The Hierarchy Problem : It's Solutions (?) and Their Collider Signatures

* * *

- Succeses of the Standard Model
- What IS the Hierarchy Problem?

  $\Rightarrow$ Related Problems.... { Fine-tuning
EWSB
⋮

- Possible 'Solutions'...
- Signatures at future colliders...

  LHC and LC...

- Summary / Conclusions

T.G.Rizzo
11/03

The Standard Model of Particle Physics

Symmetry: $\overset{(QCD)}{SU(3)_C} \times \overbrace{\underbrace{SU(2)_L \times U(1)_Y}_{EWK}}^{\text{Spontaneously broken}}$

Particles: **spin-1/2 "matter" fermions**

- 3 Generations of Quarks ($N_C = 3$)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- 3 Generations of Leptons ($N_C = 1$)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

spin-1 gauge bosons – "force carriers"

- 8 gluons (*g*) mediate strong interactions
- Photon (γ) mediates electromagnetism
- $W^\pm$ and Z mediate the weak interactions

⟶ [Higgs boson ?]

This structure is experimentally confirmed!

? ⟶ GRAVITY ??

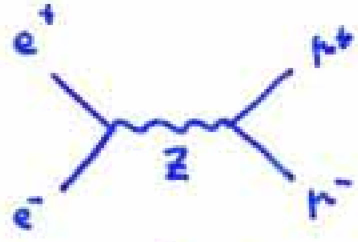
The SM generally agrees w/ precision data at the <u>0.1%</u> level or better...†

$\left\{ \begin{array}{l} M_W|_{Th} \simeq 5\text{ppm} \\ m_W|_{exp} \simeq 44\text{ppm} \end{array} \right\}$

→ full 1-loop calculations completed

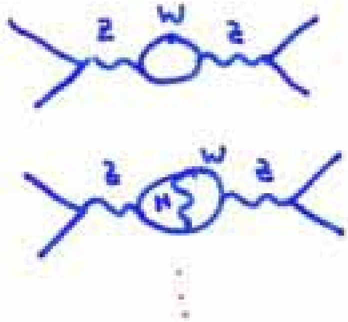
→ almost all 2-loop + many important 3-loop diagrams calculated....

(QED : $(g-2)_e$ has been done to 4-loops !!
but the SM is *much* *more* complicated !)



'tree' level

$O(\alpha)$



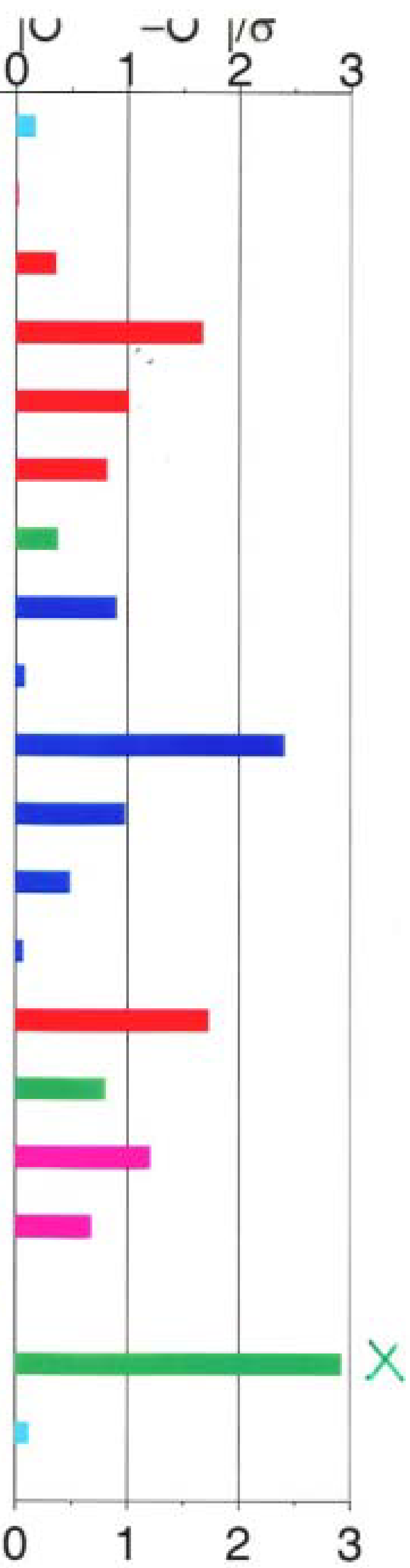
$O(\alpha^2)$ 1-loop

$O(\alpha^3)$ 2-loop *etc*

- *However* many issues still remain .. as do *many* unanswered questions....

† + plans to go another factor of 10 in future collider experiments

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90



Collider data from LEP / SLC
+ Tevatron
⊕ DIS + APV

"Why is gravity so much weaker than EM ?"

In SM language this is rephrased ...

$$\text{Why is} \quad \underbrace{M_{planck} \simeq \sqrt{G_N^{-1}}}_{\sim 10^{19}\ \text{GeV}} \gg \underbrace{M_{weak} \simeq \sqrt{G_F^{-1}}}_{\sim 1\ \text{TeV}} \ ?$$

→ the (gauge) Hierarchy problem $(10^{15}!)$

- Another (related ?) problem :

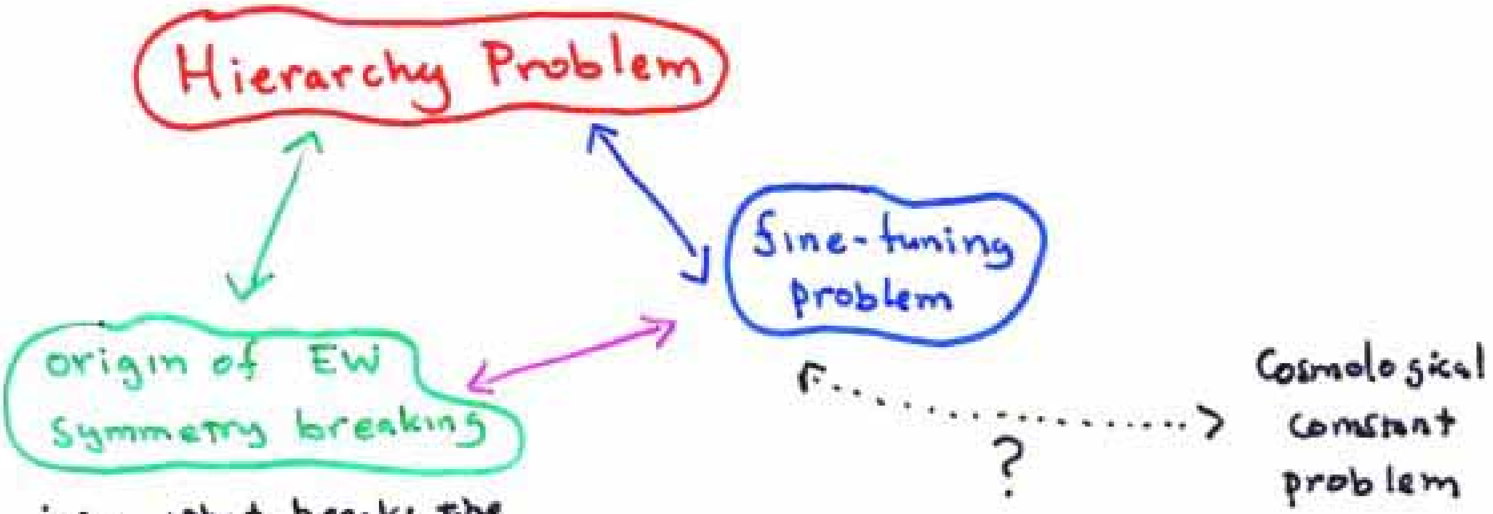
$$\Big[\Lambda_{\substack{cosmological\\constant}}\Big]^{1/4} \sim M_{pl} \longleftrightarrow \text{the only scale in GR!!}$$

$$\underline{\text{instead}} \qquad \sim 10^{-3}\ \text{eV}! \qquad (10^{120}!)^{1/4}$$

Note the curiosity : $M_{pl}\left(M_W/M_{pl}\right)^2 \sim 10^{-3}\ \text{eV}$!

⇒ is This telling us something ??

- The HP is related to other issues in the SM ..... many 'solutions' deal with these.



i.e, what breaks the symmetry at ~1TeV?

(if unbroken, no HP!)

loop correction in SM w/ cutoff Λ : $\sim \int^{\Lambda} \frac{d^4k}{k^4} \cdots$

large loop momenta

momentum flowing in a loop Feynman graph

gauges : $\frac{\delta m_W^2}{m_W^2} \sim \frac{\alpha}{4\pi} \ln \frac{\Lambda}{m_W}$

fermions : $\frac{\delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \ln \Lambda / m_e$

∴ are '<u>log-sencitive</u>' to cut-off. Even if $\Lambda \sim M_{pl}$ these corrections are not <u>too</u> large since $\frac{\alpha}{4\pi} << 1$

- Logs occur because of gauge/chiral symmetries
- What about the Higgs scalar† in the SM?

No protection!

† naive method of EWSB

$$m_H^2 = m_{H_0}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}\,\underset{\uparrow}{\Lambda^2}\left\{m_H^2 + 2m_W^2 + m_Z^2 \overset{\text{N.B.!}}{\swarrow} - 4m_t^2 + \cdots\right\}^{\dagger}$$

QUADRATICALLY sensitive to Λ !!

We expect $m_H \sim 125\,\text{GeV}$ or so in SM [Fig]

if $\Lambda \sim M_{Pl}$, $m_{H_0}^2 + C\{\ \}$ have to cancel by <u>30</u> significant figures!

<u>Fine-tuning problem</u> : Clearly

$$\text{EWSB} \leftrightarrow \underset{\text{scale}}{\text{TeV}} \longleftrightarrow \underset{\text{tuning}}{\text{fine}} \longleftrightarrow \text{H.P.}$$

if $m_H \sim m_{Pl}$ no problem!

'Solutions' clearly link all 3 problems

$\dagger$ and $m_H^2 + m_Z^2 + 2m_W^2 - 4m_t^2 \cdots \neq 0$!

not allowed by <u>data</u> (this is fine-tuning too!)

⊕ want to remove these divergences at higher order as well

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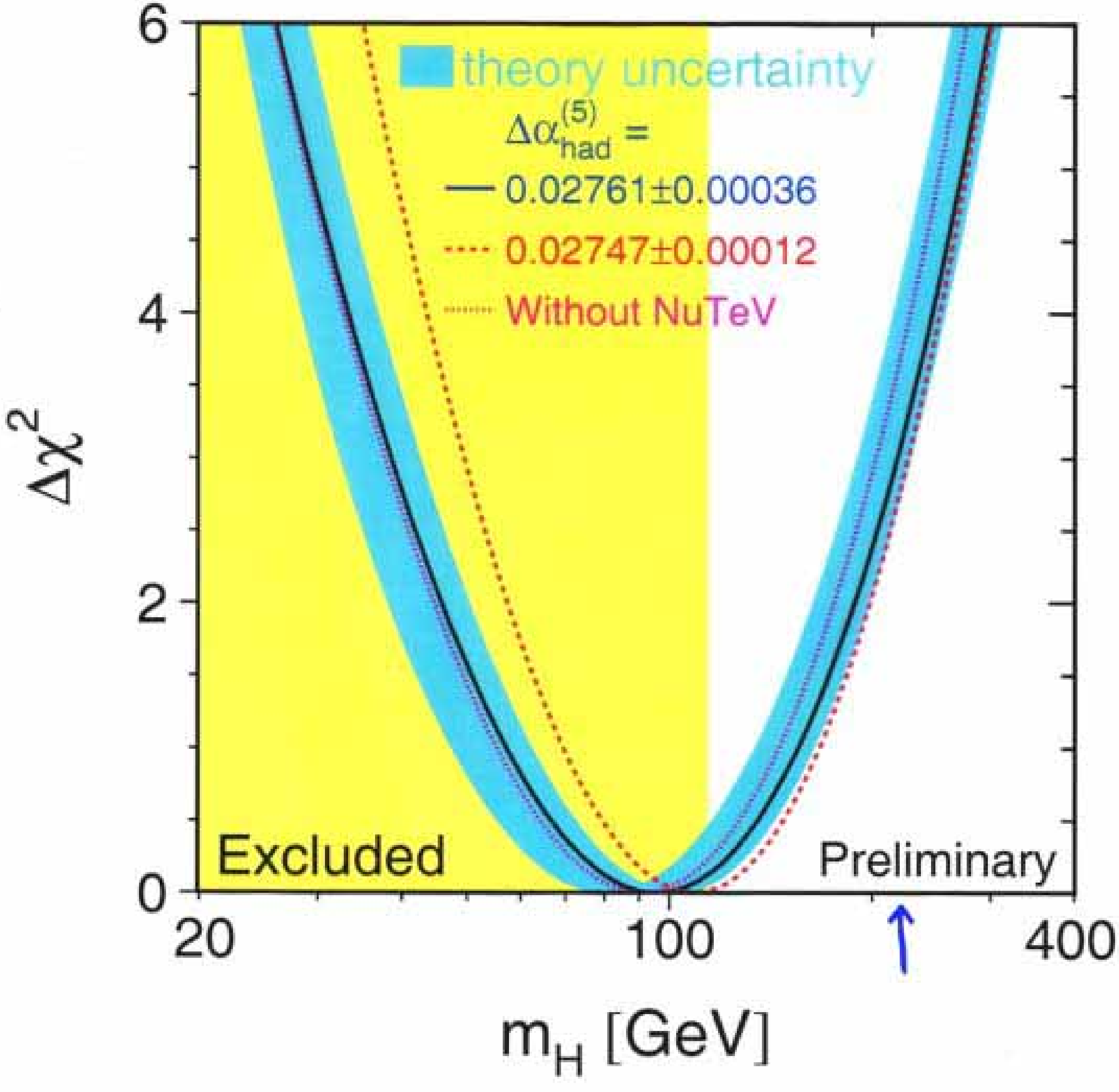
The SM ⊕ existing data places a strong upper bound on $m_H \lesssim 219$ GeV.

Direct searches → $m_H \gtrsim 114$ GeV.



How do we get

$$\frac{3G_F}{4\sqrt{2}\pi^2}\Lambda^2\left\{\cdots\right\} \sim (100\text{-}200\ \text{GeV})^2 \quad ?$$

"Solutions"

perturbative weakly-coupled dynamics { Supersymmetry (SUSY) ['80]†
"Little Higgs" (LH) ['02]

Idea: add a symmetry { and new particles associated with it } to make $\Lambda \to \log \Lambda^2$

Strong dynamics: { technicolor ['79]

Idea: replace Higgs by condensates - not favored by EW data - won't discuss here

avoid the problem { M_{pl} is really ~ few TeV ['95]
no Higgs at all : warped ED w/ mixed BC ['03]

(rather complicated)

$\dagger$ most 'familiar'

‡ They couple exactly the same as do SM fields - only differ by spin-½ + mass

New particles in SUSY Theory †, ‡

- Spin ½ quarks ⇒ spin 0 squarks
- Spin ½ leptons ⇒ spin 0 sleptons
- Spin 1 gauge bosons ⇒spin ½ gauginos
- Spin 0 Higgs ⇒spin ½ Higgsino

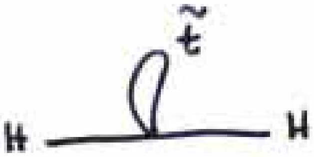
} neutralinos
charginos

Experimentalists dream….many particles to search for!

What mass scale?

Supersymmetry is broken….no scalar with mass of electron

† recall we 'doubled' the # of particles before thanks to Dirac
- anti particles !!



subleading term

$$\Delta m_H^2\Big|_{top} \sim \alpha\left\{\Lambda^2\left(m_t^2 - m_t^2\right) + N\left(m_{\tilde t}^2 - m_t^2\right)\ln\frac{\Delta}{M_W} + \dots\right\}$$

top loop

Stop loop ⟷ (same couplings)

recall fermion sign

kinematic mass in loop

cancels!

$$\Delta m_H^2 \sim \underbrace{|m_{susy}^2 - m_{sm}^2|}_{\text{can't be too big}} \ln \Lambda/M_W$$

$\lesssim$ TeV or so

$\boxed{\text{now}}$

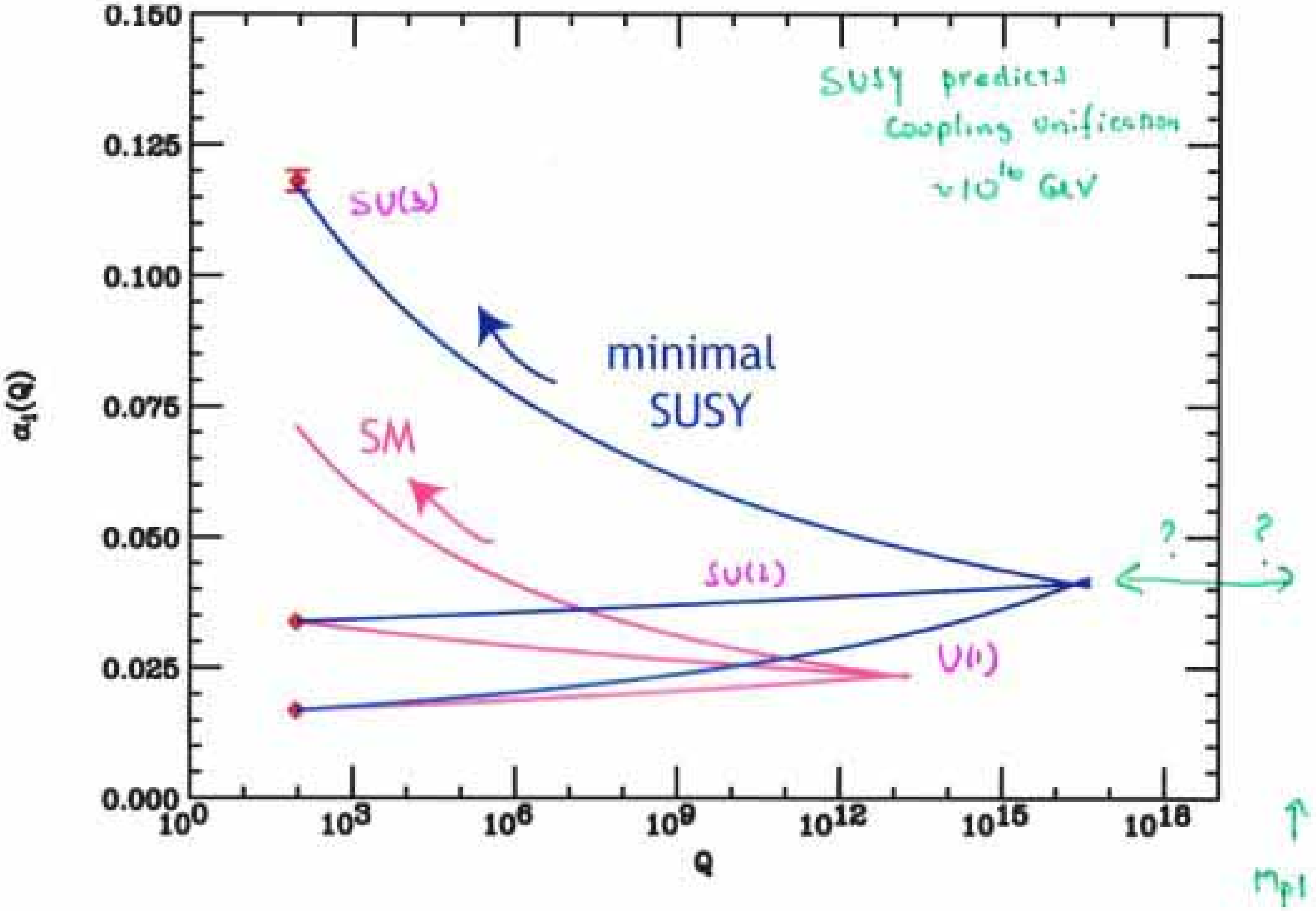
In fact: no $\alpha^n\Lambda^2$ terms <u>at all</u>

If $m_{susy} = m_{sm}$ $\Delta m_H^2 = 0$! but $m_{susy} \neq m_{sm}$!

SUSY is a <u>broken</u> symmetry - how ??

(many ideas...)

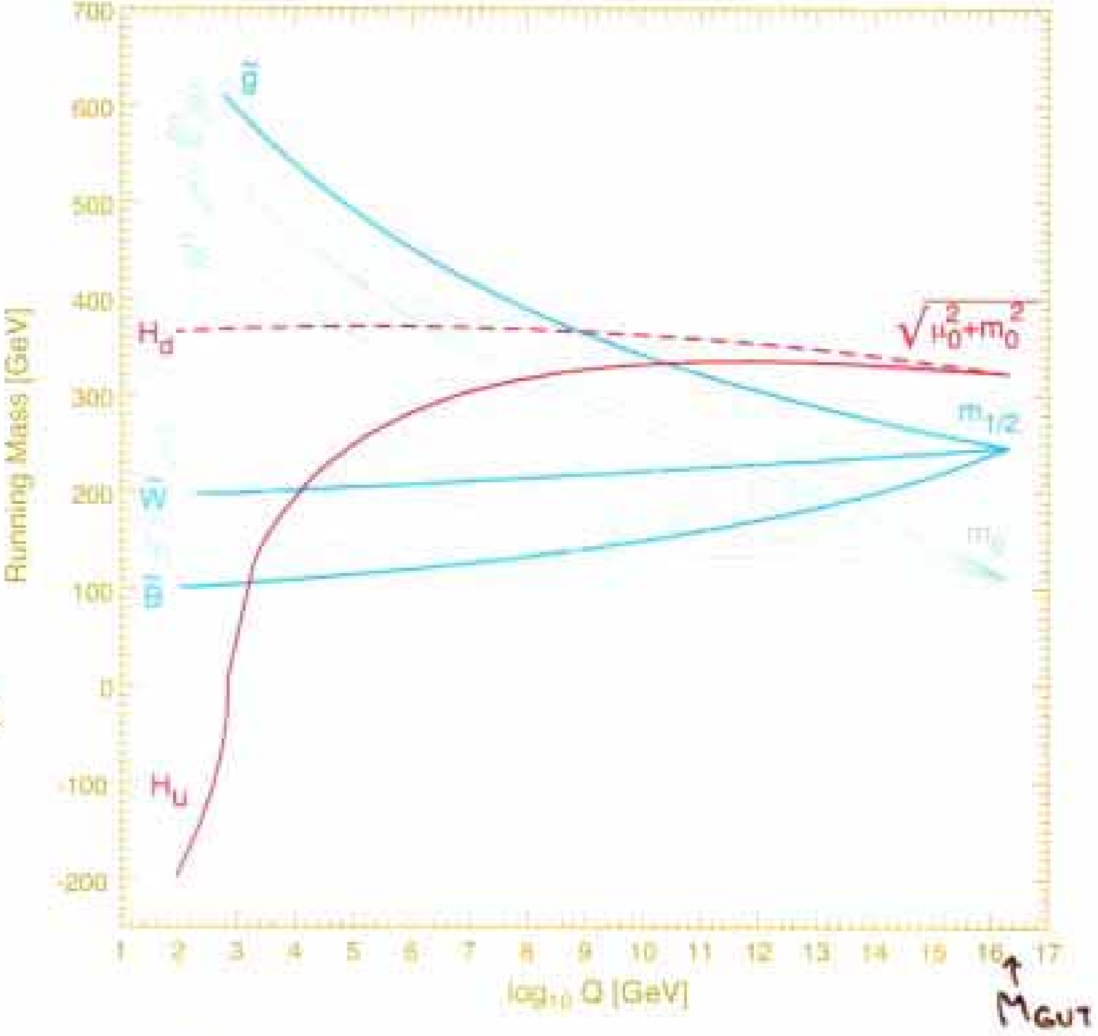
- Nice things about SUSY :
  - allows for <u>coupling unification</u> $M \sim 10^{16}$ GeV
  - 'radiative' breaking of SM via RGE and big $m_{top} \simeq 175$ GeV



SUSY predicts coupling unification $\sim 10^{16}$ GeV

For heavy top, SSB may follow naturally in SUSY

Higgs
mass driven
negative
by RGE



... (sign of M^2 indicated)

Kane, *et al.* (hep-ph/9312272, *Phys. Rev. D***49**, 6173 (1994))

(cont)

- Perhaps a better fit to Precision data (?)
- Lightest SUSY particle (χ^0_1) is a dark matter candidate
- Should be found at LHC / LC (linear e^+e^- collider)

$\rightarrow$ discover it at LHC...

measure masses / spins / couplings at LC

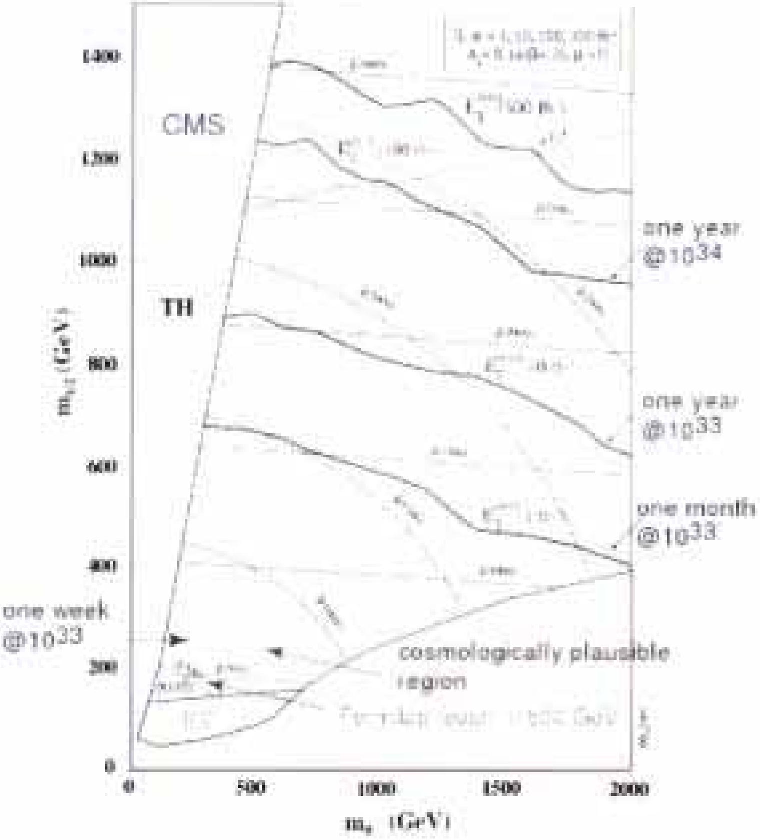
+ verify its SUSY!

- link to Superstrings

SUSY 'stabilizes' the hierarchy but does not explain why it occurs... nor why it is a broken symmetry

If no SUSY signs at LHC - theory probably dead!

•LHC/Tevatron will find SUSY



Catania, CMS

- Discovery of many SUSY particles is straightforward
- Untangling spectrum is difficult

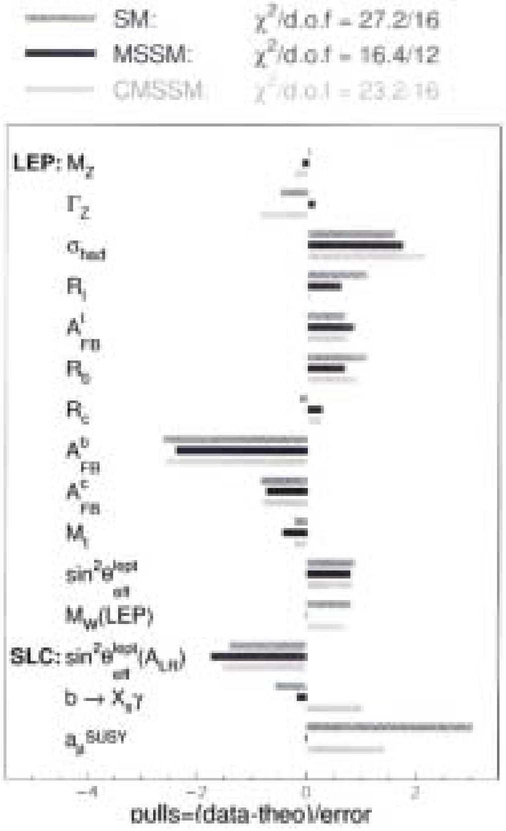
  ⇒ all particles produced together
- SUSY mass differences from cascade decays;eg

$$\tilde{q}_L \rightarrow \tilde{\chi}_2{}^0 q \rightarrow \tilde{l}^{\,\pm} l^{\mp}$$
$$\rightarrow \tilde{\chi}_1{}^0 l^+ l^- q$$

- $M_{\chi 0}$ limits extraction of other masses

Precision measurements can't tell you source of new physics

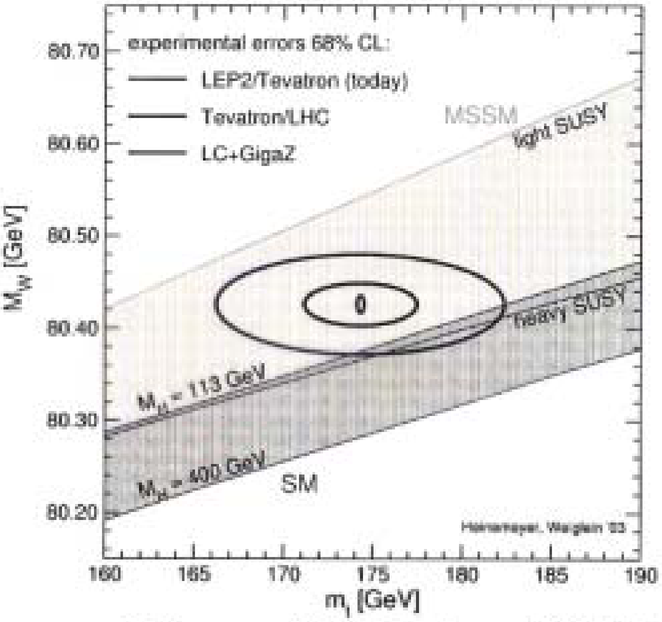
- Example: try to fit precision data to MSSM



deBoer & Sanders, hep-ph/0307049

MSSM slightly better fit (17% prob)
vs SM (5% prob)

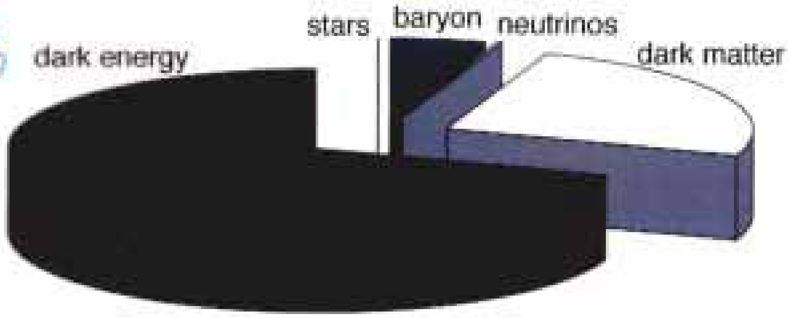
MSSM prefers "light" SUSY



Heinemeyer & Weiglein, hep-ph/0307177

What is the universe made of?

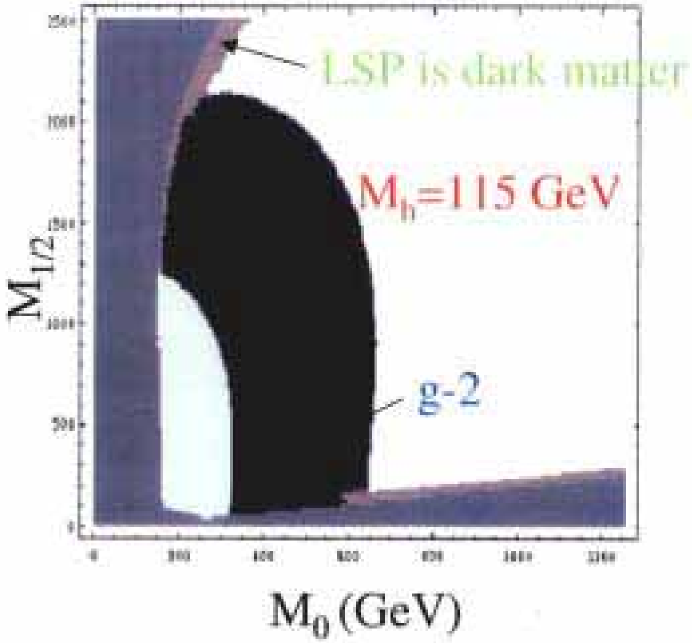
- Stars and galaxies are only 0.1%
- Neutrinos are ~0.1–10%
- Electrons and protons are ~5%
- Dark Matter ~25%
- Dark Energy ~70%



H. Murayama

Supersymmetry provides understanding of dark matter?

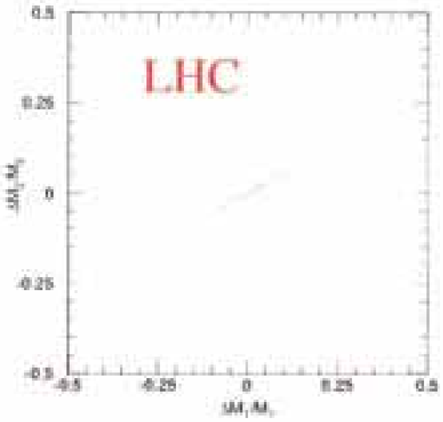
- Lightest SUSY particle (LSP) could be dark matter candidate!
- LSP is weakly interacting, neutral, and stable
- LSP in range of LC/LHC
- LC can determine LSP mass; check dark matter predictions



Drees, hep-ph/0210142

LHC & LC improves SUSY mass resolution

- LSP mass constrained at LHC at 10% level



Bachacou, Hinchliffe, Paige, hep-ph/9907518

⇒LC input improves accuracy significantly

- Take LSP mass as input from LC

(GeV)	LHC	LHC+ LC(.2%)	LHC+ LC (1%)
$\Delta m(\tilde{\chi}_1^0)$	9.2	.2	1
$\Delta m(\tilde{l}_R)$	9.2	.5	1
$\Delta m(\tilde{\chi}_2^0)$	9.0	.3	1
$\Delta m(\tilde{b}_1)$	23	17	17
$\Delta m(\tilde{q}_L)$	15	5	5

Weiglein, LHC/LC Study

Little Higgs : less ambitious → "Higgs is a pseudogoldstone boson of a non-linearly realized broken symmetry." - whoa!

Global symmetry G broken (G → H) → massless Goldstone bosons → radiative masses for GB generated PGB

now 'gauge' a subgroup of H

Enlarge symmetry of Higgs field → extra matter couplings

looks like SUSY

But these guys have the <u>same</u> spin as SM ones! w/ opposite sign couplings [careful group theory]

- New particles at $\sim 4\pi M_{weak} \sim$ 1-3 TeV
- New 'scale' at $\sim (4\pi)^2 M_{weak} \sim$ 10-20 TeV $= \tilde{\Lambda}$

$$\Delta m_H^2 \sim \alpha \left\{ 0 \cdot \tilde{\Lambda}^2 + N \ln \tilde{\Lambda}/m_W \right\} + N' \alpha^2 \tilde{\Lambda}^2$$

$\tilde{\Lambda}^2$ terms pushed to 2-loops ∴ small if $\tilde{\Lambda} \lesssim$ 10-20 TeV

Delays H.P. until after $\tilde{\Lambda}$ ... new theory is required.. - not a real 'solution'

↳ " Ultraviolet Completion '

→ Why is $\tilde{\Lambda}$ ($\sim$ 10-20 TeV) present + not M_{pl} ?

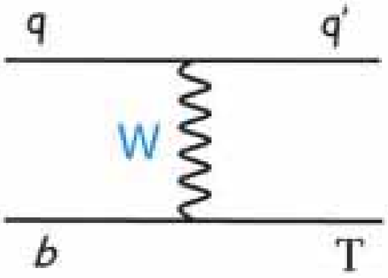
" The SM is not applicable above $\tilde{\Lambda}$." Hmmm...

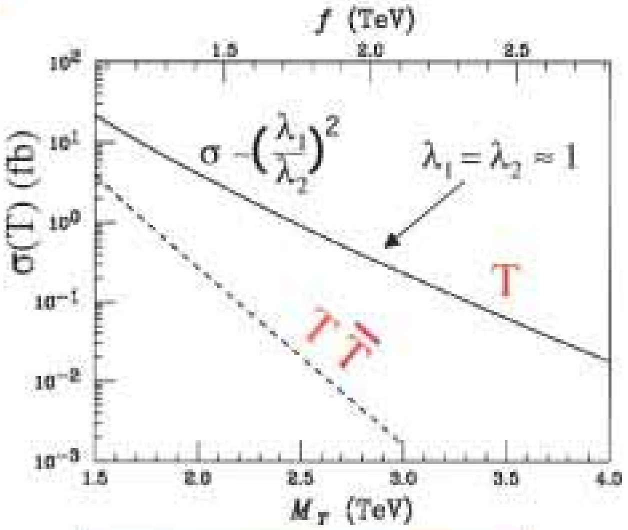
⇒ To test the scenario, find t', W', Z' etc at ~ TeV w/ right couplings.

This can be done at LHC / LC ....

heavy top T

- Production mechanism = Wb fusion





BR

- $T \to bW$ 50 %
- $T \to tZ$ 25 %
- $T \to th$ 25 %

λ_1, λ_2 Yukawa couplings

$$\frac{\Gamma}{M} \approx \frac{1}{16\pi} \approx 2\ \%$$

Search for Z_H

$q\bar{q} \longrightarrow Z_H \longrightarrow e^+e^-$

$\mu^+\mu^-$ not used due to invariant mass resolution

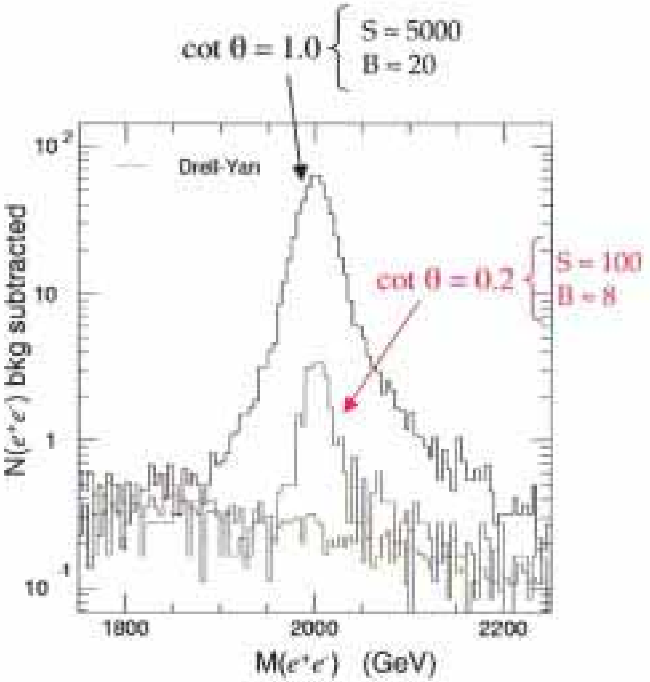
Selection cuts:

- 2 isolated electrons with $p_T > 20$ GeV and $|\eta| < 2.5$
- minimum invariant mass equal to 800 GeV

Background:

Drell-Yan ($q\bar{q} \rightarrow Z/\gamma \rightarrow e^+e^-$)
other bkg's are under evaluation

$M(Z_H) = 2$ TeV $\quad \mathcal{L} = 3\cdot10^5$ pb^{-1}

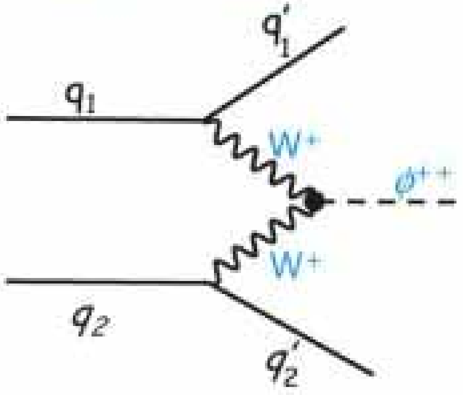


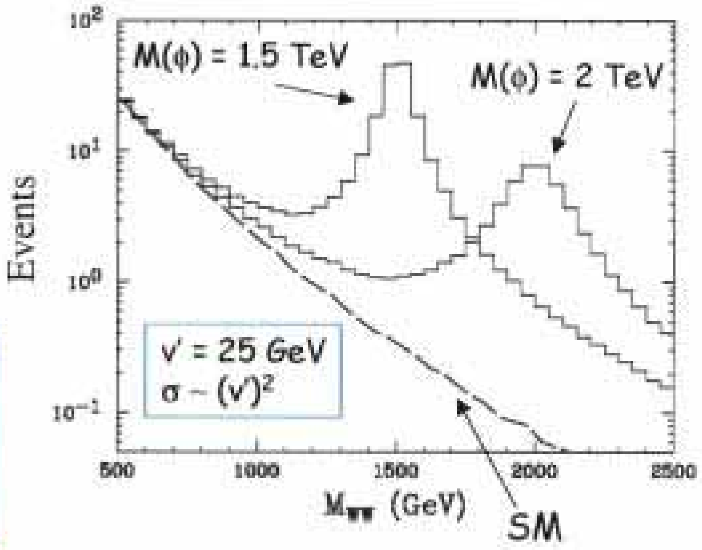
New Higgs ϕ^{++}

- Production: VBF mechanism
(vector boson fusion)

$L = 3 \cdot 10^5$ pb^{-1}

$W^+W^+ \to \phi^{++} \to W^+W^+$



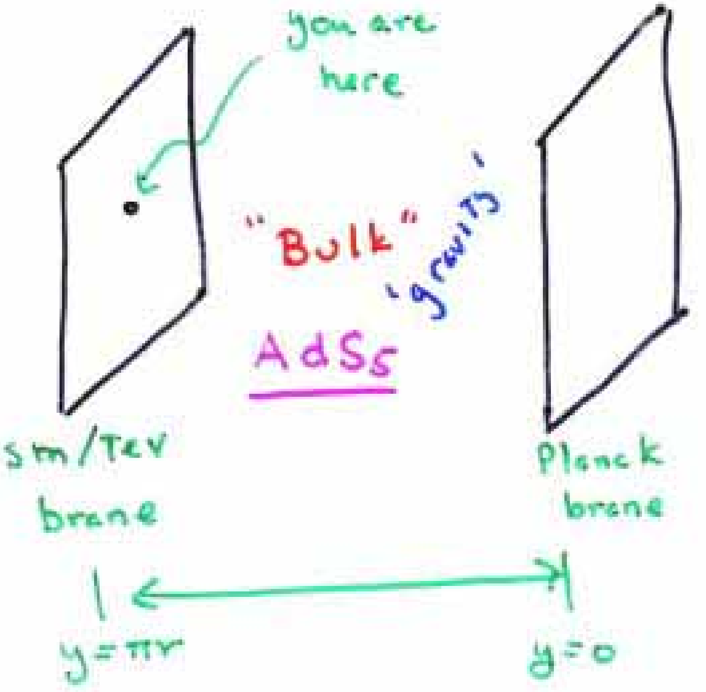


$$\text{Decays}\begin{cases}\phi^{++} \to W^+W^+ \\ \phi^{++} \to \underbrace{\tau^+\,\tau^+, e^+e^+, \ldots}_{\text{might be suppressed}}\end{cases}$$

To 'avoid' the HP we need Extra Dimensions!

Randall - Sundrum

set-up



- 2, 4-d surfaces 'branes' in 1 extra finite dimension

- The space between is curved a la G.R.

  - anti deSitter Space (const. neg. curvature)

    $R = -20k^2$

    (Ricci curvature)

$$ds^2 = \underbrace{e^{-2ky}}_{\text{warp factor (!)}} \delta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

$$\boxed{k \sim M_{pl}}$$

→ Any mass$^{(M)}$ you write down is naturally $\sim M_{pl}$

BUT if $kr \sim 10$ we'd observe $m \sim e^{-kr\pi} M$

which is ~TeV. [Example]

[We can get $kr \sim 10$ naturally]

→ No large numbers! $\boxed{\Lambda \longrightarrow \text{TeV}}$

Hierarchy is an artifact of the warping of space

How do we test this ??

Kaluza-Klein Excitations : gravity is 'trapped' in the extra dim 'box' ⇒ momentum quantization

$$P^2 = \underbrace{p_\mu p^\mu}_{m^2} + \underbrace{p_5 p^5}_{\llcorner \text{ some quantized set of values}} \quad m_n^2$$

- If space were <u>flat</u> $\quad p_5 = n/r$ from <u>QM</u>
- Here we have AdS_5 $\quad p_5 = x_n k e^{-\pi k r_c}$

↳ $J_1(x_n) = 0$

a Bessel function !

graviton KK's ..

m_n^{KK} ~ few hundred GeV - few TeV

couple to matter as $\quad \sim \frac{1}{\Lambda_\pi} T_{\mu\nu} h^{\mu\nu}_{(n)}$

w/ $\quad \Lambda_\pi = M_{Pl}\, e^{-kr_c\pi}$

~ few TeV

These are massive, Spin-2 resonances you can see at a collider...

$$\boxed{\Lambda \to \Lambda_\pi}$$

- Spin-2
- Branching fractions

} is it a graviton KK ?

Imagine the Higgs field on the TeV brane..

$$S = \int d^4x \, dy \, \sqrt{-g} \left\{ g^{\mu\nu} \partial_\mu H^+ \partial_\nu H - \lambda \left(H^2 - v_0^2 \right)^2 \right\} \delta(y - \pi r)$$

$\sqrt{-g} \leftrightarrow \left\{ \left[e^{-2ky} \right]^4 \right\}^{1/2}$

$g^{\mu\nu} \leftarrow e^{2ky} \delta^{\mu\nu}$

$v_0^2 \uparrow$ Higgs vev $\sim M_{pl}$

$$S = \int d^4x \left\{ e^{-2kr_c\pi} \partial_\mu H^+ \partial^\mu H - e^{-4kr_c\pi} \lambda \left(H^2 - v_0^2 \right)^2 \right\}$$

let $H \to e^{kr_c\pi} \hat{H}$

$$S = \int d^4x \left\{ \partial_\mu \hat{H}^+ \partial^\mu \hat{H} - \lambda \left(\hat{H}^2 - \underbrace{v_0^2 e^{-2kr_c\pi}}_{\text{vev is TeV !}} \right)^2 \right\}$$

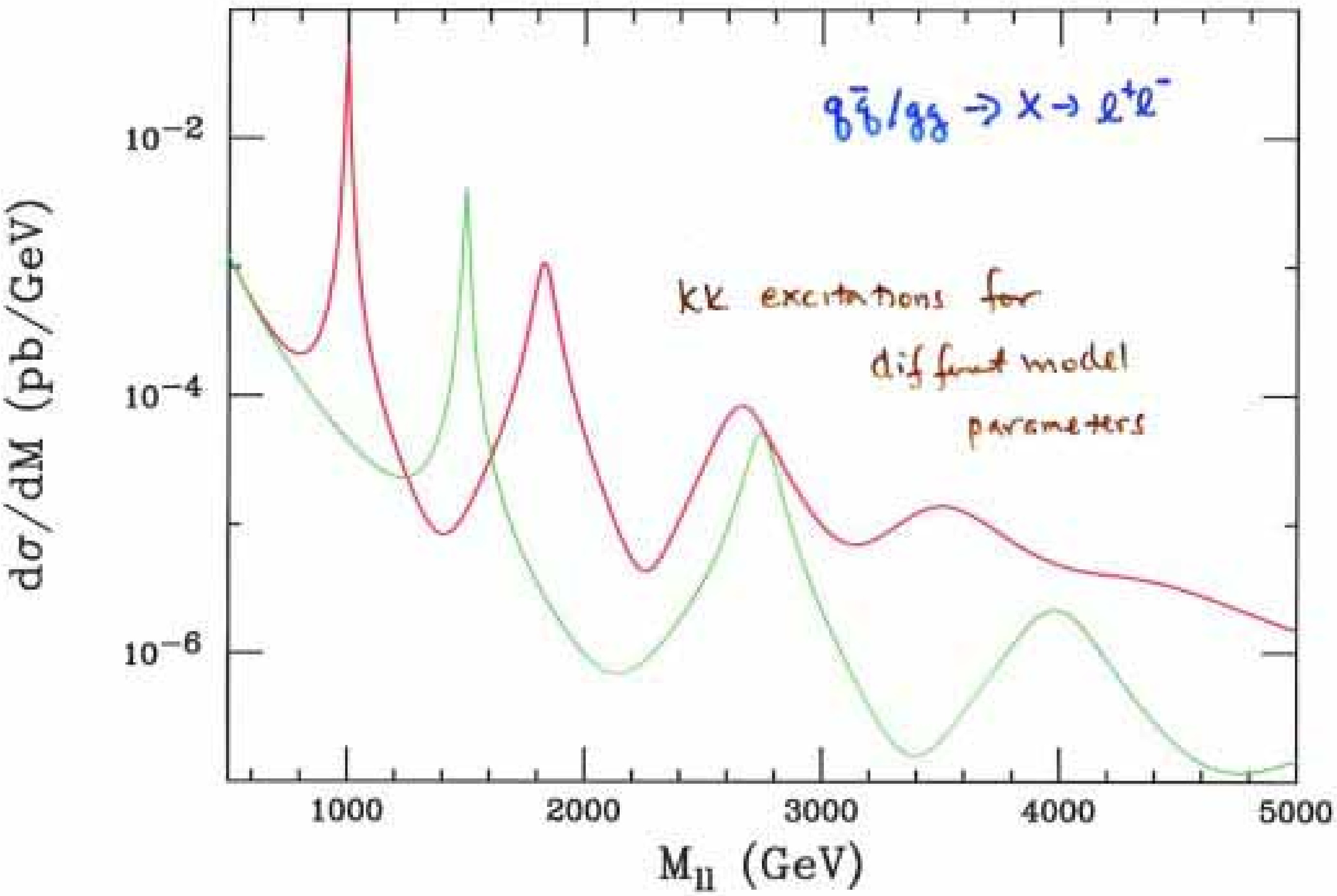
"canonically" normalized field..

- the one we'd just write down...

$\uparrow$ mass scale associated w/ Higgs are TeV

Amazingly simple!

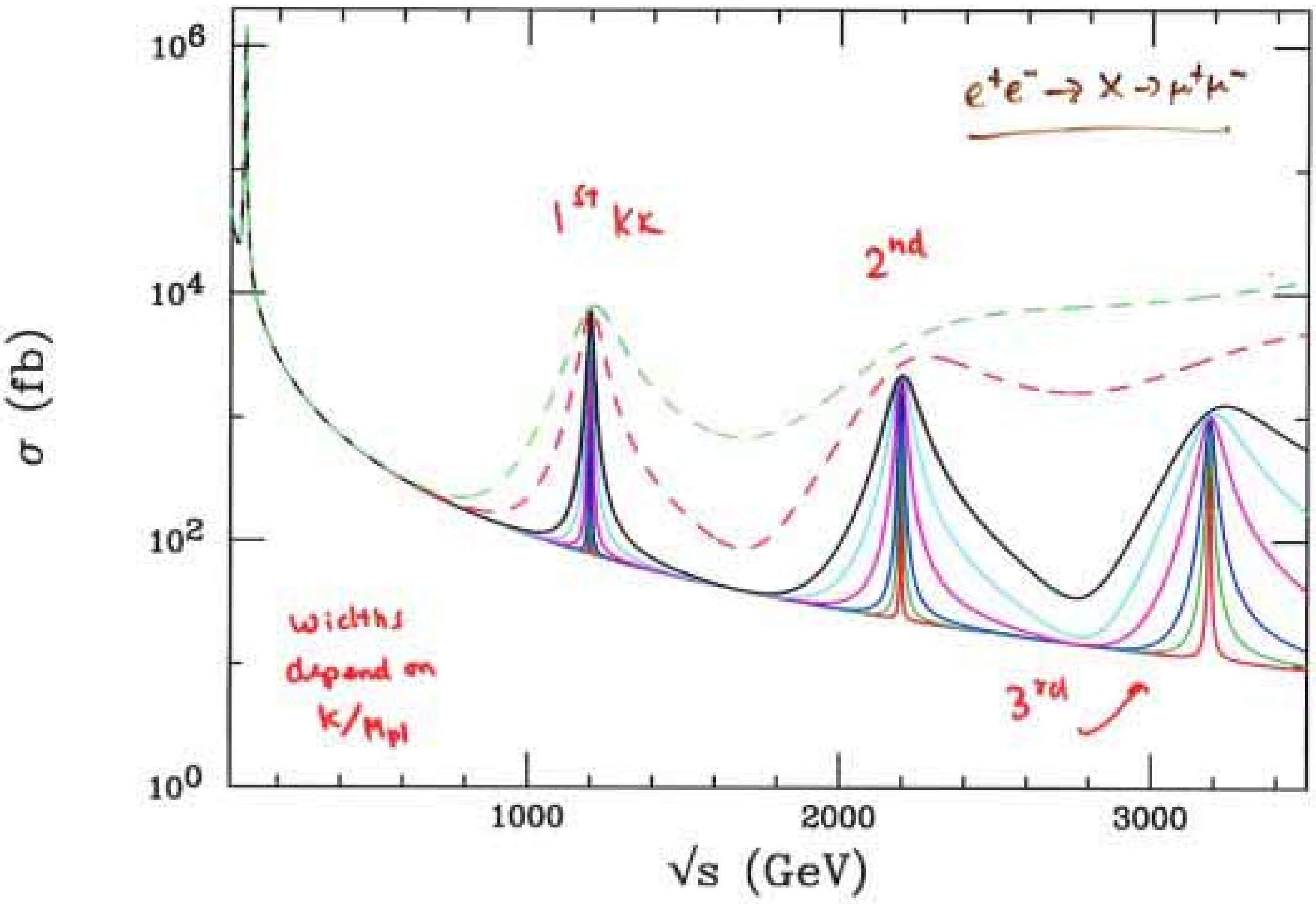
graviton resonance production at LHC



$q\bar{q}/gg \to X \to \ell^+\ell^-$

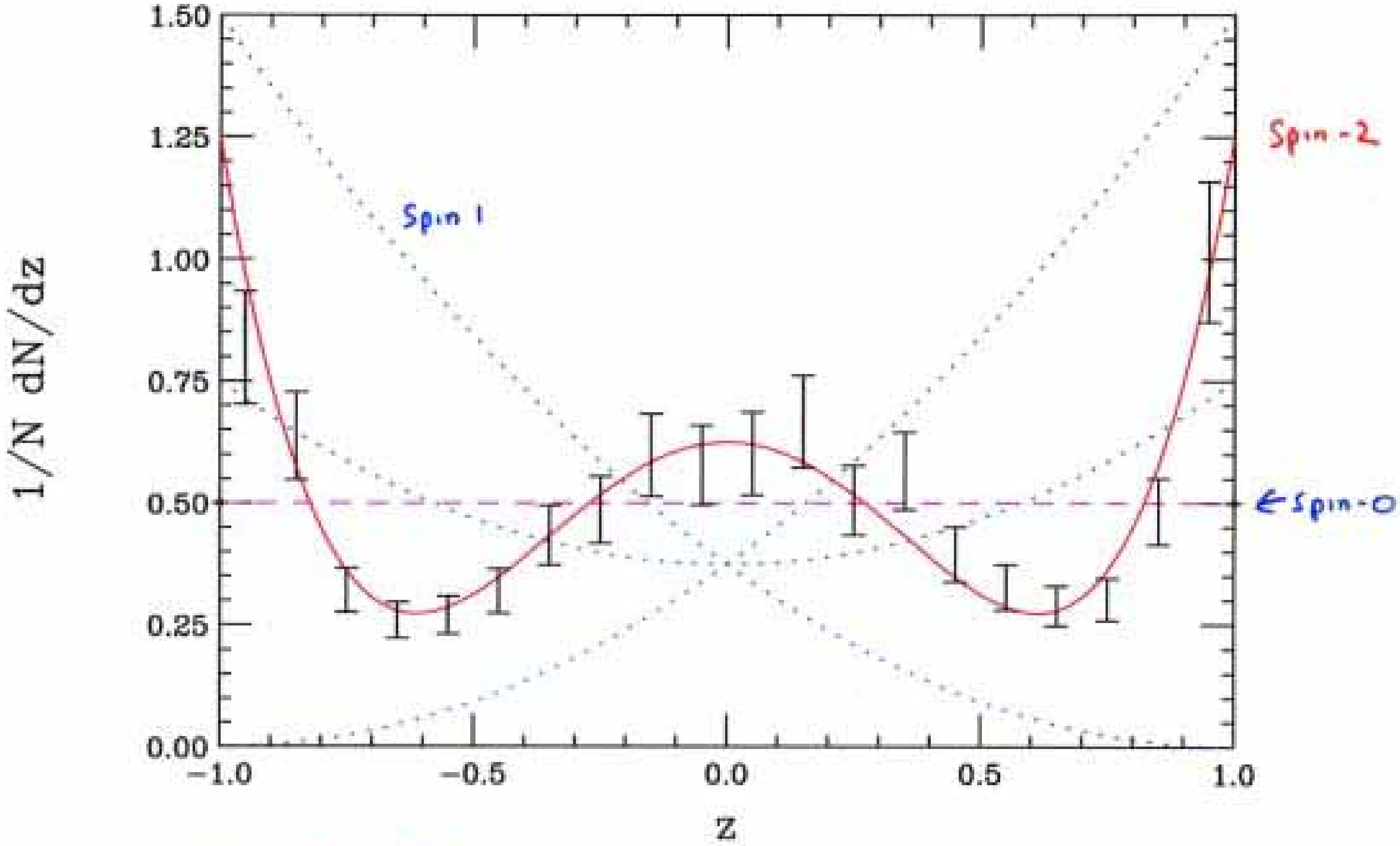
KK excitations for diff model parameters

gravitons at TeV scale LC



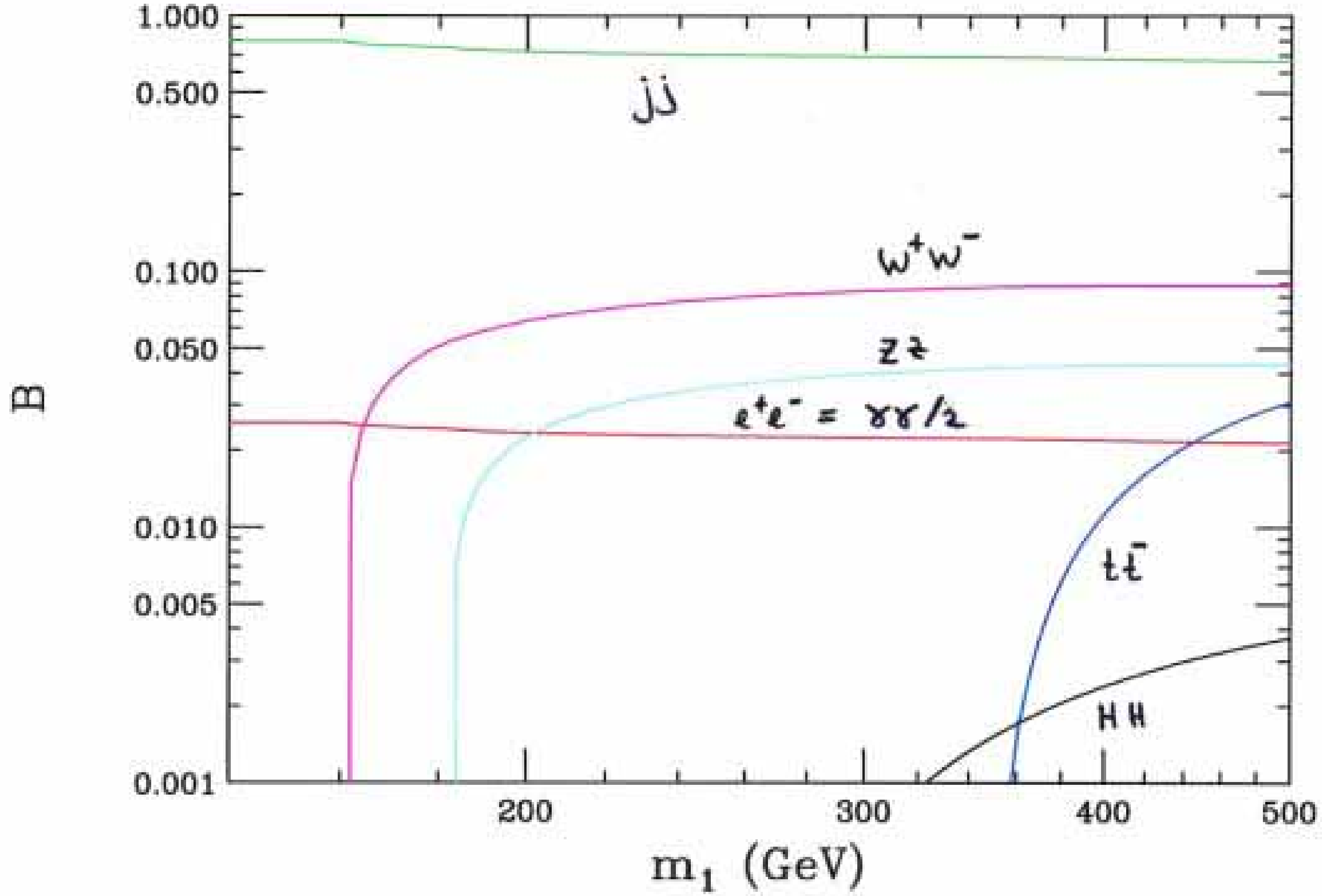
angular distributions determine

resonance spin



Spin 2 ??

Decay branching fractions for gravitons



No Higgs at All

- a massless 4-d field has 2 d.o.f A_μ

  " " " 3 d.o.f $\{A_\mu, A_5\}$

  ↑ in 4d, an extra scalar

Can A_5 be the Higgs?

- it would be nice since (i) no Higgs 'by-hand' and (ii) gauge invariance protects A_5 mass

⇒ Not trivially obvious this can be made to work

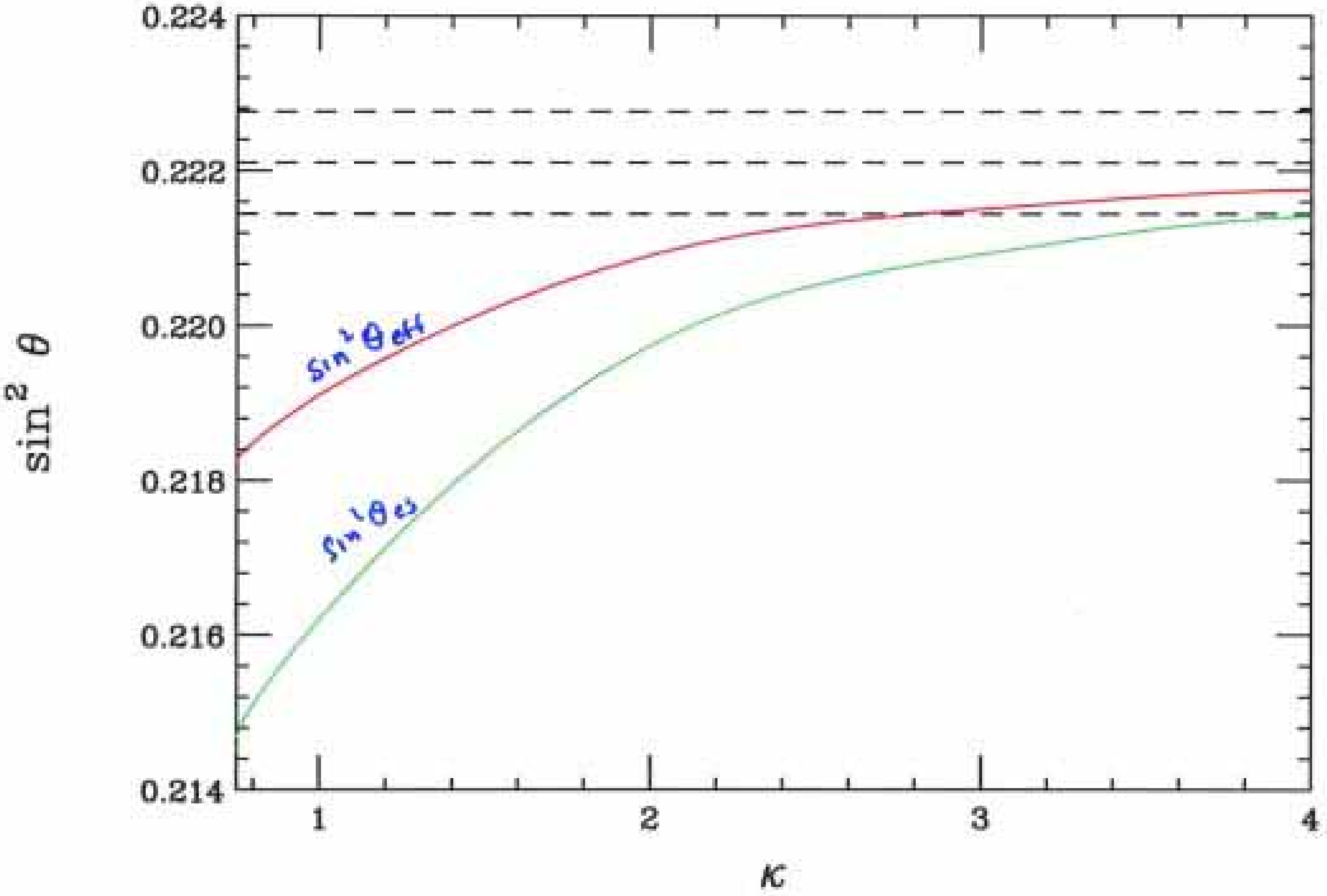
e.g, in SU(2) A_5 is a triplet but we know H is a doublet to get M_W/M_Z correct...

This is a hot research area at present BUT it appears that (at least approximate) a model NOW EXISTS with all the right features...

Csaki, Grojean
Pilo, Terning, Nomura

- We are exploring this + extension of the's model now to see how well it works....

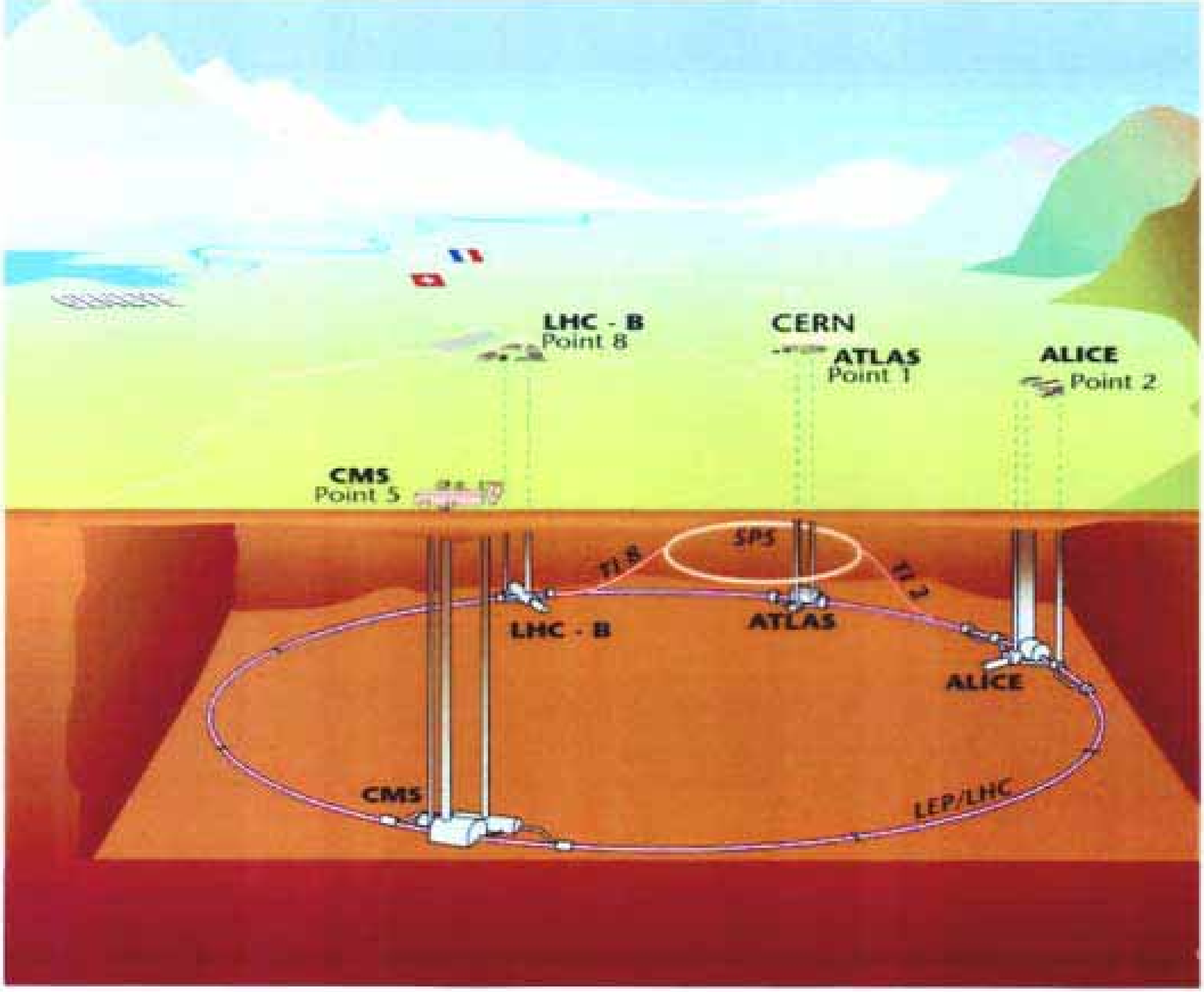
Davoudiasl,
Hewett, Lillie +
TGR

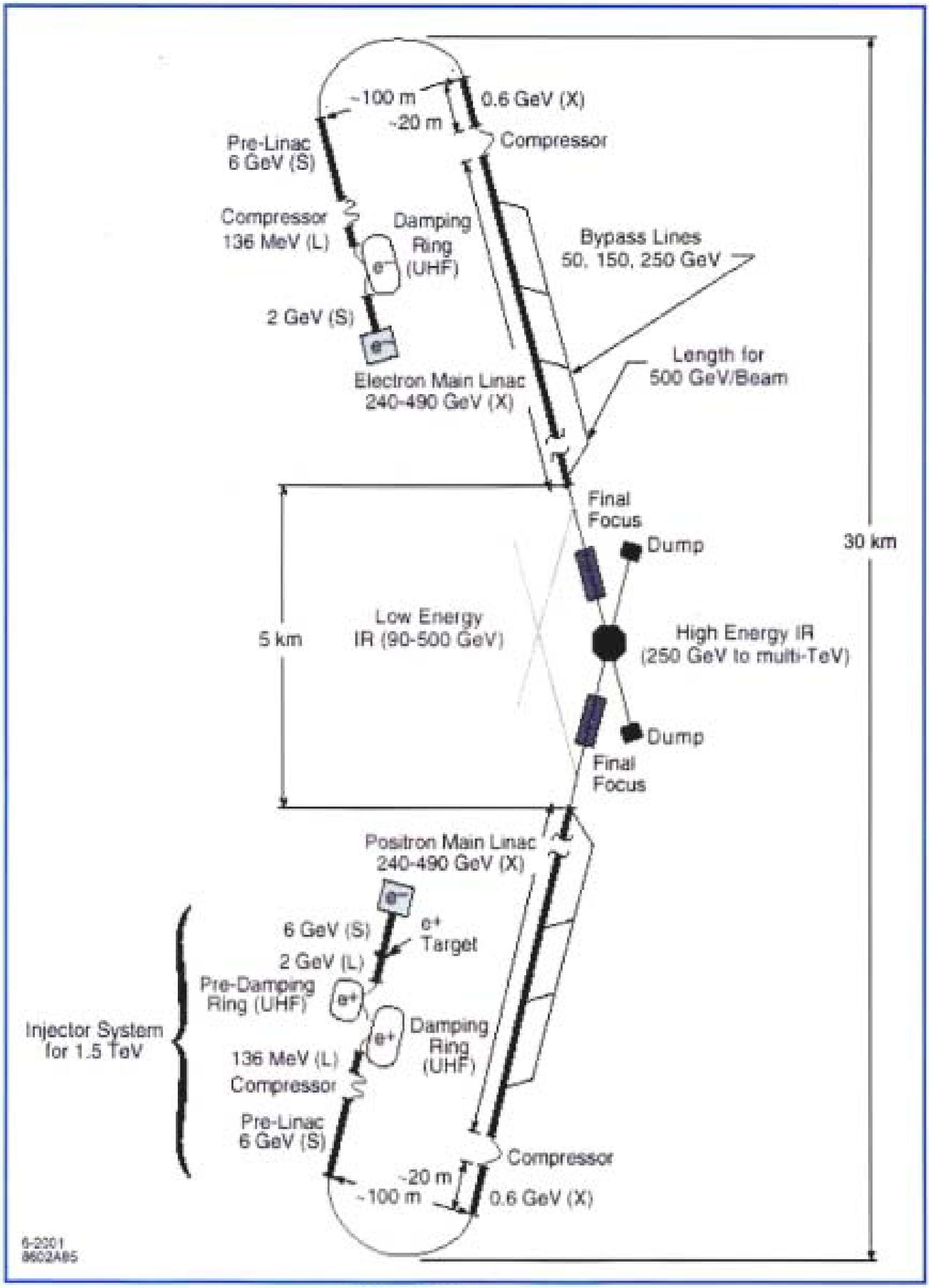

0.224
0.222
0.220
0.218
0.216
0.214
1
2
3
4
$\sin^2\theta$
κ
$\sin^2\theta_{eff}$
$\sin^2\theta_{es}$

Summary + Conclusions

- The HP is difficult, but some partial sol'ns have been proposed
- The HP is intimately linked to EWSB and fine-tuning problems
  - maybe also to the cosmological constant problem as well!
- Each sol'n leads to testable predictions at the TeV we're only now beginning to probe
- The LHC + LC will provide critical info. needed to attack this problem further.
- While we wait, there's lots of work to do!

Overall view of the LHC experiments.

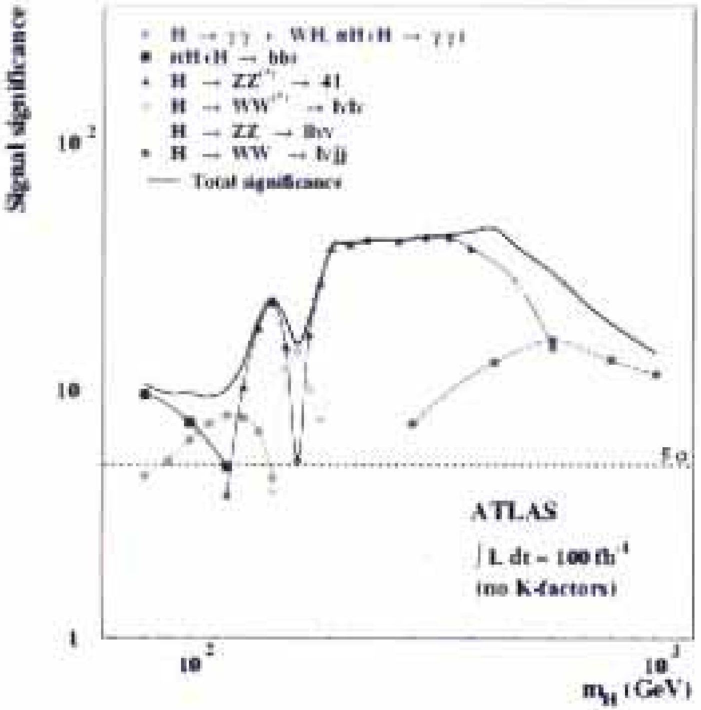



~100 m
~20 m
0.6 GeV (X)
Compressor
Pre-Linac
6 GeV (S)
Compressor
136 MeV (L)
Damping
Ring
(UHF)
e⁻
Bypass Lines
50, 150, 250 GeV
2 GeV (S)
e⁻
Length for
500 GeV/Beam
Electron Main Linac
240-490 GeV (X)
Final
Focus
Dump
30 km
5 km
Low Energy
IR (90-500 GeV)
High Energy IR
(250 GeV to multi-TeV)
Dump
Final
Focus
Positron Main Linac
240-490 GeV (X)
e⁻
6 GeV (S)
e⁺
Target
2 GeV (L)
Pre-Damping
Ring (UHF)
e⁺
Injector System
for 1.5 TeV
e⁺
Damping
Ring
(UHF)
136 MeV (L)
Compressor
Pre-Linac
6 GeV (S)
Compressor
~20 m
~100 m
0.6 GeV (X)
6-2001
8602A85

NLC Layout

CERN Large Hadron Collider (LHC)

- pp interactions at $\sqrt{s}$ =14 TeV
- LHC will discover Higgs boson if it exists
- Sensitive to M_h from 100-1000 GeV
- Higgs signal in just a few channels
- Physics circa 2008

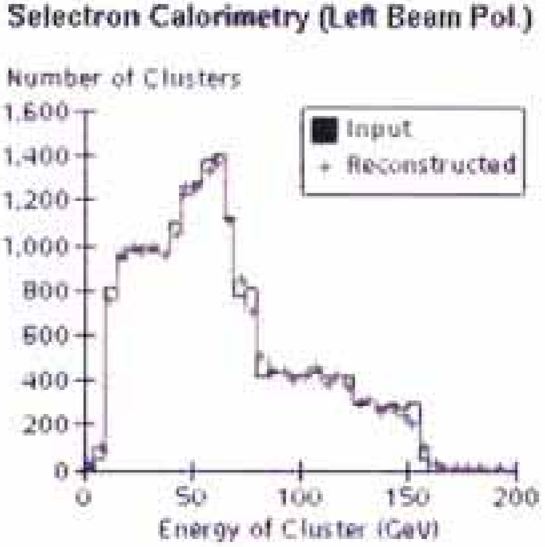


ATLAS TDR

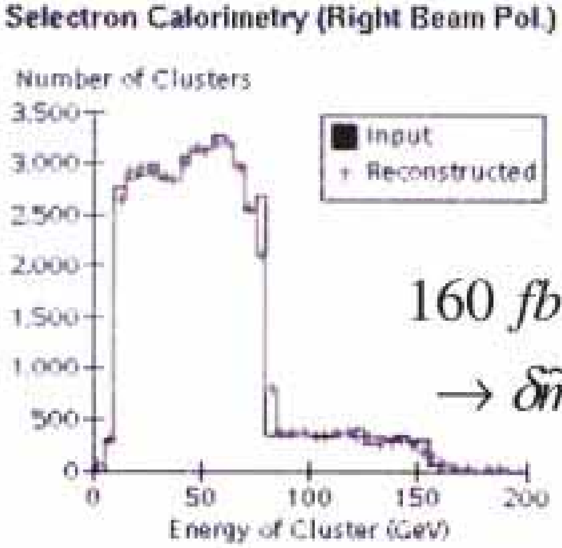
LC mass measurements from endpoints

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

$$m_{\tilde{l}}^{\;2} = \frac{sE_{\max}E_{\min}}{(E_{\max}+E_{\min})^2}\ ,\ 1-\frac{m_{\tilde{\chi}_1^{\,0}}^{\;\;2}}{m_{\tilde{l}^2}^{\;\;2}}$$



Selectron Calorimetry (Left Beam Pol.)



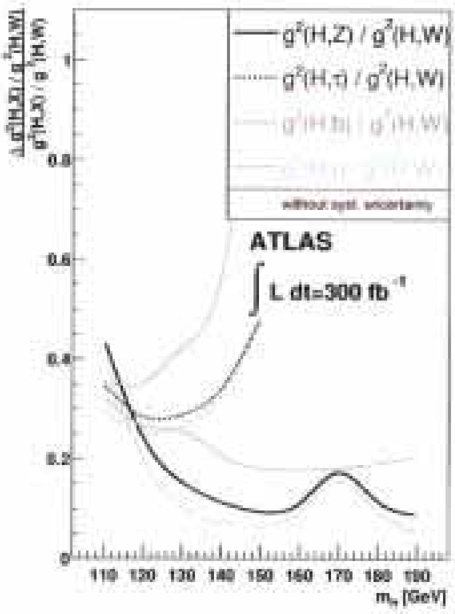
Selectron Calorimetry (Right Beam Pol.)

$160\ fb^{-1}$

$\to \delta\tilde{m}_e \approx .4\,GeV$

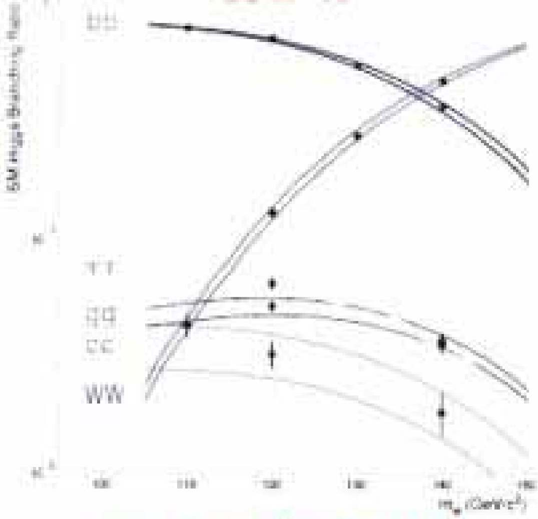
Once we find the Higgs, we need to measure its couplings

Ratios of coupling constants measured quite precisely at LHC



Duhrssen, ATL-PHYS-2003-030

LC measures couplings to a few %



e⁺e⁻ LC at √s=350 GeV

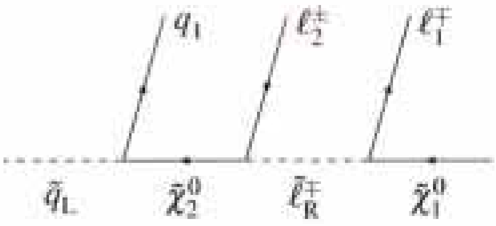
$L=500\ fb^{-1}$, $M_H=120$ GeV

Battaglia & Desch, hep-ph/0101165

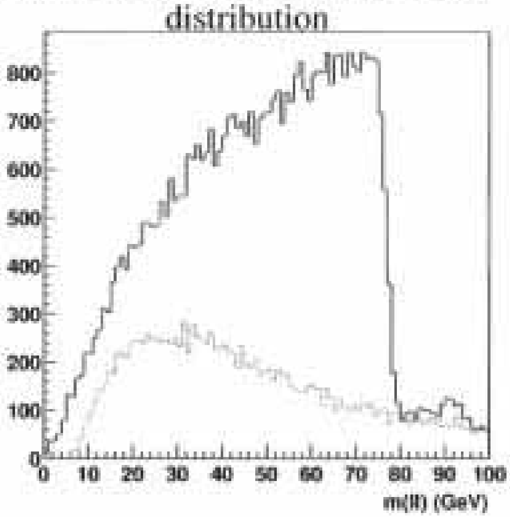
Linear Collider is the place!

Measuring SUSY masses at hadron colliders

- Complicated decay chains
- Main tool: dilepton edge from $\boxed{\tilde{\chi}_2^0 \to l^+ l^- \tilde{\chi}_1^0}$
- Sbottom/squark and gluino reconstruction
- Proportional to mass differernces: strong mass correlations



Same flavor-opposite sign lepton distribution



Invariant qll mass