The Tevatron Reach to New Physics

Rick Van Kooten
Indiana University/DØ

Physics at the LHC: Early Challenges

Kellogg Biological Station, Michigan State University
15 – 16 May 2007

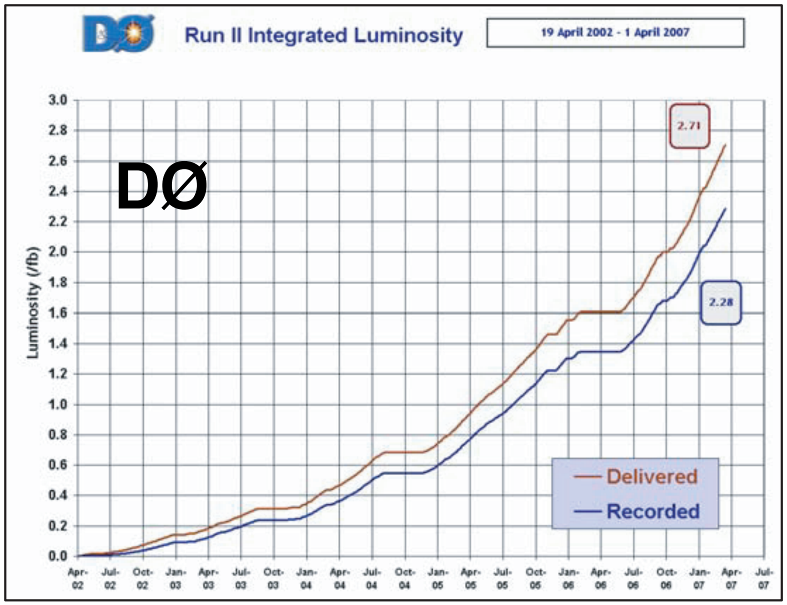
Outline

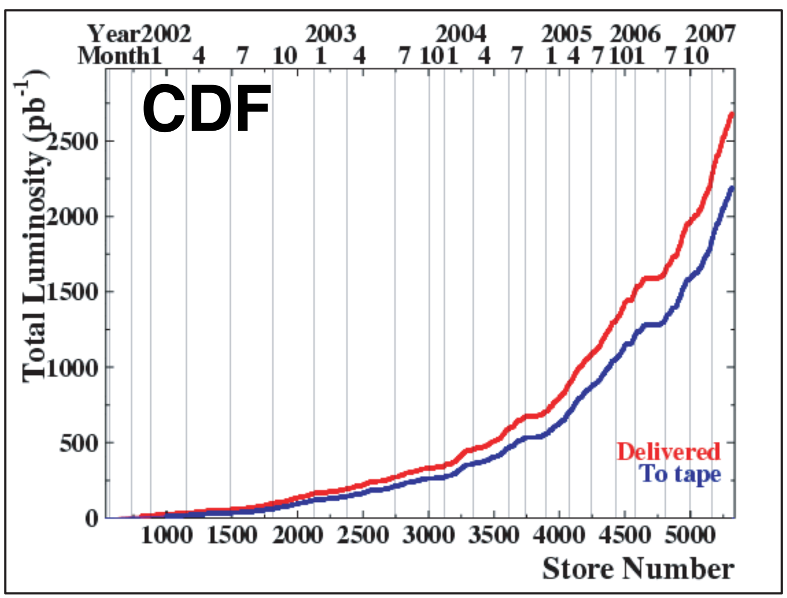
Not a comprehensive summary

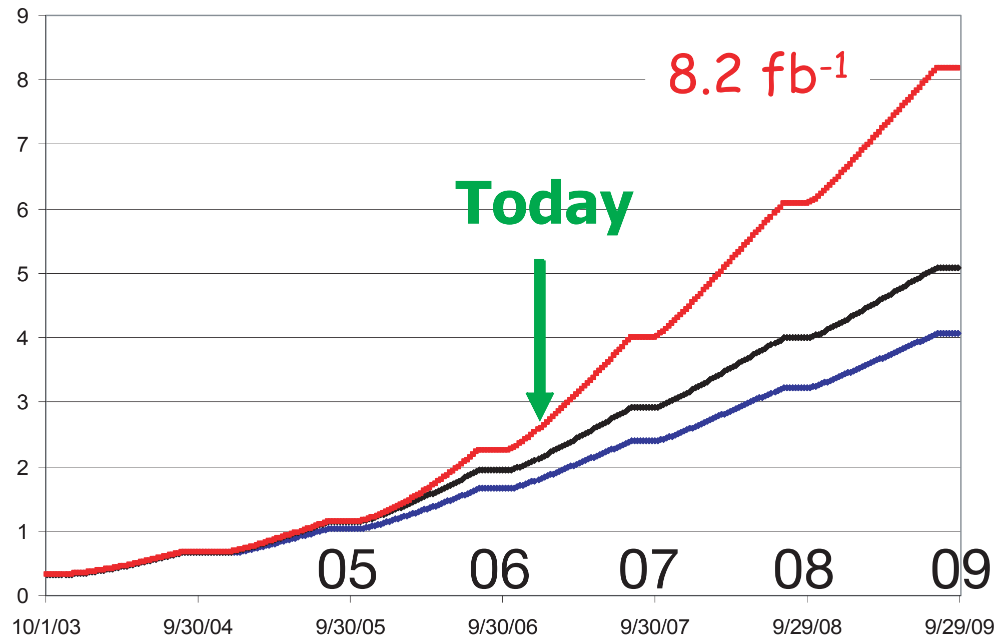
- Machine schedule, timeline
- Implications of Tevatron precision EW
  - top
  - *W* mass
  - rare decays
- Direct searches: prospects and current excesses
  - SM Higgs
  - SUSY Higgs
  - SUSY
  - Other

(hey we're the ones with data!)

Tevatron Performance & Prospects







- Tevatron running with peak luminosities of 300 x 10^{30} cm^{-2} s^{-1}
- Each experiment has recorded ~2.8 fb^{-1} of data and have results on up to 2 fb^{-1}
- Performance on track for 6 – 8 fb^{-1} delivered by 2009

Tevatron Performance & Prospects

- Will we in fact run in 2009?

  Likely. P5 was initially asking for in depth review, now requesting much less of physics justification for 2009 running

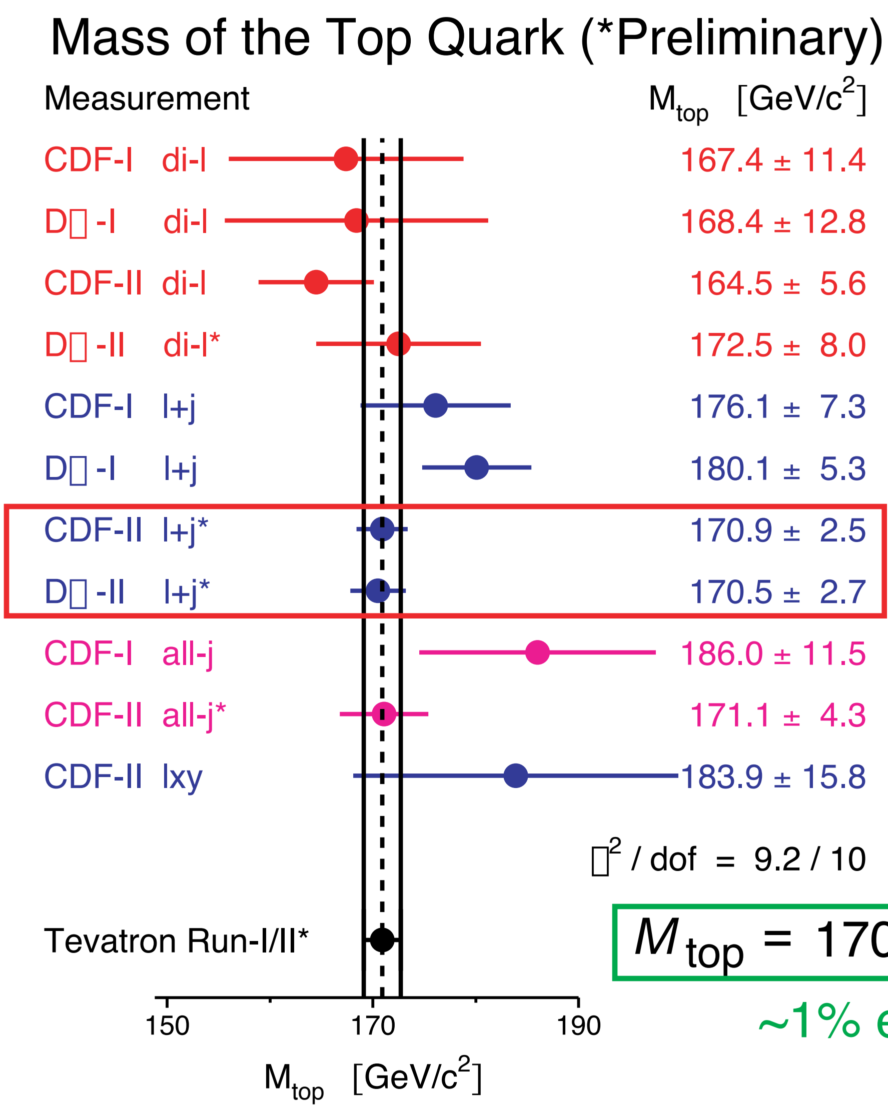
- 2010?

  Discussions on usefulness in FNAL Steering Group

  (estimate of extra delivered int. lumi in FY2010 is 2.0 fb^{-1} or extra ~30% with respect to the end of FY2009)

  Detector upgrades/different detector? and other ~crazy ideas

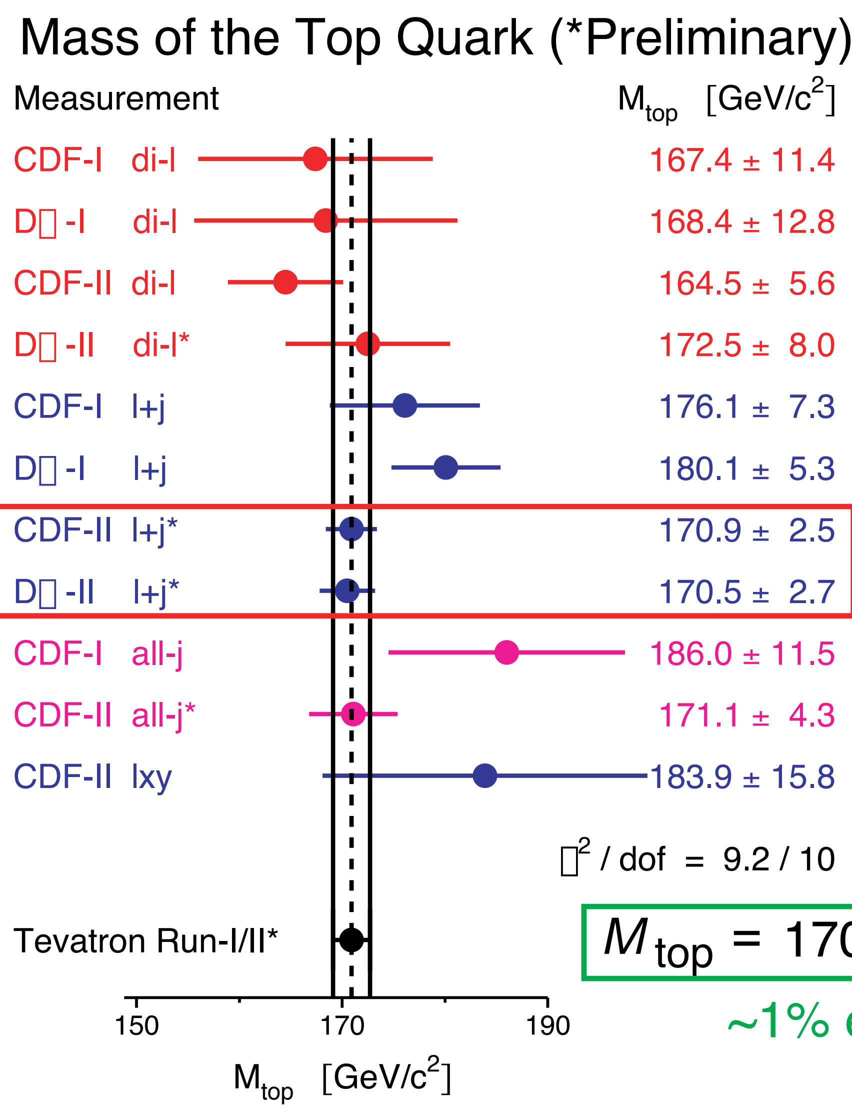
Bread & Butter



M_{top} = 170.9 ± 1.8 GeV

~1% error !!

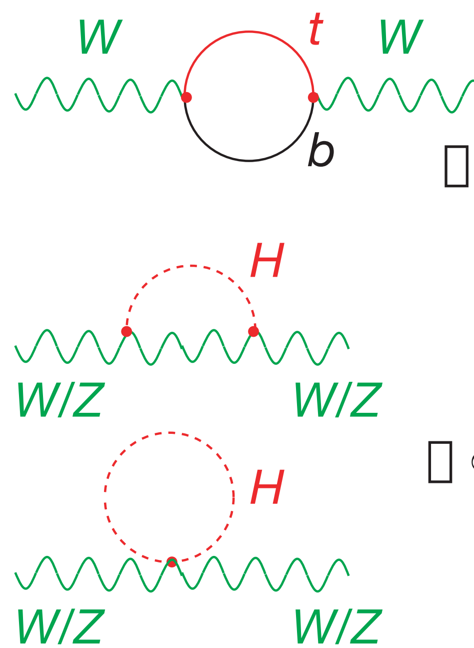
Bread & Butter



M_{top} = 170.9 ± 1.8 GeV

~1% error !!

Electroweak radiative corrections, probe Higgs mass ***indirectly***:



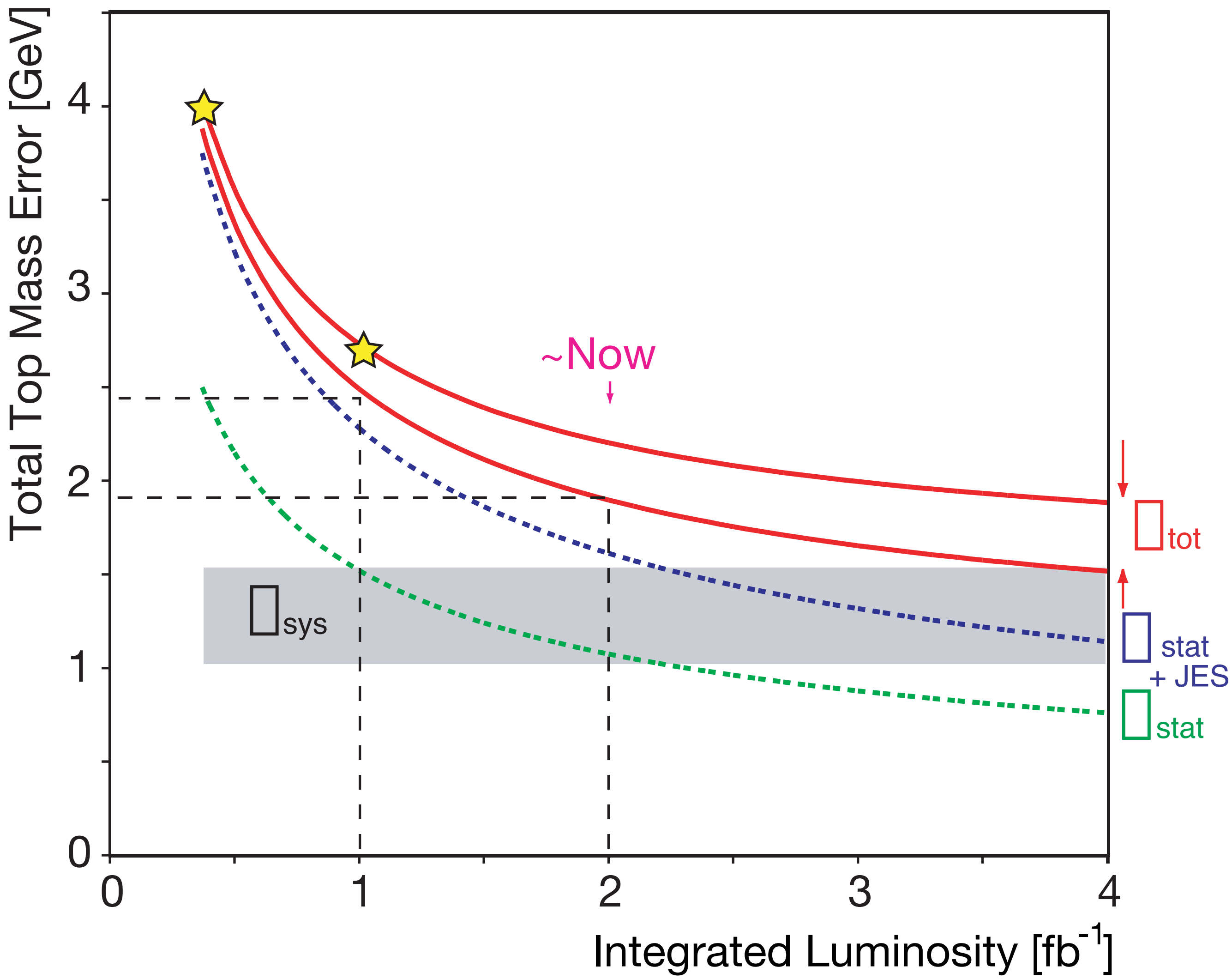
$\square \propto G_F M_{top}^2$

$\square \propto \log \frac{M_{Higgs}}{M_W}$

Top Quark Mass

D0 Lepton + jets: 170.5 ± 2.5 (stat. +JES) ± 1.4 (syst) GeV   ~1 fb^{-1}

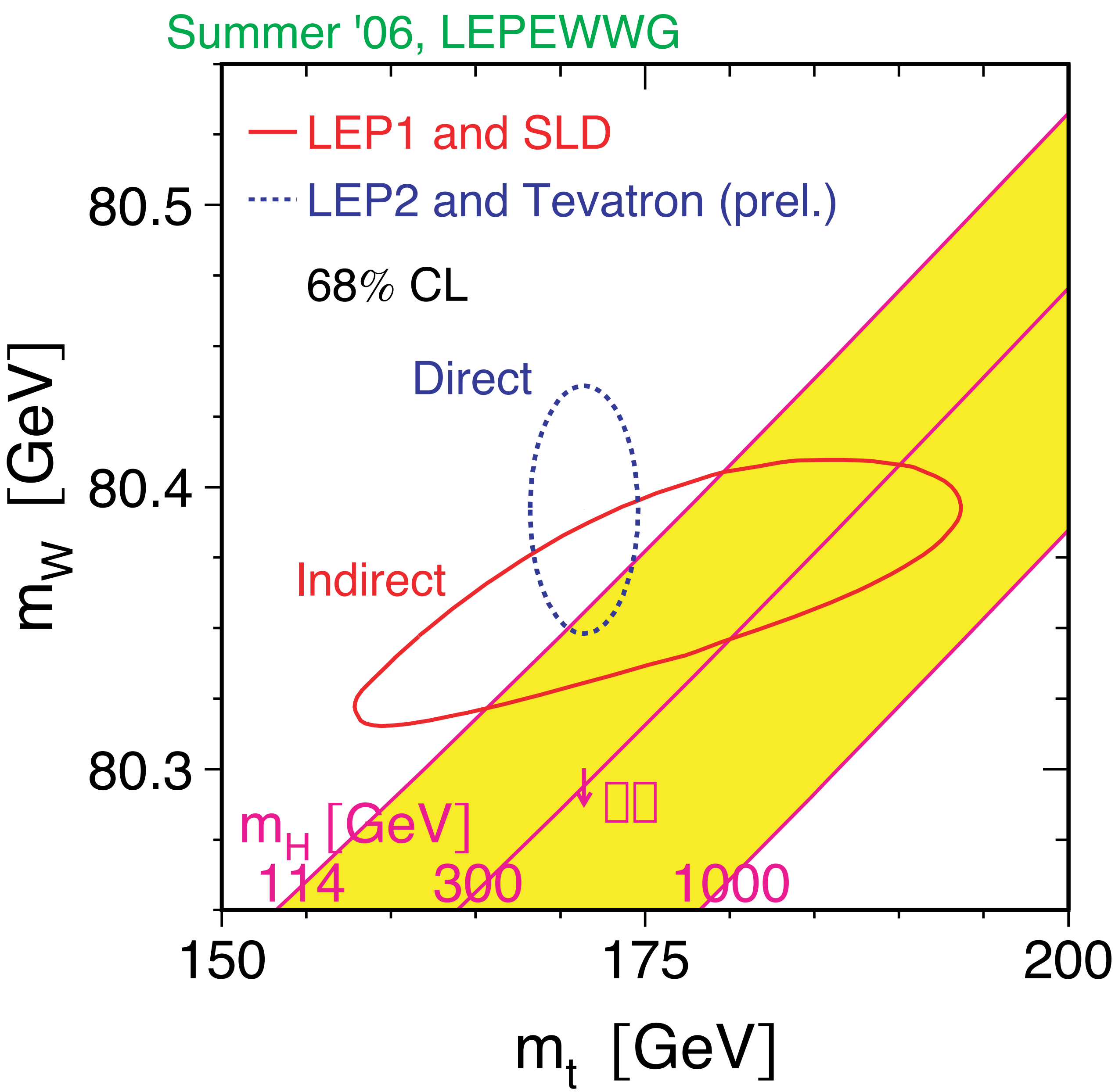
For illustrative purposes:



	Δm_{top} [GeV]
370 pb^{-1}	~4.0
1 fb^{-1}	~2.7
2 fb^{-1}	~2.0

Jet energy scale calib. done "in situ" by fitting to W mass

W Mass: Playing Precision Catch-up

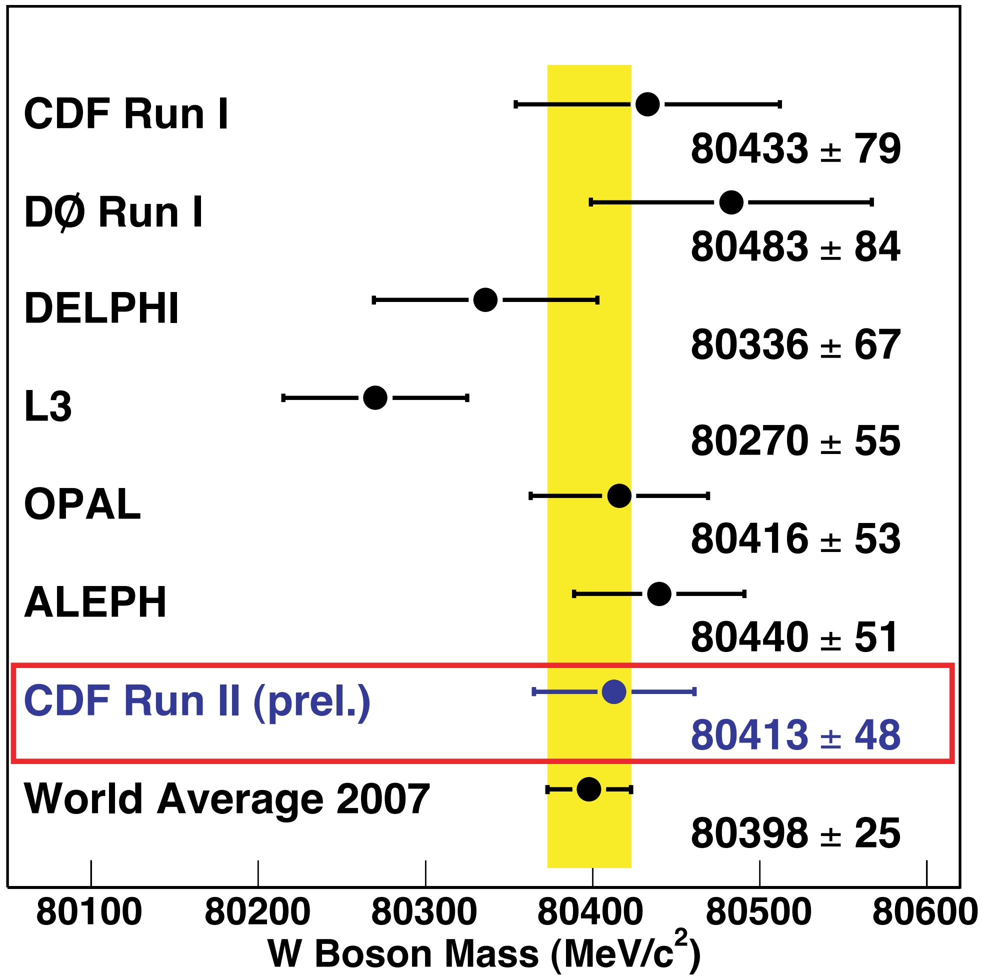


"James Bond"
Rule of Thumb:

δm_W roughly equiv. to 0.007 δm_t

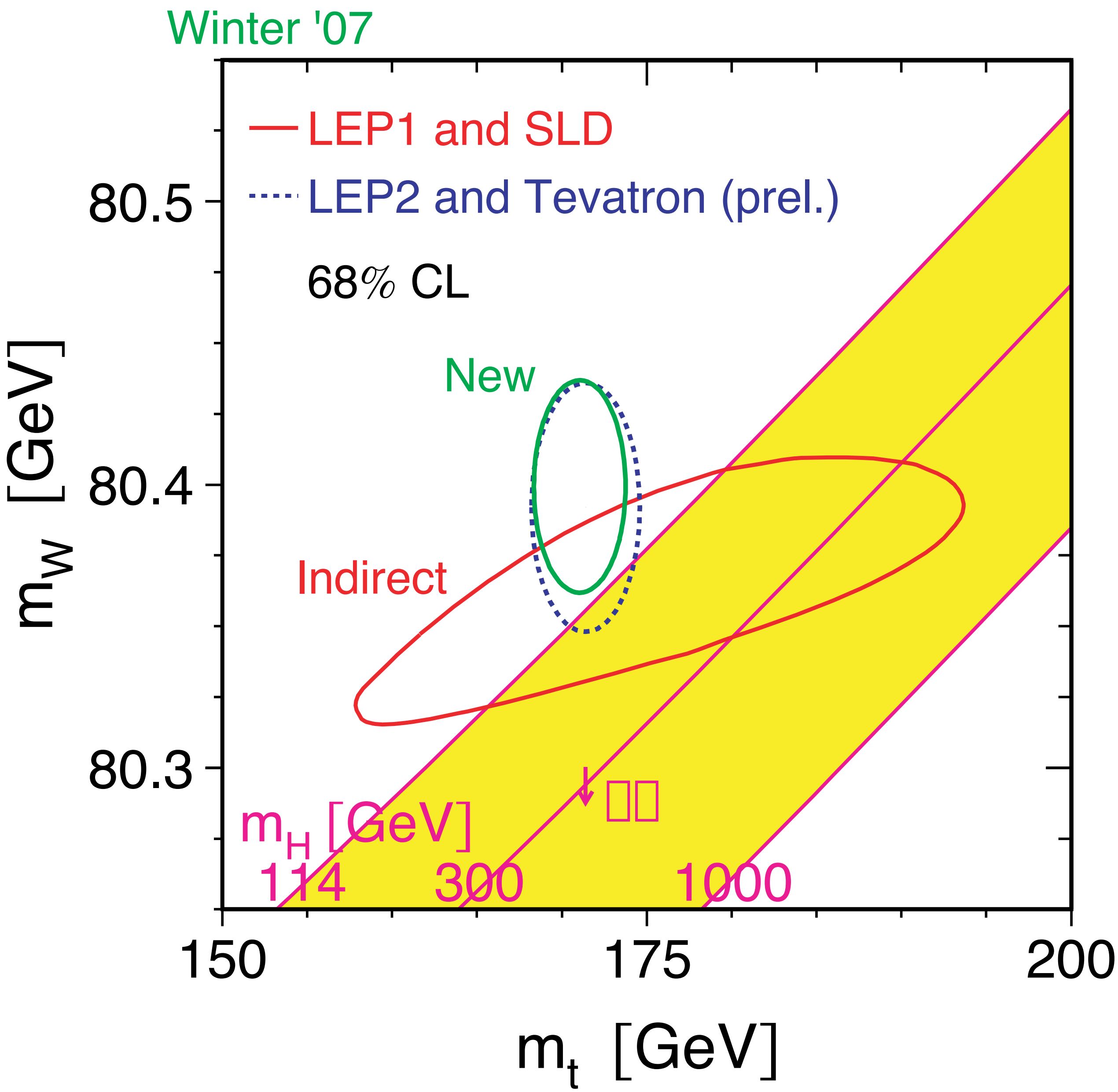
- δm_t ~ 1.8 GeV
- Equivalent constraint on M_H would come from δm_t ~ 13 MeV (0.016%!)
- Need to improve *W* mass measurement

W Mass: Playing Precision Catch-up



- CDF Winter '07: World's single most precise measurement
- Central values shifts up by 6 MeV
- Uncertainty reduced by 15% (29 to 25 MeV)

W Mass: Playing Precision Catch-up



Was

$m_H = 85^{+39}_{-28}$ GeV

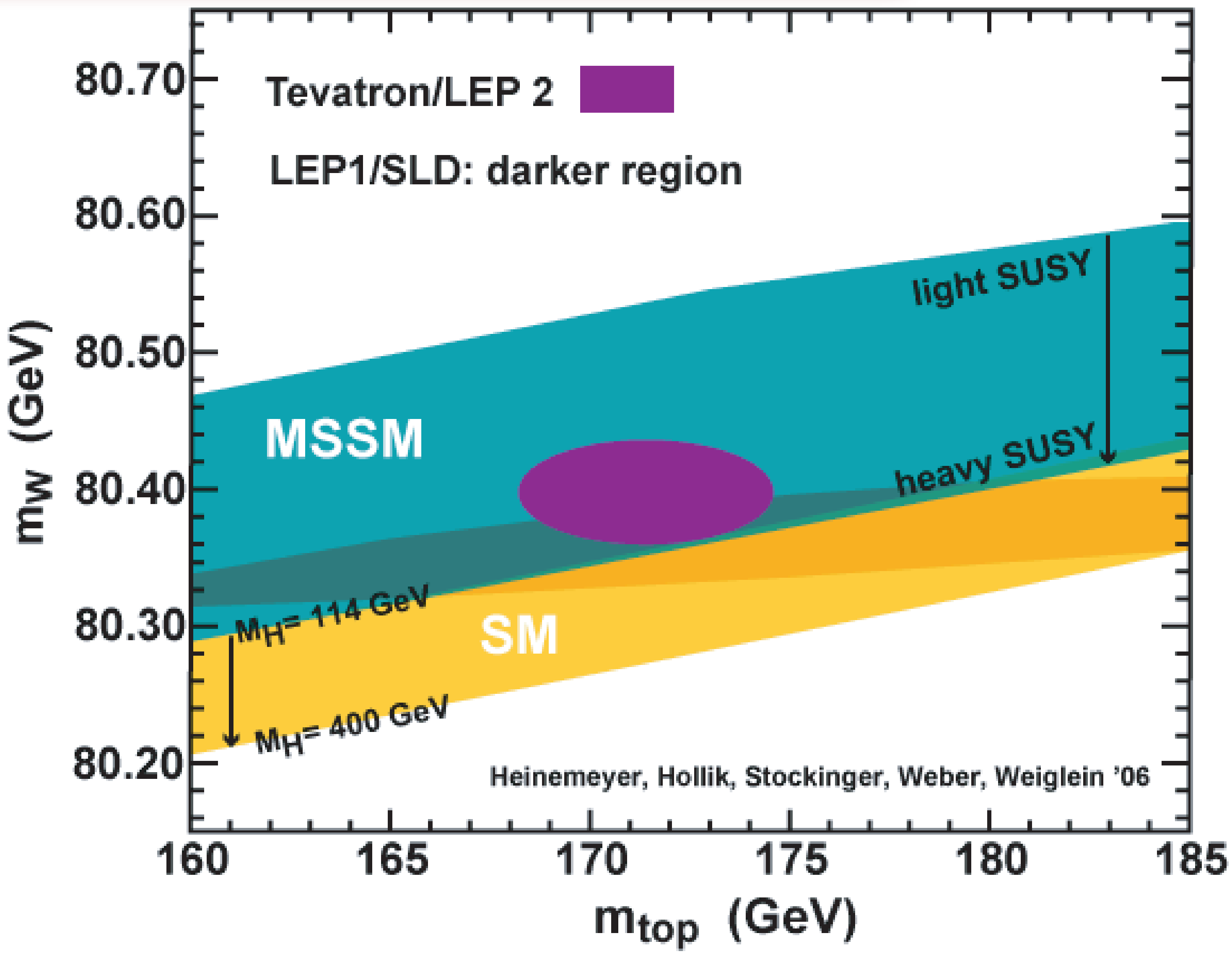
$m_H < 166$ GeV @ 95% C.L.

Now

$m_H = 80^{+36}_{-26}$ GeV

$m_H < 153$ GeV @ 95% C.L.

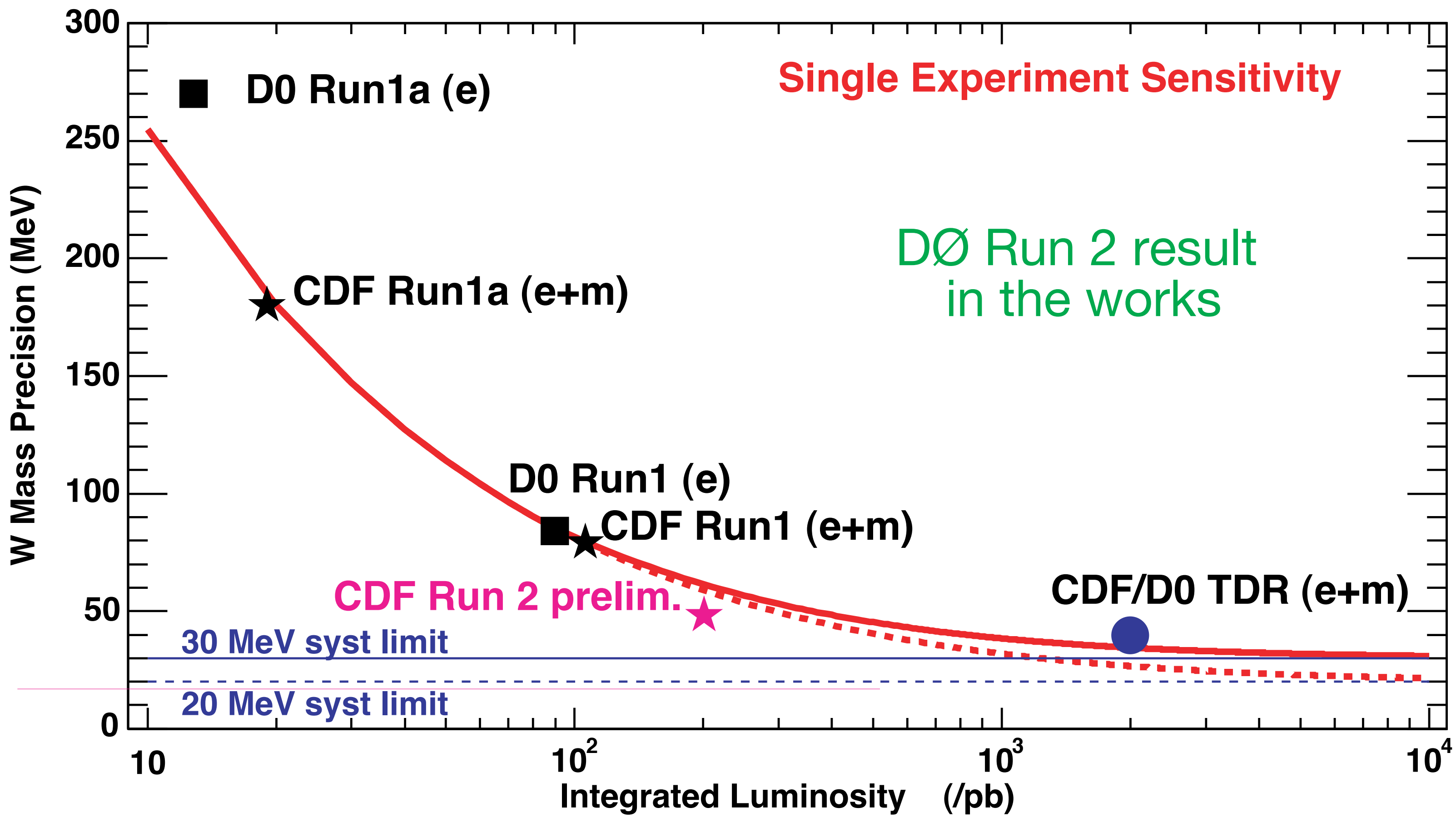
W Mass: Playing Precision Catch-up



Bodes well for SUSY

W Mass: Playing Precision Catch-up

- ... and no way to go but down in uncertainty



- and $m_{top} \lesssim$ 1.5 GeV (other theory errors?) by end of program

Last "Indirect" Search: $Br(B_s \to \mu^+\mu^-)$

Relatively easy trigger!

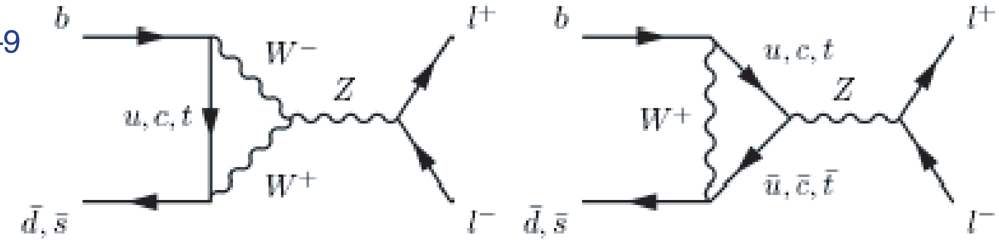
Relatively easy to reconstruct (two body)

- Excellent window into new physics
- Forbidden at tree level, highly suppressed in SM

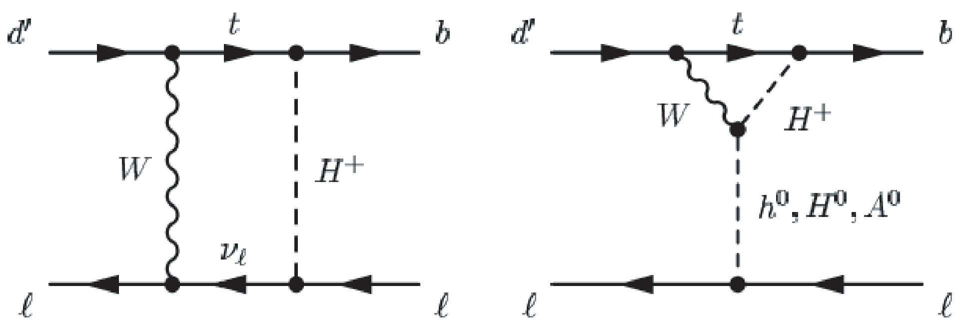
Predicted:

$Br(B_s \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$

$Br(B_d \to \mu^+\mu^-)$ suppressed by another factor of $|V_{td}/V_{ts}| \sim 0.04$



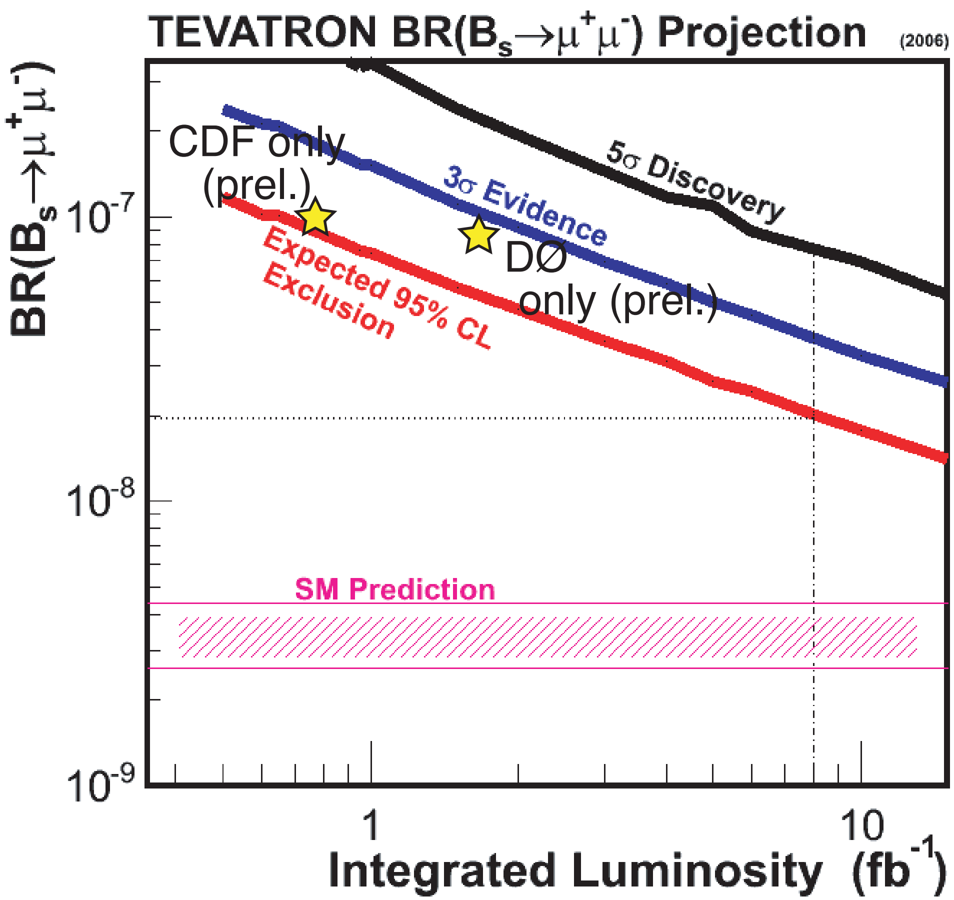
- *Br* grows as $\tan^6\beta$ in the MSSM



- Very attractive probe for any new physics with extended Higgs sectors (e.g., two Higgs doublet models)

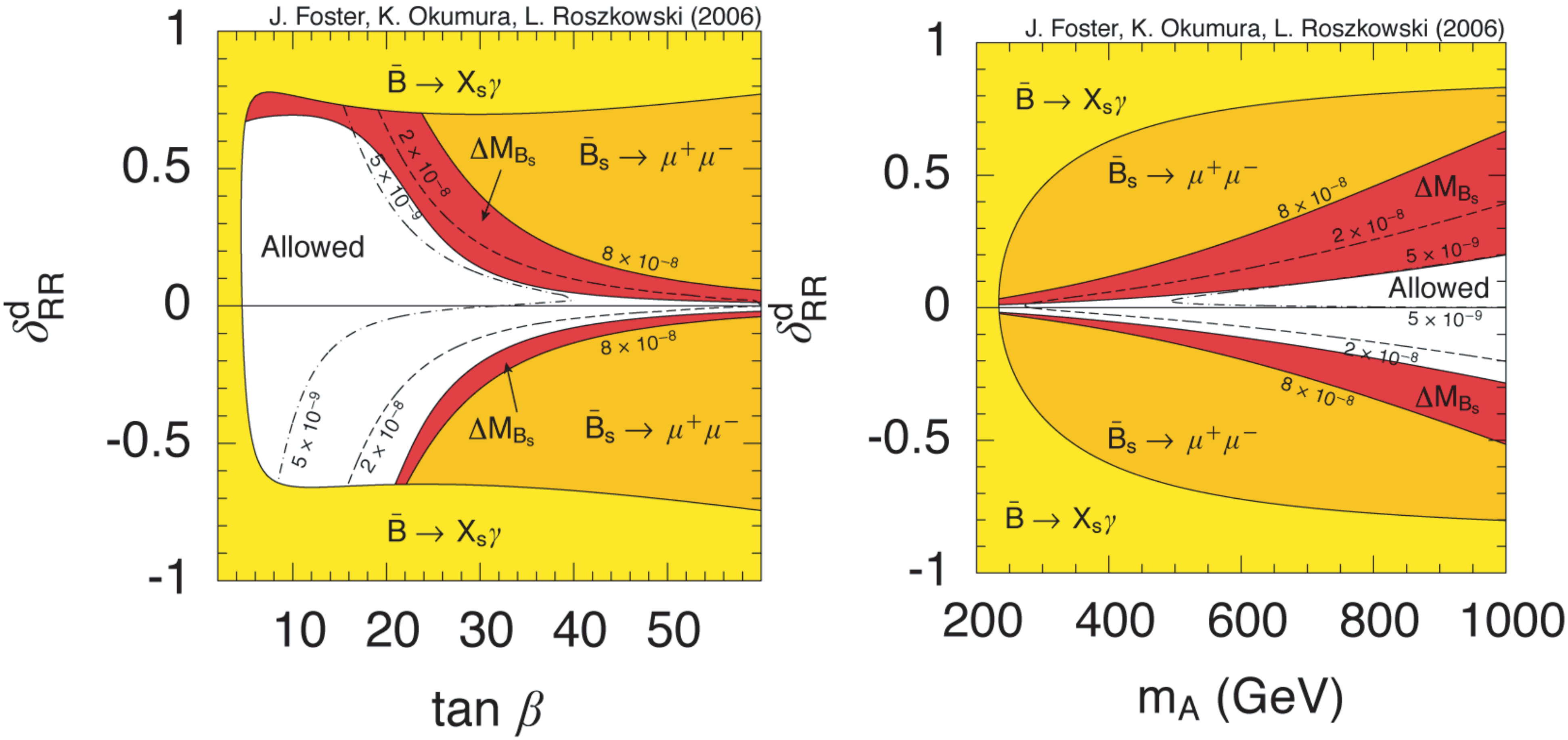
Last "Indirect" Search: $Br(B_s \to \mu^+\mu^-)$

	$\mathcal{B}(B_s \to \mu^+\mu^-)$ 90% (95%) C.L.	$\mathcal{B}(B_d \to \mu^+\mu^-)$ 90% (95%) C.L.	Int.Lum. pb^{-1}
CDF	$< 8.0\times10^{-8}$(10)	$< 2.3\times10^{-8}$(3)	780
D0	$< 7.5\times10^{-8}$(9.3)		1800



- "On track" when CDF & DØ combined
- Remember looking for an excess to indicate SUSY...

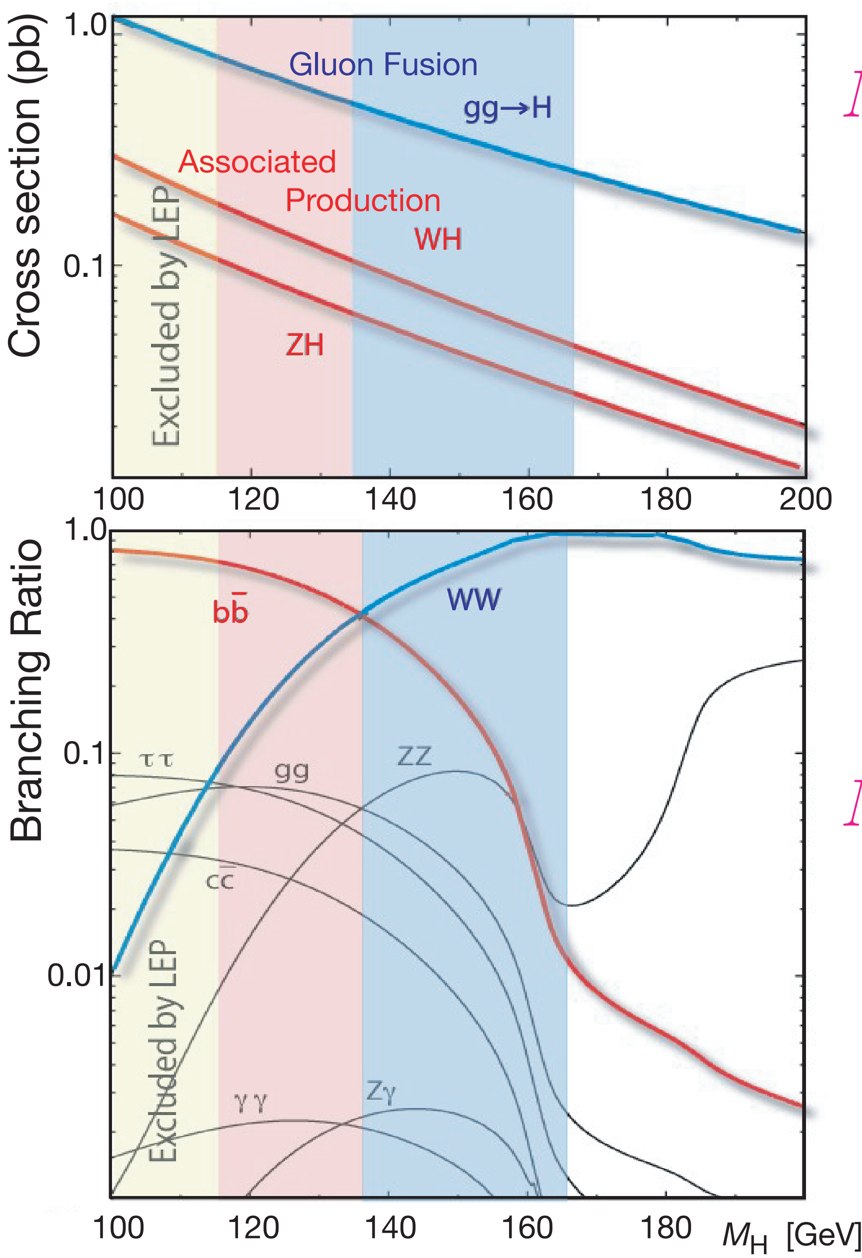
Last "Indirect" Search: $Br(B_s \to \mu^+\mu^-)$



δ_{xy} General Flavor Mixing (GFM) insertion parameters

...but nothing beats a direct search/discovery...

SM Higgs



Analysis strategy depends on mass:

$M_H < 135\,\mathrm{GeV}$

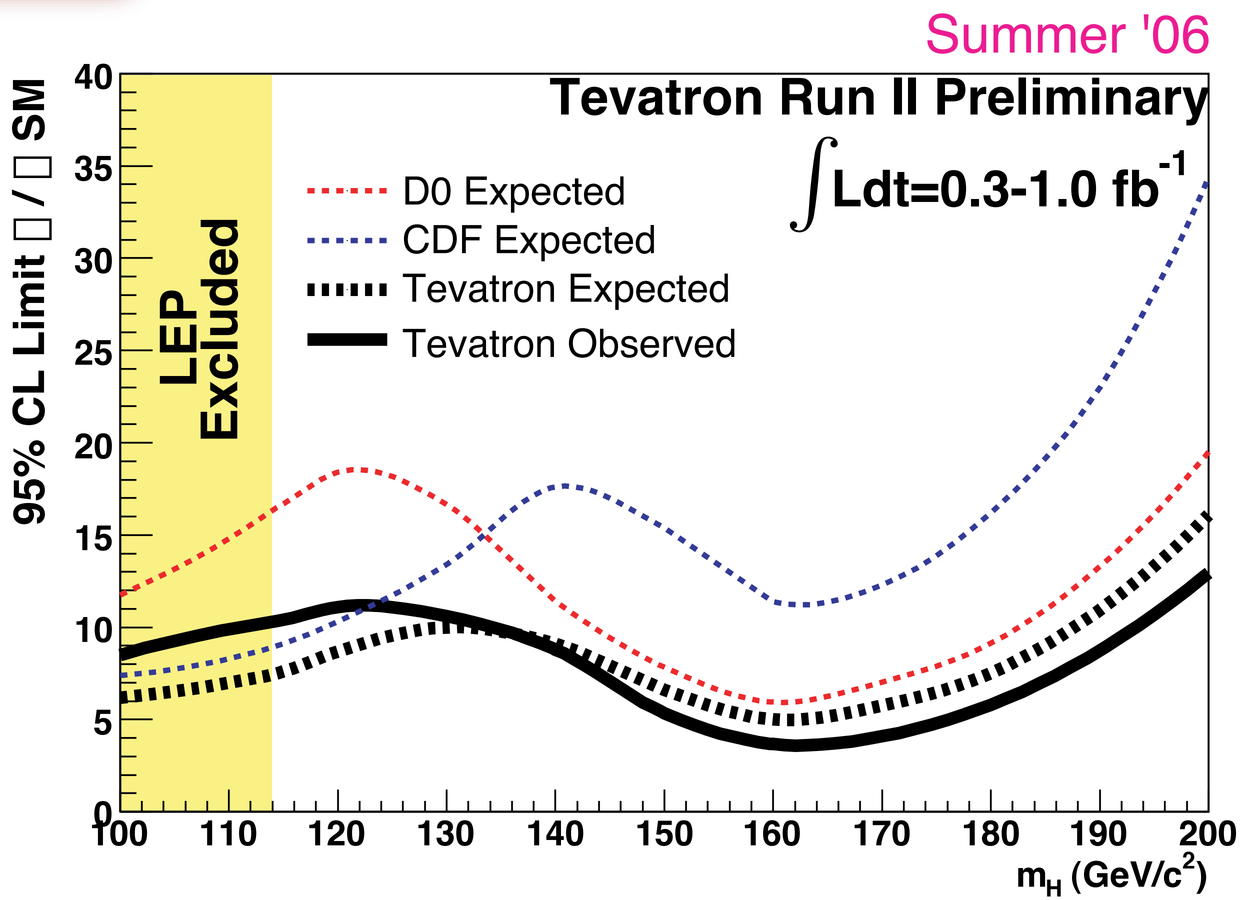
- $gg \to H \to b\bar{b}$ overwhelmed by QCD multijet background
- Stick to associated production: WH, ZH followed by $H \to b\bar{b}$ (and leptonic decays of VB's)
- Complement it with $H \to WW^*$
- Backgrounds: $Wbb, Zbb, W/Zjj$ top, QCD, diboson...

$M_H > 135\,\mathrm{GeV}$

- Use $gg \to H \to WW$ production and distinctive multilepton final states
- Backgrounds: $WW, DY, WZ, ZZ,$ $tt, tW, \tau\tau$...

SM Higgs

What was...

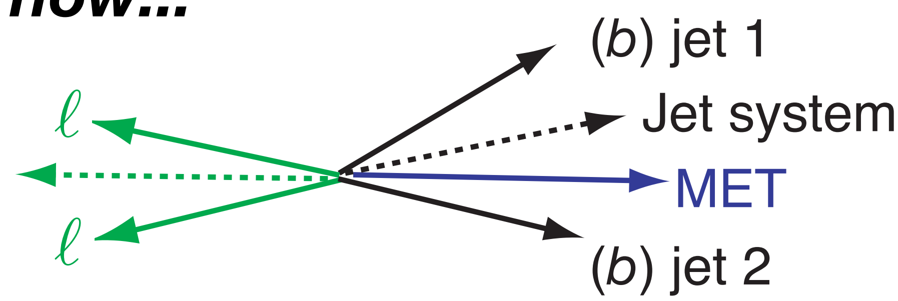


- Sixteen mutually exclusive final states for WH, ZH, WW
- Recent progress: both CDF and DØ completed low and high mass 1 fb^{-1} analyses;
  improvements in analysis techniques & systematic uncertainties.

SM Higgs

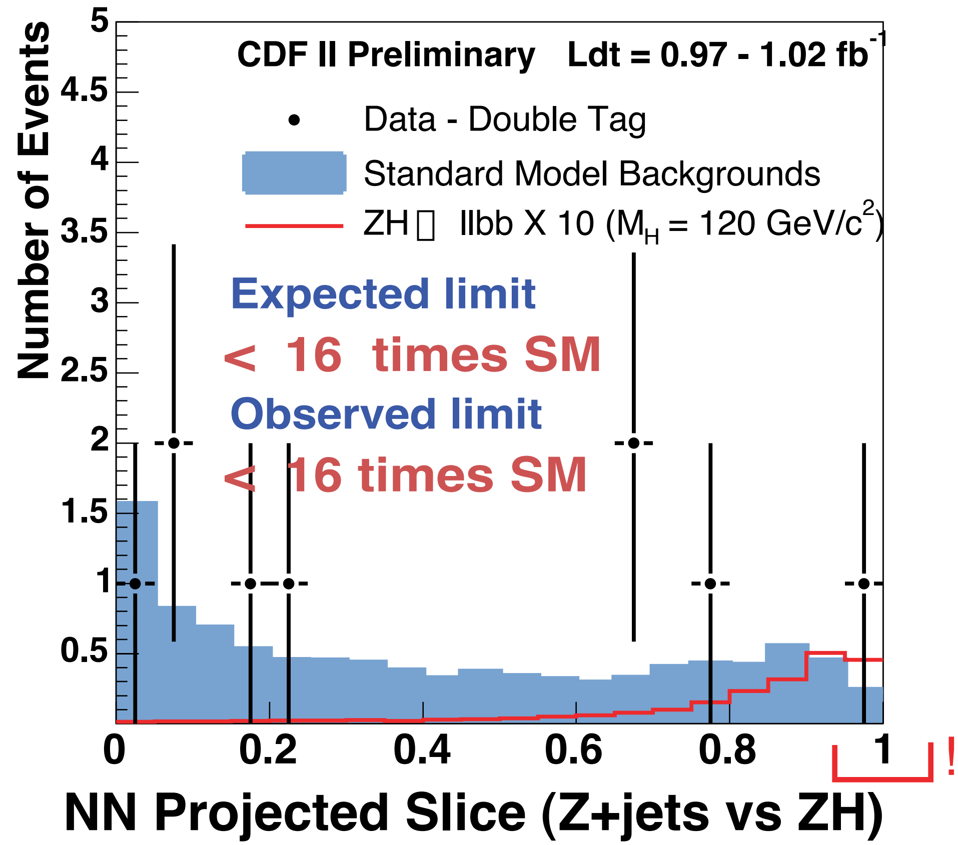
What is now...

$$ZH \to \ell^+\ell^- b\bar{b}$$



New CDF

- Reduce backgrounds
  - split data into 2 loose *b*-tags and 1 tight single *b*-tag
- Improve dijet mass resolution
  - should be no real missing tranverse *E* (MET)
  - correct jets according to projection on MET
  - improved dijet mass resolution from 17% to 10% (30% increase in effective lumi!)
- 2-dim Neural Net



(was 23 exp. /27 obs. times SM)

SM Higgs

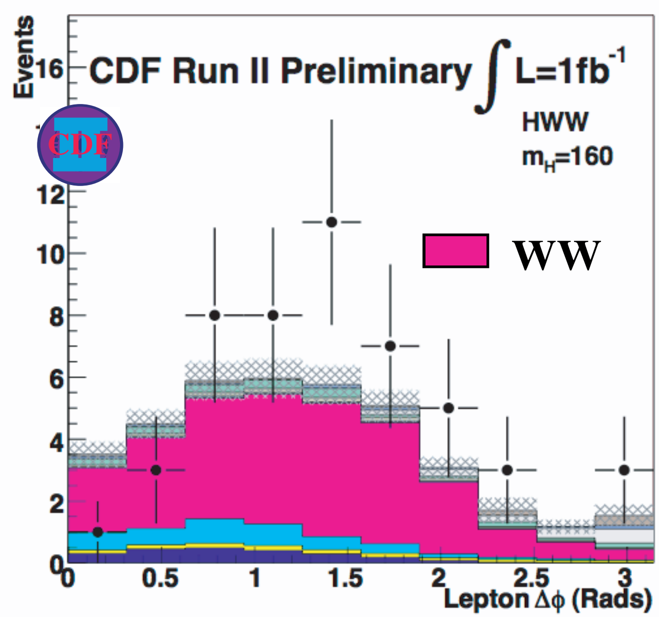
What is now...

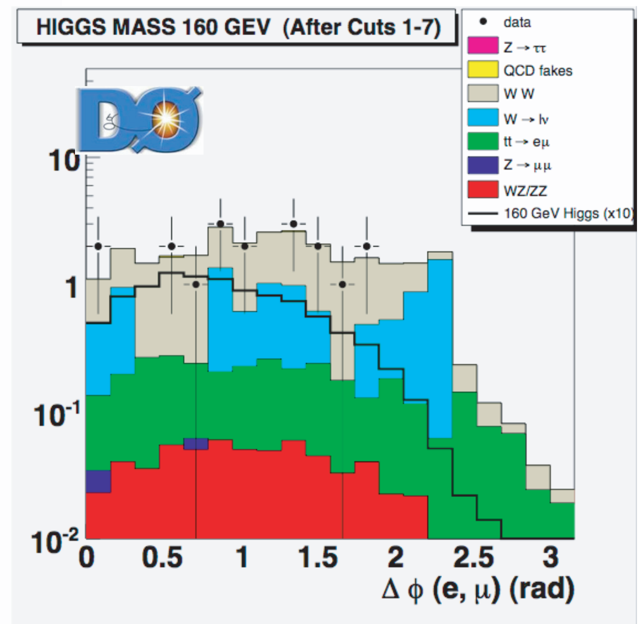
e.g., $H \rightarrow WW^{*} \rightarrow \ell^{+}\nu$
$\quad\quad\quad\quad \hookrightarrow \ell^{-}\bar{\nu}$ $\Big] \Delta\phi$

Expect. 95% CL limit (m_H= 160 GeV)

D0:
< 3.7 times SM
< 4.2 (expected)

CDF:
< 9.2 times SM
< 6.0 (expected)





- CDF has new results in same channel with advanced analysis technique
  - Improved lepton acceptance
  - Matrix Element approach

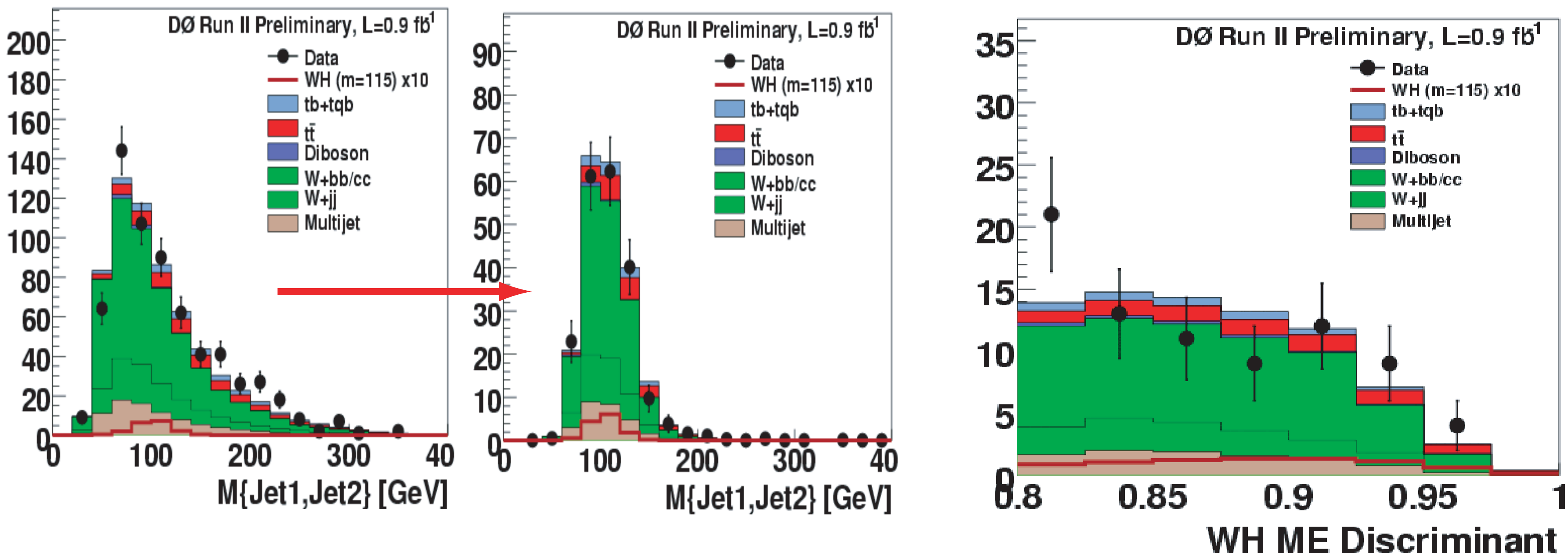
SM Higgs

What is now...

- Advanced analysis techniques: Likelihood Ratio from (tree-level) Matrix Element probabilities (4-vector input) of WH followed by $H \to b\bar{b}$ and backgrounds (and not on dijet mass alone)

$$LR = \frac{P_{\mathrm{Higgs}}(M_H)}{P_{\mathrm{Higgs}}(M_H) + \Sigma_i f_{\mathrm{bck,i}} P_{\mathrm{bck,i}}}$$

Weight by ME discriminant



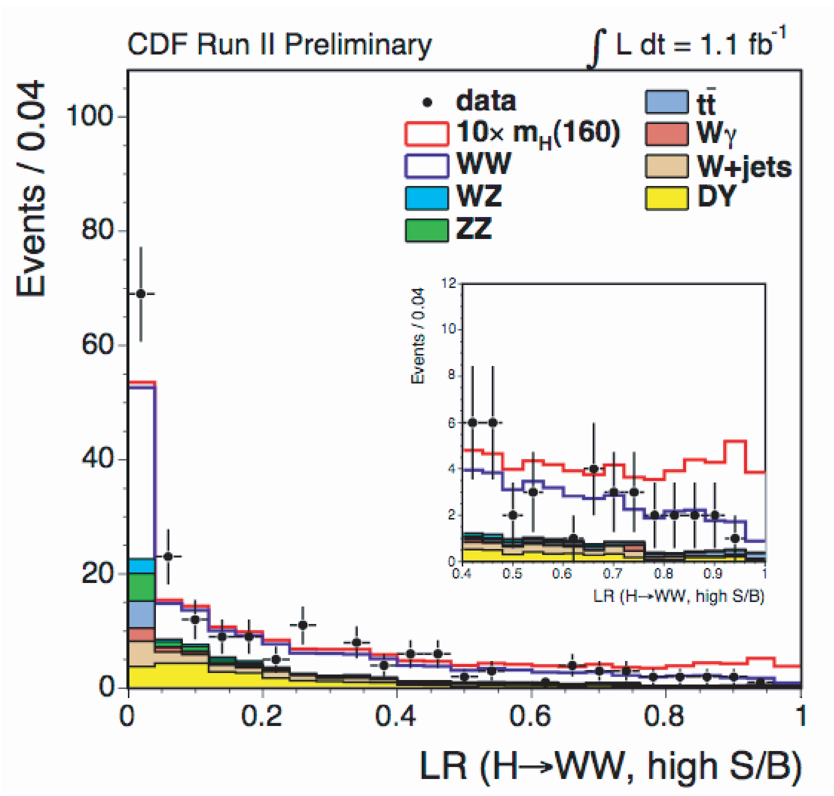
- ~35% improvement in sensitivity (c.f. single top, see earlier talk)

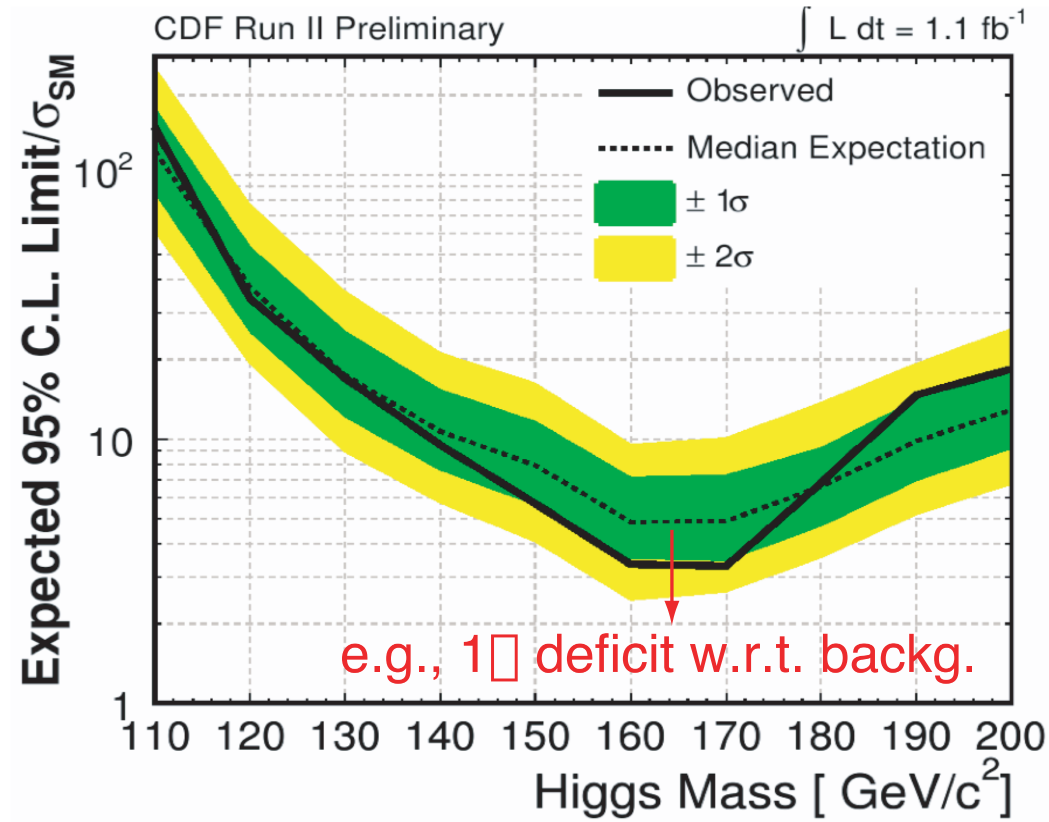
SM Higgs

Using Matrix Element LR

$$H \rightarrow WW^*$$

CDF new result
Expected limit
< 4.8 times SM
Observed limit
< 3.4 times SM





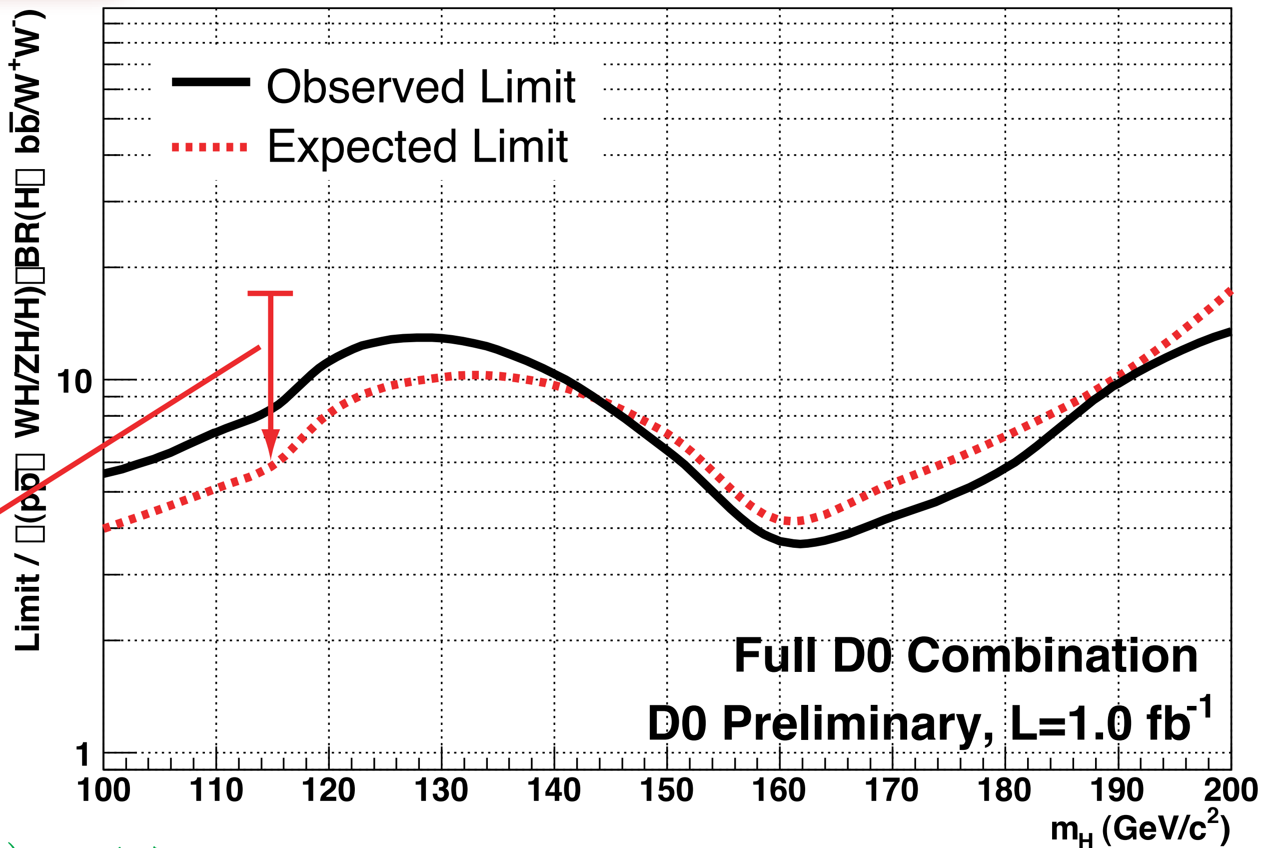
SM Higgs

Summary (Moriond '07 Summary talk)

Analysis	CDF limit ($1 fb^{-1}$) factor above SM observed (expected)	D0 limit ($1 fb^{-1}$) factor above SM observed (expected)
Z/WH→MET+bb @ 115 Technique: M_{jj}	16 (15)	14 (9.6)
WH→lνbb @ 115 Technique: M_{jj} Technique: ME	26 (17) ---	11 (8.8) 12 (9.5)
ZH→llbb @ 115 Technique: M_{jj} Technique: NN2D	--- 16 (16)	23 (22) ---
H→WW→ll@ 160 Technique: Δφ(l,l) Technique: ME	9.2 (6.0) 3.4 (4.8)	3.7 (4.2) ---
h→ τ τ @ 160 μ<0, no mixing	tan β< 69 (47)	tan β< 44 (54)

Combined Factor: 5.9 at 115 GeV

SM Higgs



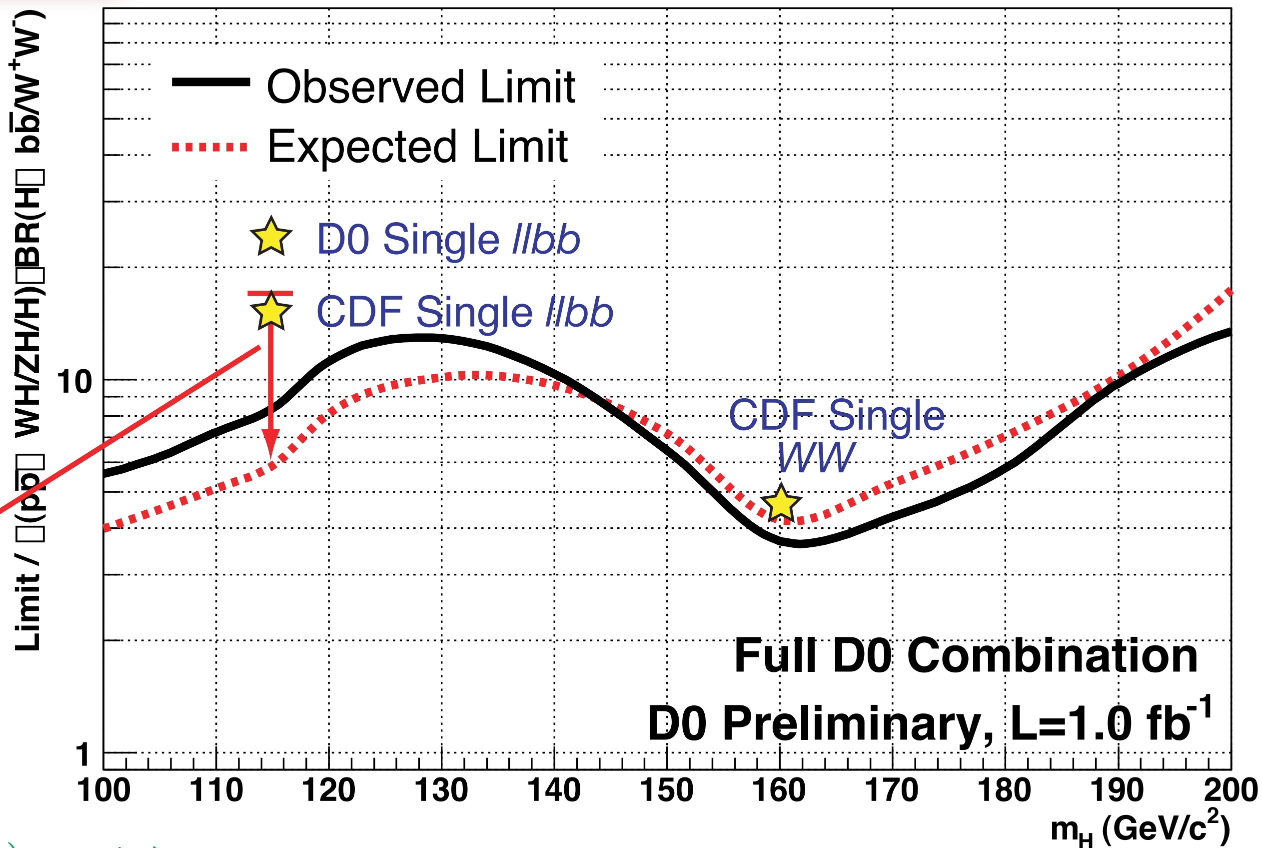
Factor x 3
Improvement

$$\sqrt{(L_{\rm new}/L_{\rm old})} \simeq 1.7$$

Scaling faster than statistics

- Single Experiment Limit competitive or better than 2006 combination
- Factor of 8.4 (5.9 expected) above SM at M_H=115 GeV
  Factor of 3.7 (4.2 expected) above SM at M_H=160 GeV

SM Higgs



Factor x 3 Improvement

$$\sqrt{(L_{\mathrm{new}}/L_{\mathrm{old}})} \simeq 1.7$$

Scaling faster than statistics

- Single Experiment Limit competitive or better than 2006 combination
- Factor of 8.4 (5.9 expected) above SM at M_H=115 GeV
  Factor of 3.7 (4.2 expected) above SM at M_H=160 GeV
- Plus a gain when both experiments combined

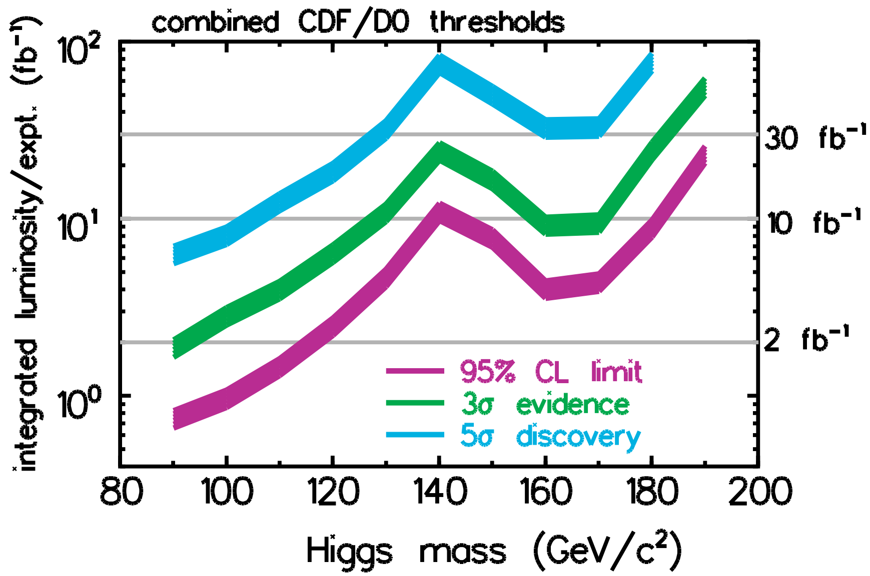
SM Higgs

At least for DØ, target numbers for gains:

Ingredient	Equiv Lumi Gain	Xsec Factor MH=115 GeV	Xsec Factor MH=160 GeV
Today with 1fb^{-1}	-	5.9	4.2
Lumi = 2 fb^{-1}	2	4.2	3.0
b-Tag (Shape + Layer0)	2	3.0	3.0
Multivariate Techniques	1.7	2.3	2.3
Improved mass resolution	1.5	1.8	2.3
New Channels	1.3/ 1.5	1.6	1.9
Reduced systematics	1.2	1.5	1.7

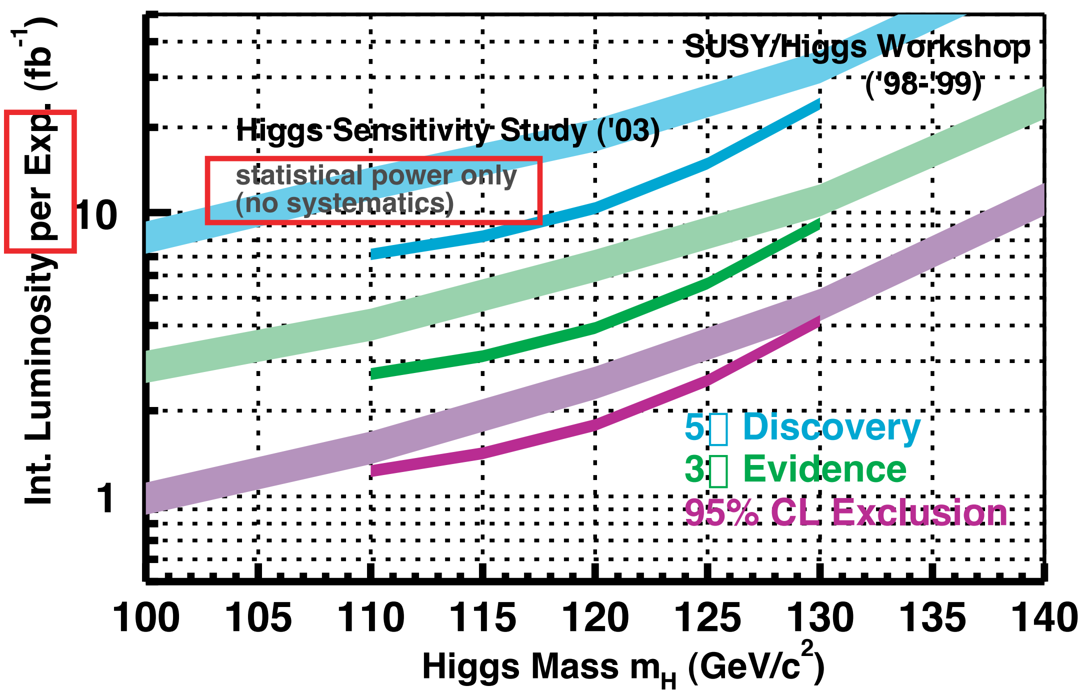
Two Experiments

SM Higgs



- Roughly on track
  for low-mass higgs

- Likely better than
  projected for
  higher-mass Higgs



SUSY Higgs

MSSM Higgs Sector

- Five physical states: $h^0, H^0, A^0, H^\pm$
- Two important parameters: $M_A, \tan\beta = v_{\mathrm{up}}/v_{\mathrm{down}}$
- LEP limits: $M_A > 93\,\mathrm{GeV}$ (higher for small $\tan\beta$)
- Enhanced production ($\propto \tan^2\beta$)
- $Br(h,H,A \to b\bar{b}) \simeq 90\%,\ Br(h,H,A \to \tau^+\tau^-) \simeq 10\%$

$$bg \to \phi b \to bbb$$
$$gg \to \phi bb \to bbbb$$

Need associated production
to cope with QCD backgrounds

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

More distinctive,
use fusion production

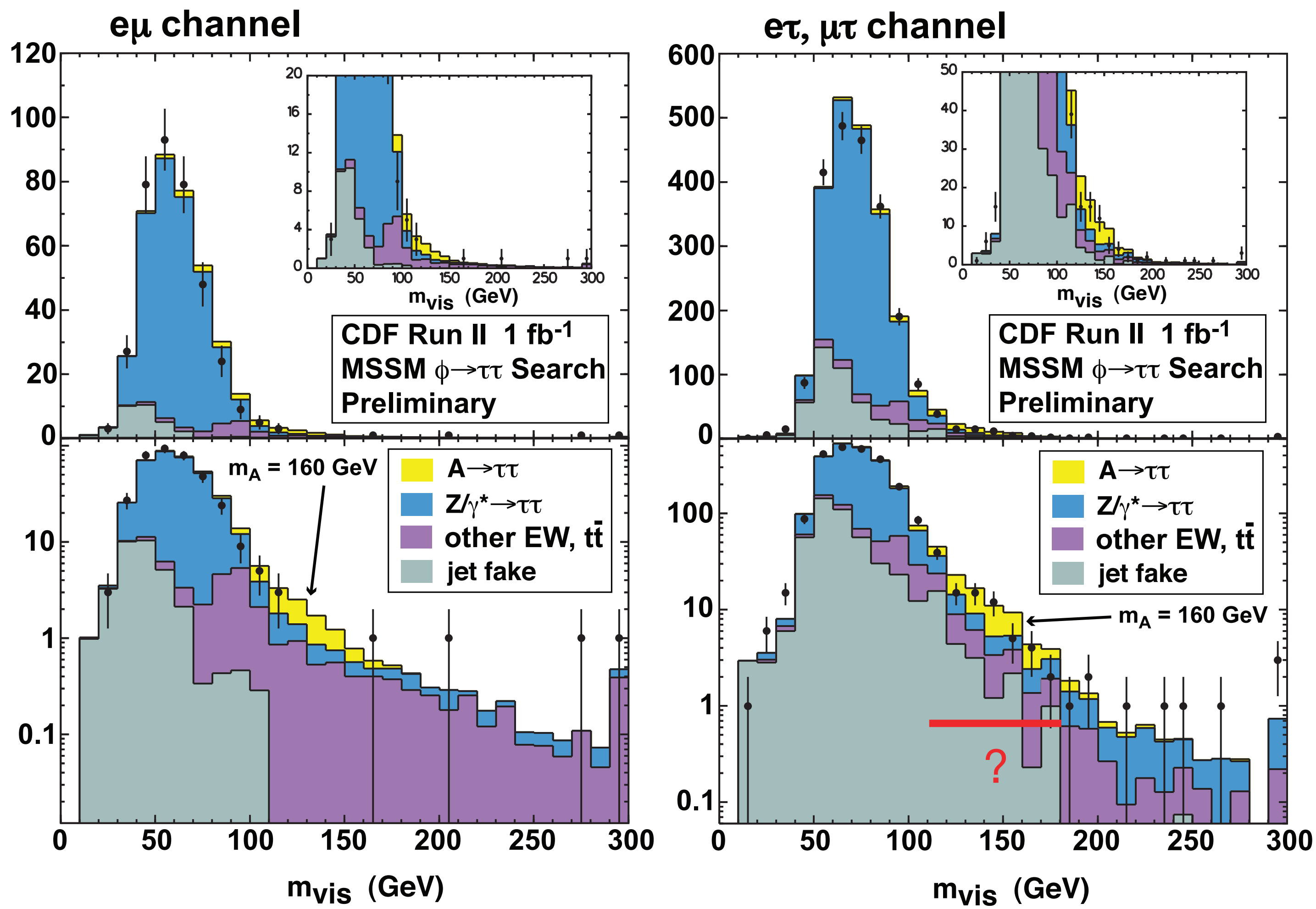
Comparable sensitivities!

SUSY Higgs

$$\phi\,(h, H, A) \to \tau^+\tau^-$$

$\tau^+ \to$ *μ, e, hadronic*; $\tau^- \to$ *μ, e, hadronic*

- After cutting on scalar mom. sum and MET:



- Best fit corresponds to $M_\phi \simeq 160\,\mathrm{GeV}$ and $\sigma \cdot Br(\phi \to \tau\tau) \simeq 2\,\mathrm{pb}$

  i.e., $\tan\beta \simeq 50$

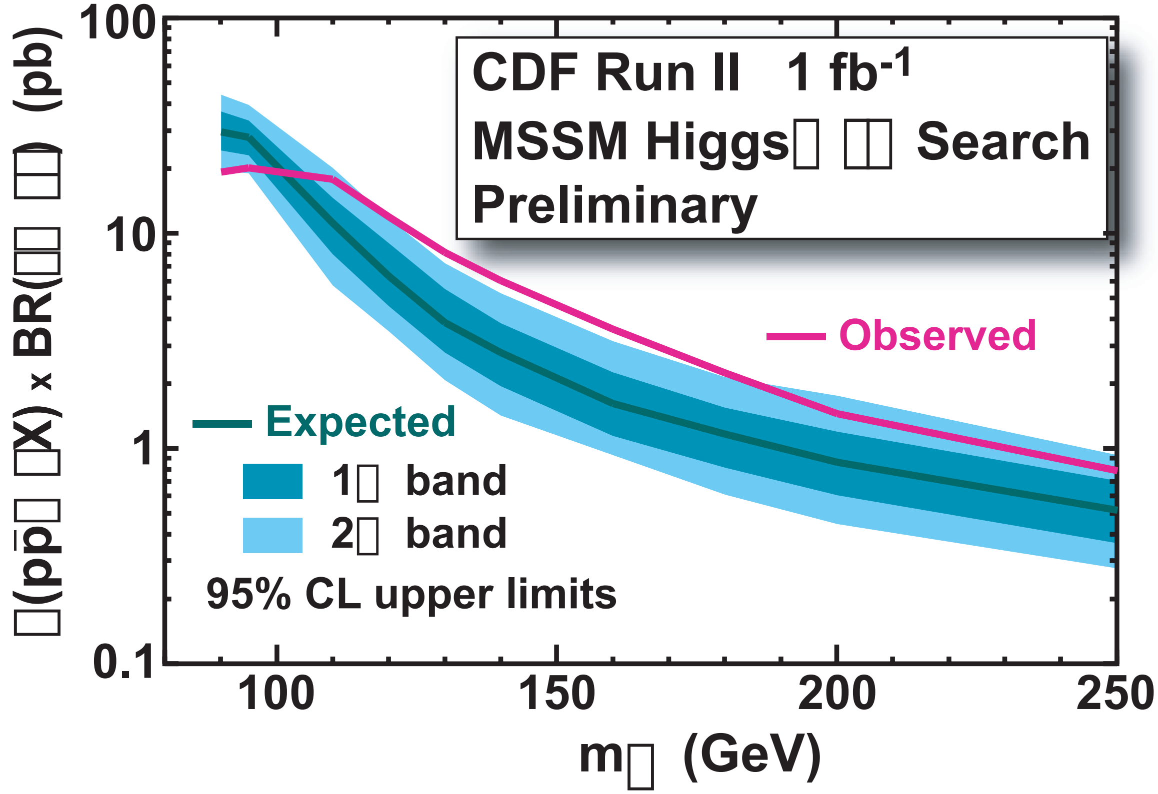
SUSY Higgs

$$\phi\,(h, H, A) \rightarrow \tau^+\tau^-$$

$\tau^- \hookrightarrow$ μ, e, hadronic

$\tau^+ \hookrightarrow$ μ, e, hadronic

- While the significance at the best-fit mass exceeds 2σ, careful analysis of all channels and all search windows shows that the overall significance of the excess is less than 2σ (simply need more data!)

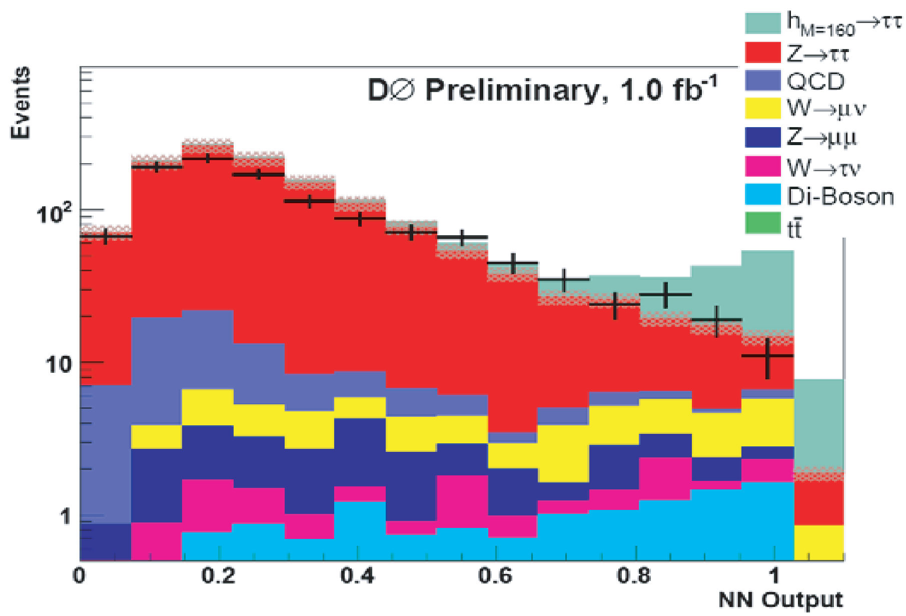


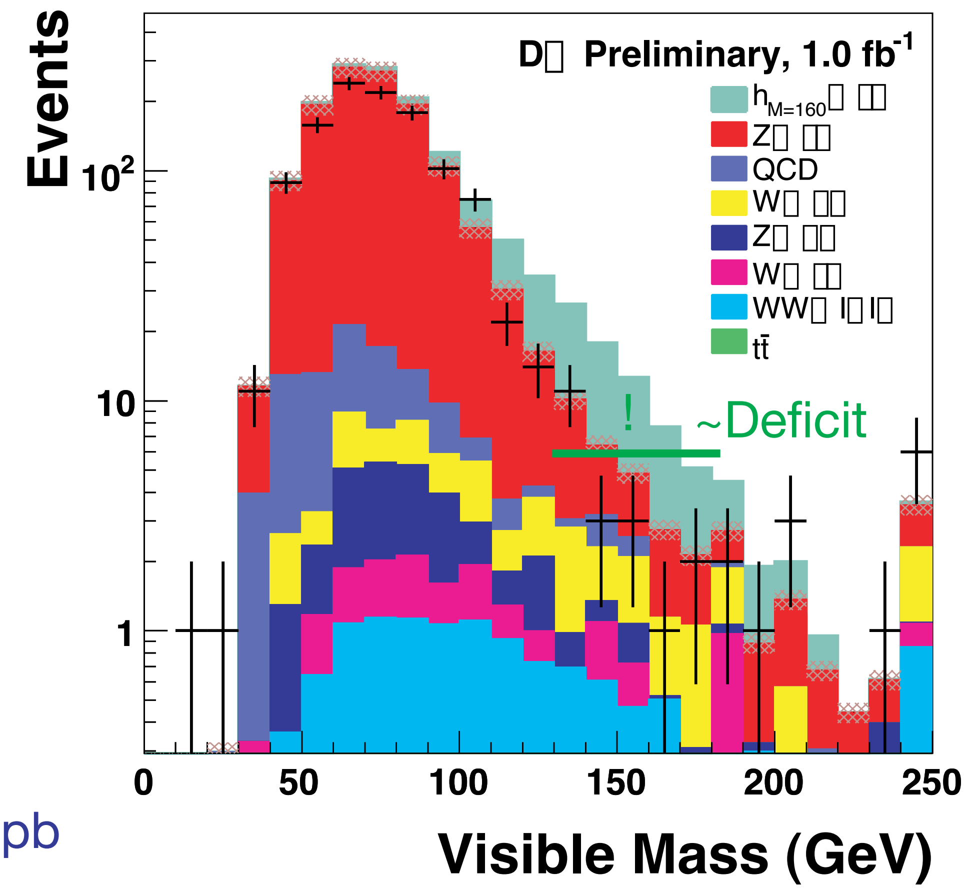
- Check with an independent sample?

SUSY Higgs

$$\phi\,(h, H, A) \rightarrow \tau^+ \tau^-$$

($\tau^+ \rightarrow \mu$, $\tau^- \rightarrow$ *hadronic*)



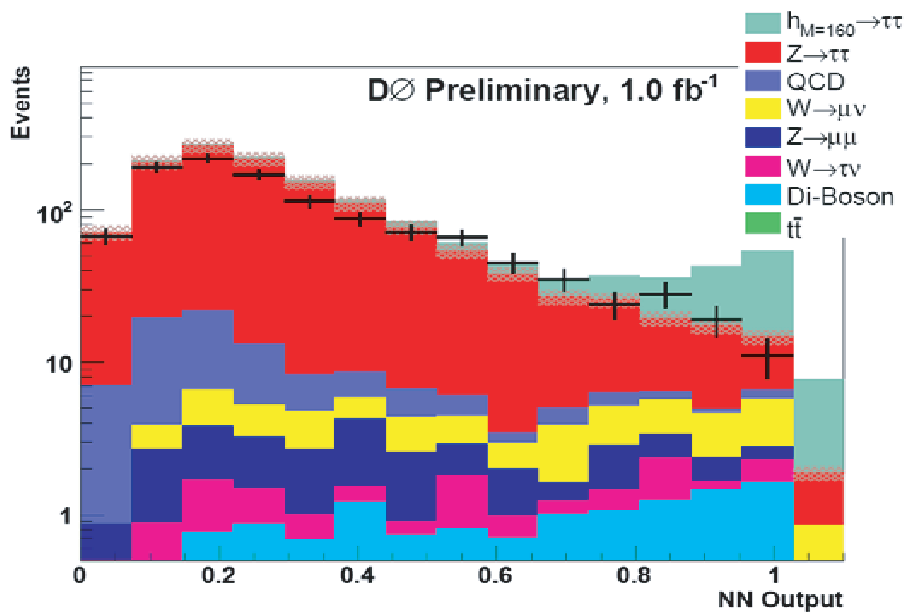


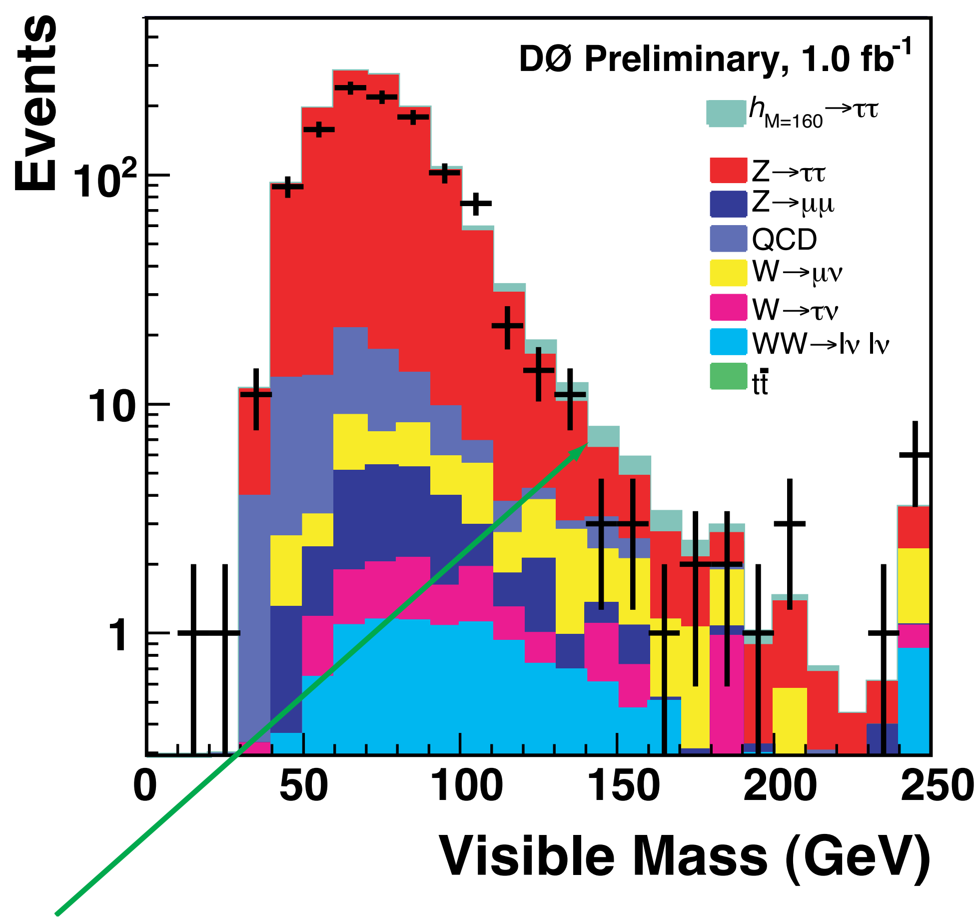
- Expected limit at 160 GeV is 1.7 pb, CDF's most likely value is 2 pb
- Observed limit is 1.2 pb which is within 1 sigma uncertainty band from 1.0 to 2.8 pb

SUSY Higgs

$$\phi\,(h, H, A) \rightarrow \tau^+\tau^-$$

$\tau^+ \rightarrow \mu$, $\tau^- \rightarrow$ *hadronic*

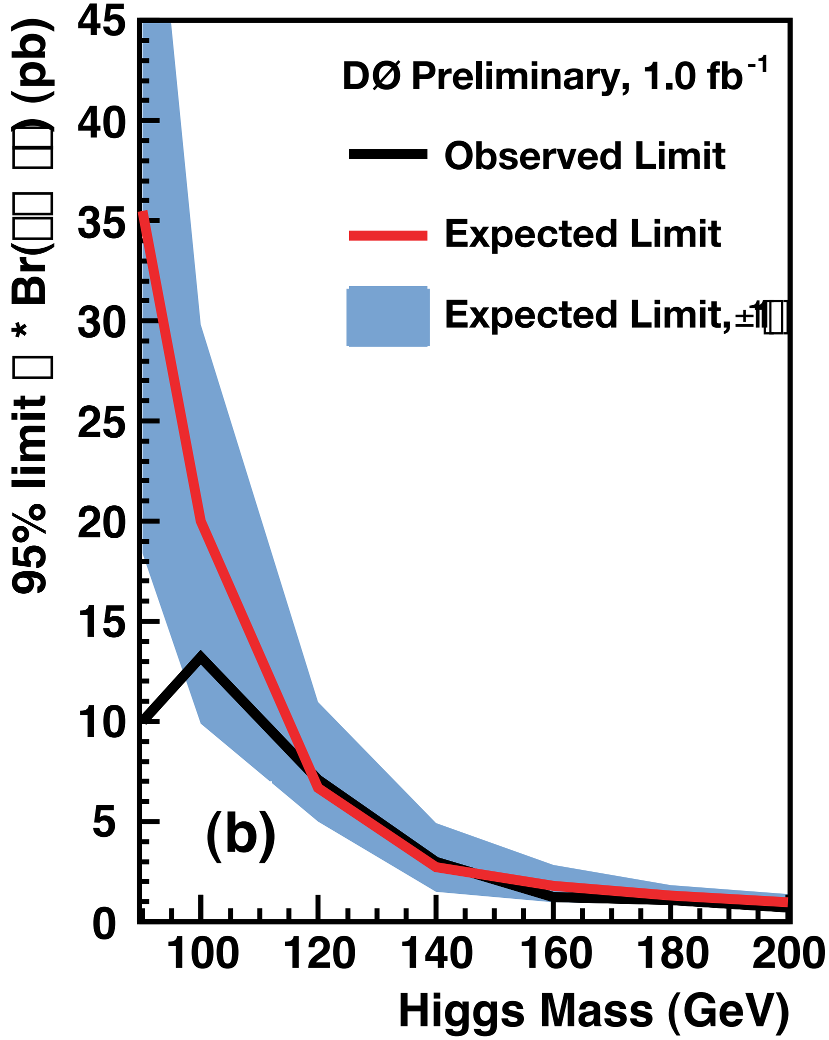


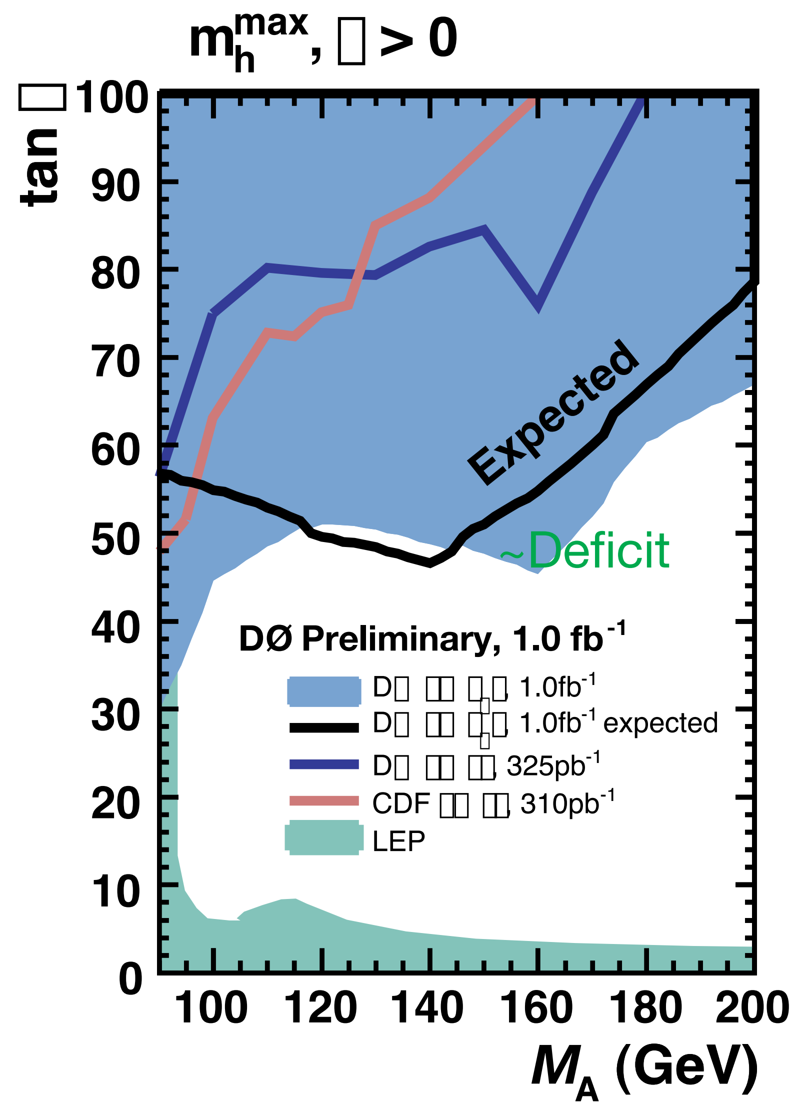


- Higgs signal normalized to CDF's most likely value of 2 pb cross section

SUSY Higgs

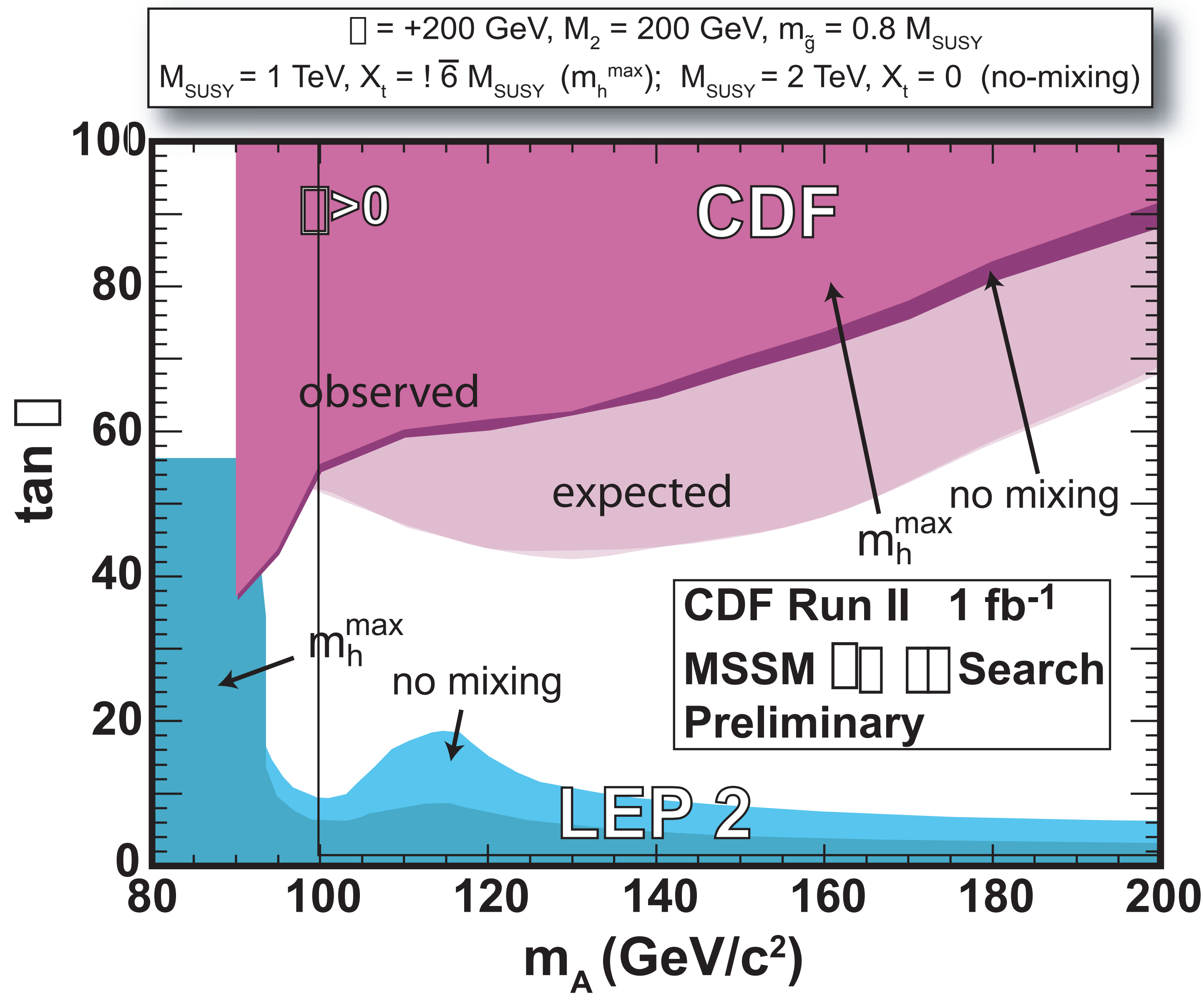
$$\phi\,(h, H, A) \rightarrow \tau^{+}\tau^{-}$$





SUSY Higgs

$$\phi\,(h, H, A) \rightarrow \tau^+\tau^-$$



SUSY Higgs

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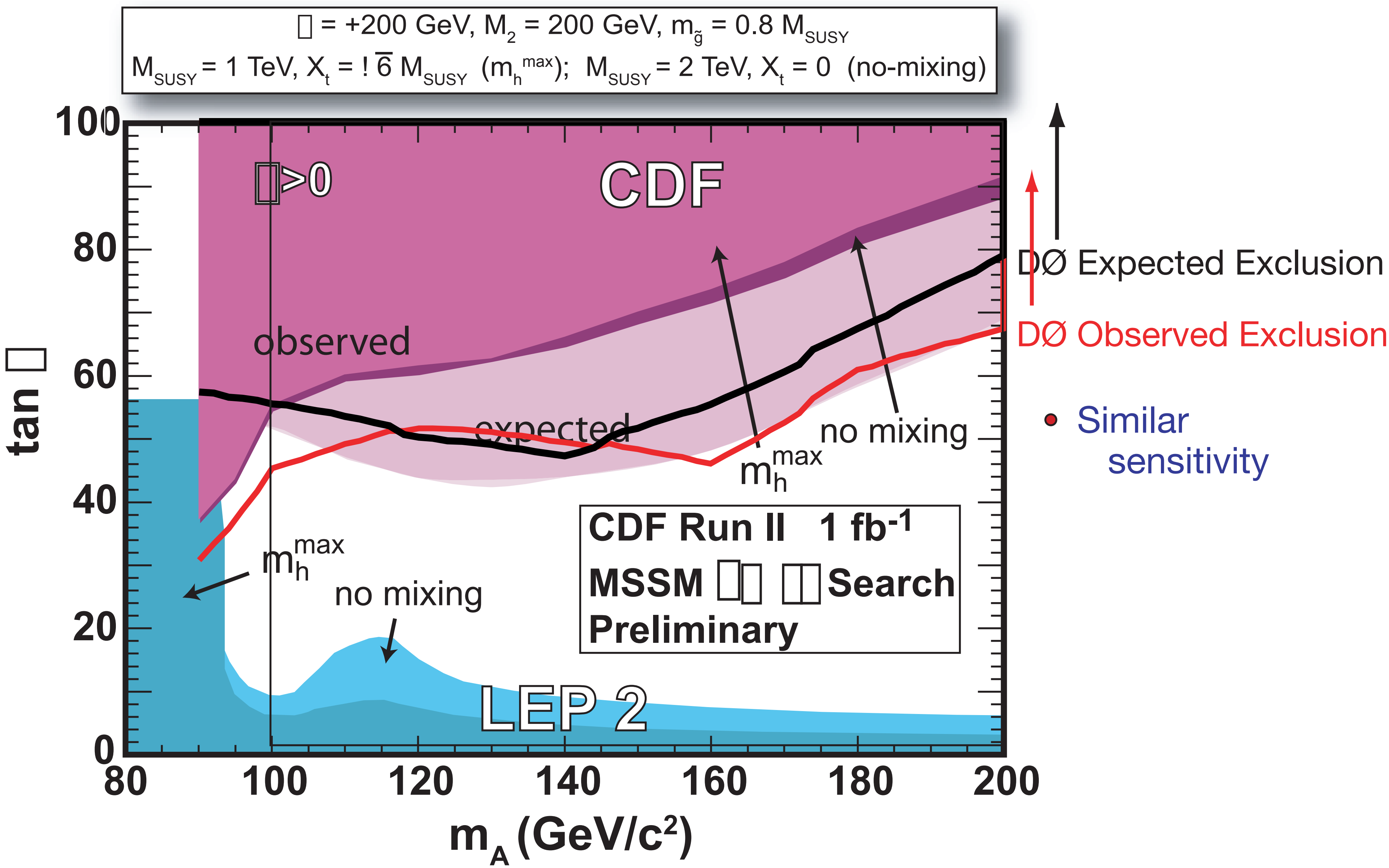
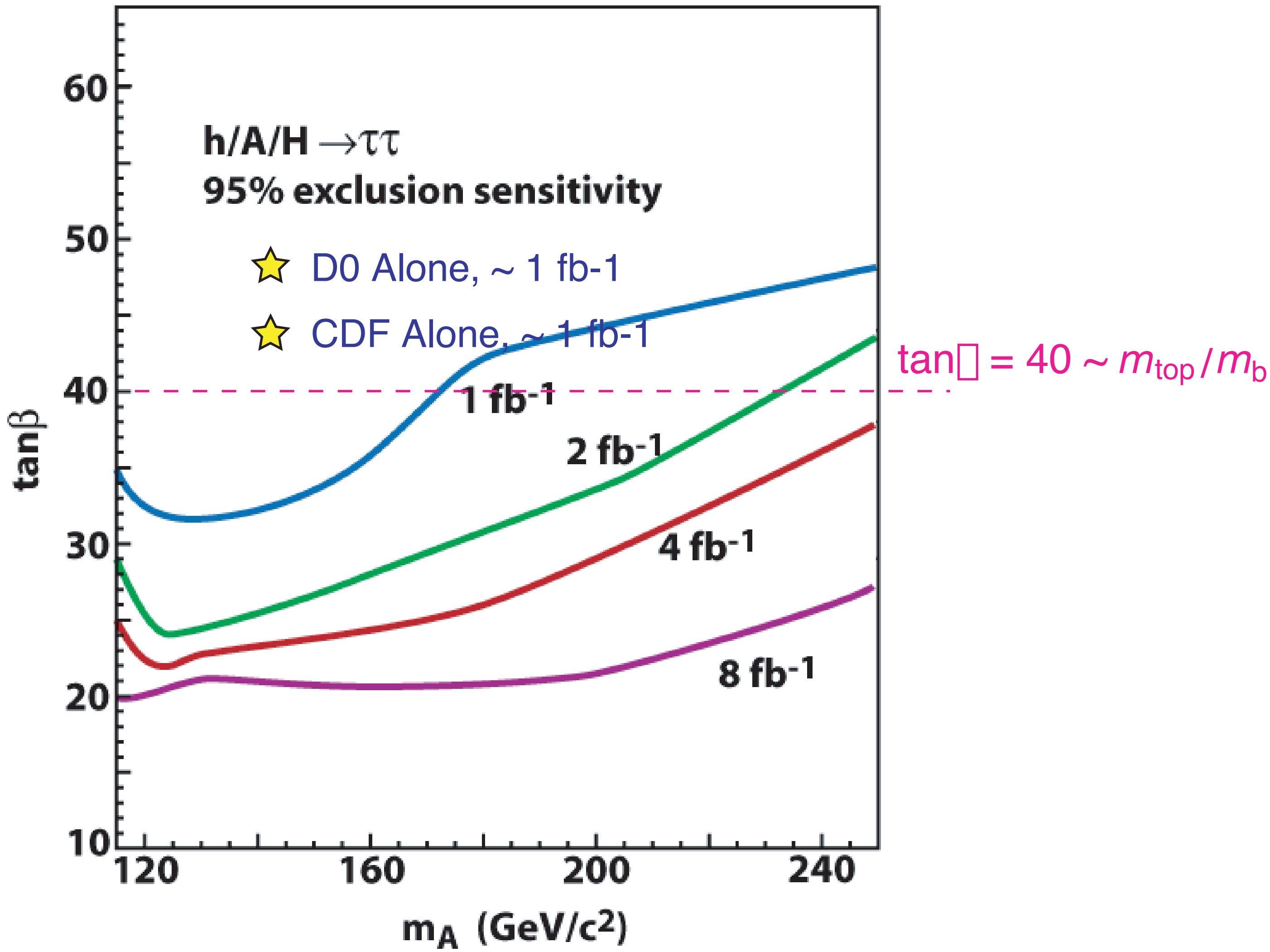


SUSY Higgs

$$\phi\,(h, H, A) \rightarrow \tau^+\tau^-$$

Old projections:



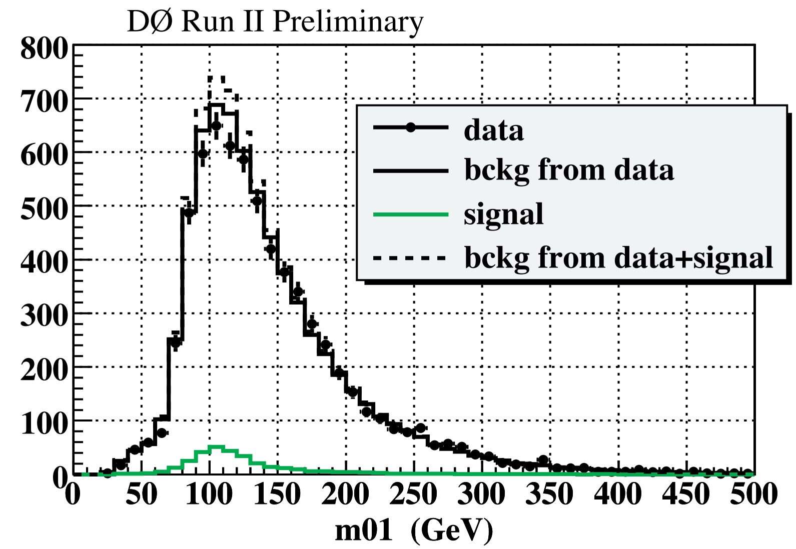
SUSY Higgs

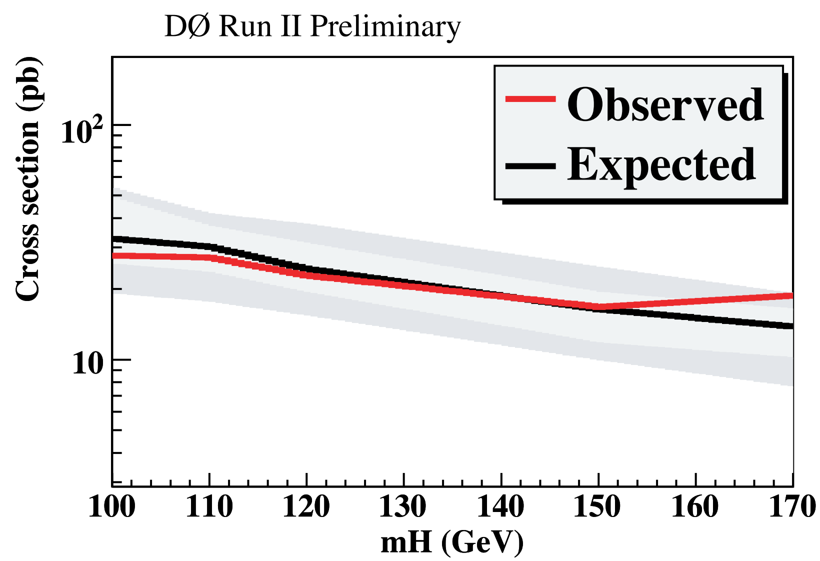
$$b(b)\phi \rightarrow bbb(b)$$

Associated Production

- *H/A* □ *bb* swamped by QCD bckg
- Look for >= 3 high-pT *b* jets
- Signal: invariant mass of two leading jets should peak at M_A
- Backgrounds (from data):
  – Shape is from the double-b-tagged data sample (taking into account kinematic bias from the 3rd b-tag)

  – Normalized outside the "signal region"





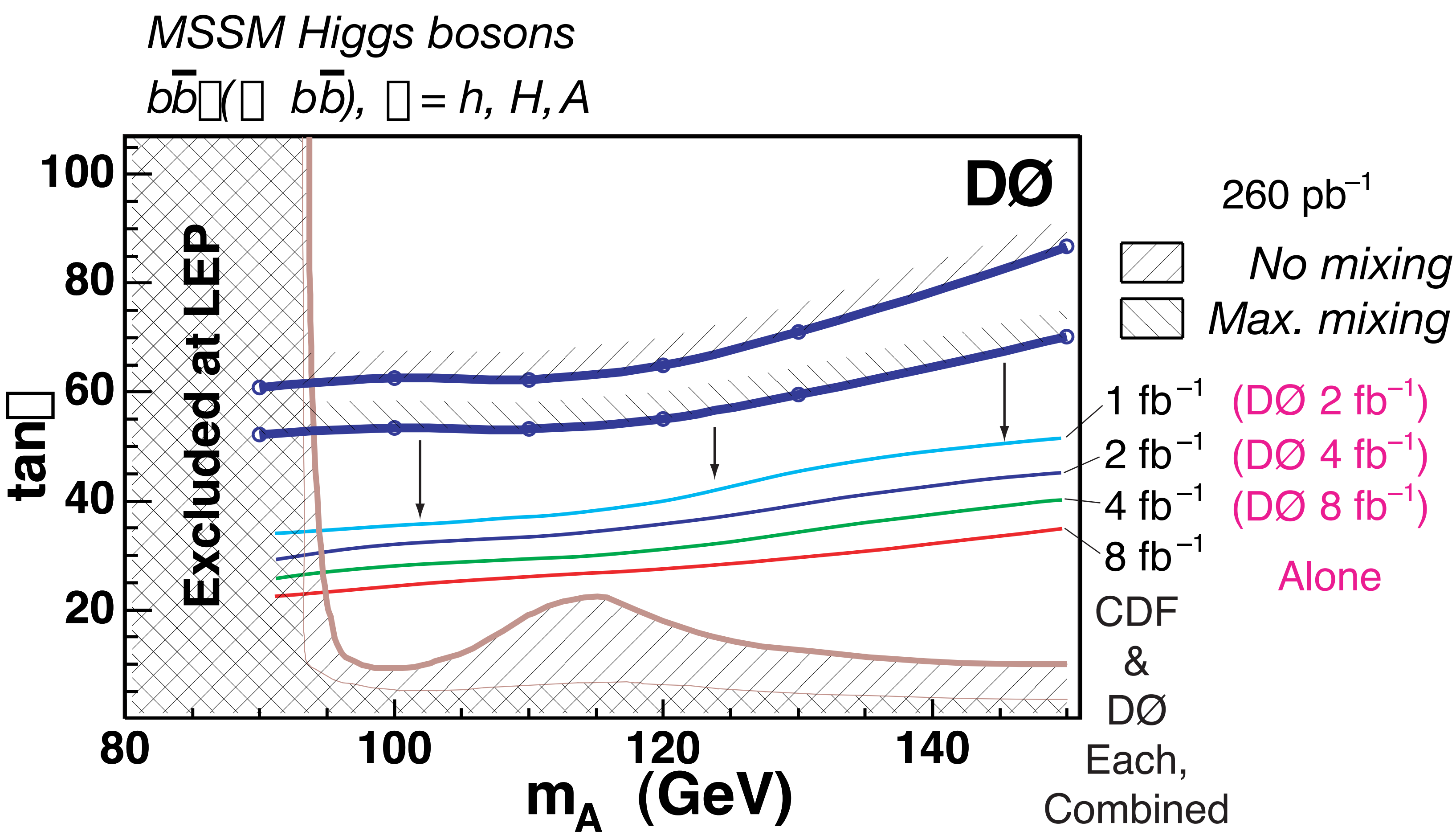
Both experiments working on updates with larger data sets

Understanding multi-*b* backgrounds ***tough***

SUSY Higgs

$$b(b)\phi \longrightarrow bbb(b)$$

Associated Production



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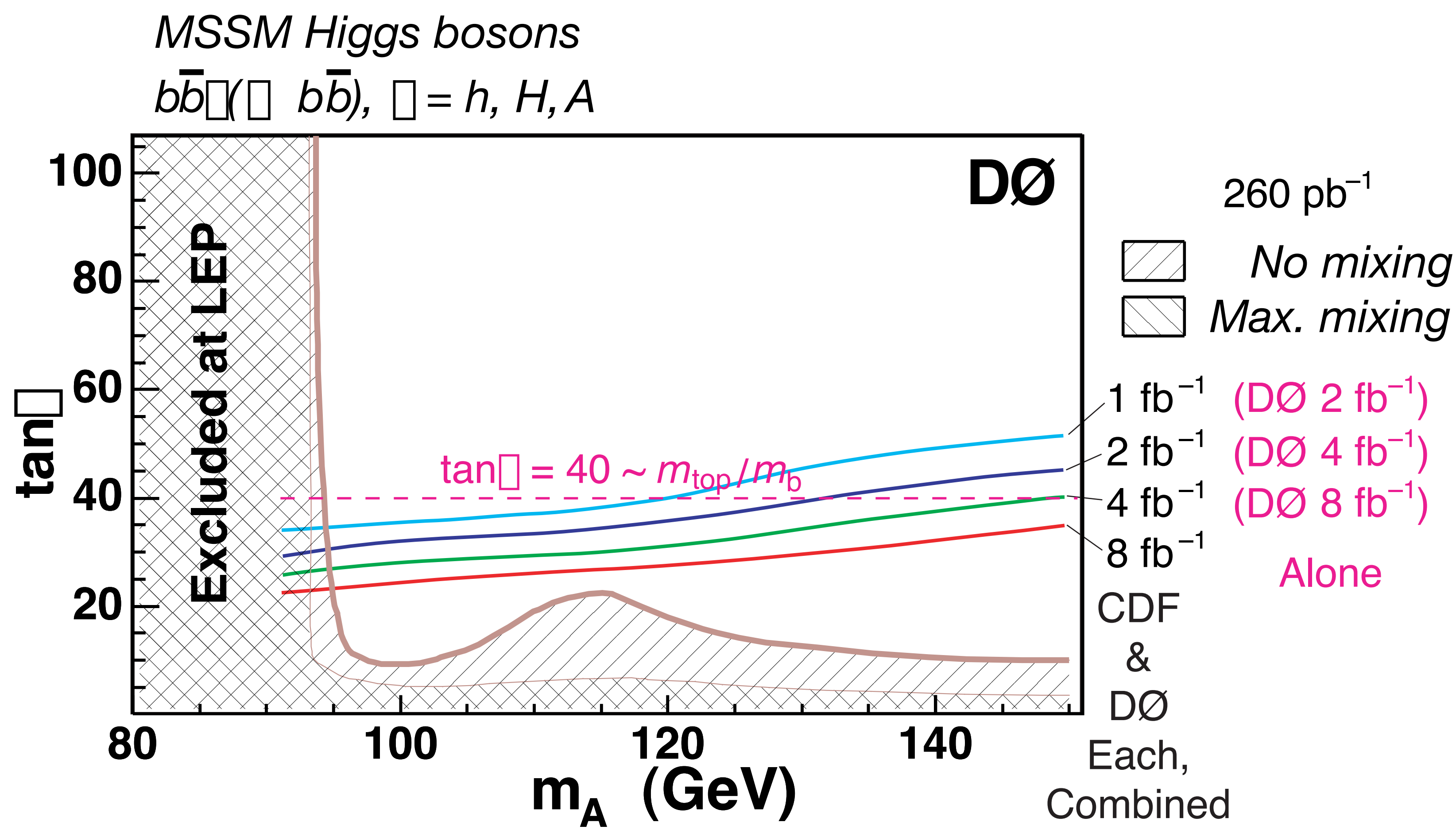
Associated Production



Charginos/Neutralinos

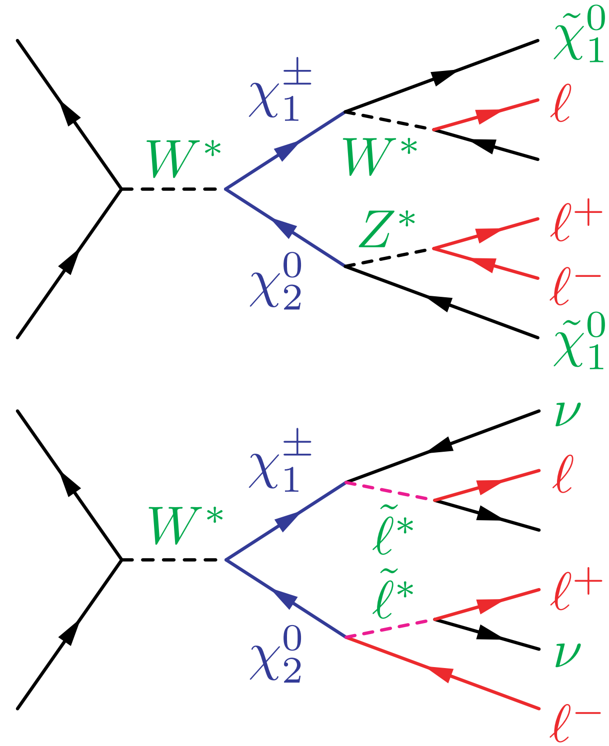
Golden signature

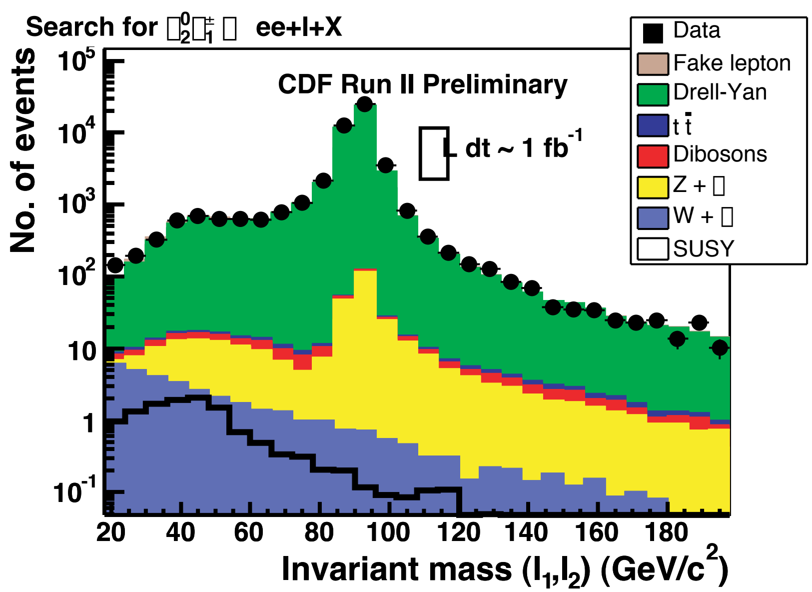
- three leptons

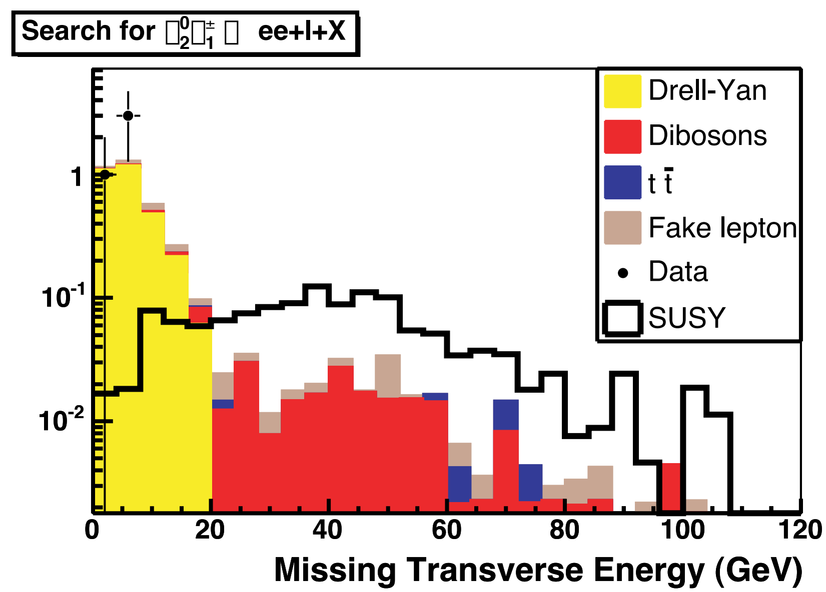
$$\sigma(p\bar{p} \to \chi_1^{\pm}\chi_2^0 \to 3\ell) \simeq 1\,\mathrm{pb}$$

General strategy

- isolated leptons (e,□)
- 2 same-sign
- 2 + track
- missing pT







Charginos/Neutralinos

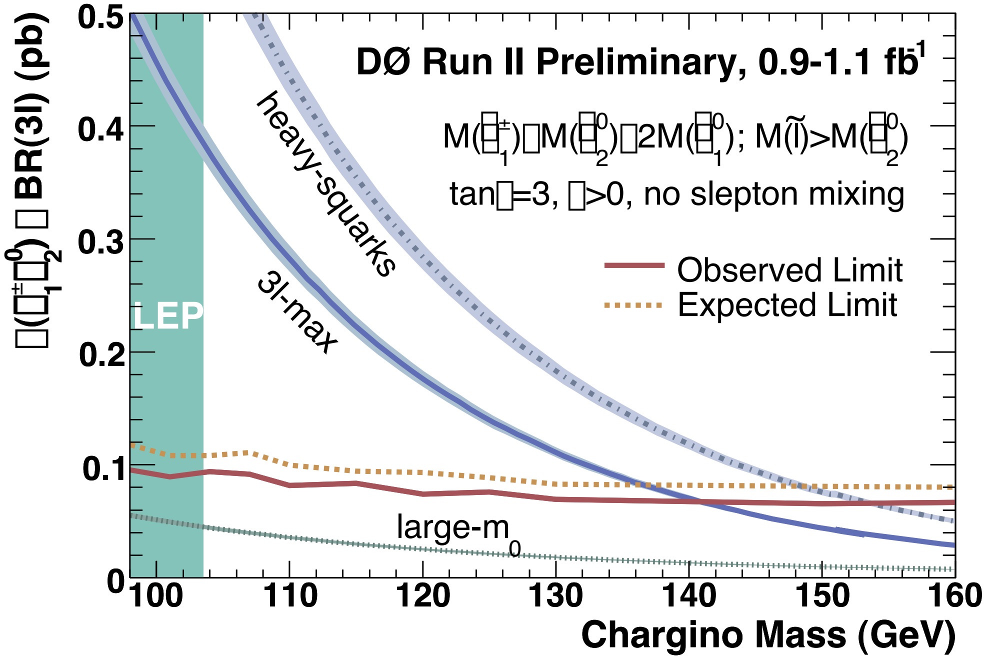
DØ (prel.):

	$\int L dt$	Expected	Obs
ee + ℓ	1.1 fb^{-1}	0.8 ± 0.7	0
□□ + ℓ	1.1 fb^{-1}	$0.3^{+0.7}_{-0.0}$	2
e□ + ℓ	1 1 fb^{-1}	$0.9^{+0.4}_{-0.1}$	0
$□^{\pm}□^{\pm}$	0.9 fb^{-1}	1.1 ± 0.4	1

CDF (prel.):

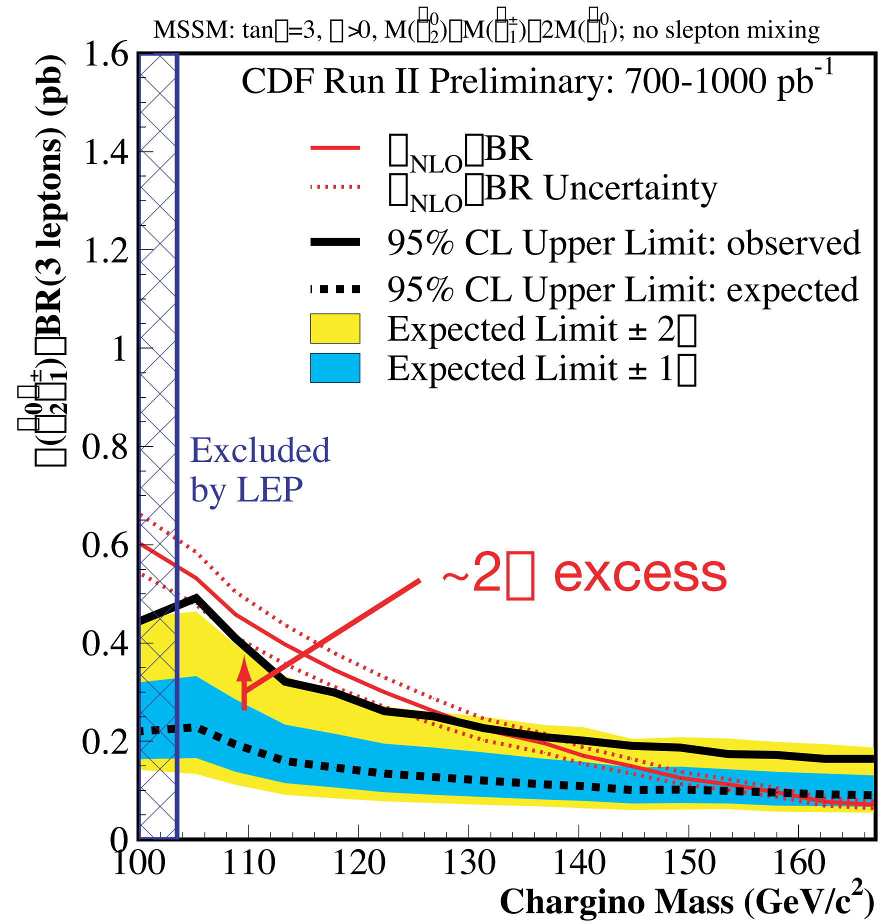
	$\int L dt$	Expected	Obs
$ee + \ell$	1 fb^{-1}	1.0 ± 0.3	3
□□ + ℓ	1 fb^{-1}	0.4 ± 0.1	1
$e \ell \ell$	1 fb^{-1}	0.8 ± 0.4	0
□$\ell \ell$	0.75 fb^{-1}	1.3 ± 0.3	1
$e^{\pm}e^{\pm}, e^{\pm}□^{\pm}$, $□^{\pm}□^{\pm}$	1 fb^{-1}	7.8 ± 1.1	13

Charginos/Neutralinos



$M(\tilde{\chi}_1^{\pm}) > 141\,\mathrm{GeV}$

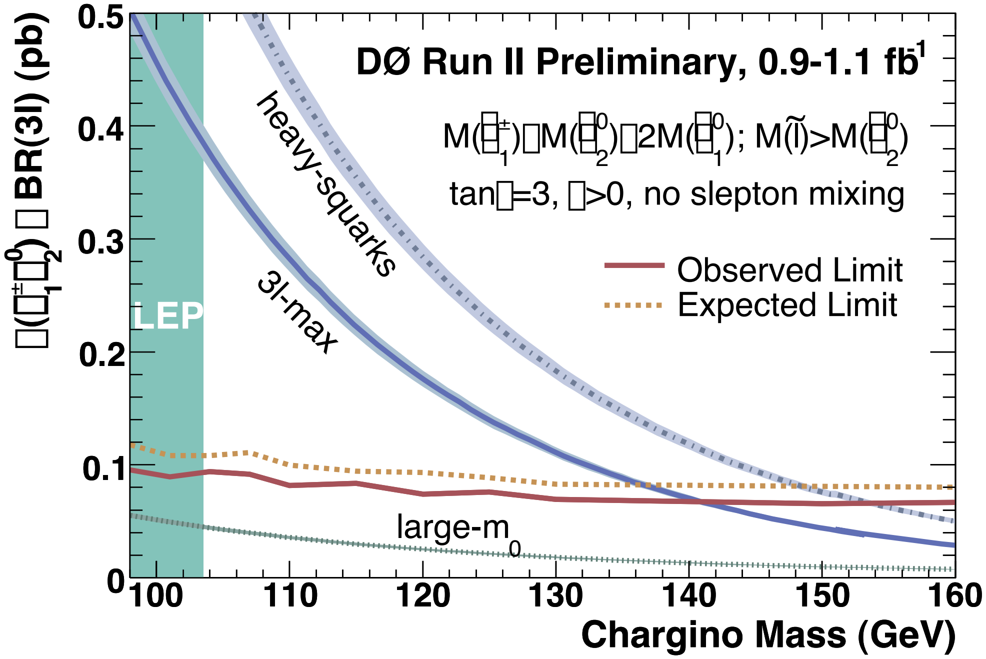
@ 95% CL



$M(\tilde{\chi}_1^{\pm}) > 130\,\mathrm{GeV}$

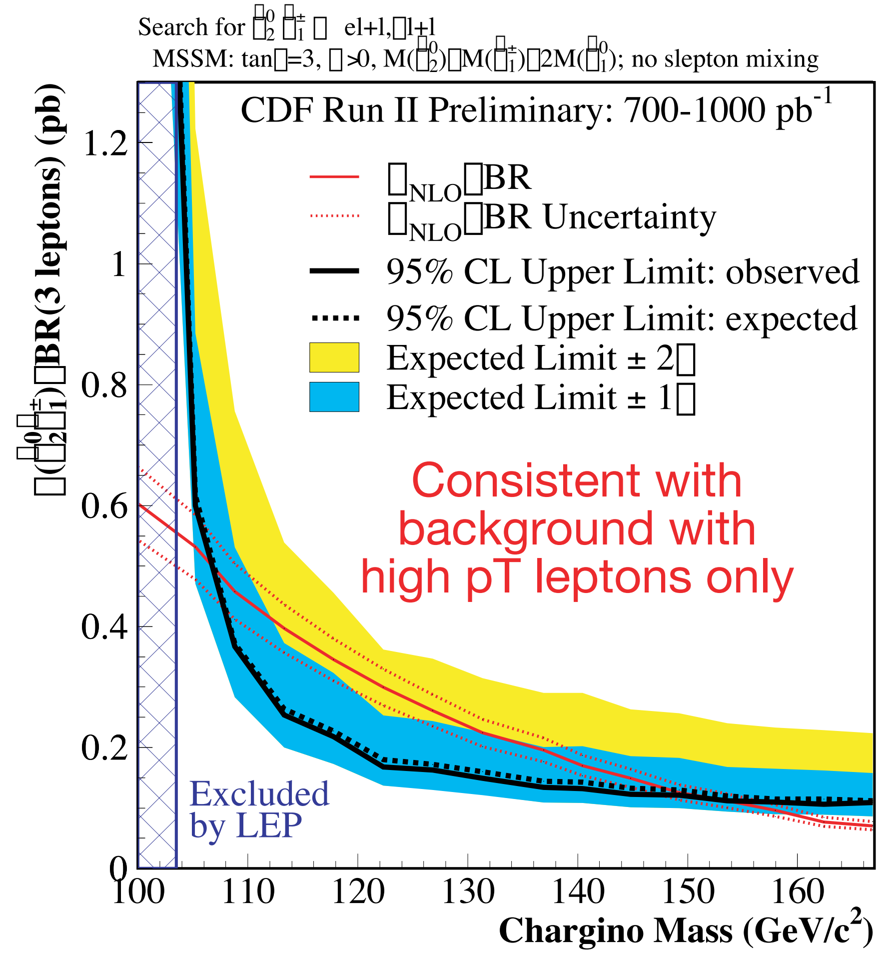
(expected > 160 GeV)

Charginos/Neutralinos



$M(\tilde{\chi}_1^{\pm}) > 141\,\mathrm{GeV}$

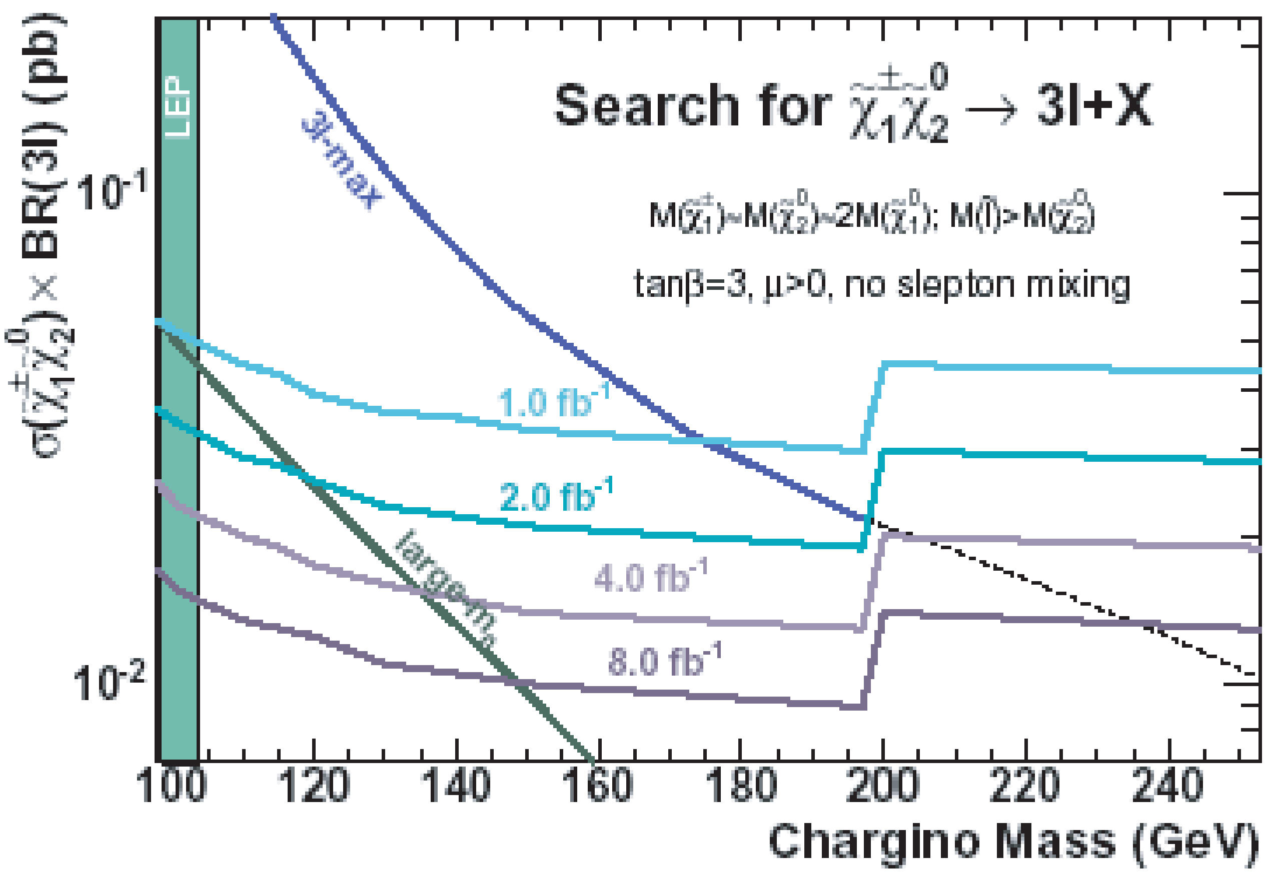
@ 95% CL



$M(\tilde{\chi}_1^{\pm}) > 150\,\mathrm{GeV}$

@ 95% CL

Charginos/Neutralinos



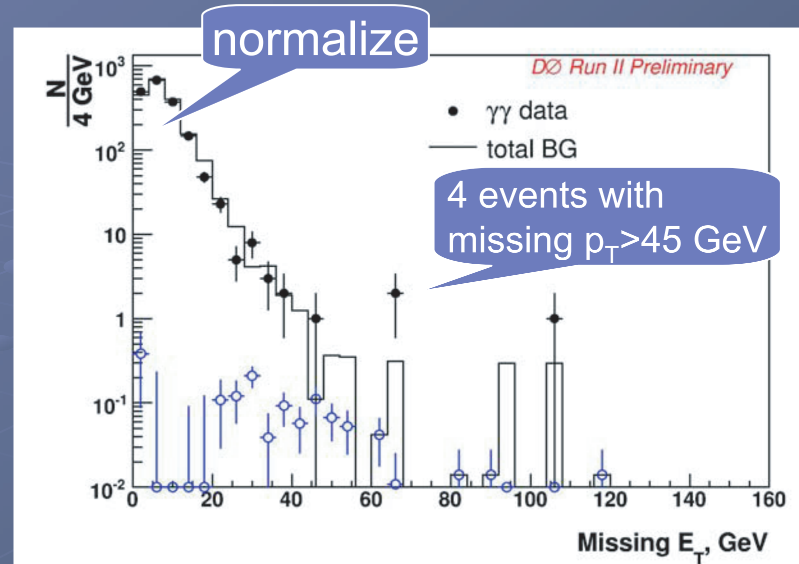
Prospects (luminosity each experiment, combined)

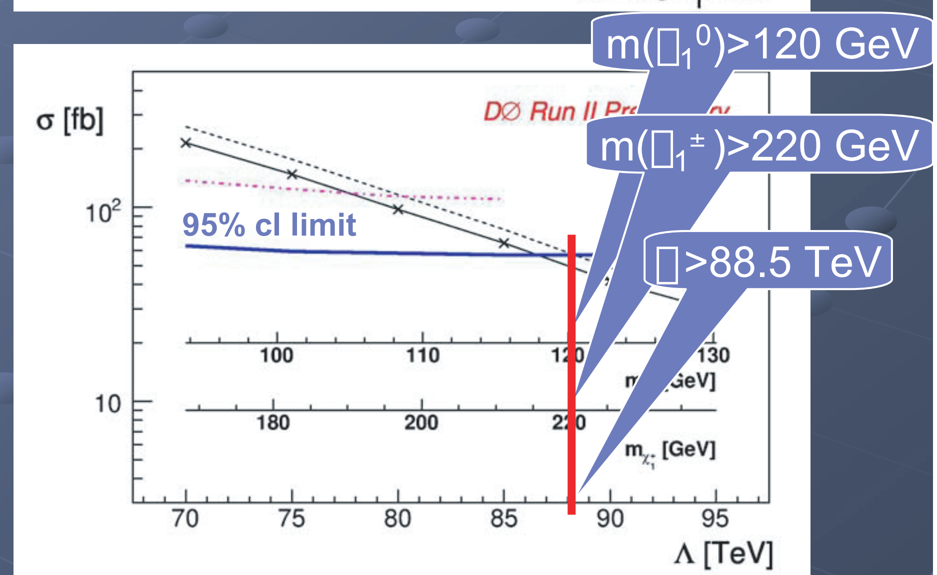
GMSB □□+ missing p_T

- GMSB
  - messenger particles couple superpartners to SUSY breaking sector
  - □ = SUSY breaking scale
  - LSP: gravitino (m<1 keV)
  - NLSP: $\tilde{□}_1^0$ □ □$\tilde{G}$
- signal

$p\bar{p}$ $\tilde{□}_2^0 \tilde{□}_1^{\pm} + X$ / $\tilde{□}_1^{m} \tilde{□}_1^{\pm} + X$ □ □□$\tilde{G}\tilde{G} + X'$

- analysis
  - Ldt = 760± 50 pb^{-1}
  - 2 photons with p_T > 25 GeV
  - missing p_T > 45 GeV
  - expect 2.1± 0.7 events



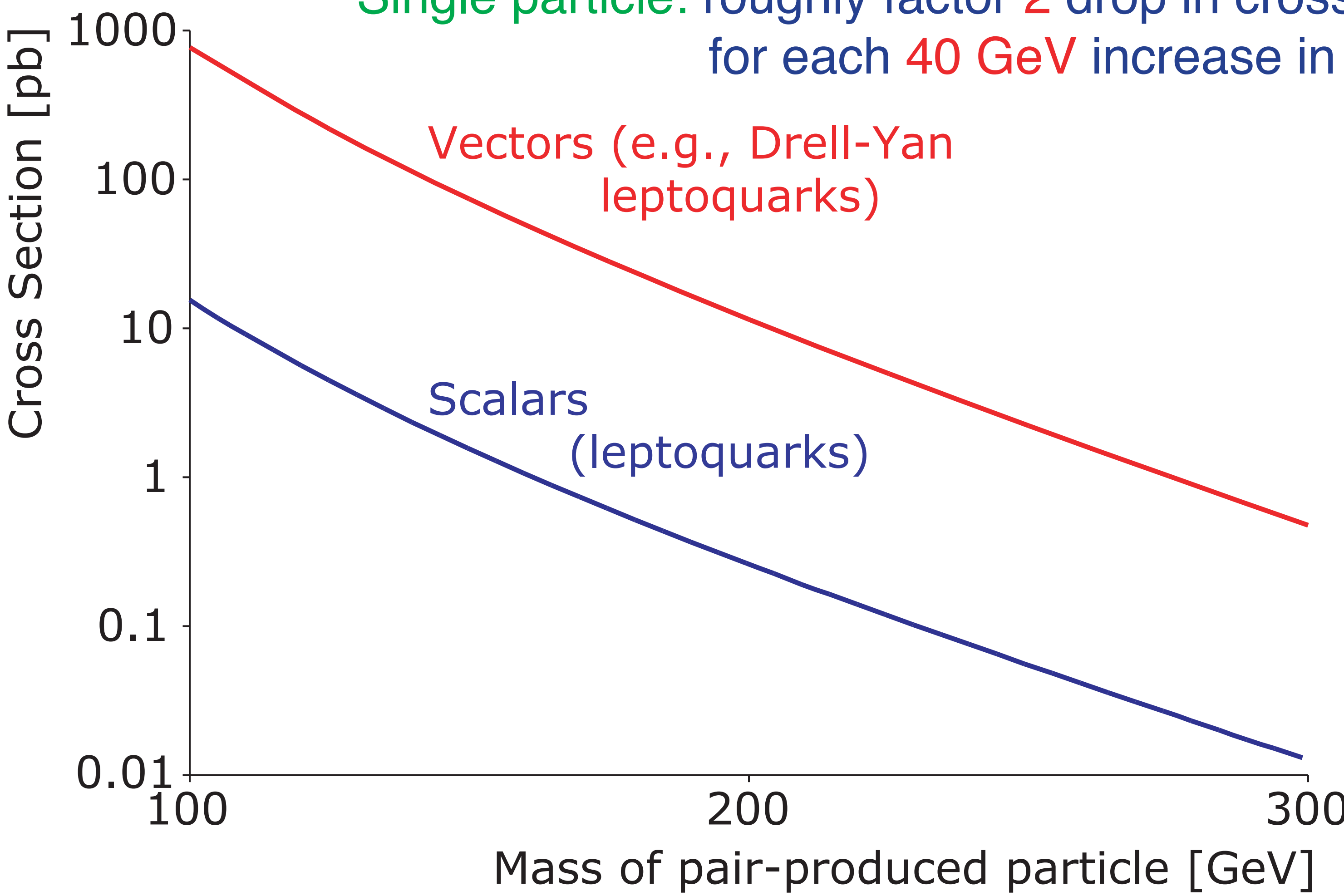


(Other) New Particle Searches

- *Rules of thumb*

Pair production: roughly factor 2 drop in cross section
for each 20 GeV increase in mass

Single particle: roughly factor 2 drop in cross section
for each 40 GeV increase in mass



(Other) New Particle Searches

- Case of statistics dominated, S/√B *roughly* constant
  - e.g., scalar leptoquarks (β=1), m > 255 GeV for 360 pb^{-1}

    For 2 fb^{-1}, limit will increase by about 20 GeV x $\log_2(2000/360)$ ~ 50 GeV
  - Trileptons, $\tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^{0} \rightarrow$ 3 leptons

    $m(\tilde{\chi}_1^{\pm}) \sim m(\tilde{\chi}_2^{0}) \sim 2m(\tilde{\chi}_2^{0})$

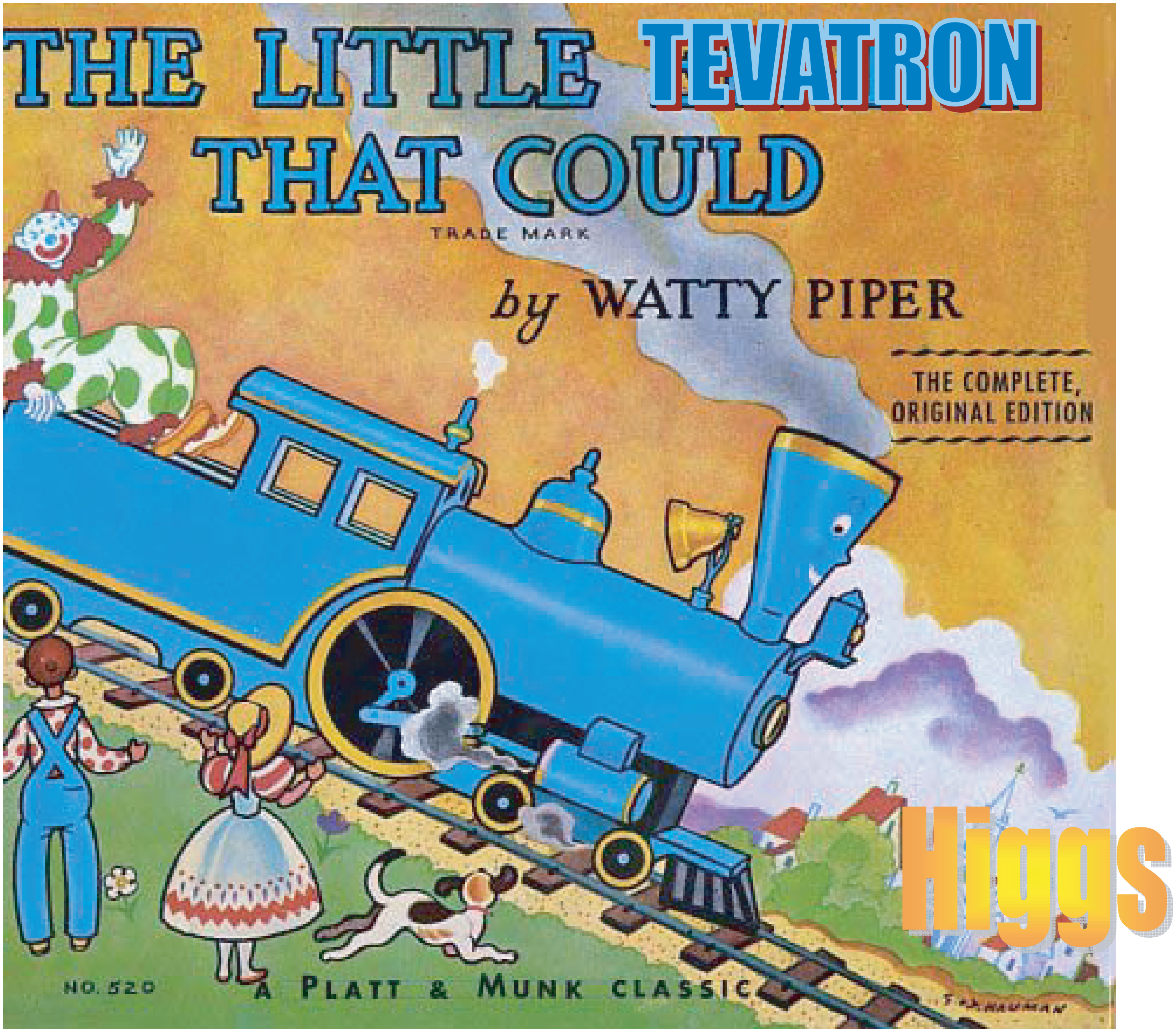
    $m(\tilde{\chi}_1^{\pm})$ > 145 GeV for ~1000 pb^{-1}

	2 fb^{-1}	4 fb^{-1}
Leptoquarks	m > 305 GeV	325 GeV
Trileptons	m > 170 GeV	190 GeV

- If systematics dominated, limit may not improve
- Compositeness energy scales and scales of Large Extra Dimensions grow even slower: $(\mathcal{L}_{int})^{1/8}$

Particle search limits will tend to start "saturating" at 2 – 3 fb^{-1}

(but will almost always keep increasing, and always give a chance for discovery!)



Courtesy Jerry Blazey