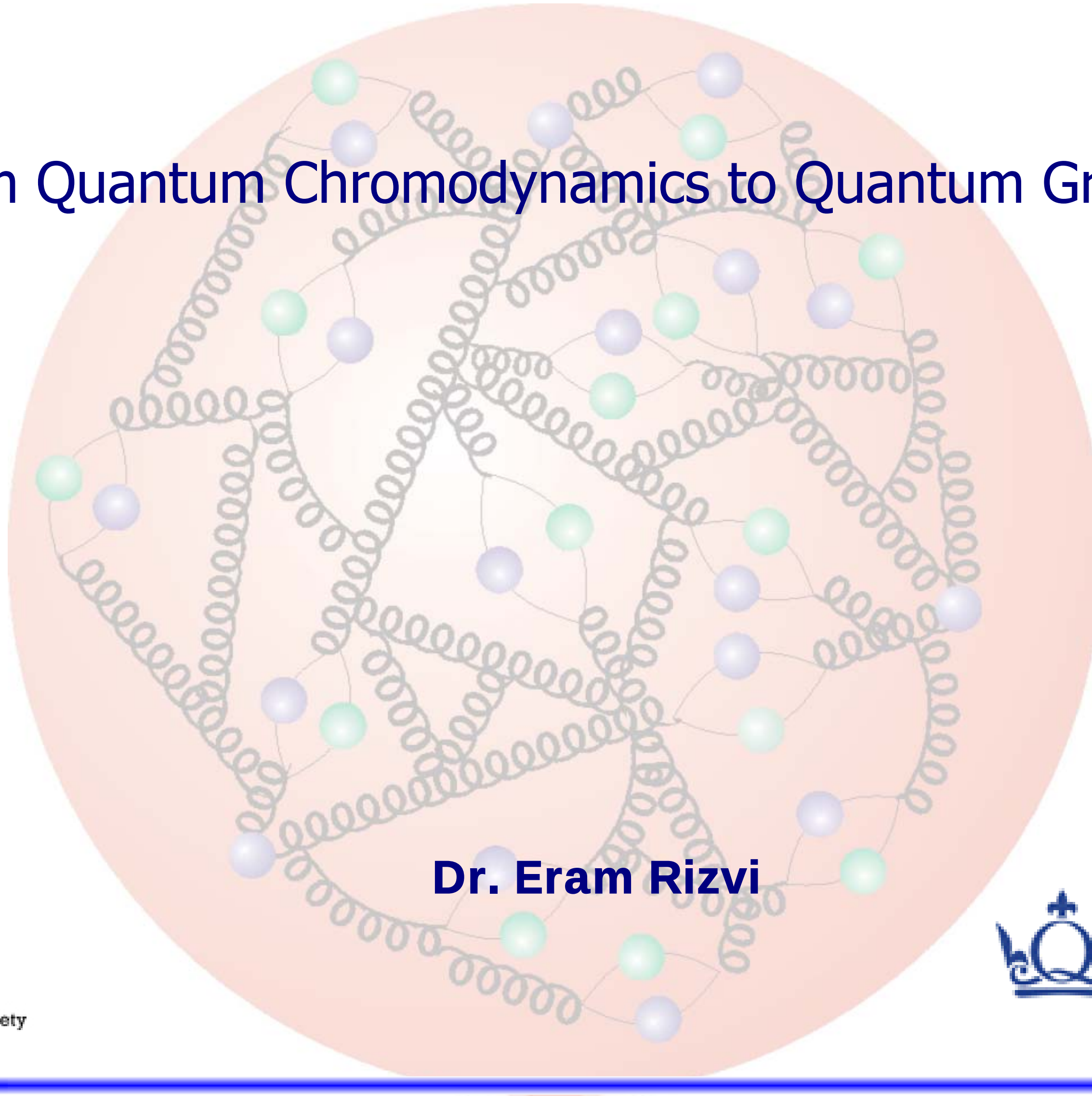
From HERA to the LHC

From Quantum Chromodynamics to Quantum Gravity



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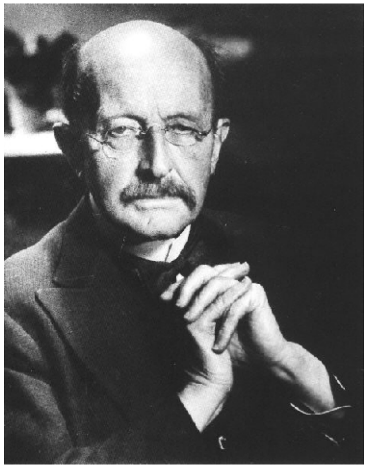
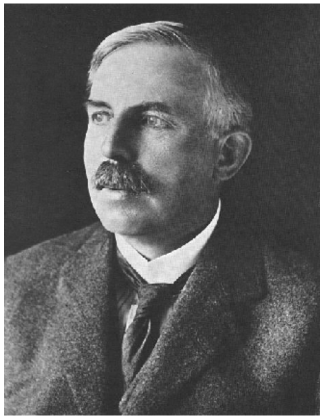
Over 100 years of discovery and experimentation

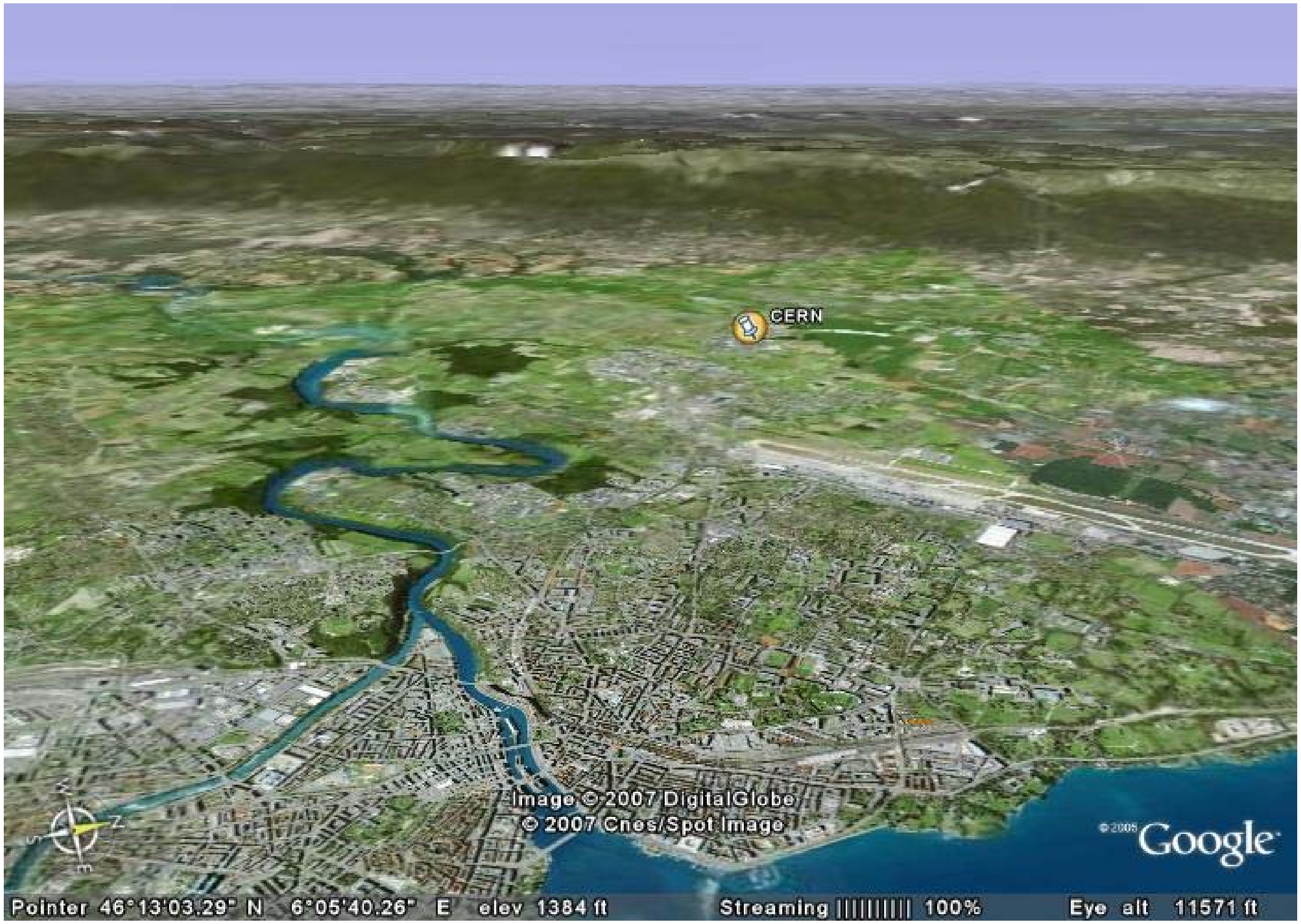
- Discovery of electron - Thompson, 1897
- Birth of quantum physics - Planck, 1900
- Relativity - Einstein, 1905
- Nuclear scattering experiment - Rutherford, 1911



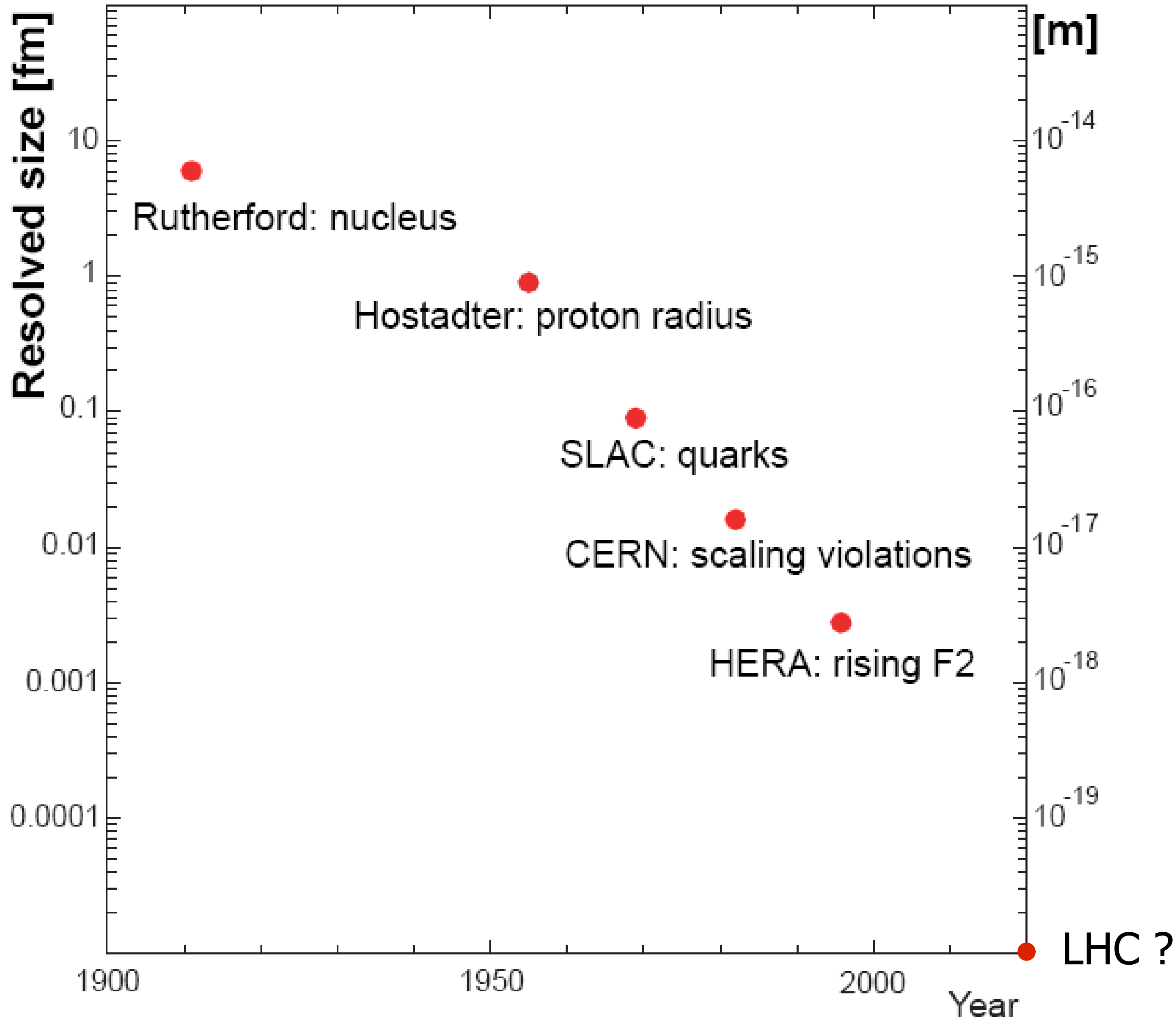


... what have we learnt ?

Particle Physics is a global enterprise: experiments in all continents (incl. antarctica!)
I will concentrate on H1 and ATLAS



... But what have we learnt ?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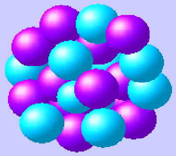
Rutherford: nucleus
Hostadter: proton radius
SLAC: quarks
CERN: scaling violations
HERA: rising F2
LHC ?
1900
1950
2000
Year

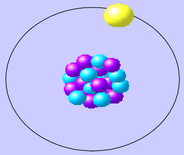
The Standard Model

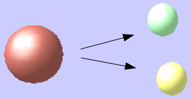
Worlds most successful theory to date - Describes fundamental constituents of matter

u d s c b t		quarks: strong, weak, electromagnetic
e	μ τ	charged leptons: weak, electromagnetic
ν_e	ν_μ ν_τ	neutrinos: weak

gluons	Strong: holds atomic nucleus together
photons	Electromagnetic: binds atom together
W and Z bosons	Weak: radioactive decay processes





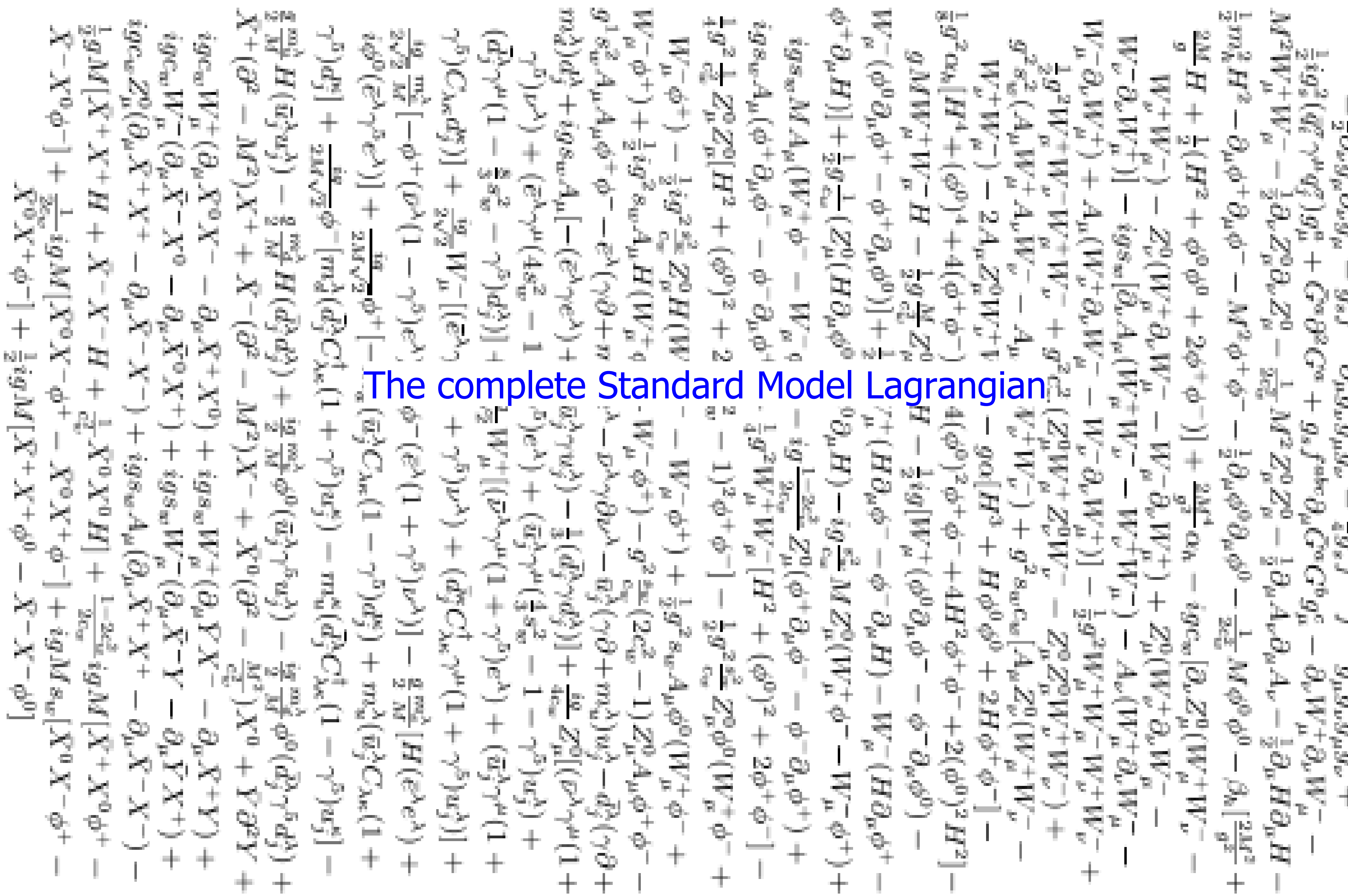


No description of Gravity at sub-atomic level

Electromagnetic & Weak parts of Standard Model are known extremely precisely

Theory of strong interactions is less well known

The Standard Model



The complete Standard Model Lagrangian

Based on perturbation theory & relativistic quantum mechanics
given us the language of Feynman diagrams to calc cross sections

Potential = V + V'

V gives rise to stationary stable, time independent states

V' is a weak additional potential leading to transitions between states $\psi_i \rightarrow \psi_f$

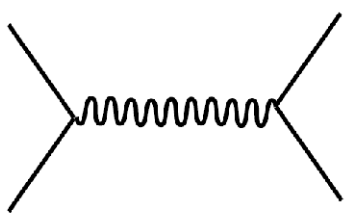
$$\sigma = \frac{2\pi}{\hbar} |V'_{fi}|^2 \rho(E_f)$$

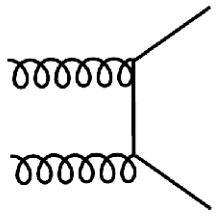
$\rho(E_f)$ density of final states and flux factors

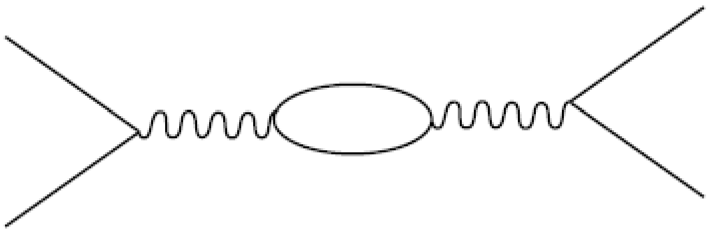
$V'_{fi} = \int \psi^*_f V_{fi} \psi_i dv$ is known as the matrix element for the scattering process

V' contains the standard model Lagrangian describes the dynamics of all interactions

Series expansion in powers of couplings α between particles for each force







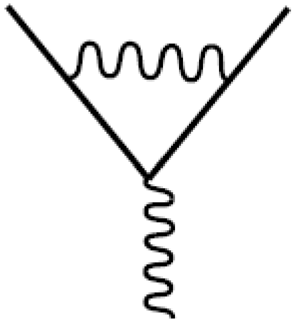
Quantum mechanics predicts the gyromagnetic ratio of the electron g=2 (ratio of magnetic dipole moment to it's spin)

Experiment measures g_{exp}=2.0023193043738 ± 0.0000000000082

Discrepancy of g-2 due to radiative corrections

Electron emits and reabsorbs additional photons

Corresponds to higher terms in perturbative series expansion



$$\frac{g_{theory} - 2}{2} = 1159652140(28) \times 10^{-12}$$

$$\frac{g_{exp} - 2}{2} = 1159652186.9(4.1) \times 10^{-12}$$

Phenomenal agreement between theory and experiment! 4 parts in 10^8

QED (quantum electrodynamics) is humanity's most successful theory

Demonstrates understanding of our universe to unprecedented precsion

Equivalent to measuring distance from me to centre of moon and asking if we should measure from top of head or my waist!

... but all is not well...

Standard Model is lacking:

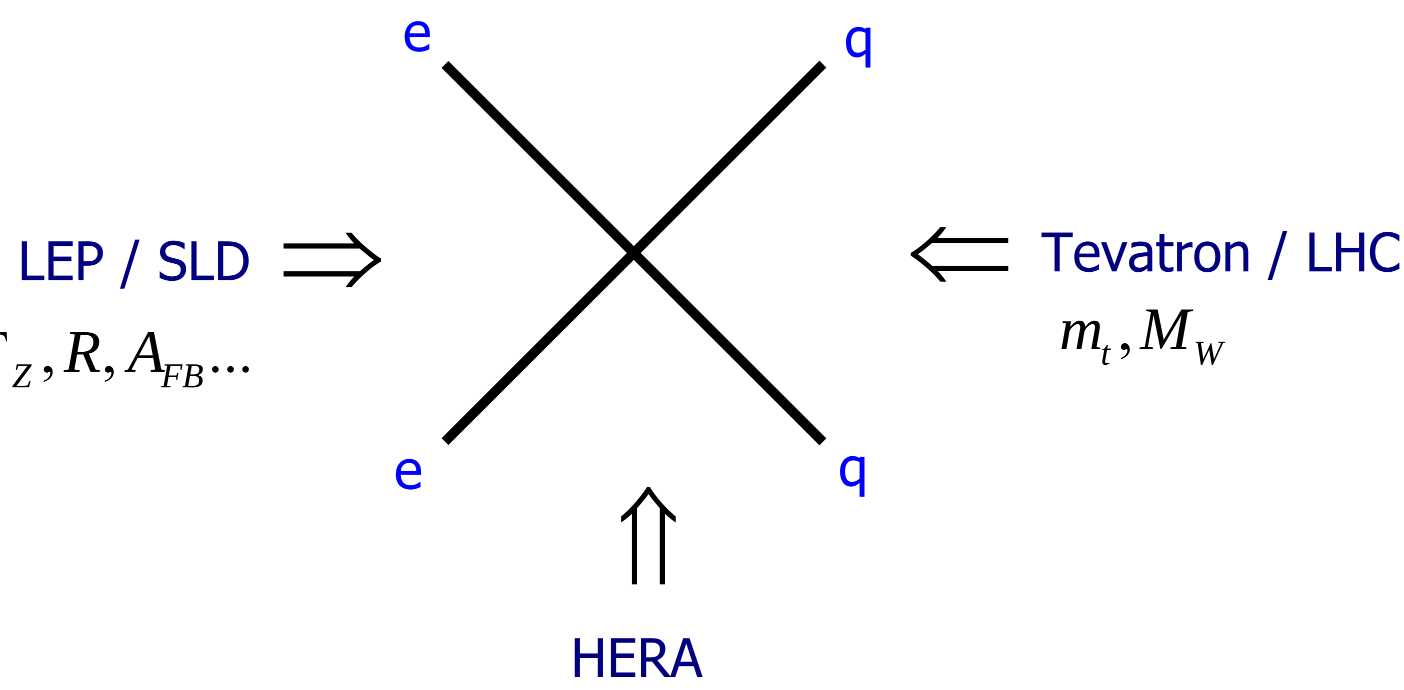
- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level
- where is all the antimatter in the universe?

Too many free parameters - need to be determined from experiment:
(Compare to Newtonian gravity - one free parameter: G)

- 12 particle masses: 6 quarks, 3 charged leptons, 3 neutrinos
- 3 boson masses ($W^{\pm}$, Z^0, H^0)
- 3 coupling constants: EM, Strong, Weak
- 4 quark mixing parameters
- 4 neutrino mixing parameters

What are the current collider experiments doing?

Colliders Probing the ElectroWeak Scale



$M_Z, \Gamma_Z, R, A_{FB} \ldots$

m_t, M_W

HERA probes t-channel of gauge boson exchange

- sensitive to propagator masses and EW couplings
- requires Parton Distribution Functions (PDFs)

$$\sigma(ep) \propto \sum \sigma(eq) \otimes \text{PDFs}$$

$$\text{EW} \otimes \text{QCD}$$

HERA collides e (27 GeV) and p (~1 TeV)
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

At fixed $\sqrt{s}$: two kinematic variables: x & Q^2

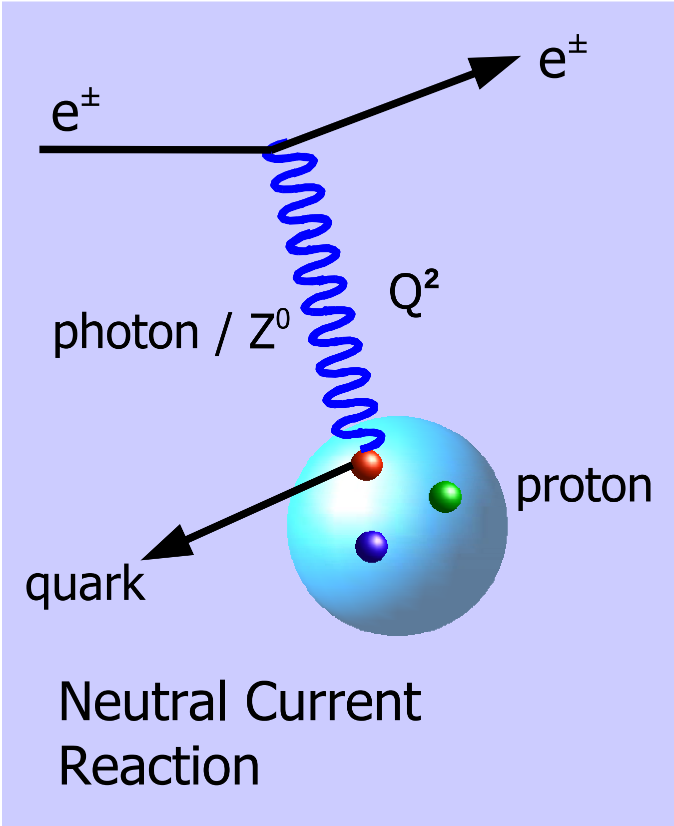
$Q^2 = s\ x\ y$

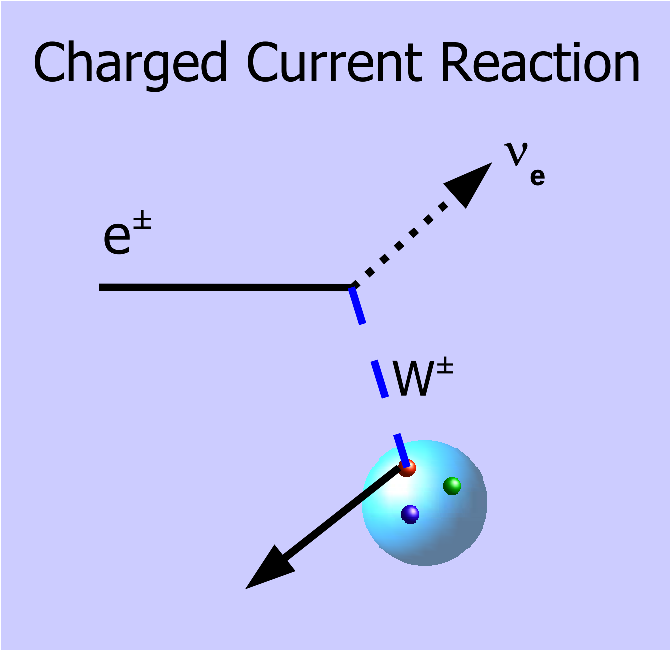
Q^2 = "resolving power" of probe

High Q^2 : resolve 1/1000th size of proton

x = momentum fraction of proton carried by quark

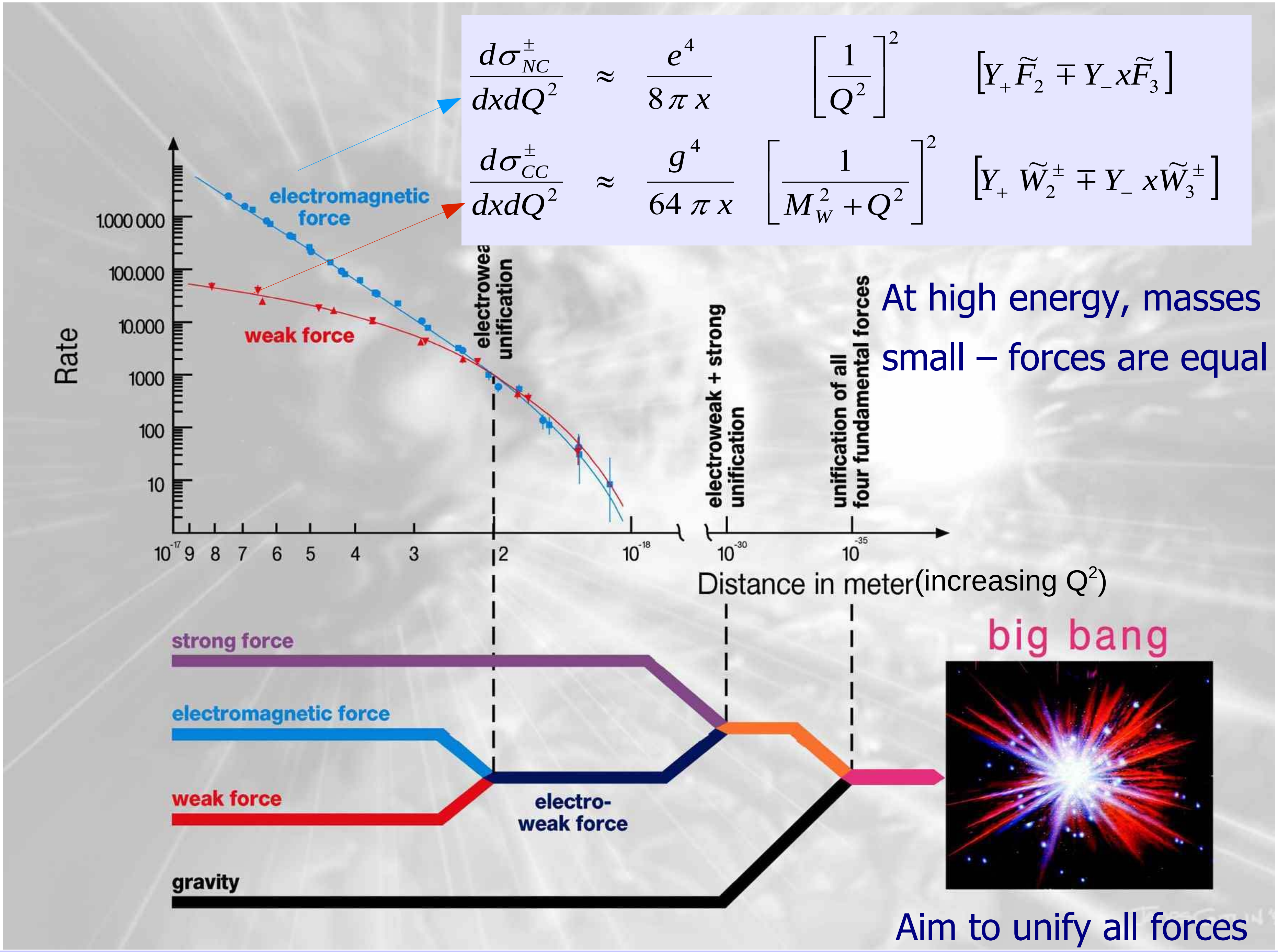
HERA: ~10^{-6} - 1





$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2 \left[Y_+ \tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm}\right]$$



At high energy, masses small – forces are equal

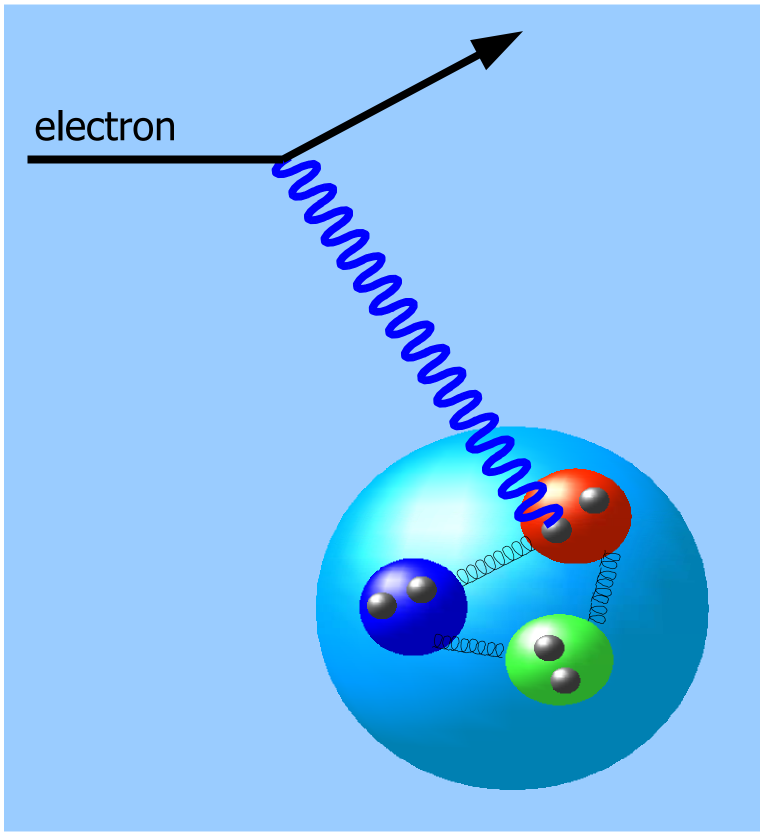
Aim to unify all forces

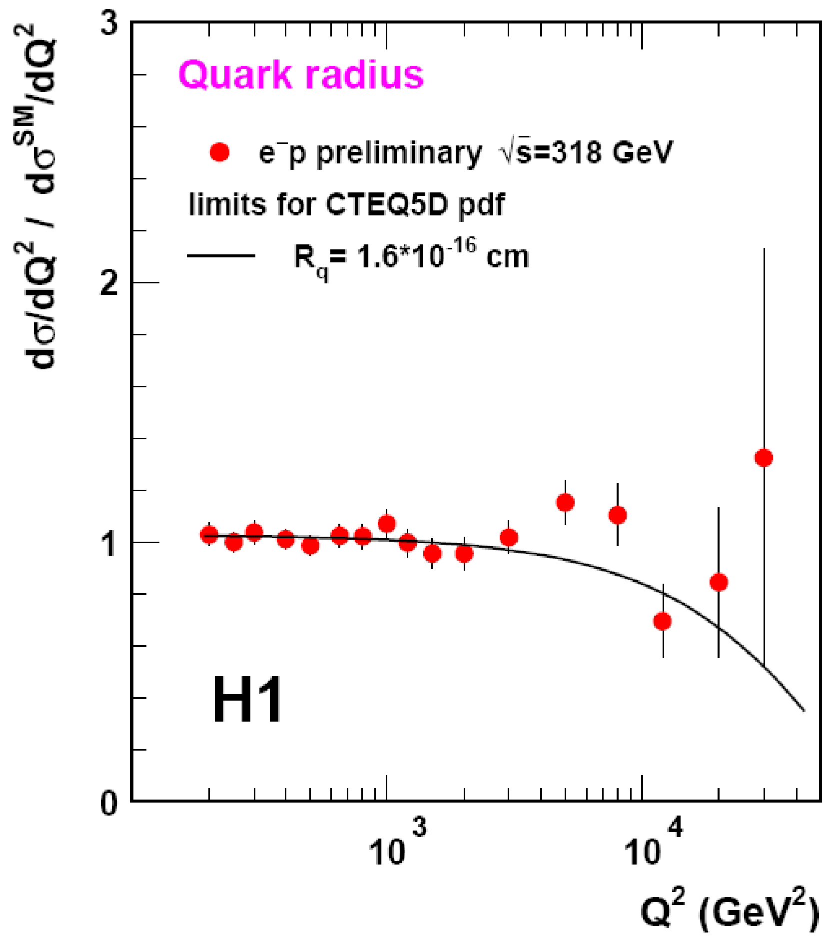
The H1Collaboration (1995)

Make measurements of highest possible precision

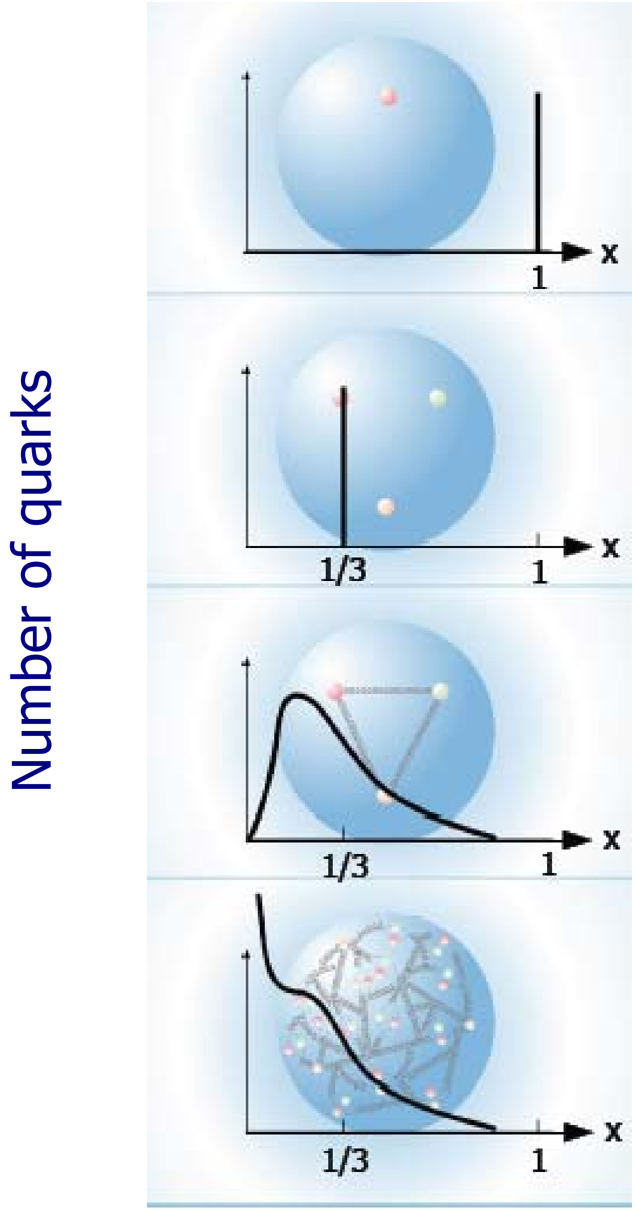
Search for deviations from expectation

Can use highest Q^2 photons to look for quark sub-structure





Already data exclude quark radius > 1.6×10^{-18} m



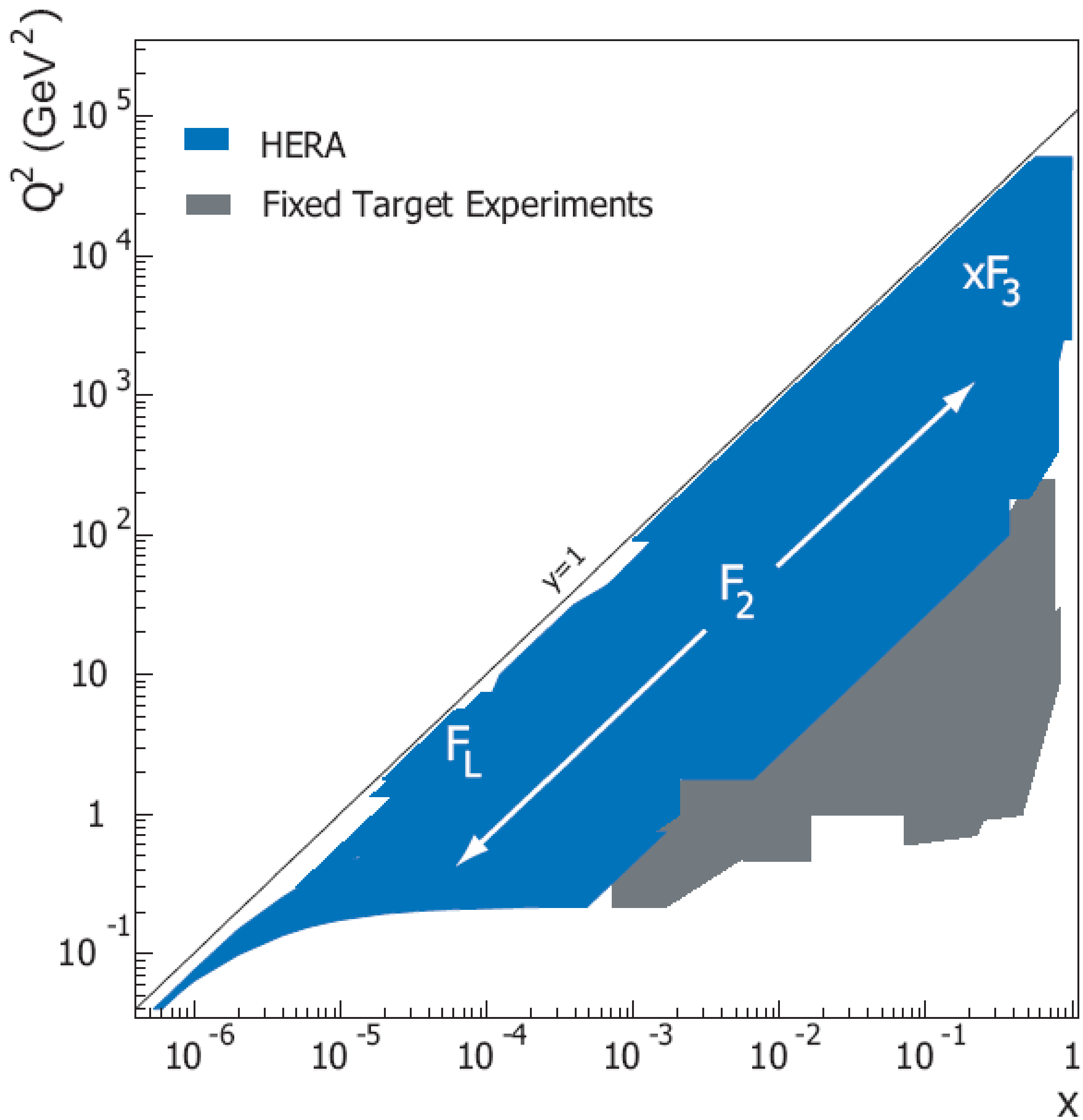
Proton = 1 quark

Proton = 3 independent quarks

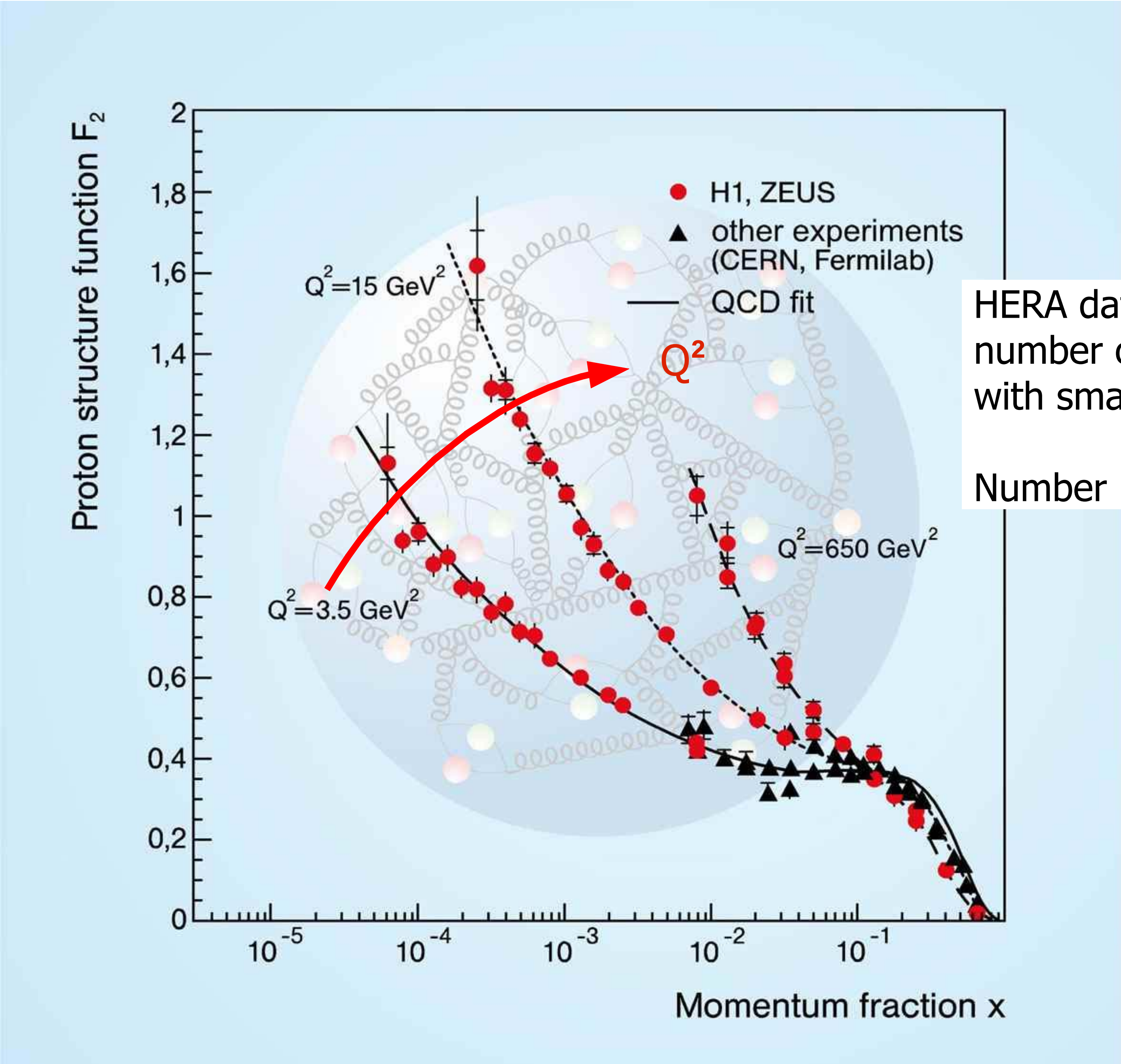
Proton = 3 coupled quarks

Proton = 3 coupled quarks bound by dynamic gluons creating “sea” of quark/anti-quark pairs at small momentum fractions

This is the region explored by HERA



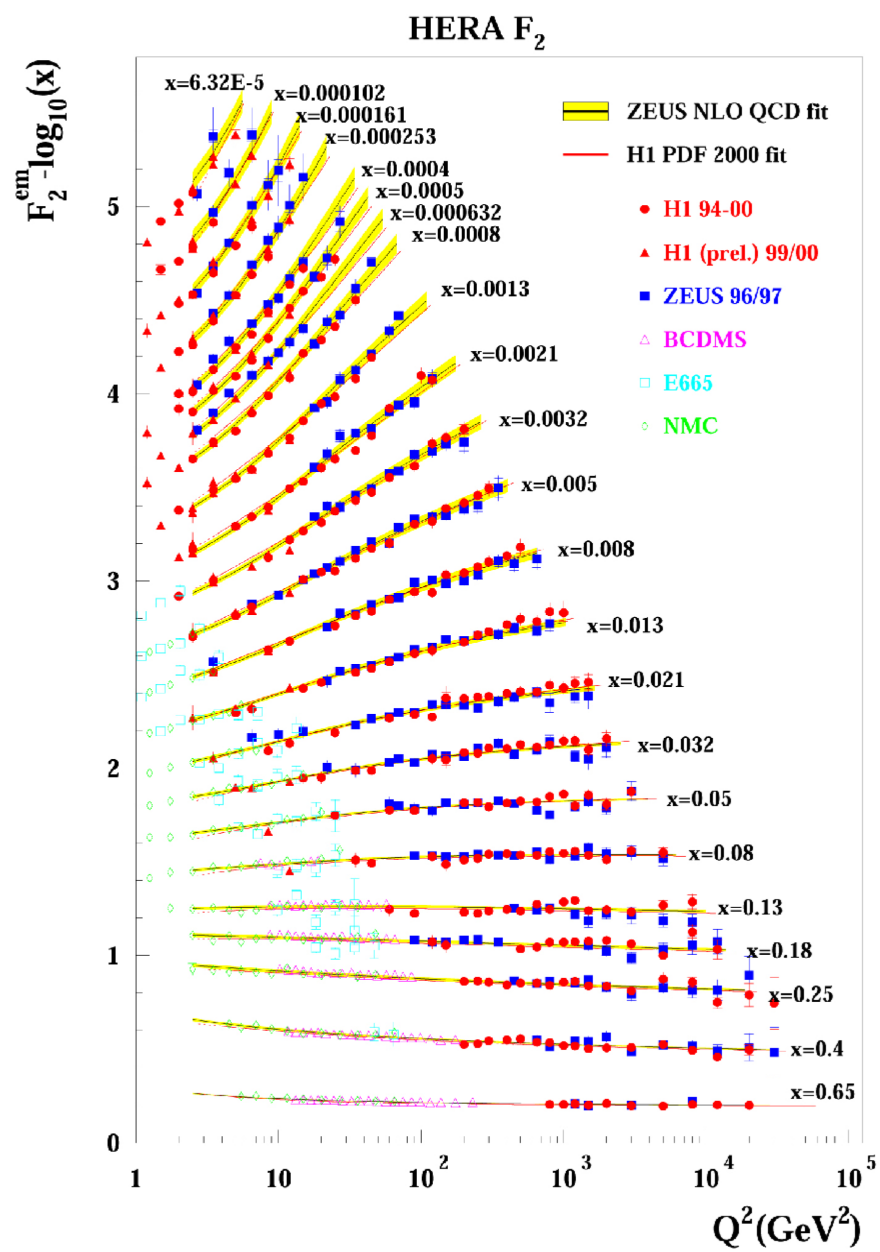
Proton Structure

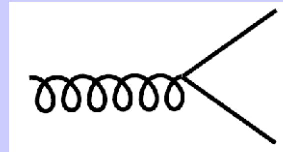


HERA data show a rising number of quarks & gluons with small momentum fractions x

Number increases as Q^2 increases

Proton Structure



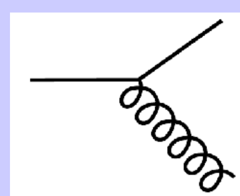


Low x: gluon splitting

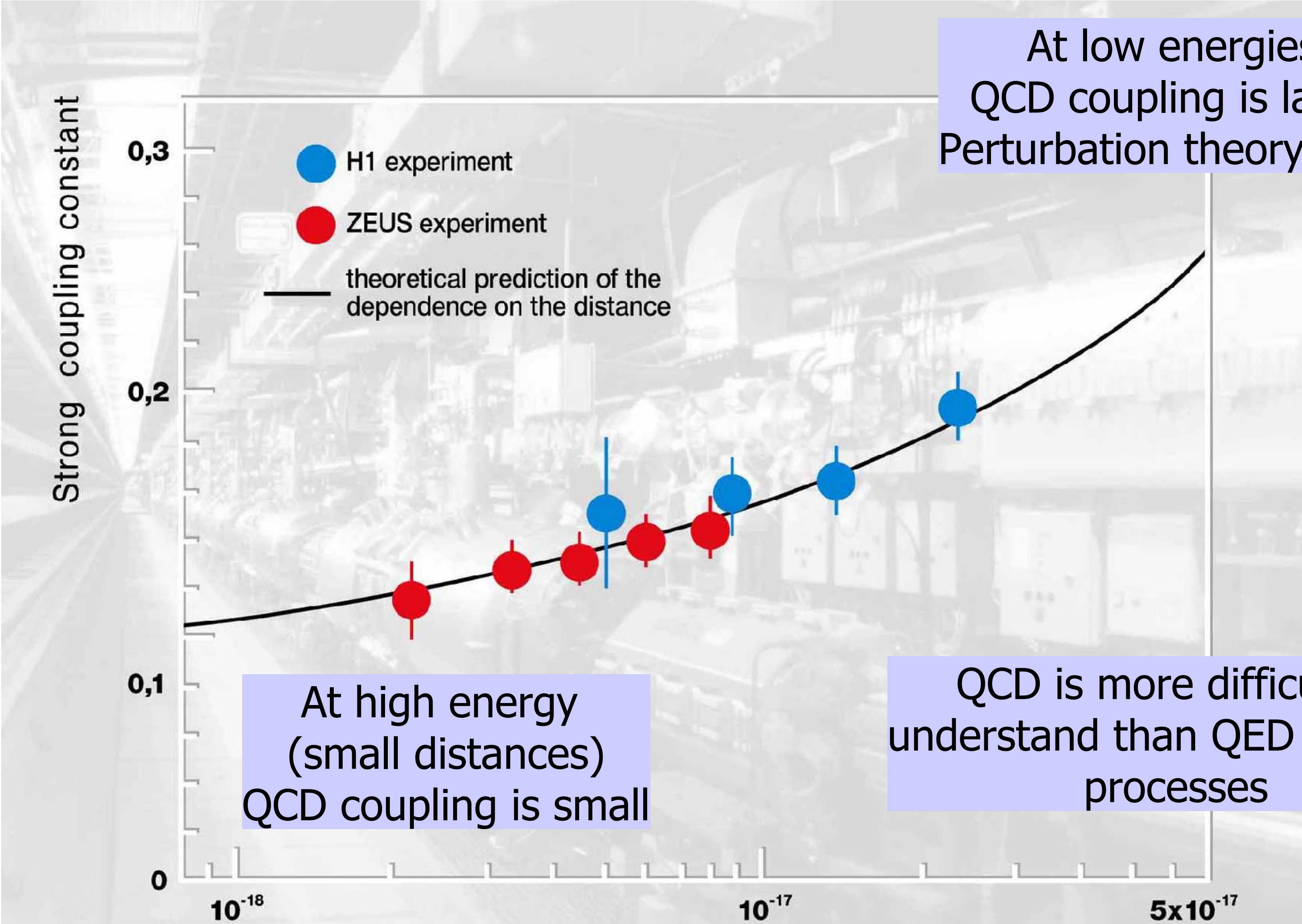
At low x the proton is exploding with particles!

Measurements well described by QCD theory

HERA has given us a precise map of the proton - a good understanding of QCD



High x: gluon emission



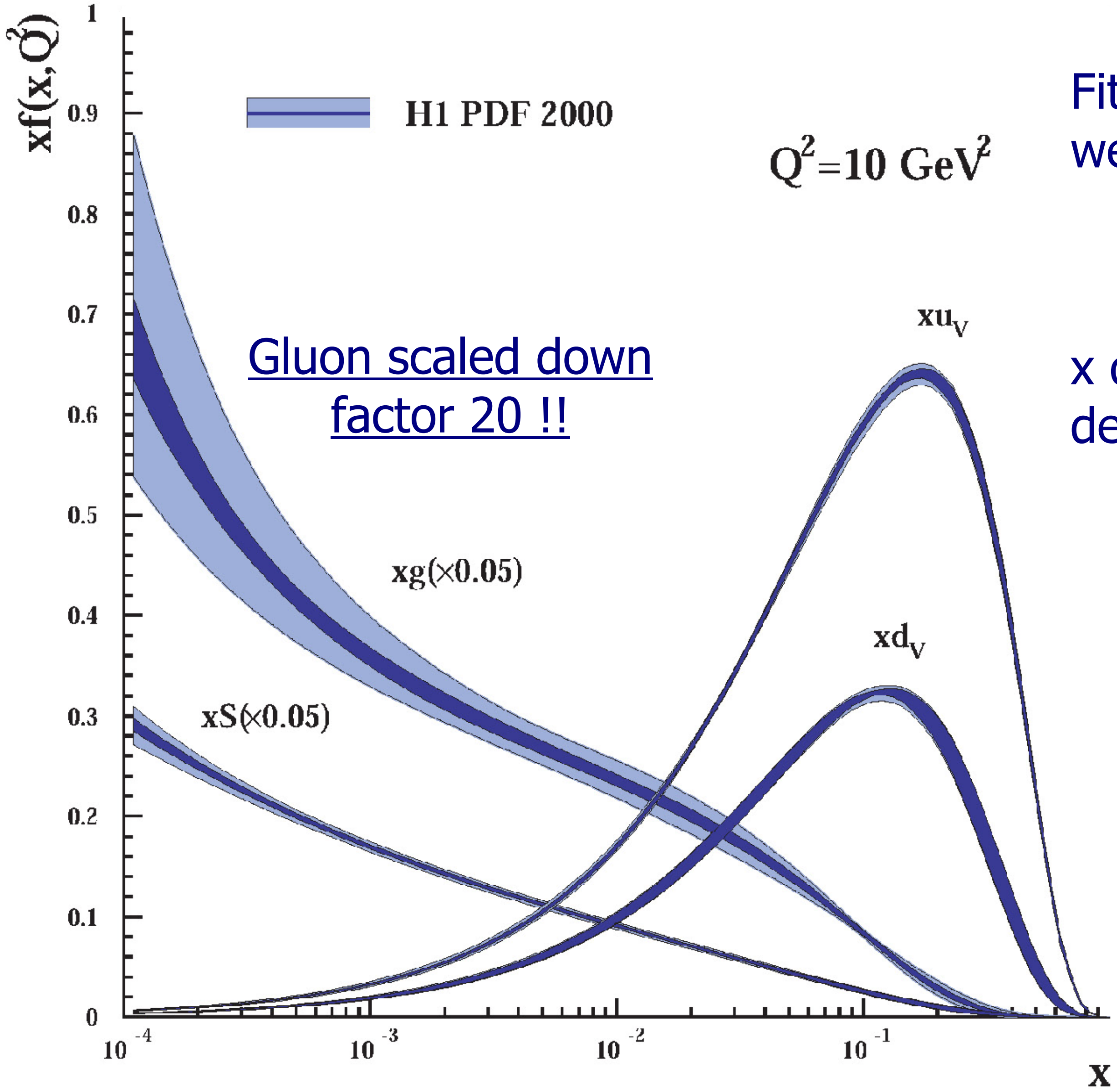
← Energy

Distance in meter →

At low energies
QCD coupling is large
Perturbation theory fails!

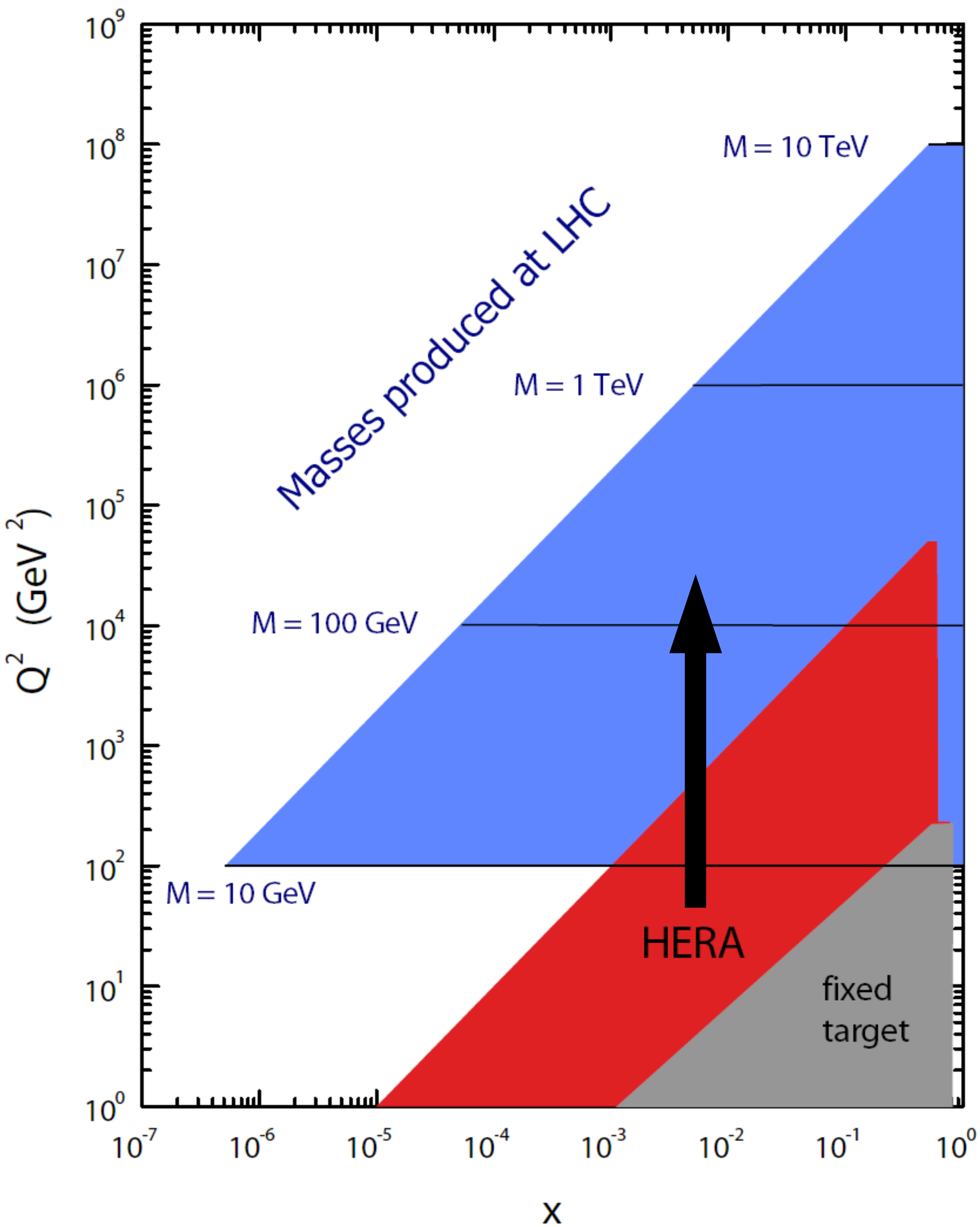
At high energy
(small distances)
QCD coupling is small

QCD is more difficult to understand than QED or Weak processes



Fit data: extract momentum weighted quark / gluon distributions

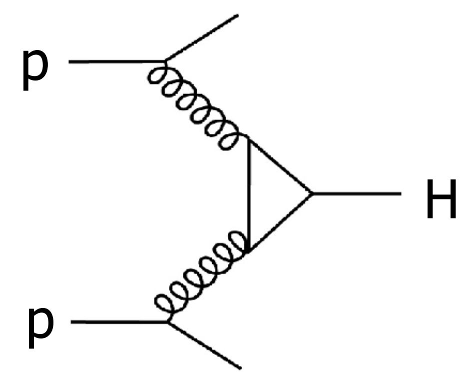
x dependence can only be determined from data



Large Hadron Collider: next generation proton accelerator being built in Geneva

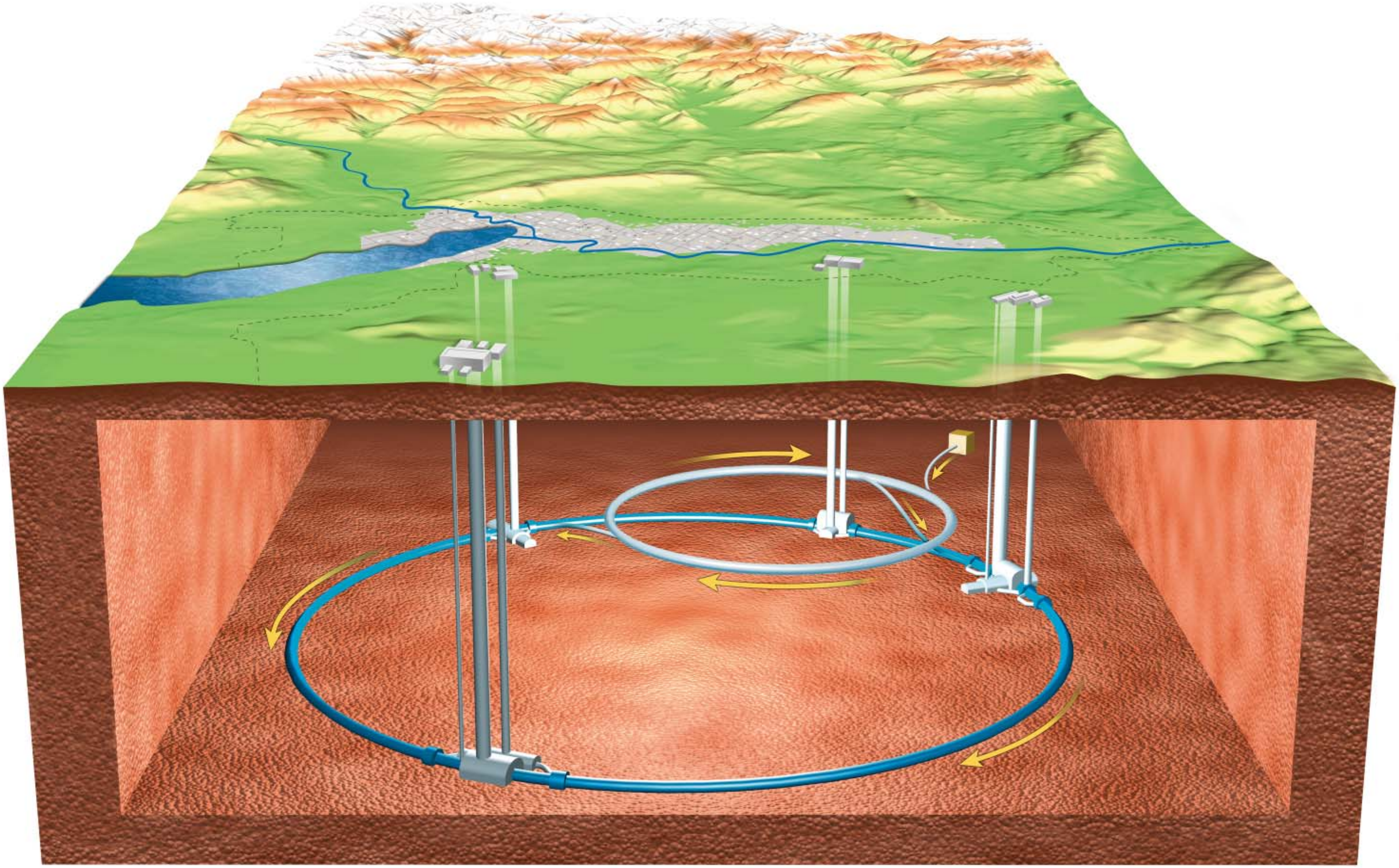
HERA densities extrapolate into LHC region

LHC = gluon collider



HERA data crucial in calculations of new physics & measurements at LHC

The Large Hadron Collider



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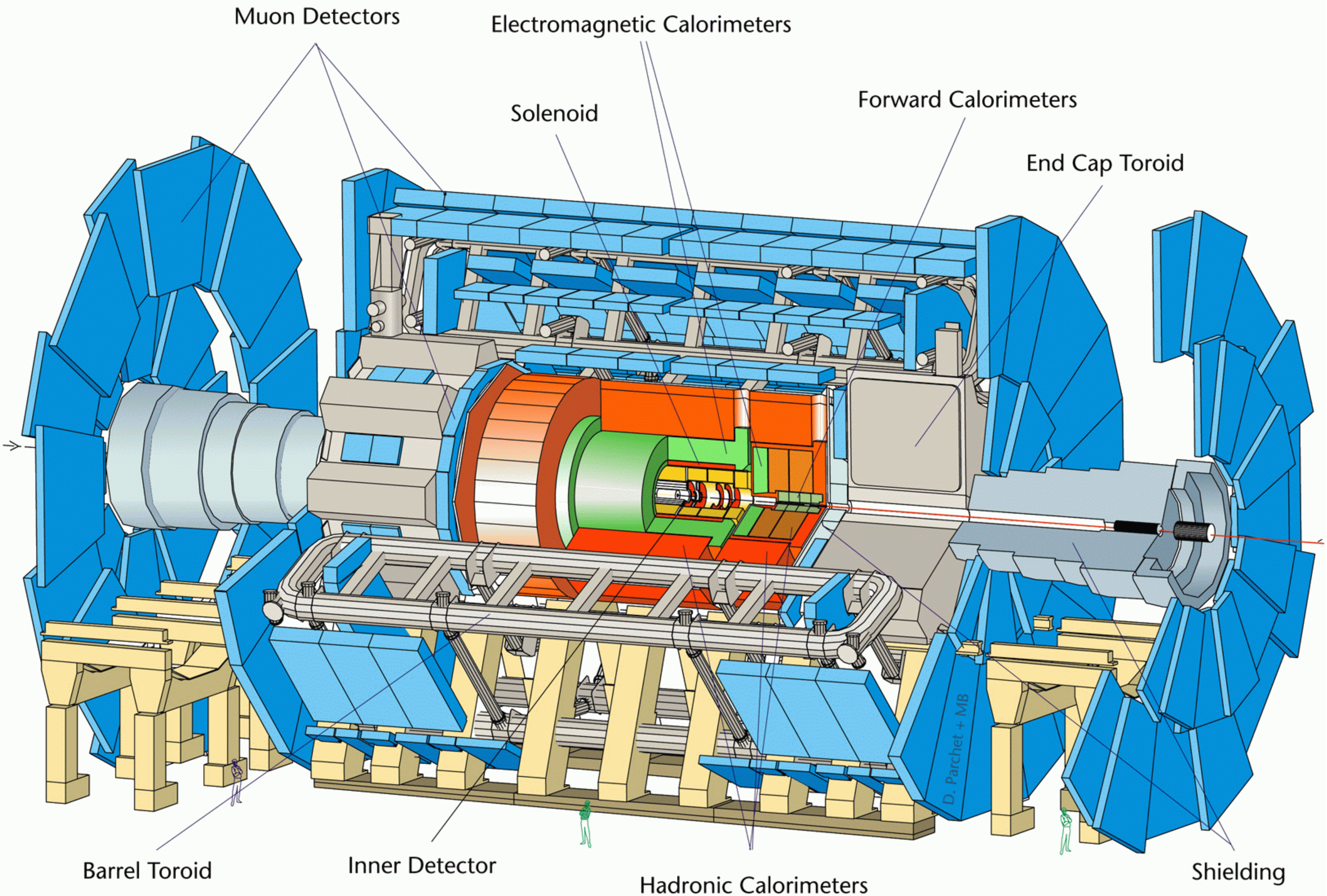
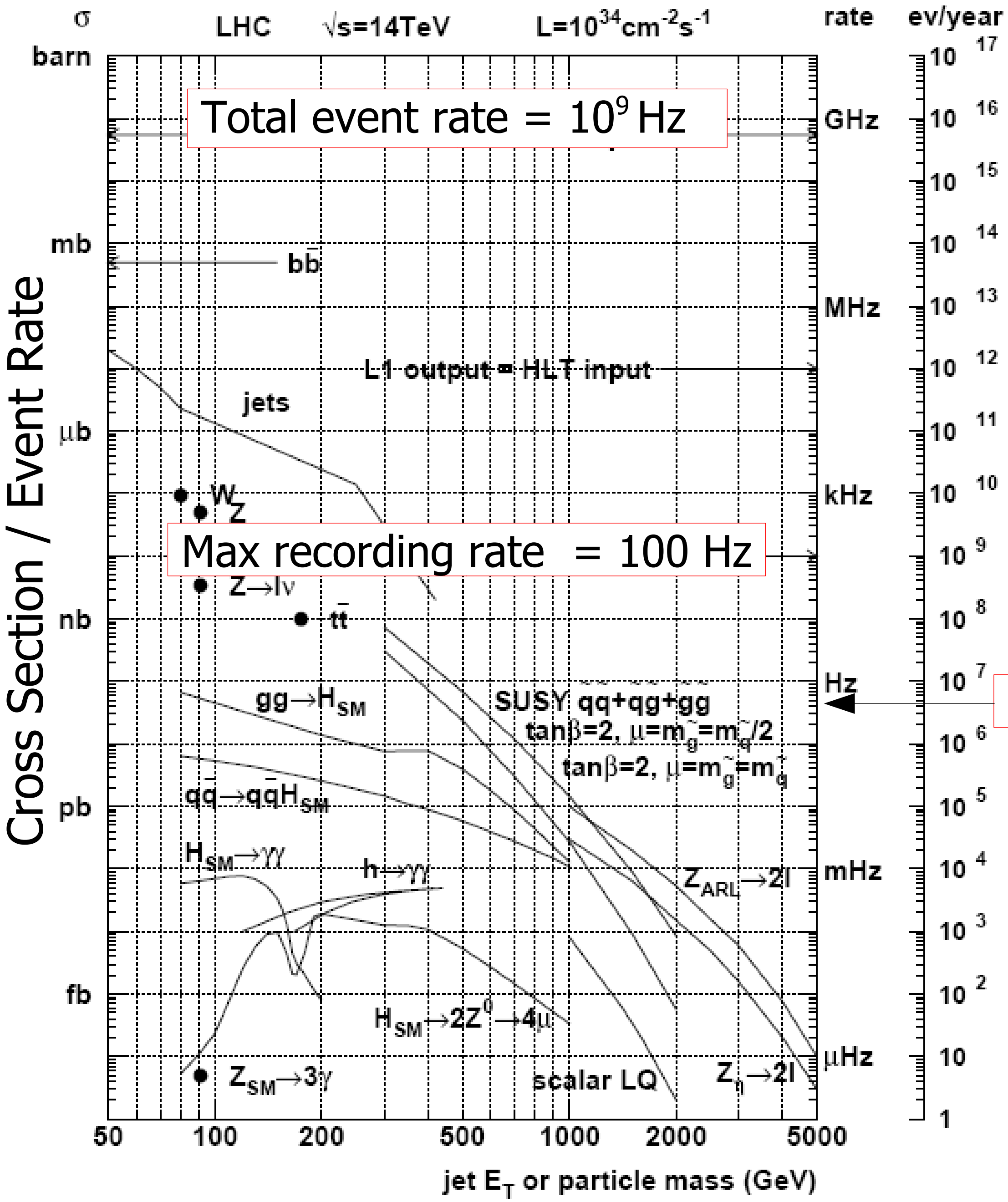
The ATLAS Experiment



LHC will collide protons at 7 TeV (7000 GeV)
27 km circumference ring
1200 superconducting dipole magnets ~ 9 T field
3000 tons of magnets supercooled to 1.9K
Each beam has energy equivalent to 100 kph Eurostar train
Proton bunches collide in bunches every 25 ns
Beams have transverse size ~15 μm (human hair ~20 μm)
20 interactions every bunch crossing
Particles from one collision still travelling when next collision occurs!
One of the largest scientific / technological projects ever undertaken

> 10^8 electronic channels
8×10^8 proton-proton interactions/second
2×10^{-4} Higgs per second
10 Petabytes of data a year
(10 Million GBytes = 14 Million CDs)



Rate of 100 GeV Higgs production

Huge event rates

New physics swamped!

Need to filter events 1:10^7 online

Like trying to find a cheap plumber from entire human population in 2 μs

What are we looking for?

Almost all the visible mass of universe is due to massless QCD effects
Energy associated with quark and gluon interactions $\rightarrow$ proton & neutron mass

Higgs particle postulated to explain masses of fundamental particles

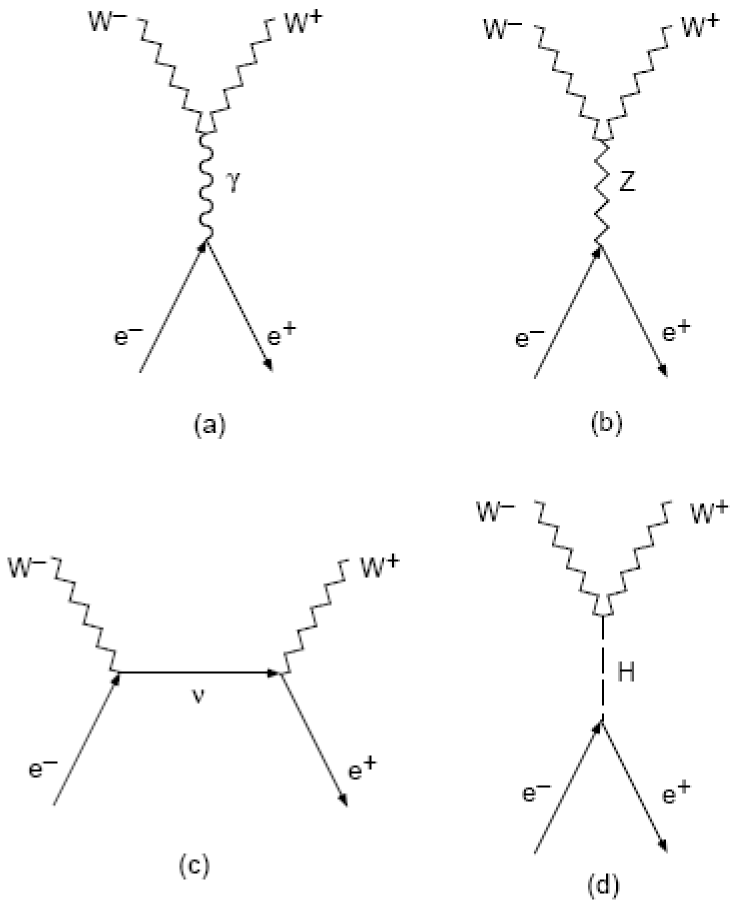
Gauge theory predicts force carrier particles to be massless e.g. photon & gluon
But $W^{\pm}$ & Z^0 boson have large masses ~80-90 GeV (proton~1 GeV)

Higgs properties are well known except its mass!

Direct searches: m_H>114 GeV

Examine energy dependence of scattering processes
Process (a) and (b) are well behaved as energy increases
Process (c) becomes larger than total e^+e^- cross section! (unitarity is violated)

Higgs-like particle is <u>needed</u> to cancel $e^+e^- \rightarrow W^+W^-$ scattering divergences



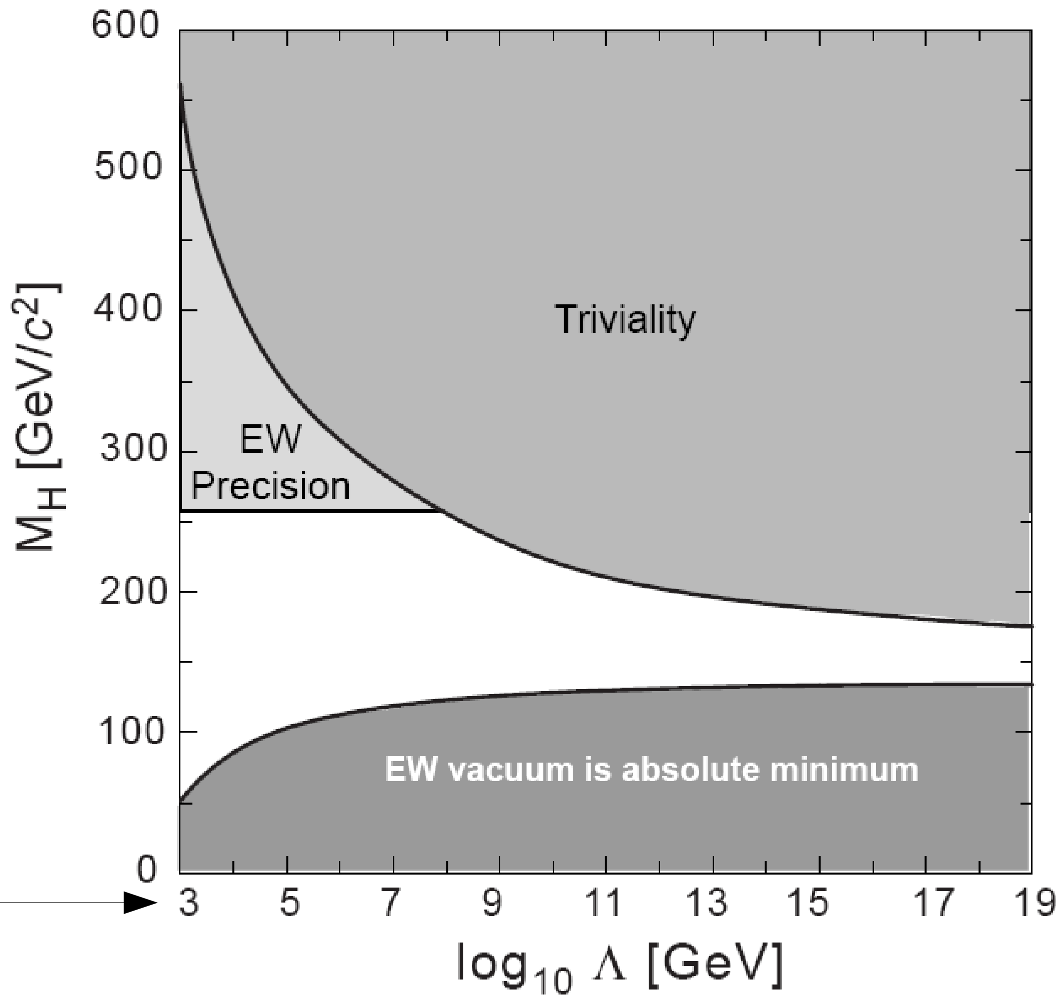
Requires Standard Model Higgs to be <~1TeV

If Standard Model is correct we will find the Higgs at the LHC!

If Standard Model is wrong some new particle must do this job

win-win situation!

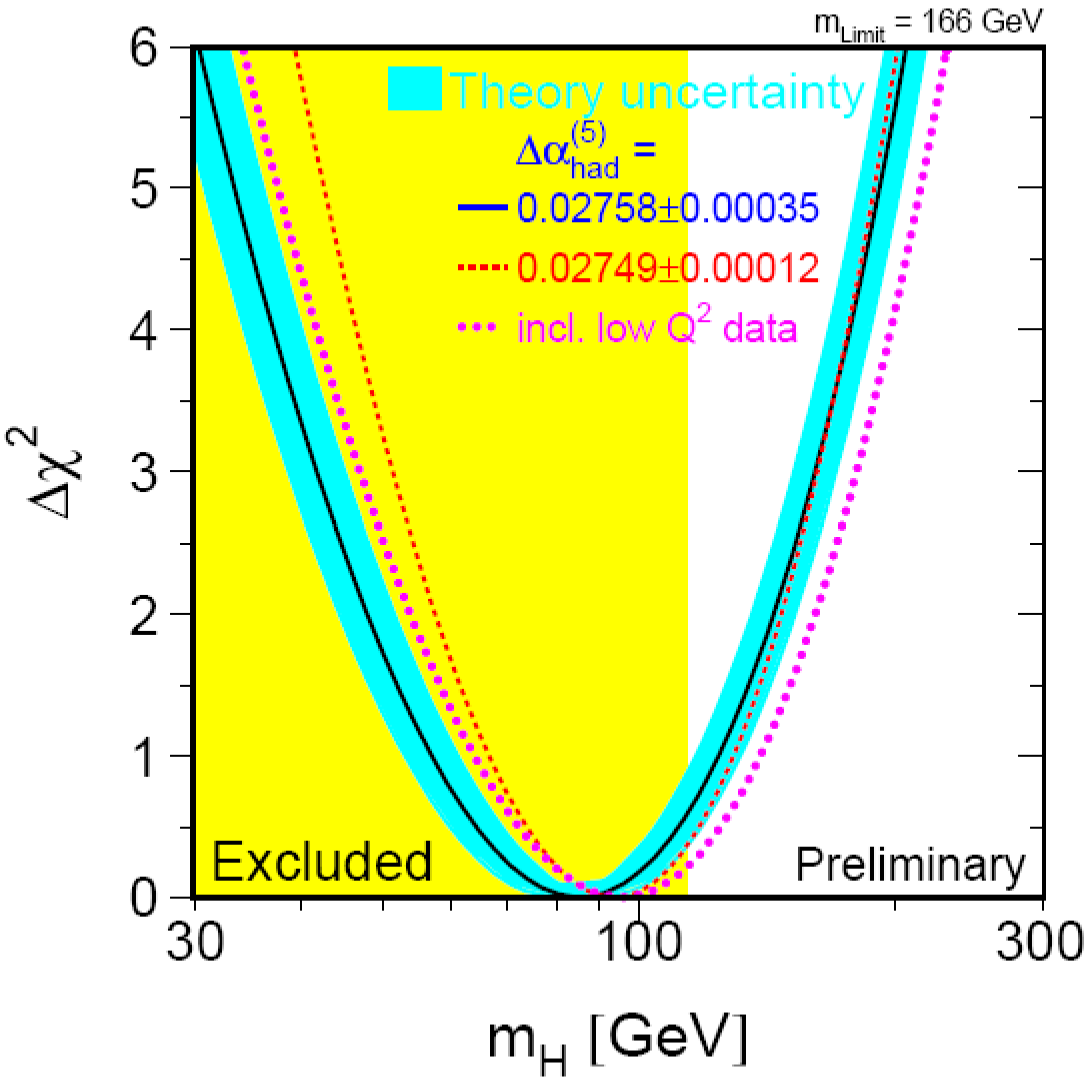
Even if Standrad Model Higgs doesn't exist, a Higgs-like particle must!
Place bounds on mass of Higgs-like particle by requiring self consistency of theory



1 TeV → 3 ← 10^{19} GeV !!!

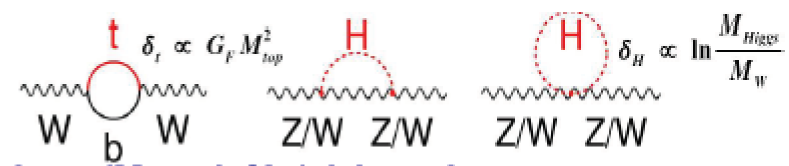
Energy scale at which new physics appears

But we should have already seen it!



Precise measurements at low energy are sensitive to Higgs loops

Perturbations on a perturbation!



Measurements at E < m_H are logarithmically sensitive to m_H

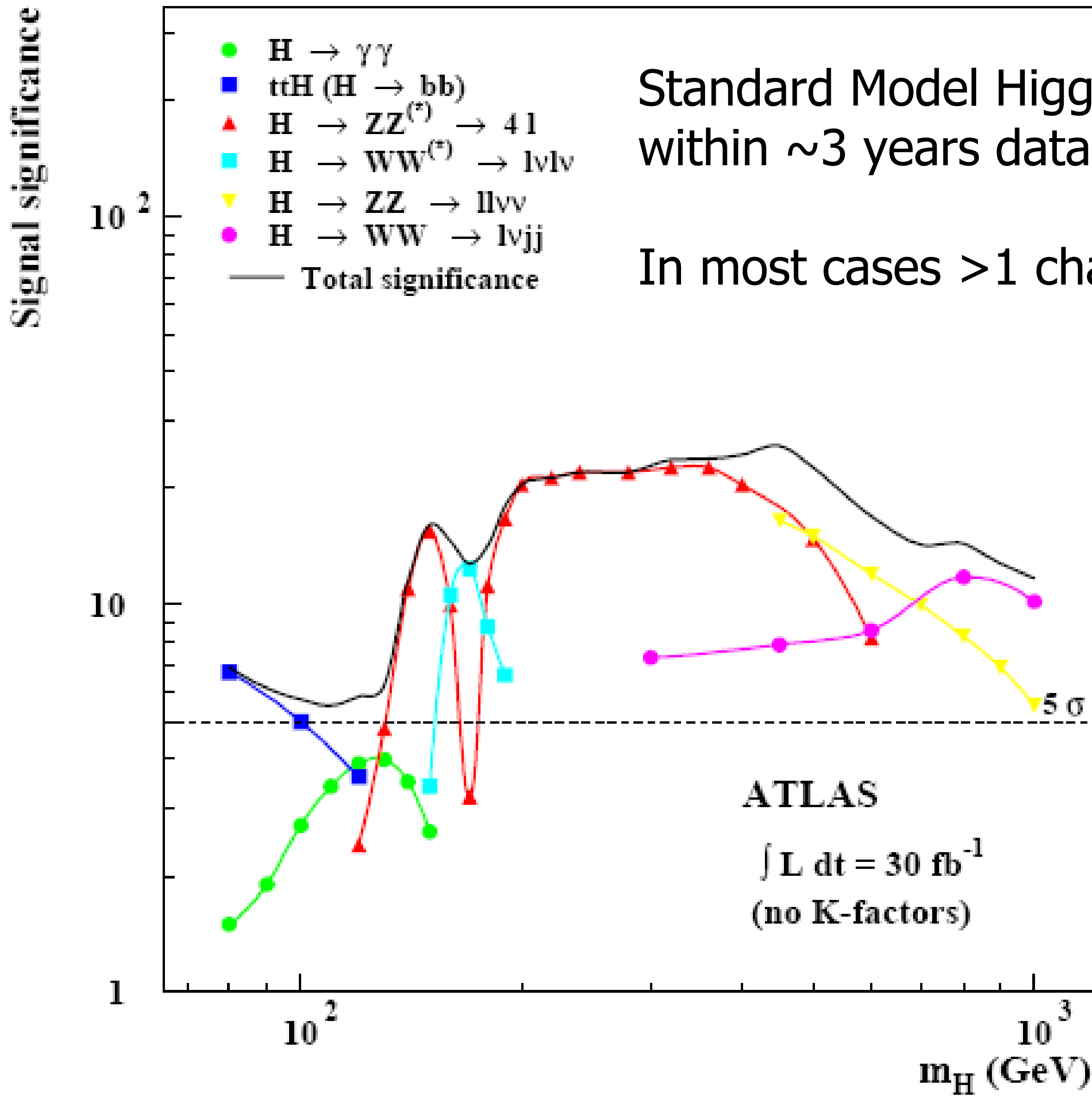
Confront data & theory: χ^2 test

Indicates light Higgs !

68% prob of SM Higgs in range 85^{+39}_{-28} GeV

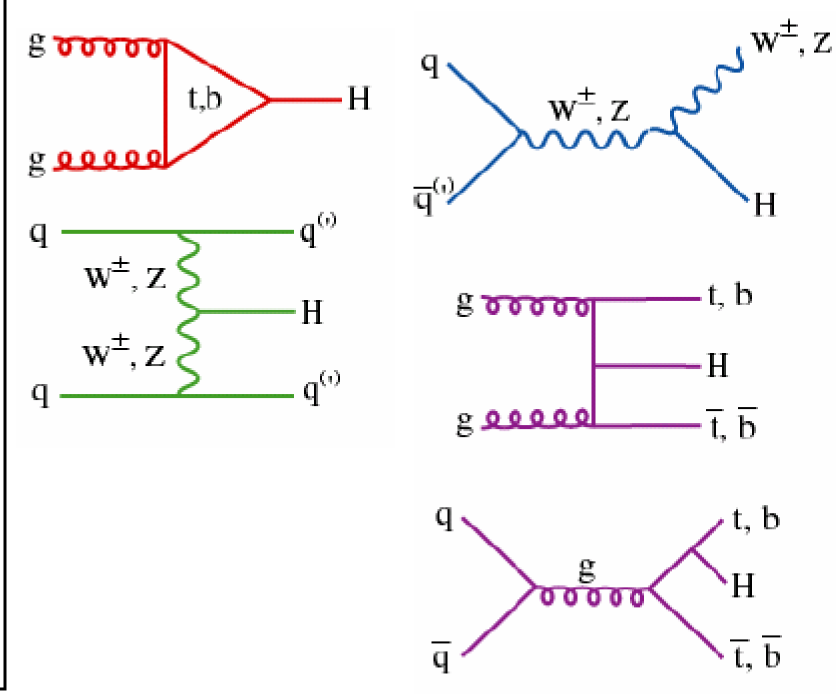
95% prob of SM Higgs < 166 GeV

Liklihood of NOT being a statistical fluctuation vs Higgs mass



Standard Model Higgs discovered over full mass range within ~3 years data taking

In most cases >1 channel for discovery



What are the alternatives to the Standard Model?

Best bet is Supersymmetry (SUSY)

Theoretically elegant - extends symmetry ideas of the Standard Model
Invokes a symmetry between fermions and bosons
(integer and half integer spin particles)

Immediately double number of particles
Each SM particle has a superpartner sparticle

quarks (spin ½)	↔	squarks (spin 0)
leptons (spin ½)	↔	sleptons (spin 0)
photon (spin 1)	↔	photino (spin ½)
W,Z (spin 1)	↔	Wino, Zino (spin ½)
Higgs (spin 0)	↔	Higgsino (spin ½)

None of these has been observed
105 new parameters required by theory - So why bother??

- Naturally extends to quantum gravity
- Provides a candidate for dark matter
- SUSY solves hierarchy problem
- Brings about GUT unification of couplings
- Some general assumptions can reduce parameters to 5

What are GUTs?

Grand unified theories: quantum gravity

Expect this to occur at energy scales when couplings reach strength of gravity

Construct a quantity with dimensions of energy or length from constants of relativity, quantum mechanics & gravity: c, ħ, G

$$E_{planck} = \sqrt{\frac{\hbar c}{G}} = 10^{19} \text{ GeV} \qquad L_{planck} = \sqrt{\frac{G\hbar}{c^3}} = 10^{-35} \text{ m}$$

Dark Matter Candidates

Astronomical observation show that ~25% of universe is dark matter

It should be cold (i.e. non-relativistic) and stable (does not decay)

Must be non-charged (or will interact with photons)

Must be only weakly interacting

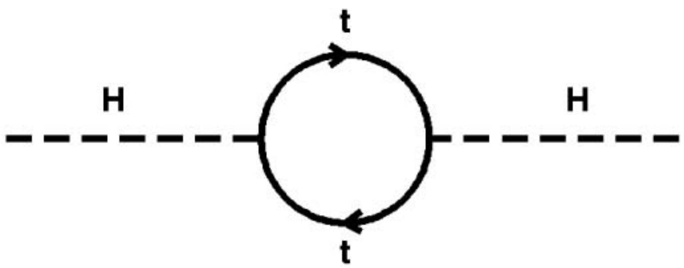
Cannot be neutrons - free neutrons decay

Cannot be neutrinos - mass too small

The lightest SUSY particle (LSP) is a prime dark matter candidate!

Hierarchy Problem

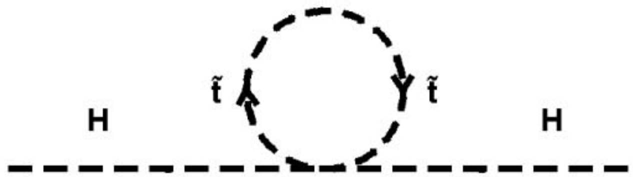
Why is Higgs mass (~1 TeV) so much smaller than the Planck scale (10^{19} GeV)?
Such calculations need to take account virtual fluctuations



Higgs interacts with all spin ½ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections are quadratically divergent upto 10^{19} GeV
If SM valid upto Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
<u>Seems</u> unnatural
Only a problem for the Higgs (only SM particle with spin 0)

New SUSY sparticles (e.g. stop squark) contribute and cancel identically

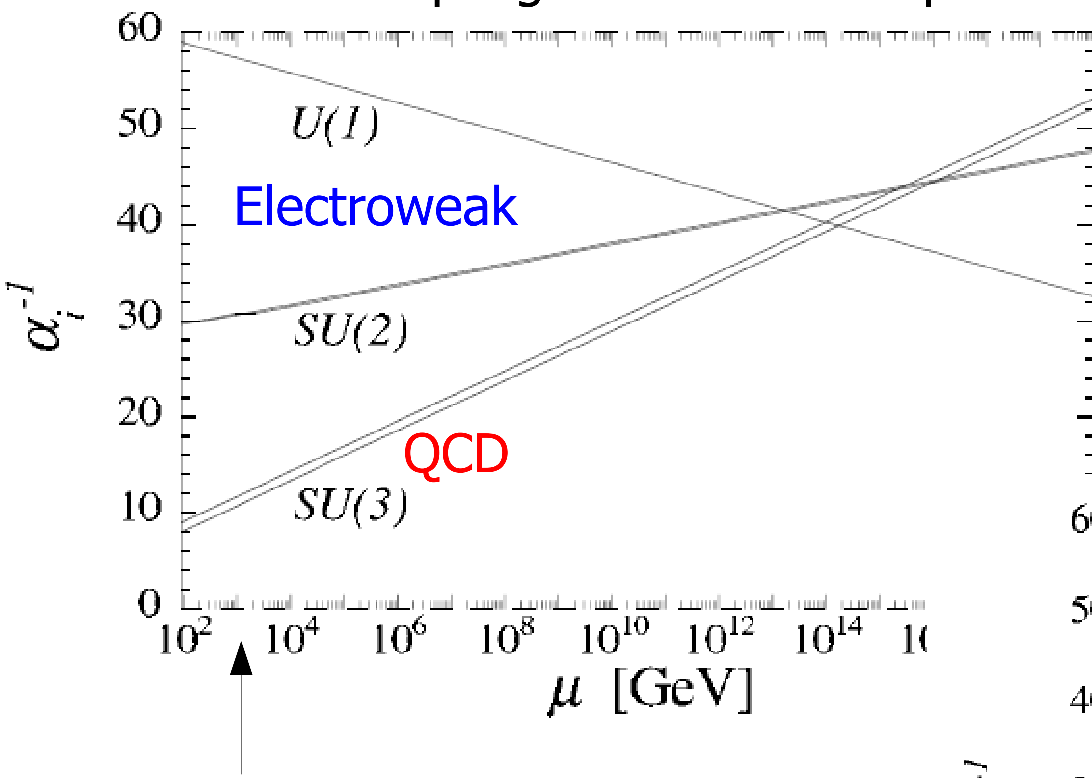


Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

GUT Unification

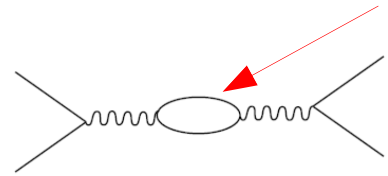
Another of SUSYs charms:

Coupling constants extrapolated to Planck scale do not intersect

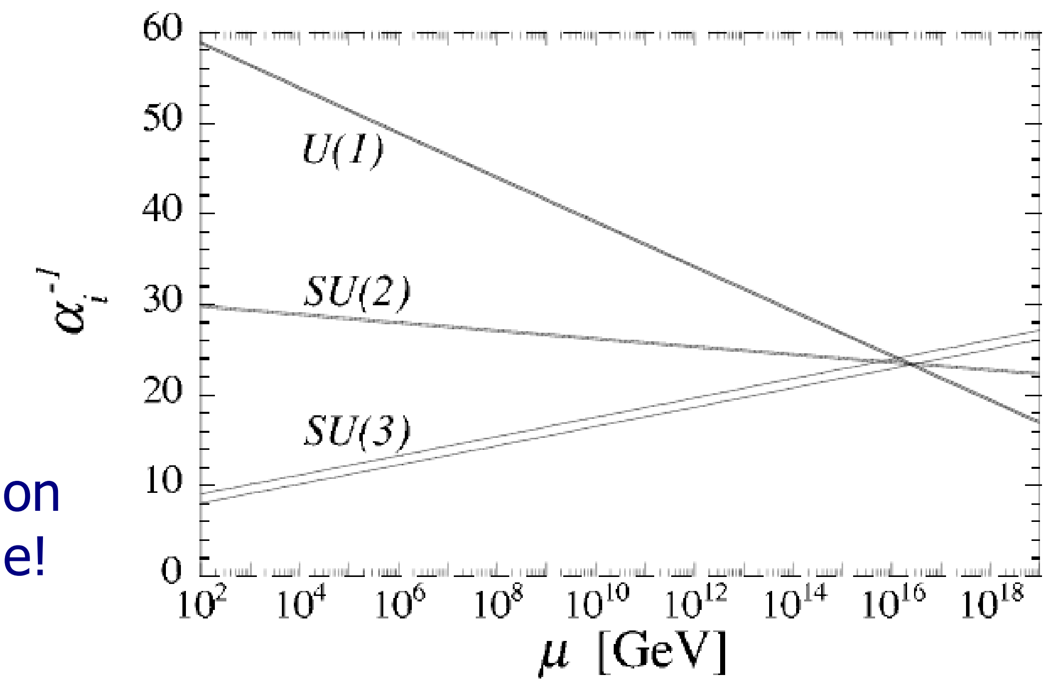


Current measurements

16 orders of magnitude extrapolation!
Involves including all particle loops



New SUSY particles = different loops
= different extrapolation



Incorporating SUSY into extrapolation
brings unification below Planck scale!

Quantum Gravity

Supersymmetry is a particular form of string theory
String theory aims to describe physics of Planck scale - domain of quantum gravity
Impossible to reach in any collider!

Some quantum gravity theories line in 10 or 11 dimesional space!
- predict gravitons propagate in extra dimensions size of Planck length
- (graviton = postulated force carrier of gravity)

Explains why gravity is 10^{23} times weaker than Weak force - gravity is diluted

But: If extra dimensions large (~0.1mm) quantum gravity could be seen at TeV scale
Gravity has never been tested at such short distances!
LHC could open the possibility of creating mini-black holes & gravitons
- laboratory for testing quantum gravity!!!

Mini black holes will evaporate via Hawking radiation
- experimentally look for particle decays with Black Body spectrum at Hawking Temp

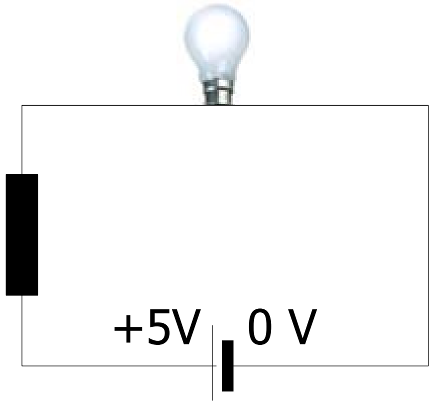
$$T \approx \frac{(n+1)}{4\pi R}$$

n = number of extra dimensions
R = radius of compacted dimension

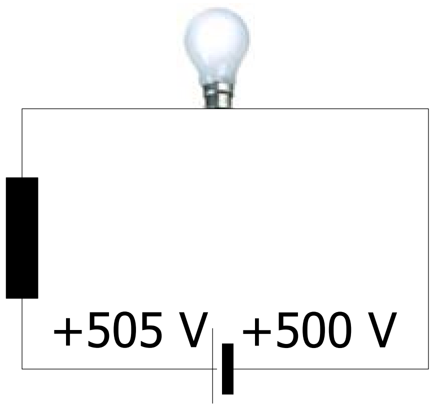
Summary

We're living in exciting times
Discovery potential of the LHC is huge
- Higgs discovery
- physics of b quarks
- supersymmetry
- new phases of matter
- quantum gravity
- precision measurement of EW sector
- ...something we haven't thought of yet

Lots of work to be done in next few years!



A gauge transformation is one in which a symmetry transformation leaves the physics unchanged



Both circuits behave identically
Circuit is only sensitive to potential differences
Change the ground potential of the earth and see no difference!
Leads to concept of charge conservation

In electromagnetism we are insensitive to phase α of EM radiation
Could globally change the phase at all points in universe: no difference
global gauge transformation
What happens if we demand local phase transformations? $\alpha \to \alpha(x,t)$

If we demand local phase invariance AND consistent physics then we must alter Maxwells equations

The alterations required to accommodate these changes introduce a new field
- interaction of charged particle with an EM field - the photon!

This can be applied to many situations:
local gauge invariance introduces new fields & particles:

Electromagnetism	photon
Quantum chromodynamics	gluons
Weak force	$W^{\pm}$ and Z^0

Intimately related to symmetries and conservation laws