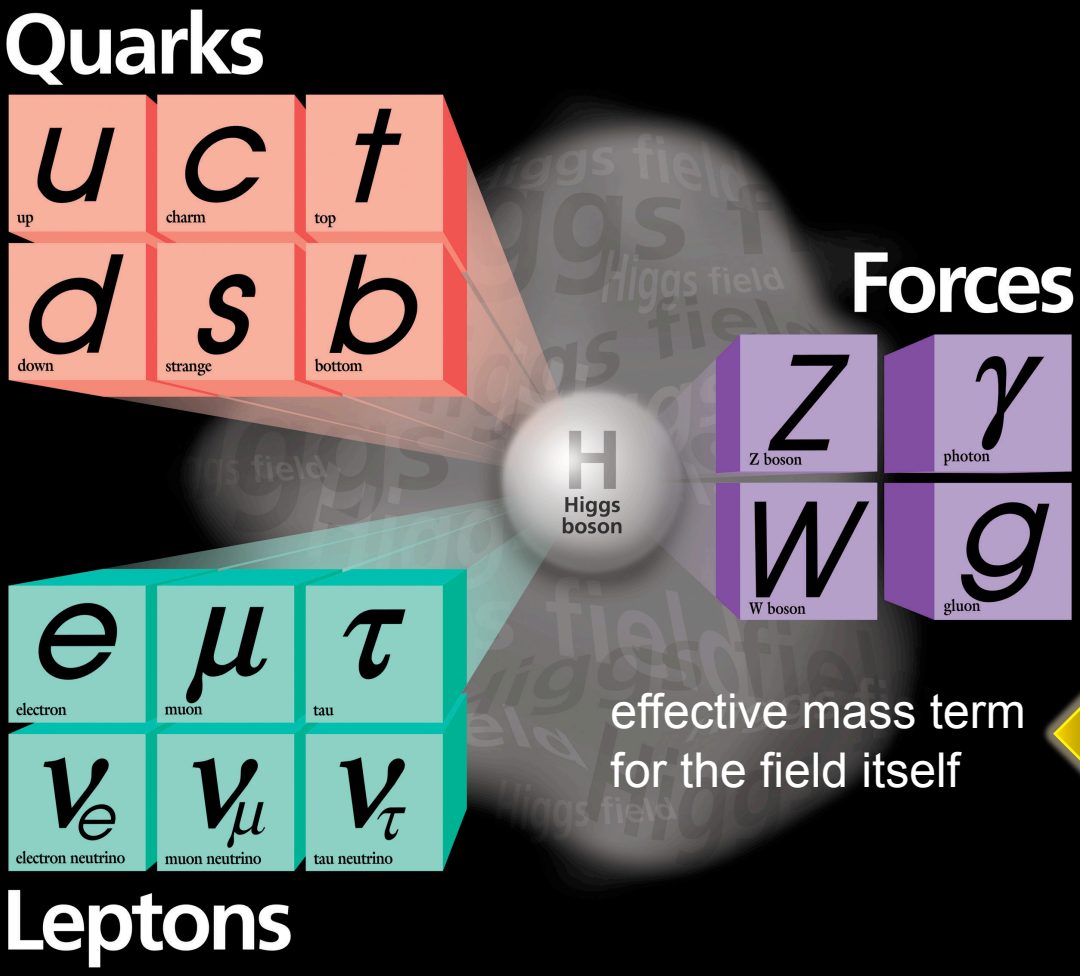
Search for the Higgs boson

The quest began: over 20 years ago
Ends: ????

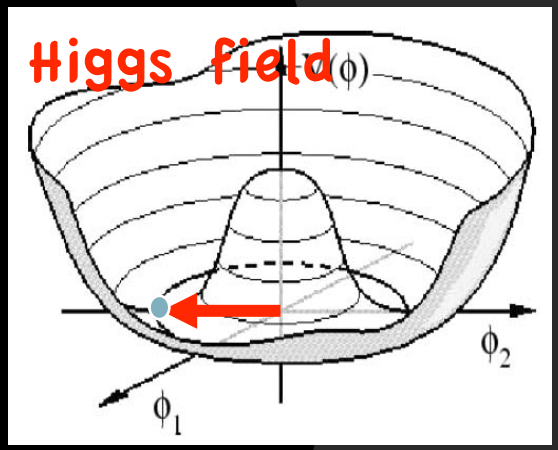
Sergo Jindariani (FNAL)

Tevatron 25th Anniversary Symposium

Missing piece in the SM:



effective mass terms for gauge bosons

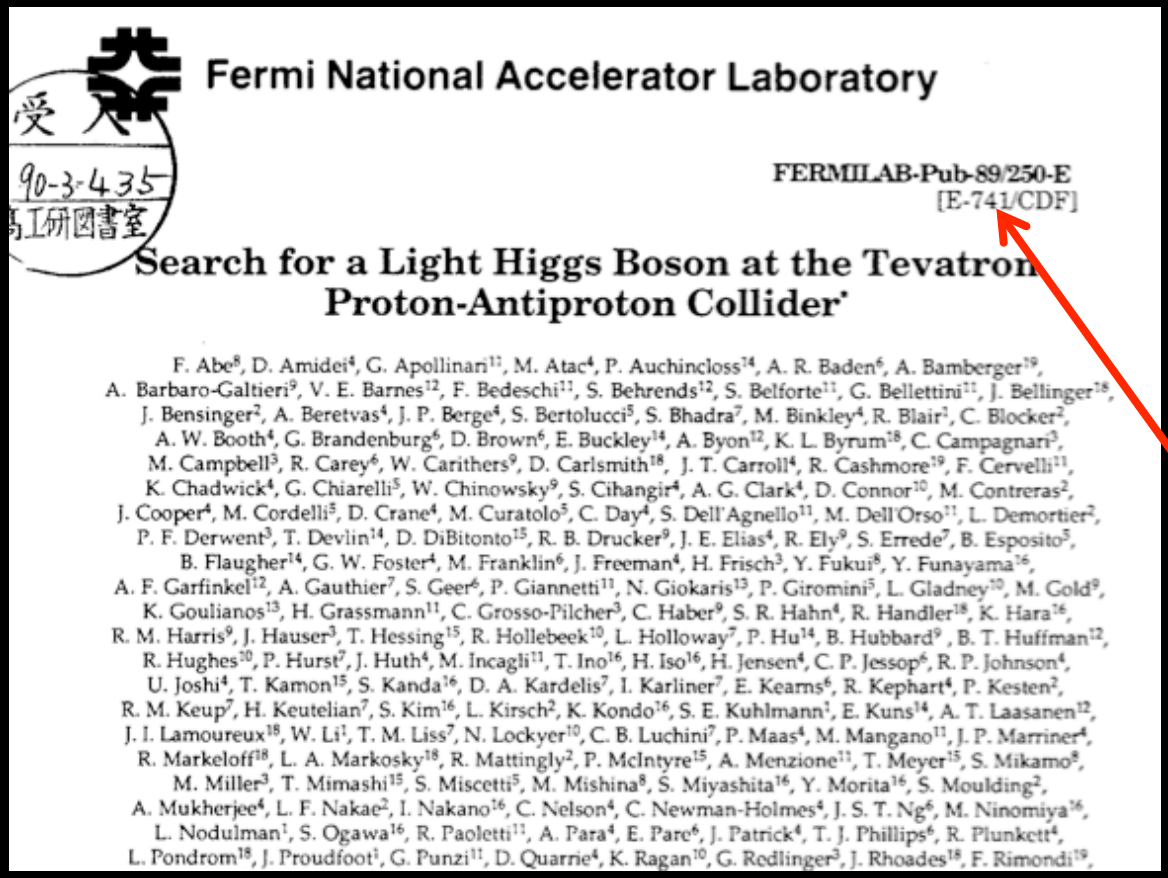


effective mass term for the field itself

effective fermion masses

When was the first Higgs exclusion from the Tevatron published?

First Higgs exclusion from the Tevatron:



Fermi National Accelerator Laboratory

FERMILAB-Pub-89/250-E
[E-741/CDF]

Search for a Light Higgs Boson at the Tevatron Proton-Antiproton Collider*

F. Abe[8], D. Amidei[4], G. Apollinari[11], M. Atac[4], P. Auchincloss[14], A. R. Baden[6], A. Bamberger[19], A. Barbaro-Galtieri[9], V. E. Barnes[12], F. Bedeschi[11], S. Behrends[12], S. Belforte[11], G. Bellettini[11], J. Bellinger[18], J. Bensinger[2], A. Beretvas[4], J. P. Berge[4], S. Bertolucci[5], S. Bhadra[7], M. Binkley[4], R. Blair[1], C. Blocker[2], A. W. Booth[4], G. Brandenburg[6], D. Brown[6], E. Buckley[14], A. Byon[12], K. L. Byrum[18], C. Campagnari[3], M. Campbell[3], R. Carey[6], W. Carithers[9], D. Carlsmith[18], J. T. Carroll[4], R. Cashmore[19], F. Cervelli[11], K. Chadwick[4], G. Chiarelli[5], W. Chinowsky[9], S. Cihangir[4], A. G. Clark[4], D. Connor[10], M. Contreras[2], J. Cooper[4], M. Cordelli[5], D. Crane[4], M. Curatolo[5], C. Day[4], S. Dell'Agnello[11], M. Dell'Orso[11], L. Demortier[2], P. F. Derwent[3], T. Devlin[14], D. DiBitonto[15], R. B. Drucker[9], J. E. Elias[4], R. Ely[9], S. Errede[7], B. Esposito[5], B. Flaugher[14], G. W. Foster[4], M. Franklin[6], J. Freeman[4], H. Frisch[3], Y. Fukui[8], Y. Funayama[16], A. F. Garfinkel[12], A. Gauthier[7], S. Geer[6], P. Giannetti[11], N. Giokaris[13], P. Giromini[5], L. Gladney[10], M. Gold[9], K. Goulianos[13], H. Grassmann[11], C. Grosso-Pilcher[3], C. Haber[9], S. R. Hahn[4], R. Handler[18], K. Hara[16], R. M. Harris[9], J. Hauser[3], T. Hessing[15], R. Hollebeek[10], L. Holloway[7], P. Hu[14], B. Hubbard[9], B. T. Huffman[12], R. Hughes[10], P. Hurst[7], J. Huth[4], M. Incagli[11], T. Ino[16], H. Iso[16], H. Jensen[4], C. P. Jessop[6], R. P. Johnson[4], U. Joshi[4], T. Kamon[15], S. Kanda[16], D. A. Kardelis[7], I. Karliner[7], E. Kearns[6], R. Kephart[4], P. Kesten[2], R. M. Keup[7], H. Keutelian[7], S. Kim[16], L. Kirsch[2], K. Kondo[16], S. E. Kuhlmann[1], E. Kuns[14], A. T. Laasanen[12], J. I. Lamoureux[18], W. Li[1], T. M. Liss[7], N. Lockyer[10], C. B. Luchini[7], P. Maas[4], M. Mangano[11], J. P. Marriner[4], R. Markeloff[18], L. A. Markosky[18], R. Mattingly[2], P. McIntyre[15], A. Menzione[11], T. Meyer[15], S. Mikamo[8], M. Miller[3], T. Mimashi[15], S. Miscetti[5], M. Mishina[8], S. Miyashita[16], Y. Morita[16], S. Moulding[2], A. Mukherjee[4], L. F. Nakae[2], I. Nakano[16], C. Nelson[4], C. Newman-Holmes[4], J. S. T. Ng[6], M. Ninomiya[16], L. Nodulman[1], S. Ogawa[16], R. Paoletti[11], A. Para[4], E. Pare[6], J. Patrick[4], T. J. Phillips[6], R. Plunkett[4], L. Pondrom[18], J. Proudfoot[1], G. Punzi[11], D. Quarrie[4], K. Ragan[10], G. Redlinger[3], J. Rhoades[18], F. Rimondi[19],

Dated 1989, accepted to PRD. Published in 1990

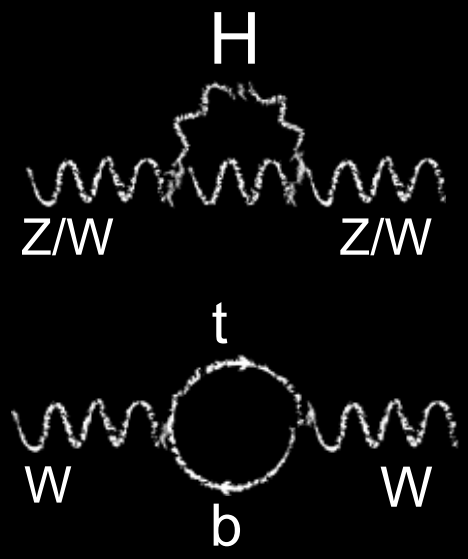
Excluded $200 < M_H < 1100$ MeV with 90% certainty

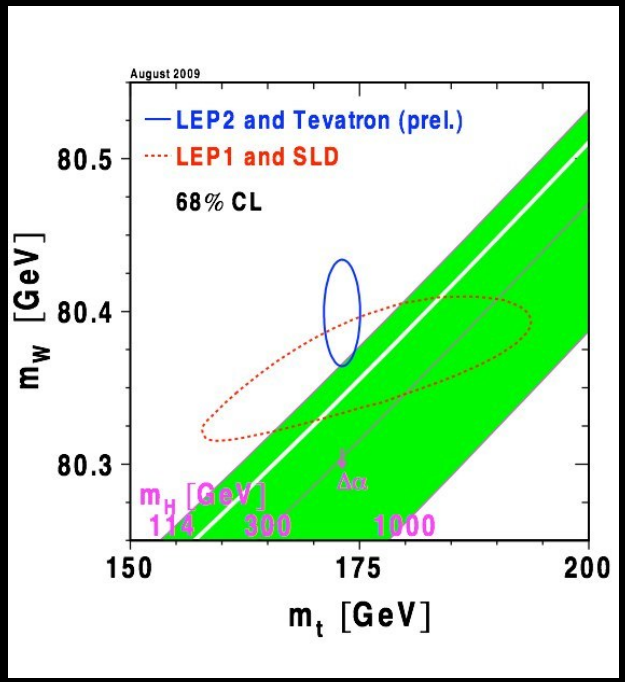
8 authors are doing Tevatron Higgs analysis 20 years later

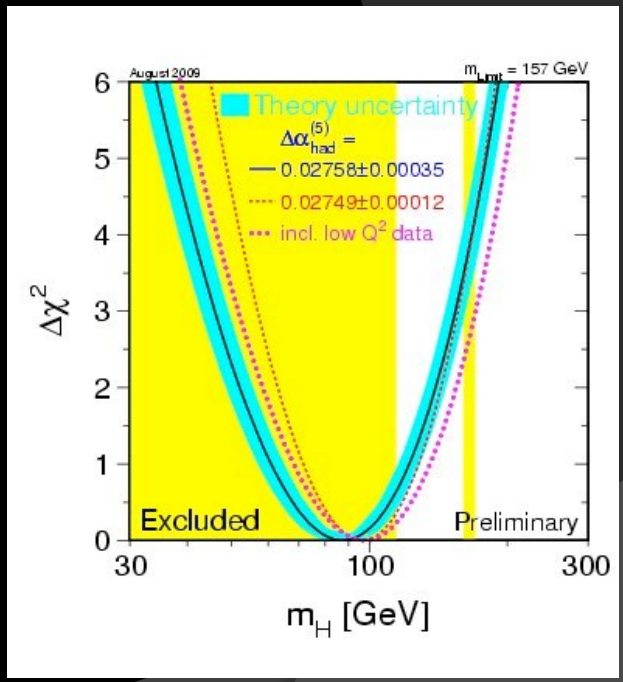
Constraints:

- **Direct search at LEP:** $M_H > 114.4$ GeV
- Electroweak and top measurements provide constraints on Higgs mass
- A fit of precision EWK data yields: $M_H < 186$ GeV at 95% CL

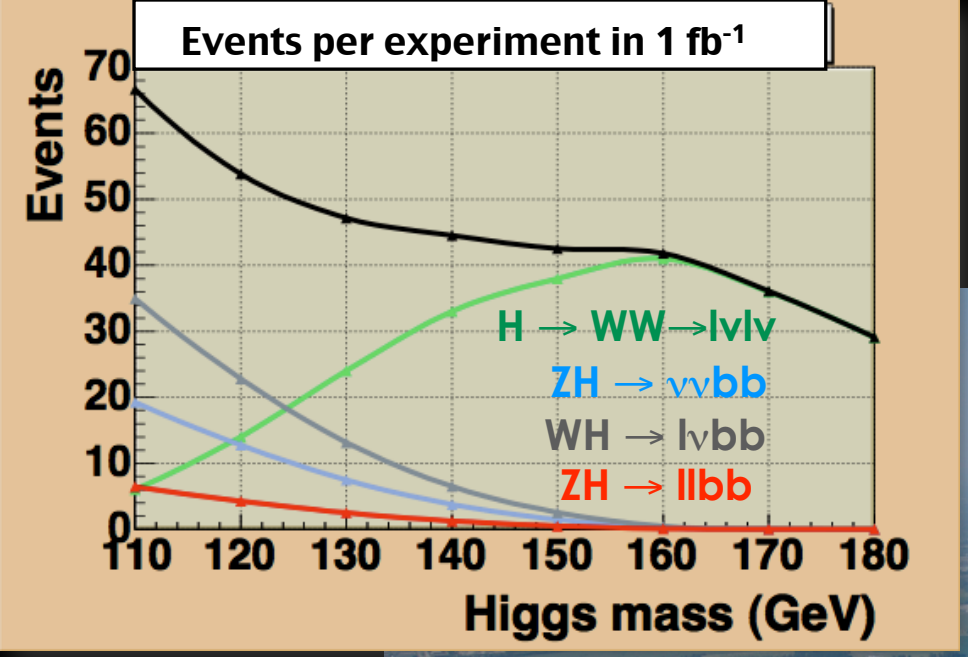
New M_{top}
CDF+D0 :
173.3 ± 1.1 GeV

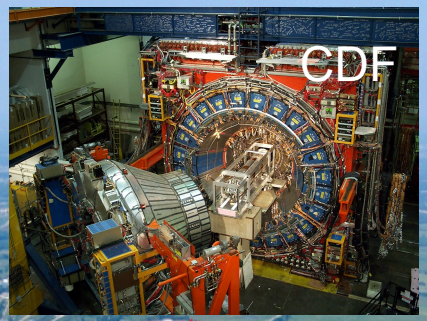






Probing mass range 100-200 GeV is crucial

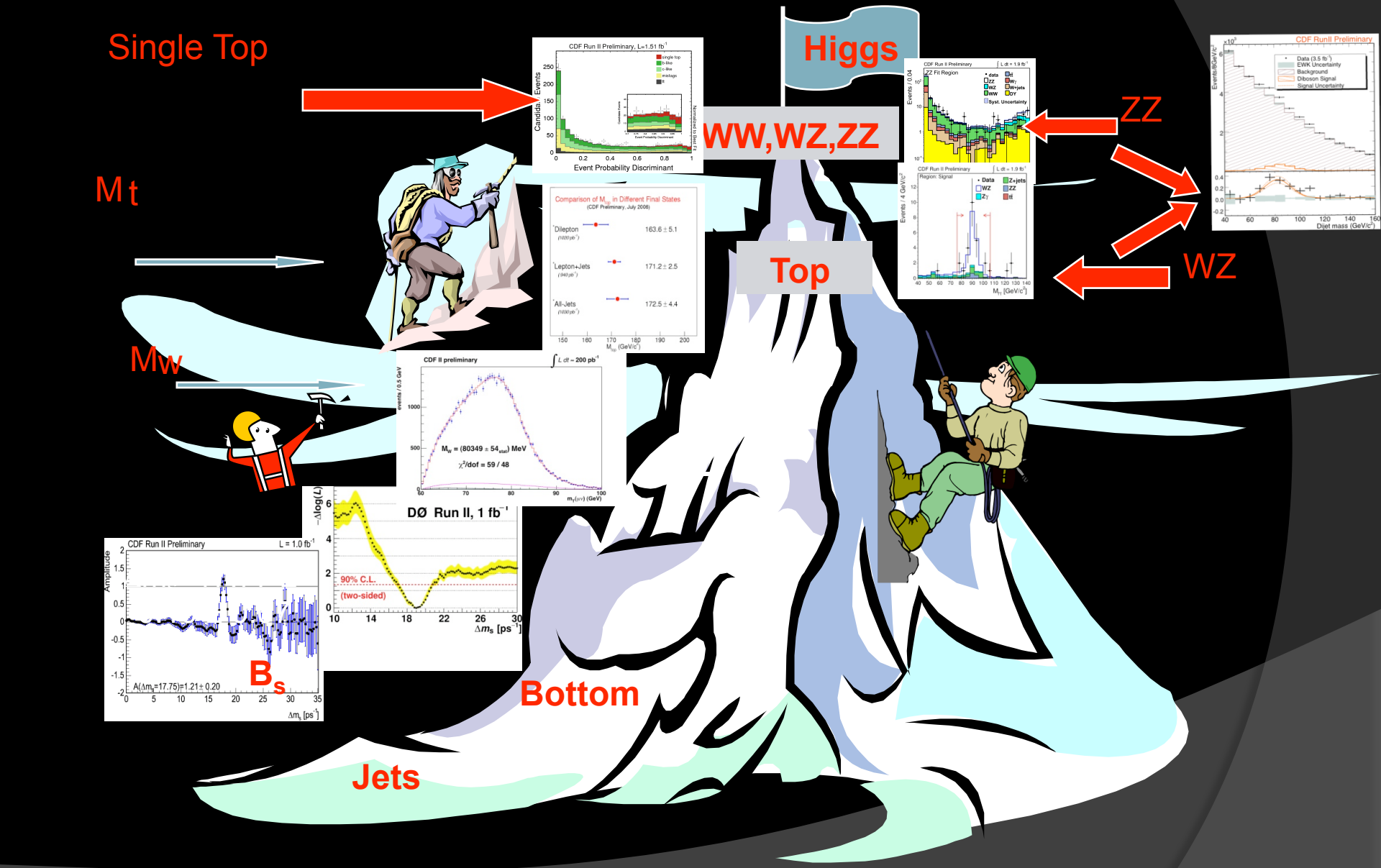




Support from other divisions is crucial for the success of the Higgs program

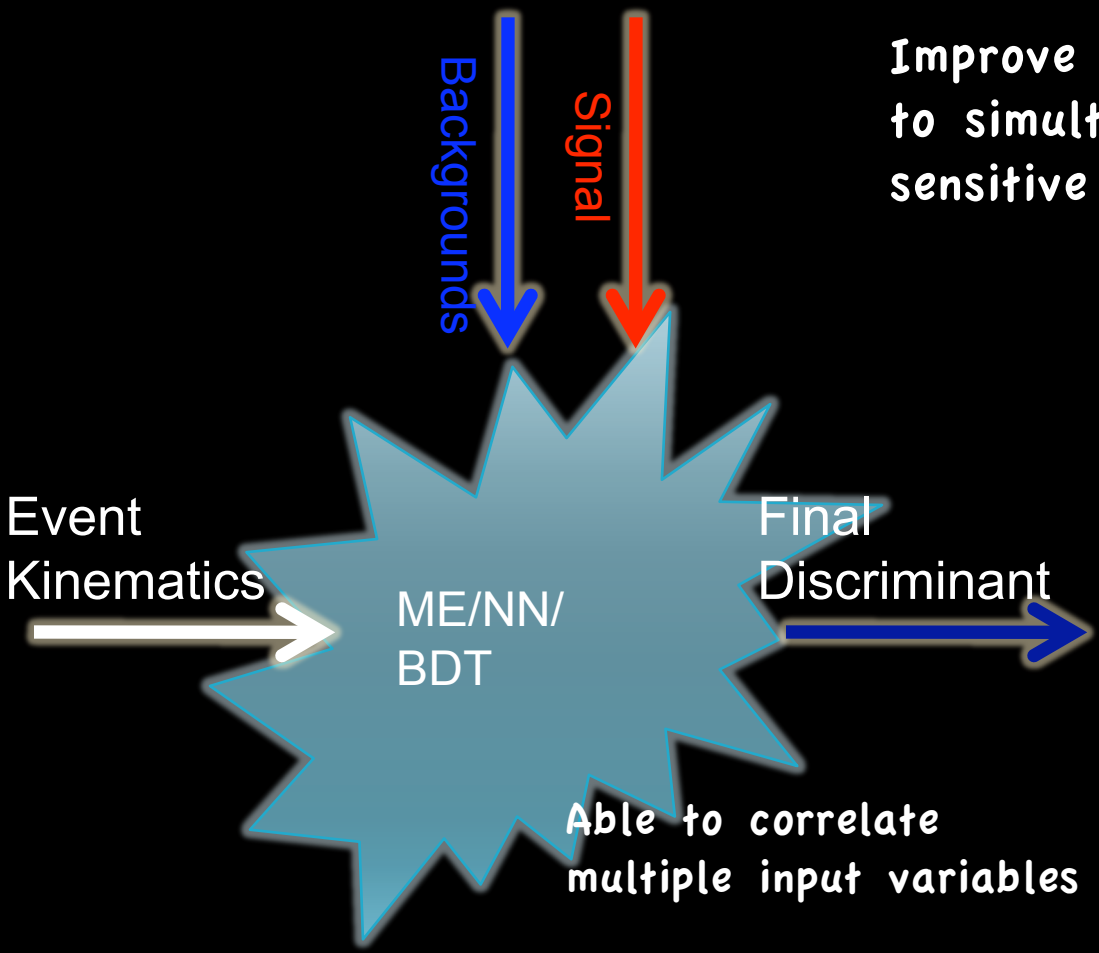
- Accelerator Division
- Technical Division
- Pbar source
- Computing Division
-DOE and NSF

Getting to the Higgs :

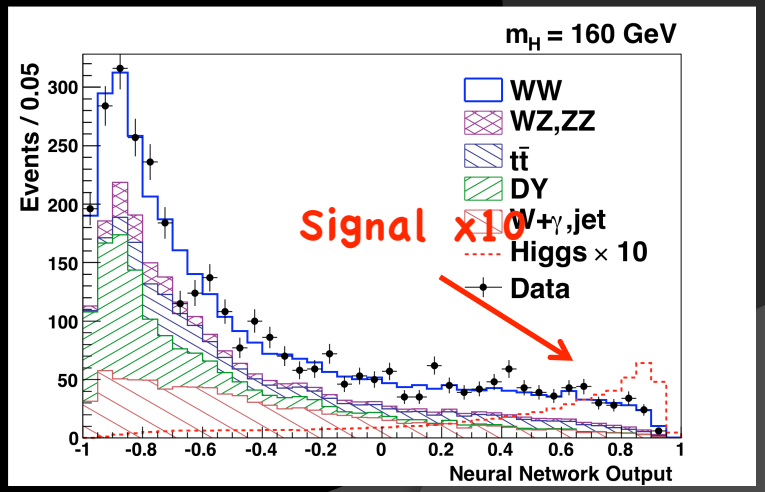


Multivariate Analysis (MVA):

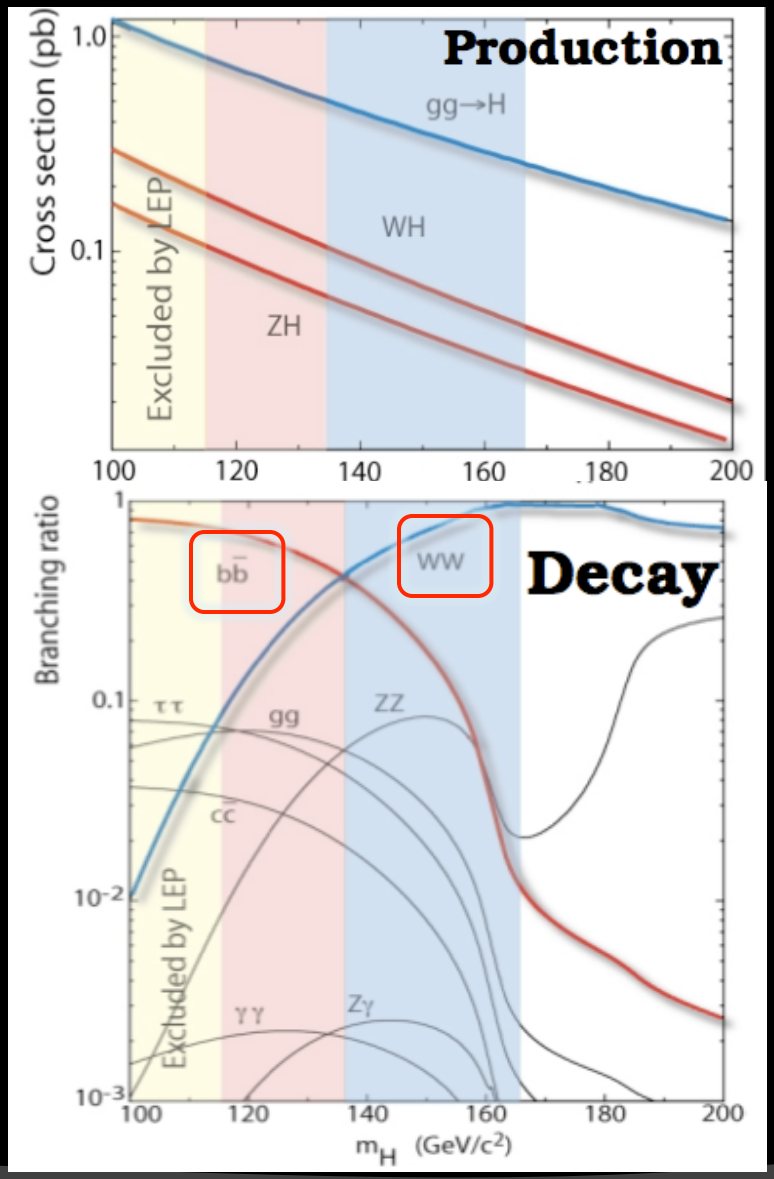
Tevatron physics has fundamentally changed the way community views MVAs:



Improve analysis by ~20% compared to simultaneous fit of the two most sensitive variables

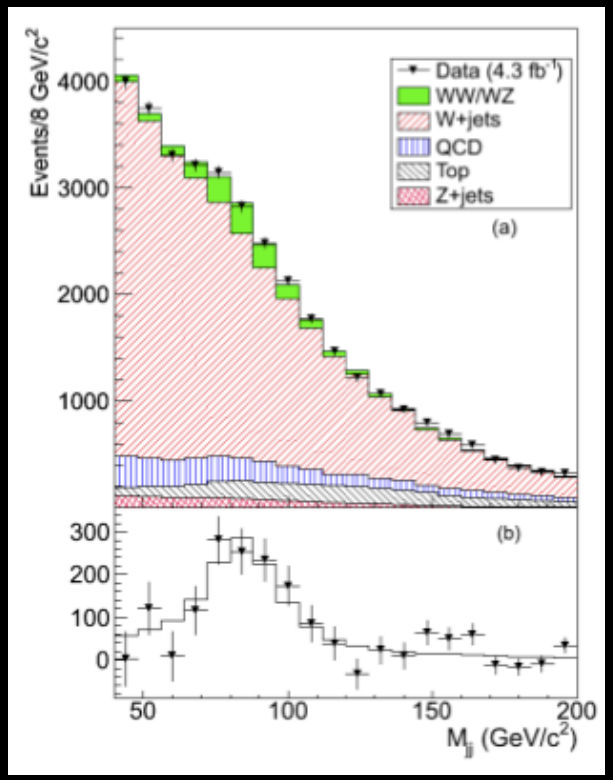


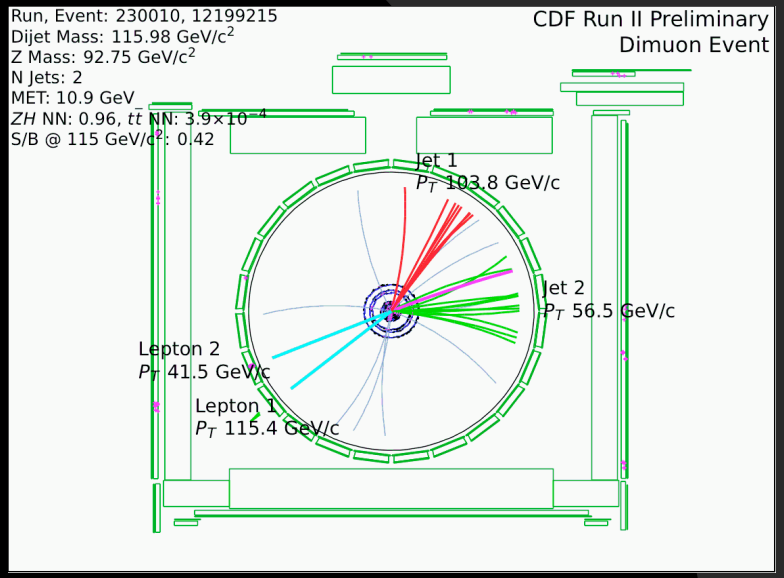
SM Higgs at the Tevatron



Primary Search Channels:

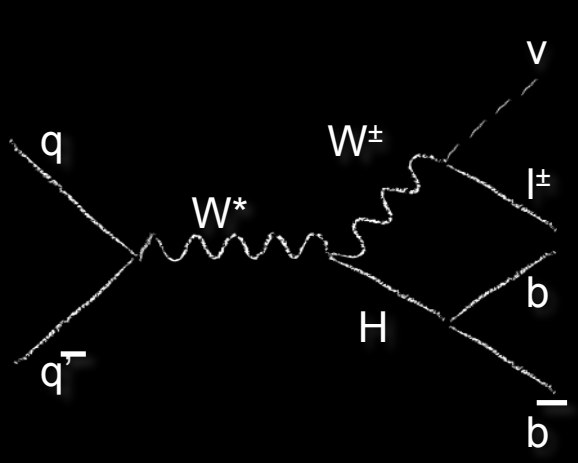
	Low Mass	High Mass
Primary Production:	WH, ZH	gg->H
Decay:	H -> bb	H -> WW
Main modes:	bb+lν bb+νν bb+ll	ll+νν
Important features:	• B-tagging • Dijet resolution	• Lepton acceptance • Angular correlations

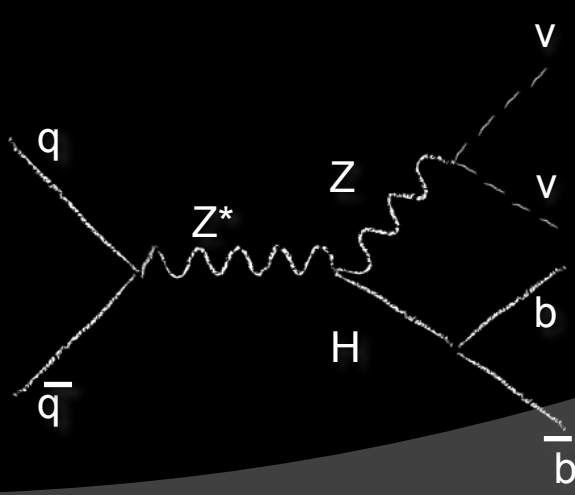


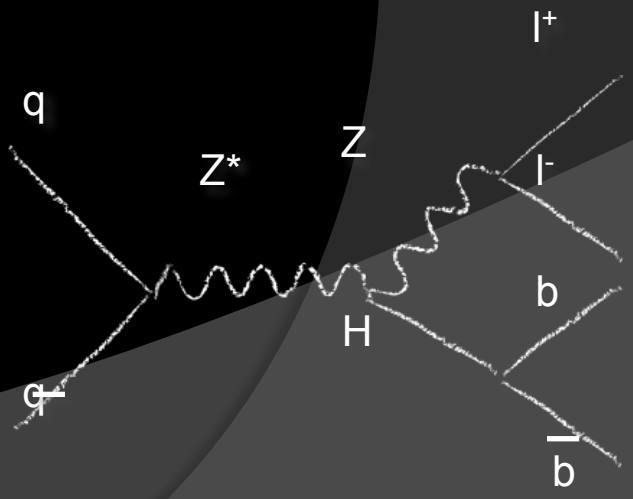


Low Mass Higgs Search

Hunting for dijet resonance

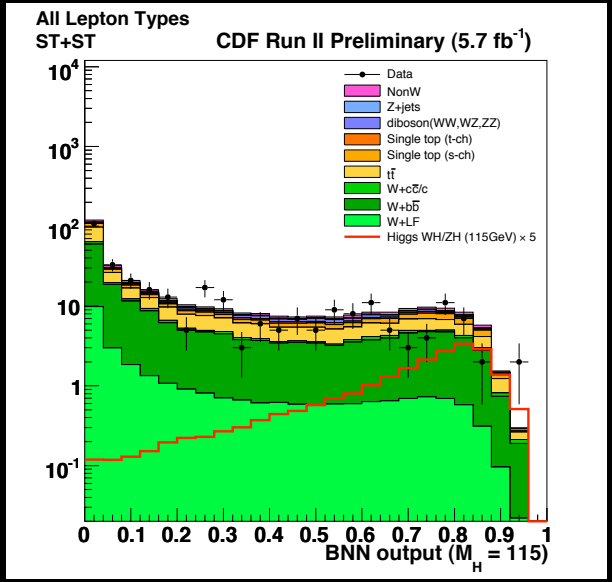




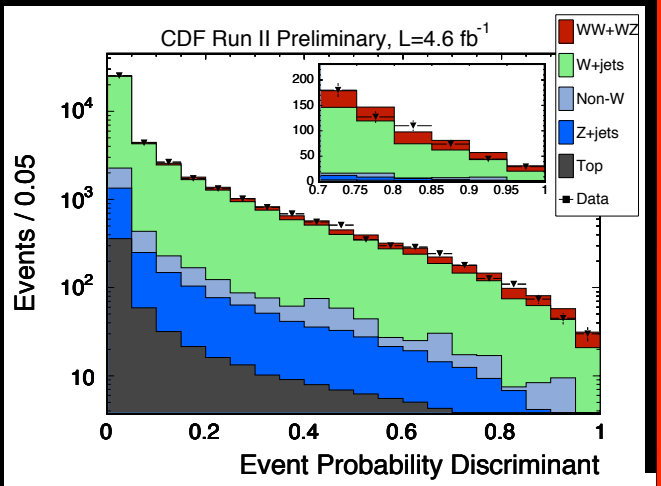


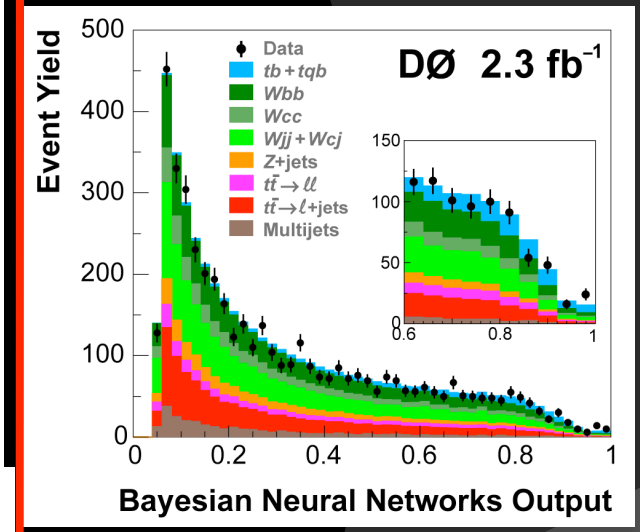
WH → lvbb

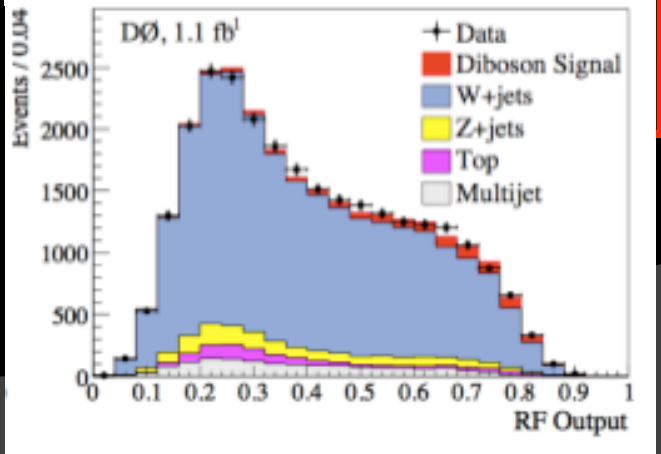
- Largest signal yield
- But also large backgrounds



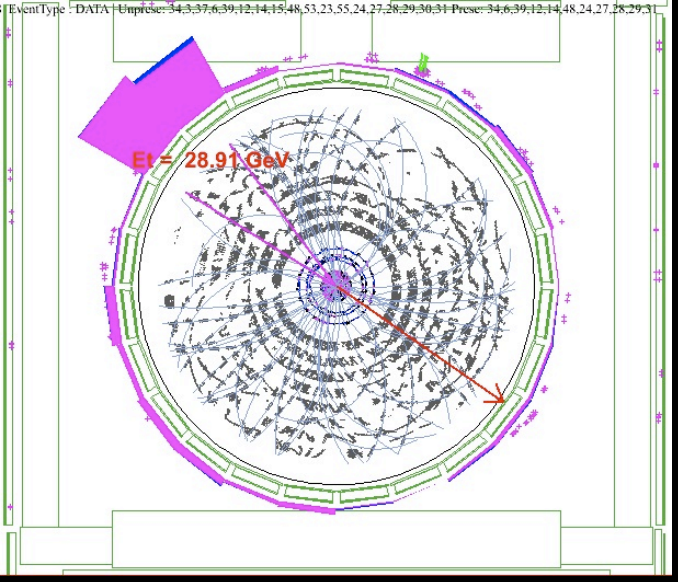
Single top – big step towards the Higgs (similar signature)
March 2009



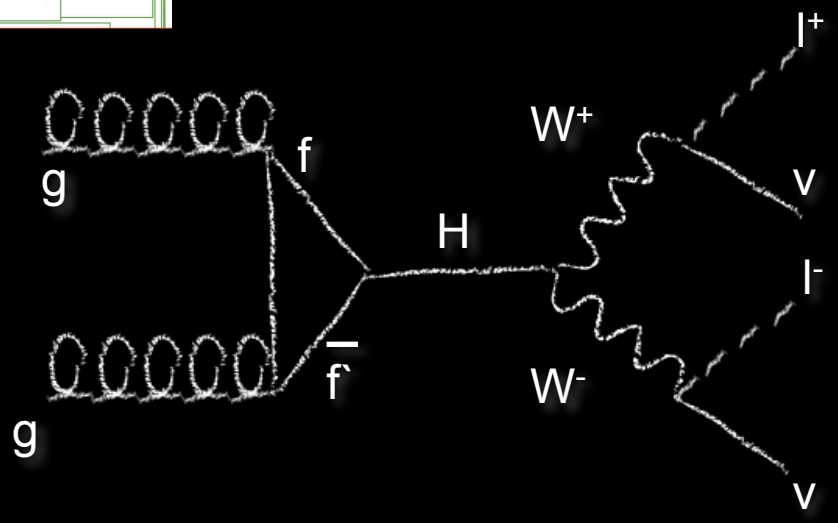




Diboson observation in WZ/ZZ → lvjj
Late 2009



High Mass Higgs Search

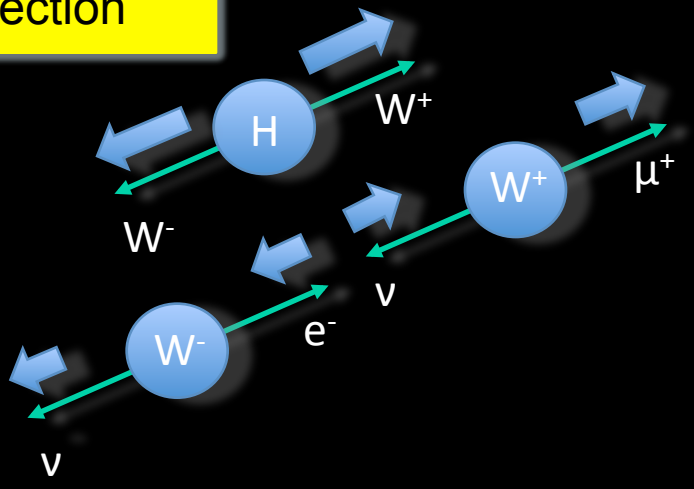


No resonance - smeared by neutrinos

Looking for excess of events with Higgs-like kinematic properties

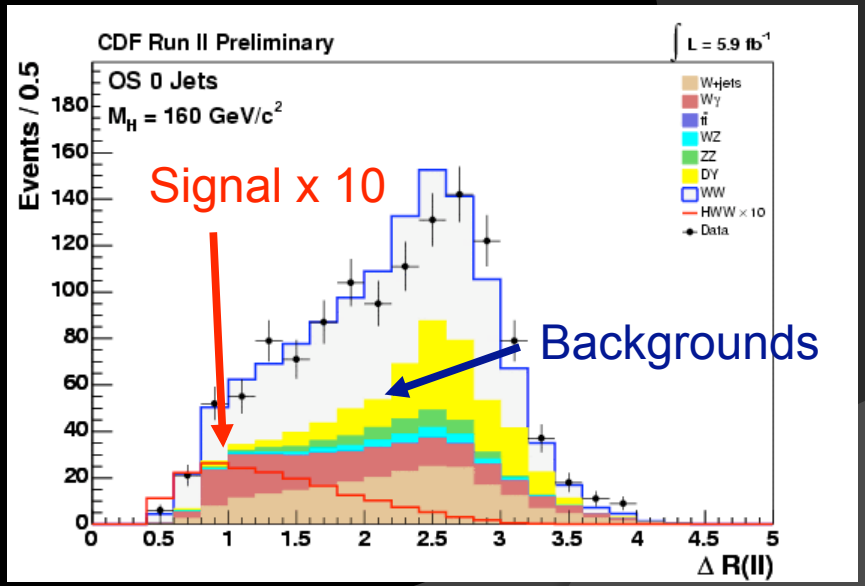
- Most important channel for $M_H > 125$ GeV
- Contributes down to 115 GeV

Spin correlation: Leptons go in the same direction

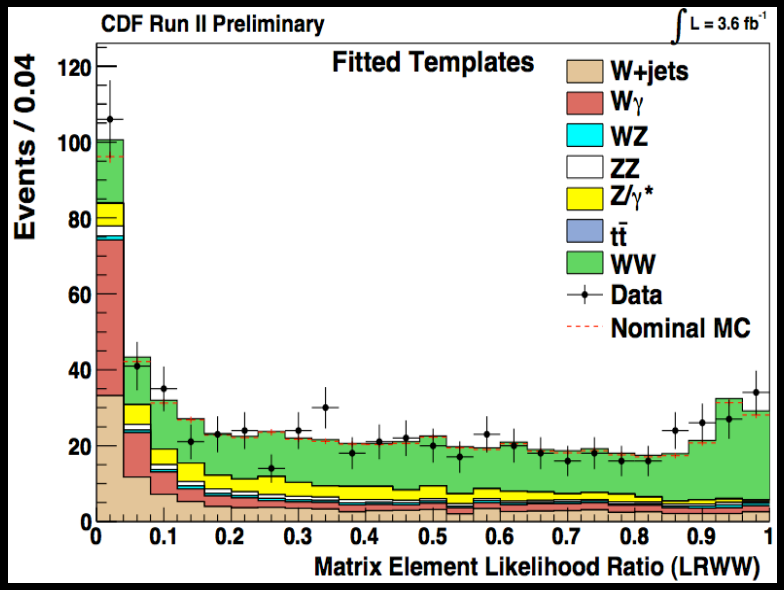


Dilepton opening angle is the strongest background discriminant

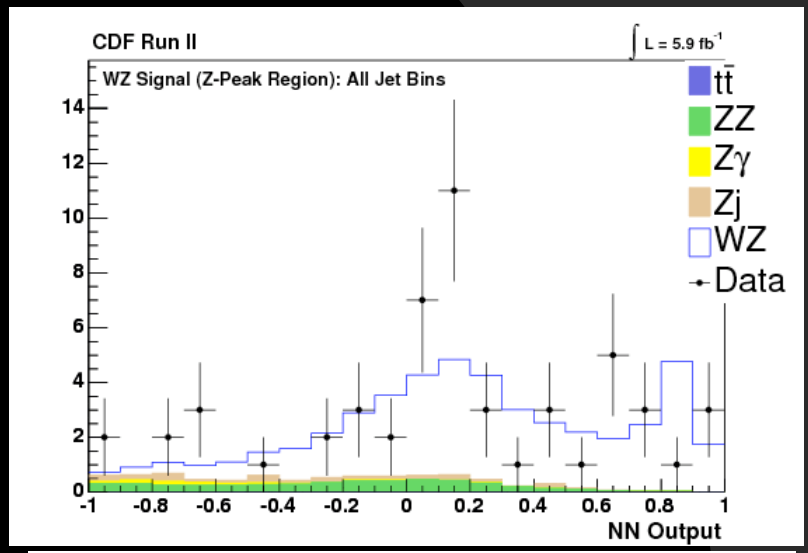
Main challenge: to distinguish signal from EWK WW pair production:



Validate tools in measurements of cross-sections for observed SM processes:

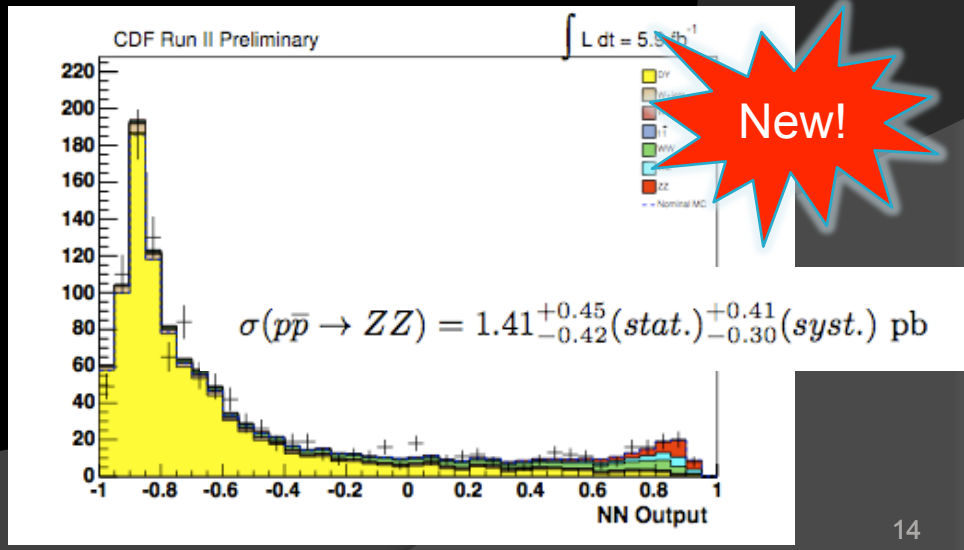


$\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9\ (\text{stat.})^{+1.6}_{-1.4}\ (\text{syst.})\ [\text{pb}]$
Syst. **includes** 5.9% luminosity uncertainty



$\sigma(p\bar{p} \to WZ) = 3.7 \pm 0.6(\text{stat})^{+0.6}_{-0.4}(\text{syst})(\text{pb})$

- Final states with 2 or 3 leptons + MET
- All in excellent agreement with NLO predictions



$\sigma(p\bar{p} \to ZZ) = 1.41^{+0.45}_{-0.42}(stat.)^{+0.41}_{-0.30}(syst.)\ \text{pb}$

Channel	Expt	Dataset ICHEP2010	Increase since Nov. 2009 combination
H → WW	D0	6.7	24%
H → WW	CDF	5.9	23%
WH → lνbb	CDF	5.7	30%
WH → lνbb	D0	5.3	6%
ZH/WH→METbb	CDF	5.7	60%
ZH/WH→METbb	D0	6.4	23%
ZH → llbb	CDF	5.7	40%
ZH → llbb	D0	6.2	45%
H → γγ	CDF	5.4	New!
H → γγ	D0	4.2	0%
H → ττ	CDF	2.3	15%
H → ττ	D0	4.9	0%
ZH/WH→qqbb	CDF	4	100%
ttH	D0	2.1	0%

Each channel represents several "sub-channels"

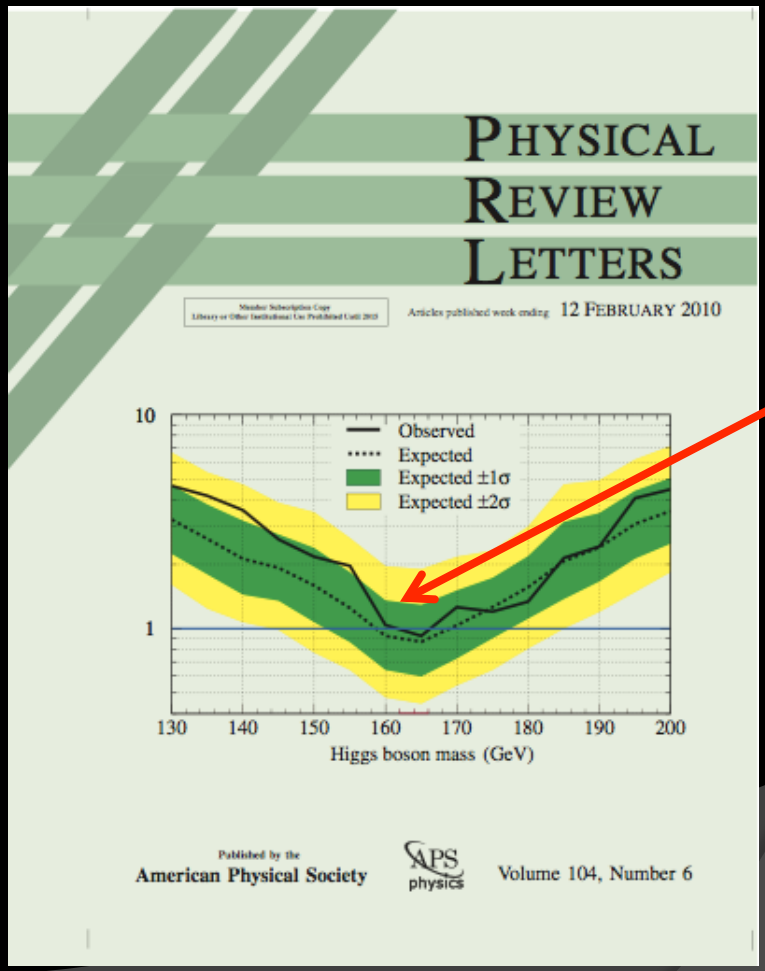
H→WW Sub-channels
opposite sign leptons + 0-jets
opposite sign leptons + 1-jets
opposite sign leptons + 2-jets
opposite sign leptons , low M_{ll}
same sign leptons
trileptons, no Z candidate
trileptons, Z candidate, 1-jet
trileptons, Z candidate, 2-jet
electron + hadronic tau
muon + hadronic tau
leptons + jets

Hard work by many CDF and D0 analyzers made this possible

Tevatron Combination:

One experiment is not enough - need to combine CDF and DO results

High mass result featured on PRL cover page



First published Standard Model Higgs exclusion since LEP times

"Wine and Cheese" seminar

Tevatron Combination:

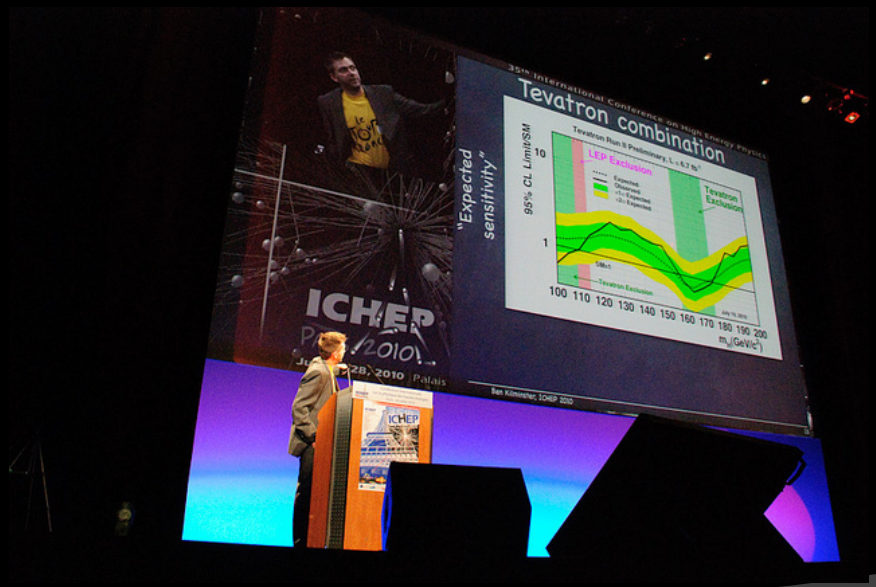
Typically once a year, for major conferences

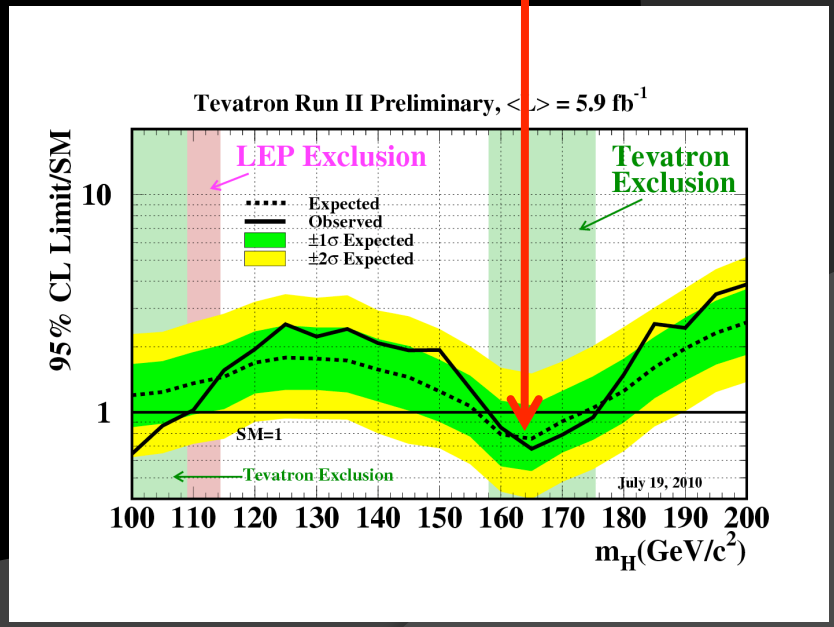
Ben Kilminster presenting latest Tevatron combination at ICHEP'10

- Sensitivity better than $2x\sigma_{SM}$ across the mass range
- High mass exclusion:

  $158<M_H<175$ GeV

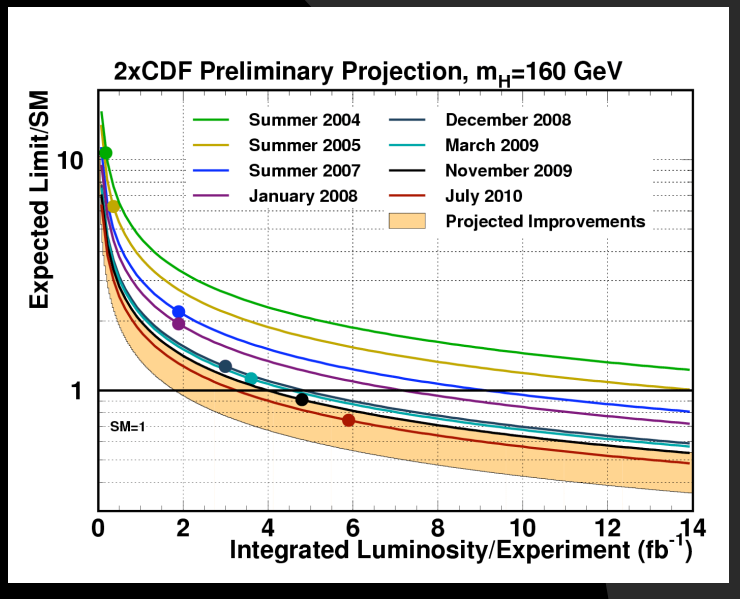
  Exp: $156<M_H<173$ GeV





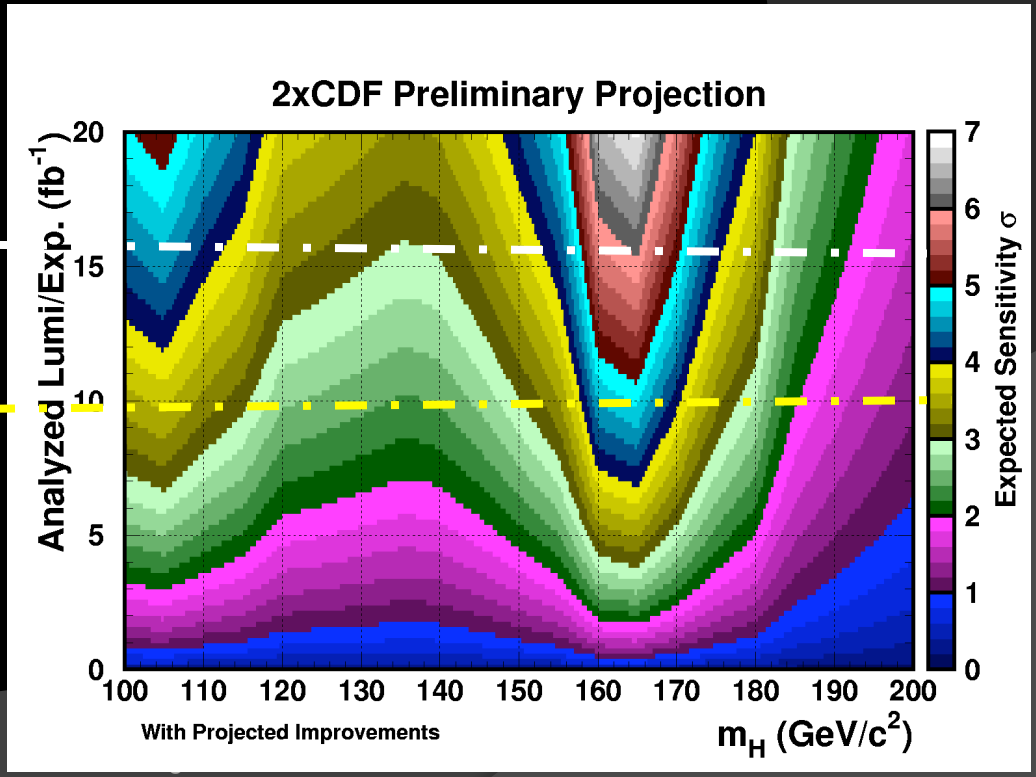
Prospects:

160 GeV Progress since 2004



16 fb^{-1} *
>3σ (Evidence) sensitivity over mass range 100-185 GeV

10 fb^{-1} (end of 2011)
sensitivity to exclude Higgs over the mass range



* **16 fb^{-1}** Is based on the proposed Run 3

Outlook:

- So, 25 years later…

Tevatron is still a discovery machine

- … we have a dedicated team of scientists advancing Higgs physics at the Tevatron…

- … we have not yet discovered the Higgs… but we excluded a large chunk of allowed mass range …
- … and how the journey ends...remains to be seen

Backup

General Analysis Strategy

High Pt Electron and Muon data

Verify modeling of main BGs

Control regions

Apply loose dilepton+MET selection

Signal Region S/B ~1/60

S/B ~1/25

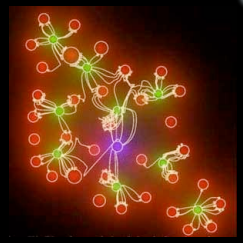
Channel1

Channel2

….

Separate into channels based on lepton purity, S&BG composition

Multivariate Techniques



S/B ~1/1

Template1

Templatel2

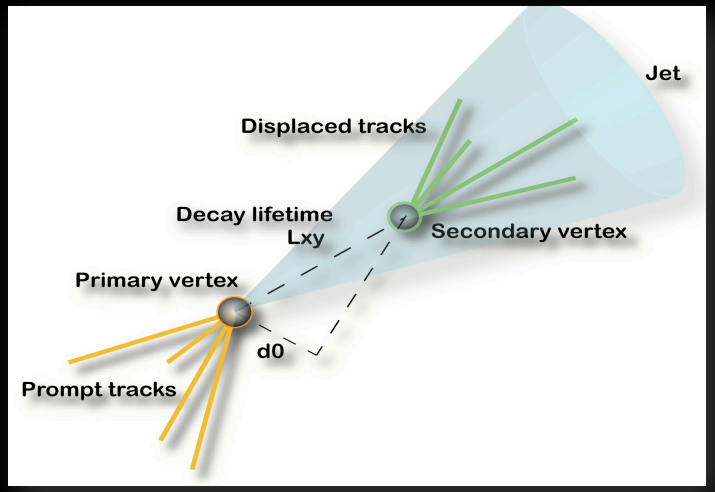
….

Systematics and correlations

Results: Limits or signal significance

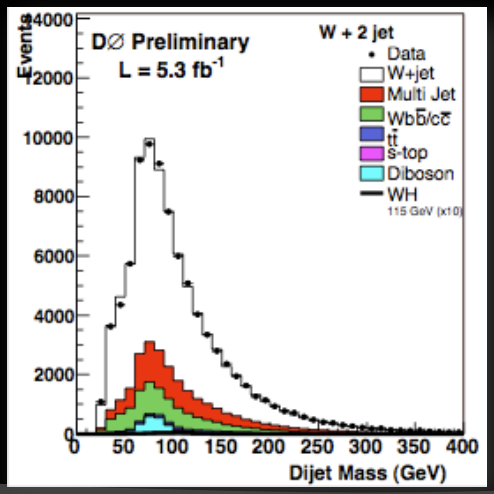
Tools: b-jet identification

Low mass searches depend heavily on "b-tagging"

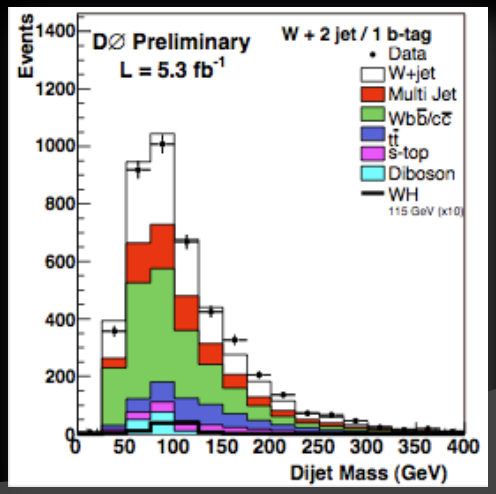


- Ability to distinguish b-jets from light quark or gluon jets
- Several b-tagging algortihms
  - Typical efficiency 50-70%
  - Mistag rate 1-5%

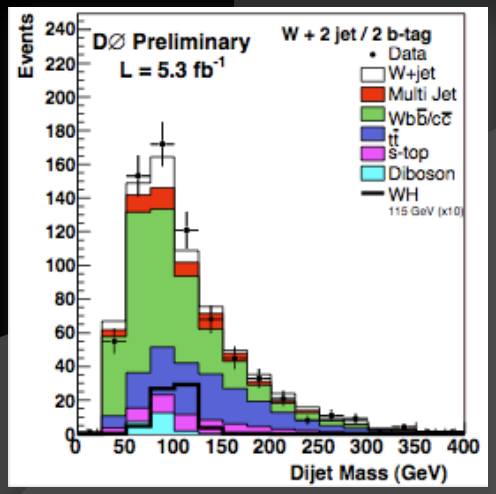
Reduce Backgrounds:



1 tag →



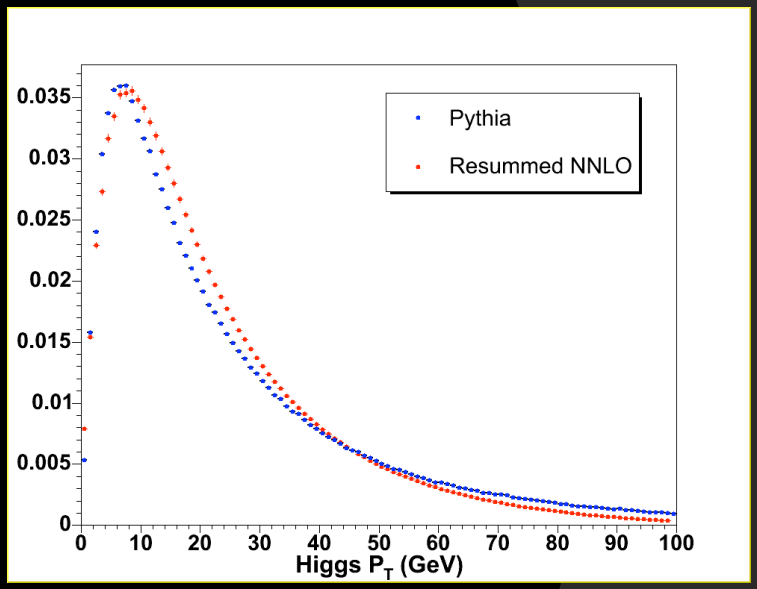
2 tags →



Signal, more on the gluon fusion

- Event kinematics Modeled using Pythia which is LO with soft gluon resummations
- Re-weight the PYTHIA events at generator to match the Higgs p_T spectrum obtained from the NNLL calculation
- Since our signal acceptance is determined from this re-weighted event sample, we believe that normalizing to the NNLL inclusive cross section is self-consistent

Anastasiou et al., arXiv:0905.3529v2

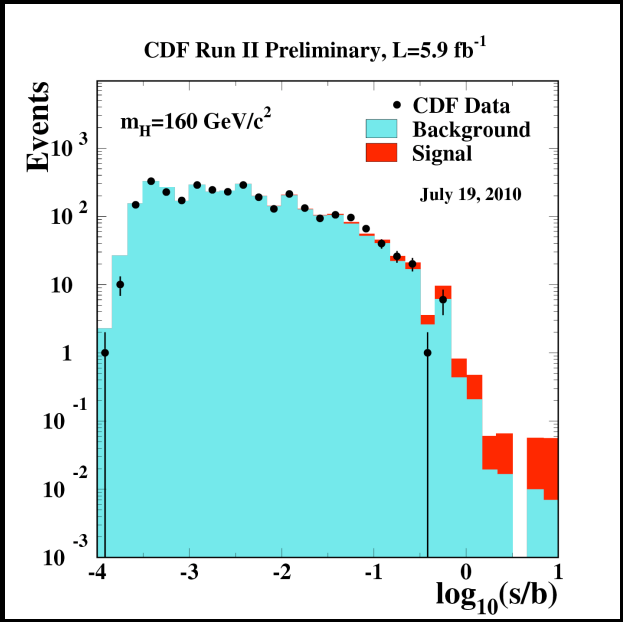


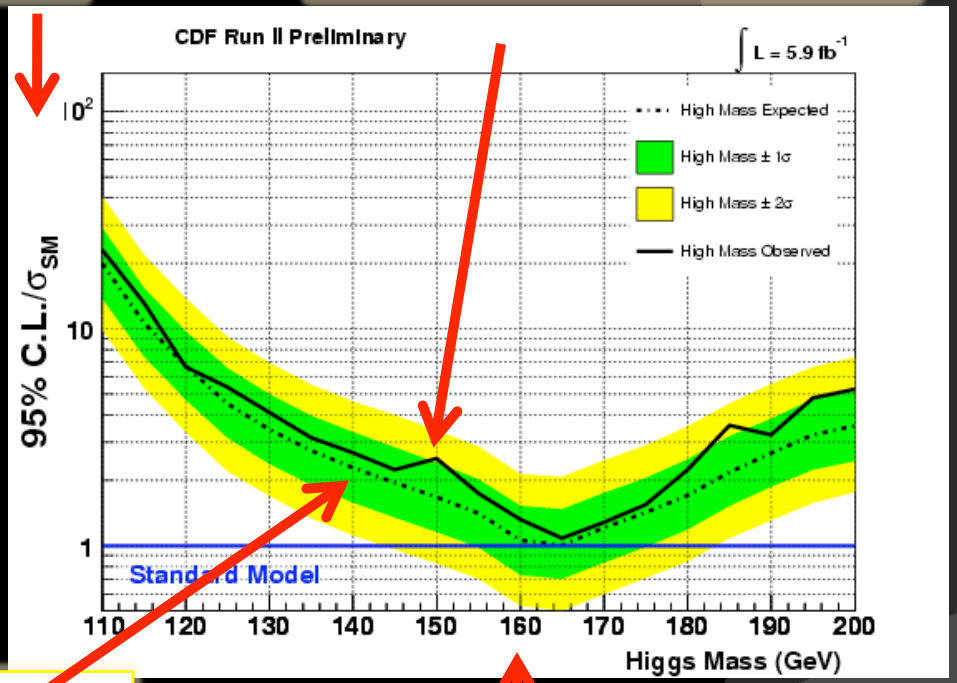
Ichep 2010 CDF result

At Mh=165 GeV
CDF: Exp/σ_{SM}: 1.00
Obs/σ_{SM}: 1.08

Upper cross section limit for Higgs production relative to SM prediction

Observed limit (solid line) from data

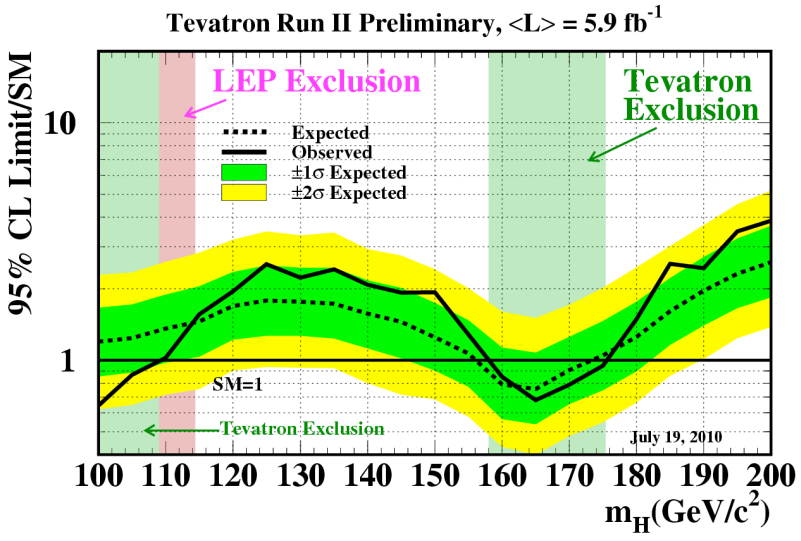


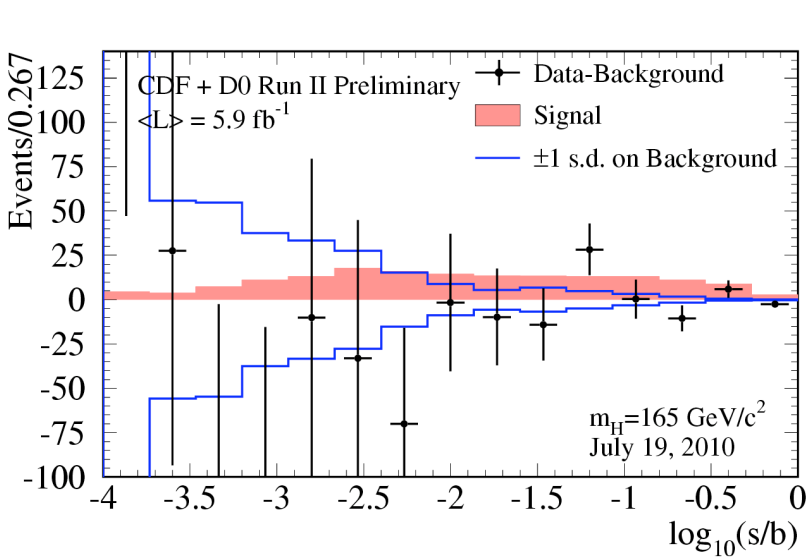


Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

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

Tevatron Combination:

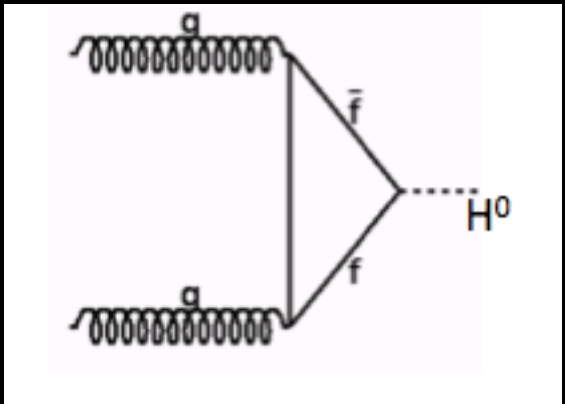




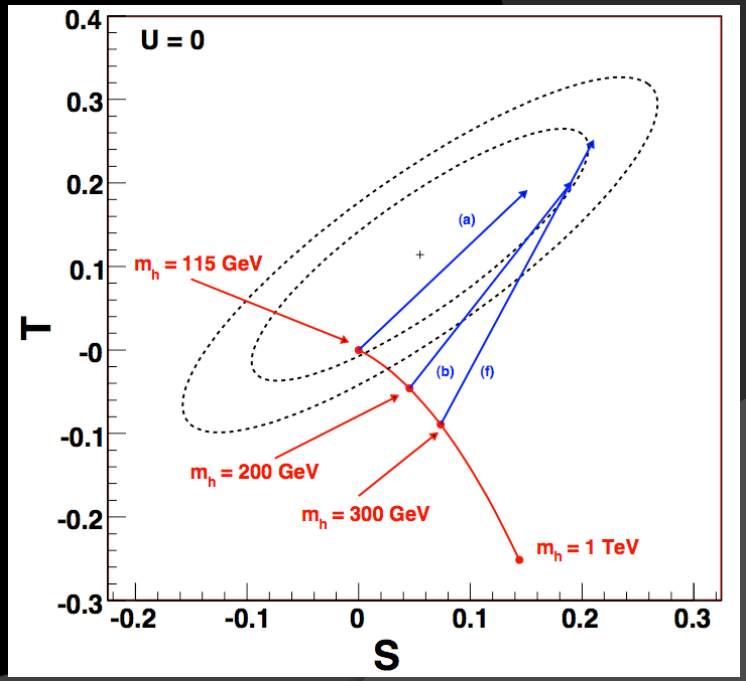
- Prev exclusion 162-166 featured on PRL cover page
- Current:
  - Observed exclusion 158 < m_H < 175 GeV
  - Expected exclusion 156 < m_H < 173 GeV

Going beyond SM:

… or what if there are 4 generations of fermions ?



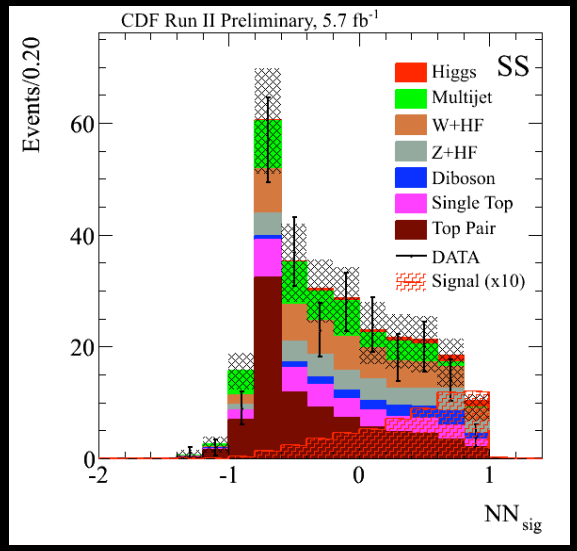
Four Generations and Higgs Physics
Kribs, Tait, Spannowsky, Plehn
Phys.Rev.D76:075016,2007.
arXiv:0706.3718 [hep-ph]

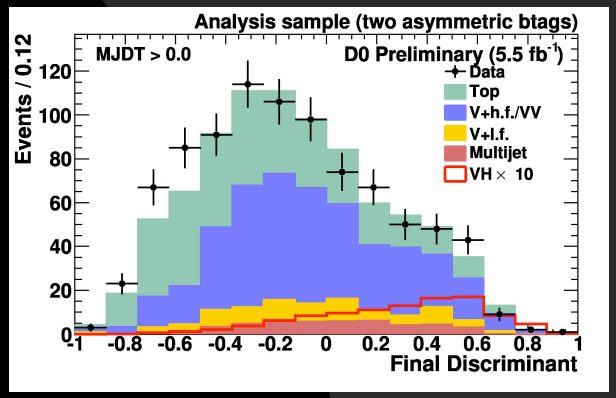


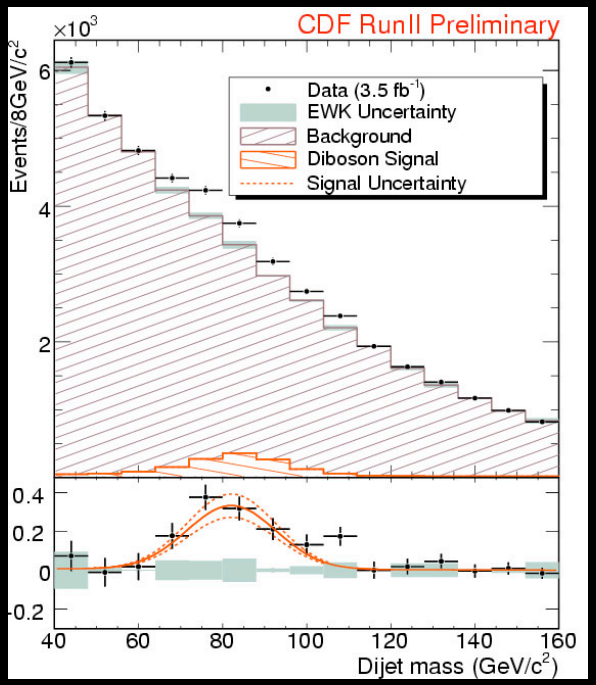
- Presence of additional high mass quarks enhances gg→H production by as much as a factor of nine - also modifies Higgs branching ratios
- Small modifications to default CDF/DO high mass searches
  - Remove WH, ZH, and VBF signal contributions : retrain discriminates for gg→H only

VH → vvbb

- Main BG: QCD with fake MET
- designated NN for QCD rejection

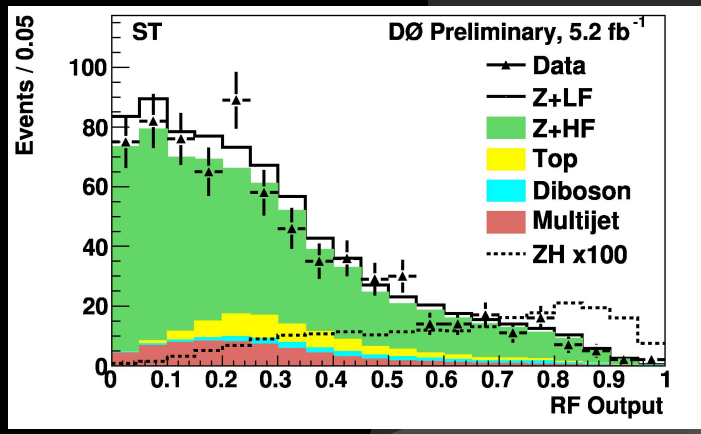






ZH → llbb

- Cleanest channel
- But lowest signal yield (1 event/fb^{-1})
- Kinematic fit to improve di-jet resolution

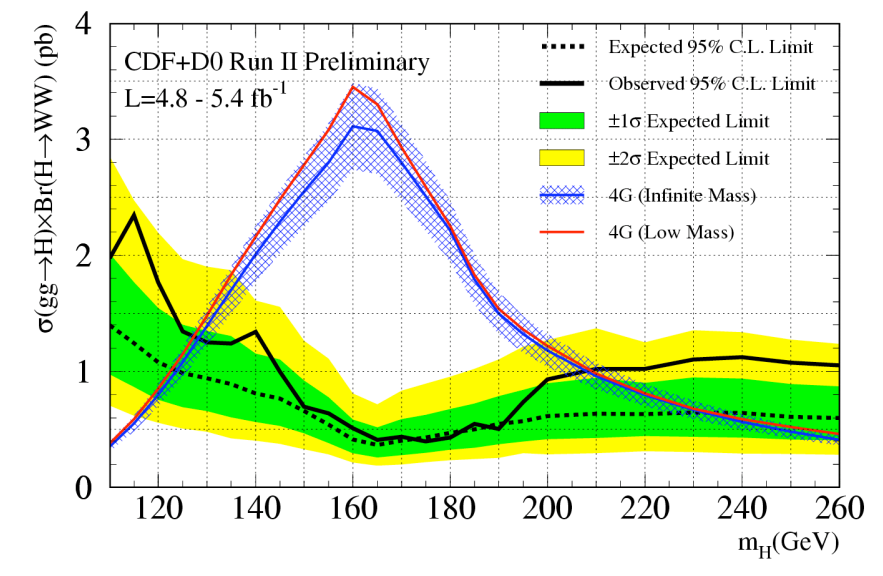


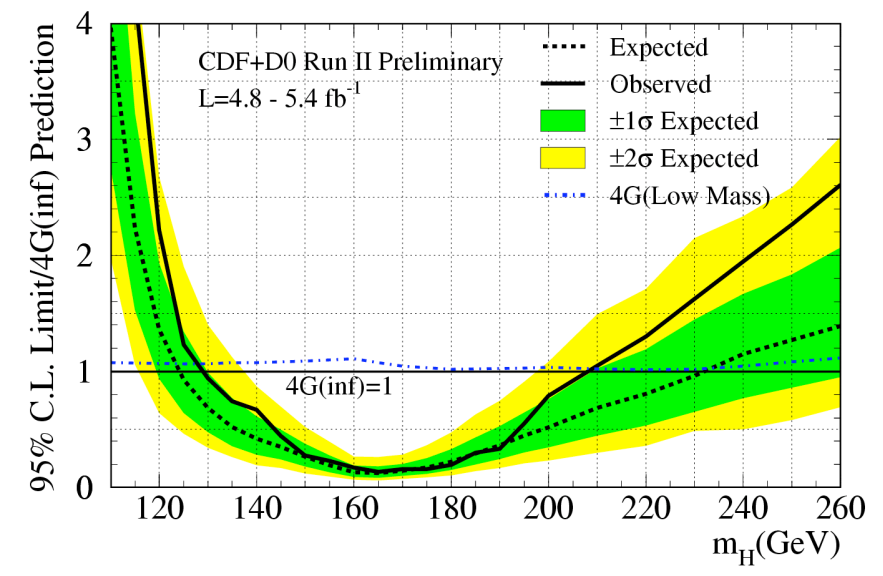
Diboson observation in WZ/ZZ → vvjj

Summer 2009

Going beyond SM:

… or what if there are 4 generations of fermions ?





- Cross section times branching ratio limits for gg→H→WW
- Theoretical predictions from Anastasiou, Boughezal, and Furlan - arXiv:1003.4677 [hep-ph] (2010)
- Observed exclusion 130 < m_H < 210 GeV