Higgs boson searches at the Tevatron

MISSING PARTICLE:

Name: Higgs boson

Age: 13.7 billion years

Missing: 45 years

Birthday: Every few days at Fermilab

Favorite trait: Mass

Favorite particle: top quark

Favorite Hangout: Tevatron

Ben Kilminster

Fermilab

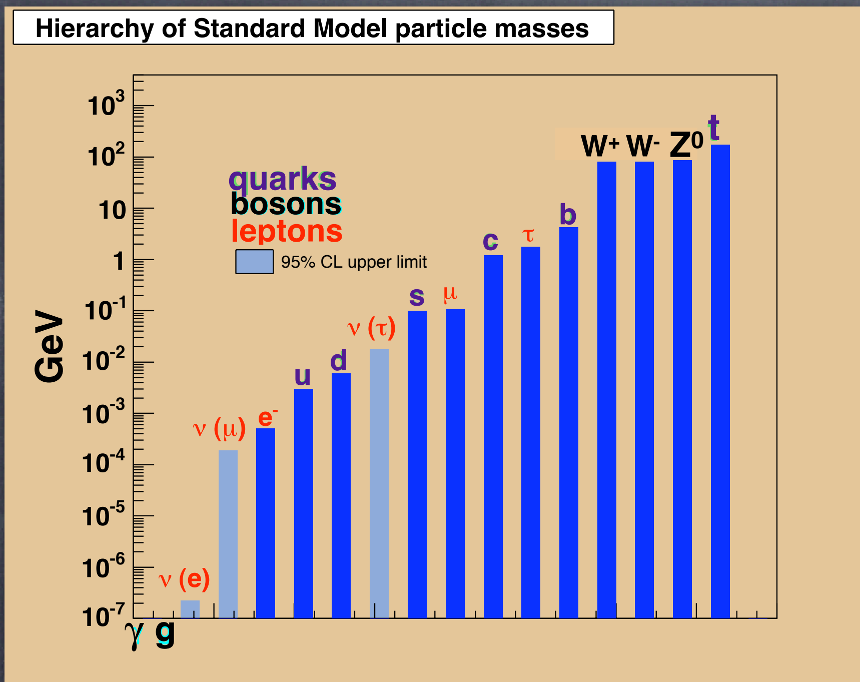
on behalf of

CDF & DO

ICHEP 2010

July 26, 2010

How to generate mass & break electroweak symmetry ?



Higgs mechanism :
Non-zero field permeating the universe generates mass

- W and Z bosons gain mass through degrees of freedom of Higgs field
- Fermions gain mass interacting with the Higgs field
- New particle Higgs boson predicted

- Finding the Higgs boson
  - Means Higgs field exists
    - Means we confirm our theory for the origin of mass

Recent headlines

- “Higgs” or media favorite : “God particle”

Old faithful Tevatron collider leads race to Higgs

Has elusive God particle finally been discovered?

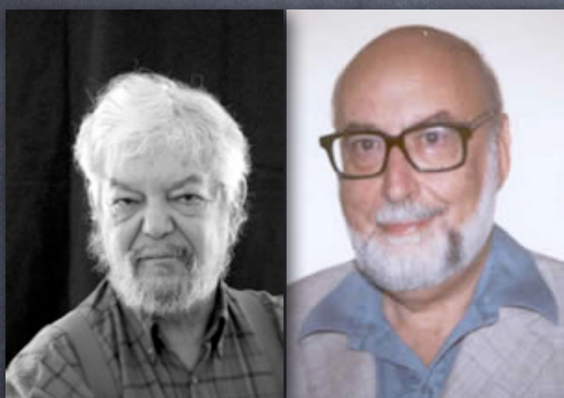
Did Someone Just Find the 'God Particle'?

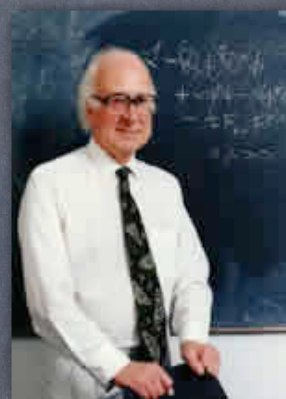
HIGGS BOSON DISCOVERED? NOT SO FAST.

Human buzz that God particle is found

2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."





Brout Englert Higgs Hagen Guralnik Kibble

PRL 13, 321-323 (1964) PRL 13, 508-509 (1964) PRL 13, 585-587 (1964)

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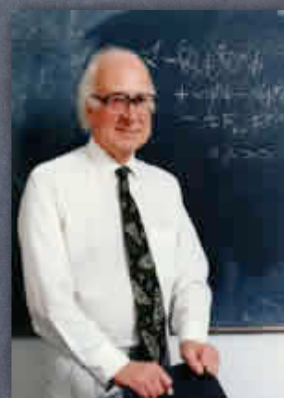
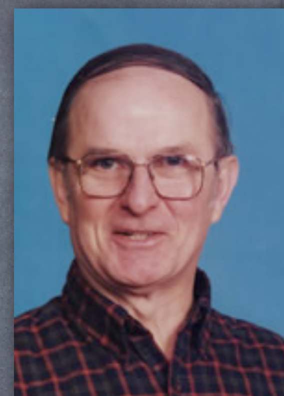


Higgs



Hagen

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PRL 13, 321-323 (1964)

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So in honor of B-E-H-H-G-K authors ...

Re-energize newspaper headlines

- "BEHHGK boson" alternative to "God particle" ?

Discovery BEHHGK'ns

At Fermilab's BEHHGK and call

Mal BEHHGK evasif en France

Every last BEHHGK

Got BEHHGK?

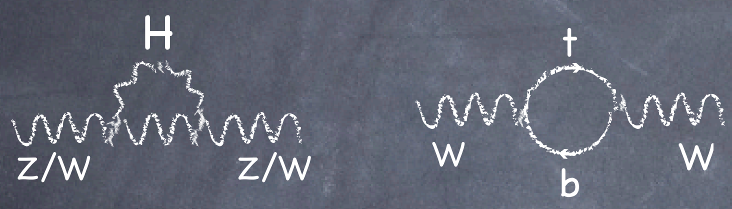
Fermilab pulls BEHHGK from background

What the BEHHGK ?

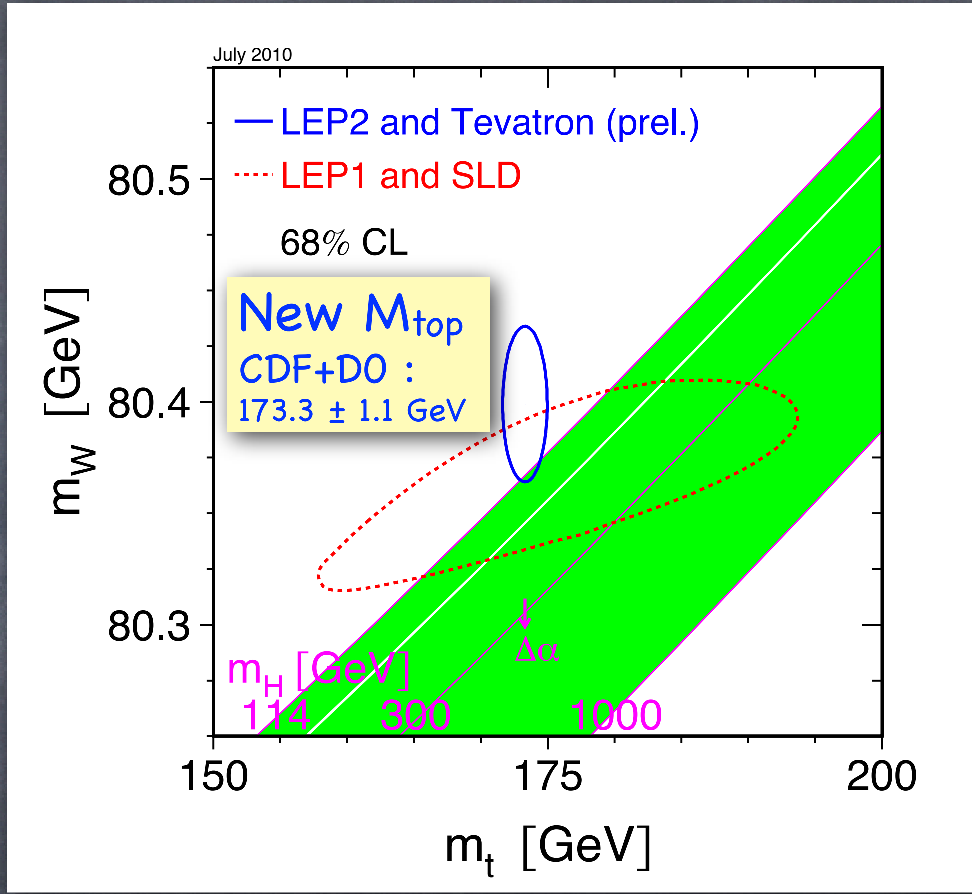
Constraints on Higgs mass

- Electroweak constraints

  $\ln M_H \propto \Delta M_W \propto M_t^2$



  - Other precision electroweak observables
- LEP direct searches
  - $m_H > 114.4$ GeV @ 95% CL
- Tevatron direct searches ...



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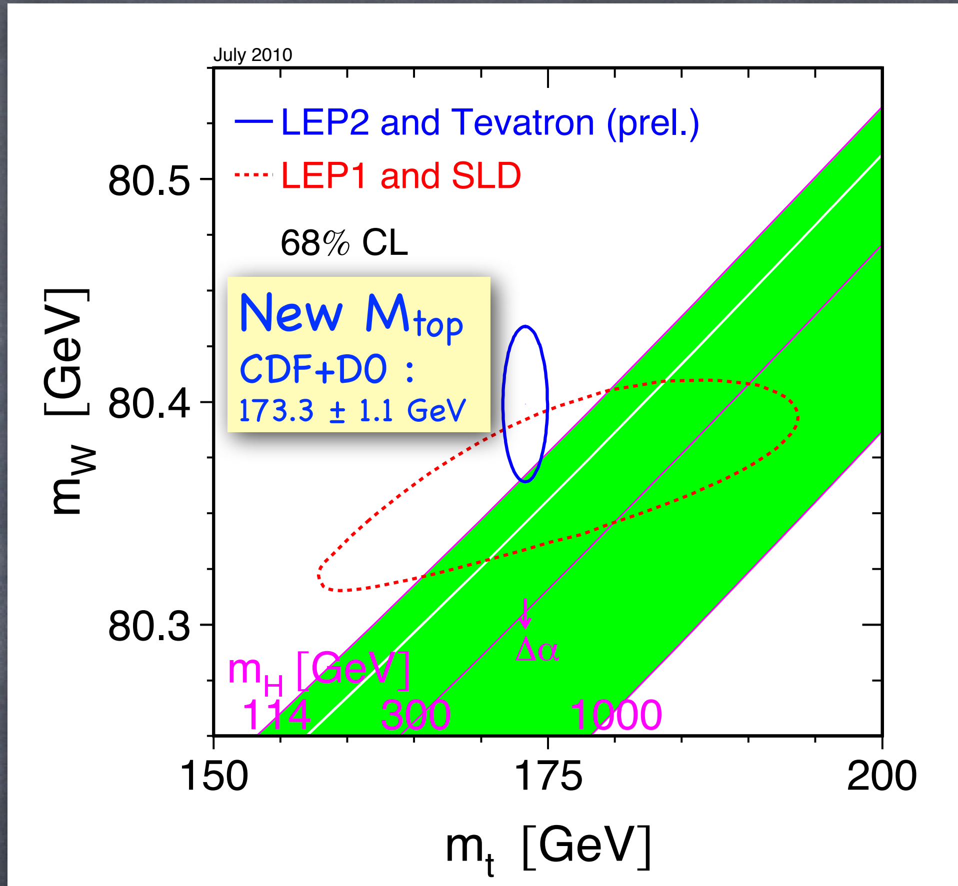


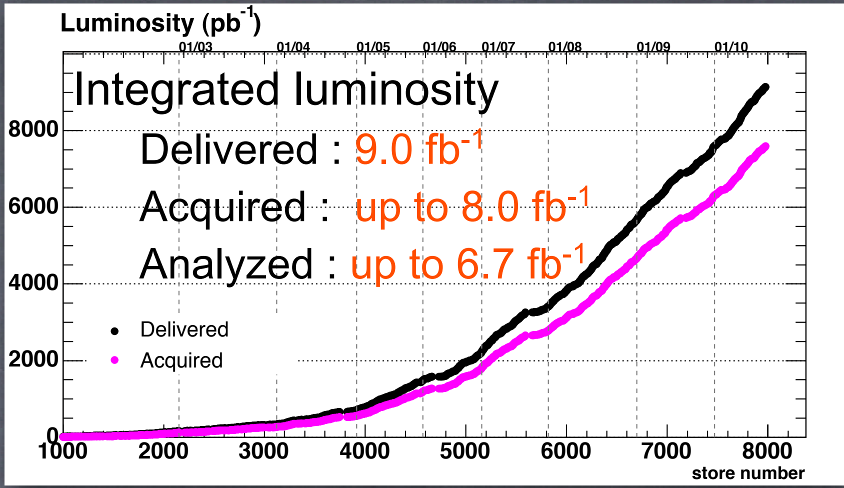
Precision Fit finds

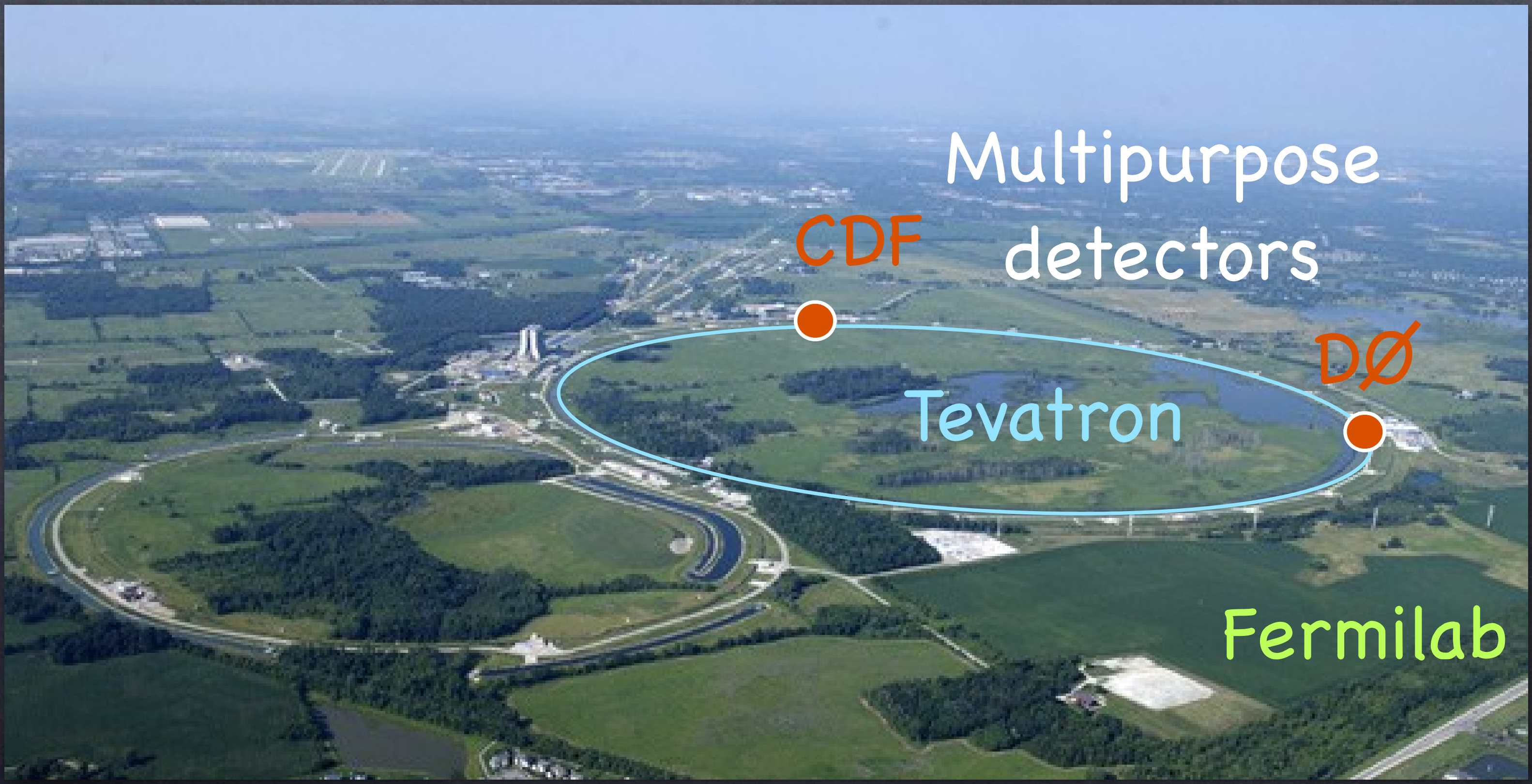
$m_H = 89.0\ ^{+35}_{-26}$ GeV

$m_H < 158$ GeV @ 95% CL

Tevatron

- $p\,\bar{p}$ collisions with $\sqrt{s}$ = 1.96 TeV
- Two collider experiments, CDF & D0





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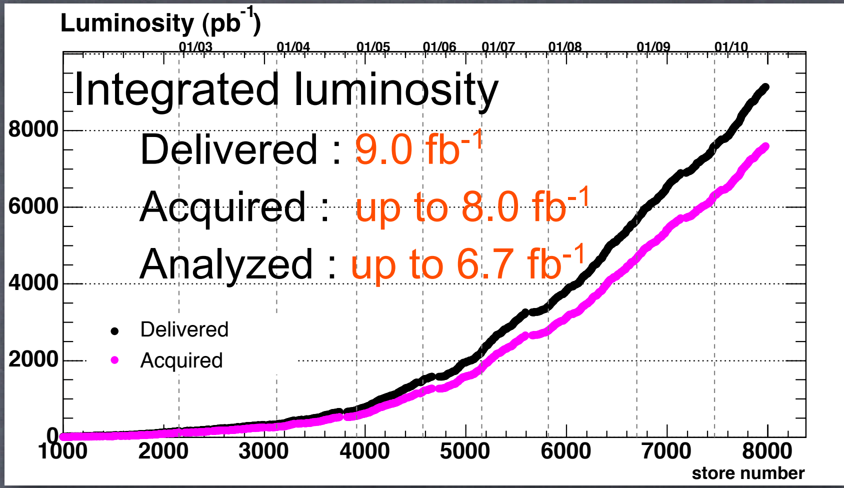

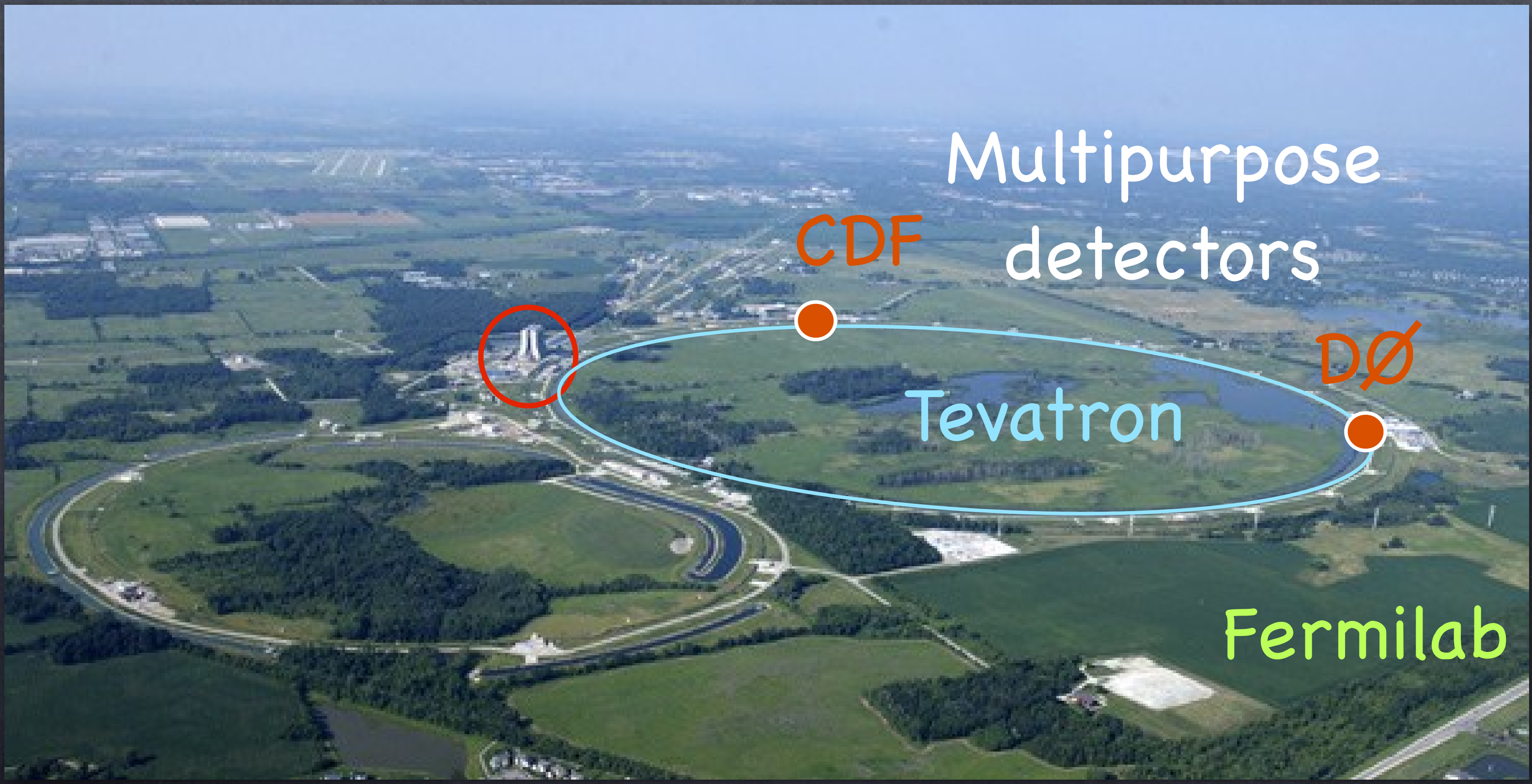

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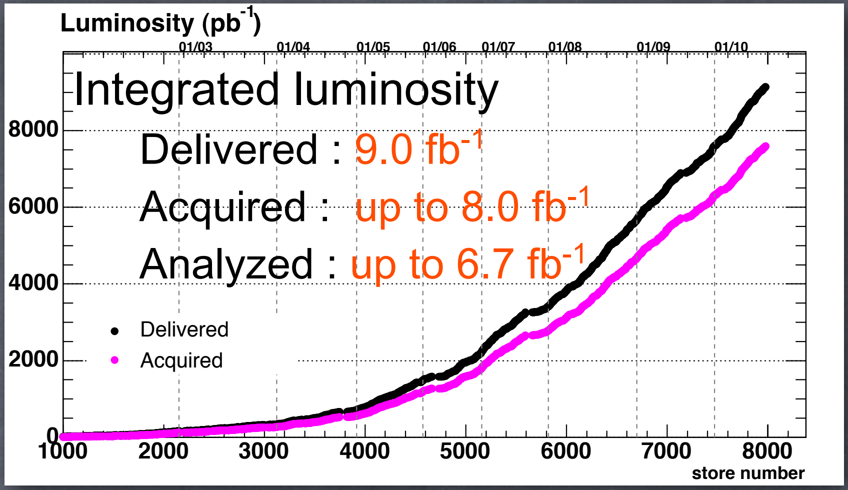

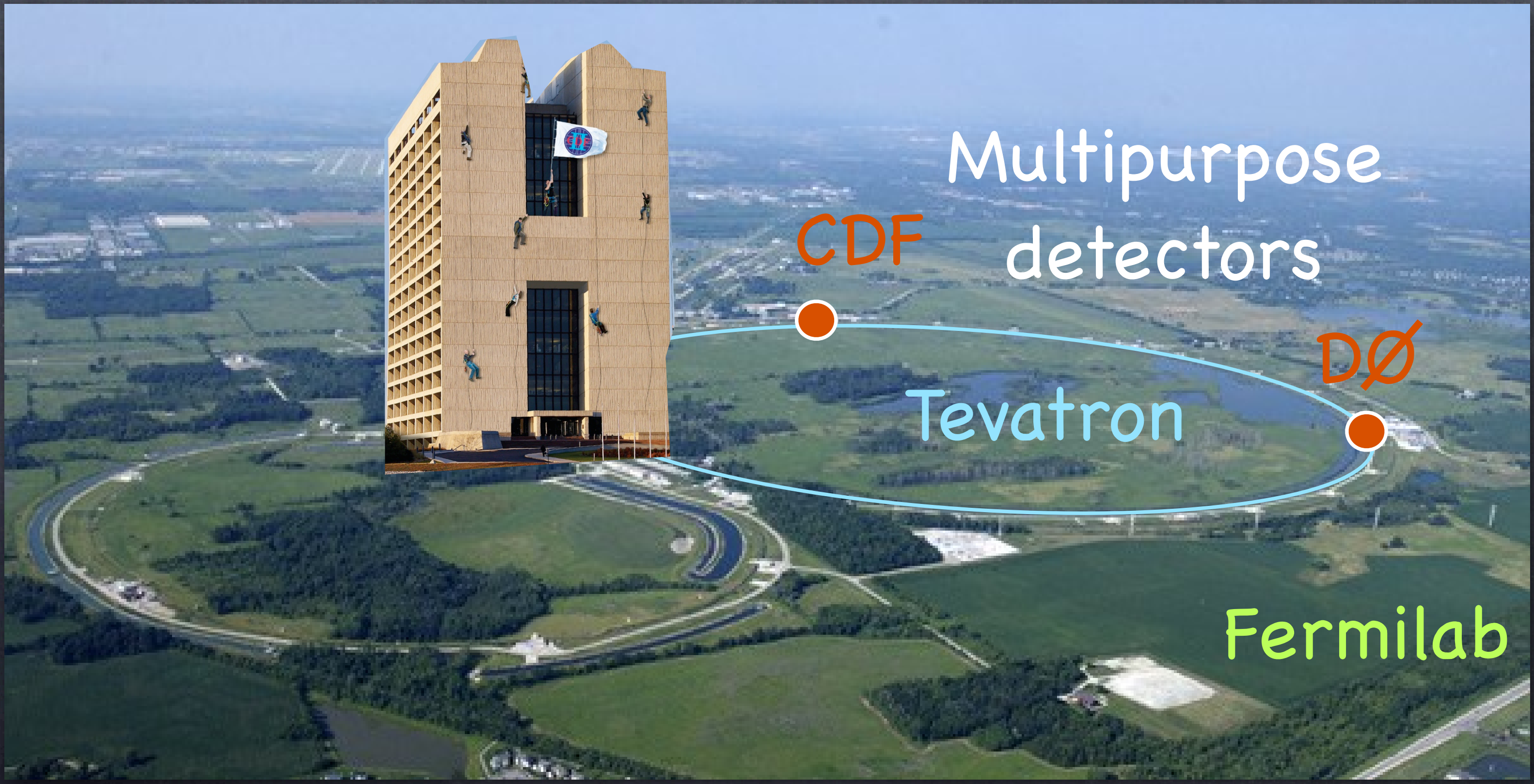

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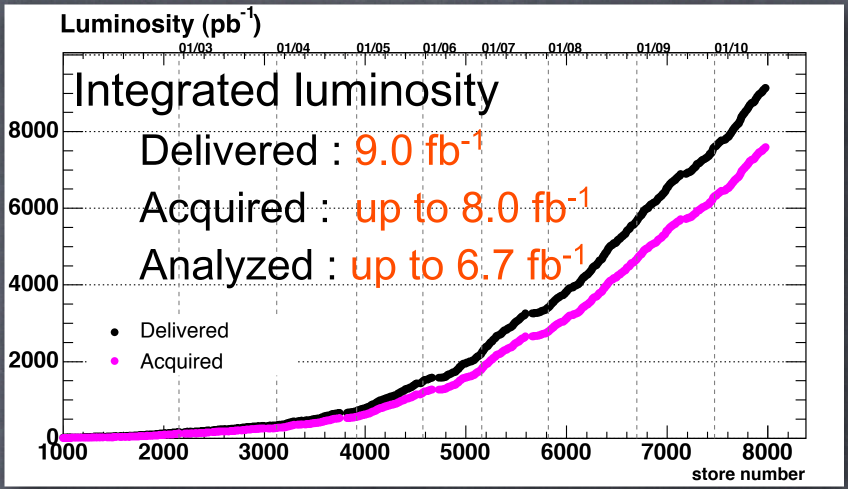
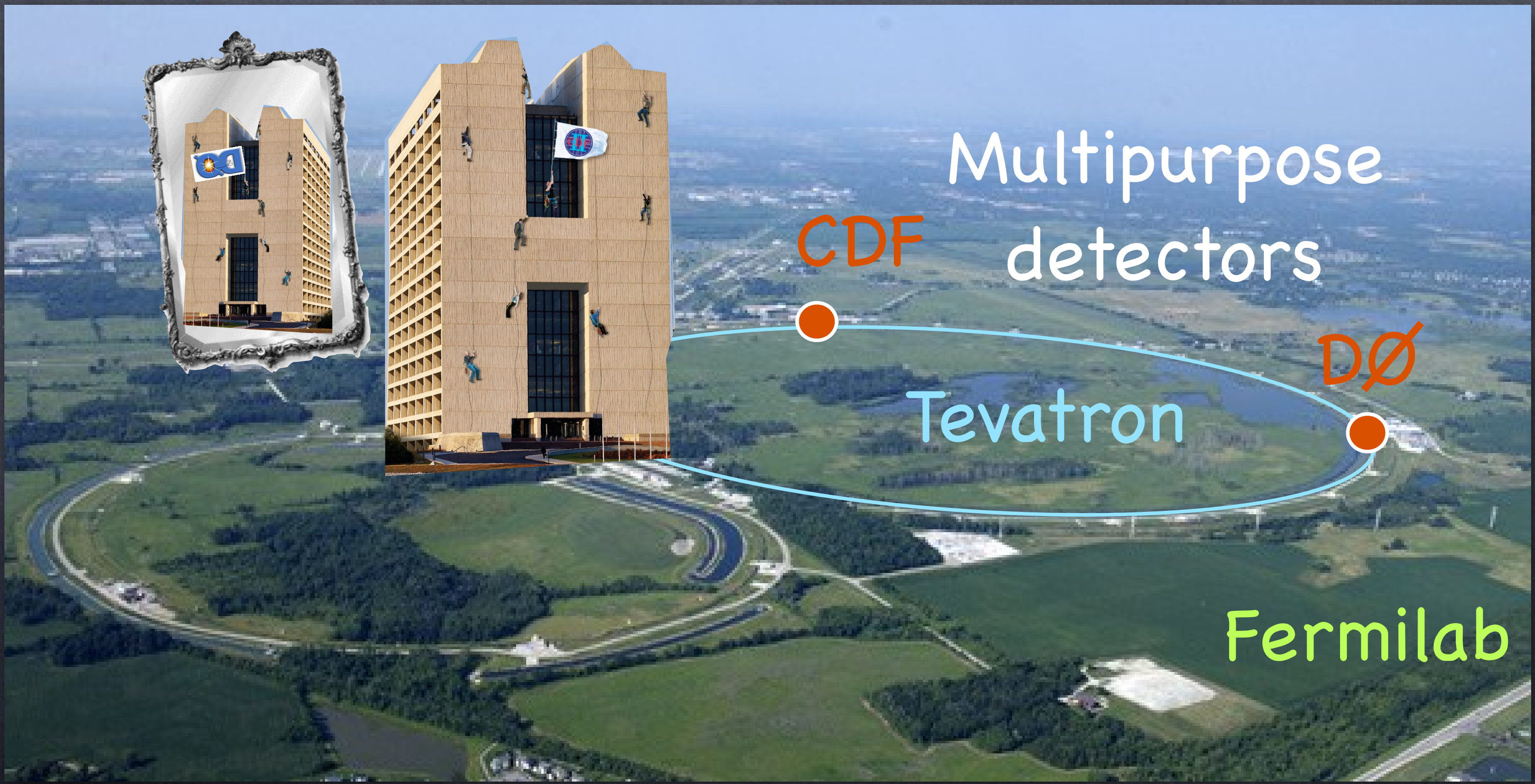
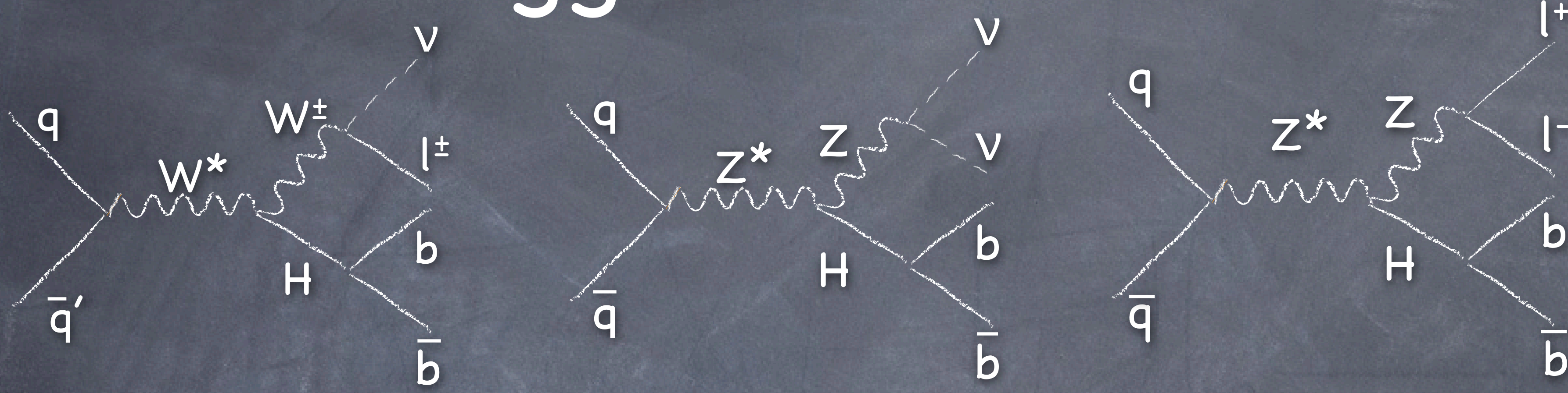
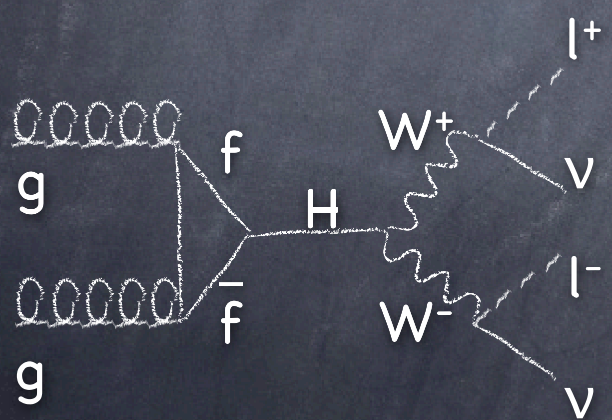


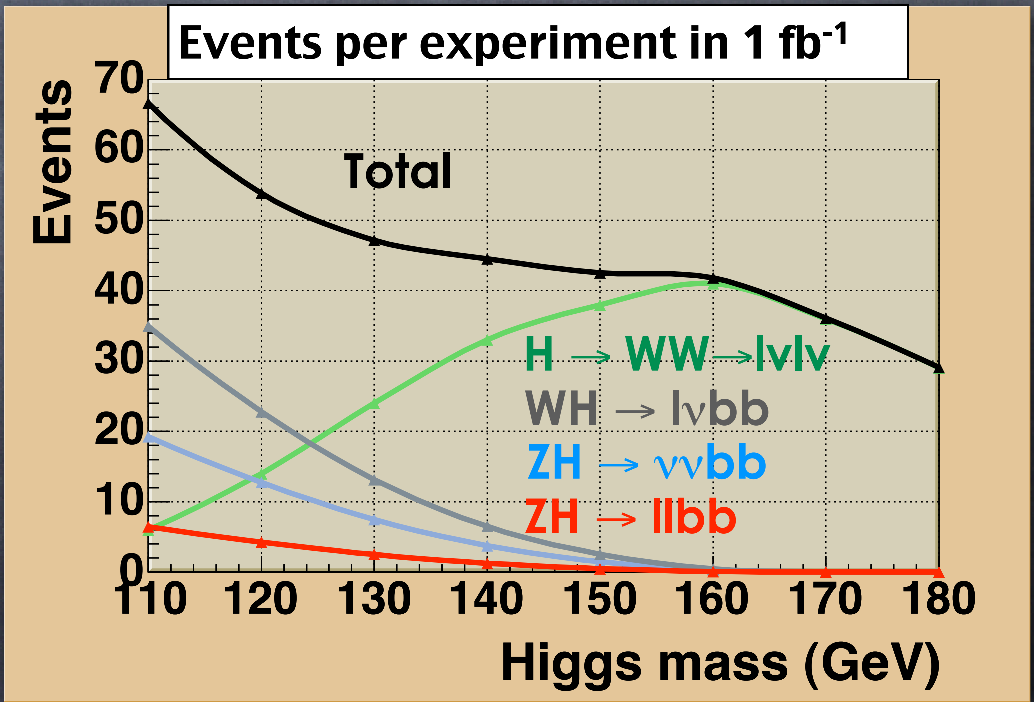


SM Higgs at the Tevatron



Main decay modes





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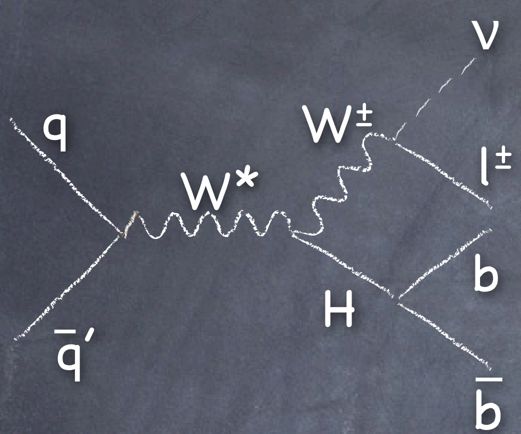

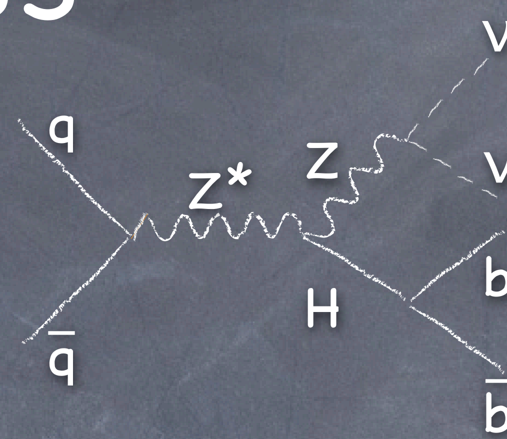

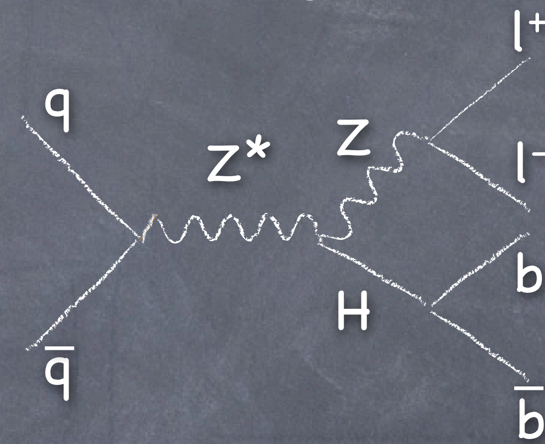

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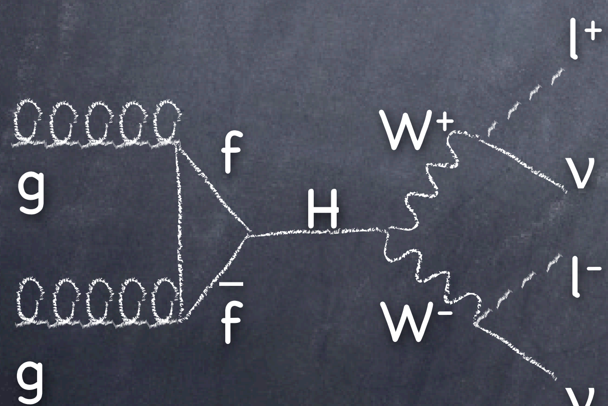

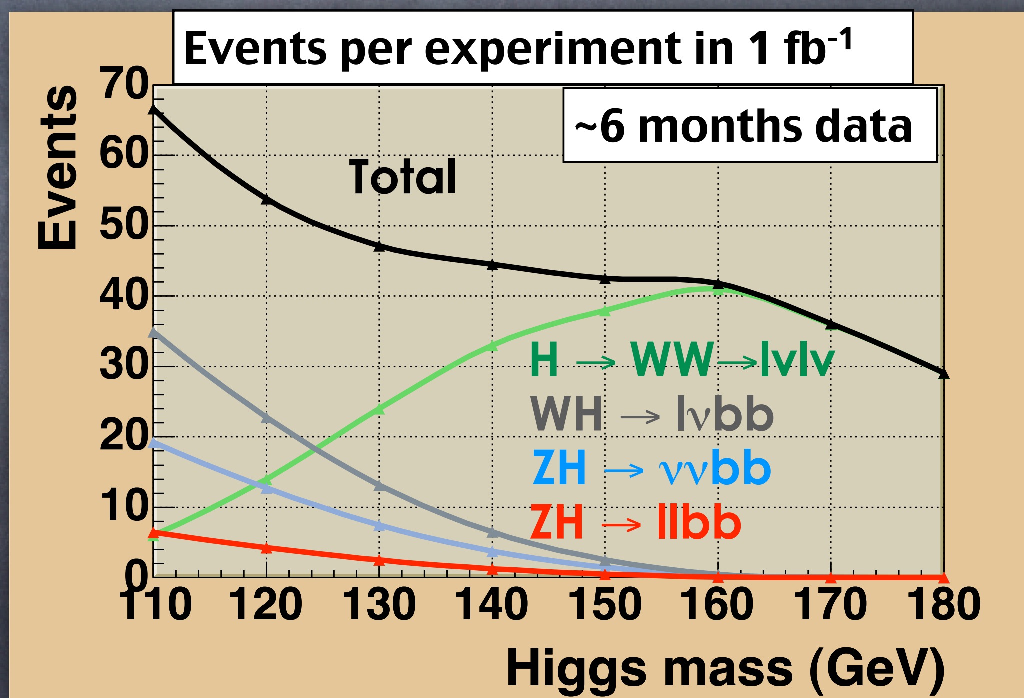

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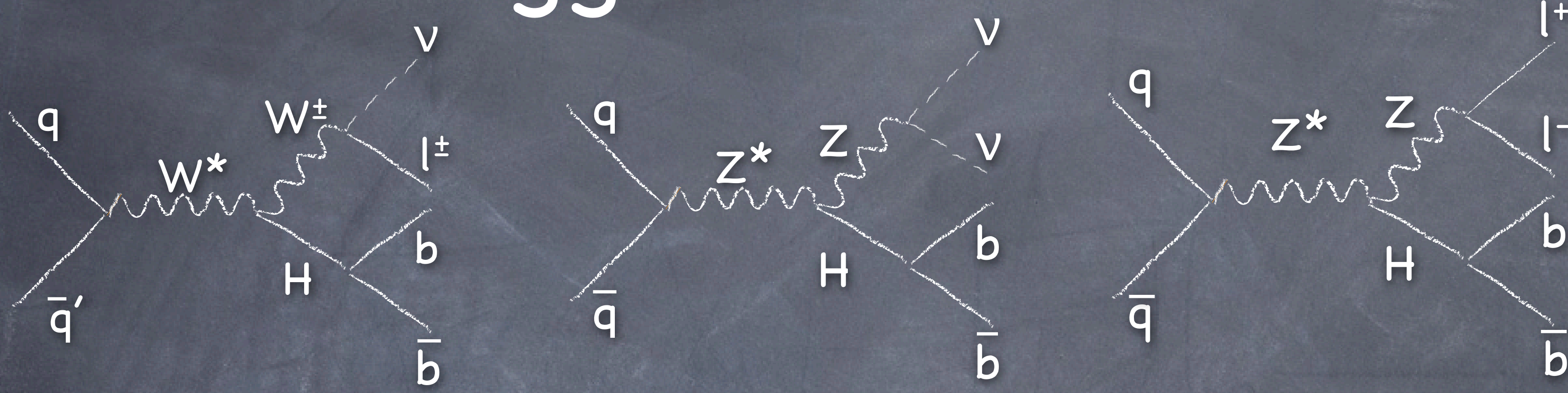

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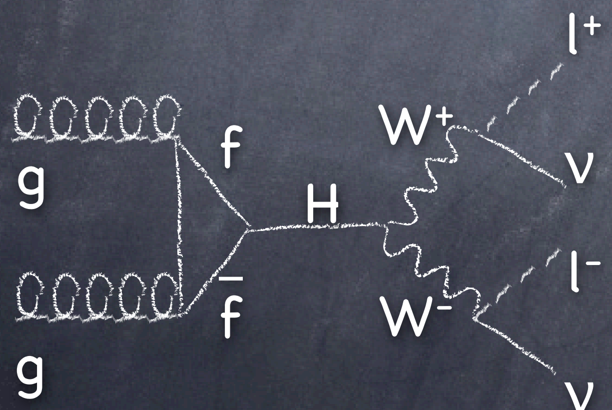
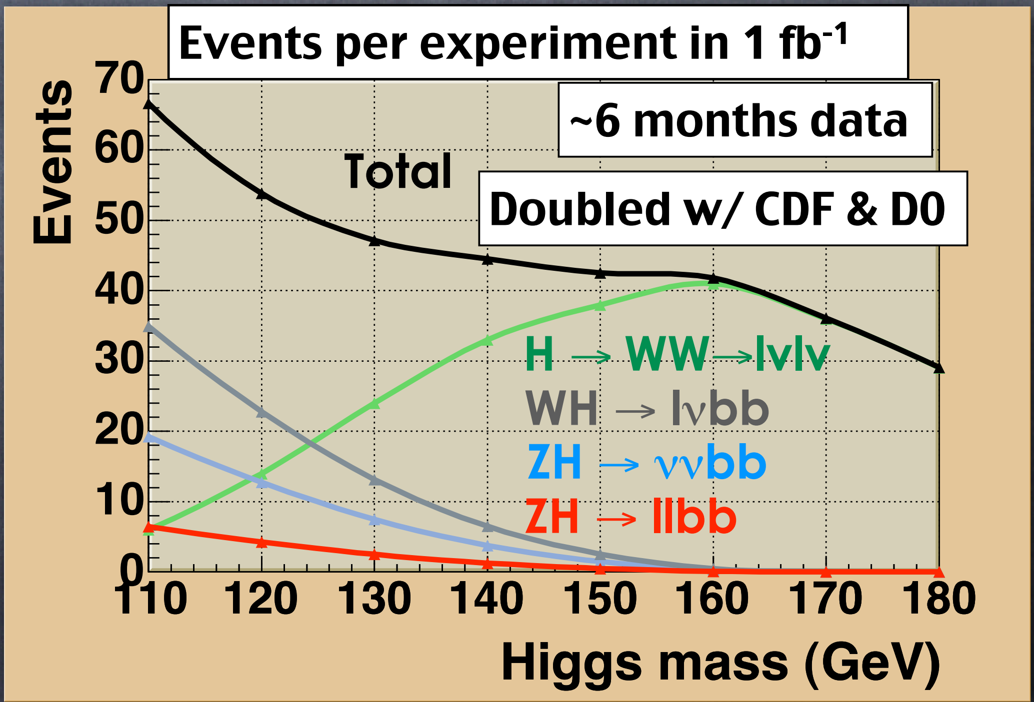
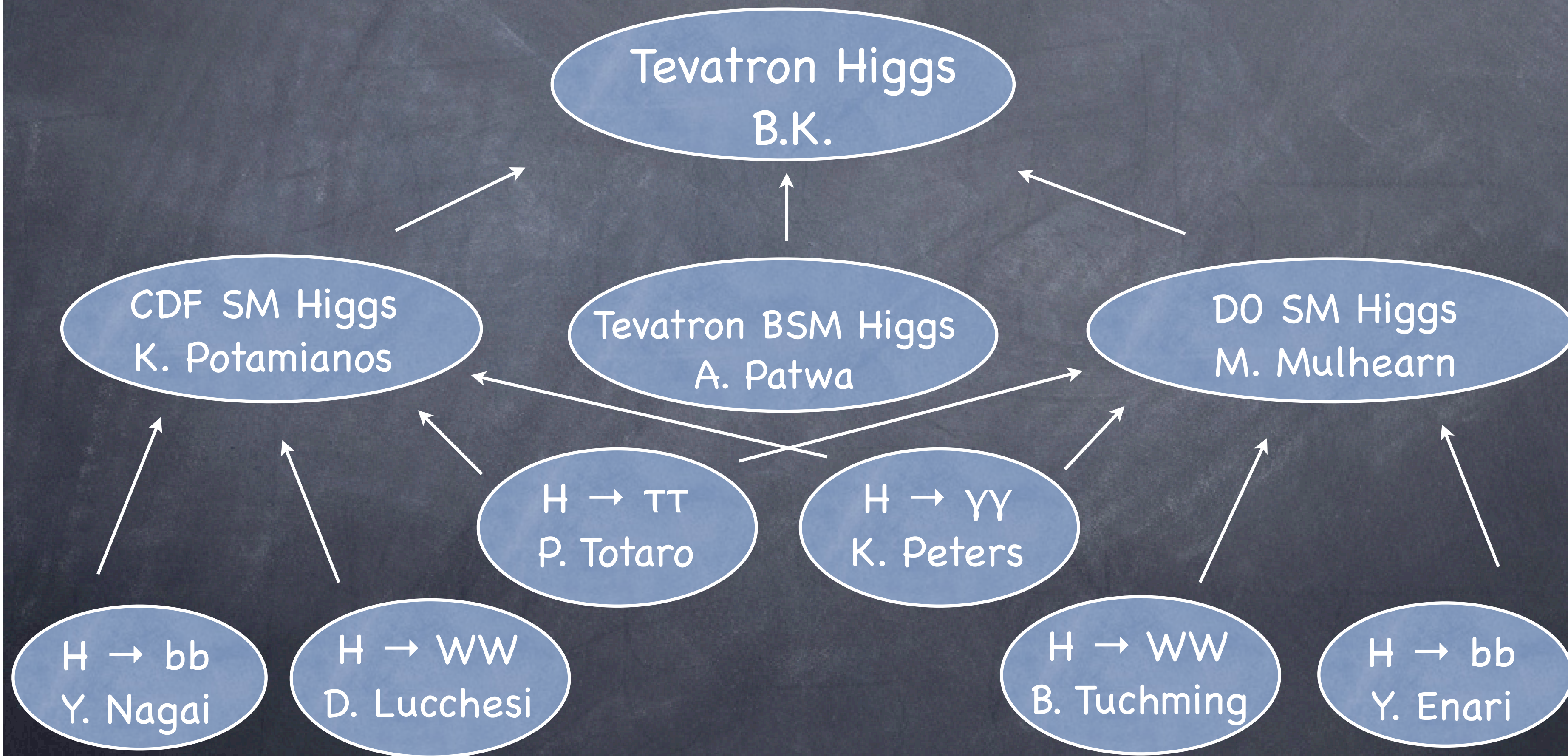




Foundation of presentations

- ICHEP Tevatron Higgs talks
  - Covered variety of Higgs searches and analysis techniques



Tevatron Higgs storyline

- How to build an advanced Higgs analysis program
  - Start with basic analysis for particular channel
  - Bootstrap special techniques to gain sensitivity
    - Improve acceptance
      - Loosen lepton ID & b-tag requirements
      - Add backup triggers
      - Relax kinematic selection
    - But... backgrounds increase & become more difficult to model
      - Incorporate specialized background rejection techniques
      - Don't cut, separate out events into categories with alike S/sqrt(B)
        - High S/sqrt(B) gives best signal sensitivity
        - Low S/sqrt(B) gives best background constraints
      - Use multivariate techniques to distinguish signal events from bkgd
      - Background modeling checks ! Data must stay well modeled !
- Repeat for each Higgs topology per grad student
- Combine modes taking into account uncertainties correlated between backgrounds

Higgs acceptance

Higgs rate small, we reconstruct additional topologies

Production:

$gg \rightarrow H$

$qq \rightarrow H + W$

$qq \rightarrow H + Z$

$qq \rightarrow H + qq$

Decay:

$H \rightarrow WW$

$H \rightarrow bb$

$H \rightarrow \tau\tau$

$H \rightarrow \gamma\gamma$

W , Z decays :

$W \rightarrow l\nu$

$Z \rightarrow ll$

$Z \rightarrow \nu\nu$

$W \rightarrow \tau\nu$

$W \rightarrow qq$

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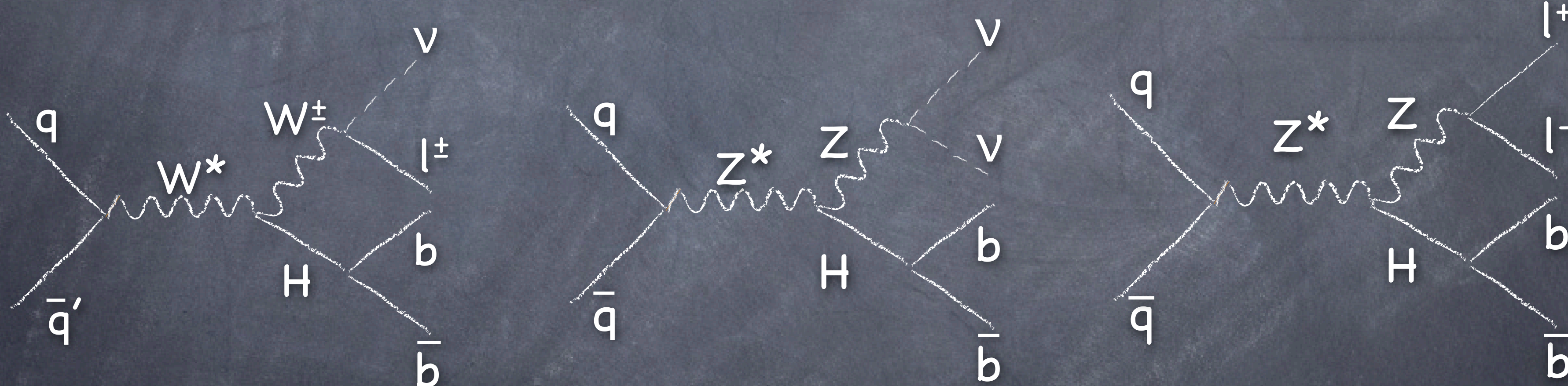
For example :
$qq \rightarrow HZ \rightarrow WWZ \rightarrow l\nu llqq$

Select : electrons, muons, MET, jets

Low mass Higgs searches

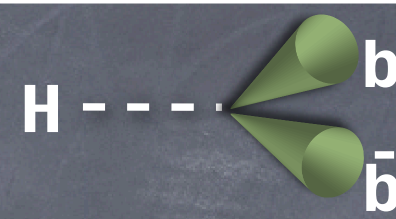
Primary searches similar topology

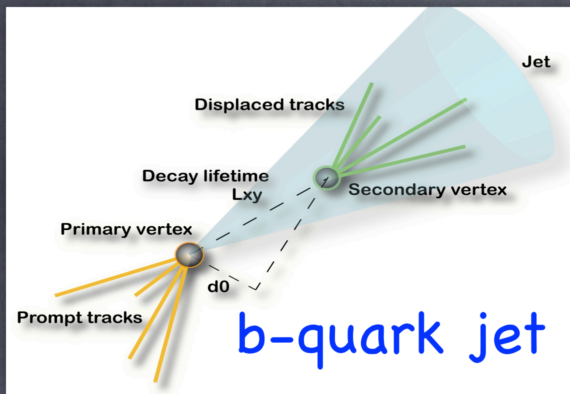


Main backgrounds : W+jets, Z+jets

Goal: search for dijet resonance

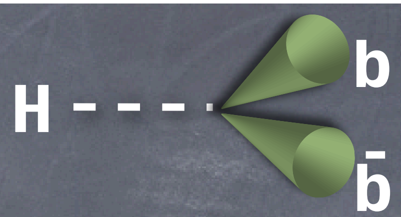
Identifying H → bb





- The "b-tag"
- Distinguishes b-quark jets from light (u,d,s, g) jets
  - Separates W+bb/Z+bb from W+light flavor / Z+ light flavor jets

Identifying H → bb



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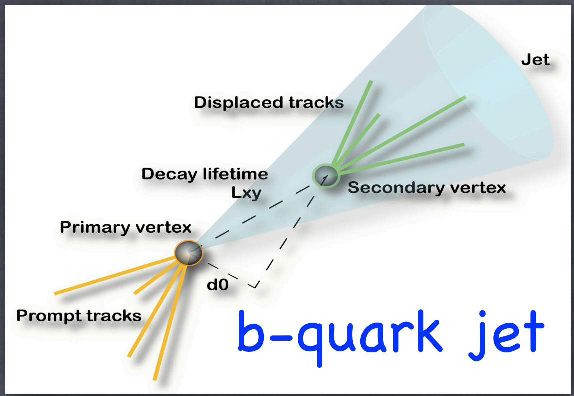
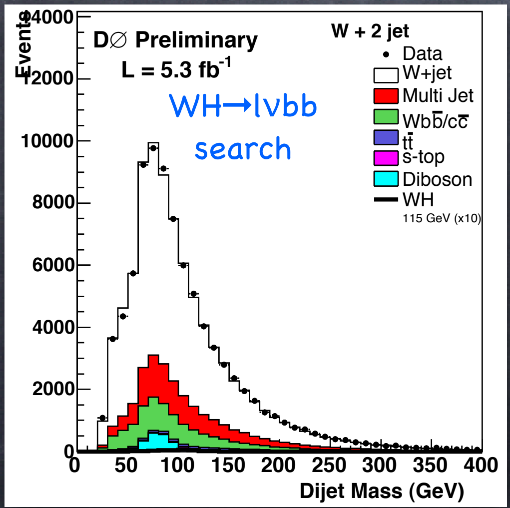
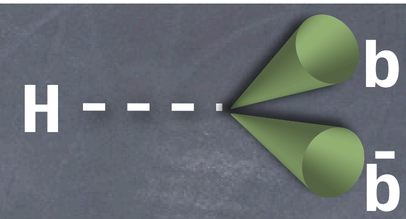
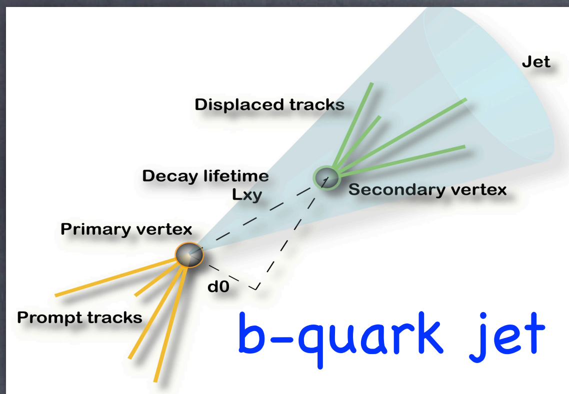




Dijet mass is most sensitive variable to distinguish H → bb from falling background spectrum

Identifying H → bb





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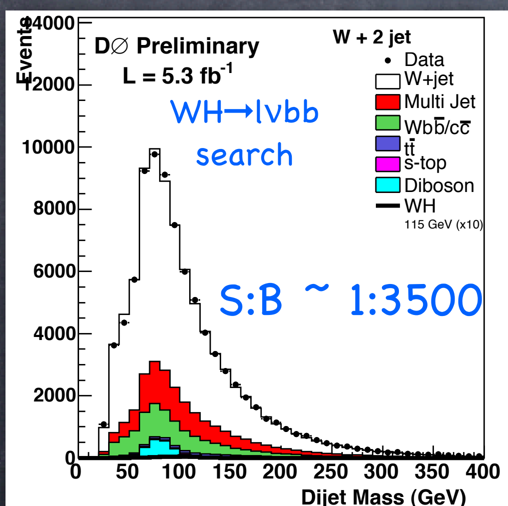
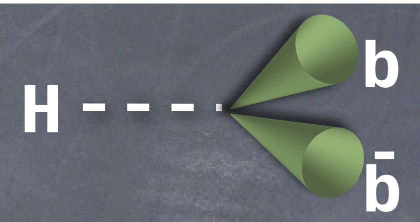
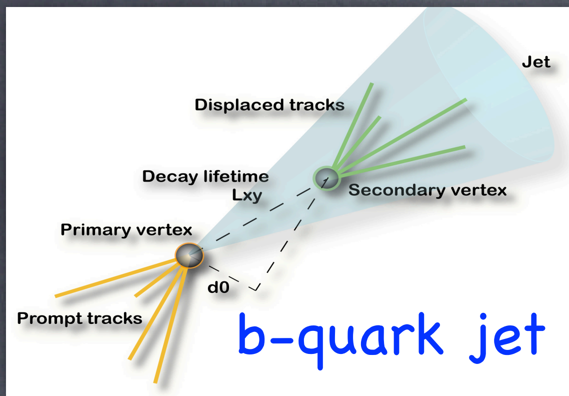


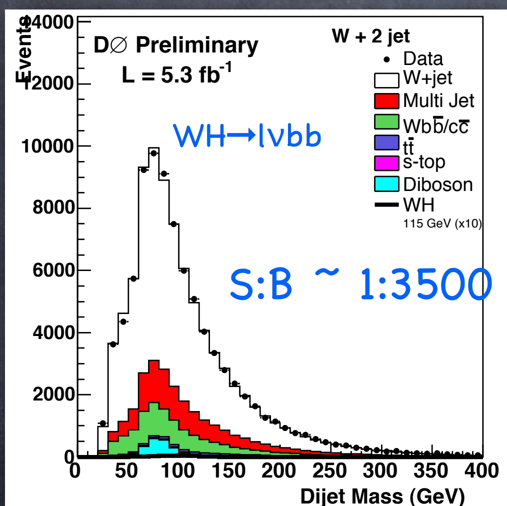
Dijet mass is most sensitive variable to distinguish H → bb from falling background spectrum

1. Before b-tag, poor S/B
   - High statistics sample of W+jets/Z+jets to tests kinematic modeling of important variables (control region)

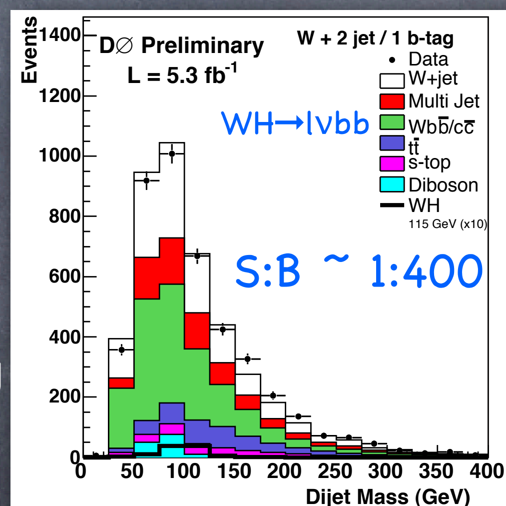
Identifying H → bb



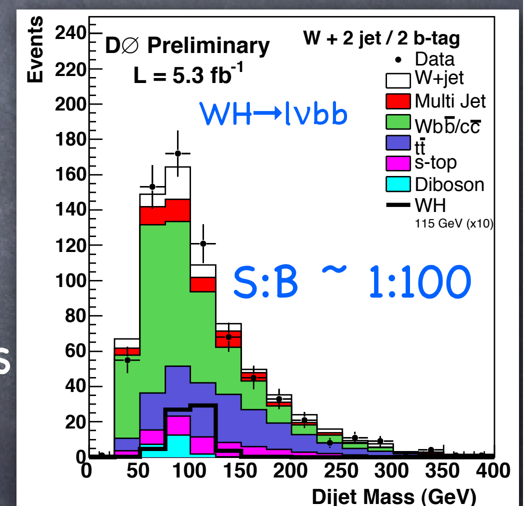




1 b-tag



2 b-tags

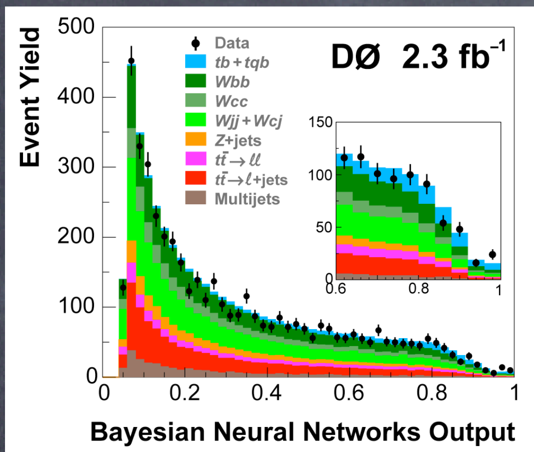


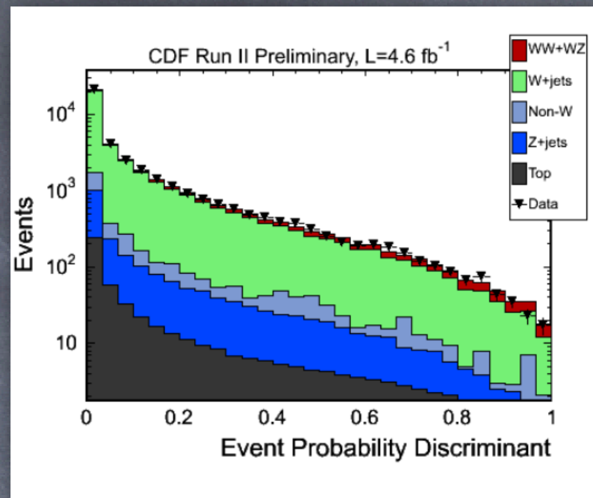
2. After 1 or 2 b-tags
- Signal region with enhanced signal / background

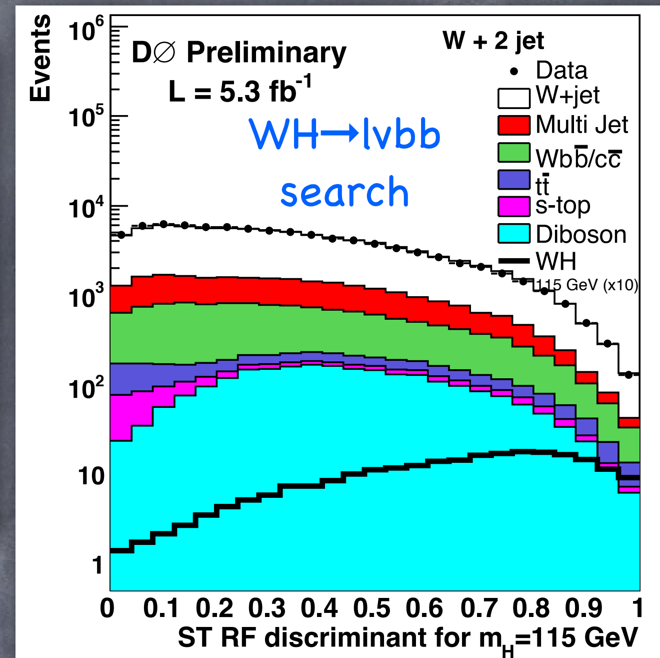
Multivariate techniques

- Multivariate analysis techniques
  - Used in all TeV Higgs analyses
- Functions transform multiple inputs into single discriminant tuned for identifying a single process
- Algorithms have similar performance :
  - NN = Neural Net
  - ME = Matrix Element
  - BDT = Boosted Decision Trees
    - RF = "random forest" of decision trees
- Improve analyses by ~20% with respect to leading two variables
  - Correlations useful
    - ie, if M_{jj} is consistent with Higgs, so better be sum E_T and missing transverse energy
  - Caveat : our primary sensitivity gains in recent years don't come from multivariate techniques
    - Mainly from improved signal acceptance
      - Looser lepton ID
      - Better b-tagging, etc.

Gaining faith in multivariate methods







Single top observation
t+q → lνjj (with b-tag)

Similar to WH → lνbb

Neural Network :
Us : $\sigma(t) = 4.70^{+1.18}_{-0.93}$ pb
SM : $\sigma = 3.46 \pm 1.8$ pb

Diboson observation :
WW + WZ → lνjj

Similar to WH → lνbb

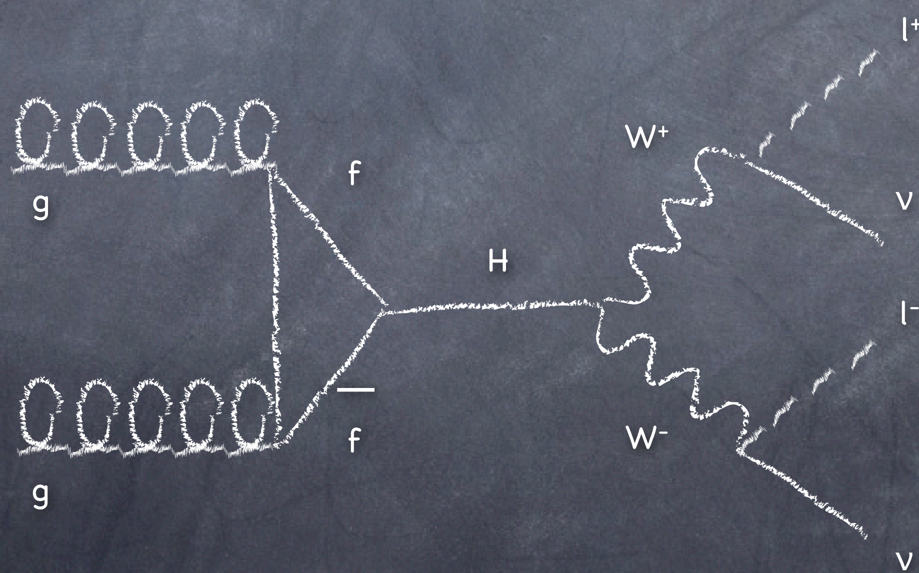
Matrix Element :
Us: $\sigma(WW+WZ) = 16.6^{+3.5}_{-3.0}$ pb
SM : $\sigma = 15.1 \pm 0.8$ pb

WH sample before b-tag
- Similar to WH → lνbb
- Actual control region for WH
- Same object kinematics
- Statistics = 30 * tagged sample
- Random Forest trained on :
  - Masses of jets
  - P_T of combinations
  - Angular separations

High Mass Higgs search

m_H > 125 GeV

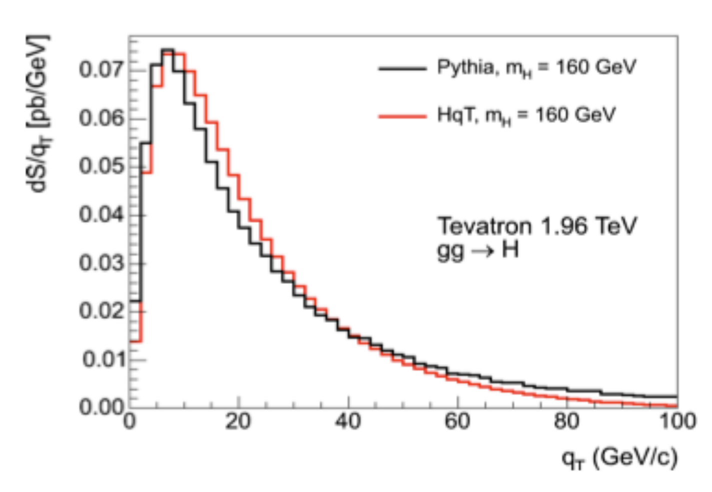
H → WW most important channel



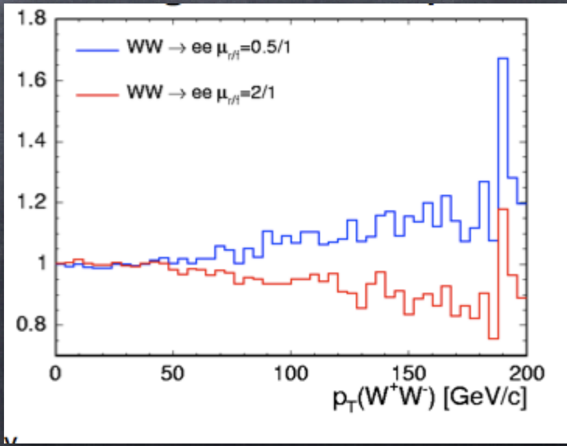
Theory & uncertainties

- We make use of well-motivated and state of the art gluon fusion cross-section calculations and uncertainties
  - gg → H uses NNLL + NNLO calculations
    - "Next to Next to Leading Log/Order"
  - de Florian & Grazzini (Phys.Lett.B674:291-294, 2009)
    - Soft-gluon resummation treatment
    - MSTW2008 Parton Density Function
  - Anastasiou, Boughezal, Petriello (JHEP:0904:003, 2009)
    - Proper treatment of b-quarks at NLO
    - Inclusion of two-loop electroweak effects
- For those interested in a detailed explanation of our choices and comparison with more extreme approaches :

http://tevnphwg.fnal.gov/results/SMHPubWinter2010/gghtheoryreplies_may2010.html



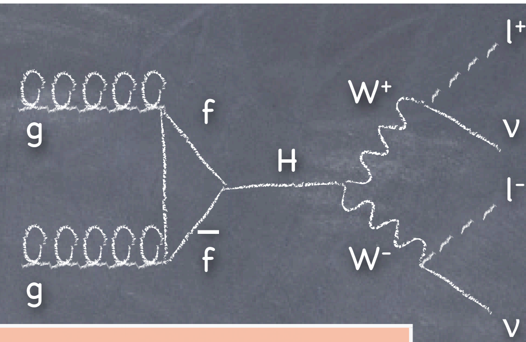
Reweight PYTHIA Higgs kinematics to full NNLL calculation



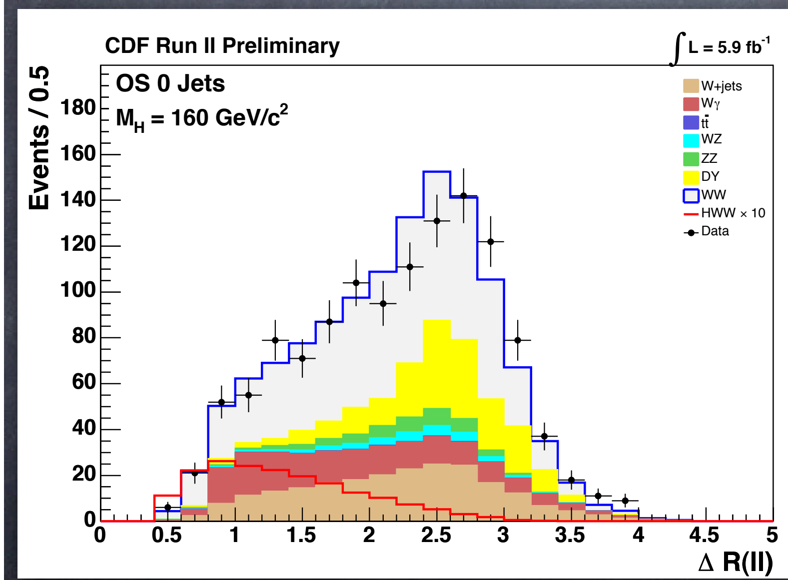
Consider same variations for dominant WW bkg

Basic H → WW analysis

Signature: Opposite charge leptons, high MET, no jets



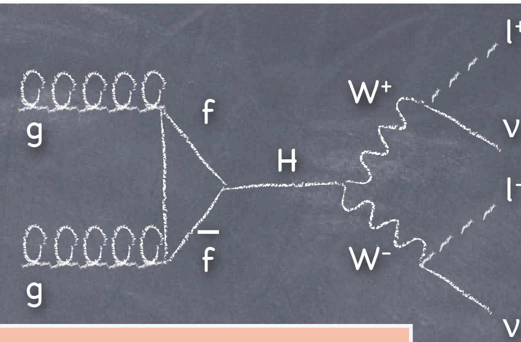
Main Signal	Main BKGs	Key discriminant
gg → H	WW, Wγ	ΔR leptons = "Angle" between leptons



Spin 0 H → WW

Spin 1 Z → WW

Basic H → WW analysis



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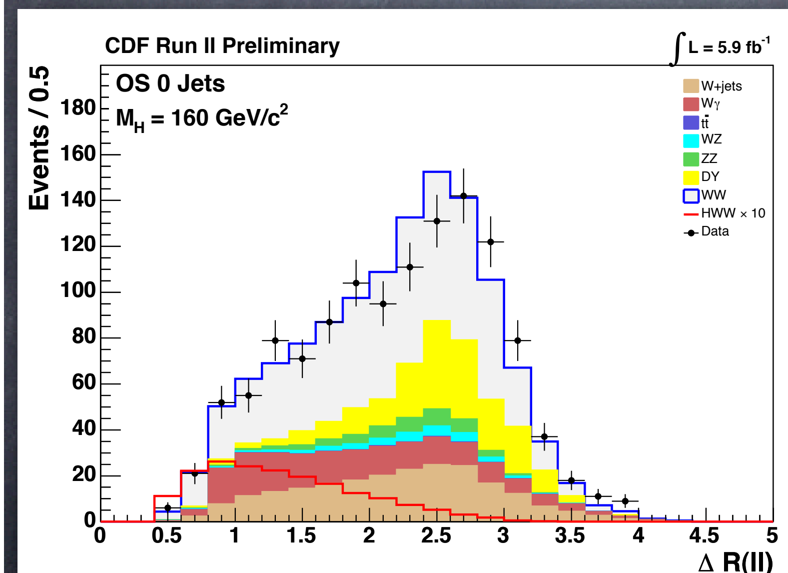
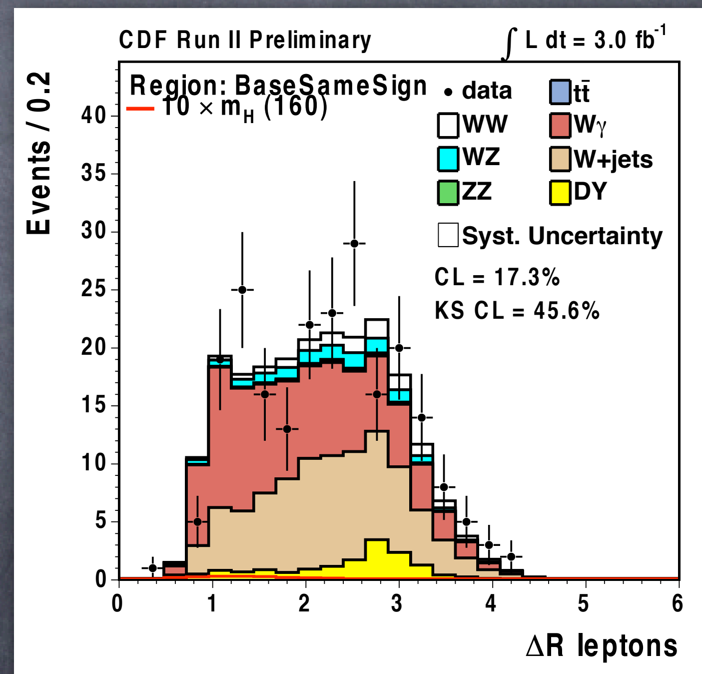


Spin 0 H → WW

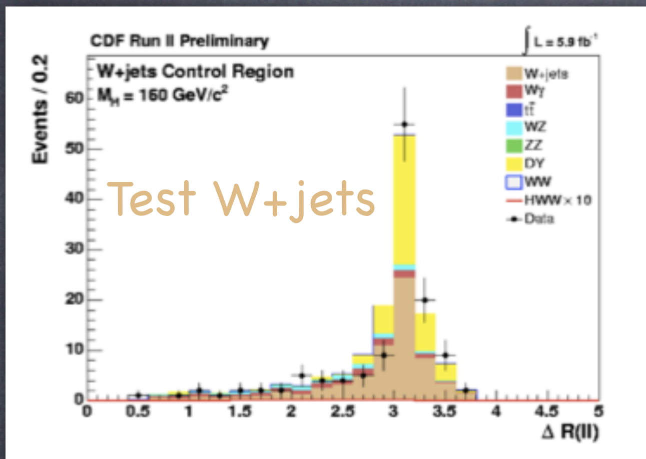
Spin 1 Z → WW

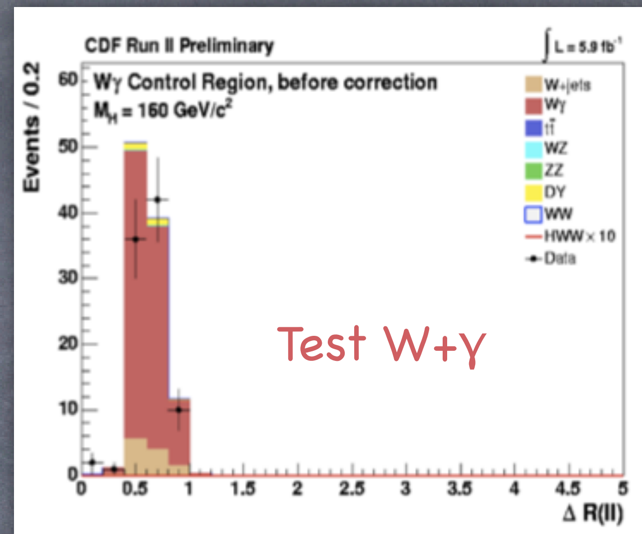
Fakes & conversions: Can check Same Sign modeling



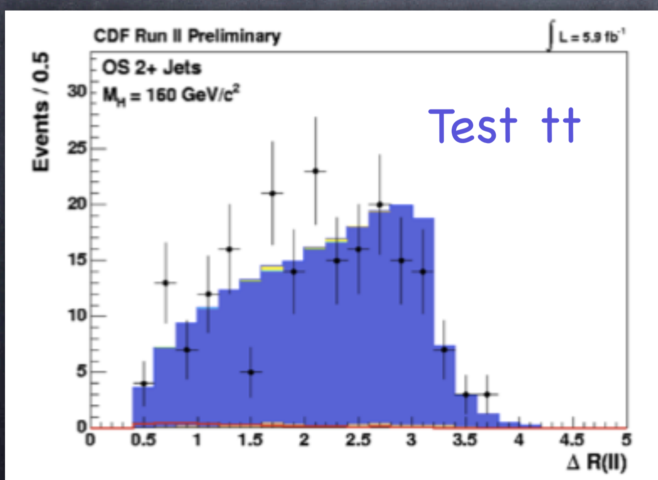
Validating background models

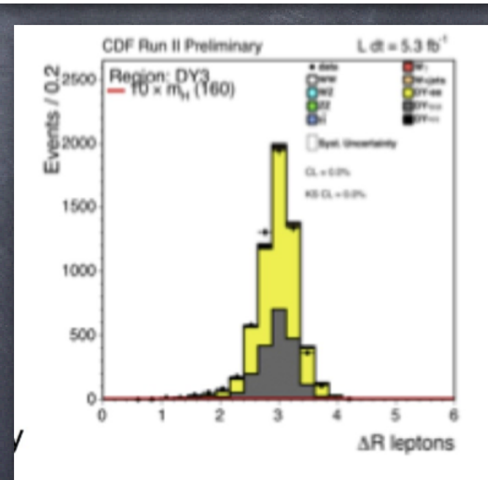
- H→WW topologies have different main backgrounds:
  - Isolate control regions to test rate & shape of dominant backgrounds





Most sensitive kinematic variable $dR(l_1,l_2)$





Test Drell-Yan

Summary of low & high mass results

Channel	Expt	Dataset now	Increase since Nov. 2009 combination
$H \rightarrow WW$	D0	6.7	24%
$H \rightarrow WW$	CDF	5.9	23%
$WH \rightarrow l\nu bb$	CDF	5.7	30%
$WH \rightarrow l\nu bb$	D0	5.3	6%
ZH/WH→METbb	CDF	5.7	60%
ZH/WH→METbb	D0	6.4	23%
$ZH \rightarrow llbb$	CDF	5.7	40%
$ZH \rightarrow llbb$	D0	6.2	45%
$H \rightarrow \gamma\gamma$	CDF	5.4	New!
$H \rightarrow \gamma\gamma$	D0	4.2	0%
$H \rightarrow \tau\tau$	CDF	2.3	15%
$H \rightarrow \tau\tau$	D0	4.9	0%
ZH/WH→qqbb	CDF	4	100%
ttH	D0	2.1	0%

Summary of low & high mass results

Channel	Expt	Dataset now	Increase since Nov. 2009 combination
H → WW	D0	6.7	24%
H → WW	CDF	5.9	23%
WH → lvbb	CDF	5.7	30%
WH → lvbb	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

New

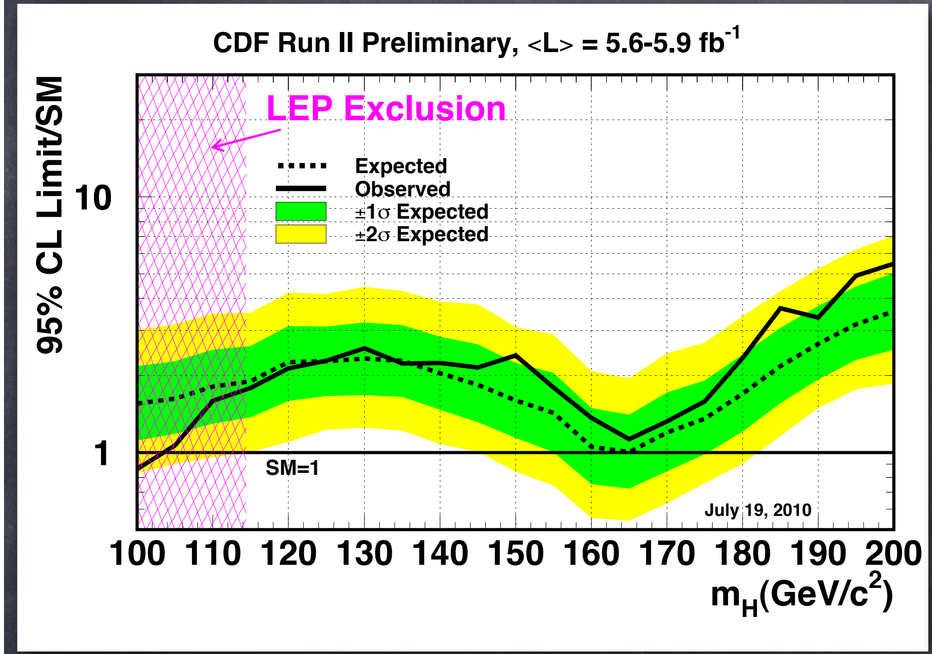
CDF & D0 Combinations

Each experiment combines all its searches to produce one set of limits

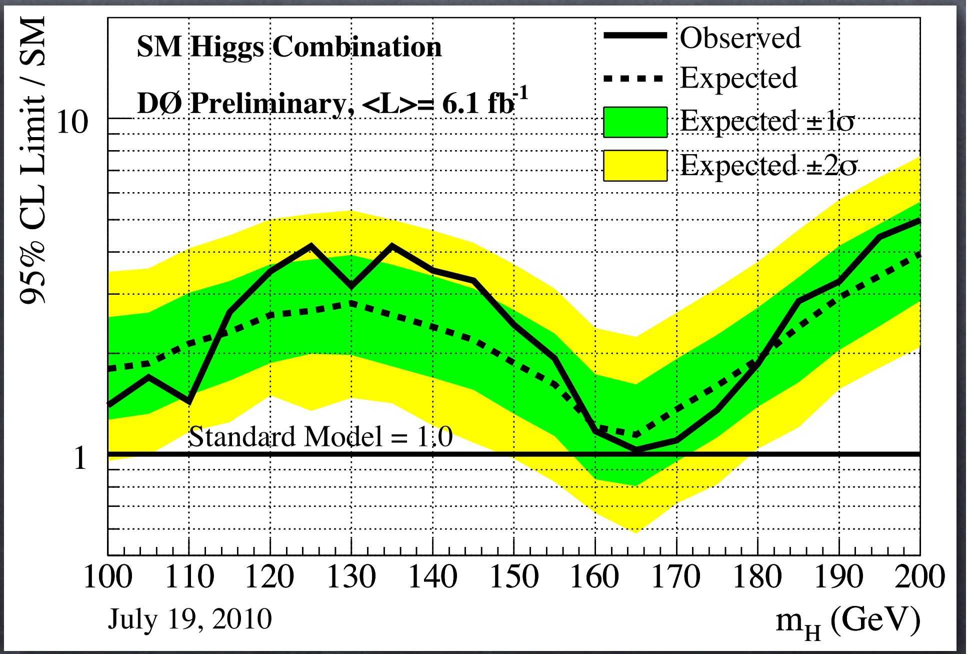
CDF & D0 combinations

Shown first on July 23, 2010

CDF's limits



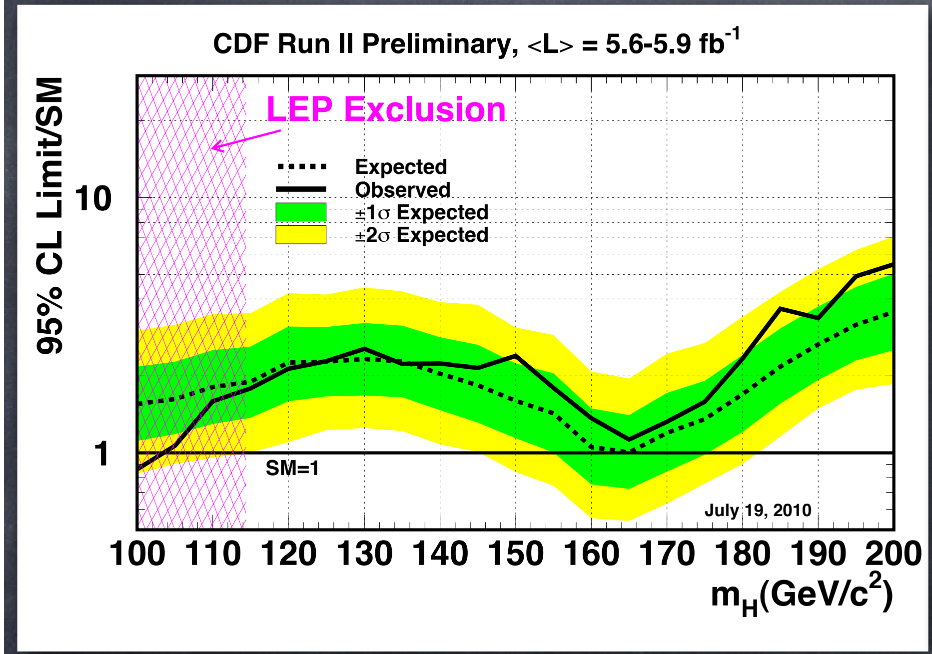
D0's limits



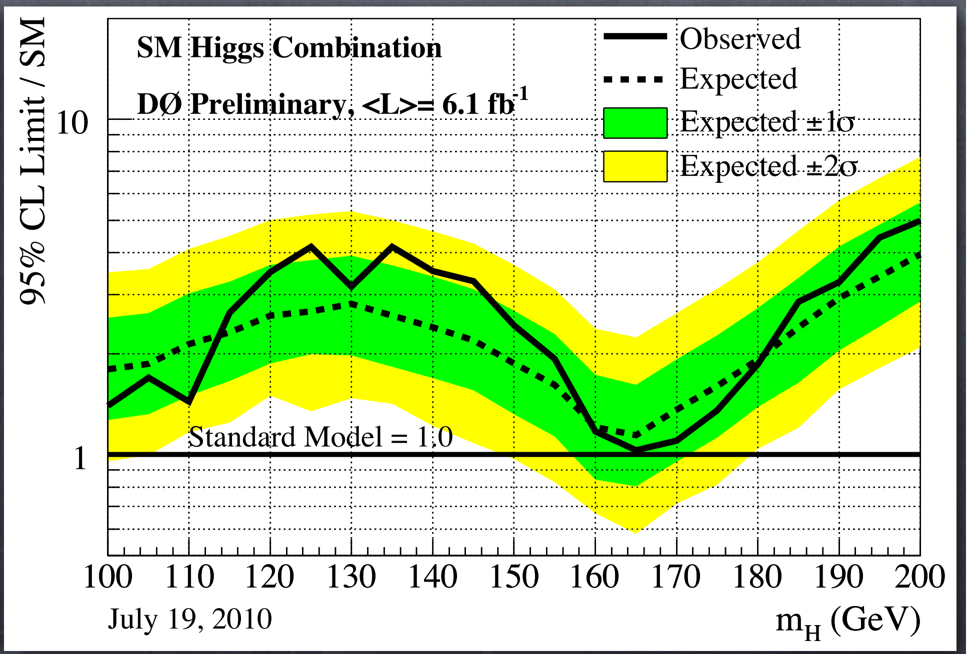
CDF & D0 combinations

Shown first on July 23, 2010

CDF's limits



D0's limits



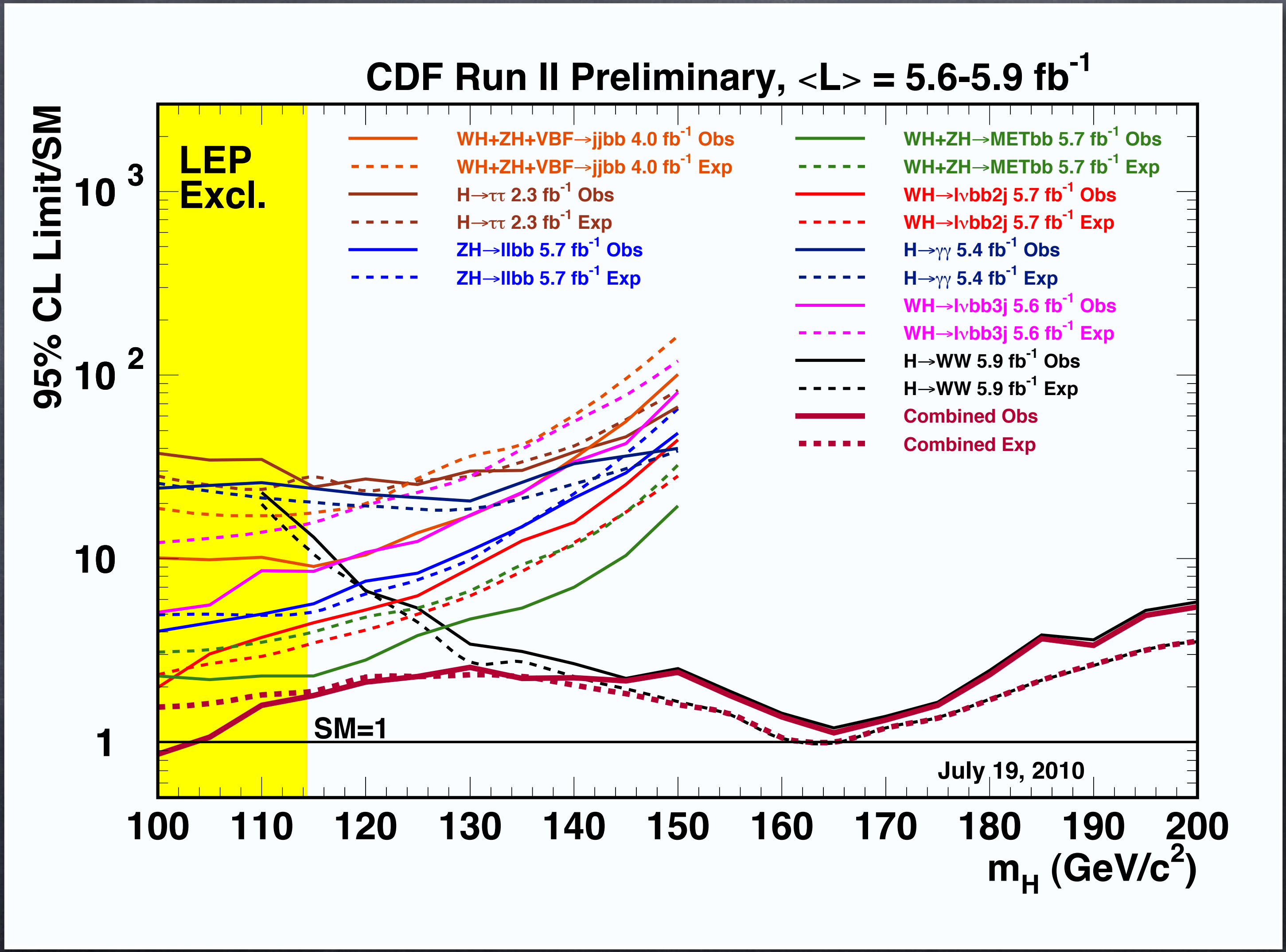
CDF achieves expected exclusion at 165 GeV

D0 almost achieves observed exclusion at 165 GeV

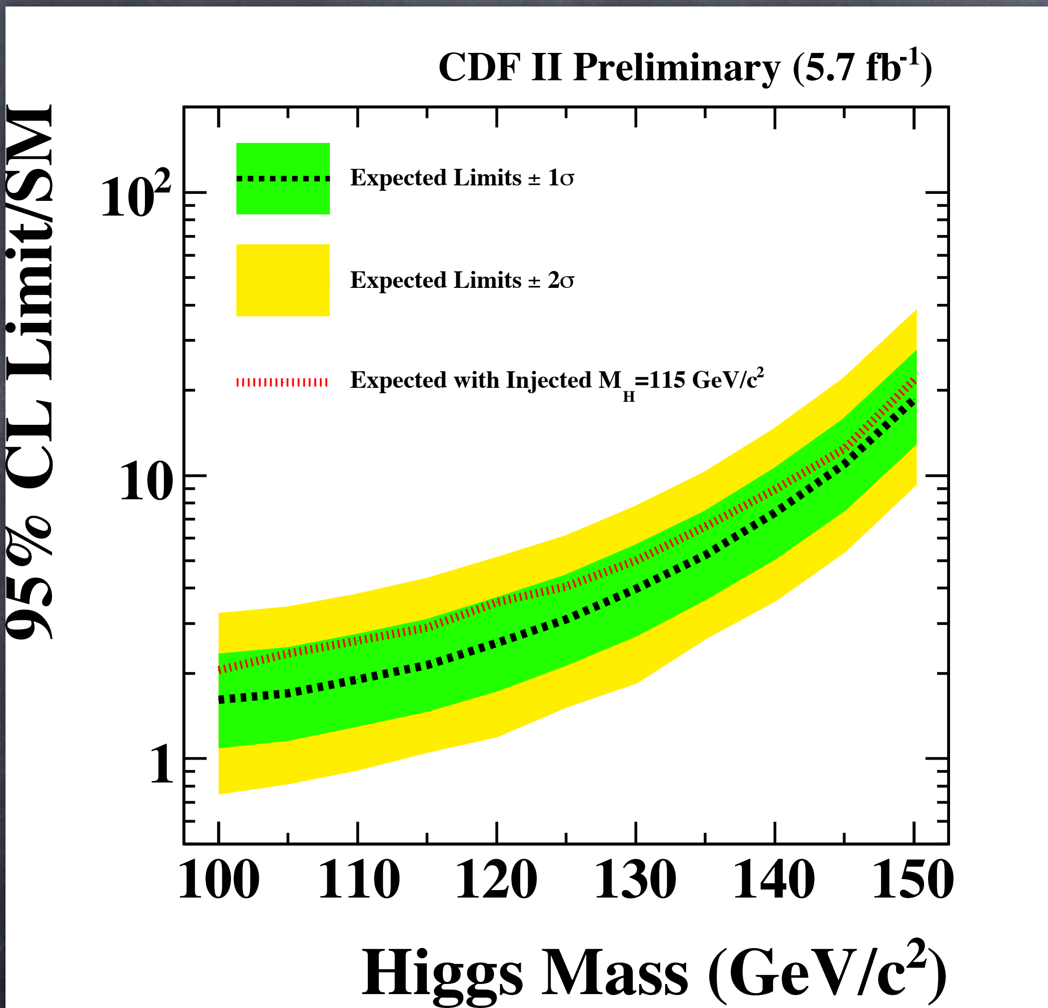
@ m_H = 100 GeV, both set observed limits below expected

Closing in on low mass LEP exclusion

What goes into the combination?



What would a signal look like ?



CDF test:

* Inject m_H = 115 GeV signal into pseudoexperiments

(just CDF ZH→llbb, WH→lνbb, ZH→ννbb)

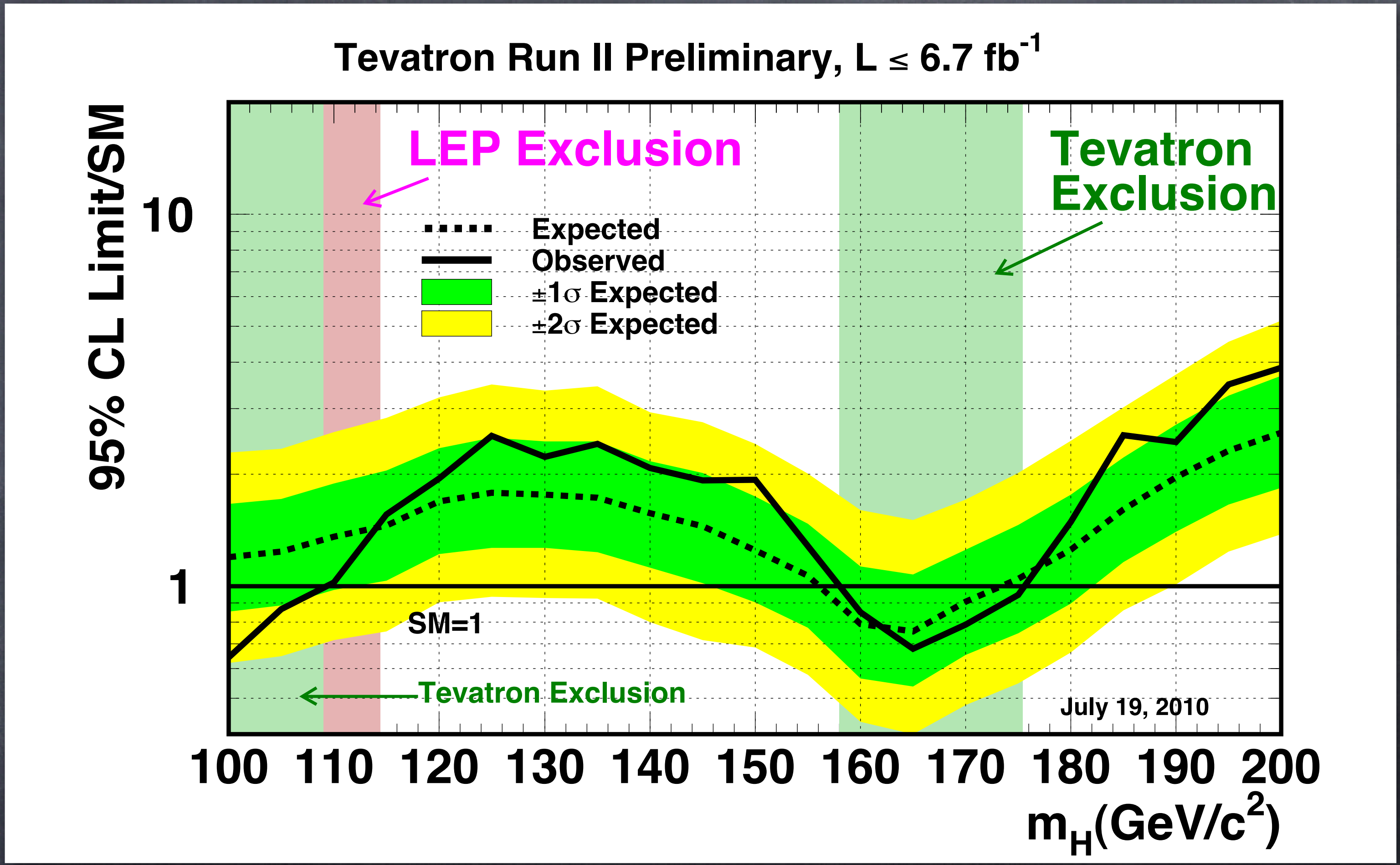
1 sigma high effect would get more pronounced with other channels and D0 as well

And now,
here is the
Tevatron (CDF + D0)
combination

… Please scroll down …

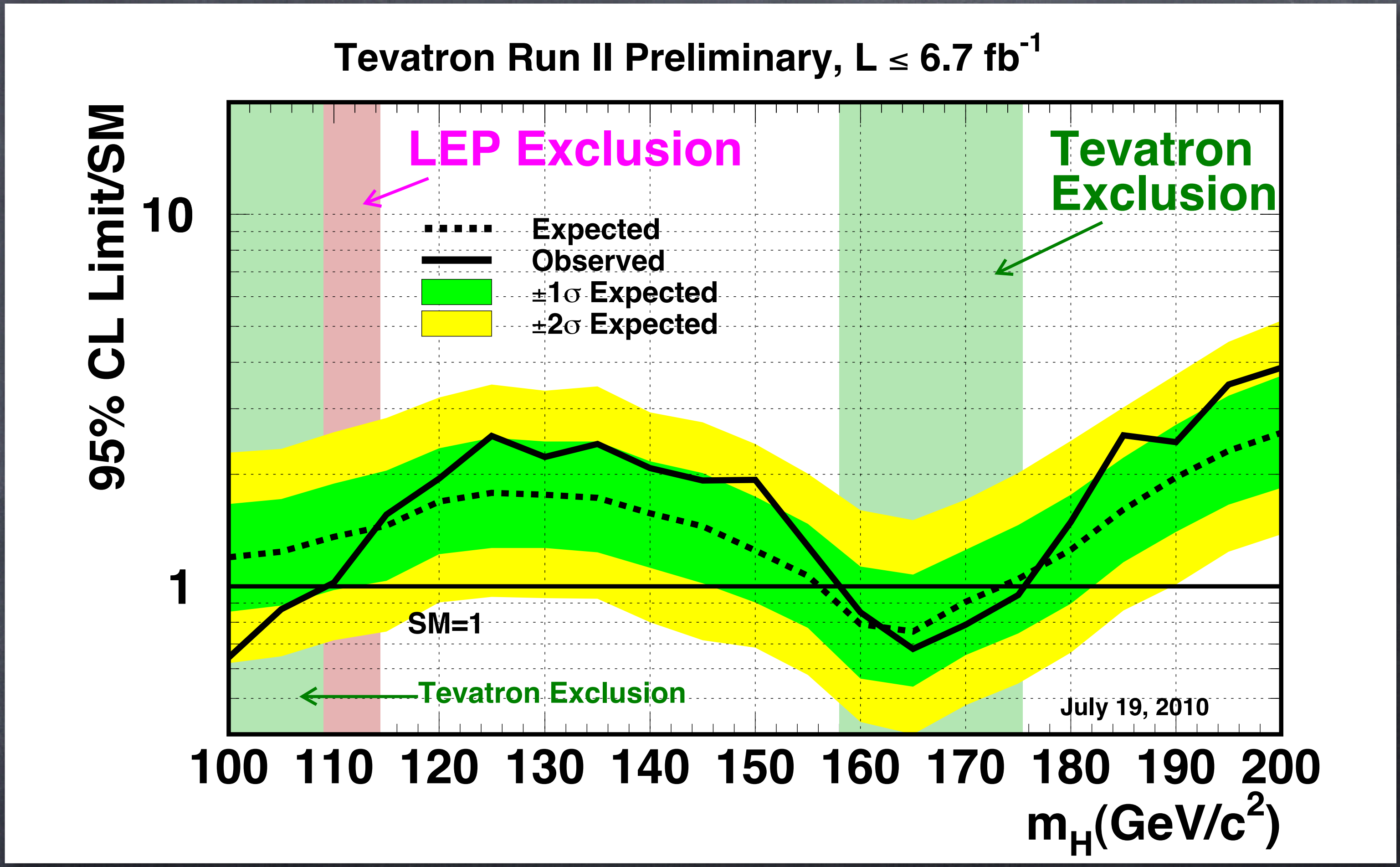
Tevatron combination

"Expected sensitivity"



Tevatron combination

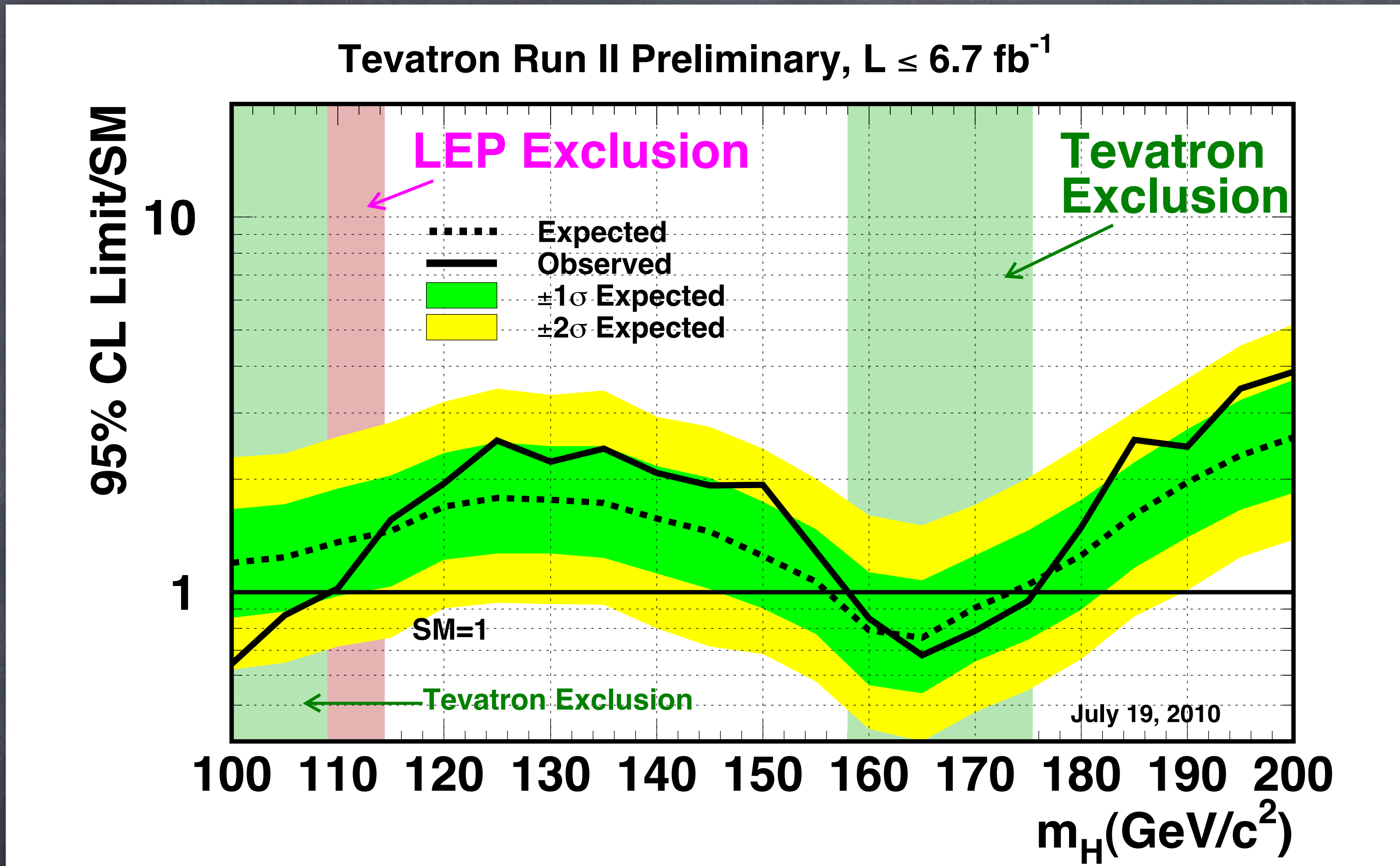
"Expected sensitivity"



- High mass 95% CL exclusion :
  - $158 < m_H < 175$ GeV
    - 4 times previous (162 – 166 GeV)
    - Expected ($156 < m_H < 175$ GeV)

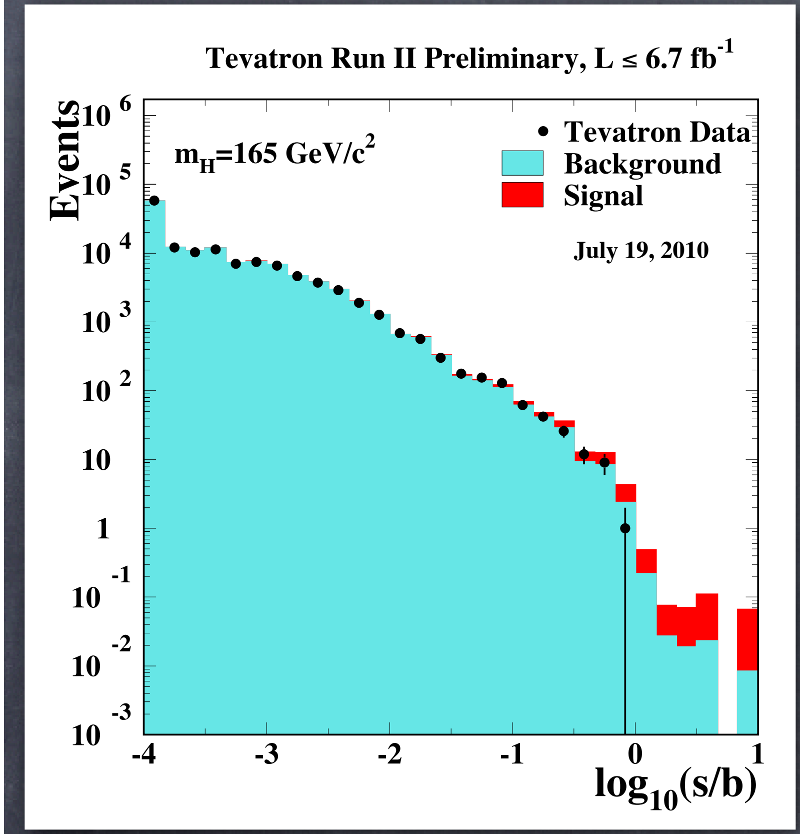
Tevatron combination

"Expected sensitivity"

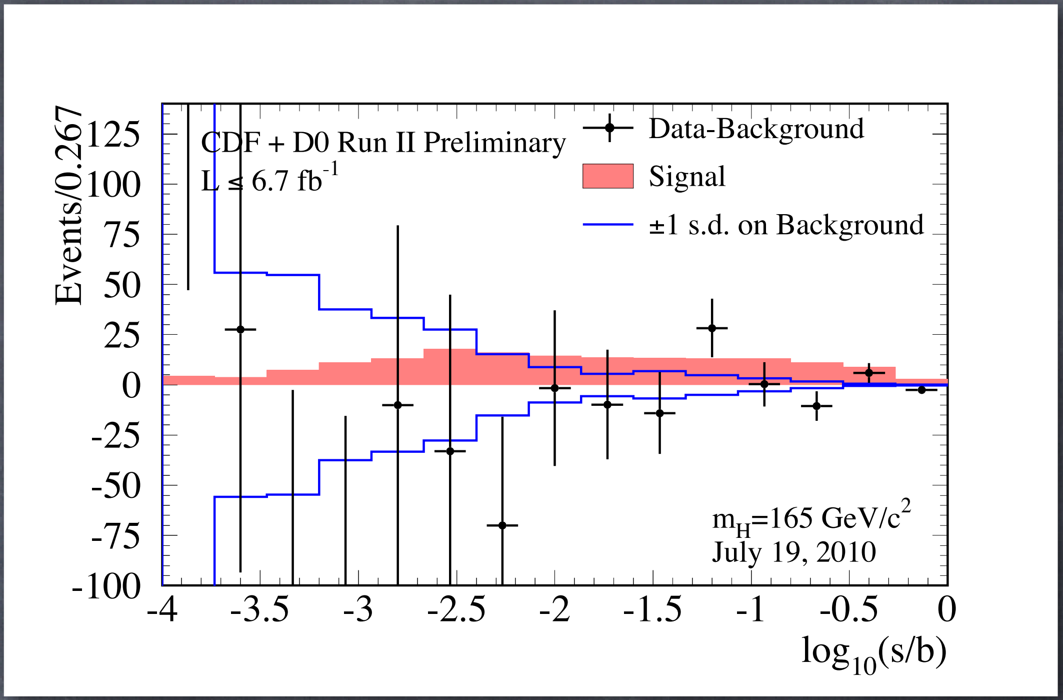


- Low mass sensitivity approaching LEP exclusion :
  - Expected 1.45*SM @ 115 GeV
  - Expected 1.24*SM @ 105 GeV
- High mass 95% CL exclusion :
  - $158 < m_H < 175$ GeV
    - 4 times previous (162 - 166 GeV)
    - Expected ($156 < m_H < 175$ GeV)

Hypothesis : m_H = 165 GeV

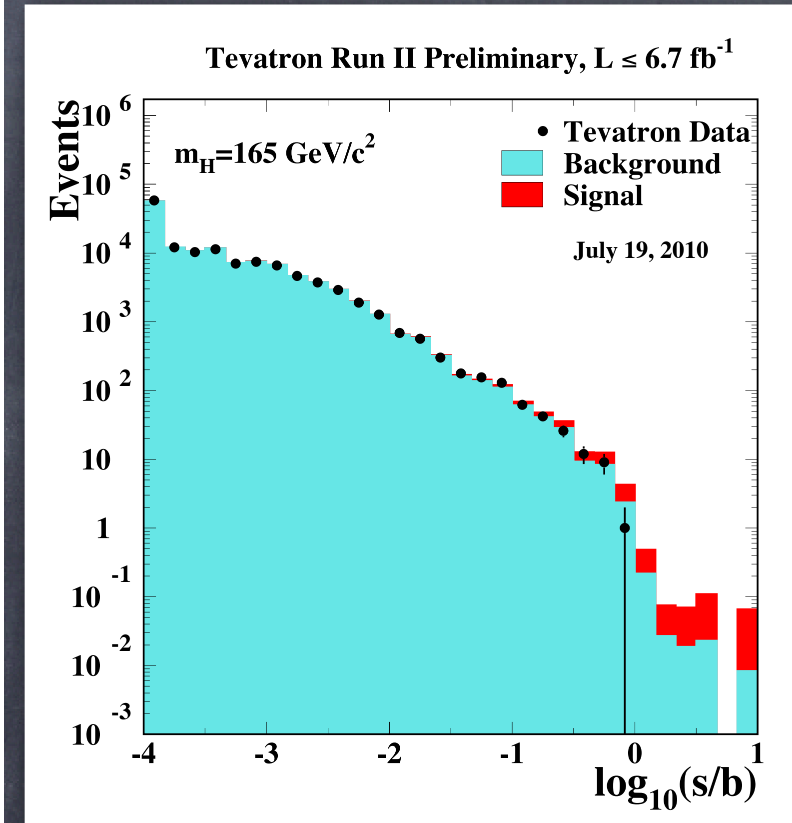


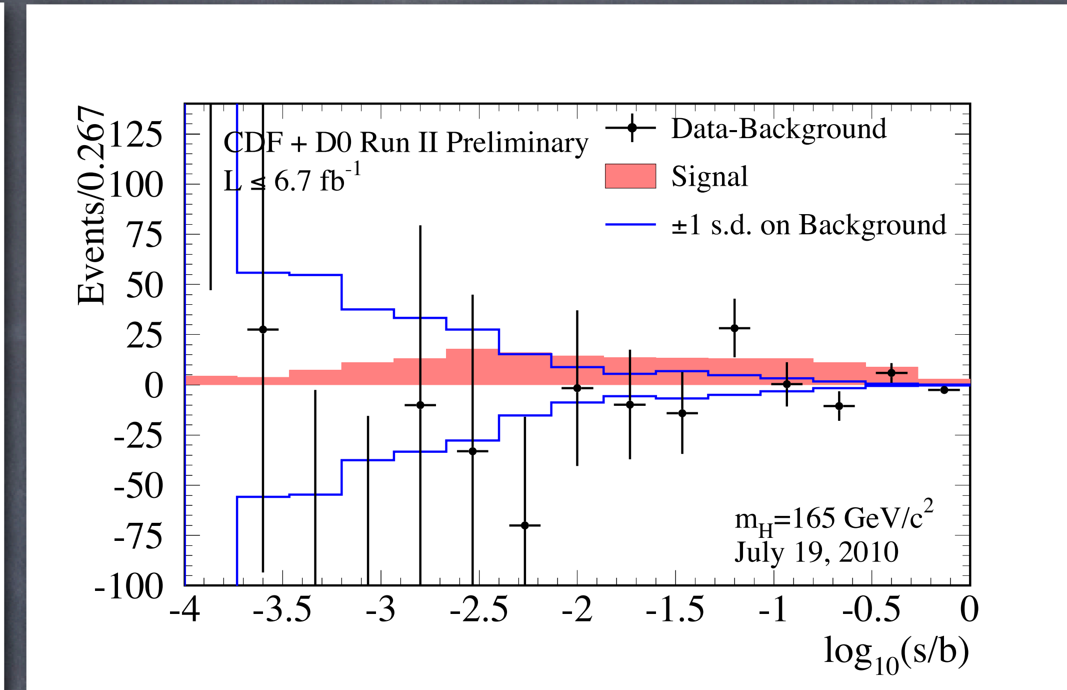
All bins of all sub-channels of all channels



Data - Background shown compared to signal in red

Hypothesis : m_H = 165 GeV





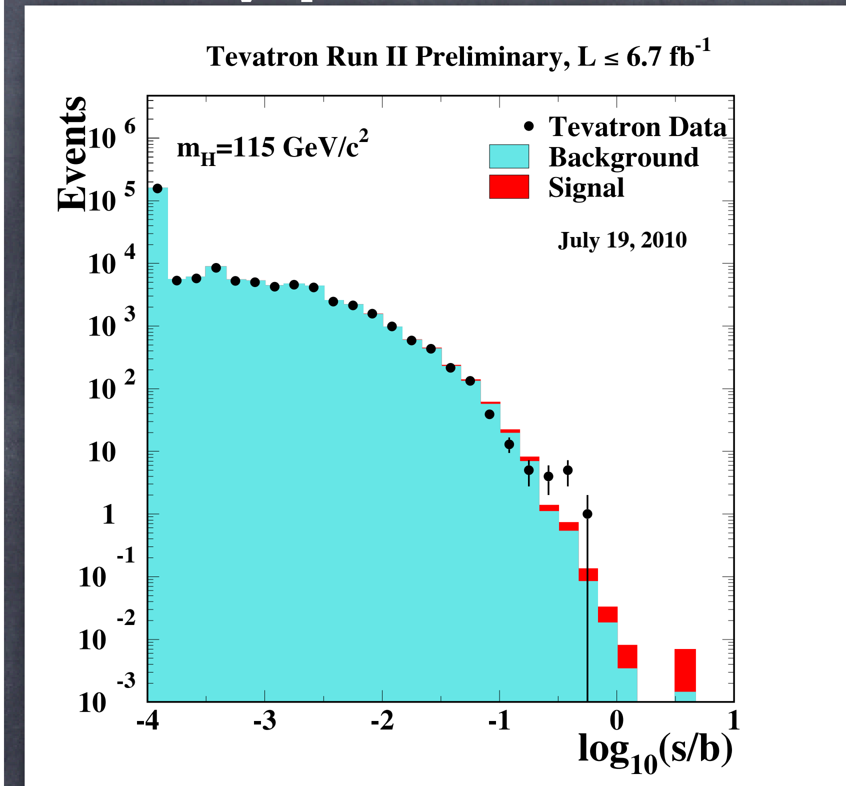
All bins of all sub-channels of all channels

Data - Background shown compared to signal in red

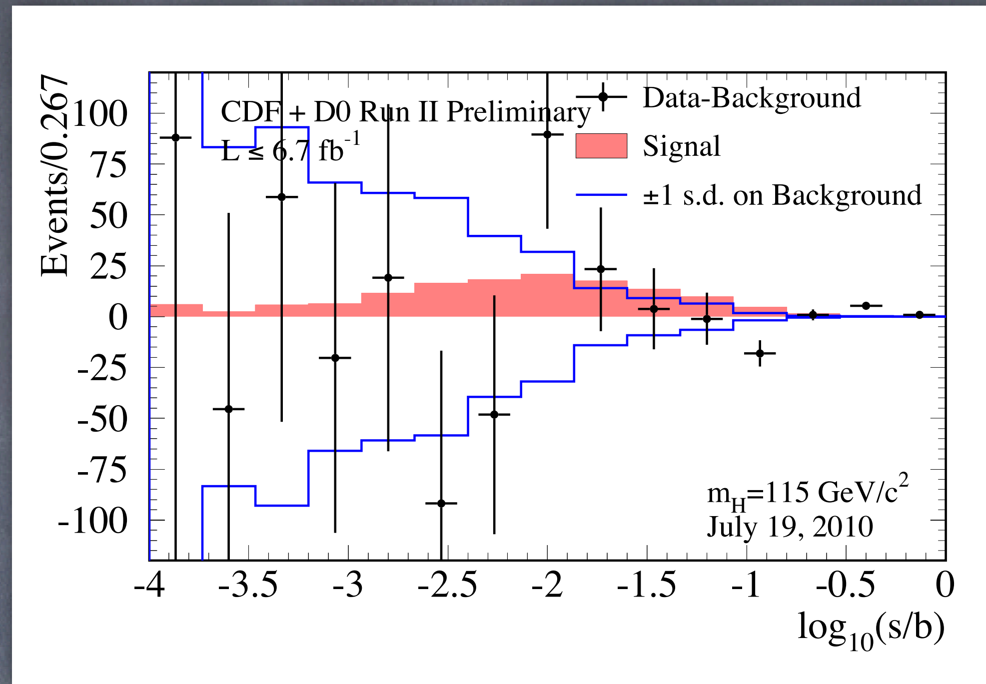
Excellent modeling, consistent with no signal :

Exclusion at 165 GeV

Hypothesis : m_H = 115 GeV

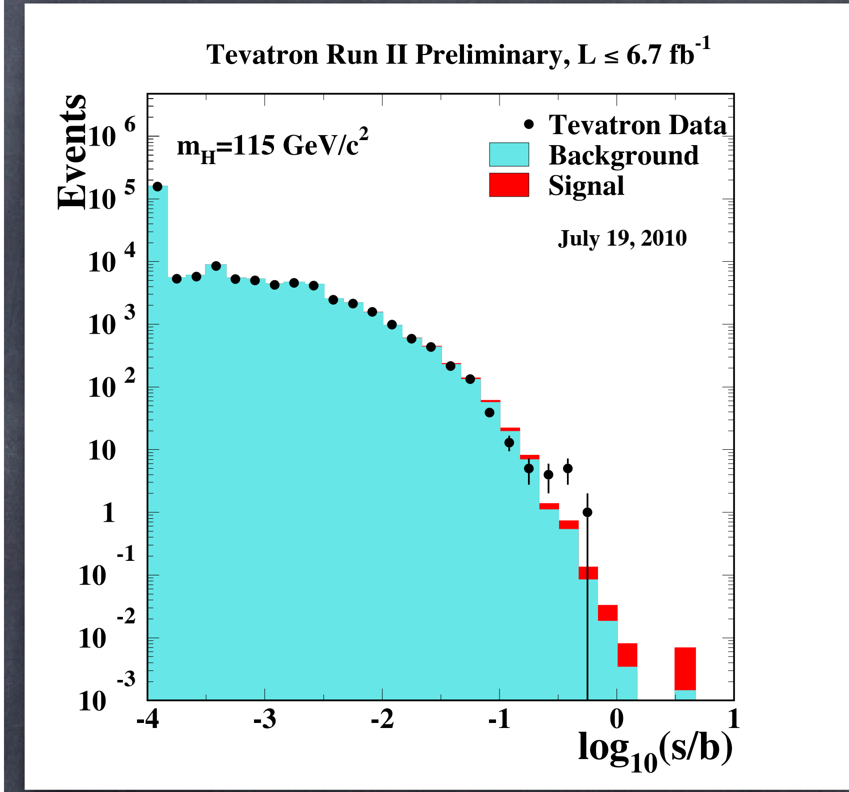


All bins of all sub-channels of all channels

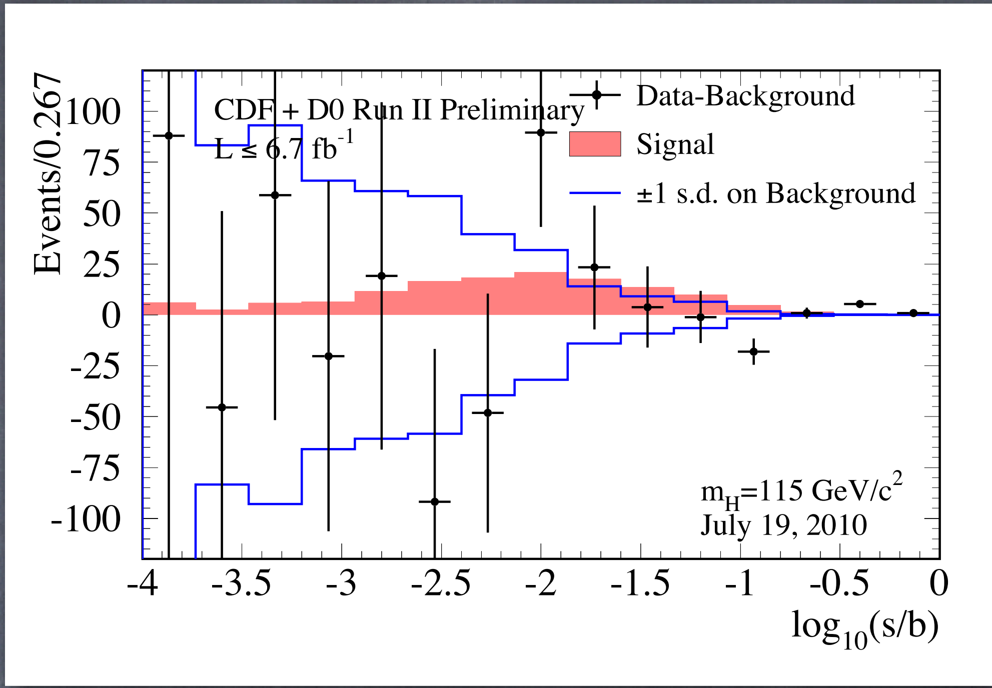


Data - Background shown compared to signal in red

Hypothesis : m_H = 115 GeV



All bins of all sub-channels of all channels



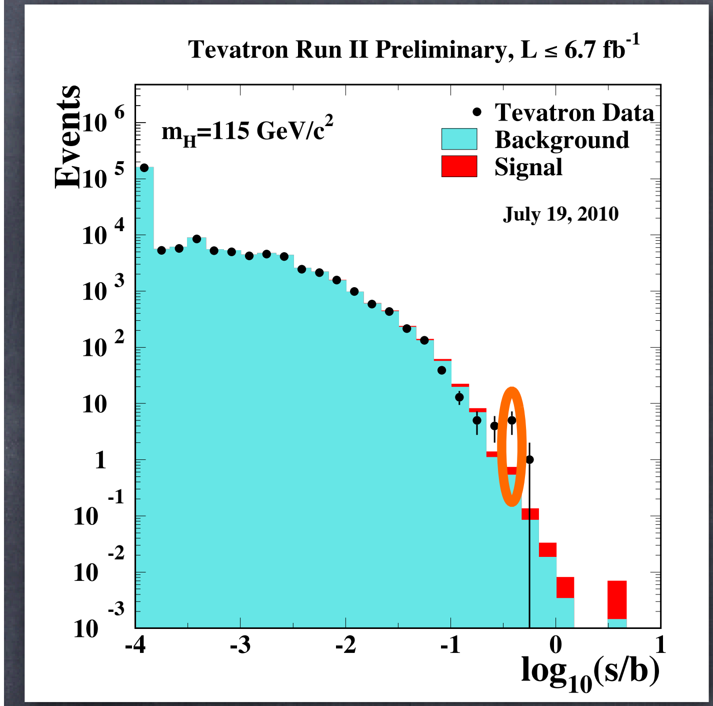
Data - Background shown compared to signal in red

Fluctuations: Excess and deficit average out :

Expected limit 1.45*SM

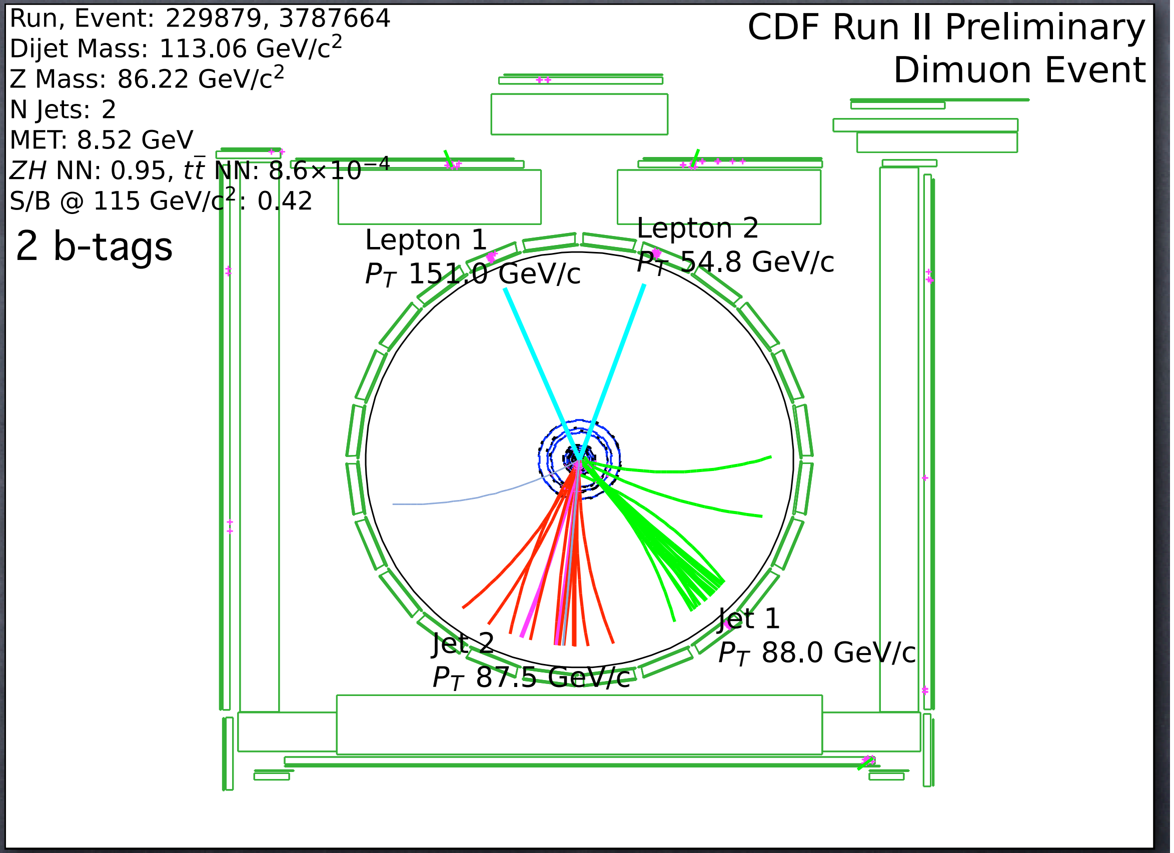
Observed limit 1.56*SM

Hypothesis : m_H = 115 GeV



Data : 5 events,
Expectation 0.8 events
S:B ~ 1:2

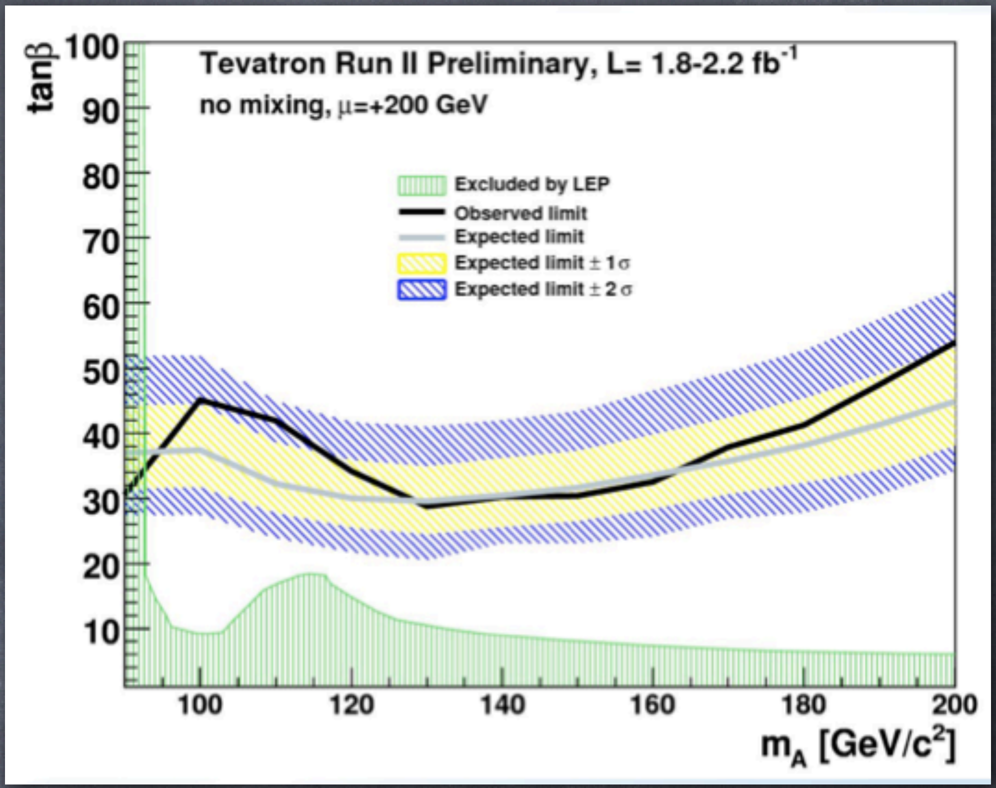
Candidate event



Beyond SM Higgs

Search for Supersymmetric Higgs boson

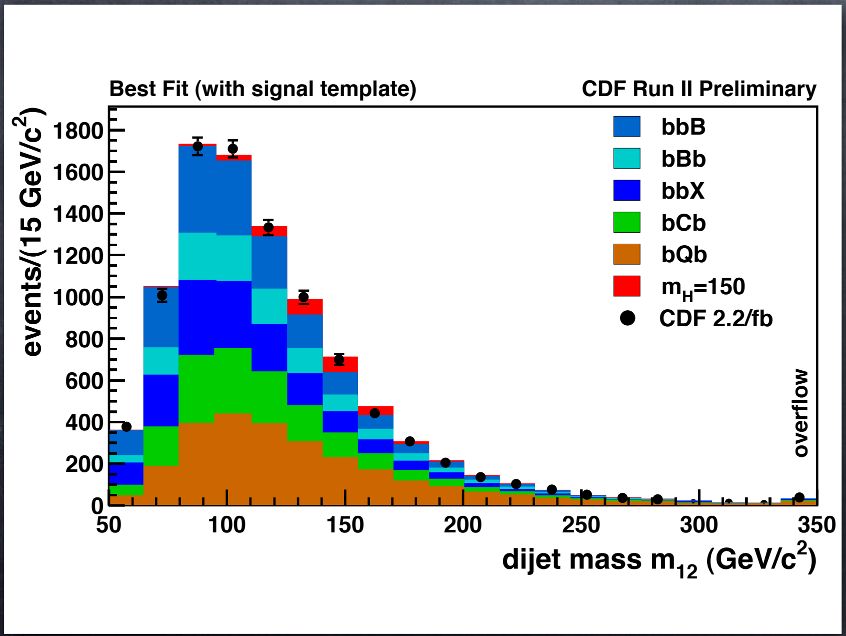
- Supersymmetric models extend Higgs sector
  - $\Phi = (H^0, A^0, h^0)$, and $H^\pm$
  - Introduces $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$ parameter
    - $\sigma(\Phi)$ enhanced by $(\tan\beta)^2 \sim 1000$ over SM
- Branching ratio
  - ~ 90% bb, 10% $\tau\tau$
- Tevatron has comprehensive MSSM Higgs program
  - $\Phi \to \tau\tau$
  - Φ+b $\to$ bb+b
  - Φ+b $\to$ $\tau\tau$+b

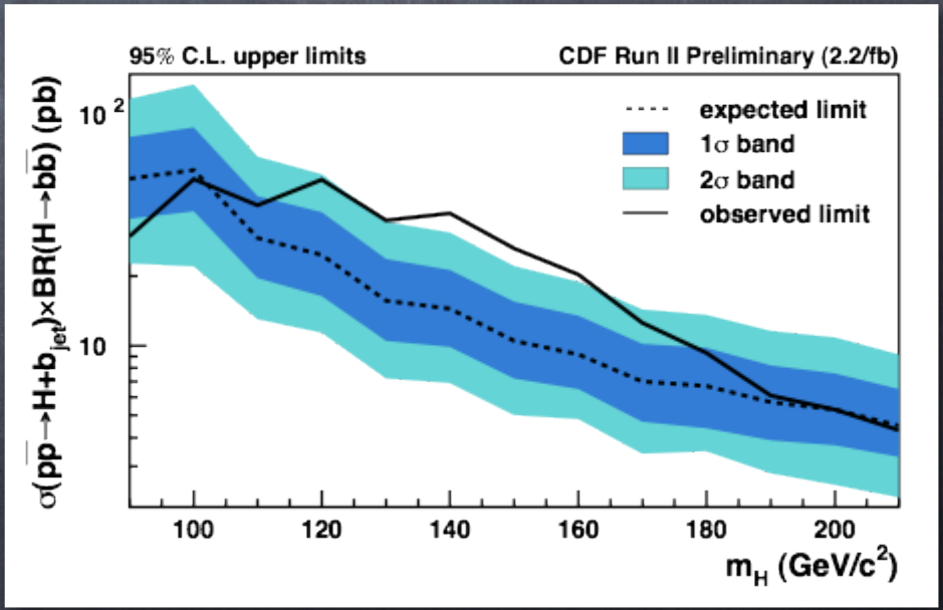


- CDF & D0 combined search for $\Phi \to \tau\tau$ with 2 fb^{-1}
  - Probes interesting value of $\tan\beta \sim m_t/m_b \sim 30$

Search for Supersymmetric Higgs boson

- MSSM Higgs 3b search (Φ+b→ bb+b)
  - Complements MSSM H → ττ search
  - Relies on CDF's trigger-level b-tagging used in b physics
  - New version of analysis 2x more acceptance
    - m_H = 140 GeV most significant excess
      - P-value = 0.9% (5.7% with trials factor)





Search for Supersymmetric Higgs boson

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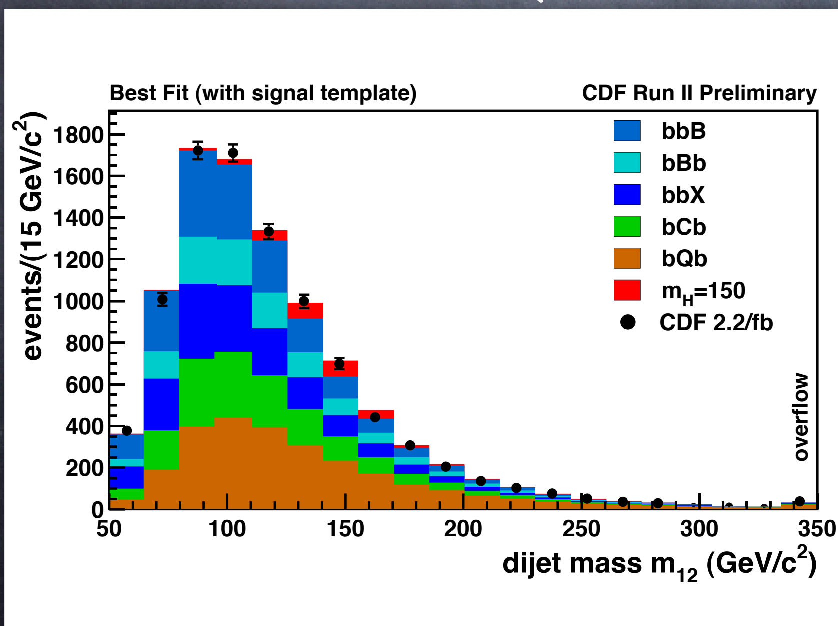
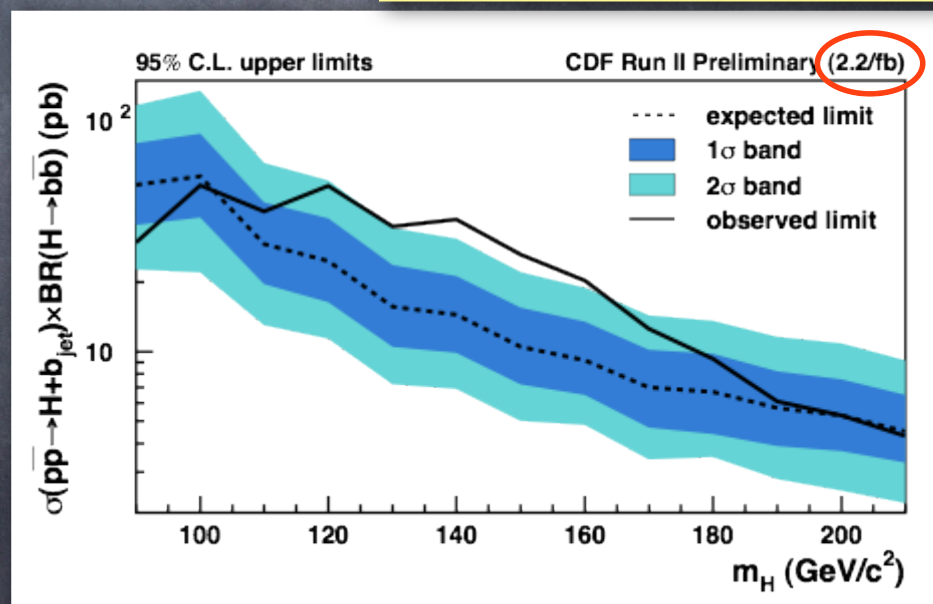
  - New version of analysis 2x more acceptance
    - m_H = 140 GeV most significant excess
      - P-value = 0.9% (5.7% with trials factor)

Sorry ! This 2 σ excess is the closest we have to a discovery :(

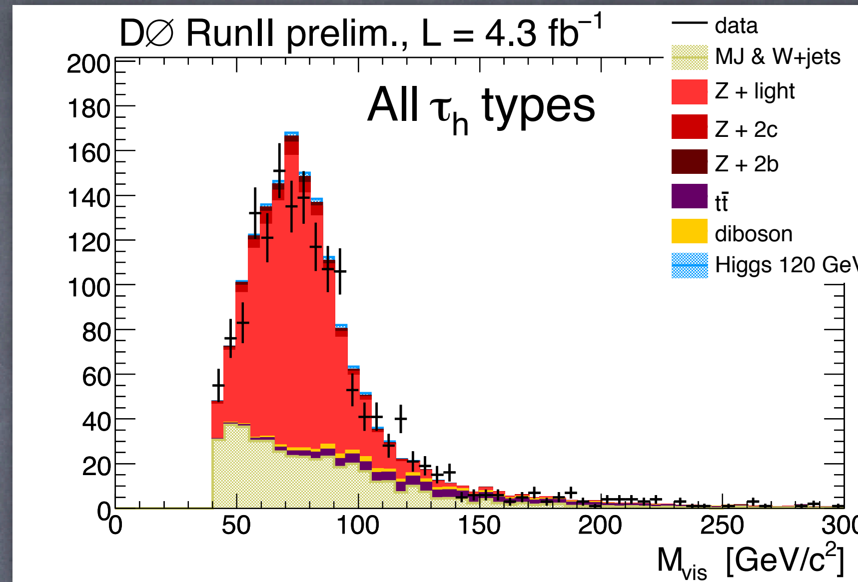
but lets keep an eye on it as we add new data :)

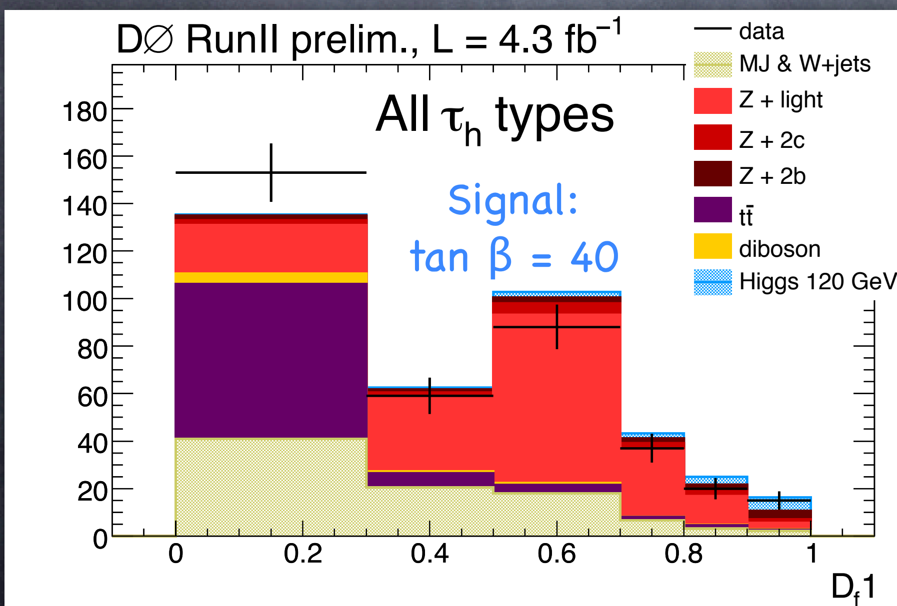


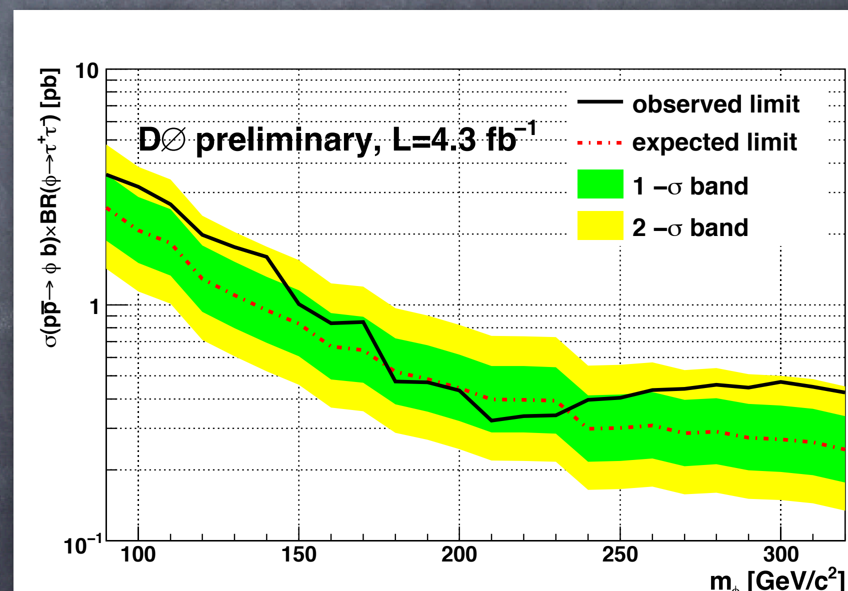


New MSSM Higgs search

- DØ's $\Phi \rightarrow \tau\tau + b$
  - Does not suffer radiative corrections which increase Higgs width as in $\Phi \rightarrow bb + b$
  - Exclusive from $\Phi \rightarrow \tau\tau$
    - Provides similar sensitivity

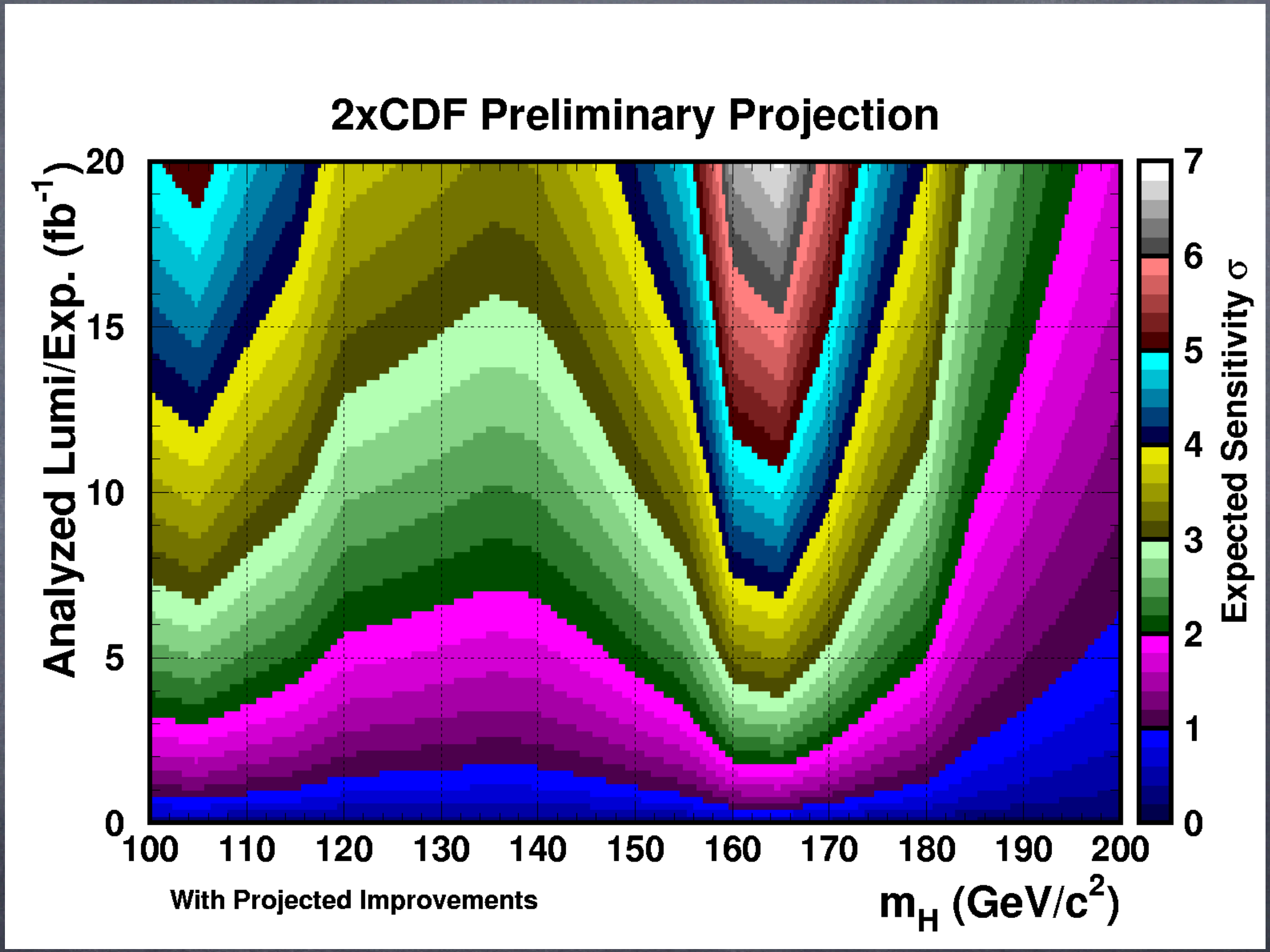




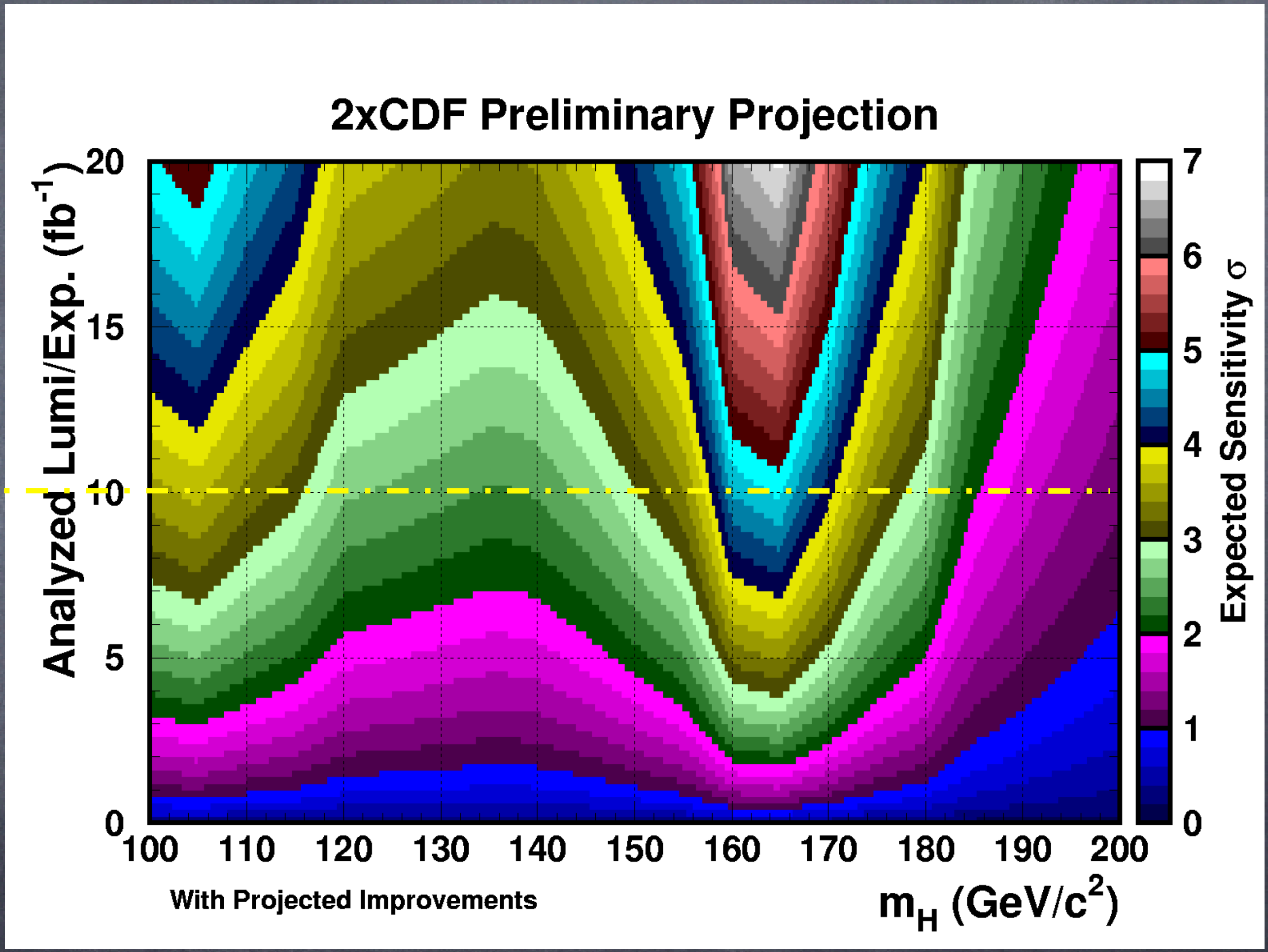


SM Higgs Projections

Prospects for Higgs evidence



Prospects for Higgs evidence



End of 2011:

> 2.4 σ expected sensitivity across mass range

3 σ at 115 GeV

Prospects for Higgs evidence

~16 fb^{-1} :*

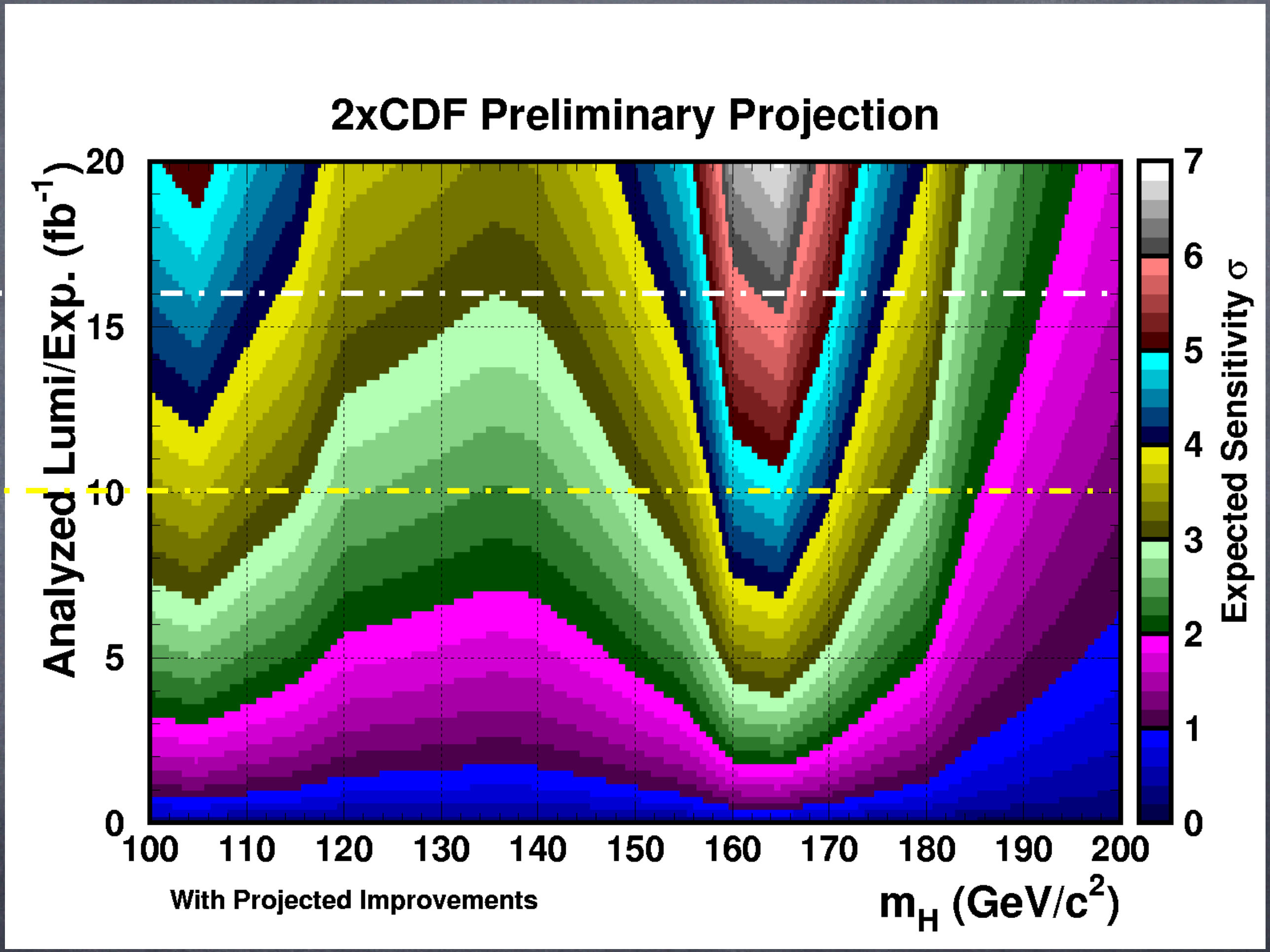
> 3 σ expected sensitivity from 100 - 185 GeV

4 σ @ 115 GeV

End of 2011:

> 2.4 σ expected sensitivity across mass range

3 σ at 115 GeV



* 16 fb^{-1} : based on "Run III" proposal to run 3 more years

You've got mail

To: TEV Higgs working group

"Nice new results ! We just ran this for you ...

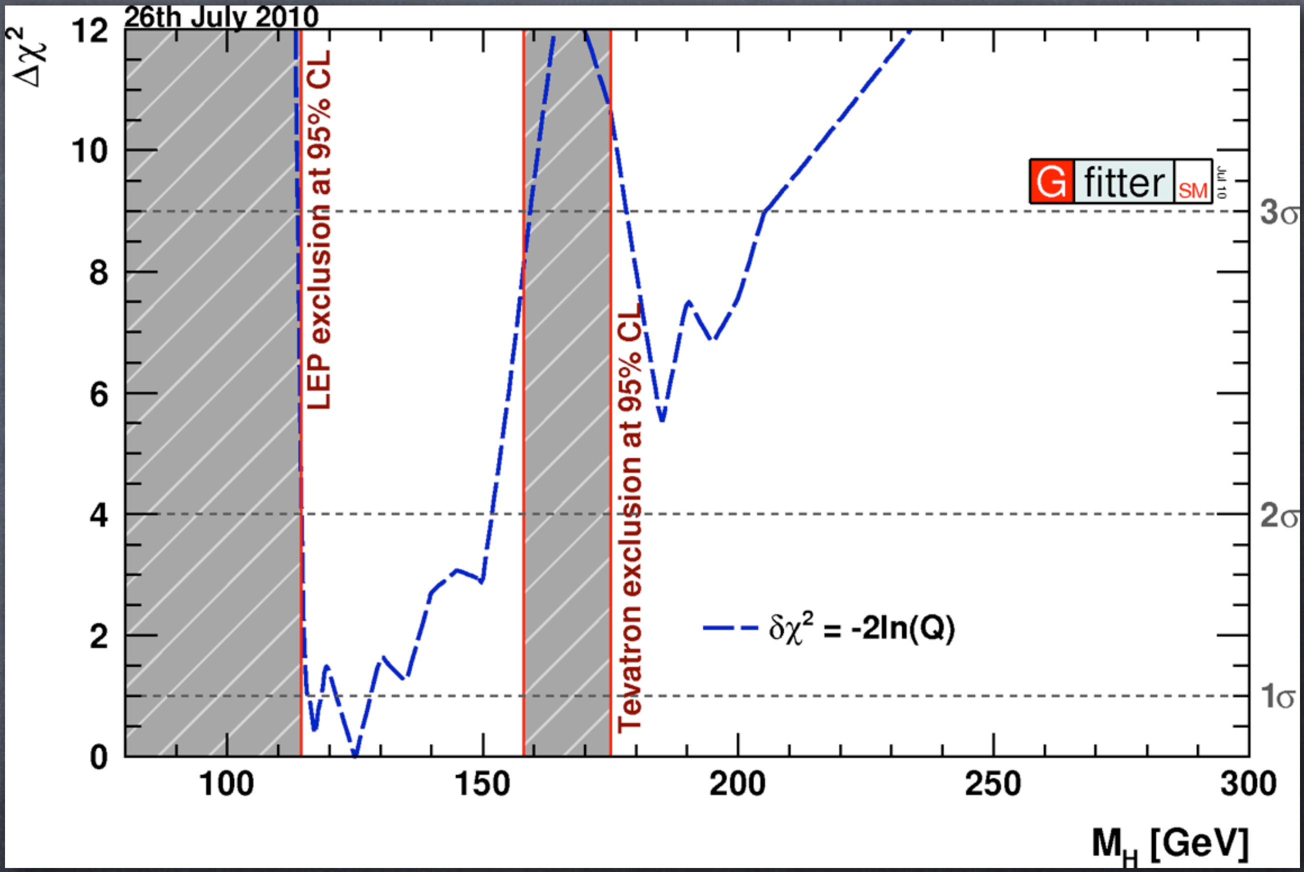
minimum:

$m_H =$ 125.029 GeV

1 sigma range(s):
[115.752, 118.411]
[121.342, 128.053]

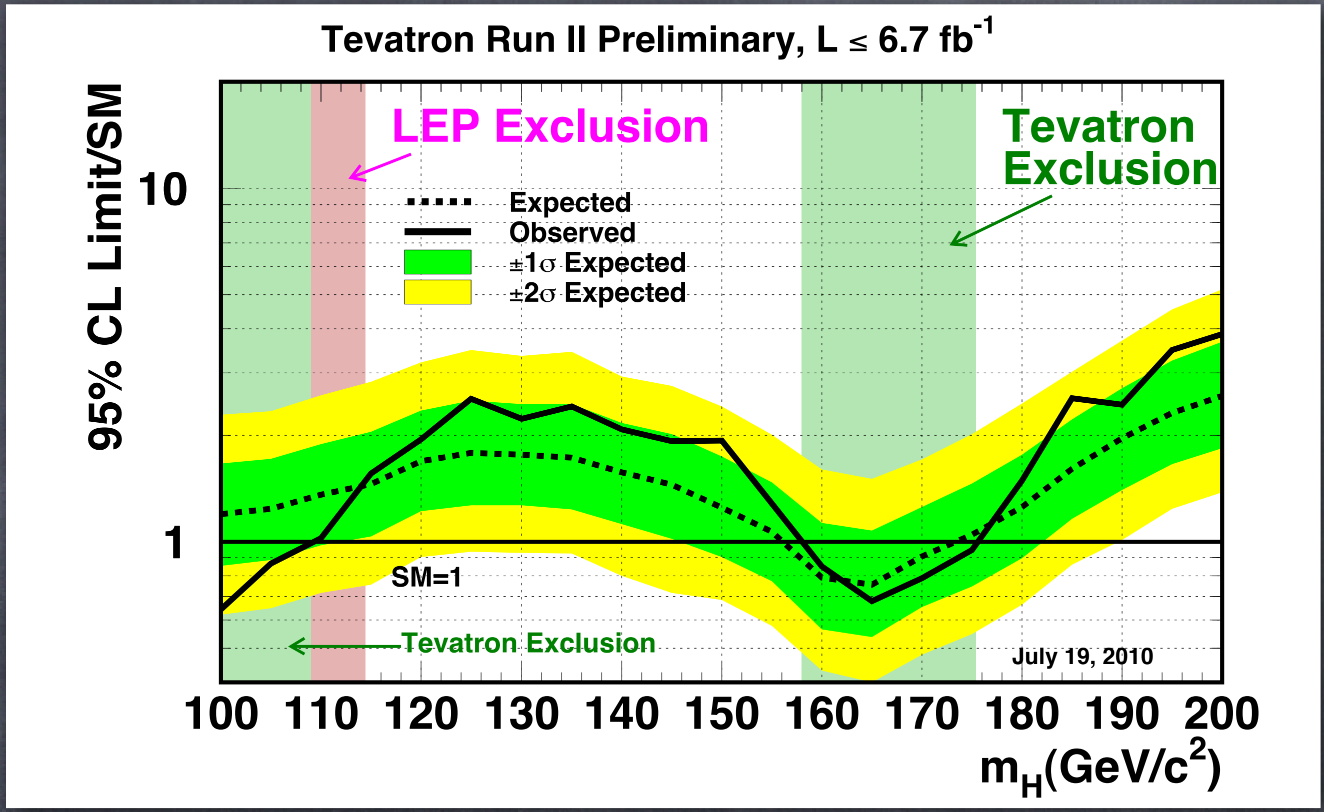
2 sigma range(s):
[114.577, 151.804]

3 sigma range(s):
[113.81, 159.307]
[178.124, 205.285]



95 % CL upper Limit is 151.537 GeV !!!
99 % CL upper Limit is 155.988 GeV !!!

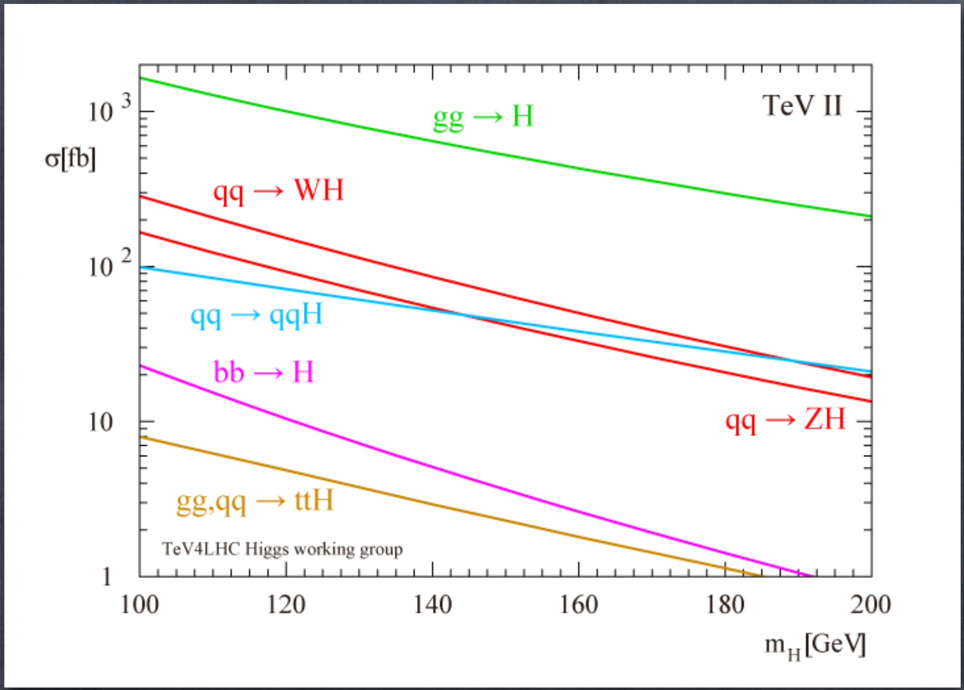
Conclusions



- Higgs has no place to hide !
  - Squeezing allowed mass from both sides
    - 95% CL Exclusion 158 < m_H < 175 GeV (about expected)
    - Limit 1.5*SM @ 115 GeV
- BSM searches : consistent with SM
  - 2 sigma is largest discrepancy in CDF MSSM H→bb (so far)

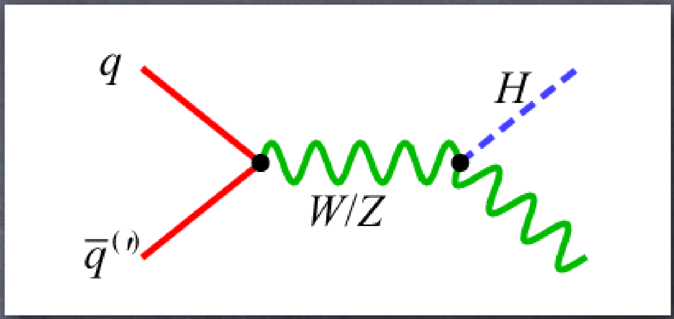
BACKUPS

Tevatron Higgs production modes



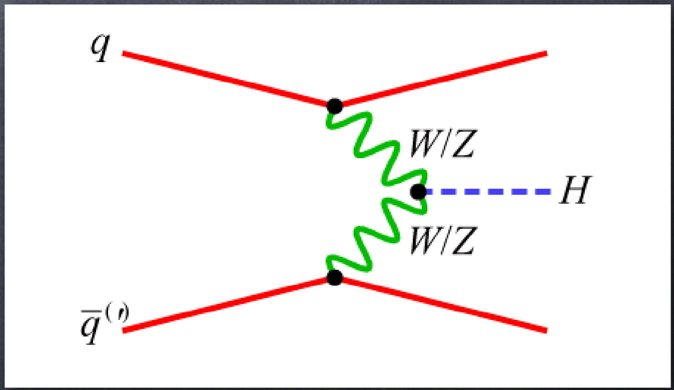
Production with W or Z

σ(gg → H) = 0.01 - 0.3 pb



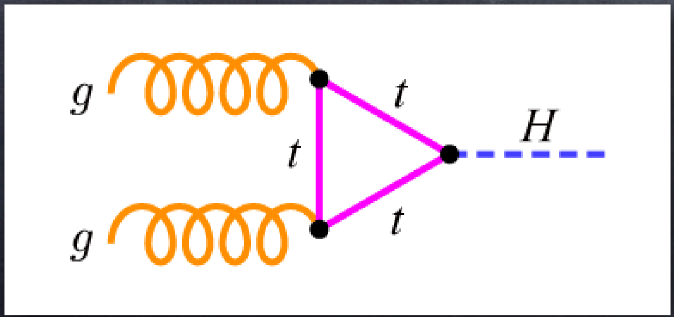
Vector boson fusion

σ(gg → H) = 0.02 - 0.1 pb



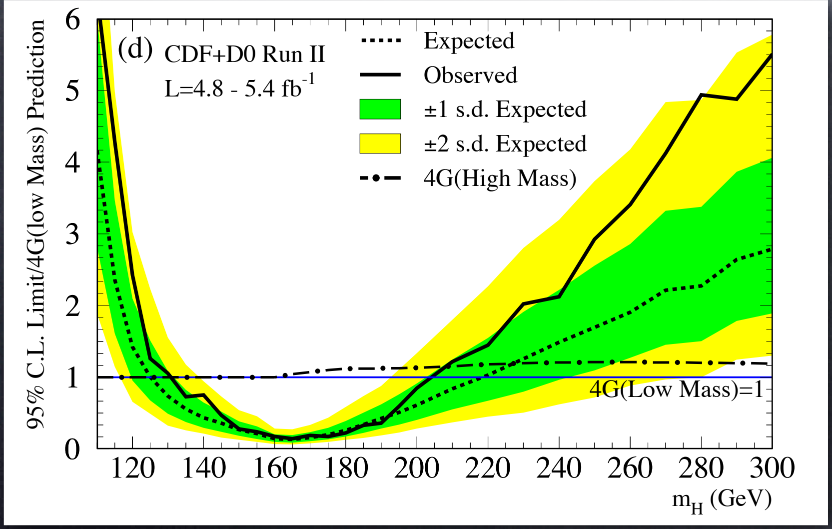
Gluon fusion

σ(gg → H) = 0.2 - 1 pb



Search for Higgs with 4 quark generations

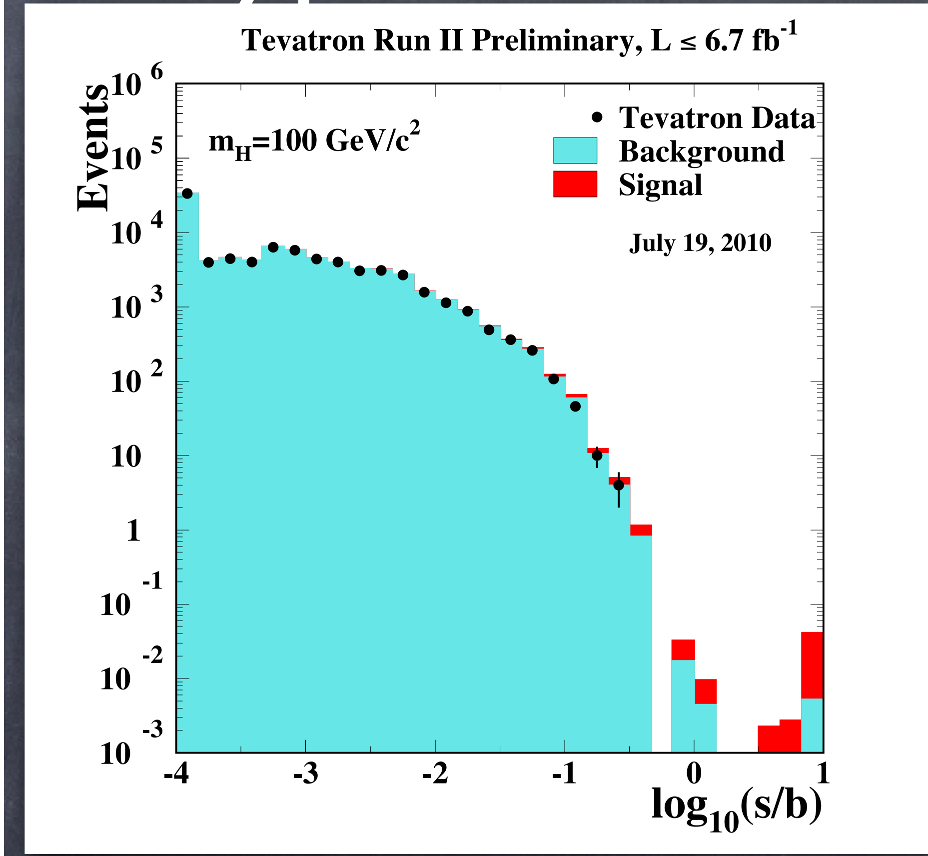
- 4th quark generation popular theory to resolve SM discrepancies and produce new CP violation
- Analysis :
  - $gg \rightarrow H$ production enhanced if new 4th generation quarks more massive than top
    - $m_H < 300$ GeV electroweak precision fits @ 68%C.L.
  - Use existing $H \rightarrow WW$ analysis framework



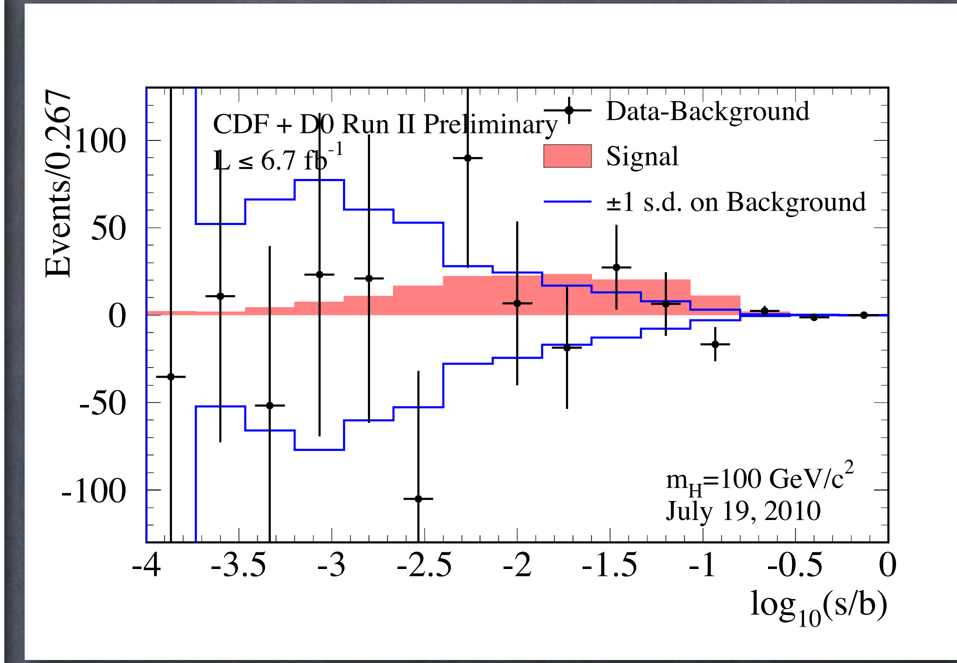
Excess could signal both evidence for Higgs boson, and evidence for 4th generation of quarks

CDF + D0 combination :
$131 < m_H < 204$ GeV excluded

Hypothesis : m_H = 100 GeV



All bins of all sub-channels of all channels

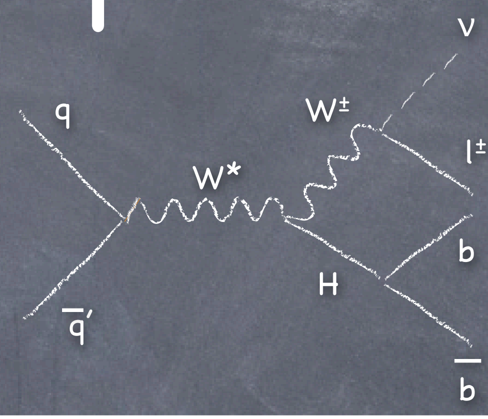


Data - Background shown compared to signal in red

Decent modeling, clear deficit of signal:
Exclusion at 100 GeV

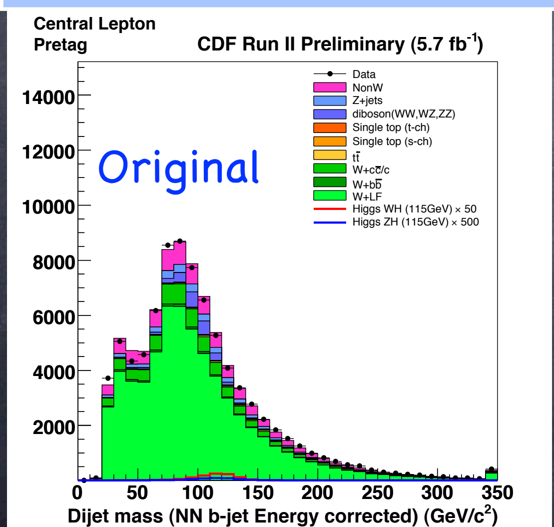
Increasing Higgs acceptance

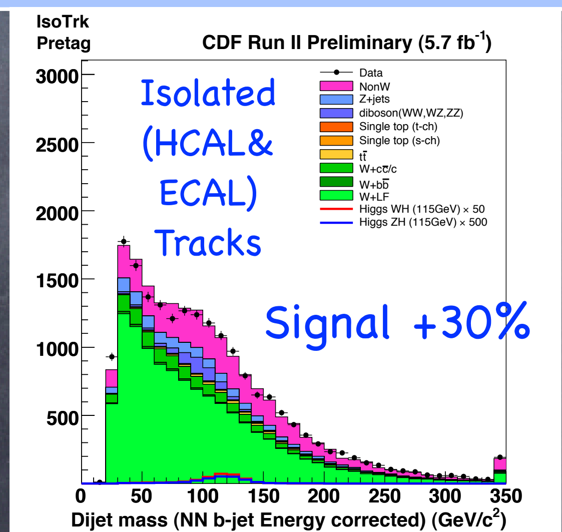
- Originally: tight triggers & lepton ID
- Now: suite of triggers and loose lepton ID
  - Challenge : Model important kinematics for increasingly poorly reconstructed events

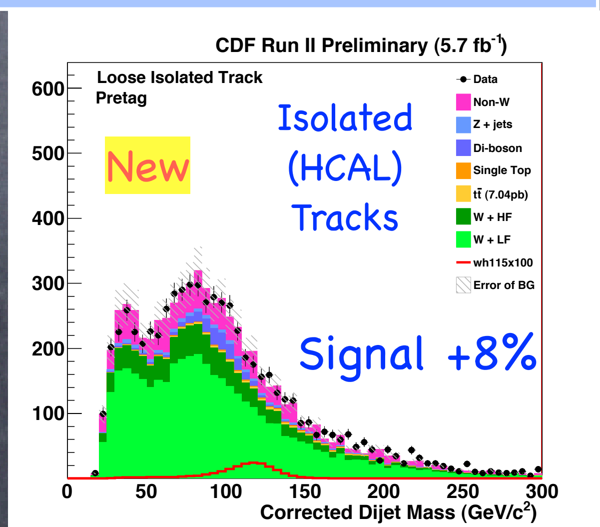


- For instance, CDF WH→lνbb analysis :

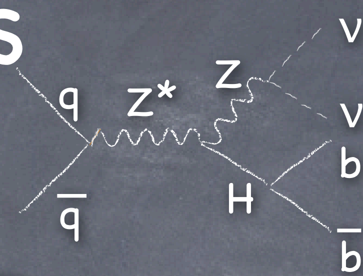
Standard central lepton triggers	... if none...	Partially reconstructed muons from missing transverse energy (MET) triggers	... if none...	Partially reconstructed electrons from MET triggers



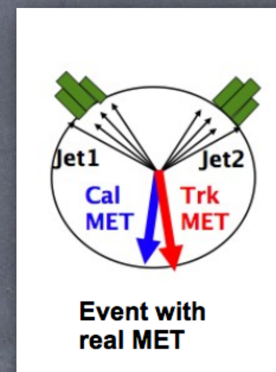


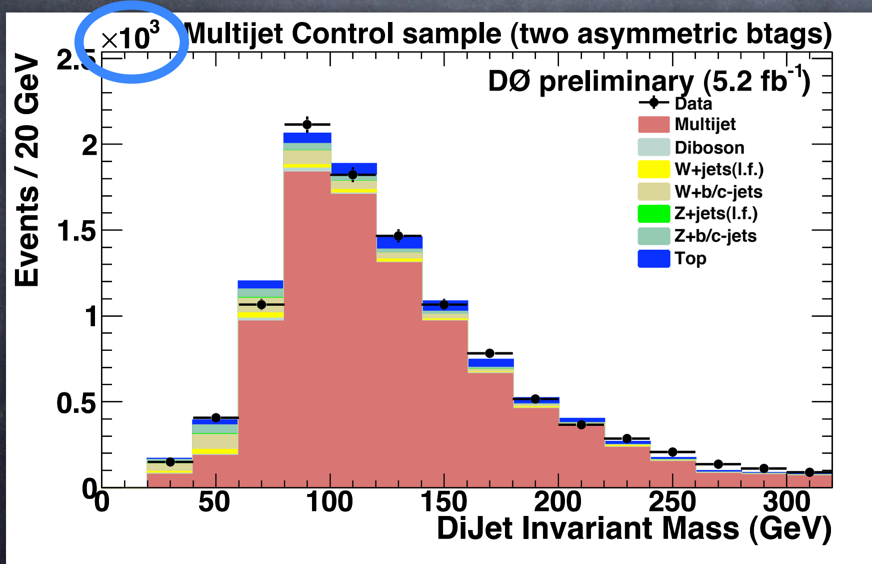


Removing difficult backgrounds



- Higgs signals can have large MET
  - ZH → ννbb, WH → lνbb (lepton missed)
  - Large QCD multijet with mismeasured jets
  - Peaks near where signal expected in M_{jj}
- Multijet removal techniques save this channel
  - MET significance
  - Missing track P_T (MPT)
  - Topological requirements





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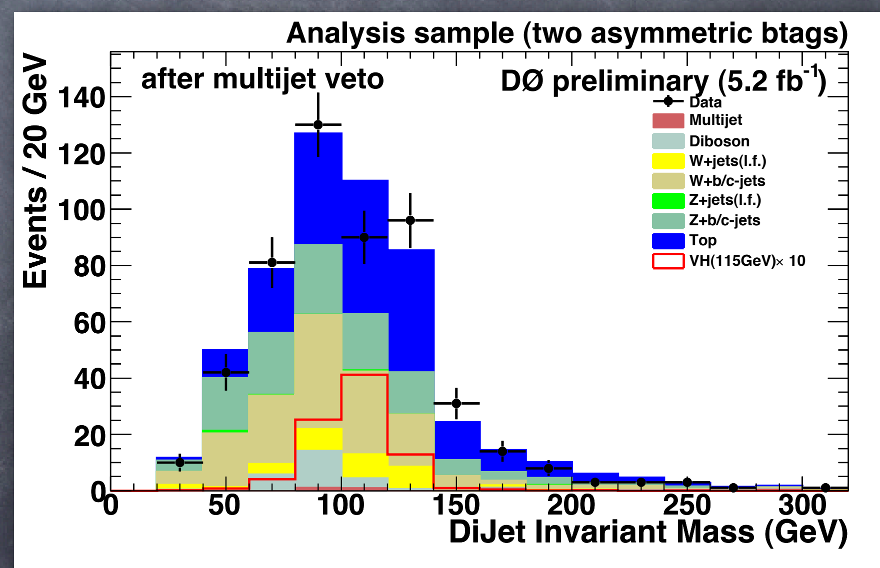
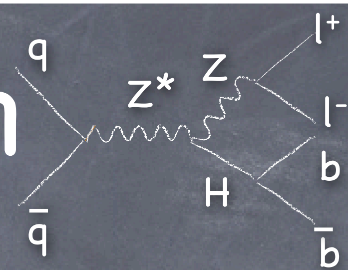
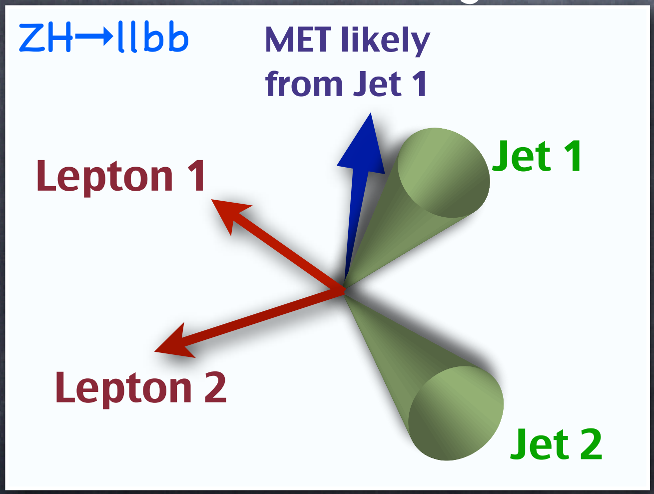


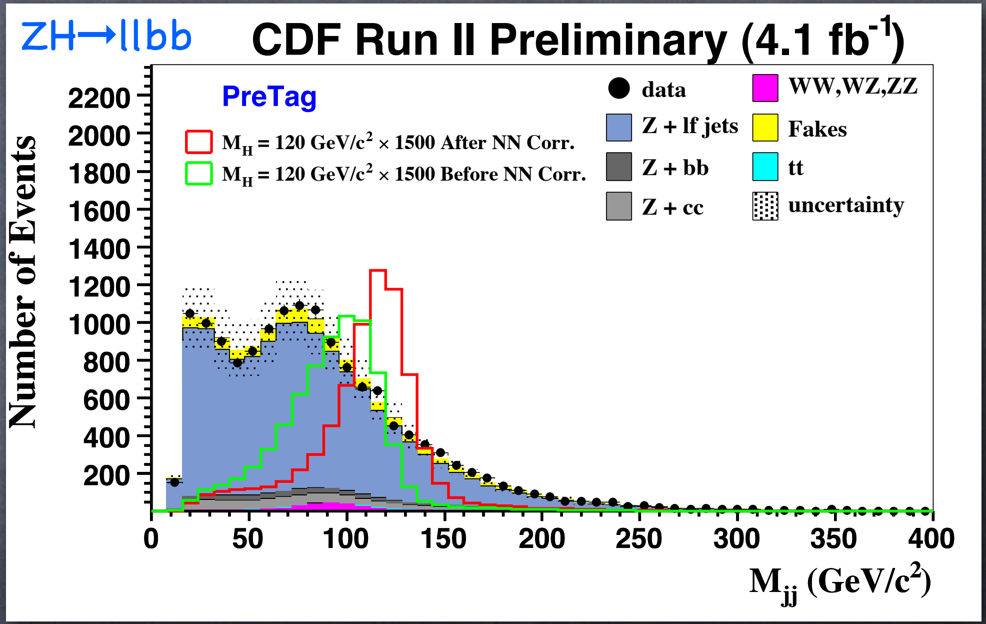
Improving M_{bb} resolution



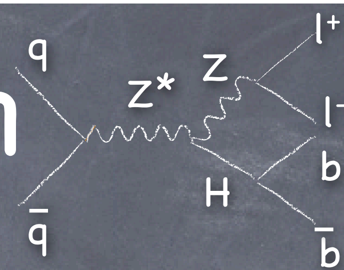
- $H \rightarrow bb$ signal significance enhanced by improving M_{jj} resolution

Apply MET constraint to correct jet energies





Improving M_{bb} resolution



- $H \rightarrow bb$ signal significance enhanced by improving M_{jj} resolution

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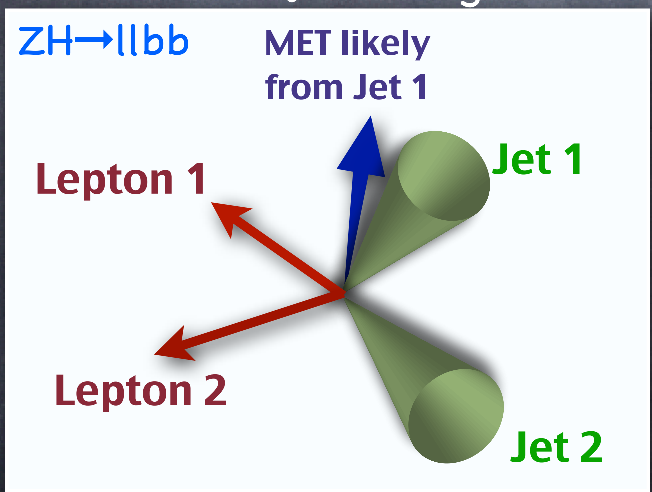

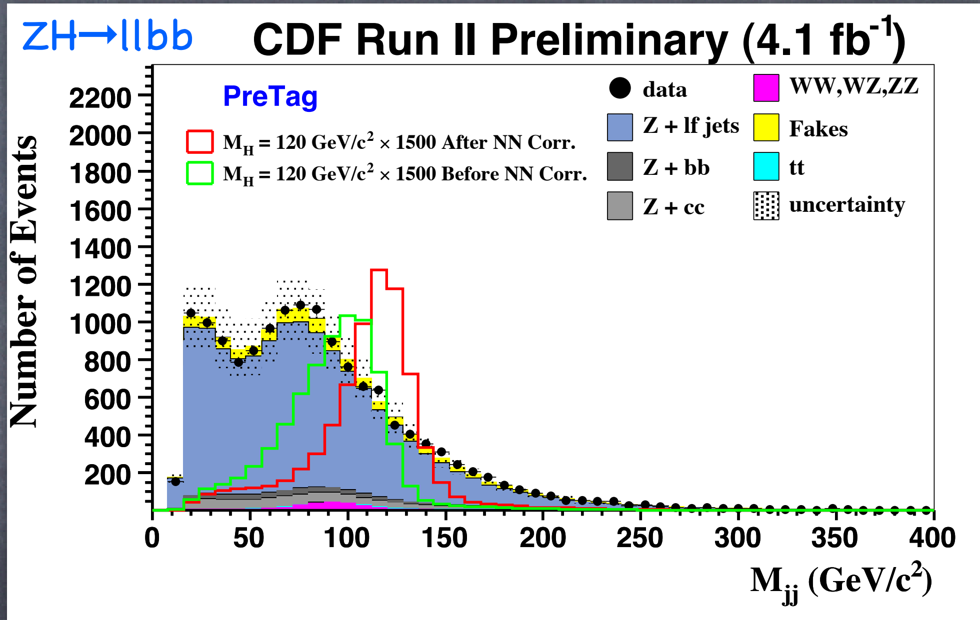

- M_{jj} resolution improvements in other analyses :
  - Track momenta within jets additional constraint (~ "particle flow")
  - Displaced vertex info to determine boost of b-hadron

Every last Higgs event at low mass

Analyses become more challenging

- $H \rightarrow \tau\tau$ decay modes
  - BR ($H \rightarrow \tau\tau$) 10 times smaller than $H \rightarrow bb$
  - Jets from vector boson & associated production reduce background
- $H \rightarrow \gamma\gamma$ decay modes
  - BR ($H \rightarrow \gamma\gamma$) 300 times smaller than $H \rightarrow bb$
  - Narrow resonance 3 GeV compared to 16 GeV $H \rightarrow bb$
- $Z/W + H \rightarrow qq + bb$
  - All-jets final state means enormous multijet backgrounds
  - Largest expected signal
- $WH \rightarrow \tau\nu bb$
  - Low selection efficiency, due to large QCD backgrounds
  - Exclusive trigger improves WH selection efficiency