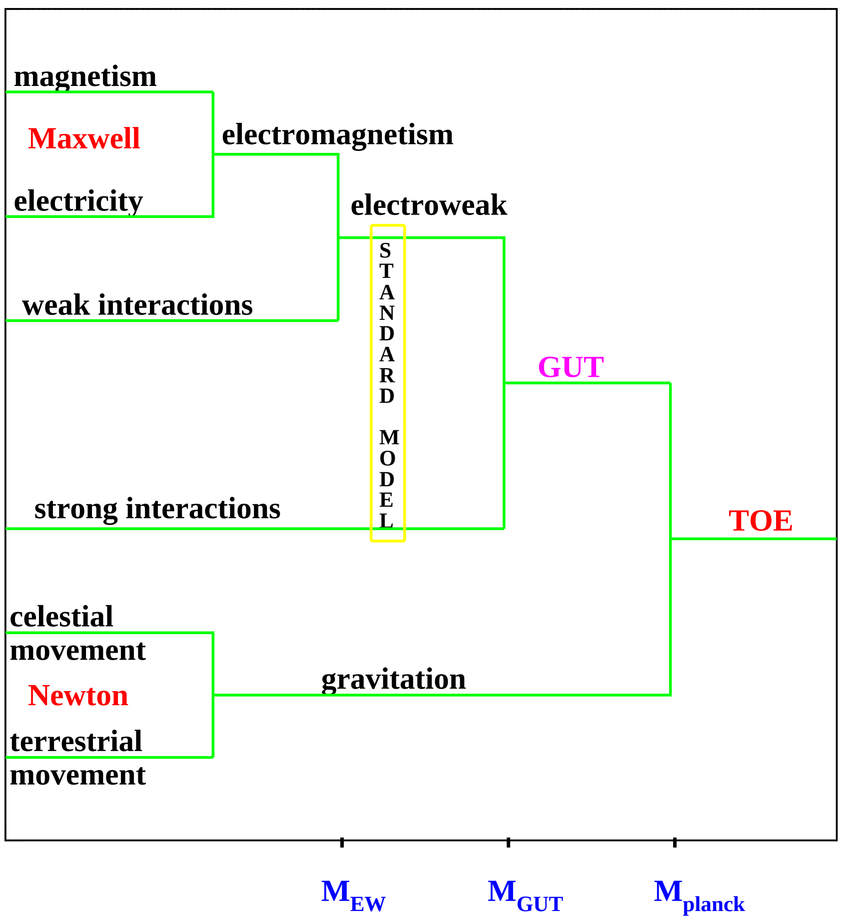
The Search for Supersymmetry

- Introduction the Standard Model of Particle Physics
- Introduction to Collider Physics
- Successes of the Standard Model
- What the Standard Model Does Not Do
- Physics Beyond the Standard Model
- Introduction to Supersymmetry
- Searching for Supersymmetry
- Dark Matter Searches
- Future Prospects
- Other Scenarios
- Summary

Force Unifications



Standard Model does NOT account for gravitational interactions

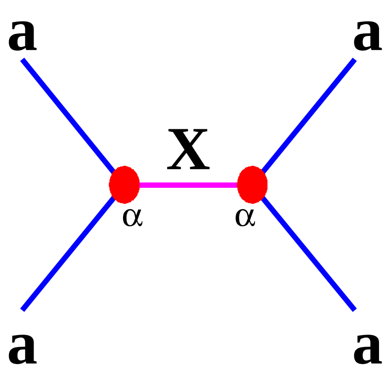
Planck Scale (or Planck Mass)

is defined as the energy scale at which gravitational interactions become of the same strength as SM interactions

The Standard Model

Describes the FUNDAMENTAL PARTICLES and their INTERACTIONS

All known FORCES are mediated by PARTICLE EXCHANGE



Effective strength of an interaction depends on

- **the coupling strength at the vertex**
- **the mass of the exchanged particle M_X**

Force	Effective Strength	Process
Strong	10^0	Nuclear binding
Electromagnetic	10^{-2}	Electron-nucleus binding
Weak	10^{-5}	Radioactive β decay

The Standard Model

SPIN-½ MATTER PARTICLES interact via the exchange of SPIN-1 BOSONS

MATTER PARTICLES – three generations of quarks and leptons

			|Q|
$\begin{pmatrix} \mathbf{e} \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$	1 0
$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}$	$\begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}$	$\begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}$	$\frac{2}{3}$ $\frac{1}{3}$

$$\mathbf{m}_e < \mathbf{m}_\mu < \mathbf{m}_\tau$$
$$\mathbf{m}_\nu = 0$$

Each quark comes in three 'colour' changes

Mass increases with generation:

$M_{u,d}$ ~ 0.3 GeV

⬇

M_t ~ 170 GeV

GAUGE BOSONS – mediate the interaction of the fundamental fermions

γ	1	**Gauge particle of electromagnetism (carries no electric charge)**
$\mathbf{W}^\pm, \mathbf{Z}^0$	3	**Gauge particles of the weak interaction (each carries weak charge)**
g	8	**Gauge particles of the strong interaction (each gluon carries a colour and an anti-colour charge charge)**

All Standard Model fermions and gauge bosons have been experimentally observed

There is one more particle in the SM – the Higgs Boson. This is vital to the SM but remains experimentally undetected

Spontaneous Symmetry Breaking

Initial Attempts to unify the weak and electromagnetic interactions failed because while M(γ) = 0 , the relative strength of the weak interaction requires

M(weak gauge boson) ~ 100 GeV

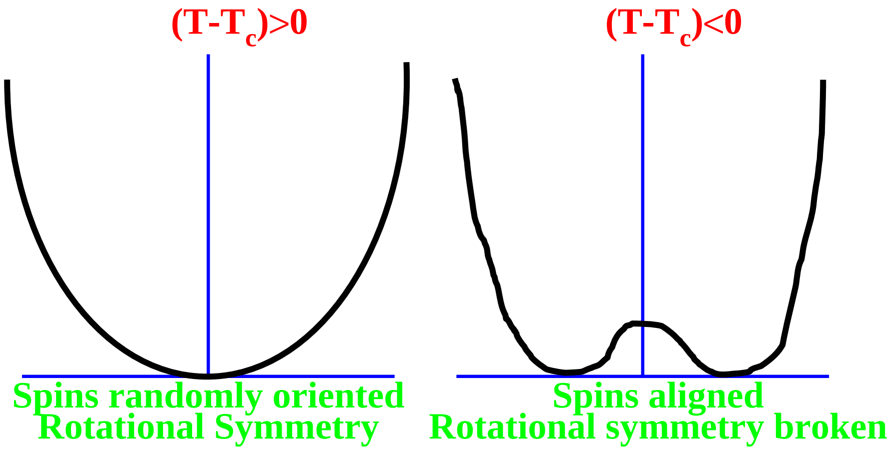
The SM is formulated in terms of MASSLESS particles

Introduction of explicit mass terms destroys a vital property of the theory

In the SM, masses for the weak interaction gauge bosons are generated via SPONTANEOUS SYMMETRY BREAKING

SSB may occur in systems where the equations describing the system have a SYMMETRY which is NOT OBEYED by the GROUND STATE

Consider a ferromagnet at temperatures above and below the Curie point:



Electroweak Unification

In the Standard Model SSB is introduced 'by hand' by introducing new fields

(4 degrees of freedom)

And and interaction potential $V(\mu^2, \lambda)$ **with** μ^2 **analogous to T-T$_c$**

Choosing $\mu^2 < 0 \quad \Rightarrow$ **Spontaneous Symmetry Breaking**

The 4 degrees of freedom

- **three masses (one each for W^+, W^-, Z^0)**
- **One physical spin-0 (scalar) particle (the Higgs Boson)**

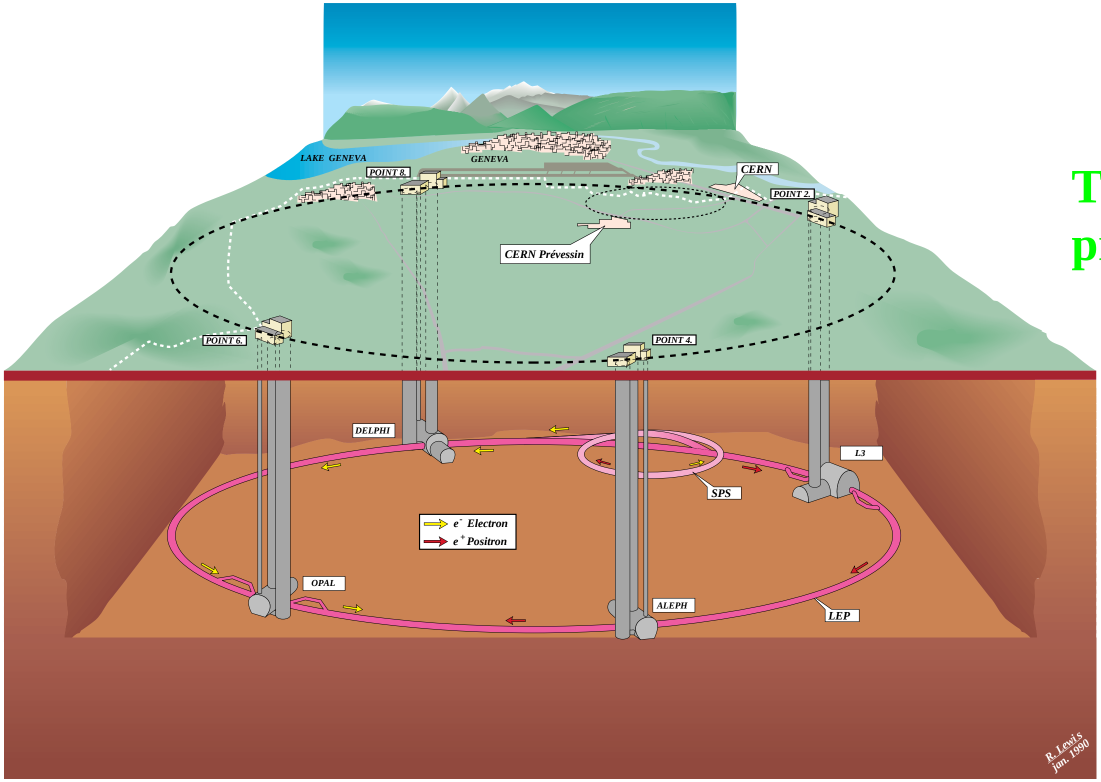
The mass of the Higgs boson is NOT predicted by the theory

The masses of the W and Z are related by the weak-mixing angle $\sin^2 \vartheta_W = 1 - \frac{M_Z^2}{M_W^2}$

The W and Z bosons were both discovered at CERN in 1984 (at the predicted masses) !

→ **Design and construction of the Large Electron Positron Collider at CERN**

The LEP e^+e^- Collider at CERN



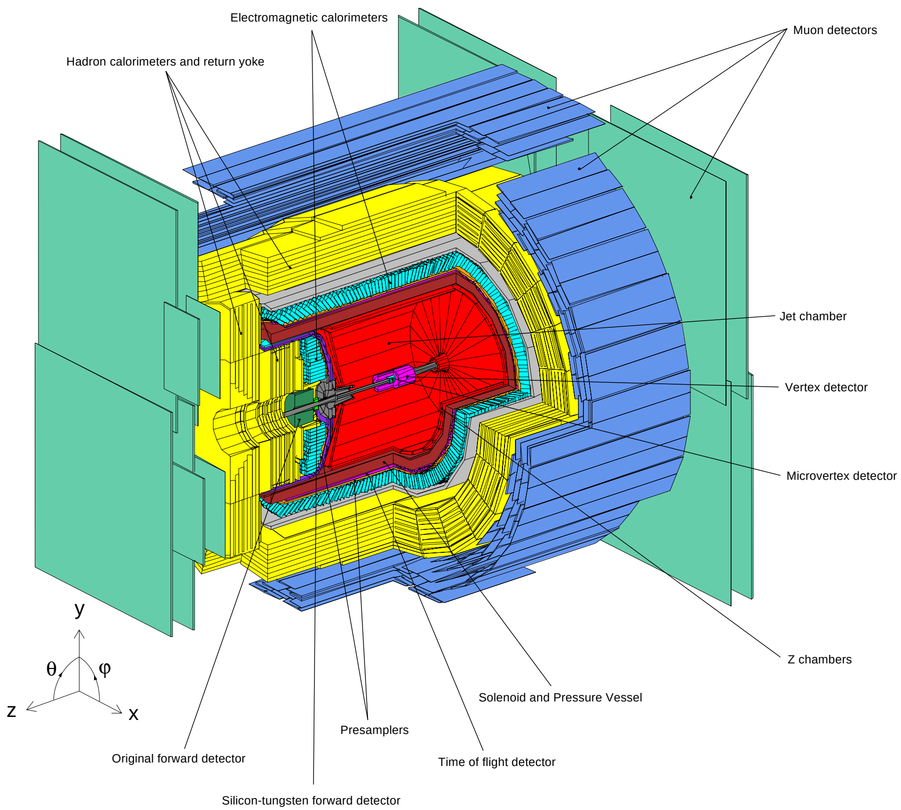
Two phase experimental program planned:

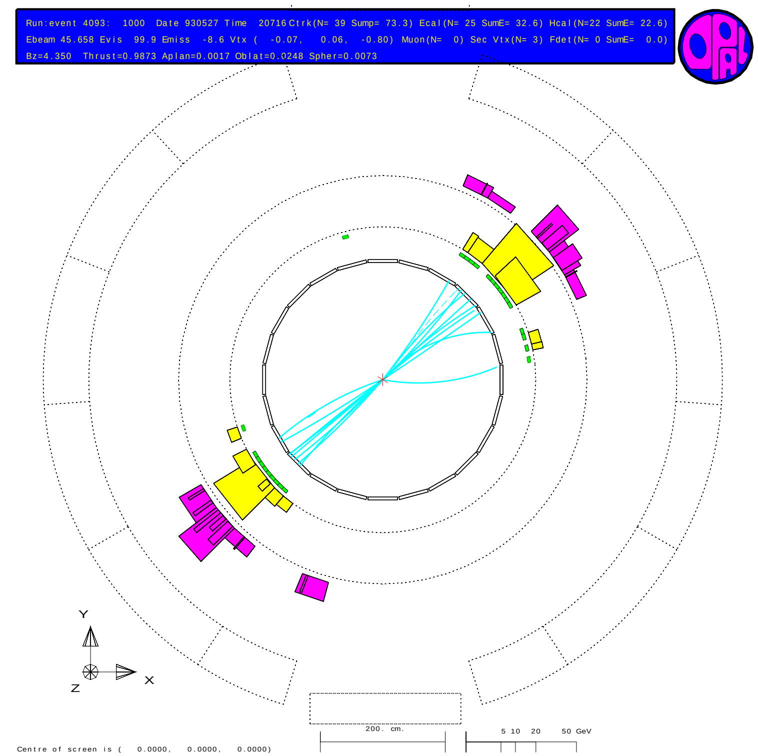
Phase 1 - precision measurements of the Z^0 ($E_{cm} = M_Z$) completed

Phase 2 – precision measurements of the W ($E_{cm} > 2M_W$) ends soon (Sept/2000)

Most recent running has been at energies up to 209 GeV

The OPAL Detector at LEP



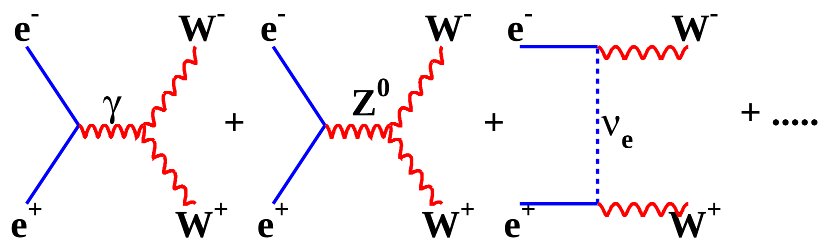


$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow \text{hadron jets}$$

Some Basic Collider Physics

How does one calculate the rate for some physics process at a collider ?

$\mathcal{M}$ = sum of all contributing processes (diagrams) – here for $e^+e^- \rightarrow W^+W^-$



Define CROSS-SECTION $\sigma \propto |\mathcal{M}|^2$ **(units of length²)**

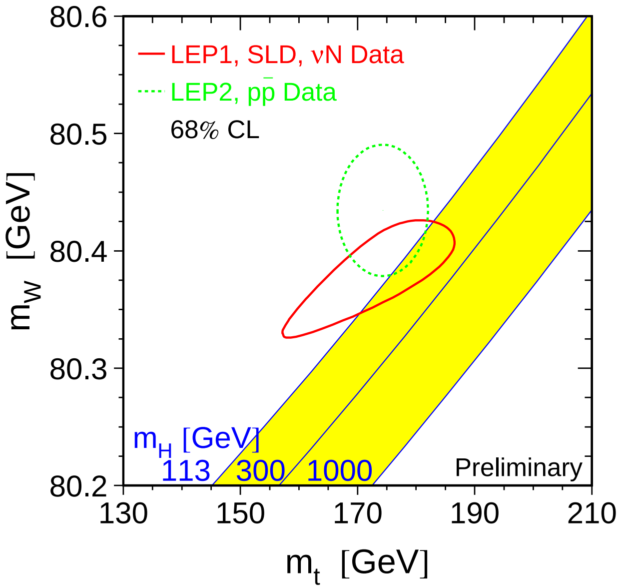
Define LUMINOSITY $\mathcal{L} \propto \dfrac{f \bullet n_{bunch} \bullet N^{e^+} \bullet N^{e^-}}{A}$

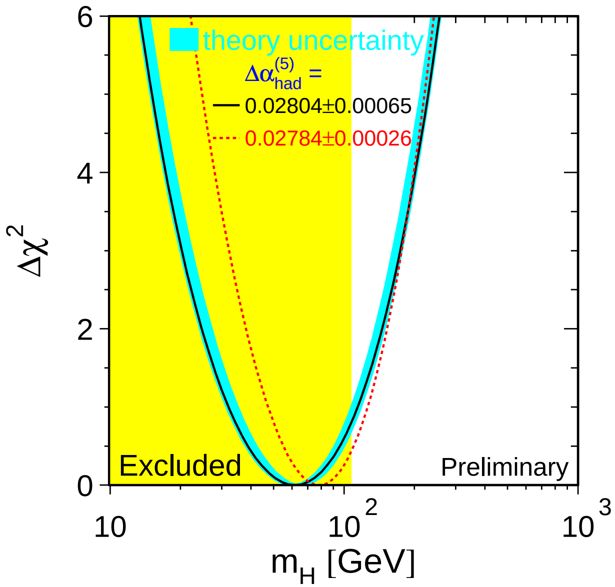
~ cross-sectional size of the beams

- **Instantaneous production rate** $N = \mathcal{L}\,\sigma$
- **Size of data samples typically quoted in** $\int \mathcal{L}\,dt$ **(pb^{-1})**
- **Number of events in data sample given by** $N = \sigma \int \mathcal{L}\,dt$

Standard Model Electroweak Summary

The Standard Model is very healthy (unfortunately ?)





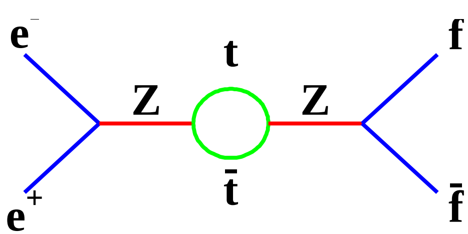
Higgs mass from EW fit

$$\mathbf{M}^{\mathbf{SMfit}}_{\mathbf{Higgs}} < 170\ \mathbf{GeV}\ @\,95\%\ \mathbf{CL}$$

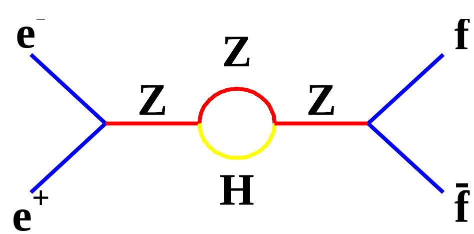
LEP direct search limit

$$\mathbf{M}^{\mathbf{SM}}_{\mathbf{Higgs}} > 113.3\ \mathbf{GeV}\ @\,95\%\ \mathbf{CL}$$

Electroweak quantities affected by virtual particle loops



$(M_t/M_W)^2$



$\ln(M_H/M_W)$

$$\sin^2\vartheta_W = 1 - \frac{M_Z^2}{M_W^2}$$

The SM Does Not Do Everything

Some examples:

Quarks and leptons are unrelated fundamental fermions, yet their electric charges are related by simple ratios. Why should this be the case ?

particle	ν	d	u	e
$\lvert \mathbf{Q} \rvert$	0	$\frac{1}{3}$	$\frac{2}{3}$	1

What causes the hierarchy in the fermion masses ? (these are free parameters in the SM)

$M_{u,d} \sim 0.3$ GeV $\rightarrow$ $M_t \sim 170$ GeV

What causes electroweak symmetry breaking ? (Higgs mechanism for SSB put in by hand)

GRAND UNIFIED THEORIES attempt to provide answers by postulating that the strong and electroweak forces unify to a single force at some high energy scale (M_{GUT})

- **there is a single force with coupling** α_{GUT}
- **quarks and leptons are related**

instead of $\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ **we get** $\begin{pmatrix} e^- \\ \nu_e \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \end{pmatrix}$

Colour indices: red, green, blue

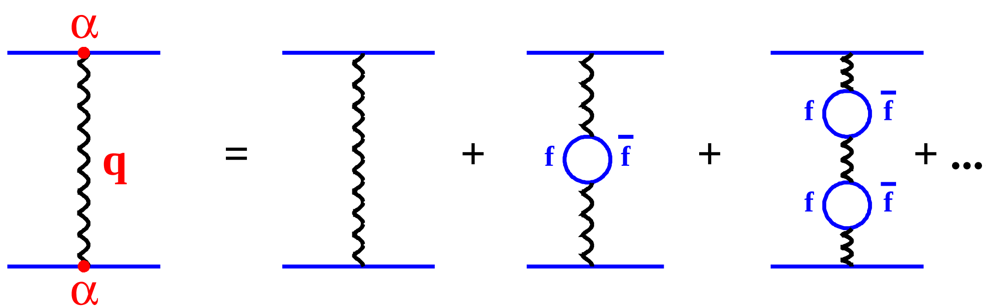
The structure of the theory requires that the charge in this multiplet sum to 0

$$Q(\nu_e) + Q(e^-) + 3Q(\bar{d}) = 0$$

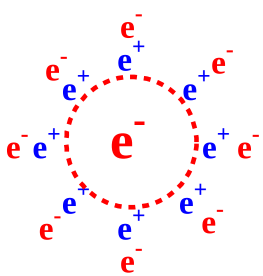
SUCCESS ! But there are problems too

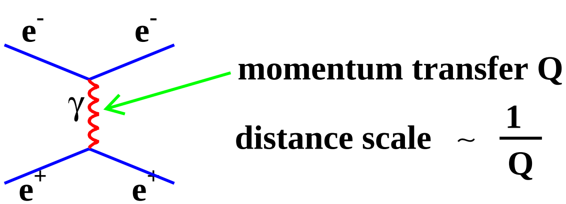
Running of Coupling Strengths

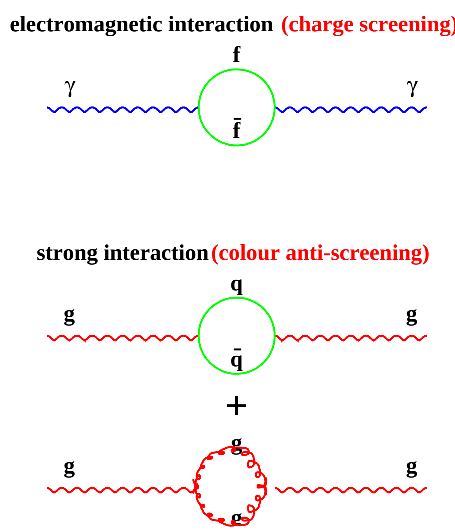
Imagine measuring the electromagetic coupling strength via ee scattering

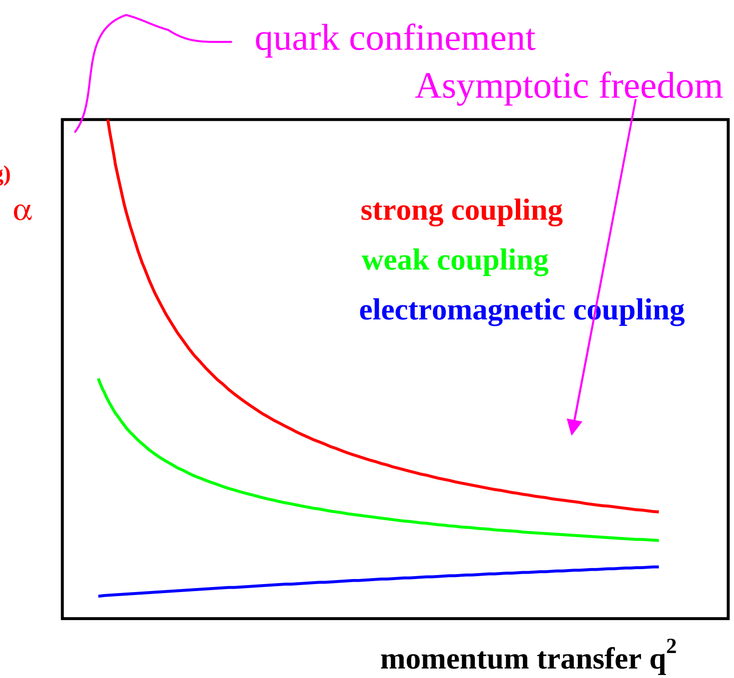


Charge Screening – the observed charge depends on the energy scale



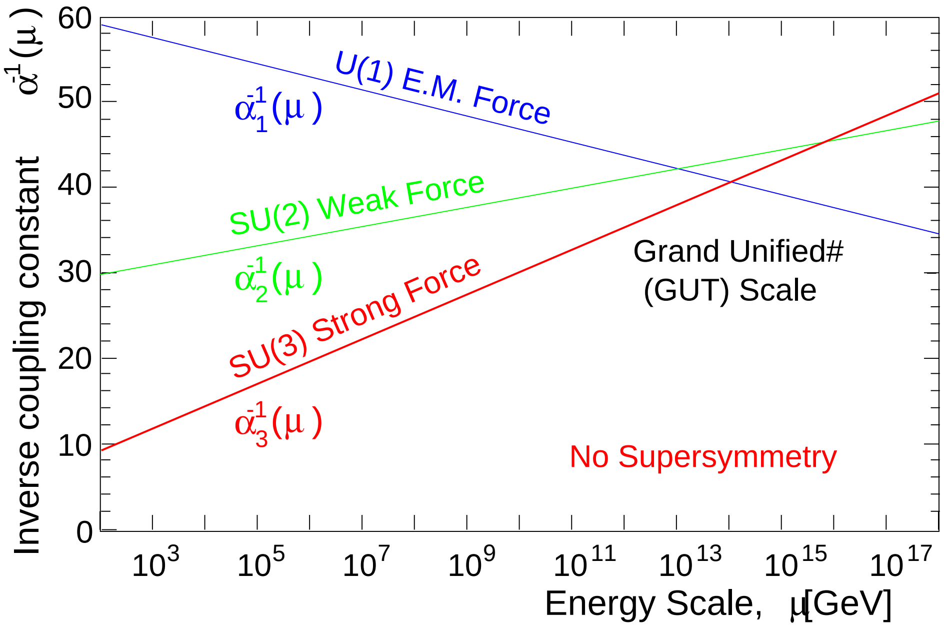


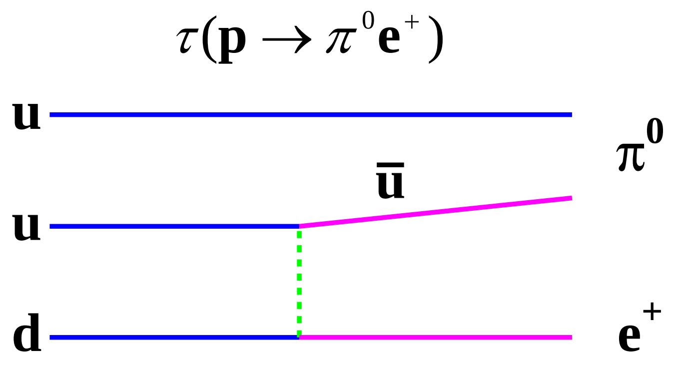




Some GUT Problems

For a single force with a single coupling at M_{GUT} expect $\alpha_1 = \alpha_2 = \alpha_3$





(+ other diagrams)

Quark-lepton relationship ⇨ **proton decay**

Simplest models predict $\tau(\mathbf{p} \to \pi^0 \mathbf{e}^+) \sim 10^{28} - 10^{31}$ **years**

Inconsistent with experimental results $\tau(\mathbf{p} \to \pi^0 \mathbf{e}^+) > 4.4 \times 10^{33}$ **years @ 90%CL**

(from SuperKamiokande)

The Naturalness Problem

Masses in SM get radiative corrections $\mathbf{M_{physical} = M_0 + \delta M}$

Naturalness (aesthetic criterion) requires $\mathbf{O(M_{physical}) \approx O(M_0) \approx O(\delta M)}$

i.e. no fine tuning

This is not true for fundamental scalars (Higgs) for which $(\delta \mathbf{M})^2 \propto \Lambda^2$

where Λ **is the highest energy to which the theory remains valid**

So for $\mathbf{M_H}$ **< 1 TeV (SM bias) require either**

$\Lambda \approx 1\mathbf{TeV}$ **i.e. SM breaks down at 1 TeV, OR**

Some symmetry exists which can produces

$\mathbf{O(\delta M) \approx O(M_H)}$ **independent of** Λ

Such a symmetry exists → **<u>Supersymmetry</u>**

Supersymmetry

Each SM boson (fermion) has a fermionic (bosonic) supersymmetric partner with IDENTICAL MASS and Standard Model COUPLINGS

leptons ↔ **sleptons**

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix} \begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_\mu \end{pmatrix} \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix}$$

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

quarks ↔ **squarks**

$W^\pm$	$\tilde{W}^\pm$	**gauginos**
Z^0	$\tilde{Z}^0$	
γ	$\tilde{\gamma}$	
h^0	$\tilde{h}^0$	**higgsinos**
H^0	$\tilde{H}^0$	
A^0	$\tilde{A}^0$	
$H^\pm$	$\tilde{H}^\pm$	
g	$\tilde{g}$	**gluinos**

This defines the particle content of the Minimal Supersymmetric Standard Model or MSSM

Mass eigenstates are mixtures of gauginos and higgsinos

2 Charginos $\tilde{\chi}^\pm_{i=1,2}$

4 Neutralinos $\tilde{\chi}^0_{j=1,4}$

Supersymmetry is a Broken Symmetry

Supersymmetry requires a doubling of the particle spectrum. Is this cost excessive ?

It has been successful before (anti-matter) BUT

$$\mathbf{M_{e^+} = M_{e^-}} \qquad\qquad \mathbf{M_e \neq M_{\tilde{e}}}$$

We do not see supersymmetric matter made of snucleons and selectrons

⇒ **Supersymmetry is a <u>BROKEN SYMMETRY</u>**

But …. If supersymmetry is to solve the NATURALNESS PROBLEM, we require

$$\mathbf{M_{SUSY} \leq 1\ TeV}$$

This is often referred to as <u>WEAK-SCALE SUPERSYMMETRY</u>

R-parity

R-Parity is a quantum number which distinguishes SM and supersymmetric particles

$$\mathbf{R} = (-1)^{3(\mathbf{B}-\mathbf{L})+2\mathbf{S}}$$

Most supersymmetric models assume R-Parity Conservation

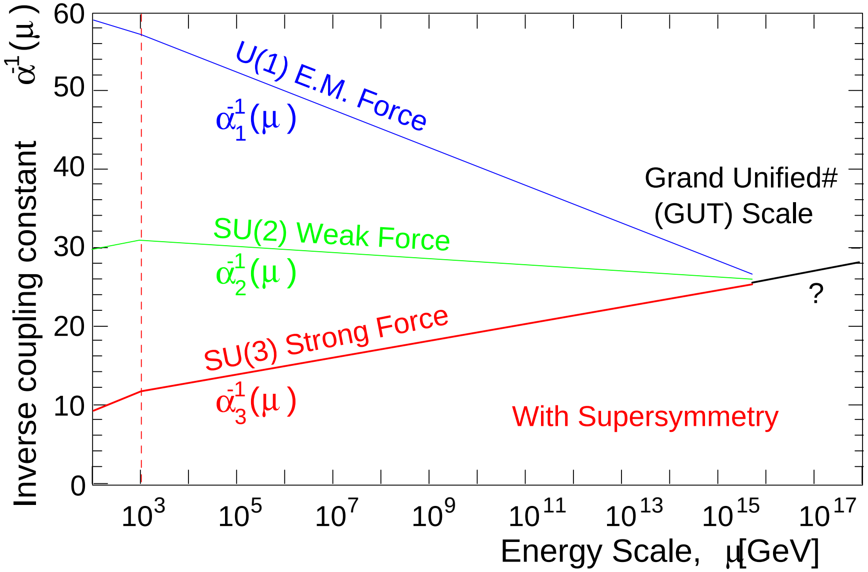
This has two important consequences:

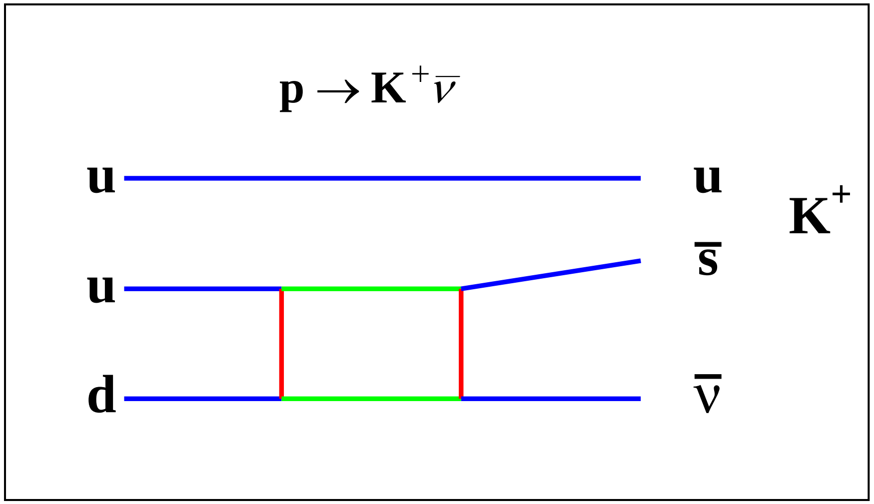
- **Supersymmetric particles must be produced in pairs**
- **There must be some Lightest Supersymmetric Particle or LSP**

This LSP is usually the lightest neutralino $\tilde{\chi}_1^0$ and is a good Cold Dark Matter candidate or WIMP (Weakly Interacting Massive Particle)

Coupling Constant Evolution - SUSY

Force unification revisited (now with MSSM particle content)





We still have a quark-lepton relationship and therefore proton decay. Dominant mode in SUSY GUTs is $p \to K^+ \bar{\nu}$

in SUSY GUTs $\tau(p \to \pi^0 e^+) = 10^{38 \pm 1}$ **years**

Model predictions vary: $\tau(p \to K^+ \bar{\nu}) \sim 10^{30} - 10^{36}$ **years**

Experimental limits $\tau(p \to K^+ \bar{\nu}) > 1.9 \times 10^{33}$ **years @ 95% CL (Super K)**

Super Kamiokande detector will probe lifetimes up to 10^{34} years

Supersymmetric Model Parameters

MSSM has 105 free parameters (in addition to the 19 free parameters of the SM) !!!

- **masses**
- **couplings**
- **mixing angles**
- **other parameters arising from supersymmetry breaking**

Frequently results of supersymmetric particle searches are interpreted within the framework of the Constrained MSSM which assumes that many free paramters of the MSSM unify at the GUT scale

↓

5 parameter Constrained MSSM

Other Features of Supersymmetric GUTS

- **Unification of free parameters at the GUT scale (as for the couplings)**

- **Can provide a correct prediction of** $\sin^2 \vartheta_W$ **(experimentally 0.2198 +/- .0021)**

- **Mechanismm for Electroweak symmetry breaking:**
  - μ^2 **positive at the GUT scale but 'runs' negative at the EW scale**

- **Mass prediction for the lightest higgs !**
  - **$M(h^0) < 130$ GeV (MSSM)**
  - **$M(h^0) < 150$ GeV (Supersymmetry in general)**

- **May allow for unification with gravity:**
  - **Most string theories are supersymmetric**

Sensitivity to New-Particle Production

REQUIREMENTS for DIRECT OBSERVATION of a particle X with mass M_X

- **X production (some process) must be kinematically accessible**
- **the production process must have** $\sigma > (\int L\, dt)^{-1}$

  - **for instance for** $e^+e^- \to XX$
    if $\sigma(e^+e^- \to XX) = 0.1\,\text{pb}$ **require**
    $$\left.\right\} \begin{array}{l} E_{CM} > 2M_X \\ (\int L\, dt)^{-1} > 10\,\text{pb}^{-1} \end{array}$$

NON-OBSERVATION of a PROCESS implies only that the CROSS-SECTION is lower than the sensitivity of the data sample

One can EXCLUDE A MODEL if it predicts a cross-section that is excluded

One can EXCLUDE THE EXISTENCE OF PARTICLE X only if the cross-section (at a given energy) is a function of the mass only or if other relevant parameters are scanned

CROSS-SECTION LIMITS are typically ~ model independent (measurements)

MASS LIMITS are typically model dependent (interpretations of measurements)

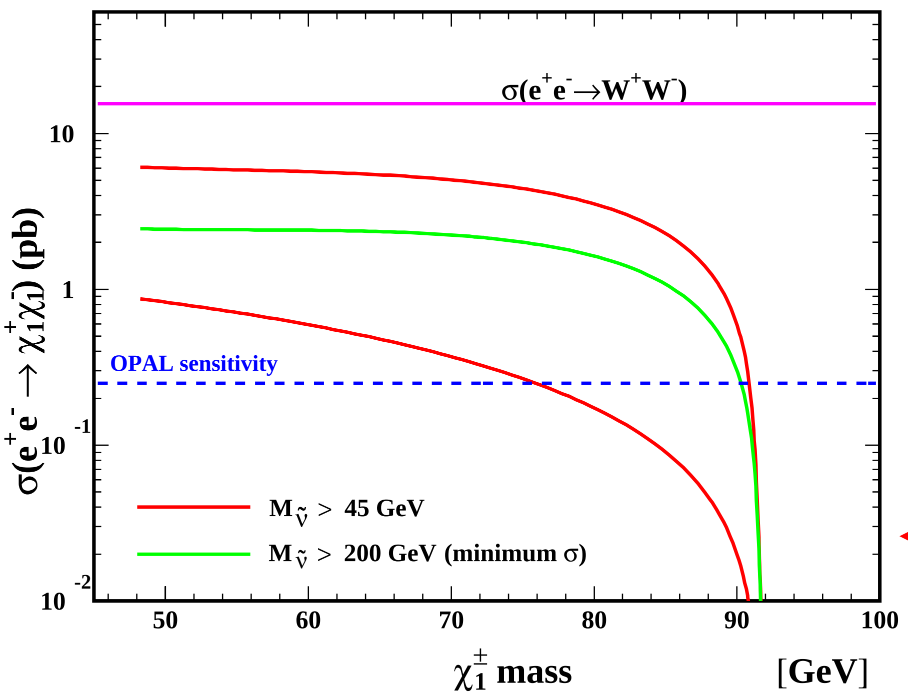
Supersymmetric Particle Searches at LEP

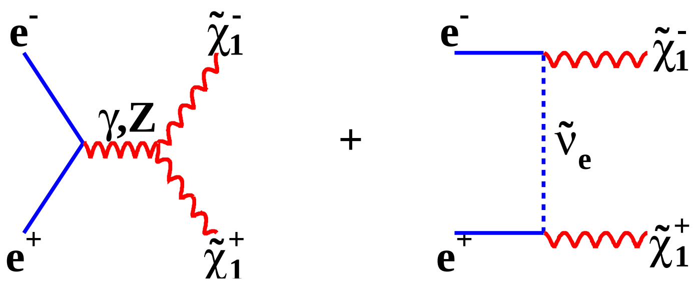
LEP is an electroweak machine

Best candidates for SUSY searches are the lowest mass charginos and neutralinos

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

Best discovery channel at LEP $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$



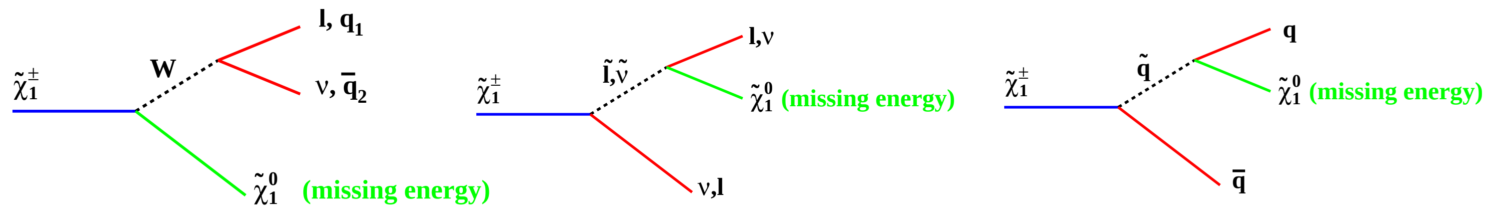


processes interfere destructively

← **E_{cm} = 183 GeV**

Chargino Decays – Experimental Signatures

Decay Mode



Experimental Signature

lepton + missing energy hadron jets + missing energy	lepton + missing energy	hadron jets + missing energy

> $\tilde{\chi}_1^0$ **is massive and interacts only weakly with matter (i.e. the detector)**
> ⇒ **carries off missing (undetected) energy**

So for $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ **experimental signatures are:**

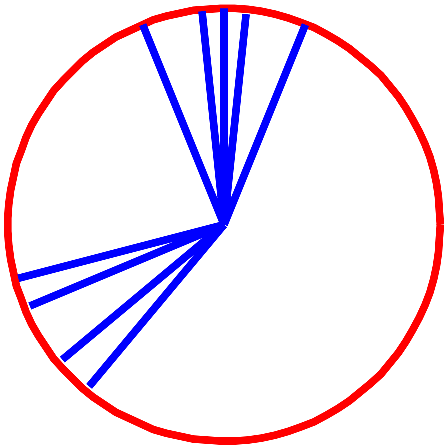
Experimental Signature	SM background
jets + missing energy	$e^+e^- \rightarrow ZZ \rightarrow (q\bar{q})(\nu\bar{\nu})$
jets + leptons + missing energy	$e^+e^- \rightarrow W^+W^- \rightarrow (q\bar{q}')(l\nu)$
2 leptons + missing energy	$e^+e^- \rightarrow W^+W^- \rightarrow (l\nu)(l'\nu)$

Missing energy is carried off by neutrinos

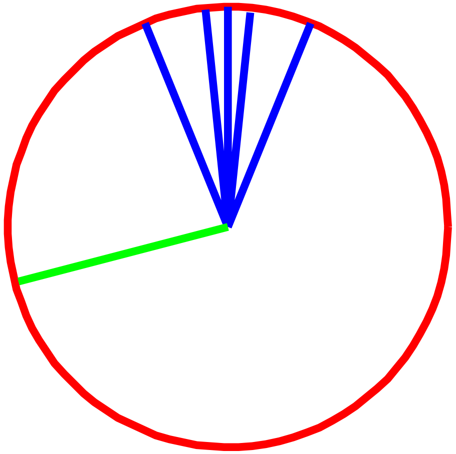
Experimental Signatures Cont'd

So what do these events look like in the detector ?

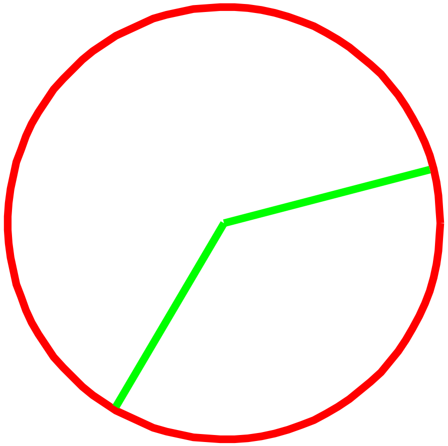
jets + missing energy



jet + lepton + missing energy

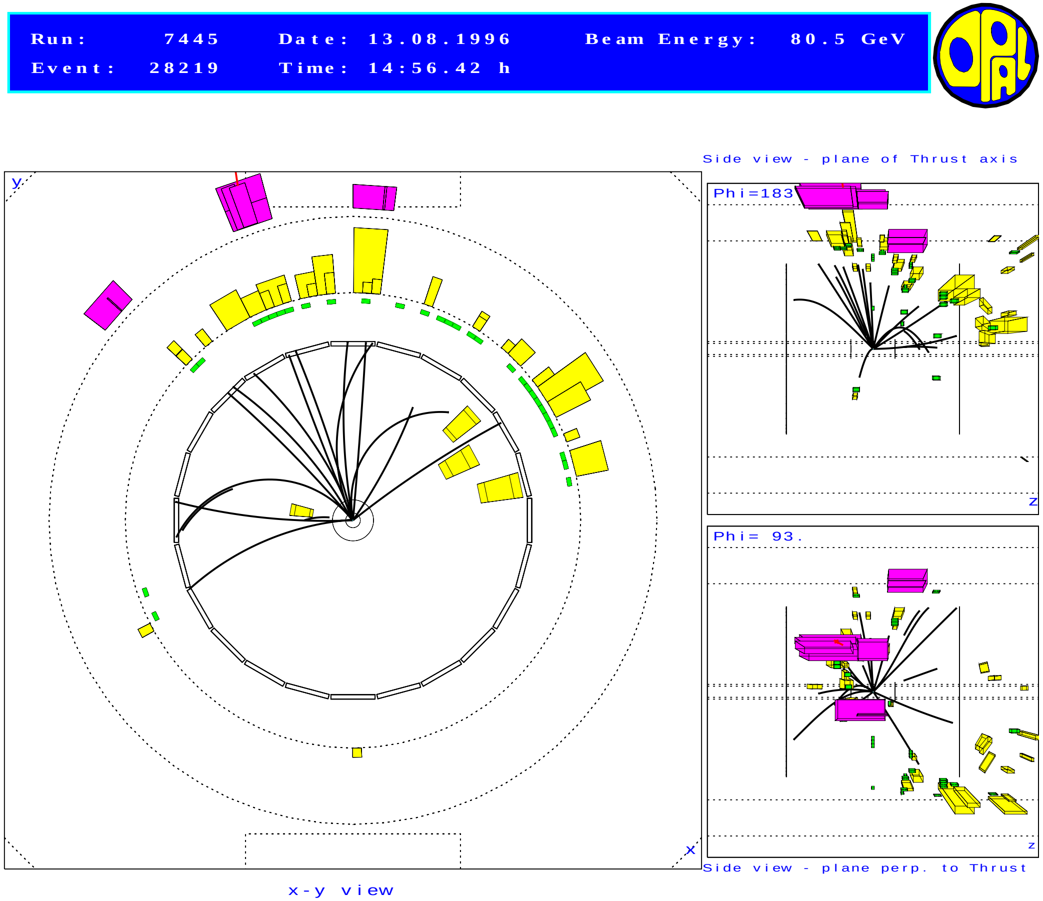


2 leptons + missing energy



Look for an excess of such events over expected SM background

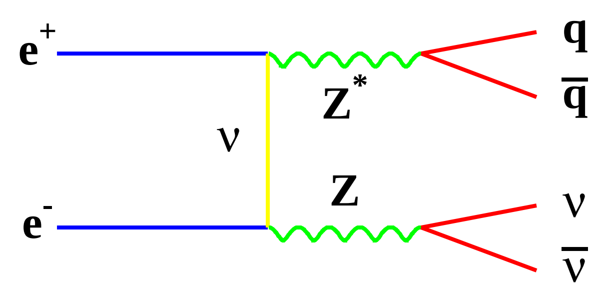
A Chargino Candidate Event



jets + missing energy channel

Also consistent with coming from a SM process:

$$M_{miss} = (E^2_{miss} - P^2_{miss})^{1/2} \sim M_Z$$



Missing energy carried off by neutrinos ?

Cross-section Limits

Signal for new physics is an excess of events above the SM backgrounds

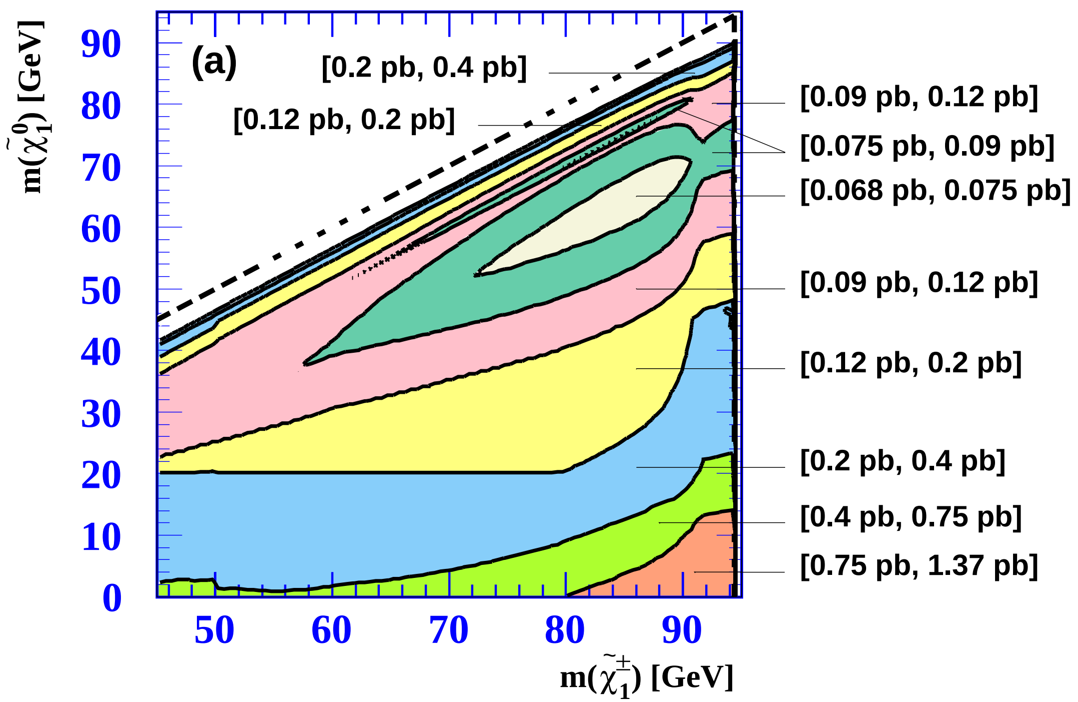
But ….

N_{events}(selected) consistent with N_{events}(expected from SM processes)

Place limits on $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-)$

in plane of $M(\tilde{\chi}_1^0)$ **vs** $M(\tilde{\chi}_1^\pm)$

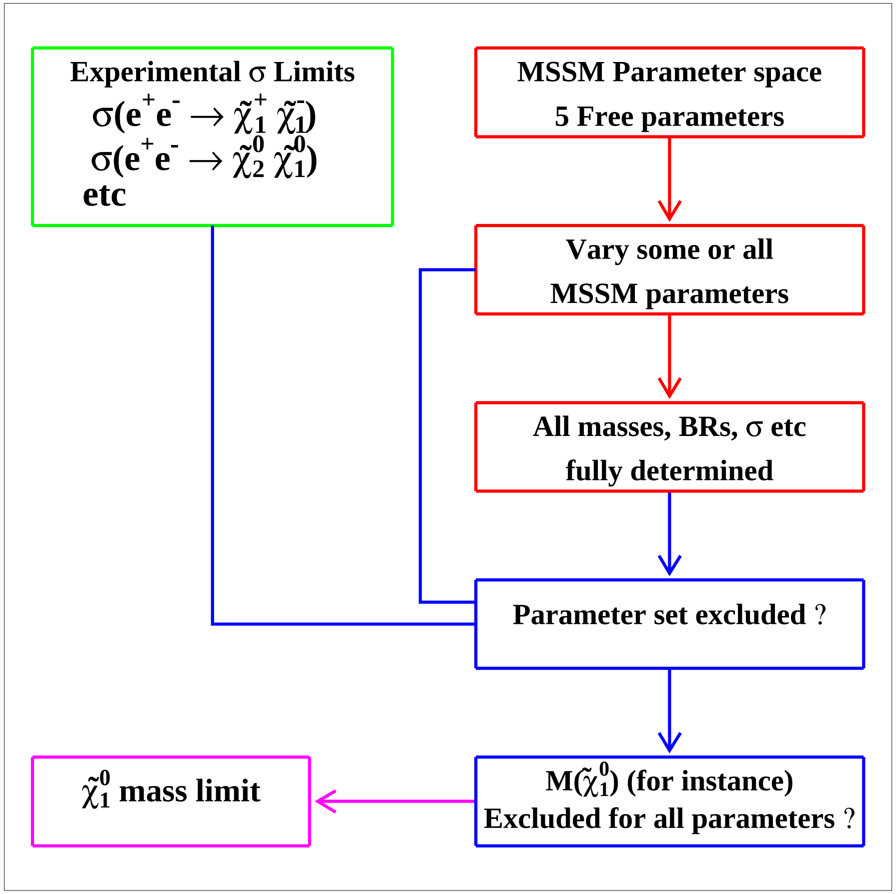
OPAL



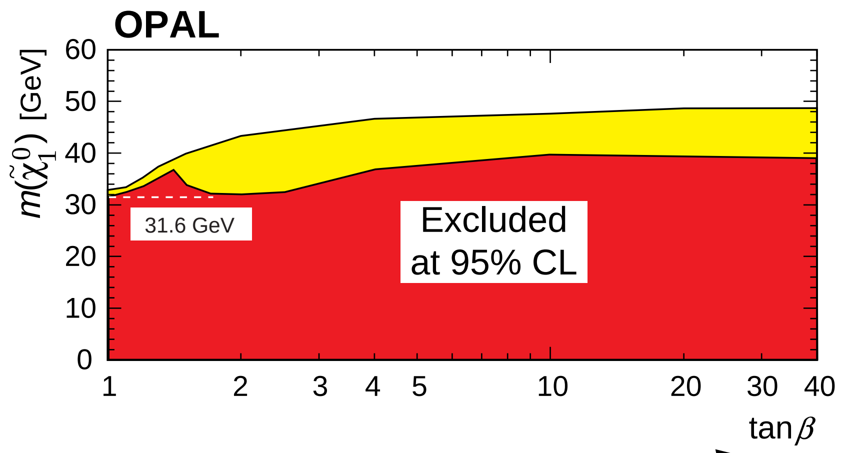
These results are at E_{cm} = 189 GeV

Mass Limits for Supersymmetric Particles

Model dependent mass limits can be set by scanning the CMSSM parameter space and comparing predicted cross-sections with experimental limits



Mass limit for MSSS Cold Dark Matter Candidate



last scan parameter

$$\mathbf{M}(\tilde{\chi}_1^0) > 31.6\ \mathbf{GeV}\ @\ 95\%\ \mathbf{CL}$$

Dark Matter

Matter whose existence has been inferred only via its gravitational effects

There is extensive evidence that much of this is non-baryonic

⇨ **weakly interacting particles**

- **hot dark matter (relativistic) e.g. neutrinos**
- **cold dark matter (non-relativistic)**

Weakly
Interacting
Massive
Particles
S

$\tilde{\chi}_1^0$ **is an excellent CDM candidate in most of the MSSM parameter space**

Strong evidence comes from the rotation curves of spiral galaxies

Expect $\mathbf{v(r)} \propto \frac{1}{\mathbf{r}}$ **Observe v(r) ~ independent of r**

This FLAT ROATATION CURVE implies that $\mathbf{M} \propto \mathbf{r}$

This is the expected mass profile of a self gravitating ball of ideal gas at a uniform temperature

Direct Dark Matter Searches

In the early universe $\mathbf{e^+e^- \rightarrow XX}$ **Production**

For T>>T$_X$ $\mathbf{XX \rightarrow e^+e^-}$ **Annihilation**

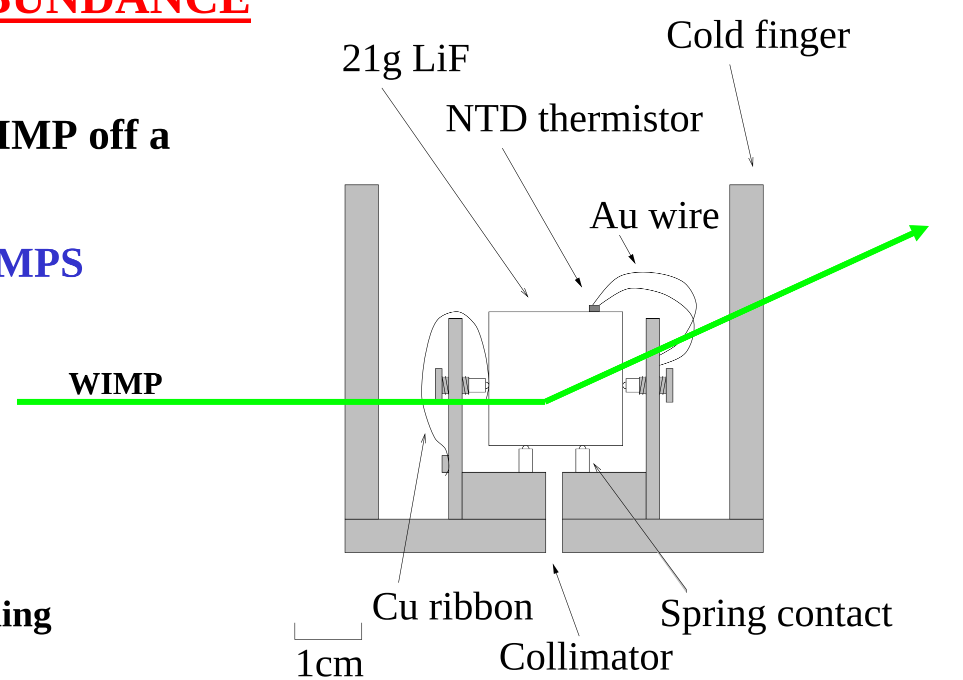
WIMP number density in equilibrium with e^-, e^+, γ

For T < T$_X$ the WIMP number density drops until the mean free path for annihilation exceeds the size of the universe

RELIC ABUNDANCE

Cross-section for elastic scattering of a WIMP off a nucleus calculable with specific models

Can do direct searches for WIMPS

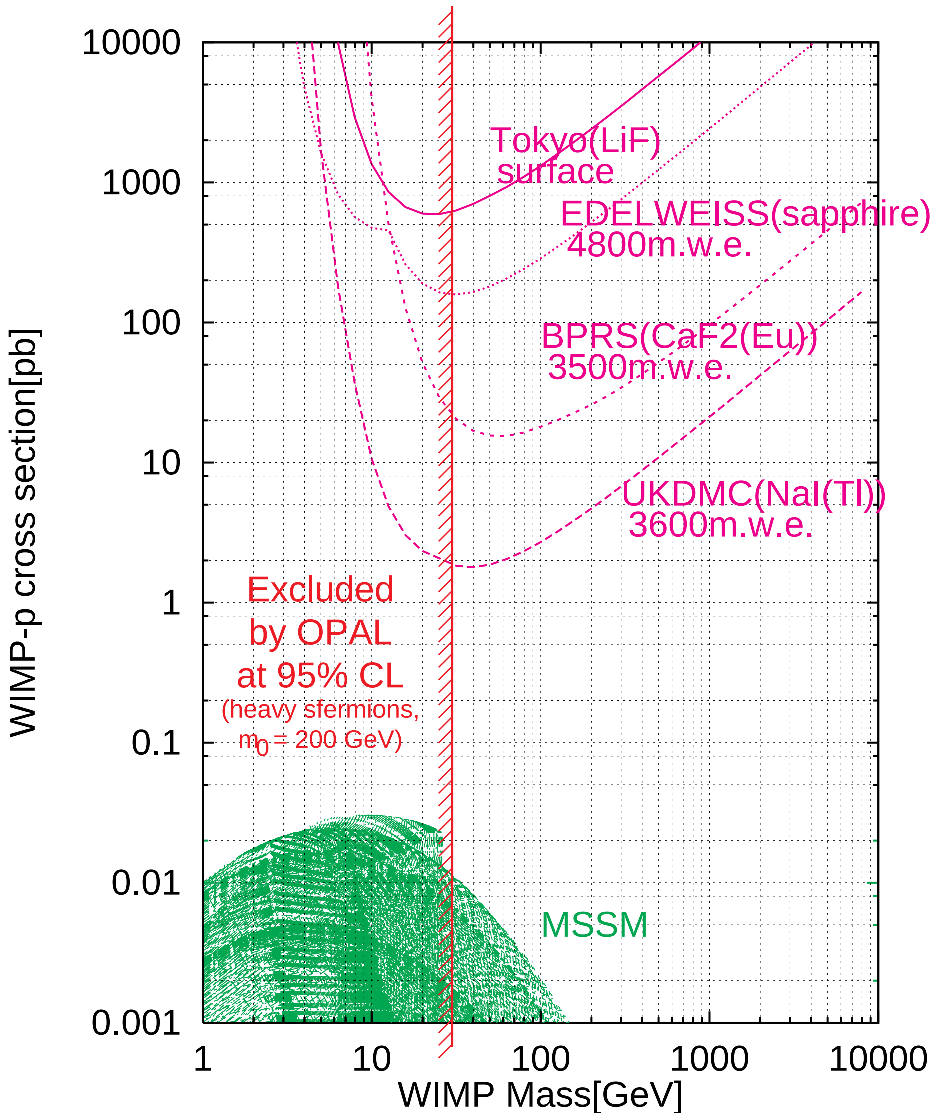


Apparatus at 10 mK

Requires proper shielding

bolometer

Dark Matter – Experimental Summary



Tokyo LiF detector will reach WIMP-p cross-section of 0.01pb

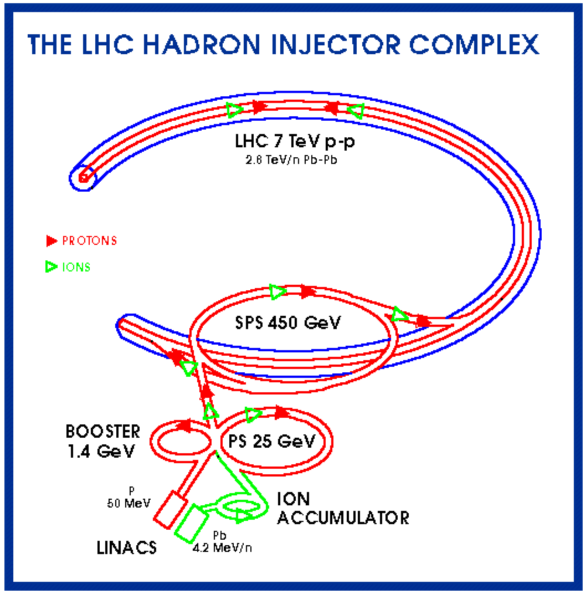
UPDATE:

Lots of experiments, including Canadian experiement PICASSO

OPAL limit indicated is somewhat dated

The LHC pp Collider at CERN

14 TeV pp collider to be installed in the existing LEP ring
First collisions scheduled for 2005



Two general purpose detectors approved for LHC

ATLAS (+ Canada) and CMS

Main objectives: Discover the new TeV scale physics

- **Discovery of the Higgs**
- **Discover of Weak-Scale SUSY or fully exclude it**

The LHC is a strong-interaction machine

⇒ **SUSY production rates will be highest for $\tilde{q}$ and $\tilde{g}$**

LHC Low-luminosity running ⇒ 10^4 pb^{-1} / year (3 years)

LHC High-luminosity running ⇒ 10^5 pb^{-1} / year (3+ years)

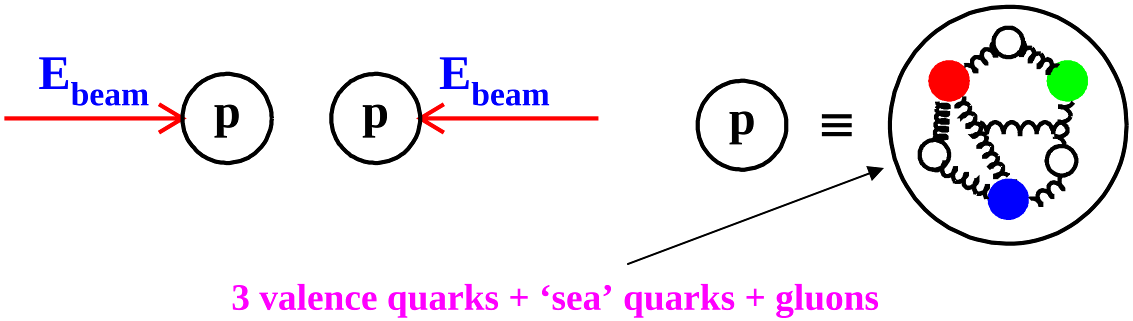
cross-sections for supersymmetric particle production can be enormous !

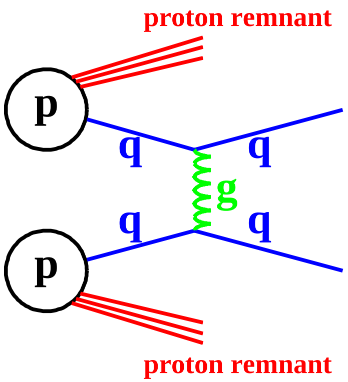
⇒ **$10^2 - 10^3$ pb** **(recall $N = \sigma \int L \; dt$)**

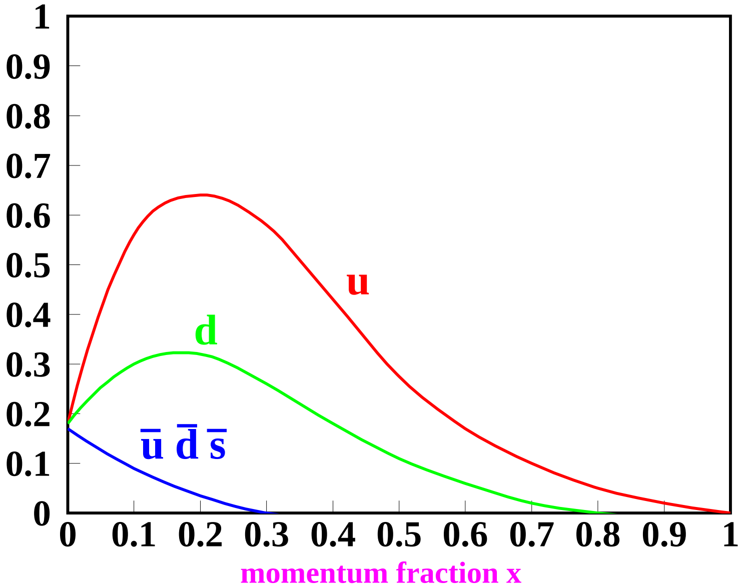
New Particle Searches at Hadron Colliders

Hadon Colliders can achieve higher centre-of-mass energies than electron-positron machines ….. BUT

E_{CM} of constituent collision $\neq 2\times \mathbf{E_{beam}}$





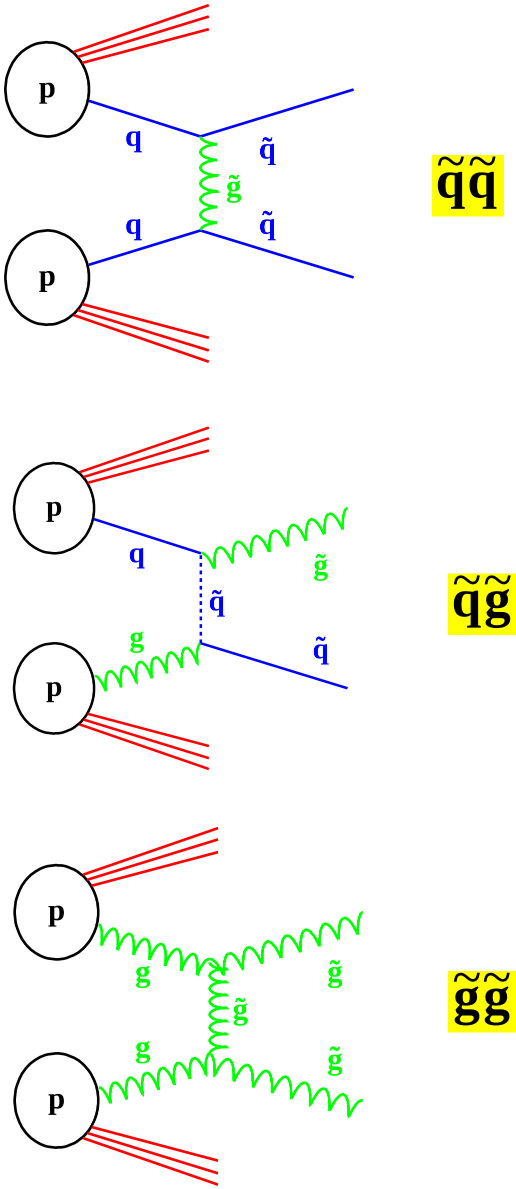


Gluons carry ~ 50% of the protons momentum

Collision is between two particles each carrying some fraction x of the protons momentum

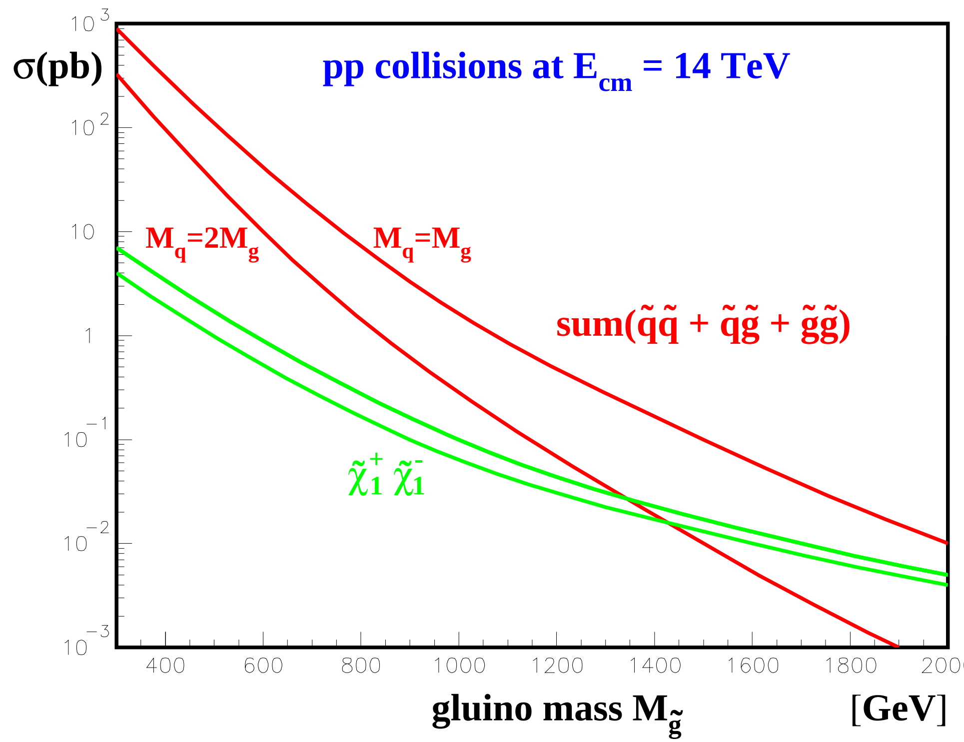
$$0 < \mathbf{x} < 1 \quad \Rightarrow \quad 0 < \mathbf{E_{CM}^{effective}} < 2\mathbf{E_{beam}}$$

Supersymmetric Particle Production at LHC



LHC will discover (with 10 pb^{-1}):

- ➢ $\tilde{g}$ **and** $\tilde{q}$ **up to ~ 2 TeV**
- ➢ $\tilde{l}, \tilde{\chi}_j^0, \tilde{\chi}_i^\pm$ **over a more restricted range**



Conclusions

General arguments → **NEED FOR PHYSICS BEYOND THE SM**

Some of these arguments → **NEW PHYSICS AT THE TeV SCALE**

SUPERSYMMETRY is a serious candidate for the description of this new physics

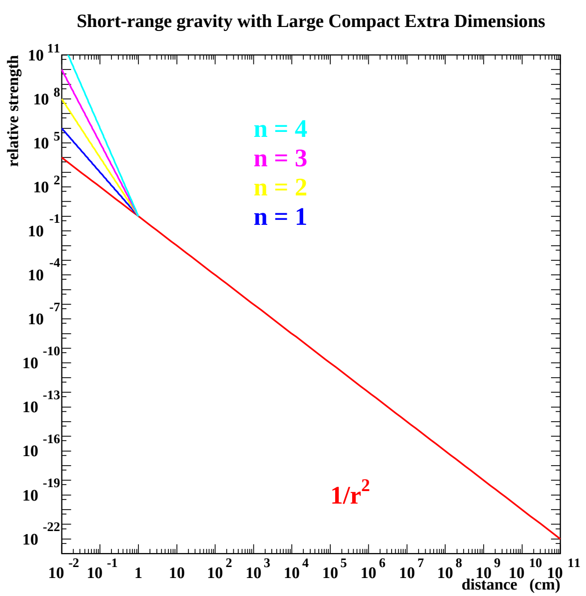
WEAK SCALE SUPERSYMMETRY (relevant to the naturalness problem) might be accessible at current colliders. If not, it will be DISCOVERED OR EXCLUDED by the LHC experiments

The Latest Theoretical Vogue: Large Extra Dimensions

- **Hierarchy problem:** $\mathbf{M_{EW} / M_{planck}} \approx 10^{-17}$
- **Postulate M_{planck} effective energy scale, not fundamental**
- **Assume n compact spatial dimensions of (compactified) radius R**

$$V(r) = \frac{m_1 m_2}{M_D^{2+n}} \bullet \frac{1}{r^{n+1}} \qquad (r \ll R)$$

$$V(r) = \left\{ \frac{m_1 m_2}{M_D^{n+2}} \bullet \frac{1}{R^n} \right\} \frac{1}{r} \qquad (r \gg R)$$



Effective 4-dimensional M_{planck} then given by

Requiring $M_D \sim M_{EW}$ → $R \sim 10^{(30/n)-17}$ cm

n=1 → R ~ 10^{13}cm -
excluded by $1/r^2$ tests of gravity

n=2 → R ~0.1-1mm -
limited to very high M_D by SN1987 data

There are other models with infinite sized extra dimensions (non-factorizable space-time geometry) for which n=1 is not excluded