SUSY Higgs Searches at the Tevatron/LHC

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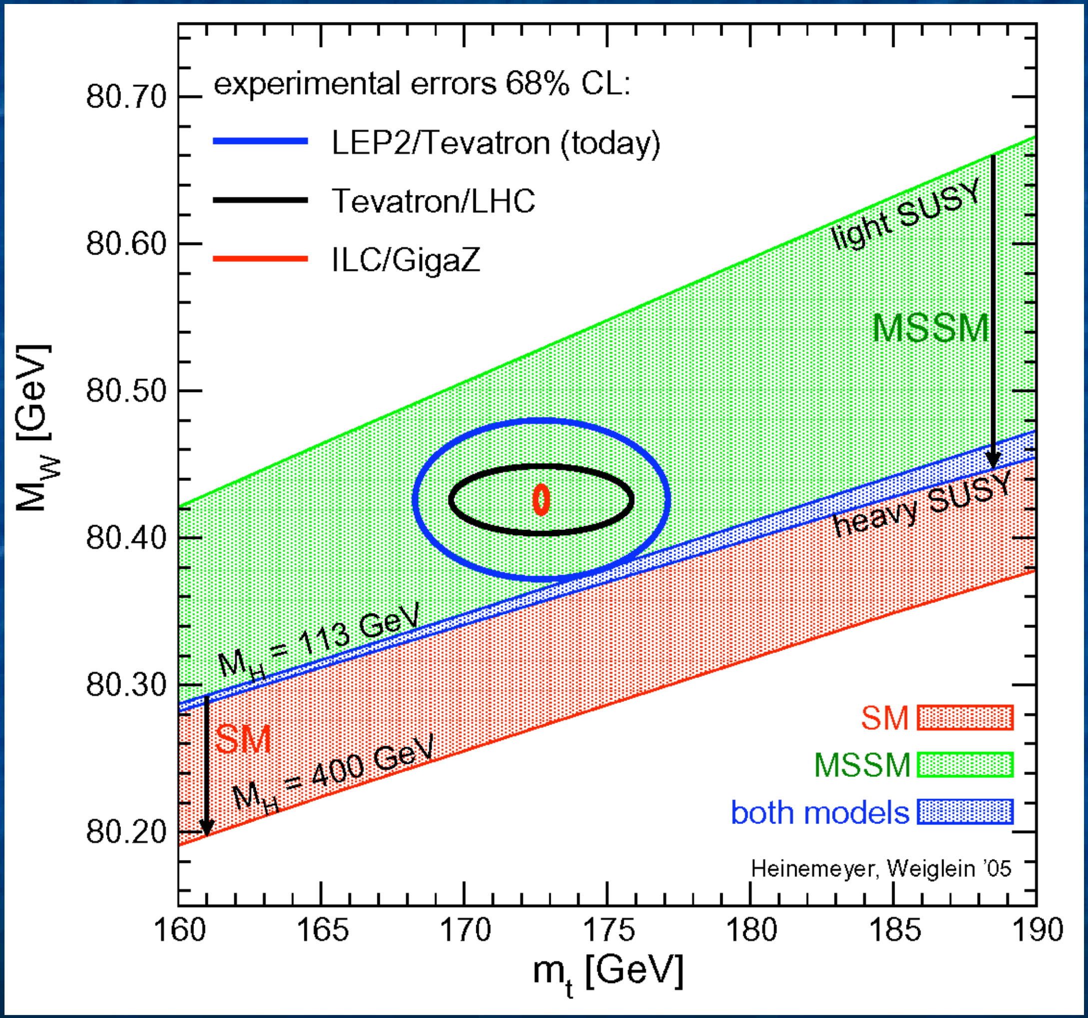
PiTP
IAS Princeton, Summer 2005

Preferences from M_W and m_{top}



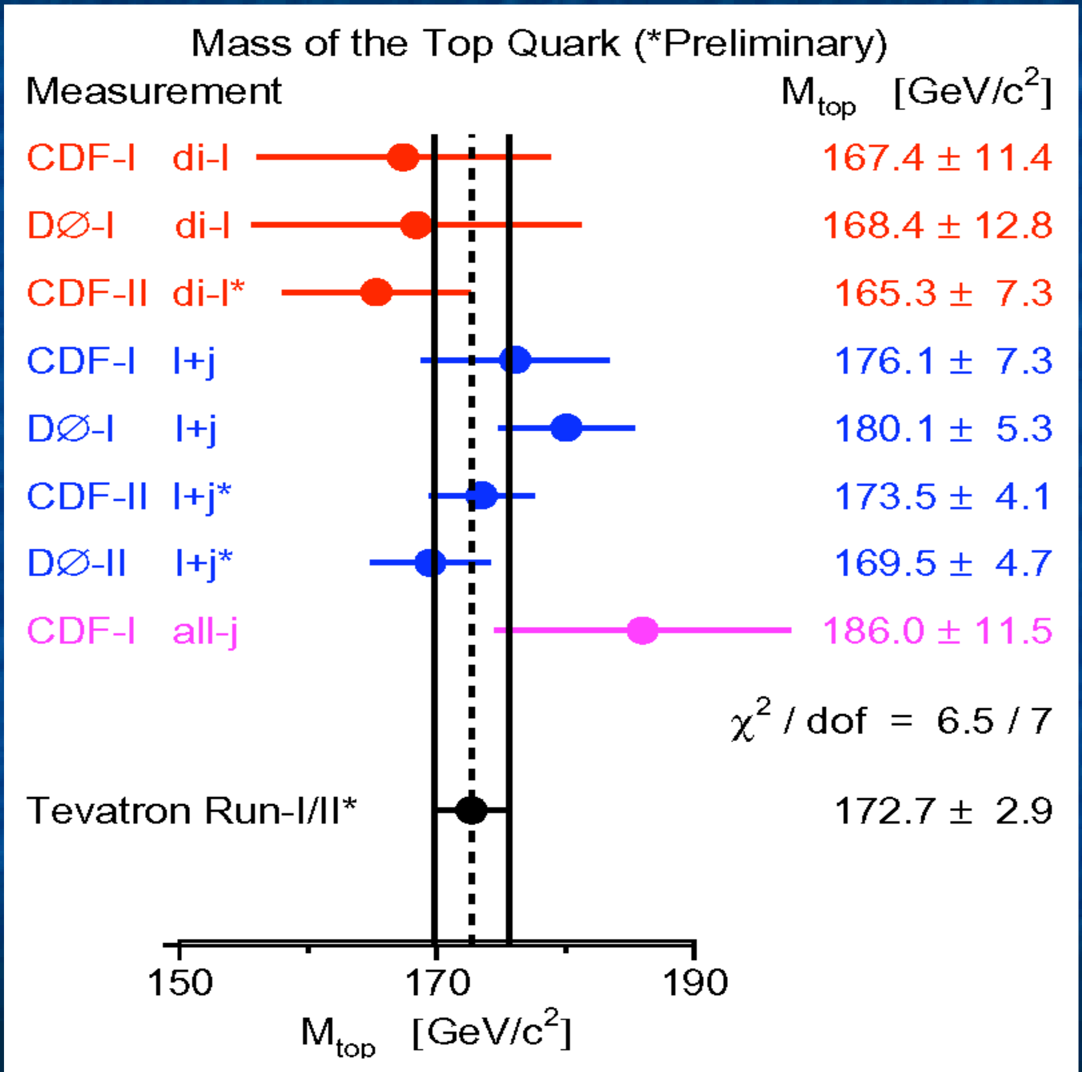
- Error on m_{top} no longer dominates

M_{top} = 172.7 ± 2.9 GeV

New CDF/D0 Mass Combination

- W self-energy may be decisive once M_W improves

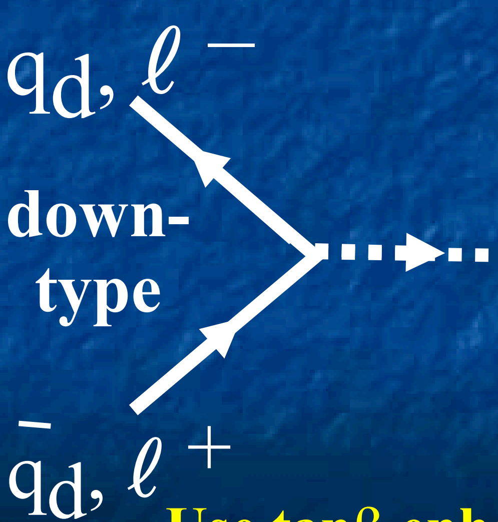
New Top Mass Combination



- This includes new preliminary measurements (based on 320 pb^{-1}) from CDF/D0 which simultaneously fit the jet energy scale with the hadronic W mass constraint
- The correlated systematical error is of order ~1.7 GeV

SUSY Guidance

- Lightest Higgs mass compatible with high tanβ region for wide range of stop mixing

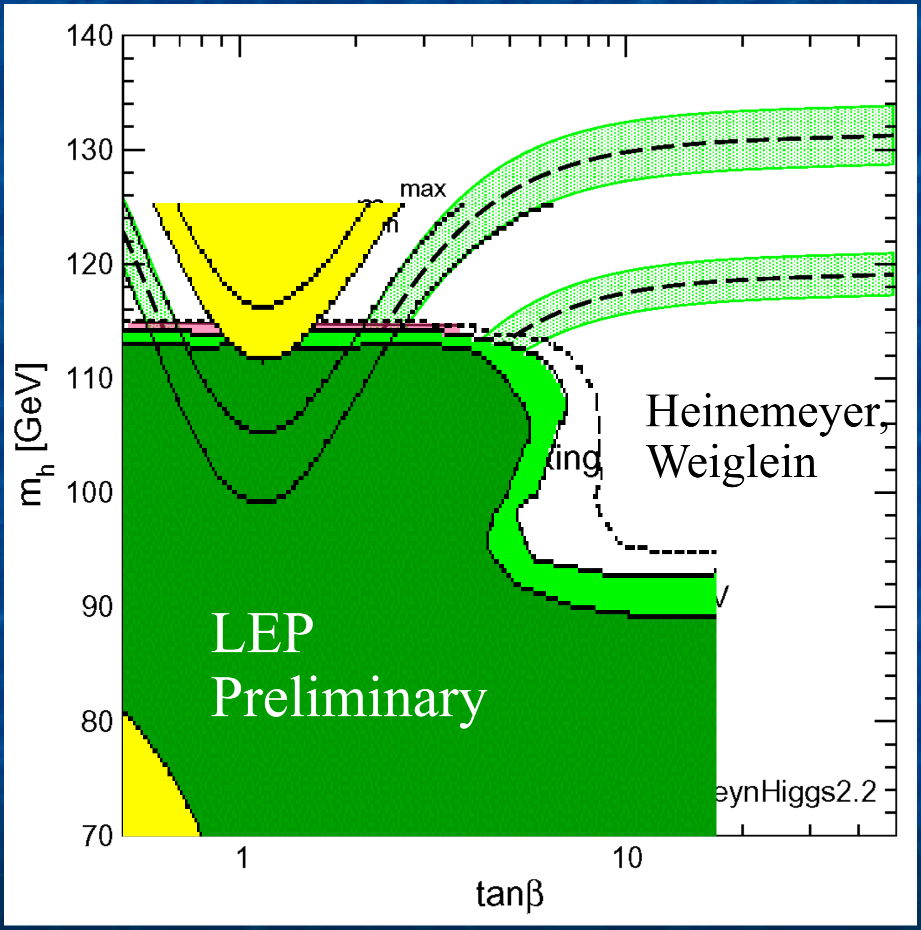


h: $-\dfrac{\sin\alpha}{\cos\beta}$

H: $\dfrac{\cos\alpha}{\cos\beta}$

A: $\dfrac{\sin\beta}{\cos\beta}$

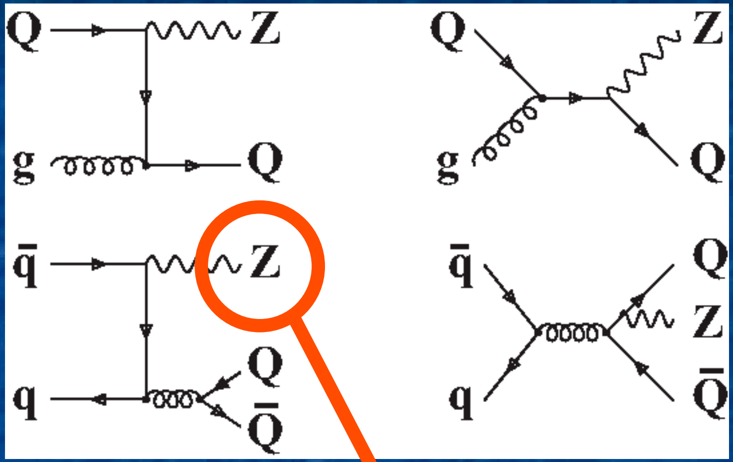
Use tanβ enhancement!

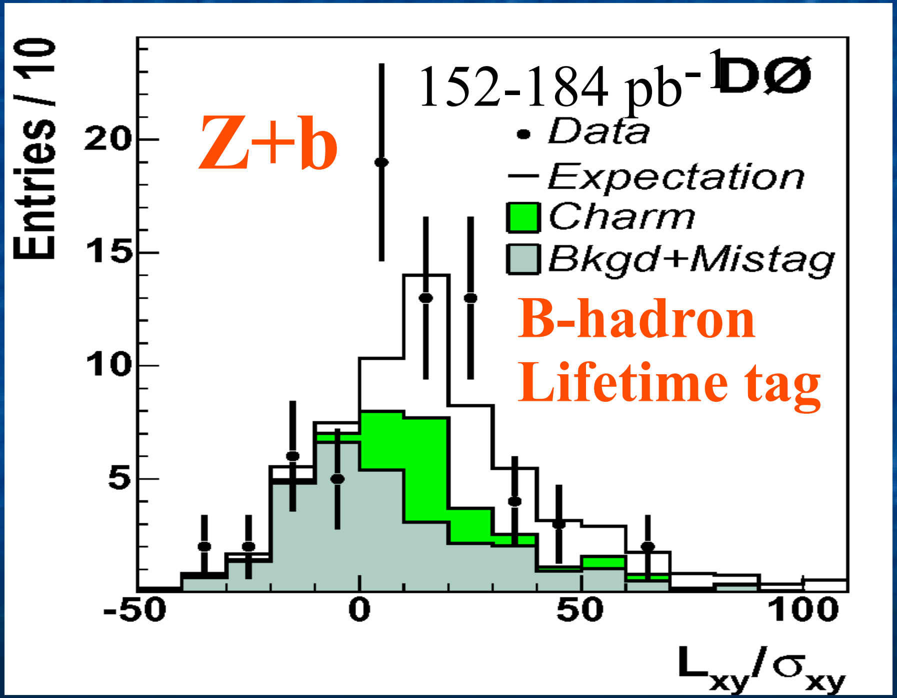


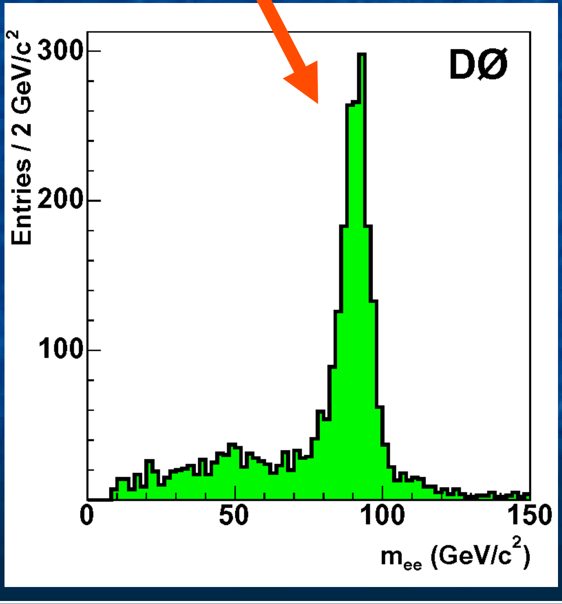
Large b-Production

- But how well known…

Use Leptonically Decaying Z's as a probe!



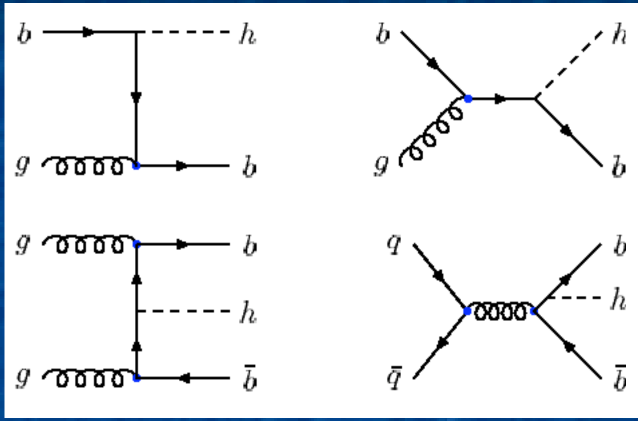


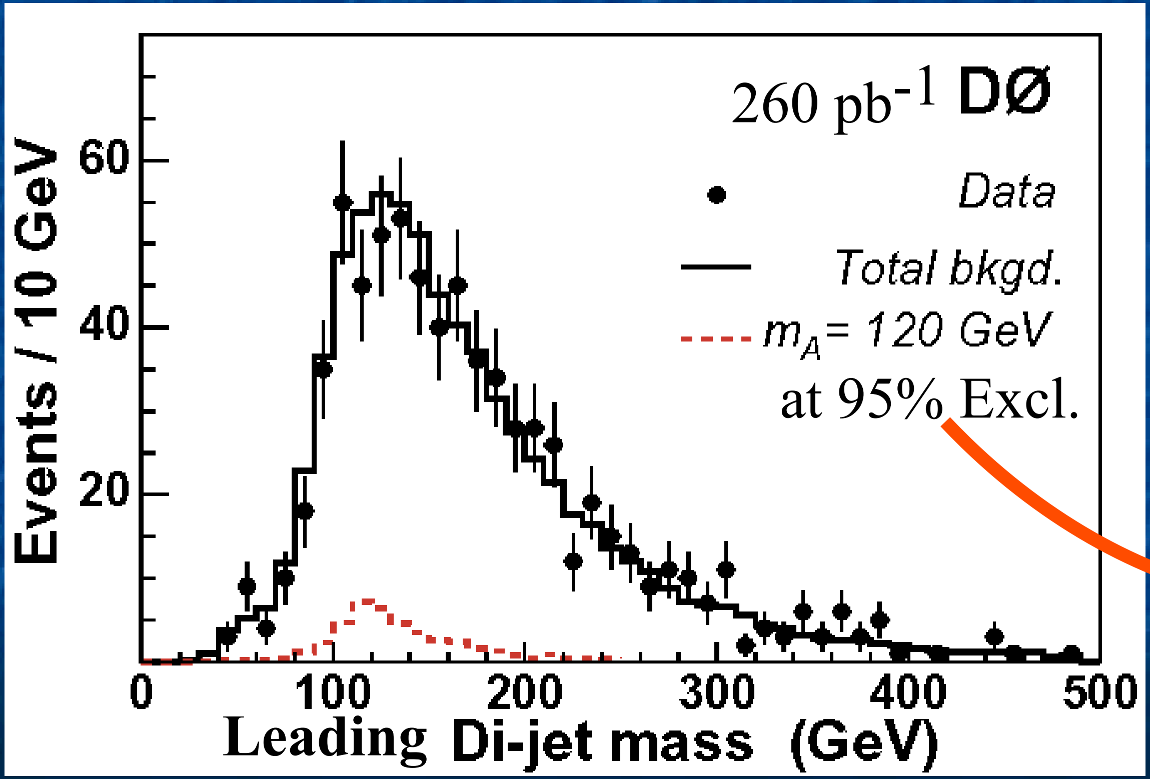


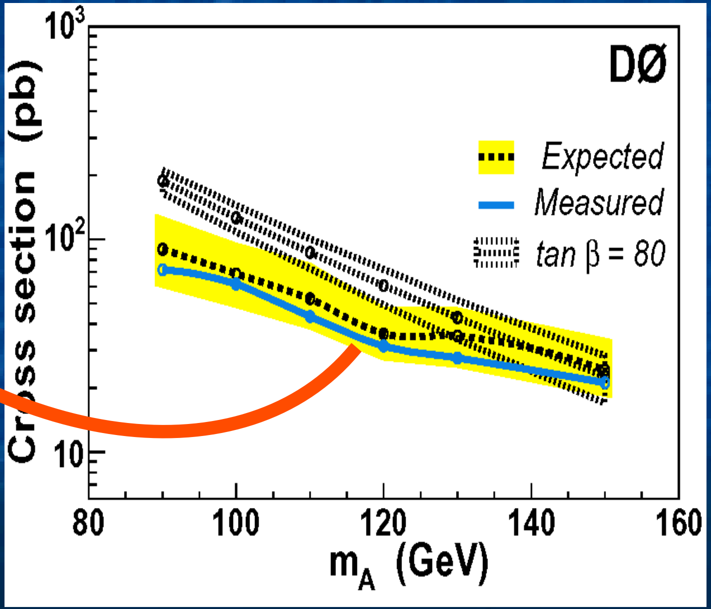
PRL 94, 161801 (2005)

MSSM Higgs b(b)φ Search

- b(b)φ → b(b)bb φ=h/A or H/A
  - At least 3 b-tagged jets
  - Data-derived background shape





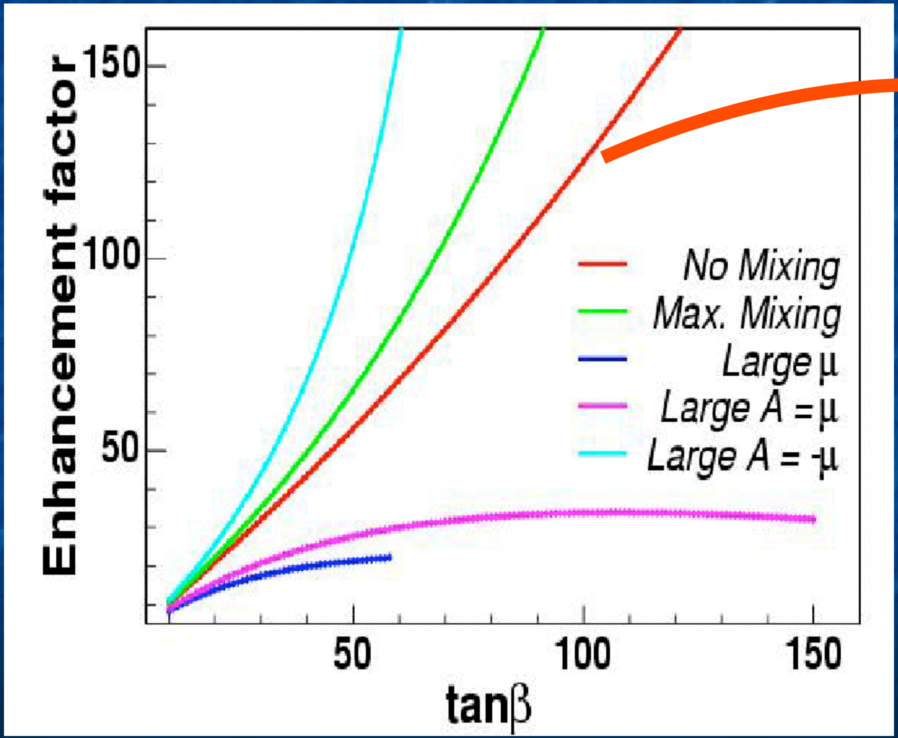


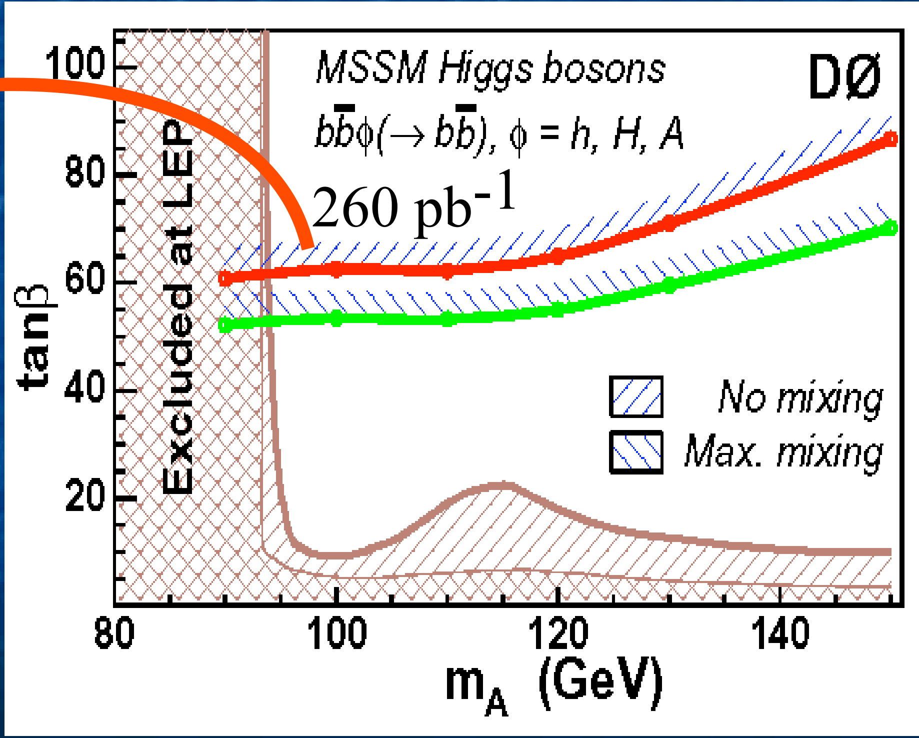
Submitted to PRL

b(b)ϕ Limits: tan^{2}β Enhancement

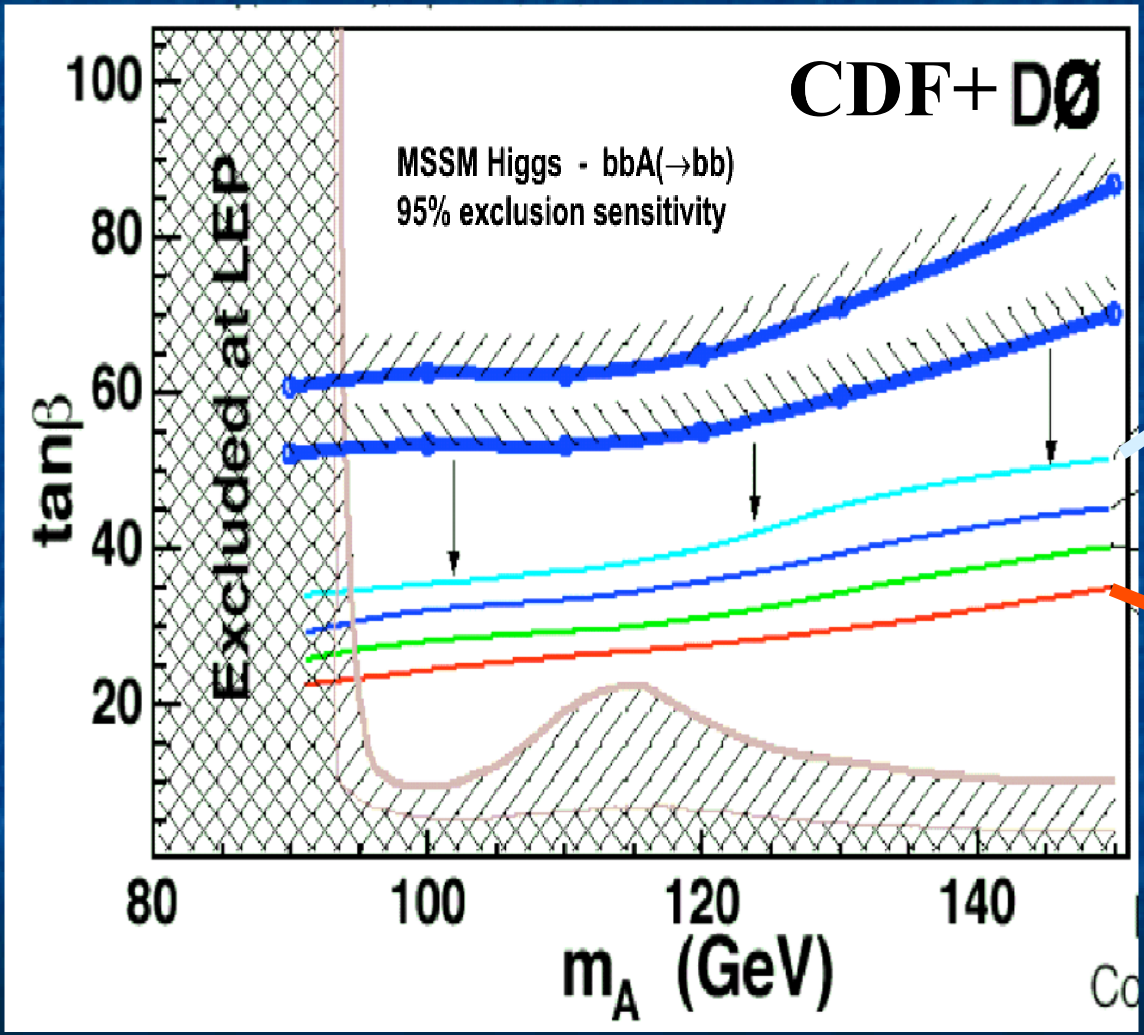
Enhancement depends on loop corrections (Δ_b) and SUSY parameters:

$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{9+(1+\Delta_b)^2}$$





b(b)ϕ Projections



Tevatron will probe below

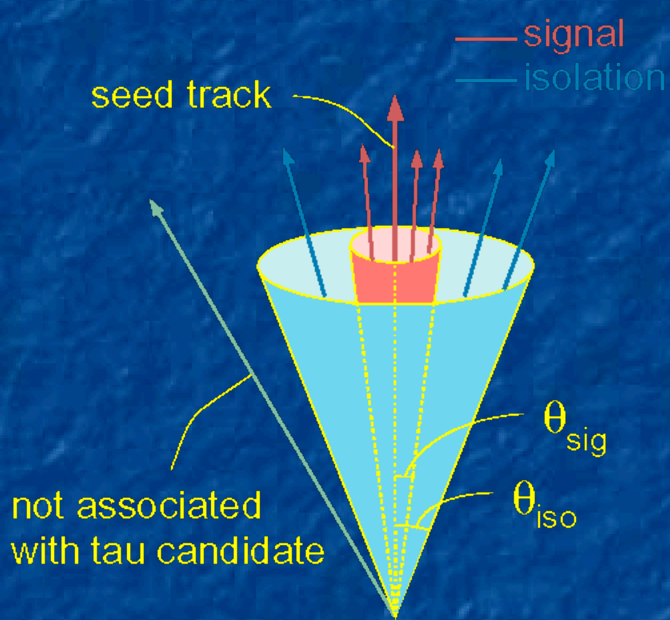
$$\tan\beta = \frac{m_t}{m_b}\ !$$

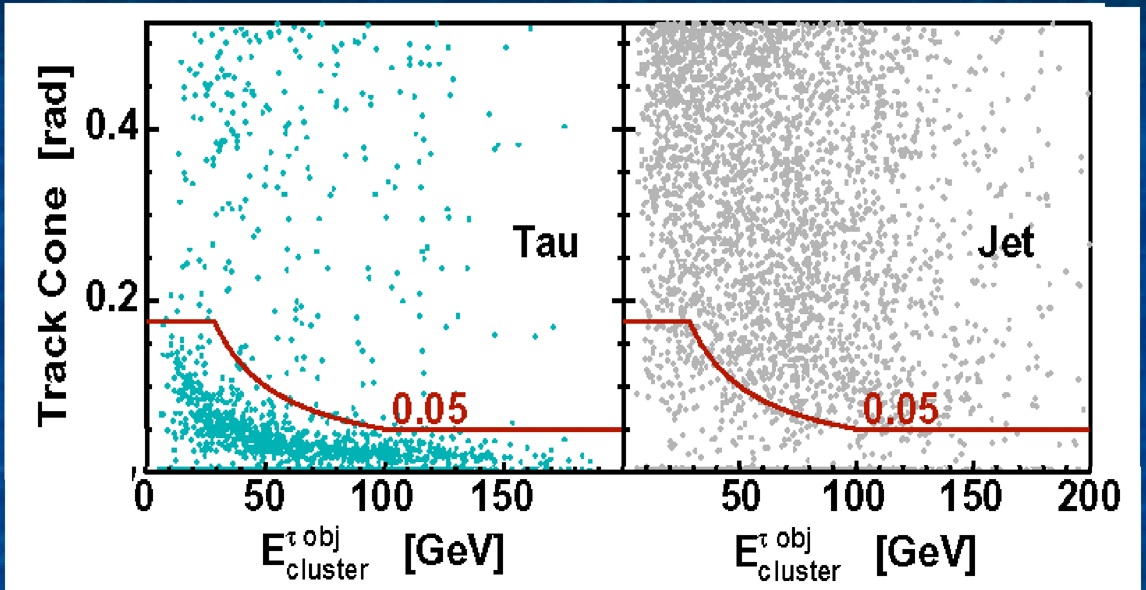
1 fb^{-1}
2 fb^{-1}
4 fb^{-1}
8 fb^{-1}

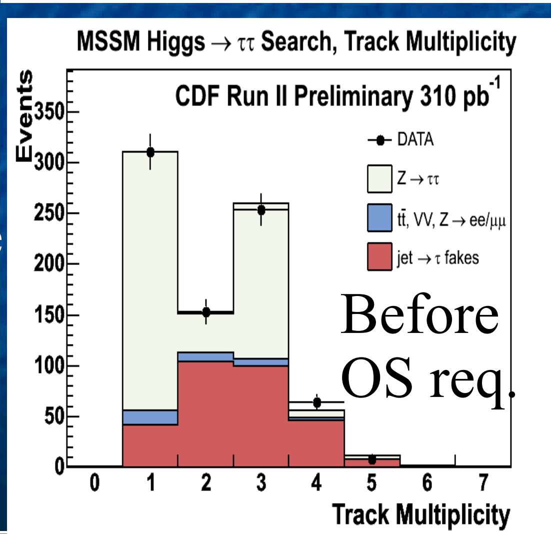
Projection based on existing analysis: Doesn't include proposed b-tag improvements

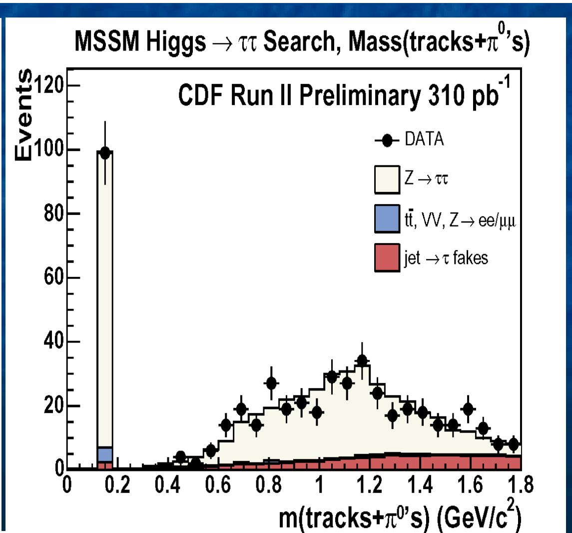
Higgs Decays to τ-leptons

- τ-Identification Methods (CDF)





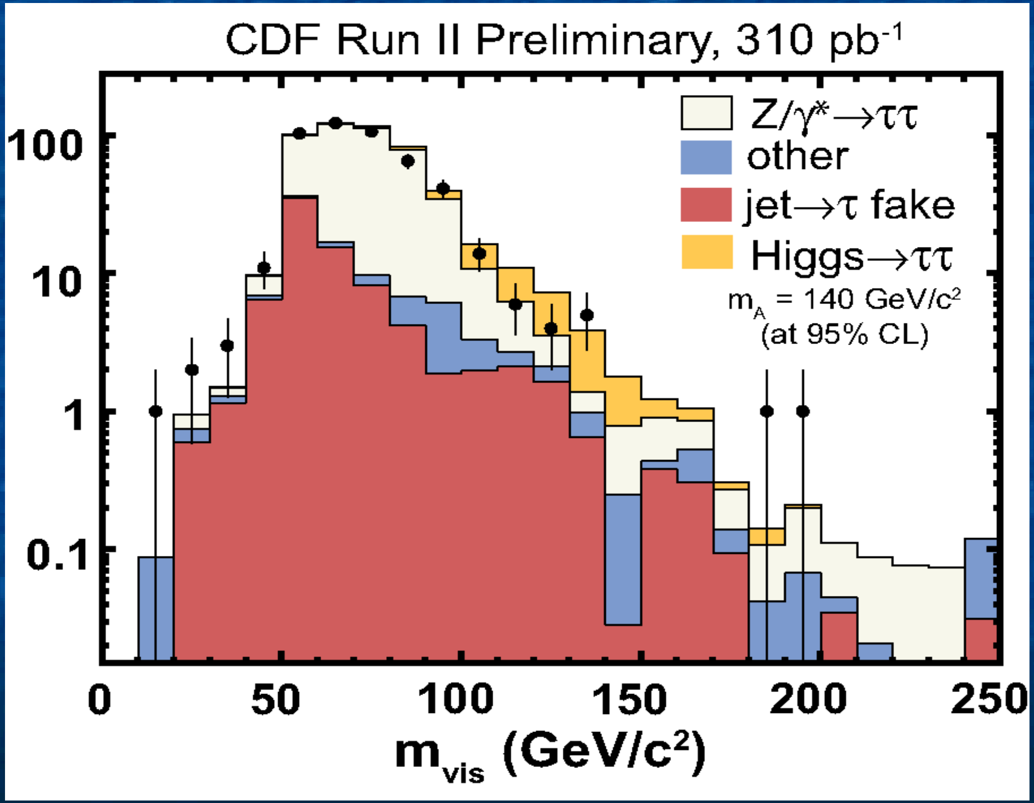


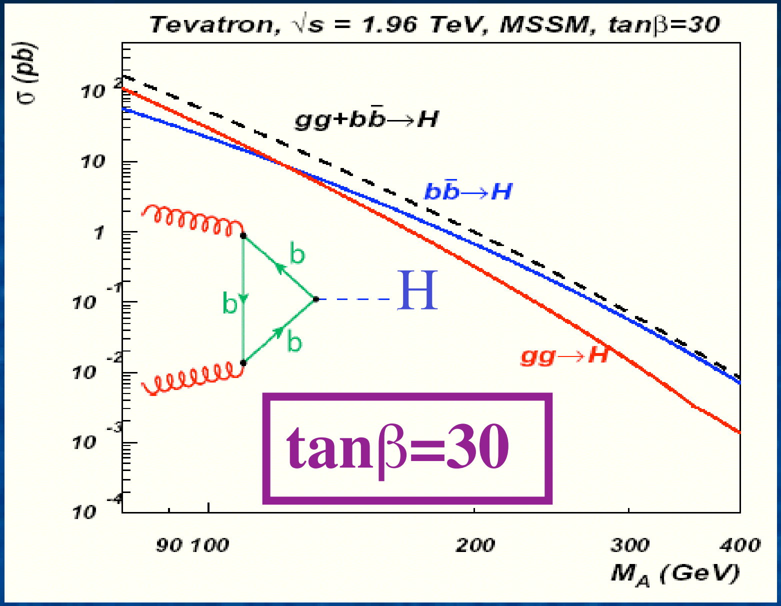


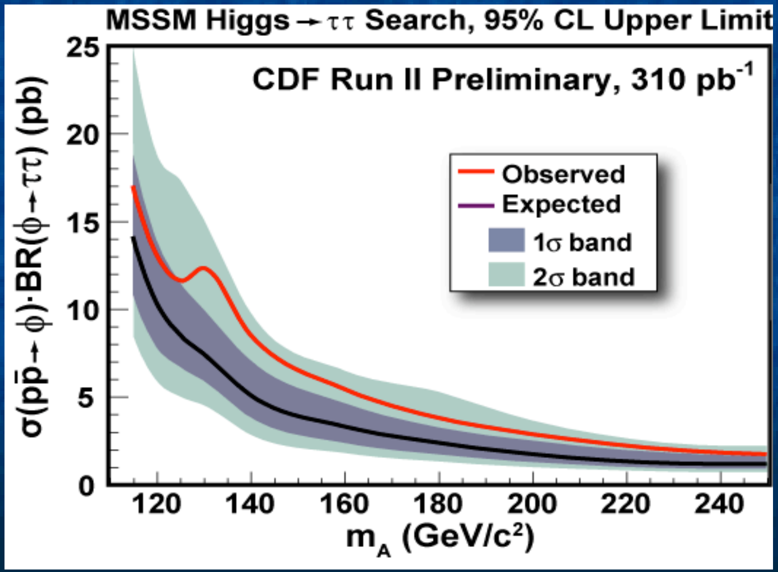
Method yields a rich sample of taus with the expected visible masses and track multiplicities from $Z \rightarrow \tau\tau$

h/H/A→ττ Search

- Visible Mass is the final search variable:



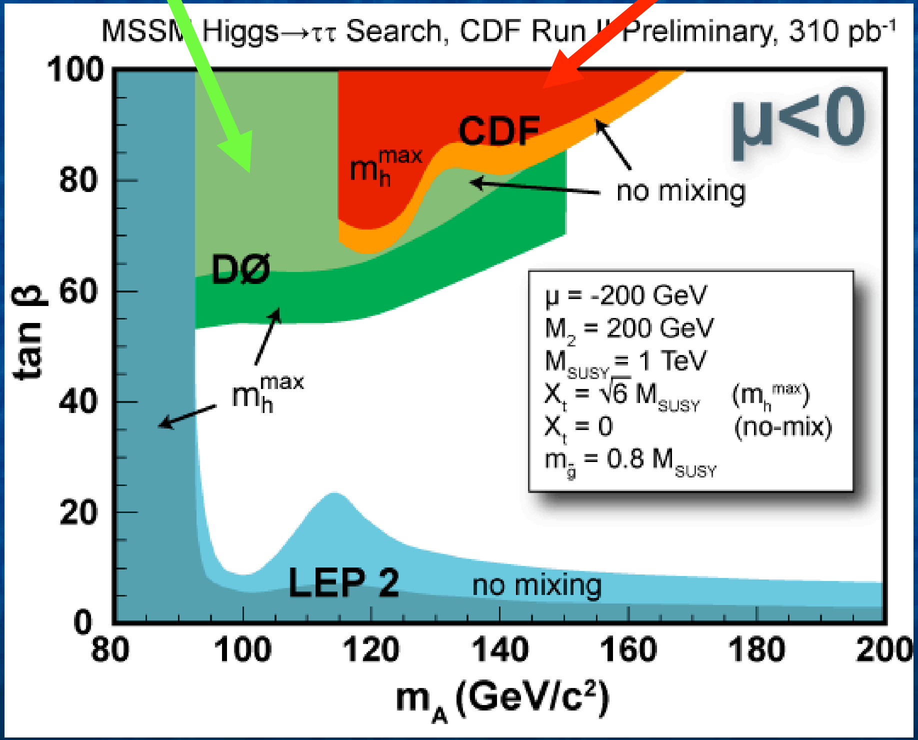


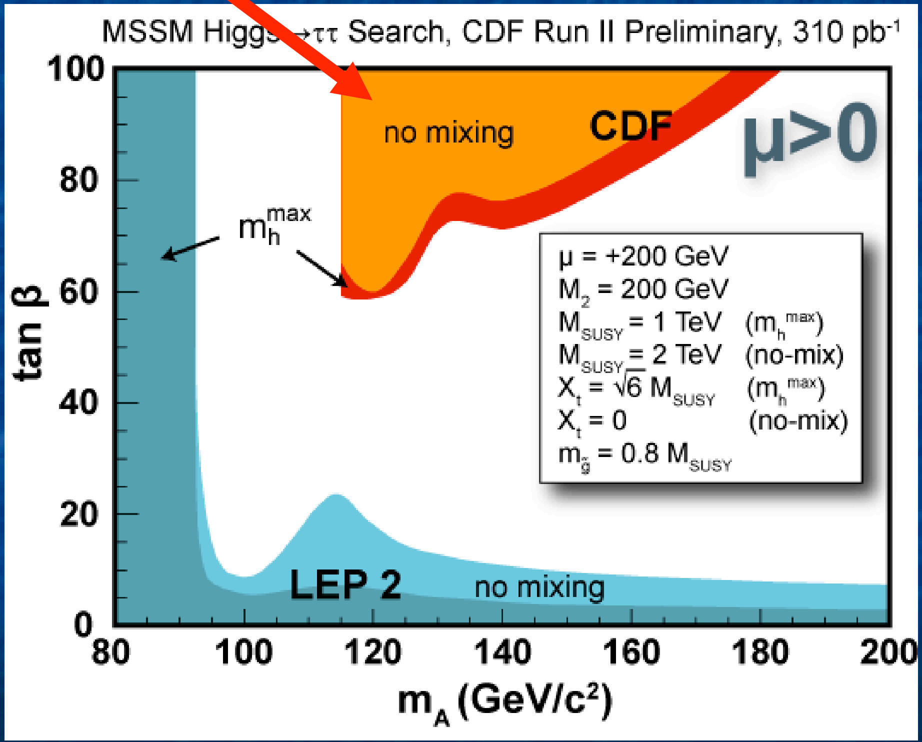


MSSM Higgs→ττ Search

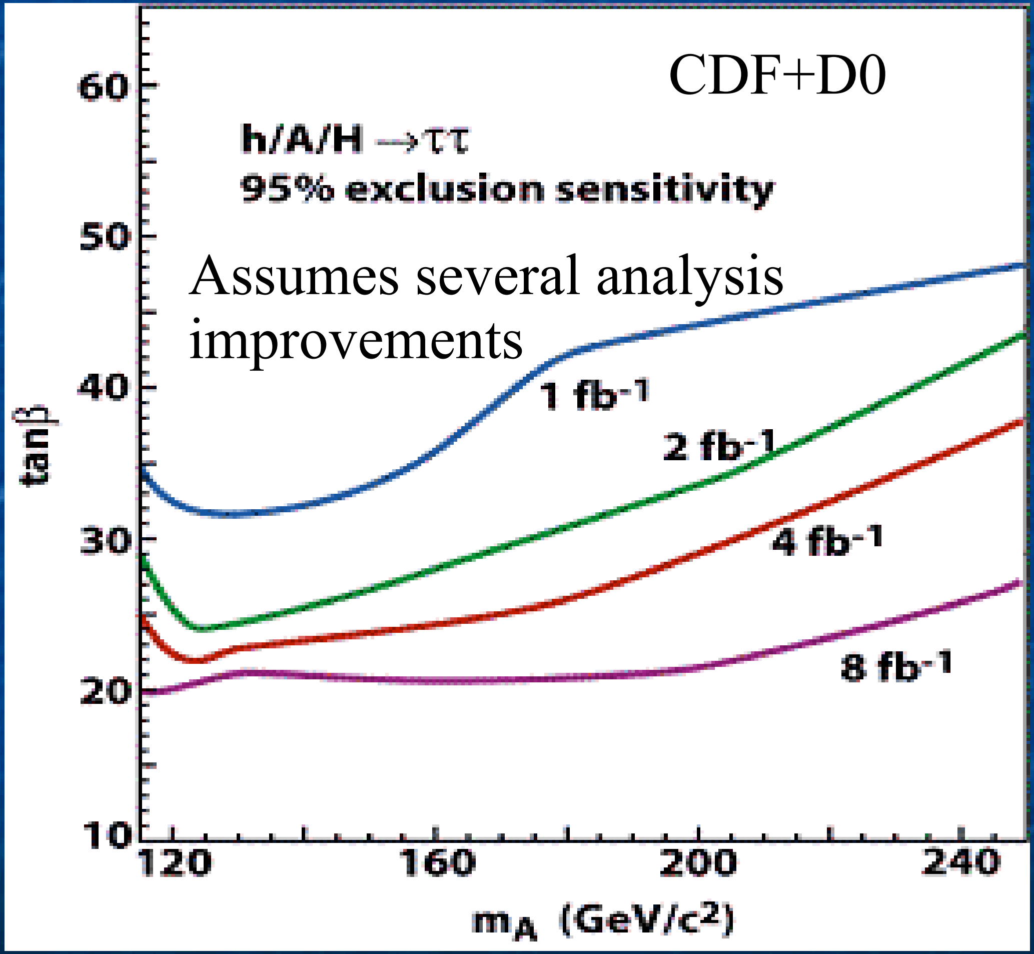
- tanβ Exclusion Limits:

b(b)φ





Higgs→ττ Projections

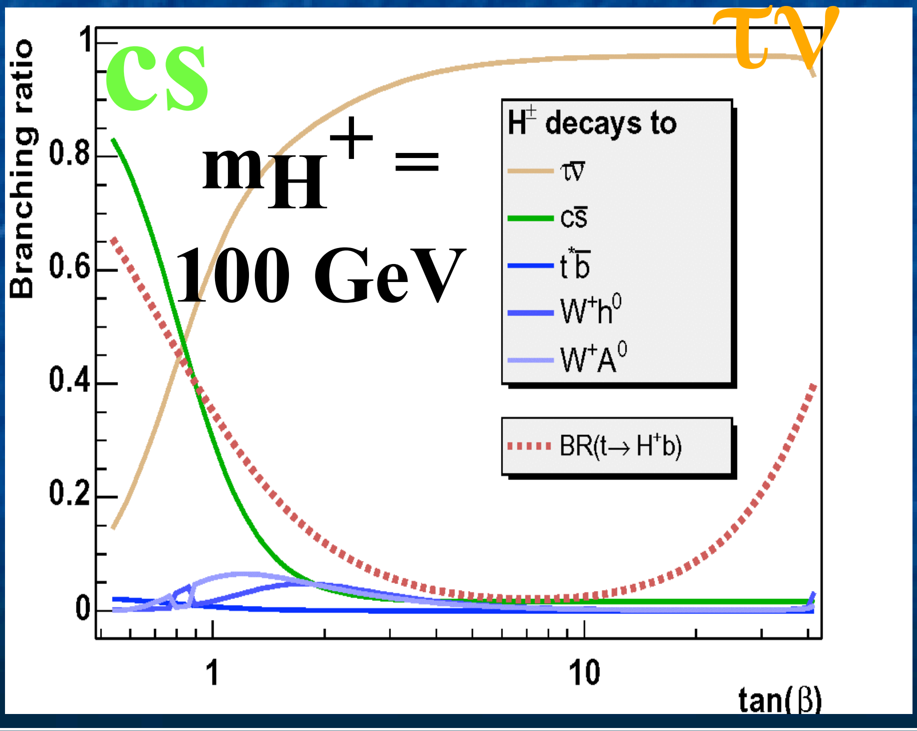


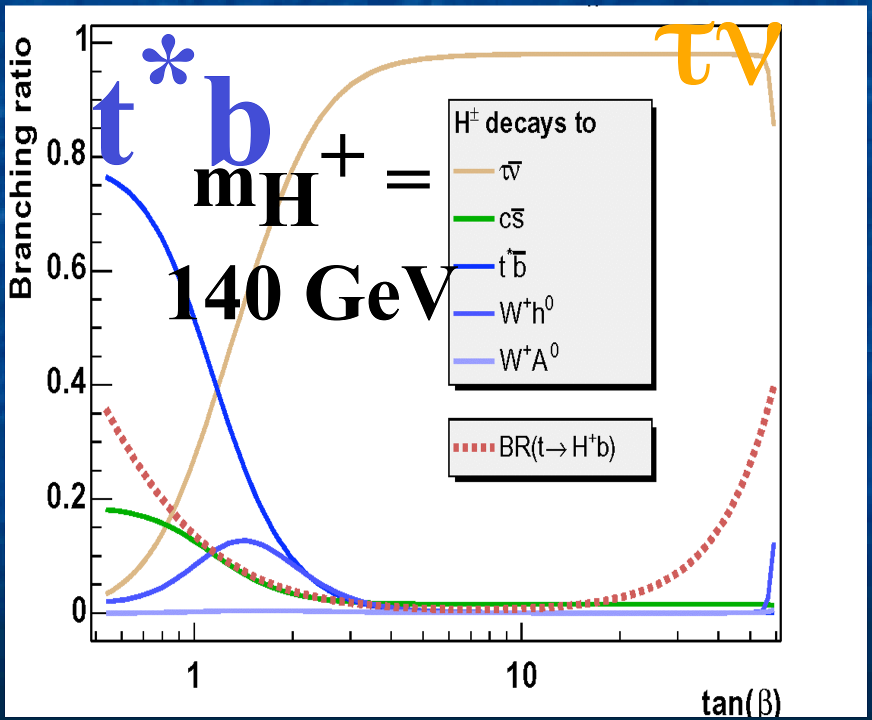
- Higgs→ττ and b(b)ϕ will reach similar sensitivities at the same time

Opens up exciting prospects for learning more about SUSY as y_b and y_τ see different loop-corrections

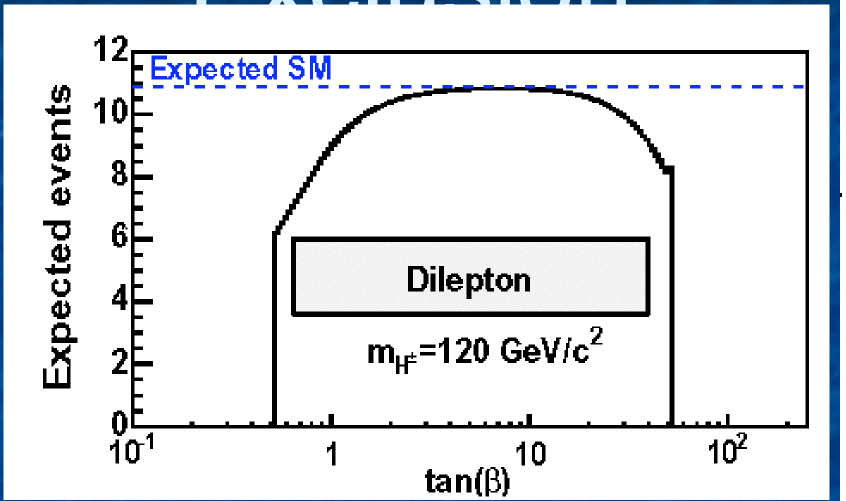
Charged Higgs from top quark decay

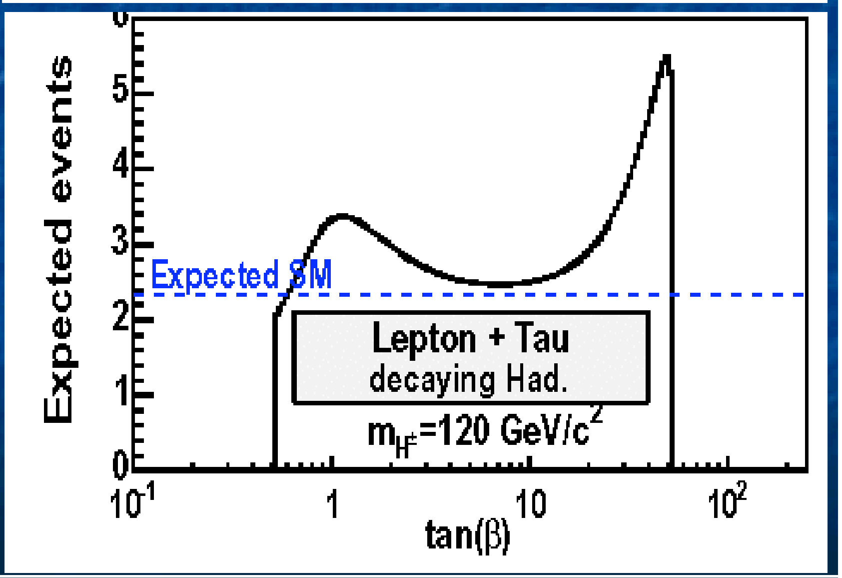
- Predicted to substantially modify top quark Branching Ratios at high and low tanβ
- Additional sensitivity in lepton + τ channel

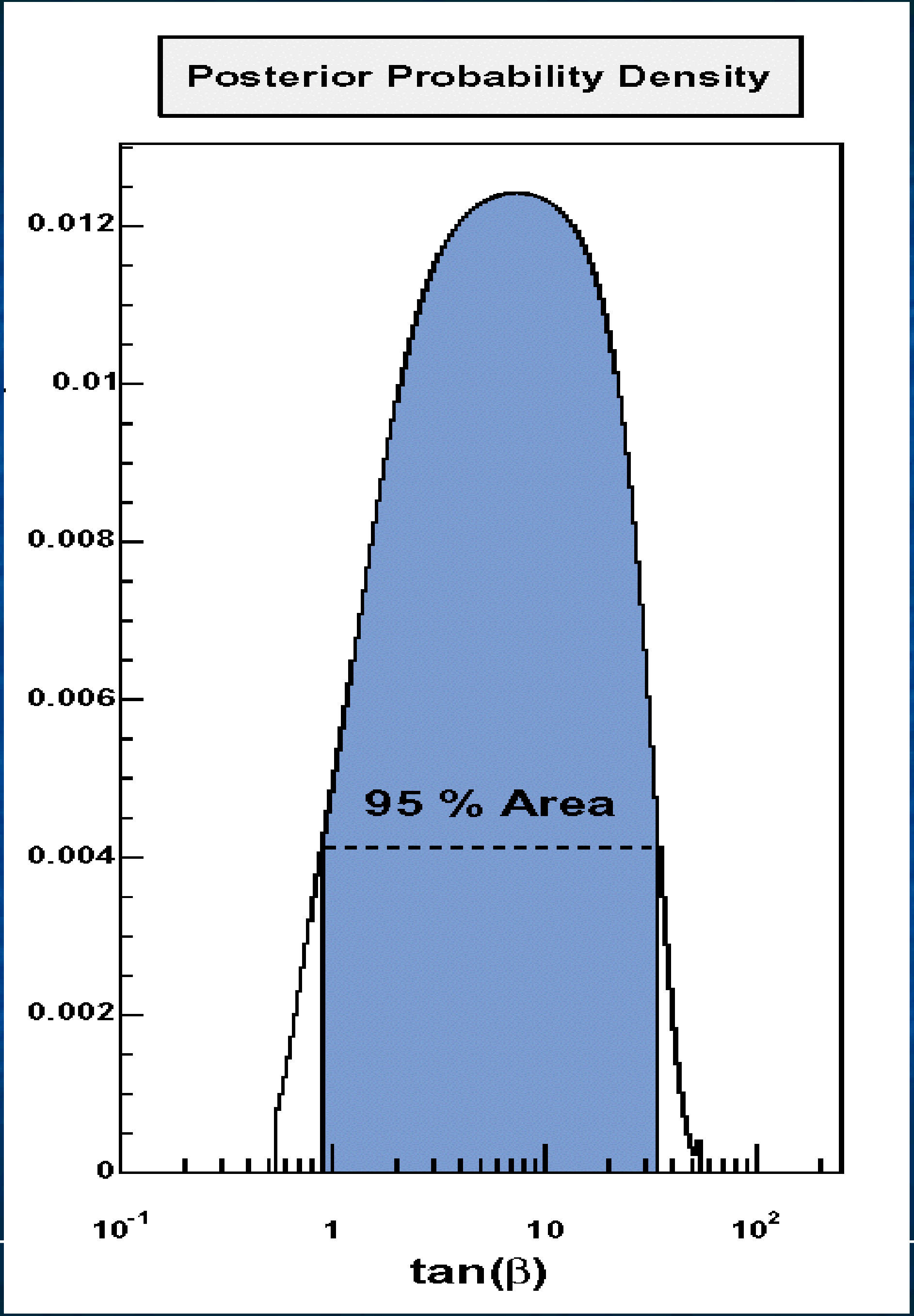




H^+ tanβ Exclusion

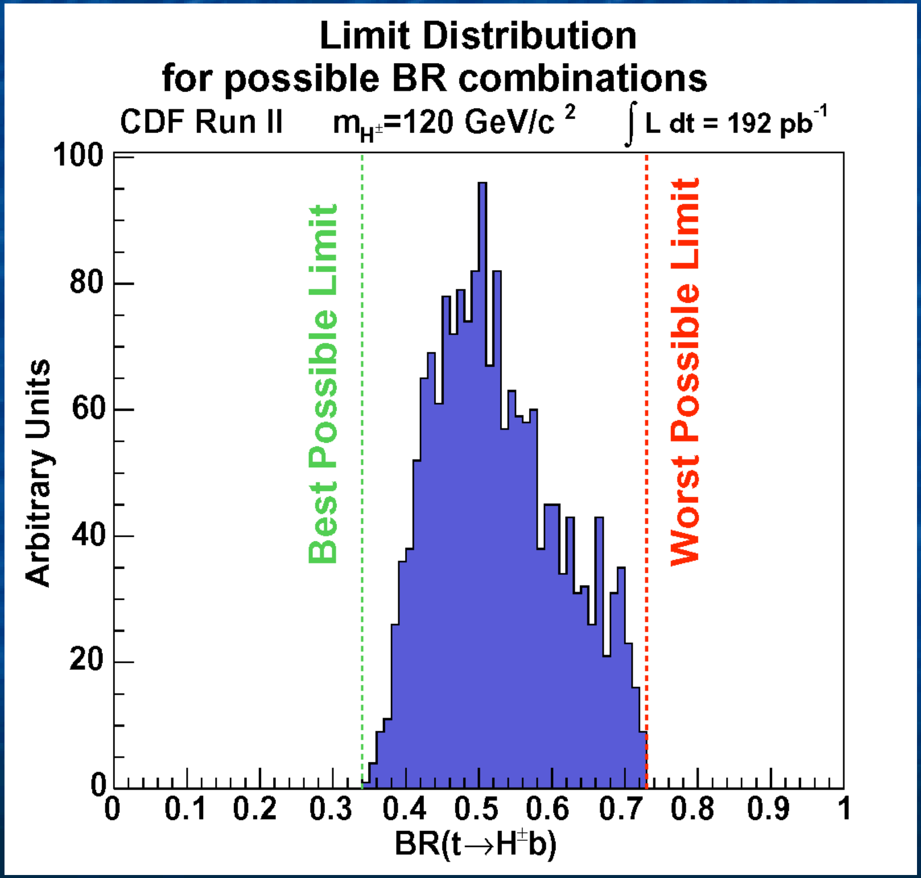


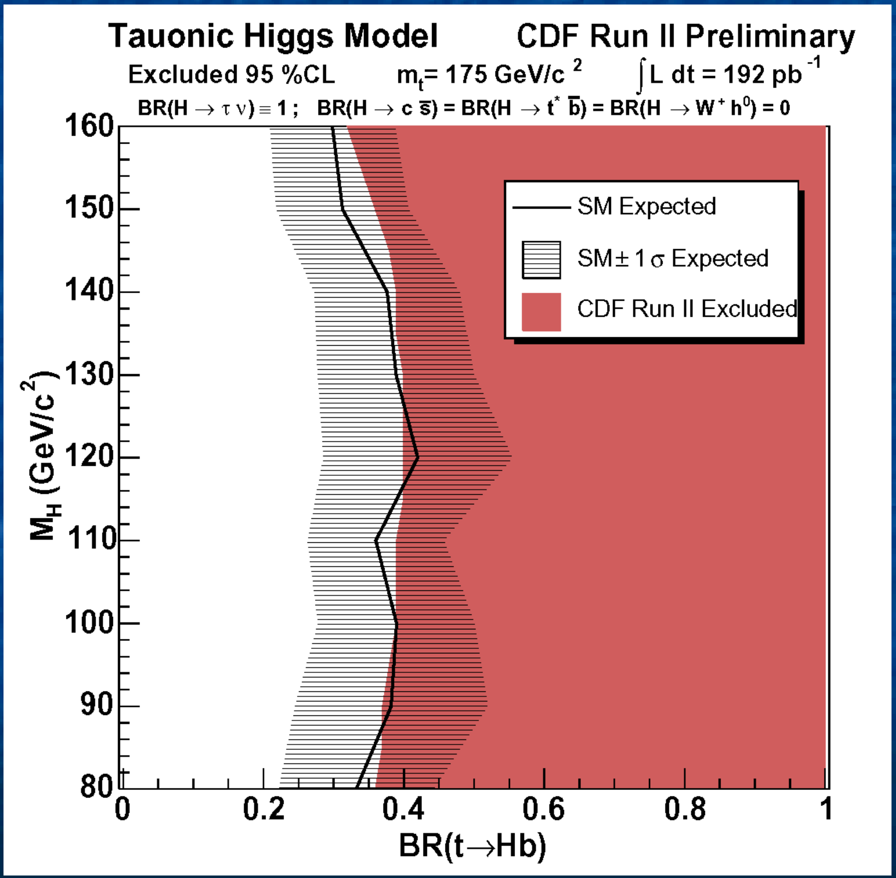




Br(t→H⁺b) Exclusion for Br(H⁺→τν)=1

- Range of Exclusions Br<0.4 to Br<0.7 depending on MSSM parameters





H⁺→cs Search in progress

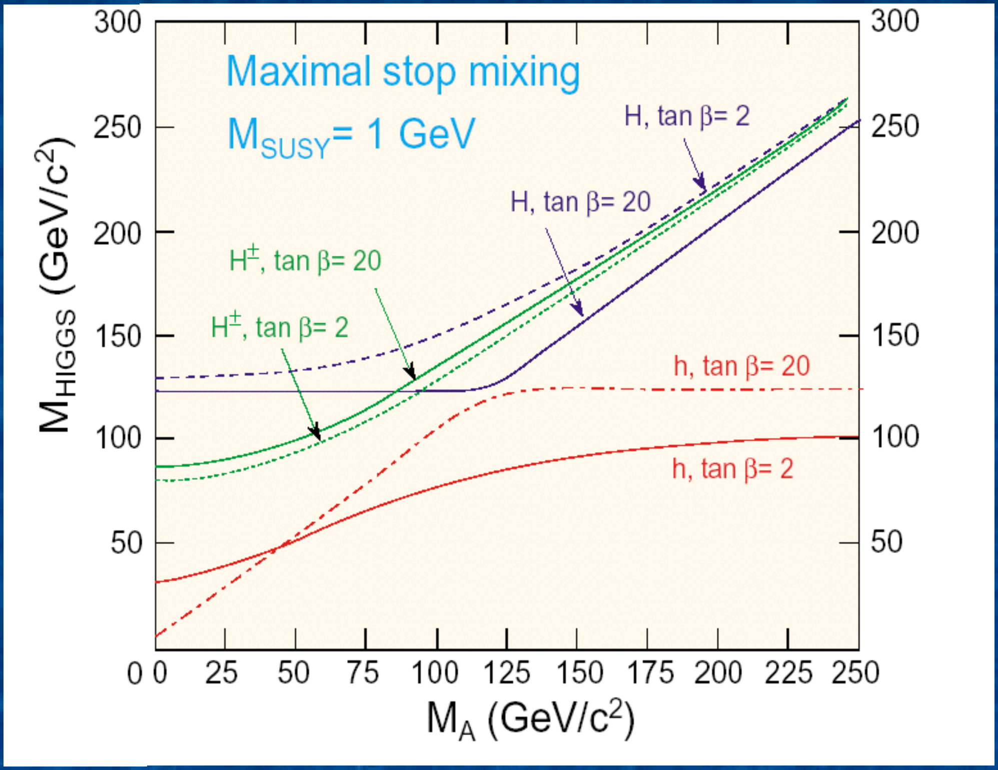
MSSM Higgs Searches

- Two Higgs doublets model

  5 Higgs bosons:

  - 2 Neutral scalars h,H
  - 1 Neutral pseudo-scalar A
  - 2 Charged scalars $H^{\pm}$

- In the MSSM Higgs sector masses and couplings are determined by two independent parameters



- Most common choice:
- tanβ – ratio of vacuum expectation values of the two doublets
- M_A – mass of pseudo-scalar Higgs boson

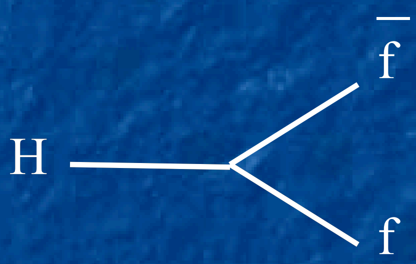
In the MSSM:
$M_h \lesssim 135$ GeV

Neutral MSSM Higgs bosons

- Decoupling limit ($M_A \gtrsim 200$ GeV)
  - h behaves SM-like
  - Standard model searches directly apply
  - $M_H \sim M_A \sim M_{H\pm}$
- $M_A = O(M_Z)$ and large $\tan\beta$
  - H behaves similarly to SM Higgs (SM searches apply)
- In other cases for large $\tan\beta$ and $M_A < 200$ GeV
  - A → WW,ZZ never allowed at tree level
  - h,H→ WW,ZZ highly suppressed
  - h,H,A almost exclusively decay into bb and $\tau\tau$
- Large M_A small $\tan\beta$
  - H,A decays almost 100% into tt
  - for lower masses (200-300 GeV) also H → hh and A → Zh
- If SUSY particles are light the Higgs bosons may decay into s-particles

MSSM Higgs Couplings to Fermions

Higgs couplings to fermions:



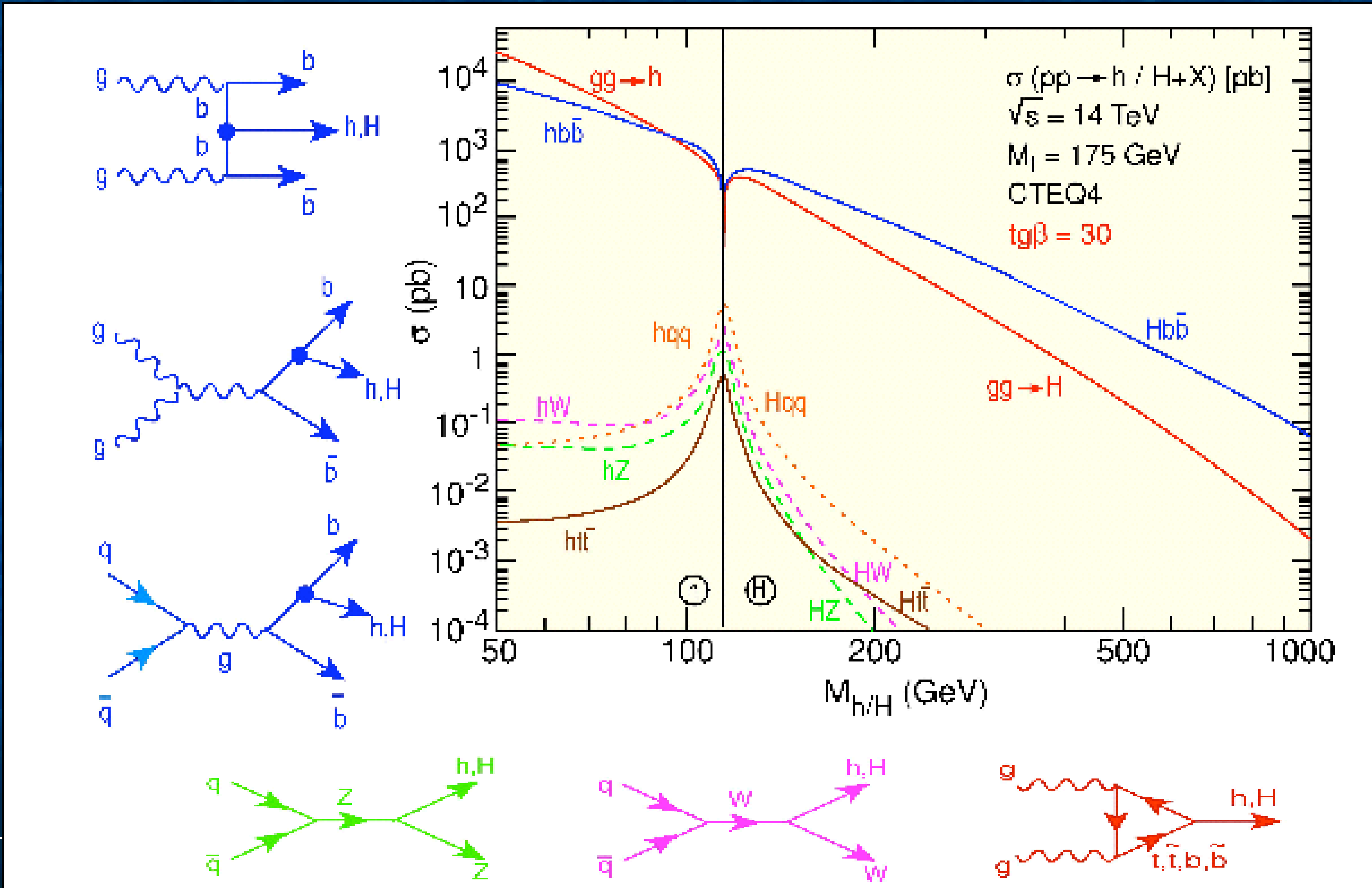
$$g_{htt} \propto m_t \frac{\cos\alpha}{\sin\beta} \qquad g_{hbb} \propto m_b \frac{-\sin\alpha}{\cos\beta}$$

$$g_{Htt} \propto m_t \frac{\sin\alpha}{\sin\beta} \qquad g_{Hbb} \propto m_b \frac{\cos\alpha}{\cos\beta}$$

$$g_{Att} \propto m_t \cot\beta \qquad g_{Abb} \propto m_b \tan\beta$$

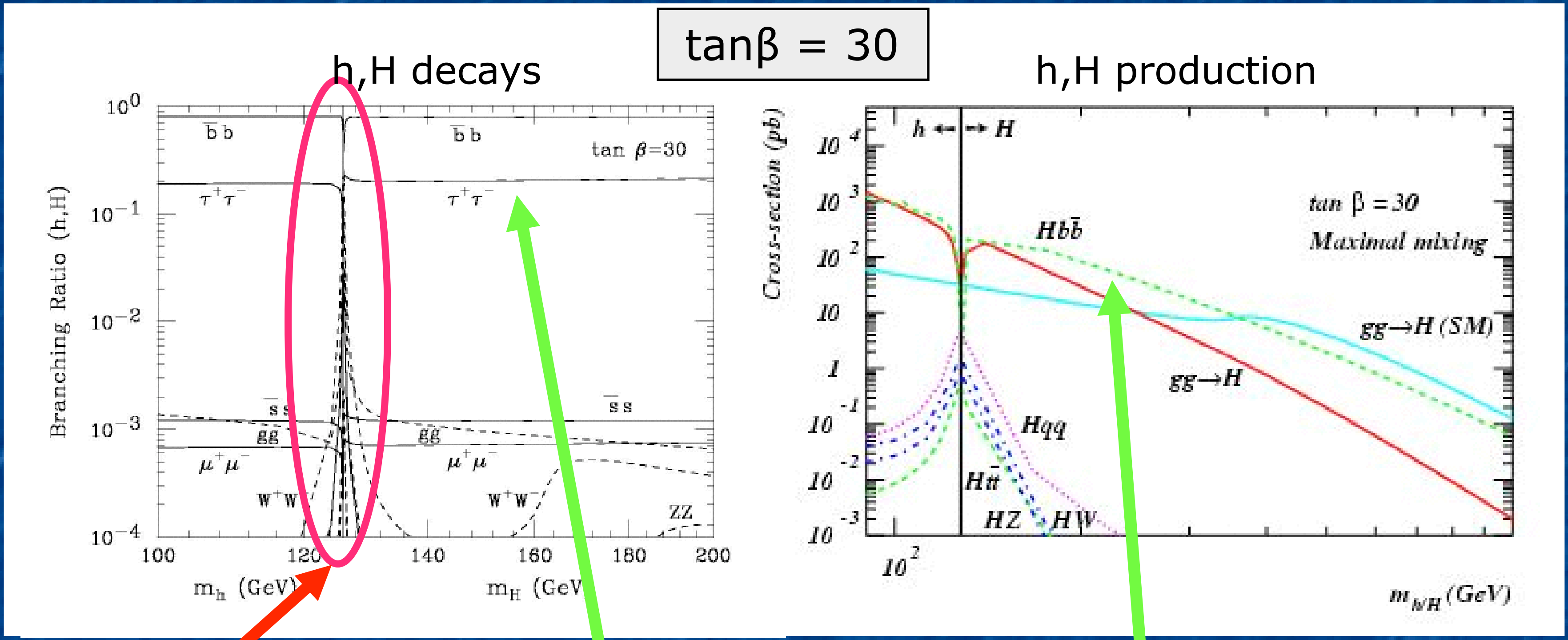
- **proportional to mass → 3rd generation favored**
- **tan β enhances couplings to down-type fermions**

MSSM Higgs Production



h,H Production and Decay

tanβ = 30

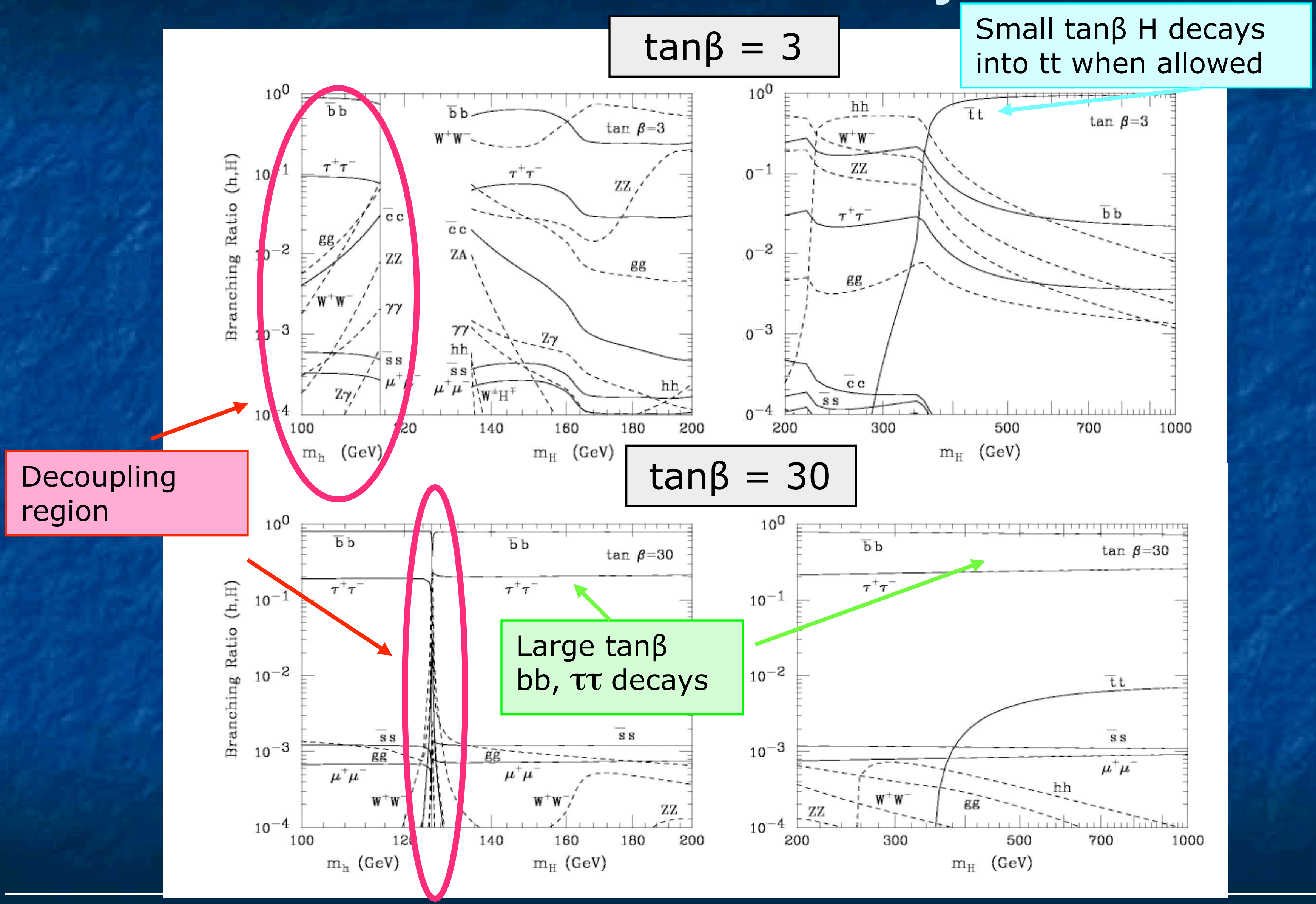


Decoupling region

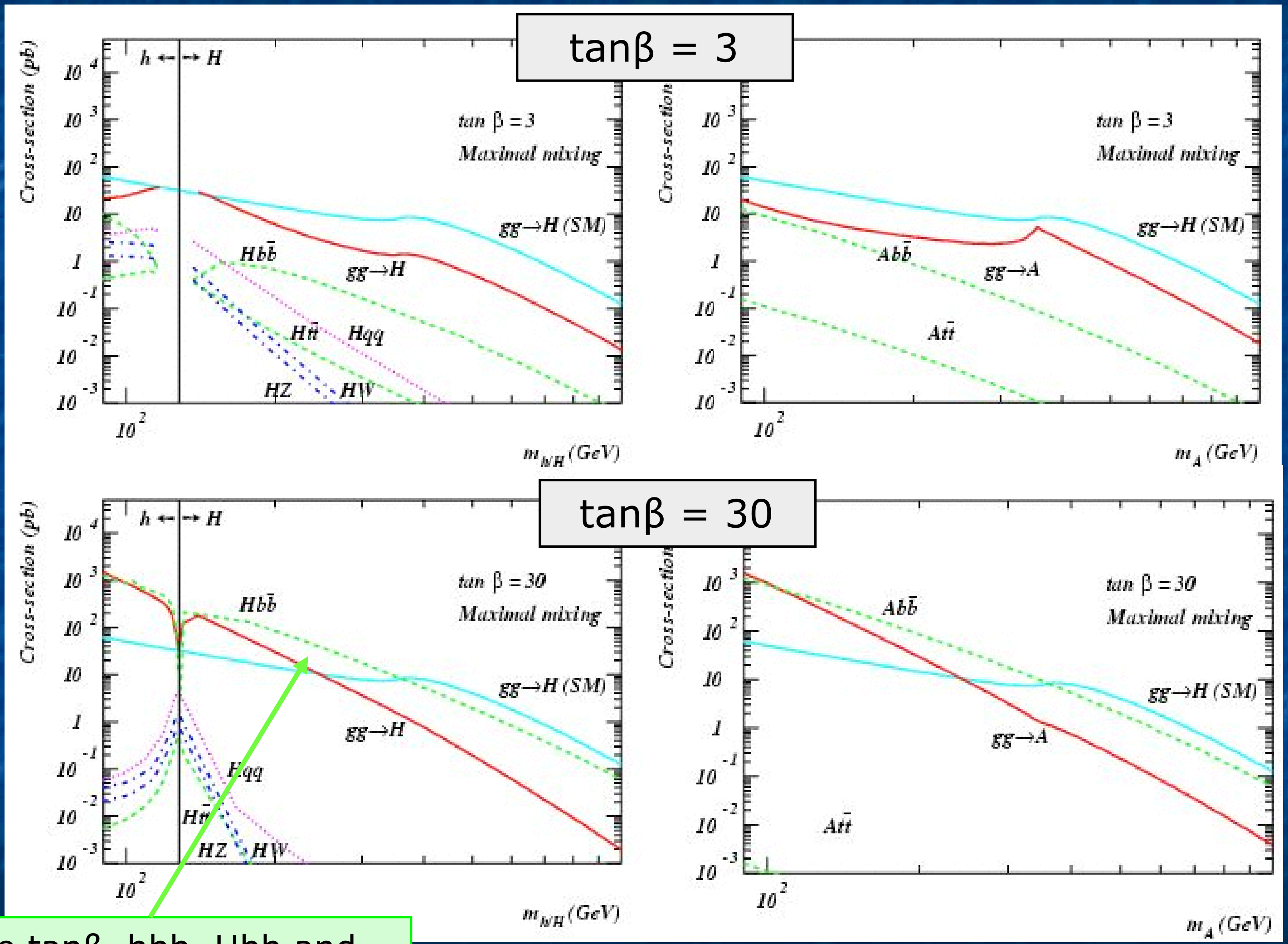
Large tanβ mainly bb, ττ decays

Large tanβ hbb, Hbb (and Abb) production dominates

MSSM h,H Decays



MSSM Production Processes

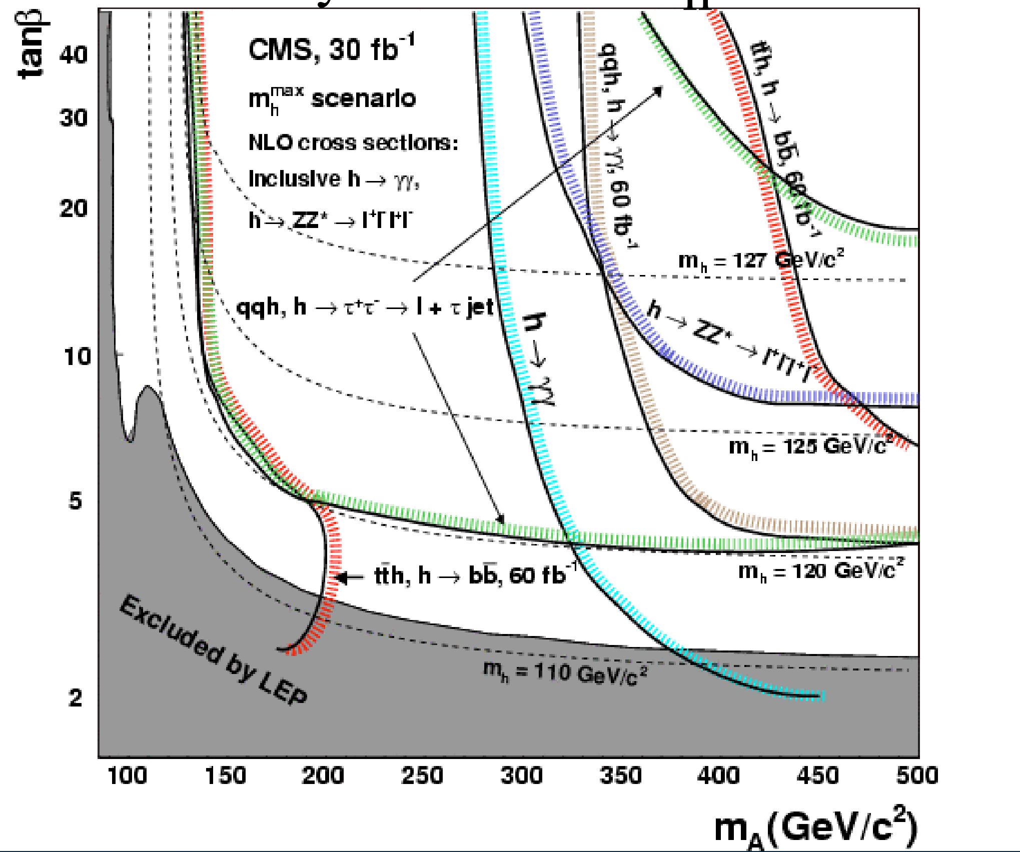


Large tanβ hbb, Hbb and Abb production dominates

h Discovery from SM Higgs Searches

- **In a large part of the MSSM parameter space SM Higgs searches are effective to find the MSSM h boson**

5σ discovery contours in m_h^{max} scenario

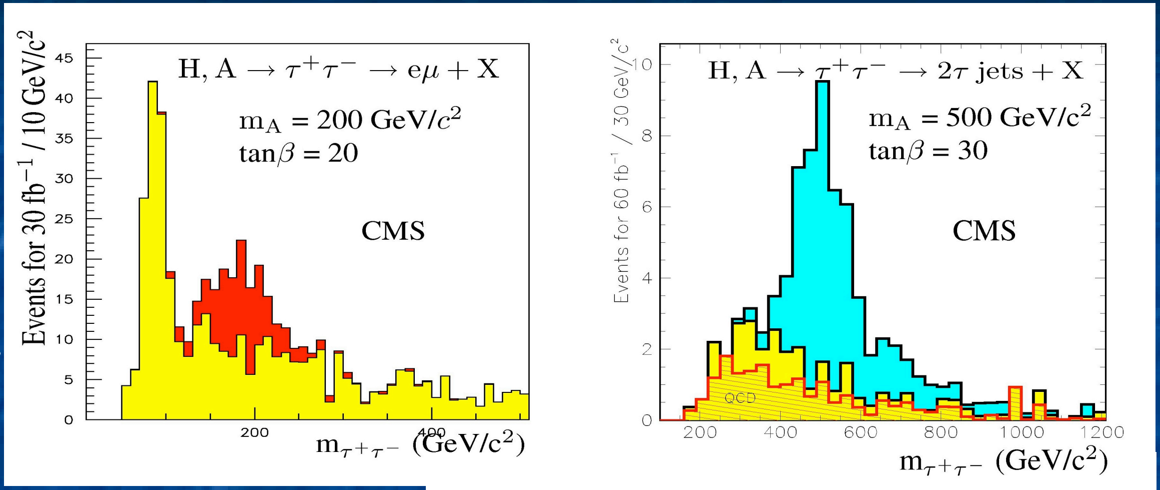


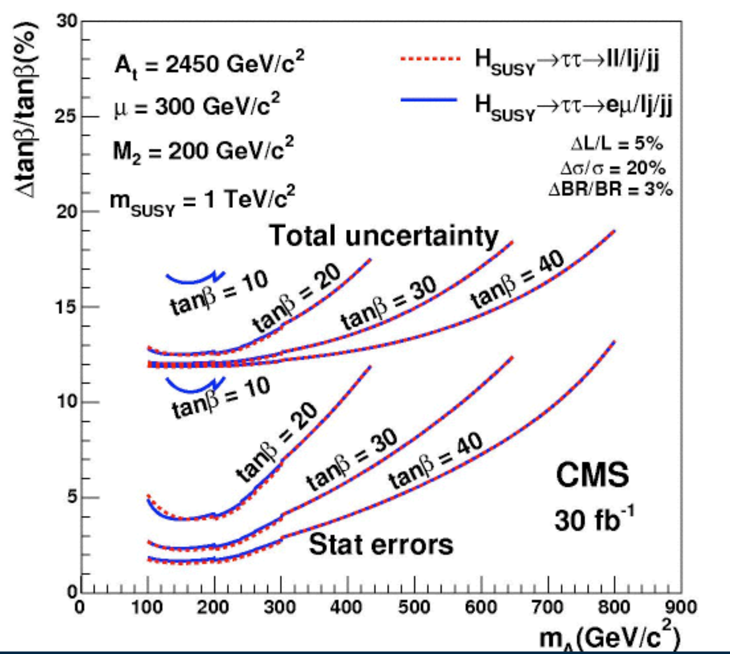
- In the decoupling region if h observed hard to distinguish SM from MSSM
- Search for H, A and $H^{\pm}$
- For large tanβ exploit the large cross section of Higgs boson production in association with a bb pair
  - *bbH,A → bbττ*
  - *bbH,A → bbμμ*
  - *bbH,A → bbbb (very difficult)*

bbH,A → bbττ

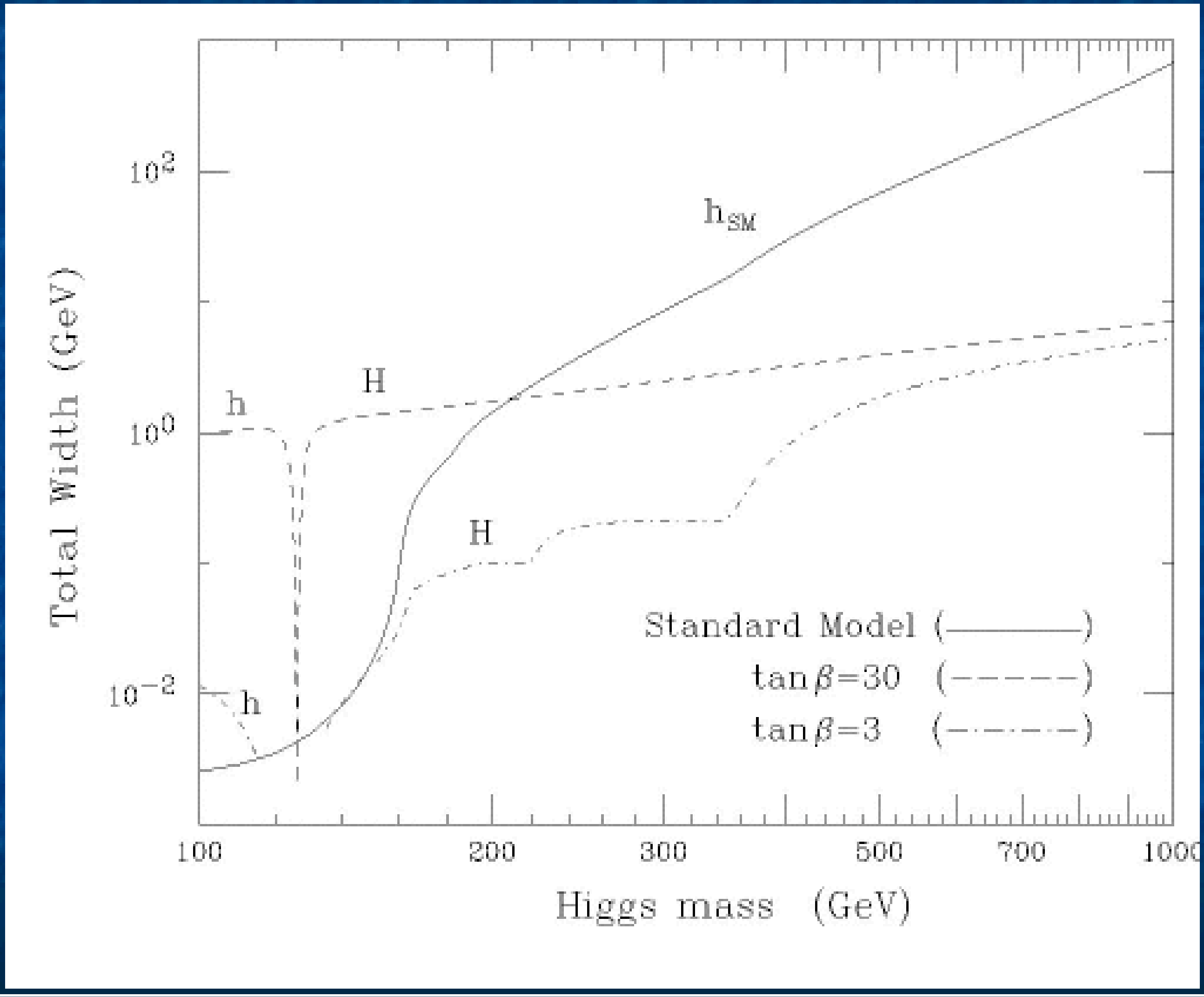
bbH,A → bbττ

- for $M_H \lesssim 400$ GeV
  - ττ → ℓ νν ℓ νν
  - ττ → ℓ νν had ν
- Higher mass also add
  - ττ → had ν had ν
- b-tagging, τ id and missing E_T are the basic ingredients
- From the cross section measurement it is possible to extract the value of tanβ
- tanβ uncertainty due to variation of SUSY parameters (m_h^{max} scenario) in a range ±20% is ~15%





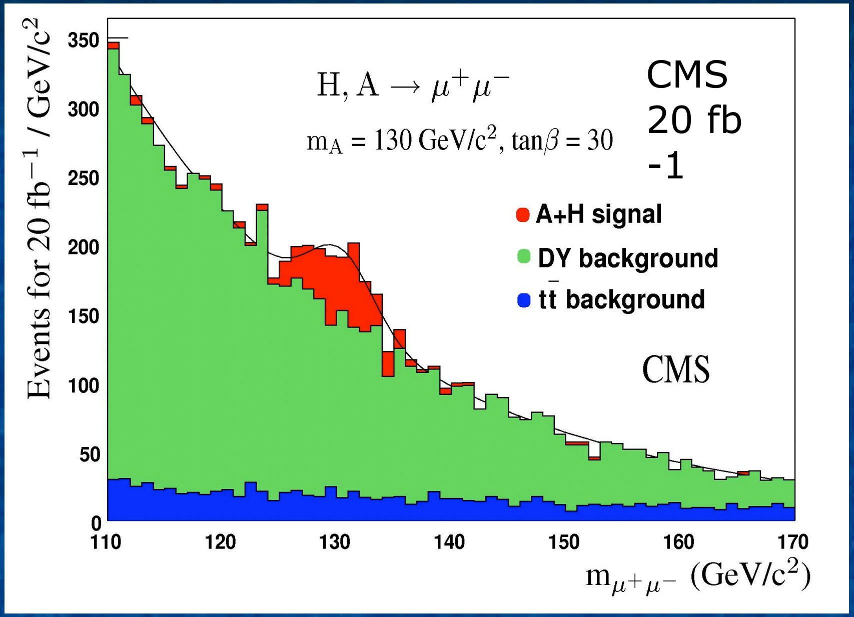
Higgs Width in the MSSM

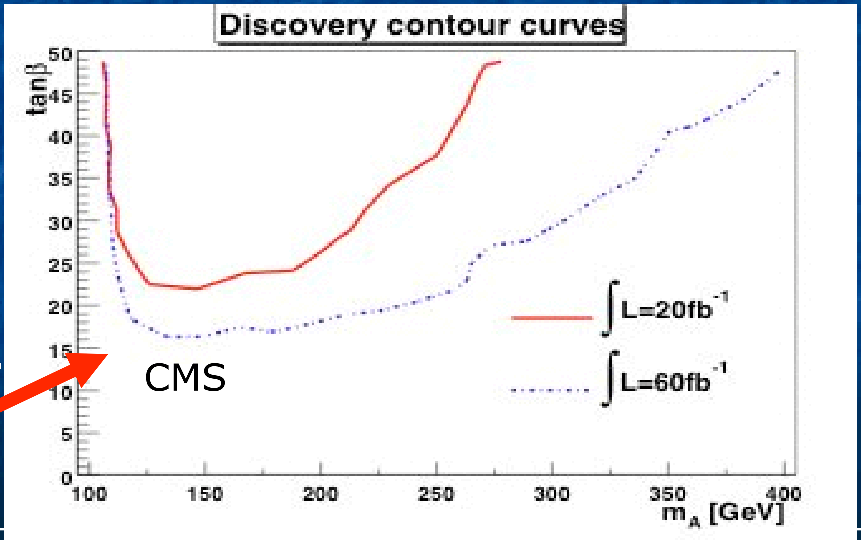


bbH,A → bbμμ

H,A→μμ

- low rate, BR(H→μμ) ~10^{-3}
- high efficiency
- precise mass measurement (μμ mass resolution ~1%)
- Main backgrounds:
  - *Z/γ** → μμ
  - *tt* → μμ *X*
- Selection requires 2 muons, b-tagging and central jet veto

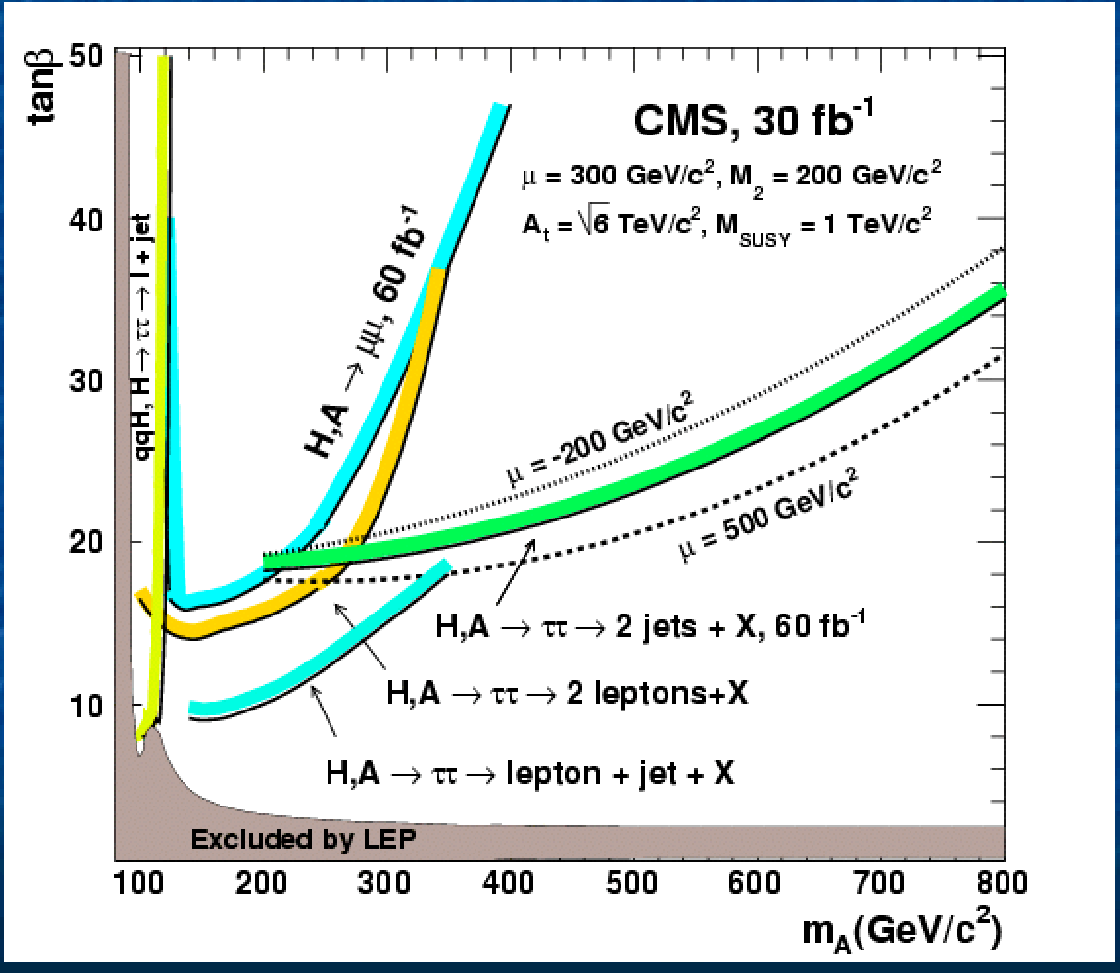




5σ discovery contours

H,A Discovery Contours

- 5σ discovery regions in the m_h^{max} scenario

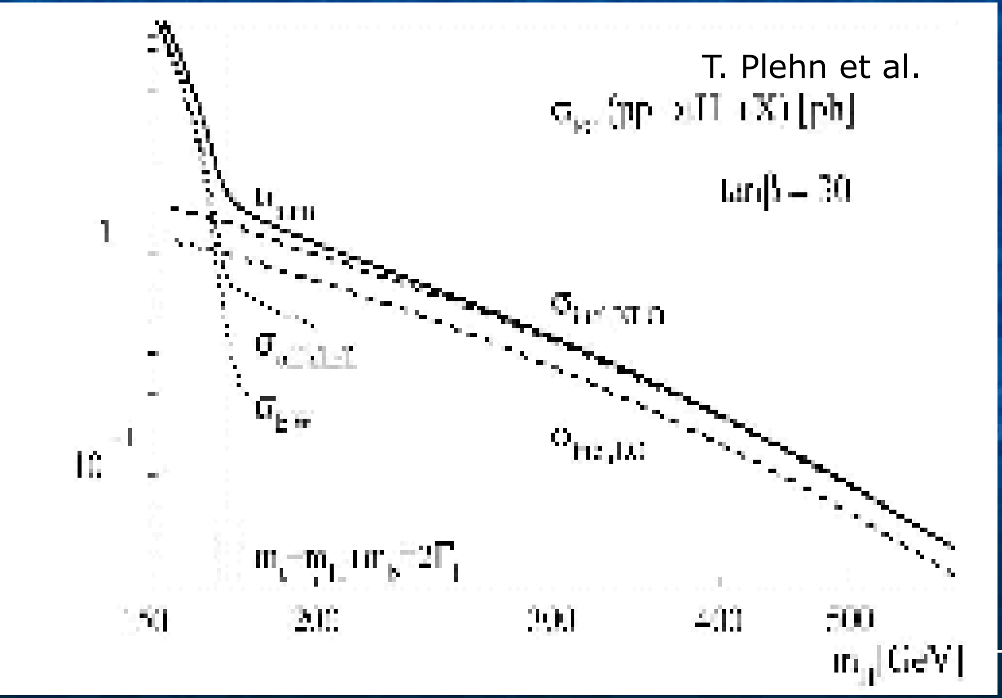


Charged Higgs bosons $H^{\pm}$

$M_{H^\pm} < m_t - m_b$

- Mainly produced in top decays $tt \rightarrow tH^{\pm}b$

includes top decays



$M_{H^\pm} > m_t + m_b$

- Mainly produced in association with a t quark ($gb \rightarrow tH^{\pm}$)
- $BR(H^{\pm} \rightarrow tb) \sim 100\%$ for small tanβ
- $H^{\pm} \rightarrow tb$ decay dominates but $BR(H^{\pm} \rightarrow \tau\nu)$ still sizeable for large tanβ

Analyses are in progress for the mass region $M_{H^\pm} \sim m_{top}$

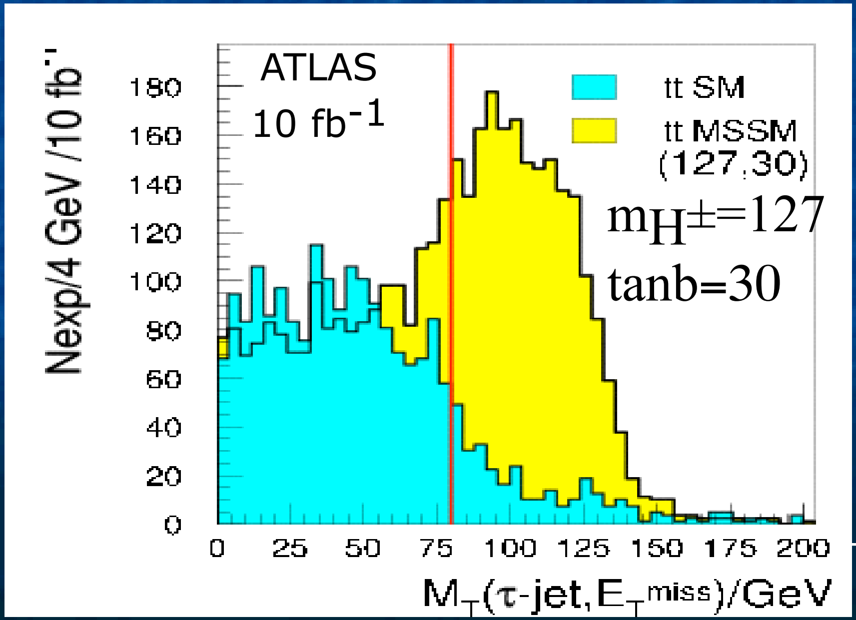
Charged Higgs Search $H^{\pm} \rightarrow \tau\nu$

$M_{H\pm} < m_t - m_b$

- § $tt \rightarrow bH^{\pm}bW \rightarrow b\tau\nu b \ell \nu$
- § $tt \rightarrow b\tau\nu bqq$

§ Use transverse M_T mass built with τ jet + missing E_T

§ tt background has $M_T < M_W$



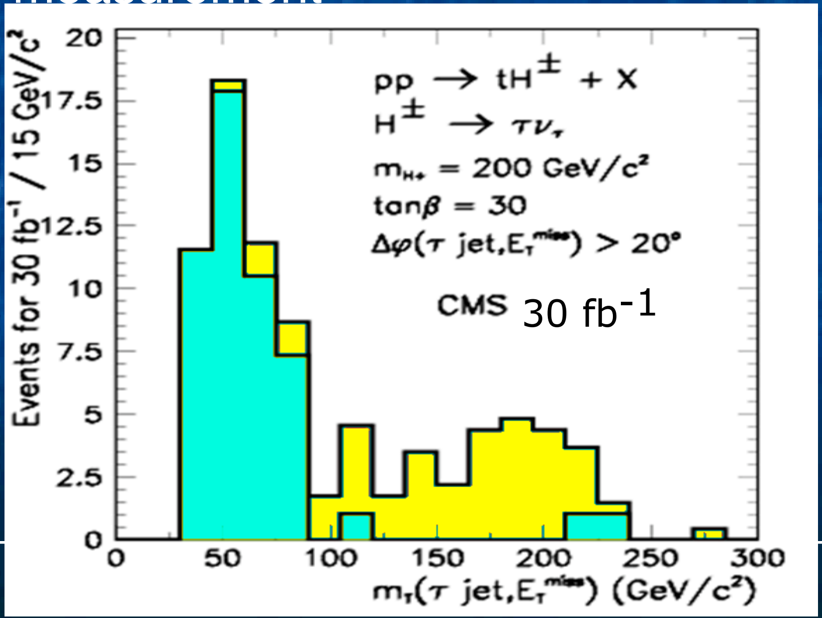
$M_{H\pm} > m_t + m_b$

§ $gb \rightarrow tH^{\pm}$ with $H^{\pm} \rightarrow \tau\nu$ and $t \rightarrow bqq$

§ Exploit helicity correlations

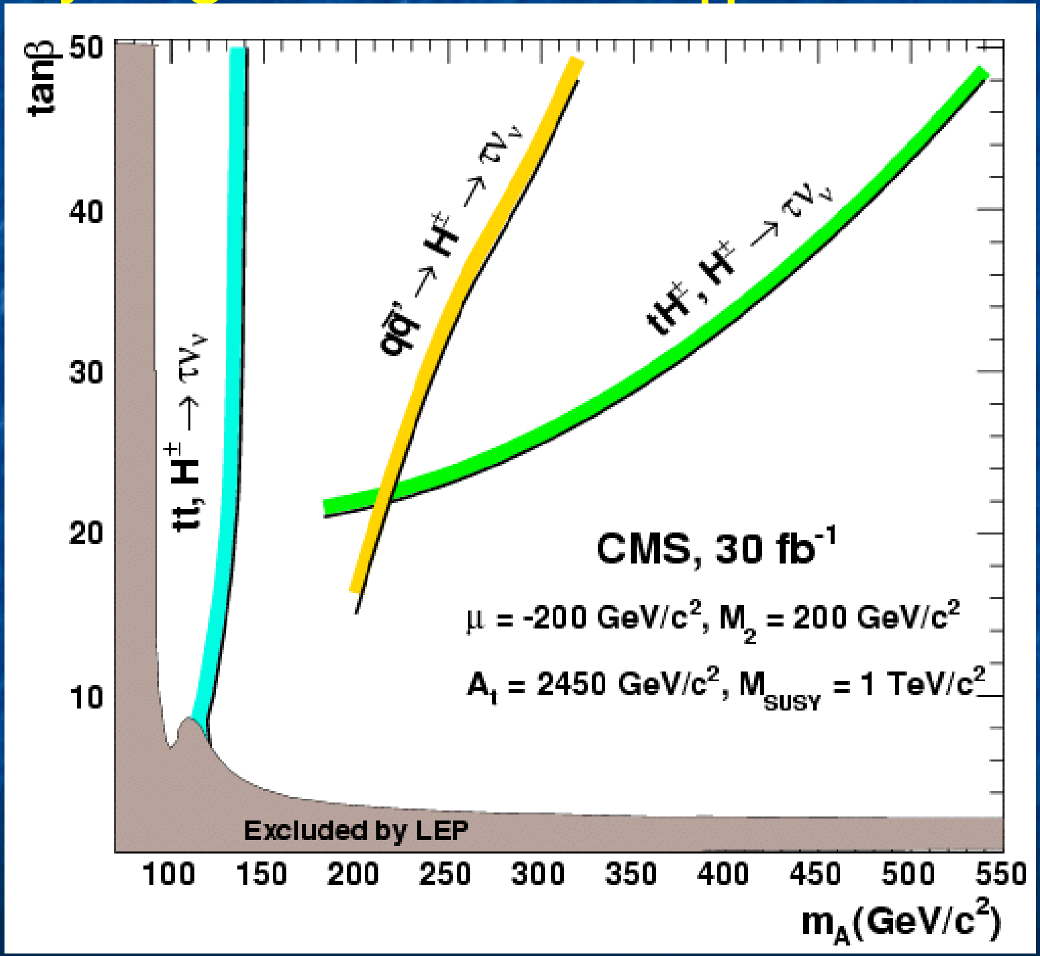
§ Similar endpoint of M_T at M_W for the background

§ M_T can also be used for Higgs mass measurement



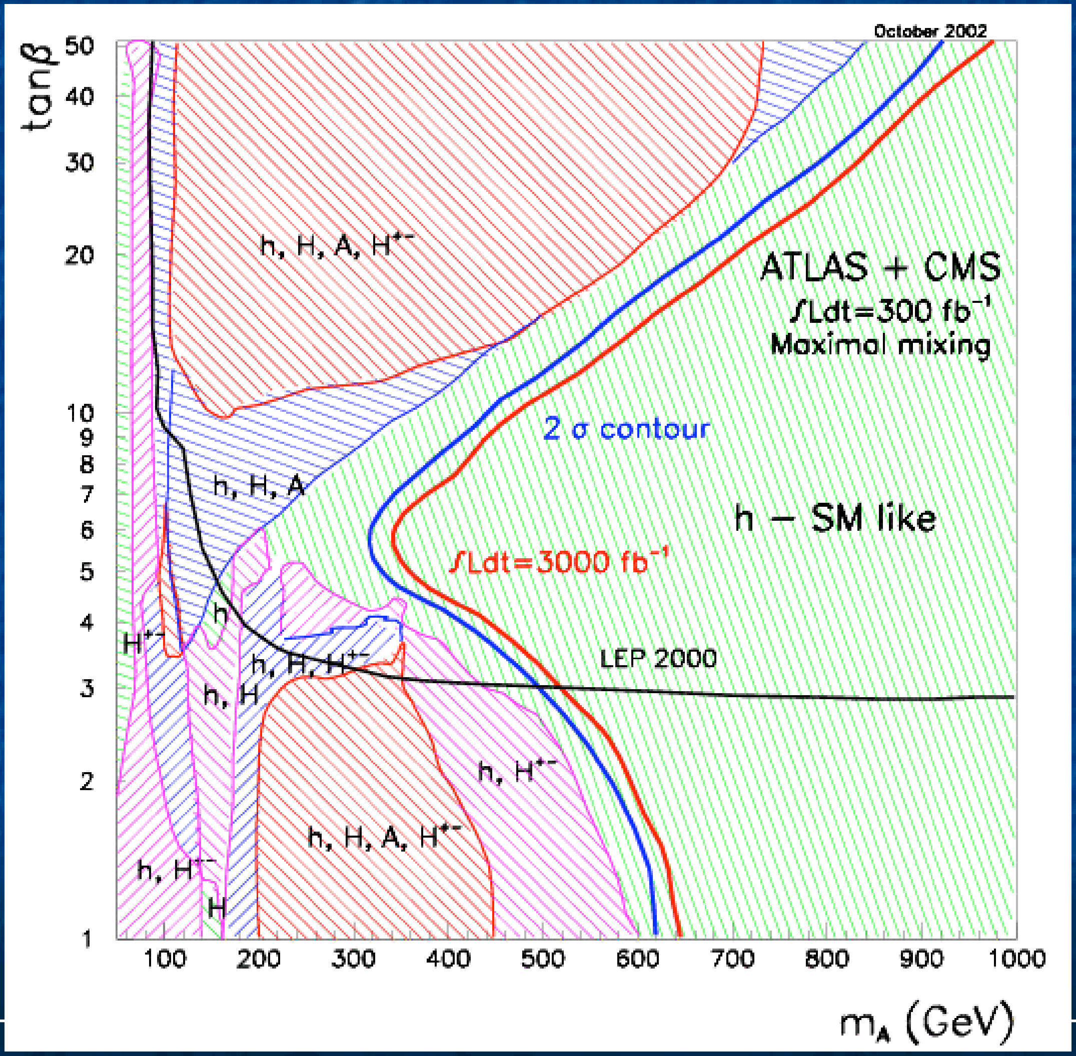
Charged Higgs boson Discovery Contours

5σ discovery regions for the m_h^{max} scenario



Higgs boson visibility in the MSSM

5σ discovery regions for the m_h^{max} scenario



- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

(Charged Higgs only counted once)

All the plane is covered but there is a large area where only h can be seen

MSSM Higgs bosons and SUSY particles

§ References:

- § J.F.Gunion and H.E.Haber,

  Higgs Bosons in Supersymmetric Models,

  Nucl. Phys. B272 (1986) 1.

  Nucl. Phys. B278 (1986) 449.

  Nucl. Phys. B307 (1988) 445.

  Errata, hep-ph/9301205

• If SUSY particles are lighter than Higgs bosons we could have a rich variety of decays, including:

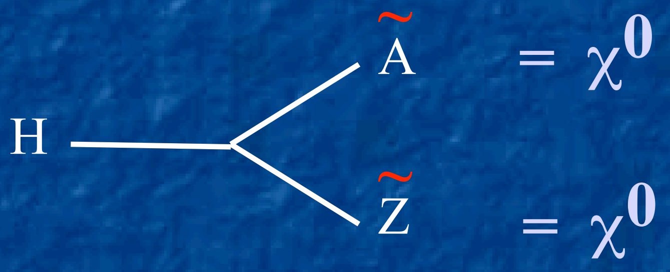
– $A,H \rightarrow c_{20}c_{20}$

– $H^{\pm} \rightarrow c_{2,30}c_{1,2}^{\pm}$

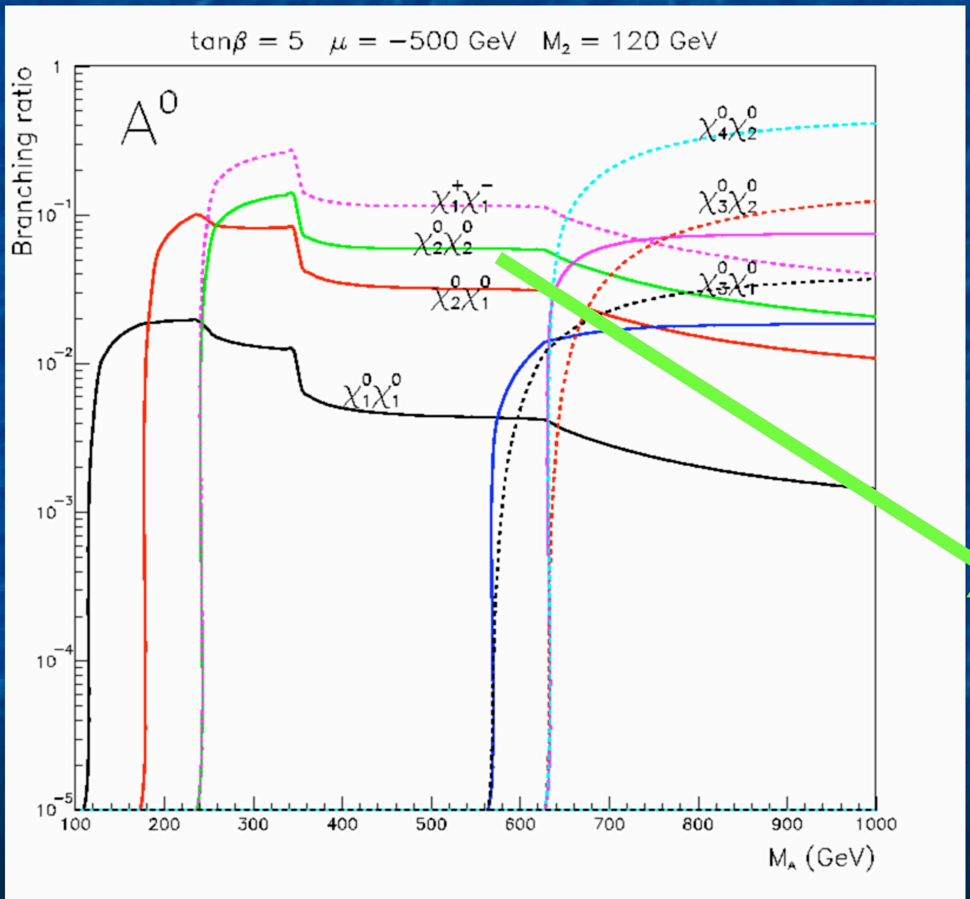
– $h \rightarrow c_{10}\, c_{10}$

SUSY Decays of the Higgs

MSSM Higgs coupling:



(neutralinos)



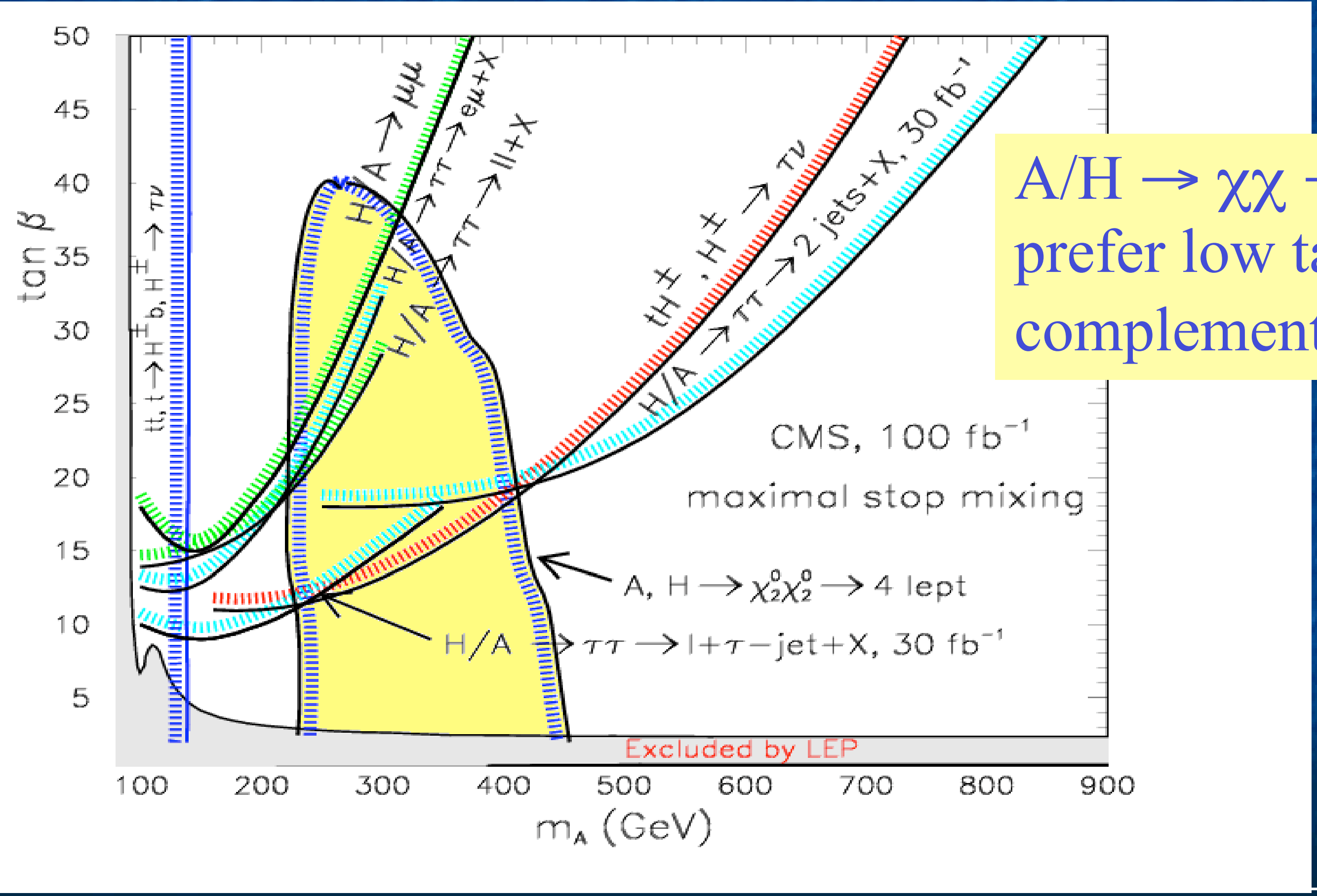
Most promising decay channel:

$A, H \rightarrow \chi_2^0\,\chi_2^0 \rightarrow 4l + E_T^{miss}$

$l^+ l^- \chi_1^0$

SUSY Decays of the Higgs

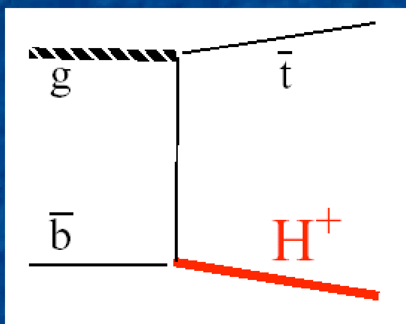
Example discovery reach:



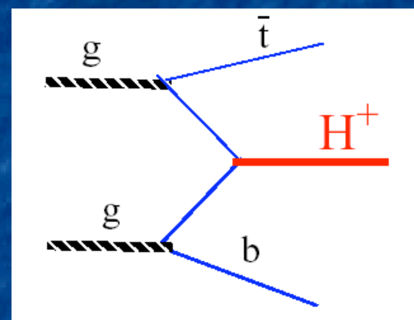
A/H → χχ → 4 leptons prefer low tan β, complementary to A/H → ττ

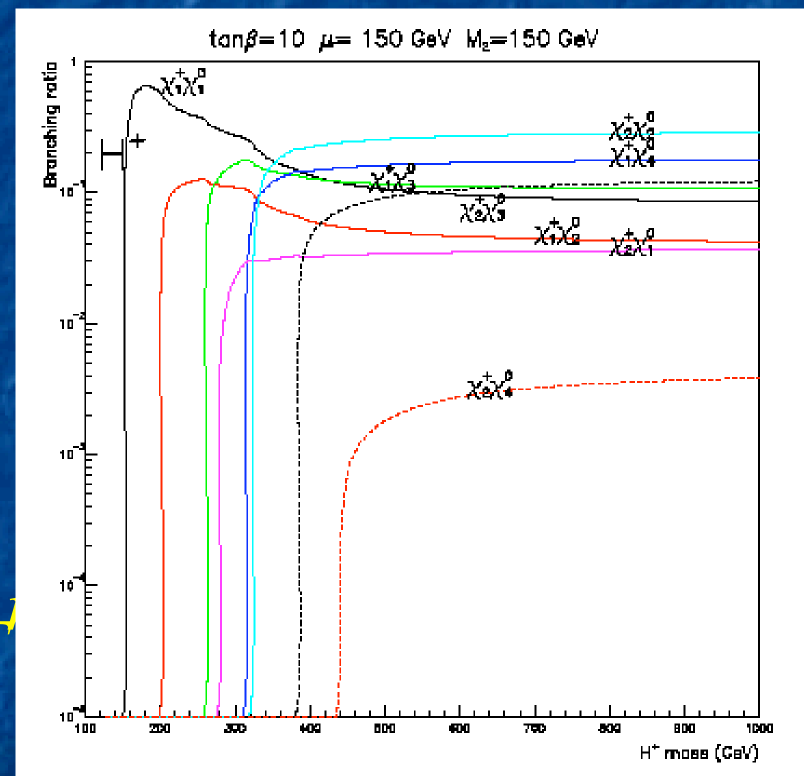
Similar Ideas for H±

Analogous production mechanism for H± :



+





Analogous decay mode:

$H^{\pm} \rightarrow \chi_{2,3}^{0}\, \chi_{1,2}^{\pm} \rightarrow 3l + E_T$

→ only 3 leptons, need to reconstruct additional top (t→bjj)

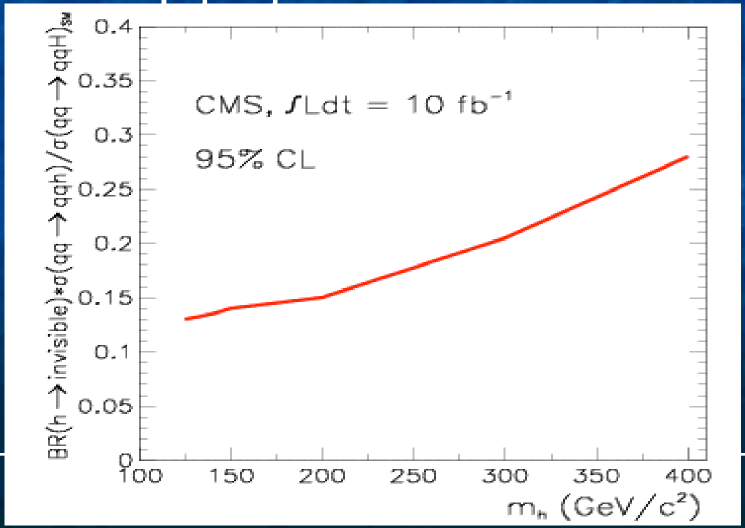
Invisible decays of the Higgs Boson

- Weak boson fusion production is the most sensitive process
- Trigger on forward jets + missing E_T
- Selection:
  - forward jet tagging, central jet-veto, M(jet jet)
  - lepton veto, missing E^T
  - Δφ jet-jet small

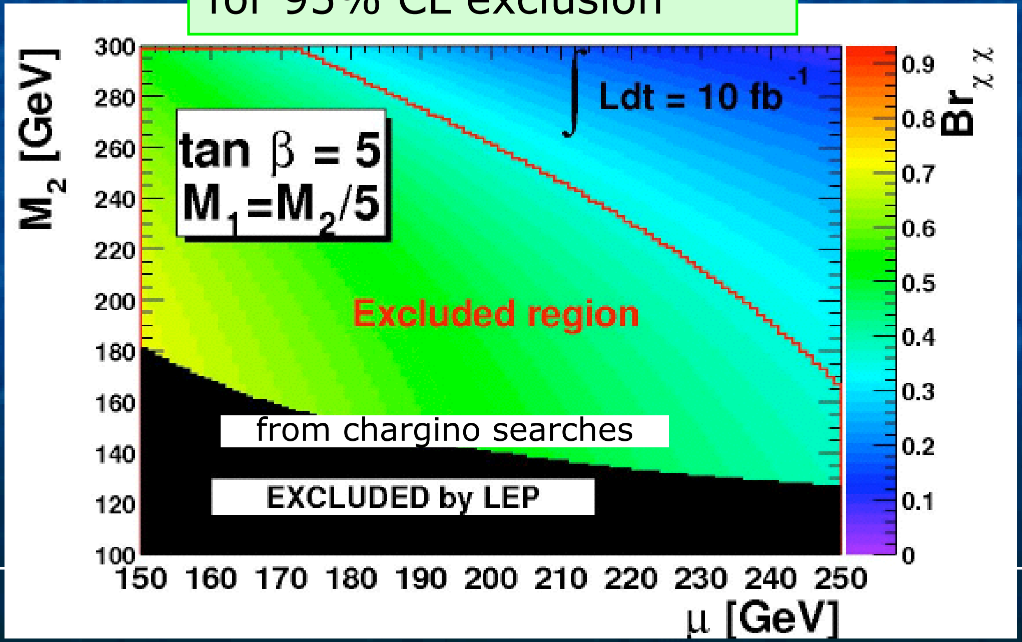
If we do not require gaugino mass unification and M1<<M2

Mχ can be rather small and

BR(h → χχ) can be very large

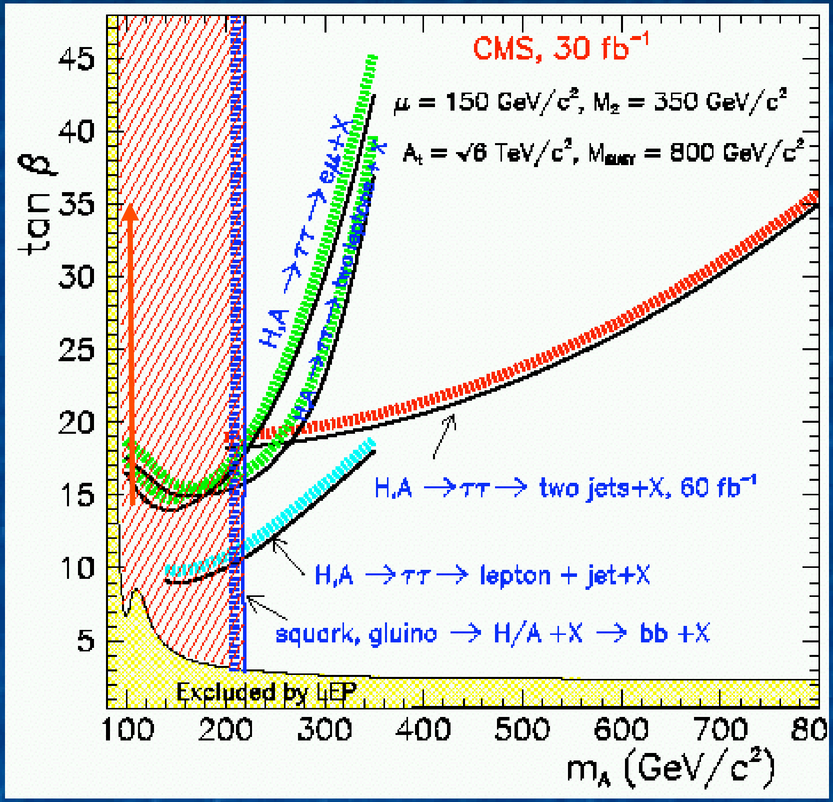


ATLAS - Accessible region for 95% CL exclusion



MSSM Higgs bosons and SUSY particles

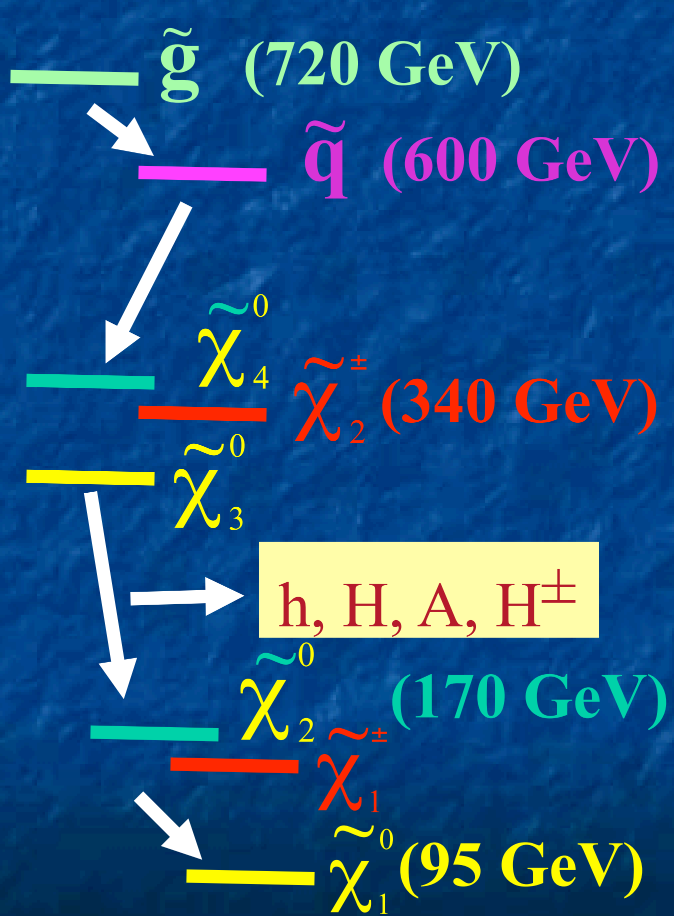
- Higgs bosons could be produced in gauginos decays:
  - $\chi_2 \rightarrow$ h,H,A χ_1
  - $\chi_1^{\pm} \rightarrow H^{\pm}\chi_1$
- Different cascades possible involving heavier gauginos
- Search for h,H $\rightarrow$ bb
- Neutralinos and charginos would be copiously produced in the decays of squarks and gluinos



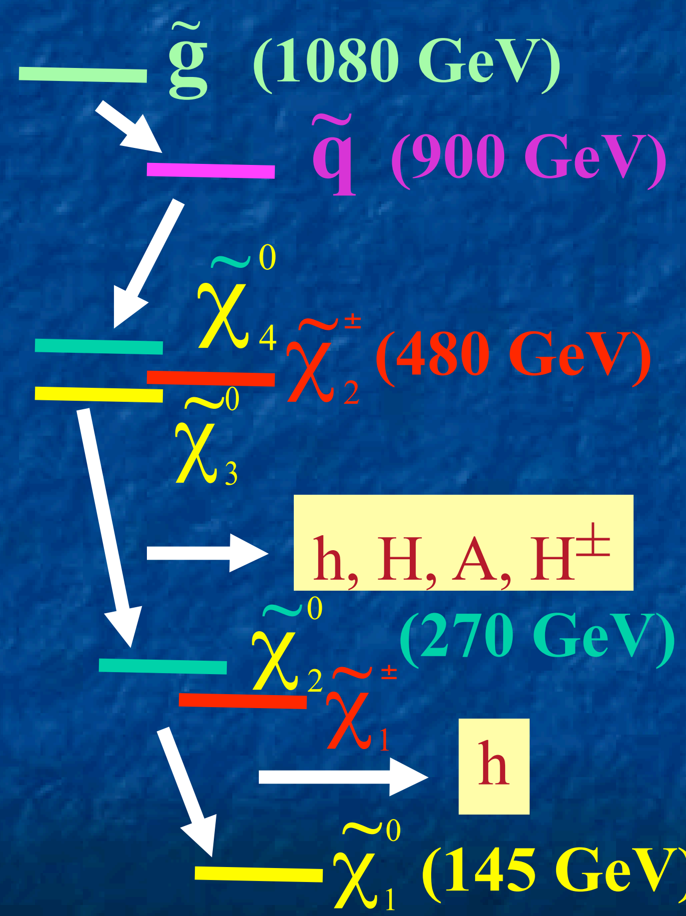
Possible to observe
SUSY → h,H,A
with h,H,A → bb

Higgs Production in Sparticle Cascades

Scenario 1 (big cascades)

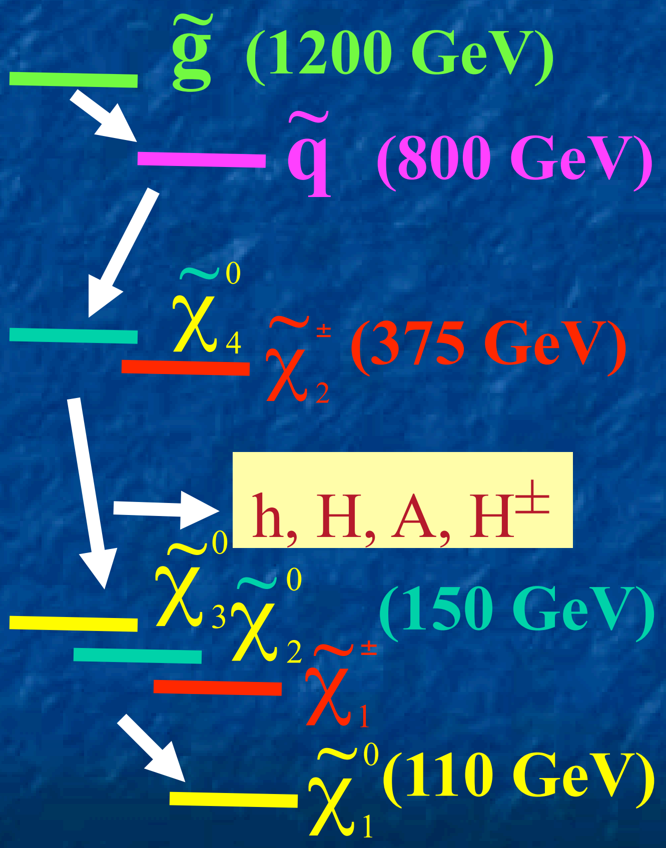


Scenario 2 (little + big cascades)

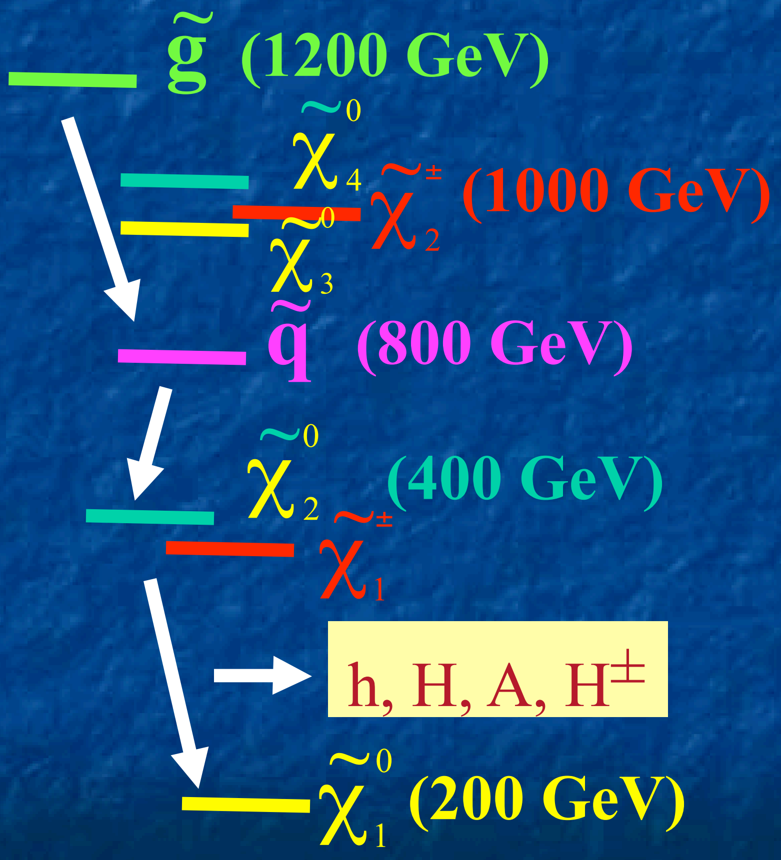


More Possibilities

Scenario 3 (big cascades)

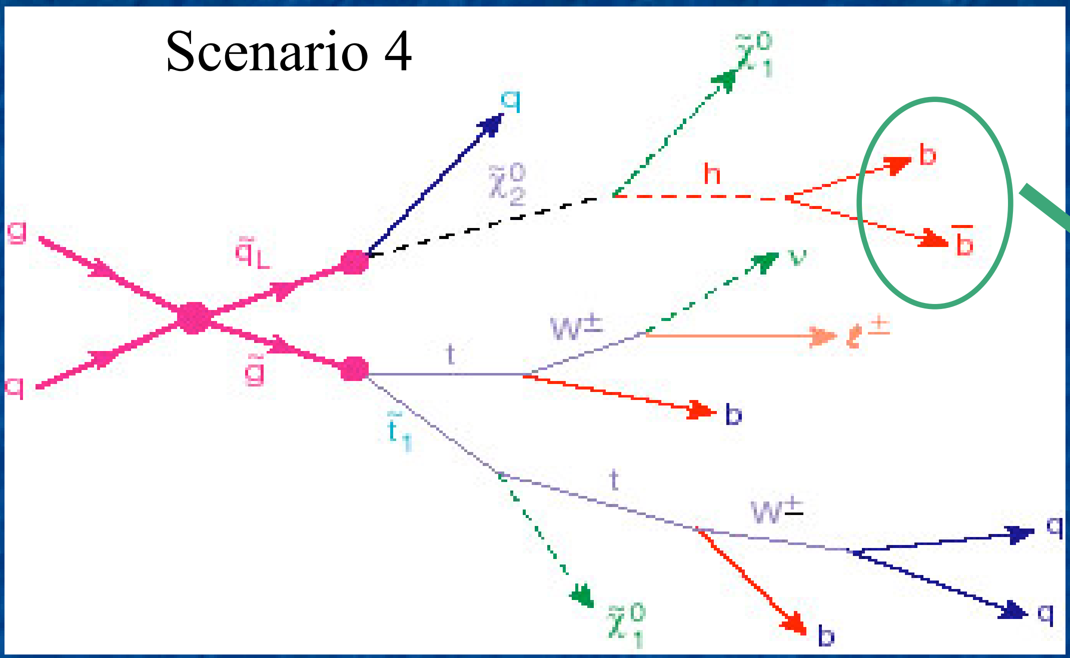


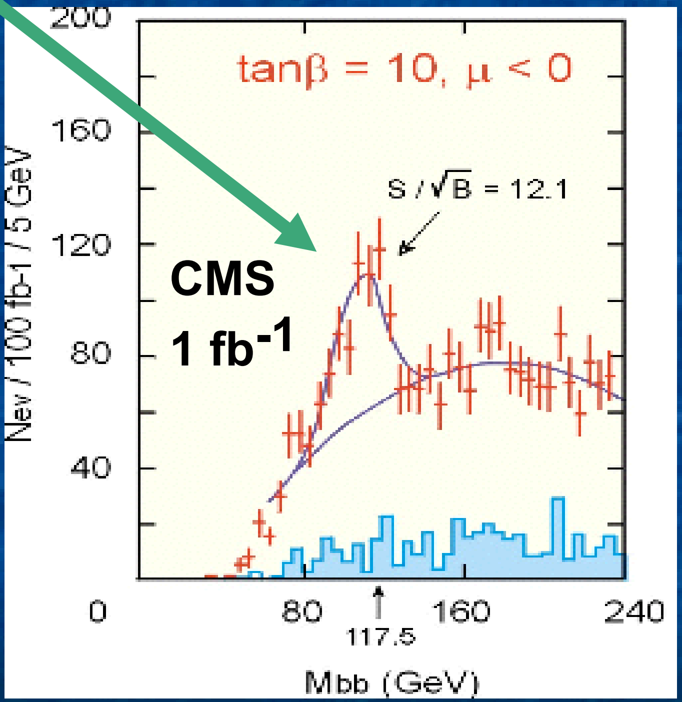
Scenario 4 (little cascades)



h à bb production in squark/gluino cascades

SUSY events are readily selected from jets and missing E_T





Inclusive reconstruction of Higgs decays is simply a matter of combinatorics

Perfect marriage of SUSY and Higgs at the LHC!

Lightest Higgs Boson

- Lightest Higgs boson is SM-like for large M_A

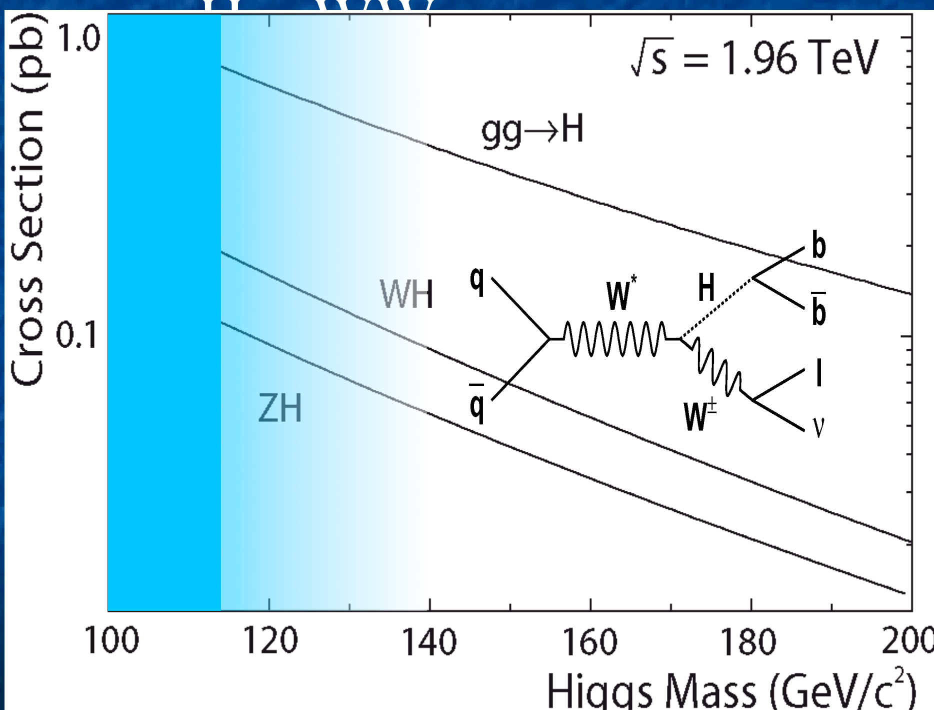
$$\tan 2\alpha = \tan 2\beta \left(\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \right)$$

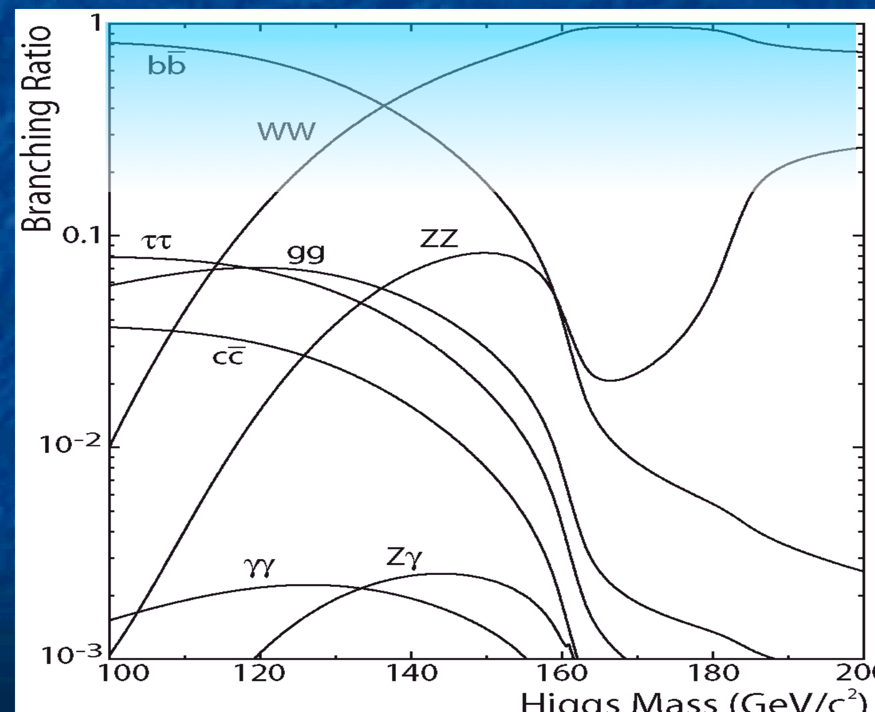
$$M_A \approx M_H \approx M_{H^\pm} \quad \text{(decoupling limit)}$$

- Given the difficulty of detecting the h→bb decay at the LHC, the Tevatron provides a potentially essential probe of this low mass channel

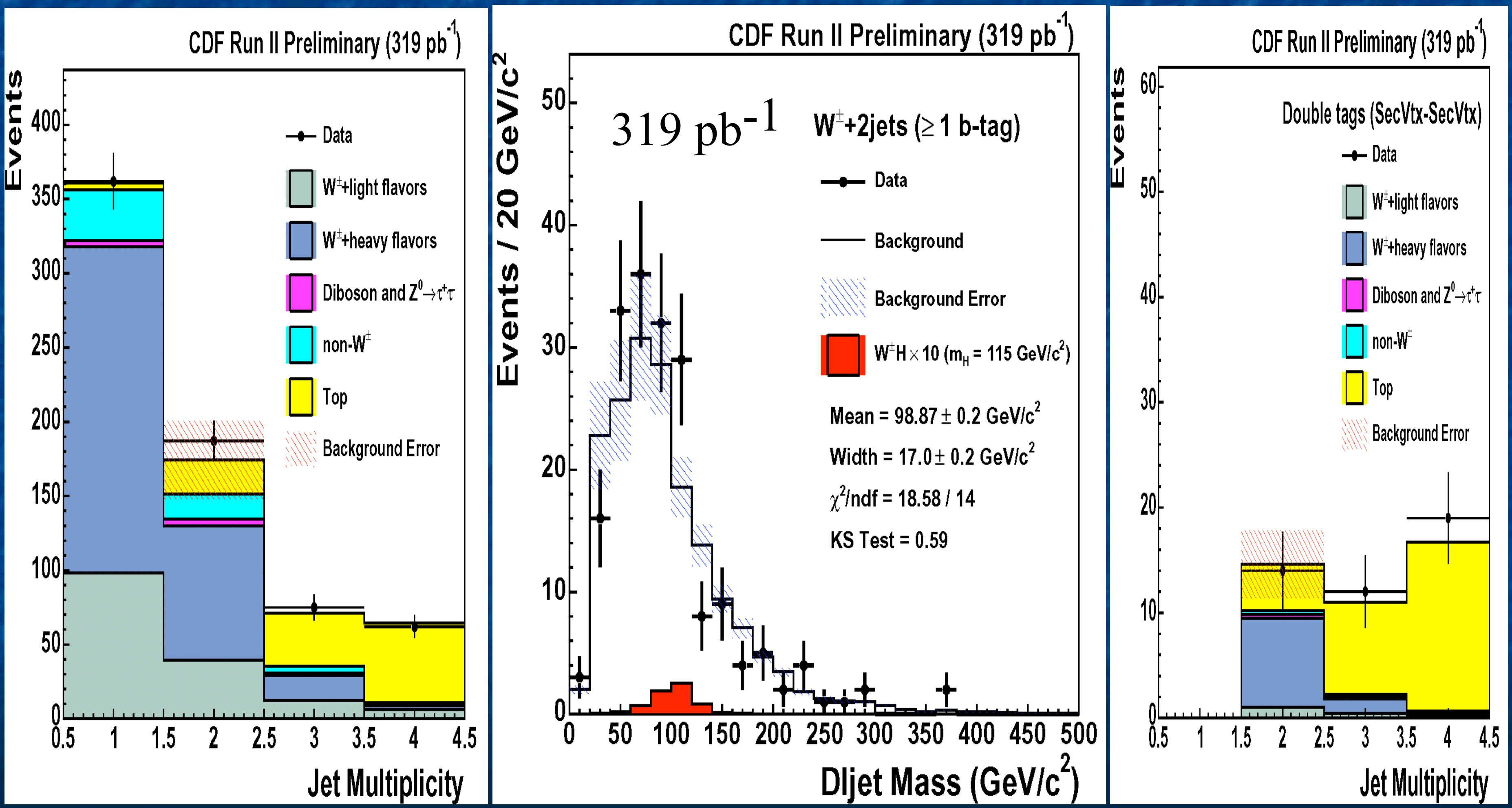
Tevatron Low Mass Higgs Search

- Maximum sensitivity requires a combination of CDF/D0 search channels:
  - WH→ $\ell\nu bb$, ZH→ $\nu\nu bb$ & $\ell\ell bb$, WH→WWW*,





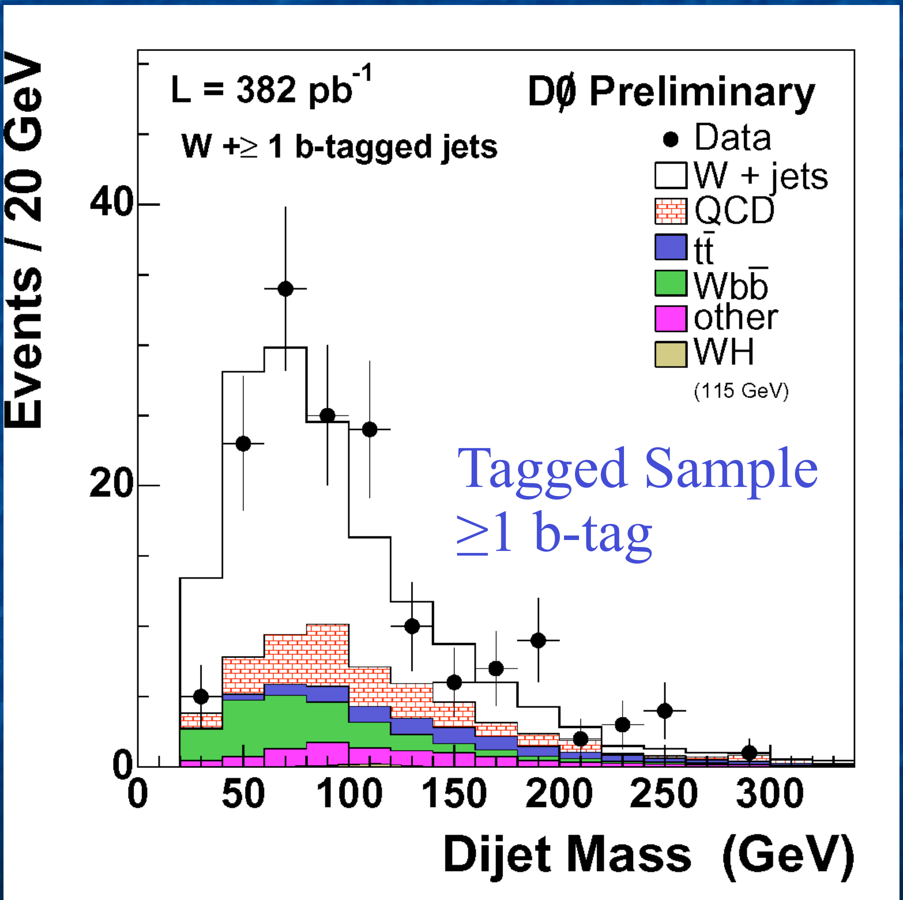
ℓ nbb Search (CDF)

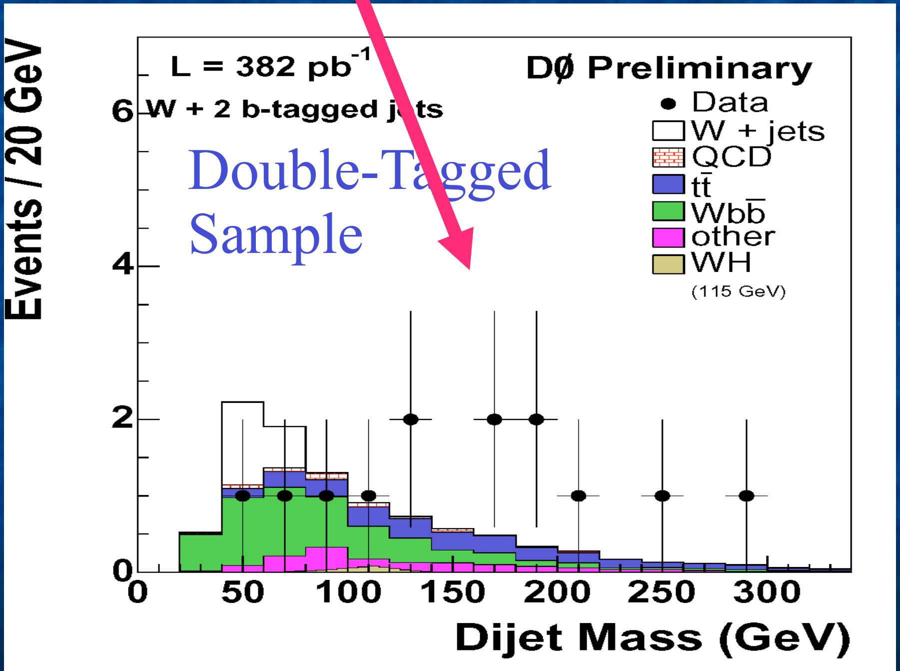


enbb Search (DØ)

- μνbb in Progress…

Expect	0.14 ± 0.03	WH
	4.29 ± 1.03	Wbb
	5.73 ± 1.45	tt+other
Total	10.2 ± 2.4 events	
Observe	13	

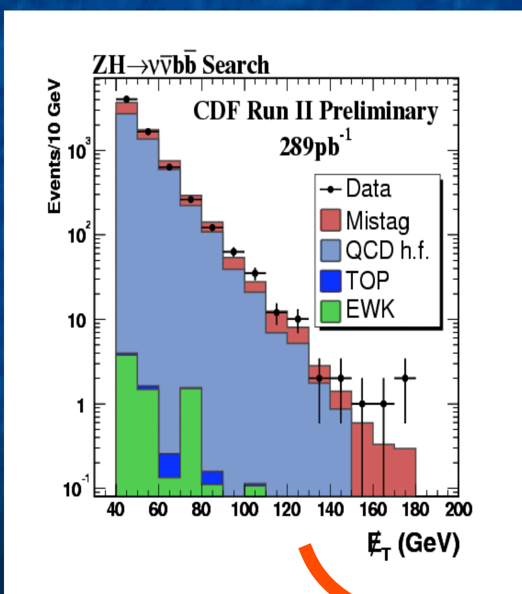


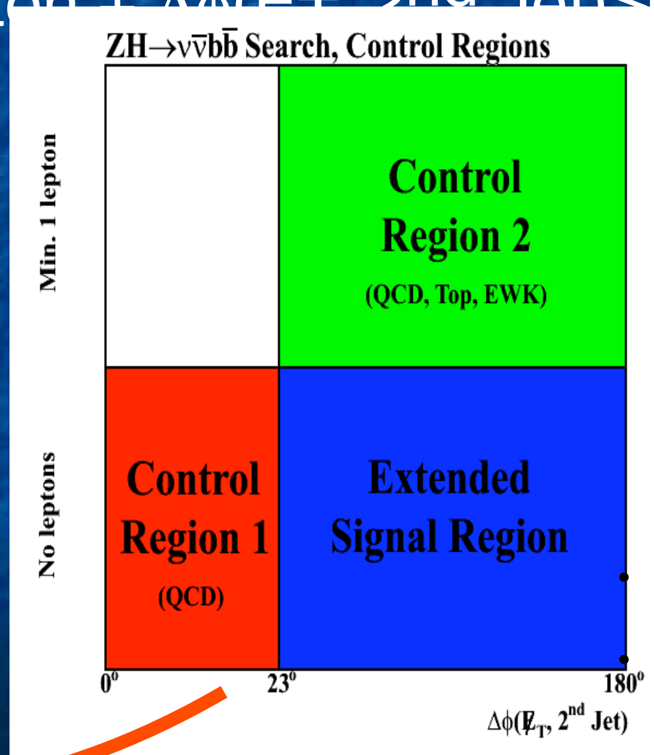


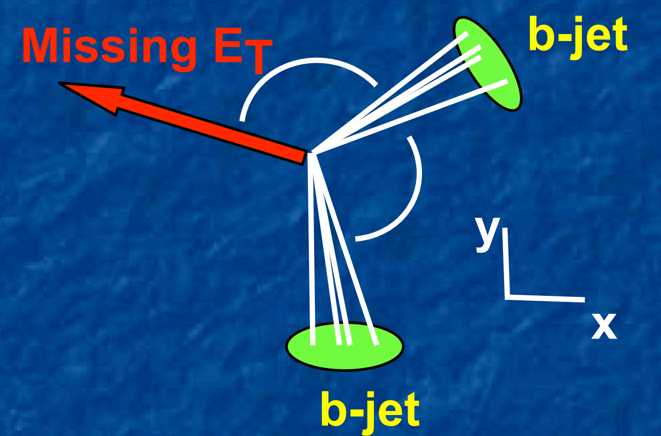
Missing Energy Channel (CDF)

- Two Control Regions:
  - No Leptons + $\Delta\phi(\not{E}_T, 2^{nd}$ Jet$)<0.4$ (QCD H.F.)
  - Min. 1 Lepton + $\Delta\phi(\not{E}_T, 2^{nd}$ Jet$)>0.4$ (Top, EWK, QCD)

Control Region 1





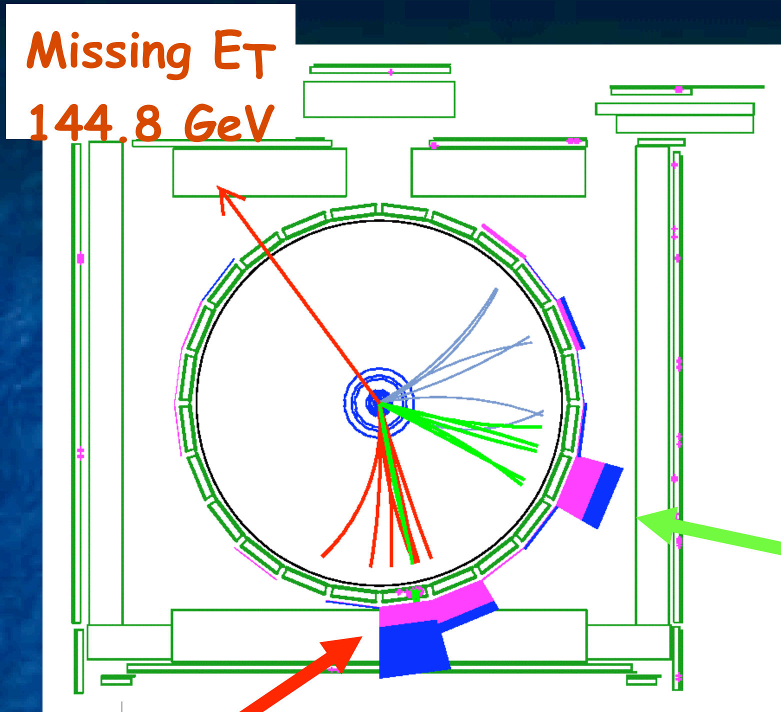


Large $\not{E}_T$

Two jets

(one b-tagged)

Missing Energy Event (CDF)

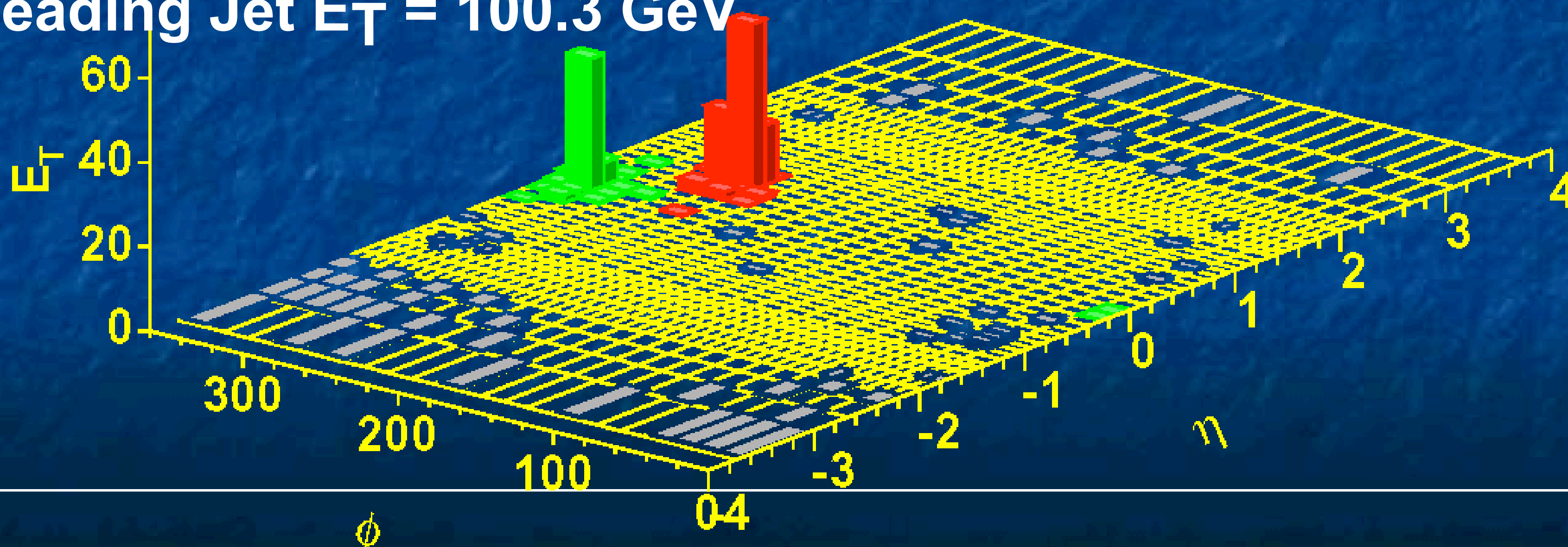


Double tagged event

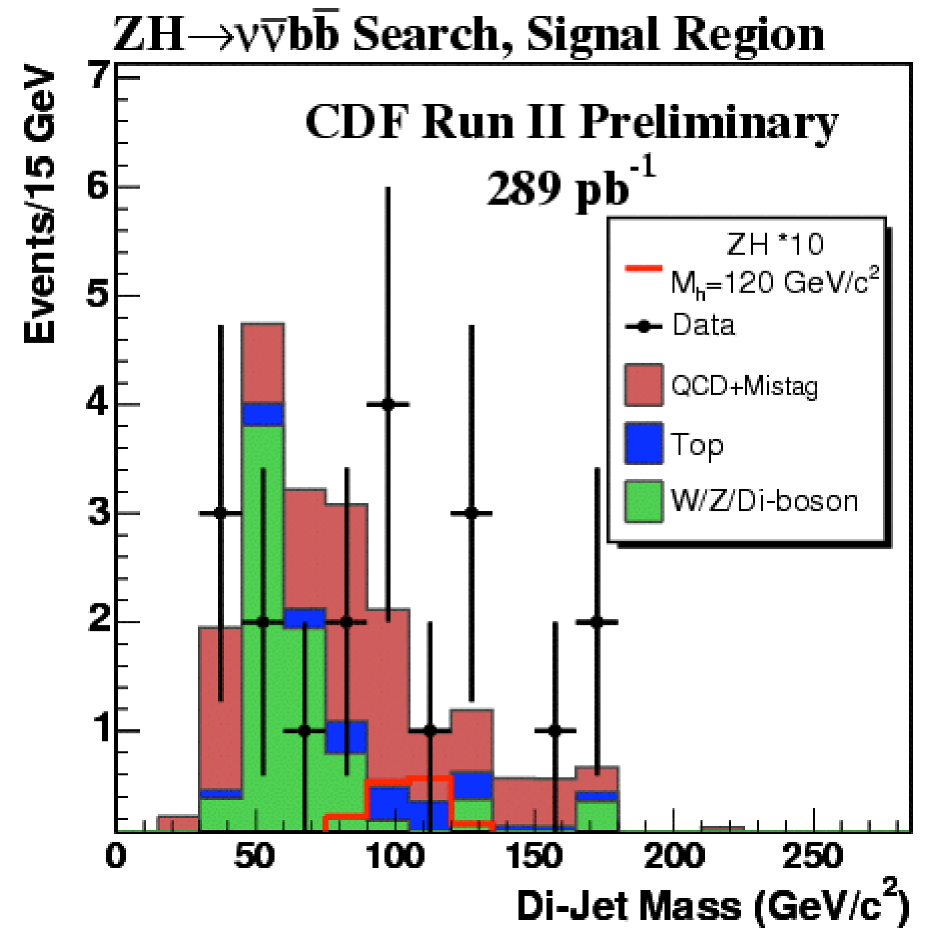
Di-jet invariant mass = 82 GeV

Second Jet E_T = 54.7 GeV

Leading Jet E_T = 100.3 GeV



Missing Energy Channel (CDF)

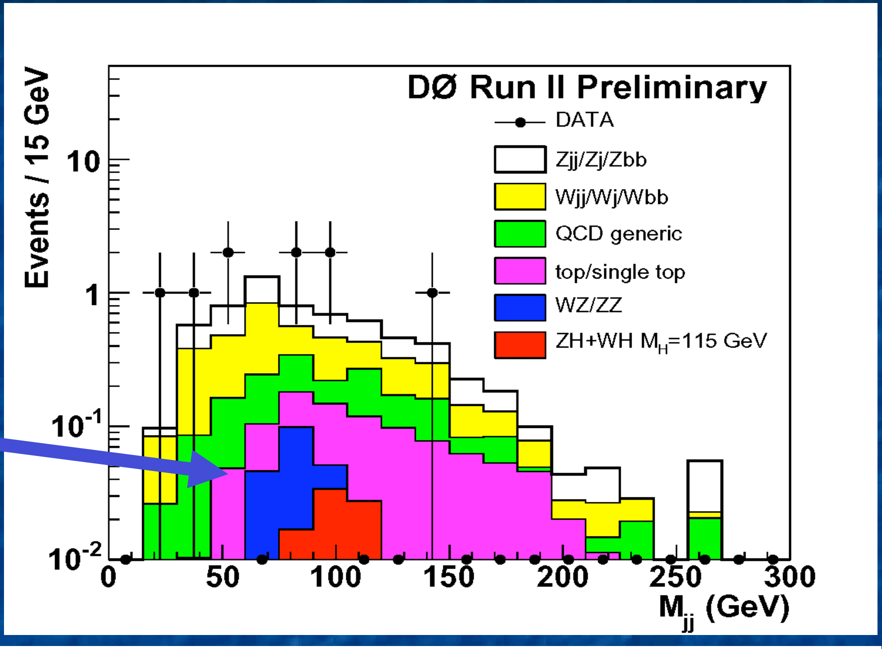


Process	Signal Region
QCD multi-jet	2.6 ± 1.7
TOP	2.1 ± 0.4
Di-boson	1.1 ± 0.2
W + h.f.	3.7 ± 2.6
Z + h.f.	3.2 ± 1.2
Mistag	7.0 ± 1.0
Total Expected BCK	19.7 ± 3.5
Observed	19

Selection cut	ZH 120 (288.9 pb^{-1})
Di-jet mass cut (100,140)	**0.126±0.016**

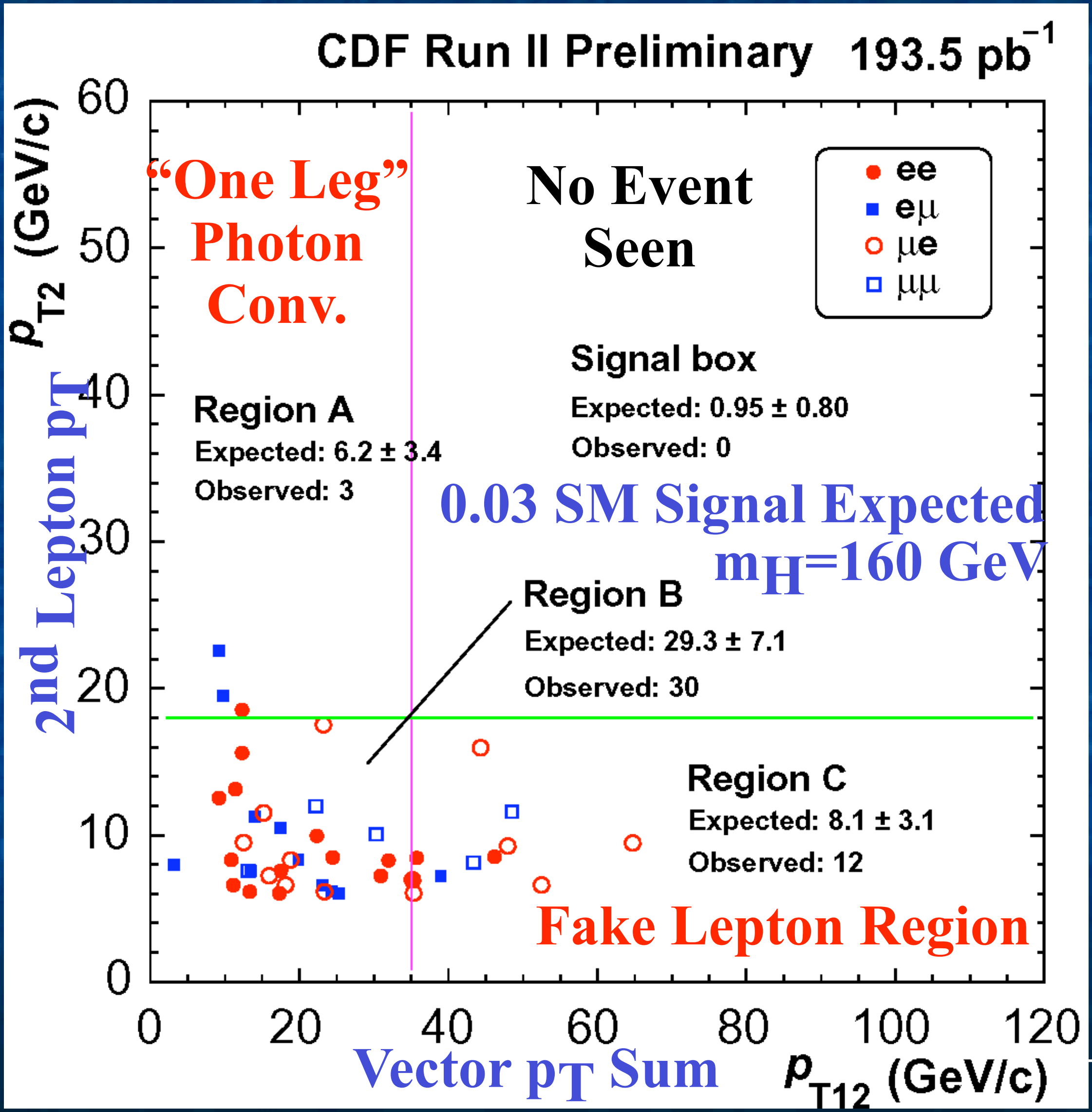
Missing Energy Channel (DØ)

- Cross-efficiency important
  - WH→ ℓ nbb (lost ℓ)
  - ZH→nnbb
- 3x Larger WZ/ZZ Signal
  - Similar dijet bb mass peak

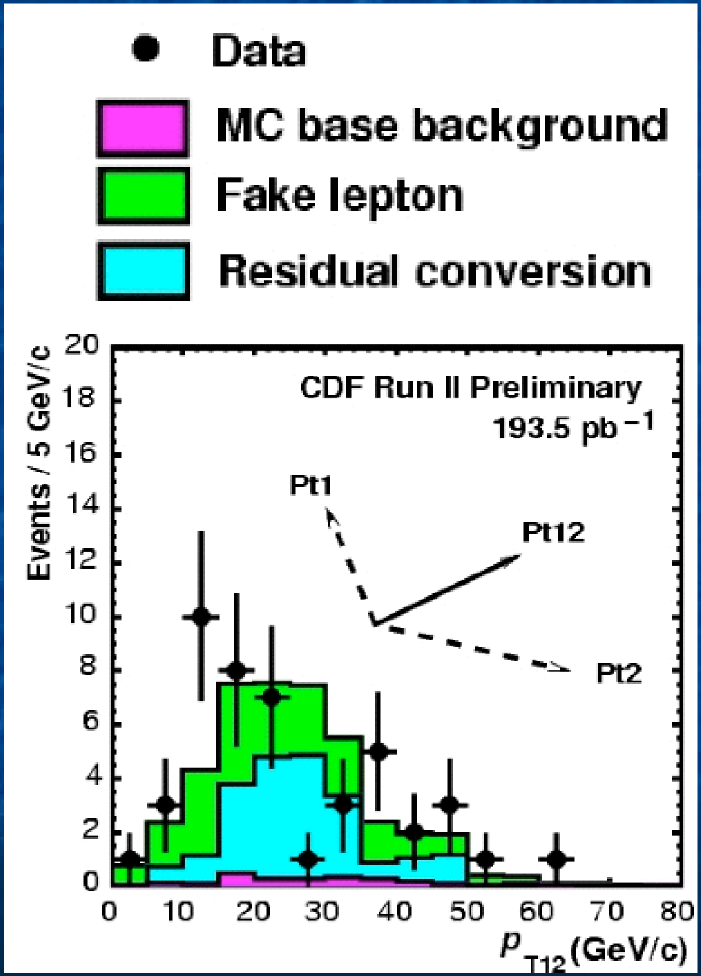


Mass (GeV) Window	105 [70,120]	115 [80,130]	125 [90,140]	135 [100,150]
Data	4	3	2	2
ZH/WH	0.11	0.082	0.060	0.034
Total bkgd.	2.75 ± 0.88	2.19 ± 0.72	1.93 ± 0.66	1.71 ± 0.57
Expected limit (pb)	8.8	7.5	6.0	6.5
Limit @95% C.L. (pb)	12.2	9.3	7.7	8.5

WH→WWW* (CDF)



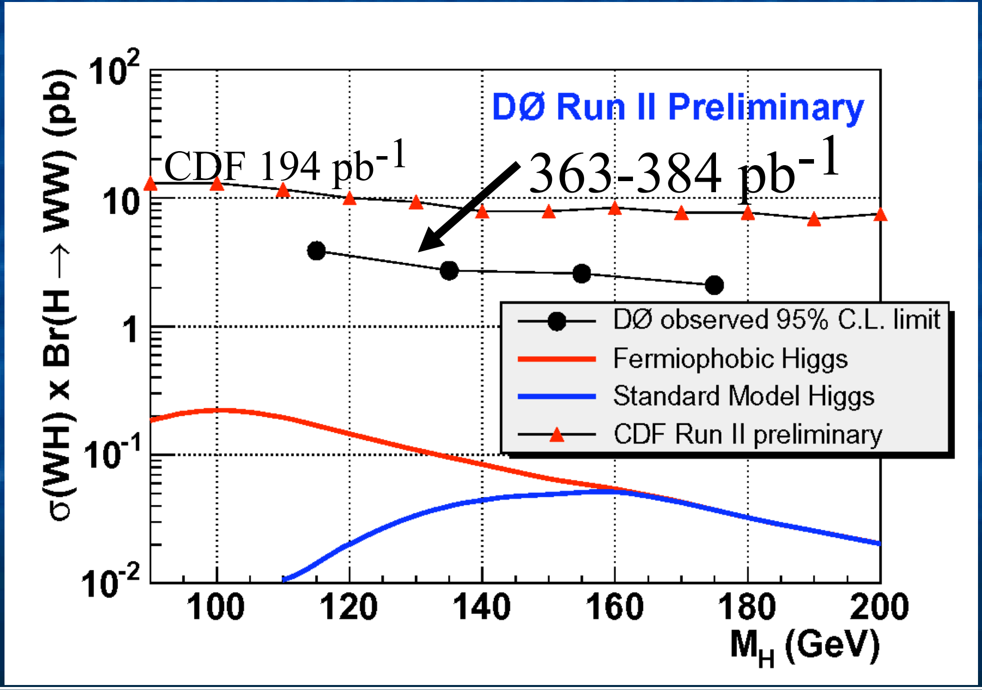
Same-Sign Dilepton Search



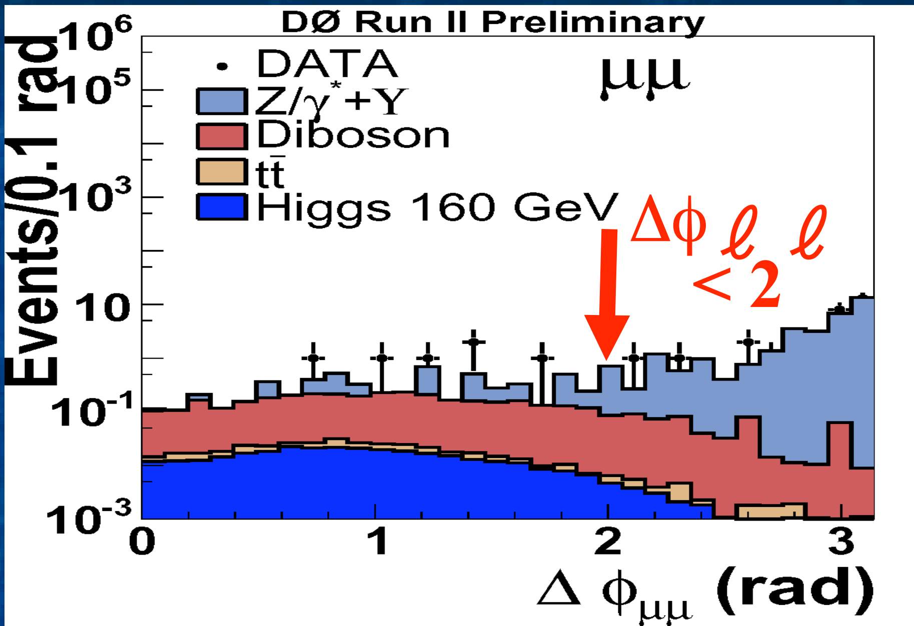
WH→WWW* (DØ)

- $WWW^* \to \ell^\pm \ell^\pm + X$
  - Same-Sign Dileptons
- Important bridge across 130-160 GeV "Gap" from H→bb and inclusive H→WW
- Background from $WZ \to \ell n \ell \ell$

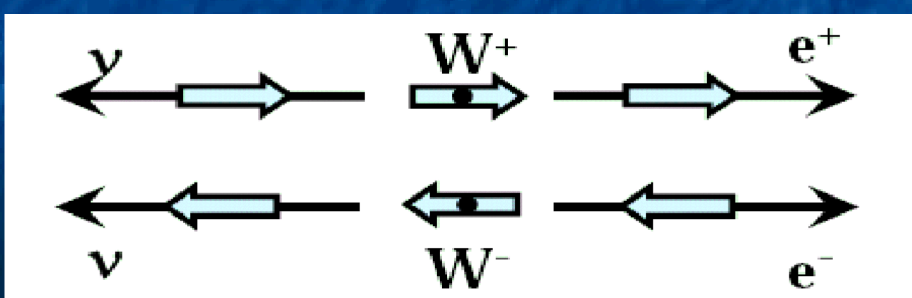
	ee	eμ	μμ
Observed data	1	3	2
Total bkgd	0.70	4.32	3.72



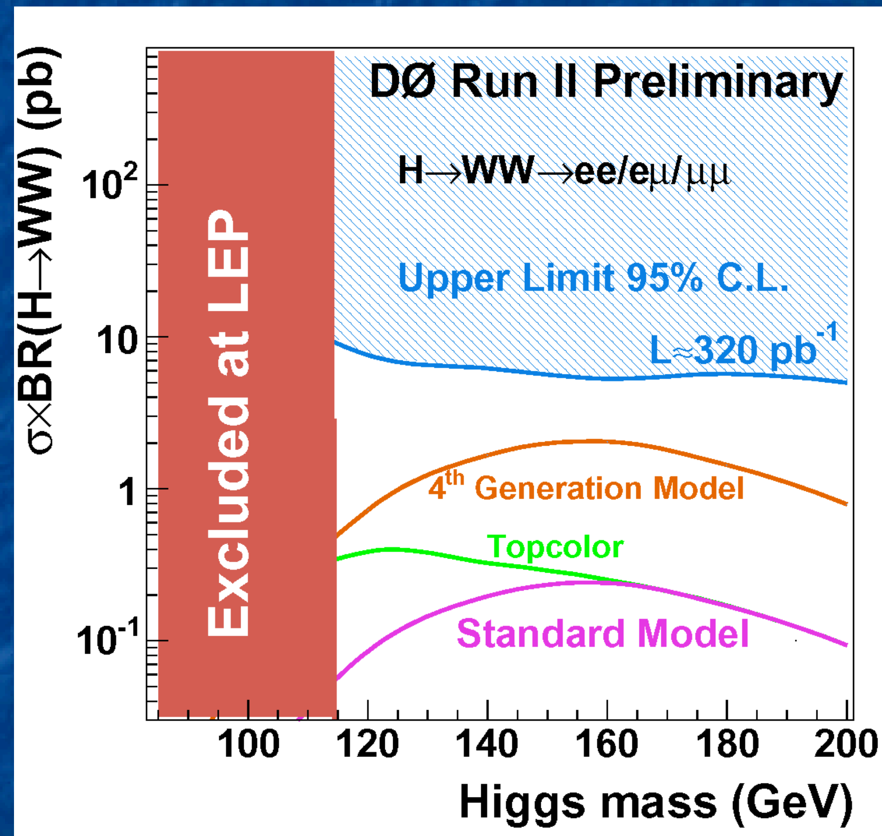
H→WW (DØ)



Leptons from Higgs tend to point in same direction



Apply $\Delta\phi_{\ell\ell} < 2$

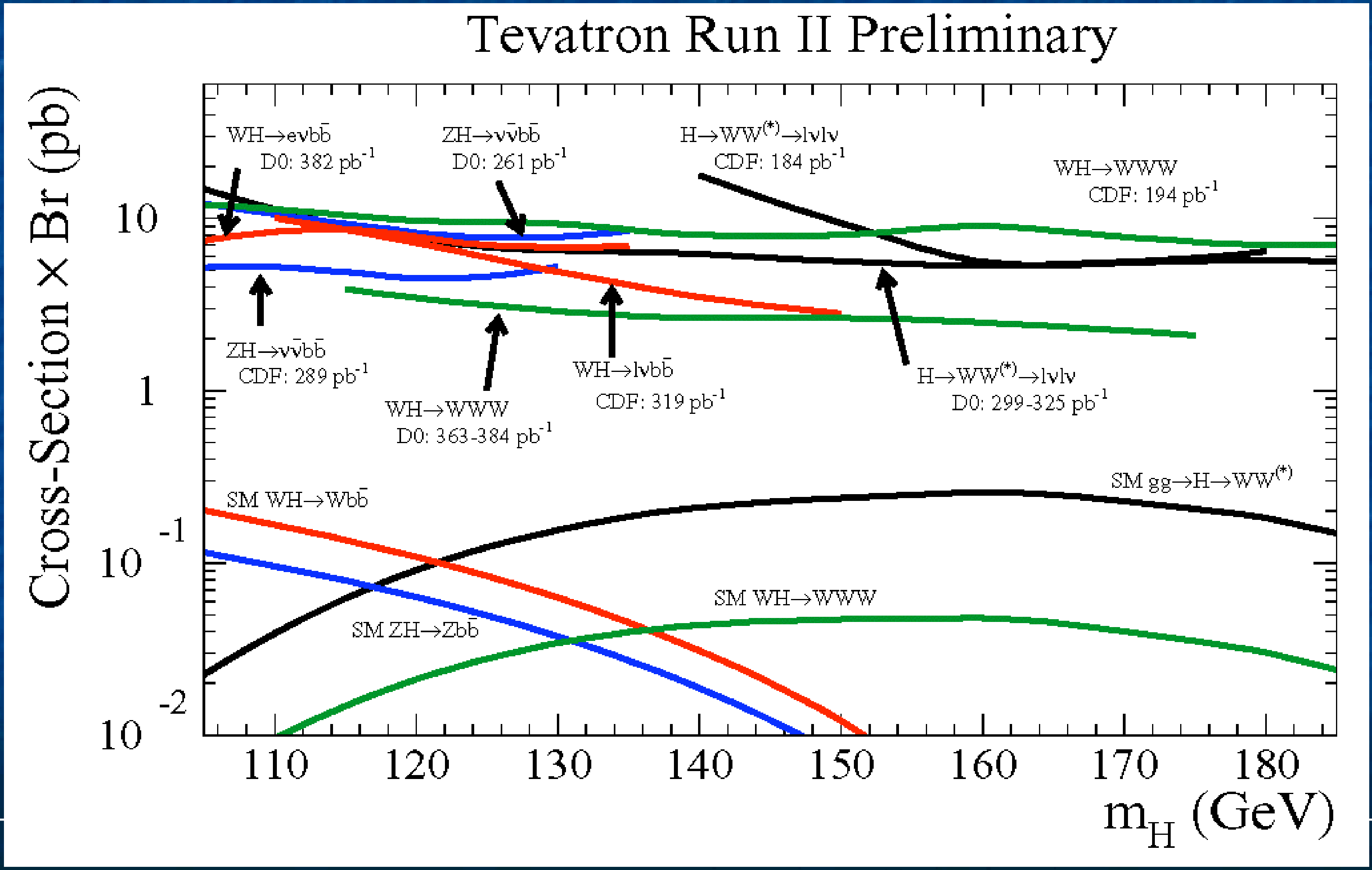


WW cross section measured

$\sigma_{WW} = 13.8^{+4.3}_{-3.8}\ (\text{st.})^{+1.2}_{-0.9}\ (\text{sy.}) \pm 0.9$ pb

PRL 94, 151801 (2005)

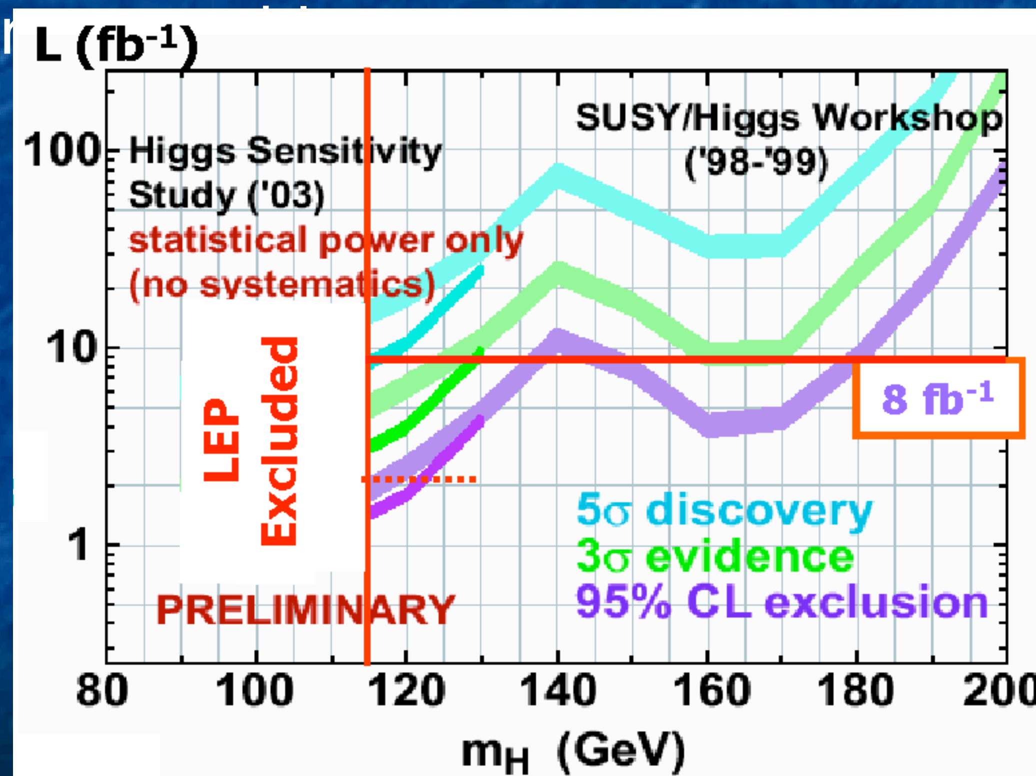
Overview of CDF/DØ SM Higgs Searches



Prospects for SM Higgs Search

$WH \rightarrow e\nu bb$ M_H = 115 GeV	DØ RunII 382 pb^{-1}	HSS scaled to 382 pb^{-1} e-only
Dijet mass window	[85,135]	[100,136]
Dijet mass resolution	14 ± 1 %	10 %
Signal events (S)	0.12 ± 0.03	0.48
Background events (B)	2.37 ± 0.59	5.79
Significance ($S/\sqrt{B}$)	0.08	0.20

- Current analyses sensitivities are lower than used for projections, but differences appear to be

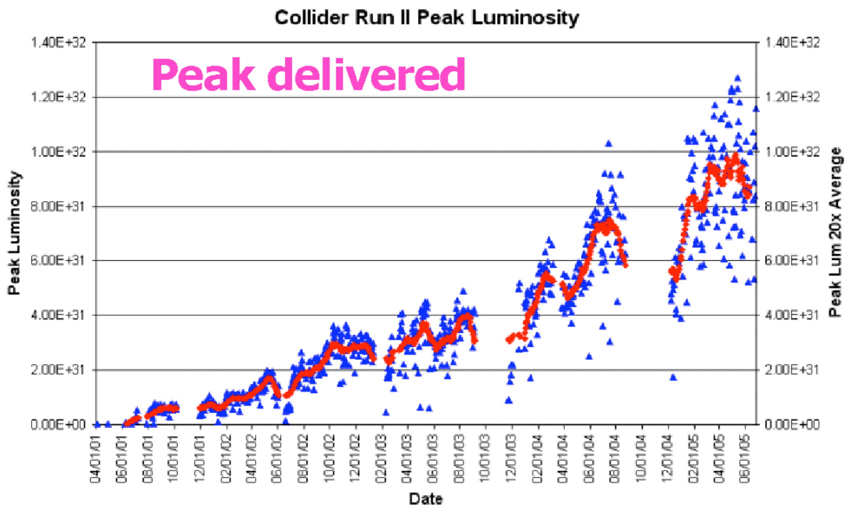


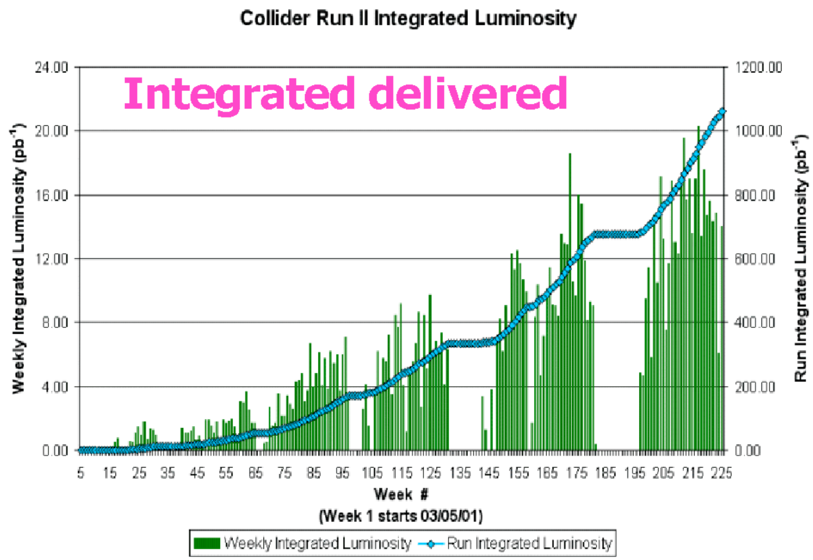
Tevatron Higgs Search Summary

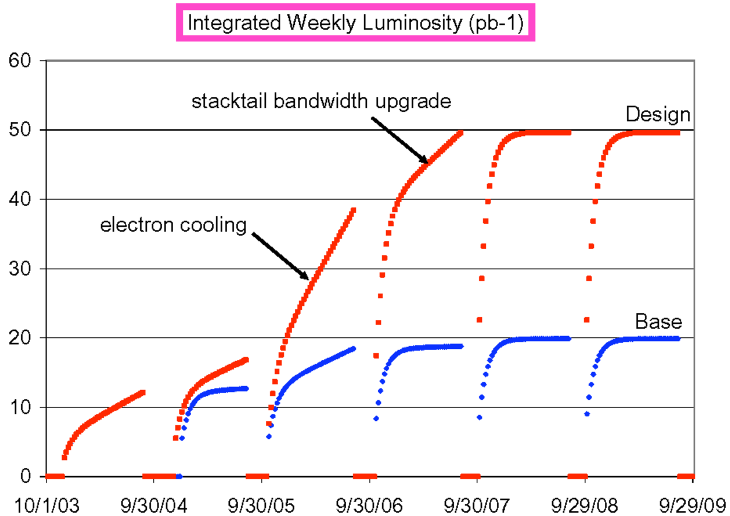
- MSSM tanβ enhancement searches
  - b(b)φ & Higgs→tt already sensitive to tanb~50-60
  - Plans to add b(b)f→b(b)tt
  - t→H^{+}b, H^{+}→tn results (Plans to add H^{+}→c$\bar{s}$)
- SM Higgs searches
  - Full complement of search channels with first results
  - Will be important to benchmark search sensitivity with WZ diboson production with Z→bb
  - ~1 fb^{-1} to analyze by Fall

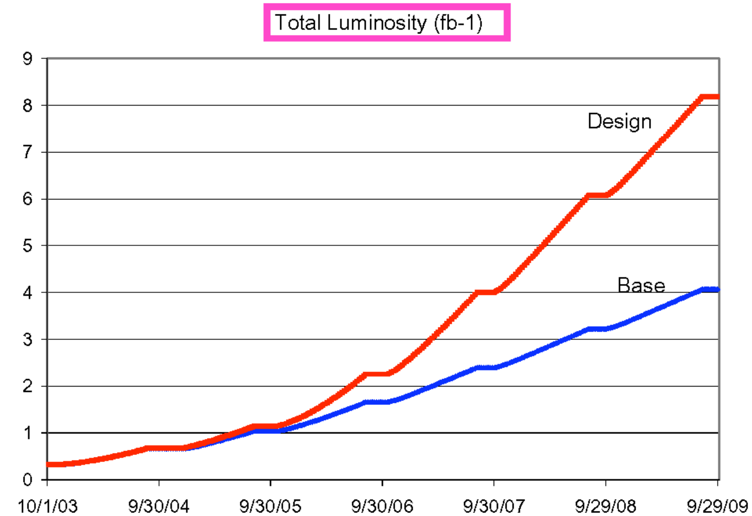
Backup Plots & Tables

Tevatron Performance



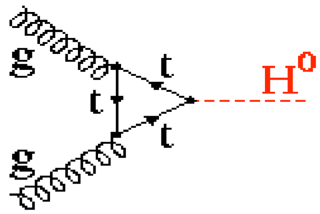






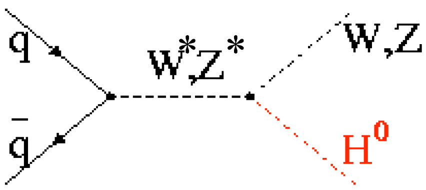
SM Higgs Production Processes

- **Gluon fusion: $gg \to H$**



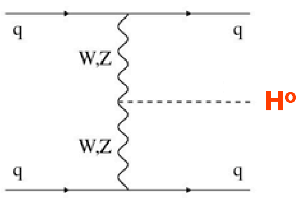
$\sigma = 0.70$ pb
for $M(H) = 120$ Gev/c^2
with QCD NLO correction

- **Higgsstrahlung: $q\bar{q} \to VH$**



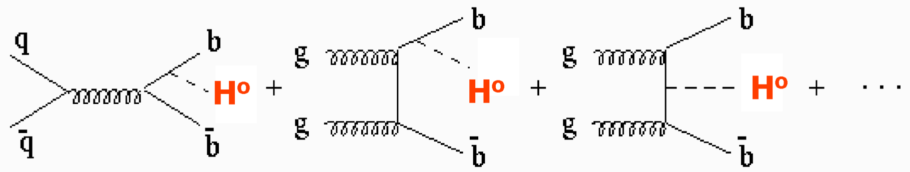
WH: $\sigma = 0.16$ pb
ZH: $\sigma = 0.10$ pb

- **Vector Boson fusion: $q\bar{q} \to q\bar{q}H$**



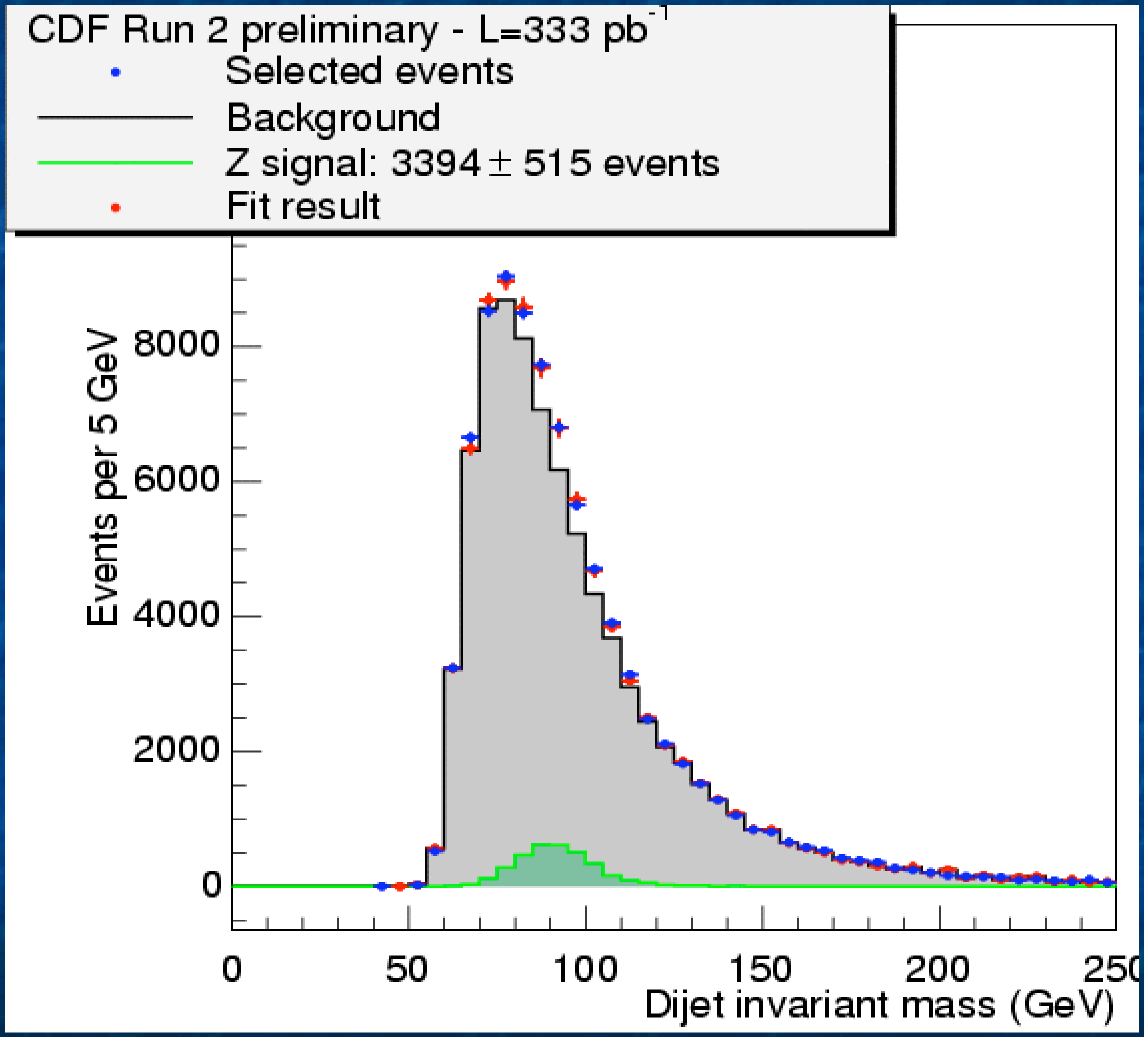
$\sigma = 0.10$ pb

- **Radiation off heavy quark: $q\bar{q} \to t\bar{t}H, b\bar{b}H$**



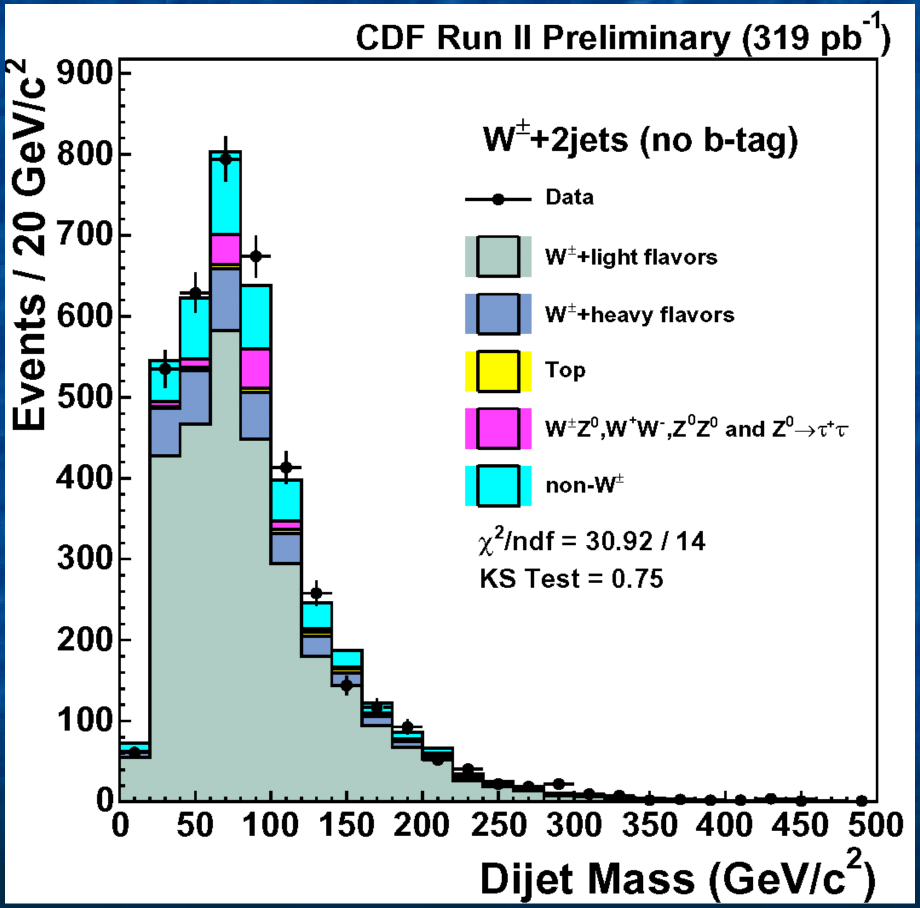
$\sigma = 0.004$ pb

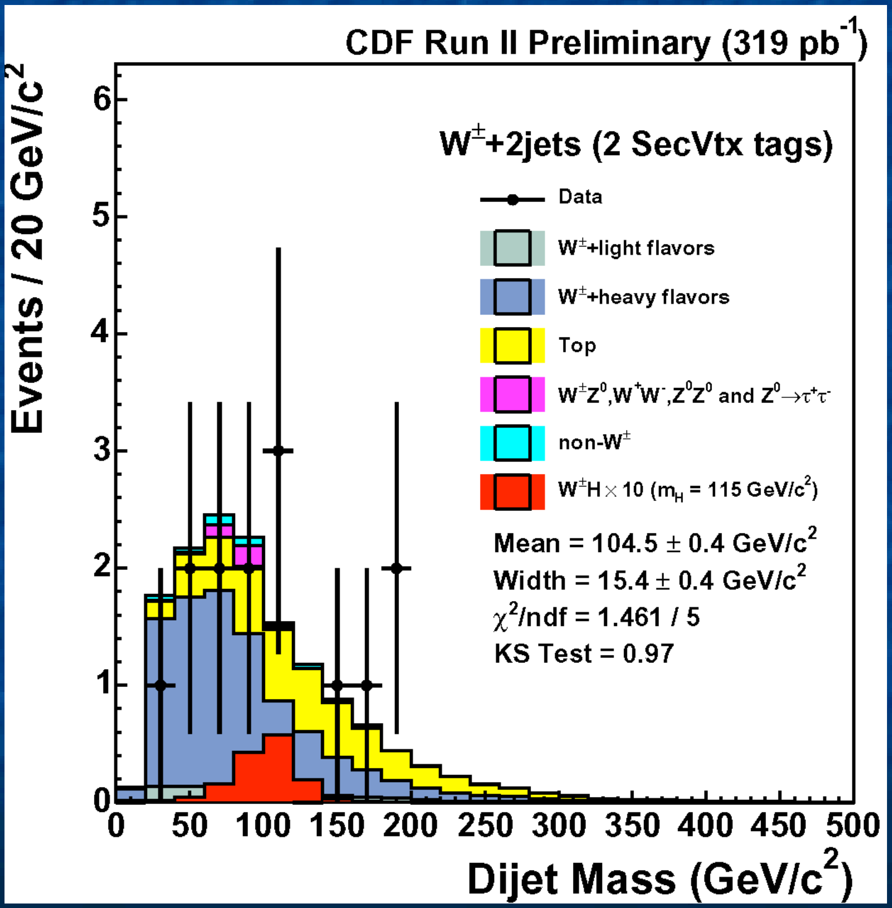
Z→bb (CDF)



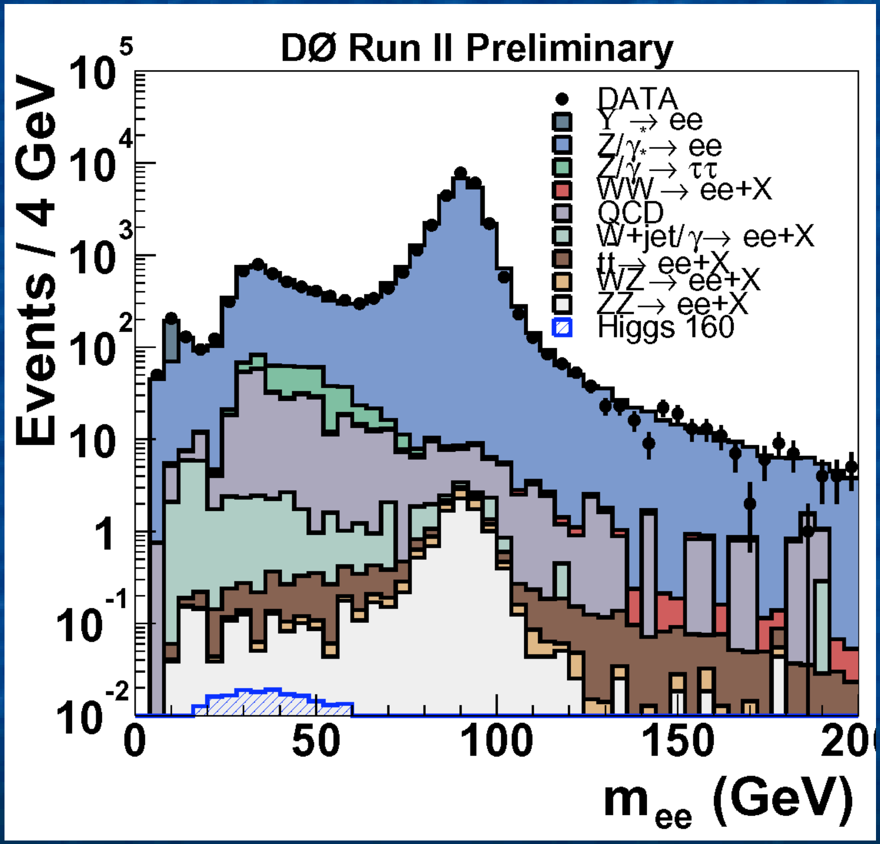
CDF Run 2 preliminary - L=333 pb⁻¹
Selected events
Background
Z signal: 3394 ± 515 events
Fit result
Events per 5 GeV
8000
6000
4000
2000
0
0
50
100
150
200
250
Dijet invariant mass (GeV)

ℓ nbb Search (CDF)

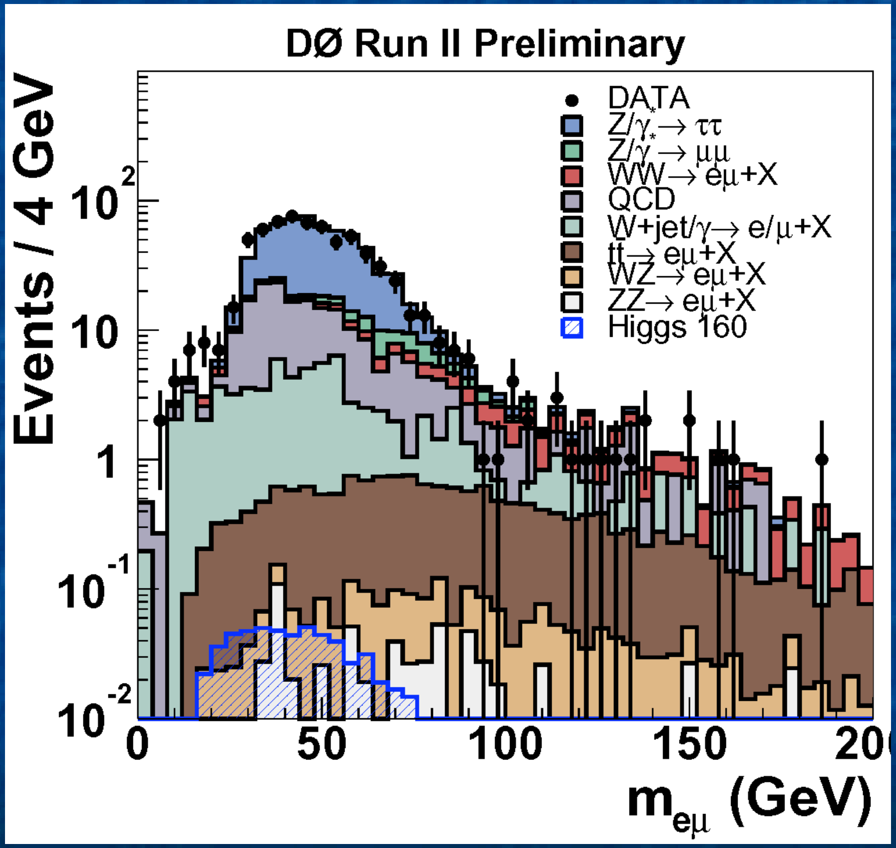




H→WW (DØ)



DØ Run II Preliminary
Events / 4 GeV
DATA
Υ → ee
Z/γ* → ee
Z/γ* → ττ
WW → ee+X
QCD
W+jet/γ → ee+X
tt → ee+X
WZ → ee+X
ZZ → ee+X
Higgs 160
m_ee (GeV)

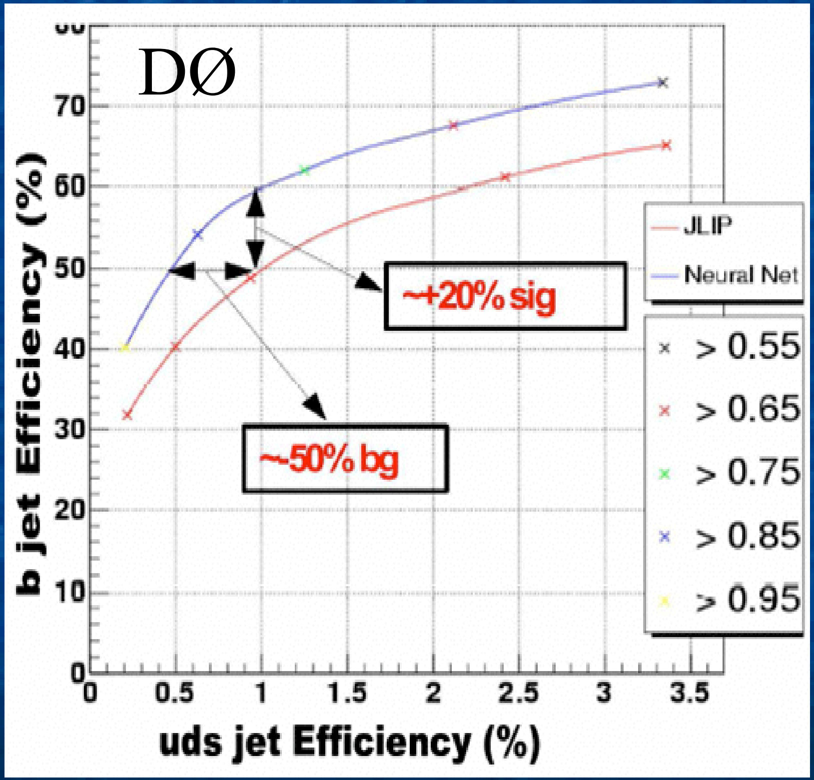


DØ Run II Preliminary
Events / 4 GeV
DATA
Z/γ* → ττ
Z/γ* → μμ
WW → eμ+X
QCD
W+jet/γ → e/μ+X
tt → eμ+X
WZ → eμ+X
ZZ → eμ+X
Higgs 160
m_eμ (GeV)

Improvements to b-tagging

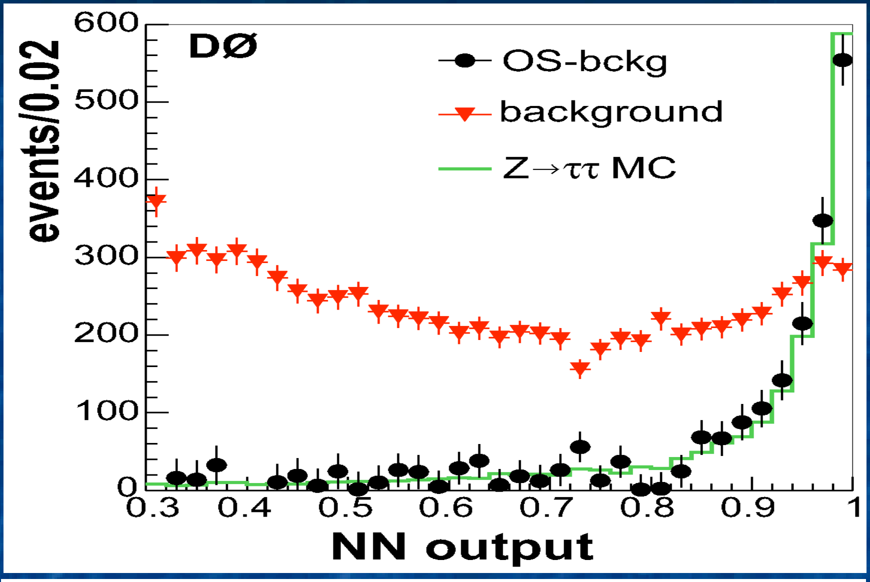
- Analysis depends on strongly on b-tag
- Neural Net b-tagging

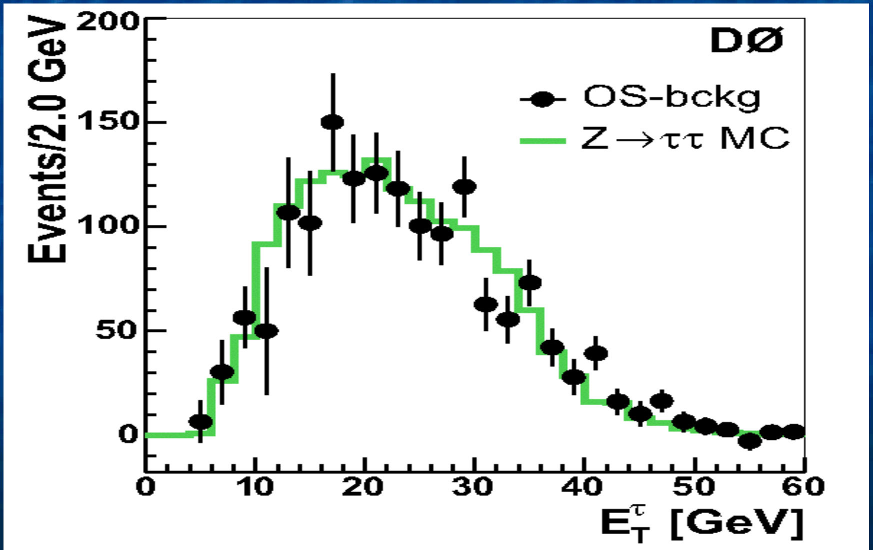
Operating Point	~ Fake Rate	~ b Efficiency
Tight	0.25 %	44 %
Medium	0.5 %	52 %
Loose	1.0 %	57 %
$Loose^2$	2.0 %	64 %
$Loose^3$	3.0 %	68 %
$Loose^4$	4.0 %	70 %



Z→ττ as a benchmark

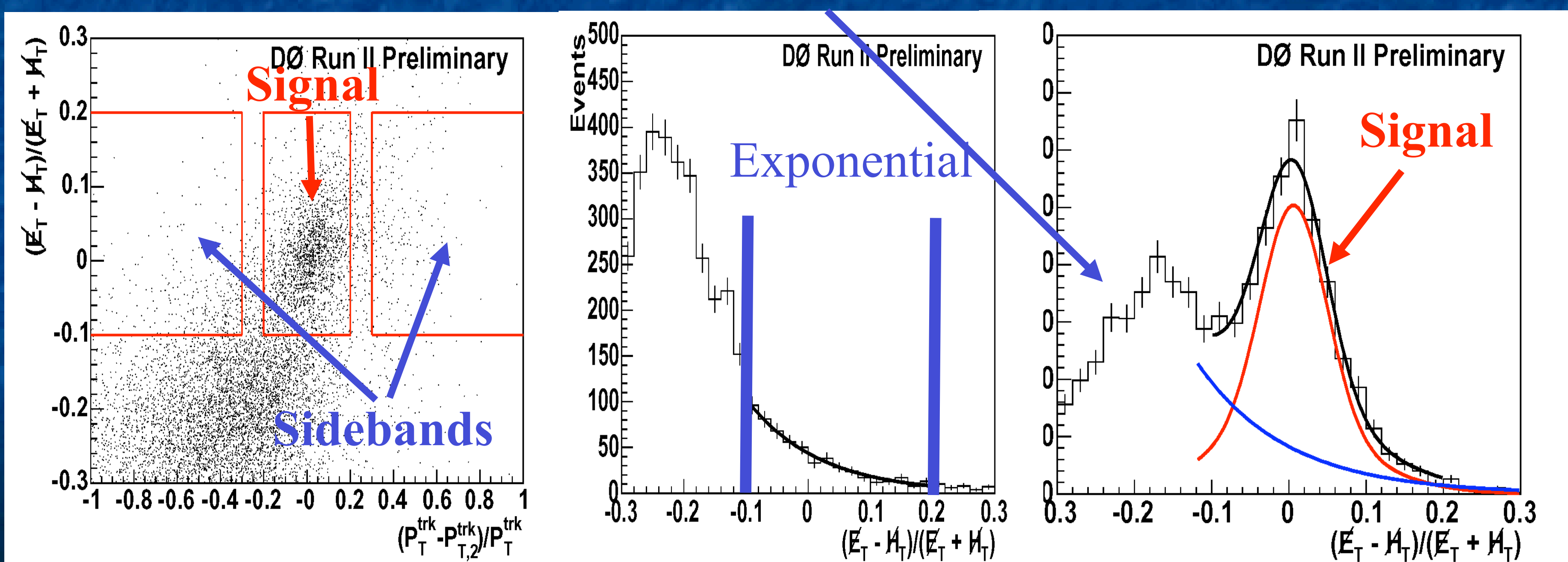
- DØ Neural Network τ-Selection
  - Variables:
    - Shower Profile
    - Calorimeter Isolation
    - Track Isolation
    - Charged Momentum Frac
    - Opening Angle
    - Etc.
  - 3 Types:
    - π-like
    - ρ-like
    - Multi-prong





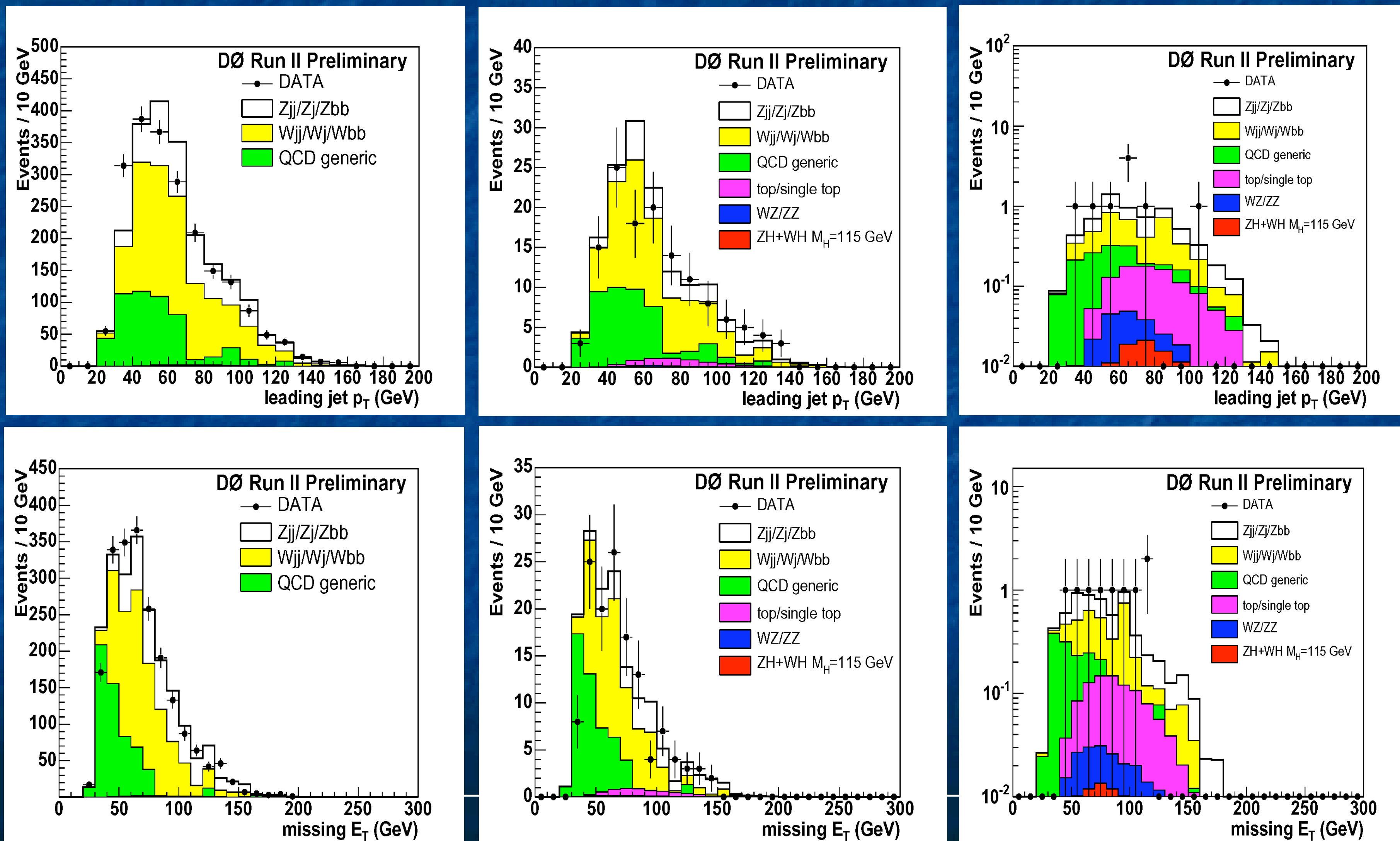
Missing Energy Channel (DØ)

- Trigger on event w/ large $\not{E}_T$ & acoplanar jets
- Instrumental $\not{E}_T$ backgrounds (Data-driven estimation)
  - Asymmetries computed: Asym($\not{E}_T$,$\not{H}_T$) and Asym(Σ p_T^{trk},p_{T2}^{trk})

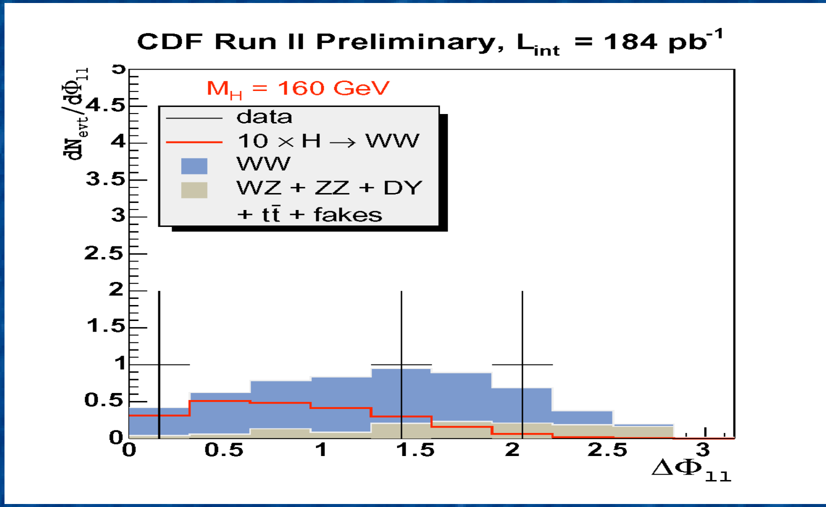


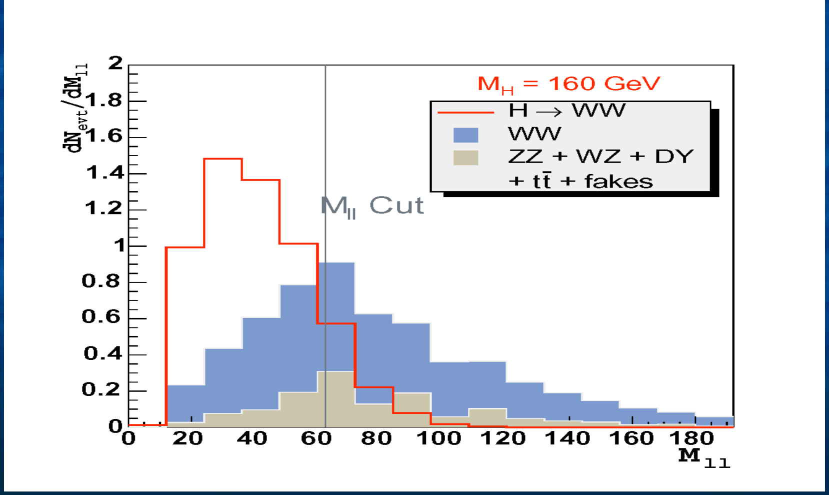
Missing Energy Channel (DØ)

No b-tag **Single b-tag** **Double b-tag**



H→WW (CDF)





Cluster mass:

$$M_C = \sqrt{\left(p_T^{ll}\right)^2 + M_{ll}^2}$$