LP'09 - Hamburg, 22 August '09

Particle Physics in the LHC Era and beyond

Guido Altarelli
Roma Tre/CERN

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This is not a summary!!
What is it? You will see!

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable, hence highly predictive.
And is well supported by the data.

However, we expect corrections from higher energies

e.g. from the TeV scale (LHC!)
the GUT scale
the Planck scale

But even as a low energy effective theory it is not satisfactory

QCD + the gauge part of the EW theory are fine,
but the Higgs sector is so far only a conjecture

QCD

QCD stands as a very solid building block of the SM

No essential problems of principle in its foundations
Comparison with experiment is excellent

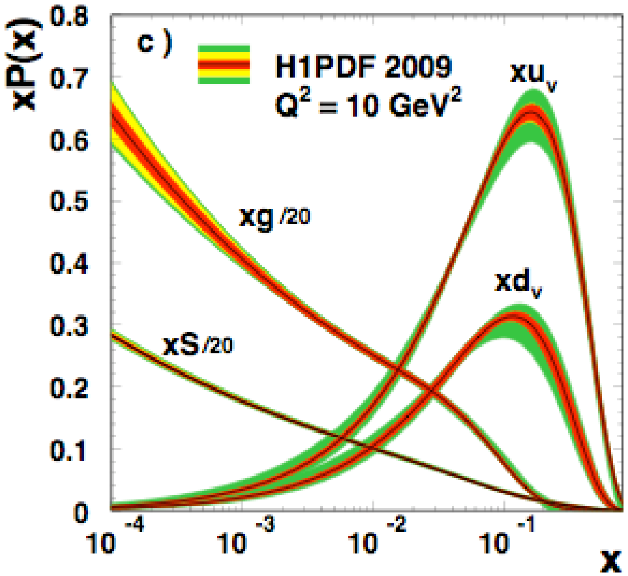
A complex theory and it is difficult to make its content explicit

Marvelous progress in techniques to extract precise predictions (higher order perturbative, resummation, event simulation, non perturbative, lattice.....)

Very important for the LHC preparation: understanding QCD processes is a prerequisite for all possible discoveries

Great experimental work
on testing QCD
over the years

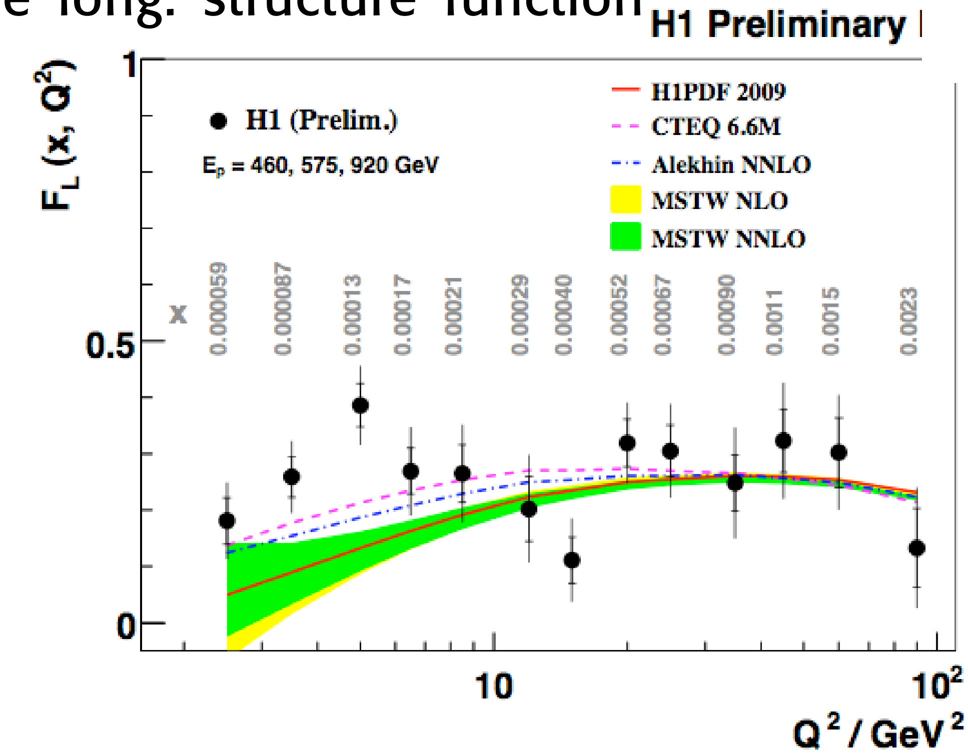
S. Glazov
M. Ruspa

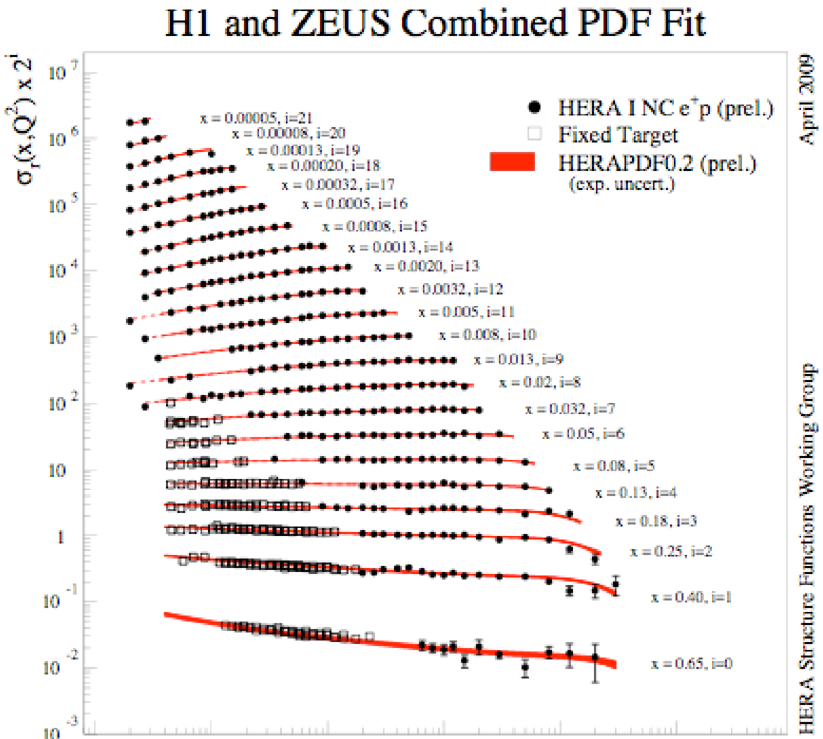


D. Hasch

A tribute to HERA

the long. structure function





the scaling violations

QCD at the Tevatron also great

M. Wobisch

How do we get predictions from QCD?

- Non perturbative methods

•Lattice simulations (great continuous progress)

•Effective lagrangians

* Chiral lagrangians
* Heavy quark effective theories
* SCET
* NRQCD
* AdS/CFT correspondence ••••••

•QCD sum rules

•Potential models (quarkonium)

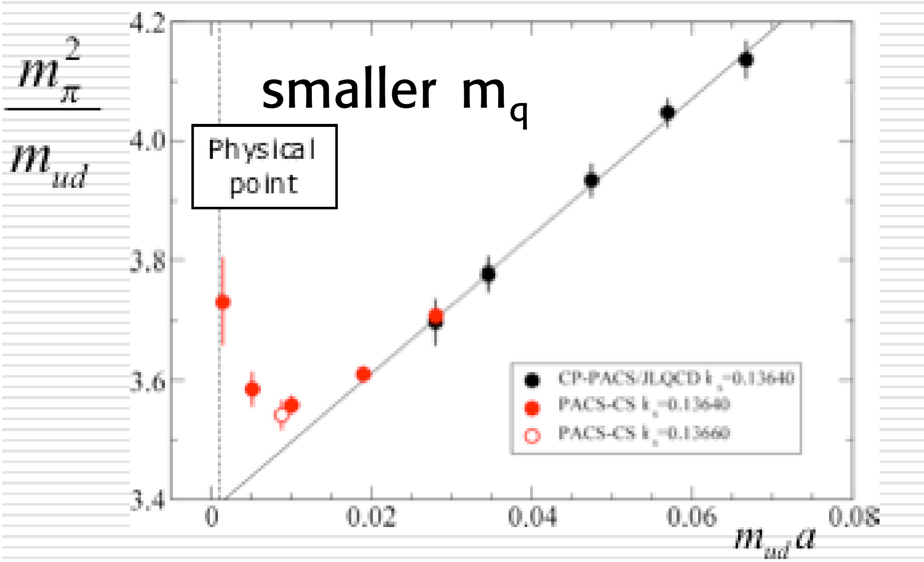
- Perturbative approach

Based on asymptotic freedom.

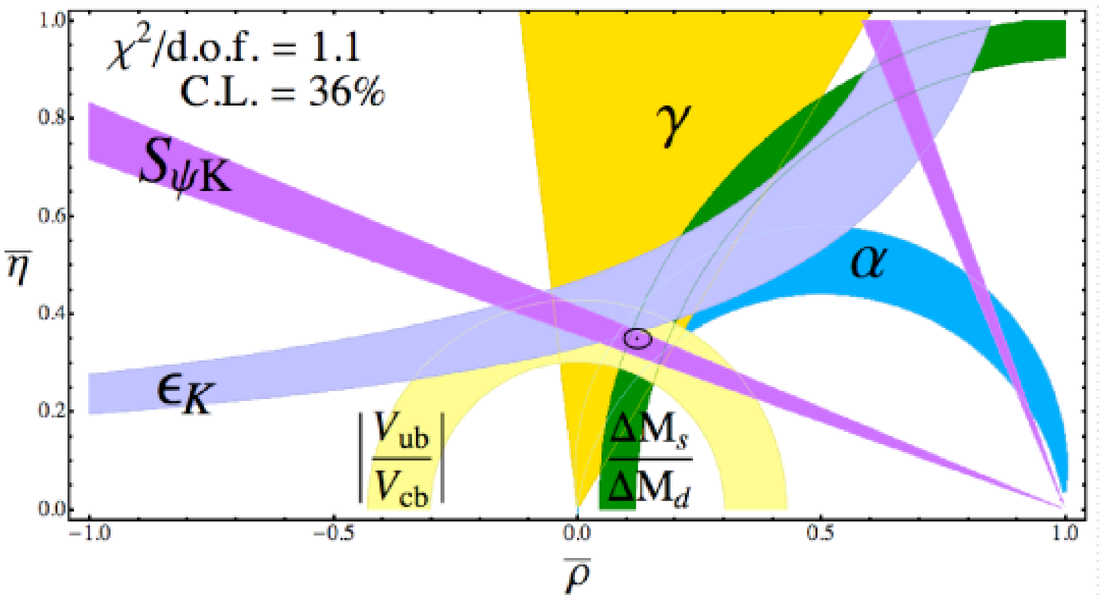
It still remains the main quantitative connection to experiment. Also difficult: α_s relatively large

Great progress in lattice QCD

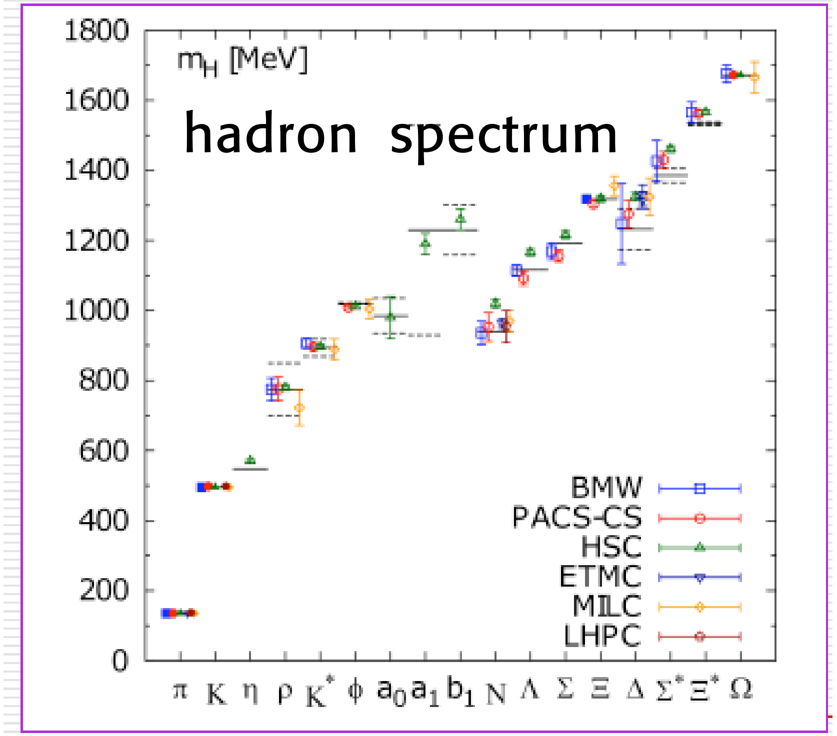
A. Ukawa



flavour physics



From postdiction to prediction



Unquenching

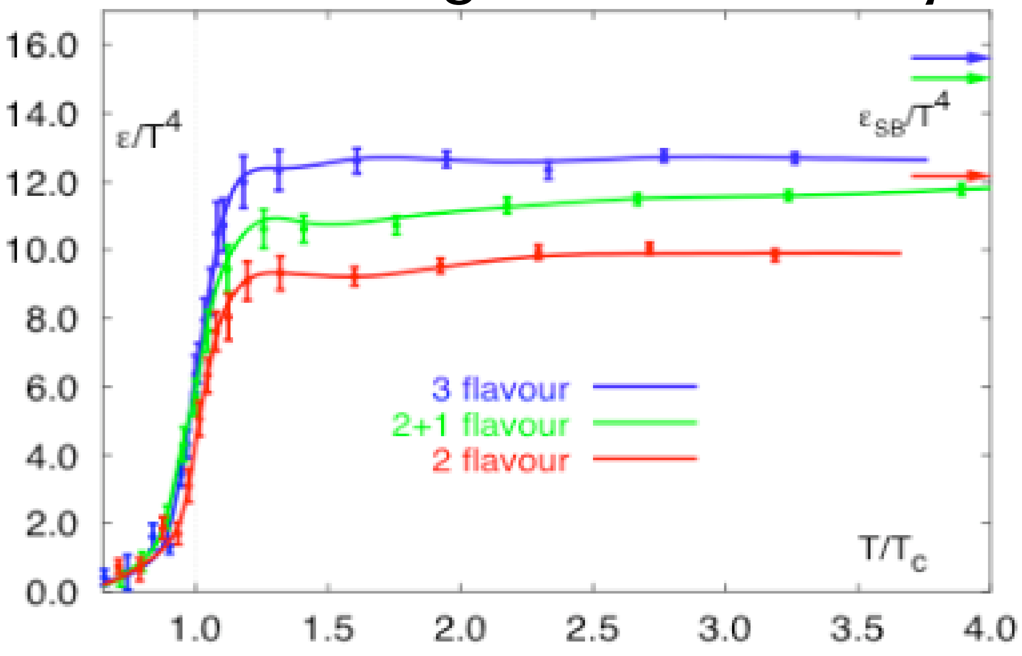
a -> smaller

L -> larger

m_q -> 0

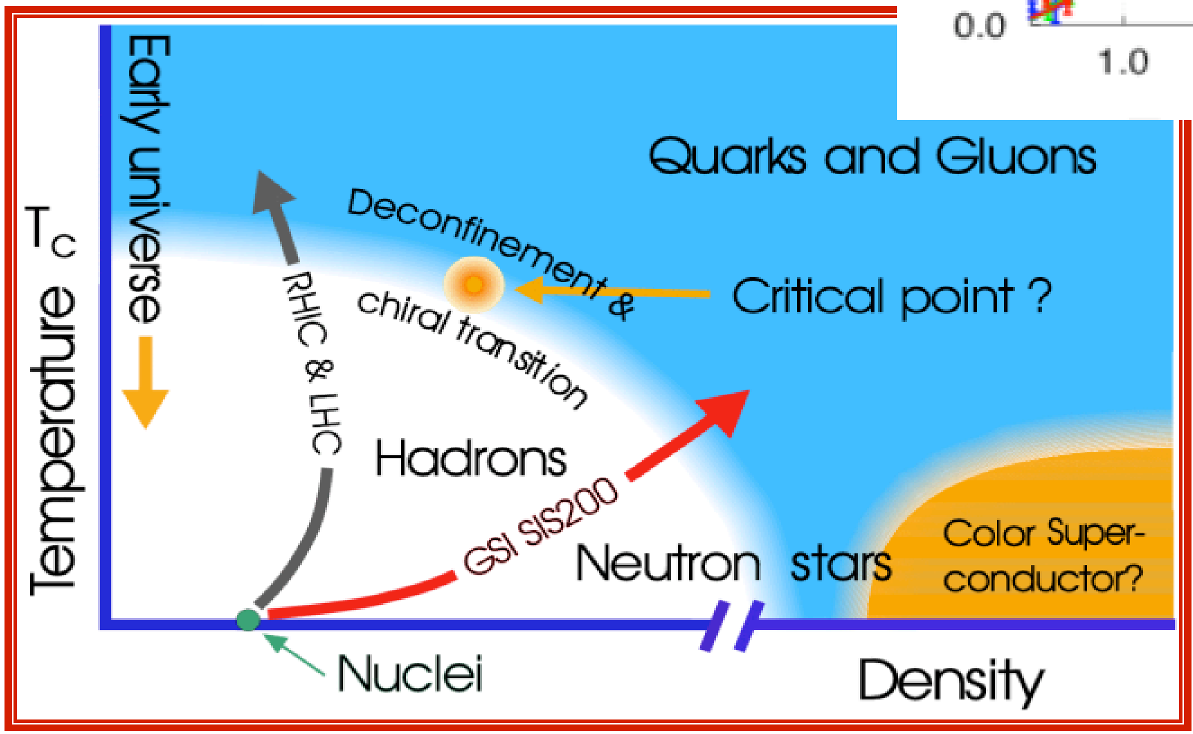
The QCD phase diagram

high T and density



Studied on the lattice and probed by colliding heavy ions at SPS, RHIC, LHC

T. Peitzmann

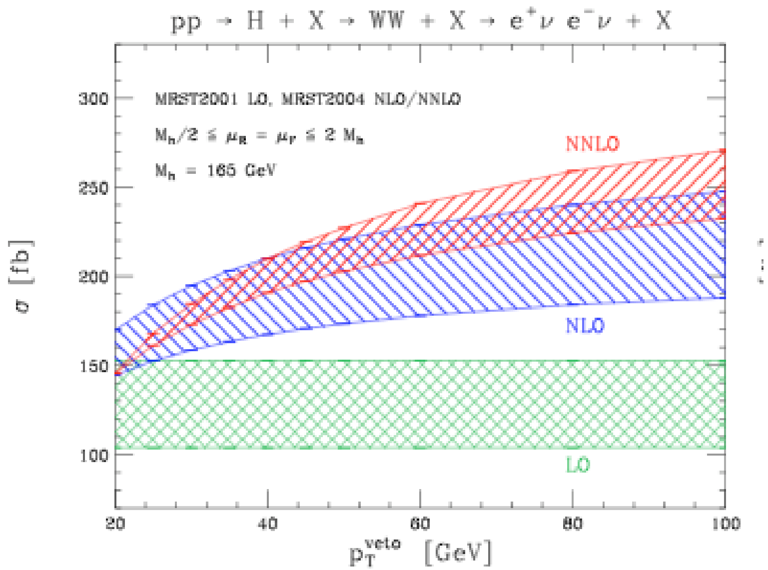


Establishing confinement
Studying deconfinement & chiral restoration
Quark-gluon plasma

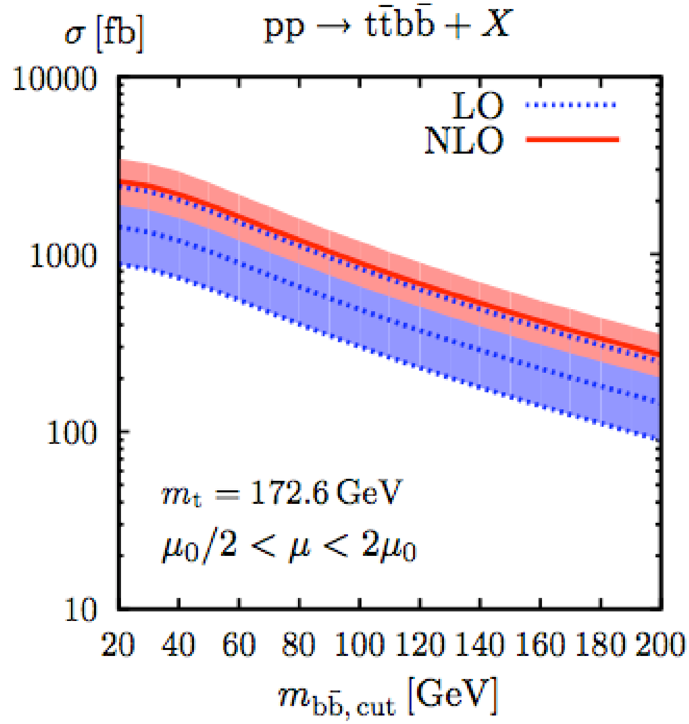
T. Renk

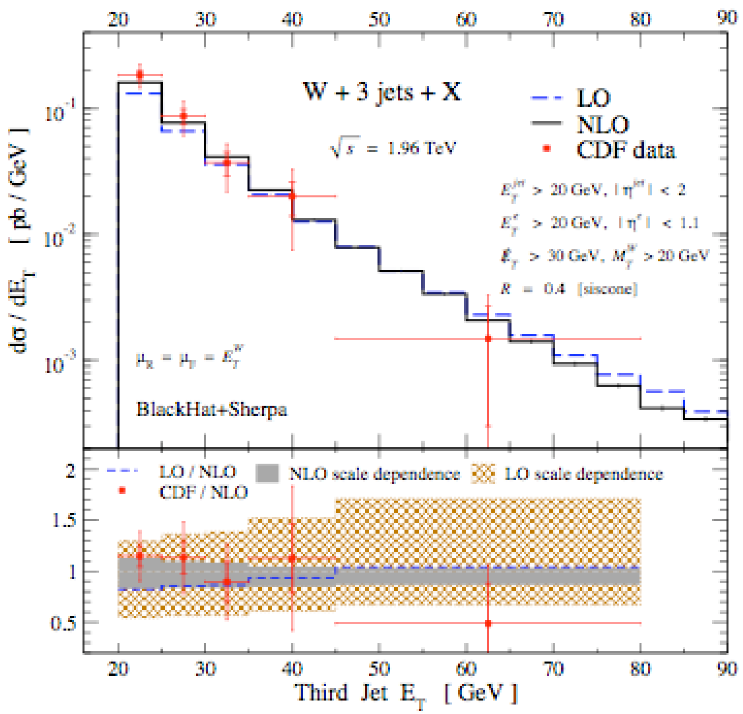
QCD for LHC

N. Glover via G. Weiglein

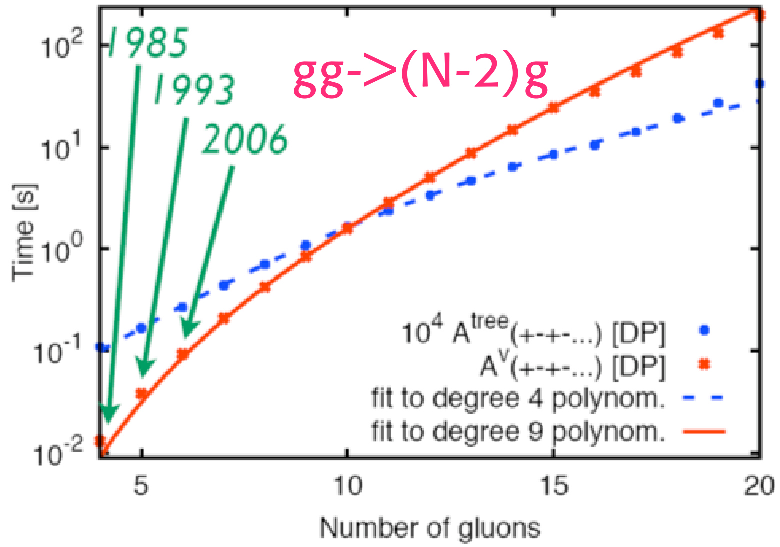


S. Dittmeier





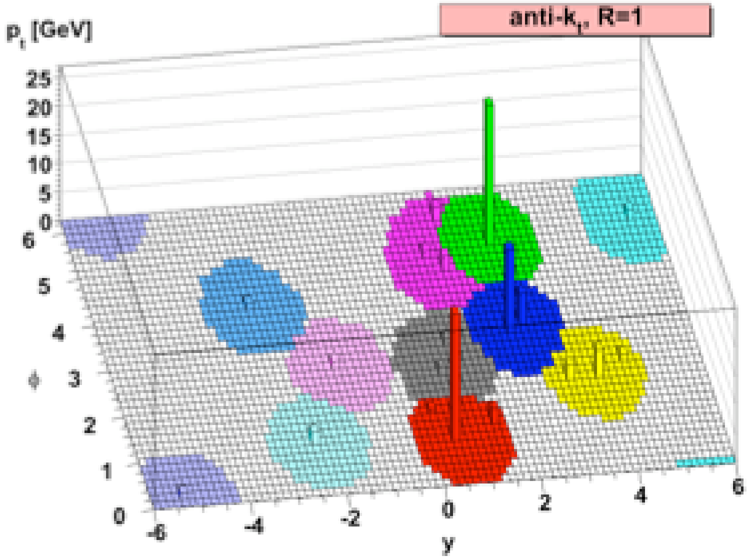
Fantastic technical skill!!

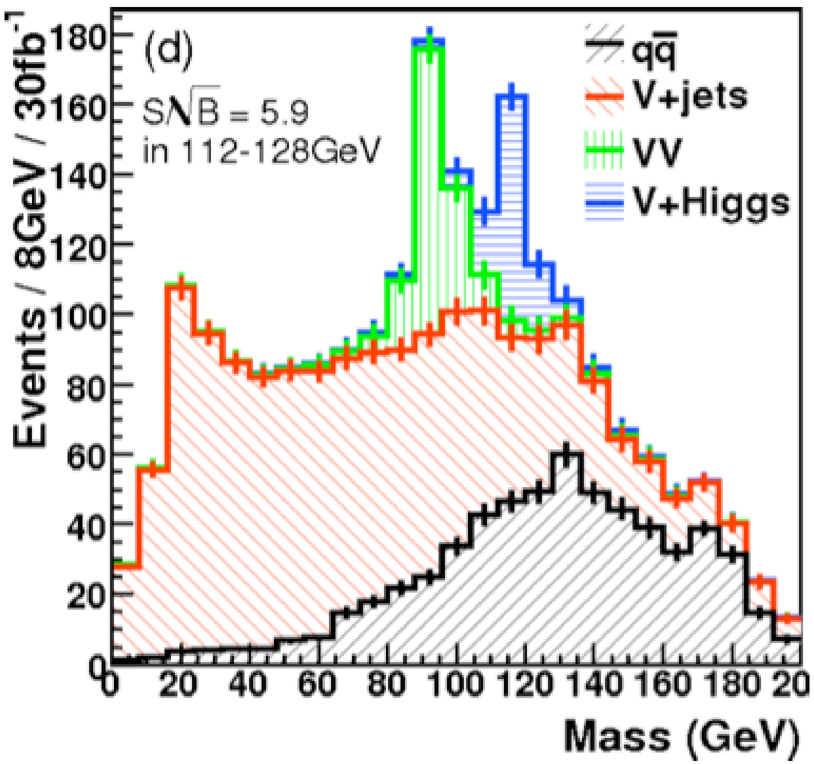


Important work on jet recombination algorithms

G. Salam et al

SISCone, anti-k_T





It is essential that a correct jet finding is implemented by LHC experiments for an optimal matching of theory and experiment

QCD event simulation

A big boost in the preparation to LHC experiments

General algorithms for computer NLO calculations

eg the dipole formalism — Catani, Seymour,.....

the antenna pattern — Kosower....

Matching matrix elements and parton showers

e.g. MC@NLO based on HERWIG — Frixione, Nason, Webber

POWHEG — Nason, Ridolfi

Perturbative (+ resumm.s)

$$d\sigma = A\alpha_S^N [\, 1 + (c_{1,1}L + c_{1,0})\alpha_S + (c_{2,2}L^2 + c_{2,1}L + +c_{2,0})\alpha_S^2 + \ldots \,]$$

L= large log eg L=log(p_T/m)

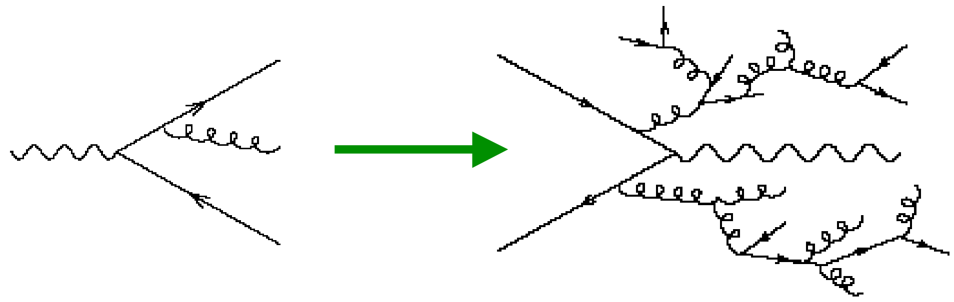
Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

collinear emissions factorize

$$d\sigma_{q\bar{q}g} = d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

$$t = (p_q + p_g)^2 \longrightarrow 0$$



hadronization added

The LHC physics run will soon start, ... hopefully!

After the incident on Sept.19 '08 we must wait till Nov. '09
[LEP was closed at the end of 2000] Start at 3.5 TeV per beam

Top physics priorities at the LHC (ATLAS&CMS):

- Clarify the EW symmetry breaking sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

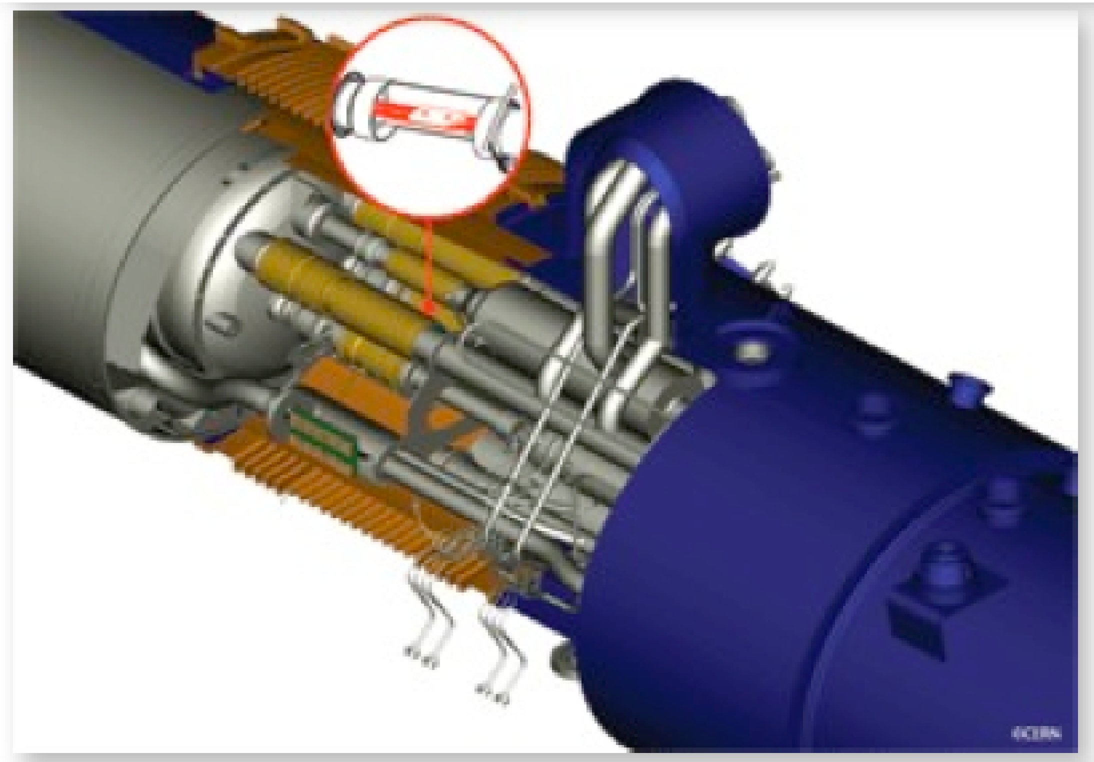
Also:

- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

⊕ At this point, fresh input from experiment is badly needed

H. Burkhardt

The LHC is scheduled to restart in mid November'09. First collisions will be at injection energy and the first high energy physics run at 3.5 TeV beam energy. During 2010 the energy will be increased towards 5 TeV. A run with lead-ions is scheduled towards the end of the run later in 2010.



Aiming at collecting $\sim 200\ pb^{-1}$ of data in the run

The experiments are ready

K. Jon-And
R. Cousins
P. Braun-Munzinger
A. Golutvin

The future of particle physics rests on the LHC

The LHC (with the luminosity upgrade) has the potential to last for 15-20 years (+ LHeC?) ← M. Nessi

Still the LHC cannot be all:

- a worldwide effort in neutrino physics is under way
  T2K, DChooz, RENO, Daya Bay, NOνA, ...
- CKM and CP viol.: NA62....., SuperB factories,... M. Georgi
- "small" experiments of capital importance
  e.g. τ&c, MEG, KATRIN, 0νββ, (g-2), EDM's, Dark Matter,.....
  Y. Wang C. Weinheimer B. Shwartz
- astroparticle: FERMI, PAMELA....., AUGER, ICECUBE, ANTARES...
  M. Mostafa, M. Punch, P-O Hulth.
  LIGO, VIRGO.... F. Fidecaro

The next big step: ILC, CLIC, μ factory..... E. Eisen
⊕ depends on the LHC outcome in the first few years

Status of MEG $\mu^+ \rightarrow e^+ \gamma$

T. Mori

Large neutrino mixing angles + SUSY GUT's make a signal near the present limit plausible

Present limit on Br $1.1\ 10^{-11}$

MEG 2008 $3\ 10^{-11}$

Present MEG sensitivity $1\text{-}2\ 10^{-11}$

Data taking resumes in September

Ultimate sensitivity $10^{-12}\ \text{-}10^{-13}$

The Higgs problem is central in particle physics today

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

Origin of quadratic
divergences.
Hierarchy problem

Possible instability
depending on m_H

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

The Standard EW theory: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W^A_\nu - \partial_\nu W^A_\mu - ig\varepsilon_{ABC} W^A_\mu W^B_\nu]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + g W^A_\mu t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = |[\partial_\mu - ig W^A_\mu t^A - ig' B_\mu \frac{Y}{2}]\phi|^2 +$$

$$+ V[\phi^\dagger\phi] + \bar{\psi}\Gamma\psi\phi + \text{h.c}$$

with $V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{\text{symm}}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{\text{Higgs}}$: ~ untested

All we know from experiment about the SM Higgs:

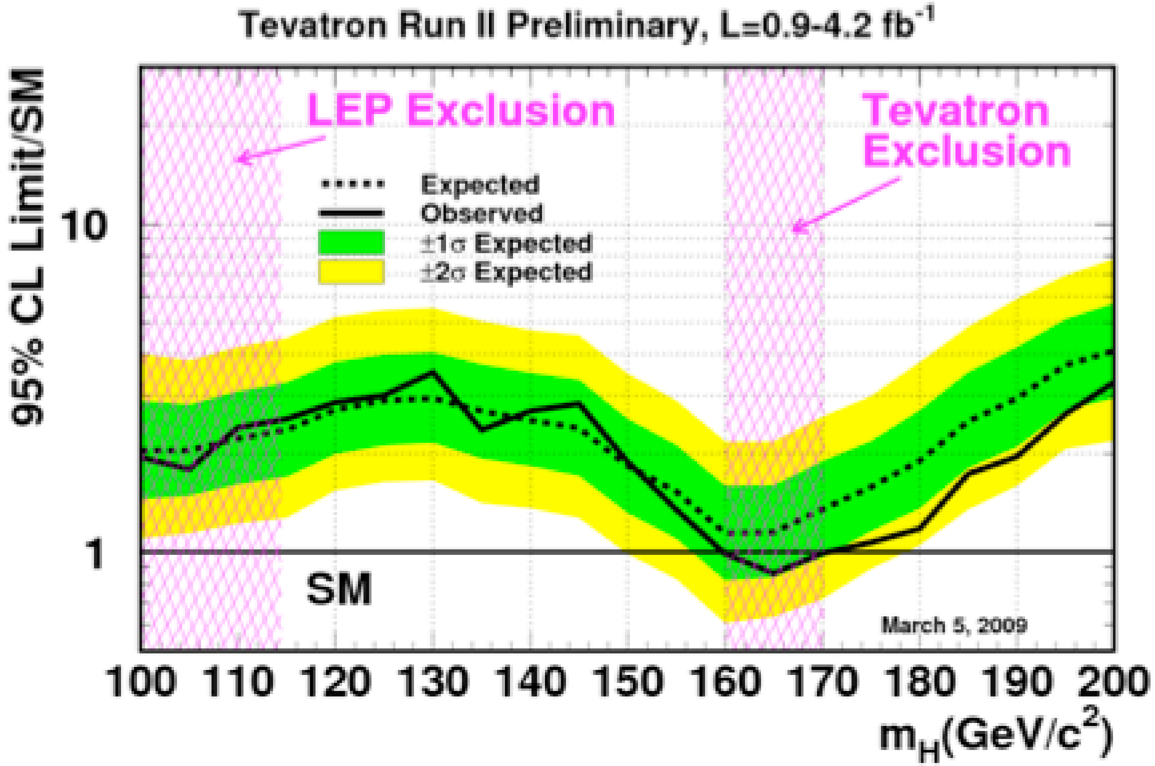
No Higgs seen at LEP2 -> $m_H > 114.4$ GeV (95%cl)

Rad. corr's -> $m_H < 186$ GeV (95%cl, incl. direct search bound)

$v = \langle\phi\rangle = \sim 174$ GeV ; $m_W = m_Z \cos\theta_W$ ⟶ doublet Higgs

In the H search the Tevatron is now reaching the SM sensitivity

G. Bernardi



- The Tevatron experiments are now in position to put constraints on the SM Higgs from direct searches
- **SM Higgs with $160<m_H<170$ GeV excluded at 95% CL**

12 fb^{-1} by '11: could exclude $115 < m_H < 185$ GeV !!!

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

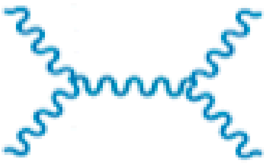
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

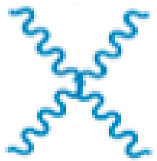
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; …]

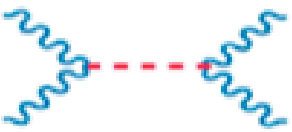
Zwirner

An example: $\mathcal{A}(W_L^+ W_L^- \to Z_L Z_L) \quad (s \gg m_W^2)$





$$i \frac{s}{v^2}$$



$$-i \frac{s^2}{v^2(s - m_h^2)}$$

$$\rightarrow \quad -i \frac{m_h^2}{v^2} \frac{s}{s - m_h^2}$$

If no Higgs then something must happen!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

  W′, Z′
  KK recurrences
  resonances from a strong sector
  ......

C. Grojean
S. Pokorski

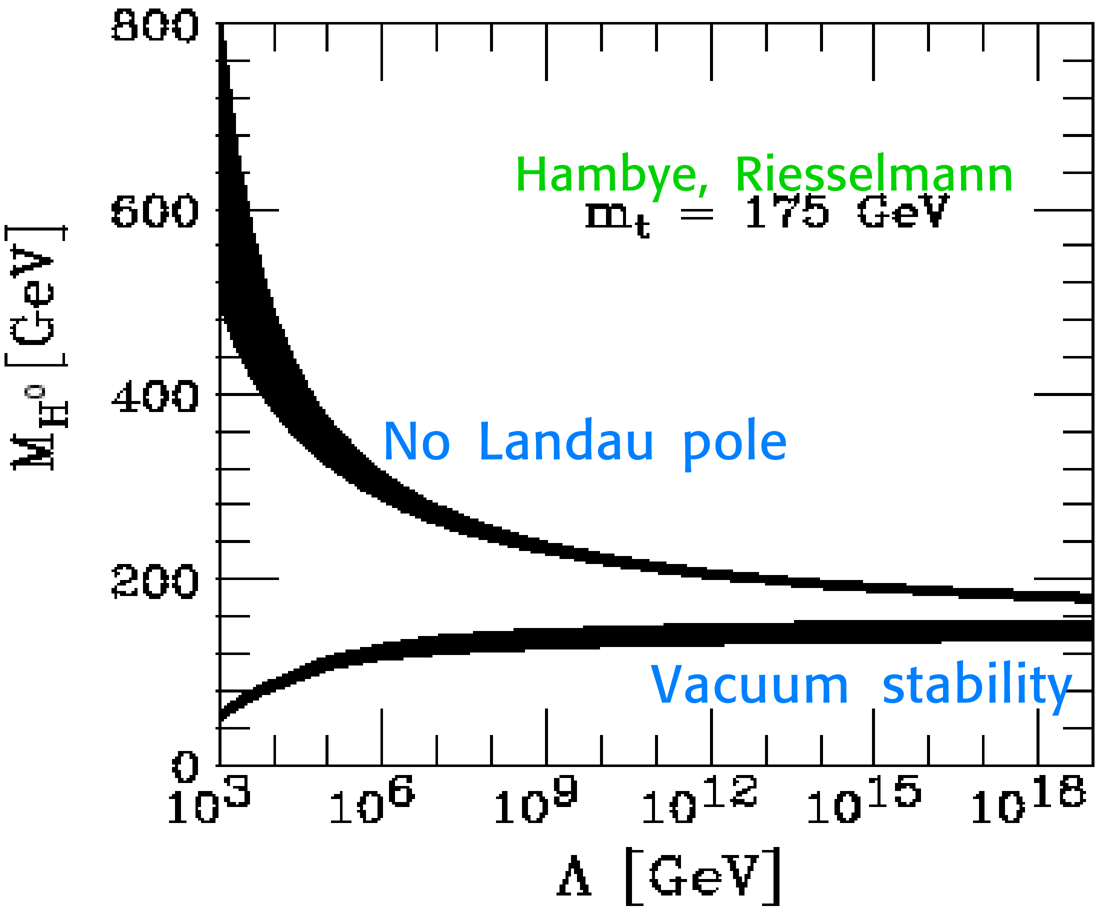
Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ

Lower limit: Vacuum (meta)stability

The LHC was designed to cover the whole range



If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Lower now because of m_t → $128 \text{ GeV} < m_H < 180 \text{ GeV}$

Status of the SM Higgs fit

F. Canelli

Winter '09

Rad Corr.s -> Sensitive to log m_H

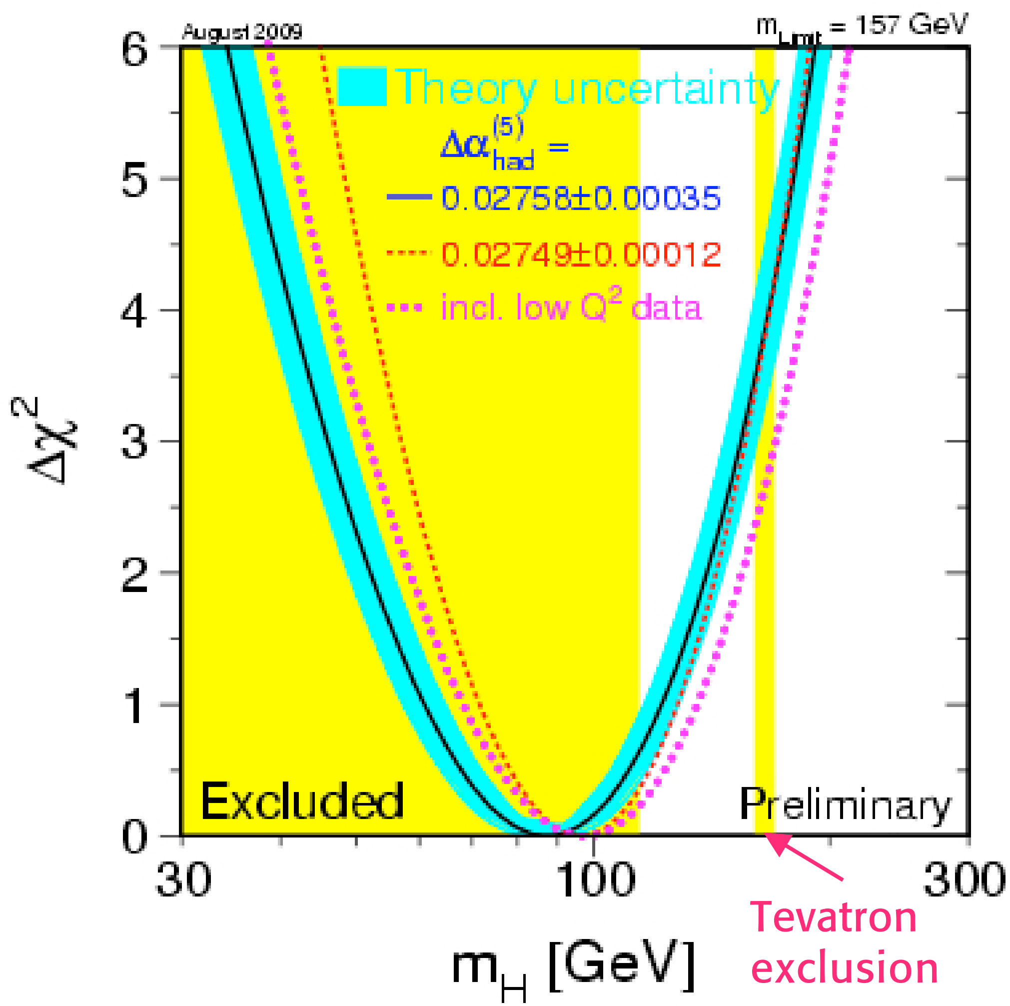
$\log_{10} m_H(\mathrm{GeV}) = 1.94 \pm 0.15$

$m_H = 87+35-26$ GeV

This is a great triumph for the SM: ~right in the narrow allowed range $\log_{10} m_H \sim 2 - 3$

Direct search: $m_H > 114.4$ GeV

Radiative corr's indicate a light H



Tevatron exclusion

At 95 % cl

$m_H < 157$ GeV (rad corr.'s)

$m_H < 186$ GeV (incl. direct search bound)

Is it possible that the Higgs is not found at the LHC?

Here "Higgs" means the "the EW symmetry breaking mechanism"

Looks pretty unlikely!!

The LHC discovery range is large enough: $m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

A heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > \sim$ TeV)

e.g. strongly interacting WW or WZ scattering

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

The SM good agreement with the data favours forms of new physics that keep at least some Higgs light

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it!

→ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour problem
- •••••

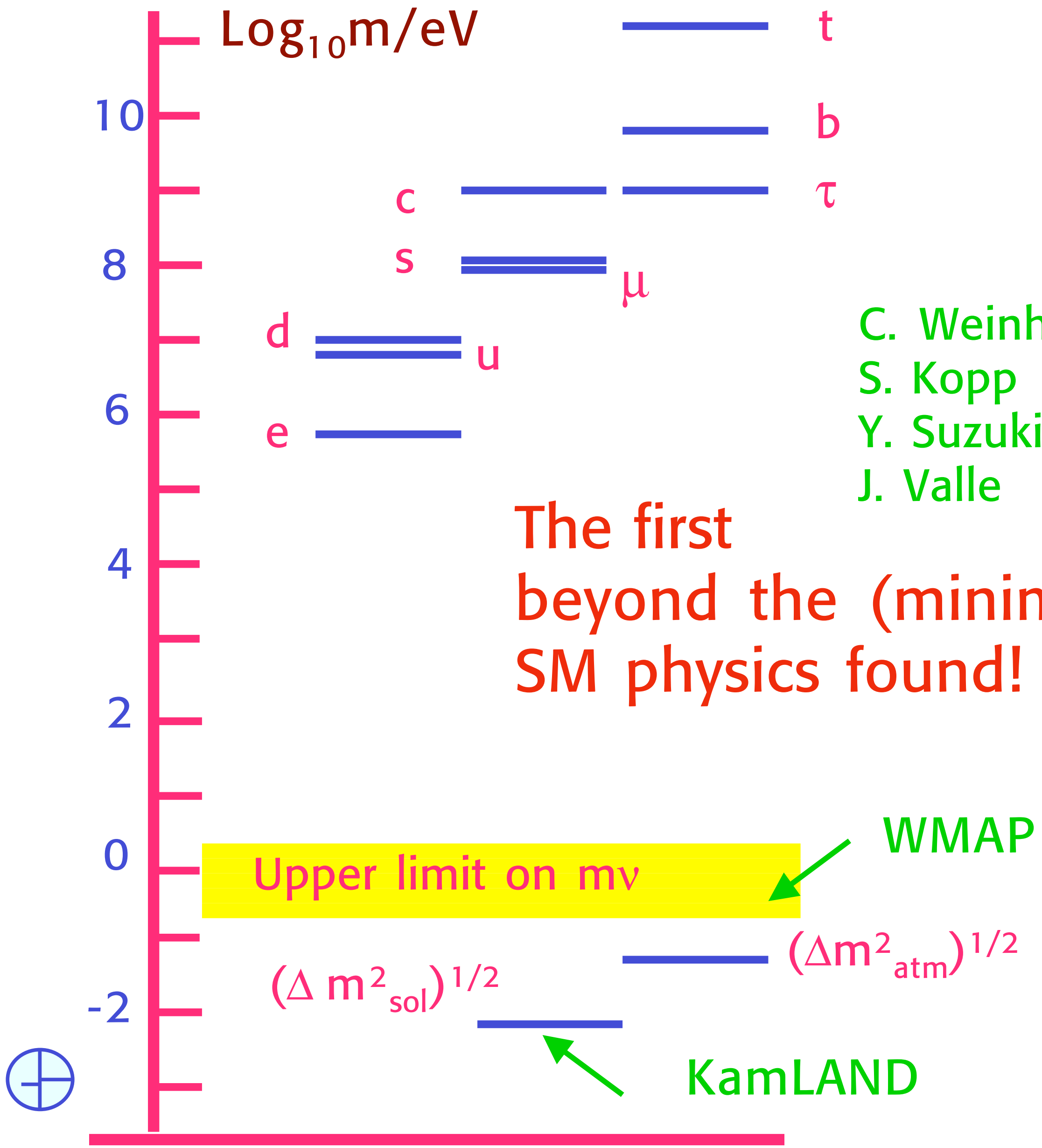
and experimental clues:

- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy
- •••••

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter

S. Pokorski

ν masses and mixings



C. Weinheimer
S. Kopp
Y. Suzuki
J. Valle

The first
beyond the (minimal)
SM physics found!

Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Neutrino masses point to M_{GUT}, well fit into the SUSY picture and in GUT's

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

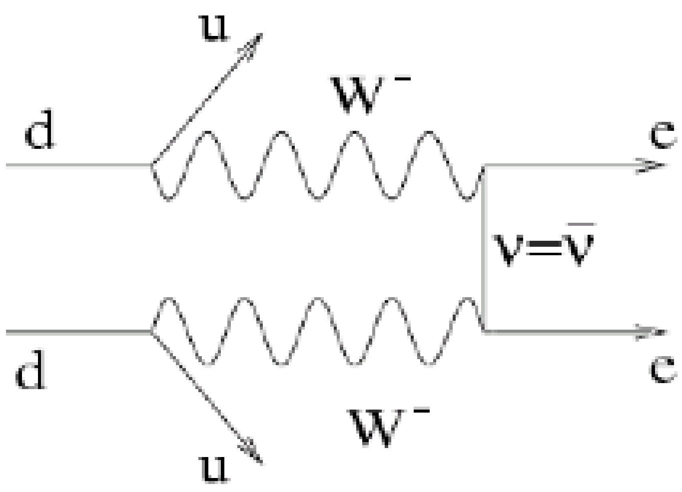
$M \sim 10^{14} - 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

A signal in $0\nu\beta\beta$ would be an essential confirmation

All we know from experiment on ν masses strongly indicates that ν's are Majorana particles and that L is not conserved (but a direct proof still does not exist).

Detection of 0νββ would be a proof of L non conservation. Thus a big effort is devoted to improving present limits and possibly to find a signal.



0νββ = dd -> uue⁻e⁻

Heidelberg-Moscow
IGEX
Cuoricino
Nemo
Sokotvina
CUORE
GERDA
•••••

C. Weinheimer

Baryogenesis by decay of heavy Majorana ν's

J. Valle

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

Buchmuller,Yanagida, Plumacher, Ellis, Lola, Giudice et al, Fujii et al ….

Only survives if Δ(B-L) is not zero
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

In particular the bound was derived for hierarchy

$m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher; Giudice et al; Pilaftsis et al; Hambye et al

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Dark Matter

WMAP, SDSS, 2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$
Most is Dark Matter and Dark Energy

K. Olive

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable (introduced to solve strong CPV)
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

J. Jackel

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: Weakly Interacting Massive Particle
with m ~ 10^1-10^3 GeV

For WIMP's in thermal equilibrium after inflation the density is:

$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

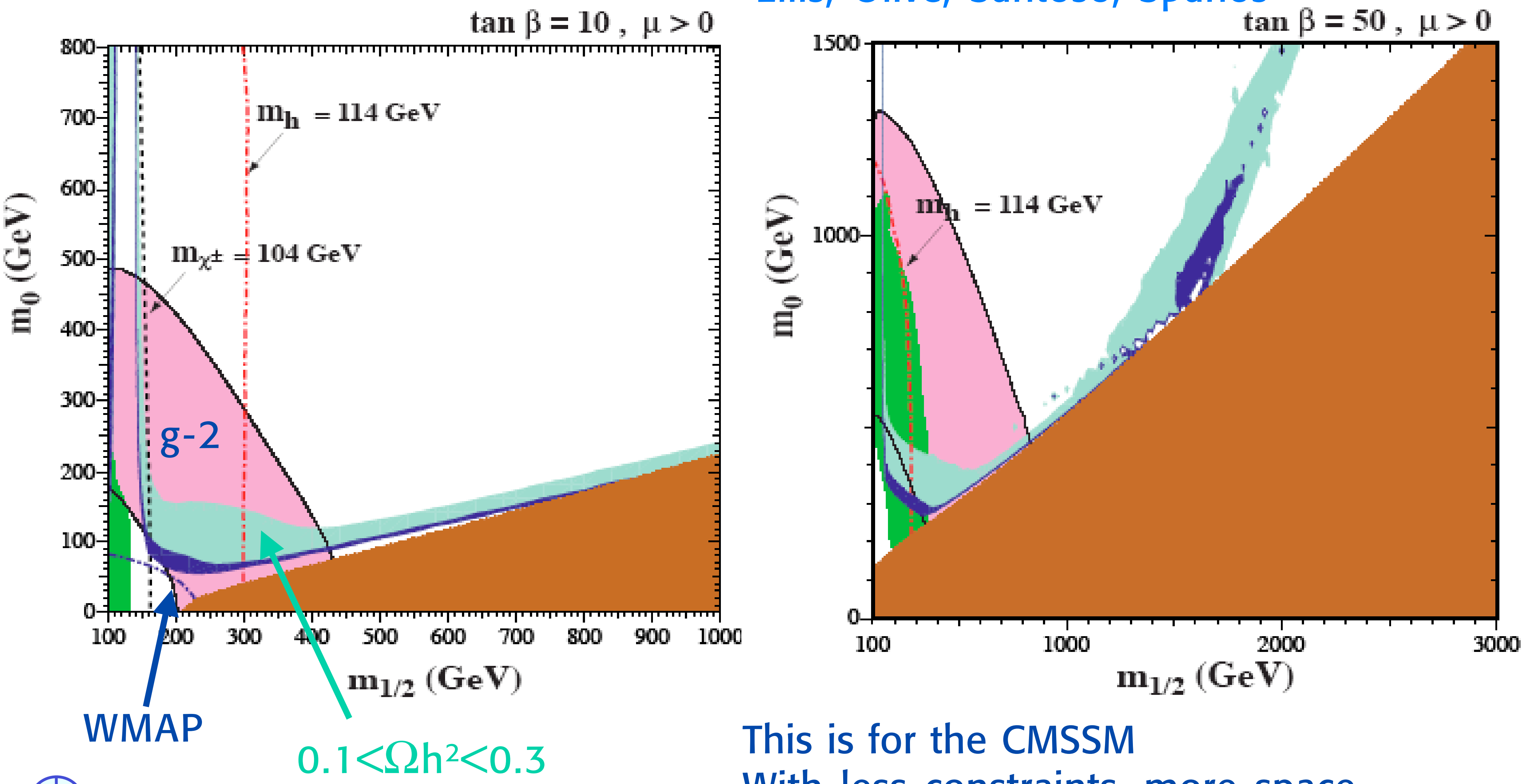
can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

LHC will tell yes or no to WIMPS

SUSY Dark Matter: best candidate the neutralino
[in SUSY the gravitino is a non-WIMP alternative]

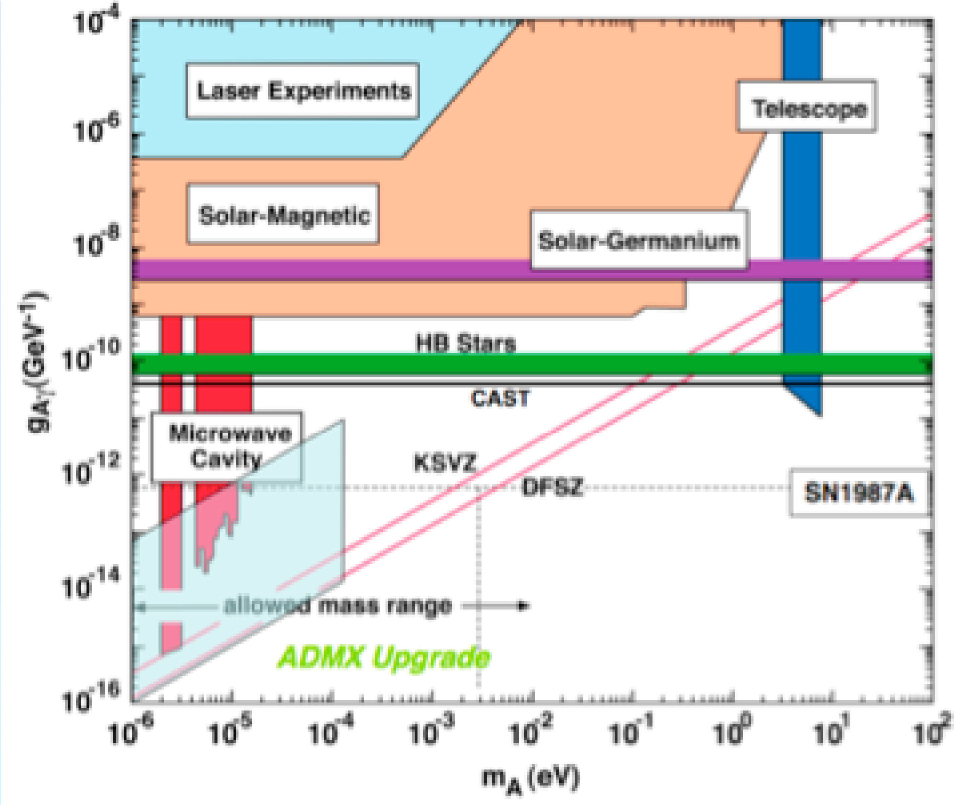
Ellis, Olive, Santoso, Spanos



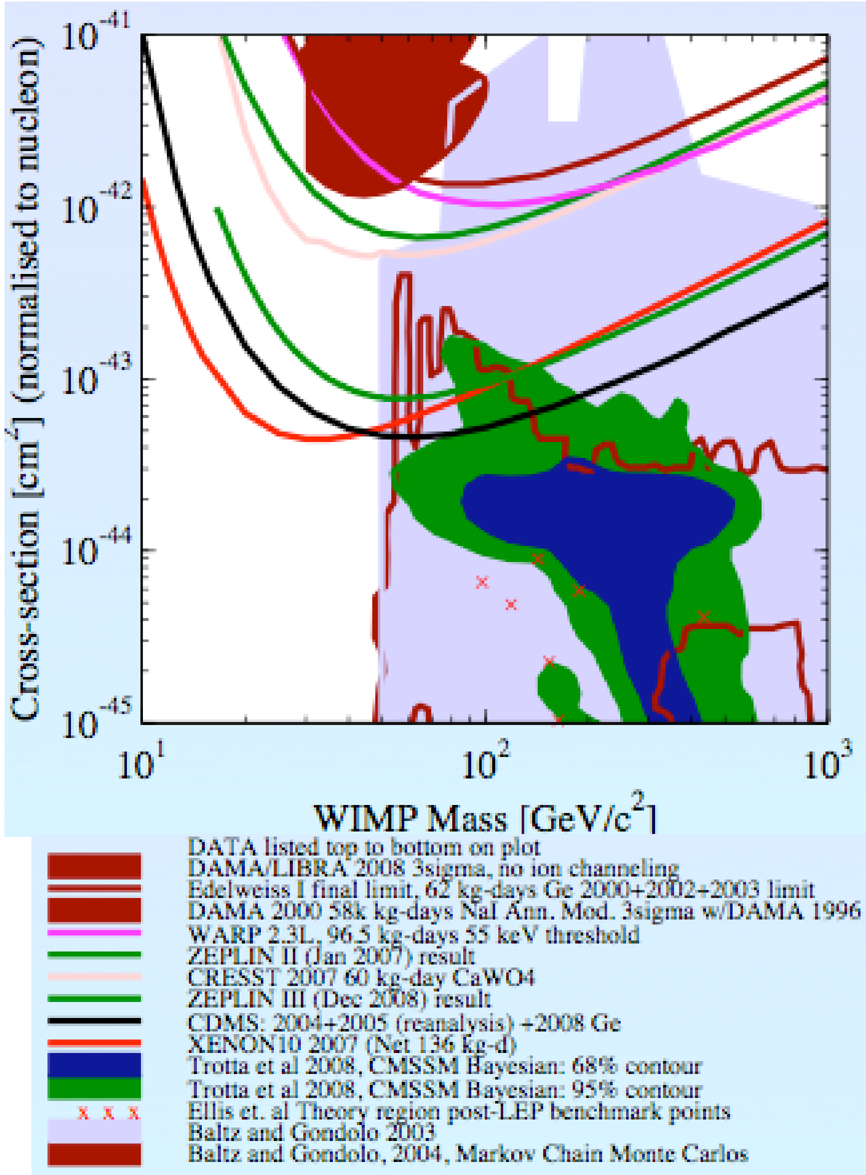
This is for the CMSSM
With less constraints, more space

N. Smith

It is not easy to reach the sensitivity for Axions as DM



Direct WIMP search



Experimental hints for dark matter?

Annual modulations (DAMA/LIBRA)

e+ excess in cosmic rays detectors (PAMELA)

ATIC bump now disfavoured (FERMI)

γ excess (EGRET) now disfavoured (FERMI)

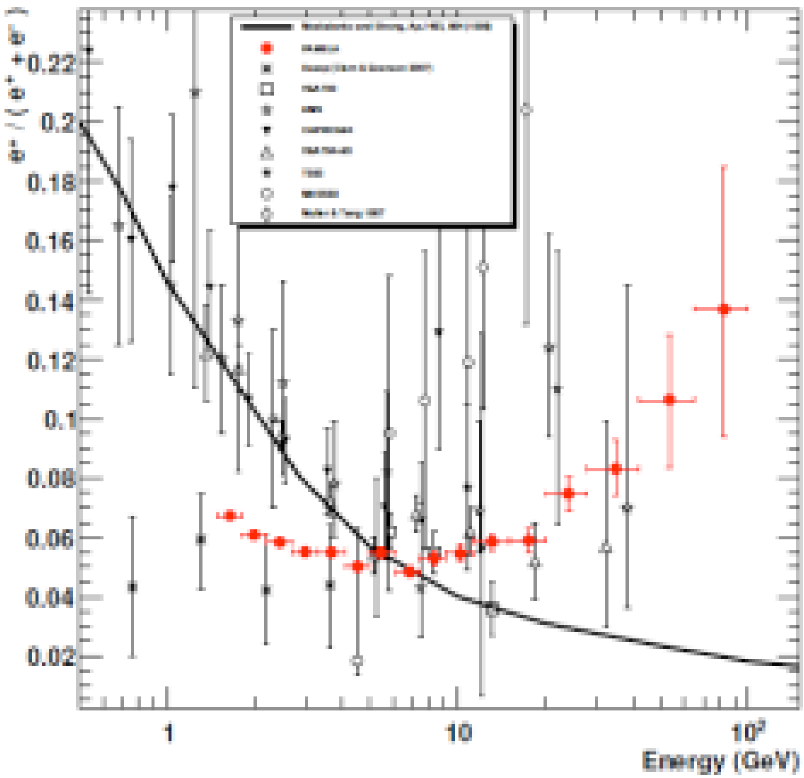
....

If really those effects are signals of DM, they point to more exotic forms of DM

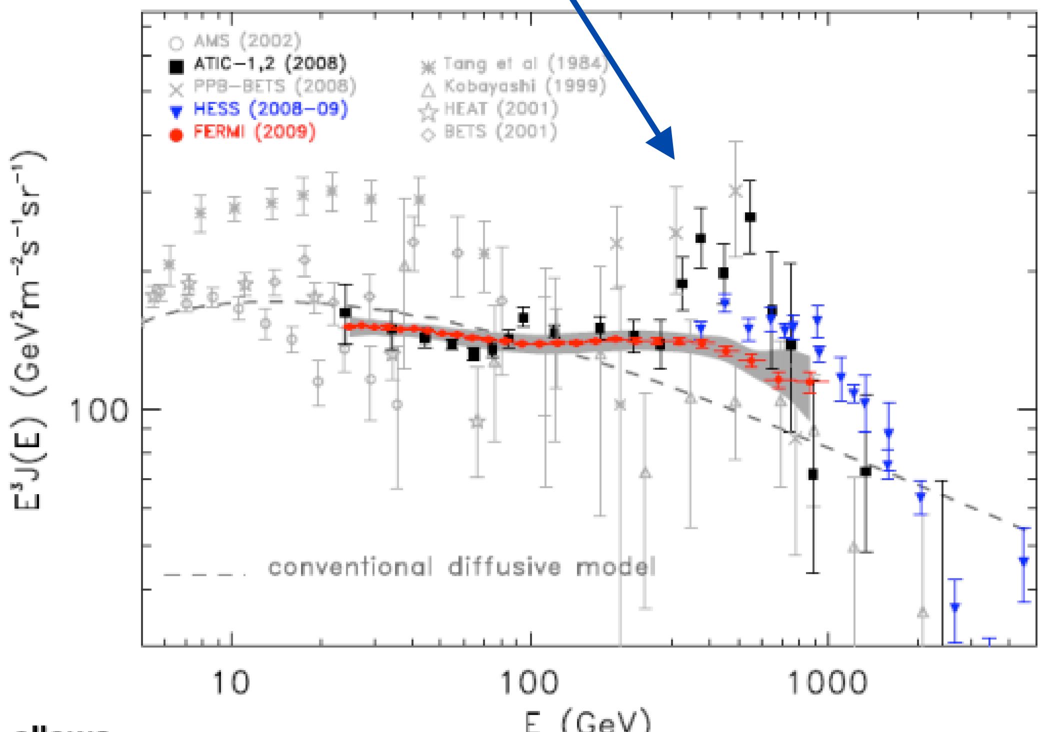
Arkani-Hamed et al, '08
Cirelli et al, '08

B. Atwood

The PAMELA e⁺ excess



The ATIC bump in e spectrum not confirmed by FERMI



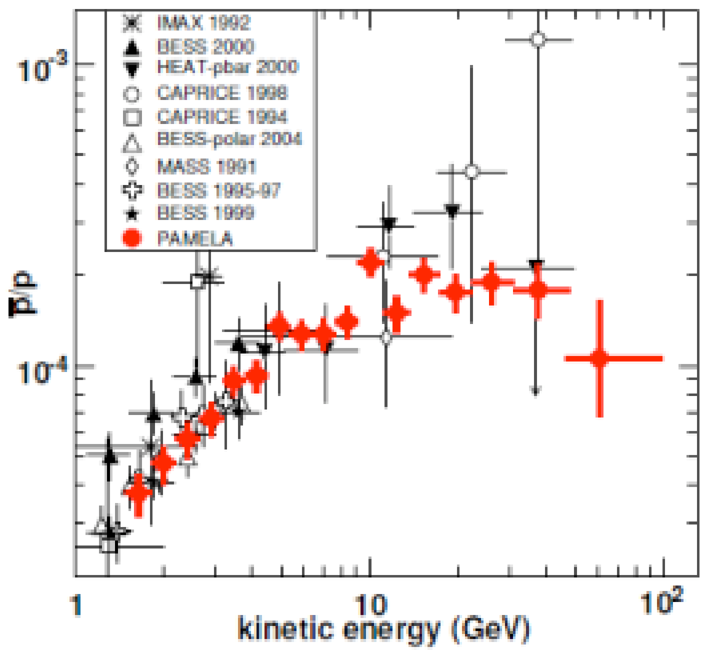
allows

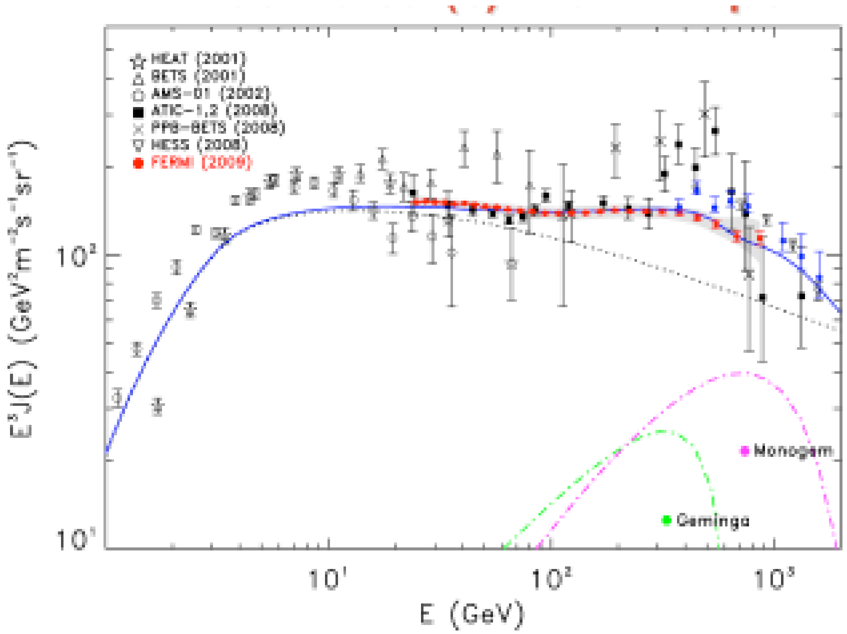
> 200 papers

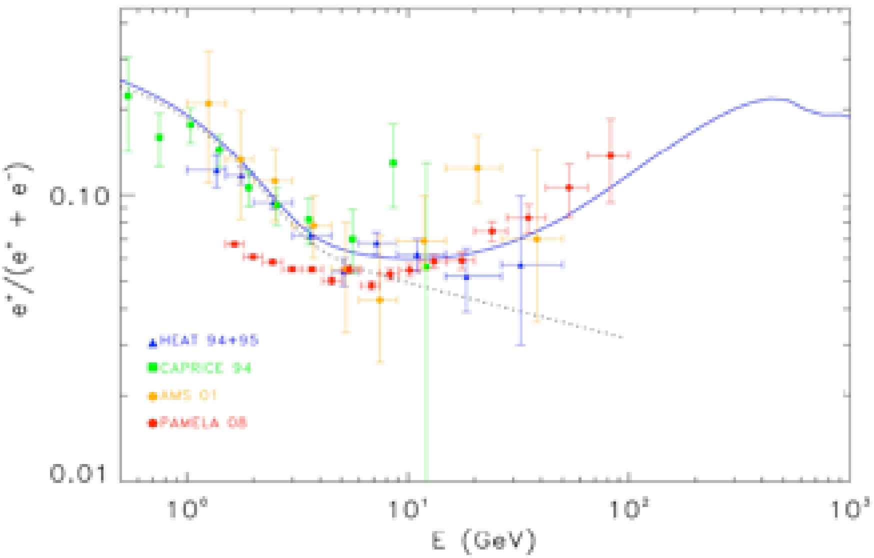
If DM would need large masses and enhanced cross-sections

An astrophysical interpretation appears possible

nothing in antiprotons (PAMELA) →





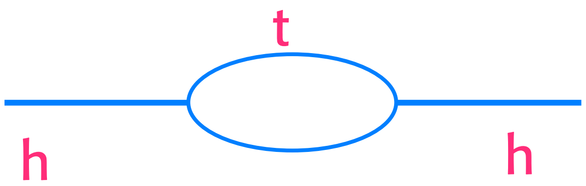


the blu curves:
pulsars within 1Kpc
with some parameter fitting

For the low energy theory: the "little hierarchy" problem:

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

This hierarchy problem demands new physics near the weak scale

$\Lambda \sim o(1\text{TeV})$

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be so close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top
- some new fermion
  - t′
  - KK recurrences of the top
  - ......

C. Grojean
S. Pokorski

Precision Flavour Physics

Another area where the SM is good, too good.....

With new physics at ~ TeV one would expect
the SM suppression of FCNC and the CKM
mechanism for CP violation to be sizably modified.

But this is not the case

an intriguing mystery and a major challenge for models of
new physics

Adding effective operators to SM generally leads to very large Λ

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2}$$

G. Isidori

c_{NP}:

- ~ 1 —(tree/strong + generic flavour)→ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ —(loop + generic flavour)→ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ —(tree/strong + MFV)→ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ —(loop + MFV)→ $\Lambda \gtrsim 0.5$ TeV [K & B]

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{NP} \sim (y_t V_{tb}^* V_{td})^2$ (or anyway small)

we get a bound on Λ in the TeV range

S. Prell
T. Iijima
G. Hiller
T. Komatsubara

eg in Minimal Flavour Violation (MFV) models

D'Ambrosio, Giudice, Isidori, Strumia'02

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY} - m_{ord}$ → top loop $\Lambda \sim m_{stop}$

  The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

  Strongly disfavoured by LEP. Coming back in new forms

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

  "Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that "bring" M_{Pl} down to o(1TeV)

Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

The anthropic route

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.75$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \mathrm{eV})^4 \sim (0.1\mathrm{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

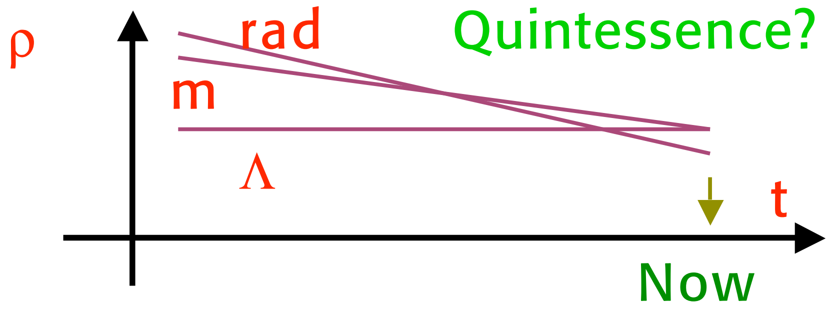
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\,\rho_{obs}$

Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 \sim 10^{59}\,\rho_{obs}$

It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

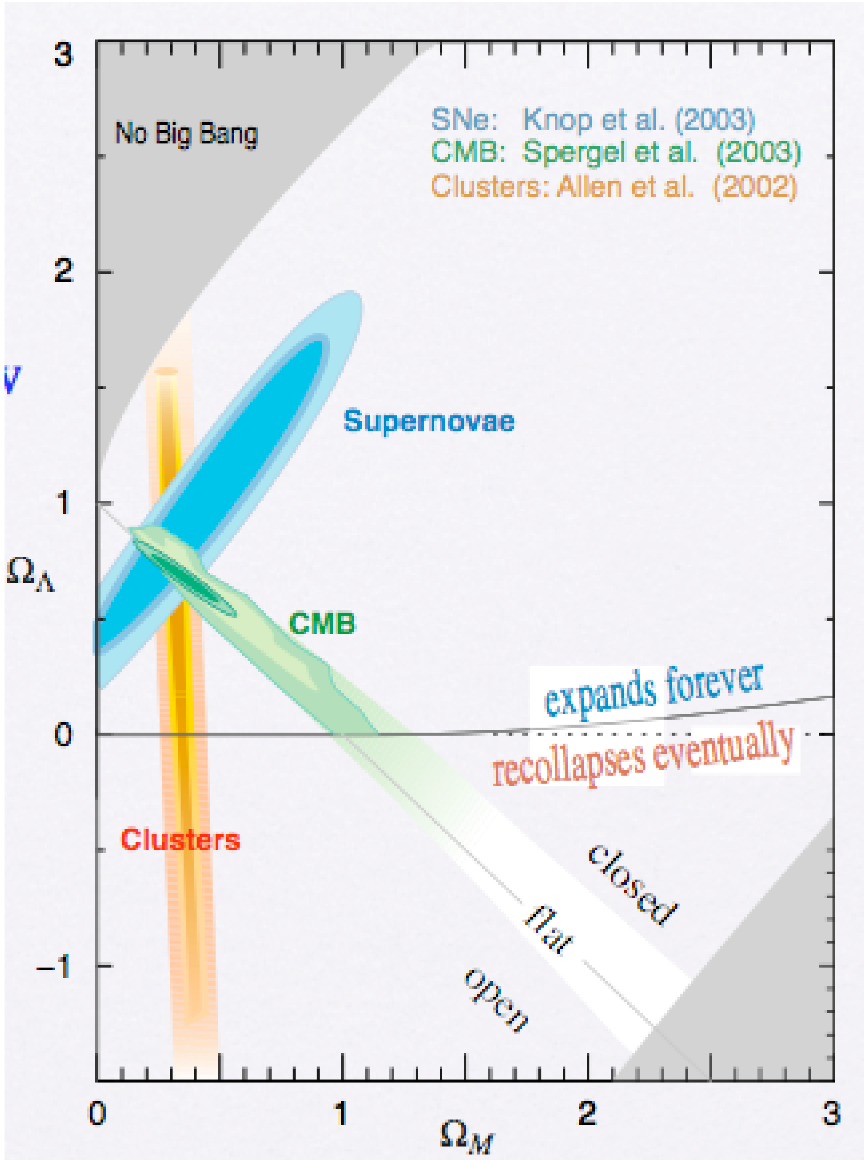
Other problem:
"Why now"?

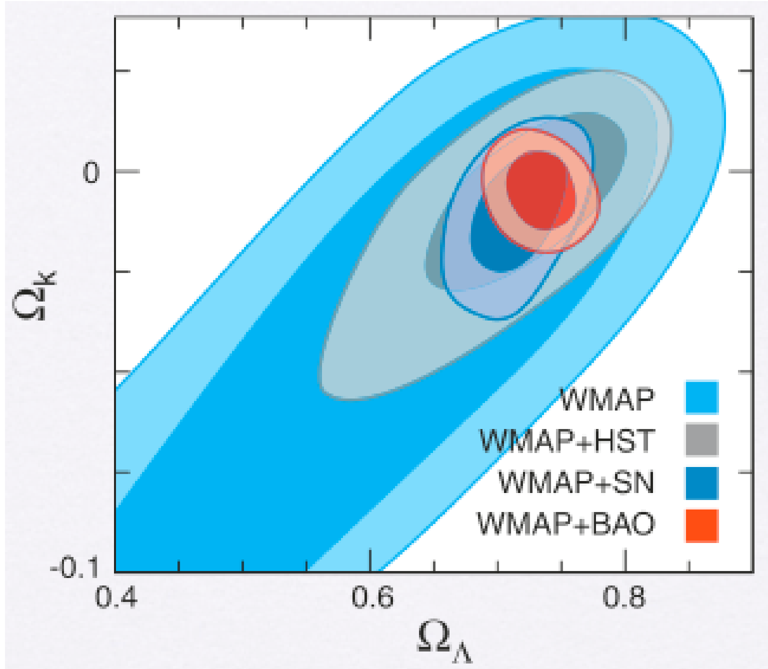


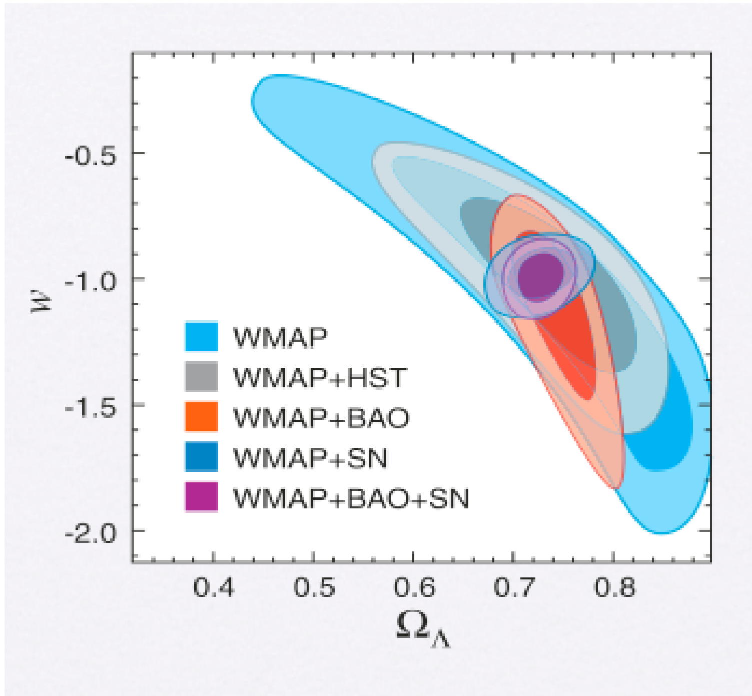
"Quintessence"
Λ as a vev of a field ϕ?

Coupled to gauge singlet matter, eg ν_R, to solve magnitude and why now?

K. Olive


No Big Bang
SNe: Knop et al. (2003)
CMB: Spergel et al. (2003)
Clusters: Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
0
1
2
3
−1


WMAP
WMAP+HST
WMAP+SN
WMAP+BAO
Ω_k
Ω_Λ
0
-0.1
0.4
0.6
0.8


WMAP
WMAP+HST
WMAP+BAO
WMAP+SN
WMAP+BAO+SN
w
Ω_Λ
-0.5
-1.0
-1.5
-2.0
0.4
0.5
0.6
0.7
0.8

Is naturalness relevant?

Speculative physics reasons to doubt:

- The empirical value of the cosmological constant Λ poses a tremendous, unsolved naturalness problem

  yet the value of Λ is close to the Weinberg upper bound for galaxy formation

- Possibly our Universe is just one of infinitely many continuously created from the vacuum by quantum fluctuations

- Different physics in different Universes according to the multitude of string theory solutions ($\sim 10^{500}$)

Perhaps we live in a very unlikely Universe but one that allows our existence

I find applying the anthropic principle to the SM hierarchy problem not appropriate

After all we can find plenty of models that reduce the fine tuning from 10^{14} to 10^{2}:
so why make our Universe so terribly unlikely?

The case of the cosmological constant is a lot different:
the context is not as fully specified as the for the SM
(quantum gravity, string cosmology, branes in extra dims.,
wormholes thru different Universes....)

SUSY: boson fermion symmetry

The hierarchy problem: $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$

In broken SUSY Λ^2 is replaced by $(m_{stop}{}^2 - m_t{}^2)\log\Lambda$

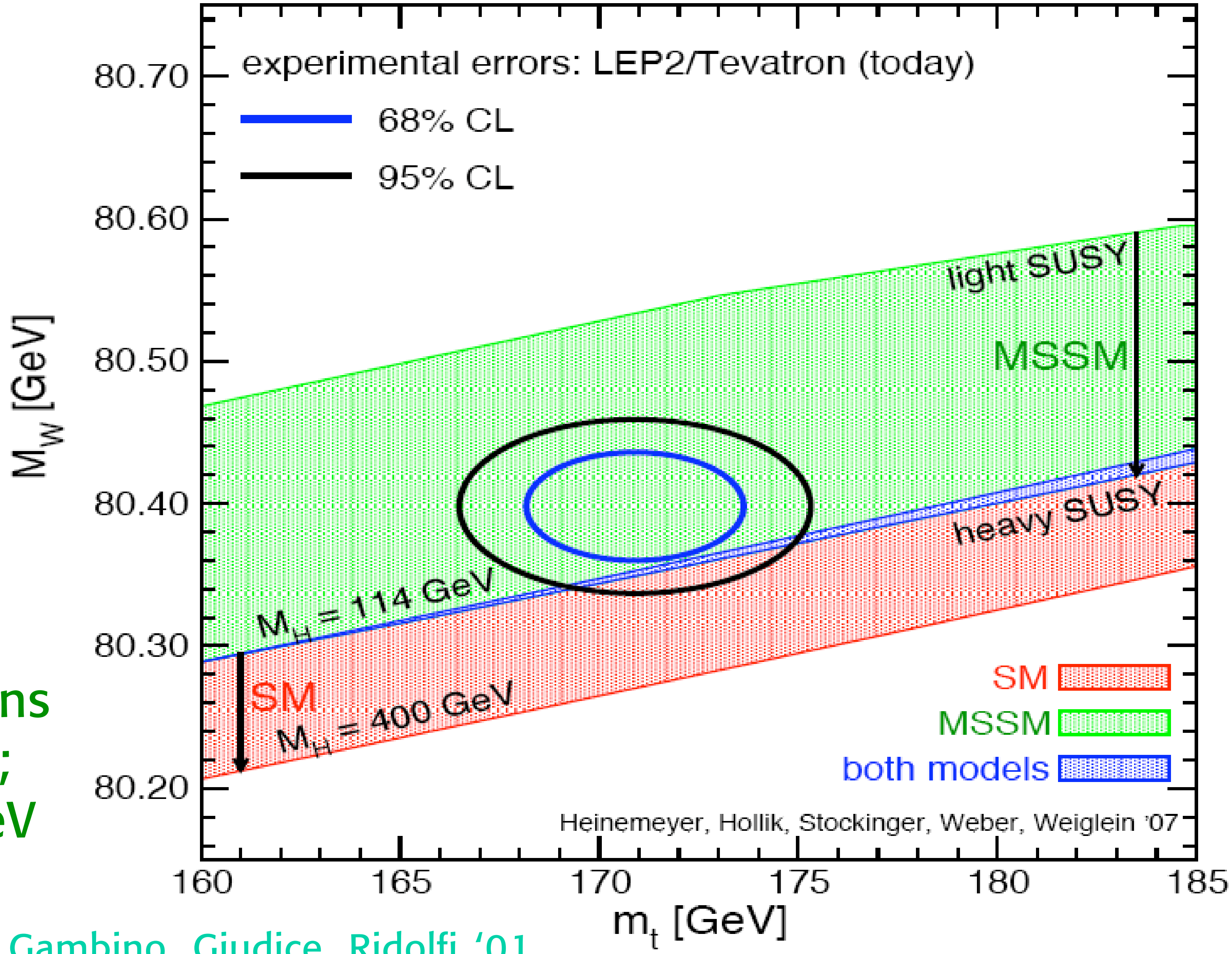
$m_H > 114.4$ GeV, $m_{\chi+} > 100$ GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

O. Gonzales Lopez

Yet SUSY is a completely specified, consistent, computable model, perturbative up to M_{Pl} quantitatively in agreement with coupling unification (GUT's) (unique among NP models) and has a good DM candidate: the neutralino (actually more than one).

Remains the reference model for NP

SUSY effects could modify the SM fit



"light SUSY"=
= light s-leptons
and charginos;
s-quarks ~1 TeV

G.A, Caravaglios, Gambino, Giudice, Ridolfi '01

A recent study indicates that m_h goes up in CMSSM when $b \to s\gamma$, a_μ, Ω_{DM} are added

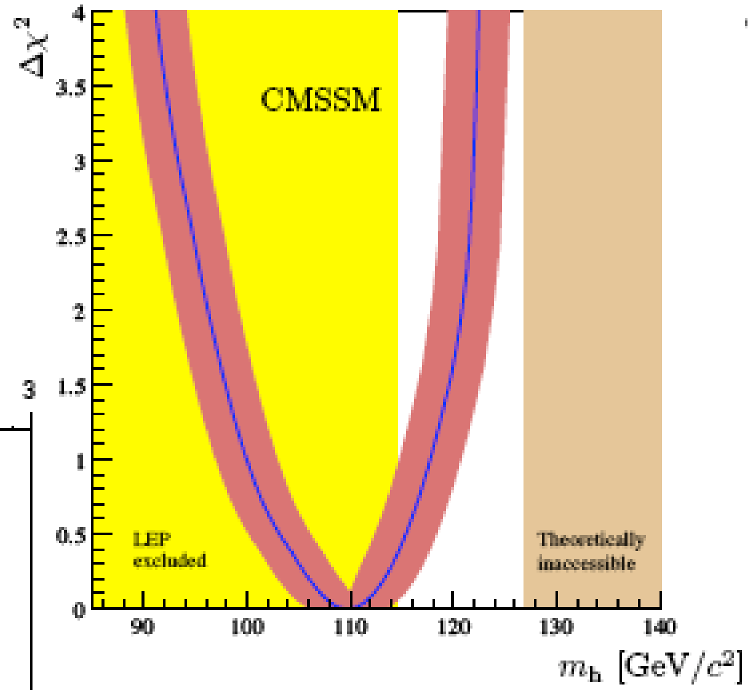
O. Buchmuller et al '07, '08 [0808.4128]

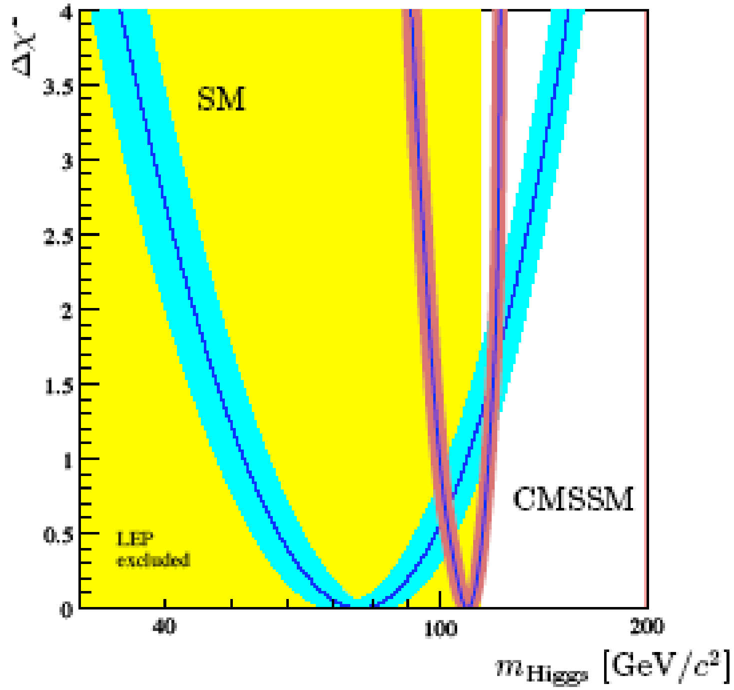
also:
J. Ellis et al '07

CMSSM

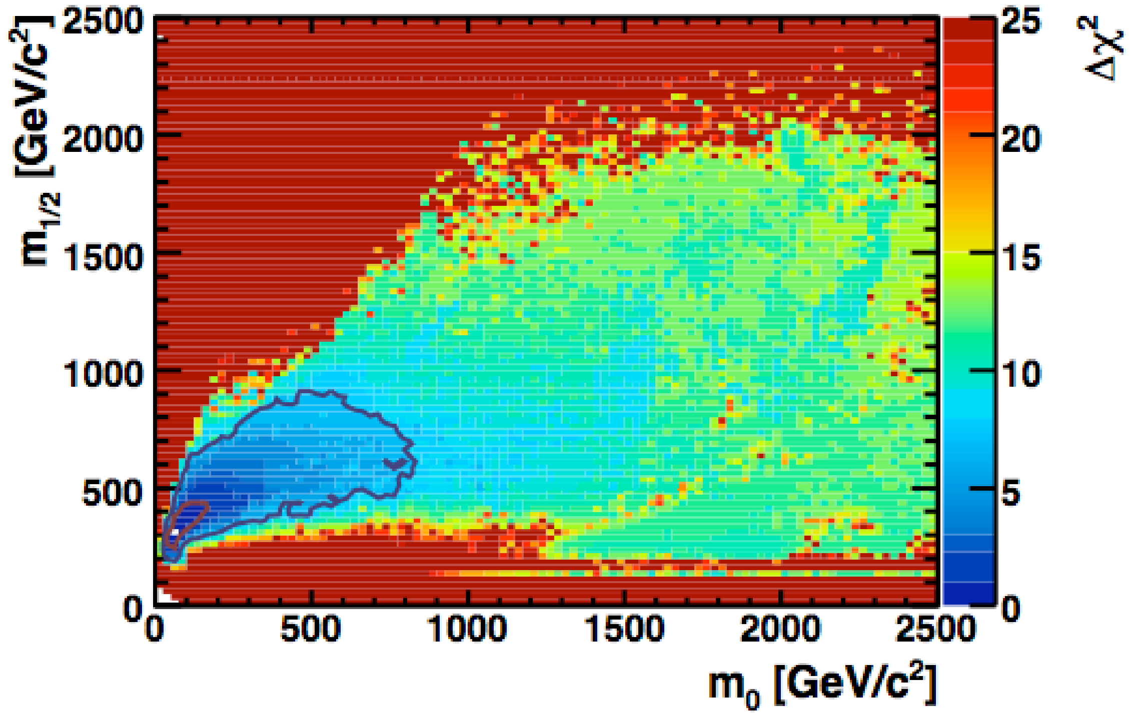
Variable	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02774
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952
σ_{had}^0 [nb]	41.540 ± 0.037	41.486
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01641
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21613
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.382
m_t [GeV]	170.9 ± 1.8	170.8
$R(b \to s\gamma)$	1.13 ± 0.12	1.12
$B_s \to \mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113

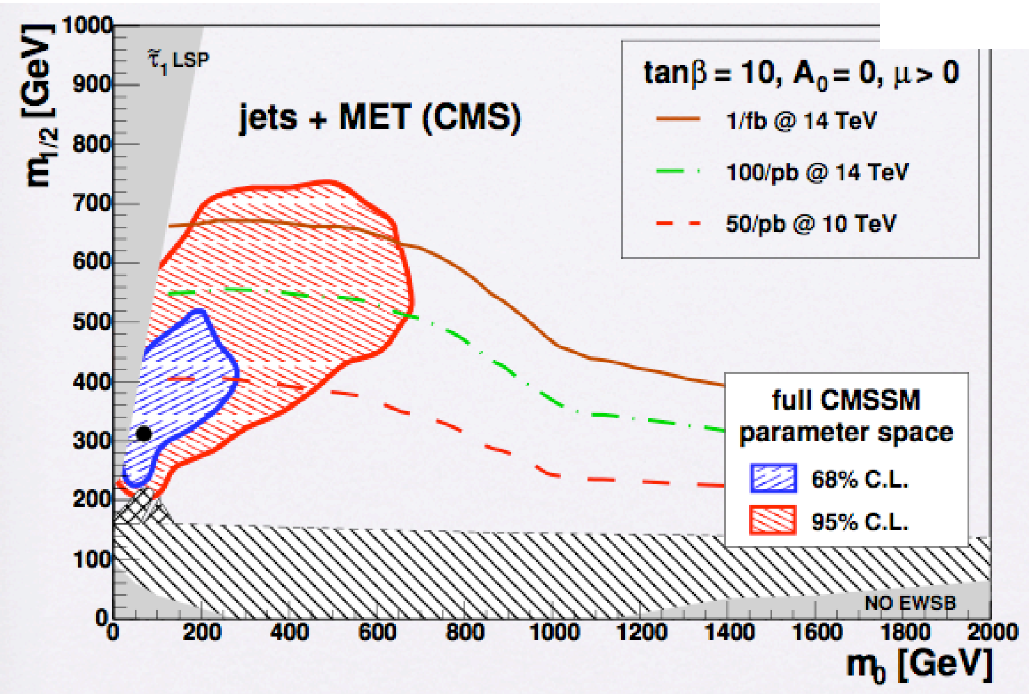
$|O^{meas} - O^{fit}|/\sigma^{meas}$ (0, 1, 2, 3); $B_s \to \mu\mu$: N/A (upper limit)





relatively light SUSY
is indicated





accesssible at the LHC

Little Higgs Models

Georgi (moose)/Arkani-Hamed et al/Low, Skiba, Smith/Kaplan, Schmaltz/Chang,Wacker/Gregoire et al

$$G \supset [SU(2) \otimes U(1)]^2 \supset SU(2) \otimes U(1)$$

global — gauged — SM

H is (pseudo)-Goldstone boson of G: takes mass only at 2-loops (needs breaking of 2 subgroups or 2 couplings)

recall: $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$ $\qquad$ $G_F \sim g^2 \rightarrow g^4$

cutoff Λ $\qquad$ ~10 TeV

Λ^2 divergences canceled by:

$\delta m^2_{H\|top}$	new coloured fermion χ with Q=2/3	~1 TeV
$\delta m^2_{H\|gauge}$	W', Z', γ'	
$\delta m^2_{H\|Higgs}$	new scalars	

⊕ 2 Higgs doublets $\qquad$ ~0.2 TeV

With some tension Little Higgs models can work.

T parity interchanges the two SU(2)xU(1) groups Cheng, Low

Standard gauge bosons are T even, heavy ones are T odd

Lightest T-odd particle stable --> Dark Matter

Technically sophisticated. But the main drawback is:
Little Higgs provides just a postponement:
UV completion beyond ~10 TeV? GUT's?

Still important as it offers well specified signals and signatures for searching at the LHC:
a light Higgs, a new top-like fermion χ to damp the top loop, new W', Z' for the W, Z loops,.....

Extra Dimensions (ED)

String Theory ---> ED at M_{Pl}

Perhaps ED have a direct impact on physics below M_{Pl}

Exciting possibilities (a large domain of contemporary BSM)

- GUT's in ED (M_{GUT})
- ED as (part of the) solution of the hierarchy probem (M_{EW})
- EW symmetry breaking from ED (M_{EW})

Generic feature of extra dim. models:

compact dim. → Kaluza-Klein (KK) modes

$p=n/R$ $m^2=n^2/R^2$ (quantization in a box)

Many possibilities:

- SM fields on a brane or in bulk

cfr: • Gravity always on bulk

- Factorized metric:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j$$

- Warped metric: Randall-Sundrum (R-S)

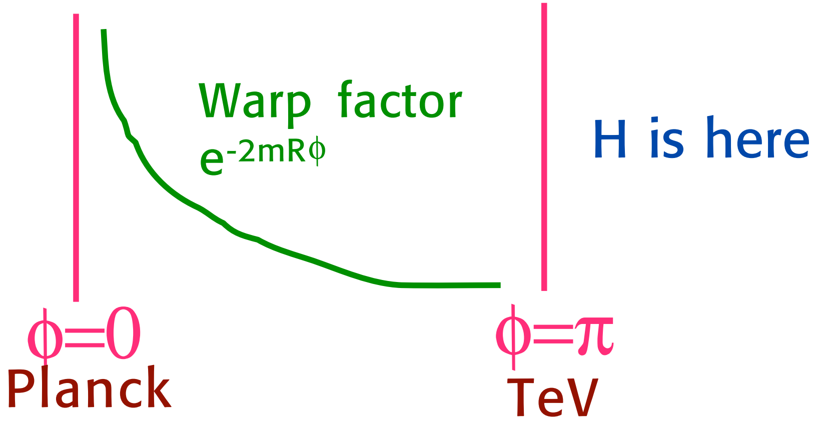
$$ds^2 = e^{-2mR|\varphi|} \eta_{\mu\nu} dx^\mu dx^\nu - R^2 \varphi^2$$

$m_{weak}=M_{Pl}\exp(-mR\pi)$ → $Rm \sim 12$

emerges as the most promising

Randall-Sundrum: $ds^2 = e^{-2mR|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu - R^2\varphi^2$

C. Grojean
S. Kachru



This non-fact.ble metric is solution of Einstein eq.s with 2 branes at $\phi=0,\pi$ and specified 5-dim cosmological term

All SM particles in bulk except the H

$m \sim M_{Pl}$ for all mR: $m^2 \sim M_{Pl}^2(1-e^{-2mR\phi})$

All 4-dim masses m_4 are scaled down with respect to 5-dim masses $m_5 \sim M_{Pl}$ by the warp factor: $m_4 = M_{Pl}e^{-mR\pi}$

The hierarchy problem demands that $mR \sim 12$: not too large!!

R not large in this case!

Stabilization of mR at a compatible value can be assured by a scalar field in the bulk with a suitable potential

⊕ ↘ "radion"

Goldberger, Wise

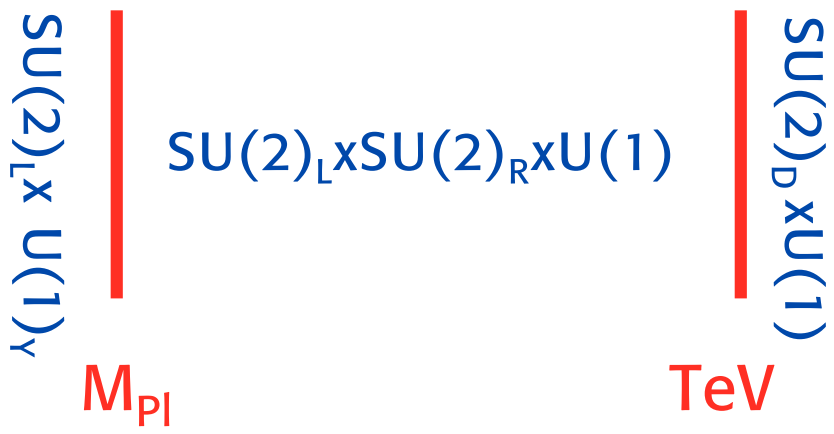
Applications

C. Grojean

- **Gauge Symmetry Breaking (Higgsless theories)**

Csaki et al/Nomura/Davoudiasl et al/Barbieri, Pomarol, Rattazzi;....

The only models were no Higgs would be found at LHC.
But signals of new physics would be observed



Warped R-S background

Symmetries broken by Boundary Conditions (BC) on the branes

Altogether only $U(1)_Q$ unbroken

- Unitarity breaking (no Higgs) delayed by KK recurrences
- Dirac fermions on the bulk (L and R doublets). Only one chirality has a zero mode on the brane

With no Higgs unitarity violations, eg:

$$A\left(W_L^+ W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}$$

At E ~ 1.2 TeV unitarity is violated

In Higgsless models unitarity is restored by exchange of infinite KK recurrences, or the breaking is delayed by a finite number

$Z_k = k_{th}$ KK

Cancellation guaranteed by sum rules implied by 5-dim symmetry

$$g_{WWWW}^2 - e^2 - \sum_k g_{WWZ_k}^2 = 0\ ;$$

$$4M_W^2\, g_{WWWW}^2 - 3\sum_k g_{WWZ_k}^2 M_{Z_k^2} = 0\ .$$

No convincing, realistic Higgsless model for EW symmetry breaking emerged so far:

Serious problems with EW precision tests

e.g. Barbieri, Pomarol, Rattazzi '03 ; Chivukula et al

also with Z->bb

m_W fixes the KK gap and it is not sufficiently large

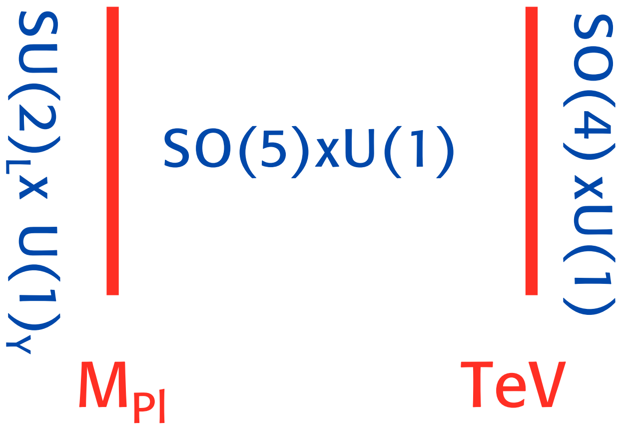
Substantial fine tuning required

Best try: Cacciapaglia et al '06

However be alerted of possible signals at the LHC: no Higgs but KK recurrences of W, Z and additional gauge bosons

- Composite Higgs in a 5-dim holographic theory

Agashe, Contino, Pomarol……



Warped R-S background

A new way to look at walking technicolor using AdS/CFT corresp.

All SM fields in the bulk (but the Higgs is localised on the TeV brane)

As in Little Higgs models

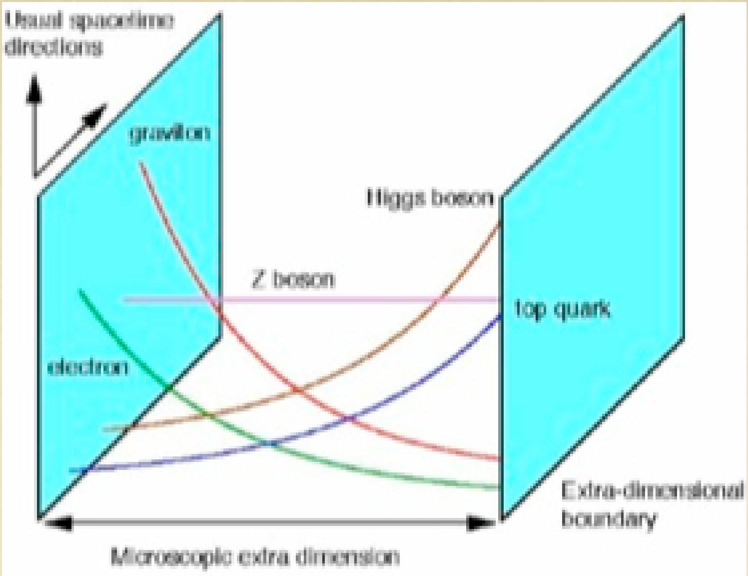
The Higgs is a PGB and EW symmetry breaking is triggered by bulk effects (in 4-dim the bulk appears as a strong sector).

The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

The Higgs is rather light: $m_H < 185$ GeV

⊕ Also in these models a sizable fine-tuning is required

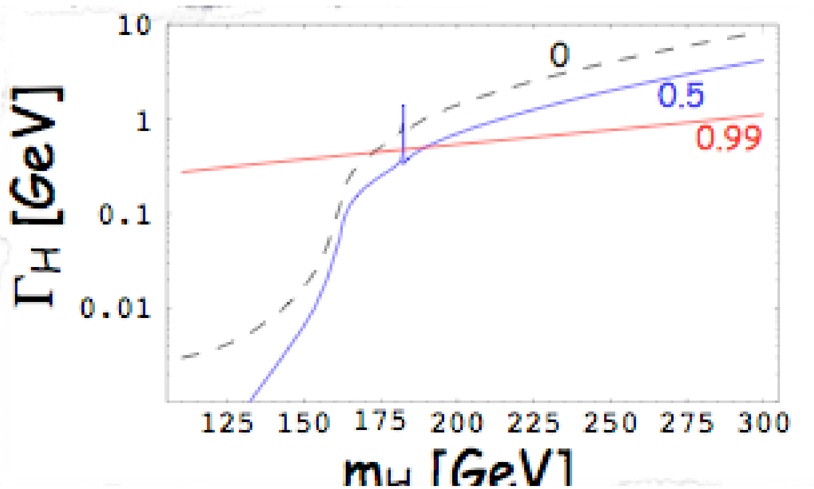
S. Kachru

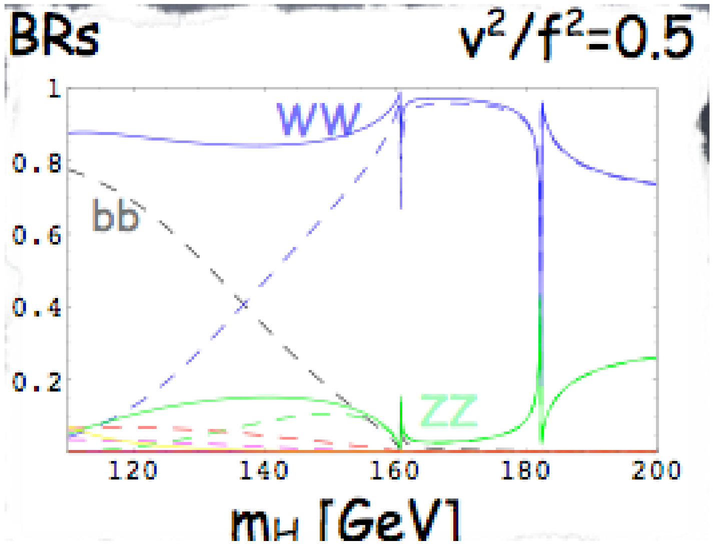


A qualitative description of flavour

Higgs couplings modified

C. Grojean





Lessons from model building

In all the new physics models we mentioned

there is a light Higgs ($<$ 200 GeV)

[except in Higgsless models (if any) but new light new vector bosons exist in this case]

there is at least a % fine tuning

Fine tuning appears to be imposed on us by the data

In conclusion

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then must find something else

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?

No, it is "approximately impossible"

As the last speaker, on behalf of all participants,
I thank the Organizers who have done really a great job.
This Symposium presented a very complete picture of our field in a most confortable setting and with the exciting Hamburg background