Search for New Particles

Eilam Gross Weizmann Institute of Science

The searchers:

Mainly LEP e^+e^-

Aleph Delphi L3 Opal

Year	E_{CM} GeV	Lum/Exp
1996	161	10 pb^{-1}
1996	172	10 pb^{-1}
1997	183	55 pb^{-1}
1998	**189**	**175 pb^{-1}**
1999	**192**	**~ 27 pb^{-1}**
1999	**196**	**~ 27 pb^{-1}**

TEVATRON: CDF D0

$P\bar{P}$ 1800 GeV ~110 pb^{-1}/exp

HERA:			H1	ZEUS
'94-'97	e^+P	300 GeV	37 pb^{-1}	47 pb^{-1}
'98-'99	e^-P	318 GeV	14 pb^{-1}	16 pb^{-1}

Acknowledgments & Credits

- F. Gianotti, A. Kirk, E. Perez, M. Kuze, J. Qian, J.Conway, F. Borzumati, G. Mikenberg, P. Igo-Kemenes

  Most of the input from P.S. 7

  Beyond the SM: F. Gianotti, A. Masiero
- SM Higgs: A. Read, J. Valls, J Mnich
- SUSY Higgs: P. Gay, J. Valls, M. Teresa-Roco, G. Weiglein
- SUSY: H. Nowak, L. Serin, F. Ledroit, C. Rembser, N. Brummer, A. Savoy-Navarro
- Exotica: A.Kounine, G. Landsberg. M. Oreglia, E. Perez, D. Dominici
- LEP 196: F. Cerutti, M. Gruwe, S. Gentile, M. Pimenta
- Glueballs: A. Kirk

Appologies...

APPOLOGIES TO THOSE WHO WERE FORGOTTEN

LEP:

Aleph
Delphi
L3
Opal

ADLO=Combined LEP

Similar results from the other experiments

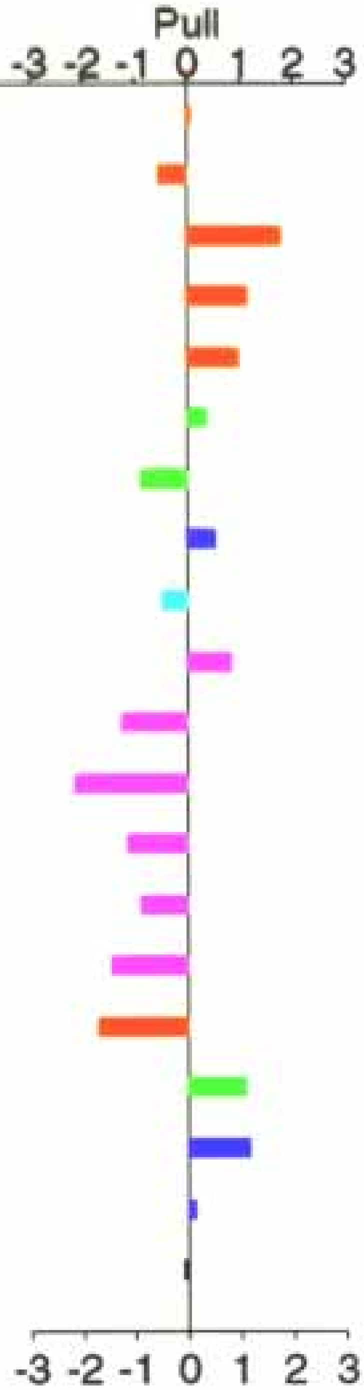
All numbers are given in GeV unless indicated otherwise!

The Standard Model is Very Healthy

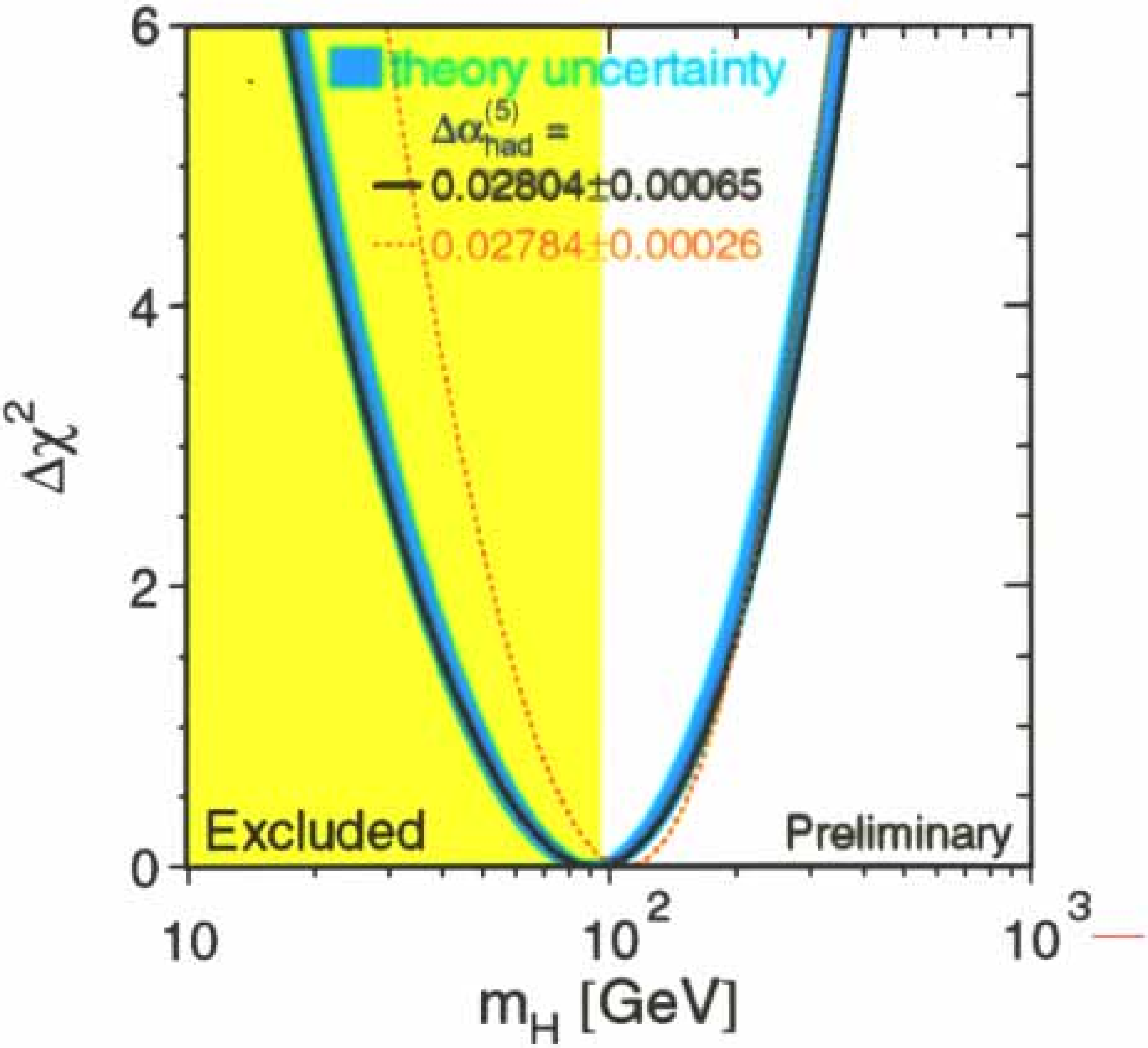
Desperately seeking for a Higgs boson

Tampere 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.07
Γ_Z [GeV]	2.4944 ± 0.0024	-.53
σ^0_{hadr} [nb]	41.544 ± 0.037	1.78
R_e	20.768 ± 0.024	1.15
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.96
A_e	0.1483 ± 0.0051	.35
A_τ	0.1425 ± 0.0044	-.91
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.51
m_W [GeV]	80.350 ± 0.056	-.48
R_b	0.21642 ± 0.00073	.83
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0984 ± 0.0020	-2.15
$A^{0,c}_{fb}$	0.0691 ± 0.0037	-1.15
A_b	0.912 ± 0.025	-.90
A_c	0.630 ± 0.026	-1.45
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.71
$\sin^2\theta_W$	0.2255 ± 0.0021	1.09
m_W [GeV]	80.448 ± 0.062	1.15
m_t [GeV]	174.3 ± 5.1	.13
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.10



Fit to Electroweak PM



Eidelman, Jegerlehner

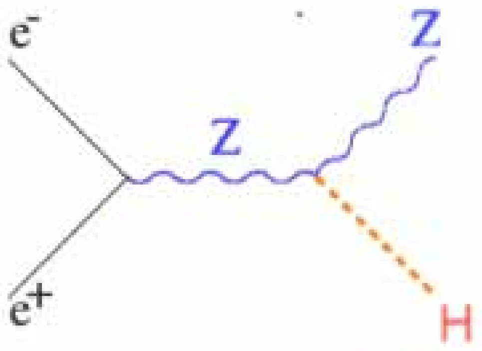
$$m_H = 92^{+78}_{-45} \Rightarrow m_H < 245 \;\; GeV$$

Davier, Hocker

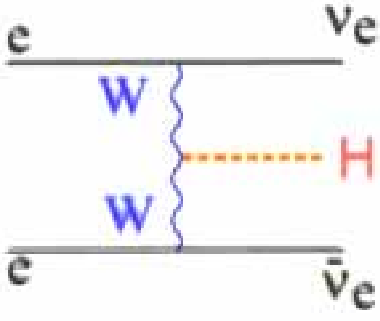
$$m_H = 109^{+67}_{-44} \Rightarrow m_H < 243 \;\; GeV$$

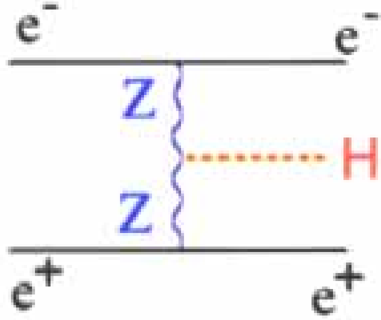
SM Higgs Production at LEP

Bjorken-HiggsStrahlung



WW and ZZ fusion



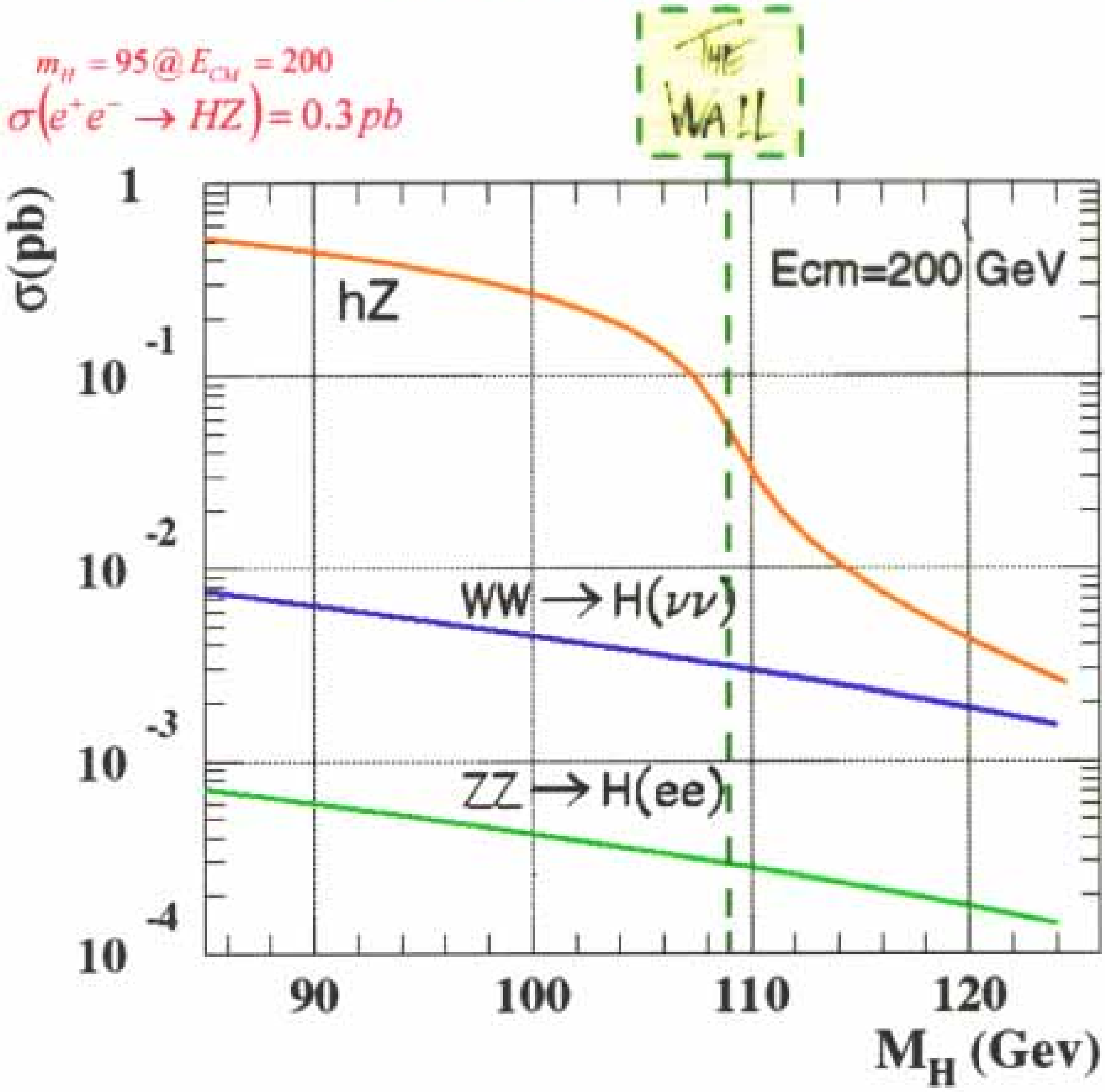


$m_H < E_{CM} - m_Z$

$m_H = 109$ GeV

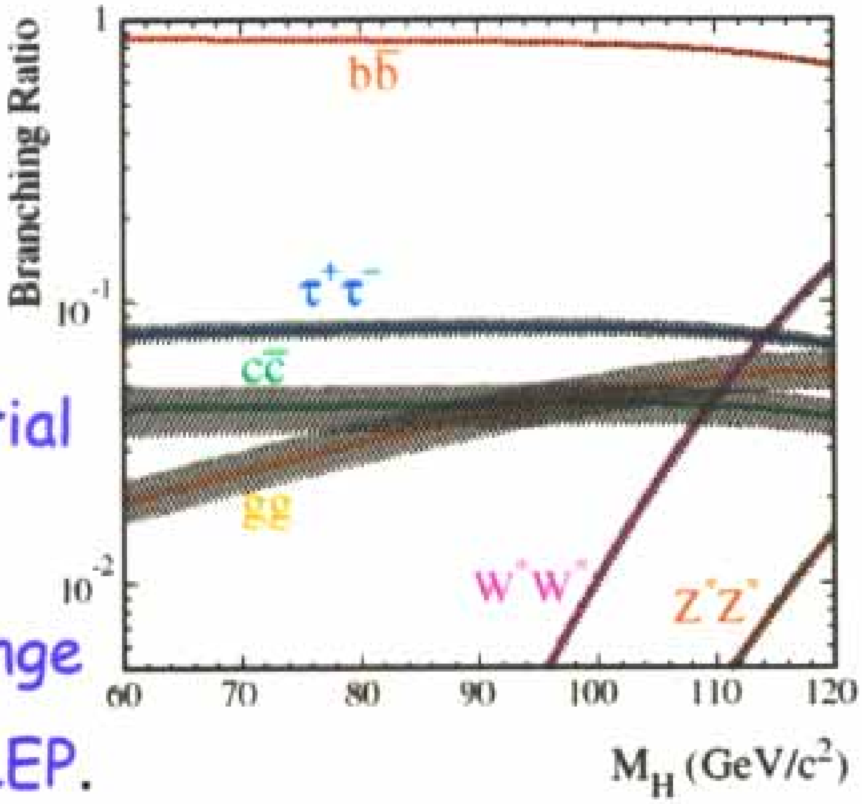
$m_H = 95 @ E_{CM} = 200$

$\sigma(e^+e^- \rightarrow HZ) = 0.3\,pb$

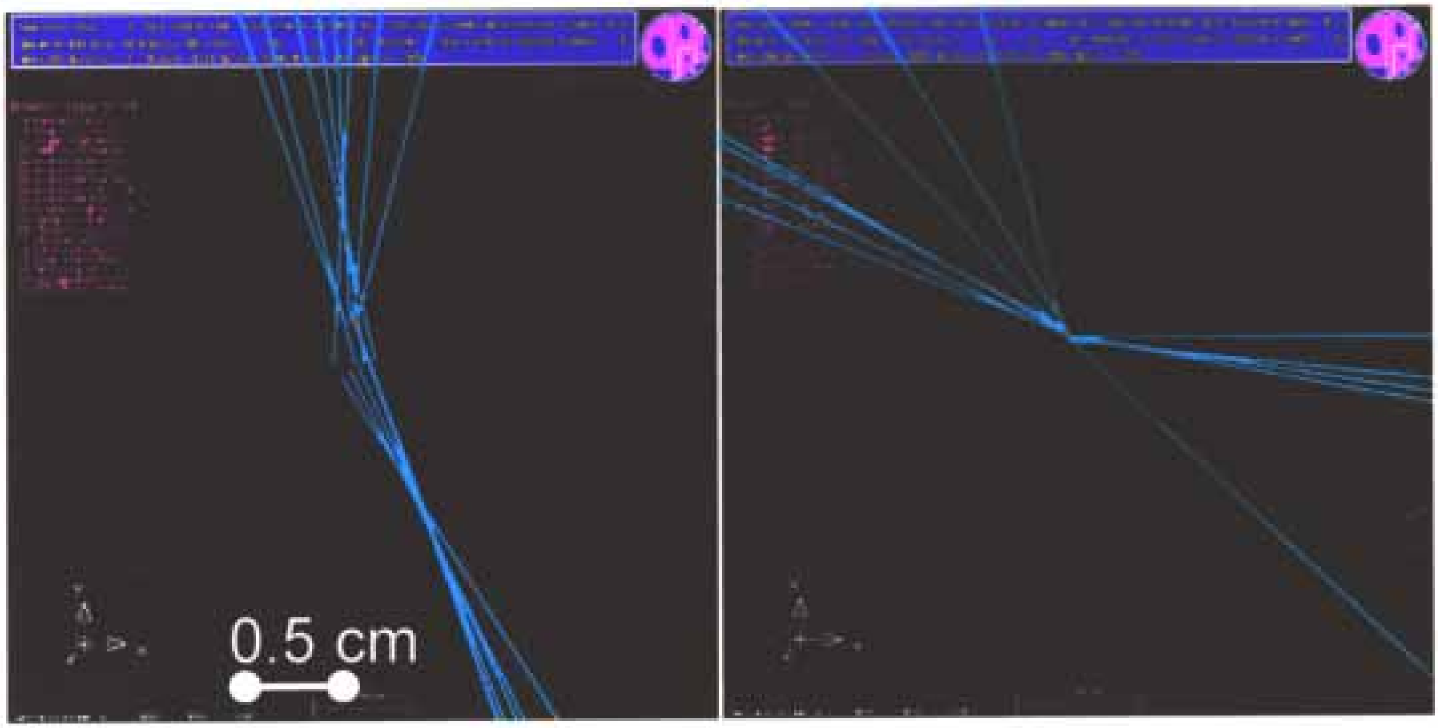


Higgs Decays to bottom quarks

- A Higgs boson decays >85% to $b\bar{b}$
- b-tag is essential to tag Higgs in the mass range accessible at LEP.



$$e^+e^- \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b} \qquad e^+e^- \rightarrow ZZ \rightarrow \nu\nu q\bar{q}$$

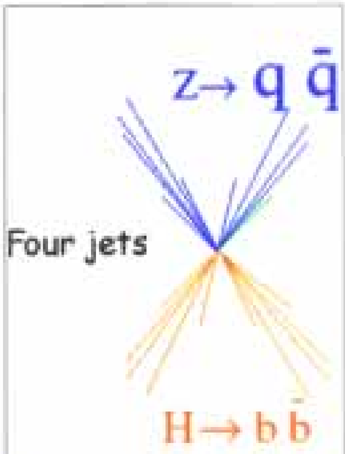


Higgs Search Topologies at LEP

$$H \to b\bar{b}(\sim 85\%), \tau^+\tau^-(\sim 8\%)$$

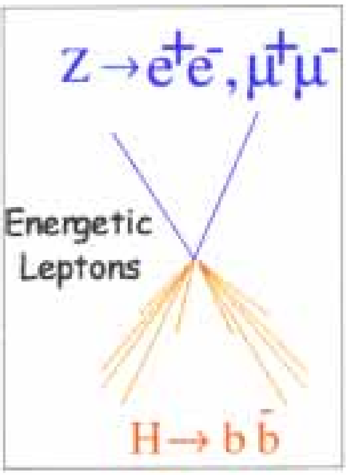
$$Z \to q\bar{q}(70\%), \nu\bar{\nu}(20\%),$$

$$e^+e^- + \mu^+\mu^-(6.6\%), \tau^+\tau^-(3.3\%)$$



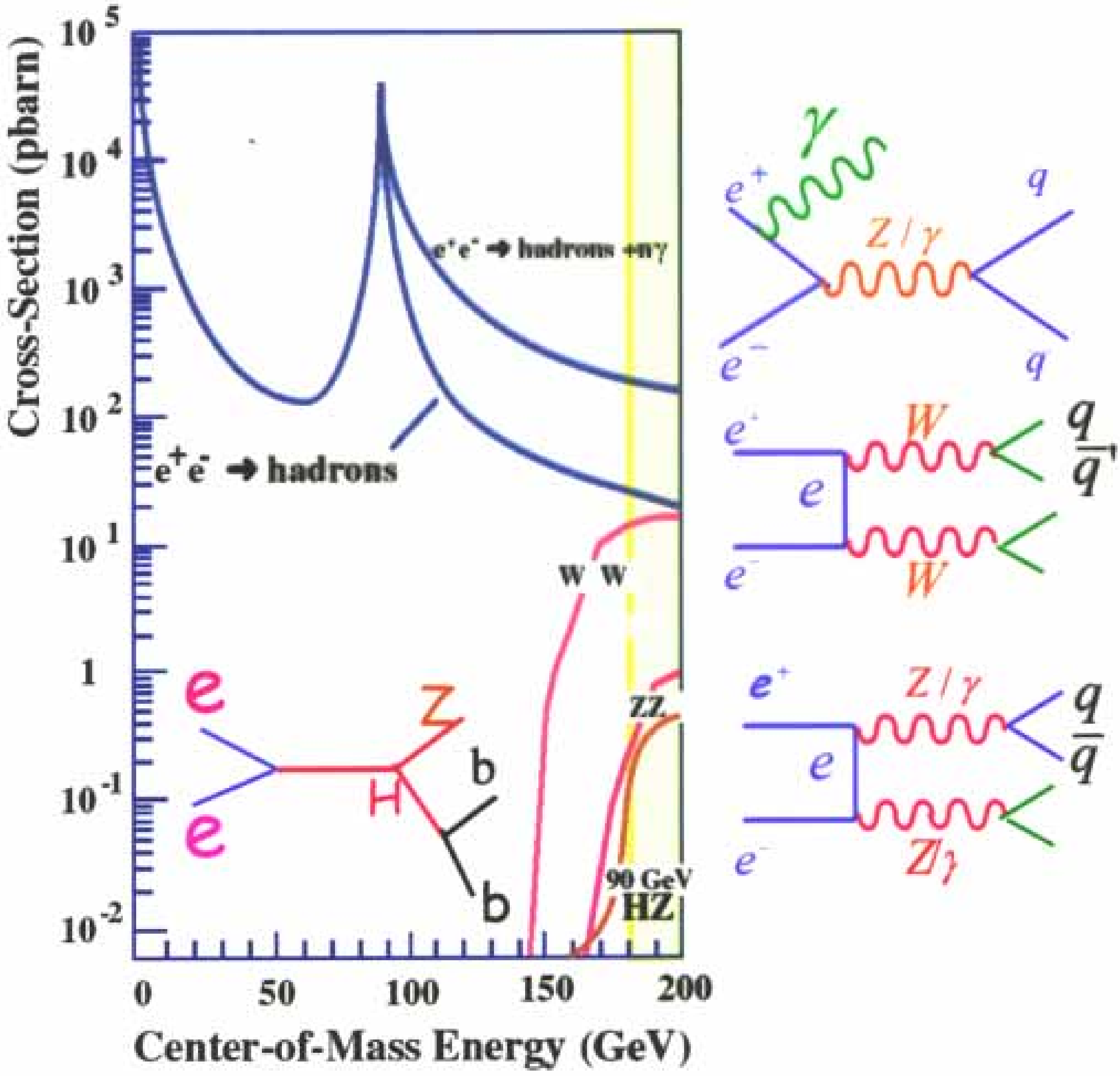
- Energy-momentum conservation
- The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson
- eff 30-40%

- The recoil mass of the 2 b-tagged jets is compatible with a Z boson
- eff 30-40%



- 2 high energetic leptons with a mass compatible with a Z boson recoil against 2 jets.
- Clean channel, high eff ~50-60%

Backgrounds (LEP): Z Z, W W & q q γ

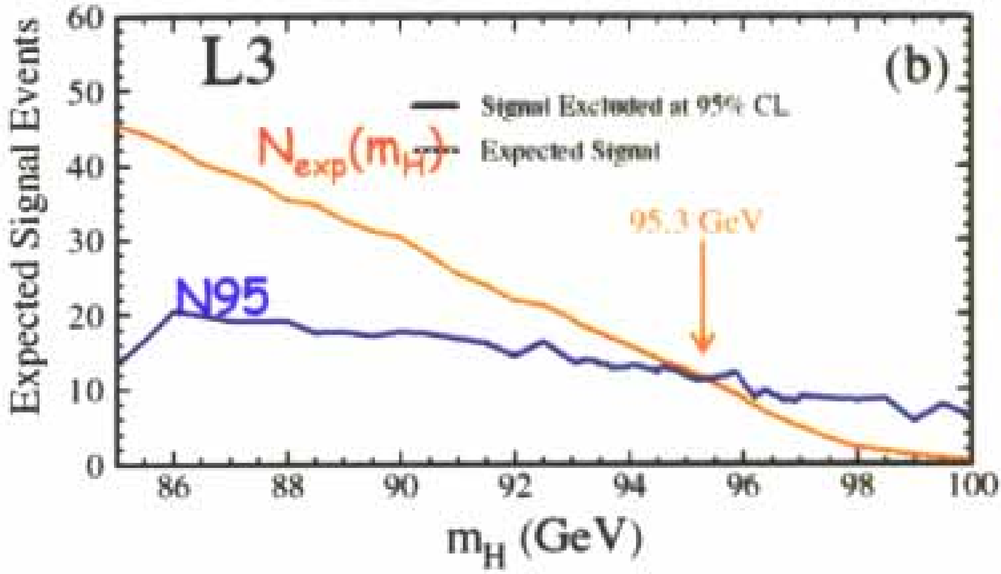


- The most severe background is the 91 GeV Higgs-like irreducible ZZ production.
- Higgs decays to b-quarks >85% of the times.
  Only good b-tag will reduce ZZ and WW bg's.

$$Z \longrightarrow bb = 15\%$$

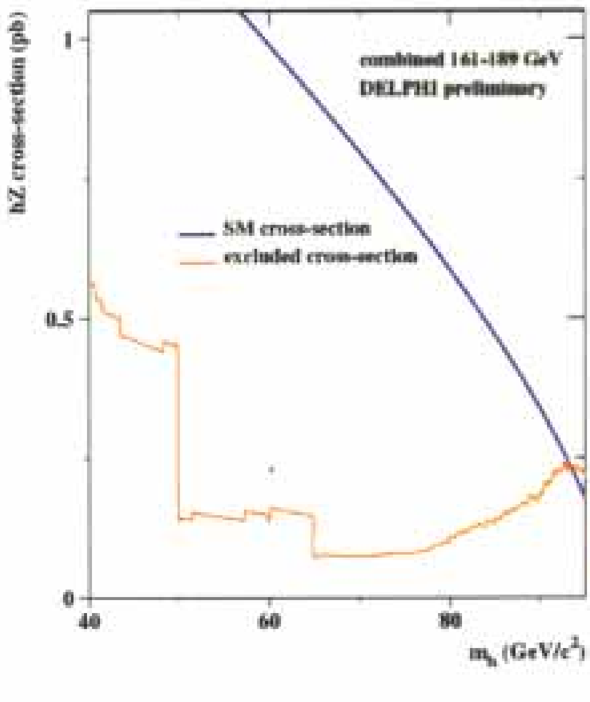
Deriving Limits - Classical Approach

If $N_{exp}(m_H) \geq N_{95}(m)$ a Higgs boson with a mass $m \leq m_H$ is excluded at the 95% Confidence Level



L189
m_H>95.3

L196
m_H>96



DELPHI 189
m_H>94.1 GeV

Observed and Expected Limits

A simplified explanation

A Higgs boson with a mass m_H is excluded if the probability $\Pr ob\left(X_{s+b}(m_H) \leq X_{obs}\right) \leq 5\%$

i.e. $CL_S(m_H) < 5\%$ or $CL = 1 - CL_s > 95\%$

To estimate an experiment sensitivity to find the Higgs boson, one can generate gedanken background experiments and "measure" the CL for each.

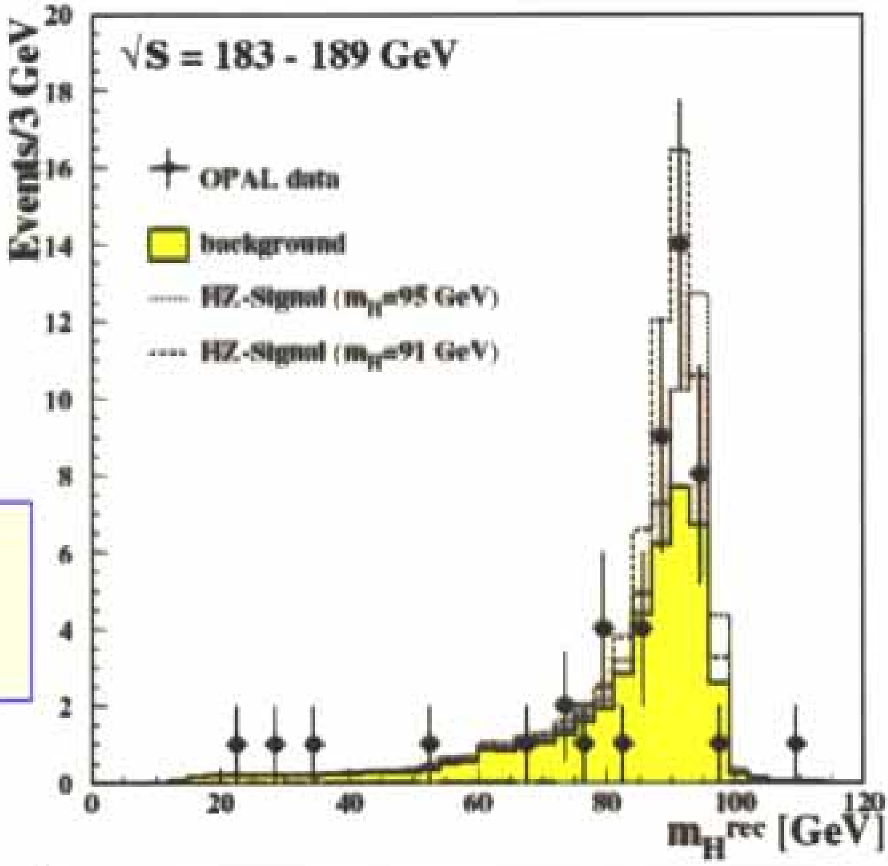
The experiment's sensitivity is expressed in terms of m_H for which the average CL

$$\left\langle CL_s(m_H) \right\rangle \equiv \left\langle 1 - CL(m_H) \right\rangle = 5\%$$

Note: m_H which satisfies $\left\langle CL_s(m_H) \right\rangle = 5\%$ is called the Expected Limit

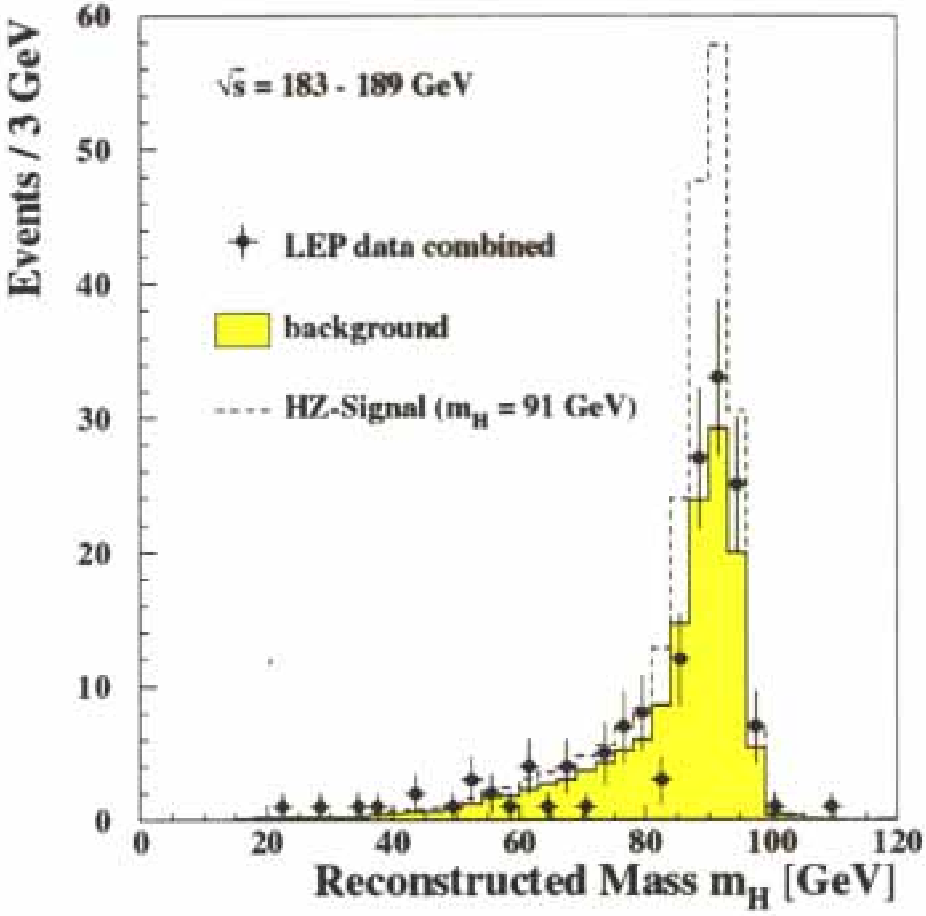
Almost the Nondiscovery of the Year

OPAL 189

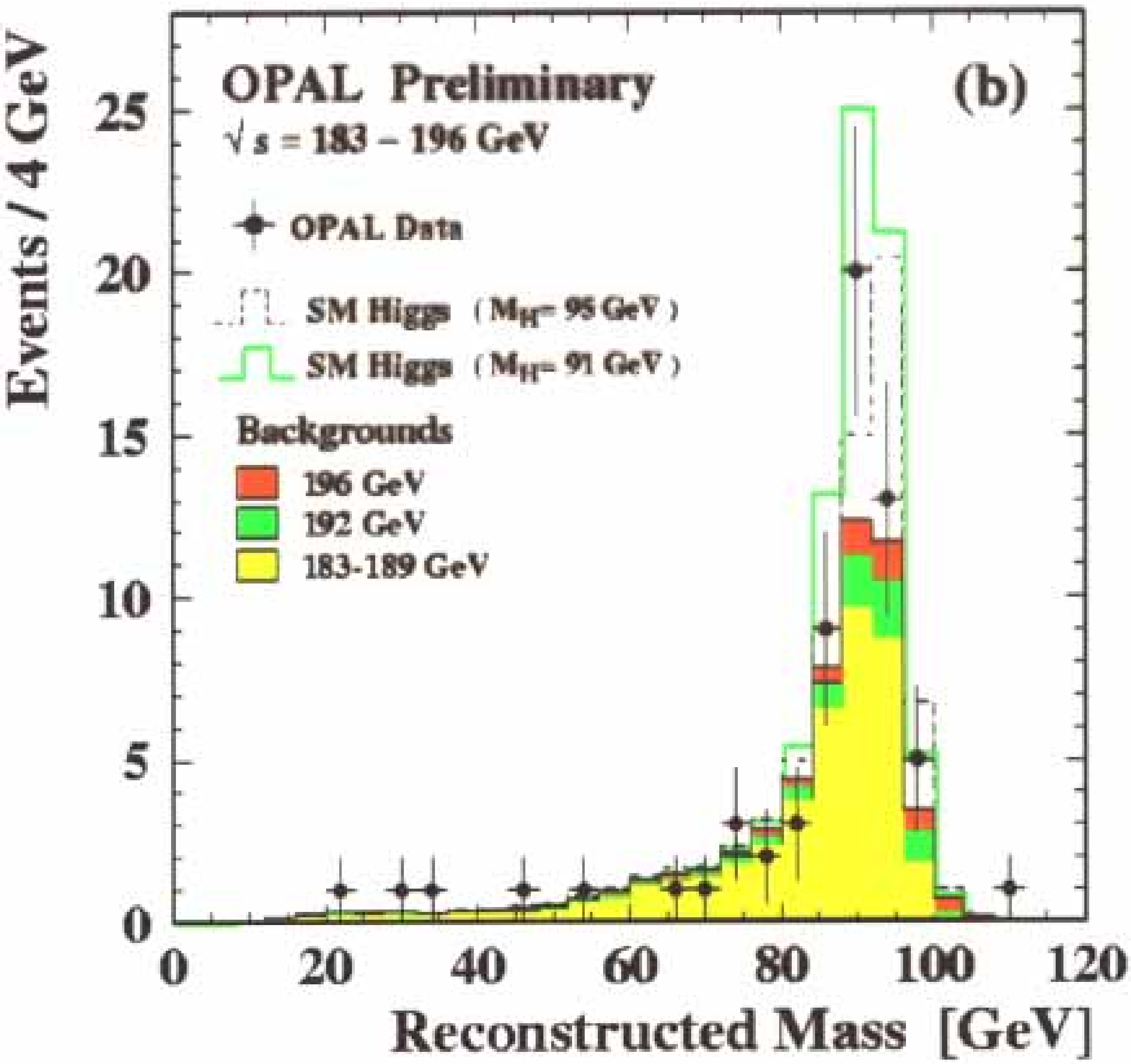


OPAL 189
m_H >91.0 (obs)
94.9 (exp)

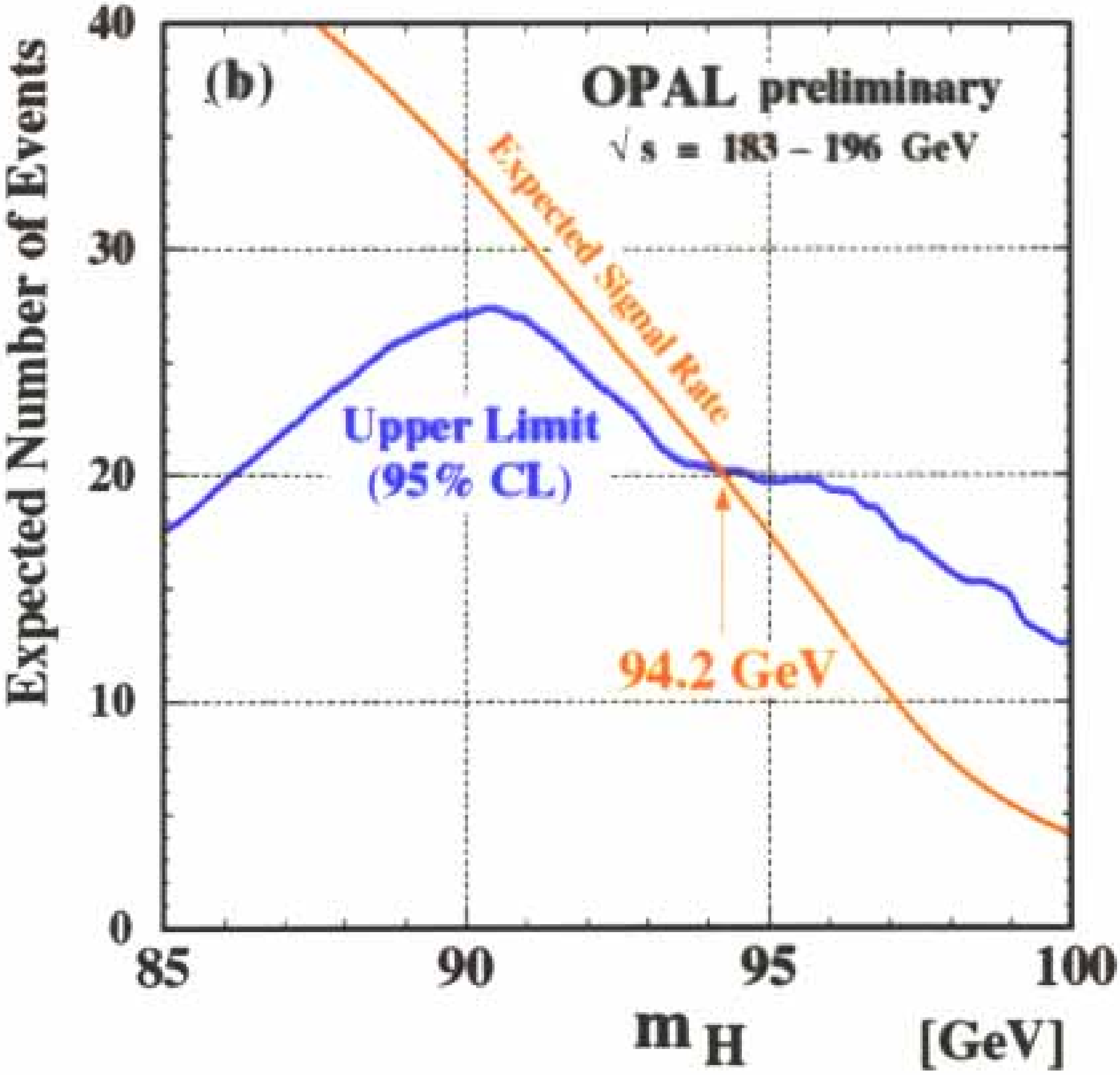
ADLO 189



OPAL Higgs Search at 196 GeV



Over the OPAL Hill at 196 GeV



OPAL 196

m_H >94.2 (obs)

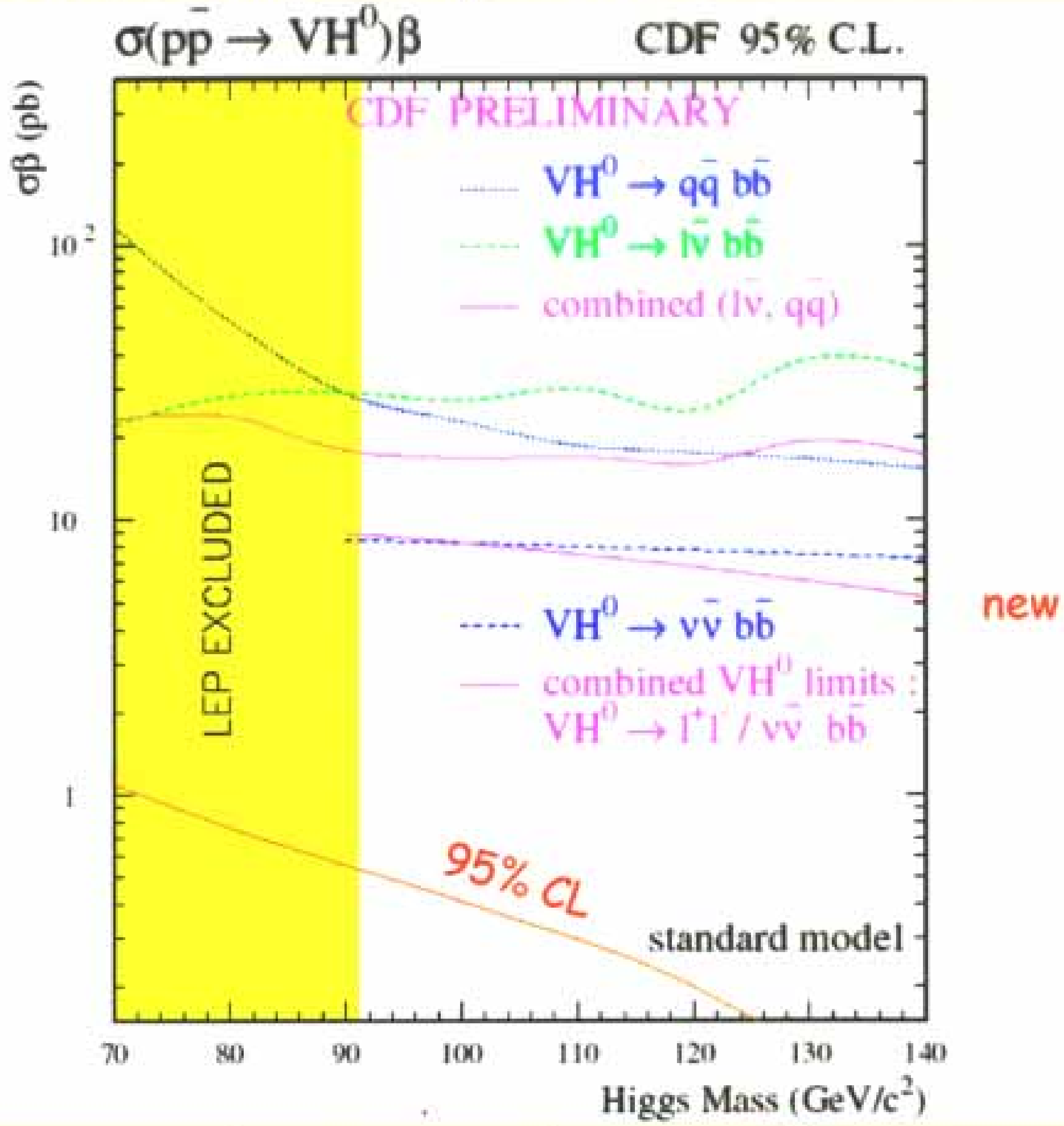
96.0 (exp)

Tevatron SM Higgs Limits

Eventhough the $gg \to H$ is the dominant process

the $WH \to \ell \nu b\bar{b}, q\bar{q}' b\bar{b}, \; ZH \to \nu\bar{\nu} b\bar{b}, \ell^+ \ell^- b\bar{b}$

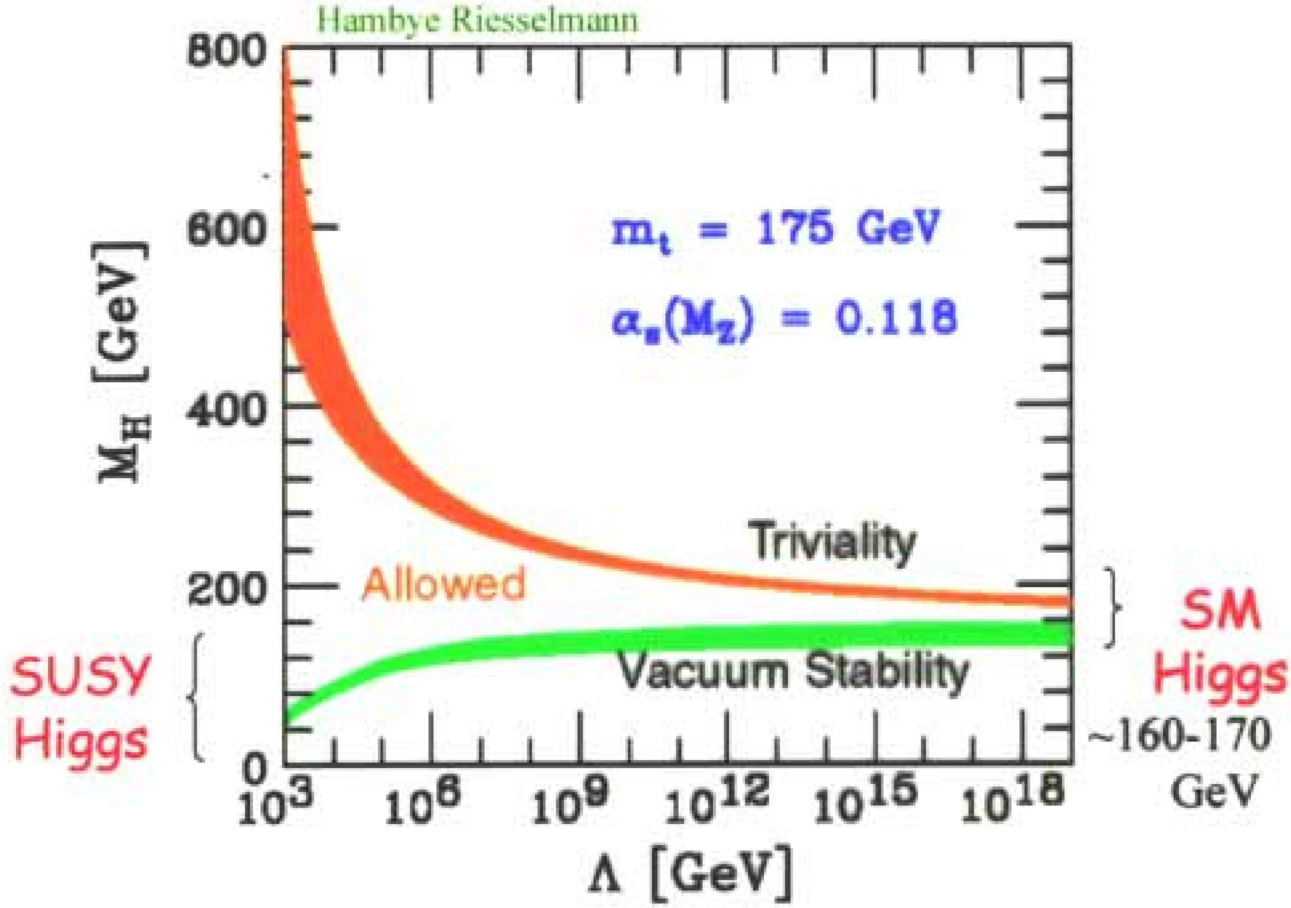
are the most accessible processes .



However, the story ain't over till its over:

- SUSY Higgs
- Tevatron Run II

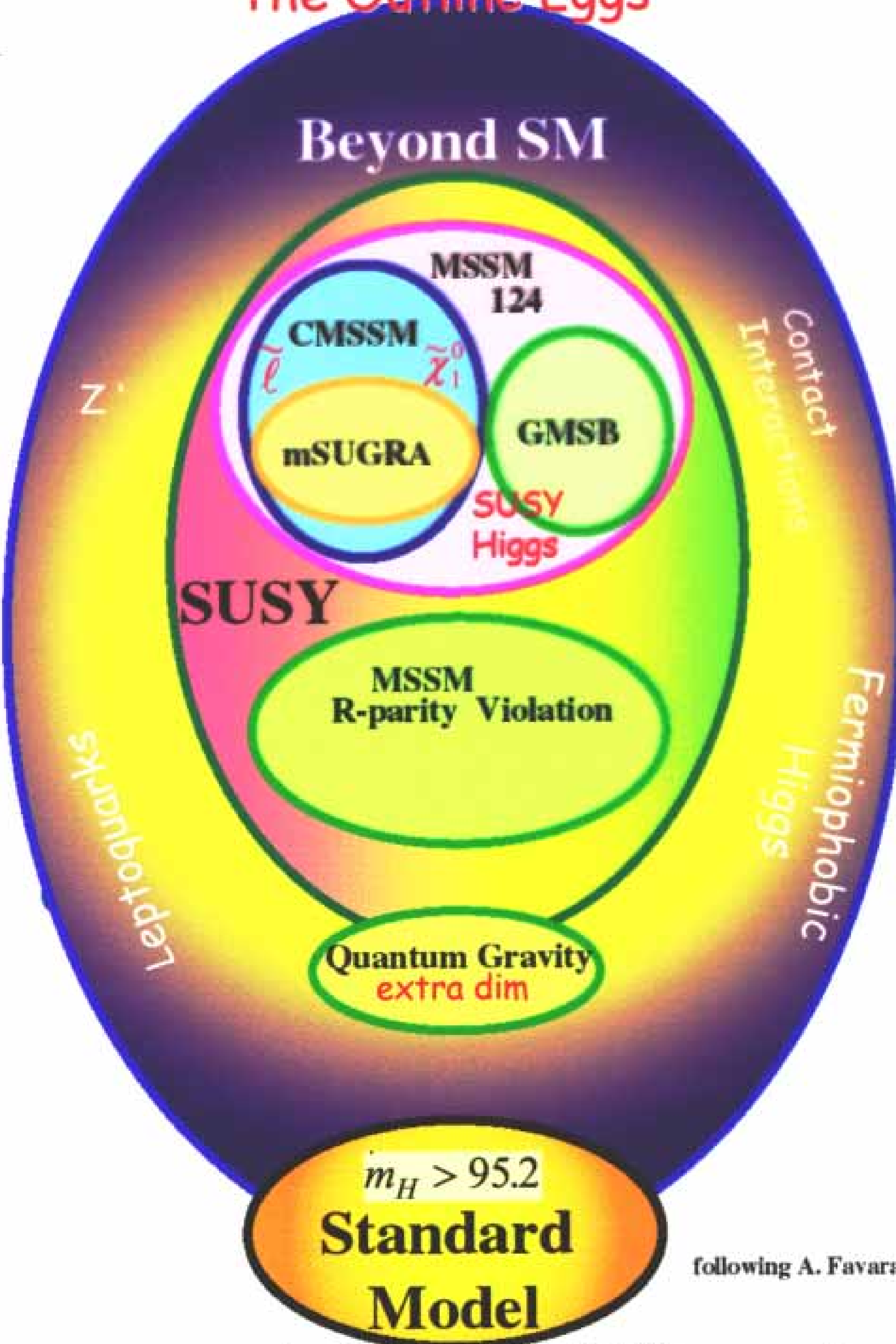
Do We Expect a Higgs Boson? New Physics Around the Corner?



... If a Higgs is discovered at LEP then there is New physics around the corner

Around the corner = Beyond the SM

The Outline Eggs



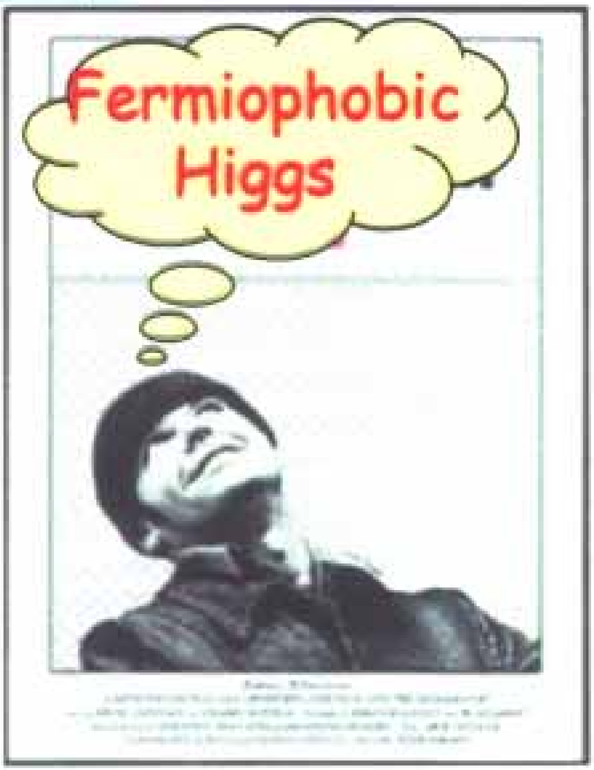
following A. Favara

One Higgs Over the Cuckoos Nest

$HZ\gamma,\ H\gamma\gamma$ SM suppressed

$70 < m_H < 150 \Rightarrow \sigma(ee \to H\gamma) \sim 0.02 - 0.2\ fb$

$BR(H \to \gamma\gamma) \sim 10^{-3}$

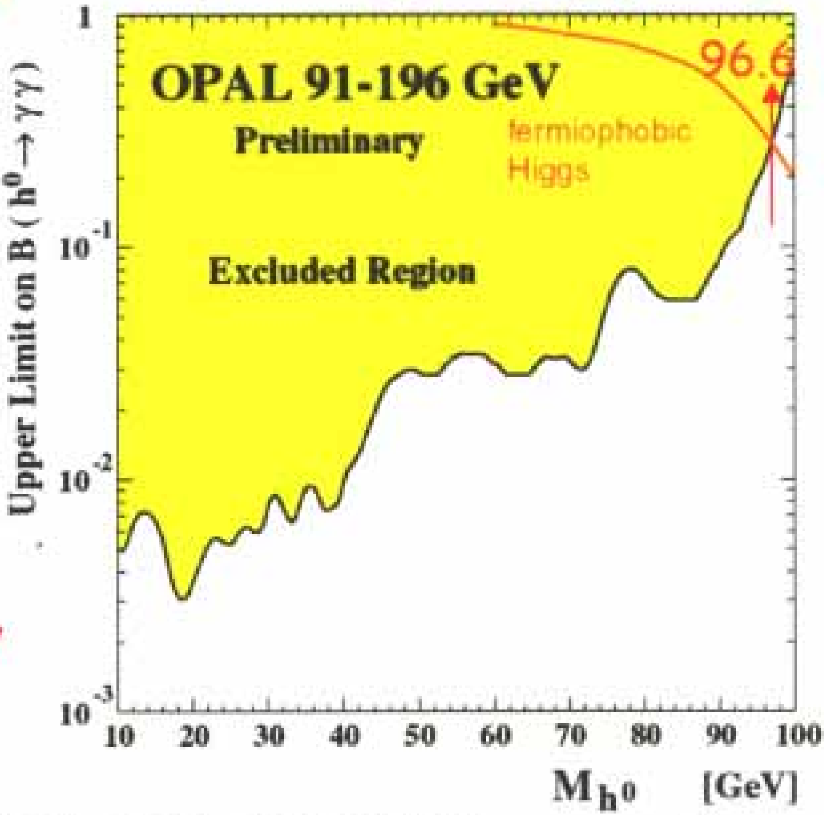


Enhancements can occur via
- composite models (related to anomalous TGV couplings)
- specific extentions of the SM with "fermiophobic" Higgs

That include
- Bosonic Higgs
- Type I 2HDM with fermiophobic couplings

Signature @ LEP: Muliphotons (+Missing Energy) (+ Jets)

Limits on anomalous couplings were also derived

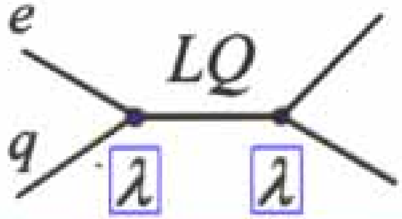


LEP $m_H >$ 96-97 GeV

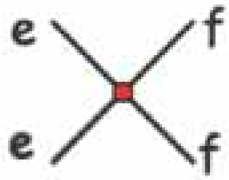
CDF/D0 $m_H >$ 79,82 GeV

Contact Interactions:
Learning from the SM

Composite fermions or new heavy mediators



$$\frac{\lambda^2}{m_{LQ}^2} \Rightarrow \frac{1}{\Lambda^2}$$



$$\mathrm{L} = \mathrm{L}_{SM} + \frac{4\pi}{1+\delta_{ef}} \sum_{i,j=R,L} \pm \eta_{ij}^{\pm} \frac{1}{\Lambda_{\pm}^2} \left(\bar{e}_i \gamma^{\mu} e_i\right)\left(\bar{f}_j \gamma_{\mu} f_j\right)$$

$\eta_{ij}^{\pm} = 1$ Characterizes the model

APV $\Rightarrow$ Λ>10 TeV for PV terms

Limits set by looking for deviations from SM predictions

$$\frac{\partial\sigma(ee \to f\bar{f})}{\partial\cos\theta} = \frac{\partial\sigma^{SM}}{\partial\cos\theta} + c_2(s,\cos\theta)\frac{1}{\Lambda^2} + c_4(s,\cos\theta)\frac{1}{\Lambda^4}$$

(also σ, A_{FB}, R_b,...)

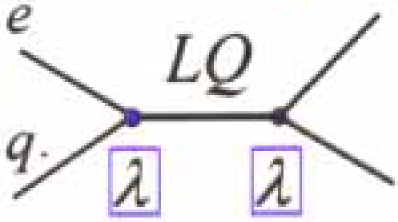
Selected Results (up to 30 models were probed)

	Aleph	*Delphi*	*L3*	*OPAL*	*D0*	*ZEUS*
	eeqq	*eeℓℓ*	*eeℓℓ*	*eeℓℓ*	*eeqq*	*eeqq*
$VV(-)$	9.2	12.7	12.3	11.5	6.1	5
$VV(+)$	9.6	14.7	10.2	13.4	4.9	4.7
$AA(-)$	10.4	10.9	8.8	10.9	5.5	3.7
$AA(+)$	10.5	8.0	9.0	10.6	4.7	2.6

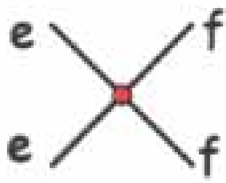
TeV

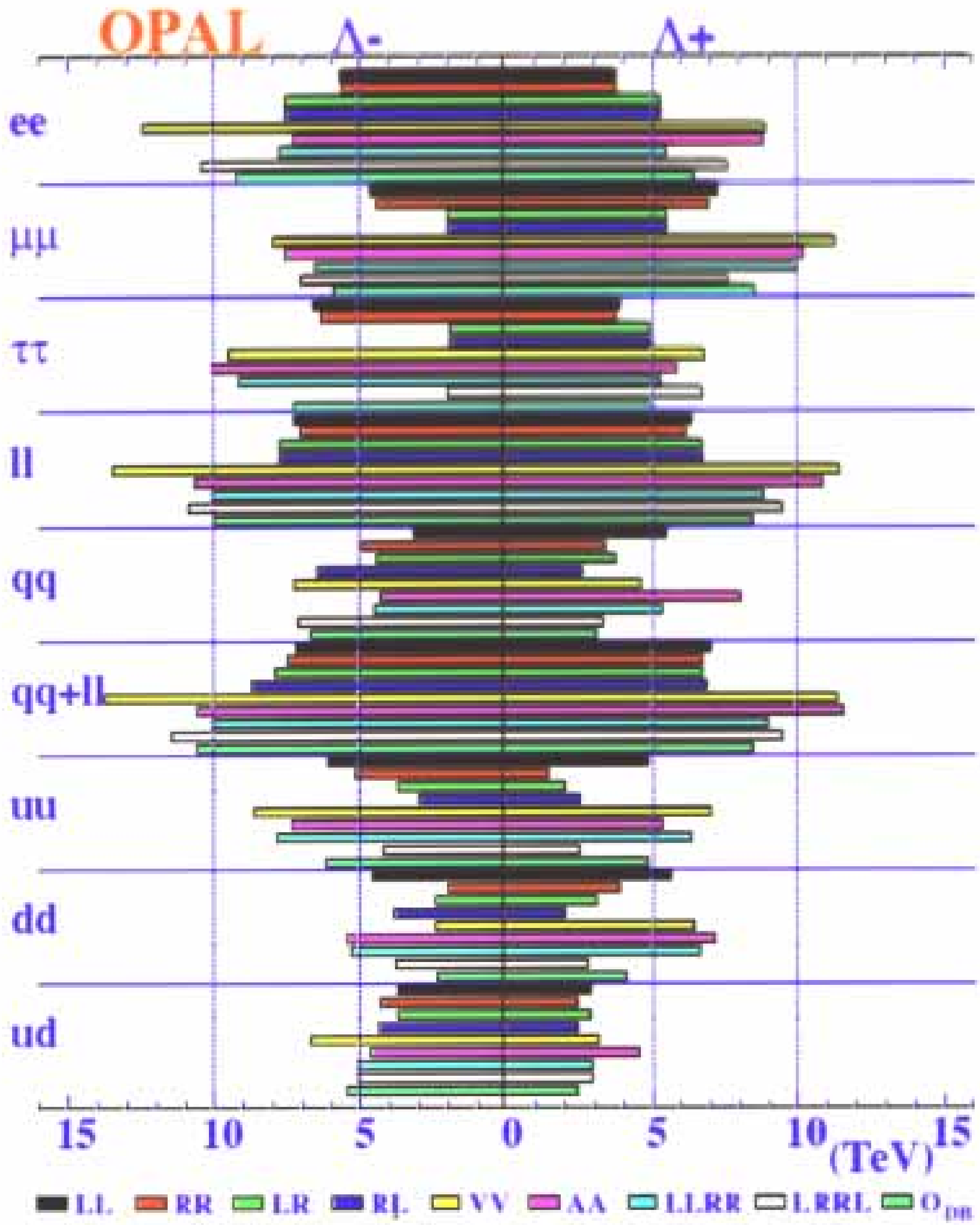
Contact Interactions - Learning From the SM

Composite fermions or new heavy mediators



$$\frac{\lambda^2}{m_{LQ}^2} \Rightarrow \frac{1}{\Lambda^2}$$





TEVATRON
LEP
HERA

$$\Lambda > 5-14\ TeV$$

Search for Compactified Dimensions

Some models propose Gravitons propagate in compactified higher dimensional space

In these models the Planck mass in D=n+4 dimensions is given by $M_D \sim M_{EW}$

$$M_D^{n+2} = \frac{M_P^2}{R^n} \Rightarrow \begin{cases} n=2 \;\; R \sim 1\,mm \quad (D=6\;) \\ n=7 \; R \sim 1\,fm \quad (D=11) \end{cases}$$

visible effects on $ee \to f\bar{f}, \gamma\gamma$ angular dist.

e.g.

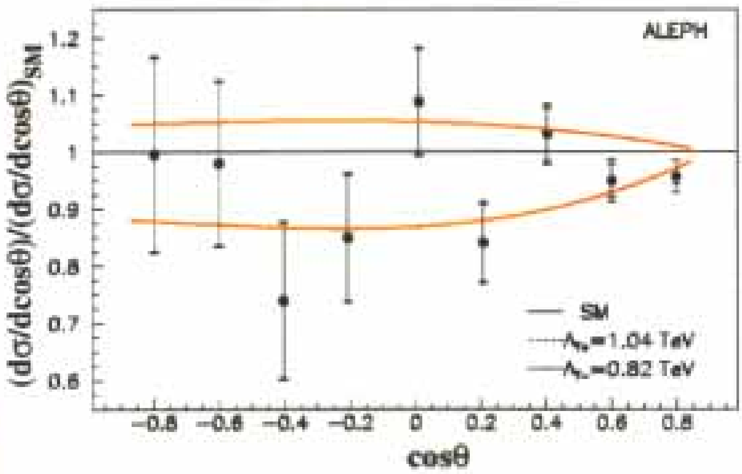
$$\frac{\partial\sigma\left(ee \to f\bar{f}\right)}{\partial\cos\theta} = \frac{\partial\sigma^{SM}}{\partial\cos\theta} \pm a_4(s,\cos\theta)\frac{1}{\Lambda^4} + a_8(s,\cos\theta)\frac{1}{\Lambda^8}$$

Similar to contact int. yet higher powers of the scale $\Lambda \sim O(M_D)$

ALEPH	$f\bar{f}+\gamma\gamma$
$\Lambda(+)$	1120
$\Lambda(-)$	840

OPAL	$\mu\mu$	$\tau\tau$	$\gamma\gamma$
$\Lambda(+)$	600	630	660
$\Lambda(-)$	630	500	634

GeV



Also from direct search $e^+e^- \to \gamma G$

limits on M_D,n

For n=2-6 M_D>990-490 GeV (ALEPH)

M_D>1110-530 GeV (DELPHI)

M_D>945-489 GeV (L3)

Giudice et. a

Search for Extra Gauge Bosons (Z')

GUT: $E(6) \supset SO(10)\times U(1)_\chi \supset SU(5)\times U(1)_\psi \supset SM$

$$Z' = Z_\psi \sin\theta_{E6} + Z_\chi \cos\theta_{E6}$$

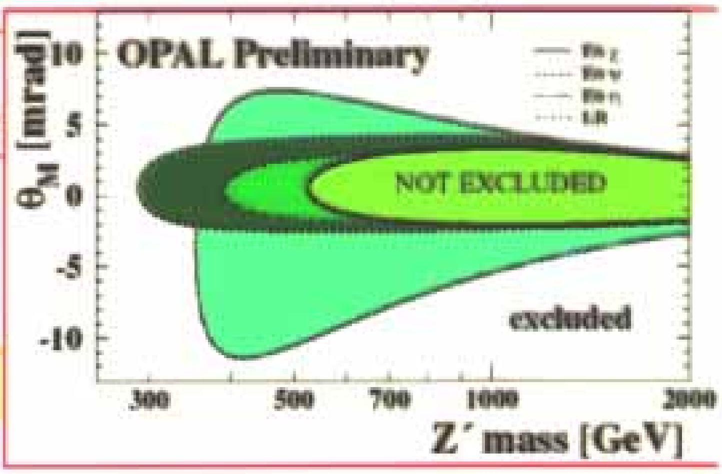
Models considered: $\chi_{(\theta_{E6}=0)}$, $\psi_{(\theta_{E6}=\pi/2)}$, $\eta_{(\theta_{E6}=-\arctan\sqrt{5/3})}$

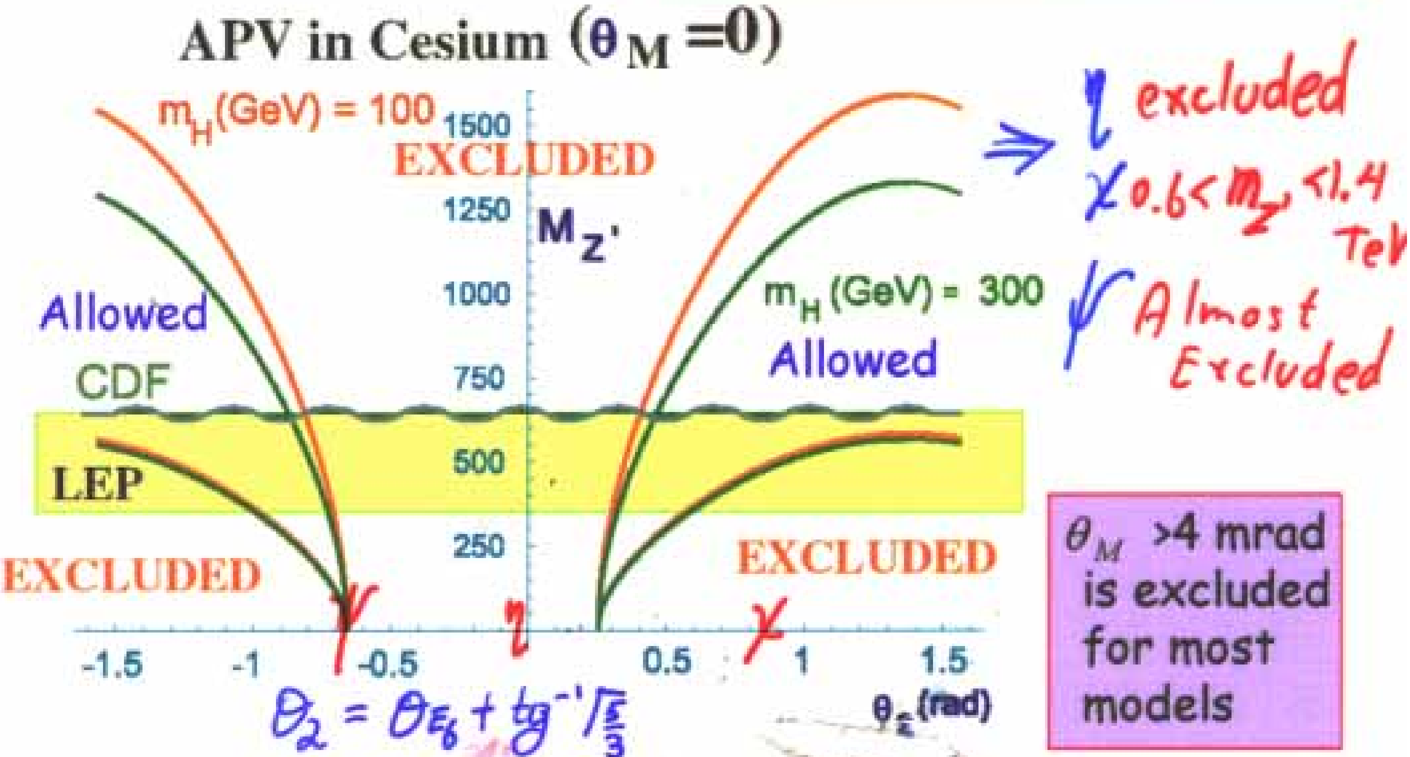
Z and Z' mix with an angle θ_M
measurable effects on SM observables (σ, A_{FB})

at LEP 2 (sensitive to $m_{Z'}$) and LEP1 (Γ_Z)

	A $\theta_M = 0$	D	L	O	CDF direct
χ	458	430	380	589	595
ψ	285	345	256	307	590
η	295	305	300	392	620

GeV





θ_M >4 mrad is excluded for most models

Leptoquarks

LQ are colored objects that carry both B and L numbers and assumed to interact directly with the SM fermions

Low energy constraints ⇒ Assume chiral couplings λ_L, λ_R
or take $\lambda_L \lambda_R \sim 0$ constraints into account

FCNC ⇒ Assume LQ couple to one generation
LFV also considered (HERA)

LQ are classified by spin and their SU(3)xSU(2)xU(1) charges
Scalrs (S_I), Vectors (V_I) F=3B+L
I=SU(2) ISOSPIN

Decay Modes:

$$LQ \rightarrow \ell q, \ell\bar{q}, \nu q, \nu\bar{q} \Rightarrow \quad |Q| = \frac{1}{3}, \frac{2}{3}, \frac{4}{3}, \frac{5}{3}$$

	$F=0$	$\lvert Q$	$F=+2$	$\lvert Q$	$F=-2$	$\lvert Q$
$LQ \rightarrow$	$\ell^+ q, \ell^- \bar{q}$	$\frac{2}{3}, \frac{5}{3}$	$\ell^- q$	$\frac{1}{3}, \frac{4}{3}$	$\ell^+ \bar{q}$	$\frac{1}{3}, \frac{4}{3}$
$LQ \rightarrow$	$\bar{\nu} q, \nu\bar{q}$	$\frac{1}{3}, \frac{2}{3}$	νq	$\frac{1}{3}, \frac{2}{3}$	$\overline{\nu q}$	$\frac{1}{3}, \frac{2}{3}$

Note: $\tilde{u}_L \Leftrightarrow \hat{s}_1$ ⇒limits on $\lambda_{121}, \lambda_{131}$

Leptoquarks (Tevatron)

D0: 2^{nd} generation LQ

$$LQ\overline{LQ} \rightarrow \mu q\ \nu q,\ \mu q\ \mu q \Rightarrow$$

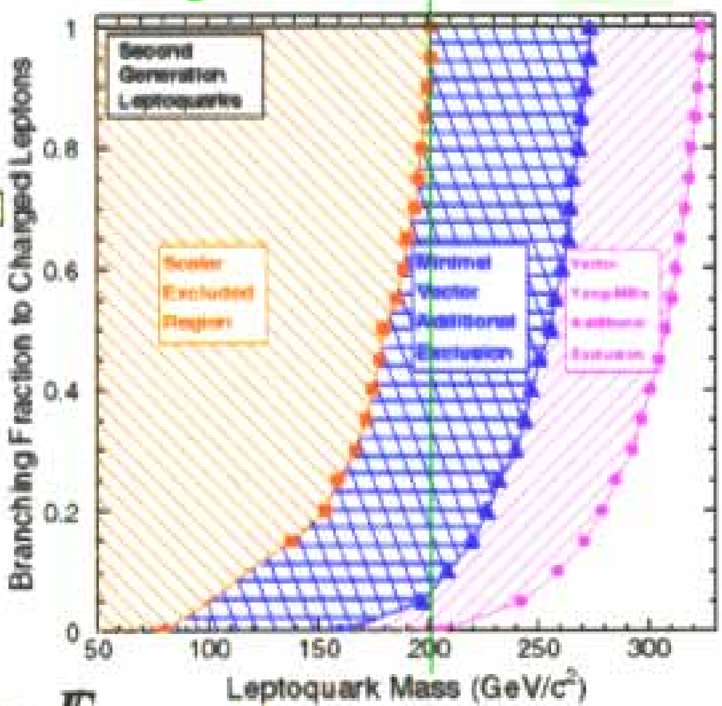
search for μ+jets+ $\not{E}_T$
$\mu\mu$+jets

For $\beta=1$

$m_s > 202\ GeV$	CDF
$200\ GeV$	D0

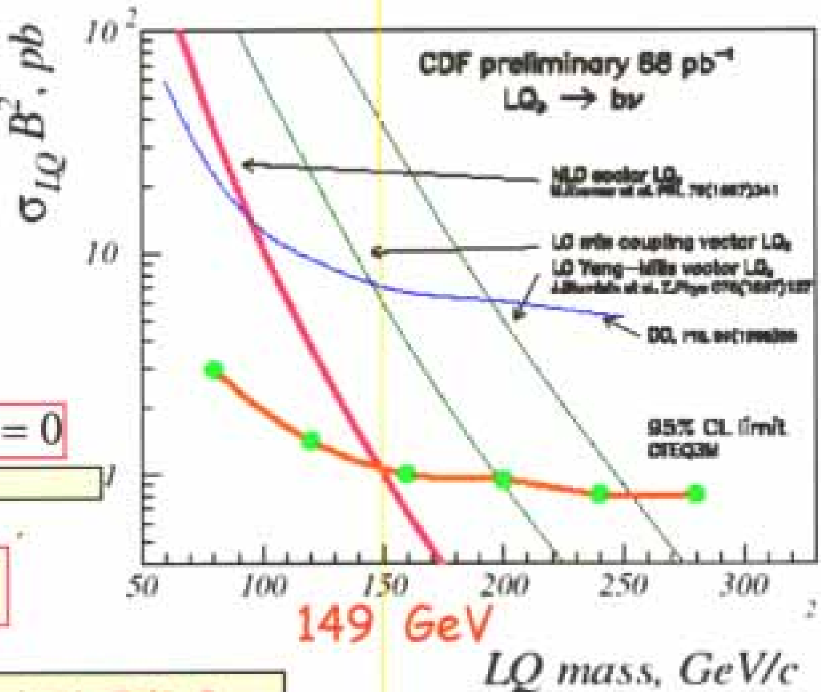
Independent of coupling

$\beta = BR(LQ \rightarrow \mu q)$



CDF: 3^{rd} generation LQ

$$LQ\overline{LQ} \rightarrow b\nu\, b\nu \Rightarrow \text{2 b jets} + \not{E}_T$$



$\beta = 0$

$m_s > 149\ GeV$	CDF
$94\ GeV$	D0

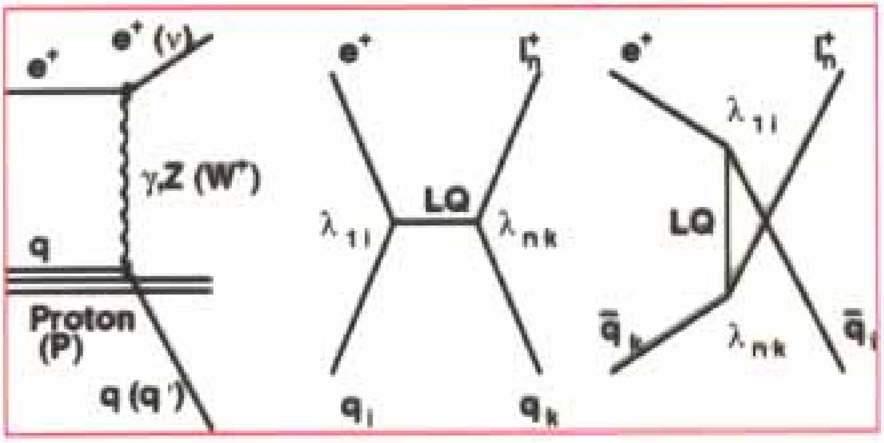
Independent of coupling

1st Generation Excluded CDF/D0 up to 242 GeV

Independent of coupling

Leptoquarks (HERA)

LQ signature similar to DIS @ high Q^2



u-channel is suppressed by kinematics for scalar LQs

In the s-channel for Scalar LQs $\frac{\partial\sigma}{\partial y} = flat$

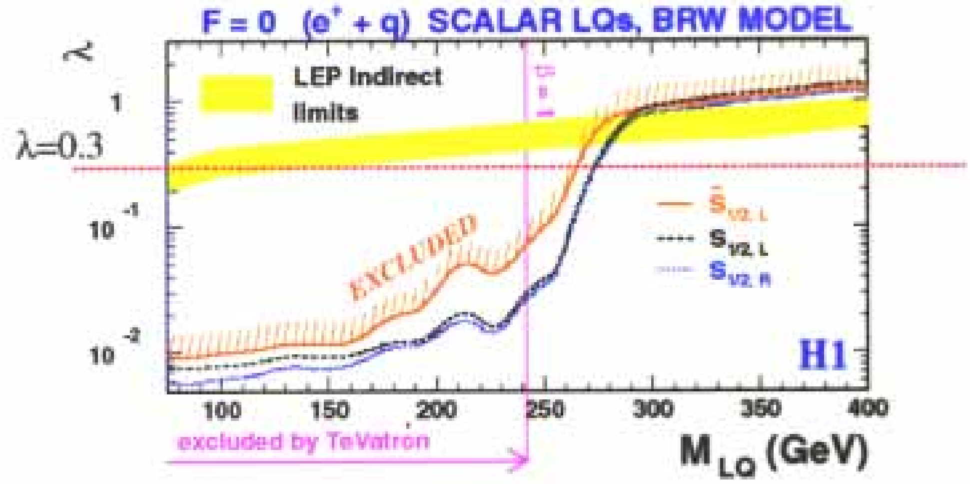
$y = \frac{1}{2}(1+\cos\theta^*)$

θ^* Angle of lepton in ep CM

For Vector LQ $\frac{\partial\sigma}{\partial y} \propto (1-y)^2$

For SM DIS (photon exchange) $\frac{\partial\sigma}{\partial y} \propto \frac{1}{y^2}$

Search sensitive also to $m_{LQ} > \sqrt{s_{ep}}$ (up to 400 GeV)

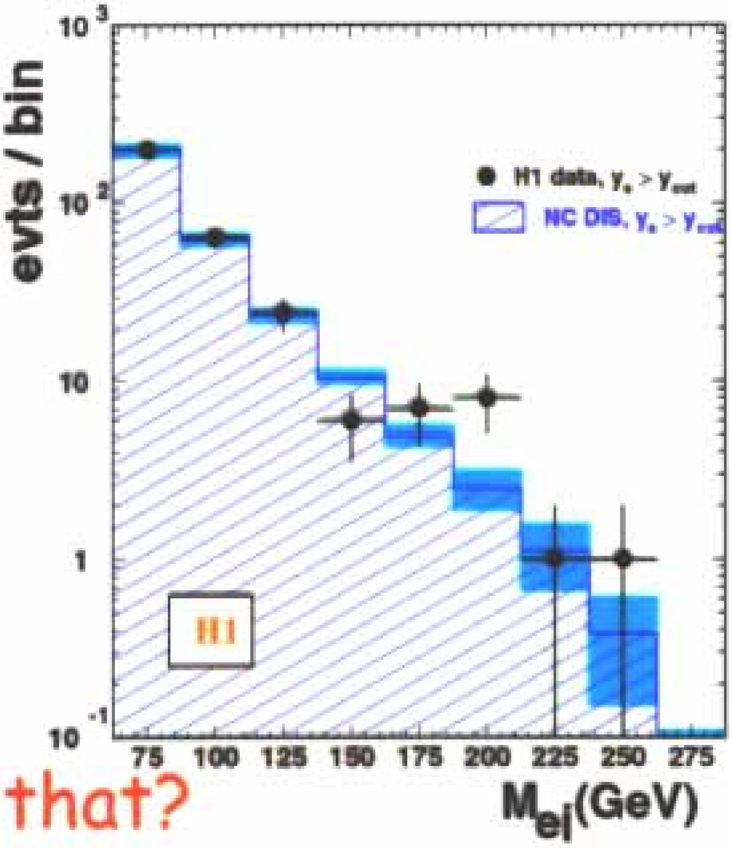


$For\ \lambda = 0.3, m_S^{LQ} > 270, m_V^{LQ} > 284\ \ GeV$

The Nondiscovery of the Year! HERA's Leptoquarks

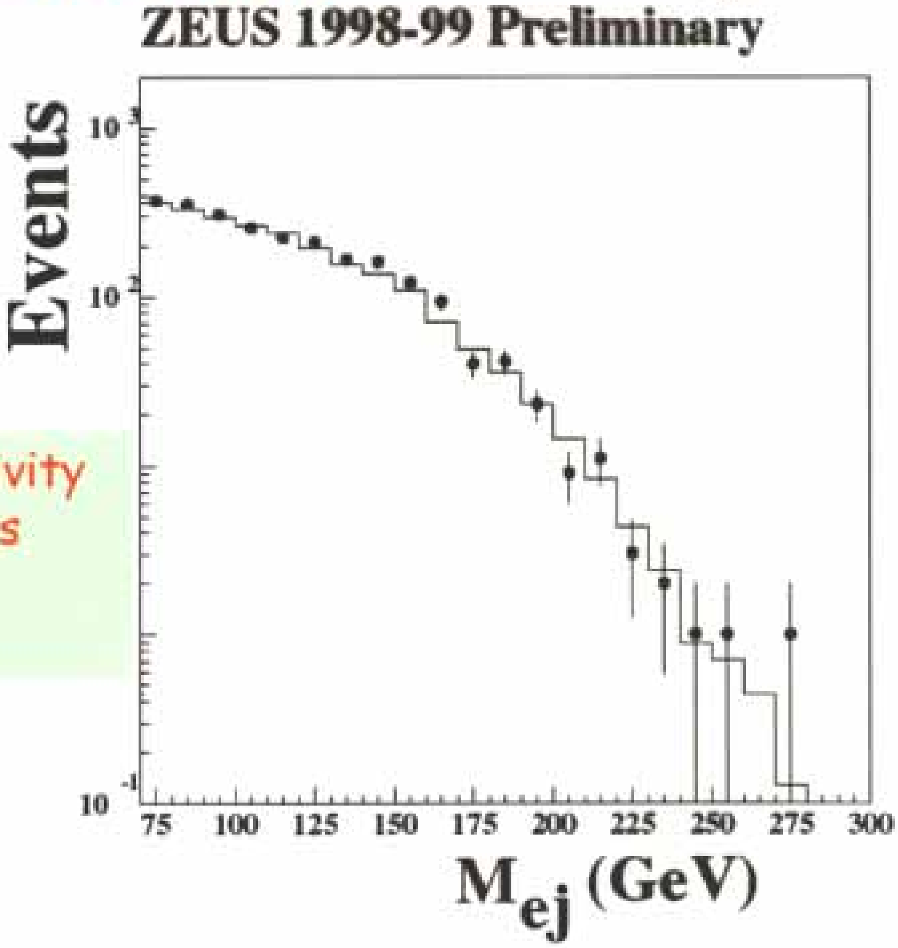
Remember that?

H1 e^+P 37 pb^{-1}
1994-1997



Then, how about that?

Zeus e^-P
16 pb^{-1}
1998-1999



Excellent sensitivity for e^-q (F=2) LQs

Better than e^+q

Leptoquarks (LEP)

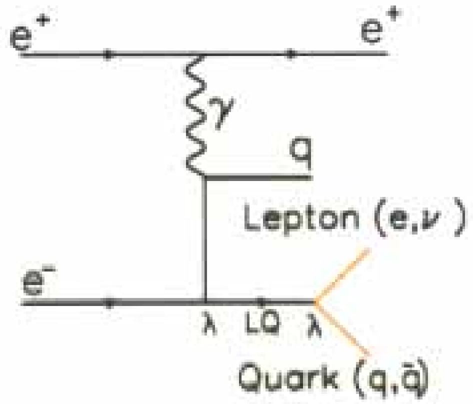
direct $\left(\beta = 1, \lambda = \sqrt{4\pi\alpha}\right)$

$\lvert Q \rvert$	1/3, 5/3 S	1/3, 5/3 V	4/3, 2/3 S	4/3, 2/3 V
Aleph*	172	183	157	155
Delphi*	171	181	153	164

GeV

*worst case

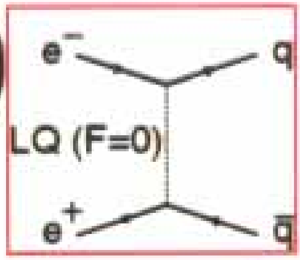
Close to kinematical limit!

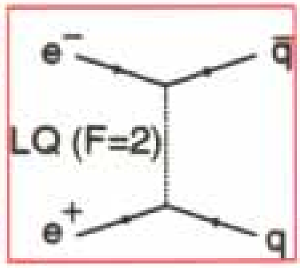


reach $\sqrt{s}$

$\sim \lambda \cdot \beta$

indirect $\left(\lambda_{L,R} = \sqrt{4\pi\alpha}\right)$



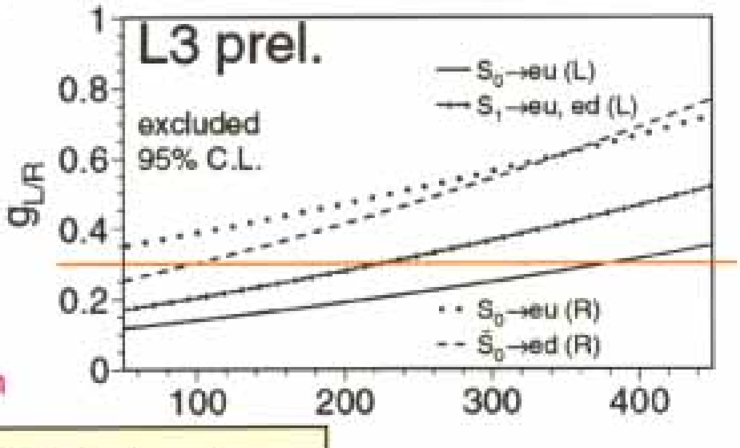


$\sim \lambda^2$

exp	gen	s_{0L}	s_{1L}	$V_{1/2L}$	V_{1L}
A	$1^{st}, 2^{nd}$	310	370	140	590
L	$1^{st}, 2^{nd}$	370	220	210	440
A	3^{rd}	xxx	710	220	450

GeV

$$\sigma\left(e^+e^- \rightarrow f\bar{f}\right) = \sigma_{SM} + \sigma_{LQ}(\lambda^2)$$



From Leptoquarks to Rp violation

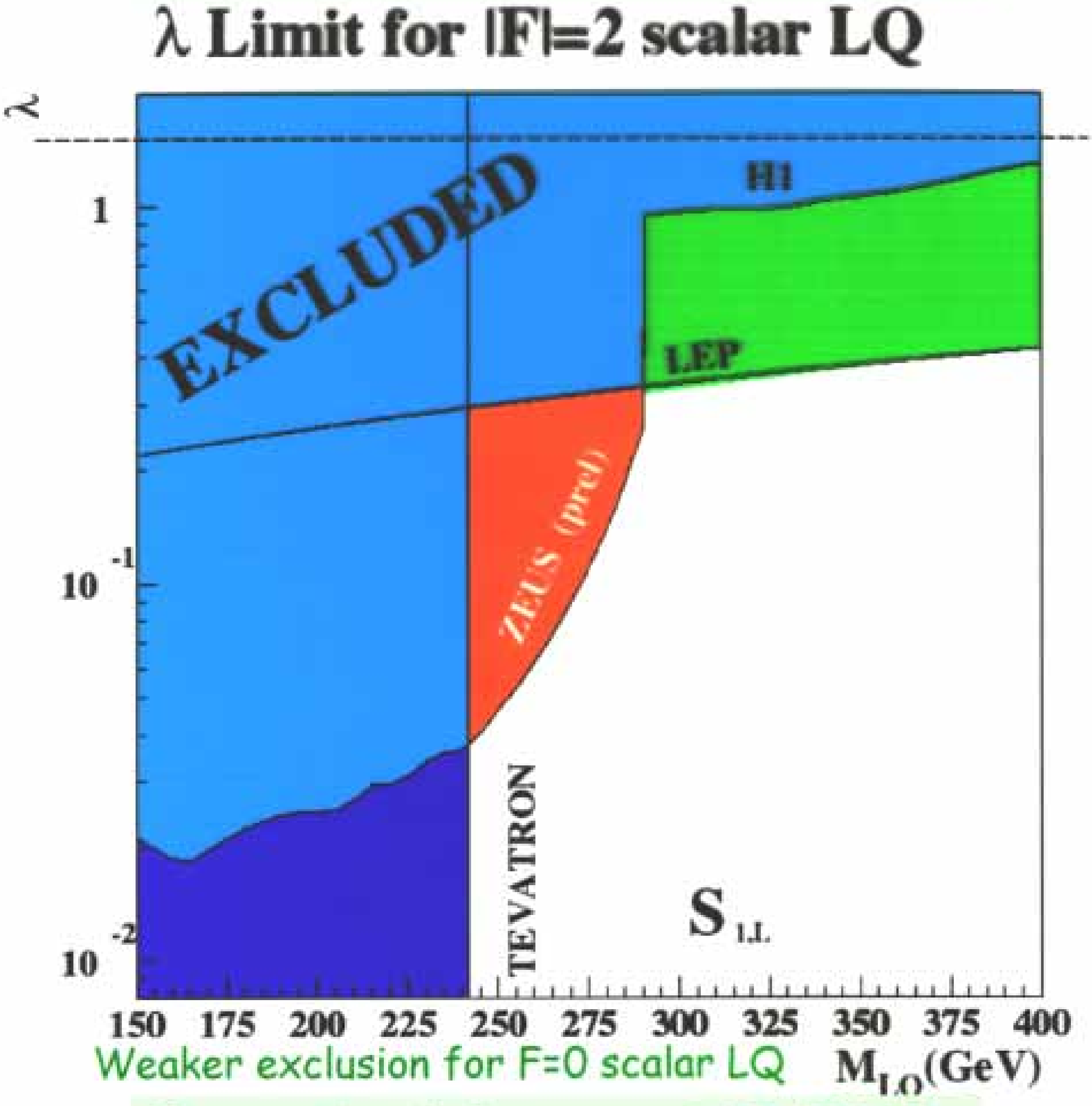
Note: $\tilde{u}_L \Leftrightarrow \hat{s}_1 \Rightarrow$ limits on $\lambda_{121}, \lambda_{131}$,

Leptoquarks - HERA vs LEP & CDF

HERA

$e^+p \ (F=0, valence; \ F=-2, sea)$

$e^-p \ (F=2, valence; \ F=0, sea)$



Weaker exclusion for F=0 scalar LQ

For scalar LQs: m_{LQ}>242 (CDF)

For F=2 Leptoquarks (1st gen),

$\lambda < 0.4 \ \ for \ \ \forall m_{LQ} < 400$

Technicolor

Dynamical Breaking of EW symmetry

The Straw Man Model

Limits from CDF

$\rho_T \to W\pi_T, \omega_T \to \gamma\pi_T$

should be reevaluated in ~~terms~~ $\gamma\pi_T$ of the pars that control $\rho \to \gamma\pi_T$

LEP is entering the game (L3)

$m_{\pi_T},\ m_{\rho_T},\ \sin\chi\,(mix\,W_L,\pi_T),\ Q$

Assume degeneracy of spin 0 TH
spin 1 TH

$BR(\pi_T \to bc,bb) \sim 50-90\%$

TC ... Extended/Walking
Top Color...
Straw Man...

Signals:

$\sigma(ee \to WW) < 0.47\ \ pb$

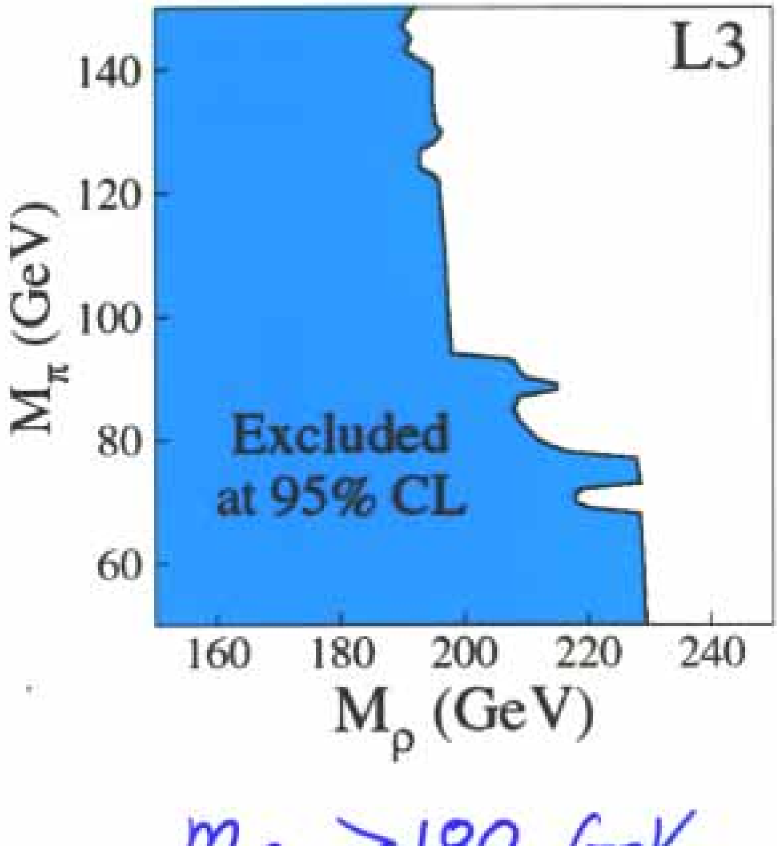
$ee \to W_L\pi_T \to \ell\nu bc$

$ee \to \pi_T\pi_T \to bcbc$

$ee \to \gamma\pi_T \to \gamma bb$

Exclusion within the model via scan

$0 < \sin\chi < 1,\ \ Q = -1, \frac{5}{3}$



$m_{\rho_T} > 180$ GeV

Straw Man Model

Glueball Searches

Lattice QCD ⇒
Existence of glueballs (bound states of gluons)

Quarkonia states might mix with gluons ⇒

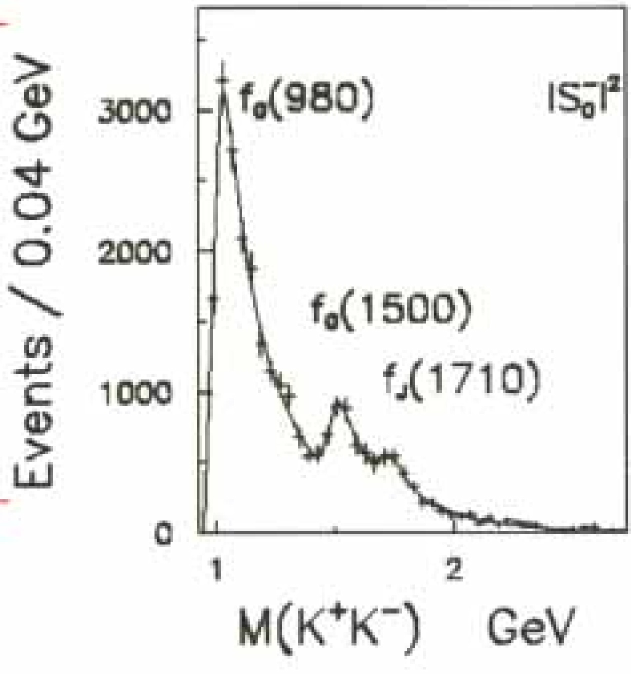
The mixture of the two I=0 scalar nonet states might mix with a scalar glueball to give the
$f_0(1370)$, $f_0(1500)$, $f_J(1710)$

This picture will be invalidated if the $f_J(1710)$ will turn out to be a state with J=2

Like a typical $s\bar{s}$ state, $f_J(1710)$ has a dominant $k\bar{k}$ decay mode, however, it is not observed in hypercharge exchange $k^- p$ collisions!

Even if it is proven to be a dominant J=0 state the question is WHAT IS IT?

A new partial wave analysis of the centrally produced KK system in 450 GeV pp collisions (WA102) states observe peaks in the S-wave corresponding to $f_0(1500)$ and $f_J(1710)$ with J=0!



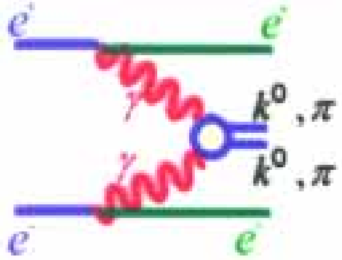
Glueballs at LEP?

Glueballs will be produced in rich gluonic environments however they won't couple directly to photons ⇒

The $\Gamma(Glueball \to \gamma\gamma)$ is very small ⇒

Searching for resonances in $\gamma\gamma$ collisions and measuring their partial width is of extreme importance!

Both Aleph and L3 search for resonances via $\gamma\gamma$ collisions.



Aleph sets upper limits on the $\gamma\gamma$ widths of $f_0(1500)$ and $f_J(1710)$ via their non observed decay to $\pi^+\pi^-$

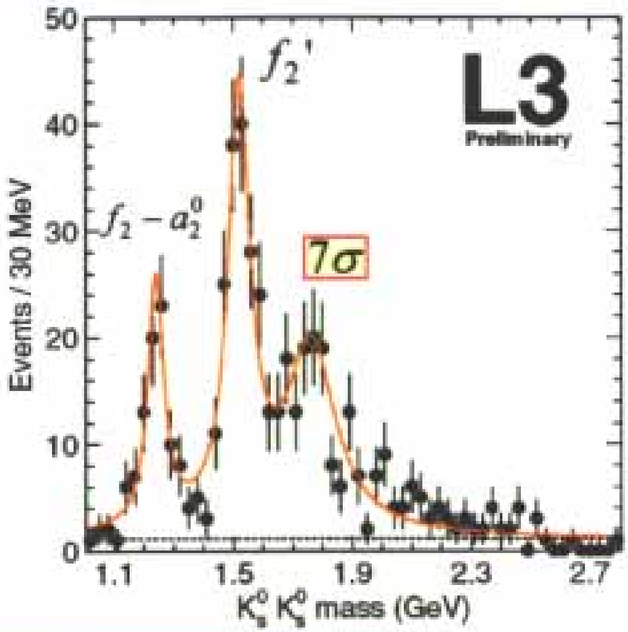
Aleph

$$\Gamma_{\gamma\gamma}(f_0(1500)) \times BR(\pi^+\pi^-) < 0.31\ KeV$$

$$\Gamma_{\gamma\gamma}(f_J(1710)) \times BR(\pi^+\pi^-) < 0.55\ KeV$$

L3 are using the decay mode to $R \to k_s^0 k_s^0 \to \pi^+\pi^-\pi^+\pi^-$

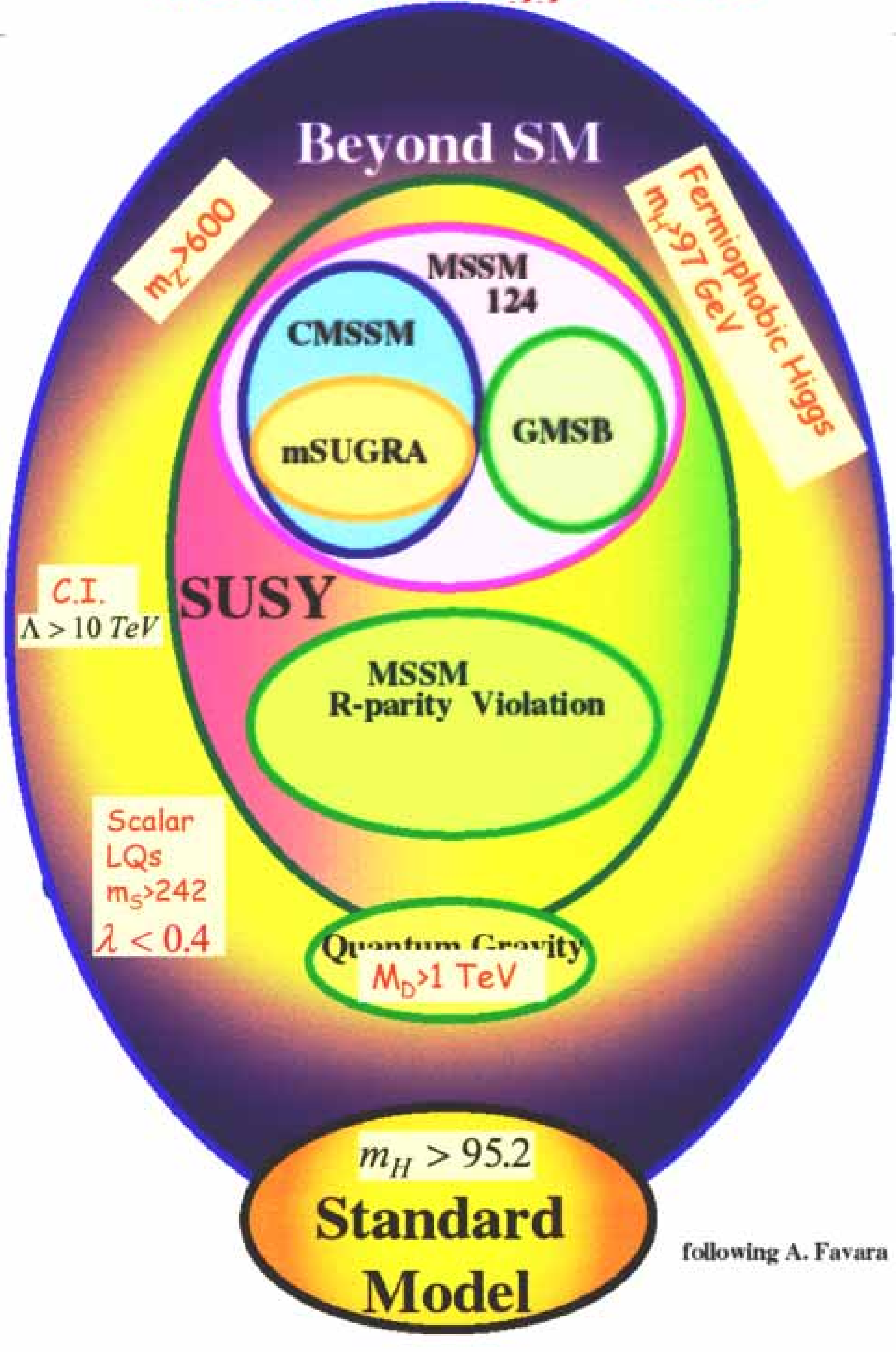
L3 clearly observes $f'_2(1525)$, R(1750) (?) and no evidence for yet another glueball candidate $\xi(2230)$



By studying angular distributions of the two kaons in the $\gamma\gamma$ CM they deduce a possible presence of both spin 2 and spin 0 waves in the R(1750).

Supporting evidences for $f_J(1710)$ with J=0

The Searches Eggs - Cntd



following A. Favara

Super Symmetry Parameters

mSUGRA (Tevatron,LEP)

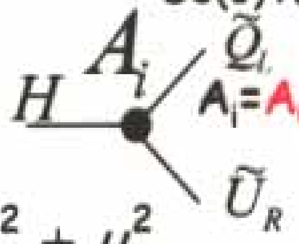
MSSM-124
2 Higgs Doublets H_1, H_2; R_p
At GUT (10^{16} GeV)

$$m_{\tilde{f}} = m_0$$

$$M3 = M_2 = M_1 = m_{1/2}$$

SU(3) X SU(2) X U(1)

CMSSM (LEP)



$$m_{H_i}^2 = m_0^2 + \mu^2$$

$m_0, m_{1/2}, A_0, B_0, \mu_0$:GUT: $m_0, m_{1/2}, A_0, B_0, \mu_0, m_{H_1}, m_{H_2}$

$$\frac{\partial V}{\partial H_i} = 0 \qquad \frac{\partial V}{\partial H_i} = 0$$

Low Energy

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$$

$$tg\beta = \frac{\langle v_{up} \rangle}{\langle v_{down} \rangle} = \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

$(m_0), (m_{1/2}), A_t, tg\beta, sign(\mu)$ — 5 pars

$m_S, M_2, A_t, \mu, tg\beta, m_A$ — 6 pars

($tg\beta, m_A$): Tree Higgs Sector

MSSM (s)particles

Spin	0	1/2	1
Gauge Sector	H^0, h^0, A^0	$\tilde{B}$, $\tilde{H}$, $\tilde{h}$, $\tilde{W}$ } $\tilde{\chi}_i^0$ neutralinos; $\tilde{\chi}_1^0$ LSP	γ, z^0
	$H^{\pm}$	$\tilde{H}^{\pm}$ $\chi_{1,2}^{\pm}$ $\tilde{W}^{\pm}$ charginos	$W^{\pm}$
		$\tilde{g}$ gluino	g
Particles Sector	sleptons, sneutrinos $\tilde{\ell}_{R,L}, \tilde{\nu}$	ℓ, ν	
	$\tilde{q}_{R,L}$ squarks	q	

In GMSB the LSP
is the Gravitino $\tilde{G}$ (spin 3/2)

Search for Squarks

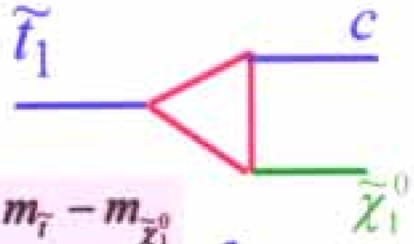
Typical sfermion mass hierarchy: $m_{\tilde{q}} >> m_{\tilde{\ell}_L} \sim m_{\tilde{\upsilon}} > m_{\tilde{\ell}_R}$

$$M^2_{\tilde{f}} = \begin{pmatrix} \sim m^2_{\tilde{f}_L} & \sim m_f^2 \tilde{A}_f \\ \sim m_f^2 \tilde{A}_f & \sim m^2_{\tilde{f}_R} \end{pmatrix} \xrightarrow{\text{mixing}} \tilde{t}_1, \tilde{b}_1, \tilde{\tau}_1$$

Might be LIGHT

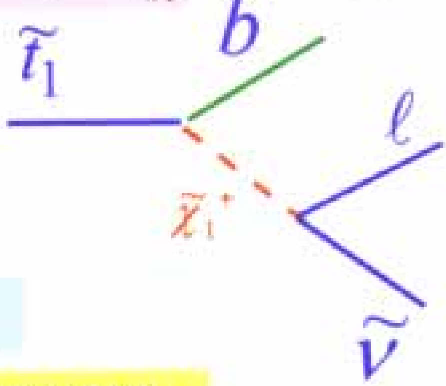
$\tilde{t}_1$ Might be the lightest sfermion
Production cross section depends on the mixing
e.g. for ~56^0 the light stop decouples from the Z.

Decay modes are either via an FCNC loop $\tilde{t}_1 \to c\tilde{\chi}$



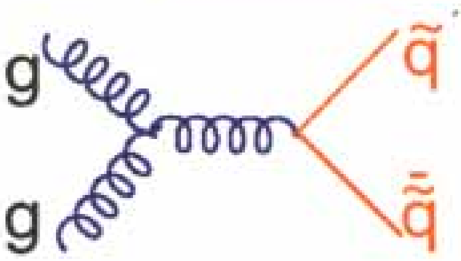
Efficiency drops for small $\Delta M \equiv m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

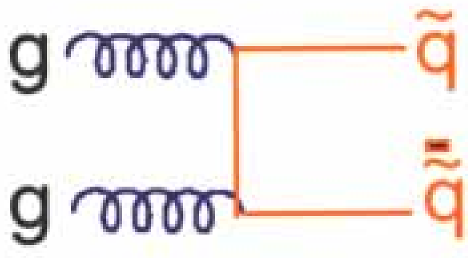
or if kinematics allows $\tilde{t}_1 \to bl\tilde{\nu}$



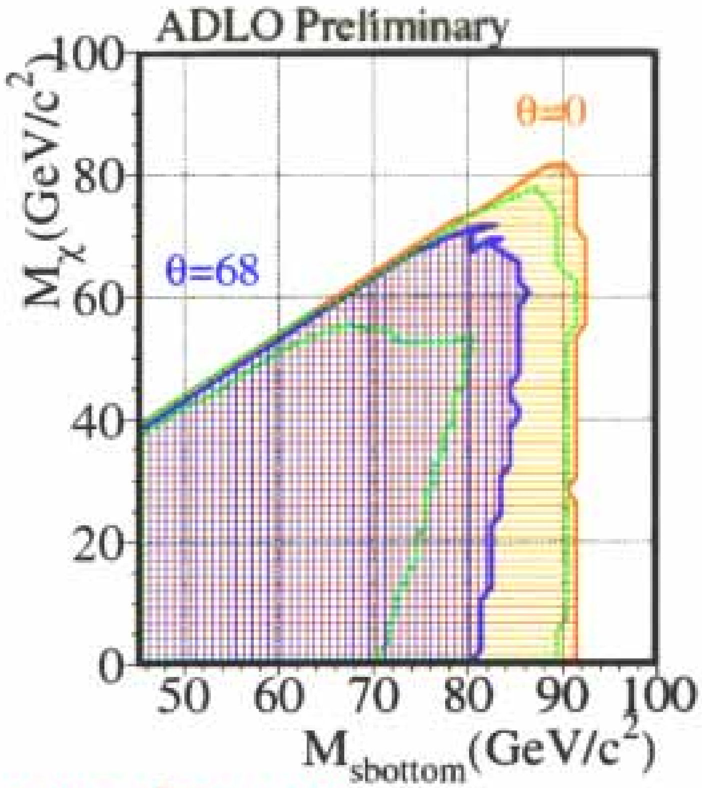
Production: $e^+e^- \to \tilde{q}\overline{\tilde{q}}$ (LEP)

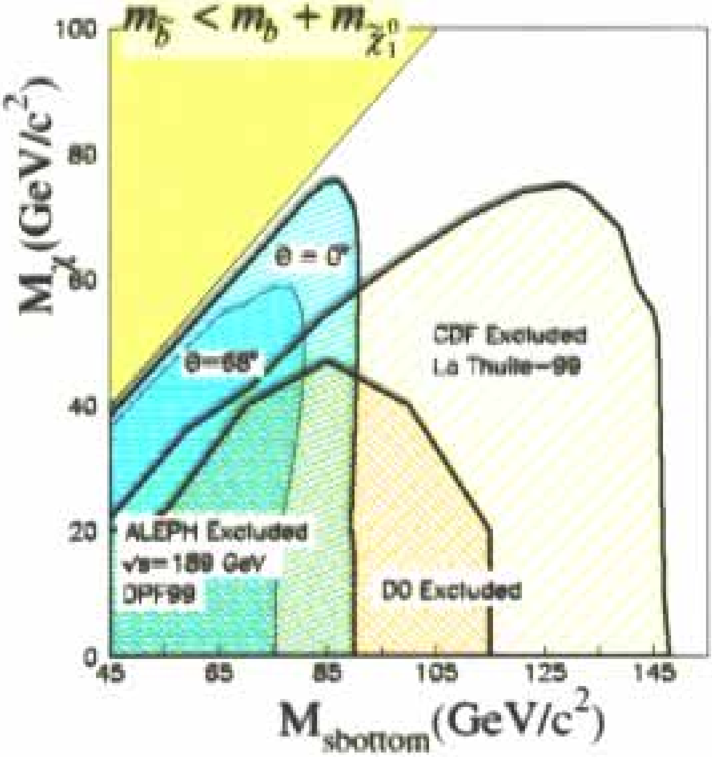
$gg, qq \to \tilde{q}\overline{\tilde{q}}$ (TEVATRON)





Limits on Squark Masses





$\Delta M \equiv m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

ADLO 189

$m_{\tilde{t}(\tilde{b})} >$

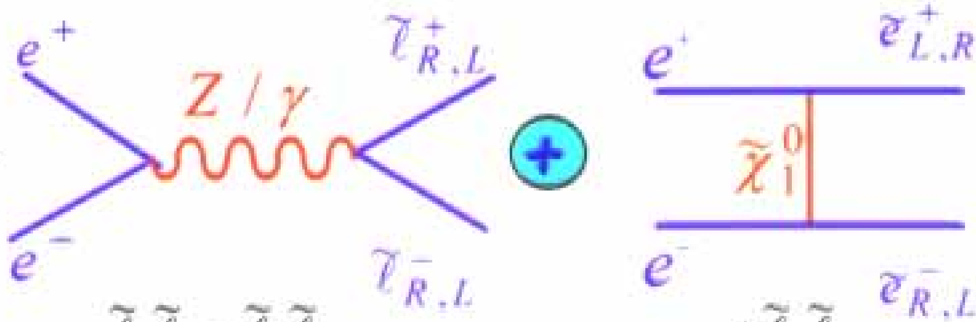
ΔM>20 Channel	θ=0	θ=max σ
$\tilde{t} \to c\tilde{\chi}_1^0$	90	87
$\tilde{t} \to b\tilde{\nu}$	92	90
$\tilde{b} \to b\tilde{\chi}_1^0$	91	81

TEVATRON has larger reach in mass but is limited (by missing E_T trigger) for small ΔM

The 196 preliminary results for individual experiments are at the same level as the combined LEP 189 results

Limits on Slepton Masses

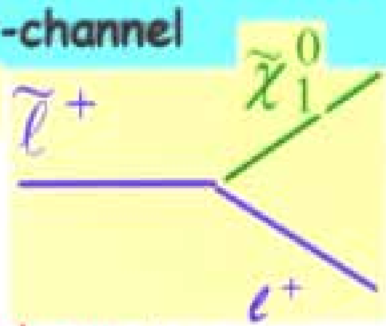
Production at LEP



$e^+e^- \rightarrow \tilde{\ell}_L\tilde{\ell}_L + \tilde{\ell}_R\tilde{\ell}_R + \tilde{\ell}_L\tilde{\ell}_R$

Production cross section is enhanced for Gaugino like Neutralino via the t-channel

Main decay mode



Topology:
2 acoplanar leptons

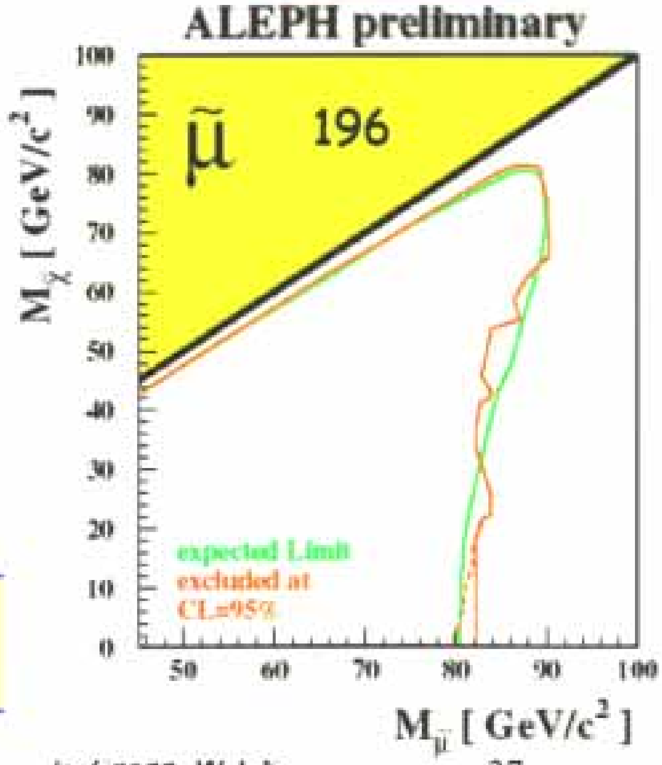
⇨ Eff strongly depends on $\Delta m = m_{\tilde{\ell}} - m_{\tilde{\chi}^0_1}$

The small ΔM region can be covered by t-channel single electron topology (ALEPH): $e^+e^- \rightarrow \tilde{e}_L\tilde{e}_R \rightarrow e\tilde{\chi}^0_1(e)\tilde{\chi}^0_1$

$m_{\tilde{e}_L} > m_{\tilde{e}_R}$

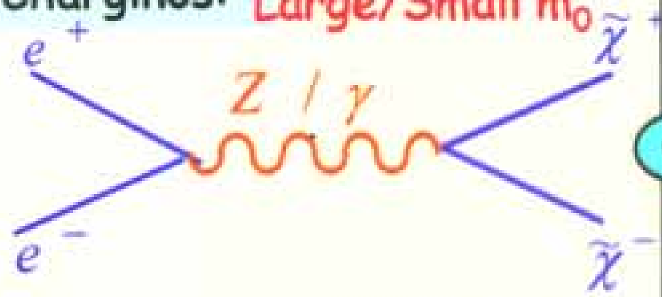
ADLO 189	ALEPH 196
$\Delta M > 15$	$m_{\tilde{\chi}^0_1} = 0$
$m_{\tilde{e}} > 89$	91
$m_{\tilde{\mu}} > 84$	82
$m_{\tilde{\tau}} > 71$	71

Stable Sleptons
Excluded up to 90-97 GeV (LEP)



Gauginos ($\widetilde{B},\widetilde{W}$) & Higgsinos ($\widetilde{H}$) at LEP

Charginos: Large/Small m_0



$$\sigma \sim O(pb)@190\ GeV$$

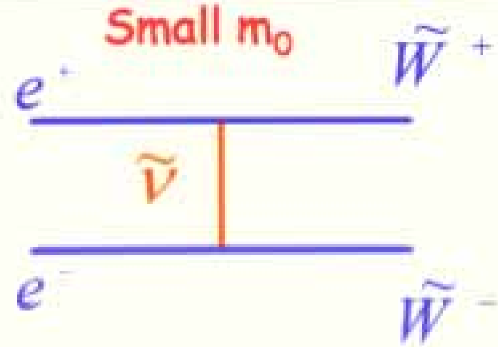
$$\widetilde{\chi}^+ \rightarrow \widetilde{\chi}_1^0 + W$$

Impact on Gaugino & Higgsino regions

$|\mu| >> M_2$ $\quad$ $|\mu| << M_2$

Loss of sensitivity when $\Delta M = m_{\widetilde{\chi}^+} - m_{\widetilde{\chi}_1^0}$ is very small (Deep Higgsino $|\mu| << M_2$ region)

Small m_0



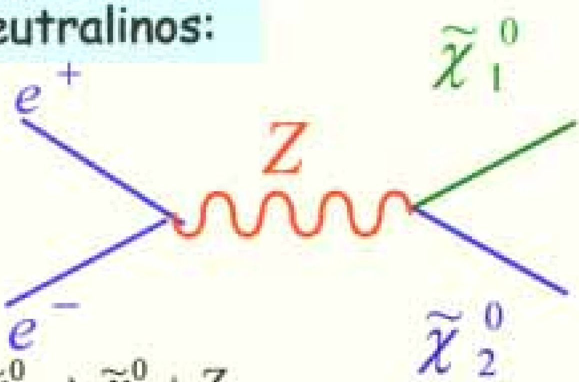
$$\widetilde{\chi}^+ \rightarrow \ell\widetilde{\nu}, \widetilde{\ell}\nu$$

Destructive interference in the Gaugino region

$|\mu| >> M_2$

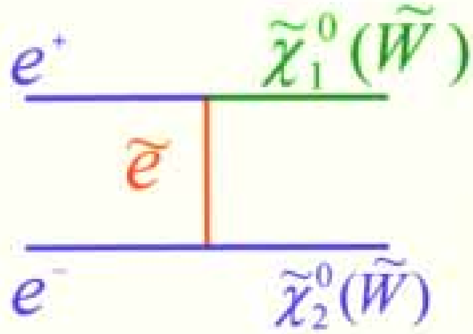
Loss of sensitivity when $\Delta M = m_{\widetilde{\chi}^+} - m_{\widetilde{\nu}}$ is very small

Neutralinos:



$\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 + Z$ (Higgsino)

In some regions of par space (e.g. Gaug/Higgs) $(\mu \sim -1/2\ M_2)$ the loop decay is competitive $\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 + \gamma$



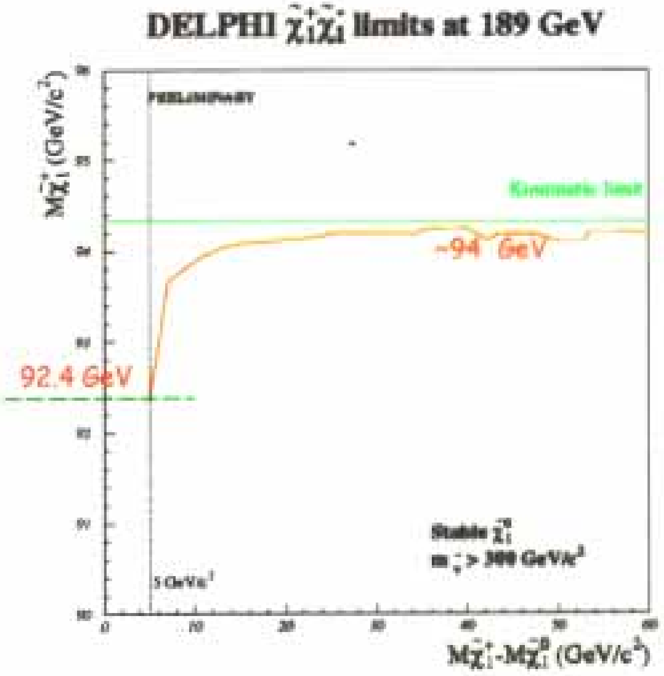
$\widetilde{\chi}_i^0 \rightarrow \widetilde{\ell}^\pm \ell^\mp$ (Gaugino)

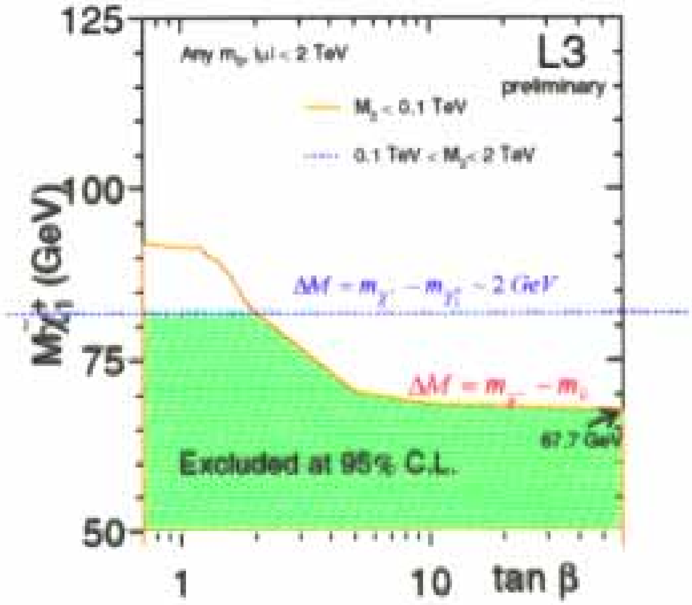
$\widetilde{\chi}_i^0 \rightarrow \widetilde{\nu}\nu$

Loss of sensitivity when $\Delta M = m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ is small

TOPOLOGIES: jets and/or leptons + missing energy

Charginos Limits





High $m_0 \rightarrow \Delta M$ limited

$\Delta M \equiv m_{\tilde{\chi}^+} - m_{\tilde{\chi}^0}$

Arbitrary m_0 (Light Neutrino)

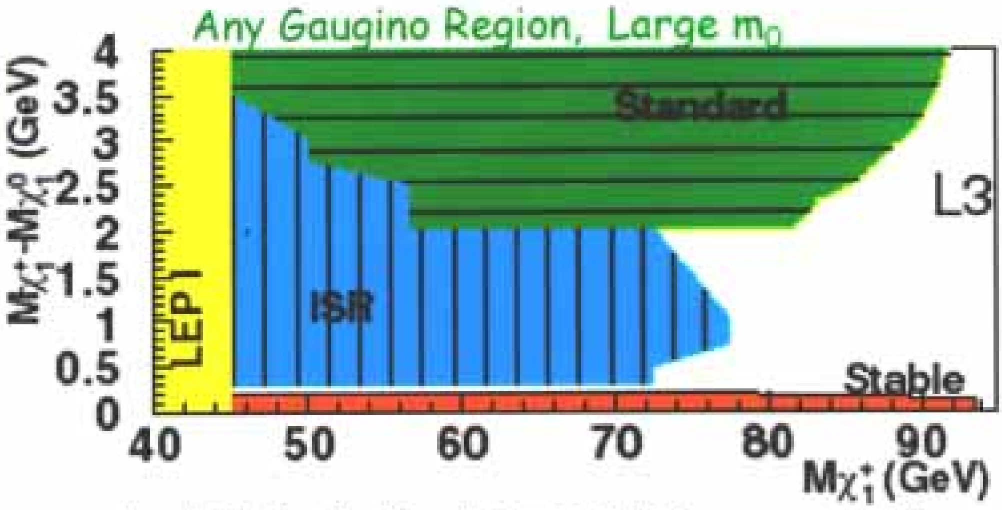
$m_{\tilde{\chi}^+} > 67.7\ (L\ 189)$

$\Delta M \leq 200\ MeV$	Stable Charginos excluded up to the kin limit
$200 < \Delta M < 300\ MeV$	Hard to access
$300 \leq \Delta M < 3\ GeV$	Low vis en+charged tracks+hard ISR photon
$\Delta M > 3\ GeV$	Standard Charginos search

To tell from $\gamma\gamma$

$\Delta M > 0.3$ GeV

$m_{\tilde{\chi}^+} > 72\ GeV$



Exclusion in the (μ, M_2) Plane

All searches were drafted to set limits in the (μ, M_2) plane

$$m_{\tilde{\chi}^0} = f(\mu, tg\beta, M_2, (M_1, m_0))$$

$$m_{\tilde{\chi}^+} = f(\mu, tg\beta, M_2, (m_0))$$

$$m_{\tilde{\ell}} = f(\cos 2\beta, M_2, m_0)$$

$$m_{\tilde{t}} = f(\cos 2\beta, M_2, mix(A_t - \mu\, tg\beta), m_0)$$

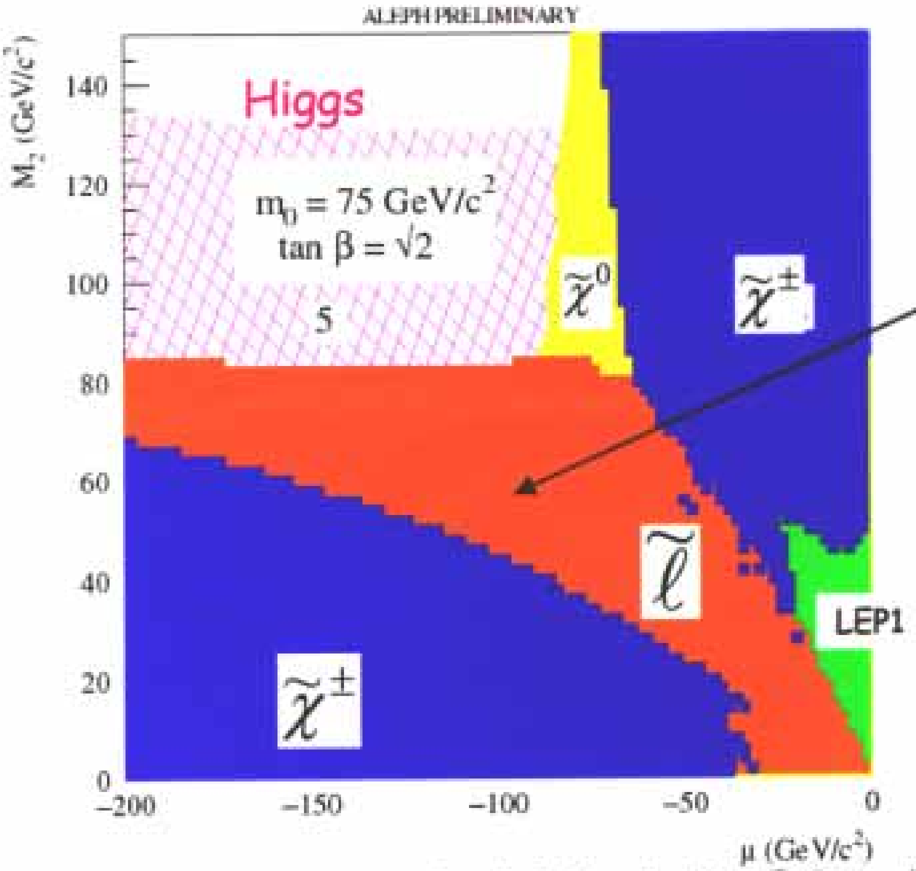
$$m_h = f(mix(A_t - \mu\, tg\beta), m_0)$$

The direct searches complement each other e.g.

Constraints from $m_{\tilde{t}}$ for large $\tilde{t}$ mixing

Constraints from m_h for small $\tilde{t}$ mixing (small m_h shift)

Each excluded point in the (μ, M_2) plane excludes some $m_{\tilde{\chi}^0}$



Somewhere here there is a point for $tg\beta=1$ which gives the limiting case for $m_{\tilde{\chi}^0}$

One needs to probe m_h=96 GeV in order to probe this point

Limit on the Neutralino LSP Mass

Each excluded point in the (μ, M_2) plane excludes some $m_{\tilde{\chi}^0}$

CMSSM

Any m_0

(GeV)	
32.3	A 189
31.2	D 189
32.5	L 189
31.6	O 189

Large m_0

$m_{\tilde{\chi}^0} >$ (GeV)	
32.3->34	A 196
31.2->32.4	D 196
32.5->34.8	L 196
32.8->34.5	O 196

mSUGRA

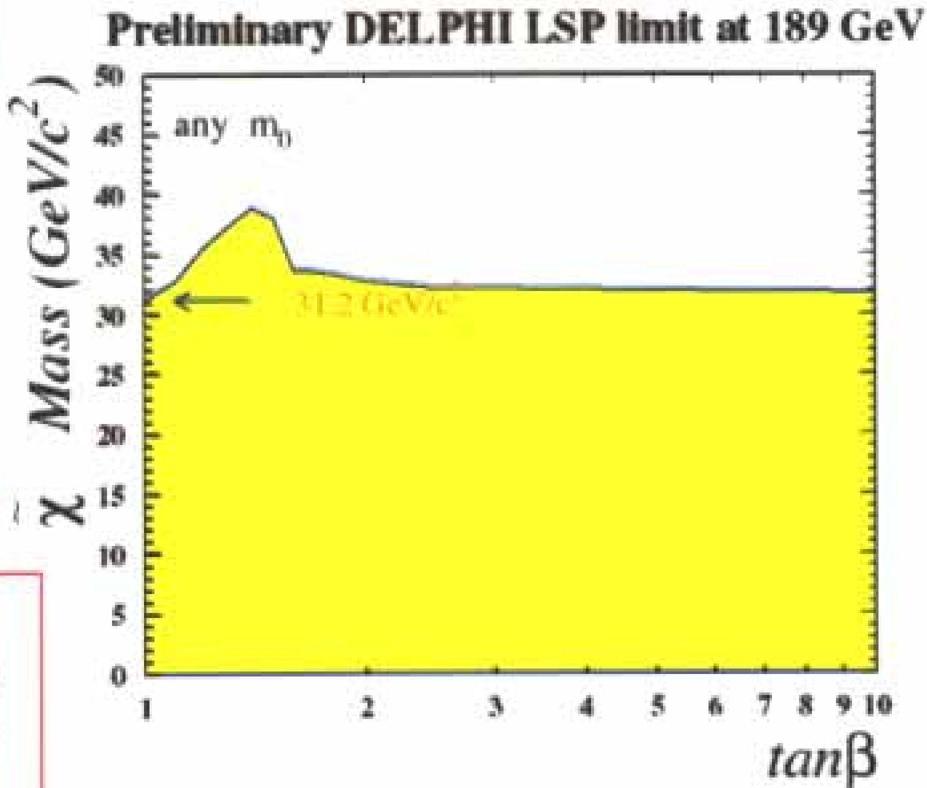
Combined LEP 189

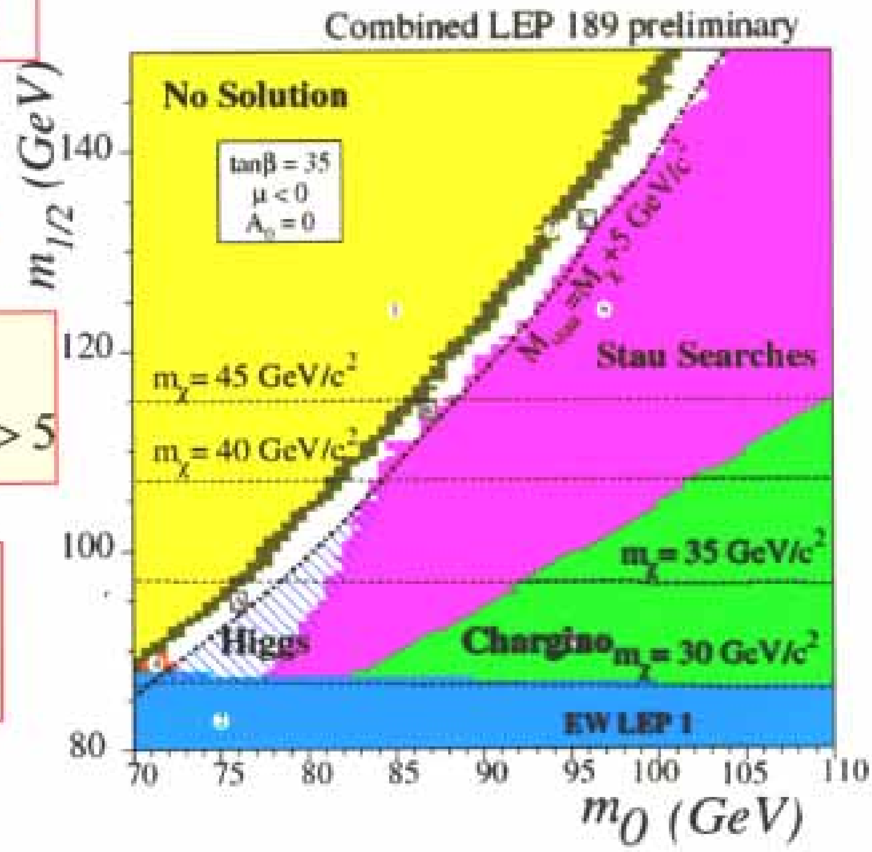
$m_{\tilde{\chi}_1^0} > 44 \ GeV$

$for \ \ A_0 = 0, m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0} > 5$

$m_{\tilde{\chi}_1^0} > 36 \ GeV$

$for \ \ tg\beta < 10 \ \forall \ A_0$





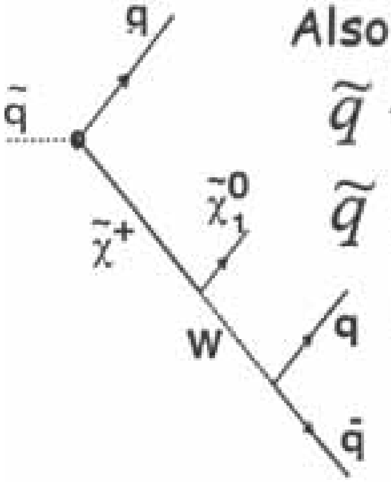
gluinos in mSUGRA

TEVATRON is the proper machine to search for gluinos

Production: $p\bar{p} \rightarrow \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}\ + X$

Decays: $\tilde{q} \rightarrow q\tilde{\chi}^0 \quad \tilde{g} \rightarrow \tilde{q}q \rightarrow qq\tilde{\chi}^0$

$\Rightarrow \quad jets + \not{E}_T$



Also:

$\tilde{q} \rightarrow q\tilde{\chi}^0_2 \rightarrow q\ell\ell\tilde{\chi}^0_1$

$\tilde{q} \rightarrow q\tilde{\chi}^+ \rightarrow q\ \tilde{\chi}^0_1 q\bar{q}$

$\Rightarrow \quad di\ lepton + jets + \not{E}_T$

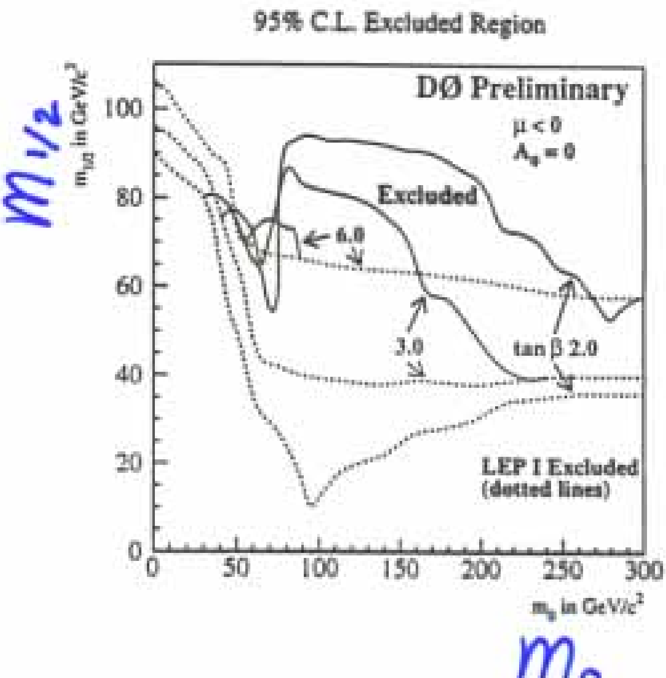
For $m_0 < 300$ GeV

$tg\beta < 10$

$m_{\tilde{g}} > 129$ GeV

$m_{\tilde{q}} > 138$ GeV

Similar results from CDF



Dip $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \nu\bar{\nu}$

Gauge Mediated Susy Breaking (GMSB)

Somewhere in the desert there are N SU(5) messenger

multiplets (at a scale M_{mess}) that mediate the

SUSY breaking (at $\sqrt{F} \sim 10^2$-10^4 TeV) down to earth.

As a result $M_i^2 \propto N^2 \Lambda^2 \alpha_i^2, \quad m_{\tilde{f}}^2 \propto 2N\Lambda^2$

and $\Lambda \sim F / M_{mess}$

EWSB $\rightarrow tg\beta, sign(\mu)$

The model parameters are therefore:

$$N, M_{mess}, \Lambda, tg\beta, sign(\mu)$$

Typical values (also used in scans):

$$\Lambda \sim 1-10 \quad TeV, M_{mess} \sim \Lambda - 1000\Lambda, N = 1-5$$

Most important phenomenological consequence:

$$m_{\tilde{G}} = F / \sqrt{3} M_P \sim O(100eV) \longrightarrow \tilde{G} \quad \text{LSP}$$

GMSB topologies @ LEP

$$M_i^2 \propto N^2 \Lambda^2 \alpha_i^2, \quad m_{\tilde{f}}^2 \propto 2N\Lambda^2$$

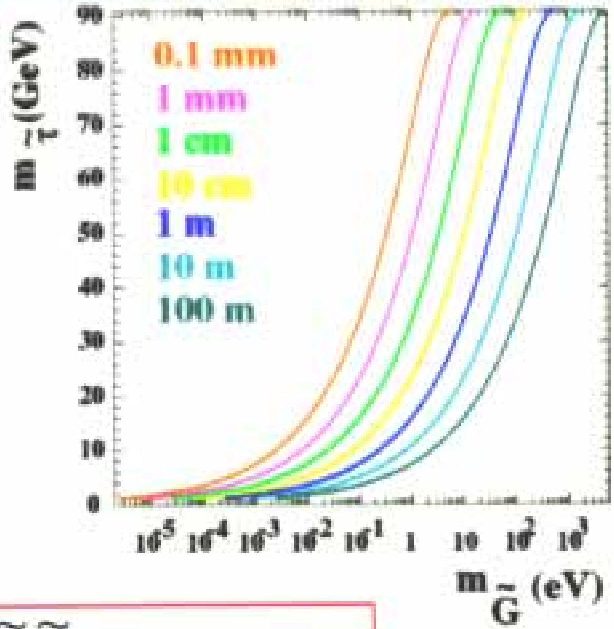
NLSP might have a lifetime

$$Small\ \ N \Rightarrow \qquad NLSP = \tilde{\chi}_1^0$$

$$\Rightarrow Large\ \ N\,(\tilde{f}\ \ Mix) \Rightarrow NLSP = \tilde{\tau}_1$$

$$Large\ \ N\,(No\ Mix) \Rightarrow CLSP = \tilde{\ell}$$

$$L_{NLSP} \propto m_{\tilde{G}}^2 / m_{NLSP}^5$$



NLSP decays

$$\tilde{\ell} \to \tilde{G}\ell$$

$$\tilde{\chi}_1^0 \to \tilde{G}\gamma$$

Rich Topologies:

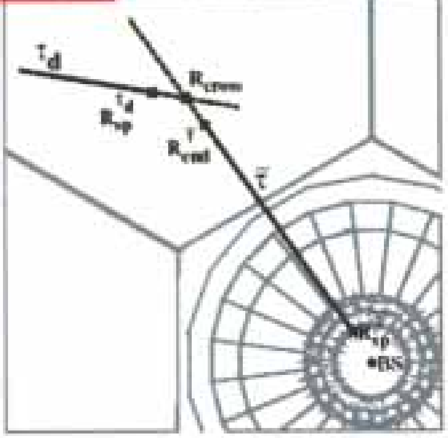
$$\tilde{\chi}_1^0\ NSLP: e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$$

$$e^+e^- \to \tilde{\ell}\tilde{\ell} \to \ell\tilde{\chi}_1^0\ell\tilde{\chi}_1^0 \to \ell\ell\gamma\gamma\tilde{G}\tilde{G}$$

$$\tilde{\ell}\ \ NLSP: e^+e^- \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{G}\tilde{G}$$

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \ell\tilde{\ell}\ell\tilde{\ell} \to \ell\ell\ell\ell\tilde{G}\tilde{G}$$

From non-pointing γ's and acoplanar photons or leptons to kinks and stable charged sleptons



2 γ's + Missing Energy or The event that revived GMSB

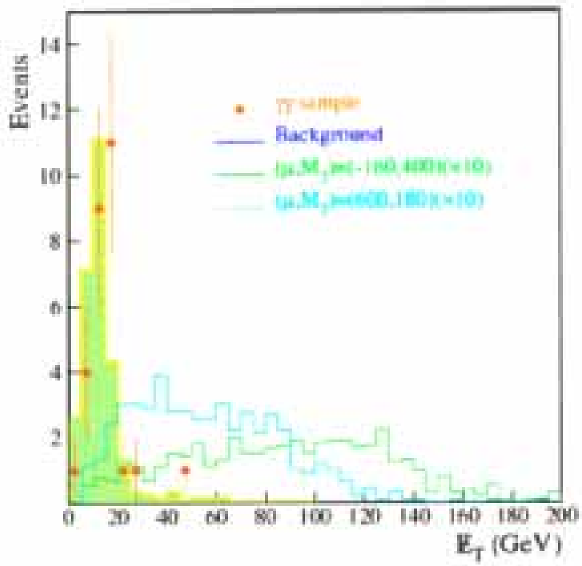
CDF event (Phys. Rev. Lett. 81 (1998) 1791): $e^+e^-\gamma\gamma \not{E}$

SUSY most popular interpretation:
(Lopez, Nanopulos, Phys Rev D55(1997)4450,......)

$$q\bar{q} \rightarrow \tilde{e}_R\tilde{e}_R \rightarrow ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\gamma\gamma\tilde{G}\tilde{G}$$

Bino

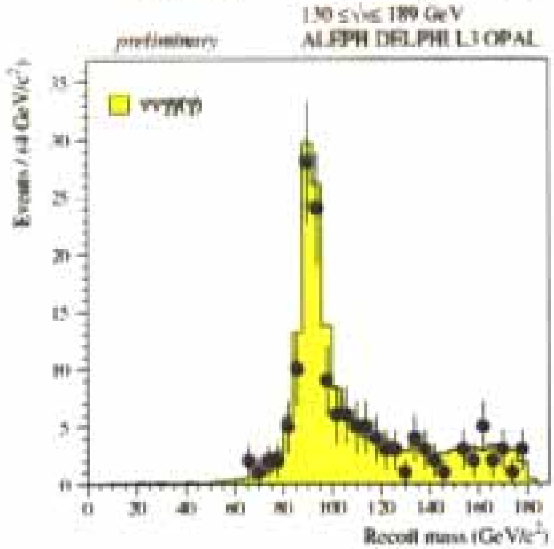
At Tevatron (D0)
2 events obs, 2.3 ±0.9 exp

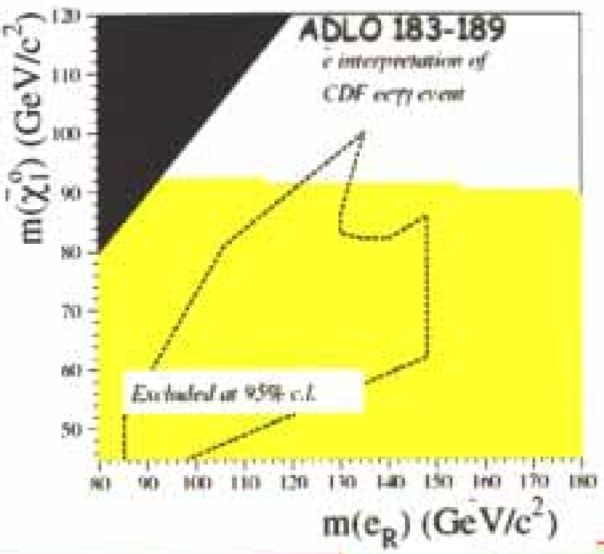


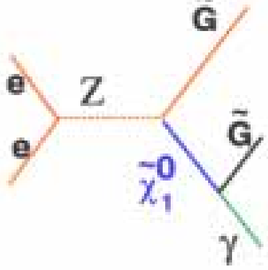
Not much space left...

At LEP (t-channel Binos)

$$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}) \sim O(pb)$$







Super light gravitino scenario

LEP One photon $e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \Rightarrow m_{\tilde{G}} > 10^{-5}\ eV$ (not GMSB)

CDF high E_T monojet $p\bar{p} \rightarrow \tilde{G}\tilde{G}g,\ \tilde{G}\tilde{G}q \Rightarrow m_{\tilde{G}} > 10^{-5}\ eV$

Some Limits on NLSP in GMSB

$\tilde{\tau}_1$ NLSP

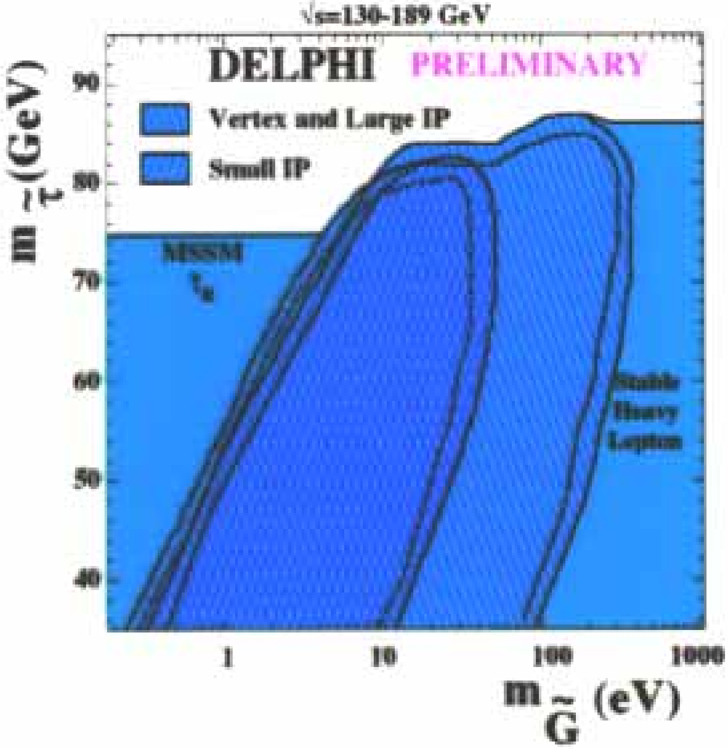
$m_{\tilde{\tau}_1} > 76\ GeV$ D189

$m_{\tilde{\tau}_1} > 67\ GeV$ A189

$\tilde{\ell}$ NLSP

$m_{\tilde{\ell}} > 79\ GeV$ D189

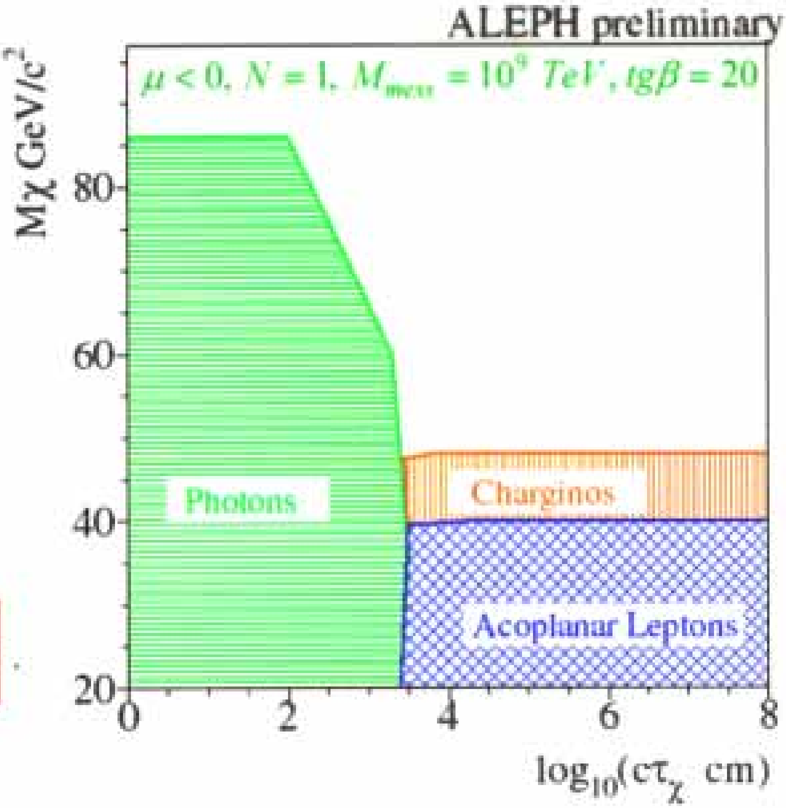
$m_{\tilde{\ell}} > 85\ GeV$ A189



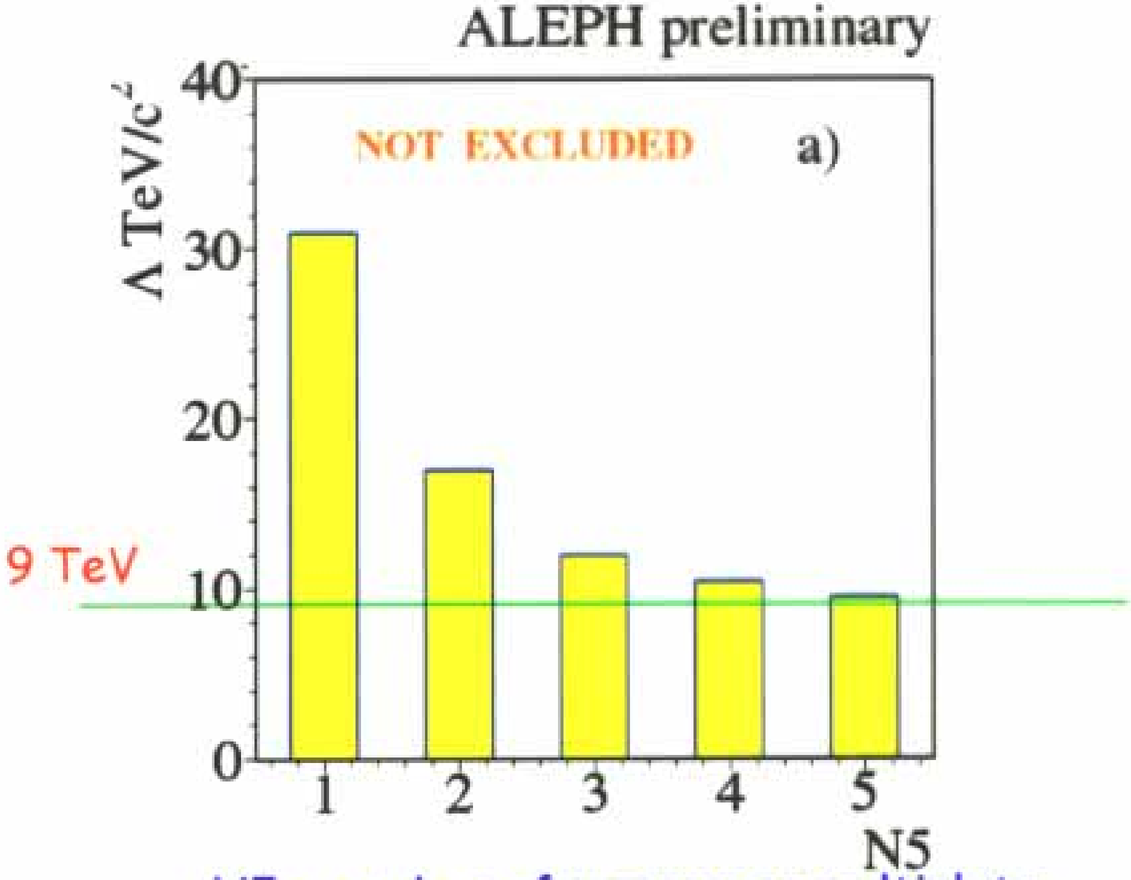
$\tilde{\chi}_1^0$ NLSP

For Neutralino NLSP decaying inside the detector, non-pointing photon analysis is used.
For longer lifetimes indirect exclusion via charginos and slepton searches.

$m_{\tilde{\chi}_1^0} > 45\ GeV\ \forall\ m_{\tilde{G}}$



Limits on Λ in GMSB



N5 - number of messenger multiplets

DELPHI

Aleph

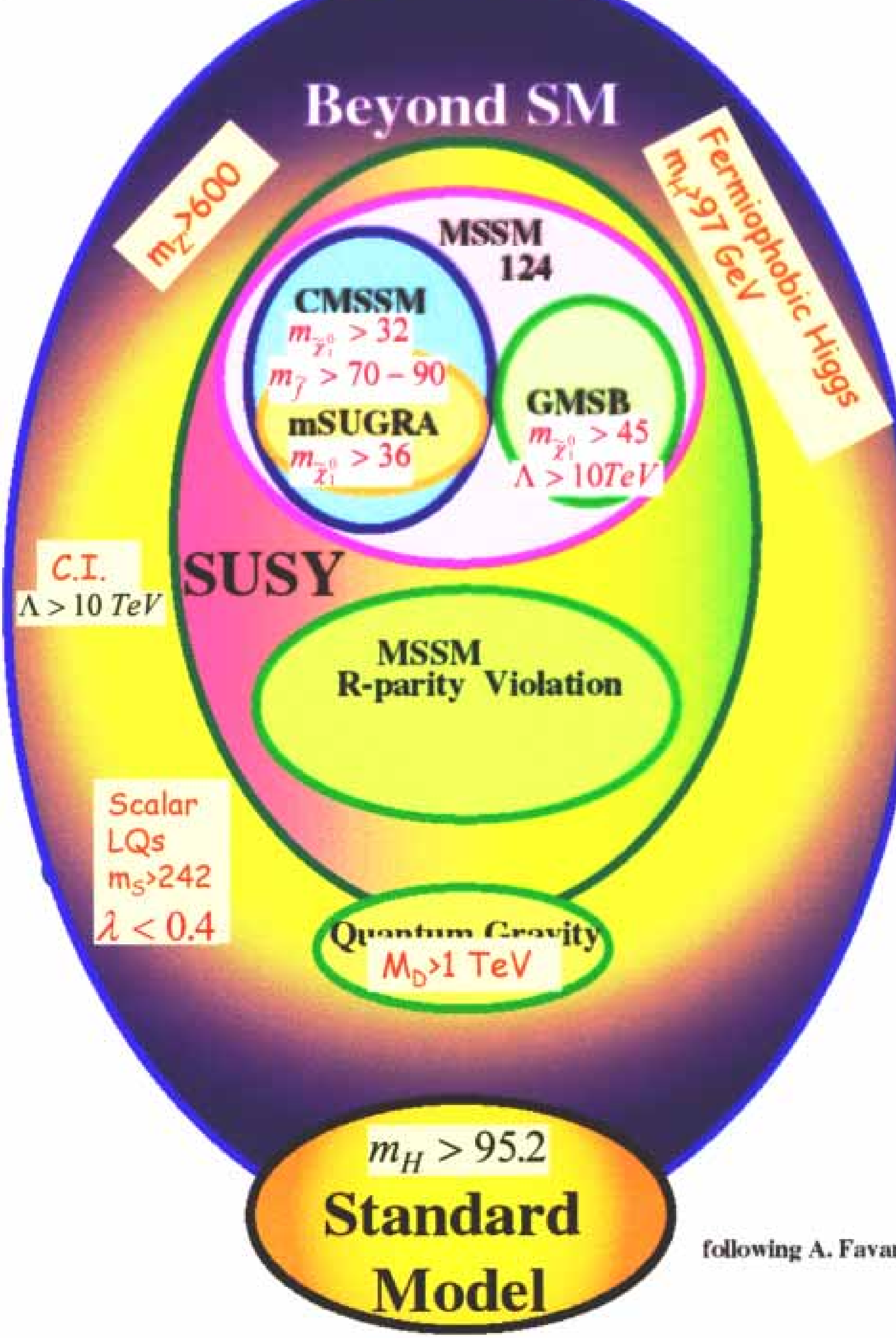
Dimopoulus et al.
PRD54(1996)3238

$\Lambda > 9 \ TeV$

Cheung et. Al.
PRD58(1998)15008

$\Lambda > 14.8 \ TeV$

The Searches Eggs - Cntd



following A. Favara

R_P Violation

$$R_P = \begin{cases} +1 & particles \\ -1 & Susy\_particles \end{cases} \Rightarrow$$

SUSY particles are produced in pairs
B & L conservation

$\not{R}_P \Rightarrow$
- LSP decays to standard particles via B and L violation
- LSP need not anymore be natural or colorless
- Gone are the days of SUSY missing energy signature

$$W_{\not{R}_P} = \underbrace{\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k}_{\text{L violation}} + \underbrace{\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k}_{\text{B violation}}$$

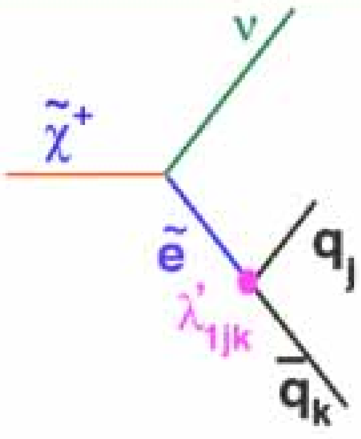
⇒ 45 parameters in addition to CMSSM 6 parameters

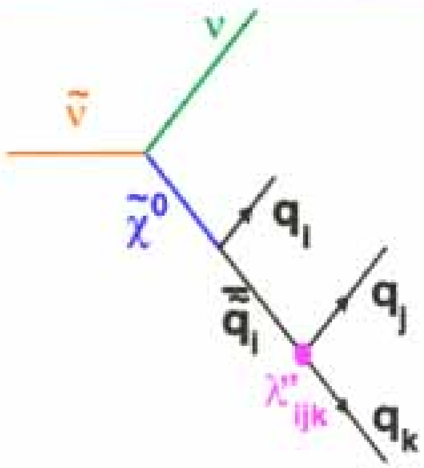
From non observation of lepton universality,proton decay etc...
(H. Dreiner: hep-ph/9707435;G.Bhattacharyya:hep-ph/9709395)
one gets numerous limits on the λ couplings of the order

$\lambda < 0.05,\ \lambda' < 0.4,\ \lambda'' < 1$ $\lambda_{133} < 0.003\ (\nu_e\ \ mass)$

Assumptions: One Term Dominates!
Decay at or close to IP $\Rightarrow \lambda > 10^{-4}, 10^{-7}\ \ (LSP = \tilde{\chi}^0, \tilde{f})$

$\not{R}_P$ is manifested directly in the decay of the produced particle	$\not{R}_P$ is manifested indirectly in the decay of the LSP (large m_0)





$R_P V$ Production

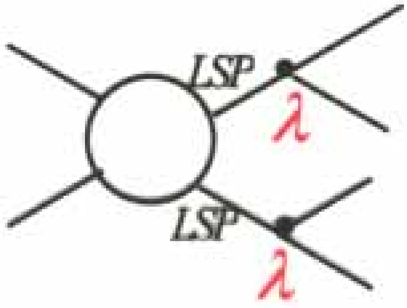
Associate Production

σ is independent of λ

(in most cases assume BR=1)

$\Rightarrow$ Limits on LSP masses

Mass reach $\sqrt{s}/2$



Single Production

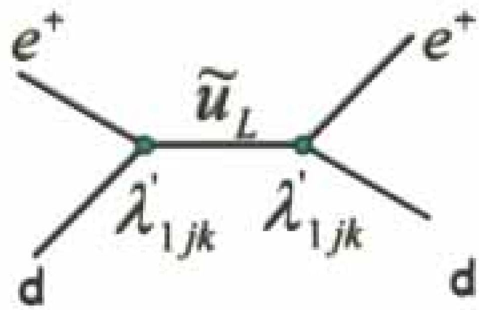
Initial states probe λ

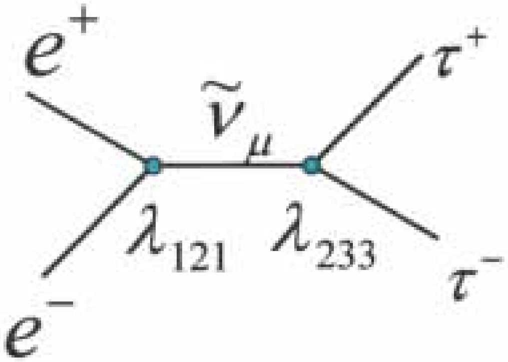
$\Rightarrow$ Limits on λ vs LSP mass

Mass reach $\sqrt{s}$,

Limits in λ vs mass.

HERA "leptoquark"



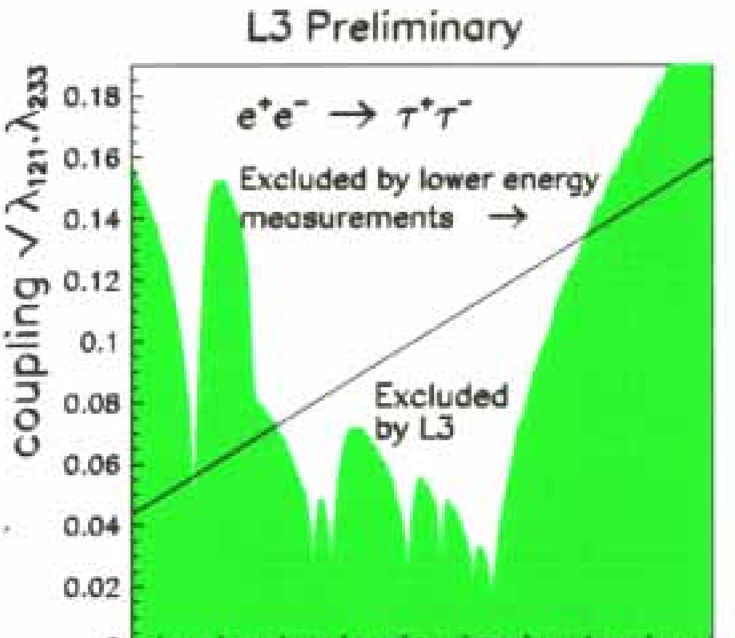


Look for deviations from SM pair production and A_{FB}

$$R_\tau = \frac{\Gamma(\tau \to e\nu\bar{\nu})}{\Gamma(\tau \to \mu\nu\bar{\nu})} \Rightarrow \lambda_{233} < 0.06\frac{m}{100}$$

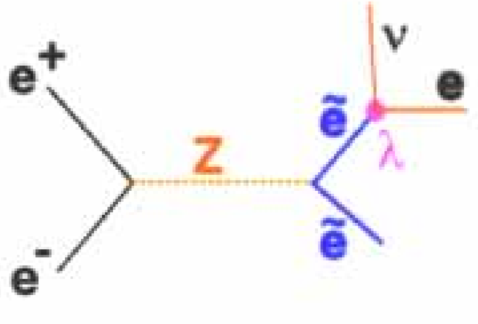
CC universality

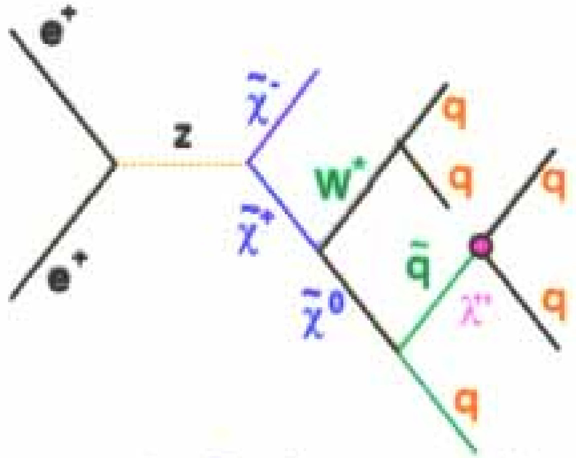
$$\Rightarrow \lambda_{121} < 0.05\frac{m(GeV)}{100}$$



RpV Topologies @ LEP

From 2 leptons + E_{miss} to 10 jets without E_{miss}





The nonzero R_p decay operator dictates the final states toplogy

$$\lambda'_{ijk} \quad \tilde{\ell}_i, \tilde{\nu}_i \rightarrow u_j \bar{d}_k, d_j \bar{d}_k \Rightarrow 4 \ jets\,(+\not{E})$$

$$\lambda''_{ijk} \quad \tilde{u}_i, \tilde{d}_j \rightarrow d_j \bar{d}_k, \bar{u}_i \bar{d}_k \Rightarrow 4 \ jets\,(+\not{E})$$

$(\lambda, \lambda')\, m_{\tilde{\nu}_\mu} > 78,5$ (dir, A189)

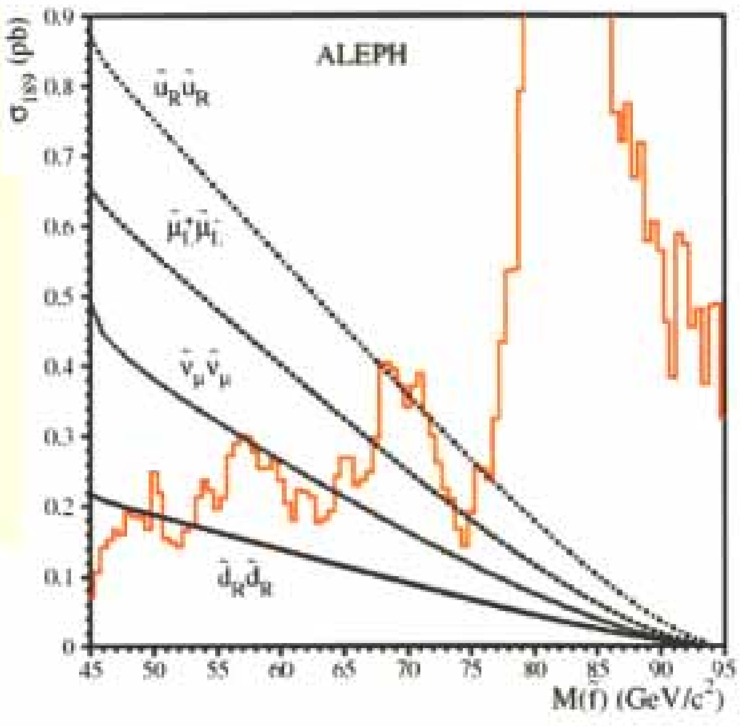
$(\lambda')\quad m_{\tilde{\mu}_L} > 67$ (dir A 189)

$(\lambda)\quad m_{\tilde{\tau}_R} > 74$ (direct, O189)

$(\lambda')\, m_{\tilde{\tau}_R} > 45$ (indirect, A189)

$(\lambda)\quad m_{\tilde{\nu}} > 78$ (dir, ind, D189)

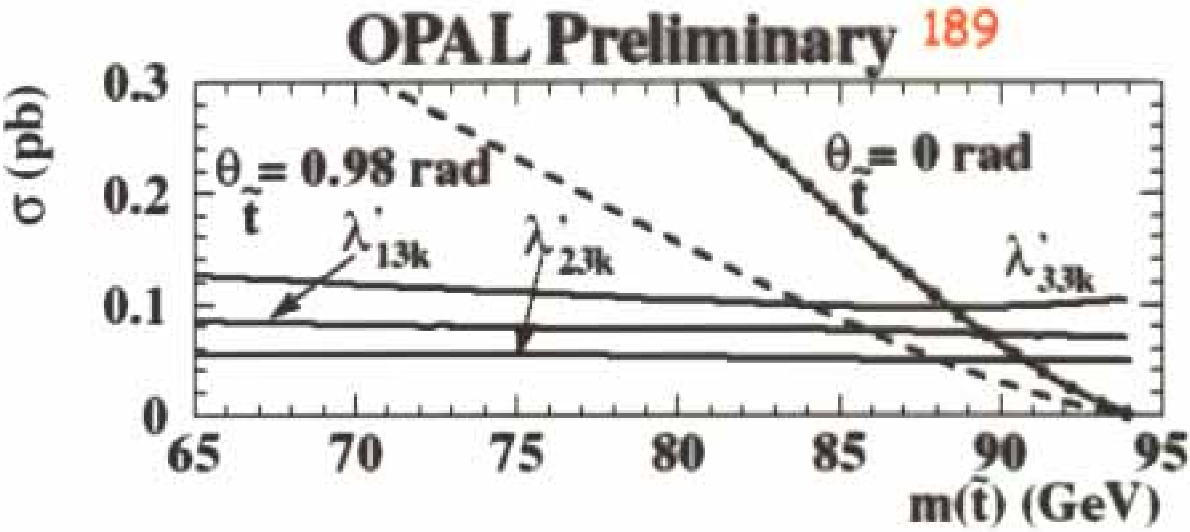
$(\lambda)\quad m_{\tilde{e}_R} > 84$ (indirect, D189)



Sensitivity is comparable to MSSM R_p conserved

Sometimes, even better (☺)

Limits on Squarks



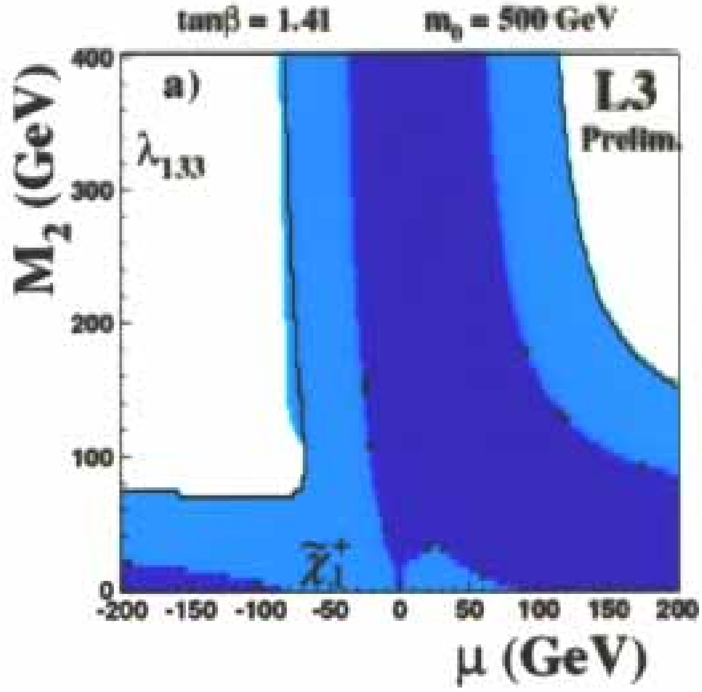
	$\theta_{\tilde{t}} = 0$	$\theta_{\tilde{t}} = 0.98$
$(\lambda'_{13k})\ \tilde{t}_1 \to eq$	89	86 GeV
$(\lambda'_{23k})\ \tilde{t}_1 \to \mu q$	90	88
$(\lambda'_{33k})\ \tilde{t}_1 \to \tau q$	88	84
$(\lambda'')\ \tilde{t}_1 \to qq$	88	79

Sensitivity is comparable to MSSM R_p conserved

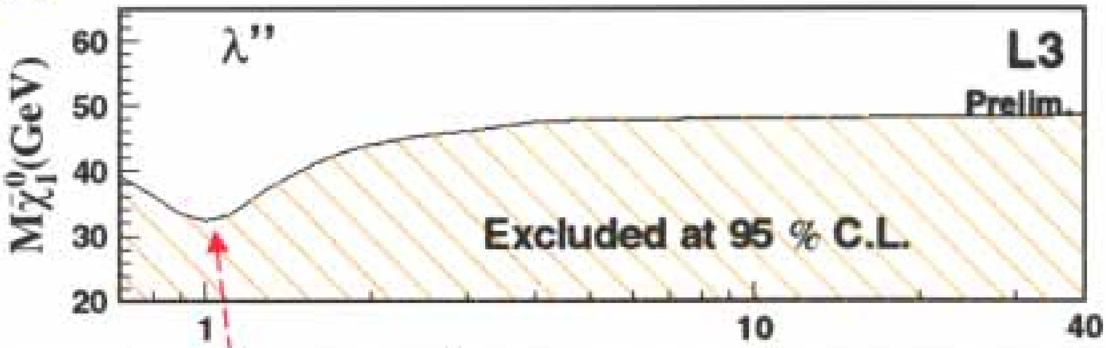
Limits on Gaugino Masses

Methods are the same as MSSM except that the final search topology depends on which R_p operator $\lambda(\lambda',\lambda'')\neq 0$

In particular one can set a limit on the LSP



Limits are comparable or better than R_p conserved case!



	$UDD(\lambda'')$	$LQD(\lambda')$	$LLE(\lambda)$
$\tilde{\chi}_1^0$	32.5 GeV	29.9 GeV	30.5 GeV
$\tilde{\chi}_1^+$	94.2 GeV	94.3 GeV	94.3 GeV

Sensitivity is comparable to MSSM R_p conserved

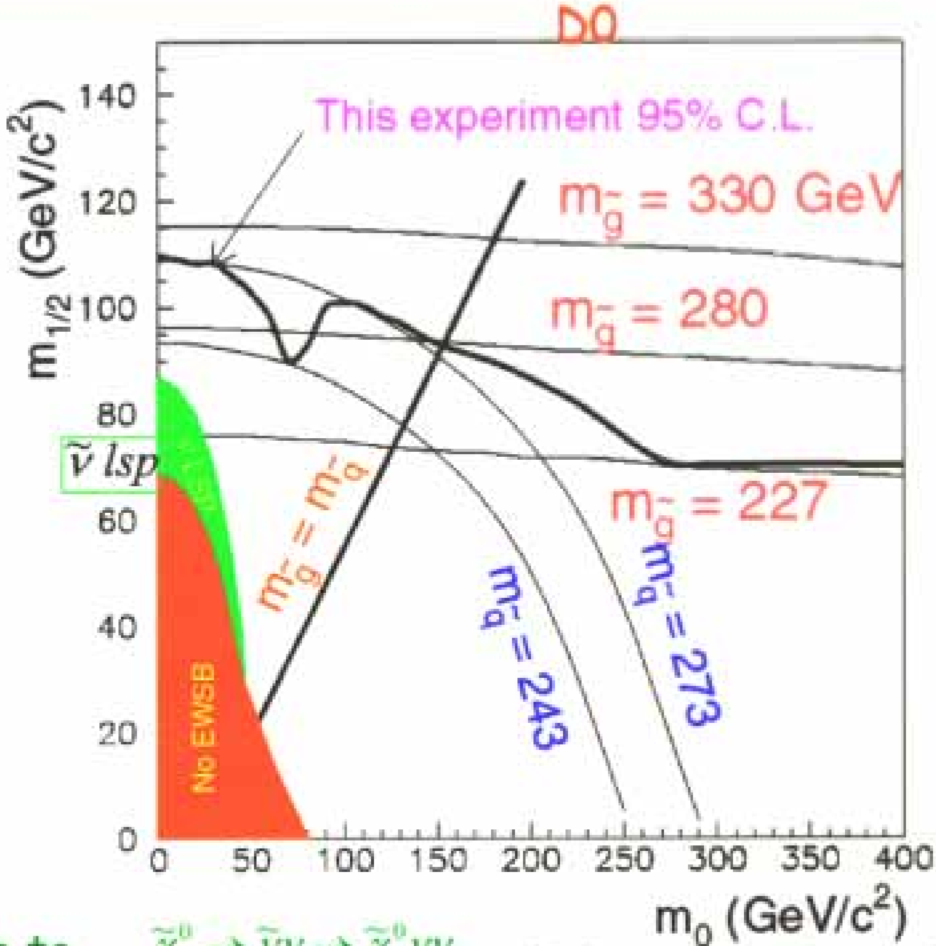
R_PV at the TEVATRON

CDF searched likesign dielectron events with two jets

$$\lambda'_{121} \quad p\bar{p} \to \tilde{g}\tilde{g} \to \bar{c}\tilde{c}\,\bar{c}\tilde{c} \to \bar{c}\bar{c}(e^+d)(e^+d)$$

D0 focused on λ'_{122} searching for 2 electrons with four jets

$$p\bar{p} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to e(\tilde{e})e(\tilde{e}) \to eeq\bar{q}q\bar{q}$$



Dip due to $\tilde{\chi}_2^0 \to \tilde{\nu}\nu \to \tilde{\chi}_1^0\nu\nu$

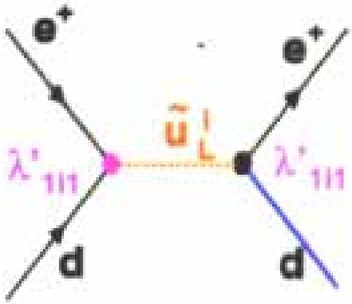
Null results interpreted in mSUGRA
tgβ=2,6 μ<0 A_0=0

For $m_{\tilde{q}} = m_{\tilde{g}}$ the corresponding limit is 277 GeV

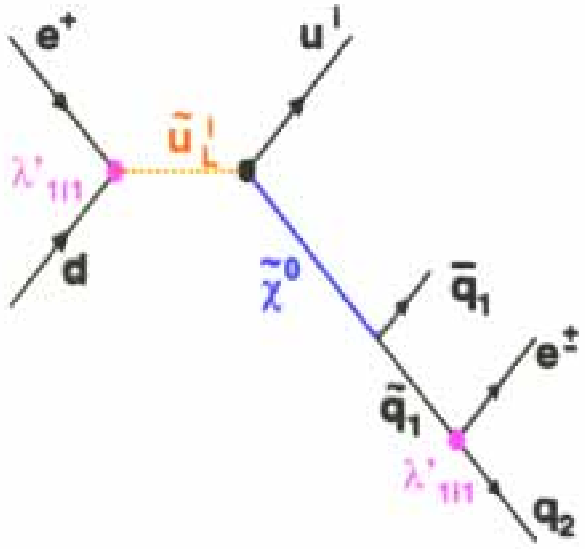
Sensitivity is comparable to MSSM R_p conserved

(tgβ=2, sensitivity is poor for higher values of tgβ)

R_PV at ZEUS

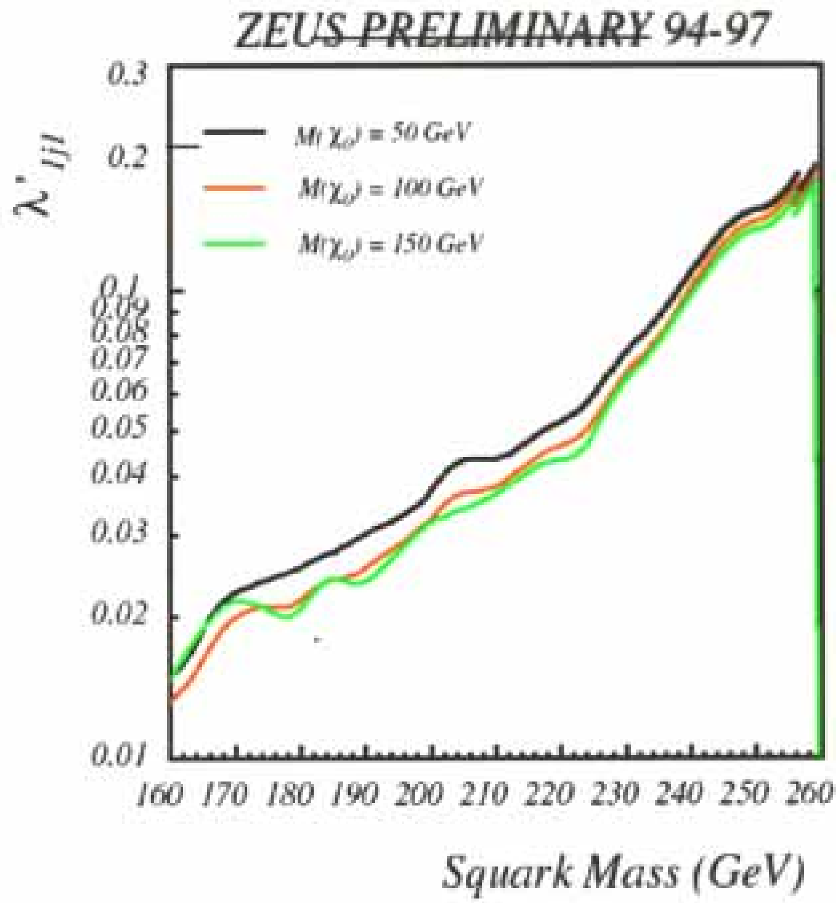


$\sim \lambda'^2_{1jk}$



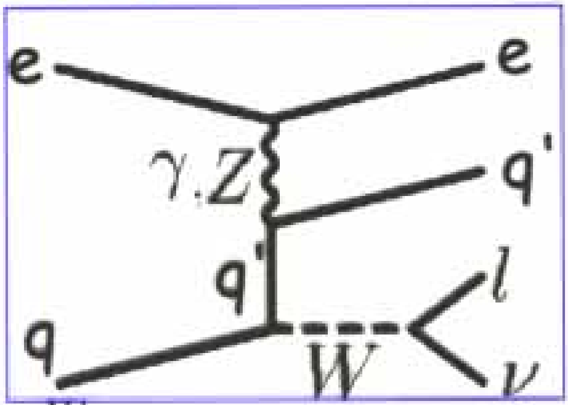
Signature: $e^+q, \quad e^{\pm}qqq$

Ignore decays involving $\tilde{u} \rightarrow d\tilde{\chi}^+$ and $\tilde{u} \rightarrow u\tilde{\chi}^0_2$



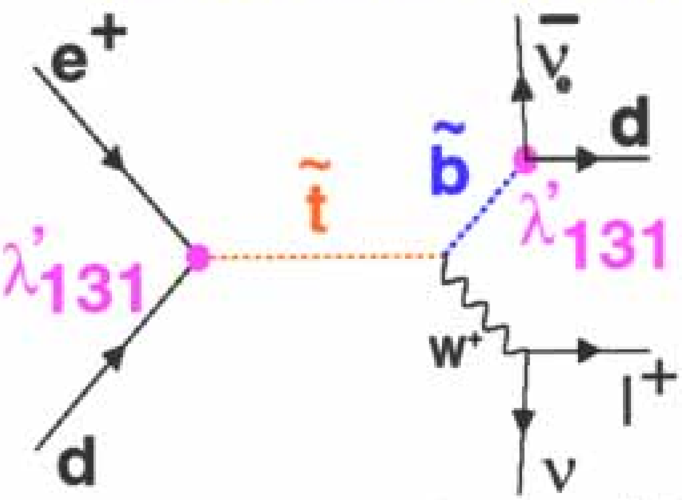
H1 's Isolated Leptons + Jets + E_T Miss
Last Year's Anomaly

	Process	Obs	Exp
H1	$e^+p \to e^- X + \not{P}_T$	1	2.4
	$e^+p \to \mu^\pm X + \not{P}_T$	5	0.8
Zeus	$e^+p \to e^+ X + \not{P}_T$	3	3.0
	$e^+p \to \mu^\pm X + \not{P}_T$	0	1.4



⇒ Calculate on shell $\sigma(ep \to eW + X)$

A possible explanation for H1 events: SUSY RpV



Kinematics is not incompatible with

$m_{\tilde{t}} \sim 200,$

$m_{\tilde{b}} \sim 90 - 120\ GeV$

However, expect also $W \to jets$

$N_{obs}(W \to had) = 3 \qquad N_{exp}^{SM}(W \to had) = 4.7 \pm 0.7$

For $m_{\tilde{t}} \sim 200,\ m_{\tilde{b}} \sim 100\ GeV$

Assuming $eff(W \to had) = eff(W \to \mu\nu)$

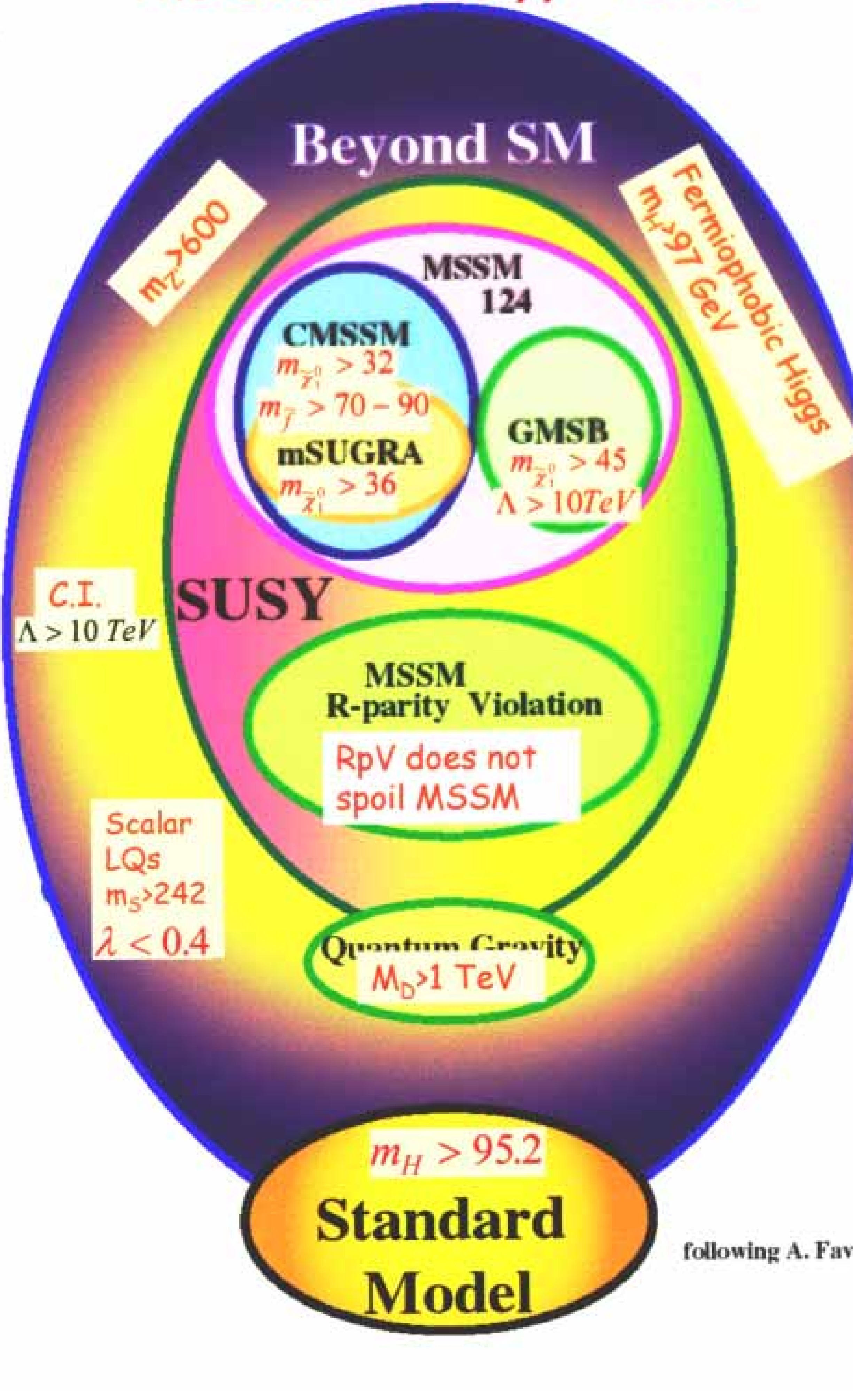
$N_{exp}(W \to \mu\nu) < 0.36$ @90% C.L.

⇒ Possibility of RpV is ruled out!

Moreover, $e^- p$ cannot lead to $\tilde{t}$ production
Zeus observe 2 high p_T (>10 GeV) electron and 0 muon events consistent with SM expectations of 1.6 (0.8+0.8)
H1 observes 0 such events with a SM expectation of (0.4+0.4)

ZEUS observe no anomalies with e^+p/e^-p data taken so far

The Searches Eggs - Cntd



following A. Favara

Back to MSSM & SUSY Higgs

H_1^0, H_2^0 : Real parts mix with an angle $\alpha \rightarrow$ h,H

Imaginary part (not eaten by Z) $\rightarrow$ A

In total 5 Higgs bosons and two angles:

$$H^{\pm}, h, H, A \qquad tg\beta = \frac{v_u}{v_d}, \alpha$$

Higgs bosons produced via $e^+e^- \rightarrow hZ, hA$

$$g_{hz}^2 + g_{hA}^2 = 1$$

Tree level:
2 pars (m_h,m_A) or $(tg\beta, m_h)$ or $(tg\beta, m_A)$
determines α and the mass spectrum:

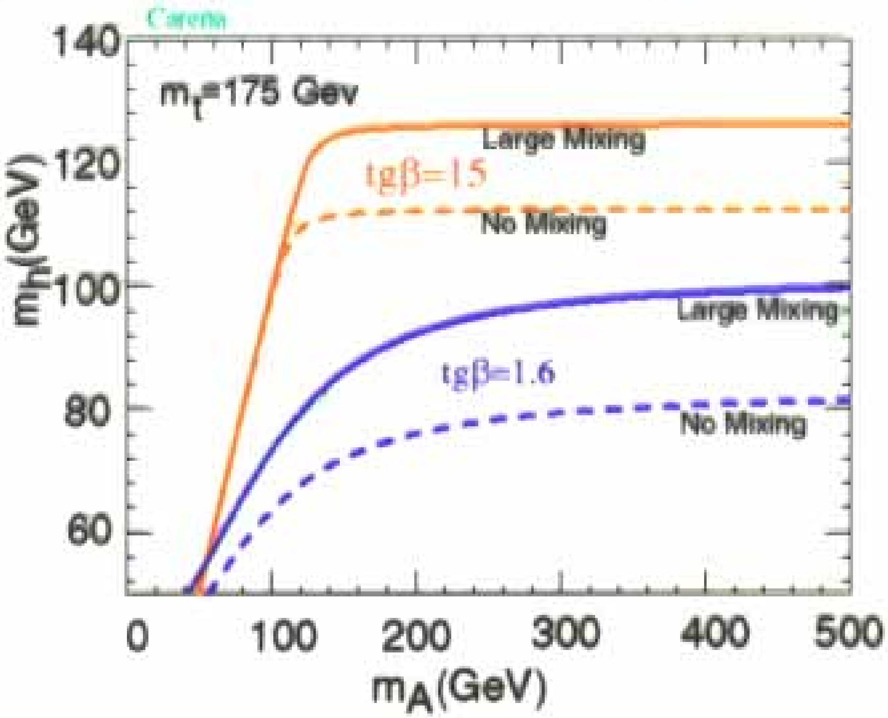
$$m_h = m_Z \, |\cos 2\beta| \leq m_Z \longrightarrow$$

LEP 2 must discover the light Higgs boson or MSSM is out, but ALLAS
MSSM is saved by
Radiative corrections that shift the Higgs mass upward

The light MSSM Higgs boson mass

Rad corrections → Max light Higgs mass depends on soft SUSY breaking parameters

$$m_h^2 \sim \frac{m_t^4}{v^2} f_2\left(\widetilde{A}_t, \log\frac{m_s^2}{m_t^2}\right)$$



Benchmarks

$m_s = 1TeV,\ \mu = -0.1 m_s,\ M_2 = 1.6TeV$

No Mixing in the stop sector: $A_t = 0,\ \ m_h < 115\ \ GeV$

Max Mixing in the stop sector: $A_t = \sqrt{6} m_s,\ \ m_h < 130\ \ GeV$

$$m_{H^\pm} \gtrsim m_W$$

Invisible Higgs Decays

- MSSM R_p conserved $h \to \tilde{\chi}_1 \tilde{\chi}_1$

  or nearly invisible (OPAL)

  $h \to \tilde{\chi}_2 \tilde{\chi}_1 \to \tilde{\chi}_1 \tilde{\chi}_1 + Z^* / \gamma$ with very small Δm

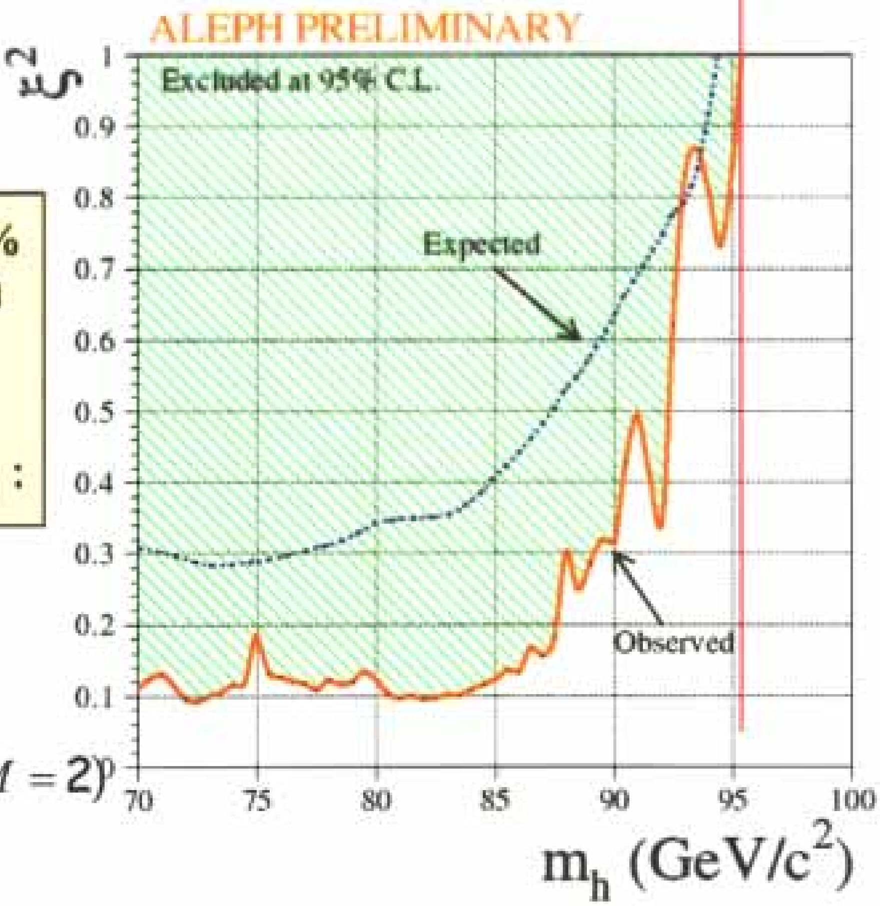
- R_p violating $h \to JJ$; J is a Majoron (Goldstone Boson via SSB of Lepton # U(1)) which couples only to ν_R

$m_{h_{inv}} > 95.4$ GeV

$$\xi^2 \equiv \frac{\sigma_{h_{inv} Z}}{\sigma_{h_{SM} Z}}$$

If the $BR(h \to inv) = 100\%$ and if the cross section is SM like than the excluded m_h (in GeV) is :

ALEPH 189	95.4
DELPHI 189	93.8
OPAL 196	91.8
OPAL 189 (n.i.)	87.7 ($\Delta M = 2$)



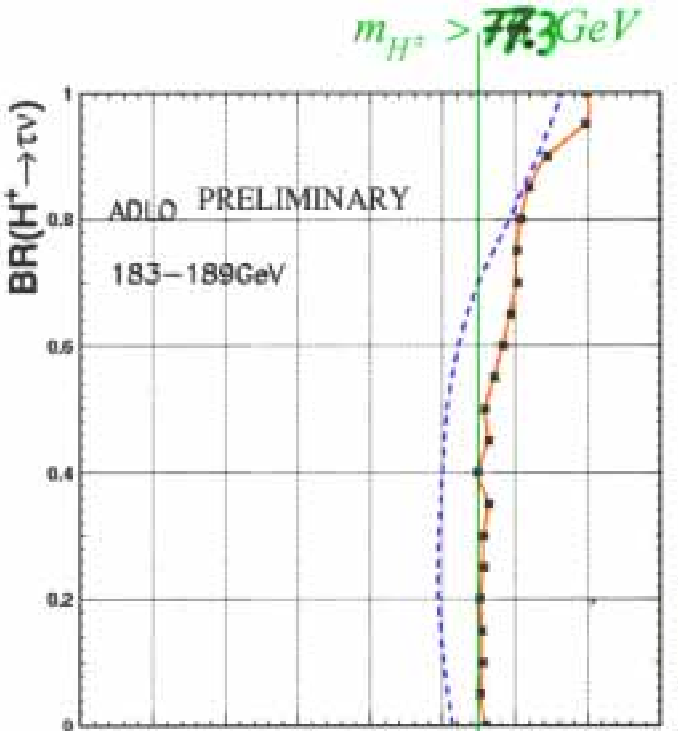
Charged Higgs at LEP

- In most of the SUSY parameters space $m_{H^\pm} > m_{W^\pm}$
  - $H^\pm \rightarrow \tau^\pm \nu, c\bar{s}$

    large tgβ prefers $\tau^\pm \nu$ decays.

  - Large BG: signature is $W^\pm$ alike, especially for heavier charged Higgses

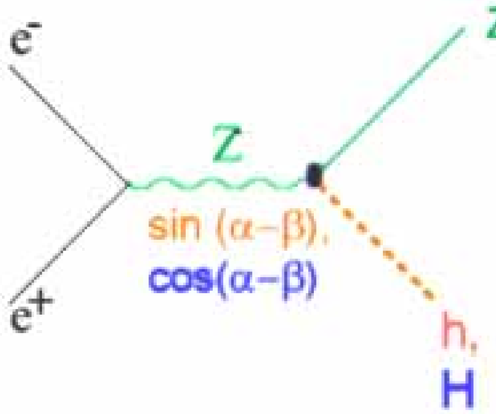
  - If a charged Higgs is discovered at LEP II, it will probably be lighter than that predicted by MSSM and it will indicate either physics beyond the MSSM or some obscure set of MSSM parameters.



	Obs	Exp
ALEPH 189	65.5	69.5
DELPHI 189	66.9	
L3 189	67.5	
OPAL 196	68.7	70.0
ADLO 189	~~76.0~~ 77.3	~75

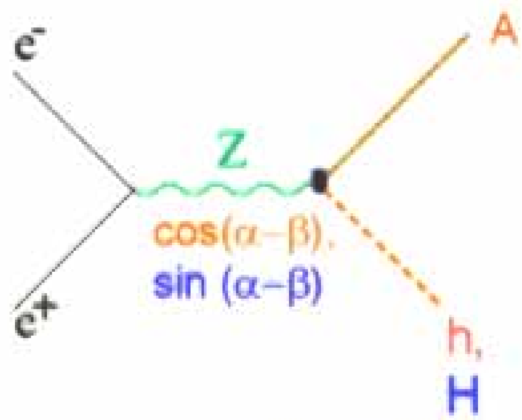
Not yet in the interesting region

Neutral Susy Higgs Production & Decay at LEP



$$\sigma_{hz} = \sigma_{HZ}^{SM} \sin^2(\alpha - \beta)$$

SM like topologies



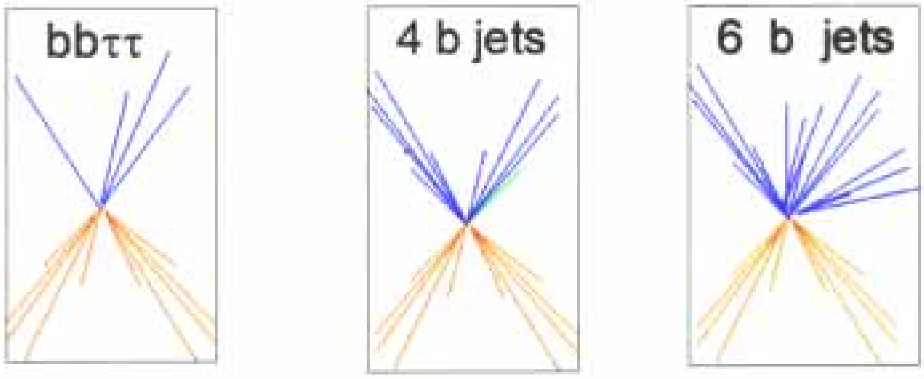
$$\sigma_{hA} = \sigma_{HZ}^{SM} \lambda \cos^2(\alpha - \beta)$$

λ Kinematical factor

Complementarity

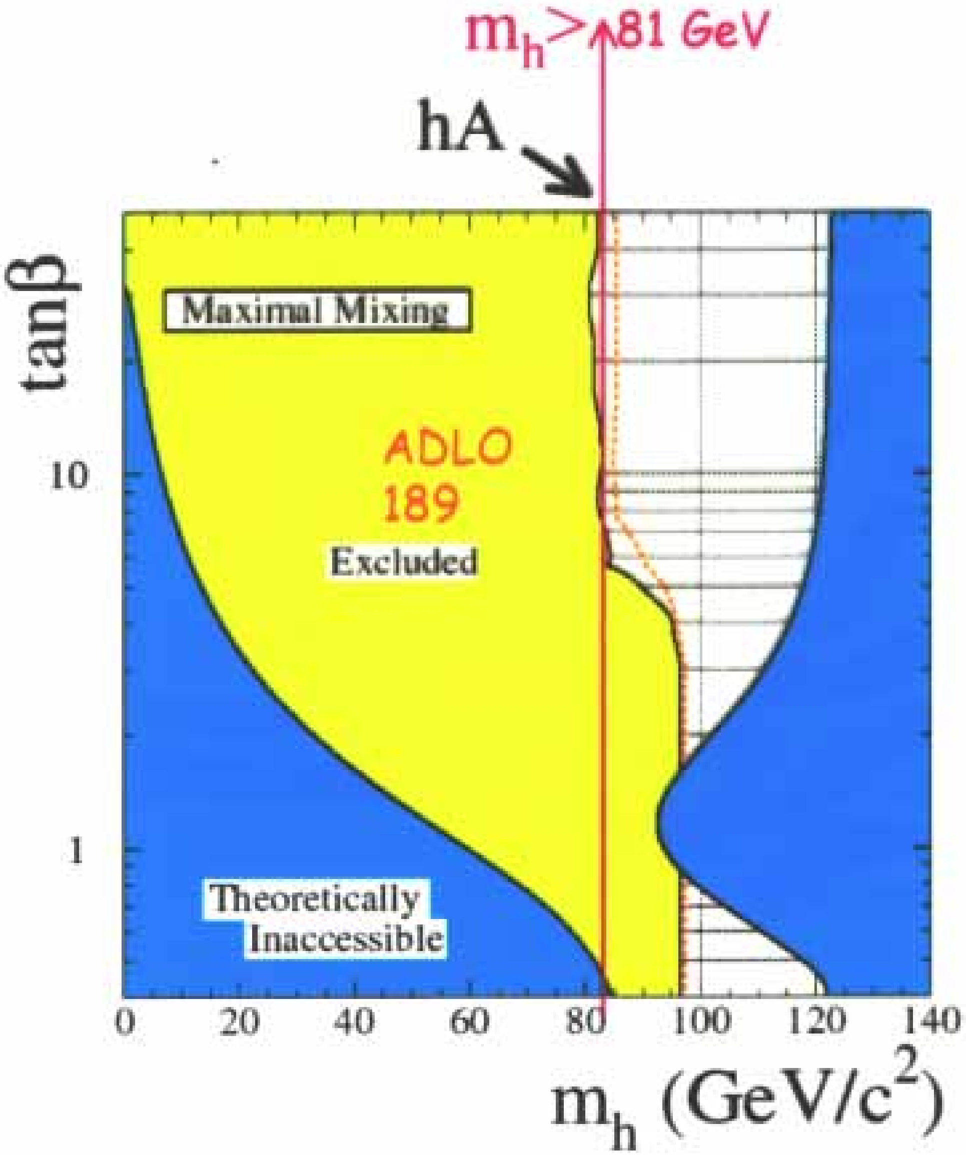
h,A decay modes:

- Rad corrections $\Rightarrow$ possible $m_h > 2m_A \Rightarrow h \to AA$
- $g_{hb\bar{b},h\tau\tau} \sim \frac{\sin\alpha}{\cos\beta}$, $g_{Ab\bar{b},A\tau\tau} \sim tg\beta$ $\begin{cases} tg\beta > 1 : h, A \to b\bar{b}\ (>85\%), \tau^+\tau^- \\ tg\beta < 1 : h, A \to c\bar{c} \end{cases}$
- hA main search topologies:



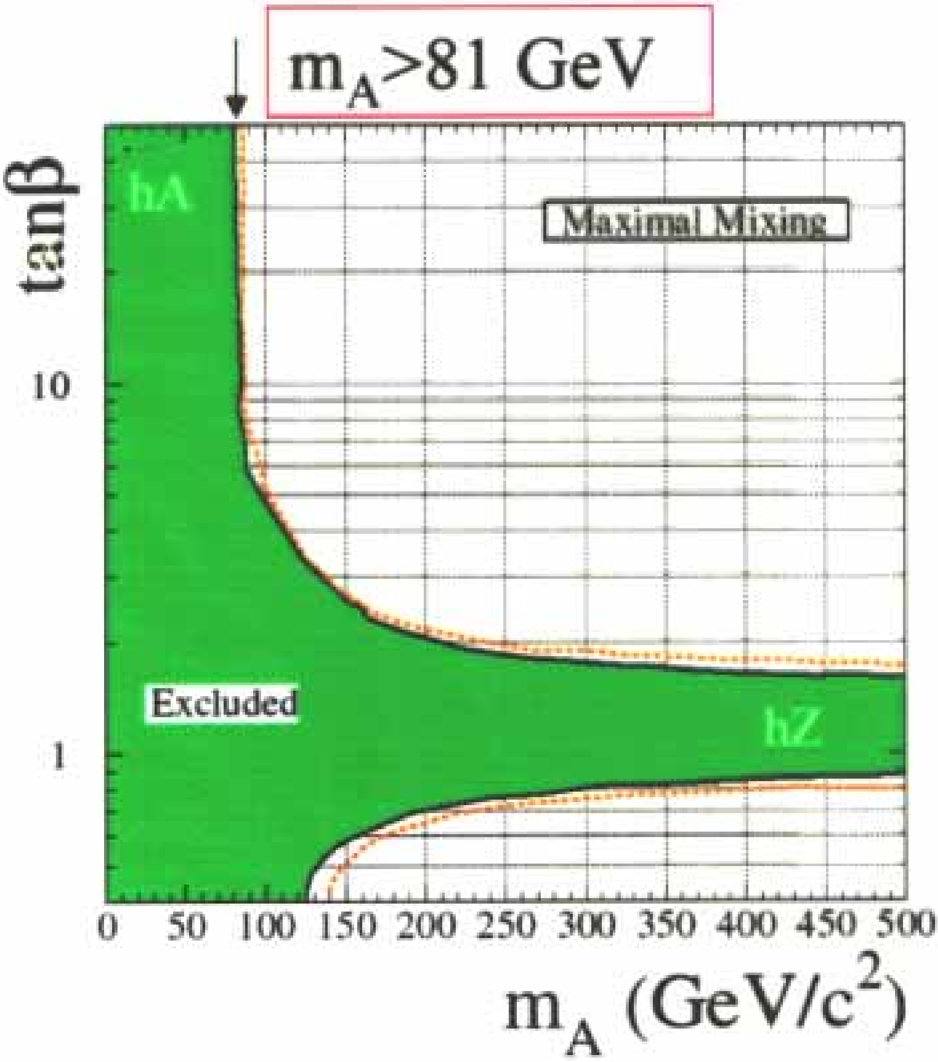
b tag essential

Limits on m_h from LEP



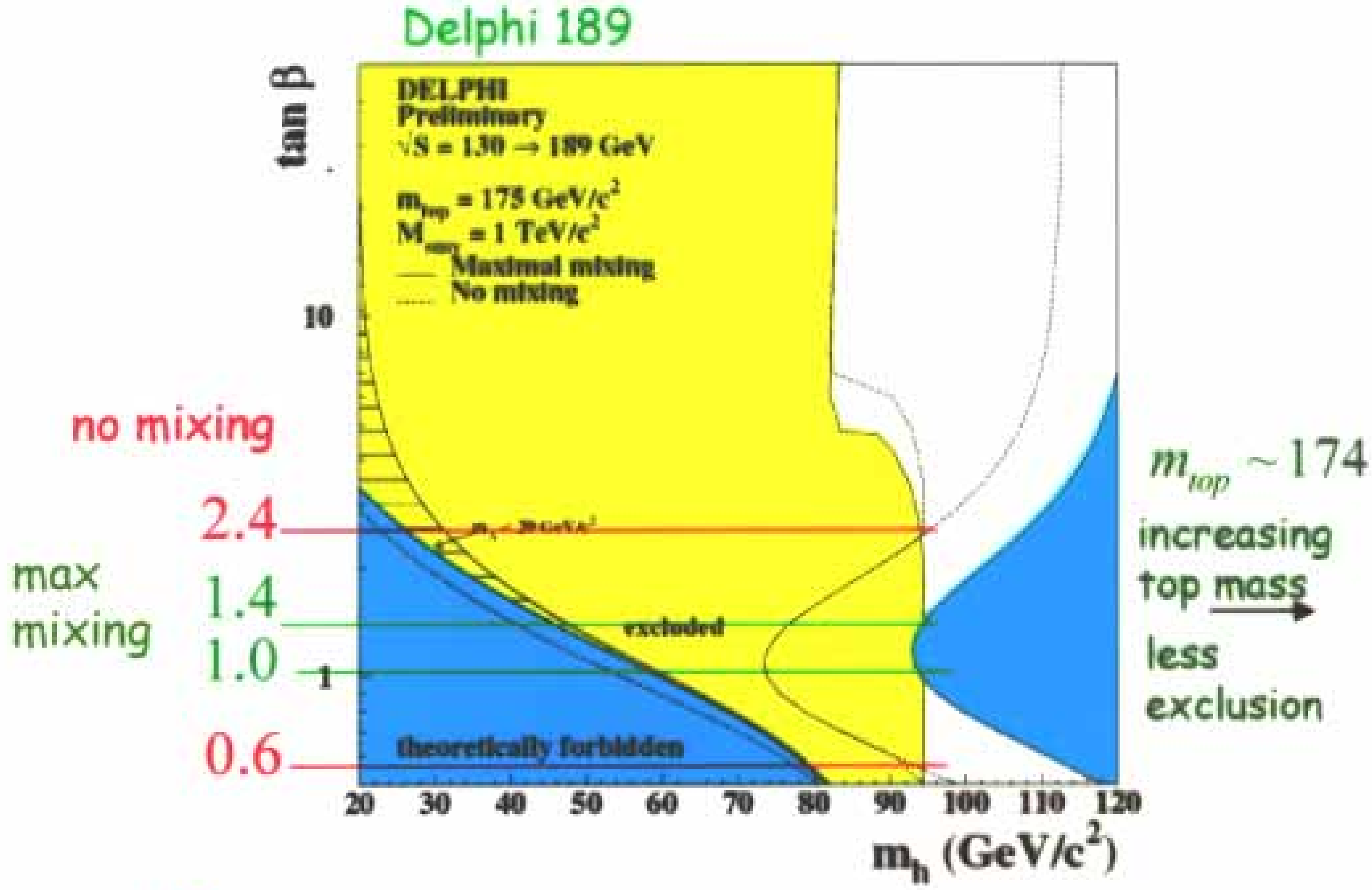
- L3 189 m_h> 76 GeV
- ALEPH 196 m_h>83.8 (exp 85.0)
- DELPHI 189 m_h>82.1 (exp 81.1) GeV
- OPAL 196 m_h>74.3 (exp 78.0) GeV
- ADLO 189 m_h>80.7 (exp 85.7) GeV

Results: Limits on m_A



- ALEPH 189 m_A>83.1 GeV
- DELPHI 189 m_A>83.2 (expected 82.2) GeV
- OPAL 189 m_A>76.1 (expected 79.1) GeV
- L3 189 m_A>76.0 GeV
- ADLO 189 m_A>80.9 (expected 85.7) GeV

Results: Limits on tg β



$m_{top} = 175$

	No Mixing	Max Mixing
• ADLO 189	$0.55 < tg\beta < 2.6$	$0.9 < tg\beta < 1.55$
• OPAL 196	$0.70 < tg\beta < 2.23$	$1.03 < tg\beta < 1.31$
• DELPHI 189	$0.60 < tg\beta < 2.4$	$1.0 < tg\beta < 1.4$

. Low IRFP tg β solutions on the edge of exclusion!
However, if the top mass is heavier (180) and in particular for μ >0 the IRFP can still survive.

Beyond the MSSM Benchmarks

- Why? To identify pathological points where e.g.
  - $\sin^2(\alpha-\beta)$ is very small; h is accessible kinematically, yet A is too heavy to be probed via hA production.
  - The $BR(h \to b\bar{b})$ is abnormally very small .
- Method: In addition to $(tg\beta, m_A)$ Scan over all SUSY parameters with $m_{top} = 165 - 185$ and find all (m_0, M_2, μ, A_t) physical nonexcluded points

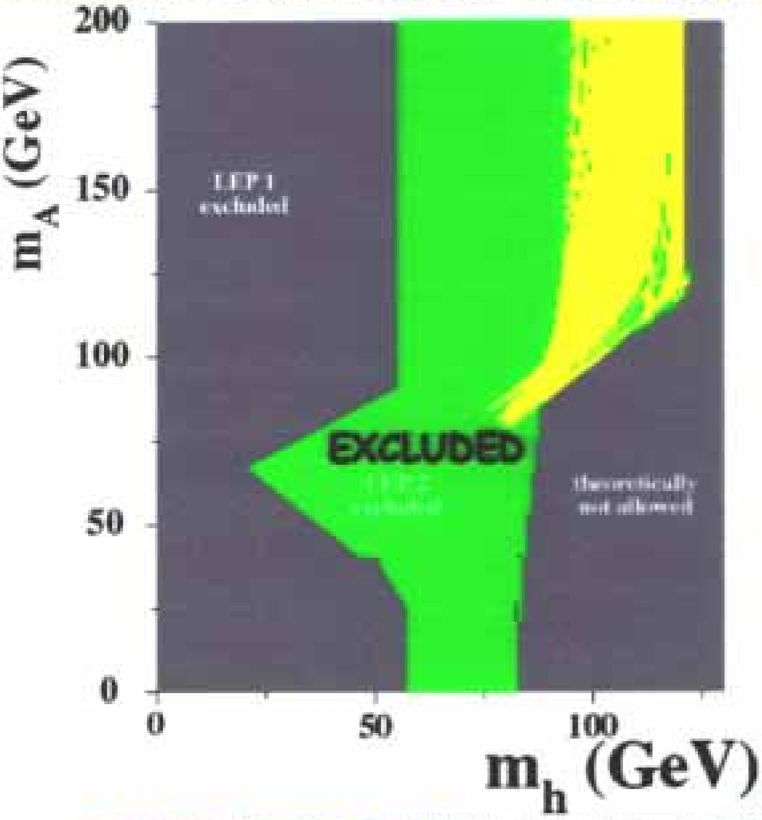
  - Apply PM results (LEP 1 and $b \to s\gamma$ (Delphi))
  - Apply results from SUSY searches
  - Use invisible higgs searches $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - No charge color breaking (CCB) minima in the MSSM lagrangian:

    (OPAL) $A_t^2 + 3\mu^2 < x(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2); \quad x = 7.5$

Results: General MSSM Scan

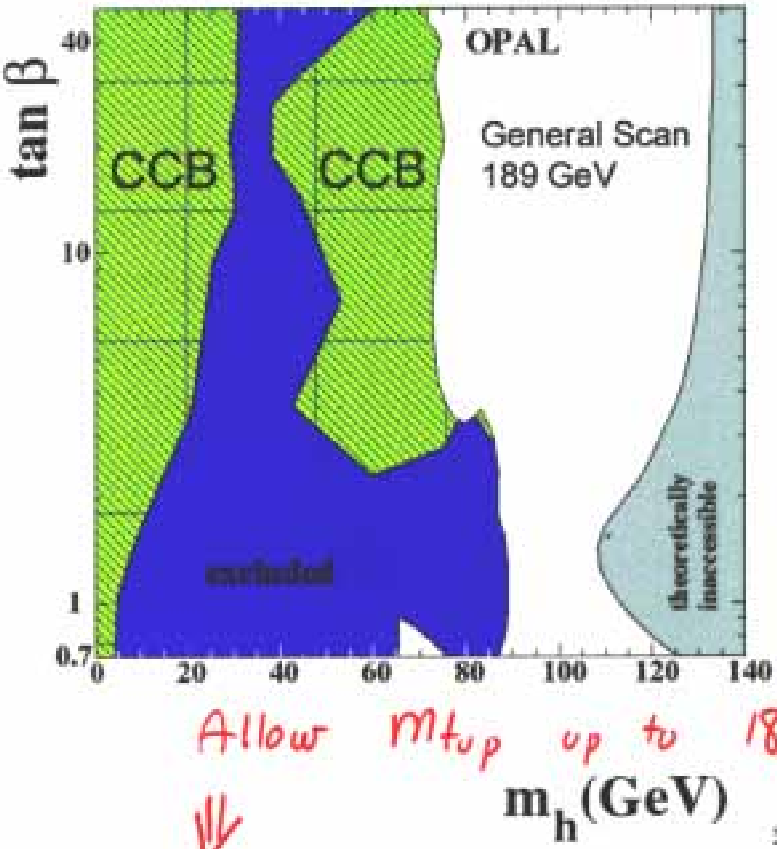
$\sin^2(\alpha - \beta)$ is very small; h is accessible kinematically .yet A is too heavy to be probed via hA production

Up to 37 000 000 sets of points were tested per experiment! (ALEPH)



DELPHI 189

MSSM Scan	Maximal Mixing
$m_h > 75$	$m_h > 82.1$
$m_A > 80$ GeV	$m_A > 83.2$ GeV



OPAL 189

MSSM Scan	Maximal Mixing
$m_h > 72.2$	$m_h > 74.8$
$m_A > 76$ GeV	$m_A > 76.5$ GeV

$tg\beta > 1$

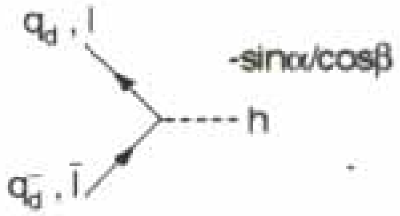
General scan reveals a slight degradation of sensitivity

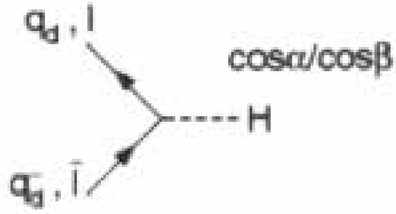
Allow m_{top} up to 185, small M_2 values

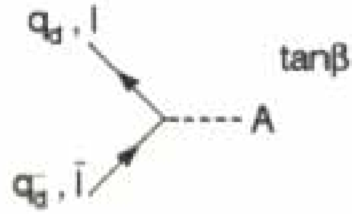
⇓

$tg\beta$ limits are gone!

Tevatron SUSY Higgs Search

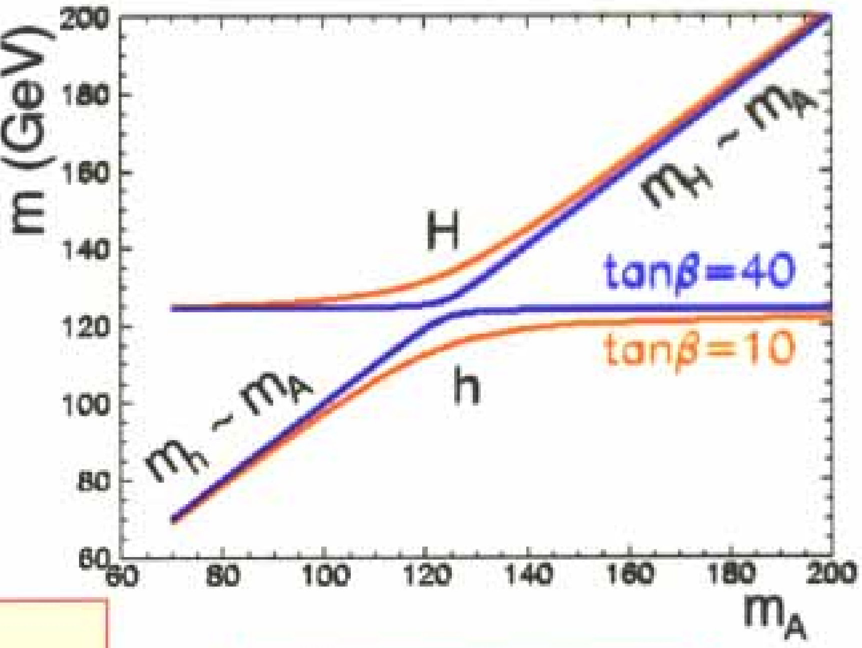






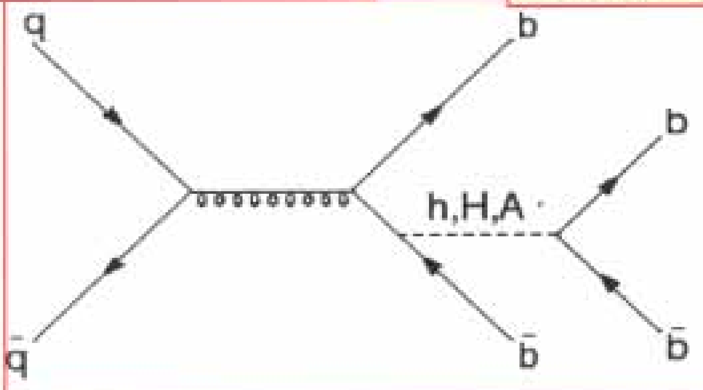
$$tg\beta >> 1 \Rightarrow \quad \frac{1}{\cos\beta} \sim tg\beta >> 1 \quad \Rightarrow$$

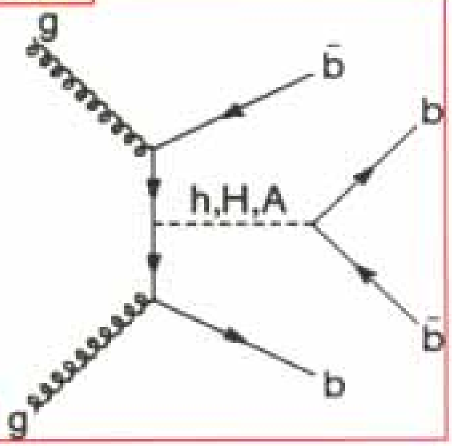
Dominant $H, h, A \rightarrow b\bar{b}$ + some more interesting things...



Large Cross sections:

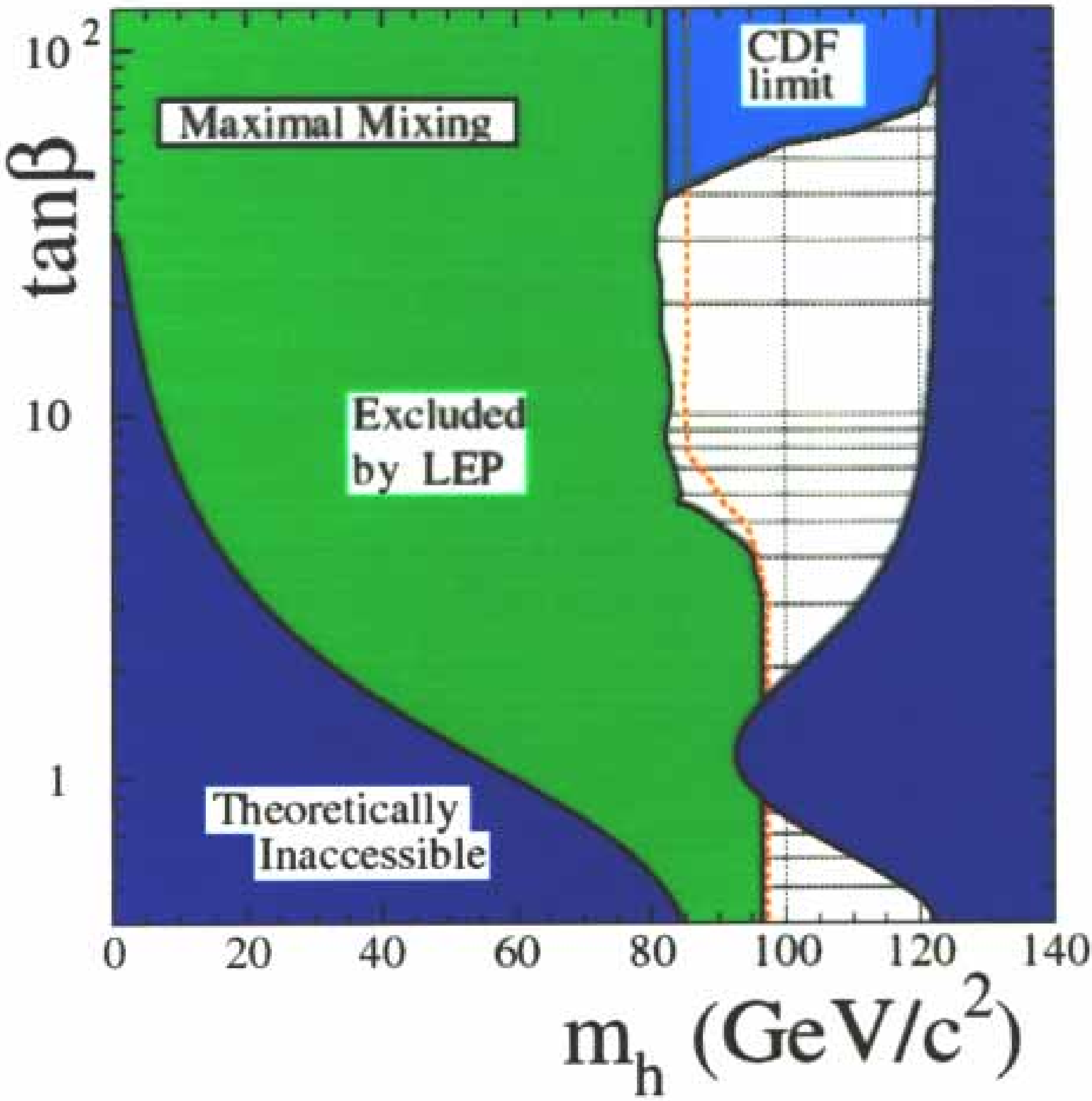
Triple Tags (CDF)





$$\sigma(bbh(H) + bbA) \sim O(10 - 100\ \ pb)$$

CDF are Cooking



Impressive

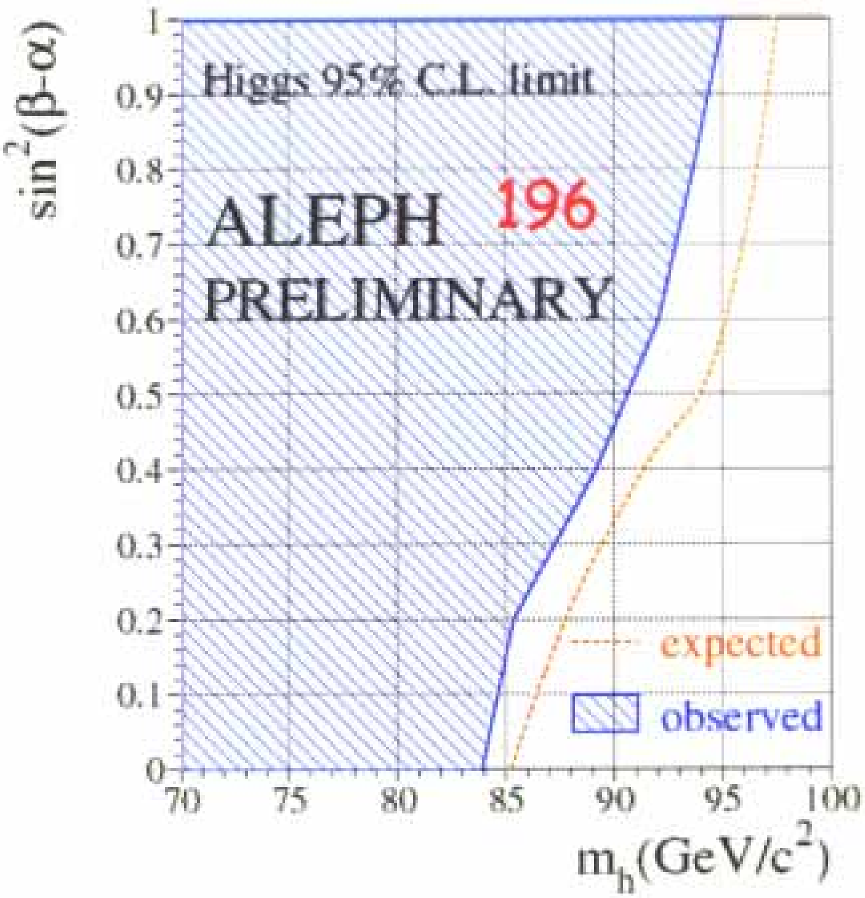
More bullets in the heart of IRFP

Back to Aleph SM Higgs Search

In principal hA (4b's) searches have some sensitivity to hZ 4-jets final states.

hZ+hA analysis $\sin^2(\alpha-\beta)=1 \Rightarrow \sigma_{hz} = \sigma_{HZ}^{SM} \sin^2(\alpha-\beta)$

$m_H >$ 94.9 (97.4)
obs exp



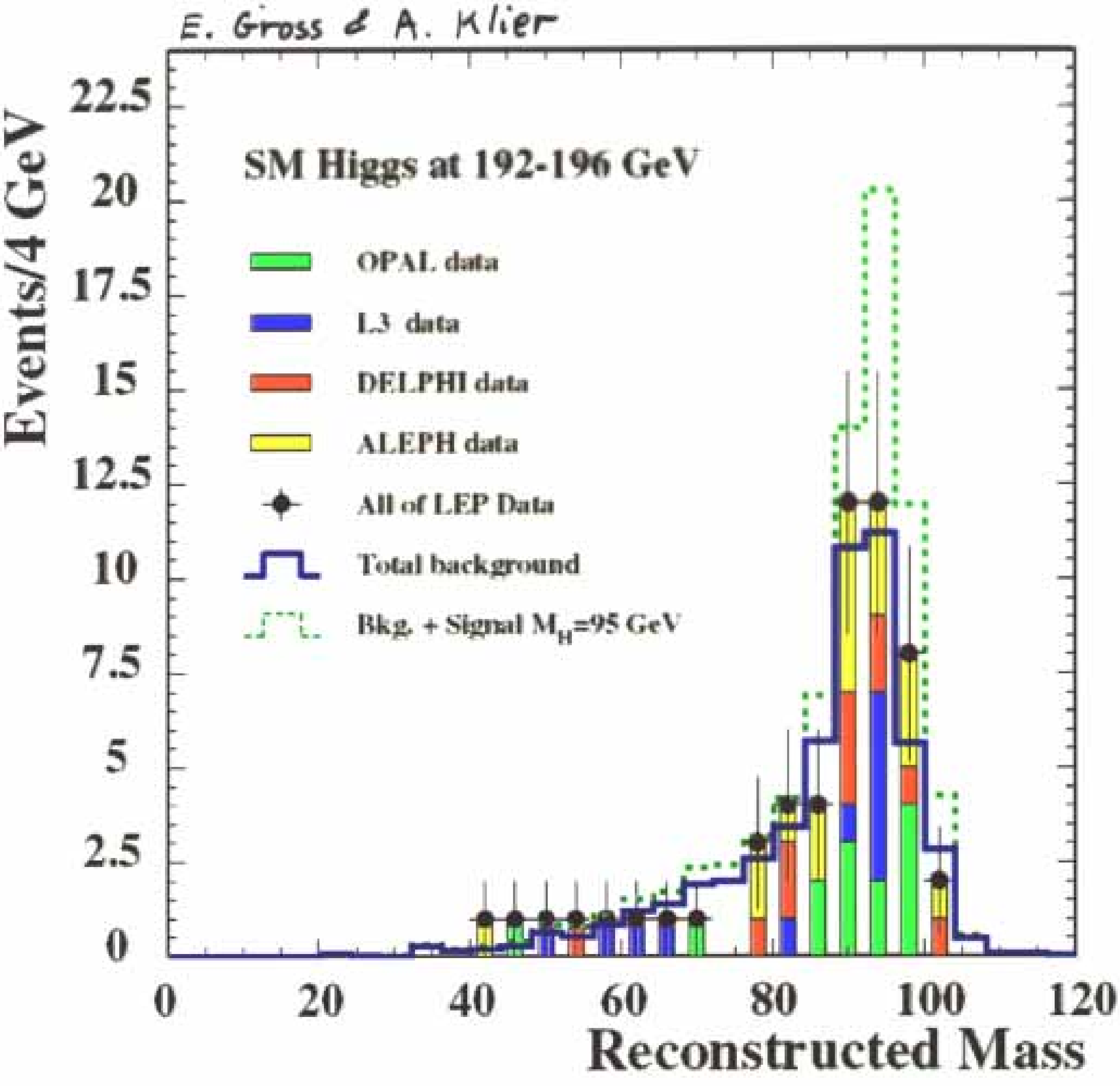
A 189 m_H>92.9 (obs) 95.9 (exp)
A 196 m_H>94.9 (obs) 97.4 (exp)

LEP SM Higgs Limits

			$m_H >$	
		Luminosity 192-196	Expected	Observed
ALEPH	196	54 pb^{-1}	97.4	94.7 GeV
L3	196	60 pb^{-1}		96
OPAL	196	50 pb^{-1}	96.0	94.2
DELPHI	189		94.6	94.1
		Luminosity		
ADLO 183	220 (combined)		90.2	89.7
ADLO 189	691 (combined)		97.2	95.2
ADLO 200	600 (combined)		108.5	Predicted

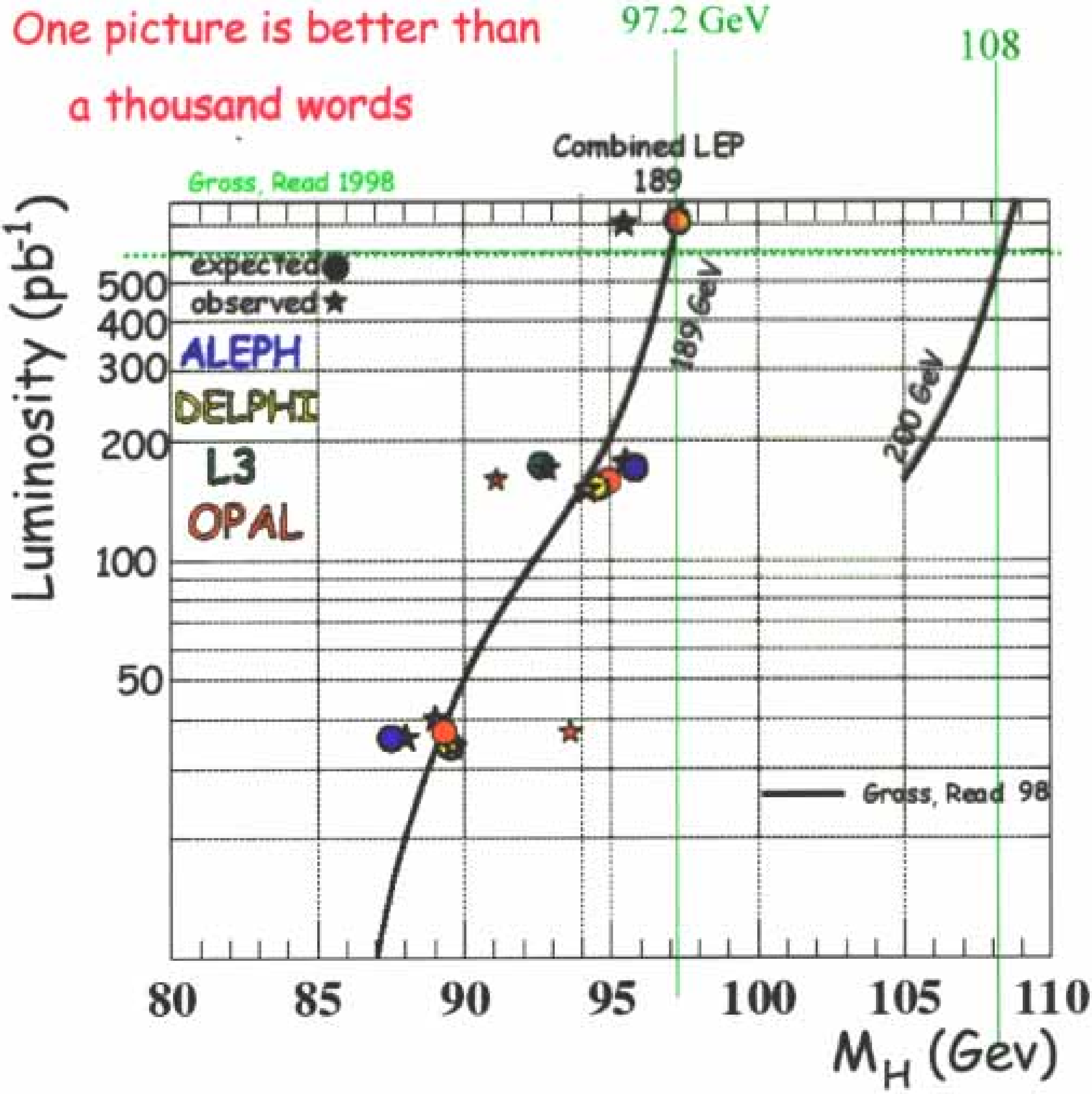
Combined LEP 192-196 GeV ("unofficial")

A. Klier , S. Yamashita (OPAL), A. Dominguez (L3), J. Marco (DELPHI), P. McNamara (ALEPH)



Predictions and Observations LEP

One picture is better than a thousand words

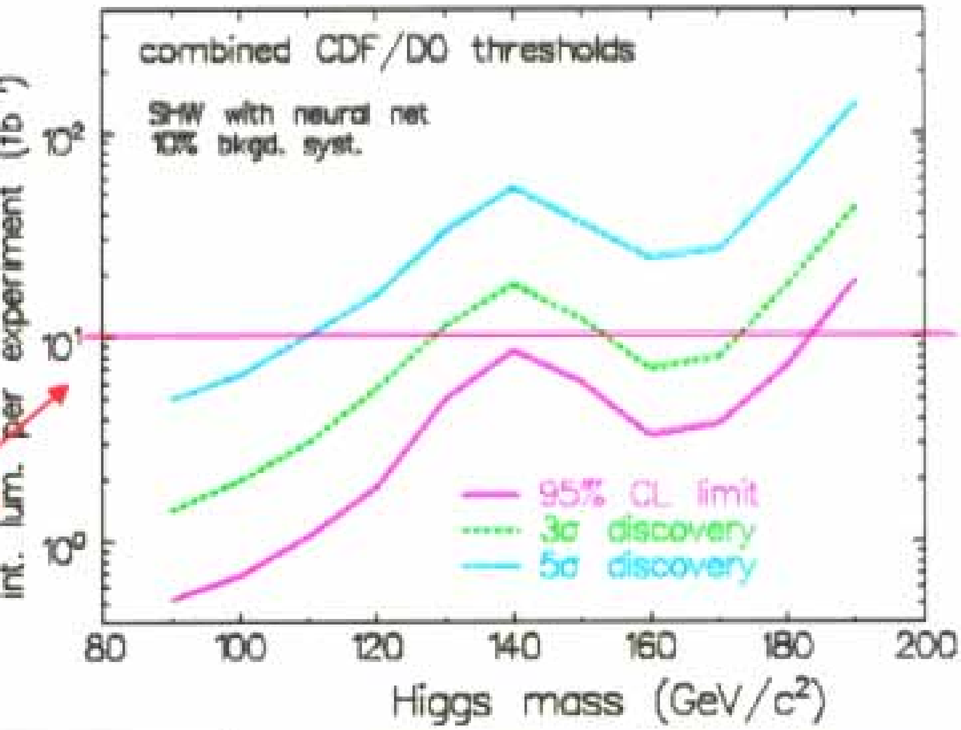


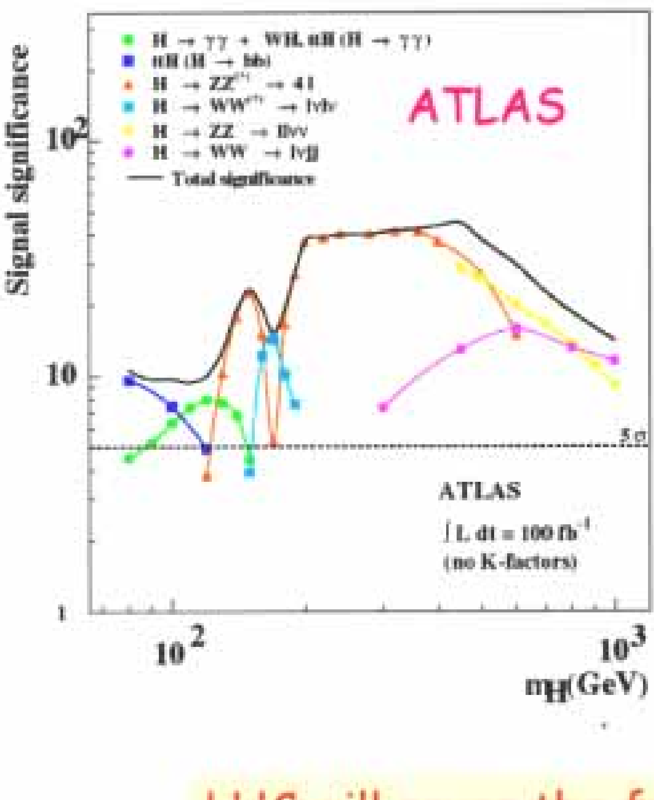
- With 150 pb^{-1} per experiment (600 pb^{-1} total) at 200 GeV the expected final exclusion sensitivity of LEP is around 108 GeV (close to kinematical limit)

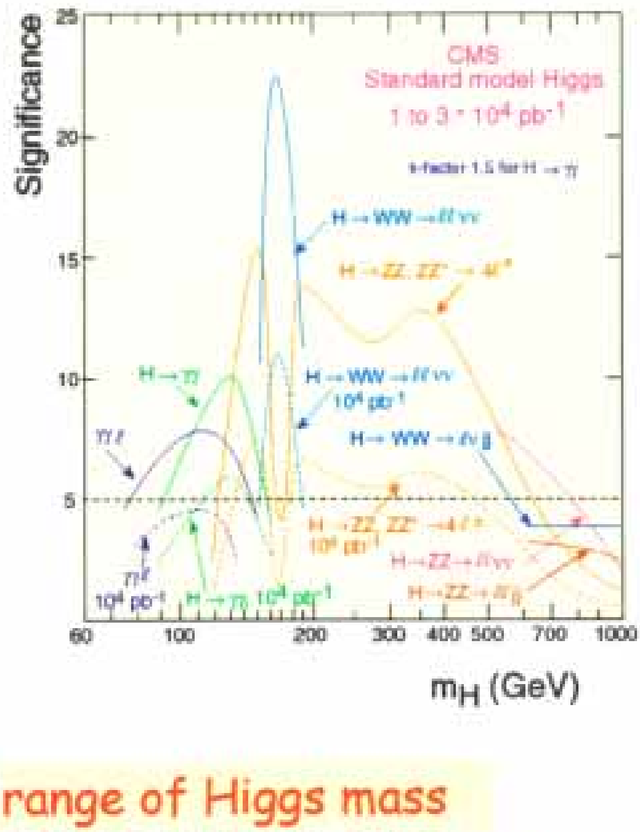
Hadronic Colliders
SM Higgs Prospects

Will the Tevatron have a second MAJOR Discovery??

$10\ fb^{-1} = 100 \times 100 pb^{-1}$



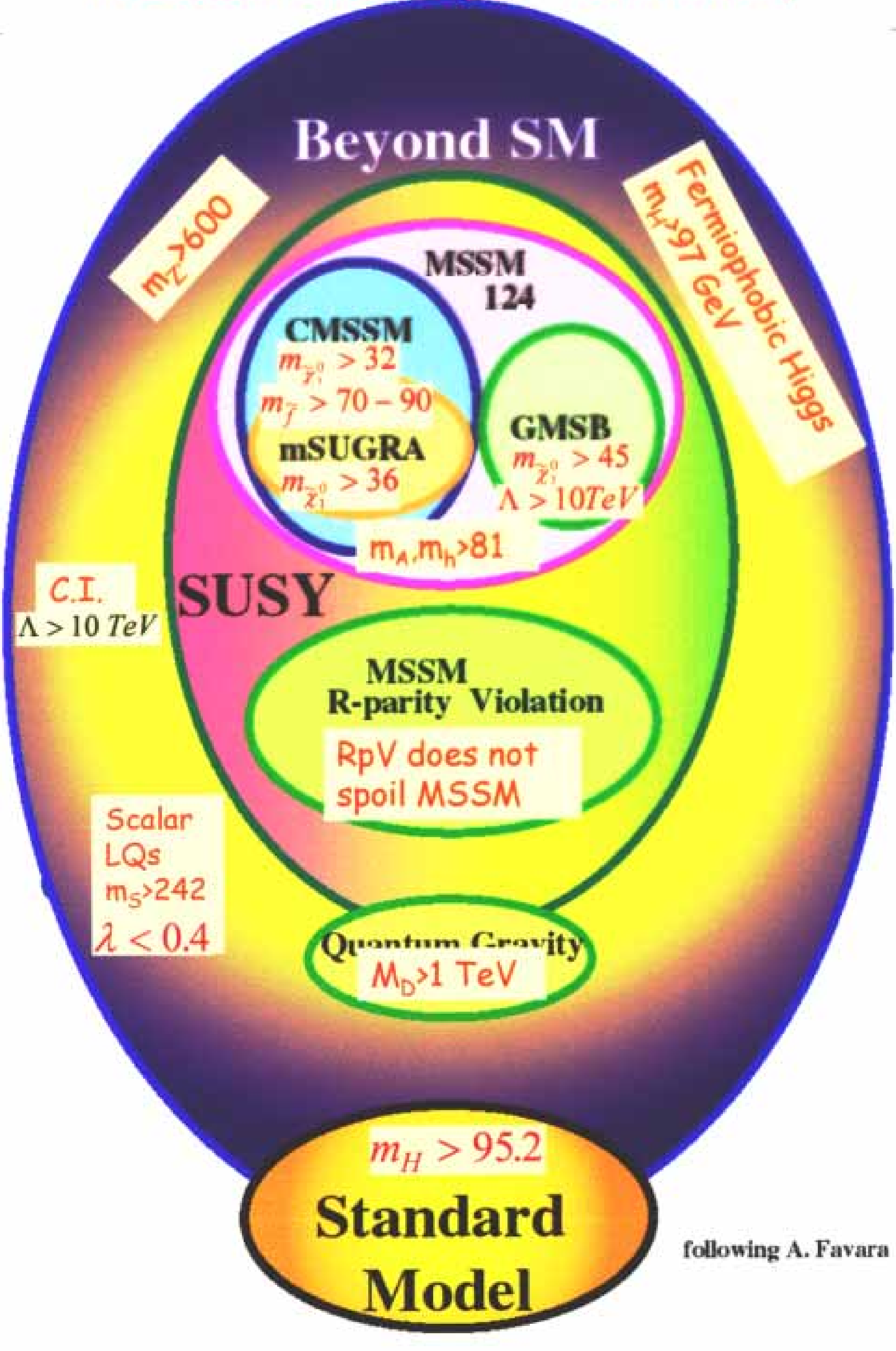




LHC will cover the full range of Higgs mass

and Spectrum!

The Searches Eggs - Summary



Conclusions

- The Standard Model Higgs was not discovered yet LEP limit

  m_H>95.2 GeV at the 95% CL.

- If SUSY is "the new SM" then more than just one Higgs boson is still missing there, SUSY was not discovered yet.

- LEP is exploring corners and started to fill holes (RpV, SUSY Higgs)

- HERA started to produce interesting results in electron-proton collisions. Leptoquarks were not discovered, they were excluded...

- TEVATRON is seriously preparing to Run II which will provide for the first time sensitivity for Higgs searches!.

- LEP is entering its final stages (196 - 200 GeV) hoping to probe a higgs boson up to 108 GeV (discovery power is 104 GeV)

- The new data (LEP, HERA) agrees WELL with all SM expectations

- Theory predicts a SM Higgs boson around the corner. Vacuum stability set the corner way above LEP sensitivity (>160 GeV), but certainly within TEVATRON and LHC in a few years to come. However a light SUSY Higgs is still on the map for LEP.

- LEP collected over 80 pb^{-1} (per exp) at E_{CM}=192 -196 GeV and is wishing and hoping for a discovery, maybe in ICHEP 2000!