HIGGS BOSON SEARCHES AT THE TEVATRON

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On behalf of the CDF and D0 Collaborations

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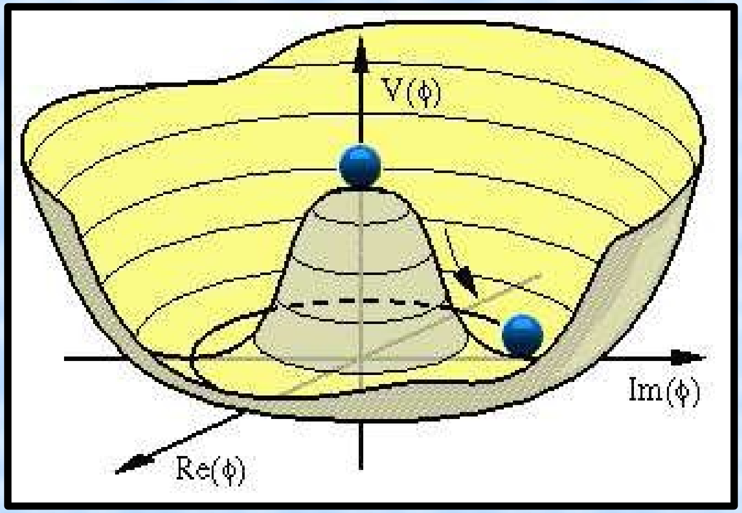
OUTLINE

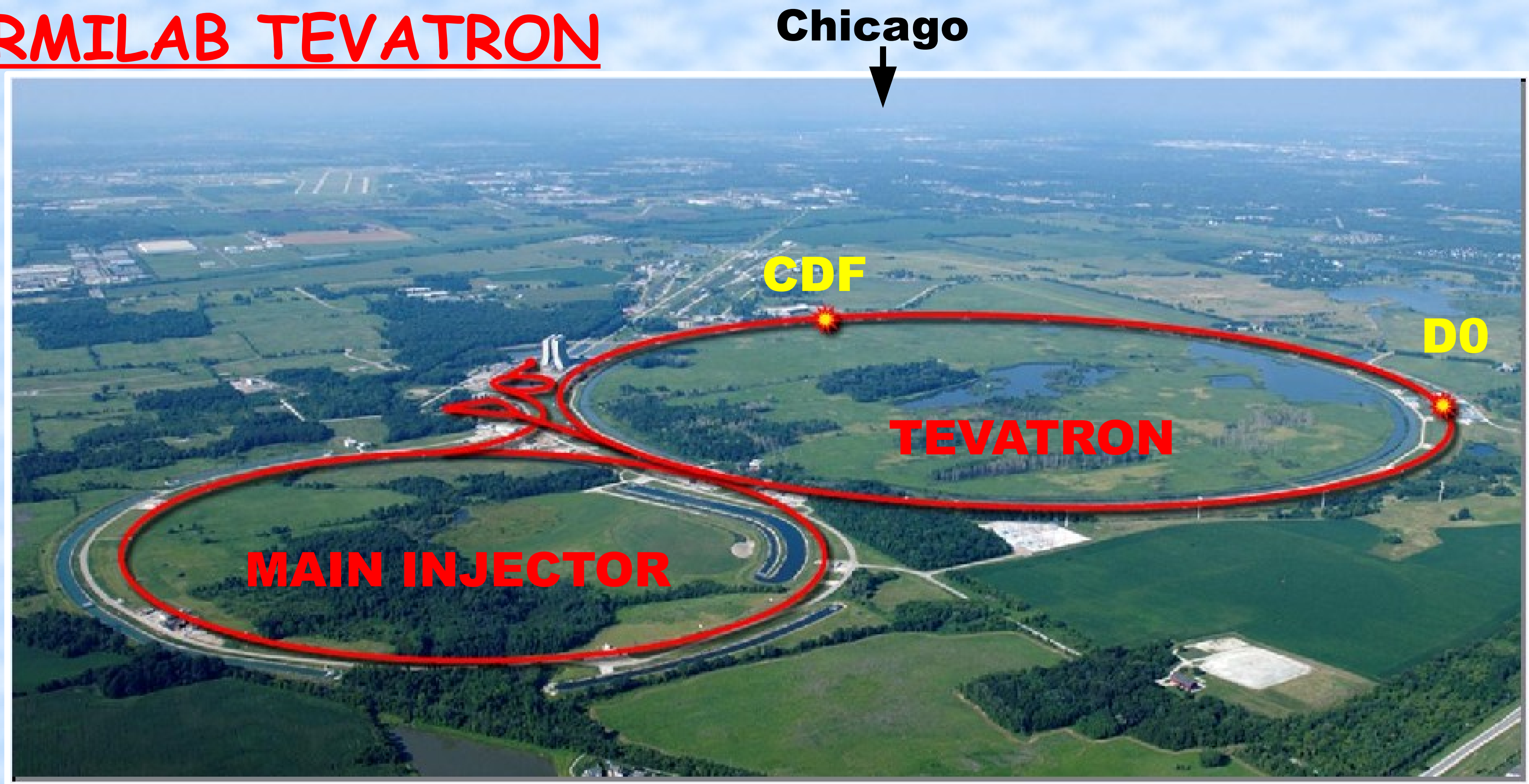
- Fermilab and Tevatron: Introduction.
- CDF and D0 Detectors.
- Standard Model (SM) Higgs.
- SM Analyses Results.
- Beyond Standard Model.
- Beyond SM Analyses Results.
- Conclusions.

"MEXICAN HAT"

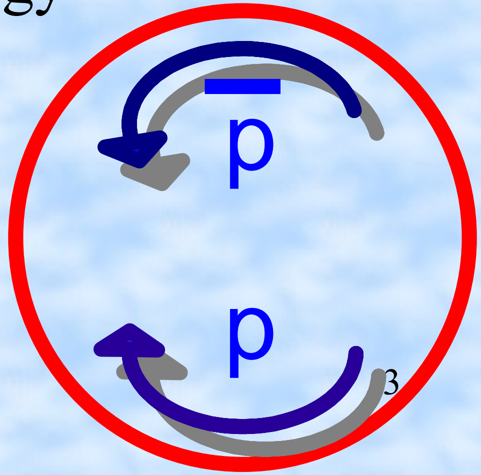


$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 ; \quad \mu^2<0 \quad \lambda>0$$

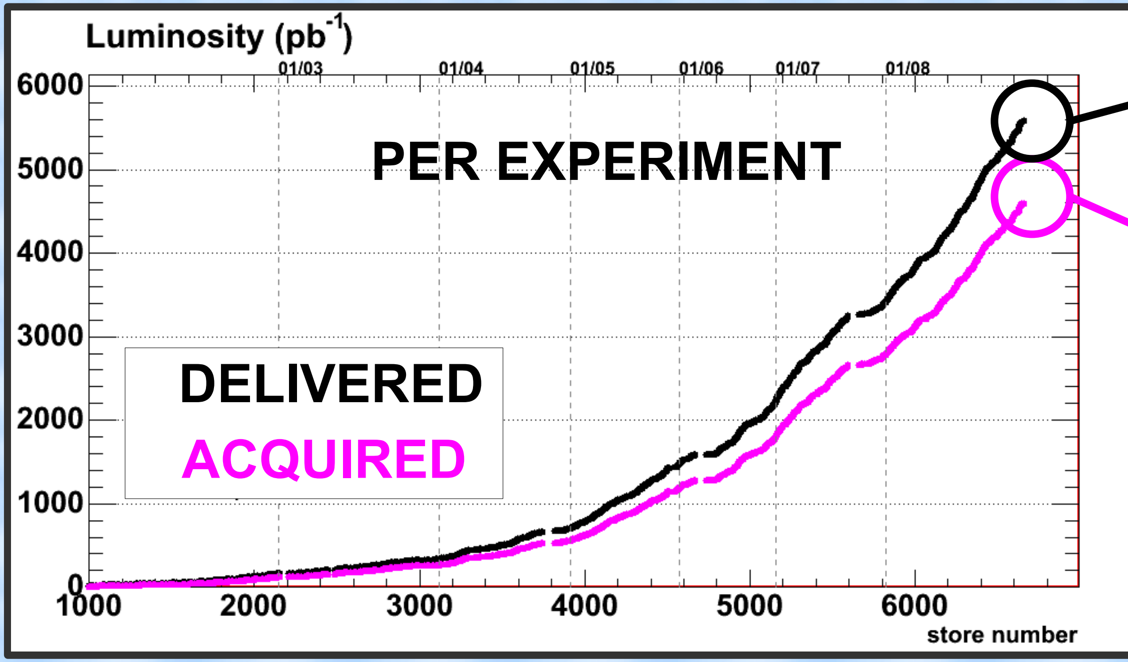
FERMILAB TEVATRON



- Fermilab is home to the Tevatron, the world's highest-energy particle accelerator and collider.
- proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV.
- Tevatron is performing really well:
  6-8 fb^{-1} expected by the end of 2009.



LUMINOSITY AND DATA TAKING



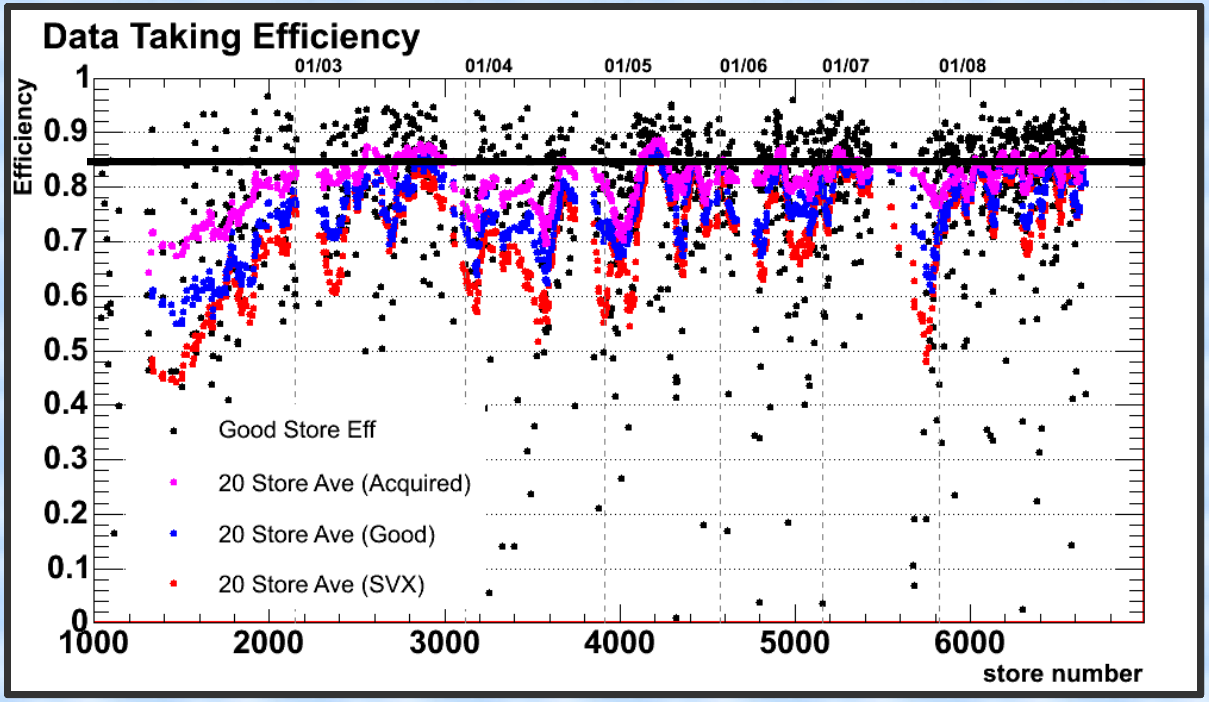
Total delivered = 5.5 fb^{-1}

Total Acquired = 4.58 fb^{-1}

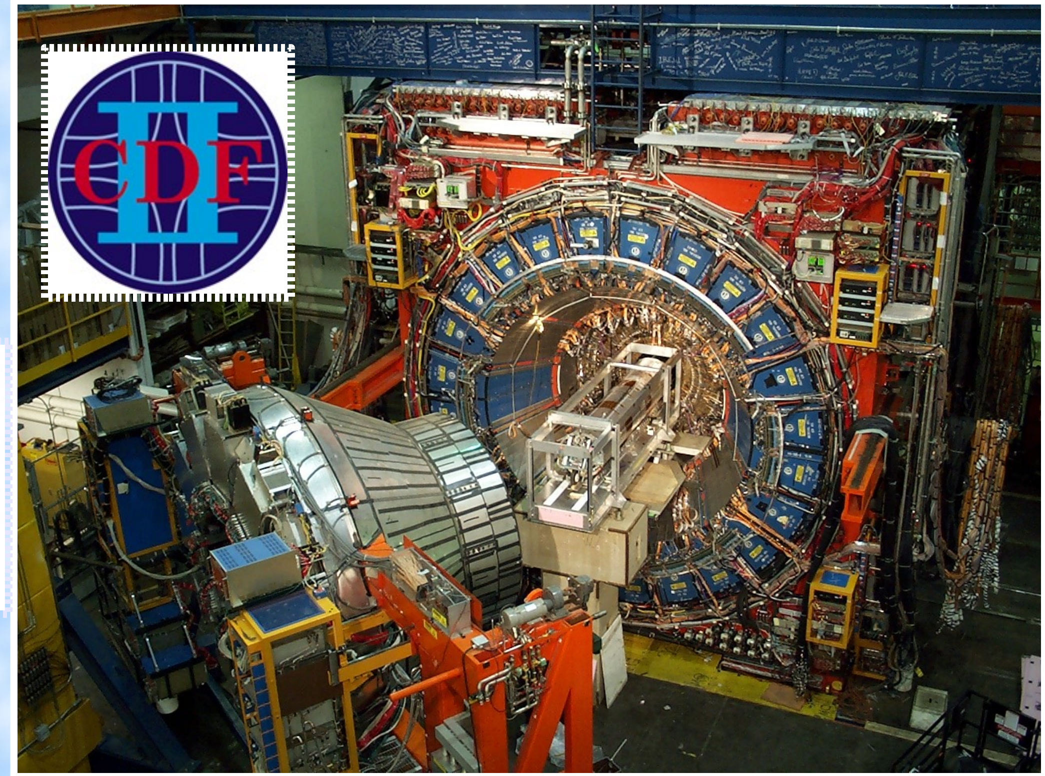
The best initial luminosity:

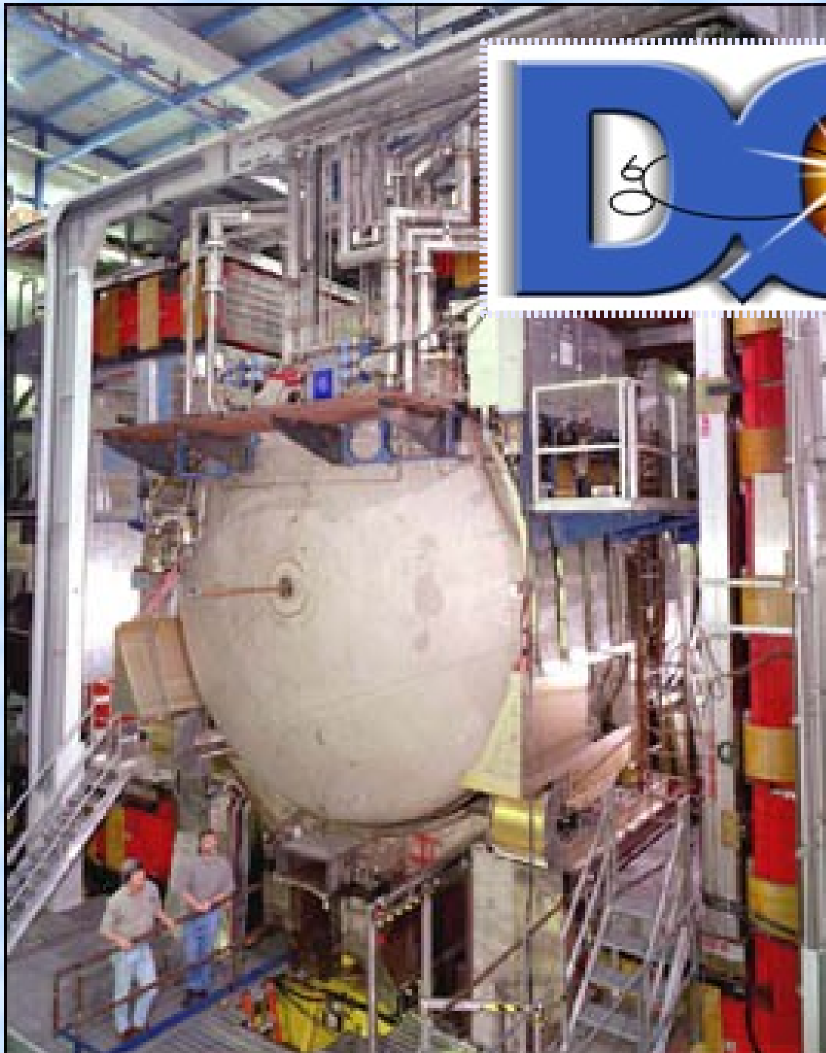
3.61×10^{32} cm^{-2} s^{-1}

Data Taking Average Efficiency ~82%



DETECTORS AT FERMILAB





Data analyses with 2 ***multipurpose*** detectors, **CDF** and **D0**:

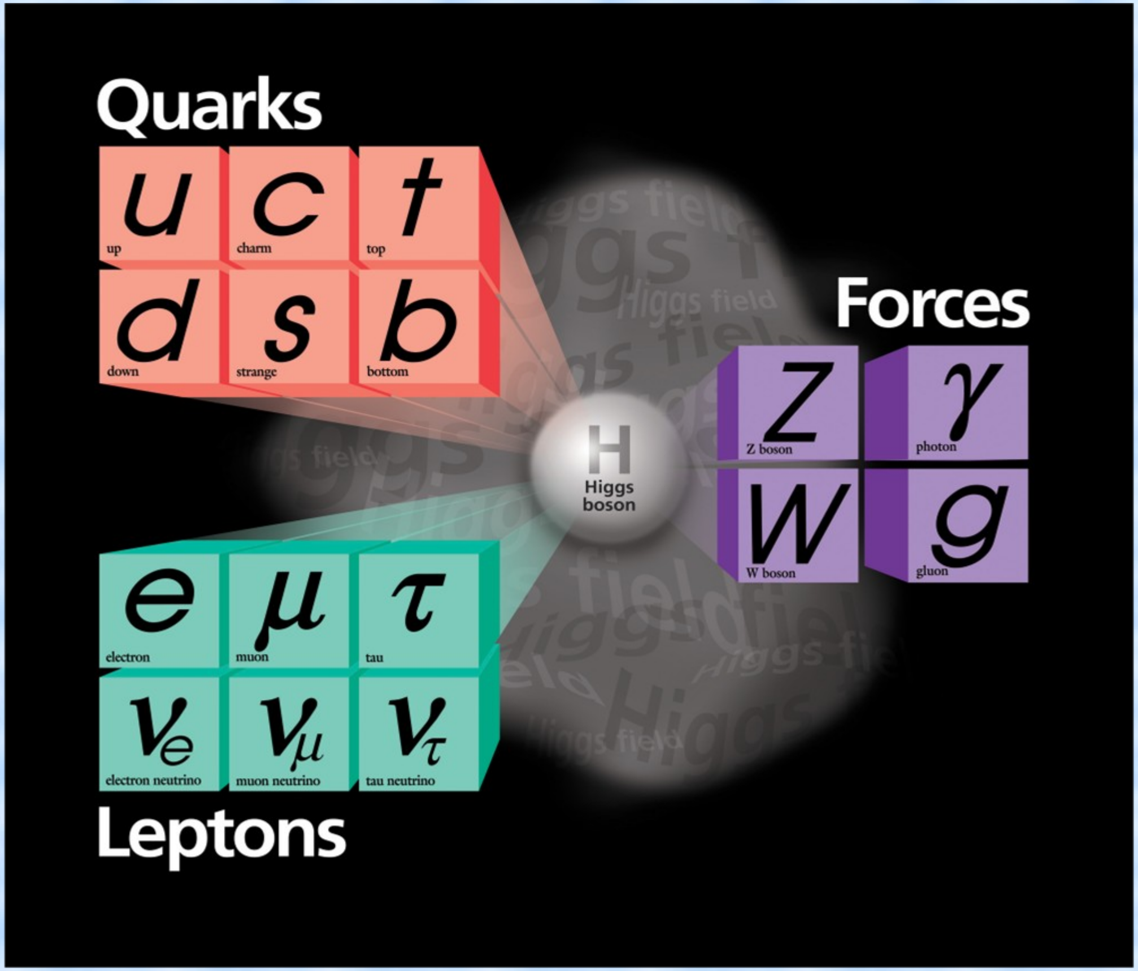
- ✗ Silicon vertex detectors for b-tagging.
- ✗ Charged particle tracker in magnetic field.
- ✗ EM+HAD calorimeter for e,mu id.
- ✗ Muon detectors for muon id.

HIGGS BOSON

✔ The search for the Higgs boson is one of the most active areas of research at the Tevatron.

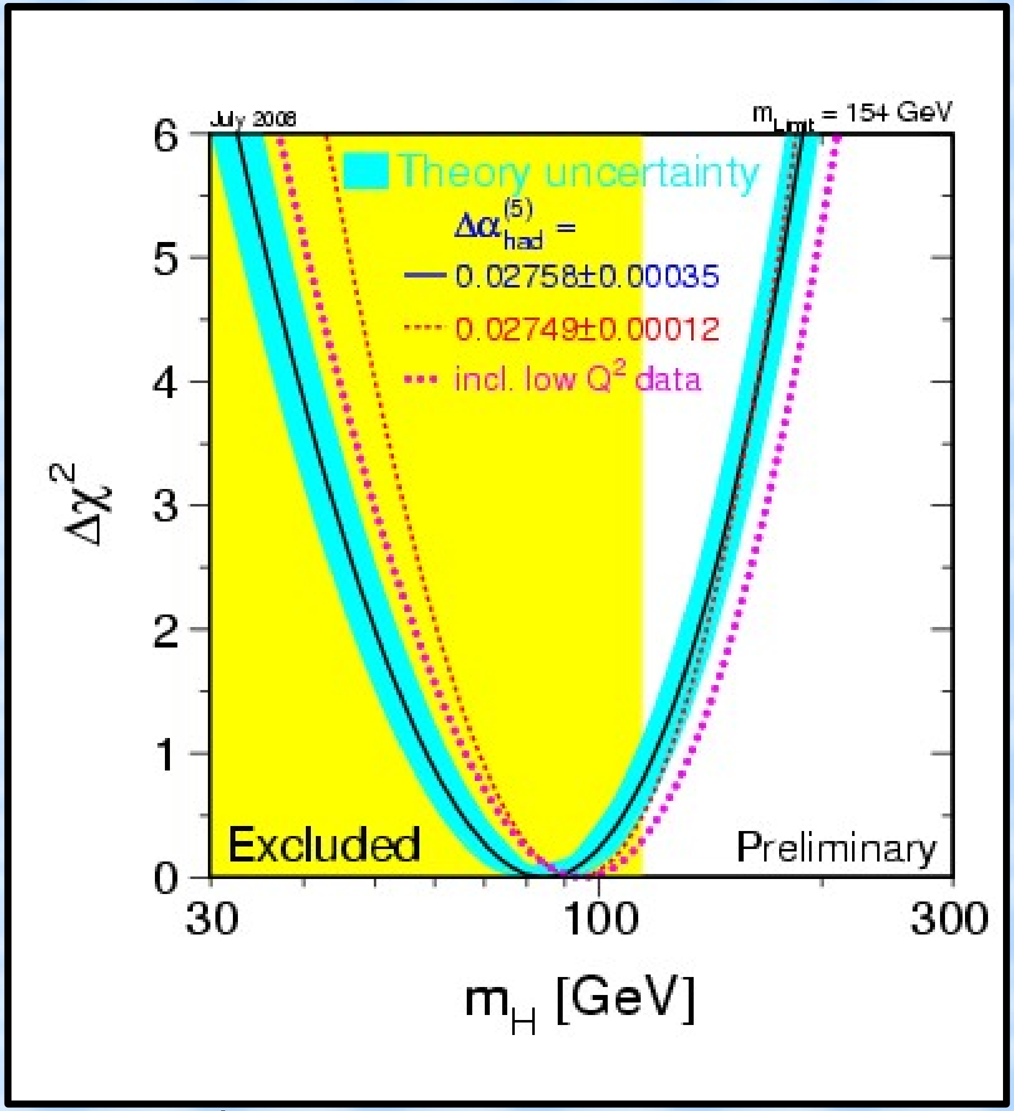
✔ The Higgs boson is the only SM particle that has not been observed.

✔ It requires an exceptionally large amount of energy and beam luminosity to **create** and **observe** at high energy colliders due to small cross sections and large backgrounds.



Only ~40 Higgs events are expected to be produced per fb^{-1} at each experiment in detectable channels

In the **standard model (SM)**, the Higgs boson is crucial to the understanding of **electroweak symmetry breaking** and the **mass generation** of electroweak gauge bosons and fermions.



Higher order diagrams involving Higgs Bosons enter as corrections to SM predictions for EWK processes

- Direct searches at **LEP**: $m_H > 114.4$ GeV/c^2 at 95% C.L.
- Indirect **EWK** constraints: $m_H < 154$ GeV/c^2

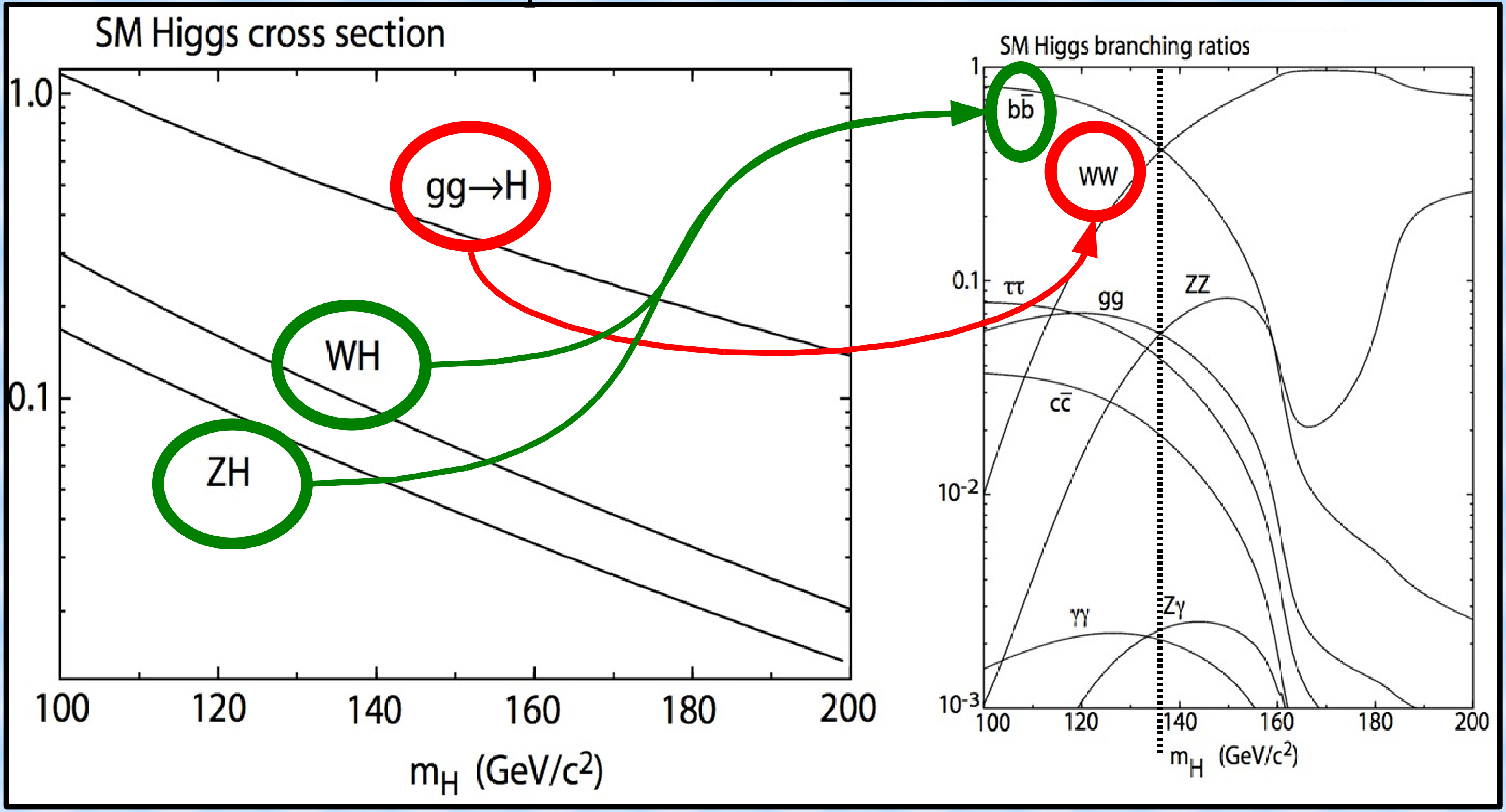
SM HIGGS CROSS SECTIONS AND BR

High mass Higgs region (m_H>135 GeV/c^2):

- H → WW dominant decay.
- Gluon fusion production search (gg → H).

Low mass Higgs region (m_H<135 GeV/c^2):

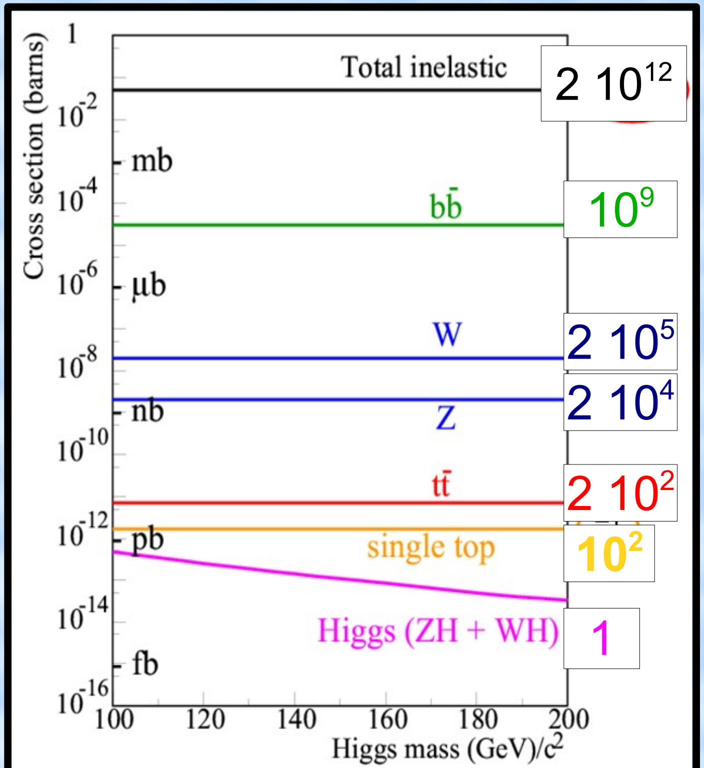
- H → bb dominant decay.
- Search for associated W/Z production.



ANALYSIS STRUCTURE

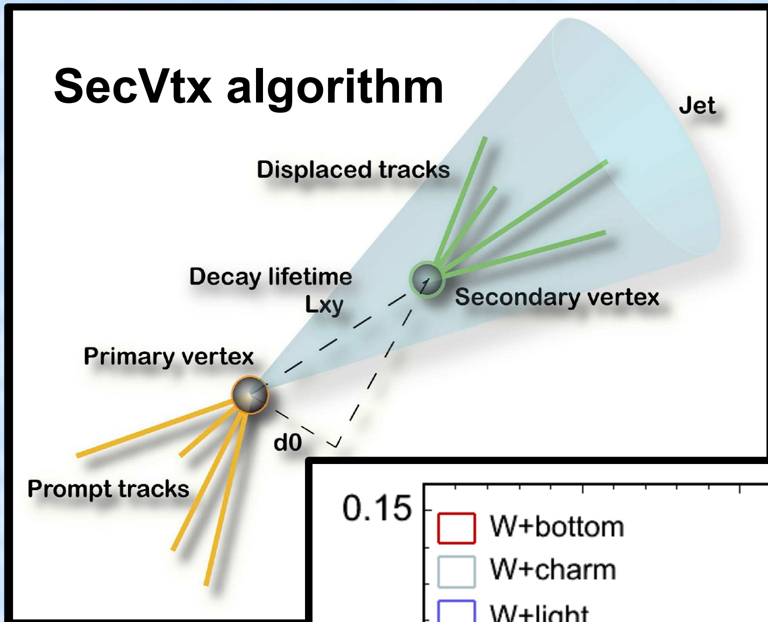
DATA & MC SAMPLES → EVENT SELECTION → BKG ESTIMATION → MULTIVARIATE TECHNIQUES → SYSTEMATIC UNCERTAINTIES → RESULTS

MULTIVARIATE TECHNIQUES:
- Neural Networks (NN)
- Matrix Element (ME)
- Boosted Decision Trees (BDT)



THE CHALLENGE IS TO DISTINGUISH A SMALL SIGNAL FROM ALL THE HUGE BACKGROUNDS

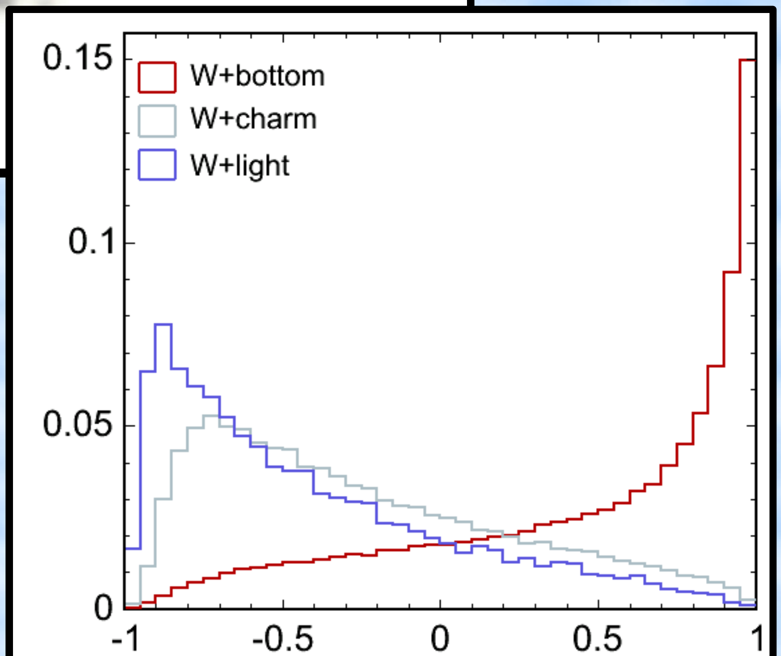
ANALYSIS TOOLS

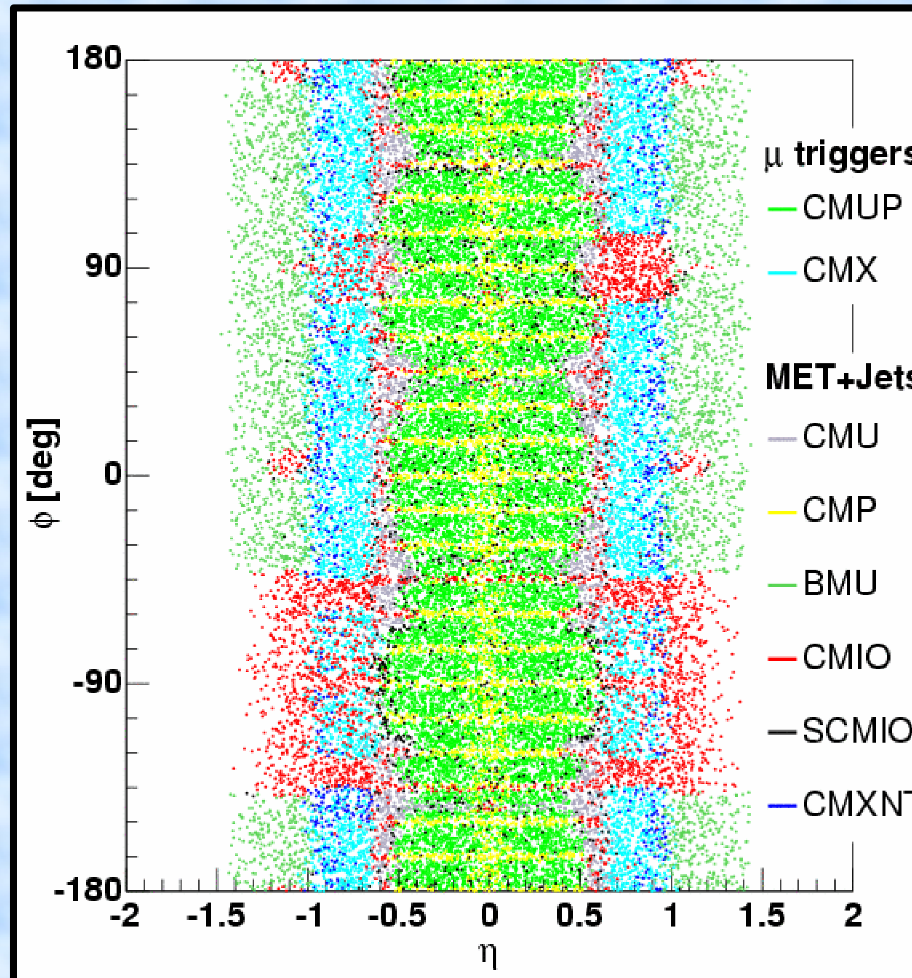


Multiple b-quark tagging algorithms:

✔ **DØ:** NN tagger based on b-lifetime information, with multiple operating points.

✔ **CDF:** Secondary Vertex and Jet Probability algorithms. Additional NN flavor separators.



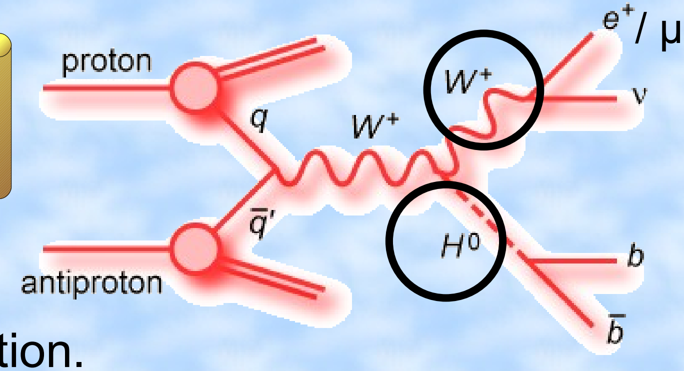


Maximize lepton acceptance:

✔ Separate into different lepton categories based on S/B.

Low Mass

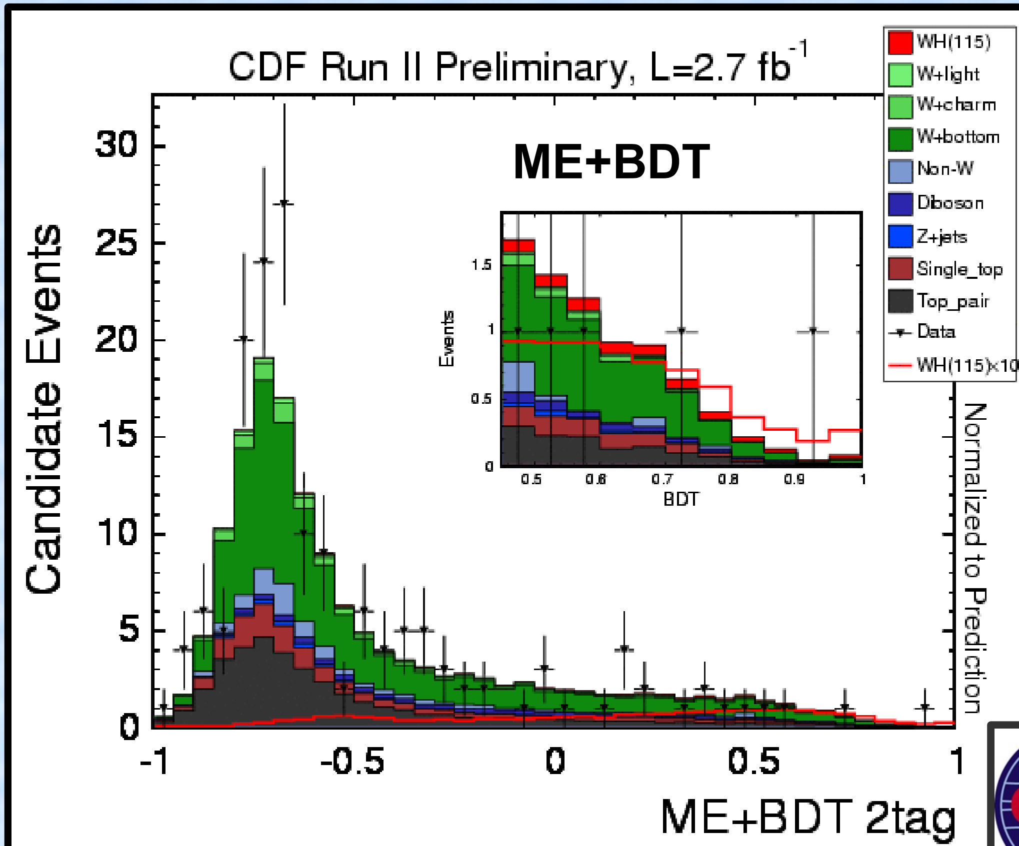
WH → lνbb

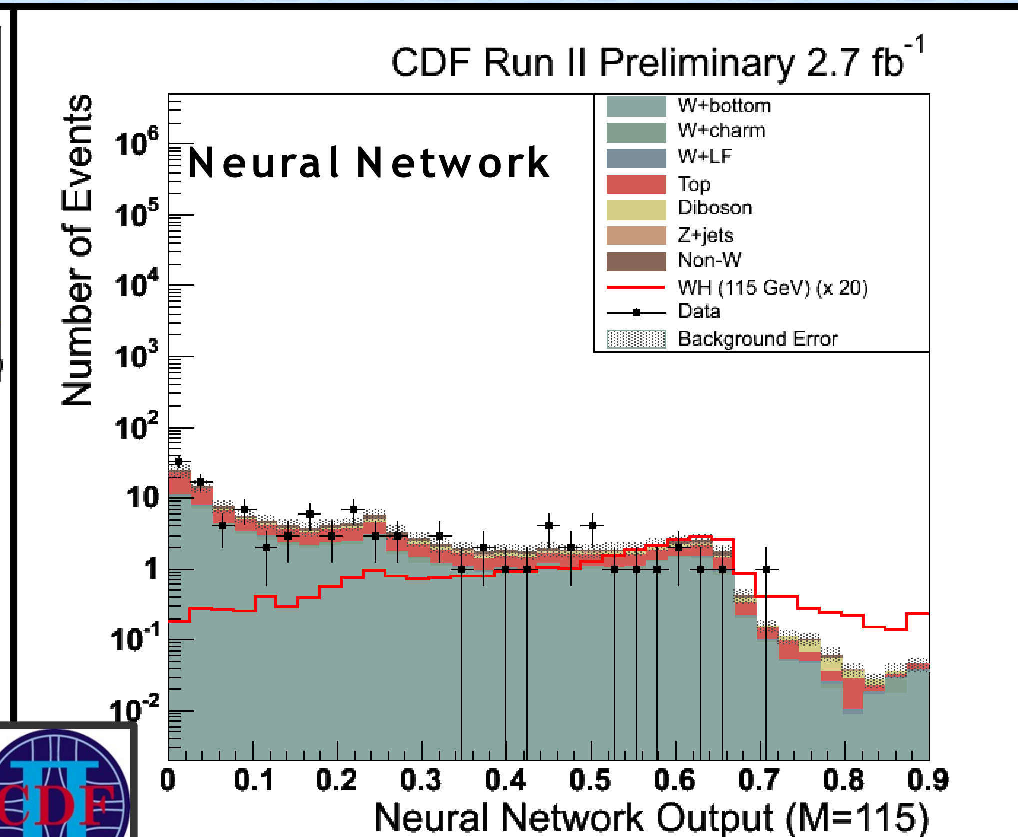


Dedicated trigger: High p_T leptons, and MET+jets.

In CDF, 2 WH analysis are performed
- Same selection.
- Same background treatment.
- Different analysis techniques
  - **ME + BDT**
  - **NN**

These two results are combined to have the final WH → lνbb limit (next page).





EVENT PROBABILITY DENSITIES:

Transfer Function

$$P(p_l,p_{j1},p_{j2}) = 1/\sigma \int dp_{j1}dp_{j2}dp_{v} \sum\Phi_4|M(p_i)^2| \, f(q_1)f(q_2)/|q_1||q_2| \, W_{jet}\,(E_{jet},E_{part})$$

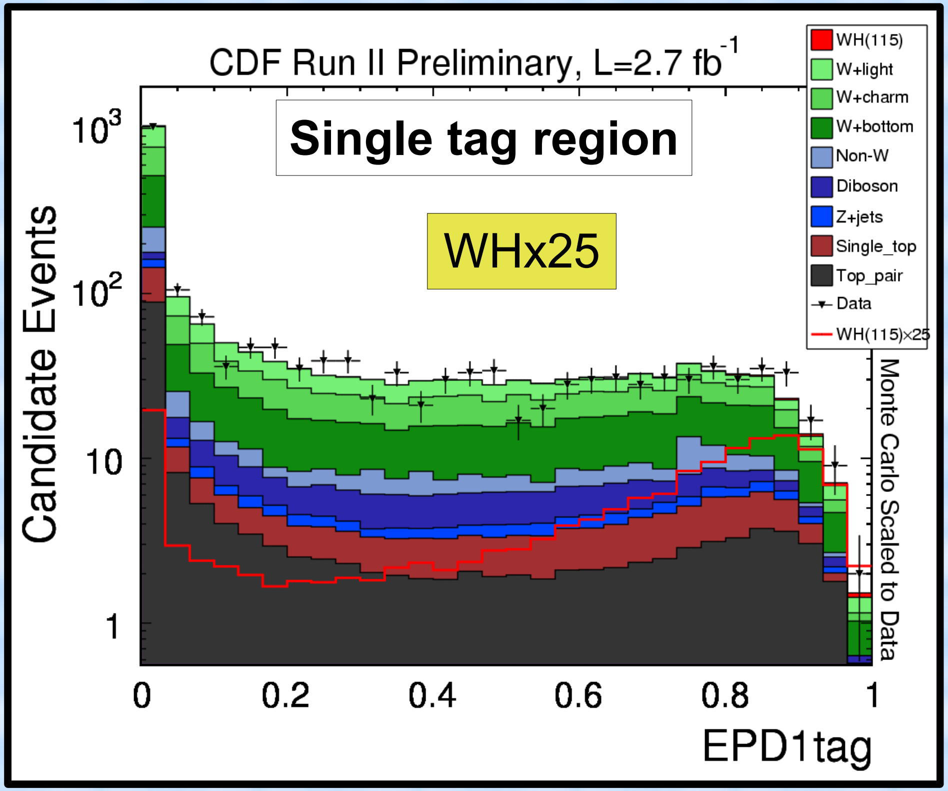
Parton Distribution Functions

Phase Space Factor

Matrix Elements

Inputs:
lepton and jet 4-vectors – no other information needed!

Backgrounds peak to zero and signal peaks higher



Event Probablity Discriminant
(EPD) = $P_s / P_s + P_{bkg}$

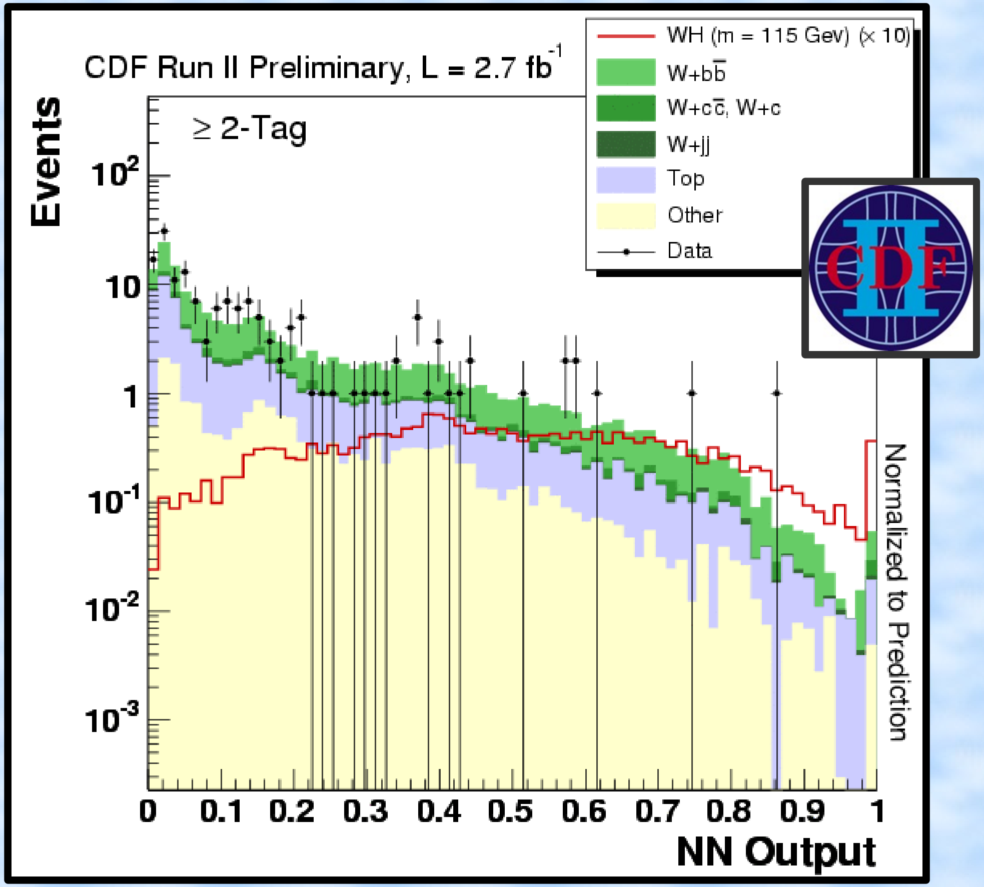
Low Mass

WH → lνbb

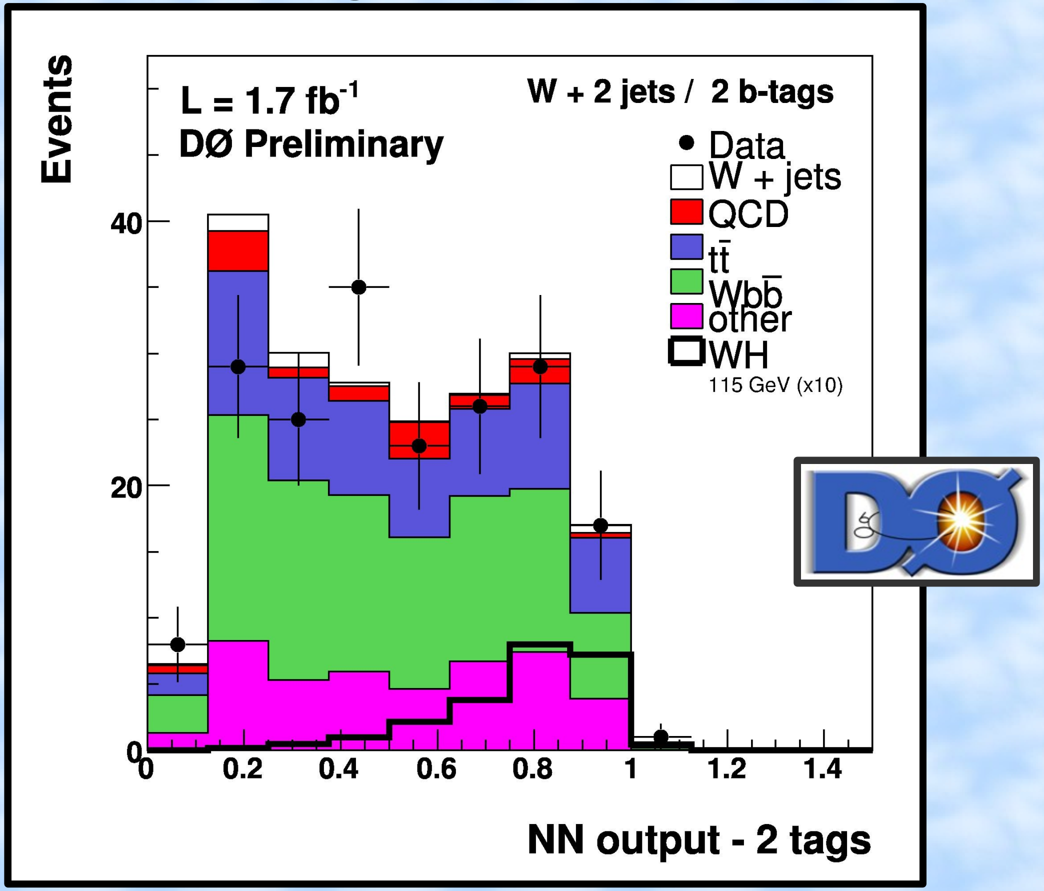
✔ This is the ***most sensitive*** production channel at the **Tevatron** for a m_H < ~135 GeV/c^2

Analysis	Lumi (fb^{-1})	Exp. / SM	Obs. / SM
D0 (115 GeV/c^2)	**1.7**	**8.9**	**10.9**
CDF (115 GeV/c^2)	**2.7**	**4.8**	**5.6**

Combine ME+BDT & NN



Selected using a Neural Network



Low Mass

ZH → lνbb

Analysis	Lumi (fb^{-1})	Exp. / SM	Obs. / SM
D0, NN & BDT(115 GeV/c^2)	**2.3**	**12.3**	**11.0**
CDF, NN (115 GeV/c^2)	**2.7**	**9.9**	**7.1**
CDF, ME (120 GeV/c^2)	**2.0**	**15.0**	**14.2**

✔ **Event Selection:** 2 high p_T leptons (ee/μμ) and b-jets.

✔ **Main Background:** Z+jets.

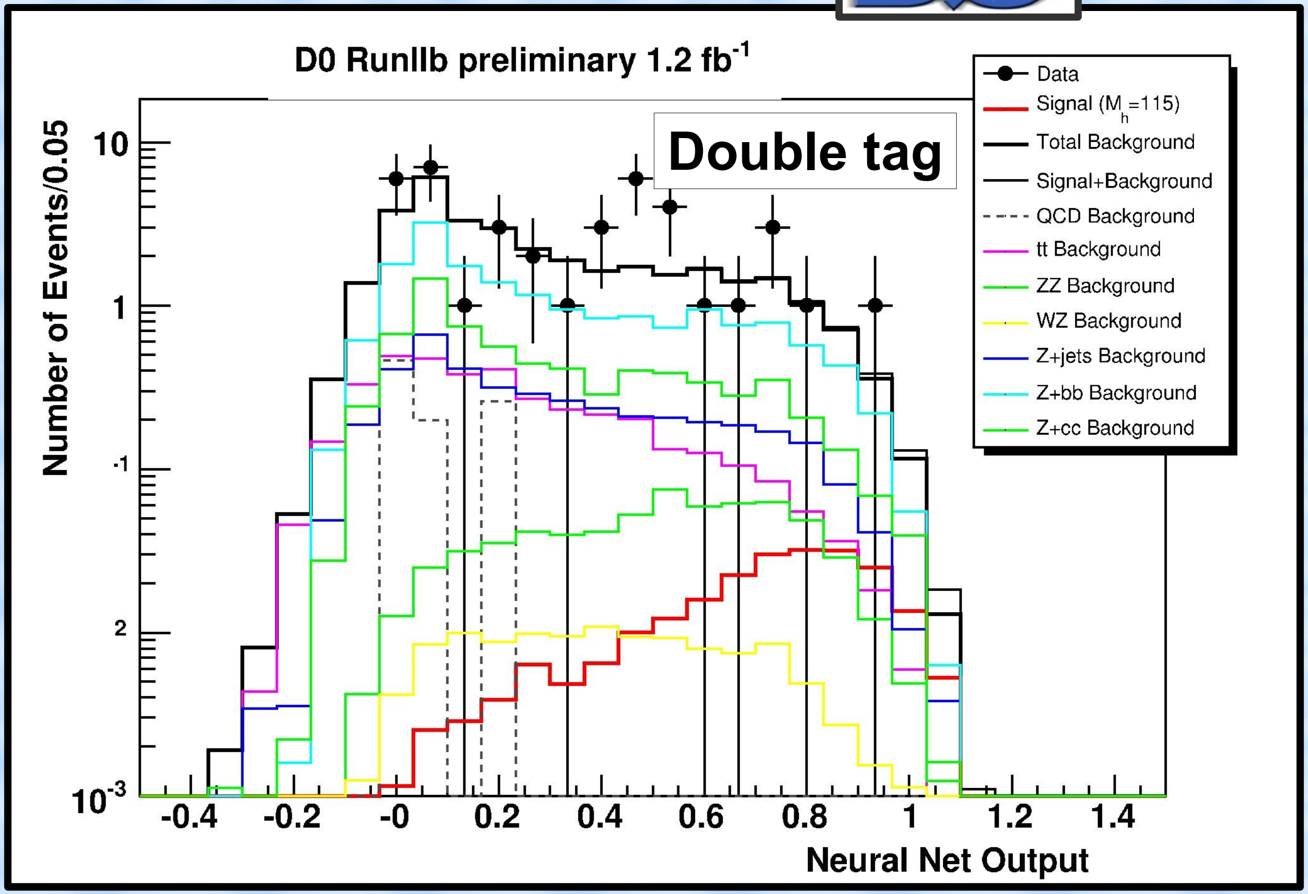
✔ **Analysis techniques:**

D0: NN and BDT discriminants.

CDF:

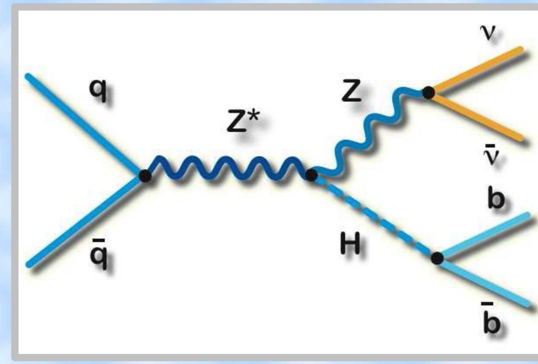
a) **2D NN analysis:** improved dijet mass resolution with METprojection technique.

b) **New ME analysis**.



Low Mass

VH → ννbb



SIGNATURE

MET

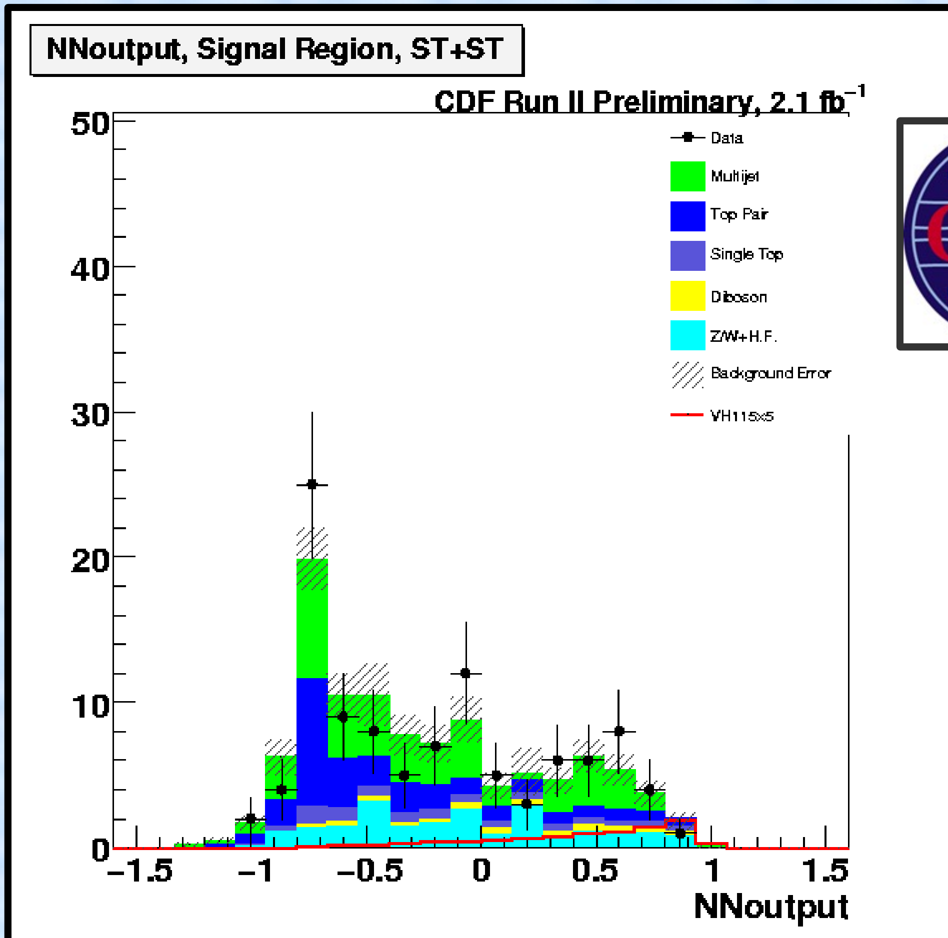
+

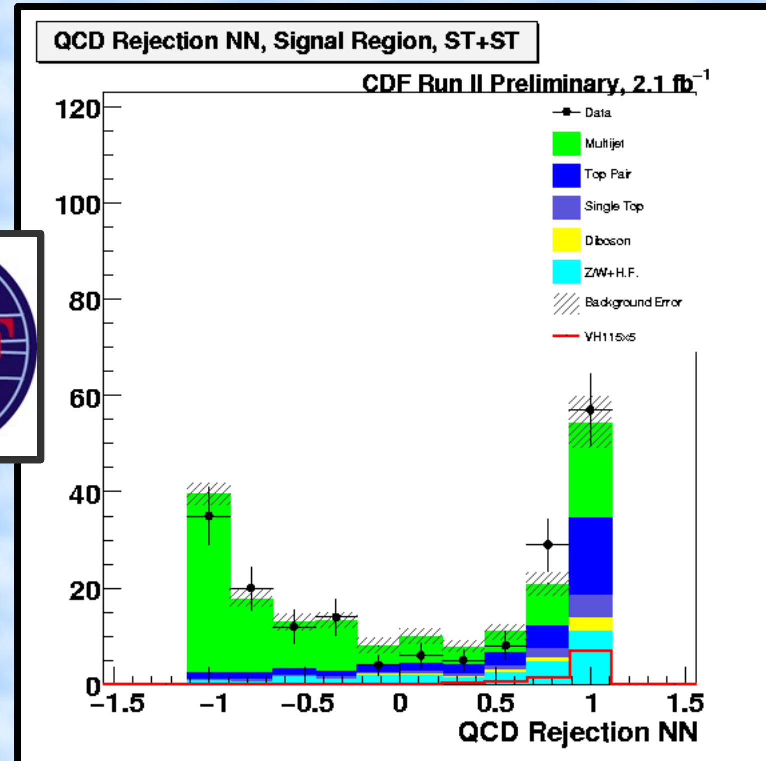
JETS

✔ **Main background:** QCD multijet processes. In CDF, a data-driven model for QCD background removal is used.

✔ **Other backgrounds:** top, single top, dibosons, W+jets, Z+jets...

✔ 3 orthogonal tag categories and 3 jet bin.





✔ **For a Higgs mass of 115 GeV/c^2**

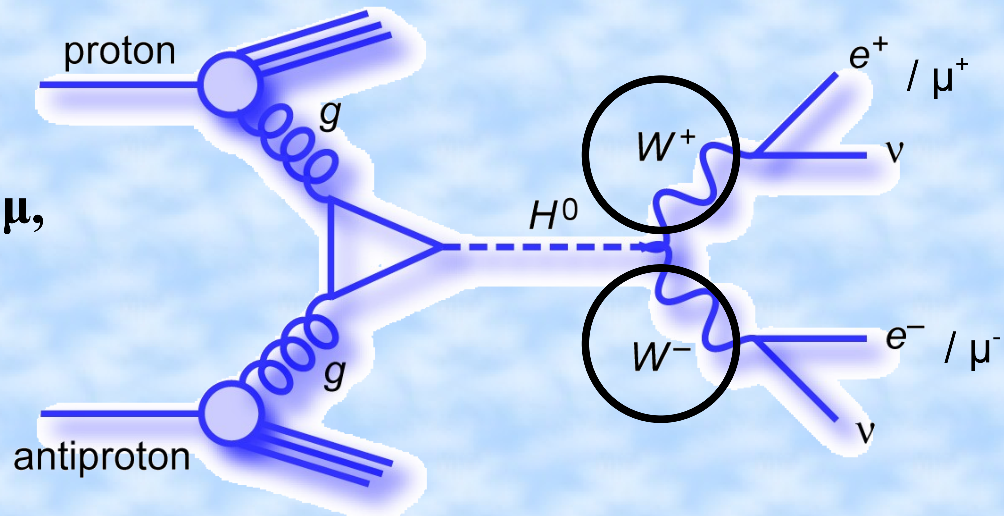
EXP.	Lumi (fb^{-1})	Exp. / SM	Obs. / SM
D0	2.1	7.0	5.7
CDF	2.1	5.6	6.9

gg → H → WW$^{(*)}$ → ll'νν (l,l'=e,mu)

✔ Most sensitive Higgs search at the Tevatron

✔ **Signature:** 2 high p_T leptons + MET.
✔ Leptons in same directions due to spin correlation.
✔ Different background composition: *WW*, Drell-Yan, *tt*...

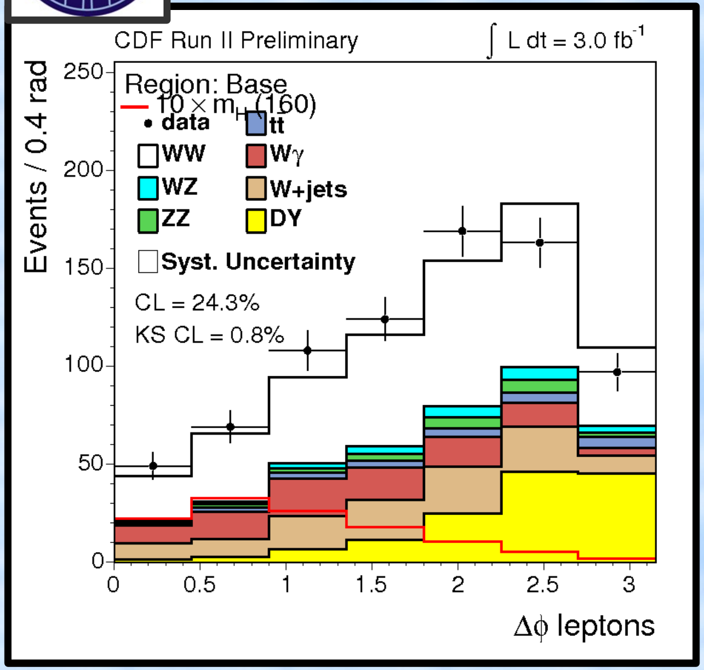
Final states: e^+e^-, eμ, or $\mu^+\mu^-$ and 2 ν.



✔ There are several production mechanisms besides gluon fusion:
WH → WWW, ZH → WWW, V.B.F H → WW
✔ New dedicated analyses in different 0, 1, 2 jet bins.
✔Analyses optimized for each jet bin.

Both experiments approaching SM sensitivity

gg → H → WW$^{(*)}$ → ll'νν (l,l'=e,mu)



ΔΦ between the leptons is the most discriminating variable for the 0 jet bin.

WW background distinguish by the spin correlation of the leptons.

CDF, H → WW, 0 jets

Process	# of events
ttbar	0.96 ± 0.19
Drell-Yan	66.88 ± 15.20
WW	280.42 ± 38.99
WZ	12.17 ± 1.93
ZZ	17.29 ± 2.74
W+jets	83.61 ± 20.09
Wγ	79.15 ± 21.12
Total bkg	**540.48 ± 64.81**
gg → H	8.38 ± 1.29
Total Signal	**8.38 ± 1.29**
Data	**552**

CDF, H → WW, 0, 1, ≥2 jets

CDF Run II Preliminary $\int \mathcal{L} = 3\ fb^{-1}$

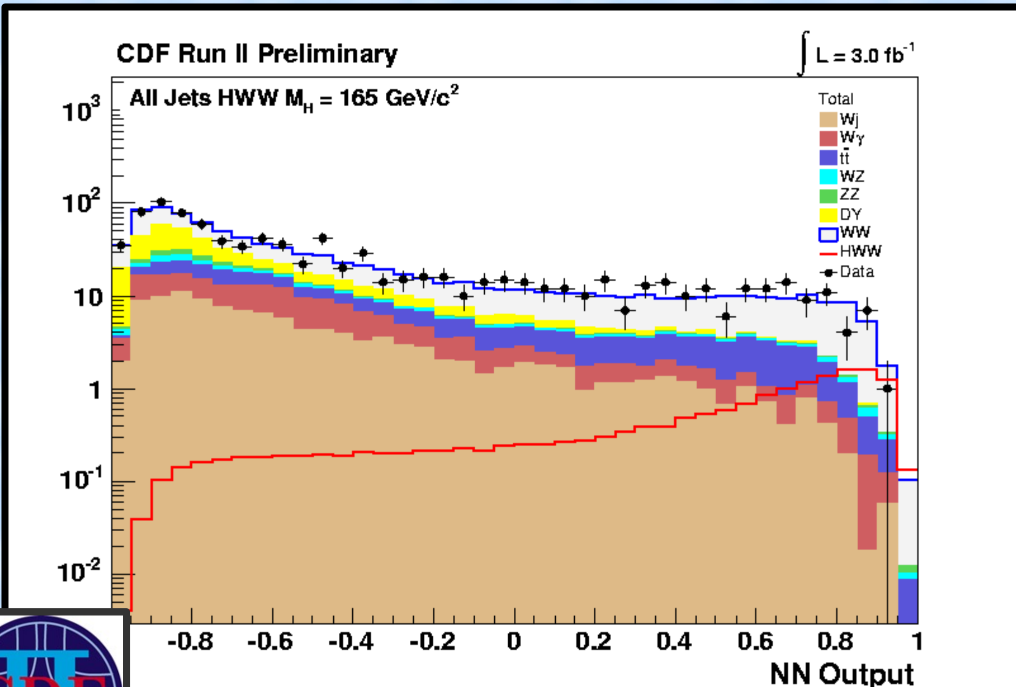
	110	120	130	140	145	150	155	160	165	170	175	180	190	200
$-2\sigma/\sigma_{SM}$	20.05	6.42	3.03	1.95	1.69	1.43	1.15	0.88	0.84	0.96	1.21	1.42	2.26	3.04
$-1\sigma/\sigma_{SM}$	27.38	8.80	4.20	2.70	2.34	1.93	1.58	1.20	1.14	1.34	1.67	1.96	3.17	4.23
Median/σ_{SM}	**38.90**	**12.61**	**6.05**	**3.86**	**3.35**	**2.79**	**2.29**	**1.71**	**1.62**	**1.92**	**2.39**	**2.82**	**4.63**	**6.16**
$+1\sigma/\sigma_{SM}$	56.09	18.02	8.70	5.55	4.84	4.02	3.36	2.45	2.34	2.74	3.46	4.08	6.77	8.99
$+2\sigma/\sigma_{SM}$	78.70	25.44	12.21	7.74	6.75	5.64	4.71	3.40	3.36	3.89	4.86	5.68	9.56	12.79
Observed/σ_{SM}	**57.89**	**13.98**	**6.13**	**4.03**	**3.35**	**3.25**	**2.33**	**1.56**	**1.72**	**1.91**	**2.01**	**2.82**	**5.26**	**10.35**

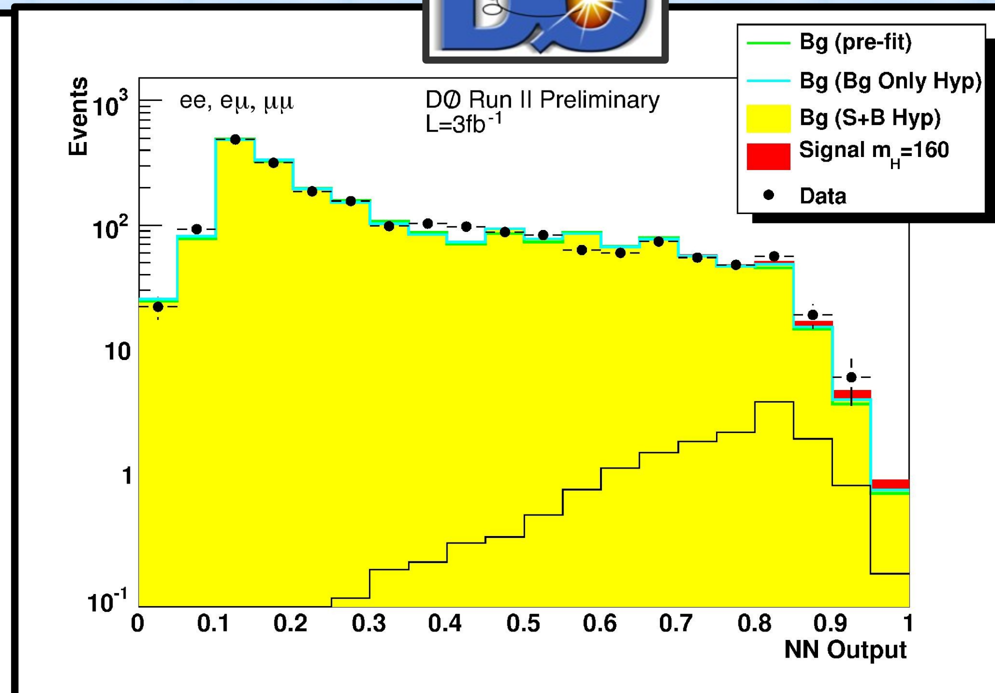
$H \rightarrow WW^{(*)} \rightarrow ll'\nu\nu$, $\int L = 3.0\ fb^{-1}$

High Mass

CDF Search for Higgs to WW* Production using a Combined Matrix Element and NN Technique

NN is used in each of the three di-lepton channels



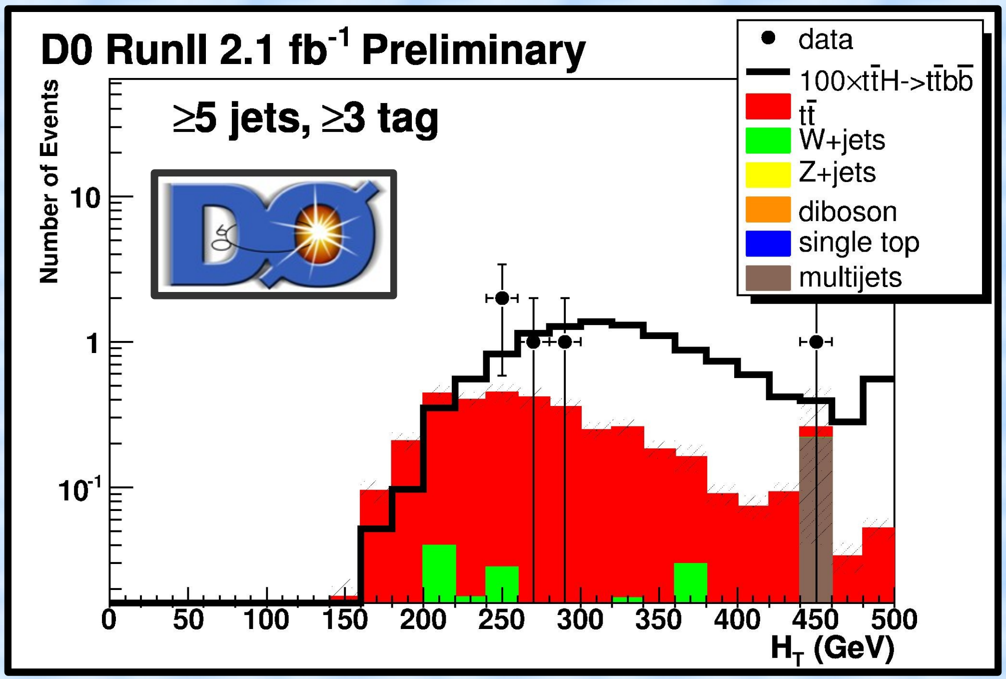


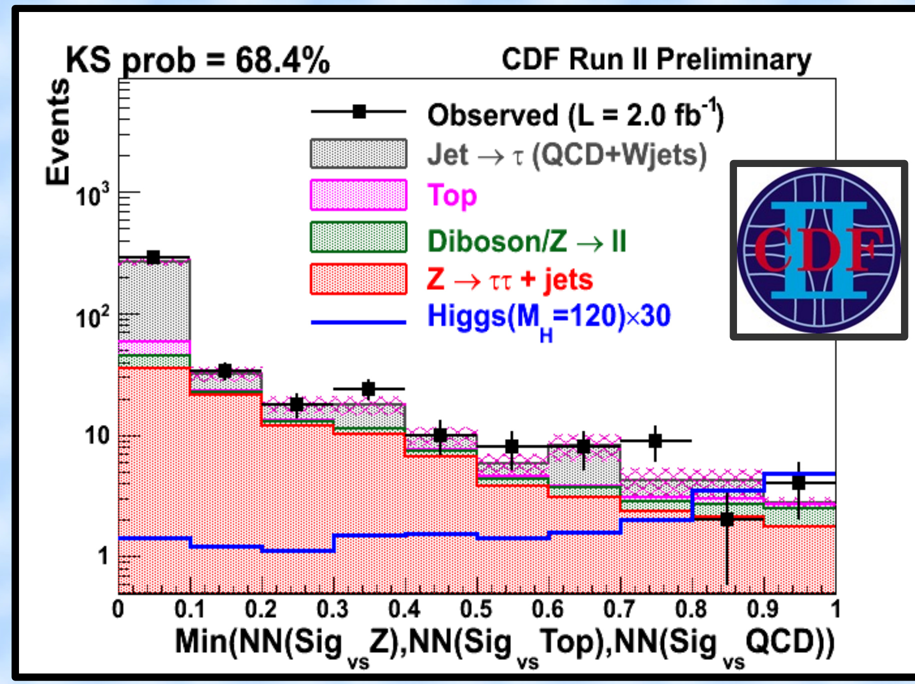
EXPERIMENT	EXP. Limit/SM m_H=165 GeV/c^2	OBS. Limit/SM m_H=165 GeV/c^2
DØ	1.9	2.0
CDF	1.6	1.7

ADDITIONAL CHANNELS

Many other SM Higgs searches, not as sensitive but contribute in combination.

Analysis	Lumi (fb^{-1})	Exp. / SM	Obs. / SM
D0, ttH → lνbbbbqq	2.1	45.3	63.9
D0, H → γγ	2.7	23.2	30.8
CDF, H → ττ	2.0	24.8	30.5



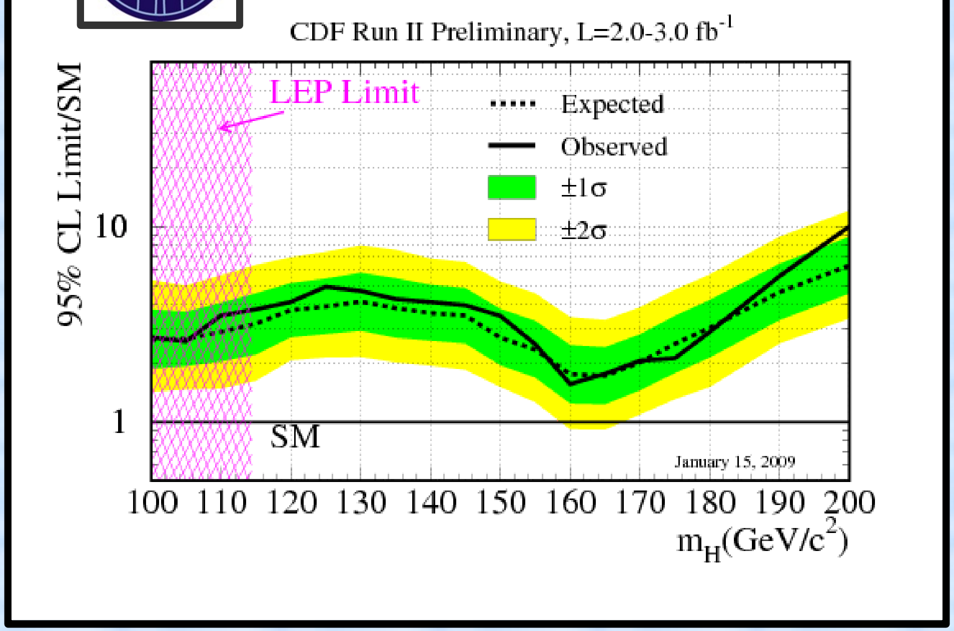


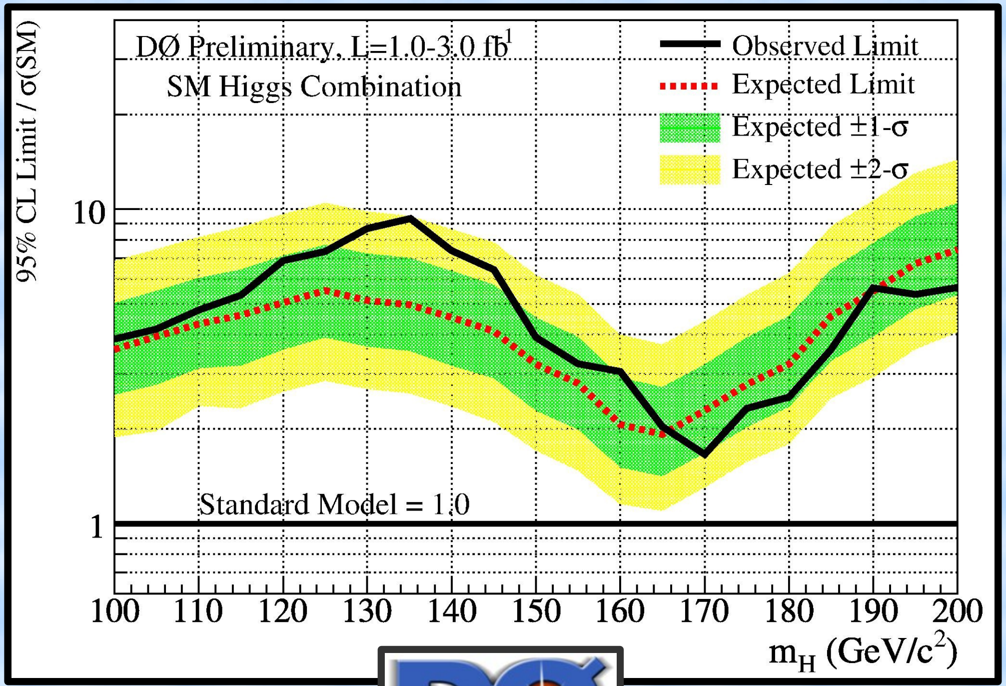
- **Signature:** 1 lepton + MET + 4 jets.
- 12 channels (4, ≥5 jets) x (1, 2, ≥3 b-tags).
- Scalar sum of jets (H_T) to extract signal.

Four signal processes considered:

- W(→ qq') H(→ $\tau^+\tau^-$)
- Z(→ qq) H(→ $\tau^+\tau^-$)
- VBF qHq'→ q' $\tau^+\tau^-$q
- gg → H → $\tau^+\tau^-$

INDIVIDUAL EXPERIMENTS COMBINATION





$100 < m_H < 200$ GeV/c^2

Contributing production processes:
- Associated production (W/Z).
- Gluon fusion.
- Vector boson fusion.

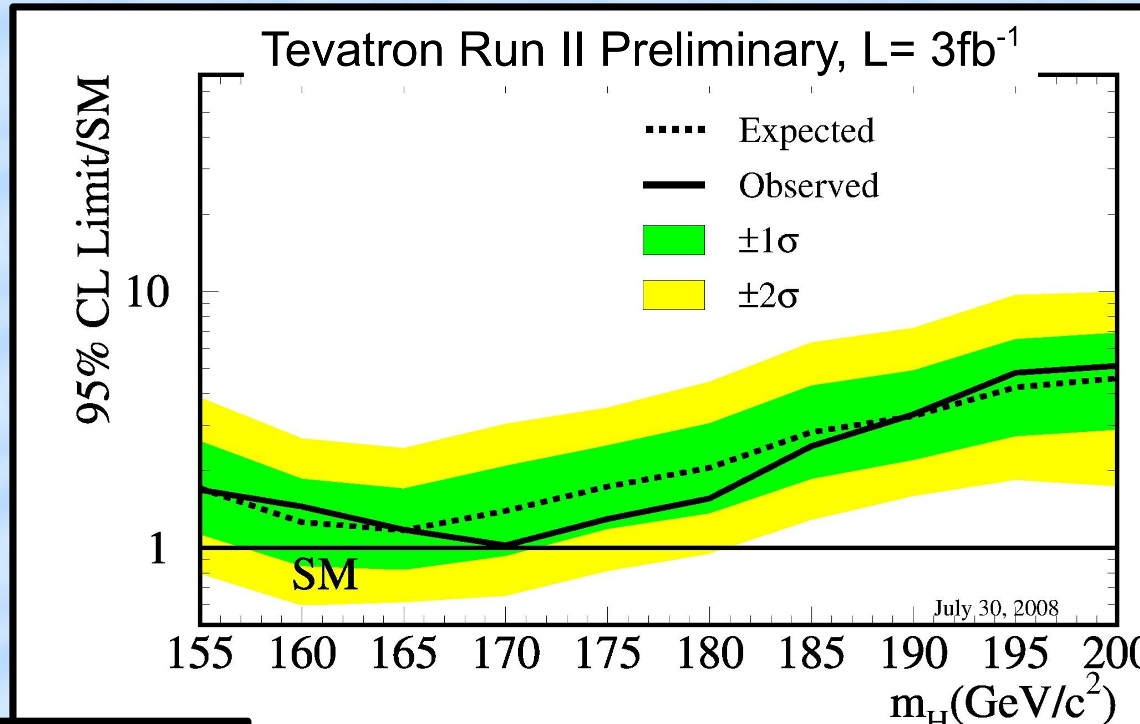
EXPERIMENT	EXP.(OBS)/SM m_H=115 GeV/c^2	EXP.(OBS)/SM m_H=165 GeV/c^2
D0	4.6 (5.3)	1.9 (2.0)
CDF	3.1 (3.7)	1.6 (1.8)

Analyses are conducted with integrated luminosities from **1.1 to 3.0 fb^{-1}**

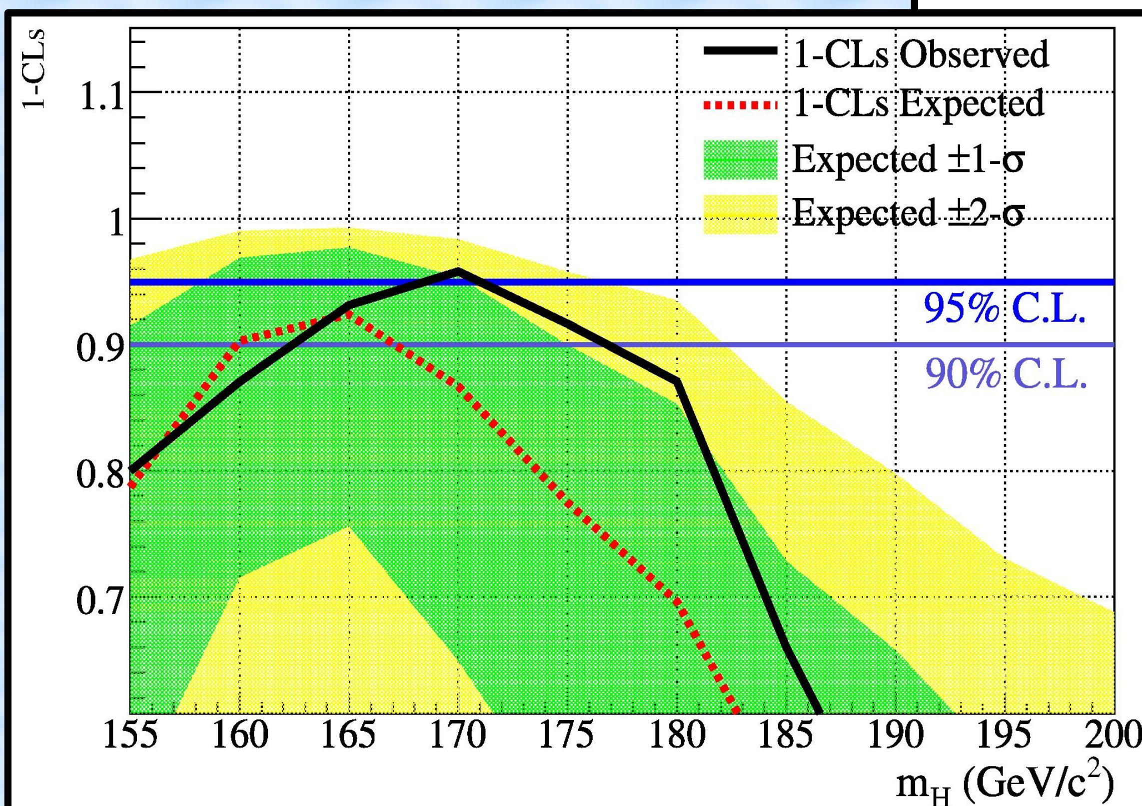
SM TEVATRON HIGH MASS COMBINATION

Combine results from CDF and D0 searches for SM Higgs boson.

Systematics and their correlation between channels and experiments taken into account.



Results presented at ICHEP 2008, Philadelphia



Tevatron high mass combination:

✔ We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV/c^2.

✔ First direct exclusion since LEP!

RESULT 3 fb^{-1}	EXP.(OBS.)/SM m_H=165 GeV/c^2
D0 + CDF	1.2 (1.2)

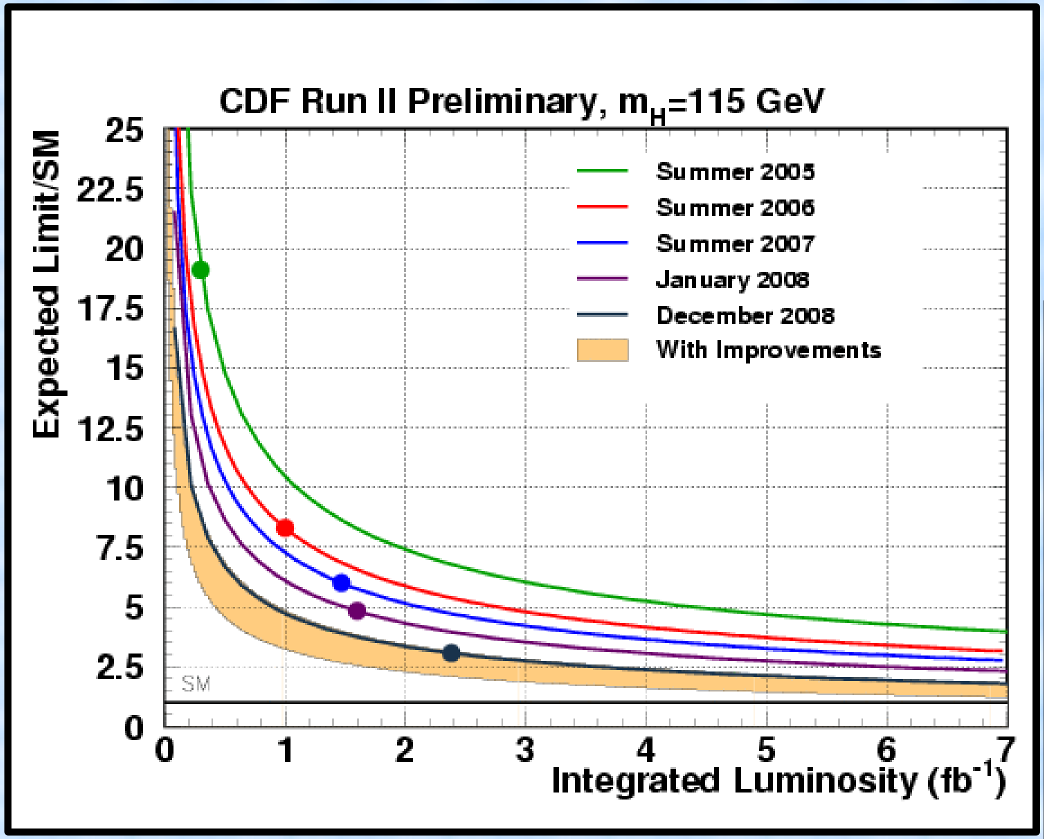
The low mass region is challenging, but in the next Tevatron combination the expected limit should fall below:

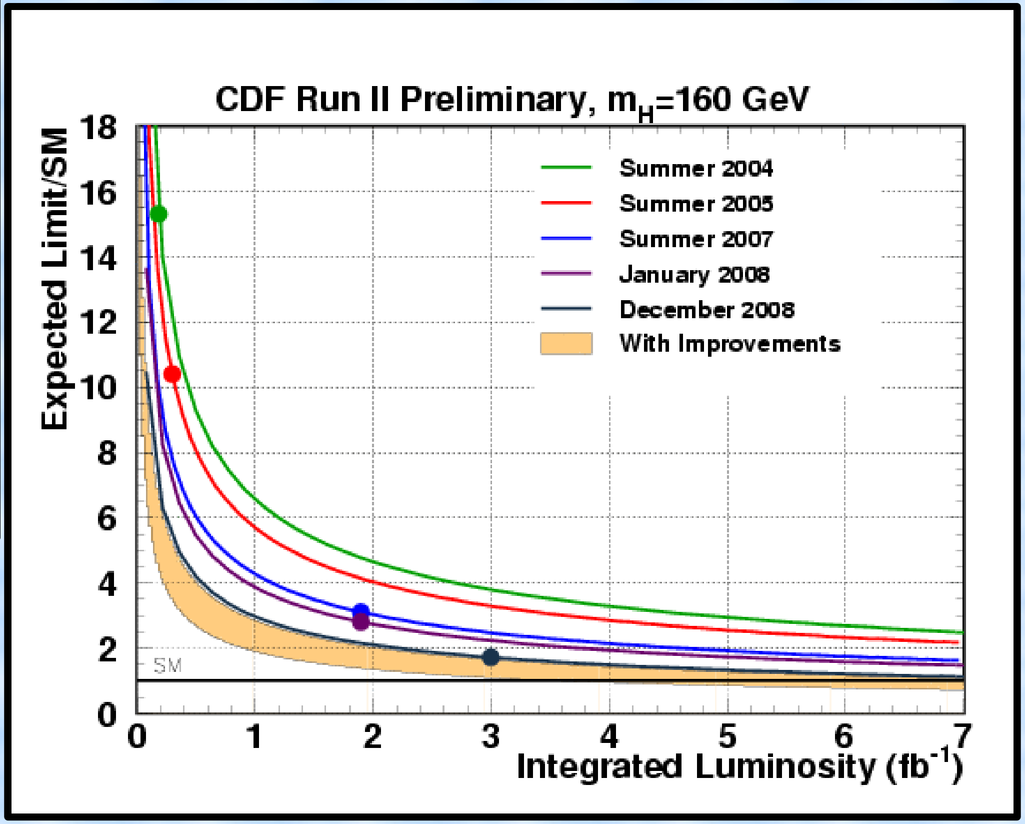
~3 x SM for m_H = 115 GeV/c^2

Achieved & Projected

There is still room for improvements:

- Increase in acceptance.
- Sophisticated analysis tools.
- B-tagging.
- jet/MET resolutions.





We are sensitive to a Higgs of 160 GeV/c^2

"Beyond the Standard Model"

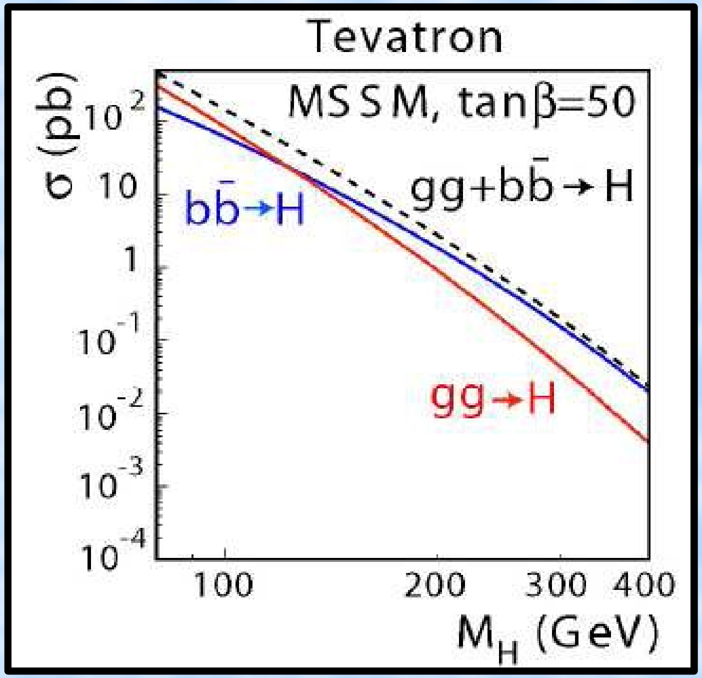
✔ The **Minimal Supersymmetric Standard Model (MSSM)** is the minimal extension to the SM that realizes supersymmetry.

In the MSSM, 5 Higgs bosons remain after EW symmetry breaking:

✗ 3 neutral: h, H, and A - denoted as Φ.

✗ 2 charged: $H^{\pm}$.

MSSM

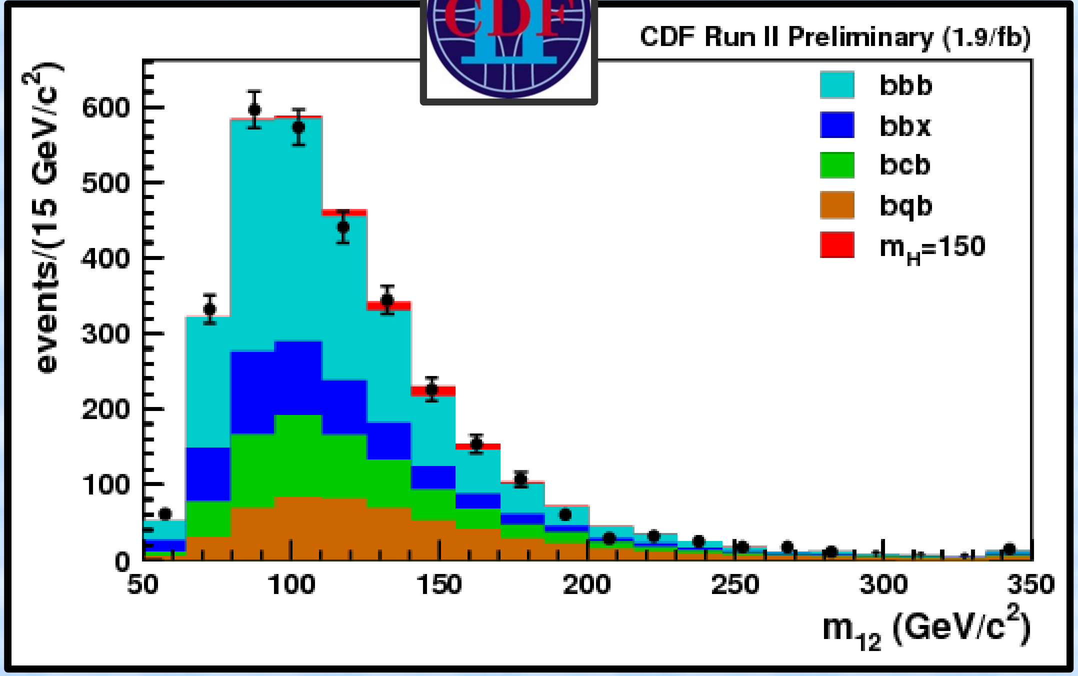


MSSM processes (next pages):

- $b\Phi \rightarrow bbb$
- $b\Phi \rightarrow b\tau\tau$
- $\Phi \rightarrow \tau\tau$

bΦ → bbb (multi-b-jets)

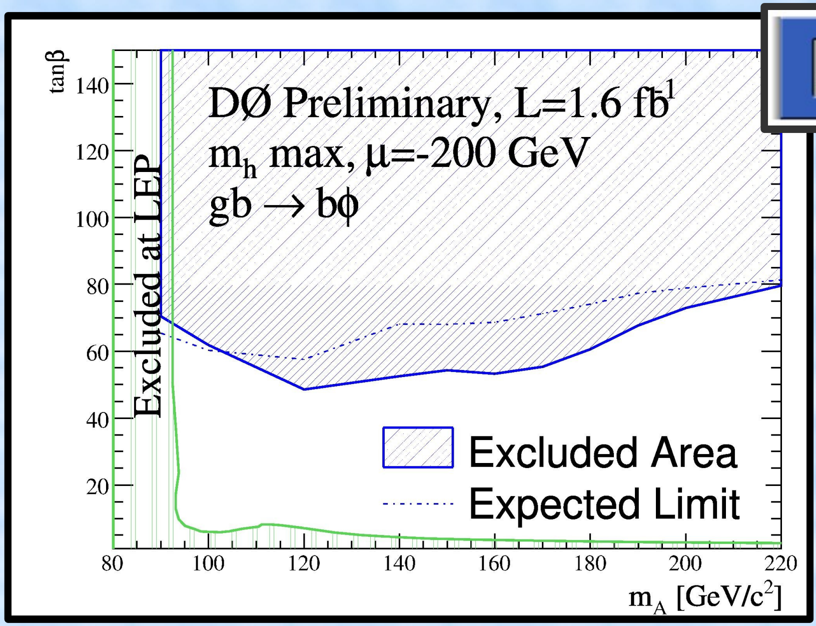
MSSM



- This process could be observable in supersymmetric models with high values of tanβ.
- **Event signature**: at least 3 b-jets.

  Data required (trigger): 2 central clusters with E_T>15 GeV, the third jet E_T>10 GeV.

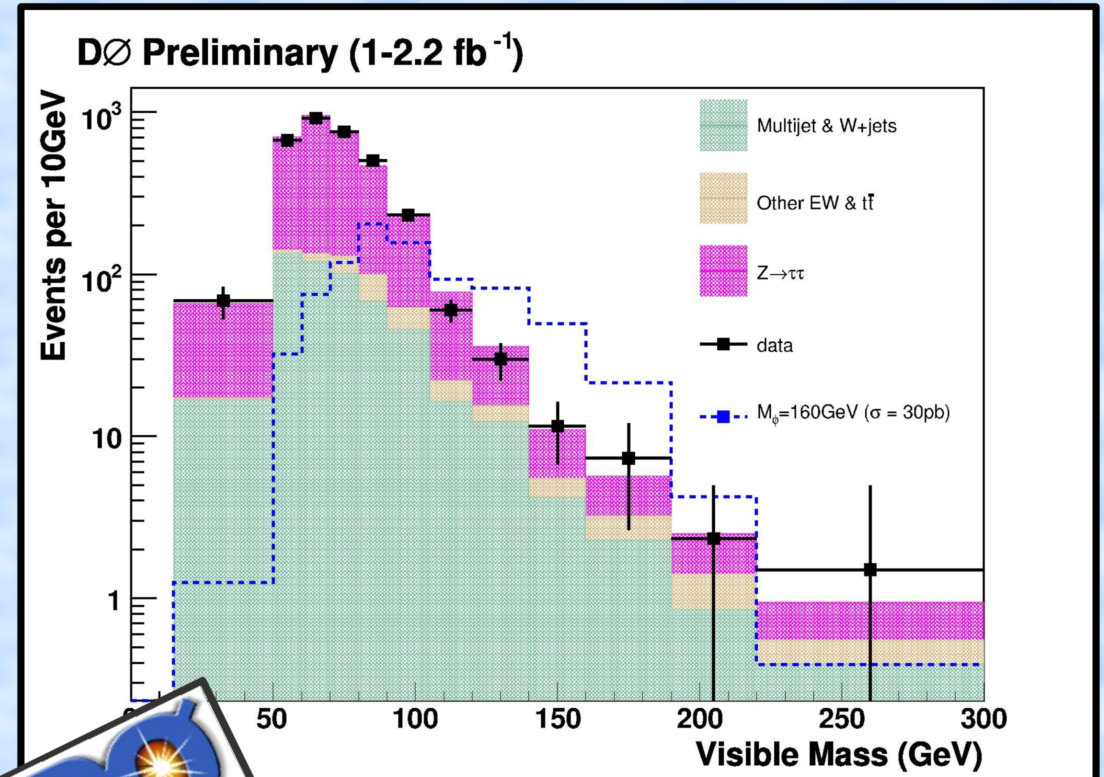
  Offline: three jets with E_T>20 GeV, |η| < 2.
- This final state suffers from a large multijet background.
- The dijet mass of the 2 leading jets in the events (m12) used , in triple tag events, to separate **Higgs signal** from **background** events.



RESULTS

EXP.	LUMI	EXP. (OBS.) pb m_H = 90GeV/c^2	EXP. (OBS.) pb m_H= 200GeV/c^2
CDF	1.9 fb^{-1}	77 (57)	6.1 (4.1)
D0	1.6 fb^{-1}	149 (201)	7.7 (6.2)

MSSM

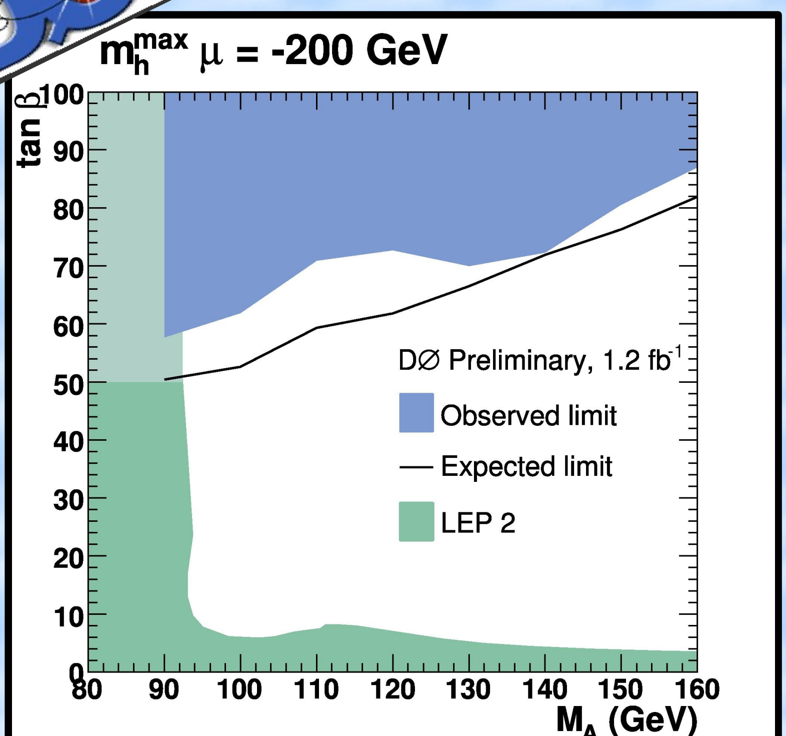


Φ (=H; h;A) $\rightarrow \tau^+ \tau^-$

Search requires the tau pairs to decay into $\tau_e \tau_{had}$, $\tau_\mu \tau_{had}$, or $\tau_e \tau_\mu$

Backgrounds:

- W+jets
- Top
- $Z \rightarrow \tau^+ \tau^-$
- Others...



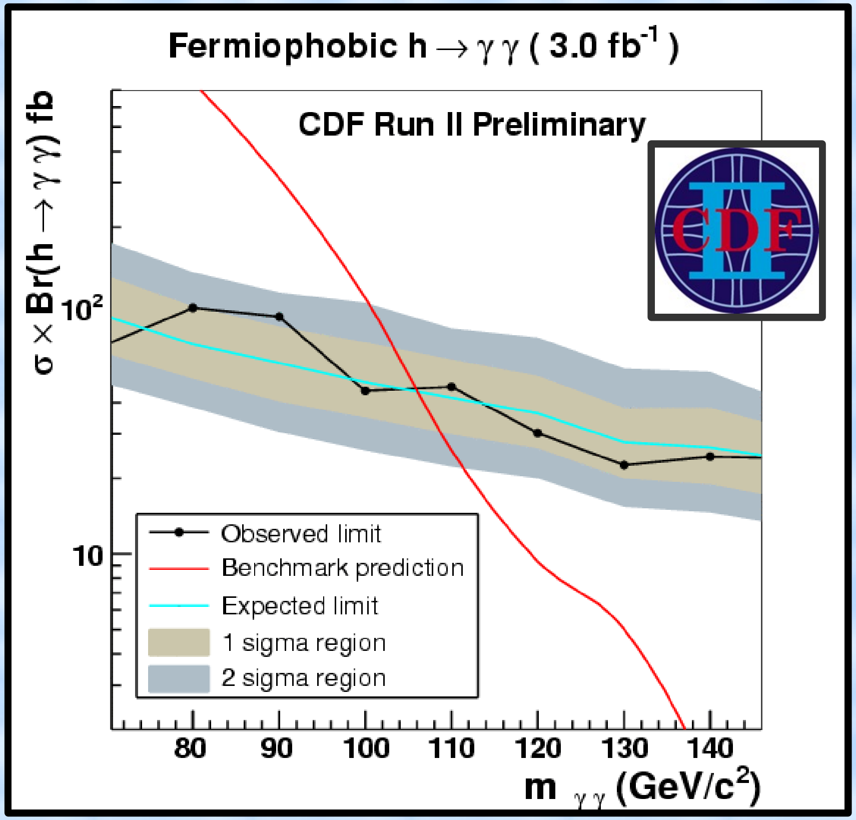
Φ (=H; h;A)+b $\rightarrow$ b τ τ

✔ The final state includes a μ candidate, a $\tau_{hadronic}$ candidate, and a jet tagged as a b-quark jet.

✔ The bττ channel offers a much cleaner final state than the bbb channel, giving the two channels similar sensitivities.

✔ Exclusion limits are set at the 95% C.L. for several supersymmetric scenarios.

FERMIOPHOBIC HIGGS

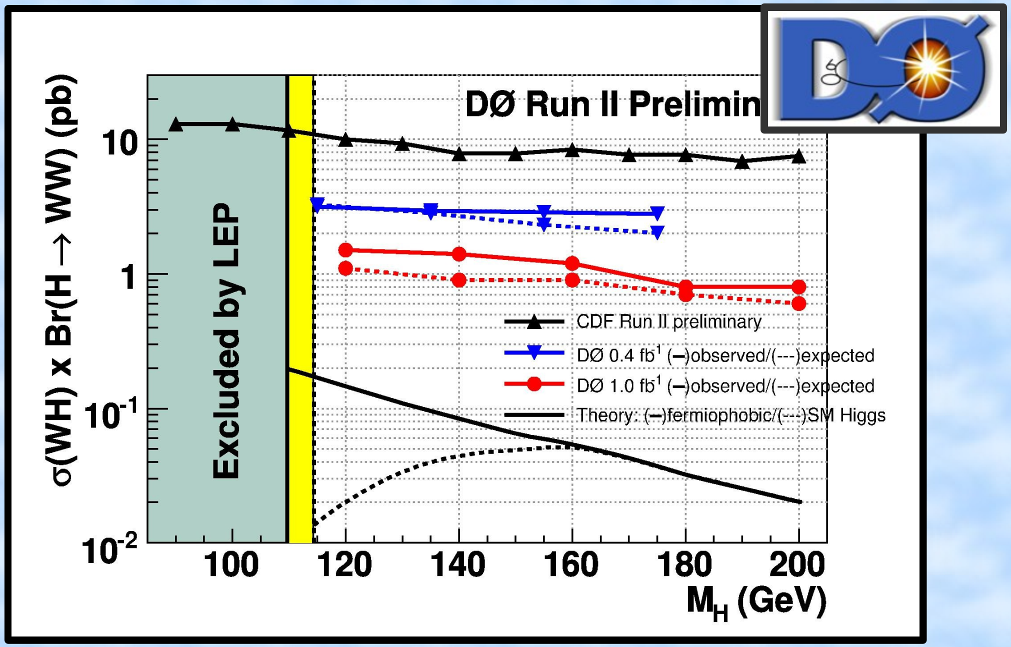


$H \to \gamma\gamma$

✔ Photon energy resolution better than jets.

✔ Look for peak in di-photon mass.

✔ SM-like search but branching ratio is enhanced in fermiophobic model.



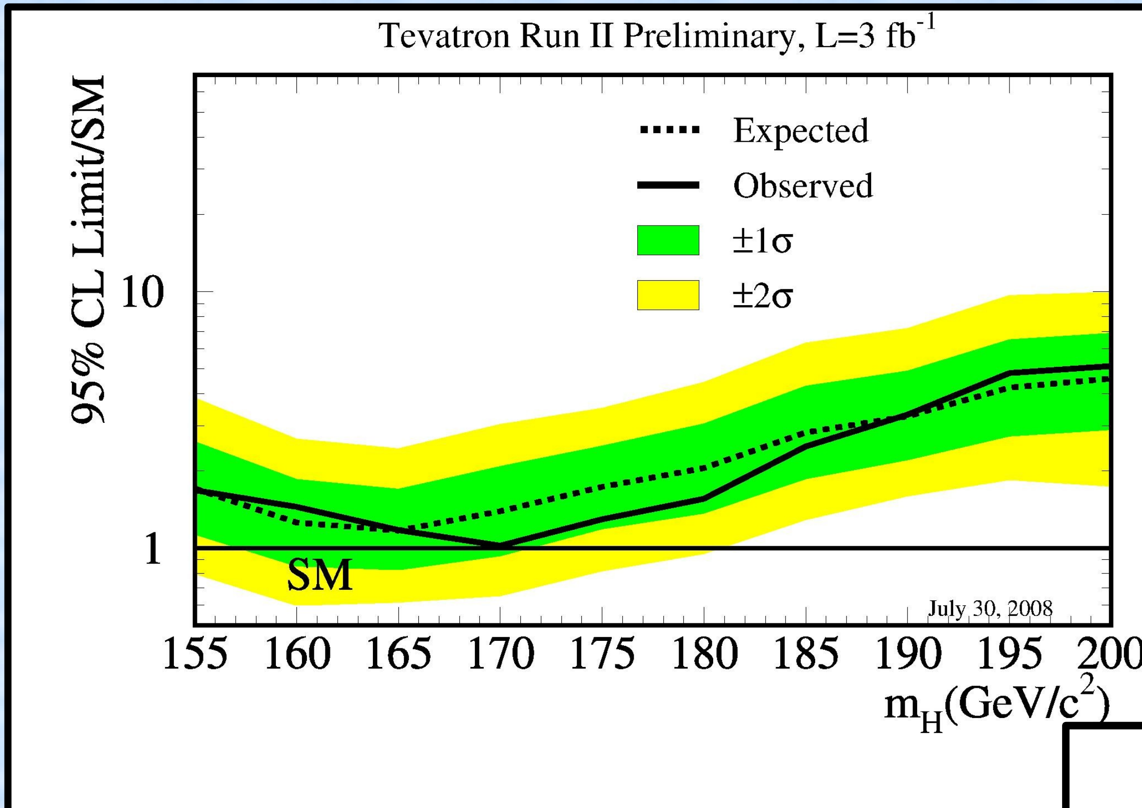
$WH \to WWW$

✔ Look for same-sign leptons.

✔ Also sensitive to SM at high mass.

✔ At low mass more sensitive if *H* is fermiophobic.

CONCLUSIONS



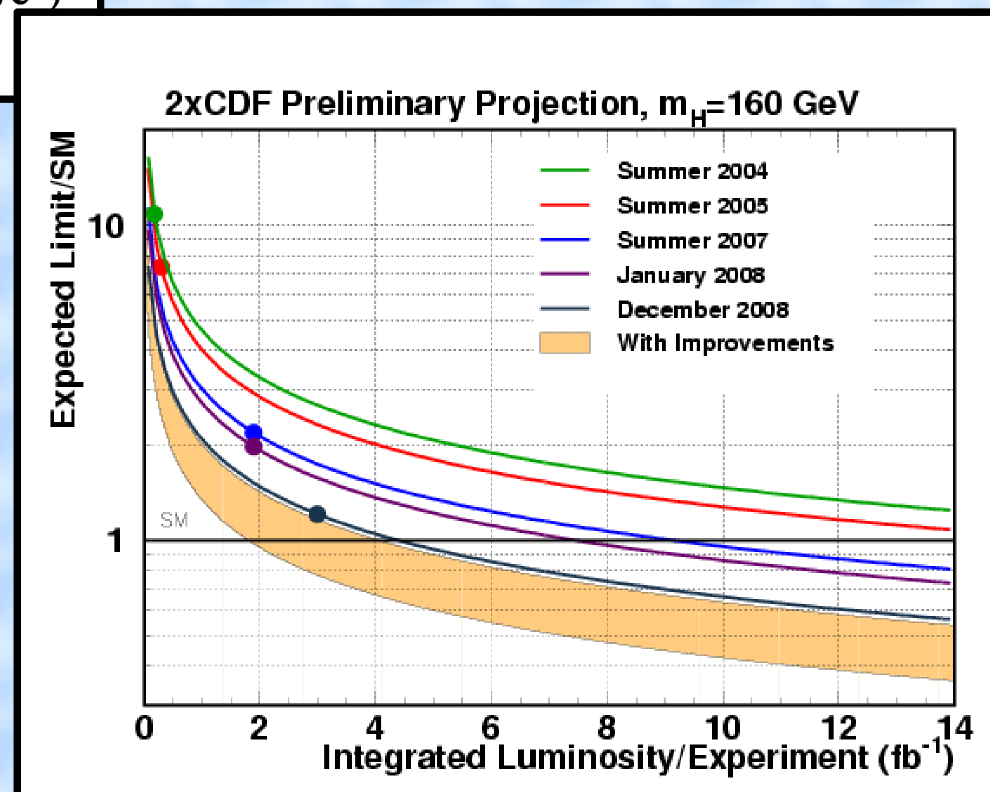
- Tevatron is running really well.
- The Higgs boson search is in its most exciting era ever.
- Reaching sensitivity to SM Higgs over full mass range and beyond SM Higgs boson.

NO evidence for signal found yet.

We exclude at 95% C.L. a SM Higgs boson of 170 GeV/c^2

We are sensitive to a Higgs of 160 GeV/c^2

Stay tuned for further improvements!



Bárbara Álvarez- U. de Oviedo

THANK YOU!!!

BACK UP SLIDES

Only ~40 Higgs events are expected to be produced per fb^{-1} at each experiment in detectable channels