevatron exclusion now at **99.5% CL** for some masses

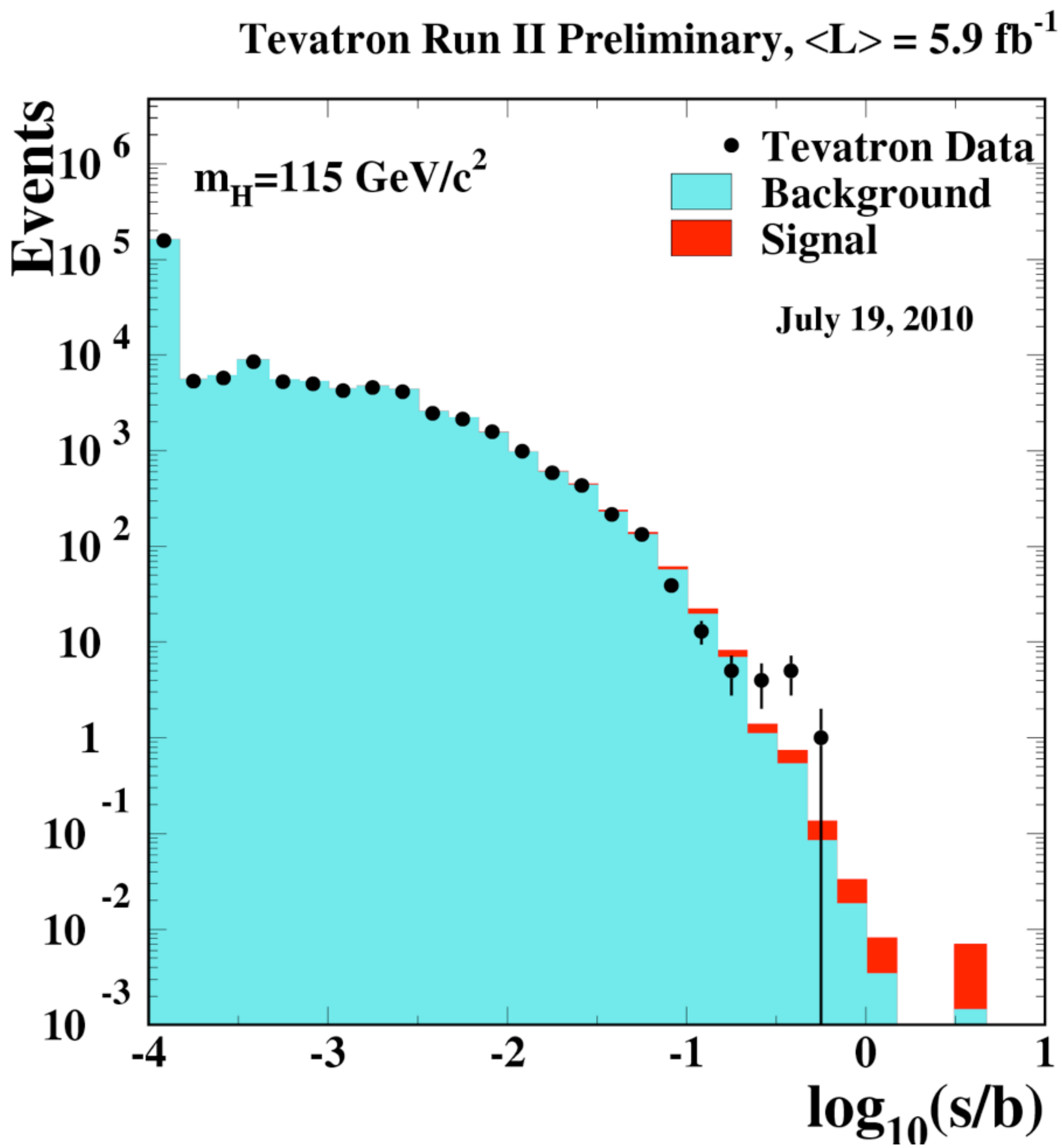
- CDF and D0 strategies continue to be to leave the Higgs nowhere to hide
- End of Run 2 (this year) will leave ~10 fb^{-1} of data for each experiment
  - As always, more analysis improvements are underway
  - Plenty left to do- expect new results soon!

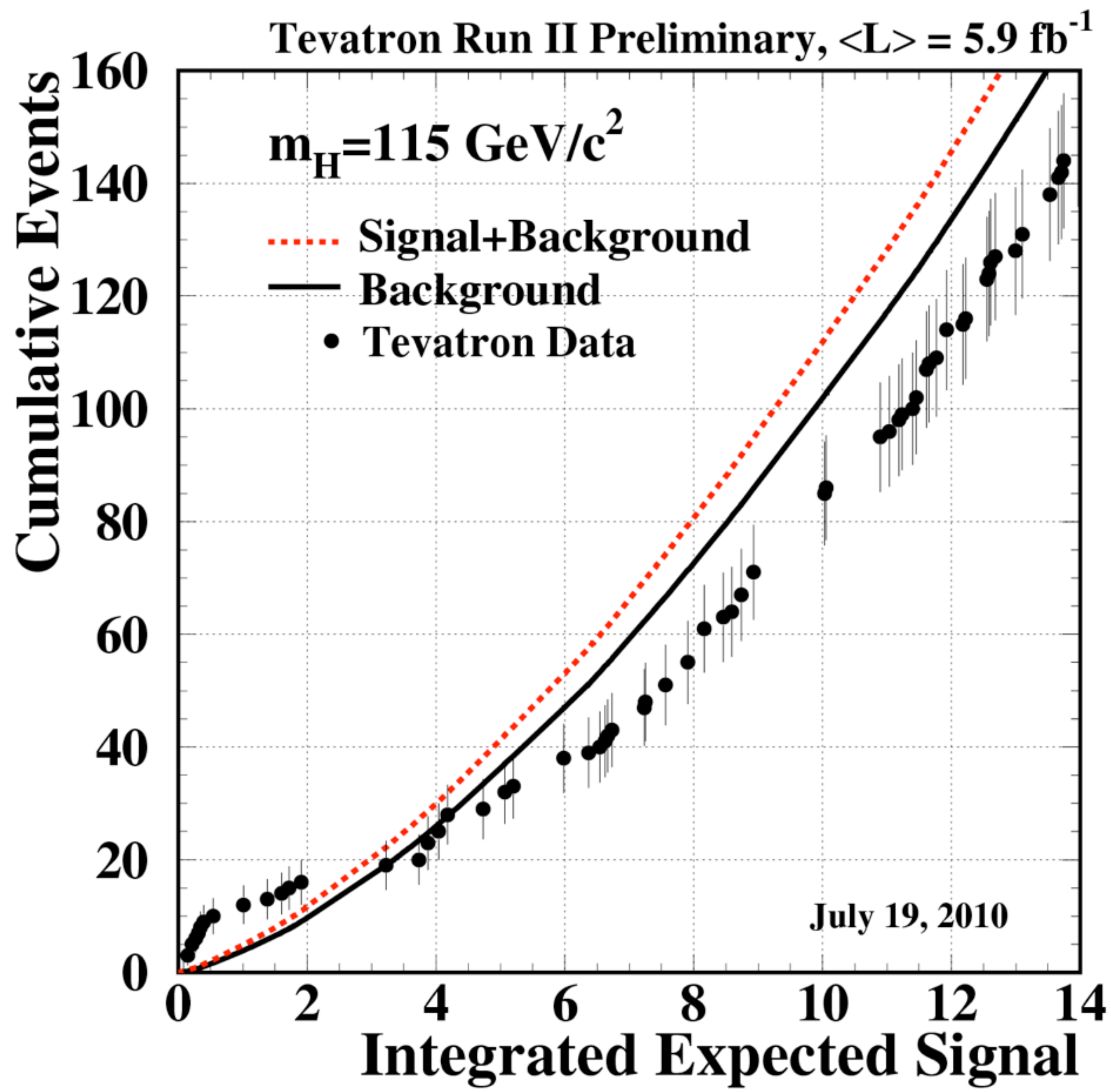
Backup

LLR from CLs method



Data distributions: low mass





Theoretical Issues

- Are we treating cross-section uncertainty due to scale variations (μ_R & μ_F) correctly?
  - We obtain gluon fusion cross sections from:

D. de Florian, M. Grazzini, Phys. Lett. **B674**, 291-294 (2009). [arXiv:0901.2427 [hep-ph]].

C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- Use a scale variation factor of 2 from the central value to estimate impact of potential high-order contributions
- Authors confirm high-order effects are small
- Another recent publication argues for even smaller scale uncertainties

V. Ahrens, T. Becher, M. Neubert *et al.*, Eur. Phys. J. **C62**, 333-353 (2009). [arXiv:0809.4283 [hep-ph]];

V. Ahrens, T. Becher, M. Neubert *et al.*, [arXiv:1008.3162 [hep-ph]].

- We feel our treatment is adequate, if not conservative, and generally supported by the theoretical community

Theoretical issues (II)

- Do we need additional uncertainties assigned to our gluon fusion cross section resulting from EFT approach used to integrate loop contributions?
- Such an uncertainty is already included:

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- Uncertainties on gluon fusion cross sections used in our searches include ~2% to account for this
- Authors find entirely removing corrections from light quark diagrams changes the total cross section by less than 4%
- We feel our treatment of EFT effects is sound