CDF実験のヒッグス粒子探索の結果

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Outline

- Standard Model and Higgs Boson
- Tevatron and CDF Detector
- SM Higgs Searches at CDF
- Future Prospects
- Conclusions

Standard Model and Higgs Boson

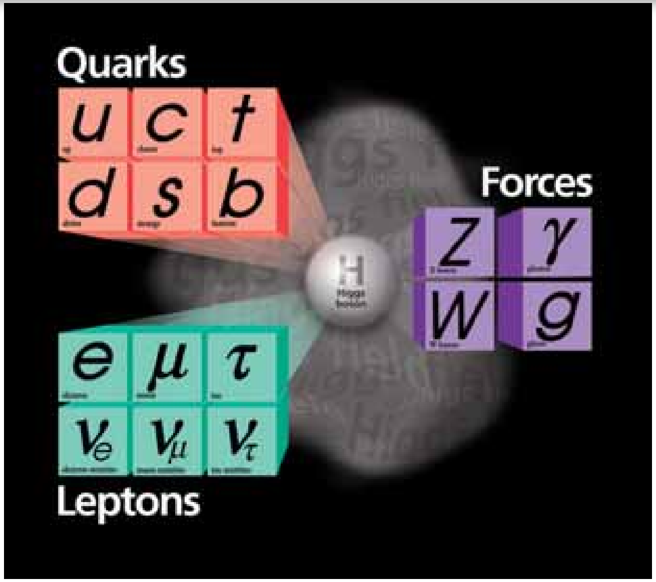
Standard Model Higgs Boson

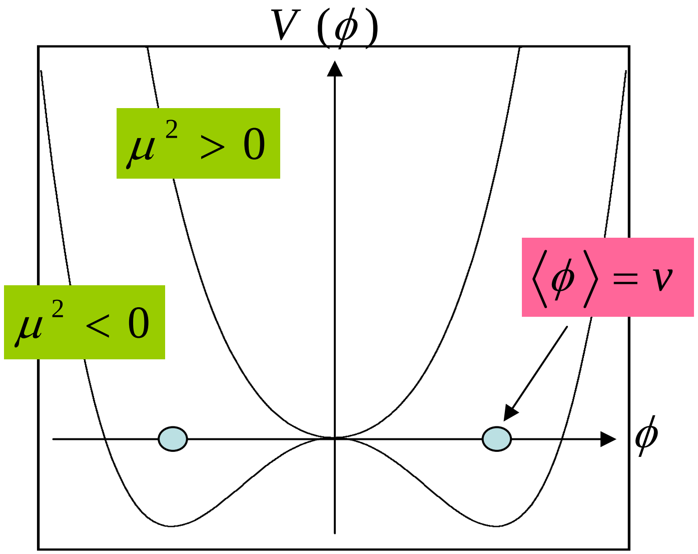
Standard Model

- Gauge theory: $SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$
- Left (right) handed fermion = $SU_L(2)$ doublet (singlet)

Higgs boson

- Elementary complex scalar
- No color, $SU_L(2)$ doublet, Y = +1/2
- Responsible for the spontaneous breaking of the electroweak (EW) gauge symmetry
  - Gauge boson masses
- Physical state
  - $T_3 = -1/2$, Y = +1/2, Q = 0
- Also assumed to generate fermion masses
- No experimental confirmation



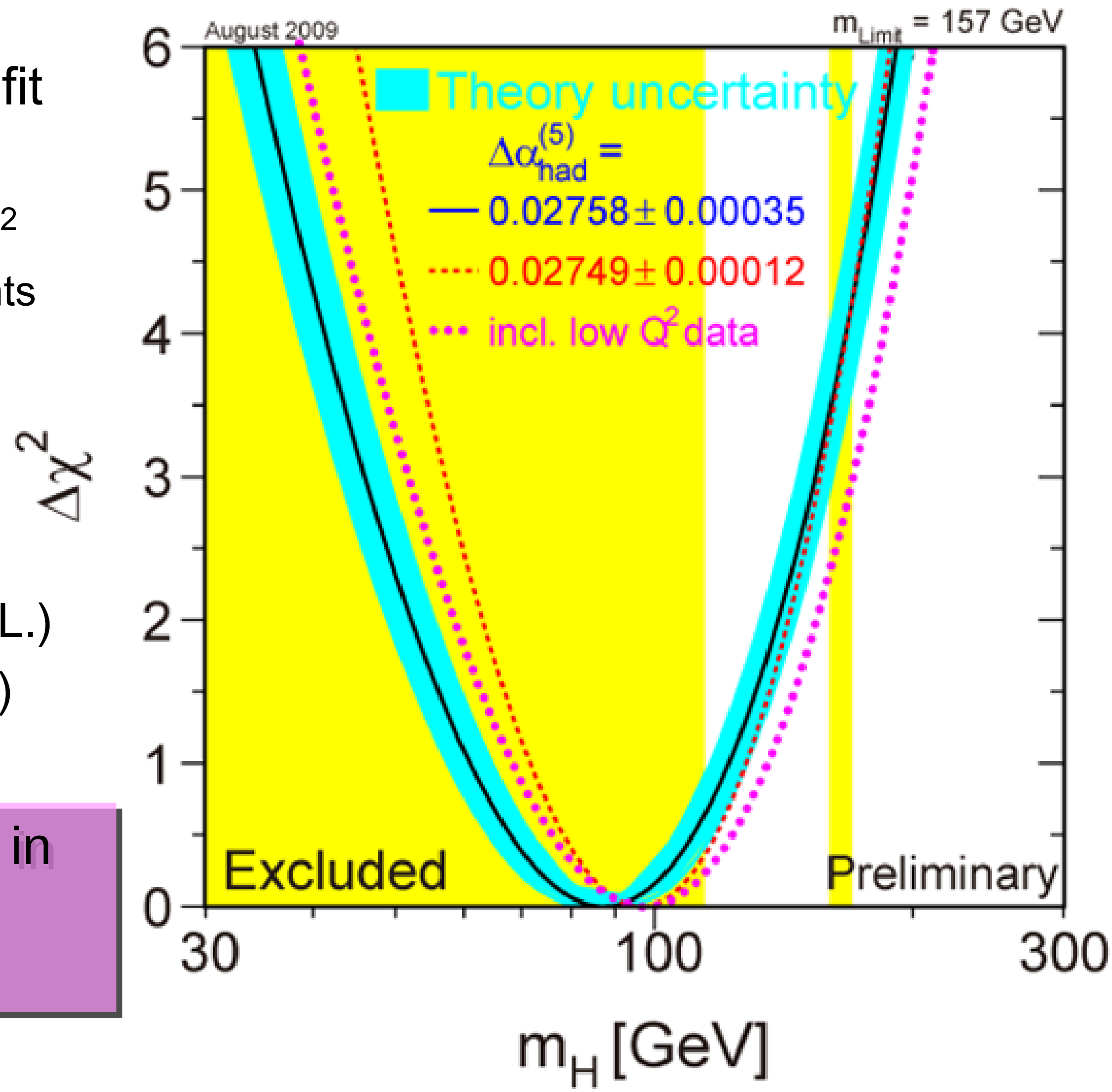


$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Status of SM Higgs

- Indirect limit from global EW fit
  - $m_t = 173.1 \pm 1.3$ GeV/c^2
  - $m_W = 80.399 \pm 0.023$ GeV/c^2
  - and precision EW measurements at LEP and SLD
  - $m_H = 87^{+35}_{-26}$ GeV/c^2
- Direct search at LEP
  - $m_H > 114.4$ GeV/c^2 (95% C.L.)
  - $m_H < 186$ GeV/c^2 (95% C.L.)

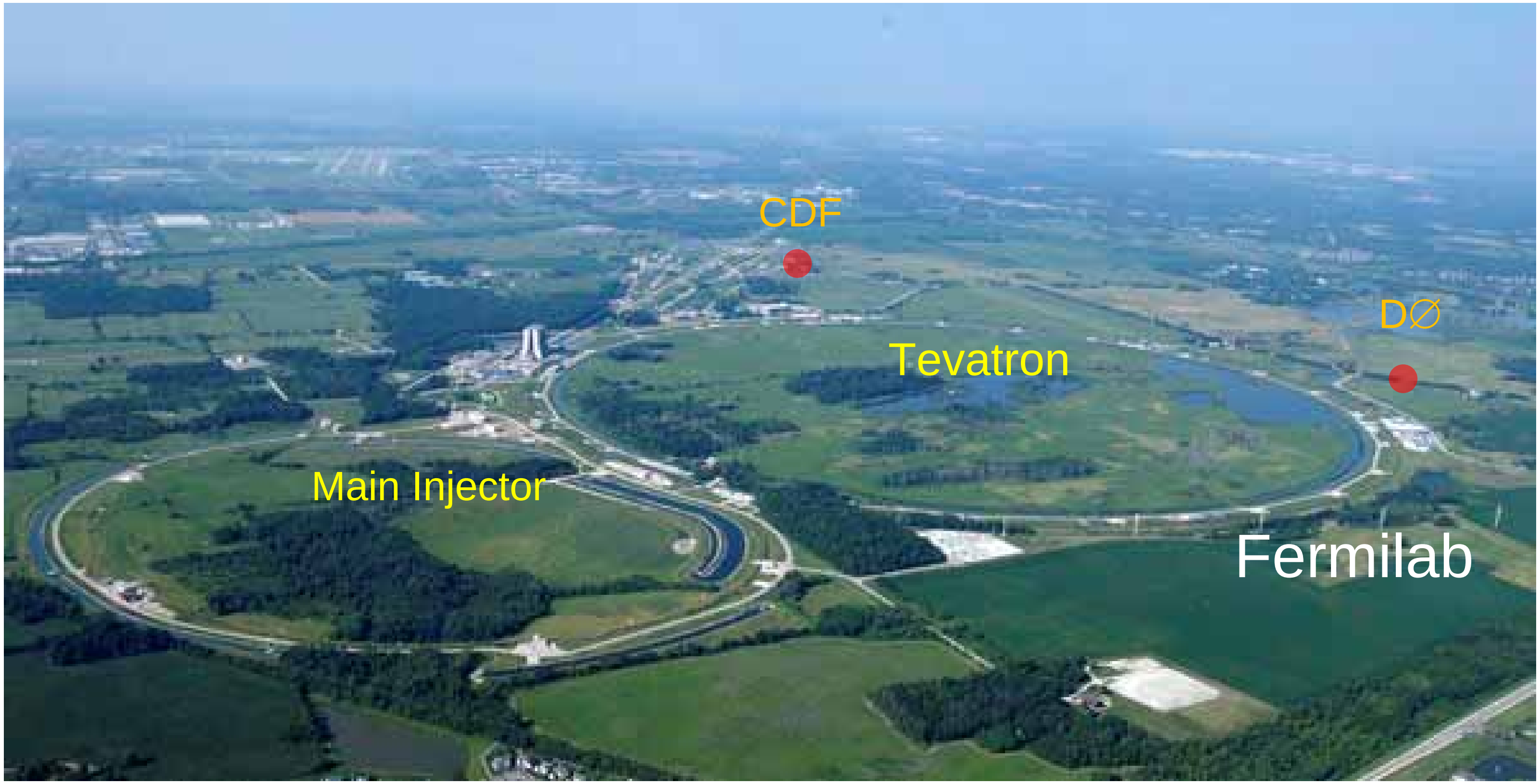
CDF and DØ are probing Higgs in the most probable region :
$100 < M_H < 200$ GeV/c^2



Tevatron and CDF Detector

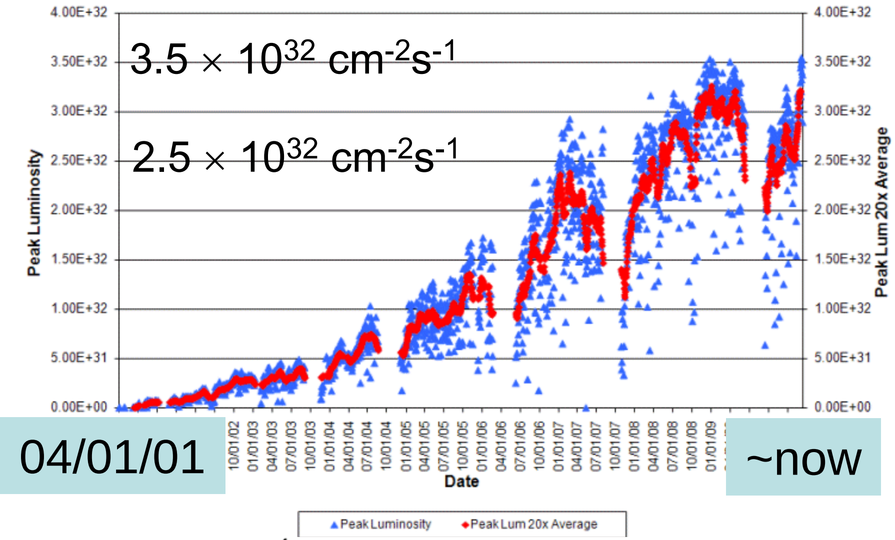
Tevatron Accelerator

- Proton-antiproton collider at $\sqrt{s}$ = 1.96 TeV
- 36×36 bunch, bunch space 396 ns
- Np~10000e9, Npbar~3000e9, typical peak luminosity ~ 0.3 nb^{-1}/s
- Store duration ~ 12 hrs
- Two major detectors at collision points : CDF and DØ

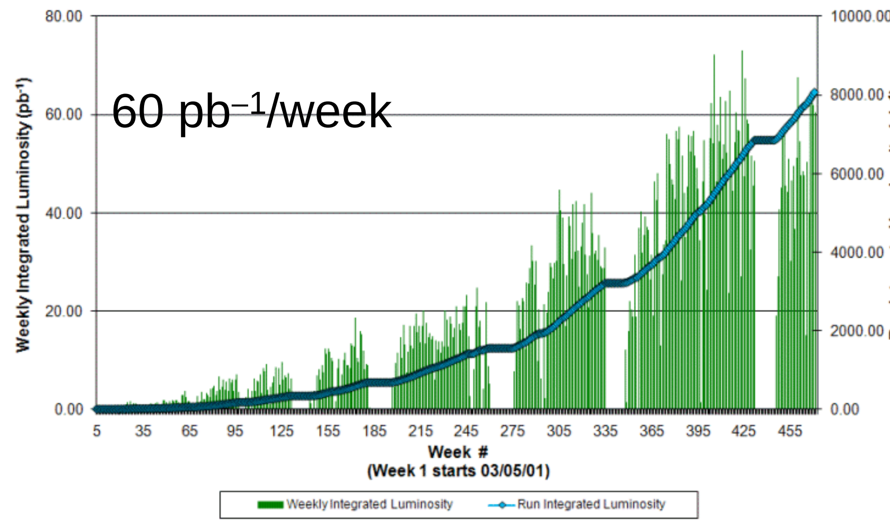


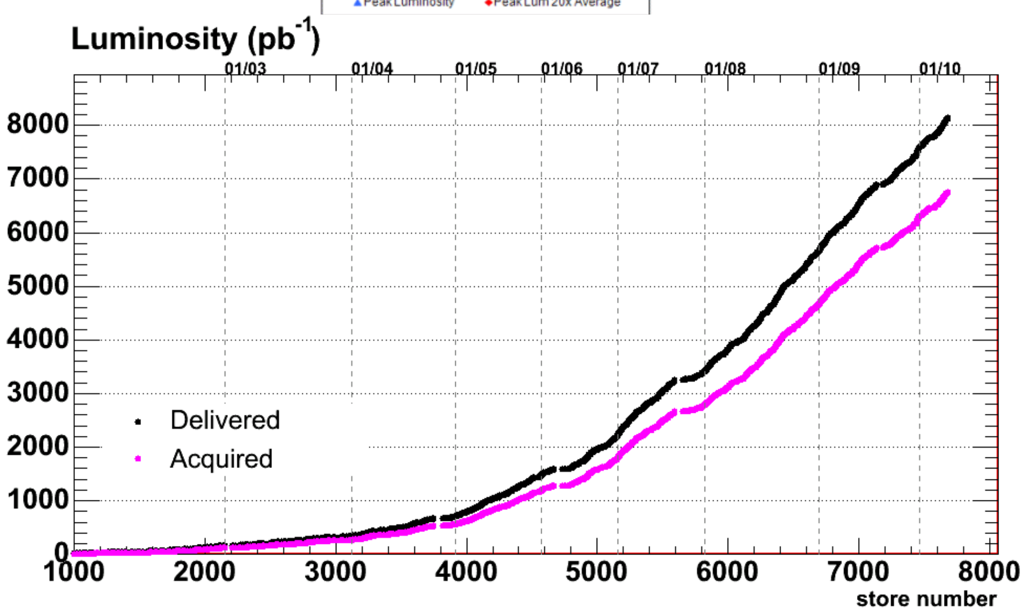
Tevatron Luminosity Progress

Peak luminosity



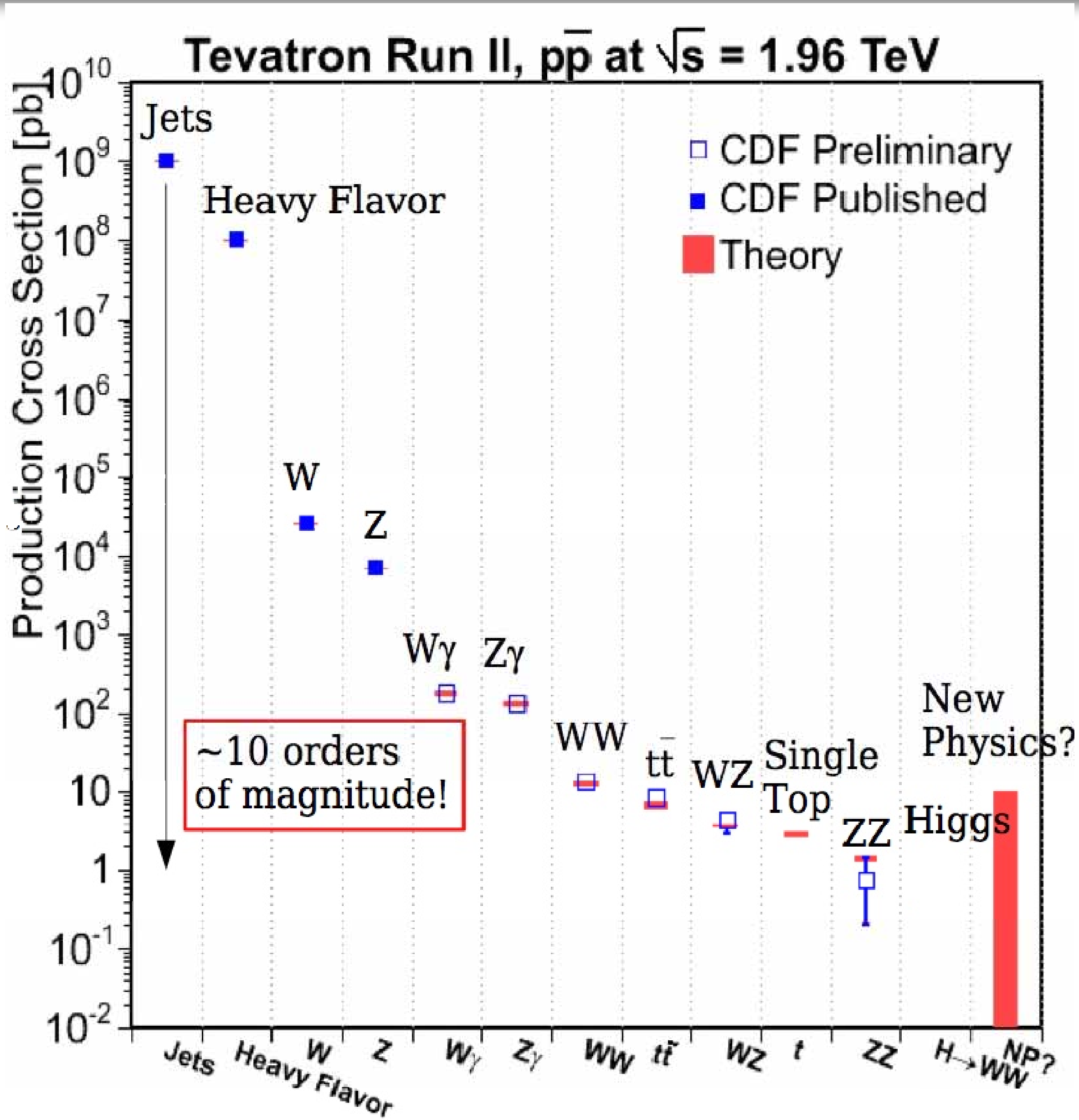
Total and weekly delivered





- Weekly integrated : 50~60 pb^{-1}
- Integrated luminosity
  - Delivered : 8.2 fb^{-1}
  - Acquired : 6.8 fb^{-1}
  - Analyzed : 5.4 fb^{-1}

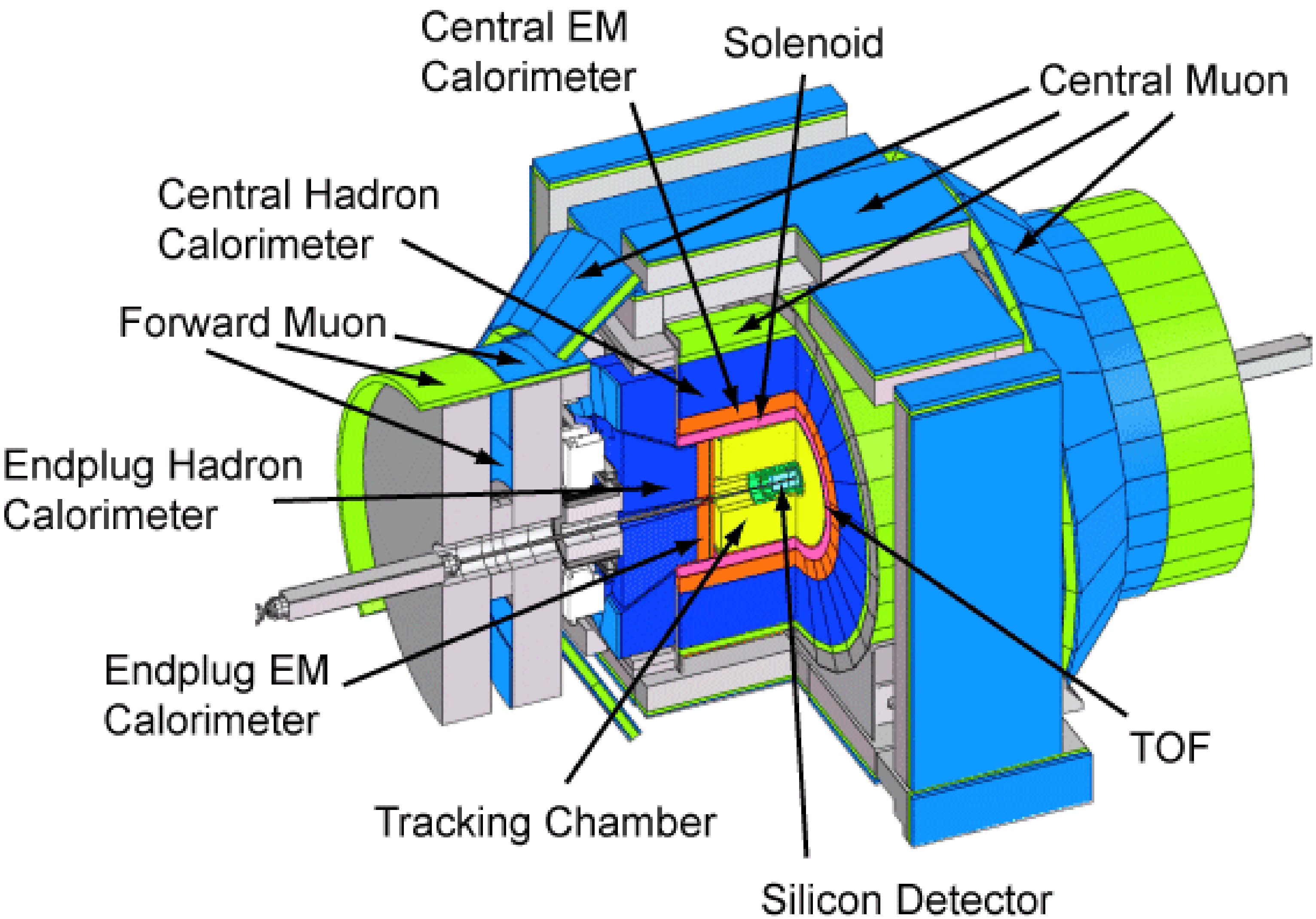
Proton-Antiproton Collisions



CDF Experiment

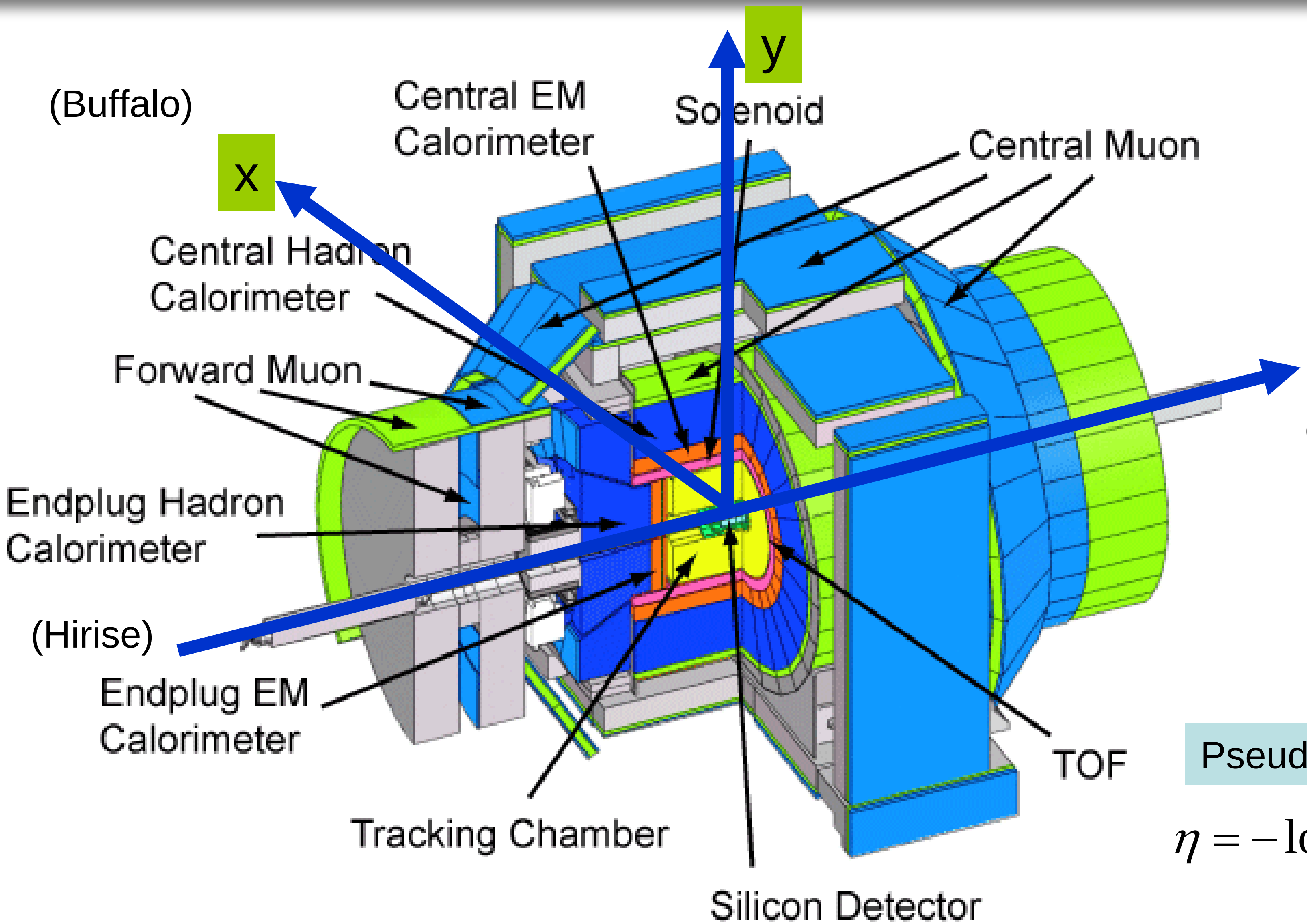
		Integrated luminosity	Collaboration size
1981.01	TDR		87
1984–85	Beam tests		
1985.10	First collisions	~20 events	
1987.01–87.05	Test run	25 nb^{-1}	190
1988.06–89.05	Run 0	4.4 pb^{-1}	
1990–92	Beam tests		$\sqrt{s}$ = 1.8 TeV (1985.10–96.02)
1992.04–93.05	Run Ia	19 pb^{-1}	358
1993.12–95.08	Run Ib	80 pb^{-1} (Run Ia–Ic total: **106** pb^{-1})	
1995.10–96.02	Run Ic	7 pb^{-1}	
–2000.Fall	Upgrades		
2000.Fall–01.Spring	Comissionning		
2001.03–	Run II		~750 $\sqrt{s}$ = 1.96 TeV

CDF Detector



Calorimeters: projective tower geometry

CDF Detector

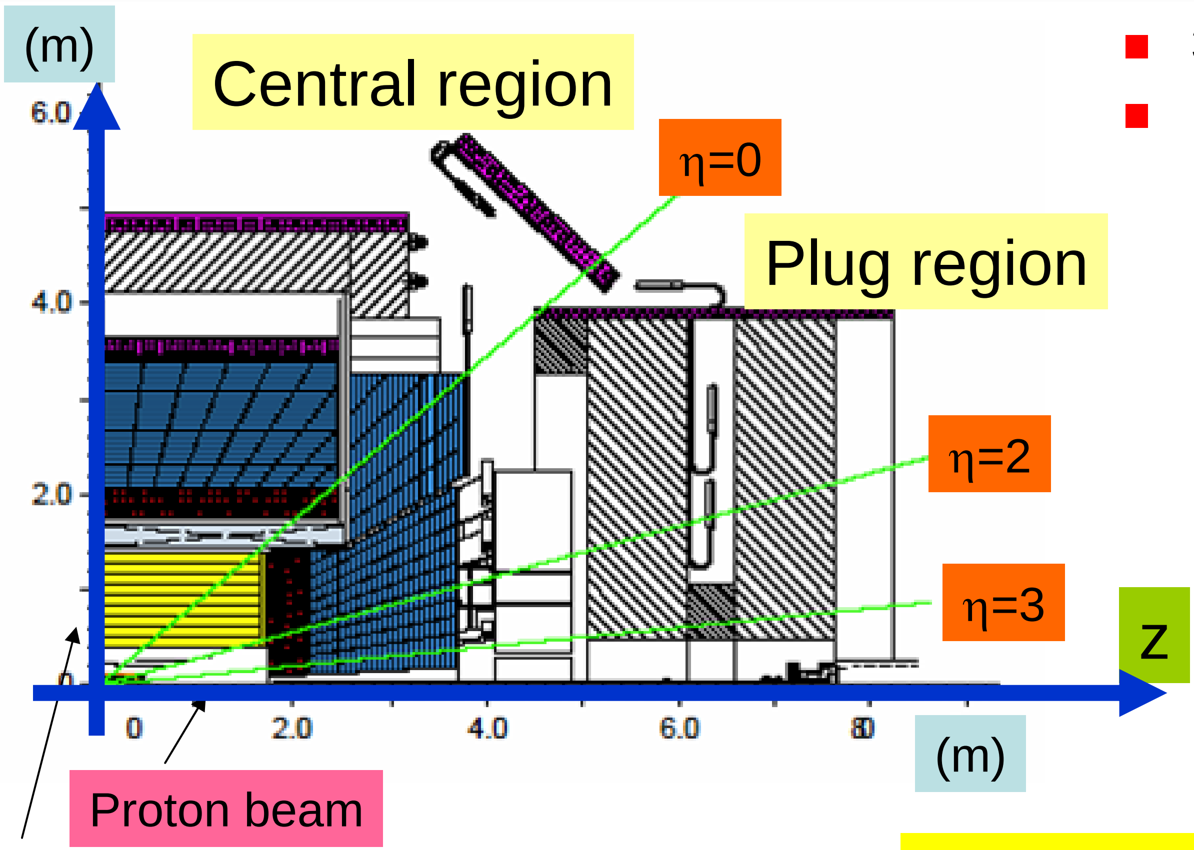


Pseudo-rapidity

$$\eta = -\log\left(\tan\frac{\theta}{2}\right)$$

Calorimeters: projective tower geometry

CDF Detector



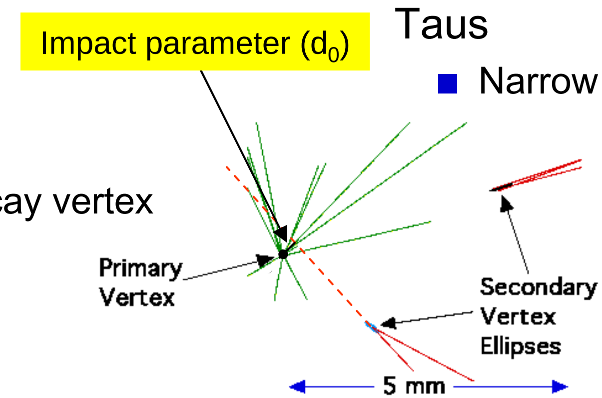
- 3-level trigger system
- Particle identification
  - Photons
    - EM cluster w/o track
  - Electrons
    - EM cluster w/o track
  - Muons
    - Muon detectors at the outermost position
  - Neutrinos
    - Momentum imbalance in the transverse plane
  - Quarks
    - Jets (calorimeter clusters)
  - Taus
    - Narrow jets w/ 1 or 3 tracks

Transverse

$$p_T = p \sin\theta$$

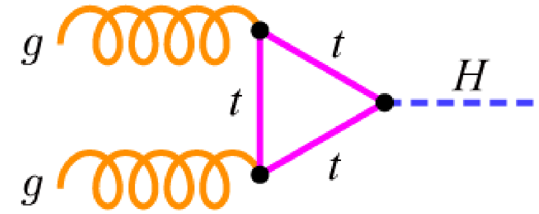
$$E_T = E \sin\theta$$

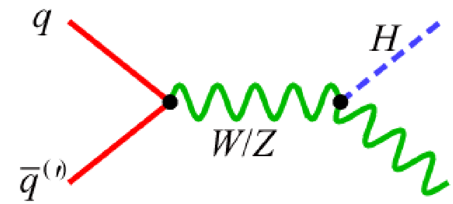
- Heavy flavor quarks (b, c)
  - Identification = "tagging"
  - Displaced secondary decay vertex
  - Large impact parameter
  - Semileptonic decay

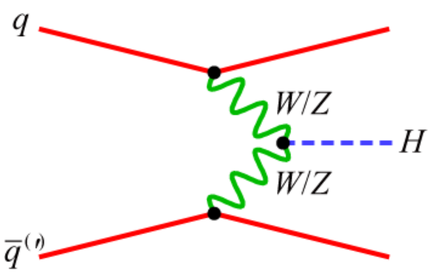


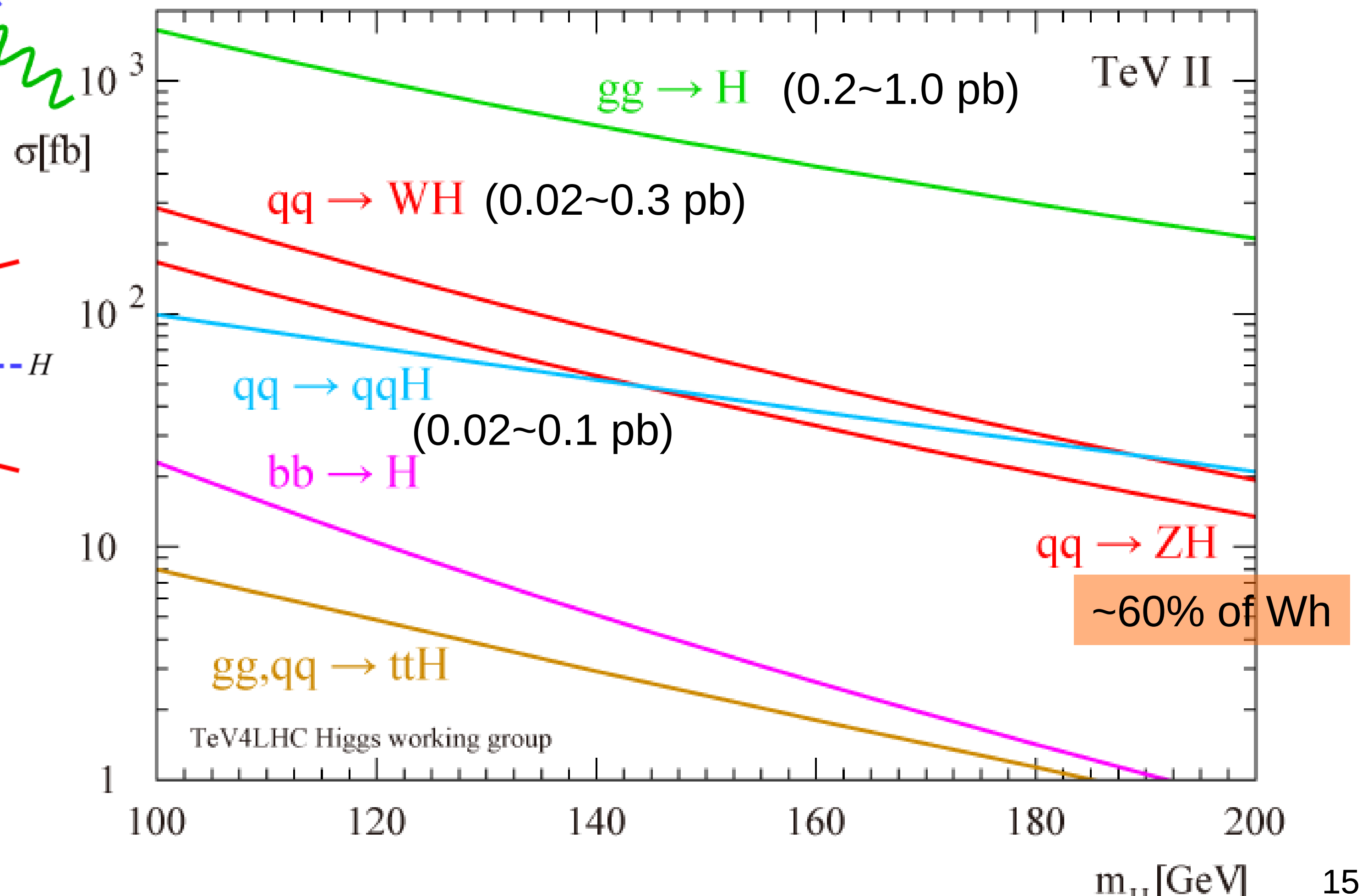
SM Higgs Searches at CDF

SM Higgs Production at the Tevatron

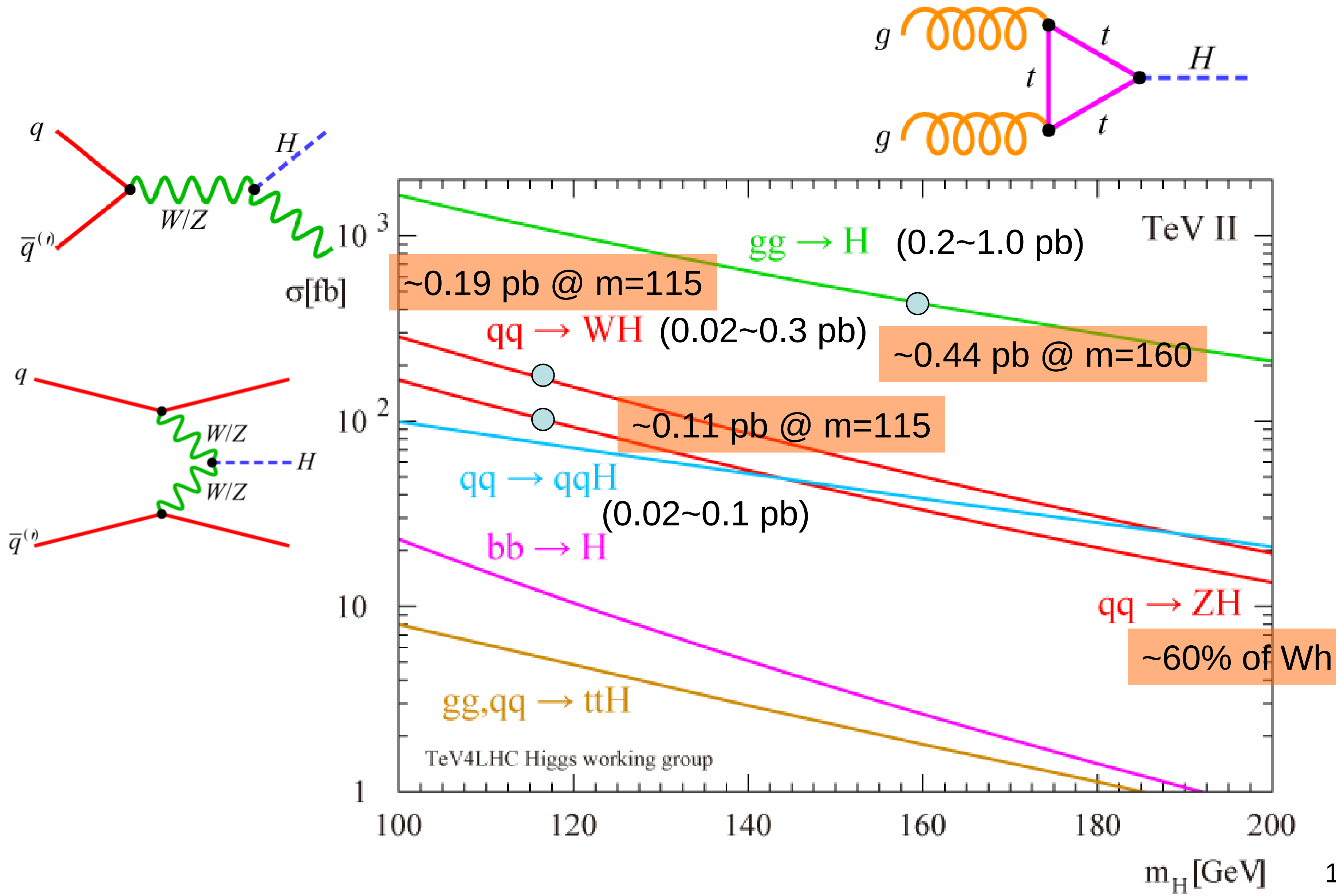




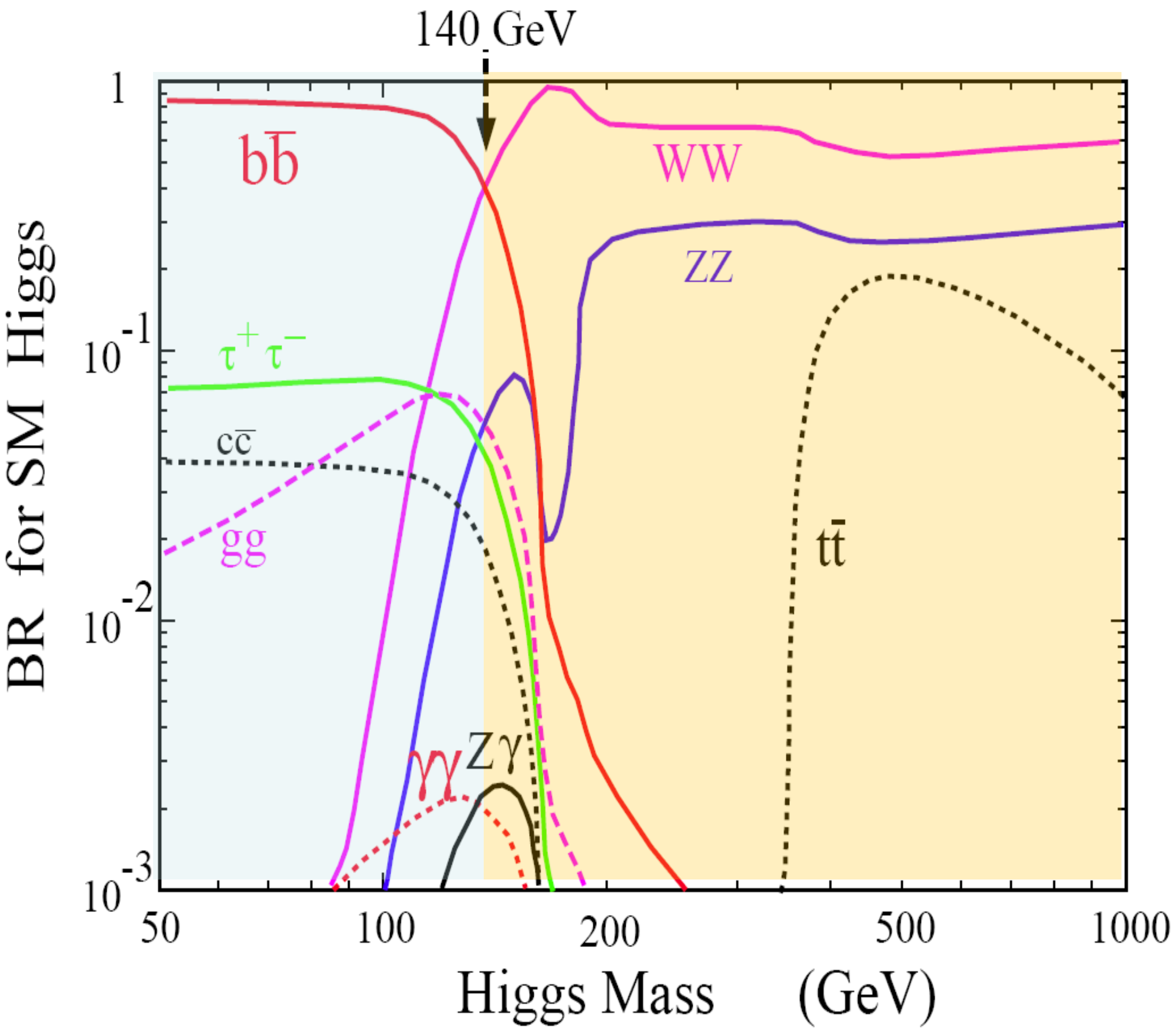




SM Higgs Production at the Tevatron



Higgs Decays



- Low mass (< 140GeV/c^2)
  - bb is dominant.
    - 73% @ m=115
- High mass (> 140GeV/c^2)
  - WW is dominant.
    - ~92% @ m=160

Search Channels

$$\ell = e\,,\,\mu$$

Higgs production and W/Z decays	Higgs decays	
	$h \to bb$	$h \to WW \to (\ell\nu)(\ell\nu)$
h	Too large QCD BG	2ℓ (opposite-sign=OS) + missing E_T
$Wh \to (\ell\nu)h$	ℓ + missing E_T + 2b	2ℓ (OS)/2ℓ (like-sign=LS)/3ℓ + missing E_T
$Zh \to (\nu\nu)h$	Missing E_T + 2b	2ℓ (OS) + missing E_T
$\to (\ell\ell)h$	2ℓ (OS) + 2b	Multilepton + missing E_T
qqH	Too large QCD BG	2ℓ (OS) + missing E_T

CDF Papers of SM Higgs Searches

Run I	$Wh \to (\ell\nu)(bb)$	PRL 79, 3819	1997	109 pb^{-1}
	$Vh \to (jj)(bb)$	PRL 81, 5748	1998	91 pb^{-1}
	$Zh \to (\ell\ell)(bb), (\nu\nu)(bb)$	PRL 95, 051801	2005	106 pb^{-1}
Run II	$Wh \to (\ell\nu)(bb)$	PRL 96, 081803	2006	320 pb^{-1}
	$h \to WW$	PRL 97, 081802	2006	360 pb^{-1}
	$Wh \to (\ell\nu)(bb)$	PRL 100, 041801	2008	1000 pb^{-1}
		PRD 78, 032008	2008	1000 pb^{-1}
	$Zh \to (\nu\nu)(bb)$	PRL 100, 211801	2008	1000 pb^{-1}
	$Zh \to (\ell\ell)(bb)$	PRL 101, 251803	2008	1000 pb^{-1}
	$h \to WW$	PRL 102, 021802	2009	3000 pb^{-1}
	$Wh \to (\ell\nu)(bb)$	PRD 80, 012002	2009	1900 pb^{-1}
	$Wh \to (\ell\nu)(bb)$	PRL 103, 101802	2009	2700 pb^{-1}

Analysis Overview

- Event selection
  - Trigger selection
  - Kinematical and geometrical acceptance
  - Particle identification
  - Topological selection
- Efficiency and background estimation
  - ε = 0.2 ~ 2% from $\sigma(h) \cdot B(h \to XX)$
  - $\Delta\varepsilon/\varepsilon$ = 10~20%
  - $\Delta B/B$ = 10~20%
- Result
  - Limit on the production cross section
    - Use distributions of some variables
    - Binned maximum likelihood method
    - Bayesian interpretation in most cases

Analysis Overview

Bayesian

- $p(n \mid S, B) = \dfrac{e^{-\mu}\mu^{n}}{n!}, \qquad \mu = S + B = L(\sigma B_F)\varepsilon + B$
- $p(n_{\text{obs}} \mid S, B) \rightarrow \underbrace{p(S, B \mid n_{\text{obs}})}_{\text{Posterior probability density}} \underbrace{\pi(S, B)}_{\text{Prior probability density}} dS\,dB$

Posterior probability density

Prior probability density

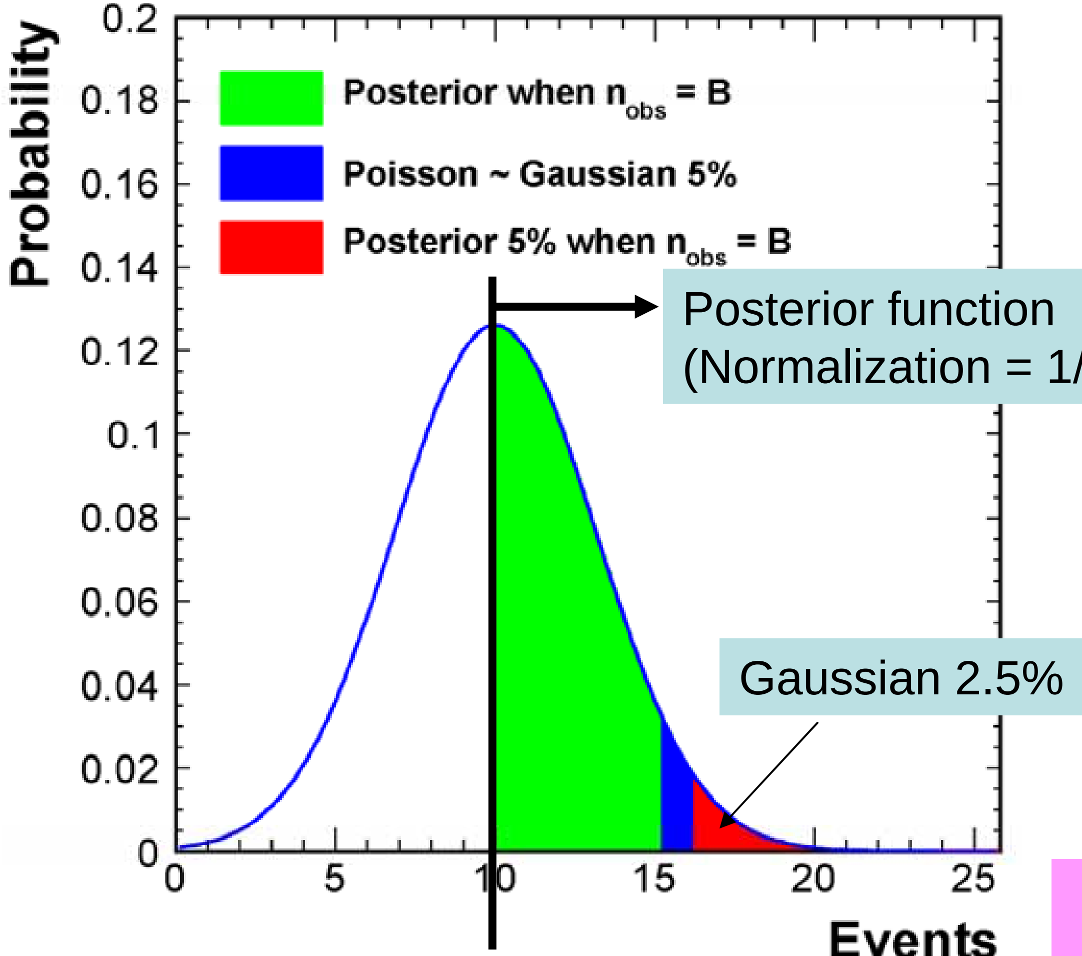
- $p(S \mid n_{\text{obs}})dS = \dfrac{\int dB\, p(S, B \mid n_{\text{obs}})\pi(S, B)}{\iint dB\,dS\;\, p(S, B \mid n_{\text{obs}})\pi(S, B)}$

Marginalization

Nuisance parameter

Analysis Overview

Bayesian 95% credibility limit



For illustration

- Flat prior for S
- Exact B (prior = δ function)
- Poisson~Gaussian,

S << B, n_{obs}=B

$$\frac{e^{-(S+B)}(S+B)^n}{n!}$$

$$\sim \frac{1}{\sqrt{2\pi(S+B)}} e^{-\frac{1}{2}\left(\frac{n-S-B}{\sqrt{S+B}}\right)^2}$$

$$\sim \frac{1}{\sqrt{2\pi B}} e^{-\frac{1}{2}\left(\frac{S}{\sqrt{B}}\right)^2}$$

Gaussian 2.5% =1.96σ~2σ

→ S_{95} ~ 2√B

S_{95}/S ~ 2√B/S

Analysis Overview

For distributions

- $$\prod_{i=\text{bin}} p(n_i \mid S_i, B_i)$$

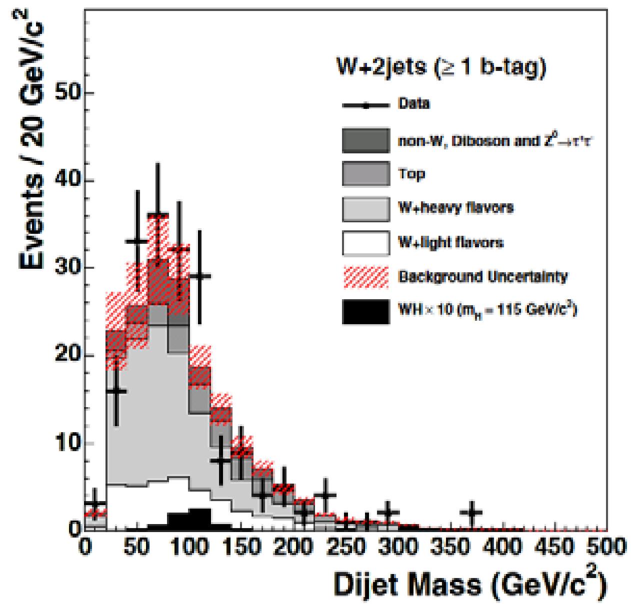
Combining different channels

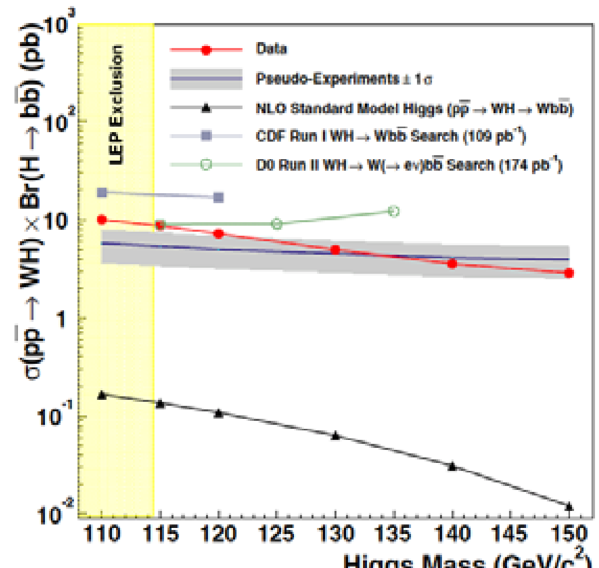
- $$\left(\prod_{i=\text{channel}} p(n_i \mid S_i, B_i) \right) \pi(B)$$

Common (correlated) nuisance parameters

(1) Wh→(ℓν)(bb), 2006

- L = 320 pb^{-1}
- High p_T inclusive lepton trigger
- Lepton + 2j + missing E_T signature
- ≥1b tagging
  - Secondary vertex
  - Semileptonic decay w/ large d_0
- S(m=115) ~ 2 fb, B ~ 550 fb
  - W+bb dominant
  - S/√B/√L~0.09
- M_{bb} distribution for limits
- b jet specific energy correction
- 1b ⊕ 2b (independent likelihood)
- Expected limit ~ 6 pb (m=115)
  - ε ~ 1.5%, B ~ 175
  - S_{95} ~ 6×320×0.015 ~ 29 ev
  - 29/√175 ~ 2.2

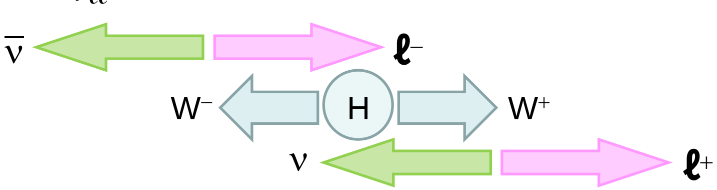


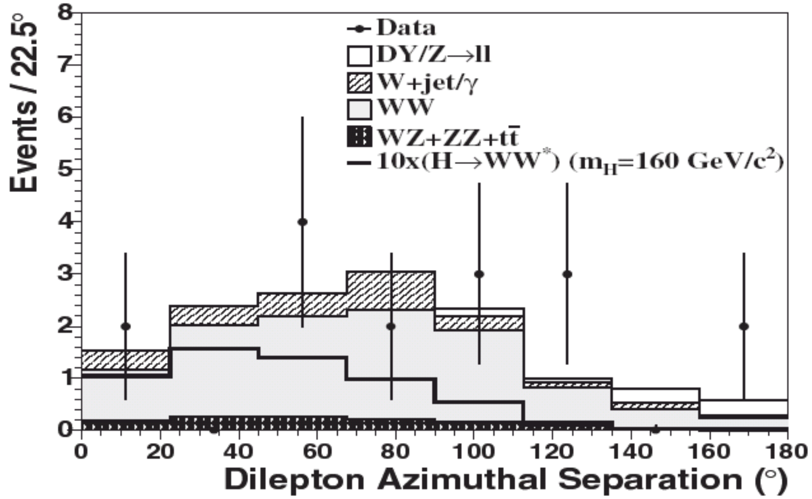


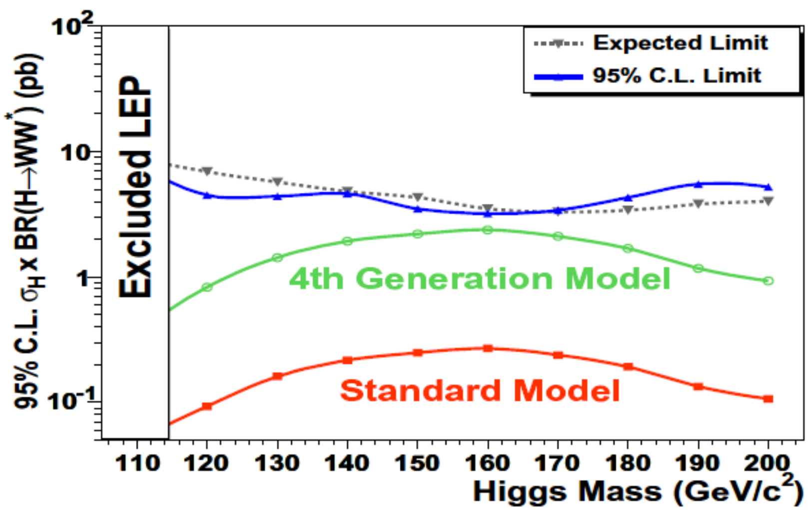
Expected limit
- Frequentist view
- BG-only pseudo-experiments → limits (median)

(1) h→WW, 2006

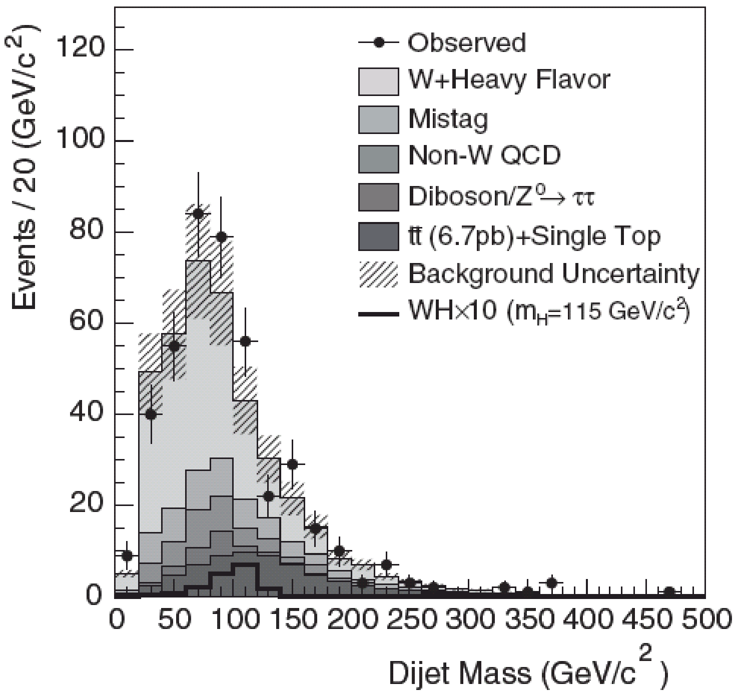
- 360 pb^{-1}
- Triggers
  - High p_T inclusive lepton trigger
  - Plug electrons + missing E_T trigger
- Plug electrons
- Topological cut
  - Drell-Yan veto
    - $M_{\ell\ell}$>16 GeV (cc/bb resonance veto)
    - $M_{\ell\ell}<m_h$-5 GeV
    - Large missing E_T
    - Fake missing E_T veto ($Z\to\tau\tau$ veto)
  - Jet veto (tt veto)
- S(m=160) ~ 1.6 fb, B ~ 39 fb
  - WW dominant
  - S/√B/√L~0.26
- $\Delta\phi_{\ell\ell}$ distribution for limits

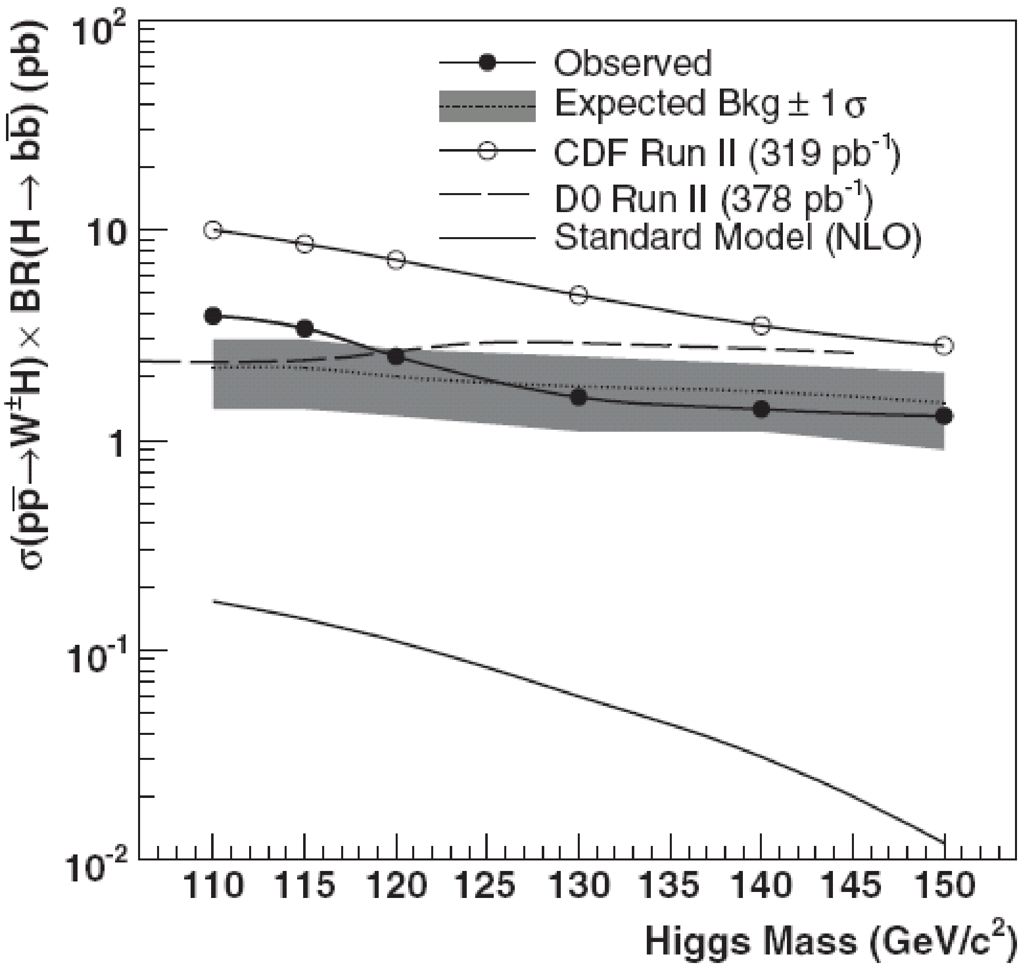






(2) Wh→(ℓν)(bb), 2008

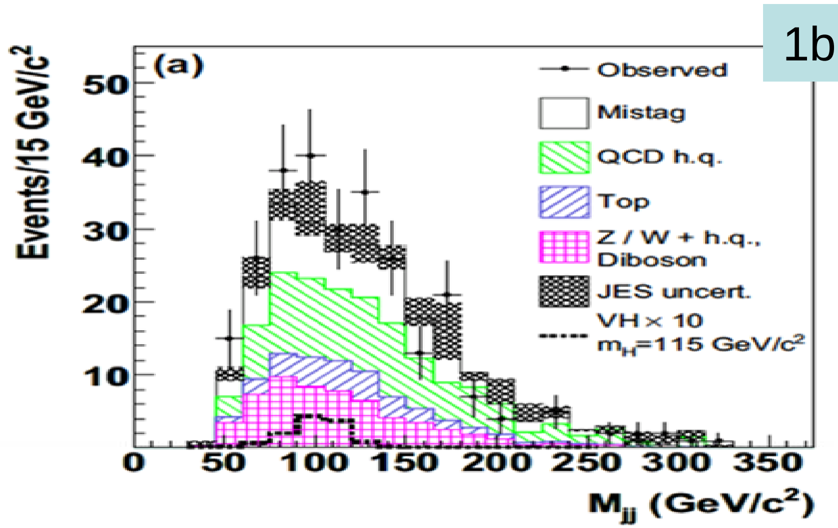


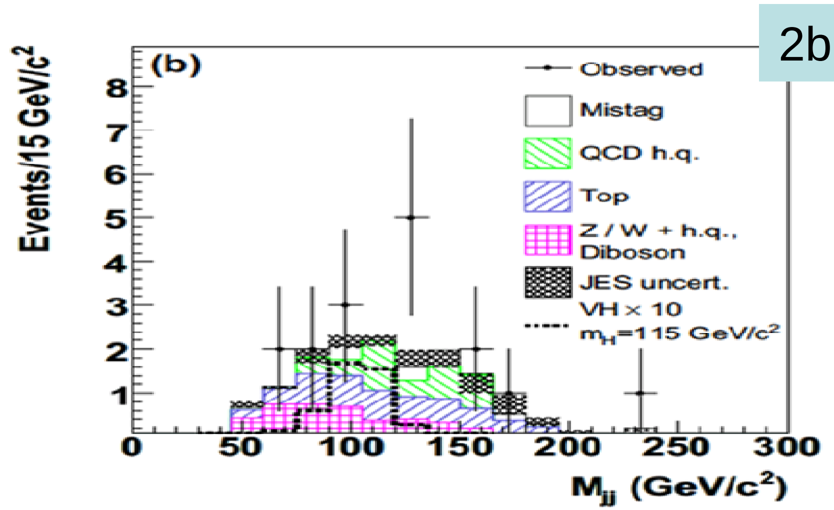


- $L = 1\ fb^{-1}$
- Neural net (NN) b tagging
  - +5% improve
- 1b ⊕ 2b
  - +20% improve
- S(m=115) ~ 2.1 fb, B ~ 440 fb
  - S/√B/√L~0.10 (cf. 0.09)

(1) Zh→(νν)(bb), 2008

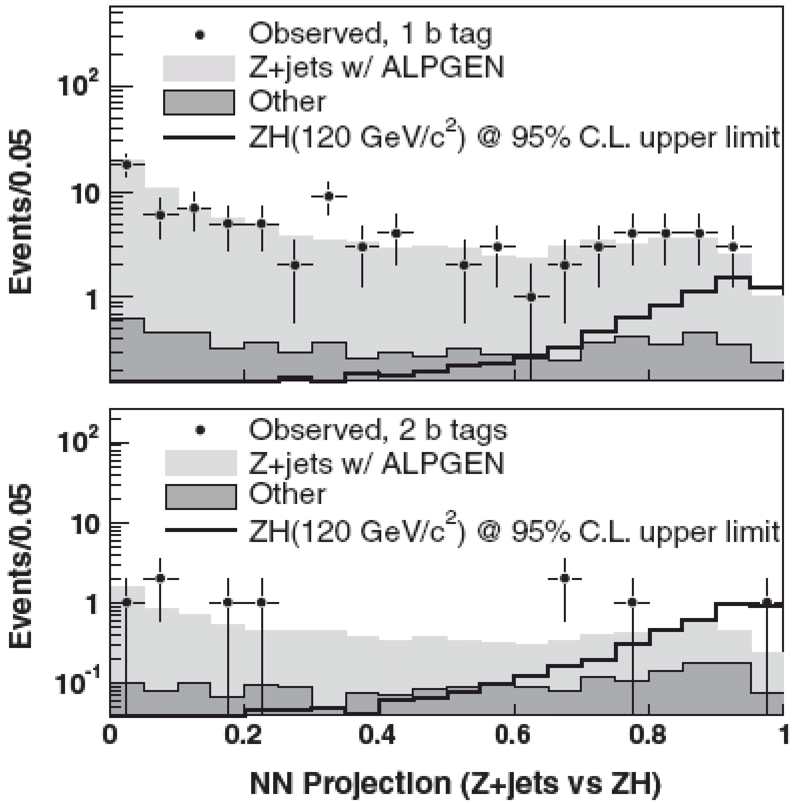
- L = 1 fb^{-1}
- Missing E_T trigger
- Include missing lepton + bb from Wh
- 2 or 3 jets
- ≥1b tag
- M_{bb} distribution for limits
- Introduction of control regions (CR)
  - Check of ε and BG estimation
  - Calibration of ε and BG
  - CR in this analysis
    - CR1 = Multijet signature
    - CR2 = One lepton
- S(m=115) ~ 1.6 fb, B ~ 260 fb
  - QCD (fake missing E_T) dominant
  - $S/\sqrt{B}/\sqrt{L}$~0.10
  - Sensitivity (νν)(bb) ~ (ℓν)(bb)





(1) Zh→(ℓℓ)(bb), 2008

- L = 1 fb^{-1}
- Higi p_T inclusive lepton trigger
- Added plug electrons as the 2nd lepton
- NN jet energy correction
  - Mass resolution 18% → 11%
- 1b ⊕ 2b
- 2D NN outputs for limits
  - Zh vs. Zbb
  - Zh vs. tt
- S(m=115) ~ 0.81 fb, B ~ 110 fb
  - S/√B/√L~0.08 (Run I ~ 0.10)
    - Worse than Run I
    - But expected limit is ~ 4 times better than L scaling

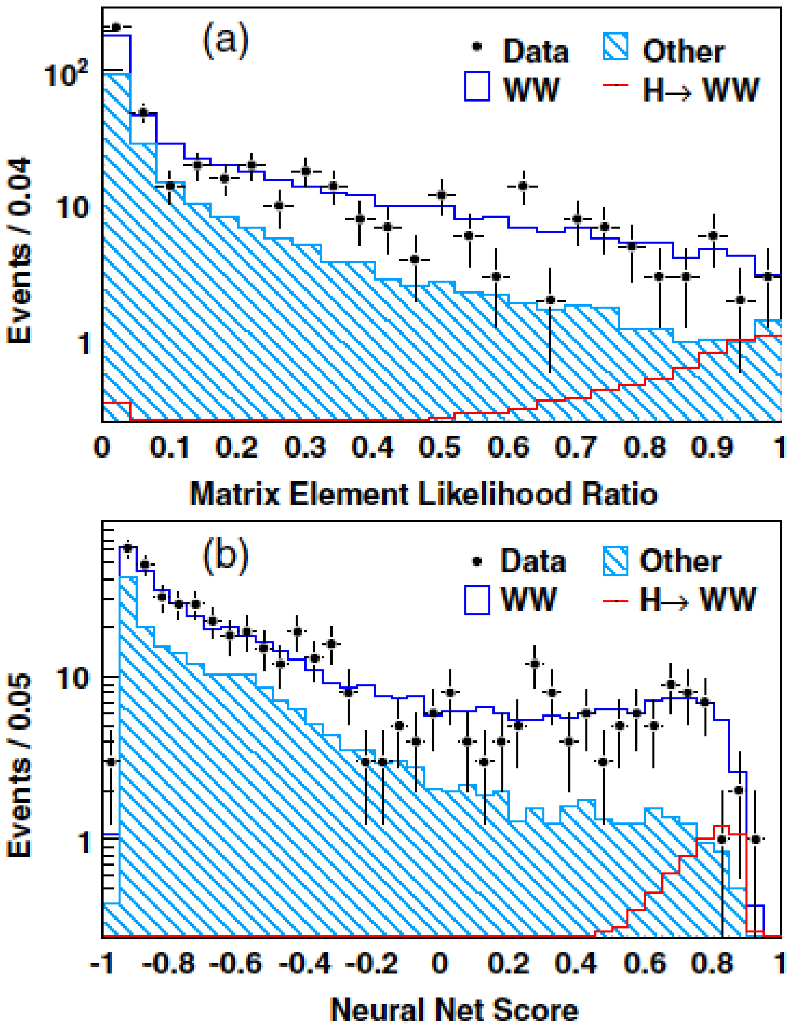


(2) h→WW, 2009

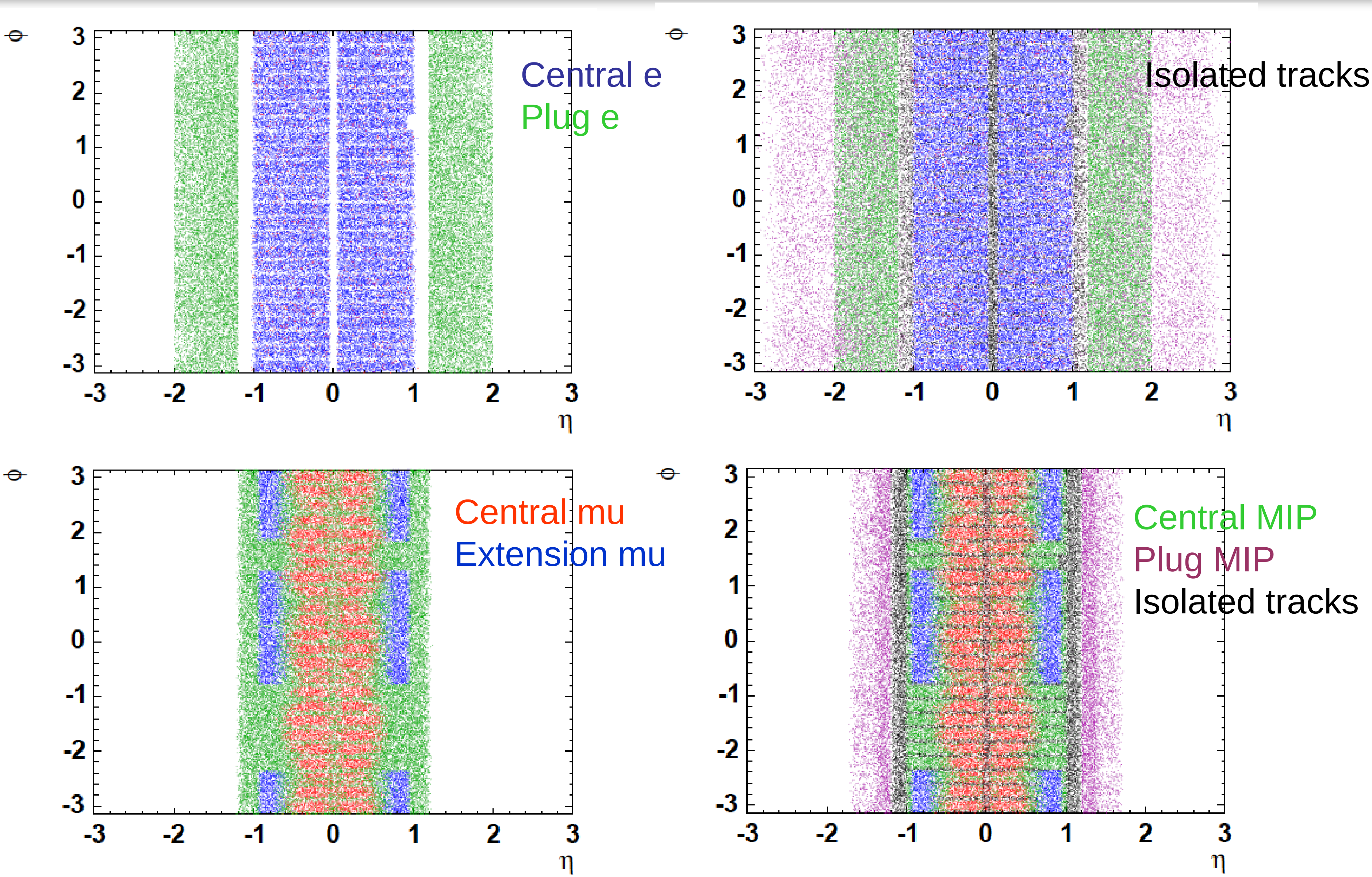
- 3 fb^{-1}
- More lepton categories
  - MIP tracks
  - Isolated tracks passing detector cracks
- Matrix-element-based probability (ME)

$$p(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle}\int \underbrace{\frac{d\sigma_{LO}}{d\vec{y}}}_{\text{ME}}\underbrace{\varepsilon(\vec{y})}_{\text{Efficiency}}\underbrace{G(\vec{x}_{obs},\vec{y})}_{\text{Detector response}}d\vec{y}$$

- High S/B ⊕ Low S/B
- NN for limits
- S(m=160) ~ 3.9 fb, B ~ 260 fb
  - S/√B/√L~0.24 (cf. 0.26)
  - Expected limit ~50% improvement other than L scaling

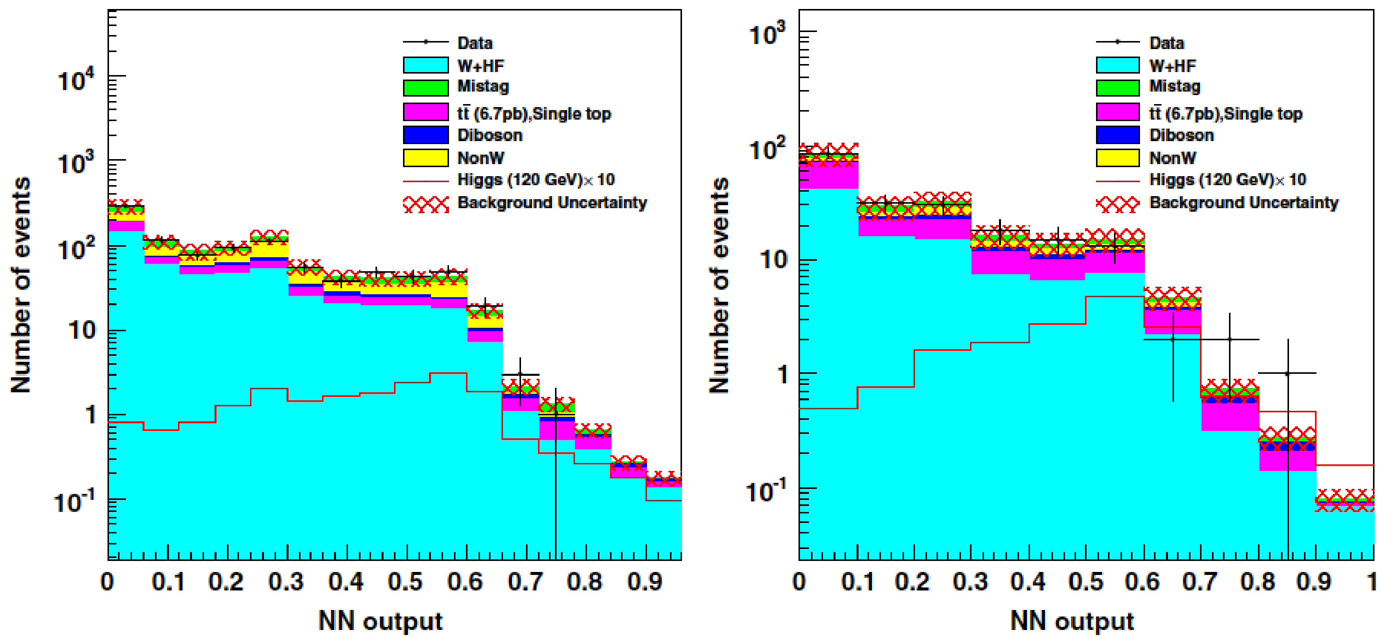


(2) h→WW, 2009



φ
η
Central e
Plug e
Isolated tracks
Central mu
Extension mu
Central MIP
Plug MIP
Isolated tracks

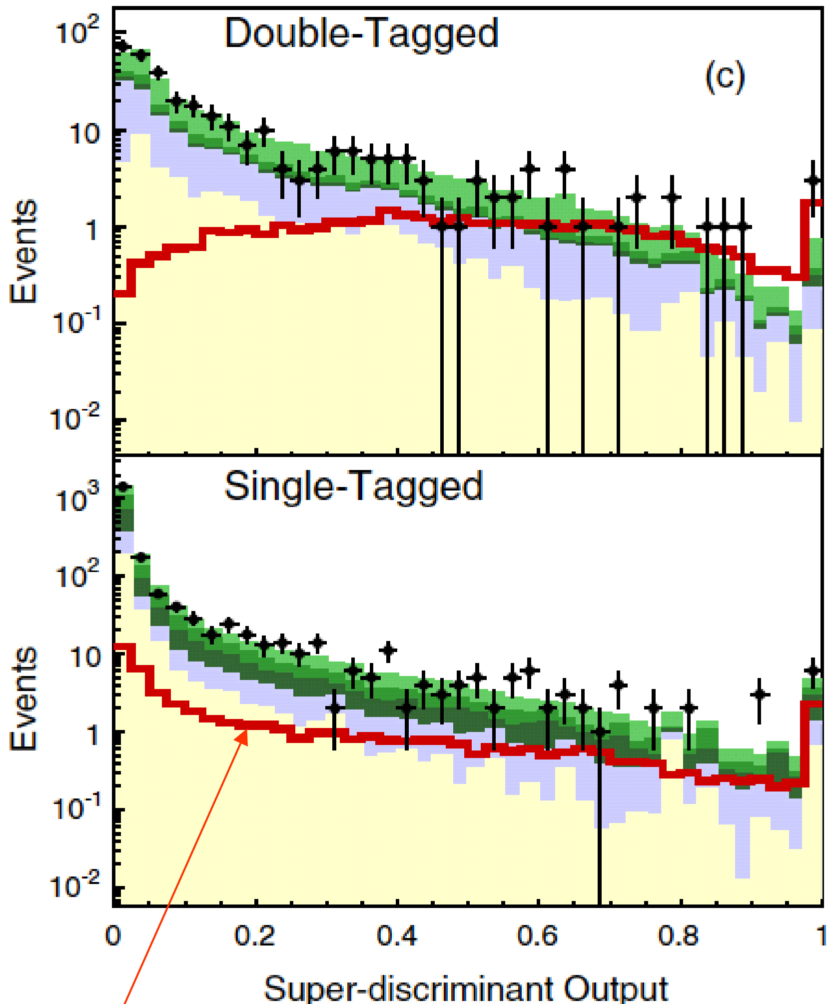
(3) Wh→(ℓν)(bb), 2009



- L = 1.9 fb^{-1}
- Added missing E_T + plug electron trigger
- Added plug electrons
- Add d_0-based b-tagging
- NN for limits
- S(m=115) ~ 2.3 fb, B ~ 660 fb
  - S/√B/√L~0.09 (cf. 0.10)
  - Expected limit ~ 40% improvement

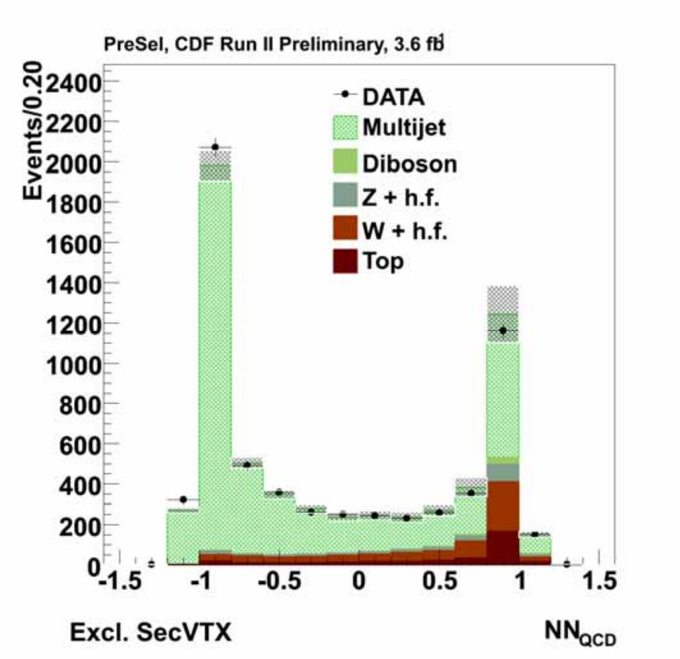
(4) Wh→(ℓν)(bb), 2009

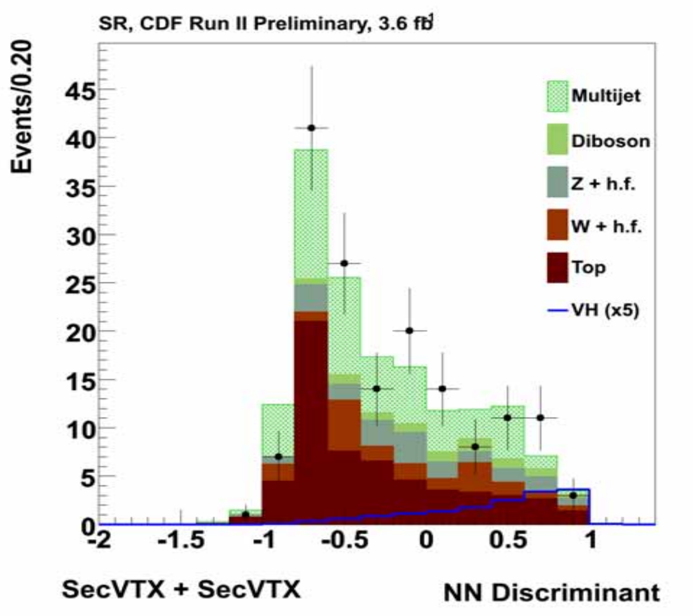
- L = 2.7 fb^{-1}
- Added missing E_T + 2j trigger
- Isolated tracks as leptons
  - 30% acceptance gain
- ME→BDT
  - 15% sensitivity gain
- NN + MEBDT → NN (Super discriminant)
  - 15% sensitivity gain
- S(m=115) ~ 3.2 fb, B ~ 820 fb
  - S/√B/√L~0.11 (cf. 0.09)
  - Expected limit ~ 50% improvement



10 times SM higgs (m=115)

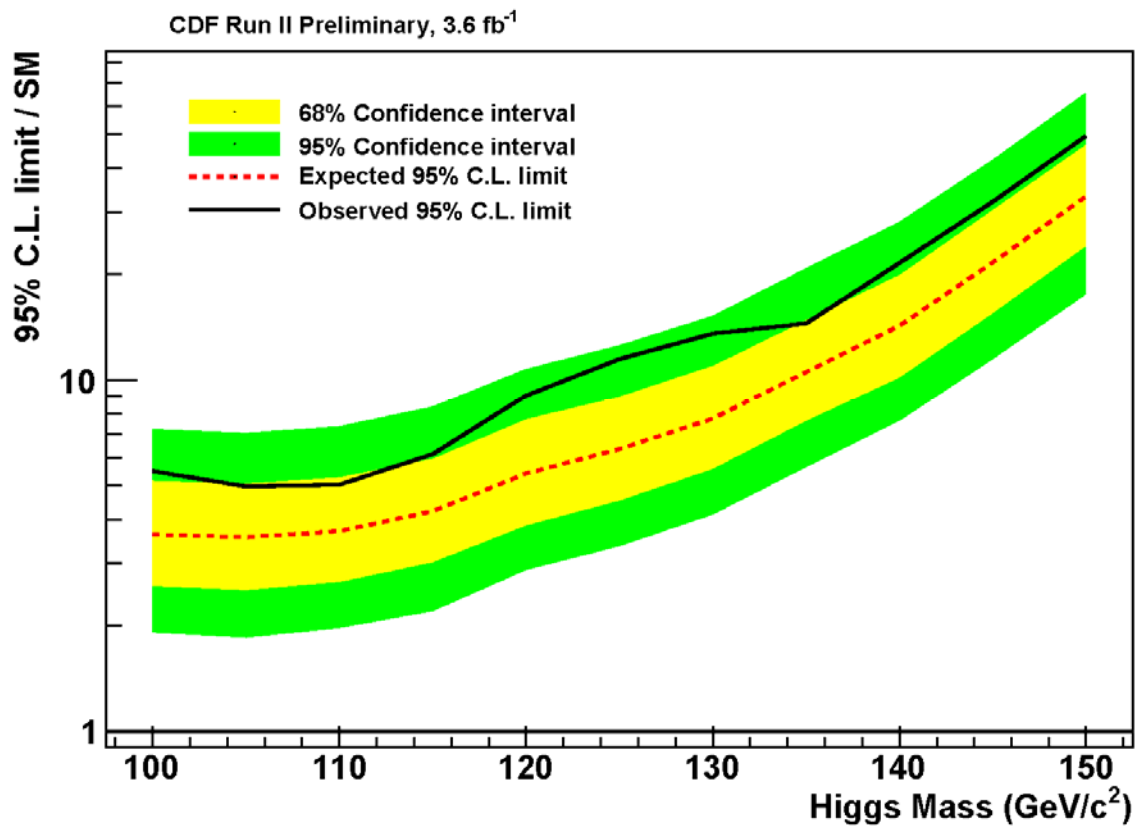
(2) Zh→(νν)(bb), now





- L = 3.6 fb^{-1}
- Missing p_T to reduce QCD
- Added d_0-based b tagging
- Two staged NN
  - QCD rejection
  - Other BG

(2) Zh→(νν)(bb), now

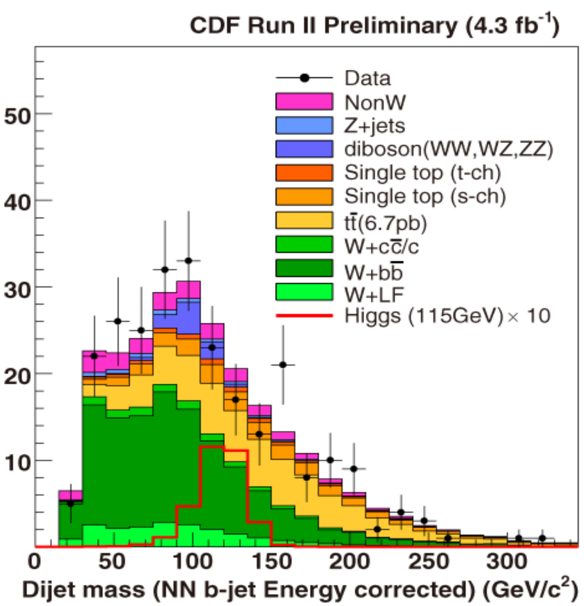


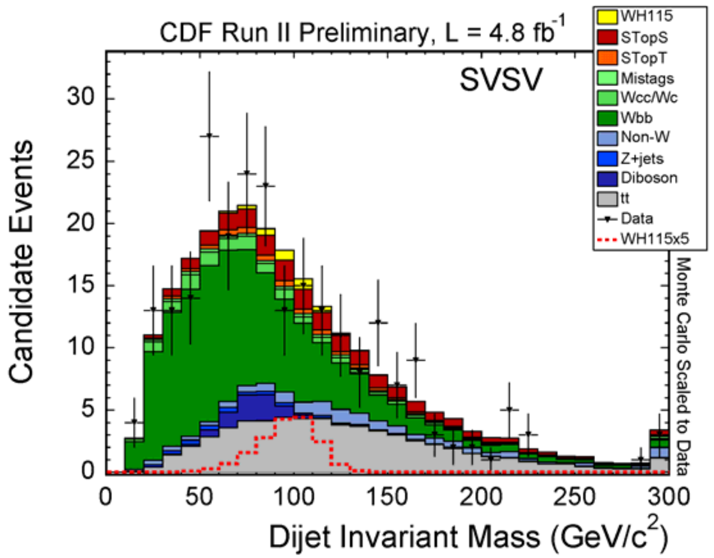
For M_H = 115 GeV/c^2 w/ 3.6 fb^{-1}
Expected limit : 4.2 × σ_{SM}
Observed limit : 6.1 × σ_{SM}

- S(m=115) ~ 3.4 fb, B = 810 fB
  - S/√B/√L~0.12 (cf. 0.10)
- ~70% improvement

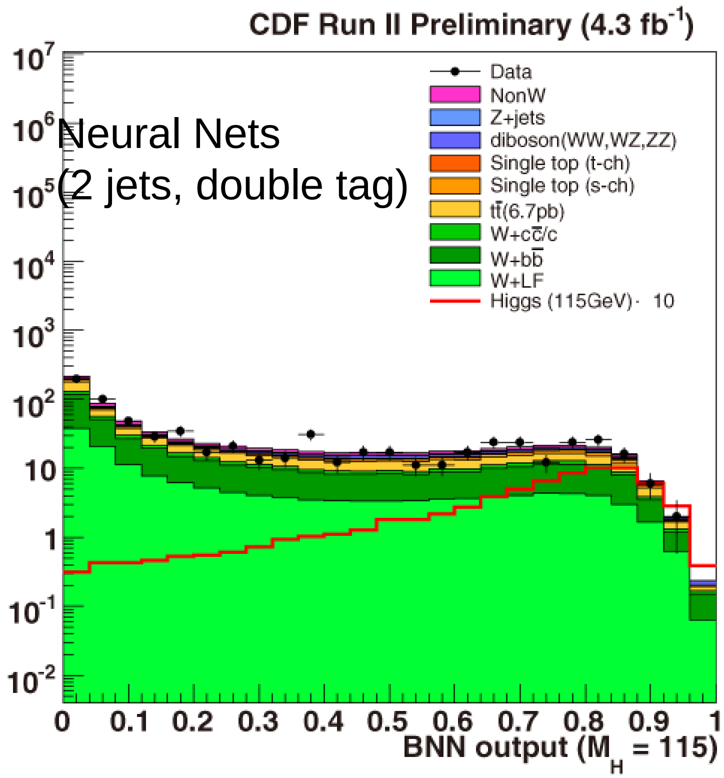
(5) Wh→(ℓν)(bb), now

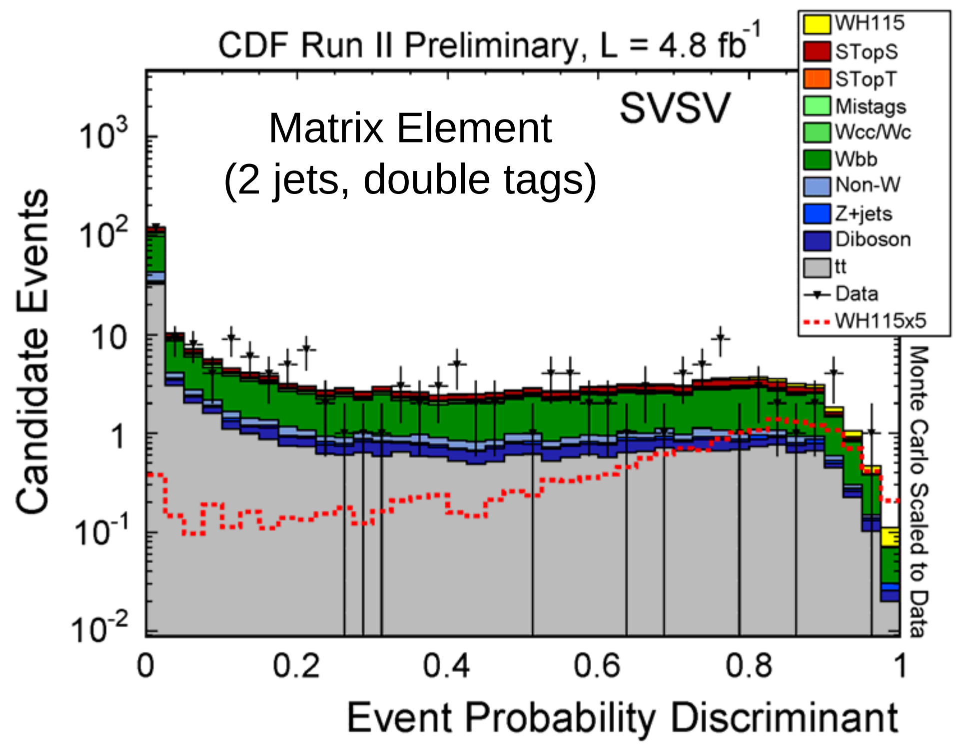
- Two analyses to be combined
  - NN
  - ME
- NN
  - L = 4.3 fb^{-1}
  - Not much new things
  - Bayesian NN
  - S(m=115) ~ 3.2 fb, B ~ 930 fb
    - $S/\sqrt{B}/\sqrt{L}$~0.11
- ME
  - L = 4.8 fb^{-1}
  - Not much new things
  - Added 3 jets
  - 2j ⊕ 3j
  - S(m=115) ~ 3.9 fb, B ~ 1200 fb
    - $S/\sqrt{B}/\sqrt{L}$~0.11





(5) Wh→(ℓν)(bb), now

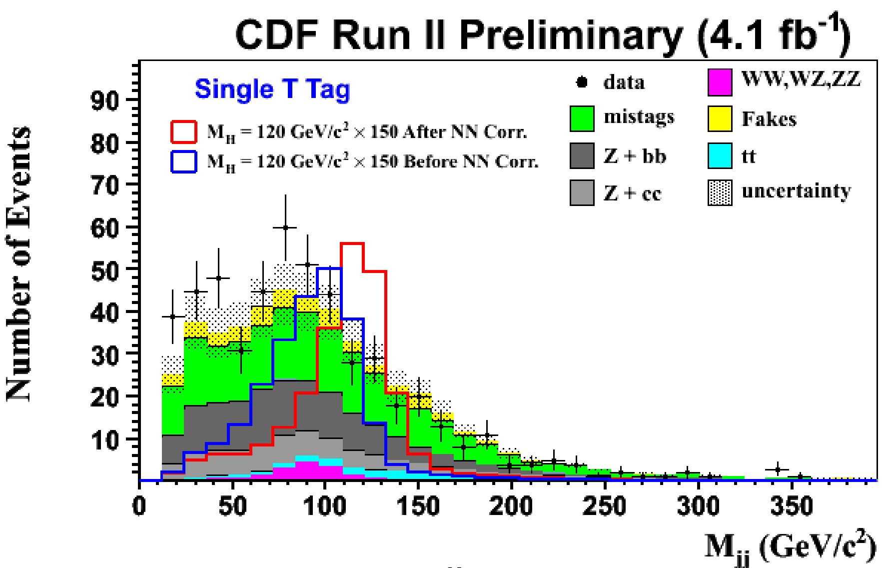




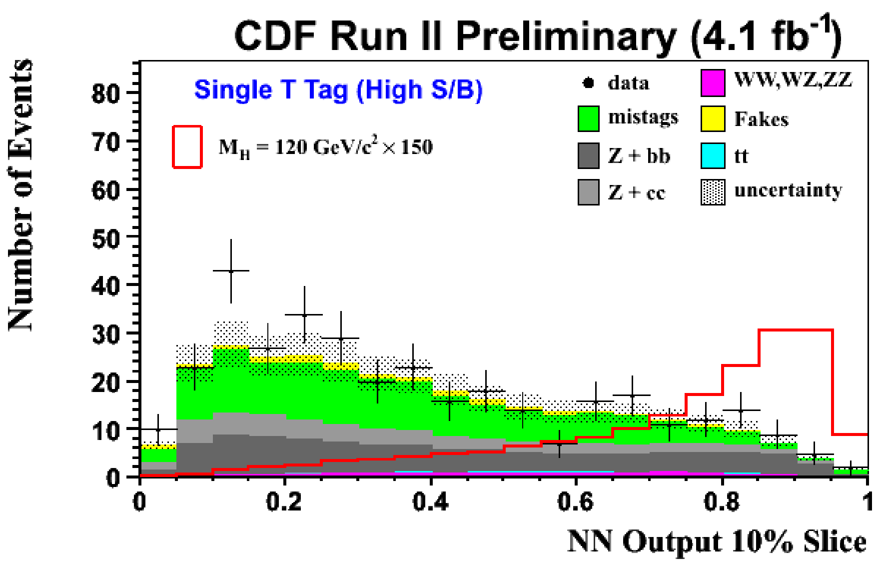
M_H = 115 GeV/c²	Expected limit	Observed limit	Luminosity
CDF (NN)	$4.0 \times \sigma_{SM}$	$5.3 \times \sigma_{SM}$	4.3 fb^{-1}
CDF (ME)	$3.8 \times \sigma_{SM}$	$3.3 \times \sigma_{SM}$	4.8 fb^{-1}

(2) Zh→(ℓℓ)(bb), now

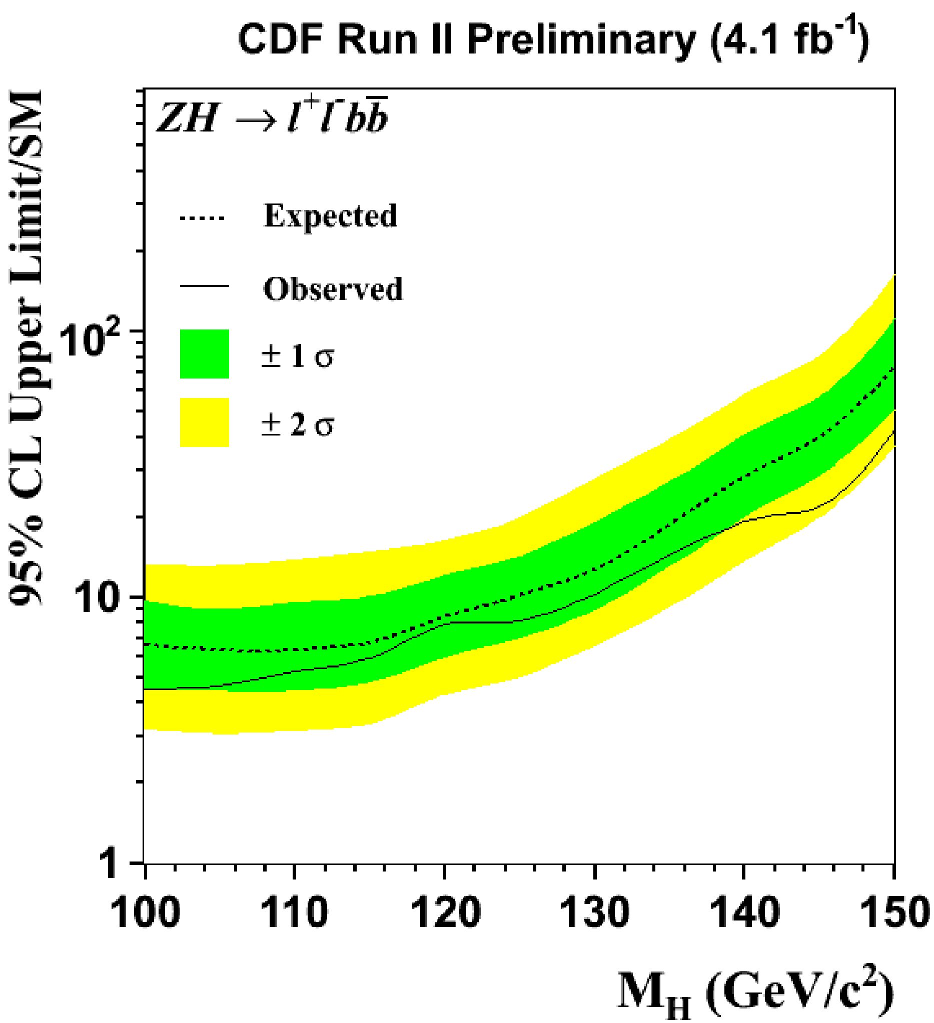
- 4.1 fb^{-1}
- Added the trackless trigger
- ≥2j
- High S/B ⊕ low S/B
- Isolated tracks
- b-tagging
  - NN-based filter
  - d_0-based tagger
- ME → 2D NN



Dijet mass



(2) Zh→(ℓℓ)(bb), now

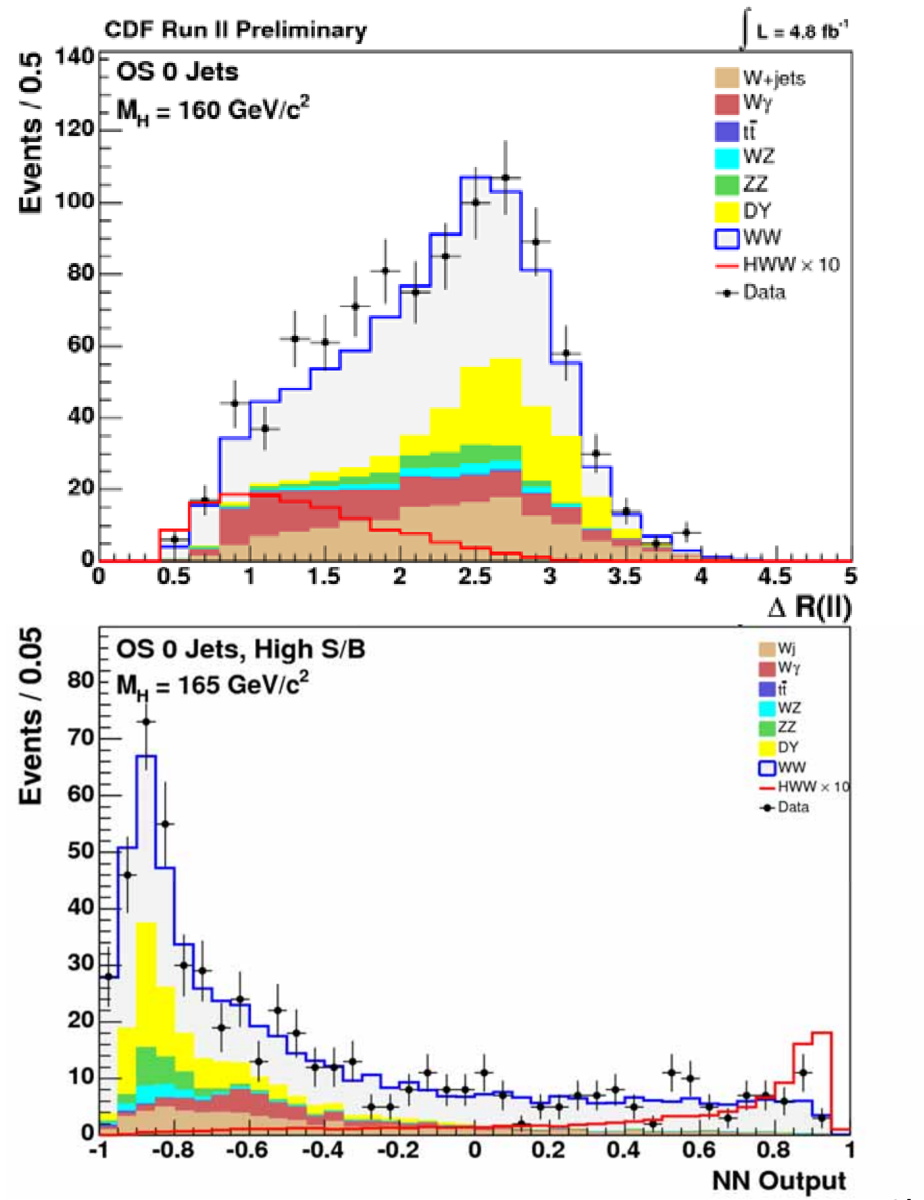


For M_H = 115 GeV/c^2 w/ 4.1 fb^{-1}
Expected limit : 6.8 × σ_{SM}
Observed limit : 5.9 × σ_{SM}

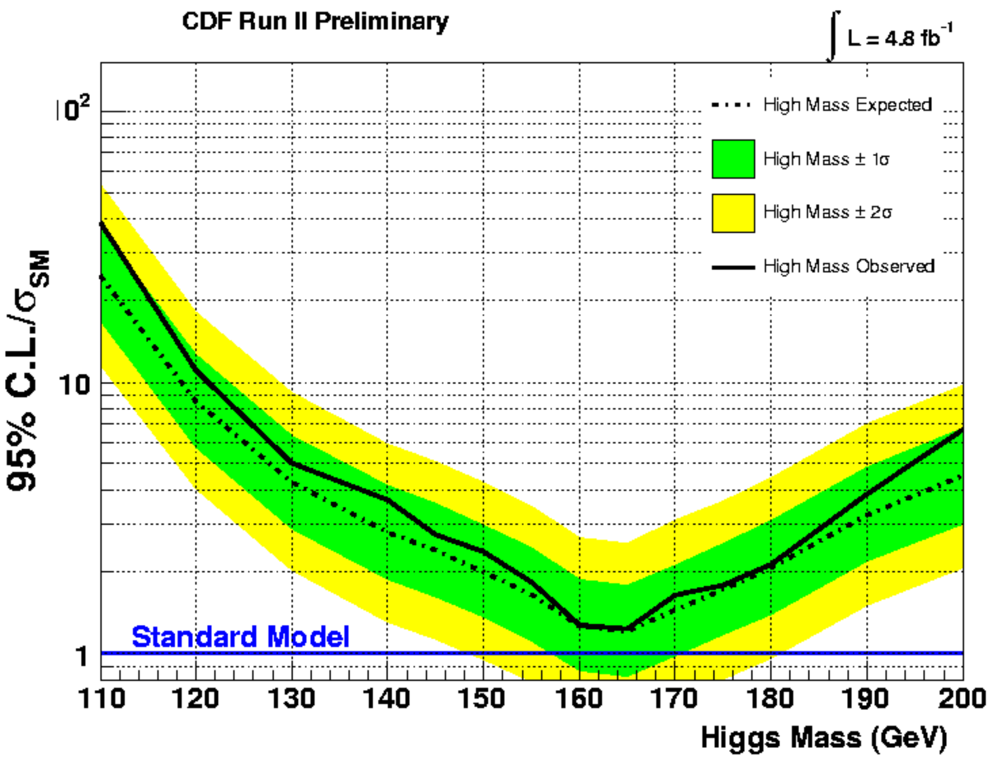
- S(m=115) ~ 0.88 fb, B ~ 140 fb
  - S/√B/√L~0.07 (cf. 0.08)
- +16% improvement

(3) h→WW, now

- 4.8 fb^{-1}
- 0j ⊕ 1j ⊕ ≥2j
- ME-NN for 0j
- Added Vh, qqh
- Lowered $M_{\ell\ell}$ cut
- Likelihood electron ID
- NN for each sub-sample



(3) h→WW, now



For M_H = 165 GeV/c^2 w/ 4.8 fb^{-1}
Expected limit : 1.21 × σ_{SM}
Observed limit : 1.23 × σ_{SM}

- S(m=160) ~ 6.6 fb, B ~ 360 fb
  - S/√B/√L~0.35 (cf. 0.24)
- +44% improvement

CDF SM Higgs Combination

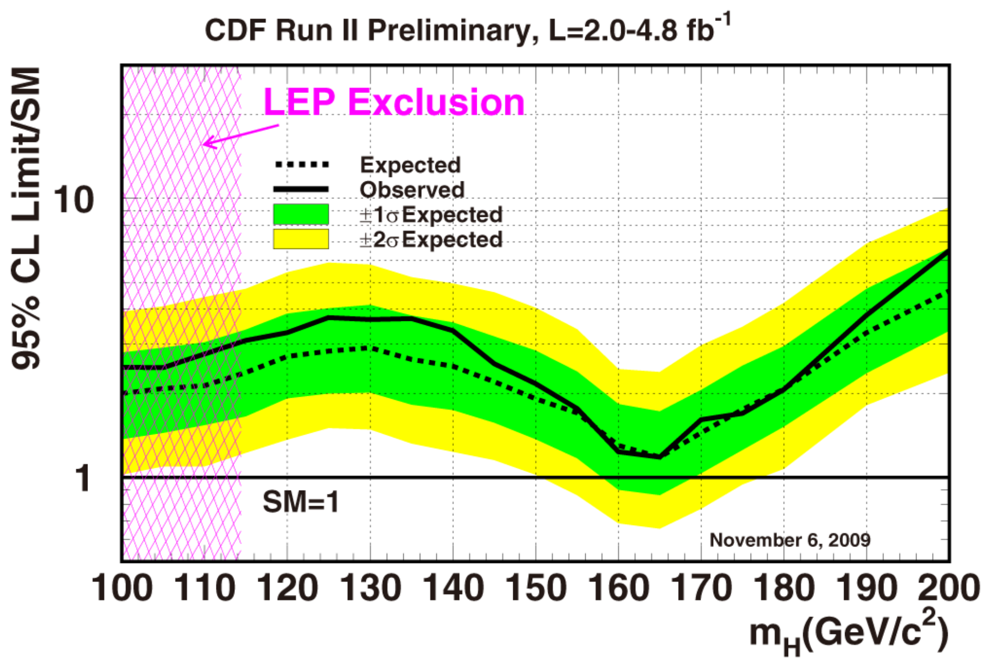
- CDF combined results with L = 2.0 - 4.8 fb^{-1}

Included channels

WH → ℓνbb (4.3 fb^{-1})
VH → $\not{E}_T$ + bb (3.6 fb^{-1})
ZH → ℓℓbb (4.1 fb^{-1})
VH, VBF, ggH
→ 2 jets + ττ (2.0 fb^{-1})
VH → 2 jets + bb (2.0 fb^{-1})
ggH → WW* → ℓνℓν (4.8 fb^{-1})
VH → VWW* (4.8 fb^{-1})

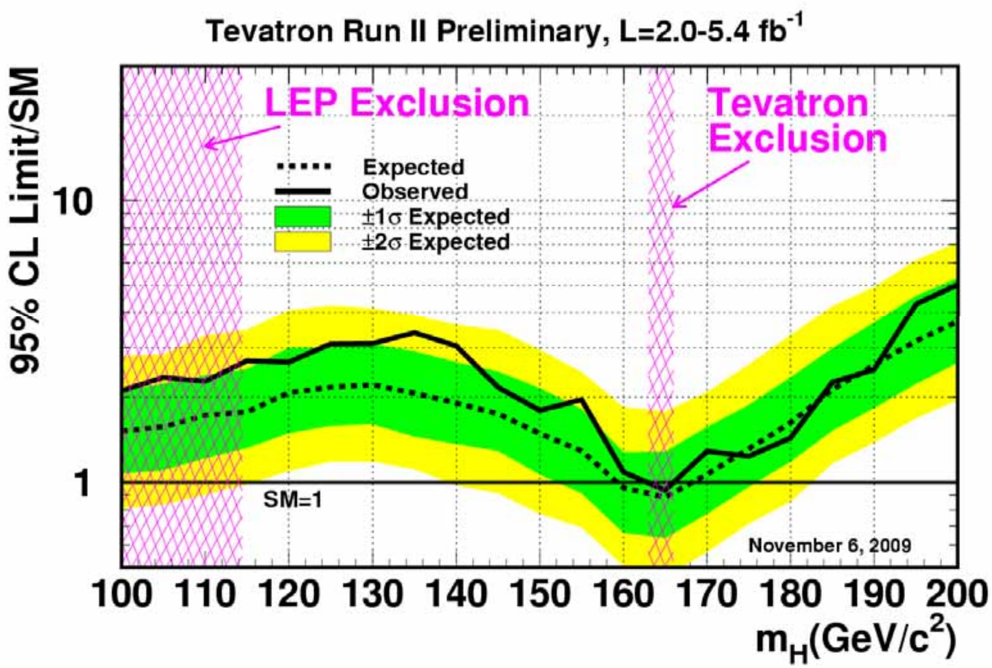
For M_H = 115 GeV/c^2
Expected limit : 2.38 × σ_{SM}
Observed limit : 3.12 × σ_{SM}

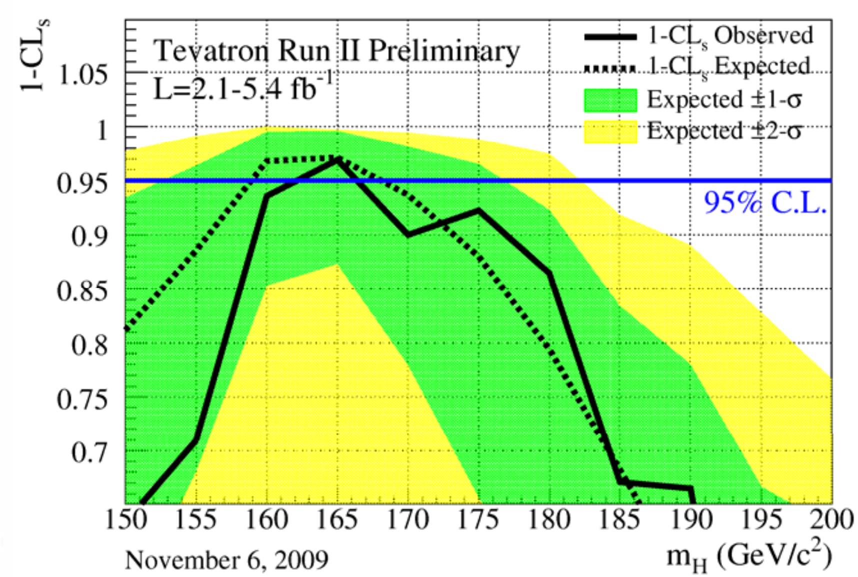
For M_H = 165 GeV/c^2
Expected limit : 1.19 × σ_{SM}
Observed limit : 1.18 × σ_{SM}



Tevatron SM Higgs Combination

- Combined results of CDF and DØ with L = 2.0 – 5.4 fb^{-1}
  - Systematics correlation b/w experiments are taken into account.





Observed (expected) limit at M_H = 115 GeV/c^2 : 2.70 (1.78) × σ_{SM}
Excluded mass range at 95% C.L. : 163 - 166 GeV/c^2
(Expected exclusion range : 159 – 168 GeV/c^2)

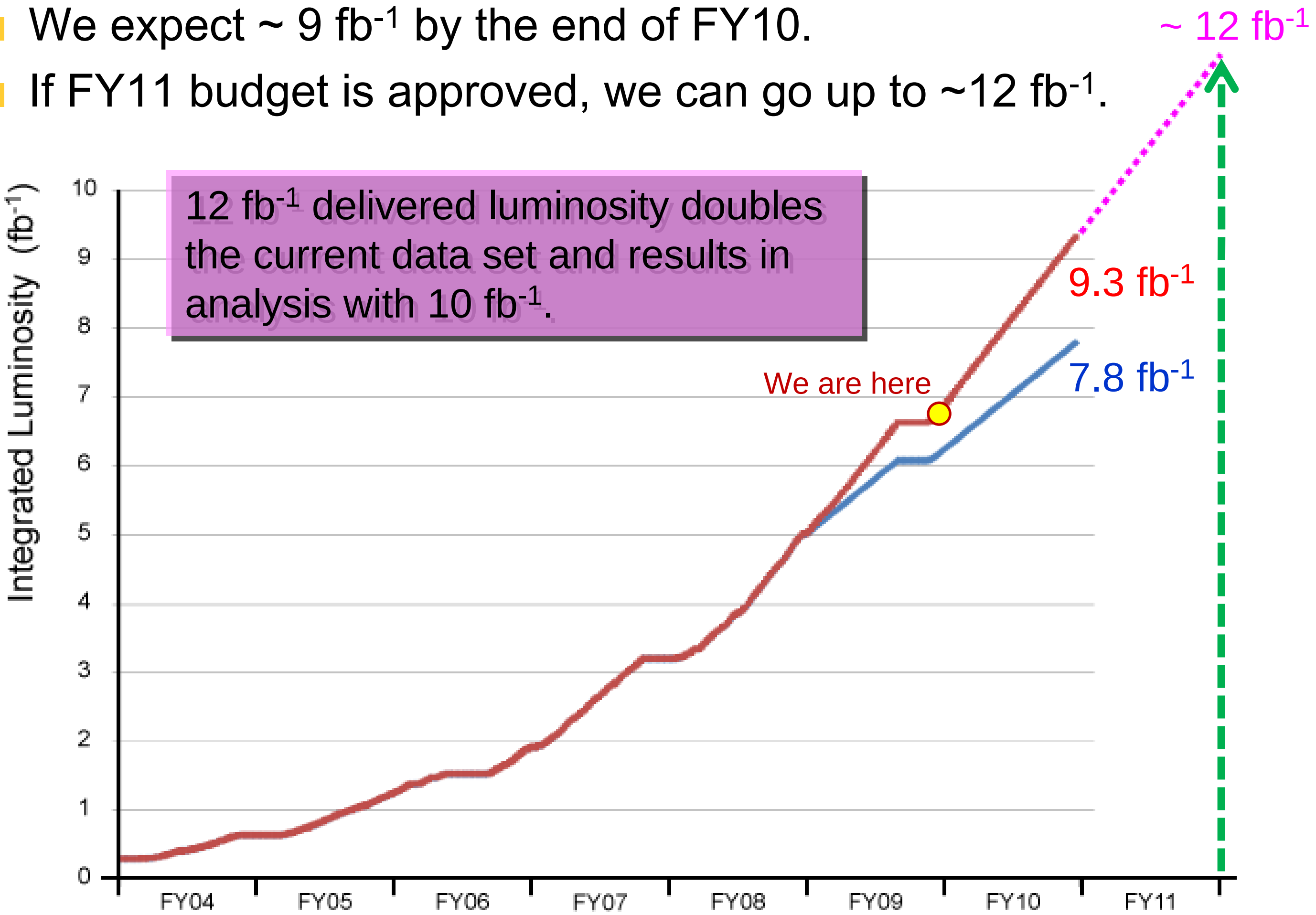
arXiv:0911.3930[hep-ex]

as of November 2009

Future Prospects

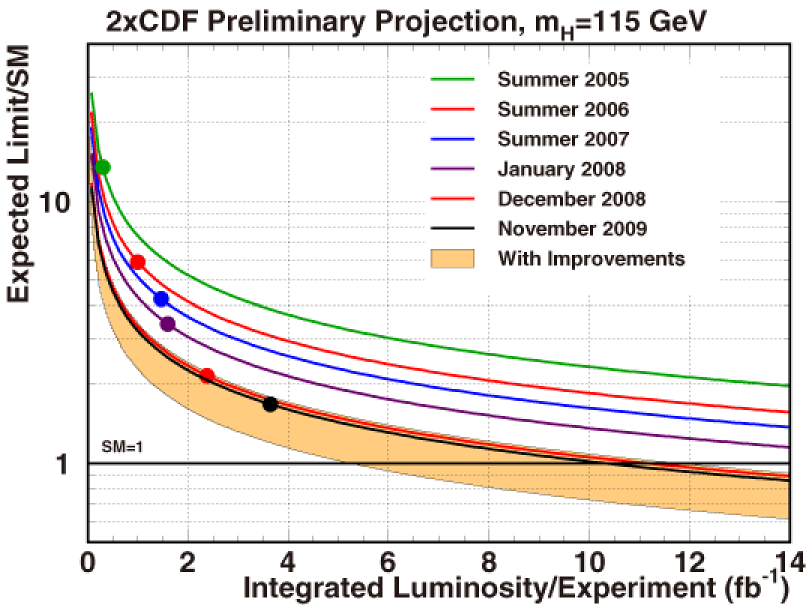
Luminosity Prospects

- Tevatron performance and projection
  - We expect ~ 9 fb^{-1} by the end of FY10.
  - If FY11 budget is approved, we can go up to ~12 fb^{-1}.

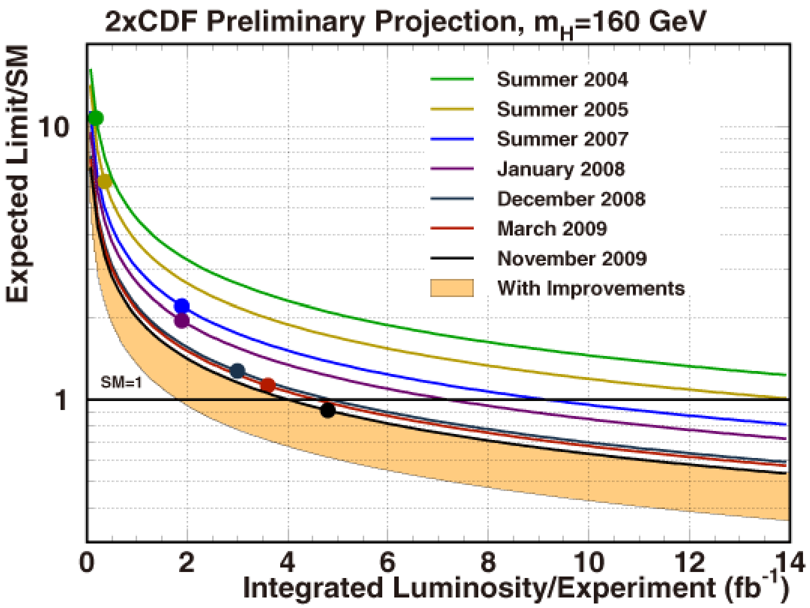


SM Higgs Sensitivity Prospects

For M_H = 115 GeV/c^2

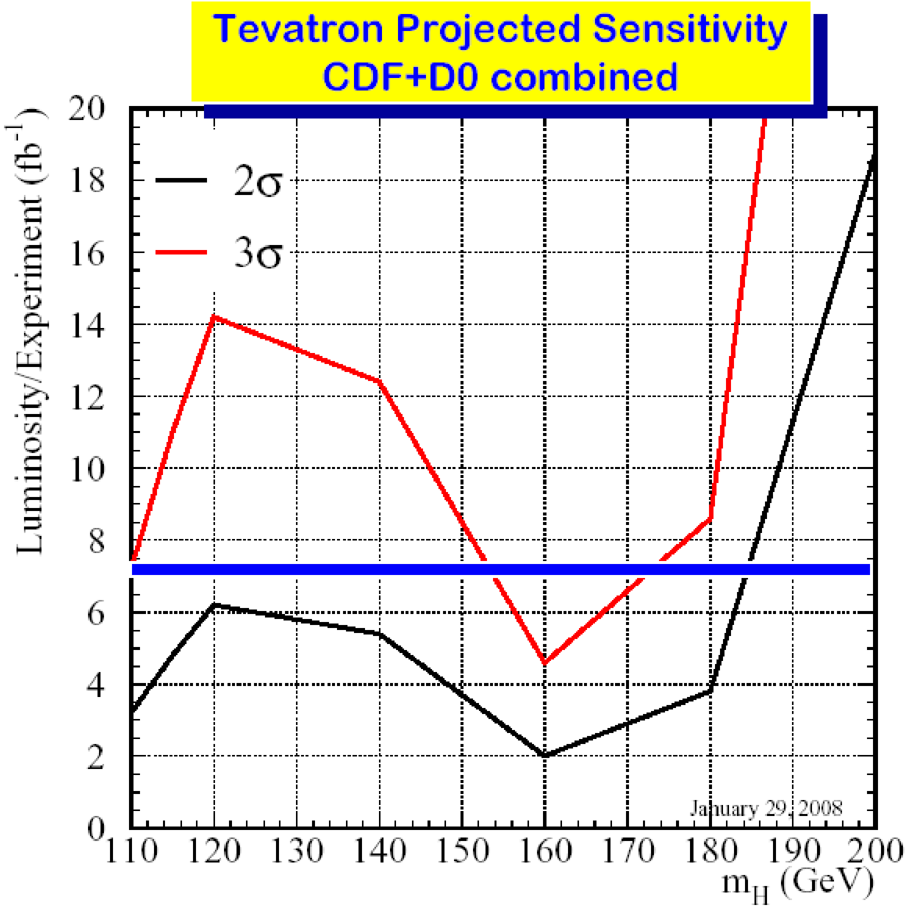


For M_H = 160 GeV/c^2



- Analysis improvements help the sensitivity increase better than 1/sqrt(L).
  - Expect to reach 115GeV Higgs with 6~10 fb^{-1}

SM Higgs Sensitivity Prospects



If CDF and D∅ analyze 7 fb^{-1} each,

m_h < 180 GeV/c^2 would all be excluded if not there

Conclusions

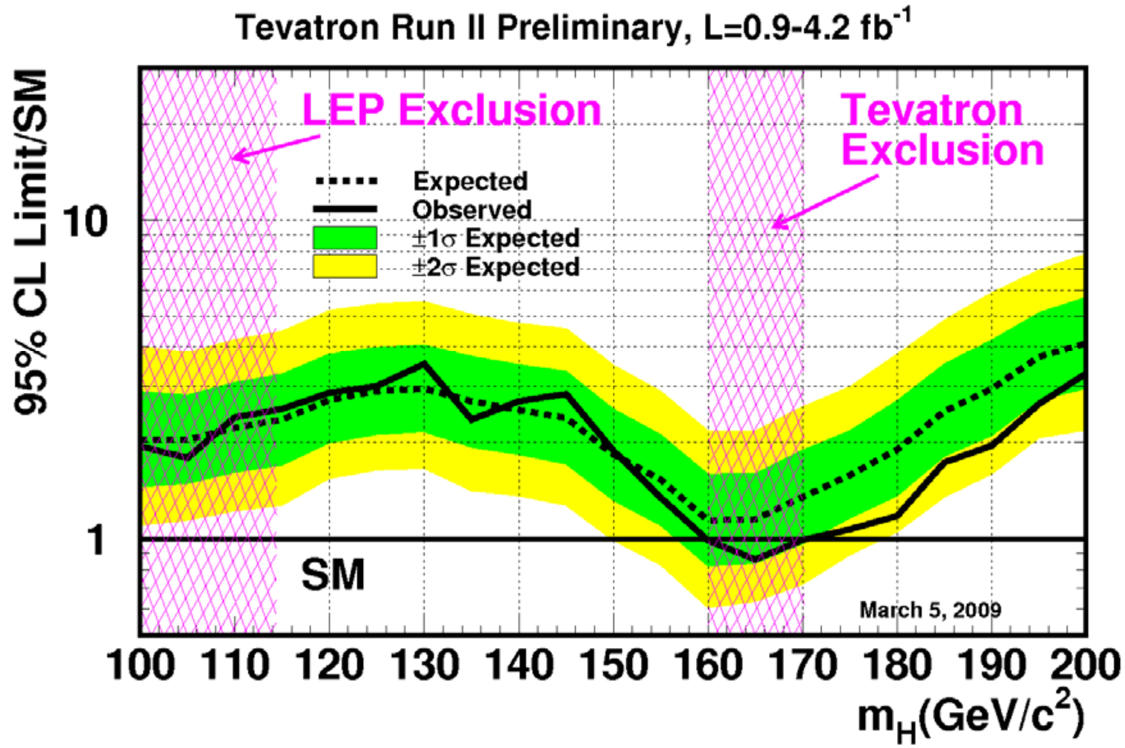
- Tevatron and the CDF detector are performing very well.
  - Delivered 8.2 fb^{-1}, Acquired 6.8 fb^{-1}, Analyzed 5.4 fb^{-1}
  - Expect ~ 9 fb^{-1} by the end of FY10
  - ➢ We all thank accelerator people for excellent beam !

- SM Higgs searches are in progress in various production and decay channels.

- Increasing luminosity, analysis improvements, …
  We can go further !

Backup Slides

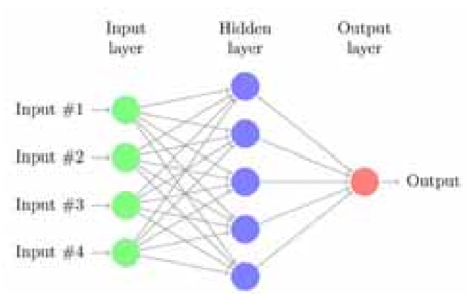
Spring 2009 Result



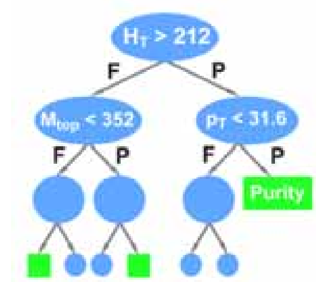
Multivariate Techniques

- Both experiments use advanced multivariate techniques, which combine information from kinematical, topological and particle identification variables, to enhance the signal/background discrimination.

Artificial Neural Networks (NN)

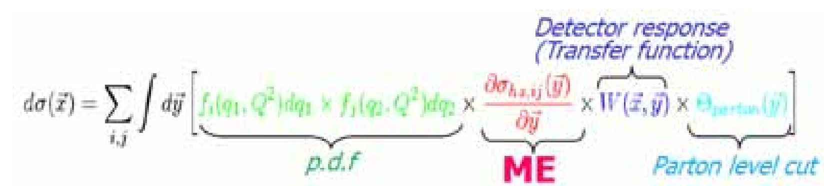


Boosted Decision Trees (BDT)

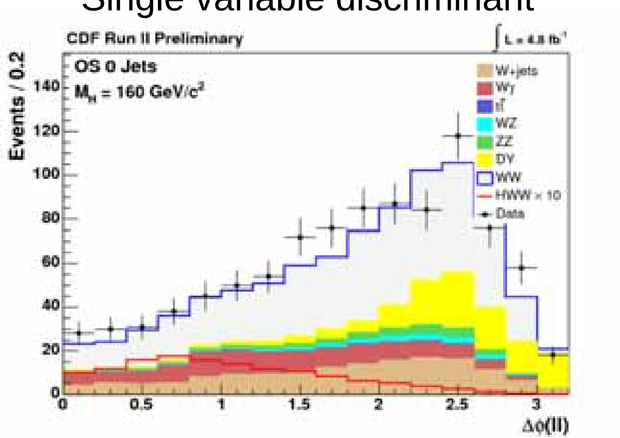


Matrix Element (ME)

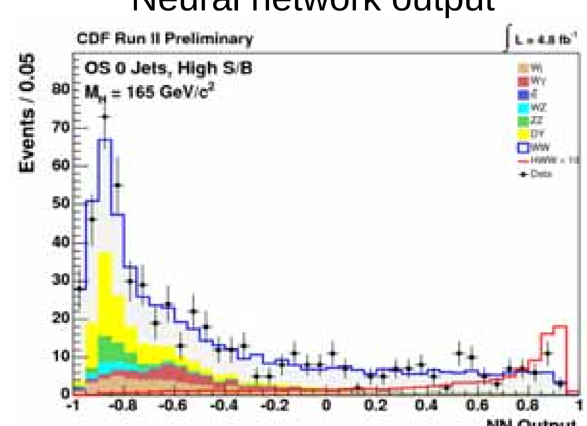
Calculating event probability integrating the LO matrix elements



Single variable discriminant



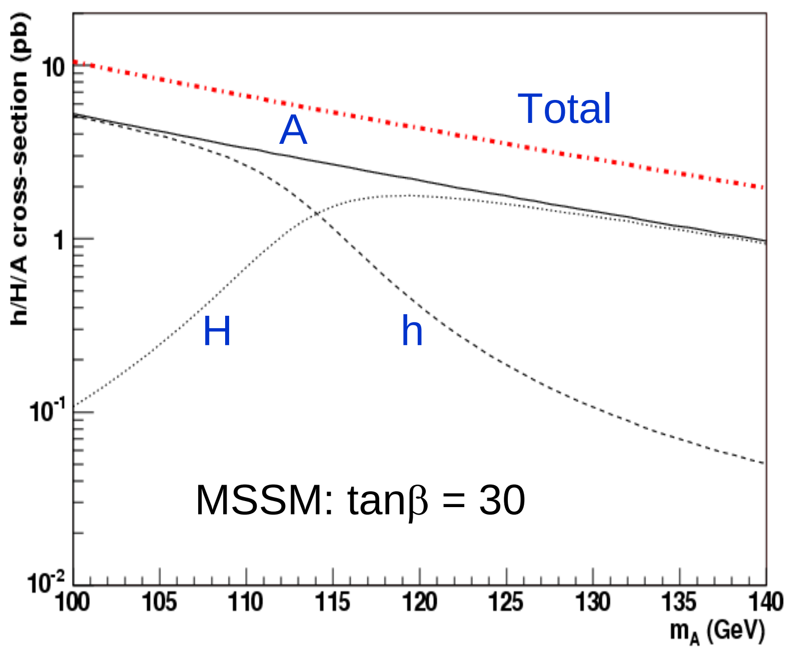
Neural network output



Higgs Bosons Beyond the SM

MSSM Higgs at the Tevatron

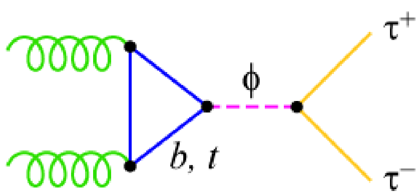
- Two-Higgs-doublet fields provide 5 physical Higgs bosons.
  - 3 neutral : ϕ = h, H, A
  - 2 charged : $H^{\pm}$
  - ➢ Phenomenology described at tree level by $\tan\beta$ and M_A.
- Neutral Higgs
  - Coupling to d-type quarks enhanced by $\tan\beta \Rightarrow \sigma_{\phi} \propto \tan^2\beta$
  - $Br(\phi \to \tau\tau)$ ~10%, $Br(\phi \to bb)$ ~90% for low and intermediate masses
- Charged Higgs
  - For ($M_{H+} < M_t - M_b$), a top quark can decay into $H^{\pm}b$.



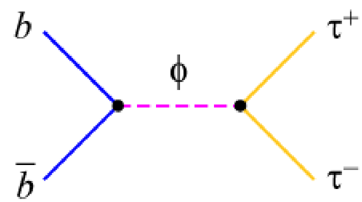
Tevatron has sensitivity for some MSSM scenarios.

MSSM Neutral Higgs : $\phi \to \tau^+\tau^-$

- gg, bb $\to \phi \to \tau\tau$

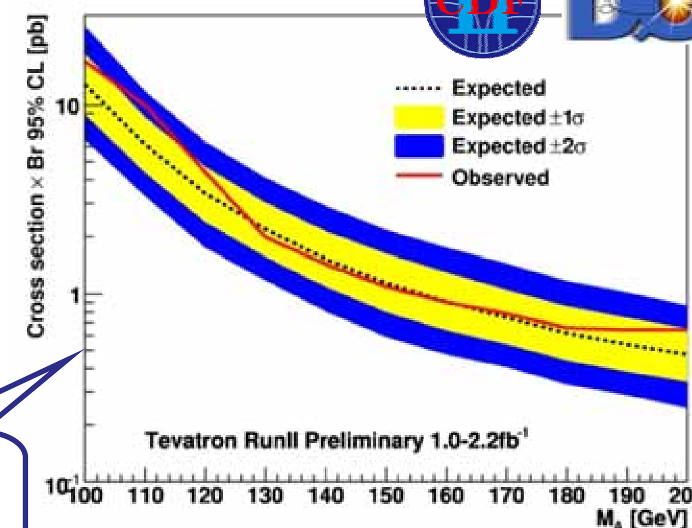


gluon fusion

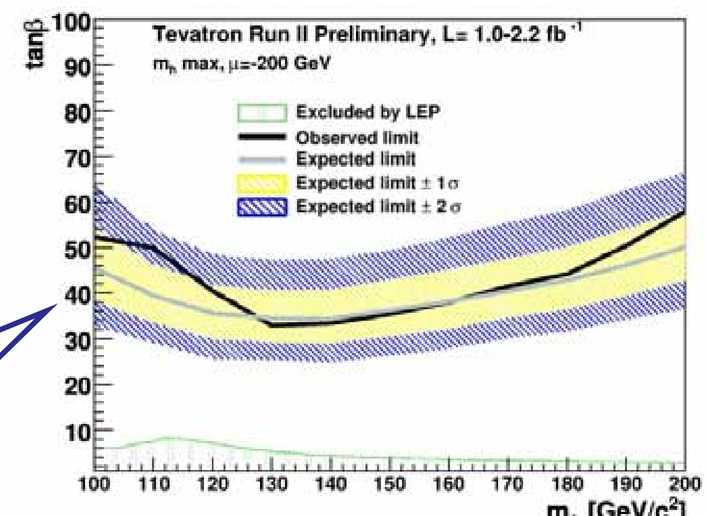


bb fusion

- Tau pairs are identified in $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, and $\tau_\mu\tau_{had}$.
- Background :
  - $Z \to \tau\tau$, $Z \to ee/\mu\mu$
  - Diboson, tt, W + jets
- Combined CDF and DØ results



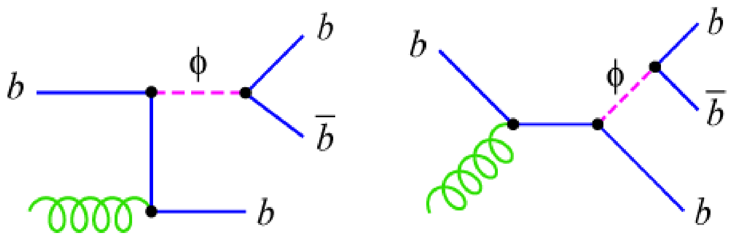
Model independent limit



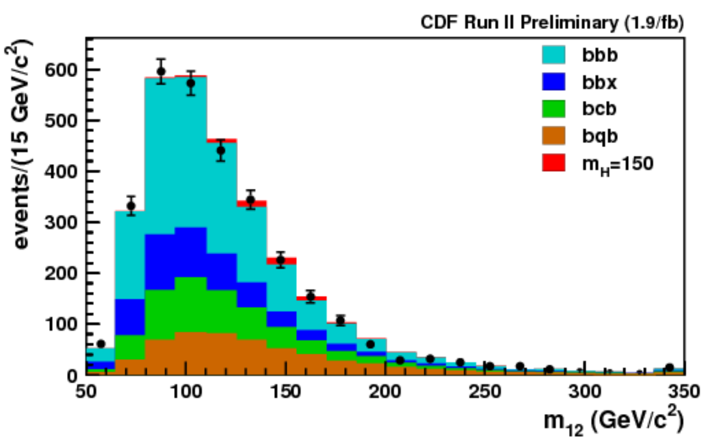
Interpretation to typical MSSM scenario :
Maximal stop mixing
$\mu = -200$GeV

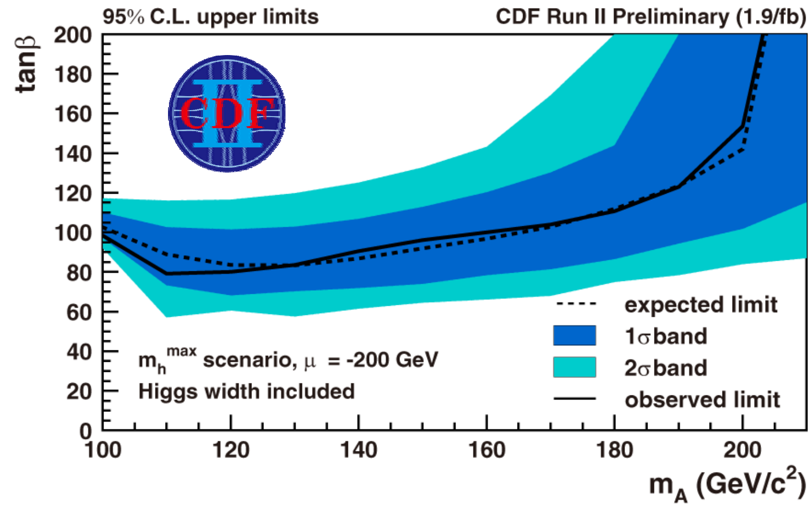
MSSM Neutral Higgs : ϕb → bbb

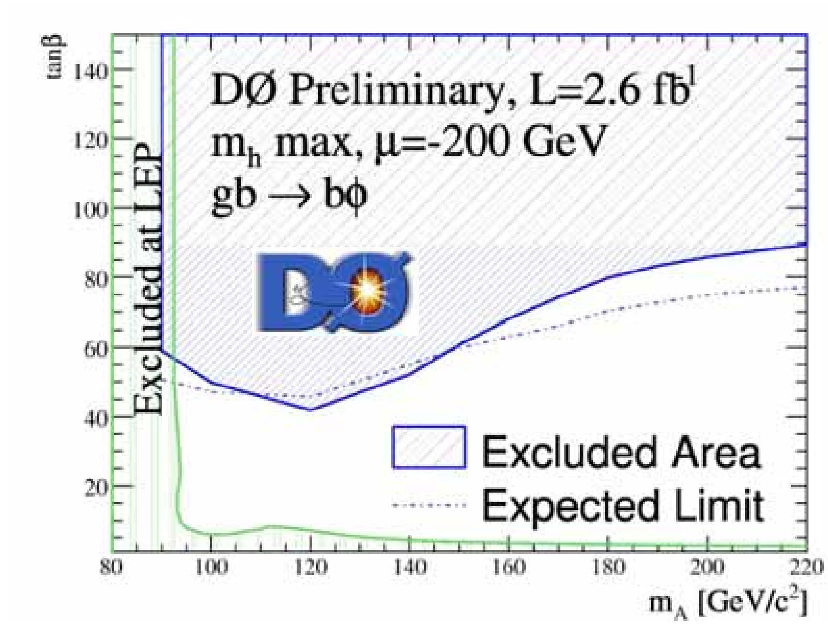
- gb → ϕb → bbb



- Required 3 b-tagged jets.
- Large multijet background
- Search for peak in dijet mass
  - CDF : 1.9 fb^{-1}, DØ : 2.6 fb^{-1}

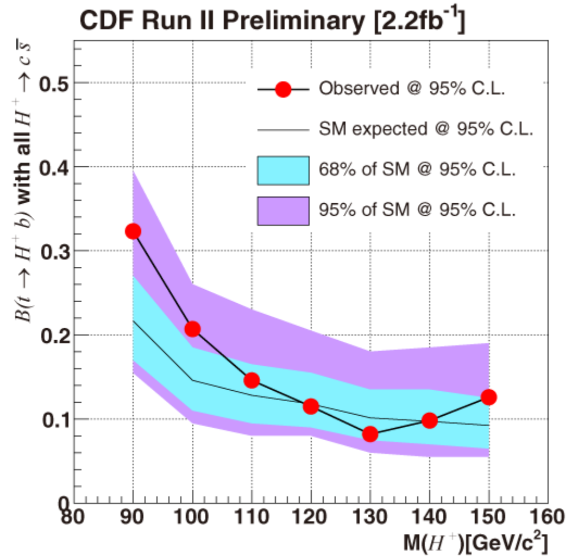


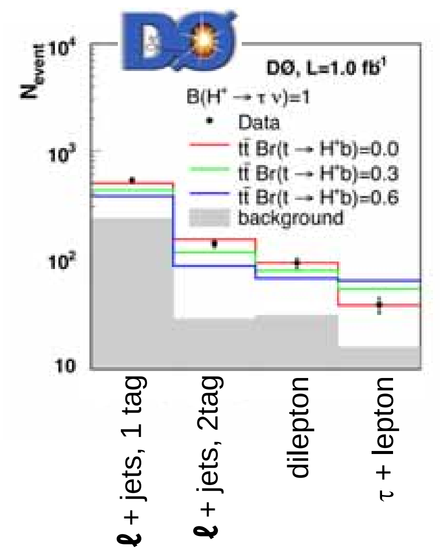


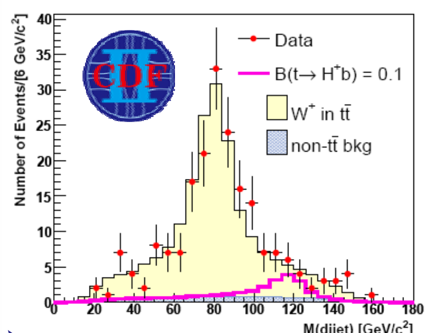


MSSM Charged Higgs

- Search for $H^{\pm}$ in top decays
  - $t \rightarrow H^{\pm}b$
    - $H^{\pm} \rightarrow cs$ (for small $\tan\beta$)
    - $H^{\pm} \rightarrow \tau\nu$ (for large $\tan\beta$)
  - If $H^{\pm}$ exists, there would be deviation from the SM prediction for the final states of tt decay.

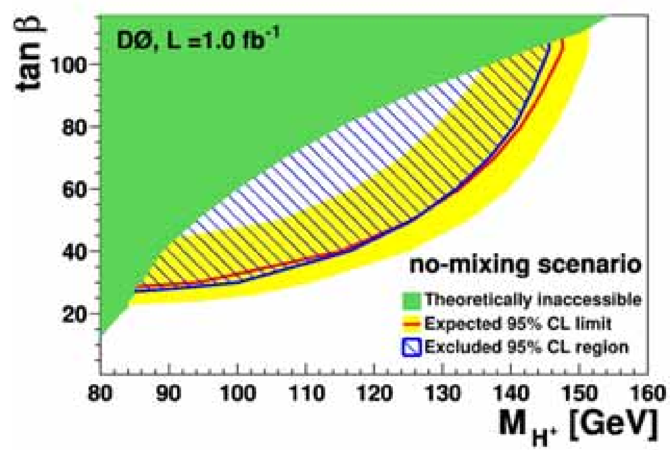






Dijet mass

Consistent with SM



Fermiophobic Higgs

- In some BSM models, Higgs couplings to fermions are suppressed.
  - ⇒ Higgs decays to vector bosons are significantly increased.
  - Low mass region : H → γγ
  - High mass region : H → WW/ZZ
- Benchmark scenario
  - No fermion couplings and SM couplings to vector boson