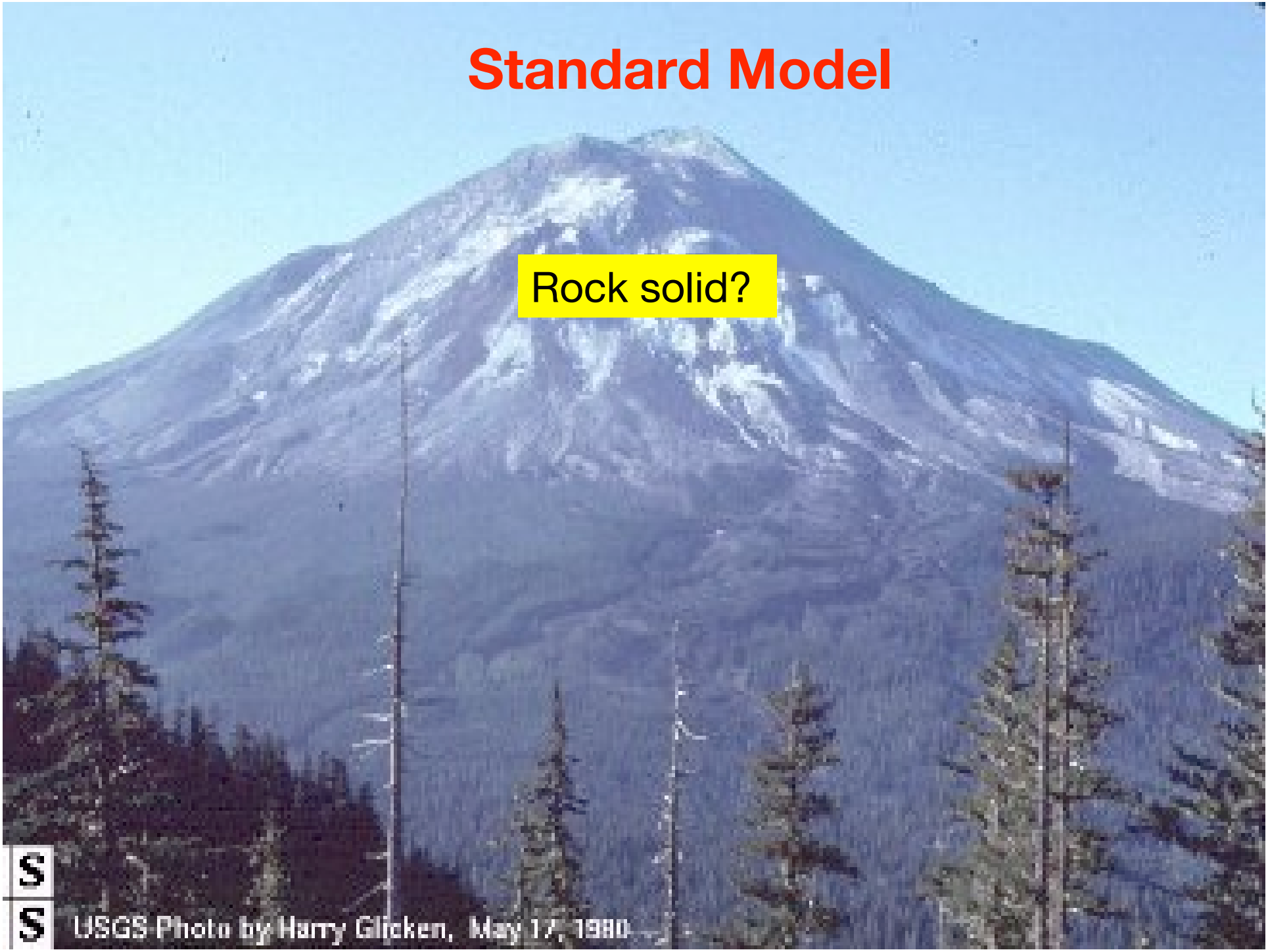
Multi-fb^{-1} Predictions for the Physics Reach of the Tevatron

For the CDF and DØ Collaborations

Beate Heinemann
University of Liverpool

Tevatron Connection, 06/25/05

Standard Model



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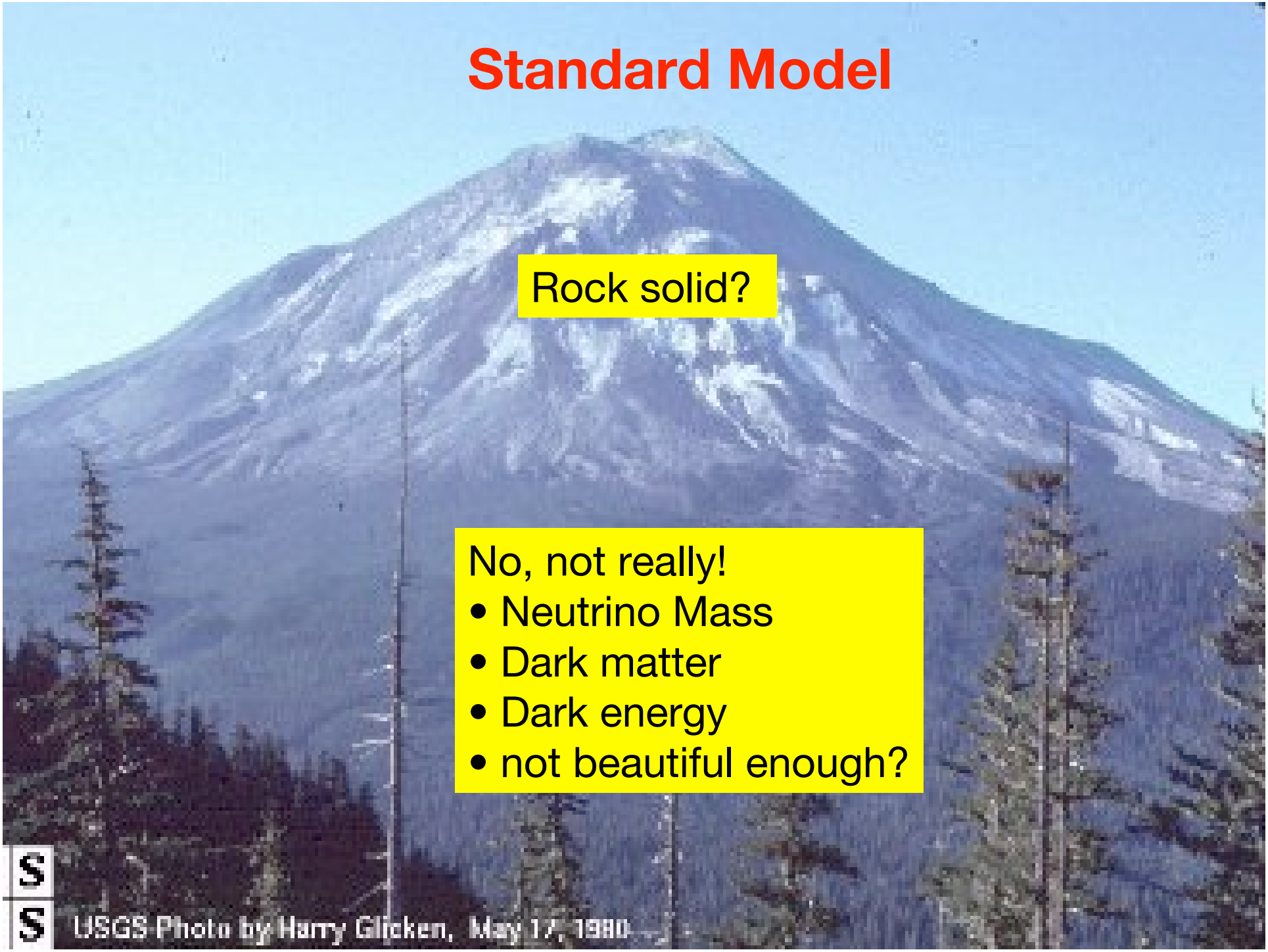


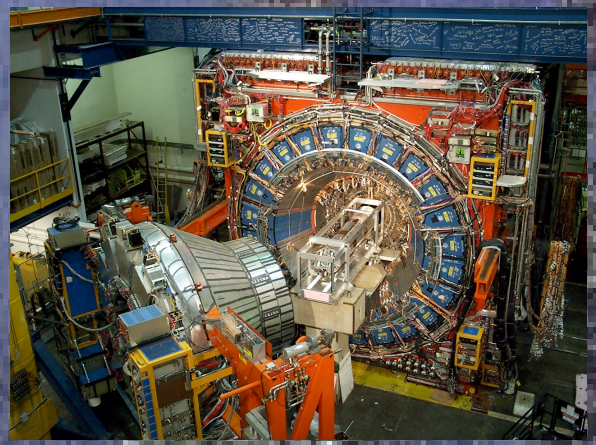
Rock solid?

No, not really!

- Neutrino Mass
- Dark matter
- Dark energy
- not beautiful enough?

Standard Model

ATTACK!!!

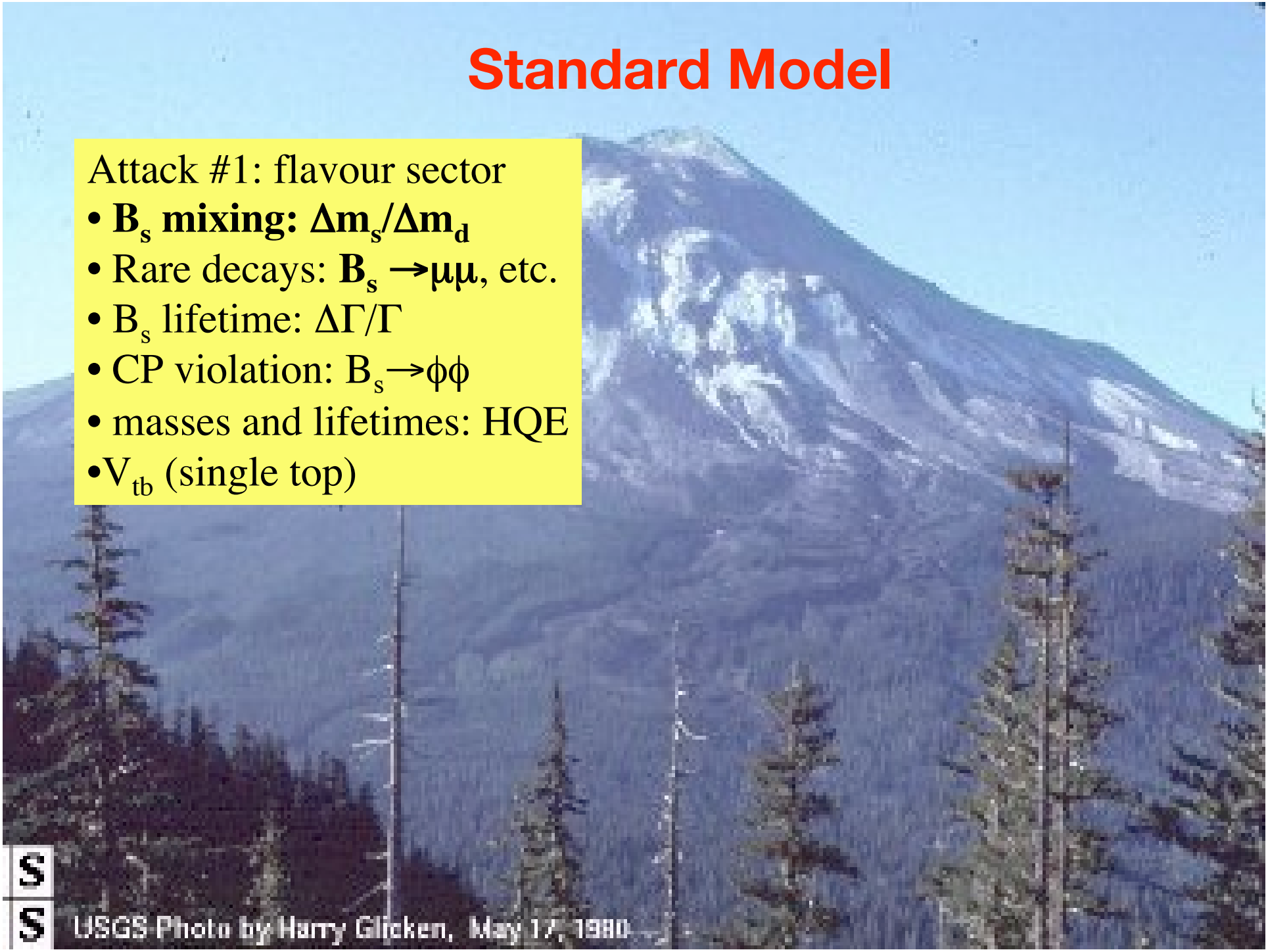


USGS Photo by Harry Glicken, May 17, 1980

Standard Model

Attack #1: flavour sector

- **B_s mixing: $\Delta m_s/\Delta m_d$**
- Rare decays: **$B_s \to \mu\mu$**, etc.
- B_s lifetime: $\Delta\Gamma/\Gamma$
- CP violation: $B_s \to \phi\phi$
- masses and lifetimes: HQE
- V_{tb} (single top)



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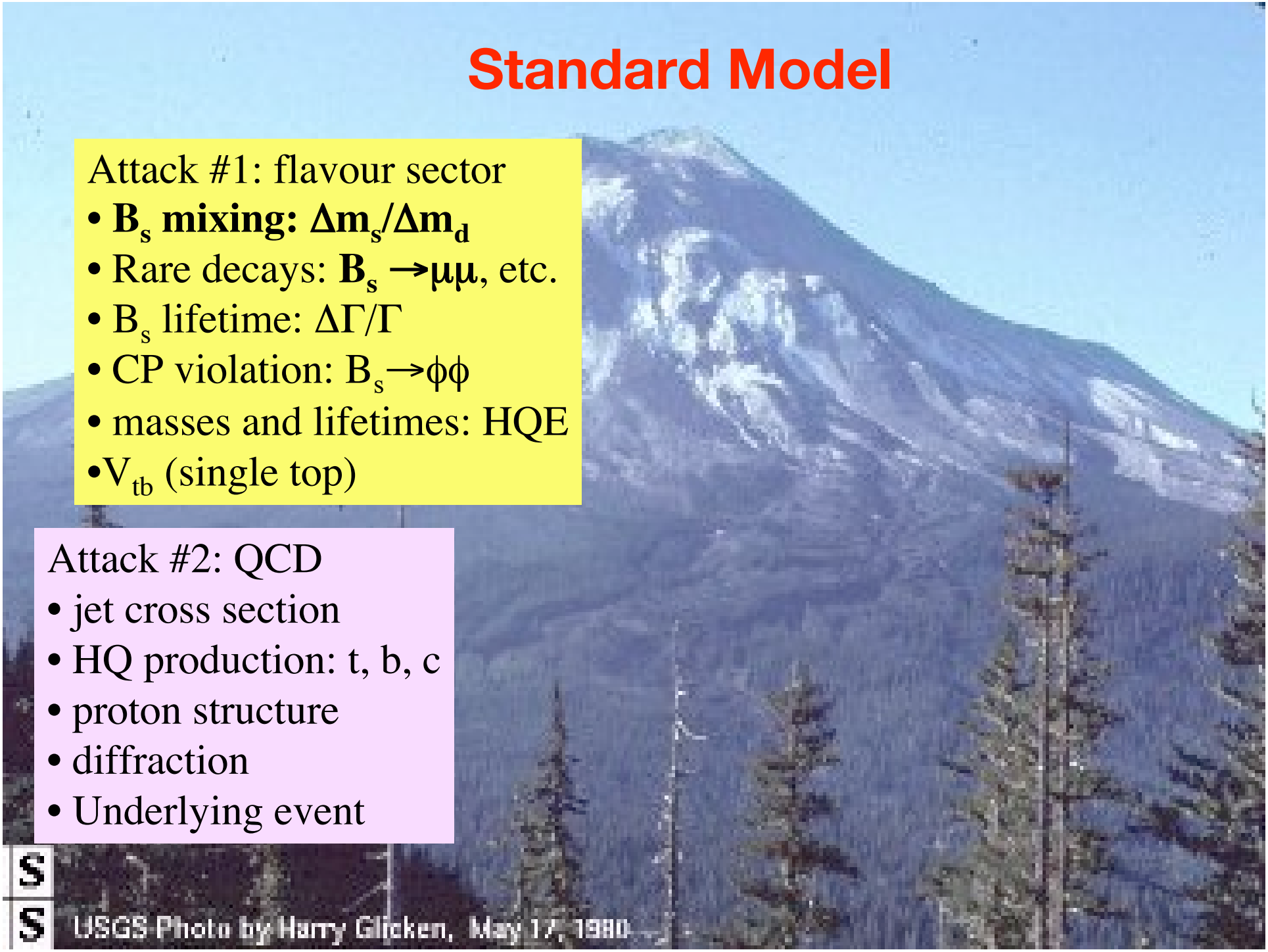
Attack #2: QCD

- jet cross section
- HQ production: t, b, c
- proton structure
- diffraction
- Underlying event



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Attack #3: electroweak sector + top
- **W mass** and width
- **top mass**
- Trilinear gauge couplings
- **Higgs boson**
- top quark decay
- top quark charge, spin

USGS Photo by Harry Glicken, May 1

Standard Model

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- V_{tb} (single top)

Attack #4:new physics searches
- **SUSY: trileptons**+squarks
- gauge sector: Z', W'
- extra dimensions
- compositeness: b', t', leptoquarks
- substructure
- **Non SM Higgs bosons**

Attack #2: QCD
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- diffraction
- Underlying event

Attack #3: electroweak sector + top
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- **top mass**
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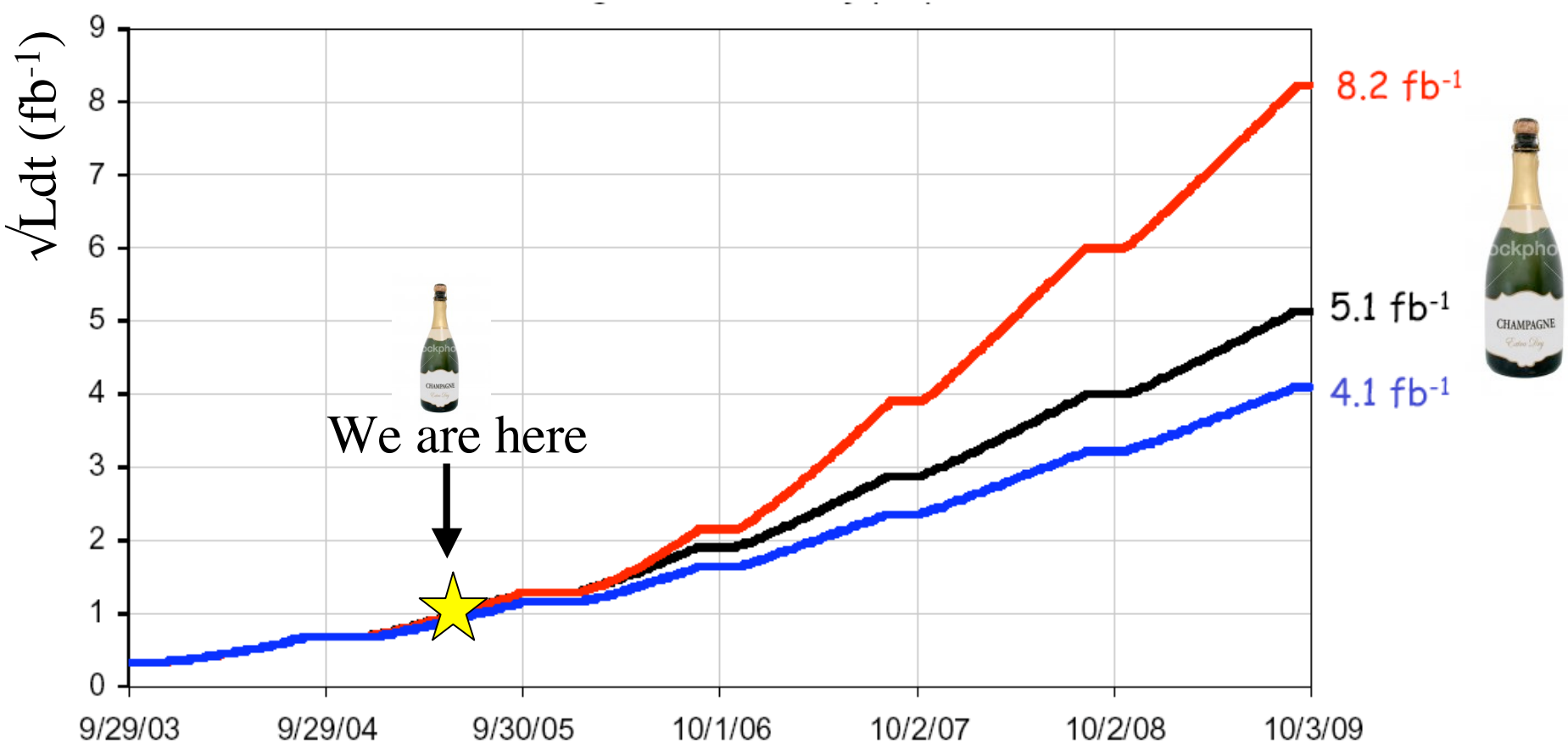
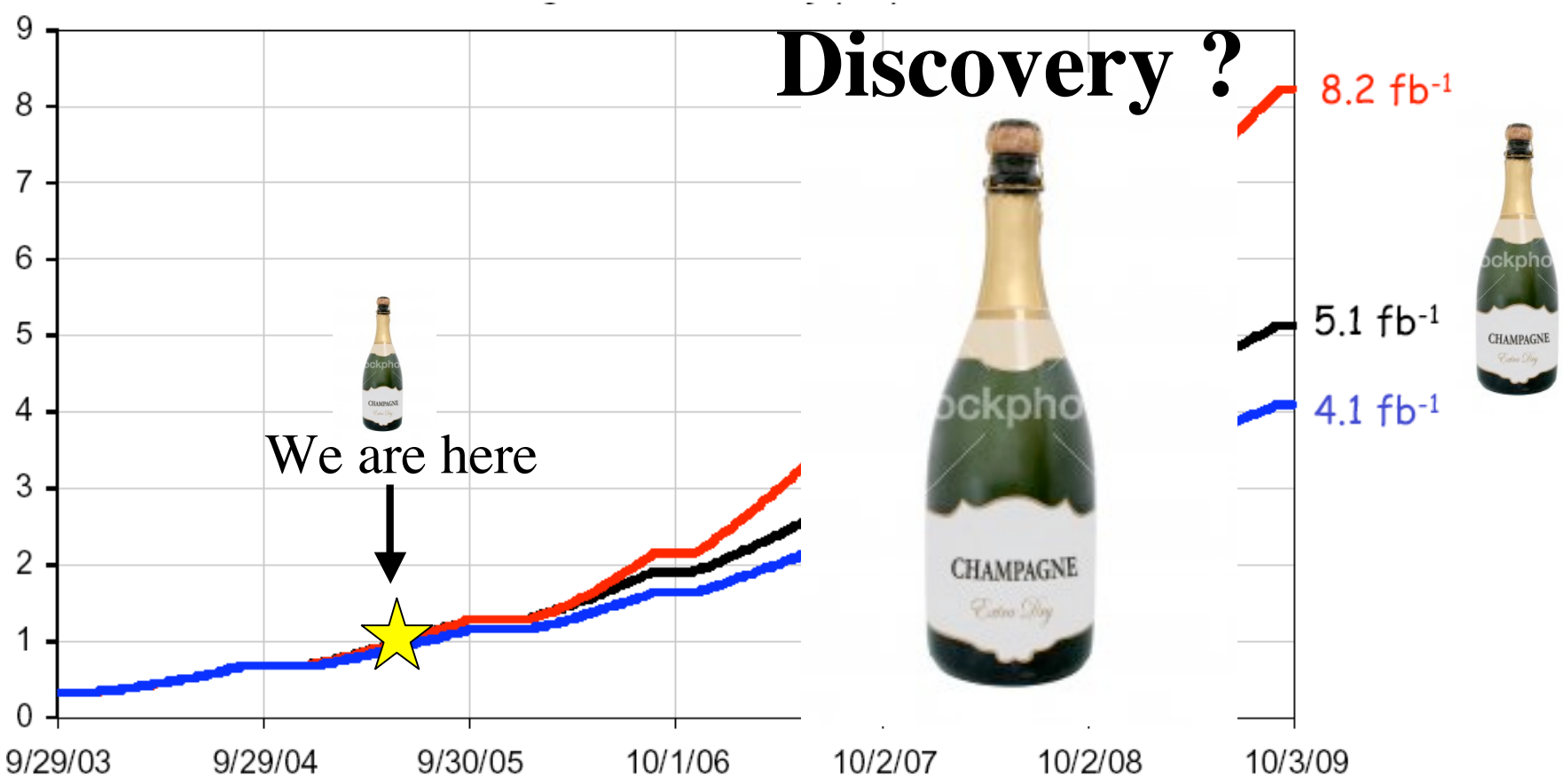
USGS Photo by Harry Glicken, May 1

Will we break the Standard Model?

Attack with Luminosity

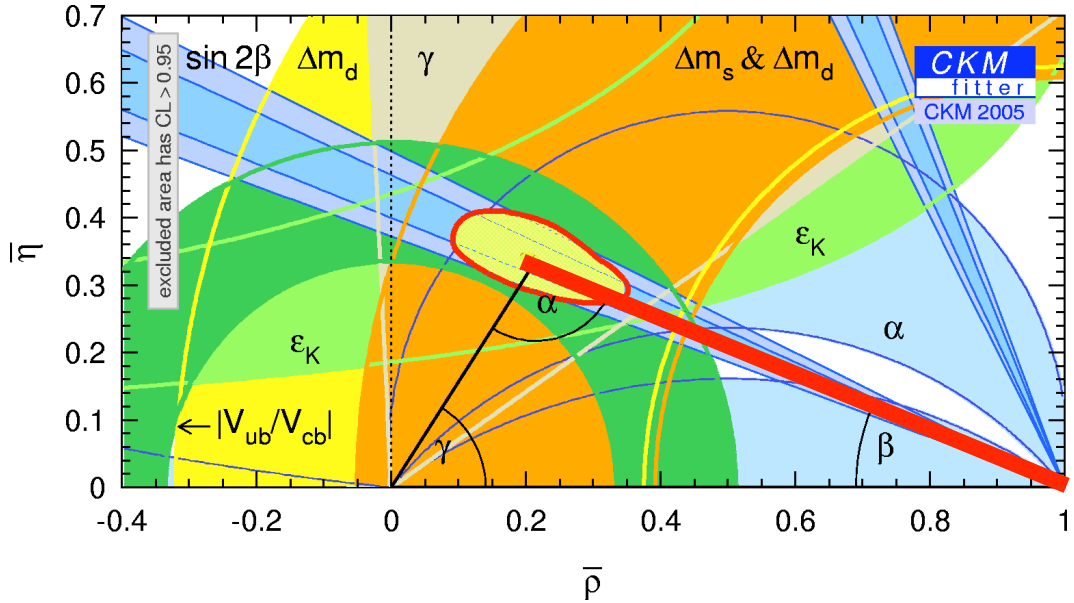


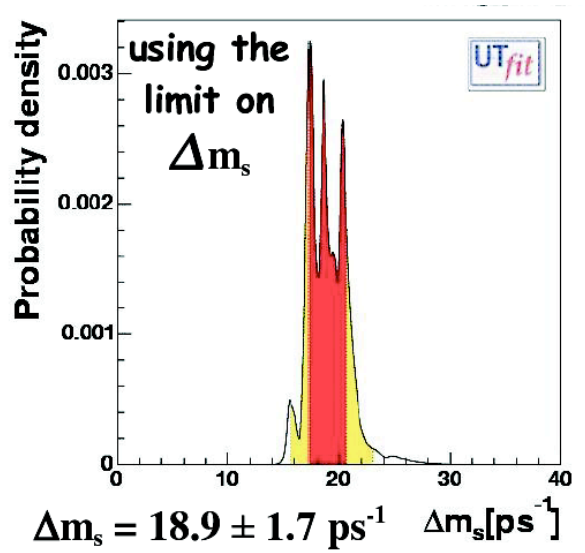
Attack with Luminosity



Flavour Sector

B_s^0- $\overline{B}_s^0$ mixing: Motivation



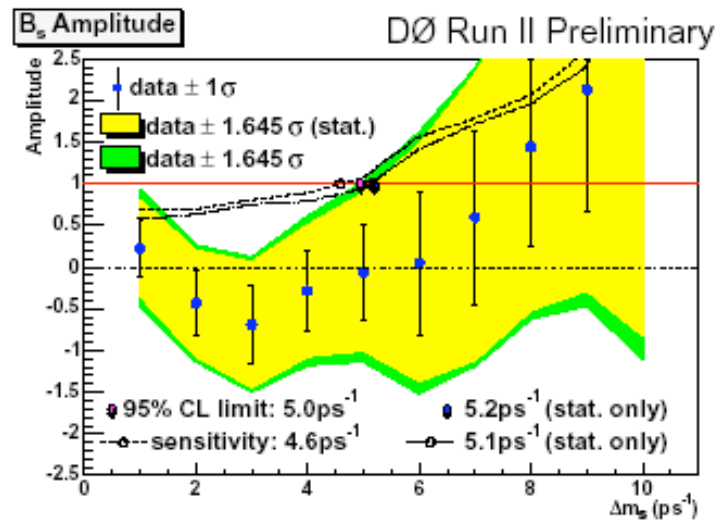


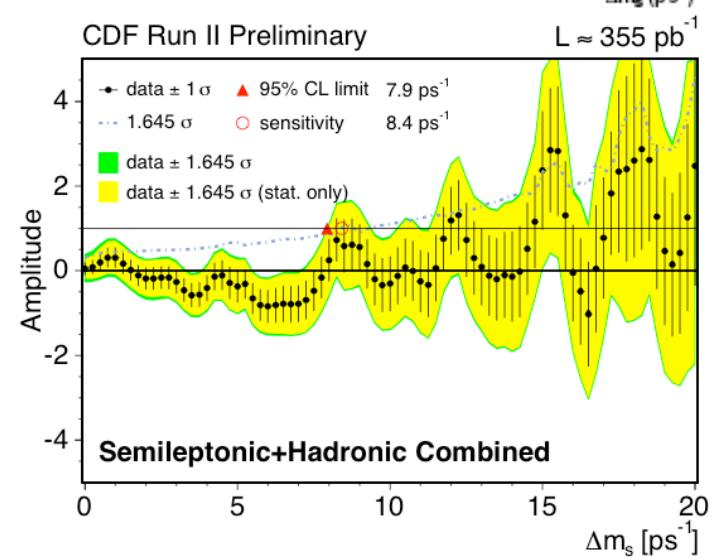
- Measure side of unitarity triangle: $\Delta m_d/\Delta m_s$
  - CKM fit: Δm_s =18.9±1.7 ps^{-1}
  - Observation will significantly shrink allowed region
- New physics:
  - 3σ if Δm_s>31 ps^{-1}
  - 5σ if Δm_s>38 ps^{-1}

B_s^0- $\overline{B}_s^0$ mixing: Present

- First measurements in spring:
  - CDF: Δm_s>7.9 ps^{-1}
  - D0: Δm_s>5.0 ps^{-1}
  - World: Δm_s>14.5 ps^{-1}
- New measurements expected soon
- Main challenges:
  - Flavour at production: εD^2
  - Vertex resolution
  - Trigger bandwidth

$$\mathcal{A}_{\text{mix}}(t) = \frac{N(t)_{\text{unmix}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmix}} + N(t)_{\text{mixed}}} = D\cos(\Delta m \cdot t)$$

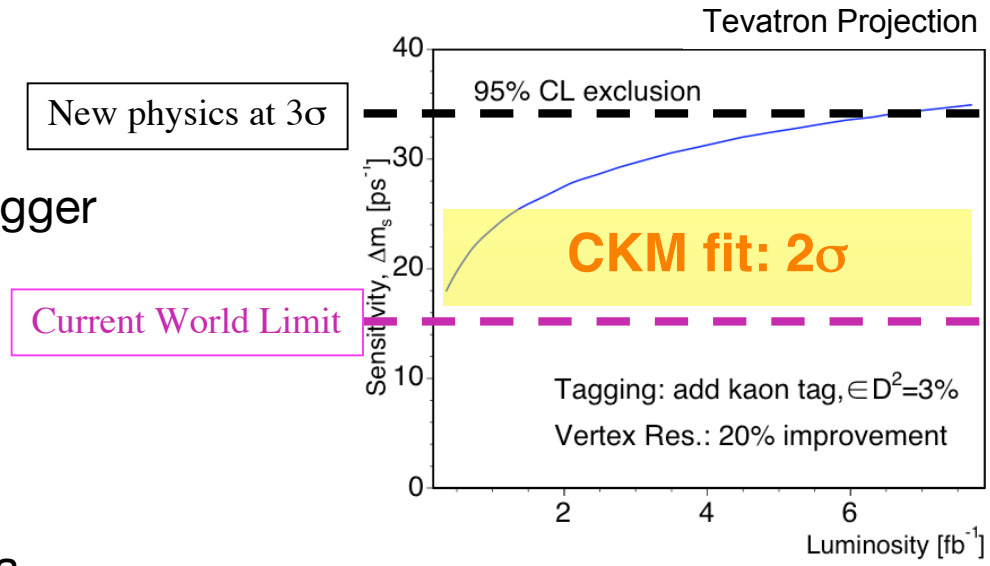


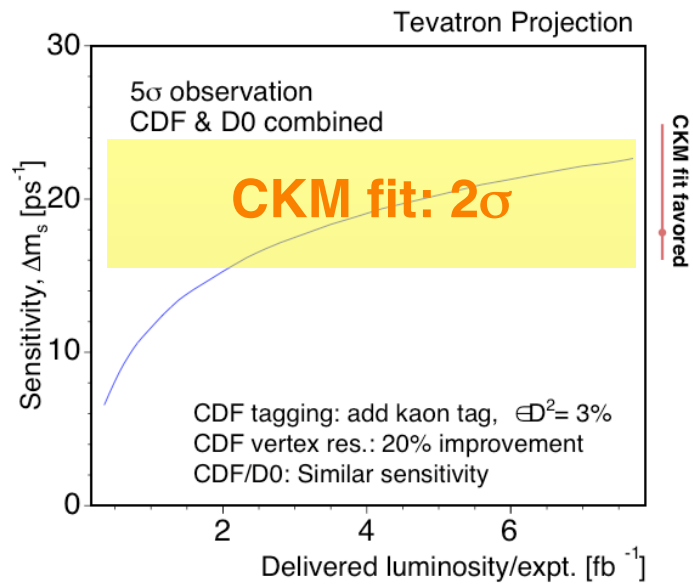


B_s mixing: Future Discovery

- CDF assume:
  - Flavour tagging:
    - Add same-side kaon tagger
    - εD^2=1.6% + 3%
  - Vertex resolution:
    - Improve by 20%
  - Trigger bandwidth:
    - Utilize 50% of CDF data
- DØ expect similar sensitivity:
  - Install Silicon L0
    - improve vertex resolution
  - Upgrade L3 trigger bandwidth

5σ Observation:
L=2 fb^{-1}: Δm_s<15 ps^{-1}
L=8 fb^{-1}: Δm_s<22 ps^{-1}





Rare Decay: $B_s \rightarrow \mu^+\mu^-$

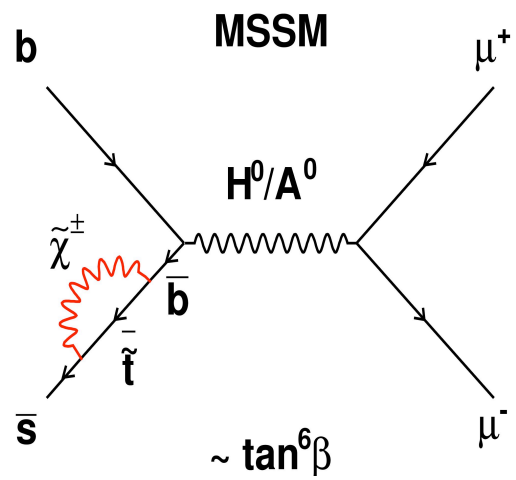
- SM rate heavily suppressed:

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

- SUSY rate may be enhanced: $\propto \tan^6\beta$

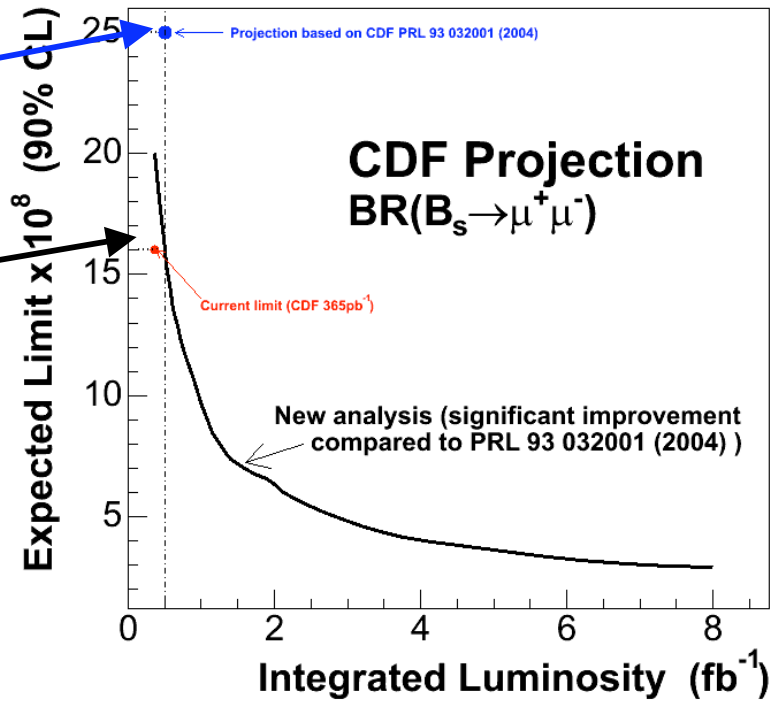
(Babu, Kolda: hep-ph/9909476+ many more)



- Results at 90% C.L.: Healthy Competition!
  1. CDF (L=171 pb^{-1}): BR < 5.8 x 10^{-7}
  2. D0 (L=240 pb^{-1}): BR < 4.1 x 10^{-7}
  3. D0 (L=300 pb^{-1}): BR < 3.0 x 10^{-7}
  4. CDF (L=364 pb^{-1}): BR < 1.6 x 10^{-7}
- New Combined CDF + D0 result: **BR<1.2x10^{-7} @ 90% C.L.**

Future of $B_s \rightarrow \mu^+\mu^-$

- We get smarter with time, too:
  - One year old CDF projection for L=500 pb^{-1} was
    - **BR<2.5 x 10^{-7}** at 90% C.L.
  - Sensitivity with new CDF analysis projection for L=500 pb^{-1}:
    - **BR<1.6x10^{-7}** at 90% C.L
- Extrapolate based on current analysis (optimized for 1 fb^{-1})
  - Assume background scales linearly with luminosity
  - Will want to re-optimize the analysis for L > 2 fb^{-1}
- D0 estimate similar sensitivity

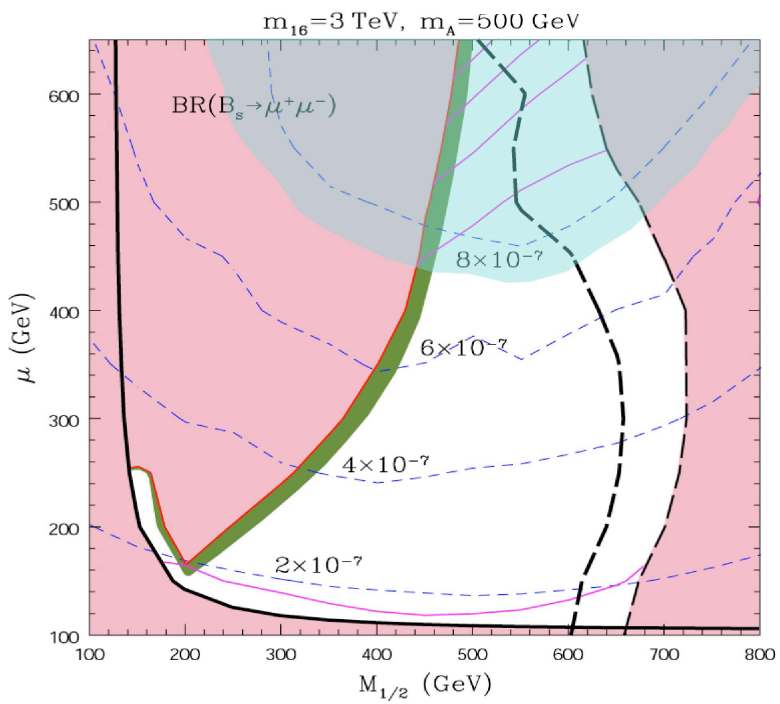


Single experiment sensitivity:
- L=2 fb^{-1}: BR<6 x 10^{-8} @ 90% C.L.
- L=8 fb^{-1}: BR<2 x 10^{-8} @ 90% C.L.

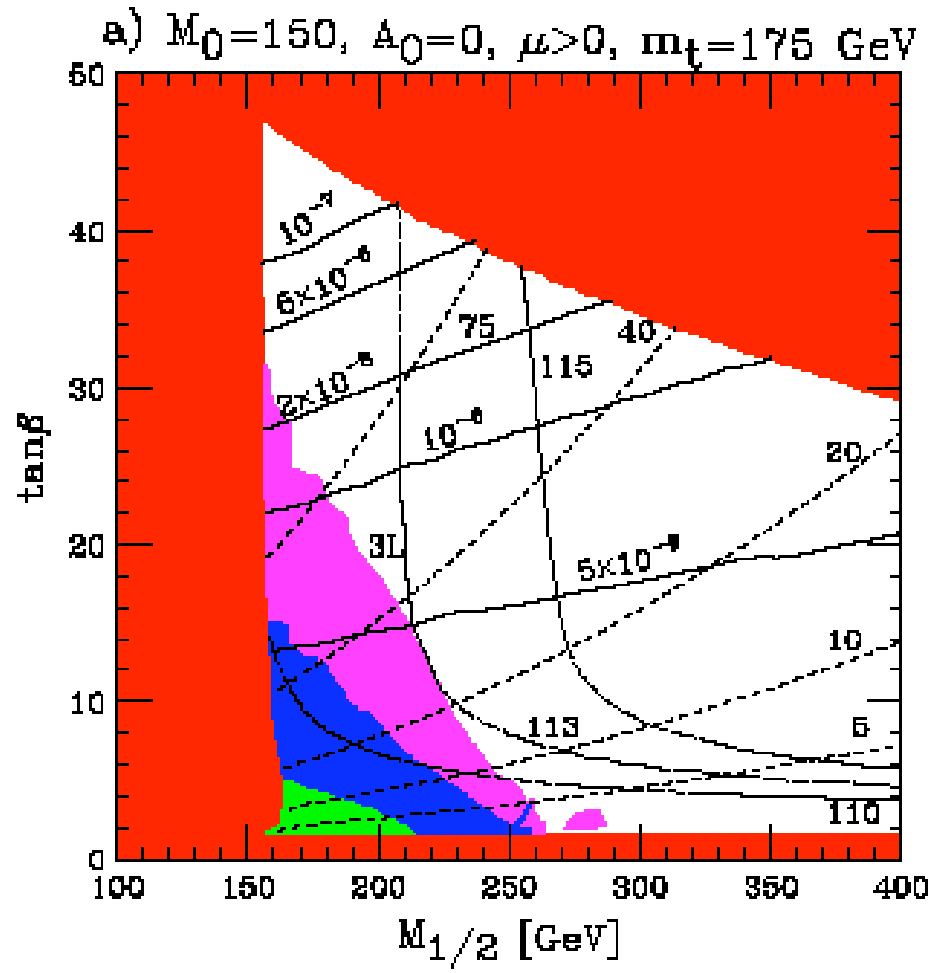
Implications on models: $B_s \to \mu\mu$

- Sensitivity at high tanβ and low m_A

R. Dermisek *et al.*, hep-ph/0304101



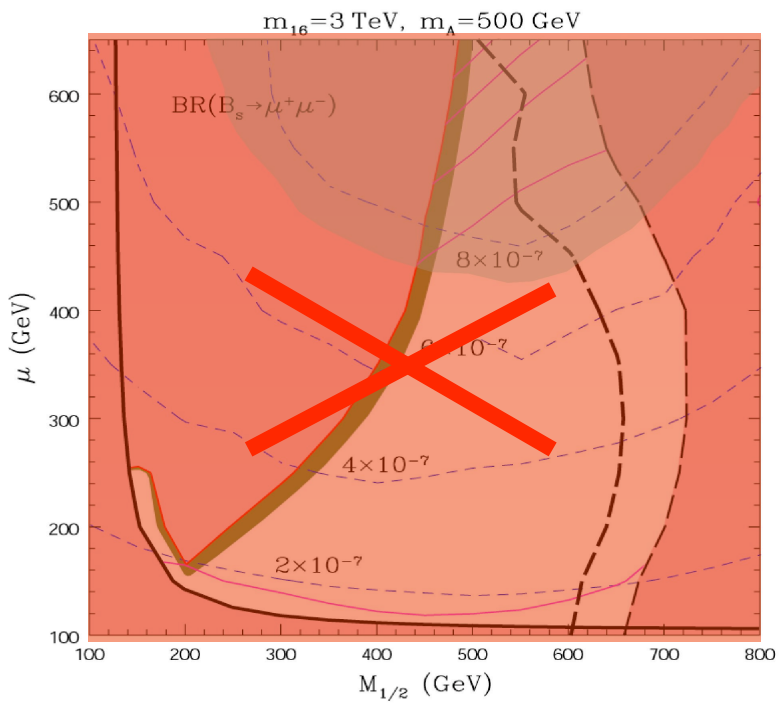
Dedes, Dreiner, Nierste, Richardson, hep-ph/0207026



Implications on models: $B_s \to \mu\mu$

- BR<2x10^{-8} restricts allowed parameter space
- depends strongly on model parameters

R. Dermisek *et al.*
hep-ph/0304101



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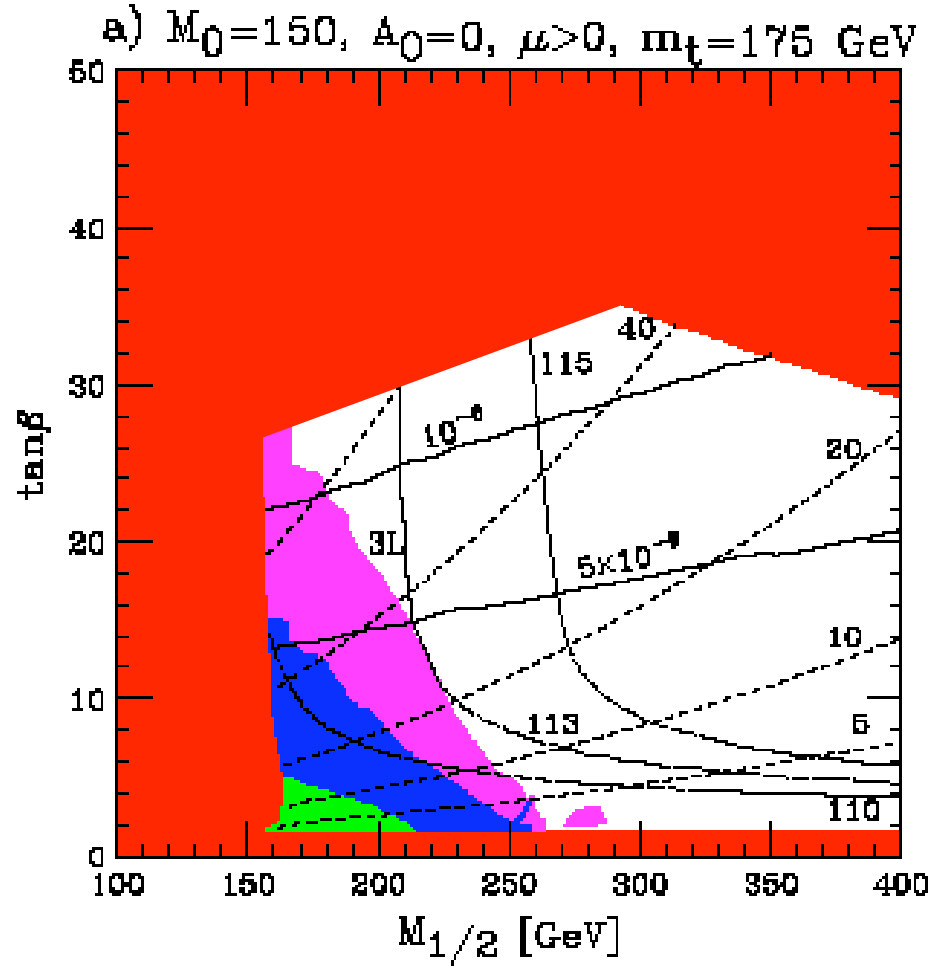
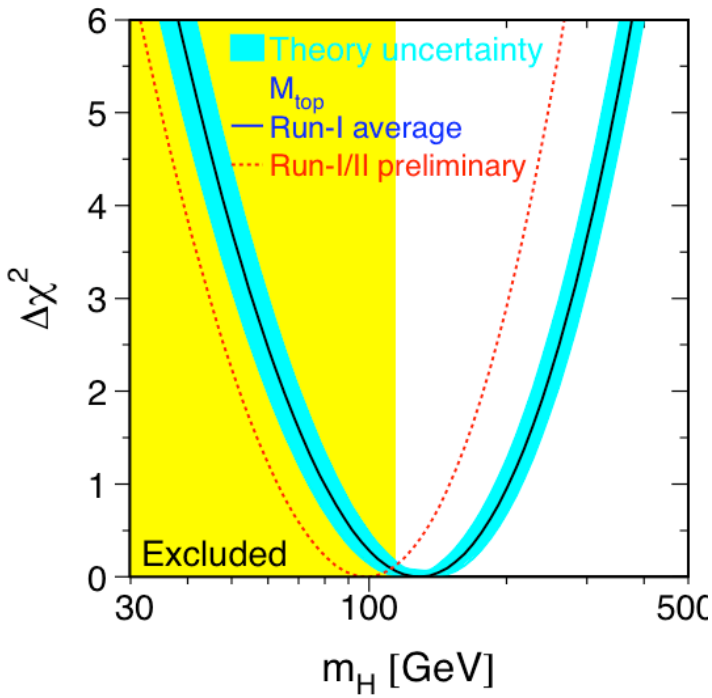


EWK Symmetry Breaking

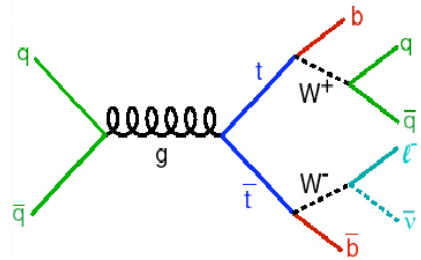
W, top and Higgs

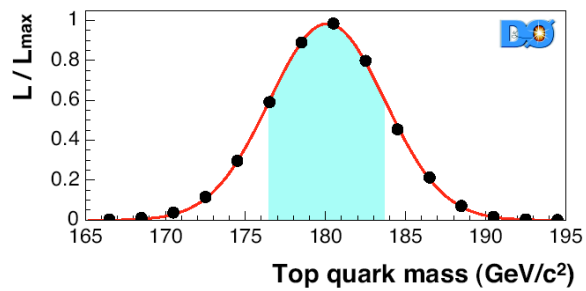
- W mass, top mass and Higgs mass related via loop corrections
- Precise knowledge of M_W and m_{top} allows us to constrain SM Higgs boson mass:
  - Run I Average: m_{top}=178.0+-4.3 GeV
    - m_H<280 GeV at 95%C.L.
  - New prel. Average: m_{top}=174.3+-3.4 GeV
    - m_H<208 GeV at 95%C.L.
- Very sensitive:
  - 4 GeV top mass shift
  - => 72 GeV shift in Higgs mass limit

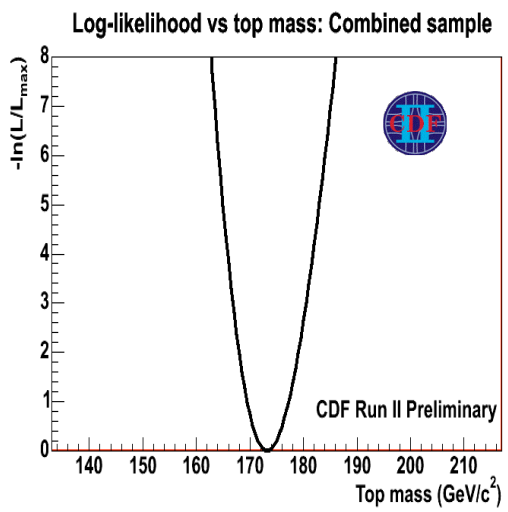


Top Quark Mass

- Using W mass constraint jets from W decay:
  - Template fit of top mass:
    - CDF Run II: $173.2^{+2.9}_{-2.8}(stat.) \pm 3.4(syst.) GeV/c^2$
  - Matrix element method:
    - D0 Run I: $180.1 \pm 3.6(stat.) \pm 3.9(syst.) GeV/c^2$
- Largest systematic uncertainty:
  - Jet energy scale
  - Will dominate even more at higher luminosity







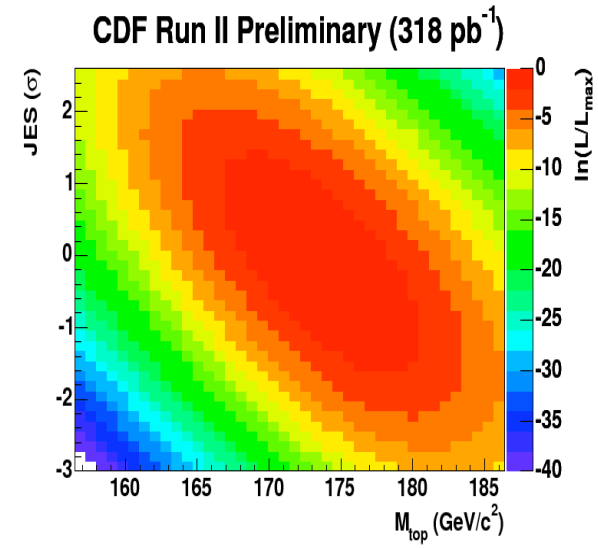
Top Mass: Systematic Uncertainties		
Source	**CDF(GeV/c²)**	**DØ(GeV/c²)**
Jet Energy Scale	3.1	3.3
B-jet energy	0.6	Incl. in Jet
Background	1.0	1.0
MC modelling	0.8	1.1
other	0.5	1.4
Total Syst. Unc.	**3.4**	**3.9**

Top Mass: Present and Future

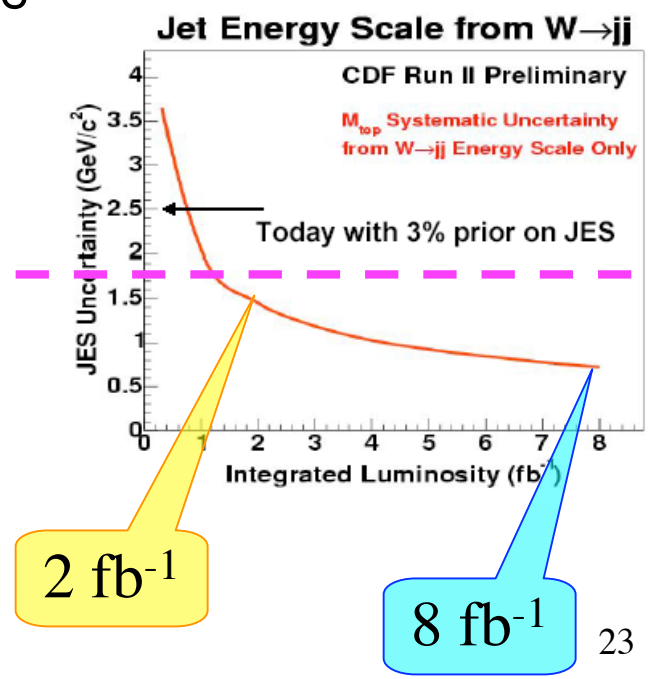
- New world's best result:

$$m_{\text{top}} = 173.5^{+2.7}_{-2.6}\,(stat.) \pm 2.5(JES) \pm 1.7\ (syst.)\ \text{GeV/c}^2$$

  - Combined fit for m_{top} and JES
  - JES becomes statistical problem!
  - New Run II measurement is better than Run I combined CDF+D0
  - D0 will soon have result using same technique



- Projection for 2 fb^{-1}
  - **Assume: JES: 1.4 GeV, other: 1.7 GeV**
  - **Δm(top) $\approx$ 1.4 $\oplus$ 1.7 GeV/c^2 = 2.2 GeV/c^2**



2 fb^{-1}:Δm(top)< ±2.5 GeV /c^2 per experiment

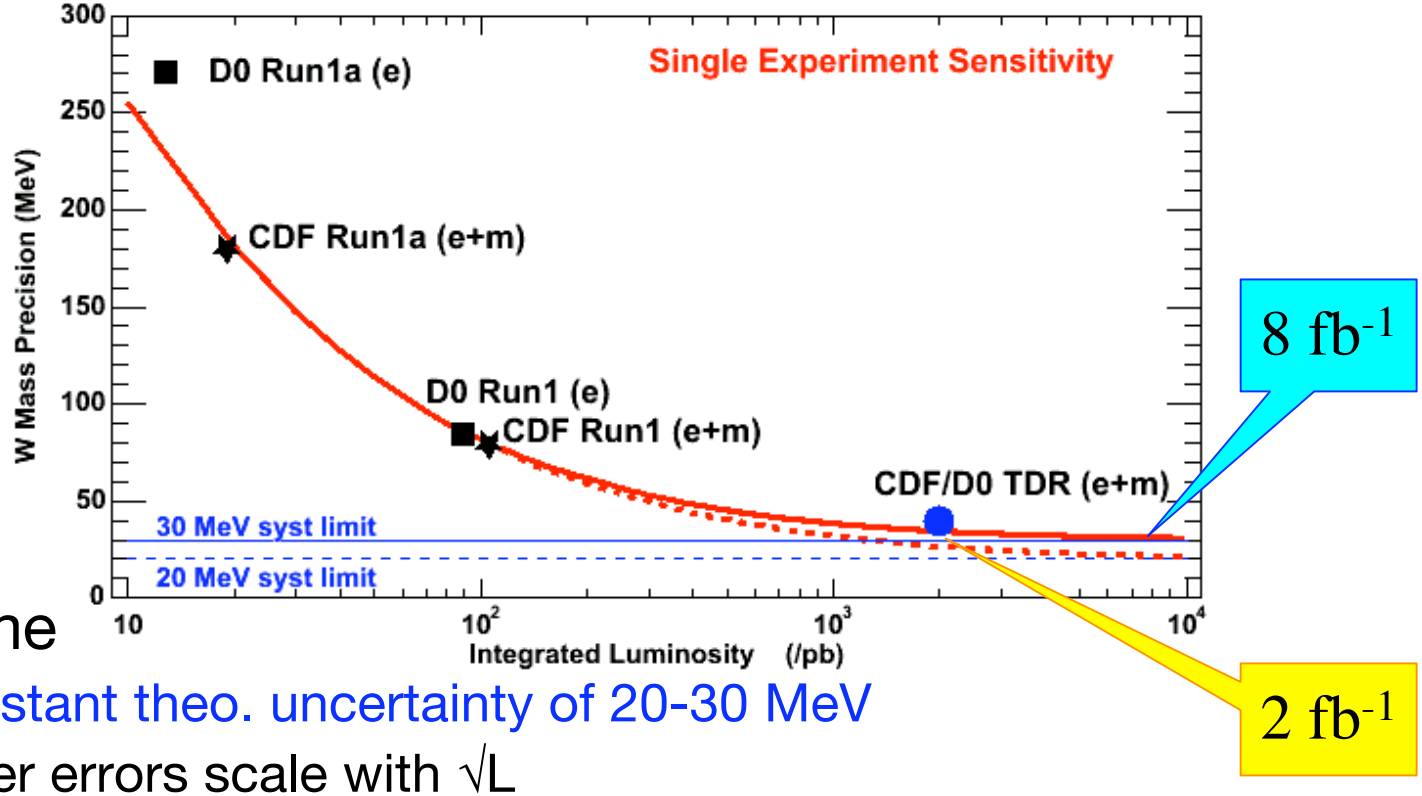
8 fb^{-1}:Δm(top)< ±2.0 GeV /c^2 per experiment

W Boson Mass: Status

	CDF Run II prel. L=200 pb^{-1}		D0 Run I: L=82 pb^{-1}	
	$W \to e\nu$	$W \to \mu\nu$	$W \to e\nu$	nature
Statistics	45	50	60	Stat.
Lepton scale+res.	70	30	59	Stat.
Recoil	50	50	37	Stat.
background	20	20	9	Stat.
Production+Decay	30	30	23	Theo.
total	105	85	84	
Comb. $e+\mu$	76 MeV		84 MeV	

- Most uncertainties scale with statistics: $\sqrt{L}$
- Production and Decay model being improved:
  - W charge asymmetry and $p_T(Z)$ spectrum constrain proton structure and $p_T(W)$
  - Decay: 2-photon radiation calculation (U. Baur)
  - Production: new improved version of ResBos
  - Expect to improve uncertainty to <20 MeV

W mass: Future

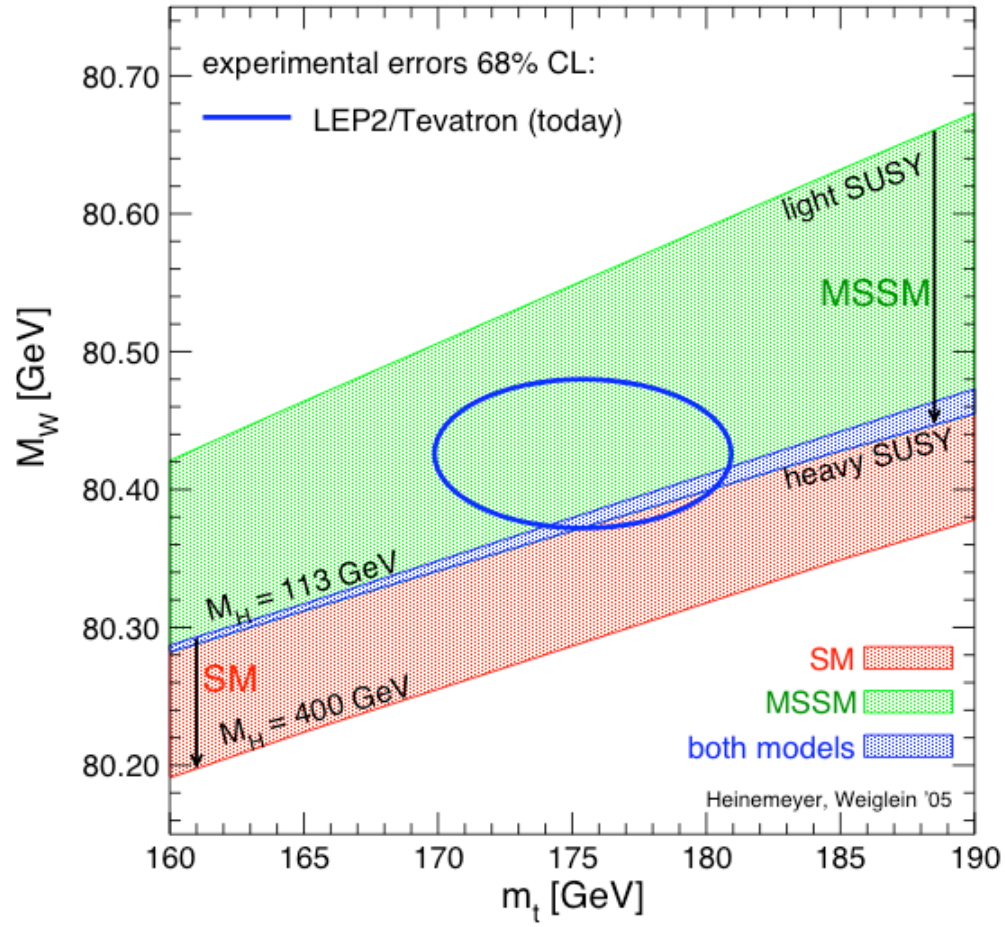


- Assume
  - constant theo. uncertainty of 20-30 MeV
  - other errors scale with $\sqrt{L}$
- Good model of data so far! Agrees with Run II TDR
- Single experiment errors:
  - L=2 fb-1: δm_W=25-35 MeV (with LEP2: δm_W=21-27 MeV)
  - L=8 fb-1: δm_W=20-30 MeV (with LEP2: δm_W=18-24 MeV)

Implications for Higgs and SUSY

New very preliminary top mass (D0+CDF): 174.3±3.4 GeV

- **Present:**
  - **Δm_{top} = 3.4 GeV**
  - **Δm_W = 34 MeV**



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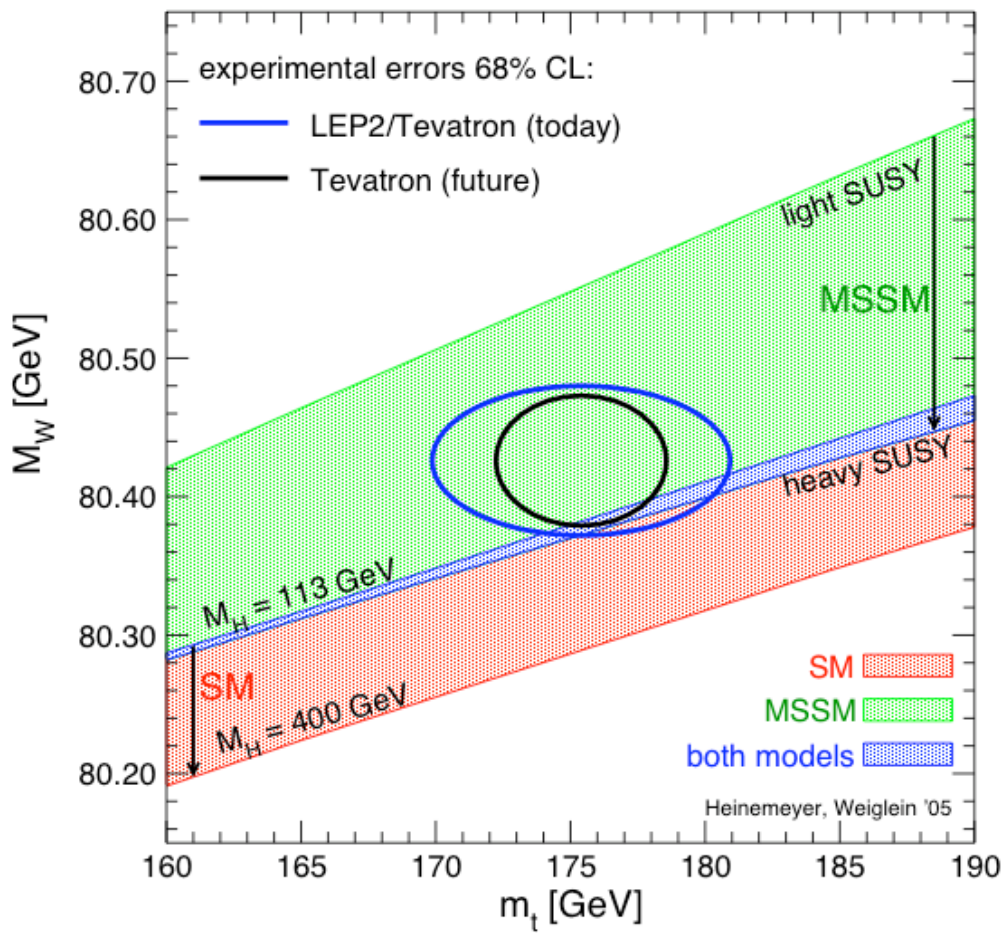
- **Definitely:**
  - **Δm_{top} = 2 GeV**
  - **Δm_W = 30 MeV**



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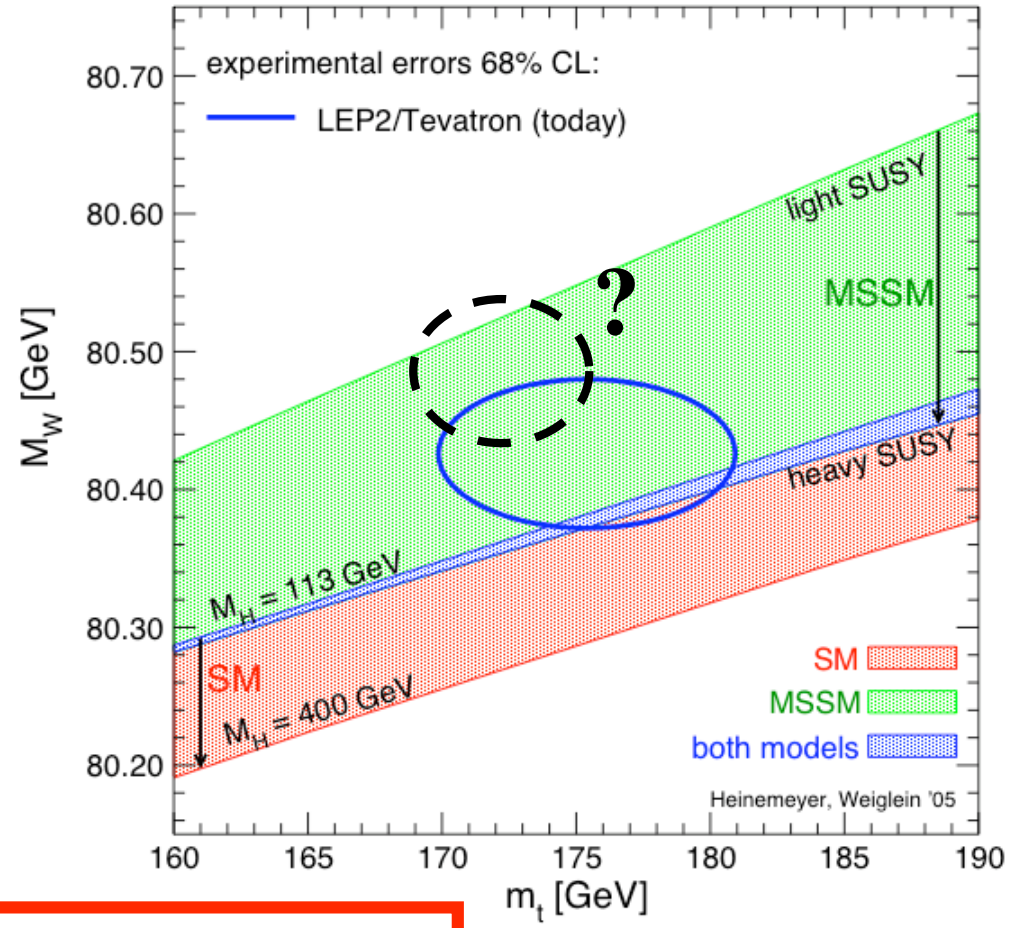
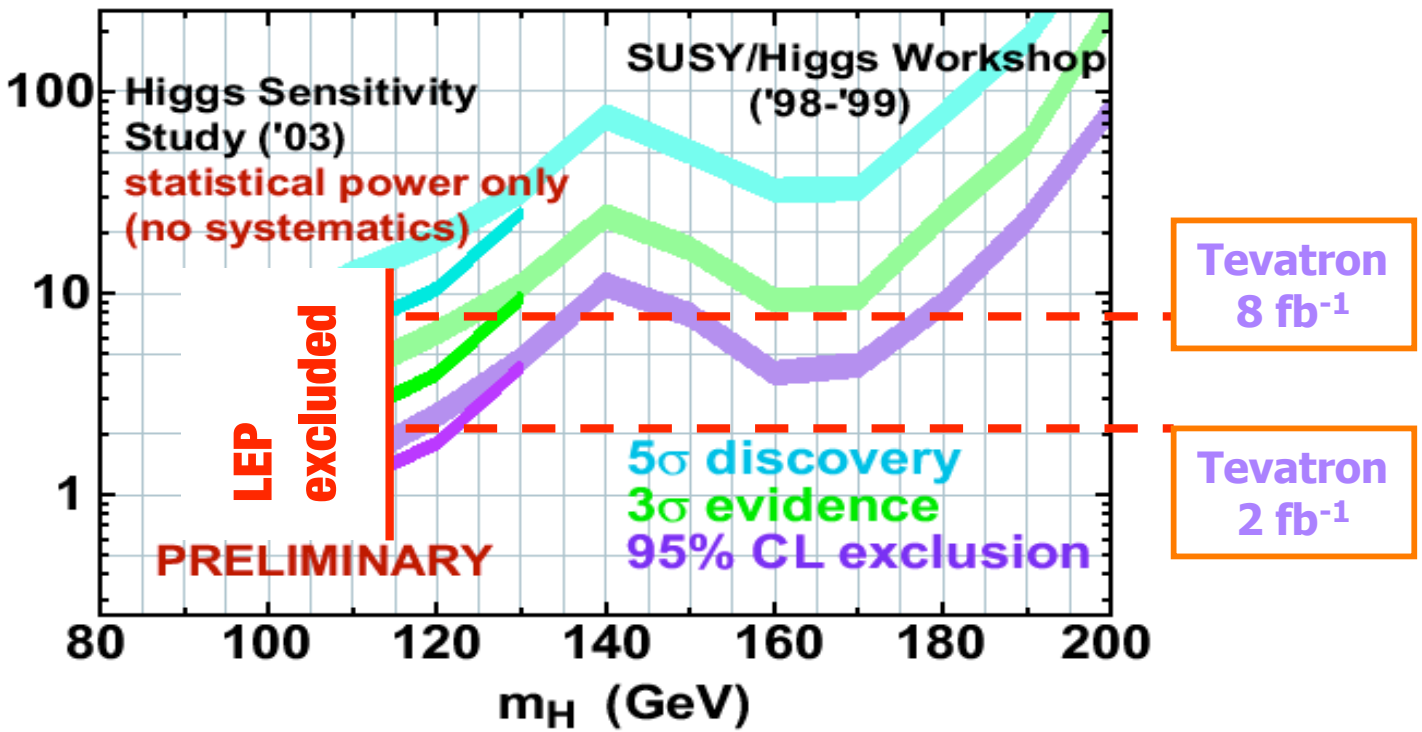


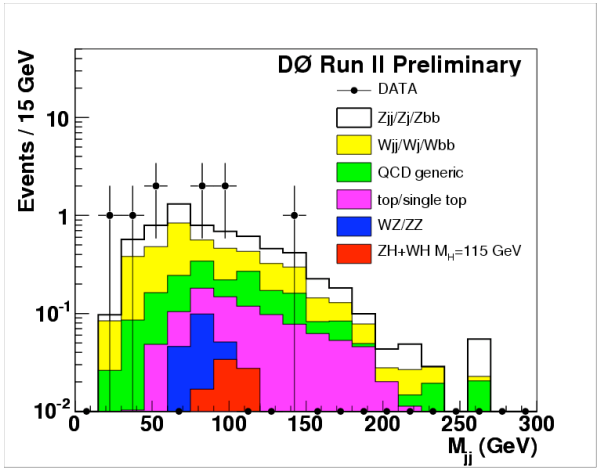
Can the Standard Model work?

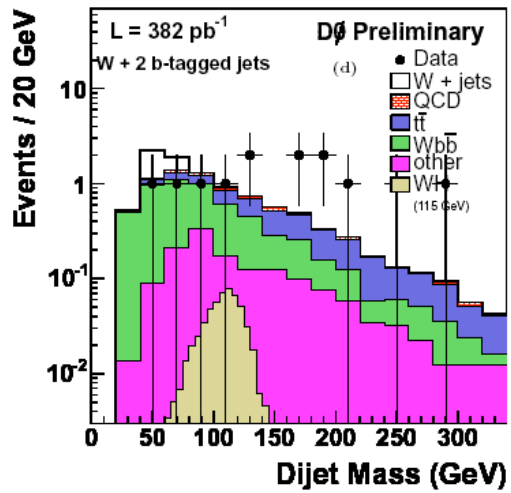
Direct Higgs Search

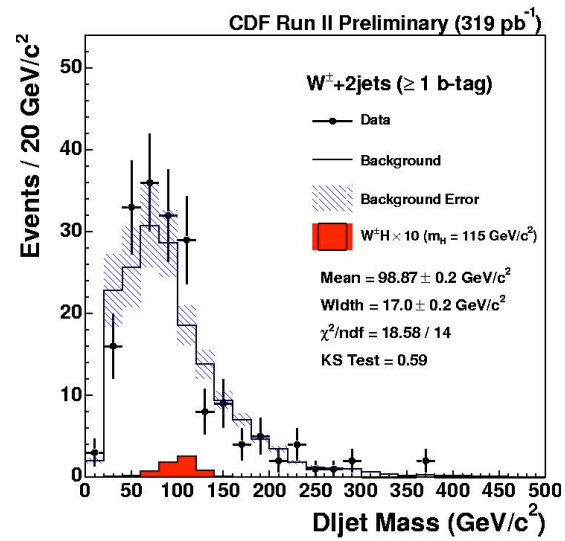


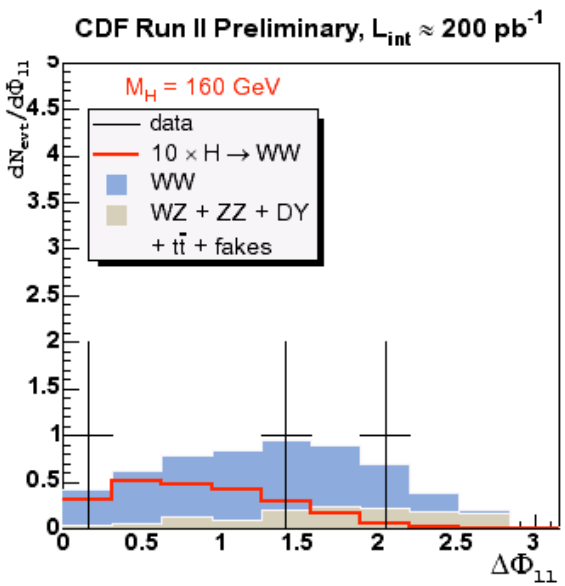
- Exclude m_H<120 GeV/c^2 with 2 fb^{-1}
- Exclude m_H<135 GeV/c^2 and m_H=155-175 GeV/c^2 with 8 fb^{-1}
  - Severely constrains SUSY! => Big impact on search strategies at LHC
- 3σ evidence for m_H<125 GeV/c^2 with 8 fb^{-1}

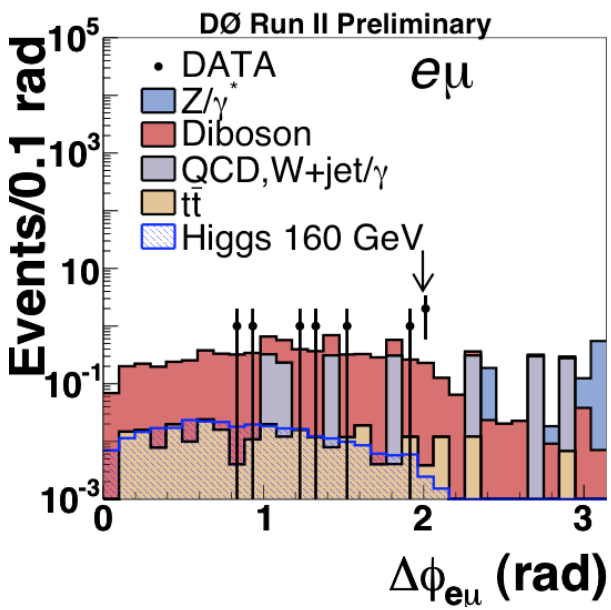
Latest Results from CDF and DØ







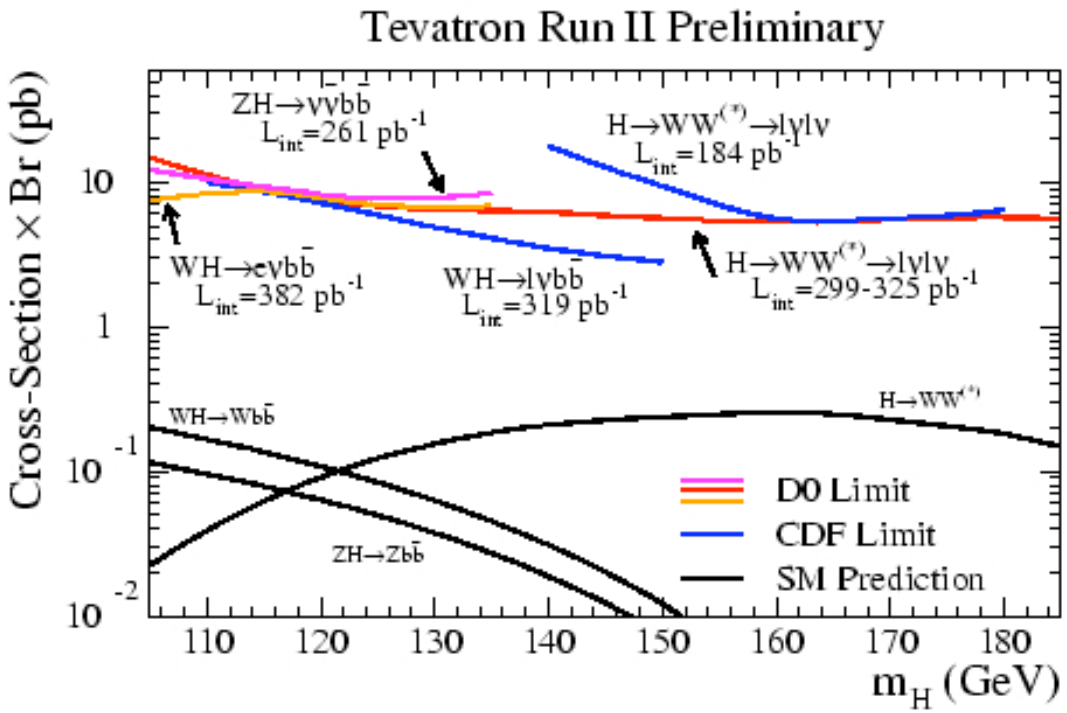




CDF and DØ started the hunt!

Current Higgs Search Results

- D0:
  - WH->lνbb
  - ZH->ννbb
  - WW->llνν
- CDF:
  - WH->lνbb
  - WW->llνν
  - WWW->$l^{\pm}l^{\pm}$ + X
- Cross section limits about 20 times larger than SM prediction



J. Ellis, ICHEP'04:
"Tevatron are closing in on the Higgs. So, if I were CERN director I would get LHC going asap."

SM Higgs: How are we doing?

Comparison of Sensitivity: $S/\sqrt{B}$			
	DØ Run 2	HSWG (w/o NN)	ratio
$WH \rightarrow l\nu bb$ ($L=380\ pb^{-1}$)	0.077	0.13	1.7
$ZH/WH \rightarrow \nu\nu bb$ ($L=261\ pb^{-1}$)	0.055	0.20	3.6
$H \rightarrow WW$ ($L\approx300\ pb^{-1}$)	0.12	0.23	1.9

- $m_H=115\ GeV/c^2$:
  - Within factor of 2-3 of HSWG prediction!
    - Improve b-tagging
    - Improve lepton acceptance
    - Improve mass resolution
    - Optimise selection
    - Use NN => x1.6

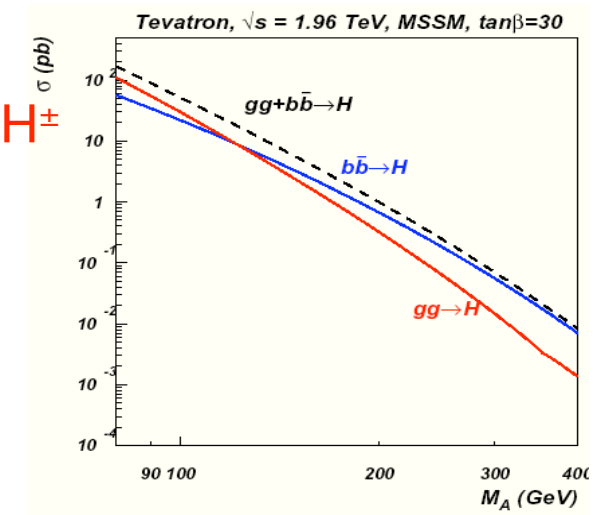
- $m_H=160\ GeV/c^2$:
  - Within factor of 2 compared to HSWG
    - Improve by reducing WW background kinematically
    - NN

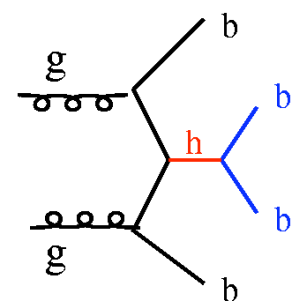
Not so badly compared to "ultimate performance" assumed by HSWG

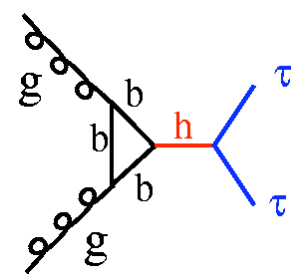
Beyond the SM

Higgs: A/H/h→bb and A/H/h→ττ

- Supersymmetry (MSSM):
  - 2 Higgs doublets => 5 Higgs bosons: h, H, A, $H^{\pm}$
- High tanβ:
  - A degenerate in mass with h or H
  - Cross sections enhanced with $\tan^2\beta$ due to enhanced coupling to down-type quarks
  - Decay into either ττ or bb:
    - BR(A →ττ) ≈ 10%, BR(A→ bb) ≈ 90%
    - Exact values depend on SUSY parameter space
- Experimentally:
  - pp → Ab+X → bbb+X
  - pp → A+X → ττ +X
- Depending on radiative corrections in SUSY different parameter space is covered



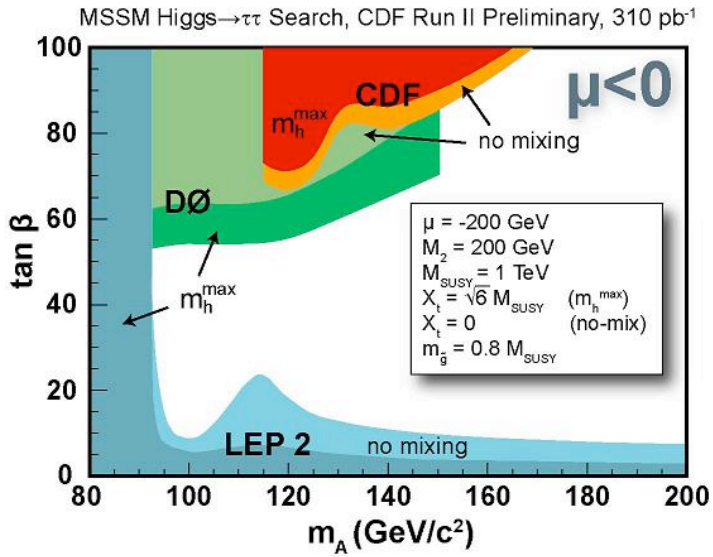


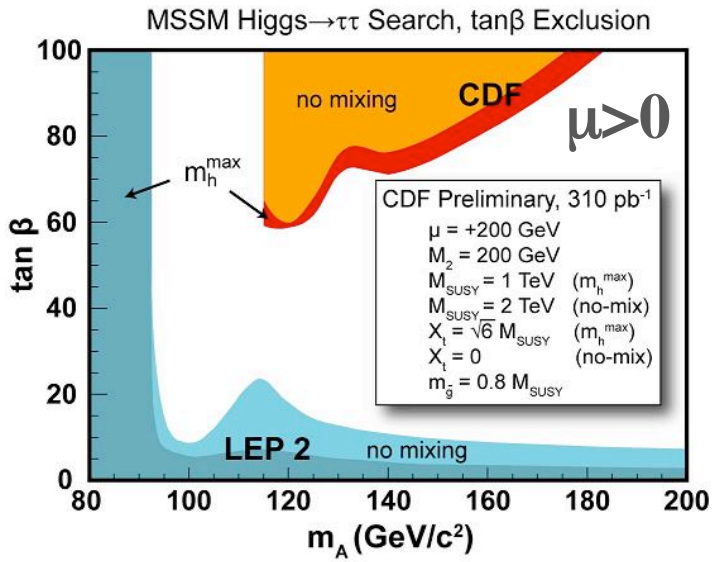


•C. Balazs, J.L.Diaz-Cruz, H.J.He, T.Tait and C.P. Yuan, PRD 59, 055016 (1999)
•M.Carena, S.Mrenna and C.Wagner, PRD 60, 075010 (1999)
•M.Carena, S.Mrenna and C.Wagner, PRD 62, 055008 (2000)

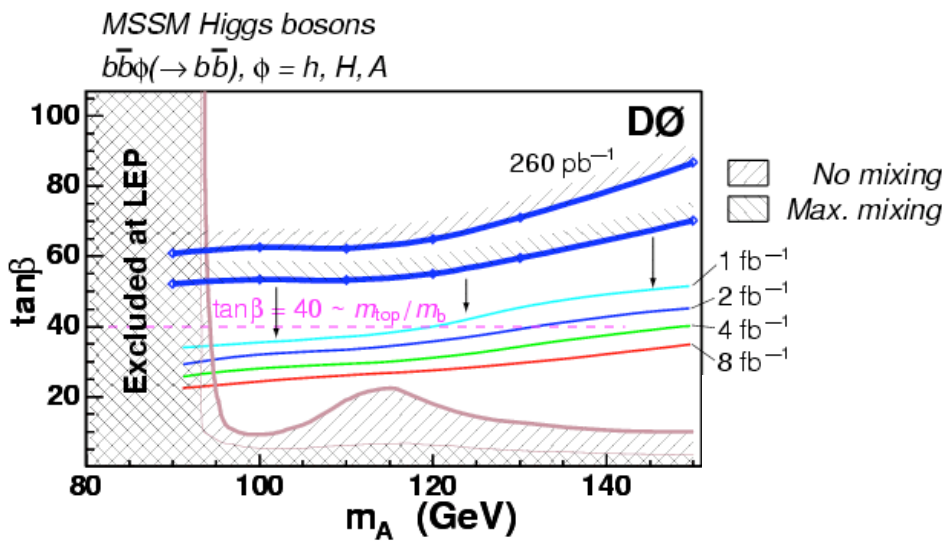
MSSM Higgs: Current Results

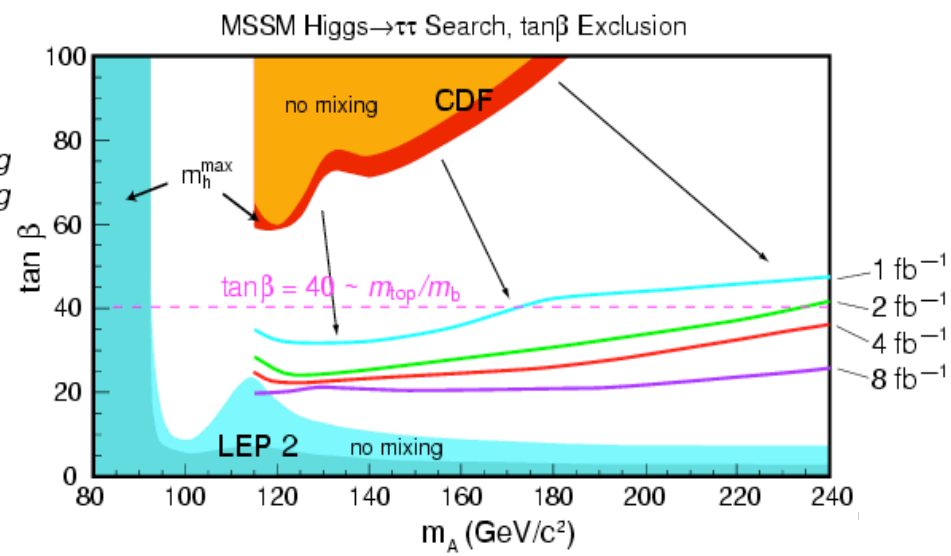
- **pp → bA+X→bbb+X (DØ)**
  - Best sensitivity for $\mu<0$
  - Lower sensitivity for $\mu>0$
- **pp → A+X→ ττ+X (CDF)**
  - Sensitive for $\mu>0$ and $\mu<0$, best for $\mu>0$
  - Slight excess at 130 GeV/c^2 "weakens limit"
- Nice complementarity of two channels
  - Interactions with theorists to probe SUSY parameter space better
  - Define scenarios suitable for hadron colliders
- Triggering for both channels challenging





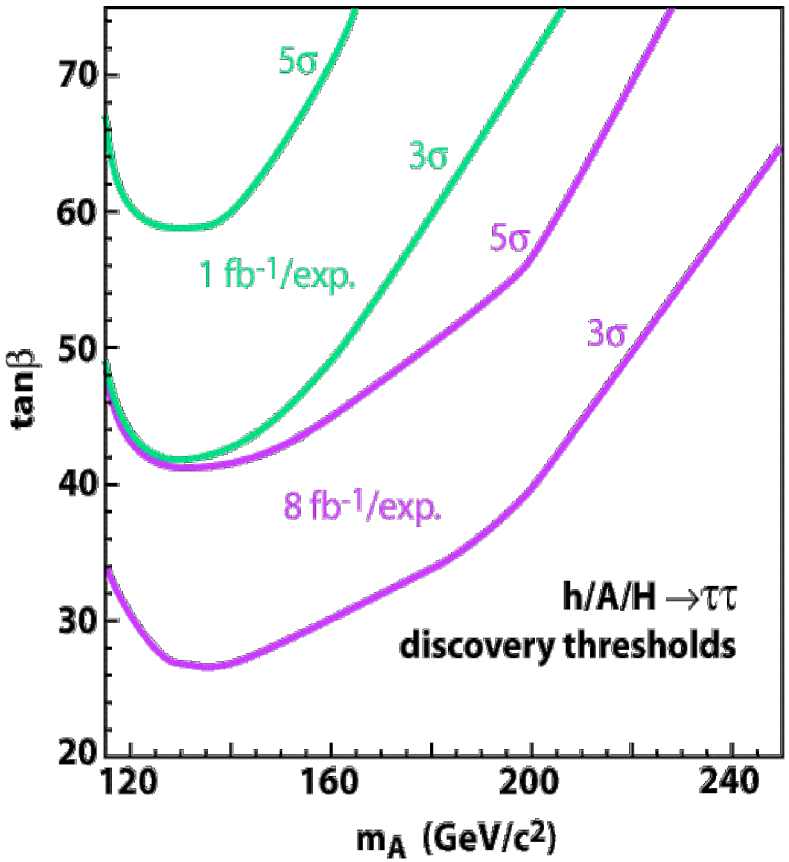
MSSM Higgs Search: Future





- Sensitivity for D0 and CDF data combined
- probe values down to tanβ=20 for $m_A \approx 140$ GeV/c2
- tanβ=40≈m_{top}/m_b reached for m_A<240 GeV/c^2

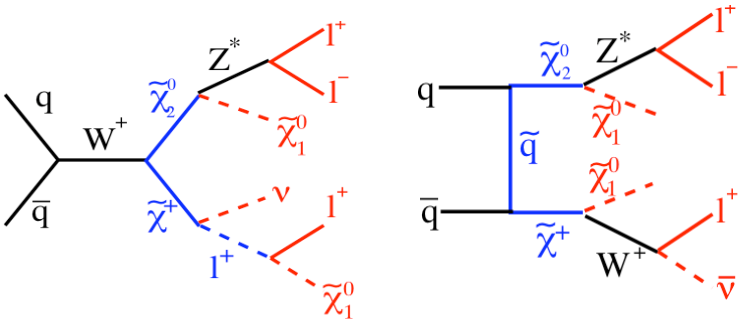
MSSM Higgs: Evidence/Discovery?

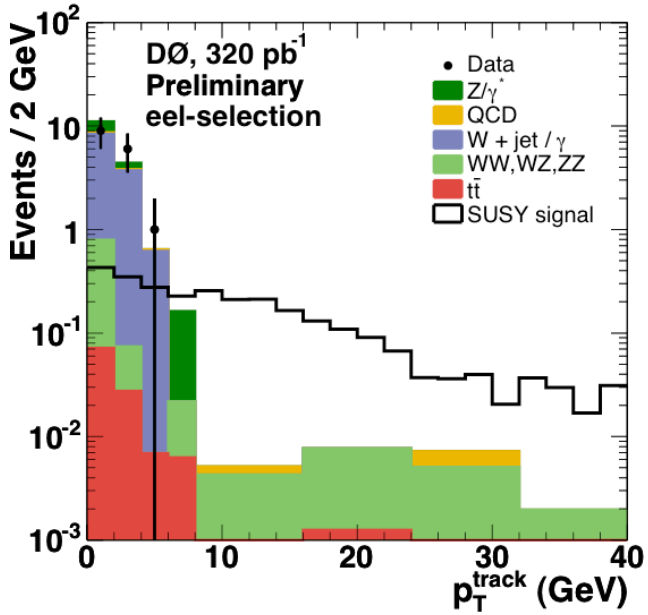


Discovery possible for tanβ>40!

SUSY Trileptons

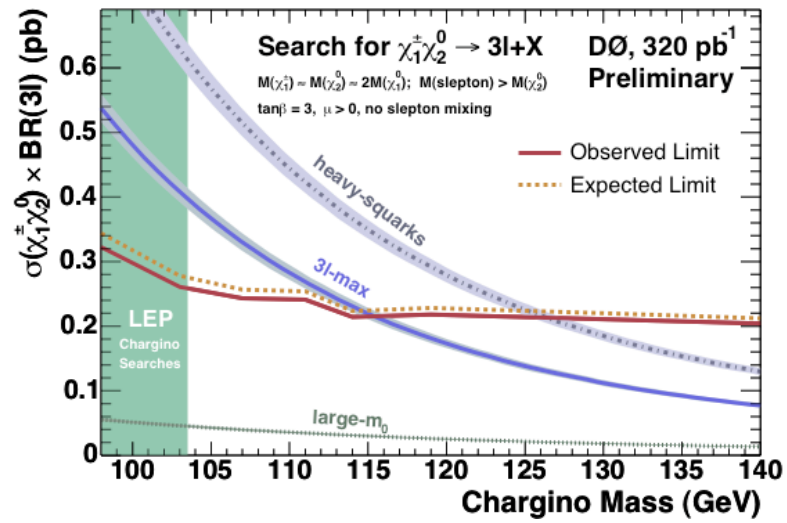
- mSUGRA:
  - SUSY broken at GUT scale
  - Neutralino χ^0_1 LSP
- Trilepton Signature
  - Chargino-neutralino production
  - Low SM backgrounds
- Current DØ analysis:
  - 2 l (l=e,μ,τ) + isolated track or $\mu^\pm\mu^\pm$
  - $\not{E}_t$ +topological cuts
  - Analysis most sensitive at low tanβ
  - BG expectation: 2.9±0.8 events
  - Observed: 3 events

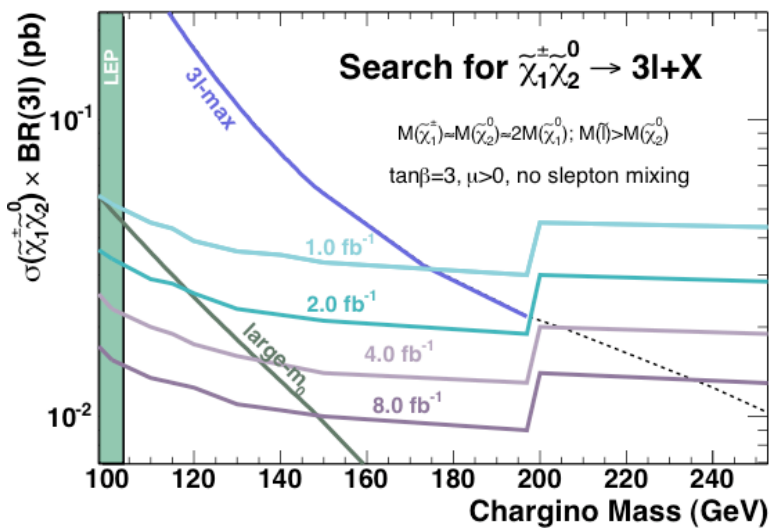




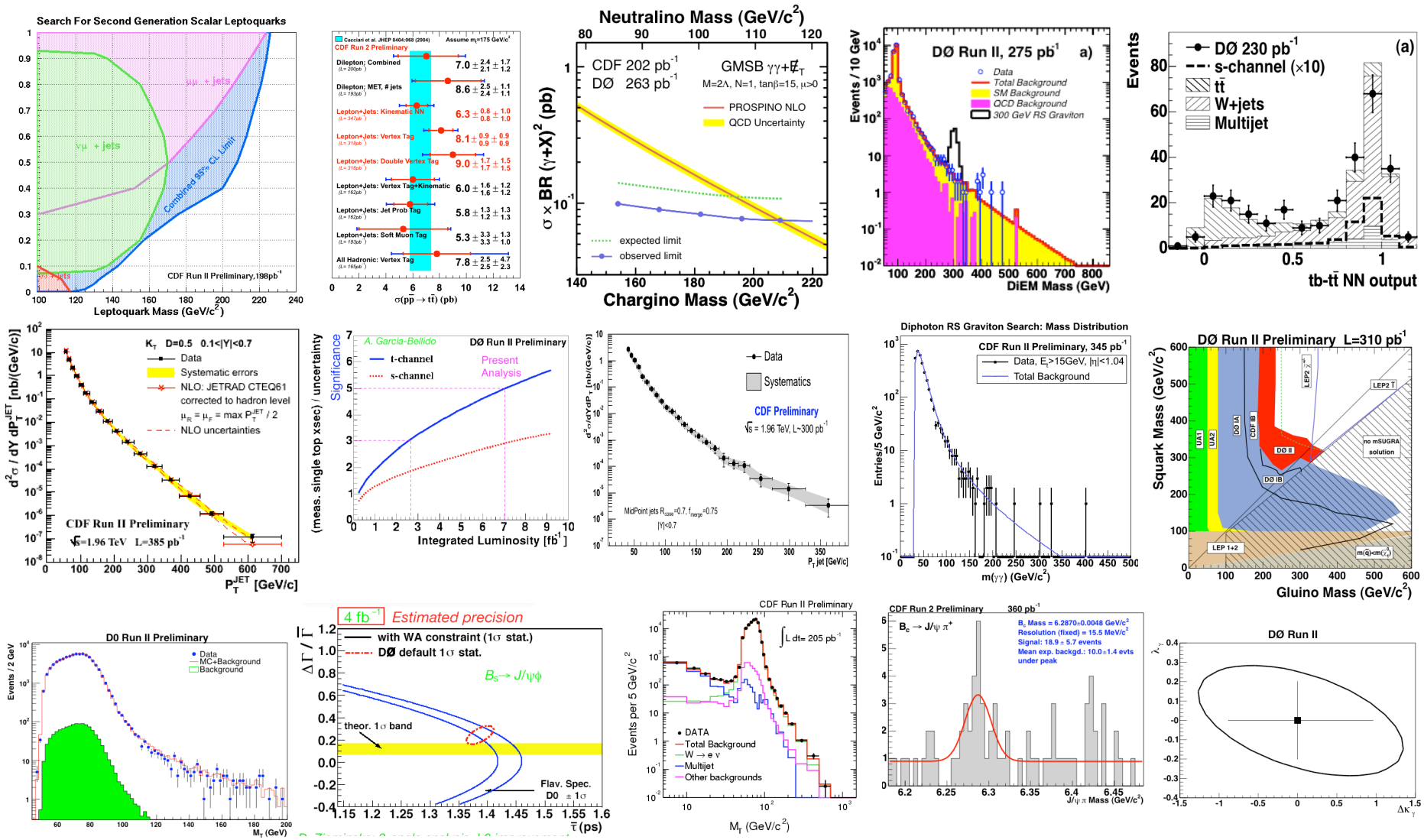
Trileptons: Present and Future

- Current result: σxBR<0.2-0.3 pb
  - 3l-max scenario:
    - Sleptons light
    - Optimistic mSUGRA
  - Large m_0 scenario:
    - Sleptons heavy
    - Pessimistic mSUGRA
  - Current data probe optimistic scenario
- Future:
  - Cross section limit 0.05-0.01 pb
  - Probe chargino masses up to 150-240 GeV/c^2
    - LSP masses: 75-120 GeV/c^2





And so much more!!!!



Even more…but did not fit on slide

Conclusions

- Tevatron experiments **attack the Standard Model** from **many sides**:
  - Flavour sector
  - Strong interaction
  - Electroweak and Higgs sector
  - New physics
- New Projections from D0 and CDF are based on **full Run II analyses**:
  - More **reliable** than pre-Run II projections
  - **Competition** between CDF and D0 helps
  - We are getting **smarter** with time!
- Pursuing **many analyses** since we don't know what is there to be **discovered!**

Standard Model after Tevatron Attack?

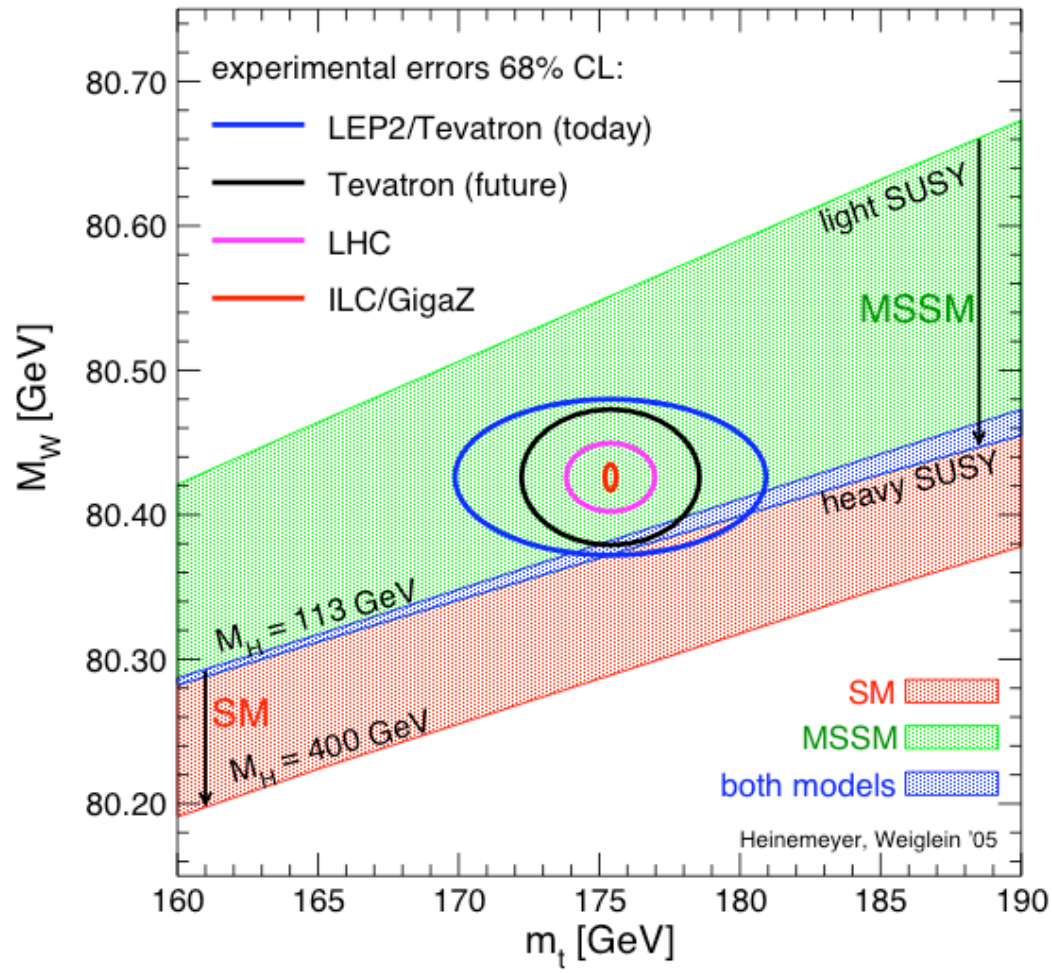
Summary I

	$\int Ldt = 2\ fb^{-1}$	$\int Ldt = 8\ fb^{-1}$
B_s mixing: 95% C.L. excl.	$\Delta m_s > 27\ ps^{-1}$	$\Delta m_s > 35\ ps^{-1}$
B_s mixing: 5σ obs.	$\Delta m_s < 15\ ps^{-1}$	$\Delta m_s < 23\ ps^{-1}$
$B_s \rightarrow \mu\mu$: 95% C.L. excl. / expt.	BR < 6×10^{-8}	BR<2×10^{-8}
W mass uncertaintity / expt.	25-35 MeV	20-30 MeV
Top mass uncertainty / expt.	1.7-2.2 GeV	1.2-1.8 GeV
m_H: 95% C.L. excl.	>120 GeV/c^2	>135 GeV/c^2
m_H: 3σ obs.	-	<125 GeV/c^2
MSSM A: $\mu<0$: 95% C.L. excl.	$\tan\beta<40$	$\tan\beta<30$
MSSM A: $\mu>0$: 95% C.L. excl.	$\tan\beta<25$	$\tan\beta<20$
MSSM A: $\mu>0$: 5σ obs.	$\tan\beta<60$	$\tan\beta<40$
Trileptons: $m(\chi^{\pm})$ excl. @95% C.L.	120-210 GeV/c^2	150-250 GeV/c^2

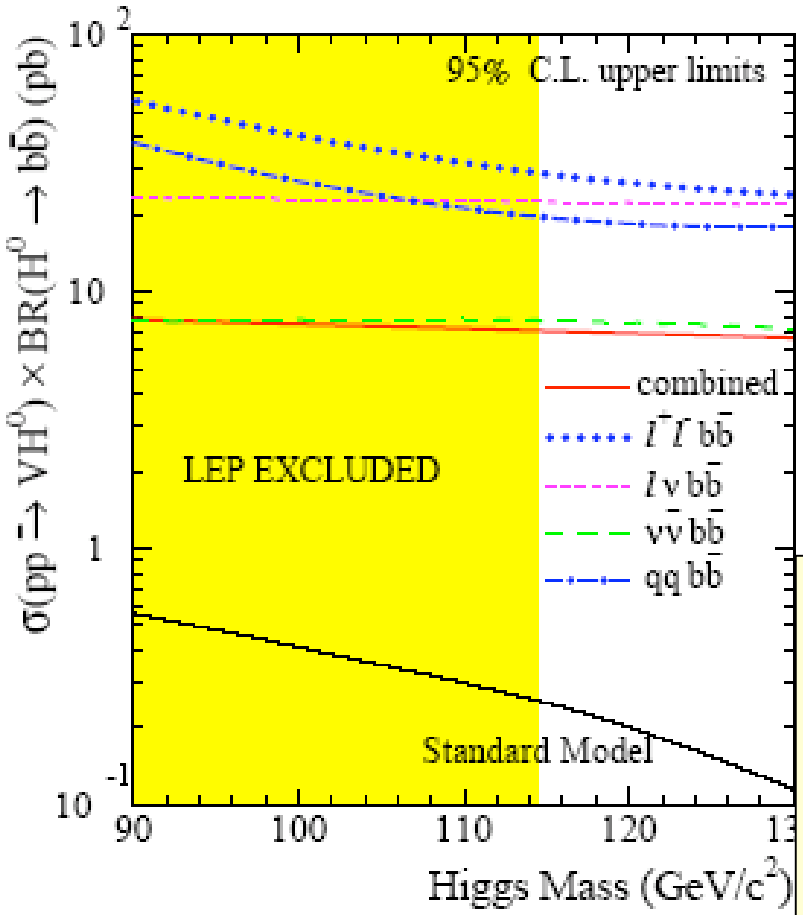
Implications for Higgs and SUSY

New top mass (D0+CDF): 174.3 ± 3.4 GeV

- **Present:**
  - Δm_{top} = 3.4 GeV
  - Δm_W = 34 MeV
- **Definitely:**
  - Δm_{top} = 2 GeV
  - Δm_W = 30 MeV
- **LHC:**
  - Δm_{top} = 1 GeV
  - Δm_W = 20 MeV
- **ILC:**
  - Δm_{top} = 0.1 GeV
  - Δm_W = 10 MeV



Run I Combination / Sensitivities



Channel	Measured (expected) upper limits (pb) $M_H = 90$	$M_H = 110$	$M_H = 130$
$\ell^+\ell^- b\bar{b}$	55.6 (36)	31.8 (24)	23.8 (25)
$\nu\bar{\nu}\, b\bar{b}$ (ST)	20.8 (30)	20.8 (21)	18.4 (17)
$\nu\bar{\nu}\, b\bar{b}$ (DT)	10.4 (17)	9.2 (14)	8.0 (12)
$\nu\bar{\nu}\, b\bar{b}$ (ST+DT)	7.6 (13)	7.8 (11)	7.4 (8.8)
$\ell\nu\, b\bar{b}$ (ST)	30.0 (18)	29.4 (15)	27.6 (12)
$\ell\nu\, b\bar{b}$ (DT)	31.0 (24)	26.6 (19)	24.2 (18)
$\ell\nu\, b\bar{b}$ (ST+DT)	23.2 (13)	22.6 (11)	21.6 (9.0)
$q\bar{q}'\, b\bar{b}$	38.2 (77)	21.2 (43)	17.8 (29)
All combined	7.8 (7.1)	7.2 (5.7)	6.6 (4.7)

Expected "sensitivity" similar for WH and ZH channels (@ m_H=110 GeV ➔limit of 11 pb for 106 pb^{-1} e+mu, SingleTag+DoubleTag)

Combination of all channels allows to go from 19 pb in a single channel (WH-DT) down to 6 pb

Run II vs Run I:expected limit 12 pb@ D0-RunII for WH-DT instead of 19 pb @CDF-Run I, with equivalent lumi (174 pb^{-1} e-chan. vs. 106 pb^{-1} e+mu-chan.)
- For WH-ST, expected limit 8 pb @ CDF-Run II vs. 15 pb @ CDF-Run I ➔ PROGRESS

PRL - hep-ex/0503039

from G. Bernardi

SM Higgs: Detailed Comparison

$WH \rightarrow e\nu bb$: $L=380\ pb^{-1}$			
	D0 Run 2	HSWG	ratio
S	0.12	0.33	0.36
B	2.37	5.76	0.41
$S/\sqrt{B}$	0.077	0.13	0.56

$\nu\nu bb$ (ZH): $L=280\ pb^{-1}$			
	D0 Run 2	HSWG	ratio
S	0.082	1.0	0.08
B	2.19	24	0.09
$S/\sqrt{B}$	0.055	0.20	0.275

$WW \rightarrow l\nu l\nu$: $L=300\ pb^{-1}$			
	D0 Run 2	HSWG	ratio
S	0.55	0.5	1.1
B	17.7	4.4	4.0
$S/\sqrt{B}$	0.12	0.23	0.5

Low mass Higgs

- Need to increase signal and background

High mass Higgs

- Need to reduce background

Assumptions for MSSM Higgs

$bA+X \rightarrow bbb+X$

- Systematic error reduced from 21% to 10%
- B-tagging efficiency increased from 30% to 40%

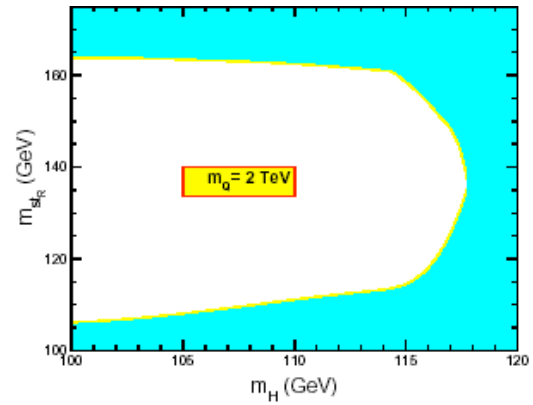
$A+X \rightarrow \tau\tau+X$

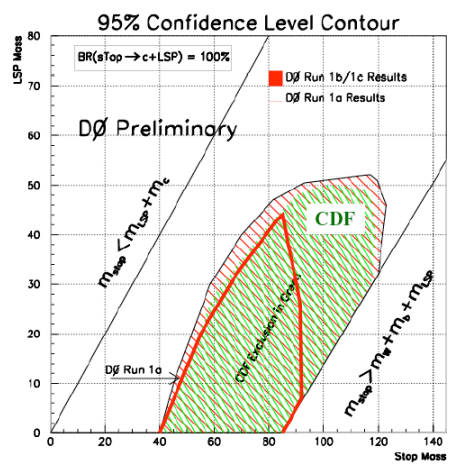
- 30% sensitivity improvement due to
  - addition of more channels
  - Improved mass reconstruction
- Tau momentum scale error reduced
- Gluon parton density function:
  - Improved knowledge when 4 fb^{-1} are collected

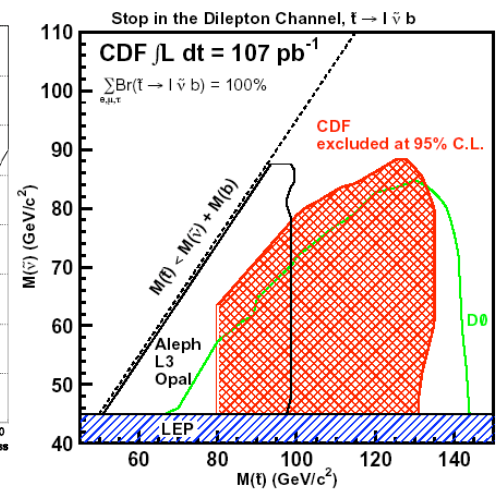
Light Stop Quark

- Baryogenesis prefers stop quark and Higgs boson to be light
  - m(H)<117 GeV/c2
  - m($\tilde{t}$)<165 GeV/c2
- Good discovery reach at the Tevatron:
  - $\tilde{t} \rightarrow \tilde{\chi}^0 c$
  - $\tilde{t} \rightarrow l\tilde{\nu}b$
  - $\tilde{t} \rightarrow \tilde{\chi}^{\pm} b \rightarrow l\nu b$
- Depends on masses of $\tilde{\chi}^0$, $\tilde{\chi}^{\pm}$, $\tilde{t}$ and $\tilde{\nu}$

[Carena, Quiros, Wagner, 1998]

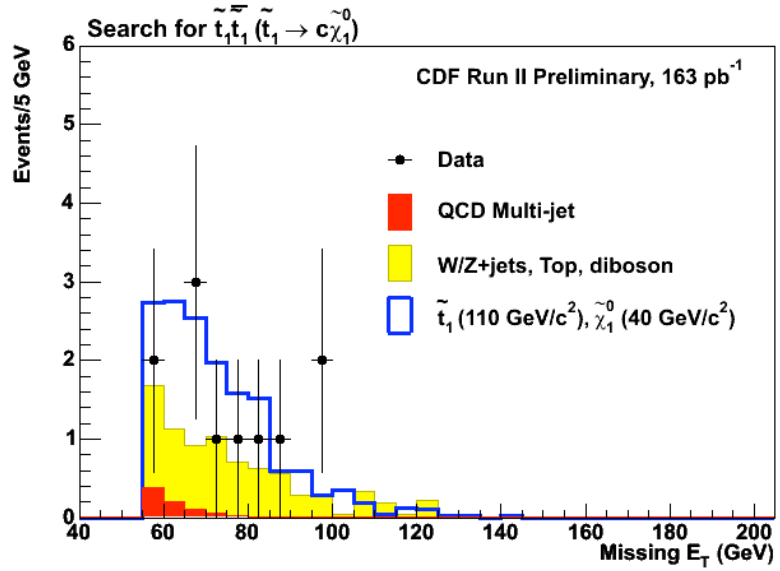


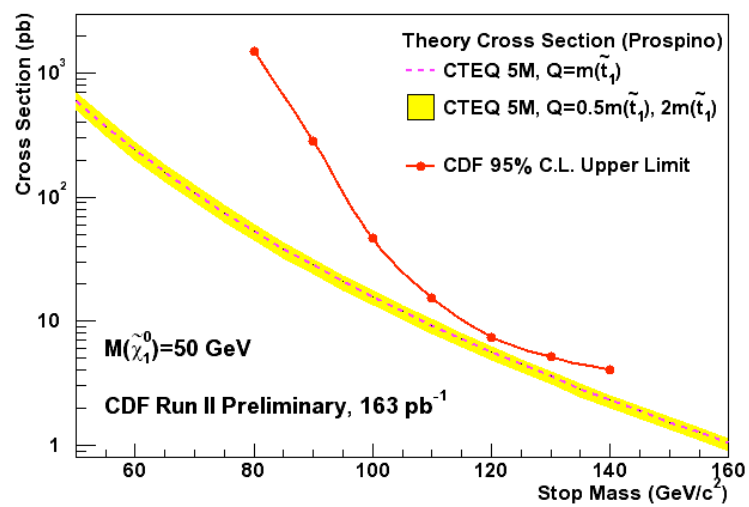




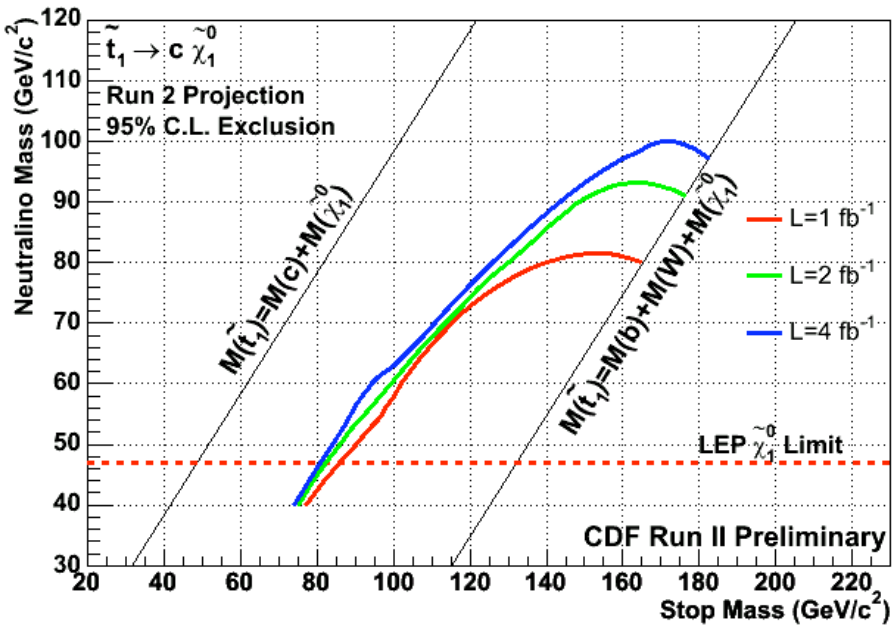
Light stop: Results

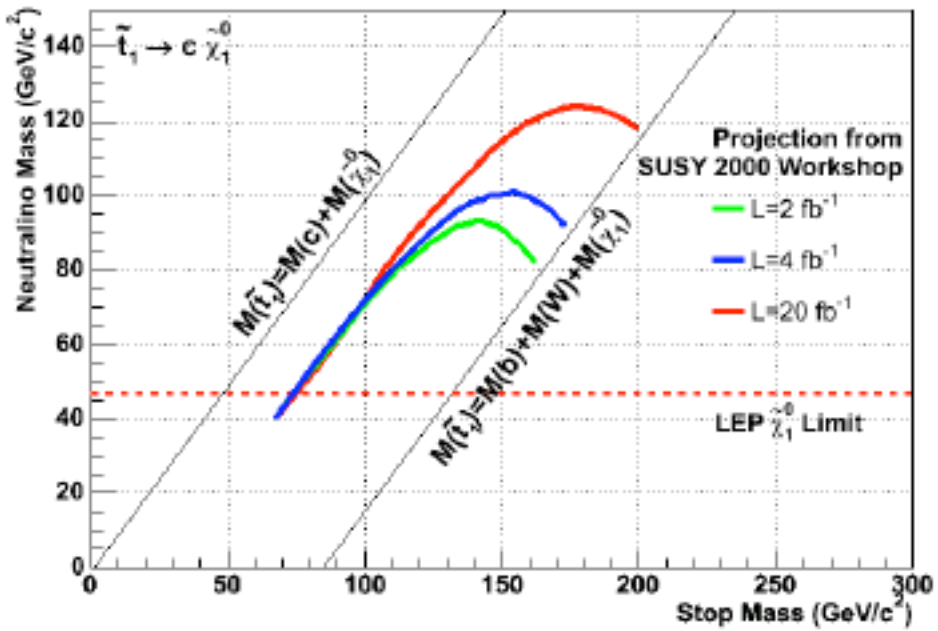
- Current analysis:
  - E_T>55 GeV
  - charm tagging (jet probability)
  - Background: 8.3+2.3-1.7
  - Observed: 11
- Assumptions:
  - BG scales with lumi
  - Reduce syst. unc. by about a factor of 2:
    - Charm tagging
    - jet energy scale
    - background
    - ISR/FSR
  - No reoptimisation





Light stop: Projections





- E.g. at $m(\chi^0_1)$=80 GeV/c2:
  - New projection: m(t)=130-165 GeV/c2 excluded
  - SUSY2000 Workshop: m(t)=110-165 GeV/c2 excluded
- Stop mass a little worse than SUSY 2000 workshop projection:
  - Further improvements when lowering E_T cut
  - Reoptimise selection cuts at high lumi