The Role of Theory

From "a model" to
"The Standard Model"
and searches beyond

Special colloquium for the thirtieth
anniversary of the start of operations of LEP

John Ellis

KING'S College LONDON

Context: the Gauge Theory Revolution

1971/2

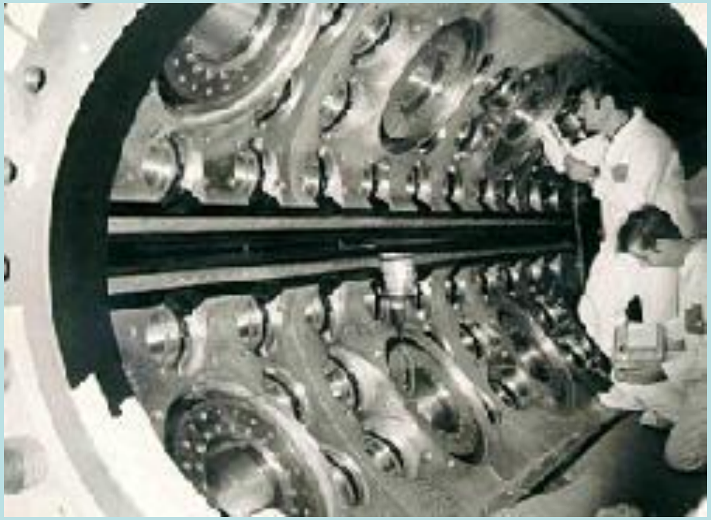
- `t Hooft and Veltman: renormalizable

1973

- Kobayashi and Maskawa show how to include CP violation in the Standard Model with 6 quarks

1973

- Neutral currents in Gargamelle



1974

- J/Ψ discovered

1975 Tau lepton discovered

1975/6 Charmed particles discovered

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

1976

Pioneering Study of Scaling for High-Energy e^+e^- Colliders

Burt Richter on sabbatical leave at CERN 1975/6

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/ISR-LTD/76-9

VERY HIGH ENERGY ELECTRON-POSITRON COLLIDING BEAMS FOR THE STUDY OF THE WEAK INTERACTIONS

B. Richter*)

CERN

ABSTRACT

We consider the design of very high energy electron-positron colliding-beam storage rings for use primarily as a tool for investigating the weak interactions. These devices appear to be a very powerful tool for determining the properties of these interactions. Experimental possibilities are described, a cost minimization technique is developed, and a model machine is designed to operate at centre-of-mass energies of up to 200 GeV. Costs are discussed, and problems delineated that must be solved before such a machine can be finally designed.

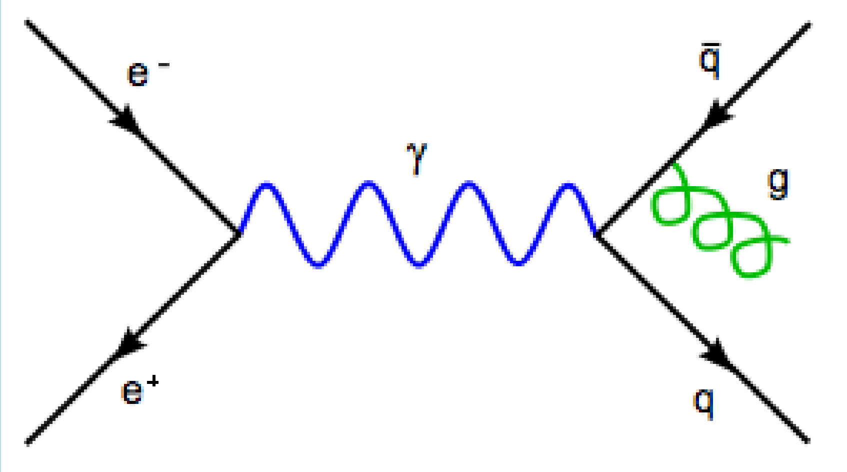
Geneva - 19 March 1974

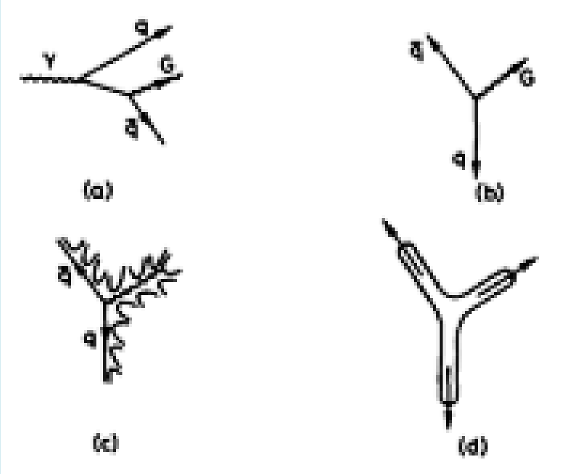
*) Visitor from Stanford Linear Accelerator Center, Stanford, California.

1976

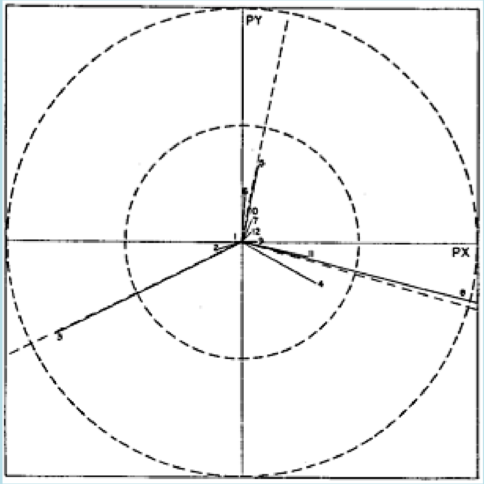
Gluon Radiation in e^+e^- Annihilation

JE, Gaillard & Ross





- Gluon discovery method
- Jets of hadrons produced by gluons detected at DESY (Hamburg) in 1979
- **Second force particle discovered**
- Big topic at LEP



1976

First LEP Physics Study

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

GENEVA
1976

First step in a long
experiment/theory collaboration

III- THEORETICAL REMARKS

J. Ellis, M.K. Gaillard

Contents :

1977

Sensitivity to Top Mass

Nuclear Physics B123 (1977) 89–99

LIMIT ON MASS DIFFERENCES IN THE WEINBERG MODEL

M. VELTMAN
Institute for Theoretical Physics, University of Utrecht, Netherlands

Effects ~ m_t^2

Received 7 February 1977

Within the Weinberg model mass differences between members of a multiplet generate further mass differences between the neutral and charged vector bosons. The experimental situation on the Weinberg model leads to an upper limit of about 800 GeV on mass differences within a multiplet. No limit on the average mass can be deduced.

1977

Sensitivity to Higgs Mass

Effects ~ ln m_H
"Screening Theorem"

Vol. B8 (1977) ACTA PHYSICA POLONICA No 6

SECOND THRESHOLD IN WEAK INTERACTIONS

By M. Veltman

Institute for Theoretical Physics, University of Utrecht*

and

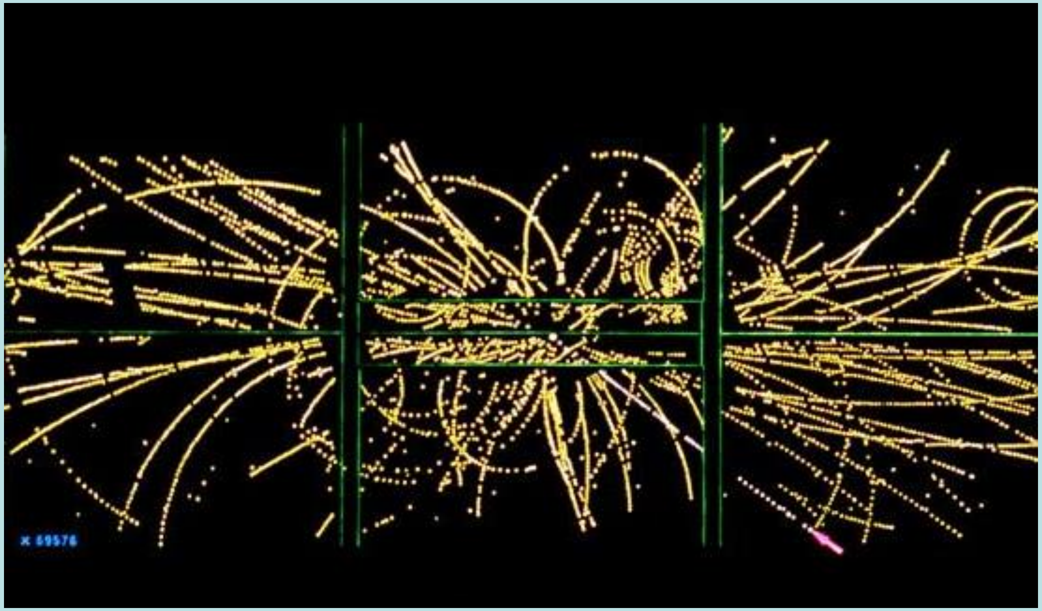
Max-Planck Institut für Physik und Astrophysik, München

(Received January 7, 1977)

The point of view that weak interactions must have a second threshold below 300 — 600 GeV is developed. Above this threshold new physics must come in. This new physics may be the Higgs system, or some other nonperturbative system possibly having some similarities to the Higgs system. The limit of large Higgs mass is thought to be relevant in this context. Radiative corrections proportional to m^2 and ln m^2, m being the Higgs mass, are calculated. Contemplation of the theory in the limit of large Higgs mass suggests that the "new physics" may contain breakdown of μ-e universality and other than V–A neutrino interactions already at relatively low energies.

1983

Discovery of the W and Z



How did it get so heavy?

- The top quark still undiscovered
- The search for the Higgs moved up the agenda

1986

Prospects for LEP Searches

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AT LEP

Edited by
John Ellis and Roberto Peccei

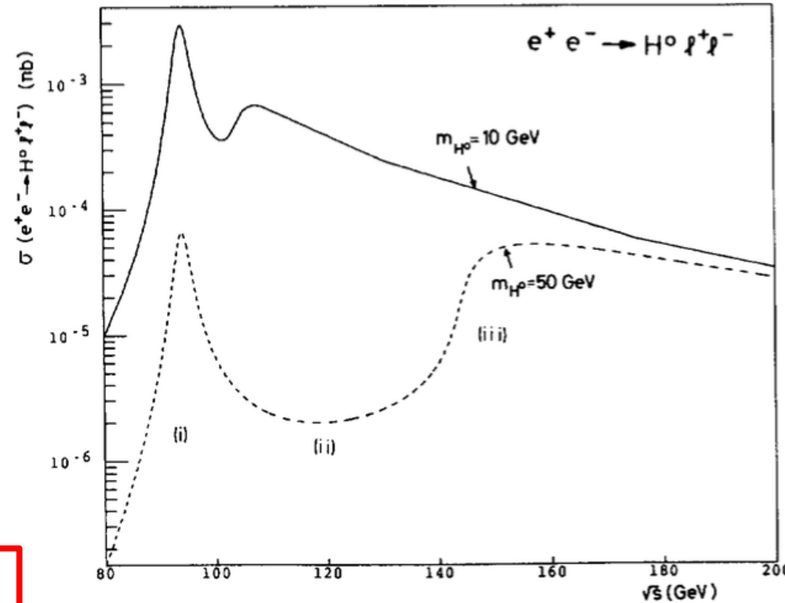
297

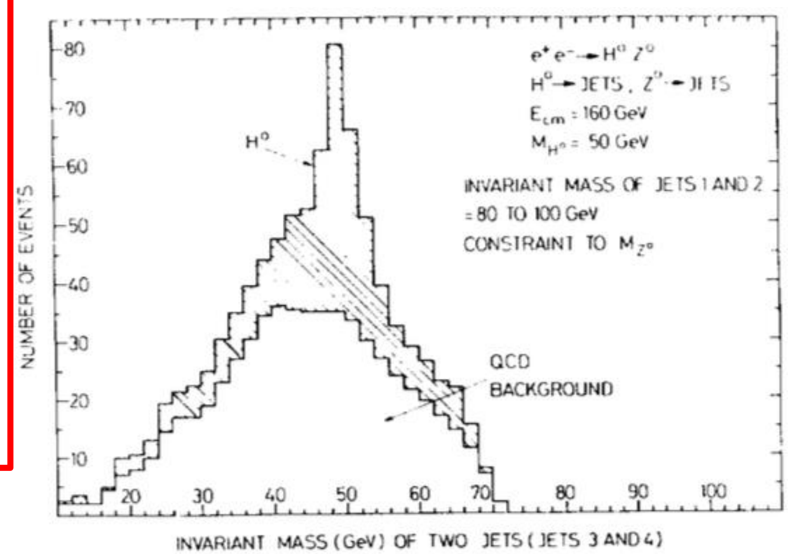
NEW PARTICLES

H. Baer, J. Berdugo, F. Bianchi, F. Carminati, Y. Chang, M. Chen,
C. Dionisi, J. Ellis, P. Folegati, M. Martinez, C. Matteuzzi, P. Mättig,
G. Mikenberg, S. Ritz, P. Sorba, X. Tata, W. Venus, H.G. Wu,
Sau Lan Wu, A. Yagil, G. Yekutieli and G. Zobernig

CONTENTS

GENEVA
1986





Where are the top and Higgs?

Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

Veltman

- Sensitivity to top mass is quadratic: $\frac{3G_F}{8\pi^2\sqrt{2}} m_t^2$

- Sensitivity to Higgs mass is logarithmic:

$$\frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

$$\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$$

1987

Estimating the Top Quark Mass

- **Needed as a partner of the bottom quark**
- Not discovered in 1975 or 1984
- Many speculations about its mass
- Indication of large mass from B physics
- Estimate from radiative corrections in neutral currents

  "In the minimal standard model with ρ = 1 and equal Higgs and Z masses we find that ***m_t < 168 GeV*** *at 90% confidence level"*
- Not so bad!

NEUTRAL CURRENTS WITHIN AND BEYOND THE STANDARD MODEL

G. COSTA[1], J. ELLIS[2], G.L. FOGLI[3], D.V. NANOPOULOS[4] and F. ZWIRNER[5]

CERN, Geneva, Switzerland

Received 29 June 1987

Into the LEP Era

1980s

- Yellow Reports: several groups calculated radiative corrections to LEP observables
- Including effects of top and Higgs loops
- Estimated accuracy of m_Z measurement ~ 50 MeV
- No calculation of potential accuracy in estimate of m_t, m_H

1989

Z Physics at LEP 1

ATION EUROPÉENNE POUR LA RECHERCI
N EUROPEAN ORGANIZATION FOR NÚCLE

Z PHYSICS AT LEP 1

Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzeį

Volume 1: STANDARD PHYSICS

Co-ordinated and supervised by G. Altarelli

GENEVA
1989

ORGANISATION EUROPÉENNE POUR LA REC
CERN EUROPEAN ORGANIZATION FOR

Z PHYSICS AT LEP

Edited by
Guido Altarelli, Ronald Kleiss and Claudi

Volume 2: HIGGS SEARCH AND NE

Co-ordinated and supervised by G. Altarelli an

GENEVA
1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUC
CERN EUROPEAN ORGANIZATION FOR NÚCLEAR RESI

Z PHYSICS AT LEP 1

Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

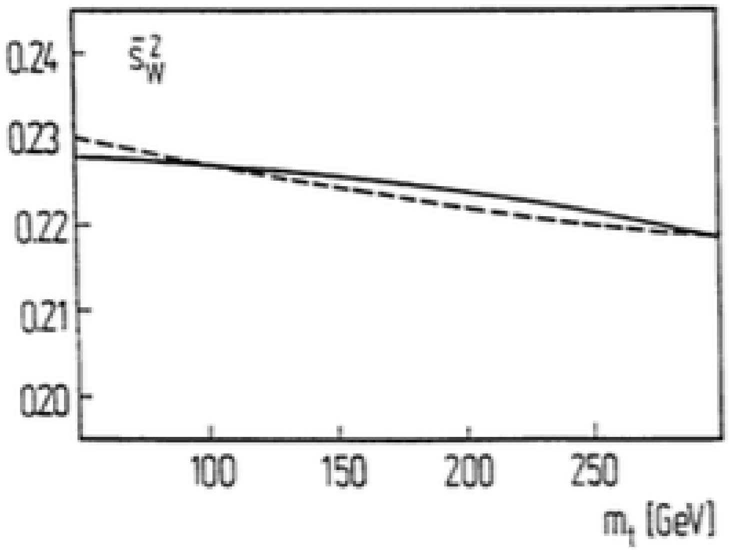
Volume 3: EVENT GENERATORS AND SOFTWARE

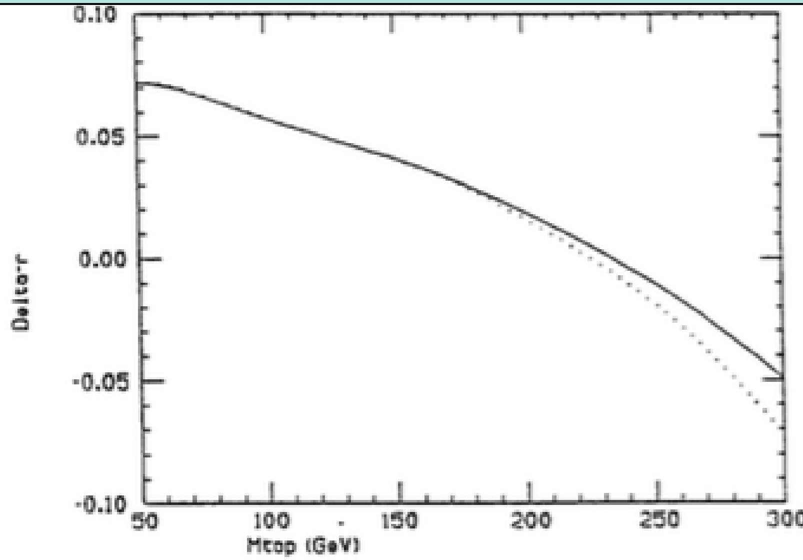
Co-ordinated and supervised by R. Kleiss

GENEVA
1989

1989

Z Physics at LEP 1





7 Conclusions

In this report we have analyzed the general structure of the higher order electroweak effects relevant for LEP/SLC experiments. We have discussed in detail the on-shell renormalization scheme but also compared our results with those obtained by different authors. The set of formulae includes all vector boson self energy parts, the relevant vertex functions, and box contributions. Some approximate analytical expressions for various quantities (asymmetries, Z decay widths), incorporating the leading terms, have also been presented. Together with the QED corrections, generally dominant but theoretically under control, the discussed weak corrections provide the basic ingredients for precision tests of the Standard Model. If the "minimal" model is correct the calculations of the various observables have to reproduce the experimental results with a choice of the unknown parameters m_t and M_H within a reasonable range (50 GeV $< m_t <$ 200 GeV as favored by present experimental data, 10 GeV$< M_H <$ 1TeV as required for a consistent weak coupling interpretation of the theory). If agreement is found the high precision measurements will considerably restrict the allowed area in the space of the unknown parameters. In this sense the inclusion of radiative corrections is not only a necessity but also a benefit: providing a unique chance to test the quantum structure of the Standard Model and its empirically unknown part.

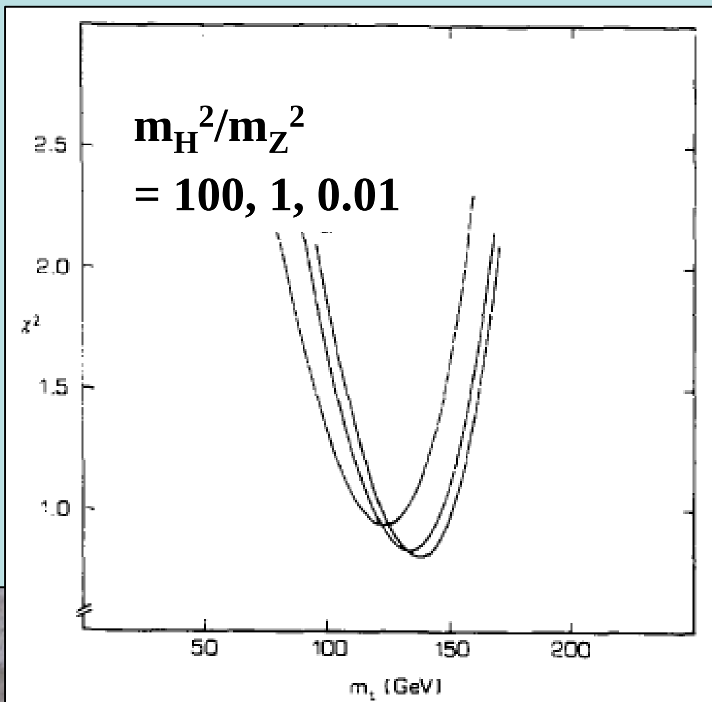
1989

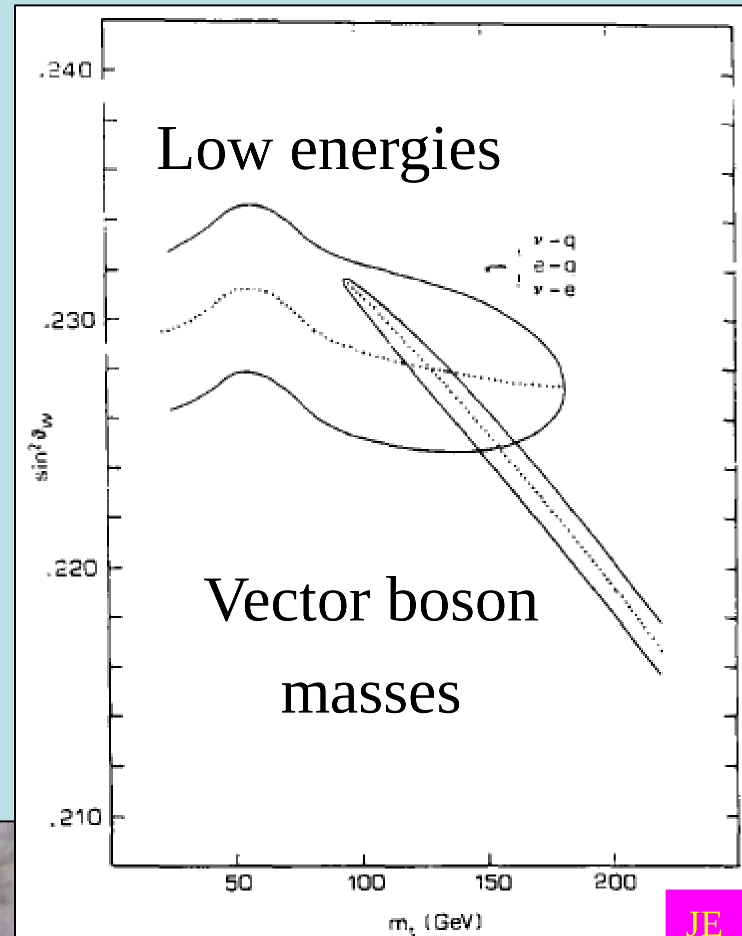
The Top Mass after First Precise m_Z

- In combination with low-energy measurements

$$\boxed{m_t = 132^{+31}_{-37}\ \mathrm{GeV}}$$

- A first discussion of m_H





JE & Fogli

1989

Cosmic Neutrino Counting Then

- Neutrinos from Supernova 1987A: **$N_\nu < 6$**
- Big Bang Nucleosynthesis: neutron lifetime (τ_n), baryon/entropy ratio (η_{10}), ^4He (Y_p), D + ^3He, Li abundances:

$$N_\nu = 3.0 - 0.8 \ln \eta_{10} + 19\left(\frac{Y_p - 0.228}{0.228}\right) - 15\left(\frac{\tau_n - 889.8}{889.8}\right)$$

- Using knowledge of other abundances:

$$N_\nu \leq 3.4 + 20\left(\frac{Y_p^{max} - 0.240}{0.240}\right)$$

- Current upper limit on $Y_p = 0.250$ ➔ **$N_\nu < 4.2$**

2019

Cosmic Neutrino Counting Today

- Big Bang Nucleosynthesis:

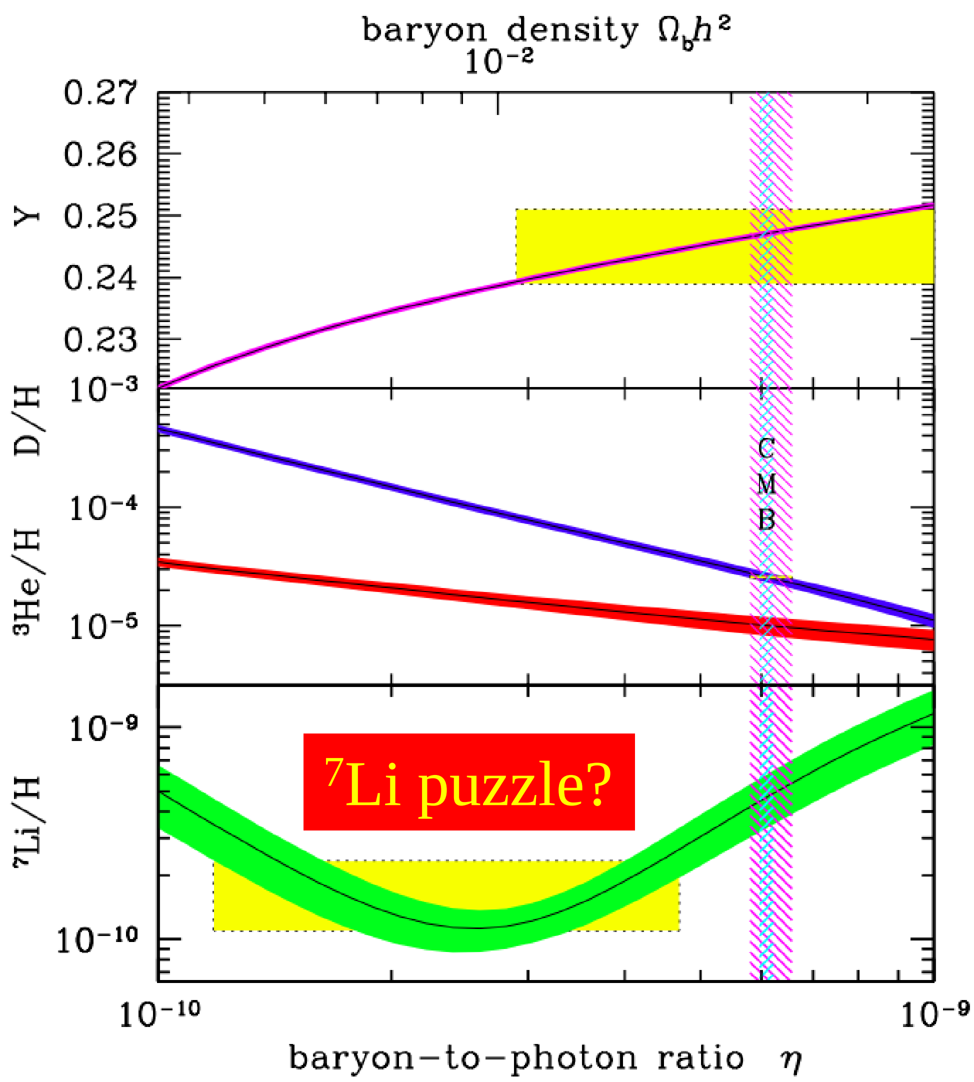
$$2.3 < N_\nu < 3.4$$

- Cosmic Microwave Background:

$$N_\nu^{\rm CMB} = 3.13 \pm 0.31$$

- Combination of BBN and CMB:

$$\boxed{N_\nu = 2.88 \pm 0.16}$$

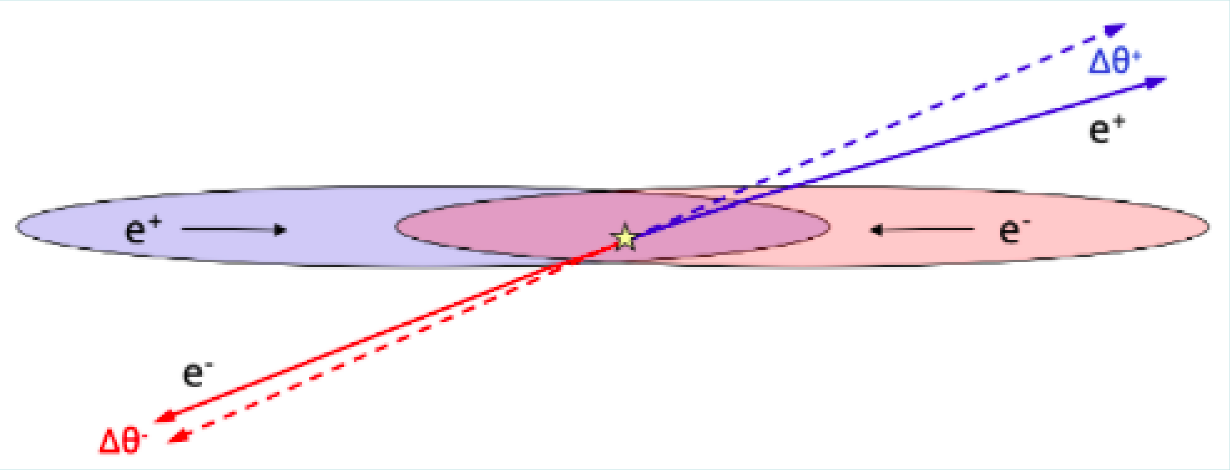


2019

Voutsinas, Perez, Dam & Janot, arXiv:1908.01704

LEP Neutrino Counting Today

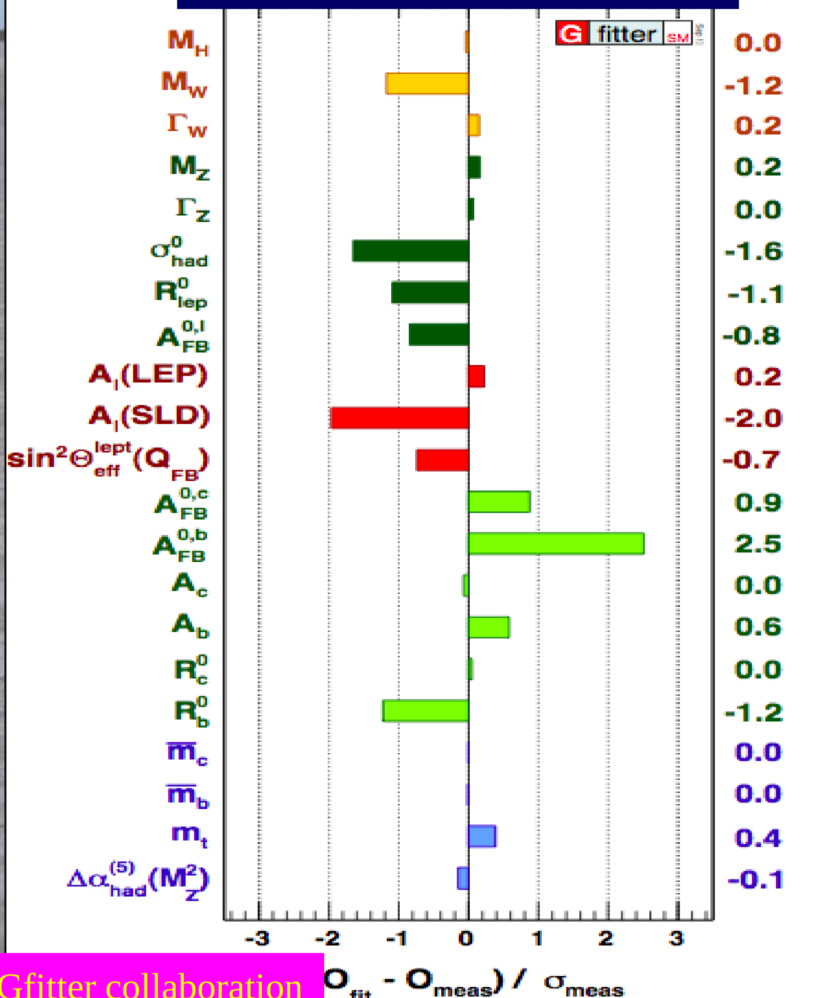
- Official LEP result: $N_\nu = 2.9840 \pm 0.0082$
- Electromagnetic effects of dense bunches modify the effective acceptance of luminometers, biasing luminosity measurement by ~ 0.1%



- Modified LEP estimate: $\boxed{N_\nu = 2.9919 \pm 0.0081}$

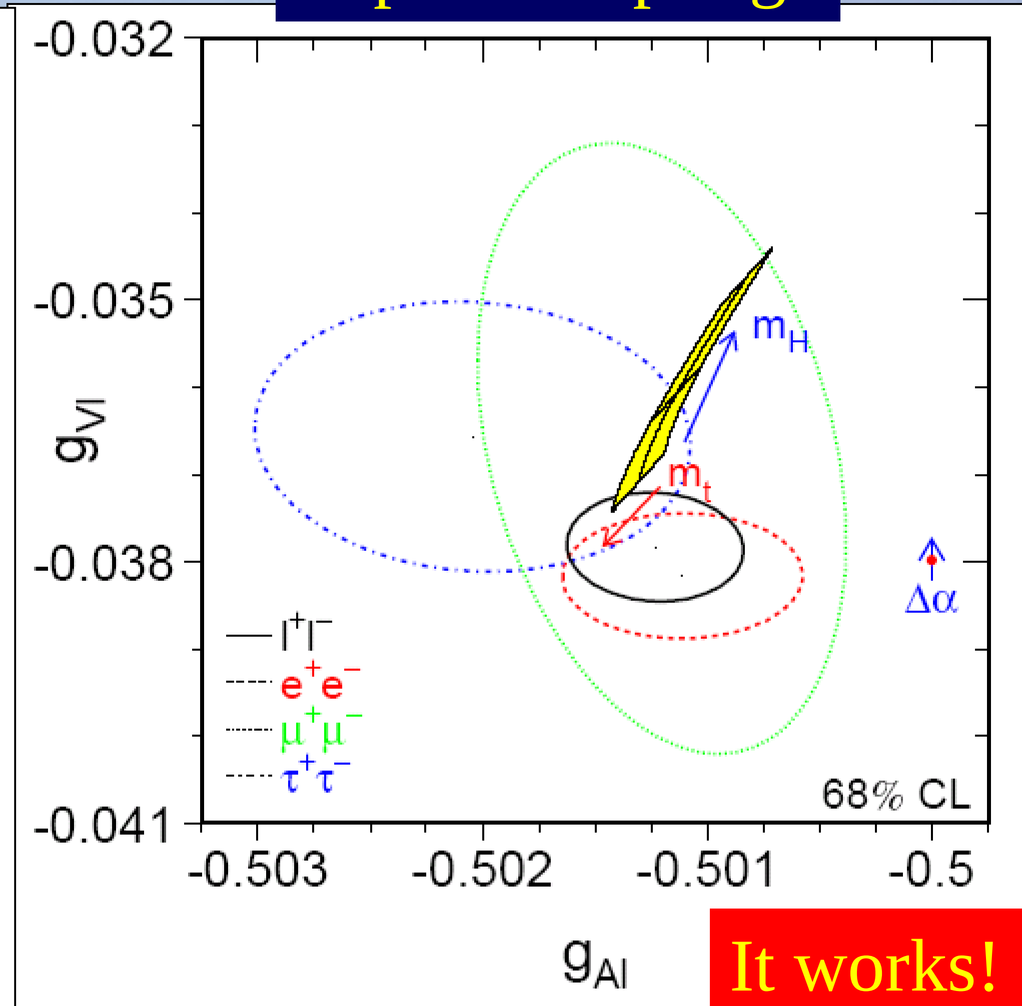
Precision Tests of the Standard Model

Pulls in global fit



Gfitter collaboration

Lepton couplings



It works!

LEP Electroweak Working Group

LEP Electroweak Gwoup Travay la

Source: http://lepewwg.web.cern.ch/LEPEWWG/

LEP Electroweak Gwoup Travay la (LEP EWWG) konbine mezi yo nan kat LEP eksperyans alèf a, DELPHI, L3 ak OPAL sou electroweak observable, tankou seksyon kwa, mas ak divès kalite akoupleman nan bozon yo lou kalib electroweak, byen pran an kont komen nan ensètitid sistematik. Rezilta sa yo konbine electroweak presizyon yo Lè sa a, pibliye kòm `` pi bon"mwayèn yo ESE, LEP, konfwonte teyori tankou modèl la Creole nan fizik patikil. Nou menm tou nou konpare oswa konbine rezilta LEP ak rezilta electroweak nan esperyans ak lòt, ki miyòNuTeV, CDF, DIII ak SLD.
Rezilta soti nan CDF nan eksperyans Tevatron ak DIII yo konbine pa Tevatron Group la ap travay Electroweak. An patikilye, konbinezon nan mas la nan tèt kark la ak mas ak lajè nan W bozon a yo te itilize nan analyse yo Creole-ki gen konpòtman egzanplè isit la.

Konbinezon ak analyse yo fèt ak pibliye ak preliminè mezi anjeneral de fwa nan yon ane: nan sezon livè (alantou fevriye / mas), ak nan sezon ete (alantou Jiyè). Rezilta yo, figi sa yo ak detaye ekri-ups yo afiche anba-a.

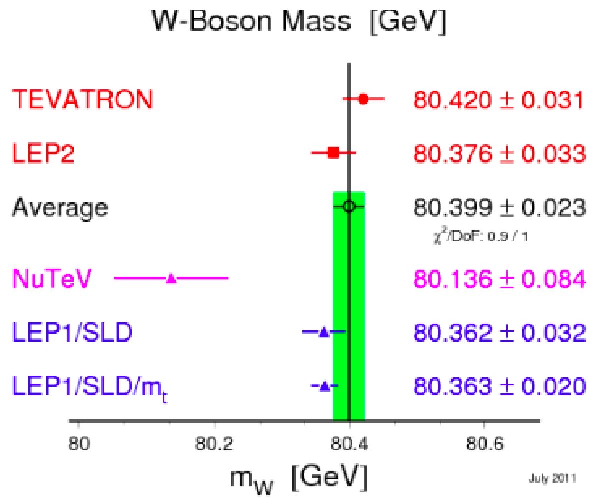
Pou kesyon ak kòmantè, kontakte: Martin Grünewald (E-Mail Pa gen-Spam: Martin DOT Grunewald NAN nonmen DOT ch)

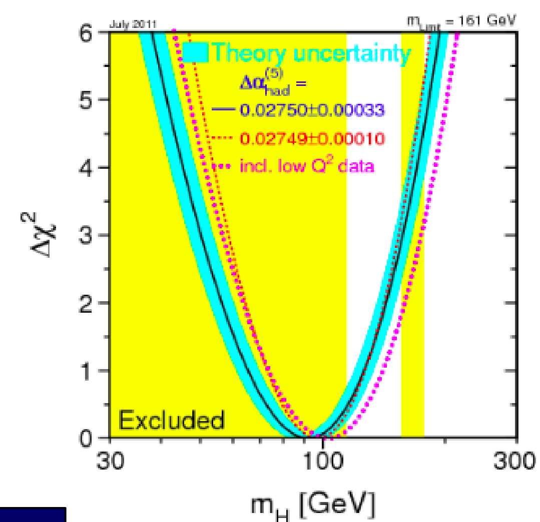
NEW! Ki dènye nouvèl sou JIYÈ 2011:

Konbinezon sa yo ki soti LEPEWWG a yo te itilize yo fè tès sevè ki gen konpòtman egzanplè an Creole nan fizik patikil lè w konpare rezilta yo egzak ak prediksyon teyori. Konklizyon a se ke an ki gen konpòtman egzanplè Minim Creole se kapab dekri prèske tout mezi pou LEP ki olye byen; pa gen okenn bezwen impérieux pou entwodwi nouvo fenomèn pase sa yo te prevwa nan ki gen konpòtman egzanplè an Creole. Anplis de sa, exploiter relasyon teyori, rezilta yo eksperimantal pèmèt nou, pami lòt bagay, nou ka prevwa mas patikil yo lou fondamantal, tankou tèt kark la ak bozon a W, ki fè yo Lè sa a, konpare ak mezi yo dirèk. Sa a chèk Correct nan prediksyon la e konsa nan teyori a nan zòn sa a. Tablo a ba sou bò gòch la montre sa a konparezon pou mas la nan W bozon la: pati nan tèt yo a montre mezi dirèk, pati anba a montre kontrent yo endirèk ki valab nan ki gen konpòtman egzanplè a Minim Creole.
Apa yo montre se mezi ki soti nan NuTeV kolaborasyon a, ki dènyèman te pibliye rezilta final li sou rapò a kounye a net chaje reyaksyon aktyèl nan Neutrino-nukleon simen. Sa a mezi, lè entèprete kòm yon mezi pou mas la nan W bozon a, montre yon devyasyon enteresan, nan nivo a 2.6 2.8 devyasyon estanda, ki soti nan kontrent yo lòt endirèk.

Nan enterè patikilye se contrainte an sou mas la nan HIGGS bozon a, paske sa a engredyan fondamantal nan ki gen konpòtman egzanplè an Creole pa te obsève ankò. Figi a sou bò gòch la montre koub la Delta-chi2 sòti nan wo-Q2 mezi electroweak presizyon, fèt nan LEP ak pa SLD, CDF, ak D0, menm jan yon fonksyon nan mas la HIGGS-bozon, an konsideran ki gen konpòtman egzanplè an Creole yo dwe repons ki kòrèk la teyori nan lanati. Valè a pi pito pou mas li yo,, ki koresponn a minimòm la yo nan koub la se nan 92 GeV, ak yon ensètitid eksperimantal ki fèt sou+34 ak -26 GeV (nan 68 pousan nivo konfyans sòti nan Delta chi2 = 1 pou liy an nwa, kidonk pa pran ensèten a teyorik yo montre a tankou gwoup la ble nan kont). Sa a se rezilta sèlman ti kras ki afekte nan rezilta yo ba-Q2 tankou mezi a NuTeV diskite pi wo.
Pandan ke sa a se pa yon prèv ke Creole-ki gen konpòtman egzanplè HIGGS bozon a aktyèlman ki egziste, li sèvi kòm yon gid nan sa ki ranje mas yo gade pou li. Mezi yo electroweak presizyon di nou ke mas la nan Creole-ki gen konpòtman egzanplè HIGGS bozon a se pi ba pase sou 161 GeV (yon sèl-sided 95 pousan nivo konfyans anwo limite sòti nan Delta chi2 = 2.7 pou gwoup la ble, konsa gen ladan tou de eksperimantal la a ak teyorik ensèten). Limit sa a ap ogmante a 185 GeV lè limit la ki gen ladan rechèch LEP-2 dirèk de 114 GeV yo montre nan jòn (gade anba a).

Tevatron eksperyans CDF a ak DIII tou rechèch pou Creole-ki gen konpòtman egzanplè HIGGS bozon a; ki pi resan rezilta a konbine (jiyè 2011) eksepte ranje a mas a 156 GeV 177 GeV nan 95% CL.





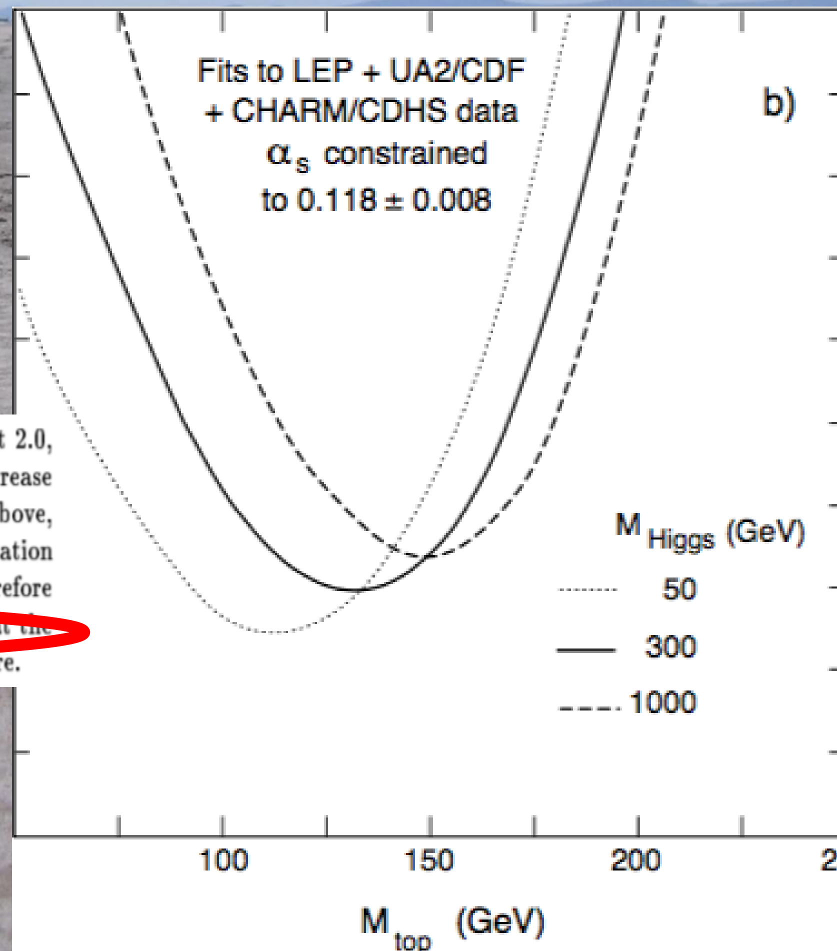
Translation into Haïtian creole

1991

	α_s unconstrained	α_s constrained	α_s unconstrained + Collider and ν data	α_s constrained + Collider and ν data
M_t (GeV)	$94^{+53}_{-...}\,^{+23}_{-24}$	$124^{+40}_{-56}\,^{+21}_{-21}$	$124^{+28}_{-31}\,^{+16}_{-18}$	$132^{+27}_{-31}\,^{+18}_{-19}$
α_s	$0.141 \pm 0.017 \pm 0.002$	0.123 ± 0.007	0.138 ± 0.015	0.123 ± 0.007
χ^2/ d.o.f.	0.3/2	2.2/3	1.5/5	3.0/6
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	-	$0.2337 \pm 0.0014\,^{+0.0001}_{-0.0004}$	$0.2337 \pm 0.0010\,^{+0.0003}_{-0.0004}$	$0.2335 \pm 0.0009\,^{+0.0001}_{-0.0004}$
$\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$	-	$0.2299^{+0.0067}_{-0.0048}$	0.2299 ± 0.0033	0.2290 ± 0.0033
M_W (GeV)	-	$80.01^{+0.27}_{-0.37}$	80.01 ± 0.19	80.06 ± 0.19

LEP Electroweak Working Group

At present, the increase in χ^2 when M_H is changed between the two extreme values is about 2.0, which does not allow the derivation of any meaningful constraints on M_H. In addition, an increase of 1.4 out of 2.0 is traced back to the contribution of the $\Gamma_{b\bar{b}}/\Gamma_{had}$ measurement. As stated above, the measurement of $\Gamma_{b\bar{b}}/\Gamma_{had}$ 'artificially' constrains M_t. The rest of the data give a determination of M_t which is strongly correlated with the assumed value of M_H used as input to the fit. Therefore the inclusion of the $\Gamma_{b\bar{b}}/\Gamma_{had}$ measurement also artificially constrains M_H. Our conclusion is that the present increase in χ^2 with M_H is artificial and hence its interpretation has to be taken with care.

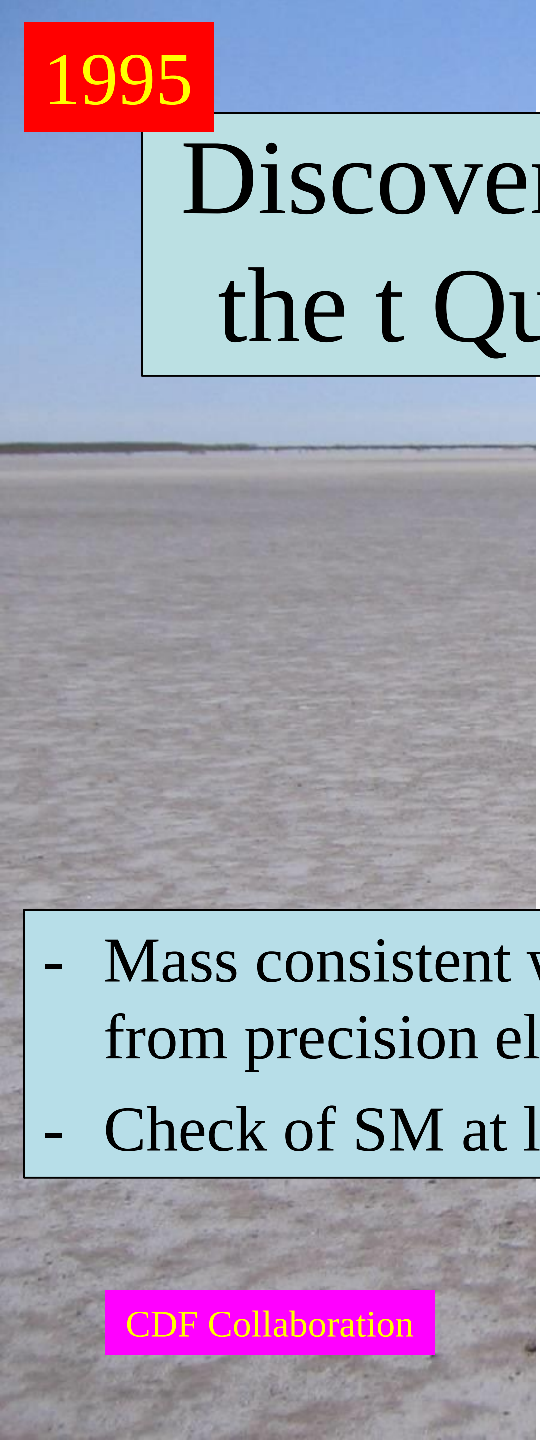


1993

$$m_t = 164\,^{+16}_{-17}\,^{+19}_{-21}\ \text{GeV}$$

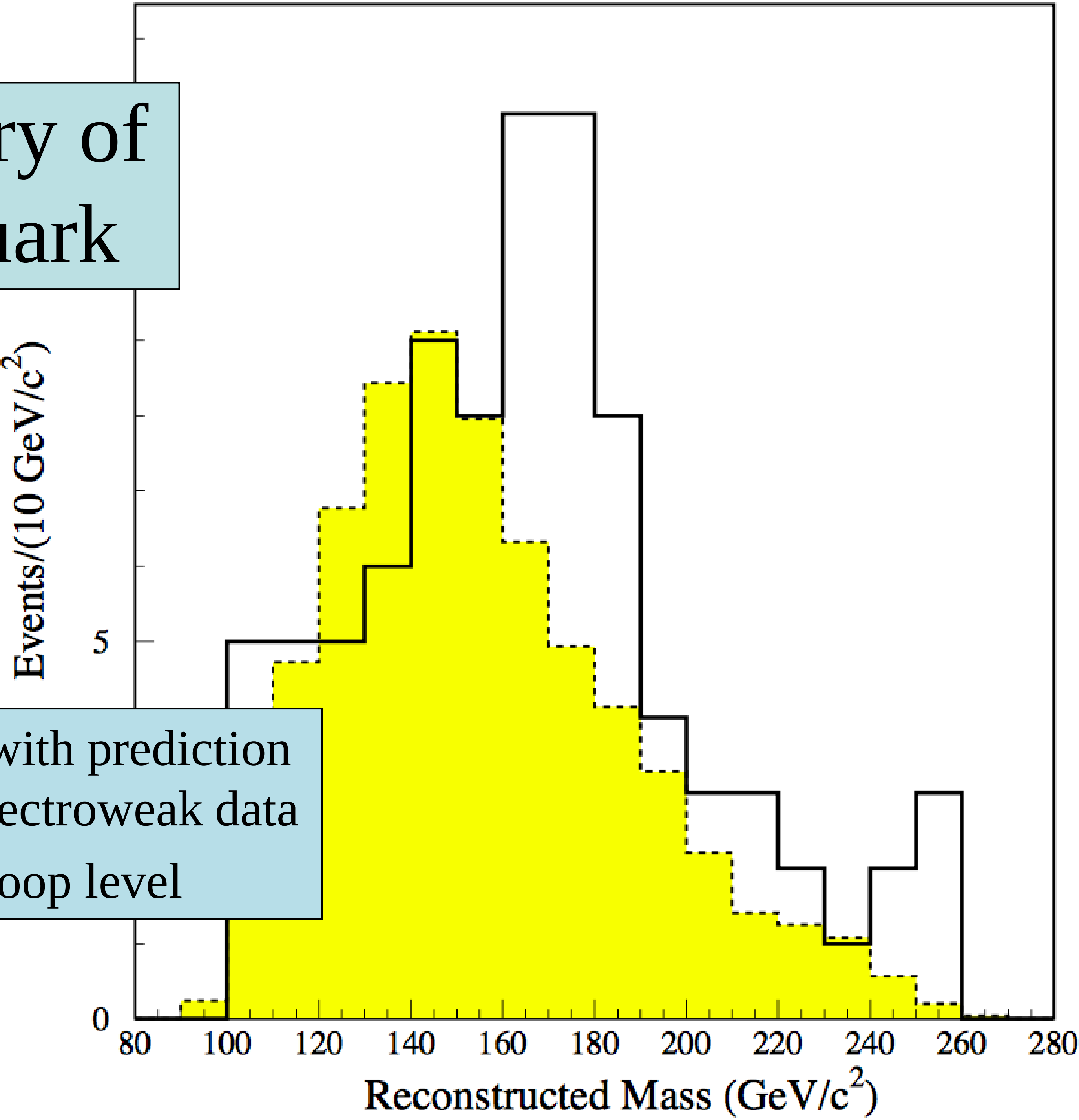
1994

$$m_t = 174 \pm 10\,^{+13}_{-14}\ \text{GeV}$$



1995

Discovery of the t Quark



- Mass consistent with prediction from precision electroweak data
- Check of SM at loop level

CDF Collaboration

Nobel Prize 1999

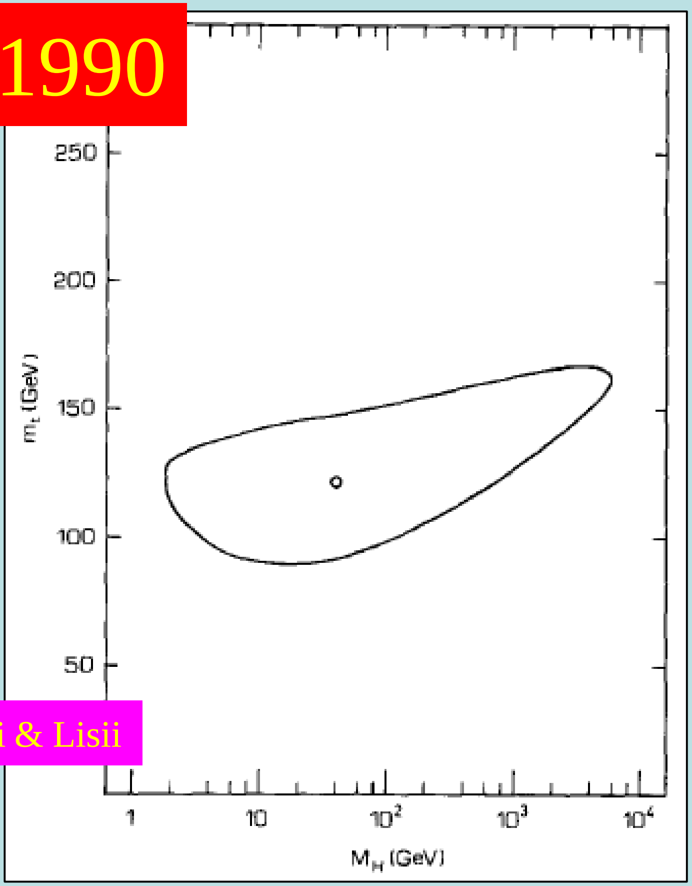
“The Theory’s Predictions Verified”

- “… it was only through ‘t Hooft’s and Veltman’s work that more precise prediction of physical quantities involving properties of W and Z could start. **Large quantities of W and Z have recently been produced under controlled conditions at the LEP accelerator at CERN.** Comparisons between measurements and calculations have all the time showed great agreement, thus supporting the theory’s predictions.”
- “One particular quantity obtained with ‘t Hooft’s and Veltman’s calculation method **based on CERN results is the mass of the *top quark***, the heavier of the two quarks included in the third family in the model. **This quark was observed directly for the first time in 1995 at the Fermilab in the USA, but its mass had been predicted several years earlier.** Here too, agreement between experiment and theory was satisfactory.”
- **“When can we expect the next great discovery?”**

Estimating the Higgs mass

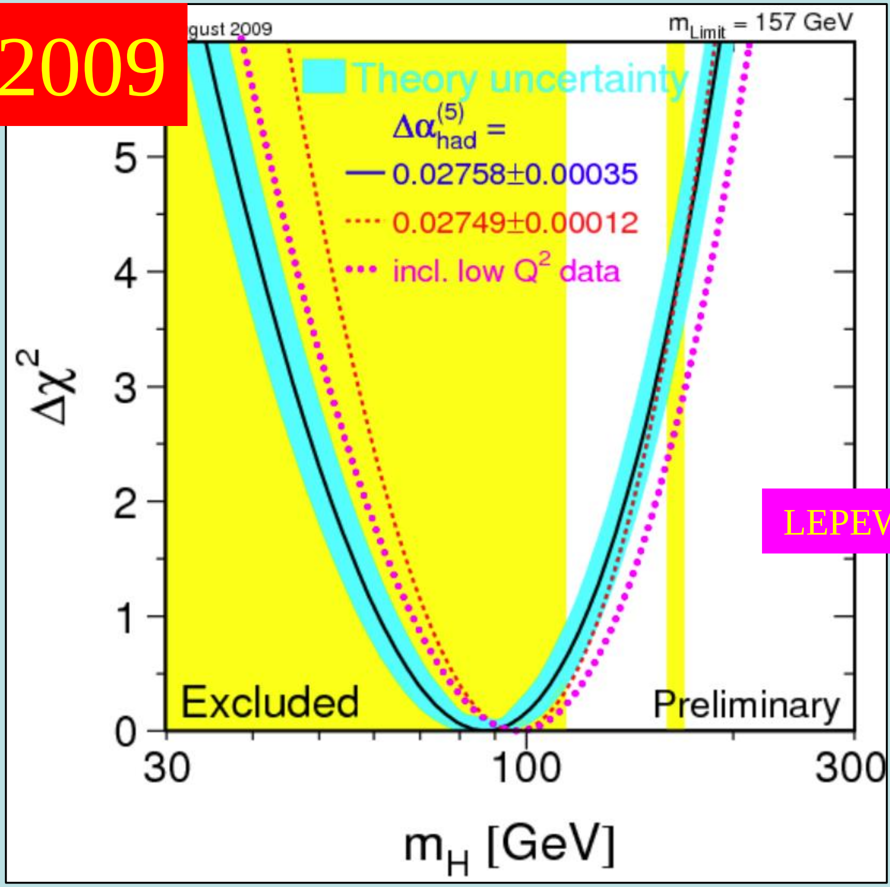
- From early attempts **to the blue band plot**

1990



JE, Fogli & Lisii

2009

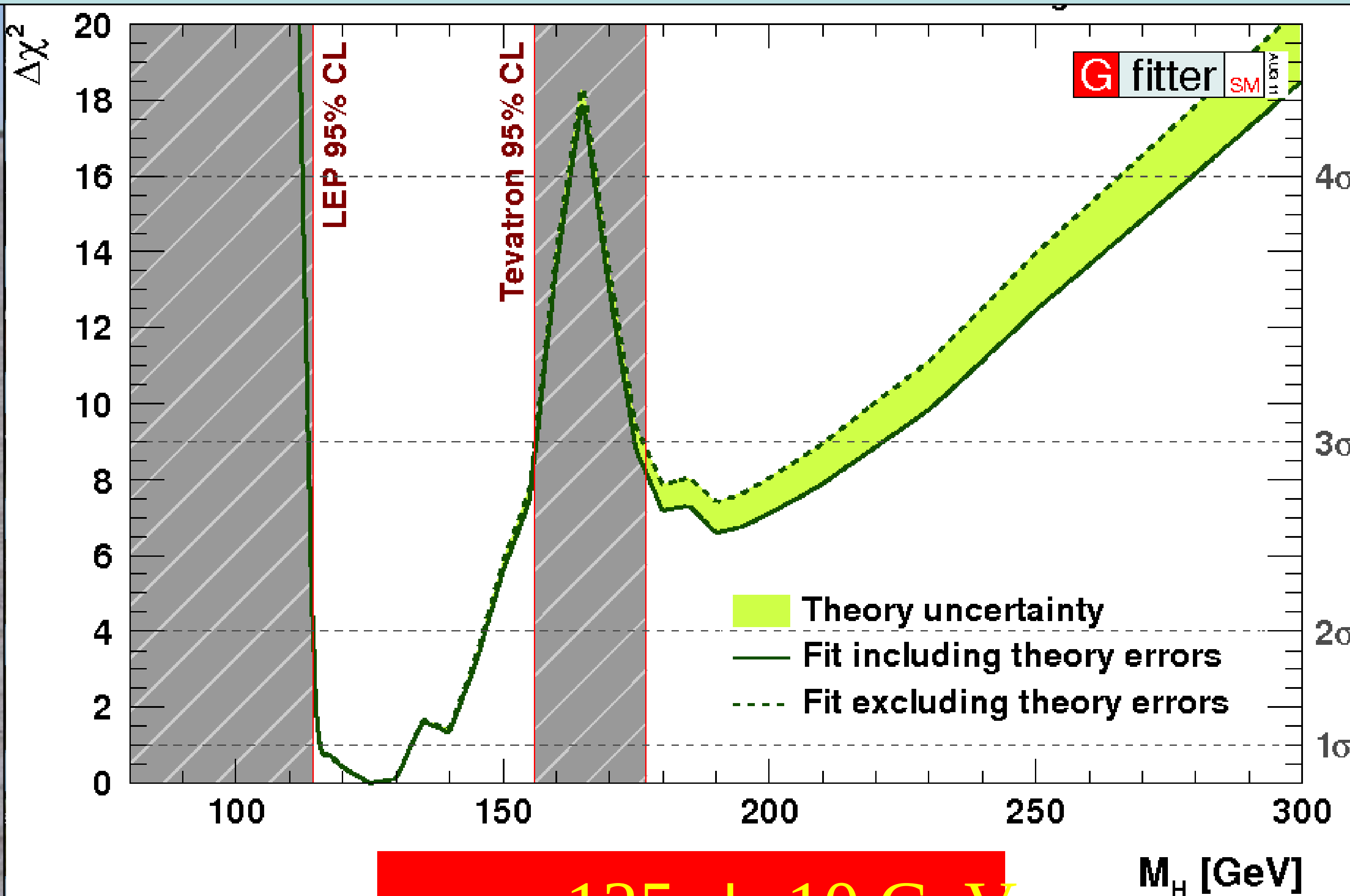


LEPEWWG

- Difficult before the discovery of the top quark

2011

Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

Gfitter collaboration

Standard Model as an Effective Field Theory

- Supplement Standard Model with higher-dimensional interactions generated by new physics at scale Λ

Buchmueller & Wyler, 1986

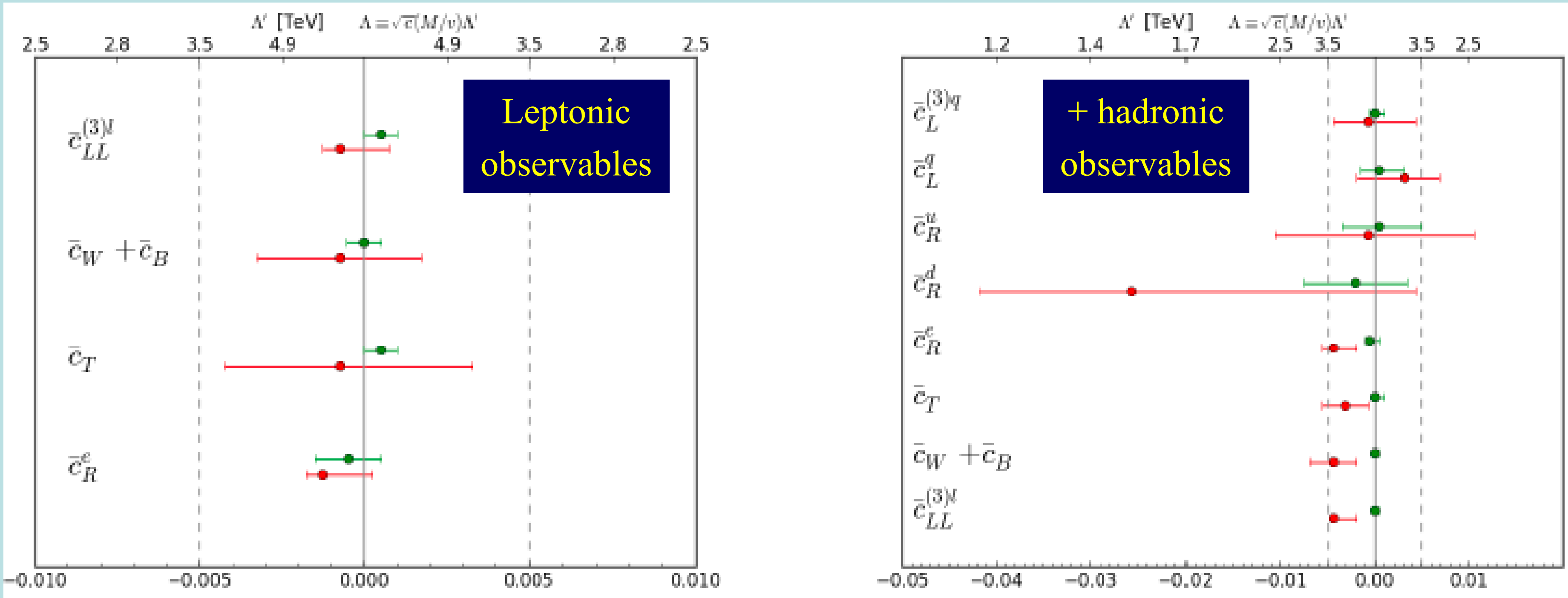
- Leading dimension-6 operators:

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$$

- Use data to constrain operator coefficients
- Look for indirect effects of physics beyond the Standard Model

Previous Fit to Electroweak Precision Data

- Constraints from LEP et al. data

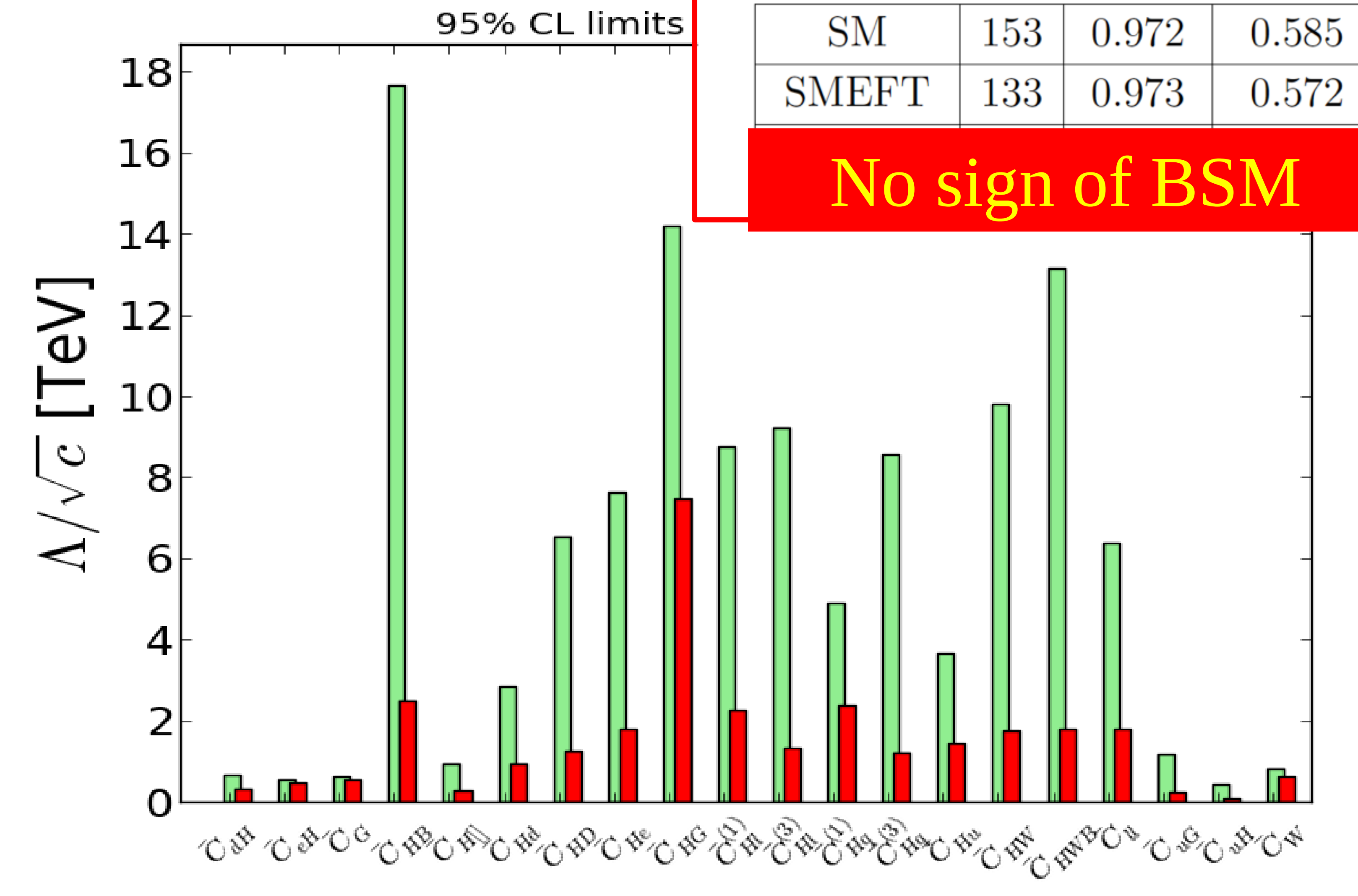


- **Fits to individual dimension-6 operators**
- **Global fit to all operators together**
- **New physics > TeV scale?**

JE, Sanz & Tevong You, arXiv:1410.7703

JE, Murphy, Sanz & You, arXiv:1803.03252

Using all LEP & LHC Data

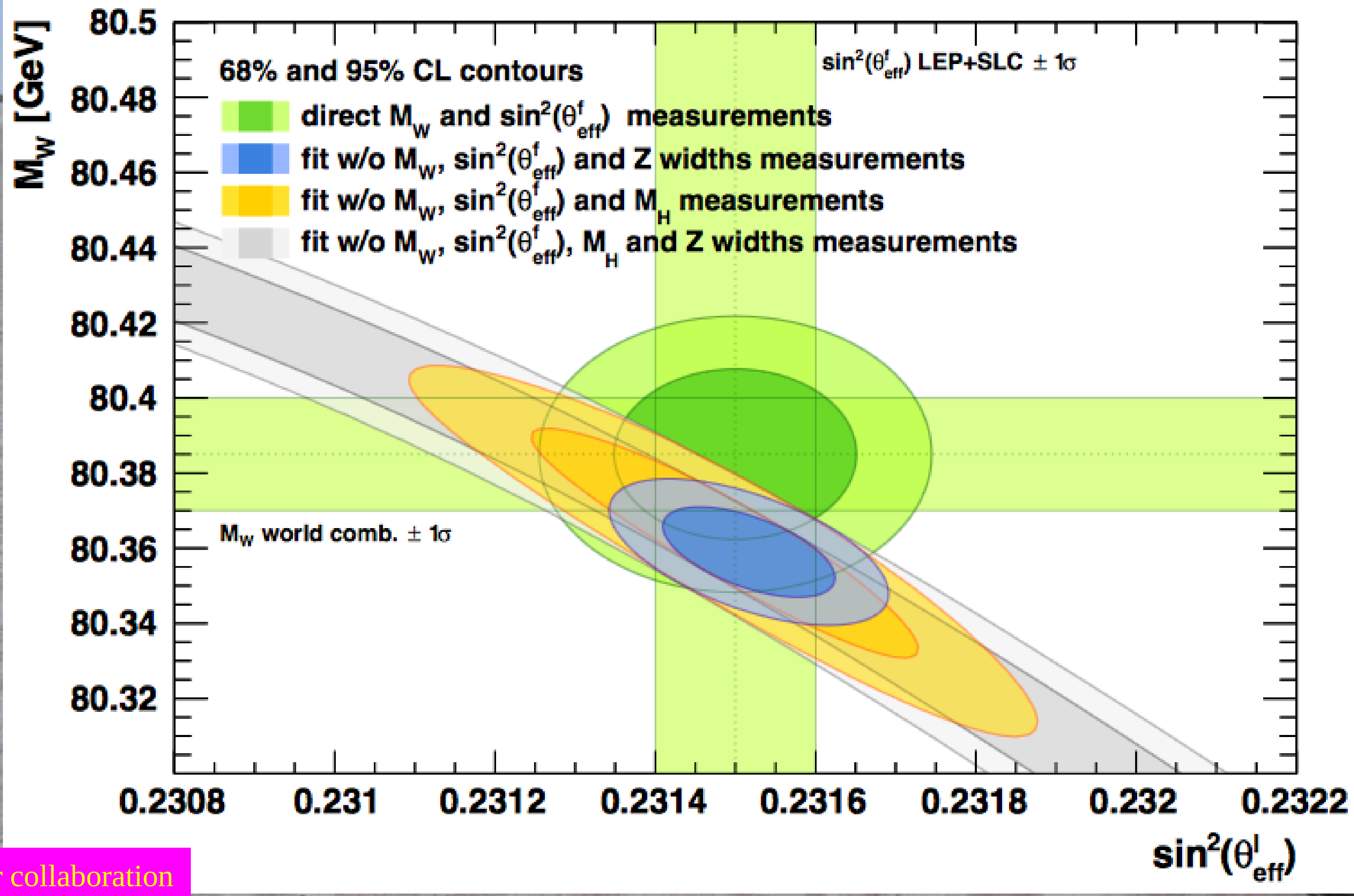


Theory	χ^2	$\chi^2/n_{\rm d}$	p-value
SM	153	0.972	0.585
SMEFT	133	0.973	0.572

No sign of BSM

2014

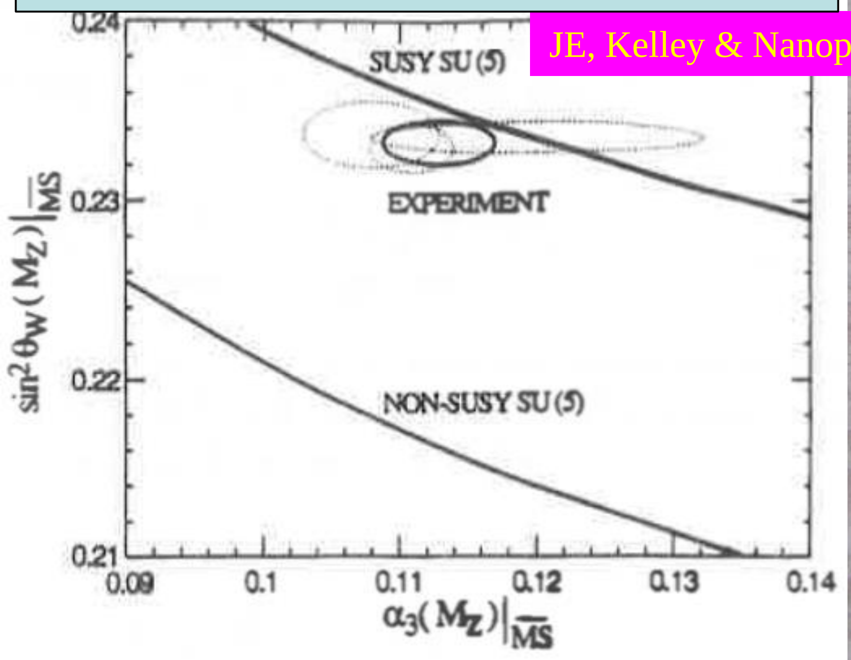
Measurement of $\sin^2\theta_W$



Gfitter collaboration

1991 Circumstantial Evidence for Supersymmetric Grand Unification

"The precision of $\sin^2\theta_w(m_z)$ extracted from LEP data (0.233±0.001) confirms the prediction of minimal supersymmetric GUTs (0.235±0.004) within the errors of about 2%"



JE, Kelley & Nanopoulos

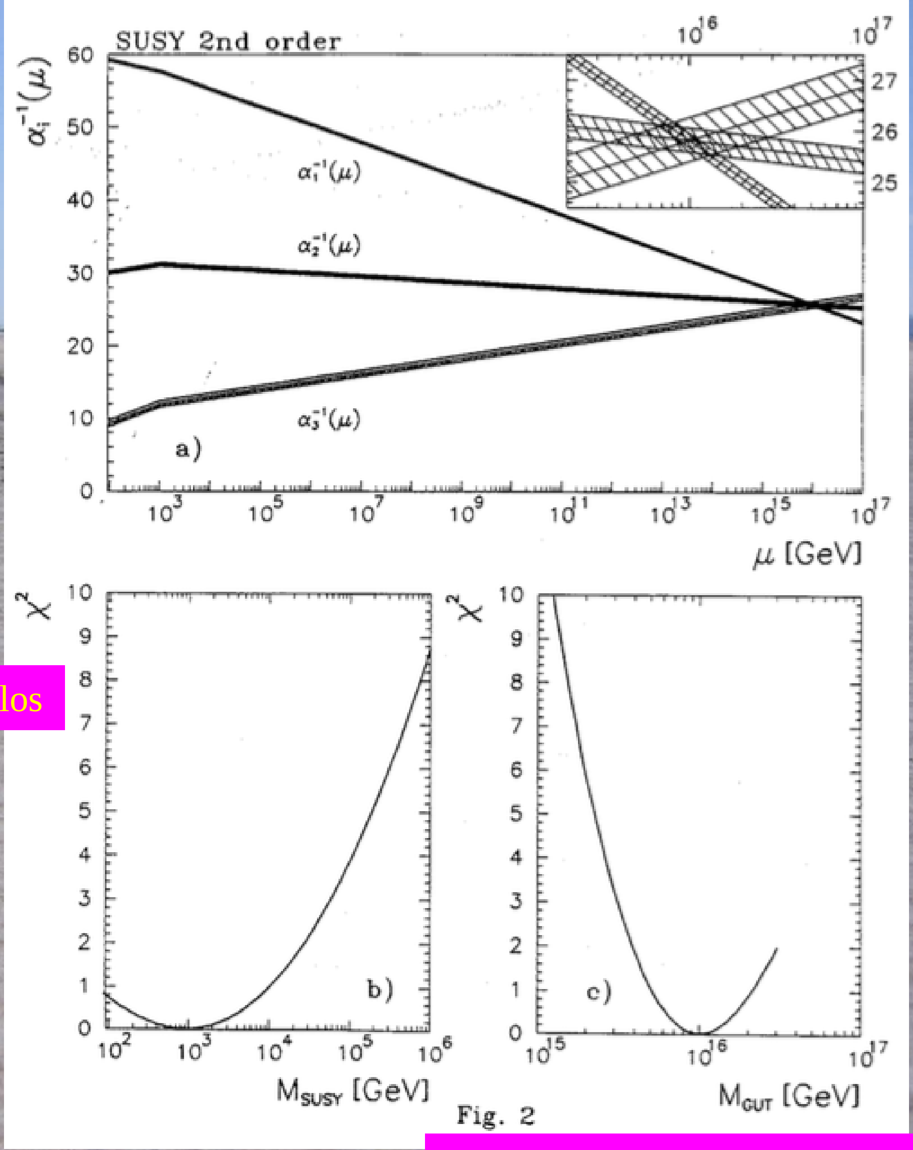
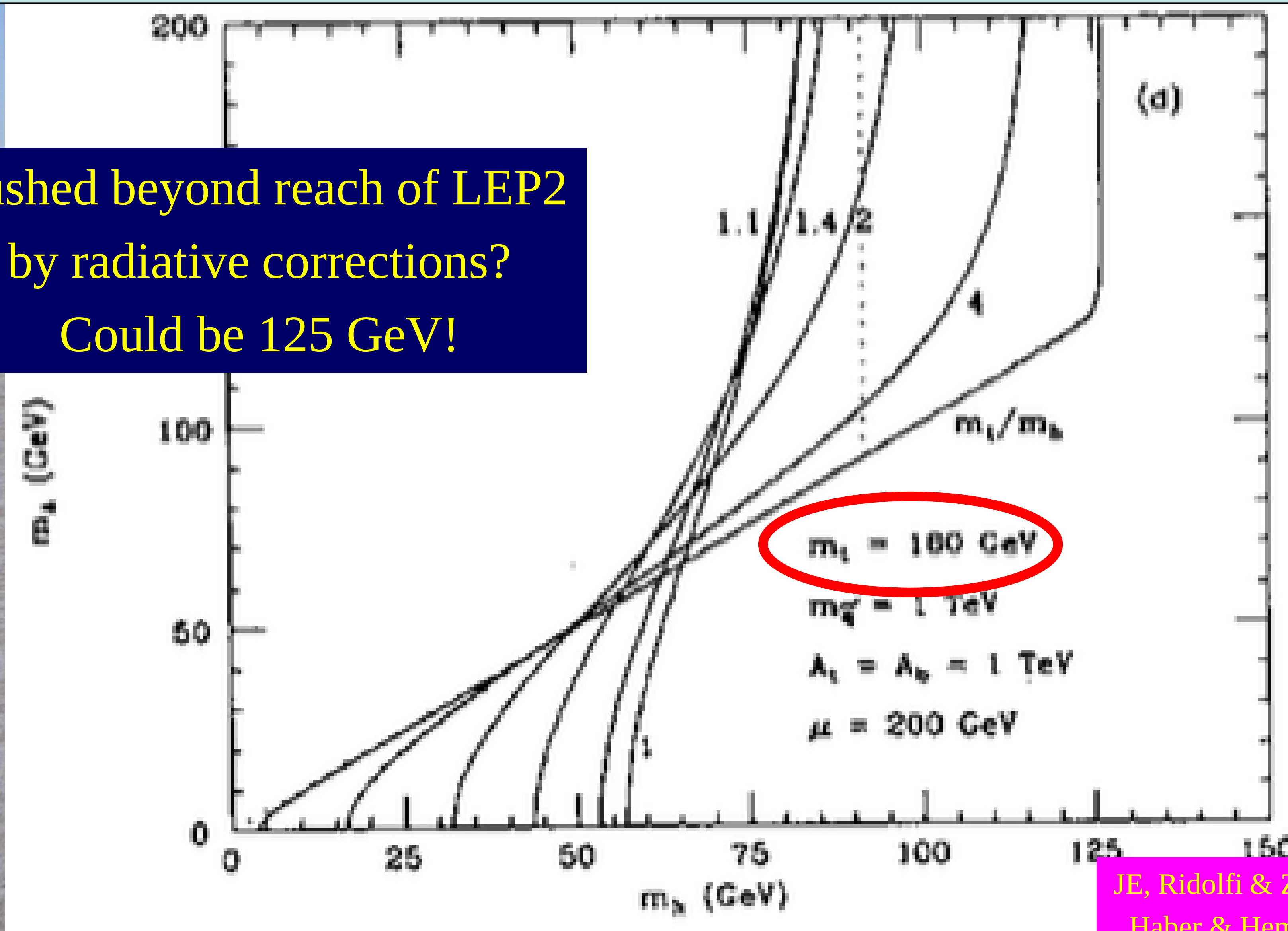


Fig. 2

Amaldi, de Boer & Furstenau

1990/1

Higgs Mass in Supersymmetry



Pushed beyond reach of LEP2
by radiative corrections?
Could be 125 GeV!

JE, Ridolfi & Zwirner;
Haber & Hempfling

LEP SUSY Working Group

Joint

LEP 2 **S U S Y**

Working Group

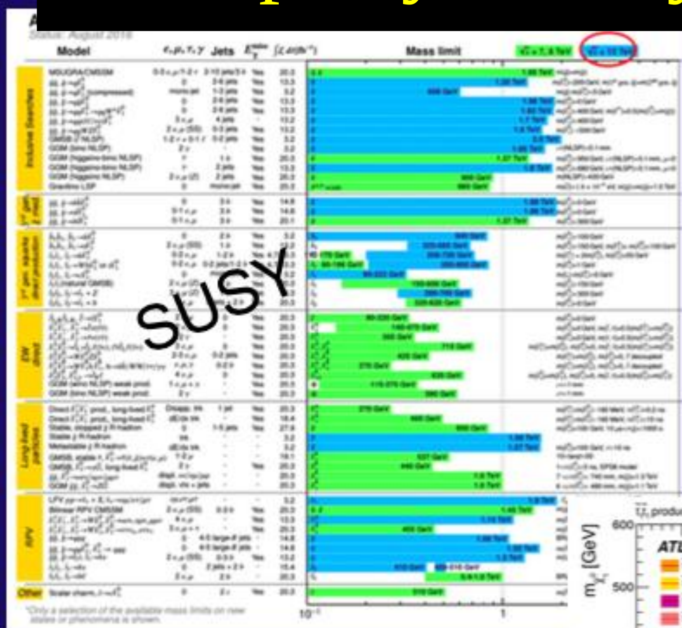
ALEPH, DELPHI, L3, OPAL Experiments

This page provides public information from the LEP2 SUSY Working Group whose purpose is to combine the results obtained by the four LEP experiments, Aleph, Delphi, L3 and Opal in the area of SUSY particle searches at LEP2.
The Web pages are identified by a number defined by the Working Group.
Results should be quoted as :
LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/yy-nn (http://lepsusy.web.cern.ch/lepsusy/Welcome.html).

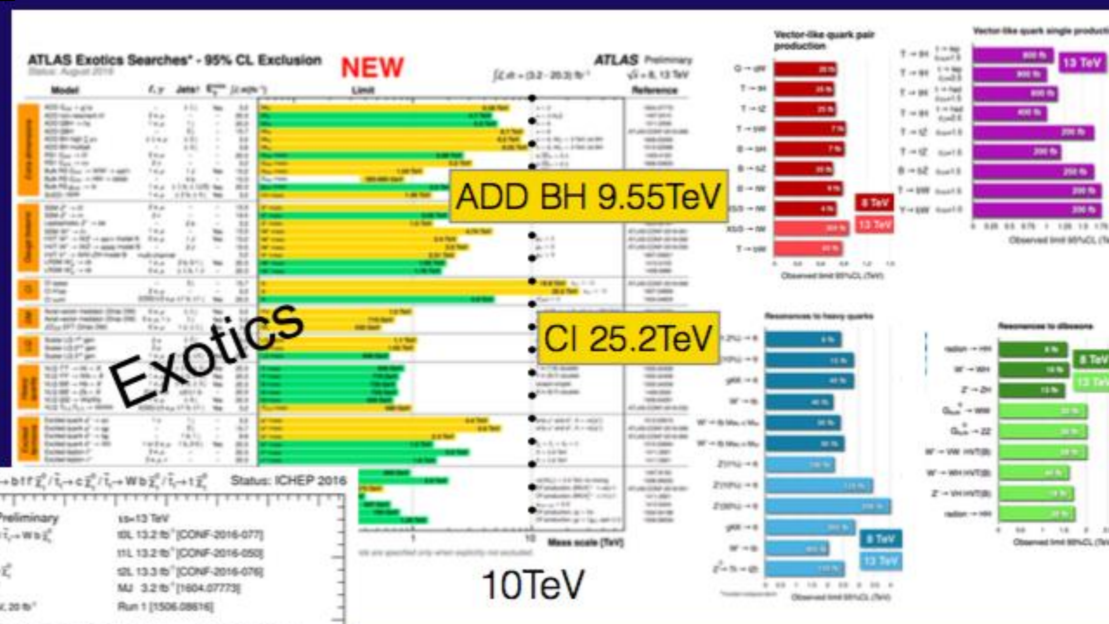
Desperately seeking SUSY

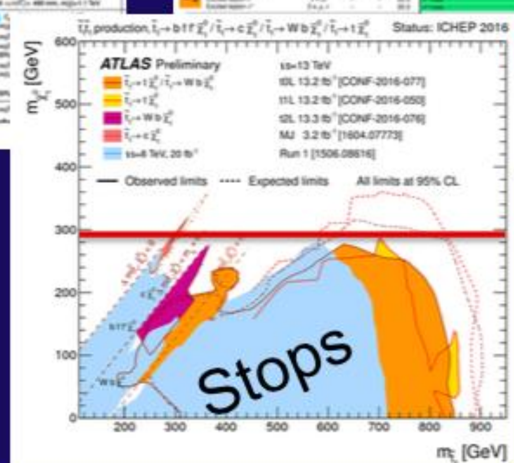
Nothing (yet) at the LHC, either

No supersymmetry



Nothing else





More of same?
Unexplored nooks?
Novel signatures?

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**


We still believe in supersymmetry
You must be joking

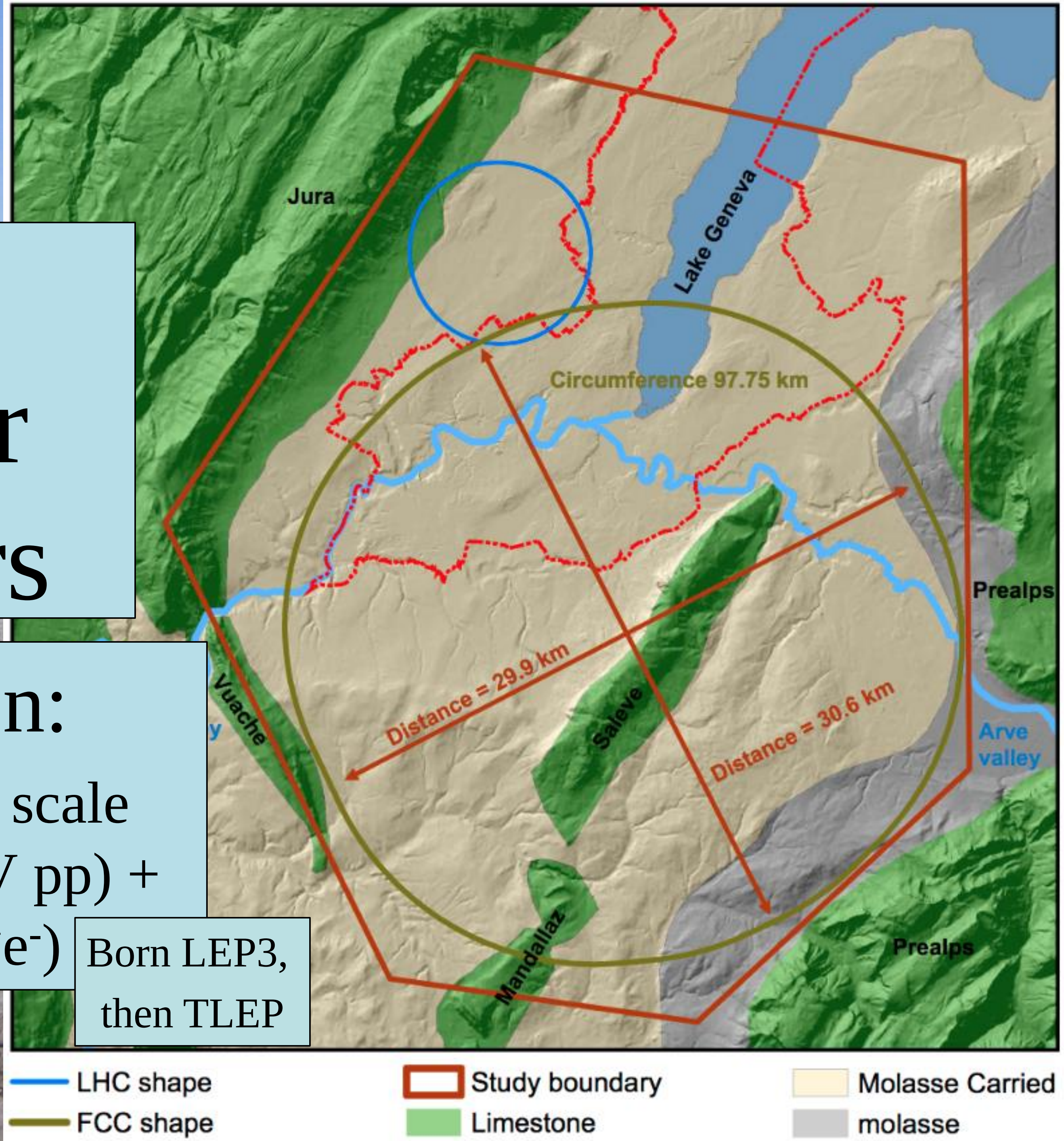
FCC
hh ee he

Future Circular Colliders

The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

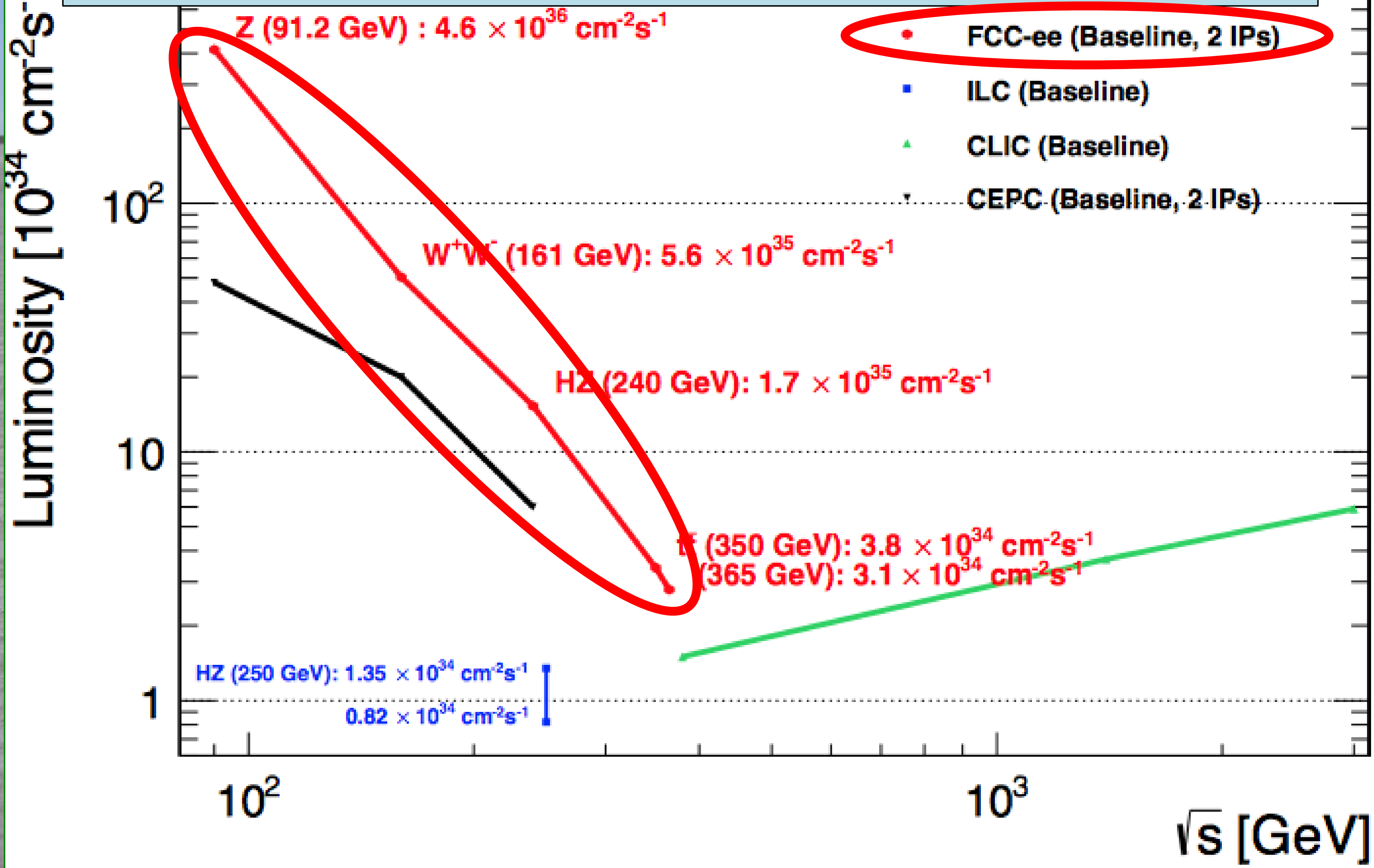
Born LEP3, then TLEP



CEPC-SPPC

Preliminary Conceptual Design Report

Projected e^+e^- Colliders: Luminosity vs Energy



Precision Electroweak Measurements

Present and future EWPO errors

Blondel et al, arXiv:1809.01830

	$\delta\Gamma_Z$ [MeV]	δR_l [10^{-4}]	δR_b [10^{-5}]	$\delta \sin^2\theta^{l}_{\rm eff}$ [10^{-6}]	$\delta \sin^2\theta^{b}_{\rm eff}$ [10^{-5}]
Present EWPO errors					
EXP1	2.3	250	66	160	1600
TH1	0.5	50	15	45	5
FCC-ee-Z EWPO error estimations					
EXP2	0.1	10	$2 \div 6$	6	70

Comparison of future EWPO errors with TH estimates

FCC-ee-Z EWPO error estimations				
	$\delta\Gamma_Z$ [MeV]	δR_l [10^{-4}]	δR_b [10^{-5}]	$\delta \sin^2\theta^{l}_{\rm eff}$ [10^{-5}]
EXP2 [40]	0.1	10	$2 \div 6$	6
TH1-new	0.4	60	10	45
TH2	0.15	15	5	15
TH3	< 0.07	< 7	< 3	< 7

Where did LEP take us?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},-2/3)$

Top mass

Only 3 generations

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi} \not{D} \psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

Tested < 0.1% at LEP

Indirect evidence

What lies beyond?