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BSM physics at the LHC

Winter School on
Strings, Supergravity and Gauge Theories

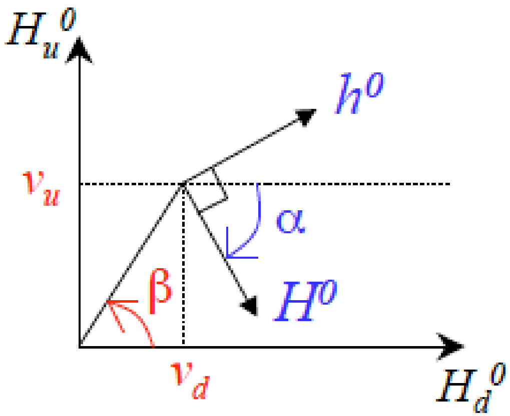
CERN, 9-13 February 2009

Plan of the lectures

1. A critical overview of the SM
2. Bottom-up approaches to BSM
3. SUSY: if so, which incarnation?
4. Other BSM ideas for the LHC

MSSM Higgs boson searches

Modified couplings:



	$d\bar{d}\,,\, l^+l^-$	$u\bar{u}$	W^+W^-, ZZ
h	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$
H	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$
A	$-i\gamma_5\tan\beta$	$-i\gamma_5\cot\beta$	0

- Coupling to vector bosons are never stronger than in SM
- Coupling to SM fermions can be much stronger, e.g. bottom and tau couplings for large values of tan(beta)

Decoupling limit (towards the "unnatural" SM):

$$m_A^2 \gg m_Z^2 \quad \Rightarrow \quad h \sim h_{SM} \quad \& \quad \alpha \sim (\beta - \pi/2)$$

(H,A,H^+,H^-) = nearly degenerate decoupling heavy doublet

MSSM Higgs boson searches at LEP

Complementarity

(barring very special regions of parameter space)

$\sigma(e^+ e^- \to h\ Z) \propto \sin^2(\beta - \alpha)$

sizeable when only h light

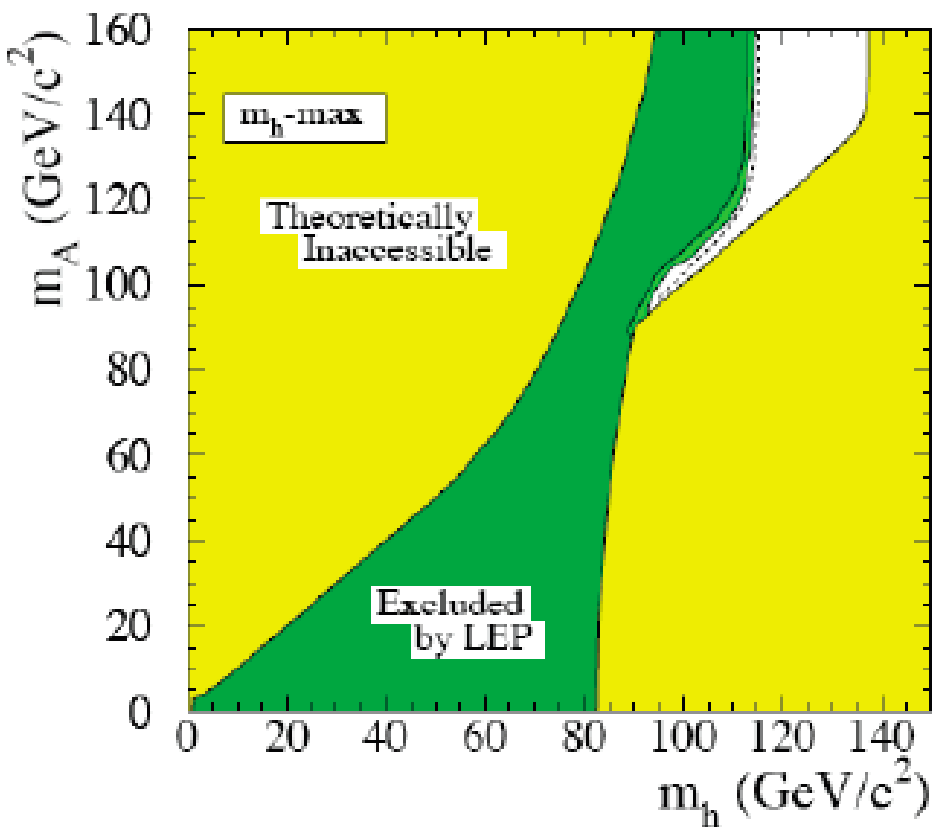
$\sigma(e^+ e^- \to h\ A) \propto \cos^2(\beta - \alpha)$

sizeable for h, A both light

m_h, m_A > 93 GeV at 95% c.l

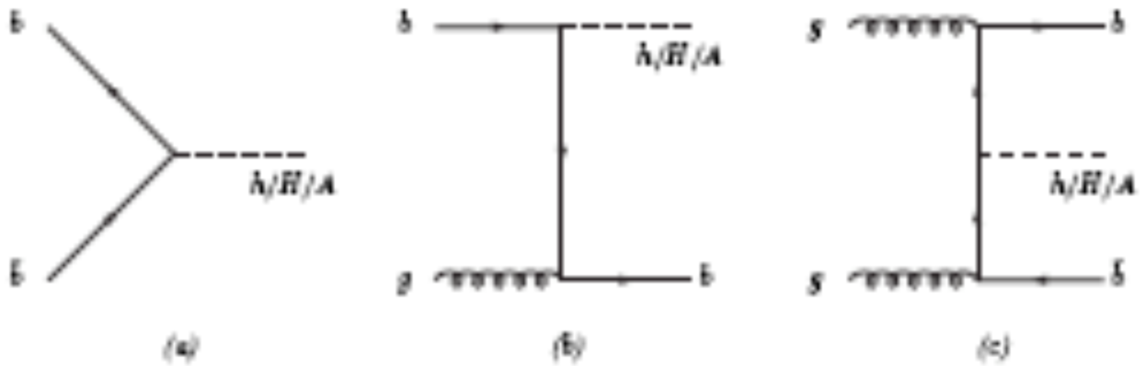
in most parameter space

m_h > 114 GeV for $m_A >> m_Z$



MSSM Higgs production at hadron colliders

For the MSSM neutral Higgs bosons, the production mechanisms are the same as for the SM Higgs, with modified couplings: possible strong enhancements [for large tan(beta)] of gluon-gluon fusion (via the bottom loop) and of associated production with b-bar



For the charged Higgs boson above the top quark scale, the dominant mechanism (among several ones) is the associated production of H^- t bbar or H^+ tbar b

MSSM Higgs Tevatron searches

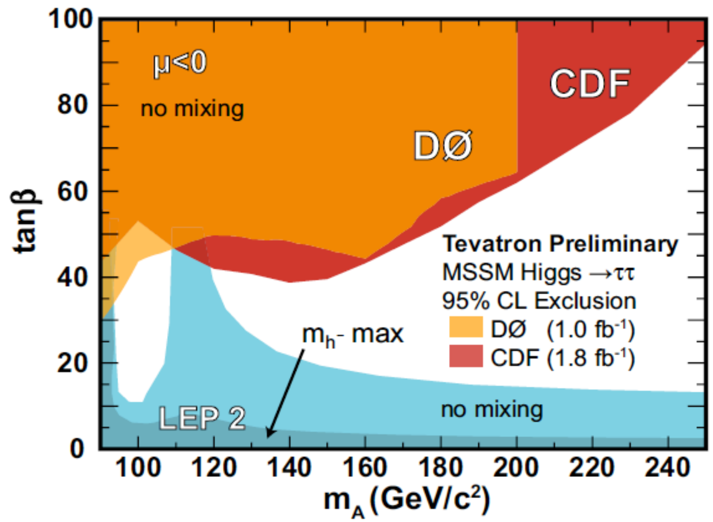
Tevatron only sensitive for very large tan(beta)~m_t/m_b, when (h,H,A) couplings to b and tau strongly enhanced [non-trivial constraints, however, from rare B-decays]
Bounds difficult to interpret: strong model-dependence due to large 1-loop threshold corrections to bottom mass

Decay modes: b-bbar (~90%) tau-tau (~10%)

Possible signals (Phi=h,H,A):

Phi → b-bbar with 1 or 2 b-jets

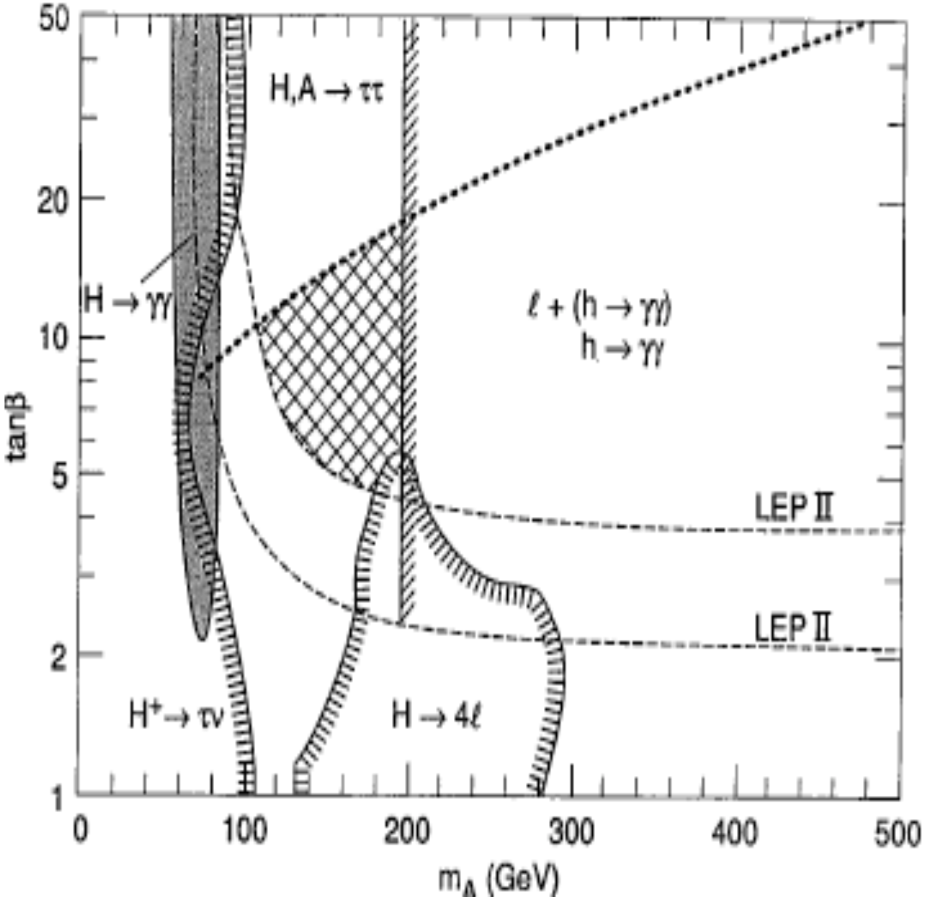
Inclusive Phi → tau-tau



In addition, some sensitivity to t → H^+ b decays

MSSM Higgs boson searches at the LHC

An ultra-simplified initial study
(and a personal memory)



[Z.Kunszt & FZ, LHC workshop, Aachen 1990]

Huge amount of work by now, it would take very long to describe it

A very complicated problem:
- Many parameters
- Many new particles around

(even in "constrained" MSSM)

SUSY-Higgs searches intertwined with SUSY-particle searches

"Benchmark scenarios" used so far to optimize detectors and analyses

But data will drive the analyses as long as they come and are progressively understood

Other BSM ideas for the LHC

What if naturalness fails for the weak scale?
(as it may fail for the vacuum energy scale)
A logical possibility, although not my favourite

Light SM Higgs boson and nothing else at the LHC
(called by some, on Apr 1, supersplit supersymmetry)

- A triumph for the SM
- A triumph for the LHC (mach. & exper.)
- A failure for many theorists
- Hard to understand what comes next

In the meantime, can consider solutions to the
SM naturalness problem alternative to SUSY
all predict testable new physics at the LHC scale
useful alternatives in a broad preparatory effort

Alternatives to SUSY at the TeV scale

Many 4D models, classifiable in three broad categories:

1. (Naturally) light Higgs

Mass protected by an approximate shift symmetry

2. Heavy Higgs

Higgs as a composite field of a new strong interaction
(with no extra symmetry to protect its mass)

3. No Higgs (no physical spin-0 particle)

Unitarity recovered via other states

There are ways of interpolating among the three classes

There are also higher-dimensional models, trying to link the Fermi and KK scales (ADD, RS, Higgsless, gauge-Higgs,…)
Correspondence with 4D models via `holography'
(phenomenological application of AdS/CFT)

Extra dimensions: generalities & ADD

Naturally predicted by string theory, but no prediction about their size (mass scale m_{KK} of first KK excitations)

Idea: relate m_{KK} (or M_S or M_D) to the TeV scale (hierarchy)

$\Downarrow$

potentially relevant for LHC (KK excitations of SM fields)

Dynamical problem: understand origin & stability of m_{KK}

(A)ADD models: $M_{KK} << \text{TeV}$ (very large volume)

flat bulk with gravity only, M_D~TeV, SM on 3-brane

Simplest versions suffer strong astrophysical constraints and essentially uncalculable effects of virtual KK particles

Signals of KK gravitons potentially detectable at colliders:

Photons + missing energy, mono-jets + missing energy

SM in flat extra dimensions

Often discussed, for simplicity, in D=5 on S^1/Z_2

May be combined with susy broken in the compactification

(i)

Gauge bosons in the bulk, fermions and Higgs on 3-brane

Very strong bounds from EW precision data

Indirect sensitivity can be pushed further at the LHC

(ii) Universal Extra Dimensions

All SM fields in the bulk with flat profiles

P_5 conservation broken to discrete KK-parity

➔ No single production and TL exchange of KK-odd

➔LKP stable and possible Dark Matter candidate

Tevatron: M_{KK}>3-500 GeV   LHC sensitive to M_{KK}~1.5 TeV

Randall-Sundrum type models

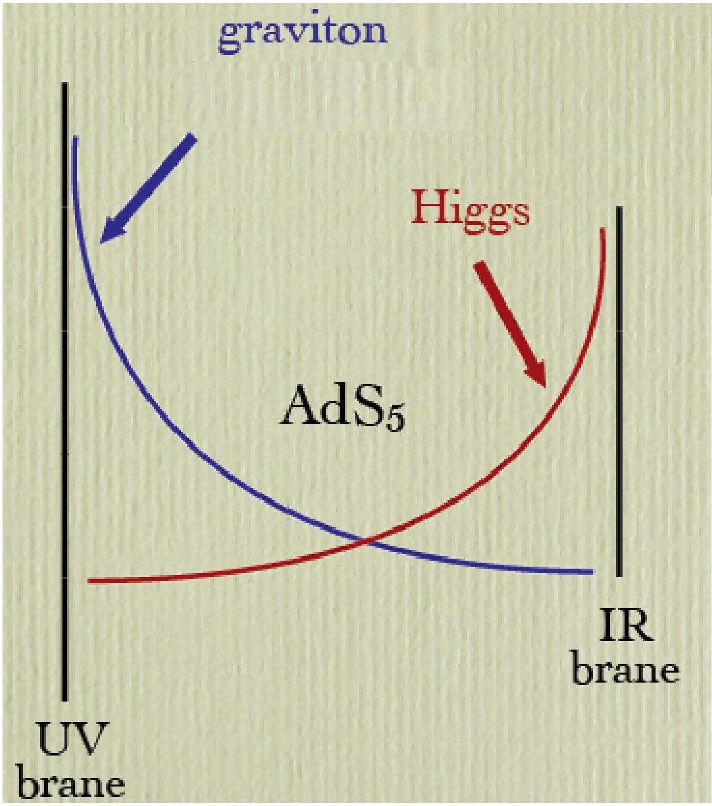
M_W/M_P hierarchy related with warp factor ~ exp($-M_PR$)

highly curved (AdS_5) background cut-off by 2 branes

Graviton near UV brane, Higgs field on (near) IR brane

`Holographic' interpretation: bulk fields elementary,

Higgs (partially) composite of localized strong interaction



$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

$k \sim M_{Pl}$

$k\, e^{-2k\pi R} \sim \text{TeV}$

$0 \leq y \leq \pi R$

Some (ongoing) effort needed to pass precision tests: SM gauge fields in the bulk, arrange for custodial symmetry, flavour breaking via fermion profiles or back to MFV for localized fermions

Signatures for the LHC:

- KK gluon (t-tbar pairs) up to 5 TeV
- KK graviton (ttbar, ZZ)

Little Higgs Models

[Georgi-Kaplan; ArkaniHamed-Cohen-Georgi; …]

- Higgs is light because GB of a global symmetry (G→H)
- Explicitly breaking (PGB) for quartic/Yukawa couplings
- Collective symmetry breaking → mass only at two loops

$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2 \quad \delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2$$

quadratic divergences cancelled by same spin partners (heavy top, gauge bosons, scalars at the scale f ~ 1 TeV)

Cut-off scale pushed to $\Lambda \sim 4\pi f \sim 10\ TeV$

- Problems with EW precision tests (need to introduce custodial symmetry + T-parity + extra complications)
- A potential dark-matter candidate (LTP)
- LHC signals similar to supersymmetry (R → T)

Gauge-Higgs unification

[Manton; Hosotani; …]:

Higgs boson = extra-dimensional component of gauge field

Needs G larger than SU(2)xU(1) to obtain a doublet Higgs

G can be broken to SU(2)xU(1) by (field-theory) orbifold

Local Higgs mass terms forbidden by D>4 gauge invariance

Finite contributions to m_H only upon compactification

In flat space, problems with EW & flavour PT, m_t, m_h, m_{KK}

Again, custodial symmetry and warped background can help

e.g. SO(5)➔SO(4) by orbifolding has custodial symmetry

Group structure of models very similar to Little Higgs:

correspondence via "deconstruction" and "mooses/quivers"

(Light) Composite Higgs Models

[Agashe-Contino-Pomarol; …]

Strong dynamics with global G➔H at a scale f ~ 1 TeV

Composite light PGB Higgs doublet in G/H

$SU(2)_L xU(1)_Y$ in H, broken by Higgs VEV $v < f$

Example:

$SO(5)xU(1)_{B-L}$ ➔ $SO(4)xU(1)_{B-L} \sim SU(2)_L xSU(2)_R xU(1)_{B-L}$

Phenomenology:

hVV couplings suppressed by $Sqrt[1-v^2/f^2]$

Unitarity violation $A(VV) \sim s/f^2$

(partially) compensated by KK vector boson exchanges

Need also "KK quarks" to keep the Higgs light

Q_{KK} ➔ $Q_3 V$, $Q_3 h$ where Q_3 = top or bottom quark

Interpolate between SM and Technicolor:

SM: $v/f=0$ TC: $v/f=1$

Can we make it without a Higgs boson?

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

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

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

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

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

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

No-lose theorem and technicolor

$A(W_L W_L)$ saturate unitarity at $E \sim 4\,\mathrm{pi}\, m_W/g \sim 1.2$ TeV

Effective description: electroweak chiral Lagrangians
SU(2)xU(1) non-linearly realized: GB only & no Higgs
Uncalculable contributions to EW precision tests
Typical size too large to agree with present data

Anyway, new states must appear to restore unitarity

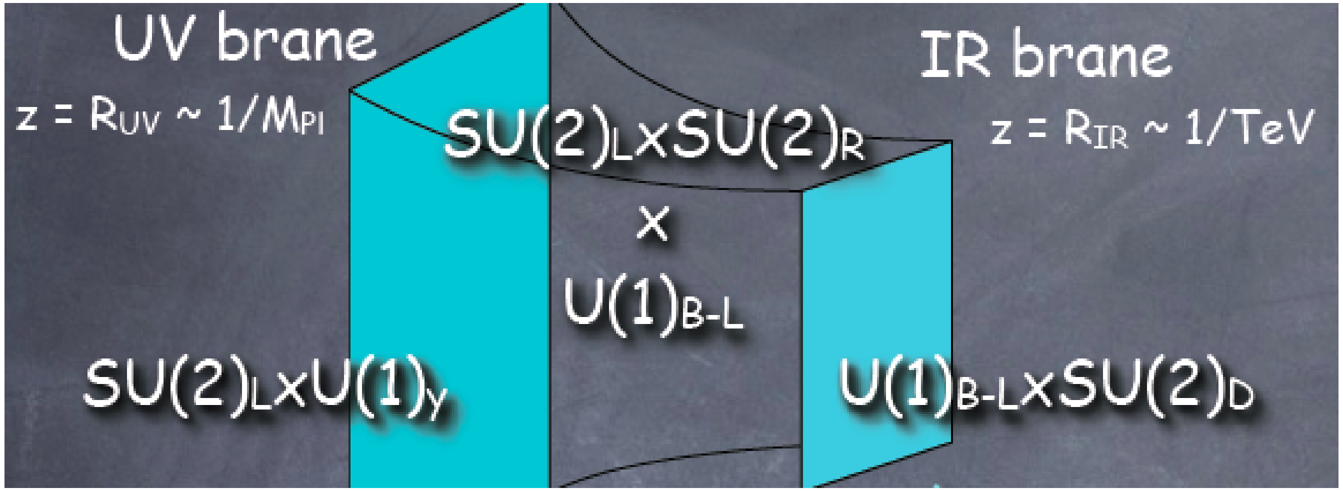
Traditional models with no Higgs: technicolor
(and extended technicolor for flavour breaking)
The `Goldstone' bosons in (W_L,Z_L) are bound states of a new (QCD-like?) strong interaction (see superconductors)
Unitarity restored, e.g., by a vector techni-rho resonance

strongly disfavoured by EW+flavor precision tests
(if QCD-like, otherwise uncalculable non-pert. dynamics)

Higgsless models in extra dimensions

[Csaki, Grojean, Murayama, Pilo, Terning 03; …]

Unitarity `postponed' by KK resonances of SM gauge fields
(the main phenomenological signature at the LHC)
Serious problems with EW precision tests: only partially
solved with custodial symmetry and warped background



Like a RS model with bulk gauge fields but no Higgs
EW gauge symmetry broken by boundary conditions

LHC signals: qq→qqV_{kk}, q qbar→V_{kk} with V_{kk}→VV, t tbar

BSM variations in the gauge sector:

Extra U(1) factor ➔ massive neutral Z′ boson

Pragmatic motivation: "easy" (?) LHC signal Z′ ➔ $l^+ l^-$

Theory motivation #1: rank > 4 GUTs [SO(10) , E_6 , …]

e.g. SO(10) ➔ $SU(3)_C x SU(2)_L x SU(2)_R x U(1)_{B-L}$ ➔ $SU(3)_C x SU(2)_L x U(1)_Y x U(1)_{Y'}$ with Higgs in the 45

Theory motivation #2: type-II models with D-branes

e.g. N parallel D-branes: U(N) ➔ SU(N) x U(1)

Multiple U(1) factors frequent in realistic models

Residual U(1)s can be anomalous/non-anomalous

Discuss now for simplicity non-anomalous SO(10) case

borrowing from [Contino, 0804.3195] and refs therein

LEP bounds on Z′

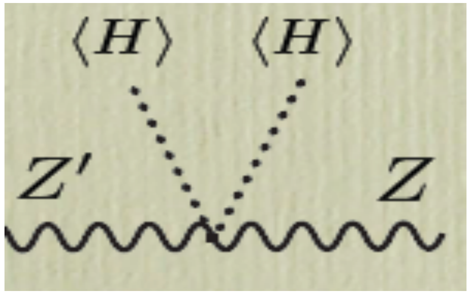
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu$$ (diagonal kin. and mass term)

$$+ g_{Z'} Z'_\mu \sum_f \bar{f} z_f \gamma^\mu f + g_{Z'} (H^\dagger z_H Z'_\mu i D^\mu H + h.c.) + \ldots$$

(couplings to SM fermions) (Z-Z′ mixing after EWSB)

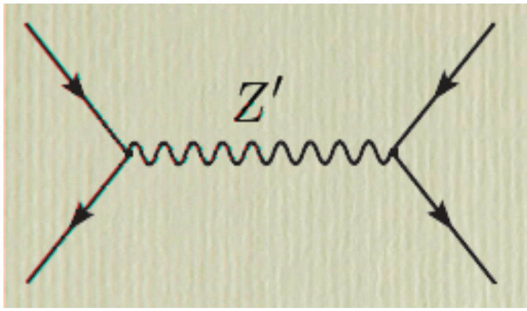
LEP-1 Z-pole data mostly constrain Z-Z′ mixing

$$|\theta| < \mathcal{O}(10^{-3})$$



$$\theta \sim \frac{g_{Z'}}{g_Z} \frac{M_Z^2}{M_{Z'}^2} z_H$$

LEP-2 (off-pole) data constrain 4-fermion effective operators



$$\sim \frac{g^2_{Z'}}{M^2_{Z'}} z_e z_f$$

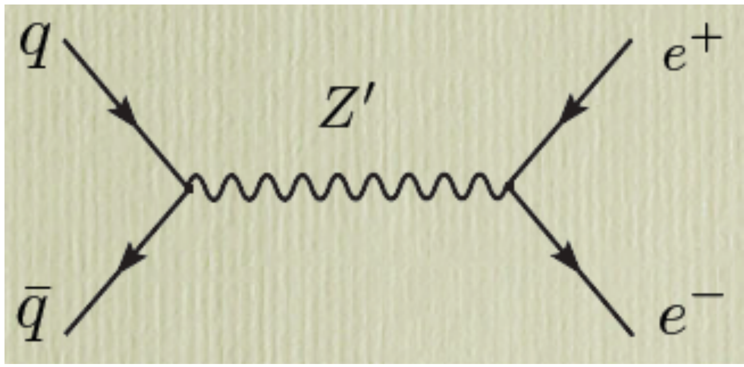
Tevatron bounds on Z′

More difficult to parametrize in a simple way!

Typical bounds are on $\sigma(Z') \cdot BR(Z' \to l^+ l^-)$

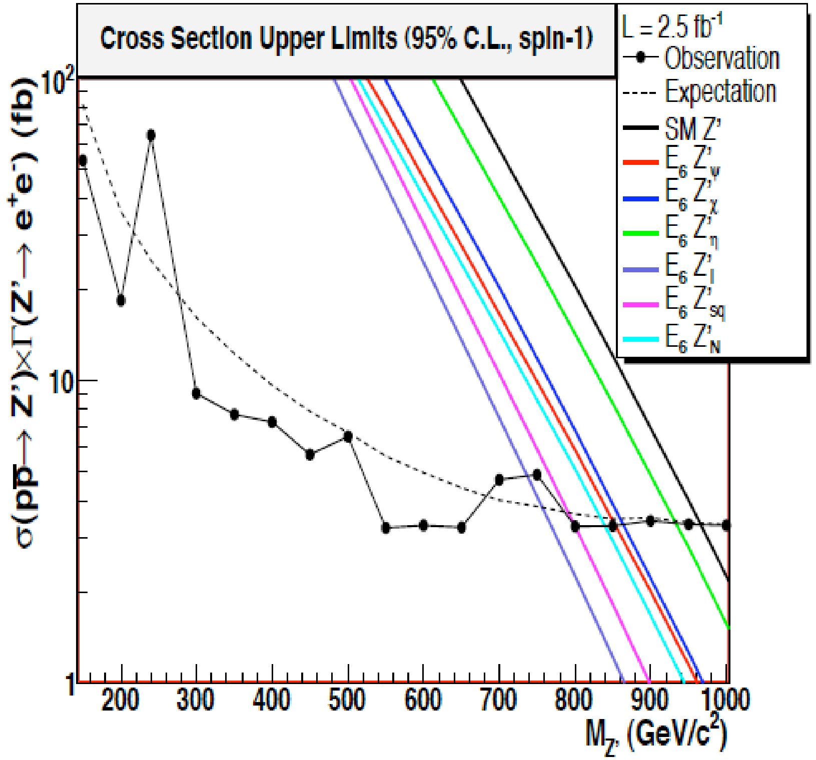
But (already at leading order):

$$\sigma(Z') = g_{Z'}^2\, f(z_q, z_u, z_d, s, M_{Z'}^2)$$



where f depends on the PDF

CDF Run II Preliminary

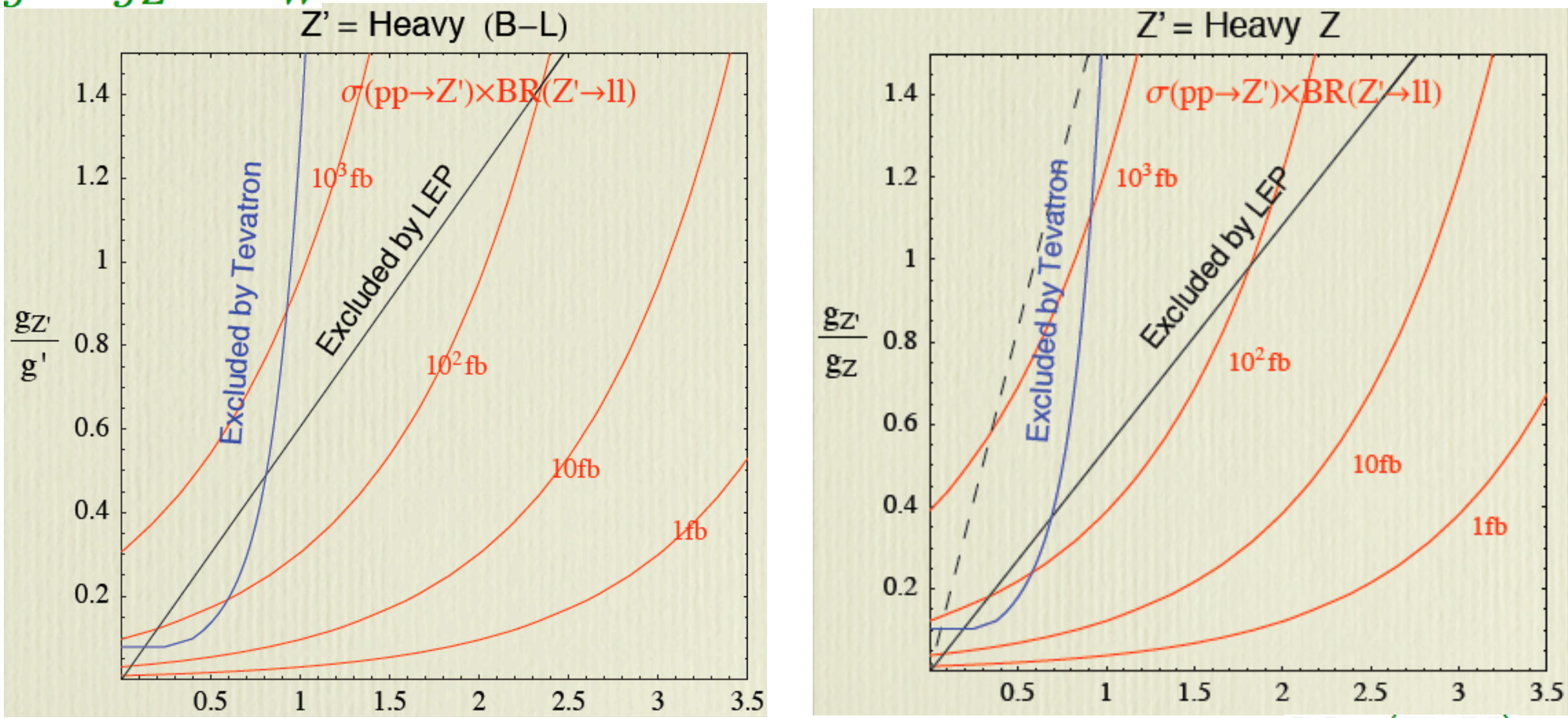


Really an "easy" LHC signal?

Normalization of $g_{Z'}$ and identity of Y' model-dependent

A couple of purely representative plots is given below

$g' = g_Z \sin\theta_W$



[Contino, Perugia 08] $M_{Z'}(TeV)$

What is sure vs. likely vs. possible

Sure:

the Higgs mechanism breaks the EW gauge symmetry, with either a Higgs particle with mass < 1 TeV, or a strongly interacting sector with new physics below a couple of TeV

New states must appear at the TeV scale (beyond the SM states we have already observed)

Very likely:

there is at least one Higgs particle with mass $\ll 1$ TeV

Likely:

Higgs particle is accompanied by new physics at the TeV scale to preserve naturalness.

Supersymmetry (perhaps MSSM) still the best candidate, insufficient confidence to ignore other possible candidates

Non-trivial to be as successful phenomenologically as the SM!

(Temporary) conclusions

- Data alone favour a light SM Higgs and no new physics at the TeV scale, but not in a completely clear-cut way

- Naturalness can still be used as strong guiding principle
- It unambiguously predicts new physics at the TeV scale
- Precision tests: new physics must have special properties

- Supersymmetry still the most plausible candidate, but we would have expected it to show up already!
- We may be missing important aspects of susy breaking

- Healthy to have alternatives for new physics at the LHC

Outlook

Today, no model of new physics fully satisfactory
(naturalness vs. precision tests, and more)

- At the SpS (discovery of the W and Z bosons) all their relevant properties were known before
- At the Tevatron (discovery of the top quark) there was only a 30% uncertainty on its mass
- At the LHC, we know that something must be there, but we (theorists) are still unable to tell exactly what Analogy between the QCD scale and the Fermi scale

LHC experimentalists will be soon in a privileged position: may take the lead in defining the input for a new more fundamental theory replacing the SM! And the active generation of theorists will have the opportunity to find it!