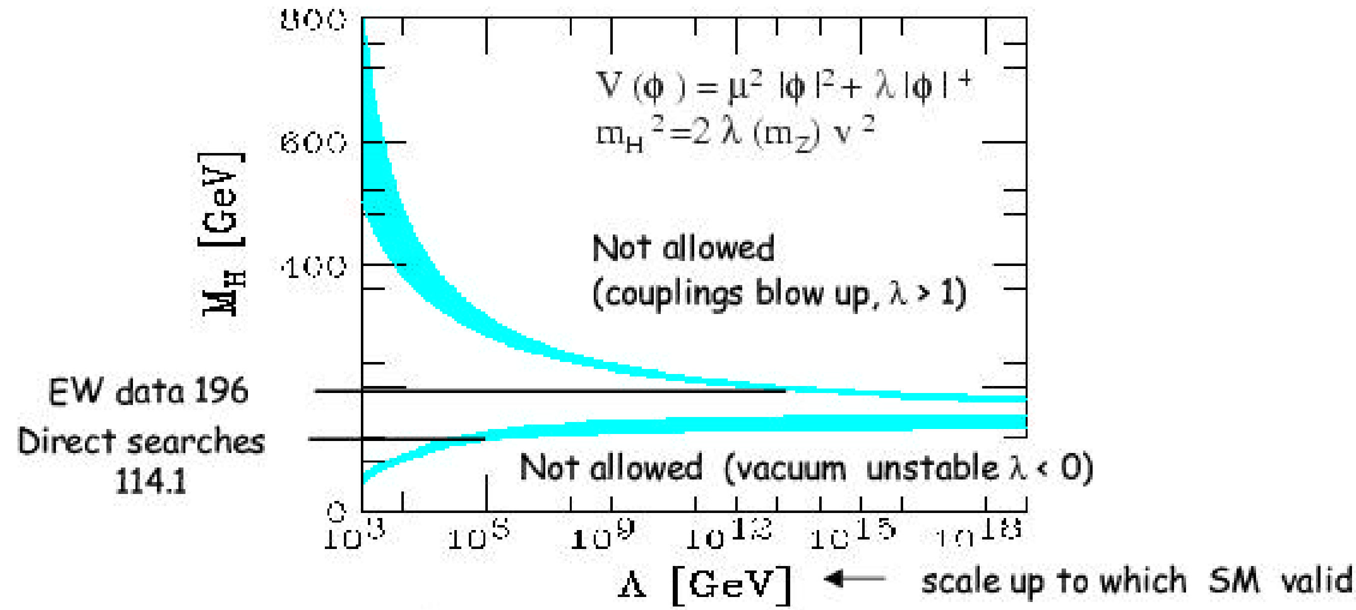
PART 3

What is wrong with the SM ?



- $m_H \approx 115$ GeV : New Physics for $\Lambda < 10^6$ GeV

  $130 < m_H < 180$ GeV : SM valid up to $\Lambda \sim M_{planck}$ (VERY boring ...)

- "Naturalness" problem :

  radiative corrections = = $\delta m_H^2 \sim \Lambda^2$ → diverge for large Λ

- "Hierarchy" problem: why $M_{EW}/M_{Planck} \sim 10^{-17}$?

+ flavour/family problem, coupling unification,
  gravity incorporation, ν masses/oscillations, ...

?

All this calls for

A more fundamental theory of which SM is low-E approximation → New Physics

Difficult task : solve SM problems without contradicting EW data

Best candidates : Supersymmetry, Extra-dimensions, Technicolour ← all predict New Physics at ≈ **TeV scale**

→ strong motivation for LHC : discovery reach up to m ≈ 5 TeV

Fabiola Gianotti, Physics at LHC, Pisa, April 2002

Search for SUperSYmmetry

SUPERSYMMETRY

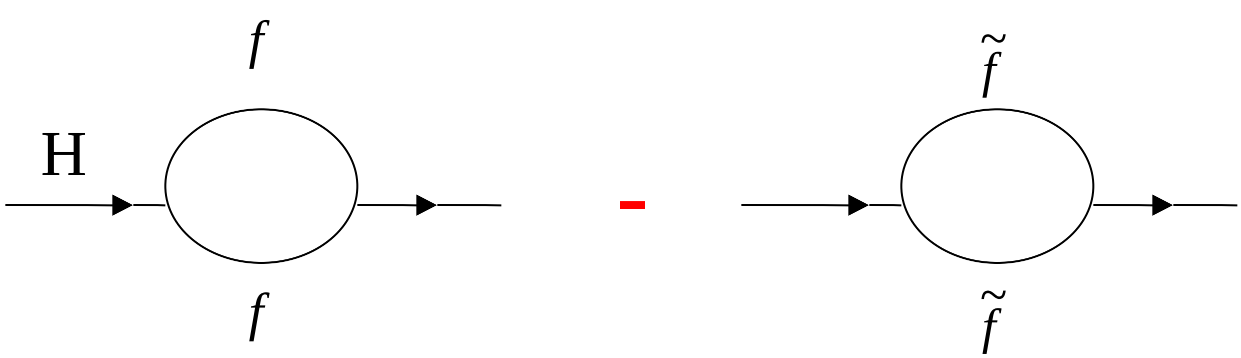
Symmetry between fermions (matter) and bosons (forces)

for each particle *p* with spin s, there exists a SUSY partner $\tilde{p}$ with spin s-1/2.

Ex. :	q (s=1/2)	→	$\tilde{q}$	(s=0)	squarks
	g (s=1)	→	$\tilde{g}$	(s=1/2)	gluino

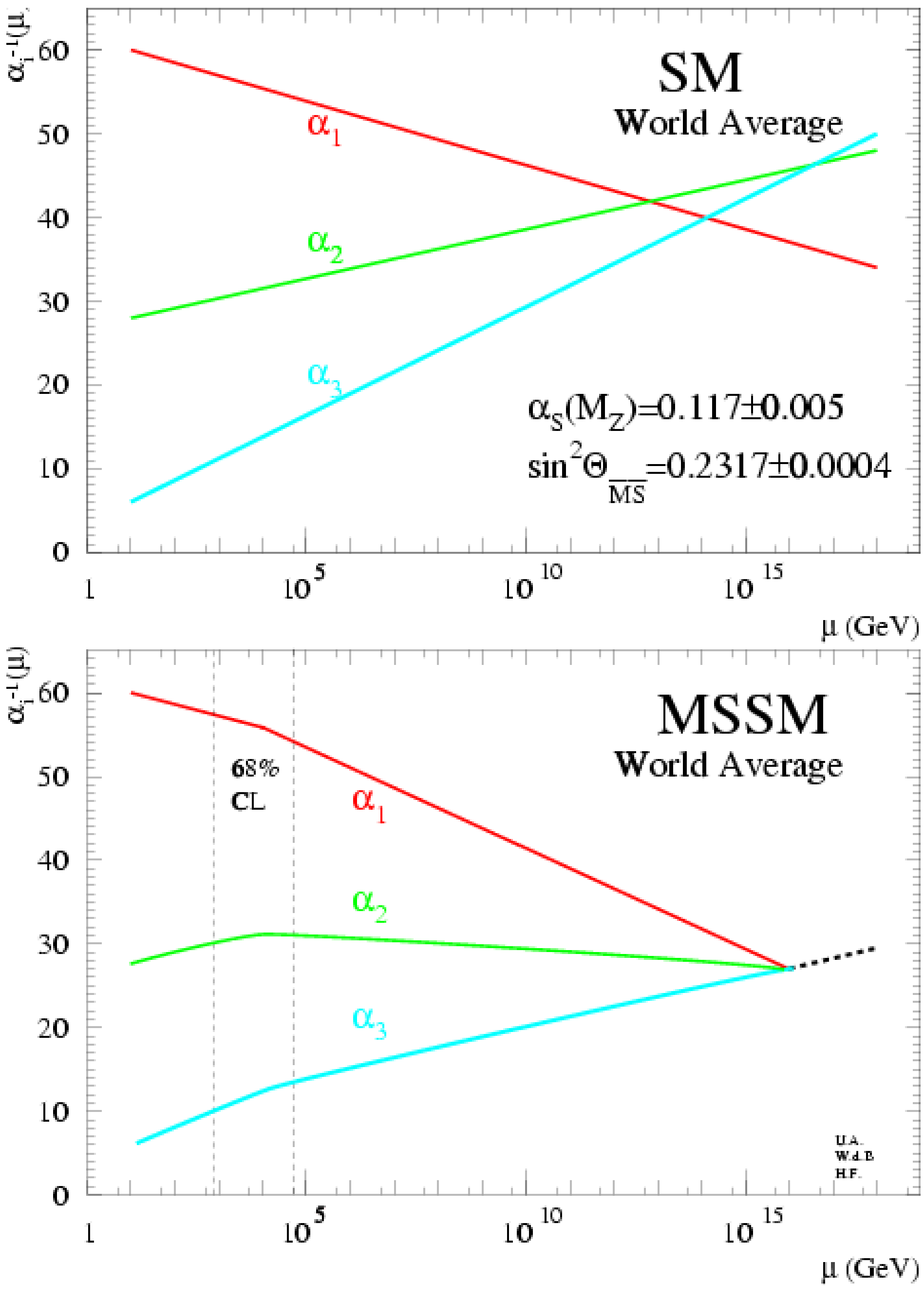
Motivations:

- Unification fermions-bosons and matter-forces is attractive
- Solves problems of SM, e.g. divergence of Higgs mass :



Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq$ TeV.

- Measured coupling constants unify at GUT scale in SUSY but not in SM.



- Provides candidate for cold dark matter (LSP)

- Does not contradict predictions of SM at low energy → not ruled out by present experiments.
  Predicts a light Higgs (m_h < 130 GeV)

- Ingredient of string theories that many consider best candidate for unified theory including gravity

  However: no experimental evidence for SUSY as yet

⬇

Either SUSY does not exist

OR

m_{SUSY} large (>> 100 GeV) → not accessible to present machines

⬇

LHC should say "final word" about SUSY if $m_{SUSY} \leq$ a few TeV

Drawback : many new particles predicted

Here : Minimal Supersymmetric extension of the Standard Model (MSSM) which has minimal particle content

MSSM particle spectrum :

5 Higgs bosons : h, H, A, $H^{\pm}$

quarks	→	squarks	$\tilde{u}, \tilde{d}$, etc.
leptons	→	sleptons	$\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.
$W^{\pm}$	→	winos	→ $\chi^{\pm}_1, \chi^{\pm}_2$ 2 charginos
$H^{\pm}$	→	charged higgsino	
γ	→	photino	→ $\chi^0_{1,2,3,4}$ 4 neutralinos
Z	→	zino	
h, H	→	neutral higgsino	
g	→	gluino	$\tilde{g}$

Masses not known. However charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Present limits : $m_{\tilde{l}, \chi^{\pm}}$ > 90-100 GeV LEP

$m_{\tilde{q}, \tilde{g}}$ > 250 GeV Tevatron Run 1

400 GeV Tevatron Run 2

SUSY phenomenology

There is a multiplicative quantum number:

R-parity $R_p =$ + 1 SM particles ; - 1 SUSY particles

which is conserved in most popular models (considered here).

Consequences:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

LSP is also weakly interacting (for cosmological reasons, candidate for cold dark matter)

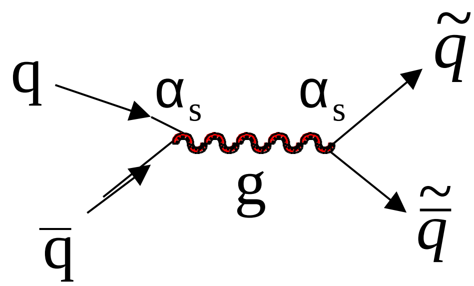
→ LSP behaves like a ν → escapes detection
→ E_T^{miss} (typical SUSY signature)

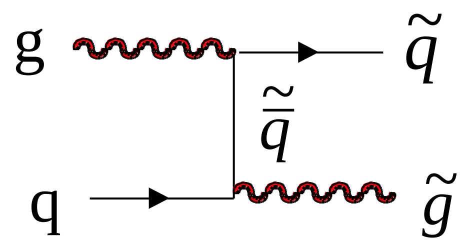
Most models : LSP ≡ χ^0_1

Production of SUSY particles at LHC

- Squarks and gluinos produced via strong processes
  $\rightarrow$ large cross-section

Ex.:

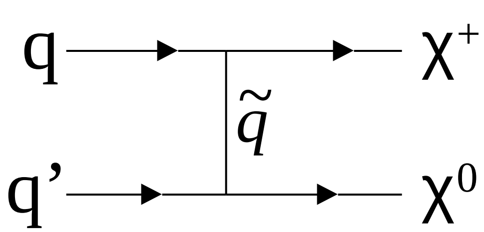




$m_{\tilde{q},\tilde{g}} \sim 1$ TeV $\quad \sigma \quad 1$pb $\rightarrow 10^4$ events per year
produced at low L

- Charginos, neutralinos, sleptons produced via electroweak processes $\rightarrow$ much smaller rate

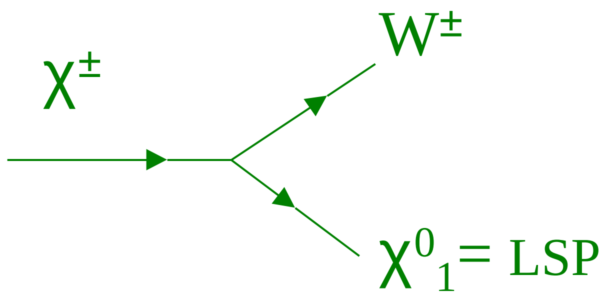
Ex.

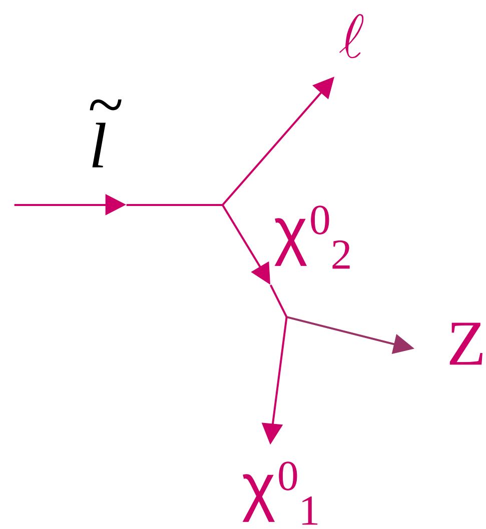


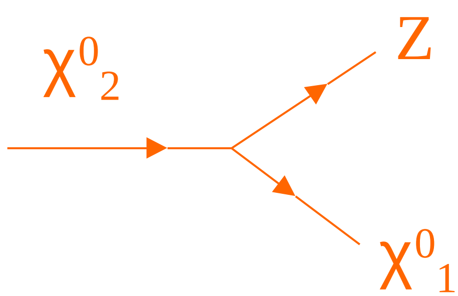
$\sigma \approx$ pb $\quad m_\chi \approx 150$ GeV

$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ are dominant SUSY processes at LHC
if kinematically accessible

Decays of SUSY particles : some examples

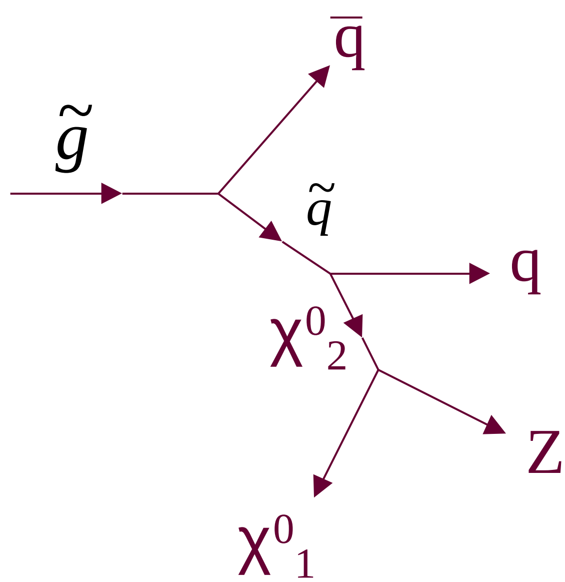






$\tilde{q}, \tilde{g}$ heavier → more complicated decay chains

Ex.



Cascade decays involving many leptons and /or jets + missing energy (from LSP)

Exact decay chains depend on model parameters (particle masses, etc.)

However : whatever the model is, we know that

$\tilde{q}, \tilde{g}$ are heavy (m > 250 GeV)

↓

decays through cascades favoured

many high-p_T jets/leptons/W/Z in the final state + E_T^{miss}

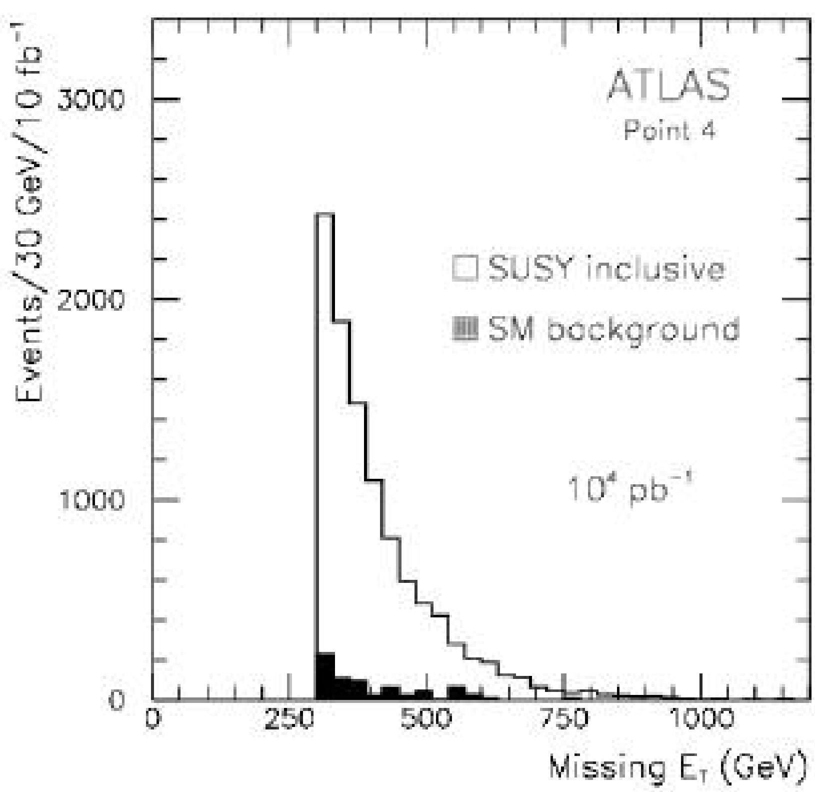
↓

at LHC is easy to extract SUSY signal from SM background

Example: if Nature had chosen the following point in the parameter space:

$m_{\tilde{q}} \approx 900$ GeV	$m_{\chi^\pm} \approx 150$ GeV
$m_{\tilde{g}} \approx 600$ GeV	$m_{\chi^0} \approx 80$ GeV

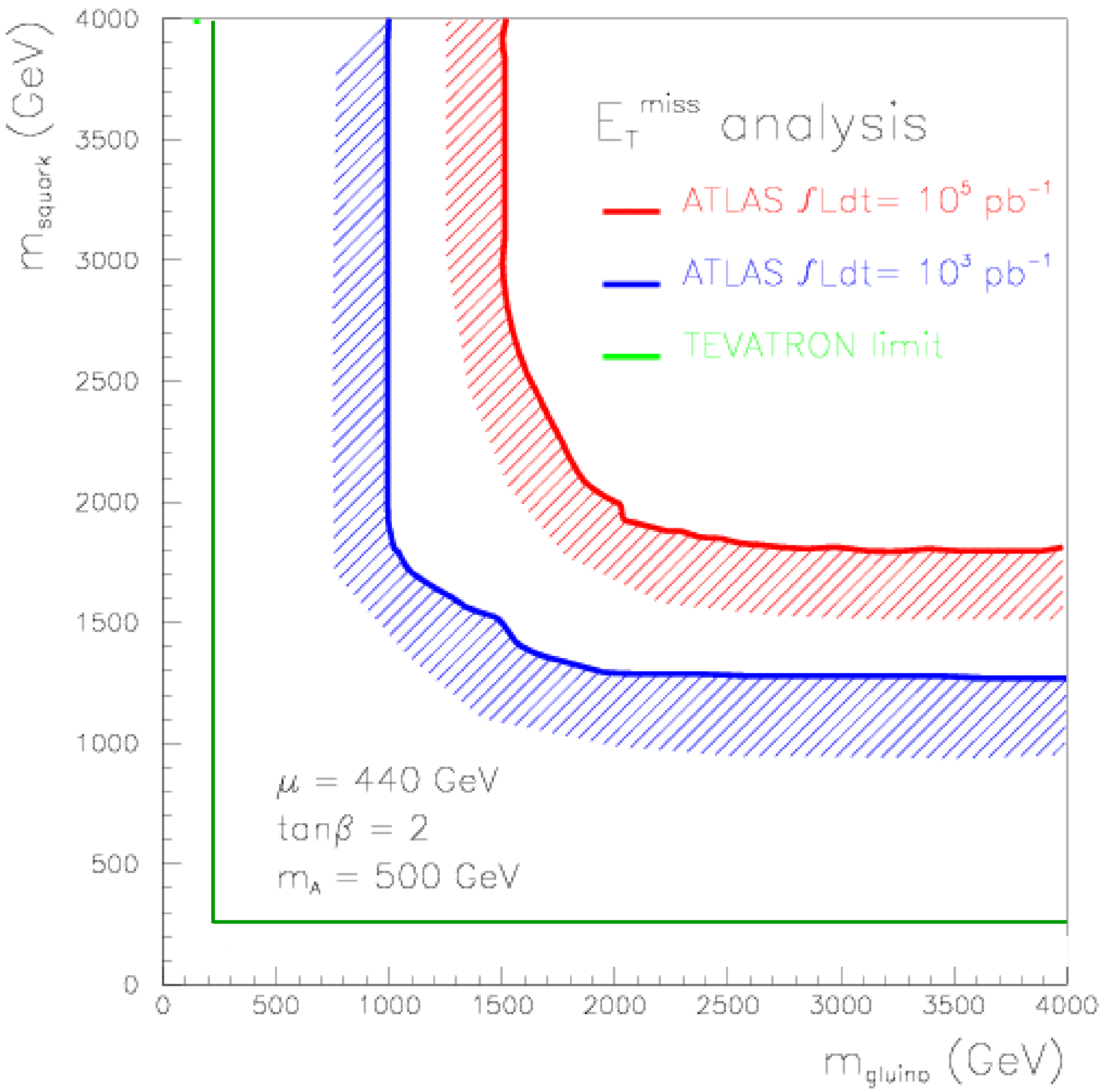
Requiring : $E_T^{miss} > 300$ GeV
5 jets $p_T > 150, 150, 100, 100, 90$ GeV



In one year at low L:
$N_S = 11600$ events
$N_B = 560$ events

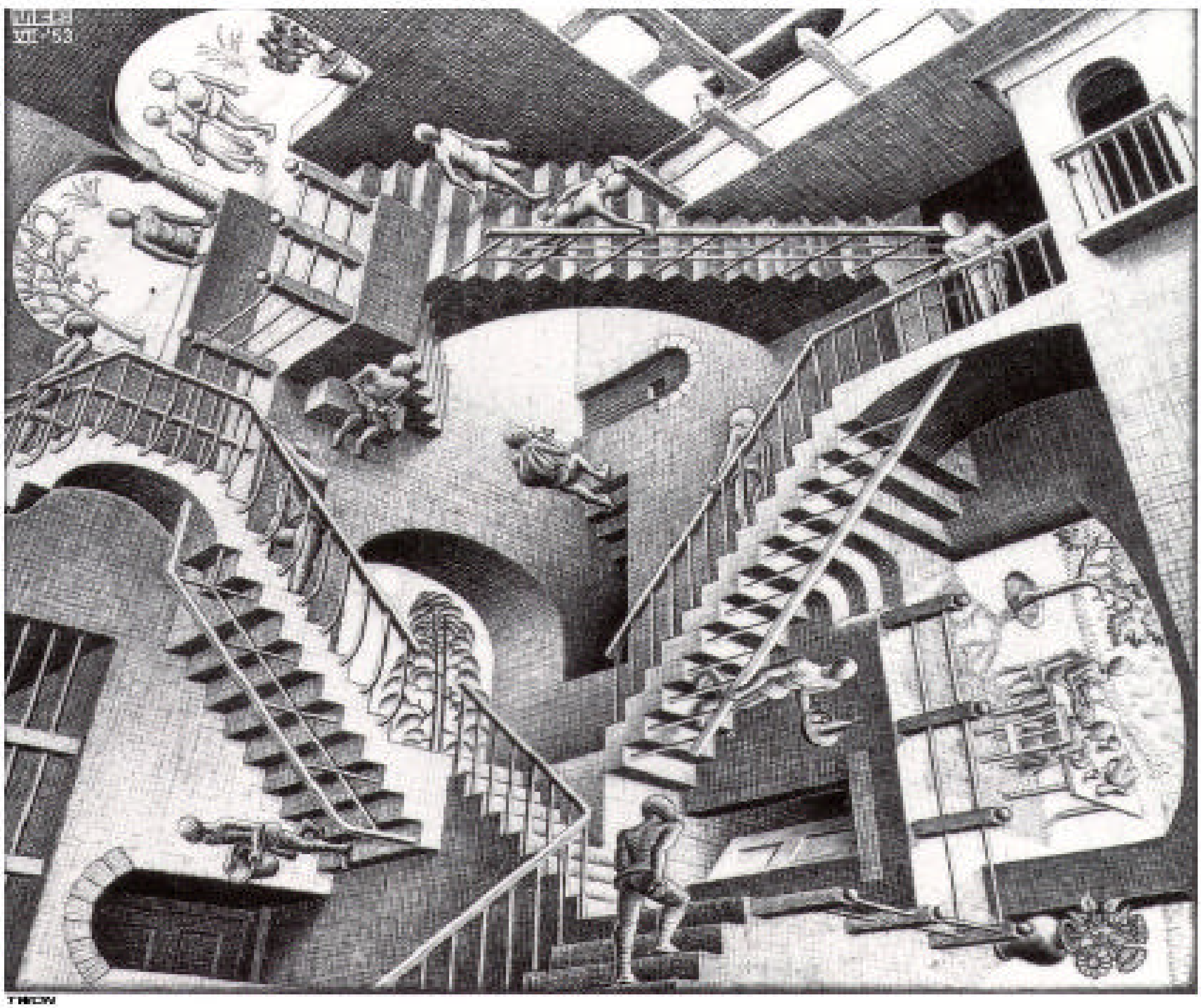
S ~ 500 !!

With similar analysis, discover or exclude $\tilde{q}, \tilde{g}$ with masses up to 1.5-2 TeV in one year at high luminosity (L = 10^{34} cm^{-2} s^{-1})



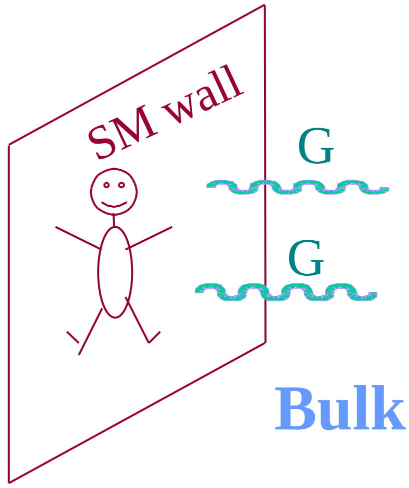
→ if SUSY exists, it will be easy and fast to discover at LHC up to m ~ 2.5 TeV thanks to large x-section and clean signature. Many precision measurements of sparticle masses possible.

Search for Extra-dimensions



> 700 theoretical papers over last 2.5 years

Arkani-Hamed, Dimopoulos, Dvali (ADD)



If gravity propagates
in 4 + n dimensions,
a gravity scale $\mathbf{M_S \approx 1\ TeV}$ is possible
→ hierarchy problem solved

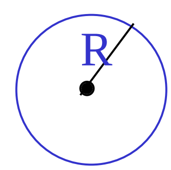
$$V_4(r) \sim \frac{1}{M_{Pl}^2}\frac{1}{r}$$
$$V_{4+n}(r) \sim \frac{1}{M_S^{n+2}R^n}\frac{1}{r}$$

at large distance ➡ $M_{Pl}^2 \approx M_S^{n+2} R^n$

n, R = number and size of extra-dimensions

- If $M_S \approx 1$ TeV :
  - n=1 $R \approx 10^{13}$ m → excluded by macroscopic gravity
  - n=2 $R \approx 0.7$ mm → limit of small- scale gravity experiments
  - ….
  - n=7 $R \approx 1$ Fm

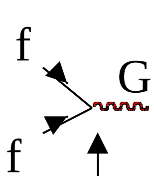
➡ Extra-dimensions are compactified over R < mm



- Gravitons in Extra-dimensions get quantised mass:

$$m_k \sim \frac{k}{R} \qquad k = 1, \ldots \infty$$
$$\Delta m \sim \frac{1}{R} \qquad \text{e.g. } \Delta m \sim 400 \text{ eV } n = 3$$

→ continuous tower of massive gravitons (Kaluza Klein excitations)

σ [] $\sim \frac{1}{M_{Pl}^2} N_{kk} \sim \frac{1}{M_{Pl}^2}\left(\frac{\sqrt{s}}{\Delta m}\right)^n \sim \frac{1}{M_{Pl}^2}\sqrt{s}^{\,n} R^n \sim \boxed{\frac{\sqrt{s}^{\,n}}{M_S^{n+2}}}$

Due to the large number of G_{kk}, the coupling SM particles - Gravitons becomes of EW strength

- Only one scale in particle physics : EW scale
- Can test geometry of universe and quantum gravity in the lab

Constraints and searches from:

- cosmology, astrophysics
- test of Newton force down to R ≤ mm
- colliders

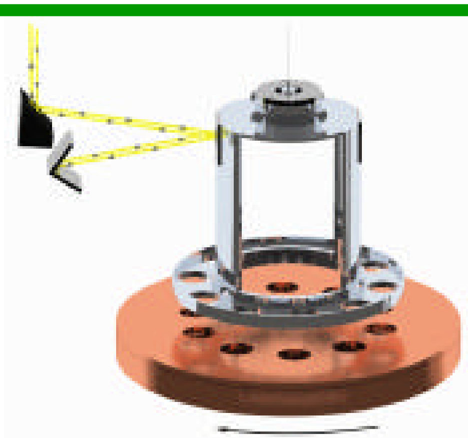
Supernova SN1987A cooling by ν emission (IBM, Superkamiokande) → bounds on cooling via G_{kk} emission:

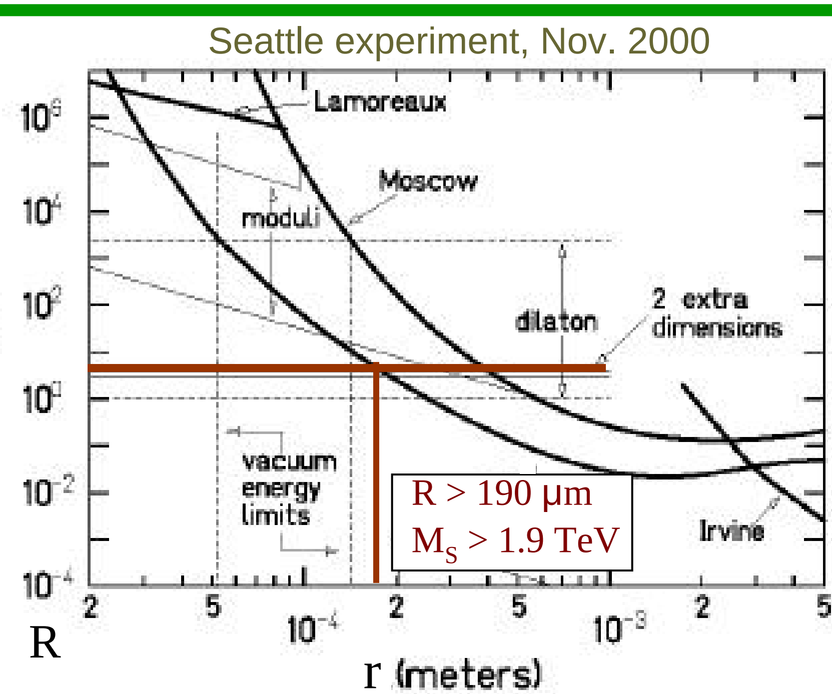
M_S > 31 (2.7) TeV n=2 (3)

Distorsion of cosmic diffuse γ radiation spectrum (COMPTEL) due to $G_{kk} \to \gamma\gamma$:

M_S > 100 (5) TeV n=2 (3)

large uncertainties but n=2 disfavoured





$$V(r) \sim \frac{1}{r^{1+n}} \quad r << R$$

$$V(r) \sim \frac{1}{r}\left[1+\alpha\, e^{-r/R}\right] \quad r ♦ R$$

Note : ~ no constraints from precision measurements:

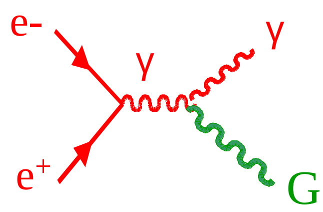
-- contributions of G_{kk} loops to EW observables

$$\sim \left(\frac{m_Z}{M_s}\right)^{n+2} \leq 10^{-4} \quad \text{for } n ? 2$$

Searches at LEP

(only available Collider results today)

Direct graviton production e.g.

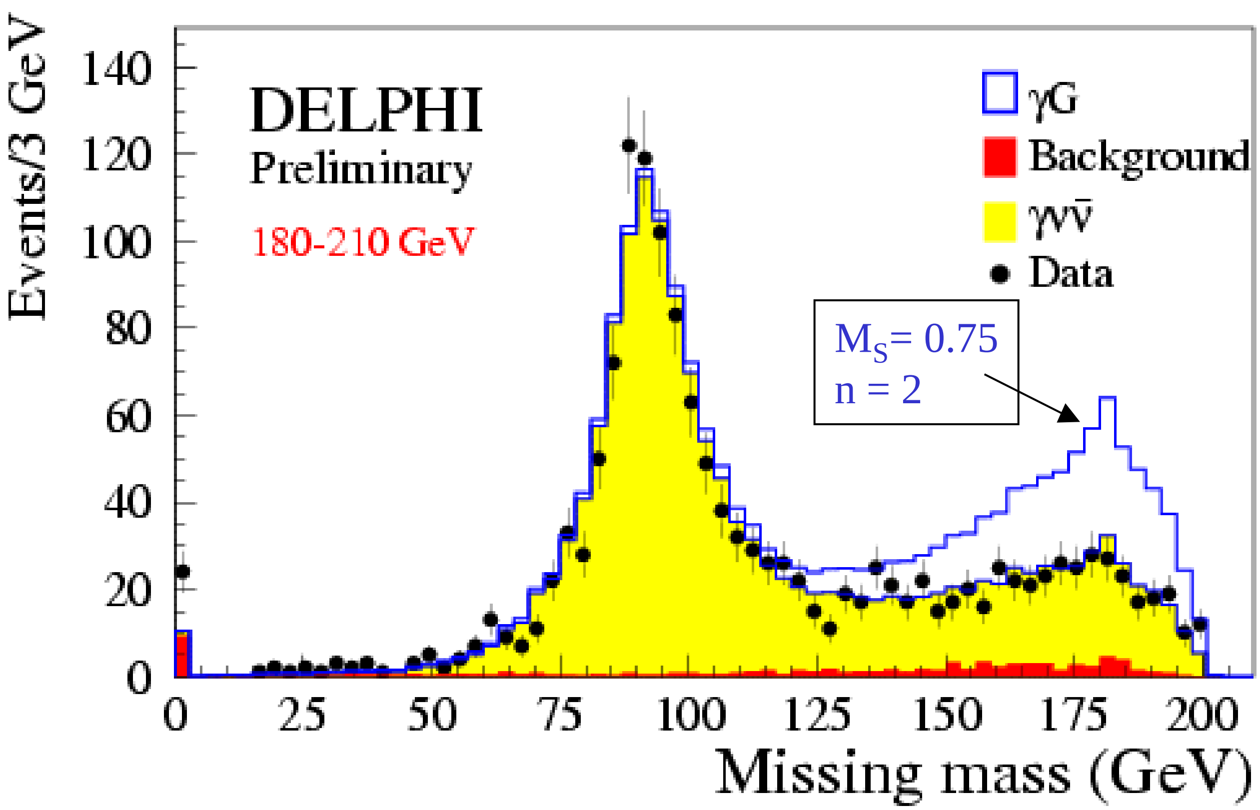


→ signature is $\gamma + \not{E}$

$$\sigma \sim \frac{\sqrt{s}^{\,n}}{M_S^{\,n+2}}$$

N_{kk} increases with $\sqrt{s}$

m_k increases with M_S, n

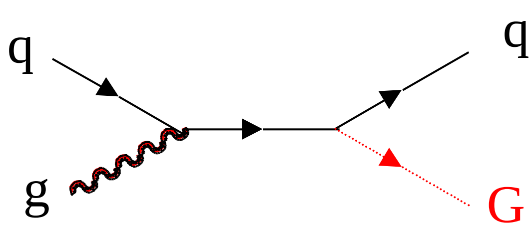


Lower limits on M_S

	n = 2	n = 3	n = 4	n = 5	n = 6
ALEPH	1.28	0.97	0.78	0.66	0.57
DELPHI	1.38		0.84		0.58
L3	1.45	1.09	0.87	0.72	0.61
OPAL ($\sqrt{s} \leq 189$)	1.09	0.86	0.71	0.60	0.53

Searches at LHC

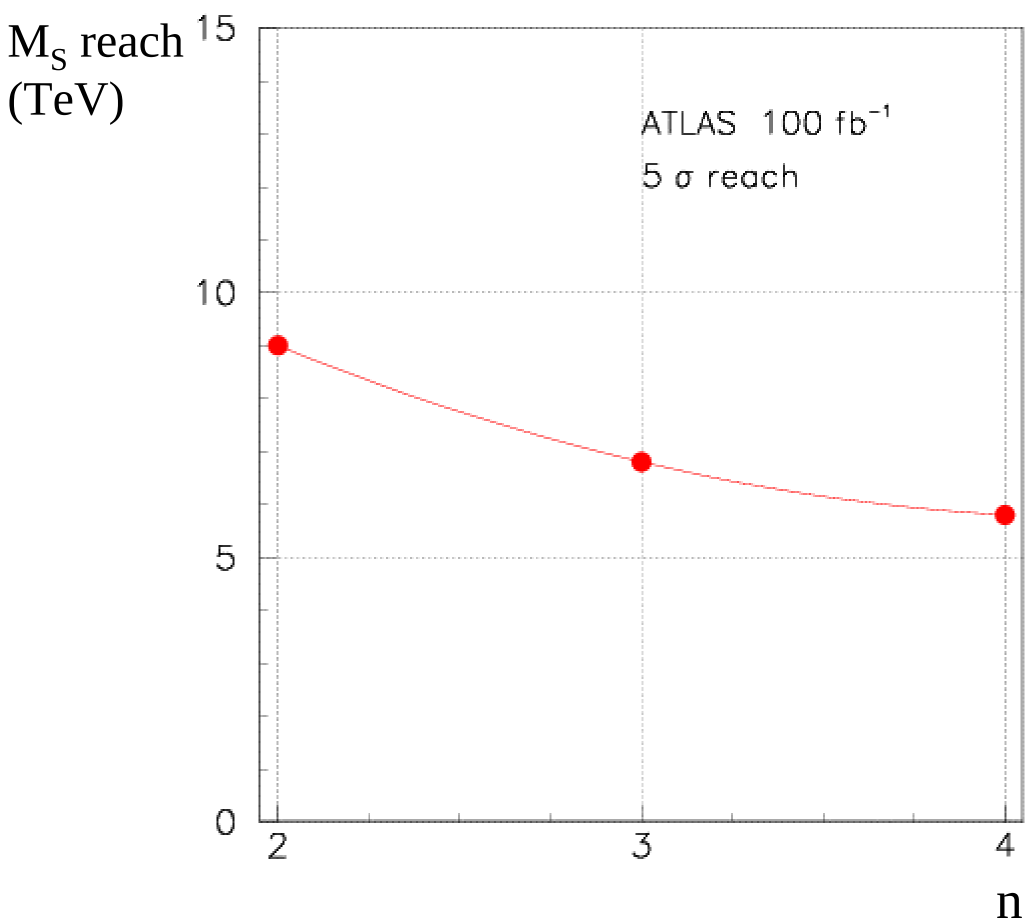
Direct Graviton production:



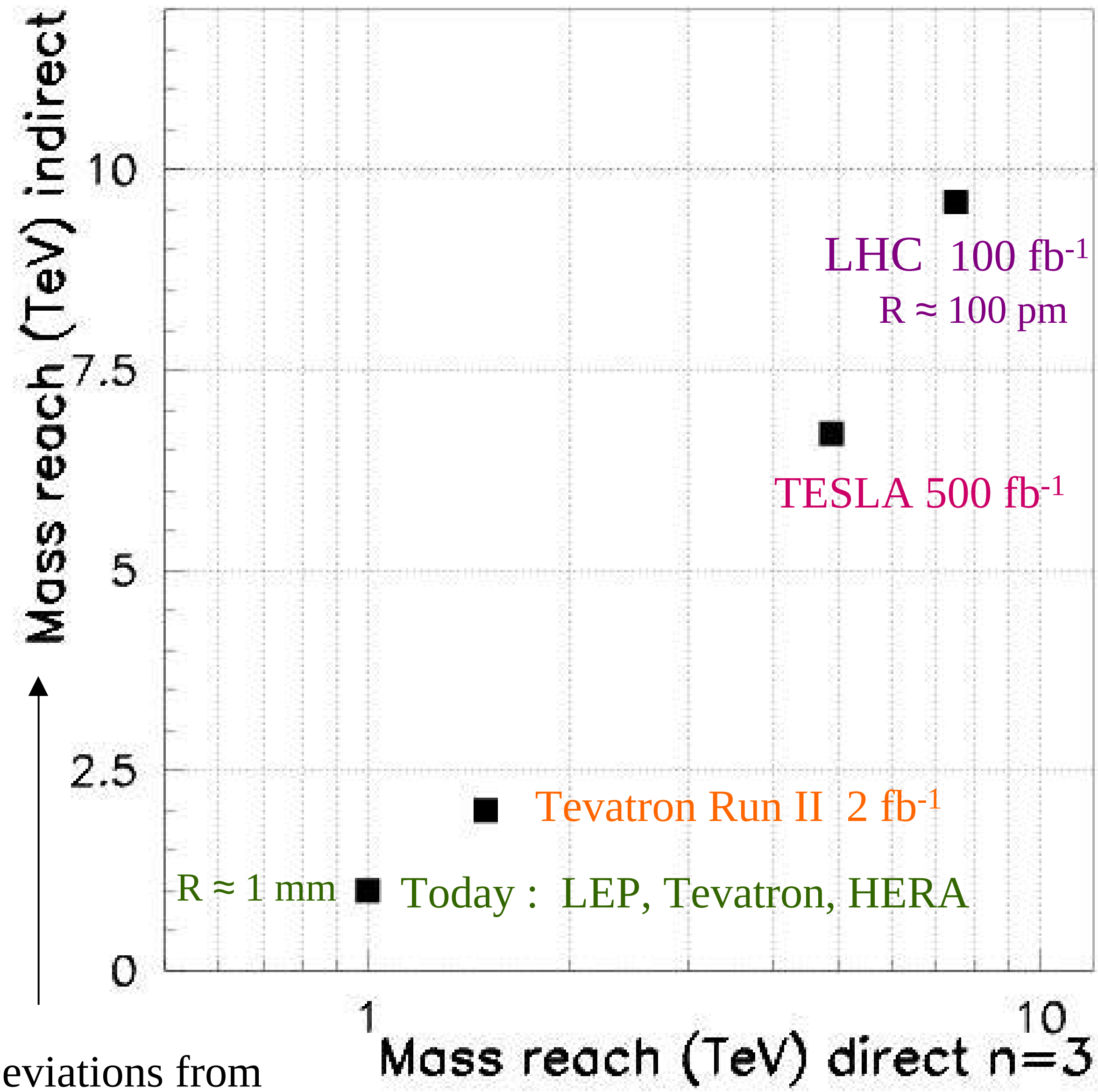
→ topology is
jet(s) + missing E_T

$$\sigma \quad \frac{1}{M_S^{\,n+2}}$$

M_S = gravity scale
n = number of extra-dimensions



95% C.L reach on M_S (TeV) from direct (n=3) and indirect searches



Deviations from SM cross-sections from virtual G exchange

If nothing found below 10 TeV, ADD theories will lose most of their appeal

CONCLUSIONS

LHC : most difficult and ambitious high-energy physics project ever realised (human and financial resources, technical challenges, complexity, ….)

Very broad and crucial physics goals:
understand the origin of masses,
look for physics beyond the SM,
precision measurements of known particles.

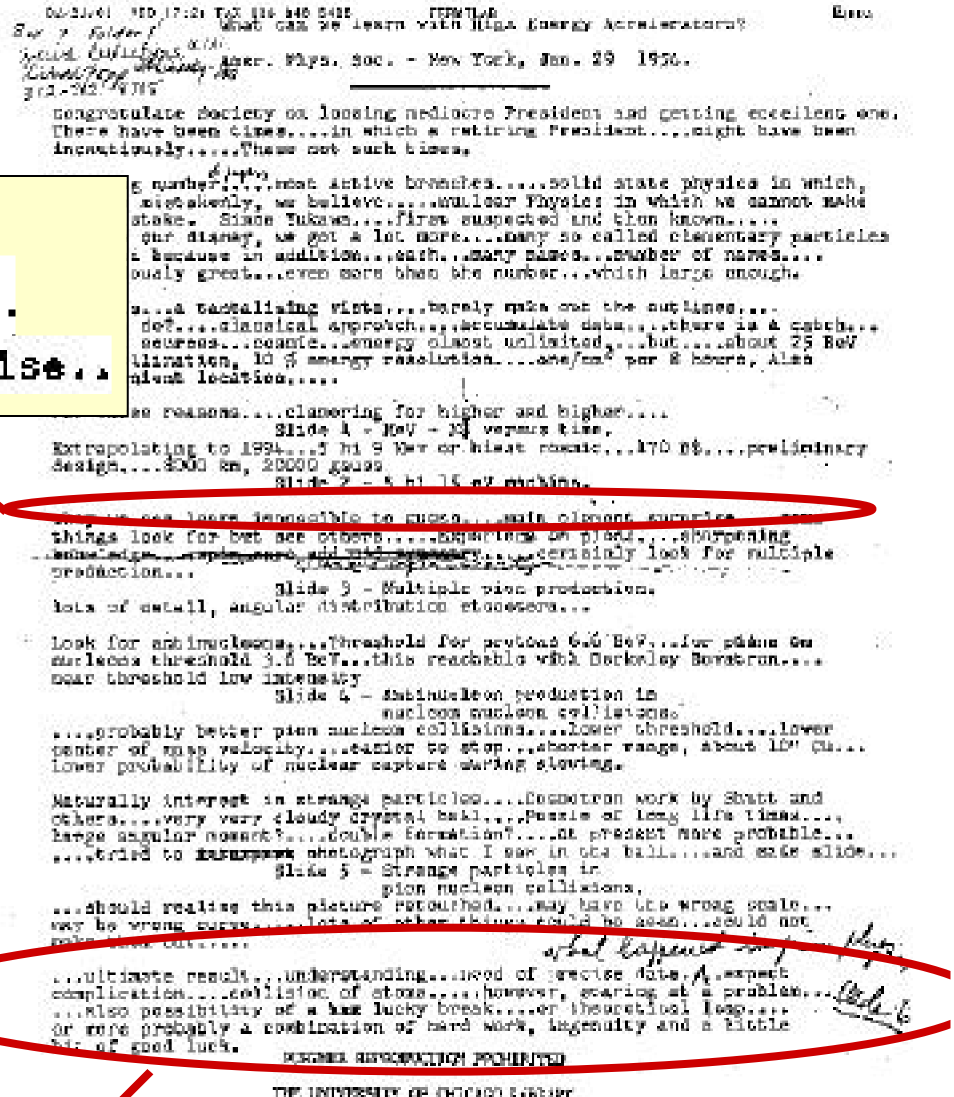
In particular: can say the final word about
-- SM Higgs mechanism
-- low-E SUSY

It will most likely modify our understanding of Nature

E. Fermi, preparatory notes for a talk on

"What can we learn with High Energy Accelerators ? "

given to the American Physical Society, NY, Jan. 29th 1954


What can we learn with High Energy Accelerators?

Amer. Phys. Soc. - New York, Jan. 29 1954.

Congratulate Society on loosing mediocre President and getting excellent one. There have been times....in which a retiring President....might have been [illegible]ly.....These not such times.

...g number.....most active branches.....solid state physics in which, ...mistakenly, we believe.....nuclear Physics in which we cannot make ...stake. Since Yukawa....first suspected and then known..... ...our dismay, we got a lot more....many so called elementary particles ...because in addition...each...many names...number of names.... ...ously great...even more than the number...which large enough.

...s...a tantalizing vista....barely make out the outlines.... ...def....classical approach....accumulate data....there is a catch.... ...sources...cosmic...energy almost unlimited....but....about 25 BeV ...llimation, 10 % energy resolution....one/cm² per 8 hours. Also ...ient location....

...ese reasons....clamoring for higher and higher....

Slide 1 - MeV - [illegible] versus time.

Extrapolating to 1994....5 hi 9 Mev or [illegible] cosmic...170 B$....preliminary design....8000 km, 20000 gauss

Slide 2 - 5 hi 15 eV machine.

What we can learn impossible to guess....main element surprise.... some things look for but see others.....Experience on [illegible]....sharpening knowledge... certainly look for multiple production...

Slide 3 - Multiple pion production.

lots of detail, angular distribution etcetera...

Look for antinucleons....threshold for protons 6.6 BeV....for pions on nucleons threshold 3.6 BeV...this reachable with Berkeley Bevatron.... near threshold low intensity

Slide 4 - Antinucleon production in nucleon nucleon collisions.

....probably better pion nucleon collisions....lower threshold....lower center of mass velocity....easier to stop....shorter range, about 10" Cu.... lower probability of nuclear capture during slowing.

Naturally interest in strange particles....Cosmotron work by Shutt and others.....very very cloudy crystal ball....Puzzle of long life times...., large angular moment?....double formation?....at present more probable... ....tried to photograph what I saw in the ball....and made slide...

Slide 5 - Strange particles in pion nucleon collisions.

....should realize this picture retouched....may have the wrong scale... may be wrong curves.....lots of other things could be seen...could not make them out.....

....ultimate result....understanding....need of precise data....expect complication....collision of atoms.....however, staring at a problem... ...also possibility of a lucky break....or theoretical leap.... or more probably a combination of hard work, ingenuity and a little bit of good luck.

FURTHER REPRODUCTION PROHIBITED

THE UNIVERSITY OF CHICAGO LIBRARY

What we can learn

impossible to guess.

...main element surprise...

Slide 6

however, staring at a problem...

...also possibility of a lucky break...

...or theoretical leap...

or more probably a combination of hard work,

ingenuity and a little bit of good luck.

End of lectures