Physics at the Tevatron

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Physics at RUN 2 of the Tevatron :

- Introduction: What do we know today?

– Precision data from LEP, SLC, Tevatron
$\Longrightarrow$ Standard Model (SM) provides an excellent fit to all observables
– There is one missing ingredient in the SM

The Higgs boson

$\Longrightarrow$ responsable for giving mass to all other particles
The mass of the SM Higgs is an unknown parameter

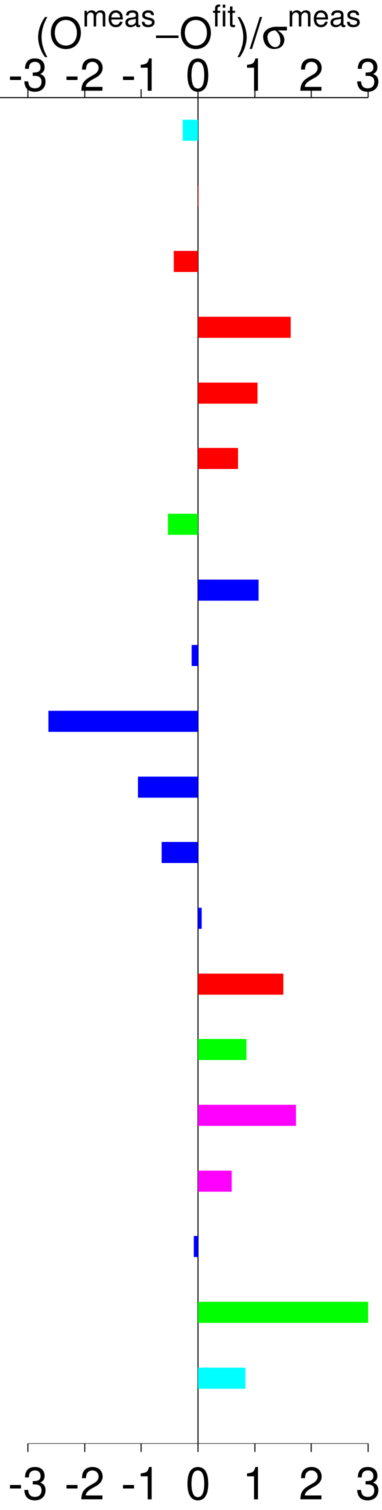
- How these issues may be connected?

– Precision data: M_t, M_W, $\sin^2\theta_W \rightarrow m_H$ (indirect)
– Direct m_H searches (LEP)

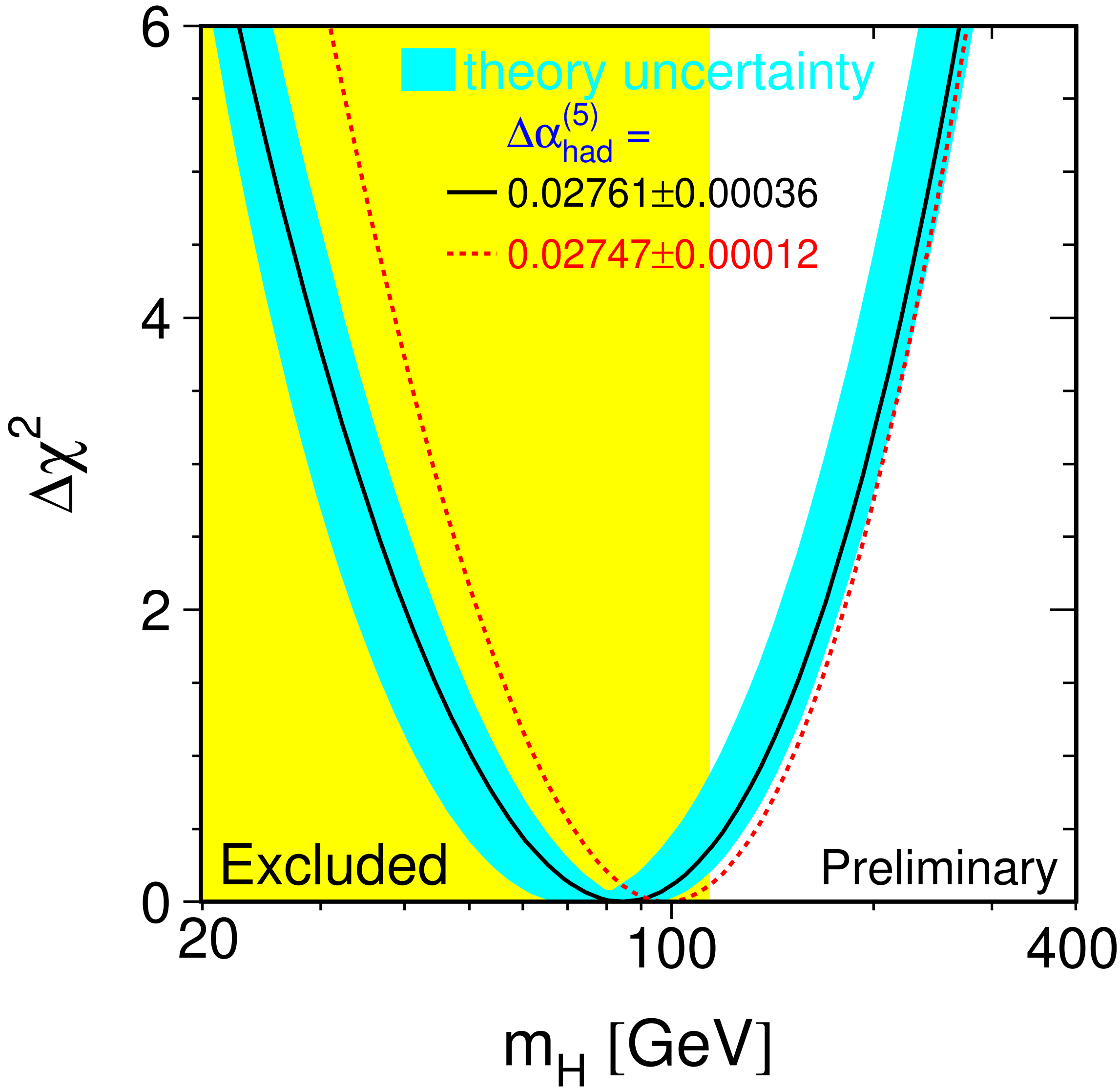
Standard Model Vs New Physics (NP)

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84



Limits on the Standard Model Higgs Boson Mass from Precision EW Data



$m_H = 85^{+54}_{-34}$ GeV LEPEWWG '02

$m_H < 196$ GeV at 95 % C.L.

Standard Model strongly prefers a light Higgs

What can we learn from RUN 2?

- Precision measurements:

  Top Physics (explore hints for NP)

  W Mass

$\rightarrow M_t$–M_W–M_H Correlation

  $A_{\mathrm{FB}} \leftrightarrow \sin^2\theta_W$

- Direct Standard Model Higgs Searches

Explore masses beyond LEP bound and probe the tantalizing hint from LEP?

- New Physics Searches

Explore some channels with excess over SM predictions at RUN 1 and search for:

  Supersymmetry

  New Exotic Quarks

  Strong Dynamics

- Explore new ideas : Extra Dimensions

- B Physics

Top Quark Physics

Upgraded Tevatron $\Longrightarrow$ first possibility of precise measurements of top quark properties

- top quark mass
- top electroweak and strong interactions
- test SM production mechanisms and decays or find hints for new physics

– $\sqrt{s} = 2$ TeV $\rightarrow$ 37 % higher $\sigma_{t\bar{t}}$ than in Run 1 + factor 20 to 100 or more increase in total integrated Luminosity

– CDF and DØ Detectors

increased acceptance/efficiency for top quark events $\rightarrow$ *improved b-tagging plus lepton identification*

example: CDF $\sigma_{t\bar{t}}$ in $l + jets$ channel $\rightarrow$ factor 2 (3.5) improvement with 1 (2) b tagging

Top Quark Physics

Upgraded Tevatron $\Longrightarrow$ first possibility of precise measurements of top quark properties

- top quark mass: high precision in M_t important to $\Longrightarrow$ exploit precision in M_W in the context of electroweak precision measurements

- top electroweak and strong interactions
  - accurate meas. of $\sigma_{t\bar{t}}$ (5–10 %) $\Longrightarrow$ precision test of SM QCD or if $\sigma_{t\bar{t}} > \sigma_{t\bar{t}}^{SM}$ $\Longrightarrow$ non-SM prod. mechanism
  - Measurement of CKM matrix element $|V_{tb}|$ (5–13 %): best via meas. of $\Gamma(t \to bW)$ in single top production

- test SM production mechanisms and decays or find hints for new physics
  - probe ELW top couplings via W polariz. in top decays
  - search for Anomalously large rare top decays: $t \to c\gamma$, ... and Non-SM decays: $t \to H^{\pm}b$, $t \to \tilde{t}\tilde{\chi}$

- $\sqrt{s} = 2$ TeV $\to$ 37 % higher $\sigma_{t\bar{t}}$ than in Run 1 + factor 20 to 100 or more increase in total integrated Luminosity

Precision Measurements: Top Quark Mass, W Mass and $\sin^2\theta_W$

Run 1 measurements: CDF and DØ

$$M_t = 174.3 \pm 5.1 \text{ GeV}$$

$$M_W = 80.452 \pm 0.062 \text{ GeV}$$

$A_{\rm FB}$ measured at Z pole $\Longrightarrow$ meas. of $\sin^2\theta_W$.

$$u\bar{u} + d\bar{d} \to Z \to \ell^+\ell^-.$$

CDF Run 1: $\quad A_{\rm FB} = 0.070 \pm 0.015_{\rm stat} \pm 0.004_{\rm syst}$

Run 2 Expectations [per experiment]:

$\int\mathcal{L}$ [fb^{-1}]	2	10	15	30
δM_t [GeV]	≈ 3	≈ 2		≈ 1
δM_W [MeV]	30		20	15
$\delta A_{\rm FB}$ (stat.)		0.0016		0.0009
$\delta\sin^2\theta^*_W$		0.00028		0.00016

e and μ channels + 2 experiments

This will help understand the discrepancy in $\sin^2\theta_W$ from A_l(SLD) and $A^b_{\rm FB}$

Top Quark Mass

Run 1 measurements: CDF and DØ $\rightarrow$ world average

$$M_t = 174.3 \pm 5.1 \text{ GeV}$$

Run 2 estimates based on Run 1:

$$\delta M_t \simeq 3 \ (\ 2) \text{ GeV} \qquad \text{if } \int \mathcal{L} dt = 2 \ (\geq 10) \text{ fb}^{-1}$$

Using double b-tagging plus better energy calibration method at Run 2, combining the dilepton and the lepton plus jets event top samples and both experiments
$\Longrightarrow \delta M_t \simeq 1$ GeV with about 15 fb^{-1}

high precision in M_t important to

$\Longrightarrow$ exploit precision in M_W in the context of electroweak precision measurements

$\Longrightarrow$ get information on SM param.: Yukawa coupling
$\longrightarrow Y_t = M_t^{\bar{MS}}/v \simeq 1 \qquad (v = 174$ GeV, Higgs v.e.v)

$$\Downarrow$$

explore connection between Y_t and $Y_b \longrightarrow$ test Grand Unified Models

TABLES FROM MICHAEL WIN02

$t\bar{t}$ Cross Section

strong interactions best tested in top production

Run 1 meas. in agreement with theory within 1 σ:

$\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4}$ pb (CDF) $\qquad \sigma_{t\bar{t}} = 5.9 \pm 1.7$ pb (DØ)

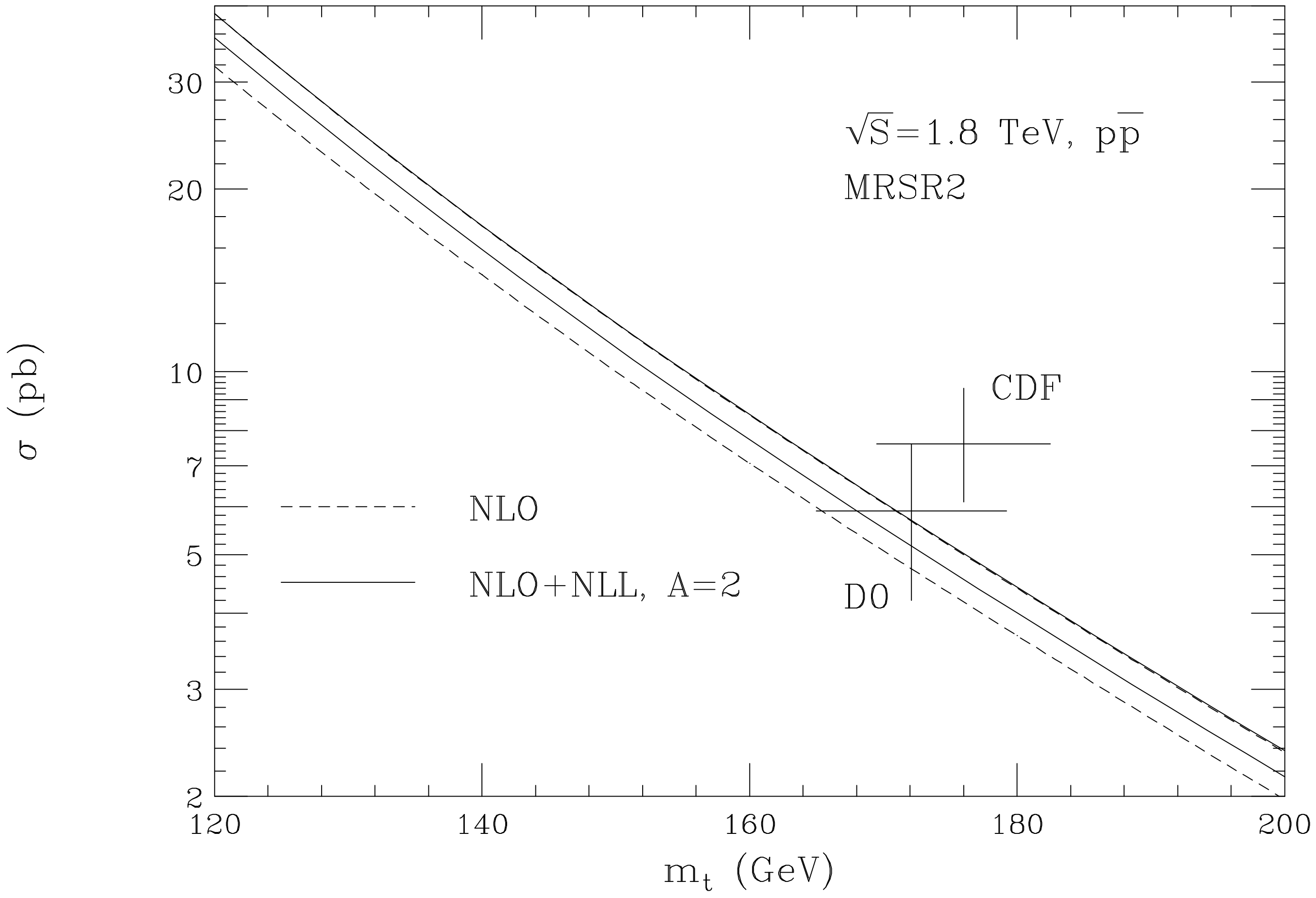
Run 2 expected uncertainty:

$\frac{\delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \simeq 9\ \%\ (5\ \%)$ $\qquad$ if $\int \mathcal{L}dt = 2\ (\geq 10)\ \text{fb}^{-1}$

accurate meas. of $\sigma_{t\bar{t}} \Longrightarrow$ precision test of SM QCD
or if $\sigma_{t\bar{t}} > \sigma^{SM}_{t\bar{t}} \Longrightarrow$ non-SM prod. mechanism

Search for $t\bar{t}$ resonances in the invariant mass ($M_{t\bar{t}}$) spectrum:
extensions of the SM $\rightarrow$ resonant topcolor Z', multiscale technicolor...

$t\bar{t}$ Cross Section at $\sqrt{s}$= 1.8 TeV



Cross section for $t\bar{t}$ production at the Tevatron *vs.* the top quark mass. Dashed band is from NLO in the strong interaction. Upper lines $\mu = m_t/2$, lower lines $\mu = 2m_t$. Solid band includes soft-gluon resummation at NLL. From Bonciani, Catani, Mangano and Nason '98.

Top Weak Interactions

– Measurement of CKM matrix element V_{tb}

$\Longrightarrow$ strength of top-bottom transition

- careful counting of W + 2,1,0 b-tags allows meas.

$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

with 3, 1, 0.5 % accuracy if $\int \mathcal{L}dt \simeq$ 2, 10, 30 fb^{-1}

However, unless one uses 3 generation unitarity bound, high accuracy in $\frac{BR(t\to Wb)}{BR(t\to Wq)}$ does not translate into high accuracy for V_{tb}

- Single Top Production: $qq' \to \bar{b}t$ and $qb \to qt$

$\Longrightarrow$ production rate is a measure of $\Gamma(t \to bW)$ and hence of V_{tb}

$V_{tb}^{SM} \simeq 1$, at the Tevatron, assuming no anomalous coupl. precision in $|V_{tb}|$ of 13, 6, 5% if $\int \mathcal{L}dt \simeq$ 2, 10, 30 fb^{-1}

– W Polarization in Top Decays

Top decays before hadronization $\Longrightarrow$ decay products carry helicity information from fundamental couplings

SM: top decays to left-h. or longitudinal W bosons

$$\frac{W_{long}}{W_{left}} = \frac{1}{2}\frac{M_t^2}{M_W^2} \Longrightarrow BR(t \to bW_{long}) \simeq 70\%$$

at Run 2: determine W$_{long}$ fraction with 5 to 2 % accuracy via charged lepton angular distribution

$\Longrightarrow$ Probe Electroweak Top Couplings

Other Hints for Physics Beyond the SM

– Anomalously large rare top decays

SM: branching fraction of FCNC top decays $\simeq 10^{-10}$

$\Longrightarrow$ observation of $t \to c\gamma, cZ, (Ws), Hc \Longrightarrow$ new physics: some possibilities at Run 2

– Non-SM decays: $t \to H^{\pm}b$, $t \to \tilde{t}\tilde{\chi}$

measurement of $\sigma_{ll}/\sigma_{l+jets} \neq 1 \Longrightarrow$ non W decays

$\delta\left(\frac{\sigma_{ll}}{\sigma_{l+jets}}\right) \to$ 10 to 4.5 % at Run 2

W Mass Measurement

one of the primary goals of the upgraded Tevatron

$\Longrightarrow$ Hadron collider combined :

$$M_W = 80.452 \pm 0.062\text{GeV}$$

important component of world average

extracted from fit to W transverse mass distribution which peaks sharply at M_W vicinity

RUN 2 Expectations for M_W:

Run 2a $\longrightarrow \pm$ 30 MeV per experiment
(2 fb^{-1})

Run 2b $\longrightarrow \pm$ 20 – 15 MeV per experiment
(15 – 30 fb^{-1})

Tevatron: best future measurement till a LC

(Unless heroic effort at LHC)

Run 2b+ will employ a variety of methods:
M_T, p_T^ℓ, and the 'ratio method'

- For M_T & p_T^ℓ, fit MC templates to the data.
- In the ratio method, real Z data is rescaled (and re-smeared) to fit the W data. Developed by DØ, most experimental and some theoretical uncertainties reduced, at the cost of statistical sensitivity.
- In all cases the statistical error falls far below the systematic error.
- The main systematics in the M_T, p_T^ℓ and the ratio methods differ, so they can be used to check for consistency at the level of 10 MeV or so.

uncertainty	0.82	2	15	30 fb^{-1}
statistical	**96**	**19**	**7**	**5**
prod'n & decay model	**30**	**14**	**13**	**13**
p_T^W (1)	10	5	5	5
PDF's (1)	22	5	5	5
radiative decays (1)	15	10	10	10
W width	10	6	5	5
detector model	**57**	**13**	**8**	**8**
cal. linearity	20	7	3	2
cal. uniformity	10	2	1	1
energy resolution	25	5	2	2
recoil resolution	24	4	2	1
recoil response	20	4	1	1
backgrounds	**11**	**2**	**1**	**1**
hadrons	10	2	1	1
$Z \to e^+e^-$	5	1	0	0
total systematic	**66**	**19**	**16**	**15**
total	**116**	**27**	**17**	**16**

Transverse Mass: Extrapol. DØ Run 1 $W \to e\nu$

(1) estimated by FNAL QCD/WZ study group

Ratio Method

An (optimistic) extrapolation from DØ results.

uncertainty	0.82	2	15	30 fb^{-1}
statistical	**211**	**44**	**16**	**11**
total systematic	**50**	**10**	**4**	**3**
total	**217**	**44**	**16**	**12**

Note the statistical error is larger & the systematic error is smaller than the M_T error. This competes with the M_T method only at the highest luminosities.

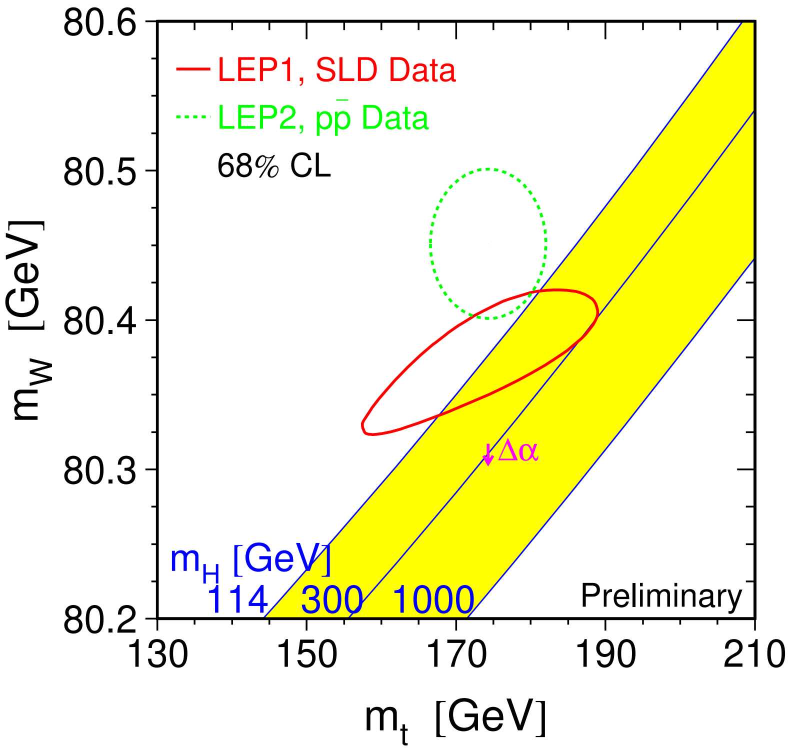
One method, one channel, one experiment → 15 MeV. Systematics differ partially between methods, and between channels.

Projection: 15 MeV, perhaps 10 MeV.

M_t–M_W–M_H Correlation

- Direct M_t and M_W meas. from LEP and Tevatron
- Indirect M_t and M_W determination from SM fit to precision data (LEP, SLD, νN)
- SM relationship for M_t–M_W–M_H

$\Longrightarrow$ crucial information on M_H



Light SM Higgs Boson $\longrightarrow$ strongly favoured by data

$\delta M_t \sim 3\ (2)$ GeV $\Longleftrightarrow$ $\delta M_W \sim 20\ (12)$ MeV

Maximal use of the obtained δM_t, δM_W accuracy

$\sin^2\theta_W$ from $A_{\rm FB}$

Same as the forward-backward asymmetry measured at LEP, in principle

$$u\bar{u} + d\bar{d} \to Z \to \ell^+\ell^-.$$

$A_{\rm FB}$ measured at Z pole $\Longrightarrow$ meas. of $\sin^2\theta_W$.

CDF Run 1: $\quad A_{\rm FB} = 0.070 \pm 0.015_{\rm stat} \pm 0.004_{\rm syst}$

Taking the statistical error to scale as $1/\sqrt{\mathcal{L}}$,

$\delta A_{\rm FB stat} = 0.0016$ for 10 fb^{-1}, $\qquad$ 0.0009 for 30 fb^{-1}

Systematic and theoretical uncertainties are expected to be much smaller than the statistical error.

The e and μ channels have essentially the same sensitivity. Combining 2 channels from 2 experiments,

- $\delta\sin^2\theta_W \approx 0.00028$ for 10 fb^{-1}
  0.00016 for 30 fb^{-1}.

(The current *world average* is $\delta\sin^2\theta_W = 0.00017$.)

This will help understand the discrepancy in $\sin^2\theta_W$ from A_l(SLD) and $A^b_{\rm FB}$

At Present: $A^b_{\mathrm{FB}} = 0.0994 \pm 0.0017$ and

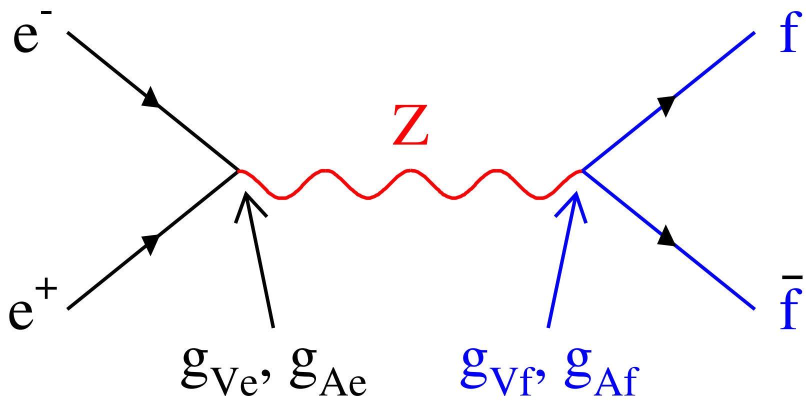
$A^b_{\mathrm{FB}}(SM) = 0.1039$ almost 3 σ away.

On the other hand $A_b(SLD)$, agrees within 1 σ

What are these Asymmetries?

SM: $\sin^2\theta_W$ is defined by vector and axial couplings

$$\sin^2\theta_W = \frac{-1}{4Q}\,(1 - \frac{g_V}{g_A}).$$



Asymmetries depend on special combination of g_V and g_A:

$$\mathcal{A}_f = \frac{2\,g_{V_f}\,g_{A_f}}{g^2_{V_f} + g^2_{A_f}}$$

For example,

$$A_{LR} = \frac{1}{\mathcal{P}_e}\,\mathcal{A}_e \qquad \text{and} \qquad A^b_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$$

$\mathcal{P}_e$ is the e^- beam polarization

A_{LR} from SLD

- polarized beams are unique to SLC
- switch $\mathcal{P}(e^-)$ between -0.75 and +0.75 while $\mathcal{P}(e^+) = 0$
- count events in an inclusive manner – simple!
- The great challenge was obtaining high polarization, and in knowing its actual value. ($\delta\mathcal{P}_e = 0.6\%$)
- clean, simple, powerful... *the world's best single measurement*

$$\boxed{\sin^2\theta_W = 0.23098 \pm 0.00026}$$

- beautiful for its clarity and robustness

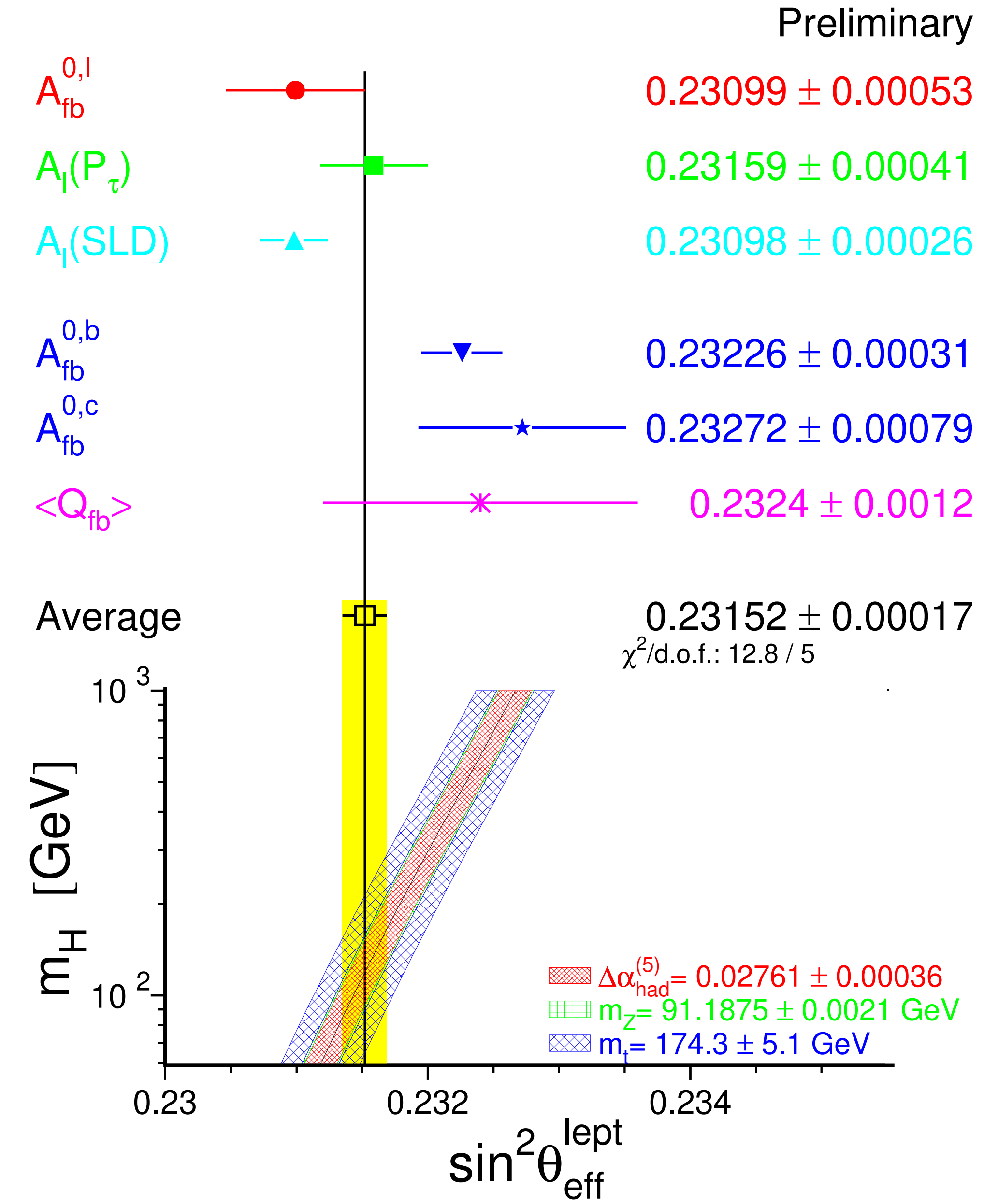
$A_{FB}^{0,b}$ from LEP

- $\mathcal{A}_e$ extracted from $A_{FB}^{0,b}$
- beams are unpolarized – all the business is in the final state
- tag b-flavor in a variety of ways: high-p_T leptons, kaon tagging, vertex charge, jet charge, etc.
- required very careful tuning and control of b-physics in Monte Carlo.
- hard, yet…
  the world's second best measurement
  $$\boxed{\sin^2\theta_W = 0.23226 \pm 0.00031}$$
- an impressive *tour de force*

Compilation of $\sin^2\theta_W$ measurements

Compare the two most precise values:

they disagree at the 3σ level!



The χ^2/d.o.f is mediocre. There is a problem here!

Possible Solutions:

$\boxed{\text{Standard Model Vs New Physics}}$

- Standard Model $\Longrightarrow$ Prefers a light Higgs.

  Discrepancy in $A^b_{\rm FB}$ due to:

• Systematic errors • Statistical fluctuations

Within the SM, value of $A^b_{\rm FB}$ determines $\sin^2\theta_W$

What happens if we ignore the result of the hadronic asymmetries?

$$\boxed{\sin^2\theta_W|_{had.} = 0.2322 \pm 0.0003}$$

and consider only the leptonic ones (A_l(SLD) and $A_l(A^l_{\rm FB})$) ?

$$\boxed{\sin^2\theta_W|_{lept.} = 0.2310 \pm 0.0006}$$

The EW-fit value of m_H (already below its direct lower bound) will be pushed to lower values

($m_H \leq 50$ GeV) A lose-lose situation for the SM ?

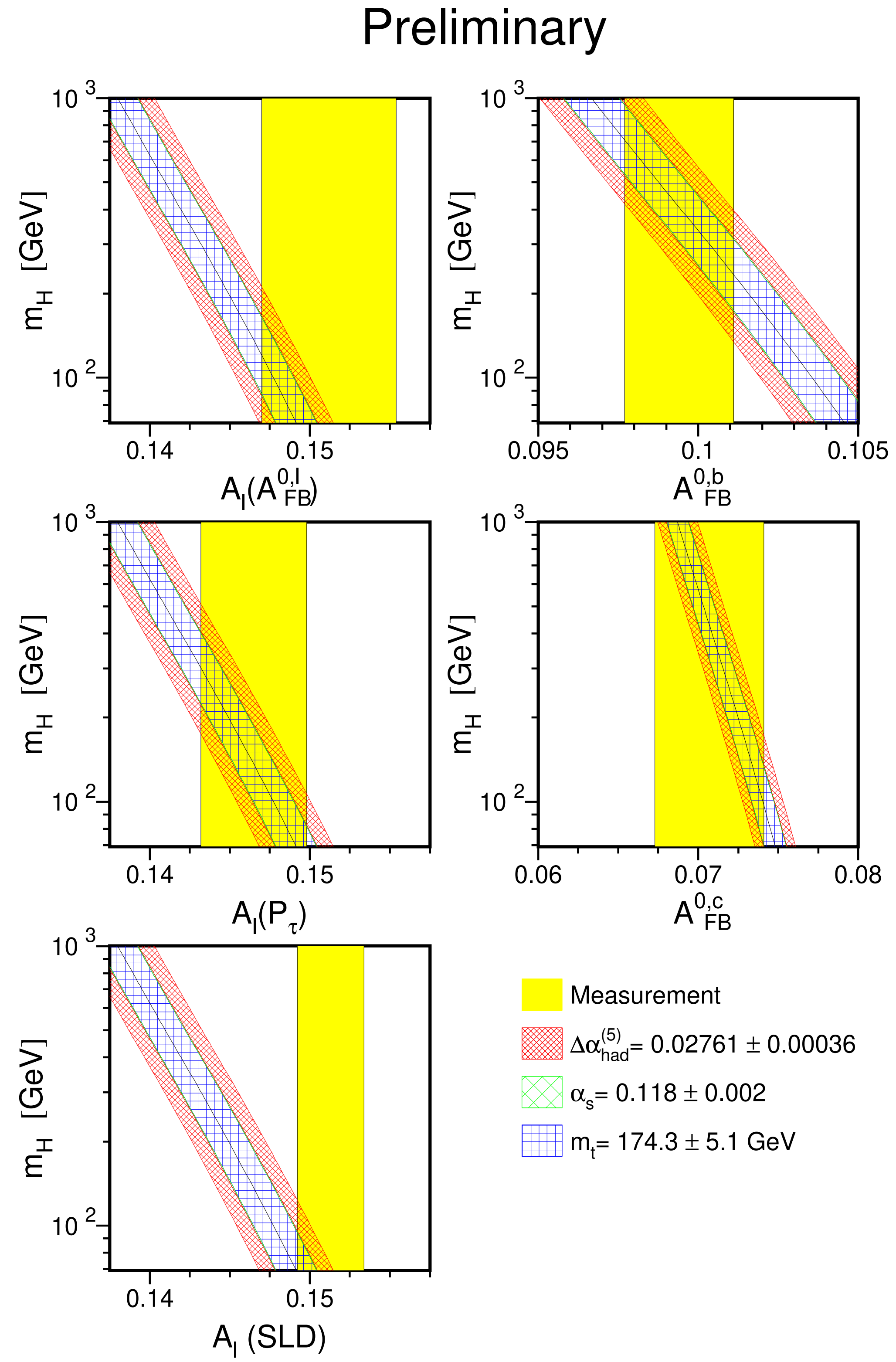
Chanowitz'01

The fit to the b-couplings determines:

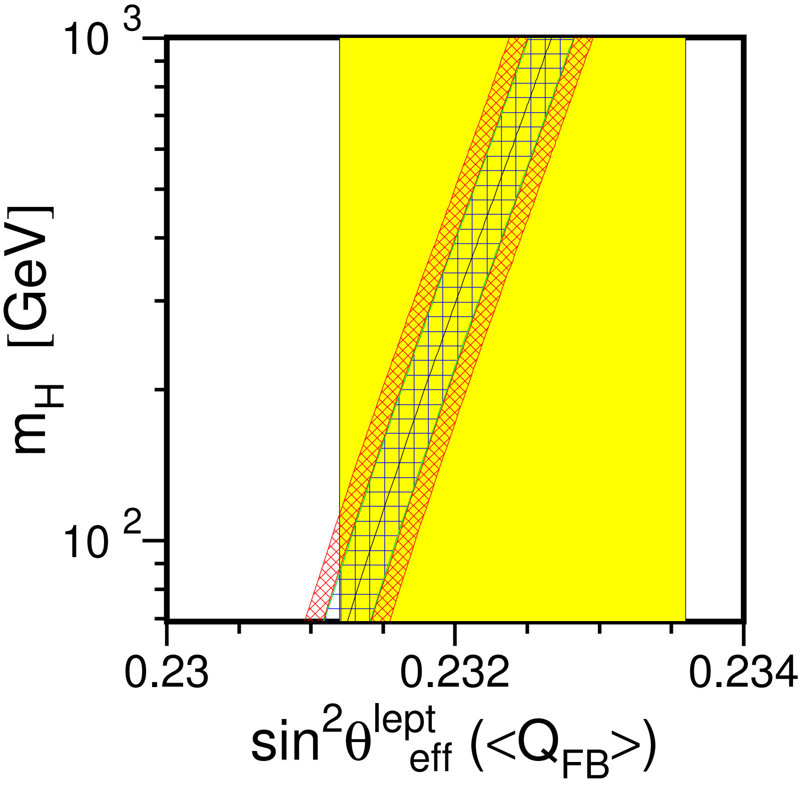
$(\bar{g}^b_L, \bar{g}^b_R) \approx (+0.992\, g^b_L(SM), \pm 1.26\, g^b_R(SM))$

With $g_{V(A)} = g_L + (-) g_R$

Comparison of $(A_{\rm FB}^{b})^{\rm theo}$, $(A_{\rm FB}^{l})^{\rm theo}$ and $A_l(SLD)^{\rm theo}$ to their measured values to infer m_H.



Comparison of $\sin^2\theta_W^{\rm theo}$ to $\sin^2\theta_W^{\rm meas}$ to infer m_H, if only hadronic asymmetries considered.



Blue band shows $\delta M_t = 5.1$ GeV, and red band shows $\Delta\alpha^{(5)}_{\rm had} = 0.00036$.
(they are added linearly)

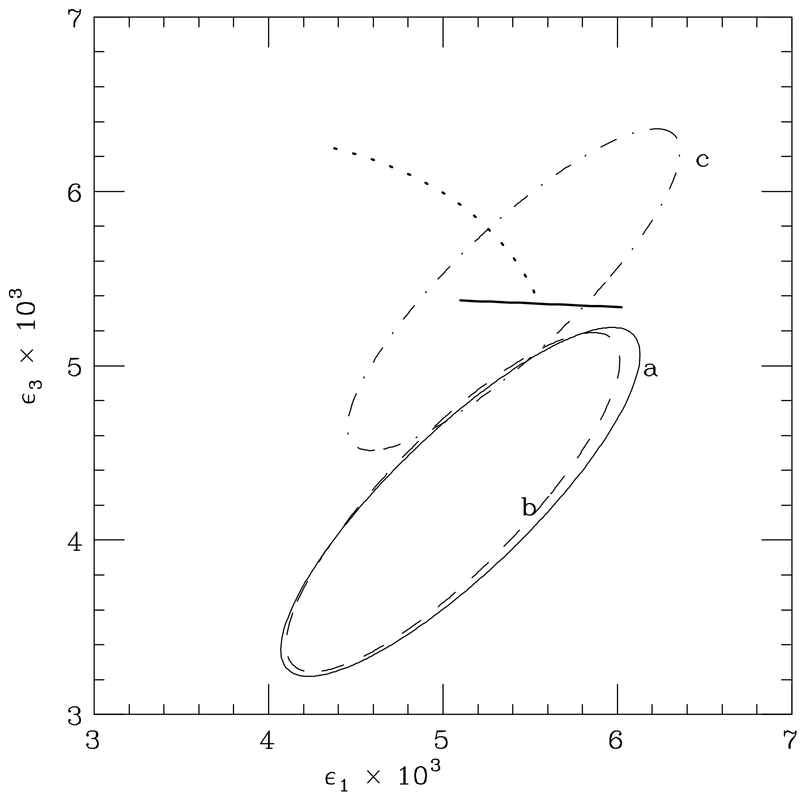
LEPEWWG `hep-ex/0112021`

New Physics Solutions to the A^b_{FB} Problem:

- Ignore the hadronic asymmetries and invoke new physics to fit the data with a larger Higgs mass.

Altarelli et al. '01: Ignore the hadronic asymmetries, the quality and stability of the fit improves dramatically.

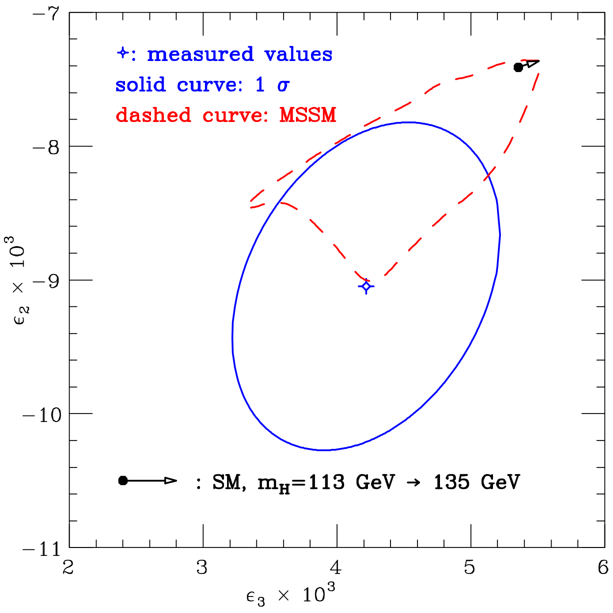
The main effect of the hadronic asymmetries is to push the fit of S (prop. to $-\epsilon_3$) to smaller values, allowing the fit with larger values of m_H.

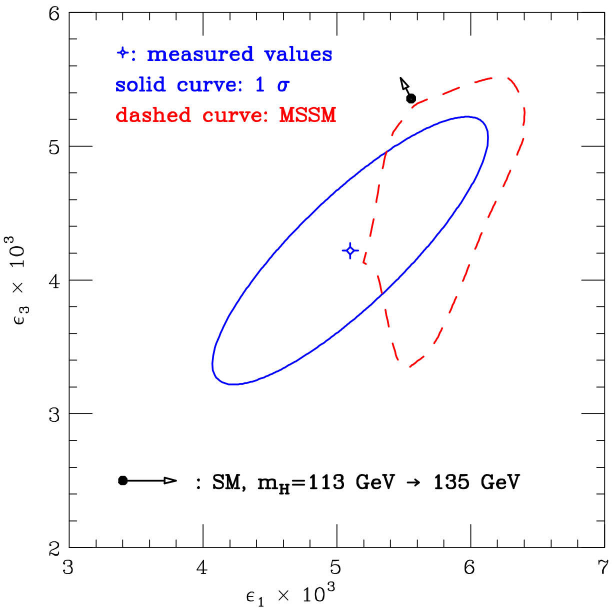


1 σ ellipses in the precision ELW param. $\epsilon_1 - \epsilon_3$ plane: a: includes all leptonic asymm.; b: same plus hadronic partial widths; c: same as b plus hadronic asymmetries. Dotted curve: SM prediction for M_t=174.3 GeV and m_H = 113-500 GeV range

SUPERSYMMETRY:
with light superpartners of the neutrino and gauge bosons

New Physics leading to positive contributions to S and negative to U (to m_W) desirable.





Solid curve as before. Dashed curve: MSSM prediction for 96 GeV $\leq m_{\tilde{e}_L} \leq$ 300 GeV and chargino masses between 105 and 300 GeV. Other SUSY particles of order 1 TeV.

Light sneutrinos (and charged sleptons)
perform the job remarkably well.
$m_{\tilde{e}_L}$ should be below approx. 150 GeV.

Improved results for light and gaugino like charginos.

Tevatron searches: Trilepton signature from $\chi^\pm \chi^0_2$ with $\chi^\pm$ decaying into leptons and χ^0_2 decaying into missing energy or lepton-slepton promising !

Exotic Quark Solution to the $A^b_{\rm FB}$ Problem

- Assume $A^b_{\rm FB}$ measurement is correct and find New Physics which modifies the b-couplings, and also the oblique ELW parameters: S, T and U.

New b-quark like state, which mix with the bottom can do the job.

Easiest possibility: Mirror quarks (to cancel anomalies) with the same quantum numbers as the left- and right-handed bottom.

The mirrors of the new left- and right down-quarks have exotic couplings and mix with the bottom quark changing its couplings to the Z

Defining the new heavy states as

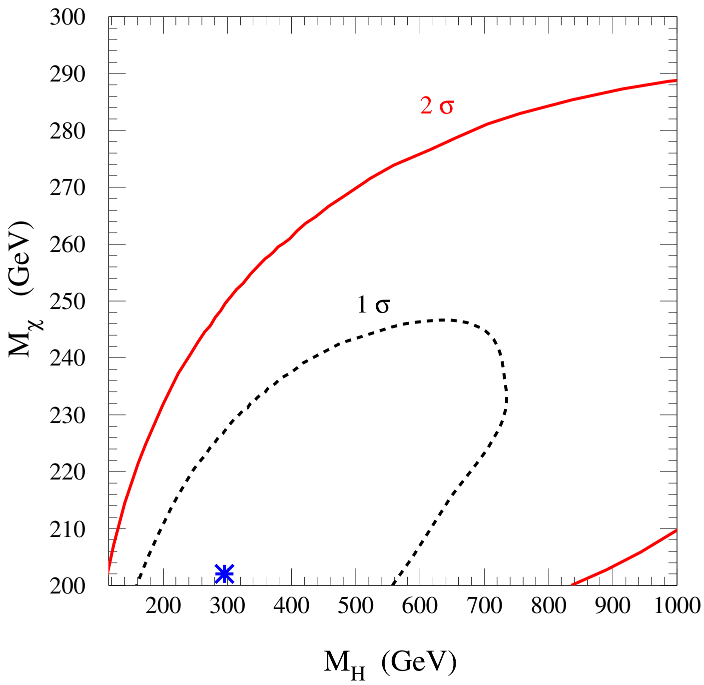
$$(\omega, \chi)_{L,R} \tag{1}$$

this possibility works for small masses
$m_\chi < 250$ GeV and $m_\omega \simeq 1.2 m_\chi$
with small mixing of χ with the top.

For a given value of the mixing between ω_R and b_R, A^b_{FB} is well fitted, while the contributions to S, T and U are such that the overall fit is improved.

MIRROR FERMIONS

Improved fit to all measured Asymmetries and all other ELW observables (pull less than 2 σ)



Tevatron searches:

For $m_{\chi,\omega} < 320$ GeV, the χ and ω samples of the Tevatron at 1 fb^{-1} will be of the same order as the top sample at Run I.

Hence, χ should be discovered in the mode $\chi \to b\, W^+$

ω should decay into $\omega \to b\ Z$ with few fb^{-1}.

Higgs boson beyond the reach of the Tevatron.

Higgs Physics

Within the Standard Model:

- LEP final results $\Longrightarrow M_H \geq 114.1$ GeV
  Hint of a Higgs at about 115 GeV ??

- Recall: estimate from electroweak data:
  $\Longrightarrow M_H \leq 196$ GeV at 95 % C.L.

$$\Downarrow$$

Upgraded Tevatron $\longrightarrow$ good sensitivity precisely in this mass region

$\downarrow$

Next chance to reveal mechanism of Electroweak Symmetry Breaking

Higgs Physics

Within the Standard Model:

- LEP final results $\Longrightarrow M_H \geq 114.1$ GeV
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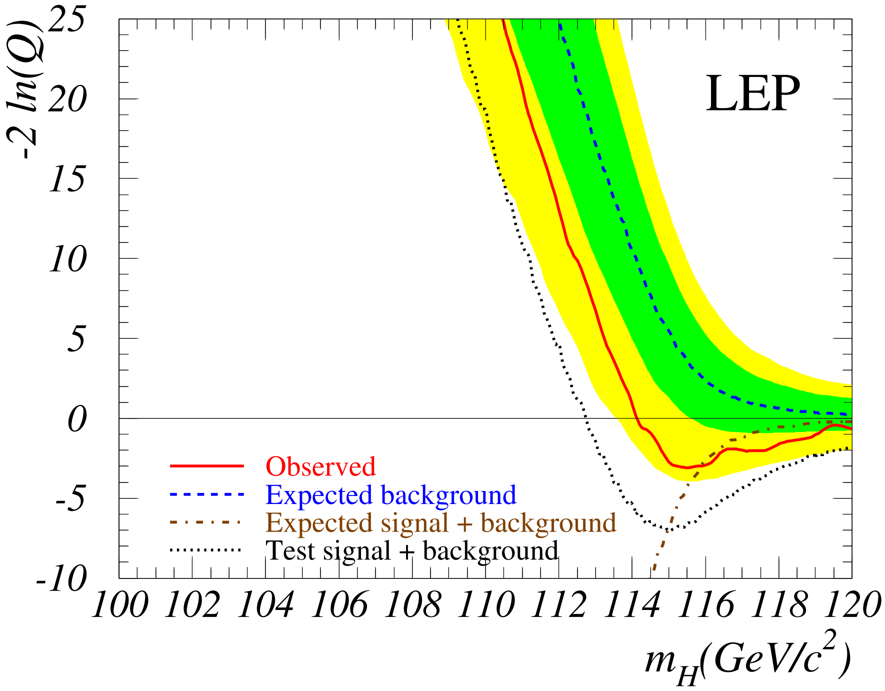


Recall: ELW data $\Longrightarrow M_H \leq 196$ GeV at 95 % C.L.

$\Downarrow$

Upgraded Tevatron $\longrightarrow$ good sensitivity precisely in this mass region

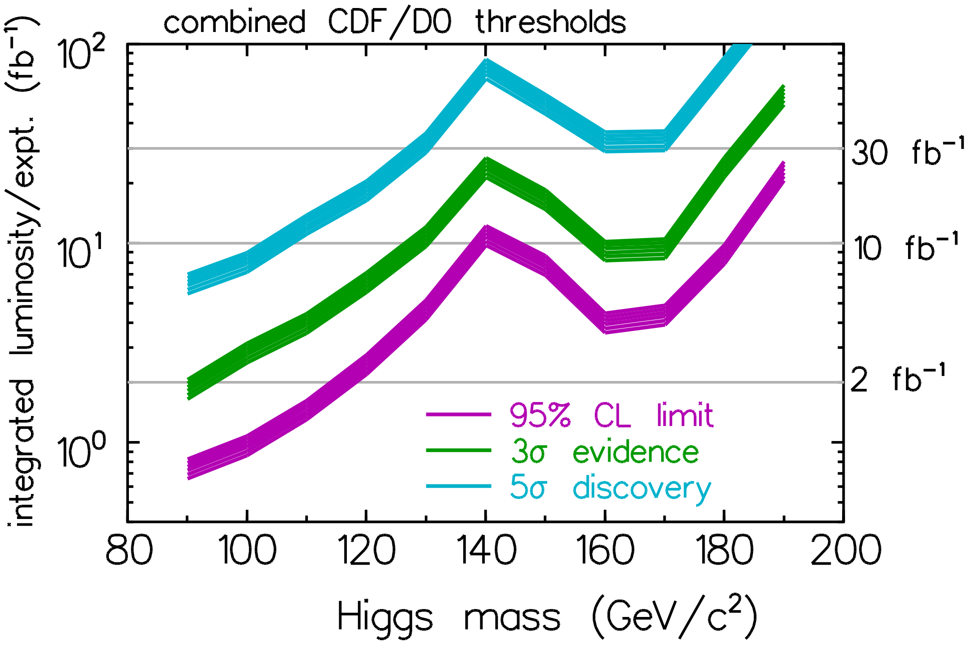
$\downarrow$

Next chance to reveal mechanism of Electroweak Symmetry Breaking

SM Higgs Prospects at the Tevatron

Higgs/SUSY Workshop & Higgs WG Report results

- $M_H \leq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to Vb\bar{b}$ (V = W,Z)
- $M_H \geq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to VWW^*$
  $\Longrightarrow p\bar{p} \to H \to WW^*$



- $M_H \leq 180$ GeV $\Longrightarrow$ 95 % C.L. excl. $\to$ 10 fb^{-1}/*exp.*
  3σ evidence $\to$ 20 fb^{-1}/*exp.* 5σ discovery $\to\approx$ 60 fb^{-1}/*exp.*
- $M_H \leq 130$ GeV $\Longrightarrow$ 5σ with 30 fb^{-1}/*exp.*
- $M_H \approx 115$ GeV (LEP Hint?) $\Longrightarrow$ 3σ with $\approx$ 5 fb^{-1}/*exp.*
  $\Longrightarrow$ 5σ with $\approx$ 15 fb^{-1}/*exp.*

Other Channels: $H \to \tau\tau$ under study
$t\bar{t}H \to t\bar{t}b\bar{b}$ prelim. studies, seems difficult

Beyond the Standard Model

• Models with no fundamental scalars
Higgs $\rightarrow$ composite of fund. fermions
New Physics signatures at the TeV scale

• Models with fundamental scalars:
SUPERSYMMETRY $\Longrightarrow$ each fermion (boson) of the SM has its bosonic (fermionic) superpartner

$$\Downarrow$$

- is easily consistent with present electroweak precision data
- solves naturalness problem of the SM Higgs sector if SUSY particles not far above 1 TeV
- allows for unification of all known interactions
- provides a source of new physics which

demands a LIGHT HIGGS

The MSSM Higgs Sector

2 CP-even states h, H $\longrightarrow$ mixing angle α
1 CP-odd A 1 charged Higgs $\mathrm{H}^{\pm}$

- At tree level:

$$m_h \leq M_Z$$

Input param. $\longrightarrow$ m_A and $\tan\beta \equiv v_2/v_1$

- After quantum effects:

mass spectrum depends on M_t and the stop and sbottom sectors:

$$m_h \lesssim 135\mathrm{GeV}$$

$\Longrightarrow$ stringent direct test of the MSSM

– Effect of rad. corrections on Higgs couplings to fermions and gauge bosons

- change basic relation $\frac{g_{\phi b\bar{b}}}{g_{\phi\tau\tau}} \neq \frac{M_b}{M_\tau}$
- strong suppression of $BR(\phi \to b\bar{b})$

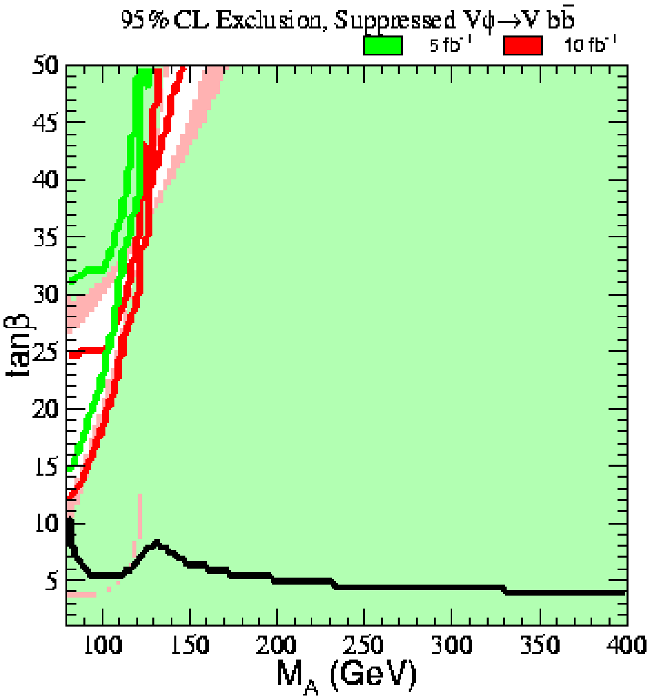
$\Longrightarrow$ depending on the MSSM param. space $\to$ change drastically the Higgs bosons search strategies.

To define potential of a collider for Higgs searches it is necessary to explore the most challenging configurations

MSSM Higgs Sector Studies

Higgs/SUSY Workshop & Higgs WG Report results

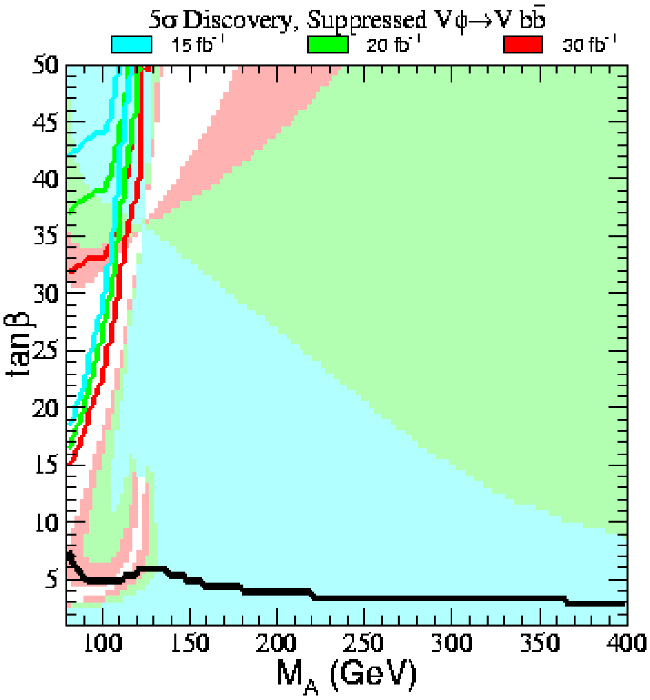
- most challenging case: $M_h^{max} \approx$120 GeV but important regions of suppressed $h/Hb\bar{b}$ coupling



shaded areas: $p\bar{p} \to Vh/H \to Vb\bar{b}$

green/red lines: $p\bar{p} \to \phi b\bar{b} \to b\bar{b}b\bar{b}$
ϕ = A/h or A/H

black solid line: LEP limit



- good exclusion if no signal with 5–10 fb^{-1}/*exp.*
- good coverage for discovery $\longrightarrow$ > 15 fb^{-1}/*exp.*

CP Violation & the MSSM Higgs Sector

SUSY Breaking parameters in the stop/sbottom/gluino sector *may be complex*
$\rightarrow$ CP Violation induced through loop effects

• mixing between the 3 neutral states

h, H, A $\rightarrow$ H_1, H_2 H_3 mixed CP parity states

• upper bound on lightest Higgs mass remains the same

$$m_{H_1} \leq 135 \mathrm{GeV}$$

• couplings of Higgs bosons to gauge bosons and fermions can crucially differ from CP conserving case

$\Longrightarrow$ CP violation $\rightarrow$ important phenomenological consequences on LEP results and on Tevatron/LHC expectations $\Longrightarrow$ *example*

Note: CPV necessary for Electroweak Baryogenesis
$\Longrightarrow$ when testing ELW Baryogenesis through Higgs physics, CPV studies of Higgs sector neccesary

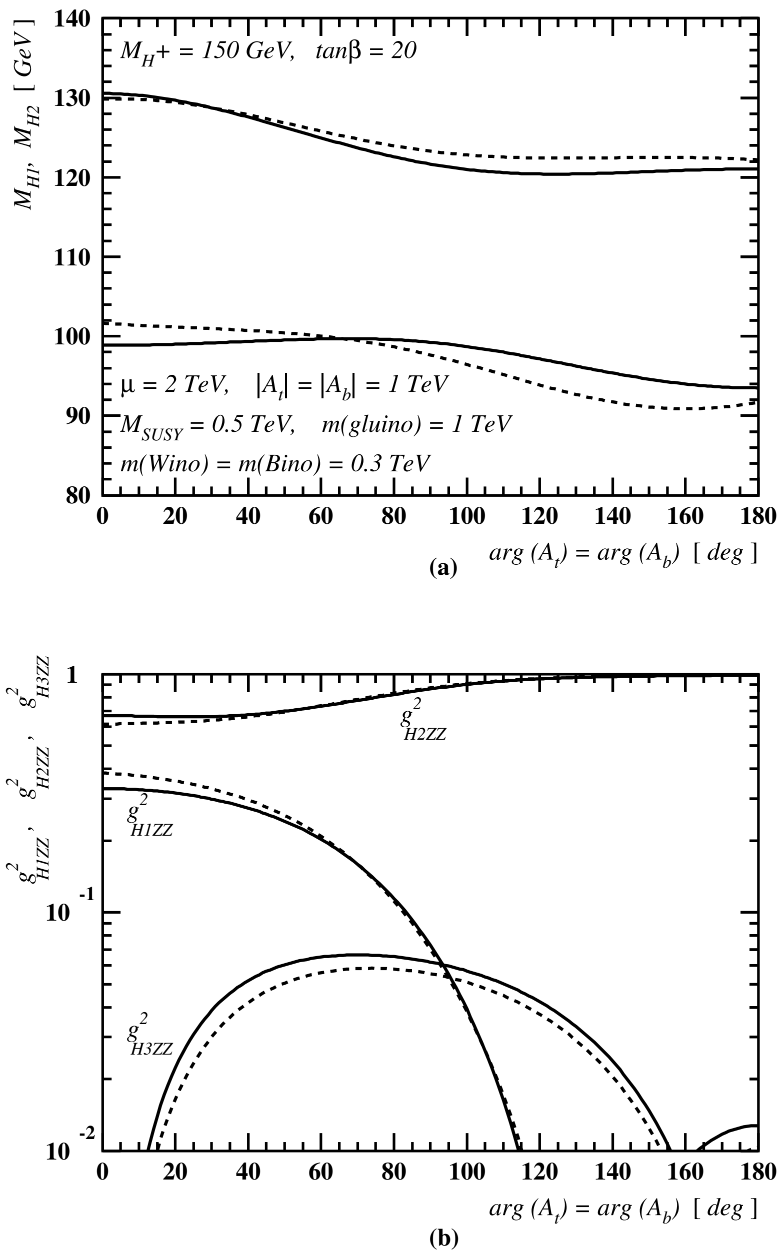
CP-Violating Higgs Bosons at the Tevatron

Large $\tan\beta$ scenario and sizeable phase of A_t (stop mixing param.), $arg(A_t) \geq 90^o$

- interesting case: $M_{H_1} \approx 90$ GeV but out of LEP reach, all other channels: ZH_2, ZH_3, H_1H_2, H_1H_3 kin. inaccessible.

- $M_{H_1} \rightarrow$ also very difficult at the Tevatron due to small $g^2_{H_1VV}$ coupl.

M_{H_1}, M_{H_2}, small variation with CP violating phase of A_t, but strong variation of the couplings



– The Tevatron will detect $M_{H_2} \sim 120$ GeV if sufficient integrated Luminosity (≥ 15 fb^{-1}) collected

SUSY Searches at the Tevatron

- Tevatron has discovery reach far beyond LEP

- Many signatures require new experimental techniques or new triggers: Some RUN 2 Innovations

• Photon-pointing to tag delayed photon decays(DØ).
• Tracking + TOF to tag heavy charged particles (CDF).
• b-tagging with higher acceptance and purity.
• Higher lepton acceptance.
• Level 2 displaced vertex + $\not\!\!E_T$ trigger (CDF).
• Level 2 low p_T tau triggers (CDF+DØ).

- Mechanism of SUSY breaking not well understood. Models of SUSY breaking are not simple

$$\Downarrow$$

Different SUSY breaking scenarios $\longrightarrow$ crucially different patterns of low energy spectrum –production and decays–

- Important to develop a comprehensive search strategy $\longrightarrow$ simulations exploring main signals in different SUSY breaking scenarios necessary:

• Gravity-Mediated • Gauge-mediated
• Anomaly mediated • with R Parity Violation

Sugra Scenarios

Specific Minimal–Sugra features:

Including electroweak symmetry breaking condition,
$\Longrightarrow$ the whole SUSY particle spectrum defined by:

$m_0 \longrightarrow$ universal scalar mass
$M_{1/2} \longrightarrow$ universal gaugino mass
$A_0 \longrightarrow$ universal cubic coupling scaling factor
$\tan\beta = \frac{v_2}{v_1} \longrightarrow$ ratio of Higgs v.e.v.'s
sign of $\mu \longrightarrow$ SUSY Higgs mass parameter

Spectrum

$$2m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq \frac{1}{3} M_{\tilde{g}} \simeq \mathcal{O}(M_{1/2})$$

$$m_{\tilde{\chi}_3^0} \simeq m_{\tilde{\chi}_4^0} \simeq m_{\tilde{\chi}_2^\pm} \simeq |\mu| \gg m_{\tilde{\chi}_1^\pm}$$

- *if* $m_0 \gg M_{1/2} \longrightarrow m_{\tilde{q}_{1,2}} \simeq m_{\tilde{l}} > M_{\tilde{g}}$
- *if* $m_0 \ll M_{1/2} \longrightarrow M_{\tilde{g}} > m_{\tilde{q}_{1,2}} > m_{\tilde{b}} > m_{\tilde{t}} > m_{\tilde{l}} \simeq M_{\tilde{W}}$
  $M_{\tilde{W}} > m_{\tilde{l}_R} \simeq M_{\tilde{B}}$

Signatures in MSUGRA

Supersymmetric particles odd under P_R
with R-parity: $P_R = (-1)^{3B+L+2S}$

- If R-parity Conserved: LSP Stable
  $\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

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$A_0 \longrightarrow$ universal cubic coupling scaling factor
$\tan\beta = \frac{v_2}{v_1} \longrightarrow$ ratio of Higgs v.e.v.'s
sign of $\mu \longrightarrow$ SUSY Higgs mass parameter

radiative ELW symm. breaking $\Longrightarrow$ in general
$|\mu| \gg M_{1/2}$

- light neutralino/chargino states $\longrightarrow$ gaugino like
- heavy states $\longrightarrow$ higgsino-like

$$2m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq \frac{1}{3} M_{\tilde{g}} \simeq \mathcal{O}(M_{1/2})$$

$$m_{\tilde{\chi}_3^0} \simeq m_{\tilde{\chi}_4^0} \simeq m_{\tilde{\chi}_2^\pm} \simeq |\mu| \gg m_{\tilde{\chi}_1^\pm}$$

Furthermore:

- *if* $m_0 \gg M_{1/2} \longrightarrow m_{\tilde{q}_{1,2}} \simeq m_{\tilde{l}} > M_{\tilde{g}}$
- *if* $m_0 \ll M_{1/2} \longrightarrow M_{\tilde{g}} > m_{\tilde{q}_{1,2}} > m_{\tilde{b}} > m_{\tilde{t}} > m_{\tilde{l}} \simeq M_{\tilde{W}}$

$$M_{\tilde{W}} > m_{\tilde{l}_R} \simeq M_{\tilde{B}}$$

Extensions of MSUGRA:

– CP Violation

• complex phases for all soft SUSY breaking parameters, but at least two cannot be rotated away choosing those as ϕ_μ and ϕ_A
$\Longrightarrow$ six param. determine the sparticle spectrum:

$$m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \phi_\mu,\ \phi_A$$

• Interesting constraints on SUSY param. space from EDM's of electron and u,d quarks

$$\left(\frac{d_f}{e}\right)^{1l.} \sim 10^{-25}\mathrm{cm}\frac{(\mathrm{Im}\mu, \mathrm{Im}A_f)}{max.(m_{\tilde{f}}, m_\lambda)}\left(\frac{1\mathrm{TeV}}{max.(m_{\tilde{f}}, m_\lambda)}\right)^2\left(\frac{m_f}{10\mathrm{MeV}}\right)$$

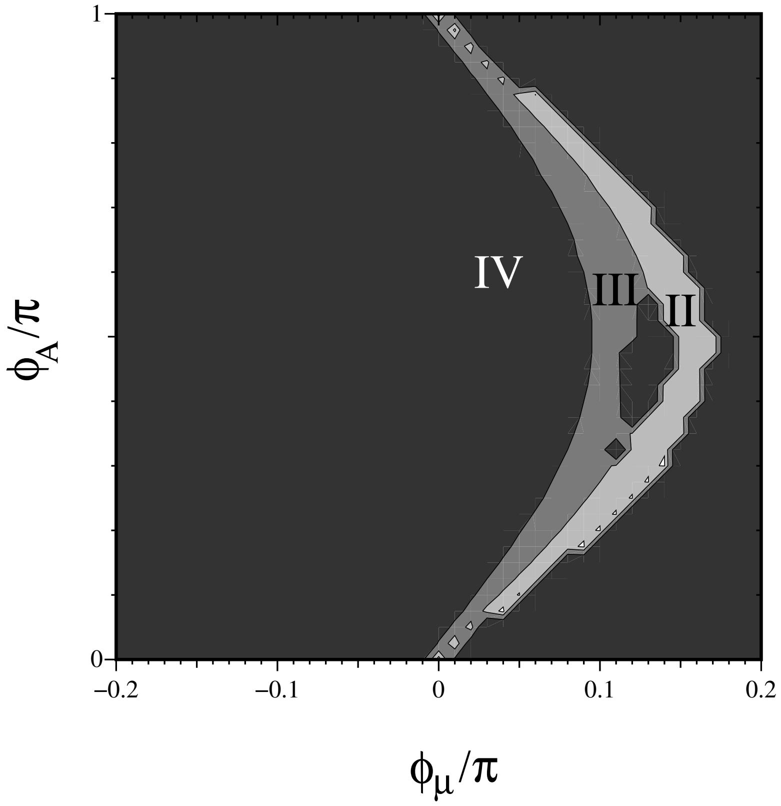
To resolve the one-loop CP crisis:

• $\mathrm{Im}\mu/|\mu|, \mathrm{Im}A_f/A_f \leq 10^{-2}$, with $(m_{\tilde{f}}, m_\lambda) \sim 200\,\mathrm{GeV}$

• CP phases ~ 1, but $m_{\tilde{f}} > 1$ TeV for $\tilde{f} = \tilde{e}, \tilde{u}, \tilde{d}, \tilde{\nu}_L$

• Cancellations between different EDM terms

$$\Downarrow$$



Required values of $M_{1/2}$ to satisfy electron and neutron EDM's for $\tan\beta$ =2, m_0 = 100 GeV, A_0 = 1 TeV. Zones labelled II, III and IV correspond to: 200 GeV $\leq M_{1/2}^{min} \leq$300 GeV, 300 GeV $\leq M_{1/2}^{min} \leq$450 GeV and $M_{1/2}^{min} \geq$450 GeV

• Two-loop contributions to EDM's $\Longrightarrow$ constraints on CPV parameters of 3rd. gen. squarks, specially for large $\tan\beta \longrightarrow$ important for Higgs physics

- CPV makes more difficult to reconstruct param. of SUSY particles from experimental data

– Non-Universality of Soft Terms

Universality of soft terms comes from assumption that Kähler potential does not have generational dependent couplings with hidden sector

Relaxing this $\longrightarrow$ non-univ. scalar masses
$\Longrightarrow$ FCNC constraints
However, Higgs sector univ. or 3rd. generation sector univ. is not strongly contrained

Non-universality produces identifiable signatures at low energy

– R-Parity Violation

Supersymmetric particles odd under P_R
with R-parity: $P_R = (-1)^{3B+L+2S}$

Analysis of MSUGRA signatures depend strongly on R-parity invariance or violation

If R-parity conserved $\Longrightarrow$ LSP stable
$\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

Gauge-Mediated SUSY breaking Scenarios

- Superpartner masses proportional to $\Lambda = F/M$
  $\sqrt{F}$: intrinsic SUSY breaking scale
  M: mass scale of the messenger sector
- Minimal set of parameters: Λ, M, $\tan\beta$, $sign(\mu)$

– Hierarchy of SUSY particle masses $\longrightarrow$ related to gauge couplings

– Special feature $\longrightarrow$ light (gravitino) Goldstino

$m_{\tilde{G}} \sim F/M_{Pl} \sim 10^{-6} - 10^{-9} GeV$

If R-parity conserved, heavy particles cascade to lighter ones and NLSP $\longrightarrow$ SM partner + $\tilde{G}$

Signatures of low energy SUSY breaking

⋆ NLSP can have prompt decays:
Signature of SUSY pair: 2 hard photons + $\not{E}_T$from $\tilde{G}$
⋆ macroscopic decay length but within the detector:
displaced photons; high ionizing track (HIT) with a kink to a minimum ionizing track (MIT), ...
(smoking gun of low energy SUSY)
⋆ decay well outside the detector: $\not{E}_T$like SUGRA

Gauge-Mediated SUSY breaking Scenarios

- Superpartner masses proportional to $\Lambda = F/M$

  $\sqrt{F}$: intrinsic SUSY breaking scale

  M: mass scale of the messenger sector

- Minimal set of parameters:

$$\Lambda,\ M,\ \mathrm{N},\ \tan\beta,\ sign(\mu),\ C_G$$

N: number of messenger generations, C_G: constant relating SUSY breaking scale felt by the messangers and F

– Hierarchy of SUSY particle masses $\longrightarrow$ related to gauge couplings

$m_{\tilde{q}}/m_{\tilde{l}_L} \propto \alpha_3/\alpha_2$

$m_{\tilde{g}} \propto m_{\tilde{q}}$ $\qquad$ $m_{\tilde{W}} \propto m_{\tilde{l}_L}$ $\qquad$ $m_{\tilde{B}} \propto m_{\tilde{l}_R}$

Similar to SUGRA:

$m_{\tilde{g}}/m_{\tilde{W}} \propto \alpha_3/\alpha_2$ and $m_{\tilde{W}}/m_{\tilde{B}} \propto \alpha_2/\alpha_1$

– Special feature $\longrightarrow$ light (gravitino) Goldstino

$m_{\tilde{G}} \sim F/M_{Pl} \sim 10^{-14}\ \ M/[GeV]$

The Goldstino couples to each SM particle and the corresponding SM superpartner with strength 1/F

If R-parity conserved, heavy particles cascade to lighter ones and NLSP $\longrightarrow$ SM partner + $\tilde{G}$

Decay modes to the Goldstino in various NLSP scenarios.

NLSP	Decay to the Goldstino
Bino-like Neutralino	$\tilde{\chi}_1^0 \to \gamma\ \tilde{G}$
Higgsino-like Neutralino	$\tilde{\chi}_1^0 \to (h, Z, \gamma)\ \tilde{G}$
Stau	$\tilde{\tau} \to \tau\ \tilde{G}$
Slepton Co-NLSP	$\tilde{l} \to l\ \tilde{G}$
Squark	$\tilde{q} \to (q, q'W)\ \tilde{G}$
Gluino	$\tilde{g} \to g\ \tilde{G}$

Decay Length of the NLSP

$\Downarrow$

if $\sqrt{F} \gg$ a few 10^6 GeV $\longrightarrow$ decay outside the detector
if $\sqrt{F} <$ a few 10^6 GeV $\longrightarrow$ may decay inside the detector

– Three relevant ranges of NLSP decay lengths:

• prompt decays $\Longrightarrow$ particles appear as originating from interaction point

$$\Downarrow$$

Signature of SUSY pair: 2 hard photons + $\not\!\!E_T$ from $\tilde{G}$

• macroscopic decay length but within the detector (smoking gun of low energy SUSY)

$$\Downarrow$$

$\star$ displaced photons (accurate photon pointing);
$\star$ ID of high momentum partons from secondary vertices;
$\star$ high ionizing track (HIT) with a kink to a minimum ionizing track (MIT) or a tau jet

• decay length well outside the detector:

$$\Downarrow$$

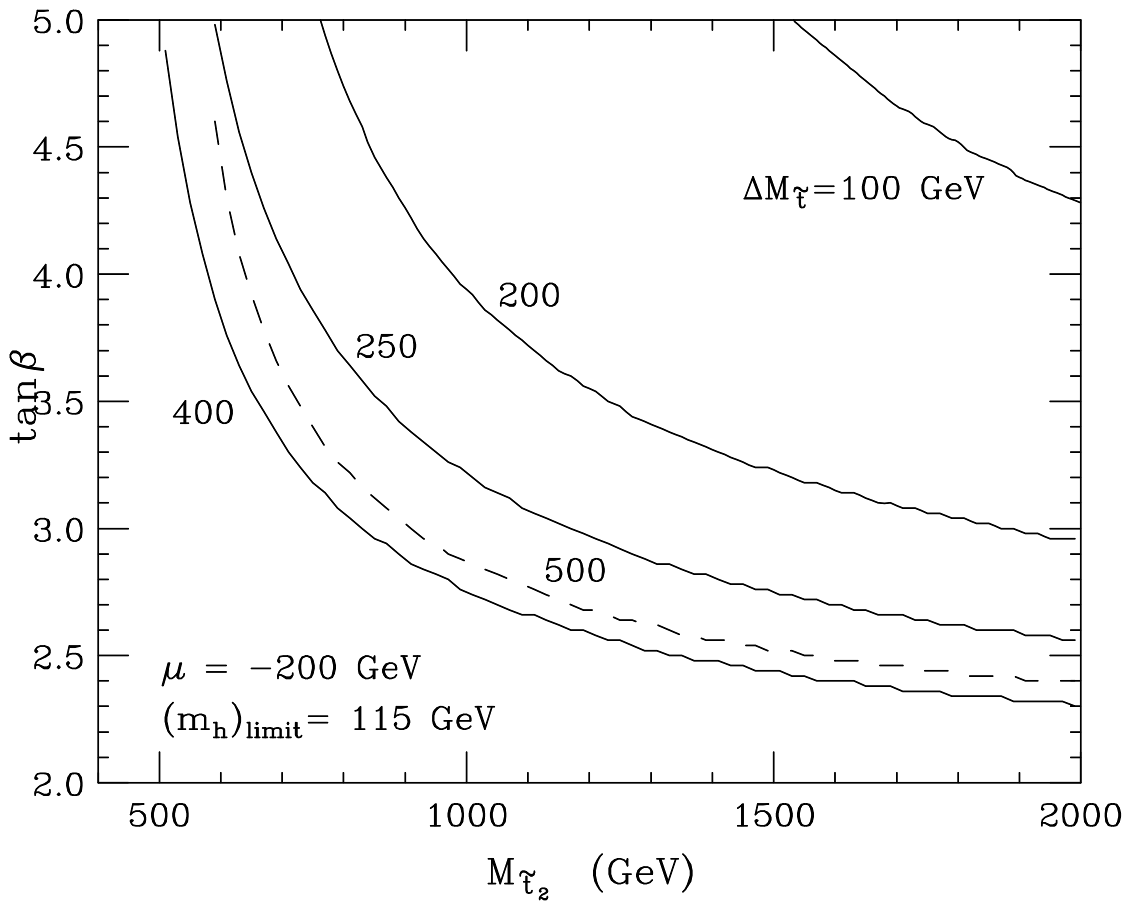
$\star$ if neutralino-like NLSP $\rightarrow$ $\not\!\!E_T$ like SUGRA
$\star$ if slepton NLSP $\rightarrow$ HIT without much $\not\!\!E_T$,
time of flight in the search for slow moving leptons.

Indirect Information on SUSY from Experiment

- Higgs mass constraints from LEP

$\Longrightarrow$ impose important constraints on SUSY breaking models and 3rd gen. squark masses.

Model Independent bounds on $\tan\beta$ as a function of heaviest stop mass for different values of the stop mass splitting $\Delta M_{\tilde{t}} = m_{\tilde{t}_2} - m_{\tilde{t}_1}$, for $m_h = 115$ GeV

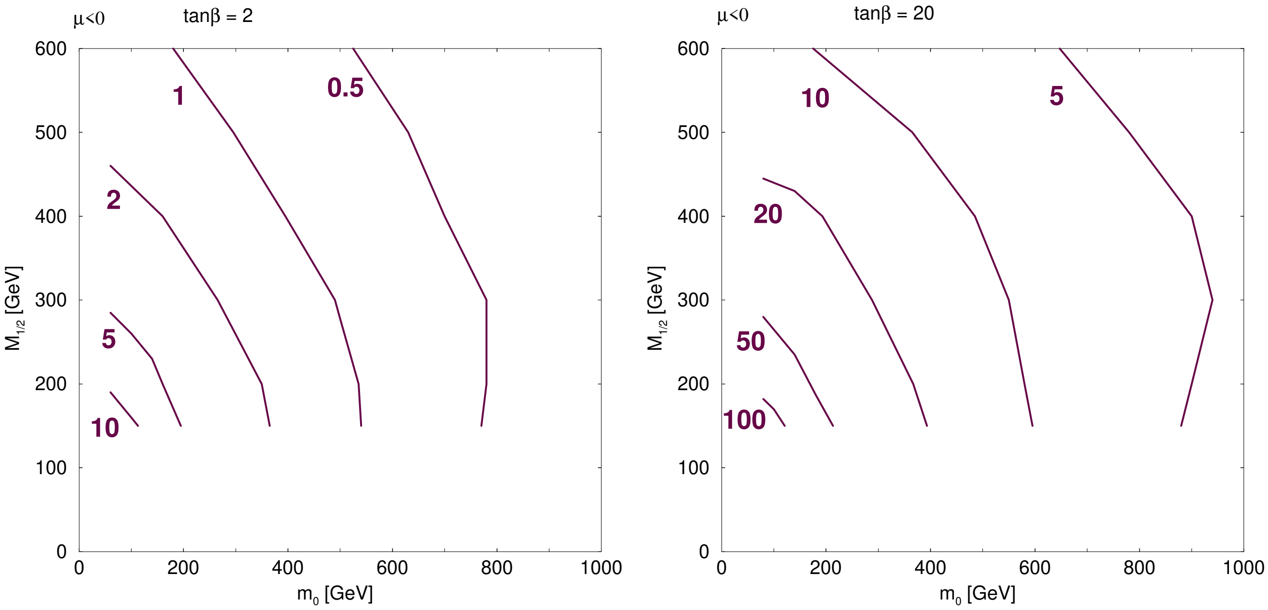


• Recent measurement of $(g-2)_\mu$ at Brookhaven yields a 2.6 Sigma deviation from SM prediction:

$$a_\mu^{exp} - a_\mu^{SM} = (42 \pm 16) \times 10^{-10}$$

If confirmed by 2000 data $\Longrightarrow$ favours SUSY with light charginos/sneutrinos/neutrinos/smuons:

$$\delta a_\mu^{SUSY} \simeq 15 \times 10^{-10} \left(\frac{100\mathrm{GeV}}{\tilde{m}}\right)^2 \tan\beta$$



Contour lines of constant $\delta a_\mu^{SUSY} \times 10^{10}$ for $\tan\beta = 2,\ 20$.

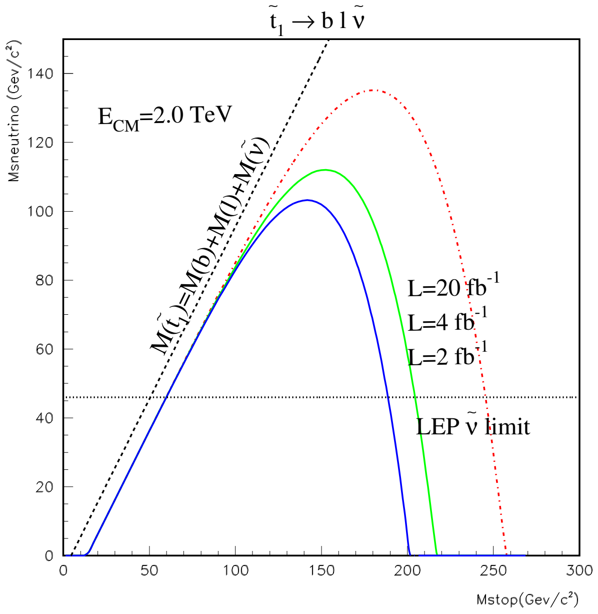
– to contribute to δa_μ^{SUSY} in the required amount $\rightarrow$ generic SUSY masses $\tilde{m} \simeq 60\sqrt{\tan\beta} \Longrightarrow 100 - 500$ GeV

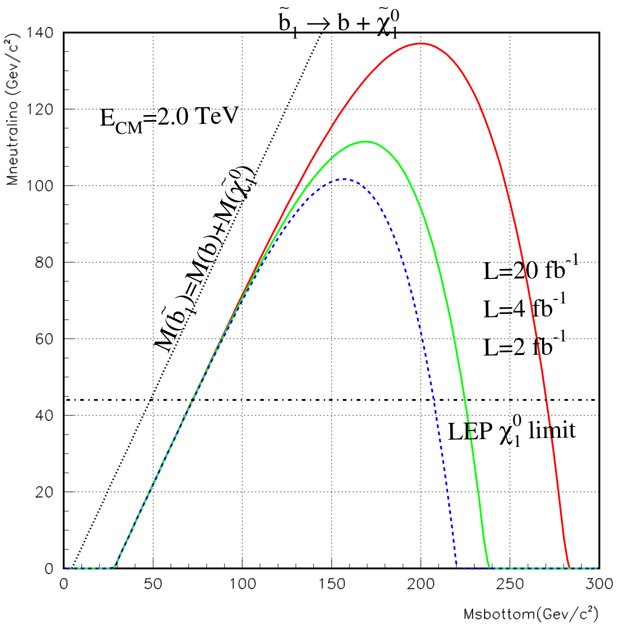
$\Longrightarrow$ at the Tevatron reach !

In comb. with $b \rightarrow s\gamma$ meas. from CLEO: rules out simplest anomaly mediated SUSY models.

Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge– and Anomaly–Mediated) $\longrightarrow$ $\tilde{t}$'s and $\tilde{b}$'s quite light





With $\int \mathcal{L}dt = 2\ (20)\ \mathrm{fb}^{-1}$

$m_{\tilde{t}_1} \leq 185/190\ (260/250)$ GeV in $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}/\tilde{t}_1 \to bl\tilde{\nu}$

$m_{\tilde{t}_1} \leq 160\ (200)$ GeV in $\tilde{t}_1 \to c\tilde{\chi}_1^0$

$m_{\tilde{b}_1} \leq 210\ (270)$ GeV in $\tilde{b}_1 \to b\tilde{\chi}_1^0$

- New Studies: jets + photons + $\not{E}_T$, with 2 to 4 fb^{-1}

$\tilde{t} \to c\gamma\tilde{G}$ and $\tilde{t} \to bW\gamma\tilde{G} \Longrightarrow m_{\tilde{t}_1} \leq 300$ GeV

$\tilde{q} \to q\gamma\tilde{G} \Longrightarrow m_{\tilde{q}} \leq 400$ GeV

Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge– and Anomaly–Mediated) $\longrightarrow$ $\tilde{t}$'s and $\tilde{b}$'s quite light

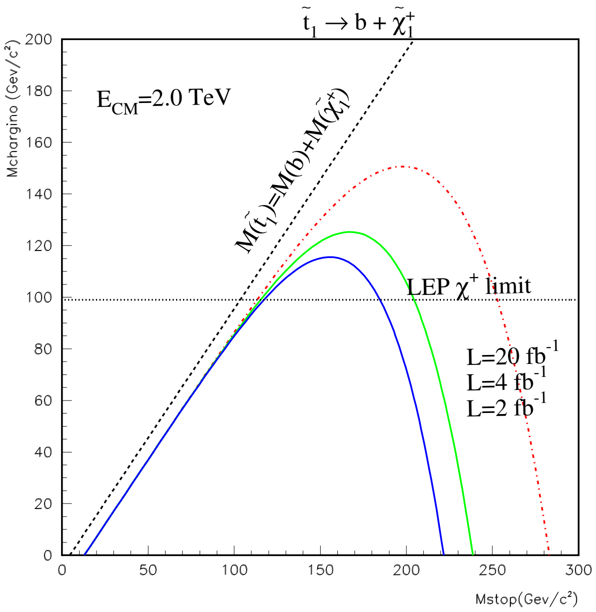
- If $m_{\tilde{t}_1} > m_{\tilde{\chi}_1^\pm} + m_b$ or $> M_W + m_{\tilde{\chi}_1^0} + m_b$ or $> m_l + m_{\tilde{\nu}} + m_b$ or $> m_{\tilde{l}} + m_\nu + m_b$

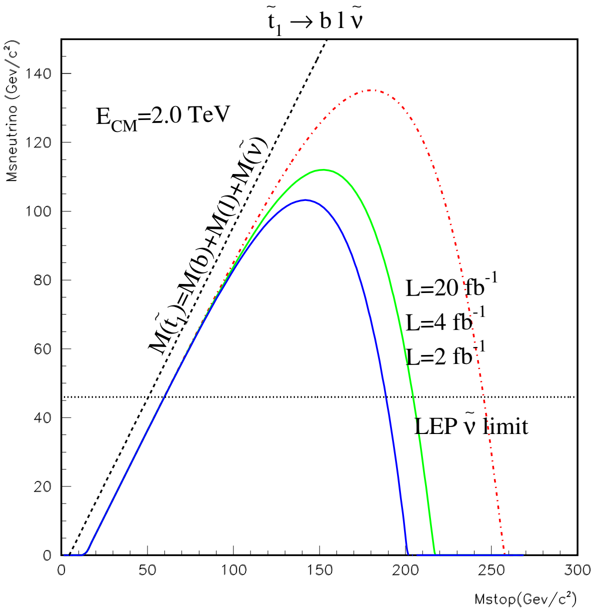
$\Longrightarrow \tilde{t}_1 \to b\tilde{\chi}_1^{\pm(*)} \to b\tilde{\chi}_1^0 f\bar{f}'$ with $f\bar{f}' = l\bar{\nu}$ or $q\bar{q}'$

Signals: 2b jets + 2 W's + $\not{E}_T$, 2b jets + 2l's +$\not{E}_T$

$\Downarrow$

Selection: b-jet + jet + l + $\not{E}_T$, 2l's + jet + $\not{E}_T$



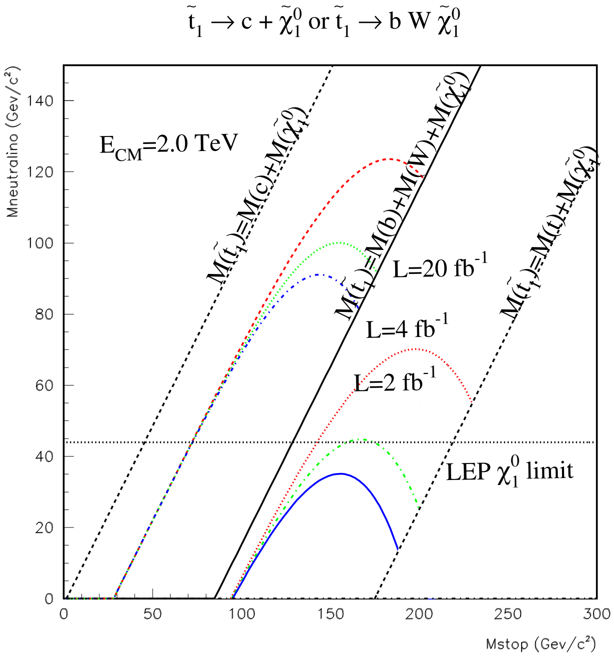


• If the above modes not kinematically allowed

$\tilde{t}_1 \to c\tilde{\chi}_1^0$

(via $b\tilde{\chi}_1^\pm$ loop)

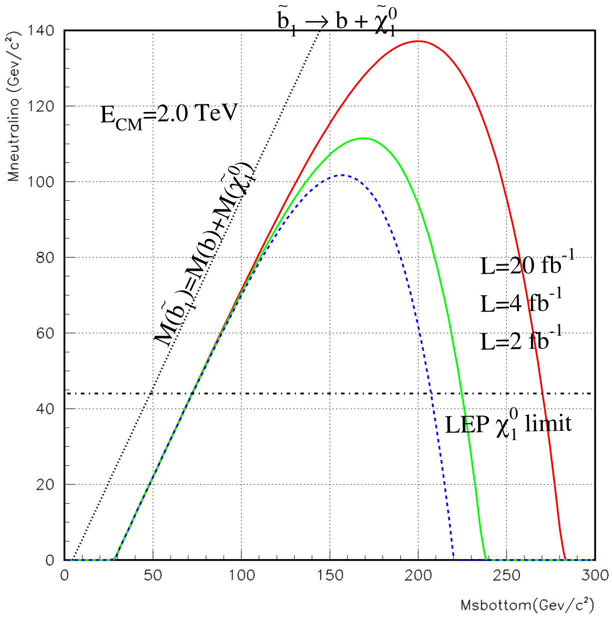
Signal/Selection:
2c jets + $\not\!\!E_T$



• Sbottoms:

$\Longrightarrow \tilde{b}_1 \to b\tilde{\chi}_1^0$

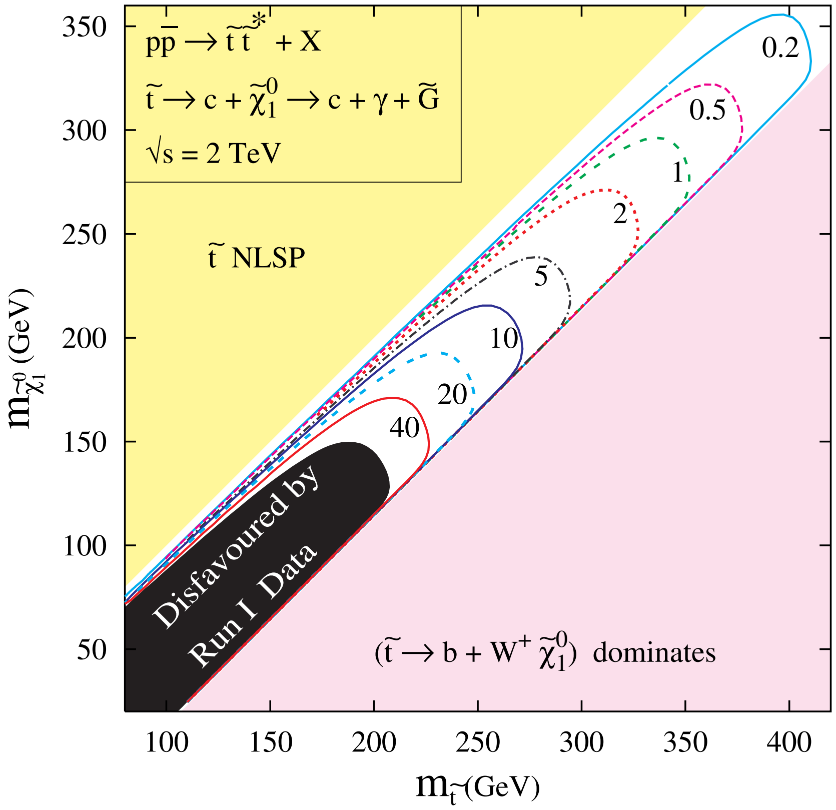
100 % BR
if $m_{\tilde{\chi}_2^0} > m_{\tilde{b}} - m_b$



if $\tilde{b} \to b\tilde{\chi}_2^0$ allowed, limit degraded in 30-40 GeV

Stop Searches in Low Energy SUSY Breaking Models

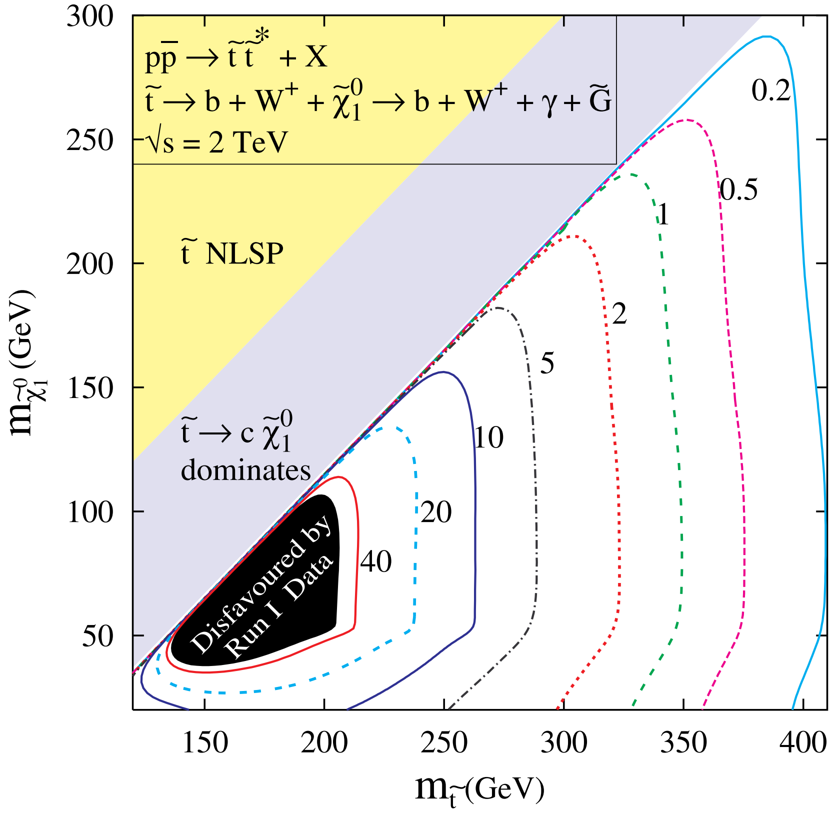
Considering the stops to be the NLSP, look for signatures with jets, γ's and $\not{E}_T$ (small SM backgds.)



Cross sections for stop pair production in fb, with $\tilde{t} \to c\gamma\tilde{G}$ and Signal/selection $jj\gamma\gamma\not{E}_T$

$\int \mathcal{L}$	σ_S 5σ dis.	S	B	Max. $m_{\tilde{t}}$ (2 body)
2 fb^{-1}	6 fb	12	4	290 GeV
4 fb^{-1}	3.5 fb	14	8	315 GeV
15 fb^{-1}	1.8 fb	27	30	330 GeV
30 fb^{-1}	1.3 fb	39	60	340 GeV

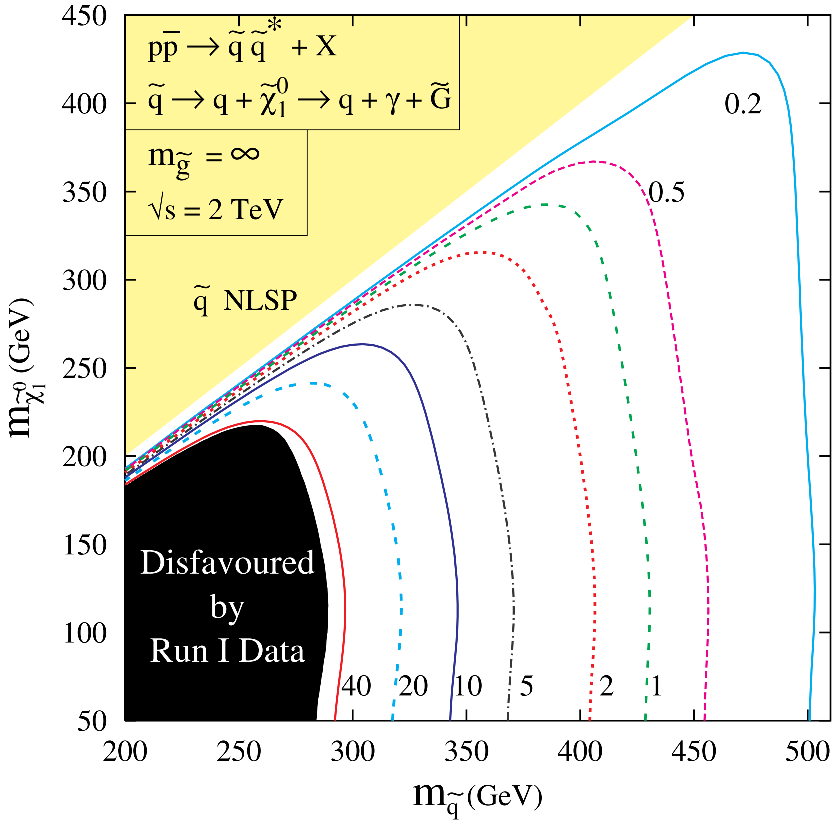
Cross sections for stop pair production in fb, with $\tilde{t} \to bW\gamma\tilde{G}$ and Signal/selection $bbWW\gamma\gamma\not{E}_T$



Maximum stop mass reach

$\int \mathcal{L}$	σ_S 5-event dis.	Max. $m_{\tilde{t}}$ (3 body)
2 fb^{-1}	2.5 fb	315 GeV
4 fb^{-1}	1.3 fb	330 GeV
15 fb^{-1}	0.33 fb	380 GeV
30 fb^{-1}	0.17 fb	415 GeV

Cross sections for squark pair production in fb, with 10 deg. squarks, with $\tilde{q} \to q\gamma\tilde{G}$



Maximum squark mass reach, heavy gluino limit

$\int \mathcal{L}$	σ_S 5σ dis.	S	B	Max. $m_{\tilde{q}}$
2 fb^{-1}	5 fb	10	4	370 GeV
4 fb^{-1}	3.5 fb	14	8	385 GeV
15 fb^{-1}	1.8 fb	27	30	410 GeV
30 fb^{-1}	1.3 fb	39	60	425 GeV

Stop, Sbottom and Squark Mass Reach at RUN 2

In summary:

With $\int \mathcal{L}dt = 2\ (20)\ \mathrm{fb}^{-1}$

$m_{\tilde{t}_1} \leq 185/190\ (260/250)$ GeV in $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm} / \tilde{t}_1 \to bl\tilde{\nu}$

$m_{\tilde{t}_1} \leq 160\ (200)$ GeV in $\tilde{t}_1 \to c\tilde{\chi}_1^0$

$m_{\tilde{b}_1} \leq 210\ (270)$ GeV in $\tilde{b}_1 \to b\tilde{\chi}_1^0$

- NEW STUDIES: jets + photons + $\not{E}_T$

Stop Mass reach up to 300 GeV
with only $\int \mathcal{L}dt = 2$ to $4\ \mathrm{fb}^{-1}$

Squark Mass reach up to 400 GeV
with only $\int \mathcal{L}dt = 2$ to $4\ \mathrm{fb}^{-1}$

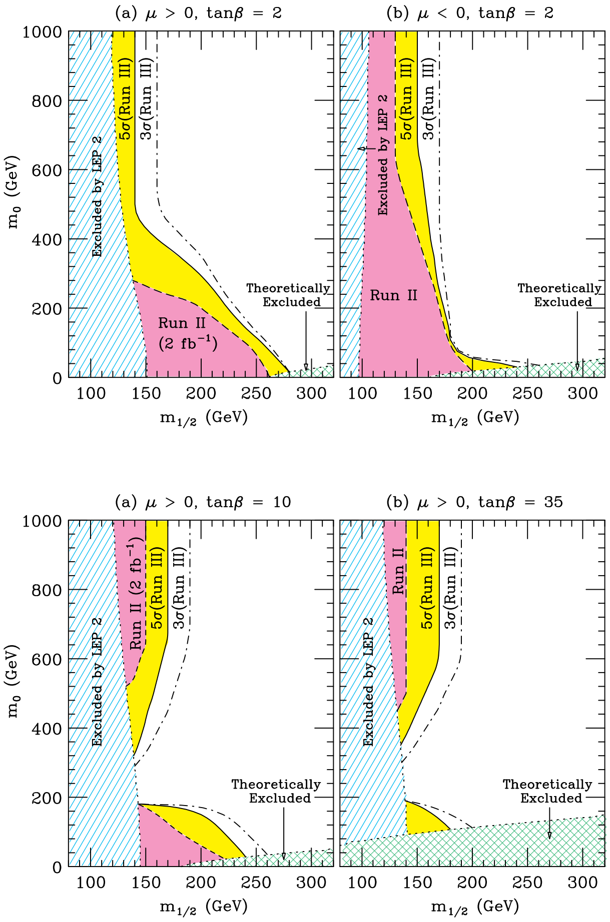
Interesting: light right-handed stops $m_{\tilde{t}_R} \sim 150$ GeV
+ MSSM Higgs $m_h \sim$ 100-115 GeV
$\Longrightarrow$ compatible with ELW Baryogenesis Mechanism
Tevatron Run2 reach for Higgs and stops
$\Longrightarrow$ probe Baryogenesis at the Electroweak scale !

SUGRA Trilepton Mode and SUSY signatures with Taus at the Tevatron

– Golden mode: $p\bar{p} \to \chi_1^{\pm}\chi_2^0 \to 3\ell + X$

Models with light staus: worst case scenario

Lots of τ's. The leptonic tau decays are soft $\to$ harder to identify, cuts need to be re-optimized



Discovery reach at RUN 2b as high as:

(SUSY/Higgs SUGRA report)

$m_{\tilde{\chi}_1^{\pm}} \sim 110$ to 200 GeV $\qquad m_{\tilde{g}} \sim 400$ to 600 GeV

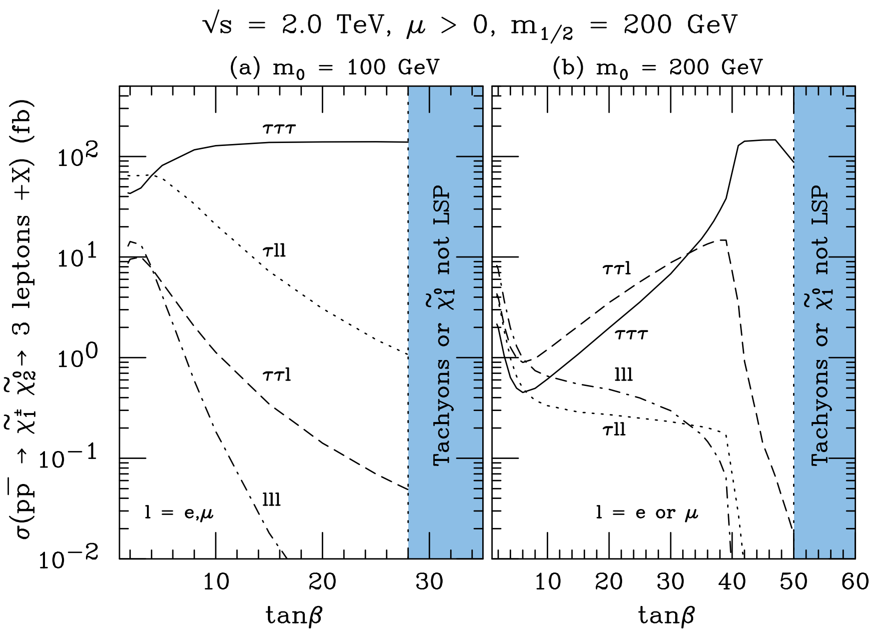
SUGRA Trilepton Mode and SUSY Signatures with Taus at the Tevatron

- Golden channel at the Tevatron

$p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3l + \not{E}_T \qquad\qquad l = e, \mu$

– worst case scenario:

in many models (SUGRA, Gauge mediated):
staus are light ($m_{\tilde{\tau}} < m_{\tilde{\chi}_1^{\pm}}$ or $m_{\tilde{\chi}_2^0}$)
$\Longrightarrow$ golden mode ineffective. Instead, lots of τ's



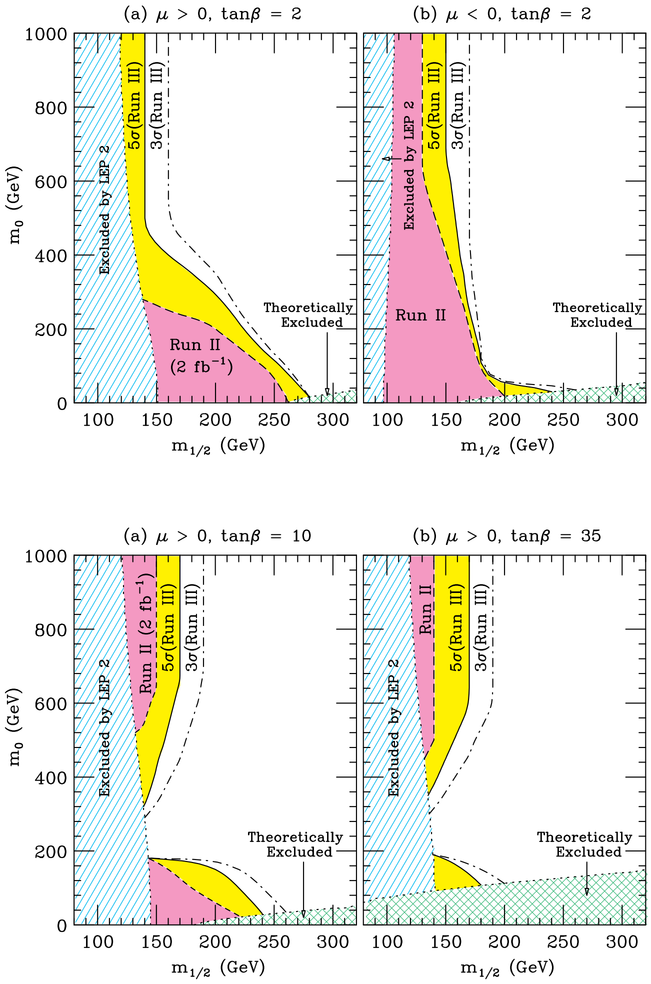
The leptonic tau decays are soft $\Longrightarrow$ harder to identify and cuts need to be re-optimized

Background processes (W^*Z^*, $W^*\gamma^*$) previously unaccounted for are big –need to be cut optimized–

With soft but realistic p_T accep. cuts
$\Longrightarrow$ tau modes contribute importantly

RUN 2 Potential in the mode: $p\bar{p} \rightarrow$ SUSYparticles $\rightarrow 3l + X$

(SUSY/Higgs SUGRA report)



- low $\tan\beta \rightarrow M_{1/2}$ as high as 250 GeV
- large $\tan\beta \rightarrow M_{1/2}$ as high as 140–180 GeV

this includes leptonic tau channels

$m_{\tilde{\chi}_1^\pm} \sim$ 110 to 200 GeV $\qquad M_{\tilde{g}} \sim$ 400 to 600 GeV

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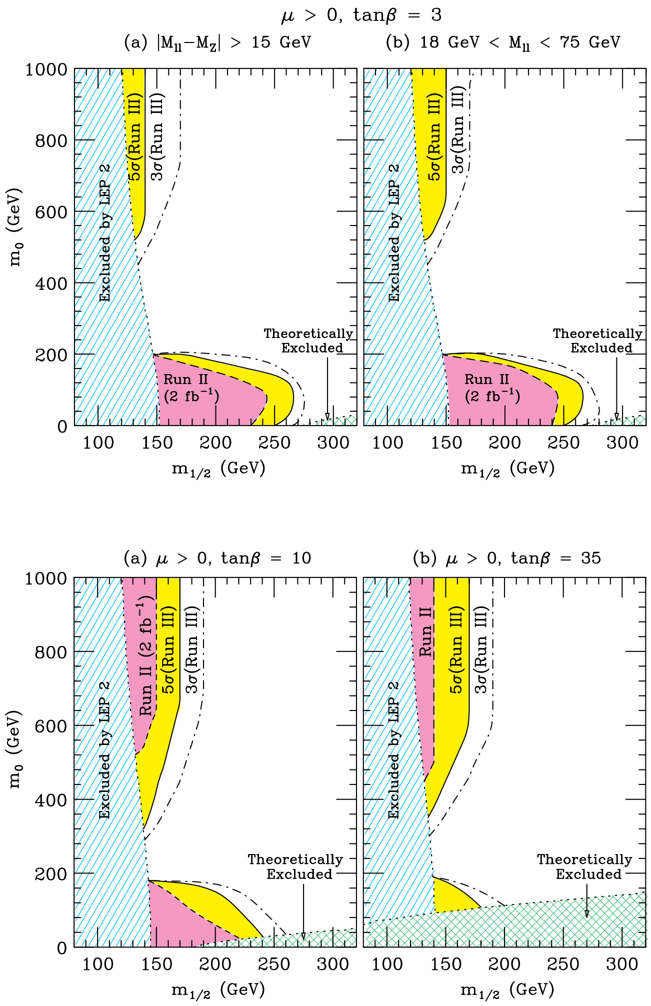

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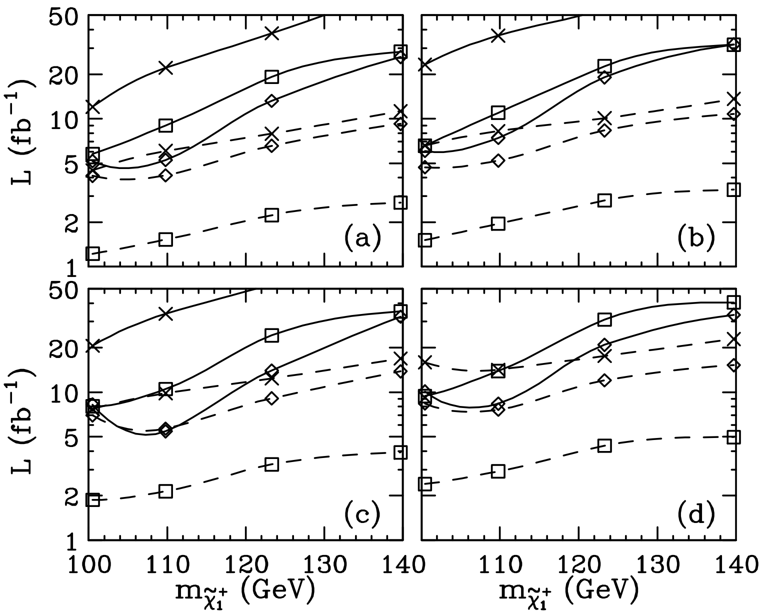
- large $\tan\beta \to M_{1/2}$ as high as 140–180 GeV

this includes leptonic tau channels

$m_{\tilde{\chi}_1^\pm} \sim$ 110 to 200 GeV $\qquad M_{\tilde{g}} \sim$ 400 to 600 GeV

• Light $\tilde{\tau}$ and direct detection of τ's via their hadronic decays

total integrated luminosity needed for a 3 σ (solid) and a 5 σ (dashed) for trileptons (x) and dileptons (□), like-sign dileptons (◇) plus a tau jet

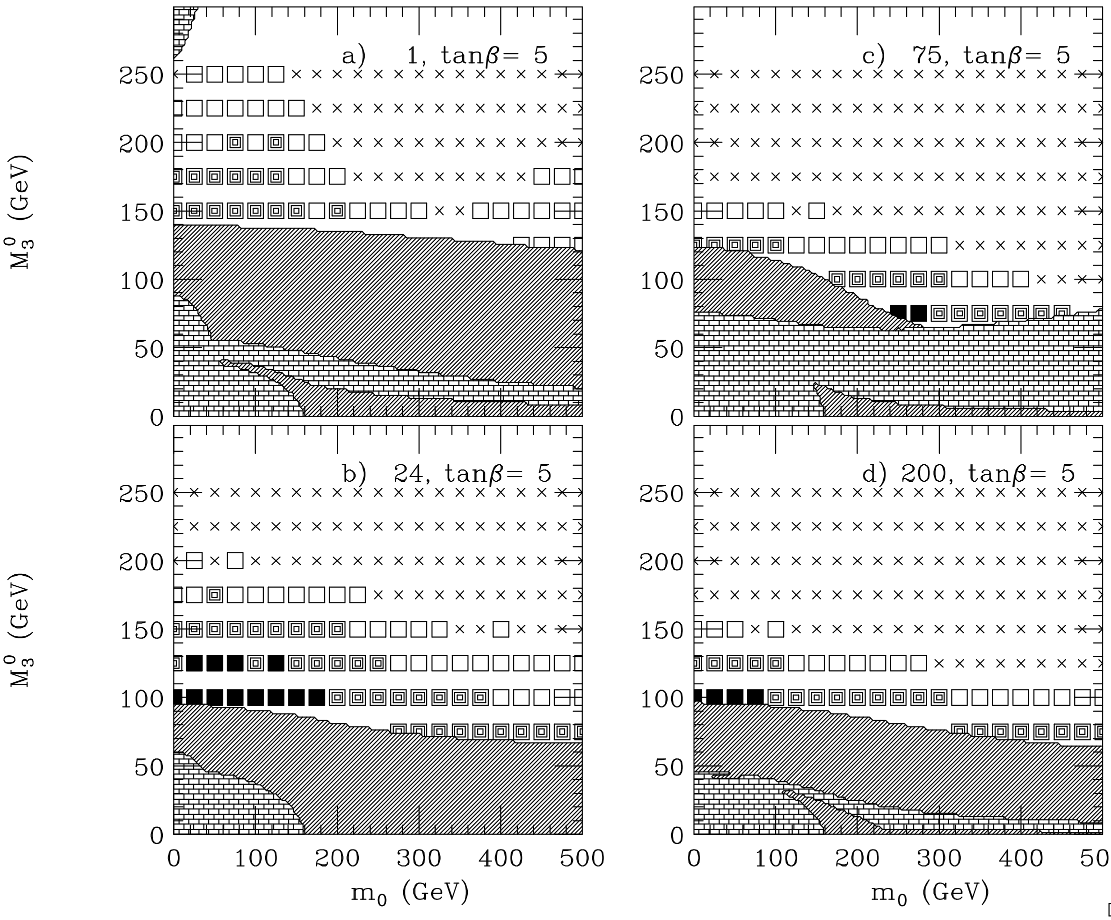


– Comparison of trilepton mode with dileptons plus tau jet and like-sign dileptons plus a tau jet

$\longrightarrow$ shows good sensitivity in tau jet channels

(better study of tau trigger eff. needed)

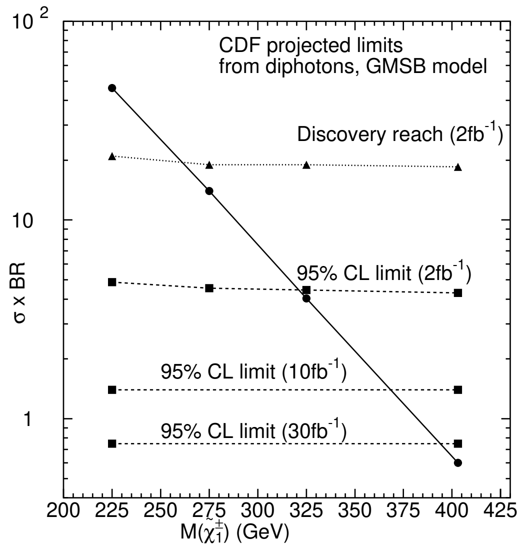
Nonuniversal gaugino Masses: Implications for Tevatron SUSY searches

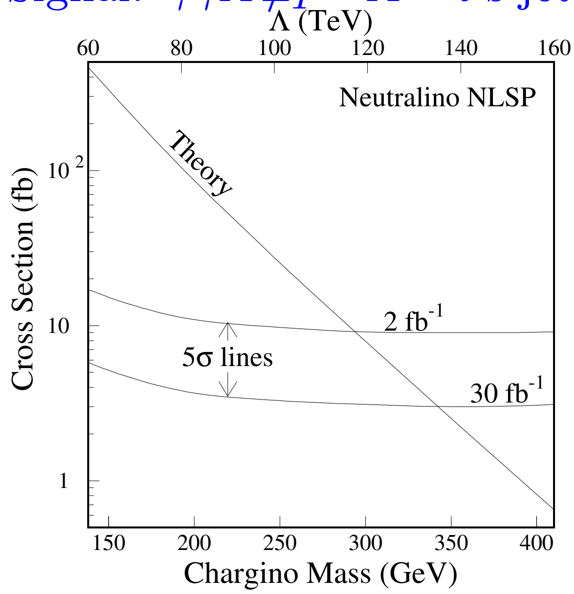


[CUMULATIVE]

Gauge-mediated Tevatron reach

- Bino-like NLSP: $\tilde{\chi}_1^0 \to \gamma \tilde{G}$ Signal: $\gamma\gamma X \not{E}_T$ $X = \ell$'s jets



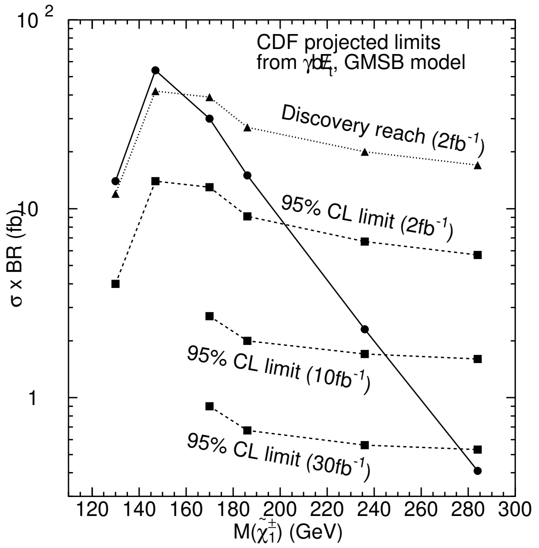


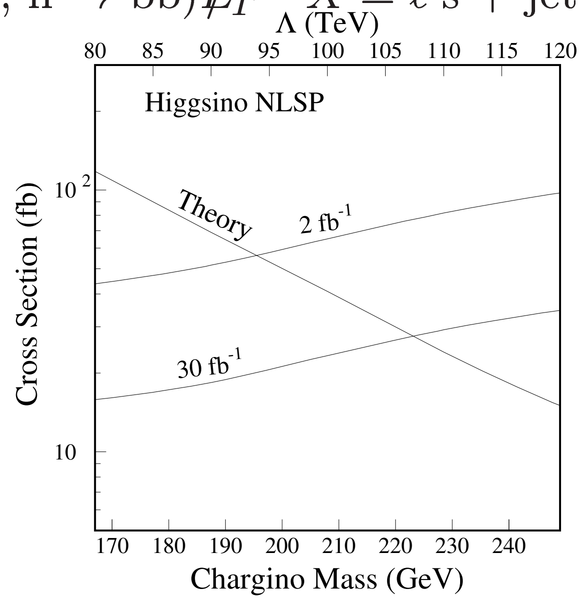
$M_{\tilde{\chi}^{\pm}} \sim$ 300–400 GeV *(excl.)* & 280–350 GeV *(disc.)*

- Higgsino-like NLSP:

$\tilde{\chi}_1^0 \to (h, Z, \gamma)\tilde{G}$ Signal: γ b $\not{E}_T X$

Diboson Signatures (Z $\to$ ll/jj; h $\to$ bb)$\not{E}_T$ $X = \ell$'s + jets





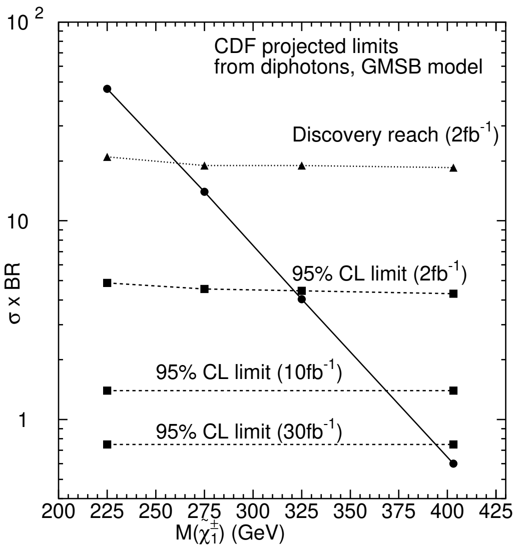
$\to m_{\tilde{\chi}_1^{\pm}}$ to 200, 250, 280 GeV (95% C.L.) for 2, 10, 30 fb^{-1}

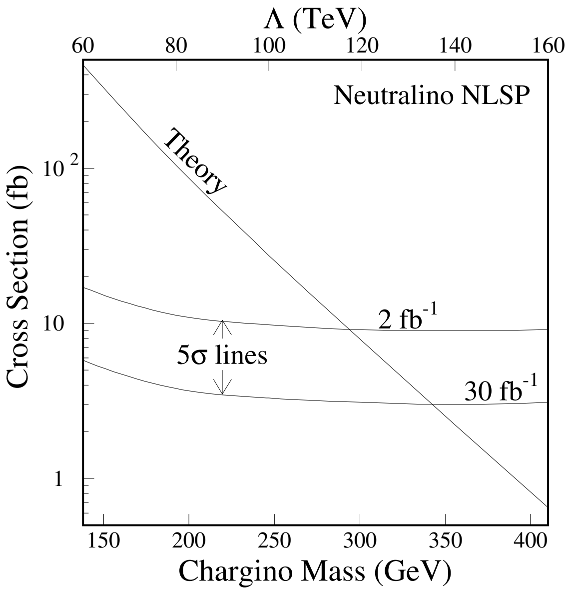
Gauge-mediated diphoton Tevatron reach

SUSY/Higgs Gauge Mediation Report

- Bino-like NLSP: $\tilde{\chi}_1^0 \to \gamma \tilde{G}$ Signal: $\gamma\gamma X \not{E}_T$ $X = \ell$'s jets

- Prompt decays

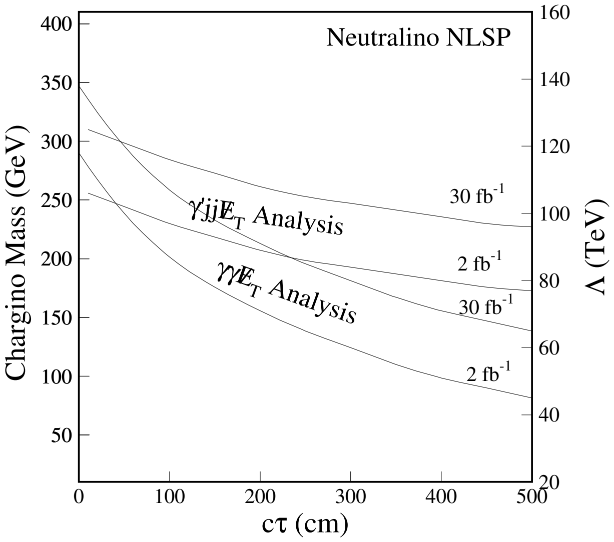




$M_{\tilde{\chi}^\pm} \sim$ 300–400 GeV *(excl.)* & 280–350 GeV *(disc.)*

- Non-prompt decays and photon pointing

it is possible to identify a displaced photon from a secondary vertex and possibly det. decay length using TOF



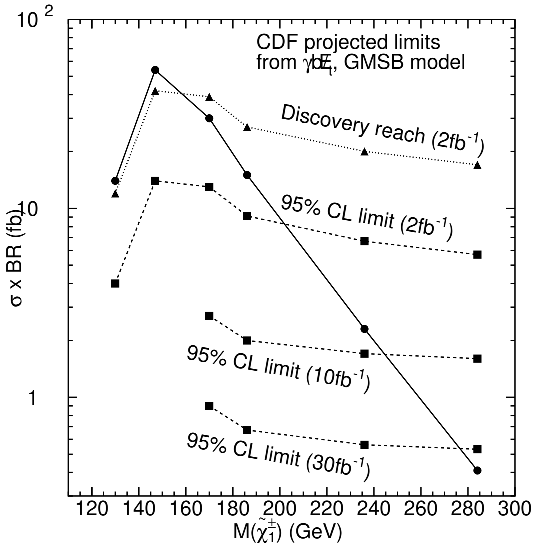
Meas. of decay length → meas. of SUSY breaking scale

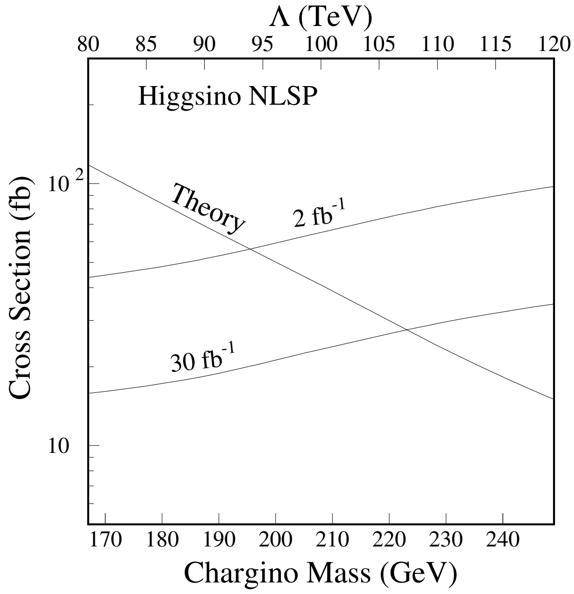
– Higgsino-like NLSP:

$\tilde{\chi}_1^0 \to (h, Z, \gamma)\tilde{G}$ Signal: $(hh, h\gamma, hZ, Z\gamma, ZZ, \gamma\gamma)X \not{E}_T$

Diboson Signatures (Z $\to$ ll/jj; h $\to$ bb)$\not{E}_T$ $X = \ell$'s + jets

- Prompt decays: γ b $\not{E}_T$X channel





$\to m_{\tilde{\chi}_1^\pm}$ to 200, 250, 280 GeV (95% C.L.) for 2, 10, 30 fb^{-1}

$b\bar{b}\not{E}_T X$ channel $\longrightarrow$ less sensitivity; $Z \to \ell^+\ell^-$ $\longrightarrow$ useful

- Non-prompt decays
(few 100 TeV $\leq \sqrt{F} \leq$ few 1000 TeV)

$\Longrightarrow$ displaced γ's or secondary vertices from $b\bar{b}$, jj, $\ell^+\ell^-$

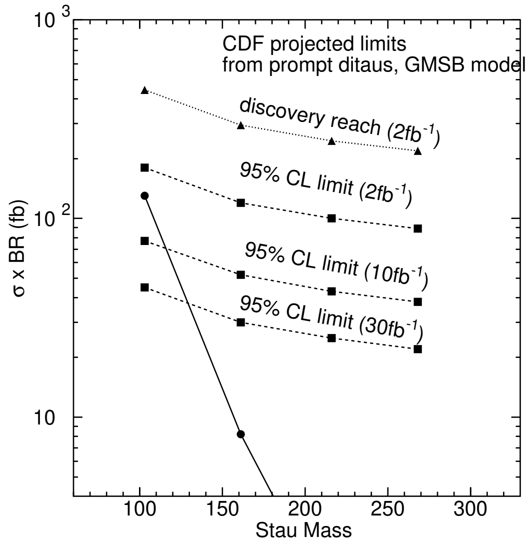
Search for displaced Z's using large E_T displaced jet with finite impact parameter or diplaced l's should be explored.

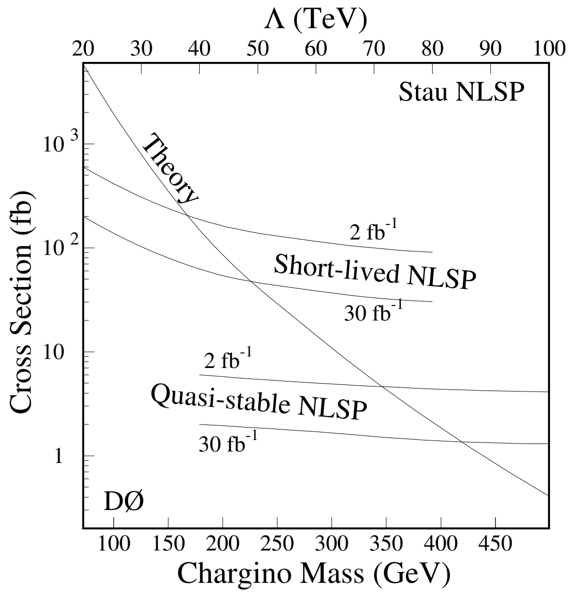
- If $\sqrt{F} \geq$ few 1000 TeV $\Longrightarrow$ outside detector decay looks like traditional $\tilde{\chi}_1^0$ LSP

– Stau NLSP: $\tilde{\tau}_1 \to \tau \tilde{G}$

prompt decays: *Signal:* 2 high-p_T τ's + high $\not\!\!E_T$

$\tau \to$leptonic or hadronic decays





CDF: $m_{\tilde{\tau}} \to$ 100–130 GeV
95% CL for 2–30 fb^{-1}
(improved for direct τ triggers...)

DØ: $m_{\tilde{\tau}} \to$ 80–120 GeV
5σ discovery for 2–30 fb^{-1}

- quasi-stable $\tilde{\tau}$'s:

Signal: highly-ionizing tracks, extra μ-like tracks

CDF: 2 fb^{-1} $\Longrightarrow$

$m_{\tilde{\tau}} > 150$ GeV *(excl.)*

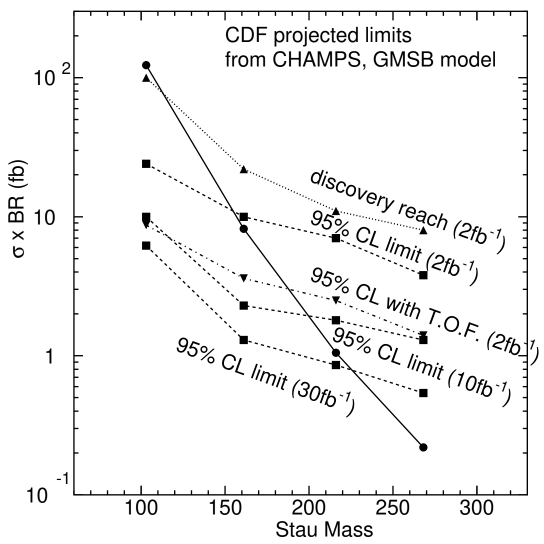
~ 110 GeV *(disc.)*

10–30 fb^{-1} $\Longrightarrow$

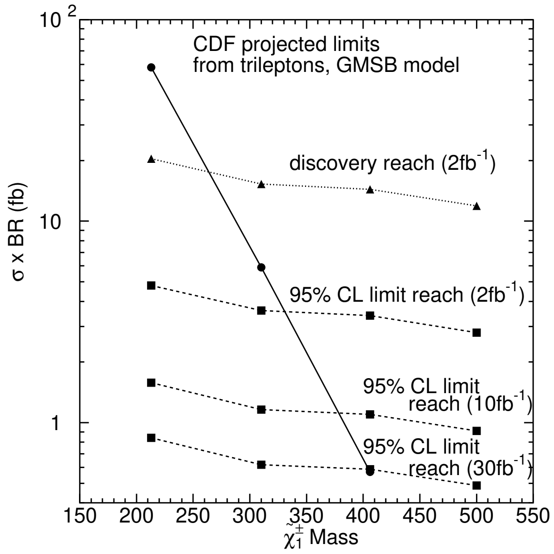
$m_{\tilde{\tau}} > 200$–225 GeV *(excl.)*

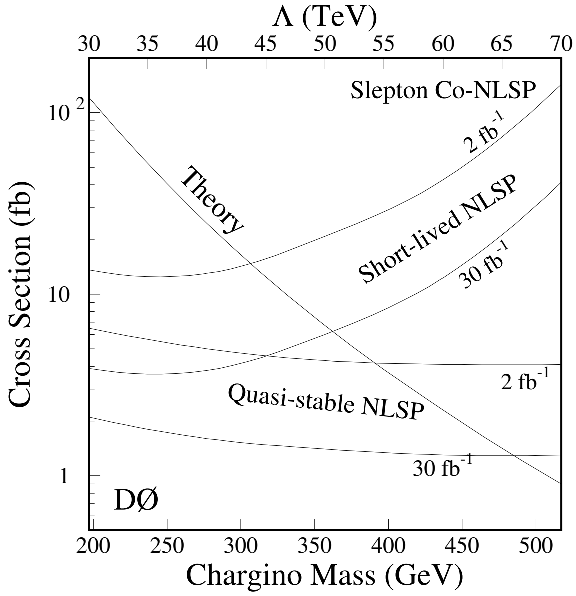
DØ: 2–30 fb^{-1} $\Longrightarrow$

$m_{\tilde{\tau}} \sim 175$–220 GeV *(disc.)*



– Slepton CO-NLSP:





Signatures

- $\not\!\!E_T$ → useful for searches with stable LSP
- Trileptons → signature for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, R-parity violation
- Dileptons → search for squarks/gluinos, chargino/neutralino, R-parity violation
- Flavor Tagging + leptons + $\not\!\!E_T$ → search for stops/sbottoms
- Photons → distinctive signature in gauge-mediated models
- charged tracks with no $\not\!\!E_T$ → gauge-mediated, long-lived staus

Tevatron searches for extra dimensions

If SM particles confined to 4-d. brane but gravity can propagate into Extra Dimensions

$M_{Pl}^2 = M^{2+d} R^d$ M = effective Planck scale in 4+d

in 4-d world, gravity can be seen as cumulative effect of Kaluza-Klein modes of the graviton

Non-observation of anomalous gravity effects
$\Longrightarrow$ R $\leq$ 0.2 mm.

At the Tevatron: can look for the effects caused by the creation of real or virtual KK gravitons $\rightarrow$ Any KK graviton couples very weakly to ordinary matter but the total number of modes may be huge $\propto (\sqrt{s}R)^d$

- jets + $\not{E}_T$ signatures from massive graviton emission
$\sigma \propto (\sqrt{s}/M)^{d+2}$: strongly dep. on # of dim. d

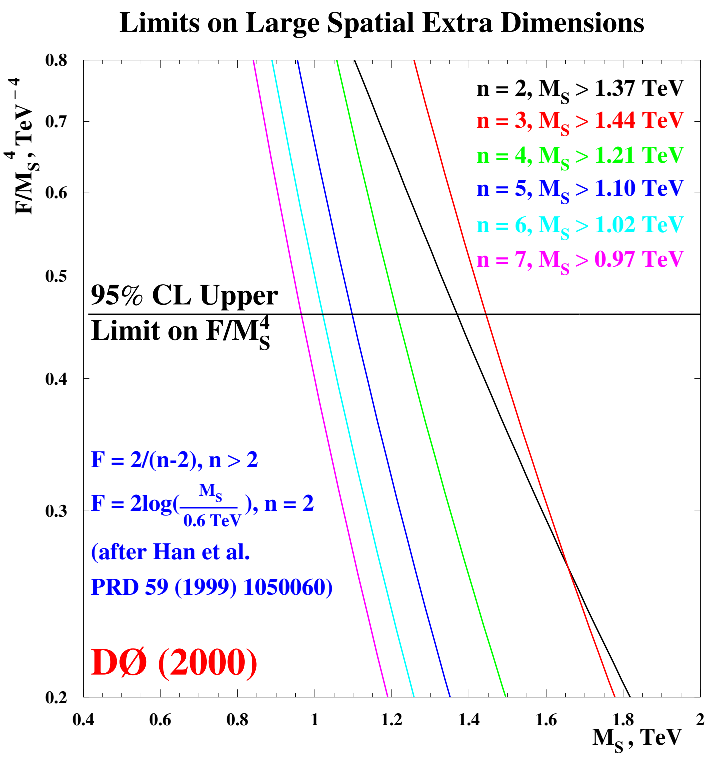
- Drell-Yan plus diphoton signatures from virtual graviton exchange.

$$\sigma_{ll,\gamma\gamma} \propto \sigma^{SM} + \sigma^{SM-KKmodes} + \sigma^{KKmodes}$$
$$\sigma^{SM-KKmodes} \propto c^{d-2}\ (\sqrt{s}/M)^4$$
$$\sigma^{KKmodes} \propto c^{2d-4}\ (\sqrt{s}/M)^8$$

with $\Lambda_{cutoff} = c\ M$

Drell-Yan and Diphoton Production via Virtual graviton exchange

95% C.L. lower limits on the effective Planck Scale M at Run 1



95% C.L. lower limits on the effective Planck scale M from virtual graviton exchange at Run 2:

Run 2a $\Longrightarrow$ 1.3–2.5 TeV

Run 2b $\Longrightarrow$ 1.7–3.5 TeV

B Physics

- B physics program complementary to direct searches of new physics
- Both CDF and DØ $\rightarrow$ major upgrades
$\Longrightarrow$ vastly improved B physics potential at Run 2
- Tevatron: main source of B_s before the LHC era

Measurements that test the SM and can reveal new physics

◇ Test CP violation:

$B^0 \rightarrow J/\psi K_s$ $\qquad\qquad$ $B_s \rightarrow J/\psi\phi$

◇ Measure $\frac{|V_{td}|}{|V_{ts}|}$ via B_s mixing

◇ Rare Decays

CP Violation Golden Mode: $B^0 \to J/\psi K_s$

measurement of the time dependent asymmetry

$$A_{CP} = \frac{N(\bar{B}^0 \to \psi K_s) - N(B^0 \to \psi K_s)}{N(\bar{B}^0 \to \psi K_s) + N(B^0 \to \psi K_s)} = \sin(2\beta_{\psi K}) \sin(\Delta m_{B_d} t)$$

in SM $\sin(2\beta_{\psi K}) = \sin(2\beta) \qquad \beta \equiv arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$

the time integrated asymmetry:

$A_{CP} = \frac{x_d}{1+x_d^2} \sin(2\beta_{\psi K}) \qquad x_d = \tau(B_d)\Delta m_{B_d}$

The measured asymm. involves a flavor-tag dilution factor D

The uncertainty in $\sin(2\beta_{\psi K}) \propto \frac{1}{\sqrt{\epsilon D^2 N}}$

$\epsilon =$ flavor-tag eff. (Run2: ϵD$^2 \approx 50\%$ improv.)

At present:

$\sin(2\beta_{\psi K}) = 0.75 \pm 0.09 \pm 0.04$ (BaBar)
$\sin(2\beta_{\psi K}) = 0.82 \pm 0.12 \pm 0.05$ (Belle)
$\sin(2\beta_{\psi K}) = 0.79 \ ^{+0.41}_{-0.44}$ CDF

In models with new CP violation $\Longrightarrow$
$\sin(2\beta_{\psi K}) \neq \sin(2\beta)$ or SM predic. for $\sin(2\beta)$ may have additional contributions

Measurement of B_s Mixing $\Longrightarrow x_s$

- ratio of B_d to B_s mixing

$\Longleftrightarrow$ measurement of x_d and x_s

determines $|V_{td}|/|V_{ts}|$ (cancell. QCD uncertainties)

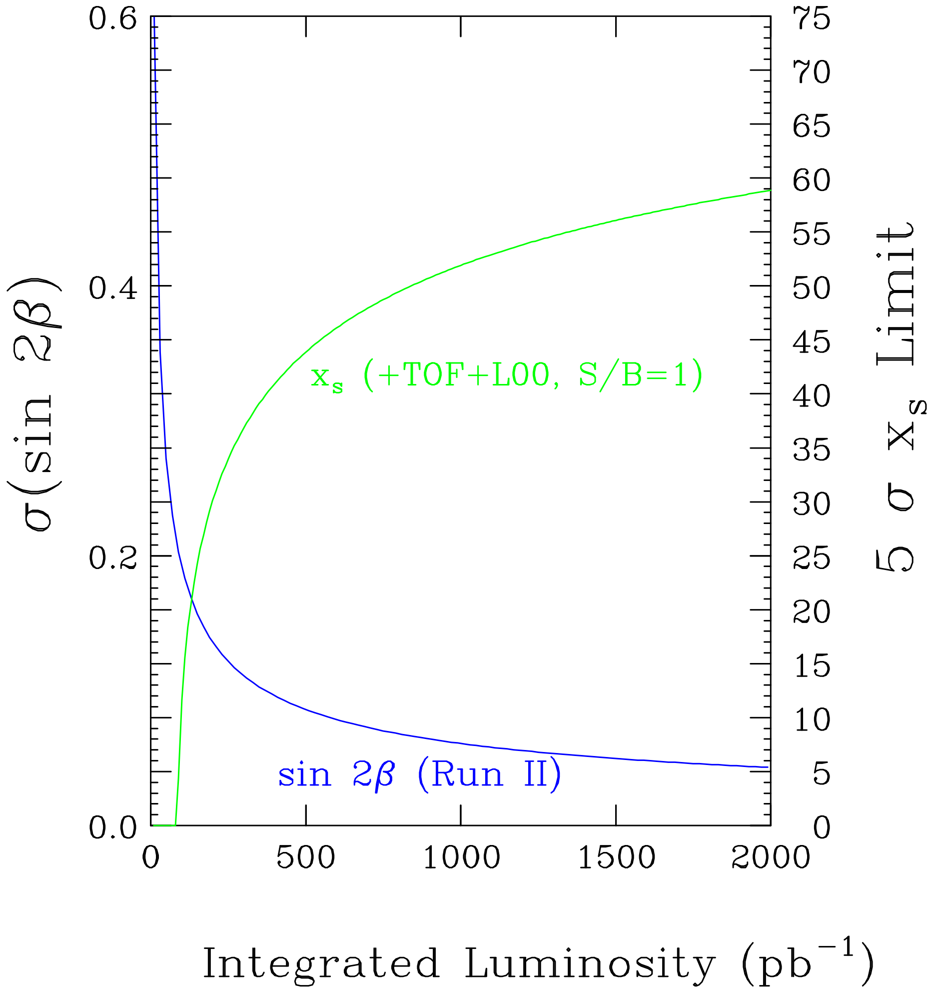
$$\frac{\Delta m_{B_s}}{\Delta m_{B_d}} = \frac{|V_{ts}|^2}{|V_{td}|^2} \frac{M_{B_s}}{M_{B_d}} \xi^2$$

but needs lattice calculation
at present $\xi^2 = \frac{f^2_{B_s} B_{b_s}}{f^2_{B_d} B_{b_d}} \approx (1.17 \pm 0.06)^2$
(unquenched computation necessary)

Within the SM: x_s range between 20 and 45 $\rightarrow$ from global analysis of unitarity triangle

to get past current limit ($x_s > 22.5$), need fully reconstructed B_s decays
$\Longrightarrow$ with dedicated trigger for semileptonic decays ($B_s \rightarrow D_s l \nu$) $\Longrightarrow x_s \rightarrow 30$)
best option: SVX based, all hadronic trigger
($B_s \rightarrow D_s \pi(3\pi), D_s \rightarrow \phi\pi, K^* K$)

Run 2a Projections for $\sin(2\beta_{\psi K})$ and x_s

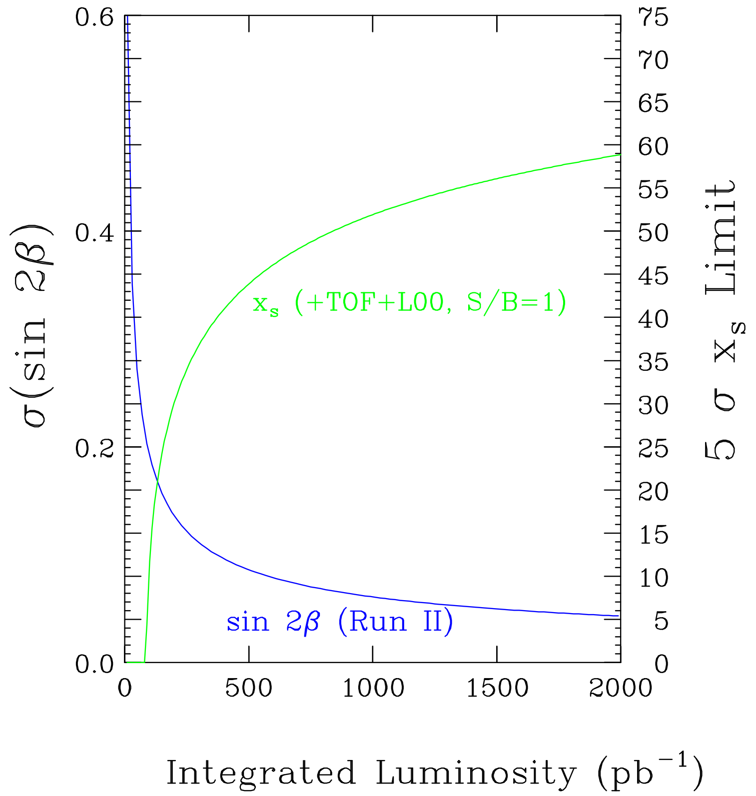


- $\sin(2\beta)$ CDF/DØ meas. will be competitive with Belle and BaBar
- x_s meas. requires silicon vertex trigger for $x_s > 30$
- once there is a 5σ observation of x_s $\rightarrow$ it is a very precise meas. (a few % uncertainty)

Run 2a Projections for $\sin(2\beta_{\psi K})$ and x_s

Measurement of B_s Mixing $\Longrightarrow$ x_s determines $|V_{td}|/|V_{ts}|$

- once there is a 5σ observation of x_s $\rightarrow$ it is a very precise meas. (a few % uncertainty)



In SM $\sin(2\beta_{\psi K}) = \sin(2\beta)$ $\qquad \beta \equiv arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right]$

- Tevatron Run 2: measurement of the asymmetry in $B^0 \rightarrow J/\psi K_s$ will be competitive with Belle & BaBar

In models with new CP violation $\Longrightarrow$ $\sin(2\beta_{\psi K}) \neq \sin(2\beta)$ or SM predic. for $\sin(2\beta)$ may have additional contrib.

- The Tevatron B physics program complementary to direct searches of new physics

Overview

Tevatron Run 2 $\Longrightarrow$ very rich and broad physics potential

- Starting from the first few hundred pb^{-1}:

• B Physics: CP Violation

$\Longrightarrow \sin(2\beta_{\psi K}) \rightarrow$ tests new physics

- With increasing integrated Luminosity ($\geq 2\ \mathrm{fb}^{-1}$):

• precise meas. of M_t, M_W and A_{FB}

$\Longrightarrow$ implacable test of the SM!

• *Furthermore*, search for new physics via top physics.

• SUSY particle Searches:

$m_{\tilde{t}} \sim 160 - 300$ GeV, $m_{\tilde{b}} \sim 200 - 400$ GeV,
$m_{\tilde{\chi}^{\pm}} \sim 100 - 350$ GeV, $m_{\tilde{g}} \sim 400 - 600$ GeV

test many different scenarios

• Search for Exotic Physics and Extra Dimensions

- Maximal demand on total integrated luminosity and detectors performance:

• Higgs Physics:

SM $\Longrightarrow$ test Higgs mass region preferred by precision data
Probe MSSM through its Higgs sector

High integrated Luminosity $\Longrightarrow\ \simeq 15\ \mathrm{fb}^{-1}$
top priority for Higgs search at the Tevatron.