The Physics Behind the LHC

G.F. Giudice

CERN, July 6, 2006

Main goal of LHC:

discover mechanism of EW breaking &
origin of elementary particle masses

but

What does it mean?

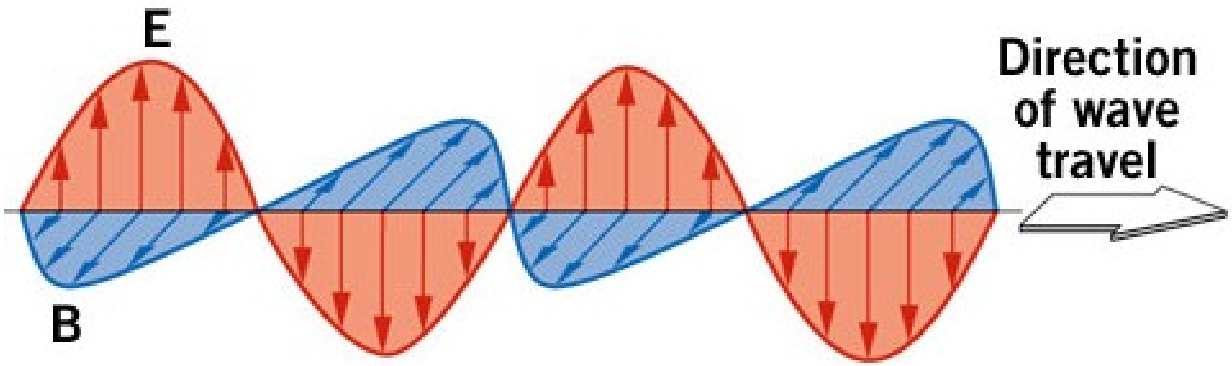
What's the problem of EW breaking?

What's so mysterious in particle masses?

In quantum theory:

particle ⇔ wave

photon ⇔ EM wave

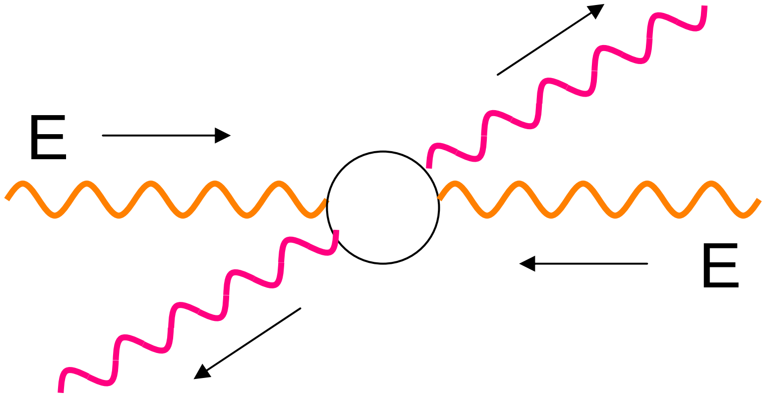


Oscillations perpendicular to direction of motion

The EM wave has only 2 independent polarizations

Just an empirical fact, but a very lucky one

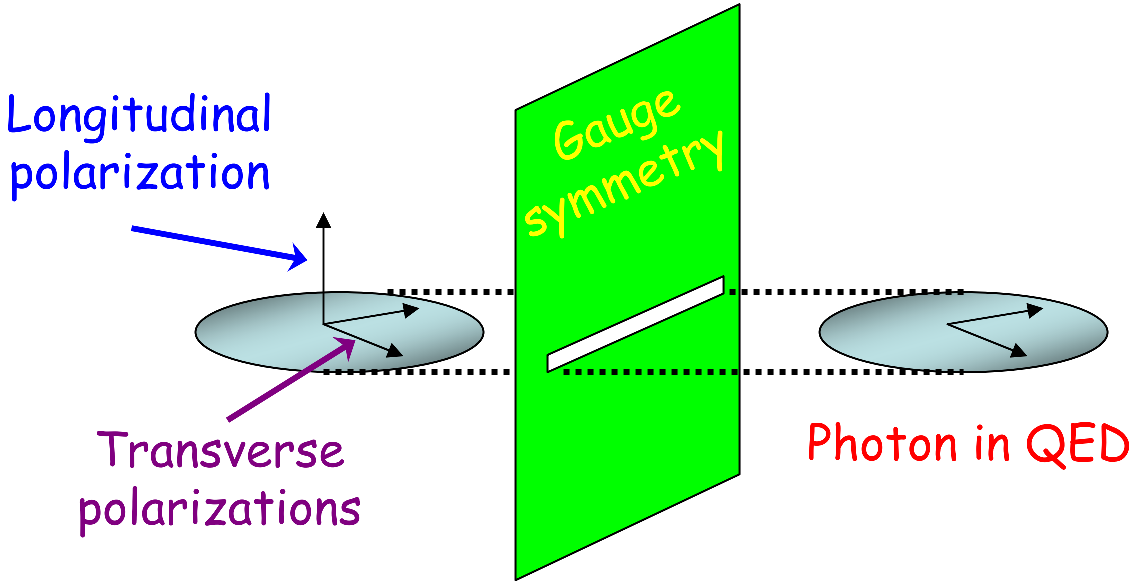
If 3rd polarization existed



Scattering probability grows with E

Nonsense at large E: probability larger than 100%

In QED, 3rd pol. does not exist ⇒ gauge symmetry

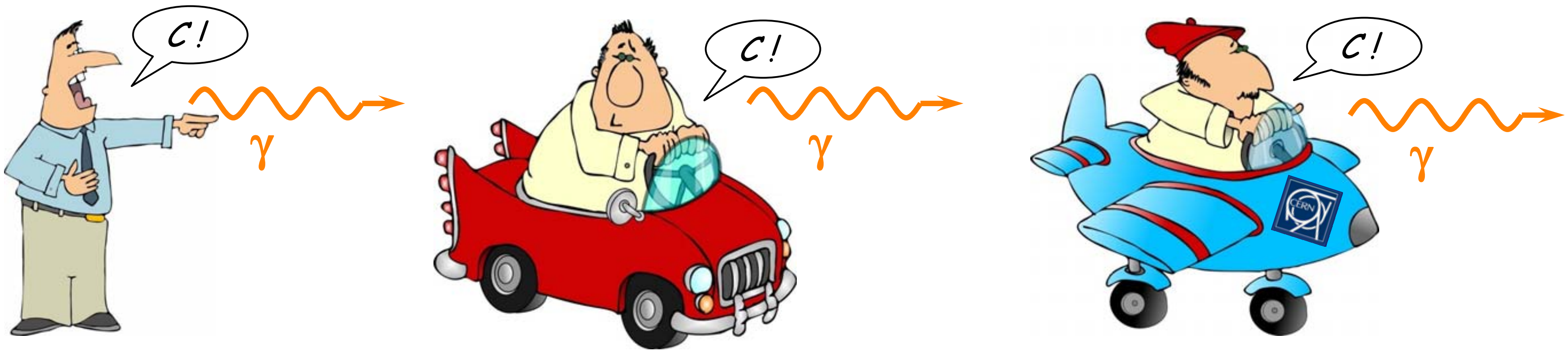


Gauge symmetry is essential to make theory free of nonsense

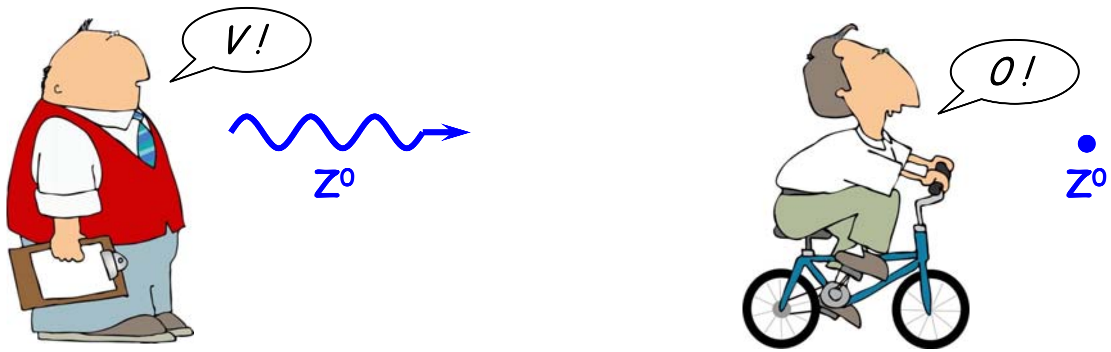
The "gauge trick" cannot work for massive particles

Why?

Einstein relativity: *c* is the same in every reference frame



I can choose a frame where a massive particle is at rest



In that frame: how can I distinguish longitudinal from transverse polarizations?

We have to live with 3 pol. $\Rightarrow$ nonsense in HE scattering!

gauge symmetry ⇔ massless γ ⇔ sensible HE theory

LEP has proved that Z^0 and $W^{\pm}$ interactions are well described by a gauge theory (EW symmetry)

M_Z and M_W break EW ⇒ nonsense in HE collisions

Where does nonsense appear?

E > 1 TeV

That's why we need LHC to investigate the phenomenon

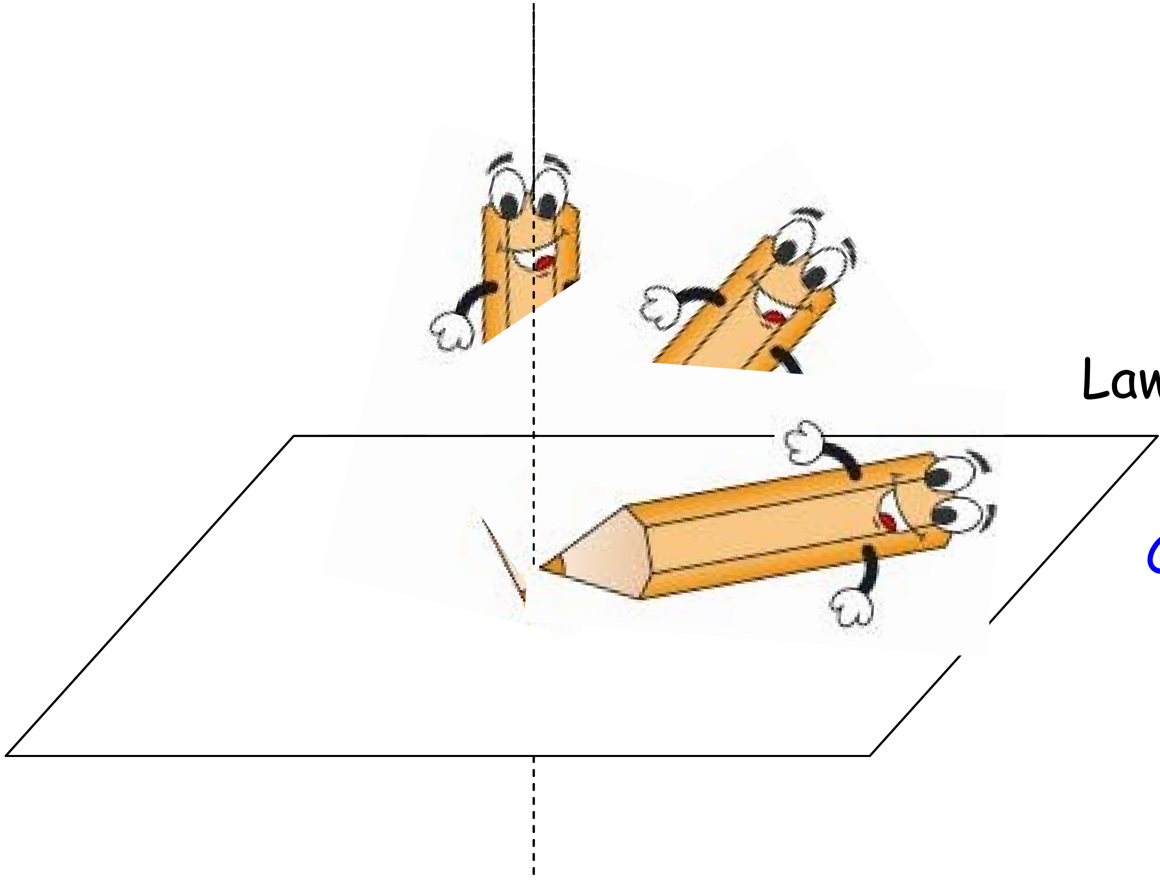
- generate M_Z and M_W
- no nonsense at HE

Most likely solution: Higgs mechanism

EW symmetry is spontaneously broken

What does it mean?

Symmetry of equations, not of solutions



Laws invariant under rotation

Configuration not invariant

With spontaneously broken symmetry, mass relations implied by exact symmetry can be modified

Equations invariant under exchange u ↕ d

⇒ solutions with $M_u = M_d$

or solutions with $M_u > M_d$ possible,

as long as $M_d > M_u$ also exists

Characteristic of SBS ⇒ degeneracy of solutions

Quantum interpretation ⇒ zero-energy excitation ⇒ massless particle

Goldstone 1961

Goldstone boson main obstacle to apply SBS to EW

Solution found by Brout, Englert, Higgs (1964) and implemented to EW by Weinberg, Salam (1967)

In the presence of gauge interactions, zero-energy excitation absorbed by gauge field $\Rightarrow$ massive gauge particle and no Goldstone boson

Less intuitive? Less familiar?

QuickTime™ and a
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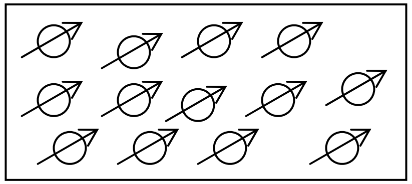
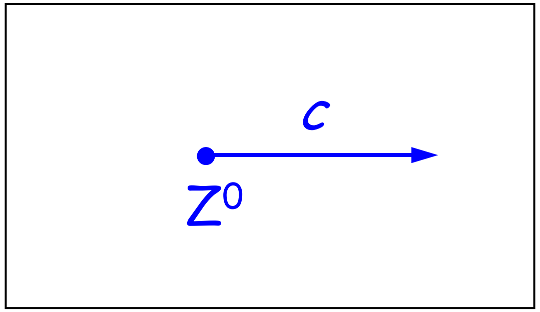
Higgs mechanism already discovered at LHC !
(even without ATLAS & CMS)

How does the Higgs mechanism explain EW breaking?

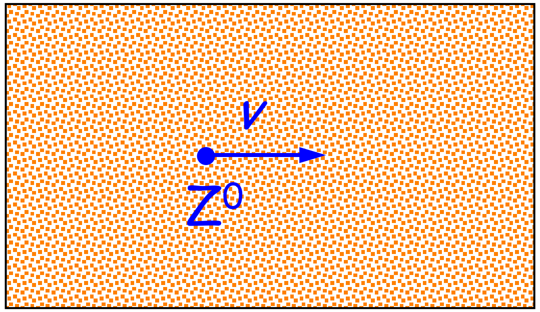
Higgs field fills space with uniform distribution of EW charge



This distribution affects particle propagation



empty space



Higgs-filled space

Higgs field behaves like dilute molasses

- large distances $\rightarrow$ mass
- small distances $\rightarrow$ no effect

The problem: → gauge symmetry & massless particles
→ massive particles and nonsense at HE

The solution: **Higgs mechanism**

large distances (low energy) → massive particles

small distances (high energy) → gauge invariance

⇓

no nonsense at HE

The EW symmetry is just hidden

W, *Z*, γ are the same particle

Since EW charge distribution carries no electric charge $\Rightarrow M_Z$, $M_W \neq 0$, $M_\gamma = 0$

How can LHC test the Higgs mechanism?

In relativistic quantum theory field $\Leftrightarrow$ particle $\Rightarrow$ Higgs boson

Particle mass $\Rightarrow$ how much it is dragged by Higgs field

Coupling of Higgs to 

are proportional to M_p

M_H only free parameter: it measures Higgs self-coupling

From LEP: 114 GeV < M_H < 220 GeV

Excluded by direct searches (114 GeV)

Inferred from EW data (theoretical bias) (220 GeV)

We do not wish to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Ellis Gaillard Nanopoulos (1976)

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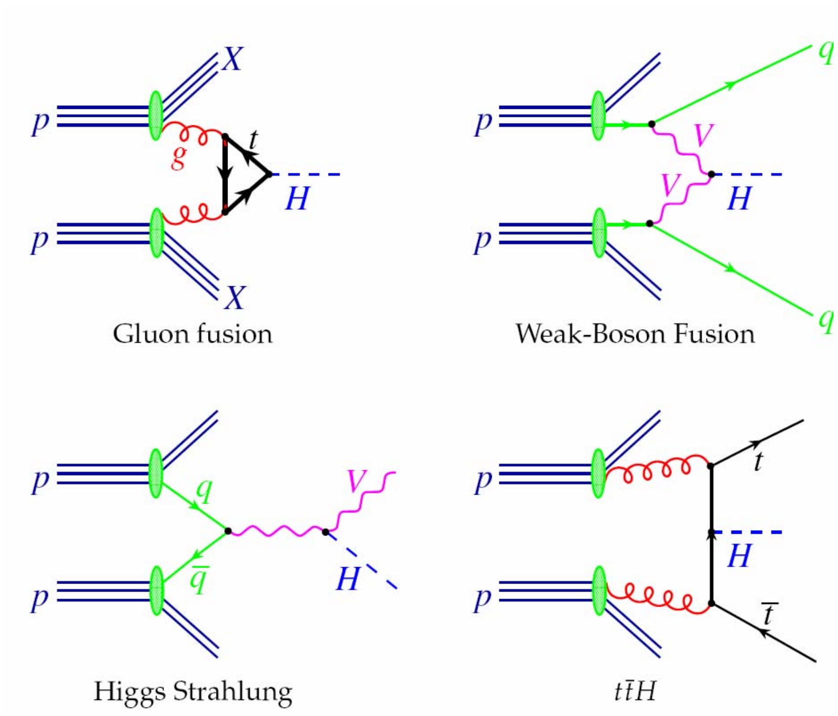
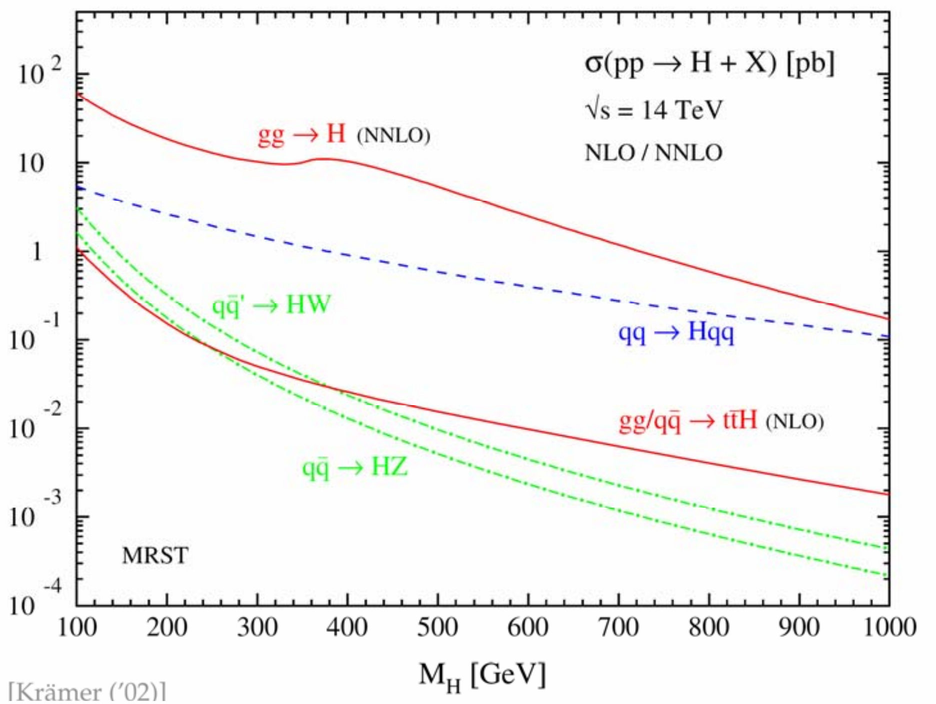
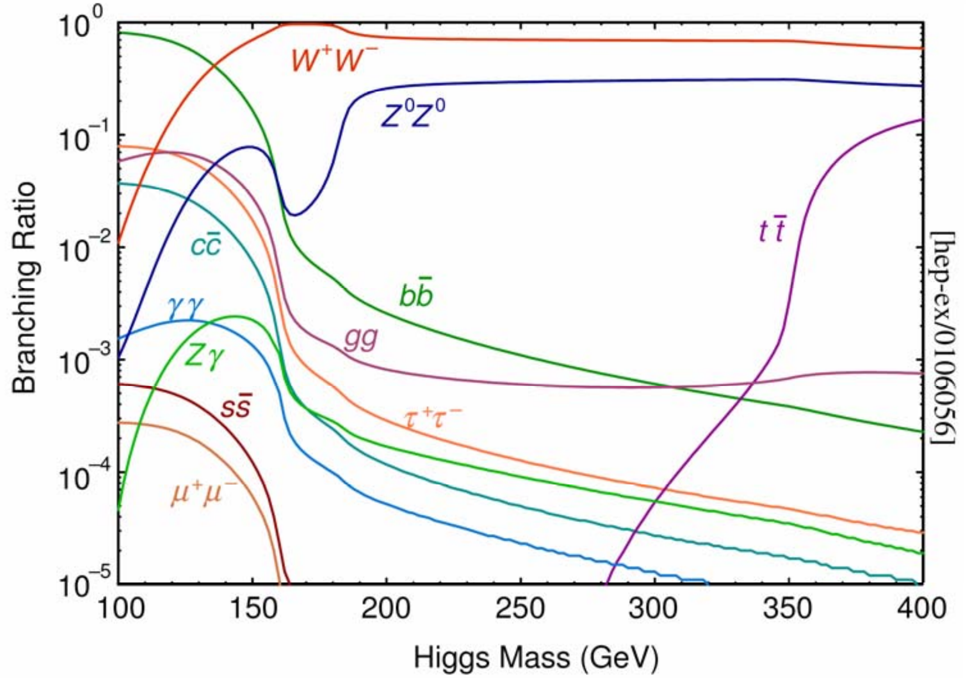


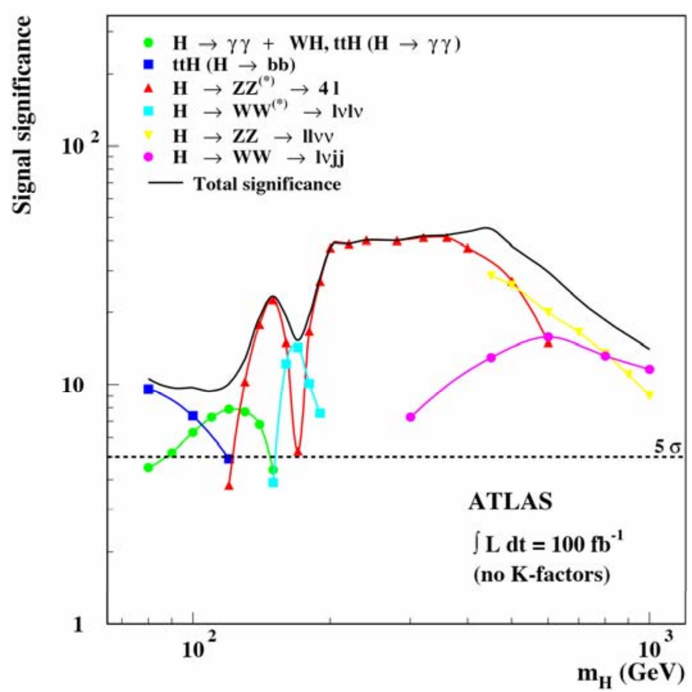
p
X
g
t
H
Gluon fusion
q
V
H
Weak-Boson Fusion
q
$\bar{q}$
V
H
Higgs Strahlung
t
H
$\bar{t}$
$t\bar{t}H$

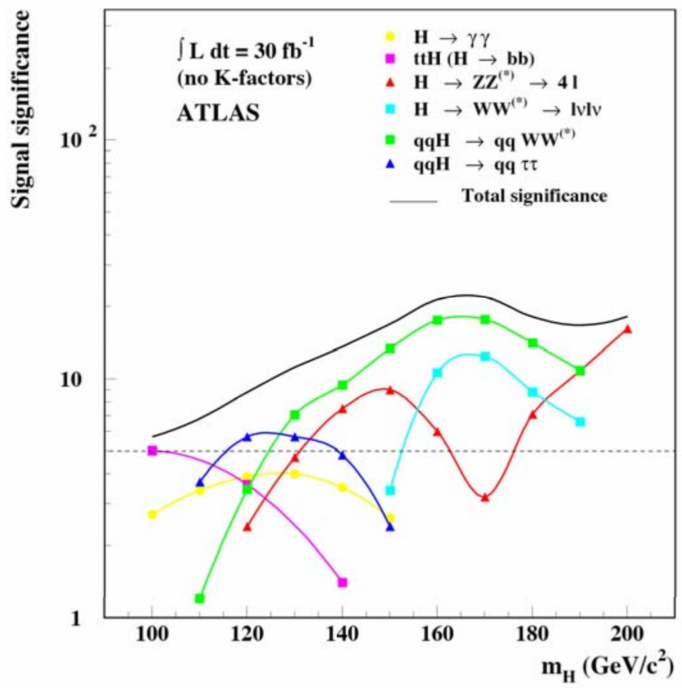


σ(pp → H + X) [pb]
√s = 14 TeV
NLO / NNLO
gg → H (NNLO)
qq̄' → HW
qq → Hqq
gg/qq̄ → tt̄H (NLO)
qq̄ → HZ
MRST
M_H [GeV]
[Krämer ('02)]



Branching Ratio
Higgs Mass (GeV)
W⁺W⁻
Z⁰Z⁰
tt̄
cc̄
bb̄
γγ
gg
Zγ
ss̄
τ⁺τ⁻
μ⁺μ⁻
[hep-ex/0106056]





- Test different production and decay channels to verify that Higgs couplings are proportional to mass (5-15% errors can be reached)

- Test variations of Higgs mechanism with several fields

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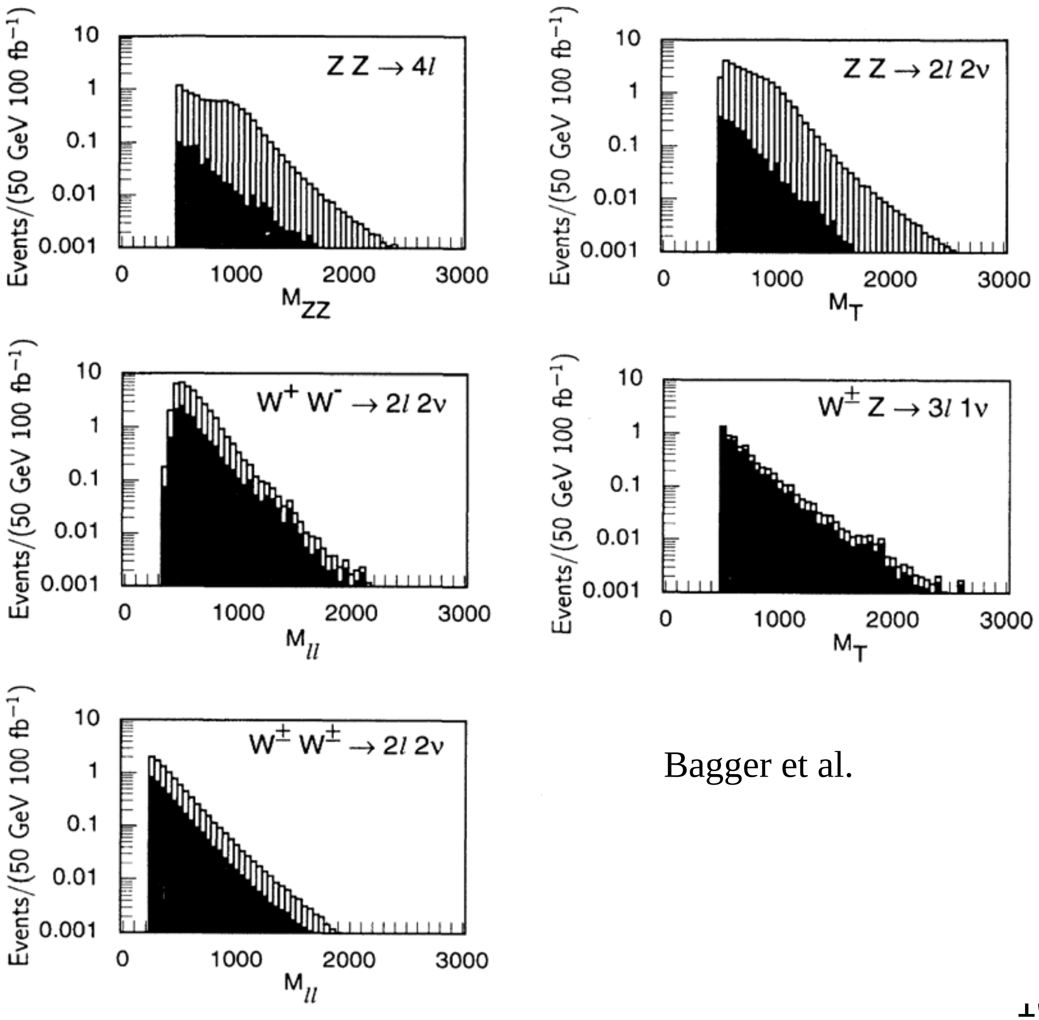
m_H = 120 GeV
L = 300 fb^{-1}

What if Higgs is not seen?

Test energy growth of gauge boson scattering

A "no-lose theorem" for LHC?



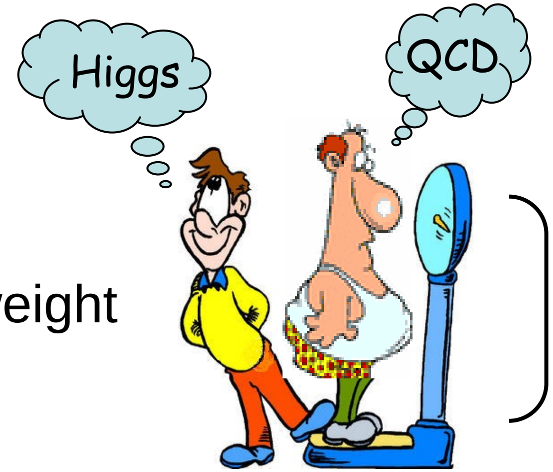
Bagger et al.

What will we learn from the Higgs discovery?

Unveil the new phenomenon that gives rise to a fundamental scale in physics (Fermi)

It is not particles with which nature is sparing, but principles

but only 1% of my weight



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Complete our understanding of the SM by determining its last missing ingredient

Higgs is simplest solution, but other forces could be responsible for the “EW charge density” that breaks EW

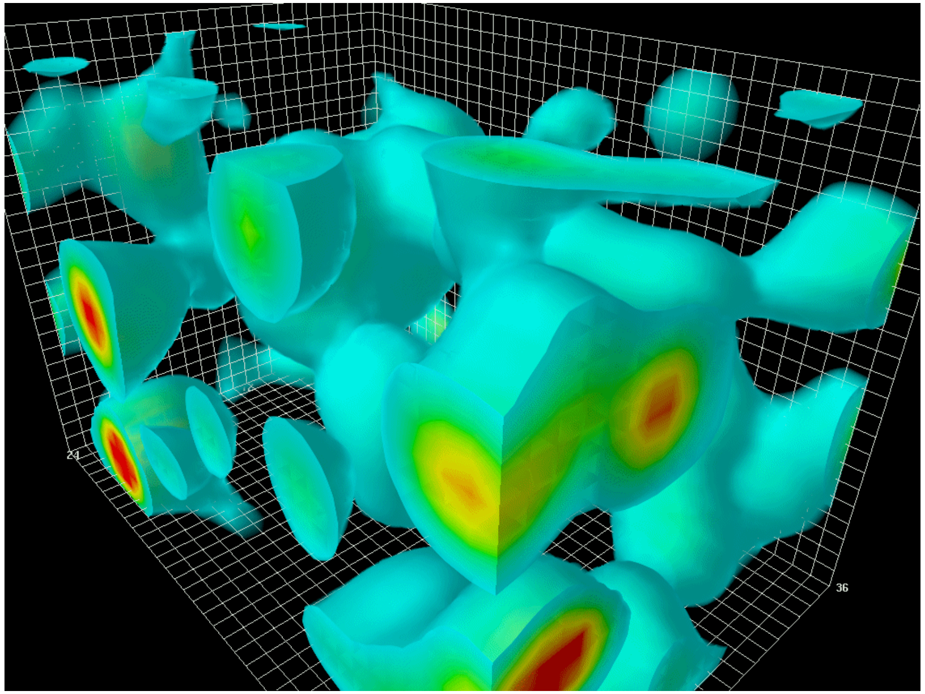
Disturbing issues related to Higgs

(but not inconsistencies)

- Quarks, leptons, gauge bosons neatly arranged in symmetric and repetitive structures. Higgs?
- The “EW charge density” gives a contribution to the energy density of the universe 10^{56} times too large. (Part of an even bigger problem). Has gravity anything to do with EW breaking?
- The puzzle of the hierarchy problem

In quantum theory, the vacuum is a busy place

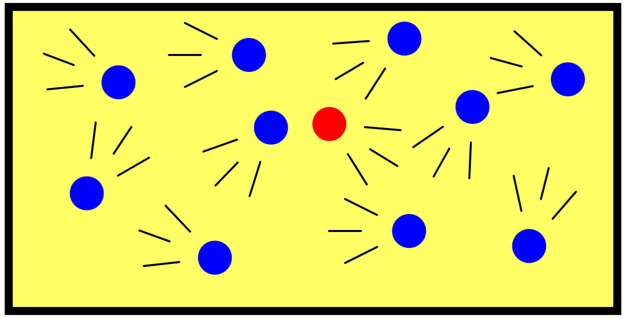
Particle-antiparticle pairs can be produced out of nothing, borrowing an energy *E* for a time *t* $E \ t \leq \hbar$



Virtual particles are like ordinary particles, but have unusual mass-energy relations

The Higgs field propagating in vacuum “feel” them with strength $E \Rightarrow \delta m_H \approx E_{max}$ (maximum energy of virtual particles)

temperature
T

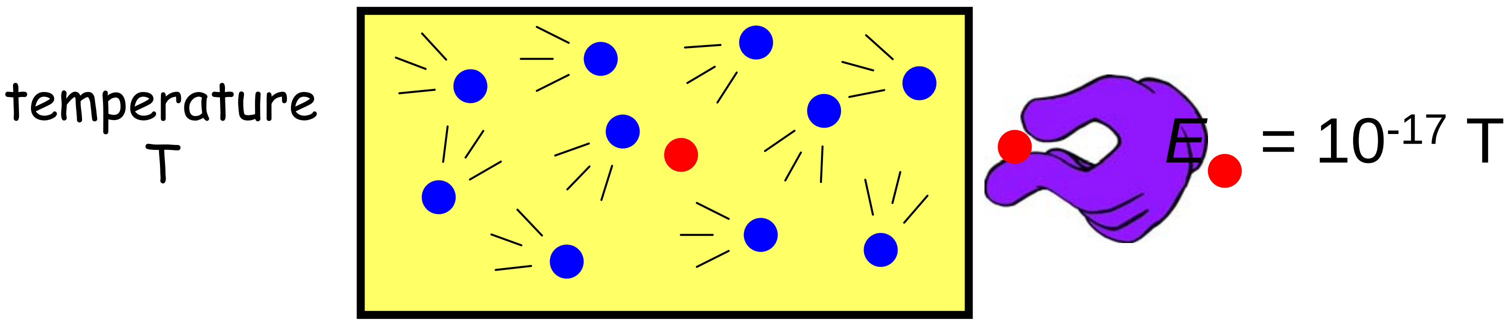


If ● interacts with ●, after a while, we expect $E \approx T$

$\delta m_H \approx E_{max}$ What is the maximum energy?

$M_{GUT} = 10^{16}$ GeV? $M_{Pl} = 10^{19}$ GeV?

Having $M_W << M_{Pl}$ requires tuning up to 34th digit !



The "stability" of the hierarchy M_W / M_{Pl} requires an explanation

Higgs mass is "screened" at energies above $m_H \Rightarrow$ new forces and new particles within LHC energy range

What is the new phenomenon?
Enter pure speculation…

Concept of symmetry central in modern physics

invariance of physics laws under transformation of dynamical variables

Now fundamental and familiar concept, but hard to accept in the beginning

Ex.: Earth's motion does not affect *c*

Lorentz tried to derive it from EM

dynamics determine symmetries

Einstein postulates *c* is constant (invariance under velocity changes of observer)

symmetries determine dynamics

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Einstein simply postulates what we have deduced, with some difficulty and not always satisfactorily, from the fundamental equations of the electromagnetic field

General relativity deeply rooted in symmetry

SM: great success of symmetry principle

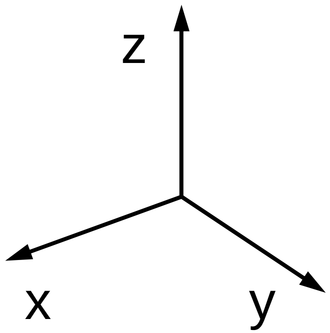
Impose $SU(3)\times SU(2)\times U(1) \Rightarrow$ determine particle dynamics of strong, weak and EM forces

Will symmetries completely determine the properties of the “final theory”?

Or new principles are needed to go beyond our present understanding?

In ‘70 a new symmetry was discovered

Supersymmetry: invariance under exchange of particles with different spin $\Rightarrow$ involves space-time



3-d space

translations/rotations

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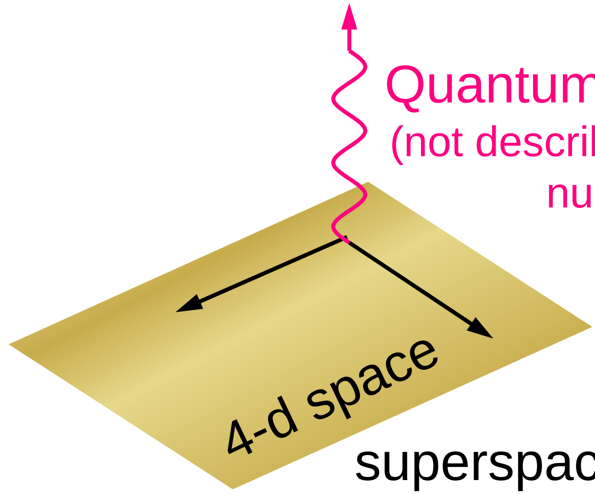
4-d space-time

Poincaré

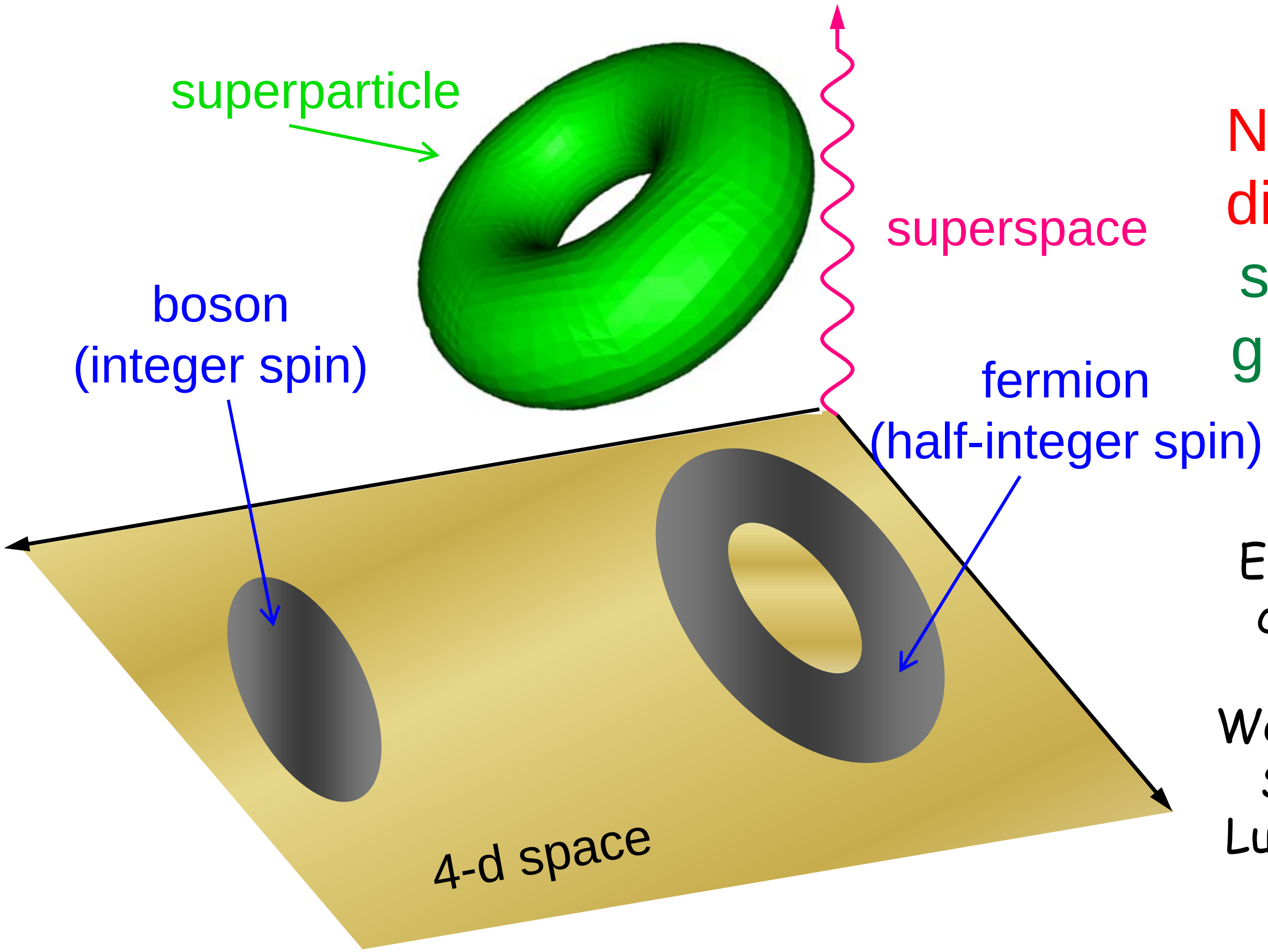


superspace

supersymmetry

Just a mathematical curiosity?

- includes (super)gravity $\Rightarrow$ unification of all forces?
- no HE sensitivity of m_H $\Rightarrow$ solution to hierarchy?



New particles to be discovered at LHC: squarks, sleptons, gluinos, charginos, neutralinos

Even the best commit capital sins; 7-quark model by Glashow-Weinberg (1977): Pride, Sloth, Envy, Wrath, Lust, Gluttony, Avarice

Discovery of supersymmetry: not just some more particles

New principle
- symmetry to explain M_W / M_{Pl}
- new concept of space
- deep connection with gravity

Strongly-interacting sparticles (squarks & gluinos) copiously produced at LHC

$\sigma(\text{TeV } \tilde{g}) \approx \text{pb}$

LHC with 100 $\text{fb}^{-1} \Rightarrow 10^5$ gluinos Can probe up to $M_g \approx 2.5$ TeV

Weakly-interacting sparticles mostly produced in cascades

Limits are more model-dependent

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Measurement of spins and couplings to confirm supersymmetry

With leptons, *m* (or Δ*m*) measurements possible at few %

Unique window for HE phenomena like unification and susy-breaking mechanism

1990-93 LEP1: the moment of glory for supersymmetry

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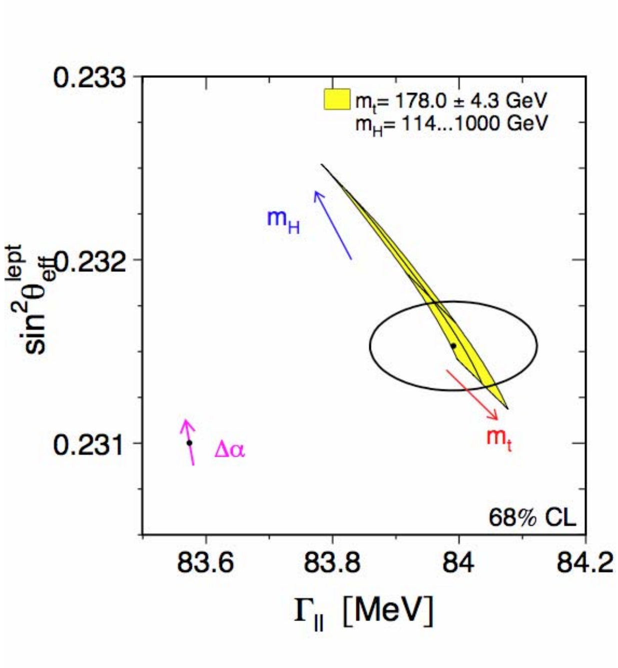
Supersymmetry (and not SM) leads to successful gauge-coupling unification

EW data: Supersymmetry passes the test

Technicolor, its competitor, falls in disgrace

A rescaled form of QCD, where a new strong force is responsible for EW breaking



1995-99 Data from *K* and *B* physics worry theoreticians

The problem: Susy breaking does not respect SM accidental symmetries

The reaction: New ways of implementing susy breaking are found: gauge mediation, anomaly mediation, gaugino mediation…

The result: Supersymmetry signals at the LHC could be very different: $\not{E}_T$ accompanied by hard photons, multijets, taus; metastable charged or coloured particles

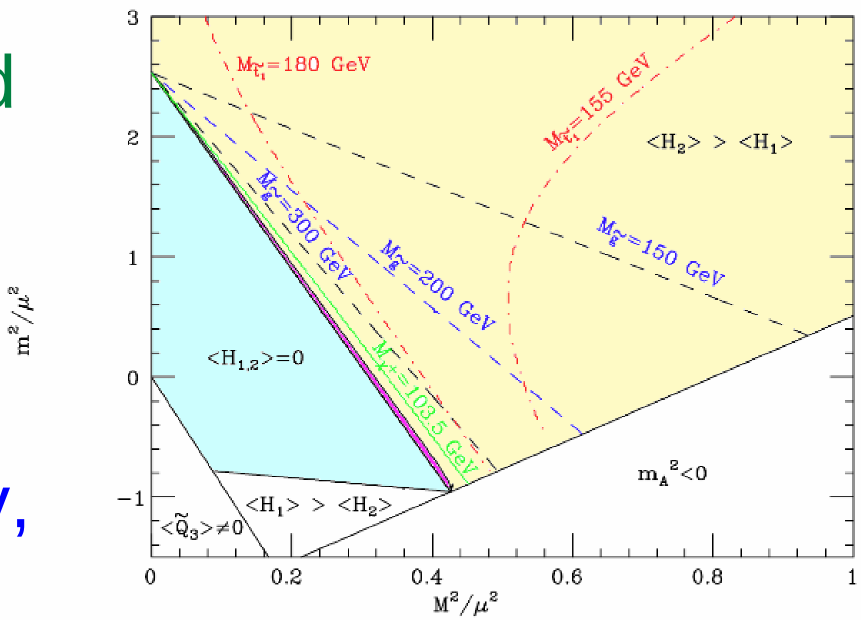
2000 LEP2: the crisis

The prediction of supersymmetry for new particles with $M \approx M_Z$ and a light Higgs is not confirmed

Supersymmetry is cornered

The reaction:

Alternative approaches: extra dimensions, little Higgs, Higgless, Split Susy, superlittle Higgs…



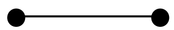
2008-… LHC: the final chapter

Will supersymmetry be discovered???

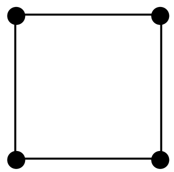
Extra dimensions

Inspiring public's curiosity as it brings science-fiction words into play (new dimensions, warped space, parallel universes, quantum-gravity crash, man-made black holes, …)

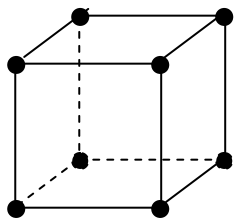
Hard to visualize, easy to imagine



0-d → 1-d connect two points



1-d → 2-d connect two lines



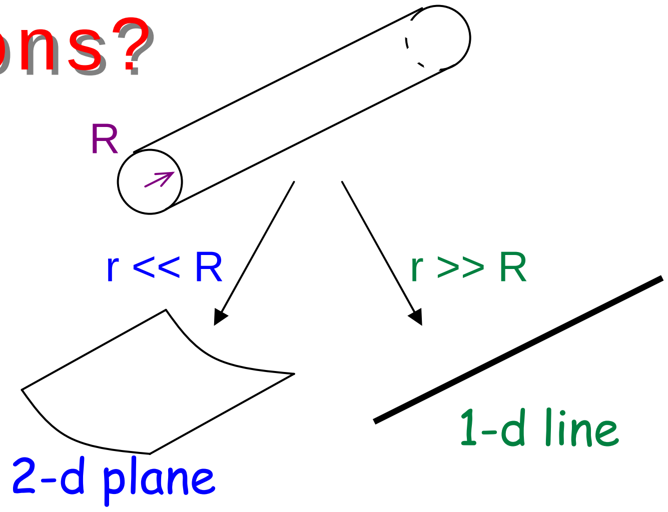
2-d → 3-d connect two squares

"hypercube" 3-d → 4-d connect two cubes

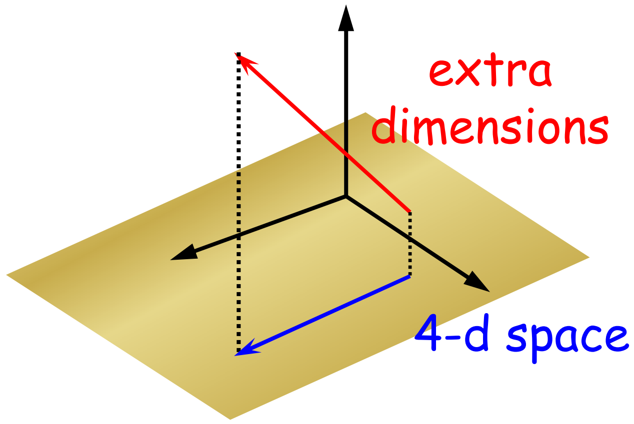
…. keep on going

How to hide extra dimensions?

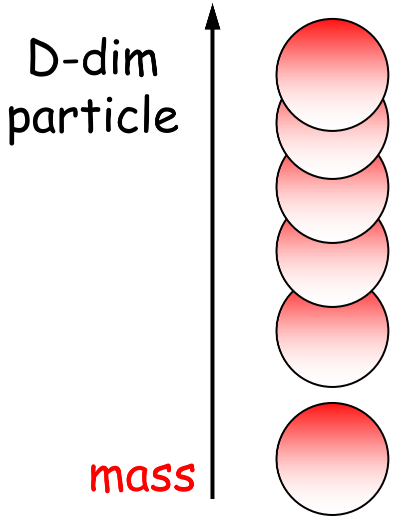
- confine particles to subspaces
- curled up (compactified) spaces



How to observe extra dimensions?



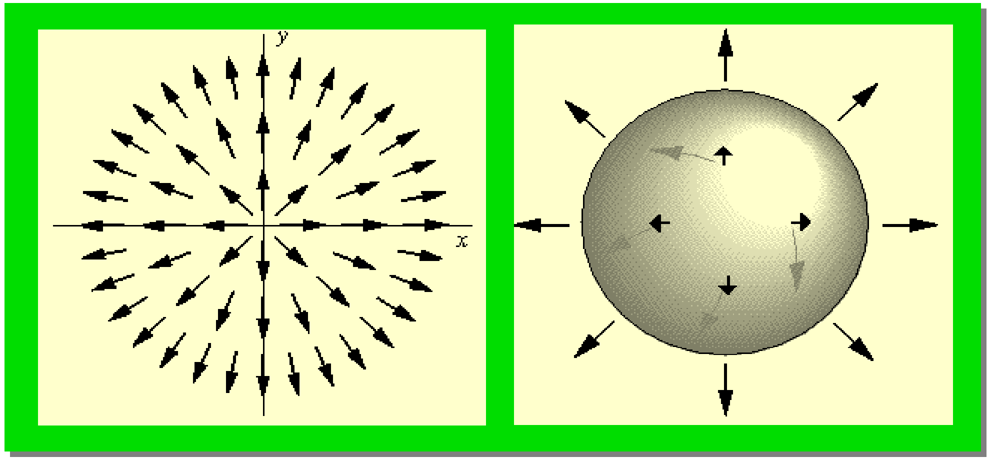
$$E^2 = \vec{p}^{\,2} + \underbrace{p^2_{extra} + m^2}_{\text{KK mass}}$$



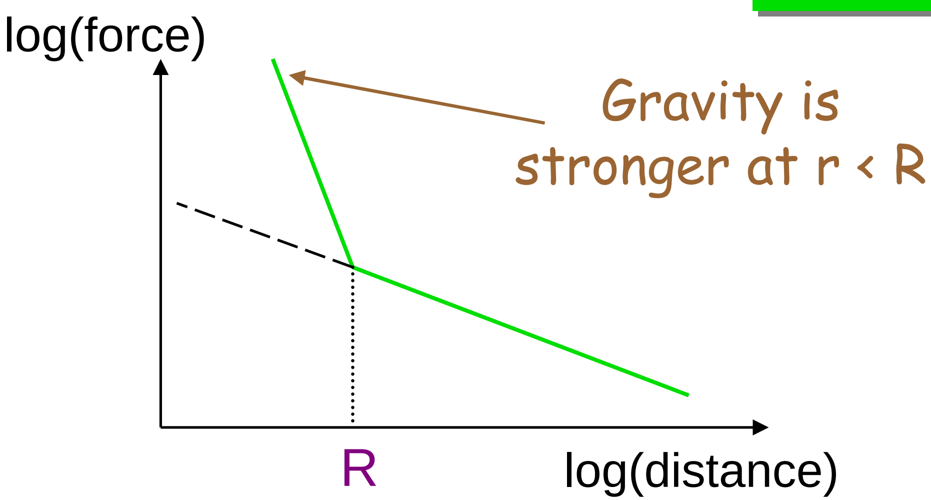
From KK mass spectrum we can measure the geometry of extra dimensions

Why should extra dimensions be relevant at the weak scale?

Modify gravity: instead of explaining $M_W << M_{Pl}$, make $M_W \approx M_{Pl}$



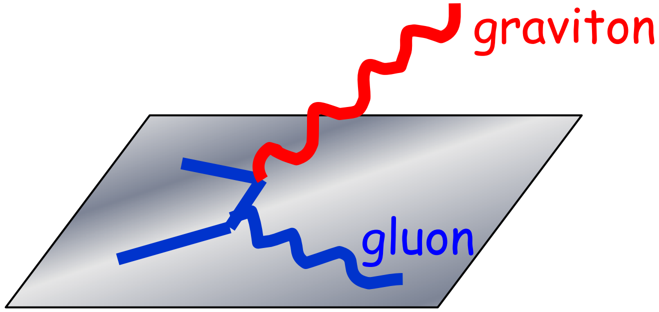
Newton's law in D spatial dims: $F \propto \frac{1}{r^{D-1}}$

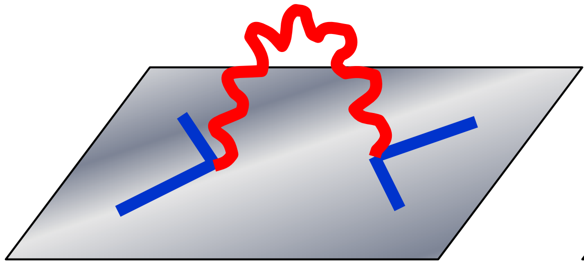


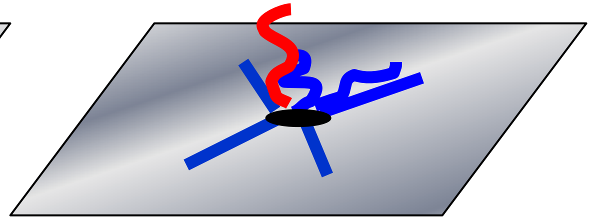
At r ≈ 10^{-17} cm gravity is as strong as gauge inter. ⇒ no hierarchy

Arkani-Hamed, Dimopoulos, Dvali

Probing gravity at the LHC?







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Gravitational wave
jet + $\not{E}_T$

Gravitational deflection
dijet

Black hole
multiparticle event

Long shot? If gravity becomes strong at TeV,
why hasn't LEP seen any indirect effect?

Extra dimensions can be warped (non-trivial gravitational field in vacuum configuration)

Randall Sundrum

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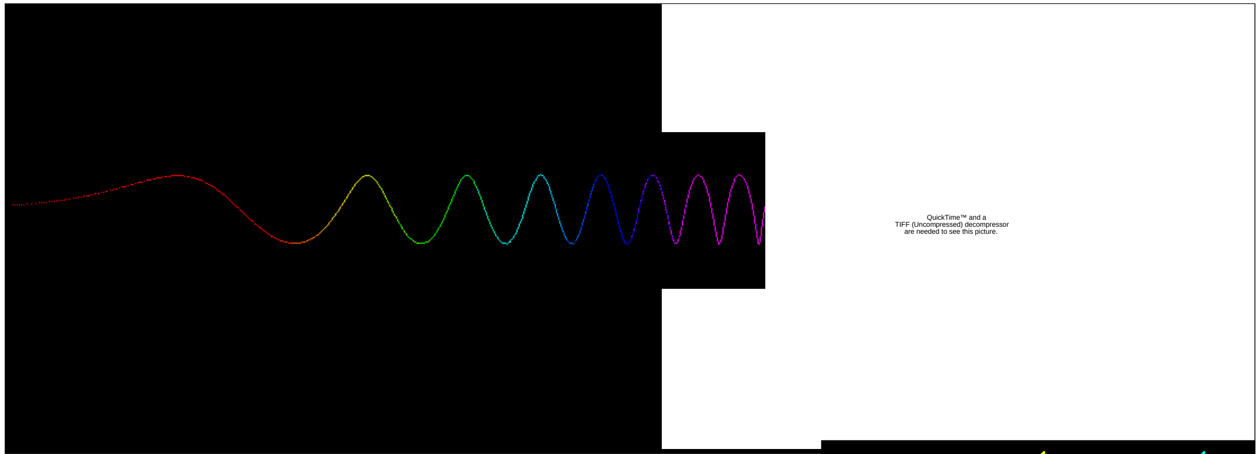
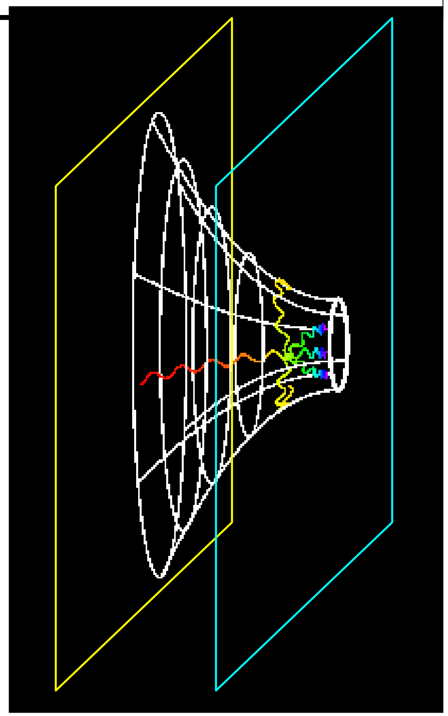


In brane-world gravity is weak because its effect is redshifted

LHC can observe warped gravitons with weak-scale masses

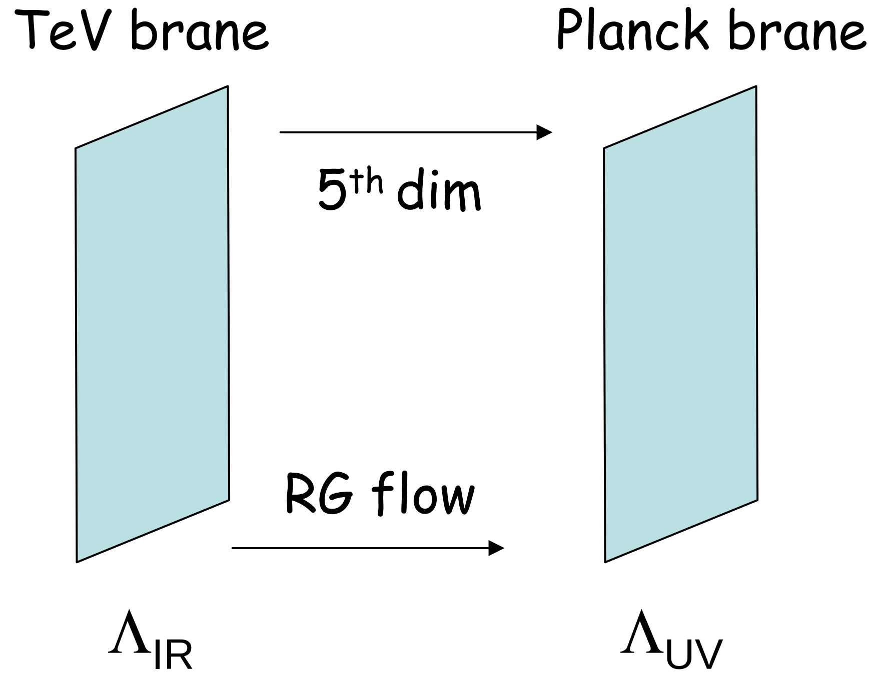


Unexpected results:

SM in warped extra dims ⇔ strongly-int'ing 4-d theory

KK excitations ⇔ "hadrons" of new strong force

Technicolor strikes back?



New developments in extra dims strongly influenced new constructions

Hierarchy requires a symmetry to have $m_H \approx 0$

(Supersymmetry is an example)

Gauge symmetry?

In extra dimensions, gauge particles have new polarizations (spin-0); Higgs-gauge unification?

Goldstone boson?

Like π in QCD $$\frac{m_\pi^2}{m_\rho^2} = 0.03$$

The difficulty is to obtain large m_t and large hierarchy

Little Higgs: extra protection by canceling leading contribution to m_H from E_{max}

Deep connection among different approaches

- many new states accessible to LHC
- new unknown physics not far (~ 10 TeV)

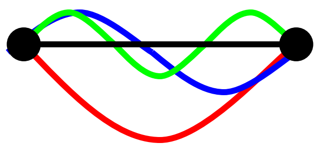
Extra dims can extend validity of Higgsless theory

$$4d \quad \Rightarrow \quad E_{\max} \approx \frac{4\pi m_W}{g} \approx \text{TeV}$$

$$5d \quad \Rightarrow \quad E_{\max} \approx \frac{24\pi^3}{g_5^2} \approx \frac{12\pi^2 m_W}{g^2} \approx 10\ \text{TeV}$$

KK gauge bosons partially replace the Higgs effect

Breaking symmetries with extra dimensions



no zero modes in restricted extra-D spaces
(Scherk-Schwarz mechanism)

What cosmology has to say about the weak scale

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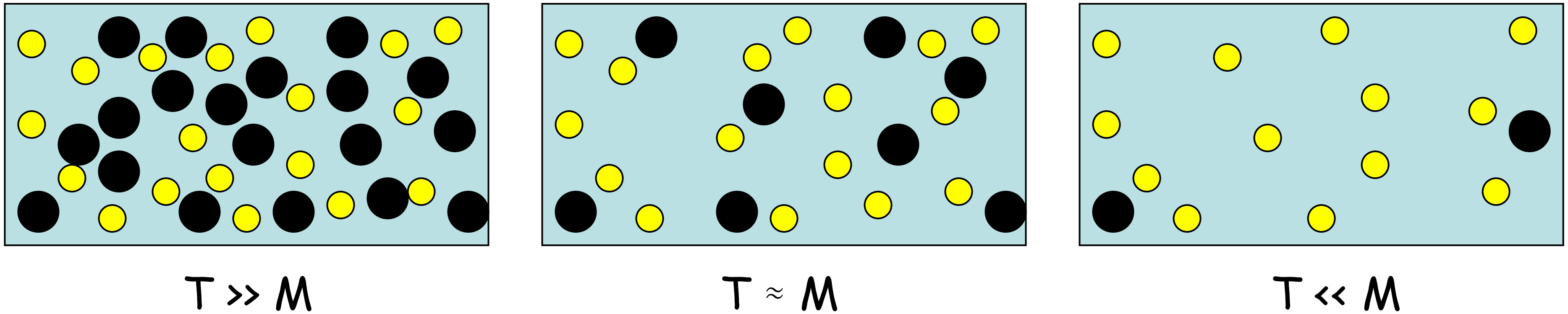
DARK MATTER

- rotational curves of galaxies
- weak gravitational lensing of distant galaxies
- velocity dispersion of galaxy satellites
- structure formation in N-body simulations

If stable massive particle is in thermal equilibrium in the early universe, its density today can be computed



$$\sigma = \frac{k}{128\pi M^2} \qquad \Omega_{DM} = \frac{0.22}{k}\left(\frac{M}{\text{TeV}}\right)^2$$

Coincidence with weak scale justified in many particle-physics models

Will LHC discover a new form of stable matter?

- excess of $\not{E}_T$ is a model-independent signal
- often colored particles decaying into DM are present
- reconstruct present DM density from collider data

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are needed to see this picture.

- direct and indirect DM searches depend on unknown DM distribution in galactic halo
- information from collider required

DARK ENERGY

Cosmological constant?

$\rho_\Lambda^{1/4} = 10^{-3}$ eV Similar (and more acute) problem as hierarchy

Is there any explanation using symmetries or dynamics?

The LHC will probably not tell us what Dark Energy is, but it will tell us something about principles of naturalness

TWO OPTIONS

- SM valid up to $E_{max} \approx$ TeV and replaced by new theory

Argument works

Cancellation of	Existence of
electron self-energy	positron
π^+-π^0 mass difference	ρ
K_L-K_S mass difference	charm
gauge anomaly	top

Not free from problems: why no echoes from TeV region?

- E_{max} >> TeV $\Rightarrow$ why m_H and $\rho_\Lambda^{1/4} << E_{max}$?

reject effective-theory approach?

LHC will tell us which is Nature's choice

Complexity

life ← biochemistry ← atomic physics ← SM ← “final theory”

Microscopic probes

Breaking of naturalness would require new principles

- the “final theory” is a complex phenomenon with IR/UV interplay
- some of the particle-physics parameters are “environmental”

The multiverse

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

CONCLUSIONS

LHC at work:

Unveiling the mechanism of EW breaking

Higgs?
Unconventional Higgs?
Alternative dynamics?

If Higgs is found,

New physics at EW scale curing the UV sensitivity?
New principle in particle physics?

A new form of stable matter?

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