Higgs Searches at the Tevatron

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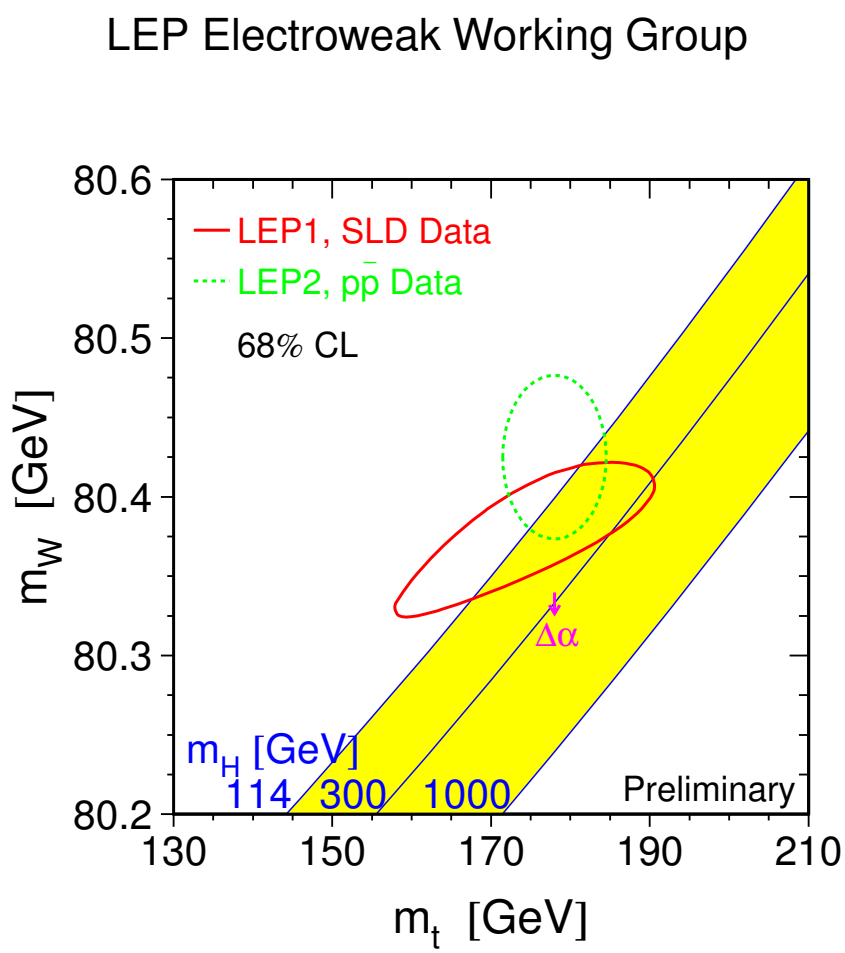
Outline:

- Introduction.
- SM Higgs Results.
- Non-SM Higgs Results.
- Summary.

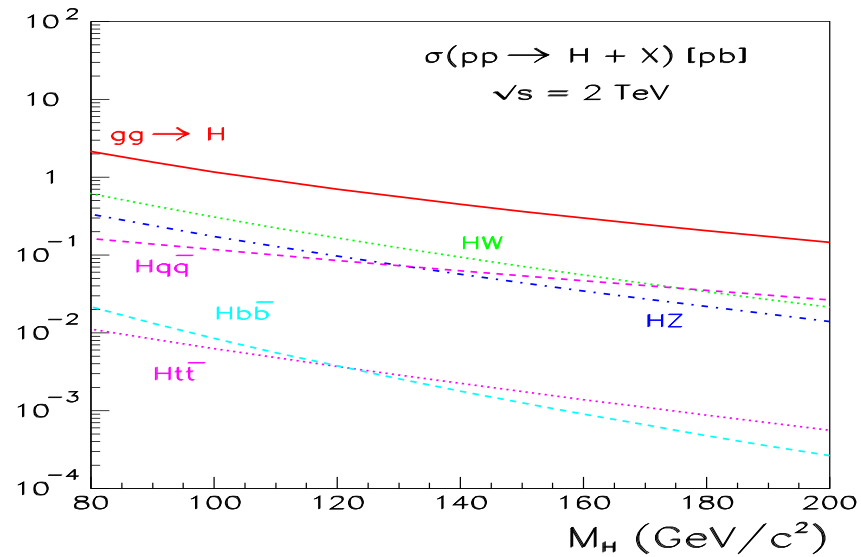
Indirect Constraints

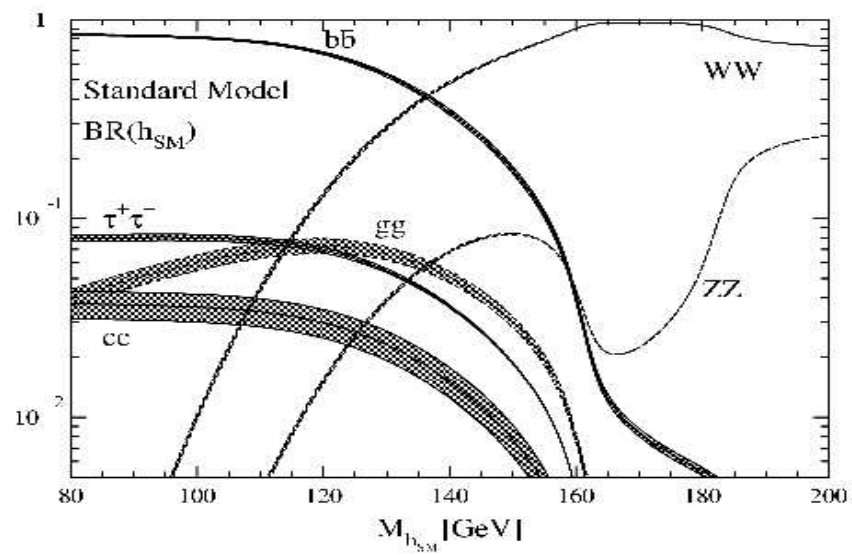
- Tevatron experiments can set indirect constraints on the Higgs mass via precision measurements of the W boson and top quark masses.
- Not the focus of this talk.



Standard Model Higgs

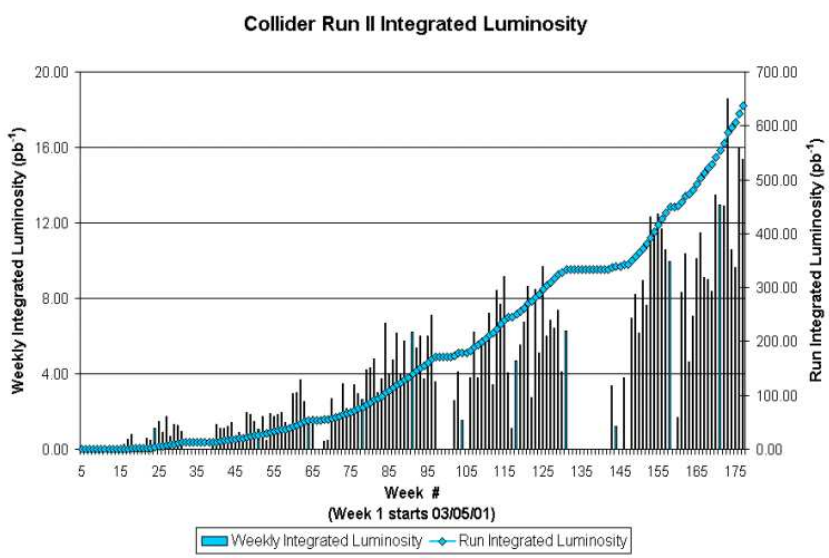
- For $m_H \lesssim 140$ GeV:
  - $H \to b\bar{b}$ dominates.
  - $gg \to H$ hopeless due to QCD background.
  - Look for associated W/Z production with leptonic decays.
- For higher masses:
  - $H \to WW$ dominates.
  - Can look for $gg \to H \to WW$.
- Cross section ~ 0.1 pb.
- Other channels:
  - $Hb\bar{b}$, $Ht\bar{t}$ have spectacular signatures, but $\sigma \sim 5$ fb.
- SM extensions may enhance $hb\bar{b}$, $H \to \gamma\gamma$.



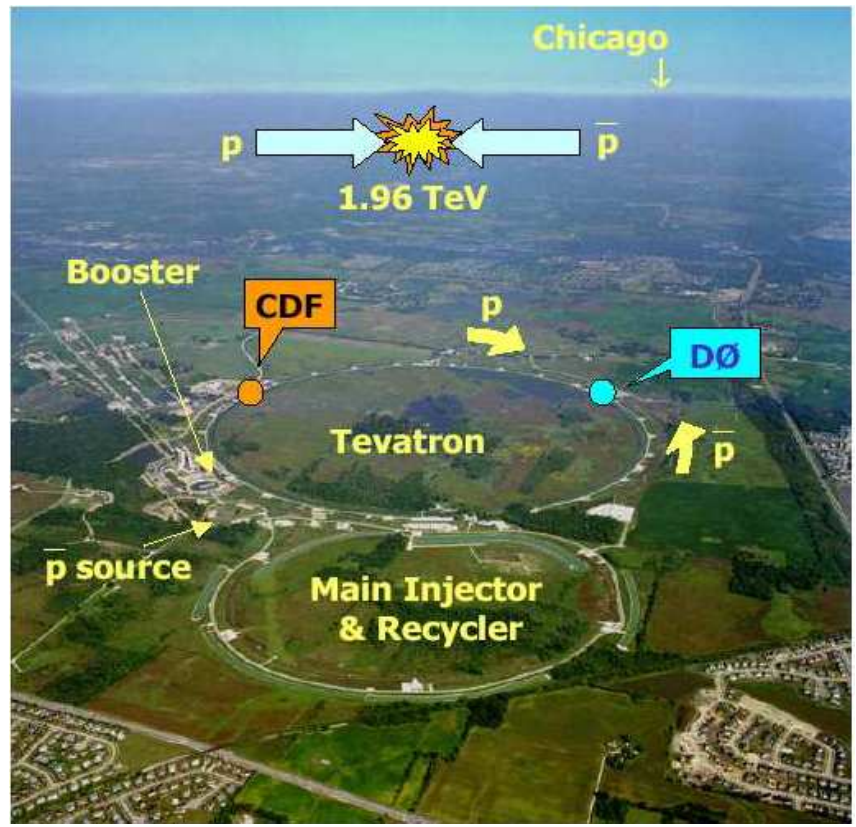


Fermilab Tevatron

- Until the LHC turns on, this is the only place in the world capable of probing the Higgs sector.
- Collides p on $\bar{p}$ at $\sqrt{s} = 1.96$ TeV.
- Bunch spacing: 396 ns. (36x36 bunches)
- Peak luminosity: 80–100×10^{30}.

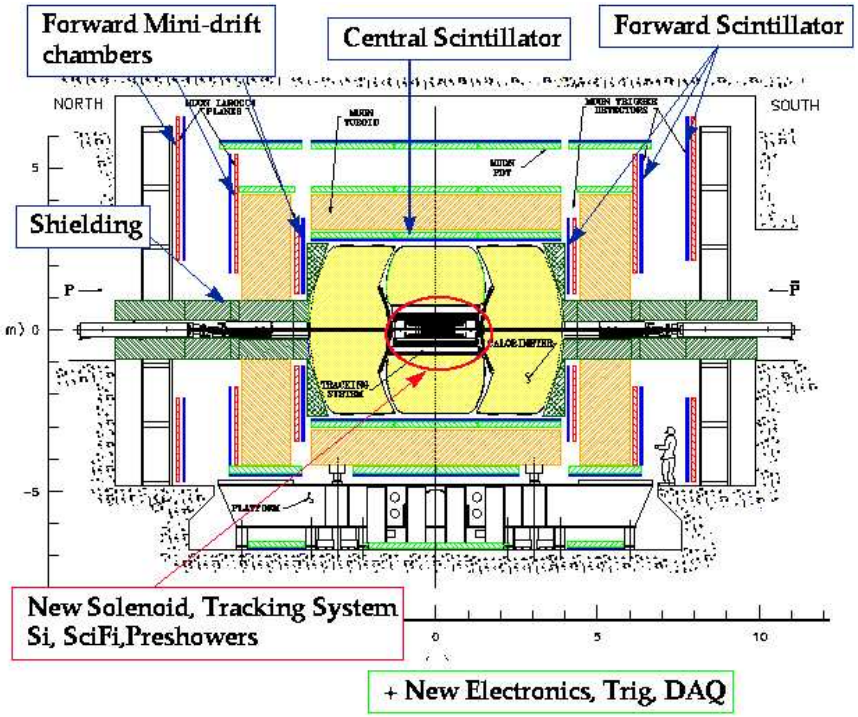


- Exceeded luminosity goals for 2004!
- Total delivered: $> 600\,\text{pb}^{-1}$.

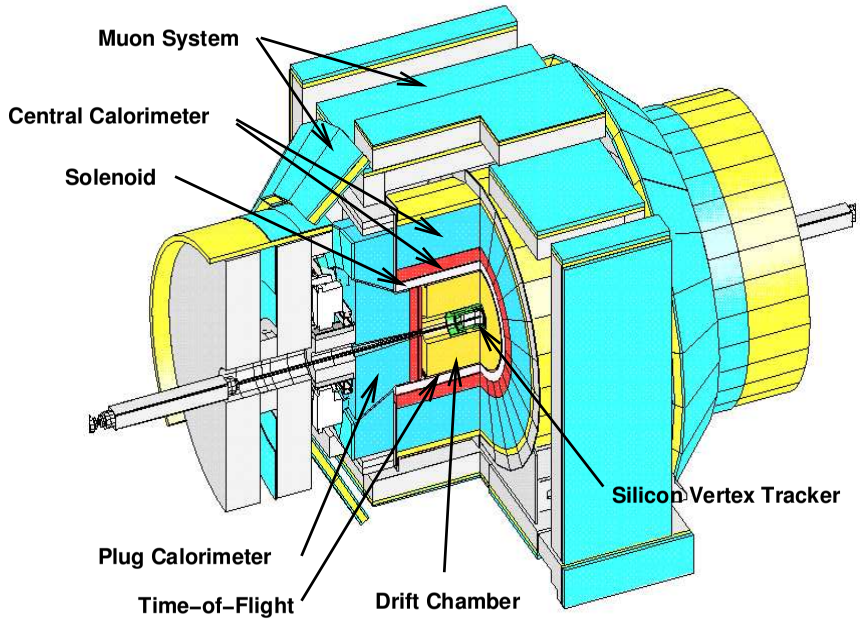


Tevatron Experiments

DØ

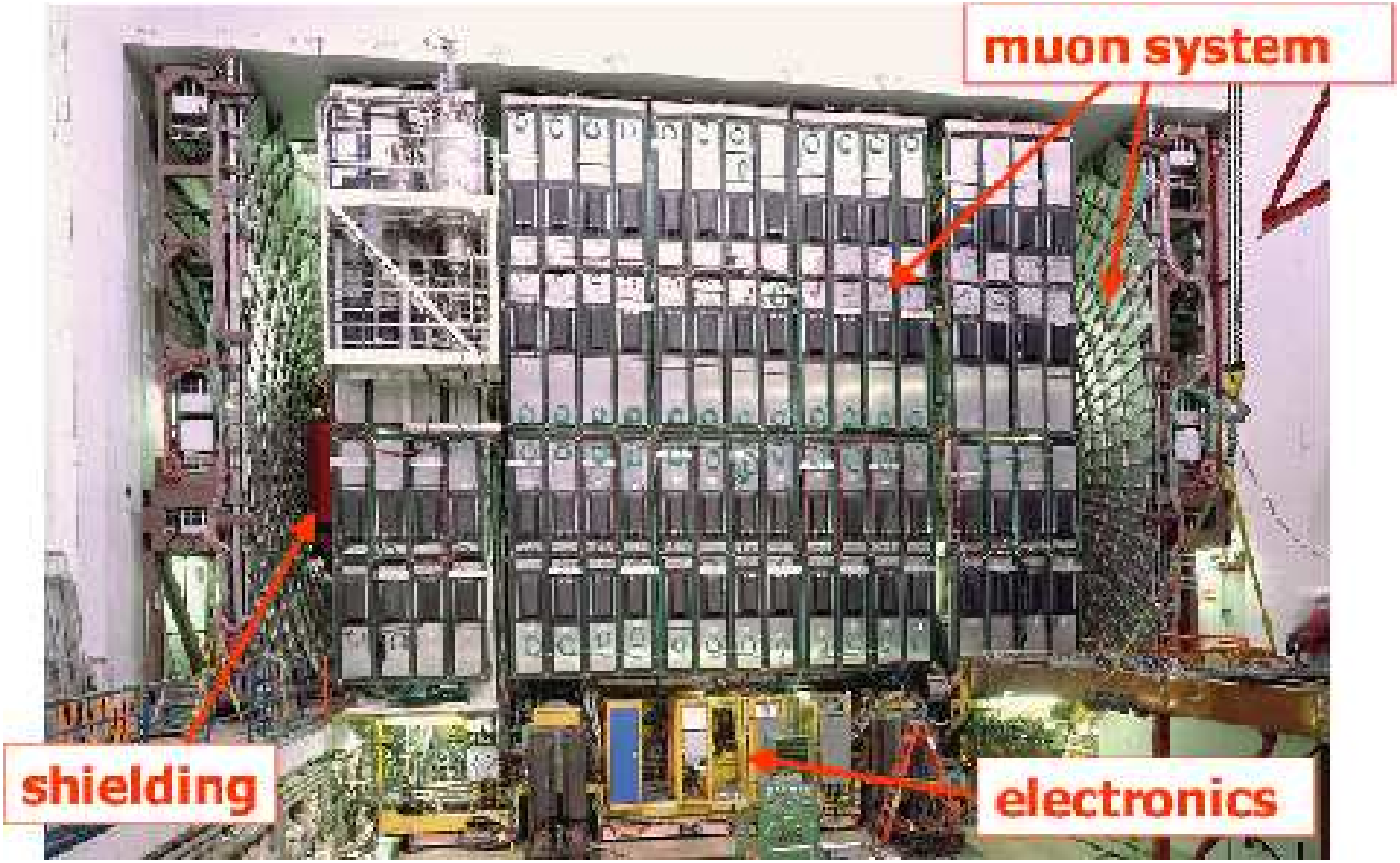


CDF



Both feature: tracking in central B-field, silicon vertex tracker, outer tracking, calorimetry, muon system.

DØ



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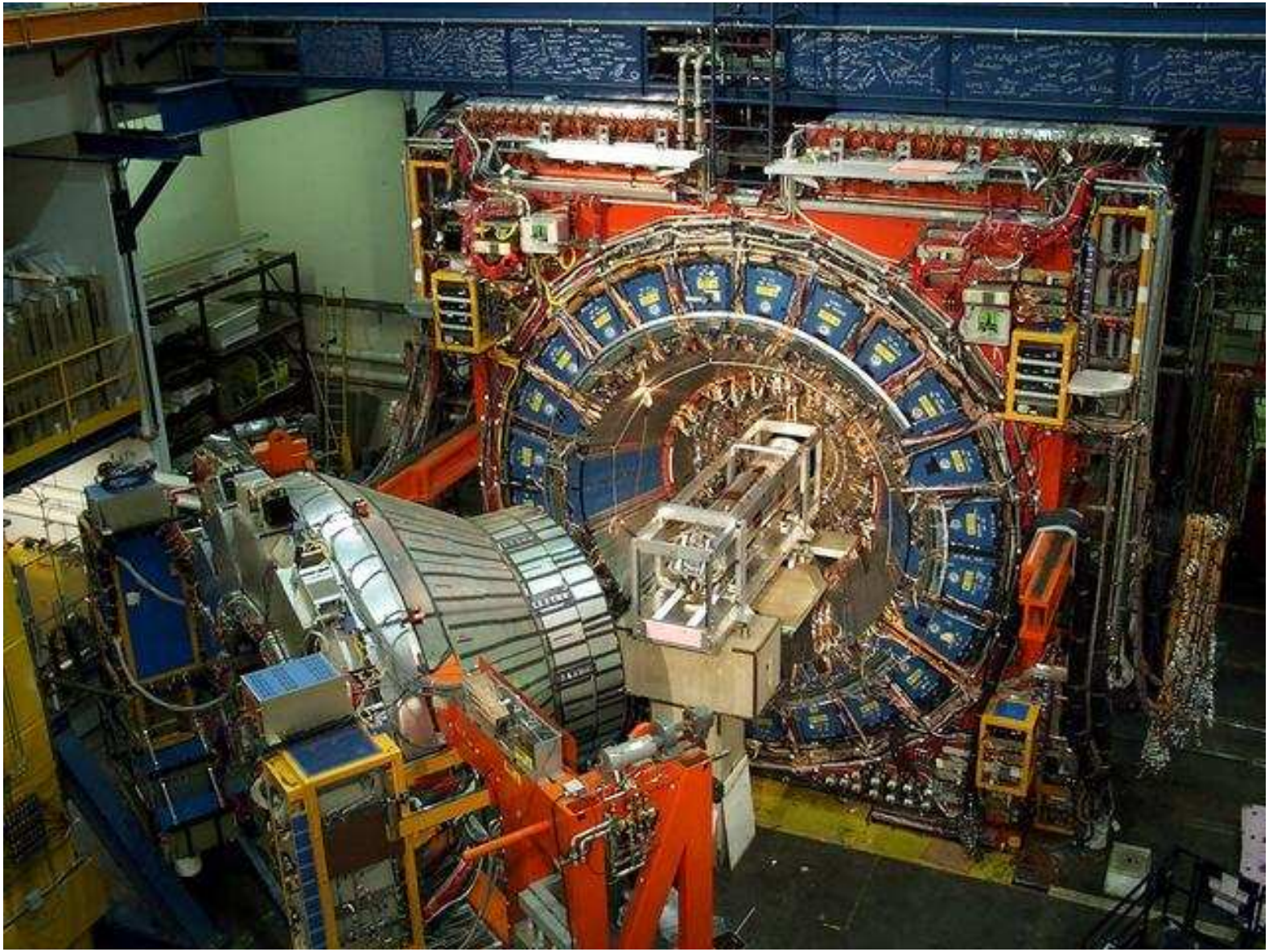
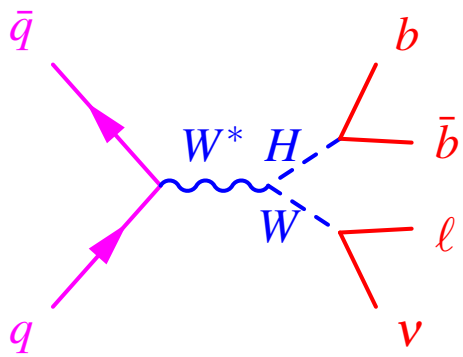


$WH \to \ell\nu b\bar{b}$

Signal



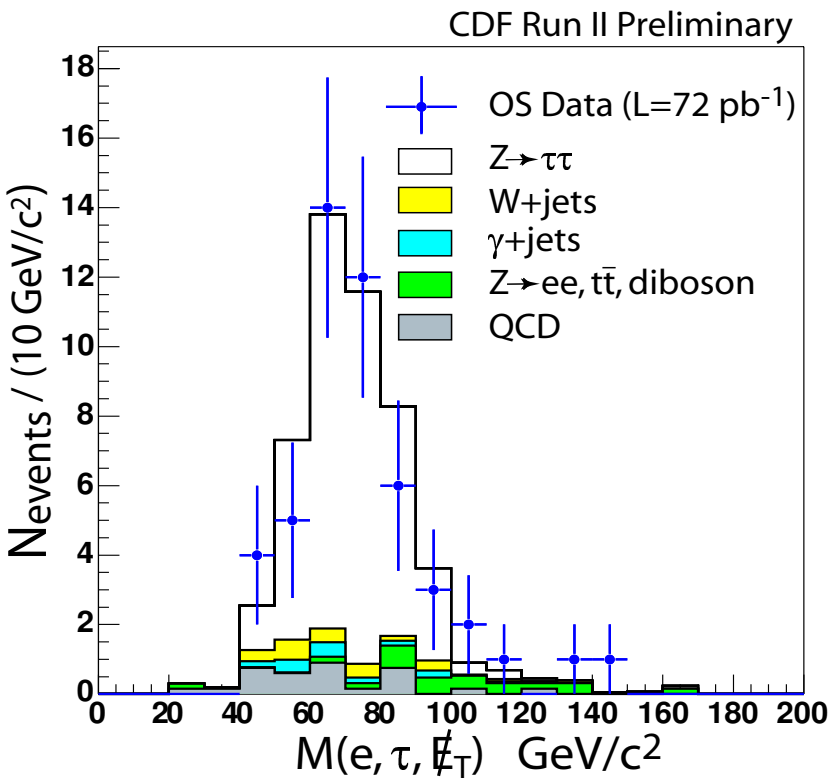
- "Golden" channel for the Tevatron experiments.
- Final state:
  - High-p_T lepton.
  - Large $\not{E}_T$.
  - Two b-jets.
- Essential capabilities:
  - Good, efficient lepton ID.
  - b-tagging.
  - $m(b\bar{b})$ resolution.

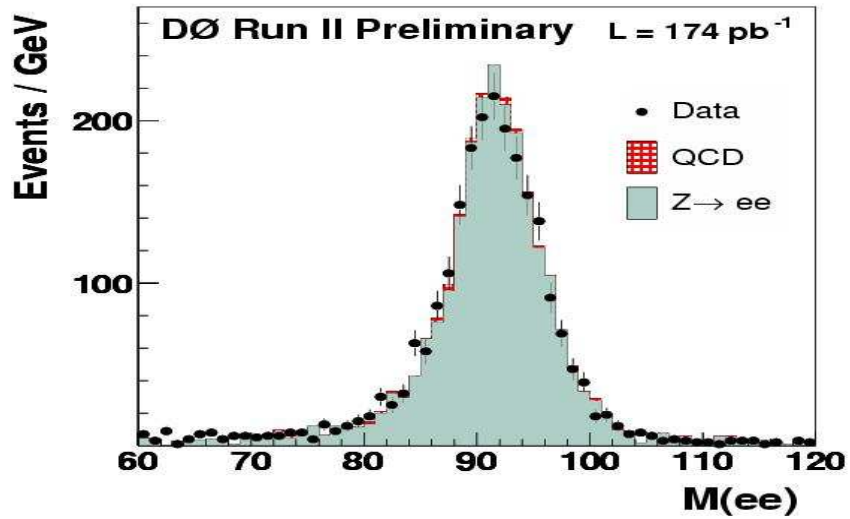
Backgrounds

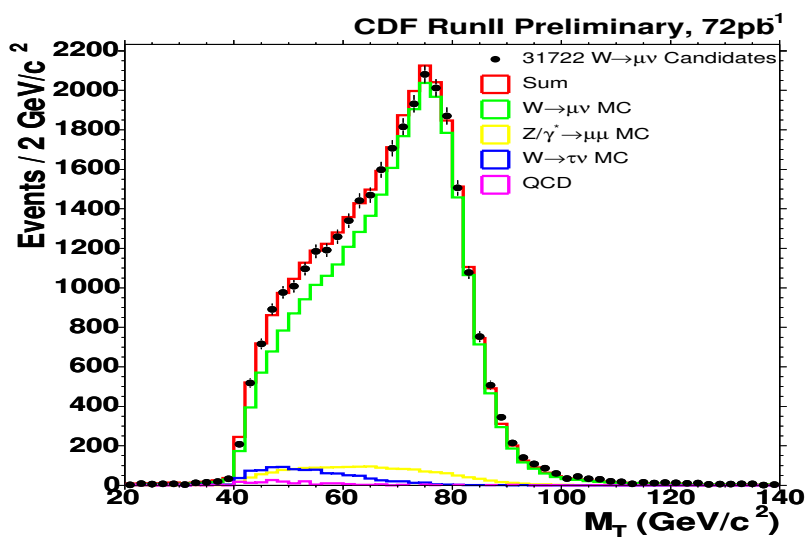
- Light quark production: $p\bar{p} \to jjj \ldots$
- Heavy flavor production: $p\bar{p} \to b\bar{b}j \ldots$
- $W+$ light jets: $p\bar{p} \to Wjj$
  - Suppress with lepton, $\not{E}_T$, b-tagging cuts.
- $t\bar{t}$: $p\bar{p} \to \ell\nu q\bar{q}b\bar{b}$, $p\bar{p} \to \ell\nu\ell\nu b\bar{b}$.
  - $\uparrow$ A significant background!
  - Veto on extra leptons or jets.
- $Wb\bar{b}$ ($Wc\bar{c}$) $\leftarrow$ Major background!
- $p\bar{p} \to t\bar{b} \to \ell\nu b\bar{b}$
- $p\bar{p} \to WZ \to \ell\nu b\bar{b}$
  - Look for $m(b\bar{b})$ mass peak.
  - Other event kinematics.

Lepton ID

- Examples of $W/Z \rightarrow$ lepton plots for e, μ, and τ.

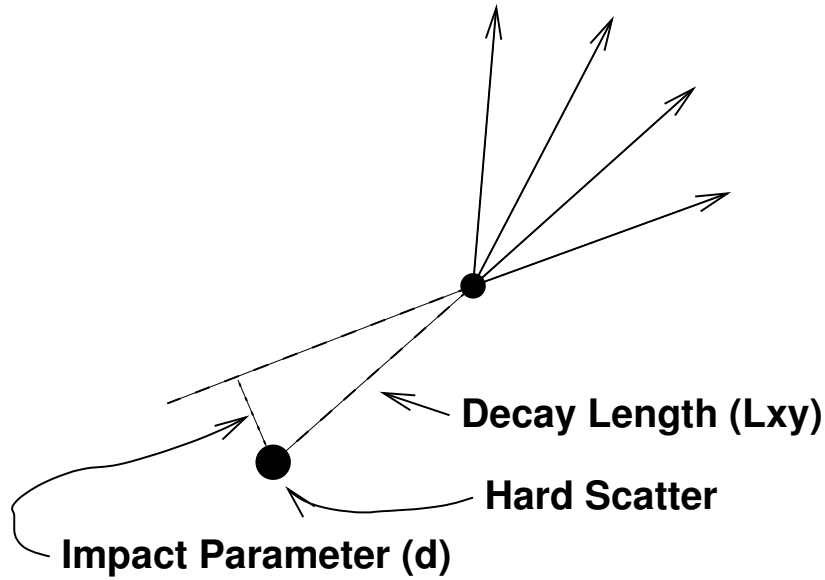






B tagging

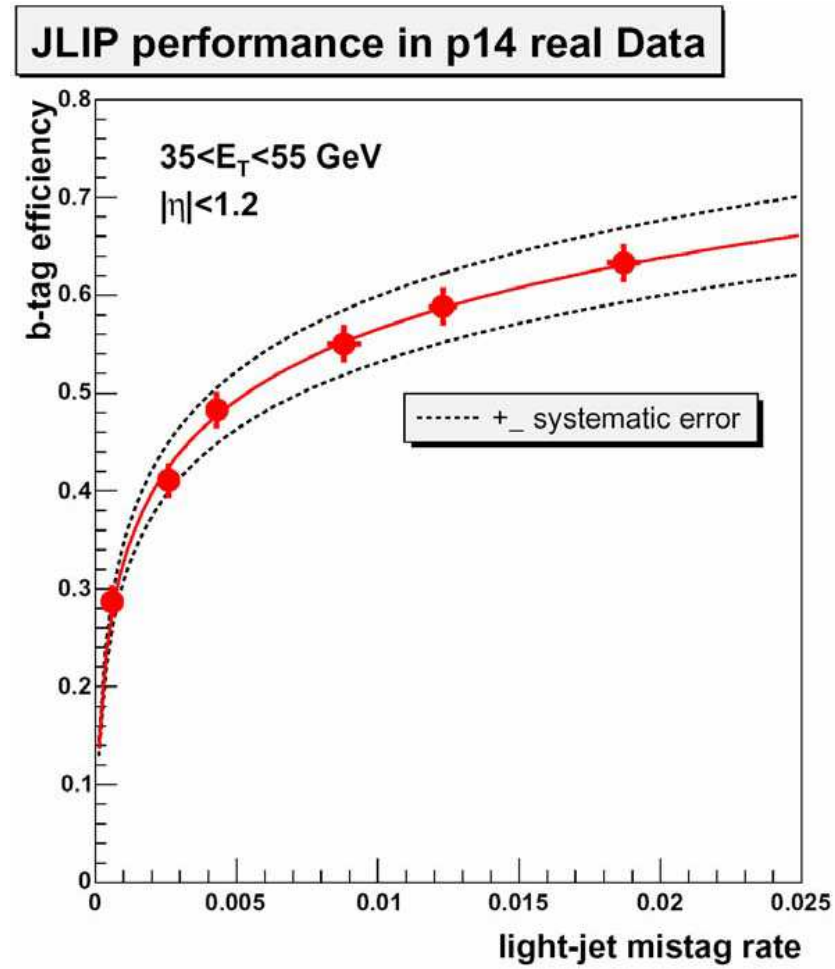
- Being able to identify jets containing b quarks is essential for many Higgs analyses.
- E.g., separate $Wb\bar{b}$ from Wjj.
- Can look for semileptonic b decays: $b \to (e/\mu)\nu c$, but branching ratio is low and leptons are soft.
- B mesons have a relatively long lifetime.
- Travel about ~ 1 mm before decaying.
- Decay gives ~ 4 charged tracks.
- Look for tracks or vertices displaced from primary vertex.



- Important parameters:
  - Impact parameter resolution: $d/\sigma(d)$.
  - Decay length resolution: $L_{xy}/\sigma(L_{xy})$
- Numerous tagging algorithms have been developed by both experiments.

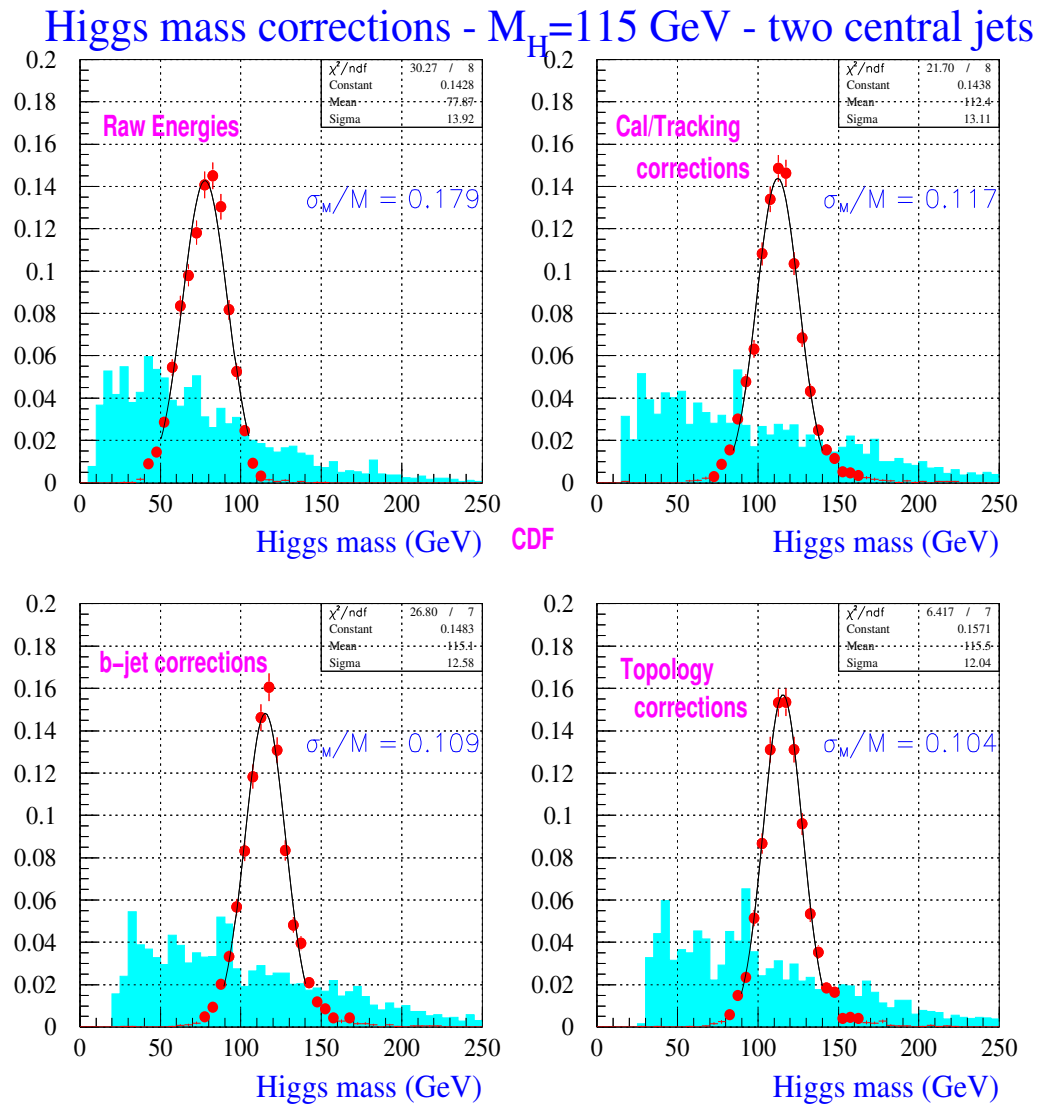
B tagging

- Example: DØ JLIP algorithm.
- Jet Lifetime Impact Parameter.
- Uses impact parameter significance.
- Tabulate $P_{\mathrm{PV}}(d/\sigma(d))$.
  - Probability for track to come from primary vertex, as a function of impact parameter significance.
  - Bin according to p_T, number of hits, etc.
- Combine probabilities for all tracks in a jet.
- Typical performance (for jets with good tracks):
  - $\sim 50\%$ tagging efficiency
  - For $\sim 0.5\%$ mistag rate.



Dijet Resolution

- Common element in many Higgs analyses: $h \to b\bar{b}$.
- Want to be able to reconstruct Higgs mass peak in $m(b\bar{b})$ to discriminate against background.
- $m(b\bar{b})$ is one of the most powerful variables available!
- Dijet mass resolution is important.
  - Improving resolution from 12% to 10% is equivalent to a 20% luminosity difference.
- Right: CDF studies on central jets.
- $\sim 10\%$ seems achievable.



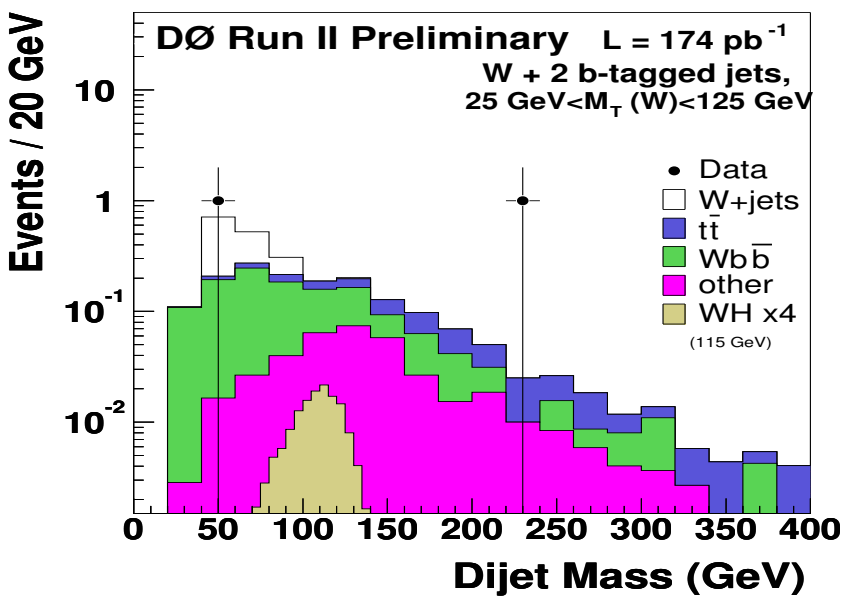
$WH \to \ell\nu b\bar{b}$ results

Both: Large lepton p_T, $\not{E}_T$, jet E_T. Exactly two jets.

DØ

$\ell \equiv$ electrons only $\quad 25 < M_T^W < 125$

Two b-tags



Observed	2
Background	0.9 ± 0.4
Expected WH (m_H=115)	0.03 ± 0.1

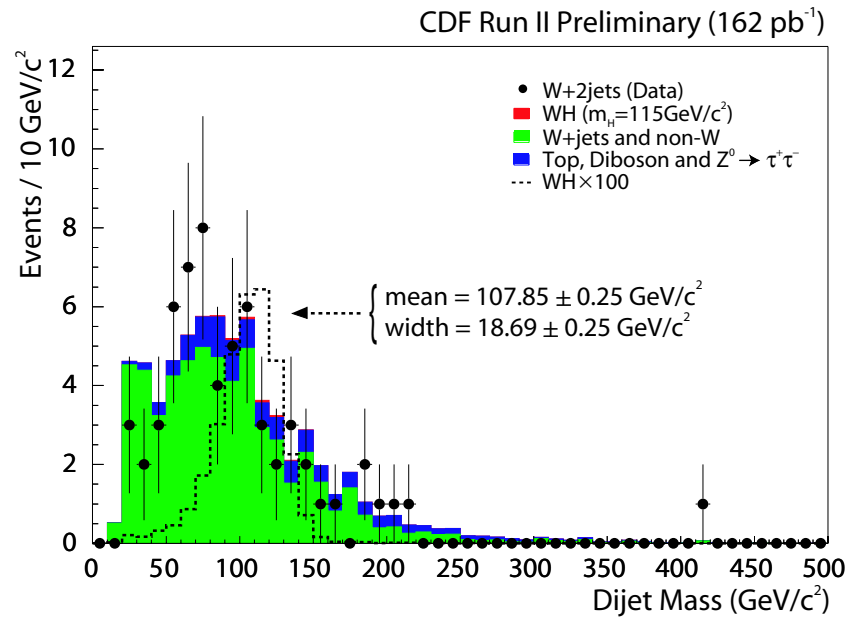
$\sigma(WH) \times B(H \to b\bar{b}) < 12.4$ pb @ 115

$\sigma(Wb\bar{b}) < 20.3$ pb

CDF

$\ell \equiv e$ or μ $\quad$ Extra lepton veto

One b-tag

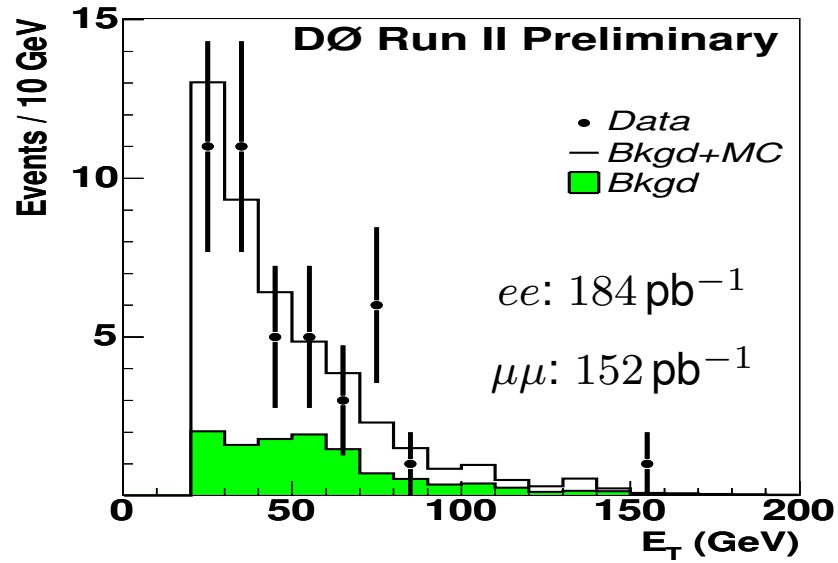


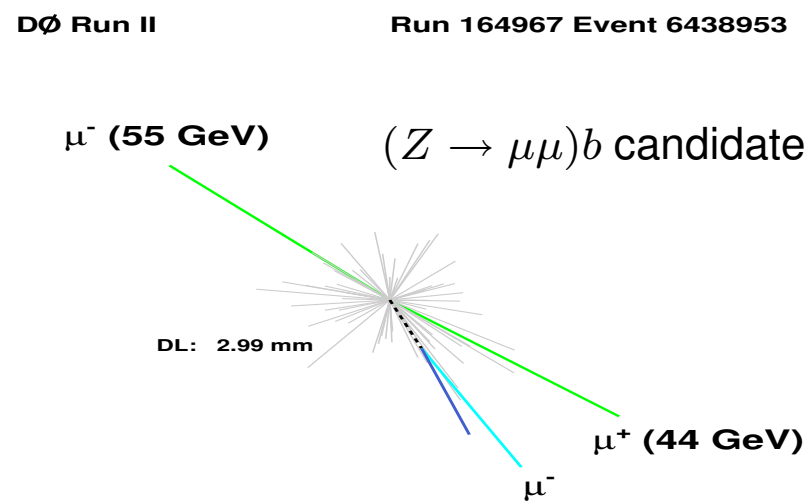
Observed	62
Background	60.55 ± 4.43
Expected WH (m_H=115)	0.29

$\sigma(WH) \times B(H \to b\bar{b}) < 5$ pb @ 115

$(Z \to ee/\mu\mu)b$ Studies

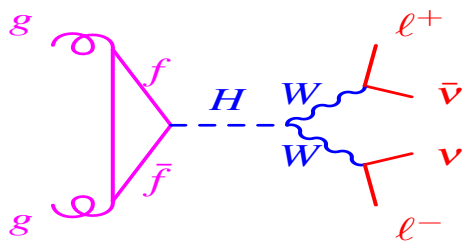
- Measure the ratio $(Z+b)/(Z+j)$.
  - Study backgrounds for ZH.
  - Probe PDF of b-quarks.
- Signature:
  - Two isolated, high-p_T leptons.
  - Dilepton mass near m_Z.
  - Jet $E_T > 20$ GeV and $|\eta| < 2.5$.
- Backgrounds estimated from data.
  - QCD fakes and mistags.
- Systematics:
  - b-tagging efficiency: 16%.
  - Jet energy scale: 10%.
  - Background estimation: 6%.
- Result:
  - $\sigma(Z+b)/\sigma(Z+j) = 0.024 \pm 0.005(\text{stat})^{+0.005}_{-0.004}(\text{syst})$
- Agrees with NLO calc ~ 0.02 (`hep-ph/0312024`).



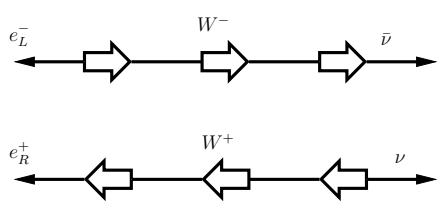


$(Z \to \mu\mu)b$ candidate

$H \to WW^*$

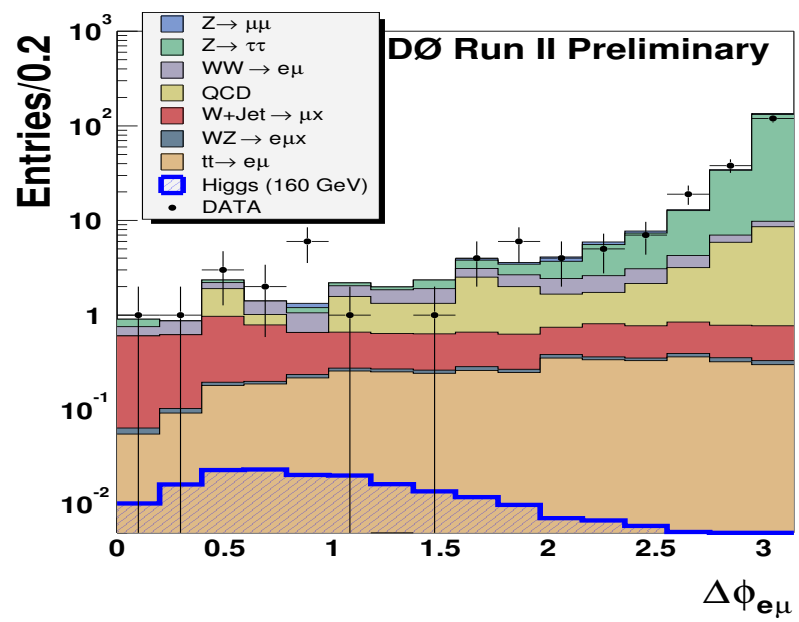


- Best mode at the Tevatron for $m_H >\sim 140$ GeV.
- Signature:
  - Two isolated, high-p_T leptons.
  - Large $\not{E}_T$.
  - Small jet activity.
- Spins of W's are correlated; leptons tend to go in the same direction.
  - Small $m(\ell\ell)$.
  - Small $\Delta\phi(\ell\ell)$.



- Backgrounds:
  - Electroweak WW production.
  - $Z/\gamma \to \ell\ell$ with mismeasured $\not{E}_T$.
  - $W + \text{jets}$ with fake lepton.
  - ZZ, WZ.

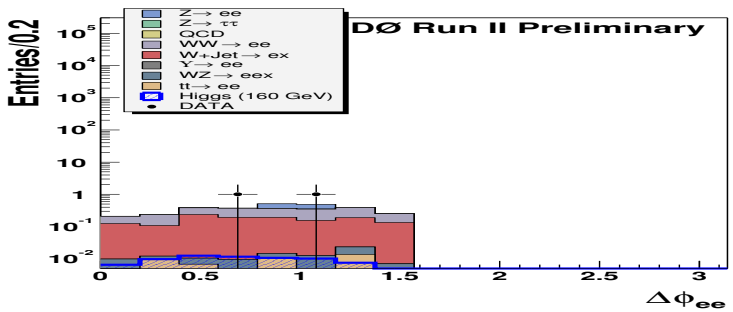
DØ $e\mu$ channel: $158\,\text{pb}^{-1}$
After lepton preselection only

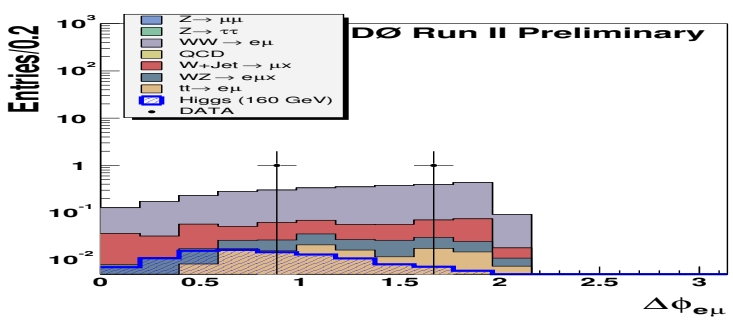


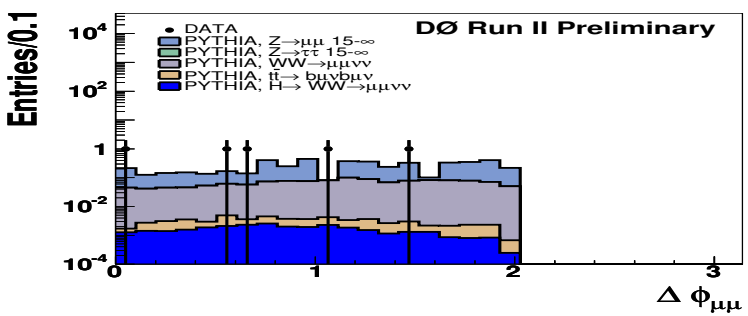
$H \to WW^* \to ee, e\mu, \mu\mu$

DØ

- Channels separate: $\sim 160\,\text{pb}^{-1}$.
- $\Delta\phi(ee) < 1.5$, $\Delta\phi(e\mu/\mu\mu) < 2.0$.

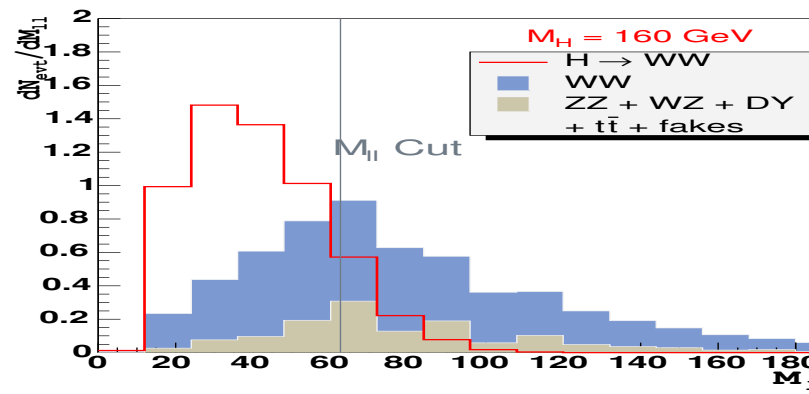




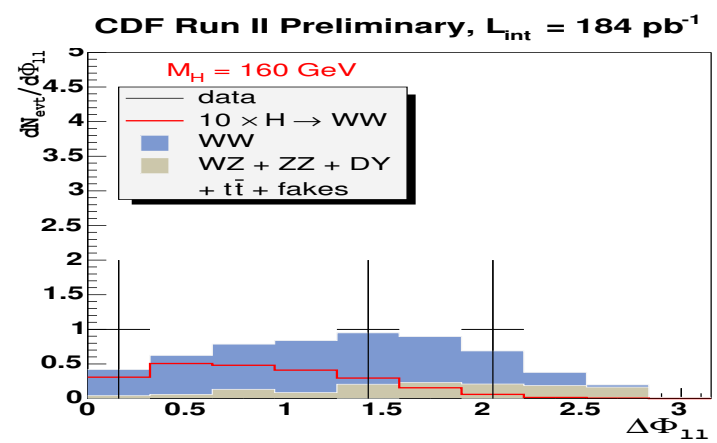


CDF

- Channels combined: $\sim 184\,\text{pb}^{-1}$.
- $m(\ell\ell) < m_H/2$.



- Fit $\Delta\phi(\ell\ell)$ to get limit.



$H \to WW^*$ Results

DØ

	ee	$e\mu$	$\mu\mu$
Observed	2	2	5
Expected	2.7 ± 0.4	3.1 ± 0.3	5.3 ± 0.6

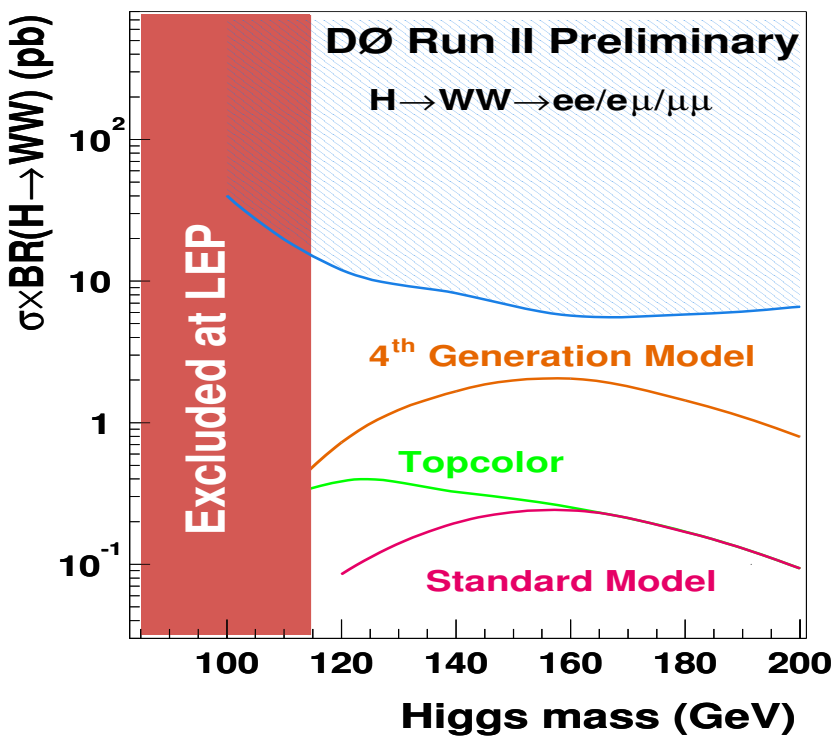
$\sigma \times B(H \to WW) < 5.7\,\text{pb}$

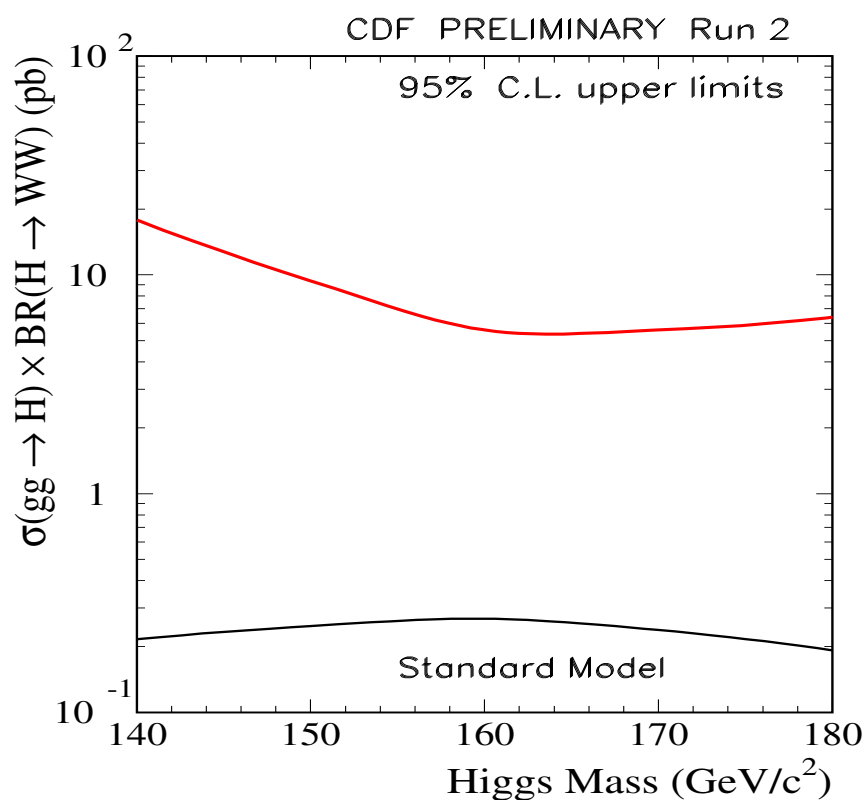
CDF

	All
Observed	3
Expected	5.8 ± 0.6

$\sigma \times B(H \to WW) < 5.6\,\text{pb}$

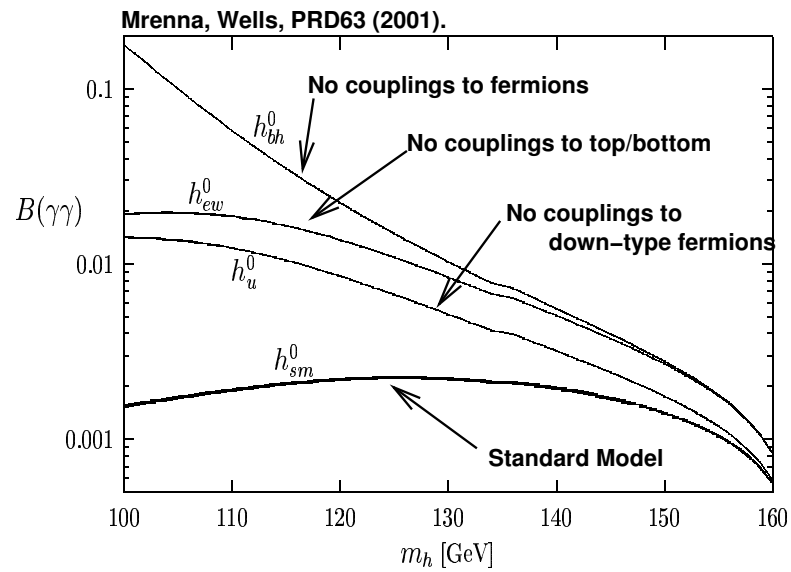
$\leftarrow m_H = 160 \rightarrow$





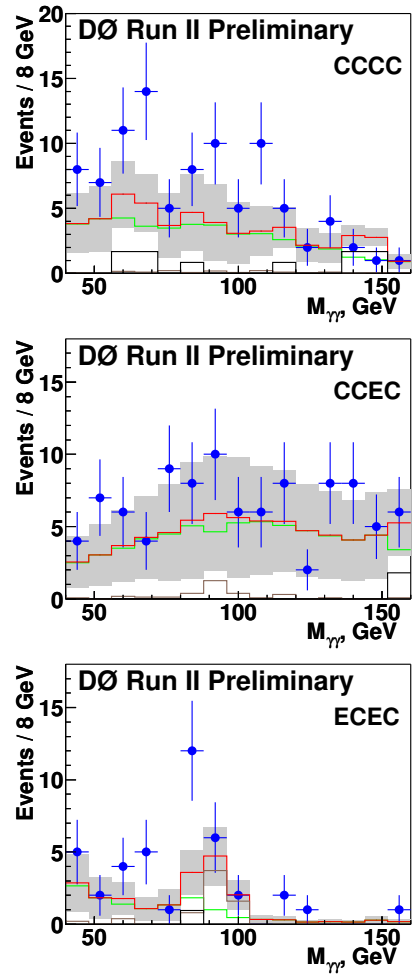
Higgs Decays to γ Pairs

- The branching ratio of $H \to \gamma\gamma$ in the Standard Model is very small.
  - 10^{-3}–10^{-4}.
  - Not feasible for the Tevatron.
- Some extensions to the Standard Model predict suppressed coupling of Higgs to various classes of fermions.
  - Fermiophobic Higgs (no coupling to any fermions).
  - Topcolor (the only fermion the Higgs couples to is the top quark).
- With other decay modes suppressed, $H \to \gamma\gamma$ is enhanced.



Search for $H \to \gamma\gamma$

- DØ analysis from $\sim 191\,\text{pb}^{-1}$.
- Require two photons > 25 GeV.
  - Isolated EM clusters with no associated tracks.
  - Shower shape cuts.
- $p_T(\gamma\gamma) > 35$ GeV.
- Classify events based on location of photon candidates:
  - CC: Central calorimeter.
  - EC: Endcap calorimeter.
- Data shown on right.
  - Blue: Data
  - Red: Total SM expectation
  - Gray: SM expectation error band
  - Green: QCD background
  - Brown: Drell-Yan $Z/\gamma \to ee$
  - Black: Direct $\gamma\gamma$.



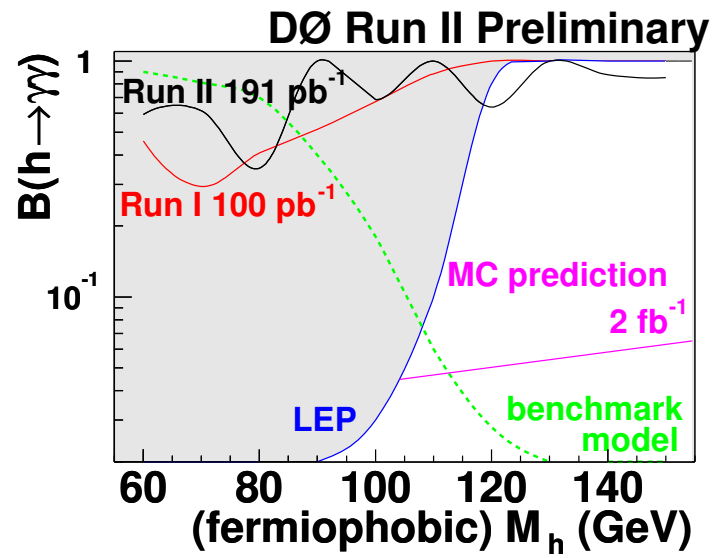
data = 93.0
bkgd = 52.4 +- 28.0
QCD = 42.7 +- 28.0
DY = 1.4 +- 1.3
$\gamma\gamma$ = 8.3 +- 0.6

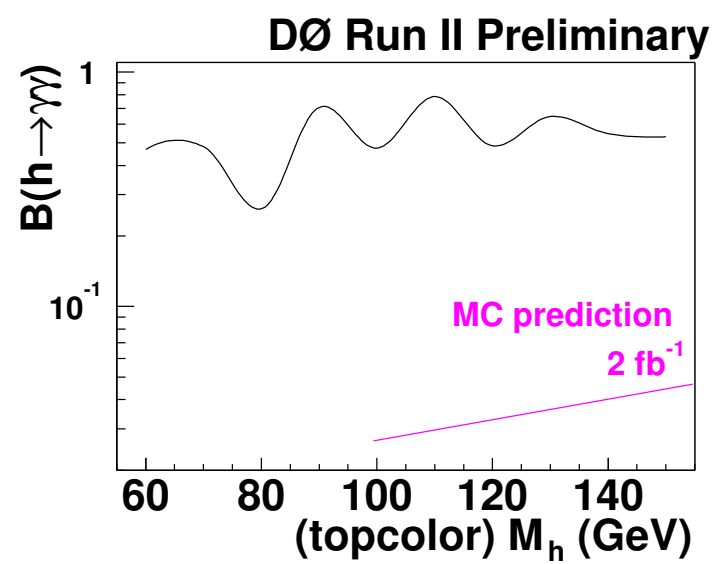
data = 97.0
bkgd = 68.8 +- 45.8
QCD = 64.0 +- 45.7
DY = 3.0 +- 3.0
$\gamma\gamma$ = 1.8 +- 0.1

data = 41.0
bkgd = 20.8 +- 10.4
QCD = 13.1 +- 10.0
DY = 6.7 +- 3.0
$\gamma\gamma$ = 1.0 +- 0.1

Search for $H \to \gamma\gamma$: Results

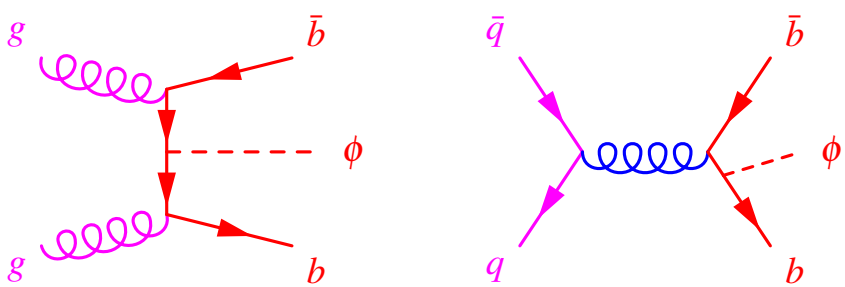
- Use CC-CC and CC-EC events.
- Make final mass window cut in $m(\gamma\gamma)$.
- Varies with m_H.
- Width varies:
  - ~ 6 GeV for $m_H = 60$.
  - ~ 10 GeV for $m_H = 150$.
- Derive 95% limits for fermiophobic and topcolor scenarios.
- Results:
  - Black: Branching ratio limit.
  - Green: One particular model.
  - Magenta: Expected Tevatron exclusion limit for $2\,\text{fb}^{-1}$.



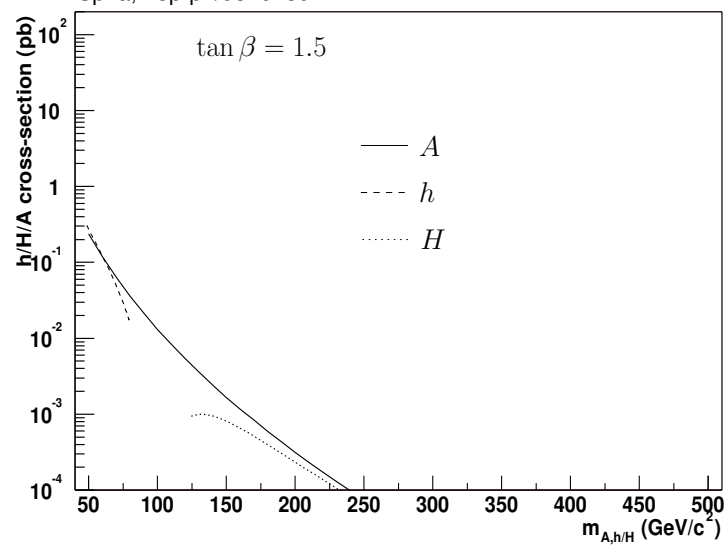


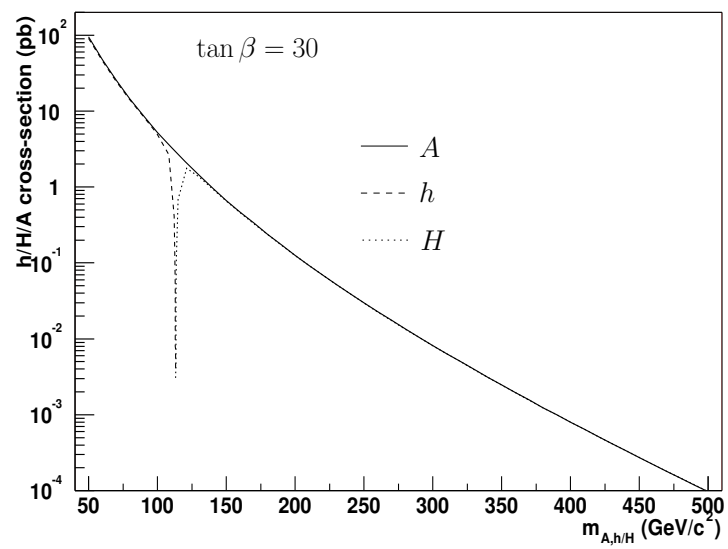
MSSM Higgs

- In supersymmetric models, there are five physical Higgs scalars:
  - CP-even: h, H.
  - CP-odd: A.
  - Charged: $H^{\pm}$.
- Two free parameters:
  - One Higgs mass.
  - $\tan\beta$
- For neutral scalars $\phi \equiv h/H/A$, $b\phi$ coupling is enhanced by $\tan\beta$.
- Look for $\phi b\bar{b}$ production, with $\phi \longrightarrow b\bar{b}$.



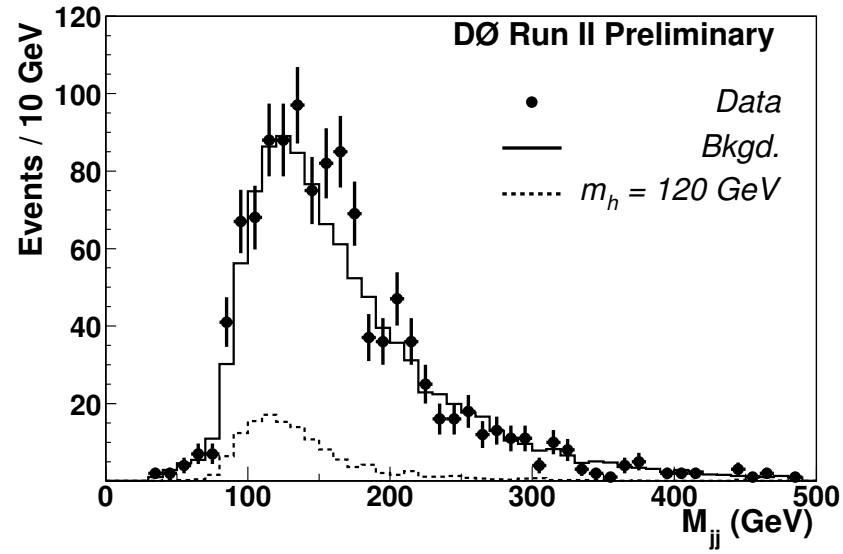
Spira, hep-ph/9810289.

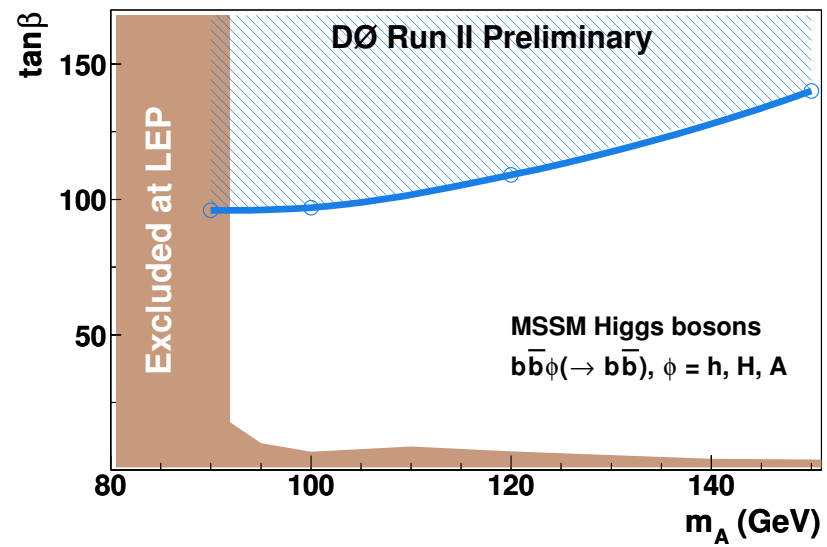




DØ MSSM Higgs Search

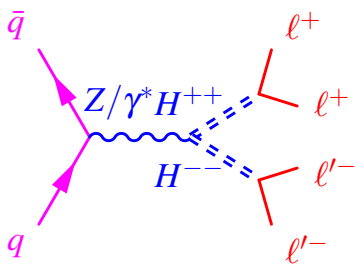
- Data: $\sim 131\,\text{pb}^{-1}$.
- Require at least 3 b-tagged jets.
- Jet E_T, $|\eta|$ cuts and maximum jets allowed depend on m_H.
- At $m_H = 100$:
  - Jet $E_T > 40, > 35, > 15$.
  - $|\eta| < 2.5$.
  - $N_j <= 4$.
- Backgrounds:
  - QCD light jets.
  - QCD $b\bar{b}j$, $c\bar{c}j$.
  - $b\bar{b}b\bar{b}$, $(Z \to b\bar{b})j$, $t\bar{t}$.
- Plot $m(jj)$ for leading two jets and fit to sum of signal and background.
- Set 95% C.L. limit.

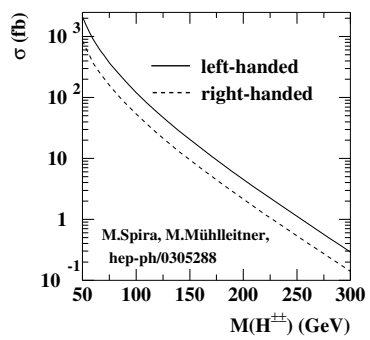




Doubly-charged Higgs

- Some models predict doubly-charged Higgs bosons: H^{++}, H^{--}.
  - Example: L-R symmetric model.
  - Model has parity symmetry at high energies.
  - Parity nonconservation appears at low energies via SSB.
  - Requires Higgs triplet.
- Production at Tevatron via Z/γ^*:

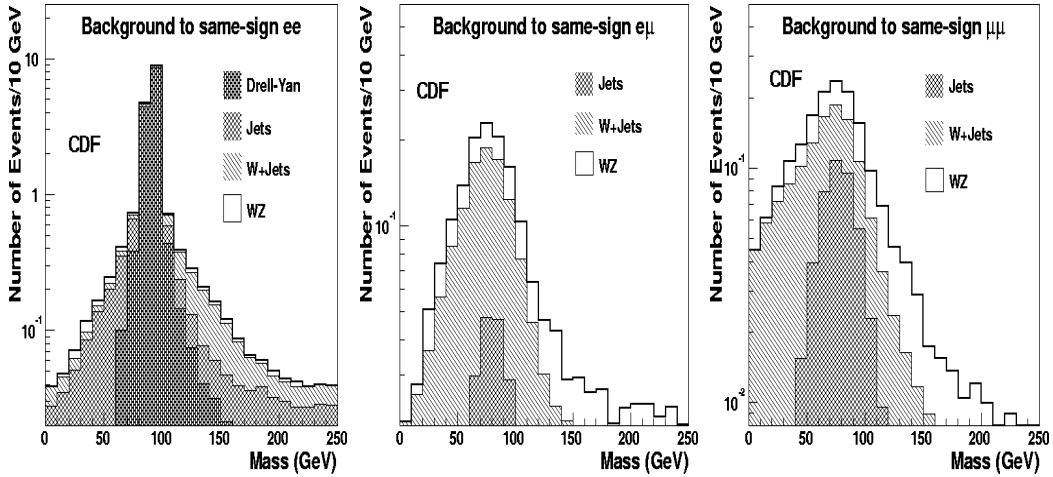


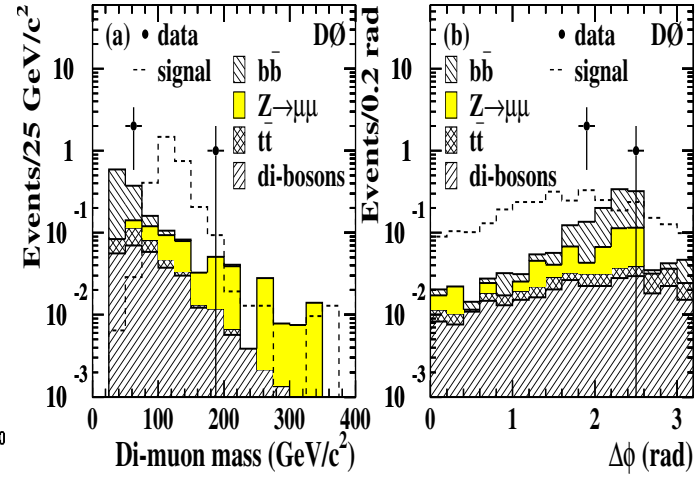


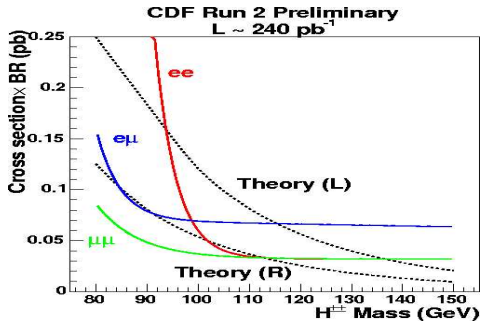
- Decays for $m(H^{++})$ likely to be dominantly like-sign lepton pairs.
- Branching ratios not well constrained.

- Look for like-sign lepton pairs.
  - ee, $e\mu$, $\mu\mu$.
- High-p_T.
- Isolated.
- Backgrounds:
  - $b\bar{b}$
  - $W + \text{jets}$
  - $Z \to \ell\ell$
  - WZ, WW
  - $t\bar{t}$

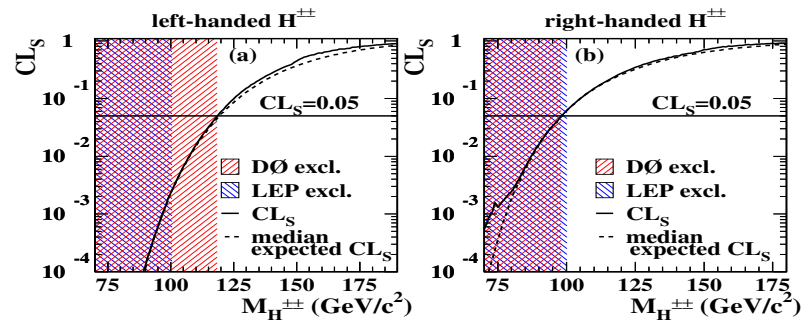
Doubly-charged Higgs Results





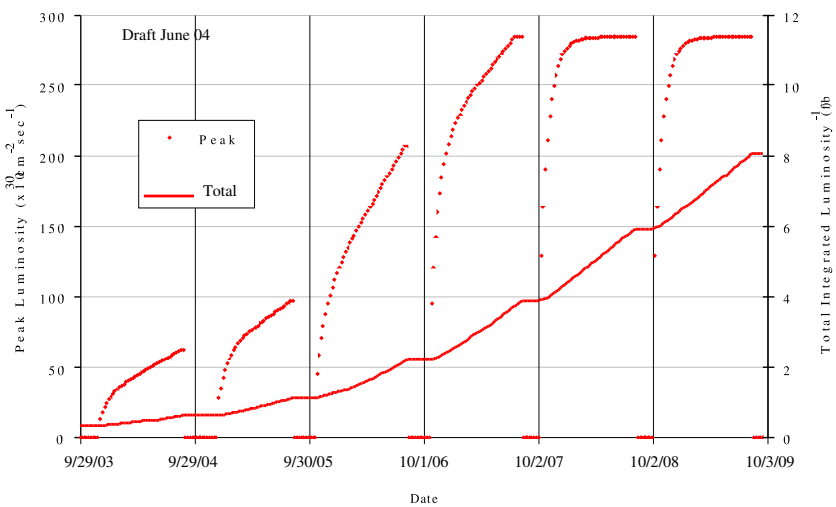


← CDF
DØ→



	CDF: $240\,\text{pb}^{-1}$ $m(\ell\ell) > 80$				DØ: $113\,\text{pb}^{-1}$			
	Bkg	Data	$m(H_L^{++})$	$m(H_R^{++})$	Bkg	Data	$m(H_L^{++})$	$m(H_R^{++}$
ee	$1.5^{+0.9}_{-0.6}$	0	> 133					
$\mu\mu$	$0.8^{+0.5}_{-0.4}$	0	> 136	> 113	1.5 ± 0.4	3	> 118.4	> 98.2
$e\mu$	0.4 ± 0.2	0	> 115					

Long-term Higgs Sensitivity

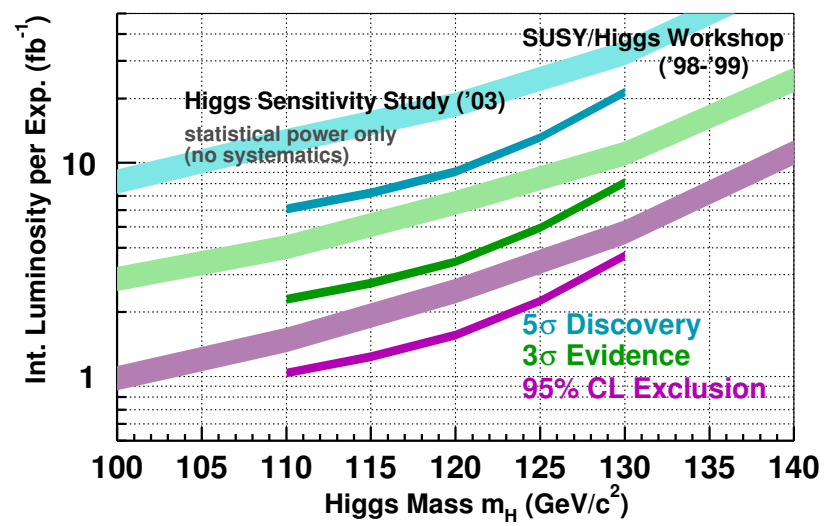


- Base projection:
  Exclude 115–130.
  3σ evidence up to ~ 120–125.
- Design projection:
  3σ evidence up to ~ 130.
  5σ discovery up to ~ 115–120.
- Caveat: Study assumed upgrades of vertex detectors (now canceled).

- Accelerator luminosity projections:
  - $\sim 8\,\text{fb}^{-1}$ by end of 2009 for design (challenging) projection.
- Base projection (conservative):
  - Allowing for schedule slippage and underperformance.

  $\sim 4\,\text{fb}^{-1}$ by end of 2009.

Tevatron Higgs Sensitivity Study 2003:



Summary

- Only a couple hundred pb^{-1} analyzed so far.
- About half of what's been recorded.
- Results so far focused on
  - Understanding detector response.
  - Understanding background processes.
- Tevatron can already set competitive limits for some non-SM processes.
- Tevatron is performing better than predicted for 2004.
- Data will keep accumulating.

- SM Higgs is very challenging to find. But if performance projections hold, we'll have sensitivity to interesting range of Higgs masses.

References

- CDF results:
  `http://www-cdf.fnal.gov/physics/exotic/exotic.html`
- DØ results:
  `http://www-d0.fnal.gov/Run2Physics/WWW/results/HIGGS/higgs.htm`
- 2003 Higgs Sensitivity Study:
  `http://www-d0.fnal.gov/Run2Physics/higgs_sensitivity_study.html`
- 2000 Higgs Working Group Report:
  `hep-ph/0010338`