Lighting up the Higgs Sector with Photons at CDF

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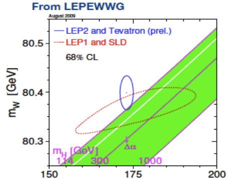
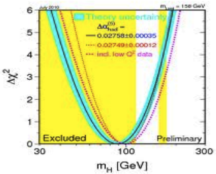
Table of Contents

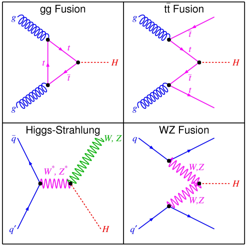
Introduction

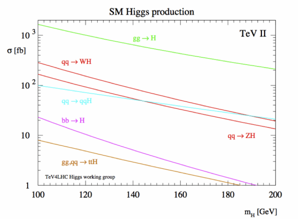
- ElectroWeak Symmetry Breaking
  - SM allows for Higgs mechanism
  - Manifests itself as a heavy spin-0 boson
- SM predicts most properties and decay channels of Higgs but not its mass
- Experimental evidence so far:
  - Direct searches at LEP exclude $m_H < 114$ GeV
  - Direct searches exclude Higgs masses in range(s)
    - Tevatron: 157−175 GeV
    - LHC: 146-232, 256-282, 296-466 GeV (ATLAS)
  - Indirect constraints from precision measurements (m_W and m_T) in favor of low mass Higgs: $m_H < 157$ GeV
- Tevatron still has advantage over LHC in low mass Higgs search

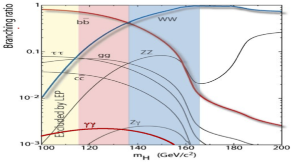




Higgs Production and Decay Modes







- Three production mechanisms
  - gluon-gluon fusion (1000 fb @ 120 GeV)
  - Associated production (225 fb @ 120 GeV)
  - Vector boson fusion (70 fb @ 120 GeV)

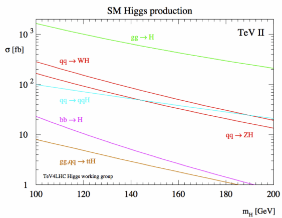
Tevatron Higgs Searches Strategy

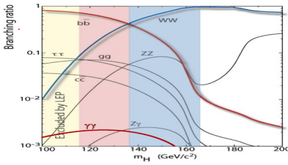
- At Tevatron Higgs boson production is a very rare process
- The search strategy is driven by the Higgs boson dominant decay modes:
  - Low mass $m_H < 135$ GeV
    - $H \rightarrow bb$
    - $gg \rightarrow H$ not possible due to over-whelming multi-jet background
    - Associated production provides cleaner experimental signature
  - High mass $m_H > 135$ GeV
    - $H \rightarrow WW$
    - Since the leptonic W decays provide clean final states, can take advantage of higher gluon fusion production cross section.
- What about other channels ?

NO CHANNEL SHOULD BE LEFT BEHIND

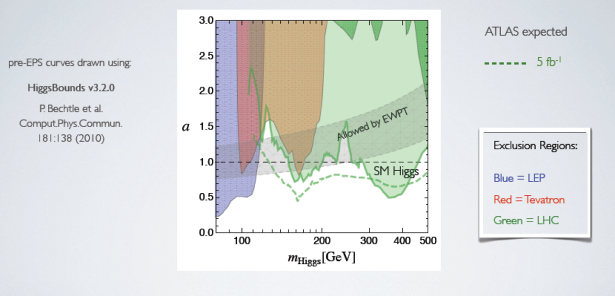
Diphoton Search Motivation

- Advantages of Diphoton Channel
  - Contributes sensitivity to the search in transition region 125 GeV
  - Three production mechanisms ($H \to b\bar{b}$, VH only)
  - Great mass resolution
    - Mass resolution limited only by EM calorimeter
    - 1 σ width 3 GeV or less (Mjj width is 16 GeV)
    - Great background discrimination using $M_{\gamma\gamma}$
    - Search for narrow resonance
    - use sideband fits to estimate background
- Disadvantage
  - Very low branching ratio





Current and Projected Constraints on SM Higgs



Plot taken from Roberto Contino. Let's try a non SM Higgs

Fermiophobic Higgs Model

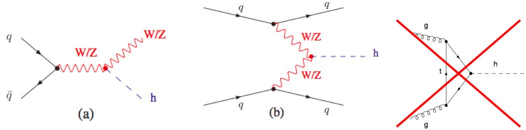
- In the SM, the spontaneous symmetry breaking (SSB) mechanism requires a single doublet complex scalar field.
- But does nature follow this minimal version or require multi Higgs sector ?
  - Thus, extended Higgs sectors with
    - Doublet fields (considered in this talk)
    - A. Barroso, L. Brucher, and R. Santos, Phys. Rev. D 60, 035005 (1999)
    - There are triplets as well
    - J. F. Gunion,R. Vega, and J. Wudka, Phys. Rev. D 42, 1673 (1990)
  - The symmetry breaking mechanism responsible for giving masses to gauge bosons is separate from that which generates the fermion masses
    - $\rightarrow$ 5 Higgses

2 Higgs Doublet Models

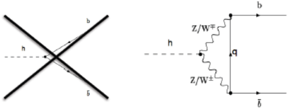
- Two Higgs Doublet Model (2HDM)
  $\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$, $\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$
- The vacuum expectation values
  $< \phi_1 >= \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$, $< \phi_2 >= \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- 5 Physical Higgs Particles
  h^0, H^0, A^0, H^+, and H^-,
- 2HDM type-I
  - ϕ_1 does not couple with fermions, but ϕ_2 does
  - α, mixing angle in neutral Higgs sector, h^0 and H^0
  - If $\cos\alpha \to 0$,
    - $h^0 f\bar{f} \to 0$, Thus " fermiophobia"
      "N.B. SUSY does not endorse fermiophobia"
    - $h^0 \to h_f$ (fermiphobic Higgs or Bosonic Higgs)

Production and Decay Modes

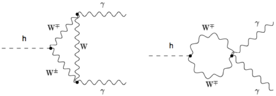
Production mechanisms

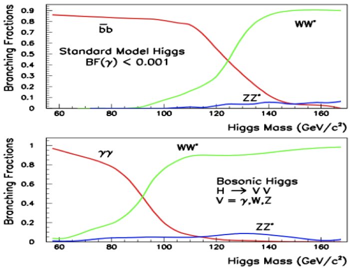


The b decay no longer dominant



Dominant low mass decay mode in $H \rightarrow \gamma\gamma$

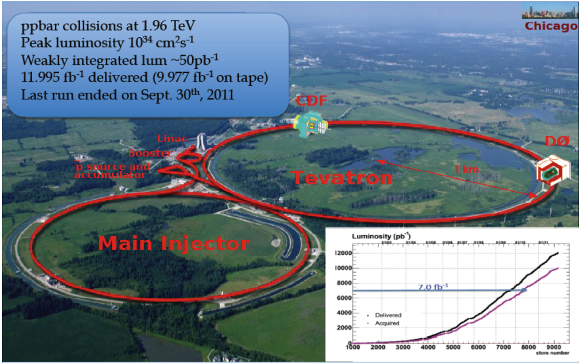




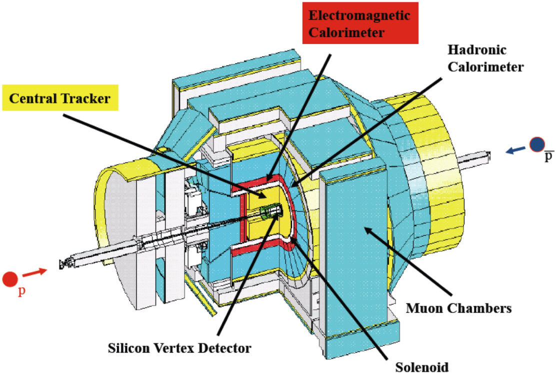
Summary of Cross Sections and Branching Ratios

M_H (GeV/c^2)	σ_{GF} (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H \to \gamma\gamma)$ (%)	$B(h_f \to \gamma\gamma)$ (%)
100	1821.8	291.9	169.8	100.1	0.15	18.2
105	1584.7	248.4	145.9	92.3	0.17	10.6
110	1385.0	212.0	125.7	85.1	0.19	6.2
115	1215.9	174.5	103.9	78.6	0.20	3.8
120	1072.3	150.1	90.2	72.7	0.21	2.8
125	949.3	129.5	78.5	67.1	0.22	2.2
130	842.9	112.0	68.5	62.1	0.22	1.9
135	750.8	97.2	60.0	57.5	0.21	1.2
140	670.6	84.6	52.7	53.2	0.19	0.6
145	600.6	73.7	46.3	49.4	0.17	0.3
150	539.1	64.4	40.8	45.8	0.14	0.2

Tevatron and CDF Performance

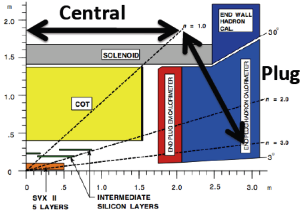


The CDF Detector



Photon Identification I

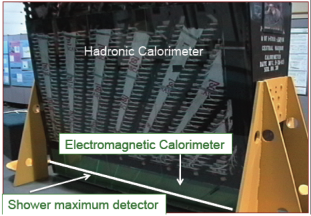
- Central
  - $|\eta| < 1.1$
- Plug "aka. Forward in ATLAS"
  - $1.2 < |\eta| < 2.8$
  - Tracking efficiency lower than in central region
  - Easier to miss a track and reconstruct fake object as a photon
  - Higher backgrounds for plug photons
  - We do not consider the Plug-Plug channel



Photon Identification II

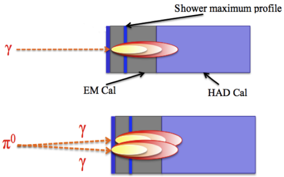
calorimeter segmentation:

- $\Delta\eta \times \Delta\phi$ 0.1 × 15 ($|\eta| < 1$)
- Not fine enough to fully reject π^0/η jets



Shower max detector

- 6 radiation lengths into EM calorimeter
- Fine segmentation
- Good resolution to reject $\pi^0/\eta \to \gamma\gamma$
- Refines EM cluster position measurement to better match associated tracks
- Photon ID criteria
    - Compact EM cluster and Isolation
    - Absence of high momentum track associated with cluster
    - Profile (lateral shower shape) consistent with that of a prompt γ
    - Plug ID based on these variables. CC uses them for a NN ID



Central Photon ID

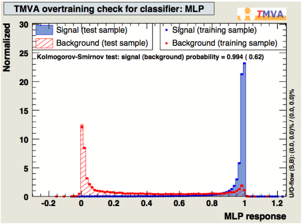
- Loose requirements
  - Fiducial in shower max detector
  - Ratio of hadronic to electromagnetic transverse energy (Had/EM) $< 12.5\%$
  - Calorimeter isolation
    - $I = E_T^{Tot}(\Delta R < 0.4) - E_T^{EM}$
    - Cut slides with E_T^{EM}
  - Track Isolation
    - $\sum_{\Delta R<0.4, trk|z_0 - z_{trk}|<5cm} p_T^{trk}$ <5 GeV
- Track veto
  - Number tracks $<= 1$
  - If 1, then $p_T^{trk1} < 1$ GeV
- Cut on NN Output (next slide)
- Plug ID is cut based approach

Central Photon ID (NN)

NN discriminant constructed from seven well understood variables:

- Ratio of hadronic to EM transverse energy
- Shape in shower max compared to expectation
- Calorimeter Isolation
- Track isolation
- Ratio of energy at SMX to total EM energy
- Lateral sharing of energy between towers compared to expectation
- the first paper that will publish this new ID

Trained using inclusive photon MC and jet MC

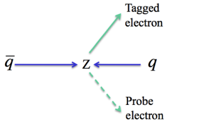


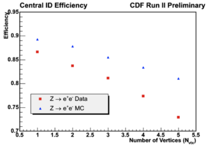
NN increases

- γ efficiency by 5%
- BG rejection by 12%
- $H \rightarrow \gamma\gamma$ sensitivity by 9%

Central Photon ID Efficiency

- ID efficiency checked in data and MC from $Z \rightarrow e^+e^-$ decays
- Z mass constraint to get pure sample of e
- Effect of pile-up seen through N_{vtx} dependence
- Net efficiencies, ϵ_{vtx} folded into N_{vtx} distribution of diphoton data and signal MC
- Total systematic uncertainty of 2% from:
  - Differences between electron vs photon response (checked in MC)
  - Data taking period dependence
  - Fits made to Z mass distribution





- Net photon ID efficiency: Data: 83.2% MC: 87.8%
- MC scale factor of 94.8% applied

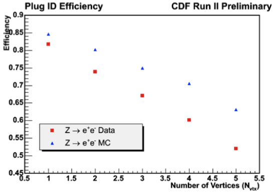
Plug Photon ID Efficiency

Standard CDF Cut-Based ID

- Fiducial in shower max detector
- Ratio of hadronic to EM transverse energy $< 5\%$
- Calorimeter isolation < 2 GeV
- Track isolation < 2 GeV
- Shape in shower max compared to expectation

Same Efficiency Technique as for Central Photons

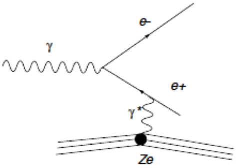
- MC scale factor of 90.7% applied
- Total systematic uncertainty of 4.5%

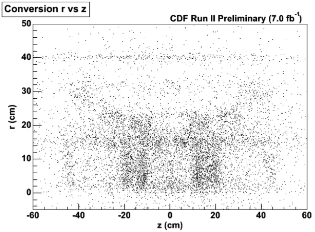


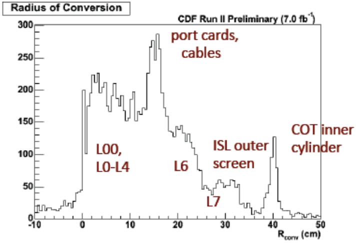
Photon ID efficiency:

- Data: 73.2%
- MC: 80.6%

Photon Conversion







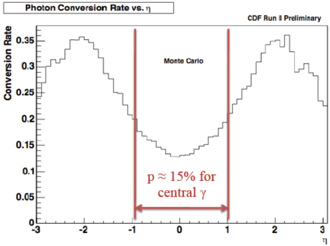
- Occurs in presence of detector material
- More material, higher the probability of converting
- Collinear tracks moving in approximately same direction

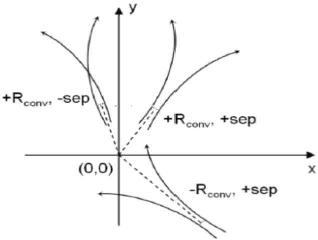
Conversion Identification I

- Use central only
- Then for two photons,% of events lost from a single central γ converting is:
  - 26% for CC channel
  - 15% for CP channel

Nomenclature

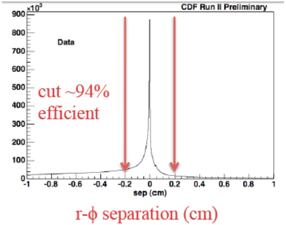
- Radius of Conversion: radial distance from center detector where the two tracks are parallel.
- Separation: spatial separation between the tracks in the $r - \phi$ plane at this radial location. < 0 if tracks cross each other.

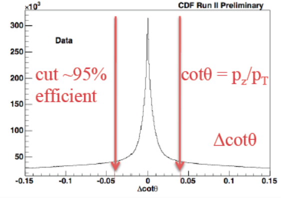




Conversion Identification II

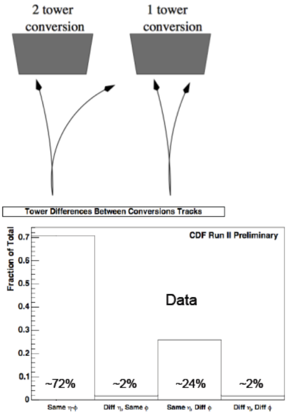
- Base selection
  - $|\eta| < 1.1$
  - Oppositely signed high quality tracks
  - Proximity: r$-\phi$ sep and $\Delta cot\theta$
  - e^+ ($\gamma \rightarrow e^+e^-$) trident veto photon radiated via bremmstrahlung
  - $R_{conv} > 2.0$ cm to remove fake conversion and Dalitz decays
- Including conversion increases Higgs sensitivity by 13%





Types of Conversion Events

- Two types:
  - Tracks fall into same phi tower/wedge (72%)
  - Tracks fall into different phi tower/wedge (24%)
- A small percentage fall into different η towers, but are ignored for this analysis
- For cases where track is in a different phi tower/wedge, it is interesting to look at the:
  - Proportion in an adjacent wedge
  - Pt spectrum for these cases



Event Selection

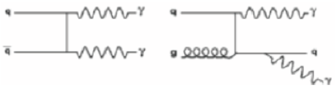
- Inclusive photon trigger
  - Single photon $E_T > 25$ GeV
  - Get trigger efficiencies from TrigSim
    - 100% for CC and > 90% for other channels
- Use photon ID as described
- Photon $p_T > 15$ GeV
- Four orthogonal diphoton categories:
  - Central-central photons (CC)
  - Central-plug photons (CP)
  - Central-central conversion (C'C)
  - Central-plug conversion (C'P)

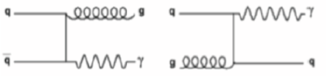
Fermiophobic Higgs

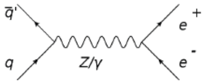
- No gluon-gluon process
- Optimize for VH and VBF processes
- Split into 3 diphoton p_T bins
  - High:p_T >75 GeV
  - Medium:(35< p_T <75) GeV
  - Low:p_T <35 GeV
- 4 diphoton categories $\times$ 3p_T bins
  - 12 channels in total

Background Composition

- Regular Photon Backgrounds
- Real SM photons via QCD interactions
- Jets faking a photon (mostly from $\pi^0/\eta \rightarrow \gamma\gamma$)
- Misidentified electrons such as in Drell-Yan $Z/\gamma \rightarrow e^+e^-$
- Conversion backgrounds
- Real SM photons converting
- Photons from π^0/η jets converting
- Combinatorics
- Conversions from Dalitz decay

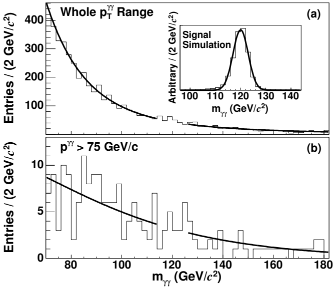






Background Modelling

- Assume a null hypothesis
- Fit made to sideband regions of $M_{\gamma\gamma}$ distribution
- Use polynomial times exponential to model data
- Fit is interpolated into the 12 GeV signal region
- CP and C'P contaminated by Z background
  - Add Breit-Wigner to model that
- No significant resonance observed so will set limits on $\sigma \times Br(H \to \gamma\gamma)$



Animated plots

Background Rate Uncertainty

- Fit parameters fluctuated according to statistical errors
- Maximum difference of resulting background yields from original fit in signal region recorded
- Then symmetrized to obtain rate uncertainty for each test mass and channel
- BG rate uncertainties were found to be
  - 8% or less in case of SM
  - 12% or less in case of fermiophobic Higgs
  - except high p_T bin 27%

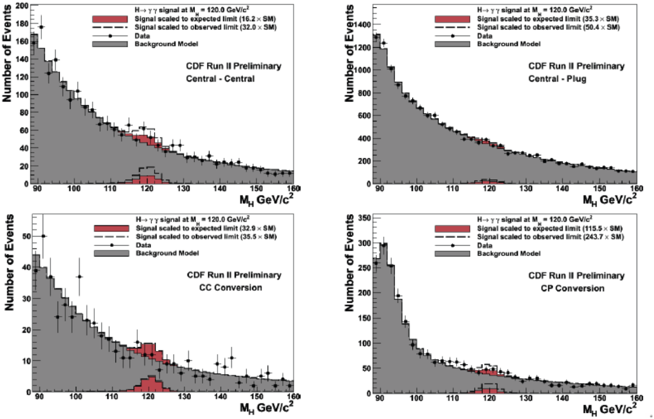
Systematics Uncertainties

$\int \mathcal{L} = 7.0\ \mathrm{fb}^{-1}$	Systematic Errors on Signal (%) CC	CP	C'C	C'P
Luminosity	6	6	6	6
σ_{ggH}*	14	14	14	14
σ_{VH}	7	7	7	7
σ_{VBF}	5	5	5	5
PDF	5 (2)	2	5 (2)	2
ISR/FSR	6	8 (6)	4 (8)	10 (6)
Energy Scale	0.2	0.8	0.1	0.8
Trigger Efficiency	1	2 (1)	2	8
Z Vertex	0.2	0.2	0.2	0.2
Conversion ID	–	–	7	7
Material Uncertainty	0.4	3.0	0.2	3.0
Photon/Electron ID	1.0	2.8	1.0	2.6
Run Dependence	3.0	2.5	1.5	2.0
Data/MC fits	0.4	0.8	1.5	2.0
$p_T^{\gamma\gamma}$ PYTHIA/NLO**	4	4	4	4

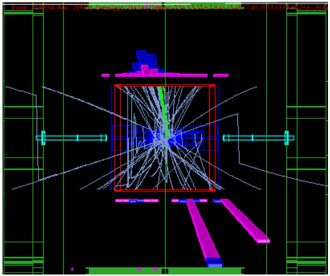
*Only to SM search. **Only to fermiophobic search.

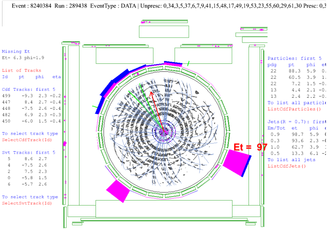
The inclusion of systematic uncertainties in the SM (fermiophobic) limit calculation degrades the limit on $\sigma \times B(H \to \gamma\gamma)$ by 15% (9%) where the effect of the uncertainty on the background estimate is dominant at 10% (6%).

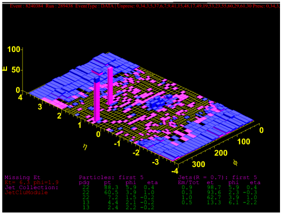
Mass Distribution



What the Higgs will look like in CDF ?

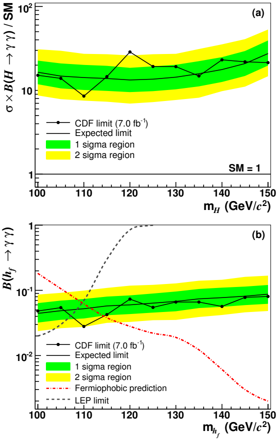






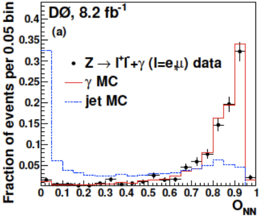
Results

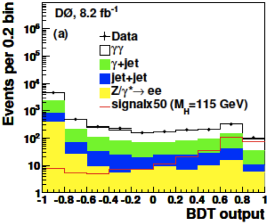
- No obvious evidence of a narrow peak in the diphoton mass spectrum. Thus, we set limits.
- SM Higgs results
  - Expected limit of 13.3xSM at 120 GeV
  - Observed limit outside 2σ band at 120 GeV, but reduced to $< 2\sigma$ after trial factor taken into account
    first Run II SM search in this channel
- Fermiophobic Higgs results
  - Observed (expected) 95% C.L. limits on $B(h_f \to \gamma\gamma)$ exclude a Fermiophobic Higgs boson with masses $<$ 114 GeV (111 GeV)
  - A limit of 114 GeV is currently the worlds best limit on a h_f Higgs



D0 Diphoton Search

- Unlike CDF where we used data-driven background modeling, D0 decomposes the background.
- uses NN for Photon ID
    - trained on Jet vs. Photon MC
    - validated with $Z \to ll + \gamma$ data
    - Reject candidates with low NN output
- BDT for final $H \to \gamma\gamma$ discriminant
- 5 variable
    - $M_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, E_T^1, E_T^2, and $\Delta\phi_{\gamma\gamma}$





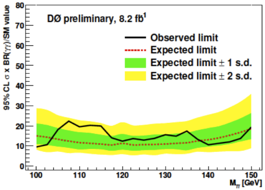
D0 Diphoton Results from 8.2 fb^{-1}

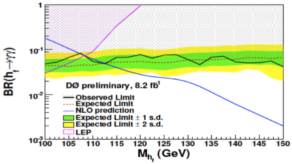
SM Analysis

- Observed for 120 GeV 12.4 $\times$ SM
- Expected for 120 GeV 11.3 $\times$ SM

Fermiophobic Higgs Search

- Excludes a fermiophobic Higgs bosons with masses $<$ 112.9 GeV





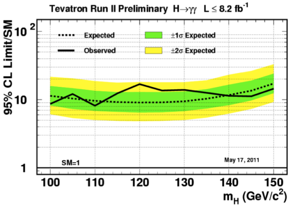
Tevatron Combination

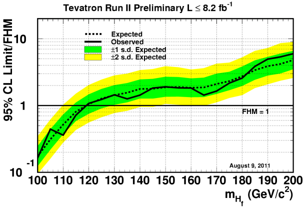
SM Combination

- Observed at 120: 16.9 $\times$ SM
- Expected at 120: 9.1 $\times$ SM
- Combination significantly extends the sensitivity of the separate CDF/D0 results

Fermiophobic Combination

- Excludes fermiophobic Higgs boson with masses $<$ 119 GeV





The diphoton Analysis at CDF with full data set

- The full data set (10 fb^{-1}) is almost ready
- Will update both analyses, SM and fermiophobic Higgs
- Time scale: end of the year
- Possible Improvements
  - Add NN selection using some distinct kinematics of the Higgs (a la D0)
  - NN Plug photon ID

Conclusion

- Showed results of diphoton resonance search with many improvements
  - NN on central photon ID (9%)
  - Conversion (13%)
  - Added more p_T bins in Fermiophobic case (15%)
- No excess was seen, so we set limits

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