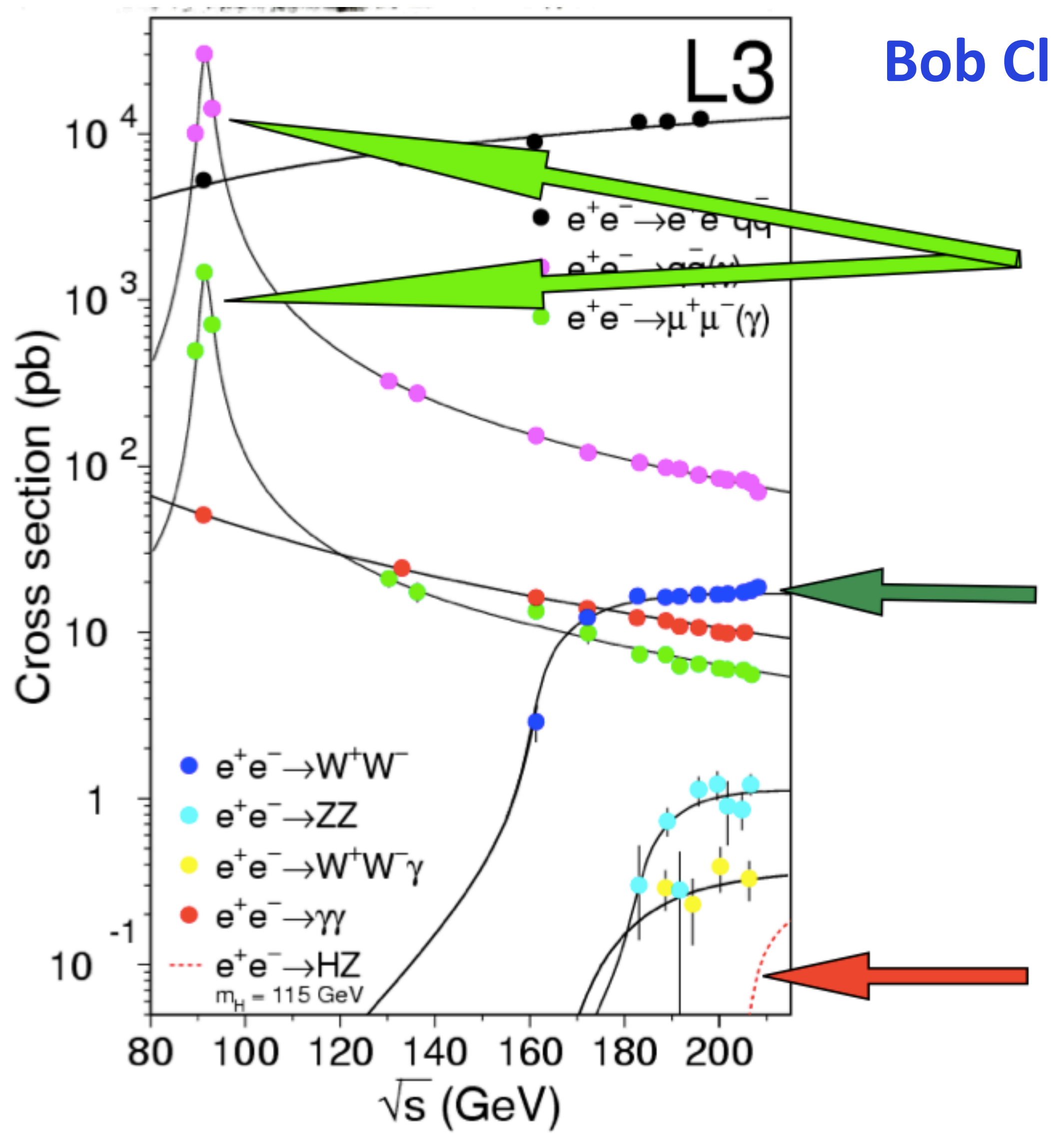
Higgs and other searches at LEP

Daniel Treille

CERN honorarius

LEP30 (28 nov 2019)

Bob Clare



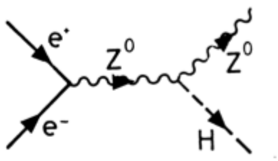
about 17M Z

about 40k W

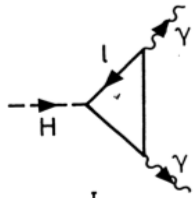
about 0 H

This talk

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON John Ellis, Mary.K.Gaillard, D.V.Nanopoulos, CERN TH.2093-CERN 30 oct 1975



(a)



I_l

J/Ψ 74 Tau 75 KM 73
Charm 76 Y 77

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

PDG 88 In summary the only cast-iron constraint on the Higgs mass Is M_H>14MeV. Theoretical arguments and bounds from B, Y and K decays probably excludes the range below 4 GeV

Search for Neutral Higgs at LEP 200
Presented by Sau Lan Wu
ECFA Workshop on LEP 200,
Aachen 1986 CERN-EP/87-40

Again, we conclude that at E_{cm} = 200 GeV, $500pb^{-1}$ integrated luminosity, one can get significant signals of Higgs masses up to about 70 GeV from the process $e^+e^- \to H^oZ^o \to$ 4 jets. It is difficult to extend the Higgs mass to 80 GeV (due to $W^\pm$) or 90 GeV (due to Z^o). Above 90 GeV, the rate reduces and a more sophisticated analysis method will be required to extract the Higgs signals.

POSSIBILITIES FOR THE FUTURE OF LEP
Ecole d'été de PN et PP, LAPP, sept.1989
CERN-EP/90-30

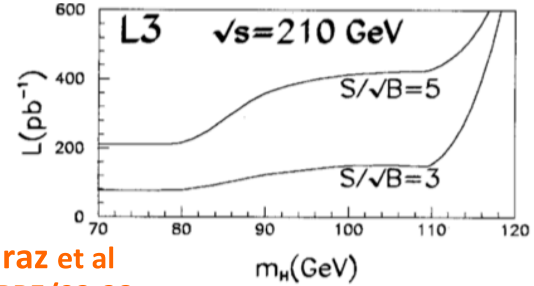
"However, if an efficient tagging of the bb final state is performed, this may not be the case. Table 19 shows that the rate of ee→bbl⁺l⁻ is significantly modified if the Higgs is present. More study is needed - and is worthwhile- since the presence of a scalar in the vicinity of m_Z has been advocated. This would again be an argument in favour of effectively reaching √s= 200 GeV at LEP."

Table 19 Case $m_H = m_Z$ at LEP2

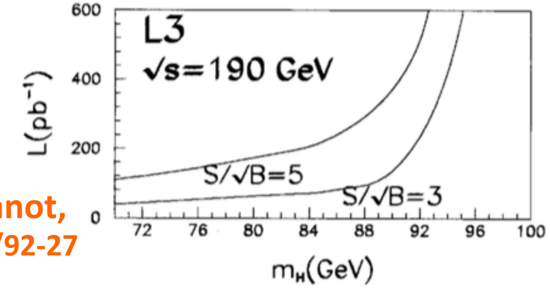
$\int L\,dt$ = 500 pb⁻¹, √s = 200 GeV

Signal:	ee →	Z ↓ ee, μμ, ττ, νν̄	+	H ↓ 100% bb̄
Main background:	ee →	Z ↓ ee, μμ, ττ, νν̄	+	Z ↓ 15% bb̄

Parameter	Signal	Background
Cross-section (pb)	0.11	0.11
No. of events	55	55

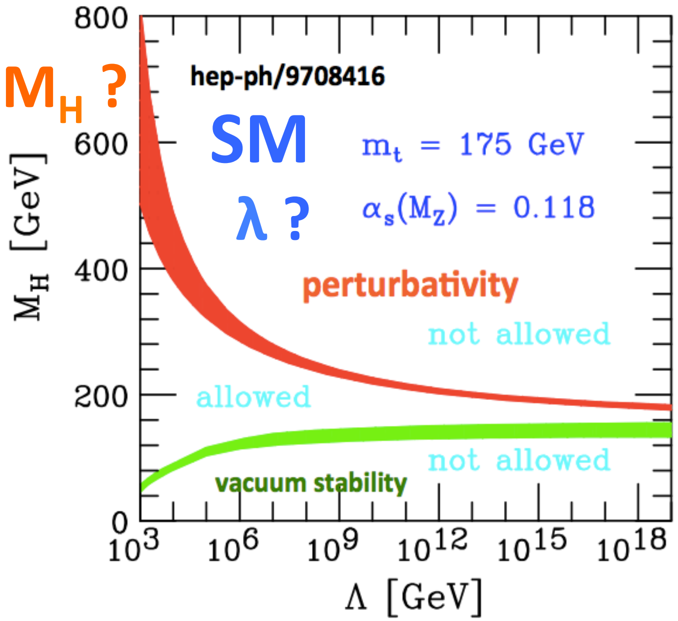


J.Alcaraz et al
CERN-PPE/93-28



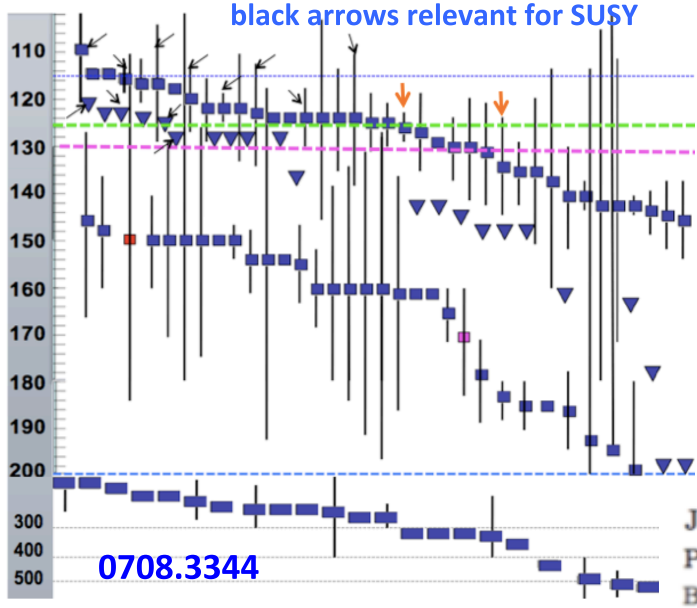
P.Janot,
LAL/92-27

reach M_H = √s −100 GeV adding the 4 exp^ts, more channels, more work → $M_H = \sqrt{s} - M_Z$



all Higgs mass"predictions"

black arrows relevant for SUSY



SUSY

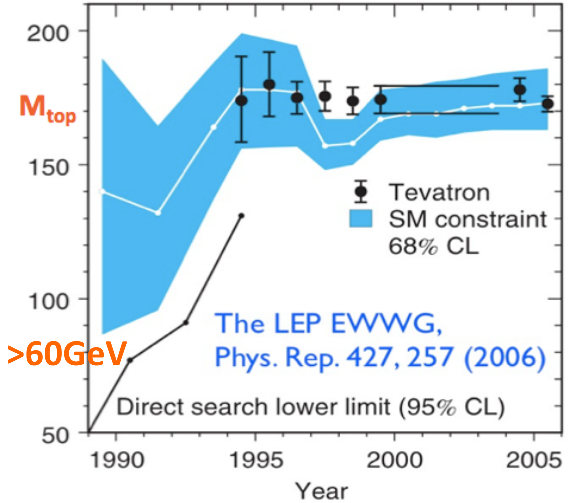
A tempting goal

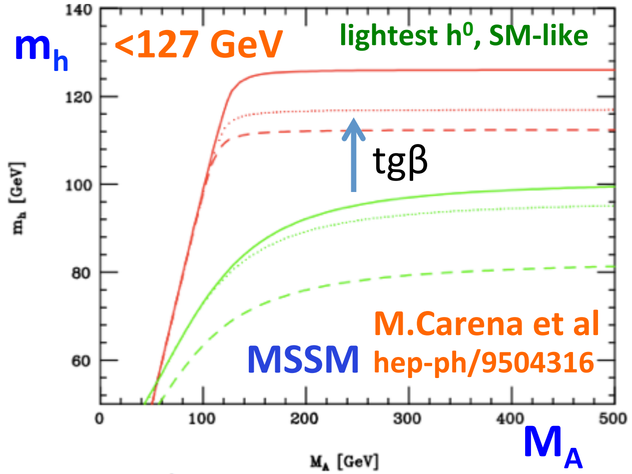
$\lambda = (1/4)(g'^2+g^2)\cos^2 2\beta$

$$m_{h^0}^2 \leq M_Z^2 \cos^2 2\beta$$

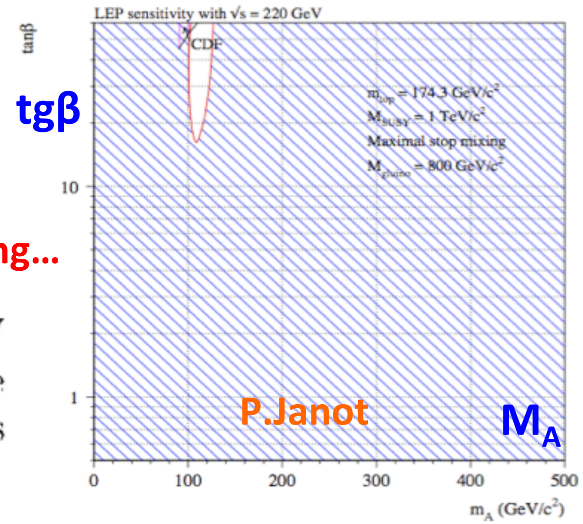
$$\Delta(m_h^2) = \frac{3m_t^4}{4\pi^2 v^2} \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

approx.





J.R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B **257** (1991) 83 and B **262** (1991) 477.
Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. **85** (1991) 1 and Phys. Lett. B **262** (1991) 54.
H.E. Haber and R. Hempfling, Phys. Rev. Lett. **66** (1991) 1815.



check whether such a boson <130 GeV exists or not. Both answers rewarding…

The CM energy required to do so would be $\sqrt{s} \sim 210$ GeV (220 GeV) for $m_t < 150$ GeV (170 GeV). This is shown in Fig. 36 (Janot 92). The plane is covered, at a 5σ significance level for discovery, except for a tie-shaped region at the border between the two regions where the significance is between 3 and 5σ.

Rep.Prog.Phys 57 (1994)

√s ?

PROSPECTS FOR ENERGY AND LUMINOSITY AT LEP2 S.Myers, C.Wyss

CERN 96-01 vol.1, p.23.

equipped zones

Phase	Point 2			Pt 4	Pt 6		Pt 8	Totals			Total MV max
(Cavity type)	Cu	Nb & prot.	NbCu	NbCu	Cu	NbCu	NbCu	Cu	Nb	NbCu	(MV)
IV	26	24	40	72	26	64	72	52	24	248	2884
Maximum energy upgrade with present cryoplants											
Y3	0	24	72	96	0	96	96	0	24	360	3880
All-out Maximum Energy configuration											

finally 288 SC

$\sqrt[4]{4/3}$

223 GeV

K.Hubner
Phys. Rep. 403-404 (2004)

The maximum energy of LEP 2 was determined by the decision in 1996 to discontinue the industrial production of the superconducting cavities. Whether the potential of LEP should have been better fully exploited up to its reasonable limit of 220 GeV in the center-of-mass and whether this would have lead to the discovery of the Higgs particle as a number of models seemed to suggest [36, 37], is a matter of speculation. The quest for the Higgs particle will hopefully end with the results obtained by the Tevatron and the LHC. In any case, LEP will stand as a landmark in the development of particle accelerators.

E.Picasso Eur. Phys. J. H 36, 551–562 (2011)

… to run LEP in a successive phase [14], at an energy of about 100 GeV and a gradient of 5 MV/m, or at an energy slightly greater with a gradient of 7 MV/m [15]. The 5th of May 1986 at the Eleven International Cryogenic Engineering Conference in West Berlin, P. Bernard, H. Lengeler, G. Passardi, J. Schmidt, F. Stierling and myself foresaw the installation of a maximum of 384 cavities for a total length of 652 m. With the final beam optics and electric gradient, this number of cavities would have enabled us to reach at least 220 GeV in the centre-of-mass, since the magnets had been designed for a maximum energy of 125 GeV.

The increase in energy was certainly a great success beyond expectations, credit for this must be duly given to the skill and competence of the LEP groups.

Like some other people I feel somewhat sorry about the fact that it was not foreseen to bring the energy of LEP to a maximum, by the installation of the greatest number of superconducting cavities.

LEP Note 524 (CERN/EF/RF85-1)
dated 8 January 1985

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, M. L. Ferrer, A. Marini, P. Monacelli, A. Nigro, M. Nigro, L. Paoluzi, I. Peruzzi, G. Piano-Mortari, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti and F. Vanoli : MEASUREMENT OF THE J/ψ (3100) DECAY WIDTHS INTO e^+e^- AND $\mu^+\mu^-$ AT ADONE.

ADONE trauma

LNF-75/36(P)
8 Luglio 1975

SUSY, ambience

Schwitters in Moriond 82

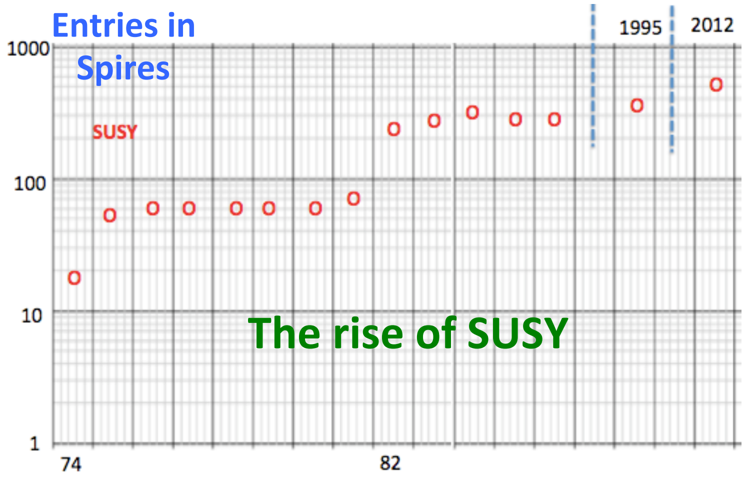
"Even experimentalists cannot fail to be infected by the enthusiasm of the super theorists"

LSP as Dark Matter?

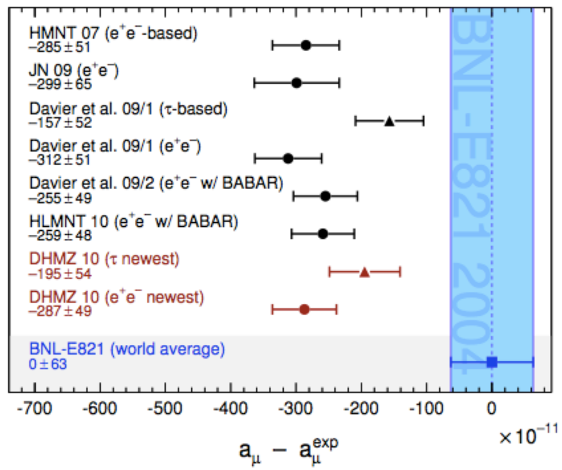
not MACHOS, etc,
why not axion? Fayet Moriond 81,
P.Sikivie in audience

bolometers versus warm liquids
B.Sadoulet 91

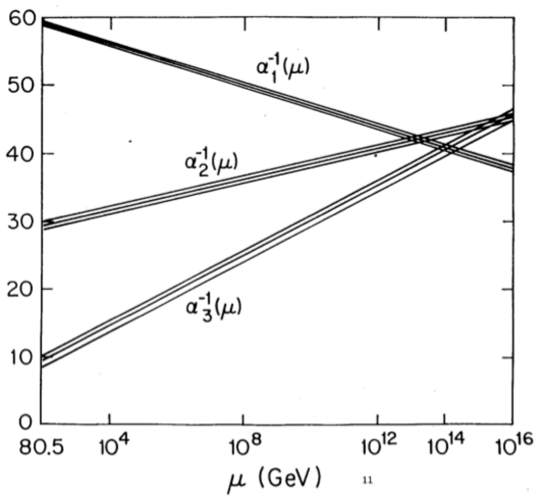
Barbieri 93 We were told by Gordy Kane [48] that there are "eight indications that nature is supersymmetric at the electroweak scale". He agrees that one solid argument would be enough, in fact better than eight vague ones, but - he says - many indirect arguments can give, altogether, a significant indication.



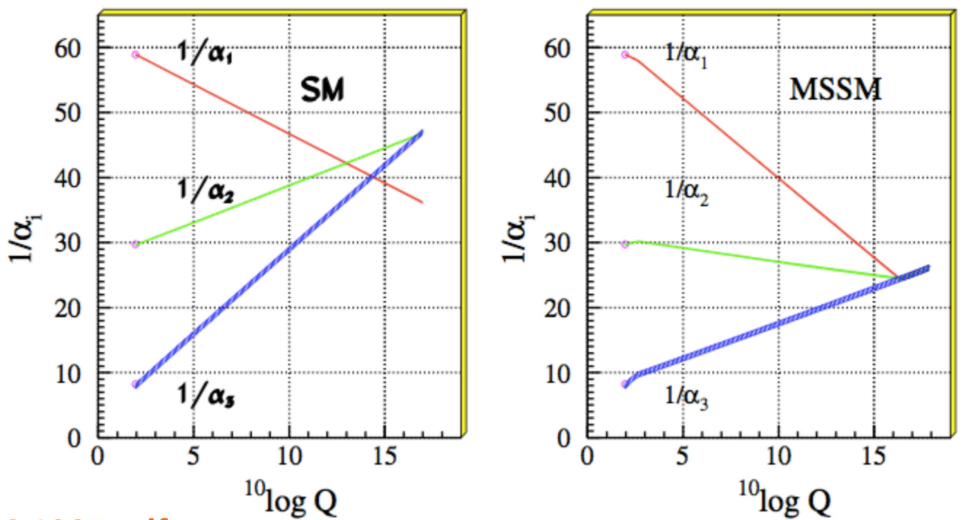
g−2 of the muon 1010.4180



Phys. Lett. B249, 441, 1990



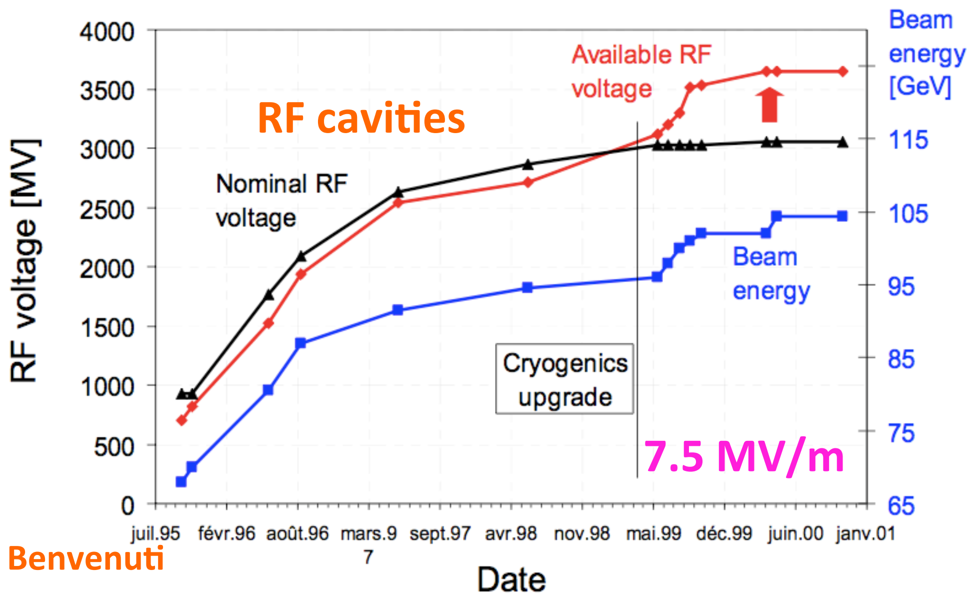
Unification of couplings



http://cds.cern.ch/record/177514/files/PhysRevD.36.1385.pdf

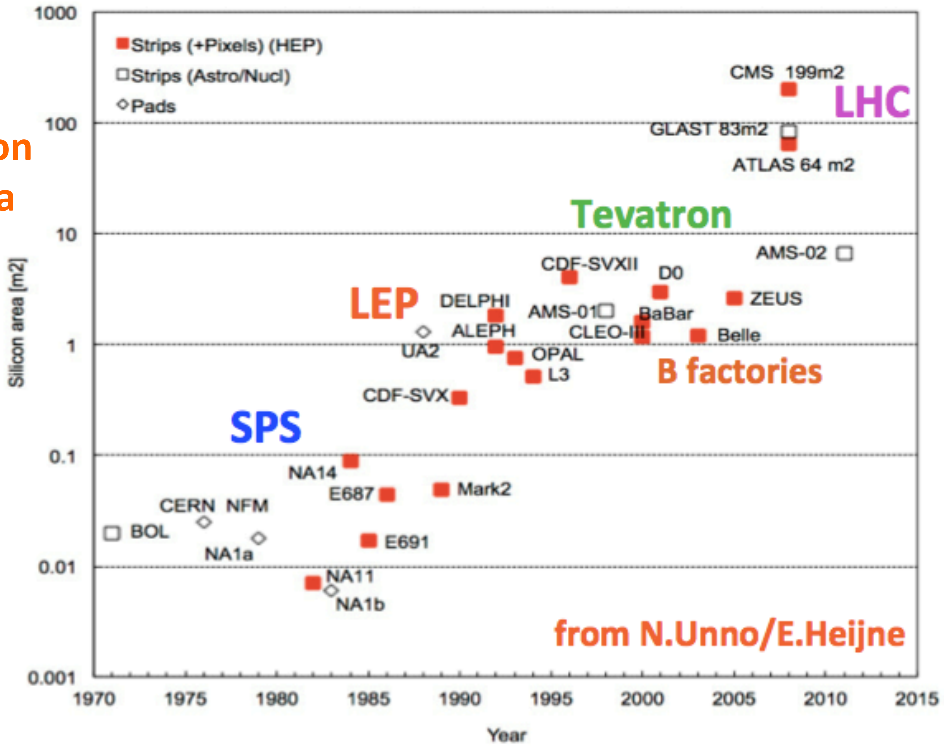
Phys.Lett. B260 (1991) 447-455

Homework well done....

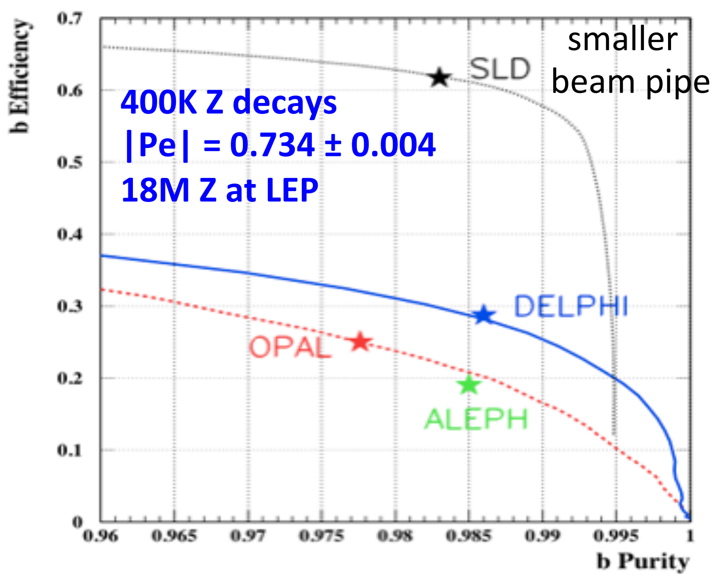


C. Benvenuti

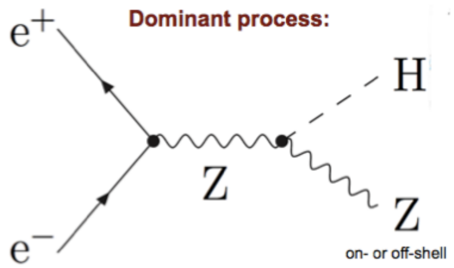
Silicon area



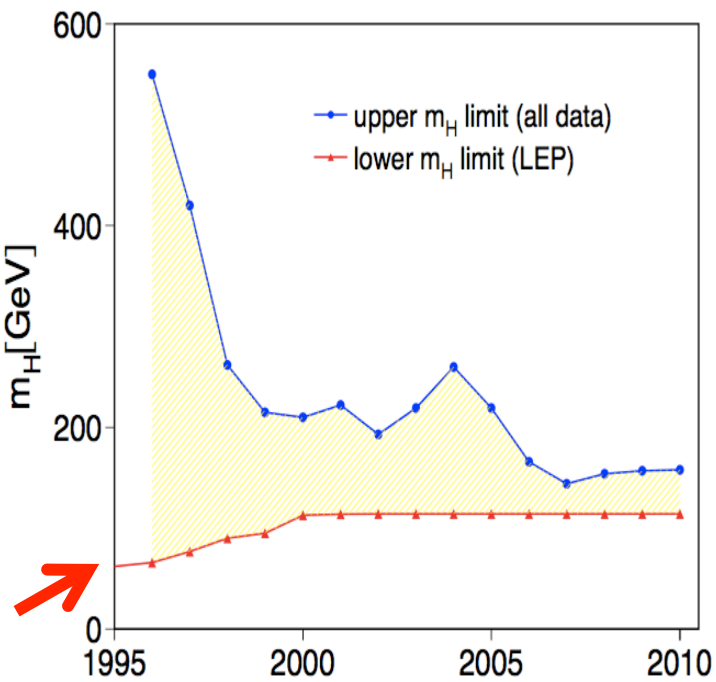
B-tag

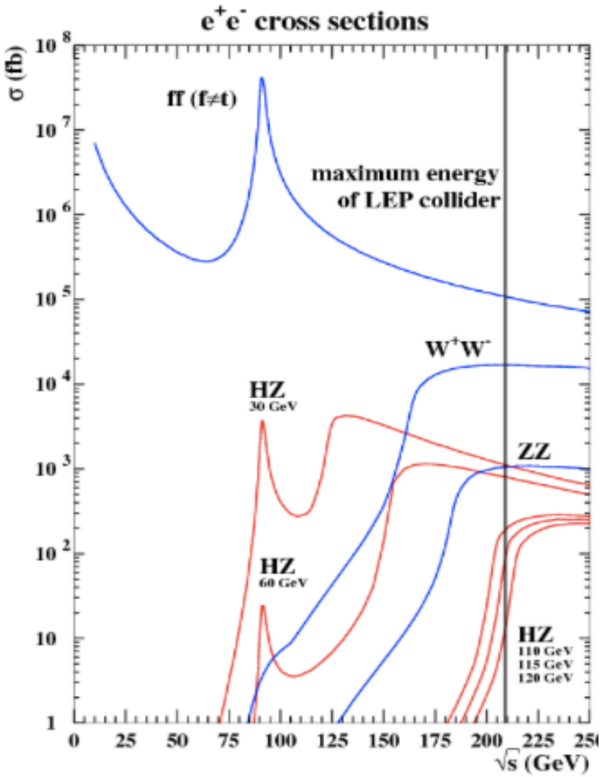


What happened



Channel	Topology	BR
4 jets	J J b $\bar{b}$	~ 64 %
2 b-jets + missing momentum (Z→νν)	$\vec{p}_{Miss}$ b $\bar{b}$	~ 18 %
2 b-jets + lepton pair (Z→ll)	l^+ l^- b $\bar{b}$	~ 9 %



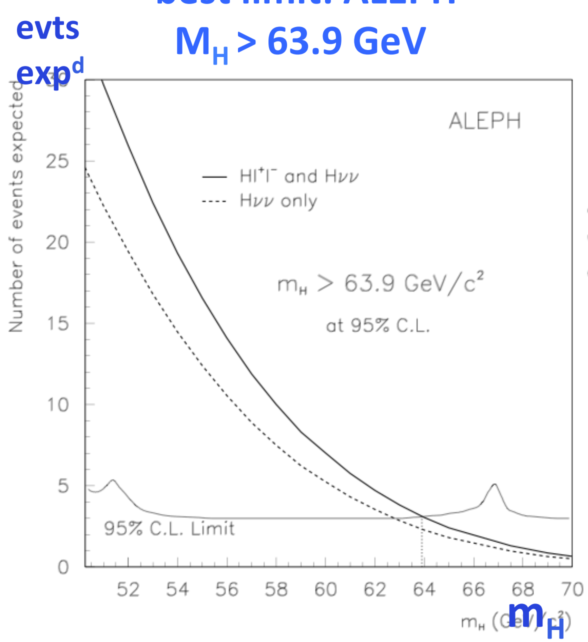


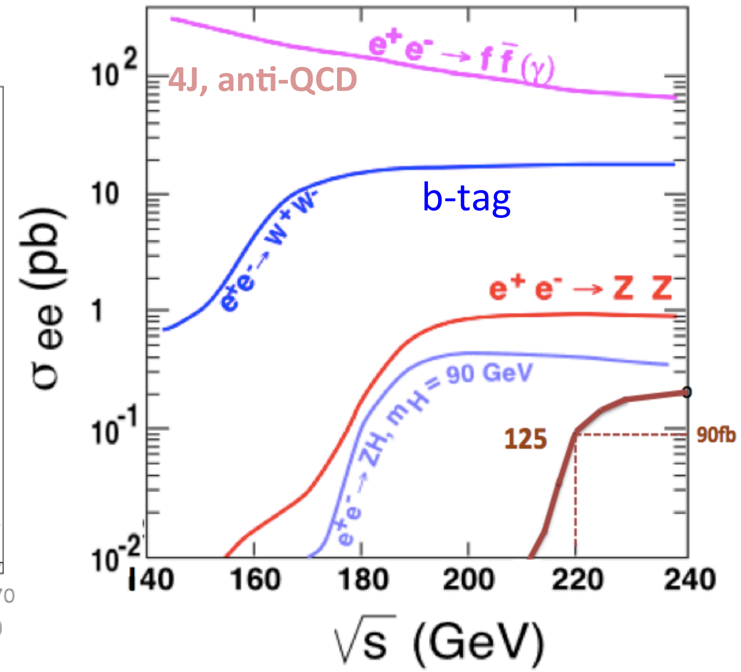
Search at LEP1

no excess observed

best limit: ALEPH

$M_H > 63.9$ GeV





The 2000 odyssey

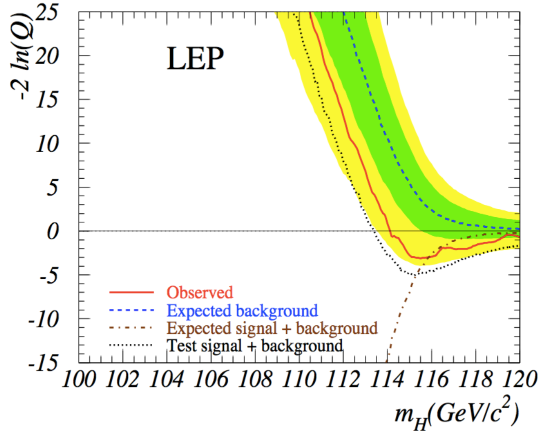
- **Chronology in 2000:**
  - by midsummer: one high-mass candidate in ALEPH, 4 jets, reconstructed mass ~114 GeV
  - by Sep 5: two more 4-jet candidates in ALEPH
  - by Nov 3: 70% more data at E_{CM} ~ 206.6 GeV
  - out of the 10 evts with largest $(s/b)_{115}$:
    - 7 of them 4-jet candidates
    - 6 of them from ALEPH
    - one (disputed) high s/b candidate in L3 (missing energy channel)
    - 2 from OPAL
    - 1 from DELPHI

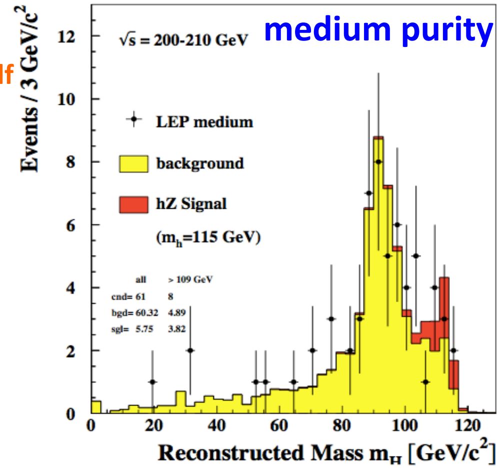
From G.Dissertori

from : Kado, Tully, Annu. Rev. Nucl. Part. Sci. 2002

	EXP	$\sqrt{s}$(GeV)	Channel	M (GeV)	s/b	w
1	ALEPH	206.7	4-jet	114.3	4.6	1.73
2	ALEPH	206.7	4-jet	112.9	2.4	1.21
3	ALEPH	206.5	4-jet	110.0	0.9	0.64
4	L3	206.4	E-miss	115.0	0.7	0.53
5	OPAL	206.6	4-jet	110.7	0.7	0.53
6	DELPHI	206.7	4-jet	114.3	0.6	0.49
7	ALEPH	205.0	Lept	118.1	0.6	0.47
8	ALEPH	208.1	Tau	115.4	0.5	0.41
9	OPAL	205.4	4-jet	112.6	0.5	0.40
10	ALEPH	206.5	4-jet	114.5	0.5	0.40

http://inspirehep.net/record/1303708/files/hep2001_128.pdf



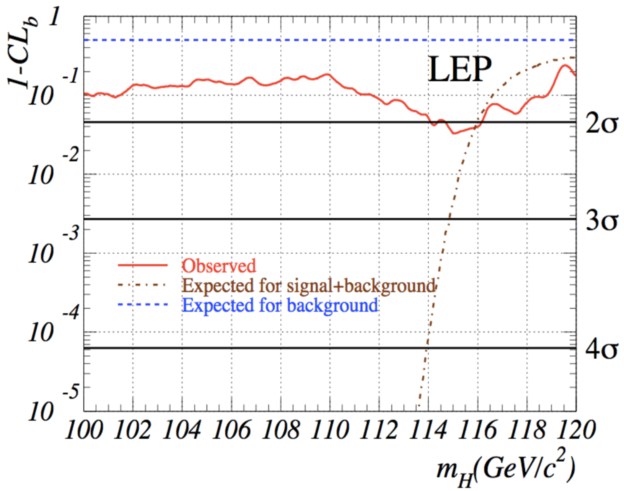


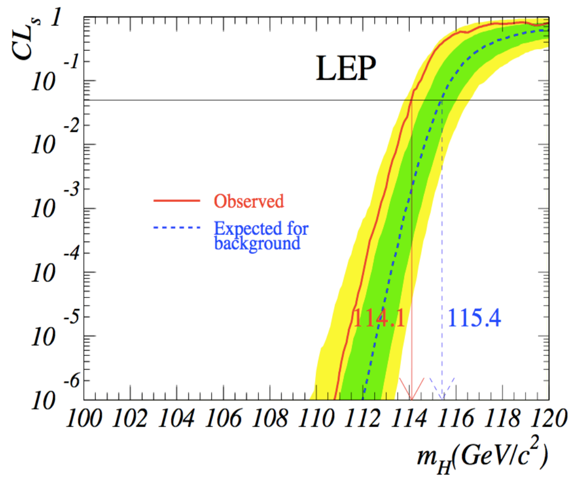
s/b value for each event used as a weight assigned to it. Adding of all of them gives the final estimator, the likelihood ratio $-2\ln Q = 2s_{tot} - 2\,\Sigma_i\, N_i \ln[1 + s_i/b_i]$

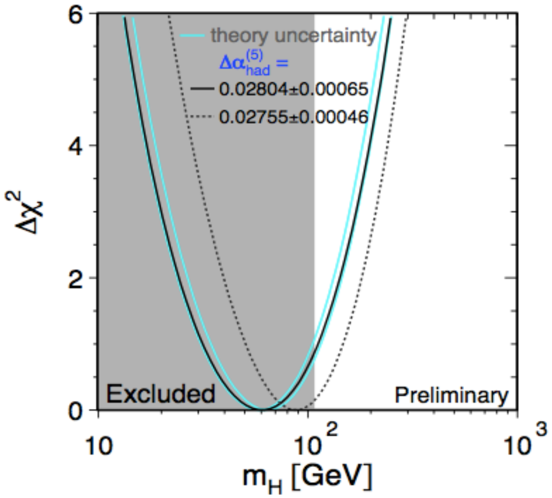
CL estimated using a MC method, where estimator distributions are built for the B only hypothesis and for the B+S hypothesis. Separation = sensitivity.

Discovery estimator, $1-CL_B$, computed as the integral in the distribution below the point marked by the estimator value observed in the data. Reflects departure from SM.

CL_S, conservatively defined as CL_{S+B}/CL_B, used for the limit. Results in different channel from the LEP experiments combined by the LEP Higgs Working Group.

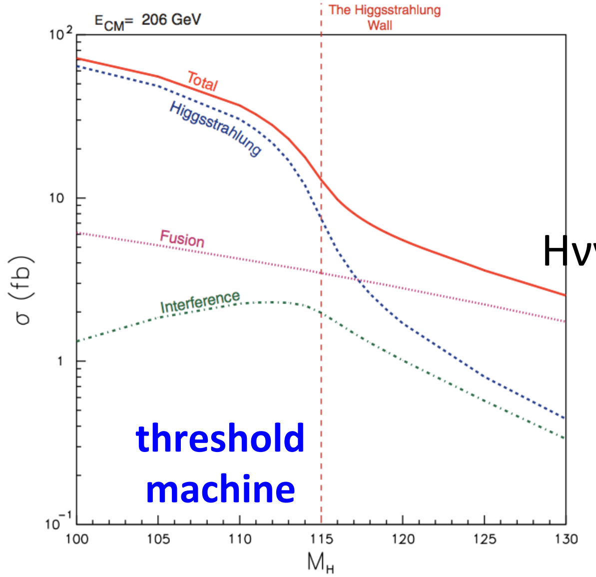






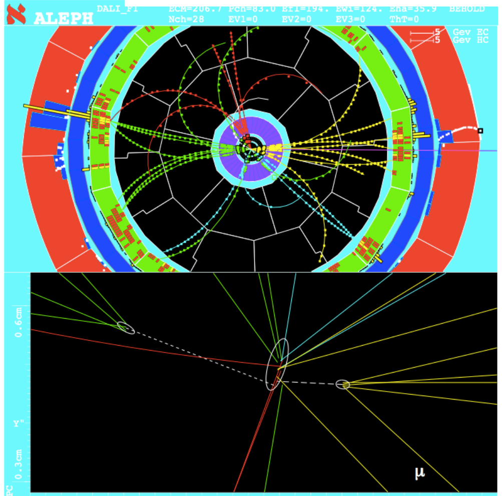
in the last year, crash against the higgsstrahlung barrier for $M_H = \sqrt{s} - M_Z$, namely 115 GeV

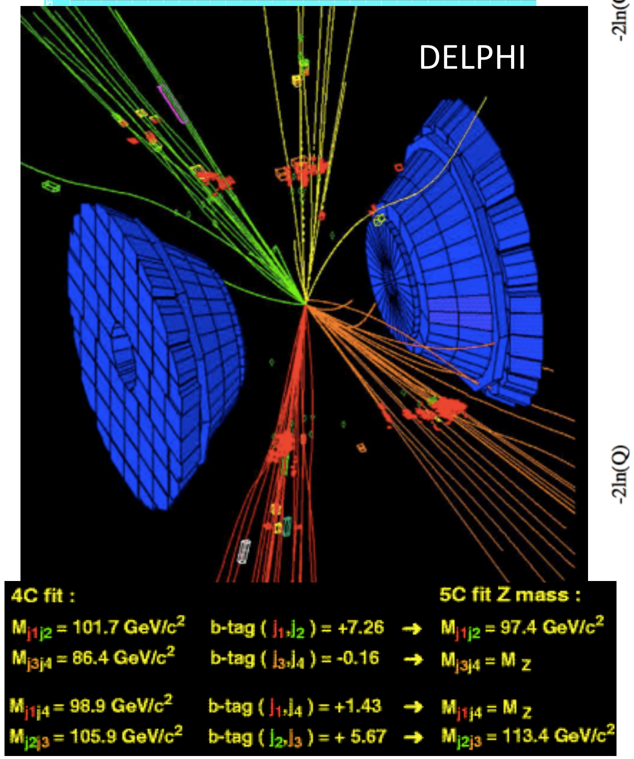
J.Marco Independently, the pairing for the mass reconstruction is done: the six possible configurations for jet assignment to the Z and Higgs dijets are considered, and for each one the result of a fit fixing the Z dijet mass to the nominal Z mass value, and the probability for the jet b-tagging values corresponding to the Higgs di-jet, are taken into account to build a likelihood used to select the adequate pairing. Only one single mass value is selected coming from the corresponding 5-C fit.



Hνν

threshold machine





nothing in sight...

fermiophobic Higgs > 108.2 GeV (95% CL)

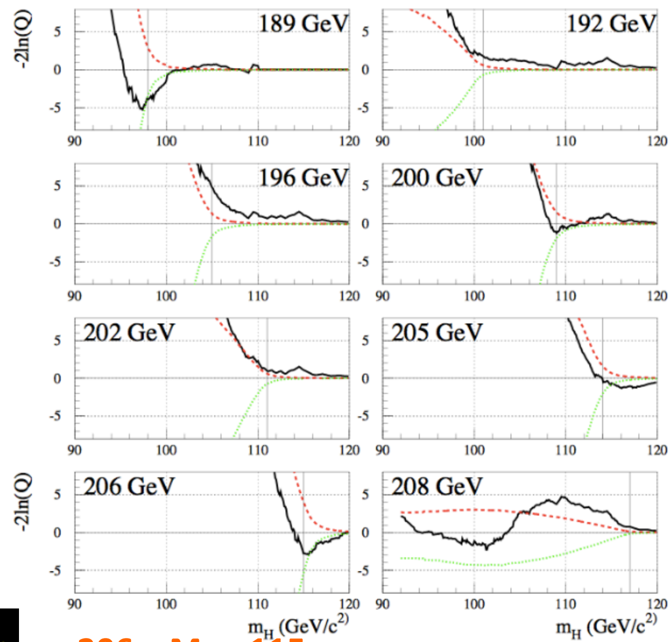
invisible Higgs > 114.4 GeV (95% CL)

charged Higgs > 78.6 GeV (95% CL), independent of BR($H \to \tau\nu_\tau$)

http://inspirehep.net/record/571708/files/hep2001_145.pdf

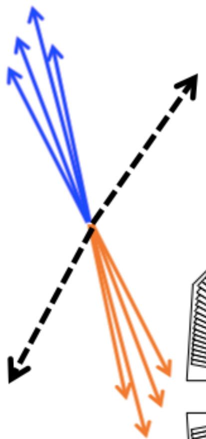
189 – M_Z = 98

hep-ex/0107029



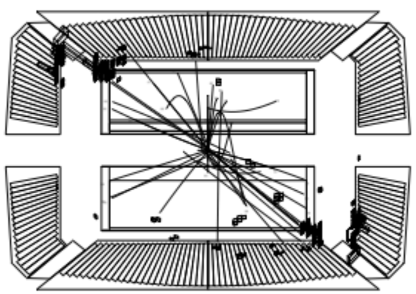
206 – M_Z = 115

we rediscovered the existence of backgrounds



HZ with Z->νν

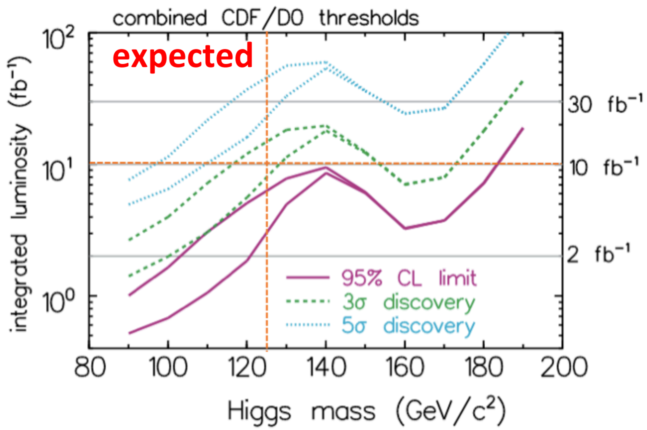
Two-jet at rest: automatically rescaled at 115 GeV



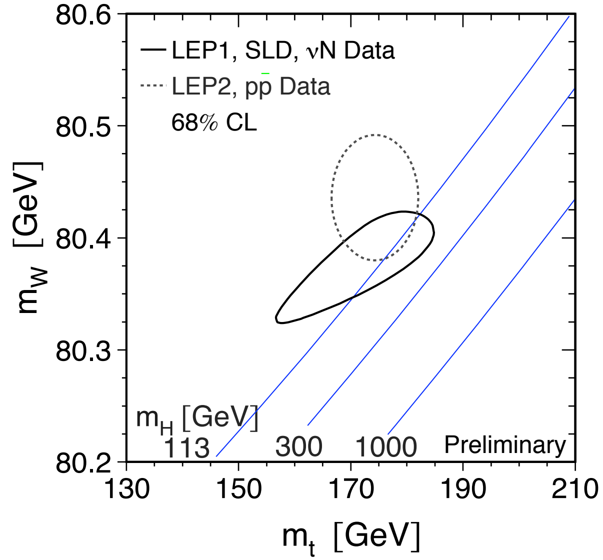
and ended in confusion...

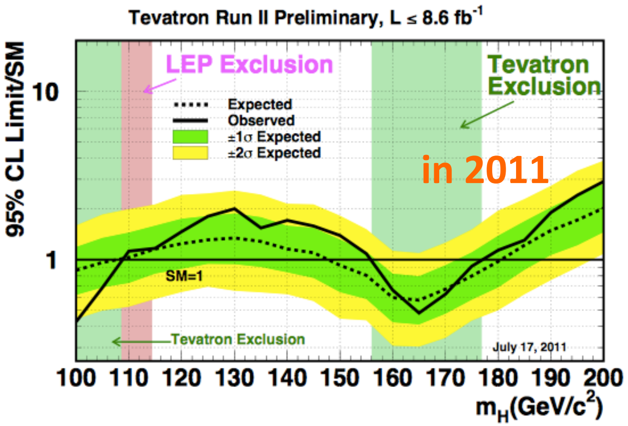
Tevatron

… substantial gain in reach at the Tevatron with integrated luminosity increasing from 10 fb^{-1} to 25-30 fb^{-1}.With the larger integrated luminosity, a Higgs search at the Tevatron should be able to probe essentially the entire parameter space of these models. While a discovery would be very exciting, a negative result would severely constrain our ideas about how weak scale supersymmetry is realized. hep-ph/9807262



hep-ph/0204104





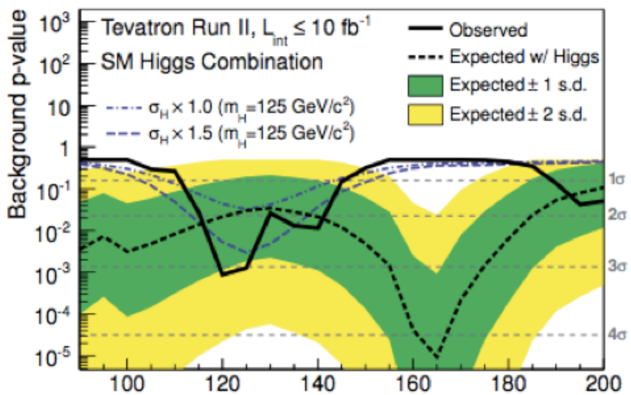
LEP archived data

great, but treat with care..

suspense….

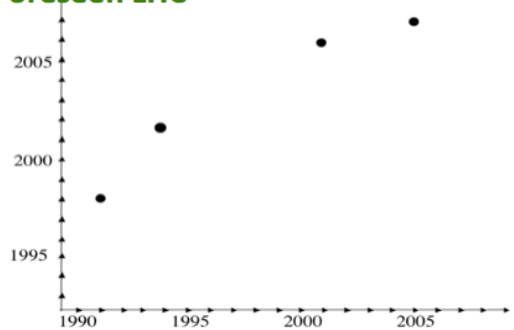
But what a great machine!

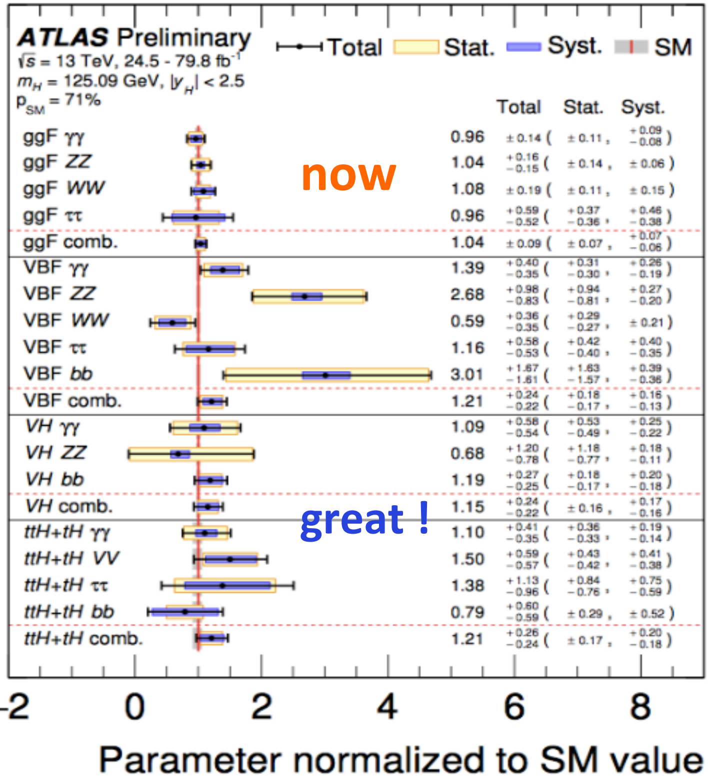
http://inspirehep.net/record/1467915/files/
10.1016_j.nuclphysbps.2015.09.131.pdf



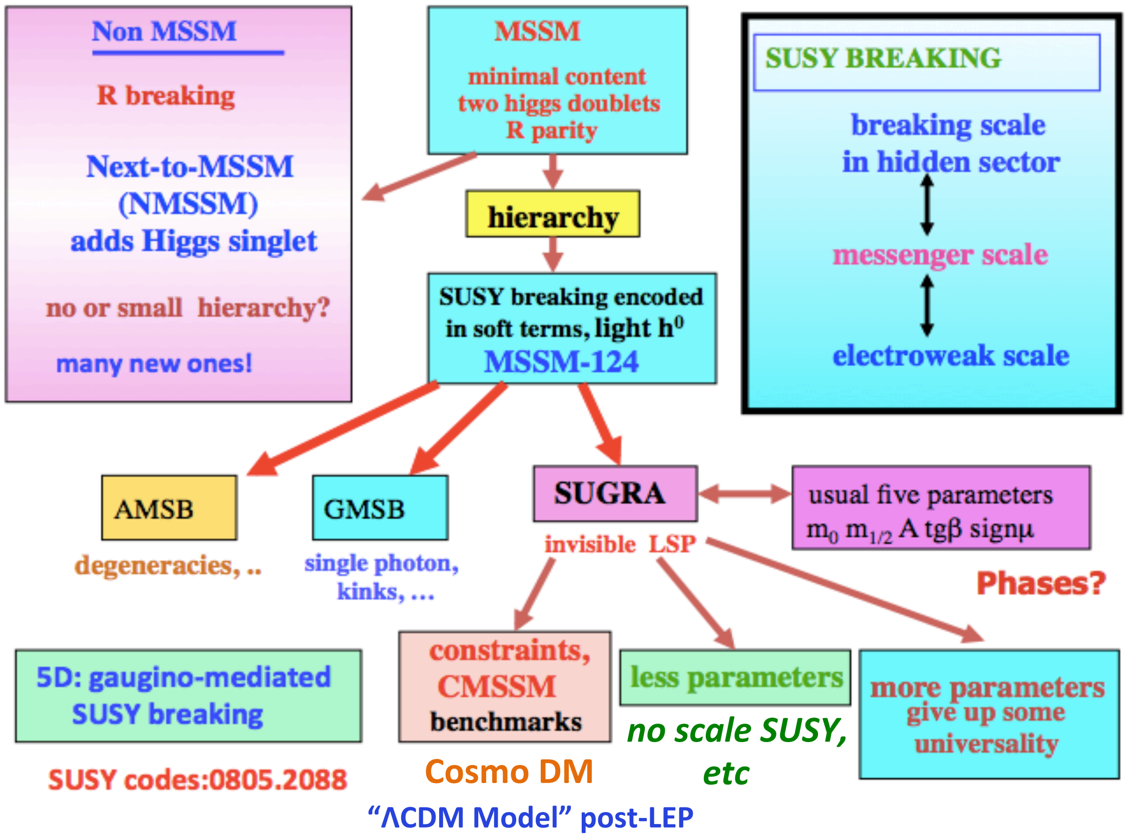
not far away…

Foreseen LHC



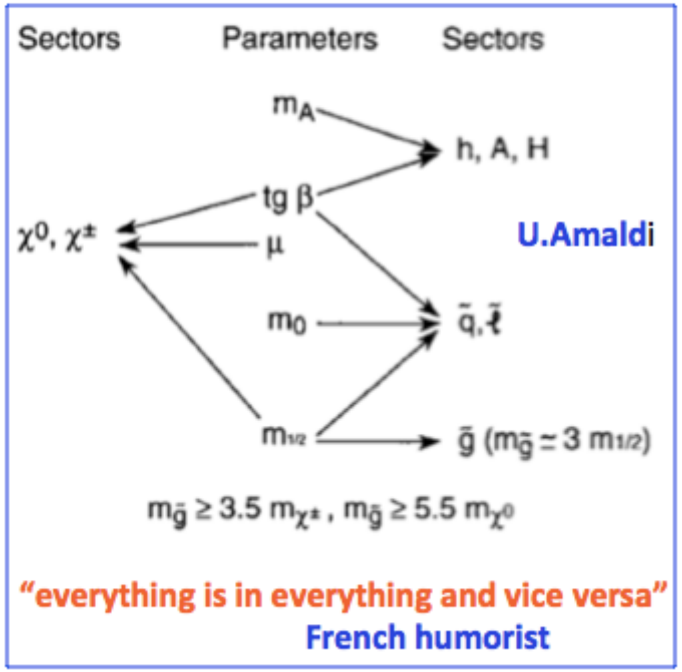


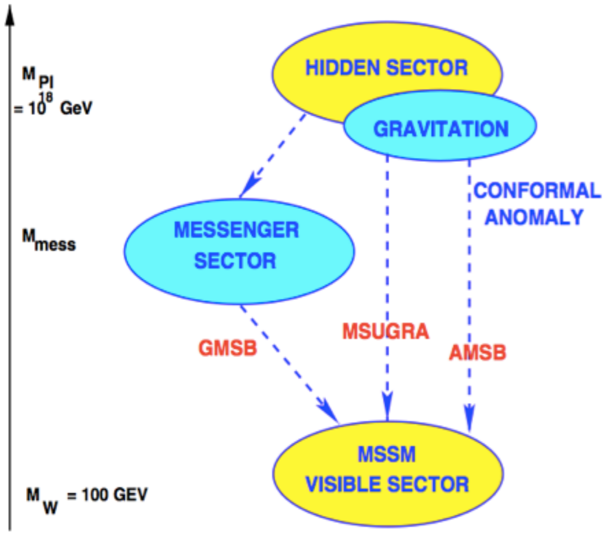
All's well that ends well!

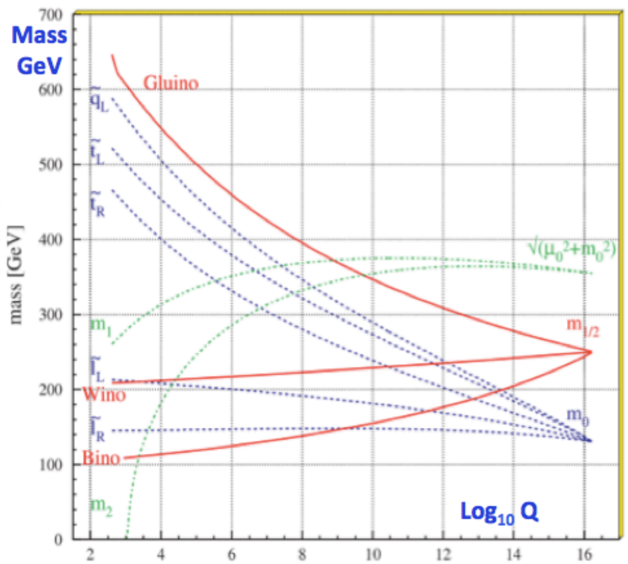


Scenario	Parameters	EWSB
SUGRA	$m_0, m_{1/2}, A_0, \tan\beta, \mu$	no
MSUGRA	$m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$	yes
CMSSM	$m_0, m_{1/2}, A_0, \tan\beta, \mu, m_A$	yes

Common scalar mass, common gaugino mass at GUT, Trilin. coupling, Higgs v.e.v. ratio, Higgs mixing mass Term, Pseudosc.neutral Higgs mass







$$M_3 \equiv M_{\tilde{g}} \simeq 2.7 m_{1/2},$$
$$M_2(M_Z) \simeq 0.8 m_{1/2},$$
$$M_1(M_Z) \simeq 0.4 m_{1/2}.$$

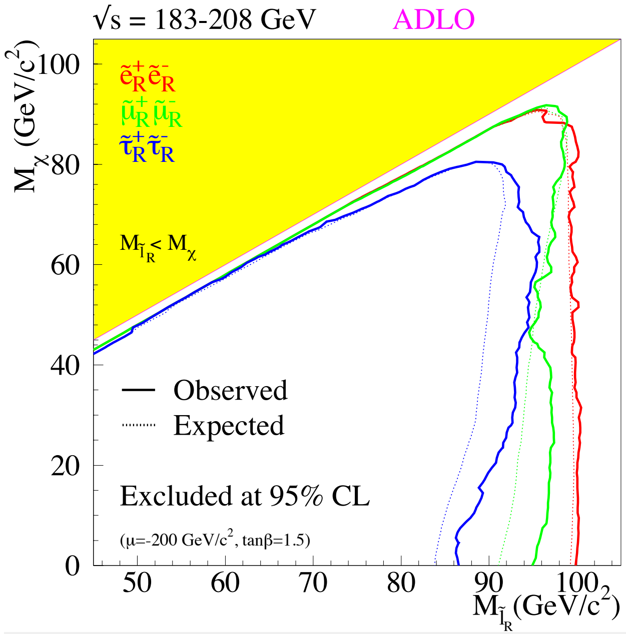
$M_2 \ll |\mu|$ **Bino LSP**

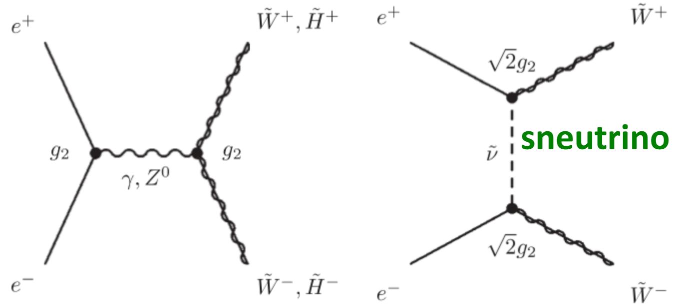
$M_2 \gg |\mu|$ **Higgsino LSP**

SUSY Crucial role of the LEP SUSY Group, L.Pape *et al* www.cern.ch › lepsusy › Welcome

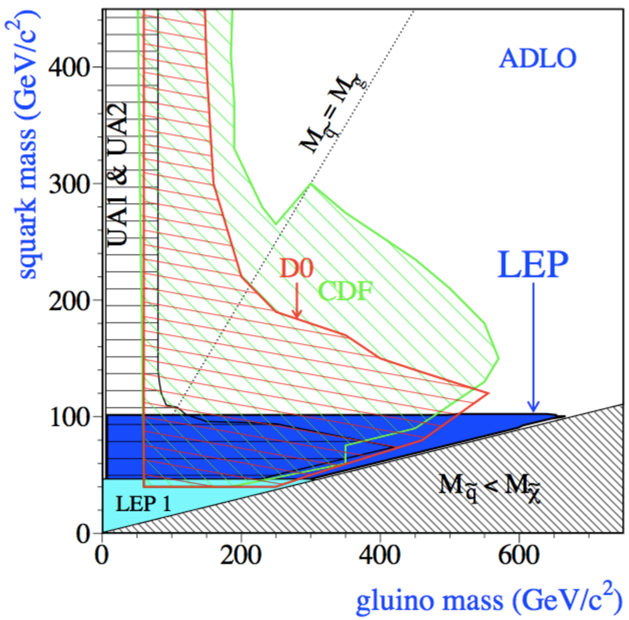
sleptons

neutralinos play a role
(e.g. selectron c.s.)
unification of gaugino masses
limits given for R-sleptons
μ=−200 GeV tgβ=1.5



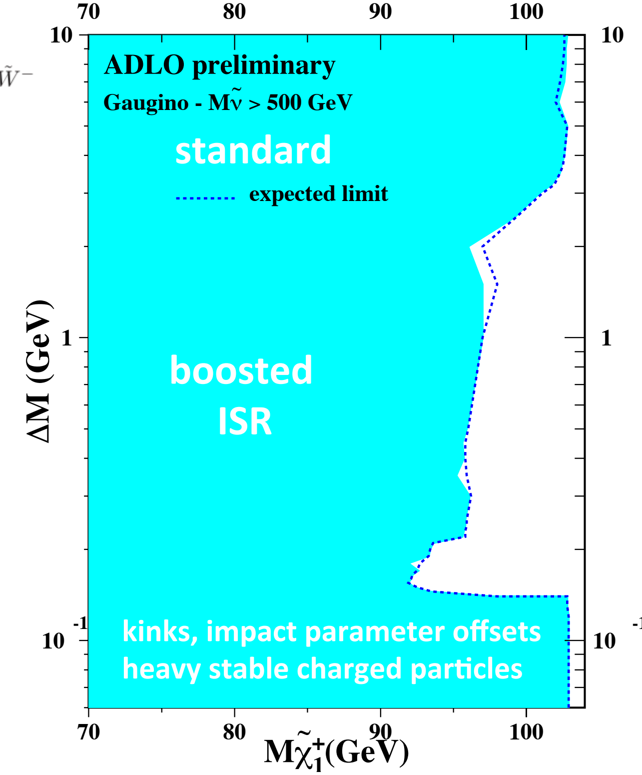


gluino and squarks



charginos

degeneracy in the gaugino region (large m_0)



Examples of Mass Lower Limits (@ *95% Confidence Level*):

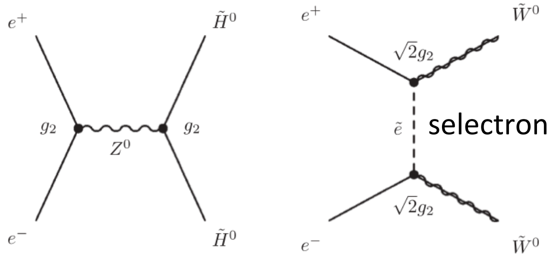
Channel	Comment	Neutralino Mass	Observed Slepton Mass Lower Limit	Expected Slepton Mass Lower Limit
Selectron	RR coupling	0 GeV 40 GeV	99.9 GeV 99.9 GeV	99.3 GeV 99.4 GeV
Smuon	RR coupling	0 GeV 40 GeV	94.9 GeV 96.6 GeV	91.1 GeV 94.6 GeV
Stau	Z decoupled	0 GeV 40 GeV	86.6 GeV 92.6 GeV	83.8 GeV 88.5 GeV
	RR coupling	0 GeV 40 GeV	86.6 GeV 93.2 GeV	83.8 GeV 89.2 GeV

Channel	M(squark) - M(LSP)	Observed mass limit no mixing	Observed mass limit max mixing
stop -> c chi	20 GeV 40 GeV 60 GeV	100 GeV 98 GeV 98 GeV	98 GeV 95 GeV 95 GeV
sbottom -> b chi	20 GeV 40 GeV 60 GeV	99 GeV 99 GeV 99 GeV	95 GeV 95 GeV 94 GeV
stop -> b l snu	20 GeV 40 GeV	99 GeV 99 GeV	96 GeV 97 GeV

Channel	M(obtained) >	M(expected) >
Chargino	103.5 GeV	103.3 GeV

Channel	M(obtained) >	M(expected) >
Chargino	91.9 GeV	91.9 GeV

LSP



MSSM with lowest order gaugino and sfermion mass unification at GUT scale

1. For **tanβ < 3.3** the lower limit is set at **large M_0**:

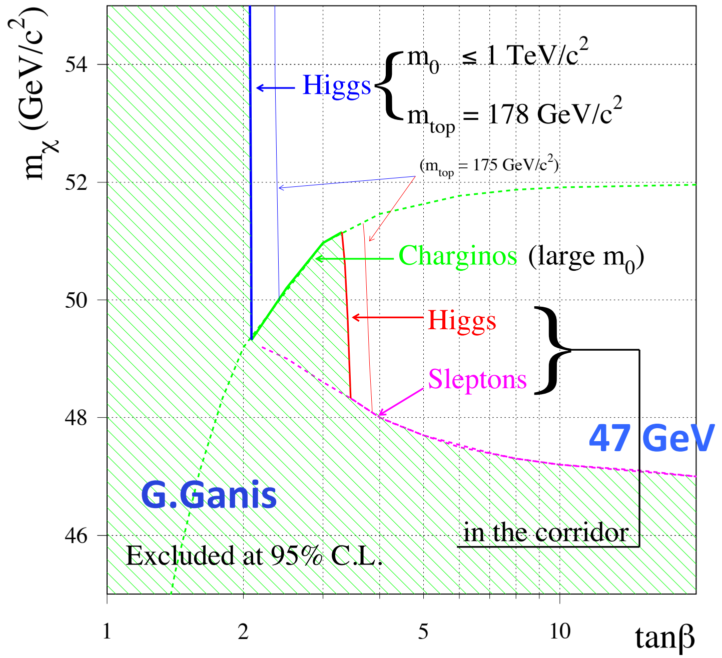
   + by Higgs boson searches for **tanβ < 2.1** ;
   + by chargino searches for **2.1 < tanβ < 3.3**

2. For **tanβ > 3.3** the limit is set at **small M_0** :

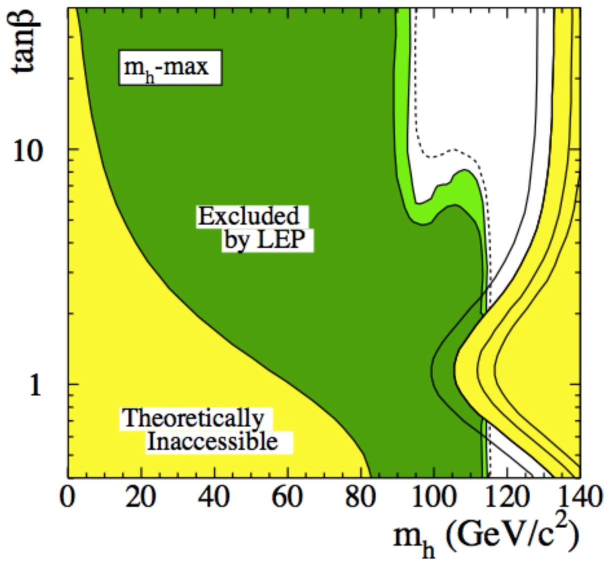
   + by the Higgs boson searches for **tanβ < 3.45** ;
   + by slepton searches for **tanβ > 3.45** .

95% C.L. $M_0 < 1$ TeV/c^2 and $M_{top} = 178$ GeV/c^2.

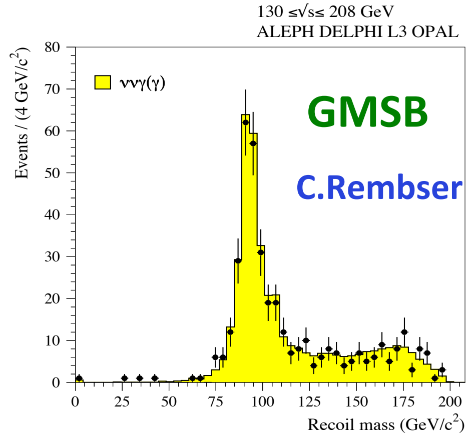
with LEP Combined Results

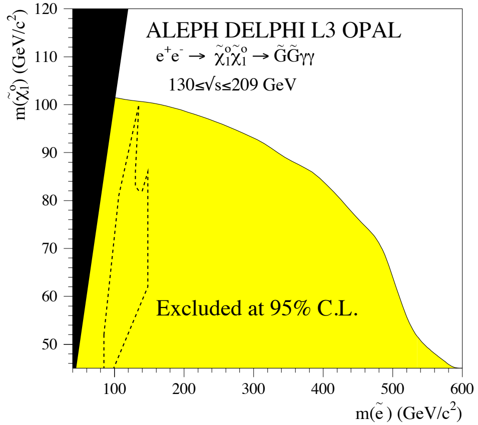


MSSM lightest Higgs boson



Acoplanar γ pairs Gravitino-LSP





RPV decays

Pair production of leptons
Only one Yukawa at a time
Light neutralino > 10 GeV
Delta M > 3 GeV

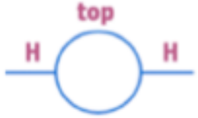
Channel	M(obtained) >	M(expected) >	M(obtained) >	M(expected) >
	M(Chi0) = 40 GeV		DeltaM > 3 GeV	
selectron	100.3 GeV	98.9 GeV	96.6 GeV	92.9 GeV
smuon	98.0 GeV	95.9 GeV	96.9 GeV	92.9 GeV
stau	96.9 GeV	95.0 GeV	95.9 GeV	92.0 GeV
snu_el	100.1 GeV	99.8 GeV	98.9 GeV	99.1 GeV
snu_mu	87.1 GeV	90.7 GeV	84.5 GeV	86.0 GeV

Loopholes ? hep-ph/0310037 Lower limit on the neutralino mass in the general MSSM >18 GeV

The 'LEP paradox' R.Barbieri, A.Strumia hep-ph/0007265

Is there a Higgs? Where is it? Is supersymmetry there? Where is it? By discussing these questions, we call attention to the 'LEP paradox', which is how we see the naturalness problem of the Fermi scale after a decade of electroweak precision measurements, mostly done at LEP.

- A light h with m_h < 200 GeV or so
- A cutoff Λ for n.r. operators contributing to the prec. EW obs. ≥ 5 TeV



→ $\delta M_H^2(top) \approx G_F M_{top}^2 \Lambda^2 \approx (0.3\,\Lambda)^2 \approx 2\ \mathrm{TeV}^2$

Fine tuning ? minimization of the 1-loop scalar of the Higgs potential

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \qquad \Delta_{BG} \equiv \max|\Delta_p| \qquad \Delta_p \equiv \frac{\partial \ln M_Z^2}{\partial \ln p_i}$$

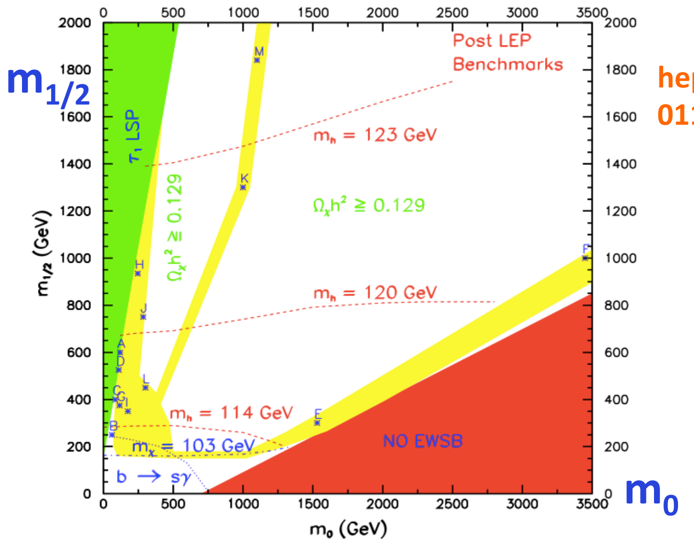
Supersymmetric Unification Without Low Energy Supersymmetry And Signatures for Fine-Tuning at the LHC hep-th/0405159

Nima Arkani-Hamed, Savas Dimopoulos

Folded Supersymmetry and the LEP Paradox hep-ph/0609152

Post-LEP CMSSM Benchmarks for Supersymmetry

M. Battaglia,[1] A. De Roeck,[1] J. Ellis,[1] F. Gianotti,[1] K. T. Matchev,[1] K. Olive,[2] L. Pape,[1] and G. W. Wilson[3]



hep-ph/0112013

Let hundred flowers blossom…

Ignore the hierarchy problem → "anthropic" reasoning

Solve the hierarchy problem

The Big One		The Small One, or LEP Paradox	
4 dim	> 4 dim	4 dim	> 4 dim
SUSY	flat ADD	SUSY variants (Split, Folded, ..)	"Little" RS
MSSM, but "tension"? NMSSM, ...	UED	Little Higgs	Gauge-Higgs unification
	warped RS1	Holographic Technicolor	
Technicolor, but T ? Walking TC	RS2	Higgsless	Higgsless

A Large Mass Hierarchy from a Small Extra Dimension

Lisa Randall

Joseph Henry Laboratories, Princeton University, Princeton, NJ 085

and

Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Raman Sundrum

Department of Physics, Boston University, Boston, MA 02215, USA

hep-ph/9905221

Search for Extra Spatial Dimensions and TeV Scale Quantum Gravity at LEP

CERN-OPEN-99-269

The ALEPH Collaboration

CERN–EP/2001-059

1 August 2001

Search for Technicolor with DELPHI

DELPHI Collaboration

hep-ex/0110056

hep-ph/0308038
Saclay t03/112

Towards a Realistic Model of Higgsless Electroweak Symmetry Breaking

Csaba Csáki[a], Christophe Grojean[b], Luigi Pilo[b], and John Terning[c]

hep-ph/0308038

mostly in view of LHC .....

Conclusions

LEP marvelous time, machine and experiments
Checking the SM with exquisite precision
Wonderful measurement machine, but could have been also a discovery machine
in the usual sense of the word

4 experiments, 4 x luminosity (ADLO, a great first), specificities in each one
Many invaluable cross-checks, both in measurements and the treatment of “fluctuations”

Close collaboration of theorists and experimentalists
Even more essential for the possible future Higgs factory, Tera Z

A necessary step on the way to LHC: m^2 Si.det., scint.crystals, actors, management
of large collaborations, etc
LEP-LHC in same tunnel: a well thought scenario covering five decades

Through its non-discoveries of BSM physics, started considering many BSM scenarios,
enriching the phenomenology at LHC and largely disproved by the 125 GeV boson discovery

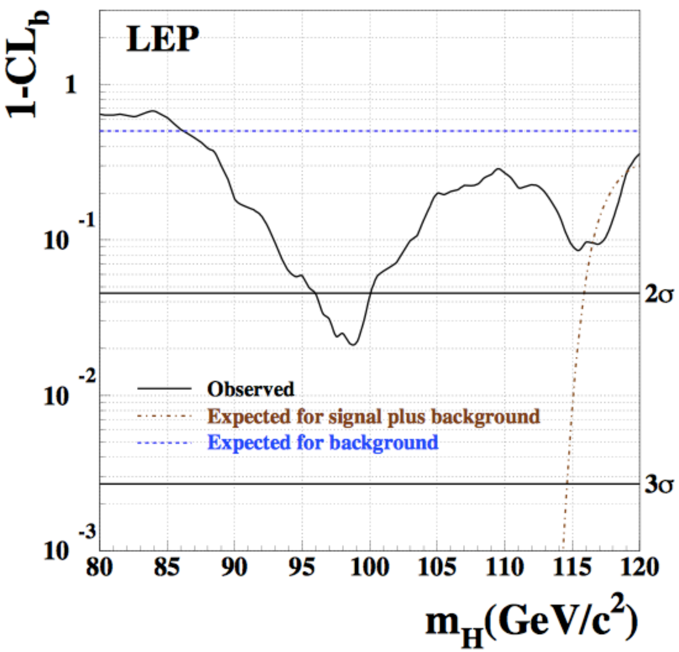
When $L=10^{34}$ was advocated in 87, not unanimously expected that the LHC experiments
would perform so well, ensuring both subtle searches and high-quality measurements

A warm tribute should be paid to many actors, machine and experiments, e.g. technical
coordinators of the experiments and great experts of cutting-edge technologies.

Back up

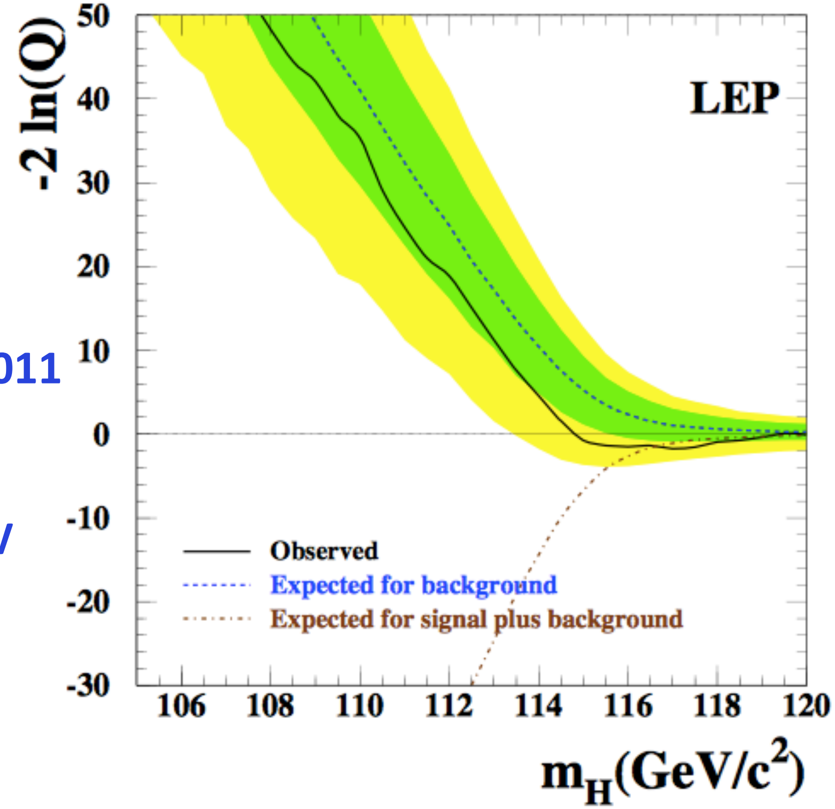
	Experiment	E_{cm}(GeV)	Final state topology	m_H^{rec} (GeV/c^2)	$\ln(1+s/b)$ at 115 GeV/c^2
1	ALEPH	206.6	Four-jet	114.1	1.76
2	ALEPH	206.6	Four-jet	114.4	1.44
3	ALEPH	206.4	Four-jet	109.9	0.59
4	L3	206.4	Missing energy	115.0	0.53
5	ALEPH	205.1	Leptonic	117.3	0.49
6	ALEPH	208.0	Tau	115.2	0.45
7	OPAL	206.4	Four-jet	111.2	0.43
8	ALEPH	206.4	Four-jet	114.4	0.41
9	L3	206.4	Four-jet	108.3	0.30
10	DELPHI	206.6	Four-jet	110.7	0.28
11	ALEPH	207.4	Four-jet	102.8	0.27
12	DELPHI	206.6	Four-jet	97.4	0.23
13	OPAL	201.5	Missing energy	108.2	0.22
14	L3	206.4	Missing energy	110.1	0.21
15	ALEPH	206.5	Four-jet	114.2	0.19
16	DELPHI	206.6	Four-jet	108.2	0.19
17	L3	206.6	Four-jet	109.6	0.18

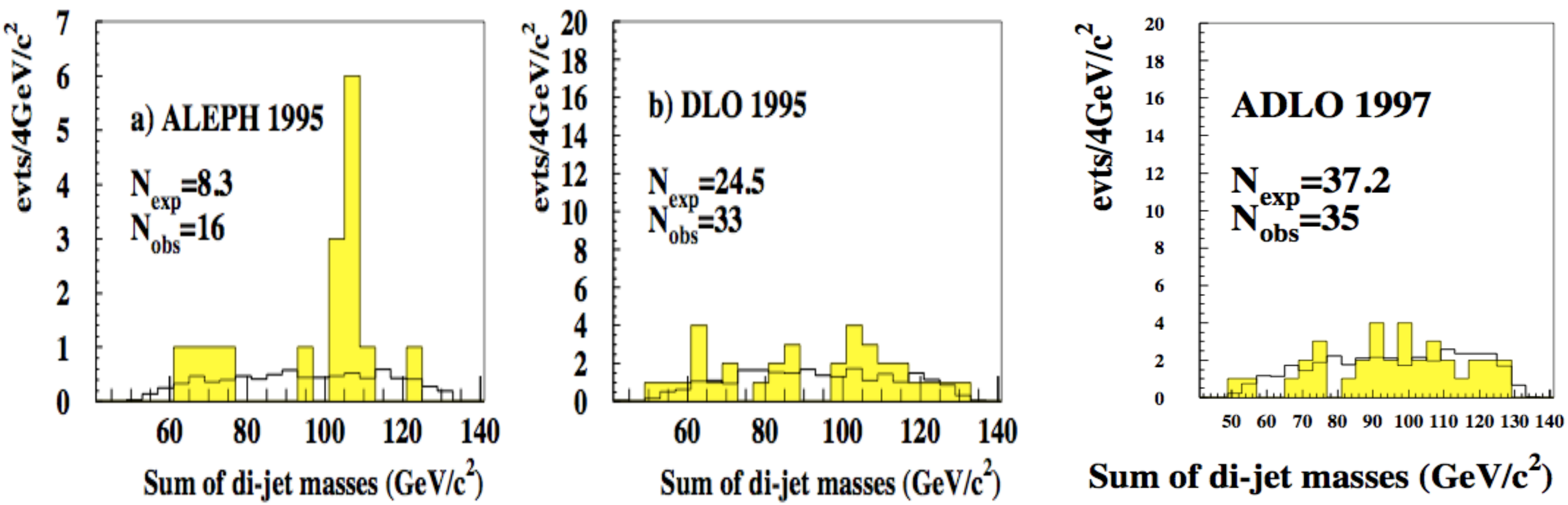
	$1-CL_b$	CL_{s+b}
LEP	0.09	0.15
ALEPH	3.3×10^{-3}	0.87
DELPHI	0.79	0.03
L3	0.33	0.30
OPAL	0.50	0.14
Four-jet	0.05	0.44
All but four-jet	0.37	0.10



CERN-EP/2003-011
13 March 2003

Limit: 114.4 GeV

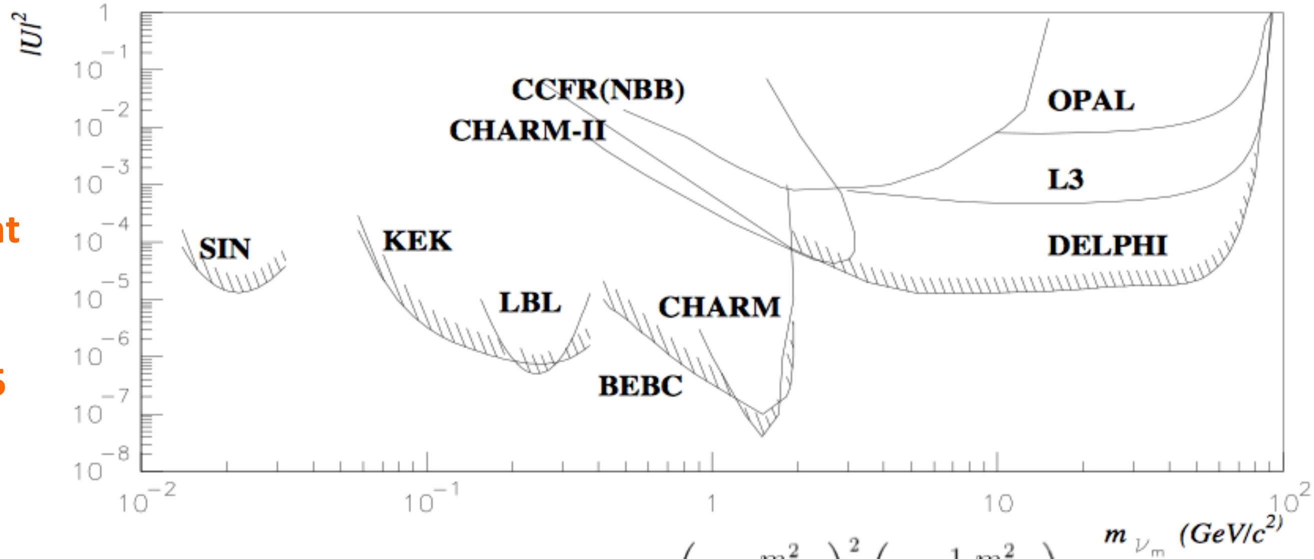




only two experiments (or a single one) may lead to tricky situations..

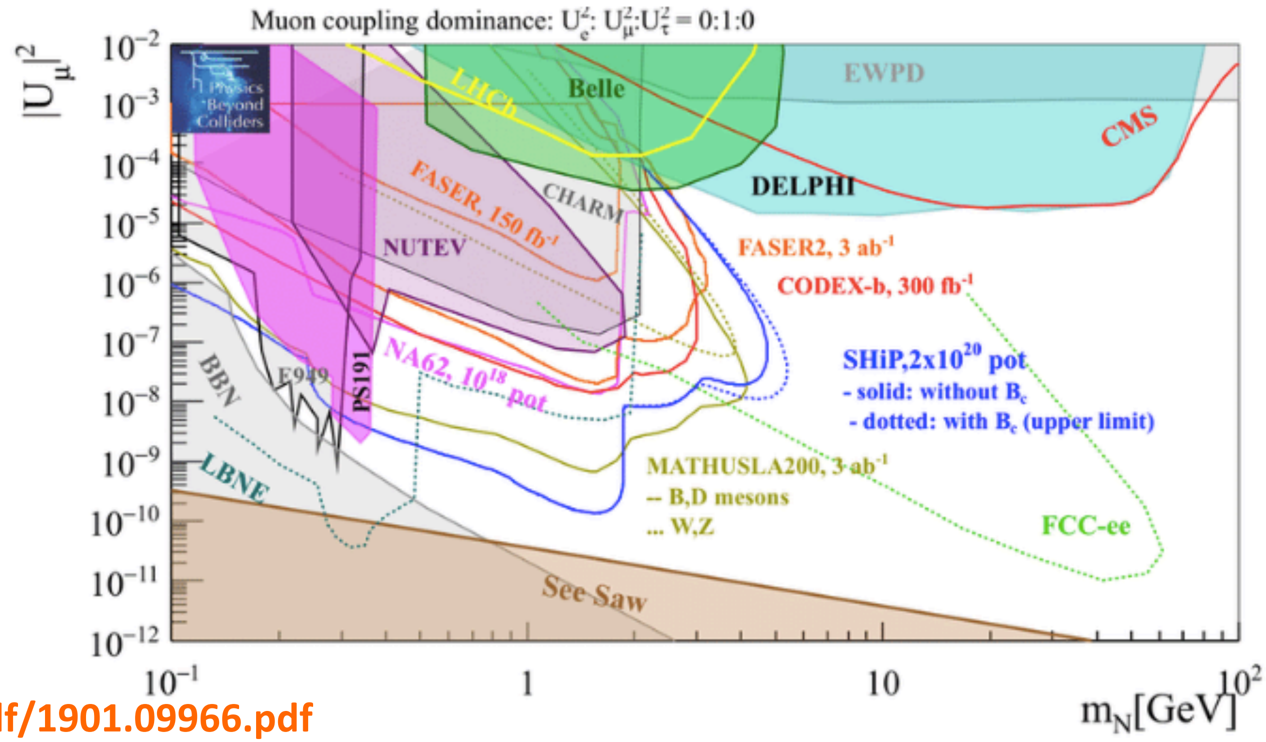
Mixing matrix element

CERN-PPE/96-195

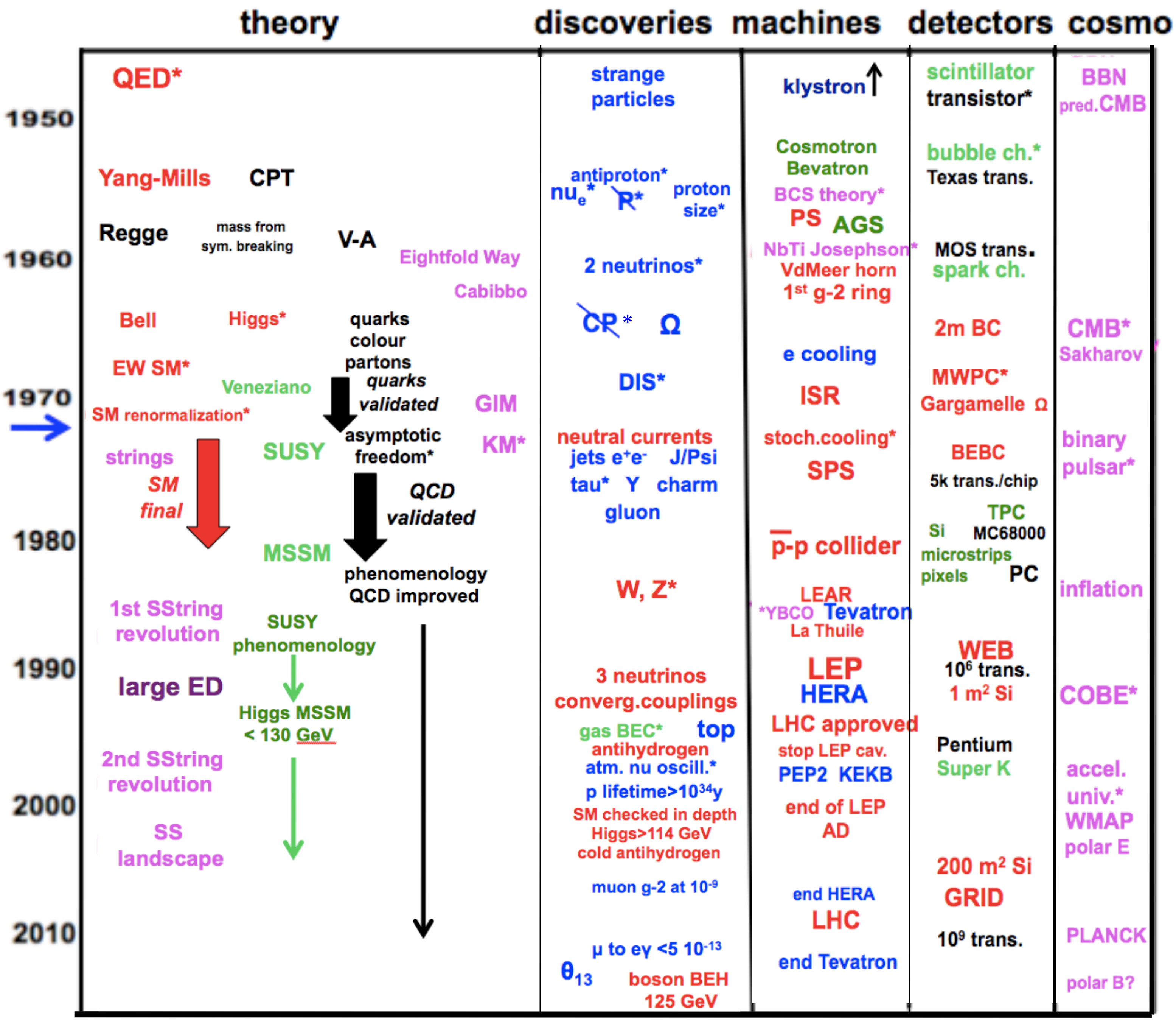


$$BR\,(Z^0 \to \nu_m \overline{\nu}) = BR\,(Z^0 \to \nu \bar{\nu})\;|U|^2\;\left(1 - \frac{m^2_{\nu_m}}{m_{Z^0}{}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m^2_{\nu_m}}{m_{Z^0}{}^2}\right)$$

Heavy Neutral leptons



https://arxiv.org/pdf/1901.09966.pdf



AM

* means NP

PM

D.T.
June
2014