The Search for the Higgs at the Tevatron

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on behalf of

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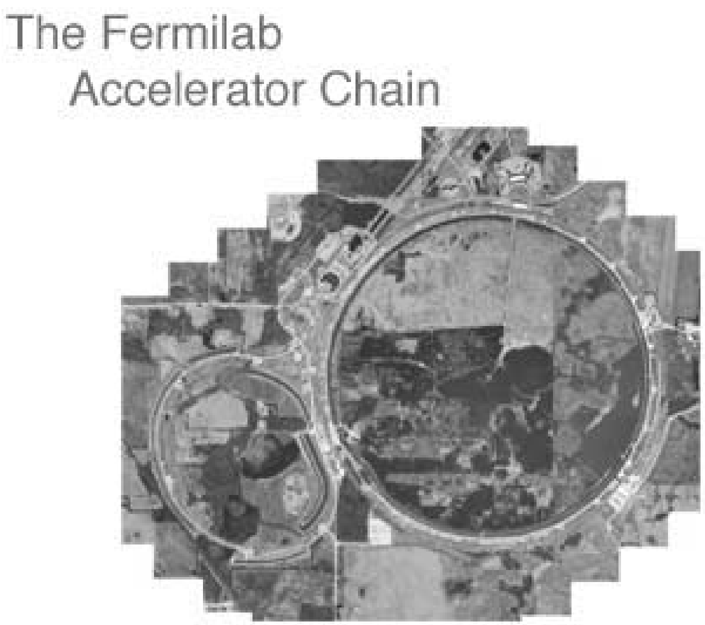
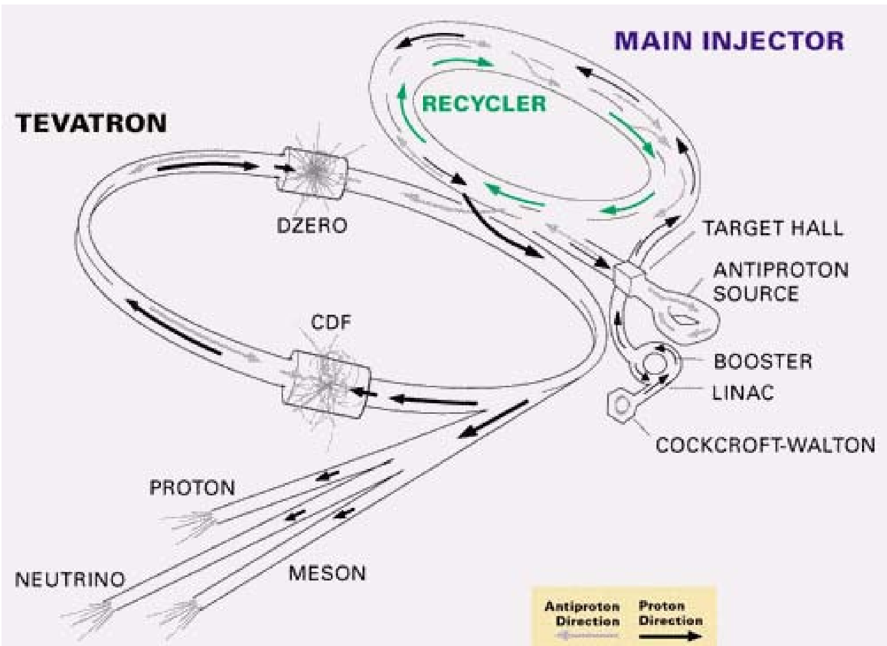
OUTLINE

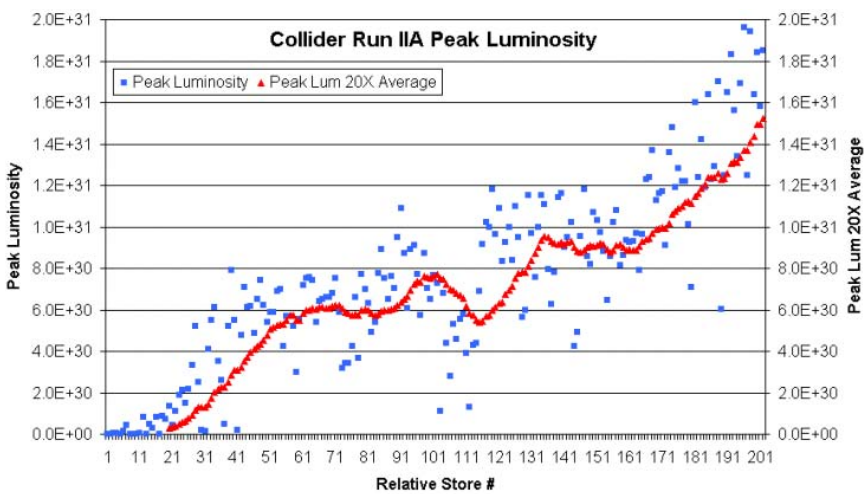
- ACCELERATOR UPGRADE AND STATUS
- DETECTOR UPGRADES FOR RUN II
- BOUNDS ON THE HIGGS MASS
- HIGGS DECAY MODES
- HIGGS PRODUCTION AT TEVATRON
- OVERVIEW OF RUN I RESULTS
- RUN II SEARCHES
  - ⇝ new tools/first results
- RUN II EXTRAPOLATIONS
- BEYOND THE SM
- CONCLUSIONS



☑ ACCELERATOR UPGRADE AND STATUS

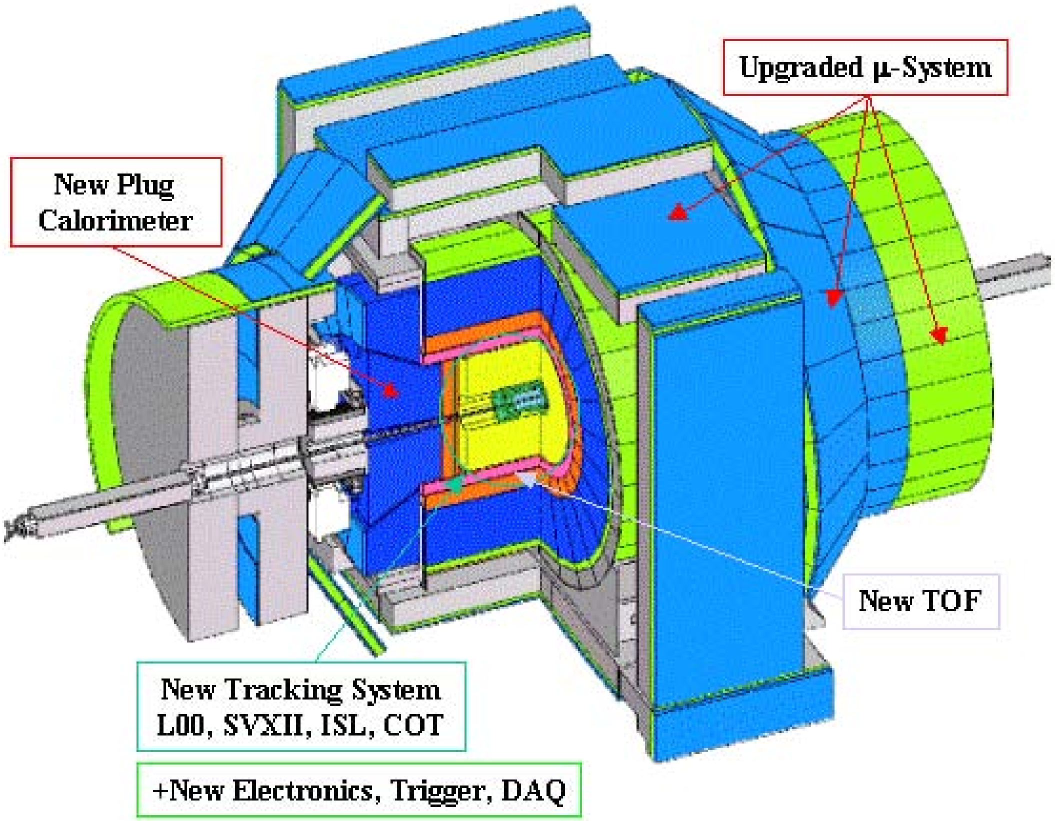


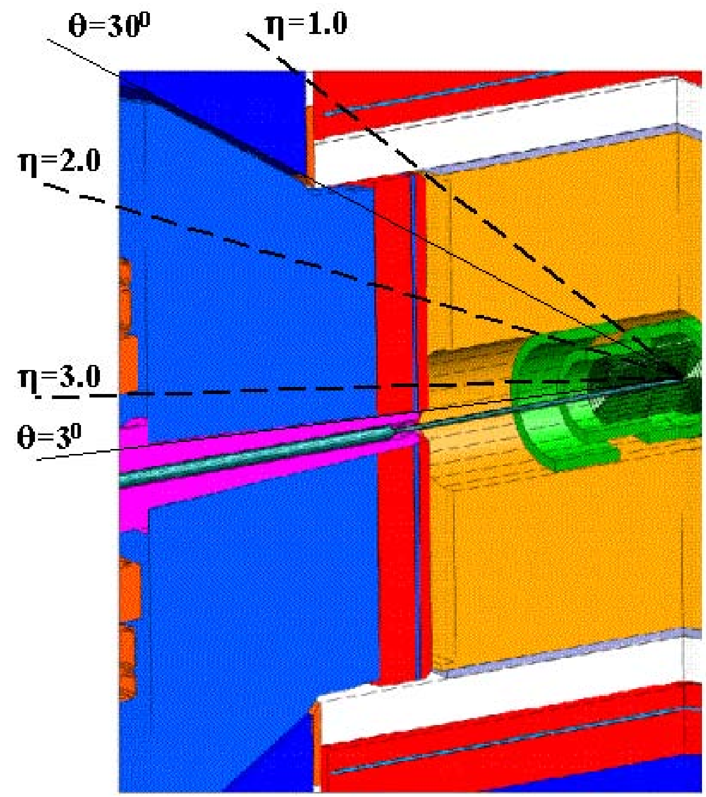
	Run I	Run IIa	Run IIb
E_{beam} [GeV]	900	980	980
$\mathcal{L}_{peak}$ [cm^{-2} s^{-1}]	1.6×10^{31}	2.0×10^{32}	5.0×10^{32}
$N_{bunches}$ $(p\times\bar{p})$	6×6	36×36	140×103
Δt_{bunch} [ns]	3500	396	132
$\overline{N}_{int/crossing}$	2.8	5.8	4.9
Run period	1992-96	2001-04	2004-07+
$\int\mathcal{L}dt$/expt.	118 pb^{-1}	2 fb^{-1}	13 fb^{-1}



- ACHIEVED $\mathcal{L} = 2.0\times10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- HOPE FOR FULL $\mathcal{L}$ BY END OF YEAR

☑ DETECTORS STATUS – CDF





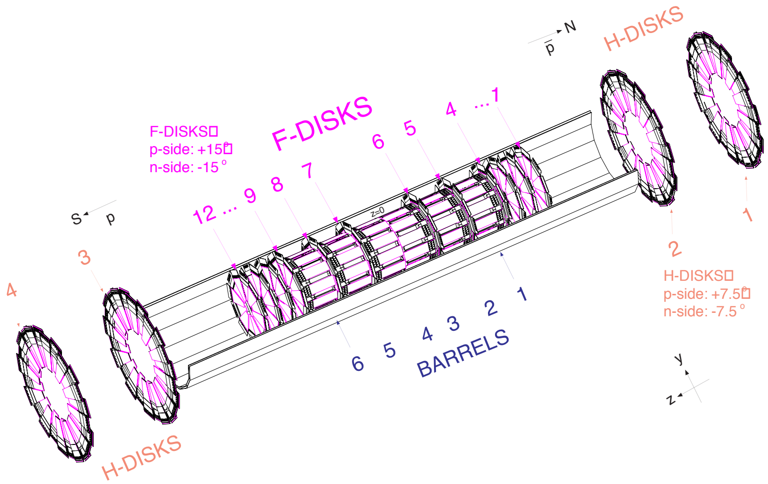
✓ b-TAGGING OUT TO $|\eta| \simeq 2.0$ ← L00, SVX II, ISL

✓ ELECTRON ID OUT TO $|\eta| \simeq 2.0$ ← NEW PLUGS+TRACKING

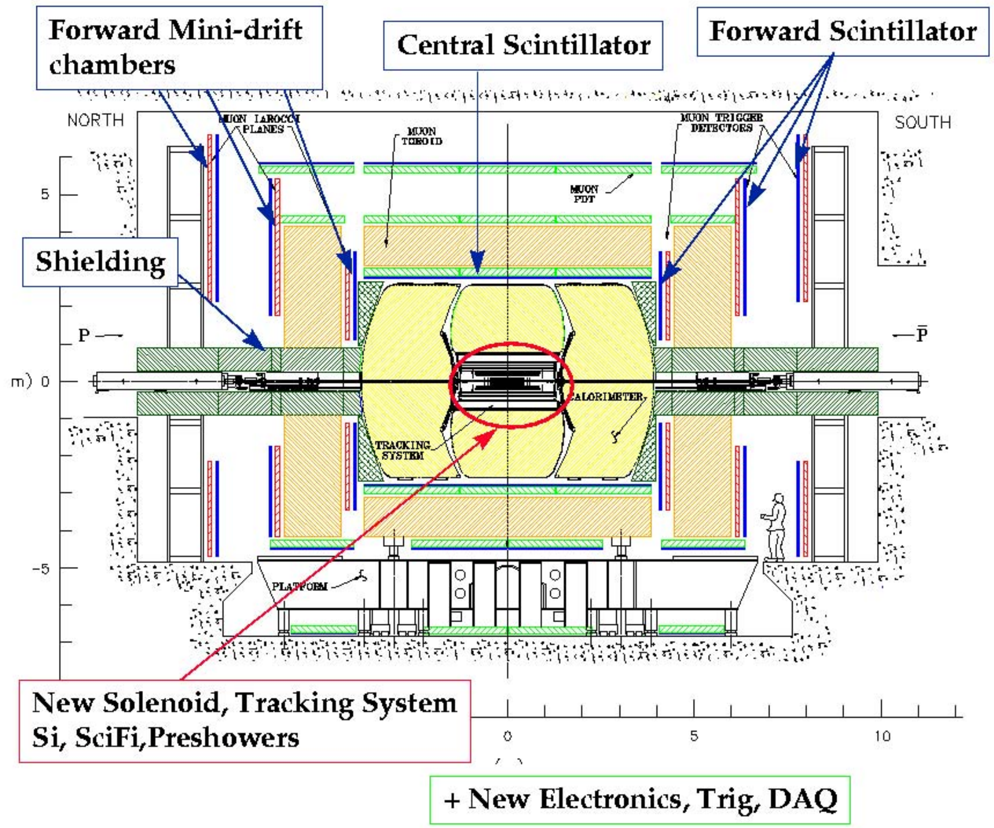
✓ MUON ID OUT TO $|\eta| = 2.0$ ← IMU+TRACKING

☑ Detectors Status – DØ

◇ barrel structure shorter than in SVX II (75cm vs. 90cm)...



◇ ...but disk assemblies provide high-η coverage



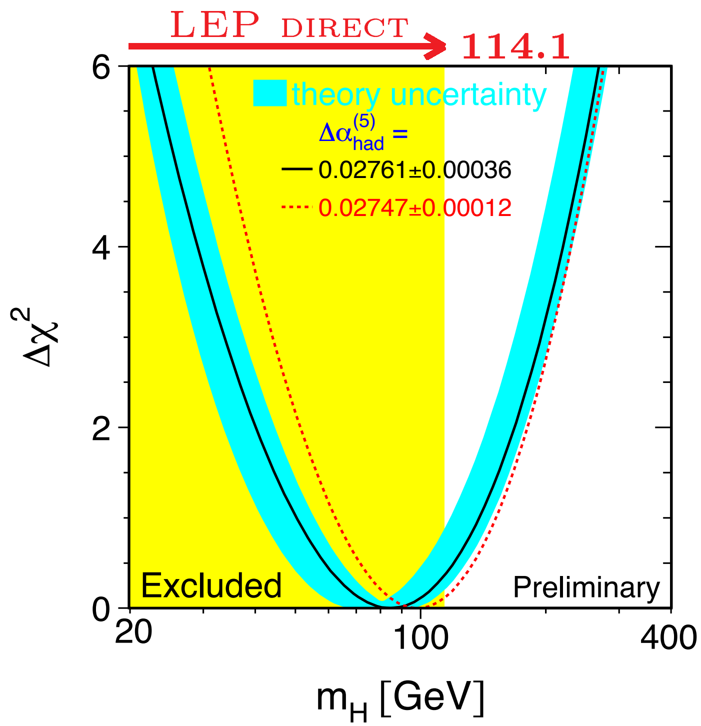
✓ tracking out to $|\eta| \simeq 3.0$ ← SMT, CFT+2 T solenoid

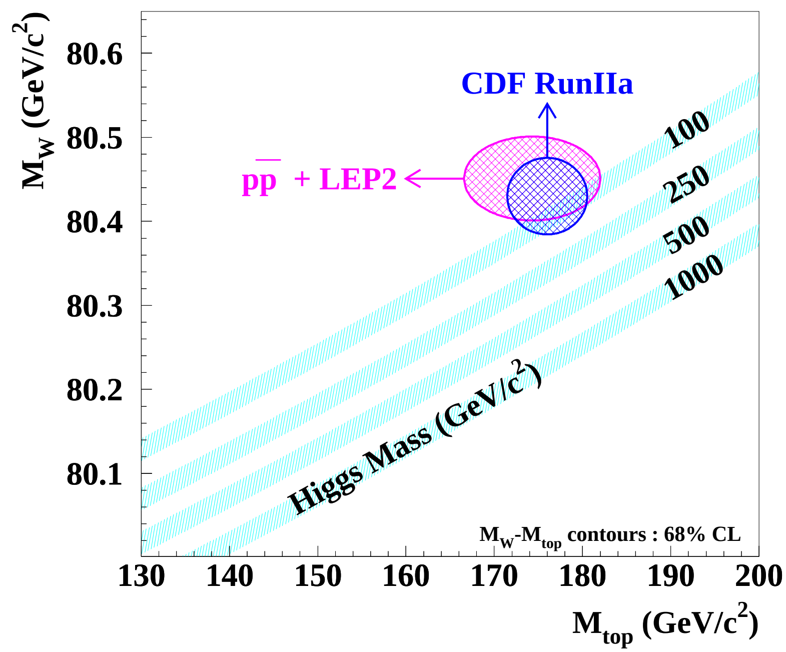
✓ electron ID out to $|\eta| = 2.5$ ← preradiators+tracking

✓ muon ID out to $|\eta| = 2.5$ ← MDT+tracking

☑ BOUNDS ON THE HIGGS MASS

UNTIL DIRECT OBSERVATION, PRECISION EWK MEASUREMENTS ARE THE ONLY KEY TO $M_{\rm H}$





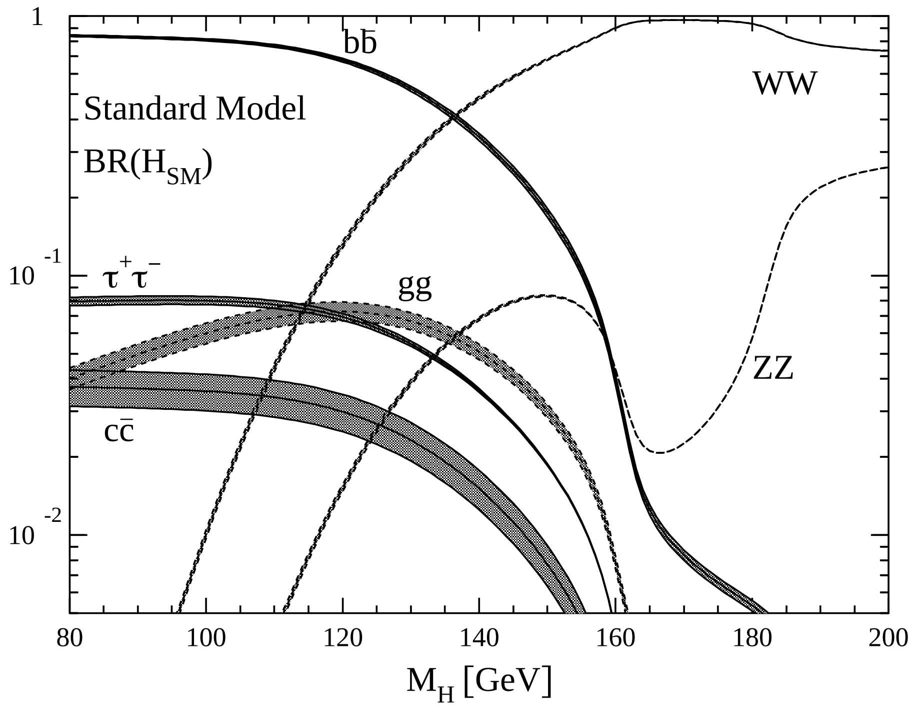
RESULT OF GLOBAL FIT:

$$M_{\rm H} = 85^{+54}_{-34}\,{\rm GeV}/c^2 \;\; @ \;\; 68\% \; C.L.$$

$$M_{\rm H} < 196\,{\rm GeV}/c^2 \;\; @ \;\; 95\% \; C.L.$$

LIGHT HIGGS SEEMS TO BE PREFERRED BY DATA

☑ HIGGS DECAY MODES



M_H ONLY UNKNOWN PARAMETER OF THE SM HIGGS SECTOR

⇓

GIVEN M_H, PRODUCTION AND DECAY MODES ARE CALCULABLE

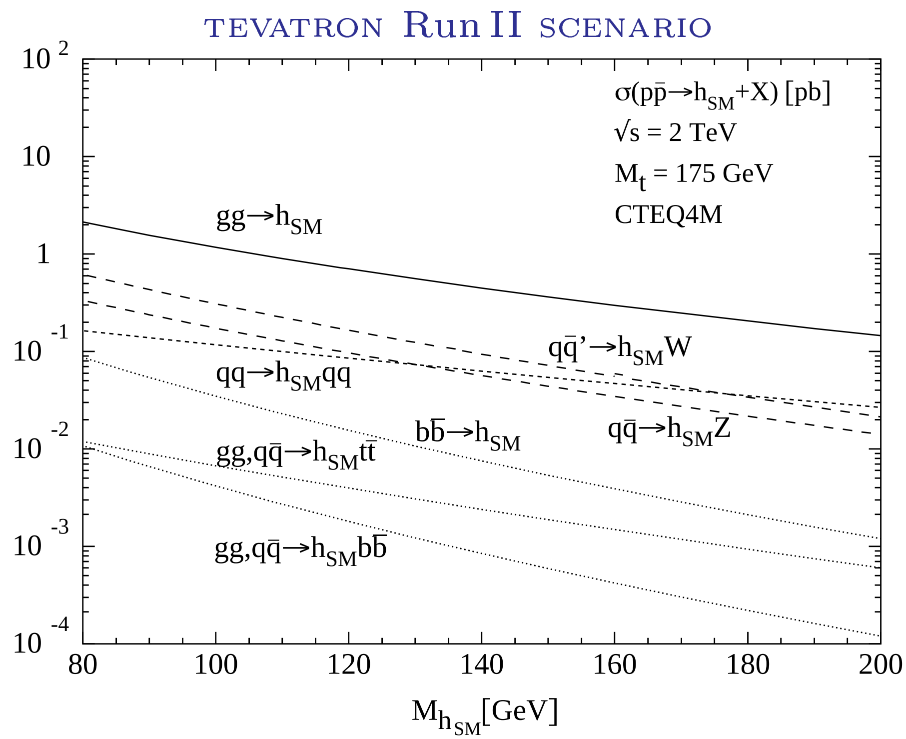
$H^0 \to b\bar{b}$

$H^0 \to WW$

TWO DOMINANT DECAY MODES:

- ☐ $H^0 \to b\bar{b}$ FOR $M_H \lesssim 135\,\mathrm{GeV}/c^2$
- ☐ $H^0 \to W^+W^-$ FOR $M_H \gtrsim 135\,\mathrm{GeV}/c^2$

☑ HIGGS PRODUCTION MODES AT THE TEVATRON



$H^0 \to b\bar{b}$ ⟵

$H^0 \to WW$ ⟶

✓ GLUON FUSION:

- DOMINANT $\forall M_H$: $\sigma(H^0) \sim 1$ pb
- FOR $M_H \lesssim 135$ GeV/c^2, $H^0 \to b\bar{b}$ SWAMPS IN BACKGROUND
- BETTER WITH $H^0 \to W^+W^-$

✓ HIGGSSTRAHLUNG:

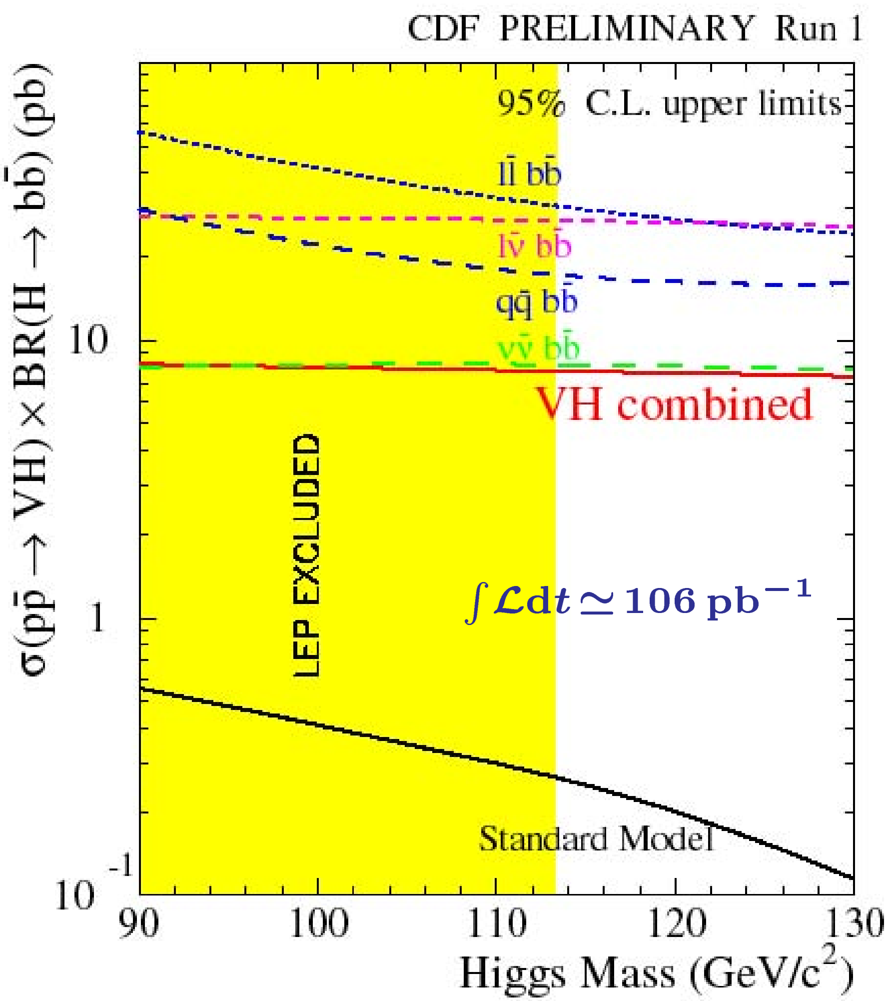
- $\sigma(VH^0) \sim 0.2$ pb…
- …BUT $V = Z^0, W^\pm$ DECAYS HELP BACKGROUND REJECTION

✓ $H^0 t\bar{t}$:

- TINY: $\sigma(H^0 t\bar{t}) \sim \mathcal{O}(1$ fb$)$…
- …BUT SPECTACULAR MULTIJET (4 b-JETS) FOR $M_H \lesssim 135$ GeV/c^2

! K-FACTOR .7 MAKES IT HARDER

☑ OVERVIEW OF RUN I RESULTS



FACTOR ~30 BELOW SM

✓ CDF: VH^0, $H^0 \to b\bar{b}$

COMBINED SENSITIVITY:

- ⇝ L BINNED IN $M_{b\bar{b}}$
- ⇝ BACKGROUNDS – $\mathcal{A}$ CORRELATION
- ⇝ $\min(-\ln L)$ WRT σ_{VH}
- ⇝ ALL CHANNELS

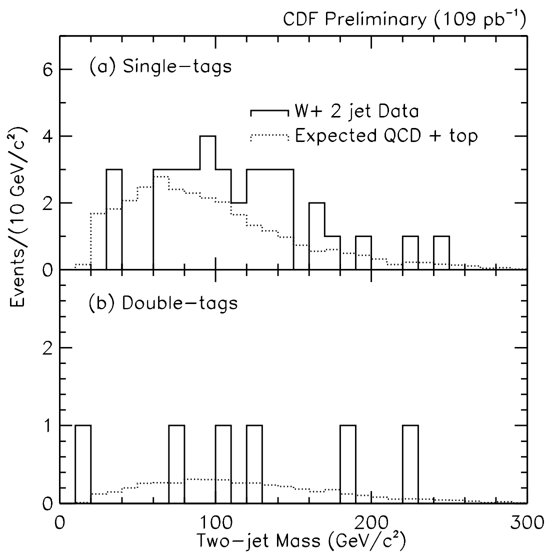
M_H [GeV/c^2]	$\sigma^{95}_{VH} \cdot \beta(H \to b\bar{b})$ [pb]	$\sqrt{s} = 1.8$ TeV SM PREDICTION
90	**8.2**	0.55
110	**7.8**	0.30
130	**7.4**	0.12

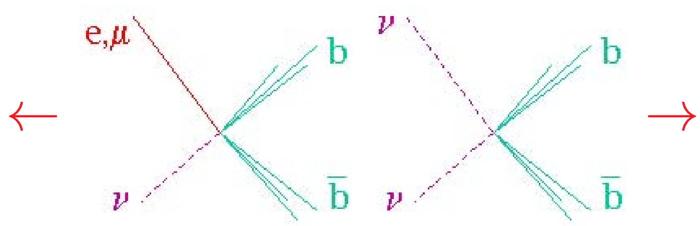
✓ DØ: VH^0, $H^0 \to jj$

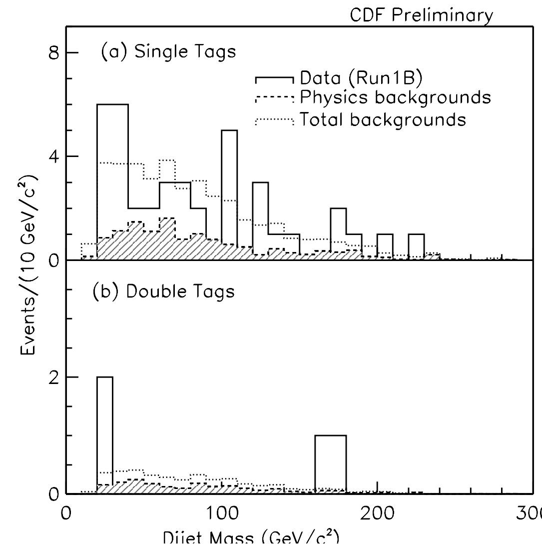
- ⇝ $\sigma^{95}_{WH} \cdot \beta(W \to e\nu_e) = 2.0\,\mathrm{pb}$
- ⇝ $\sigma^{95}_{ZH} \cdot \beta(Z \to e^+e^-) = 0.8\,\mathrm{pb}$

→ @ $M_H = 115\,\mathrm{GeV}/c^2$

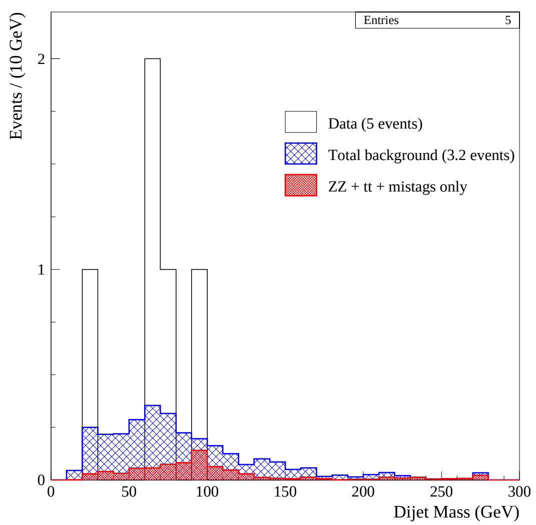
☑ Overview of Run I Results – CDF

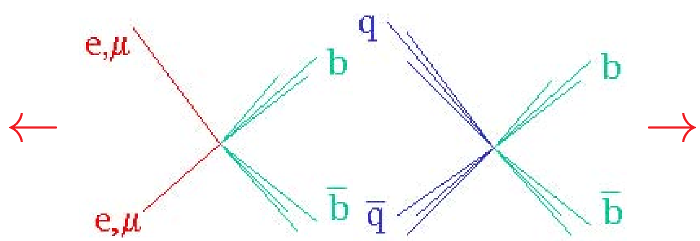


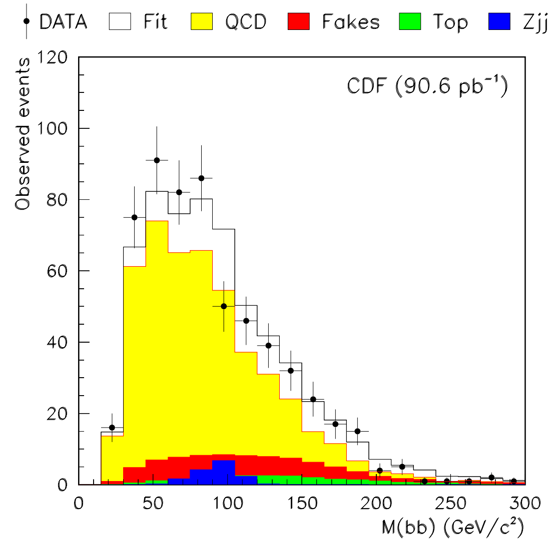




NO SIGNIFICANT EXCESS IN M_{jj} DISTRIBUTIONS







☑ RUN II SEARCHES – $M_{\mathrm{H}} \lesssim 135\ \mathrm{GeV}/c^2$

- HIGGSSTRAHLUNG: ALL SHEARCH CHANNELS SHARE $\mathrm{H}^0 \to \mathrm{b}\overline{\mathrm{b}}$

✓ $\mathrm{ZH} \to \nu_\ell \overline{\nu}_\ell \mathrm{b}\overline{\mathrm{b}}$

⇝ MOST SENSITIVE IN Run I

⇝ REQUIRES $\not{E}_T$ TRIGGER...

⇝ BKG: QCD, $\mathrm{Zb}\overline{\mathrm{b}}$, ZZ, $\mathrm{t}\overline{\mathrm{t}}$

✓ $\mathrm{ZH} \to \ell\overline{\ell}\mathrm{b}\overline{\mathrm{b}}$

⇝ BKG: $\mathrm{Zb}\overline{\mathrm{b}}$, ZZ, $\mathrm{t}\overline{\mathrm{t}}$

✓ $\mathrm{WH} \to \ell\overline{\nu}_\ell \mathrm{b}\overline{\mathrm{b}}$

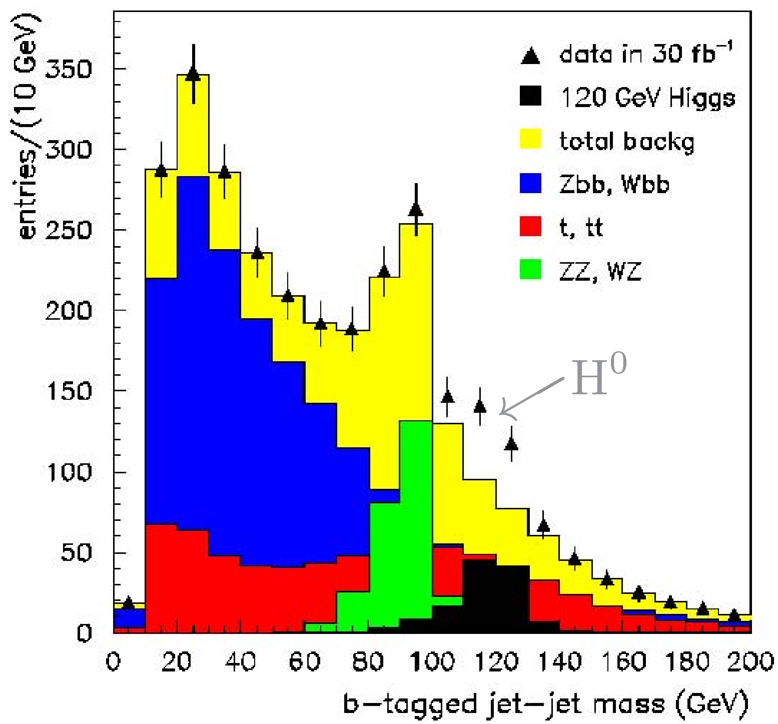
⇝ BKG: $\mathrm{Wb}\overline{\mathrm{b}}$, WZ, $\mathrm{t}\overline{\mathrm{t}}$, SINGLE t

✓ $\mathrm{VH} \to \mathrm{q}\overline{\mathrm{q}}^{(\prime)} \mathrm{b}\overline{\mathrm{b}}$

⇝ LARGEST *B.R.*

⇝ HUGE QCD BKG...

ZH, $M_{\mathrm{H}} = 120\ \mathrm{GeV}/c^2$



$15\ \mathrm{fb}^{-1}$/*expt.*

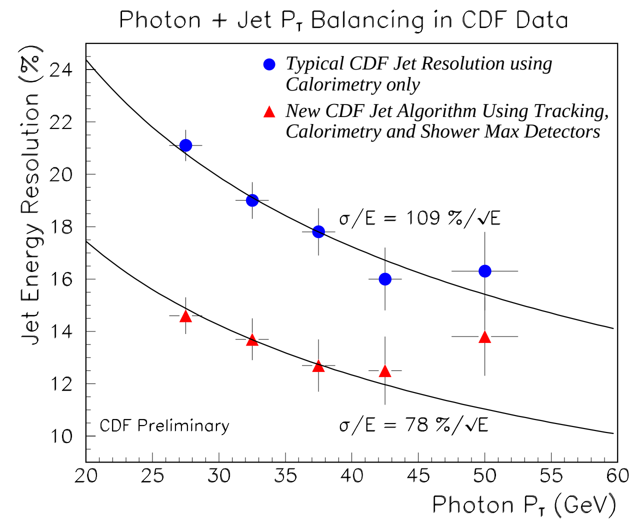
NEW: DISPLACED TRACKS $+ \not{E}_T/\Sigma E_T$ @ TRIGGER LEVEL

☑ Run II Searches – New Tools (1)

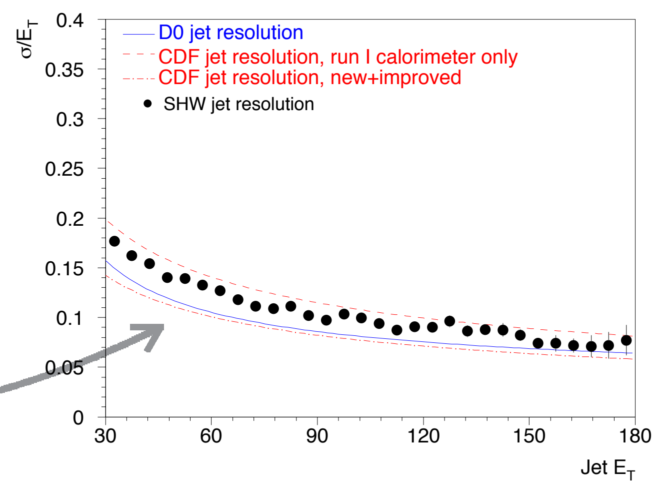
Run I sensitivity to Higgs far from SM prediction

→ still, analyses have focused on what is needed ←

- ✓ jet E_T resolution
  - ⇝ $M_{b\bar{b}}$ resolution
- ✓ b-tagging techniques
- ✓ lepton acceptance
  - ⇝ later in this talk...

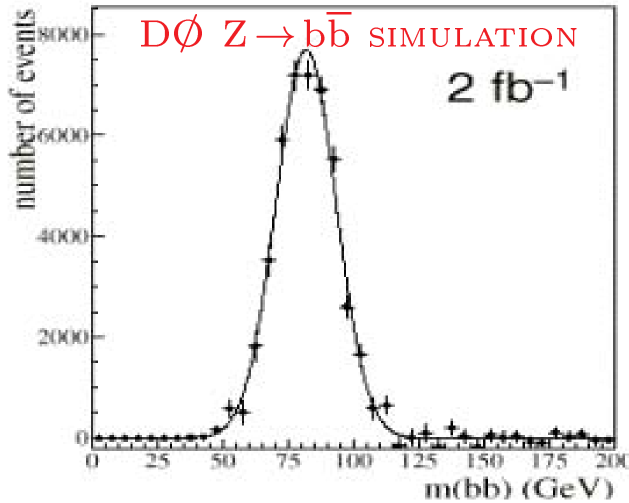


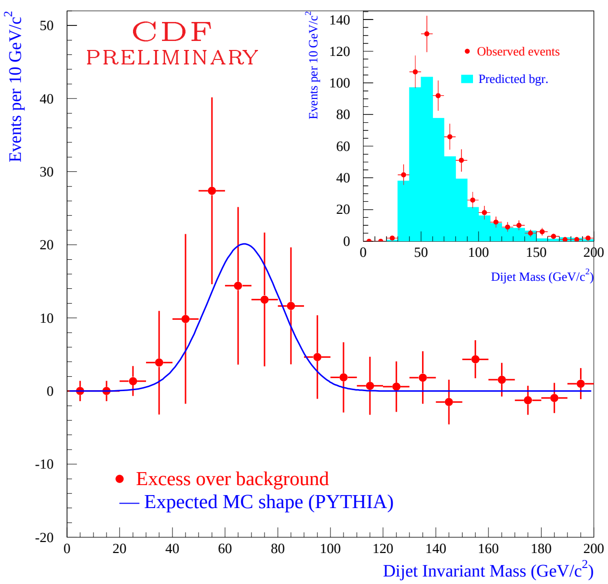
- jet E_T resolution
  - → crucial for M_{jj} estimates
  - ⇝ correct calorimetry info with tracking/shower max
  - → ∼30% improved resolution

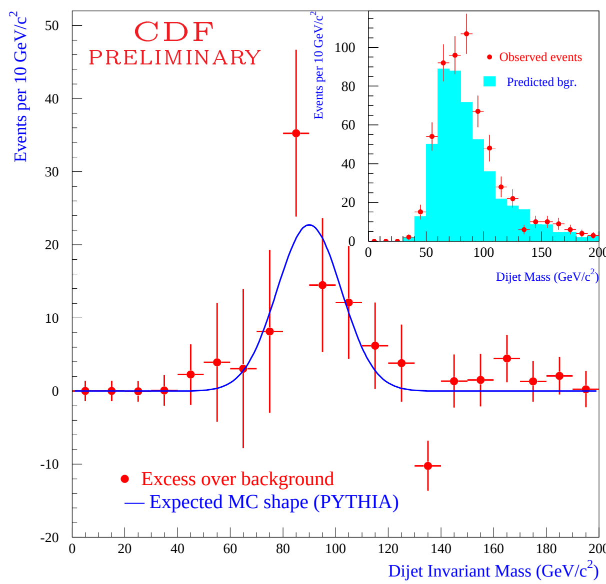


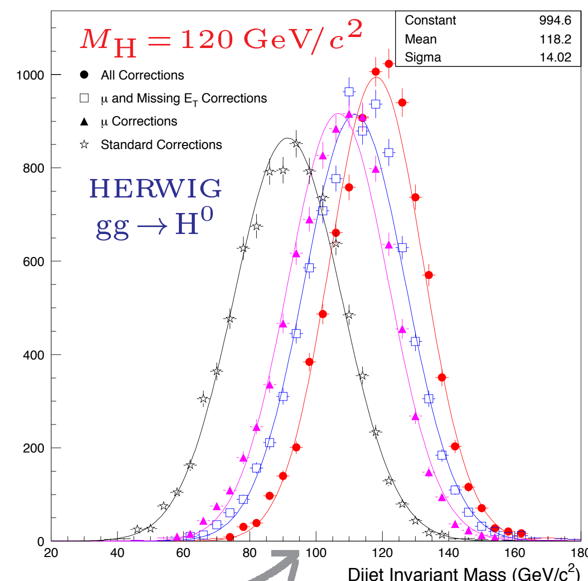
☑ RUN II SEARCHES – NEW TOOLS (2)

- $M_{b\bar{b}}$ RESOLUTION
  - → FIRST STUDIED ON $Z \to b\bar{b}$
  - → CORRECTIONS FOR BACK-TO-BACK b-JETS
  - → ONE $b \to \mu X$ ASSUMED
  - → CORRECT FOR: P_μ, $\not{E}_T$, CHARGED FRACTION
  - ⇒ $\sigma_M / M_{b\bar{b}}$ IMPROVES BY $\sim 40\%$
  - ⇒ WORK IN PROGRESS FOR $VH^0, H^0 \to b\bar{b}$...





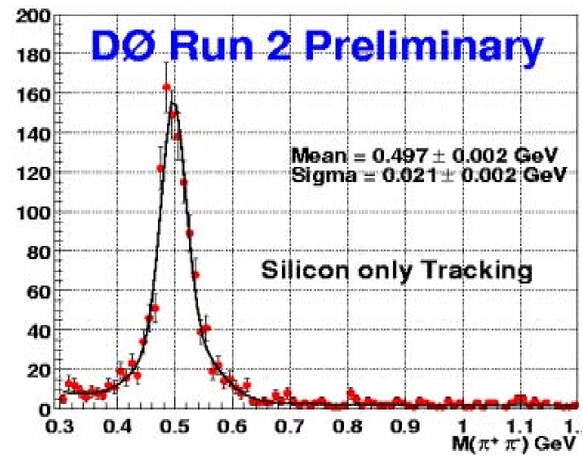




DIFFERENT FRAGMENTATION/RESONANCE

☑ Run II Searches – New Tools (3)

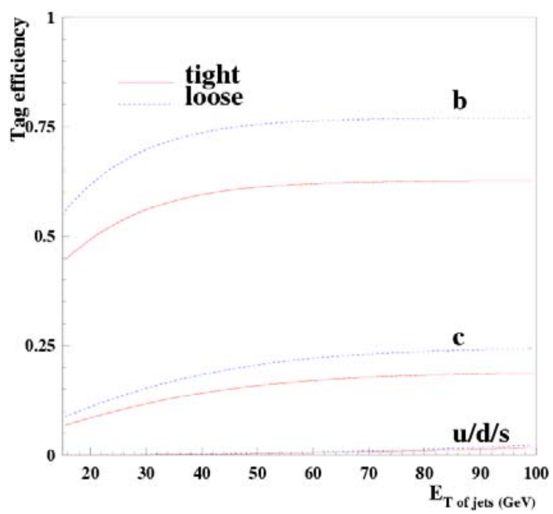
- b-tagging
  - → large d_0 2D tracks at trigger level
  - → secondary vertexing up to $|\eta| \sim 2$
  - → 3D Si-tracking for reducing mistags
  - → loose tagging via SLT, jet probability



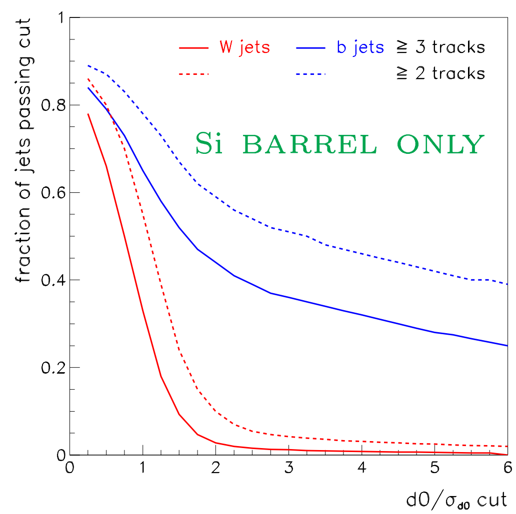
Silicon Vertex Tracker

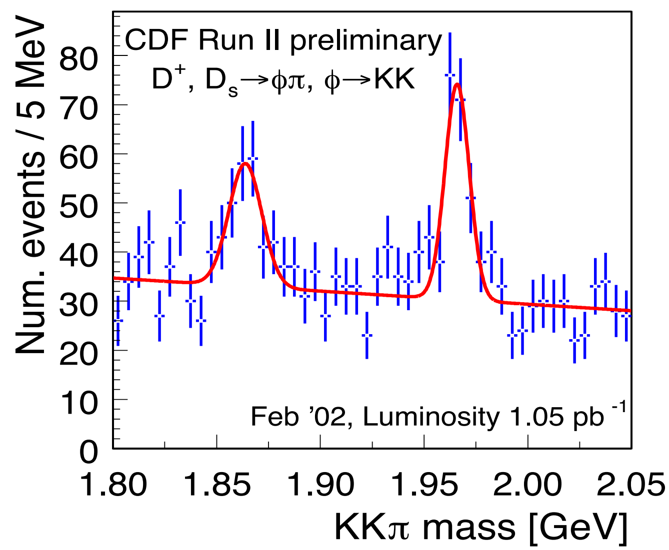
$\sigma(d_0) \simeq 45\,\mu$m

CDF Run I efficiencies
Run II acceptancies



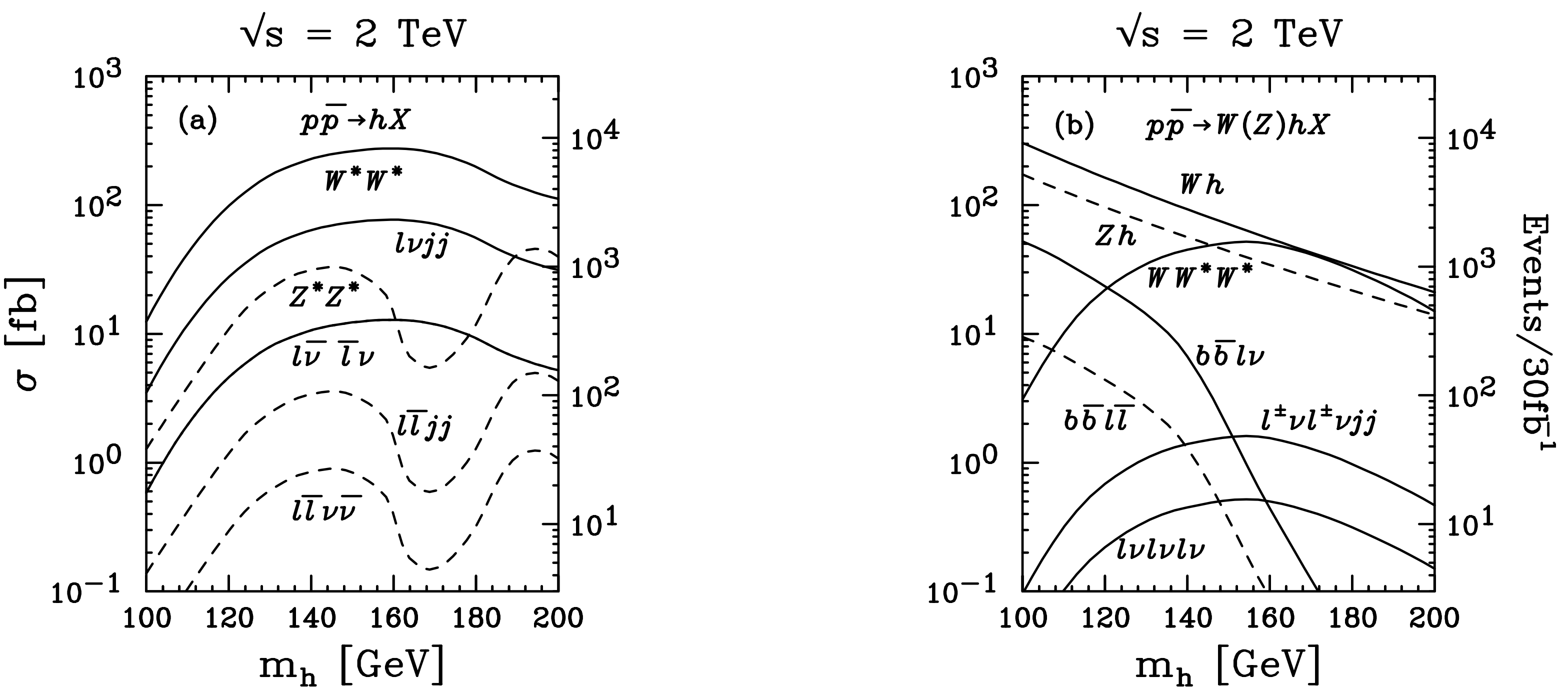
DØ $t\bar{t}$ simulation
$E_T(jet) \geqslant 15$ GeV





☑ RUN II SEARCHES – $M_H \gtrsim 135\,\mathrm{GeV}/c^2$ (1)

- ALL SHEARCH CHANNELS SHARE $H^0 \to W^+W^-$



✓ $gg \to H \to W^+W^-$

⇝ $W^+W^- \to \ell^+\nu_\ell\ell^-\overline{\nu}_\ell$

⇝ BKG: DY, WW, WZ, ZZ, $t\bar{t}$, tW

✓ $p\overline{p} \to W^\pm H \to W^\pm W^+W^-$

⇝ $W^\pm W^+W^- \to \ell^\pm\nu_\ell\ell^\pm\nu_\ell\, jj$

⇝ BKG: VVV, WZ, $t\bar{t} \to \ell\nu_\ell b\overline{b}\, jj$

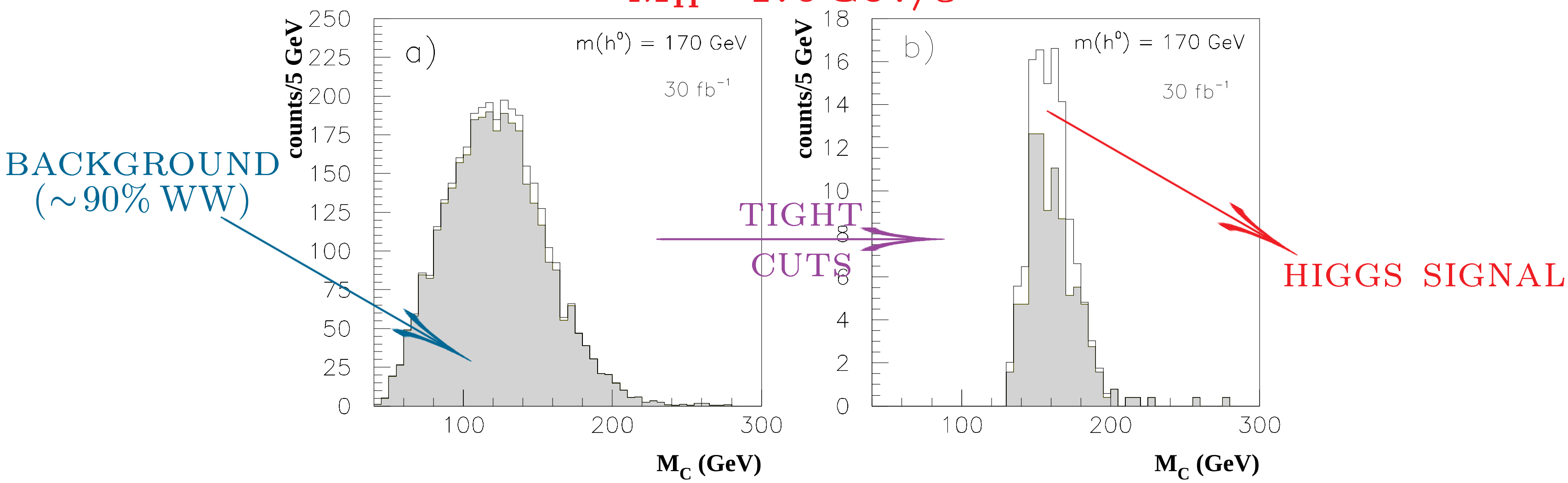
ANY MASS: BOSOPHILIC HIGGS SEARCHES

☑ Run II Searches – $M_{\rm H} \gtrsim 135\,{\rm GeV}/c^2$ (2)

- $gg \to H \to W^+W^- \to \ell^+\nu_\ell\ell^-\overline{\nu}_\ell$
  - ✓ favoured by cross-section: $\sim 10\times$ other channels
  - ⇝ after finely-tuned kinematical selection...
  - → ...sharpen mass by defining "cluster transverse mass":

$$M_C \equiv \sqrt{P_T^2(\ell\ell) + M_{\ell\ell}^2} + \not{E}_T$$

$M_{\rm H} = 170\,{\rm GeV}/c^2$

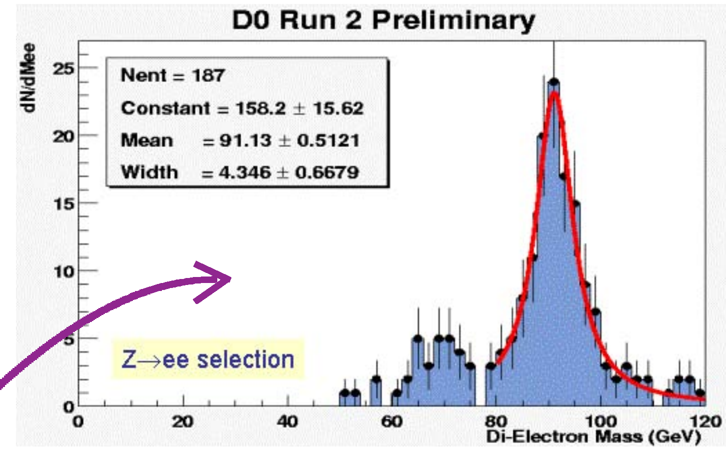


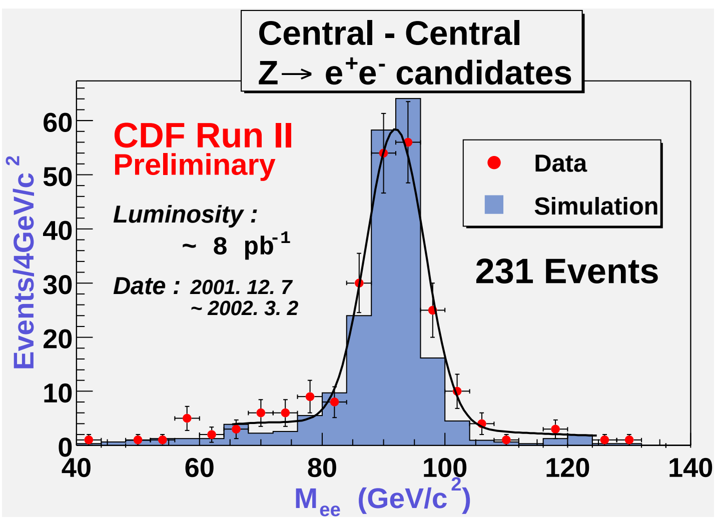
$15\,{\rm fb}^{-1}/expt.$

careful WW modelling needed

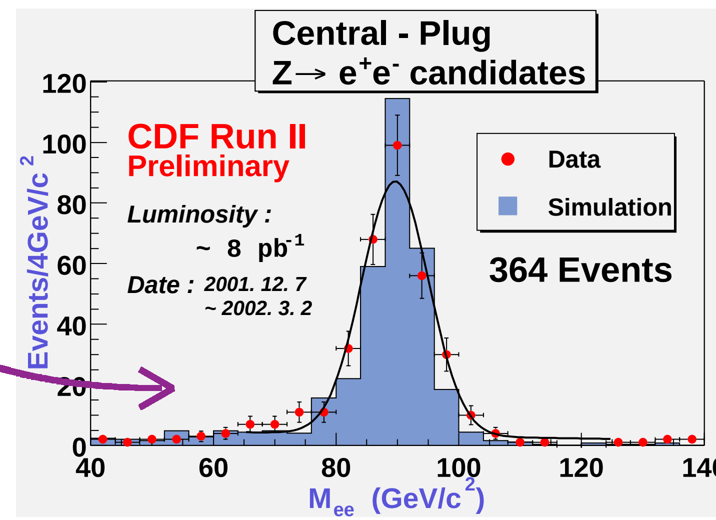
☑ Run II Searches – New Tools (4)

- lepton acceptance
  - → in Run I: $|\eta_e| \lesssim 2.4$, $|\eta_\mu| \lesssim 1.0$ (CDF)
  - → in Run II: $\sim 30\%$ more acceptance
    - ⇝ @ trigger level as well ⇜
  - → high-P_T ℓ validation on $Z \to \ell^+\ell^- \ldots$





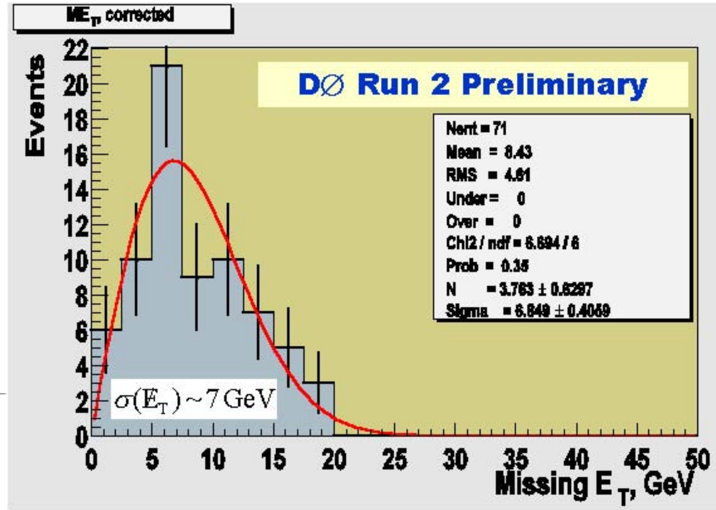
plug electrons:
no track match
required

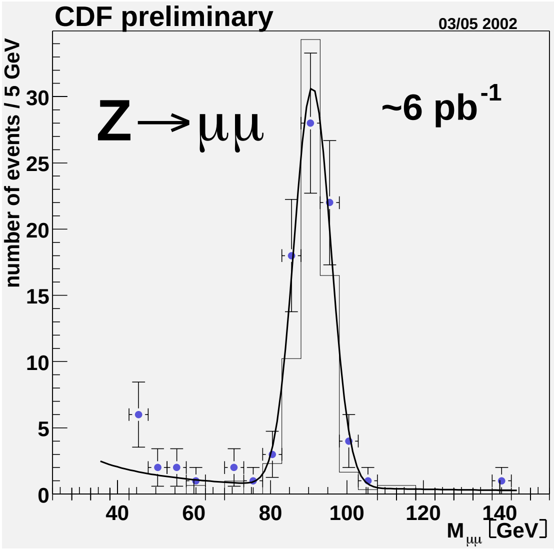


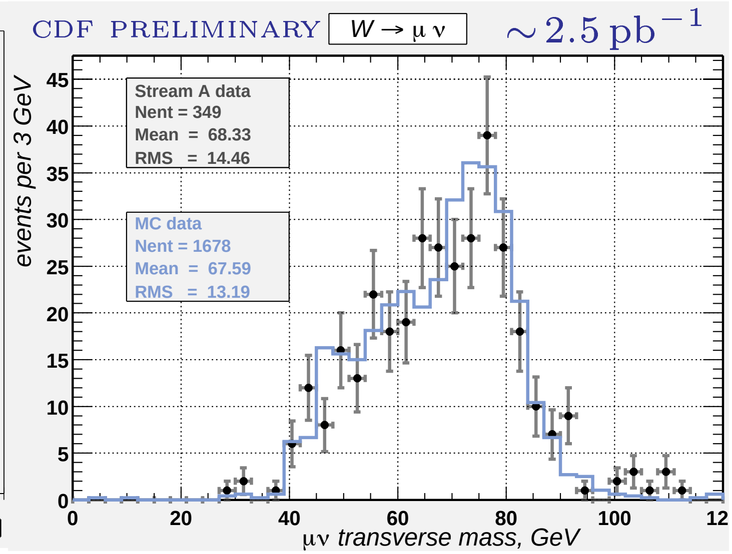
☑ RUN II SEARCHES – NEW TOOLS (5)

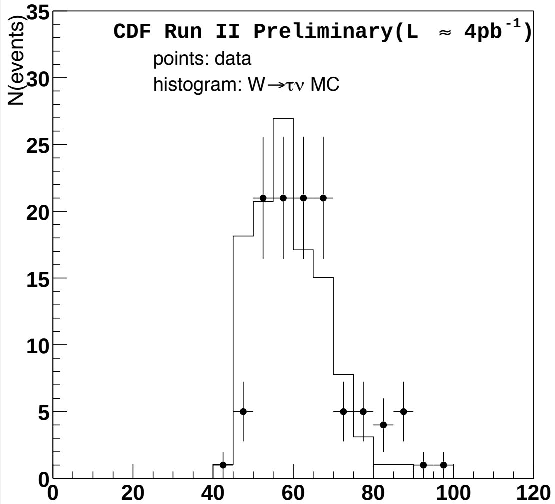
- LEPTON ACCEPTANCE (CONT'D)
  - → HIGH-P_T ℓ VALIDATION ON $Z \to \ell^+\ell^-$...
  - → ...AND ON $W \to \ell\nu_\ell$
  - ⇝ $\not{E}_T$ NEEDS CALIBRATION AS WELL...

    INCLUSIVE DI-ELECTRONS (MAINLY DY) →







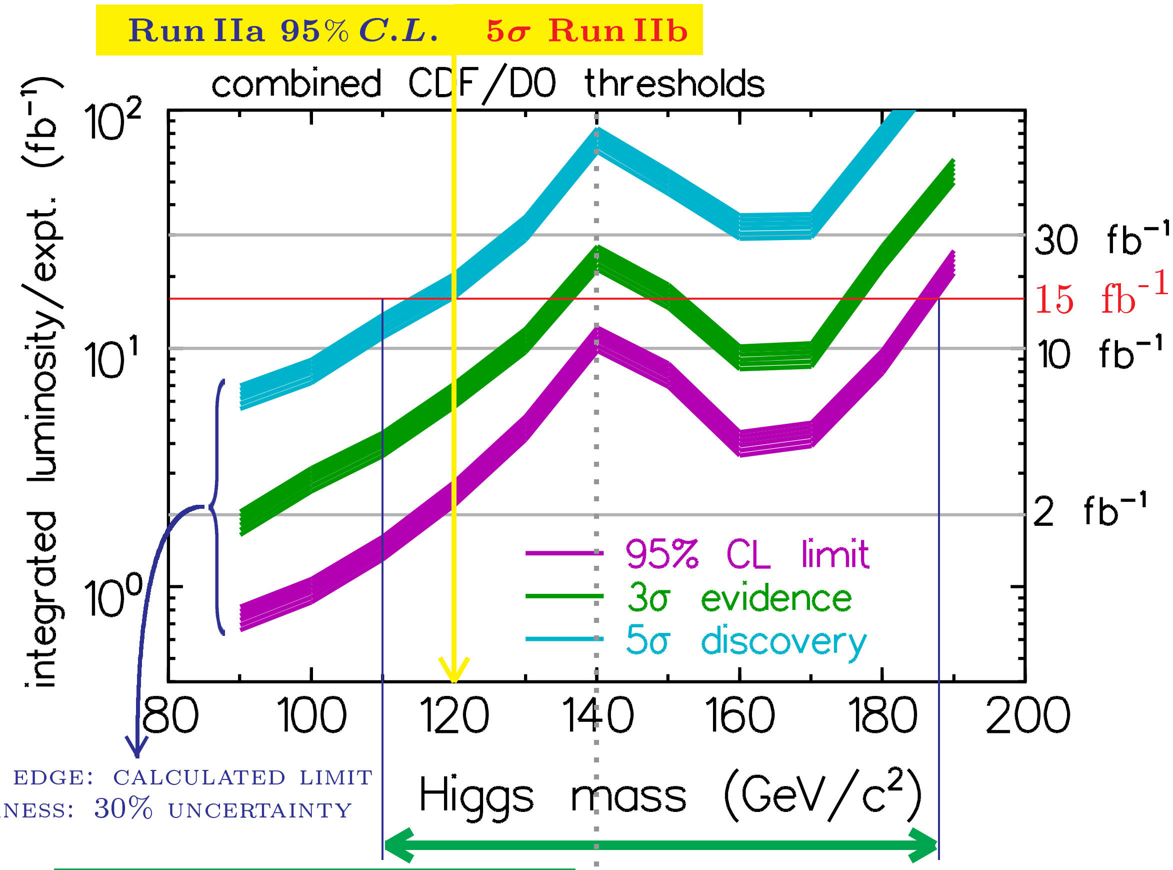


$M_T(\tau\nu)$[GeV]

WORK IN PROGRESS: τ RECONSTRUCTION

☑ Run II Extrapolations

results of simulation/interpolation of all effects



$M_{\rm H} \simeq 110 \div 190\,{\rm GeV}/c^2$

$\ell\overline{\nu}_\ell b\overline{b},\ \nu_\ell\overline{\nu}_\ell b\overline{b},\ \ell^+\ell^- b\overline{b} \Leftarrow\ \Rightarrow \ell^+\ell^-\nu_\ell\overline{\nu}_\ell,\ \ell^\pm\ell^\pm\nu_\ell\nu_\ell jj$

when the going gets tough...

☑ Beyond the SM – MSSM

- 2 HIGGS DOUBLETS – EXPANDED HIGGS SECTOR: h, H, A, $H^{\pm}$
- PROPERTIES DEPEND ON:
  - ⇝ TWO FREE PARAMETERS $(m_A, \tan\beta)$ @ TREE-LEVEL…
  - ⇝ …+ RADIATIVE CORRECTIONS $\propto \tilde{m}$, m_t , …

HIGGS SPECTRUM

⇝ $\boldsymbol{m_h \leqslant m_h^{max}} \simeq 120 \div 135\,\mathrm{GeV}/c^2$

↳ $\propto \tilde{t}$-MIXING, m_t

✓ TWO SCENARIOS:

$m_A > m_h^{max}$: $m_h \simeq m_h^{max}$, $m_H \simeq m_A$

$m_A < m_h^{max}$: $m_h \simeq m_A$, $m_H \simeq m_h^{max}$

✓ $m_H \geqslant m_h^{max}$

✓ $m_{H^\pm} > m_A$

} $\forall\, m_A, \tan\beta$

HIGGS DECAYS

✓ $h, H \rightarrow b\bar{b}, \tau^+\tau^-$ FOR LARGE $\tan\beta$

✓ $h, H \rightarrow VV$ SUPPRESSED:

⇝ $hVV \propto \sin(\beta - \alpha)$

⇝ $HVV \propto \cos(\beta - \alpha)$

✓ $A \rightarrow b\bar{b},\ \tau^+\tau^-$ $\quad\forall \tan\beta, m_A$

✓ $H^+ \rightarrow \tau^+\nu_\tau, t\bar{b}$ $\quad\forall \tan\beta$

↑ FOR $m_{H+} > m_t - m_b$

☑ Beyond the SM – Higgs Searches at the Tevatron

✓ $gg \to \phi, \ \phi = h, H, A$

⇝ $\sigma(\phi) \sim 0.03 \div 30\,\text{pb}$ ($\uparrow$ with $\tan\beta$)

⇝ swamped by background if $\phi \to b\bar{b}$

⇝ appealing if $\phi \to \tau^+\tau^-$, large $\tan\beta$

✓ $q\bar{q}, gg \to \phi b\bar{b}, \ \phi = h, H, A$

⇝ $\sigma(\phi b\bar{b}) \sim 0.1 \div 1\,\text{pb}$ ($\uparrow$ with $\tan\beta$)

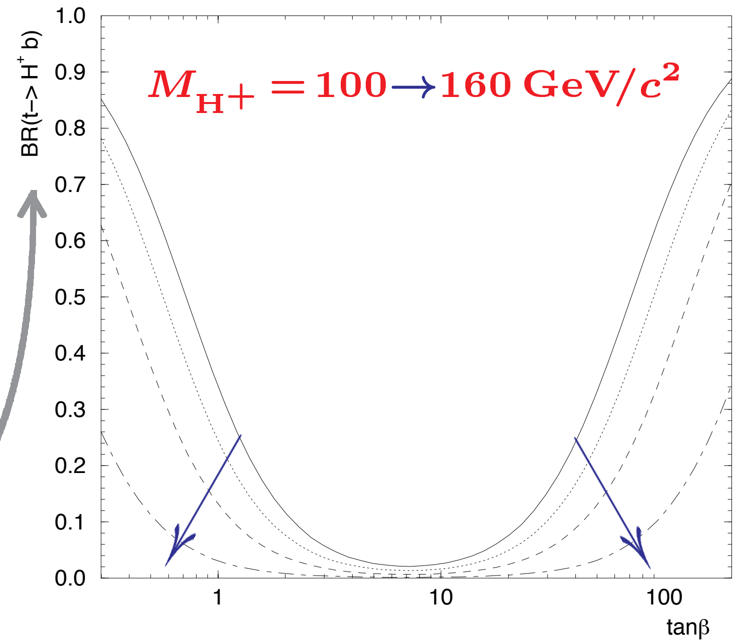
⇝ powerful signature with $\phi \to b\bar{b}$

✓ $t \to bH^+$

⇝ $B.R.(t \to bH^+) = 1 - B.R.(t \to bW^+)$

⇝ $\sigma(H^\pm X) = [1 - B.R.(t \to \bar{b}W)^2] \times \sigma(t\bar{t}X)$

$\sim 7\,\text{pb}$

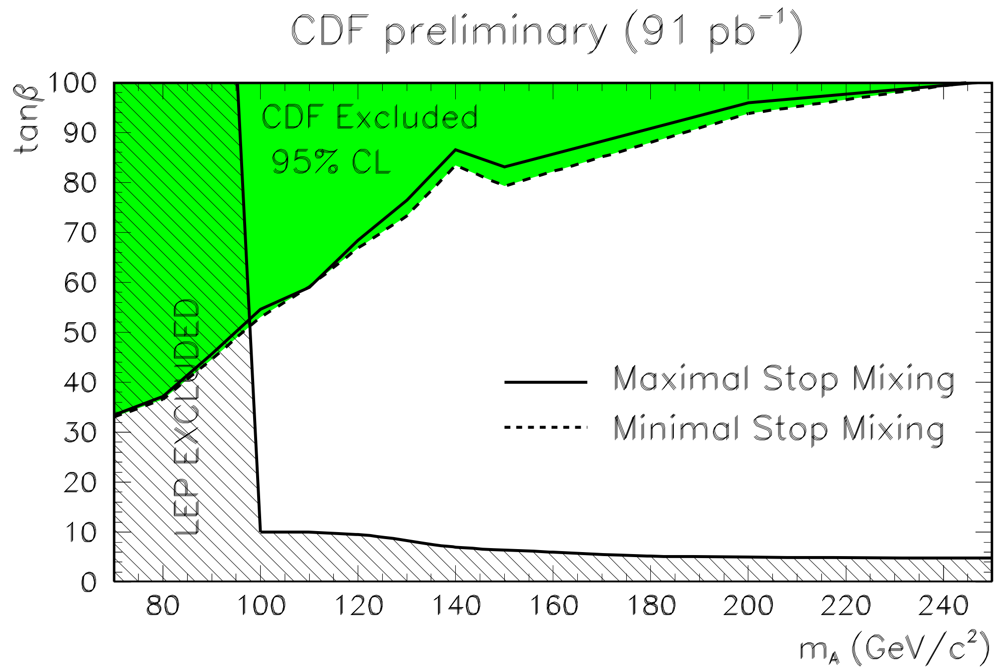


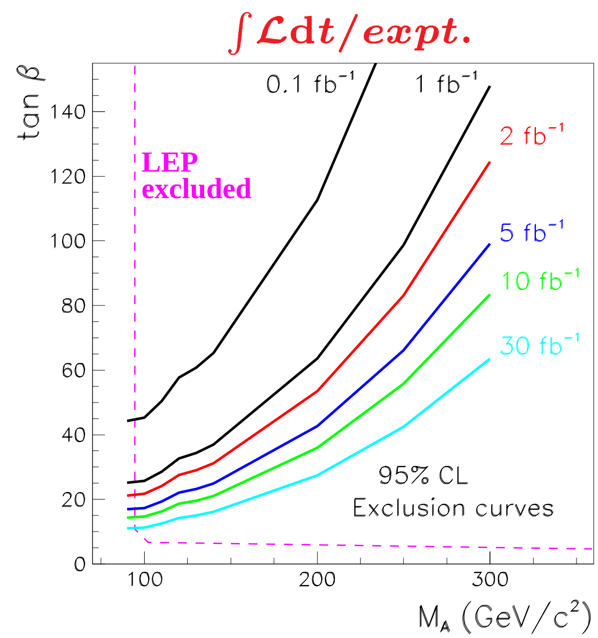
✓ $q\bar{q}^{(\prime)} \to V\phi, \ \phi = h, H$

⇝ in combination with $\phi \to b\bar{b}$ only

⇝ special mention later in this talk...

☑ Beyond the SM – ϕ Production at large $\tan\beta$

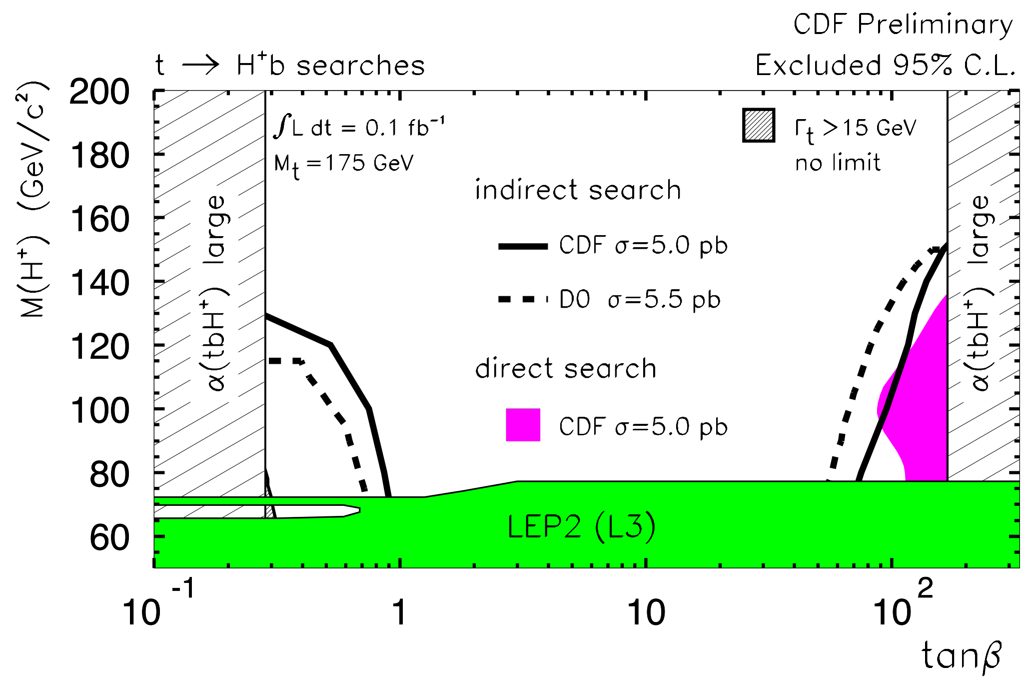


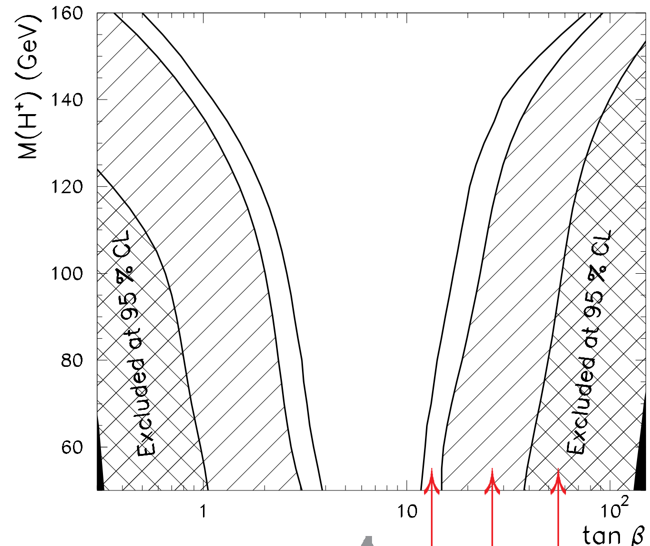


- ✓ $B.R.(\phi \to b\bar{b}) \simeq 90\%$
  - ⇝ multijet events with high b content expected
  - ⇝ $\geqslant 3$ b-jets required
- ✓ main background from QCD $gg \to b\bar{b}b\bar{b}$ production
  - ⇝ b-jets need to be well isolated

5σ discovery reach @ $5\,\mathrm{fb}^{-1}$: $m_A \lesssim 150\,\mathrm{GeV}/c^2$ for $\tan\beta = 40$

☑ BEYOND THE SM – $H^{\pm}$ PRODUCTION FROM t DECAY





$10\,\mathrm{fb}^{-1}@\sqrt{s}=2.0$ TeV

$2.0\,\mathrm{fb}^{-1}@\sqrt{s}=2.0$ TeV

$0.1\,\mathrm{fb}^{-1}@\sqrt{s}=1.8$ TeV

- ✓ SENSITIVE UP TO $m_{\mathrm{H}^+} < m_{\mathrm{t}} - m_{\mathrm{b}}$
- ✓ LOW AND LARGE $\tan\beta \Rightarrow B.R.(\mathrm{t} \to \mathrm{H}^+\mathrm{b})$ DOMINANT
- ✓ DISAPPEARANCE SEARCH:
  - ⇝ LOOK FOR SUPPRESSION IN $\mathrm{t\bar{t}}$ SM DECAYS

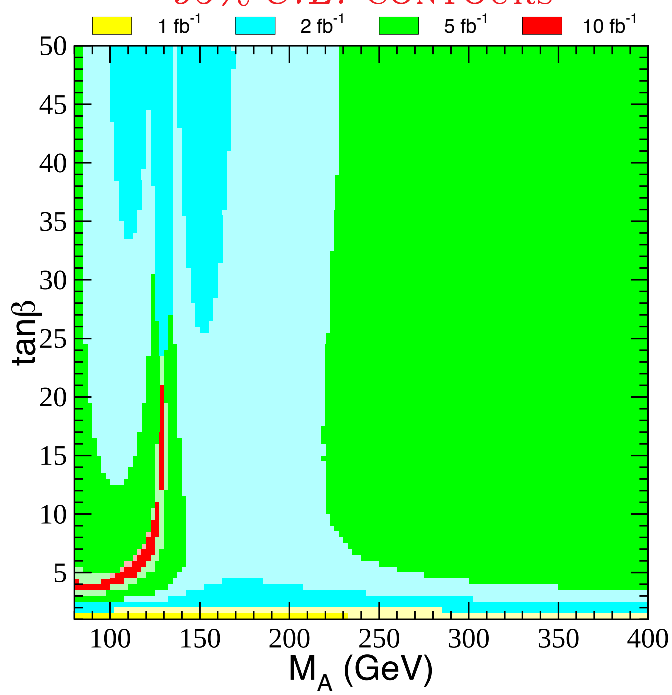
IF n_{obs} CONSISTENT WITH SM

☑ BEYOND THE SM – REINTERPRETING THE SM RESULTS

WHAT CAN BE INFERRED FROM THE SM HIGGS SEARCHES?

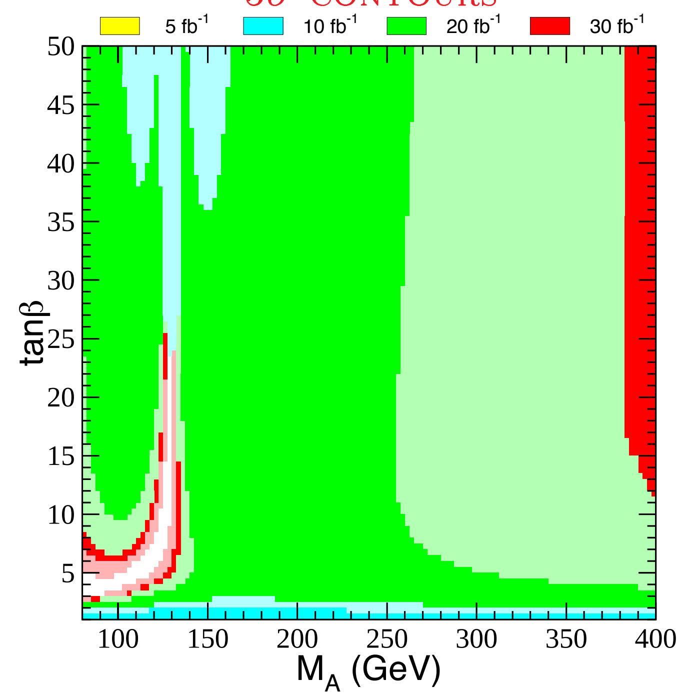
SENSITIVITY ON $M_{\rm H}$ $\longrightarrow$ SENSITIVITY ON m_ϕ $\longrightarrow$ SENSITIVITY IN $(m_{\rm A}, \tan\beta)$

95% *C.L.* CONTOURS



MAX $\tilde{t}$-MIXING

5σ CONTOURS



UNLESS $V\phi \rightarrow Vb\bar{b}$ SUPPRESSED WRT $VH^0_{\rm SM} \rightarrow Vb\bar{b}$ BY CONSPIRING PARAMETERS

LARGE PROBED REGION RESULTS FROM MSSM CONSTRAINT ON m_ϕ

☑ CONCLUSIONS

H^0_{SM}: TWO POSSIBILITIES × TWO SCENARIOS

	NO OBSERVATION	EVIDENCE
Run IIa	EXCLUDE $M_H \lesssim 120\,\mathrm{GeV}/c^2$ @ 95% *C.L.*	NEED MORE DATA...
Run IIb	EXCLUDE $M_H \lesssim 185\,\mathrm{GeV}/c^2$ @ 95% *C.L.*	5σ DISCOVERY UP TO $M_H \sim 120\,\mathrm{GeV}/c^2$

- DIRECT OBSERVATION WOULD FINALLY REVEAL THE MISSING BRICK OF THE SM
- EXCLUSION WOULD STILL UNVEIL CRUCIAL SSB MECHANISM DETAILS

⇓

$\int \mathcal{L} dt = 15\,\mathrm{fb}^{-1} / \mathit{expt.}$ COULD EXCLUDE MOST OF MSSM PARAMETER SPACE...

EXCITING NEW PHYSICS CHAPTER IS STARTING AT TEVATRON

☑ References

Search for New Physics Using QUAERO: A General Interface to D0 Event Data

Phys. Rev. Lett. **87**, 231801 (2001)

Process	$\epsilon_{\rm sig}$	$\hat{b}$	$N_{\rm data}$	$\sigma^{95}\times\beta$
$h_{175}\rightarrow \rm WW \rightarrow e\not\!\!E_T 2j$	0.02	29.6 ± 6.5	32	11.0 pb
$h_{200}\rightarrow \rm WW \rightarrow e\not\!\!E_T 2j$	0.07	66.0 ± 13.8	69	4.4 pb
$h_{225}\rightarrow \rm WW \rightarrow e\not\!\!E_T 2j$	0.06	43.1 ± 9.2	44	3.6 pb
$h_{200}\rightarrow \rm ZZ \rightarrow ee2j$	0.15	17.9 ± 3.7	15	0.6 pb
$h_{225}\rightarrow \rm ZZ \rightarrow ee2j$	0.15	18.8 ± 3.8	12	0.4 pb
$h_{250}\rightarrow \rm ZZ \rightarrow ee2j$	0.17	18.1 ± 3.7	18	0.6 pb
$\mathrm{W}h_{115}\rightarrow \rm e\not\!\!E_T 2j$	0.08	37.3 ± 8.2	32	2.0 pb
$\mathrm{Z}h_{115}\rightarrow \rm ee2j$	0.20	19.5 ± 4.1	25	0.8 pb

☑ STATISTICAL SIGNIFICANCE

→ *i.e.* 95% *C.L.*, $3\sigma, 5\sigma$

$$\mathcal{R}_{exp} \equiv \frac{(\text{STATISTICAL SIGNIFICANCE})_{chosen}}{(\text{STATISTICAL SIGNIFICANCE})_{measured}} = f\left(M_{\rm H}, \int \mathcal{L} \mathrm{d}t\right)$$

$\mathcal{R}_{exp} \times (\sigma \cdot \beta)$
$\mathcal{R}^2_{exp} \times (DATA)$
} TO ACHIEVE *chosen* STATISTICAL SIGNIFICANCE

$$\mathcal{R}_{th} \equiv \frac{\sigma_{\rm X}(\phi) \cdot \beta(\phi \rightarrow {\rm Y})}{\sigma_{\rm X}({\rm H_{SM}}) \cdot \beta({\rm H_{SM}} \rightarrow {\rm Y})} = f(m_{\rm A}, \tan\beta)$$

→ MSSM, FIXED $m_{\tilde{\rm Q}}$, $\tilde{\rm t}$-MIXING

FOR $m_\phi = M_{\rm H}$:

IF $\mathcal{R}_{th} < \mathcal{R}_{exp}$ MSSM DOES NOT ENHANCE $\sigma \cdot \beta$ ENOUGH TO ACHIEVE $(\text{STATISTICAL SIGNIFICANCE})_{chosen}$

ELSE $\mathcal{R}_{th} \geqslant \mathcal{R}_{exp}$ $(\text{STATISTICAL SIGNIFICANCE})_{chosen}$ CAN BE ACHIEVED AT CORRESPONDING $(m_{\rm A}, \tan\beta)$

MSSM FREE PARAMETERS TREATED AS INDEPENDENT